Title: Cosmology with Gravitational Lens Time Delays

Speakers: Sherry Suyu

Series: Colloquium

Date: March 20, 2019 - 2:00 PM

URL: http://pirsa.org/19030106

Abstract: Strong gravitational lenses with measured time delays between the multiple images can be used to determine the Hubble-Lemaitre constant (H0) that sets the expansion rate of the Universe. An independent determination of H0 is important to ascertain the possible need of new physics beyond the standard cosmological model, given the tension in current H0 measurements. A program initiated to measure H0 to <3.5% in precision from strongly lensed quasars is in progress, and I will present the latest results and their implications. Search is underway to find new lenses in imaging surveys. An exciting discovery of the first strongly lensed supernova offered a rare opportunity to perform a true blind test of our modeling techniques. I will outline a new research program on lensed supernovae, showing their bright prospects as a competitive and unique probe of cosmology and stellar physics.

Cosmology with Gravitational Lens Time Delays

Sherry Suyu

Max Planck Institute for Astrophysics
Technical University of Munich
Academia Sinica Institute of Astronomy and Astrophysics

Perimeter Institute Colloquium
March 20, 2019

Hubble-Lemaître Constant H_0

[Riess et al. 2016]

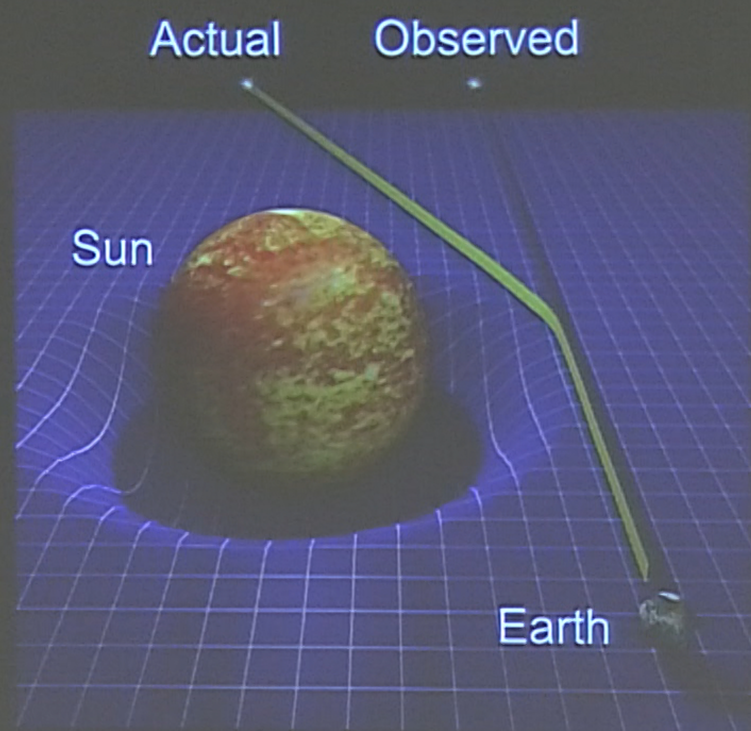
H_0 importantly sets:

- age, size of the Universe
- expansion rate: $v = H_0 d$

Tension? New physics?

➡ *Need Independent methods to overcome systematics, especially the unknown unknowns*

Gravitational Lensing



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Strong Optical Lensing

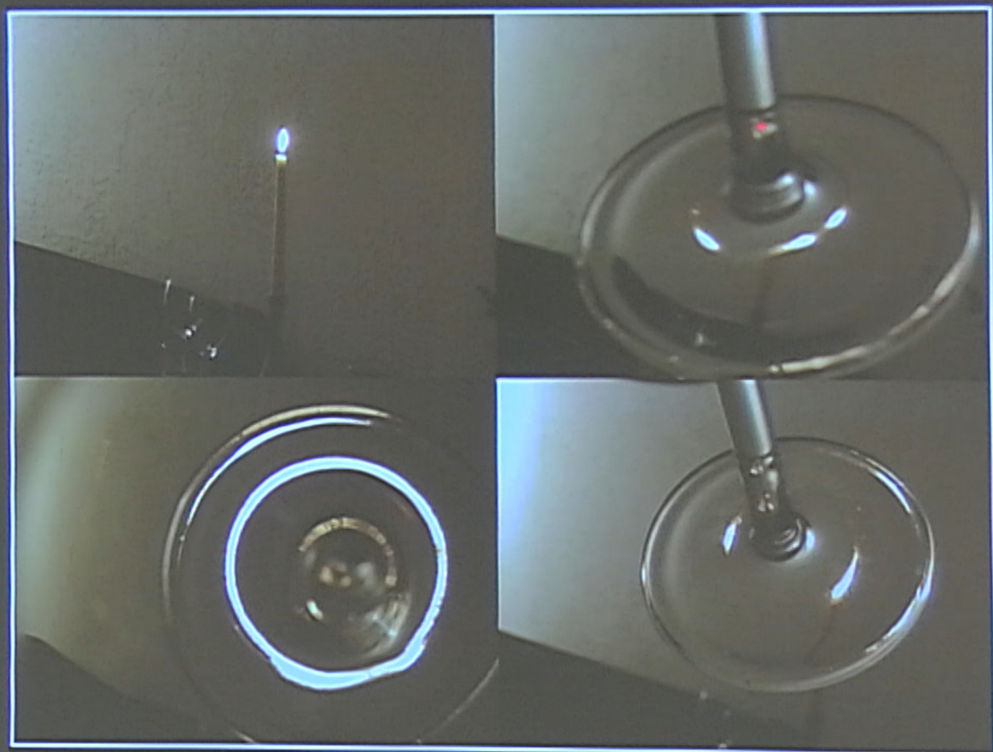
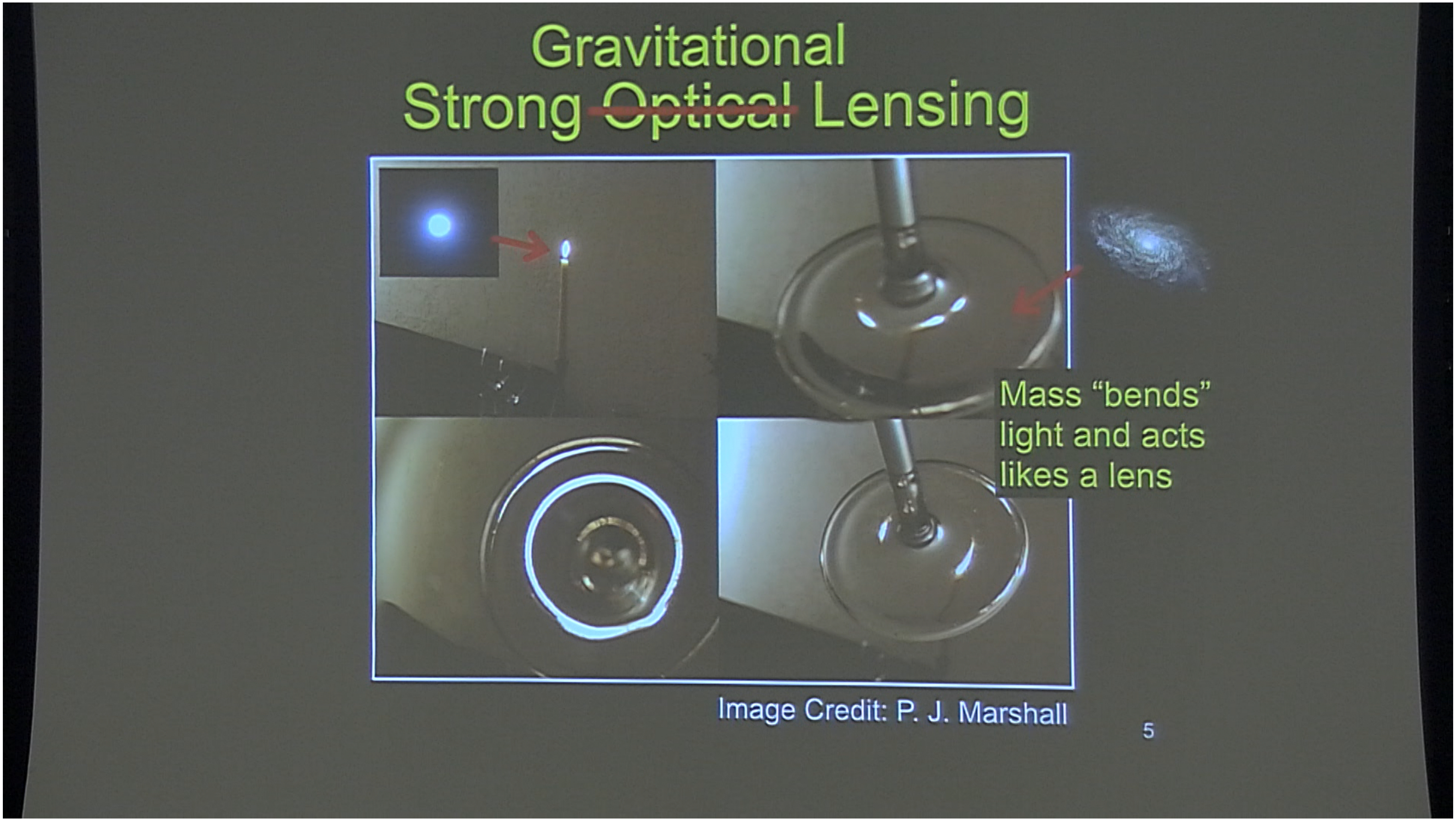
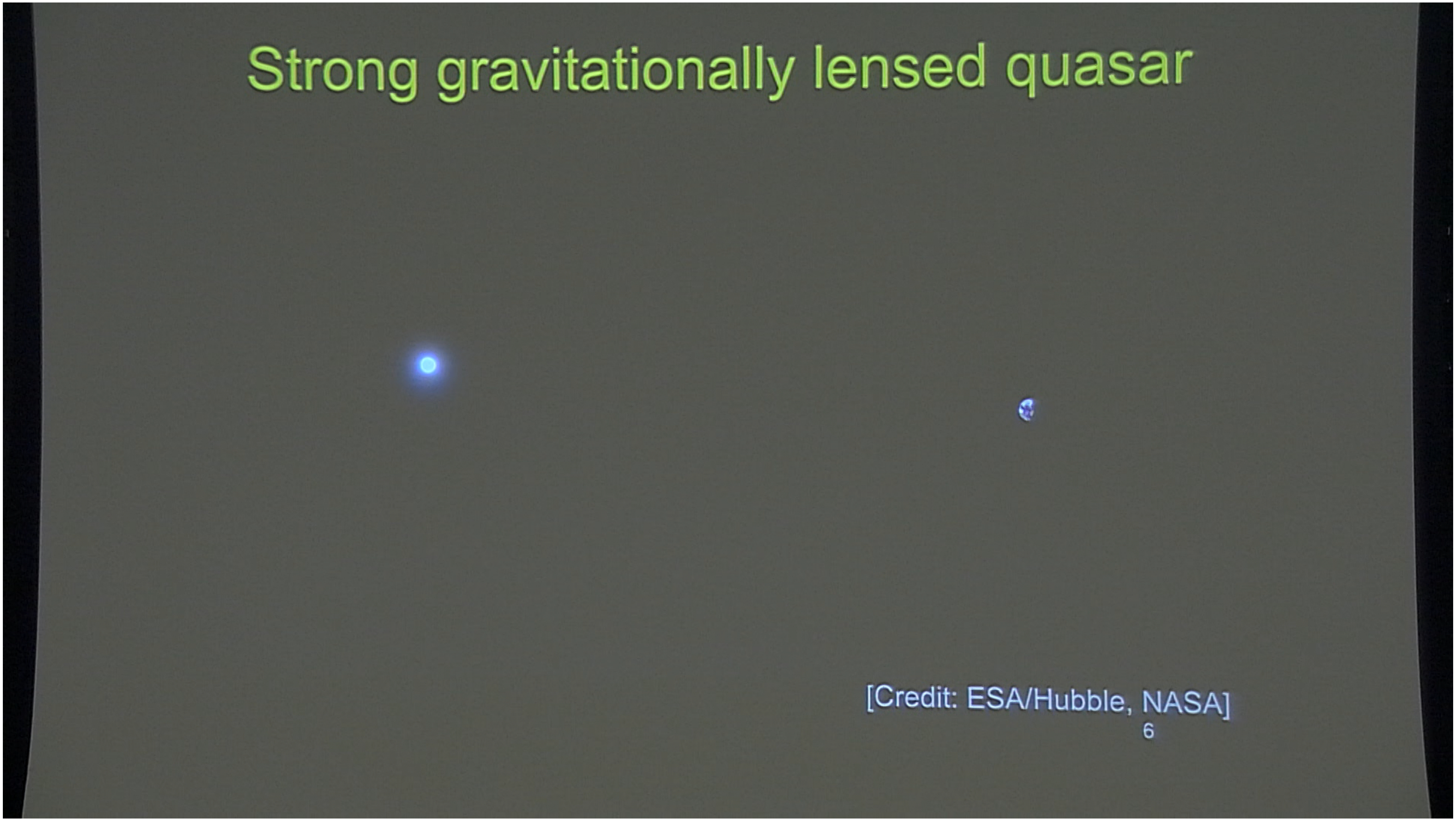


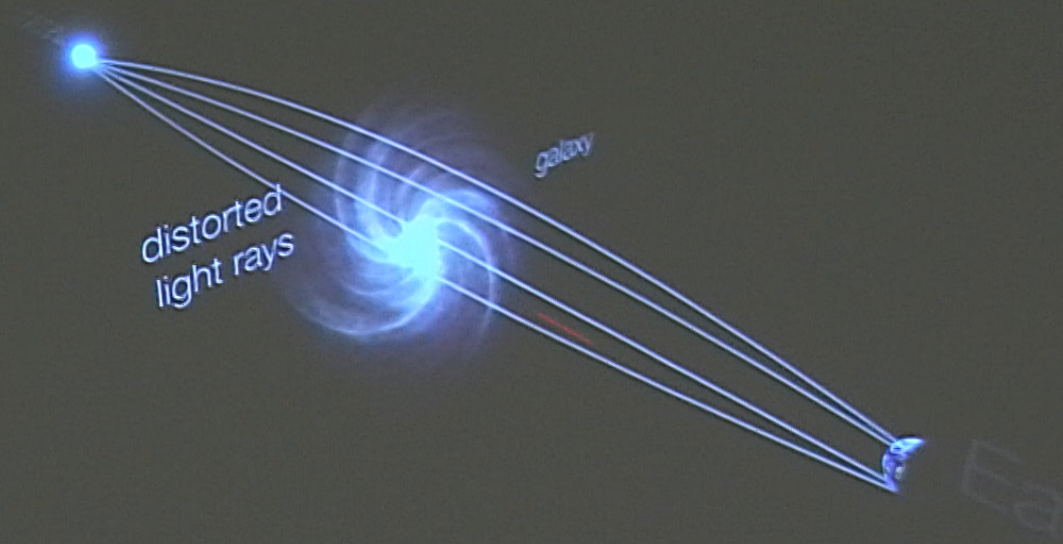
Image Credit: P. J. Marshall

4


Gravitational
Strong ~~Optical~~ Lensing
Mass “bends” light and acts likes a lens
Image Credit: P. J. Marshall
5


Strong gravitationally lensed quasar
[Credit: ESA/Hubble, NASA]
6

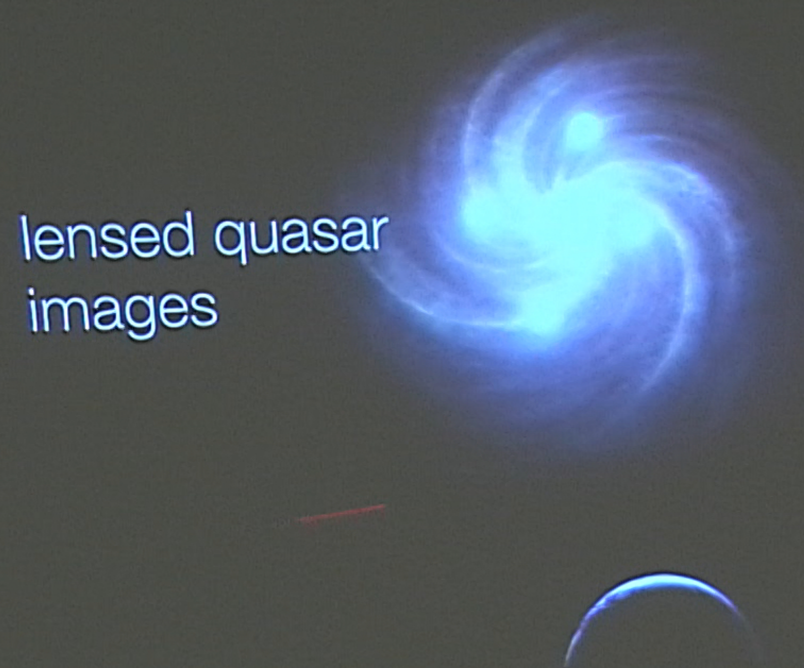
Strong gravitationally lensed quasar



[Credit: ESA/Hubble, NASA]

6

Strong gravitationally lensed quasar

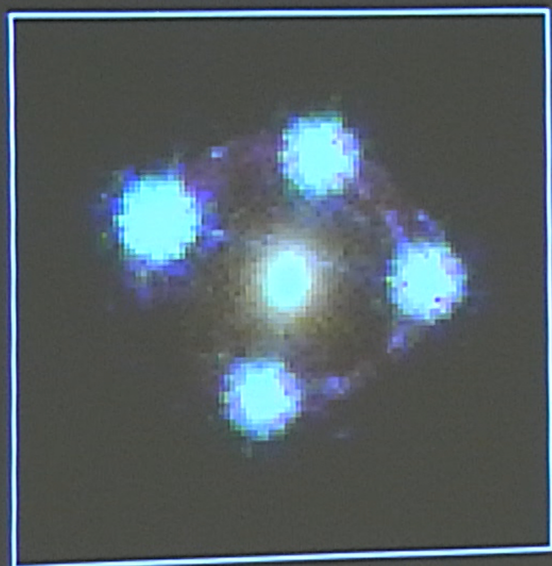


[Credit: ESA/Hubble, NASA]

6

Variability of quasar emission

HE0435-1223

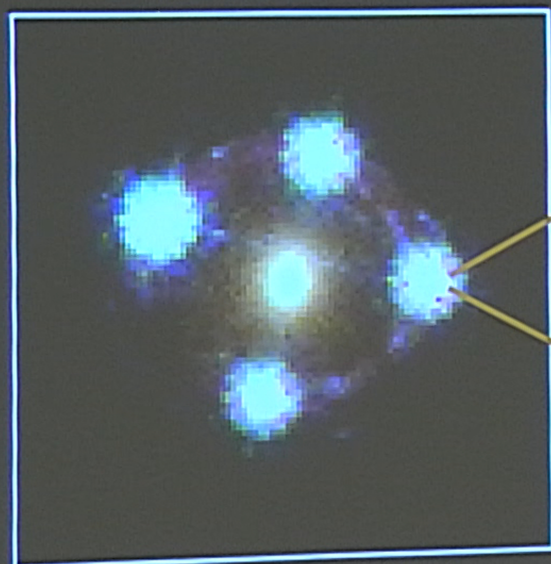


[Suyu et al. 2017]

7

Variability of quasar emission

HE0435-1223

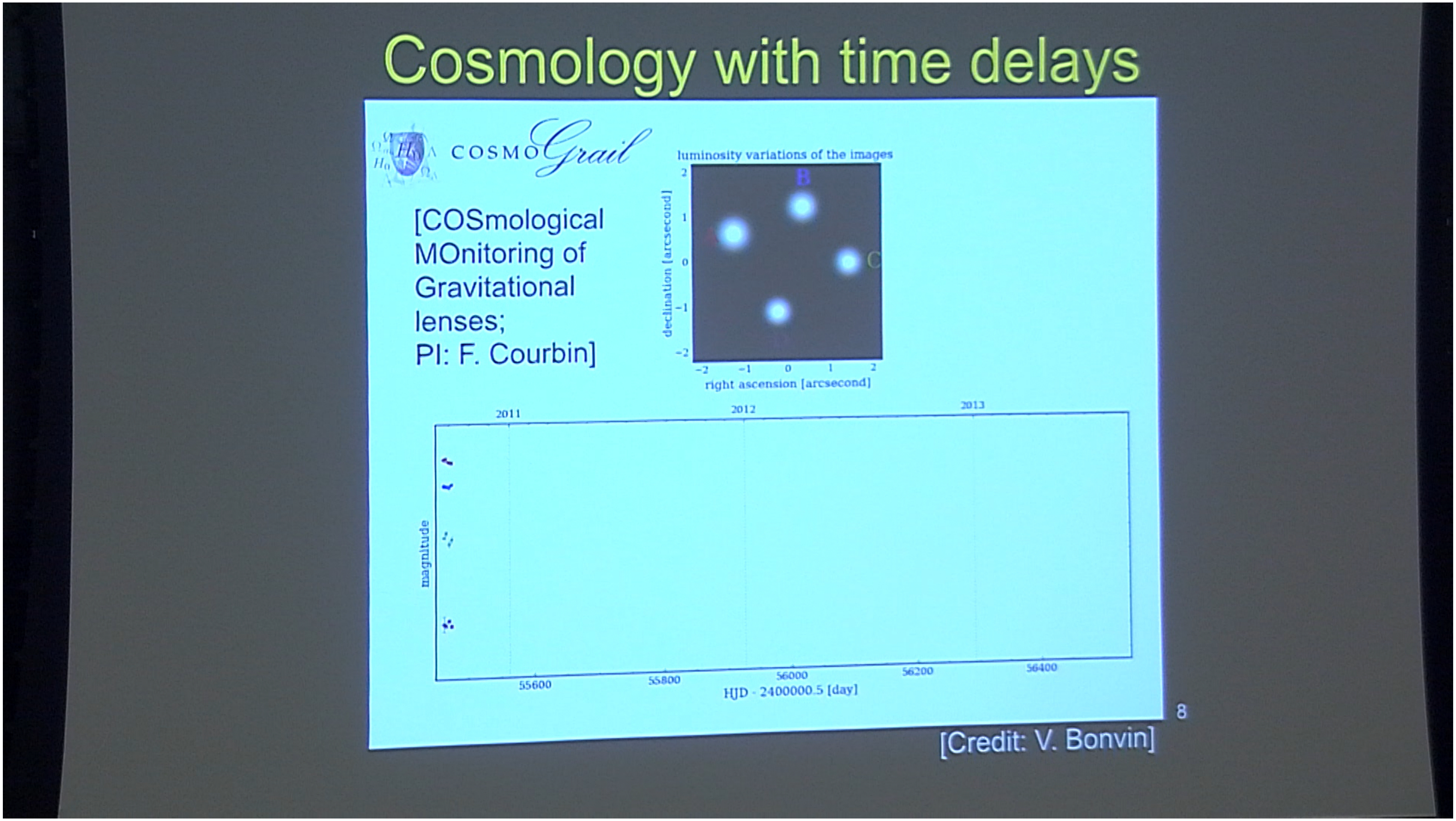


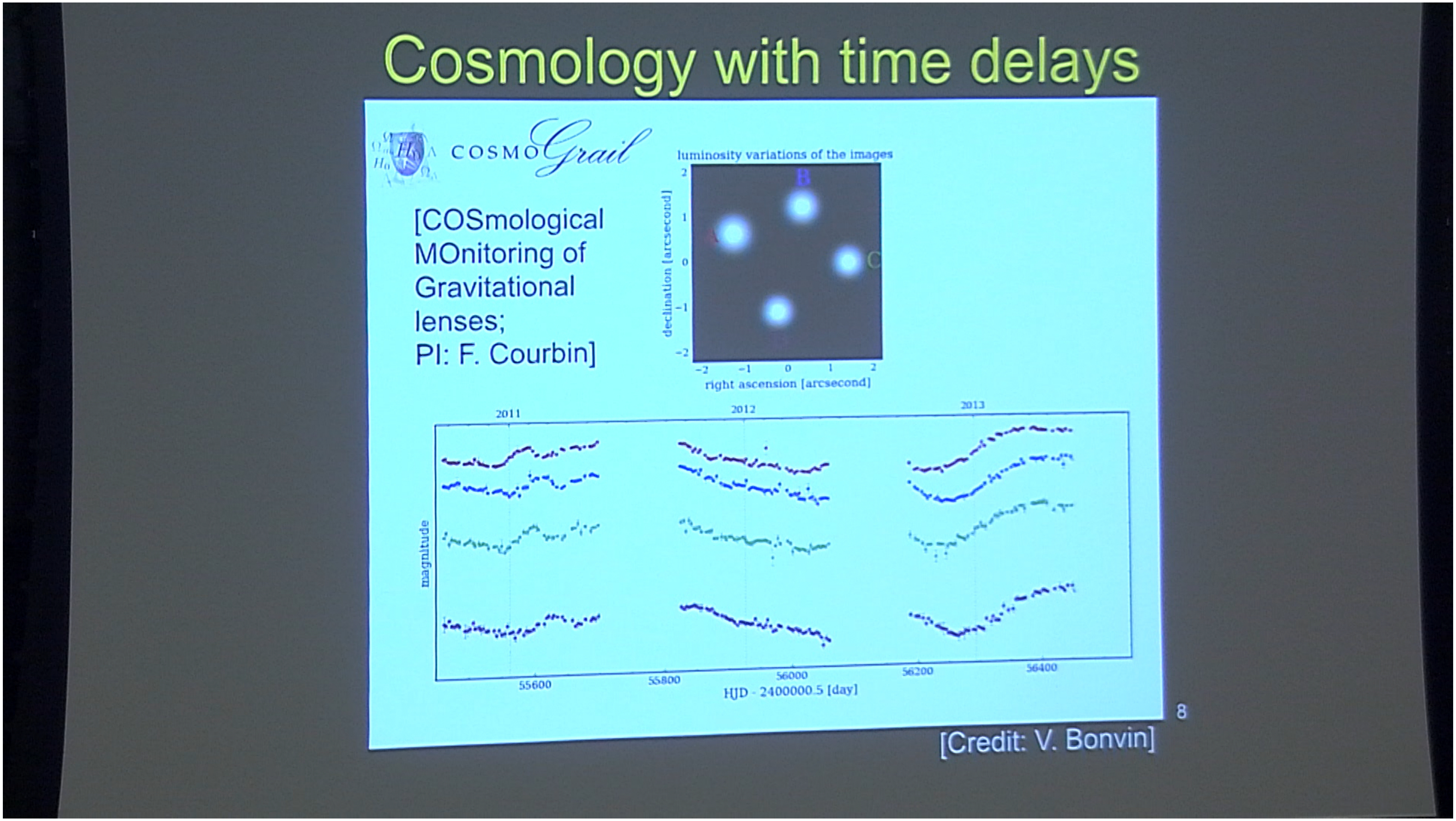
[Suyu et al. 2017]

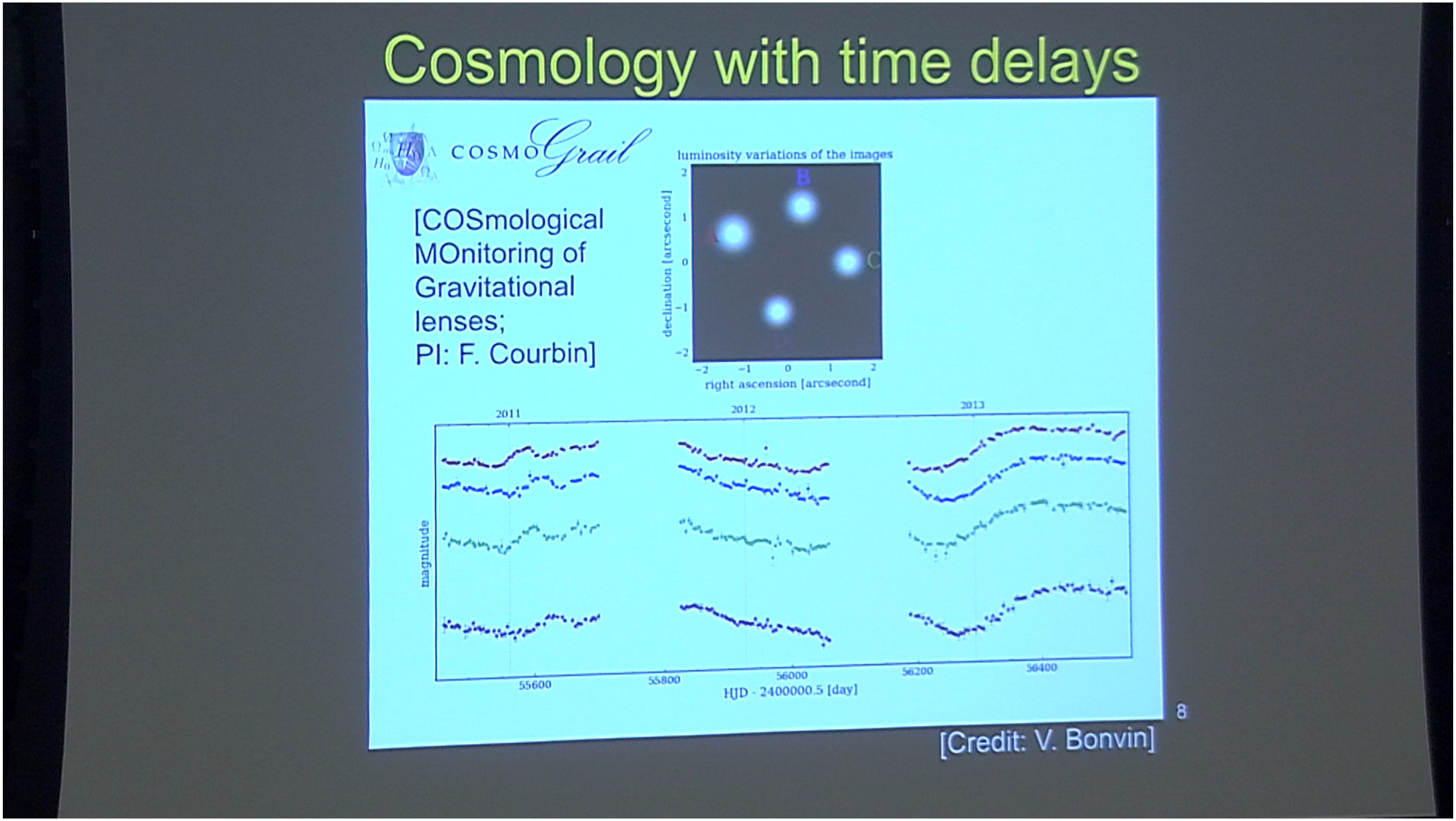
quasar powered by accretion of material onto supermassive black hole:

light emitted from quasar changes in time ("flickers")

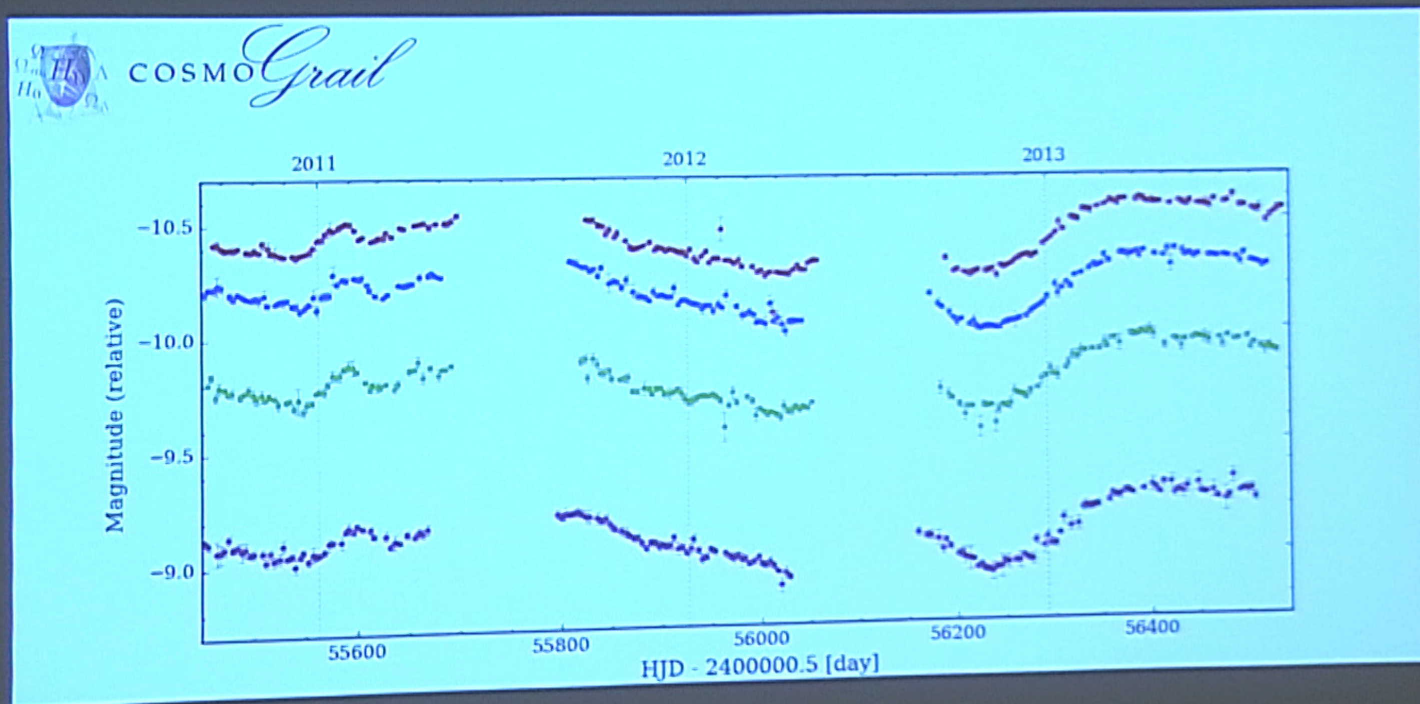
7


Cosmology with time delays
COSMOGrail
[COSmological MOnitoring of Gravitational lenses; PI: F. Courbin]
luminosity variations of the images
B
C
declination [arcsecond]
right ascension [arcsecond]
2011
2012
2013
magnitude
55600
55800
56000
56200
56400
HJD - 2400000.5 [day]
8
[Credit: V. Bonvin]


Cosmology with time delays
COSMOGrail
[COSmological MOnitoring of Gravitational lenses; PI: F. Courbin]
luminosity variations of the images
declination [arcsecond]
right ascension [arcsecond]
2011
2012
2013
magnitude
HJD - 2400000.5 [day]
8
[Credit: V. Bonvin]


Cosmology with time delays
COSMOGrail
[COSmological MOnitoring of Gravitational lenses; PI: F. Courbin]
luminosity variations of the images
B
C
declination [arcsecond]
right ascension [arcsecond]
2011
2012
2013
magnitude
55600
55800
56000
56200
56400
HJD - 2400000.5 [day]
8
[Credit: V. Bonvin]

Cosmology with time delays



9

[Credit: V. Bonvin]

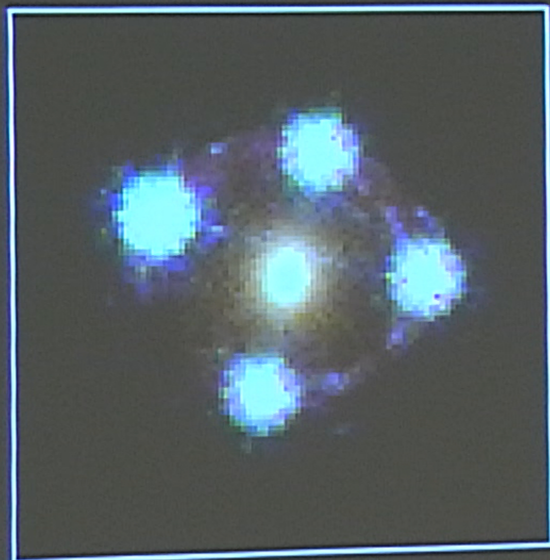
Cosmology with time delays

[Credit: V. Bonvin]

9

Cosmology with time delays

HE0435-1223



[Suyu et al. 2017]

Time delay:

$$t = \frac{1}{c} D_{\Delta t} \, \phi_{\rm lens}$$

Time-delay distance: $D_{\Delta t} \propto \frac{1}{H_0}$

Obtain from lens mass model

For cosmography, need:
(1) time delays
(2) lens mass model
(3) mass along line of sight

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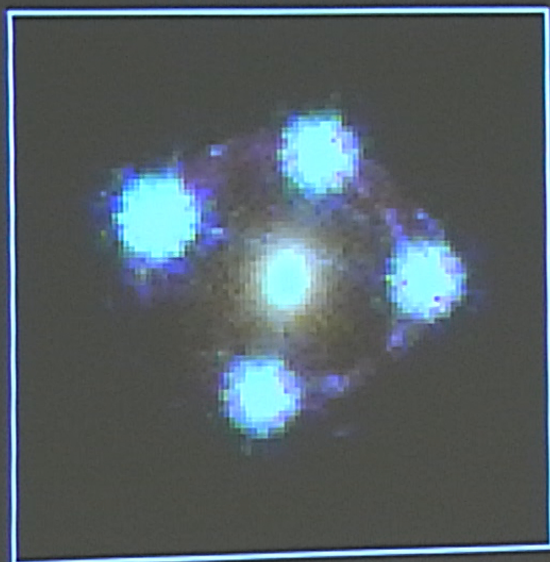
Cosmology with time delays

HE0435-1223



[Suyu et al. 2017]

Time delay:

$$t = \frac{1}{c} D_{\Delta t} \, \phi_{\mathrm{lens}}$$

Time-delay distance: $D_{\Delta t} \propto \frac{1}{H_0}$

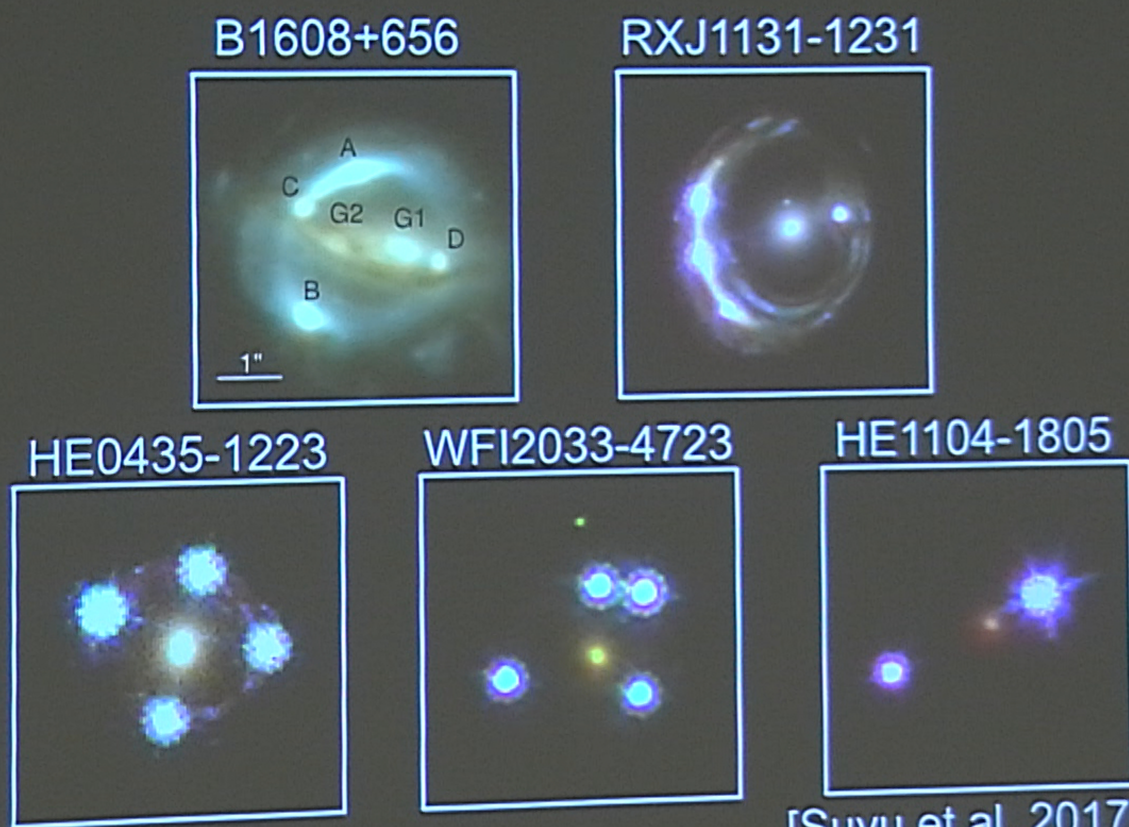
Obtain from lens mass model

For cosmography, need:
(1) time delays
(2) lens mass model
(3) mass along line of sight

Advantages:
- simple geometry & well-tested physics
- one-step physical measurement of a cosmological distance

H0LiCOW

H_0 Lenses in COSMOGRAIL's Wellspring



[Suyu et al. 2017]

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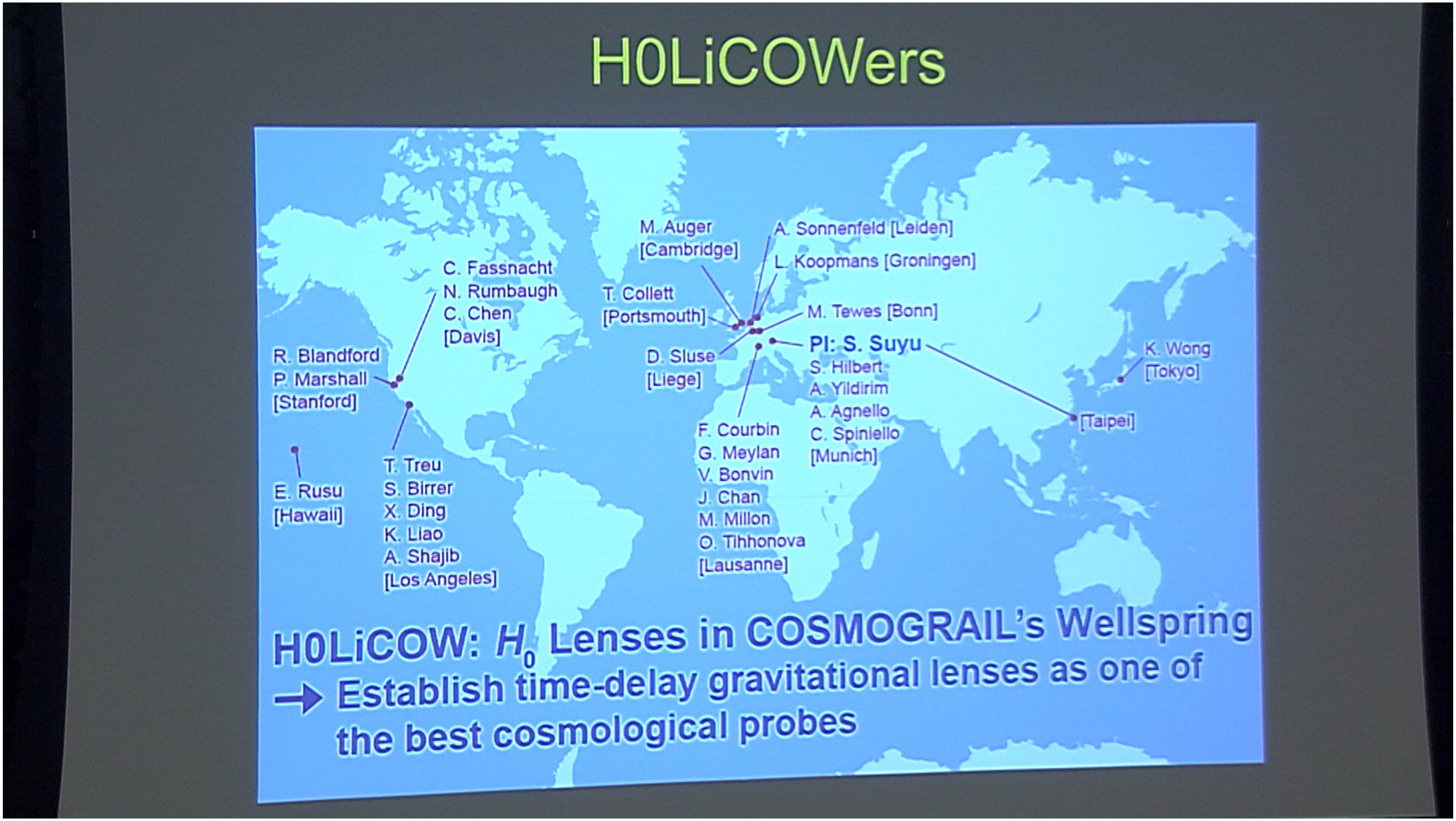
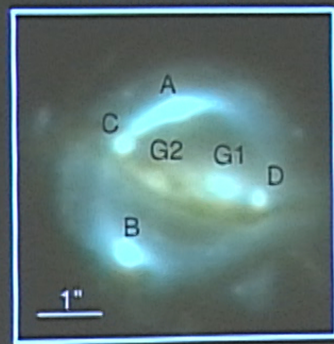

H0LiCOWers
M. Auger
[Cambridge]
A. Sonnenfeld [Leiden]
L. Koopmans [Groningen]
C. Fassnacht
N. Rumbaugh
C. Chen
[Davis]
T. Collett
[Portsmouth]
M. Tewes [Bonn]
R. Blandford
P. Marshall
[Stanford]
D. Sluse
[Liege]
PI: S. Suyu
S. Hilbert
A. Yildirim
A. Agnello
C. Spiniello
[Munich]
K. Wong
[Tokyo]
[Taipei]
E. Rusu
[Hawaii]
T. Treu
S. Birrer
X. Ding
K. Liao
A. Shajib
[Los Angeles]
F. Courbin
G. Meylan
V. Bonvin
J. Chan
M. Millon
O. Tihhonova
[Lausanne]
H0LiCOW: H_0 Lenses in COSMOGRAIL's Wellspring
→ Establish time-delay gravitational lenses as one of the best cosmological probes

H0LiCOW: latest results

B1608+656

[Suyu et al. 2010]



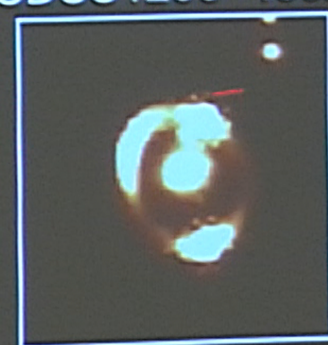
RXJ1131-1231

[Suyu et al. 2013, 2014]

HE0435-1223

[Wong, Suyu et al. 2017; Rusu et al. 2017; Sluse et al. 2017; Bonvin et al. 2017]

SDSS1206+4332

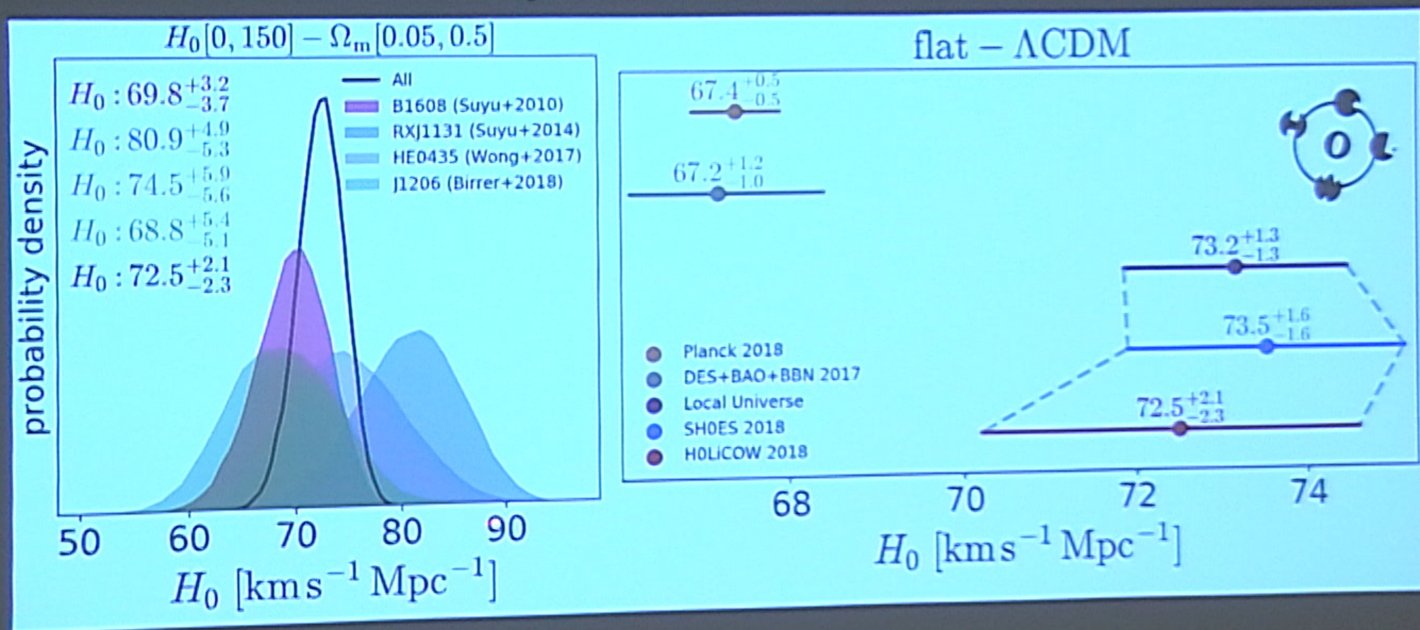


part of extended sample

[Birrer et al. 2018]

H_0 from 4 strong lenses

Blind analysis to avoid confirmation bias



H_0 with 3% precision in flat ΛCDM

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The New York Times
OUT THERE
Cosmos Controversy: The Universe Is Expanding, but How Fast?
A small discrepancy in the value of a long-sought number has fostered a debate about just how well we know the cosmos.
Forbes / Science / #WhoaScience
Support The Guardian
News Opinion Sport Culture Lifestyle
World UK Science Cities Global development Football Tech Business More
The Guardian
Across the universe
Speedy universe expansion challenges Einstein's theory
The universe is expanding faster than we thought, causing problems for cosmologists. It could even mean Einstein's theory of relativity needs revising
SUBSCRIBE
SCIENTIFIC AMERICAN
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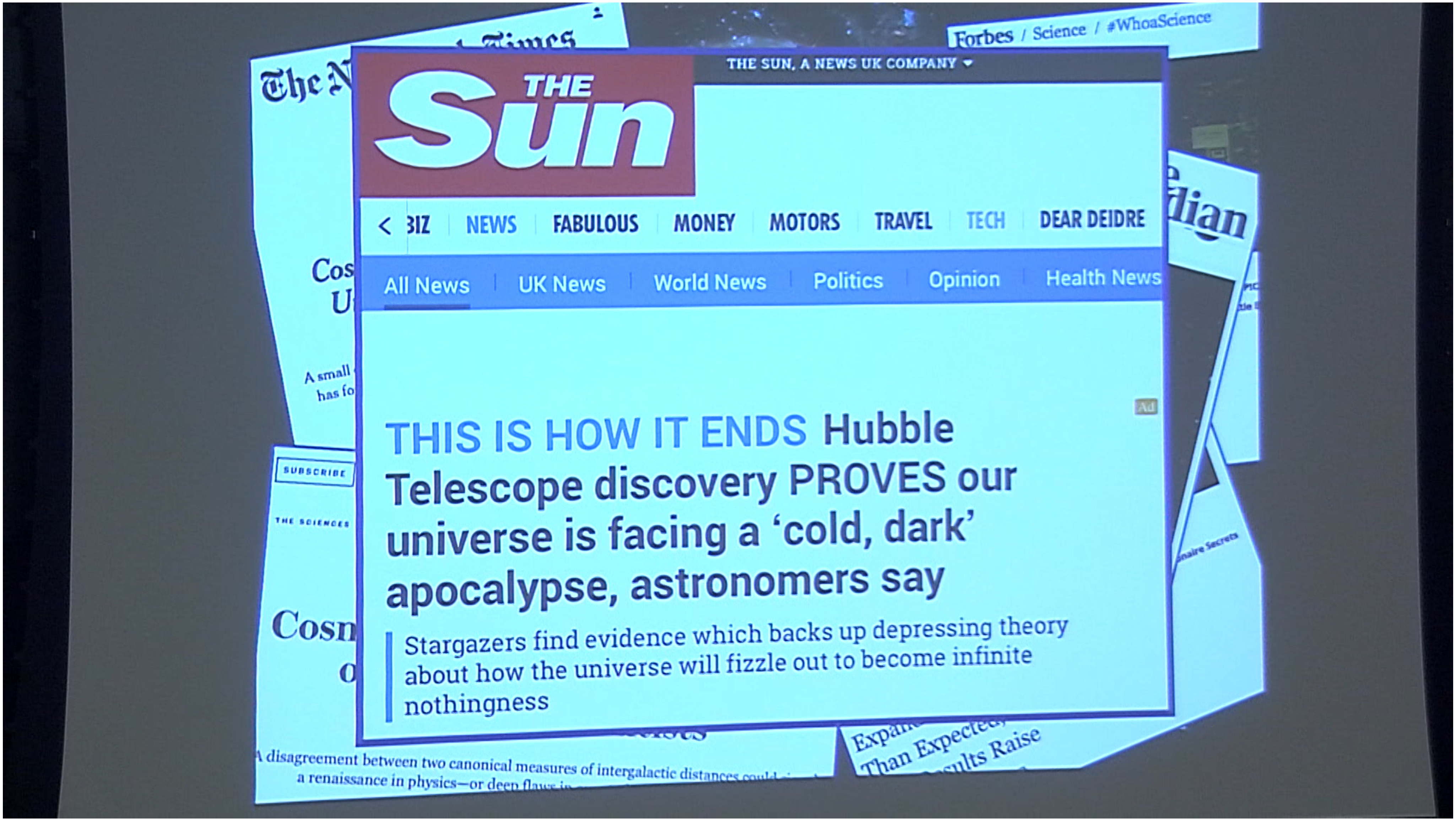
SPACE
Cosmic Conflict: Diverging Data on Universe's Expansion Polarizes Scientists
A disagreement between two canonical measures of intergalactic distances
a renaissance in physics—or deep flaws
The Universe Is Expanding Faster Than Expected, But


Forbes / Science / #WhoaScience
THE SUN, A NEWS UK COMPANY
THE Sun
BIZ | NEWS | FABULOUS | MONEY | MOTORS | TRAVEL | TECH | DEAR DEIDRE
All News | UK News | World News | Politics | Opinion | Health News
Ad
THIS IS HOW IT ENDS Hubble Telescope discovery PROVES our universe is facing a 'cold, dark' apocalypse, astronomers say
Stargazers find evidence which backs up depressing theory about how the universe will fizzle out to become infinite nothingness
SUBSCRIBE
THE SCIENCES

Looking forward

WFI2033-4723

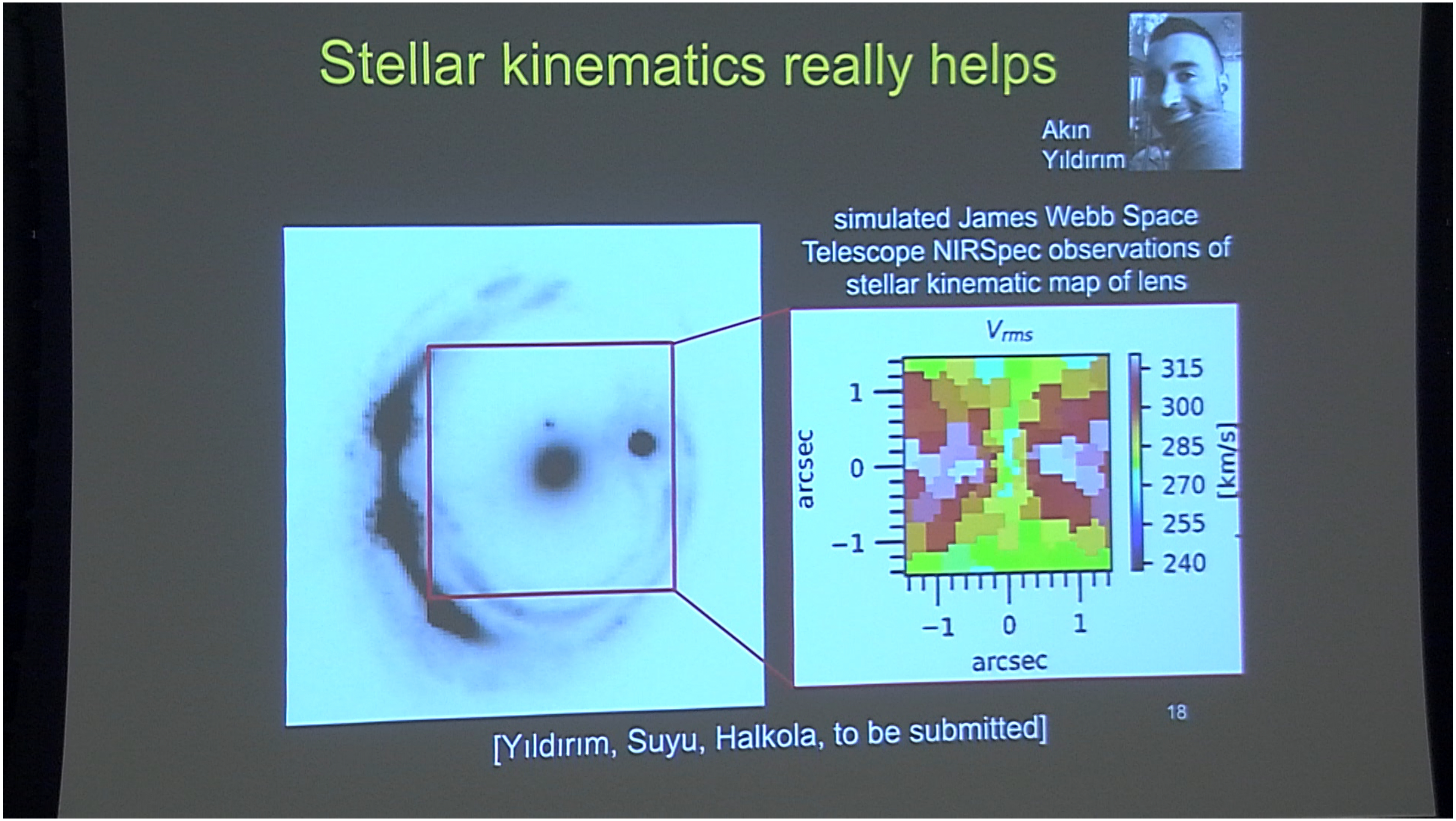
HE1104-1805

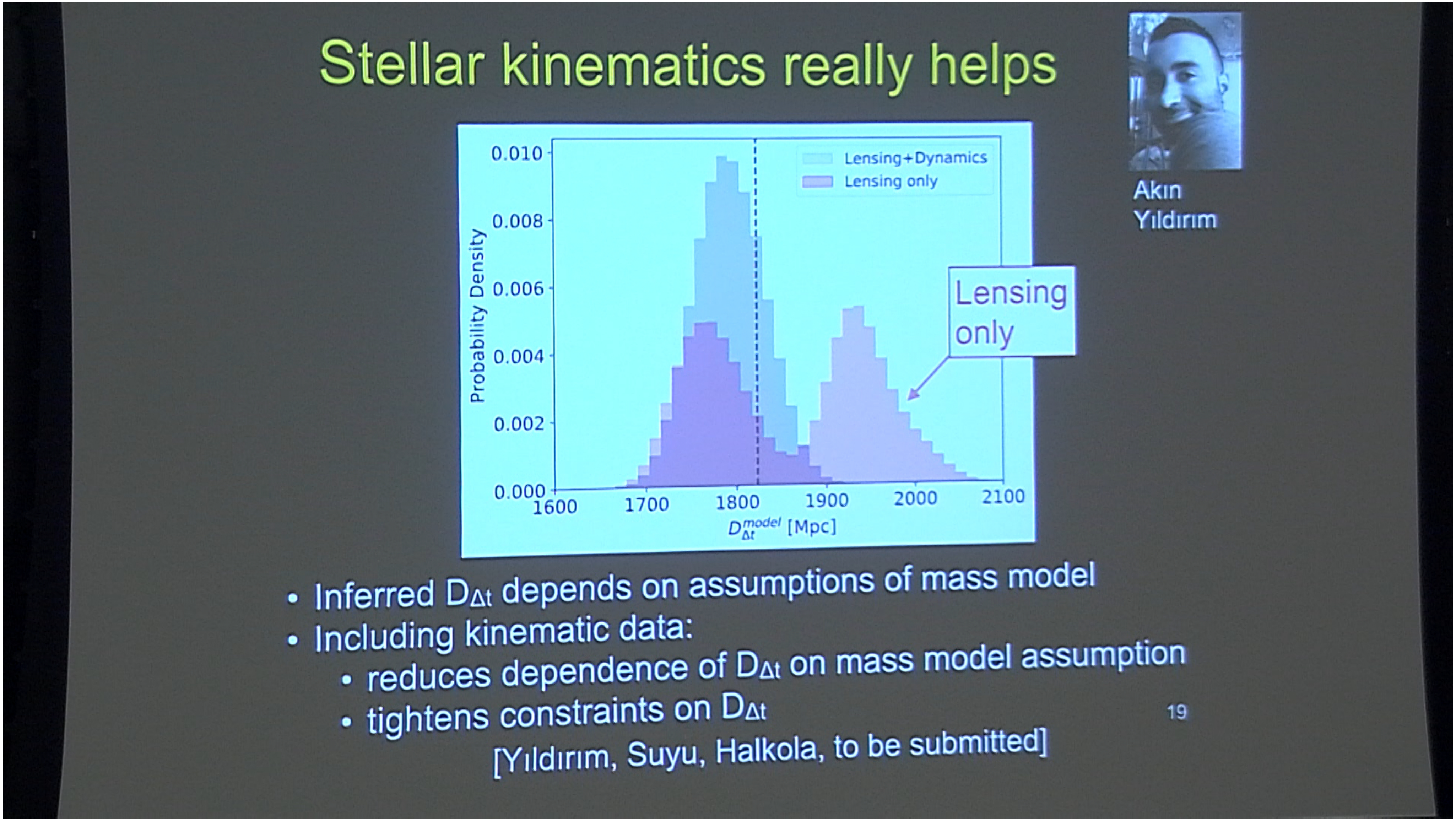
PG1115+080

WFI2033-4723:
blind analysis ongoing
[Rusu et al., Sluse et al., Wong et al., in prep.]

PG1115+080 :
blind analysis of adaptive-optics and HST images ongoing
[Chen et al., in prep.]

7


Stellar kinematics really helps
Akın Yıldırım
simulated James Webb Space Telescope NIRSpec observations of stellar kinematic map of lens
V_{rms}
arcsec
1
0
−1
−1
0
1
arcsec
315
300
285
270
255
240
[km/s]
18
[Yıldırım, Suyu, Halkola, to be submitted]


Stellar kinematics really helps
0.010
0.008
0.006
0.004
0.002
0.000
Probability Density
1600
1700
1800
1900
2000
2100
$D_{\Delta t}^{model}$ [Mpc]
Lensing+Dynamics
Lensing only
Lensing only
Akın Yıldırım
• Inferred $D_{\Delta t}$ depends on assumptions of mass model
• Including kinematic data:
• reduces dependence of $D_{\Delta t}$ on mass model assumption
• tightens constraints on $D_{\Delta t}$
[Yıldırım, Suyu, Halkola, to be submitted]
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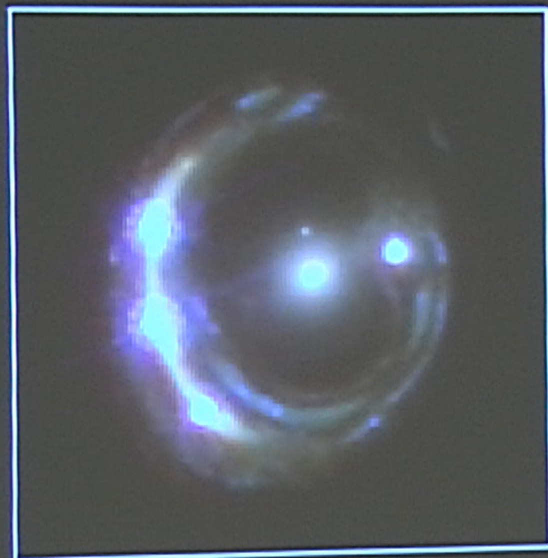
D_A to the lens

Inh Jee



Time delay:

$$\Delta t \sim GM$$

Lens velocity dispersion:

$$\sigma^2 \sim GM/r$$

Angular diameter distance:

$$D_A \sim r/\Delta\theta$$

$$\boxed{D_A \sim \frac{\Delta t}{\sigma^2 \Delta\theta}}$$

- D_A more sensitive to dark energy than $D_{\Delta t}$
- D_A insensitive to mass along LOS, but depend on anisotropy in stellar velocity dispersion
- Can measure D_A to ~15% per lens with current data

[Paraficz & Hjorth 2009; Jee, Komatsu & Suyu 2015; Jee, Suyu, Komatsu et al., submitted]

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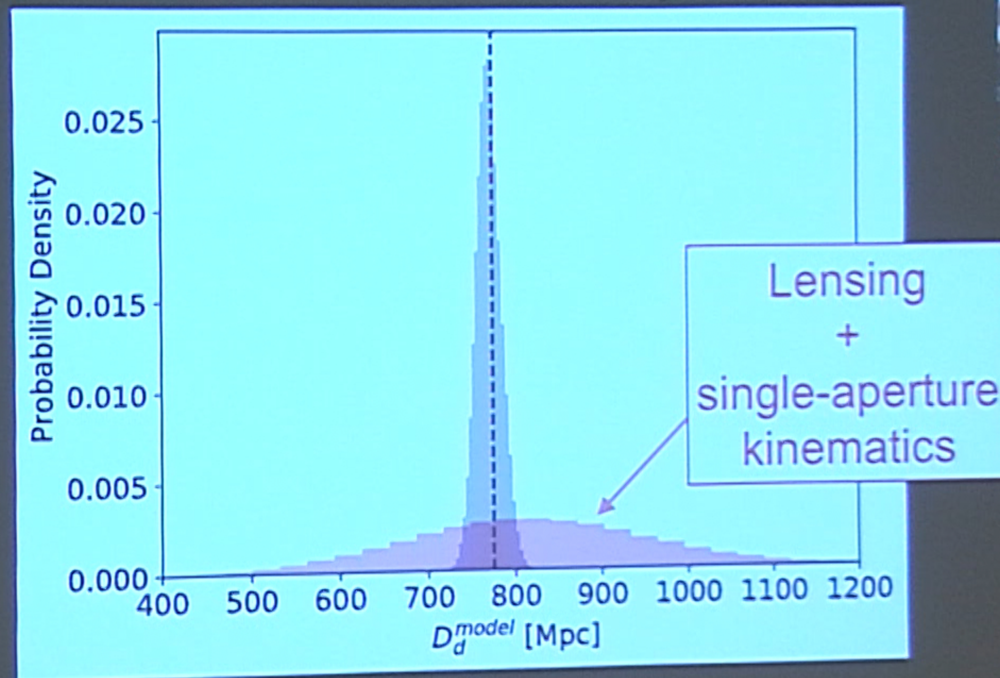
Stellar kinematics really helps



Akın
Yıldırım

Including spatially-resolved (2D) kinematic data:

- drastically reduces the uncertainty of D_A from ~15% to ~3%
- sensitive to systematic errors in kinematic measurements

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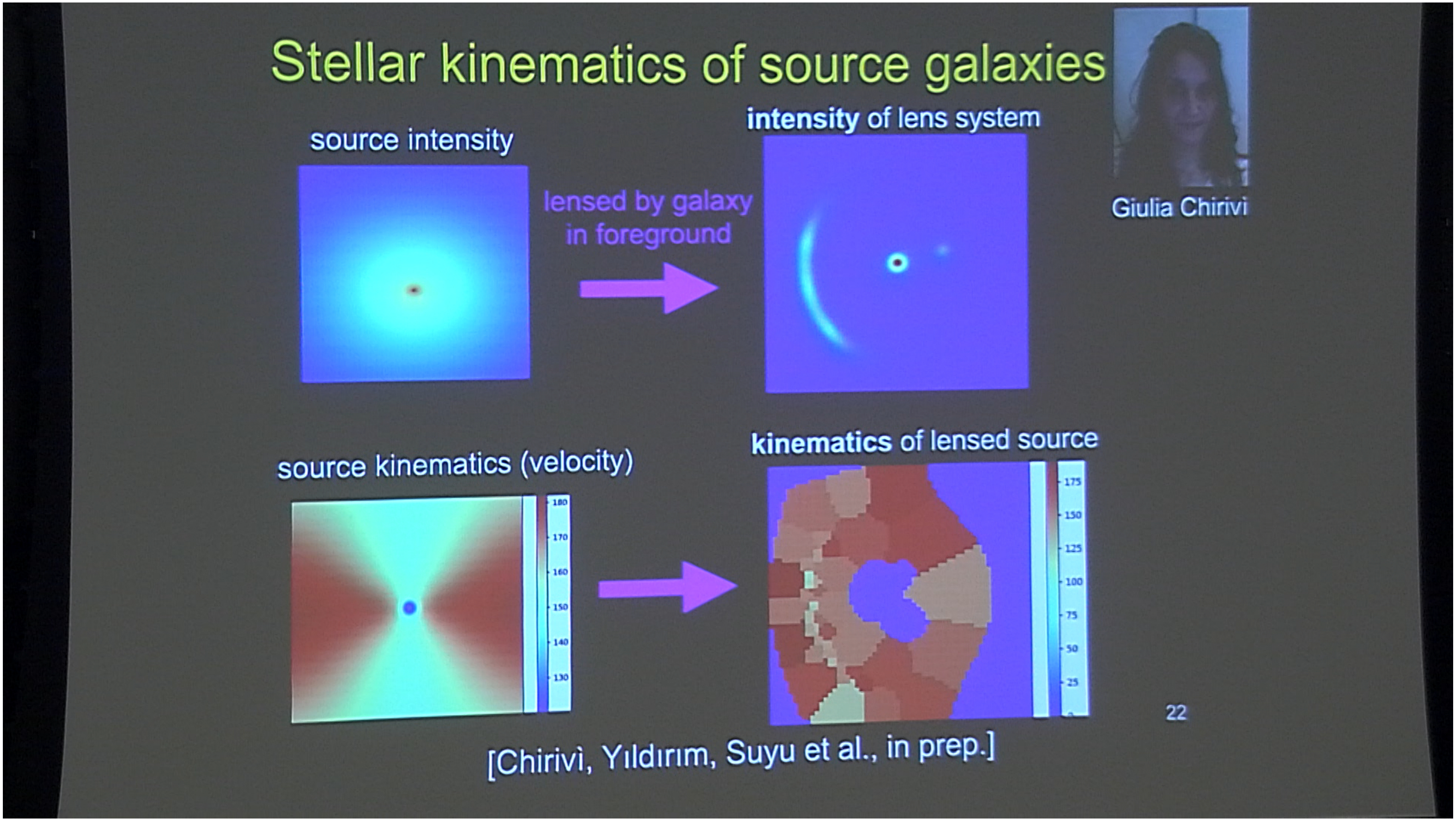
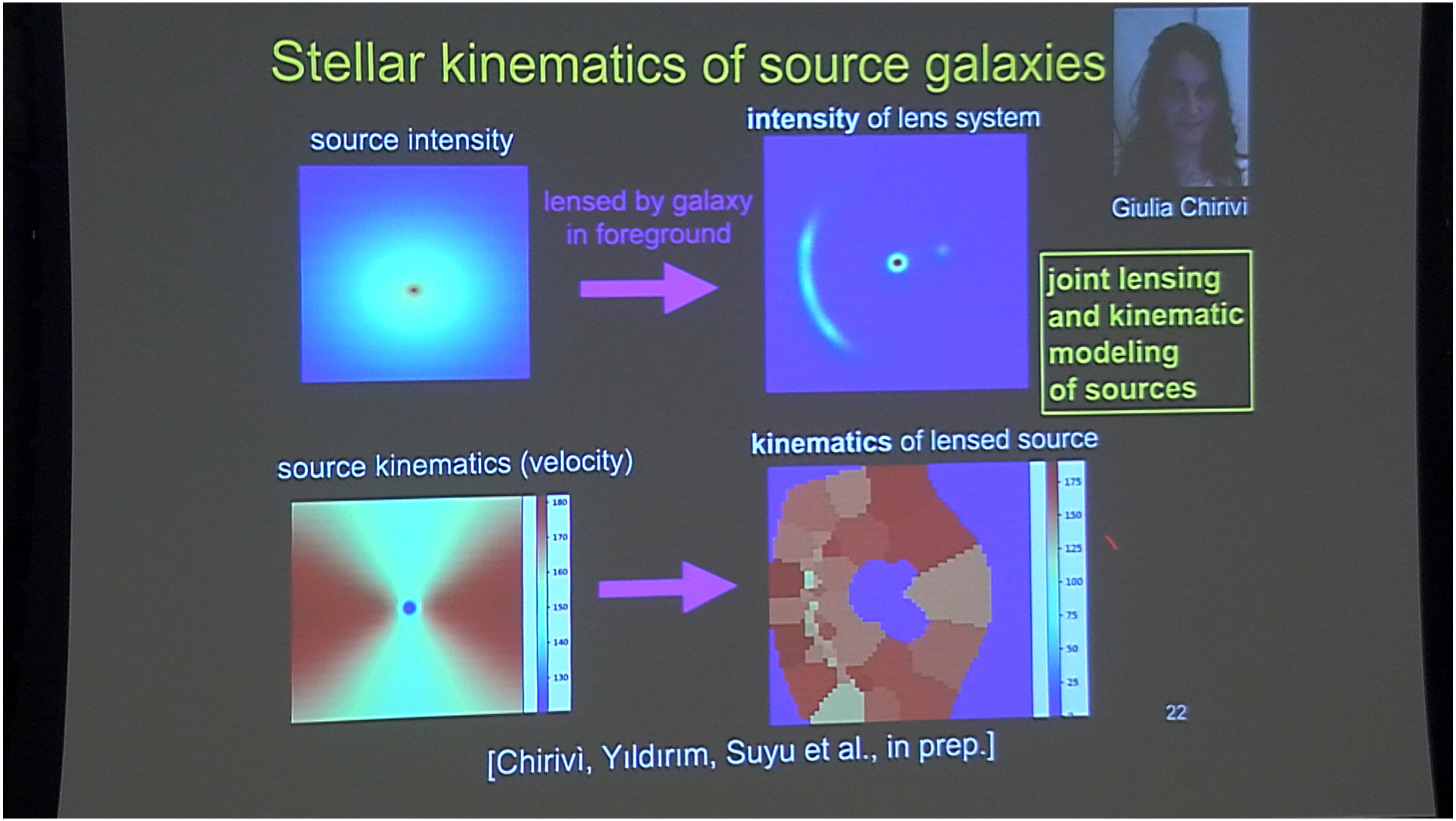
[Yıldırım, Suyu, Halkola, to be submitted]


Stellar kinematics of source galaxies
source intensity
lensed by galaxy
in foreground
intensity of lens system
Giulia Chirivì
source kinematics (velocity)
180
170
160
150
140
130
kinematics of lensed source
175
150
125
100
75
50
25
22
[Chirivì, Yıldırım, Suyu et al., in prep.]


Stellar kinematics of source galaxies
source intensity
lensed by galaxy
in foreground
intensity of lens system
Giulia Chirivi
joint lensing
and kinematic
modeling
of sources
source kinematics (velocity)
kinematics of lensed source
22
[Chirivì, Yıldırım, Suyu et al., in prep.]

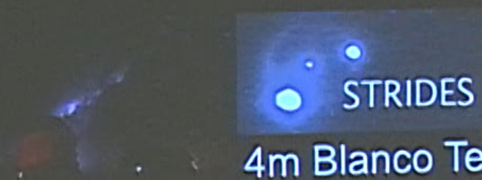
Towards hundreds of lenses

Hyper Suprime-Cam Survey

8m Subaru Telescope
Mauna Kea, Hawaii

- 1400 deg^2 with i_{limit}~26
- 2014-2019
- expect ~600 lenses [Oguri & Marshall 2010]

Dark Energy Survey



STRong-lensing Insights into Dark Energy Survey (PI: Treu)

4m Blanco Telescope, CTIO, Chile

- 5000 deg^2 with i_{limit}~24
- 2012-2017
- expect ~1100 lenses [Oguri & Marshall 2010]

Kilo Degree Survey

2.6m VLT Survey Telescope, Paranal, Chile

- 1500 deg^2 with r_{limit}~25
- 2011-~2018

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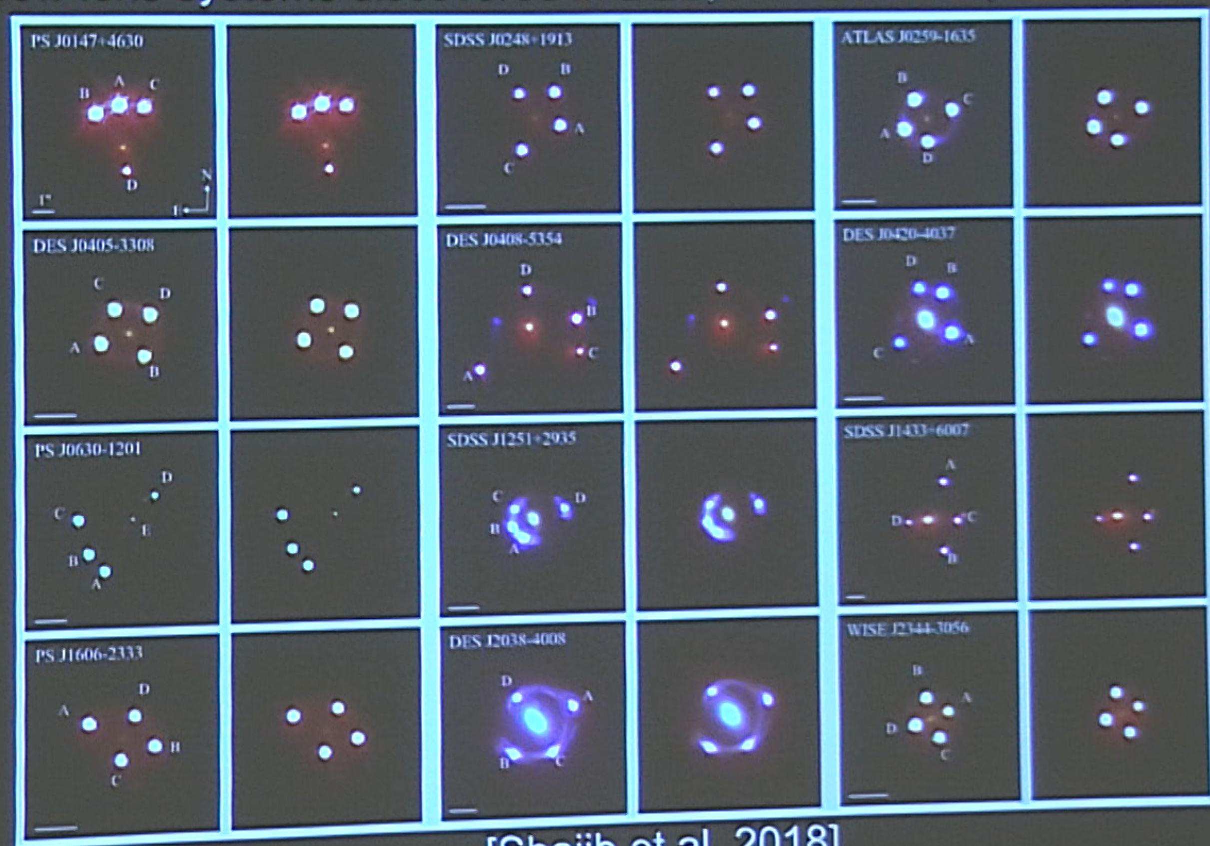
New quads imaged with HST

New lens systems discovered in DES, Pan-STARRS, SDSS, ATLAS:



[Shajib et al. 2018]

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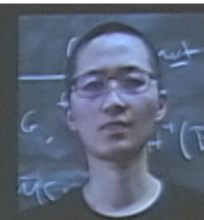
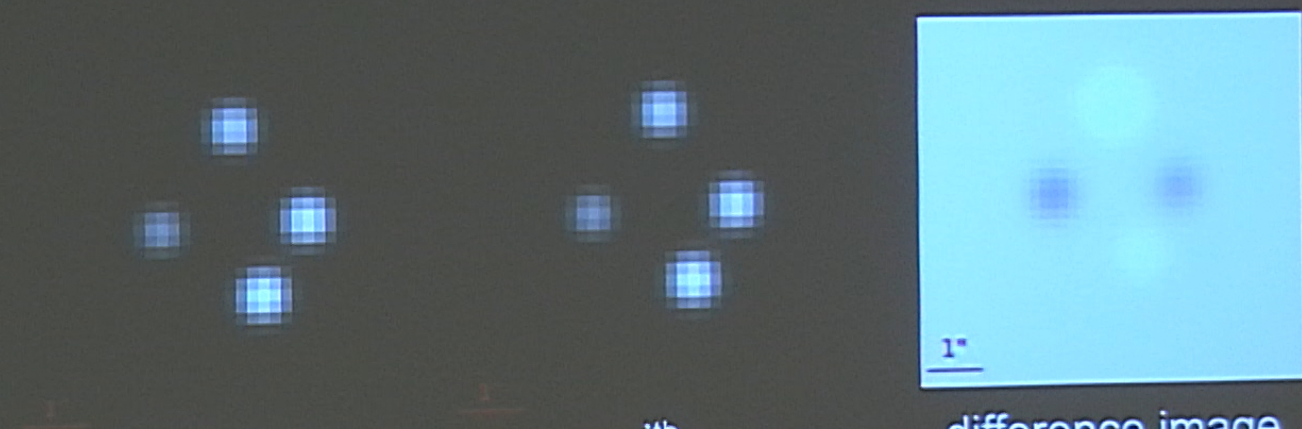
Lens search via variability



Dani Chao

If have observations at multiple epochs:



reference epoch

i^{th} epoch

difference image i^{th} epoch

[Chao et al, in prep.]

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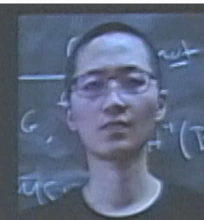
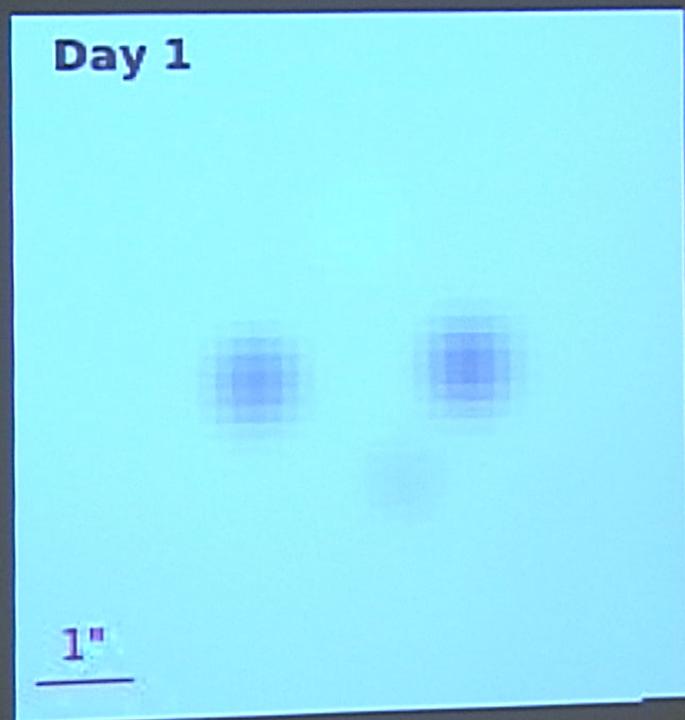
Lens search via variability



Dani Chao

Difference image, over time:



[Chao et al, in prep.]

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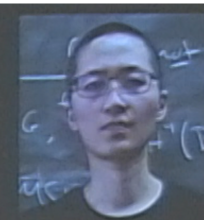
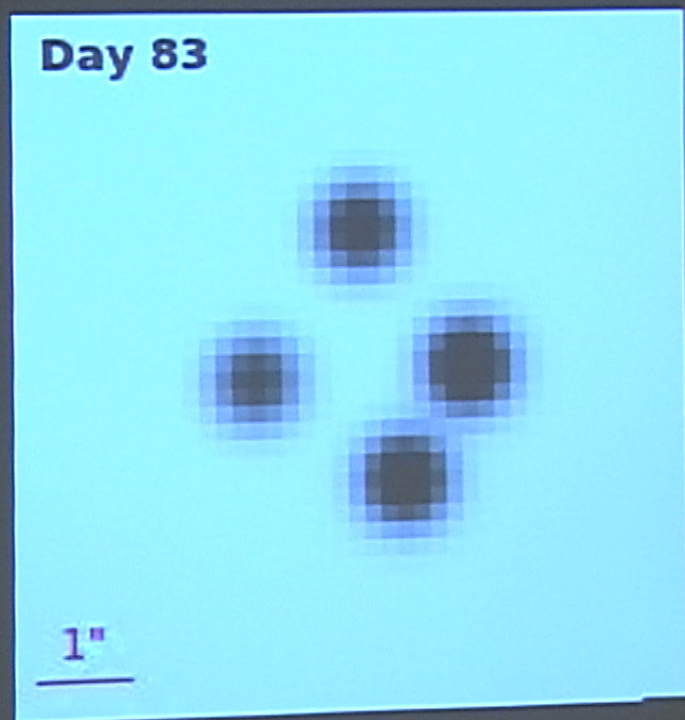
Lens search via variability



Dani Chao

Difference image, over time:

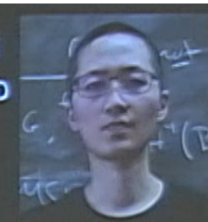


[Chao et al, in prep.]

26

Lens search via variability

Dani Chao



Difference images of Hyper Suprime-Cam survey

Detect lensed quasars using size of different image residuals:

size > $s_{threshold}$ in multiple epochs ➜ Lensed quasar candidate

size ≤ $s_{threshold}$ in multiple epochs ➜ NOT lenses

[Chao et al, in prep.]

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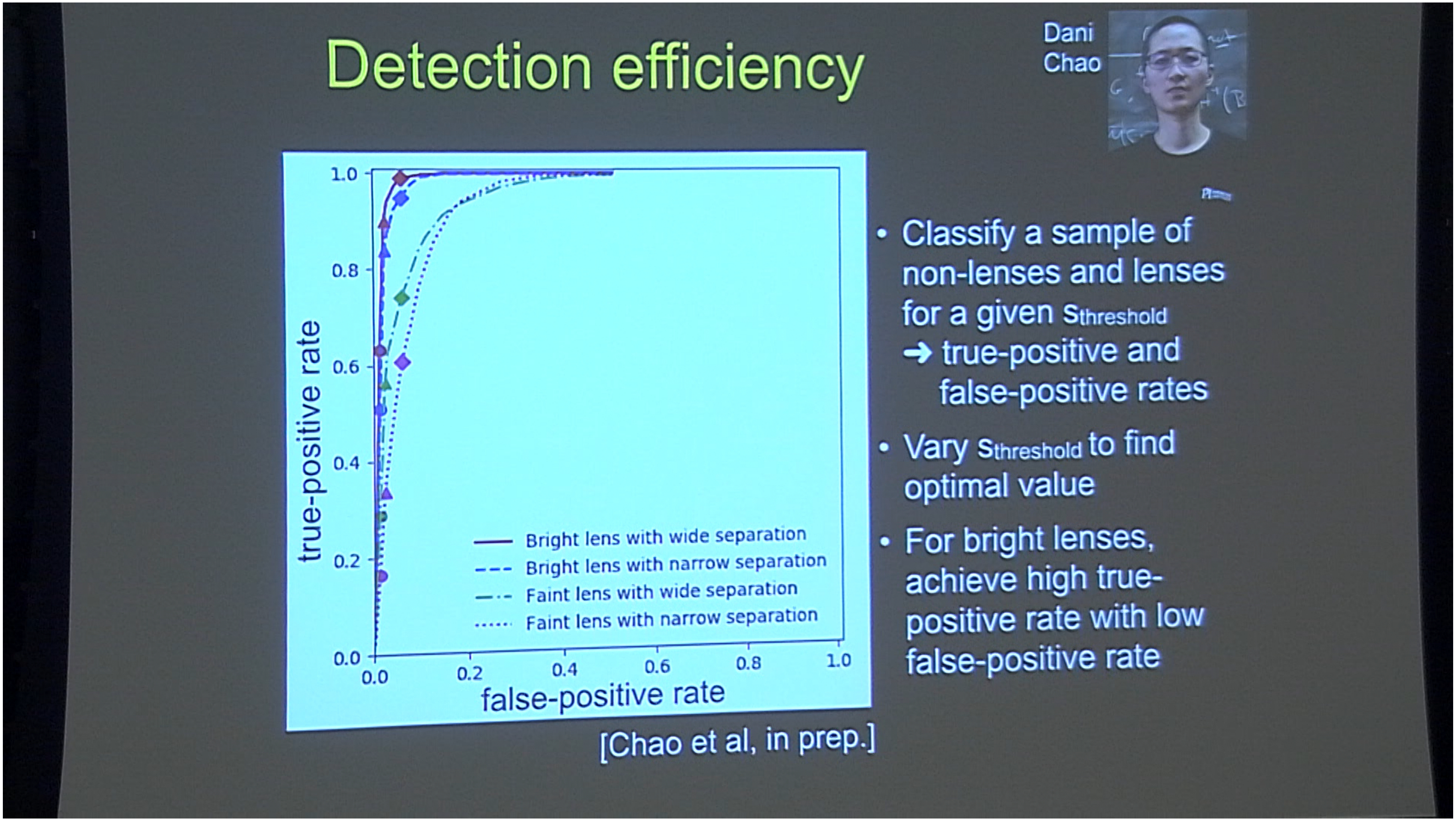
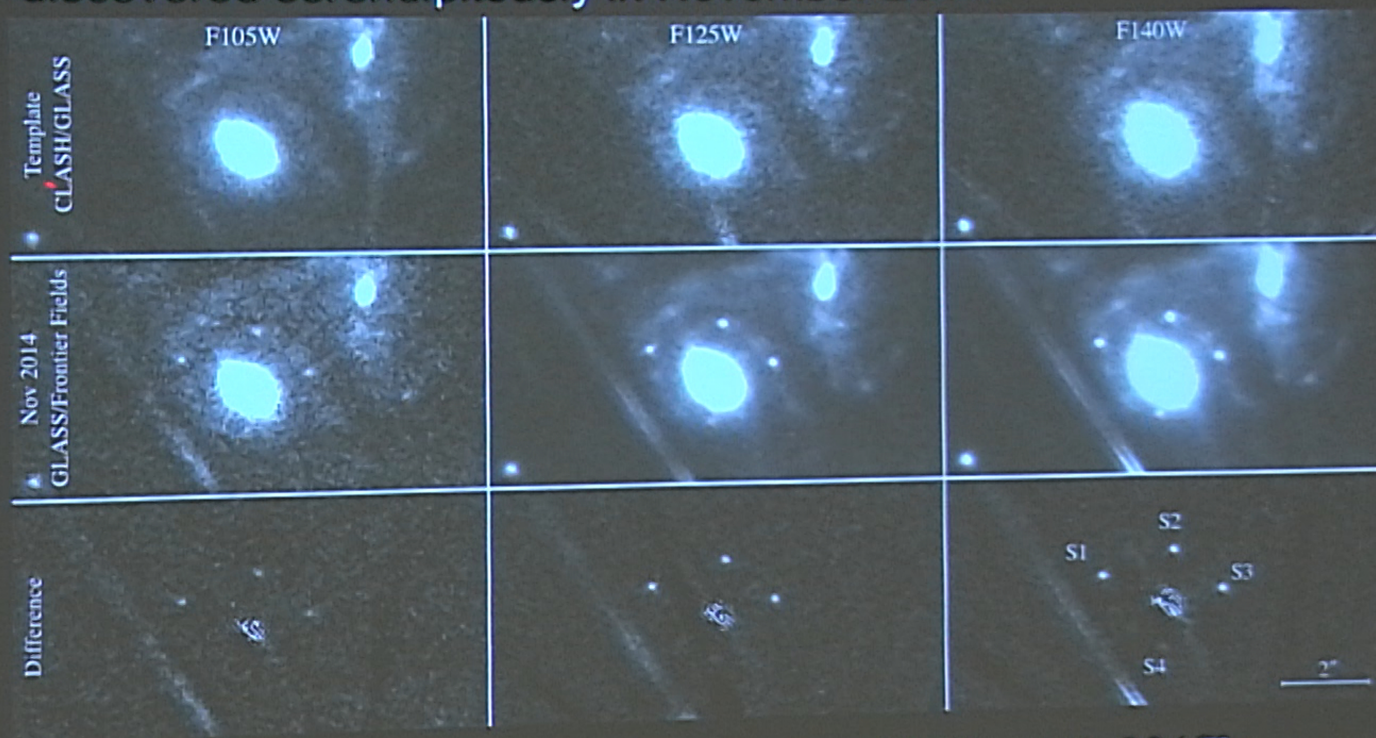

Detection efficiency
Dani Chao
true-positive rate
false-positive rate
1.0
0.8
0.6
0.4
0.2
0.0
0.0
0.2
0.4
0.6
0.8
1.0
Bright lens with wide separation
Bright lens with narrow separation
Faint lens with wide separation
Faint lens with narrow separation
[Chao et al, in prep.]
• Classify a sample of non-lenses and lenses for a given Sthreshold ➔ true-positive and false-positive rates
• Vary Sthreshold to find optimal value
• For bright lenses, achieve high true-positive rate with low false-positive rate

Strongly lensed supernova

[Kelly et al. 2015] 29

Supernova "Refsdal"

discovered serendipitously in November 2014



[Kelly et al. 2015]

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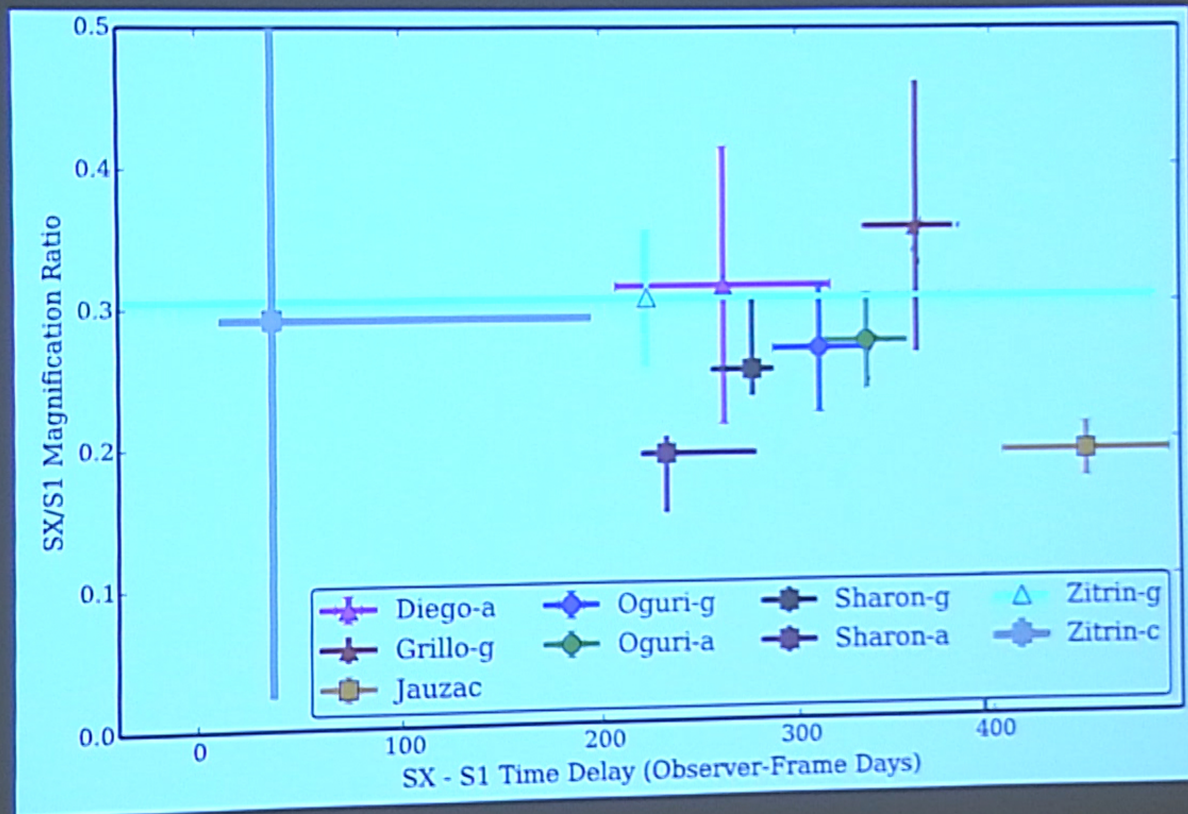
When will the other SN images appear?

Predicted magnification and delay



[Kelly et al. 2016]

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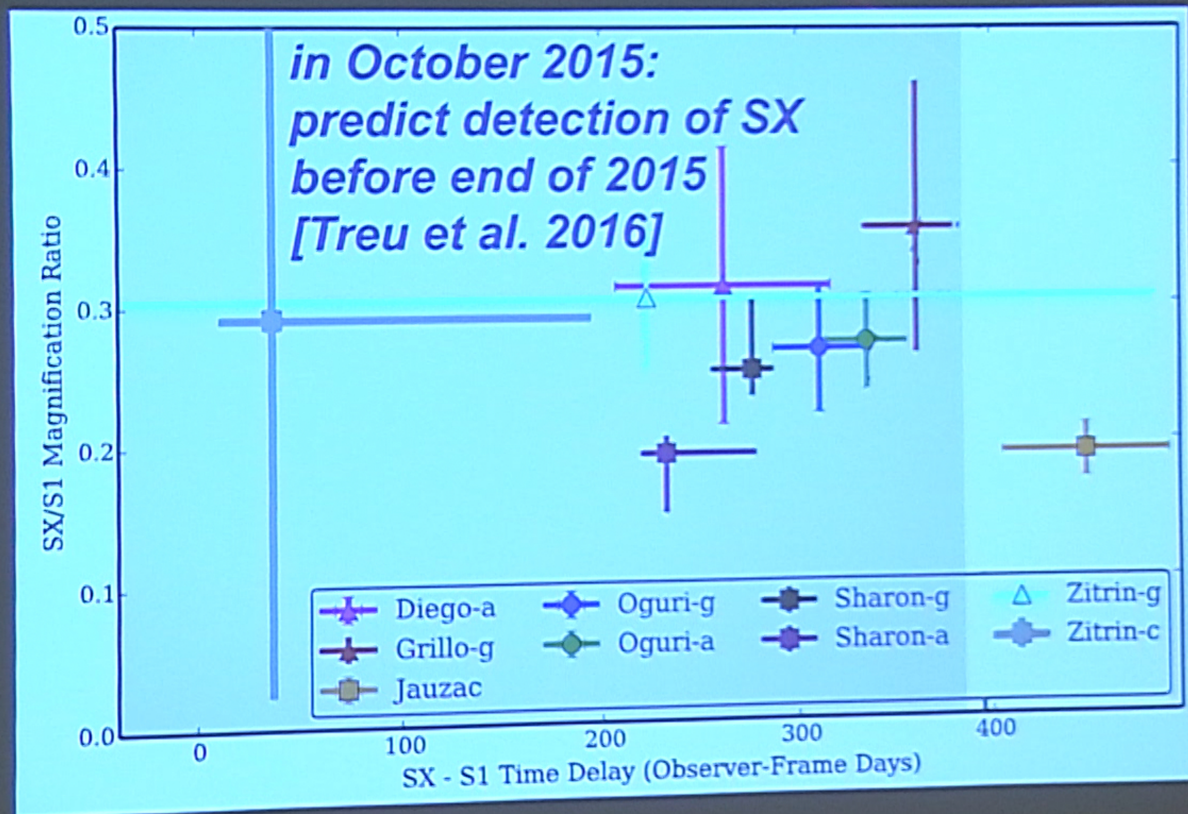
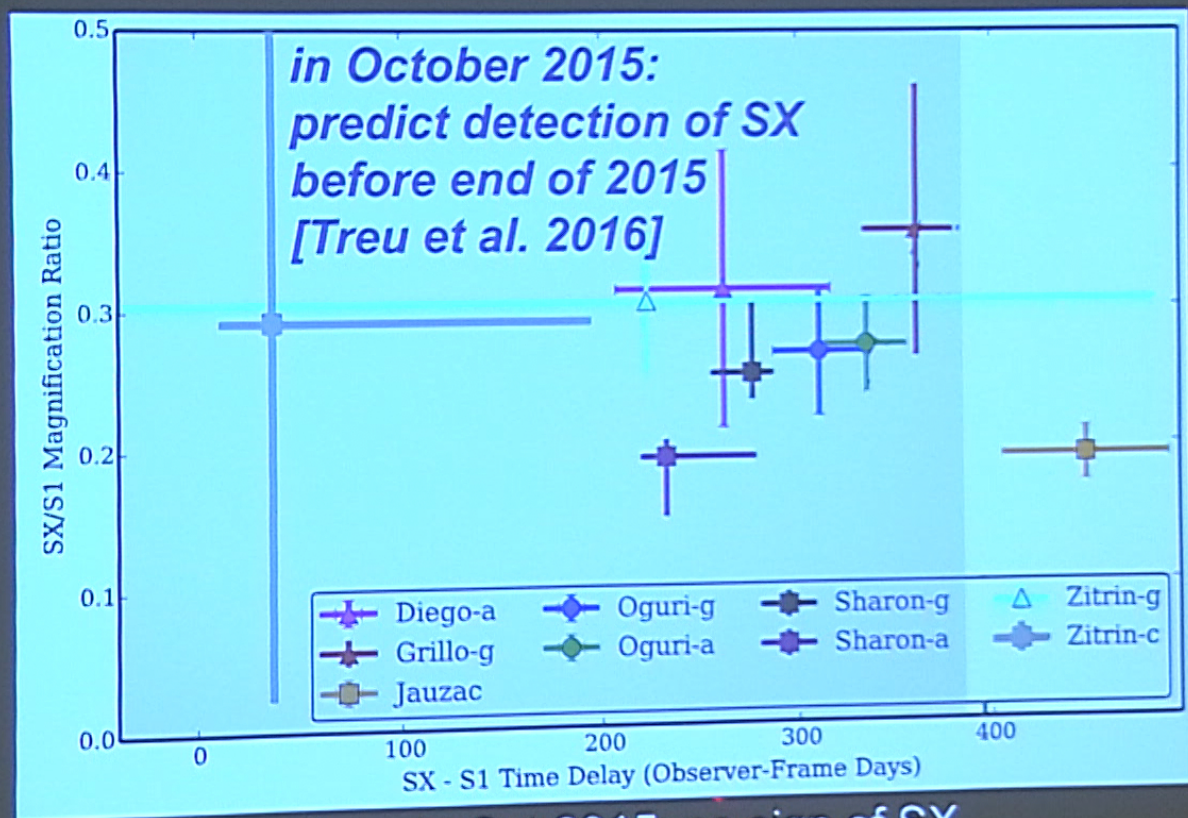
Predicted magnification and delay



[Kelly et al. 2016]

33

Predicted magnification and delay



[Kelly et al. 2016]

HST observations in Oct 2015: no sign of SX

in Nov 2015: no sign of SX…

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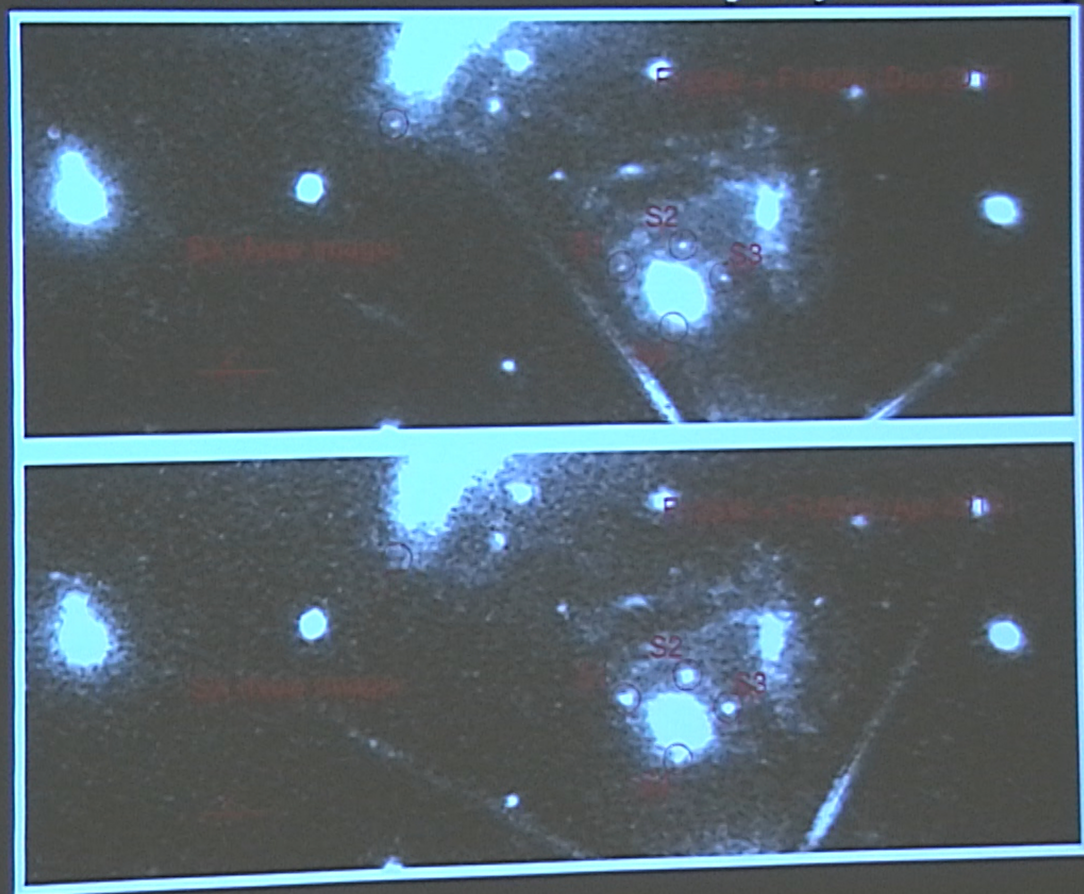
Appearance of image SX

December 2015 [Kelly et al. 2016]



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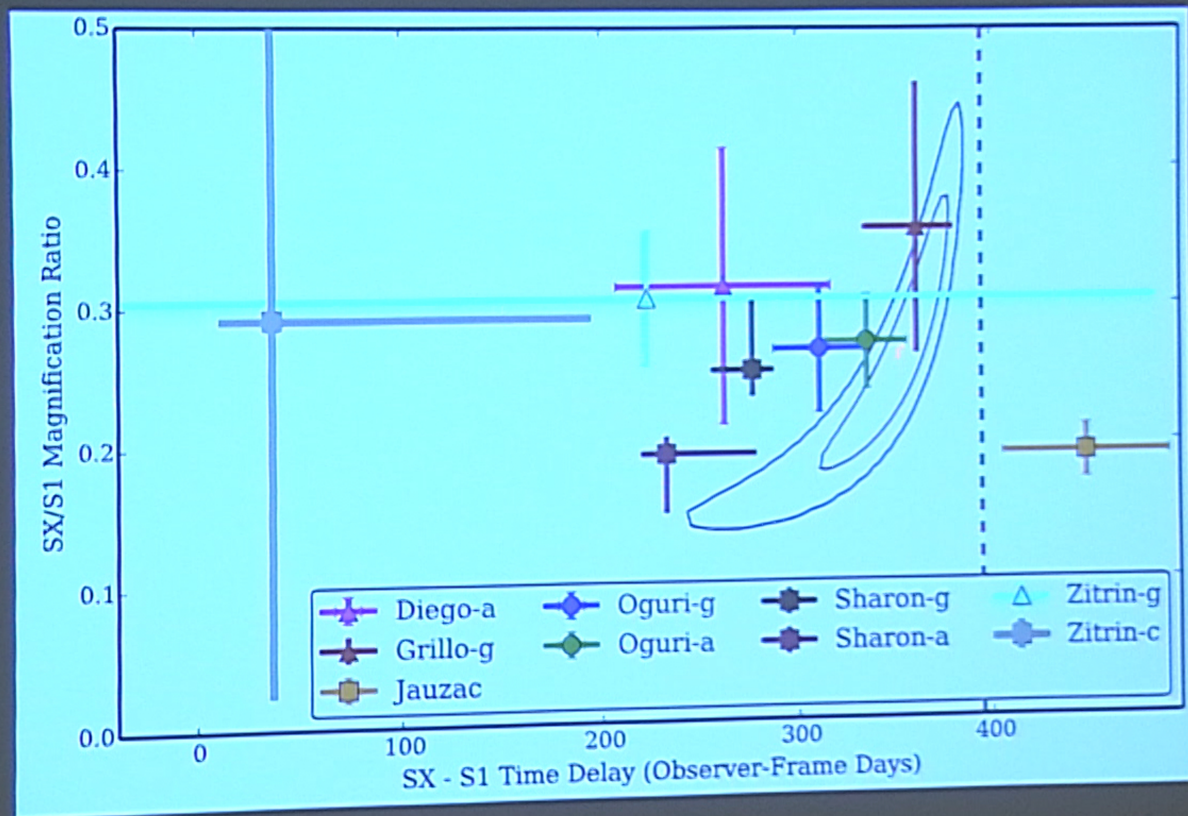
Magnification and delay



[Kelly et al. 2016] 36

Spot on!

[Kelly et al. 2016]

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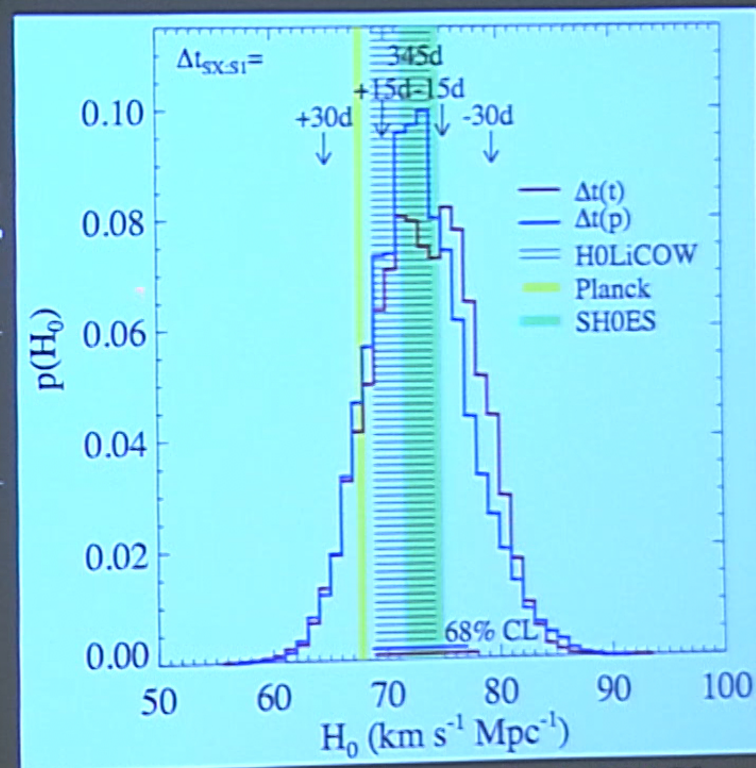
H_0 from strongly lensed supernova

feasibility study of using Supernova Refsdal for H_0 measurement



- S1-S2-S3-S4 delays from Rodney et al. (2016)
- SX-S1 delay estimated based on detection in Kelly et al. (2016)

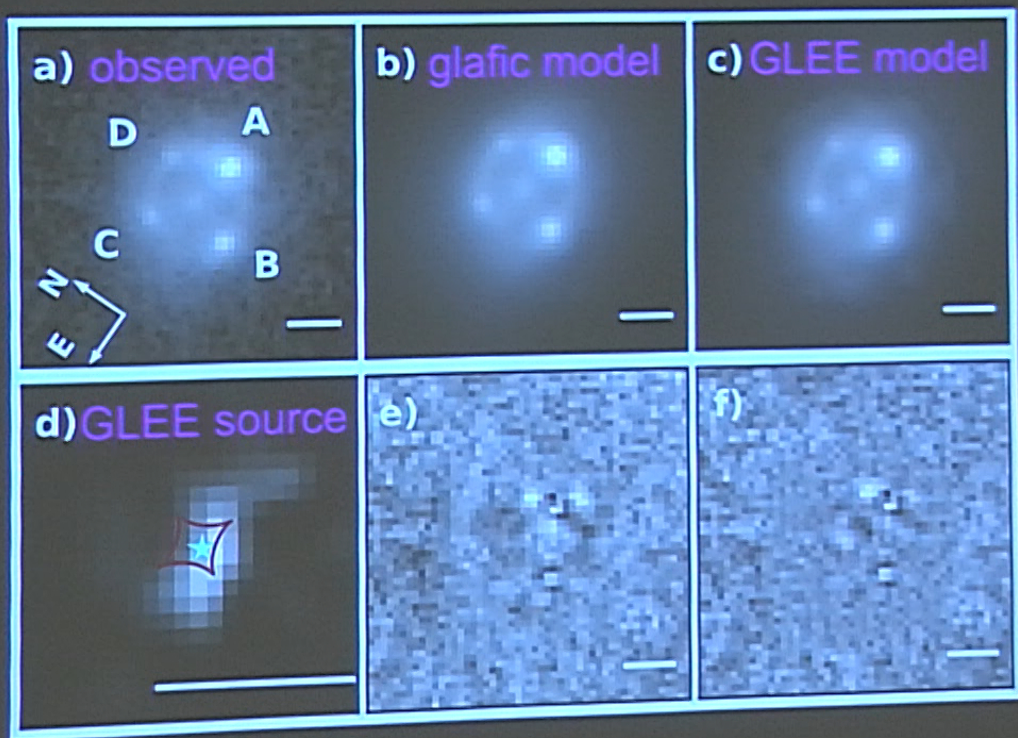
[Grillo, Rosati, Suyu et al. 2018] 38

First spatially-resolved lensed Type Ia

discovered in iPTF [Goobar et al. 2017]

Lens model predictions

Modeled the HST image with GLEE [Suyu & Halkola 2010] and glafic [Oguri 2010] to estimate the time delays [More, Suyu, Oguri et al. 2017]



find maximum relative time delay to be <1 day [More, Suyu, Oguri et al. 2017]

Stay tuned of results of monitoring and follow-up observations from iPTF team

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Cosmic Fireworks Première:

Unravelling Enigmas of Type Ia Supernova Progenitor and Cosmology through Strong Lensing

erc
European Research Council

[funded by the European Research Council with 2 million Euros]

Two longstanding puzzles:

1) What is the progenitor of Type Ia supernova?

single degenerate

White dwarf (WD) accreting from non-degenerate companion

or

double degenerate

WDs merging

2) What is dark energy?

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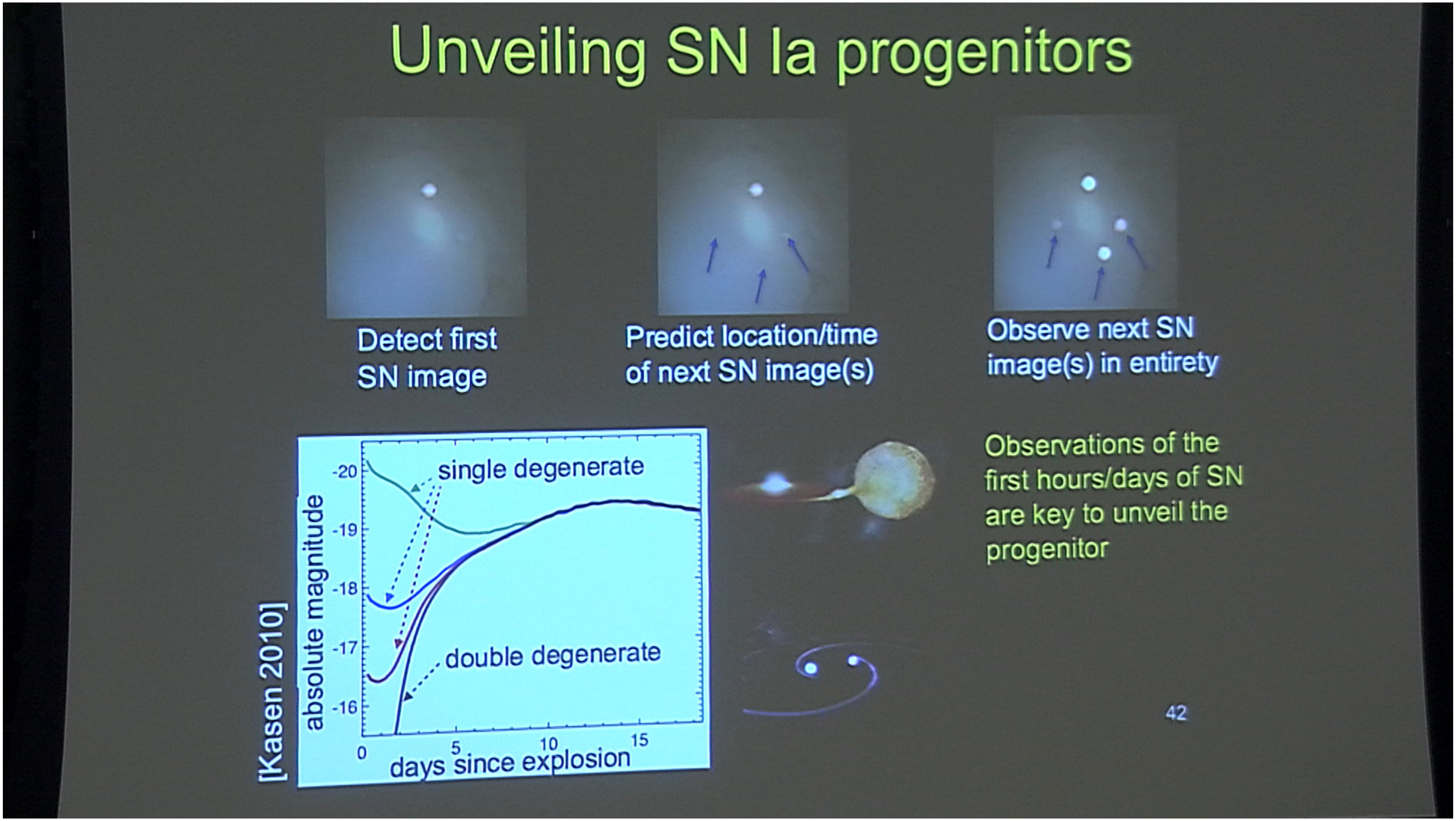
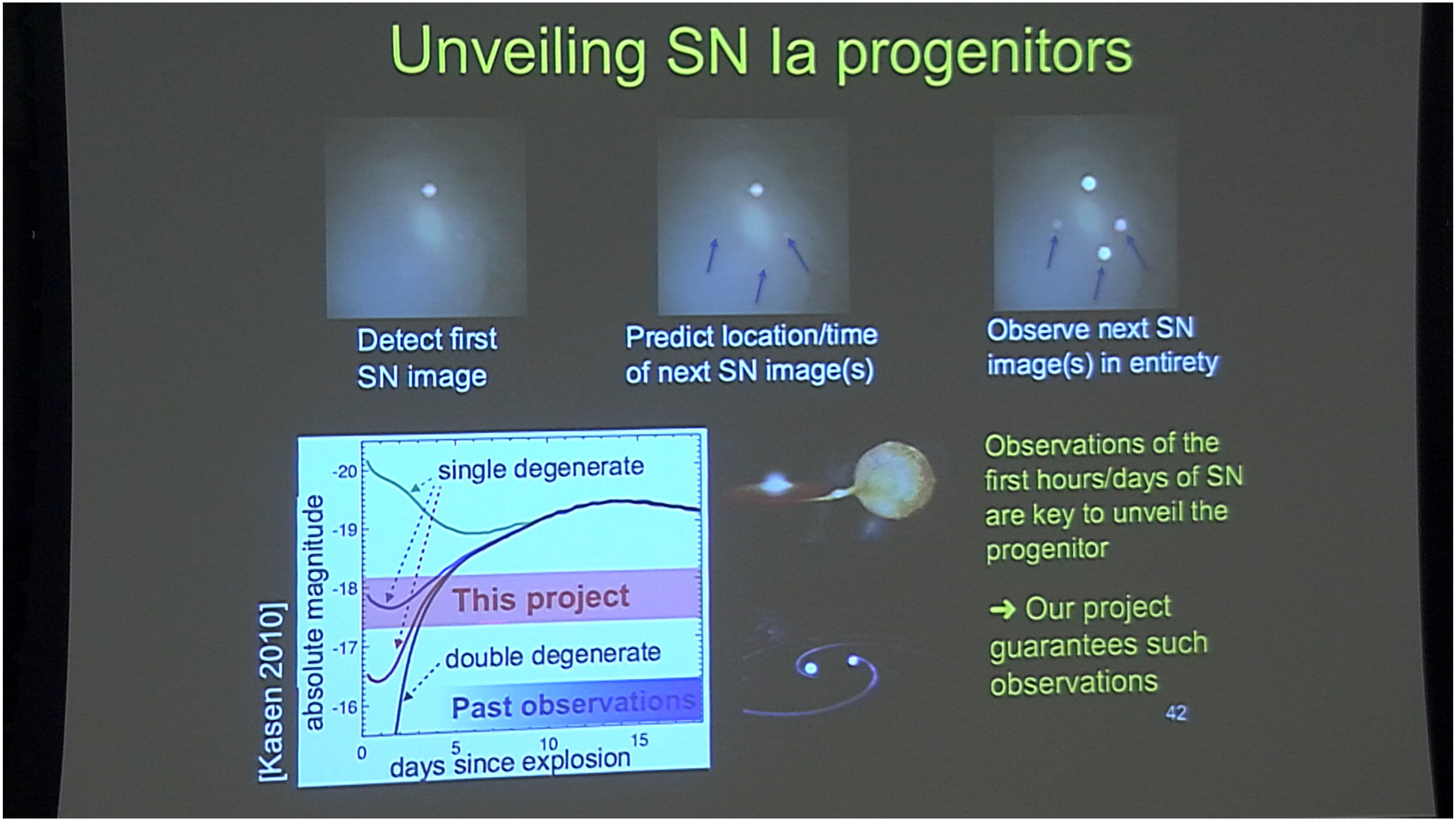

Unveiling SN Ia progenitors
Detect first SN image
Predict location/time of next SN image(s)
Observe next SN image(s) in entirety
[Kasen 2010]
absolute magnitude
-20
-19
-18
-17
-16
single degenerate
double degenerate
0
5
10
15
days since explosion
Observations of the first hours/days of SN are key to unveil the progenitor
42


Unveiling SN Ia progenitors
Detect first SN image
Predict location/time of next SN image(s)
Observe next SN image(s) in entirety
[Kasen 2010]
absolute magnitude
-20
-19
-18
-17
-16
single degenerate
This project
double degenerate
Past observations
0
5
10
15
days since explosion
Observations of the first hours/days of SN are key to unveil the progenitor
➜ Our project guarantees such observations
42

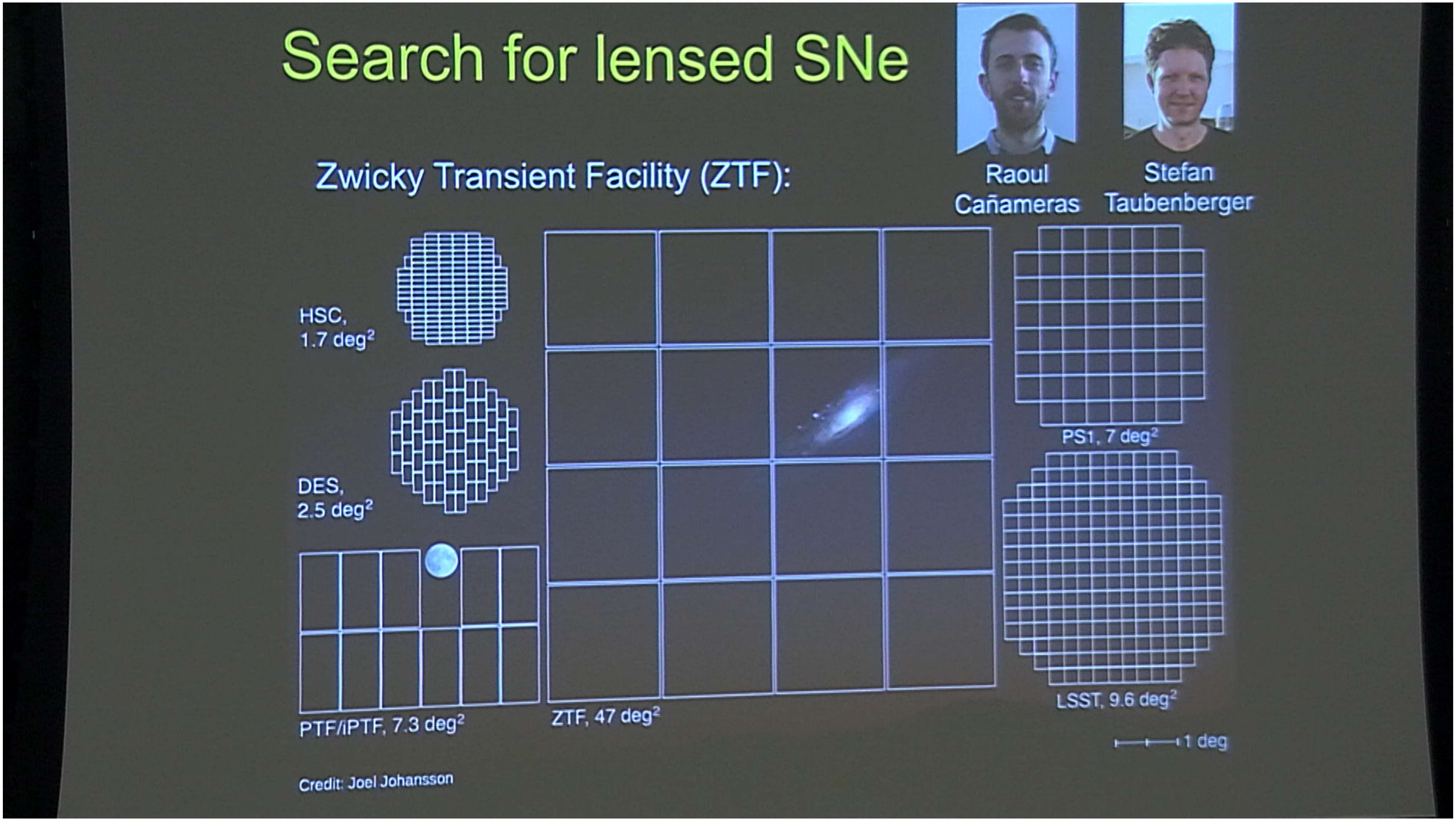
Cosmology with lensed SNe

Advantages:

- SN has characteristic light curves, enabling time-delay measurement
- Lens mass modeling is more straightforward, after SN fades (quasars outshine other components)
- SN is a standard candle

Challenges:

- Microlensing of SN by stars in the foreground lens
- Lensed SN is very rare


Search for lensed SNe
Zwicky Transient Facility (ZTF):
Raoul Cañameras
Stefan Taubenberger
HSC, 1.7 deg2
DES, 2.5 deg2
PTF/iPTF, 7.3 deg2
ZTF, 47 deg2
PS1, 7 deg2
LSST, 9.6 deg2
1 deg
Credit: Joel Johansson

Search for lensed SNe

Raoul Cañameras

Stefan Taubenberger

Zwicky Transient Facility (ZTF):

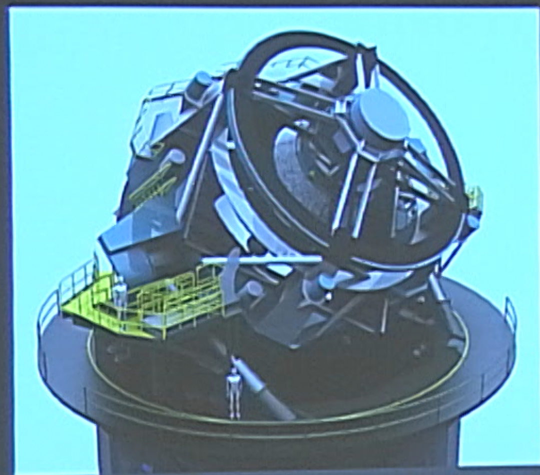
- images entire northern sky every 3 days (public part of the ZTF)
- ~10^5 alerts of transients daily
  ~10 new supernovae daily
- poor angular resolution
  ➔ cannot resolve multiple images of lensed SNe

Panoramic Survey Telescope and Rapid Response System (Pan-STARRS)

- *static* survey covers northern sky in ~0.2" pixel resolution
  ➔ can resolve lensed SNe systems (of wide separation)

Combine ZTF + Pan-STARRS to search for lensed SNe

Large Synoptic Survey Telescope (LSST)



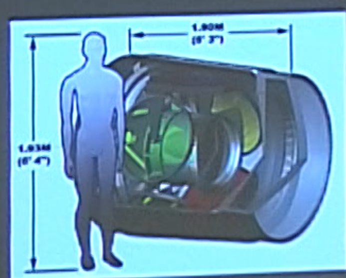
High etendue survey telescope:

- **6.7m effective aperture**
- **10 sq degree field**
- **24 mag in 30 seconds**

Visible sky mapped **every few nights**

Cerro Pachon, Chile: **0.7" seeing**

Ten year movie of the entire Southern sky



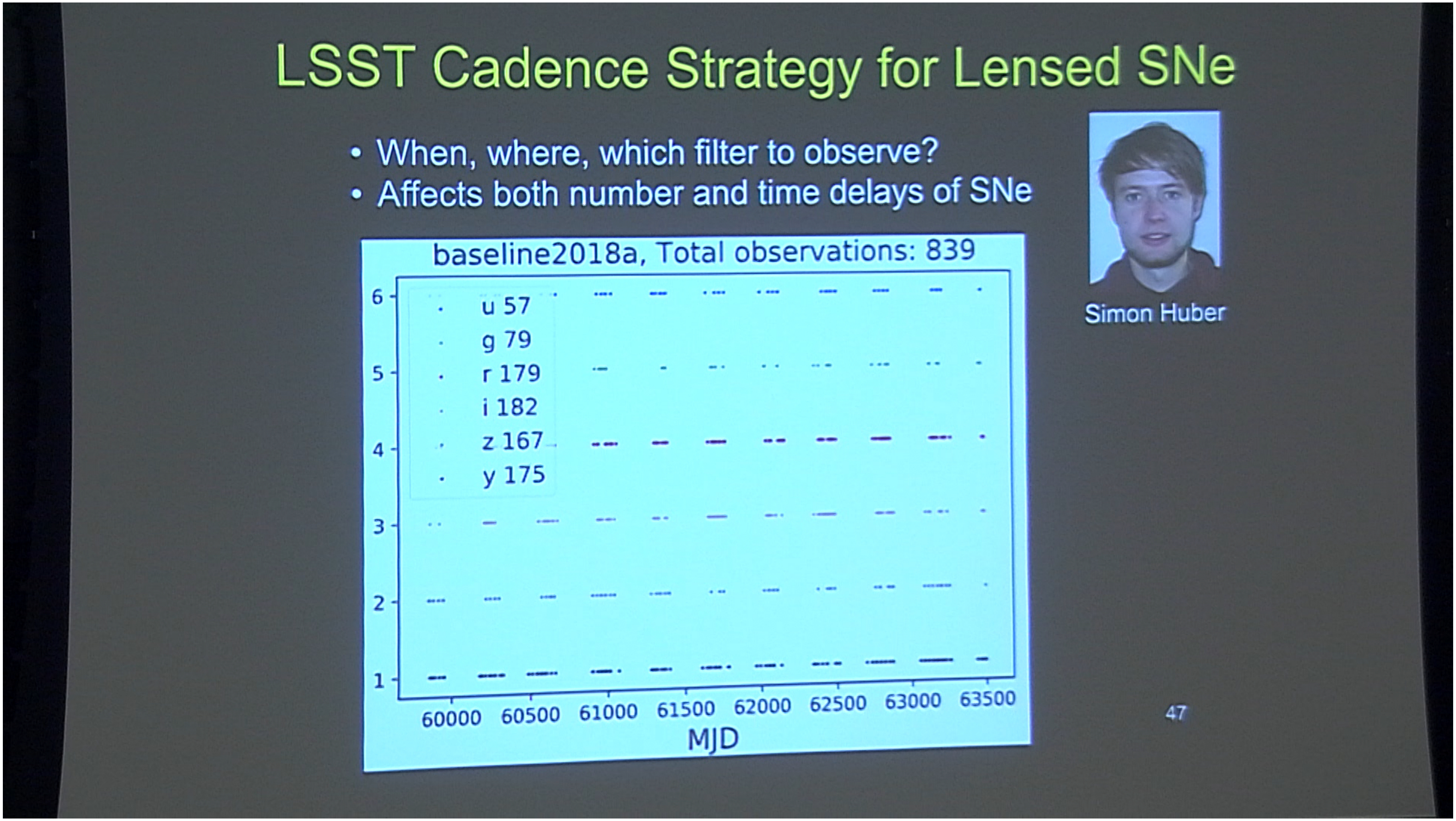
120 Petabytes of data

(1Pb = every book ever published)

First light ~2020, survey starts ~2022

Expect hundreds of lensed SNe in the 10-year LSST survey

[Oguri & Marshall 2010; Goldstein et al. 2017]


LSST Cadence Strategy for Lensed SNe
• When, where, which filter to observe?
• Affects both number and time delays of SNe
baseline2018a, Total observations: 839
u 57
g 79
r 179
i 182
z 167
y 175
1
2
3
4
5
6
60000
60500
61000
61500
62000
62500
63000
63500
MJD
Simon Huber
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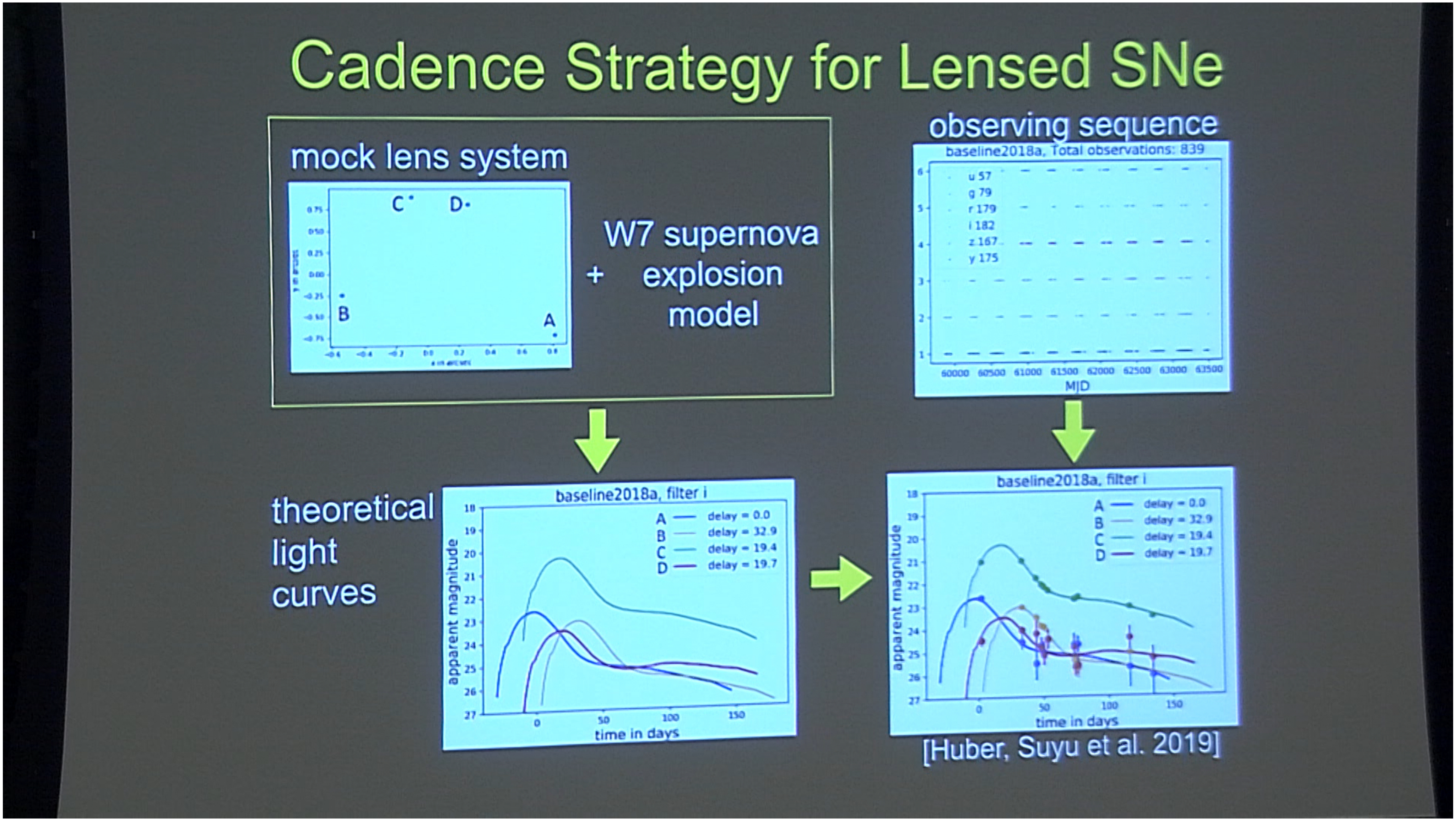
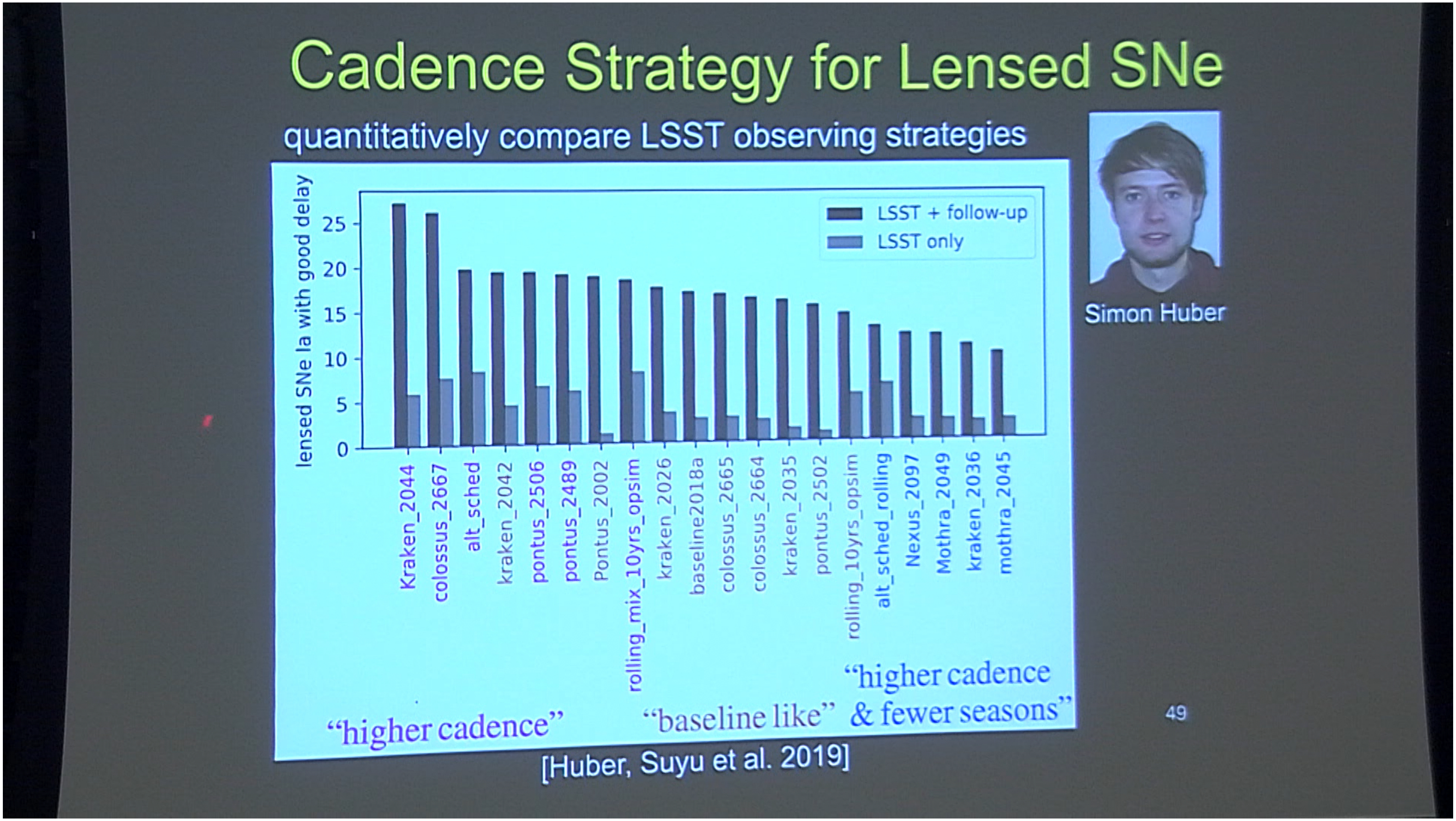


Cadence Strategy for Lensed SNe
mock lens system
C
D
B
A
+
W7 supernova explosion model
observing sequence
baseline2018a, Total observations: 839
u 57
g 79
r 179
i 182
z 167
y 175
MJD
theoretical light curves
baseline2018a, filter i
A delay = 0.0
B delay = 32.9
C delay = 19.4
D delay = 19.7
apparent magnitude
time in days
baseline2018a, filter i
A delay = 0.0
B delay = 32.9
C delay = 19.4
D delay = 19.7
apparent magnitude
time in days
[Huber, Suyu et al. 2019]


Cadence Strategy for Lensed SNe
quantitatively compare LSST observing strategies
lensed SNe Ia with good delay
0
5
10
15
20
25
LSST + follow-up
LSST only
Kraken_2044
colossus_2667
alt_sched
kraken_2042
pontus_2506
pontus_2489
Pontus_2002
rolling_mix_10yrs_opsim
kraken_2026
baseline2018a
colossus_2665
colossus_2664
kraken_2035
pontus_2502
rolling_10yrs_opsim
alt_sched_rolling
Nexus_2097
Mothra_2049
kraken_2036
mothra_2045
"higher cadence"
"baseline like"
"higher cadence & fewer seasons"
[Huber, Suyu et al. 2019]
Simon Huber
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Lens modeling with machine learning

- simulate realistic lenses
- train neural network to infer lens mass parameters
  [Hezaveh et al. 2017; Levasseur et al. 2017]

Stefan
Schuldt

[Schuldt, Suyu et al., in prep.]

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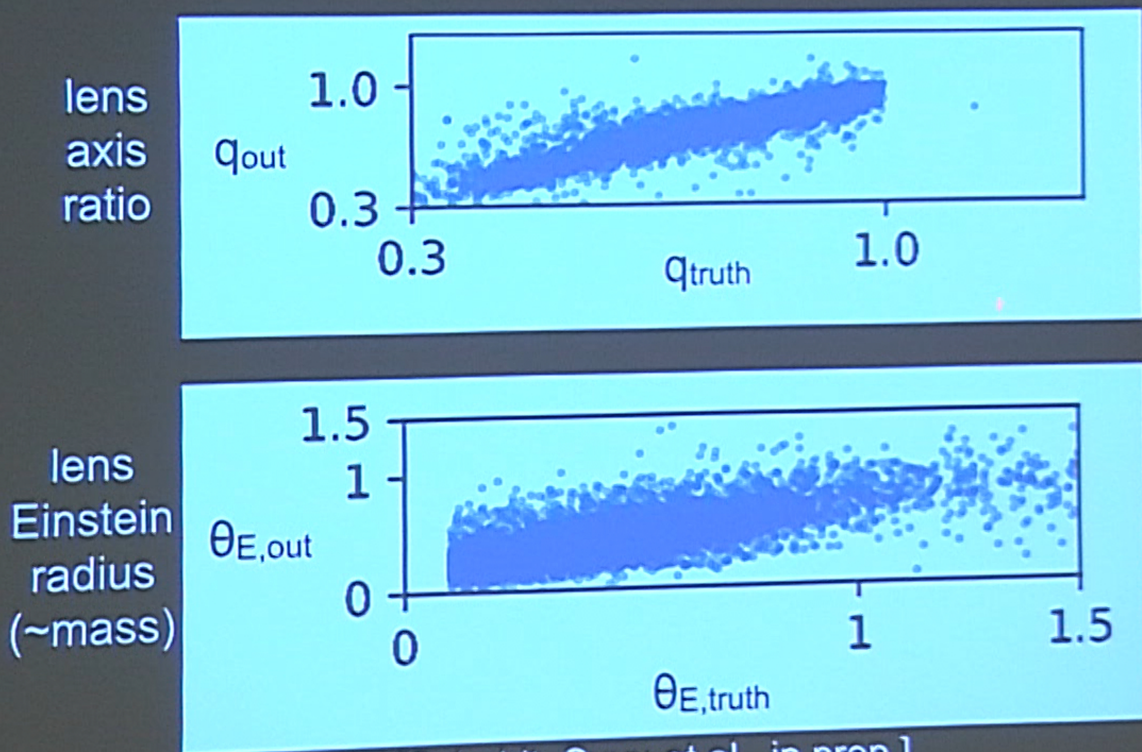
Lens modeling with machine learning

- simulate realistic lenses
- train neural network to infer lens mass parameters

Stefan Schuldt



[Schuldt, Suyu et al., in prep.]

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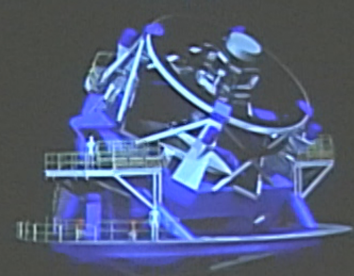
Future Prospects

Experiments and surveys in the 2020s including Euclid, LSST, and WFIRST will provide ~10,000 lensed quasars and ~100 lensed supernovae [Oguri & Marshall 2010]

Euclid

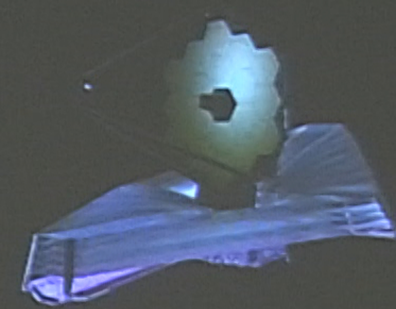
Discovery
Imaging
Spectroscopy

LSST



Discovery
Time delays
Imaging

JWST



High-resolution imaging
& spectroscopy

Summary

- With 4 time-delay lenses, a 3% measurement
  $H_0 = 72.5^{+2.1}_{-2.3}$ km/s/Mpc in flat ΛCDM
- Stellar kinematics really helps in lens mass modeling
- New method to find lensed quasars through their variability
- SN Refsdal blind test demonstrated the robustness of our cluster mass modeling approach and software GLEE
- New ERC project: lensed SNe for cosmology and supernovae physics
- Search for new lensed SNe in ZTF and PanSTARRS underway
- LSST cadence strategies for lensed SNe:
  higher cadence, longer cumulative season length
- Developing method to model lenses with machine learning
- Current and future surveys will have thousands of new time-delay lenses, providing an independent and competitive probe of cosmology and stellar physics

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