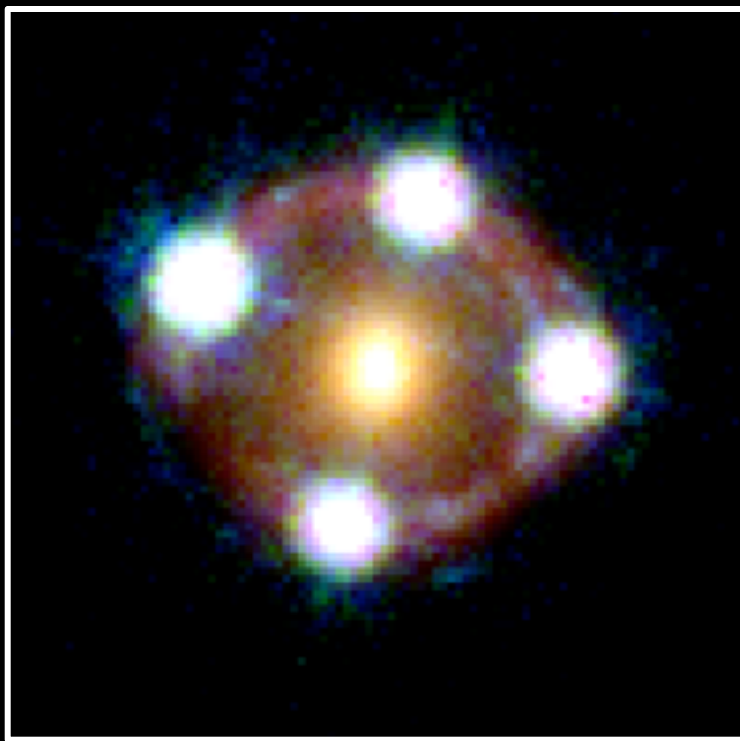
Cosmology from Gravitational Lens Time Delays

Analysis of the Time-Delay Lensed Quasar HE 0435-1223



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East Asia Core Observatories Association

国立天文台 NAOJ National Astronomical Observatory of Japan

H0LiCOW team:

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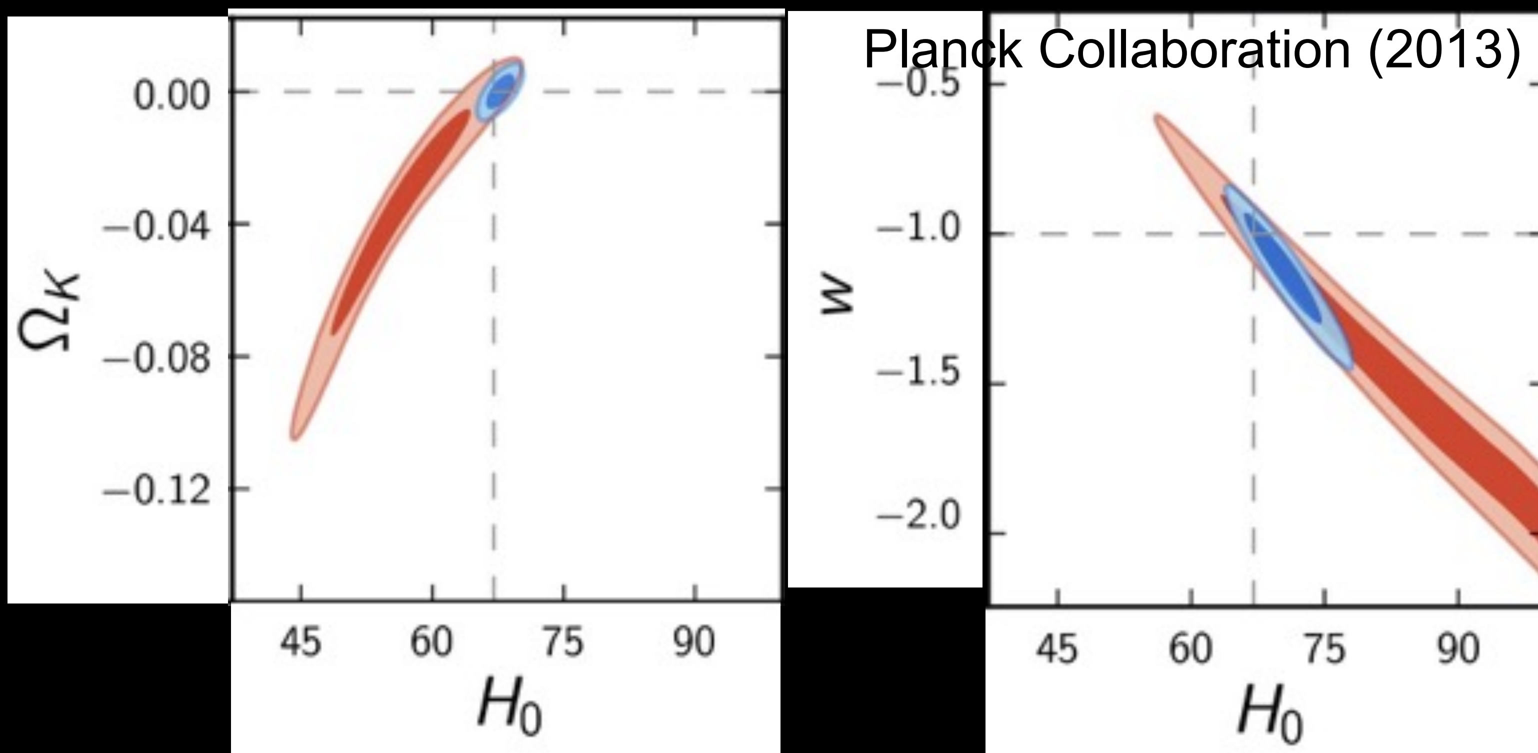
Adriano Agnello (ESO), Matt Auger (Cambridge), Roger Blandford (Stanford), Geoff Chih-Fan Chen (UC Davis), Tom Collett (Portsmouth), Frederic Courbin (EPFL), Xuheng Ding (UCLA), Chris Fassnacht (UC Davis), Yashar Hezaveh (Stanford), Stefan Hilbert (MPA), Leon Koopmans (Kapteyn), Kai Liao (UCLA), Phil Marshall (Stanford), Georges Meylan (EPFL), Danka Paraficz (EPFL), Nick Rumbaugh (UC Davis), Alessandro Sonnenfeld (IPMU), Chiara Spiniello (MPA), Malte Tewes (AIfA), Olga Tihhonova (EPFL), Tommaso Treu (UCLA), Simona Vegetti (MPA)

The Importance of an Independent H_0 Probe



Hubble constant H_0 sets:

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

H_0 provides critical independent constraints on:

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

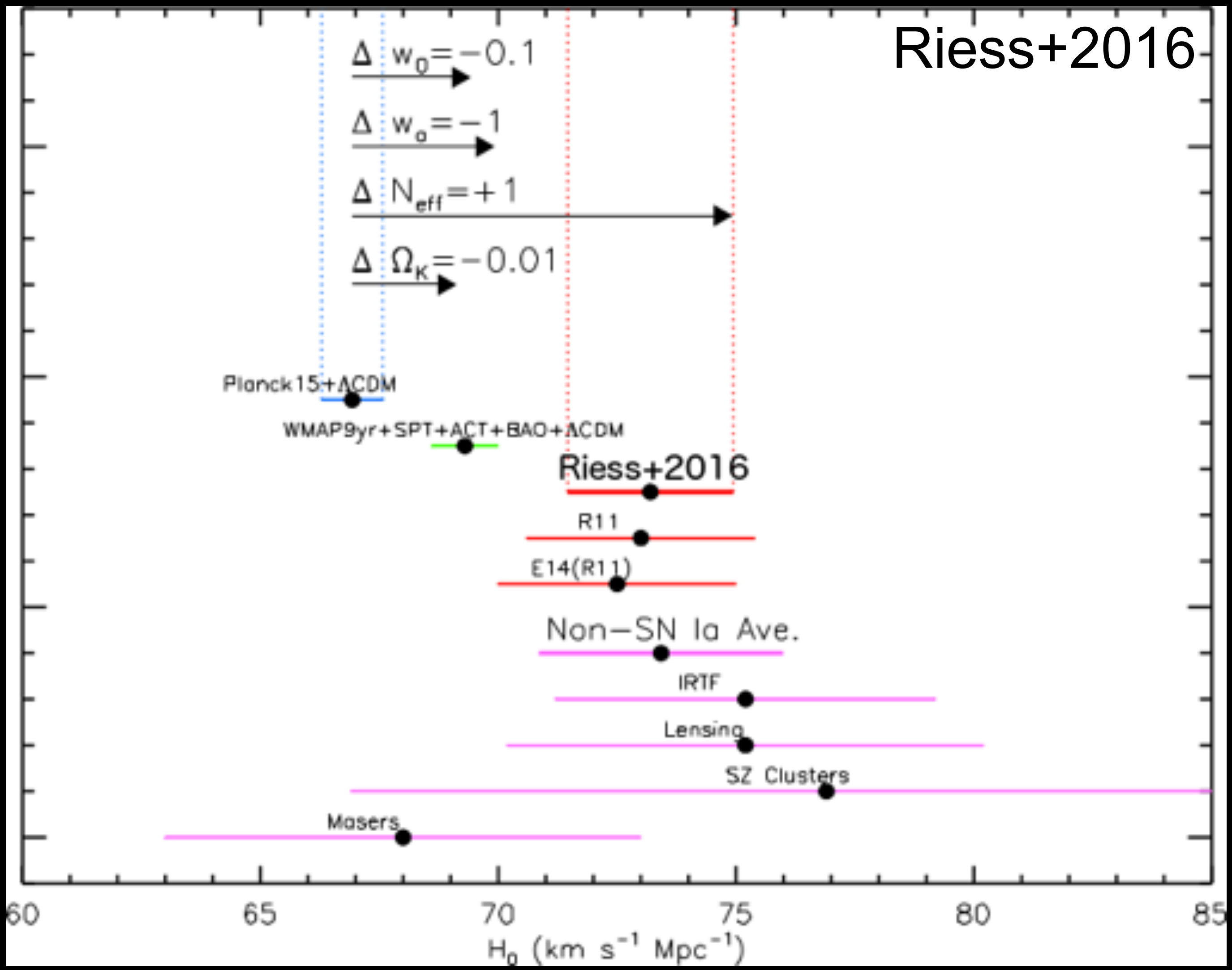
(e.g., Sekiguchi+2010, Freedman +2012, Weinberg+2013, Suyu+2013)

Planck's measurement of H_0 is highly model dependent
Strong degeneracy in H_0 if, e.g., non-flat or $w \neq -1$
Need independent H_0 measurement!

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

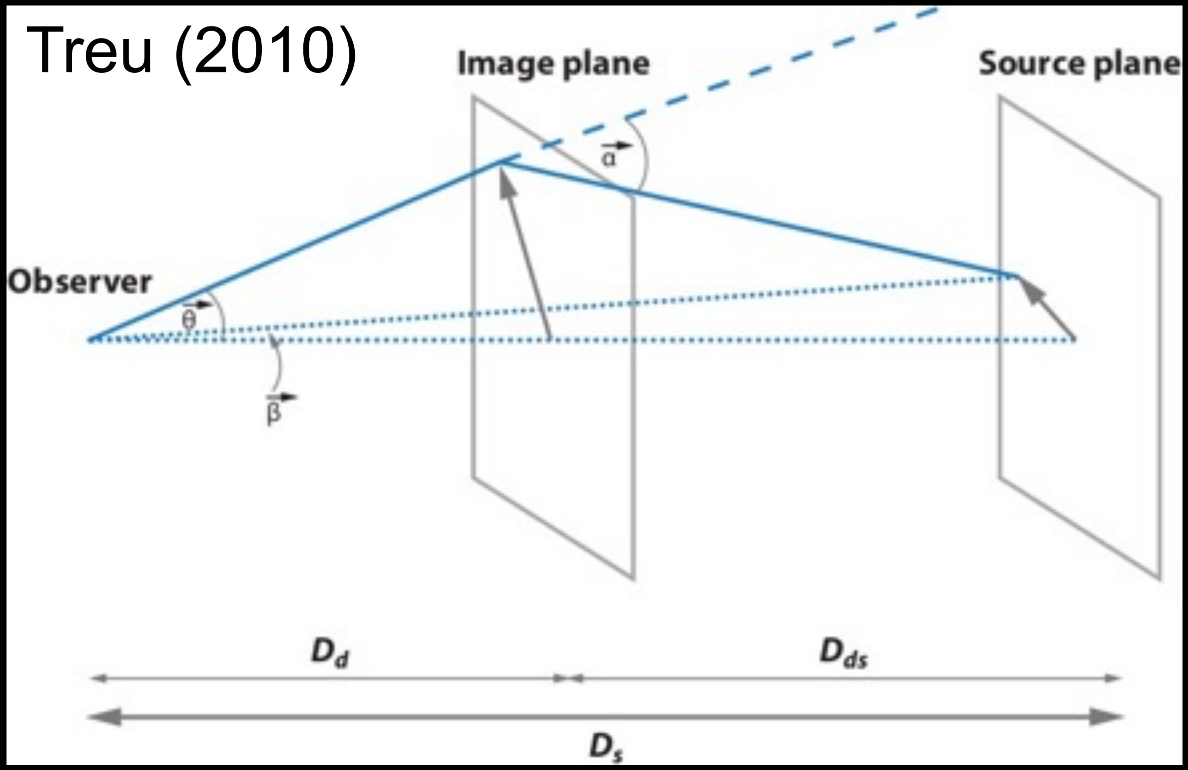
Independent H_0 Measurements

- *Planck* flat ΛCDM results suggest an H_0 value lower than other measurements
- Independent distance ladder results (Riess+2016) favor a higher H_0
- Tension? New physics? Need more precise and accurate measurement of H_0



Gravitational Lensing Time Delays

- Background object (source) magnified by foreground object (lens)
- Multiple images → create lens model
- If source is variable (e.g. quasar), there is a “time delay” between the multiple images
- Can determine “time-delay distance”, inversely proportional to H_0
- One-step method to infer H_0, independent of distance ladder



Time delay

Lens potential (from mass model)

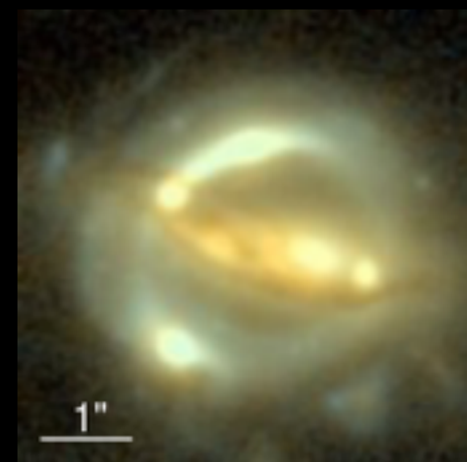
$$\Delta t = \frac{1}{c} D_{\Delta t} \phi_{lens}$$

Time-delay distance

$$D_{\Delta t} \propto H_0^{-1}$$

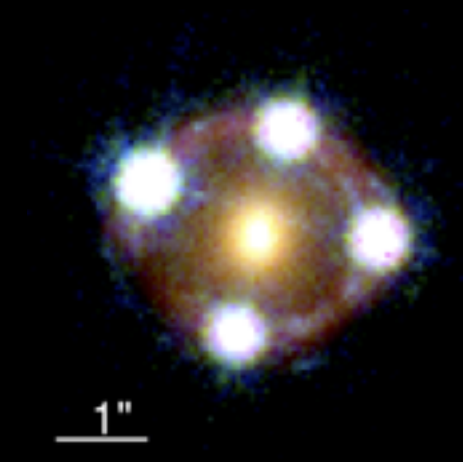
H0LiCOW: H_0 Lenses in COSMOGRAIL's Wellspring

- Detailed analysis of five time-delay lenses (Suyu+2016)
  - long term monitoring from COSMOGRAIL
  - high-resolution *HST* imaging for detailed lens modeling
  - imaging/spectroscopy to characterize mass along line of sight
- Will constrain H_0 to < 3.5% precision
- First two lenses previously analyzed (Suyu+2010, 2013)

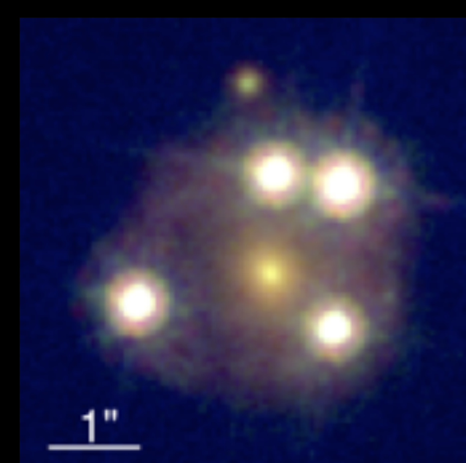


B1608+656

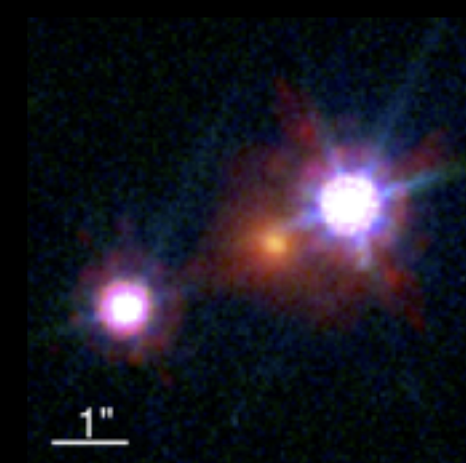
RXJ1131-1231



HE 0435-1223



WFI2033-4723



HE 1104-1805

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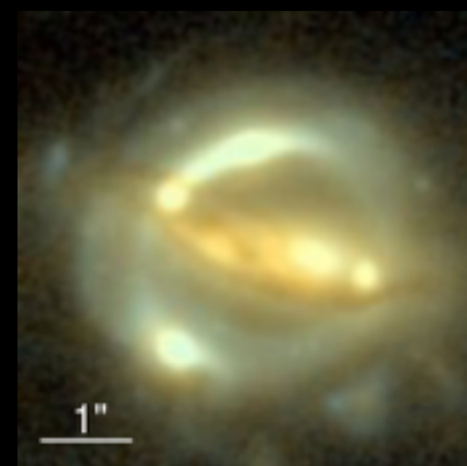

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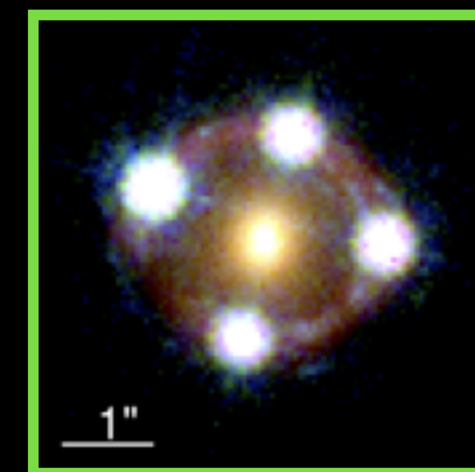

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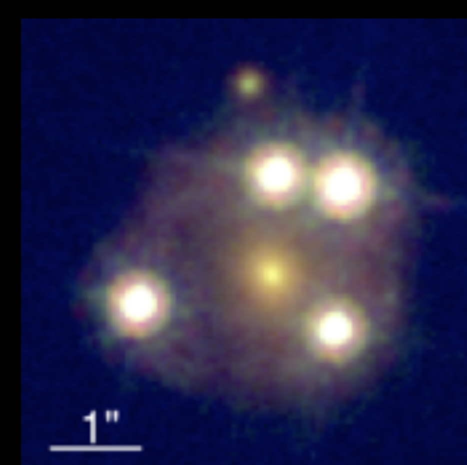

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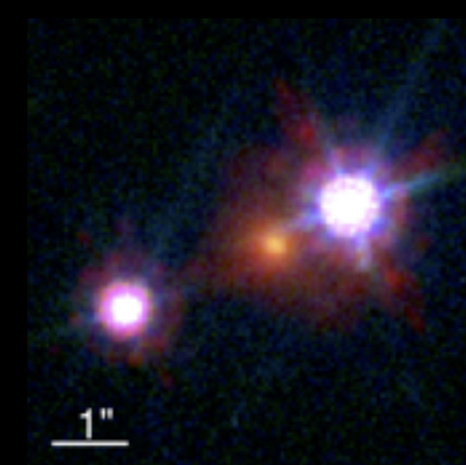
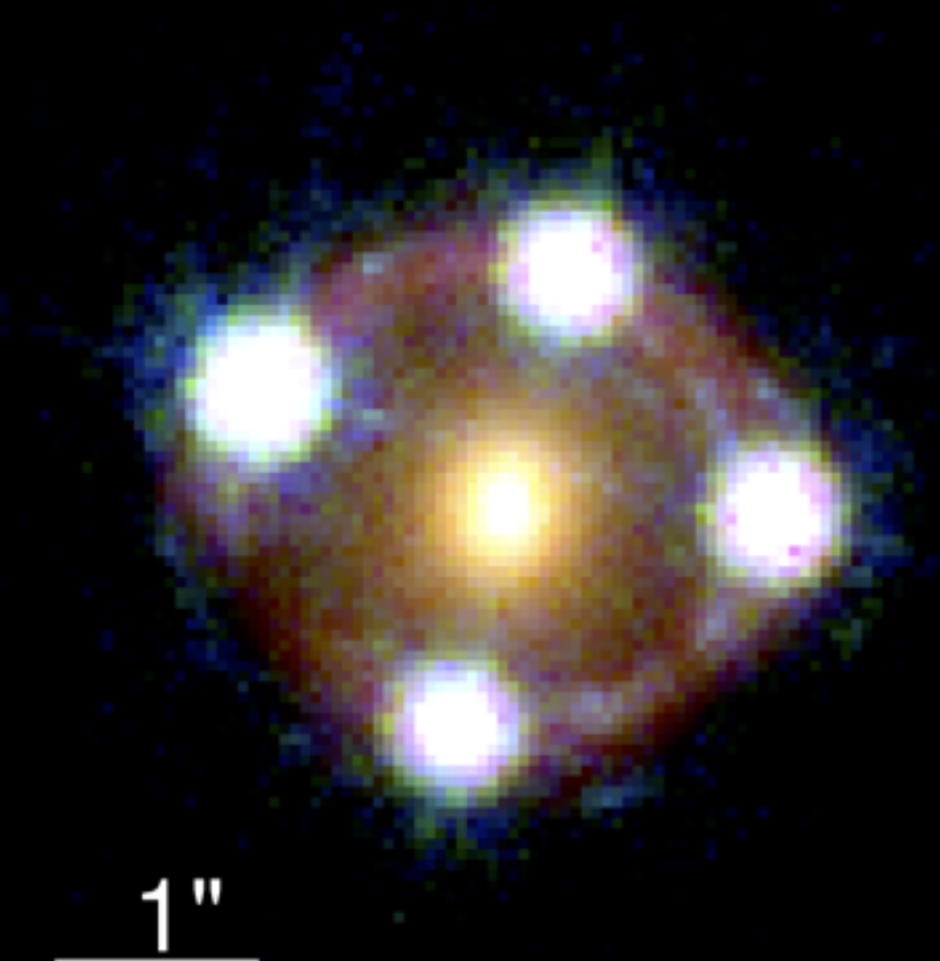


HE 1104-1805

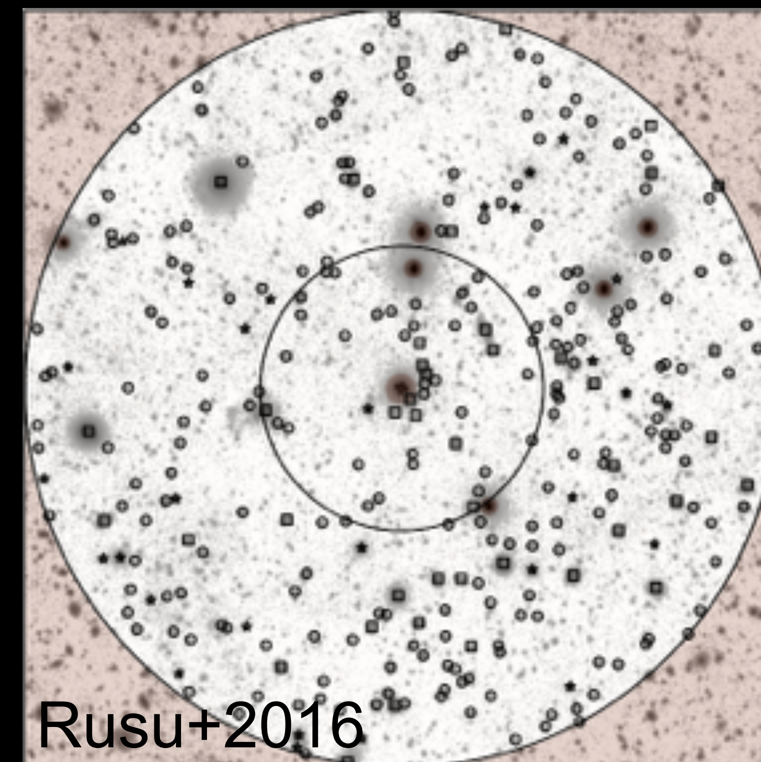
New Results from HE0435

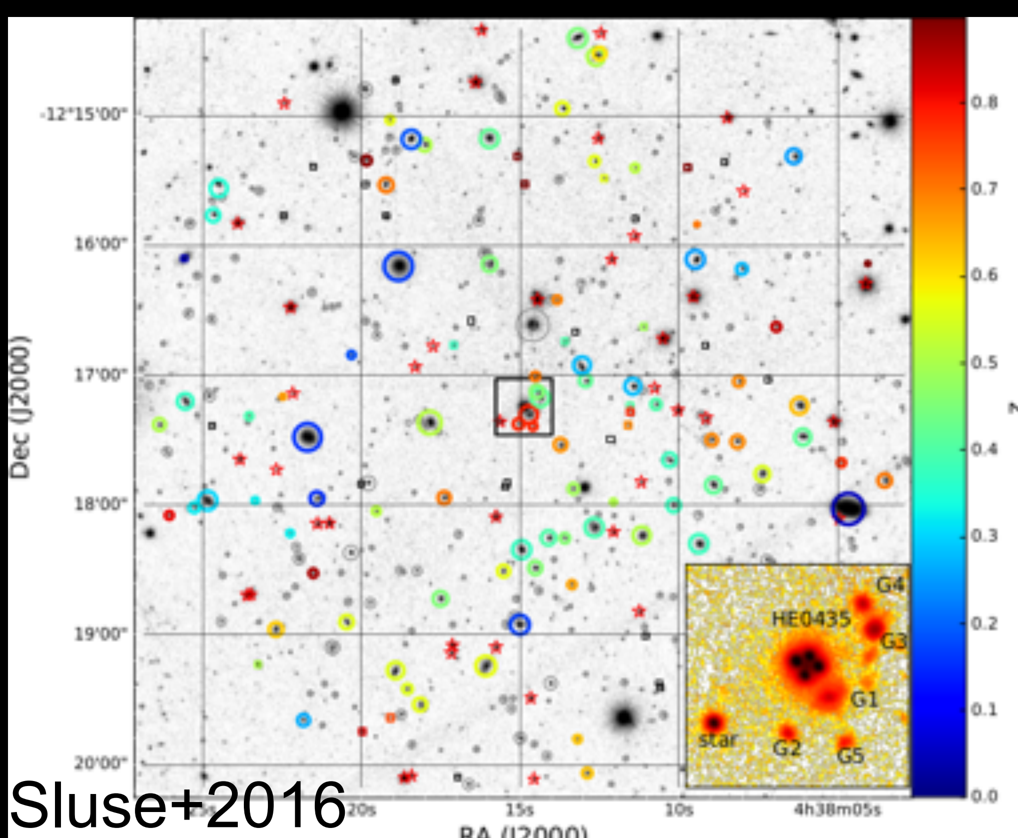
- Extensive dataset
  - *HST* imaging in 3 bands (F475W, F814W, F160W)
  - 13-year monitoring by COSMOGRAIL for accurate time delays
  - Lens velocity dispersion from Keck/LRIS
  - Spectroscopic data on LOS galaxies to get perturber redshifts
  - Multiband photometry to get photo-zs and stellar masses of LOS galaxies
- Developed new PSF reconstruction and multi-plane lensing techniques (Suyu, Wong et al. in prep.)
- Full analysis and results:
  - Rusu+2016 (LOS photo-zs/stellar masses)
  - Sluse+2016 (LOS galaxy spectroscopy)
  - Wong+2016 (Lens model)
  - Bonvin+2016 (Time-delay measurements)

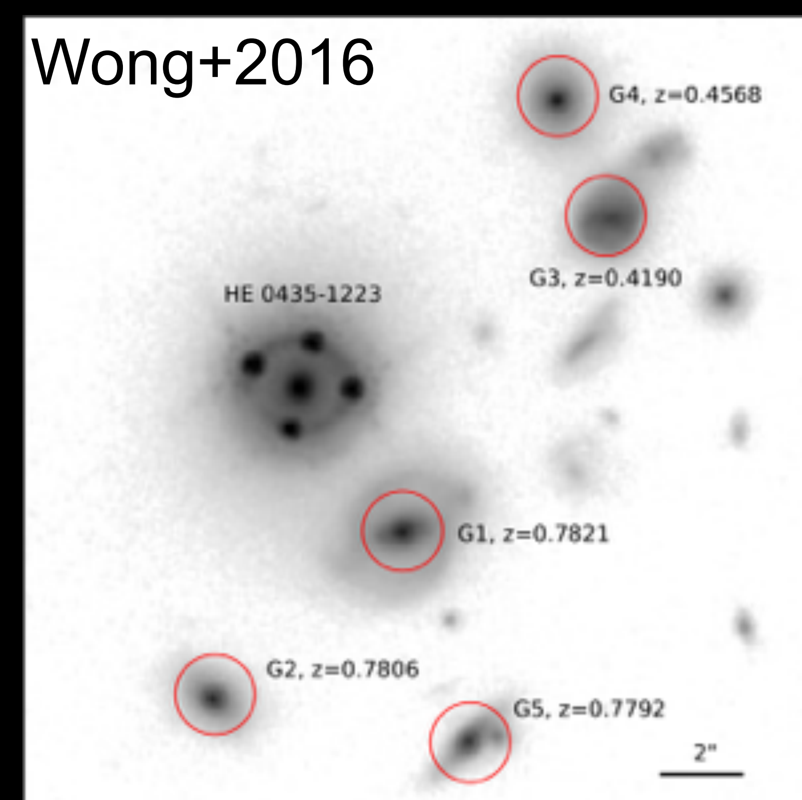


New Results from HE0435

- Account for perturbers along line of sight using weighted galaxy number counts from deep multi multi-band photometry (Rusu+2016)
- Spectroscopy to find groups, determine redshifts of most important perturbers (Sluse+2016)







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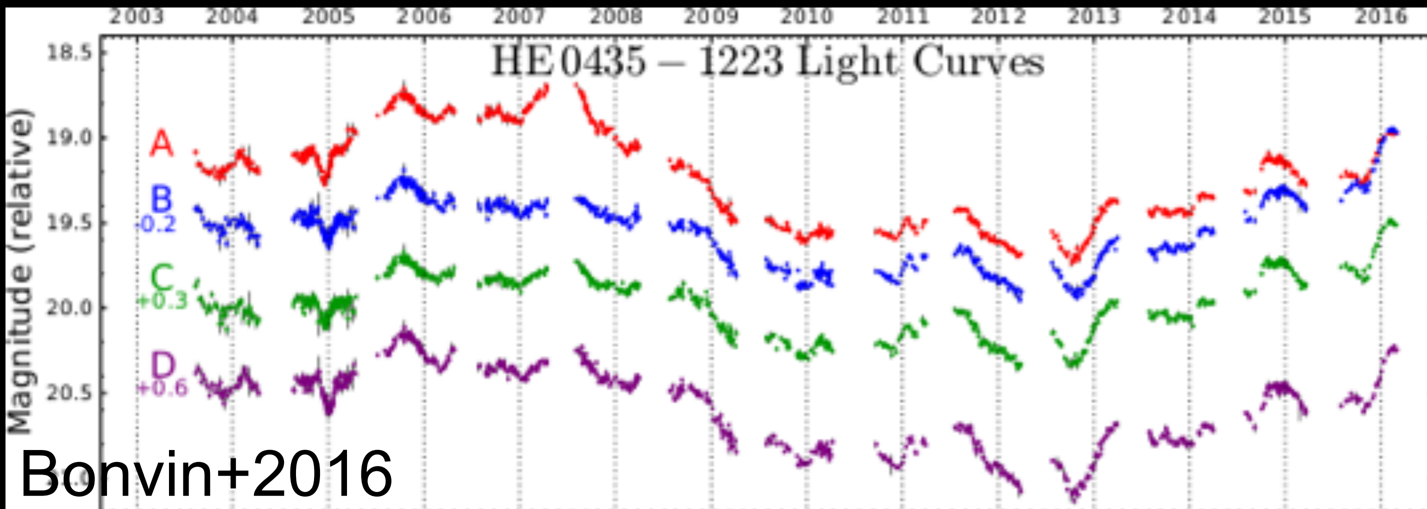
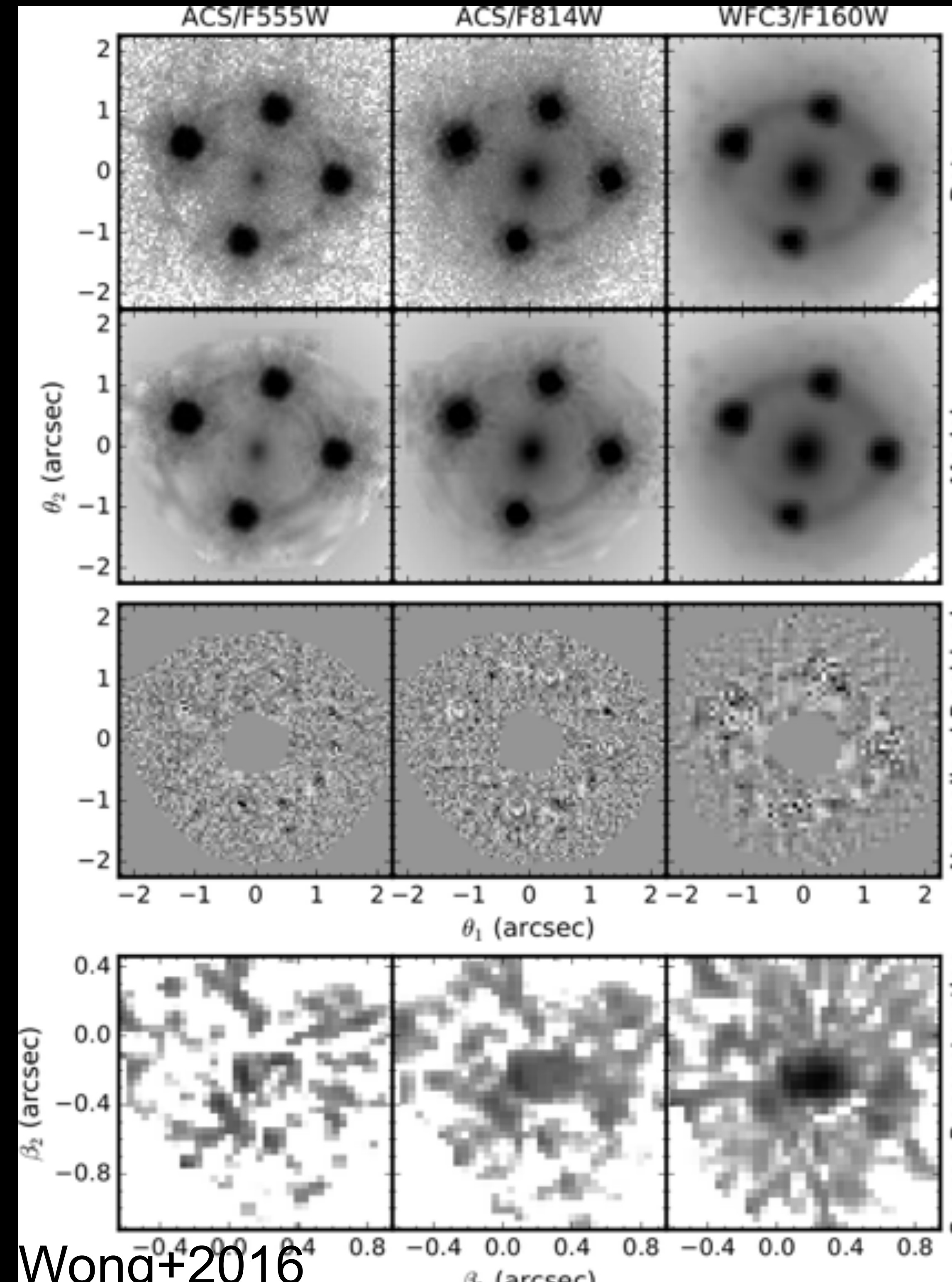


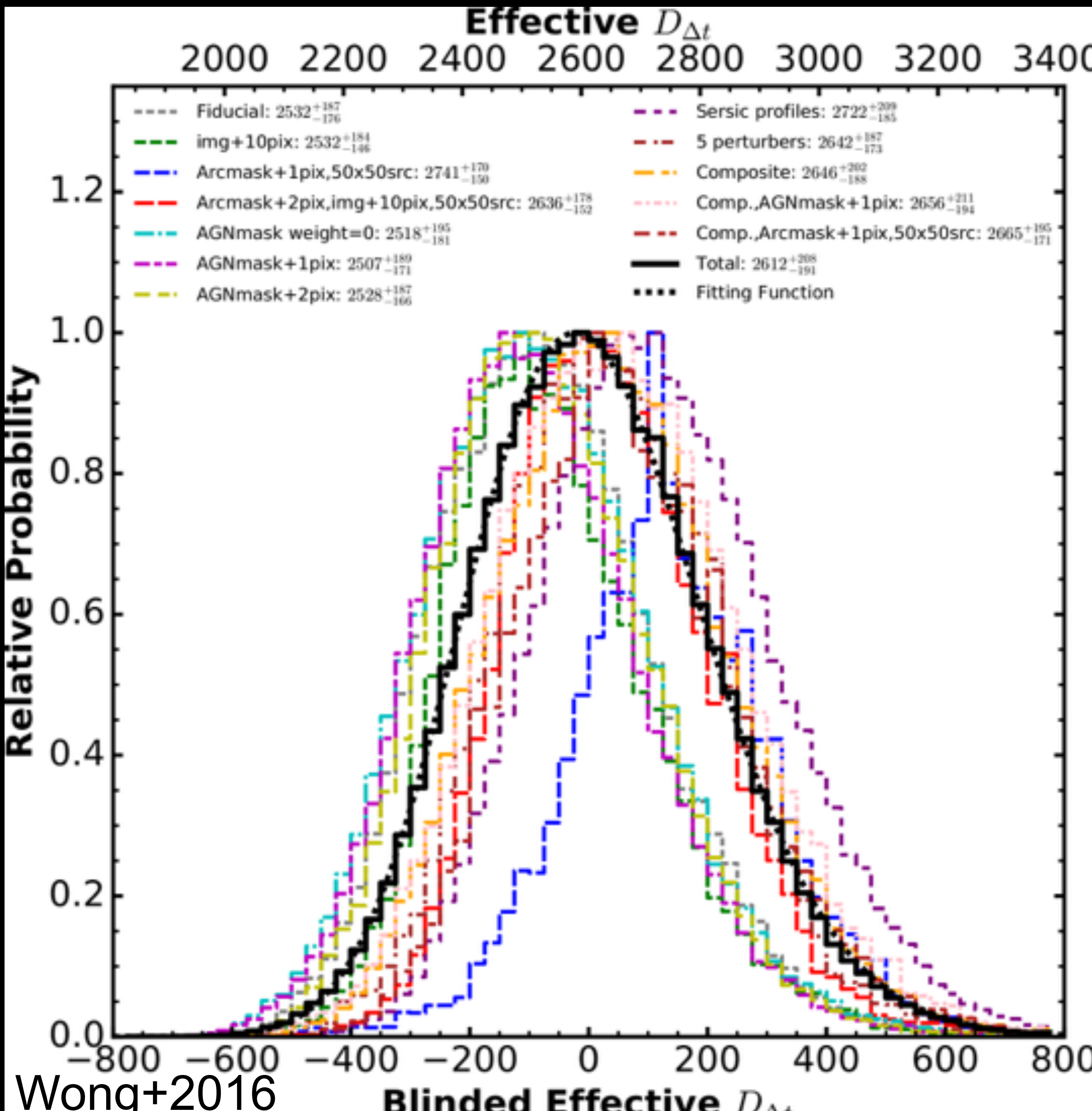
Bonvin+2016

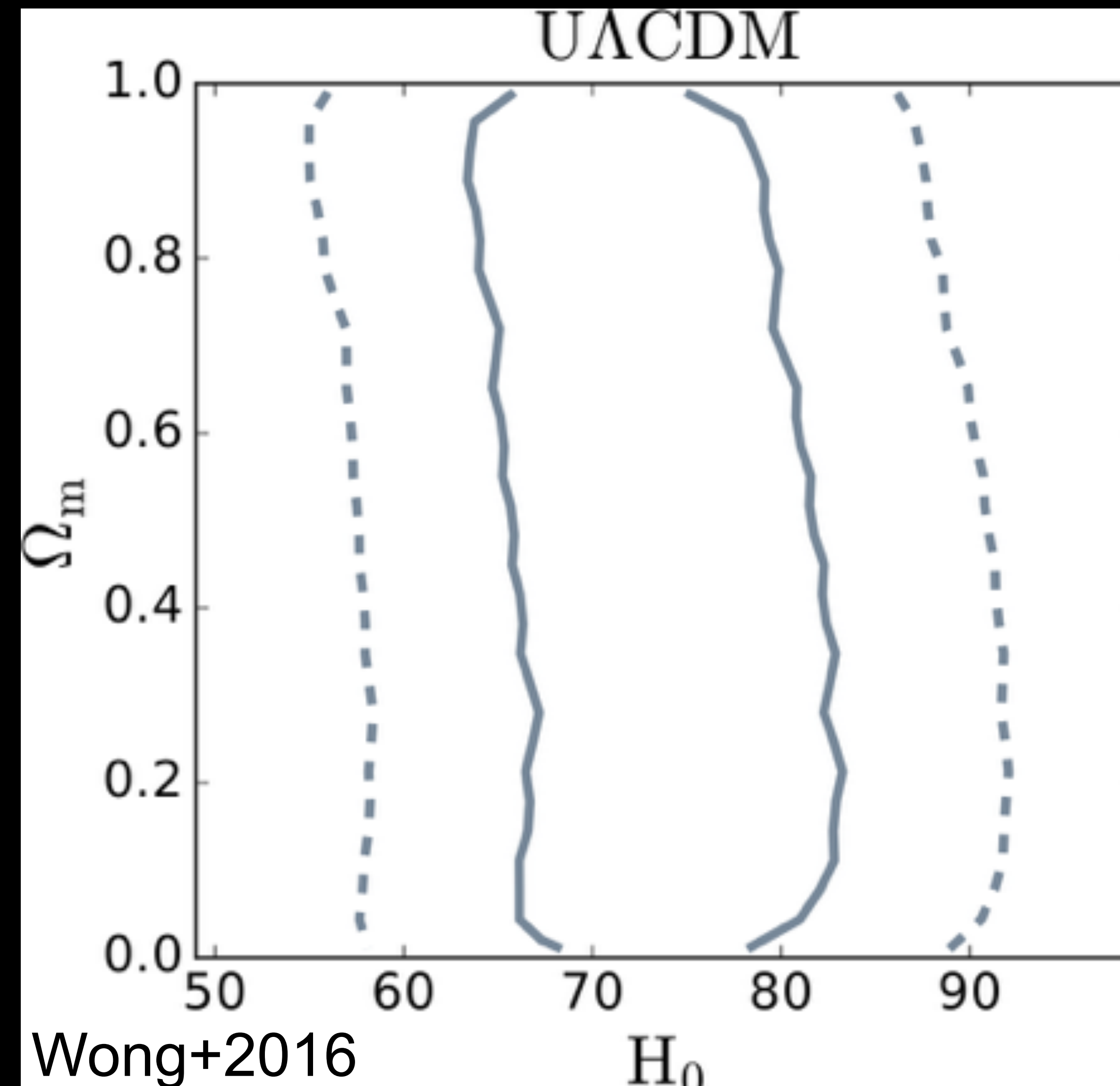
- Time delays from 13 years of monitoring (Bonvin+2016)
- Accurate lens model using *HST* imaging (Wong+2016)
- Blind analysis to avoid confirmation bias - keep cosmological parameters hidden until models are finalized



Wong+2016

New Results from HE0435



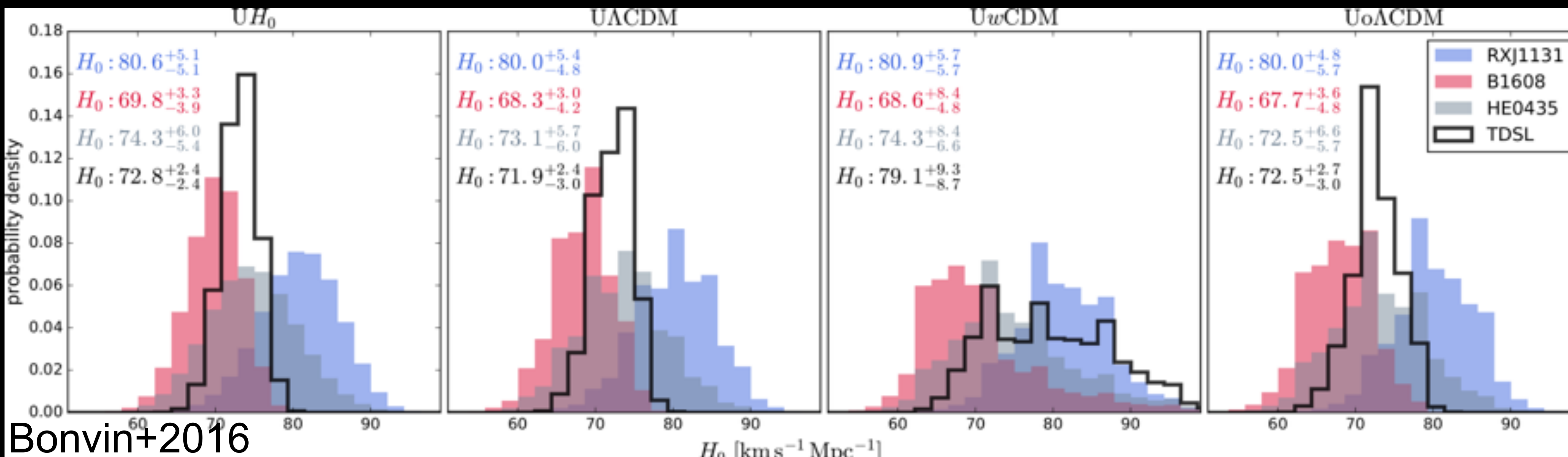


~8% constraint on $D_{\Delta t}$

$H_0 = 73.1^{+5.7}_{-6.0}$ km/s/Mpc

for flat ΛCDM cosmology

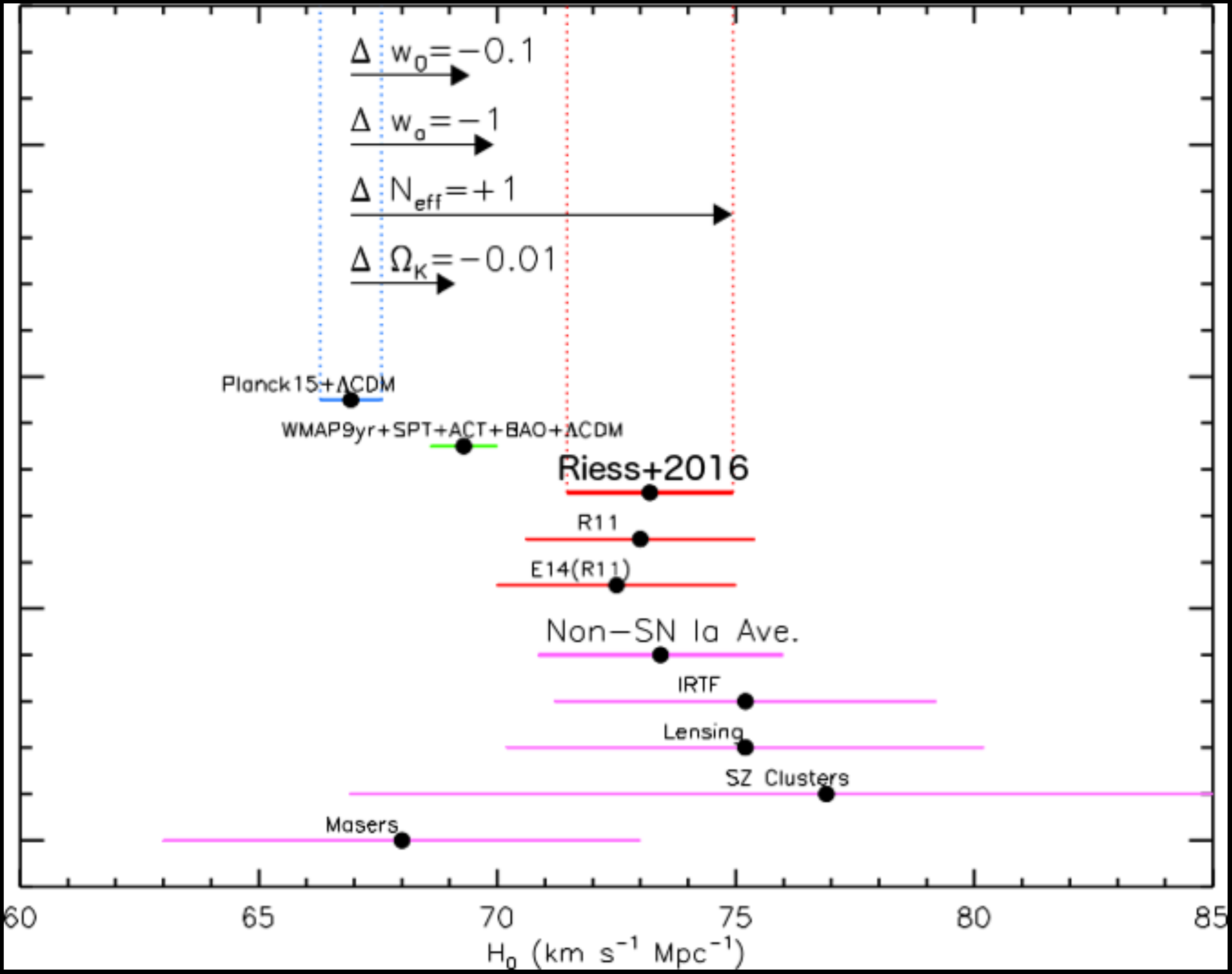
Combined Results from 3 H0LiCOW Lenses



~3.8% precision on H_0 from 3 H0LiCOW lenses

$H_0 = 71.9^{+2.4}_{-3.0}$ km/s/Mpc for flat ΛCDM cosmology

Combined Results from 3 H0LiCOW Lenses



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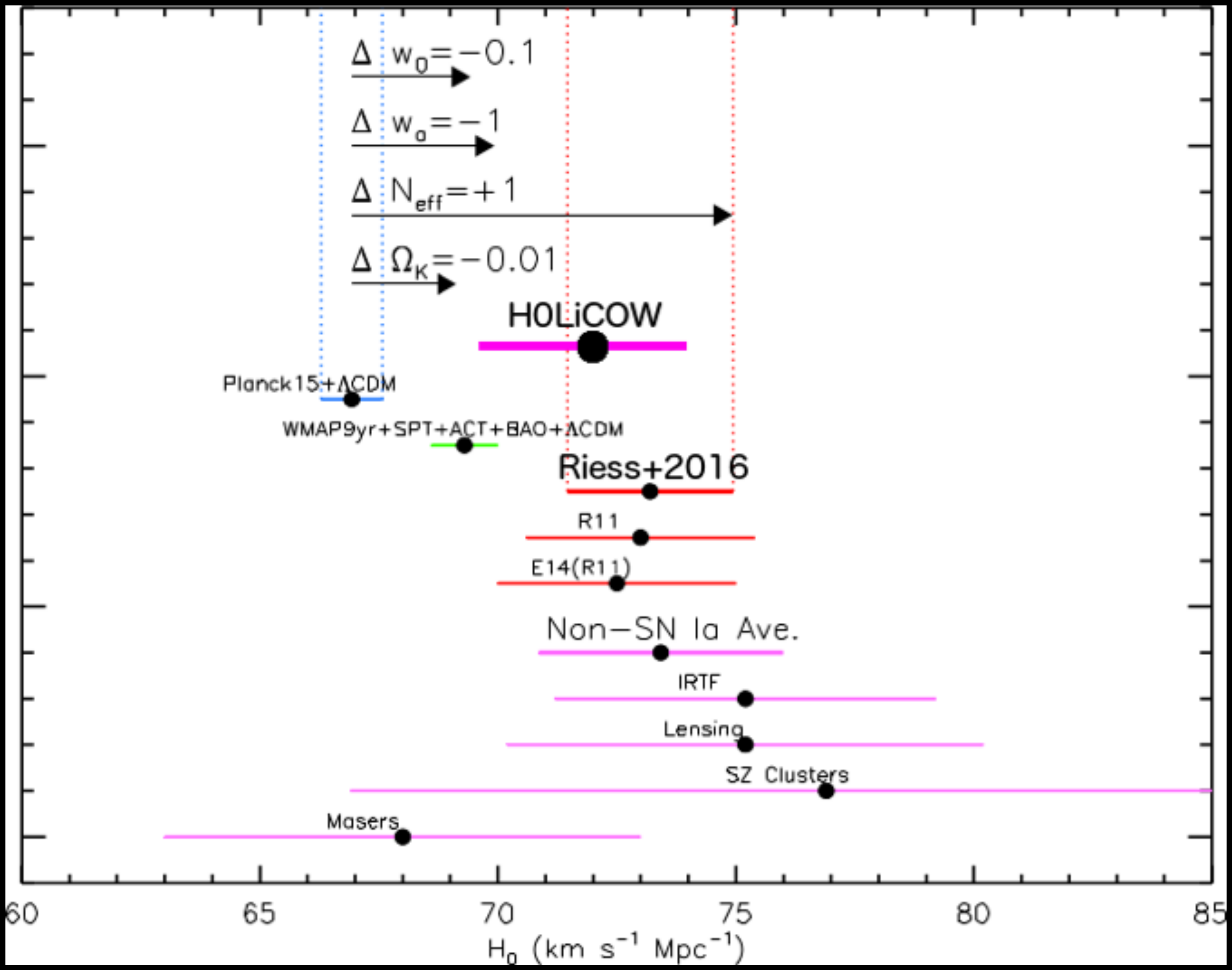

Kenneth Wong (NAOJ)

Summary

- Time-delay lenses are an independent probe of H_0
- Blind analysis of HE0435
  - time delays from COSMOGRAIL
  - deep *HST* imaging
  - wide-field imaging spectroscopy
  - velocity dispersion from Keck/LRIS
- With 3 time-delay lenses from H0LiCOW: $H_0 = 71.9^{+2.4}_{-3.0}$ km/s/Mpc in flat ΛCDM
- Full H0LiCOW sample: H_0 to < 3.5% precision from 5 lenses
- Current and future surveys will find hundreds to thousands of new time-delay lenses, providing competitive probe of cosmology