Dark Crypto*

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Abstract

We study $550 billion in dark crypto trades: off-exchange trades which do not appear on any exchange dataset. These trades are proprietary to a large brokerage firm, which routes orders to a number of competing off-exchange wholesalers. Dark crypto liquidity frequently provides price improvement over and above a hypothetical "NBBO," and we estimate customers save between $38 and $74 million annually. A lack of cryptocurrency regulation means the benefits of a cryptocurrency broker, and associated access to dark crypto liquidity, are not widely known.

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I. Introduction

Bitcoin launched in 2009 in part to disintermediate the payment system (Nakamoto (2008)). This ethos of disintermediation is reflected in much of the subsequent development of not just blockchain technology, but the entire cryptocurrency industry. Even though centralized exchanges run counter to the peer-to-peer philosophy of Bitcoin's launch, they offer retail traders direct access to a central limit order book for trading cryptocurrencies. Retail traders have driven much of the growth in volume at cryptocurrency exchanges. For example, BitMEX added 600,000 users in early 2017 (Soska, Dong, Khodaverdian, Zetlin-Jones, Routledge, and Christin (2021)), Binance added 7.5 million new customer accounts in ten months between September 2020 and July 2021 (Kawai, Christin, Routledge, Soska, and Zetlin-Jones (2023)), and the bankruptcy of FTX in November 2022 impacted over one million individual accounts.

Interestingly, even though many traders choose the disintermediated direct access to centralized exchanges, many other retail traders opt to trade through an intermediated channel via a broker. Presumably, the choice between an exchange and a broker is related to the complexity of direct trading and perhaps to the uncertain and evolving regulation surrounding cryptocurrencies. A broker may also offer more convenient transactions (e.g., the ability to purchase bitcoin using a Paypal account).

The choice of intermediated or direct access to a centralized exchange contrasts with U.S. equities markets, where retail trade is only conducted through a broker. In the equities market, brokers must seek the best possible prices for their customers, taking into account liquidity both from exchanges and from off-exchange wholesalers, and, subject to Regulation NMS, generally must execute at the National Best Bid or Offer (NBBO) or better. There is no current analogous rule for brokers in cryptocurrency to seek the crypto-equivalent of the

NBBO.

Cryptocurrency regulation in the U.S. is in its infancy, with unresolved questions about the basic definitions of cryptocurrency assets. In contrast, retail investors in equity markets obtain a variety of regulatory protections. Chief among them, retail investors work through a broker who has a duty of best execution, pursuant to which the broker must seek the best possible prices for its customers across both exchanges and off-exchange liquidity. With cryptocurrencies, many cryptocurrency exchanges directly offer trading accounts to retail customers, but they do not have a best execution duty or provide any of the quote protection of Reg NMS. As a result, retail customers trading with an exchange obtain only the prices offered by that exchange, which may not be the best prices in the market.

We study proprietary data on $550 billion in dark crypto trades In contrast to "lit" liquidity (e.g. displayed quotes on public exchanges), this dark liquidity is non-displayed, off-exchange liquidity which is only accessible through a broker, and does not appear in exchange data nor is it necessarily discernible from blockchain data. These trades are placed through a large brokerage firm, which in turn routes these orders to a number of competing off-exchange wholesalers. We evaluate these orders against a hypothetical NBBO—a national best bid or offer price—from the major U.S. cryptocurrency exchanges. Trading through a large brokerage firm enables substantial savings for retail customers, both because they are not locked in to the prices of an individual exchange, and because the prices they obtain are frequently better than that of a hypothetical NBBO. Limited cryptocurrency regulation, including a lack of best-execution requirements for firms that act as broker-dealers to individual retail customers, means that the benefits of a broker are not universally shared, as many clients opt to be direct customers of exchanges rather than use a broker. For the trades which do occur through dark crypto, there is no current reporting infrastructure

for dark crypto trades, nor for execution quality generally.[1] Consequently, most customers would not have an opportunity to observe or evaluate the potential value of dark liquidity in crypto.

Total price improvement provided by off-exchange cryptocurrency liquidity is substantial. Compared to the best bid or offer at individual exchanges, customers saved a total of 10 to 60 million USD in 2023 across the top three coins (Bitcoin, Ethereum, and Doge). Against the fee-adjusted NBBO, customers saved an average of $6,400 per day in 2023. Trading fees for cryptocurrencies are high, and which exchange dominates the NBBO is often a function of the fixed trading fees at that exchange rather than differences in on-exchange liquidity. Fees from moving cash or assets between exchanges can be substantial, and these transfer fees may prohibit customers taking advantage of changes in exchange trading fees. To capture this effect, we consider two alternative benchmarks for the NBBO. The first would be to compare each off-exchange dark crypto trade with a randomly selected exchange's fee-adjusted quote, while the second is to compare each off-exchange dark crypto trade with the fee-adjusted quote of the exchange with the second-best price. Across Bitcoin, Ethereum, and Doge trades from January 1, 2022 to December 31, 2023, we find that the broker's off-exchange liquidity resulted in price improvement to customers of $147 million compared to a randomly selected exchange's fee-adjusted quote, and $75 million compared to the second-best exchange's fee-adjusted quote.

Dark cryptocurrency liquidity is sourced from a variety of wholesalers. The number of wholesalers has increased over time, from two major wholesalers in 2020 to four major wholesalers in 2023. Top wholesaler's order share and the volatility of average effective

[1] As a point of comparison, U.S. equities have Trade Reporting Facilities which report all off-exchange trades to a consolidated tape, and all market centers, including off-exchange venues, must report monthly Rule 605 statistics on execution quality for any covered orders.

spreads have decreased substantially over this time. Wholesaler order shares are decreasing in the average effective spread charged, that is, wholesalers who charge higher average effective spreads obtain a smaller share of order flow.

In total, our results point to two major findings. First, there is substantial dark liquidity in cryptocurrencies. This liquidity is less transparent than traditional off-exchange trade in more regulated markets like U.S. equities; while on-chain cryptocurrency transfers are public on the ledger, there are almost no reporting requirements and little transparency into dark cryptocurrency transactions off-chain. Second, customers may at times obtain substantial savings through broker intermediation. While an individual exchange wants customers to trade at only that exchange (and without an equivalent to Reg NMS, crypto exchanges are able to ignore trade-throughs and competing exchange quotes), a broker can seek the best price possible for a customer, including from exchanges and from off-exchange liquidity. While the SEC has pursued many enforcement actions in cryptocurrencies, it has provided few formal rules or regulations. Our paper highlights how brokers, who can competitively source liquidity from multiple venues, have the potential to save customers millions of dollars annually.

II. Literature Review

While best execution in cryptocurrencies is a new topic, there is extensive academic literature and ongoing regulatory interest in regulating best execution in U.S. equity markets. Dyhrberg, Shkilko, and Werner (2022), Battalio and Jennings (2022), and Ernst, Malenko, Spatt, and Sun (2024) analyze competition in equities between wholesalers for broker order flow, while Battalio and Jennings (2023) and Ernst, Spatt, and Sun (2023) examine the

SEC's proposed order-by-order auctions. The nature of trading and intermediation in crypto markets and equity markets is fundamentally different. In equity markets customers do not have direct access to the exchanges and trading platforms, and trade through brokers. The brokers in equity have best execution responsibilities with respect to routing customer orders and the exchanges and other trading centers are generally restricted by Regulation NMS to execute at prices at least as good as the best price available across all exchanges. The SEC has expressed considerable concern over off-exchange dark trading, but in the crypto space we document that a broker using dark trading has resulted in substantial savings relative to customer direct accounts at exchanges. In effect, off-exchange trading through a broker is substantially enhancing the liquidity of the crypto market, and therefore intermediation by brokers is useful.

The SEC has historically capped access fees in U.S. equity markets at 30 cents per hundred shares traded. Bryzgalova, Pavlova, and Sikorskaya (2023), Ernst and Spatt (2022), and Battalio, Griffith, and Van Ness (2021) examine high transaction-based charges (as either maker-taker fees/rebates or payment for order flow (PFOF)) in options markets. While the SEC has recently adopted a much lower limit on access fees in equity markets, it has not done anything similar for options or cryptocurrency markets.

The pseudonymous nature of cryptocurrency allows some ability to unmask which wallets are associated with which players, as in Makarov and Schoar (2021). Not all wallets can be mapped, however, and many dark trades can be netted into a single on-exchange transfer. Dark crypto is considerably darker, therefore, than both U.S. equity markets (where nearly all trades are reported in milliseconds) and U.S. bond markets, where efforts to introduce more transparency are well studied, including Bessembinder, Maxwell, and Venkataraman (2006) and Edwards, Harris, and Piwowar (2007). The SEC has recently increased equity reporting

under Rule 605, which requires market centers to report aggregate monthly statistics, and this reporting has produced useful insights into how off-exchange venues compete, including in Dyhrberg et al. (2022) and Topbas and Ye (2024). Our data on dark crypto is the first of which we are aware. This market, and the potential savings for customers from accessing dark liquidity, are not well known nor easily discovered by customers or institutions.

III. Data

We analyze trading records of all cryptocurrency trades placed through a major brokerage firm from January 1, 2020 to December 31, 2023. These trades total $550 billion in trading volume for the 19 USD-denominated symbols. The exact coins and summary statistics on average daily volumes are presented in Table I. Top cryptocurrencies include DOGE ($235 billion), Bitcoin ($115 billion), Ether ($105 billion of Ether and $40 billion of Ether-classic), and Litecoin ($20 billion).

Trades placed with this broker are routed to a wholesaler (market makers which specialize in executing retail trades). Wholesalers pay a 0.35% fee (0.2% prior to May 4, 2022) to the broker for each order they obtain; all wholesalers pay an equal fee. Orders are allocated to wholesalers based on streamed quotations; for each incoming order, the wholesaler with the best quoted price obtains the order.[2] Wholesaler market shares are plotted in Figure 6. Transactions between the broker and wholesaler are dark to other market participants, as they are not reported by a major exchange data feed. The broker and wholesalers frequently settle up with an on-blockchain transfer of coins, but this transfer may include netted volume and does not provide price information to other market participants.

[2]Quotes are streamed for several different possible nominal quantities, with a 1-cent tick size for most cryptocurrencies. In the event of a quote tie, the broker evenly distributes order flow at the per-order level.

Total order flow is fairly balanced: our sample period has a total of $280 billion of buy volume and $270 billion of sell volume. Weekly imbalances, however, can deviate significantly from zero. Figure 2 presents weekly buy imbalances, defined as $\frac{\sum buy - \sum sell}{\sum buy + \sum sell}$. This weekly imbalance measure reaches as high as ±40% per week, with retail customers trading strongly directional positions in some weeks.

Average per-customer trading volume is rather modest. Table II presents summary statistics provided by the broker on monthly trading volumes across customers for the last six months of 2023. The median customer has less than $100 per month in trading volume, and trading volume by the 95th percentile of customers, by month, is less than $10,000 for five of the last six months of 2023 (and is just barely above, at $10,195, in the remaining month).

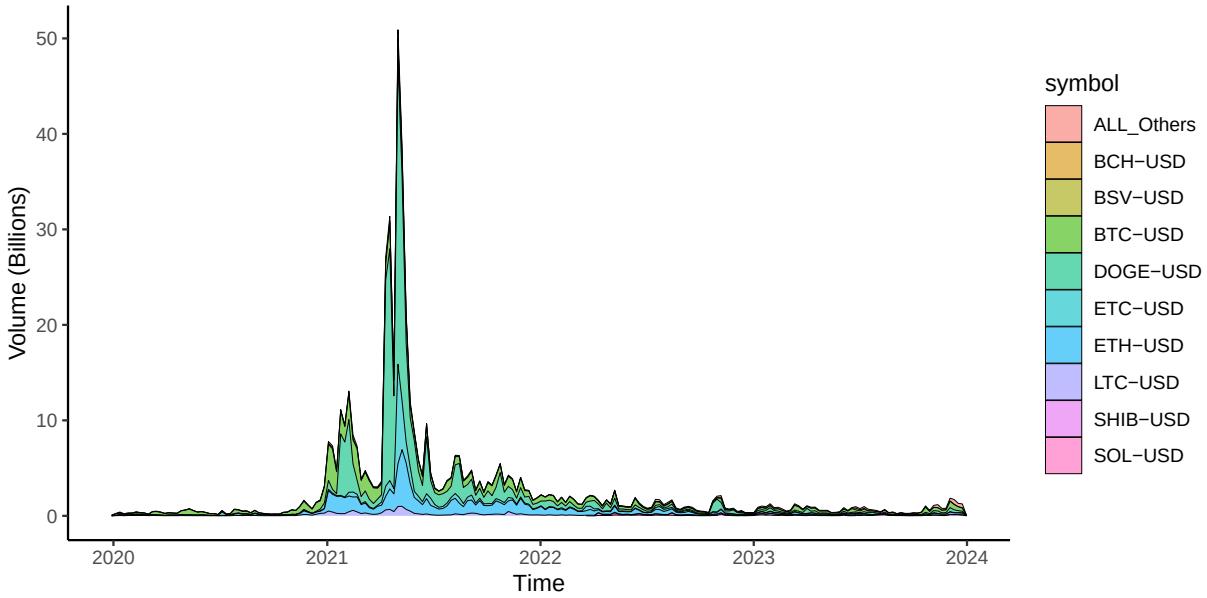
Table I: Nominal Volume. Panel A presents mean, standard deviation, and percentiles for daily trading volume in millions of USD.

Panel A: USD Symbol Nominal Volume (in Millions USD)

Symbol	Total	Mean	SD	25th Percentile	Median	75th Percentile
DOGE-USD	235331.3	161.1	639.8	5.7	22.7	78.7
BTC-USD	114604.3	78.4	110.3	19.9	41.0	87.6
ETH-USD	105678.2	72.3	123.7	9.5	25.2	89.4
ETC-USD	40489.9	27.7	149.3	2.3	5.2	15.5
LTC-USD	19750.3	13.5	24.2	2.2	4.3	12.9
SHIB-USD	5962.3	9.4	10.3	4.1	6.9	11.6
BCH-USD	9892.7	6.8	15.5	1.3	2.4	5.7
SOL-USD	2912.7	6.4	5.5	2.9	4.9	8.7
BSV-USD	5626.0	5.0	10.0	1.0	2.1	4.7
MATIC-USD	2198.7	4.9	5.0	2.2	3.4	5.5
AVAX-USD	1961.9	3.8	8.8	0.7	1.1	2.4
LINK-USD	1470.2	2.6	3.0	1.0	1.6	2.8
ADA-USD	648.0	2.1	1.6	1.1	1.7	2.7
COMP-USD	1331.8	2.1	2.0	0.7	1.4	2.7
XLM-USD	704.0	1.4	2.3	0.5	0.9	1.6
UNI-USD	554.4	1.0	1.3	0.3	0.6	1.1
AAVE-USD	353.2	0.8	1.0	0.2	0.4	1.0
USDC-USD	57.7	0.5	0.6	0.2	0.4	0.6
XTZ-USD	184.8	0.4	0.4	0.2	0.3	0.5

Figure 1. : Trading Volumes. We plot the weekly trading volume across all coins.

Panel A: All Time Horizons



Panel B: January 2022-December 2024

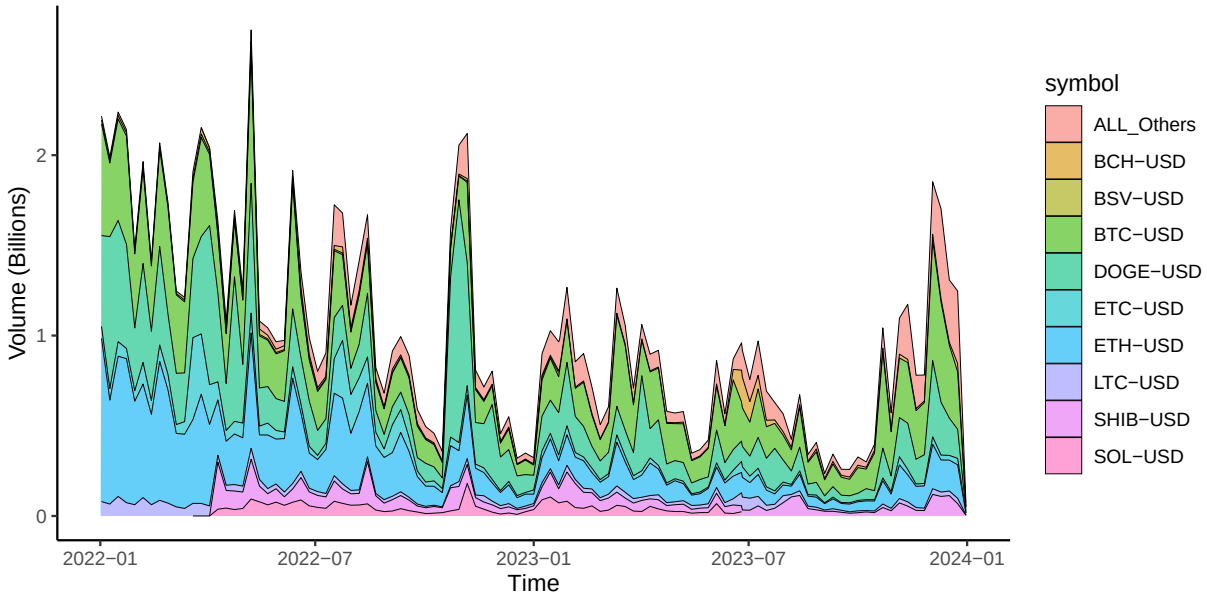


Figure 2. : Order Flow Imbalance. We plot the weekly order flow buy imbalance over time, which is the quantity $\frac{\sum buy - \sum sell}{\sum buy + \sum sell}$. We divide imbalances by coin: Panel A presents Bitcoin imbalances, Panel B presents Ethereum imbalances, Panel C presents DOGE imbalances, and Panel D presents imbalances for all other coins.

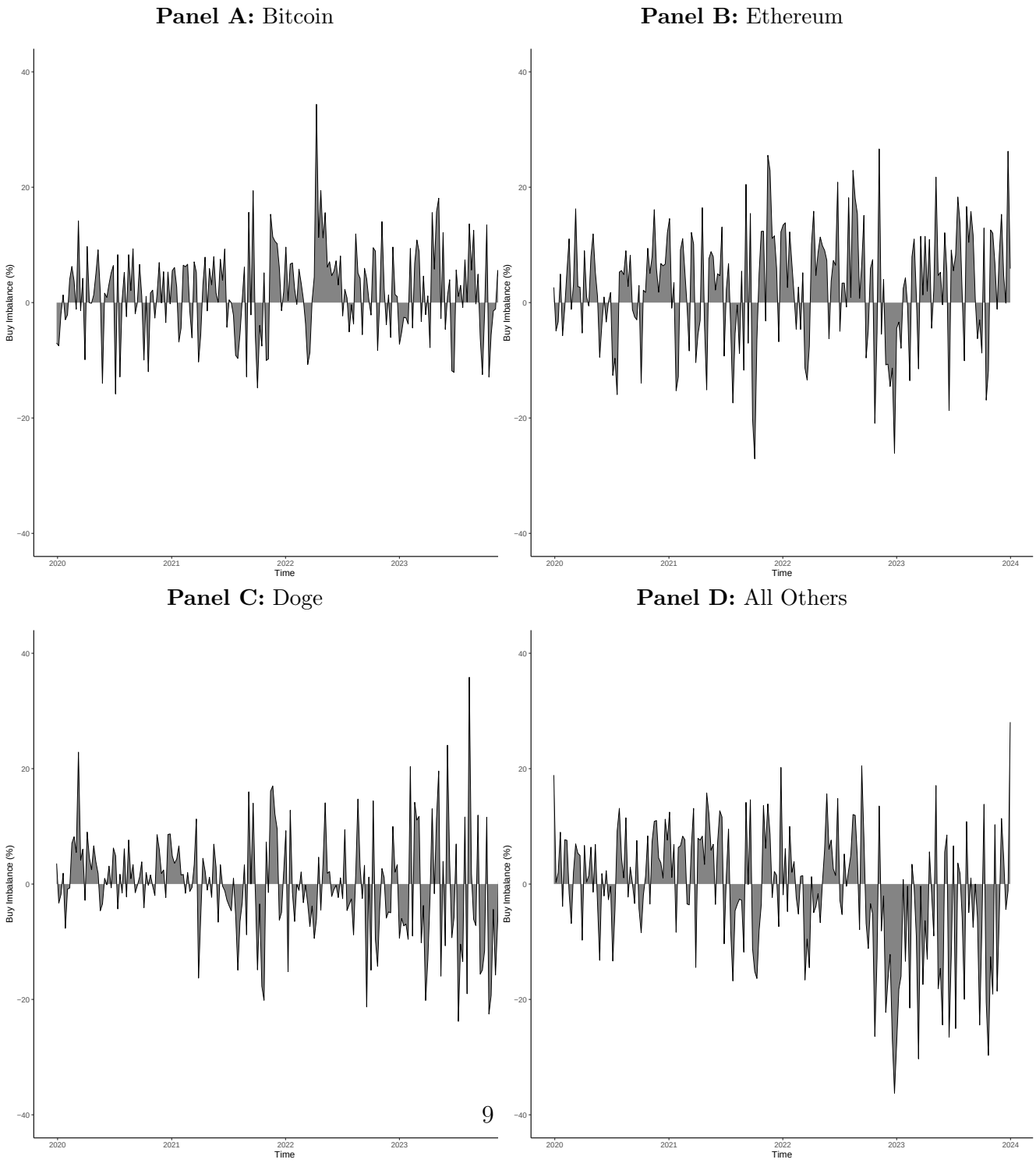


Table II: User Trading Volumes. This table presents the average, median, and 75th, 90th, and 95th percentile of cryptocurrency trading volume, in USD, across users at the broker for the last six months of 2023. Exchange pricing is based on a user's historical trade volume; to compare broker versus exchange prices, we need an estimate of the fees each user would pay on an exchange. While we do not have individual user-level data, we obtained summary statistics from the broker, including average account-level trading volumes.

Month	Average	Median	75%	90%	95%
2023-07	3,457	81	485	2,595	7,450
2023-08	2,391	81	464	2,311	6,079
2023-09	1,713	65	356	1,715	4,407
2023-10	2,725	80	490	2,543	6,799
2023-11	4,169	86	549	3,047	8,588
2023-12	5,106	95	635	3,559	10,195

IV. Broker Value

A broker is not tied to any particular exchange, but can source liquidity from any venue, including both exchanges and off-exchange wholesalers. As a result, brokers offer substantial potential savings. First, brokers can offer a product equivalent to a national best bid or offer, which is the best price across all competing exchanges. Second, with access to off-exchange dark liquidity, brokers can potentially obtain prices which are superior to that of displayed liquidity. In this section, we quantify these and analyze the components of these savings.

We first consider the construction of a hypothetical national best bid or offer (NBBO). This NBBO would be the best bid or offer price across all exchanges. One difficulty with cryptocurrency assets is that, unlike U.S. equities, they are not centrally cleared. Purchasing cryptocurrency at an exchange does not default to a transfer of cryptocurrency to a customer's private wallet, but instead creates a claim to the customer to a cryptocurrency held in the exchange's wallet. Limited cryptocurrency regulation means there can be substantial differences in how the value of this liability is determined (as the bankruptcy of FTX

illustrates). To minimize some of these differences, we focus our construction of an NBBO on U.S. or E.U.-domiciled cryptocurrency exchanges, specifically the firms Coinbase, Kraken, Gemini, Bitstamp, Binance-US, and FTX-US.

Cryptocurrency fees are considerably higher than trading fees of U.S. Exchanges.[3] To account for these fees, we construct a fee-adjusted NBBO, which accounts for taker fees charged to marketable orders by each exchange. These fees are typically volume-tiered, with higher-volume clients obtaining lower fees. Across all the exchanges we consider, the lowest volume needed to obtain any discount is more than $10,000 in monthly trading volume; as we note in Table II, over 95% of all customers of the broker would fail to qualify for any discounts in trading volume, even if their volume were concentrated at a single exchange.

Exchange fees are a large share of exchange trading costs. Figure 3 plots the share of time that each exchange sets the fee-adjusted NBBO. During several time periods, one specific exchange will have a lower trading fee, and set the fee-adjusted NBBO close to 100% of the time, which persists until either that exchange or a rival exchange adjusts trading fees.

Trades from off-exchange liquidity sourced by the broker are almost always better than the fee-adjusted NBBO. We plot an sample of broker trades against the NBBO in Figure 3, using Ethereum trades for two hours on December 1, 2023. In this sample, the average broker buy order executes at a price 0.2% better than the fee-adjusted NBBO, while the average broker sell order executes at a price 0.6% better than the fee-adjusted NBBO.

Figure 5 plots total price improvement from dark liquidity sourced by the broker over time. Panel A calculates price improvement against the fee-adjusted quotes of each individual exchange. Savings can be as high as $20 million per week against some exchanges, but are largely driven by high fees at those specific exchanges. Binance-US, briefly has very low

[3]U.S. exchanges typically charge a liquidity taking fee of 30 cents per hundred shares. For a $25 stock, this is a 1.2 basis point charge.

fees in early 2022 and has apparently superior prices to off-exchange liquidity during this time, but Binance-US trading fees return to a price closer to the industry average in August 2022, with Binance-US charging considerably higher prices than off-exchange liquidity for the remainder of our sample period. Total savings for 2022 and 2023 are reported in Table III.

Exchange fees change over time, and moving cryptocurrency assets or cash between exchanges to take advantage of lower fees can be prohibitively costly when these transfer fees exceed any potential trading fee savings. To account for the unpredictability of future fees, we consider two alternative measures to the NBBO. The first is to compare each off-exchange dark crypto trade with a randomly selected exchange's fee-adjusted quote, while the second is to compare each off-exchange dark crypto trade with the fee-adjusted quote of the exchange with the second-best price. Results of this exercise are presented in Figure 5, Panel B. Across Bitcoin, Ethereum, and Doge trades from January 1, 2022 to December 31, 2023, we find that the broker's off-exchange liquidity resulted in price improvement to customers of $147 million compared to a randomly selected exchange's fee-adjusted quote, and $75 million compared to the second-best fee-adjusted quote.

Dark liquidity in cryptocurrencies offers substantial savings over and above displayed (or lit) liquidity. To understand drivers of this price improvement, we estimate the following regression:

REGRESSION 1: *For each day t in cryptocurrency i we estimate:*

$$TotalPriceImprovementPCT_{ijt} = \alpha_0 + \alpha_1 Imbalance_{ijt} + WholesalerHHI_{ij} + \epsilon_{ijt}$$

$TotalPriceImprovementPCT$ measures the total amount of price improvement, as a percentage

of total traded value, obtained by all broker trades on that day. *Imbalance* measures the absolute value of order imbalance on that day, defined as $|\frac{\sum Buy - \sum Sell}{\sum Buy + \sum Sell}|$. *WholesalerHHI* measures the Herfindahl-Hirschman Index of wholesaler market shares, defined as a number between 0 and 1, with 1 representing a very concentrated (monopolist) market.

Results of Regression 1 are presented in Table IV. More concentration among wholesalers is associated with slightly less price improvement, with a change from 0 (perfect competition) to 1 (monopoly) associated with a decrease in price improvement of 7 to 9 basis points. Order imbalances are associated with increases in price improvement, with a 1% larger imbalance associated with a 6 to 7 basis point increase in price improvement.

We investigate competition between wholesalers in detail in Section V. Wholesalers offer price improvement when trading against retail order flow off-exchange. Their willingness to offer price improvement reflects, in part, their willingness to interact with this retail order flow, and by offering price improvement they are more likely to obtain these orders in their inventory. We therefore examine how the market forces that shape price improvement also affect the price impact of retail trades. We re-estimate Regression 1 with average price impact of retail trades as the dependent variable.

Results are presented in Table V. Larger imbalances are associated with larger average price impacts, with a 1% increase in order imbalance associated with a 1 basis point increase in price impacts at the 30-second time horizon, and a 11 basis point increase in price impacts at the 1-hour horizon. These increases in price impact are suggestive evidence that off-exchange dark cryptocurrency trades have impacts on displayed liquidity, likely mediated via wholesalers on-exchange market-making behavior. Kogan, Makarov, Niessner, and Schoar (2024) document that many cryptocurrency traders are momentum traders, and large momentum price movement could generate additional order imbalances from

retail customers; these imbalances, however, would provide an economic justification for a continuation of price movements.

Wholesaler concentration is weakly associated with larger price impacts, consistent with a potential limitation to the ability of concentrated wholesalers to fully absorb price impacts.

Table III: Total Price Improvement. We calculate the total price improvement obtained from the broker's sourcing of off-exchange crypto liquidity compared to each exchanges fee-adjusted quote for three cryptocurrencies: Bitcoin, Ethereum, and Doge. All figures are in millions of USD.

Exchange	2022 Price Improvement	2023 Price Improvement
Coinbase	117	59.6
Binance-US	-21	64.9
Kraken	431	11.5
Gemini	-	25.8
FTX-US	22	-
Bitstamp	26	2.2
Randomly Selected Exchange	109	38.2
Second-Best Exchange	46	28.6

V. Wholesaler Competition

Figure 3. : Broker Trades Against NBBO. We plot a sample of broker trades in Ethereum from two hours on December 1, 2023. The solid blue line represents the fee-adjusted National Best Offer (NBO), while the solid red line represents the fee-adjusted National Best Bid (NBB); we calculate this fee-adjusted spread from quote data from Coinbase, Kraken, Binance-US, Bitstamp, and Gemini.

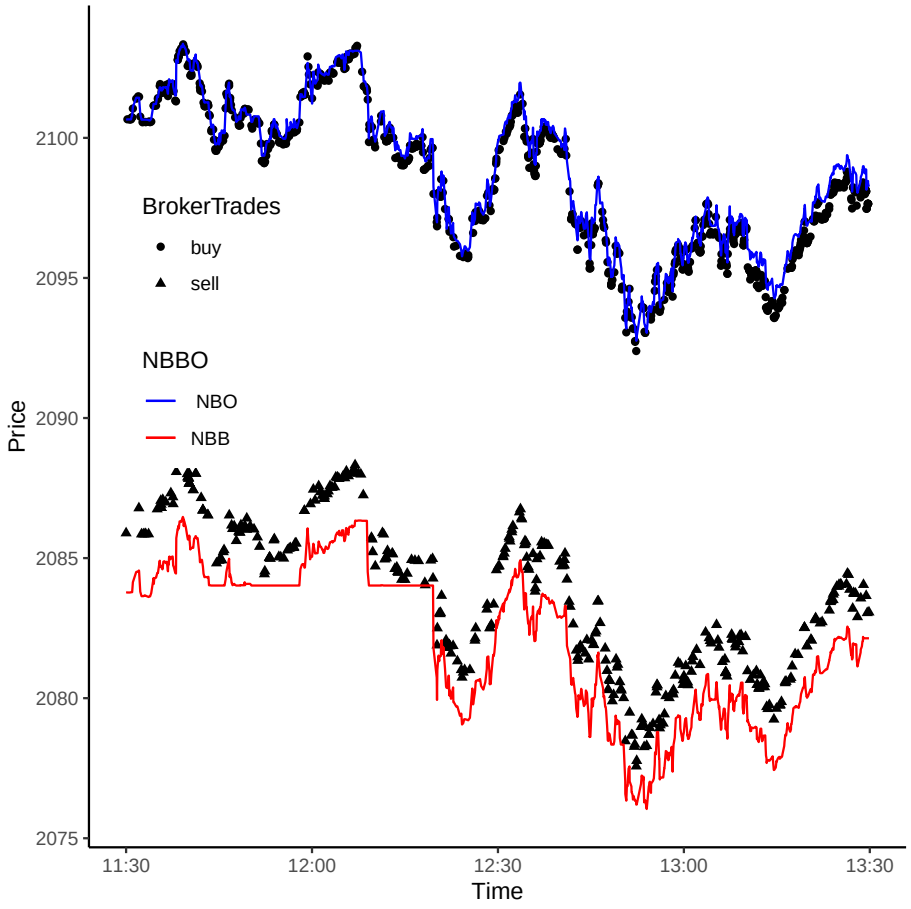


Figure 4. : NBBO Shares. Across each day of our sample, we calculate the share of time each exchange accounts for the fee-adjusted NBBO. Panel A presents results for Bitcoin, Panel B for Ethereum, and Panel C for Doge Coin. An exchange's competitiveness in the fee-adjusted NBBO is heavily dependent on fees charged by the exchange.

Panel A: Bitcoin **Panel B:** Ethereum **Panel C:** Doge

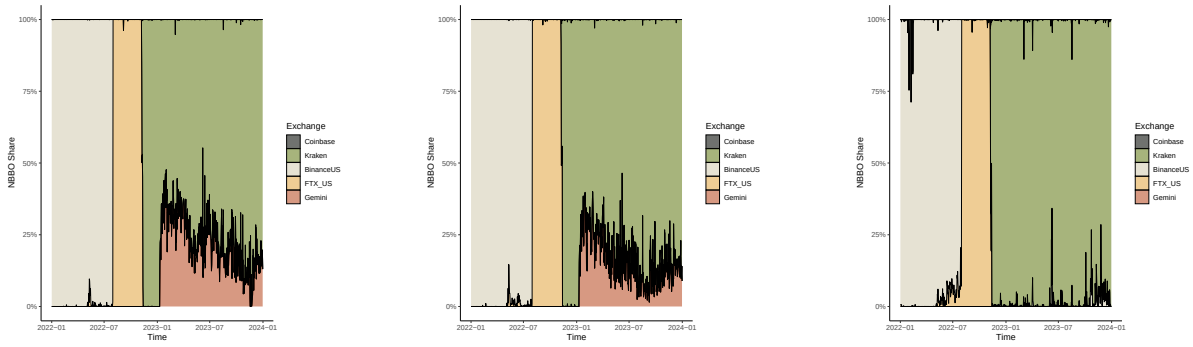
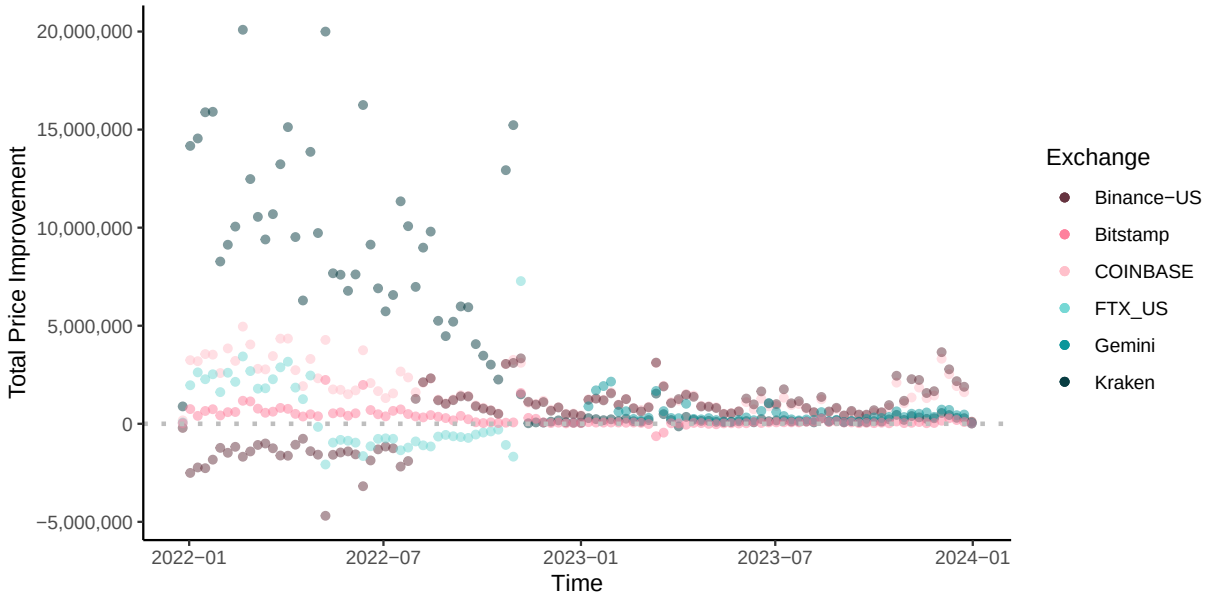


Table IV: Estimation of Regression on Price Improvement. We estimate Regression 1, which examines the relationship between market conditions and price improvement obtained through off-exchange liquidity. *TotalPriceImprovementPCT* measures the total amount of price improvement, as a percentage of total traded value, obtained by all broker trades on that day. *TotalPIPCT_2nd* is the same measure but with price improvement from the second-best priced exchange. *AbsImbalance* is the absolute value of order imbalance $|\frac{\sum Buy - \sum Sell}{\sum Buy + \sum Sell}|$. *WholesalerHHI* measures the Herfindahl-Hirschman Index of wholesaler market shares, defined between 0 and 1. Observations are at the coin-day symbol, and include Bitcoin, Ethereum, and Doge from January 1, 2022 to December 31, 2023.

	Dependent variable:	
	TotalPriceImprovementPCT	TotalPIPCT_2nd
	(1)	(2)
AbsImbalance	0.068***	0.058***
	(0.020)	(0.017)
WholesalerHHI	−0.072***	−0.090***
	(0.022)	(0.019)
Observations	2,190	2,190
R^2	0.013	0.208
Note:		*p<0.1; **p<0.05; ***p<0.01

Figure 5. : Total Price Improvement. We plot the weekly total price improvement obtained by customers across Bitcoin, Ethereum, and Doge. Panel A plots price improvement against each exchange's individual fee-adjusted quotes. Panel B plots price improvement against two hybrid calculations, the first calculates price improvement for each trade against the fee-adjusted quote of a randomly selected exchange, while the second calculates price improvement for each trade against the second-best fee-adjusted quote.

Panel A: Individual Exchanges



Panel B: Random Exchange and Second-Best Quote

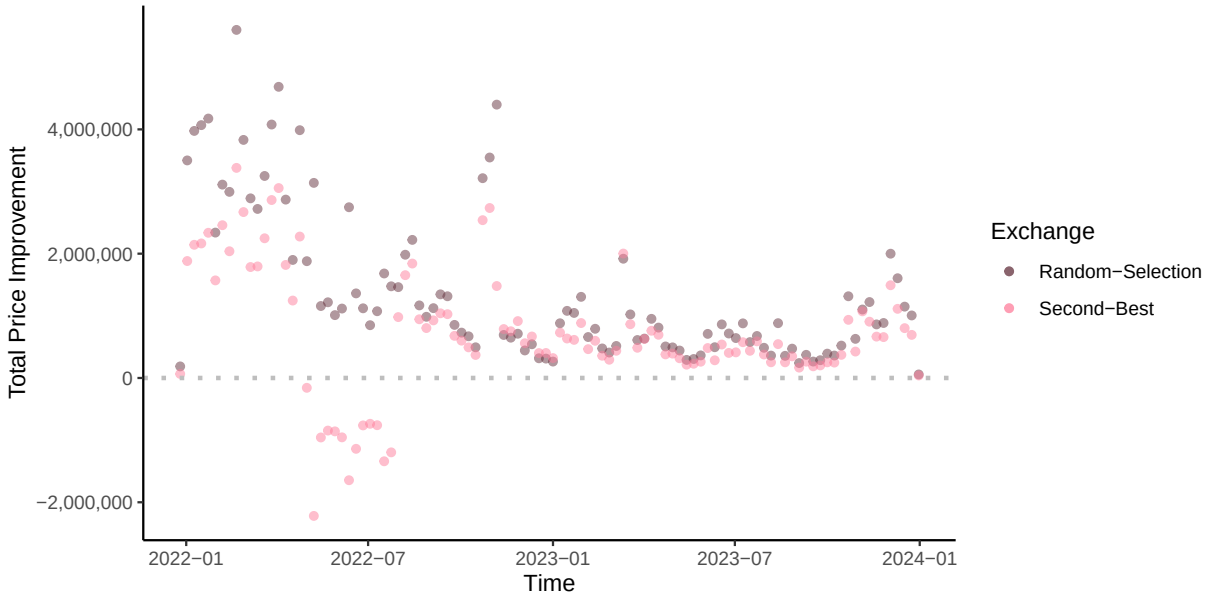


Table V: Estimation of Regression on Price Impact. We estimate Regression 1 with Price Impact as the Dependent variable. Impact measures the total price impact divided by the total days' trading volume, as a percentage, with impact measured at thirty seconds (Column 1) or one hour (Column 2). *Imbalance* is the absolute value of order imbalance $|\frac{\sum Buy - \sum Sell}{\sum Buy + \sum Sell}|$. *WholesalerHHI* measures the Herfindahl-Hirschman Index of wholesaler market shares, defined between 0 and 1. Observations are at the coin-day symbol, and include Bitcoin, Ethereum, and Doge from January 1, 2022 to December 31, 2023.

	Dependent variable:	
	Impact_30s	Impact_1H
	(1)	(2)
AbsImbalance	-0.011^{***}	-0.113^{***}
	(0.004)	(0.018)
WS_HHI	0.002	-0.035^{*}
	(0.005)	(0.020)
Observations	2,190	2,190
R^2	0.281	0.523
Adjusted R^2	-0.081	0.283
Residual Std. Error (df = 1456)	0.015	0.069
Note:	*p<0.1; **p<0.05; ***p<0.01	

When a retail customer places an order, the broker routes the order to a wholesaler for execution. This process is a competitive one: wholesalers offering better prices obtain more order flow, while wholesalers offering worse prices obtain less order flow. Wholesaler market shares are plotted in Figure 6. The number of active wholesalers has grown over time, with two major wholesalers in 2020-2021 and three major wholesalers in 2022-2023. Two wholesalers entered during this time, and one large wholesaler exited. These dynamics are roughly similar to the market for equity wholesaling, with the entry of one large wholesaler and exit of two wholesalers.

Wholesalers compete to fill orders on price. Figure 7 plots the average weekly spread charged by each wholesaler over time. The entry of additional wholesalers coincides with a considerable tightening of variation in average spreads. To analyze the relationship between spreads and performance, we estimate the following regression:

REGRESSION 2: *For each wholesaler i, time period t and crytocurrency j, we estimate:*

$$WholesalerOrderShare_{ijt} = \quad \alpha_0 + \alpha_1 EFF_{ijt} + X_{ij} + \epsilon_{ijt}$$

Wholesaler Order Share is the percentage of orders obtained by wholesaler i in cryptocurrency j on date t, demeaned by cryptocurrency and date. Spread is the average effective spread, in basis points, charged by each wholesaler, demeaned by cryptocurrency and date. Controls include the average order size of orders executed by wholesaler i in cryptocurrency j on date t, measured as a percentage of total average order size across all wholesalers and demeaned by cryptocurrency and date, and either a date fixed effect or cryptocurrency fixed effect. If brokers route according to performance, wholesalers offering lower effective spreads should obtain a larger share of order flow.

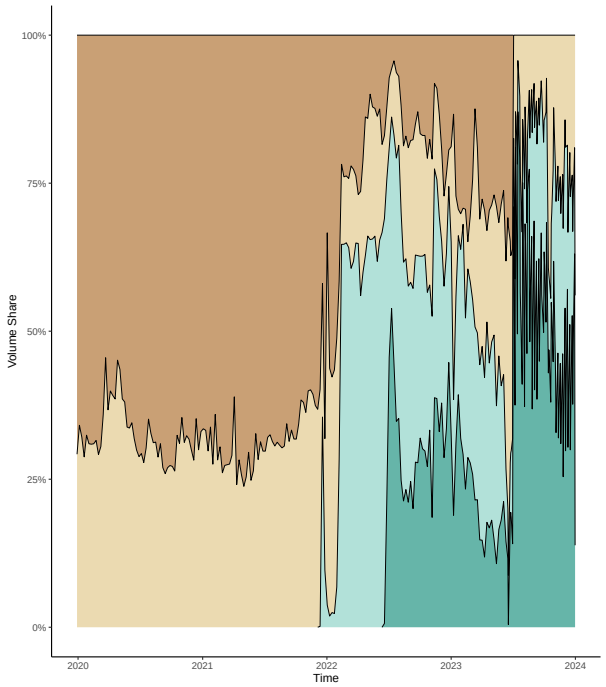
Results of Regression 2 are presented in Table VI. Higher spreads charged by wholesalers are strongly associated with lower future order share. For each 1 basis point increase in spread charged, a wholesaler can expect to receive 0.7% less order share. Larger order sizes are associated with much larger spreads, with a 1% higher average order size (relative to the mean across all wholesalers) associated with a 12.6% higher effective spread.

Table VI: Wholesaler Order Share Regression. We estimate Regression 2, which examines the relationship between wholesaler order shares and wholesaler effective spreads. Observations are at the day-coin-wholesaler level, with all data from May 5, 2022-Dec 31, 2023. Wholesaler Order Share is the percentage of orders obtained by wholesaler i in cryptocurrency j on date t, demeaned by cryptocurrency and date. Spread is the average effective spread, in basis points, charged by each wholesaler, demeaned by cryptocurrency and date.

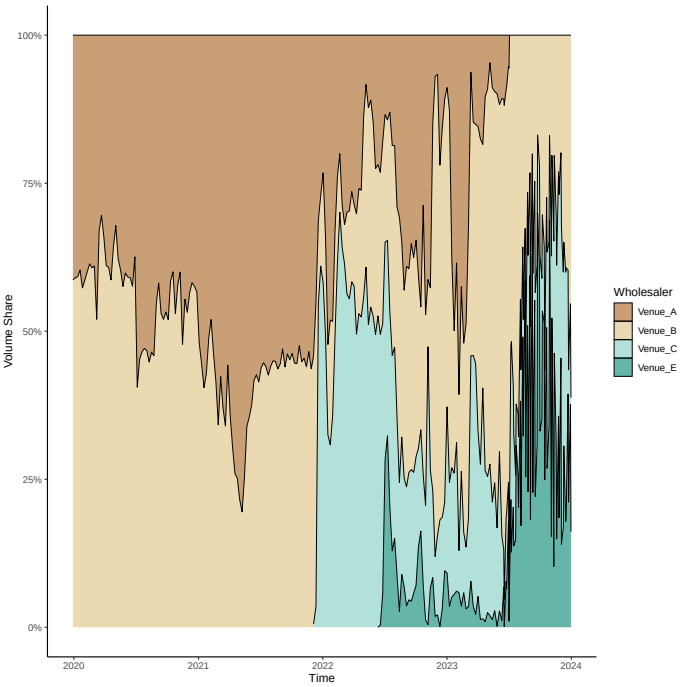
	Dependent variable:	
	Wholesaler Order Share (Demeaned)	
	(1)	(2)
Spread (BPS, demeaned)	-0.747^{***}	-0.747^{***}
	(0.043)	(0.043)
Average Order Size (demeaned)	12.643^{***}	12.643^{***}
	(0.208)	(0.210)
Observations	32,150	32,150
R^2	0.107	0.107
Note:		*p<0.1; **p<0.05; ***p<0.01

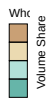
Figure 6. : Wholesaler Market Shares. We plot the weekly market share of each wholesaler over time. We divide market shares by coin: Panel A presents Bitcoin market share, Panel B presents Ethereum market share, Panel C presents DOGE market share, and Panel D presents market share for all other coins.

Panel A: Bitcoin

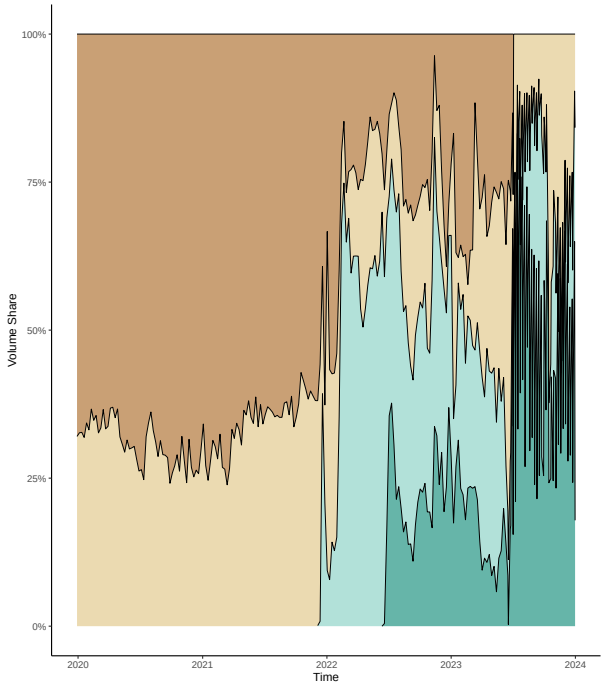


Panel B: Ethereum

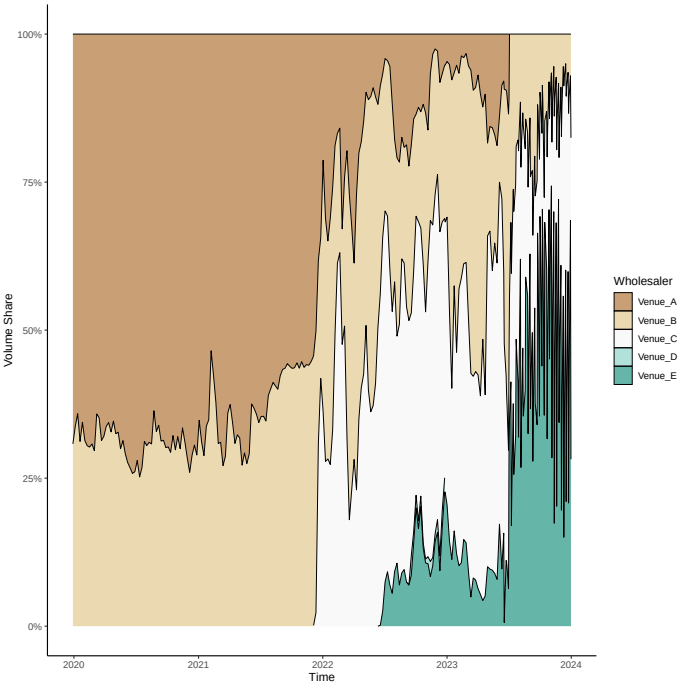




Panel C: Doge



Panel D: All Others



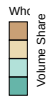
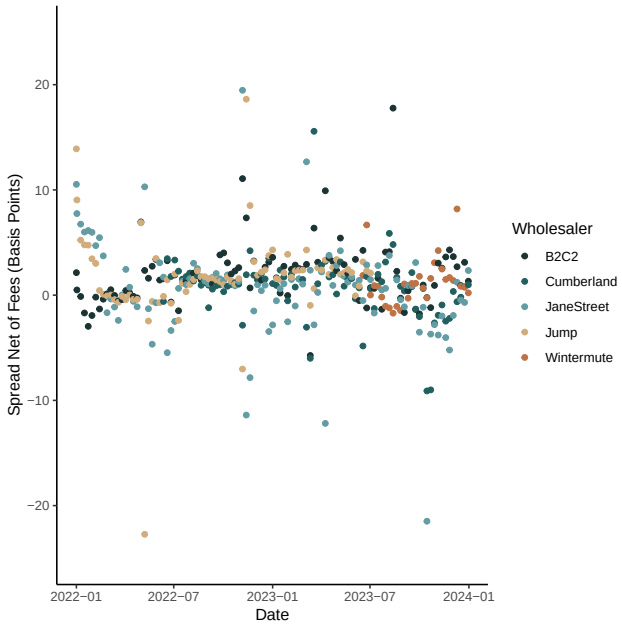
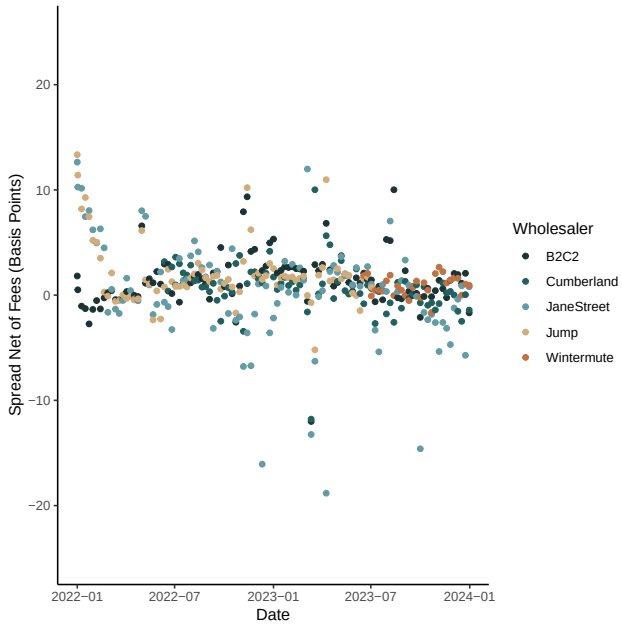


Figure 7. : Wholesaler Effective Spreads. We plot the weekly average effective spread over time. Panel A presents Bitcoin effective spreads net of transaction costs, Panel B presents Ethereum effective spreads net of transaction costs. Panel C (Bitcoin) and Panel D (Ethereum) present effective spreads including transaction costs.

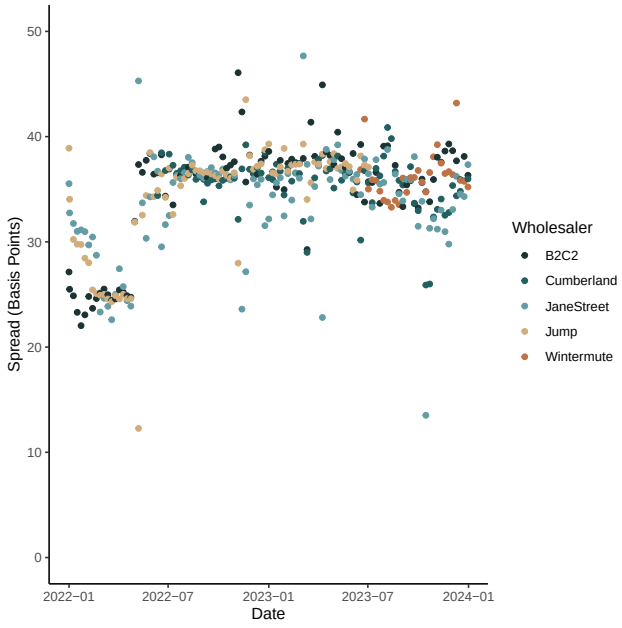
Panel A: Bitcoin - Net



Panel B: Ethereum - Net



Panel C: Bitcoin - Total



Panel D: Ethereum - Total

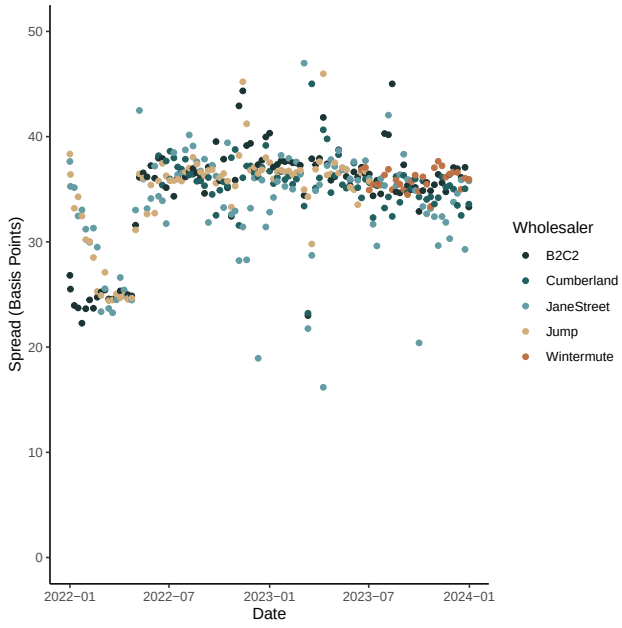
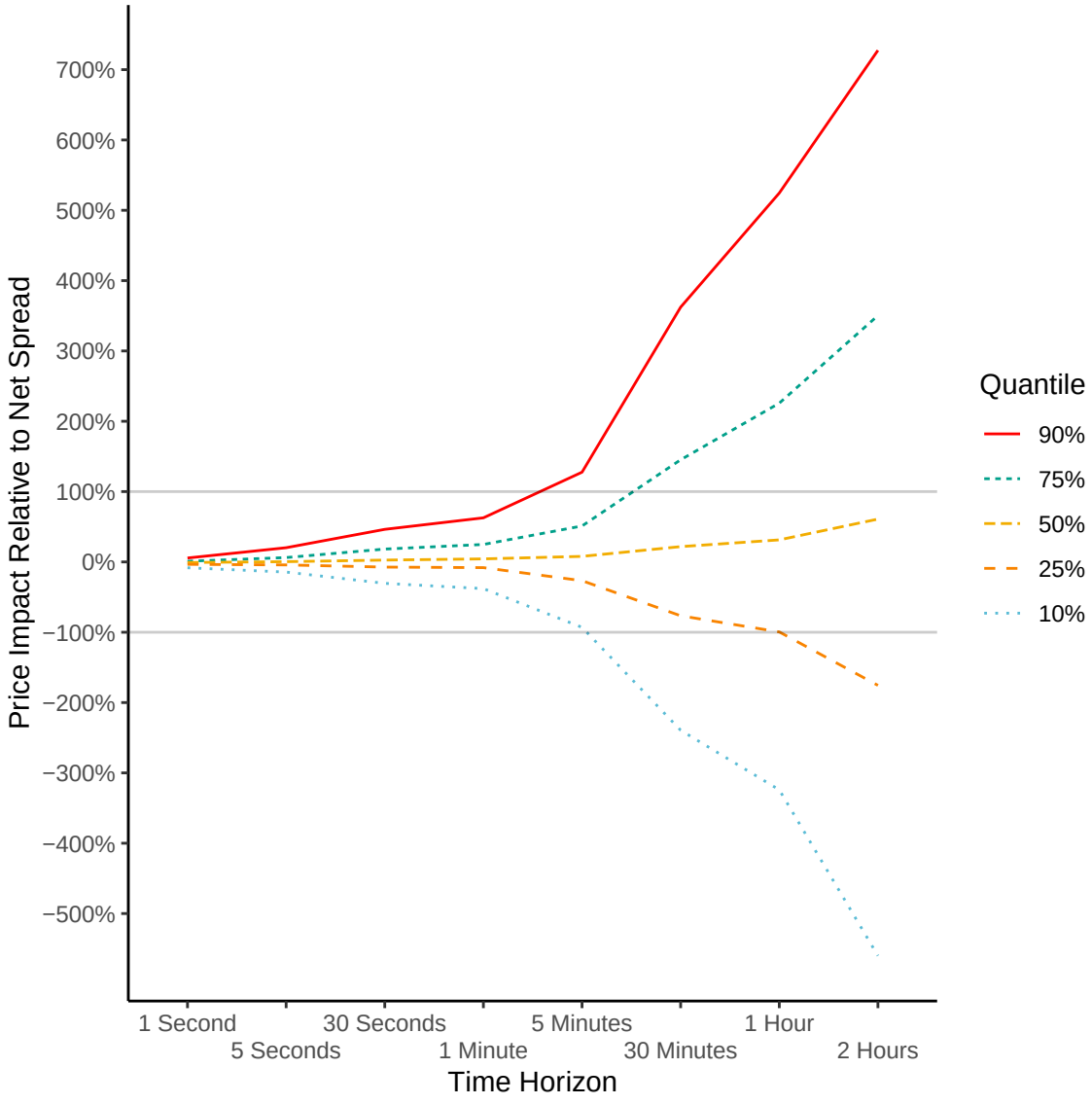


Figure 8. : Wholesaler Net Realized Spreads. We calculate total net realized spread as the daily realized spreads, summed across all trades from all wholesalers, minus the total transaction payments paid. We calculate the quantiles of total net realized spreads across days, and plot these quantiles across seven possible time horizons for calculating realized spreads.



VI. Marginal Exchange Fees

Cryptocurrencies are not centrally cleared, which presents a challenge in transaction cost analysis. U.S. equities and options are centrally cleared: whether the stock trades at exchange A or exchange B, it is backed by the same clearing mechanism and represents the exact same asset. In contrast, a crypto trade at exchange A represents a liability backed by exchange A, while a crypto trade at exchange B represents a liability backed by exchange B. Neither asset is exactly fungible, and costs to move cryptocurrencies either to a self-owned wallet or between exchanges can be considerable. Perceptions of exchange quality are difficult to observe, and the combination of exchange fee tiers and transfer fees means there is no straightforward calculation of a fee-adjusted NBBO.

In our analysis of the value of a broker, we considered two alternatives to an NBBO: a randomly chosen exchange and an exchange with the second-best fee-adjusted quote (based solely on bottom-tier take fees). Both measures offer some estimate of the fees a customer could expect from an average exchange, but in this section we seek to develop a deeper understanding of differences in fees, both explicit and implicit, across exchanges, including reasonable estimate of fees under the assumption of a marginal trader who is indifferent across exchanges.

We focus on U.S. or EU-based exchanges: Binance-US, Bitstamp, Coinbase, FTX-US, Gemini, Kraken, and Okex, and use full top-of-book data from each exchange obtained through Tardis data. For this analysis, we first construct an NBBO at one-second intervals. To define an NBBO price at date τ for coin c, we look at the most recent top-of-book price at each exchange. That is, the largest $t < \tau$, where $P_{e,c,t}$ as a price quote for exchange e for coin c at time t. Fees at exchanges mean the effective bid is $P_{e,c,t}(1 - f_{e,c,t})$ and the effective ask is $P_{e,c,t}(1 - f_{e,c,t})$ where $f_{e,c,t}$ is the exchange fee. For each date τ, we can rank

the effective prices across exchanges for both the bid and ask.

An immediate challenge in calculating an analogous NBBO for cryptocurrency is the complexity of exchange fee structures. Table VII provides an example of information about advertised fees at several U.S.-based exchanges. The fees are proportional to the trade value. However, the fee rate depends on the an individual's monthly trading volume (tiers are not unlike frequent-flyer statuses). At some points, for some popular coins, like BTC, at small volume tiers the fee is zero perhaps reflecting cross-subsidization or customer acquisition motives. As a start, we use the fee ("taker fee") in the lowest (typically, most expensive) tier. As an example, Figure 9 plots the fee-adjusted prices for a 90-minute window on 2022.03.30. During this period, the best fee-adjusted prices (NBBO) were from either Binance-US or Okex (Panel A). However, the ranking of all the other exchanges is determined completely by the fee assumptions (Panel B). With this fee assumption, this is true more generally. For much of our sample there is very little variation in which exchange is has the best fee-adjusted exchange. Figure 10 plots the frequency in a given day that an exchange ranks at the top of the book (with calculations for each second and combining the bid and ask sides, there are 172,800 observations per day). Except for the brief window (including day 2022.03.30) where Binance-US and Okex happened to have the same stated fee, only one exchange provided the best fee-adjusted price. The points on the plot where the dominating exchange flips are all where stated fees change. Finally, using this stated fee, the exchanges Coinbase, FTX-US, Gemini, and Kraken never offer the best bid or ask.

Table VII. Exchange Fees:. Comparison of Cryptocurrency Exchange Fees Across Two Dates

	Tiers	Earlier Date (e.g., Jan 2023)		Recent Date (e.g., Jan 2024)	
Exchange		**Low Tier**	**High Tier**	**Low Tier**	**High Tier**
Binance	10	0.10% / 0.10%	0.02% / 0.04%	0.08% / 0.10%	0.02% / 0.03%
Coinbase	5	0.50% / 0.60%	0.10% / 0.20%	0.40% / 0.60%	0.05% / 0.15%
Kraken	6	0.16% / 0.26%	0.00% / 0.10%	0.16% / 0.26%	0.00% / 0.10%
Gemini	4	0.25% / 0.35%	0.04% / 0.15%	0.20% / 0.40%	0.03% / 0.15%

This table samples detailed fee information collected from exchange websites (and past versions of websites from the Internet Archive). The fee tiers are based on customer trading volume at the exchange in the prior month. A trade order gets the maker fee if the trade order is not matched immediately against an order already on the order book. A trade order gets the taker fee if the trade order is matched immediately against an order already on the order book.

The focus on the posted fee in the lowest tier is arbitrary and we could explore other tiers. However, this approach does not yield an interesting NBBO-like analysis since results are so dominated by the fee and unrelated to the price quotes in the order book. A more interesting question, perhaps, is to infer the cost of the marginal trader across these exchanges. The motivating assumption is that since we observe volume at all exchanges, a marginal trader should be, on average, indifferent to trading venue. Here we will calculate an inferred fee on each exchange. This will capture the paid fees net of other benefits of the exchange (i.e., the default risk, regulatory risk, or other such costs and benefits differ across exchanges). For each day of our sample, we estimate a fee at each exchange, $\bar{f}_{e,c,d}$ so that each has an equal frequency of being top-of-book (across ask and bids).[4] Specifically, given N exchanges and

[4]The equal frequency is across exchanges that are active on that day. Of the exchanges, Bitstamp and FTX-US are not active for the whole sample.

a given coin, c, and day, d, we calculate

$$\min_{\{\bar{f}_{e,c,day}\}_{e=1}^{N}} \lambda_1 ||(x_1, ..., x_N) - (1/N, ..., 1/N)|| + \lambda_2 ||(\bar{f}_{1,c,day}, ..., \bar{f}_{N,c,day}) - (\bar{f}, ..., \bar{f})||$$

Where x_n is the frequency that exchange n is ranked as the best bid or ask given the quoted prices in the data applying the hypothetical fees, $\bar{f}_{e,c,day}$, for the N exchanges. Since we measure the quoted prices at each second, the frequency is over 172,800 bid and ask events per day. Since we focus on the relative ranking of quoted prices, the level of the fee is not identified, we regularize the fee to the arbitrary level of $\bar{f} = 0.4\%$ (which is roughly consistent with the fees we see in Table VII). In the implementation we set $\lambda_1 = 1$ and $\lambda_2 = 0.01$. With these objective weights, the frequencies at the numerically optimized implied fees is very close to the $1/N$ target.[5]

The results are plotted in Figure 11 for Bitcoin (BTC-USDT). This figure shows the implied fee calculated for each exchange for each day. The fees are all very close together; there is not the wide dispersion in fees we see in the exchanges' stated fees. Recall that the level of this analysis is determined by the estimate to be at the 0.4% level. The fees inferred for each exchange are consistent across days. For example, the inferred fee at Okex is higher than for Binance-US. That means that the quotes on Okex (before fees) are slightly better than those on Binance-US, so for both exchanges to have an equal frequency at being the best quote, the implied fee at Okex is higher than at Binance-US. Whether this reflects higher charged fees or some other differences in the exchanges (credit risk, compliance risk, etc.) is a good question.

Bitstamp in Figure 11 is interesting. The implied fee is initially low and then increases around June to November 2022 (roughly the period from the collapse of Terra-Luna to the

[5]We used the Nelder-Mead `optim` optimizer in `R` with the L2 norm as the distance measures.

bankruptcy of FTX). Figure 12 repeats the same implied fees but highlights two exchanges. Panel A highlights FTX-US. Prior to the collapse and bankruptcy the implied fee is more variable than the other exchanges. However, heading into the November 11, 2022 collapse and bankruptcy there is nothing particularly noteworthy. On the last day of trading the implied fee is very high. This reflects the high volume of trade as traders tried to close out positions and exit the exchange (withdrawals in Bitcoin were common). Panel B highlights Gemini. Note the unusually low implied fees on 2023-11-22. This date coincides with a large lawsuit between Genesis and Gemini over fallout from the FTX collapse.[6]

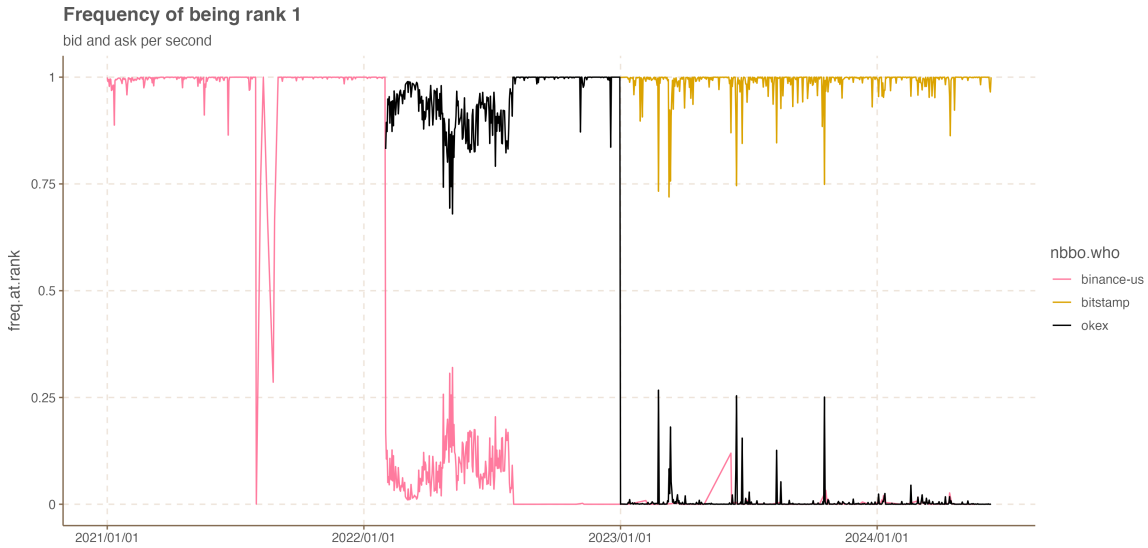
[6]See Amitoj Singh, edited by Omkar Godbole and Sandali Handagama, *Genesis Sues Gemini to Recover 'Preferential Transfers' Worth $689M*, CoinDesk, updated Mar. 8, 2024, published Nov. 22, 2023. `https://www.coindesk.com/policy/2023/11/22/genesis-sues-gemini-to-recover-preferential-transfers-worth-689m`.

Figure 9. Top-of-Book Effective Prices. The quoted price adjusted for the stated taker fee in the lowest volume tier. For 2022.03.30 11:00 to 12:30

Panel A: Binance-US and Okex

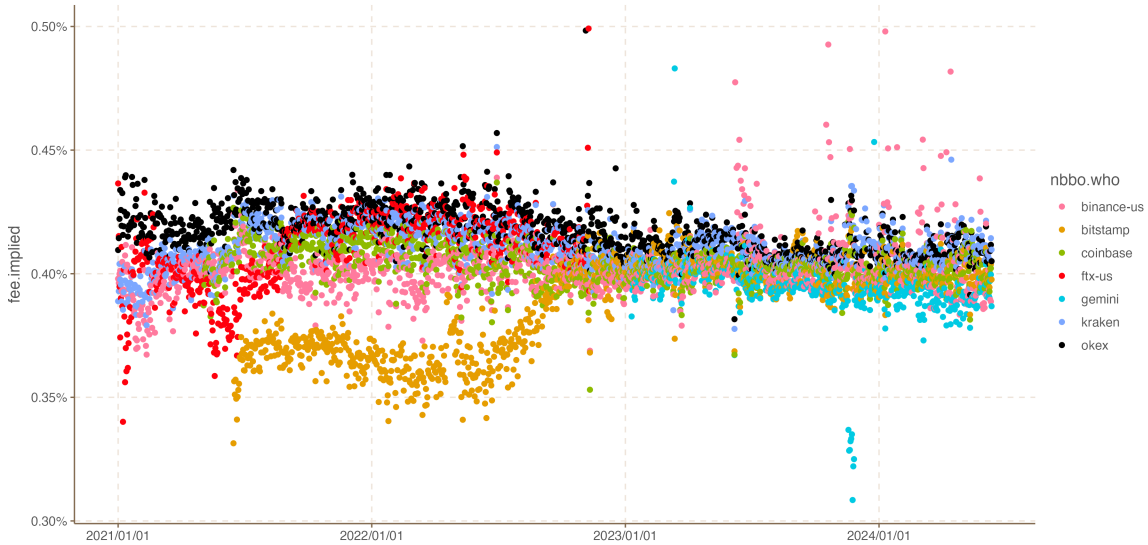
Panel B: All Exchanges

Figure 10. Frequency of Exchange as Best Price.



Using the quoted price adjusted for the stated taker fee in the lowest volume tier, the frequency in the day that an exchange is best quote (ask or bid). Shown are exchanges Binance-US, Bitstamp, Okex that constitute the bulk of the frequency. At stated fees, the exchanges Coinbase, FTX-US, Gemini, and Kraken are never the best bid or offer.

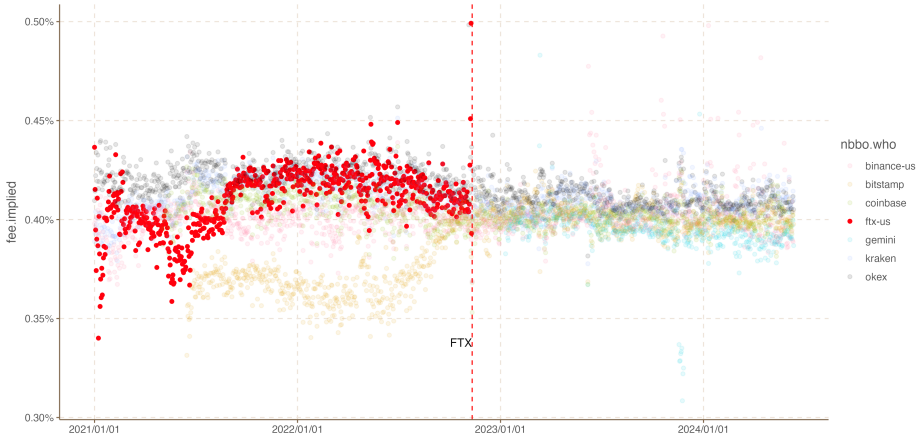
Figure 11. Implied Fees.



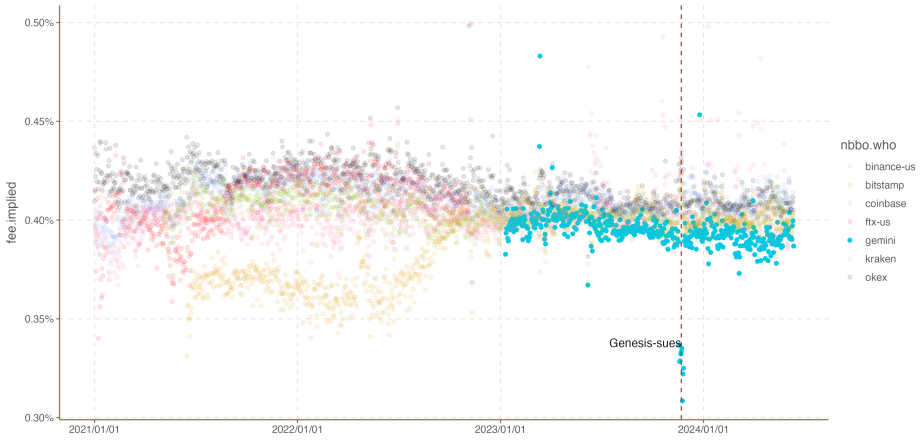
Fees are calculated per day and per exchange so that each day there is equal likelihood that each exchange is the best bid or ask.

Figure 12. Implied Fees.

Panel A: FTX-US



Panel B: Gemini



Fees are calculated per day and per exchange so that each day there is equal likelihood that each exchange is the best bid or ask.

VII. Conclusion

Cryptocurrencies have off-exchange trading just like U.S. equities, but it is considerably more opaque, as there is almost no reporting infrastructure for off-exchange trades. These trades primarily consist of retail trades, intermediated through a broker, with large market-making wholesalers. We analyze proprietary data on $550 billion in dark crypto trades placed with a large retail broker and, to our knowledge are the first to document trading in dark liquidity in cryptocurrencies.

Customers earn substantial savings through these broker-intermediated trades. Across all the major U.S. exchanges we study, over the total period of 2020-2024, customers obtain better average prices through the broker than they would through any individual exchange. Against a hypothetical NBBO, customers saved an average of $6,400 per day in 2023. Compared to a randomly selected exchange, customers saved $147 million from 2022-2023, and $75 million against whichever exchange has the second-best quote at the time of trade.

Our results highlight the benefits of a broker as an intermediary. Unlike exchanges, which seek to keep trading on their own platform regardless of better quotes at competitors, a broker has an incentive to source any liquidity, including off-exchange dark liquidity. The broker routes orders to wholesalers according to performance. Wholesalers compete for order flow, and price improvement accrues to retail customers in a similar manner to more regulated equity markets.

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