Financial asset demand is elastic: Evidence from new issues of Federal Home Loan Bank debt

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ABSTRACT

We estimate the slope of the demand curve for newly auctioned FHLB discount notes and investigate the impacts of arbitrage risk and heterogeneity of investor beliefs on demand elasticity. Our unique dataset of roughly 2,900 observations of two price-quantity pairs—the first from a pre-auction dealer survey, the second from actual auction results—provides the quantity shift necessary to identify demand. In contrast to previous findings of downward-sloping demand curves for equities, we show that demand for newly issued FHLB notes is nearly perfectly elastic during normal market conditions. We find, however, that frictions like arbitrage risk and, to a lesser extent, heterogeneity of investor beliefs negatively affect elasticity and explain the nearly 50% drop in elasticity observed during the recent financial crisis.

1. Introduction

In a frictionless world, arbitrage should produce perfectly elastic financial asset demand curves. In practice, however, the literature has identified potentially important frictions capable of inducing downward-sloping demand curves for individual securities. Asset substitution may be less than perfect when would-be arbitragers face internal or counterparty restrictions limiting leveraged trading of large positions. Individual traders may also possess different information about future cash flows or else interpret common information in alternative ways. The existence of either significant limits to arbitrage or heterogeneity of investor beliefs is consistent with the extant empirical literature's conclusion that demand functions for financial assets slope downward.

The bulk of the financial asset demand literature studies equity markets in a cross-sectional setting. We extend this literature along two dimensions. First, we examine discount notes issued by the Federal Home Loan Bank (FHLB) System, a large government-sponsored enterprise (GSE) chartered by Congress in 1932 to provide liquidity to home mortgage lenders. Compared to the typical equity security, the demand for these very high quality short-term debt securities should be much less affected by both information-based frictions and leverage constraints. Second, we observe time variation in the demand for FHLB discount notes between 1999 and 2008, with a special focus on the financial crisis beginning in August 2007.

In sharp contrast to previous results for equity securities, we find that the demand curve for FHLB discount notes is nearly perfectly elastic during normal market conditions. The point estimate for our baseline pooled sample is -45,500, which is one-to-four orders of magnitude higher than estimates for individual equities from the existing literature. We also find that this demand elasticity is time-varying and that it decreased significantly after the onset of the financial crisis. Such a crisis impact on FHLB debt demand might not be entirely surprising since GSE debt carries only an "implicit" U.S. government guarantee and the onset of a general financial crisis may affect the perceived risk of these assets. Using a framework inspired by Wurgler and Zhuravskaya (2002), we investigate whether an estimated decrease in the elasticity of demand for FHLB discount notes after August 2007 was related to observed increases in arbitrage risk and/or heterogeneity of investor beliefs. We find support for both of these conjectures.

As one of the largest dollar-denominated debt issuers, FHLB debt is worthy of study in its own right. However, its particular appeal for estimating financial asset demand is a unique dataset resulting from 2,910 discount note auctions held by the FHLB System's Office of Finance. This dataset contains pre-auction dealer rate indications that, for a given expected auction size, summarize each auction morning's market conditions. We compare these rate indications for the *expected* auction size with the corresponding auction rate results for the *actual* auction size. Assuming rational expectations, our dataset identifies *two* distinct points on the market demand schedule associated with each discount note auction that took place between January 1999 and June 2008. The unique nature and large quantity (an order of magnitude larger than those used in previous studies) of our data enhances statistical precision and alleviates endogeneity concerns.

The remainder of this paper is organized as follows. Section 2 reviews the previous literature and institutional setting. Section 3 describes and presents summary statistics for our data. Section 4 presents our main empirical results. Section 5 concludes.

2. Background

2.1. Related literature

There have been five main approaches to estimating the elasticity of demand for equities. Each of these approaches investigates whether a particular type of shock to excess demand generates significant return responses in a cross-sectional setting. Shocks studied include: (1) secondary equity distributions (Scholes, 1972; Mikkelson and Partch, 1985), (2) block trades (Kraus and Stoll, 1972), (3) stock repurchases (Bagwell, 1992), (4) initial public offerings (Kandel, Sarig, and Wohl, 1999), and (5) additions and/or re-weightings of stock indices (Shleifer, 1986).[1] All of the studies find some evidence of price impacts of their selected shock. However, these results may be attributable to contemporaneous revelations of information about firm value.[2] Kaul, Mehrotra, and Morck (2000) attempt to address this endogeneity issue by exploiting a presumably uninformative change in the weightings of the Toronto Stock Exchange 300 index to identify their price-insensitive demand shift and find evidence of downward sloping demand curves for stocks.

Extending this literature, Wurgler and Zhuravskaya (2002) argue that near-perfect substitutes for individual stocks do not exist and that unexplained return variance (a measure of "arbitrage risk") is an important determinant of cross-sectional variation in the elasticity of demand for equities. The authors re-examine individual stock additions to the S&P 500 stock index and report significantly steeper demand curves for stocks with higher levels of arbitrage

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[1] See also Garry and Goetzmann (1986), Harris and Gurel (1986), Dillon and Johnson (1991), Beneish and Whaley (1996), Lynch and Mendenhall (1997), and Kappou, Brooks and Ward (2010), among others, for US stock index data and Chakrabarti et al. (2005) for international evidence. Hau, Massa and Peress (2010) present evidence that a December 2000 reweighting of the MSCI international equity index affected exchange rates.

[2] For example, positive return impacts of stock index additions may reflect the index provider's certification of "good news" for a newly added company's prospects (Denis et al., 2003).

risk. Greenwood (2005) also uses a limits-to-arbitrage setting and finds large price impacts from a unique redefinition of Japan's Nikkei 225 index.

The elasticity of demand for debt securities has received much less attention.[3] Kamara (1994) provides some evidence of a downward-sloping demand curve for short-term Treasury notes based upon tax-related differential pricing of Treasury notes and bills. Other debt market studies in finance have focused on relative pricing of on-the-run versus off-the-run Treasury securities, especially in the context of analyzing impacts on value due to differences in liquidity and the degree of repurchase agreement market "specialness."[4] Krishnamurthy and Vissing-Jorgensen (2008) examine a possible convenience yield component of demand for aggregate US Treasury debt. They find evidence of a downward-sloping demand curve using an instrumental variables approach under the critical assumption that the ratio of total US Treasury debt to US gross domestic product is exogenous.

A significant literature analyzes bidding strategies in fixed-size auctions of new debt issues. These studies compare auction outcomes with secondary market pricing, but their data do not contain a contemporaneous *shift* in supply necessary to identify the slope of a demand curve. However, these studies do present related evidence on the question of whether auction size influences auction outcomes. Nyborg, Rydqvist and Sundaresan (2002) and Keloharju, Nyborg and Rydqvist (2005) find little sensitivity between government debt auction price outcomes and issue size. These results are consistent with near perfectly elastic demand.

[3] A large related body of work on Ricardian equivalence exists in the economics literature (e.g. Seater, 1993).

[4] See, for example, Jordan and Jordan (1997), Krishnamurthy (2002) and Sundaresan and Wang (2009).

2.2. The Federal Home Loan Bank System

The FHLB System is a major issuer in the dollar-denominated debt market, yet it has been largely neglected in the academic finance literature.[5] The FHLB System consists of 12 cooperatively owned wholesale banks designed to support housing finance and community development. FHLB members/owners may be commercial banks, thrifts, credit unions, or insurance companies. The FHLB System acts as a source of liquidity for the more than 8,100 individual financial institutions via collateralized loans called "advances." As of June 2008, FHLB advances totaled $913.9 billion – representing 68 percent of FHLB System total assets. Members most commonly pledge single-family mortgage loans to collateralize these advances, which are overcollateralized.[6] Furthermore, by statute, the FHLBs have a preferred lien position over depositors and all other claimants in the event of a member institution's default. To date, no FHLB has ever suffered a credit loss on an advance to a member.

FHLBs primarily fund themselves by issuing debt securities known as "consolidated obligations." (As of June 30 2008, debt securities provided funding for almost 93% of total FHLB assets.) Although each regional FHLB is a separate legal entity with its own board of directors, the 12 institutions are jointly and severally liable for these securities. This feature, coupled with their GSE status, results in consolidated obligations maintaining a AAA rating.[7]

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[5] See Flannery and Frame (2006) for a recent review of the FHLB System. The sparse academic literature studying the FHLB dates as far back as Silber (1973).

[6] See Stojanovic, Vaughan and Yeager (2008) for analysis relating FHLB System membership, advances, and bank risk.

[7] Ashcraft, Bech and Frame (2010) summarize the FHLB System's special GSE privileges as incorporating (1) a provision authorizing the Treasury Secretary to purchase up to $4 billion of FHLB securities, (2) the treatment of System debt as "government securities" under the Securities and Exchange Act of 1934, (3) the statutory ability to use the Federal Reserve as its fiscal agent, and (4) an exemption from the bankruptcy code by way of being considered "federal instrumentalities."

Nevertheless, the financial health of individual FHLBs may differ and this is reflected in their derivatives counterparty credit ratings.

FHLBs borrow daily using a variety of methods to provide liquidity for their members. Discount notes, with maturities up to one year, are issued through regularly scheduled auctions and a "discount note window." The FHLB System also issues a variety of longer-maturity bonds. All debt issuance and servicing is executed by the Office of Finance, a joint FHLB System facility.

Figure 1 presents an annual plot of the total amounts of FHLB discount notes issued via auctions, the average of all discount notes outstanding, and the average outstanding amounts of advances extended to members from 1999 through 2008. The FHLB System has a large footprint in the market for high credit quality short-term debt securities. As of year-end 2008, the $441 billion of FHLB discount note debt outstanding was more than one-fifth the size of the $1.9 trillion of marketable US Treasury bills held by the public. The total amount of discount notes outstanding nearly tripled between year-end 2006 and year-end 2008 as the financial crisis spurred tremendous demand for FHLB advances by member institutions.

<Insert Figure 1 here>

Ashcraft, Bech and Frame (2010) conclude that during the crisis large member institutions used FHLB advances to fund increases in their trading books, federal funds and repo lending, and non-mortgage lending most likely tied to customer drawdowns of outstanding lines of credit. They interpret the FHLB System as having provided a "lender-of-next-to-last-resort" function during the last five months of 2007. Members saw FHLB advances as funding at attractive rates without any of the stigma attached to the alternative of borrowing at the Federal Reserve Discount Window. Funding the dramatic increase in member advances generated high levels of debt issuance by the FHLB System in 2007. As we detail below, the average size of FHLB discount note auctions was much larger during the second half of 2007 and first half of 2008 than during any previous period. For example, the average size of the 4-week discount note auctions held during the first half of 2008 was $7.07 billion, more than twice that of the 1999-2006 period. For all of 2008, overnight discount note issuance averaged about $32 billion per day and total term note issuance exceeded $2.7 trillion. The special circumstances of the general credit crisis, both in terms of observed FHLB System discount note issuance and the re-pricing of credit risk documented by Taylor and Williams (2009), suggest that our empirical work should be sensitive to a potential regime shift beginning in August 2007.

Figure 2 presents time series plots of the interest rate spreads for 3-month FHLB discount notes relative to both 3-month Treasury Bills and 3-month LIBOR (in basis points). Fluctuations in these spreads indicate the existence of forces that cause FHLB discount note pricing to differ substantially from the liabilities of the Treasury and commercial banks. Examples of extreme moves in the spread to LIBOR prior to August 2007 were rare and tied to some specific events. For example, a spike in the spread to LIBOR occurred during the week of the September 11, 2001 World Trade Center attack. A larger spike and more protracted disturbance during the latter half of 1999 can be ascribed to Y2K-related financial market trading system uncertainties.[8] Nevertheless, both spread histories suggest that a clear break in rate relationships occurred around August 2007. Beginning in August 2007, the 3-month FHLB discount note rate fell substantially versus LIBOR and simultaneously rose versus the corresponding Treasury bill rate. Discount note rate spreads to both benchmarks also exhibited substantially higher variability beginning in August 2007.

[8] See Sundaresan and Wang (2009) for additional background on such Y2K-related market uncertainties.

<Insert Figure 2 here>

2.3. The FHLB discount note auction process

Discount notes are auctioned on Tuesday and Thursday of each week. The FHLBs typically auction discount notes with four standardized maturities: 4-weeks, 9-weeks, 13-weeks and 26-weeks. We focus on the 4-week, 9-week and 13-week maturities since they account for about 94% of the amounts auctioned.[9] Only members of the FHLB System's dealer selling group may bid. Bids are expressed as discount rates and entered via an electronic platform. This platform also determines the results of each auction and processes the winning bids through until settlement. As a byproduct, this platform also captures all of the data that we are using in this study.

To help guide the individual regional bank funding decisions, the Office of Finance elicits a set of "indications" from each of the dealers in its selling group. Between 9:30 and 11:00 AM on the morning of each auction day, the selling group dealers submit their projections for achievable auction rates. Because the actual size of the auction will not be determined until 11:36 AM, the dealers cannot condition their rate indications on the actual auction size. However, the Office of Finance does give the dealers an auction size range indication (e.g., say, $3 billion to $5 billion). Each dealer communicates a projected achievable auction rate range (say, 2.99% to 3.01%) back to the Office of Finance.

The Office's trading desk uses the dealer indications to produce an official desk 3-basis point rate range that is communicated to the 12 regional FHLBs. The regional banks price their advances (loans) to their own member institutions off of this desk indication. Based upon all of

[9] The 26-week discount note auctions are the smallest in average size (just under $500 million) and the most likely to be cancelled. In particular, 102 (10.4%) of the 985 26-week discount note auctions scheduled during our sample period were cancelled. In contrast, the only 4-week auctions cancelled during our sample decade were those for Tuesday, September 11, 2001 and Thursday, September 13, 2001.

this information, each regional bank determines its desired issuance quantity of each maturity and communicates these amounts to the Office of Finance by 11:31 AM. Between 11:31 AM and 11:36 AM, the Office of Finance reviews and then sums up all of the individual amounts ordered by the 12 regional banks. At 11:36 AM, the Office of Finance determines the size of each maturity's discount note auction and communicates those sizes to the dealers.

After the 11:36 AM announcement of the auction sizes, dealers may begin to submit their bids. Only members of the FHLB System's dealer selling group may bid in an auction. Thus, any non-member becomes a "customer" and must route its bid through a selling group dealer. Bids consist of a specific par amount at a specific discount rate. Dealers may submit multiple bids. Bids are accepted until 12:10 PM. The auction results are then determined and promptly communicated to the market. The results released to the market are the auction's all-in weighted average discount rate (WAR); the highest all-in discount rate accepted (the "Stop"); the percent of dealer bids accepted at the stop rate; and the ratio of the total par amount bid to the auction's issue size (the "Cover").

Recall that the dealers' rate indications are submitted prior to the Office of Finance's determination of any auction's actual size. This generates a unique data structure relevant for estimating the elasticity of discount note demand. In particular, for each day's auction, the Office of Finance records summary statistics for *two distinct points* on the market demand schedule. We base the first rate-quantity pair upon the average of the midpoints of the rate ranges *indicated* by the group of dealers and the mid-point of that day's *assumed* auction size range. We base the second rate-quantity pair on the *actual* auction rate result for that auction's *actual* issue size. These two rate-quantity pairs permit us to estimate the average discount rate response to variation in quantity (i.e., the slope of the demand curve) by relating the difference between the actual auction rate result and the morning's indicated rate (the "rate spread") to the difference between the actual auction size and the morning's assumed size (the "auction size adjustment").

Figure 3 illustrates the basic research design in discount note issue price-quantity space. Here, the n-day-to-maturity discount note issue price (P) is a linear function of a given percentage discount rate (R): $P = 100 \times \{1- [R \times (n \div 360]\}$. Figure 3 presumes that the cumulative bid curve for any auction depends on the auction's size. The *light* black solid line and its companion curve represent the indicated auction size and its associated cumulative bid curve. The *heavy* black solid line and its companion curve represent a "large" auction size and its associated cumulative bid curve. We use stars to represent the clearing price-quantity pairs for each auction. The clearing price is lower in the larger-sized auction (because the auction-clearing rate result is higher). We interpret the starred outcome for the indicated auction size ($S_{Indicated}$) as one price-quantity pair using the average of the midpoints of the dealers' *indicated* rate ranges to compute the associated clearing price. A second price-quantity pair is represented by the starred outcome for the *actual* "large" auction size (S_{Large}) using a price based upon the *actual* auction rate result. In Figure 3, we invoke rational expectations by assuming that (1) the market's average rate indication lies *on* the notional demand curve and (2) dealers anchor their indications using the mid-point of the Office of Finance's indicated auction size range. Under these assumptions, the market's pre-auction price anticipation is an unbiased estimate of the security's value for the presumed issue size that should incorporate all relevant market information. In particular, this estimate should capture all known pricing impacts of key auction outcome drivers such as concurrent money market interest rates, credit spreads and interest rate volatility. The change in the actual auction price relative to the initially anticipated price should then be driven solely by the change in actual auction size relative to the presumed size. Thus, we can estimate the elasticity of a notional market demand curve by measuring the slope of the line connecting the starred points in Figure 3.

<Insert Figure 3 here>

From the discussion above, our demand elasticity estimates depend crucially on three assumptions. First, dealers truthfully indicate their rate expectations for the indicated auction size. Second, the FHLB System does not adjust its auction sizes based on submitted dealer indications. Third, dealer valuations of FHLB discount notes are independent of the FHLB's auction size adjustments. Regarding the first assumption, the FHLB maintains a formal scorecard to monitor and assess the quality of dealer indications. The FHLB awards additional debt underwriting opportunities to the top scoring dealers. Thus, dealers face costs of not being truthful. The summary statistics presented in Section 3 are inconsistent with dealer manipulation of the indication process. Regarding the second and third assumptions, we perform a battery of econometric tests in Section 4.4. Those tests offer no evidence rejecting the validity of these assumptions.

3. Data and summary statistics

Our dataset tracks activities at both the auction and dealer levels. The auction level data includes the auction dates, discount note issuance amounts, and auction rate results, including the weighted-average rate, the stop rate, and the lowest bid rate. The dealer level data consists of individual dealer rate indications for each auction. We use maturity-matched Treasury bill rates and LIBOR to benchmark money market rate levels.

3.1. Summary statistics of FHLB discount note auctions

Table 1 summarizes the FHLB System's auction activity for our January 1999 to June 2008 sample period for 4-week, 9-week, and 13-week discount note maturities. Table 1 also clearly shows that average auction sizes during 2007 and, especially, 2008 are much higher than the full sample average size – owing to the heightened demand for FHLB advances during the crisis.

<Insert Table 1 here>

The amounts of discount notes auctioned generally range from $500 million to over $5 billion for each maturity. The precise amount set for each auction depends on the FHLB System's funding needs on that particular day. Figure 4 plots the sizes of each of the 4-week auctions for the January 1999 to June 2008 period. This figure plots the actual auction size as well as the indicated low and high size bounds communicated by the Office of Finance to the dealers to help condition their pre-auction rate indications. Figure 4 reveals substantial auction-to-auction variation in 4-week maturity discount note issuance size. The variation and unpredictability of FHLB System discount note auction sizes are much larger than the corresponding variation in the size of Treasury bill auctions.[10] The large variation in FHLB System discount note auction sizes is driven by FHLB responses to their members' changing needs for advances.

<Insert Figure 4 here >

Garbade (2007) discusses the evolution of Treasury financings from a tactical or opportunistic debt management strategy to a more regular and predictable issuance of coupon-bearing notes and bonds during the mid-1970s. The FHLB System's discount note auction calendar shares the "regular and predictable" aspect of US Treasury securities auctions regarding auction cycles and scheduled debt maturities (e.g., 4-week, 9-week, 13-week and 26-week

[10] The coefficients of variation (standard deviation/mean) for FHLB auction size range from 0.6 to 0.8, while the same values for Treasuries range from 0.3 to 0.4. Also, the R-squares of naïve autoregressions with 1 to 4 lags are less than 50% for FHLB auction sizes and greater than 75% for Treasuries.

auctions are scheduled for every Tuesday and Thursday). However, the "final hour" notification of a FHLB discount note's auction size differs sharply from the usual one-day to one-week lag of security auction size announcements by the Treasury. Again, this time line allows the Office of Finance to set auction sizes that respond to the changing needs of the regional FHLBs that, in turn, can respond flexibly to member institutions' demand for advances.[11]

Table 2 presents some descriptive statistics on dealer participation and award concentration. Again, the results are broken out for each of the three individual maturities. For example, for 4-week discount note auctions, the median number of dealers bidding is 16 and the median number of bids (of varying amounts) received by the Office of Finance is 63. The median cover ratio (defined as sum of bid amounts divided by total auctioned amount) of 3.64 reveals that the typical auction comfortably avoids the prospect of "failure" (i.e., not enough bids to absorb the announced auction size). Indeed, an understanding between the Office of Finance and its dealers stipulates that every dealer should bid at least its *pro rata* share of the auction. The bidding interest shows significant auction-to-auction variation. In particular, the cover ratio for 4-week discount note auctions is positively skewed and ranges from a low of 1.31 to a high of 15.75. Finally, the 4-week auction "award concentration ratio" – defined by Nyborg, Rydqvist, and Sundaresan (2002) as the fraction of the awards captured by the five highest individual bids – averages 0.84 and ranges between 0.53 and 1.0. Thus, the FHLB System discount note auctions are not only much larger but also have much more highly concentrated awards than corresponding results from Nyborg, Rydqvist, and Sundaresan (2002) for Swedish Treasury bill auctions, which average only 0.55 for 3-month bills.

[11] In unreported tests, we do not find any significant statistical evidence indicating that the FHLB System tactically adjusts discount note auction sizes in response to US Treasury bill issuance. Thus, we fail to find an auction-size analog to Greenwood, Hanson and Stein's (2010) "gap-filling" theory of debt issuance.

<Insert Table 2 here>

3.2. Measures of arbitrage risk and heterogeneity of investor beliefs

The August 2007 to June 2008 period was characterized by a rapid change in discount note issuance amounts and yield spreads to benchmark assets. Hence, the onset of the financial crisis in August 2007 could impact the elasticity of demand for FHLB discount notes. Furthermore, in the spirit of Wurgler and Zhuravskaya (2002), shifts in arbitrage risk and heterogeneity of investor beliefs could be the fundamental causes of any crisis-related change in FHLB discount note demand elasticity.

To test whether the response of auction rates to auction size adjustments depend upon arbitrage risk and the heterogeneity of investor beliefs, we must choose empirical proxies for these two factors. We use the cross-sectional dispersion of dealer rate indications as a measure of the heterogeneity of investor beliefs regarding fundamental asset value at the auction date. Specifically, for each auction, we compute the cross-dealer standard deviation of the mid-point of the bid and ask rate indicated by each dealer.

We measure arbitrage risk as the estimated standard error of the residuals from rolling window regressions of first differences of FHLB discount note rates on corresponding changes in other money market rates for the same maturities. The residual rate changes can be viewed as changes in the value of arbitrage trading positions (i.e., positions in FHLB discount notes hedged by other money market positions). This residual standard error measure is a money market analog to idiosyncratic risk measures in Treynor and Black (1973), Pontiff (1996, 2006), Wurgler and Zhuravskaya (2002), Mendenhall (2004), and McLean (2010).

Table 3 presents results for regressions of the daily changes in 4-week, 9-week and 13-week FHLB discount notes rates on corresponding changes in benchmark rates over the full sample. Regression specification (1) uses LIBOR deposits as the benchmark asset; specification (2) uses Treasury bills as the benchmark asset; and specification (3) includes both LIBOR deposits and Treasury bills. All three specifications are relevant for the 4-week and 13-week FHLB discount notes. However, our 1-month Treasury bill rate data begins in July of 2001, so the sample size for the 4-week discount note regressions using specifications (2) and (3) is shorter than for the corresponding LIBOR benchmark regression. Moreover, we have no 2-month Treasury rate data, so the 9-week discount note rate regression is run using only specification (1). We also present results for subsamples split before and after August 2007.

Regardless of the specification used, the estimated regressions suggest significant positive relations between changes in FHLB discount note rates and changes in benchmark rates. However, the results from all regressions also indicate that daily changes in FHLB discount note rates exhibit substantial variation that is unexplained by corresponding changes in benchmark rates. For example, the combination of LIBOR and Treasury bill rate changes explains less than 25% of the variation in daily changes in either 4-week or 13-week discount note rates suggesting that local supply and demand factors are important in discount note pricing. Thus, both the LIBOR deposits and Treasury bills are significantly less than perfect substitutes for FHLB discount notes (alone or in combination).

<Insert Table 3 here>

Moreover, the degree to which the market might view either LIBOR deposits or Treasury bills as substitutes for FHLB discount notes worsened significantly after August 2007. The standard error of the residuals ("tracking error") after August 2007 is more than *double* that of the earlier sample period for all three versions of the 4-week maturity regressions. Standard tests strongly reject the hypothesis that the regression's residual variance is constant across the two sub-periods. We use the unexplained variation in first-differences of FHLB discount note rates to measure arbitrage risk as of each auction date. To calculate this unexplained variation across time we run rolling window regressions of daily changes in FHLB discount note rates on corresponding changes in LIBOR of the same maturities. We use a rolling three-month window. The estimated standard error of the residuals from these rolling window regressions serves as our measure of arbitrage risk.

Figure 5 plots the auction date time series for both the arbitrage risk measure and the dispersion of rate indications for 4-week discount note auctions. The dispersion of dealer indicated rates fluctuates in a narrow range for most of the period, but then increases dramatically after August 2007. Our arbitrage risk measure shows two additional episodes of dislocation during the sample period: the Y2K scare and September 11, 2001.

<Insert Figure 5 here>

4. Analysis of market demand elasticity

4.1. Size-related auction rate patterns

Table 4 presents the mean and median differences between auction rates (either the weighted-average rate or the stop rate) and indicated rates. (As previously mentioned, the Office of Finance elicits a set of “indications” from each of the dealers in its selling group in the morning of each auction day.) We report separate statistics for auctions that turned out to be smaller in size than the indicated size range (“Smaller-than-Indicated”); auctions with sizes that lay within the indicated size range (“As Indicated”); and auctions that turned out to be larger in size than the indicated size range (“Larger-than-Indicated”). We also produce separate results for the pre- and post-August 2007 subsamples.

<Insert Table 4 here>

Auction size seems to matter for auction pricing. In both panels, there is a monotone positive relation between indications-adjusted auction size and rate spread. Put differently, "larger than indicated" auctions generally have a positive effect on the differences between the realized rates (either the weighted-average rate or the stop rate) and indicated rates. These results obtain for all three discount note maturities and are robust across the two sub-periods. However, the differences among the three categories are economically small, averaging about one basis point in rate difference between size categories in the pre-crisis period.

In Panel A, the spread in the "As Indicated" size subsample for 4-week discount note auctions over the pre-August 2007 period is -0.5 basis points whether measured as a mean or median. Thus, the average WAR for these 4-week discount note auctions is slightly lower than the average indications of the dealers. The results for the 9-week and 13-week auctions show a similar negative bias for the "As Indicated" subsample. During the Crisis period there is an increase in this bias for 4-week auctions (from -0.5 to -1.9), but not for the other maturities. One might expect that some degree of negative bias would be present in the data. Our dealer indication variable is an average indication across all contributing dealers, whereas the more aggressive dealers have a bigger impact *ex post* in determining any auction's WAR outcome. Panel B shows that there is no such consistent negative bias for the "As Indicated" auctions when stop rates are used in place of WAR to define the spread.[12] In the main analysis we use WAR since it represents the achieved funding cost of the FHLB. As a robustness check, we also use the stop rate data in our estimation of elasticity.

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[12] By construction, an auction's stop rate is greater than or equal to its WAR.

4.2. Estimating the slope of the demand curve

Table 5 extends the univariate analysis of Table 4 using two complementary regression approaches. The first approach directly investigates the rate impacts of variation in auction size and implicitly frames the demand elasticity question from the perspective of the FHLB System's borrowing costs. Panel A of Table 5 presents results for three alternative regression specifications that measure the corresponding rate impacts of auction size variation for a pooled sample of 4-week, 9-week and 13-week FHLB discount note auctions including maturity fixed effects. The dependent variable in all three regression models is the difference between an auction's weighted-average rate (WAR) and the mean dealer indicated rate.[13]

<Insert Table 5 here>

Model (1) uses the auction size adjustment, defined as the difference between actual and indicated auction sizes in billions of dollars, as an independent variable along with an intercept term, an intercept "Crisis" dummy (equal to one beginning in August 2007 and zero prior to that month) and a corresponding slope interaction term. The test of the hypothesis that the size adjustment variable's slope coefficient equals zero examines whether the size adjustments observed over the sample have any impact on the FHLB's discount note rate results. For example, if market demand were perfectly elastic, then any additional auctioned quantity could be absorbed at the same rate that was indicated for the assumed supply. Alternatively, if demand were less than perfectly elastic, then the resulting WAR for an auction should be higher (lower) than the morning's indicated rate for any actual auctioned quantity that is "Larger-than-

[13] In unreported analyses, we run regressions akin to those in Table 5 and 6 using auction stop rate instead of WAR. Results about elasticity are very similar in nature to the reported tables suggesting that the indication bias discussed in Section 4.1 does not affect our conclusions about the slope of the demand curve.

Indicated" ("Smaller-than-Indicated"). The slope interaction term is designed to isolate differential effects of auction size adjustment on auction rates in the post-August 2007 period.

Model (2) incorporates each of the terms in model (1), but also adds arbitrage risk and the dispersion of rate indications in both levels form and also slope interaction terms for the auction size adjustment variable. These slope interaction terms allow our measures of arbitrage risk and heterogeneity of investor beliefs to change the auction size adjustment response coefficient. In this way, we test for the impacts of these variables on demand elasticity. Models (1) and (2) are nested. Thus, we can test whether a rate impact exists; whether such a rate impact increases post-August 2007; and whether variation in arbitrage risk and heterogeneity of investor beliefs can adequately account for any post-August 2007 rate impact increase.

The results in Panel A of Table 5 provide statistical evidence that auction rates for FHLB System discount notes are positively related to the auction size adjustment. Using model (1), the size adjustment variable is significant at the 1% level. Nevertheless, the rate impact is small in magnitude and suggests that demand for FHLB discount notes is nearly perfectly elastic. The estimated slope coefficient for this pooled sample of auctions implies that an extra $1 billion of supply beyond the assumed amount increases the WAR by about 0.6 basis points over the average indicated dealer rate.

In model (1), the Crisis dummy interaction term for the size adjustment variable is positive and statistically significant. The interaction term suggests that the size adjustment impact on the rate spread variable increases from about 0.6 basis points to almost 1.0 basis point. Thus, from the issuer's perspective, the marginal cost of additional auction size increases during a crisis.

Our tests using model (2) examine whether shifts in arbitrage risk and heterogeneity of investor beliefs were the fundamental causes of the crisis-related decreases in FHLB discount note demand elasticity implied by the model (2) estimates. Recall that our arbitrage risk measure is the tracking error from a rolling regression motivated by the horizon-matched LIBOR specification (1) from Table 3.[14]

The estimates for model (2) in Panel A of Table 5 strongly support the hypothesis that arbitrage risk is a statistically significant and economically important determinant of the auction size adjustment impact on rates. The coefficient of the interaction term between tracking error and size adjustment is correctly signed and statistically significant at the 1% level. There is also some support for our dispersion of dealer rate indications variable (reflecting heterogeneity of investor beliefs) as a significant determinant of demand elasticity. The coefficient of the interaction term between the dispersion of dealer rate indications and size adjustment is correctly signed and statistically significant at the 5% level. Tests of the joint restrictions that the arbitrage risk and heterogeneity of investor beliefs interaction terms both equal zero are rejected at the 1% level. After including the tracking error and the dispersion of dealer rate indications interaction terms, the Crisis dummy interaction term loses its statistical significance. Moreover, the coefficient estimate for the size adjustment variable drops to .311 implying that arbitrage risk and heterogeneity of investor beliefs account for about half of the response associated with model (1).

Model (3) presents an alternative formulation for testing the impacts of arbitrage risk and heterogeneity of investor beliefs on the auction size adjustment effect on rates. Model (3)

[14] The LIBOR-only specification allows analysis of the 9-week discount note data and permits inclusion of the entire 4-week discount note sample. For the 4- and 13-week maturities the regressions in Table 5 yield similar results when we use the tracking error from Regression 3 in Table 3.

employs new dummy variables equal to one when each of the original tracking error and dispersion of dealer rate indications variables lie in the top quartile of its distribution (i.e., when each original variable is "high" in value). Model (3) allows for an easy calculation of the impacts of large values of tracking error and dispersion of dealer rate indications on the sensitivity of auction rate spreads (WAR minus Indicated Rate) to auction size adjustment. Both interaction terms based on these new dummy variables are significant in model (3) in Panel A of Table 5. In particular, the sensitivity of auction rates to size adjustment increases from .464 in normal conditions to .973 (= .464 + .509) when tracking error is "high" and to .694 (= .464 + .230) when dispersion of dealer rate indications is "high."

The second approach, presented in Panel B of Table 5, focuses on discount note percentage price responses to discount note percentage auction size adjustments. These regressions produce results that can be directly compared to those found in previous studies of financial asset demand elasticity. We calculate each auction's discount note price indication using the mean dealer rate indication and the corresponding discount note auction price using the weighted-average auction rate.[15] The dependent variable in all three regressions is the percentage difference between the actual auction price and the indicated price (expressed as a percentage change of the indicated price).

Model (1) uses the percentage auction size adjustment as an independent variable along with an intercept term, an intercept "Crisis" dummy (equal to one beginning in August 2007 and zero prior to that month), and a corresponding slope interaction term. This slope interaction term is designed to isolate differential percentage auction size adjustment effects in the post-August 2007 period. The percentage auction size adjustment variable is the percentage difference

[15] Recall that the n-day-to-maturity discount note issue price (P) is a linear function of the quoted percentage discount rate (R) data we analyze: $P = 100 \times \{1- [R \times (n \div 360]\}$.

between the actual amount and the indicated amount (expressed as a percentage change of the indicated amount). The test of the hypothesis that the slope coefficient equals zero examines whether the demand curve for discount notes is perfectly elastic at the indicated discount note price. Model (2) incorporates each of the terms in model (1), but also adds both tracking error and the dispersion of rate indications in both levels form and also in slope interaction terms for the percentage auction size adjustment variable.

The pooled sample results for model (1) in Panel B of Table 5 provide statistical evidence that demand for FHLB System discount notes is highly elastic, but also that demand elasticity decreased after August 2007. The interaction term suggests that the size adjustment impact on the price response variable roughly doubles after August 2007 (from about -0.020 to -0.037). Thus, the post-August 2007 elasticity of demand decreased from -50,000 to about -27,000. [16]

Our tests using model (2) examine whether shifts in arbitrage risk and heterogeneity of investor beliefs were the fundamental causes of the crisis-related decreases in FHLB discount note demand elasticity implied by the model (1) estimates. The estimates for model (2) in Panel B strongly support the hypothesis that arbitrage risk is a statistically significant and economically important determinant of demand elasticity. The coefficients for interaction terms capturing arbitrage risk and heterogeneity of investor beliefs are each correctly signed, though only the arbitrage risk measure is statistically significant. Alternatively, using in model (3), both of the auction size interaction terms are statistically significant. The demand elasticity calculated using model (3) from Panel B falls from about -71,500 to -31,250 when tracking error is "high" and to -43,500 when the dispersion of dealer rate indications is "high."

[16] To calculate this elasticity, multiply the inverse of the reported coefficient by the scaling factor of 1000: thus, 1000*(1/-0.020) = -50,000. Likewise, the post-August 2007 elasticity estimate of -27,027 is calculated as 1000 * (1/-0.037)).

Table 6 presents a companion set of disaggregated results for the individual 4-week, 9-week and 13-week discount note auction maturities. Panel A presents results based upon discount rates, while Panel B presents results based upon percentage price changes. The results for model (1) offer evidence that the auction size adjustment variable is statistically significant for all three maturities. Furthermore, the size adjustment impact on the rate spread variable increases significantly after August 2007 for the 4-week and 9-week auctions. No such effects can be detected for the 13-week auctions. The results for model (2) show larger and more significant impacts of arbitrage risk as maturity lengthens. Corresponding results for the heterogeneity of investor beliefs are significant only for 13-week notes. The model (3) regressions reveal significant coefficients for the tracking error-auction size adjustment interaction terms for all three maturities as well as significant coefficients for the dispersion of dealer rate indications-auction size interaction terms for the 9-week and 13-week maturities.

<Insert Table 6 here>

Panel B of Table 6 presents the disaggregated results for the price change regressions. The percentage auction size adjustment variable is statistically significant using model (1) for all three maturities. The results for model (1) offer evidence that the post-August 2007 size adjustment effect is important for the 4-week and 9-week auctions. The implied elasticity of demand for the 4-week discount notes falls from about -77,000 in the pre-August 2007 period to -30,000 in the post-August 2007 period. The results for model (2) show large and significant impacts of arbitrage risk for all three discount note maturities. However, the Crisis dummy interaction term for the percentage auction size adjustment effect remains significant in model (2) for only the 4-week maturity. Finally, the model (3) regressions reveal significant coefficients for the auction size adjustment interaction terms for both the tracking error and dispersion of dealer rate indications for all three maturities. The implied elasticity of demand for the 4-week discount notes falls from -100,000 to about -55,500 for high levels of tracking error and to about -71,500 for high levels of the dispersion of dealer rate indications.

Our estimates reveal that demand for FHLB System discount notes is highly elastic. The point estimate for the pooled sample during the pre-August 2007 period is -50,000. This is more than an order of magnitude higher than the -3,000 estimate presented by Scholes (1972) for individual stocks and even more dramatically different from other more recent stock elasticity estimates that range from -1 to -37 (Wurgler and Zhuravskaya, 2002). We also find that discount note elasticity can vary over time due to changes in macro-financial conditions. We find that the nearly 50% fall in discount note demand elasticity after August 2007 was largely due to concomitant rises in arbitrage risk and the heterogeneity of investor beliefs.

4.3. Addressing potential endogeneity concerns

Our estimation of demand elasticity depends crucially on the assumption that dealer valuations of FHLB discount notes are independent of the FHLB's auction size adjustments. Violation of such an exogeneity assumption is a major concern with most studies of the demand elasticity for financial assets. An abnormal increase in the supply of a financial asset may result in a reduction of its price not only because of downward sloping demand, but also because the increase in supply could reveal negative information about the value of the asset and shift the entire demand curve downwards. In the case of FHLB discount note auctions, the auction size adjustment may provide dealers with information about the intrinsic value of FHLB's debt. In particular, the dealers may learn from the FHLB's auction size adjustment about the cost of bank funding in other channels and may therefore revise their perception of the fair price for the to-be-auctioned notes. For example, an upward adjustment in issue size might signal that banks are having trouble raising funds by other means and lead dealers to raise their perception of the appropriate market-clearing discount rate. Such endogeneity could possibly bias our estimates of elasticity downward.

We perform a variety of econometric tests addressing potential endogeneity concerns. Consistent with the assumptions outlined in Section 2.3, we do not find any evidence that the intrinsic value of FHLB debt is influenced by auction size adjustments. For that matter, there is also no evidence that auction size adjustments are influenced by dealer indications. We investigate whether auction size adjustments influence the intrinsic value of FHLB debt by analyzing intraday data on benchmark FHLB bond secondary market yields (as marked by the Office of Finance throughout the day). If such auction size adjustments truly do signal shifts in the fair cost of member bank funding alternatives, then yields on outstanding benchmark FHLB debt (traded by the same major dealers in the discount note selling group) should shift to reflect this same information. Specifically, we test whether auction size adjustments (announced at 11:36 AM) have any statistically significant impacts on observed changes in yields on 2-year, 5-year and 10-year FHLB notes between 9 AM and 1 PM. In unreported regressions, regardless of the definition of the independent variable, we find no evidence of a statistical relation between intraday changes in yields on longer-maturity FHLB debt and abnormal size.

For completeness, we also investigate whether any information contained in auction indications influences the FHLB's auction size adjustments. As described in Section 2, after collecting indications from the dealers by 11 AM, the Office of Finance calculates its own indications and communicates them to the twelve FHLB banks. The banks then submit their demanded quantities, which are summed by the Office of Finance to produce a final auction size at 11:36 AM. We test whether there is any relation between abnormal auction size and abnormal indications defined as changes in the indicated auction rate spread to Libor. We find no evidence of significant impacts of changes in indicated rates on auction size adjustments – only 5.5% of the estimated slope coefficients are significantly different from zero at the 5% level and all R-squares are essentially zero. We also estimated a VAR system of size adjustment and indicated spreads to Libor and performed Granger causality tests. Again, there is no evidence that changes in indicated auction rate spread to Libor influence the quantities auctioned by the FHLBs.

4.4. Robustness tests

We perform several robustness tests of the results in Tables 5 and 6. First, we re-estimate the models after dropping the 1999-2001 or 1999-2002 periods respectively from the empirical estimation in order to better separate-out the effect of the 2007 financial crisis from other crisis events (Y2K and September 11, 2001). The unreported results from the shorter time period regressions are similar, although we lose some statistical significance on our proxy for arbitrage risk (as it becomes more positively correlated with the heterogeneity of investor beliefs variable). We also estimate the regressions only on pre-2007 data and find that the effect of arbitrage risk remains statistically significant, though the effect of heterogeneity of investor beliefs becomes insignificant.

Second, our auction size adjustment variable presumes that dealers anchor their pre-auction rate indications on the mid-point of the Office of Finance's high and low size indications. However, dealers may use other information, especially past auction size realizations, to condition their expectations of as-yet-to-be-announced auction sizes. As it happens, an eighth-order moving average process offers a reasonable statistical representation of the actual auction size data (results are very similar using fourth- or twelfth-order moving averages). In unreported results, we re-estimate the models in Table 5 with an auction size adjustment variable equal to the difference between the actual auction size and its predicted value based upon an eighth-order moving average process. The rate response estimates are qualitatively similar to those in Table 5. The overall fit of these regressions is worse than those of Table 5 – the adjusted R-squares are only about two-thirds of their Table 5 values, thus supporting our use of the mid-point of the Office of Finance's high and low size indications as an empirical proxy.

Third, to control for shifts in market conditions we add a time trend to all regressions. The results are almost identical to the original specifications.

Fourth, we investigate whether the errors in our regressions suffer from serial correlation. The Durbin-Watson statistics of the regressions range from 1.5 to 1.9, suggesting that serial correlation in the errors is not an important problem.[17]

[17]Substitution of Cochrane-Orcutt or Prais-Winsten regressions does not alter any of our conclusions.

Another factor that could affect demand elasticities for FHLB discount notes is the supply of competing debt instruments like commercial paper issued by financial institutions or US Treasury bills. Contemporaneous auctions of similar debt by other issuers might possibly increase the opportunity costs of holding FHLB paper by dealers and arbitrage-oriented traders and thereby decrease FHLB discount note auction demand elasticity. As a further unreported robustness check, we first add an interaction term between the daily issuance of financial commercial paper and auction size adjustment to the regressions in Table 5.[18] The coefficient on the interaction term is insignificant from zero and does not affect the coefficients on the remaining variables. We also collect data on auctioned amounts of similar-maturity Treasury bills and add an interaction term between Treasury bill issuance and auction size adjustment to the regressions in Table 5.[19] Neither this approach nor the use of dummy variables to capture longer-term trends in Treasury bill issuance (e.g., dummies for low-issuance and high-issuance periods) could detect negative impacts of Treasury bill issuance on FHLB demand elasticities.

In addition, we address potential concerns about (i) the difference in timing between dealer indications and auction bids and (ii) violations of the dealers' truth telling and rational expectations assumptions. Recall from Section 2 that dealers submit indications as early as 9:30 AM, while they may submit their actual auction bids as late as 12:10 PM. It is possible that new information (besides the actual auctioned amounts) relevant for FHLB discount note pricing

[18] We obtain data on daily commercial paper issuance volumes from the Federal Reserve Board. We map 20-40 day paper to the 4-week discount note auctions, 40-80 day paper to the 9-week, and greater than 80 days to the 13-week auctions. We sum the issuance on Monday and Tuesday (Wednesday and Thursday) and use that for Tuesday (Thursday) auctions of the same week.

[19] We obtain auctioned amounts directly from the Treasury. The Treasury issues 4- and 13-week Treasury bills on a weekly basis (usually on Monday or Tuesday). We do not have any meaningful number of Treasury bill issuance with maturity around nine weeks and drop the 9-week auctions from the analysis. To avoid any timing problems, we analyze only FHLB auctions held on Tuesdays.

released during this pre-auction interval affects auction results in a way that confounds our estimates. In addition, we assume that the dealer indications are truthful and, via our imposition of rational expectations, incorporate all relevant market information as of the time they are submitted. We address concerns regarding these points by adding four more variables to the models in Tables 5 and 6: (1) the change in the FHLB Office of Finance rate indications from 9 a.m. to noon for window trades in discount notes of the same maturity; (2) the daily change in the implied swaption volatility (1-month-maturity options on 1-year swaps); (3) the daily change in VIX; and (4) the daily change in the spread of 3-month Libor relative to the 3-month Treasury bill rate.

Unreported results incorporating these four controls show that only the coefficient on the changes in window trade rate indications is statistically significant. The coefficients of interest and their significance levels in the original specifications of Tables 5 and 6 remain largely unchanged. These results suggest the any market "news" that occurs during the 9:30 AM to 12:10 PM interval is largely orthogonal to our included arbitrage risk and heterogeneity of investor beliefs variables. Furthermore, the statistical insignificance of other market measures such as implied swaption volatility, the VIX and Libor-Treasury bill rate spreads offers no evidence that rejects our maintained joint hypotheses of rational expectations and dealer truth telling for the dealer indications data.

Our estimates of elasticity assume that the demand curve for discount notes is linear across all auction sizes. However, there may be more complex responses of auction rates to large surprises in auction size. We explore this possibility in the context of a piecewise linear regression by adding interaction terms of the size adjustment variable with dummies for smaller-than-indicated and larger-than-indicated auction sizes. We report the results in Table 7. When auction size is larger-than-indicated, the slope of the curve is not significantly steeper than the curve for as-indicated auctions. The smaller-than-indicated interaction term is positive and significant in all three specifications signifying a steeper demand curve over this auction size range. We attribute this result to more intense dealer competition when auction size is smaller-than-indicated.

<Insert Table 7 here>

5. Conclusion

The elasticity of demand for financial assets is a central element in asset pricing theory. This paper provides empirical estimates of the demand elasticity of short-term debt instruments using Federal Home Loan Bank System discount note auction data. Specifically, we exploit the fact that for each auction this data includes both rate indications for an expected issuance level and the actual auction results in terms of rates and issuance amounts. This effectively provides the intraday variation in prices and quantities necessary to estimate the slope of the demand curve.

Our empirical results provide strong evidence of a nearly perfectly elastic market demand curve for FHLB discount notes. However, we also show that this demand elasticity fell significantly during the credit crisis that began in August 2007. Finally, we find that the crisis-associated fall in demand elasticity can be tied to market imperfections previously identified in the literature. Arbitrage risk and, to a lesser extent, the heterogeneity of investor beliefs are found to be statistically and economically important determinants of financial asset demand elasticity.

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Table 1
Summary statistics of FHLB discount note auctions.

Year	4-Week Discount Notes			9-Week discount Notes			13-Week Discount Notes		
	Number of Auctions	Average Size ($Bil)	Total Amount Auctioned ($Bil)	Number of Auctions	Average Size ($Bil)	Total Amount Auctioned ($Bil)	Number of Auctions	Average Size ($Bil)	Total Amount Auctioned ($Bil)
1999	100	1.35	135	96	0.68	65	97	0.95	92
2000	104	2.46	256	101	0.84	85	103	1.07	111
2001	103	2.29	236	98	0.95	93	103	1.83	188
2002	104	2.44	254	103	0.75	77	104	1.52	158
2003	105	3.58	375	101	1.05	106	104	1.58	165
2004	104	3.79	394	100	1.00	100	98	1.55	152
2005	104	3.86	401	102	1.29	131	103	1.44	148
2006	103	3.78	390	101	1.18	120	104	1.73	180
2007	105	4.34	455	102	1.28	130	105	2.72	286
2008	51	7.07	360	51	1.26	64	51	3.91	199
Total	983	3.31	3,257	955	1.02	971	972	1.73	1,679

The sample period starts in January1999 and ends in June 2008. Auctions for FHLB discount notes are held every Tuesday and Thursday. Auction size is determined shortly before bidding is opened as the sum of orders by each of the twelve FHLB banks for a particular maturity. Auctions are cancelled if there is no interest from any of the twelve FHLB banks in a particular discount note maturity.

Table 2
Summary statistics of dealer participation and award concentration in FHLB discount note auctions.

Measure	4-Week Discount Notes				9-Week discount Notes				13-Week Discount Notes			
	Cover Ratio	Number of Dealers	Number of Bids	Award Conc.	Cover Ratio	Number of Dealers	Number of Bids	Award Conc.	Cover Ratio	Number of Dealers	Number of Bids	Award Conc.
Mean	4.01	15.51	65.52	0.84	5.82	15.37	42.61	0.91	5.17	15.50	52.20	0.89
Median	3.64	16.00	63.00	0.84	5.09	15.00	41.00	0.94	4.57	16.00	51.00	0.90
Std. Dev.	1.70	1.19	17.65	0.11	3.22	1.22	12.00	0.10	2.54	1.18	13.62	0.11
Min	1.31	13.00	17.00	0.53	1.43	12.00	15.00	0.55	1.38	13.00	20.00	0.55
Max	15.75	19.00	142.00	1.00	47.83	19.00	83.00	1.00	21.19	19.00	104.00	1.00
Skewness	2.03	0.84	0.79	-0.19	3.34	0.84	0.51	-1.01	2.17	0.79	0.43	-0.67
Kurtosis	10.42	4.12	4.11	2.21	34.14	4.11	2.83	3.18	9.67	4.07	3.34	2.56

The sample period starts in January1999 and ends in June 2008. Only dealers that are members of the discount note selling group are allowed to bid at the auction. The number of dealers included in the selling group during the sample period ranges from 15 to 19. Cover ratio is calculated as the sum of the amounts of all submitted bids divided by the total auctioned amount. Number of dealers equals the number of unique dealers submitting bids at an auction. Number of bids equals the number of unique bids submitted at an auction. Award concentration equals the amount allocated to the five highest-priced individual winning bids in an auction.

Table 3

Regressions of daily changes in FHLB discount note rates on maturity-matched changes in LIBOR and Treasury bill rates.

Panel A. 4-Week Discount Notes

	Regression 1		Regression 2		Regression 3	
	Pre-Crisis	Crisis	Pre-Crisis	Crisis	Pre-Crisis	Crisis
Change in LIBOR	0.329***	0.411***			0.686***	0.396***
	(14.65)	(5.34)			(17.78)	(5.29)
Change in Treasury Yield			0.193***	0.090***	0.144***	0.083***
			(11.51)	(3.67)	(9.37)	(3.61)
Intercept	-0.004	-0.881*	0.065	-1.203**	0.001	-0.699
	(-0.06)	(-1.85)	(0.85)	(-2.49)	(0.02)	(-1.50)
SER	0.032	0.069	0.029	0.071	0.026	0.067
Adjusted R^2	0.094	0.112	0.084	0.054	0.248	0.158
Number of Obs.	2069	220	1442	220	1442	220

Panel B. 9-Week Discount Notes

	Regression 1	
	Pre-Crisis	Crisis
Change in LIBOR	0.365***	0.555***
	(11.21)	(7.24)
Intercept	-0.008	-0.686*
	(-0.09)	(-1.66)
SER	0.043	0.060
Adjusted R^2	0.057	0.190
Number of Obs.	2069	220

Panel C. 13-Week Discount Notes

	Regression 1		Regression 2		Regression 3	
	Pre-Crisis	Crisis	Pre-Crisis	Crisis	Pre-Crisis	Crisis
Change in LIBOR	0.425***	0.661***			0.316***	0.613***
	(18.62)	(8.70)			(14.45)	(8.49)
Change in Treasury Yield			0.305***	0.177***	0.261***	0.148***
			(20.28)	(5.57)	(17.78)	(5.30)
Intercept	-0.013	-0.514	0.006	-0.992**	-0.002	-0.318
	(-0.22)	(-1.30)	(0.10)	(-2.35)	(-0.04)	(-0.85)
SER	0.027	0.057	0.026	0.062	0.025	0.054
Adjusted R^2	0.143	0.254	0.166	0.121	0.242	0.337
Number of Obs.	2069	220	2064	220	2064	220

Regressions of daily changes in yield on FHLB discount notes on daily changes in LIBOR (expressed as a discount rate) and/or US Treasury bill rates of same maturity. Sample period for the FHLB and LIBOR data is from January 1999 to June 2008. Data on the 1-month Treasury bill rates is available starting from July 2001. Data on 2-month Treasury Bills is not available. White robust *t*-statistics are in parenthesis. *, **, *** denote significance at 10%, 5%, and 1% level, respectively.

Table 4
Differences between the auction weighted average rate /auction stop rate and dealer indications.

Panel A. WAR minus Indicated Rate

	Pre-Crisis			Crisis		
Auction	Smaller	As Indicated	Larger	Smaller	As Indicated	Larger
4-week	-1.4	-0.5	-0.1	-3.4	-1.9	0.4
	(-1.1)	(-0.5)	(-0.3)	(-3.2)	(-1.7)	(-0.1)
9-week	-1.6	-0.9	-0.3	-3.4	-0.7	-0.5
	(-1.3)	(-0.8)	(-0.4)	(-2.9)	(-0.2)	(-0.5)
13-week	-1.3	-0.8	-0.2	-1.4	-1.0	0.4
	(-1.2)	(-0.7)	(-0.4)	(-1.3)	(-0.7)	(0.0)

Panel B. Stop Rate minus Indicated Rate

	Pre-Crisis			Crisis		
Auction	Smaller	As Indicated	Larger	Smaller	As Indicated	Larger
4-week	-0.8	0.3	0.6	-2.7	-0.8	1.4
	(-0.6)	(0.1)	(0.3)	(-2.7)	(-1.2)	(0.8)
9-week	-1.1	-0.3	0.5	-2.5	0.4	0.9
	(-0.9)	(-0.3)	(0.2)	(-2.3)	(0.5)	(-0.1)
13-week	-0.8	-0.4	0.3	-0.7	-0.4	1.4
	(-0.7)	(-0.4)	(0.1)	(-0.8)	(-0.4)	(0.9)

Panel A reports the mean (median) difference between the Auction Weighted Average Rate (WAR) and Dealer Indications. WAR is calculated as the average rate of winning bids weighted by the bid amount. The corresponding Dealer Rate Indication is measured as the average of the midpoints of individual dealer contributed rates. Panel B reports the mean (median) difference between the Auction Stop Rate and Dealer Indications. The Stop Rate is the highest winning rate in each auction. The auction data spans the period between January 1999 and June 2008. The Crisis sample period begins in August 2007. All numbers are in basis points. *Smaller* auctions are defined as auction below the lower limit of the indicated auction size; *As Indicated* auctions are auctions with sizes between the lower and upper indicated auction sizes; and *Larger* auctions are above the upper indicated auction size.

Table 5
Multivariate analysis of the relation between auction size and pricing – pooled sample.

Panel A. Dependant Variable: WAR minus Indicated Rate

	Model 1	Model 2	Model 3
Auction Size Adjustment	0.616***	0.311***	0.464***
	(13.29)	(3.49)	(15.44)
Crisis * Auction Size Adj.	0.362**	-0.089	-0.121
	(2.39)	(-0.60)	(-0.65)
TE LIBOR * Auction Size Adj.		6.152***	
		(2.70)	
Dealer Dispersion * Auction Size Adj.		12.908**	
		(2.00)	
High TE LIBOR * Auction Size Adj.			0.509***
			(3.60)
High Dealer Dispersion * Auction Size Adj.			0.230***
			(2.89)
TE LIBOR		-5.015***	
		(-3.53)	
Dealer Dispersion		-24.794***	
		(-5.35)	
High TE LIBOR			-0.196**
			(-2.04)
High Dealer Dispersion			-0.061
			(-0.81)
Crisis	-0.765***	-0.089	-0.607**
	(-3.22)	(-0.44)	(-2.35)
Constant	-0.706***	-0.337***	-0.659***
	(-16.01)	(-4.96)	(-16.27)
Number of Observations	2910	2820	2820
Adjusted R-Square	0.22	0.31	0.26

Table 5 (Cont.)
Panel B. Dependant Variable: Percentage Change in WAR Price Relative to Indicated Price

	Model 1	Model 2	Model 3
%Auction Size Adj.	-0.020***	-0.012***	-0.014***
	(-12.34)	(-4.87)	(-12.57)
Crisis * %Auction Size Adj.	-0.017***	-0.006	-0.001
	(-2.63)	(-1.03)	(-0.14)
TE LIBOR * %Auction Size Adj.		-0.216***	
		(-2.90)	
Dealer Dispersion * %Auction Size Adj.		-0.254	
		(-1.29)	
High TE LIBOR * %Auction Size Adj.			-0.018***
			(-3.02)
High Dealer Dispersion * %Auction Size Adj.			-0.009**
			(-2.26)
TE LIBOR		0.043*	
		(1.67)	
Dealer Dispersion		0.484***	
		(4.12)	
High TE LIBOR			0.002
			(0.94)
High Dealer Dispersion			0.002
			(1.12)
Crisis	0.008**	-0.003	0.007
	(2.07)	(-0.75)	(1.50)
Constant	0.005***	-0.001	0.005***
	(11.30)	(-0.47)	(7.92)
Number of Observations	2910	2820	2820
Adjusted R-Square	0.28	0.35	0.30

Auction Size Adjustment is the difference between actual auctioned amount and indicated amount in billions of dollars. *Crisis* is an indicator variable equal to one for auctions held after August 1, 2007; zero otherwise. *TE LIBOR* equals the root mean squared error of regressions of changes in FHLB yields on LIBOR using 3-month rolling windows. *Dealer Dispersion* equals the standard deviation of the midpoints of dealer indications submitted on the day of the auction. *High TE LIBOR* is a dummy equal to one if *TE LIBOR* is in the top quartile of its sample distribution. *High Dealer Dispersion* is a dummy equal to one if *Dealer Dispersion* is in the top quartile of its sample distribution. We calculate n-day-to-maturity WAR Price as P = 100 × {1- [WAR × (n÷360]}. Indicated Price is calculated analogously using average Indicated Rate in place of WAR. All regressions include fixed effects for auction maturity. *t*-statistics based on errors clustered by auction date are in parenthesis. *, **, *** denote significance at 10%, 5%, and 1% level, respectively.

Table 6

Multivariate analysis of the relation between auction size and pricing – separate regressions for each maturity.

Panel A. Dependant Variable: WAR minus Indicated Rate

	4-Week Discount Notes			9-Week discount Notes			13-Week Discount Notes		
	Model 1	Model 2	Model 3	Model 1	Model 2	Model 3	Model 1	Model 2	Model 3
Auction Size Adjustment	0.523***	0.269**	0.413***	0.955***	0.565***	0.719***	0.661***	0.231	0.484***
	(11.70)	(2.38)	(10.45)	(15.62)	(2.85)	(9.34)	(8.75)	(1.56)	(10.65)
Crisis * Auction Size Adj.	0.633***	0.278	0.312	0.961*	0.224	0.289	0.012	-0.516*	-0.783**
	(2.60)	(1.38)	(1.16)	(1.82)	(0.57)	(0.57)	(0.07)	(-1.88)	(-1.99)
TE LIBOR *		4.201*			9.525**			12.783**	
Auction Size Adj.		(1.76)			(2.40)			(2.32)	
Dealer Dispersion *		9.942			14.895			17.630*	
Auction Size Adj.		(1.22)			(1.02)			(1.68)	
High TE LIBOR *			0.362**			0.863***			0.493***
Auction Size Adj.			(2.27)			(2.68)			(2.61)
High Dealer Dispersion *			0.102			0.293**			0.664**
Auction Size Adj.			(1.30)			(2.40)			(2.12)
TE LIBOR		-6.838***			-4.005***			-2.392	
		(-2.70)			(-2.65)			(-1.03)	
Dealer Dispersion		-10.473			-22.977**			-26.293***	
		(-0.73)			(-2.20)			(-6.94)	
High TE LIBOR			-0.197			-0.344**			-0.013
			(-1.45)			(-2.46)			(-0.15)
High Dealer Dispersion			0.086			-0.136*			-0.173
			(0.75)			(-1.66)			(-0.80)
Crisis	-1.483***	-0.999**	-1.383***	-0.725**	0.022	-0.440	-0.058	0.337*	0.017
	(-4.30)	(-2.37)	(-3.52)	(-2.02)	(0.07)	(-1.18)	(-0.30)	(1.76)	(0.06)
Constant	-0.668***	-0.395**	-0.652***	-0.973***	-0.616***	-0.861***	-0.787***	-0.509***	-0.778***
	(-15.90)	(-2.38)	(-14.63)	(-29.81)	(-5.10)	(-20.98)	(-21.98)	(-8.09)	(-26.19)
Number of Observations	983	983	951	955	955	926	972	972	943
Adjusted R-Square	0.26	0.30	0.28	0.23	0.33	0.26	0.28	0.38	0.32

Table 6 (Cont.)

Panel B. Dependant Variable: Percentage Change in Price Relative to Indicated Price

	4-Week Discount Notes			9-Week discount Notes			13-Week Discount Notes		
	Model 1	Model 2	Model 3	Model 1	Model 2	Model 3	Model 1	Model 2	Model 3
%Auction Size Adjustment	-0.013***	-0.006*	-0.010***	-0.018***	-0.011***	-0.013***	-0.028***	-0.009	-0.020***
	(-10.73)	(-1.75)	(-9.66)	(-15.51)	(-2.73)	(-9.57)	(-8.72)	(-1.55)	(-9.86)
Crisis * %Auction Size Adj.	-0.027***	-0.017**	-0.020**	-0.026**	-0.012	-0.015	-0.001	0.014	0.032*
	(-3.23)	(-2.44)	(-2.28)	(-2.16)	(-1.31)	(-1.26)	(-0.10)	(1.16)	(1.81)
TE LIBOR *		-0.099**			-0.149**			-0.674**	
%Auction Size Adj.		(-1.99)			(-2.31)			(-2.54)	
Dealer Dispersion *		-0.320			-0.303			-0.436	
%Auction Size Adj.		(-1.16)			(-1.02)			(-1.06)	
High TE LIBOR *			-0.008**			-0.015***			-0.022***
%Auction Size Adj.			(-2.47)			(-2.69)			(-2.76)
High Dealer Dispersion *			-0.004*			-0.005**			-0.029**
%Auction Size Adj.			(-1.68)			(-2.44)			(-2.03)
TE LIBOR		0.045**			0.073***			0.042	
		(2.28)			(2.84)			(0.64)	
Dealer Dispersion		0.074			0.408**			0.649***	
		(0.65)			(2.36)			(7.00)	
High TE LIBOR			0.001			0.006**			-0.000
			(1.23)			(2.46)			(-0.07)
High Dealer Dispersion			-0.001			0.002*			0.004
			(-0.90)			(1.66)			(0.69)
Crisis	0.011***	0.008**	0.011***	0.013**	0.000	0.008	-0.001	-0.010*	-0.003
	(4.29)	(2.30)	(3.68)	(2.12)	(0.04)	(1.28)	(-0.18)	(-1.96)	(-0.34)
Constant	0.005***	0.003**	0.005***	0.017***	0.011***	0.015***	0.020***	0.014***	0.020***
	(15.71)	(2.47)	(15.15)	(29.88)	(5.32)	(21.08)	(22.03)	(7.82)	(26.28)
Number of Observations	983	983	951	955	955	926	972	972	943
Adjusted R-Square	0.22	0.26	0.29	0.19	0.23	0.30	0.28	0.28	0.30

Auction *Size Adjustment* is the difference between actual auctioned amount and indicated amount. *Crisis* is an indicator variable equal to one for auctions held after August 1, 2007; zero otherwise. *TE LIBOR* equals the root mean squared error of regressions of changes in FHLB yields on LIBOR using 3-month rolling windows. *Dealer Dispersion* equals the standard deviation of the midpoints of dealer indications submitted on the day of the auction. *High TE LIBOR* is a dummy equal to one if *TE LIBOR* is in the top quartile of its sample distribution. *High Dealer Dispersion* is a dummy equal to one if *Dealer Dispersion* is in the top quartile of its distribution. We calculate n-day-to-maturity WAR Price as P = 100 × {1- [WAR × (n÷360]}. Indicated Price is calculated analogously using average Indicated Rate in place of WAR. White robust *t*-statistics are in parenthesis. *, **, *** denote significance at 10%, 5%, and 1% level, respectively.

Table 7
Pooled multivariate analysis of a piecewise linear relation between auction size and pricing.

	Model 1	Model 2	Model 3
Auction Size Adjustment	0.396***	0.108	0.220
	(2.62)	(0.58)	(1.37)
Auction Size Adjustment * Smaller than Indicated	0.339**	0.299*	0.365**
	(2.23)	(1.94)	(2.36)
Auction Size Adjustment * Larger than Indicated	0.123	0.134	0.153
	(0.66)	(0.78)	(0.87)
Crisis * Auction Size Adj.	0.412***	-0.046	-0.065
	(2.66)	(-0.29)	(-0.33)
TE LIBOR * Auction Size Adj.		6.080***	
		(2.62)	
Dealer Dispersion * Auction Size Adj.		12.758**	
		(1.96)	
High TE LIBOR * Auction Size Adj.			0.508***
			(3.53)
High Dealer Dispersion * Auction Size Adj.			0.219***
			(2.64)
TE LIBOR		-5.119***	
		(-3.56)	
Dealer Dispersion		-24.597***	
		(-5.28)	
High TE LIBOR			-0.205**
			(-2.11)
High Dealer Dispersion			-0.042
			(-0.57)
Crisis	-0.748***	-0.076	-0.597**
	(-3.17)	(-0.38)	(-2.32)
Constant	-0.604***	-0.259***	-0.561***
	(-9.44)	(-2.66)	(-8.17)
Number of Observations	2910	2820	2820
Adjusted R-Square	0.24	0.31	0.26

Dependant Variable: WAR minus Indicated Rate. *Auction Size Adjustment* is the difference between actual auctioned amount and indicated amount. *Smaller than Indicated* is a dummy equal to one if the actual auction size is smaller than the lower indicated size. *Larger than Indicated* is a dummy equal to one if the actual auction size is larger than the lower indicated size. *Crisis* is an indicator variable equal to one for auctions held after August 1, 2007; zero otherwise. *TE LIBOR* equals the root mean squared error of regressions of changes in FHLB yields on LIBOR using 3-month rolling windows. *Dealer Dispersion* equals the standard deviation of the midpoints of dealer indications submitted on the day of the auction. *High TE LIBOR* is a dummy equal to one if *TE LIBOR* is in the top quartile of its sample distribution. *High Dealer Dispersion* is a dummy equal to one if *Dealer Dispersion* is in the top quartile of its distribution. All regressions include fixed effects for auction maturity. *t*-statistics based on errors clustered by auction date are in parentheses. *, **, *** denote significance at 10%, 5%, and 1% level, respectively.

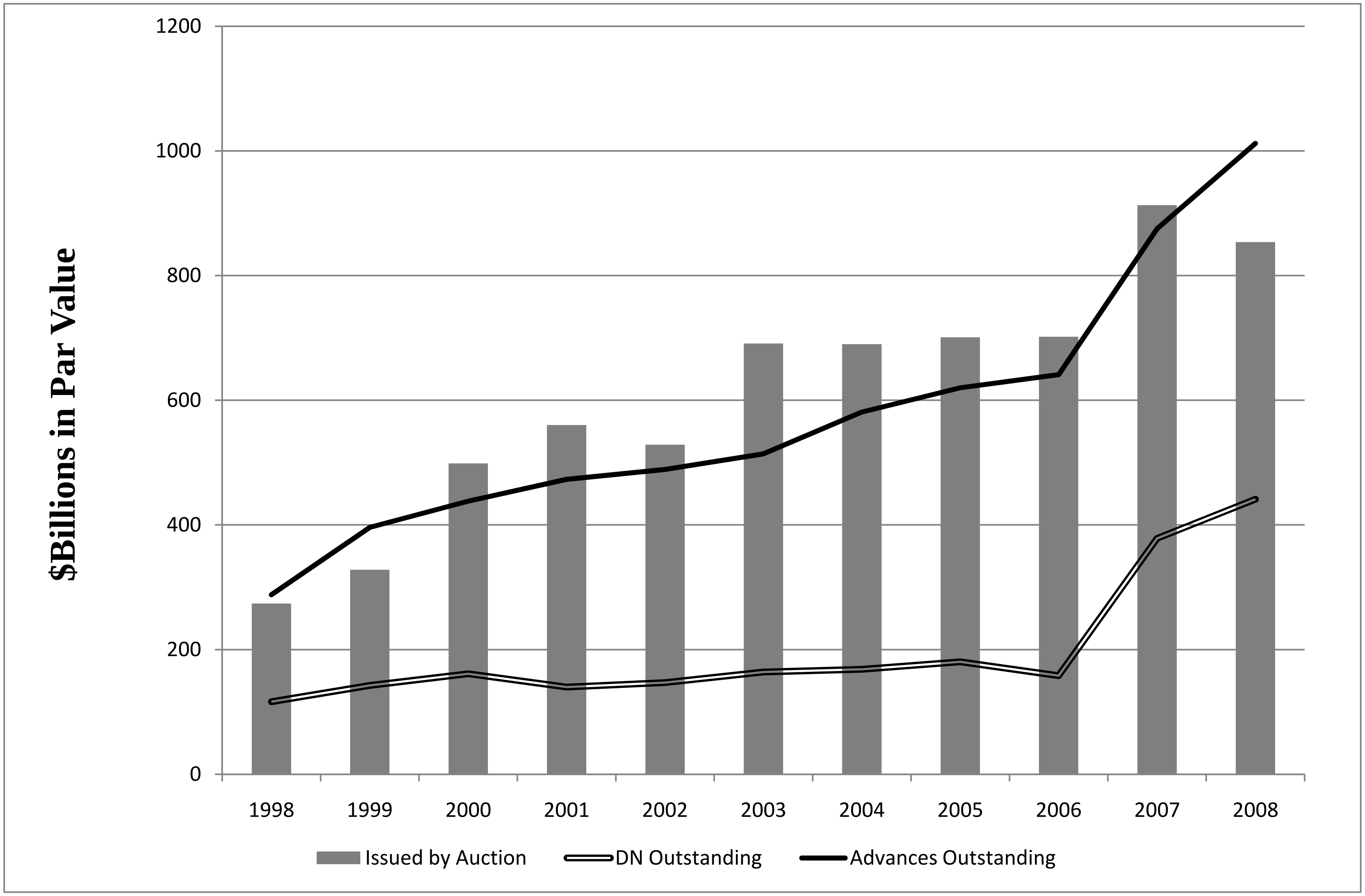

Fig 1. FHLB discount notes auction issuance, average amounts outstanding, and outstanding advances to members.
The data is available on the FHLB Office of Finance web page: http://www.fhlb-of.com/. Discount Notes (DN) Outstanding is calculated at calendar year end.

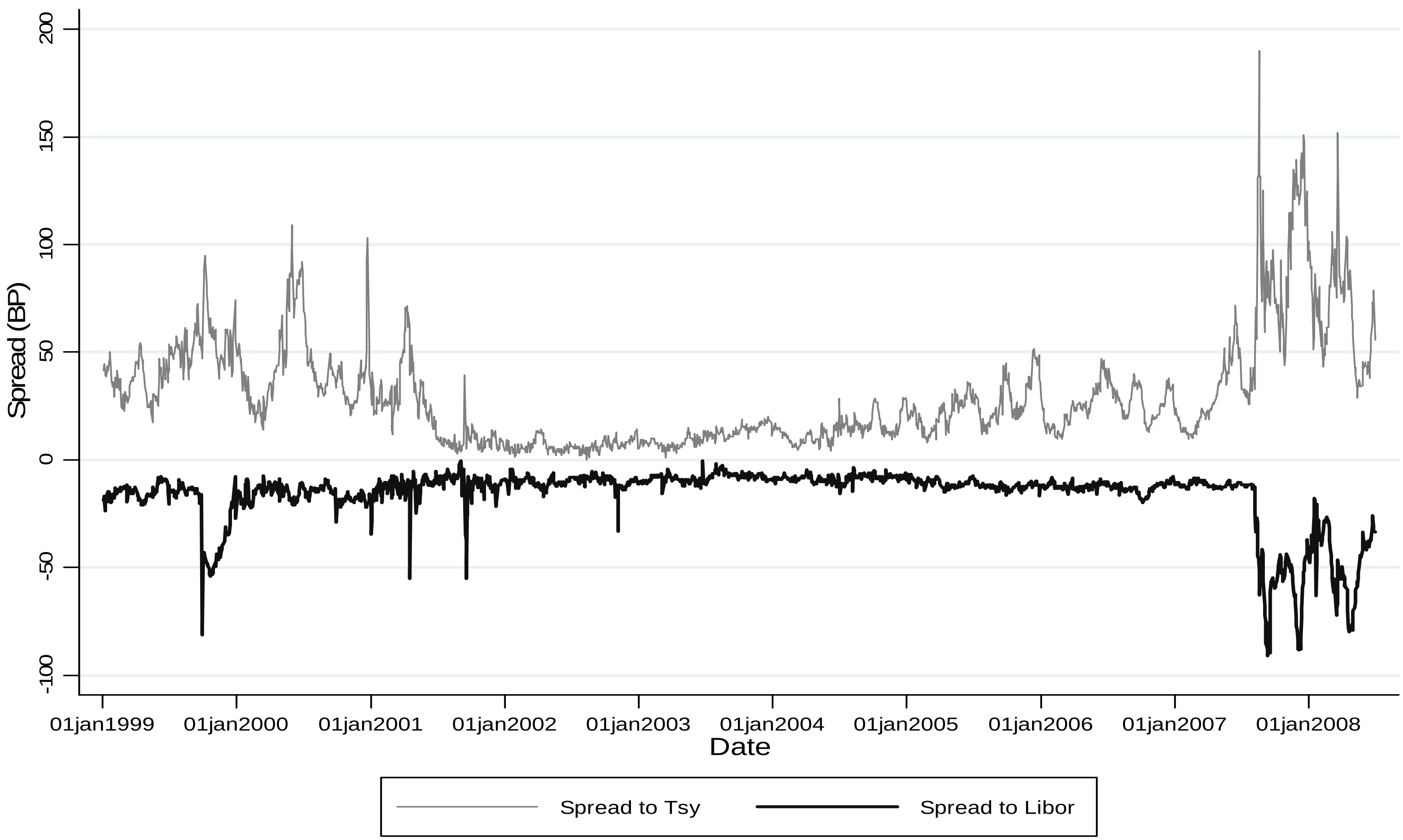

Fig. 2. Spread of 3-month FHLB discount note rate relative to 3-month Treasury bill rate and 3-month LIBOR in basis points (BP).

The data on 3-month FHLB discount notes is obtained from the Office of Finance and incorporates the outcomes of Discount Notes auctions, discount window sales and reverse inquiries. The 3-month T-bills data is obtained from FRED® at http://research.stlouisfed.org/fred2/, while 3-month LIBOR is obtained from Bloomberg.

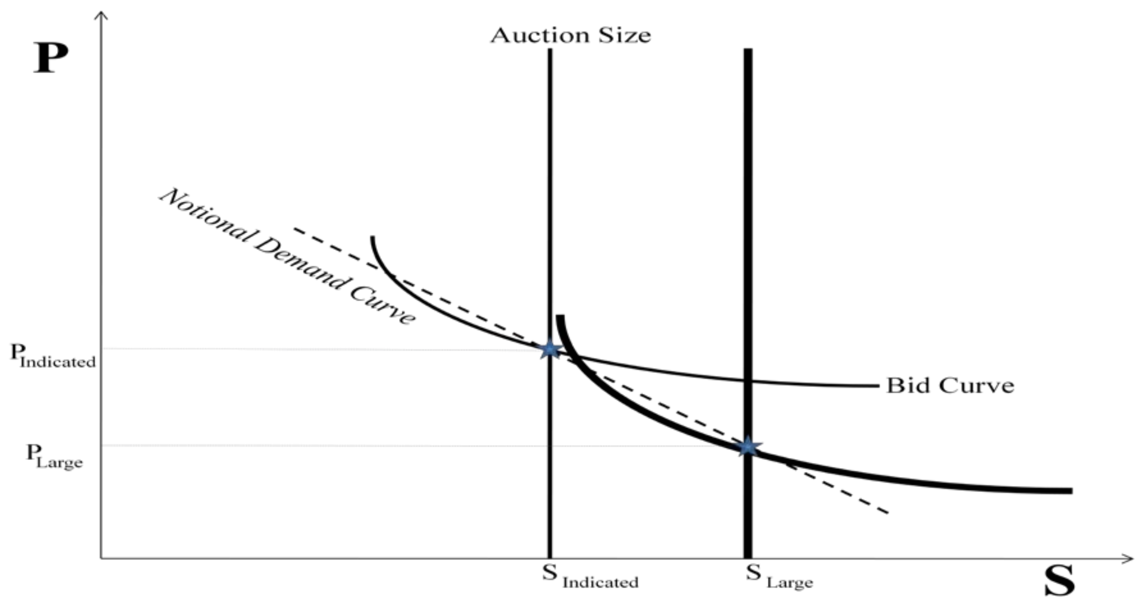

Fig. 3. The impact of Auction Size (S) on Auction Price (P).

This figure illustrates two market price-size equilibrium outcomes for two alternative auction size choices ("As Indicated" and "Large"). Companion bid curves are drawn for each auction size choice. The "Notional Demand Curve" is the Marshallian demand curve implied by the line determined by the starred equilibrium points.

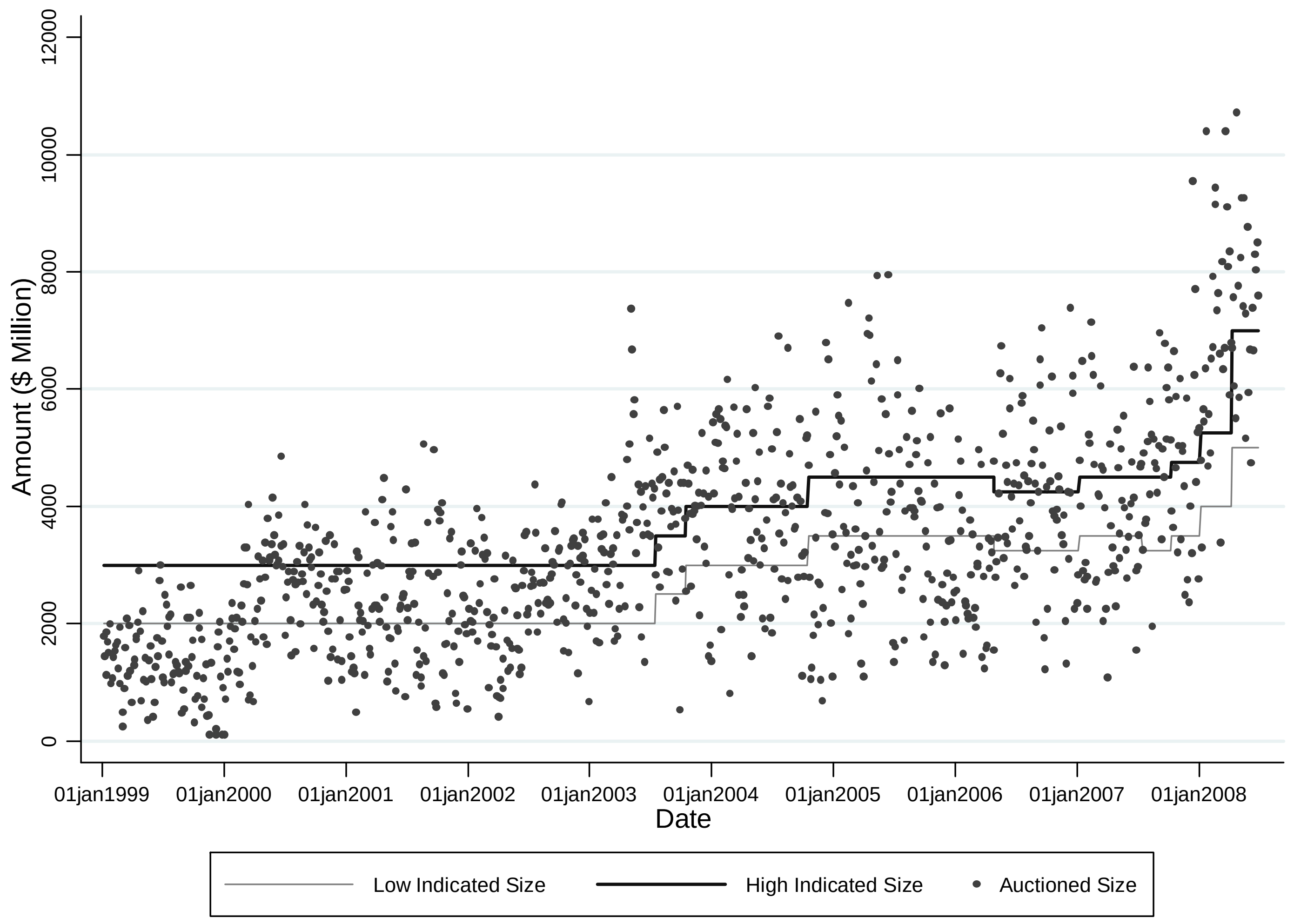

Fig. 4. Time series of auctioned amounts of 4-week FHLB discount notes.

The sample period starts on Jan 5, 1999 and ends on June 10, 2008. The High and Low Indicated size are set by the FHLB on a quarterly basis and communicated to dealers at the beginning of each quarter.

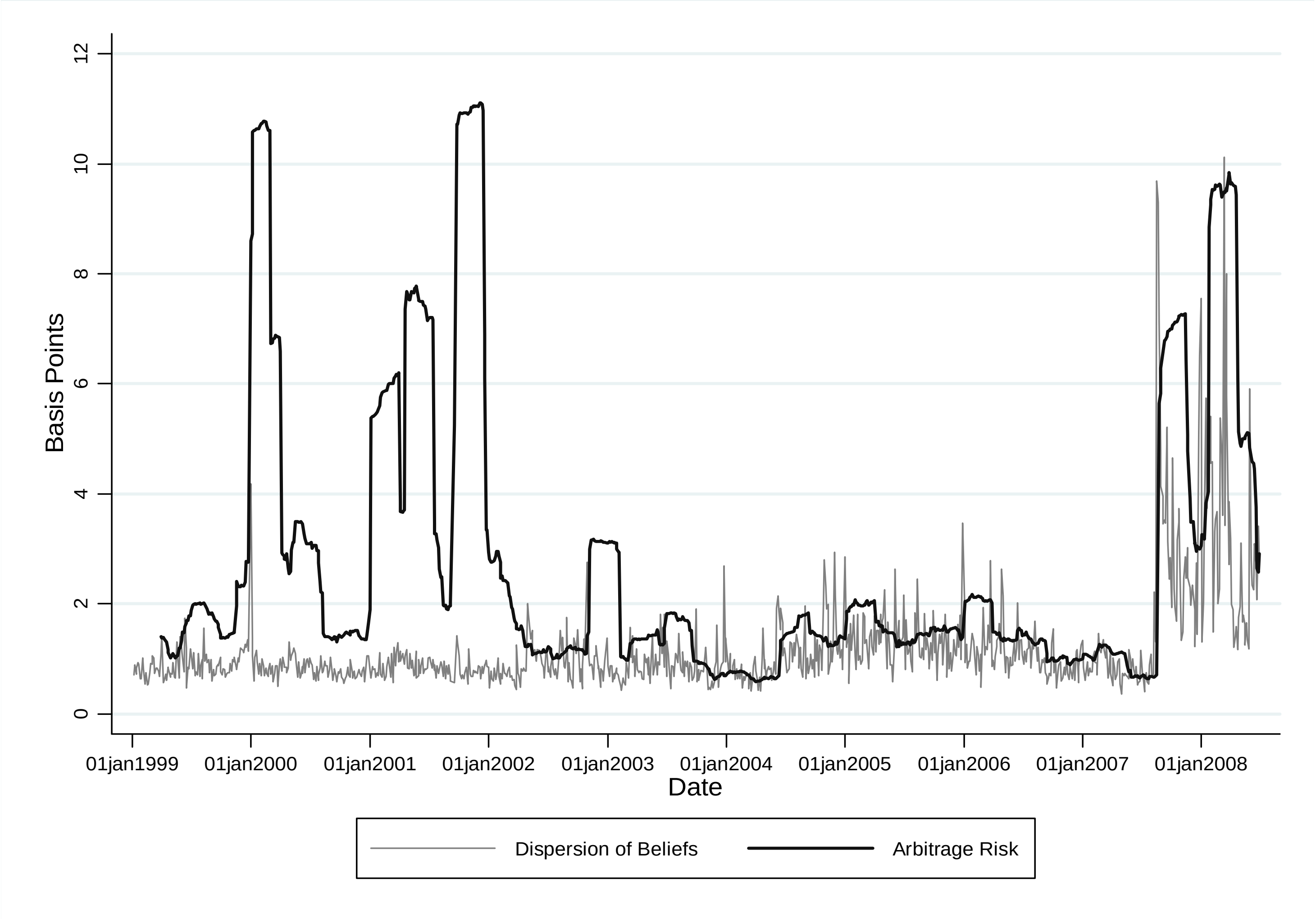

Fig. 5. Historical variation in arbitrage risk and the dispersion of dealer rate indications.

Arbitrage Risk equals the root mean squared error of regressions of changes in FHLB yields on LIBOR using 3-month rolling windows. *Dispersion* of *Beliefs* equals the standard deviation of the midpoints of dealer rate indications submitted on the day of the auction.