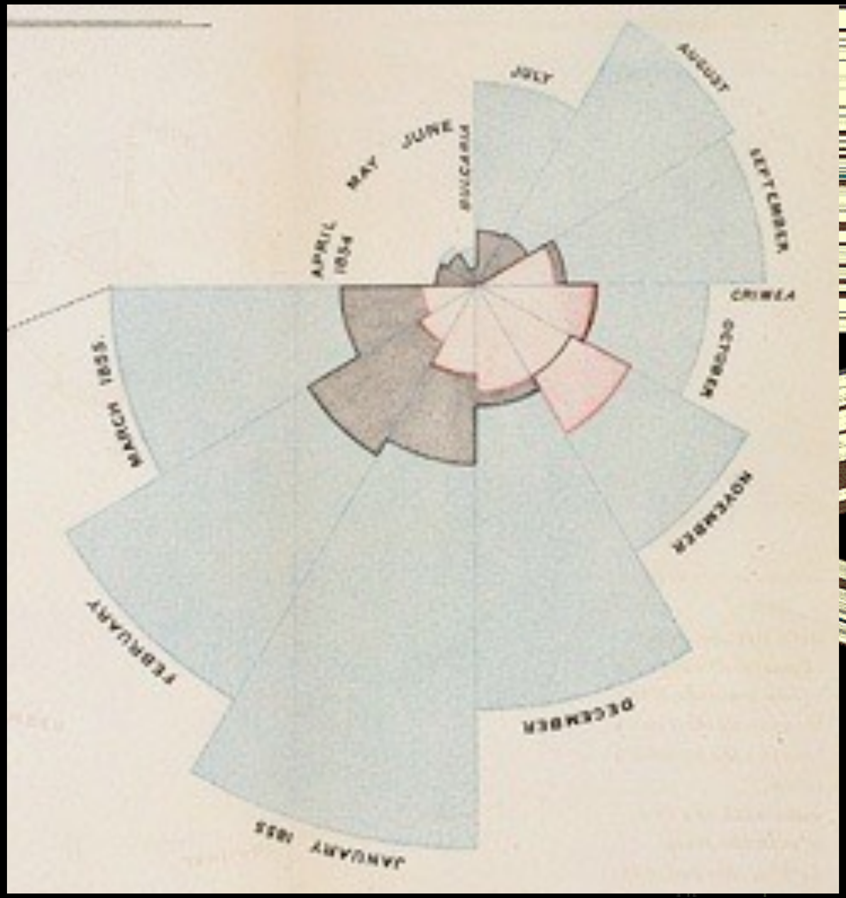
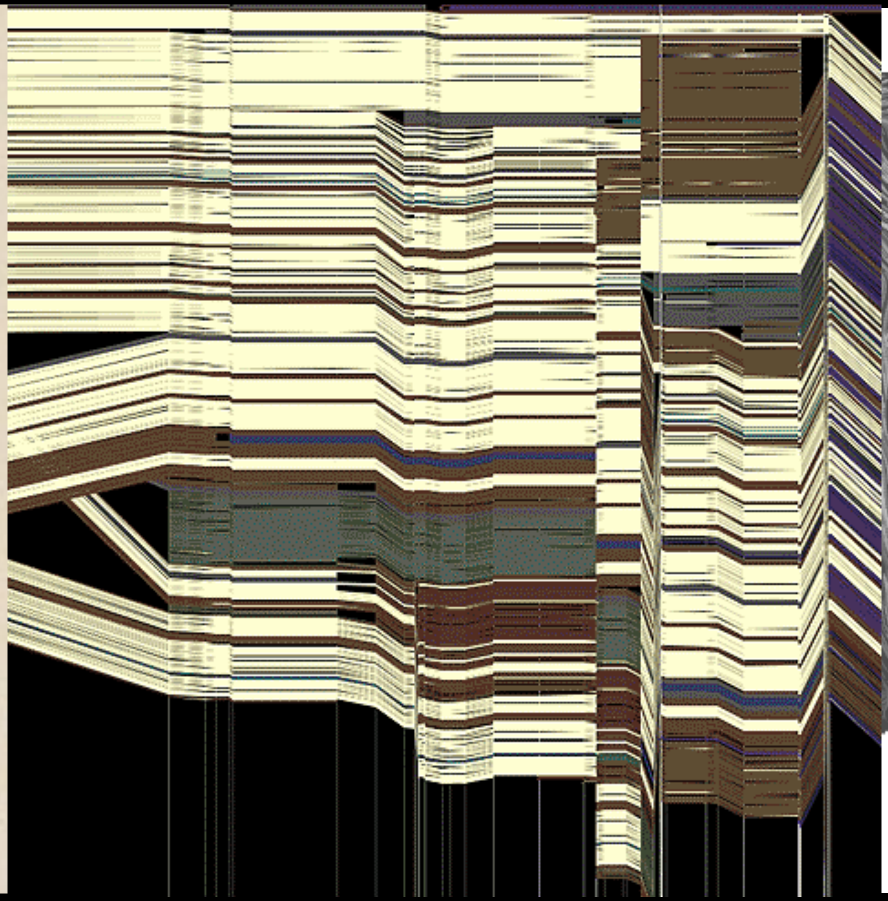
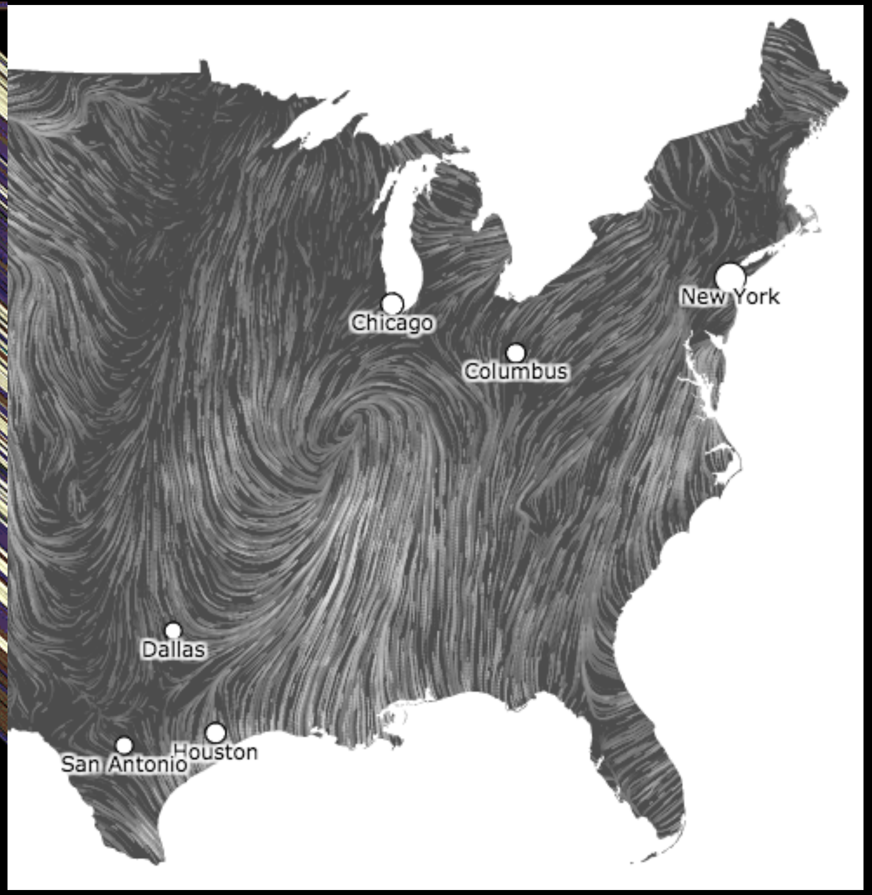
CSE 412 - Data Visualization

Scalable Visualization



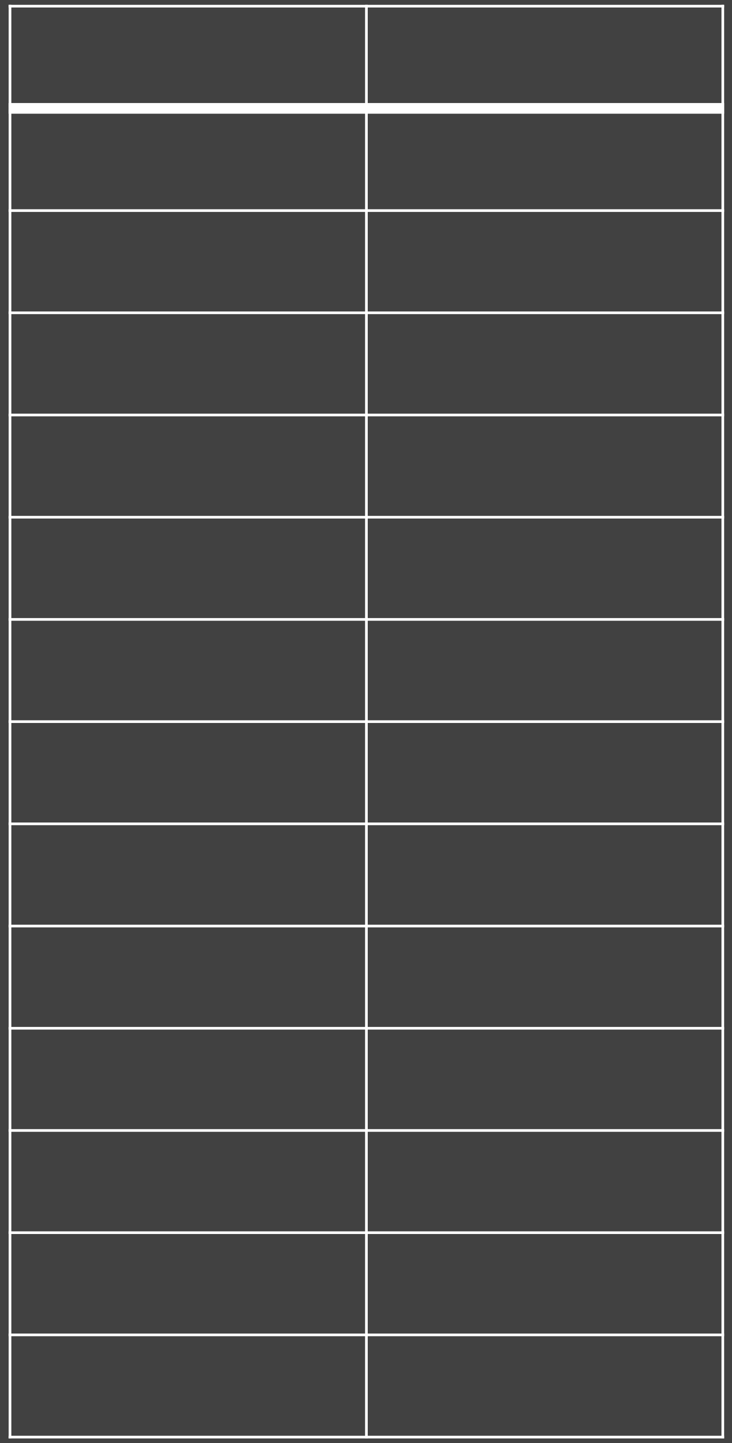




Jeffrey Heer University of Washington

Varieties of “big data”…

Tall Data



Lots of records

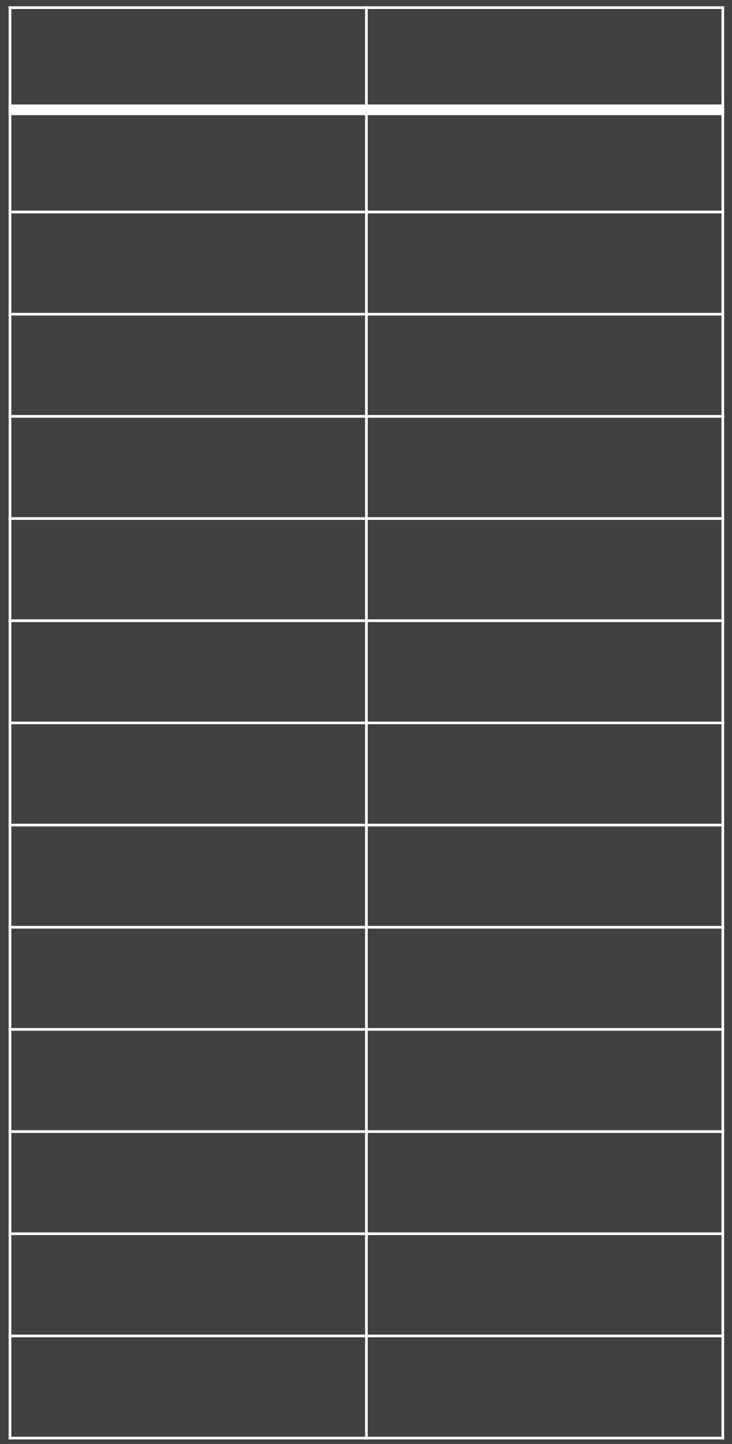
- Large DBs have petabytes or more
- *(but median DB still fits in RAM!)*

How to manage?

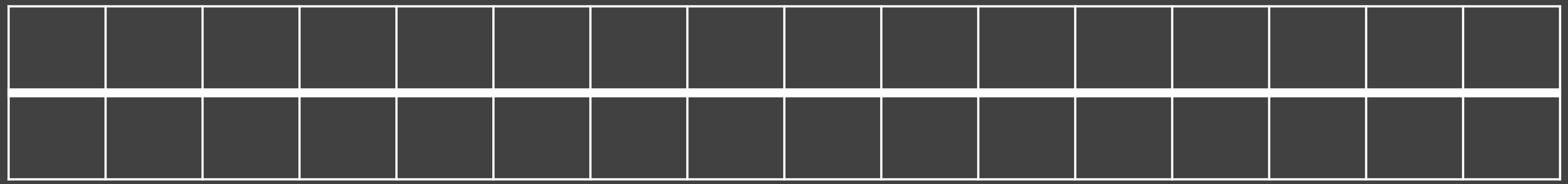
- Parallel data processing
- Reduction: Filter, aggregate
- Sample or approximate

Not just about systems. Consider perceptual / cognitive scalability.

Tall Data



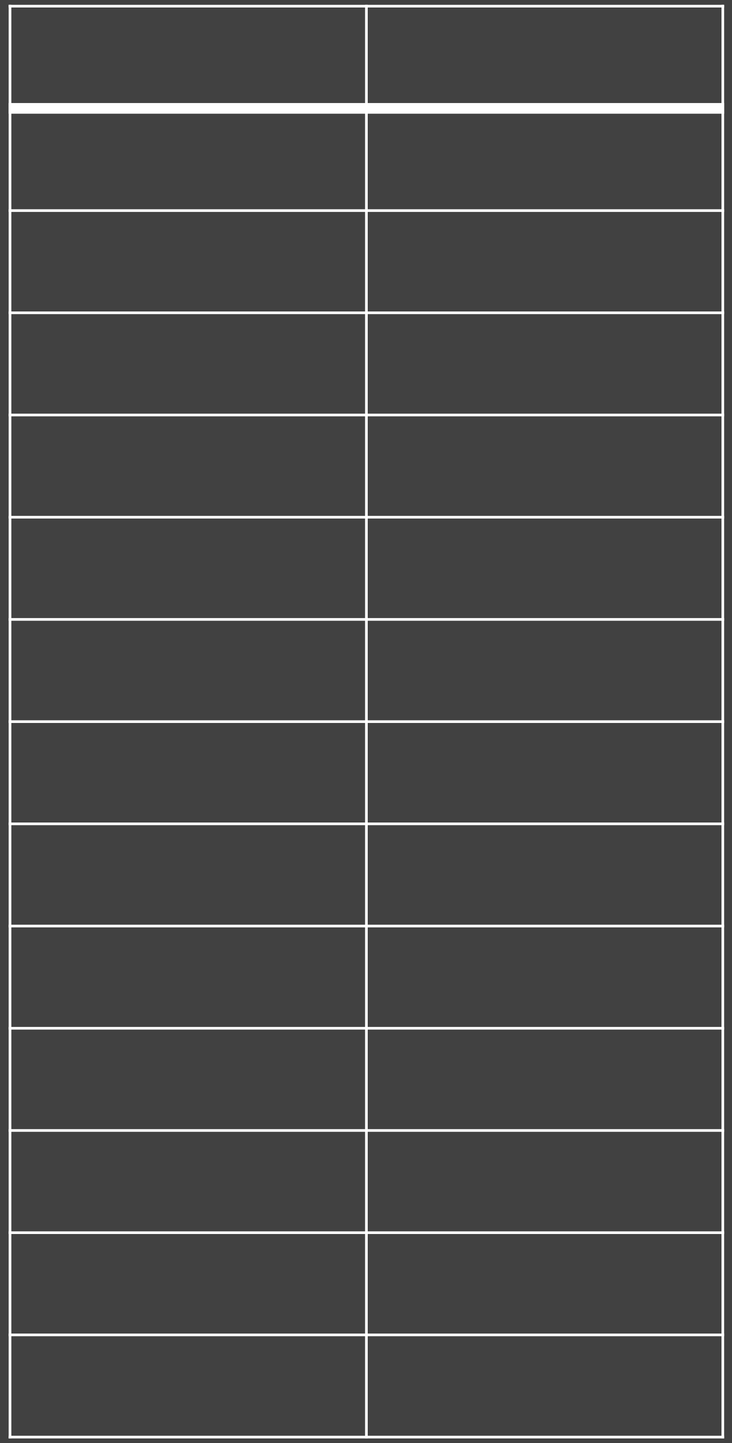
Wide data



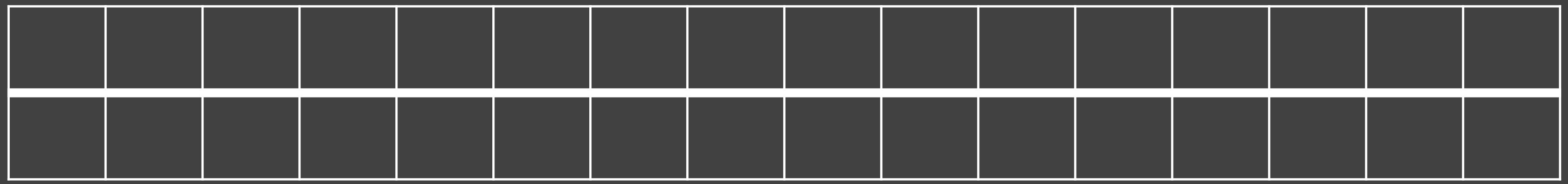
Lots of variables (100s-1000s…)
- Select relevant subset
- Dimensionality reduction
- Statistical methods can suggest and order related variables

Requires human judgment

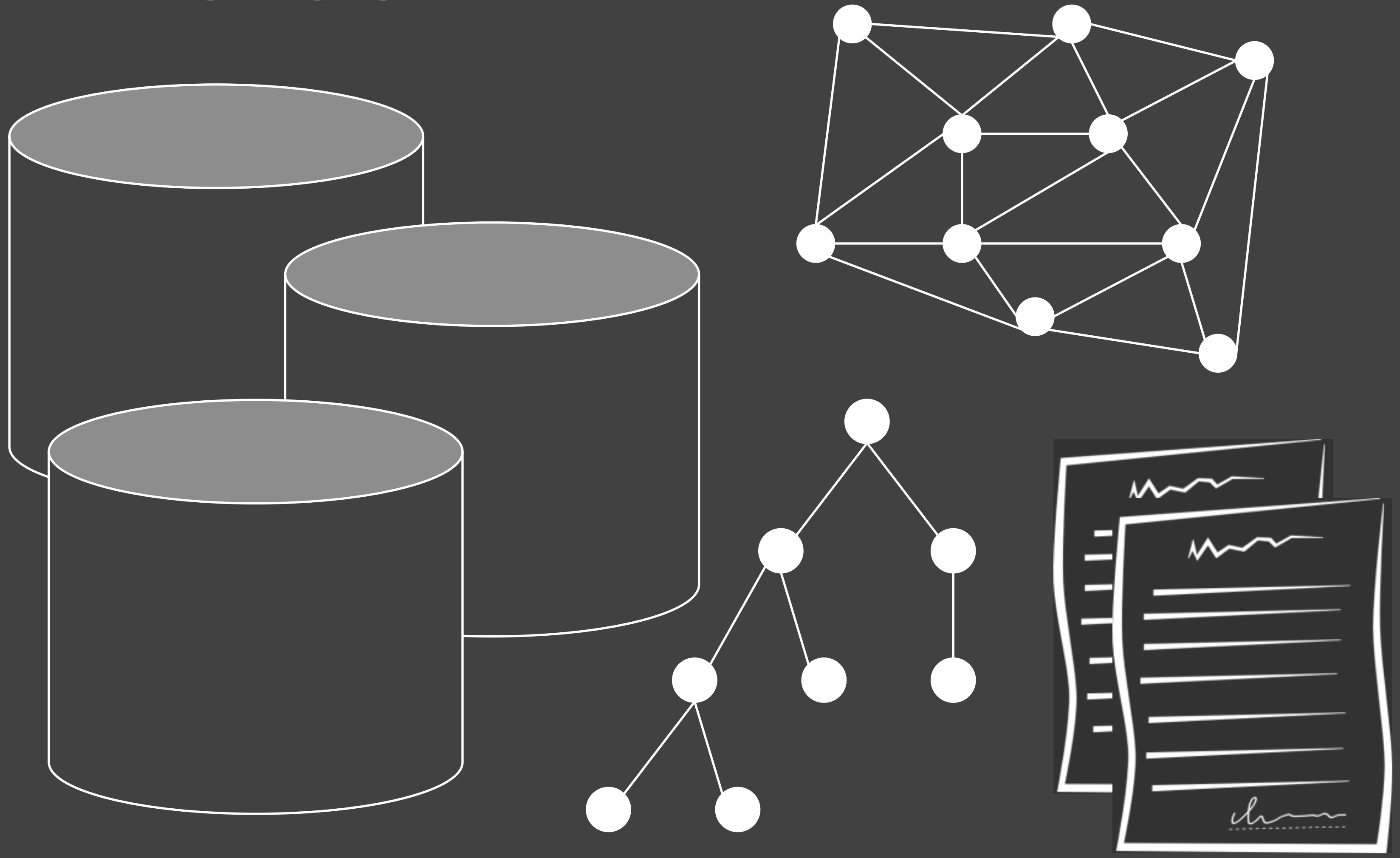
Tall Data



Wide data



Diverse data



Tall Data
Wide data
Diverse data

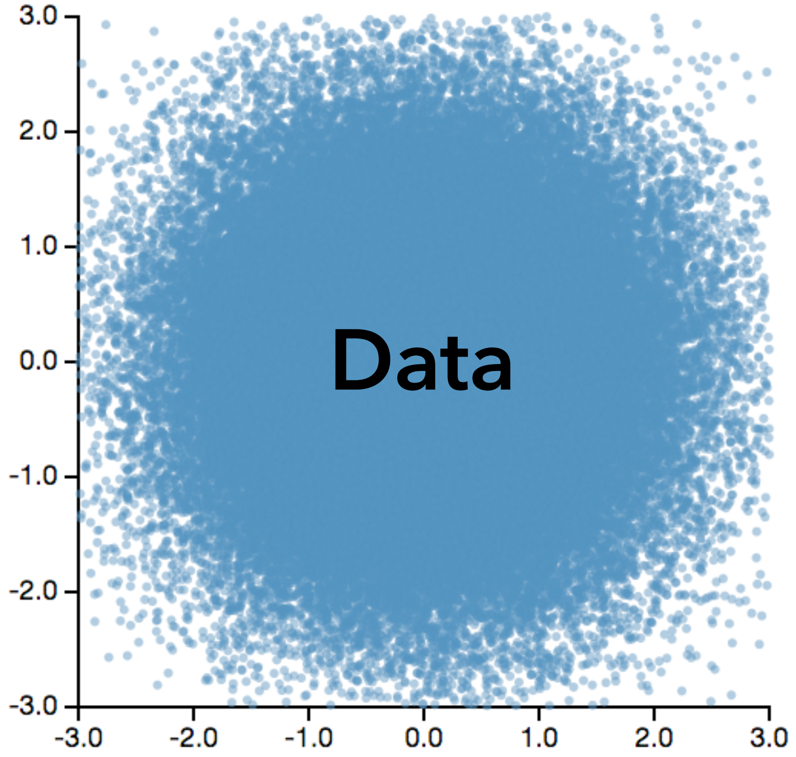
How can we visualize and interact with **billion+ record** databases in real-time?

Two Challenges:

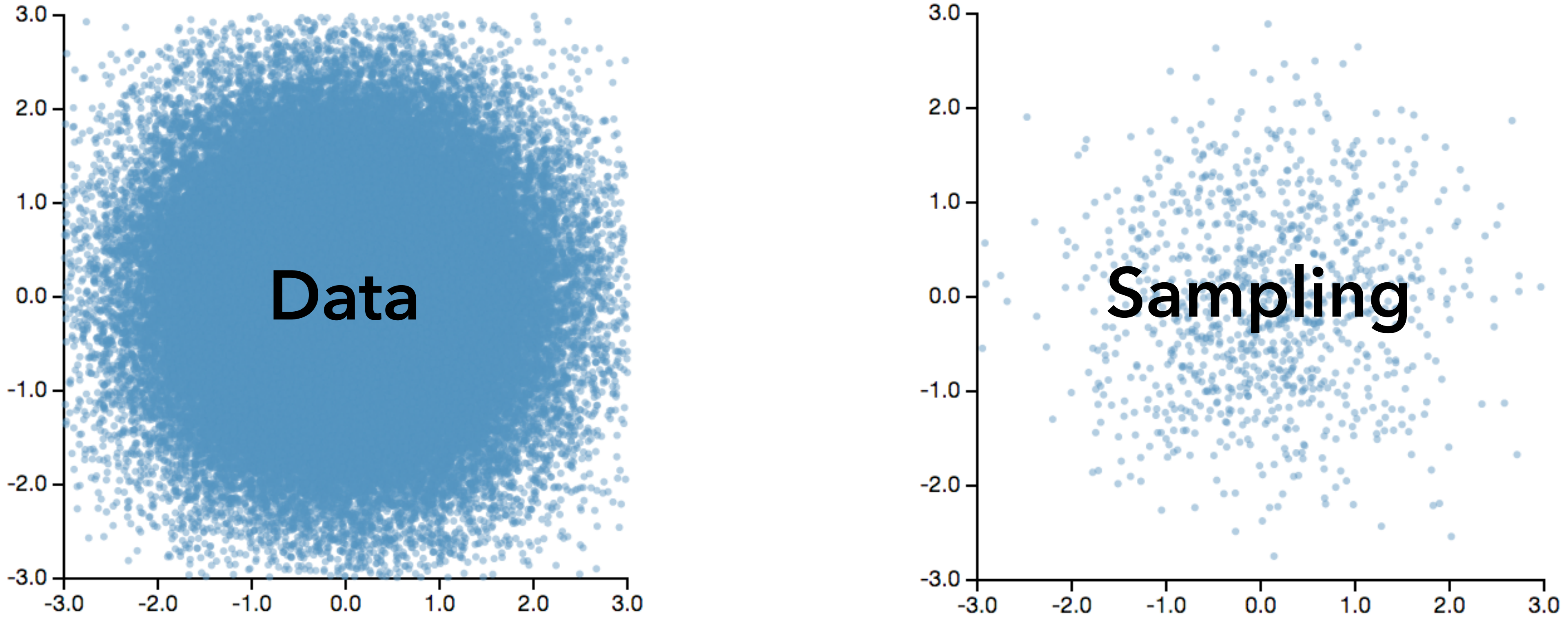
1. Effective **visual encoding**
2. Real-time **interaction**

Perceptual and interactive scalability should be limited by the **chosen resolution** of the visualized data, not the number of records.

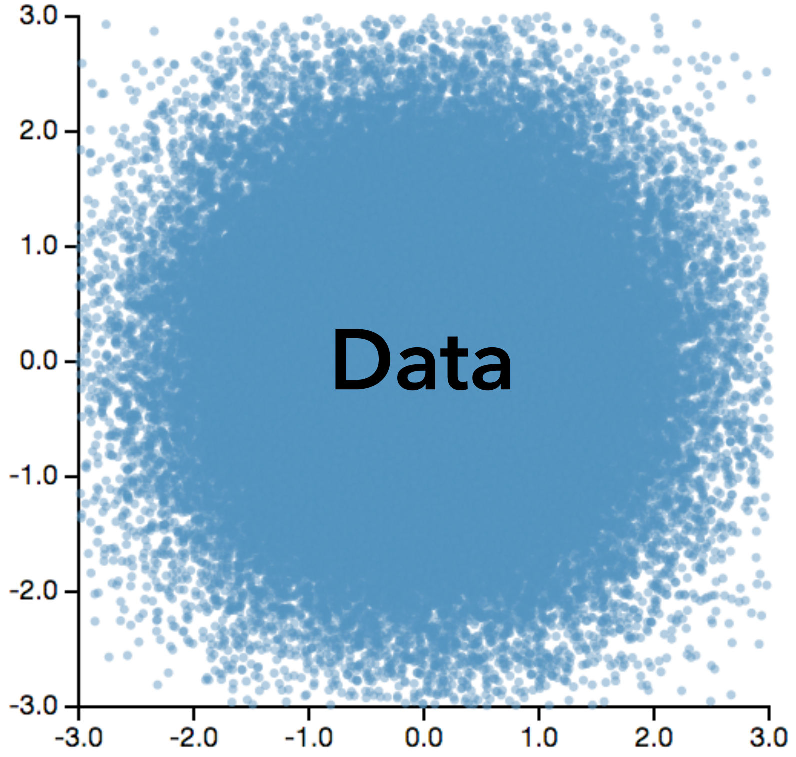
1. Visualizing Large Datasets



Data
3.0
2.0
1.0
0.0
-1.0
-2.0
-3.0
-3.0
-2.0
-1.0
0.0
1.0
2.0
3.0



Data
Sampling
3.0
2.0
1.0
0.0
-1.0
-2.0
-3.0
-3.0
-2.0
-1.0
0.0
1.0
2.0
3.0


3.0
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0.0
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Data
-3.0
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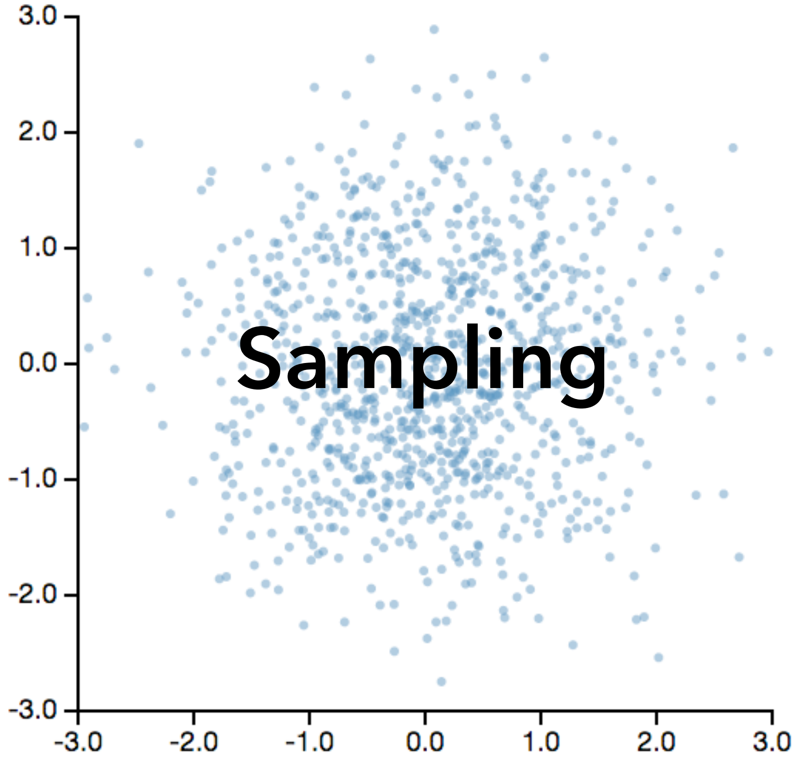
3.0
2.0
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Sampling
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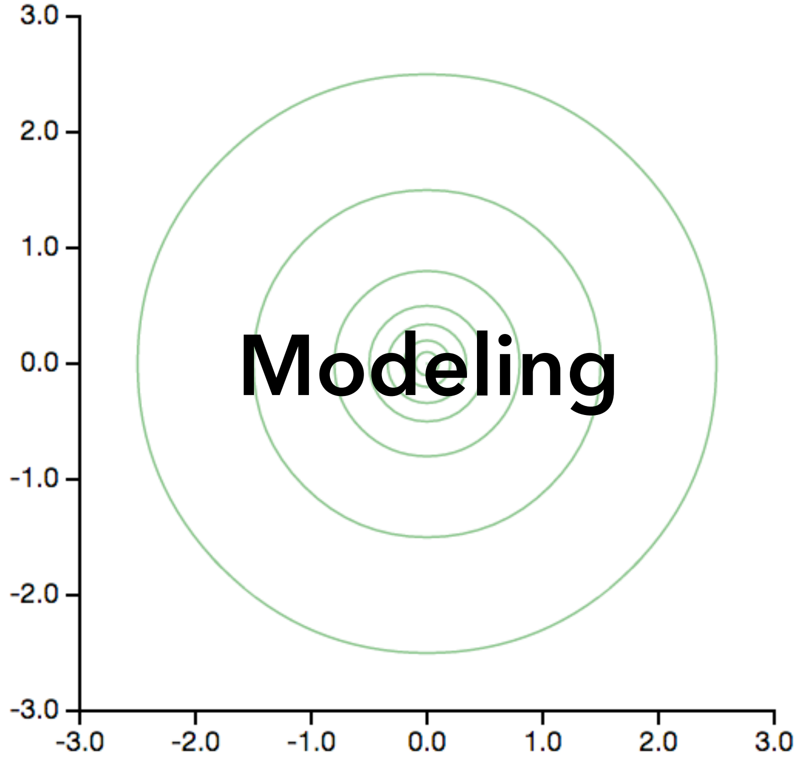
3.0
2.0
1.0
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-1.0
-2.0
-3.0
Modeling
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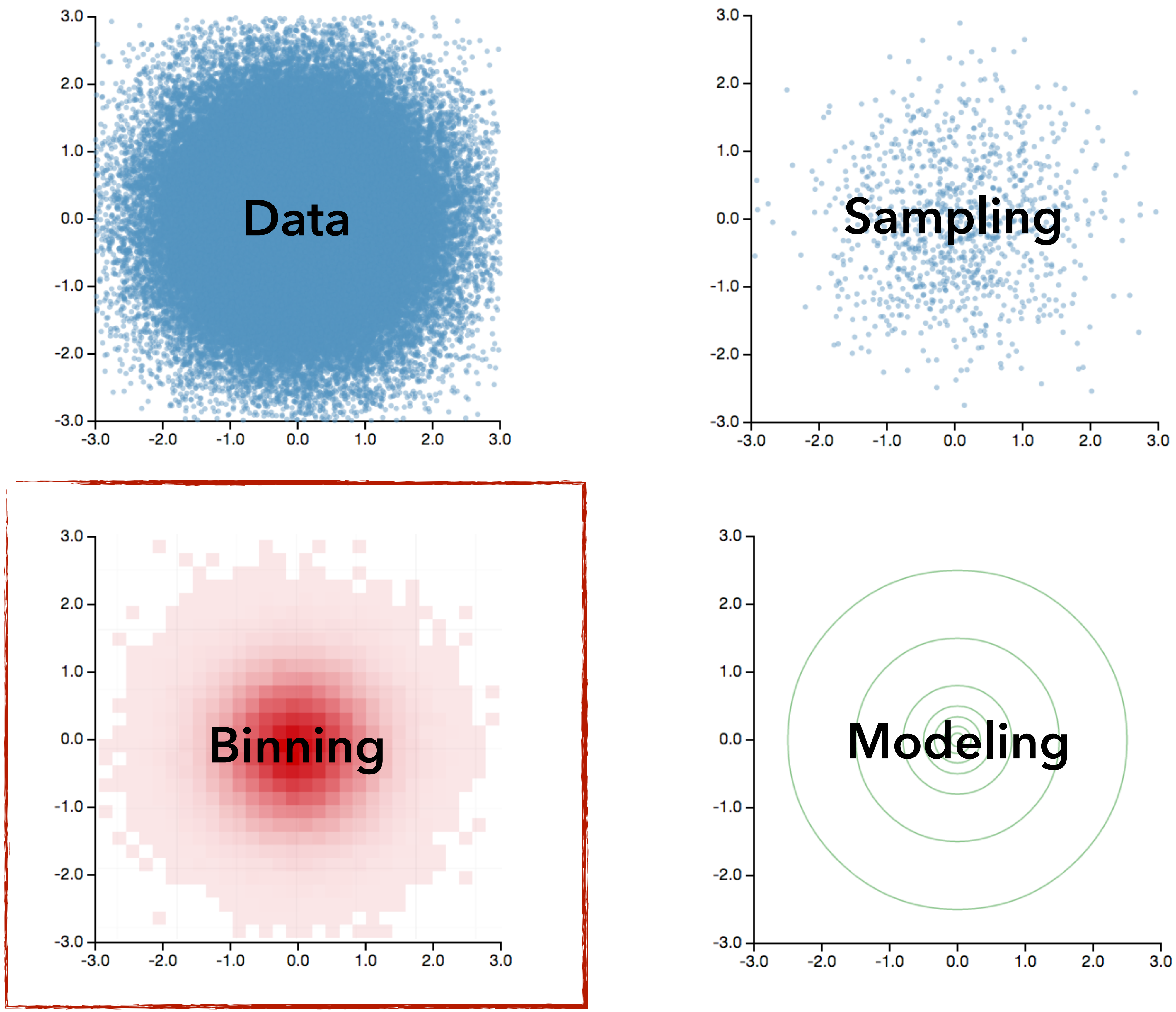
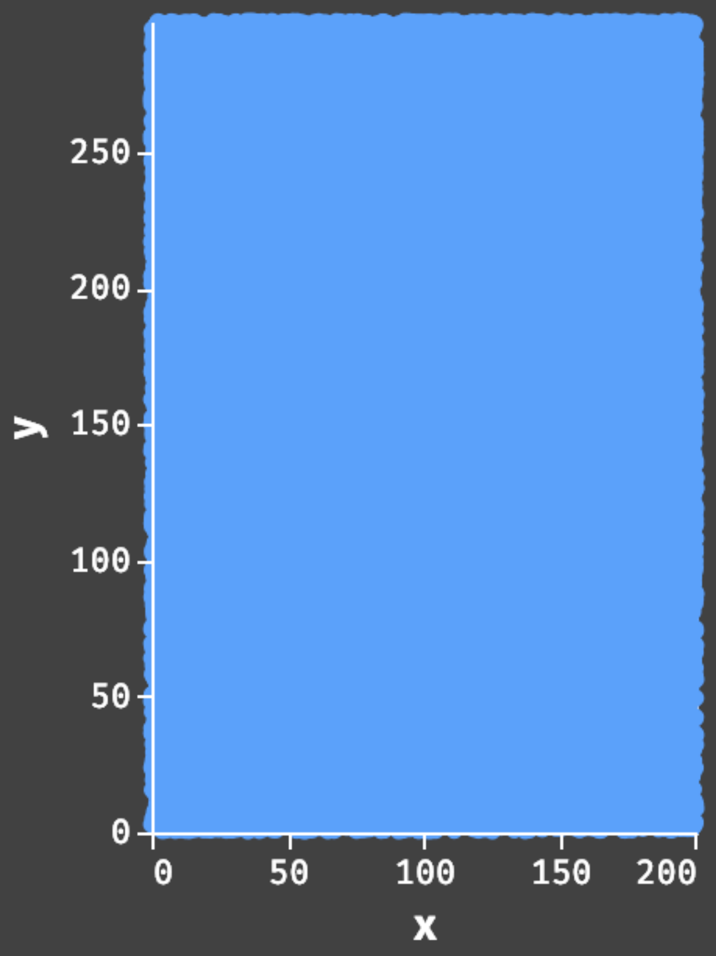
-2.0
-1.0
0.0
1.0
2.0
3.0

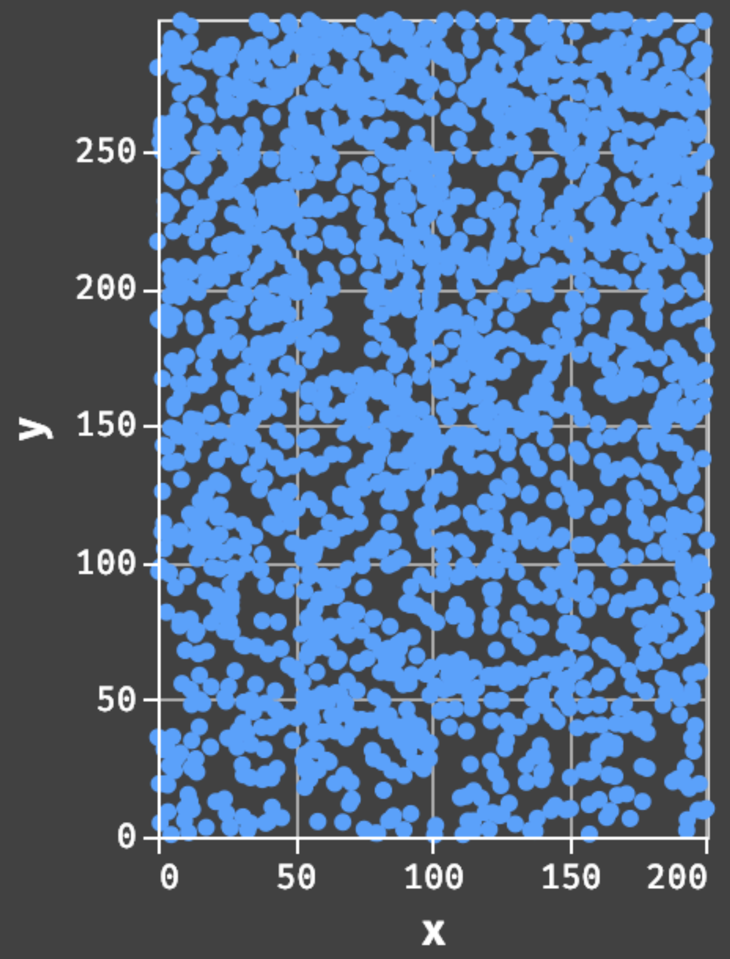


Data
Sampling
Binning
Modeling
3.0
2.0
1.0
0.0
-1.0
-2.0
-3.0
-3.0
-2.0
-1.0
0.0
1.0
2.0
3.0

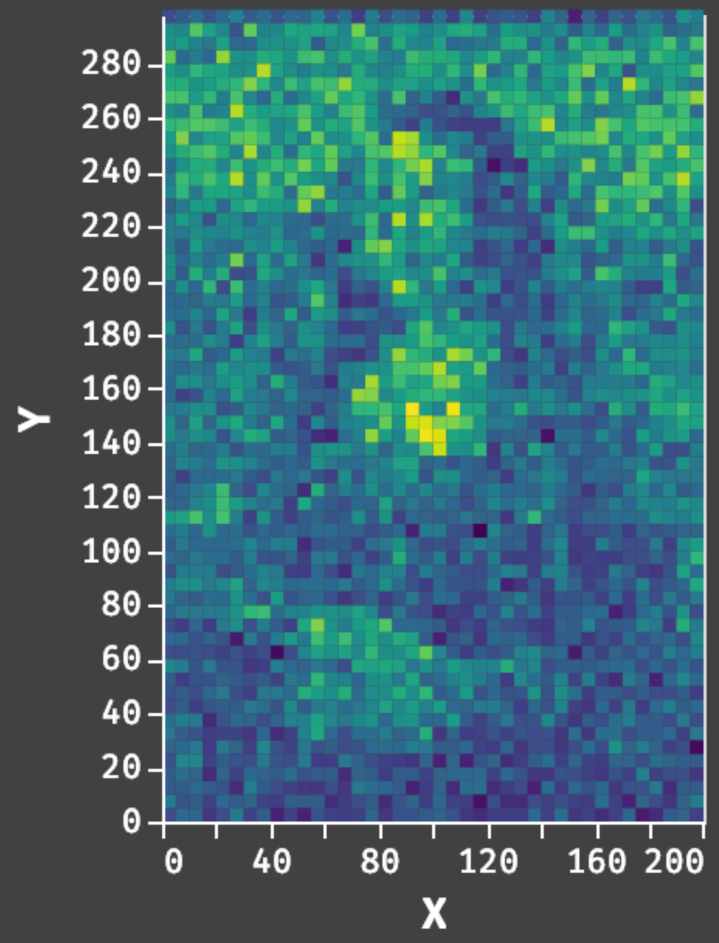
How to **Visualize** a Billion+ Records



Data



Sampling



Binned Aggregation

Decouple the visual complexity from the raw data through aggregation.

Bin > Aggregate (**> Smooth**) **> Plot**

1. Bin Divide data domain into discrete "buckets"

Categories: Already discrete (but watch out for high cardinality)

Numbers: Choose bin intervals (uniform, quantile, ...)

Time: Choose time unit: Hour, Day, Month, etc.

Geo: Bin x, y coordinates *after* cartographic projection

Bin > Aggregate (> Smooth) > Plot

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2. Aggregate Count, Sum, Average, Min, Max, ...

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3. Smooth Optional: smooth aggregates [Wickham ’13]

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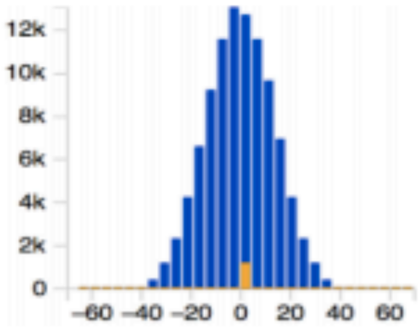
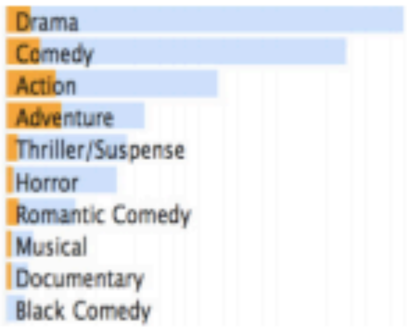
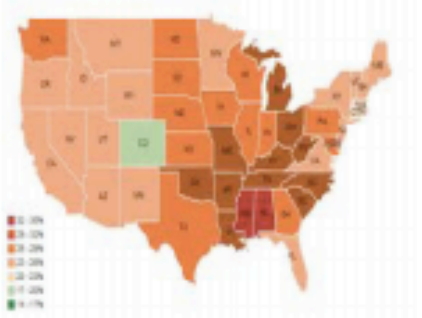
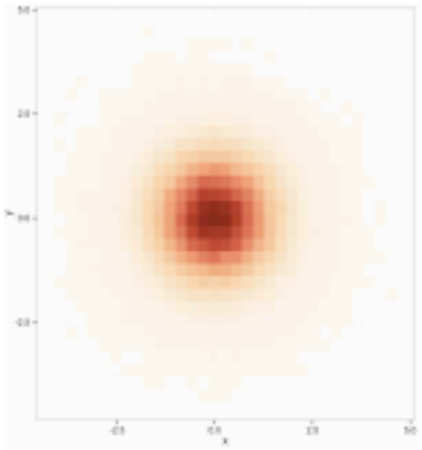
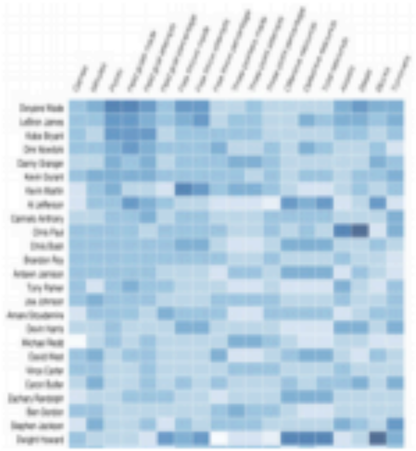
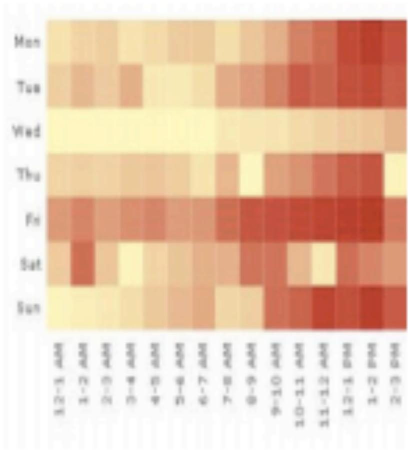
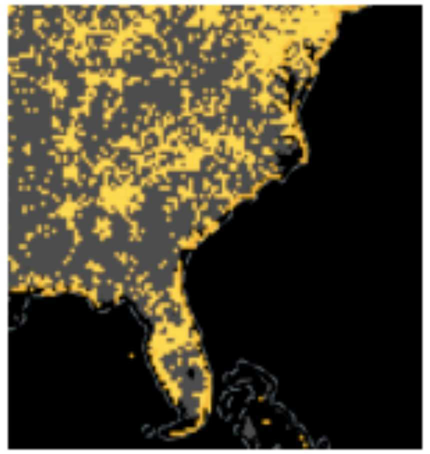
2. Aggregate Count, Sum, Average, Min, Max, ...

3. Smooth Optional: smooth aggregates [Wickham ’13]

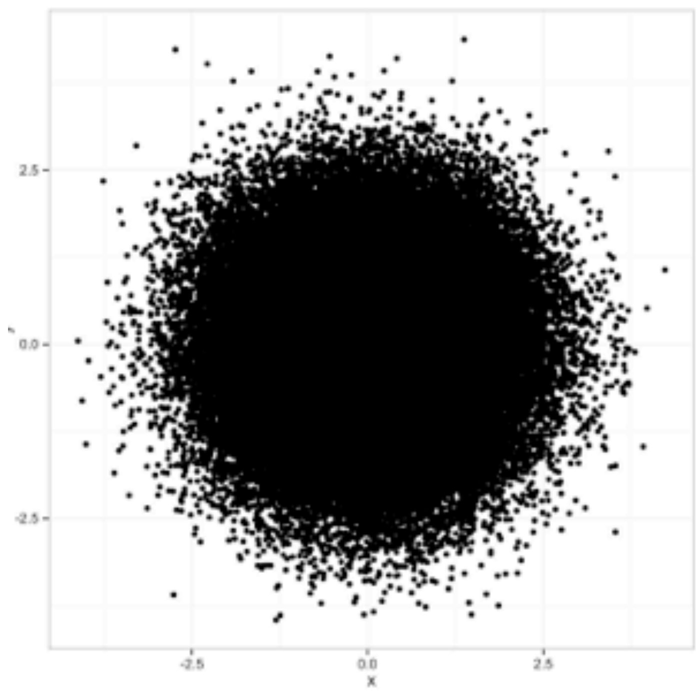
4. Plot Visualize the aggregate values

Binned Plots by Data Type

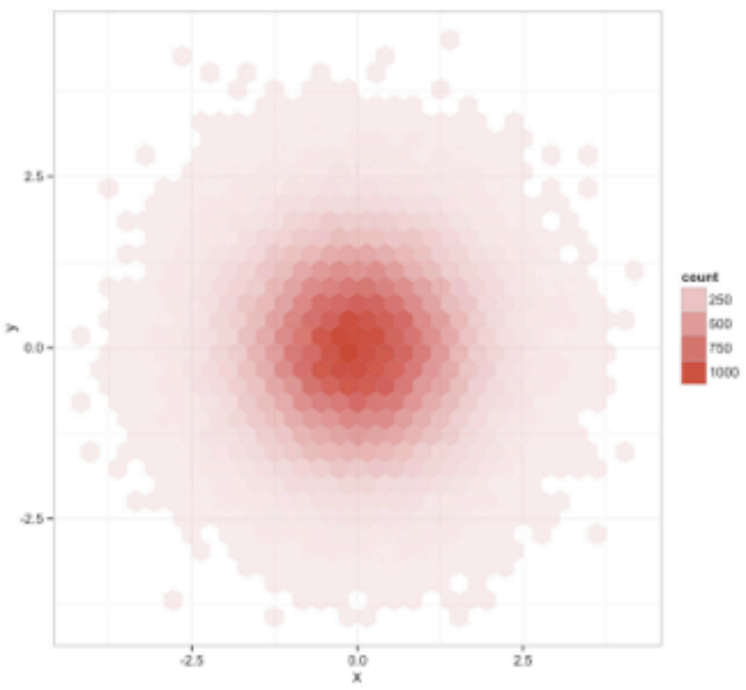
	Numeric	Ordinal	Temporal	Geographic
1D	 Histogram	 Bar Chart	 Line Graph / Area Chart	 Choropleth Map
2D	 Binned Scatter Plot	 Heatmap	 Temporal Heatmap	 Geographic Heatmap

Design Subtleties…

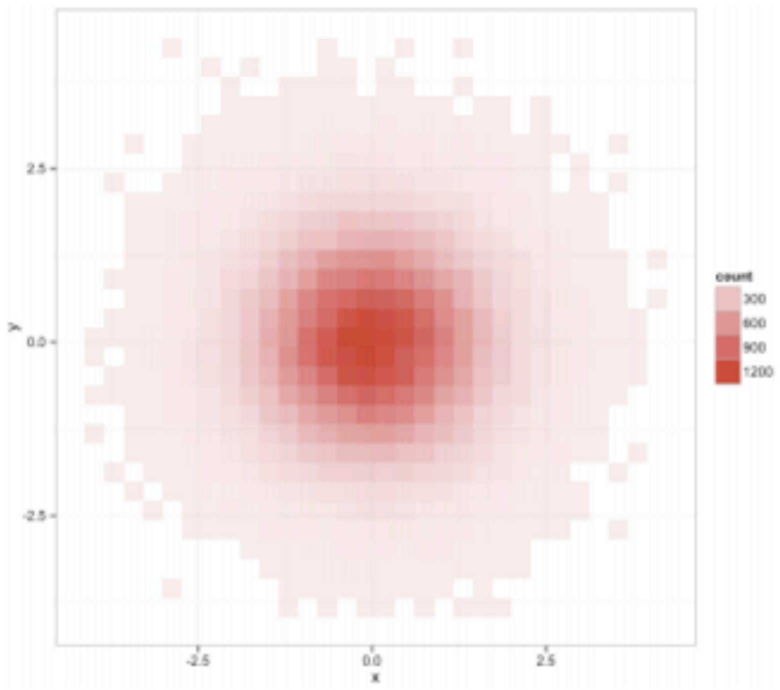
Hexagonal or Rectangular Bins?



100,000 Data Points



Hexagonal Bins

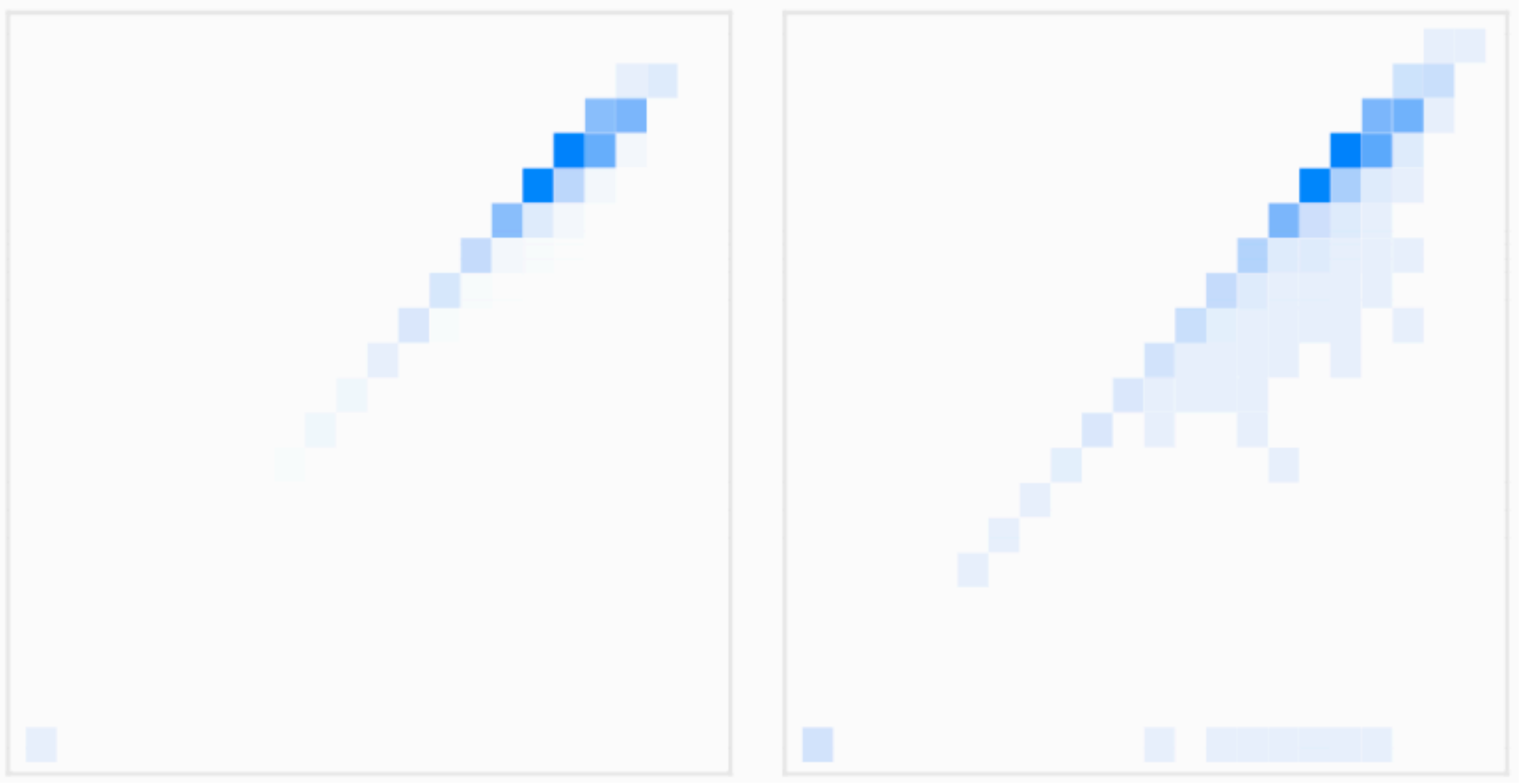


Rectangular Bins

Hex bins better estimate density for 2D plots, but the *improvement is marginal* [Scott 92].

Rectangles support *reuse* and *visual queries*.

Color Scale: Discontinuity after Zero

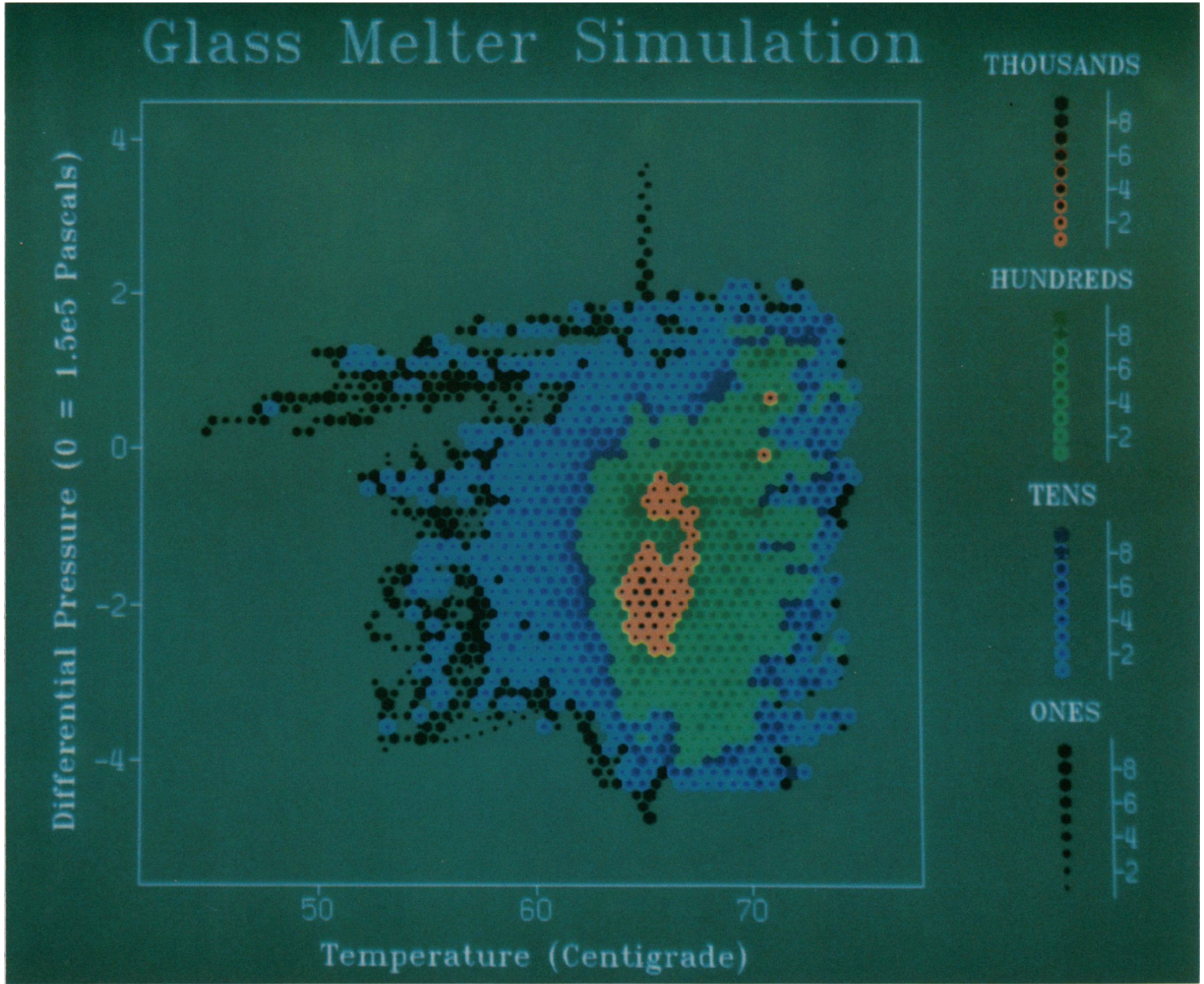


Standard Color Ramp
Counts near zero are white.

Add Discontinuity after Zero
Counts near zero remain visible.

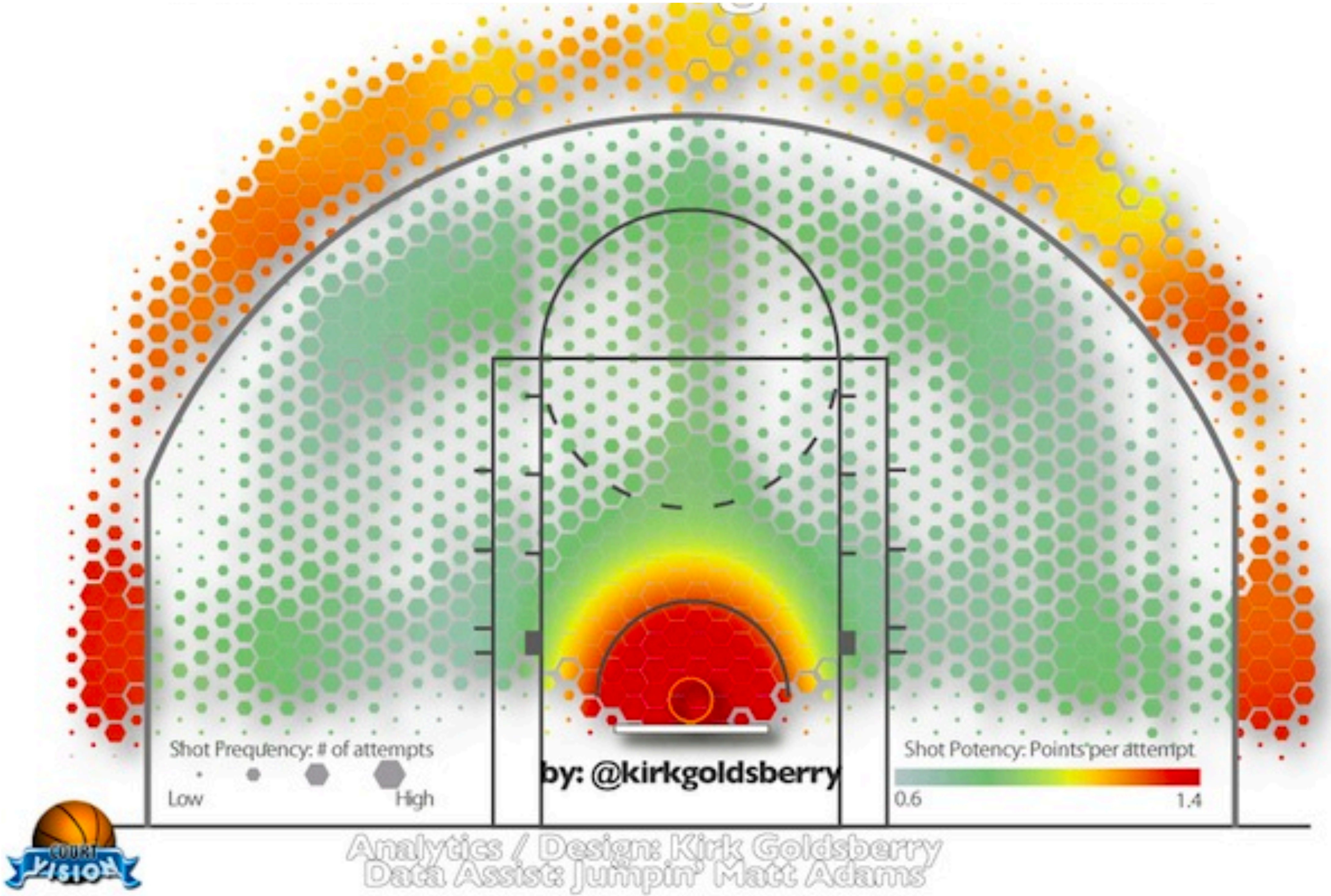
Examples

Example: Binned Scatter Plots



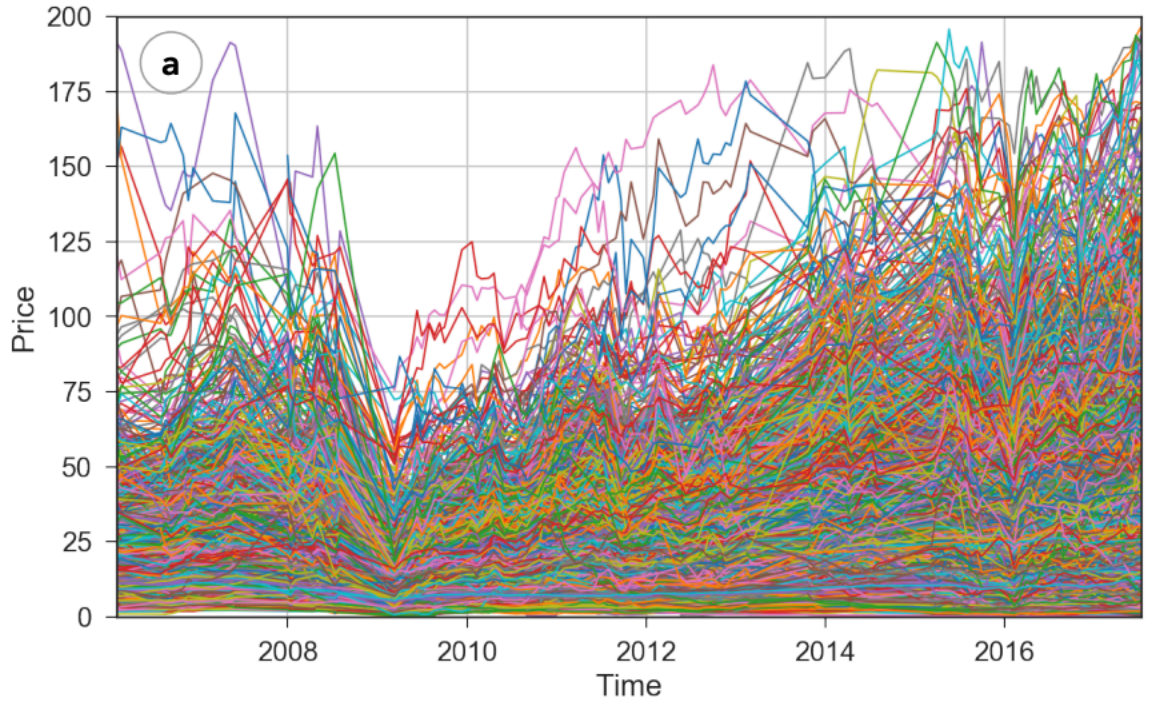
Scatterplot Matrix Techniques for Large N
[Carr et al. '87]

Example: Basketball Shot Chart

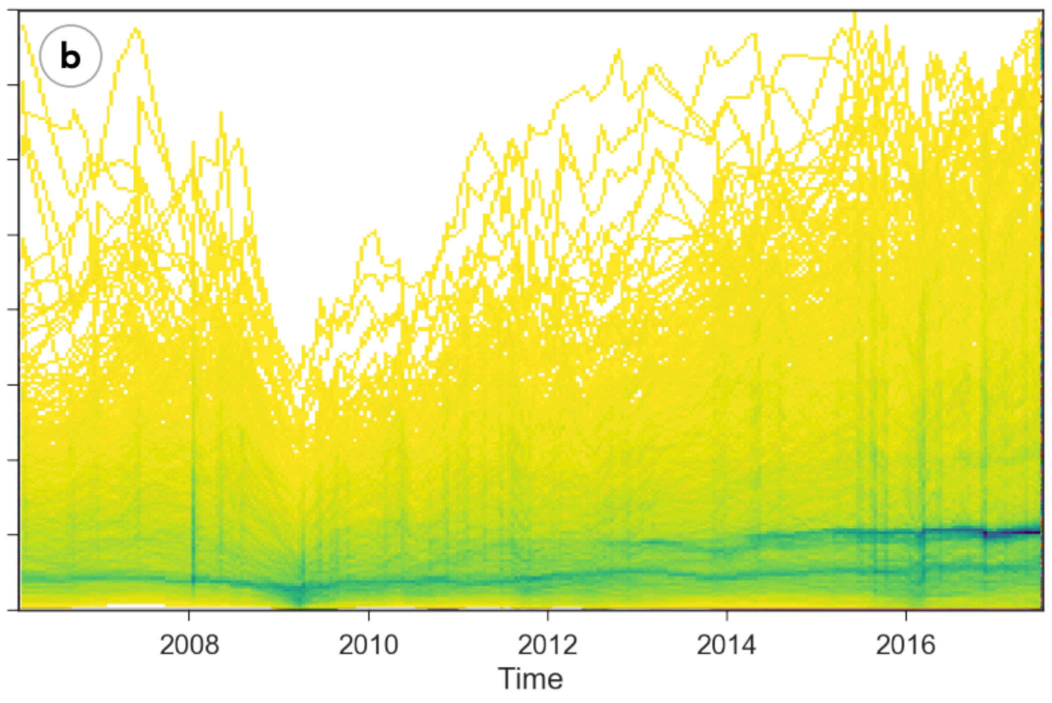


NBA Shooting 2011-12
[Goldsberry]

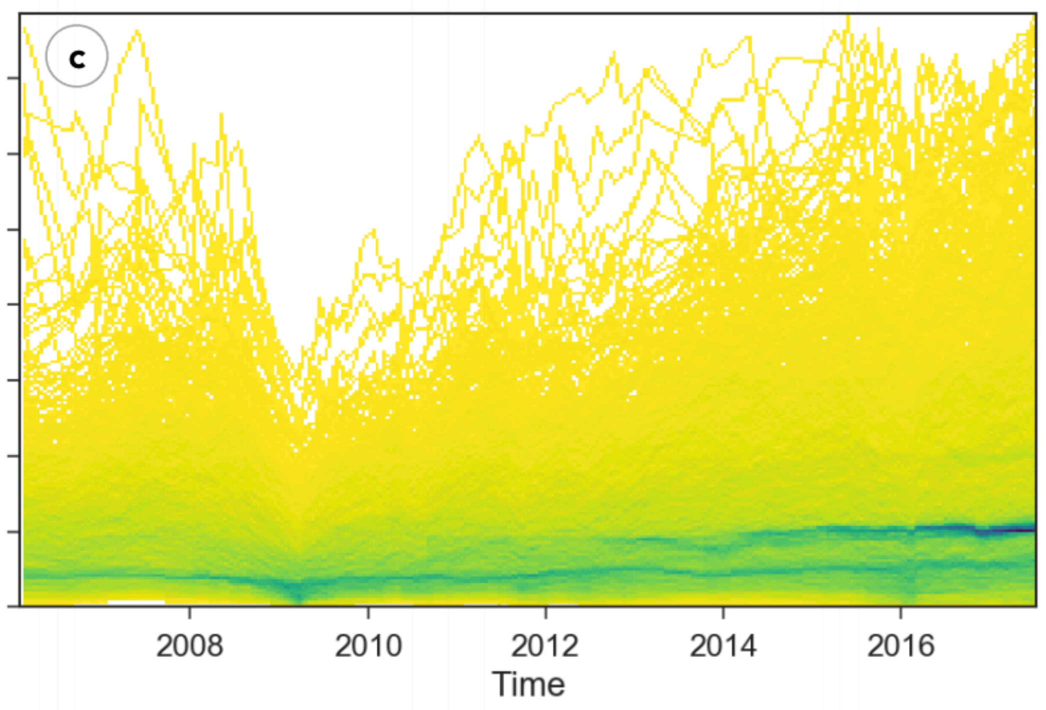
Example: Density Line Chart [Moritz & Fisher]



Line Chart



Non-Normalized Heatmap



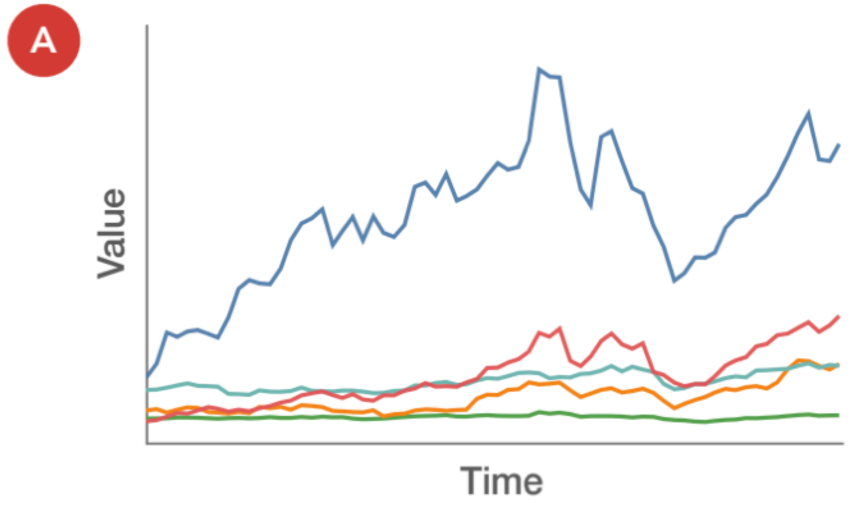
Normalized "DenseLines"

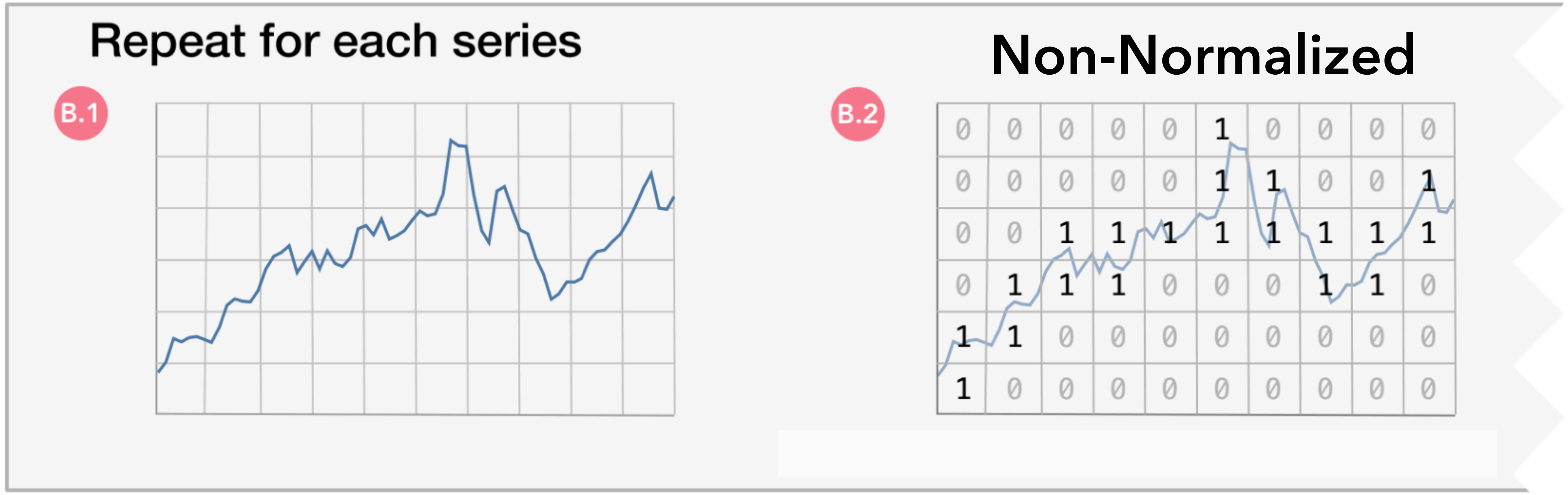
The non-normalized heatmap suffers from artifacts, seen as vertical stripes.

Binned charts convey high points across the top, a collective dip in stocks during the crash of 2008, and two distinct bands of $25 and $15 stocks.

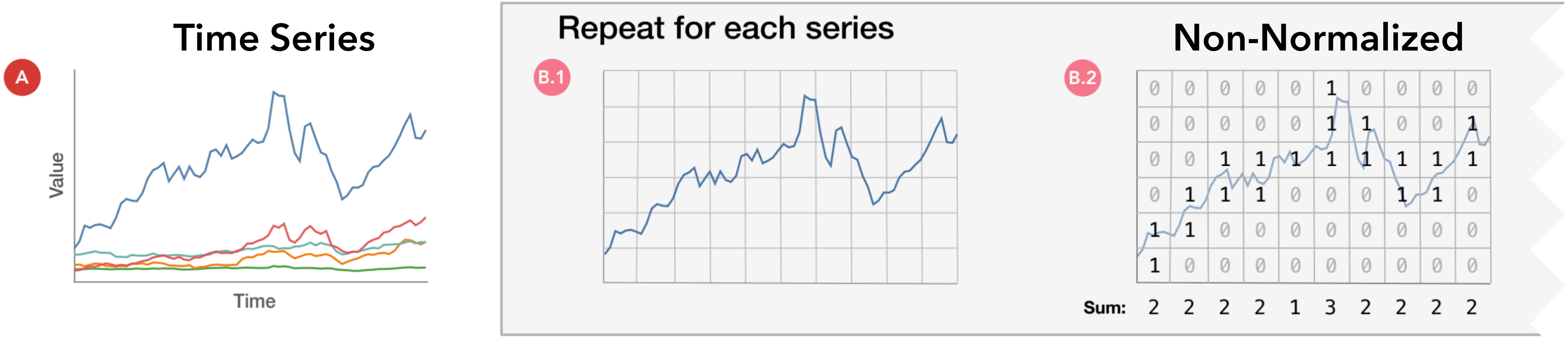
Example: Density Line Chart [Moritz & Fisher]

Time Series





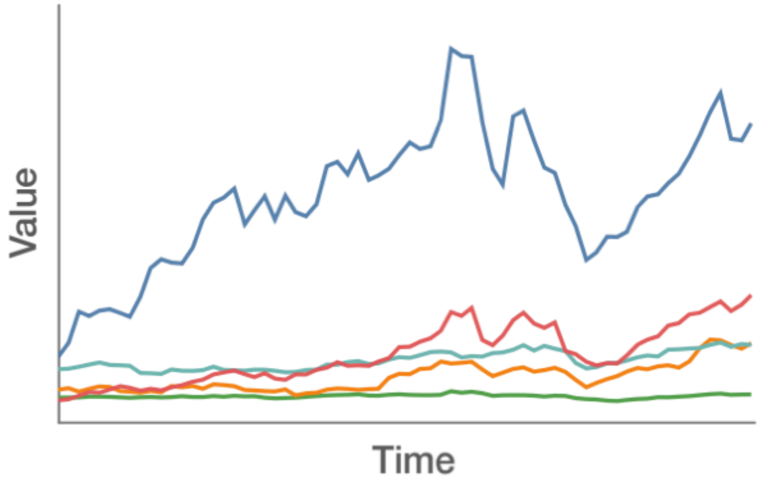
Example: Density Line Chart [Moritz & Fisher]



Example: Density Line Chart [Moritz & Fisher]

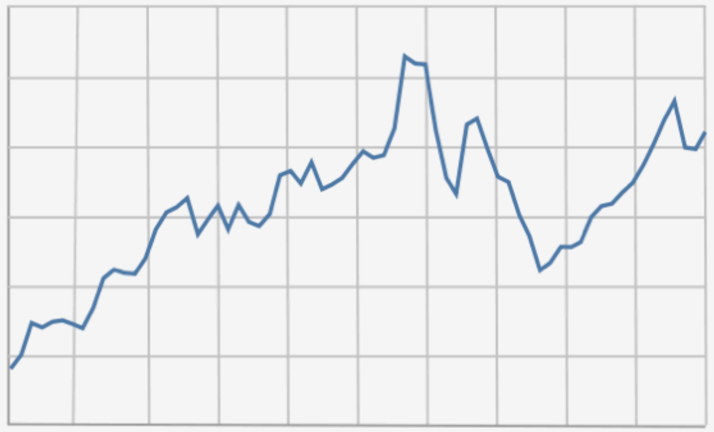
Time Series

A



Repeat for each series

B.1



Non-Normalized

B.2

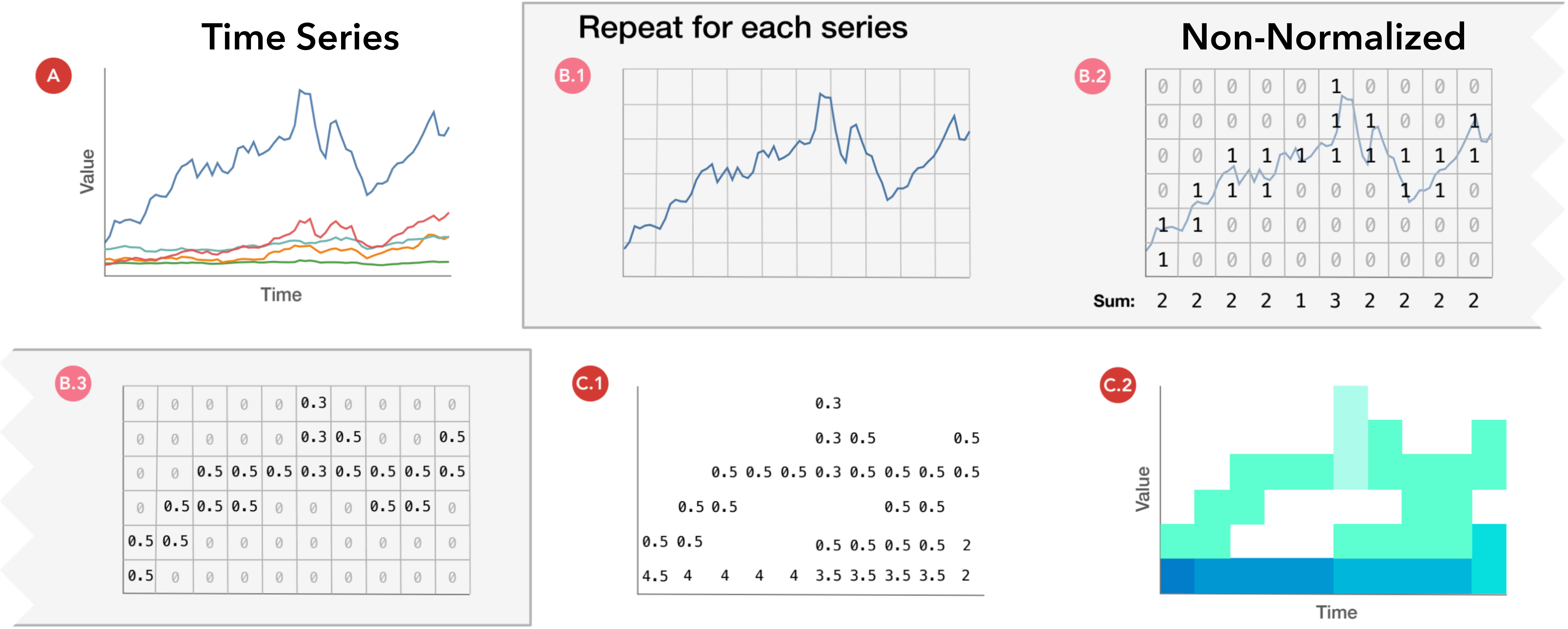
	0	0	0	0	0	1	0	0	0	0
	0	0	0	0	0	1	1	0	0	1
	0	0	1	1	1	1	1	1	1	1
	0	1	1	1	0	0	0	1	1	0
	1	1	0	0	0	0	0	0	0	0
	1	0	0	0	0	0	0	0	0	0
Sum:	2	2	2	2	1	3	2	2	2	2

B.3

0	0	0	0	0	0.3	0	0	0	0
0	0	0	0	0	0.3	0.5	0	0	0.5
0	0	0.5	0.5	0.5	0.3	0.5	0.5	0.5	0.5
0	0.5	0.5	0.5	0	0	0	0.5	0.5	0
0.5	0.5	0	0	0	0	0	0	0	0
0.5	0	0	0	0	0	0	0	0	0

Approx. Arc-Length Normalized

Example: Density Line Chart [Moritz & Fisher]



Approx. Arc-Length Normalized Aggregate Color

2. Enabling Real-Time Interaction

Interactive Scalability Strategies

1. Query Database
2. Client-Side Indexing / Data Cubes
3. Prefetching
4. Approximation

Interactive Scalability Strategies

1. Query Database Offload to a scalable backend

Tableau, for example, issues aggregation queries.

Analytical databases are designed for fast, parallel execution.

But round-trip queries to the DB may still be too slow…

2. Client-Side Indexing / Data Cubes

3. Prefetching

4. Approximation

Interactive Scalability Strategies

1. **Query Database**
2. **Client-Side Indexing / Data Cubes** Query data summaries

Build sorted indices or data cubes to quickly re-calculate aggregations as needed on the client.

3. **Prefetching**
4. **Approximation**

Interactive Scalability Strategies

1. **Query Database**
2. **Client-Side Indexing / Data Cubes**
3. **Prefetching** Request data *before* it is needed

Reduce latency by speculatively querying for data before it is needed. Requires prediction models to guess what is needed.

4. **Approximation**

Interactive Scalability Strategies

1. Query Database
2. Client-Side Indexing / Data Cubes
3. Prefetching
4. **Approximation** Give fast, approximate answers

Reduce latency by computing aggregates on a sample, ideally with approximation bounds characterizing the error.

Interactive Scalability Strategies

1. Query Database
2. Client-Side Indexing / Data Cubes
3. Prefetching
4. Approximation

These strategies are **not** mutually exclusive!

Systems can apply them in tandem.

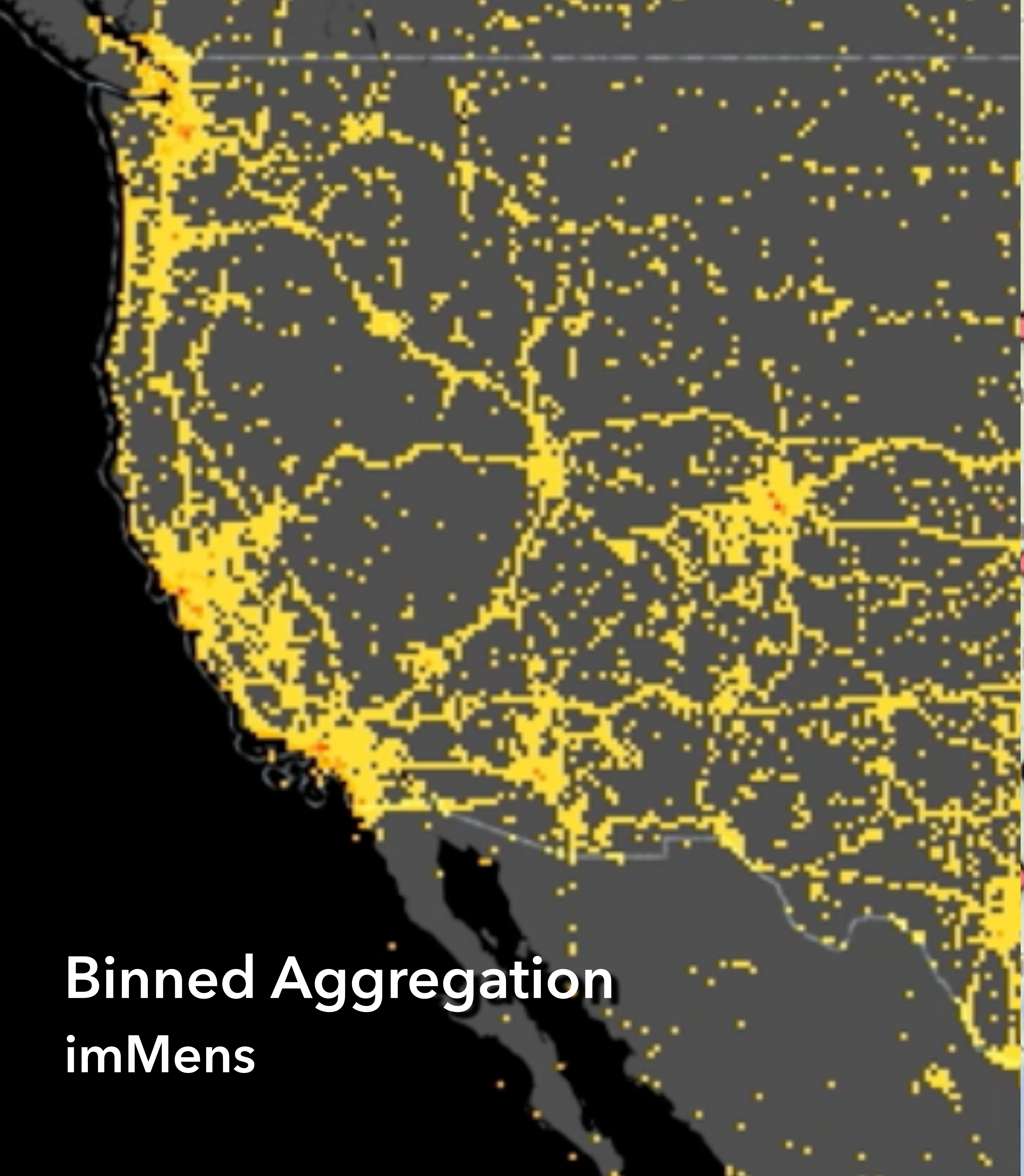
imMens

[Liu, Jiang & Heer '13]

Strategies: Client-Side Data Cubes

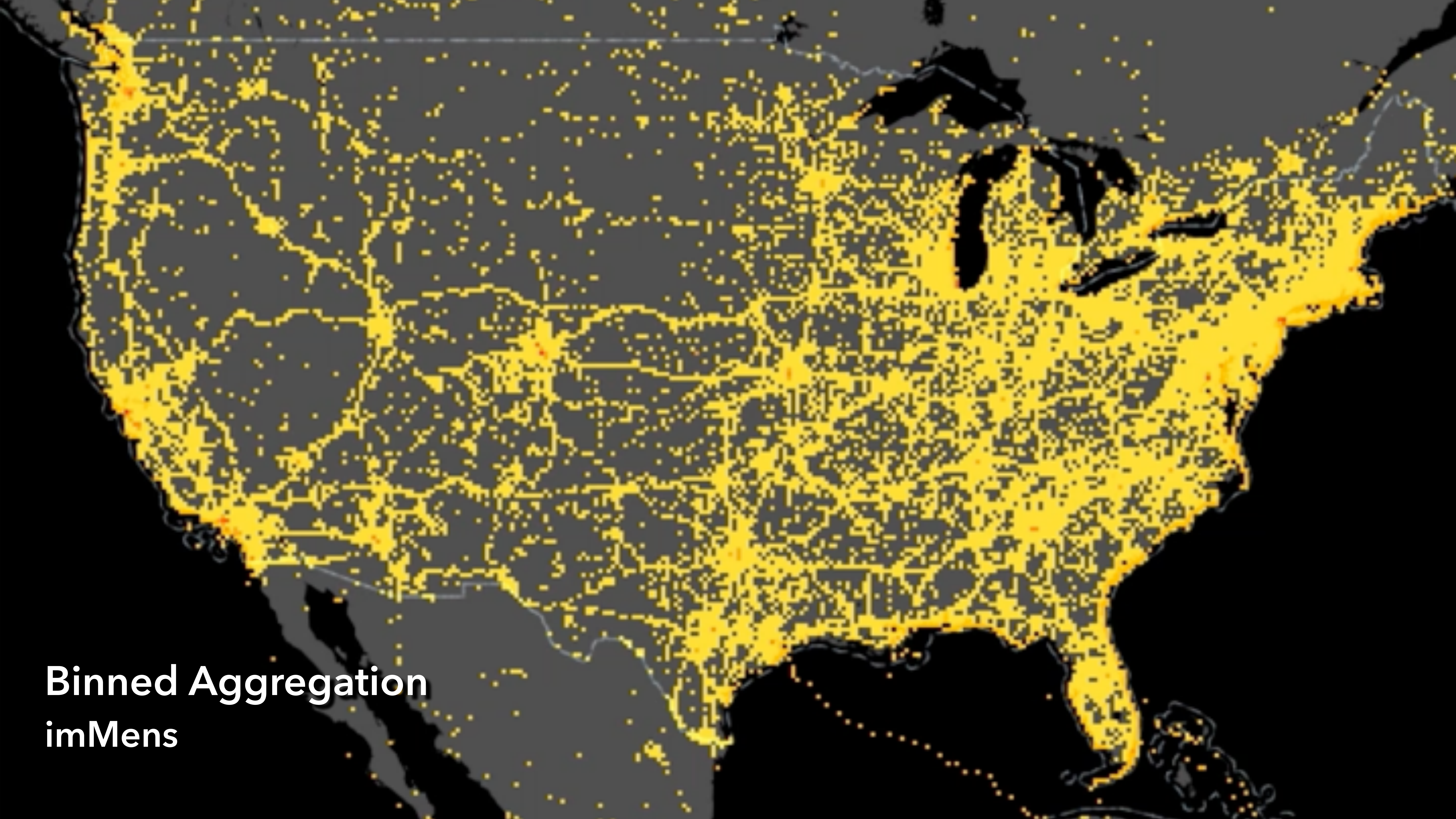
Sampling

Google Fusion Tables



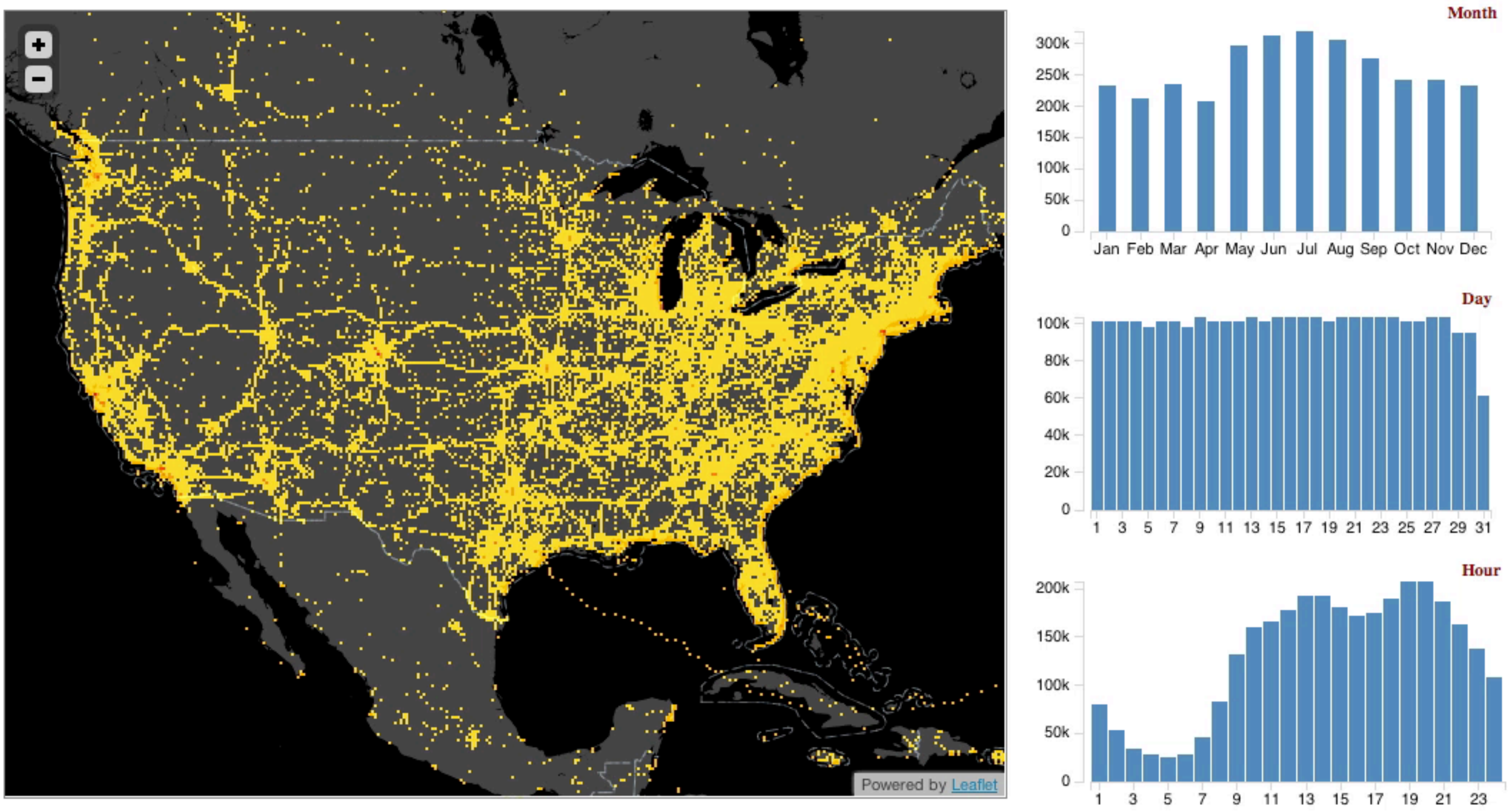
Binned Aggregation
imMens

Sampling
Google Fusion Tables



Binned Aggregation

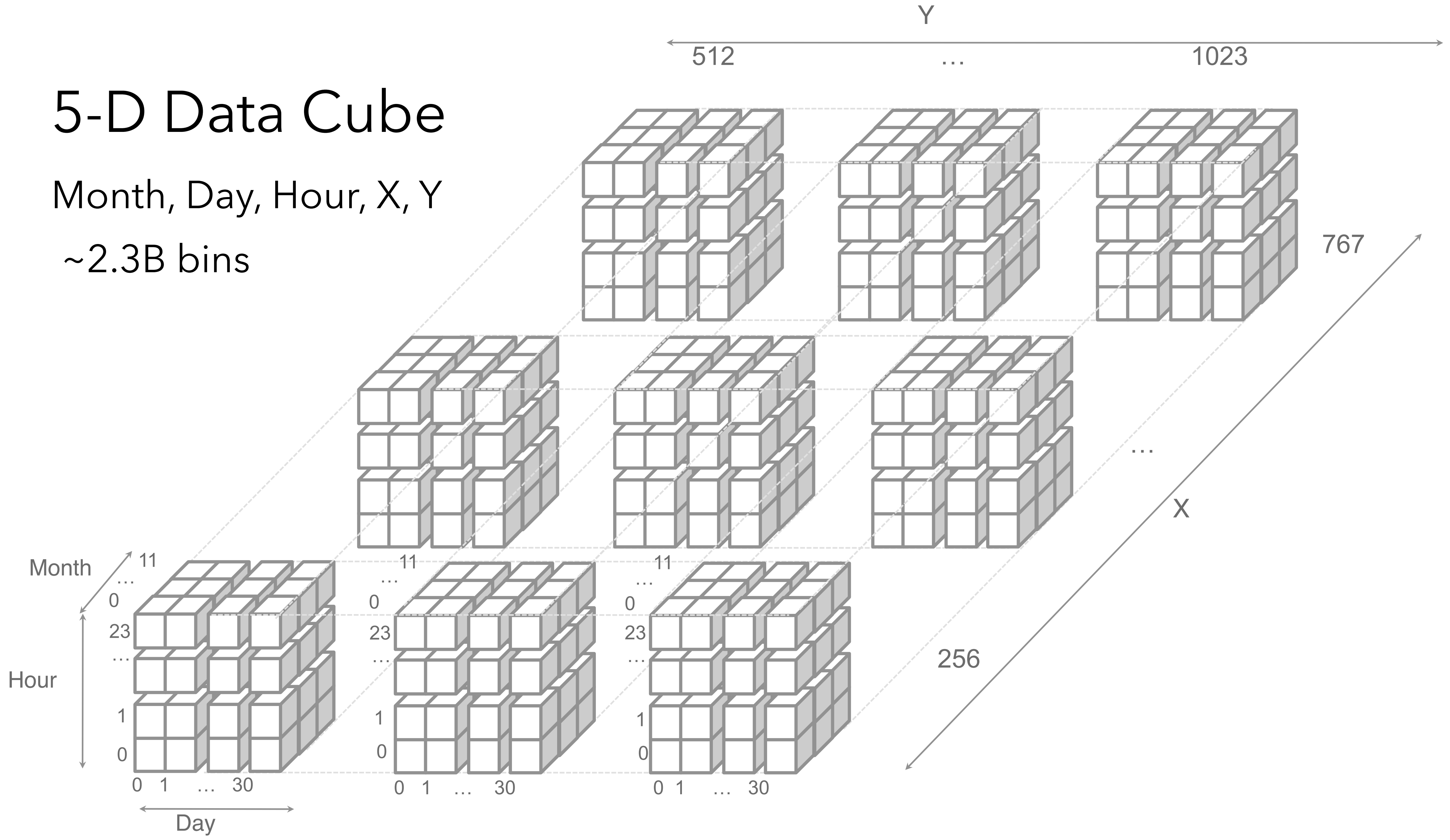
imMens


Powered by Leaflet
Month
300k
250k
200k
150k
100k
50k
0
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec
Day
100k
80k
60k
40k
20k
0
1 3 5 7 9 11 13 15 17 19 21 23 25 27 29 31
Hour
200k
150k
100k
50k
0
1 3 5 7 9 11 13 15 17 19 21 23

5-D Data Cube

Month, Day, Hour, X, Y

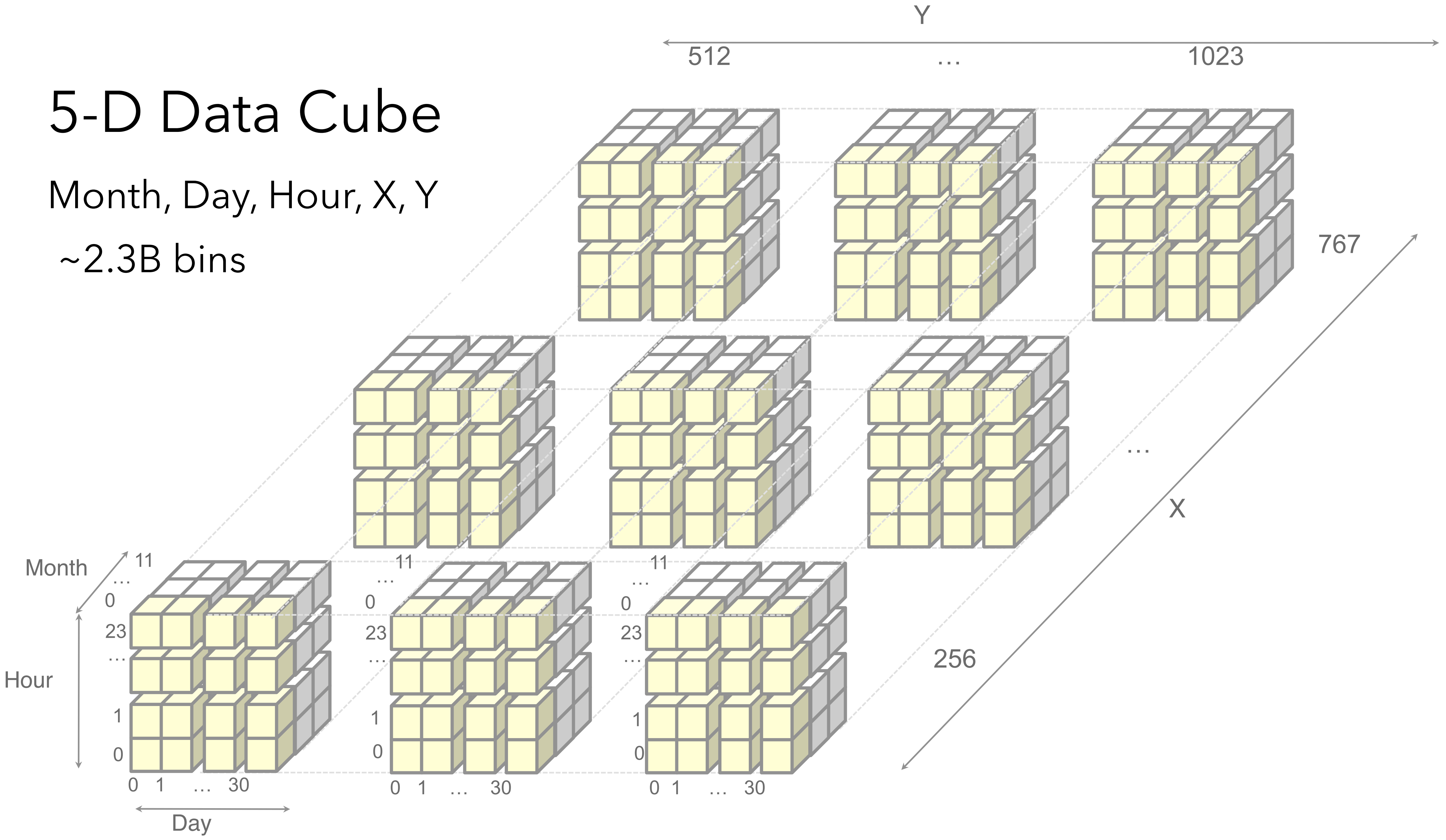
~2.3B bins

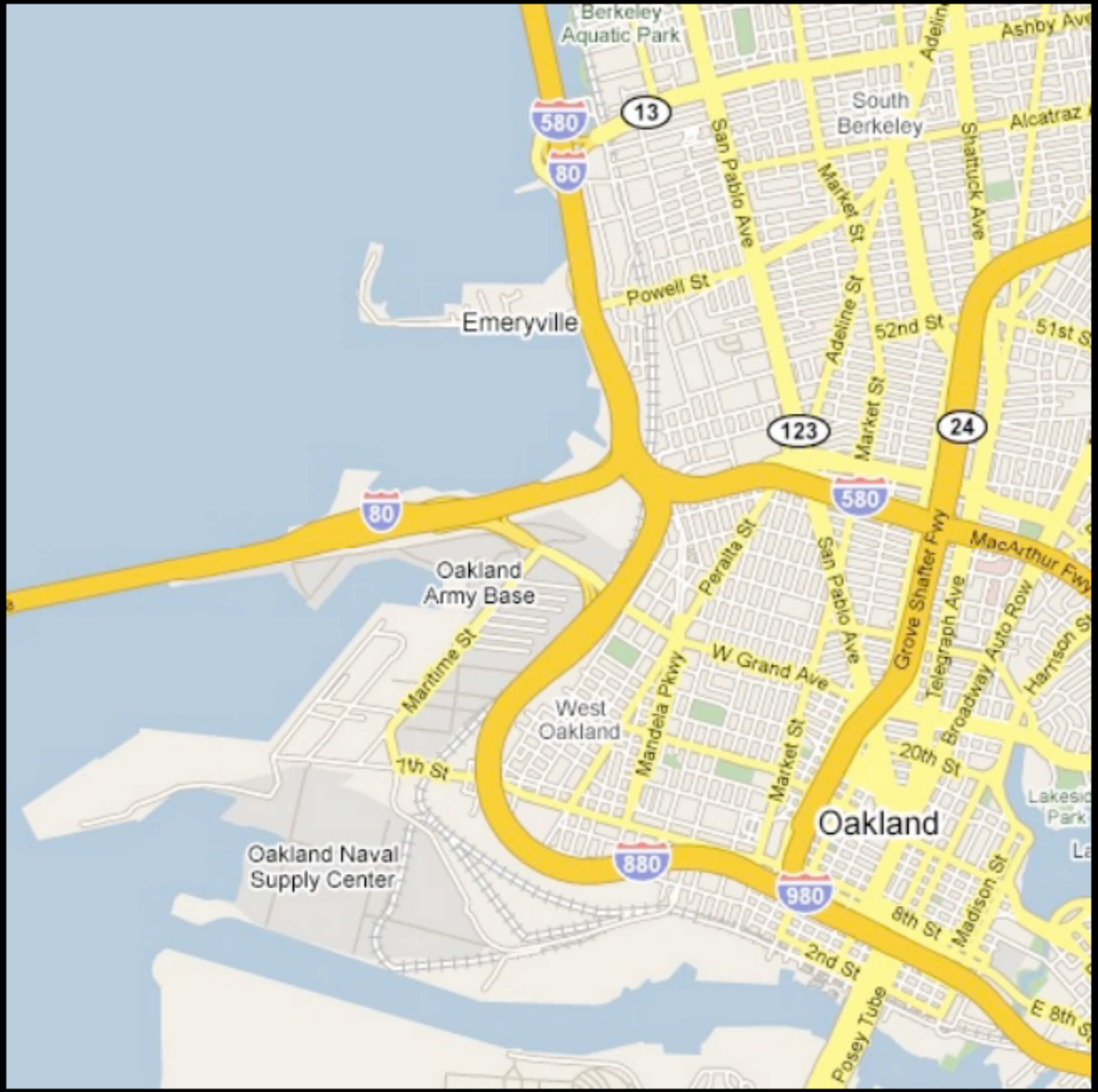


5-D Data Cube

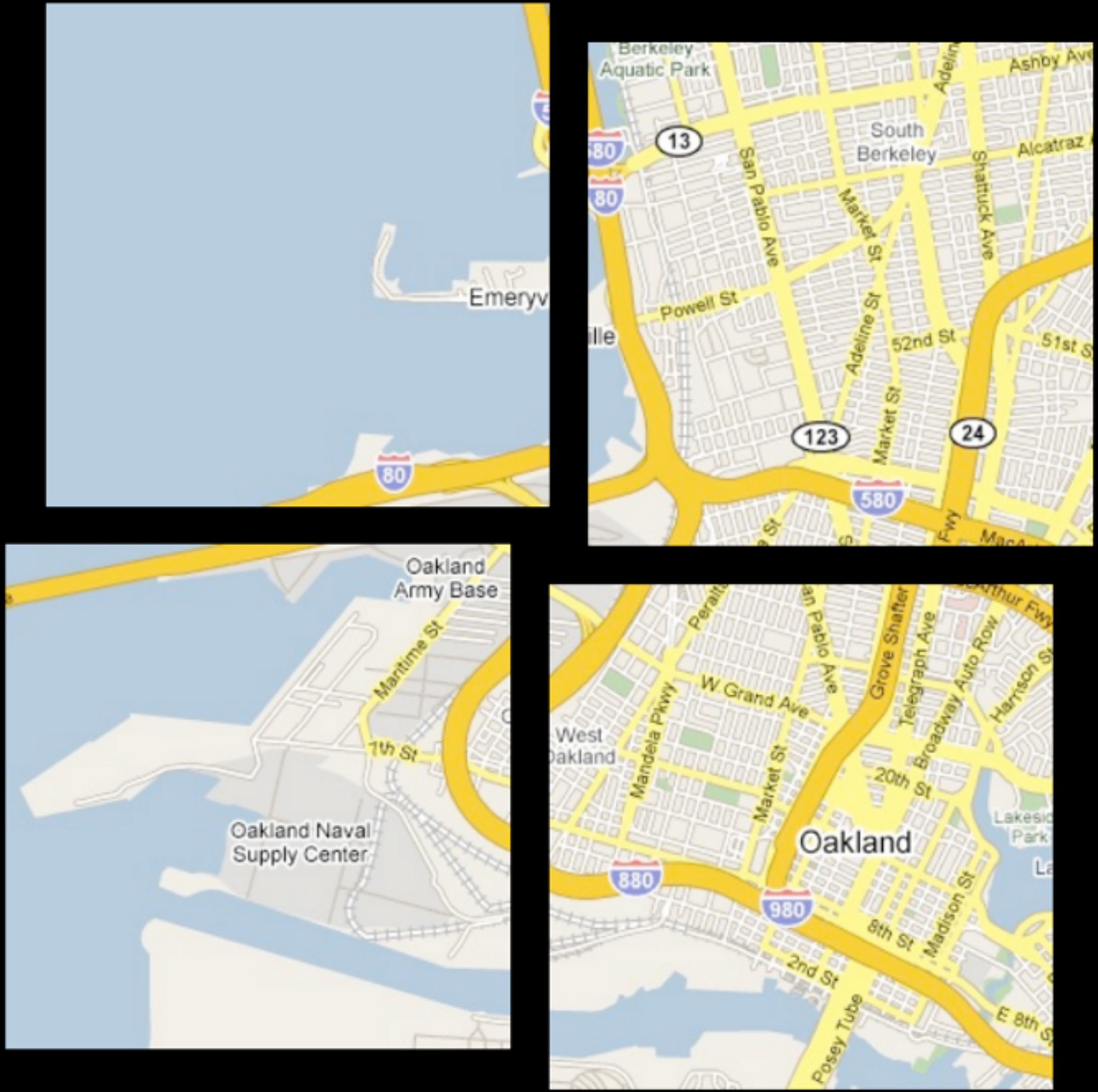
Month, Day, Hour, X, Y

~2.3B bins





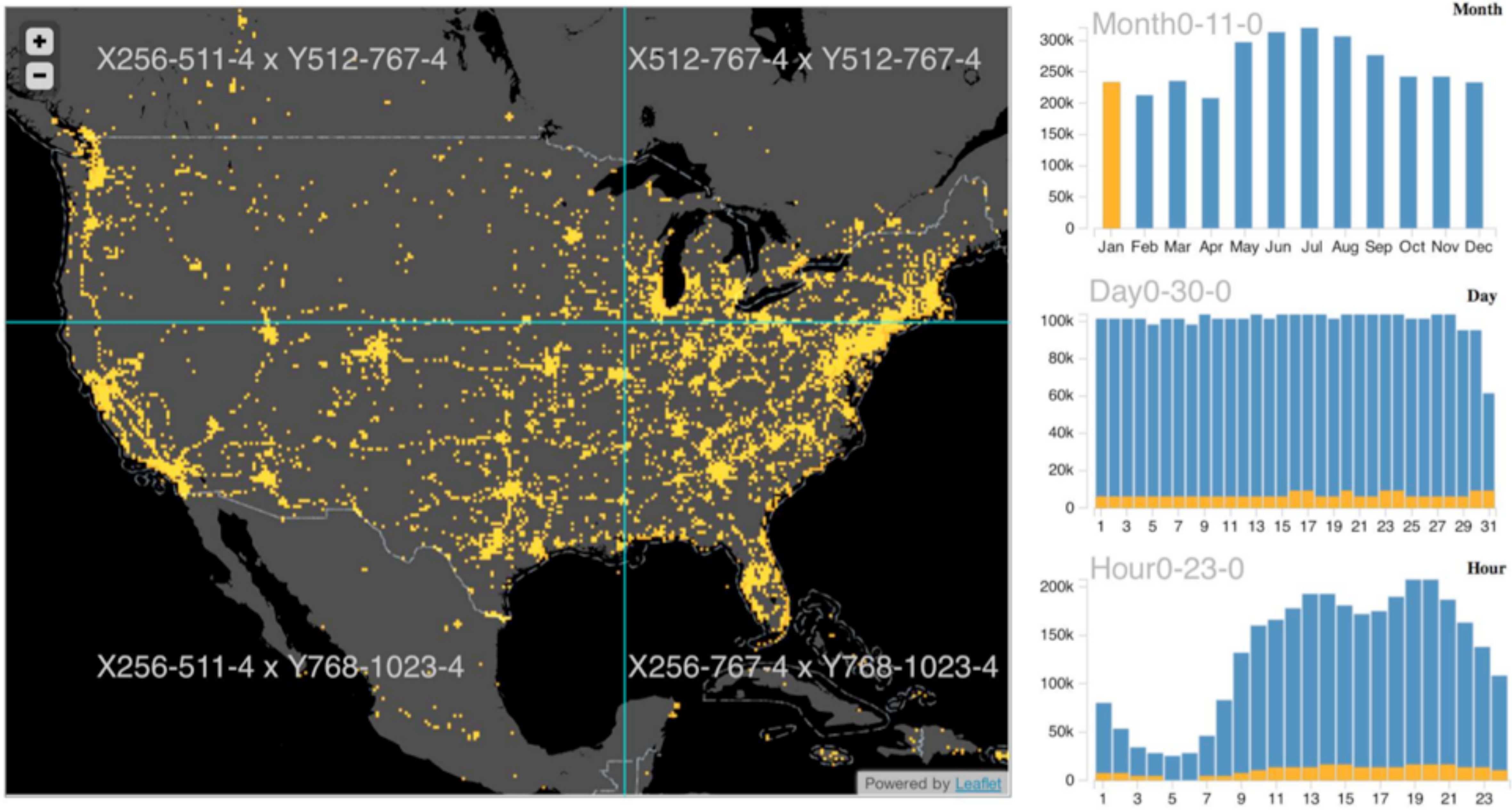
Berkeley Aquatic Park
580
13
80
South Berkeley
Ashby Ave
Alcatraz
San Pablo Ave
Market St
Shattuck Ave
Powell St
Emeryville
Adeline St
52nd St
51st St
123
24
Market St
580
80
MacArthur Fwy
Oakland Army Base
Peralta St
San Pablo Ave
Grove Shafter Fwy
Telegraph Ave
Broadway Auto Row
Harrison St
Maritime St
W Grand Ave
West Oakland
Mandela Pkwy
Market St
20th St
7th St
Oakland
Oakland Naval Supply Center
880
980
8th St
Madison St
2nd St
Posey Tube
E 8th St



Berkeley
Aquatic Park
South
Berkeley
13
580
80
San Pablo Ave
Market St
Shattuck Ave
Powell St
Adeline St
52nd St
123
24
580
80
Oakland
Army Base
Maritime St
Oakland Naval
Supply Center
West
W Grand Ave
Mandela Pkwy
Market St
Grove Shafter
Telegraph Ave
Broadway Auto Row
20th St
Oakland
880
980
8th St
Madison St
2nd St
Posey Tube

Multivariate Data Tiles

1. Send data, not pixels
2. Embed multi-dim data


X256-511-4 x Y512-767-4
X512-767-4 x Y512-767-4
X256-511-4 x Y768-1023-4
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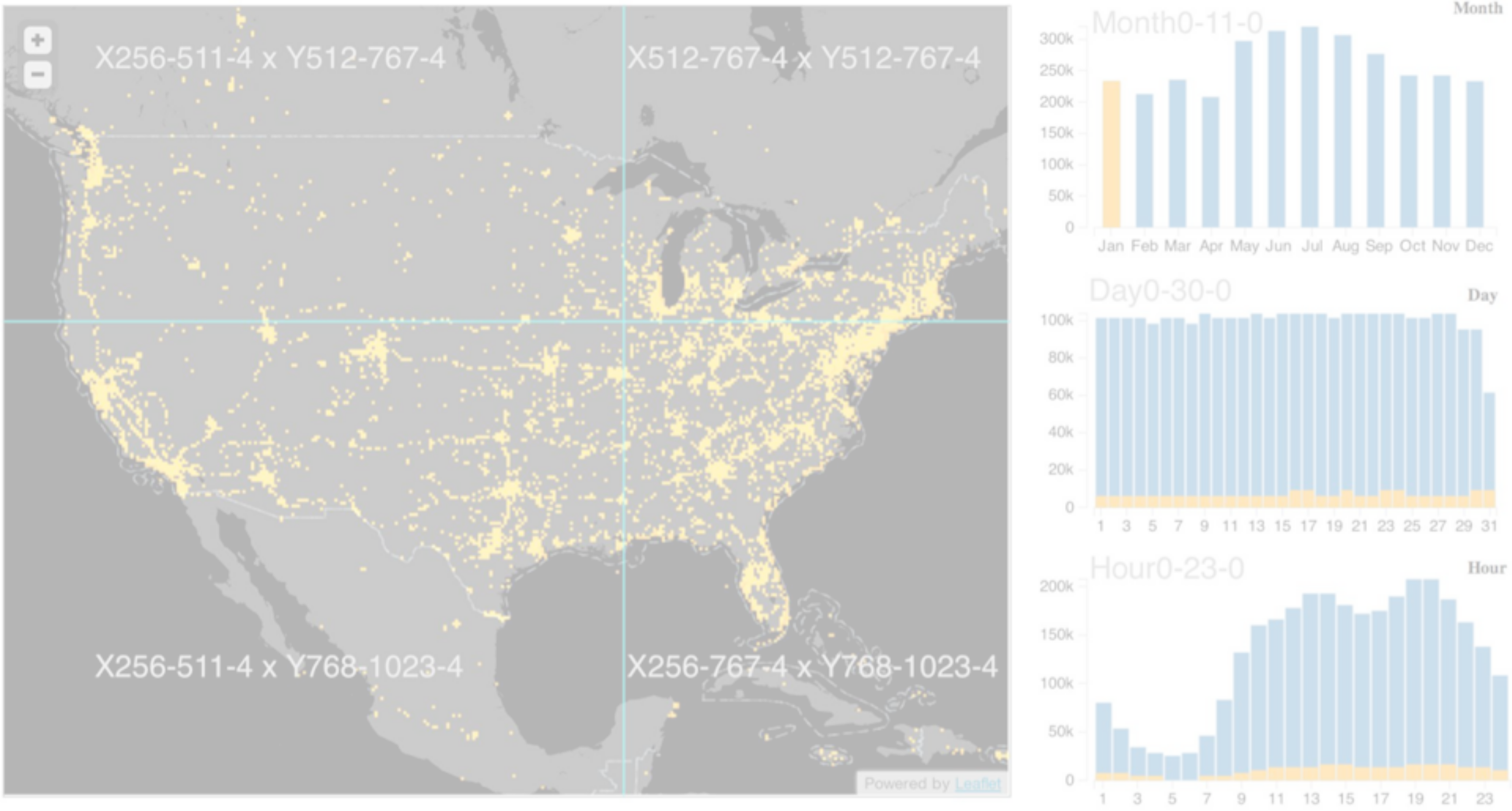
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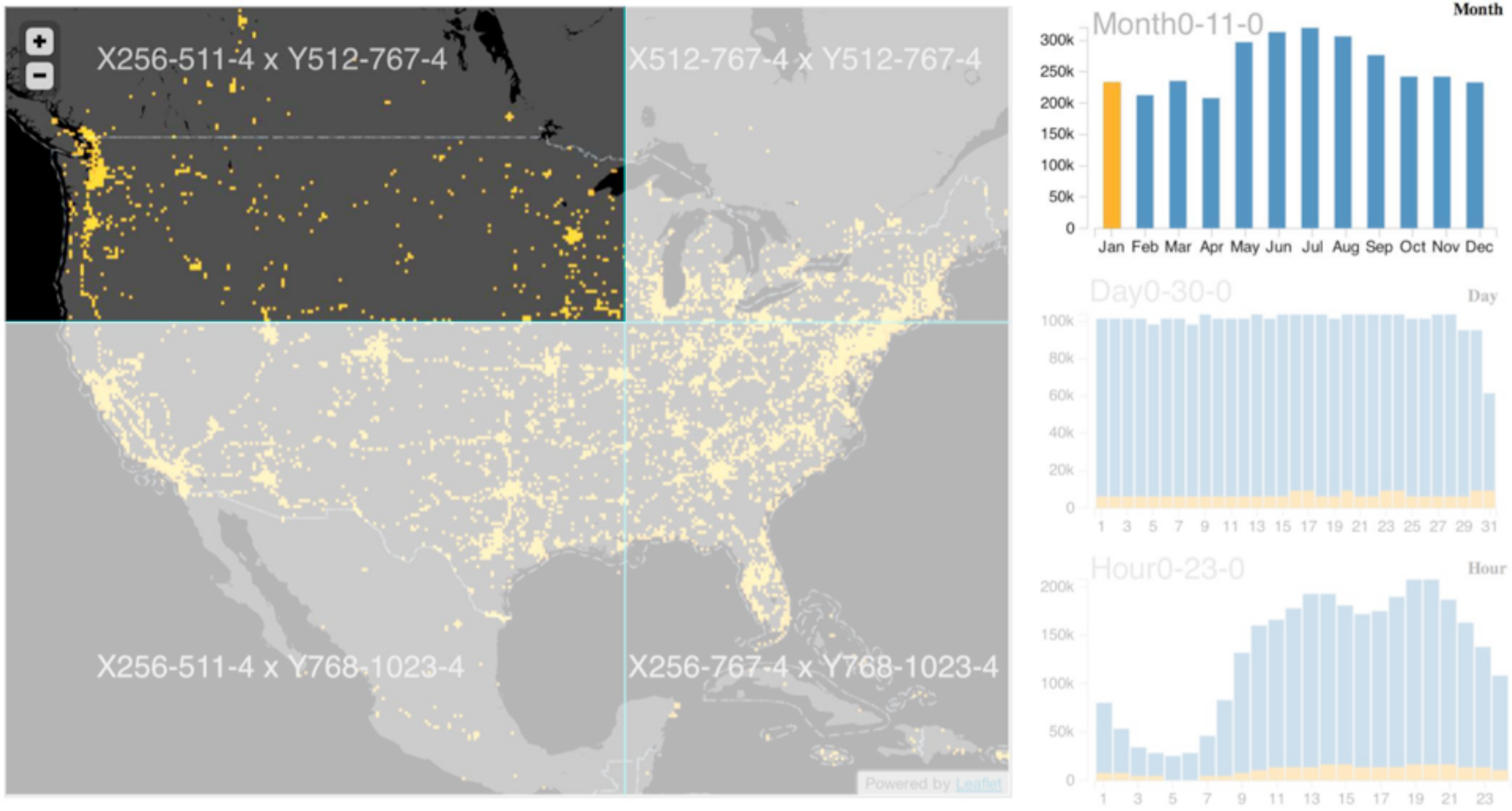

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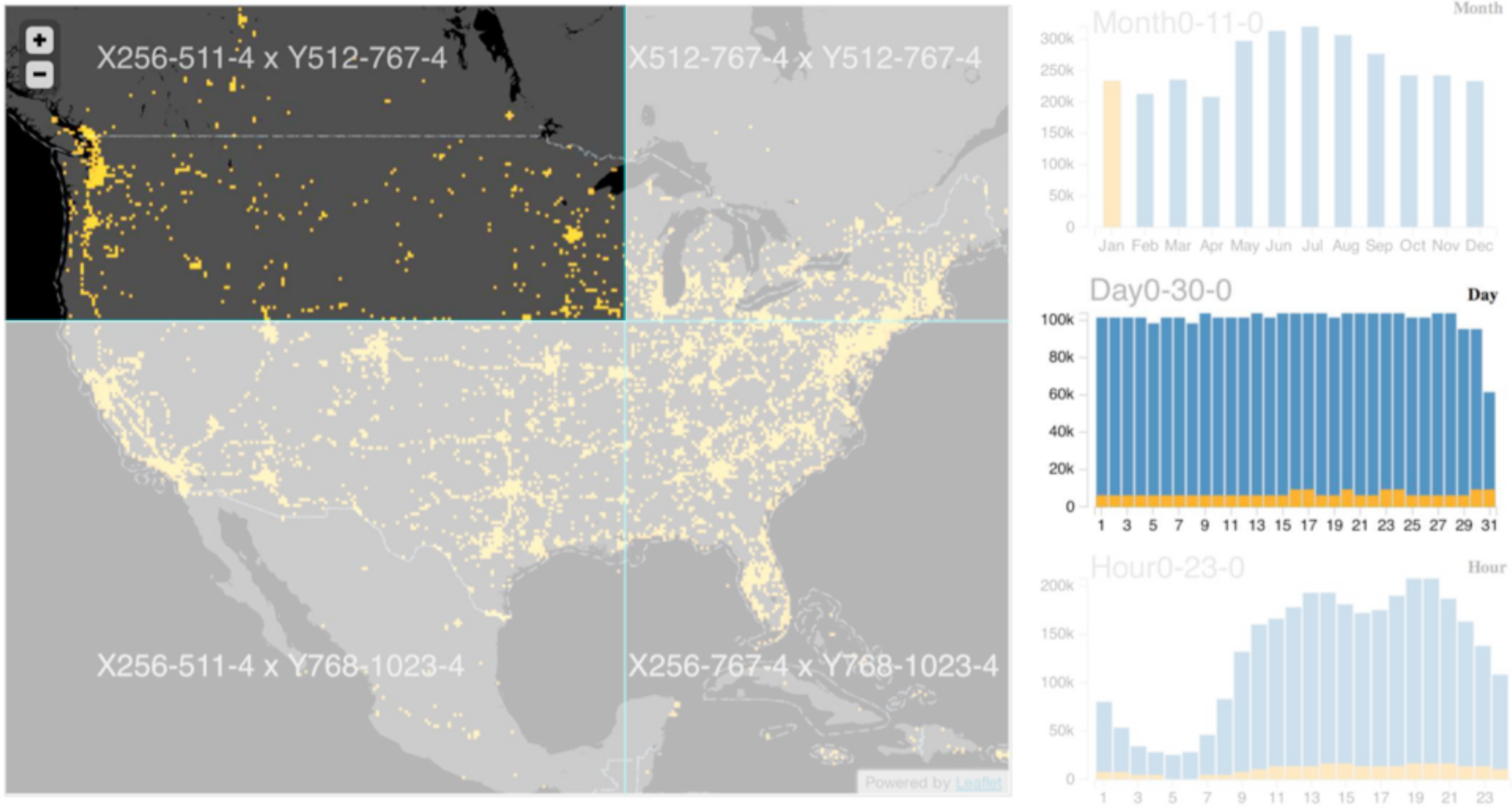
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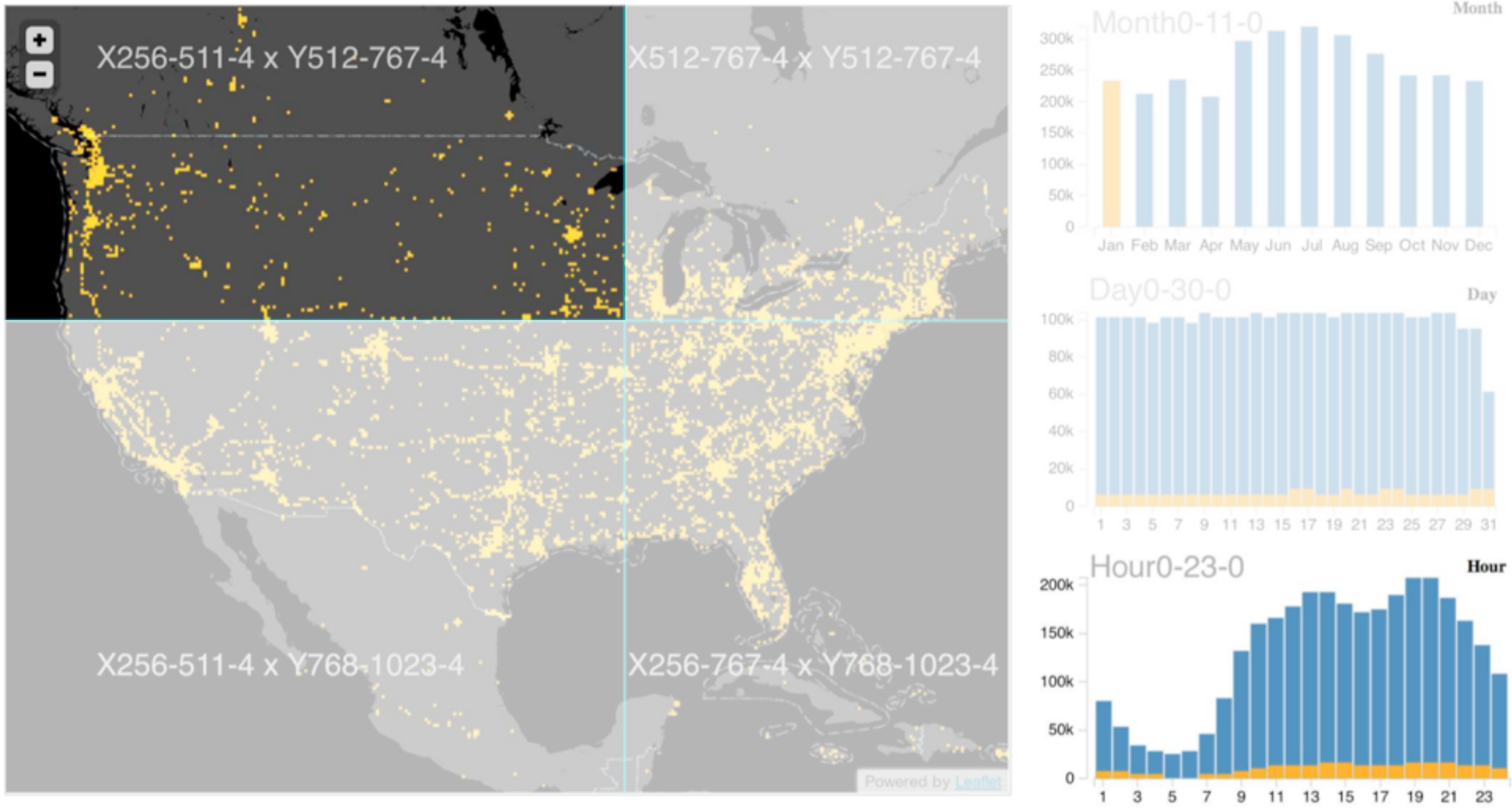
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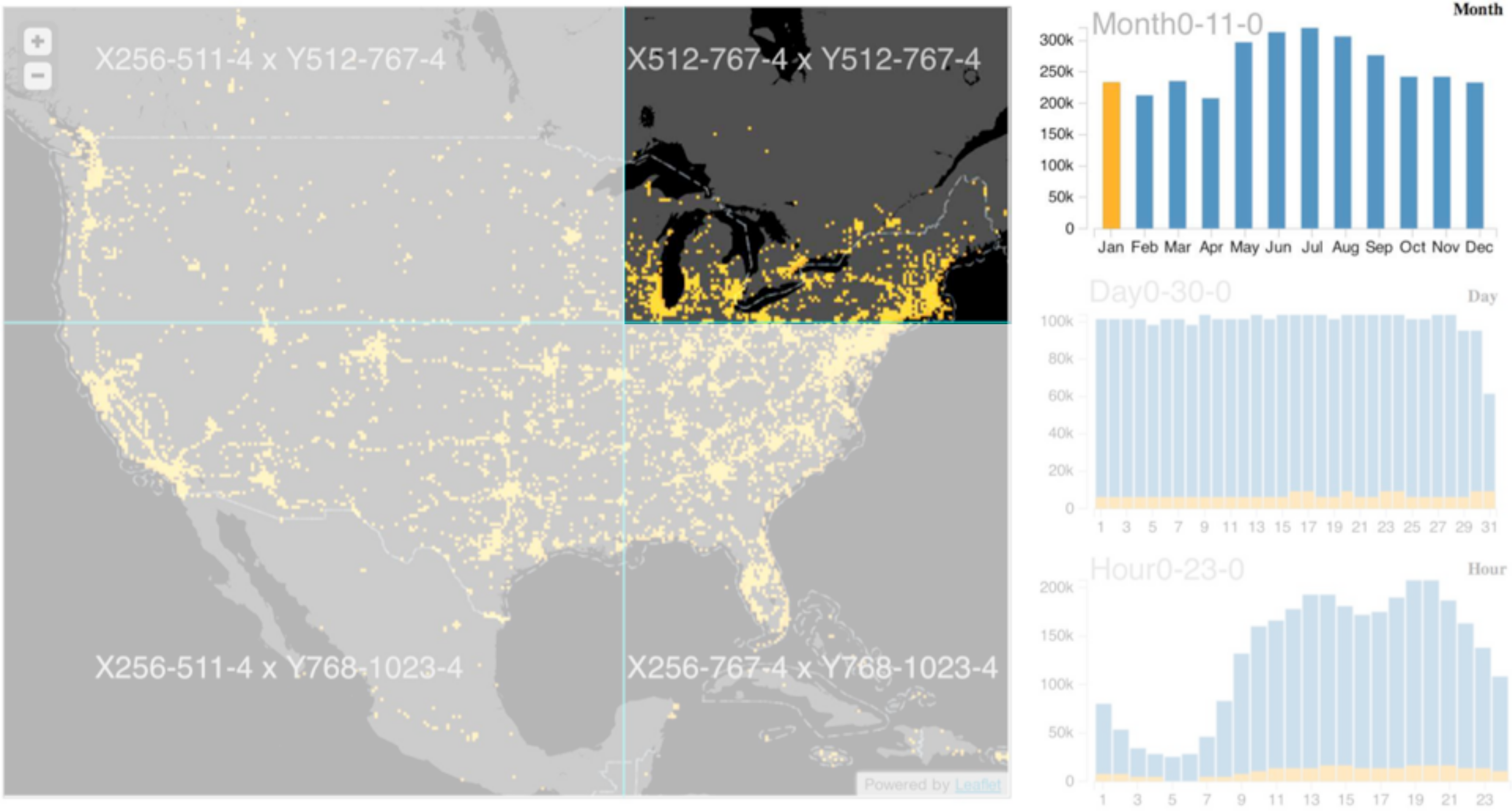
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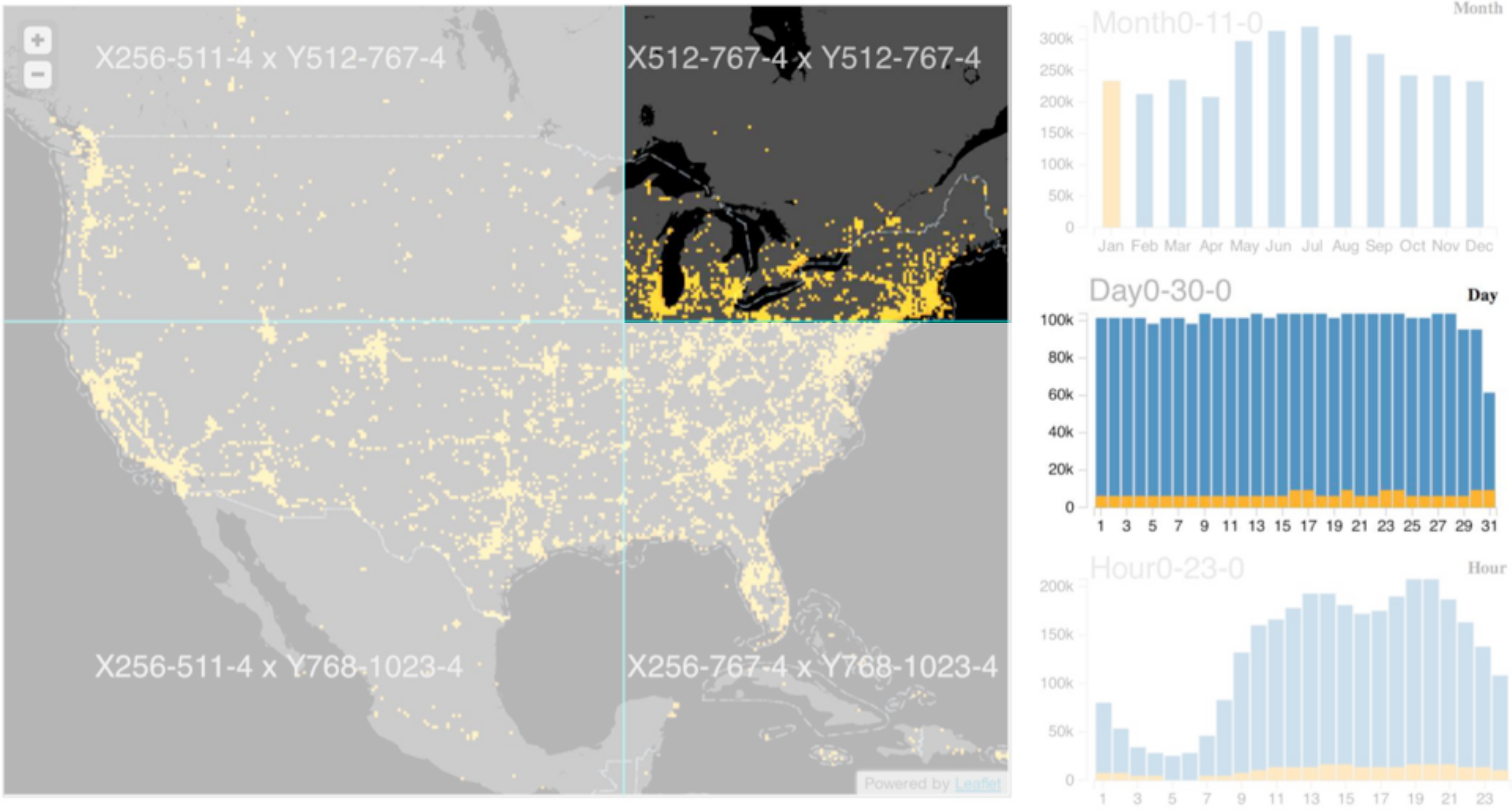
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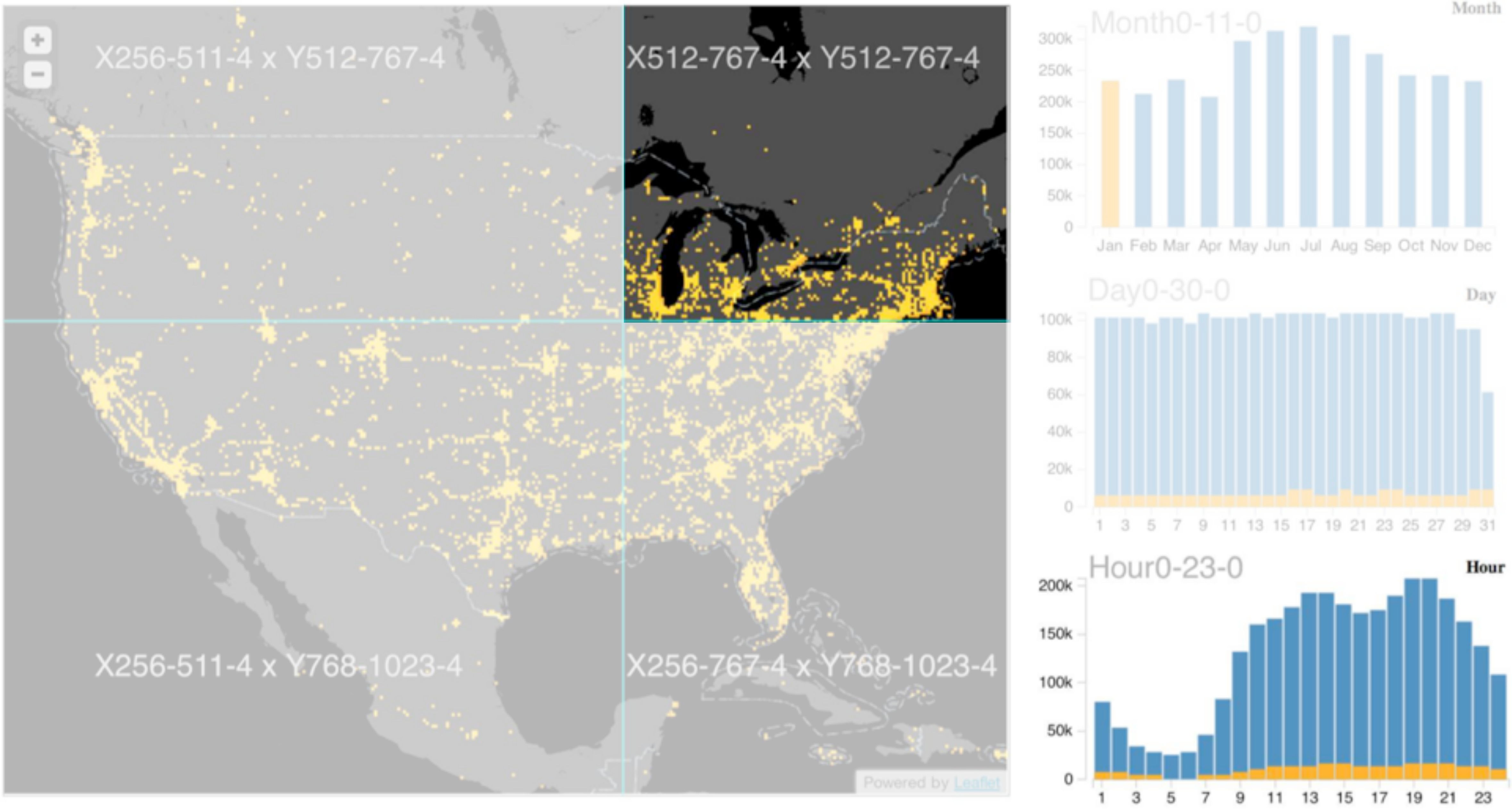

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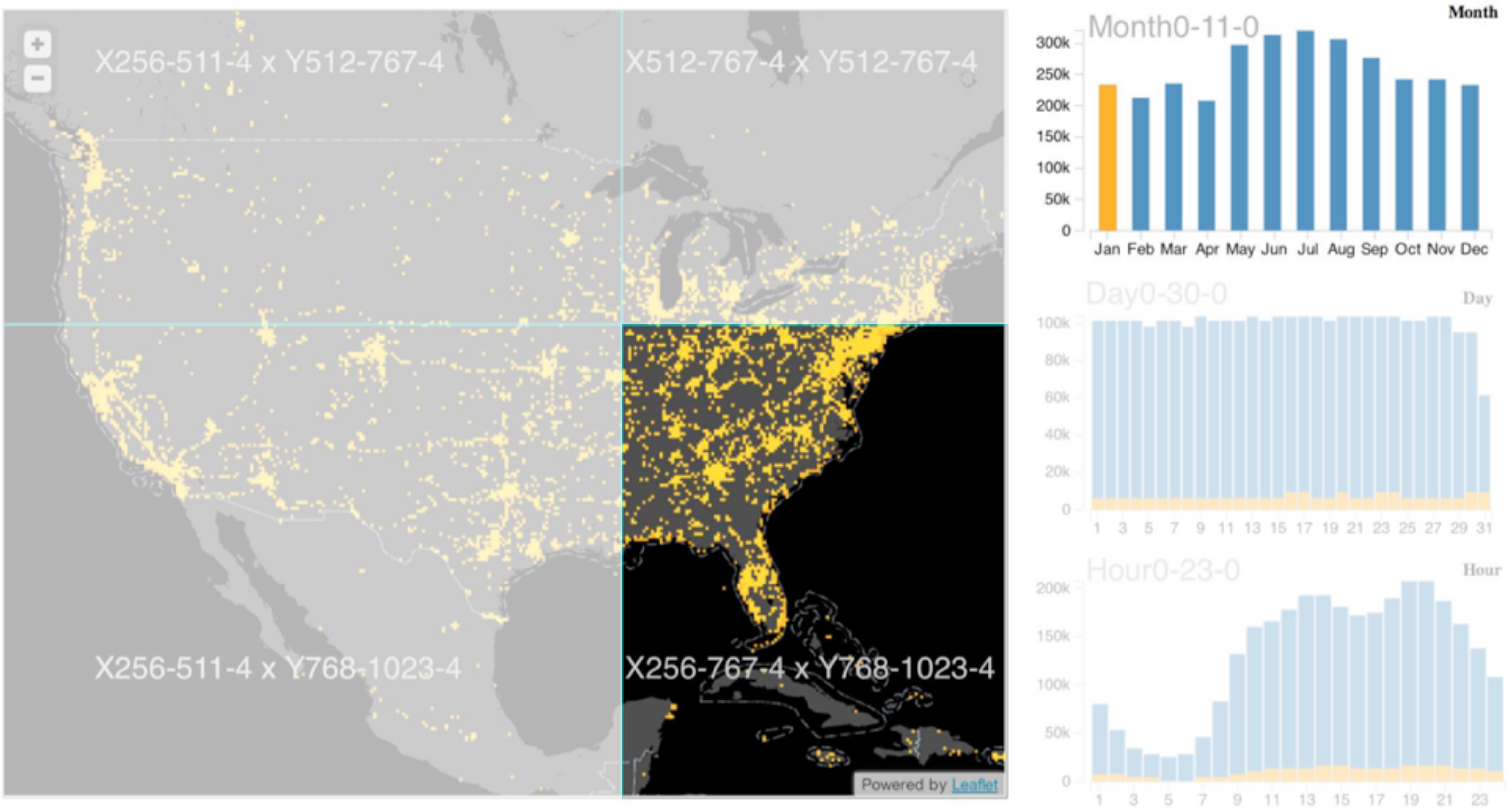
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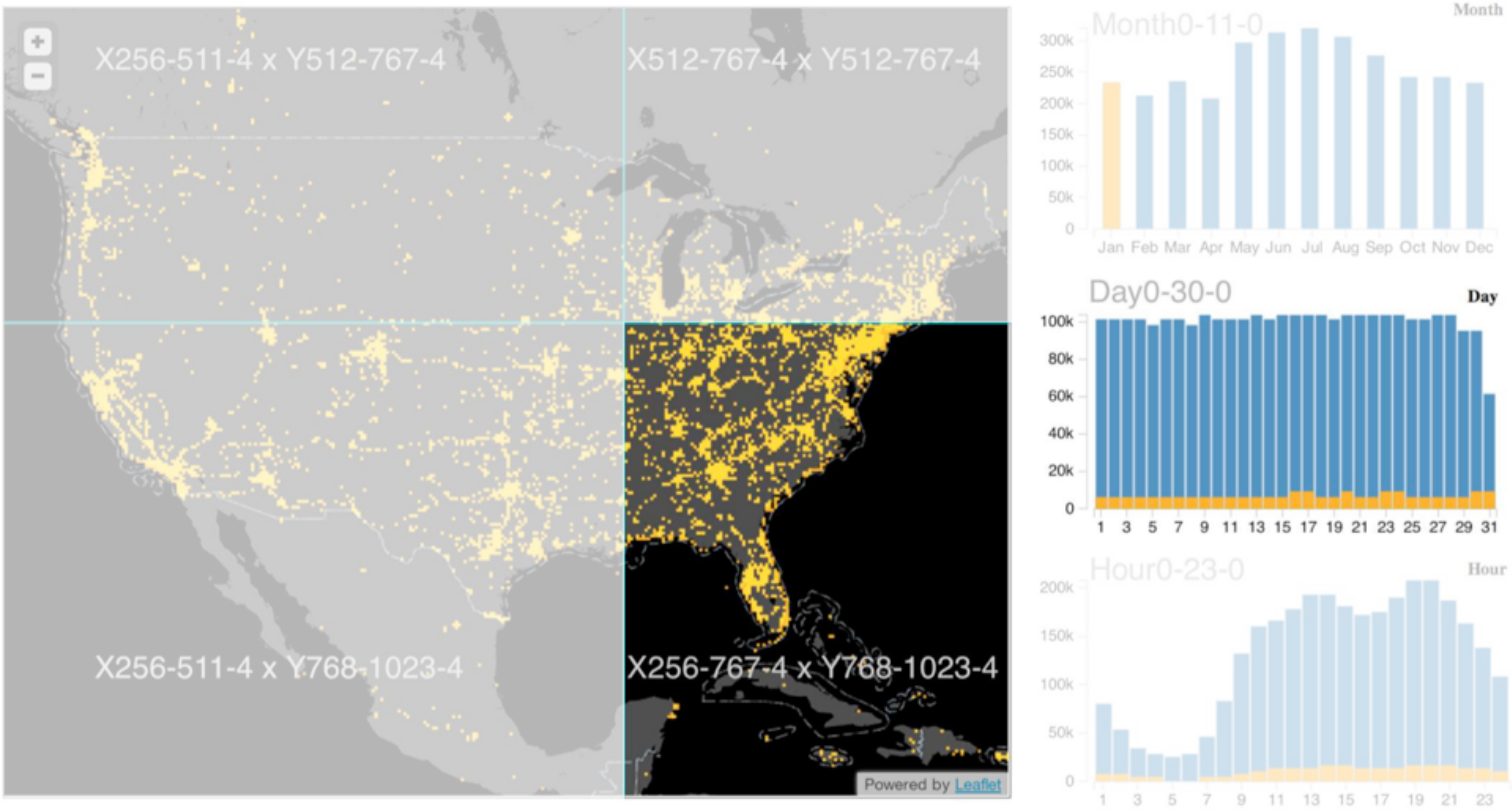

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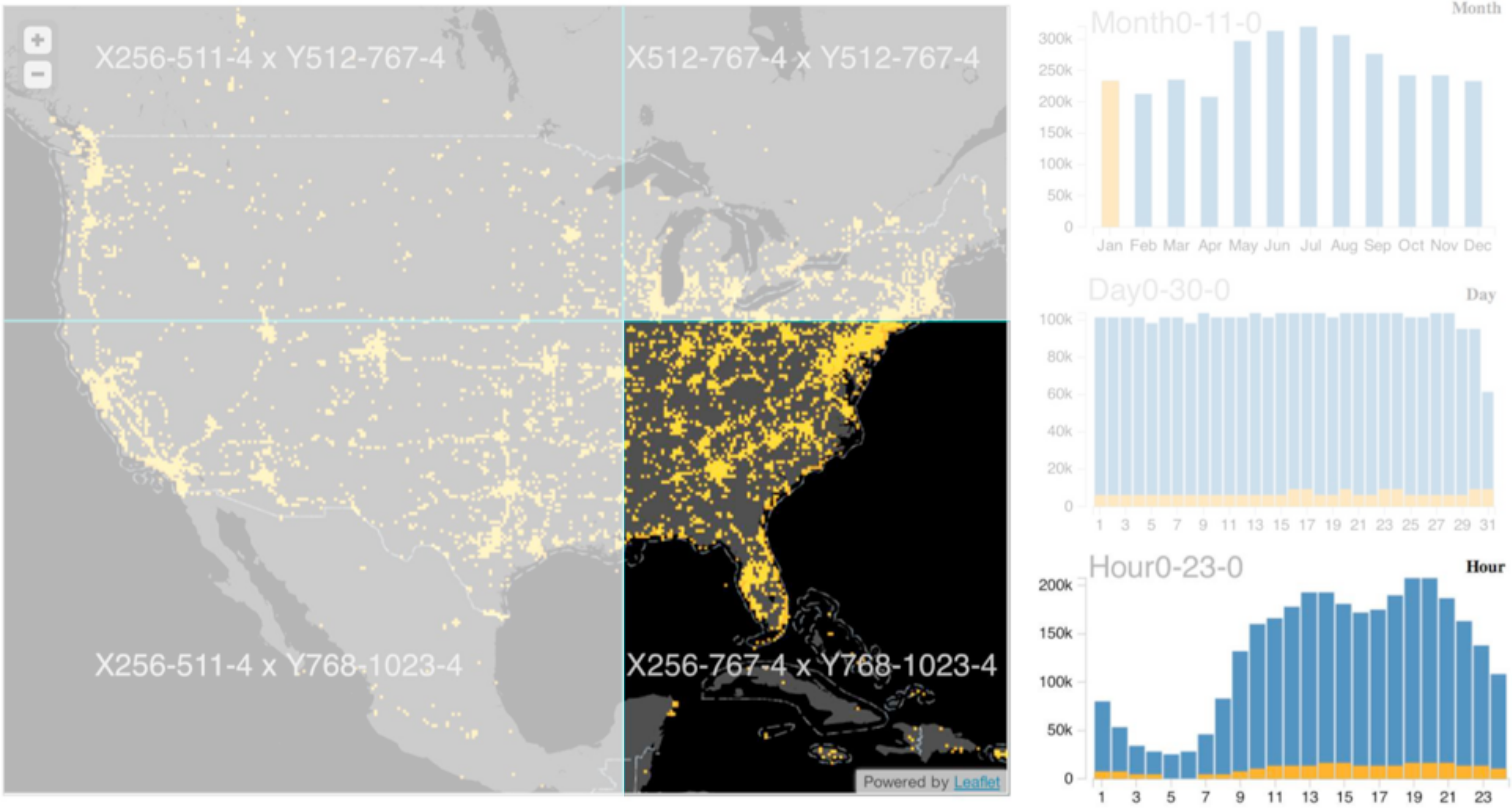

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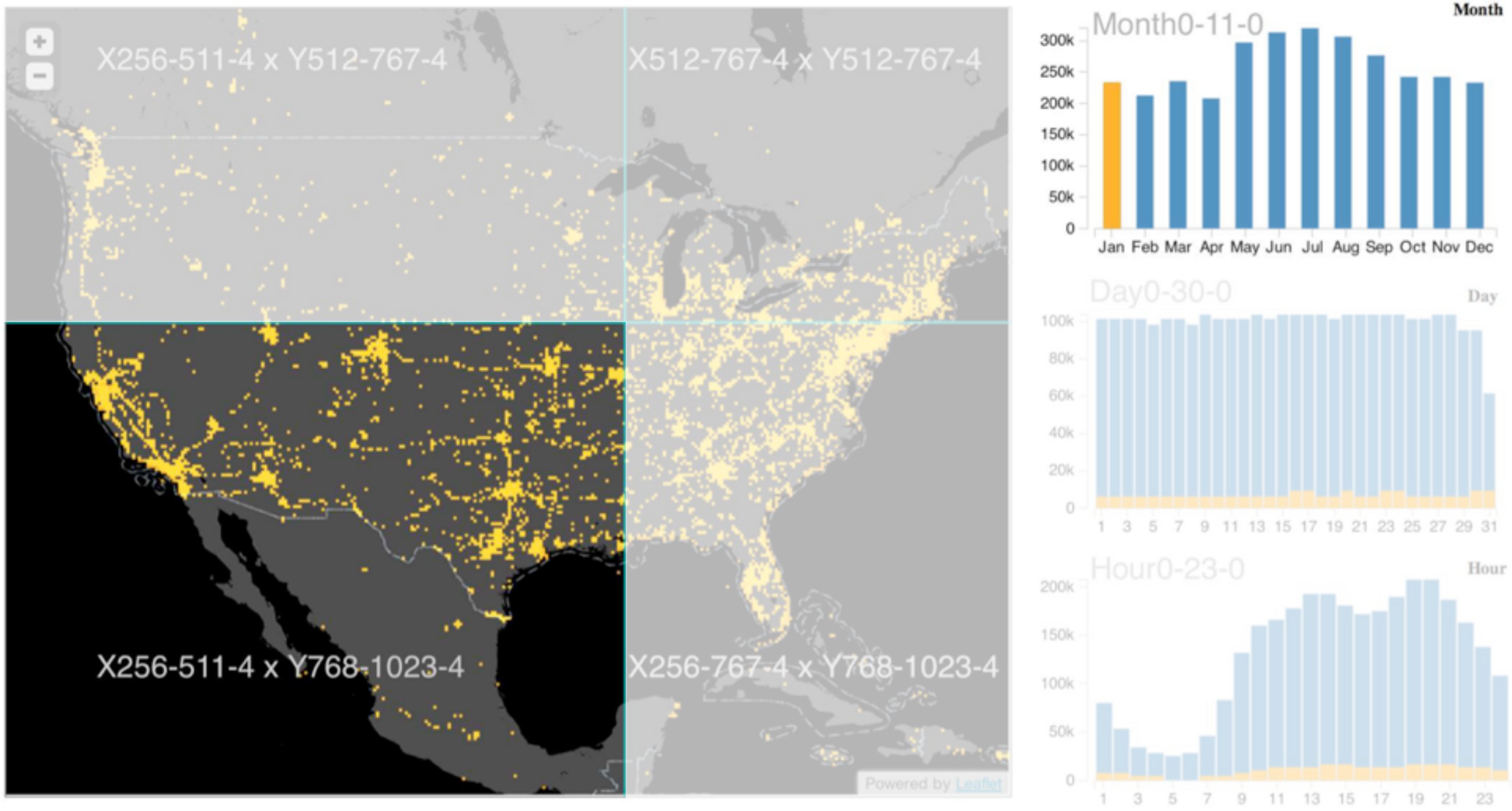

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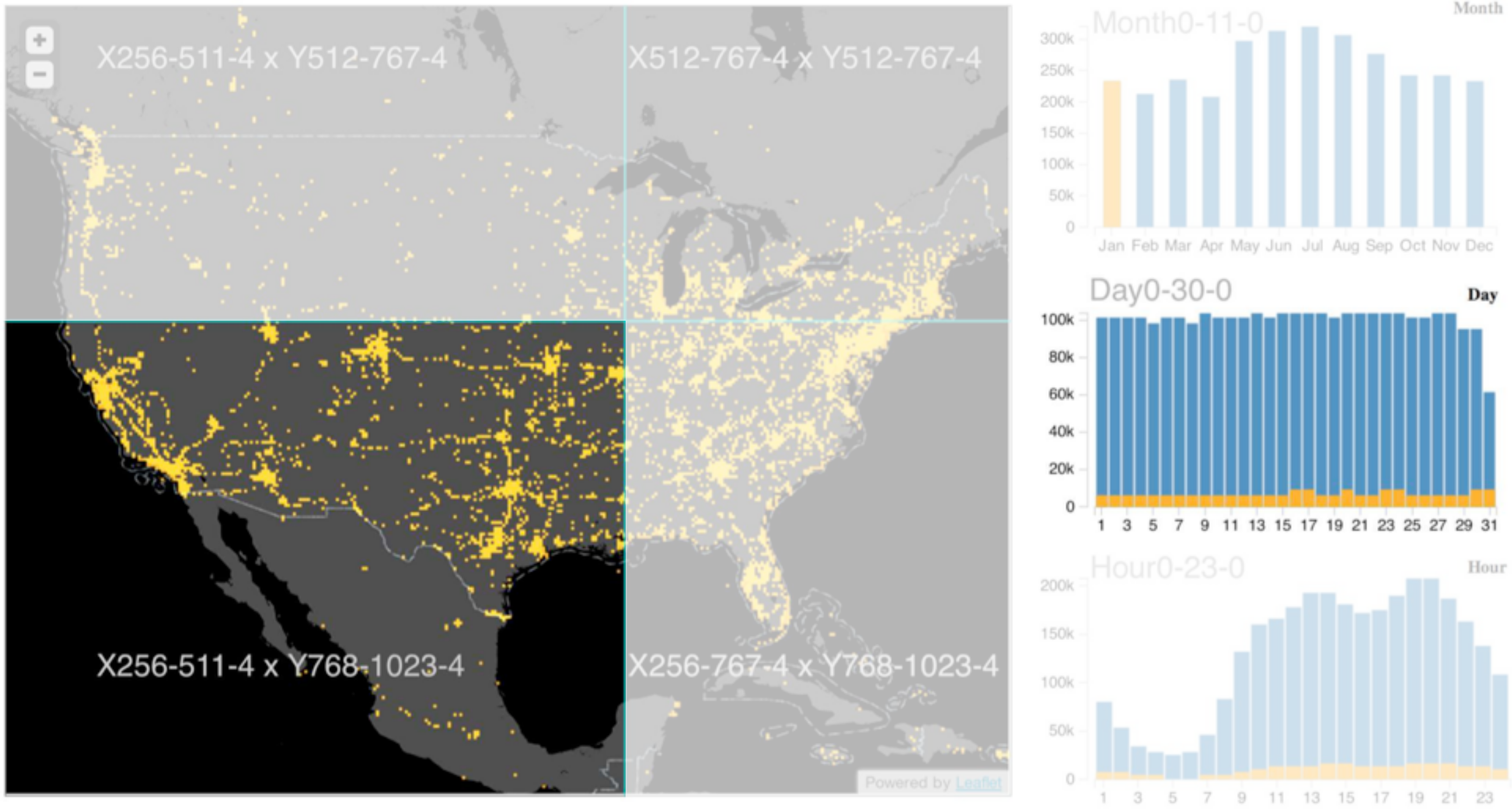

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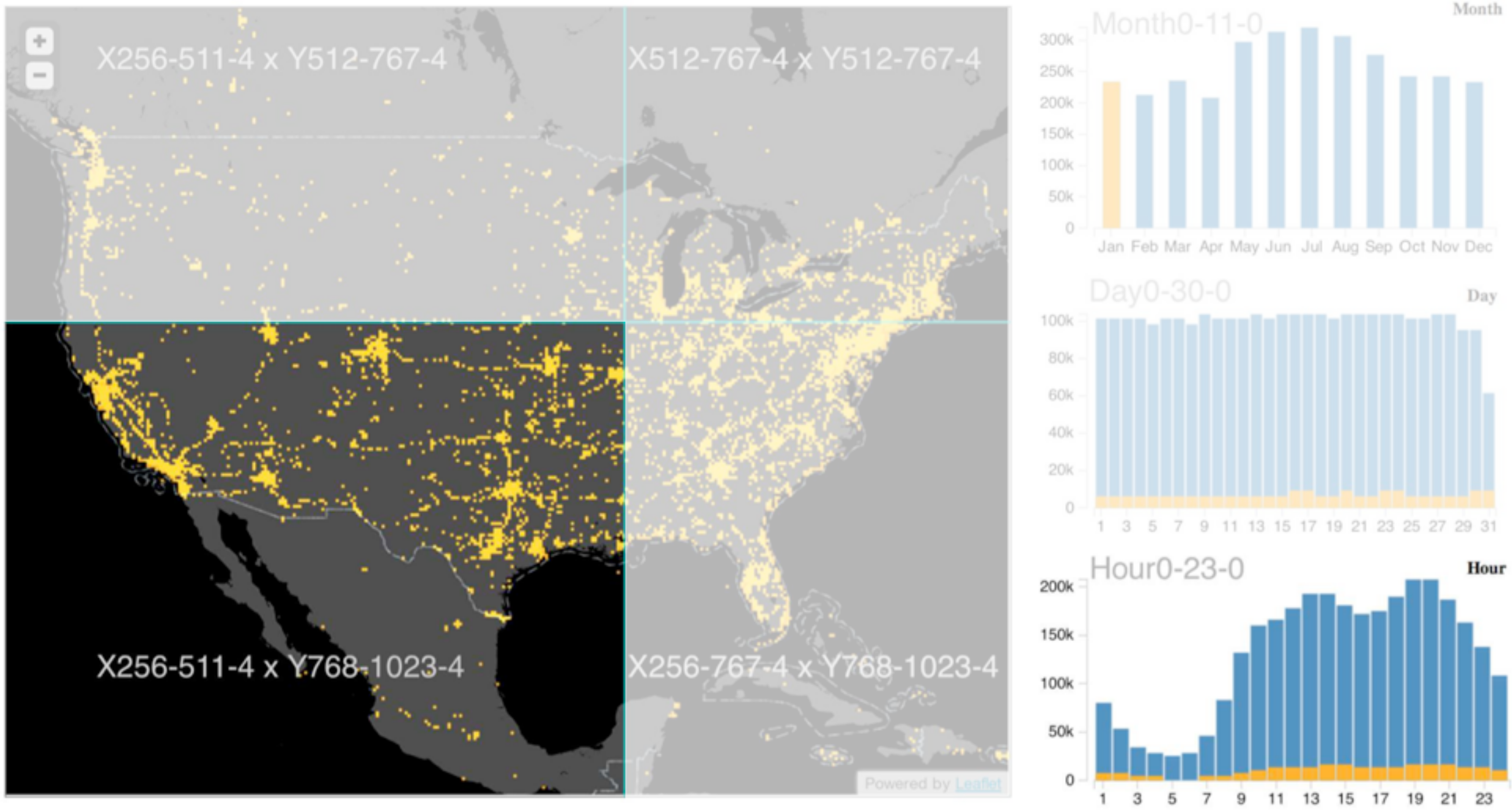

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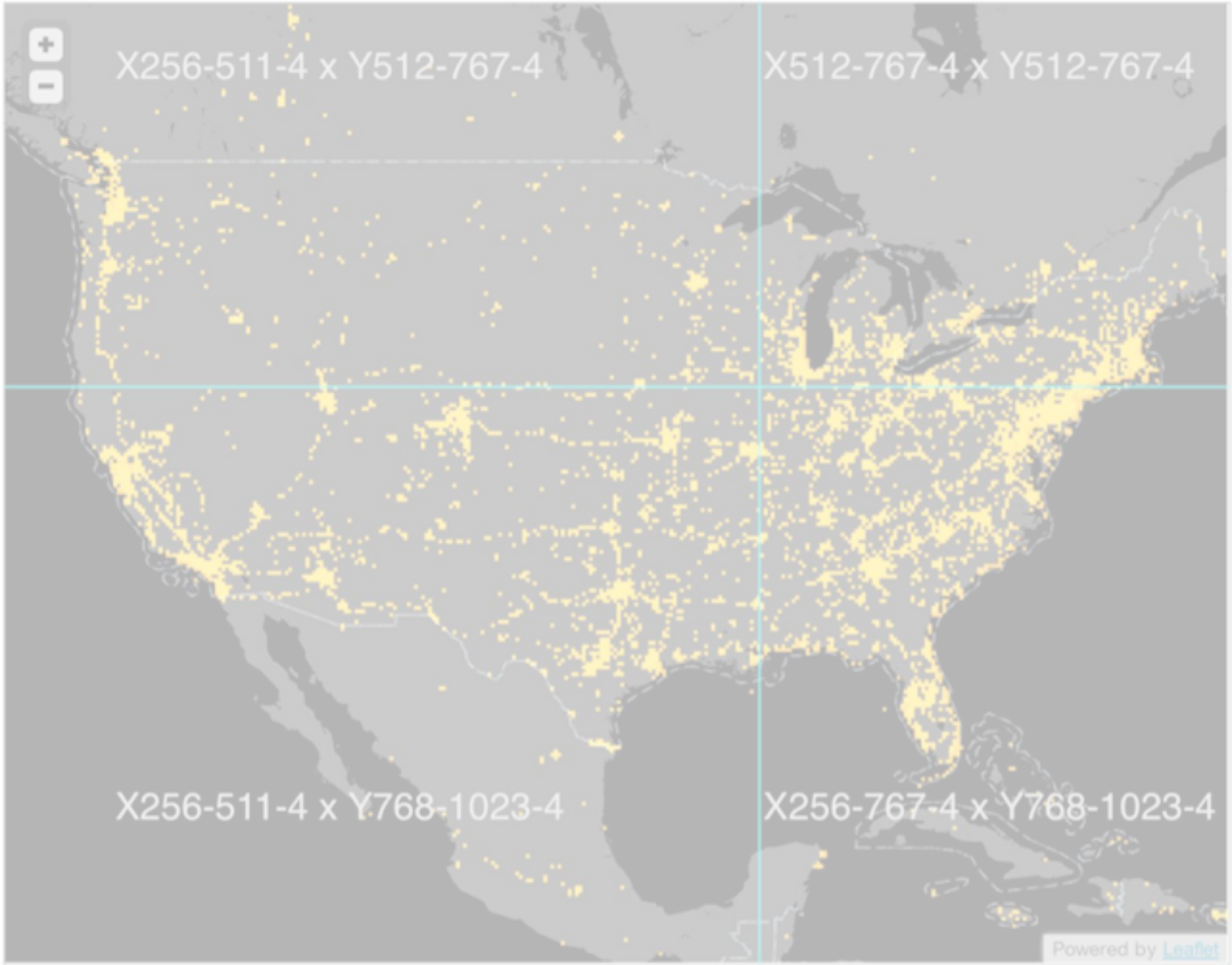

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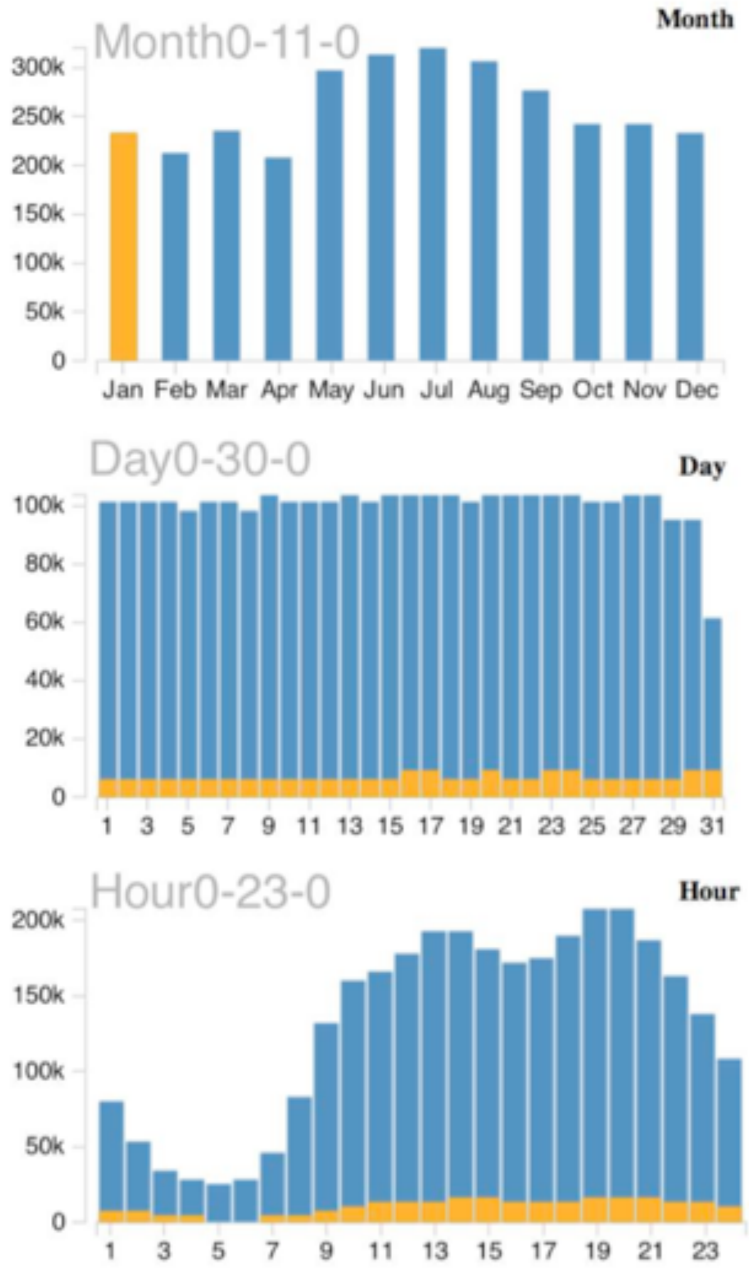

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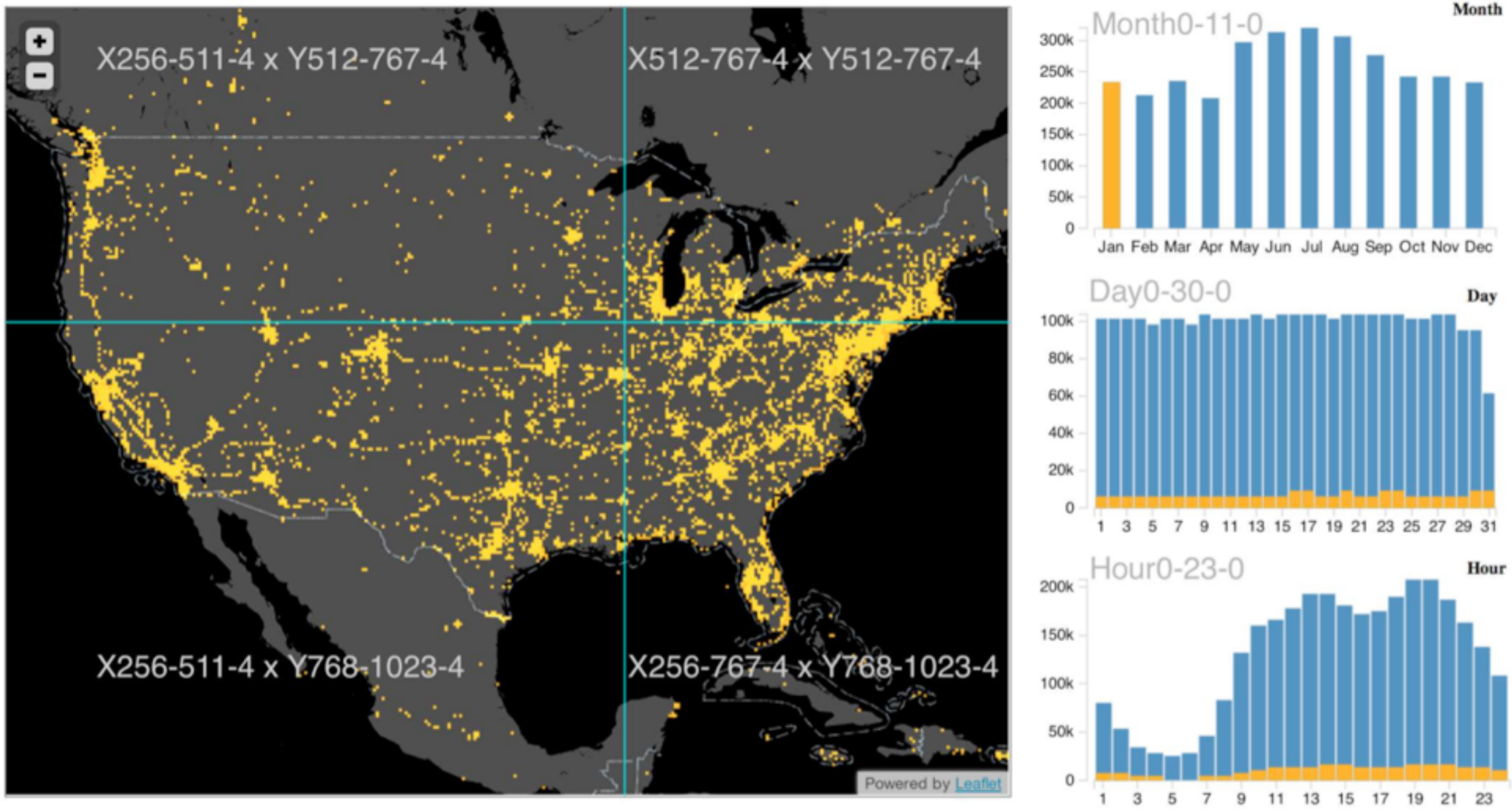

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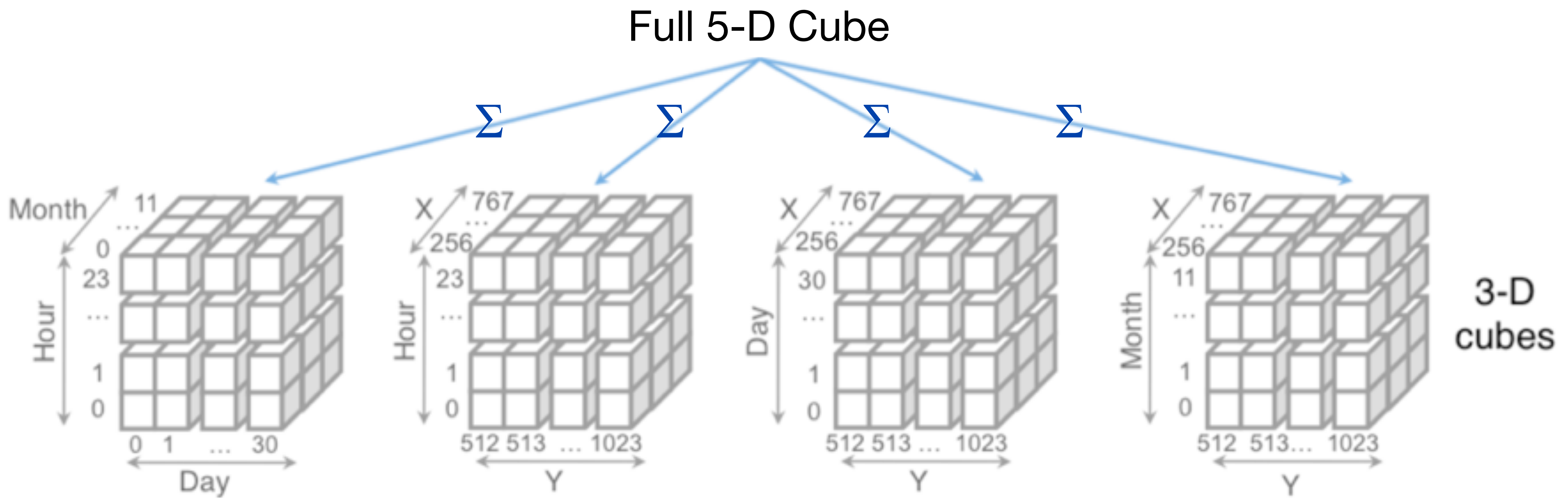
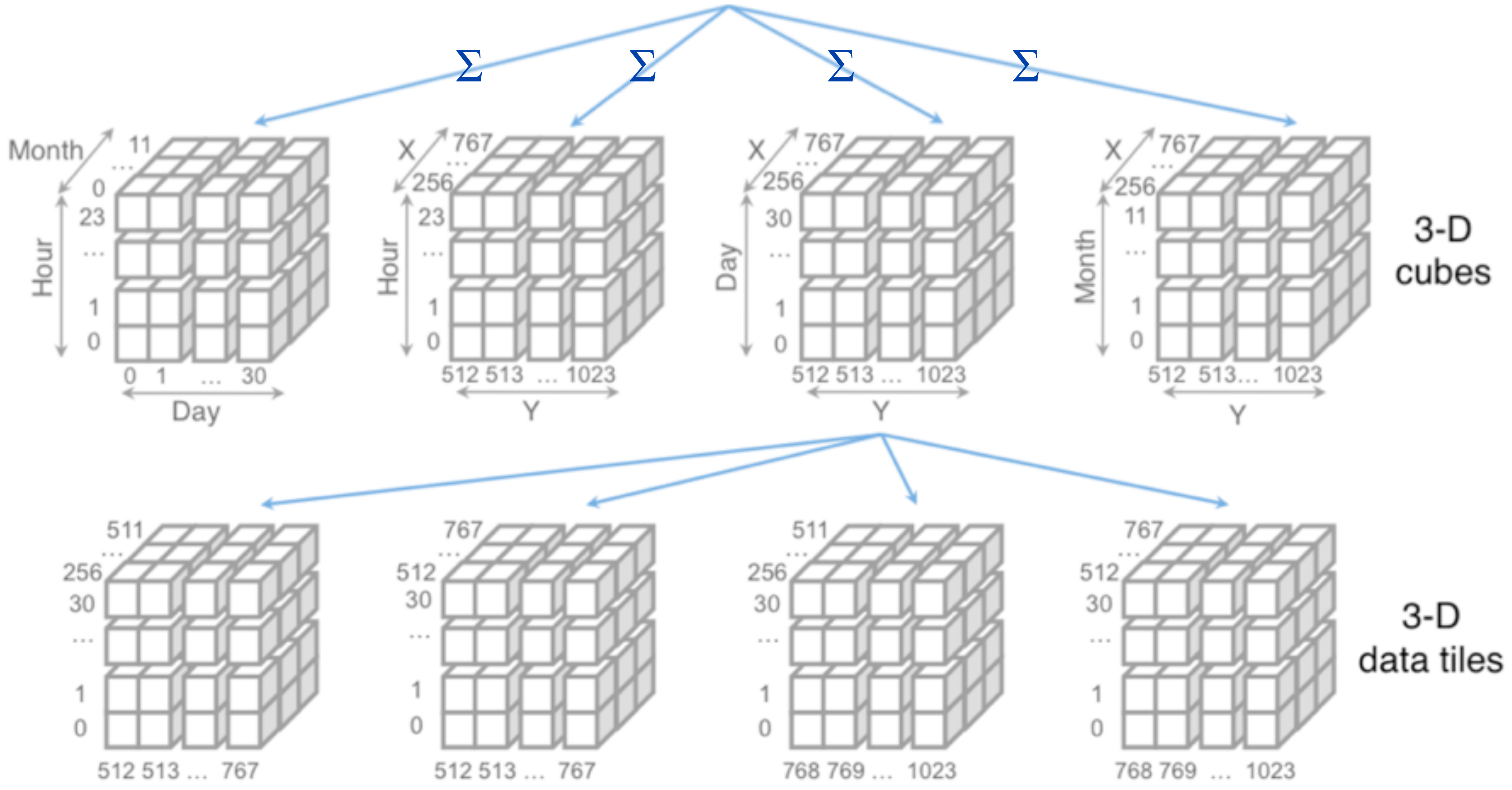
Full 5-D Cube



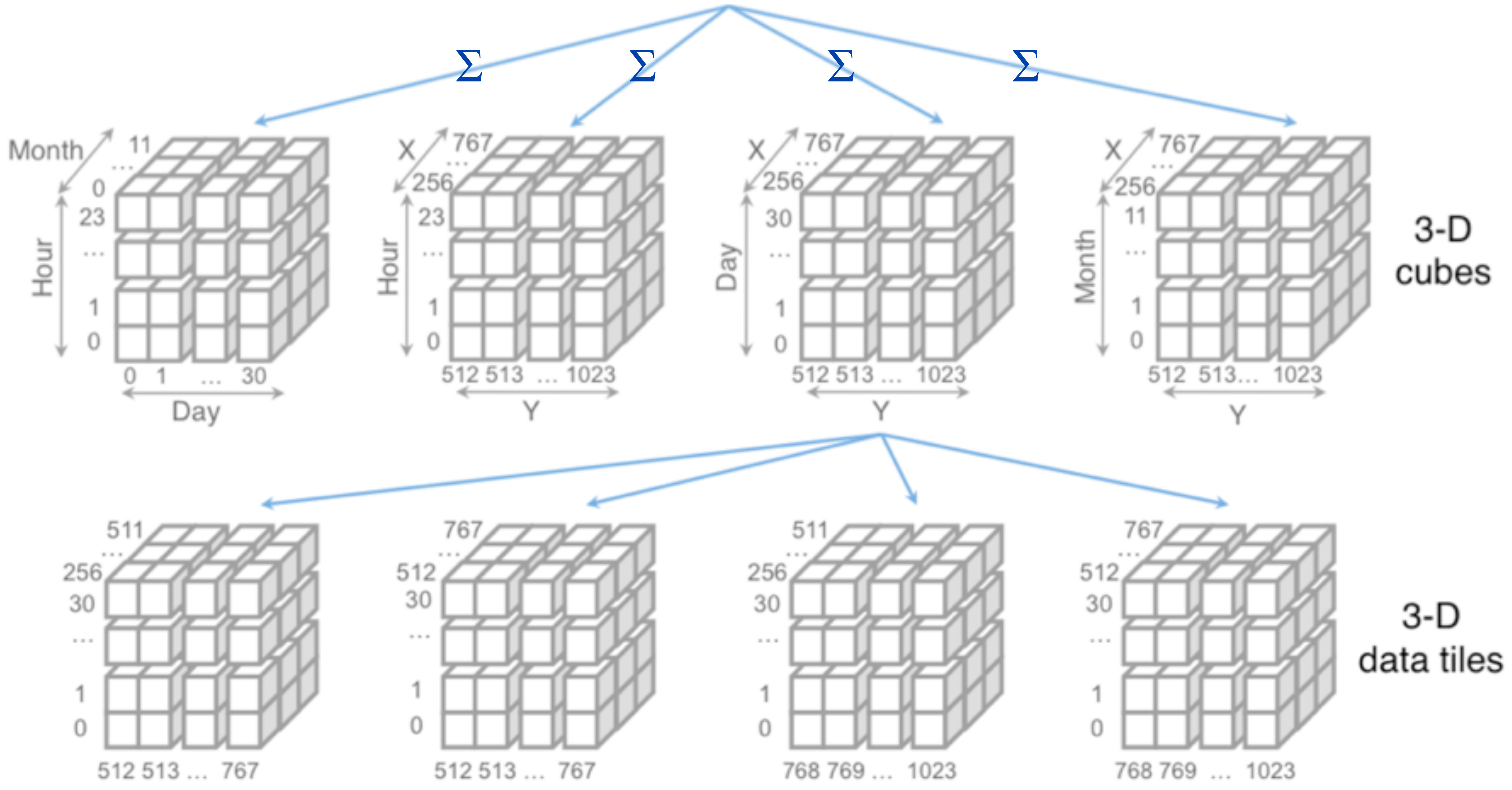
For any pair of 1D or 2D binned plots, the maximum number of dimensions needed to support brushing & linking is **four**.

Full 5-D Cube

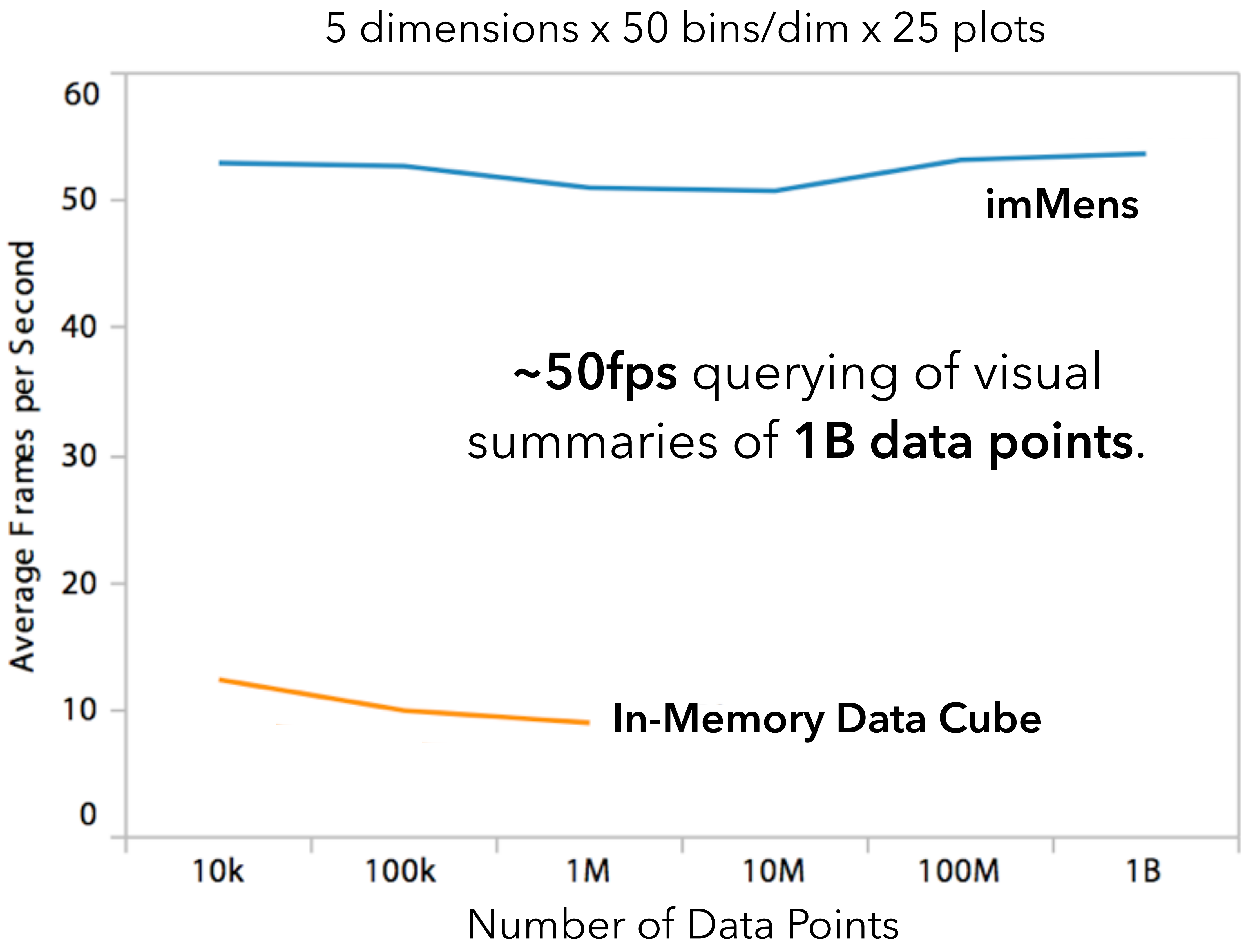


13 3-D Data Tiles

Full 5-D Cube → ~2.3B bins



13 3-D Data Tiles → ~17.6M bins (in 352KB!)


5 dimensions x 50 bins/dim x 25 plots
Average Frames per Second
60
50
40
30
20
10
0
10k
100k
1M
10M
100M
1B
Number of Data Points
imMens
In-Memory Data Cube
~50fps querying of visual summaries of 1B data points.

Limitations and Questions

But where do the multivariate data tiles come from?

They must be provided by a backend server. This can be time-consuming, particularly if supporting deep levels of zooming. imMens assumes that tiles have either been pre-computed or that a backing database can suitably generate them on demand.

Does super-low-latency interaction really matter?

Is it worth it to go to all of this trouble? (Short answer: yes!)

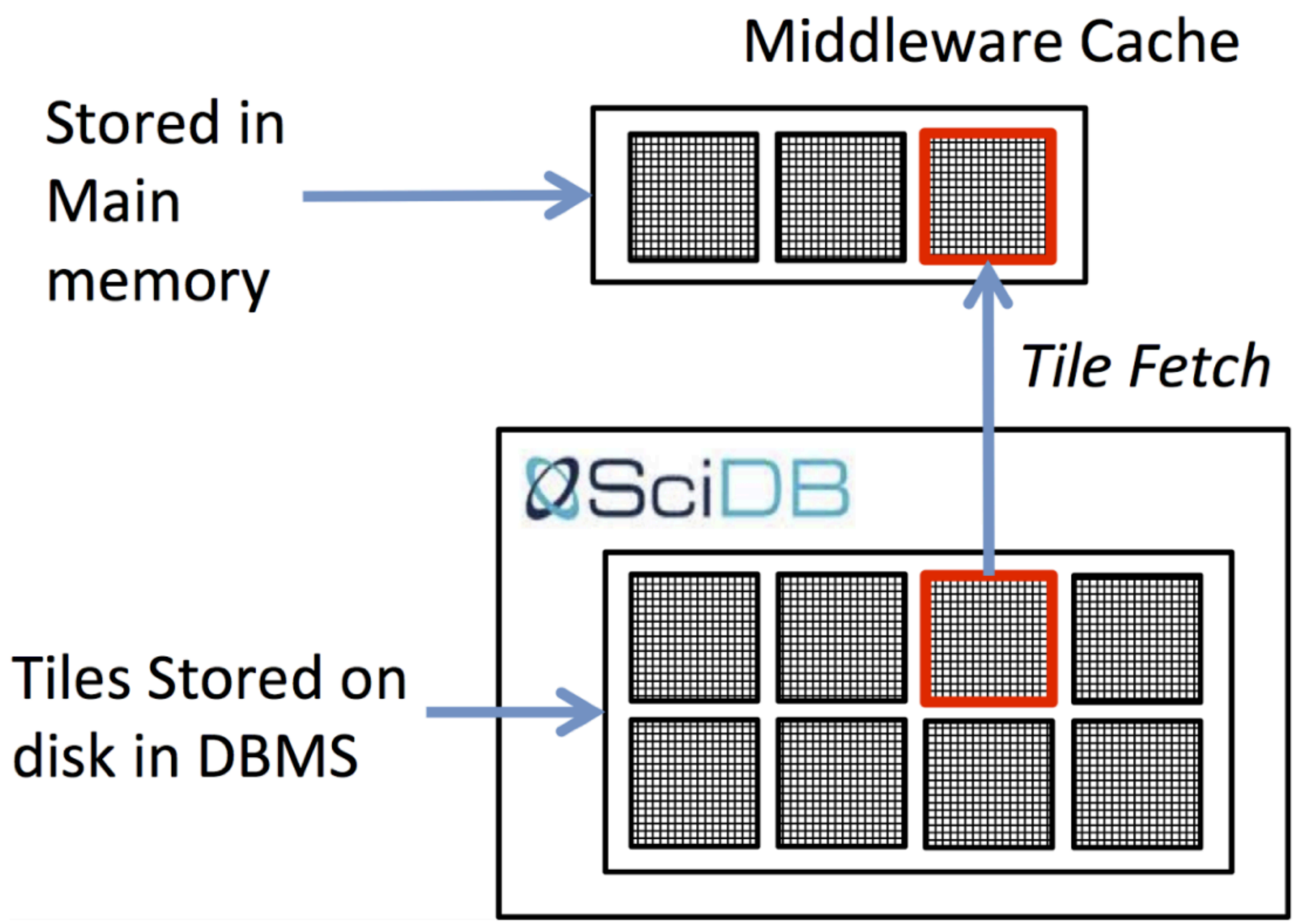
High latency leads to reduced analytic output [Liu & Heer, InfoVis 2014]

ForeCache

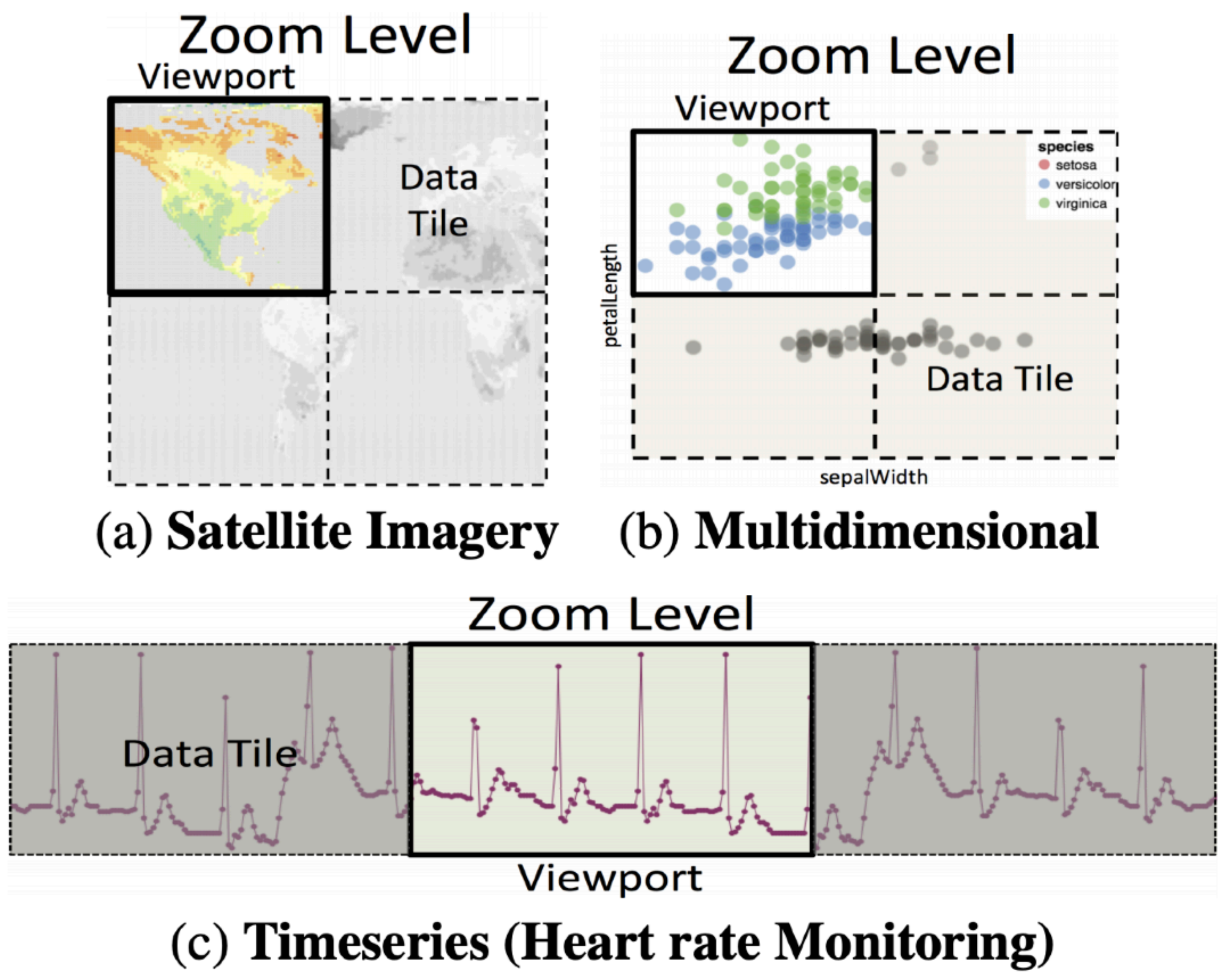
[Battle, Chang, & Stonebraker '16]

Strategies: Query Database, Prefetching

ForeCache is also a Data Tile-Based System



Manage a Cache of Tiles from DB



Example Tile-Based Views

Key Idea: Model & Predict User Behavior

1. Classify Analysis Phase

Foraging: Searching for patterns of interest
Sensemaking: Closely examine a region-of-interest (ROI)
Navigation: Transition between levels of detail

Train a machine learning classifier (SVM) to predict phase.
The input data is the activity trace of user interactions.

Key Idea: Model & Predict User Behavior

1. Classify Analysis Phase

2. Apply Prediction Models

Actions-Based: Use recent interactions to predict next ones.

You pan left twice; what is the probability you will do it again?

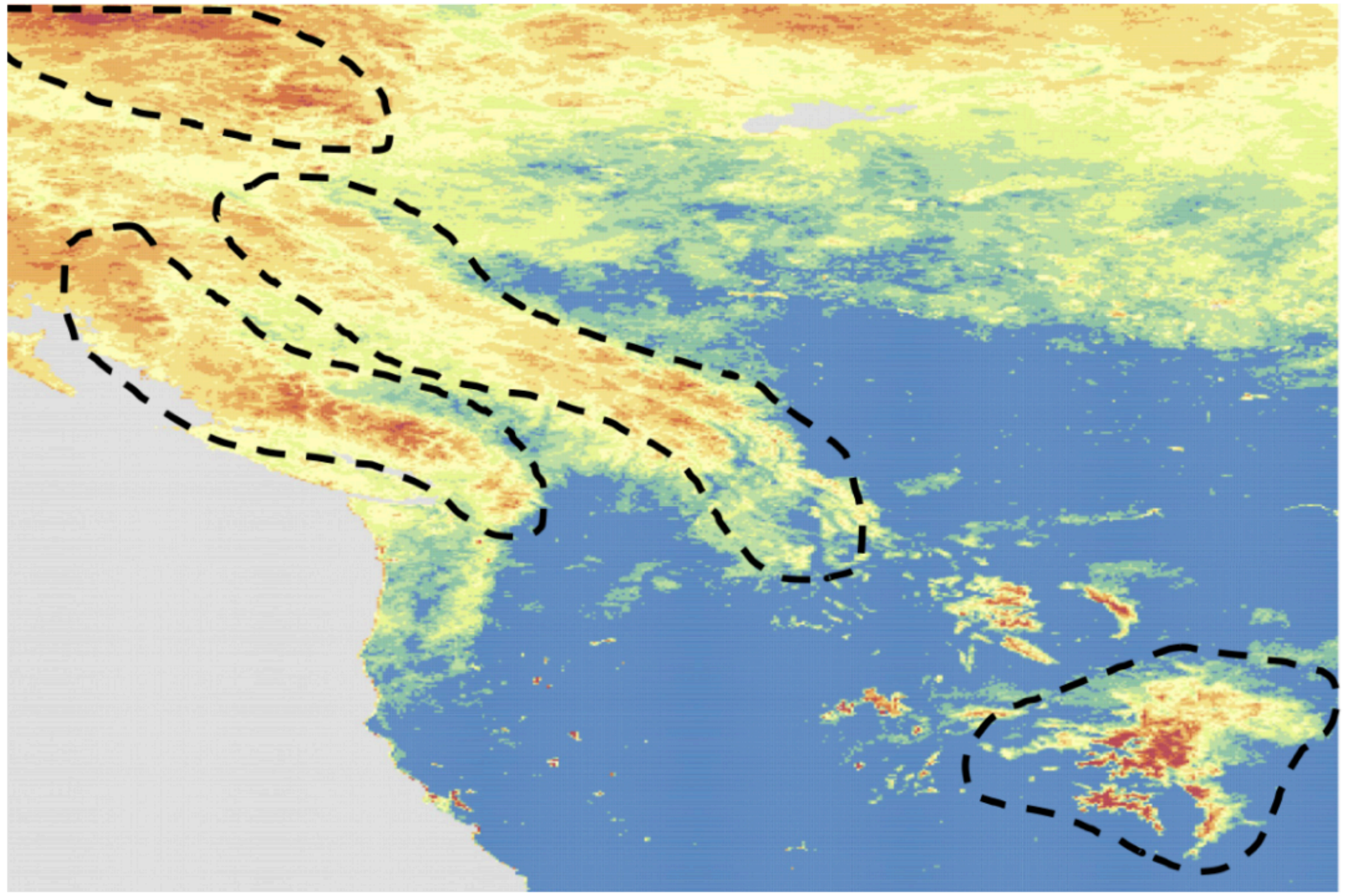
Signature-Based: Match to data characteristics of interest.

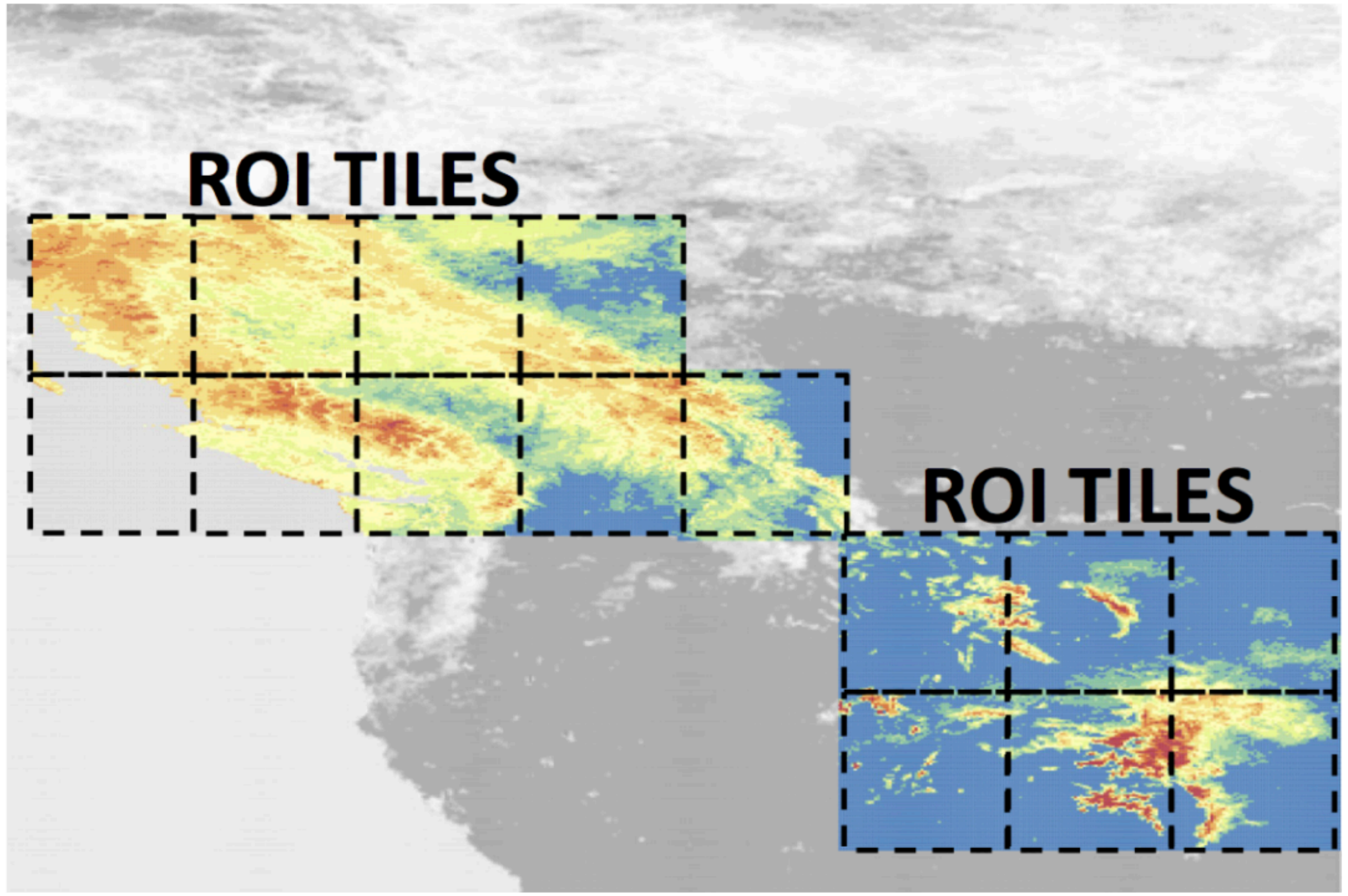
What data tiles are visually similar to current focus tiles?

These models are weighted based on the analysis phase.

Actions-Based for *navigation*. Signature-Based for *sensemaking*. Both applied equally for *foraging*.

Application: MODIS Satellite Data





Analyzing snow cover in a scientific database. ROI = Region of Interest

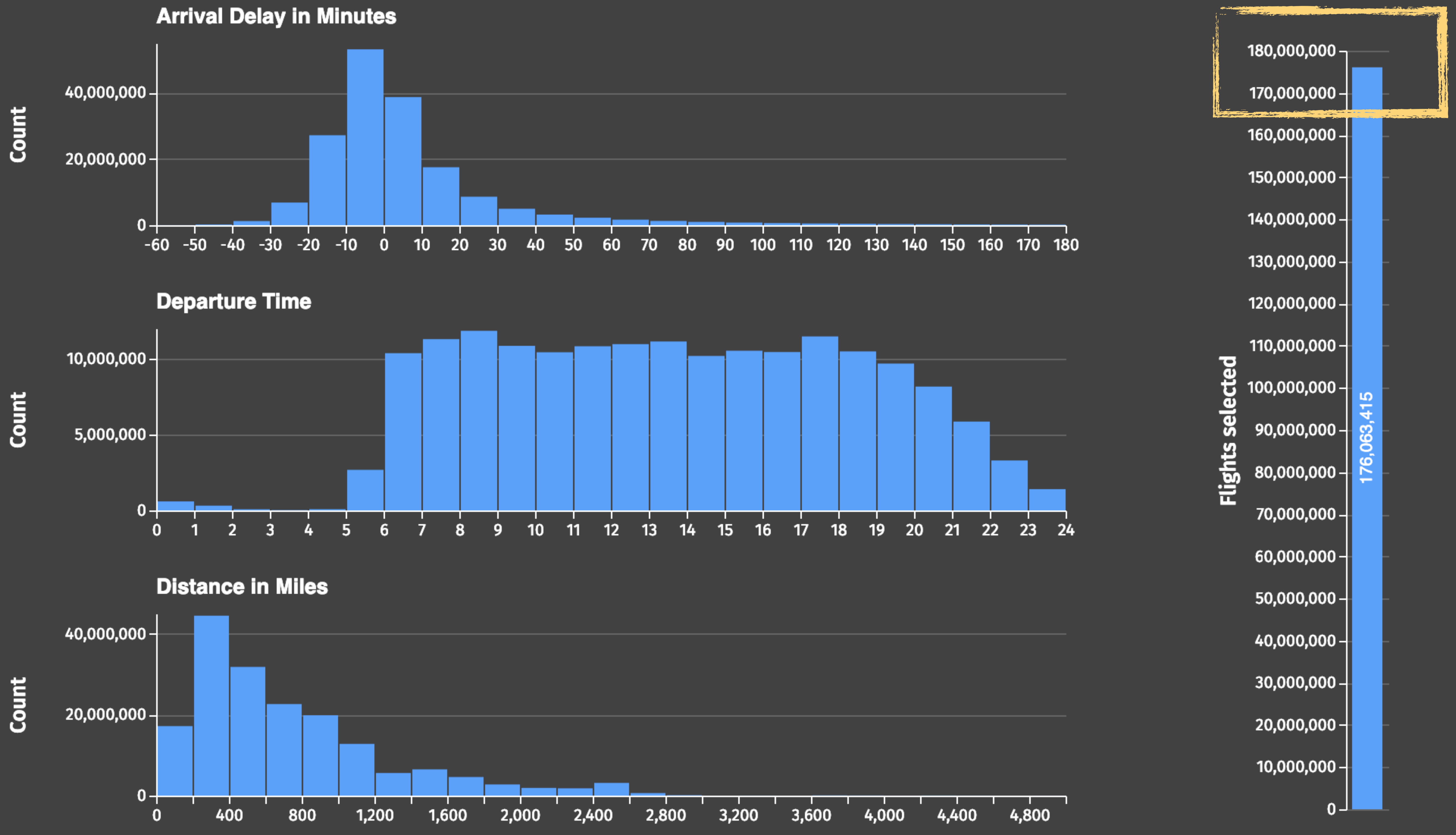
ForeCache improves latency:

- 430% better than current non-prefetching systems
- 88% better than existing prediction methods

Falcon

[Moritz, Howe, & Heer '19]

Strategies: Query Database, Client-Side Data Cubes, Prefetching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Departure Time
Count
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Distance in Miles
Count
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Flights selected
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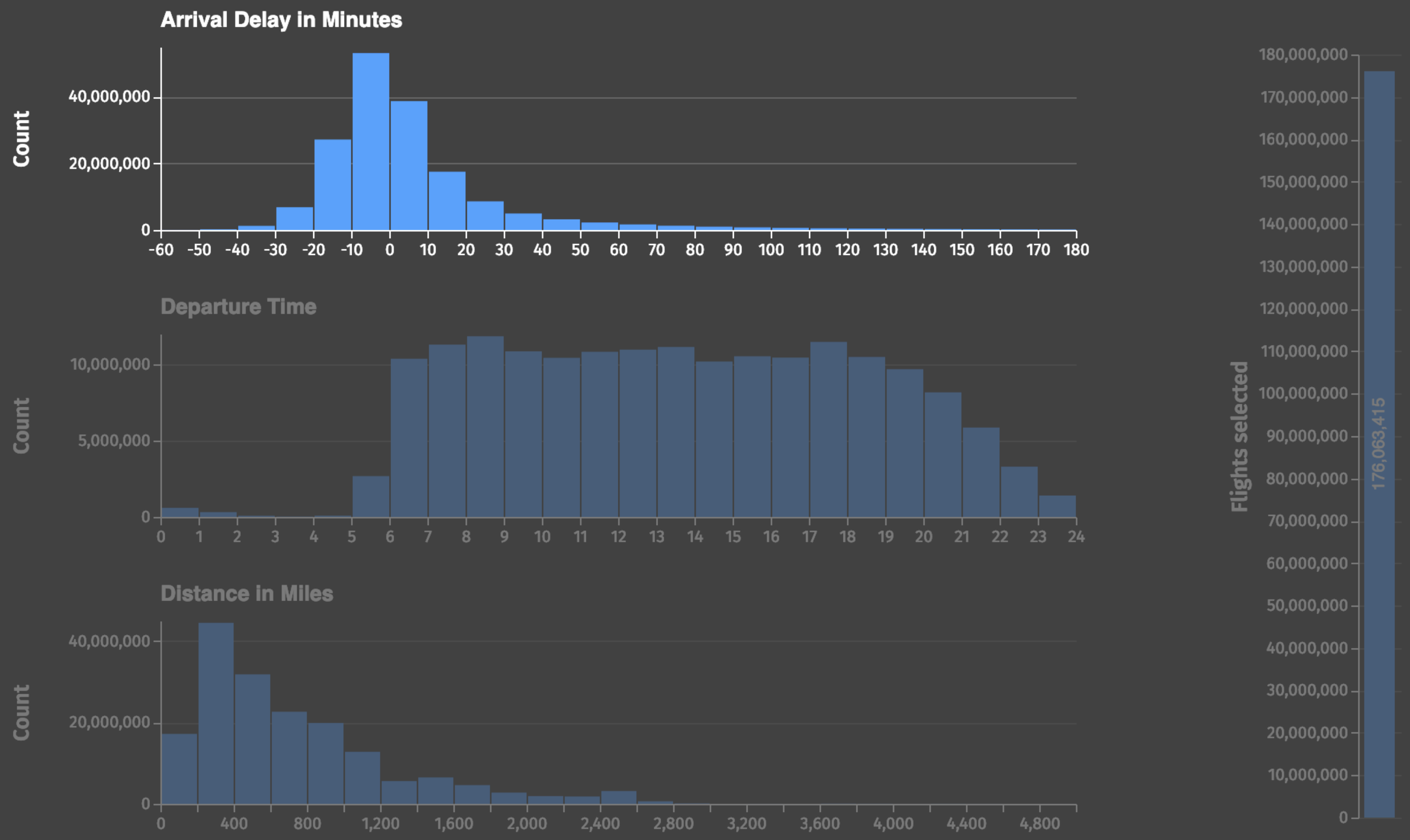

Arrival Delay in Minutes
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Distance in Miles
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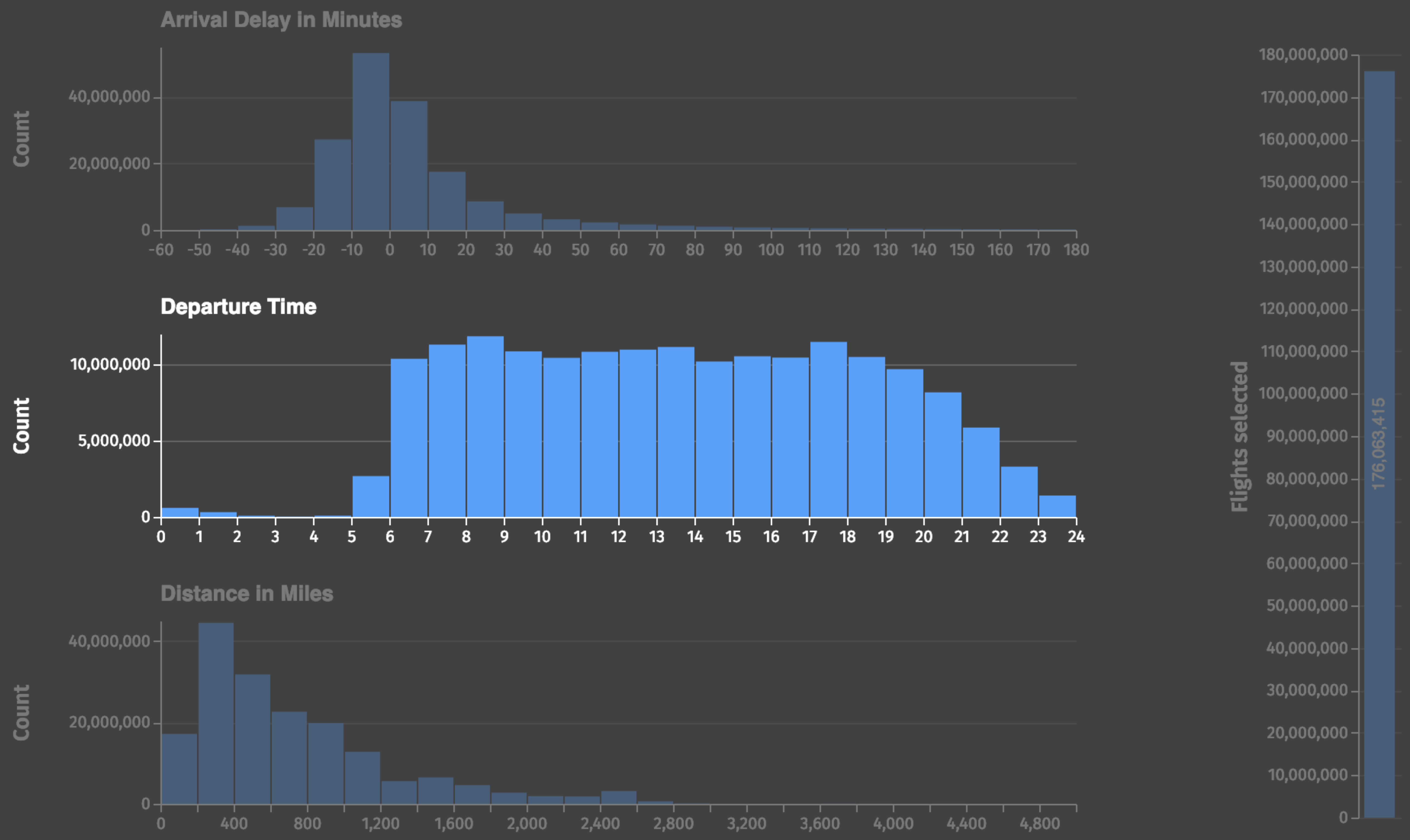
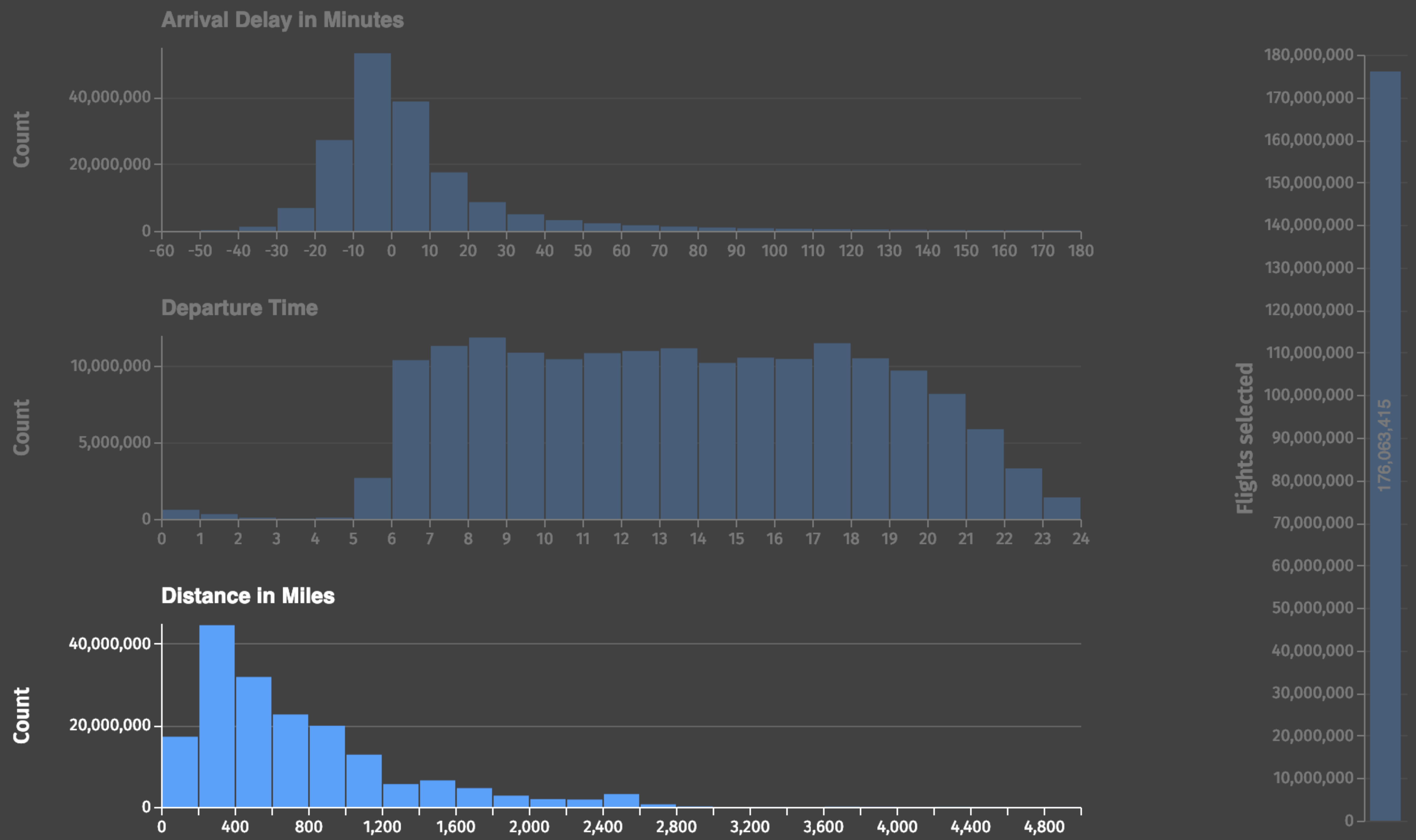


Arrival Delay in Minutes
Count
Departure Time
Count
Distance in Miles
Count
Flights selected
176,063,415


Arrival Delay in Minutes
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Distance in Miles
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Flights selected
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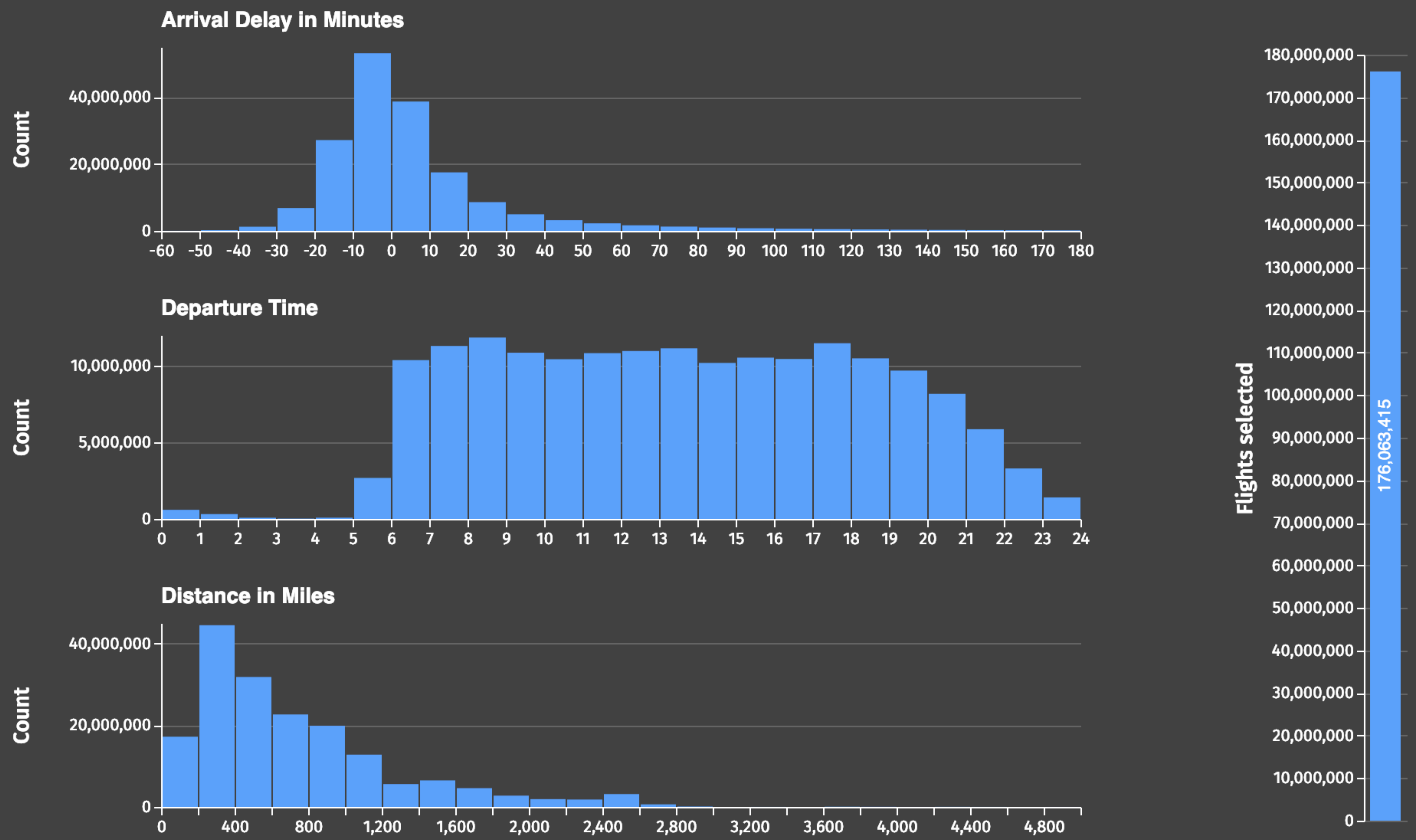

Arrival Delay in Minutes
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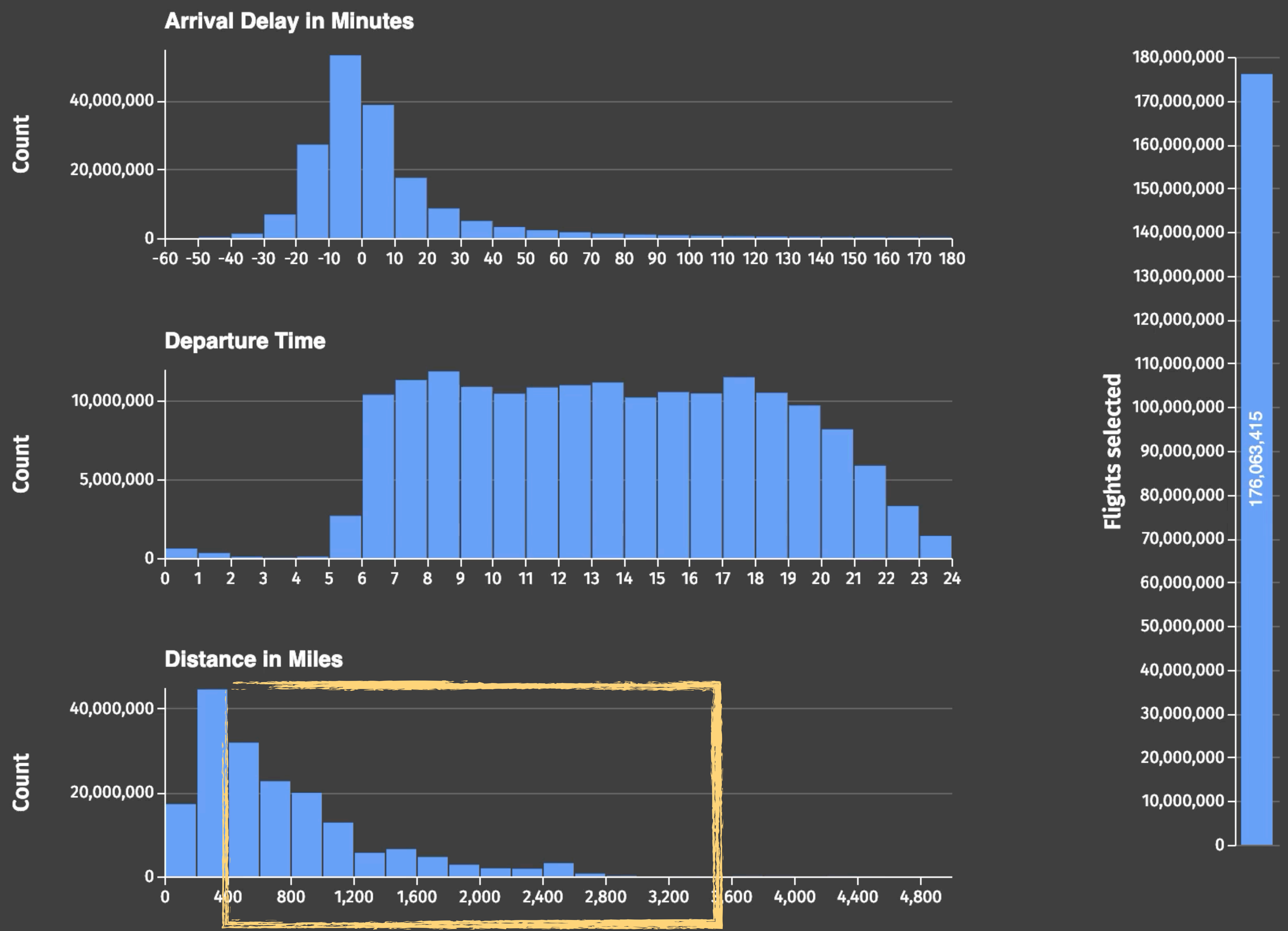
Falcon

uwdata.github.io/falcon


Arrival Delay in Minutes
Count
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20,000,000
0
-60 -50 -40 -30 -20 -10 0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180
Departure Time
Count
10,000,000
5,000,000
0
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
Distance in Miles
Count
40,000,000
20,000,000
0
0 400 800 1,200 1,600 2,000 2,400 2,800 3,200 3,600 4,000 4,400 4,800
Flights selected
176,063,415
180,000,000
170,000,000
160,000,000
150,000,000
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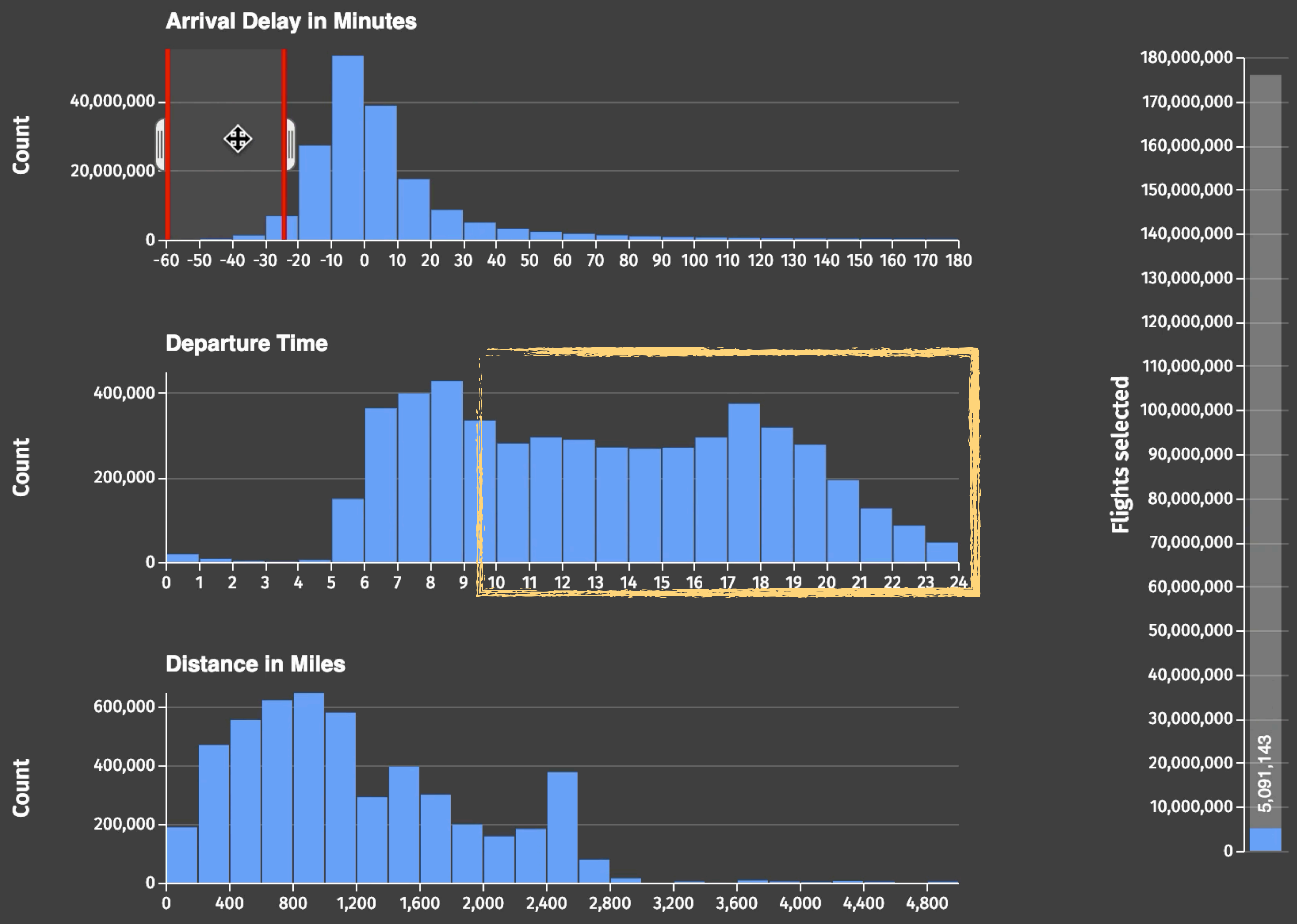
Arrival Delay in Minutes
Count
40,000,000
20,000,000
0
-60 -50 -40 -30 -20 -10 0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180
Departure Time
Count
400,000
200,000
0
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
Distance in Miles
Count
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400,000
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0 400 800 1,200 1,600 2,000 2,400 2,800 3,200 3,600 4,000 4,400 4,800
Flights selected
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160,000,000
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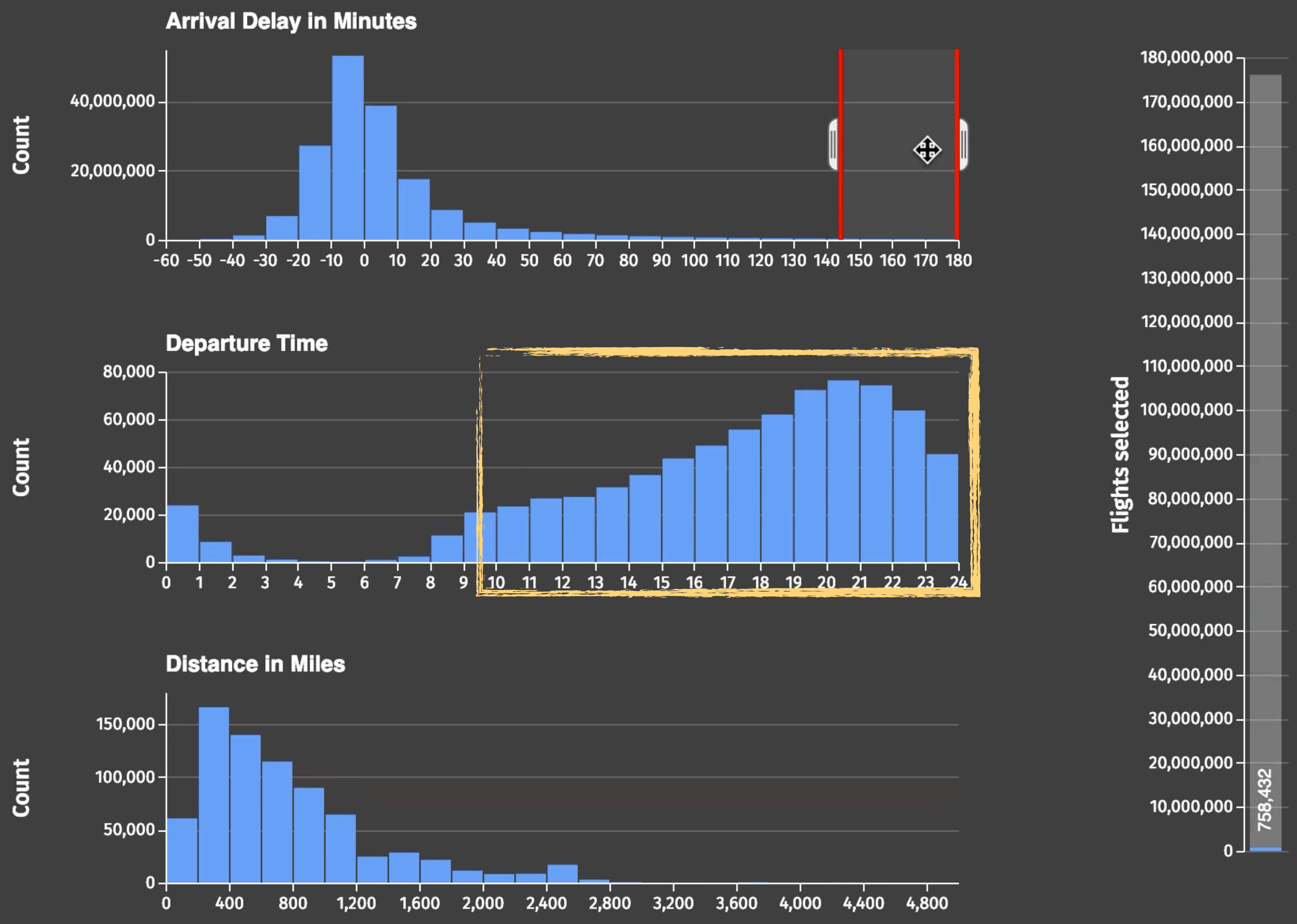
Arrival Delay in Minutes
Count
40,000,000
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0
-60 -50 -40 -30 -20 -10 0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180
Departure Time
Count
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0
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
Distance in Miles
Count
150,000
100,000
50,000
0
0 400 800 1,200 1,600 2,000 2,400 2,800 3,200 3,600 4,000 4,400 4,800
Flights selected
180,000,000
170,000,000
160,000,000
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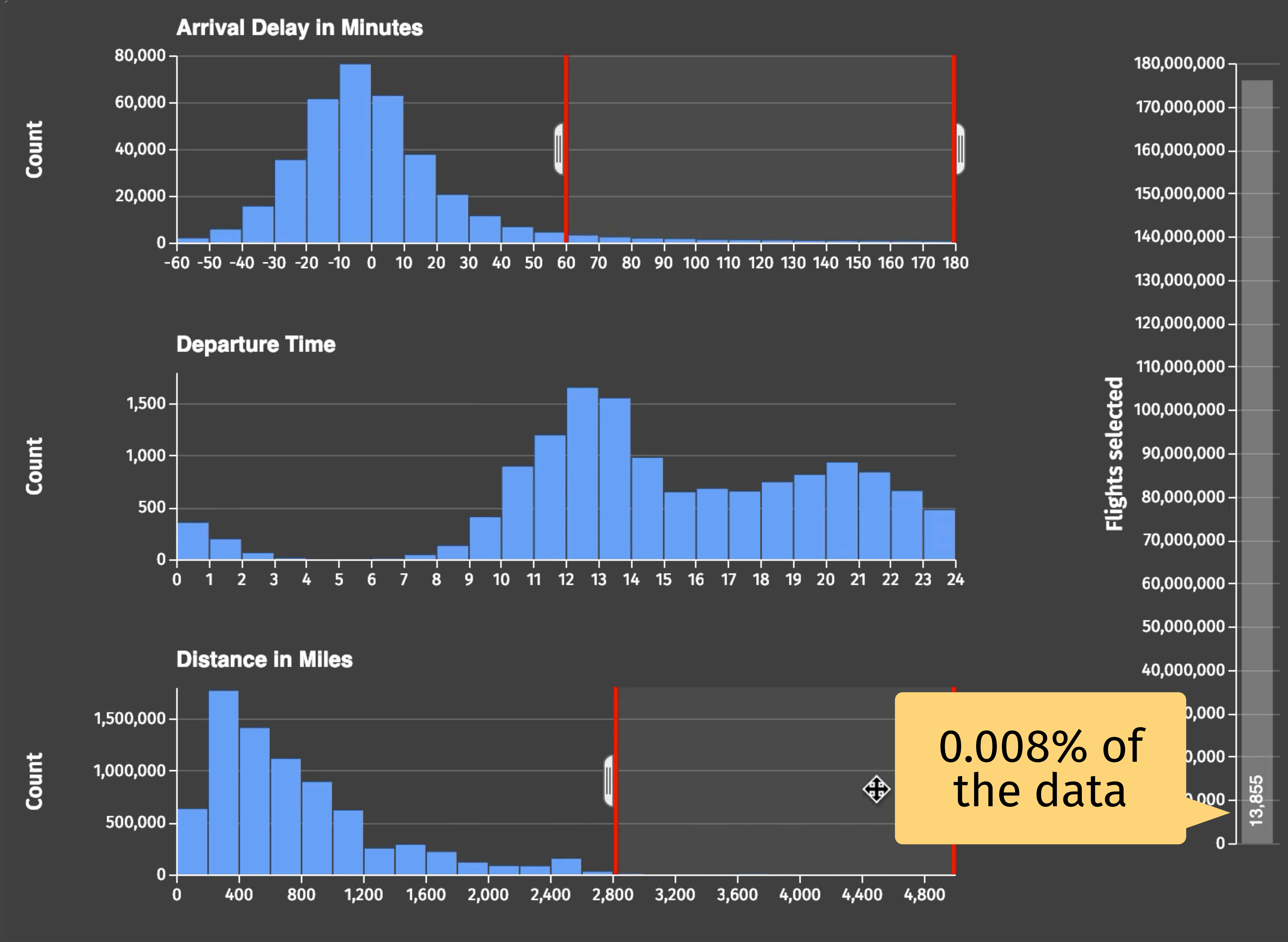
758,432


Arrival Delay in Minutes
Count
80,000
60,000
40,000
20,000
0
-60 -50 -40 -30 -20 -10 0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180
Departure Time
Count
1,500
1,000
500
0
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
Distance in Miles
Count
1,500,000
1,000,000
500,000
0
0 400 800 1,200 1,600 2,000 2,400 2,800 3,200 3,600 4,000 4,400 4,800
Flights selected
180,000,000
170,000,000
160,000,000
150,000,000
140,000,000
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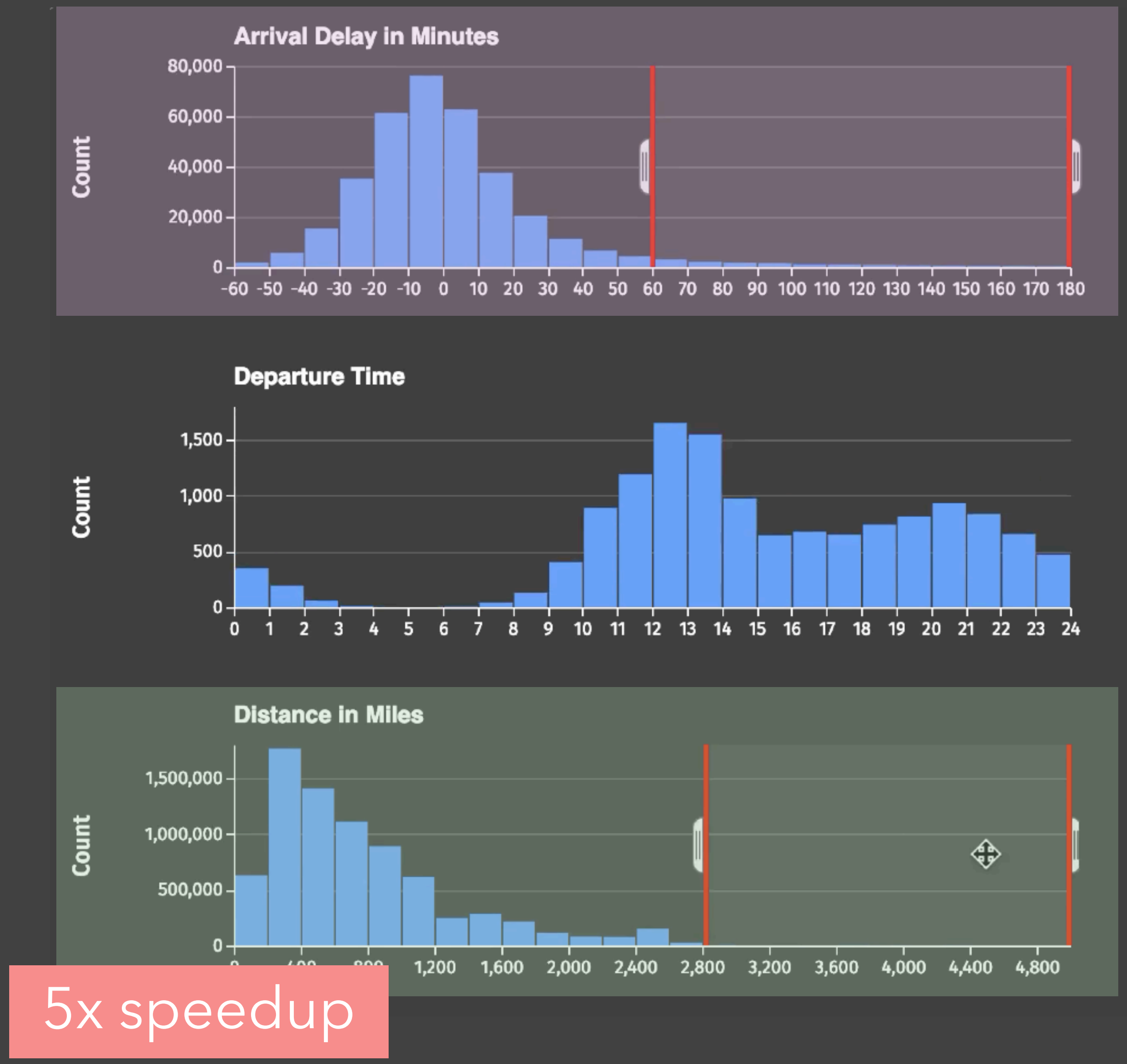
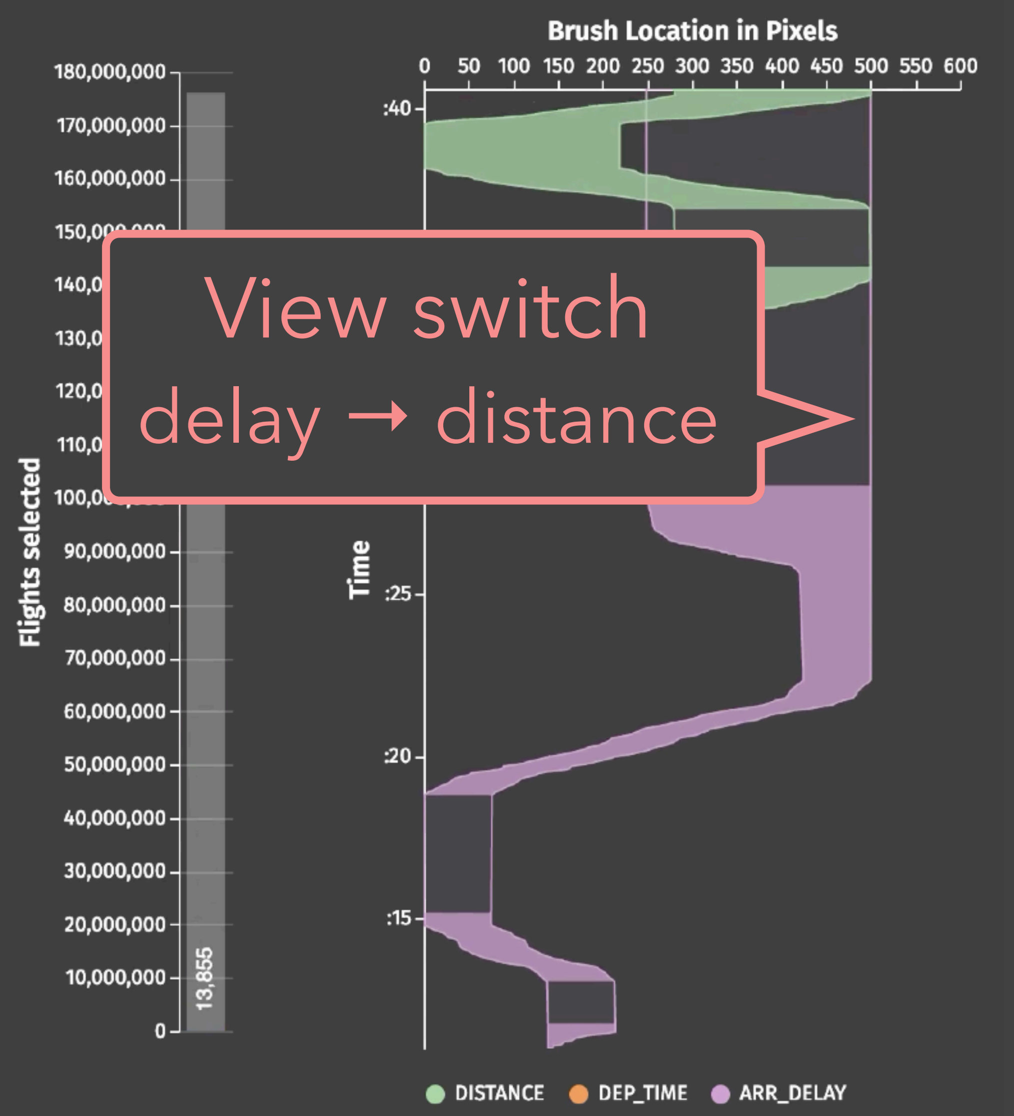
120,000,000
110,000,000
100,000,000
90,000,000
80,000,000
70,000,000
60,000,000
50,000,000
40,000,000
0
13,855
0.008% of the data

How does Falcon support fine-grained real-time interaction?

Falcon Interaction Log





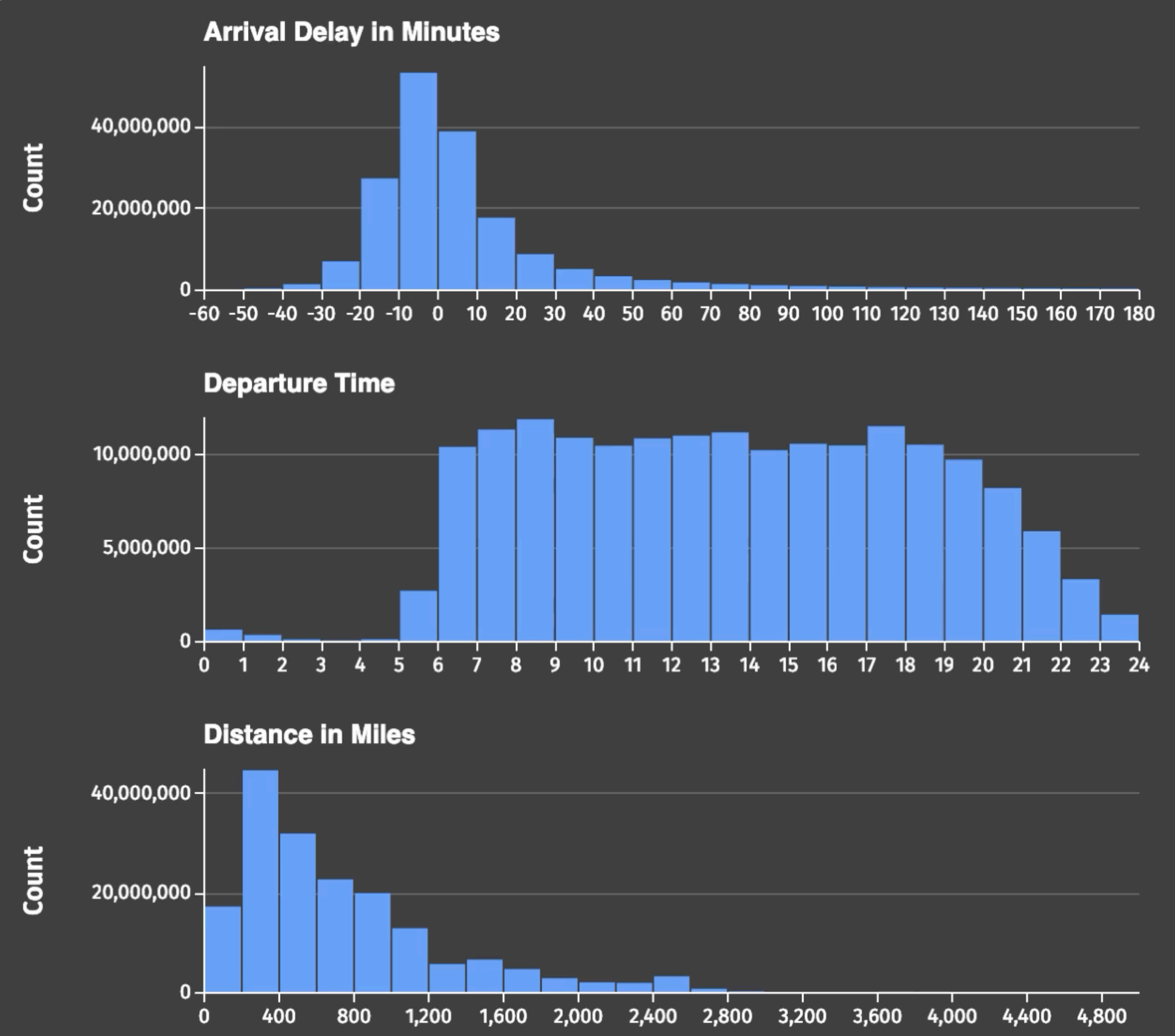
👁️ Brushing is more common and people are sensitive to latencies.

💡 Prioritize brushing latency over view switching latency.

Key Idea:

User-centered prefetching and indexing to support all brushing interactions with one view.

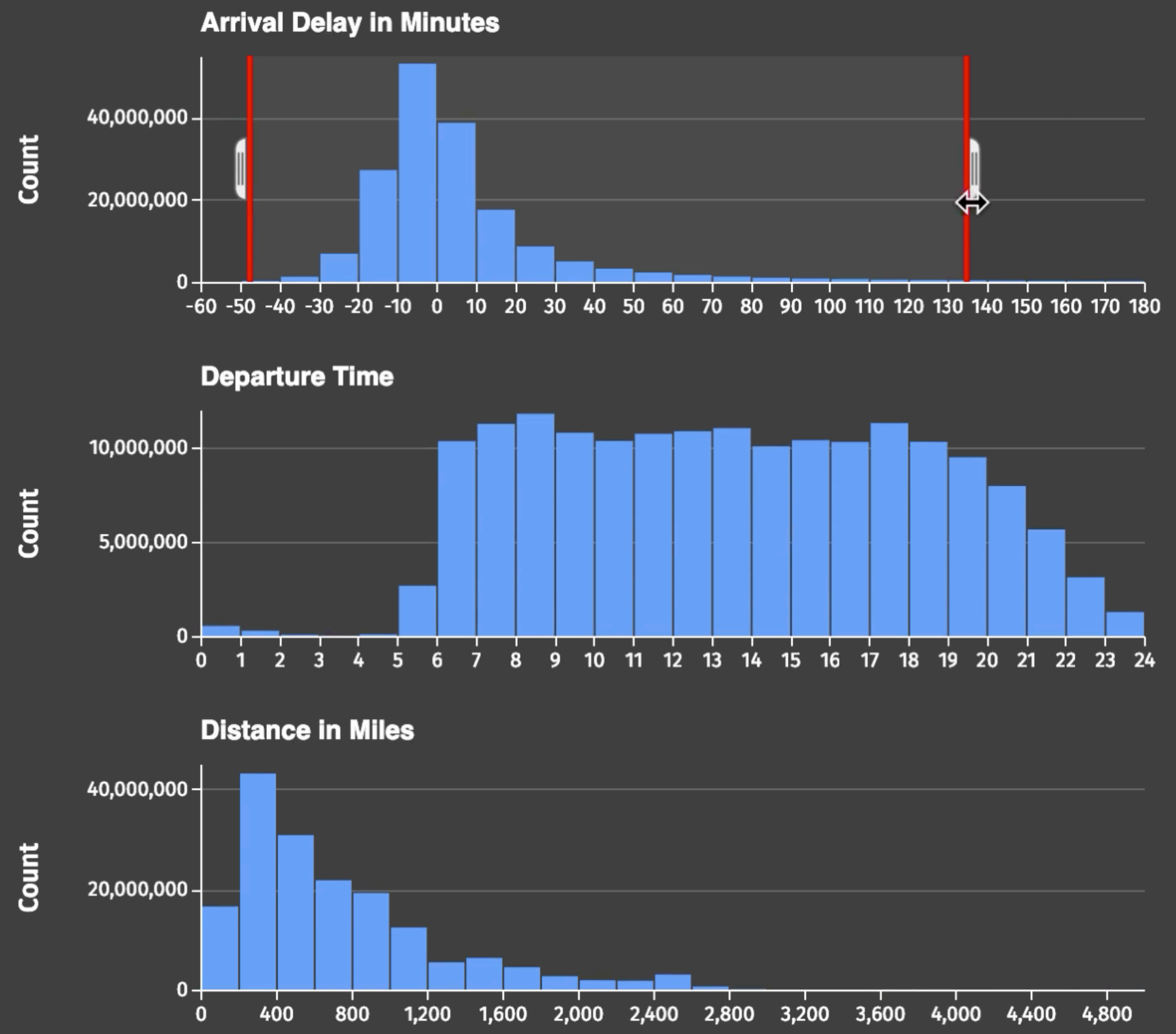
Re-compute if the user switches the view.



brushes in the precomputed view

serves requests from a data cube

Data Cube. Gray et al. *1997*.



brushes in the precomputed view

serves requests from a data cube

Data Cube. Gray et al. *1997.*

interacts with a new view

query for new data cubes

Constant data & time.
Client only.

brushes in the precomputed view

serves requests from a data cube

Data Cube. Gray et al. *1997.*

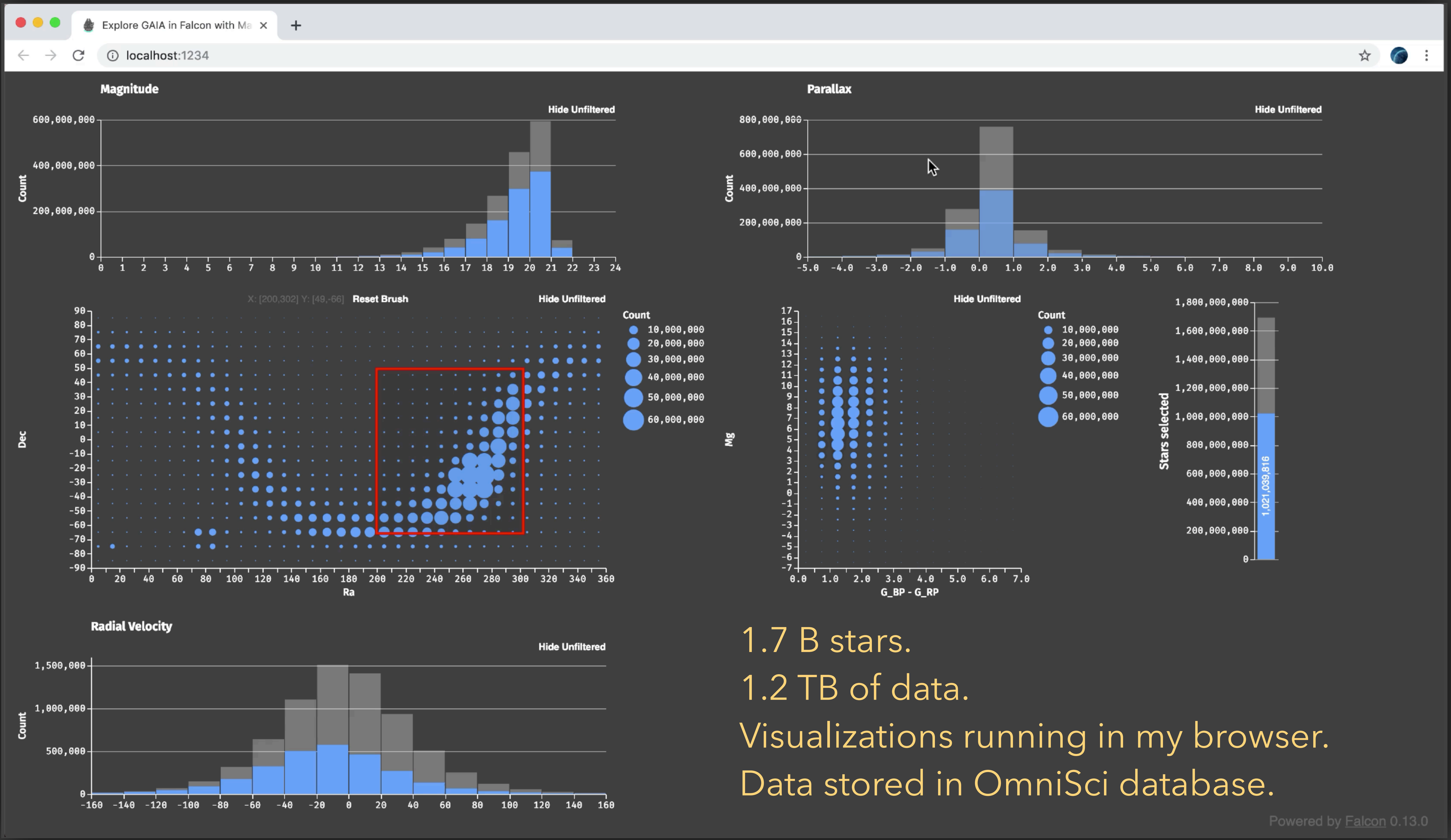
💡 Aggregation decouples interactions from queries over the raw data.

Requires one pass
over the data.

interacts with a new view

query for new data cubes

💡 View switches are **rare** and users are **not as latency sensitive** with them.


Explore GAIA in Falcon with Ma
localhost:1234
Magnitude
Hide Unfiltered
Count
600,000,000
400,000,000
200,000,000
0
Parallax
Hide Unfiltered
800,000,000
600,000,000
400,000,000
200,000,000
X: [200,302] Y: [49,-66]
Reset Brush
Hide Unfiltered
Count
10,000,000
20,000,000
30,000,000
40,000,000
50,000,000
60,000,000
Dec
Ra
Mg
G_BP - G_RP
Stars selected
1,021,039,816
Radial Velocity
Hide Unfiltered
1,500,000
1,000,000
500,000
1.7 B stars.
1.2 TB of data.
Visualizations running in my browser.
Data stored in OmniSci database.
Powered by Falcon 0.13.0

"With Falcon it feels like I'm really interacting with my data."

Data Platform Engineer at Stitch Fix

In Conclusion…

Two Challenges:

1. Effective **visual encoding**
2. Real-time **interaction**

Perceptual and interactive scalability should be limited by the **chosen resolution** of the visualized data, not the number of records.

Bin > Aggregate (> Smooth) > Plot

1. **Bin** Divide data domain into discrete “buckets”
2. **Aggregate** Count, Sum, Average, Min, Max, …
3. **Smooth** *Optional*: smooth aggregates [Wickham ’13]
4. **Plot** Visualize the aggregate values

Interactive Scalability Strategies

1. Query Database
2. Client-Side Indexing / Data Cubes
3. Prefetching
4. Approximation

These strategies are **not** mutually exclusive!
Systems can apply them in tandem.