The Cross Section of the Monetary Policy Announcement Premium

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We show that monetary policy announcements require a significant risk compensation in the cross section of equity returns. Empirically, we use the expected reduction in option-implied variance upon FOMC announcements to measure the sensitivity of stock returns to monetary policy announcement surprises. A long-short portfolio formed on the sensitivity measure produces an average FOMC announcement-day return of 31.67 bps, which is both statistically and economically significant and is robust after controlling for standard risk factors. We develop an equilibrium model to account for the dynamics of implied variances and the cross section of returns of portfolios sorted on the expected implied variance reduction following FOMC announcements.

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1 Introduction

Pre-scheduled monetary policy announcements are associated with large realizations of equity market excess returns on announcement days (see, e.g., Savor and Wilson (2013) and Lucca and Moench (2015)). Ai and Bansal (2018) demonstrate that, interpreted as risk premiums, the substantial equity market returns realized on FOMC announcement days imply that preferences in macro and finance models must satisfy generalized risk sensitivity. Because the choice of preferences is of fundamental importance in welfare analysis and policy evaluations, the existence of the monetary policy announcement premium not only is important for understanding equity market risk compensation but also provides guidance for policy-making.

This paper uses empirical evidence from the cross section of equity returns to examine the existence of the monetary policy announcement premium. We show that exposure to monetary policy announcement surprises is priced in the cross section of equity returns. As a result, market expectations about firms' sensitivity to monetary policy announcements strongly predict their equity returns on FOMC announcement days. A long-short portfolio formed on our monetary policy sensitivity measure produces an average announcement-day return of 31.67 bps, which is both statistically and economically significant, even after controlling for standard risk factors.

To evaluate whether firms with differing levels of sensitivity to monetary policy announcements also have differing expectations about their returns on announcement days, we first develop a novel measure of market expectations of sensitivity to monetary policy surprises. A natural choice would be the elasticity (or β) of firms' equity returns with respect to measures of monetary policy surprises. However, because FOMC announcements are infrequent (occurring eight times a year), estimates of β are likely to be noisy and inaccurate, especially if the true level of sensitivity varies over time. To overcome this difficulty, we use information from the option-implied variance. Our intuition is that FOMC announcements resolve uncertainty about the macroeconomy and monetary policy and are associated with reductions in the option-implied variance. Firms that are more sensitive to monetary policy announcements should experience a greater implied variance reduction after announcements. Expectations for the implied variance reduction can therefore measure sensitivity to monetary policy announcements.

We find that portfolios sorted on the expected implied variance reduction (EVR) yield a significant spread in average returns on FOMC announcement days but not on non-FOMC days. A long-short portfolio formed on our monetary policy sensitivity measure produces an average announcement-day return of 31.67 bps. In addition, the returns of EVR-sorted portfolios remain significant after controlling for market beta and other standard risk factors. To further demonstrate that the spread on the EVR-sorted portfolios reflects risk compensation for monetary policy announcements, we use measures of monetary policy announcement surprises constructed by Nakamura and Steinsson (2018) to show that i) the average monetary policy announcement surprises are indifferent from zero, and therefore rational expectations hold well in our sample period; and ii) the returns of the EVR-sorted portfolios are monotonic in their sensitivity to monetary policy surprises.

From the perspective of the cross section of equity returns, our results for the monetary policy announcement premium provide supporting evidence for previous findings associated with the macroeconomic announcement premium. Our CAPM result, however, poses a challenge to the theory as previous theoretical models and empirical findings suggest that the CAPM holds well on macroeconomic announcement days. Savor and Wilson (2014), for example, find that on announcement days the CAPM holds well for β-sorted portfolios, Fama-French size and book-to-market sorted portfolios, and industry portfolios. Wachter and Zhu (2018) and Ai, Bansal, Im, and Ying (2018) demonstrate that this pattern of the CAPM is consistent with theoretical models of announcement premiums.

To quantitatively account for the cross-sectional announcement returns, we develop a model in which FOMC announcement surprises require risk compensation because they reveal the Federal Reserve's private information about the prospects for future economic growth and in which investors' preferences satisfy generalized risk sensitivity (Ai and Bansal, 2018). In our model, aggregate economic growth is driven by a latent state variable and an i.i.d. component (short-run shocks). The Federal Reserve has private information about the true value of the latent growth variable, which is revealed through periodic monetary policy announcements. We specify a cross section of a dividend process that differs in both the sensitivity to the Federal Reserve's announcement surprises and the publicly observable contemporaneous growth rate shocks.

In our model, the size of the reduction in the implied variance on announcement days provides an accurate measure of equities' risk exposure to surprises in monetary policy announcements. Sorting firms on the implied variance reduction is equivalent to sorting on sensitivity to news in FOMC announcements. This is because on non-announcement days, investors do not observe the true value of the latent growth variable and only update their beliefs about that value based on noisy signals contained in realized economic growth. Scheduled FOMC announcements reveal the true value of the latent variable and as a result, investors' posterior beliefs jump on announcement days and reset to their true value following the announcement. Stocks that have a high exposure to policy surprises will experience a large drop in the implied variance on announcement days.

In this setup, our model matches several stylized features of the cross-sectional announcement returns. First, the average announcement-day excess return of the market is about 36.2 bps, and the spread on the announcement-day return of portfolios sorted on expected sensitivity is about 42.1 bps. Both are close to their empirical counterparts. Because of generalized risk sensitivity, announcement surprises carry news about the future prospects for the economy and are priced (Ai and Bansal, 2018). As a result, stocks that are more sensitive to monetary policy announcement surprises than others will receive a higher risk premium on announcement days.

Second, the CAPM fails to account for the FOMC announcement returns of EVR-sorted portfolios in our model. In the model, expected reductions in the implied variance accurately measure the sensitivity to policy announcement surprises. The CAPM β, however, depends both on the sensitivity of the stock return to policy announcement surprises and, more importantly, on the sensitivity to contemporaneous shocks to economic growth, which account for a quantitatively larger fraction of variations in equity market valuations. EVR-sorted portfolios therefore exhibit a large dispersion in sensitivity to policy announcement surprises but a small dispersion in CAPM β, which is not enough to account for their announcement-day returns.

Third, even though the CAPM fails to account for the expected returns of EVR-sorted portfolios, it does explain the announcement returns of β-sorted portfolios quite well. In the data, as documented by Savor and Wilson (2014), β-sorted portfolios exhibit significant differences in their announcement premiums, which can be explained by the CAPM. In our model, β-sorted portfolios exhibit a large dispersion in CAPM β but a small dispersion in sensitivity to monetary surprises, as quantitatively, β mostly reflects elasticity with respect to contemporaneous shocks to economic growth and is only weakly correlated with sensitivity to FOMC announcements. As a result, the announcement-day return of β-sorted portfolios is mostly absorbed by differences in β, making it difficult to reject the CAPM in a finite sample.

Related literature Our paper is related to the literature that emphasizes the impact of monetary policy announcements on equity market returns. Bernanke and Kuttner (2005) demonstrate that stock markets respond strongly to monetary policy announcements. Gürkaynak, Sack, and Swanson (2005) document evidence that both monetary policy action and announcements have an important impact on asset markets.

Within this literature, most closely related to our paper are several recent papers emphasizing the impact of FOMC announcements on equity market excess returns. Lucca and Moench (2015) document an FOMC pre-announcement drift. Cieslak, Morse, and Vissing-Jorgensen (2019) provide evidence for stock market returns over FOMC announcement cycles. Cieslak and Pang (2019) provide a decomposition of shocks that drive stock and bond market variations to explain stock and bond returns over the FOMC announcement cycle. Neuhierl and Weber (2018) document that the return drift around FOMC announcements depends on whether the monetary policy is expansionary or contradictory. Bollerslev, Li, and Xue (2018) find that after the FOMC meetings, both volatility and volume increase, but the intra-day volume-volatility elasticity is systematically below unity. While the above papers study the aggregate equity market excess returns around FOMC announcement days, our paper examines the heterogeneous impact of FOMC announcements on the cross section of the stock market.[1]

Our paper is also related to the broader literature on the macroeconomic announcement

[1]Relatedly, Mueller, Tahbaz-Salehi, and Vedolin (2017) and Karnaukh (2018) study the impact of FOMC announcements on the foreign exchange market.

premium. Savor and Wilson (2013) document a significant equity market return on days with major macroeconomic announcements. Brusa, Savor, and Wilson (2019) show that the same holds for many other countries. Savor and Wilson (2014) demonstrate that the CAPM holds well for macroeconomic announcement days but not for non-announcement days. Hu, Pan, Wang, and Zhu (2019) provide evidence that the option-implied variance increases before announcements and drops afterward and attribute the FOMC announcement premium to heightened stock market uncertainty. Amengual and Xiu (2018) argue that the large declines in the option-implied variance after the FOMC announcements are associated with a resolution of policy uncertainty. All of above empirical evidence is broadly consistent with our equilibrium model in which announcements resolve macroeconomic uncertainty and are associated with reductions in the option-implied variance of equity market returns.

Our work is also related to papers that study monetary policy and the cross section of equity returns. Ozdagli and Velikov (2019) use observable firm characteristics to measure the firm exposure to monetary policy and find that stocks with a more positive reaction to expansionary monetary policy surprises earn lower returns. Chava and Hsu (2019) find that financially constrained firms earn lower returns than unconstrained firms after unanticipated increases in the federal funds target rate. The above papers study monetary policies in general, but not necessarily monetary policy announcements. In fact, none of them focuses on returns realized on FOMC announcement days, nor do they find a significant premium realized following announcements.

Our theoretical model builds on recent developments in asset pricing models for the macroeconomic announcement premium. Ai and Bansal (2018) provide a revealed preference theory for the macroeconomic announcement premium. Wachter and Zhu (2018) and Ai, Bansal, Im, and Ying (2018) develop quantitative models of the announcement premium. The information channel we emphasize in our paper is consistent with recent work by Nakamura and Steinsson (2018), who provide empirical evidence and develop a theoretical model to show that Federal Reserve announcements affect beliefs not only about monetary policy but also about economic fundamentals.

The rest of the paper is organized as follows. In Section 2, we develop a measure of expected sensitivity to monetary policy announcement surprises and present cross-sectional evidence for the relationship between expected sensitivity and expected returns. In Section 3, we develop a continuous-time model with monetary policy announcements and explain cross-sectional equity returns. We present our quantitative analysis and demonstrate that our model is able to account for the stylized features of the cross-sectional FOMC announcement premium in Section 4. Section 5 concludes.

2 Empirical Evidence

In this section, we provide evidence that stocks that are more sensitive to monetary policy announcement surprises earn significantly higher premiums on FOMC announcement days. In addition, the cross section of the monetary policy announcement premium cannot be explained by the CAPM.

2.1 Measuring Expected Sensitivity

To study whether risk exposure to monetary policy announcements is priced in the cross section of equity returns, our strategy is to measure the sensitivity of firms' equity returns with respect to monetary policy announcements and to evaluate whether differences in the level of sensitivity are reflected in firms' expected returns realized on announcement days. This exercise requires constructing a firm-level measure of sensitivity with respect to FOMC announcement surprises, sorting stocks into portfolios based on such a measure, and estimating expected returns by computing the average returns of the sensitivity-sorted portfolios.

Because our purpose is to measure the expected returns of the sensitivity-sorted portfolios, the measure of sensitivity should be based on market expectations and cannot depend on information unavailable at the time of portfolio formation, to avoid any look-ahead bias. Since the FOMC makes announcements only eight times a year, any sensitivity estimates based on historical announcement data are likely to be noisy because of a lack of observations. In addition, if the true level of sensitivity is time varying, sensitivity estimates using historical announcements are likely to be inaccurate.

To overcome the above difficulty, our measure of sensitivity is based on the option-implied variance. In contrast to estimated sensitivity using historical announcement data, the option-implied variance is capable of capturing changes in market expectations in a timely manner. The construction of our measure is based on the intuition that FOMC announcements reduce uncertainty about the macroeconomy and monetary policy and are associated with reductions in the option-implied variance. In the cross section, firms that are more sensitive to monetary policy announcement surprises should experience higher implied variance reductions following announcements. To avoid look-ahead bias, we construct a measure of the expected implied variance reduction, or EVR for short. In what follows, we first present evidence on the implied variance reductions on FOMC announcement days and then detail the construction of our measure of the EVR.

Implied variance around monetary policy announcements We first establish that there are significant reductions in the option-implied variance on FOMC announcement days both at the market level and at the firm level. We also show that the firm-level implied variance reduction exhibits substantial heterogeneity. Collectively, the above evidence supports the two premises of our empirical exercises: i) the implied variance reduction can be used to measure the firm-level sensitivity to monetary policy announcement surprises, and ii) this sensitivity exhibits a considerable heterogeneity across firms.

We use the squared option-implied volatility index, VIX^2, to measure the implied variance of the market return. We obtain data on VIX from the Chicago Board Options Exchange (CBOE). The CBOE's VIX is a model-free measure of implied volatility computed from the S&P 500 index option prices. For the firm-level implied variance, on each day and for each time to maturity, we follow Bakshi, Kapadia, and Madan (2003) to estimate the implied variance by averaging the weighted prices of out-of-money puts and out-of-money calls over a wide range of strike prices. We then obtain the 7-day implied variance by interpolating or extrapolating the implied variance in the maturity dimension. We use the 7-day implied variance because the short-maturity option prices are likely to be more sensitive to announcement surprises than the long-maturity option prices. Our firm-level option data are from OptionMetrics. The sample period is from January 1996 to December 2017. In our data period, there are 176 pre-scheduled FOMC meetings. If a FOMC meeting lasts for two days, we treat the second day as the announcement day. We provide more detailed information about the firm-level implied variance and other data in the Appendix A.1.

We document the patterns of the implied variance reduction on FOMC announcement days in Table 1. Panel A of the table compares the market-level implied variance (VIX_t^2) on FOMC announcement days with the same moment one day before announcements, VIX_{t-1}^2. Consistent with the previous literature (see, e.g., Savor and Wilson, 2013), VIX significantly decreases after FOMC announcements. On average, the daily reduction in VIX^2 is about 2.41 (monthly percentage squared units). We observe the same pattern at the firm level. As shown in Panel B of Table 1, the average reduction in the implied variance at the firm level is about 4.95 and significant.

Moreover, there is evidence of significant heterogeneity in announcement-day reductions in the implied variance across firms. We rank firms by their average announcement-day implied variance reduction and plot the histogram of these reductions in Figure 1. The implied variance decreases after announcements for most of firms, and the magnitude of reduction differs substantially.

2.2 Expected Variance Reduction

Motivated by the above evidence, we measure the market-expected sensitivity to FOMC announcement surprises using the expected implied variance reduction. For a FOMC announcement day t, the expected implied variance reduction (EVR) is computed as[2]

$$EVR = IV_{t-2} - Median\ of\ Historical\ IV. \tag{1}$$

In the above equation, IV_{t-2} is the 7-day implied variance (IV) for a firm computed from the closing price of its options two days before the FOMC announcement. We use closing prices two days

[2]Note that our measure is different from the variance risk premium (VRP) in the literature; see, for example, Bollerslev, Tauchen, and Zhou (2009), Drechsler and Yaron (2011), and Bollerslev, Marrone, Xu, and Zhou (2014). The VRP is the difference between the variance under the Q-measure and that under the P-measure, whereas our measure is designed to capture the upcoming announcements, and we do not use any variance measure under the physical probability.

before announcements to ensure that our measure is not affected by the pre-FOMC announcement drift documented by Lucca and Moench (2015). The median of historical IV in equation (1) is computed as the median value of IV during day -15 and day -8, where the announcement day is normalized to day 0.[3] In our construction, the historical IV is not affected by the upcoming FOMC announcement, whereas IV_{t-2} is. A larger increase in IV_{t-2} relative to its historical level indicates the market expectation that the equity of the firm will be more sensitive to the upcoming FOMC announcement.

Our measure of the expected implied variance reduction has significant predictive powers for the actual implied variance reduction on FOMC announcement days. In equation (2), we report results from a panel regression of the actual implied variance reduction on our measure of the expected implied variance reduction. The regression coefficient on the expected variance reduction is significantly positive with a t-statistic of 8.63 (based on the day-clustered standard error) and a R^2 of 5.9%: [4]

$$Actual\ IV\ Reduction = \underset{(0.76)}{0.0019} + \underset{(8.63)}{0.2054} \times Expected\ IV\ Reduction. \tag{2}$$

The key advantage of using the implied variance to measure expected sensitivity is that the implied variance reflects market expectations in a timely manner. Alternative measures such as market β on previous announcement days do not incorporate the same forward-looking information contained in the implied variance and may not necessarily reflect market expectations on the upcoming announcement.

2.3 Return of Portfolios Sorted on EVR

Using the EVR measure constructed above, we sort stocks into decile portfolios and examine their returns on FOMC announcement days. Consider a FOMC announcement day. We compute our

[3] Our results remain robust if we use the mean value of the historical IV during the same period to adjust IV_{t-2} or if we use a longer period to measure the historical IV, such as during day -22 and day -8.

[4] In Appendix A.2, we provide other additional implied variance reduction forecasts for comparison. The results show that this model predicts the actual implied variance reduction better than others.

EVR measure for each stock two days ahead of the announcement day and sort stocks into decile portfolios using the EVR measure. Stocks in the top (bottom) portfolio have the highest (lowest) EVR and are most (least) sensitive to the upcoming FOMC announcement. We keep track of the value-weighted portfolio returns and rebalance the portfolios until the next sorting date, which is two days before the next FOMC announcement day. We repeat the above procedure and compute the average FOMC announcement-day return and non-FOMC announcement-day return for each of the portfolios.

Panel A of Table 2 reports the portfolio returns on FOMC announcement days and non-FOMC days. To save space, we present the returns for portfolios 1, 2, 9, and 10, and the return for the consolidated portfolios 3 to 8. On FOMC announcement days, the top decile portfolio with the highest expected sensitivity earns higher expected returns than the bottom decile portfolio with the lowest expected sensitivity. On average, the long-short portfolio earns a raw return of 31.67 bps on FOMC announcement days. This tradable strategy that invests only on the eight FOMC announcement days earns an average annual return of 2.53% (31.67 bps $\times$ 8). In contrast, most portfolios, as well as the long-short portfolio, do not earn significant returns on non-FOMC days. We confirm that the portfolio returns on FOMC announcement days are not driven by standard firm characteristics such as size or book-to-market ratio (B/M).

We next report results from CAPM regressions for our sorted portfolios. To distinguish between FOMC announcement days and non-FOMC announcement days, we consider the following regression:

$$R_t^i - r_{f,t} = \alpha_{Non}^i \cdot \mathbf{1}_{Non} + \alpha_{FOMC}^i \cdot \mathbf{1}_{FOMC} + \beta \left(R_t^M - r_{f,t}\right) + \varepsilon_t^i, \tag{3}$$

where R_t^i is the daily return of the sorted portfolio, R_t^M is the daily return of the market, and $r_{f,t}$ is the daily risk-free rate. The variables $\mathbf{1}_{Non}$ and $\mathbf{1}_{FOMC}$ are dummy variables that take values of 1 only on non-FOMC and FOMC announcement days, respectively. Panel B of Table 2 reports results for the above CAPM regression. Note that the FOMC dummy is monotonically increasing across portfolios and the FOMC dummy of the long-short portfolio is positive and statistically significant. The spread between the high sensitivity portfolio and the low sensitivity portfolio averages 30.70

bps on FOMC announcement days after controlling for market returns. Our results suggest that the CAPM fails to account for the cross section of returns of portfolios sorted on expected sensitivity on FOMC announcement days.

The above portfolio return results remain robust if we exclude the recent financial crisis period (July 2008 to June 2009) or if we exclude firms whose earning announcement dates coincide with the FOMC announcement days, as shown in Appendix A.2. In an unreported robustness check, we find that our results are robust even after including Fama-French three or five factors in the above regression.

2.4 CAPM for $\beta-$Sorted Portfolios

The literature has shown that the CAPM holds well on macroeconomic announcement days (see, e.g., Savor and Wilson, 2014). In this section, we present evidence for the FOMC announcement premium for CAPM $\beta-$sorted portfolios. Our sorting procedure is similar to the one using the expected sensitivity measure EVR introduced in section 2.2. For each FOMC meeting, we sort all stocks into decile portfolios based on their CAPM beta, which is calculated using the daily return during the past twelve months, two days before the FOMC announcement. We then document the daily portfolio returns until the next rebalancing date, which is two days before the next FOMC announcement day.

Panel A of Table 3 reports the portfolio returns on FOMC announcement days and non-FOMC days. We find that on FOMC days, high beta stocks do earn high expected returns: on average, the long-short portfolio can generate a raw return of 55.17 bps. On the other hand, portfolio returns on non-FOMC days are rather low with no obvious pattern. This result indicates that the CAPM may only hold on FOMC announcement days.

In Panel B, we test the CAPM using β-sorted portfolios. By construction, beta monotonically increases across the portfolios. When we further include a FOMC dummy and a non-FOMC dummy in the CAPM, the coefficients on the FOMC dummy are insignificant for all portfolios, including the long-short portfolio. This insignificant FOMC dummy is consistent with the findings in the previous literature that the returns of the β-sorted portfolios can be explained by the CAPM.

The failure of the CAPM in explaining the cross section of the EVR sorted portfolios and the success of the CAPM in accounting for the announcement returns of the β-sorted portfolios together pose a serious challenge for the structural model of the cross section of the macroeconomic announcement premium.

2.5 Exposure to Monetary Policy Announcement Surprises

We argue that the cross-sectional returns in the EVR sorted portfolios represent risk compensation for surprises in monetary policy announcements. In this section, we use two measures of monetary policy surprises constructed by Nakamura and Steinsson (2018) to provide additional evidence to support our argument. The first measure is a composite measure constructed as the first principal component of the unanticipated change over the 30-minute FOMC announcement windows in a basket of five interest rates. The second is based on changes in the federal funds rate on FOMC announcement days.

First, we show that rational expectations hold well in the period of our portfolio-sorting exercise. In Table 4, we report the first and second moments of the two measures of monetary policy surprises: the composite measure of policy news constructed in Nakamura and Steinsson (2018) (labeled as Policy News) and the changes in the federal funds rate on announcement days (labeled as FFR). Both measures of monetary policy surprises exhibit substantial variation; however, in both measures, the average surprises are not significantly different from zero. This result implies that there are no systematic biases in the market's forecast about monetary policy announcements during this period, and the market excess return and that of the portfolios sorted on expected sensitivity EVR must be compensation for risk rather than a reflection of biases in expectations.

Second, we show that the cross-sectional returns of portfolios sorted on EVR monotonically react to policy surprises. We compute the betas of portfolios sorted on EVR with respect to both measures of monetary policy surprises. We run the following regression on FOMC announcement days:

$$R_t^i - r_{f,t} = \alpha^i + \beta_{News}^i \Delta g_t + \beta_{Mkt}^i \left(R_t^M - r_{f,t} \right) + \varepsilon_t^i, \tag{4}$$

where R_t^i is the return of portfolio i, and Δg_t stands for policy surprises on FOMC announcement day t. We plot the slope coefficient of the above regression, β_{News}^i, for each of the portfolios in Figure 2.

The slope coefficient β_{News}^i is monotonically increasing for both measures of policy surprises. After an unexpected interest rate hike, the return for the high EVR portfolio increases and that for the low EVR portfolio decreases, after controlling for market returns. The fact that the high EVR portfolio is more sensitive to interest rate hikes is consistent with Nakamura and Steinsson (2018)'s interpretation that monetary policy announcements convey the Federal Reserve's private information about the economy, and surprising interest rate hikes are associated with information that economic fundamentals are stronger than expected. Consistent with the above information effect, Nakamura and Steinsson (2018) document that in response to an unexpected increase in the real interest rate (a monetary tightening), survey estimates of expected output growth rise.

To account for the expected returns of the cross section of portfolios sorted on expected sensitivity, in the next section, we develop an equilibrium model in which FOMC announcements reveal the Federal Reserve's private information about economic growth.

3 Model Setup and Solution

In this section, we set up a continuous-time equilibrium model in which the Federal Reserve's monetary policy announcements reveal its private information about the growth prospects for the economy and study the implications for the cross section of announcement returns. In our model, aggregate economic growth is driven by a latent state variable and an i.i.d. component (short-run shocks). The Federal Reserve has private information about the true value of the latent growth variable, which is revealed through periodic monetary policy announcements.

Consumption and preference We consider a continuous-time representative agent economy in which the representative agent has a recursive preference with constant risk aversion γ and intertemporal elasticity of substitution (IES) ψ. The growth rate of aggregate consumption contains a latent predictable component, x_t, and an i.i.d. component modeled by increments of Brownian motion $B_{C,t}$ with constant volatility σ:

$$\frac{dC_t}{C_t} = x_t dt + \sigma dB_{C,t}. \tag{5}$$

Similar to the model of Ai (2010), we assume that x_t is a continuous-time AR(1) process (an Ornstein-Uhlenbeck process) and unobservable to investors in the economy. The law of motion of x_t follows the process

$$dx_t = a_x \left(\bar{x} - x_t\right) dt + \sigma_x dB_{x,t}, \tag{6}$$

where $B_{x,t}$ is a Brownian motion independent of $B_{C,t}$.

Information and announcements To build a parsimonious model in which the Federal Reserve has private information about the future growth prospects for the economy, we assume that investors in the economy cannot observe the latent variable x_t. The Federal Reserve has more information about x_t than investors do, and its private information about x_t is revealed through pre-scheduled FOMC announcements.

Specifically, an investor's prior belief about x_t is represented by a normal distribution. Since the posterior distribution of x_t is also Gaussian, it can be summarized by the first two moments. We define $\hat{x}_t = \mathbb{E}_t\left[x_t\right]$ as the posterior mean and $q_t = \mathbb{E}_t\left[\left(x_t - \hat{x}_t\right)^2\right]$ as the posterior variance of x_t given information up to time t. Investors can use two sources of information to update their beliefs about x_t at time t. First, the realized consumption path contains information about x_t. Second, at pre-scheduled discrete time points $T, 2T, 3T, \cdots$, additional signals about x_t are revealed through announcements. For $n = 1, 2, 3, \cdots$, we denote s_n as the signal observed at time nT and assume $s_n = x_{nT} + \varepsilon_n$, where ε_n is i.i.d. and normally distributed with mean zero and variance σ_s^2.

At time $t = nT$, where n is an integer, investors update their beliefs based on the signals s_t

about x_t using Bayes' rule:

$$\hat{x}_{nT}^{+} = q_{nT}^{+}\left[\frac{1}{\sigma_s^2}s_n + \frac{1}{q_{nT}^{-}}\hat{x}_{nT}^{-}\right]; \qquad \frac{1}{q_{nT}^{+}} = \frac{1}{\sigma_s^2} + \frac{1}{q_{nT}^{-}}, \tag{7}$$

where $\hat{x}_{nT}^{+}$ and q_{nT}^{+} are the posterior mean and variance after announcements, and $\hat{x}_{nT}^{-}$ and q_{nT}^{-} are the posterior mean and variance before announcements, respectively.

In the interior of $(nT, (n+1)T)$, investors update their beliefs based on the observed consumption process using a Kalman-Bucy filter:

$$d\hat{x}_t = a_x(\bar{x} - \hat{x}_t)\,dt + \frac{q_t}{\sigma}d\tilde{B}_{C,t}, \tag{8}$$

where the innovation process is defined by $d\tilde{B}_{C,t} = \frac{1}{\sigma}\left[\frac{dC_t}{C_t} - \hat{x}_t dt\right]$. The posterior variance, q_t, satisfies the Riccati equation:

$$dq_t = \left[\sigma_x^2 - 2a_x q_t - \frac{1}{\sigma^2}q_t^2\right]dt. \tag{9}$$

The intuition of our results is the same as that demonstrated in Ai and Bansal (2018). In our model, the two sources of risk are consumption growth risk, as captured by the Brownian motion $d\tilde{B}_{C,t}$, and news about latent growth risk, as captured by changes in (the beliefs about) x_t. Prior to the announcements, investors do not observe the true value of x_t and update their beliefs about it with the posterior $\hat{x}_t$. Announcements are associated with immediate updates of investors' beliefs. That is, the posterior mean of x_{nT} jumps instantaneously from $\hat{x}_{nT}^{-}$ to x_{nT}^{+}.

The cross section of equity We assume that there is a cross section of equity claims, indexed by i. Equity i is the claim to the following dividend process:

$$\frac{dD_t^i}{D_t^i} = [\bar{x} + \xi_i(\hat{x}_t - \bar{x})]\,dt + \eta_i\sigma d\tilde{B}_{C,t} + \sigma_i dB_{i,t}, \tag{10}$$

where $dB_{i,t}$ is the idiosyncratic shock to each firm i, which is uncorrelated with $dB_{C,t}$ and $dB_{x,t}$. The term σ_i is the idiosyncratic volatility, and the parameters (ξ_i, η_i) measure the sensitivity of the dividend with respect to news about the latent growth risk and the consumption growth risk, respectively. We assume that ξ_i is uniformly distributed over the interval $\left[\underline{\xi}, \overline{\xi}\right]$ and η_i is uniformly distributed over $\left[\underline{\eta}, \overline{\eta}\right]$, and the distributions of ξ_i and η_i are independent.

Define the price-to-dividend ratio of firm i as $p\left(\hat{x}_t, q_t \middle| \xi_i, \eta_i\right)$, which depends on both ξ_i and η_i. The function $p\left(\hat{x}_t, q_t \middle| \xi_i, \eta_i\right)$ is defined as

$$p\left(\hat{x}_t, q_t \middle| \xi_i, \eta_i\right) D_t^i = \mathbb{E}_t\left[\int_0^\infty \frac{\pi_{t+s}}{\pi_t} D_{t+s}^i ds \middle| \hat{x}_t, q_t\right], \tag{11}$$

where the law of motion of D_t^i is given in (10) and the solution for state price density π_t is provided later in this section. For simplicity, we henceforth denote the firm-specific price-to-dividend ratio as $p^i\left(\hat{x}_t, t\right)$. The return on firm i's equity during the period $(t, t+\Delta)$ is given by

$$R_{t,t+\Delta}^i = \frac{p^i(\hat{x}_{t+\Delta}, t+\Delta)\frac{D_{t+\Delta}^i}{D_t^i} + \int_t^{t+\Delta} \frac{D_s^i}{D_t^i} ds}{p^i\left(\hat{x}_t, t\right)}.$$

Model solution In the interior of $(nT, (n+1)T)$, $n = 1, 2, \cdots$, the law of motion of the state price density, π_t, satisfies the following stochastic differential equation:

$$d\pi_t = \pi_t\left[-r\left(\hat{x}_t, q_t\right) dt - \sigma_{\pi,t} d\tilde{B}_{C,t}\right], \tag{12}$$

where

$$r\left(\hat{x}_t, q_t\right) = \rho + \frac{1}{\psi}\hat{x}_t - \frac{1}{2}\gamma\left(1 + \frac{1}{\psi}\right)\sigma^2 + \frac{\frac{1}{\psi} - \gamma}{a_x + \rho} q_t + \frac{\left(\frac{1}{\psi} - \gamma\right)\left(1 - \frac{1}{\psi}\right)}{2\left(a_x + \rho\right)^2}\left(\frac{q_t}{\sigma}\right)^2 \tag{13}$$

is the risk-free interest rate and

$$\sigma_{\pi,t} = \gamma\sigma + \frac{\gamma - \frac{1}{\psi}}{a_x + \rho}\frac{q_t}{\sigma} \tag{14}$$

is the market price of the Brownian motion risk, $\tilde{B}_{C,t}$. Equation (14) contains both the compensation for the i.i.d. shock $B_{C,t}$ and that for the changes in the belief about x_t, captured by the term $\frac{\gamma - \frac{1}{\psi}}{a_x + \rho}\frac{q_t}{\sigma}$. The two sources of fundamental risk in the economy are $B_{C,t}$ and $B_{x,t}$. However, investors do not observe x_t and cannot distinguish whether a change in consumption growth is due to $B_{C,t}$ or to innovations in $B_{x,t}$. Innovations in consumption growth, from investors' perspective, affect both the contemporaneous consumption growth rate and investors' beliefs about x_t. As in Ai (2010), $\sigma_{\pi,t}$

summarizes risk compensation from both channels.

As we show in Appendix A.3.2, each firm's price-to-dividend ratio $p^i(\hat{x}_t, t)$ must satisfy the partial differential equation of (A.16). In addition, at announcements $nT, n = 1, 2, 3, ...,$ the boundary condition satisfies

$$p^i\left(\hat{x}_{nT}^-, nT^-\right) = \frac{\mathbb{E}\left[e^{\frac{\frac{1}{\psi}-\gamma}{a_x+\rho}\hat{x}_{nT}^+} p^i\left(\hat{x}_{nT}^+, nT^+\right) \mid \hat{x}_{nT}^-, q_{nT}^-\right]}{e^{\frac{\frac{1}{\psi}-\gamma}{a_x+\rho}\hat{x}_{nT}^- + \frac{(1-\gamma)\left(\frac{1}{\psi}-\gamma\right)}{2(a_x+\rho)^2}\left[q_{nT}^- - q_{nT}^+\right]}}. \tag{15}$$

Under the assumption of generalized risk sensitivity, $\gamma > \frac{1}{\psi}$, the term $e^{\frac{\frac{1}{\psi}-\gamma}{a_x+\rho}\hat{x}_{nT}^+}$ is negatively correlated with the posterior belief, x_{nT}^+, which is updated immediately following announcements. As a result, an asset with a payoff that increases after the announcement about x_{nT}^+ requires a positive risk premium, and the magnitude of the announcement premium increases with the sensitivity of the asset's payoff with respect to announcements about x_{nT}^+.

In our model, because announcement premiums represent compensation for shocks to beliefs about $\hat{x}_t$, stocks that are more sensitive to $\hat{x}_t$ require a higher level of compensation in terms of announcement returns. The sensitivity of the stock return with respect to announcement surprises depends primarily on the parameter ξ_i. From equation (10), we see that a stock with a higher ξ_i in its dividend growth rate is more sensitive to x_t. Therefore, the price-to-dividend ratio and return respond more to news about x_t, so this stock requires a high level of risk compensation. We provide details of the model solutions in the Appendix A.3.

4 Quantitative Implications

Calibration We choose parameters to match the dynamics of consumption growth and the implied variance, and we report this calibration in Table 5. First, we choose the parameters for preference and the consumption growth rate in our model to be consistent with the standard long-run risk literature. Following Bansal and Yaron (2004) and Ai (2010) among others, we set the discount rate $\rho = 0.01$, the risk aversion $\gamma = 10$, and IES $\psi = 2$. We choose the average consumption growth $\bar{x} = 1.5\%$ and the standard deviation of consumption growth $\sigma = 3.0\%$ to match the first and second moment of aggregate consumption in the sample period of 1929-2018. We also choose the autocorrelation a_x and the standard deviation of x_t to be in line with standard long-run risk models, such as Bansal and Yaron (2004) and Ai (2010).

The parameters of investors' beliefs and the cross section of dividend processes are specific to our model. We choose the parameters of investors' beliefs and the cross section of dividend processes to match the dynamics of implied variances in our sample. We set $\sigma_i = 57\%$ to match the cross-sectional average implied variance of stocks on non-announcement days. Our model gives an implied variance of 274.23 in monthly percentage squared units, which is close to 276.21 in our data, reported in Table 1. We choose the parameter for the informativeness of FOMC announcements, $\sigma_s = 4.33\%$, so that our model matches the standard deviation of aggregate stock market returns on announcement days of 110 bps, as reported in Ai and Bansal (2018). Finally, we choose $\underline{\xi} = \underline{\eta} = 1$ and $\overline{\xi} = \overline{\eta} = 5$ to match the slope in the cross section of expected returns. The calibrated parameter values are listed in Table 5.

We simulate our model for 122 years. We discard the first 100 years and keep the remaining 22 years so that the time span of our simulation is the same as that in our data, and we can compare not only the point estimates but also the t-statistics in our model and their counterparts in the data. Our model closely matches several moments in the data that our calibration does not explicitly target. In our calibration, the average market excess returns on FOMC announcement days and non-FOMC days are 36.2 bps and 1.8 bps, very close to the same moments (36.6 bps and 2.0 bps) reported in Lucca and Moench (2015). The average drop in the implied variance in our model is 9.2 in monthly percentage squared units, comparable to the same number we reported in Table 1 in our data.

Aggregate FOMC announcement premium In Table 6, we report the average market excess returns on FOMC announcement days and non-FOMC announcement days for both the data and the model. As documented in the previous literature, the equity market earns significant average excess returns on FOMC announcement days. Our model matches this pattern in the data quite well.

The intuition behind our results is the same as that demonstrated in Ai and Bansal (2018). In our model, the two sources of risk are consumption growth risk, as captured by the Brownian motion $d\tilde{B}_{C,t}$, and news about latent growth risk, as captured by changes in (the beliefs about) x_t (i.e., $\hat{x}_{nT}^{+} - \hat{x}_{nT}^{-}$). Prior to the announcements, investors do not observe the true value of x_t and update their beliefs based on observed consumption growth. Because consumption growth is driven by Brownian motion shocks, the posterior belief, $\hat{x}_t$, updates continuously. At pre-scheduled announcement times, FOMC announcements are associated with discrete jumps in the posterior belief from $\hat{x}_{nT}^{-}$ to $\hat{x}_{nT}^{+}$.

Because investors' preferences satisfy generalized risk sensitivity, marginal utility is decreasing in the continuation value, which is a function of the posterior belief $\hat{x}_t$. Because announcements carry news about $\hat{x}_t$, they correlate with marginal utilities and are risky from the investors' perspective. As a result, stocks that are more sensitive to changes in x_t require a larger amount of compensation following announcements. We now turn to the implications of our model in the cross section of equity returns.

Portfolios sorted on expected sensitivity In our model, because announcement premiums represent compensation for shocks to beliefs about $\hat{x}_t$, stocks that are more sensitive to $\hat{x}_t$ require a higher level of compensation in terms of announcement returns. The sensitivity of stock returns with respect to announcement surprises depends primarily on the sensitivity of dividend growth with respect to announcements, ξ_i. From equation (10), we see that a stock with a higher sensitivity to future economic growth, which is captured by the parameter ξ_i, is more sensitive to x_t. Therefore, its price-to-dividend ratio and return respond more to news about x_t, and it requires a high level of risk compensation.

In our model, as we show in Appendix A.3.4, the implied variance reduction following announcements is given by

$$\Delta IV_i = \left(\frac{\xi_i - \frac{1}{\psi}}{a_x + \bar{p}^i} \right)^2 \left(\frac{q_{nT}^{-2}}{q_{nT}^{-} + \sigma_s^2} \right), \tag{16}$$

where $\bar{p}^i$ is the inverse of the steady state price-to-dividend ratio of firm i. The term ΔIV_i is a strictly increasing function of ξ_i, the sensitivity of the dividend with respect to news about latent growth. Therefore, in our model, sorting on the implied variance reduction is equivalent to sorting on sensitivity to news in FOMC announcements. In model simulations, because EVR is a perfect measure of ξ_i, high ξ_i stocks are allocated to high EVR portfolios and therefore have a high announcement-day return on average. In Table 7, we compare the average FOMC-day and non-FOMC-day return of portfolios sorted on expected sensitivity in our model and the data. Our model replicates the pattern of the FOMC announcement premiums for portfolios sorted on expected sensitivity.

In addition, the FOMC announcement premium in our model is not explained by the CAPM. We run the same CAPM regression for the portfolios sorted on expected sensitivity and compare our model output and the data counterparts in Table 8. As shown, the spread in announcement returns is large and significant across ξ-sorted portfolios, whereas β is only slightly increasing in expected sensitivity. As a result, as in the data, the coefficient on the FOMC dummy is significant for most portfolios. Moreover, our model replicates the monotonic pattern of the FOMC dummy across portfolios sorted on expected sensitivity quite well.

To understand our result, in the left panel of Figure 3, we plot the sensitivity of a stock's announcement return with respect to $\hat{x}_t$ as a function of ξ normalized by the same sensitivity measure of market return, that is, $\frac{p_x^i(\hat{x}_t,t)}{p^i(\hat{x}_t,t)} / \frac{p_x(\hat{x}_t,t)}{p(\hat{x}_t,t)}$. Because the sensitivity of the announcement return with respect to $\hat{x}_t$ depends on both ξ and η, we plot it for three different values of η: $\eta_i = 1, 3, 5$.

In our model, the dividend process is continuous, and the announcement return of a stock depends only on its price-to-dividend ratio and can be written as $\frac{p_x^i(\hat{x}_t,t)}{p^i(\hat{x}_t,t)}$. Clearly, from the figure, the sensitivity of price-to-dividend ratio with respect to announcement is increasing in ξ but decreasing in η, where the impact of η is quantitatively small. The parameter ξ determines the sensitivity of dividend growth with respect to the hidden state variable x_t, which is revealed upon announcements. As a result, the return of stocks with higher values of ξ is more sensitive to announcements. By comparison, the impact of η is much smaller.[5] Because the sensitivity of the stock returns with respect to announcement surprises depends mostly on ξ and not on η: sorting on expected sensitivity reduction is equivalent to sorting on ξ in our model.

In the right panel, we plot the local CAPM β as a function of ξ for $\eta_i = 1, 3, 5$. Local β is computed as follows:

$$\beta^i = \frac{Cov\left[dR_t^i, dR_t\right]}{Var\left[dR_t\right]} = \frac{\eta_i \sigma + \frac{p_x^i(\hat{x}_t,t)}{p^i(\hat{x}_t,t)} \frac{q_t}{\sigma}}{\eta \sigma + \frac{p_x(\hat{x}_t,t)}{p(\hat{x}_t,t)} \frac{q_t}{\sigma}}. \tag{17}$$

In our model, on non-announcement days, because investors do not observe the latent growth variable x_t, the only shock that affects stock market returns is the surprise in consumption growth, $d\tilde{B}_{C,t}$. As we have explained, innovations in consumption growth affect both the contemporaneous growth rate of consumption and the posterior belief about future consumption growth, $\hat{x}_t$. Therefore, qualitatively, the sensitivity of the stock return to contemporaneous consumption growth, captured by the parameter η_i, and the sensitivity of the stock return to the latent growth variable, determined by the parameter ξ_i, will both affect the estimated CAPM β. Therefore, the estimate of β_i increases in both ξ_i and η_i.

Quantitatively, the estimated β increases strongly with respect to η_i but only mildly with respect to ξ_i. As a result, EVR-sorted portfolios display a significant dispersion in ξ_i but a small dispersion in estimated β. In the model, although investors do not observe the true value of x_t, periodic FOMC announcements provide information about x_t, and the posterior variance of x_t, q_t, is much smaller relative to σ in equation (17). Because estimated β is more sensitive to η_i and less sensitive to ξ_i, the EVR-sorted portfolios have a small dispersion in β, which cannot fully account for the difference in the announcement returns in CAPM regressions. As shown in Table 8, the FOMC announcement dummies are quite significant and monotonically increasing in our model, as in the data.

[5] In our model, high η stocks are less sensitive to announcement surprises. Stocks with higher η require a higher risk premium and therefore have a lower cash flow duration. As a result, their price-to-dividend ratio are less sensitive to news about dividend growth rates.

Beta-sorted portfolios Savor and Wilson (2014) show that CAPM explains the announcement premiums of CAPM β-sorted portfolios very well. As we have shown in the last section, the stochastic discount factor in our model is driven by two sources of risk, and one-factor model such as the CAPM cannot fully account for the cross section of announcement premiums. However, as we demonstrate below, despite the failure of the CAPM in explaining the EVR-sorted portfolios, our model can account for the pattern of announcement returns of CAPM β-sorted portfolios quite well.

Table 9 presents the announcement premium for β-sorted portfolios in the data and the model. As in the data, the announcement premiums are significant and monotonically increasing in β in our model. The average returns on non-FOMC days are much smaller for all portfolios, as are the spreads between these portfolios. In Table 10, we present the results for the CAPM regressions for β-sorted portfolios in the model. As in the data, the coefficients for non-FOMC and FOMC dummies are both insignificant. The FOMC announcement premium in the long-short portfolio disappears once we control for market β.

To understand our results, note that β in our model is jointly determined by ξ_i and η_i. As shown in the last section, because β is not very sensitive to ξ_i, sorting on ξ_i (or equivalently sorting on expected sensitivity) does not generate significant dispersion in β, and that is why the CAPM fails to account for the returns of the cross section of portfolios sorted on expected sensitivity. However, sorting on individual firm's β, as we show in Table 9, does generate a significant dispersion in the CAPM β. Although the spread is not as great as sorting directly on ξ_i, the average ξ is still monotonically increasing in β-sorted portfolios. This explains the significant announcement premium for β- sorted portfolios. At the same time, because the CAPM β is also monotonic for β-sorted portfolios, by construction, the dispersion in the announcement premium can be fully explained by the dispersion in β in a finite sample.

5 Conclusion

In this paper, we provide empirical evidence and an equilibrium model for the cross section of FOMC announcement-day returns. We show that stocks that are more sensitive to monetary policy announcement surprises require a higher level of risk compensation following FOMC announcements. Our evidence is supportive of the recent literature that emphasizes the importance of risk compensation in macroeconomic announcements, in particular, monetary policy announcements. To account for the cross section of FOMC announcement returns, we develop an equilibrium model in which FOMC announcements reveal the Federal Reserve's private information about prospects for future economic growth and stock returns differ in their sensitivity to economic growth rates.

Table 1: Implied Variance Around FOMC Announcement Days

Panel A: VIX^2

	VIX_t^2	VIX_{t-1}^2	$VIX_t^2 - VIX_{t-1}^2$
Mean	39.526	41.940	-2.414
t-stats			(-3.39)

Panel B: Average Firm-Level Implied Variance

	IV_t	IV_{t-1}	$IV_t - IV_{t-1}$
Mean	276.210	281.165	-4.954
t-stats			(-4.58)

This table reports the implied variance changes from one day before FOMC announcement days to FOMC announcement days. In Panel A, we report changes in VIX^2 (monthly percentage squared units) around FOMC days and their time series statistics when testing whether the change is significantly different from zero. In Panel B, we report the cross-sectional average of changes in the firm-level option-implied variance (monthly percentage squared units) around FOMC announcement days and their time series statistics. The firm-level implied variance uses the 7-days maturity variance. Our full sample period is from January 1996 to December 2017 with 176 FOMC days. During this period, there are 6652 common stocks with trading options. Among these 6652 firms in our sample, there are 5446 firms with at least one observed option-implied variance on these 176 FOMC days.

Table 2: Portfolio Returns Sorted on Expected Sensitivity

Panel A: Average Returns

	1	2	$3-8$	9	10	$(10-1)$
FOMC Return	36.57	28.78	29.40	48.05	68.24	31.67
	(1.93)	(2.35)	(3.36)	(3.53)	(3.09)	(2.67)
Non-FOMC Return	3.42	3.33	3.55	4.16	3.23	-0.19
	(1.40)	(1.71)	(2.60)	(2.28)	(1.31)	(-0.15)

Panel B: CAPM

	1	2	$3-8$	9	10	$(10-1)$
CAPM Beta	1.41	1.15	0.92	1.22	1.44	0.03
Non-FOMC Dummy	-0.69	-0.19	0.57	0.49	-0.96	-0.27
	(-0.58)	(-0.21)	(1.96)	(0.66)	(-0.80)	(-0.21)
FOMC Dummy	-10.15	-9.31	-1.26	7.59	20.54	30.70
	(-1.38)	(-2.01)	(-0.80)	(1.88)	(2.48)	(2.87)

We conduct a tradable strategy two days before the FOMC announcement days. We measure firm-level sensitivity to monetary policy announcements by the expected implied variance reduction around FOMC announcements, which is the difference between the implied variance two days before the announcement (normalized to day 0) and the median value of the implied variance during day -8 and day -15. Based on this measurement, we sort firms into decile portfolios with the third portfolio containing 60% of all firms and each of the remaining four portfolios containing 10%, and document the value-weighted portfolio returns. These portfolios are rebalanced two days before the next FOMC announcement day. Panel A reports the time series average and Newey-West t-statistics (with 12 lags) of portfolio returns (basis points) on FOMC announcement days and non-FOMC announcement days. Panel B reports the daily regression results of equation (3), which include the CAPM beta and coefficients of a non-FOMC dummy and a FOMC dummy, as well as the Newey-West t-statistics.

Table 3: Portfolio Returns Sorted on CAPM Beta

Panel A: Average Returns

	1	2	$3-8$	9	10	$(10-1)$
FOMC Return	13.05	17.40	30.66	51.74	68.23	55.17
	(2.27)	(2.98)	(2.89)	(2.55)	(2.70)	(2.41)
Non-FOMC Return	3.09	3.63	3.57	2.61	4.05	0.95
	(3.25)	(3.10)	(2.30)	(1.02)	(1.33)	(0.34)

Panel B: CAPM

	1	2	$3-8$	9	10	$(10-1)$
CAPM Beta	0.47	0.68	1.02	1.58	1.73	1.26
Non-FOMC Dummy	1.13	1.19	0.32	-1.92	-0.86	-1.99
	(1.72)	(1.89)	(0.89)	(-1.68)	(-0.50)	(-0.93)
FOMC Dummy	-2.78	-4.93	-2.63	1.04	12.50	15.28
	(-0.67)	(-1.47)	(-1.67)	(0.17)	(1.46)	(1.34)

This table reports the CAMP beta-sorted portfolio results. We first compute the beta exposures of each firm based on the past 12-month daily returns two days before the FOMC announcement days. We sort firms into five portfolios with the third portfolio containing 60% of the firms and each of the remaining four portfolios containing 10% of the firms, and document the value-weighted portfolio returns. These portfolios are rebalanced two days before the next FOMC announcement days. Panel A reports the time series average and Newey-West t-statistics (with 12 lags) of the portfolio returns (basis points) on FOMC announcement days and non-FOMC announcement days. Panel B reports daily regression results of the CAPM beta, and coefficients of a non-FOMC dummy and a FOMC dummy, as well as the Newey-West t-statistics.

Table 4: Monetary Policy Shocks

	Policy News	FFR
Mean	0.0037	-0.0055
std	0.0342	0.0445
t-stat	(1.30)	(-1.50)

This table reports the average value and its t-statistics for monetary policy news shocks (Policy News) and federal funds rate (FFR) shocks from Nakamura and Steinsson (2018). The data sample spans from 1996 to 2014. The policy news shock is the first principal component of the change in five interest rates over a 30-minute window around the FOMC announcement. The federal funds rate shock is constructed using the price change of the federal funds futures over a 30-minute window around the FOMC announcement.

Table 5: Model Parameters

Parameter	Description	Values
ρ	Time Discount Rate	0.01
γ	Risk Aversion	10
ψ	IES	2
$\bar{x}$	Consumption Growth Rate Stationary Mean	1.5%
σ	Consumption Growth Rate Volatility	3%
a_x	Mean Reversion Rate of Unobserved Consumption Growth	0.085
σ_x	Volatility of Unobserved Consumption Growth Rate	0.71%
σ_i	Idiosyncratic Shock Volatility	57%
σ_s	Signal Volatility	4.33%
$[\overline{\xi}, \underline{\xi}]$	Sensitivity to News about Latent Growth	[1,5]
$[\overline{\eta}, \underline{\eta}]$	Sensitivity to Consumption Growth Risk	[1,5]

This table reports the parameter values used in the model. All parameters are annualized. We assume that announcements are made at a monthly frequency, that is, $T = \frac{1}{12}$.

Table 6: Market Excess Returns on FOMC Announcement and non-FOMC Days

	Data	
	Non-FOMC	Pre-FOMC
Excess Return	2.0	36.6
	Model	
	Non-FOMC Days	FOMC Days
Excess Return	1.8	36.2

The top panel reports the S&P 500 excess return on FOMC announcement days from Lucca and Moench (2015) (January 1980 to March 2011) and the corresponding excess returns on non-FOMC days. The bottom panel is the model-implied average daily excess returns for 400 stocks with 22 valid years (122 years of simulation and 100 years of burn-in), a total of 264 FOMC days. We simulate 500 independent sample paths with a daily frequency and report the value-weighted average excess returns on FOMC and non-FOMC days. All numbers are in basis points.

Table 7: Announcement Premium for Portfolios Sorted on Expected Sensitivity

	1	2	3-8	9	10	(10-1)
Data						
FOMC Return	36.57	28.78	29.40	48.05	68.24	31.67
	(1.93)	(2.35)	(3.36)	(3.53)	(3.09)	(2.67)
Non-FOMC Return	3.42	3.33	3.55	4.16	3.23	-0.19
	(1.40)	(1.71)	(2.60)	(2.28)	(1.31)	(-0.15)
Model	1	2	3-8	9	10	(10-1)
FOMC Return	12.87	19.09	36.28	50.95	55.02	42.16
	(1.84)	(1.95)	(2.00)	(1.95)	(1.95)	(1.86)
Non-FOMC Return	1.54	1.67	1.88	2.06	2.14	0.60
	(0.35)	(0.37)	(0.46)	(0.39)	(0.40)	(0.14)

This table documents the announcement and non-announcement returns for portfolios sorted on expected sensitivity in basis points. The top panel is based on data from January 1996 to December 2017 with 176 FOMC days. We sort stocks based on the implied variance reduction two days before FOMC dates and record the long-short portfolio returns on FOMC days. We report FOMC and non-FOMC returns on the decile portfolios, the long-short portfolio, and the associated Newey-West t-statistics (in parentheses). The bottom panel is the model-implied average daily returns in basis points and the associated Newey-West t-statistics for decile portfolios. In our simulation, we use 400 stocks with 22 valid years (122 years of simulation and 100 years of burn-in), a total of 264 FOMC days. For each stock, we simulate 500 independent daily sample paths. We then sort these 400 stocks into 10 portfolios based on expected sensitivity ξ and report the mean and t-statistics of each portfolio's excess returns on FOMC and non-FOMC days.

Table 8: CAPM for Portfolios Sorted on Expected Sensitivity

	Data					
	1	2	3-8	9	10	(10-1)
CAPM Beta	1.41	1.15	0.92	1.22	1.44	0.03
Non-FOMC Dummy	-0.69	-0.19	0.57	0.49	-0.96	-0.27
	(-0.58)	(-0.21)	(1.96)	(0.66)	(-0.80)	(-0.21)
FOMC Dummy	-10.15	-9.31	-1.26	7.59	20.54	30.70
	(-1.38)	(-2.01)	(-0.80)	(1.88)	(2.48)	(2.87)
	Model					
	1	2	3-8	9	10	(10-1)
CAPM Beta	0.62	0.72	1.00	1.23	1.29	0.67
Non-FOMC Dummy	0.40	0.34	0.05	-0.20	-0.23	-0.64
	(0.68)	(0.60)	(0.24)	(-0.36	(-0.41)	(-0.72)
FOMC Dummy	-9.34	-6.78	0.15	5.82	7.47	16.81
	(-2.91)	(-2.20)	(0.12)	(1.90)	(2.38)	(3.52)

This table documents the CAPM regression for portfolios sorted on expected sensitivity. The top panel is based on data from January 1996 to December 2017 with 176 FOMC days. We sort stocks based on the implied variance reduction two days before FOMC dates. We run a CAPM regression on the market excess return, non-FOMC dummy, and FOMC dummy. We report the CAPM beta and coefficients of the non-FOMC dummy and FOMC dummy on the decile portfolios, the long-short portfolio, and the associated Newey-West t-statistics (in parentheses). The bottom panel reports the model implied CAPM regression coefficients for decile portfolios. In the simulation, we use 400 stocks with 22 valid years (122 years of simulation and 100 years of burn-in), a total of 264 FOMC days. For each stock, we simulate 500 independent daily sample paths. We then sort these 400 stocks into 10 portfolios based on expected sensitivity ξ and run CAPM regressions on the simulated market return, non-FOMC dummy, and FOMC dummy. We report the mean and t-statistics of these regression coefficients.

Table 9: Announcement Premium for Beta-Sorted Portfolios

	Data					
	1	2	3-8	9	10	(10-1)
FOMC Return	13.05	17.40	30.66	51.74	68.23	55.17
	(2.27)	(2.98)	(2.89)	(2.55)	(2.70)	(2.41)
Non-FOMC Return	3.09	3.63	3.57	2.61	4.05	0.95
	(3.25)	(3.10)	(2.30)	(1.02)	(1.33)	(0.34)
	Model					
	1	2	3-8	9	10	(10-1)
FOMC Return	18.22	23.32	36.58	46.23	48.35	30.13
	(1.96)	(1.96)	(2.00)	(1.96)	(1.95)	(1.83)
Non-FOMC Return	1.11	1.45	1.87	2.23	2.60	1.50
	(1.61)	(1.86)	(2.45)	(2.19)	(2.24)	(1.53)
$\mathbb{E}[\xi_i]$	1.40	1.82	3.03	4.11	4.49	3.10
$\mathbb{E}[\eta_i]$	1.81	2.40	2.97	3.69	4.27	2.46

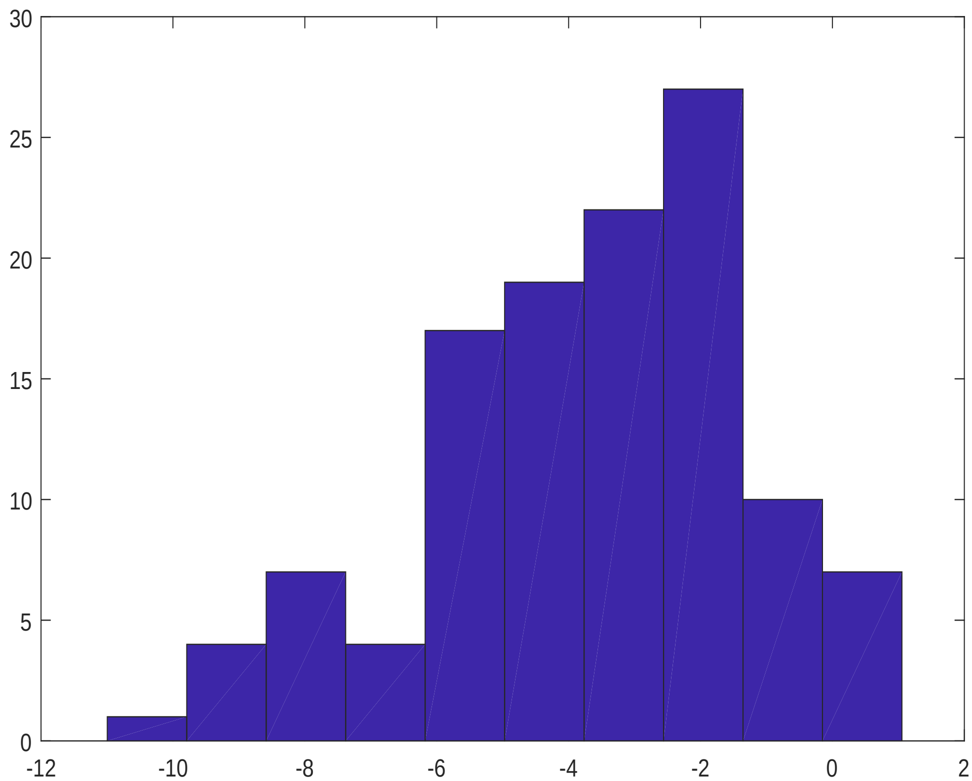
This table documents the announcement and non-announcement returns for beta-sorted portfolios in basis points. The top panel is based on data from January 1996 to December 2017 with 176 FOMC days. We sort stocks based on the CAPM regression coefficient of a single stock return on the market excess return. We report FOMC and non-FOMC returns on decile portfolios, the long-short portfolio, and the associated Newey-West t-statistics (in parentheses). The bottom panel is the model implied average returns in basis points and the associated Newey-West t-statistics for decile portfolios. In the simulation, we use 400 stocks with 22 valid years (130 years with 100 years of burn-in and 8 years of pre-sample to estimate stocks' CAPM beta coefficients), a total of 264 FOMC days. For each stock, we simulate 500 independent daily sample paths. We then sort these 400 stocks into 10 portfolios based on the estimated β coefficients and report the mean portfolio ξ, the mean portfolio η, and the mean and t-statistics of each portfolio's excess returns on FOMC and non-FOMC days.

Table 10: CAPM for Beta Sorted Portfolios

	1	2	3-8	9	10	(10-1)
Data						
	1	2	3-8	9	10	(10-1)
CAPM Beta	0.47	0.68	1.02	1.58	1.73	1.26
Non-FOMC Dummy	1.13	1.19	0.32	-1.92	-0.86	-1.99
	(1.72)	(1.89)	(0.89)	(-1.68)	(-0.50)	(-0.93)
FOMC Dummy	-2.78	-4.93	-2.63	1.04	12.50	15.28
	(-0.67)	(-1.47)	(-1.67)	(0.17)	(1.46)	(1.34)
Model						
	1	2	3-8	9	10	(10-1)
CAPM Beta	0.54	0.71	1.00	1.25	1.37	0.83
Non-FOMC Dummy	0.11	0.15	0.04	0.03	0.09	-0.03
	(0.21)	(0.27)	(0.19)	(0.05)	(0.16)	(-0.03)
FOMC Dummy	-1.19	-2.18	0.43	0.59	-1.71	-0.52
	(-0.40)	(-0.73)	(0.36)	(0.19)	(-0.58)	(-0.13)
$\mathbb{E}[\xi_i]$	1.40	1.82	3.03	4.11	4.49	3.10
$\mathbb{E}[\eta_i]$	1.81	2.40	2.97	3.69	4.27	2.46

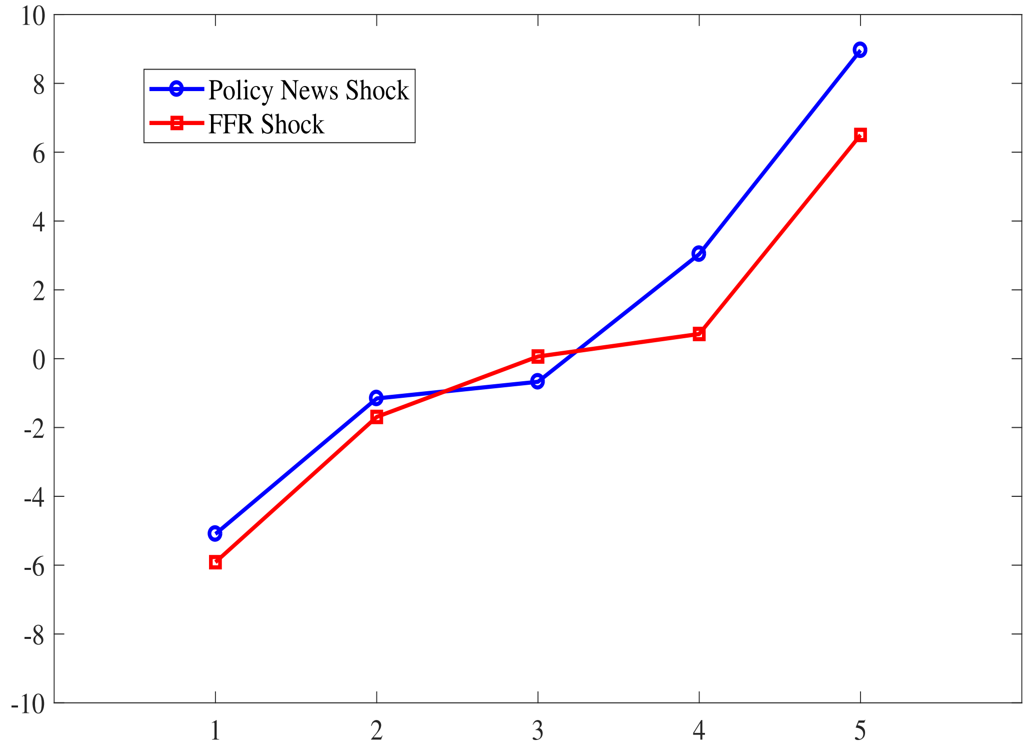
This table documents the CAPM regression for beta-sorted portfolios in basis points. The top panel is based on data from January 1996 to December 2017 with 176 FOMC days. We sort stocks based on the CAPM regression coefficient of a single stock return on the market excess return. We run the CAPM regression on the market excess return, the non-FOMC dummy, and the FOMC dummy. We report CAPM beta and coefficients of the non-FOMC dummy and FOMC dummy on the decile portfolios, the long-short portfolio and the associated Newey-West t-statistics (in parentheses). The bottom panel reports the model-implied CAPM regression coefficients for decile portfolios. In the simulation, we use 400 stocks with 22 valid years (130 years with 100 years of burn-in and 8 years of pre-sample to estimate stocks' CAPM beta coefficients), a total of 264 FOMC days. For each stock, we simulate 500 independent daily sample paths. We then sort these 400 stocks into 10 portfolios based on the estimated β coefficients and report the mean portfolio ξ, the mean portfolio η and the mean of the estimated CAPM beta, the mean and the t-statistics of the coefficients of the non-FOMC and FOMC dummies.

Figure 1: Heterogeneous Firm-Level Implied Variance Reduction Around FOMC days



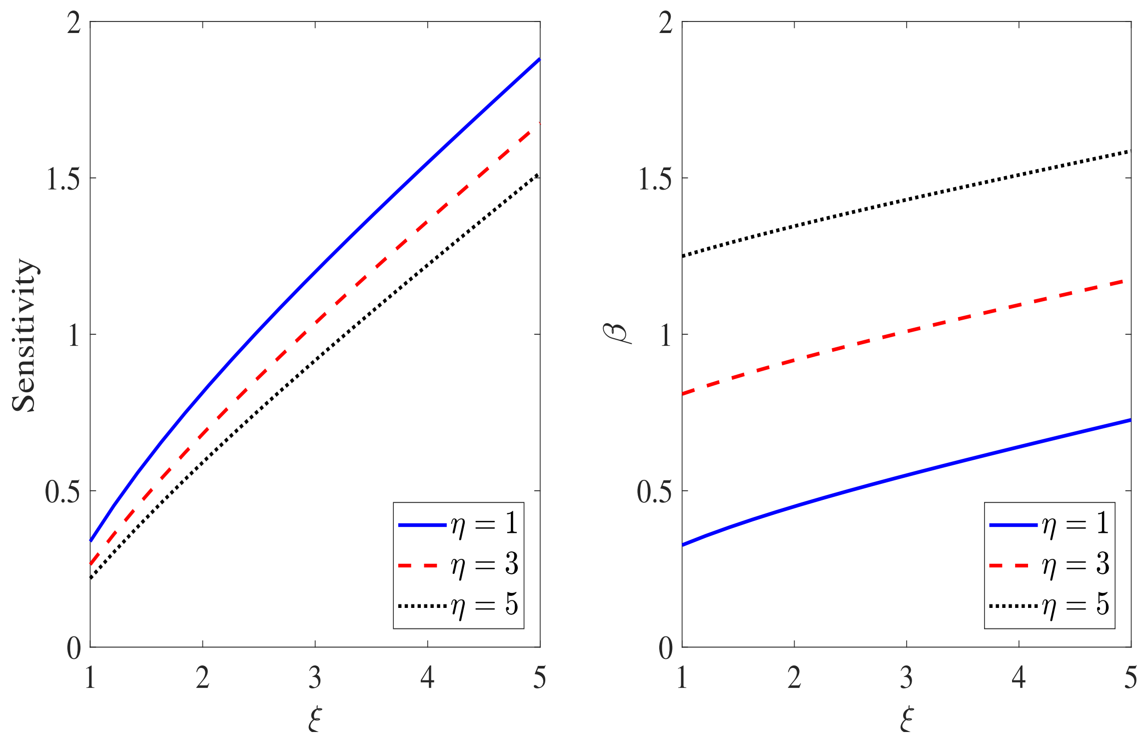
This figure plots the histogram of the time series mean of the firm-level logarithm implied variance changes (in %) around FOMC announcement days. For illustration purposes, we only report those firms with 160 or more observations out of the 176 FOMC meeting days in our data sample.

Figure 2: Portfolio Return Sensitivity to Monetary Policy Shocks



This figure plots the return sensitivity to monetary policy shocks for EVR-sorted portfolios. We regress the portfolios' excess returns on FOMC announcement-day on monetary policy news shocks or federal funds rate (FFR) shocks, controlling for the market excess returns. The line marked with blue circle (red square) plots the coefficients of monetary policy news shocks (FFR shocks). Monetary policy news shocks and FFR shocks are from Nakamura and Steinsson (2018).

Figure 3: Model Implied Sensitivity to FOMC Announcement Surprises and Market Returns



The left panel plots the sensitivity of stock returns with respect to FOMC announcement surprises, normalized by market sensitivity, as functions of ξ for different values of η, that is, $\frac{p_x^i(\bar{x},\bar{t})/p^i(\bar{x},\bar{t})}{p_x(\bar{x},\bar{t})/p(\bar{x},\bar{t})}$. The right panel plots the sensitivity of stock returns with respect to market returns, that is, CAPM β (see equation (17)). For simplicity, we fix $\bar{t} = 16$ (the middle of the month). The steady state value $\bar{x} = 1.5\%$ (see Table 5).

Appendix

A Appendix

A.1 Implied Variance and Data

In this section, we provide more details of the firm-level implied variance and other data we used in the paper. To measure the firm-level sensitivity to monetary policy announcement surprises around Federal Open Market Committee (FOMC) days, we use equity options data from OptionMetrics for the period of January 1, 1996 to December 31, 2017. We exclude options with missing or negative bid-ask spread, zero bid, or zero open interest. We restrict the sample to out-of-the-money options to estimate the model-free implied variance (Bakshi, Kapadia, and Madan (2003)). To ensure that our results are not driven by misleading prices, we follow Conrad, Dittmar, and Ghysels (2013) and exclude options that do not satisfy the standard option price bounds. We further remove options with the maturity less than 3 days. For a firm on a given day and a given maturity, we do not compute the implied variance if there are less than four OTM options.

Define $IV_t(\tau)$ as the time-t price of the τ-maturity quadratic payoff on the underlying stock, $IV_t(\tau) \equiv e^{-r_f \tau} \mathbb{E}_t^{\mathbb{Q}} \left[r_{t,t+\tau}^2 \right]$, where r_f is the continuously compounded interest rate. Bakshi, Kapadia, and Madan (2003) show that $IV_t(\tau)$ can be recovered from the prices of out-of-the-money (OTM) call and put options as follows:

$$IV_t(\tau) = \int_{S_t}^{\infty} \frac{1 - \ln(K/S_t)}{K^2/2} C_t(\tau; K)\, dK + \int_0^{S_t} \frac{1 + \ln(S_t/K)}{K^2/2} P_t(\tau; K)\, dK, \tag{A.1}$$

where S_t is the price of underlying stock, and $C_t(\tau; K)$ and $P_t(\tau; K)$ are call and put prices with maturity τ and strike K, respectively.

We compute $IV_t(\tau)$ for each firm on each day and for each days-to-maturity. In theory, computing $IV_t(\tau)$ requires a continuum of strike prices, while in practice we only observe a discrete and finite set of them. Following Jiang and Tian (2005) and others, we discretize the integrals in equation (A.1) by setting up a total of 1001 grid points in the moneyness (K/S_t) range from 1/3 to 3. First, we use cubic splines to interpolate the implied volatility inside the available moneyness range. Second, we extrapolate the implied volatility using the boundary values to fill the rest of the grid points. Third, we calculate option prices from these 1001 implied volatilities using the formula of Black and Scholes (1973).[6] Next, we compute $IV_t(\tau)$ if there are four or more OTM options (e.g., Conrad, Dittmar, and Ghysels (2013) and others). Lastly, to obtain the 7-days to maturity $IV_t(7)$ for a firm on a given day, we interpolate or extrapolate $IV_t(\tau)$ with available τ. This process yields a daily time series of the risk-neutral expected quadratic payoff for each eligible firm with a fixed maturity of 7-days. Due to the extrapolation, there are some negative values. We treat them as missing observations.

We obtain stock return data from the Center for Research in Security Prices (CRSP) and merge with the OptionMetrics data. During our data period, there are 6652 individual firms with traded options. In our empirical analysis, we only consider those stocks that have a CRSP share code of 10 or 11, and we exclude those stocks with a price less than \$5 or daily return larger than 500% or less than -500%. We also exclude stocks with annualized implied variance larger than 25.

Fama-French risk factors are from Kenneth French's Data library. Monetary policy news shocks and FFR shocks are from Nakamura and Steinsson (2018).

The dates of FOMC meetings are from the website of Federal Reserve Board. Following Savor and Wilson (2014), we only include the pre-scheduled FOMC meetings during our data period (1996-2017). There are about eight regularly pre-scheduled FOMC meetings each year. When the meeting lasts for two days, we consider the second day as the FOMC announcement day. In total, there are 176 FOMC announcement days in our data period. Among the 6652 firms in our sample, there are 5446 firms with at least one observed option-implied variance on these 176 FOMC days.

[6]We apply these steps to the calculation of individual risk-neutral expected quadratic payoffs. The individual equity options are American. Therefore, directly using the mid-quotes of individual options prices is inappropriate because the early exercise premium may confound our results. To avoid this issue, we use the implied volatilities provided by OptionMetrics. These implied volatilities are computed using a proprietary algorithm based on the Cox, Ross, and Rubinstein (1979) model, which takes the early exercise premium into account.

A.2 Additional Tables

Table A1: Firm Characteristics of the Portfolios Sorted on Expected Sensitivity

	1	2	$3-8$	9	10
Size (in $million)	4813	6899	11012	8050	4722
B/M	0.46	0.48	0.50	0.48	0.48
Amihud Illiquidity (x 10^6)	0.02	0.01	0.01	0.01	0.02

This table reports firm characteristics of the decile portfolios sorted on expected sensitivity including the average firm size (in $million) and B/M. Book equity is calculated following Davis, Fama, and French (2000) and market equity is the market capitalization calculated as stock price times the shares outstanding. We also report the value-weighted Amihud illiquidity measure multiplied by 10^6.

Table A2: Firm-Level Implied Variance Reduction Forecast

	Actual IV Reduction			
	Model 1	Model 2	Model 3	Model 4
Predicted IV Reduction	0.0466	0.0299	0.0214	-0.0002
	(1.85)	(0.99)	(3.53)	(-0.23)
Constant	-0.0018	-0.0019	-0.0011	0.0024
	(-0.78)	(-0.80)	(-0.59)	(1.13)
R-squared (%)	0.03	0.02	0.20	0.01

This table reports the results when regressing the actual implied variance (IV) reduction on various IV reduction forecasts. In column 1 (2) we use the median (mean) of IV reduction on previous FOMC days during the past twelve months as the IV reduction forecast for the upcoming FOMC announcement. In column 3 (4) we adjust IV by the median (mean) historical realized variance at the every sorting date to get the IV reduction forecast. We report the t-statistics using the day-clustered standard error in parenthesis.

Table A3: Portfolio Returns Sorted on Expected Sensitivity (Robustness Check)

Panel A: Exclude the Financial Crisis

	1	2	3 − 8	9	10	(10 − 1)
CAPM Beta	1.44	1.19	0.93	1.24	1.45	0.01
Non-FOMC Dummy	-0.94	-0.48	0.51	0.15	-1.51	-0.57
	(-0.81)	(-0.53)	(1.79)	(0.20)	(-1.27)	(-0.43)
FOMC Dummy	-14.69	-9.51	0.21	8.20	13.81	28.50
	(-2.08)	(-2.06)	(0.14)	(1.97)	(1.94)	(3.13)

Panel B: Exclude the Firm Earning Announcements

	1	2	3 − 8	9	10	(10 − 1)
CAPM Beta	1.40	1.14	0.90	1.16	1.33	-0.07
Non-FOMC Dummy	-0.66	-0.35	0.57	0.11	-0.73	-0.07
	(-0.56)	(-0.39)	(1.98)	(0.16)	(-0.62)	(-0.05)
FOMC Dummy	-10.62	-9.70	-1.03	8.05	17.80	28.42
	(-1.45)	(-2.11)	(-0.66)	(2.09)	(2.44)	(2.97)

This table reports the robustness check of our portfolio sorting results, as shown in Table 2. We report the daily regression results of equation (3), which include the CAPM beta and coefficients of a non-FOMC dummy and a FOMC dummy, as well as the Newey-West t-statistics. In Panel A, we exclude the recent financial crisis period of July 2008 to June 2009; in Panel B, we exclude those firms reporting earnings on the upcoming FOMC days when we form portfolios. We use the COMPUSTAT variable "RDQ" as the reported date of quarterly earnings. Number of firms reporting earnings on the FOMC days in our sample changes from 1 to 123. On average there are 25 firms reporting earnings on each FOMC days.

Table A4: CAPM of Portfolio Returns Controlling for VIX

Panel A: Portfolios Sorted on Expected Sensitivity

	1	2	$3-8$	9	10	$(10-1)$
CAPM Beta	1.52	1.23	0.90	1.26	1.55	0.03
Non-FOMC Dummy	-1.09	-0.47	0.64	0.35	-1.34	-0.25
	(-0.95)	(-0.53)	(2.19)	(0.47)	(-1.13)	(-0.19)
FOMC Dummy	-9.29	-8.74	-1.41	7.87	21.39	30.67
	(-1.28)	(-1.94)	(-0.90)	(1.94)	(2.60)	(2.87)

Panel B: Portfolios Sorted on CAPM Beta

	1	2	$3-8$	9	10	$(10-1)$
CAPM Beta	0.42	0.60	1.01	1.67	1.95	1.53
Non-FOMC Dummy	1.33	1.49	0.38	-2.27	-1.61	-2.94
	(2.01)	(2.40)	(1.05)	(-1.98)	(-0.97)	(-1.40)
FOMC Dummy	-3.22	-5.59	-2.75	1.84	14.18	17.41
	(-0.78)	(-1.69)	(-1.76)	(0.31)	(1.70)	(1.56)

This table reports CAPM beta and the regression coefficients of the non-FOMC dummy and the FOMC dummy in the following regression:

$$R_t^i - r_{f,t} = \alpha_{Non}^i \cdot \mathbf{1}_{Non} + \alpha_{FOMC}^i \cdot \mathbf{1}_{FOMC} + \beta \left(R_t^M - r_{f,t} \right) + \gamma \Delta VIX_t^2 + \varepsilon_t^i,$$

where R_t^i is the daily return of the portfolio i, R_t^M is the daily return of the market, and $r_{f,t}$ is the daily risk-free rate. ΔVIX_t^2 is the daily change in VIX^2. $\mathbf{1}_{Non}$ and $\mathbf{1}_{FOMC}$ are dummy variables that take a value of 1 only on non-FOMC and FOMC announcement days, respectively.

A.3 Details of the Continuous-time Model

A.3.1 Value Function of the Representative Agent

Ricatti equation solution Because announcements provide information containing the true value of x_t at nT, the posterior variance after each announcement drops from q_{nT}^- to $q_{nT}^+ = q_0$. In the interior of $(0,T)$, the standard optimal filtering implies that the posterior mean and variance of x_t are given by equations (8) and (9). It is easy to see that q_t is deterministic and has a closed form solution

$$q\left(t\right)=\frac{\sigma_{x}^{2}\left(1-e^{-2\hat{a}\left(t+t^{*}\right)}\right)}{\left(\hat{a}-a_{x}\right)e^{-2\hat{a}\left(t+t^{*}\right)}+a_{x}+\hat{a}},\tag{A.2}$$

where $\hat{a}=\sqrt{a_{x}^{2}+\left(\sigma_{x}/\sigma\right)^{2}}$ and $t^{*}=\frac{1}{2\hat{a}}\ln\frac{\sigma_{x}^{2}+\left(\hat{a}-a_{x}\right)q_{0}}{\sigma_{x}^{2}-\left(\hat{a}+a_{x}\right)q_{0}}$.

Preference Using the results from Duffie and Epstein (1992), the representative agent's preference is specified by a pair of aggregators $(f,\mathcal{A})$ such that the utility of the representative agent, V_t, is the solution to the following stochastic differential equation:

$$dV_t=[-f(C_t,V_t)-\frac{1}{2}\mathcal{A}(V_t)||\sigma_V(t)||^2]dt+\sigma_V(t)dB_t,$$

for some square-integrable process $\sigma_V(t)$. We adopt the convenient normalization $\mathcal{A}(V)=0$ as Duffie and Epstein (1992), where the normalized aggregator $\bar{f}$ is,

$$\bar{f}(C_t,V_t)=\frac{\rho}{1-1/\psi}\frac{C_t^{1-1/\psi}-\left(\left(1-\gamma\right)V_t\right)^{\frac{1-1/\psi}{1-\gamma}}}{\left(\left(1-\gamma\right)V_t\right)^{\frac{1-1/\psi}{1-\gamma}-1}}\tag{A.3}$$

for $\psi\neq1$ and

$$\bar{f}(C,V)=\rho\left\{\left(1-\gamma\right)V\ln C-V\ln\left[\left(1-\gamma\right)V\right]\right\}$$

for unit IES ($\psi=1$).

Hamilton–Jacobi–Bellman (HJB) equation for the recursive utility satisfies

$$\bar{f}\left(C_t,V\left(\hat{x}_t,t,C_t\right)\right)+\mathcal{L}\left[V\left(\hat{x}_t,t,C_t\right)\right]=0.\tag{A.4}$$

Due to homogeneity, consider the value function of the form

$$V\left(\hat{x}_t,t,C_t\right)=\frac{1}{1-\gamma}H\left(\hat{x}_t,t\right)C_t^{1-\gamma},\tag{A.5}$$

where $H(\hat{x}_t, t)$ satisfies the following HJB equation:

$$\begin{aligned} 0 &= \frac{\rho}{1-\frac{1}{\psi}}\left(H(\hat{x}_t,t)^{-\frac{1-\frac{1}{\psi}}{1-\gamma}}-1\right)+\left(\hat{x}_t-\frac{1}{2}\gamma\sigma^2\right)+\frac{1}{1-\gamma}\frac{H_t(\hat{x}_t,t)}{H(\hat{x}_t,t)} \\ &+\left[\frac{1}{1-\gamma}a_x(\bar{x}-\hat{x}_t)+q_t\right]\frac{H_x(\hat{x}_t,t)}{H(\hat{x}_t,t)}+\frac{1}{2(1-\gamma)}\frac{H_{xx}(\hat{x}_t,t)}{H(\hat{x}_t,t)}\left(\frac{q_t}{\sigma}\right)^2. \end{aligned} \tag{A.6}$$

Proof. Given (A.3), we have

$$\bar{f}(C_t,V)=\frac{\rho}{1-\frac{1}{\psi}}C_t^{1-\gamma}\left[H(\hat{x}_t,t)^{1-\frac{1-\frac{1}{\psi}}{1-\gamma}}-H(\hat{x}_t,t)\right].$$

Furthermore, using Ito's lemma we get

$$\begin{aligned} \frac{d\left[H(\hat{x}_t,t)C_t^{1-\gamma}\right]}{C_t^{1-\gamma}} &= (1-\gamma)H(\hat{x}_t,t)\left(\hat{x}_t dt+\sigma d\tilde{B}_{C,t}\right)-\frac{1}{2}\gamma(1-\gamma)H(\hat{x}_t,t)\sigma^2 dt \\ &+H_t(\hat{x}_t,t)dt+H_x(\hat{x}_t,t)\left[a_x(\bar{x}-\hat{x}_t)dt+\frac{q_t}{\sigma}d\tilde{B}_{C,t}\right] \\ &+\frac{1}{2}H_{xx}(\hat{x}_t,t)\left(\frac{q_t}{\sigma}\right)^2 dt+(1-\gamma)H_x(\hat{x}_t,t)q_t dt, \end{aligned}$$

$$\begin{aligned} \frac{\mathcal{L}[V(\hat{x}_t,t,C_t)]}{C_t^{1-\gamma}}=\frac{\mathcal{L}\left[H(\hat{x}_t,t)C_t^{1-\gamma}\right]}{(1-\gamma)C_t^{1-\gamma}} &= \left(\hat{x}_t-\frac{1}{2}\gamma\sigma^2\right)H(\hat{x}_t,t)+\frac{1}{(1-\gamma)}\Big[H_t(\hat{x}_t,t) \\ &+H_x(\hat{x}_t,t)a_x(\bar{x}-\hat{x}_t)+\frac{1}{2}H_{xx}(\hat{x}_t,t)\left(\frac{q_t}{\sigma}\right)^2\Big]+H_x(\hat{x}_t,t)q_t. \end{aligned}$$

Therefore, divide both sides of (A.4) by $C_t^{1-\gamma}H(\hat{x}_t,t)$, we get (A.6). □

Guess $H(x_t,t)$ takes the exponential form: $H(x_t,t)=e^{Bx_t+h(t)}$. Therefore, $H_t(\hat{x}_t,t)=H(x_t,t)h'(t)$, $H_x(\hat{x}_t,t)=BH(x_t,t)$, $H_{xx}(\hat{x}_t,t)=B^2H(x_t,t)$. Substituting them into (A.6), we would get

$$\begin{aligned} 0 &= \frac{\rho(1-\gamma)}{1-\frac{1}{\psi}}\left(e^{-\frac{1-\frac{1}{\psi}}{1-\gamma}[B\hat{x}_t+h(t)]}-1\right)+(1-\gamma)\left(\hat{x}_t-\frac{1}{2}\gamma\sigma^2\right)+h'(t) \\ &+[a_x(\bar{x}-\hat{x}_t)+(1-\gamma)q_t]B+\frac{1}{2}B^2\left(\frac{q_t}{\sigma}\right)^2. \end{aligned}$$

Using $e^z - 1 \approx z$ to approximate and simplify, the above equation becomes

$$0 = -\rho \left[B\hat{x}_t + h(t)\right] + (1-\gamma)\left(\hat{x}_t - \frac{1}{2}\gamma\sigma^2\right) + h'(t) + \left[a_x(\bar{x} - \hat{x}_t) + (1-\gamma) q_t\right] B + \frac{1}{2}B^2\left(\frac{q_t}{\sigma}\right)^2.$$

Matching the coefficients of $\hat{x}_t$ and t yields:

$$B = \frac{1-\gamma}{a_x + \rho}, \tag{A.7}$$

$$h'(t) = \rho h(t) + \frac{1}{2}\gamma(1-\gamma)\sigma^2 - Ba_x\bar{x} - (1-\gamma) Bq_t - \frac{1}{2}B^2\left(\frac{q_t}{\sigma}\right)^2. \tag{A.8}$$

$h(t)$ can be solved completely by using the following boundary condition.

Boundary conditions Assume there are pre-determined announcements every period at time nT $(n = 1, 2, \ldots)$. On non-announcement days, investors solve optimization problems in the interior $(0^+ \leq t \leq nT^-, n = 1, 2, \ldots)$. On the announcement days, investors solve the optimization problems at the boundary. For simplicity, denote $t = 0 = nT^+$ as the moment right *after* the announcement (or at the announcement), and $t = T = nT^-$ as the moment right *before* the announcement. The boundary condition satisfies:

$$H\left(\hat{x}_{nT}^-, T\right) = \mathbb{E}\left[H(x_{nT}, 0) \,|\hat{x}_{nT}^-, q(T)\right], \ n = 1, 2, \ldots. \tag{A.9}$$

where $x_t \sim (\hat{x}_t, q_t)$.

The intuition is, the continuation value of the H function right before the announcement must equal to its expected value right after the announcement, conditional on the information at nT^- (before the announcement).

Using the conjectured functional form, the boundary condition can be rewritten as,

$$\begin{aligned} e^{B\hat{x}_{nT}^- + h(T)} &= \mathbb{E}\left[e^{Bx_{nT} + h(0)} |\hat{x}_{nT}^-, q(T)\right] \\ &= e^{B\hat{x}_{nT}^- + \frac{1}{2}B^2 q(T) + h(0)}, \end{aligned}$$

which gives

$$h(T) = h(0) + \frac{1}{2}B^2 q(T). \tag{A.10}$$

Equation (A.8) and (A.10) could be jointly used to solve the $h(t)$ function in closed form. Note that in order to solve for asset prices, we do not really need the functional form of $h(t)$. However, we need it in order to compute welfare gains.

A.3.2 Asset Prices

State price density and the risk-free rate For $n = 1, 2, \cdots$, in the interior of $(nT, (n+1)T)$, the law of motion of the state price density, π_t, satisfies the stochastic differential equation (12), where the risk-free interest rate is

$$r(\hat{x}_t, t) = \rho + \frac{1}{\psi}\hat{x}_t - \frac{1}{2}\gamma\left(1 + \frac{1}{\psi}\right)\sigma^2 + \frac{\frac{1}{\psi} - \gamma}{1 - \gamma}\frac{H_x(\hat{x}_t, t)}{H(\hat{x}_t, t)}q_t + \frac{\left(\frac{1}{\psi} - \gamma\right)\left(1 - \frac{1}{\psi}\right)}{2(1-\gamma)^2}\left(\frac{H_x(\hat{x}_t, t)}{H(\hat{x}_t, t)}\frac{q_t}{\sigma}\right)^2, \tag{A.11}$$

and the market price of the Brownian motion risk is

$$\sigma_\pi(t) = \gamma\sigma - \frac{\frac{1}{\psi} - \gamma}{1 - \gamma}\frac{H_x(\hat{x}_t, t)}{H(\hat{x}_t, t)}\frac{q_t}{\sigma}. \tag{A.12}$$

Proof. Pricing kernel is defined as

$$\frac{d\pi_t}{\pi_t} = \frac{d\bar{f}_C(C, V)}{f_C(C, V)} + \bar{f}_V(C, V)\,dt, \tag{A.13}$$

where $\bar{f}_C(C, V) = \rho H(\hat{x}_t, t)^{\frac{\frac{1}{\psi}-\gamma}{1-\gamma}} C_t^{-\gamma}$; $\bar{f}_V(C, V) = \rho\frac{\frac{1}{\psi}-\gamma}{1-\frac{1}{\psi}}H(\hat{x}_t, t)^{-\frac{1-\frac{1}{\psi}}{1-\gamma}} - \rho\frac{1-\gamma}{1-\frac{1}{\psi}}$.

Applying Ito's lemma,

$$
\begin{aligned}
\frac{d\bar{f}_C(C,V)}{f_C(C,V)} = \frac{d[H^{\frac{\frac{1}{\psi}-\gamma}{1-\gamma}}C_t^{-\gamma}]}{H^{\frac{\frac{1}{\psi}-\gamma}{1-\gamma}}C_t^{-\gamma}} &= \Bigg\{-\gamma\hat{x}_t + \frac{1}{2}\gamma(\gamma+1)\sigma^2 + \frac{\frac{1}{\psi}-\gamma}{1-\gamma}\frac{H_t}{H} + \frac{\frac{1}{\psi}-\gamma}{1-\gamma}\frac{H_x}{H}a_x(\bar{x}-\hat{x}_t) \\
&\quad + \frac{1}{2}\left[\frac{\left(\frac{1}{\psi}-\gamma\right)\left(\frac{1}{\psi}-1\right)}{(1-\gamma)^2}\left(\frac{H_x}{H}\right)^2 + \frac{\frac{1}{\psi}-\gamma}{1-\gamma}\frac{H_{xx}}{H}\right]\left(\frac{q_t}{\sigma}\right)^2 \\
&\quad - \gamma\frac{\frac{1}{\psi}-\gamma}{1-\gamma}\frac{H_x}{H}q_t\Bigg\}dt + \left[-\gamma\sigma + \frac{\frac{1}{\psi}-\gamma}{1-\gamma}\frac{H_x(\hat{x}_t,t)}{H(\hat{x}_t,t)}\frac{q_t}{\sigma}\right]d\tilde{B}_{C,t}.
\end{aligned}
$$

Matching the drift and diffusion of (12) and (A.13), we can get (A.12) and

$$
\begin{aligned}
r(\hat{x}_t,t) &= -\frac{\frac{1}{\psi}-\gamma}{1-\gamma}\left\{\frac{H_t}{H} + \frac{H_x}{H}a_x(\bar{x}-\hat{x}_t) + \frac{1}{2}\left[\frac{\frac{1}{\psi}-1}{1-\gamma}\left(\frac{H_x}{H}\right)^2 + \frac{H_{xx}}{H}\right]\left(\frac{q_t}{\sigma}\right)^2 - \gamma\frac{H_x}{H}q_t\right\} \\
&\quad + \gamma\hat{x}_t - \frac{1}{2}\gamma(\gamma+1)\sigma^2 - \rho\frac{\frac{1}{\psi}-\gamma}{1-\frac{1}{\psi}}H(\hat{x}_t,t)^{-\frac{1-\frac{1}{\psi}}{1-\gamma}} + \rho\frac{1-\gamma}{1-\frac{1}{\psi}}. \qquad \text{(A.14)}
\end{aligned}
$$

Use the HJB equation to simplify $r(\hat{x}_t,t)$ by multiplying $\left(\frac{1}{\psi}-\gamma\right)$ on both sides of (A.6), we have

$$
\begin{aligned}
0 &= \rho\frac{\frac{1}{\psi}-\gamma}{1-\frac{1}{\psi}}\left(H(\hat{x}_t,t)^{-\frac{1-\frac{1}{\psi}}{1-\gamma}} - 1\right) + \left(\frac{1}{\psi}-\gamma\right)\left(\hat{x}_t - \frac{1}{2}\gamma\sigma^2\right) + \frac{\frac{1}{\psi}-\gamma}{1-\gamma}\frac{H_t(\hat{x}_t,t)}{H(\hat{x}_t,t)} \\
&\quad + \left(\frac{1}{\psi}-\gamma\right)\left[\frac{1}{1-\gamma}a_x(\bar{x}-\hat{x}_t) + q_t\right]\frac{H_x(\hat{x}_t,t)}{H(\hat{x}_t,t)} + \frac{\frac{1}{\psi}-\gamma}{2(1-\gamma)}\frac{H_{xx}(\hat{x}_t,t)}{H(\hat{x}_t,t)}\left(\frac{q_t}{\sigma}\right)^2,
\end{aligned}
$$

and adding up with (A.14), we can get equation (A.11). Finally, substituting $H(x_t,t) = e^{\frac{1-\gamma}{a_x+\rho}x_t + h(t)}$ back, we will get (13) and (14). □

Price-to-dividend ratio Denote $p^i(\hat{x}_t,t)$ as the price-to-dividend ratio for firm i. The present value relationship (11) implies that

$$
\pi_t D_t^i + \lim_{\Delta\to 0}\frac{1}{\Delta}\left\{\mathbb{E}_t\left[\pi_{t+\Delta}p^i(\hat{x}_{t+\Delta},t+\Delta)D_{t+\Delta}^i\right] - \pi_t p^i(\hat{x}_t,t)D_t^i\right\} = 0 \qquad \text{(A.15)}
$$

The above equation can be used to show that $p^i(\hat{x}_t, t)$ must satisfy the following PDE:

$$1 - p^i(\hat{x}_t, t)\,\varpi^i(\hat{x}_t, t) + p^i_t(\hat{x}_t, t) - p^i_x(\hat{x}_t, t)\,\nu^i(\hat{x}_t, t) + \frac{1}{2}p^i_{xx}(\hat{x}_t, t)\left(\frac{q_t}{\sigma}\right)^2 = 0, \tag{A.16}$$

where $\varpi^i(\hat{x}_t, t)$ and $\nu^i(\hat{x}_t, t)$ are defined by:

$$\begin{aligned}
\varpi^i(\hat{x}_t, t) &= \rho - \frac{1}{2}\gamma\left(1 + \frac{1}{\psi}\right)\sigma^2 + \gamma\sigma^2\eta_i + \frac{1}{\psi}\hat{x}_t - \bar{x} - \xi_i(\hat{x}_t - \bar{x}) \\
&\quad + \frac{\frac{1}{\psi} - \gamma}{a_x + \rho} q_t(1 - \eta_i) + \frac{1}{2}\frac{\left(\frac{1}{\psi} - \gamma\right)\left(1 - \frac{1}{\psi}\right)}{(a_x + \rho)^2}\left(\frac{q_t}{\sigma}\right)^2, \\
\nu^i(\hat{x}_t, t) &= a_x(\hat{x}_t - \bar{x}) + (\gamma - \eta_i)\,q_t - \frac{\frac{1}{\psi} - \gamma}{a_x + \rho}\left(\frac{q_t}{\sigma}\right)^2.
\end{aligned}$$

Proof. Equation (A.15) implies

$$1 + p^i(\hat{x}_t, t)\frac{\mathcal{L}\left[\pi_t p^i(\hat{x}_t, t)\,D_t\right]}{\pi_t p^i(\hat{x}_t, t)\,D_t} = 0.$$

Using Ito's lemma and equation (10) and (12), we have

$$\begin{aligned}
\frac{\mathcal{L}\left[\pi_t p^i(\hat{x}_t, t)\,D_t\right]}{\pi_t p^i(\hat{x}_t, t)\,D_t} &= -r(\hat{x}_t, t) + \frac{1}{p^i(\hat{x}_t, t)}\left[p^i_t(\hat{x}_t, t) + p^i_x(\hat{x}_t, t)\,a_x(\bar{x} - \hat{x}_t) + \frac{1}{2}p^i_{xx}(\hat{x}_t, t)\frac{q_t^2}{\sigma^2}\right] \\
&\quad + \left[\bar{x} + \xi_i(\hat{x}_t - \bar{x})\right] + \frac{p^i_x(\hat{x}_t, t)}{p^i(\hat{x}_t, t)} q_t\eta_i \\
&\quad - \left(\gamma\sigma - \frac{\frac{1}{\psi} - \gamma}{1 - \gamma}\frac{H_x(\hat{x}_t, t)}{H(\hat{x}_t, t)}\frac{q_t}{\sigma}\right)\left[\eta_i\sigma + \frac{p^i_x(\hat{x}_t, t)}{p^i(\hat{x}_t, t)}\frac{q_t}{\sigma}\right].
\end{aligned}$$

Then we can derive the PDE for firm i's price-to-dividend ratio as

$$\begin{aligned}
&-\rho - \frac{1}{\psi}\hat{x}_t + \frac{1}{2}\gamma\left(1 + \frac{1}{\psi}\right)\sigma^2 + \frac{\gamma - \frac{1}{\psi}}{1 - \gamma}\frac{H_x(\hat{x}_t, t)}{H(\hat{x}_t, t)}q_t - \frac{1}{2}\frac{\left(\frac{1}{\psi} - \gamma\right)\left(1 - \frac{1}{\psi}\right)}{(1 - \gamma)^2}\left(\frac{H_x(\hat{x}_t, t)}{H(\hat{x}_t, t)}\frac{q_t}{\sigma}\right)^2 \\
&\quad + \frac{1}{p^i(\hat{x}_t, t)}\left[1 + p^i_t(\hat{x}_t, t) + p^i_x(\hat{x}_t, t)\,a_x(\bar{x} - \hat{x}_t) + \frac{1}{2}p^i_{xx}(\hat{x}_t, t)\frac{q_t}{\sigma^2}\right] \\
&\quad + \bar{x} + \xi_i(\hat{x}_t - \bar{x}) + \frac{p^i_x(\hat{x}_t, t)}{p^i(\hat{x}_t, t)}q_t\eta_i - \left(\gamma\sigma - \frac{\frac{1}{\psi} - \gamma}{1 - \gamma}\frac{H_{xx}(\hat{x}_t, t)}{H(\hat{x}_t, t)}\frac{q_t}{\sigma}\right)\left[\eta_i\sigma + \frac{p^i_x(\hat{x}_t, t)}{p^i(\hat{x}_t, t)}\frac{q_t}{\sigma}\right] = 0.
\end{aligned}$$

Using $\frac{H_x(\hat{x}_t,t)}{H(\hat{x}_t,t)} = \frac{1-\gamma}{a_x+\rho}$, we can rewrite the above equation to get (A.16). $\square$

In order to pin down the price-to-dividend ratio in terms of PDE as shown in equation (A.16), we next solve the boundary condition. Denote $p^i(\hat{x},0) = p^i(\hat{x},nT^+)$ and $p^i(\hat{x},T) = p^i(\hat{x},nT^-)$, and the boundary condition (15) can be derived as follows.

In general, under the recursive utility, the stochastic discount factor for a small interval Δ is,

$$SDF_{t,t+\Delta} = e^{-\rho\Delta}\left(\frac{C_{t+\Delta}}{C_t}\right)^{-\frac{1}{\psi}}\left[\frac{W_{t+\Delta}}{\left(\mathbb{E}\left[W_{t+\Delta}^{1-\gamma}\right]\right)^{\frac{1}{1-\gamma}}}\right]^{\frac{1}{\psi}-\gamma},$$

where $W_t = [(1-\gamma)V(\hat{x}_t,t,C_t)]^{\frac{1}{1-\gamma}}$. Thus,

$$SDF_{t,t+\Delta} = e^{-\rho\Delta}\left(\frac{C_{t+\Delta}}{C_t}\right)^{-\frac{1}{\psi}}\left[\frac{\left(H_{t+\Delta}C_{t+\Delta}^{1-\gamma}\right)^{\frac{1}{1-\gamma}}}{\left(\mathbb{E}\left[H_{t+\Delta}C_{t+\Delta}^{1-\gamma}\right]\right)^{\frac{1}{1-\gamma}}}\right]^{\frac{1}{\psi}-\gamma}.$$

At the announcement, $\Delta \to 0$, therefore,

$$SDF_{t,t+\Delta} = \frac{H_{t+\Delta}^{\frac{\frac{1}{\psi}-\gamma}{1-\gamma}}}{\mathbb{E}\left[H_{t+\Delta}\right]^{\frac{\frac{1}{\psi}-\gamma}{1-\gamma}}} = \frac{e^{\frac{\frac{1}{\psi}-\gamma}{a_x+\rho}\hat{x}_t}}{\mathbb{E}\left[e^{\frac{1-\gamma}{a_x+\rho}\hat{x}_t}\right]^{\frac{\frac{1}{\psi}-\gamma}{1-\gamma}}}.$$

The boundary condition for the price-to-dividend ratio at the announcement nT can be derived as:

$$\begin{aligned} p^i\left(\hat{x}_{nT}^-, nT^-\right) &= \mathbb{E}\left[\frac{e^{\frac{\frac{1}{\psi}-\gamma}{a_x+\rho}\hat{x}_{nT}^+}p^i\left(\hat{x}_{nT}^+, nT^+\right)}{\mathbb{E}\left[e^{\frac{1-\gamma}{a_x+\rho}\hat{x}_{nT}^+}\right]^{\frac{\frac{1}{\psi}-\gamma}{1-\gamma}}} \mid \hat{x}_{nT}^-, q_T^-\right] = \frac{\mathbb{E}\left[e^{\frac{\frac{1}{\psi}-\gamma}{a_x+\rho}\hat{x}_{nT}^+}p^i\left(\hat{x}_{nT}^+, nT^+\right) \mid \hat{x}_{nT}^-, q_{nT}^-\right]}{\left(e^{\frac{1-\gamma}{a_x+\rho}\hat{x}_{nT}^- + \frac{1}{2}\left(\frac{1-\gamma}{a_x+\rho}\right)^2\left[q_{nT}^- - q_{nT}^+\right]}\right)^{\frac{\frac{1}{\psi}-\gamma}{1-\gamma}}} \\ &= \frac{\mathbb{E}\left[e^{\frac{\frac{1}{\psi}-\gamma}{a_x+\rho}\hat{x}_{nT}^+}p^i\left(\hat{x}_{nT}^+, nT^+\right) \mid \hat{x}_{nT}^-, q_{nT}^-\right]}{e^{\frac{\frac{1}{\psi}-\gamma}{a_x+\rho}\hat{x}_{nT}^- + \frac{(1-\gamma)\left(\frac{1}{\psi}-\gamma\right)}{2(a_x+\rho)^2}\left[q_{nT}^- - q_{nT}^+\right]}}, \end{aligned}$$

which corresponds to equation (15) in the main text. Combining this boundary condition with equation (A.16) would pin down the solutions for each firm's price-to-dividend ratio.

Risk premium We define the cumulative return as

$$\frac{dR_t^i}{R_t^i} = \mu_{R,t}^i dt + \sigma_{R,t}^i d\tilde{B}_{C,t} + \sigma_i dB_{i,t} \tag{A.17}$$

where $\mu_{R,t}^i$ and $\sigma_{R,t}^i$ are the risky asset return and volatility for firm i, respectively,

$$\begin{aligned} \mu_{R,t}^i &= \frac{1}{p^i(\hat{x}_t,t)}\left[1 + p_t^i(\hat{x}_t,t) + p_x^i(\hat{x}_t,t)\,a_x(\bar{x}-\hat{x}_t) + \frac{1}{2}p_{xx}^i(\hat{x}_t,t)\frac{q_t^2}{\sigma^2}\right] \\ &\quad + \bar{x} + \xi_i(\hat{x}_t-\bar{x}) + \frac{p_x^i(\hat{x}_t,t)}{p^i(\hat{x}_t,t)}q_t\eta_i, && \text{(A.18)} \\ \sigma_{R,t}^i &= \eta_i\sigma + \frac{p_x^i(\hat{x}_t,t)}{p^i(\hat{x}_t,t)}\frac{q_t}{\sigma}. && \text{(A.19)} \end{aligned}$$

In the interior of $(nT,(n+1)T)$, the instantaneous risk premium is

$$\mu_{R,t} - r(\hat{x}_t,t) = \left[\gamma\sigma - \frac{\frac{1}{\psi}-\gamma}{a_x+\rho}\frac{q_t}{\sigma}\right]\left[\eta_i\sigma + \frac{p_x^i(\hat{x}_t,t)}{p^i(\hat{x}_t,t)}\frac{q_t}{\sigma}\right]. \tag{A.20}$$

Proof. The cumulative return can be computed as

$$\frac{dR_t^i}{R_t^i} = \frac{1}{p^i(\hat{x}_t,t)\,D_t^i}\left[D_t^i dt + d\left[p^i(\hat{x}_t,t)\,D_t^i\right]\right].$$

Applying Ito's lemma, we have

$$\begin{aligned} \frac{d\left[p^i(\hat{x}_t,t)\,D_t^i\right]}{p^i(\hat{x}_t,t)\,D_t^i} &= \left\{\frac{1}{p^i(\hat{x}_t,t)}\left[p_t^i(\hat{x}_t,t) + p_x^i(\hat{x}_t,t)\,a_x(\bar{x}-\hat{x}_t) + \frac{1}{2}p_{xx}^i(\hat{x}_t,t)\frac{q_t^2}{\sigma^2}\right]\right. \\ &\quad \left. + \bar{x} + \xi_i(\hat{x}_t-\bar{x}) + \frac{p_x^i(\hat{x}_t,t)}{p^i(\hat{x}_t,t)}q_t\eta_i\right\}dt + \left[\eta_i\sigma + \frac{p_x^i(\hat{x}_t,t)}{p^i(\hat{x}_t,t)}\frac{q_t}{\sigma}\right]d\tilde{B}_{C,t} + dB_{i,t}. \end{aligned}$$

Matching the drift and diffusion terms with equation (A.17), we can get (A.18) and (A.19).

The instantaneous risk premium (A.20) can be obtained from

$$
\begin{aligned}
\mu^i_{R,t} - r(\hat{x}_t, t) &= -Cov_t\left[\frac{d\left[p^i(\hat{x}_t, t) D^i_t\right]}{p^i(\hat{x}_t, t) D^i_t}, \frac{d\pi_t}{\pi_t}\right] \\
&= \left[\gamma\sigma - \frac{\frac{1}{\psi} - \gamma}{1-\gamma}\frac{H_x(\hat{x}_t, t)}{H(\hat{x}_t, t)}\frac{q_t}{\sigma}\right]\left[\eta_i\sigma + \frac{p^i_x(\hat{x}_t, t)}{p^i(\hat{x}_t, t)}\frac{q_t}{\sigma}\right] \\
&= \gamma\eta_i\sigma^2 + \left[\gamma\frac{p^i_x(\hat{x}_t, t)}{p^i(\hat{x}_t, t)} - \frac{\frac{1}{\psi} - \gamma}{1-\gamma}\eta_i\frac{H_x(\hat{x}_t, t)}{H(\hat{x}_t, t)}\right]q_t - \frac{\frac{1}{\psi} - \gamma}{1-\gamma}\frac{H_x(\hat{x}_t, t)}{H(\hat{x}_t, t)}\frac{p^i_x(\hat{x}_t, t)}{p^i(\hat{x}_t, t)}\left(\frac{q_t}{\sigma}\right)^2.
\end{aligned}
$$

□

A.3.3 Expected Sensitivity

Guess the price-to-dividend ratio having the exponential form: $p(\hat{x}_t, t) = e^{A\hat{x}_t + g(t)}$. Substituting this into (A.16) yields,

$$
e^{-A\hat{x}_t - g(t)} - \varpi(\hat{x}_t, t) + g'(t) - A\nu(\hat{x}_t, t) + \frac{1}{2}A^2\left(\frac{q_t}{\sigma}\right)^2 = 0.
$$

Use the Taylor expansion around $\bar{x}$ (since $\hat{x}_t$ is an OU process), $e^{-A\hat{x}_t - g(t)} \approx \bar{p} - A\bar{p}(\hat{x}_t - \bar{x})$, where $\bar{p}$ is the inverse of the steady state price-to-dividend ratio. Match the coefficient of $\hat{x}_t$ yields,

$$
A = \frac{\xi - \frac{1}{\psi}}{a_x + \bar{p}}. \tag{A.21}
$$

Note that the sensitivity of each firm can be approximated as: $p^i_x(\hat{x}_t, t)/p^i(\hat{x}_t, t) = \frac{\xi_i - \frac{1}{\psi}}{a_x + \bar{p}^i}$.

A.3.4 Implied Variance Reduction

In our model, all shocks are conditional normal, and the variance of the shocks are deterministic. Therefore, the return variance under the physical and risk-neutral measure are the same. We only need to compute the variance under the physical measure. The variance before the announcement is

$$
\begin{aligned}
Var\left[\ln P(t) - \ln P\left(nT^{-}\right) \mid \hat{x}_{nT}^{-}, q_{nT}^{-}\right] &= Var\left[\ln P(t) - \ln P\left(nT^{+}\right) \mid \hat{x}_{nT}^{-}, q_{nT}^{-}\right] \\
&\quad + Var\left[\ln P\left(nT^{+}\right) - \ln P\left(nT^{-}\right) \mid \hat{x}_{nT}^{-}, q_{nT}^{-}\right].
\end{aligned}
$$

The variance after the announcement could be written as

$$
Var\left[\ln P(t) - \ln P\left(nT^{+}\right) \mid \hat{x}_{nT}^{-}, q_{nT}^{-}\right].
$$

Therefore, the implied variance reduction could be obtained by taking the difference of the above two expressions:

$$
\Delta IV = Var\left[\ln P\left(nT^{+}\right) - \ln P\left(nT^{-}\right) \mid \hat{x}_{nT}^{-}, q_{nT}^{-}\right].
$$

Because dividend is continuous upon announcements, we can get

$$
\Delta IV = Var\left[\ln p\left(nT^{+}\right) - \ln p\left(nT^{-}\right) \mid \hat{x}_{nT}^{-}, q_{nT}^{-}\right]. \tag{A.22}
$$

Therefore, for each individual firm i we have

$$
\Delta IV_i = \left(\frac{\xi_i - \frac{1}{\psi}}{a_x + \bar{p}^i}\right)^2 \left(q_{nT}^{-} - q_{nT}^{+}\right) = \left(\frac{\xi_i - \frac{1}{\psi}}{a_x + \bar{p}^i}\right)^2 \left(\frac{q_{nT}^{-2}}{q_{nT}^{-} + \sigma_s^2}\right).
$$

A.3.5 Numerical Solutions

To solve the PDE (A.16) with the boundary condition (15) for each firm i, we consider the following auxiliary problem[7]:

$$
p(\hat{x}_t, t) = \mathbb{E}\left[\int_t^T e^{-\int_t^s \varpi(\hat{x}_u, u)du} ds + e^{-\int_t^T \varpi(\hat{x}_u, u)du} p(\hat{x}_T, T)\right], \tag{A.23}
$$

[7]We fix (ξ_i, η_i) for each firm and calculate the firm-specific price-to-dividend $p^i(\hat{x}_t, t)$. The procedure is the same for each firm. Thus we drop i for simplicity.

where the state variable $\hat{x}_t$ follows the law of motion

$$d\hat{x}_t = -\nu\left(\hat{x}_t, t\right) dt + \frac{q_t}{\sigma} dB_t. \tag{A.24}$$

Note that the solution to (A.23) and (15) satisfies the same PDE. Given an initial guess of the pre-announcement price-to-dividend ratio, we can solve (A.23) by the Markov chain approximation method (Kushner and Dupuis, 2001). The major steps are:[8]

1. Start with an initial guess of a pre-announcement price-to-dividend ratio $p\left(\hat{x}_T, T\right) = 1/\rho$.

2. With the initial guess of $p\left(\hat{x}_T, T\right)$, for $t = T - \Delta$, $T - 2\Delta$, etc., we use the Markov chain approximation to compute the discounted problem in (A.23) backwards recursively:

$$p\left(\hat{x}_t, t\right) = \Delta + e^{-\varpi\left(\hat{x}_t, t\right)\Delta}\mathbb{E}\left[p\left(\hat{x}_{t+\Delta}, t+\Delta\right)\right],$$

   until we obtain $p\left(\hat{x}_t, 0\right)$.

3. Compute an updated pre-announcement price-to-dividend ratio function, $p\left(\hat{x}_T, T\right)$ using (15),

$$p^i\left(\hat{x}_T^-, T^-\right) = \frac{\mathbb{E}\left[e^{\frac{\frac{1}{\psi}-\gamma}{a_x+\rho}\hat{x}_T^+} p^i\left(\hat{x}_T^+, T^+\right) \mid \hat{x}_T^-, q_T^-\right]}{e^{\frac{\frac{1}{\psi}-\gamma}{a_x+\rho}\hat{x}_T^- + \frac{(1-\gamma)\left(\frac{1}{\psi}-\gamma\right)}{2(a_x+\rho)^2}\left[q_T^- - q_T^+\right]}}.$$

4. Go back to step 1 and iterate until the function $p\left(\hat{x}_T, T\right)$ converges.

Now we discuss the numerical details. For simplicity, define the log price-to-dividend ratio

[8] We construct a locally consistent Markov chain approximation of the diffusion process (A.24) as follows. We choose a small $d\hat{x}$, let $Q = \left|\nu\left(\hat{x}, t\right)\right| d\hat{x} + \left(\frac{q_t}{\sigma}\right)^2$, and define the time increment $\Delta = \frac{d\hat{x}^2}{Q}$ as a function of $d\hat{x}$. Define the following Markov chain on the space of $\hat{x}$:

$$\begin{aligned}
\Pr\left(\hat{x} + d\hat{x}\,|\hat{x}\right) &= \frac{1}{Q}\left[-\nu\left(\hat{x}, t\right)^+ d\hat{x} + \frac{1}{2}\left(\frac{q_t}{\sigma}\right)^2\right], \\
\Pr\left(\hat{x} - d\hat{x}\,|\hat{x}\right) &= \frac{1}{Q}\left[-\nu\left(\hat{x}, t\right)^- d\hat{x} + \frac{1}{2}\left(\frac{q_t}{\sigma}\right)^2\right].
\end{aligned}$$

One can verify that as $d\hat{x} \to 0$, the above Markov chain converges to the diffusion process (A.24). In the language of Kushner and Dupuis (2001), this is a Markov chain that is locally consistent with the diffusion process (A.24).

$\varrho(\hat{x}_t, t) \equiv \ln p(\hat{x}_t, t)$, therefore,

$$\begin{aligned}
\varrho(\hat{x}_t, t) &= \ln\left[\Delta + e^{-\varpi(\hat{x}_t,t)\Delta}\mathbb{E}\left[p\left(\hat{x}_{t+\Delta}, t+\Delta\right)\right]\right] \\
&= \ln\left[\Delta + e^{-\varpi(\hat{x}_t,t)\Delta}e^{\varrho(\hat{x}_{t+\Delta},t+\Delta)-\varrho_x(\hat{x}_t,t)\nu(\hat{x}_t,t)\Delta+\frac{1}{2}\Delta\varrho_x^2(\hat{x}_t,t)\left(\frac{q_t}{\sigma}\right)^2}\right] \\
&= \ln\left[\Delta + e^{\varrho(\hat{x}_{t+\Delta},t+\Delta)-[\varpi(\hat{x}_t,t)+\varrho_x(\hat{x}_t,t)\nu(\hat{x}_t,t)]\Delta+\frac{1}{2}\Delta\varrho_x^2(\hat{x}_t,t)\left(\frac{q_t}{\sigma}\right)^2}\right].
\end{aligned}$$

At the announcement T,

$$\varrho\left(\hat{x}_T^-, T^-\right) = \ln\mathbb{E}\left[e^{\frac{\frac{1}{\psi}-\gamma}{a_x+\rho}\hat{x}_T^+ + \varrho\left(\hat{x}_T^+,T^+\right)} \mid \hat{x}_T^-, q_T^-\right] - \left[\frac{\frac{1}{\psi}-\gamma}{a_x+\rho}\hat{x}_T^- + \frac{(1-\gamma)\left(\frac{1}{\psi}-\gamma\right)}{2\left(a_x+\rho\right)^2}\left[q_T^- - q_T^+\right]\right].$$

We approximate the expectation in two ways. First, if $\hat{x}$ is in the interior $\left[\bar{x} - 5\frac{\sigma_x}{\sqrt{2a_x}} + \max(\mathbf{n}), \bar{x} + 5\frac{\sigma_x}{\sqrt{2a_x}} + \max(\mathbf{n})\right]$, we use the Gaussian quadrature:

$$\mathbb{E}\left[e^{\frac{\frac{1}{\psi}-\gamma}{a_x+\rho}\hat{x}_T^+ + \varrho\left(\hat{x}_T^+,T^+\right)} \mid \hat{x}_T^-, q_T^-\right] = \omega' e^{\frac{\frac{1}{\psi}-\gamma}{a_x+\rho}\hat{x}_T^+ + \varrho\left(\hat{x}_T^+,T^+\right)},\ \hat{x}_T^+ = \hat{x}_T^- + \mathbf{n},$$

where nodes $\mathbf{n}$ and weights ω are random variables generated from the multivariate normal distribution.

Second, if $\hat{x}$ is close to the boundary, we use the local approximation:

$$\varrho(\hat{x}_T, T) + \varrho_x(\hat{x}_T, T)\left[\frac{\frac{1}{\psi}-\gamma}{a_x+\rho} + \frac{1}{2}\varrho_x(\hat{x}_T, T)\right]\left[q_T^- - q_T^+\right].$$

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