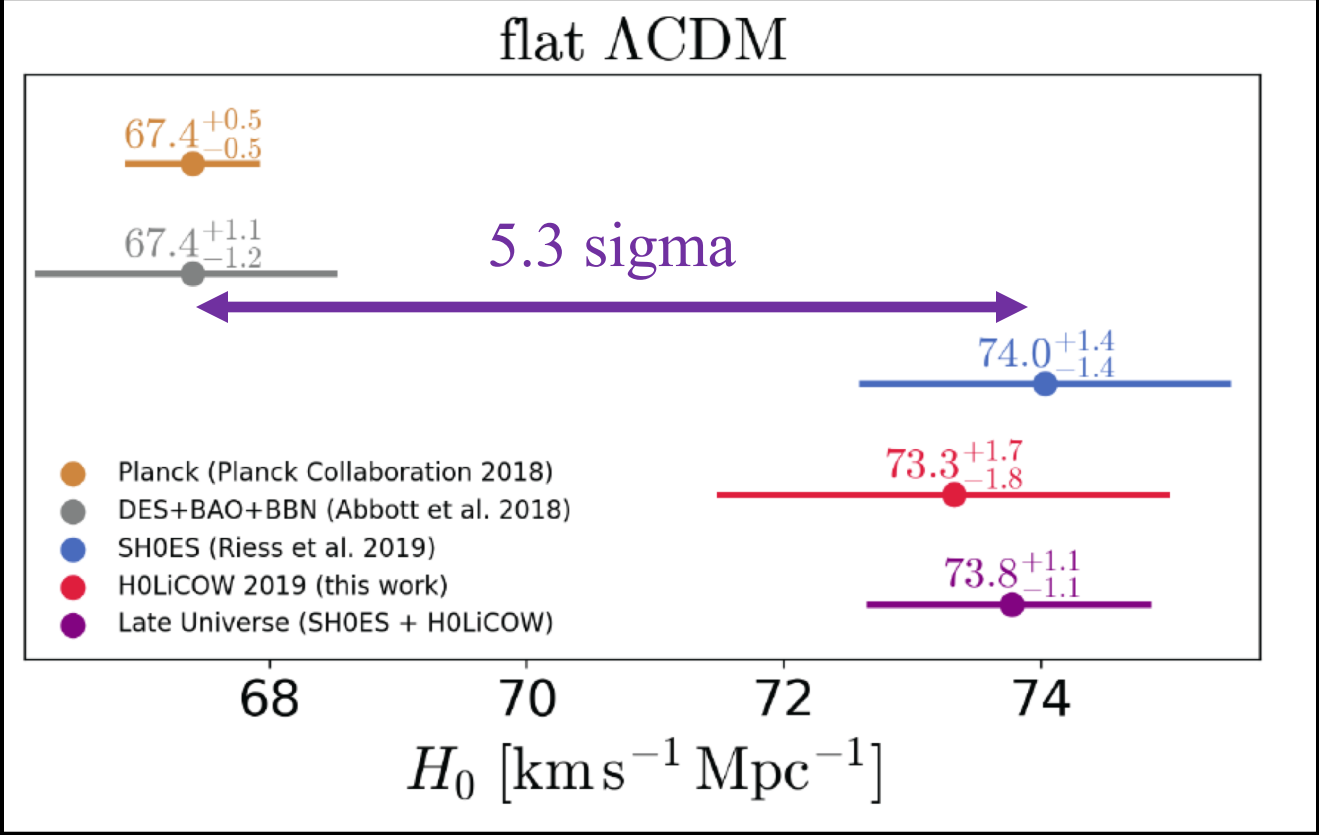
Time Delay Cosmography and the Hubble Constant ~~Tension~~ crisis



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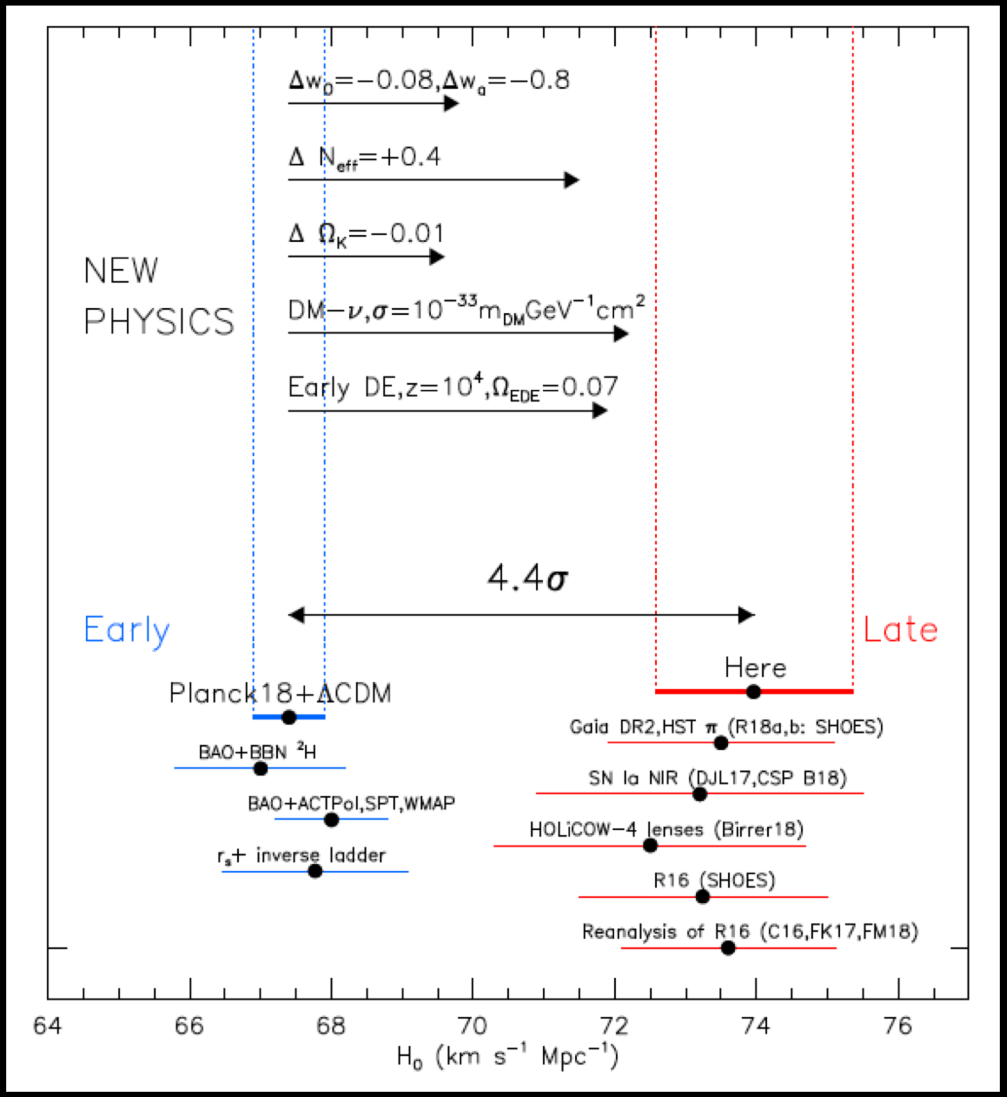
University of California Los Angeles

Outline

- Introduction. Time delay cosmography
  - How does it work?
  - A brief history
- Modern time delay cosmography and the Hubble Constant
  - Methodology – the importance of blindness
  - Recent Results
  - Systematics and data challenges
- Implications for cosmology
- Future outlook

Systematic errors or new physics?



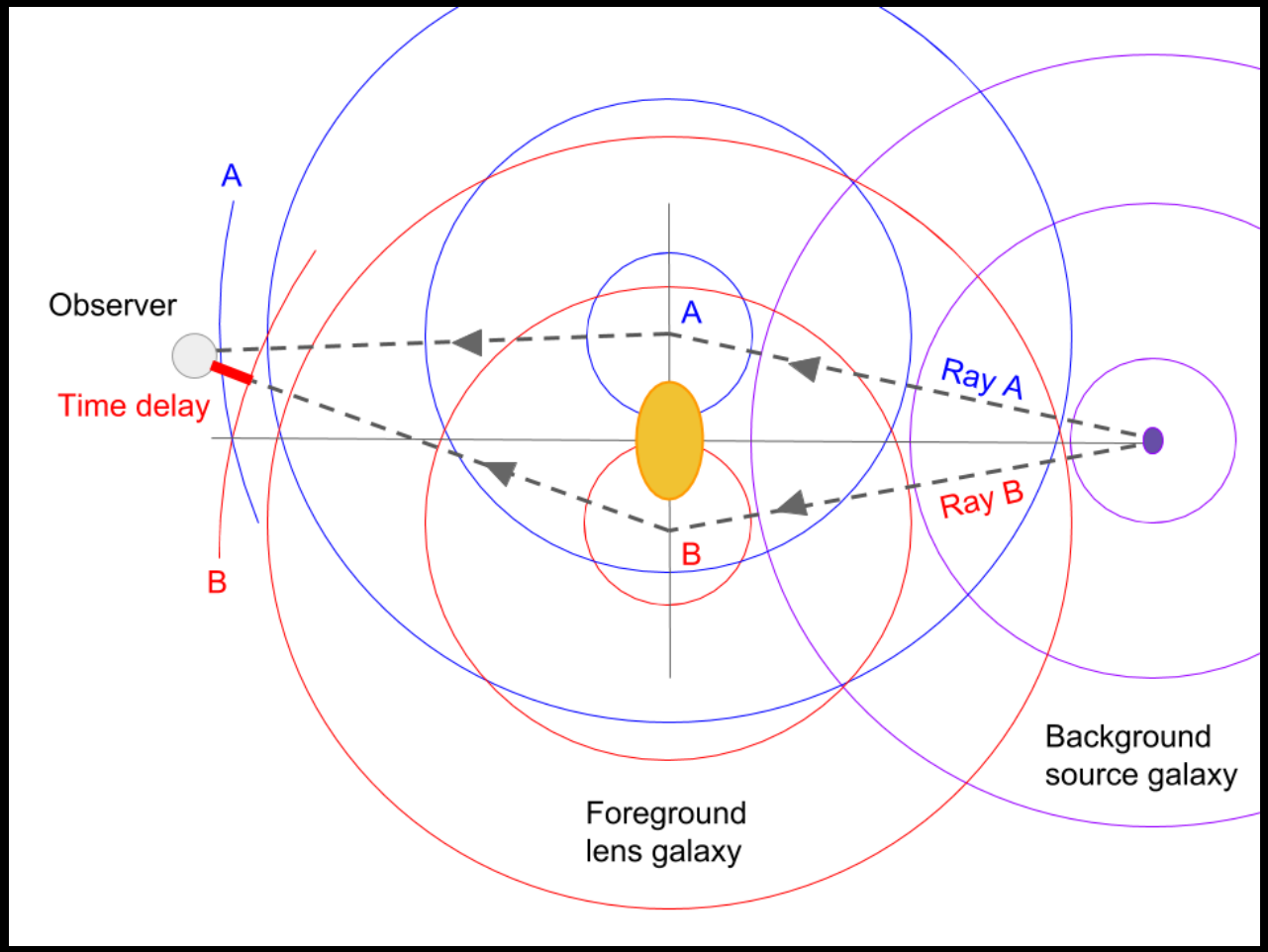
Riess et al. 2019: this morning

Time delay cosmography

What is Gravitational Lensing?

Movie courtesy of Y. Hezaveh

Cosmography from time delays: how does it work?



Treu & Marshall 2016

Time delay distance in practice

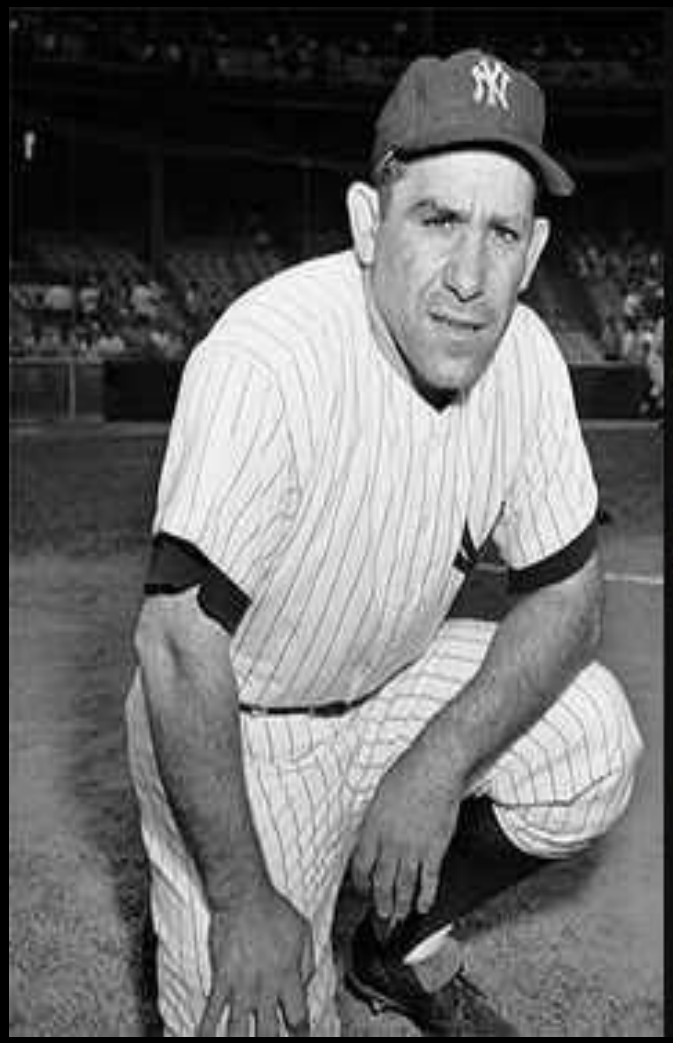
$$\Delta t \propto D_{\Delta t}(z_s, z_d) \propto H_0^{-1} f(\Omega_m, w, ...)$$

Steps:

- Measure the time-delay between two images
- Measure and model the potential
- Infer the time-delay distance
- Convert it into cosmlogical parameters

Cosmography from time delays: A brief history

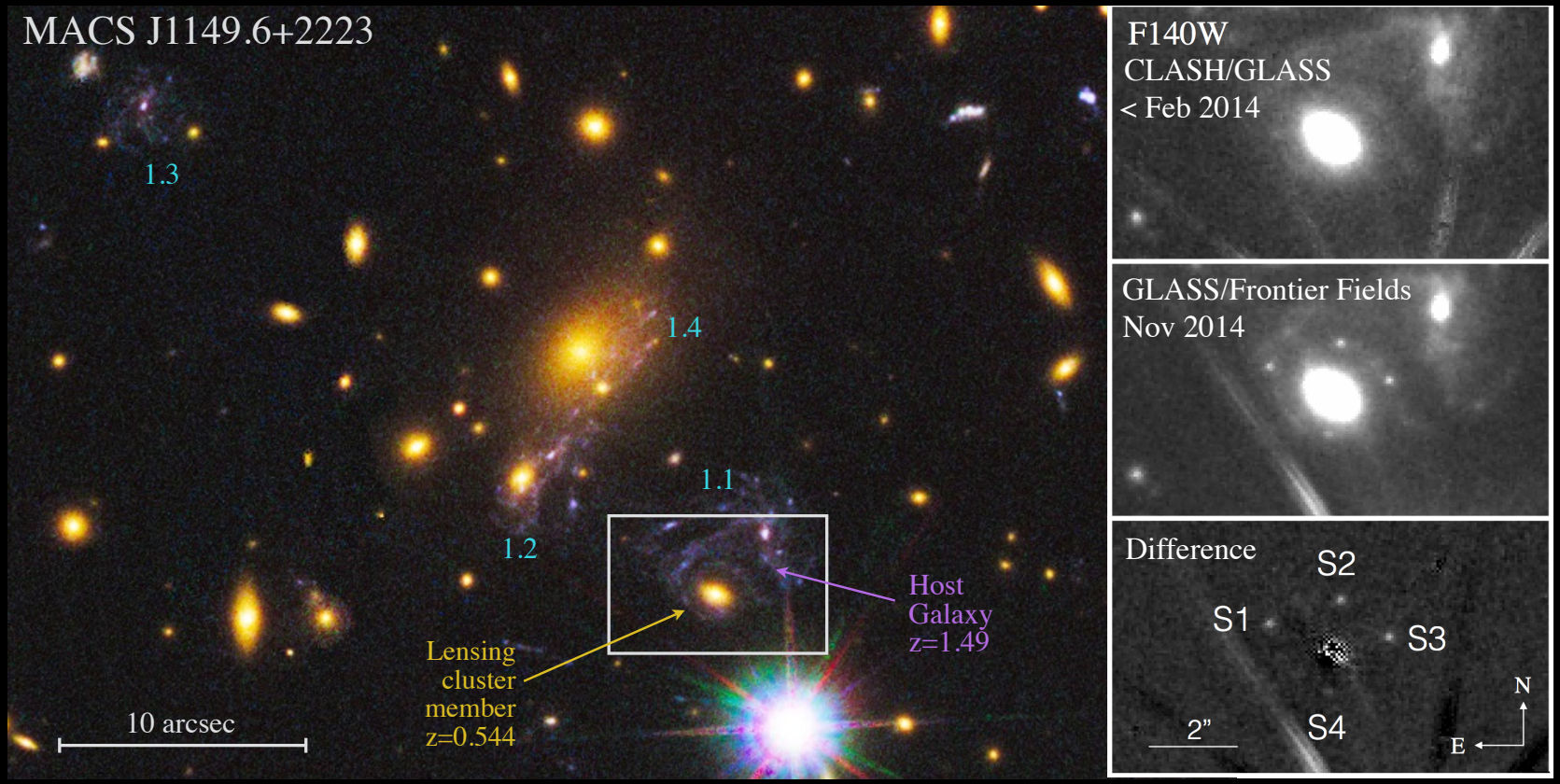
- 1964 Method proposed
- 70s First lenses discovered
- 80s First time delay measured
  - Controversy. Solution: improve sampling
- 90s First Hubble Constant measured
  - Controversy. Solution: improve mass models
- 2000s: modern monitoring (COSMOGRAIL, Fassnacht & others); stellar kinematics (Treu & Koopmans 2002); extended sources
- 2010s Putting it all together: precision measurements (6-7% from a single lens)
- 2014 first multiply imaged supernova discovered (50th anniversary of Refsdal's paper)



"In theory there is no difference between theory and practice. In practice there is."

Yogi Berra

A real life example

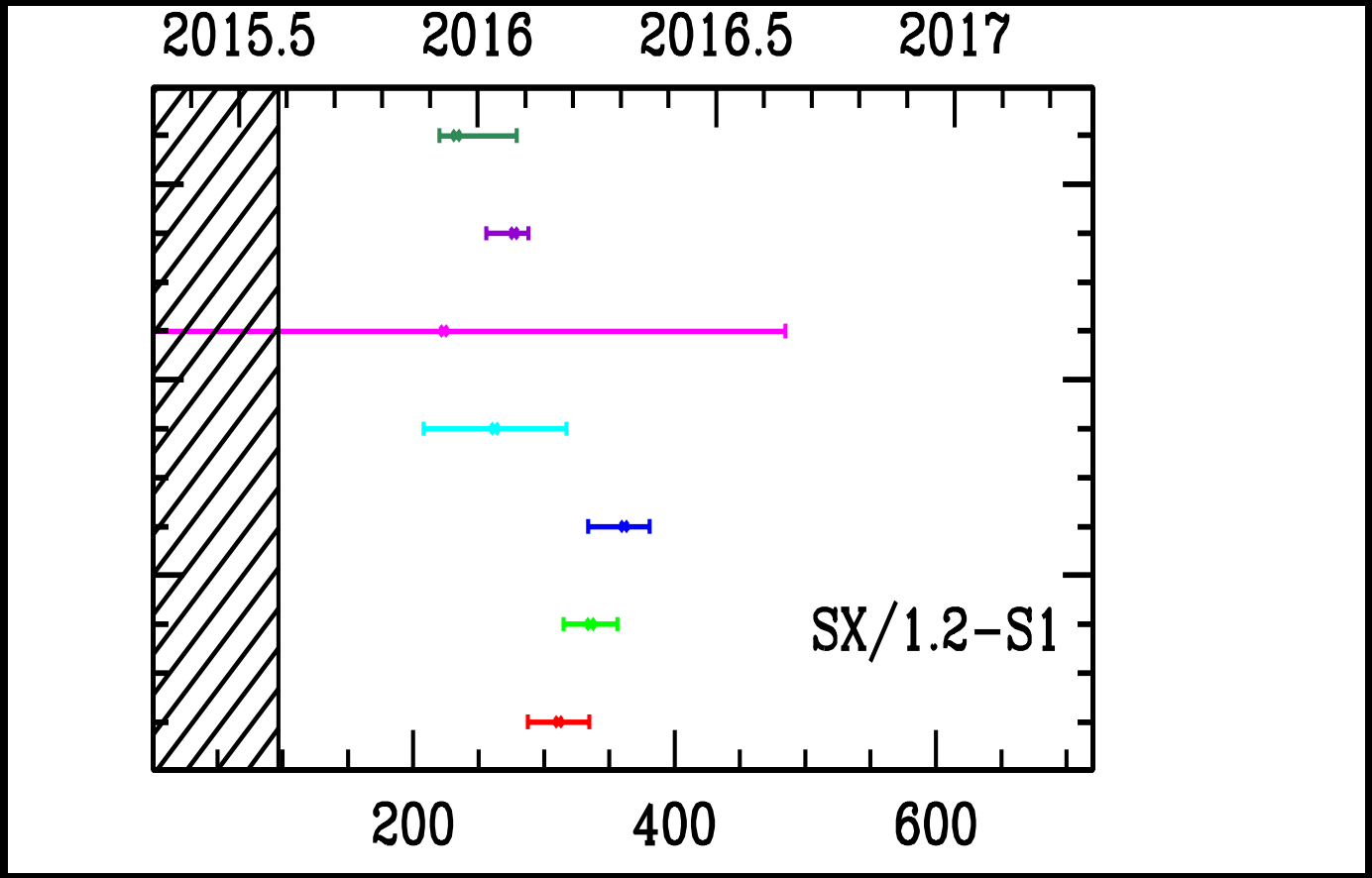


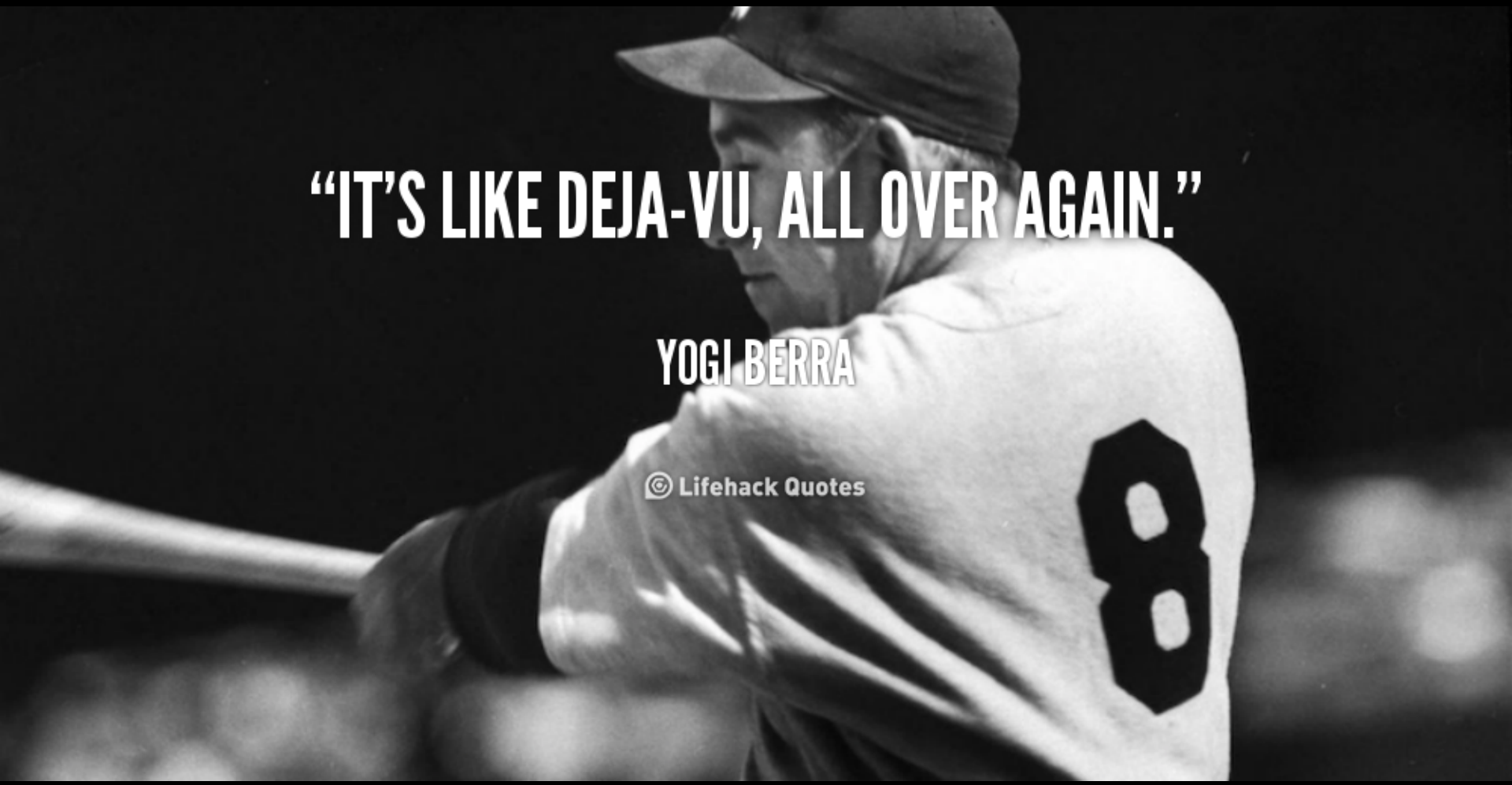
Kelly, Rodney,Treu et al. 2015

"REFSDAL" MEETS POPPER: COMPARING PREDICTIONS OF THE RE-APPEARANCE OF THE MULTIPLY IMAGED SUPERNOVA BEHIND MACSJ1149.5+2223

T. Treu[1,28], G. Brammer[2], J. M. Diego[3], C. Grillo[4], P. L. Kelly[5], M. Oguri[6,7,8], S. A. Rodney[9,10,29], P. Rosati[11], K. Sharon[12], A. Zitrin[13,29], I. Balestra[14], M. Bradač[15], T. Broadhurst[16,17], G. B. Caminha[11], A. Halkola, A. Hoag[15], M. Ishigaki[7,18], T. L. Johnson[12], W. Karman[19], R. Kawamata[20], A. Mercurio[21], K. B. Schmidt[22], L.-G. Strolger[2,23], S. H. Suyu[24], A. V. Filippenko[5], R. J. Foley[25,26], S. W. Jha[27], and B. Patel[27]

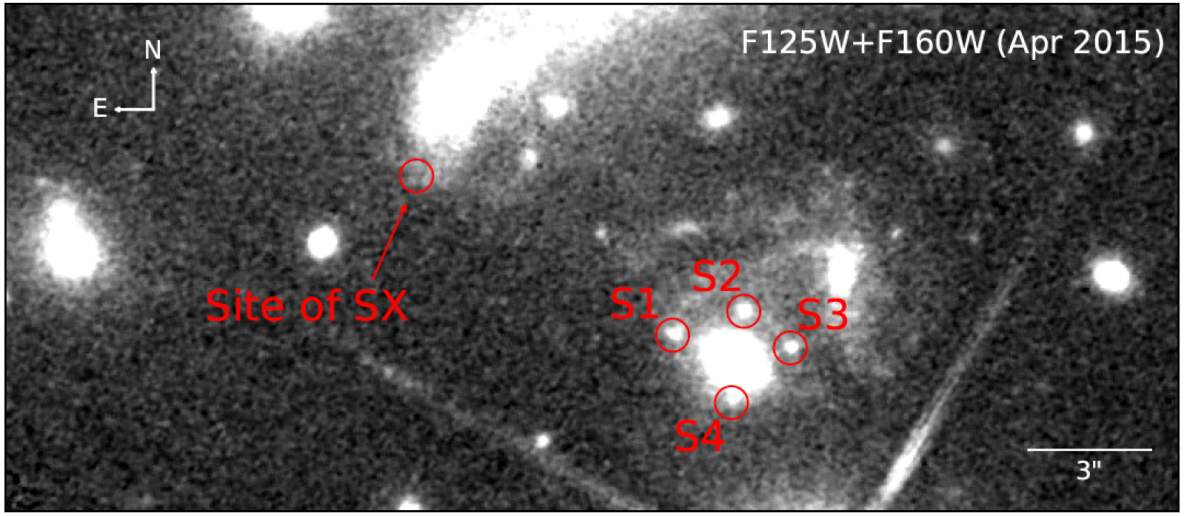
Received 2015 October 19; accepted 2015 November 24; published 2016 January 20




“IT’S LIKE DEJA-VU, ALL OVER AGAIN.”
YOGI BERRA
Lifehack Quotes

DÉJÀ VU ALL OVER AGAIN: THE REAPPEARANCE OF SUPERNOVA REFSDAL

P. L. Kelly[1], S. A. Rodney[2], T. Treu[3,4], L.-G. Strolger[5], R. J. Foley[6,7], S. W. Jha[8], J. Selsing[9], G. Brammer[5], M. Bradač[10], S. B. Cenko[11,12], O. Graur[13,14], A. V. Filippenko[1], J. Hjorth[9], C. McCully[15,16], A. Molino[17,18], M. Nonino[19], A. G. Riess[20,5], K. B. Schmidt[16,21], B. Tucker[22], A. von der Linden[23], B. J. Weiner[24], and A. Zitrin[25,26]



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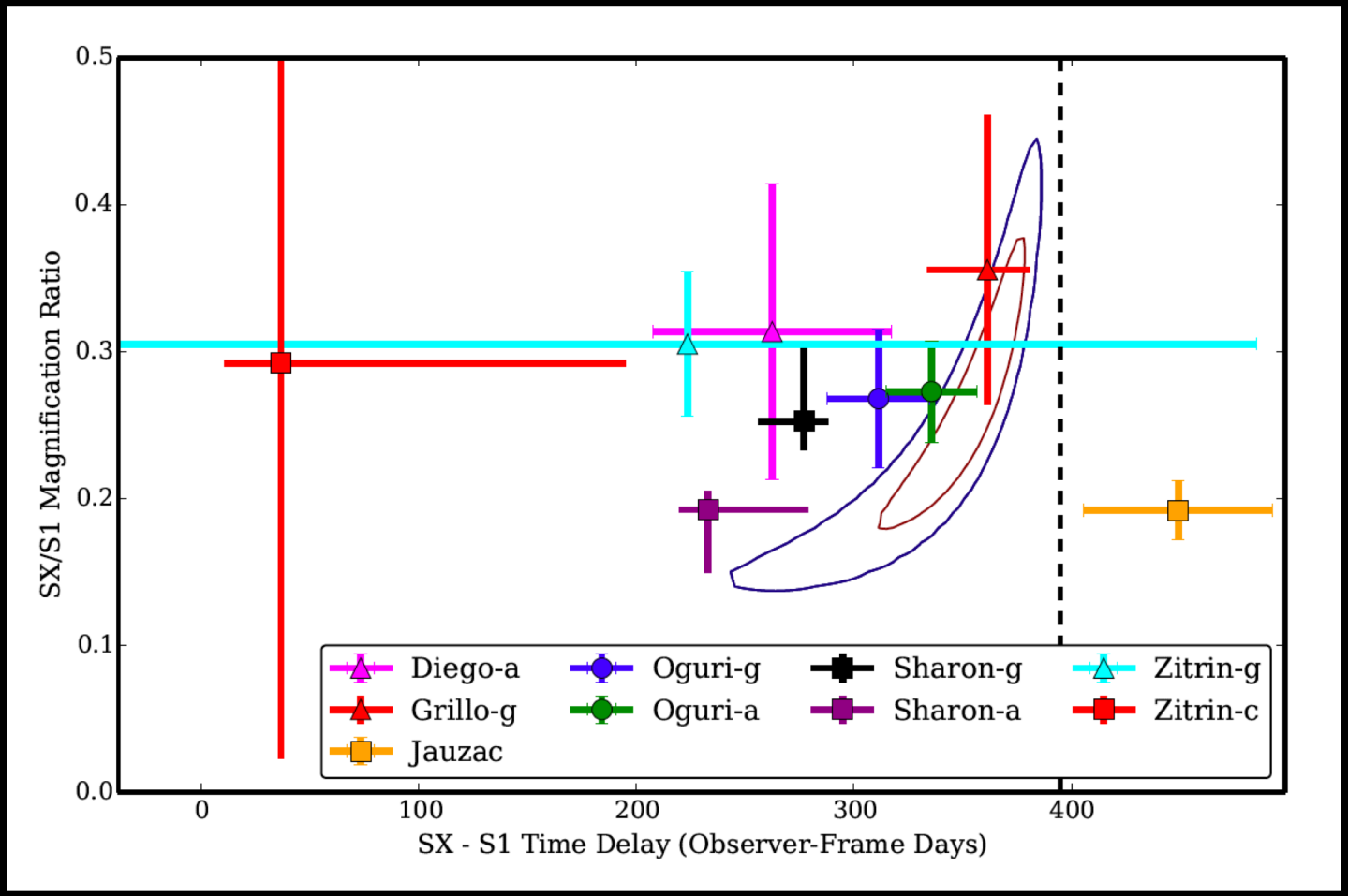
Draft version 2015/12/16



See Rodney's talk for prospects of measuring H0 from Refsdal

Modern time delay cosmography

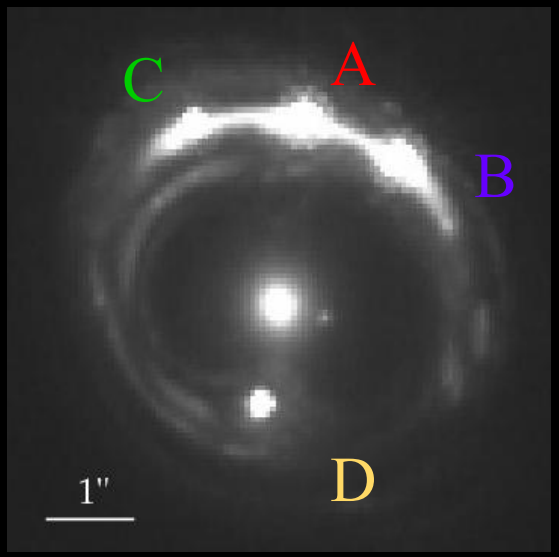
Cosmography with strong lenses: the 4 problems solved

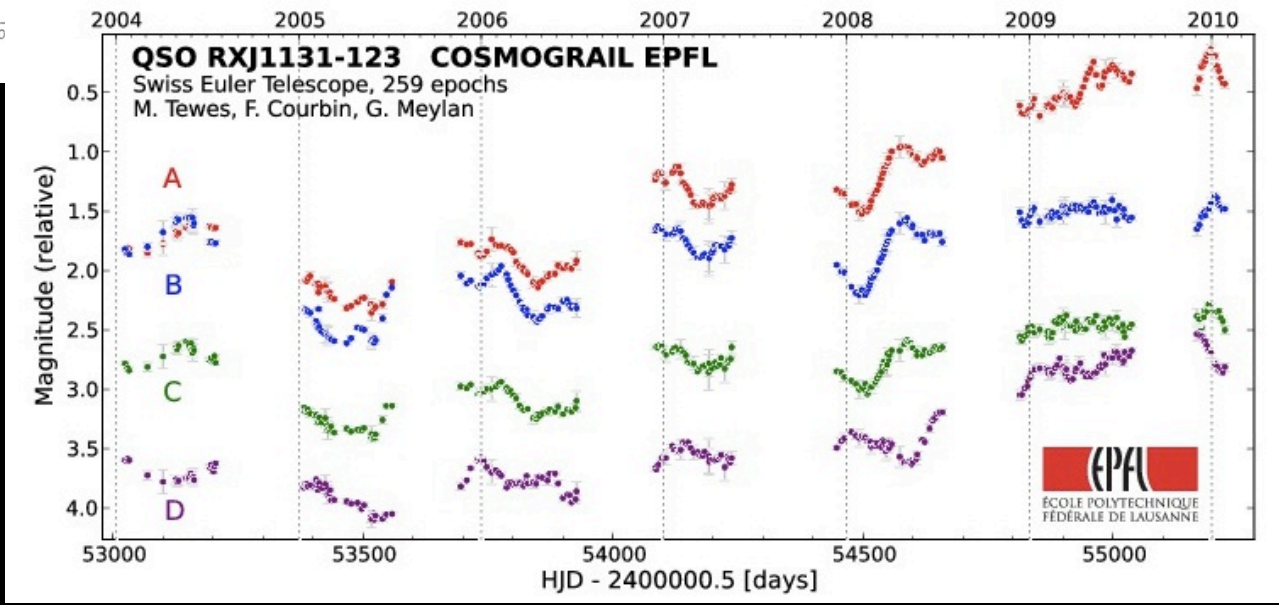
- Time delay – 2-3 %
  - Tenacious monitoring (e.g. Fassnacht et al. 2002); COSMOGRAIL (Meylan/Courbin)
- Astrometry – 10-20 mas
  - Hubble/VLA/(Adaptive Optics?)
- Lens potential (2-3%)
  - Stellar kinematics/Extended sources (Treu & Koopmans 2002; Suyu et al. 2009)
- Structure along the line of sight (2-3%)
  - Galaxy counts and numerical simulations (Suyu et al. 2010)
  - Stellar kinematics (Koopmans et al. 2003)

Cosmography with strong lenses: measuring time delays

Vanderriest et al. 1989

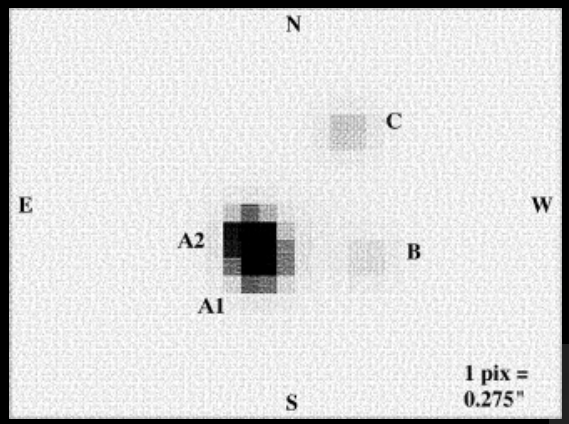
COSMOGRAIL: better data & better techniques



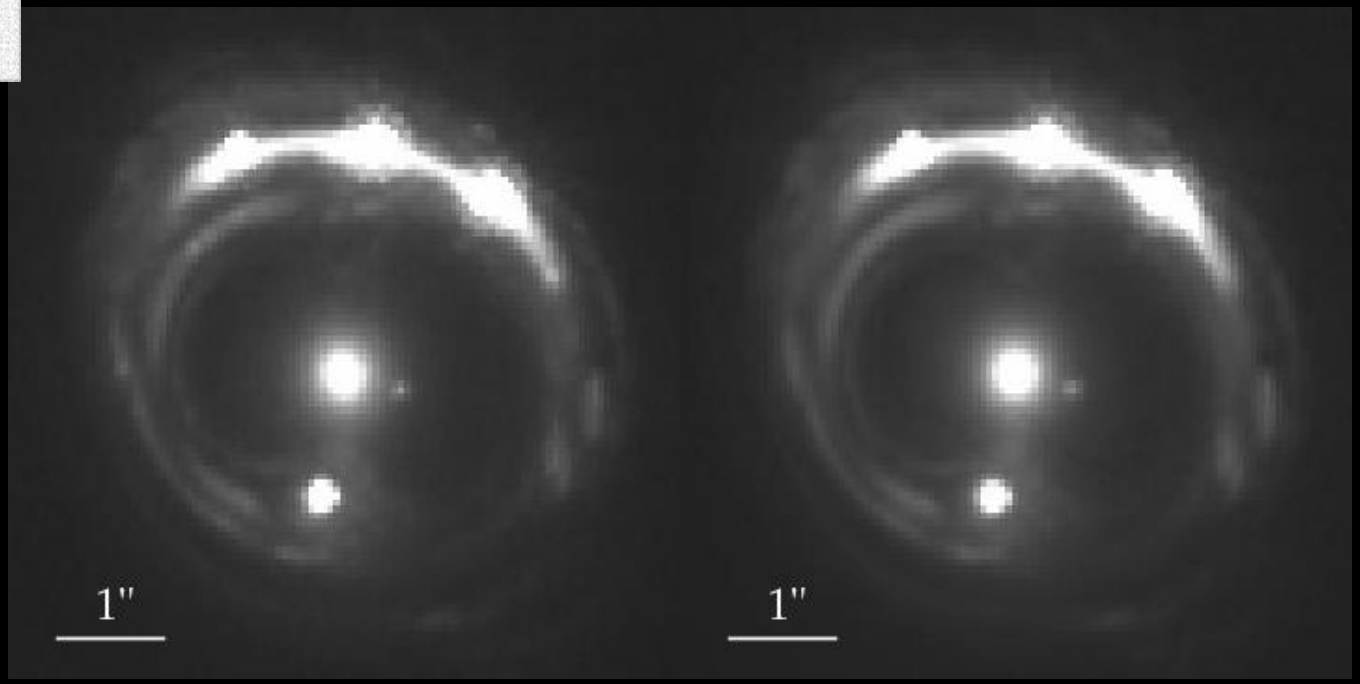


Cosmography with strong lenses: measuring the lens potential

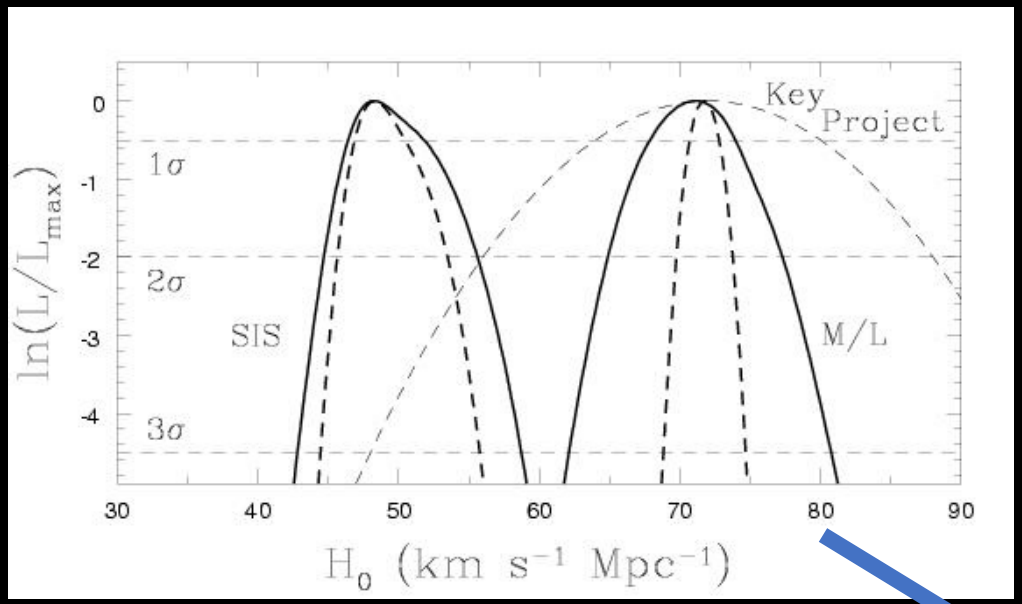
Schechter et al. 1997

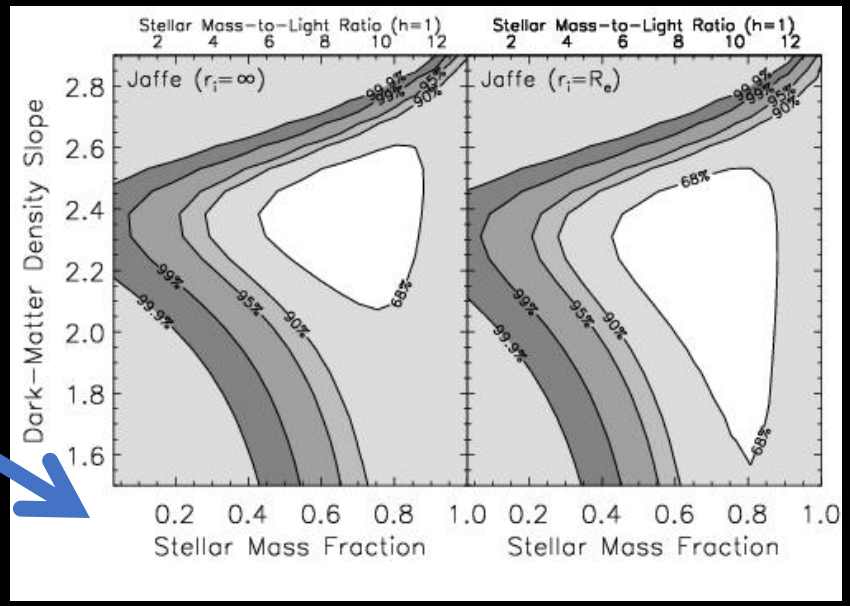


Host galaxy reconstruction; Suyu et al. 2012



Cosmography with strong lenses: measuring the lens potential

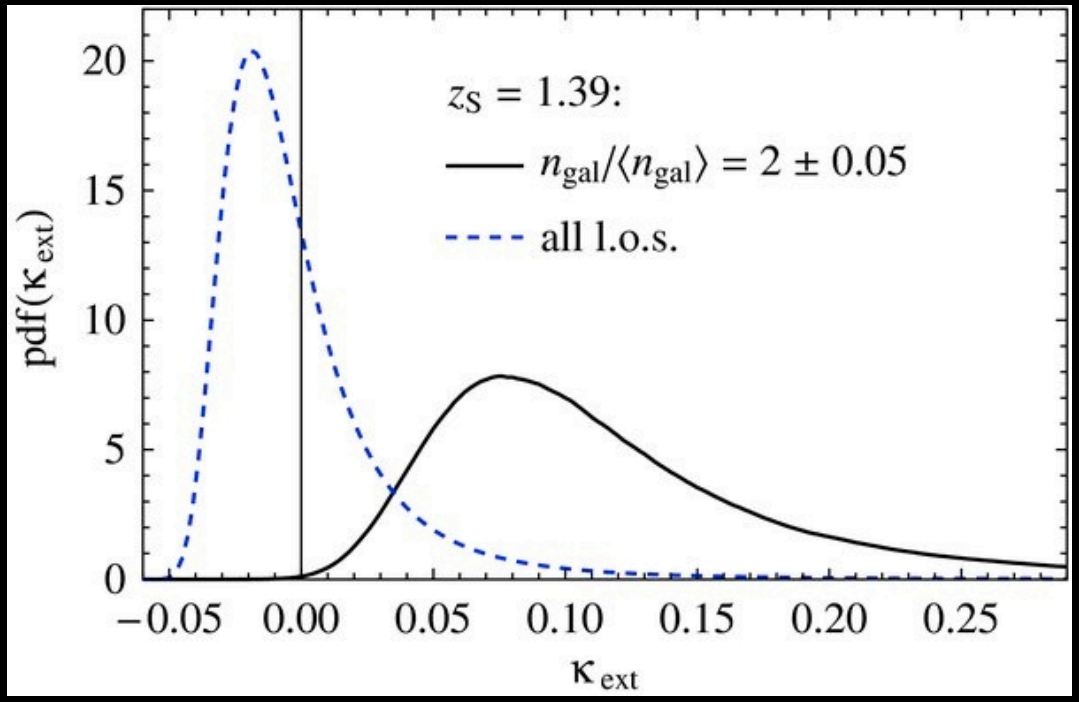




Stellar kinematics: Treu & Koopmans 2002

Cosmography with strong lenses: Structure along the line of sight

???



Suyu et al. 2010

Methodology - Blindness

- Blinding is the most effective way to avoid experimenter bias and discover unknown unknowns
- Refsdal is a rare example of a true blind test in astronomy
- "Blindness" can be achieved for example via software, by removing the average of the posterior pdf during the measurement and only revealing the average/peak just prior to publication.
  - Unblinded results are published without correction.

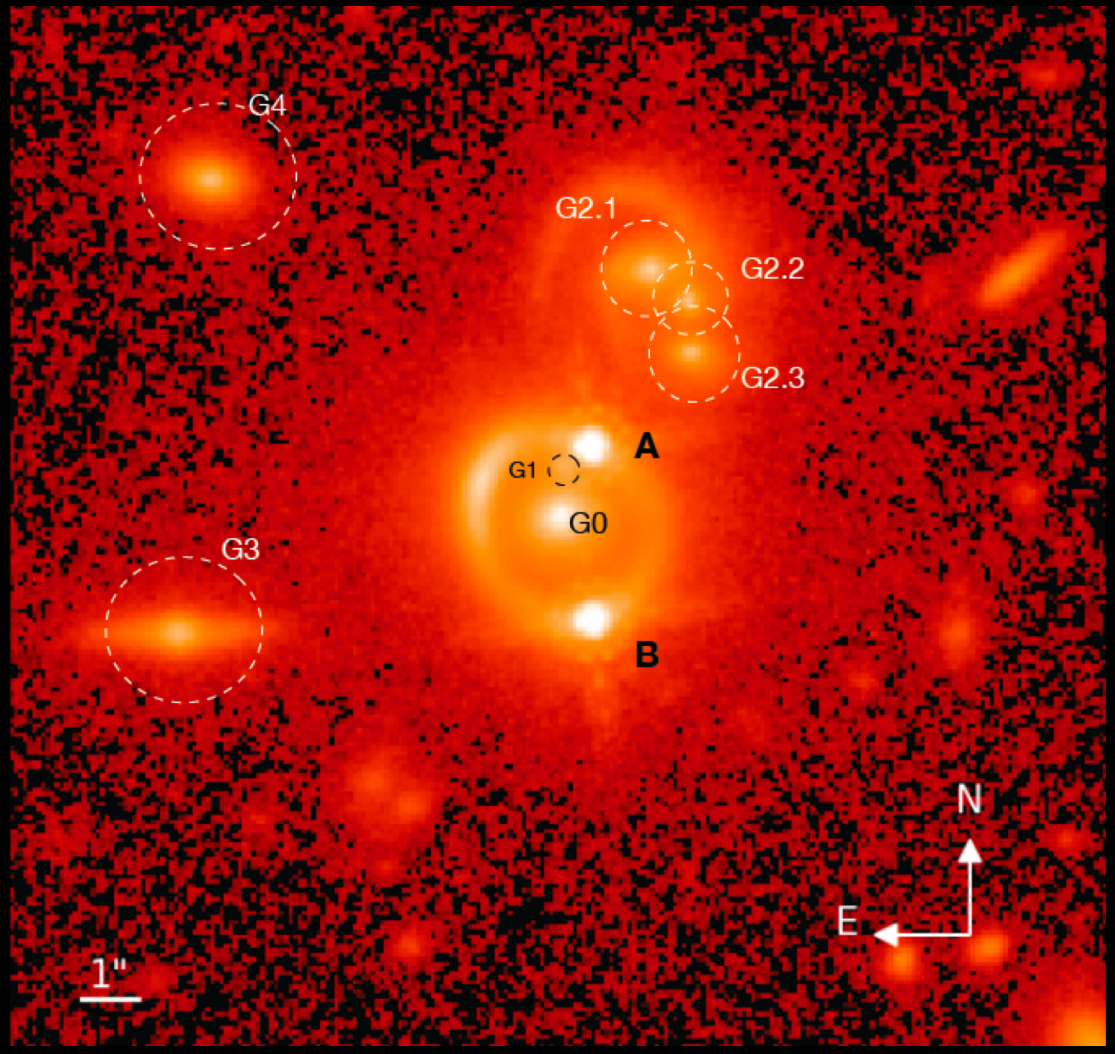
Current status

- Six-lens sample analyzed by our collaboration (H0licow and friends)
- 5/6 Analyzed blind (except first one): all of them consistent with each other
- 3/6 systems have Keck+AO data that provide consistent results with HST
- 5/6 systems analyzed with code GLEE, 1 with code LENSTRONOMY

2019 Publications

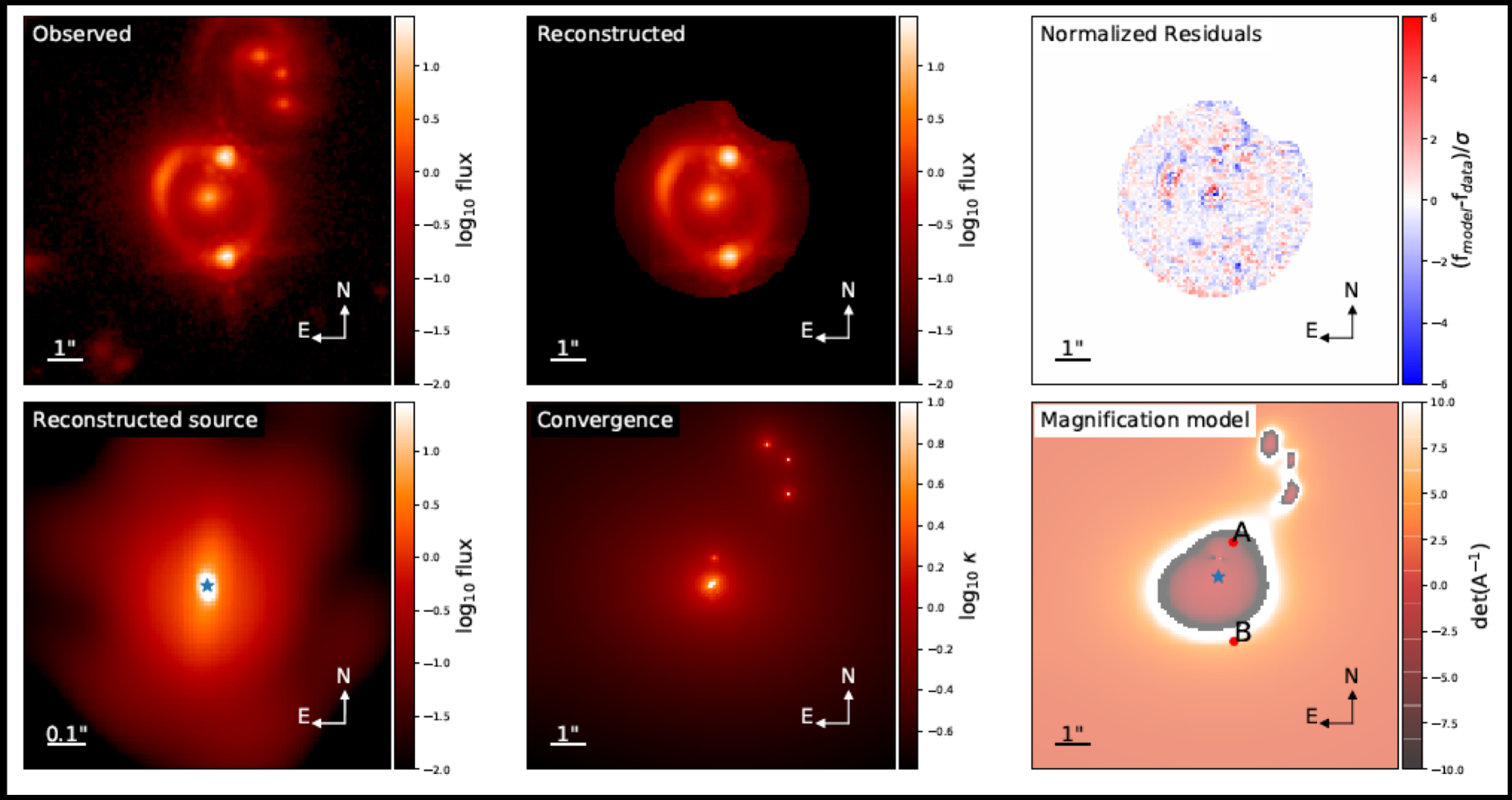
- Birrer et al. 2019, MNRAS, 448, 4726 (SDSSJ1206)
- Bonvin et al. 2019, arxiv.190508260 (WFI2033 time delay)
- Rusu et al 2019, arxiv.190509338 (WFI2033 models)
- Sluse et al. 2019, arxiv.190508800 (WFI2033 environment)
- Chen et al. 2019, arxiv.190702533 (HE0435, RXJ1131, PG1115 AO+HST; at this conference!)
- Wong et al 2019, arxiv.190704869 (cosmography from six lenses, including B1608)

Example: 1206 analysis



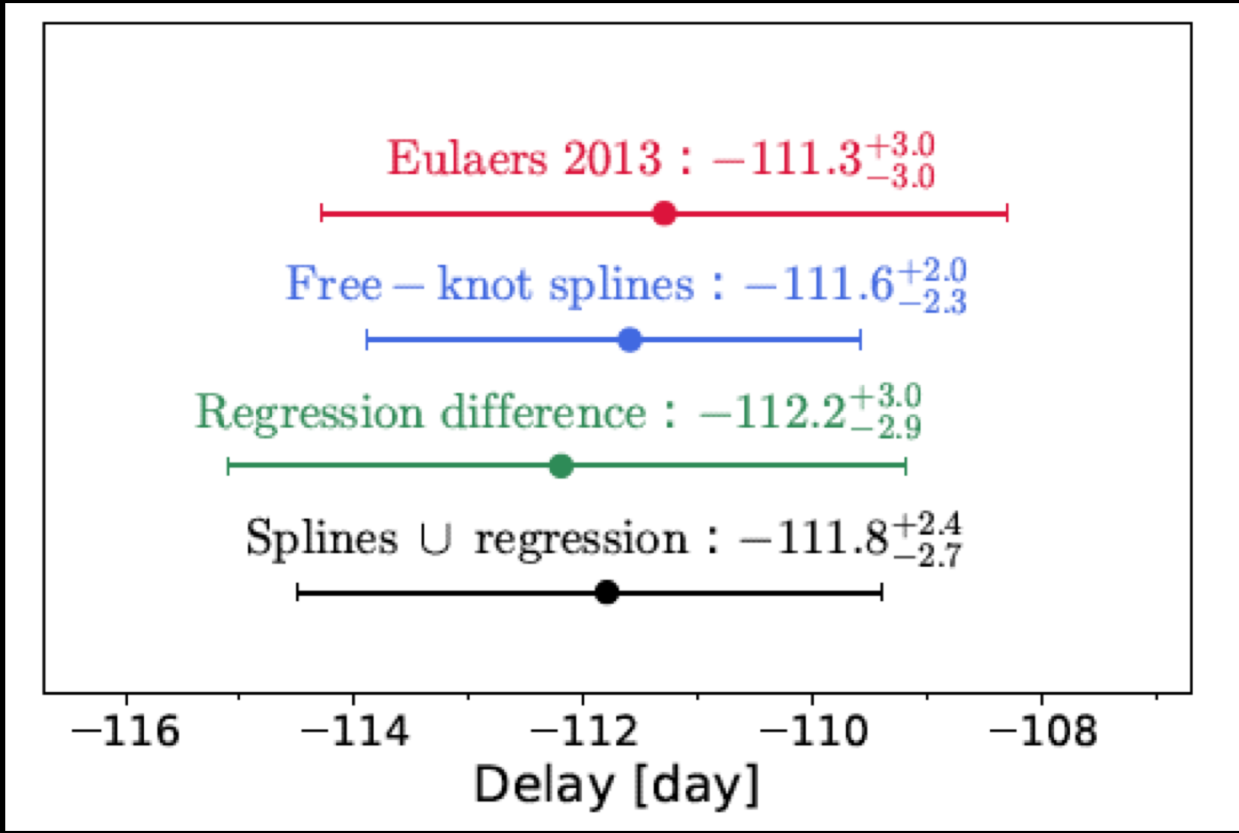
Birrer, TT et al. 2019

Example: 1206 analysis



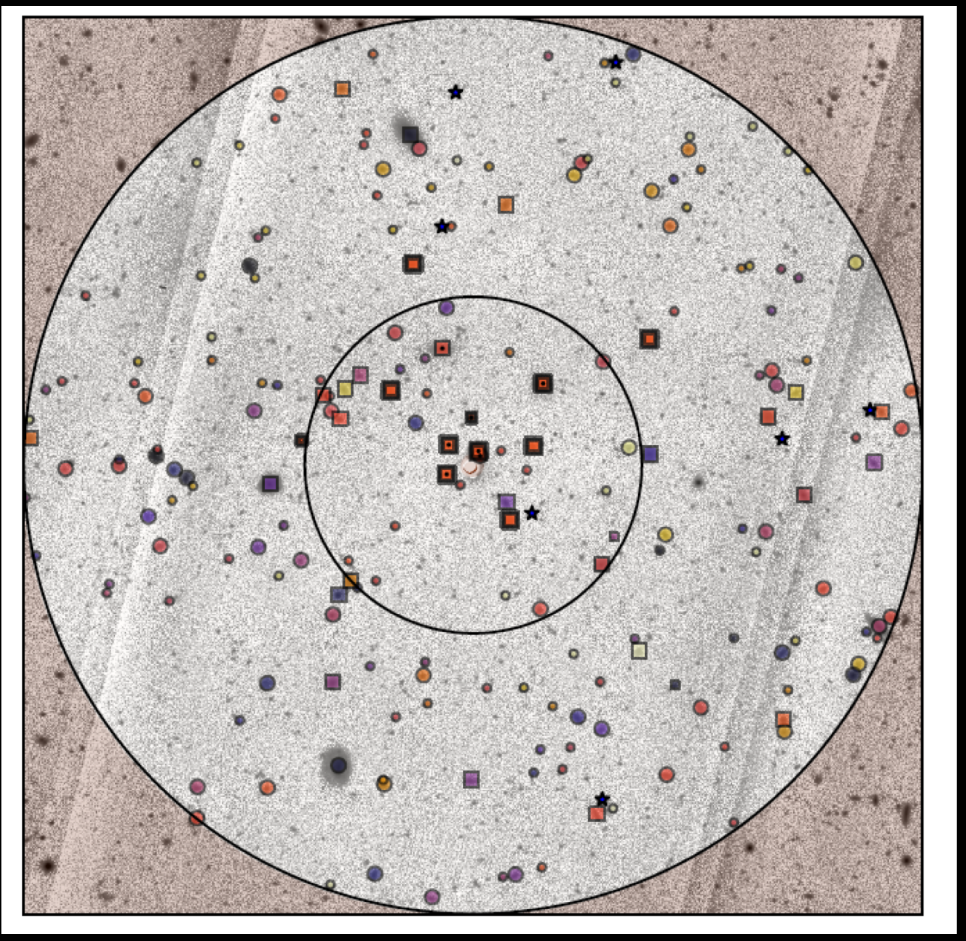
Birrer, TT et al. 2019

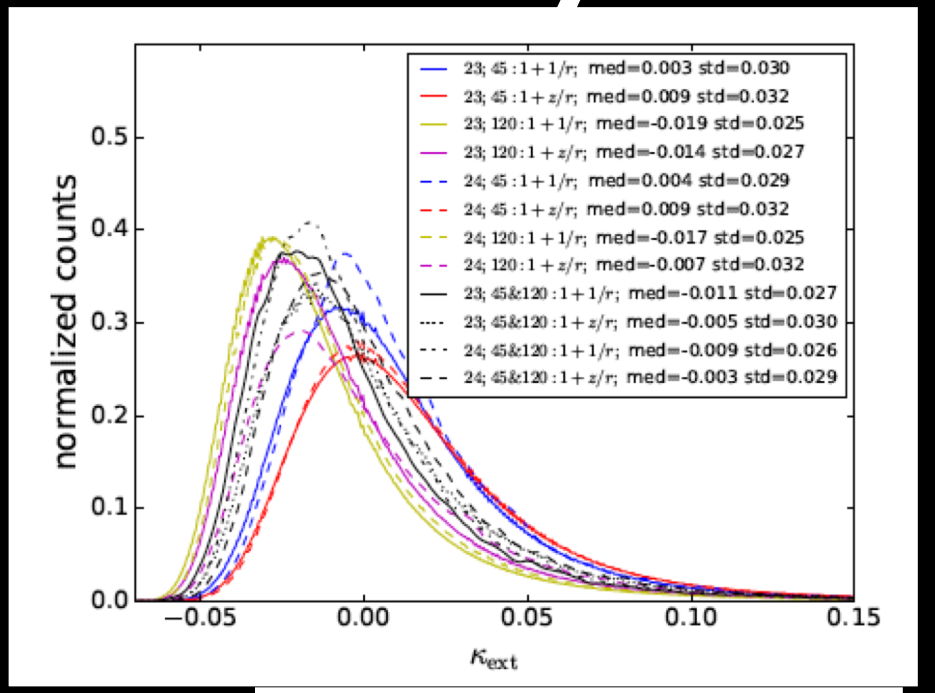
Example: 1206 analysis

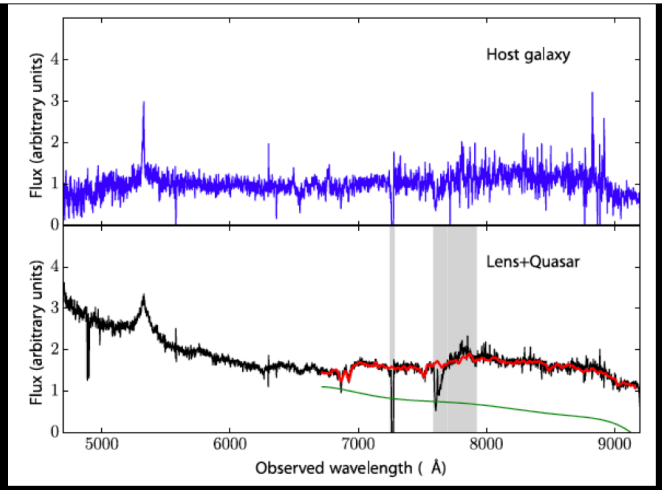


Birrer, TT et al. 2019 based on Eulaers et al. 2013

Example: 1206 analysis

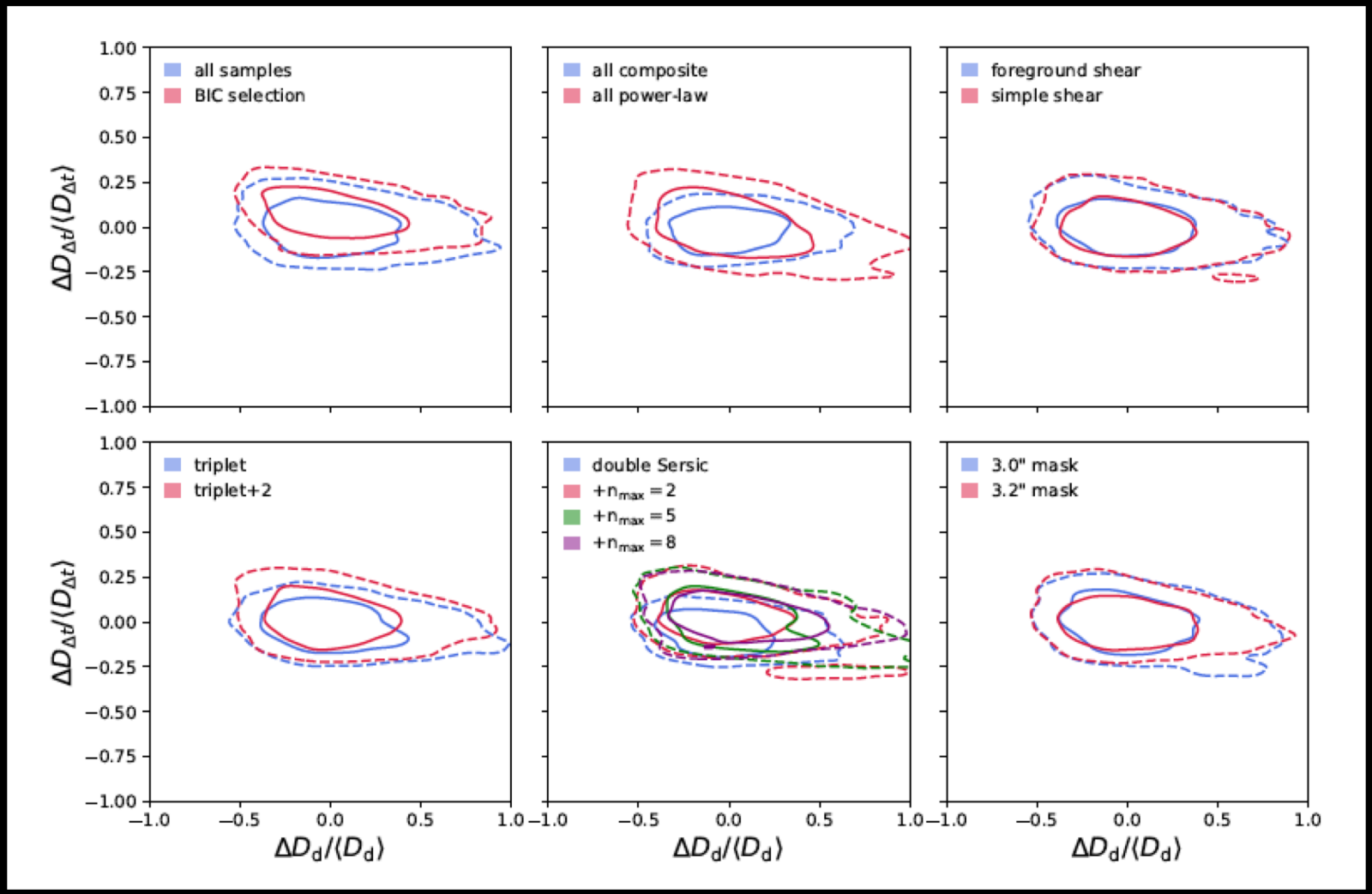






Birrer, TT et al. 2019; Agnello et al. 2016

Example: 1206 analysis



Birrer, TT et al. 2019

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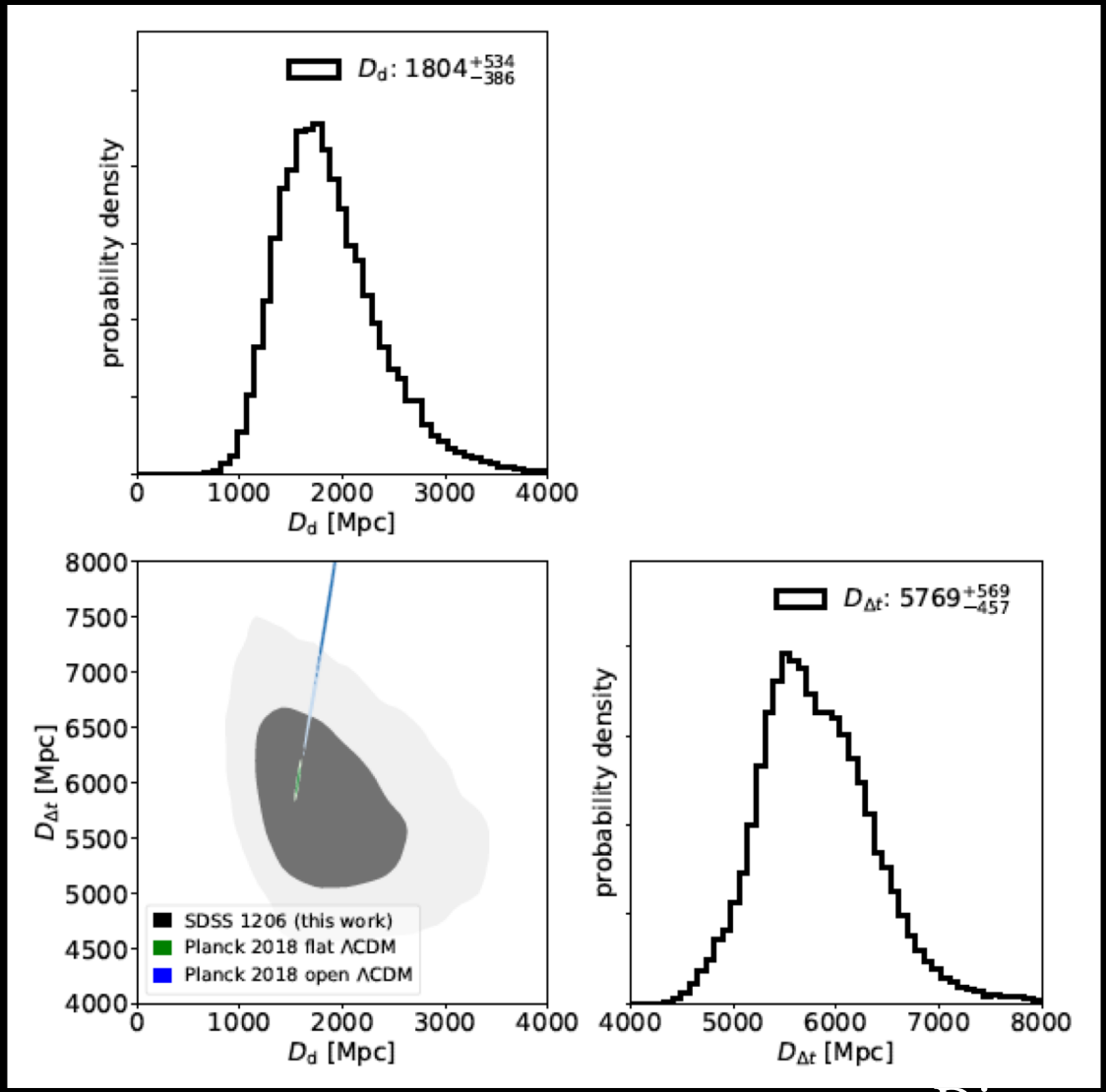
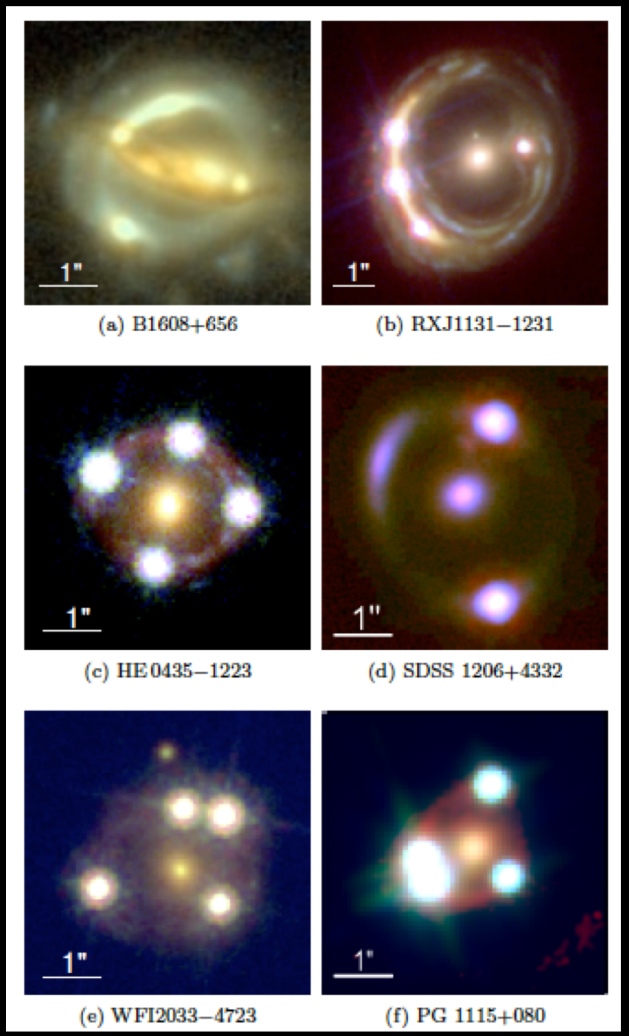
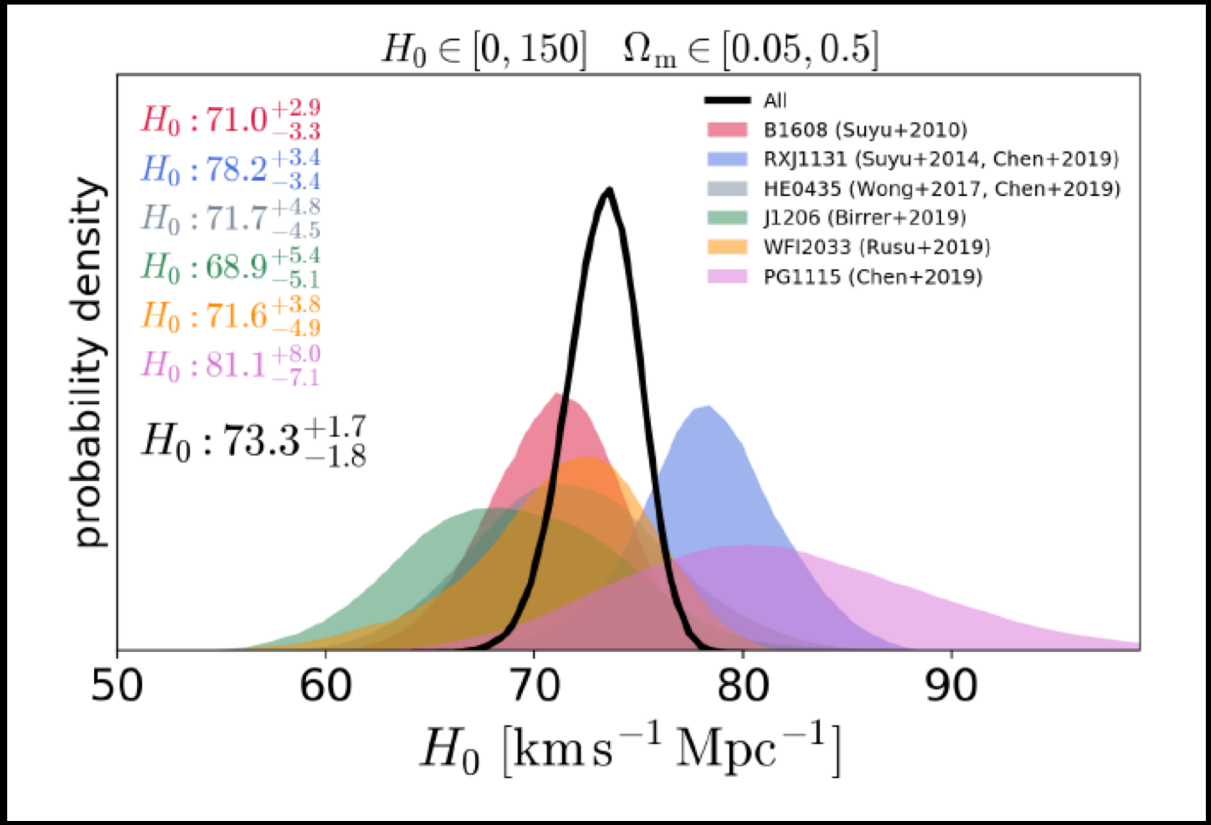


Birrer, TT et al. 2019

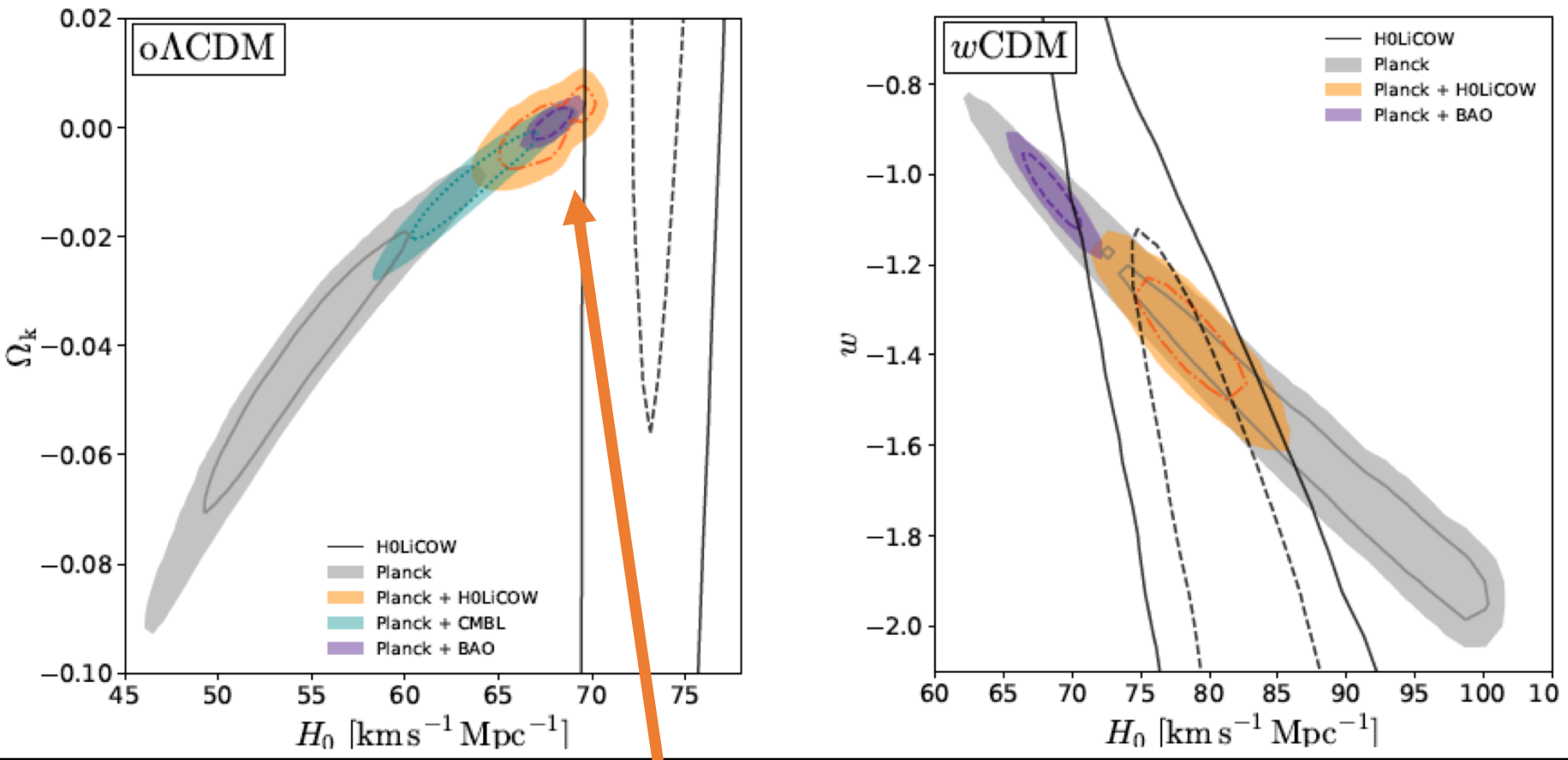
Six-Lens Sample





Wong et al. 2019

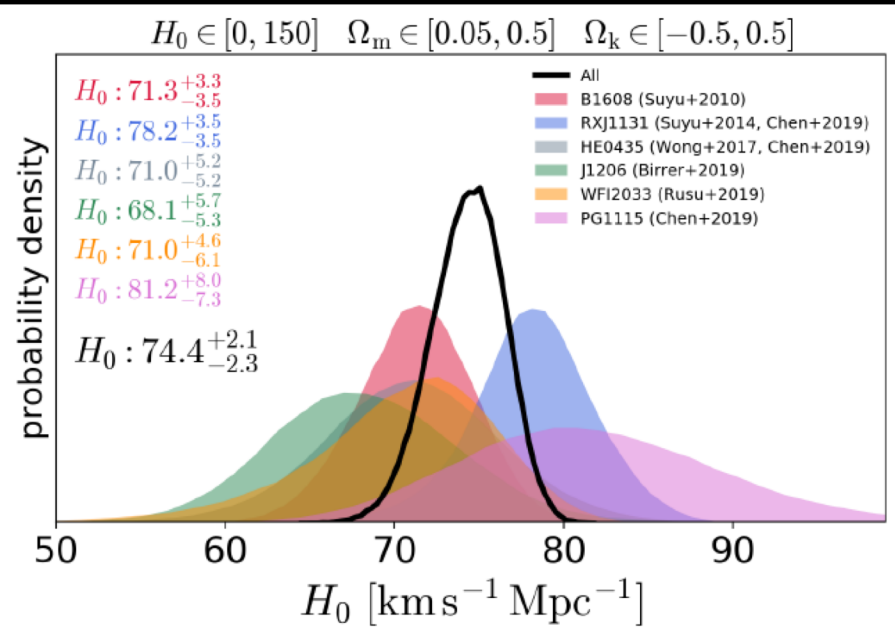
Six-Lens Sample

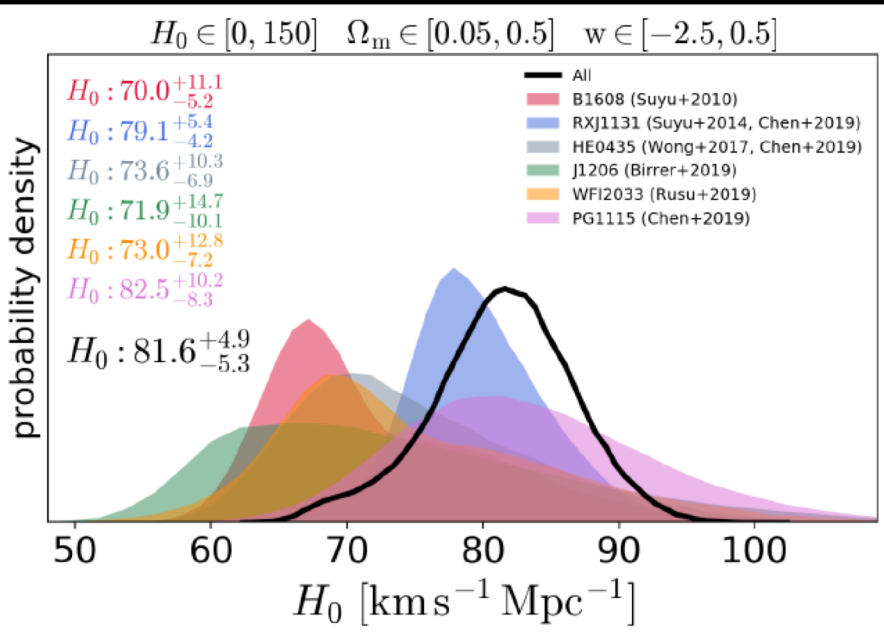


Tension!

Wong et al. 2019

Six-Lens Sample





Wong et al. 2019

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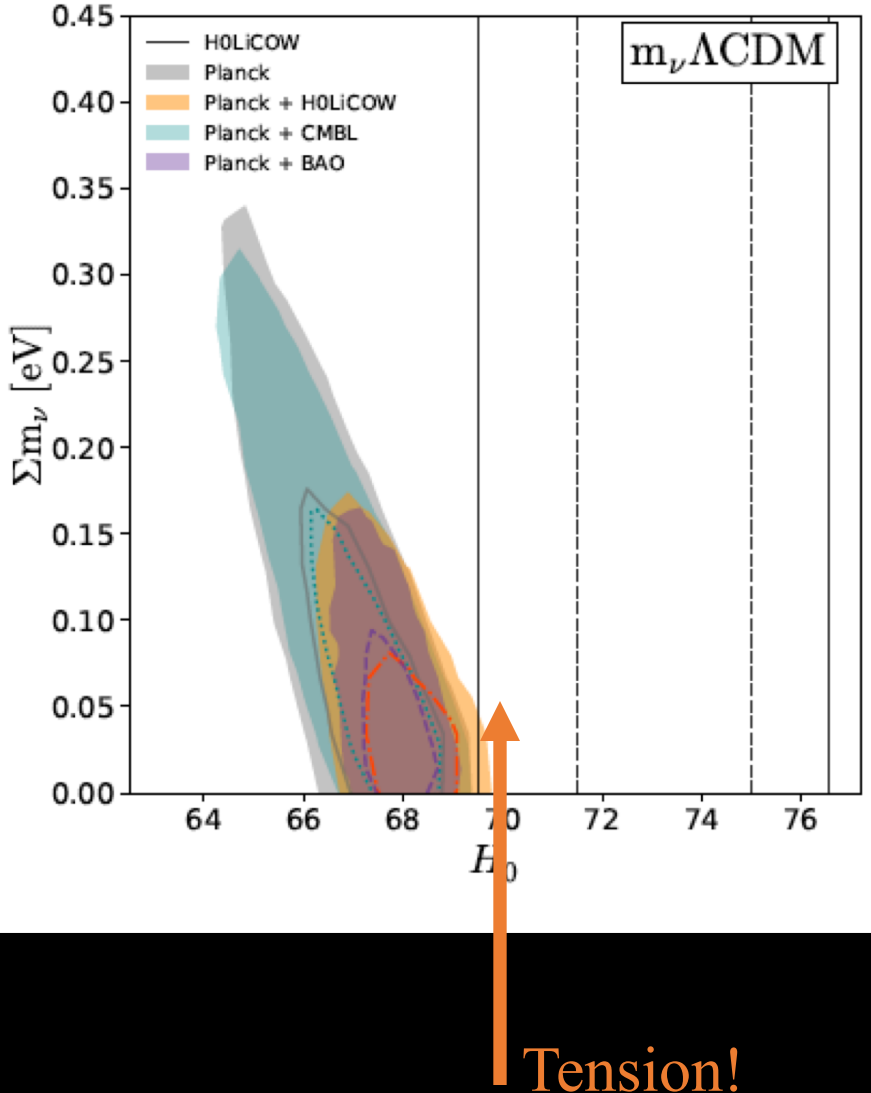
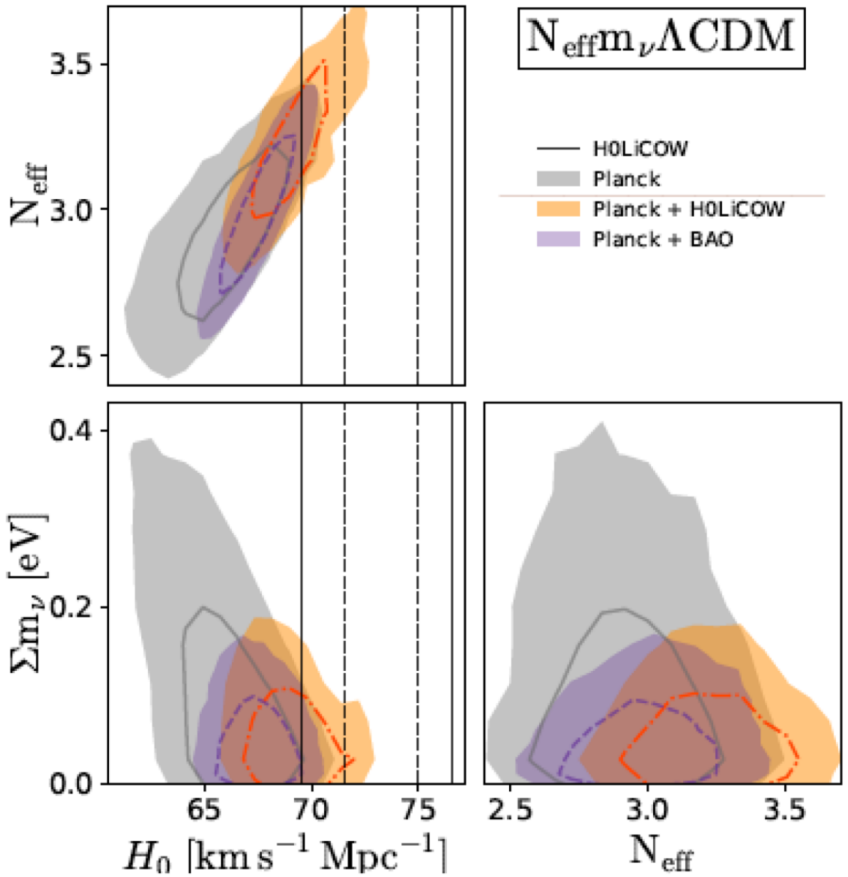
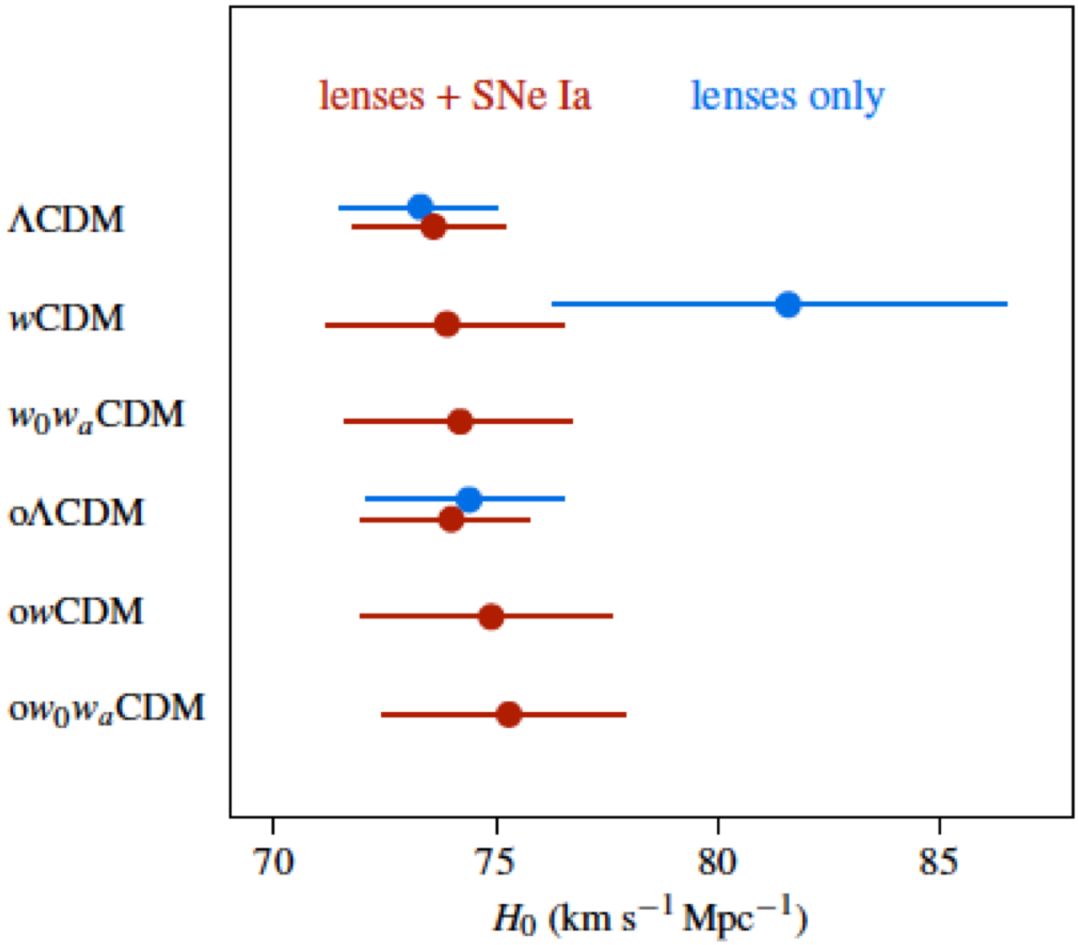




Tension!

Wong et al. 2019

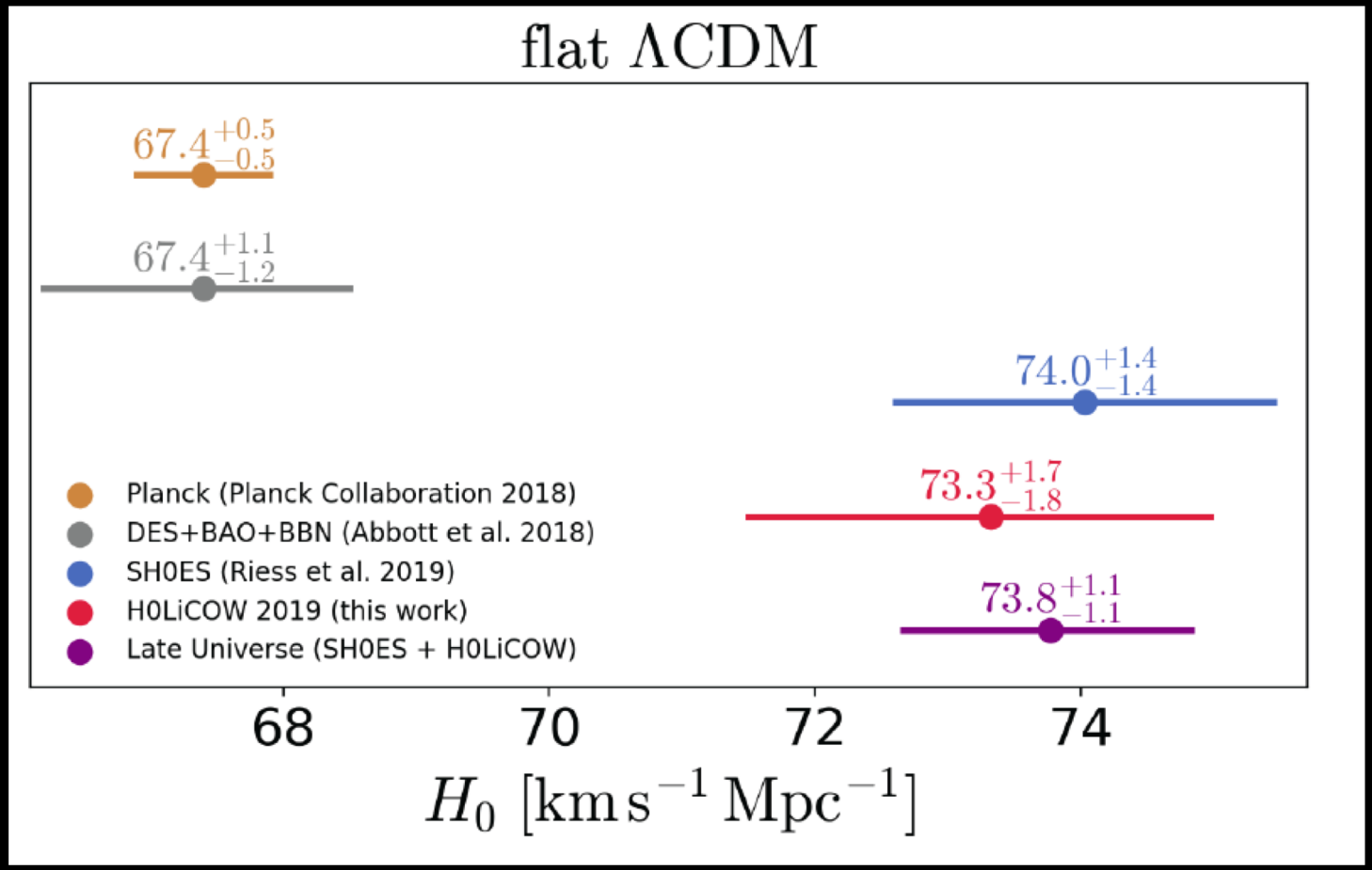
Six-Lens Sample



- Lenses as anchors to Ia.
- H0 almost independent of cosmology AND of local distance ladder

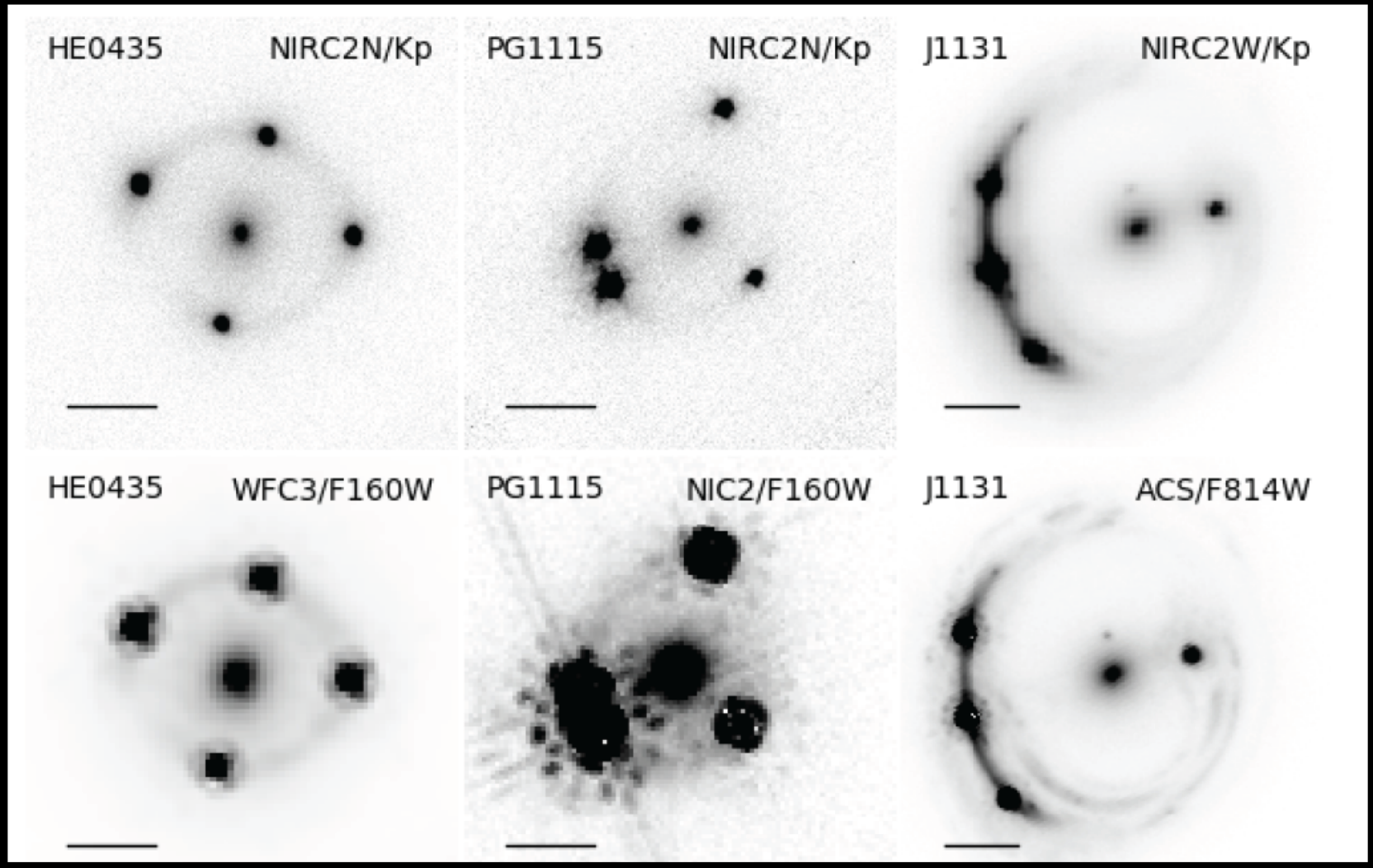
Wong et al. 2019

Results from the six-lens sample: 5.3 sigma tension



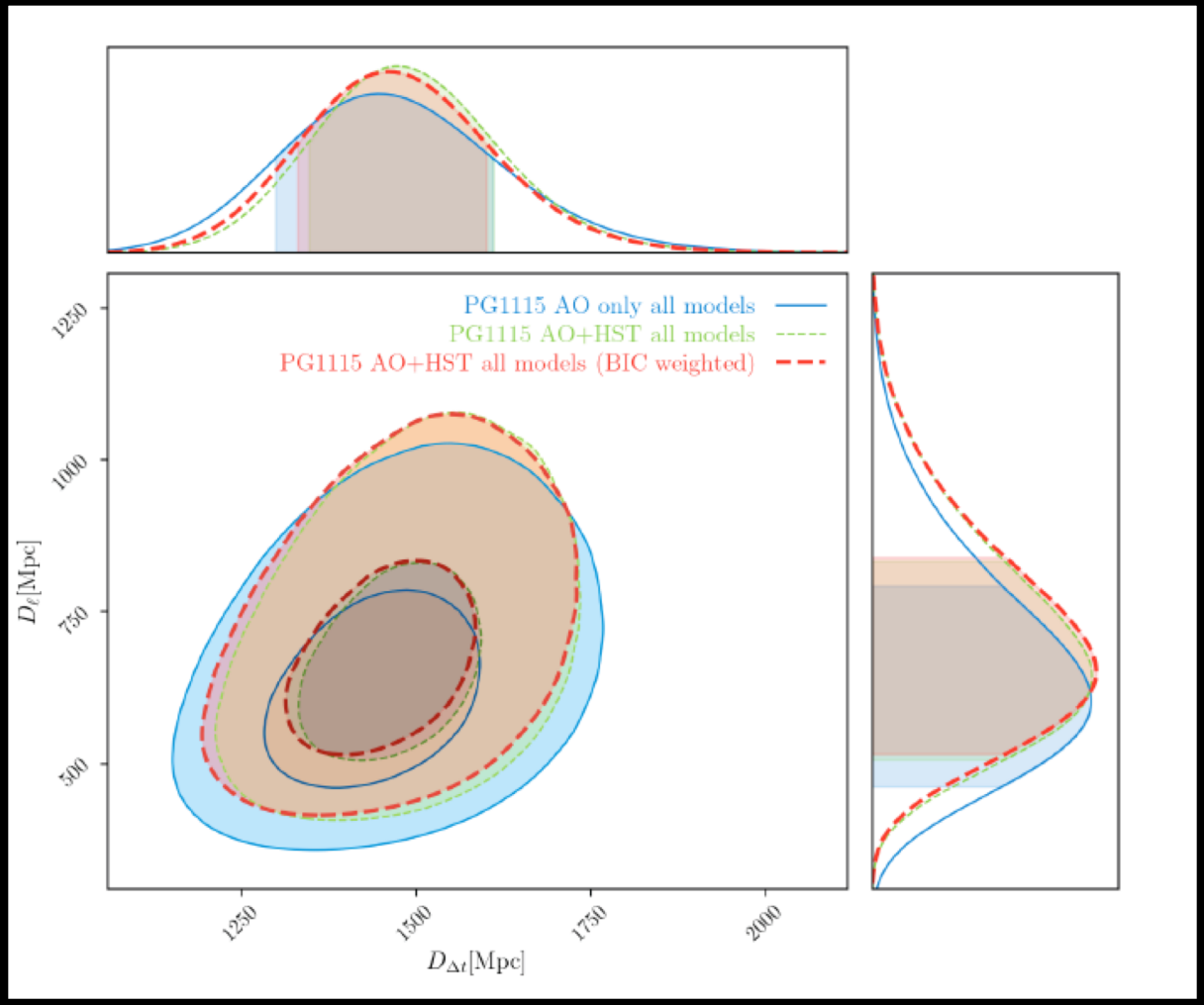
Wong et al. 2019

Checking for systematics: AO vs HST



Chen et al 2019; see poster

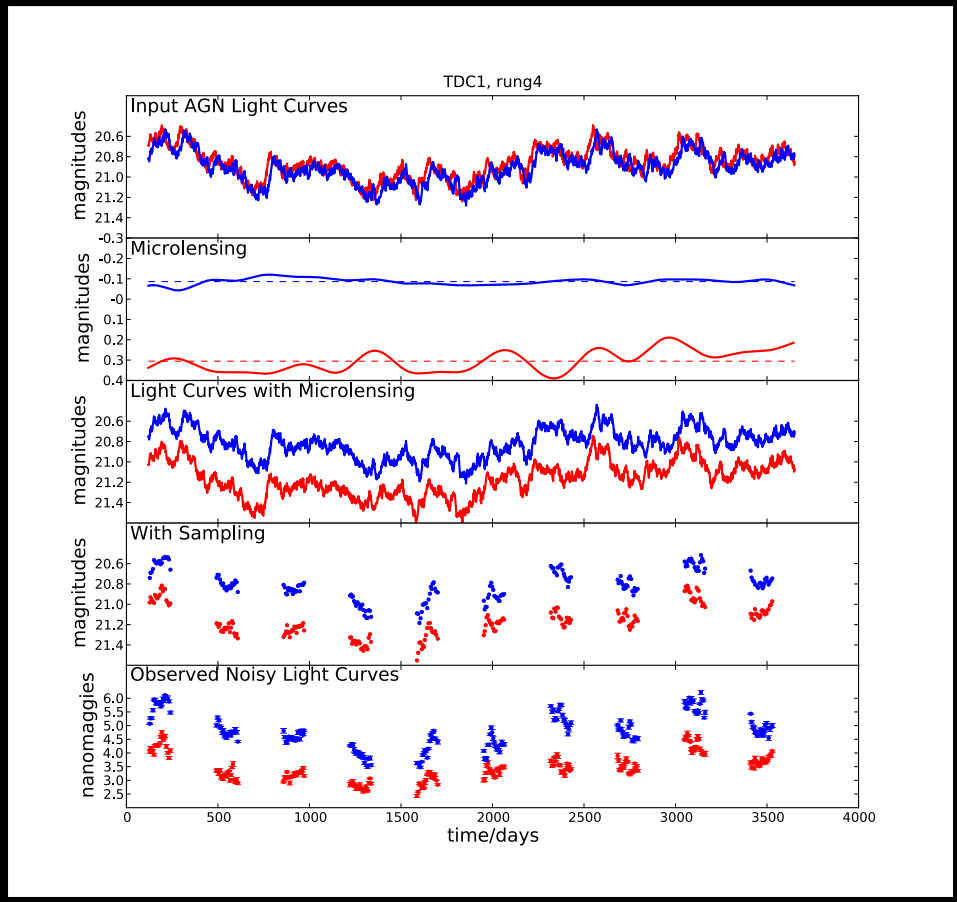
Checking for systematics: AO vs HST



Chen et al. 2019

Checking for systematics: time delay challenge

- Generated mock light curves with realistic properties
- Asked teams to recover time delay
  - 78 methods were tested
  - The best ones recovered time delay with subpercent accuracy (no bias)



Dobler et al. 2015; Liao et al. 2015

Checking for systematics: lens modeling challenge

- Generated HST images with realistic properties
- Teams were given HST images and time delays and asked to infer the Hubble constant
  - Rung 1 given exact PSF
  - Rung 2 given guess PSF (simple lens)
  - Rung 3 given guess PSF (complex lens)
- Rung 3 deadline in August

Ding et al. 2018/9

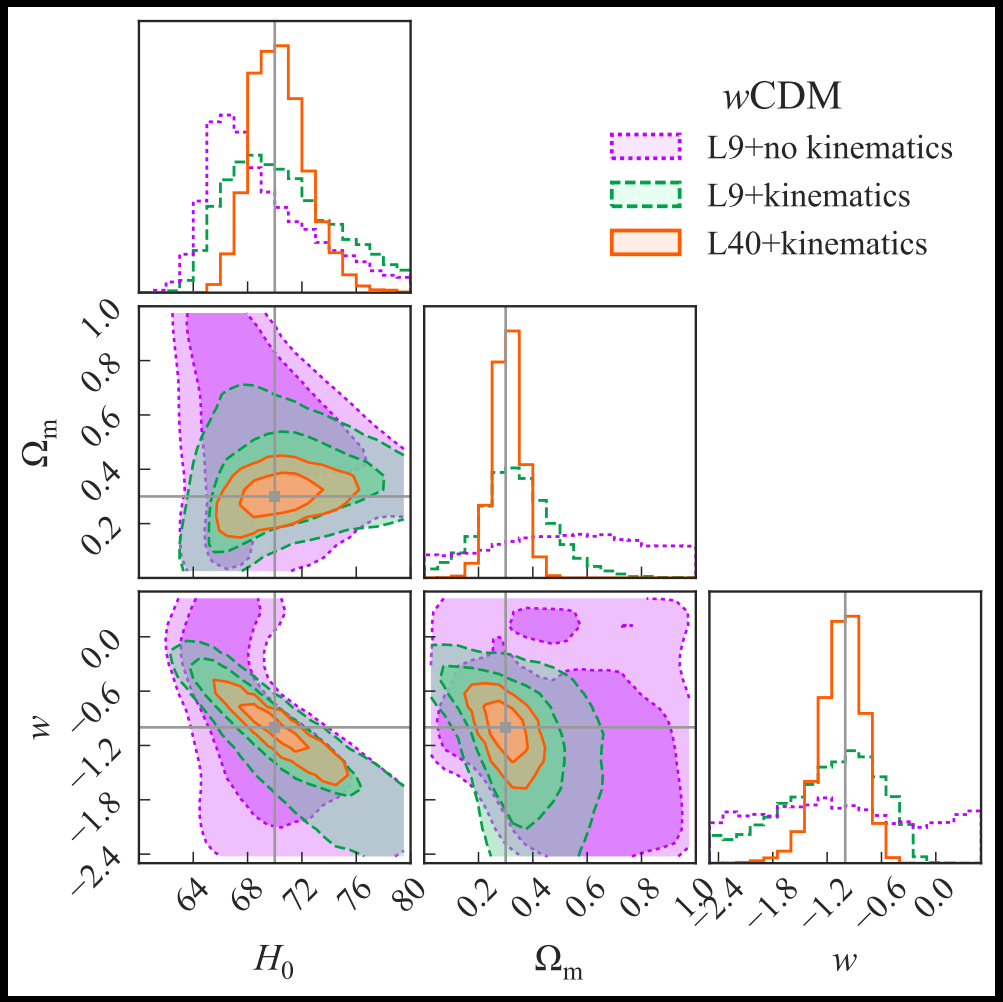
Future outlook: towards 1%

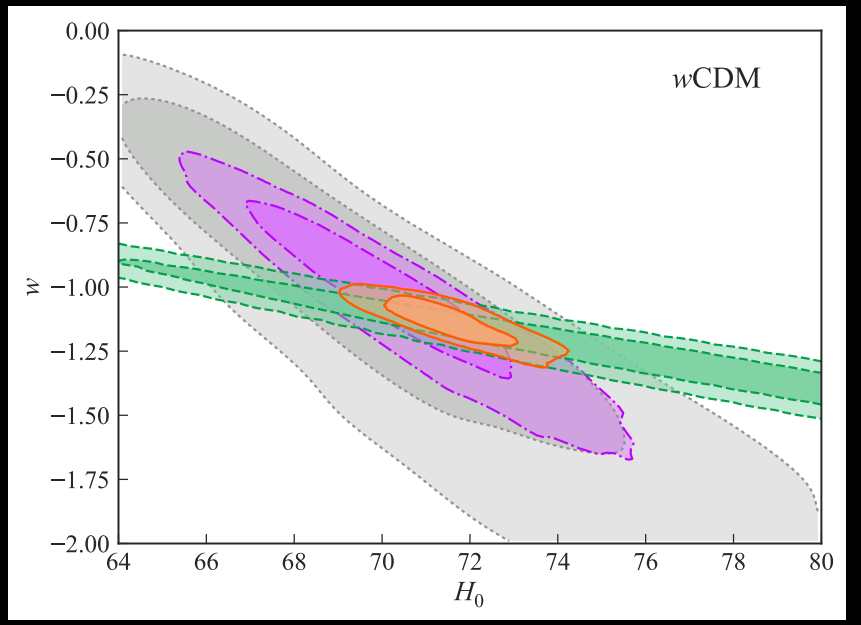
Two ways forward

- Better precision per system
- More systems (30-40 needed)

Shajib's talk

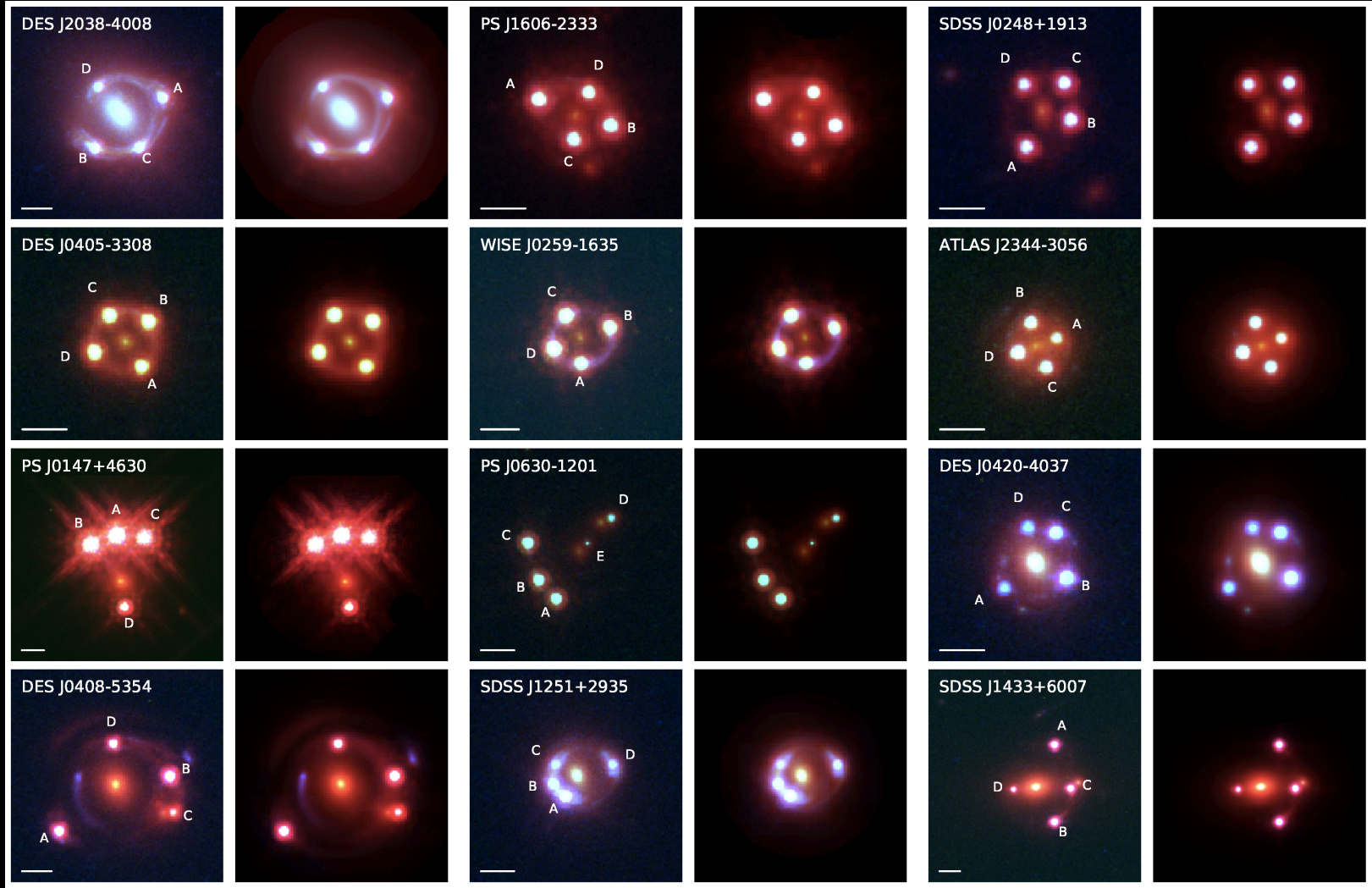
Spatially resolved kinematics breaks the mass-anisotropy degeneracy





Shajib et al. 2018

More lenses!



Shajib et al. 2019

Summary

- Time delay cosmography measures H0 to a precision comparable and completely independent of the local distance ladder method
- Combining with SHOES increase the tension with Planck and other early universe probes to >5 sigma in LCDM
- Work is under way to test systematics, including via data challenges
- We can reach <2% precision on H_0 within a year and subpercent in a few years