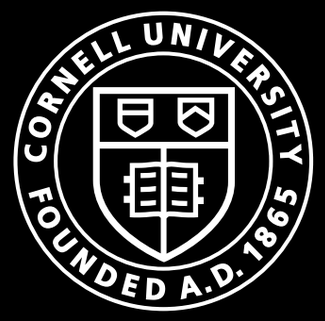
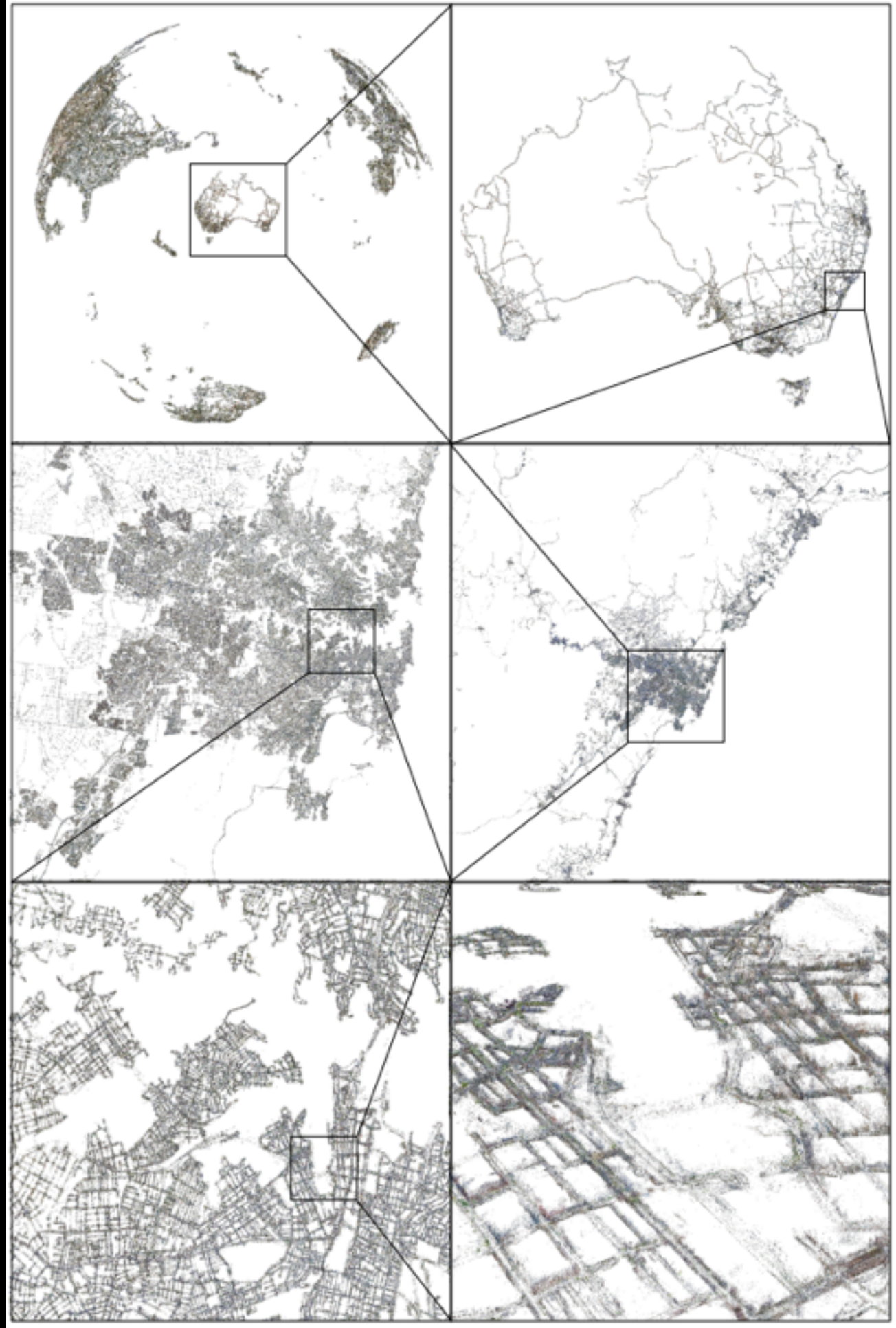
Scene Chronology

Kevin Matzen and Noah Snavely



Cornell University

Model of Dubrovnik from 1,000s of Internet photos [Agarwal 2009]



Planet-scale reconstruction

[Klingner, et. al. ICCV 2011]

Are we done with 3D modeling?

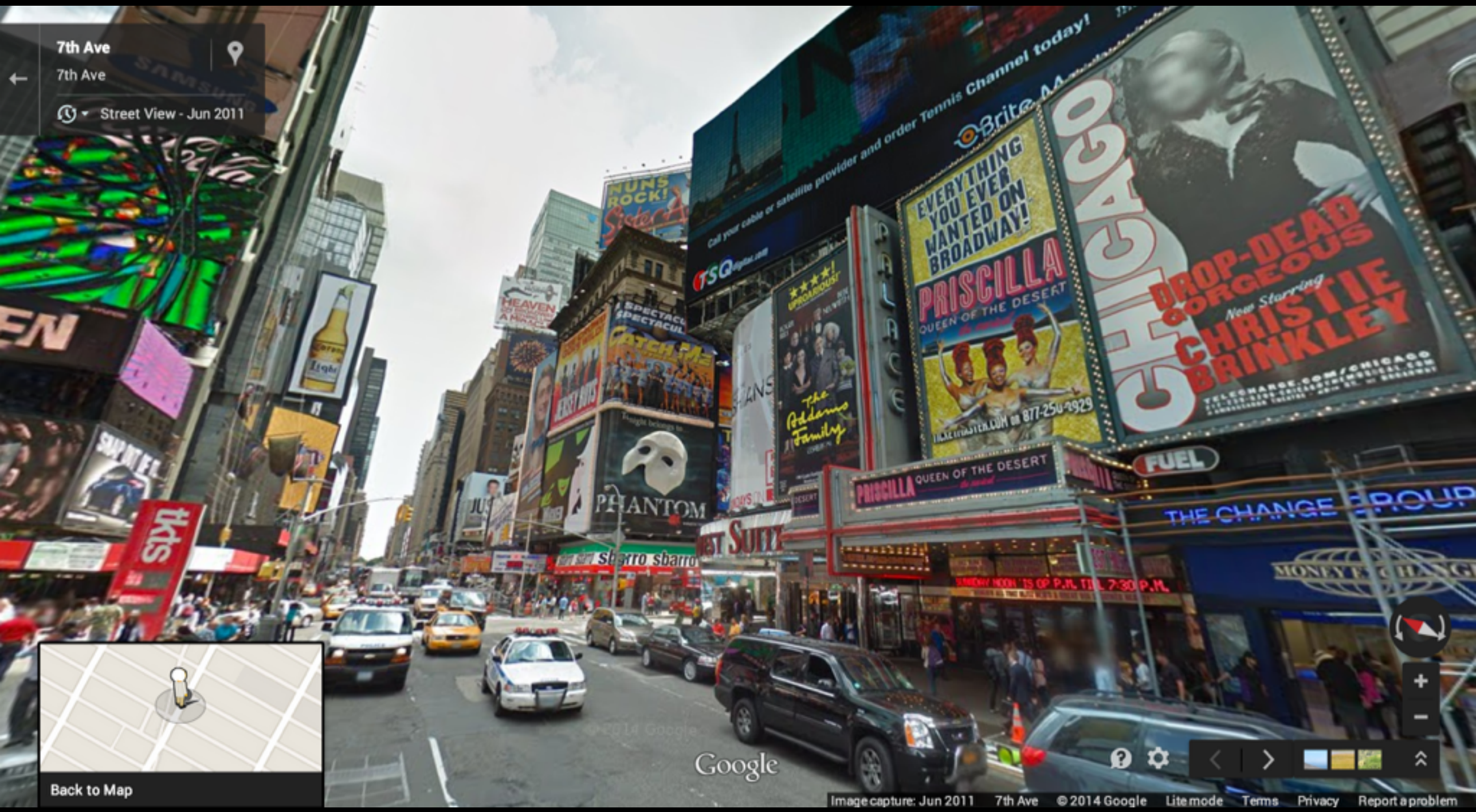
- Standard assumption: static scenes
- We know the world is constantly changing

A key ongoing challenge in 3D modeling will be reconstructing **dynamic** scenes

Times Square

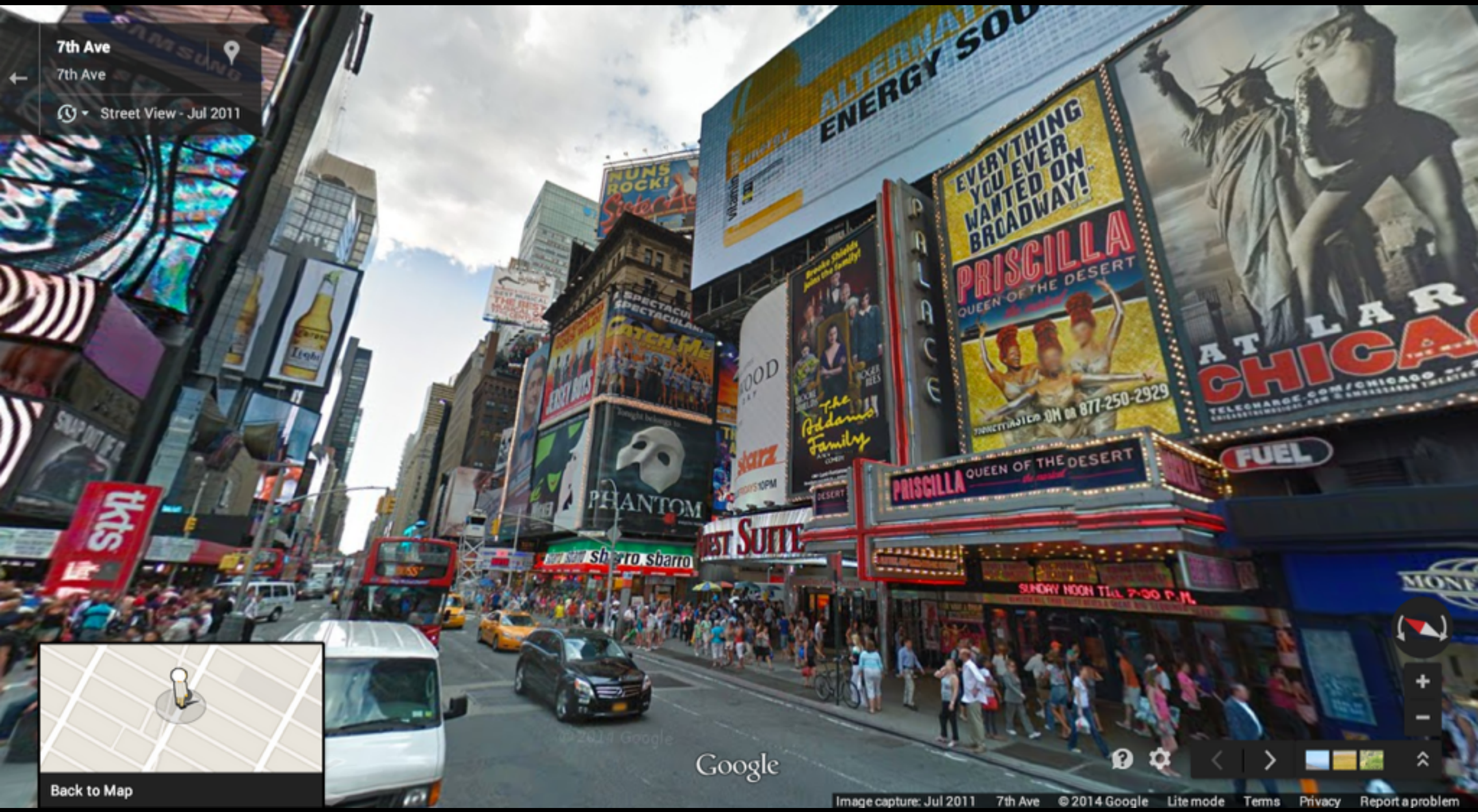
May 2009

Times Square



June 2011

Times Square



July 2011

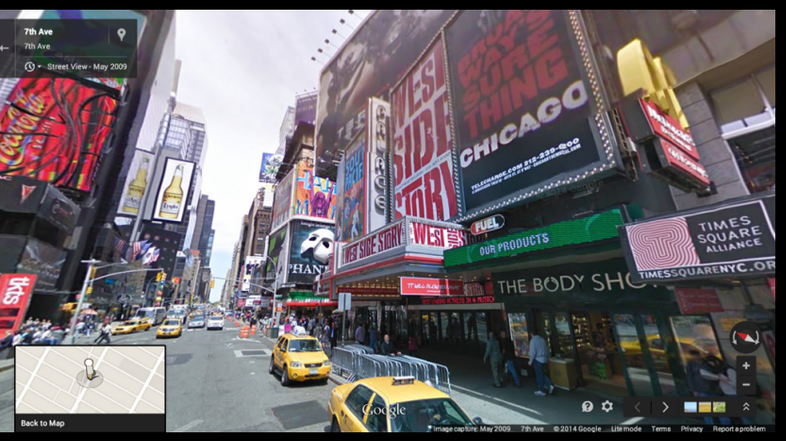
Times Square

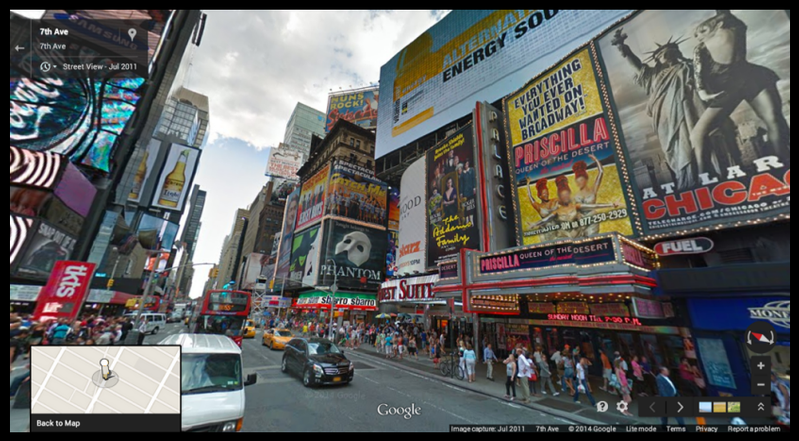
August 2011

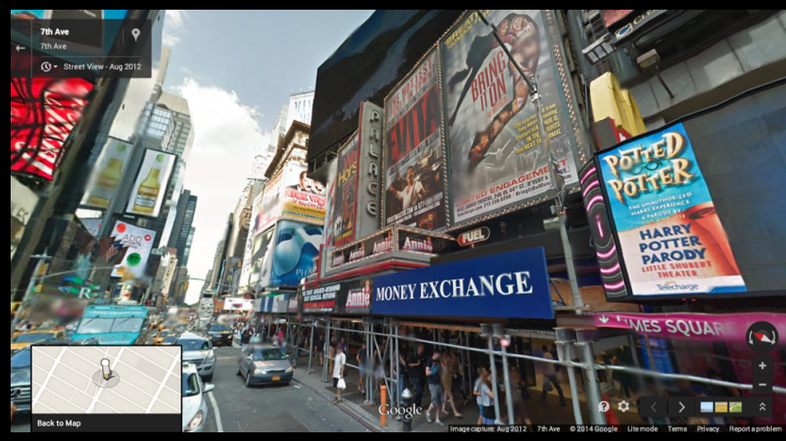
Times Square

August 2012

Times Square







Time

Goal

- Rich reconstructions
- Capturing fine-grained temporal structure
  - On the order of weeks or days
- Enabling visualizations where we can dial back to any point in time

What data to use?

What data to use?

Street View?

Structured, high spatial coverage

Low temporal resolution

What data to use?

Street View?

Structured, high spatial coverage

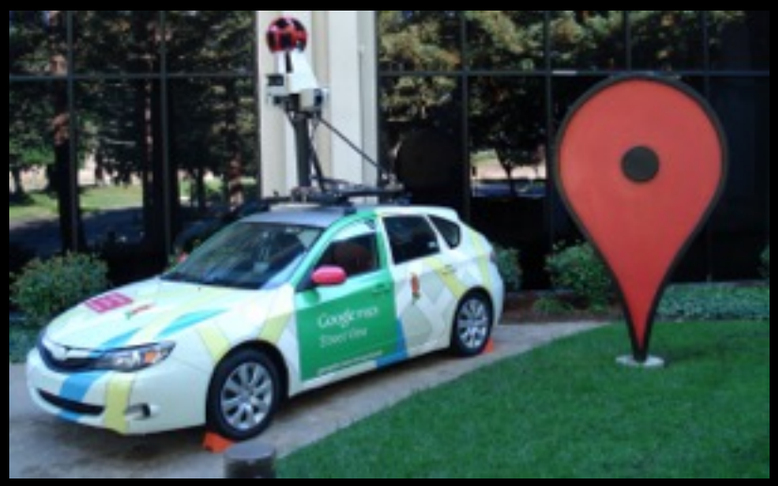
Low temporal resolution

Webcams?

High temporal resolution

Low viewpoint variation

What data to use?



Street View?

Structured, high spatial coverage

Low temporal resolution

Webcams?

High temporal resolution

Low viewpoint variation

flickr

User-generated content?

Massive collections

Unstructured

What data to use?

Street View?

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Low temporal resolution

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High temporal resolution

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flickr

User-generated content?

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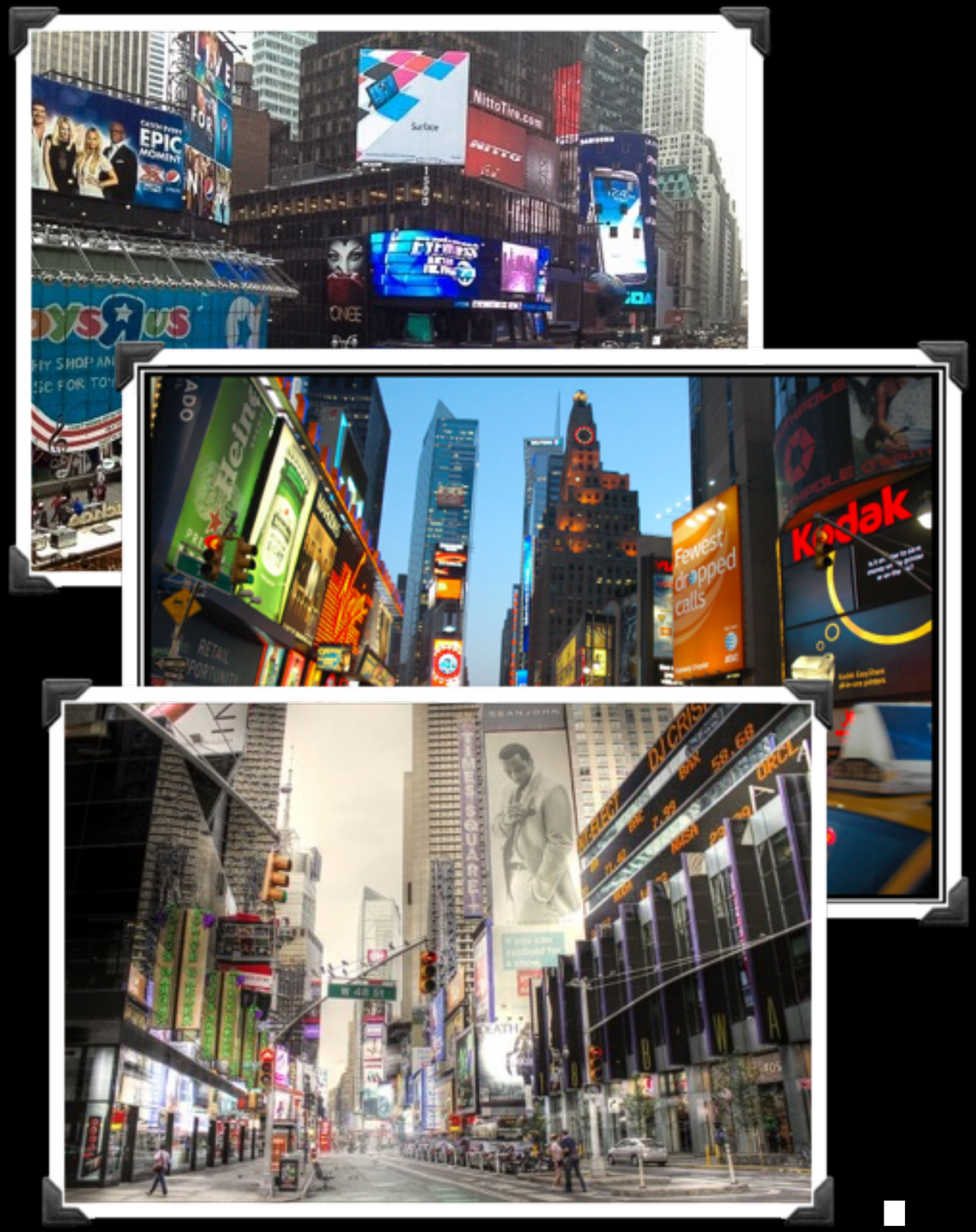
EPIC
MOMENT
Surface
NittoTire.com
Fewest dropped calls
Kodak
TIMES SQUARE

December 8, 2012
August 3, 2007
September 2, 2012
EPIC
MOMENT
Kodak
Fewest dropped calls

Challenges

- Noisy timestamps
- Irregular spatial and temporal sampling
- Large scale photo collections
  - Need to sample 4D space of photos

. . .

Related Work

[Schindler CVPR 2010]

[Pollard CVPR 2007] [Taneja ICCV 2011]
[Taneja CVPR 2013] [Ulusoy ECCV 2014] …

Related Work

[Schindler CVPR 2010]

Our scale differs significantly.
Let's rethink the whole approach.

[Pollard CVPR 2007] [Taneja ICCV 2011]
[Taneja CVPR 2013]

Contributions

New approach for reconstructing chronology of a scene from millions of unstructured photos

- New method for robustly estimating per-point time intervals for a 3D reconstruction
- New plane-time representation and segmentation algorithm
- Scalable to millions of photos

Outline

- Representation for 4D scenes
- 4D reconstruction approach
- Results

Possible 4D Representations

- 3D points augmented with time
  - Too low level
- Temporally coherent sets of 3D points
  - Basis for spatio-temporal segmentation

CATHERINE ZETA-JONES
A LITTLE NIGHT MUSIC
SEX AND THE
CARRIE ON MAY 27
HBO
CIRQUE DU SOLEIL
BANANA SHPEEL
LOVE OUT
HAIR
BEST MUSICAL REVIVAL · 2009 TONY AWARD
Tonight belongs to...
PHANTOM
WINNER! 7 TONY AWARDS
BEST MUSICAL REVIVAL
RODGERS & HAMMERSTEIN'S
SOUTH PACIFIC
PALACE
WEST SIDE STORY
TICKETMASTER.COM / 212-307-4100
CALIENTE · INCONTOURNABLE
THE INTERNATION
TELECHARGE.COM/CHICA
FUEL
THE CHAN
WEST SUITE
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MONDAY TO SATURDAY 10 A.M. - 8 P.M.

CARRIE ON MAY 27
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SEXANDTHECITYMOVIE.COM
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HAIR
BEST MUSICAL REVIVAL · 2009 TONY AWARD
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CHICAGO
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TELECHARGE.COM/CHICAGOTHEMUSICAL.COM
FUEL
THE CHAN
WEST SIDE STORY
MONDAY TO SATURDAY 10 A.M. - 8 P.M.
sbarro

Approach

CIRQUE DU SOLEIL
BANANA SHPEEL
THE CROWD
LOVE OUT
JERSEY BOYS
BEST MUSICAL
HAIR
MUSICAL REVIVAL · 2009 TONY AWARD
Tonight belongs to...
PHANTOM
CARRIE
sbarro
sbarro
sbarro

PHANTOM
Tonight belongs to...
HAIR
QUEST BOYS
THE CROWD GOES WILD
LOVE OUT

HAIR
PHANTOM

THE CROWD GOES WILD!
HAIR
PHANTOM

THE CROWD GOES WILD!
JERSEY BOYS
PHANTOM

HAIR
Tonight belongs to...
PHANTOM

Time

HAIR
PHANTOM
THE CROWD GOES WILD!
JERSEY BOYS
HAIR
PHANTOM
THE CROWD GOES WILD!
JERSEY BOYS
PHANTOM

Time

HAIR
Tonight belongs to...
PHANTOM

HAIR
PHANTOM

HAIR
PHANTOM

THE CROWD GOES WILD!
JERSEY BOYS
PHANTOM

Time

HAIR
Tonight belongs to...
PHANTOM

WICKED
BEST MUSICAL REVIVAL
2009 TONY AWARD
HAIR
BEST MUSICAL REVIVAL
A CAGE
SPECTACULAR!
SPECTACULAR!

Approach

flickr

Approach

“Times Square” flickr

Approach

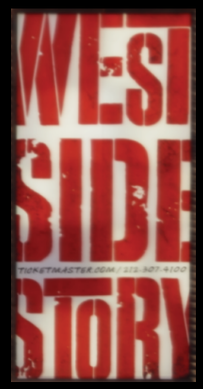
“Times Square” flickr

Approach

"Times Square" flickr

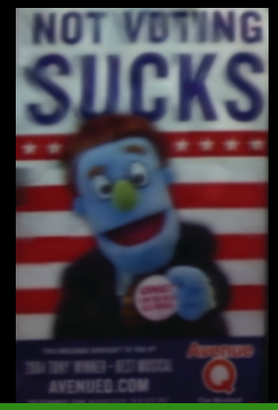
Approach

“Times Square” flickr



Approach

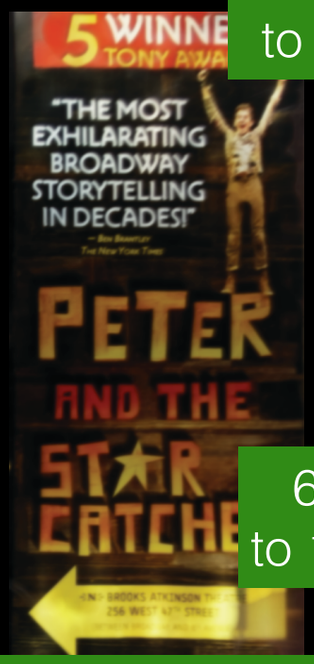
"Times Square" flickr



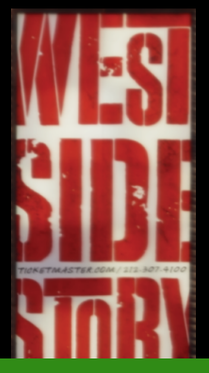
2 August 2008
to 2 January 2009

8 February 2011
to 31 July 2011

29 December 2005
to 25 November 2010

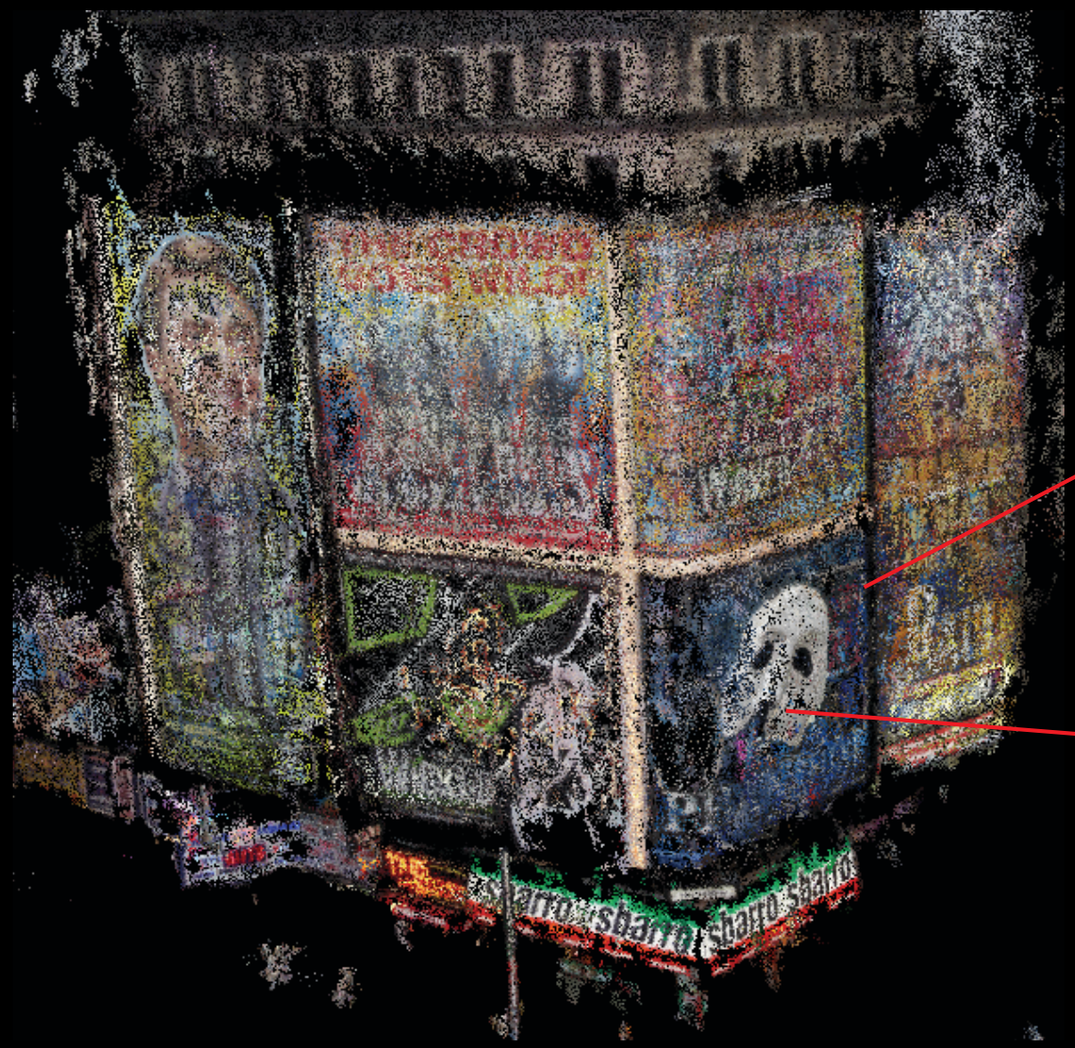


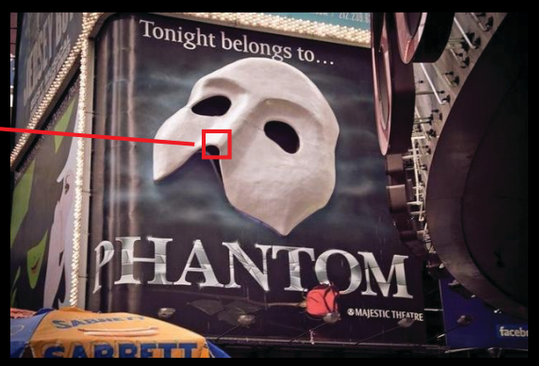
29 May 2012
to 25 December 2012

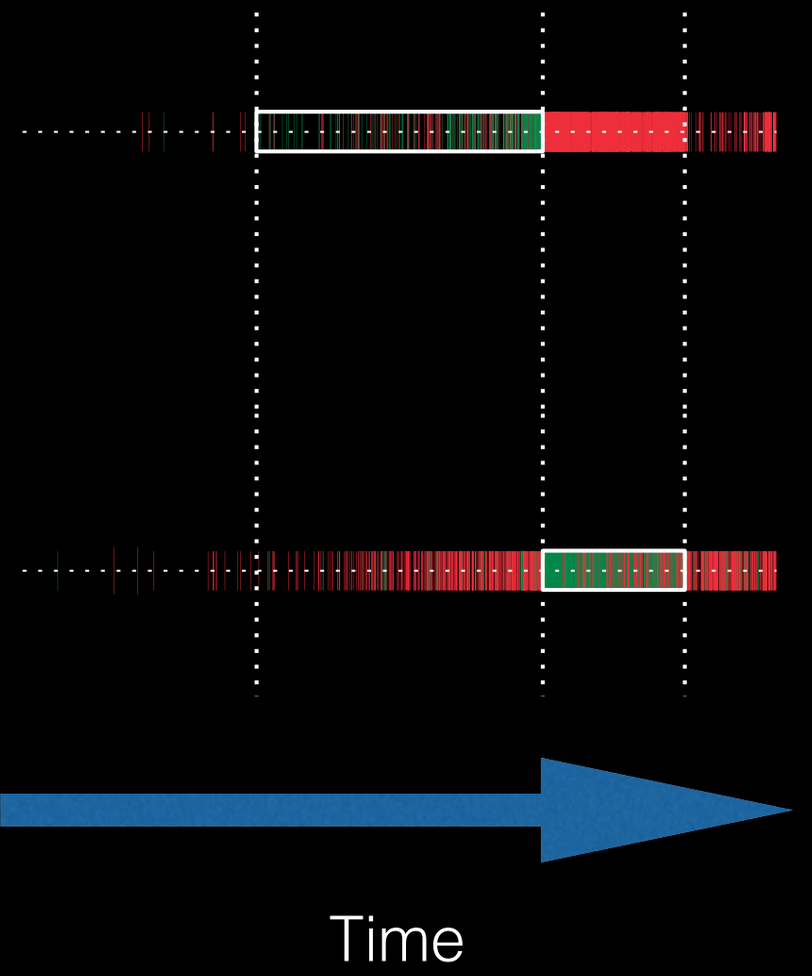


6 January 2009
to 14 January 2011

20 April 2010
to 9 September 2010







Point-based 4D Reconstruction

3D Reconstruction

Input: **Millions** of photos

[Agarwal ICCV 2009] [Furukawa PAMI 2010] [Furukawa CVPR 2010]

3D Reconstruction

Bundler

CMVS/PMVS

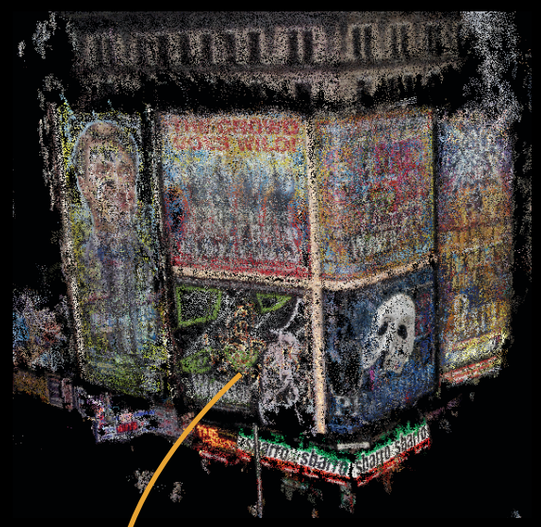
Input: **Millions** of photos

[Agarwal ICCV 2009] [Furukawa PAMI 2010] [Furukawa CVPR 2010]

3D Reconstruction

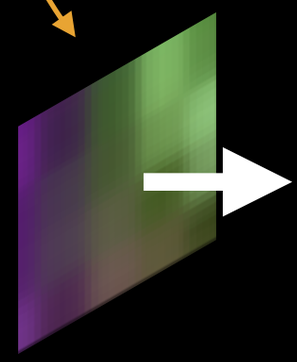
Bundler

CMVS/PMVS



Input: **Millions** of photos

Output:
(1) **Millions** of patches with position, normal, and appearance
(2) **100,000s** registered photos
(3) Visibility information



3D patch with appearance and normal

[Agarwal ICCV 2009] [Furukawa PAMI 2010] [Furukawa CVPR 2010]

When did a point exist?

When did a point exist?

2009

2014

When did a point exist?

2009

2014

When did a point exist?

2009

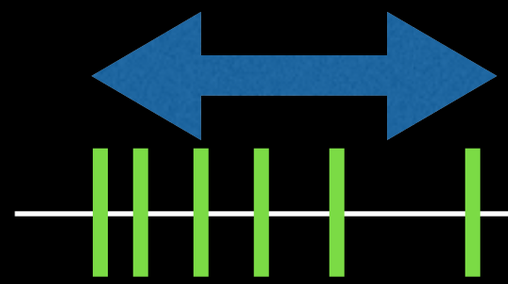
2014

When did a point exist?

2009

2014

Interval Estimation



2009

2014

Interval Estimation

Is this visibility list enough?

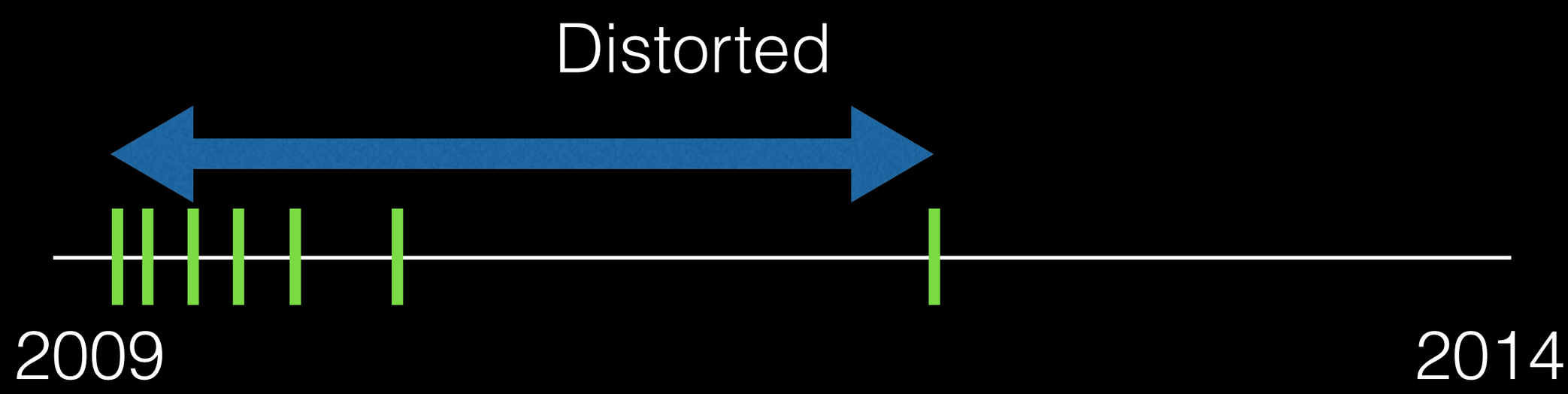
Interval Estimation

Is this visibility list enough?

Interval Estimation

Is this visibility list enough?

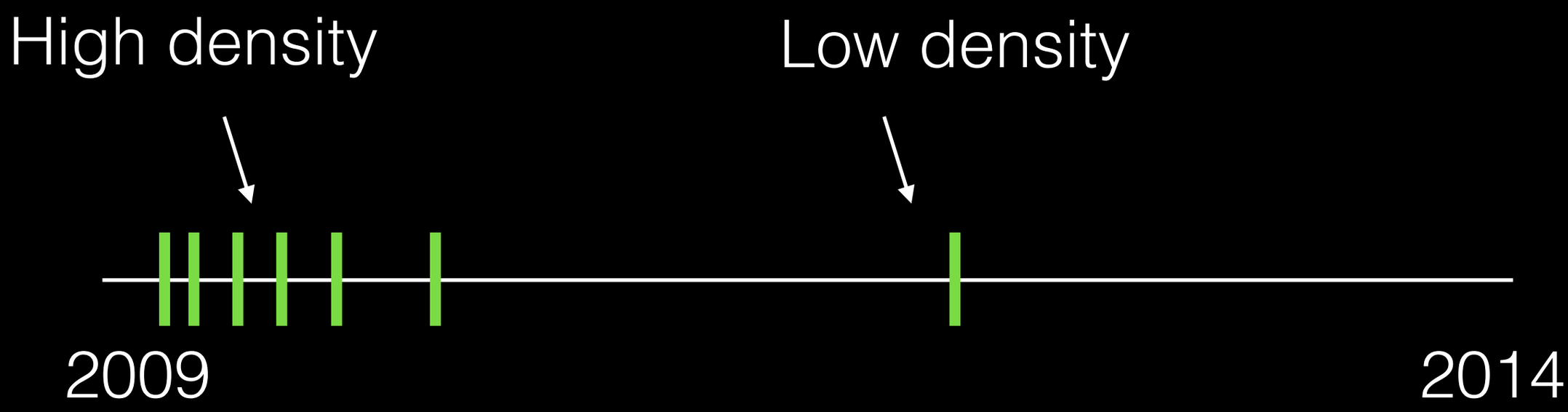
Min and max are not robust



Interval Estimation

Is this visibility list enough?

~~Min and max are not robust~~

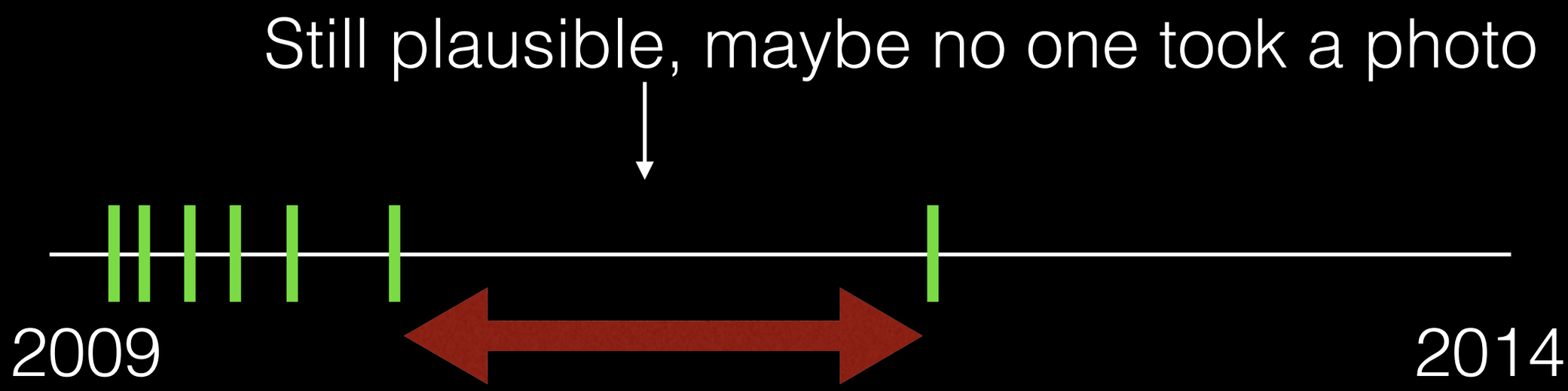


Interval Estimation

Is this visibility list enough?

~~Min and max are not robust~~

Density might be misleading



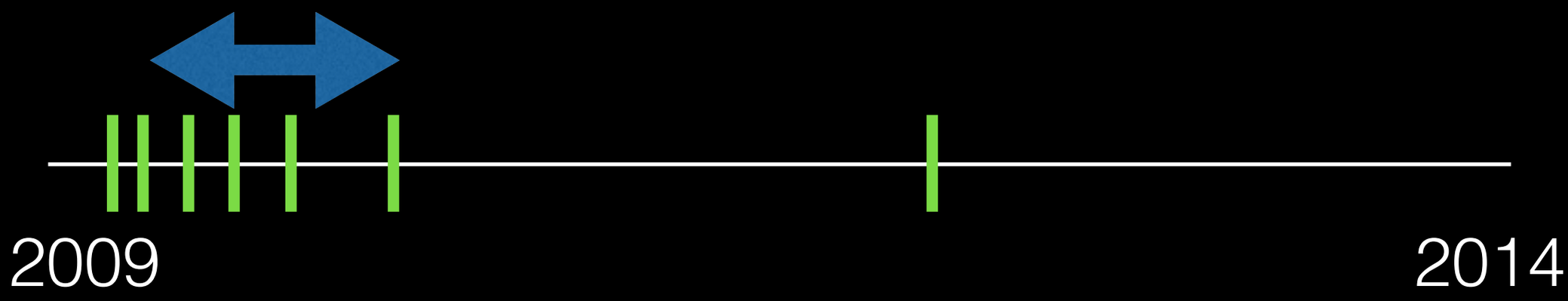
Interval Estimation

Is this visibility list enough?

~~Min and max are not robust~~

~~Density might be misleading~~

Trimming leads to systematic shrinkage



Interval Estimation

Is this visibility list enough?

~~Min and max are not robust~~

~~Density might be misleading~~

~~Trimming leads to systematic shrinkage~~

Can we make use of negative information?

Negative Observations

2009

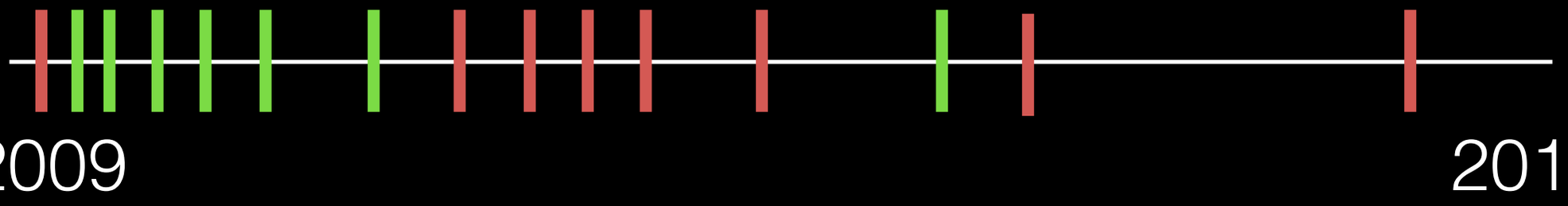
2014

Negative Observations

2009

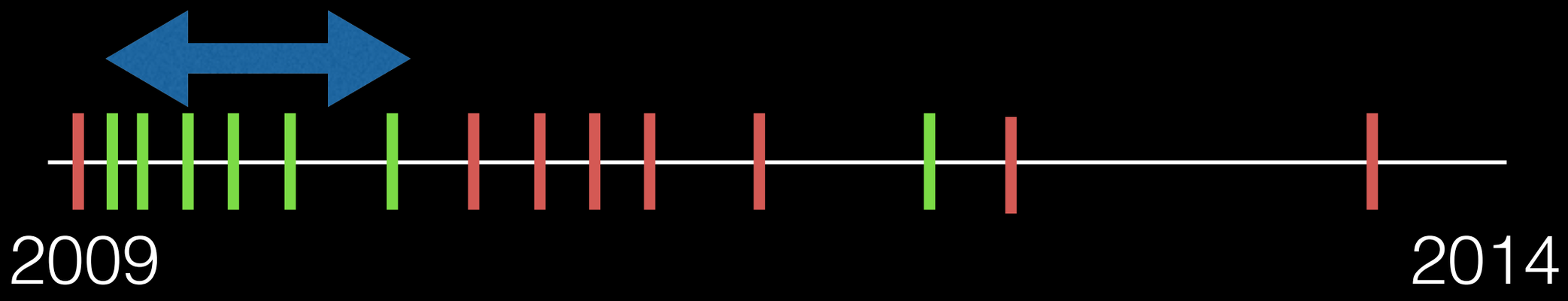
2014

Negative Observations



Negative Observations

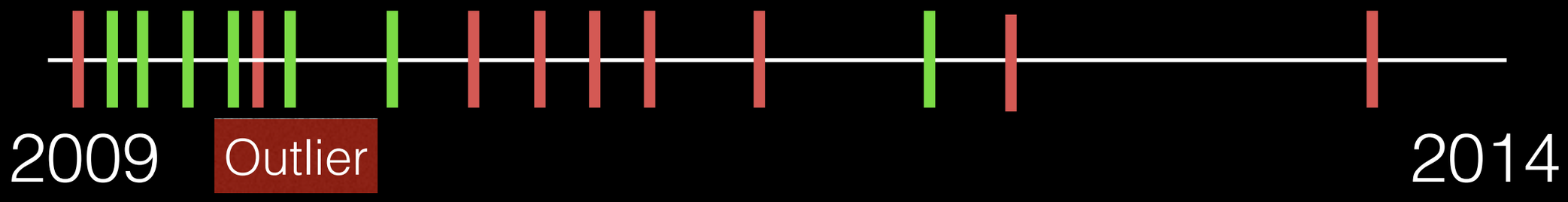
Both positive and negatives
tell a part of the story



Negative Observations

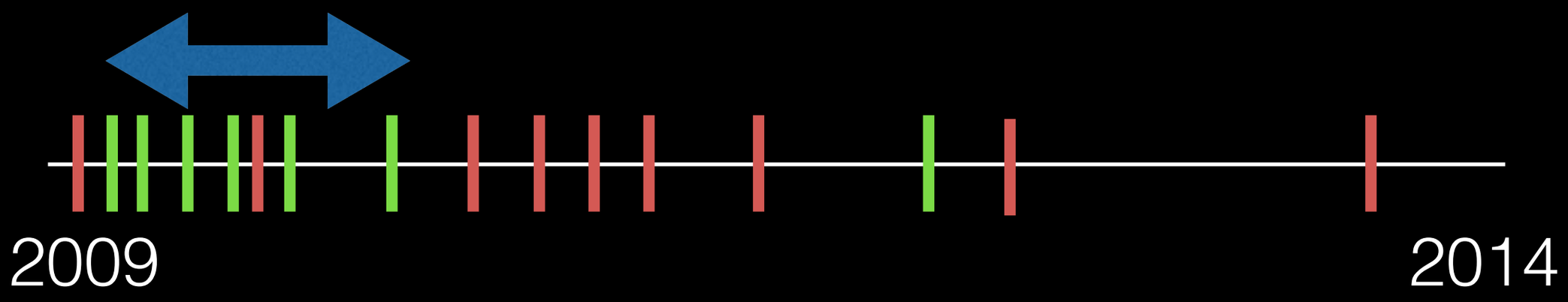
Both positive and negatives
tell a part of the story

But there can be negative outliers too

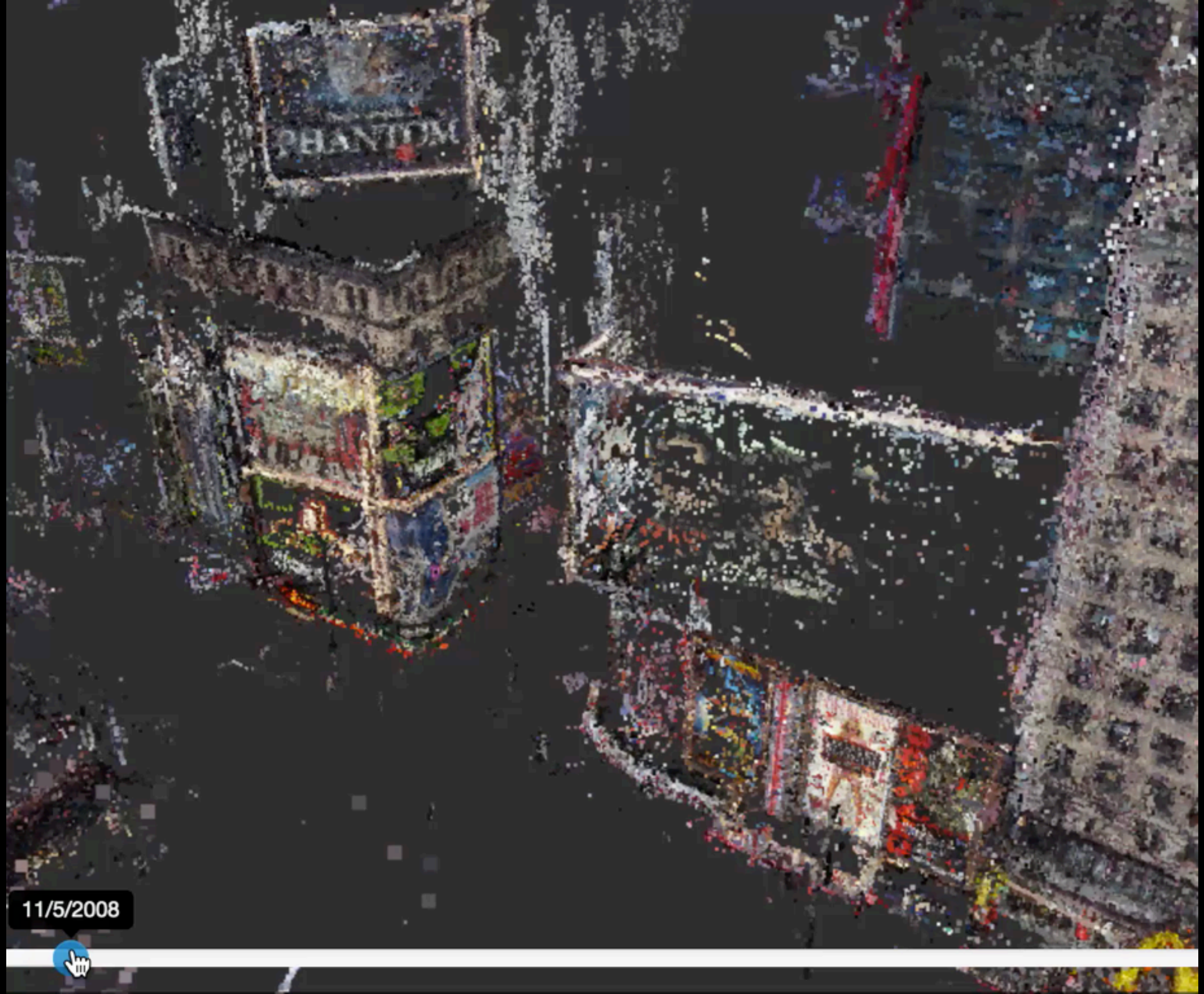


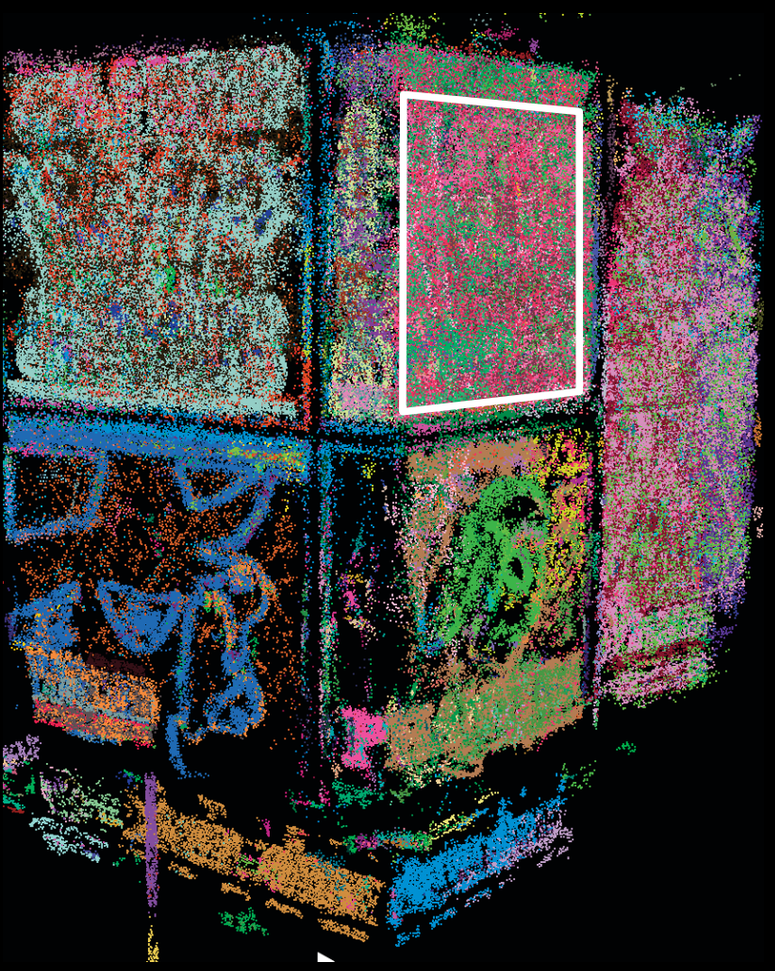
Estimating Intervals

Idea: Use F_1 score to balance precision and recall



Point-Based Visualization


PHANTOM
11/5/2008



Spatio-Temporal 4D Segmentation

Spatio-Temporal Graph

- Point-to-point affinity encodes
  - position distance
  - difference in normal
  - temporal interval overlap

RANSAC Segmentation

- Plane-Time RANSAC
  - Planar hypothesis with temporal extent
  - Find inliers
  - Removed induced subgraph
  - Apply recursively to remaining connected components

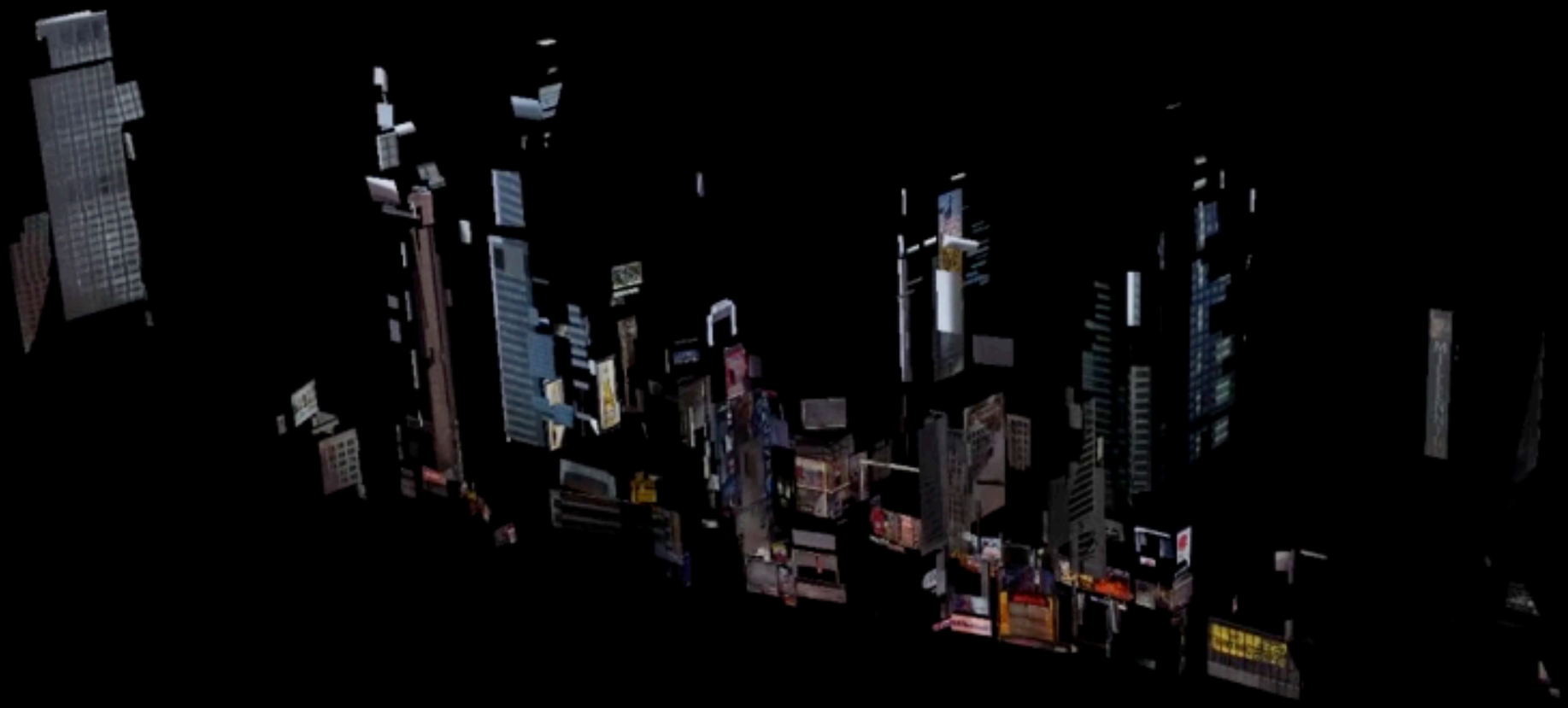
Results

Times Square - Manhattan, NYC

1.2 million photos
250k registered
13.5 million points
17 billion observations

Times Square - Manhattan, NYC

November 2008



Akihabara - Tokyo

170k photos
14k registered
1.7 million points
400 million observations

Akihabara - Tokyo

September 2010

5Pointz - Queens, NYC

48k photos
13k registered
12 million points
1.4 billion observations

5Pointz - Queens, NYC

Graffiti Archaeology, C. Curtis

GRAFFITI ARCHAEOLOGY about credits links news faq submit donate

Locations & Walls.

- bluxome:
  - eastA
  - eastB
  - eastC
- undercroft:
  - panel2
  - panel3
- cavern:
- harveys:
- olympia:
- 22nd:
- 19th:
- candle:
- florida:
- ghost:
- cove:
- belmont:
- 25th:
- williams:

Current Layer: 17 june 2006. Photos by Pierre Andrews

Zoom. Navigator.

Timeline.

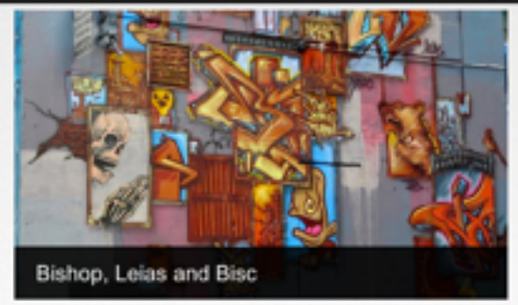
2006 2007 2008

1 2 3 4 5 6 7 8 9 11 11 12 13 14 16 17 18 20 21 22 23 24 26 27 29 31 32

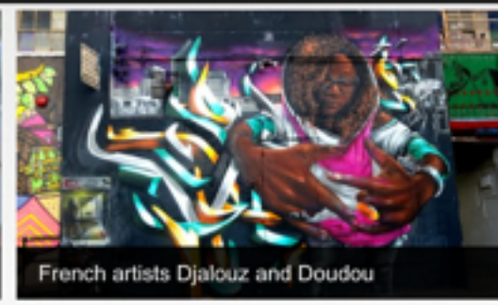
Explore Search Collections User Galleries My Galleries kmatzen@gmail.com

Google Cultural Institute

Carolina based Spagnola



Bishop, Leias and Bisc



French artists Djalouz and Doudou

Australian artist Beastman

Lois Stavsky with Houda Lazrak

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Locations & Walls.

- bluxome:
  - eastA
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- 19th:
- candle:
- florida:
- ghost:
- cove:
- belmont:
- 25th:
- williams:

Current Layer: 17 june 2006. Photos by Pierre Andrews

Our approach can derive these visualizations completely automatically

Zoom. Navigator.

Timeline.

2006 2007 2008

1 2 3 4 5 6 7 8 9 11 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32

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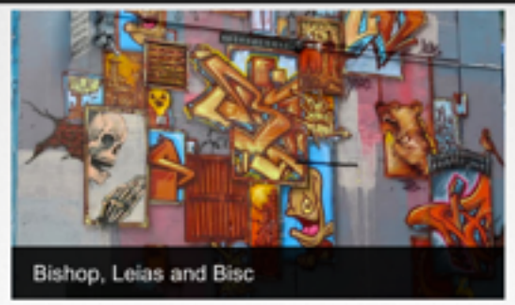
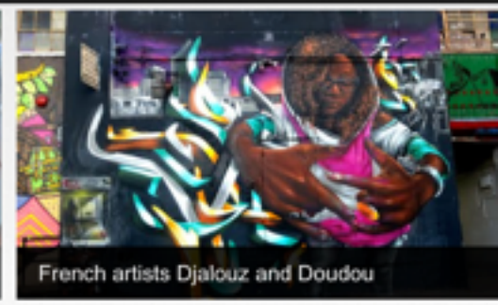
Graffiti Archaeology, C. Curtis

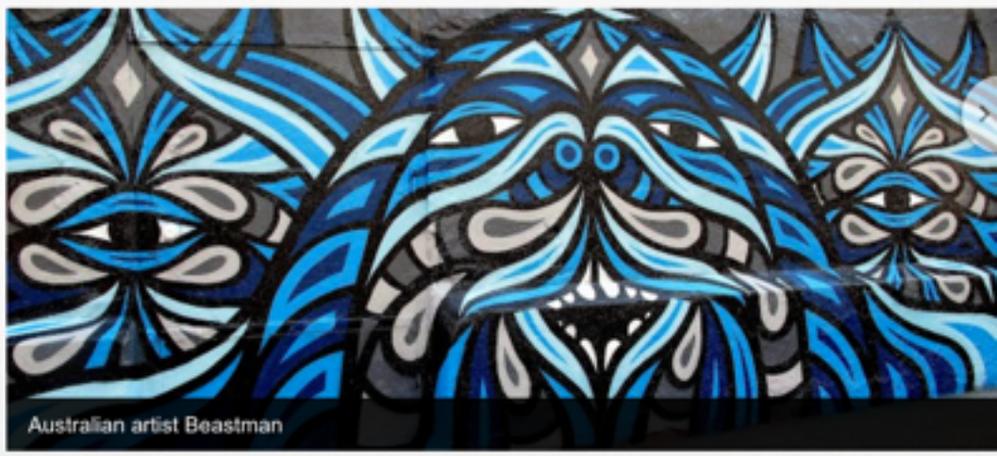
Carolina based Spagnola



Bishop, Leias and Bisc



French artists Djalouz and Doudou



Australian artist Beastman

Lois Stavsky with Houda Lazrak

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Discovered Space-Time Elements

2 August 2013 to 8 December

7 August 2012 to 3 May

25 May 2010 to 13 May 2012

5 June 2010 to 29 April 2011

31 March ‘04 to 26 August ‘13

16 April 2008 to 8 February 2014

17 July 2005 to 5 May 2008

Timestamp Prediction

5POINTZ
5PTZ.COM

Feb 09 - Dec 13

Oct 11 - Nov 13

Feb 05 - Dec 13

June 13 - Nov 13

Dec 12 - Nov 13

Dec 12 - Nov 13

April 13 - Nov 13

Feb 09 - Dec 13

Oct 11 - Nov 13

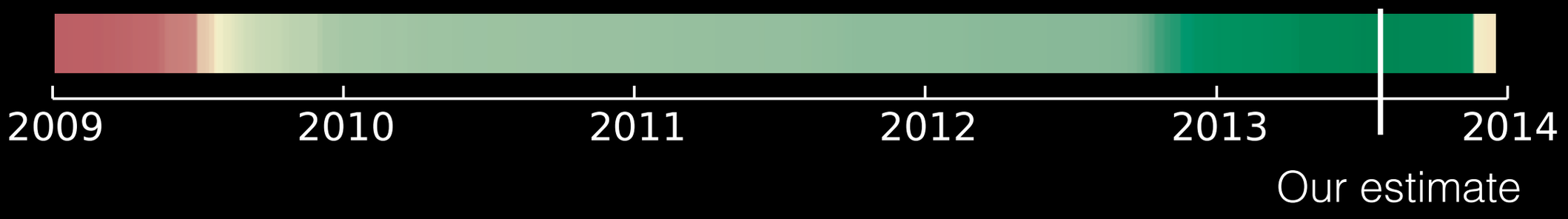
Feb 05 - Dec 13

June 13 - Nov 13

Dec 12 - Nov 13

Dec 12 - Nov 13

April 13 - Nov 13



RENT
Now.
Eternally Yours
The longest-running musical ever.
frank TV
tbs
very funny
VINCE VAUGHN PAUL GIAMATTI
FRED CLAUS
NOVEMBER 9TH
WHERE MAXIMUM PERFORMANCE LIVES
Broadway
JERSEY BOYS
WICKED
LEGALLY BLONDE
CHICAGO
McDonald's Restaurant
OPEN 24 HOURS
FRIDAY'S
tkts
Ryder
Truck Rental & Leasing
1-800-BY-RYDER
www.ryder.com
NYC TAXI
SLEEPY'S
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Our estimate
Original

Eternally Yours
The longest-running musical ever.
RENT
Now.
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FRED CLAUS
OCTOBER 31
WHERE MAXIMUM PERFORMANCE LIVES
Broadway
JERSEY BOYS
WICKED
A New Musical
LEGALLY BLONDE
CHICAGO
THE LONGEST-RUNNING MUSICAL IN BROADWAY HISTORY
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NYC TAXI
SLEEPY'S
SOLSTICE GXP
PAUL GIAMATTI
Our estimate
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Our estimate

Original

UFC
LIDDELL VS JACKSON
SURF'S UP
THE FINALS
TOYS
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2014
Our estimate
Original

IF YOU THINK THERE'S
NOTHING MORE TO
PLANET HOLLYWOOD
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ONCE IN A WHILE.
PLANETHOLLYWOOD.COM
SPRING-SUMMER
COLLECTION
2009
swiss made
swatch+ swatch+
Foot
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Our estimate
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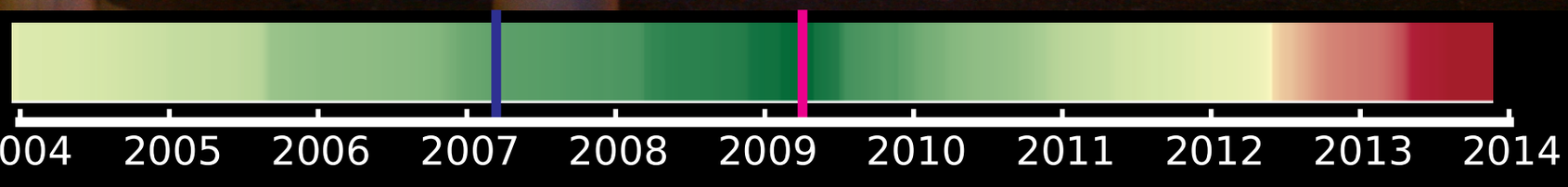
2004
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2006
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Our estimate
Original

Limitations

- Assume we can reconstruct the 3D scene
- Assumes enough redundancy to identify incorrect timestamps
- Some semantic elements are periodic
- Segmentation granularity dependent on thresholds

Conclusion

- Scalable system
- Unreliably timestamped photos to 4D reconstruction
- Two representations: (1) Point-based and (2) Semantic segmentation
- Future work
  - Moving beyond planes
  - More sophisticated timestamp prediction
  - Richer, more complete visualizations
  - Non-intersection constraints

Acknowledgements

- National Science Foundation
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- Amazon Web Services in Education

Questions?

bit.ly/cornell-chrono