

# What does the PIN model identify as private information?

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April 29<sup>th</sup>, 2016

## Abstract

We investigate whether the Easley and O'Hara (1987) PIN model's recently documented failure to identify private information arises from the model's inability to describe the data or from the model's reliance on order flows alone. We find that the PIN model mistakenly identifies private information from turnover because it is unable to describe the order flow data. We propose a model that addresses this shortcoming but also depends on order flow alone. We find that the extended model does not perform as well as the Odders-White and Ready (2008) model, which relies on both returns and order flow.

*Keywords:* Liquidity; Information Asymmetry

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\*We thank Torben Andersen, Kerry Back, Pierre Collin-Dufresne, Kevin Crotty, Zhi Da, Robert Engle, Gustavo Grullon, Terry Hendershott, Sahn-Wook Huh, Jyri Kinnunen, Pete Kyle, Yelena Larkin, Avi Wohl and seminar participants at the 2015 ITAM Conference, 2015 Annual SoFiE Conference, 2015 Annual MFS Conference, 2015 CICF, 2016 AFA Conference, Rice University, Texas A&M University, and University of Virginia (McIntire) for helpful comments. We thank Bei Dong, Edward X. Li, K. Ramesh, and Min Shen for earnings announcements time stamp data. We thank Elaine Brewer, Frank Gonzalez, Judy Hua, and Edward Martinez for computational support. Duarte and Hu are with the Jesse H. Jones School of Business at Rice University. Young is with the Michael G. Foster School of Business at the University of Washington. E-mails: jefferson.duarte@rice.edu (Duarte), eh7@rice.edu (Hu), and youngla@u.washington.edu (Young).

The Probability of Informed Trade (PIN) model, developed in a series of seminal papers including Easley and O’Hara (1987), Easley, Kiefer, O’Hara, and Paperman (1996), and Easley, Kiefer, and O’Hara (1997) has been used extensively in accounting, corporate finance and asset pricing literature as a measure of information asymmetry.<sup>1</sup> The PIN model is based on the notion, originally developed by Glosten and Milgrom (1985), that periods of informed trade can be identified by abnormally large order flow imbalances.<sup>2</sup> Recently, however, several papers have documented PIN anomalies where *PIN*s tend to be at their lowest when information asymmetry should be at its highest (e.g. Aktas, de Bodt, Declerck, and Van Oppens (2007), Benos and Jochev (2007), and Collin-Dufresne and Fos (2014a)).

We address two research questions in this paper. First, we analyze whether *PIN* mis-identifies private information because the underlying model does not fit the order flow data well. Second, the classic microstructure theories (e.g. Glosten and Milgrom (1985), and Kyle (1985)) suggest that order flow imbalances as well as variables such as prices and spreads are related to the arrival of private information. The PIN model, on the other hand, focuses solely on the response of order flow imbalance to the arrival of private information, ignoring the price response mechanisms that are described in the classic microstructure literature. We therefore analyze the extent to which including the price response mechanism is necessary to empirically identify private information arrival. The answers to these research questions are important because they imply very different agendas for this growing area of research. Specifically, if *PIN* mis-identifies private information because the model does not fit the order flow data well, then the PIN model could be extended in such a way that it still relies on order flow alone, but no longer mis-identifies private information. On the other hand, if *PIN* cannot identify private information because it ignores the price response mechanism then a different approach involving variables other than order flow is necessary to generate useful inferences about the arrival of informed trade.

To address these two research questions, we create a variable called the Conditional

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<sup>1</sup>A Google scholar search reveals that this series of PIN papers has been cited more than 3,500 times as of this writing. Examples of papers that use PIN in the finance and accounting literature include Duarte, Han, Harford, and Young (2008), Bakke and Whited (2010), Da, Gao, and Jagannathan (2011), and Akins, Ng, and Verdi (2012).

<sup>2</sup>Following the literature we define order flow imbalance as the difference between the number of buyer initiated trades less the number of seller initiated trades. In what follows, we refer to buyer initiated trades as ‘buys’, seller initiated trades as ‘sells’, and turnover as the number of buys plus sells.

Probability of an Information Event (*CPIE*). To compute the *CPIE* implied by the PIN model ( $CPIE_{PIN}$ ), we estimate the PIN model’s parameters using an entire year of data, and then use the observed market data (i.e. buys and sells) to estimate the posterior or model-implied probability of an information event for each day in our sample. We then turn to our first question and examine whether observed variation in  $CPIE_{PIN}$  is consistent with the theory underlying the PIN model. Under the PIN model, private information is identified solely from the absolute order imbalance. In practice, however, the PIN model may be a poor description of the data and model misspecification can affect the way it actually identifies private information. To test this hypothesis, we regress  $CPIE_{PIN}$  for each firm-year on absolute order imbalance, turnover, and their squared terms.

We find that the PIN model primarily identifies information events based on turnover, controlling for absolute order flow imbalance. This is inconsistent with the underlying microstructure assumptions of the model. In regressions of  $CPIE_{PIN}$  on absolute order imbalance, turnover, and their squared terms, turnover and turnover squared account for, on average, around 65% of the overall  $R^2$ . The identification of information events through turnover becomes more pronounced late in the sample with the increase in both the level and variance of turnover.<sup>3</sup> For example, for the median stock after 2002, the PIN model is essentially equivalent to a naïve model that sets the probability of a private information event equal to one on any day with turnover larger than the annual mean of daily turnover and zero otherwise. Two limitations of the PIN model combine to create this problem. First, under the PIN model, increases in expected turnover can only come about through the arrival of private information. Second, the PIN model’s restrictive distributional assumptions make it difficult for the model to match both the mean and the variance of turnover. As a result of these limitations, when confronted with actual data the model mechanically interprets periods of above average turnover as periods of private information arrival.

To show that this conflation of turnover with private information is related to the previous critiques of *PIN*, we examine an event study similar in spirit to the documented PIN anomalies. For instance, Benos and Jochev (2007) find that *PIN* is higher after earnings

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<sup>3</sup>Duarte and Young (2009) propose an extension of the PIN model that accounts for the positive correlation between buys and sells and thus improves the fit of the model. We show in Internet Appendix A that Duarte and Young (2009) model also performs poorly late in the sample.

announcements than before.<sup>4</sup> In a similar vein, we examine how well the PIN model identifies information events around earnings announcements. In contrast to Benos and Jochev (2007) however, we use  $CPIE_{PIN}$  to conduct this event study instead of  $PIN$ . There is a large literature (see Bamber, Barron, and Stevens (2011) for a review) that shows that turnover is substantially higher around earnings announcements and typically remains high for a considerable period after the announcement. Since our concern here is the PIN model’s ability to separate turnover shocks from information events, earnings announcements provide a good opportunity to examine the model’s performance and allows us to connect our results with those in previous studies. As in our full-sample regressions, our event study shows that  $CPIE_{PIN}$  is higher after announcements simply due to the higher levels of turnover in the post-announcement periods.

This mechanical conflation of increases in turnover with the arrival of private information in the PIN model is a problem because it implies that the most popular measure of private information in the literature,  $PIN$ , does not actually capture its variable of interest. There is no theoretical reason why turnover should be mechanically associated with the arrival of private information, once we control for order imbalance. On one hand, trading by informed traders may increase turnover. On the other hand, liquidity traders may postpone trading when the arrival of private information is likely leading to a negative relation between turnover and private information (e.g. Chae (2005)). Moreover, a model that naively associates turnover with private information arrival ignores the fact that turnover varies for reasons unrelated to private information. For instance, turnover can increase with disagreement (e.g. Kandel and Pearson (1995), and Banerjee and Kremer (2010)). Turnover is also subject to calendar effects because traders coordinate trade on certain days to reduce trading costs (Admati and Pfleiderer (1988)). Furthermore, turnover can vary due to portfolio rebalancing (Lo and Wang (2000)) and taxation reasons (Lakonishok and Smidt (1986)).<sup>5</sup> Hence, the PIN model (and the  $PIN$  measure) groups all sources of variation in turnover (e.g. disagreement, calen-

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<sup>4</sup>In addition, Aktas, de Bodt, Declerck, and Van Oppens (2007) find that  $PIN$  is higher after merger announcements than before.

<sup>5</sup>The literature also suggests that turnover after earnings announcements can remain high for many reasons unrelated to the arrival of private information. For instance, traditionally, the literature attributes high turnover after announcements to disagreement (e.g. Bamber, Barron, and Stevens (2011)). Karpoff (1986) suggests that high turnover after earnings announcements may also be due to divergent prior expectations, while Frazzini and Lamont (2007) attribute to small investors’ lack of attention.

dar effects, portfolio rebalancing, taxation, etc.) under the umbrella of private information arrival.

Having demonstrated that the PIN model essentially treats all shocks to turnover as private information because it fits the data so poorly, we turn to our second research question. Namely we analyze the extent to which a model that includes the price response mechanism generates better inferences about the arrival of informed trade than a model based on order flow alone. To do so, we compare an extension of the PIN model (the EPIN model) with the model developed by Odders-White and Ready (2008) (the OWR model). The EPIN model is based on the same information structure as the PIN model. The key difference is that the EPIN model fixes the PIN model's mechanical conflation of turnover and private information arrival. In contrast to the PIN and EPIN models, the OWR model is based on Kyle (1985) and uses intraday as well as overnight returns, along with order imbalance, to identify private information events.

We use the EPIN and OWR *CPIEs* ( $CPIE_{EPIN}$  and  $CPIE_{OWR}$ ) to compare the models in three different ways.<sup>6</sup> First, under the assumption that private information should arrive prior to earnings announcements, rather than after the announcement, we expect that if a model correctly identifies informed trade, its *CPIE* will increase prior to the announcement. We also anticipate that informed trading, and hence *CPIEs*, will decline rapidly after the announcement, when investors have the same (now public) information.<sup>7</sup> Second, we follow Cohen, Malloy, and Pomorski (2012) and identify instances of opportunistic insider trades. If either of the models can successfully detect opportunistic insider trading, then its *CPIE* should increase around these trades. Third, it has long been recognized in the literature (e.g. Hasbrouck (1988, 1991a,b)) that non-information related price changes (e.g. dealer inventory control) should be subsequently reversed, while information related trades should not. Therefore, if a model correctly identifies the arrival of private information, we expect that increases in its *CPIE* should be associated with smaller future price reversals. Each of

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<sup>6</sup>While the PIN and EPIN models allow for a calculation of the probability of informed trade, the OWR model does not. However, all three models have a parameter that controls the unconditional probability of an information event on a given day ( $\alpha$ ) and allow for the calculation of *CPIE*.

<sup>7</sup>There is considerable evidence suggesting the possibility of high asymmetric information prior to important announcements. See for example Brooks (1996), Meulbroek (1992) Christophe, Ferri, and Angel (2004), Amin and Lee (1997), Frazzini and Lamont (2007), and Hendershott, Livdan, and Schurhoff (2014).

these three methods of model comparison has its own unique limitations.<sup>8</sup> However, if all of these methods point to the same conclusions, it seems unlikely that our overall interpretation would be biased due to the limitations of any specific method.

In answer to our second question, we find that the OWR model performs better than the EPIN model in all three tests. Specifically, we find that the  $CPIE_{OWR}$  increases before earnings announcements and decreases rapidly after announcements, while  $CPIE_{EPIN}$  decreases before announcements.  $CPIE_{OWR}$  successfully predicts opportunistic insider trading and is strongly negatively associated with price reversals. In contrast,  $CPIE_{EPIN}$  is only weakly associated with opportunistic insider and price reversals.

We contribute to the literature because we show that private information measures based only on order flow (e.g.  $PIN$ ) perform much worse than those that include the price response mechanism, for instance the OWR's  $\alpha$ . The classic microstructure theories (e.g. Glosten and Milgrom (1985), and Kyle (1985)) describe a price response mechanism relating returns to the arrival of private information. Hence it is not surprising that a model that identifies the arrival of private information solely from order flow imbalance has worse performance than a model based on returns and order flows. However, it is perhaps surprising that the OWR model performs so much better than the EPIN model in all of our tests. This suggests that order flow, however well modeled, is insufficient to be the sole source of inferences about private information arrival. Therefore, despite the literature's strong interest in proxies of private information based on order flow alone (e.g. Easley, Kiefer, O'Hara, and Paperman (1996), Easley, Kiefer, and O'Hara (1997), and Duarte and Young (2009)) future research aimed at building measures of informed trade should also focus on variables such as prices and spreads as the classic theory suggests.

Our paper is also related to a growing literature that analyzes the extent to which  $PIN$  actually captures information asymmetry. Duarte and Young (2009) and Gan, Wei, and Johnstone (2014) show that the PIN model does not fit the order flow data well. We take these results one step further and show that *because* of this poor fit the PIN model mis-identifies the variable of interest—private information—from turnover. In addition, we extend the

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<sup>8</sup>For instance, it is possible that, for some reason, private information is more prevalent after important announcements than before.

PIN model to correct the mechanical conflation of turnover and private information arrival. This allows us to address whether order flow alone can capture private information arrival or whether we must incorporate the price response mechanism as in the OWR model. Many of the papers analyzing the  $PIN$  measure estimate  $PIN$ s around events and test whether  $PIN$  is higher before rather than after an announcement. These studies in general document that  $PIN$  is higher after announcements than before (i.e. PIN anomalies). For instance, Collin-Dufresne and Fos (2014a) find that  $PIN$  and other adverse selection measures are lower when Schedule 13D filers trade.<sup>9</sup> Easley, Engle, O’Hara, and Wu (2008) critique this line of research, noting that  $PIN$  is a stock characteristic rather than a measure of the extent to which private information is present in a given calendar time period.<sup>10</sup> To address this critique, Easley, Engle, O’Hara, and Wu (2008) develop an extension of the original model in which  $PIN$  is time-varying, and in a paper contemporaneous to ours, Brennan, Huh, and Subrahmanyam (2015) use conditional probabilities similar to  $CPIE_{PIN}$ . We contribute to this literature in two ways. First, our results indicate that these previously identified  $PIN$  anomalies are at least partially related to the strong connection between  $CPIE_{PIN}$  and turnover that we document. Second, we show that event studies that use daily measures of private information (e.g. Easley, Engle, O’Hara, and Wu (2008)) can be misleading if variation in these measures around event announcements is due to variables not necessarily related to information asymmetry. For instance, Brennan, Huh, and Subrahmanyam (2015) interpret the fact that their  $CPIE_{PIN}$  measures are higher after earnings announcements than before as evidence of informed trading. We show that  $CPIE_{PIN}$  is naively related to turnover. This suggests that the findings in Brennan, Huh, and Subrahmanyam (2015) can simply be attributed to the fact that turnover is typically much higher after earnings announcements.

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<sup>9</sup>Collin-Dufresne and Fos (2014b) partially attribute this finding to informed traders disguising their trades in periods of high liquidity or timing their trades such that market movements conceal the nature of their information. Our findings cannot speak to this possibility, instead we show that the PIN model mechanically attributes all sources of variation in turnover to the arrival of private information.

<sup>10</sup>Easley, Lopez de Prado, and O’Hara (2012) develop the volume-synchronized probability of informed trading or  $VPIN$ . We do not consider  $VPIN$  in this paper because, as Easley, Lopez de Prado, and O’Hara (2012) point out,  $VPIN$  is a measure of order flow toxicity at high frequencies rather than a stock characteristic that measures adverse selection at lower frequencies as  $PIN$  is widely used in the finance and accounting literature. Moreover, Andersen and Bondarenko (2014) provide detailed critique of the  $VPIN$  measure.

The remainder of the paper is as follows. Section 1 outlines the data we use for our empirical results. Section 2 shows that the PIN model mechanically associates variation in turnover with the arrival of private information. Section 3 extends the PIN model to deal with this shortcoming and compares a model based on order flow imbalance alone (EPIN) with a model that identifies private information from both returns and order flow (OWR). Section 4 concludes.

## 1 Data

To estimate the PIN, EPIN, and OWR models, we collect trades and quotes data for all NYSE stocks between 1993 and 2012 from the NYSE TAQ database. We require that the stocks in our sample have only one issue (i.e. one PERMNO), are common stocks (share code 10 or 11), are listed on the NYSE (exchange code 1), and have at least 200 days worth of non-missing observations for the year. Our sample contains 1,060 stocks per year on average. Despite our sample selection criteria, about 36% (25%) of the stocks in our sample are in the top (bottom) three Fama-French size deciles. For each stock in the sample, we classify each day's trades as either buys or sells, following the Lee and Ready (1991) algorithm. In our analysis, we define turnover as the sum of daily buys and sells. Internet Appendix B describes the computation of the number of buys and sells.

We estimate both the PIN and EPIN models using only the daily number of buys and sells ( $B_{i,t}$  and  $S_{i,t}$ ). The OWR model, however, also requires intraday and overnight returns as well as order imbalances. Following Odders-White and Ready (2008) we compute the intraday return at day  $t$  as the volume-weighted average price (VWAP) at  $t$  minus the opening quote midpoint at  $t$  plus dividends at time  $t$ , all divided by the opening quote midpoint at time  $t$ .<sup>11</sup> We compute the overnight return at  $t$  as the opening quote midpoint at  $t + 1$  minus the VWAP at  $t$ , all divided by the opening quote midpoint at  $t$ . The total return, or sum of the intraday and overnight returns is the open-to-open return from  $t$  to  $t + 1$ . We compute order imbalance ( $y_e$ ) as the daily share volume of buys minus the share

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<sup>11</sup>The opening quote midpoint is not available in TAQ in many instances. When the opening quote midpoint is not available, we use the matched quote of the first trade in the day as a proxy for the opening quote.

volume of sells, divided by the total share volume. We follow Odders-White and Ready and remove systematic effects from returns to obtain measures of unexpected overnight and intraday returns ( $r_{o,i,t}$  and  $r_{d,i,t}$ ). See Internet Appendix B for details.

Like Odders-White and Ready (2008), we remove days around unusual distributions or large dividends, as well as CUSIP or ticker changes. We also drop days for which we are missing overnight returns ( $r_{o,i,t}$ ), intraday returns ( $r_{d,i,t}$ ), order imbalance ( $y_e$ ), buys ( $B$ ), or sells ( $S$ ). Our empirical procedures follow those of Odders-White and Ready with two exceptions. First, OWR estimate  $y_e$  as the idiosyncratic component of net order flow divided by shares outstanding. We do not follow the same procedure as OWR in defining  $y_e$  because we find that estimating  $y_e$  as we do results in less noisy estimates. Specifically, we find that  $y_e$  defined as shares bought minus shares sold divided by shares outstanding, as in Odders-White and Ready (2008), suffers from scale effects late in the sample, when order flow is several orders of magnitude larger than shares outstanding. Second, Odders-White and Ready remove a whole trading year of data surrounding distribution events, but we only remove one trading week  $[-2,+2]$  around these events.

For the event study portion of our analysis, we examine earnings announcements. Our sample of earnings announcements includes all CRSP/COMPUSTAT firms listed in NYSE between 1995–2009 for which we have exact timestamps collected from press releases in Factiva which fall within a  $[-1,0]$  window relative to COMPUSTAT earnings announcement dates following Dong, Li, Ramesh, and Shen (2015). Because we have exact timestamps for the earnings announcements, we can cleanly separate between the pre and post event periods, thus avoiding ambiguity about when exactly the information becomes public. To avoid any confusion with respect of the timing of the events in the OWR model, we remove all announcements occurring on non-trading days. Our final sample includes 21,979 earnings announcements.

We also examine a sample of opportunistic insider trades, as defined in Cohen, Malloy, and Pomorski (2012), from the Thomson Reuters' database of insider trades. In order to classify a trader as opportunistic or routine, we require three years of consecutive insider trades. We classify a trader as routine if she places a trade in the same calendar month for at least three years. All non-routine traders' trades are classified as opportunistic. Co-

hen, Malloy, and Pomorski (2012) show that opportunistic insider trades predict abnormal returns, information events, and regulator actions, which is consistent with the presence of private information. Our event sample includes 32,676 opportunistic insider trades.

Table 1 contains summary statistics of all the variables used to estimate the models. Panel A gives summary statistics of our entire sample, Panel B displays the summary statistics for the days of earnings announcements, and Panel C displays the summary statistics for opportunistic insider trading days.

## 2 Why does PIN fail?

This section addresses whether *PIN* mis-identifies private information because the underlying model does not fit the data well. Section 2.1 briefly describes the PIN model and  $CPIE_{PIN}$ . Section 2.2 shows the results of regressions of  $CPIE_{PIN}$  on absolute order imbalance and turnover. Section 2.3 shows how  $CPIE_{PIN}$  varies around earnings announcements. The results in Sections 2.2 and 2.3 show that the PIN model identifies the arrival of private information from increases in turnover.

### 2.1 Description of the PIN model

The Easley, Kiefer, O’Hara, and Paperman (1996) PIN model posits the existence of a liquidity provider who receives buy and sell orders from both informed traders and uninformed traders. At the beginning of each day, the informed traders receive a private signal with probability  $\alpha$ . If the private signal is positive (which occurs with probability  $\delta$ ), buy orders from informed and uninformed traders arrive following a Poisson distribution with intensity  $\mu + \epsilon_B$ , while sell orders come only from the uninformed traders and arrive with intensity  $\epsilon_S$ . If the private signal is negative (with probability  $1 - \delta$ ), sell orders from informed and uninformed traders arrive following a Poisson distribution with intensity  $\mu + \epsilon_S$ , while buy orders come only from the uninformed traders and arrive with intensity  $\epsilon_B$ . If the informed traders receive no private signal, they do not trade; thus, all buy and sell orders come from the uninformed traders and arrive with intensity  $\epsilon_B$  and  $\epsilon_S$ , respectively. Fig. 1 shows a tree diagram of this model. The difference in arrival rates captures the intuition that on days with positive private information, the arrival rate of buy orders increases over and above the

normal rate of noise trading because informed traders enter the market to place buy orders. Similarly, the arrival rate of sell orders rises when the informed traders seek to sell based on their negative private signals. Therefore, the PIN model identifies the arrival of private information through increases in the absolute value of the order imbalance.

The model also ties variations in turnover to the arrival of private information. Specifically, let the indicator  $I_{i,t}$  take the value of one if an information event occurs for stock  $i$  on day  $t$ , and zero otherwise. Note that under the model the number of buys plus sells (turnover) is distributed as a Poisson random variable with intensity:

$$\lambda(I_{i,t}) = \begin{cases} \epsilon_B + \epsilon_S & \text{when } I_{i,t} = 0 \\ \epsilon_B + \epsilon_S + \mu & \text{when } I_{i,t} = 1 \end{cases} \quad (1)$$

Thus, under the PIN model, private information is *necessarily* the cause of any variation in expected daily turnover.

To formalize the concept of  $CPIE_{PIN}$ , let  $B_{i,t}$  ( $S_{i,t}$ ) represent the number of buys (sells) for stock  $i$  on day  $t$  and  $\Theta_{PIN,i} = (\alpha_i, \mu_i, \epsilon_{B_i}, \epsilon_{S_i}, \delta_i)$  represent the vector of the PIN model parameters for stock  $i$ . Let  $D_{PIN,i,t} = [\Theta_{PIN,i}, B_{i,t}, S_{i,t}]$ . The likelihood function of the Easley, Kiefer, O'Hara, and Paperman (1996) model is  $\prod_{t=1}^T L(D_{PIN,i,t})$ , where  $L(D_{PIN,i,t})$  is equal to the likelihood of observing  $B_{i,t}$  and  $S_{i,t}$  on a day without private information ( $L_{NI}(D_{PIN,i,t})$ ) added to the likelihood of  $B_{i,t}$  and  $S_{i,t}$  on a day with positive information ( $L_{I+}(D_{PIN,i,t})$ ) and to the likelihood of  $B_{i,t}$  and  $S_{i,t}$  on a day with negative information ( $L_{I-}(D_{PIN,i,t})$ ). Each of the likelihood functions ( $L_{NI}(D_{PIN,i,t})$ ,  $L_{I+}(D_{PIN,i,t})$  and  $L_{I-}(D_{PIN,i,t})$ ) corresponds to a node of the tree in Fig. 1. See Internet Appendix C for details.

Using the PIN model, for each stock-day, we compute the probability of an information event conditional both on the model parameters and on the observed total number of buys and sells. For the PIN model, we compute  $CPIE_{PIN,i,t} = P[I_{i,t} = 1 | D_{PIN,i,t}]$ . This probability is given by  $(L_{I-}(D_{PIN,i,t}) + L_{I+}(D_{PIN,i,t})) / L(D_{PIN,i,t})$ .  $CPIE_{PIN,i,t}$  represents the econometrician's posterior probability of an information event given the data observed on that day, and the underlying model parameters.

Note that if we condition down with respect to the data,  $CPIE_{PIN,i,t}$  reduces to the model's unconditional probability of information events ( $\alpha_i$ ). The unconditional probability represents the econometrician's beliefs about the likelihood of an information event before

seeing any actual orders or trades. In the absence of buy and sell data, an econometrician would assign a probability  $\alpha_i$  to an information event for stock  $i$  on day  $t$ , where  $\alpha_i = E[CPIE_{PIN,i,t}]$  and the expectation is taken with respect to the joint distribution of  $B_{i,t}$  and  $S_{i,t}$ . The *PIN* of a stock, defined as  $\frac{\alpha\mu}{\alpha\mu+\epsilon_B+\epsilon_S}$ , is the unconditional probability that any given trade is initiated by an informed trader. *CPIE* and *PIN* are linked via the unconditional probability of an information event,  $\alpha$ .

We estimate the PIN model numerically via maximum likelihood for every firm-year in our sample. The estimation procedure is similar to that used in Duarte and Young (2009). The parameter estimates are used for computing  $CPIE_{PIN}$  in Sections 2.2 and 2.3. Internet Appendix C provides details about the maximum likelihood procedure and the calculation of  $CPIE_{PIN}$ .

Table 2 contains summary statistics for the parameter estimates of the PIN model. Table 2 also contains summary statistics of the cross-sectional sample means and standard deviations of  $CPIE_{PIN}$ . The results in Table 2 show that the mean  $CPIE_{PIN}$  behaves exactly like  $\alpha$ . Hence, changes in  $CPIE_{PIN}$  and changes in the estimated  $\alpha$  are analogous. Fig. 2 Panel A shows how the distribution of  $\alpha$  changes over time. Interestingly, the PIN model  $\alpha$  increases over time, with the median PIN  $\alpha$  rising from about 30% in 1993 to 50% in 2012.<sup>12</sup> Panel B of Fig. 2 plots the time series of *PIN*. Note that *PIN* decreases over time in spite of the fact that  $\alpha$  increases. This happens because, according to the PIN model, the intensity of noise trading is increasing over time while the intensity of informed trading remains relatively flat as shown in Panel C of Fig. 2. It is important to note, however, that the time series patterns of the model parameters in Fig. 2 have no implications for how the PIN model identifies private information.

We also estimate the parameter vectors  $\Theta_{PIN,i}$  in the period  $t \in [-312, -60]$  before an earnings announcement. These parameter estimates are used to compute the *CPIEs* in Section 2.3. The summary statistics of the parameter estimates for the event studies are qualitatively similar to those in Table 2 and in Figure 2.

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<sup>12</sup>The increase in our estimated PIN model  $\alpha$  parameters is somewhat larger than that in Brennan, Huh, and Subrahmanyam (2015). This small difference arises because Brennan, Huh, and Subrahmanyam (2015) have a larger number of stocks per year due to the fact that we apply sample filters similar to those in Odders-White and Ready (2008). In fact, without these filters, the increase in our estimated PIN model  $\alpha$  parameters from 1993 to 2012 is comparable to that in Brennan, Huh, and Subrahmanyam (2015).

## 2.2 How does the PIN model identify private information?

This section analyzes how the PIN model actually identifies private information. In theory, the PIN model identifies information events from changes in the absolute order flow imbalance. Empirically, however, the PIN model may produce such a poor description of the order flow data that the model actually mis-identifies the variable of interest — private information. To analyze how the PIN model identifies private information in practice, we regress  $CPIEs$  on absolute order imbalance and turnover in Section 2.2.1. The results of these regressions show that on average 65% of the variation in  $CPIE_{PIN}$  is explained by turnover instead of absolute order imbalance. The intuition for this failure of the PIN model can be clearly seen in the scatter plot of buys and sells for Exxon-Mobil in Section 2.2.2. This scatter plot shows that the model mechanically identifies the arrival of private information from turnover. In fact, the PIN model essentially assigns probability one to the arrival of private information on any day when turnover is above the average daily turnover in the year and zero otherwise. As a result, the PIN model naively groups all sources of variation in turnover (e.g. disagreement, calendar effects, portfolio rebalancing, taxation, etc.) under the umbrella of private information arrival. In Section 2.2.3, we show that this naive identification of private information happens not only for Exxon-Mobil but also for the majority of the stocks in our sample following the increase in turnover in the early 2000s.

Given the strong connection between  $CPIEs$  and the unconditional probability of information arrival ( $\alpha$ ), our results in this section call into question the use of  $PIN$  as proxy for private information. While there are other parameters in the model (i.e.  $\mu$ ,  $\epsilon_B$  and  $\epsilon_S$ ), these parameters are jointly identified with  $\alpha$ . Hence it seems extremely unlikely that in the joint identification of the model parameters, biases in the other parameters ‘correct’ the biases in  $\alpha$  in such a way that  $PIN$  is ‘rescued’ as a reasonable proxy for private information. Thus, while our  $CPIE$  results do not speak directly to  $\mu$ ,  $\epsilon_B$  and  $\epsilon_S$ , they still call into question  $PIN$  as a measure of private information.

### 2.2.1 Regression Tests

Since there are many moments that the PIN model can fail to match, there are many tests that might reject the PIN model (e.g. Duarte and Young (2009)). Our regression tests

are not designed to analyze whether the PIN model matches particular moments in the data but instead are focused on how the PIN model identifies the fundamental variable of interest—private information. Specifically, our analysis is anchored around the regression  $CPIE_{PIN} = \alpha + \beta_0|B - S| + \beta_1|B - S|^2 + \beta_2turn + \beta_3turn^2 + \varepsilon$ . Since  $CPIE_{PIN}$  is a direct measure of private information according to the PIN model, this regression reveals how the PIN model actually identifies private information.

To formally show that the PIN model identifies private information from turnover instead of order flow, we compare the results from regressions with data created by simulating the PIN model to results from regressions with real data. To create the simulated data, we first estimate the parameters of the PIN model for each firm-year in our sample. Then, for each firm-year, we generate 1,000 artificial firm-years' worth of data (i.e.  $B_{i,t}$  and  $S_{i,t}$ ) using the estimated parameters. We then compute the  $CPIE_{PIN,i,t}$  for each trading day in a simulated trading year and regress these  $CPIEs$  absolute order flow imbalance and turnover. The results of the regressions using simulated data are useful because they reveal how the PIN model is intended to identify private information arrival and also allow us to build empirical distributions of the  $R^2$ s of the regressions of  $CPIEs$  on order imbalance and turnover under the null hypothesis that the PIN model correctly describes the order flow data.

Panel A of Table 3 presents the results of yearly multivariate regressions of  $CPIE_{PIN}$  on absolute order flow imbalance  $|B - S|$  and  $|B - S|^2$ . We add squared terms to these regressions to account for nonlinearities in the relationship between  $CPIE_{PIN}$  and  $|B - S|$ . We average the simulated results for each PERMNO-Year and report in Panel A of Table 3 the median coefficient estimates and  $t$ -statistics. The coefficients are standardized so they represent the increase in  $CPIE_{PIN}$  due to a one standard deviation increase in the corresponding independent variable. We also report the average of the median, the 5<sup>th</sup>, and the 95<sup>th</sup> percentiles of the empirical distribution of  $R^2$ s of these regressions generated by the 1,000 simulations. In general, the coefficients are highly statistically significant and the  $R^2$ s are high. This is consistent with intuition that if the model were literally true, the absolute order imbalance could be used to infer the arrival of private information.

The columns of Table 3 labeled as ' $R_{inc}^2$ ' include statistics on the increase in the  $R^2$  that

is due to the inclusion of turnover ( $turn$ ) and turnover squared ( $turn^2$ ) in the regressions. Specifically,  $R_{inc.}^2$  is equal to the difference between the  $R^2$  of the extended regression model with turnover terms and the  $R^2$  of a regression that includes only order imbalance terms. We report the average of the median, the 5<sup>th</sup>, and the 95<sup>th</sup> percentiles of the  $R_{inc.}^2$ s of these regressions across the 1,000 simulations. The incremental increase in  $R^2$ s are relatively low, with an average value of around 10%, which implies that, under the model's data generating process, turnover has only modest incremental power in explaining  $CPIE_{PIN}$ . The picture that emerges from these regressions is that if the PIN model were a perfectly accurate representation of trading activity,  $CPIE_{PIN}$  would be determined solely by the order flow imbalance on each day.

Panel B of Table 3 reports regression results for the real rather than simulated data. With the real data, the picture is very different. The  $R^2$ s of the regressions of  $CPIE_{PIN}$  on  $|B - S|$  and  $|B - S|^2$  are much smaller than those in the simulations. On the other hand, the incremental  $R^2$ s from turnover are much higher than those in Panel A. The incremental  $R^2$  also increases over time with a value of about 36% in 1993, to nearly 46% in 2012. This implies that turnover and turnover squared explain a much larger degree of variation in  $CPIE_{PIN}$  than order imbalance. In fact, the average ratio of the median  $R^2$ s,  $R_{inc.}^2 / (R^2 + R_{inc.}^2)$ , is about 65%. The difference arises because, in the real data, absolute order flow and turnover are only weakly correlated. For instance, large absolute order flow imbalances are possible when turnover is below average, and vice versa. Under the PIN model, however, the two are highly correlated.

We test the hypothesis that  $R_{inc.}^2$ s in the actual data are consistent with those generated under the PIN model. Panel B reports the average  $p$ -value (the probability of observing an  $R_{inc.}^2$  in the simulations at least as large as what we observe in the data) across all stocks, and the frequency that we reject the null at the 5% level implied by the distribution of simulated  $R_{inc.}^2$ s. The PIN model is rejected in about 89% of the stock-years in our sample, and there is on average less than a 7% chance of the PIN model generating  $R_{inc.}^2$ s as high as what we see in the data.

The results in Table 3 indicate that the PIN model identifies private information from increases in turnover, as opposed to changes in order imbalances for the majority of the

sample. These findings are inconsistent with the microstructure assumptions of the PIN model—controlling for order imbalance there should be no room for turnover in explaining private information arrival.

### 2.2.2 Exxon-Mobil Scatter Plots

To understand the intuition behind the results in Table 3, consider the scatter plot of real and simulated order flow data for Exxon-Mobil in Fig. 3. Panels A and B plot simulated and real order flow for Exxon-Mobil in 1993 and 2012 respectively, with buys on the horizontal axis and sells on the vertical axis. Real data are marked as +, and simulated data as transparent dots. The real data are shaded according to the  $CPIE$ , with darker points (+ magenta) representing low and lighter points (+ cyan) high  $CPIEs$ . Panels C and D plot the  $CPIE_{PIN}$  as function of turnover. The vertical lines in these panels represent the annual mean of daily turnover.

Panel A of Fig. 3 illustrates the central intuition behind the PIN model. The simulated data comprise three types of days, which create three distinct clusters. Two of the clusters are made up of days characterized by relatively large order flow imbalance, with a large number of sells (buys) and relatively few buys (sells). The third group of days has relatively low numbers of buys and sells because there is no private information arrival. Generalizing from this figure, days with large order flow imbalances correspond to informed traders entering the market in the PIN model.

The real data, on the other hand, show no distinct clusters in Panel A, and in Panel B of Fig. 3 the PIN model’s three clusters barely overlap with even a small portion of the data. This implies that the model cannot account for existence of the majority of the daily observations of order flow for Exxon-Mobil in 2012. In essence, the model classifies almost all daily observations as extreme outliers. The intuition for this is that the PIN model assumes that order flow is distributed as a mixture of three bivariate Poisson random variables (i.e. the three clusters in Panels A and B). The mean and the variance of a Poisson random variable are equal and, as a consequence, the Poisson mixtures behind the PIN model cannot accommodate the high level and volatility of turnover that we observe, especially in the later part of the sample.

Panels A and B also plot a line that separates the scatter plots in two regions. All the observations below (above) these lines have turnover below (above) the annual mean of daily turnover. These lines along with the  $CPIE$  color scheme for the observed data suggest that the PIN model is mechanically identifying private information from turnover. To clarify this mechanical identification, Panels C and D plot  $CPIE_{PIN}$  as function of turnover. Panels C and D show that the PIN model essentially classifies days with above average turnover as private information days (i.e.  $CPIE_{PIN}$  equal to one) and days with below average turnover as days without private information (i.e.  $CPIE_{PIN}$  equal to zero). The reason for this mechanical conflation of turnover with private information arrival is that under the PIN model expected turnover can only vary because of the arrival of private information (see Equation 1). Hence the poor fit to the turnover data along with the connection between turnover and arrival of private information in the PIN model causes the model to mechanically identify shocks to turnover as due to the arrival of private information.

Fig. 3 also emphasizes the mechanical nature of the relation between  $CPIE_{PIN}$  and turnover. In 2012, the PIN model identifies almost all days with higher than average turnover as days with private information events. Note that this identification does not necessarily relate to the possibility, suggested by Collin-Dufresne and Fos (2014b), that informed traders sometimes choose to trade on days with high liquidity or turnover. Naturally, it is possible that informed traders do in fact trade on some days with high turnover. However, the point here is that the PIN model identifies essentially *all* days with above average turnover as information events.

### 2.2.3 $CPIE_{Naive}$

Fig. 3 shows the PIN model's naive identification of private information events for one stock, and in this section we show that this is not an isolated example. In fact, the problem is widespread. To quantify how often the PIN model classifies information events as simple function of turnover we define

$$CPIE_{Naive,i,t} = \begin{cases} 0, & \text{if } turn_{i,t} < \overline{turn}_i \\ 1, & \text{if } turn_{i,t} \geq \overline{turn}_i \end{cases} \quad (2)$$

That is,  $CPIE_{Naive,i,t}$  is a dummy variable equal to one when turnover for stock  $i$  on day  $t$  ( $turn_{i,t}$ ) is larger than or equal to the annual average of daily turnover of stock  $i$  ( $\overline{turn}_i$ ) and

zero otherwise. To our knowledge there is no paper in the literature that proposes identifying private information in similar manner.<sup>13</sup> It is clear, however, from Panel D of Fig. 3 that the PIN model essentially identifies the arrival of private information for Exxon-Mobil in 2012 according to this rule. We use  $CPIE_{Naive}$  to gauge the extent to which the PIN model conflates the arrival of private information with turnover. Specifically, Panel A of Fig. 4 shows the distribution of the fraction of days for which  $CPIE_{PIN}$  is identical to  $CPIE_{Naive}$  ( $|CPIE_{PIN} - CPIE_{Naive}| < 10^{-10}$ ).  $CPIE_{PIN}$  and  $CPIE_{Naive}$  are identical for about 85% of the annual observations for the median stock since 2002.

Another way to gauge the extent to which the PIN model breaks down later in our sample period is to count the number of days that the PIN model classifies as outliers. Panel B of Fig. 4 shows the fraction of days for the median stock-year which the PIN model classifies as “outliers” (likelihoods smaller than  $10^{-10}$ ). According to the PIN model, for the median stock about 60% (90%) of the annual observations are classified as outliers in 2005 (2010).<sup>14</sup>

Figs. 3 and 4 also give the intuition for why the median PIN  $\alpha$  increases over time in Fig. 2. To see this, recall that  $\alpha$  is the unconditional expected value of  $CPIE_{PIN}$ . Therefore, as we observe more  $CPIE_{PIN}$  values approaching one, the estimated PIN  $\alpha$  must increase. In fact, the median PIN  $\alpha$  becomes close to 50% later in the sample which consistent with the fact that the PIN model assigns a  $CPIE_{PIN}$  equal to one (zero) to days with turnover above (below) the average.

### 2.3 Relating PIN anomalies to turnover

The previous section shows that the PIN model often identifies private information from turnover. The question remains, however, whether this is merely an inconsequential specification issue or whether this changes the interpretation of results in the existing literature (e.g. Aktas, de Bodt, Declerck, and Van Oppens (2007), Benos and Jochev (2007), Brennan, Huh, and Subrahmanyam (2015), and Easley, Engle, O’Hara, and Wu (2008)). To

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<sup>13</sup>Stickel and Verrecchia (1994) propose identifying information arrival in general with a similar measure, but not private information in particular.

<sup>14</sup>O’Hara, Yao, and Ye (2014) find that high-frequency trading is associated with an increase in the use of odd lot trades, which do not appear in the TAQ database. Therefore, estimates of the PIN model parameters computed using recent TAQ data may be systematically biased. More broadly, Fig. 4 indicates that even if the PIN model are estimated using data that includes odd lot trades, the model will still be badly misspecified late in the sample.

address this, we examine how well the PIN model identifies information events around earnings announcements. Turnover is typically much higher around earnings announcements (e.g. Bamber, Barron, and Stevens (2011)) hence earnings announcements provide a good laboratory to examine this question.

Unlike a standard event study, we focus on movements in  $CPIE$  rather than price movements. For each model, we examine the period  $t \in [-20, 20]$  around the event. To do so, we estimate the parameter vector  $\Theta_{PIN,i}$  in the period  $t \in [-312, -60]$  before the event and then compute the daily  $CPIEs$  for the period  $t \in [-20, 20]$  surrounding the announcement. Prior studies estimate the parameters of the model in various windows around an event in order to compute the  $PIN$ . Our procedure is different in that we estimate the parameters of the model one year prior to the event and then employ the estimated parameters as if we were an econometrician observing the market data (i.e. buys and sells) and attempting to infer whether an information event occurred. Table 1 Panel B presents summary statistics for order imbalance, intraday returns, overnight returns, number of buys, and the number of sells for earnings announcement days ( $t = 0$ ).

Panel A of Fig. 5 shows the average  $CPIE_{PIN}$  in event time for our sample of earnings announcements. The graph shows that, under the PIN model, the probability of an information event increases prior to the event, starting below 55% 20 days before the announcement and peaking above 80% on the day after the announcement. The rise in the probability of an information event prior to the announcement could be consistent with a world where informed traders generate signals about earnings and trade on this information before earnings are announced to the public. However,  $CPIE_{PIN}$  is also higher *after* the actual earnings become public information.

Panels B and C of Fig. 5 shed light on the features of the data that produce the observed pattern in the average  $CPIE_{PIN}$  in Panel A. Panel B shows the average predictions from OLS regressions of  $CPIE_{PIN}$  on order imbalance and absolute order imbalance squared across all of the stocks in the event study sample. The solid line indicates that order imbalance explains only a small fraction of the variation in  $CPIE_{PIN}$  within the event window. Panel C shows the average predictions from regressions of  $CPIE_{PIN}$  on turnover and turnover squared. The solid line indicates that the variation in  $CPIE_{PIN}$  around earnings announcements is

explained almost entirely by turnover. The intuition follows directly from the results in Section 2.2, which shows that  $CPIE_{PIN}$  is mechanically driven by turnover increases. The higher post-event turnover levels are enough to keep  $CPIE_{PIN}$  above its pre-event mean for a substantial period.

To formalize the intuition behind Panels B and C of Fig. 5, we run regressions similar to those in Table 3 using our event sample. Specifically, we run regressions of  $CPIE_{PIN}$  on absolute value of order imbalance and its squared term during the event window  $[-20,+20]$ . The results of these regressions (see Table 4) indicate that absolute order imbalance explains little of the variation in  $CPIE_{PIN}$  in the event window while turnover explains most of the variation in  $CPIE_{PIN}$ . In fact, Table 4 shows that for the median stock, adding turnover and turnover squared to these regressions nearly quadruples the  $R^2$ s.

The event study results suggest that the variation in  $PIN$  around events documented in the literature is partially related to variation in  $\alpha$  that is mechanically driven by turnover, rather than order imbalance. For instance, Benos and Jochev (2007) show that  $PIN$  increases after earnings announcements, while Aktas, de Bodt, Declerck, and Van Oppens (2007) show that  $PIN$  increases after M&A target announcements due to increases in both  $\mu$  and  $\alpha$ . Therefore, our evidence suggests that these  $PIN$  results are at least partially explained by the fact that the PIN model attributes increases in turnover to private information.

Turnover around earnings announcement can vary for many reasons unrelated to the arrival of private information. Traditionally the literature has attributed high turnover after announcements to disagreement (e.g. Bamber, Barron, and Stevens (2011)). Karpoff (1986) suggests that high turnover after earnings announcements may also be due to divergent prior expectations, while Frazzini and Lamont (2007) attributes high turnover to small investors' lack of attention. None of these studies suggest that the higher turnover around announcements is necessarily the result of increased informed trade, per se. Even the PIN model suggests that once we control for order imbalance, turnover should have little power to identify informed trade.

Another important implication of these results for the literature is that event studies based on daily measures of private information, like  $CPIE_{PIN}$  (e.g. Easley, Engle, O'Hara, and Wu (2008) and Brennan, Huh, and Subrahmanyam (2015)) can also be misleading. To

see this point consider the results in Panel A of Fig. 5. It may appear at first glance that the results in Panel A of Fig. 5 suggest that the PIN model identifies private information in a sensible way since  $CPIE_{PIN}$  increases dramatically from 55% before the announcement to over 75% on the day of the announcement then falls after the announcement, albeit over a period of weeks. However, the decomposition of the  $CPIEs$  in Panels B and C of Fig. 5 points to a different interpretation, namely that the dramatic increase in  $CPIE$  around the event is actually result of variation in turnover, which may be unrelated to the arrival of private information as we point out above.

### 3 Does order flow alone reveal private information?

The previous section shows that the PIN model mis-identifies private information arrival from increases in turnover. However, it could be that net order flow itself is such a poor indicator of private information that no model based on order flow alone is capable of identifying informed trade (e.g. Back, Crotty, and Li (2014) and Kim and Stoll (2014)). This section gauges the extent to which a model of order flows and price responses generates better inferences about the arrival of informed trade than a model based on order flow alone. To do so, we first propose an extension of the PIN model (the EPIN model) that removes the mechanical conflation of turnover and arrival of private information that plagues the PIN model. We then compare the OWR model, which infers the arrival of private information from returns and order flow, with the EPIN model, which is solely based on order flow. Section 3.1 presents the EPIN model. Section 3.2 describes the OWR model and Section 3.3 presents the results of a horse race between the OWR and the EPIN models.

#### 3.1 Extending the PIN model

Our results in Sections 2.2 and 2.3 show that the PIN model naively identifies information events from turnover. This happens because of two limitations of the PIN model. First, under the PIN model, increases in expected turnover can only come about through the arrival of private information (see Equation 1). Second, the PIN model assumes that order flow is distributed as a mixture of three bivariate Poisson random variables (i.e. the three clusters in Panels A and B of Fig. 3). This assumption is too restrictive to accommodate

the high level and volatility of turnover that we observe, especially in the later part of the sample. In this section, we propose an extension of the PIN model to fix the issues with the PIN model.

Before doing so, it is useful to formalize why the model fails in the way that we discuss above. Panel A of Fig. 6 displays a reparameterization of the PIN model in terms of three new parameters. First, the ratio of the intensity of uninformed buyer initiated trades to the intensity of the total number of uninformed trades ( $\theta = \epsilon_B/(\epsilon_B + \epsilon_S)$ ). Second, the ratio of the expected number of informed to uninformed trades on days where there is private information ( $\eta = \mu/(\epsilon_B + \epsilon_S)$ ). Third, the overall intensity of the number of buys plus sells ( $\lambda$ ). Specifically, recall that Equation 1 shows that  $\lambda$  is function of the arrival of private information, represented by the indicator  $I_{i,t}$  such that on days without private information  $\lambda(0) = \epsilon_B + \epsilon_S$  and, on days with private information,  $\lambda(1) = \epsilon_B + \epsilon_S + \mu$ . The bottom node of Panel A in Fig. 6 shows that, on days without private information, the intensity of buyer initiated trades is  $\theta \times \lambda(0)$ , while the intensity of seller initiated trades is  $(1 - \theta) \times \lambda(0)$ . On negative private information days (the central node of Panel A in Fig. 6) the ratio of the intensity of buys to the intensity of total trades drops to  $\theta/(1 + \eta)$ . Since buy orders are all uninformed and some sell orders are informed, the expected number of buys relative to the expected number of trades is smaller. Finally, on positive information days (the top node of Panel A in Fig. 6) the ratio of sells to the intensity of total trades drops to  $(1 - \theta)/(1 + \eta)$ . Since sell orders are all uninformed and some buy orders are informed, the expected number of sells relative to the expected number of trades is smaller. Therefore, Panel A of Fig. 6 is a re-parameterization of the PIN model in Fig. 1 using the parameters  $\lambda(0)$ ,  $\eta$ , and  $\theta$  instead of  $\epsilon_B$ ,  $\epsilon_S$ , and  $\mu$ .

Two limitations of the PIN model are immediately clear from the parameterization in Panel A of Fig. 6. First, increases in  $\lambda$  can only come about through the arrival of private information. That is,  $\lambda$  is function of information arrival ( $I_t$ ). Second, the PIN model does not allow for enough variability in  $\lambda$  to accommodate the high level and volatility of turnover that we observe, especially in the later part of the sample. We resolve the limitations of the PIN model while keeping its information structure with an extension of the PIN model that does two things. First, we draw  $\lambda_t$  independently of the arrival of private information.

Second, we focus on the fraction of trades represented by buys and sells rather than on the absolute amounts of buys and sells following the re-parameterization of the PIN model in Panel A of Fig. 6.

Panel B of Fig. 6 presents the tree structure for the Extended PIN model (EPIN). The EPIN model retains the microstructure intuition of the original PIN model, however, it focuses on the ratios of the expected number of buys and sells to the expected number of trades rather than on the absolute numbers of buys and sells.

Specifically, the EPIN model in Panel B of Fig. 6 draws  $\lambda_t$  from a  $Gamma(r, p/(1-p))$  distribution with shape parameter  $r$  and scale parameter  $p/(1-p)$ . The fact that  $\lambda_t$  is drawn from a  $Gamma$  distribution makes the model particularly tractable since the mixture of the  $Poisson$  and  $Gamma$  distributions is the well-known  $Negative Binomial$  distribution (see Casella and Berger (2002)). In the EPIN model, the number of trades ( $B+S$ ) is distributed as  $Negative Binomial$  (see Appendix D for proof), which dramatically simplifies the numerical estimation of the model. In the maximum likelihood estimation the order intensity ( $\lambda$ ) parameters  $r$  and  $p$  can be estimated in a first stage, independently of the remaining information structure parameters which can be estimated in a second stage.  $CPIE_{EPIN}$  is calculated in the same way as in the PIN model. Moreover, if we condition down with respect to the data,  $CPIE_{EPIN}$  reduces to the model's unconditional probability of information events ( $\alpha$ ). See Appendix D for a detailed discussion of the model, the associated  $EPIN$  measure, the likelihood function, and the  $CPIE_{EPIN}$  calculation.

To illustrate how the EPIN model works, we present a stylized example of the EPIN in Fig. 7. Analogous to the PIN model plot in Fig. 3, we plot simulated and real order flow data for Exxon-Mobil during 1993 and 2012, with buys on the horizontal axis and sells on the vertical axis. Panels A and B of Fig. 7 illustrate the central intuition behind the EPIN model. The simulated data comprise three types of days, which create three distinct clusters. Two of the clusters are made up of days characterized by a high proportion of imbalanced trades (large  $\frac{|B-S|}{B+S}$ ), with a large number of sells (buys) and relatively few buys (sells). The third group of days has a low proportion of imbalanced trades—these days have no private information arrival and are clustered around the dashed line in the center of the scatter plots.

The EPIN model implies that days with information events are the ones in which the proportion of imbalanced trades is large. An econometrician using the EPIN model, moving along the dashed line in Panels A and B, would observe that days with above average turnover—days the PIN model classifies as information events—are no longer classified as such, because higher turnover is driven by a large draw of the parameter  $\lambda_t$  under the EPIN model. Instead, the EPIN model identifies private information when moving away from the dashed line—when the proportion of imbalanced trades is high.

Panels C and D plot  $CPIE_{EPIN}$  as function of turnover. As opposed to the analogous plot of the PIN model in Fig. 3, Panels C and D do not indicate any relation between turnover and  $CPIE_{EPIN}$ .<sup>15</sup> Although the EPIN model is not a perfect description of the order flow data, it manages to fix the problem of the PIN model which mechanically identifies private information arrival from turnover.

Table 5 contains summary statistics for the parameter estimates of the EPIN model. Table 5 also contains summary statistics of the cross-sectional sample means and standard deviations of  $CPIE_{EPIN}$ . We see that the mean  $CPIE_{EPIN}$  behaves exactly like  $\alpha$ . We also estimate the EPIN model for every stock in our sample in the period  $t \in [-312, -60]$  before earnings announcements and opportunistic insider trades. These parameter estimates are used to compute the  $CPIE_{EPIN}$  in Section 3.3. The summary statistics of the parameter estimates for the event studies are qualitatively similar to those in Table 5.

### 3.2 The OWR model

Odders-White and Ready (2008) extend Kyle (1985) by allowing for days with information events and days without information events. Private information arrives before the opening of the trading day with probability  $\alpha$ . On days when private information arrives, the model assumes that the information is publically revealed after the close of trade. The OWR model identifies the arrival of private information through order flow imbalance,  $y_e$ , the intraday price response to order imbalance,  $r_d$ , and through subsequent overnight price changes,  $r_o$ .<sup>16</sup>

<sup>15</sup>Internet Appendix D shows the results of regressions of  $CPIE_{EPIN}$  on the proportion of imbalanced trades and turnover. These regressions are analogous to those that we performed with the PIN model in Table 3. The results of these regressions indicate that the EPIN model does not conflate turnover with the arrival of private information.

<sup>16</sup>We suppress the  $t$  subscript for ease of exposition.

The vector  $(y_e, r_d, r_o)$  is assumed to be multivariate normal with mean zero and a covariance matrix that differs between information days and non-information days.<sup>17</sup>

Fig. 8 shows the time line of the model. The intuition behind the OWR model is that the market maker updates prices in response to order flow because the order flow could reflect an information event. However, the subsequent price pattern is different depending on whether there actually was an information event or not. If an information event occurs, the overnight price response reflects a continuation of the market makers' intraday reaction. If no information event occurs, the overnight price response reverses the market makers' initial price reaction. Therefore, an econometrician can make inferences about the probability of an information event in the OWR model because the covariance matrix of the three variables  $(y_e, r_d, r_o)$  differs between days when private information arrives and days when only public information is available.<sup>18</sup>

To see how the covariance matrix of  $(y_e, r_d, r_o)$  differs between information and non-information days, consider first the covariance of the intraday and overnight returns,  $cov(r_o, r_d)$ . This covariance is positive for information events, reflecting the fact that the information event is not completely captured in prices during the day and the revelation of the private information means that the overnight return continues the partial intraday price reaction. In contrast,  $cov(r_o, r_d)$  is negative in the absence of an information event since the market maker's reaction to the noise trade during the day is reversed when she learns that there was no private signal.

The other moments in the covariance matrix of  $(y_e, r_d, r_o)$  are also affected by the arrival of private information. If no information event occurs, then  $Var(y_e)$  is composed of only the variances of the uninformed order flow and the noise in the data. However, if an event occurs,  $Var(y_e)$  increases because the order flow reflects at least some informed trading. Similarly,  $Var(r_d)$  is higher for an information event, because it reflects the market maker's partial reaction to the day's increased order flow. Since the private signal is revealed after

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<sup>17</sup>We follow Odders-White and Ready and remove systematic effects from returns to obtain measures of unexpected overnight and intraday returns ( $r_o$  and  $r_d$ ). See Section 1 and Internet Appendix B for a detailed description of how we compute  $y_e$ ,  $r_o$  and  $r_d$ .

<sup>18</sup>Unlike the market maker who must update prices before observing the overnight revelation of information, the econometrician in the OWR model can make inferences about the arrival of private information after viewing the overnight price response.

trading closes,  $Var(r_o)$  also increases in the wake of an information event, as it reflects the remainder of the market maker's partial reaction to the informed trade component in order flow. Likewise, information events make  $cov(y_e, r_d)$  and  $cov(y_e, r_o)$  rise. The higher covariance between order flow and intraday returns occurs because, in an information event, both order flow and the intraday return (partially) reflect the impact of informed trading. Along these same lines, because the market maker cannot separate the informed from the uninformed order flow, she is unable to fully adjust the price during the day to reflect the informed trader's private signal. However, since the private signal is publically revealed and fully reflected in prices after the close,  $cov(y_e, r_o)$  is higher during an information event.

In contrast to the PIN model, the OWR model does not contain a direct analog to the probability of informed trading ( $PIN$ ). To understand this result, note that the probability of informed trade in the PIN and EPIN models is given by the ratio of the expected number of informed trades to the expected total number of trades on a given day. Since the OWR model employs only the difference between buys and sells, it does not make assumptions about the distribution of number of trades. Thus, the OWR is mute regarding the ratio of the expected number of informed trades to expected number of trades. This may appear to be a limitation of the OWR model, but this is actually an advantage because it allows the OWR model to disentangle variations in turnover from the arrival of informed trading, much like the EPIN model.

Even though the OWR model does not have a measure analogous to the  $PIN$  measure, the OWR model admits other useful measures of private information. For instance, the OWR model has a  $CPIE_{OWR}$  which reduces to the model's unconditional probability of information events ( $\alpha$ ) if we condition down with respect to the data. Moreover, Odders-White and Ready (2008) motivate their model as a tool to separate the expected liquidity provider losses due to trading with informed traders into the frequency of private information arrival and the expected magnitude of the private information. Hence, the OWR allows for the construction of private information measures that are based on both dimensions. The PIN and EPIN models, on the other hand, focus only on the frequency of information arrival and are silent with respect to the expected magnitude of the private information. Hence, our comparison of the EPIN and OWR models with  $CPIE_{EPIN}$  and  $CPIE_{OWR}$  focuses

on the dimension of private information that both models have in common, namely the frequency of information arrival. The fact that we are using  $CPIEs$  to compare the models does not imply that we are taking the position that frequency measures are the only private information metrics that are worthy of consideration.

As with the PIN and EPIN models, we estimate the OWR model numerically via maximum likelihood. Table 6 contains summary statistics for the parameter estimates of the OWR model. Table 6 also contains summary statistics of the cross-sectional sample means and standard deviations of  $CPIE_{OWR}$ . As in the PIN and EPIN models, we see that the mean  $CPIE_{OWR}$  behaves exactly like  $\alpha$  in the OWR model. The estimated OWR  $\alpha$  parameters are in general higher than those in Odders-White and Ready (2008). This is due to the fact that our definition of  $y_e$  is different from that in Odders-White and Ready (2008) (see the discussion in Section 1 above).<sup>19</sup> Fig. 9 plots the time series of the estimated OWR  $\alpha$ . In contrast to the PIN  $\alpha$ , the OWR  $\alpha$  is decreasing over time. This pattern may indicate that private information arrival is less likely later in our sample. While interesting, understanding this pattern is outside the scope of this paper and we leave this investigation for future research. We also estimate the OWR model for each stock  $i$  in the period  $t \in [-312, -60]$  before earnings announcements and opportunistic insider trades. These parameter estimates are used to compute the  $CPIEs$  in Sections 3.3.1 and 3.3.2. The summary statistics of the parameter estimates for the event studies are qualitatively similar to those in Table 6. Internet Appendix E has a detailed description of model, its likelihood function, and the  $CPIE_{OWR}$  calculation. Appendix E also displays the results of regressions of  $CPIE_{OWR}$  similar to those that we perform with  $CPIE_{PIN}$  in Section 2.2. These regressions indicate that the OWR model identifies the arrival of private information in a way consistent with its theory.

### 3.3 A horse race between the EPIN and OWR models

A fundamental problem in the literature related to testing and proposing measures of private information is the lack of cleanly identifiable periods in which private information is present in

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<sup>19</sup>In fact, we get  $\alpha$  estimates close to those reported in Odders-White and Ready (2008) if we define  $y_e$  in the same way that they do.

the market. To address this issue, we use three different methods to analyze the performance of the OWR and EPIN models. In Section 3.3.1 we analyze how  $CPIE_{OWR}$  and  $CPIE_{EPIN}$  vary around earnings announcements. The assumption underlying this test is that private information arrival is more likely before than after the announcement. In Section 3.3.2 we analyze how  $CPIE_{OWR}$  and  $CPIE_{EPIN}$  vary around insider trading events. In Section 3.3.3 we analyze how  $CPIE_{OWR}$  and  $CPIE_{EPIN}$  are related to return autocorrelations.

Each of these three methods has its own unique limitations. For instance, it is possible that, for some reason, private information is more prevalent after important announcements than before. Other critiques could be levied against the other two methods. However, if all of these methods point to the same conclusions, it seems unlikely that our overall interpretation would be biased due to the limitations of any specific method.

### 3.3.1 Information event probabilities under the EPIN and OWR models

Panel A of Fig. 10 illustrates the average  $CPIE_{EPIN}$  in event time for our sample of earnings announcements. In contrast to the PIN model, the probability of an information event decreases from around 51% 20 days before the announcement and drops on the announcement date to around 46%. This pattern is not consistent with informed traders acting on private information before the announcement. Panel B of Fig. 10 illustrates the average  $CPIE_{OWR}$  in event time for our sample of earnings announcements. Similar to the PIN model, the probability of an information event increases from around 40% 20 days before the announcement and peaks on the announcement date at around 45%. Panel B indicates that the  $CPIE_{OWR}$  is far outside of two standard deviations from its mean (estimated between  $t \in [-40, -21]$ ) on the announcement date  $t = 0$ . This pattern is consistent with the timing of the OWR model where informed traders act on private information during the day before the public announcement which occurs overnight ( $t \in [0, 1)$ ). Unlike the PIN model, the  $CPIE_{OWR}$  drops back to its pre-event mean within a few days after the announcement. This is consistent with the intuition that there is more scope for informed trading before the announcement than after.

What causes the EPIN results to be so different from the PIN results above? Fig. 11 sheds light on this question. Panel A of Fig. 11, shows the actual  $CPIE_{EPIN}$  along with predicted

values from a regression of  $CPIE_{EPIN}$  on the proportion of imbalanced trades  $\left(\frac{|B-S|}{B+S}\right)$  and its square. The results indicate that  $CPIE_{EPIN}$  drops because the imbalance is small relative to the absolute amount of trade on the announcement day. This is consistent with the results in Easley, Engle, O'Hara, and Wu (2008), who show that in their sample of 834 announcements that the average proportion of imbalanced trades decreases on earnings announcement days. The PIN model interprets the increase in turnover as indicative of the arrival of private information, but the EPIN model, on the other hand, uses the information in the proportion of imbalanced trades to draw the opposite conclusion. Panel B provides support for this notion by showing that the  $CPIE_{EPIN}$  does not respond to increases in turnover. Panel B shows the predicted  $CPIE_{EPIN}$  based on a regression of  $CPIE_{EPIN}$  on  $\frac{|B-S|}{B+S}$  and its square. The results indicate that, consistent with the motivation for the extended model,  $CPIE_{EPIN}$  responds to the proportion of imbalanced trades and not turnover.

As we saw in Section 3.2, the OWR model identifies private information from the covariance matrix of the three variables in the model  $(y_{e,i,t}, r_{o,i,t}, r_{d,i,t})$ . Therefore, to analyze how the OWR model identifies private information around earnings announcements, we decompose  $CPIE_{OWR}$  on to the squared and interaction terms of  $(y_{e,i,t}, r_{o,i,t}, r_{d,i,t})$ . Panels A–F of Fig. 12 show that the majority of the variation in measured private information ( $CPIE_{OWR}$ ) comes from intraday returns squared (Panel B) and the interaction between the intraday and overnight returns (Panel F). Order imbalance squared (Panel A) provides no explanatory power, although the interaction between the order imbalance and returns (Panels D and E) does have some impact.

Our results suggest that order flow, however well modeled, is insufficient to be the sole source of inferences about private information arrival. Under the assumption that there is more informed trade before rather than after earnings announcements, our findings suggest that the OWR model identifies private information in a sensible way while the EPIN does not. Even though the magnitude of the increase in  $CPIE_{OWR}$  around the event date may be considered small,  $CPIE_{OWR}$  increases before the event day while  $CPIE_{EPIN}$  counter-intuitively decreases. Since both models use order flow to identify private information, the marked difference in the results highlights the importance of including the price response mechanism. The use of returns, particularly intraday returns, allows the OWR model to reach a different

and more economically sensible conclusion. Moreover, the fact that order imbalance alone explains very little of the variation in  $CPIE_{OWR}$  around earnings announcements also emphasizes the relatively low contribution of order flow relative to returns in identifying private information. Our results therefore provide empirical support for the proposition in Back, Crotty, and Li (2014) and in Kim and Stoll (2014) that researchers cannot use order flow alone to successfully identify periods of informed trade.

### 3.3.2 $CPIE_{EPIN}$ and $CPIE_{OWR}$ around insider trading

In this section we investigate whether the OWR and EPIN models are capable of identifying opportunistic insider trades using the insider trade classification scheme developed in Cohen, Malloy, and Pomorski (2012).<sup>20</sup> Cohen, Malloy, and Pomorski (2012) show that a long-short portfolio that exploits the trades of opportunistic traders (opportunistic buys minus opportunistic sells) earns value-weighted abnormal returns of 82 basis points per month (9.8 percent annualized, t-statistic=2.15). They also show that the trades of opportunistic insiders show significant predictive power for future news about the firm, and that the fraction of traders who are opportunistic in a given month is negatively related to the number of recent news releases by the SEC regarding illegal insider trading cases. Their results are all consistent with opportunistic insider trades, as opposed to routine insider trades, being based on private information. Opportunistic insider trades therefore, provide a convenient laboratory to examine the models' ability to detect the arrival of actionable private information.

Panel A (B) of Fig. 13 presents the average  $CPIE_{EPIN}$  ( $CPIE_{OWR}$ ) in event time for our sample of opportunistic insider trades. There is no clear pattern in the  $CPIE_{EPIN}$  indicating the arrival of private information before opportunistic insider trades, though there is an increase in  $CPIE_{EPIN}$  on the day of opportunistic insider trades.

In contrast, Panel B shows that the  $CPIE_{OWR}$  identifies the arrival of private information in the days leading up to an opportunistic insider trade. Beginning at  $t = -4$ , the  $CPIE_{OWR}$  is more than two standard deviations higher than the mean estimated between  $t \in [-40, 21]$ . However,  $CPIE_{OWR}$  begins to drift strongly upward and very nearly crosses the two standard deviation bound as early as day  $t = -10$ . Strikingly, at  $t = 1$ , immediately after the trade,

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<sup>20</sup>See Section 1 for a further discussion of the classification of insider trades as opportunistic.

$CPIE_{OWR}$  drops precipitously back to average levels. We interpret this as strong evidence that the OWR model’s use of both order flow and returns is successful in uncovering informed trade.

Taken together, the insider trading event study evidence further supports the claim that order flows alone may be insufficient to identify private information.  $CPIE_{EPIN}$ , which varies based only on changes in order imbalances, is unable to clearly detect the imminent arrival of insider trades.  $CPIE_{OWR}$ , on the other hand, is able to predict insider trading based on small variations in intraday and overnight returns.

### 3.3.3 Are $CPIE_{EPIN}$ and $CPIE_{OWR}$ related to return continuation?

The market microstructure literature has long held that price changes related to informed trades should not be subsequently reversed while non-information related price changes (e.g. dealer inventory control, price pressure, price discreteness etc.) are transient (e.g. Hasbrouck (1988, 1991a,b)). In this section, we investigate whether  $CPIE_{EPIN}$  and  $CPIE_{OWR}$  are associated with subsequent return reversals. In particular, we examine the relation between  $CPIEs$  and return autocorrelations. The intuition is that if a model’s  $CPIE$  on day  $t$  actually reflects a high probability of informed trade then we expect that the return on day  $t$  will be continued over the subsequent day as the information gradually becomes public and gets fully impounded in prices. To capture this idea we model return autocorrelations as linear functions of  $CPIE$ . Specifically, we consider the following regressions:  $r_{i,t+1} = \alpha + \beta_{OWR,1}r_{i,t} + \beta_{OWR,2}CPIE_{OWR,t} + \beta_{OWR,3}(r_{i,t} \times CPIE_{OWR,t}) + \varepsilon_{i,t+1}$ , and  $r_{i,t+1} = \alpha + \beta_{EPIN,1}r_{i,t} + \beta_{EPIN,2}CPIE_{EPIN,t} + \beta_{EPIN,3}(r_{i,t} \times CPIE_{EPIN,t}) + \varepsilon_{i,t+1}$ .

In the above regressions,  $r_{i,t}$  is the open-to-open, risk adjusted return ( $r_{i,d,t} + r_{i,o,t}$ ) on day  $t$ . Thus, there is no overlap between the intraday and overnight returns that are used to compute  $CPIE_{OWR,i,t}$  on day  $t$  and the return on day  $t + 1$ . The coefficients  $\beta_{OWR,2}$  and  $\beta_{EPIN,2}$  reflect the impact of the model’s  $CPIE$  on the correlation between the return on day  $t$  and the return the next trading day. We estimate the regressions above using a panel regression approach including firm and year fixed effects with standard errors clustered by firm and year. Table 7 reports the coefficient estimates and t-statistics for these regressions. The results in Table 7 show that the estimates for both  $\beta_{OWR,2}$  and  $\beta_{EPIN,2}$  are positive

and significant, indicating that both  $CPIE_{EPIN}$  and  $CPIE_{OWR}$  are associated with future return continuation. To see this note that both regressions show a tendency of daily returns to reverse because the coefficients on lagged returns in both regressions are negative. However, a one standard deviation shock to  $CPIE_{OWR}$  is associated with a 0.02 ( $0.08 \times 0.25$ ) decline in the subsequent reversal, while a one standard deviation shock to  $CPIE_{EPIN}$  is associated with only a 0.003 ( $0.006 \times 0.49$ ) drop in the subsequent reversal. Thus, while the point estimates for both the OWR and EPIN models suggest that  $CPIE_{EPIN}$  and  $CPIE_{OWR}$  capture information that has a persistent impact on prices, the effect is ten times stronger with the OWR  $CPIE$ . We view this as further evidence that including the price response mechanism allows researchers to make stronger inferences about private information arrival.

## 4 Conclusion

The  $PIN$  measure, developed in the seminal work of Easley and O'Hara (1987), Easley, Kiefer, O'Hara, and Paperman (1996), and Easley, Kiefer, and O'Hara (1997), is arguably the most widely used measure of information asymmetry in the accounting, corporate finance and asset pricing literature today. Recent work however suggests that  $PIN$  fails to capture private information (e.g. Aktas, de Bodt, Declerck, and Van Oppens (2007), Benos and Jochev (2007), and Collin-Dufresne and Fos (2014a)). This paper analyzes why the model might incorrectly identify informed trade.

Our findings indicate that the  $PIN$  model fits the data so poorly that it mechanically groups *all* sources of variation in turnover (e.g. disagreement, calendar effects, portfolio rebalancing, taxation, etc.) under the umbrella of private information arrival. This is at odds with a vast literature that suggests turnover varies for many reasons unrelated to the arrival of private information. This failure of the  $PIN$  model is particularly strong after the increase in turnover in the early 2000s. In fact, after 2002 for the median stock in our sample, the  $PIN$  model is essentially equivalent to a naïve model that assigns a probability of one to the arrival of private information on any day where turnover is above average and zero probability to the arrival of private information on any other day. These findings suggest some important insights for future research that tests, constructs, or uses proxies for informed trade.

Our results suggest that event study based tests of private information proxies (e.g. Easley, Engle, O’Hara, and Wu (2008) and Brennan, Huh, and Subrahmanyam (2015)) can be misleading if one fails to account for the fact that patterns in private information measures may simply reflect event-related patterns in turnover that have nothing to do with private information arrival. For instance, Brennan, Huh, and Subrahmanyam (2015) interpret the fact that their  $CPIE_{PIN}$  measures are higher after earnings announcements than before as evidence of informed trading. However, we show that  $CPIE_{PIN}$  is mechanically related to turnover. This suggests that the findings in Brennan, Huh, and Subrahmanyam (2015) can simply be attributed to the fact that turnover is typically much higher after earnings announcements.

Our findings also suggest that future research aimed at building measures of informed trade should focus on the price response mechanism in addition to net order because order flow, however well modeled, appears insufficient to identify private information. Specifically, we use three different methods to compare the OWR model, which infers the arrival of private information from returns and order flow, with an extension of the PIN model (the EPIN model), which is solely based on order flow but corrects the PIN model’s mechanical association of private information arrival with variation in turnover. The OWR model performs better than the EPIN model in all three tests. First, the EPIN model actually predicts a decrease in private information arrival before earnings announcements while the OWR model captures a pattern of increasing private information arrival prior to the announcement and a marked decrease after the announcement. Second,  $CPIE_{OWR}$  predicts periods of opportunistic insider trading and decreases dramatically immediately following the insider trades, while  $CPIE_{EPIN}$  displays no such clear pattern around these events. Lastly, the relation between  $CPIE_{OWR}$  and future return continuation is ten times larger than that of the  $CPIE_{EPIN}$ .

Our findings also suggest that future research in corporate finance, accounting, or asset pricing that uses information asymmetry measures should consider using proxies for private information based on the OWR model, for instance  $CPIE_{OWR}$  or its  $\alpha$ , instead of using proxies based on the PIN model (e.g.  $PIN$ ).

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Table 1: **Summary Statistics.** This table summarizes the full sample and event day ( $t=0$ ) returns, order imbalance, and number of buys and sells. We compute intraday and overnight returns as well as daily buys and sells for stocks between 1993 and 2012 using data from the NYSE TAQ database. Following Odders-White and Ready (2008), we compute the intraday return,  $r_d$ , at time  $t$  as the volume-weighted average price at  $t$  (VWAP) minus the opening quote midpoint at  $t$  plus dividends at time  $t$ , all divided by the opening quote midpoint at time  $t$ . We compute the overnight return,  $r_o$ , at  $t$  as the opening quote midpoint at  $t + 1$  minus the VWAP at  $t$ , all divided by the opening quote midpoint at  $t$ . We compute  $y_e$  as the daily total volume of buys minus total volume of sells, divided by the total volume. For the PIN and EPIN models, we use the daily total number of buys and sells. Our sample of earnings announcements includes all CRSP/COMPUSTAT firms listed in NYSE between 1995–2009 for which we have exact timestamps collected from press releases in Factiva which fall within a  $[-1,0]$  window relative to COMPUSTAT earnings announcement dates. Opportunistic insider trades are defined as in Cohen, Malloy, and Pomorski (2011).

(a) Full Sample

	N	Mean	Std	Q1	Median	Q3
$y_e$	5,286,191	2.766%	31.259%	-10.433%	3.282%	18.996%
$r_d$	5,286,191	-0.004%	1.500%	-0.707%	-0.024%	0.680%
$r_o$	5,286,191	0.003%	1.297%	-0.566%	-0.024%	0.525%
# Buys	5,286,191	1,876	6,917	37	220	1,128
# Sells	5,286,191	1,843	6,894	36	194	1,033

(b) Earnings Announcements

	N	Mean	Std	Q1	Median	Q3
$y_e$	21,979	5.099%	22.122%	-4.787%	4.373%	16.400%
$r_d$	21,979	0.002%	2.424%	-1.252%	-0.004%	1.271%
$r_o$	21,979	0.075%	2.313%	-1.042%	0.013%	1.153%
# Buys	21,979	4,572	13,491	223	956	3,421
# Sells	21,979	4,465	13,546	191	831	3,165

(c) Opportunistic Insider Trades

	N	Mean	Std	Q1	Median	Q3
$y_e$	32,676	4.980%	20.425%	-5.106%	3.874%	15.353%
$r_d$	32,676	0.151%	1.566%	-0.632%	0.086%	0.865%
$r_o$	32,676	0.056%	1.247%	-0.467%	0.020%	0.528%
# Buys	32,676	3,852	10,645	354	1,129	3,478
# Sells	32,676	3,787	10,554	300	996	3,303

Table 2: **PIN Parameter Estimates.** This table summarizes parameter estimates of the PIN model for 21,206 PERMNO-Year samples from 1993 to 2012.  $\alpha$  represents the average unconditional probability of an information event at the daily level.  $\delta$  represents the probability of good news, and  $1 - \delta$  represents the probability of bad news.  $\epsilon_B$  and  $\epsilon_S$  represent the expected number of daily buys and sells given no private information.  $\mu$  represents the expected additional order flows given an information event.  $\overline{CPIE}$  and  $\text{Std}(CPIE)$  are the PERMNO-Year mean and standard deviation of  $CPIE_{PIN}$ .

	N	Mean	Std	Q1	Median	Q3
$\alpha$	21,206	0.372	0.122	0.291	0.375	0.445
$\delta$	21,206	0.607	0.209	0.484	0.625	0.762
$\epsilon_B$	21,206	1,625	5,388	33	193	1,039
$\epsilon_S$	21,206	1,596	5,369	35	186	956
$\mu$	21,206	312	593	43	160	314
$\overline{CPIE}$	21,206	0.382	0.135	0.293	0.379	0.449
$\text{Std}(CPIE)$	21,206	0.451	0.052	0.427	0.470	0.490

Table 3: **PIN Model Regressions.** This table reports real and simulated regressions of the  $CPIE_{PIN}$  on absolute order imbalance ( $|B - S|$ ), and order imbalance squared ( $|B - S|^2$ ). In Panel A, we simulate 1,000 instances of the PIN model for each PERMNO-Year in our sample (1993–2012) and report mean standardized estimates for the median stock, along with 5%, 50%, and 95% values of the  $R^2$  ( $R_{inc.}^2$ ) values. We compute the incremental  $R_{inc.}^2$  as the  $R^2$  attributed to  $turn$  and  $turn^2$  in an extended regression model. In Panel B, we report standardized estimates for the median stock using real data, along with the median  $R^2$  and  $R_{inc.}^2$  values, and tests of the null hypothesis that the observed relation between  $CPIE_{PIN}$  and  $turn$  is consistent with the PIN model. The  $p$ -value of is the mean probability under the null of observing an  $R_{inc.}^2$  at least as large as what is observed in the real data. The % Rej. is the fraction of stocks for which we reject the null hypothesis at the 5% level.

(a) Simulated Data

	$\beta$		$t$		$R^2$			$R_{inc.}^2$		
	$ B - S $	$ B - S ^2$	$ B - S $	$ B - S ^2$	5%	50%	95%	5%	50%	95%
1993	0.437	-0.079	(10.31)	(-1.80)	71.13%	76.09%	80.38%	7.17%	10.57%	15.25%
1994	0.422	-0.072	(9.63)	(-1.67)	67.49%	73.26%	78.11%	9.39%	13.47%	18.55%
1995	0.410	-0.058	(9.68)	(-1.36)	70.32%	75.39%	79.85%	7.64%	11.39%	16.02%
1996	0.432	-0.085	(9.89)	(-1.90)	69.02%	74.28%	78.87%	8.32%	12.17%	16.97%
1997	0.450	-0.089	(10.30)	(-1.98)	71.99%	76.93%	81.12%	7.36%	10.76%	14.79%
1998	0.482	-0.104	(10.79)	(-2.36)	74.32%	78.71%	82.46%	6.65%	9.53%	13.30%
1999	0.484	-0.112	(11.03)	(-2.47)	75.62%	79.96%	83.46%	6.49%	9.36%	12.92%
2000	0.529	-0.137	(11.88)	(-3.00)	79.78%	83.36%	86.15%	4.98%	7.47%	10.45%
2001	0.638	-0.217	(13.97)	(-4.61)	83.34%	86.13%	88.57%	4.17%	6.00%	8.35%
2002	0.695	-0.260	(14.11)	(-5.30)	82.61%	85.53%	88.06%	4.83%	6.92%	9.54%
2003	0.665	-0.244	(12.38)	(-4.52)	78.88%	82.36%	85.36%	7.90%	10.56%	13.79%
2004	0.650	-0.223	(11.49)	(-4.16)	77.84%	81.38%	84.59%	8.92%	11.67%	15.03%
2005	0.658	-0.220	(12.59)	(-4.46)	80.47%	83.59%	86.45%	7.69%	10.09%	12.95%
2006	0.650	-0.221	(11.96)	(-4.35)	80.31%	83.36%	86.18%	7.76%	10.29%	13.50%
2007	0.632	-0.222	(9.40)	(-4.07)	79.72%	83.35%	86.15%	8.53%	10.93%	14.05%
2008	0.666	-0.235	(12.29)	(-4.83)	82.44%	85.25%	88.00%	6.83%	9.15%	11.78%
2009	0.709	-0.269	(14.37)	(-5.70)	84.29%	86.87%	89.20%	6.22%	8.28%	10.57%
2010	0.704	-0.261	(14.60)	(-5.68)	84.99%	87.41%	89.64%	5.66%	7.55%	9.89%
2011	0.671	-0.234	(14.13)	(-5.21)	85.91%	88.25%	90.21%	5.34%	7.28%	9.39%
2012	0.693	-0.251	(14.92)	(-5.62)	85.68%	87.98%	90.34%	5.22%	7.22%	9.50%

Table 3: PIN Model Regressions. Continued.

(b) Real Data

	$\beta$		$t$		$R^2$		$R_{inc}^2$	
	$ B - S $	$ B - S ^2$	$ B - S $	$ B - S ^2$	50%	50%	$p$ -value	% Rej.
1993	0.300	-0.073	(5.98)	(-1.43)	35.76%	36.20%	2.57%	94.07%
1994	0.264	-0.047	(5.28)	(-0.92)	32.82%	40.02%	3.36%	92.17%
1995	0.280	-0.061	(5.77)	(-1.29)	34.20%	36.97%	5.05%	89.29%
1996	0.277	-0.065	(5.69)	(-1.28)	30.92%	38.97%	3.85%	92.30%
1997	0.283	-0.073	(5.67)	(-1.36)	30.80%	38.86%	3.54%	92.99%
1998	0.274	-0.059	(5.26)	(-1.09)	30.12%	39.58%	3.54%	93.67%
1999	0.280	-0.059	(5.21)	(-1.08)	29.05%	39.46%	3.29%	94.29%
2000	0.300	-0.079	(5.48)	(-1.39)	29.99%	39.08%	2.59%	95.63%
2001	0.339	-0.111	(5.67)	(-1.87)	29.44%	39.39%	3.53%	94.76%
2002	0.279	-0.058	(4.09)	(-0.85)	23.05%	44.28%	5.59%	91.48%
2003	0.247	-0.032	(3.57)	(-0.47)	21.97%	41.86%	9.55%	84.87%
2004	0.211	-0.005	(3.14)	(-0.08)	19.55%	45.22%	8.78%	86.21%
2005	0.254	-0.053	(3.81)	(-0.81)	19.42%	46.29%	9.21%	85.47%
2006	0.251	-0.066	(3.80)	(-0.96)	16.95%	48.44%	10.83%	85.30%
2007	0.271	-0.104	(4.01)	(-1.57)	14.30%	50.32%	14.04%	82.00%
2008	0.268	-0.111	(4.00)	(-1.66)	13.78%	50.97%	11.49%	86.08%
2009	0.280	-0.117	(4.15)	(-1.74)	14.59%	49.91%	10.08%	87.58%
2010	0.291	-0.124	(4.39)	(-1.82)	15.96%	47.64%	10.62%	87.45%
2011	0.295	-0.131	(4.56)	(-2.03)	15.94%	46.60%	11.14%	86.90%
2012	0.319	-0.145	(4.96)	(-2.23)	17.56%	45.61%	13.31%	85.12%

Table 4: **PIN Regressions Around Earnings Announcements.** This table reports regression results for  $CPIE_{PIN}$  around Earnings Announcements. For each announcing firm in our sample we run regressions of  $CPIE_{PIN}$  on absolute order imbalance ( $|B - S|$ ) and absolute order imbalance squared ( $|B - S|^2$ ) from  $[-20, +20]$  and report median estimates across all the events. We compute the incremental  $R_{inc}^2$  as the increase in  $R^2$  attributed to  $turn$  and  $turn^2$  in an extended regression model. We report standardized coefficients.

$\beta$		$t$		$R^2$	$R_{inc}^2$
$ B - S $	$ B - S ^2$	$ B - S $	$ B - S ^2$	50%	50%
0.143	-0.032	(1.07)	(-0.35)	15.42%	44.44%

Table 5: **EPIN Parameter Estimates.** This table summarizes parameter estimates of the EPIN model for 21,206 PERMNO-Year samples from 1993 to 2012.  $\alpha$  represents the average unconditional probability of an information event at the daily level.  $\delta$  represents the probability of good news, and  $1 - \delta$  represents the probability of bad news. The total number of trades in any given day ( $t$ ) is drawn from a Poisson distribution with intensity  $\lambda_t$ , where  $\lambda_t$  is draw from a Gamma distribution with shape parameter  $r$  and scale parameter  $p/(1-p)$ . The number of buys on a day with no private information is draw from a Poisson distribution with intensity  $\theta \times \lambda_t$ . On days with negative news, the number of buys is drawn from a Poisson with intensity  $\theta/(1 + \eta) \times \lambda_t$ .  $\overline{CPIE}$  and  $\text{Std}(CPIE)$  are the PERMNO-Year mean and standard deviation of  $CPIE_{EPIN}$ .

	N	Mean	Std	Q1	Median	Q3
$\alpha$	21,206	0.493	0.088	0.448	0.498	0.543
$\delta$	21,206	0.495	0.184	0.372	0.492	0.616
$r$	21,206	7.210	4.724	4.056	5.976	8.960
$p$	21,206	0.948	0.080	0.932	0.984	0.997
$\theta$	21,206	0.515	0.049	0.493	0.514	0.546
$\eta$	21,206	0.316	0.242	0.152	0.240	0.413
$\overline{CPIE}$	21,206	0.494	0.087	0.449	0.499	0.543
$\text{Std}(CPIE)$	21,206	0.414	0.082	0.367	0.445	0.478

Table 6: **OWR Parameter Estimates.** This table summarizes parameter estimates of the OWR model for 21,206 PERMNO-Year samples from 1993 to 2012.  $\alpha$  represents the average unconditional probability of an information event at the daily level.  $\sigma_u$  represents the standard deviation of the order imbalance due to uninformed traders, which is observed with normally distributed noise with variance  $\sigma_z^2$ .  $\sigma_i$  represents the standard deviation of the informed trader's private signal.  $\sigma_{pd}$  and  $\sigma_{po}$  represent the standard deviation of intraday and overnight returns, respectively.  $\overline{CPIE}$  and  $\text{Std}(CPIE)$  are the PERMNO-Year mean and standard deviation of  $CPIE_{OWR}$ .

	N	Mean	Std	Q1	Median	Q3
$\alpha$	21,206	0.437	0.257	0.214	0.436	0.639
$\sigma_u$	21,206	0.075	0.068	0.022	0.062	0.109
$\sigma_z$	21,206	0.239	0.143	0.137	0.221	0.332
$\sigma_i$	21,206	0.030	0.286	0.013	0.021	0.027
$\sigma_{pd}$	21,206	0.010	0.005	0.006	0.009	0.012
$\sigma_{po}$	21,206	0.006	0.004	0.004	0.006	0.008
$\overline{CPIE}$	21,206	0.451	0.258	0.227	0.455	0.656
$\text{Std}(CPIE)$	21,206	0.137	0.047	0.109	0.142	0.171

Table 7: **Return Reversals.** This table reports regressions of the daily return at time  $t + 1$  on the return,  $CPIE$  ( $CPIE_{EPIN}$  or  $CPIE_{OWR}$ ), and the interaction at time  $t$ . Returns are measured from open to open and they are computed as the sum of the intraday ( $r_d$ ) and overnight returns ( $r_o$ ). We include stock and year fixed effects and cluster standard errors by stock and year. \* indicates statistical significance at the 10% level, \*\* at the 5%, and \*\*\* at the 1% level.

	$r_{t+1}$	
	OWR	EPIN
$r_t$	-8.883*** (-6.88)	-6.955*** (-6.91)
$CPIE_t$	0.0136*** (4.36)	
$CPIE_t \times r_t$	2.417*** (4.16)	
$CPIE_t$		0.00704*** (4.03)
$CPIE_t \times r_t$		0.271** (2.58)
$R^2(\%)$	0.61	0.54
Obs.	5,284,078	5,284,078

Figure 1: **PIN Tree.** For a given trading day, private information arrives with probability  $\alpha$ . When there is no private information, buys and sells are Poisson with intensity  $\epsilon_B$  and  $\epsilon_S$ . Private information is good news with probability  $\delta$ . The expected number of buys (sells) increases by  $\mu$  in case of good (bad) news.

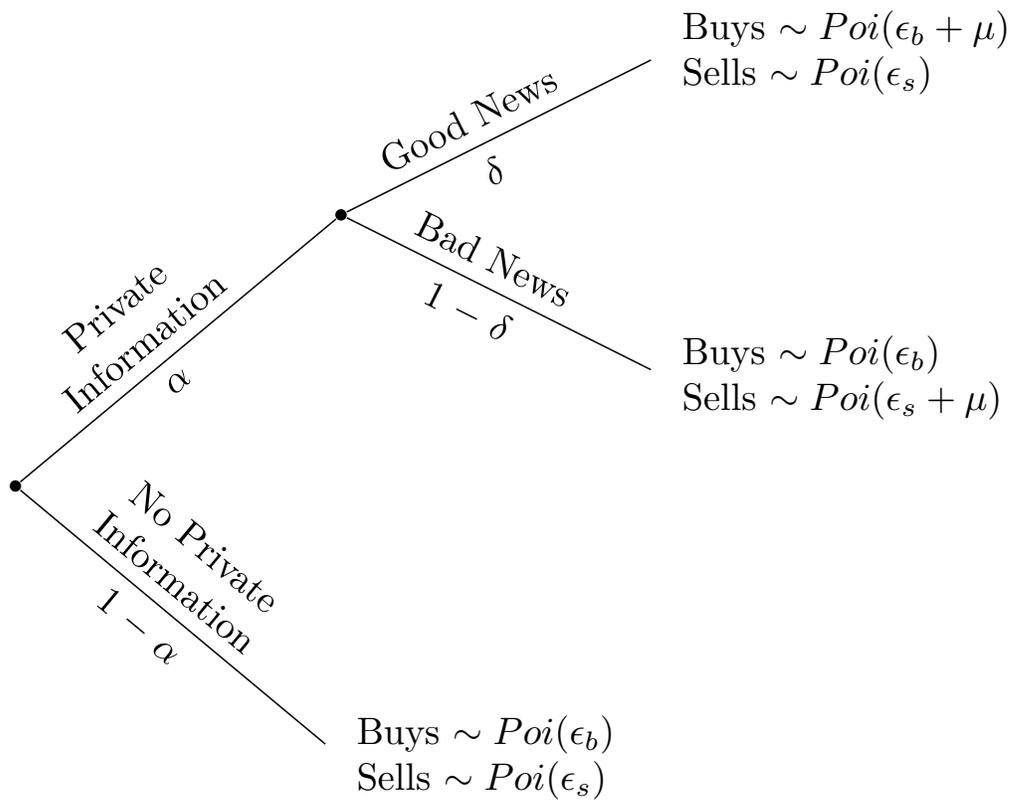
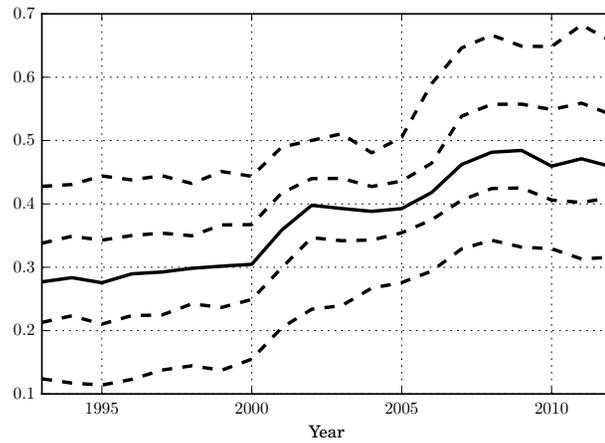
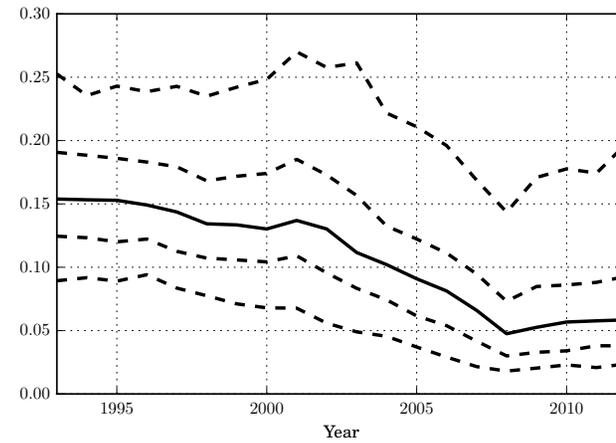


Figure 2: *PIN Parameters*. This figure shows the distribution of yearly  $\alpha$ , *PIN*, and  $\mu, \epsilon_B, \epsilon_S$  parameter estimates for the PIN model. The solid black line represents the median value, and the dotted lines represent the 5, 25, 75, and 95 percentiles.

(a) PIN  $\alpha$



(b) *PIN*



(c) PIN Parameters

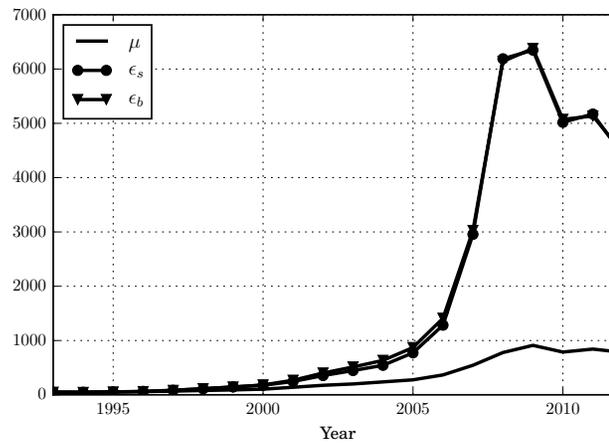
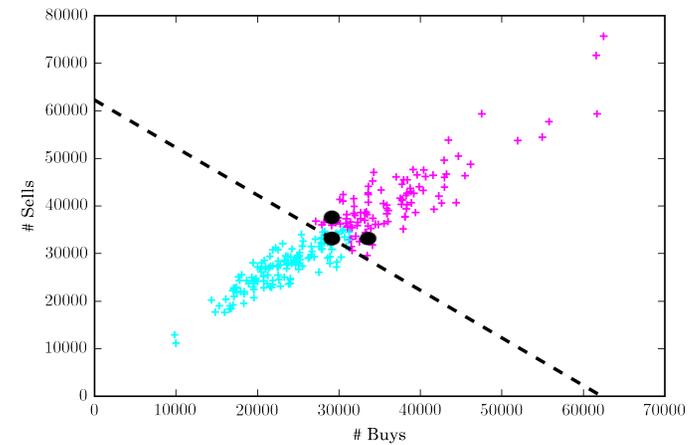
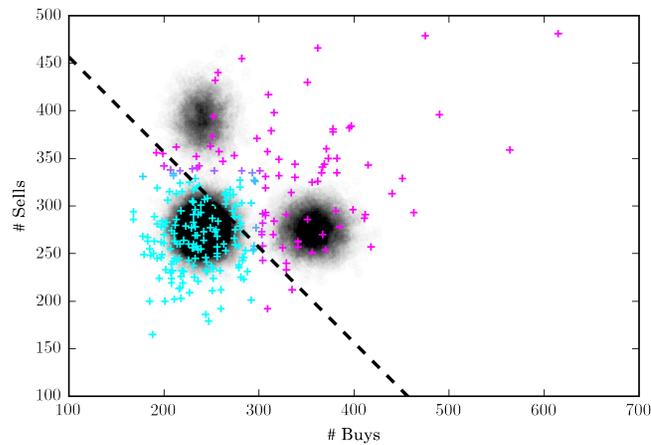


Figure 3: **XOM EO**. This figure compares the real and simulated data for XOM in 1993 and 2012 using the PIN model. In Panels A and B, the real data are marked as +. The real data are shaded according to the  $CPIE_{PIN}$ , with darker markers (+ magenta) representing high and lighter markers (+ cyan) low  $CPIEs$ . High (low) probability states in the simulated data appear as a dark (light) “cloud” of points. The PIN model has three states: no news, good news, and bad news. All the observations below (above) the dashed lines in Panels A and B have turnover below (above) the annual mean of daily turnover. Panels C and D plot the  $CPIEs$  for the real data as a function of turnover along with a dashed line indicating the mean turnover.

(a) XOM 1993

(b) XOM 2012



(c) XOM 1993

(d) XOM 2012

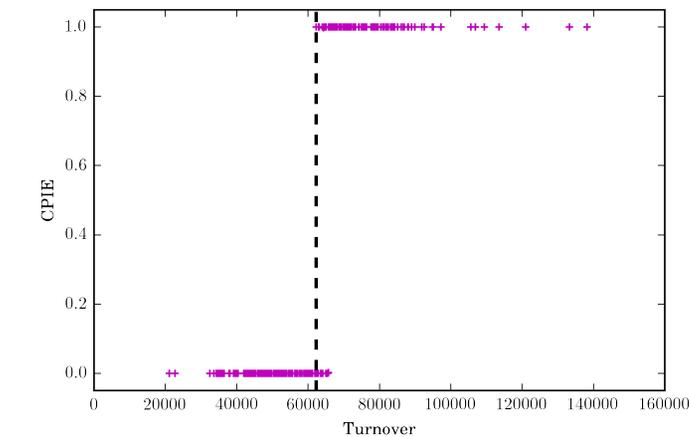
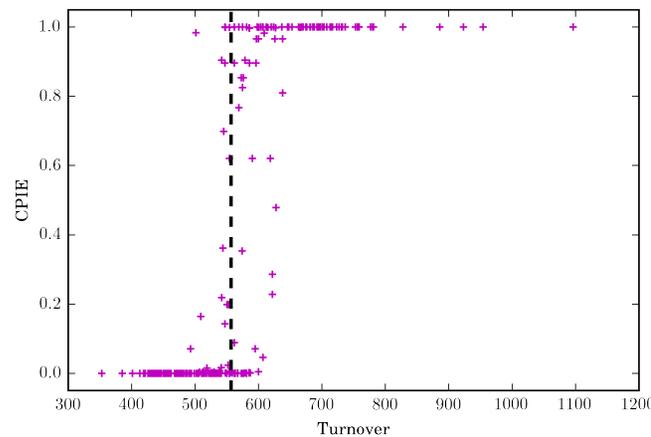
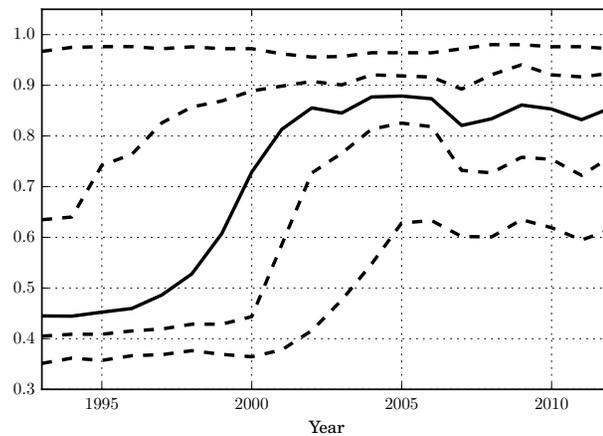


Figure 4: **Breakdown of the PIN Model.** Panel A shows the distribution of the percent of trading days in a year in which the PIN model identifies private information essentially in the same way as the naive identification scheme. That is, Panel A plots the percentage of days where the  $|CPIE_{PIN} - CPIE_{Naive}| < 10^{-10}$ .  $CPIE_{Naive}$  is one for a given stock-day if turnover is higher than the annual mean of daily turnover, and is zero otherwise. Panel B shows the distribution of the percent of days where the likelihood, given the model parameters and observed order flow data is less than  $10^{-10}$  — days, according to the model, with near-zero probability of occurring. The solid black line represents the median stock, and the dashed lines represent the 5, 25, 75, and 95 percentiles.

(a) Days with  $CPIE_{PIN} \approx CPIE_{Naive}$



(b) Days with Near-Zero Probability

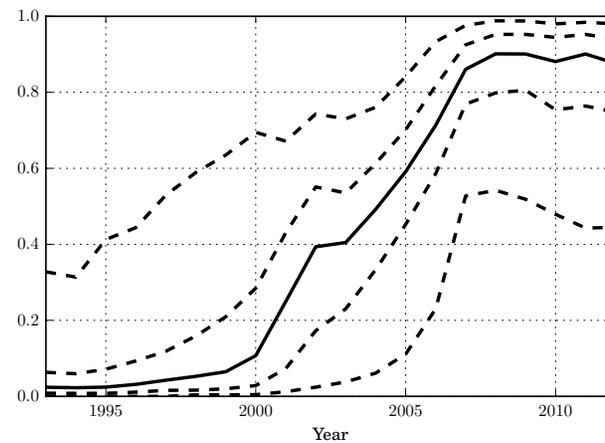
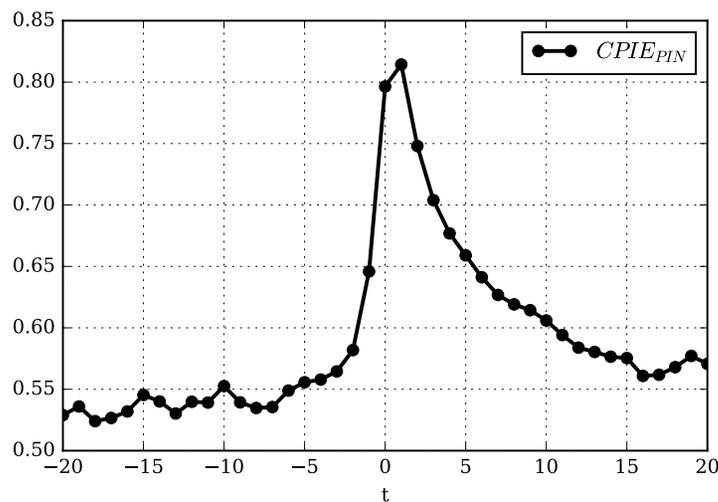
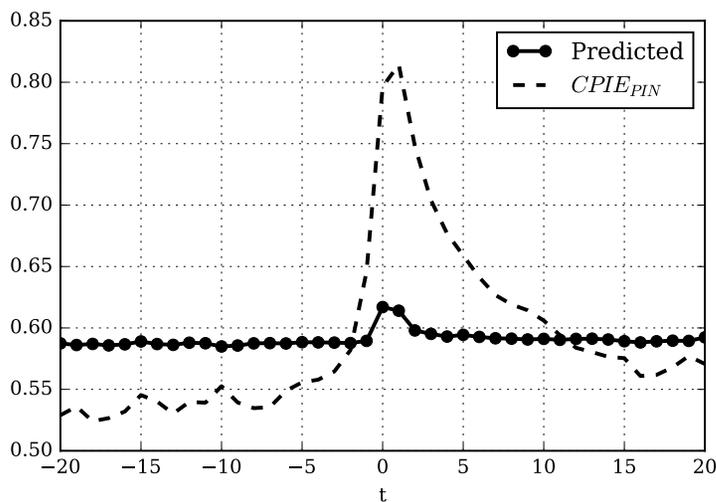


Figure 5: **Earnings Announcements - PIN**. Panel A shows the average  $CPIE_{PIN}$  for the PIN model in event time surrounding earnings announcements. Panels B and C compare the average  $CPIE_{PIN}$  with the  $CPIE_{PIN}$  predicted with either the absolute order imbalance ( $|B - S|$ ) or turnover ( $turn$ ), respectively. To obtain the predictions, we run regressions of daily  $CPIE_{PIN}$  on  $|B - S|$  or  $turn$ , and their respective squared terms.

(a)  $CPIE_{PIN}$



(b) Prediction using  $|B - S|$  and  $|B - S|^2$



(c) Prediction using  $turn$  and  $turn^2$

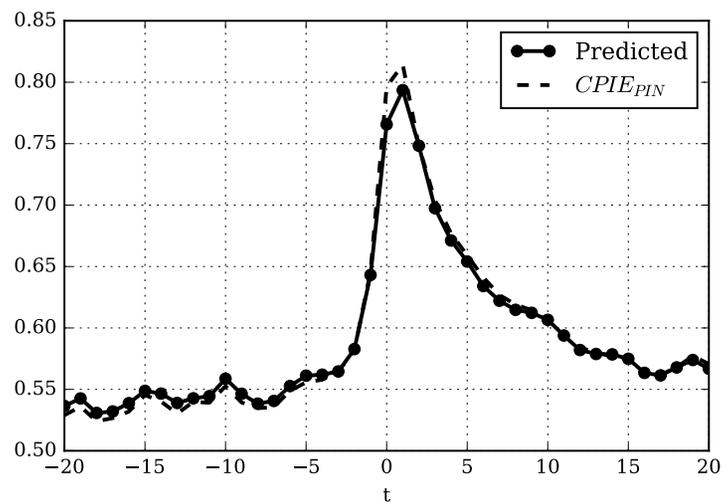


Figure 6: **EPIN Tree**. Panel A presents a re-parameterization of the PIN model in terms of ratio of the intensity of uninformed buyer initiated trades to the intensity of the total number of uninformed trades ( $\theta = \epsilon_B/(\epsilon_B + \epsilon_S)$ ), the ratio of the expected number of informed to uninformed trades on days where there is private information ( $\eta = \mu/(\epsilon_B + \epsilon_S)$ ), and the overall intensity of the number of buys plus sells as a function of the arrival of private information ( $\lambda(I_{i,t})$ ). Panel B presents the EPIN model. The EPIN model extends the PIN model by allowing the intensity of the number of trades on a given day  $t$  ( $\lambda_t$ ) to be drawn from a Gamma distribution with location and scale parameters  $r$  and  $p/(1-p)$ , respectively. The information structure remains the same as the one in the PIN model. For a given trading day, private information arrives with probability  $\alpha$ . When there is no private information, the number of buys (sells) is distributed as a Poisson with intensity  $\theta \times \lambda_t$  ( $(1-\theta) \times \lambda_t$ ). Private information is good (bad) news with probability  $\delta$  ( $1-\delta$ ). When there is good news, the number of sells (buys) is Poisson with intensity  $\frac{(1-\theta)}{1+\eta} \lambda_t$  ( $(1 - \frac{(1-\theta)}{1+\eta}) \lambda_t$ ). When there is bad news, the number of buys (sells) is Poisson with intensity  $\frac{\theta}{1+\eta} \lambda_t$  ( $(1 - \frac{\theta}{1+\eta}) \lambda_t$ ).

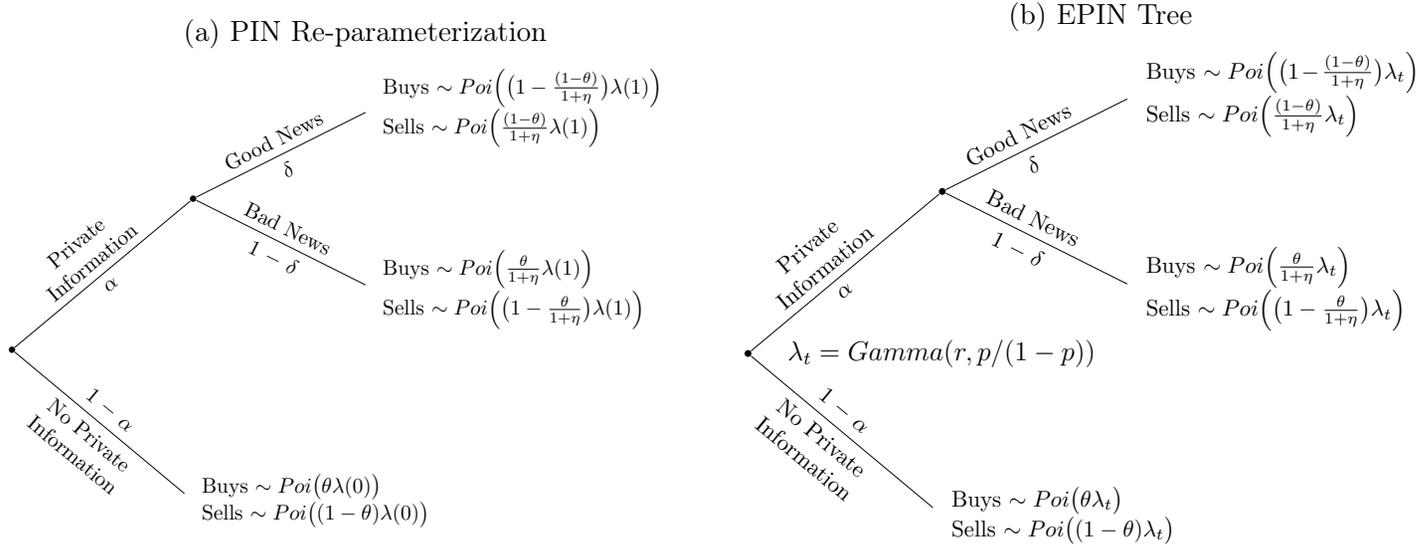
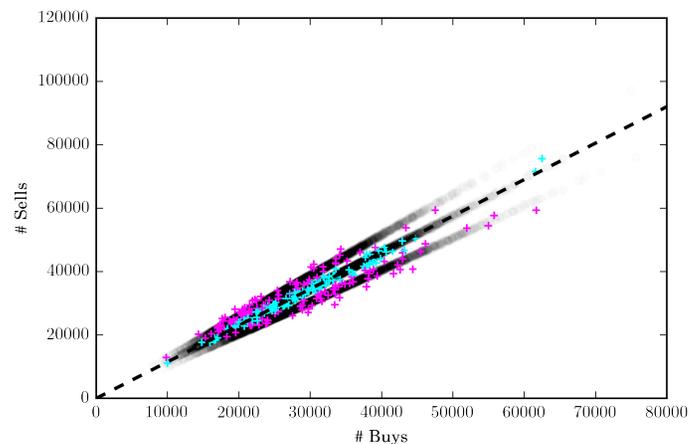
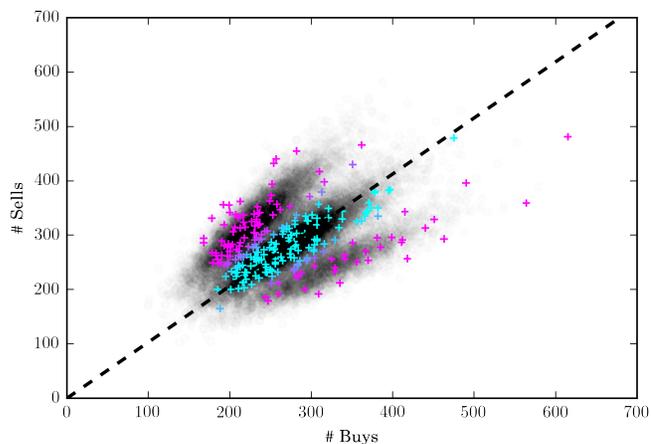


Figure 7: **XOM EPIN**. This figure compares the real and simulated data for XOM in 1993 using the EPIN model. In Panels A and B, the real data are marked as +. The real data are shaded according to the  $CPIE_{EPIN}$ , with darker markers (+ magenta) representing high and lighter markers (+ cyan) low  $CPIEs$ . The simulated data points are represented by transparent dots, such that high probability states appear as a dense, dark “cloud” of points, and low probability states appear as a light “cloud” of points. The EPIN model has three states: no news, good news, and bad news. Panels C and D plot the  $CPIE$  values for the real data as a function of turnover along with a dashed vertical line indicating the annual mean of daily turnover.

(a) XOM 1993

(b) XOM 2012



(c) XOM 1993

(d) XOM 2012

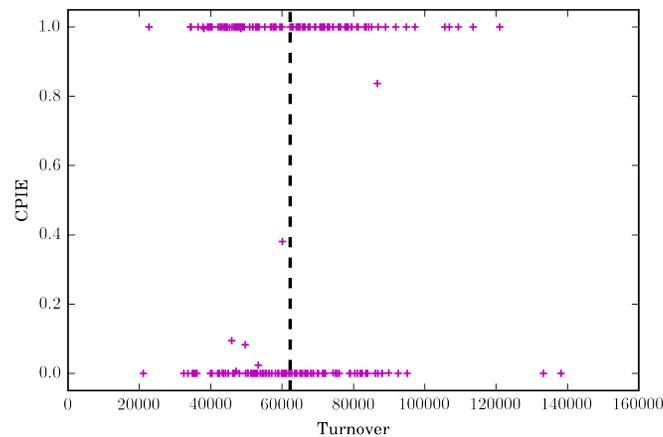
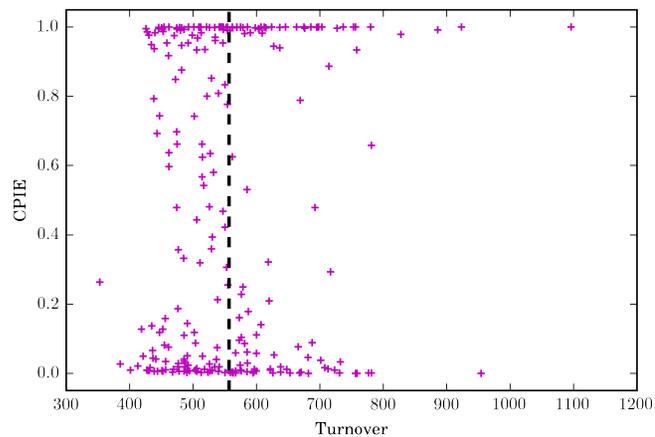


Figure 8: **OWR Tree.** In the OWR model, prior to markets opening, private information arrives with probability  $\alpha$ . Once markets open, investors submit their trades generating order imbalance ( $y_e$ ), and the intraday return ( $r_d$ ). After markets close, private information becomes public and is reflected in the overnight return ( $r_o$ ). The variables ( $y_e, r_d, r_o$ ) are normally distributed with mean zero and covariance  $\Sigma$ , where  $\Sigma$  is function of the information arrival indicator ( $I$ ). For instance, when there is no private information, there is a reversal in the returns ( $cov(r_d, r_o) < 0$ ) and when there is private information there is a continuation in the returns ( $cov(r_d, r_o) > 0$ ).

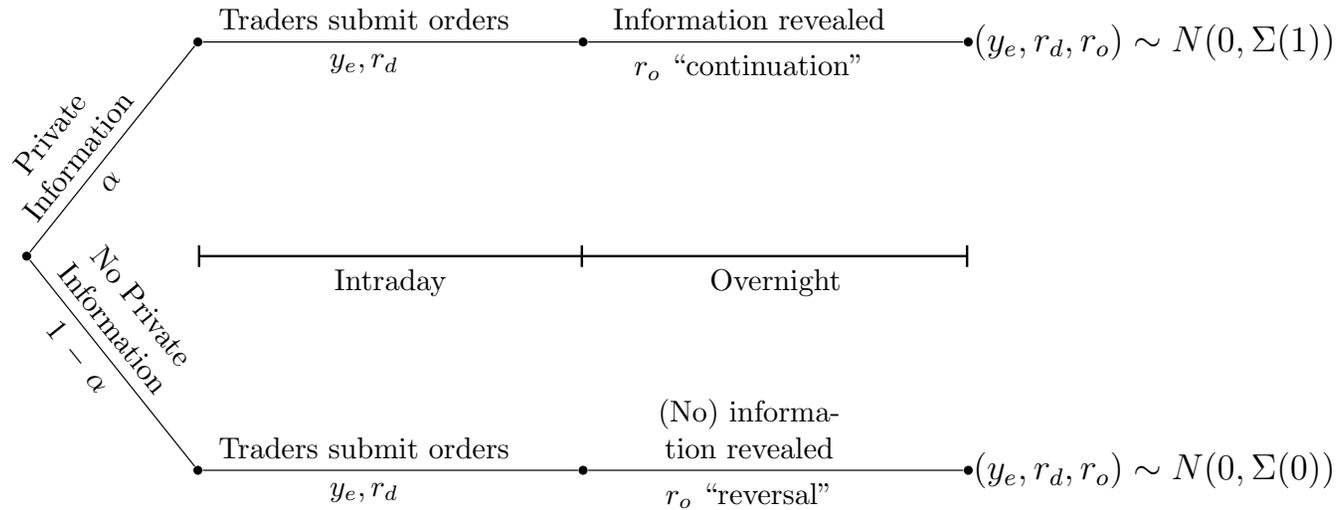


Figure 9: **OWR**  $\alpha$ . This figure shows the distribution of yearly  $\alpha$  parameter estimates for the OWR model. The solid black line represents the median value, and the dashed lines represent the 5, 25, 75, and 95 percentiles.

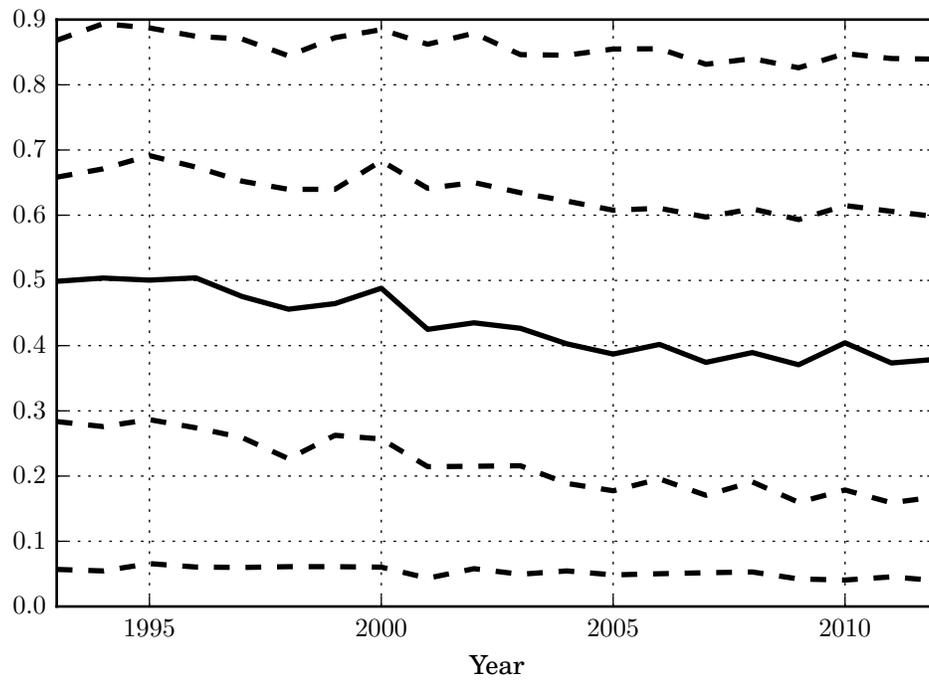
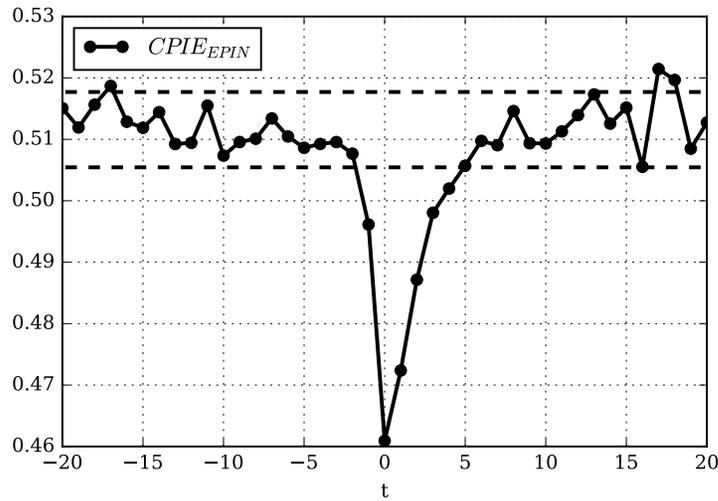


Figure 10: **Earnings Announcements.** Panel A (B) shows the average  $CPIE_{EPIN}$  ( $CPIE_{OWR}$ ) for the EPIN (OWR) model in event time surrounding earnings announcements.

(a)  $CPIE_{EPIN}$



(b)  $CPIE_{OWR}$

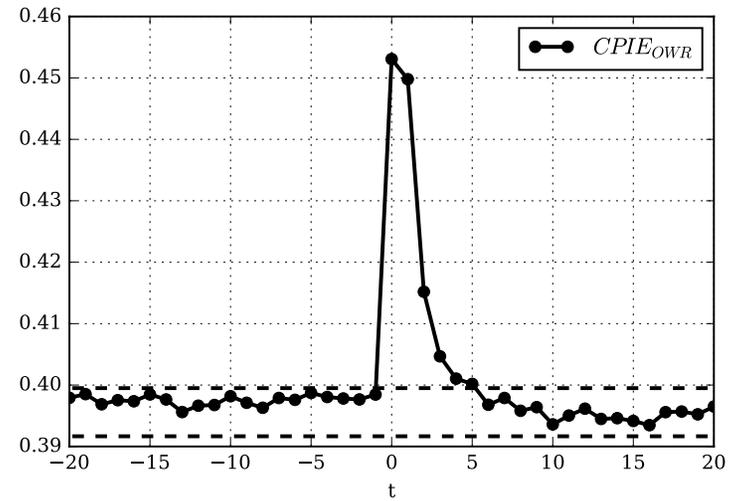


Figure 11: **Earnings Announcements - EPIN Decomposition.** Panels A and B compare the average  $CPIE_{EPIN}$  with the  $CPIE_{EPIN}$  predicted using either  $\frac{|B-S|}{B+S}$  or turnover ( $turn$ ), respectively. To obtain the predictions, we run regressions of daily  $CPIE_{EPIN}$  on  $\frac{|B-S|}{B+S}$  or  $turn$ , and their respective squared terms.

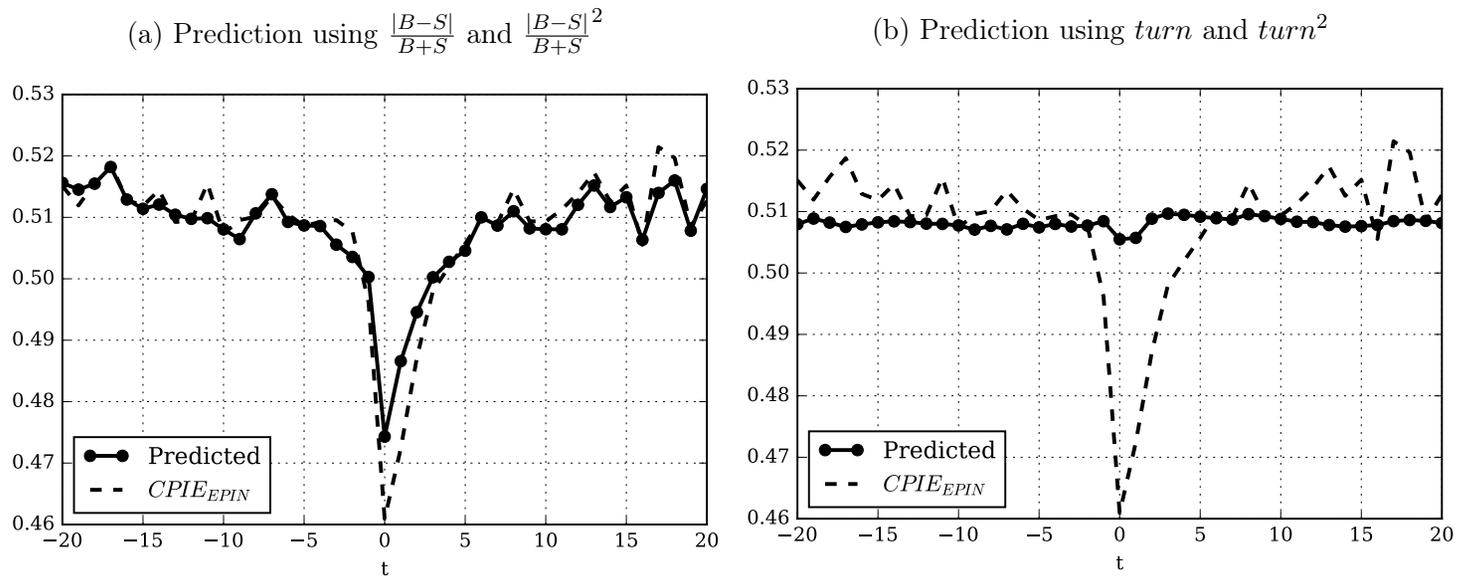
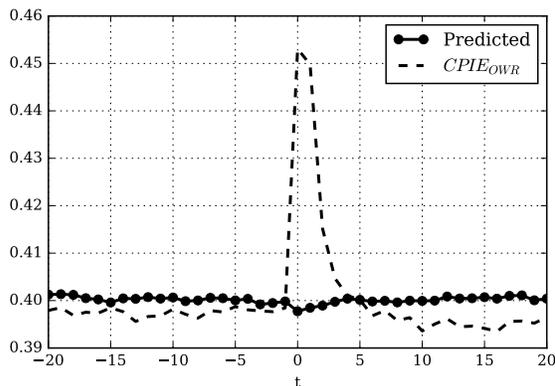
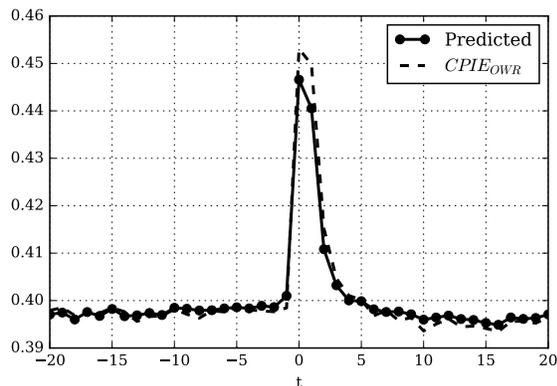


Figure 12: **Earnings Announcements - OWR Decomposition.** Panels A–F compare the average  $CPIE_{OWR}$  with the  $CPIE_{OWR}$  predicted using the squared and interaction terms of  $y_e$ ,  $r_d$ , and  $r_o$ .

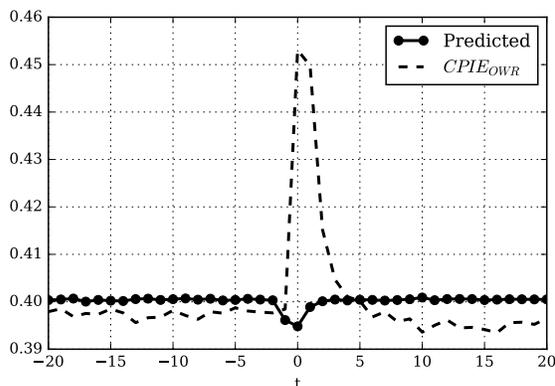
(a) Prediction using  $y_e^2$



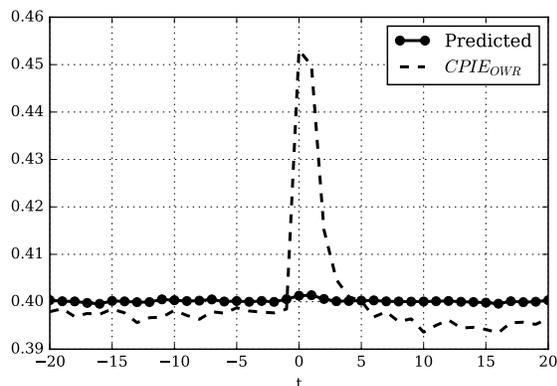
(b) Prediction using  $r_d^2$



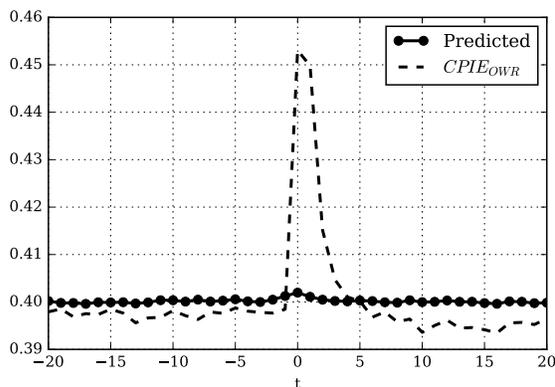
(c) Prediction using  $r_o^2$



(d) Prediction using  $y_e \times r_d$



(e) Prediction using  $y_e \times r_o$



(f) Prediction using  $r_d \times r_o$

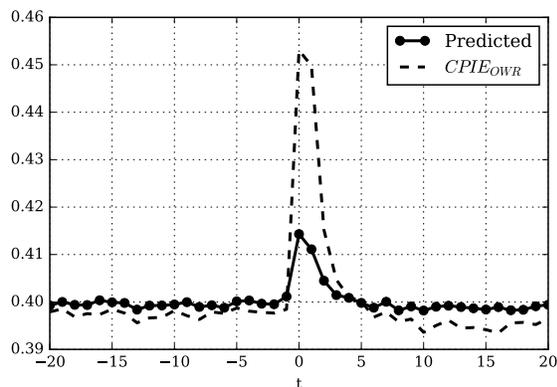


Figure 13: **Opportunistic Insider Trades.** Panel A (B) shows the average  $CPIE_{EPIN}$  ( $CPIE_{OWR}$ ) for the EPIN (OWR) model in event time surrounding opportunistic insider trades.

