Gravitational Lens Time Delays: Past, Present and Future

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The Return of de Sitter II @ MPA

Many thanks to

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Alessandro Sonnenfeld (UC SB)
Chiara Spiniello (Kapteyn Institute)
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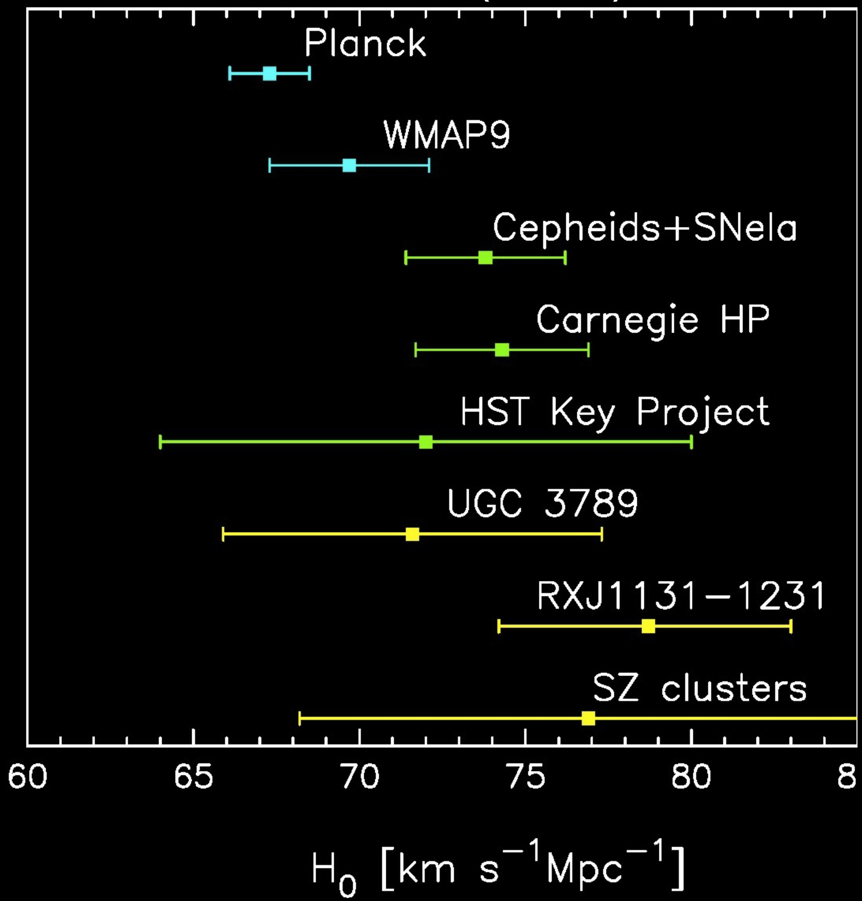
Tommaso Treu (UC SB)
Kenneth Wong (ASIAA, Taiwan)

Outline

- Motivations
- Gravitational lens time delays
- A brief history and recent advances
- Results and implications for cosmology from two time-delay lenses
- Search for new lenses in HSC survey
- Adaptive optics imaging of lenses

H_0, a key parameter

Planck collaboration (2013):



Tension? New physics?

➡ Need more precise & accurate H_0

H_0 provides critical independent constraints on

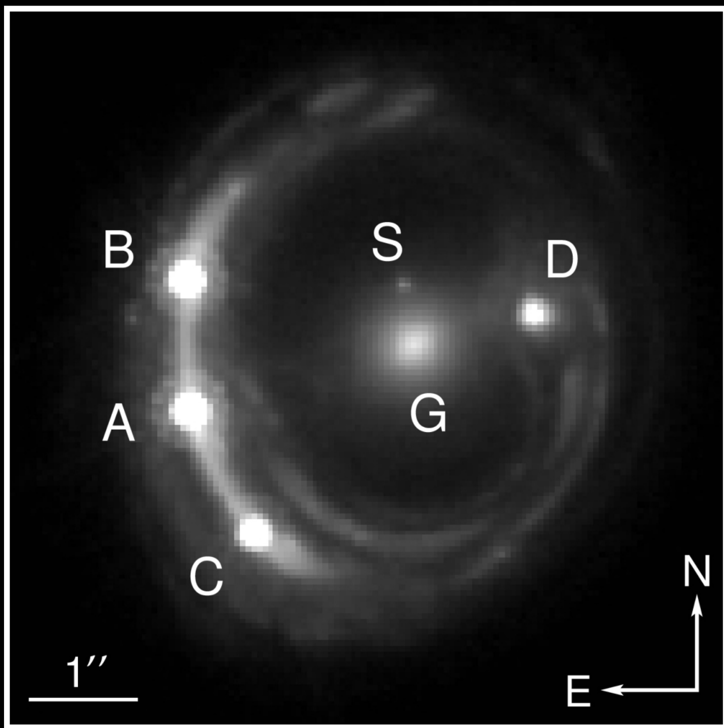
- nature of dark energy
- neutrino physics
- spatial curvature of the Universe

[e.g., Freedman et al. 2012, Suyu et al. 2012, Weinberg et al. 2012, Sekiguchi et al. 2010]

Independent methods are needed to overcome systematics, especially the unknown unknowns

Gravitational Lens Time Delays

RXJ1131-1231



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

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

Brief History

- 1964: Method proposed by Refsdal
- 1970s: First lenses discovered
- 1980s: First time delay measured
    - Controversy. Solution: improve sampling
- 1990s: First Hubble Constant measured
    - Controversy. Solution: improve mass models
- 2000s: modern monitoring (COSMOGRAIL, Fassnacht & others)
- 2010s: Putting it all together.

  Advances in 1) time delays

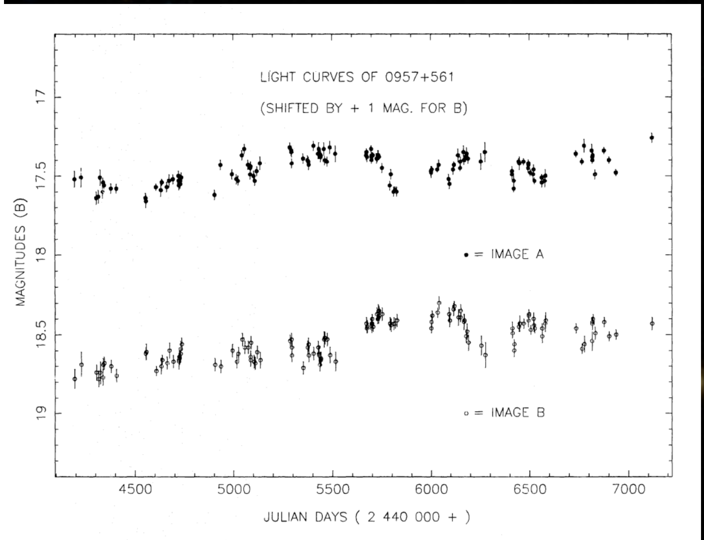
  2) lens mass model

  3) mass along line of sight

  ➡ precision measurements (5-8% from a single lens)

(1) Time Delays

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



[Vanderriest et al. 1989]

Dedicated monitoring

- **Radio**
  [e.g., Fassnacht et al. 2002]
- **Optical**
  COSMOGRAIL
  [e.g., Courbin et al. 2011, Tewes et al. 2013]

  Kochanek et al. 2006

(1) Time Delays

COSMOGrail

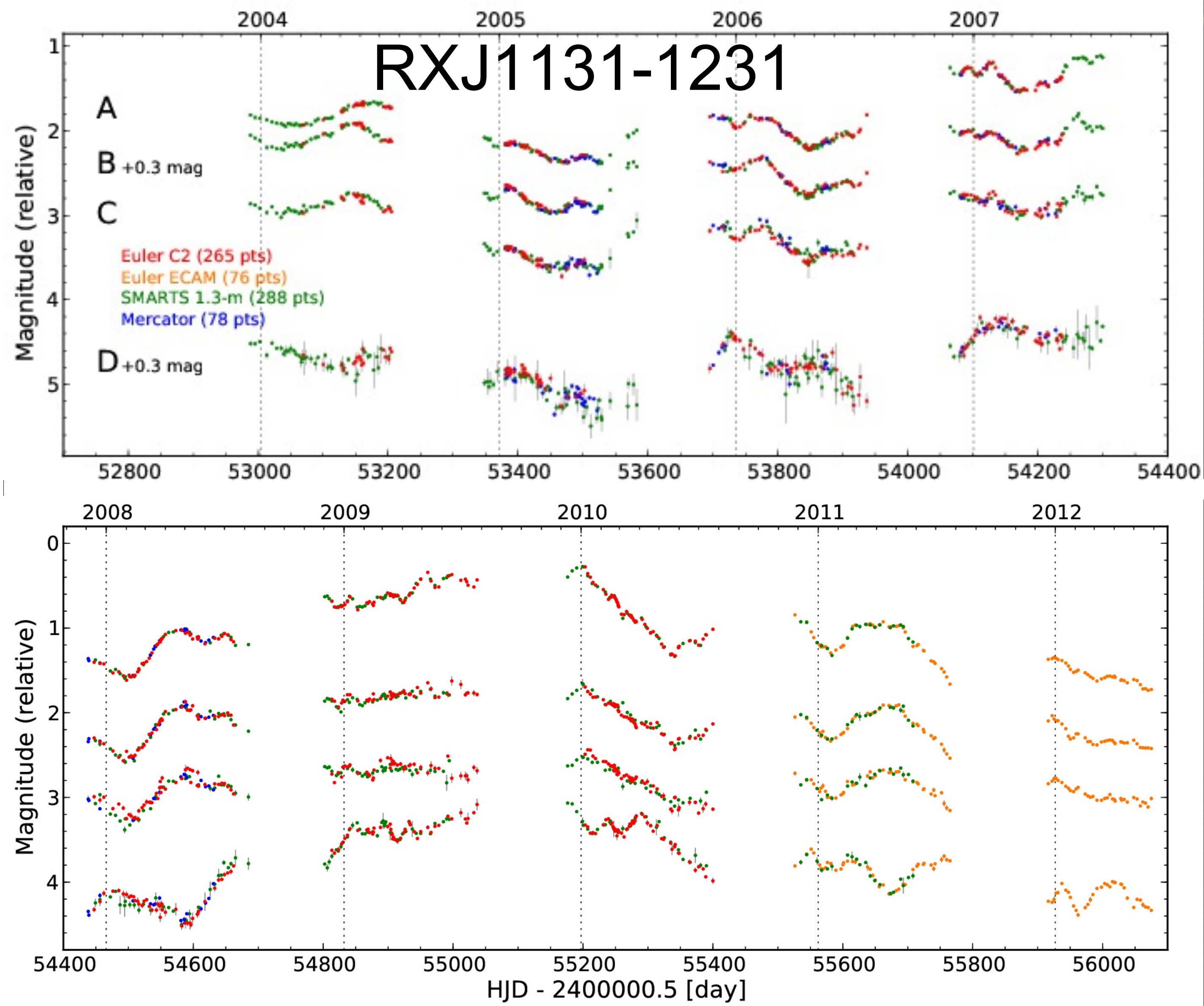
[**Cos**mological **Mo**nitoring of **Gra**v**i**tational **L**enses]

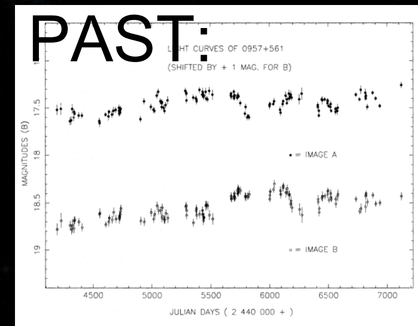
- monitoring lensed quasars since 2004 in the optical
- expect to have delays with a few percent error for ~20 lenses

EPFL: **G. Meylan, F. Courbin**, M. Tewes, C. Faure, Y. Revaz, N. Cantale
(Formerly: A. Eigenbrod, C. Vuissoz)
IIA Bangalore: T. Prabhu, C.S. Stalin, R. Kumar, D. Sahu
Univ. Bonn: D. Sluse
Univ. Liège: P. Magain, E. Eulaers, V. Chantry
UzAS Tashkent: I. Asfandiyarov
Univ. Zürich: P. Saha, J. Coles
Univ. Nottingham: S. Dye

Now also in close collaboration (monitoring, microlensing) with:
C. Kochanek, A. Mosquera (Ohio), C. Morgan, C. MacLeod, L. Hainline (USNA)

(1) Time Delays





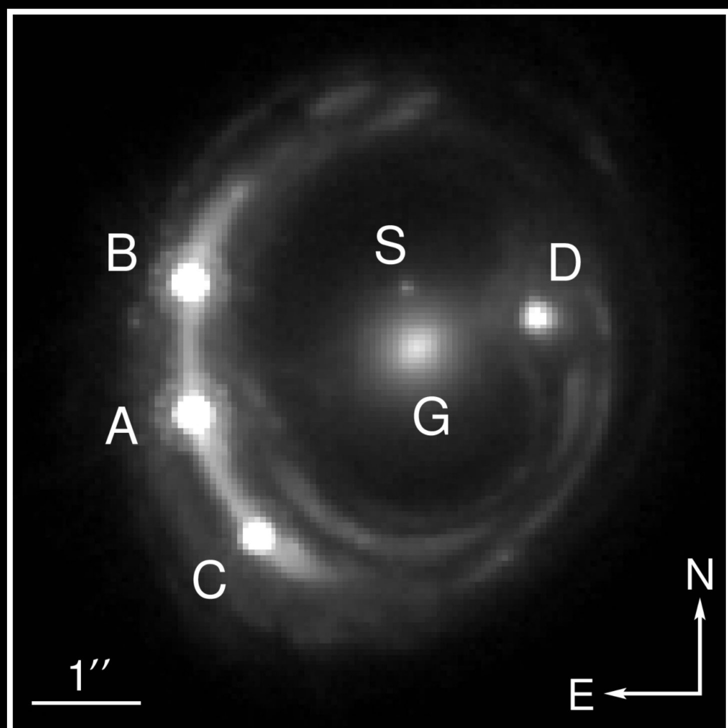
RXJ1131: Time delay with 1.5% Accuracy!

[Tewes et al. 13b]

Based on state-of-the-art curve modeling techniques [Tewes et al. 13a]

Gravitational Lens Time Delays

RXJ1131-1231



Time delay:

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

Time-delay distance:

$$D_{\Delta t} \propto \frac{1}{H_0}$$

Obtain from lens mass model

For cosmography, need:

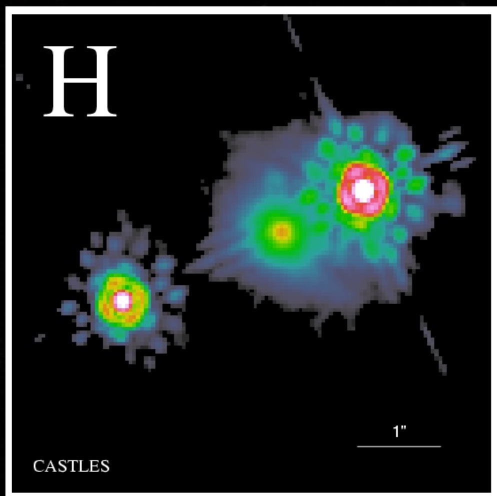
(1) time delays

$\boxed{\text{(2) lens mass model}}$

(3) mass along line of sight

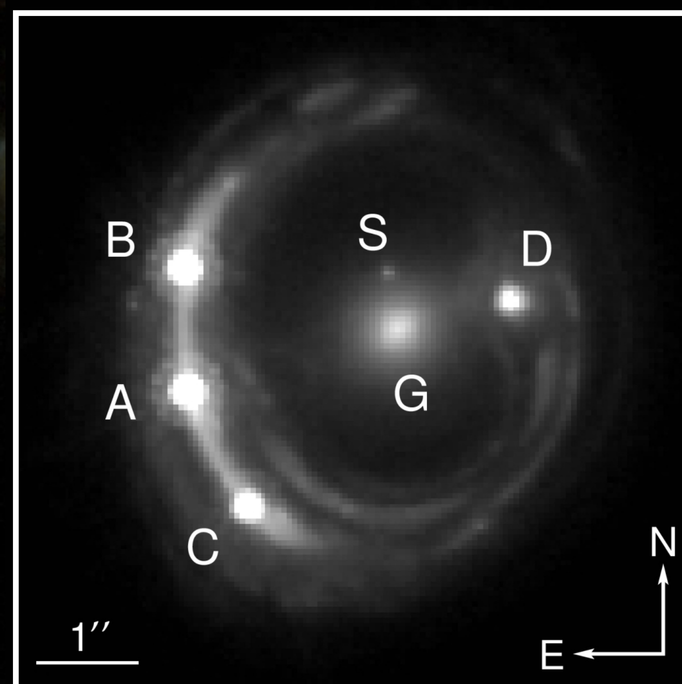
(2) Lens Mass Model

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



Used only image positions of AGN (providing few constraints)

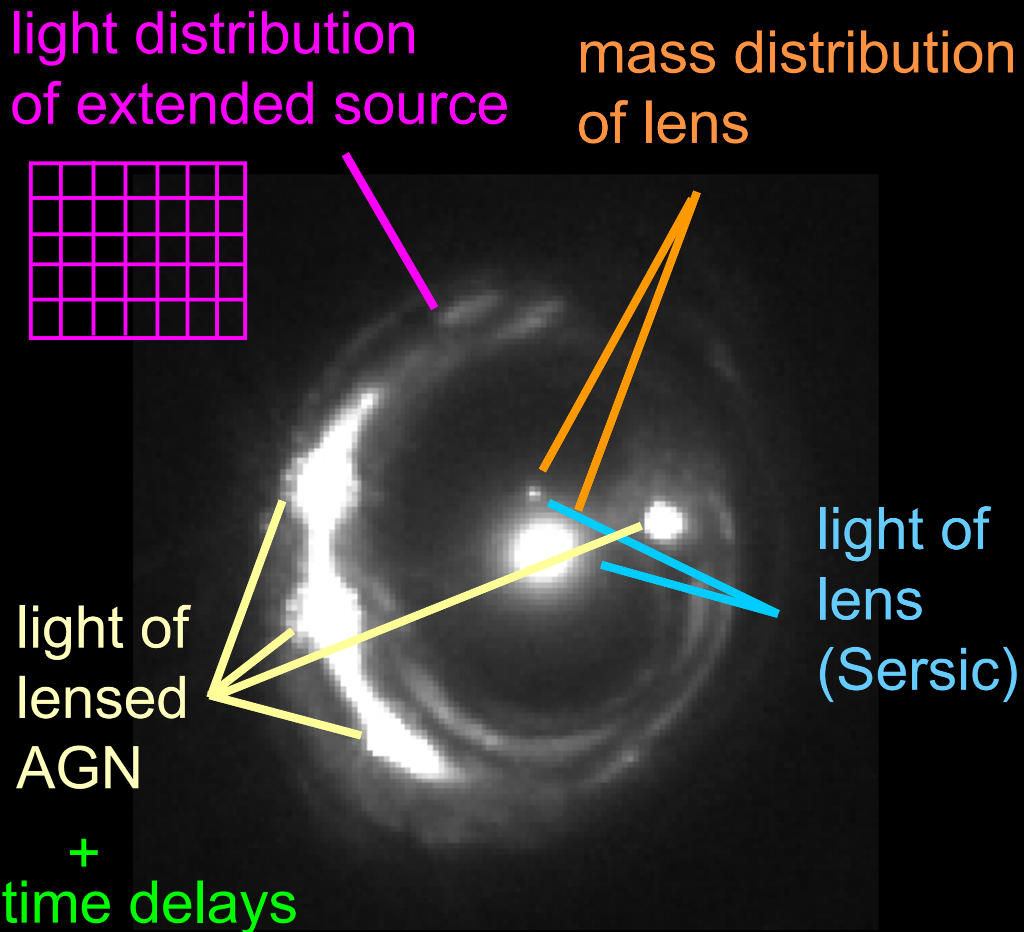
Use extended images of AGN host



S. Suyu, 2013/10/14

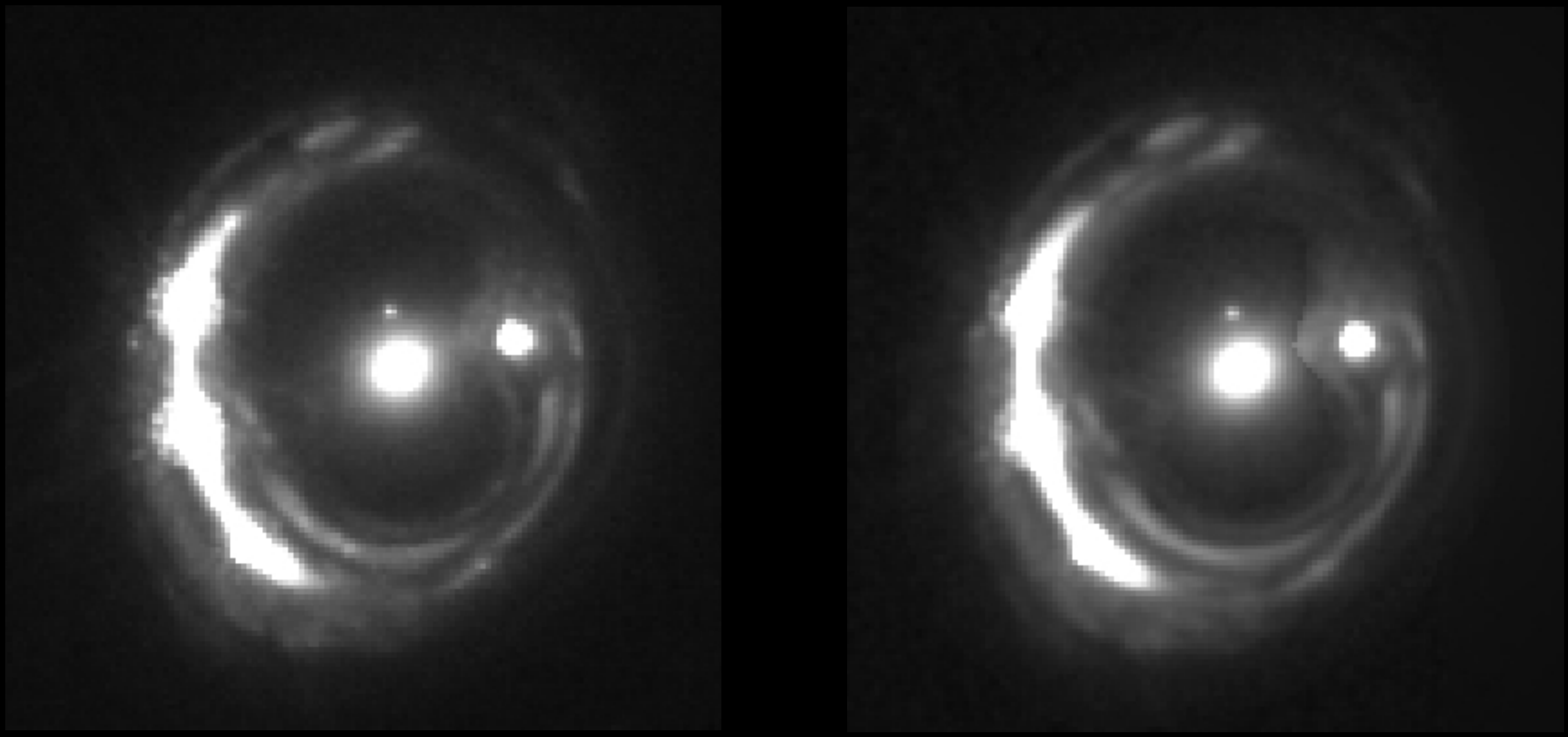
[e.g., Dye et al. 2005, Suyu et al. 2009]

(2) Lens Mass Model



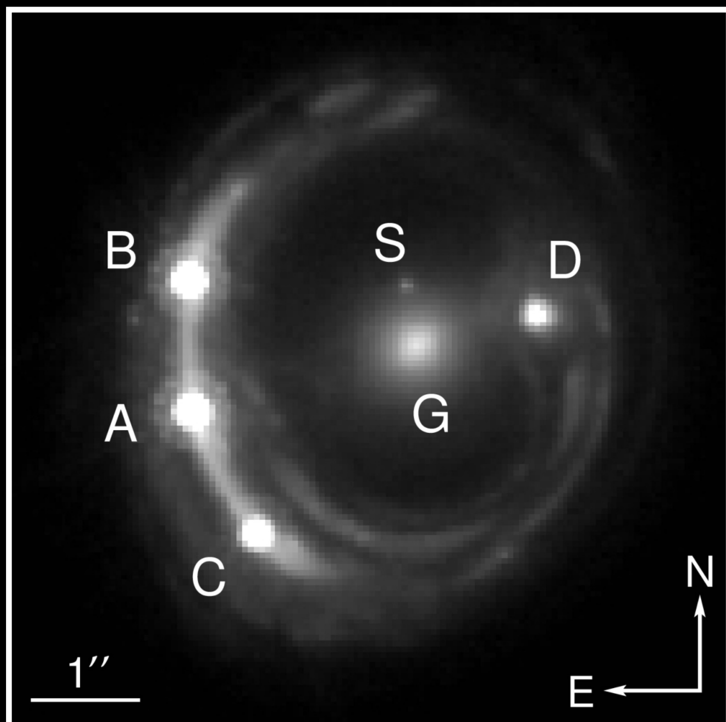
+
time delays

(2) Lens Mass Model



Gravitational Lens Time Delays

RXJ1131-1231



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:

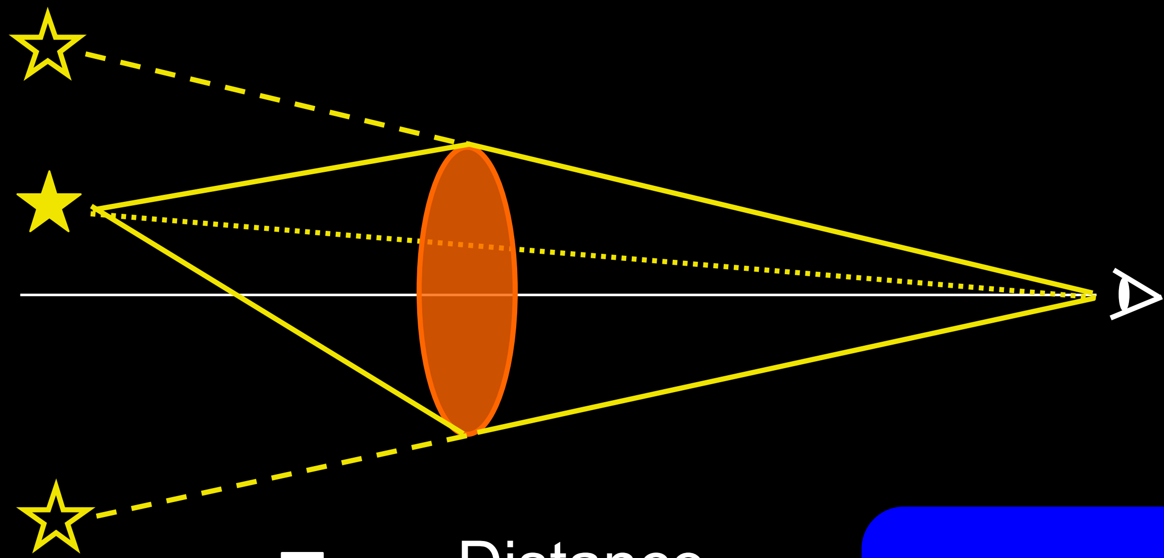
√ (1) time delays

√ (2) lens mass model

$\boxed{\text{(3) mass along line of sight}}$

(3) Mass along Line of Sight

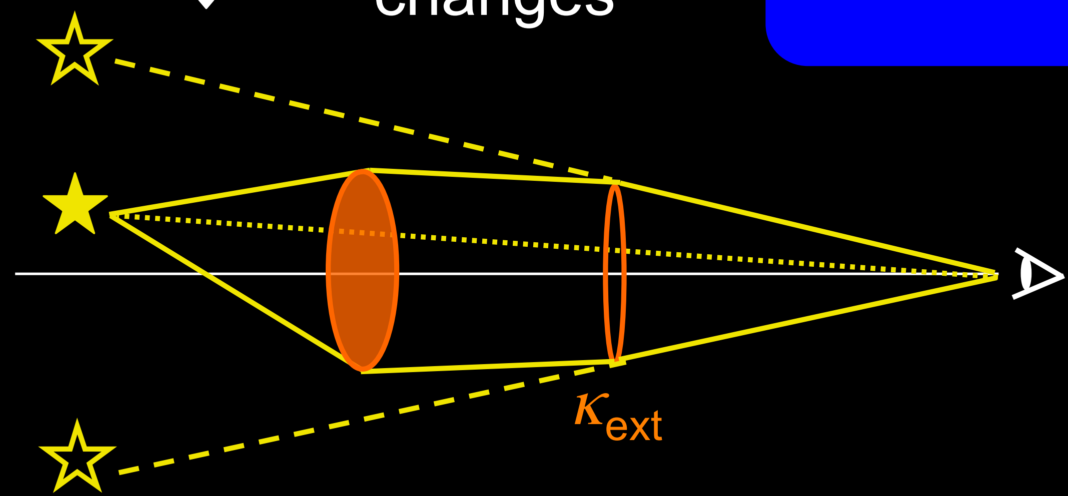
Lens
Only



Distance
measurement
changes

$$D_{\Delta t}^{\mathrm{true}} = \frac{D_{\Delta t}^{\mathrm{model}}}{1-\kappa_{\mathrm{ext}}}$$

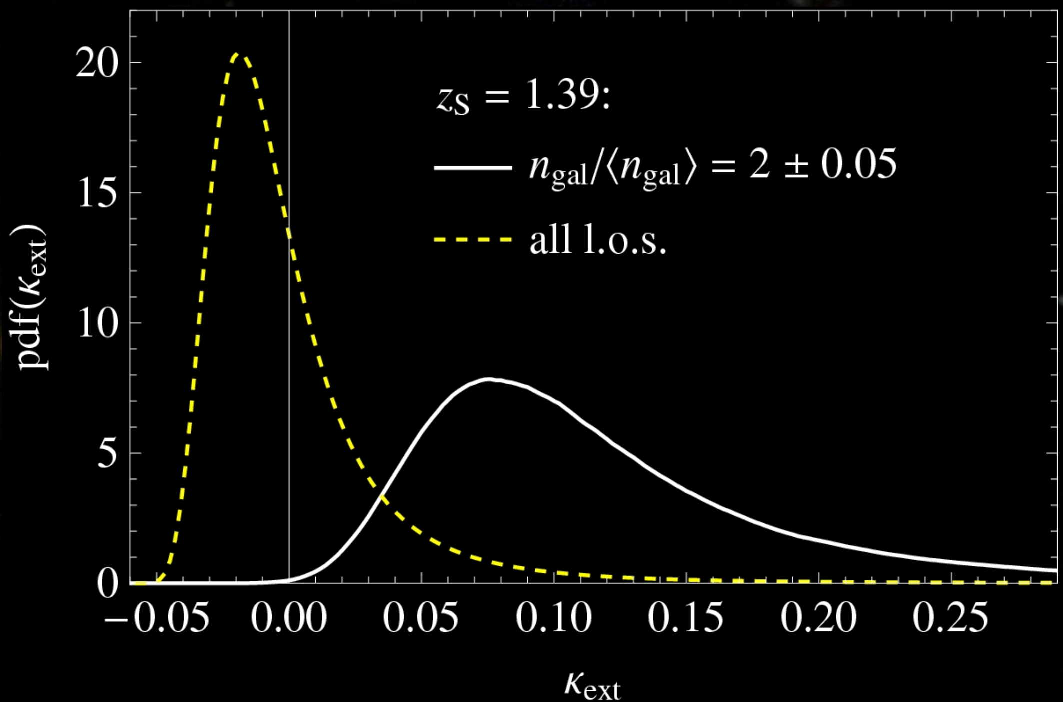
Lens with
structures
along
line of sight



(3) Mass along Line of Sight

???

galaxy number counts + Millennium Simulation



+

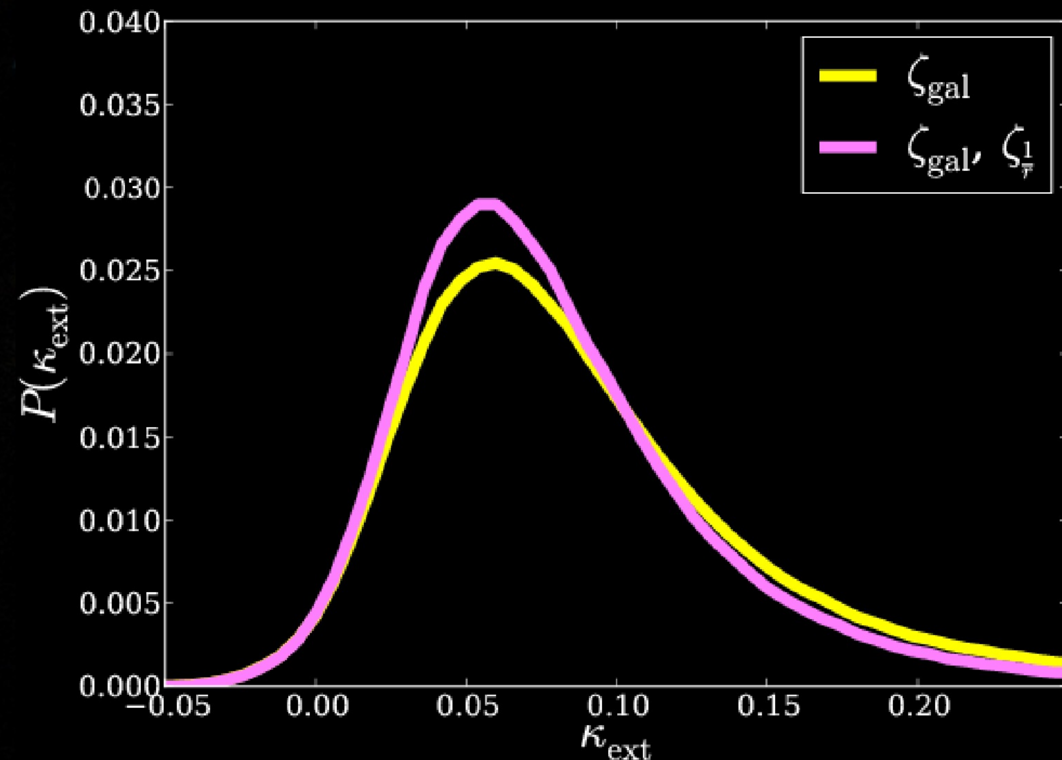
Stellar kinematics of lens further constrain κ_{ext}

[Suyu et al. 2010]

(3) Mass along Line of Sight

???

galaxy attributes + Millennium Simulation

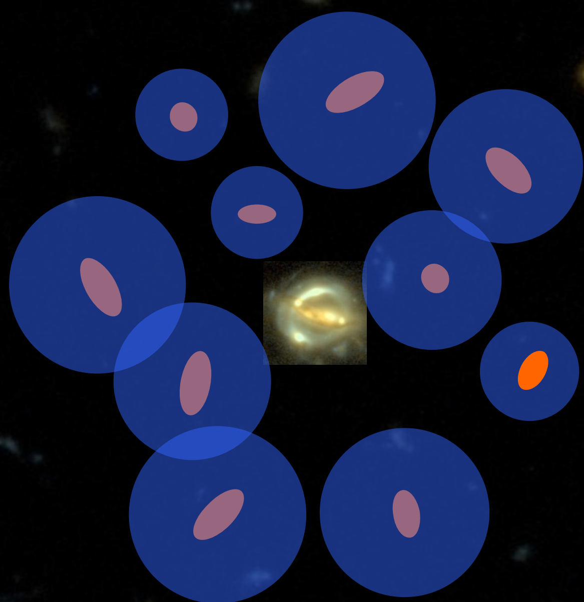


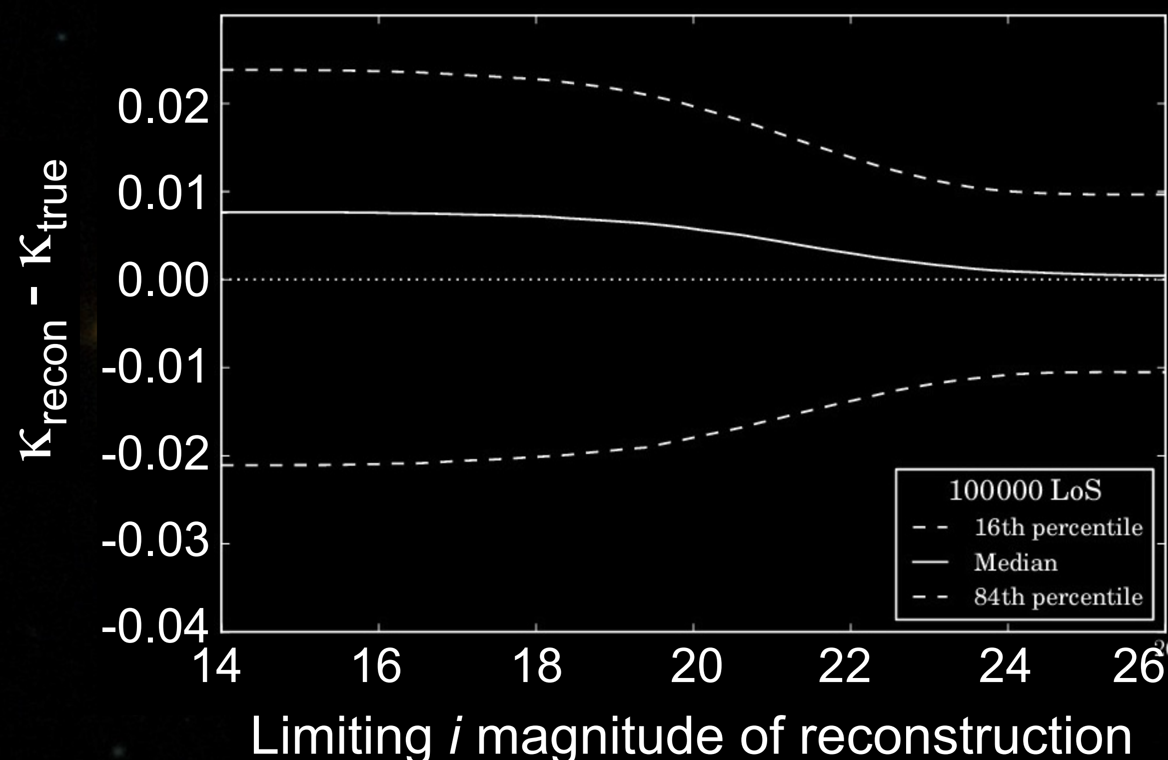
[Greene, Suyu, Treu et al. 2013]

(3) Mass along Line of Sight

galaxy mass assignment + Millennium Simulation

???

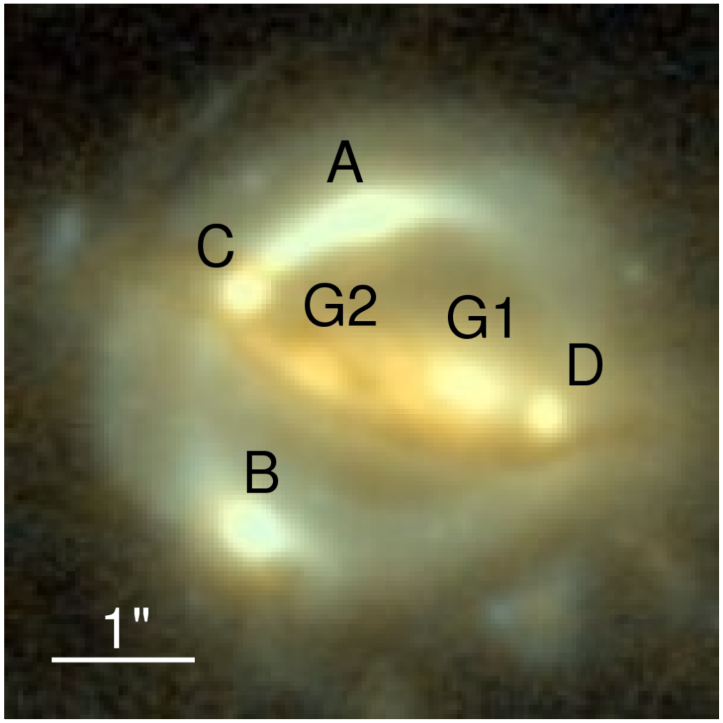




[Collett et al. 2013]

Two time-delay lenses

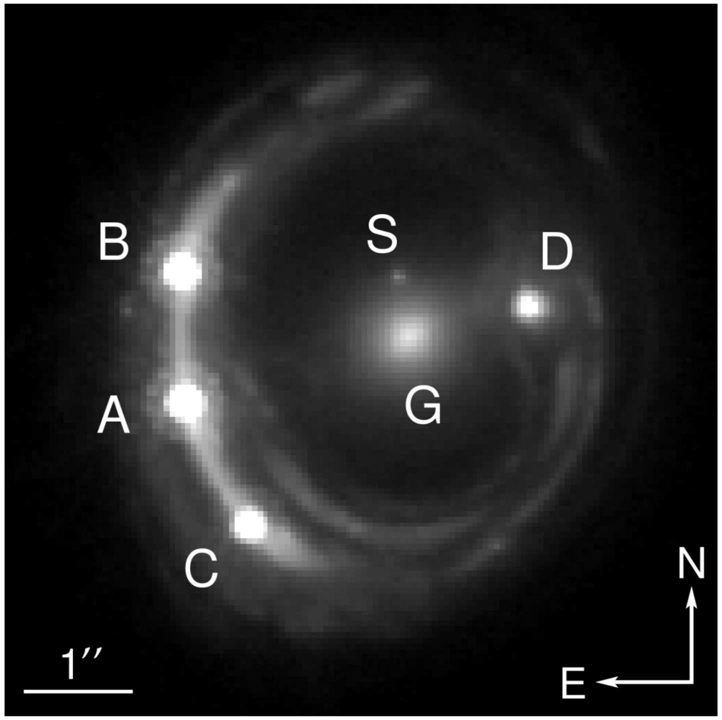
B1608+656



Discovery: Myers et al. 1995
Delays: Fassnacht et al. 2002
Modeling: Suyu et al. 2009, 2010

Pilot Study: measured $D_{\Delta t}$ to 5%

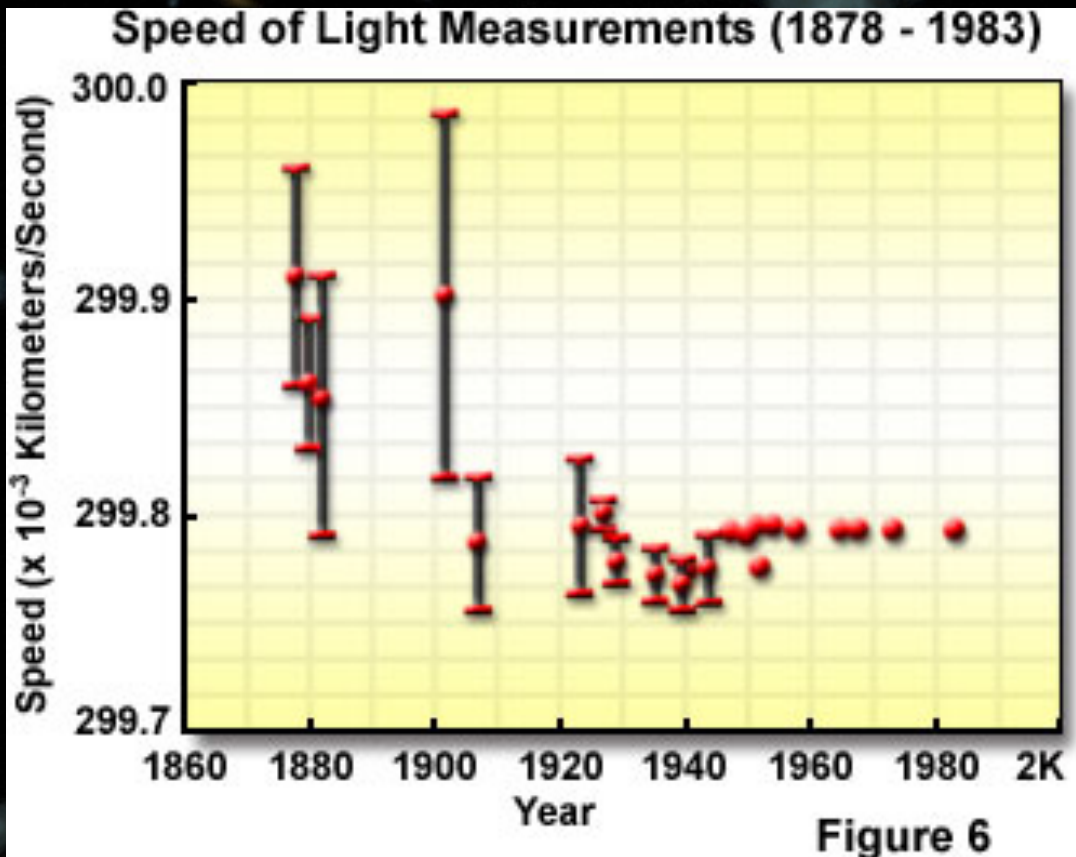
RXJ1131-1231



Discovery: Sluse et al. 2003
Delays: Tewes et al. 2012
Modeling: Suyu et al. 2013

Blind Analysis: test analysis method

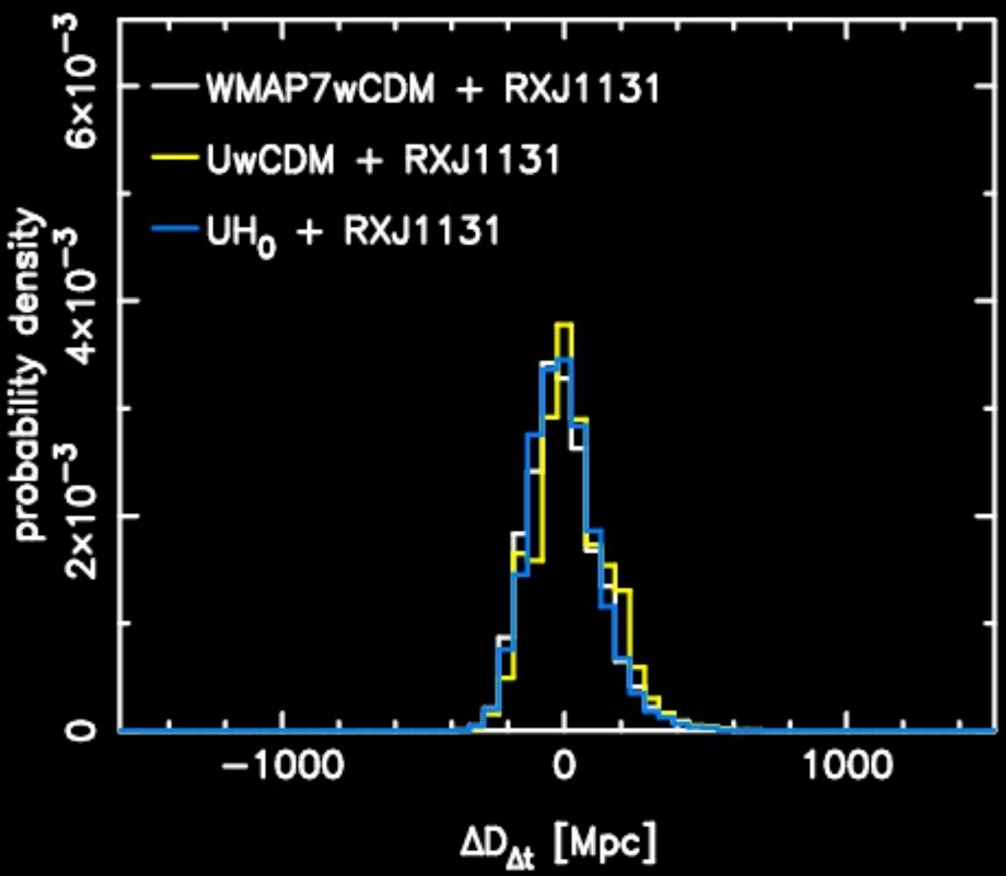
Blind Analysis



- Prevents unconscious experimenter bias
- allows us to test for the presence of residual systematics
- PDF centroids of cosmological parameters are hidden

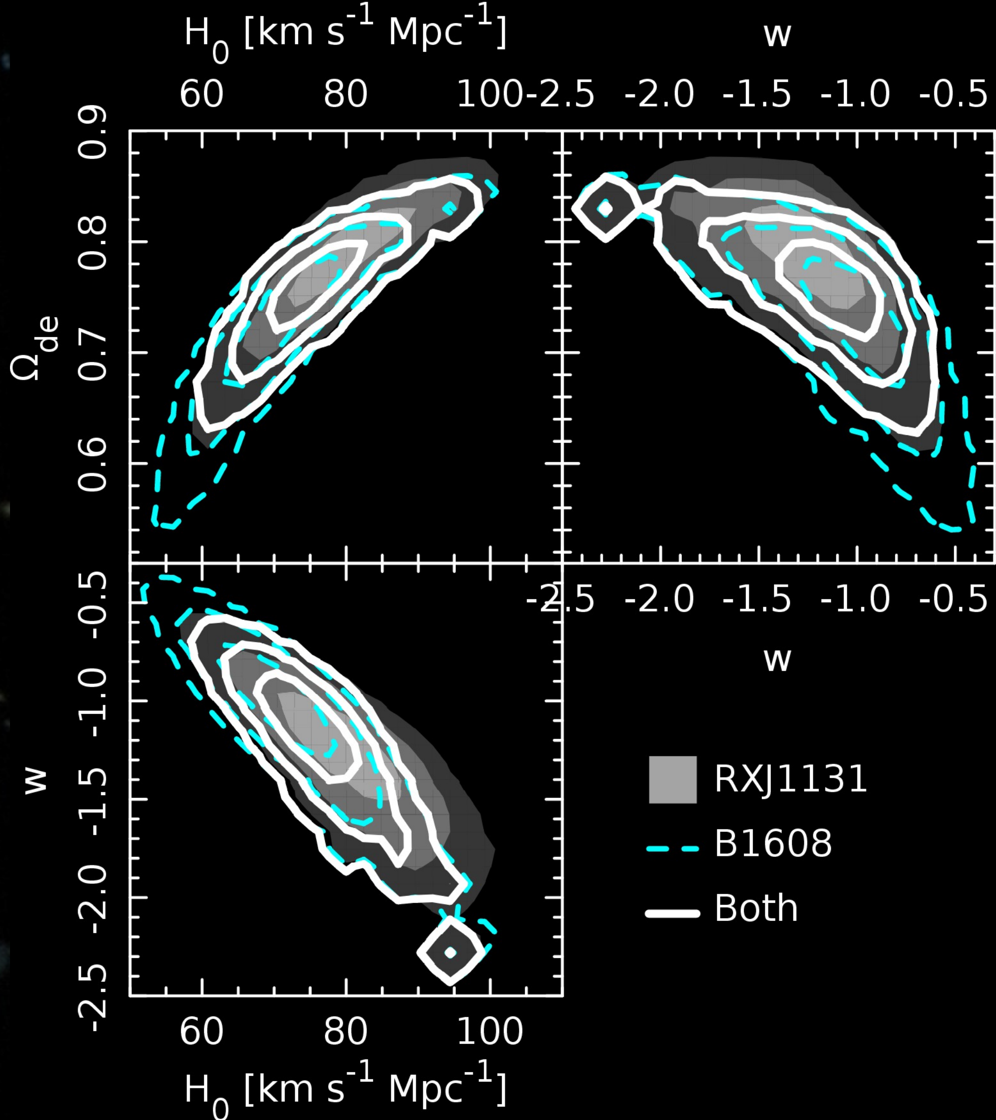
Blind Analysis

Blinded time-delay distance



- Prevents unconscious experimenter bias
- allows us to test for the presence of residual systematics
- PDF centroids of cosmological parameters are hidden
- *when ready to unblind, publish unblinded results without modification*

Constraints from Two Lenses



In combination with WMAP7 in wCDM cosmology:

$$H_0 = 75.2^{+4.4}_{-4.2}\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$$

$$\Omega_{\mathrm{de}} = 0.76^{+0.02}_{-0.03}$$

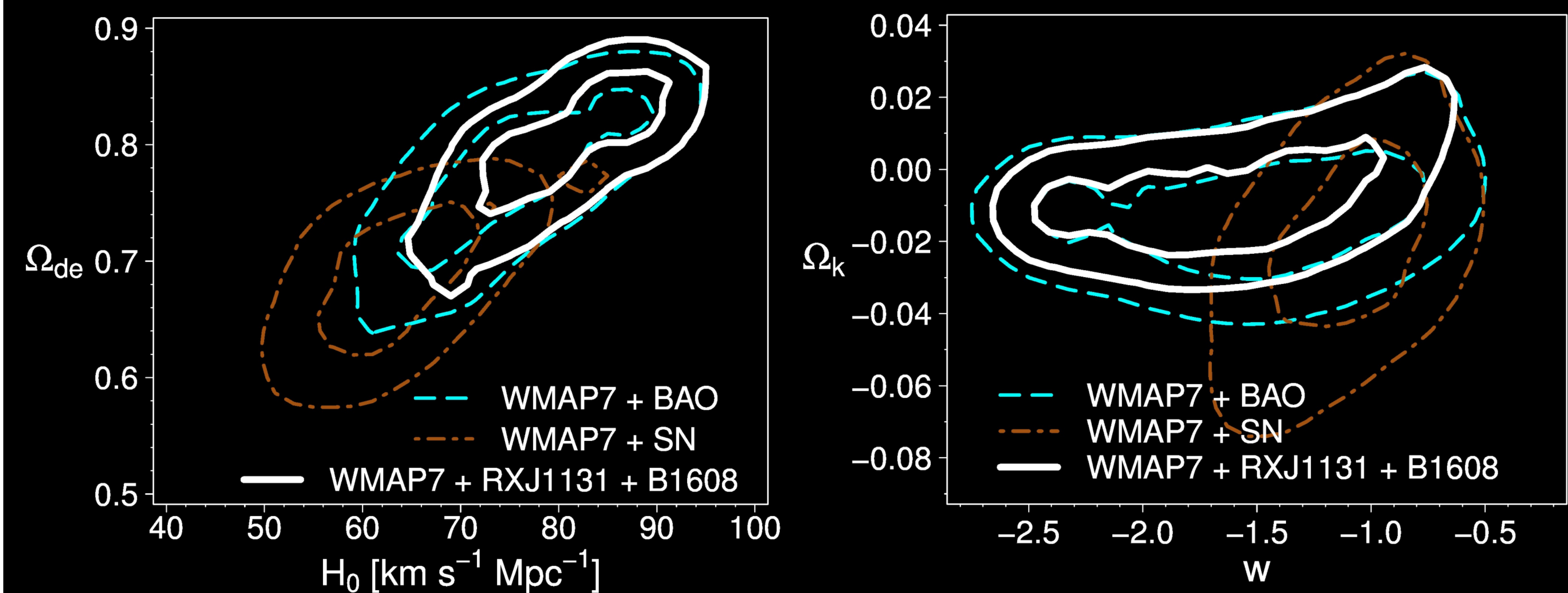
$$w = -1.14^{+0.17}_{-0.20}$$

[Suyu et al. 2013a]

Cosmological Probe Comparison

WMAP7owCDM prior

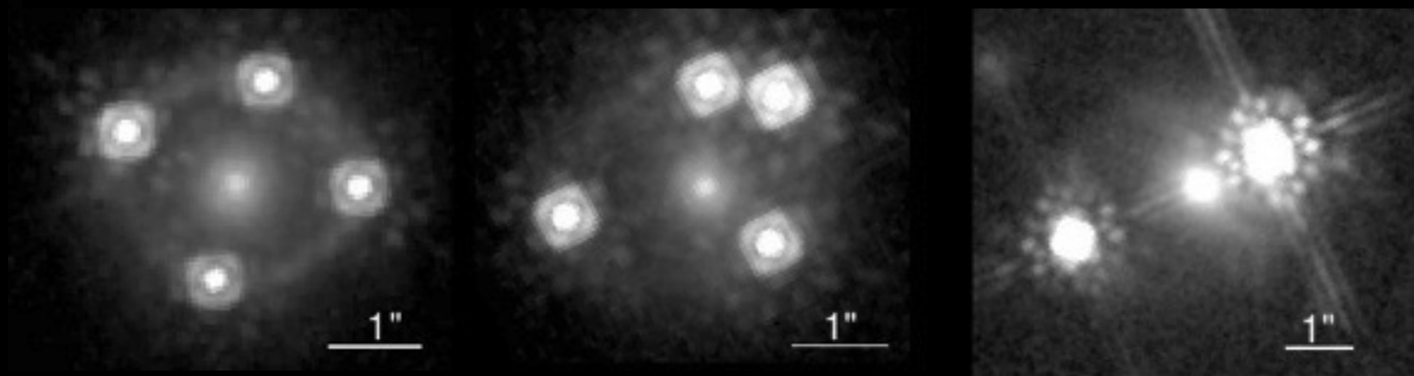
[Suyu et al. 2013a]



- contour orientations are different: complementarity b/w probes
- contour sizes are similar: lensing is a competitive probe

H0LiCOW

(H_0 Lenses in COSMOGRAIL Wellspring)



3 more lenses:

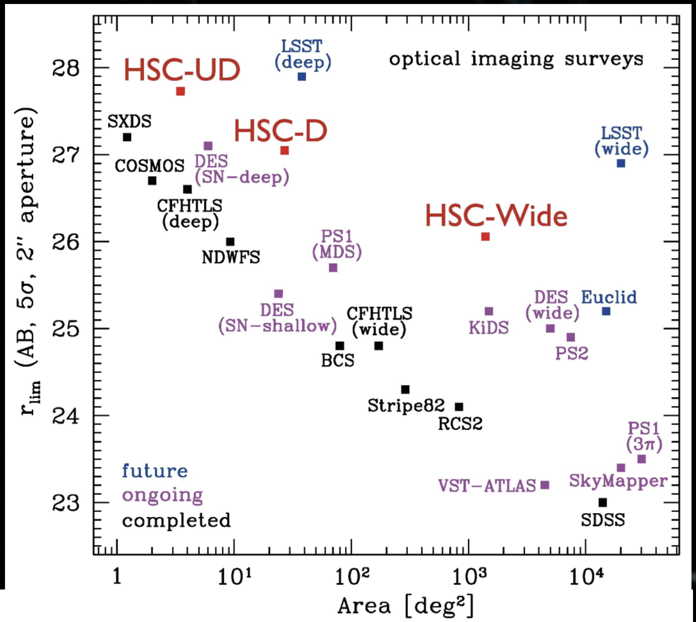
- delays with a few percent uncertainty from COSMOGRAIL
- *HST* deep imaging for modeling
- Lens galaxy spectroscopy pending
- Imaging and spectroscopy of the fields pending

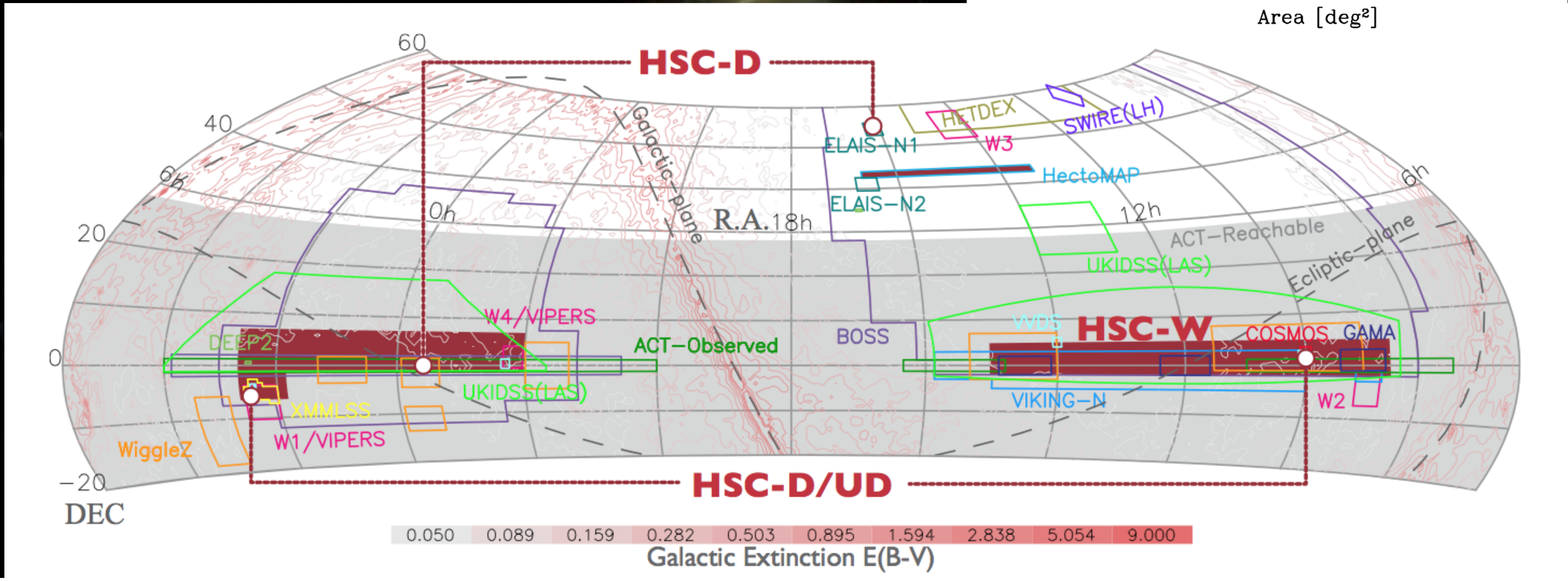
How to get more lenses?

Hyper Suprime-Cam Survey

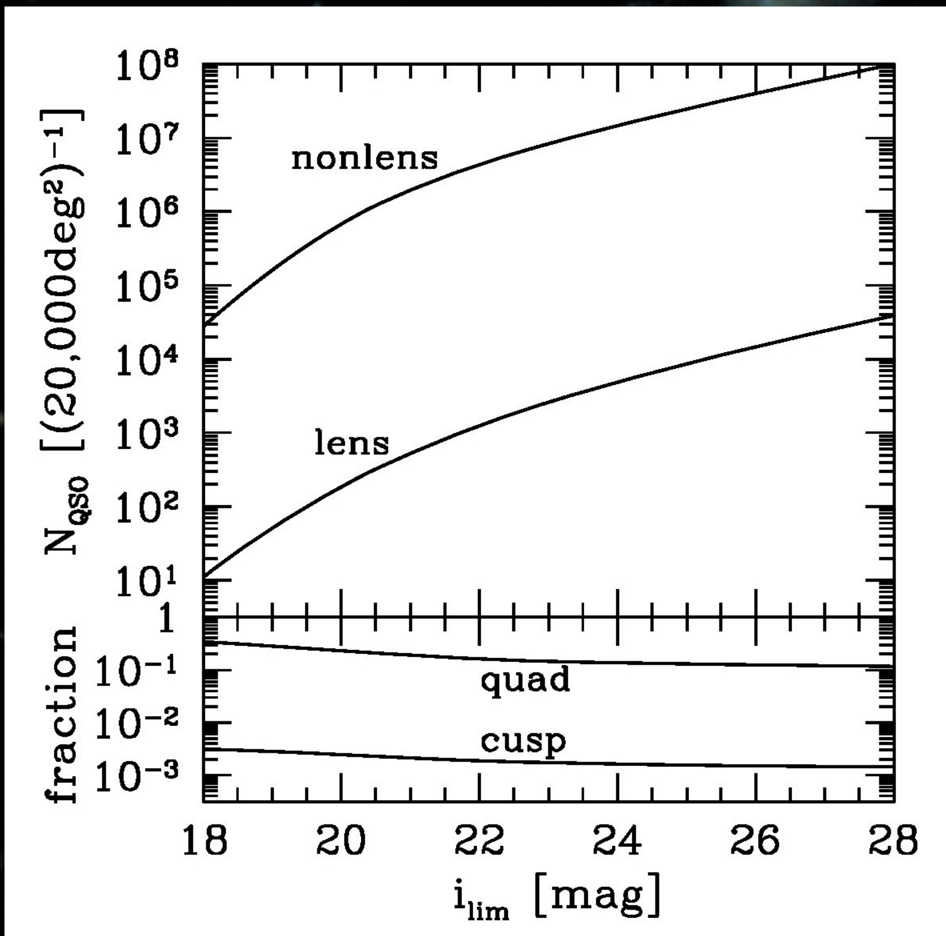
3 layers

- Wide: 1400 deg^2, grizy, r~26
- Deep: 27 deg^2, grizy+3NB, r~27
- Ultra-Deep: 3.5 deg^2 (2 pointings), grizy+3NB, r~28





Number of lenses in HSC



[Oguri & Marshall 2010]

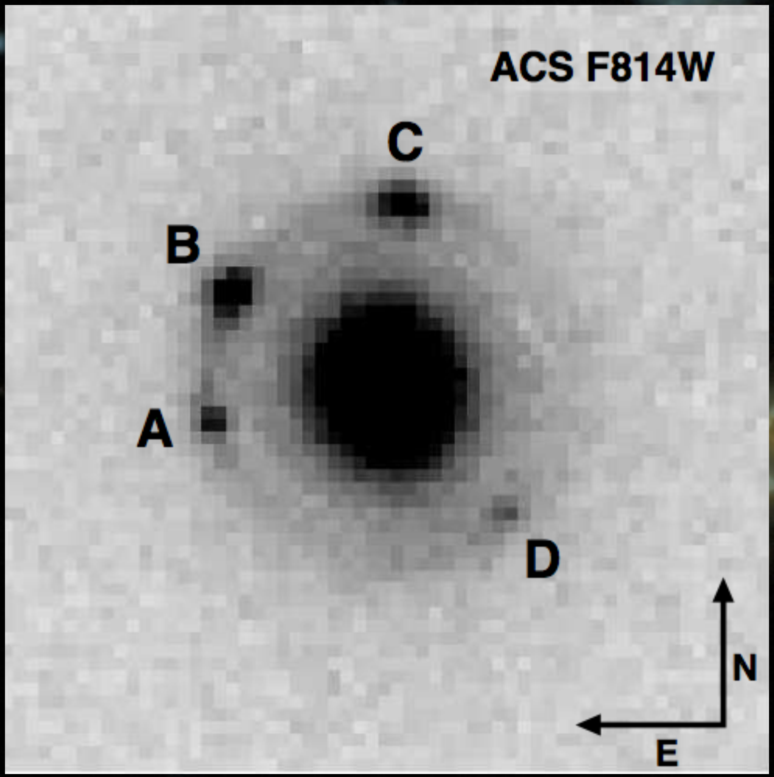
HSC-Wide:
    1400 deg^2 with r~26

HSC-Deep:
    27 deg^2 with r~27

➡ ~600 lenses
(~80 are quads)

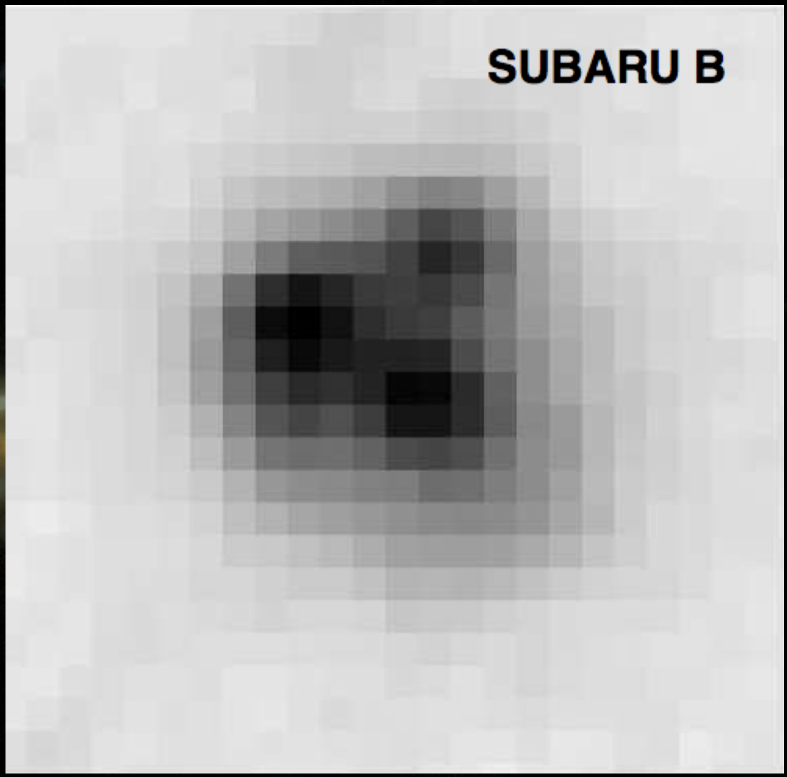
Lensed quasars from the ground

HST



[Anguita et al. 2009]

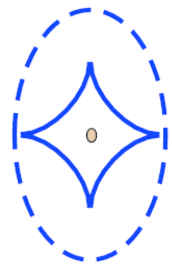
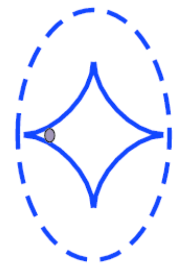
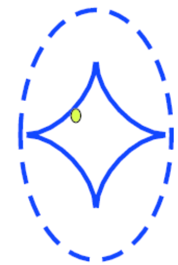
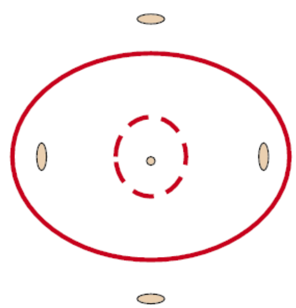
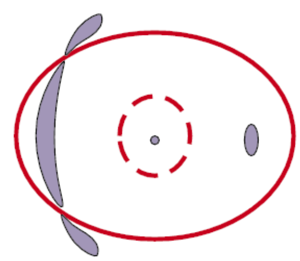
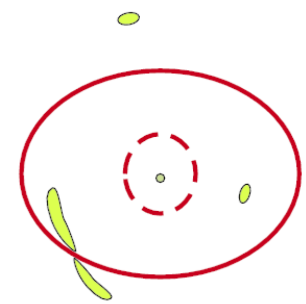
Subaru



How to tell if this is a lens?

➡ use configuration of blended images

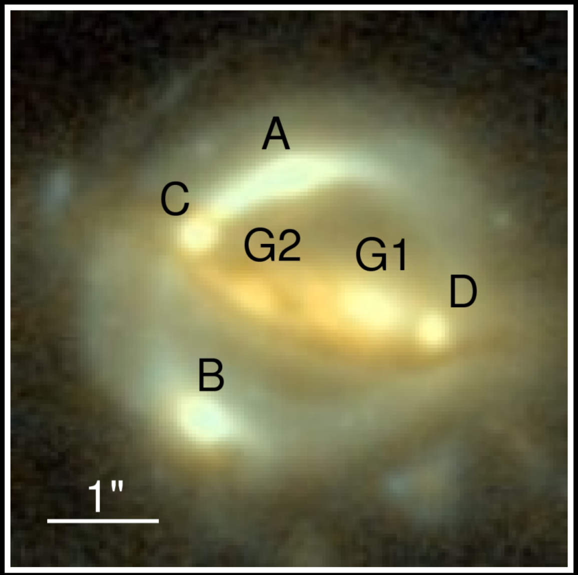
Image configurations of lenses

	Einstein Cross	Cusp Caustic	Fold Caustic
Source Plane			
Image Plane			

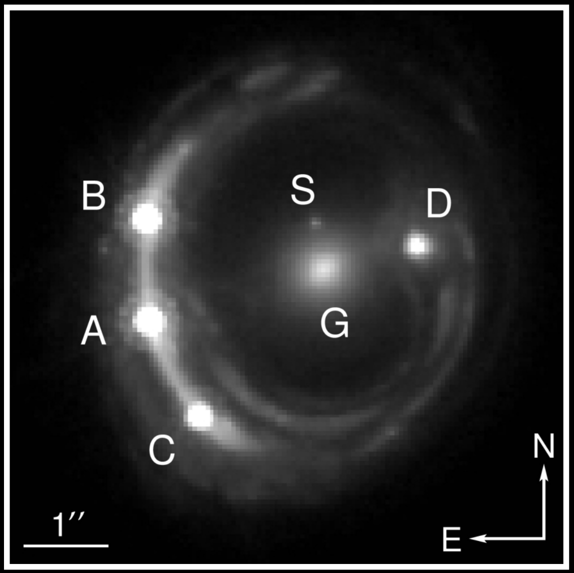
[Image credit: A. Amara]

Follow-up: requirement for lens mass modeling

- High sensitivity to detect the ring
- High angular resolution to resolve the ring
- Until now, this has meant HST observations



B1608+656 HST



RXJ1131-1231 HST

SHARP: An alternative approach

- SHARP = Strong-lensing High Angular Resolution Program
- Use laser guide star adaptive optics with Keck II Telescope
- Get resolution comparable to or better than HST, while using a mirror that has 16 times the collecting area

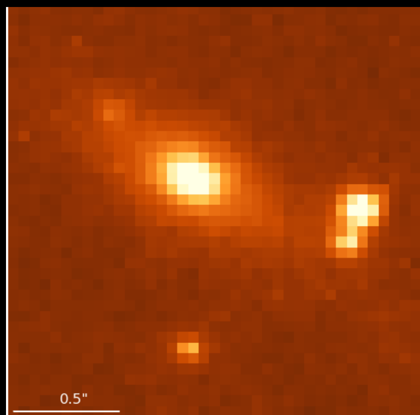
- Team SHARP:

  Chris Fassnacht, Simona Vegetti, John McKean, Dave Lagattuta, Leon Koopmans, Matt Auger

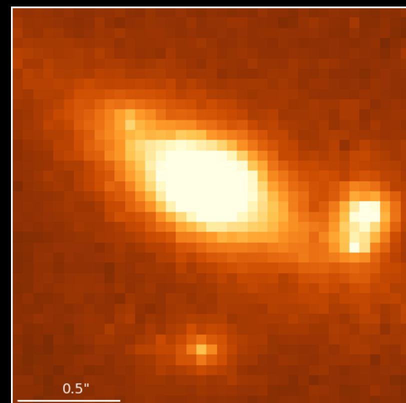
$$\boxed{\theta \sim \lambda / D}$$

[Material courtesy of Chris Fassnacht]

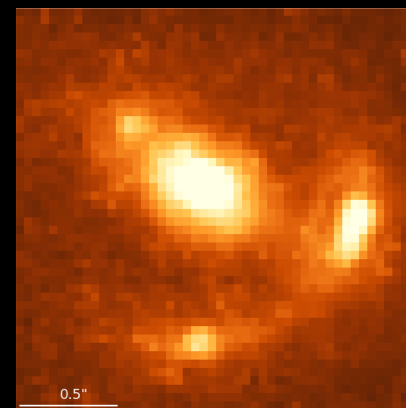
AO vs. Space: B0712+472



F555W

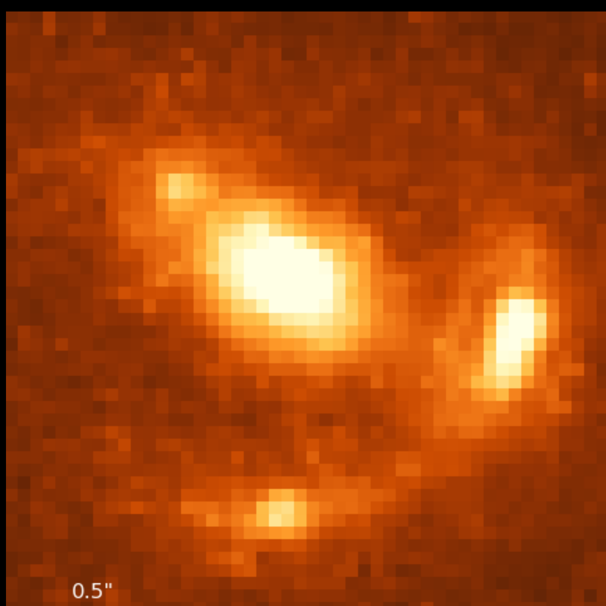


F814W



F160W

$z_l = 0.41$



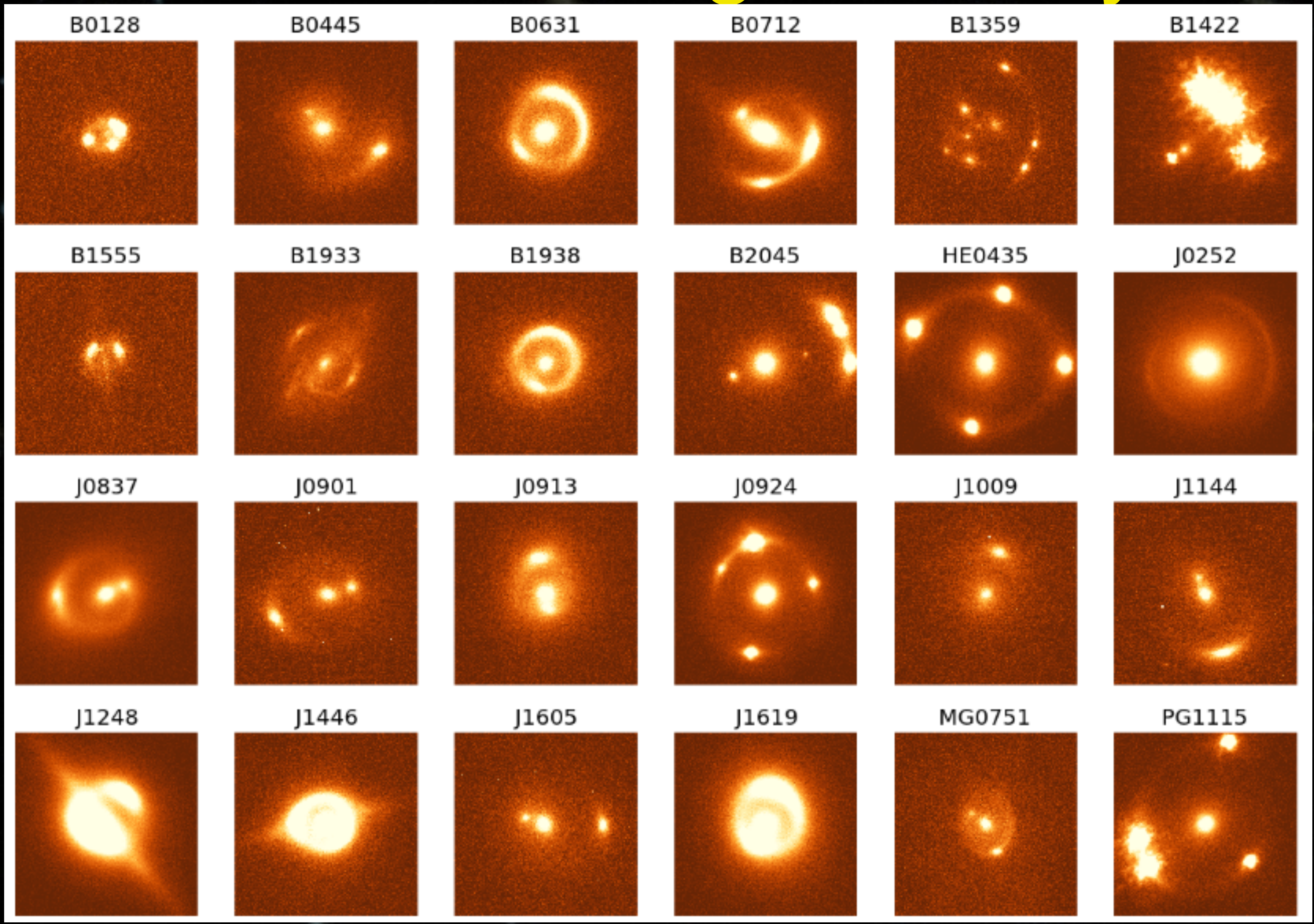
F160W, again

Keck AO K'-band

[Fassnacht et al. in prep]

[Material courtesy of Chris Fassnacht]

SHARP Image Gallery



All images are 3'' on a side [Fassnacht et al, in prep]

[Material courtesy of Chris Fassnacht]

SHARP for time-delay cosmography?

Can AO data produce similar cosmological constraints as HST data for time-delay systems?

➡ First test on RXJ1131-1231 [Chih-Fan Chen et al, in preparation]

HST/ACS F814W

Keck AO Ks (1 hr exposure)

AO would be an efficient way to follow up time-delay lenses especially given advances in current and future AO systems (e.g., Keck, VLT, Gemini, LBT, TMT, GMT, EELT)

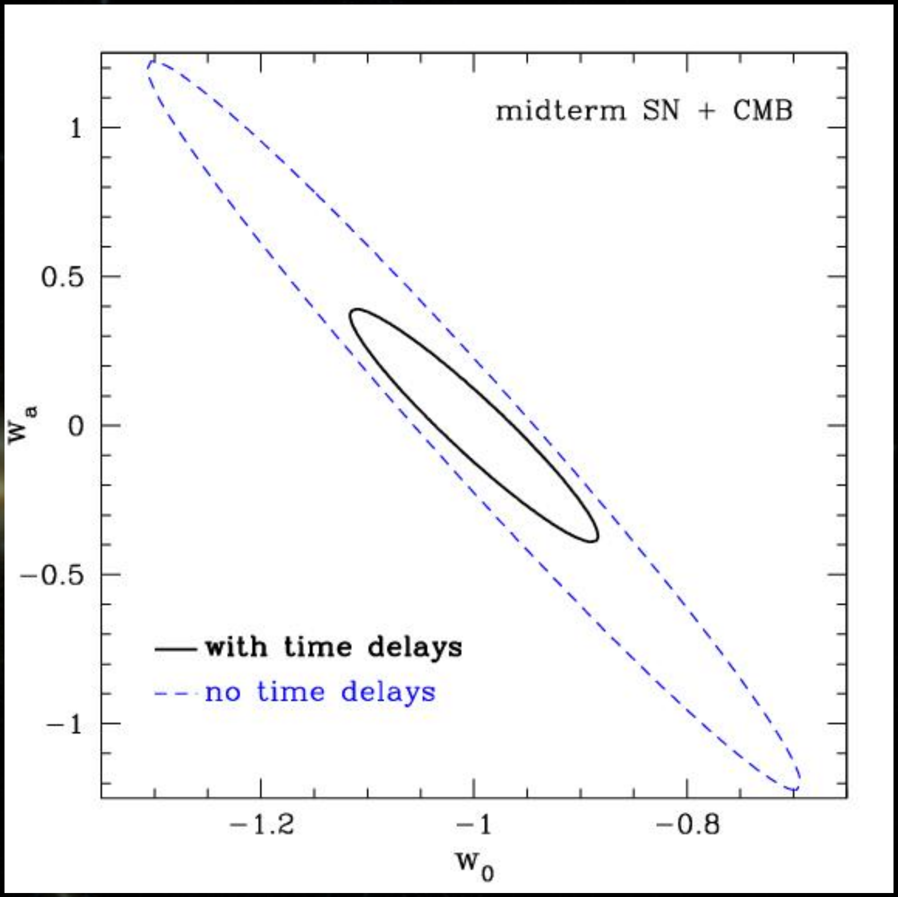
Future Prospects

[Linder 2011]

- Current and future surveys will discover hundreds of QSO lenses [Oguri & Marshall 2010]:
  HSC: ~600 (~80 quads)
  DES: ~1000 (~130 quads)
  LSST: ~8000 (~1000 quads)

When combine 150 lenses with CMB+SN:

- Area of w_a-w_0 contour tightens by a factor of ~5
- All cosmological parameters are better determined by factors of ~3 with the inclusion of time delays



Time-delay lenses are excellent complements to other probes

Summary

- Time-delay distances $D_{\Delta t}$ of each lens can be measured with uncertainties of ~5-8% including systematics
- Blind analysis of RXJ1131-1231 demonstrated robustness of method
- w and flatness constraints from lenses are comparable in precision to BAO and SN when each is combined with WMAP
- Lenses highly complement other probes
- Stay tuned for results from H0LiCOW
- Robot development is underway to find new lenses in HSC
- Work is in progress to test whether AO is viable for follow up
- Current and future surveys will find at least hundreds of time-delay lenses, providing an independent and competitive probe of cosmology