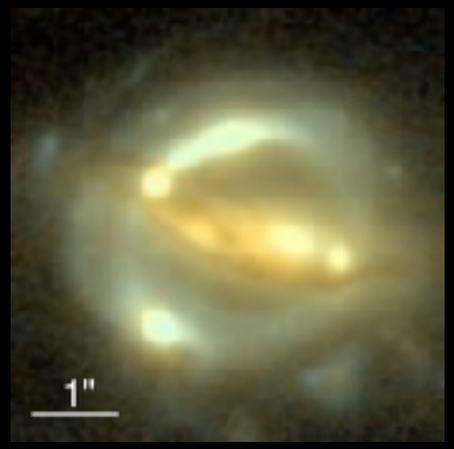
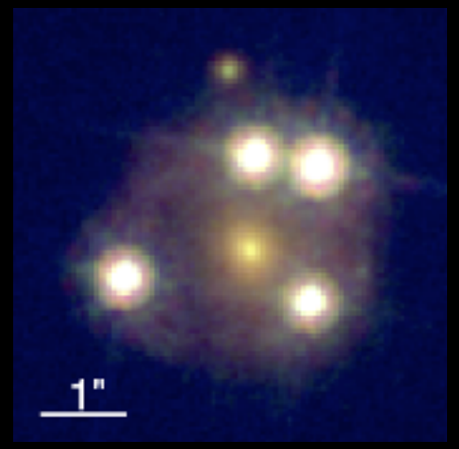
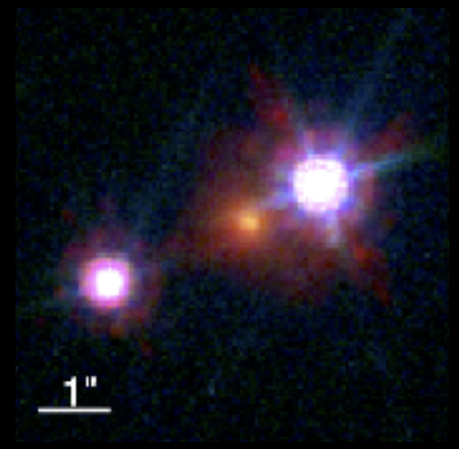
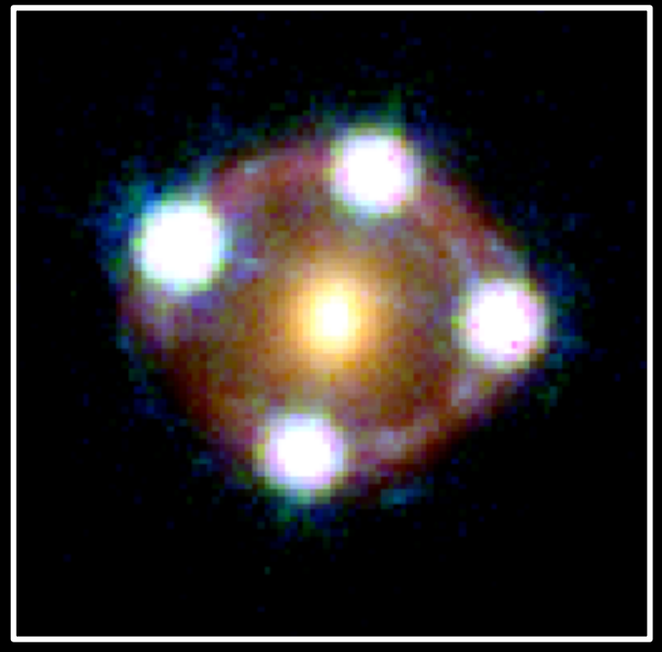
Cosmology from Gravitational Lens Time Delays

Updates on the H0LiCOW Project









Kenneth Wong

EACOA Fellow

National Astronomical Observatory of Japan

14th Asia-Pacific Regional IAU Meeting

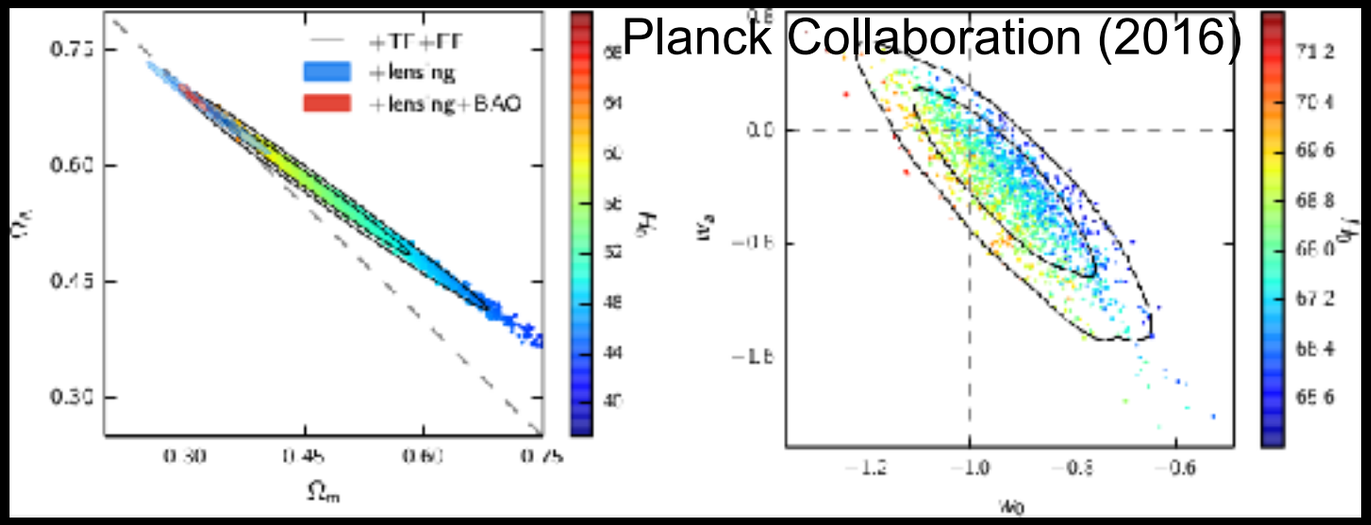
July 4, 2017

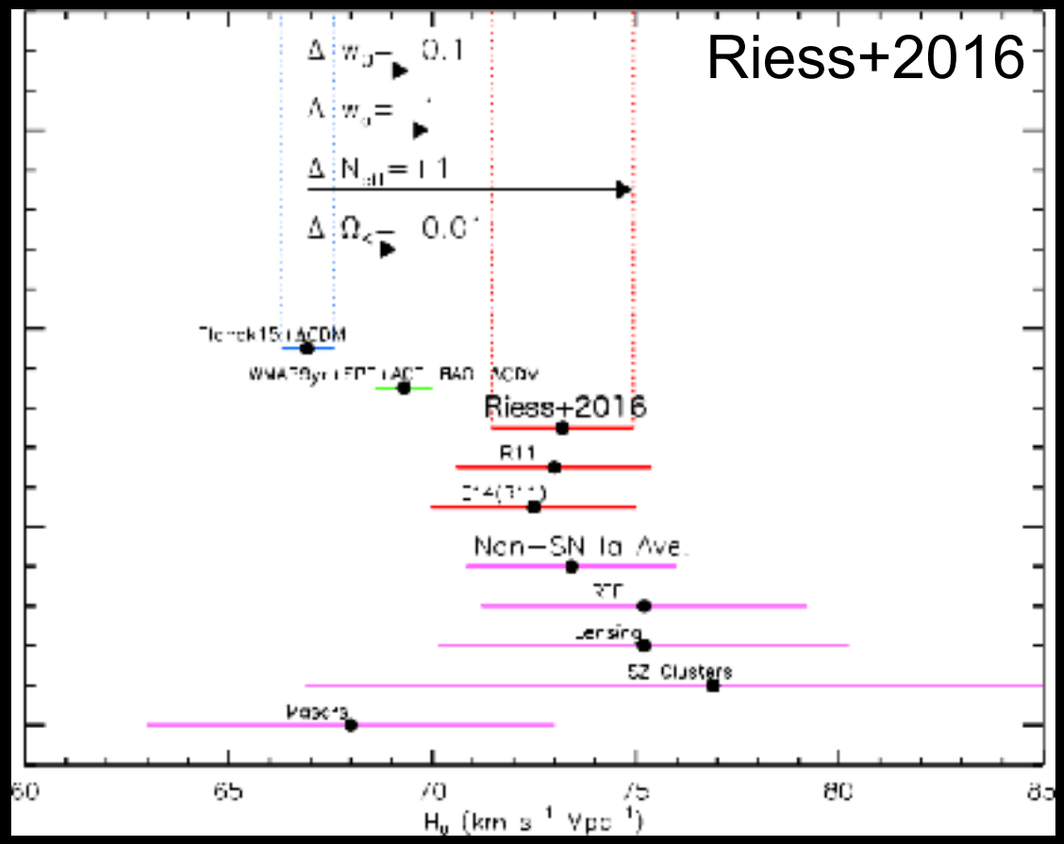
East Asia Core Observatories Association

国立天文台 NAOJ National Astronomical Observatory of Japan

Independent H_0 Measurements

- The Hubble Constant (H_0) sets the expansion rate of the universe
- *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





Strong Gravitational Lensing

- Background object (source) magnified by foreground object (lens)
- Multiple images → create lens model
- Can determine mass distribution of lens if mass along line of sight is accounted for
- Can be used to constrain cosmology

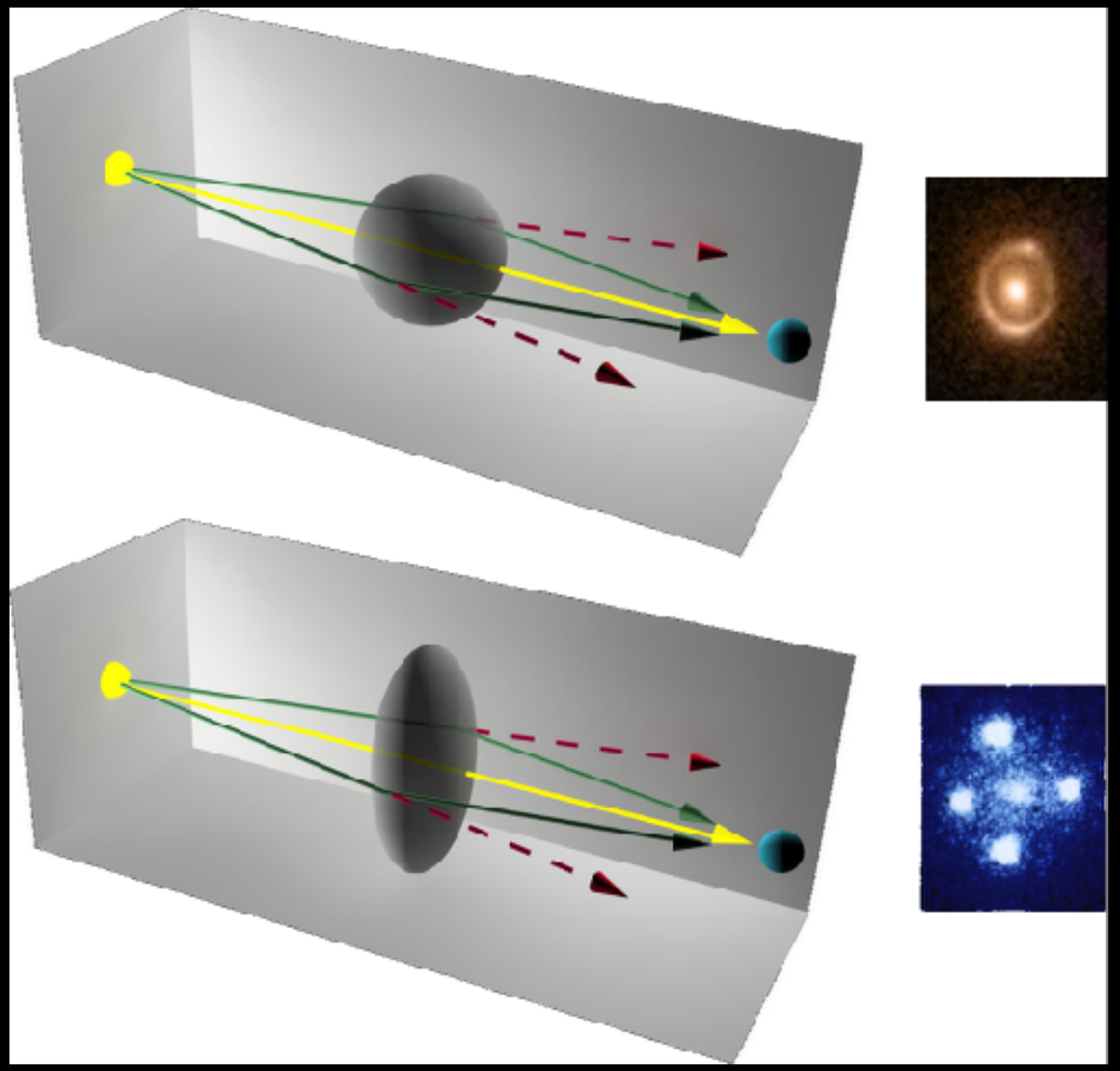
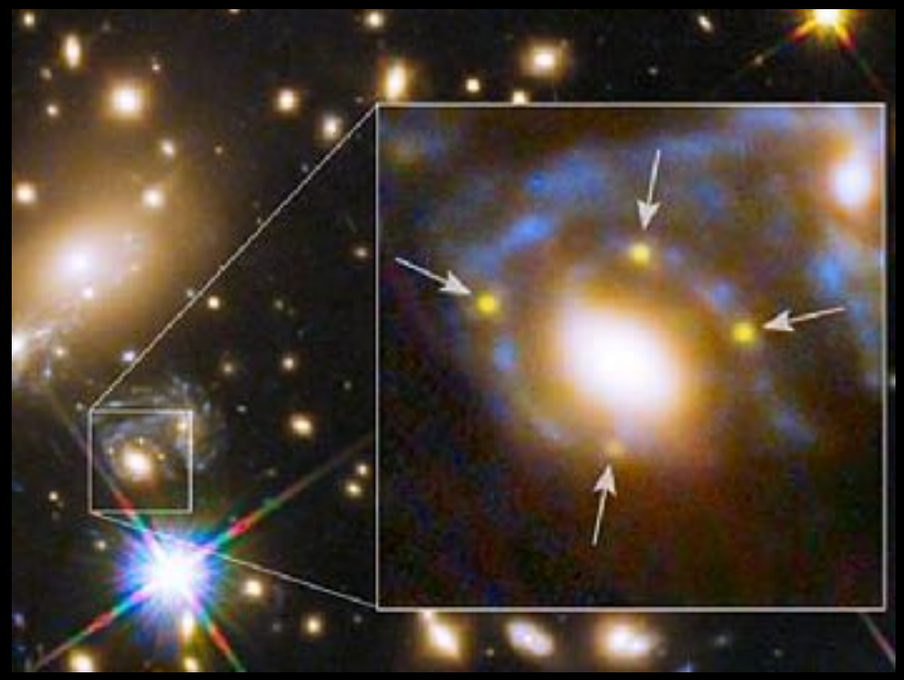


Image credit: ASIAA EPO

Gravitational Lensing Time Delays

- If source is variable, 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
- e.g., lensed supernovae (e.g. Kelly+2015, Goobar+2016), but very rare!



SNe “Refsdal”

Time delay

Lens potential (from mass model)

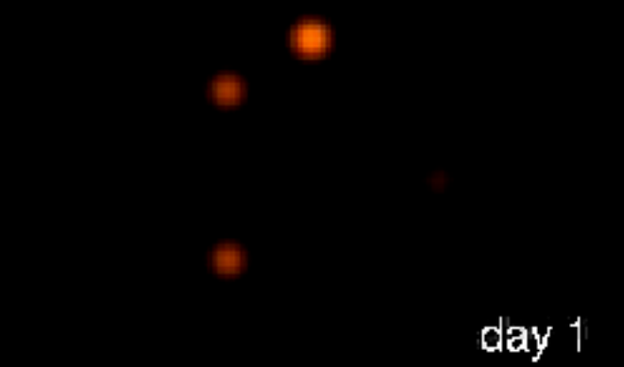
$$\Delta t = \frac{1}{c} D_{\Delta t} \phi_{lens}$$

Time-delay distance

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

Gravitational Lensing Time Delays

- Lensed quasars
  - variable on short timescales (~days)
  - can be monitored to measure time delay
  - bright and easy to detect



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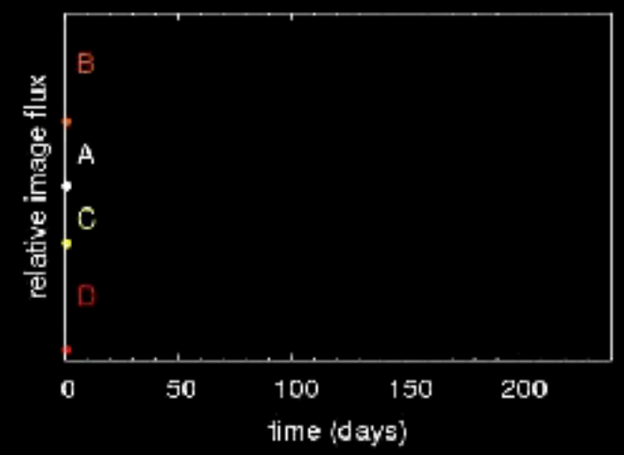

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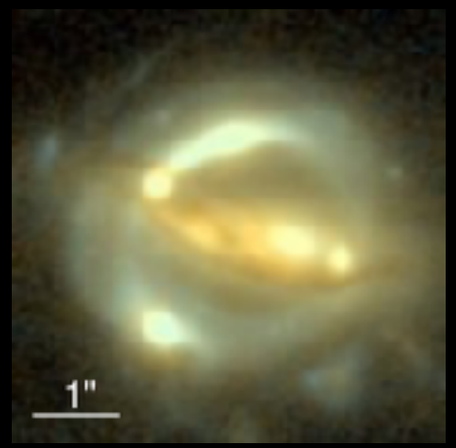
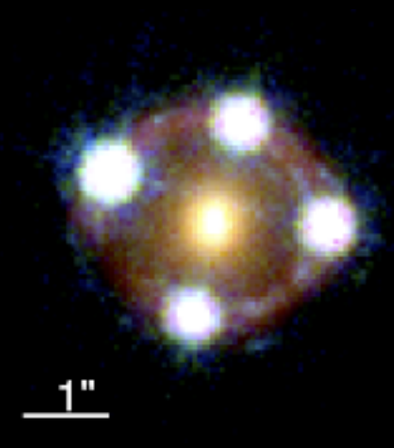
H0LiCOW: H_0 Lenses in COSMOGRAIL's Wellspring

- Detailed analysis of five time-delay lenses (Suyu+2017)
  - 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)
- Four additional lenses tentatively will be added to sample (~2% precision on H_0)

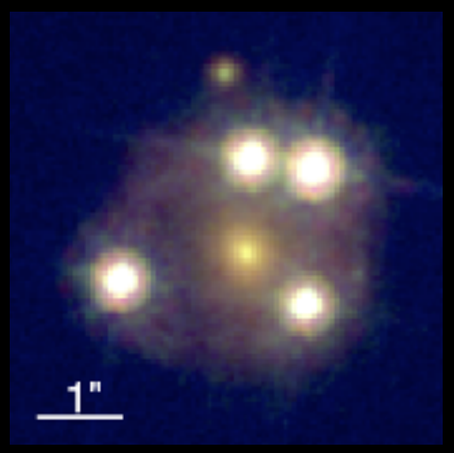


B1608+656

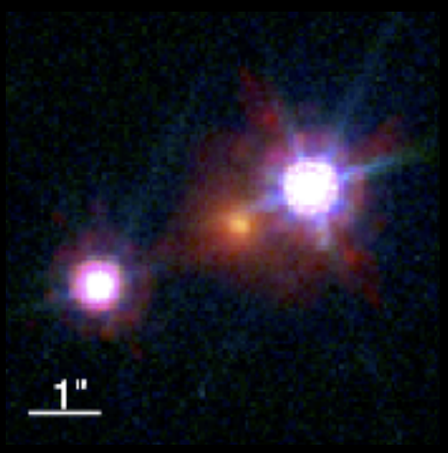
RXJ1131-1231



HE 0435-1223



WFI2033-4723



HE 1104-1805

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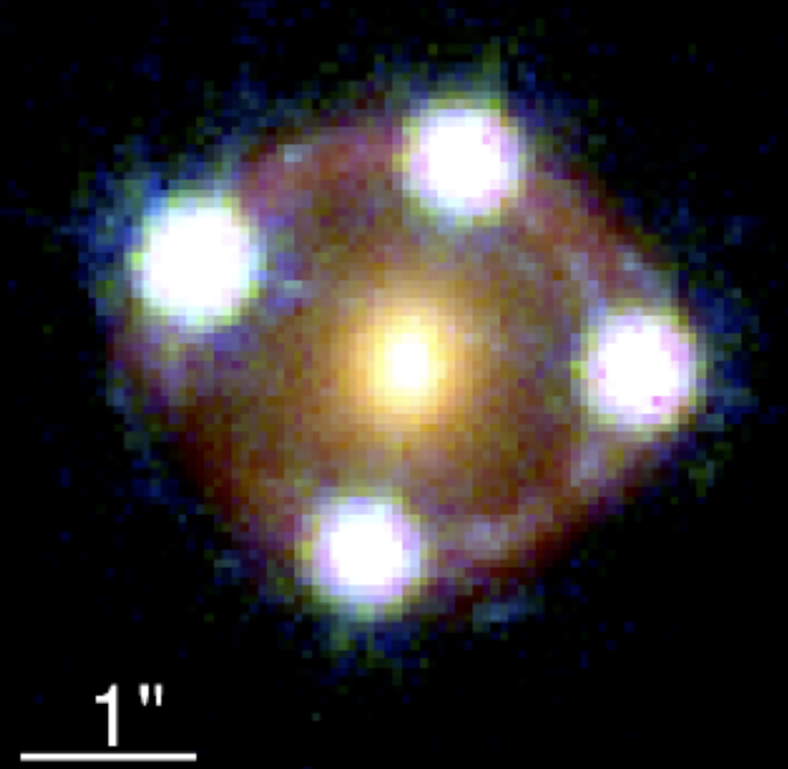
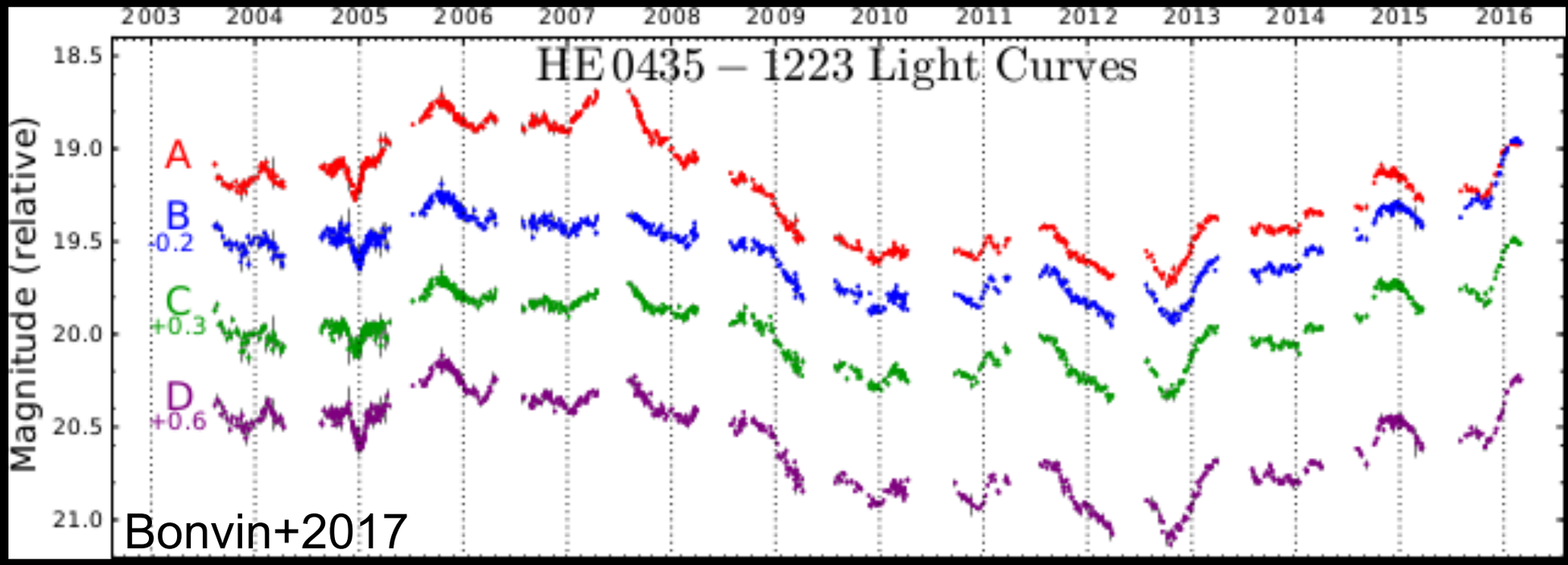
Latest Results from HE0435

- Extensive dataset
  - *HST* imaging in 3 bands (F555W, 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, KW+ in prep.)
- Full analysis and results:
  - Sluse+2017 (LOS galaxy spectroscopy)
  - Rusu+2017 (LOS photo-zs/stellar masses)
  - KW+2017 (Lens model)
  - Bonvin+2017 (Time-delay measurements)



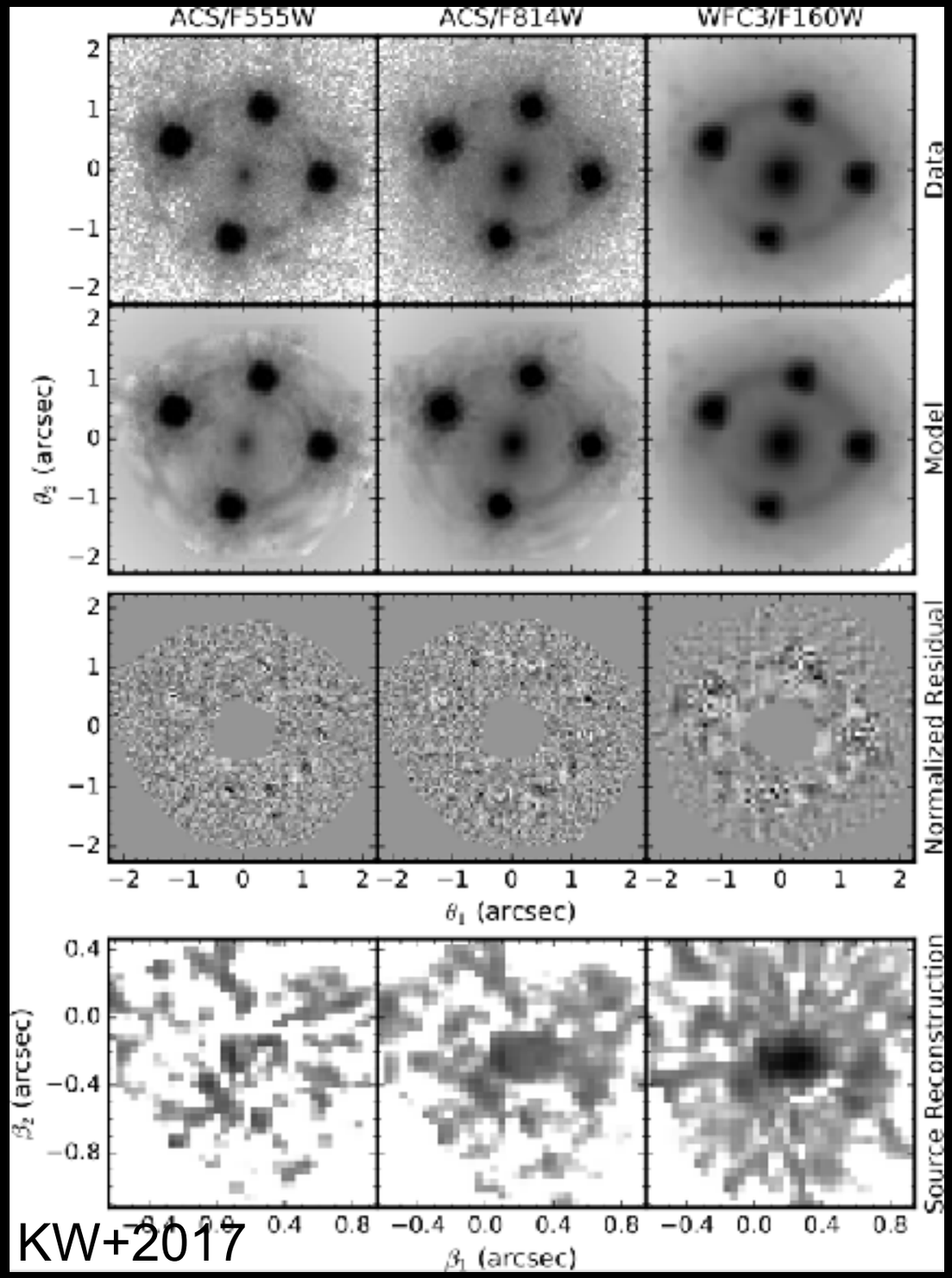
Accurate Time Delays

- COSMOGRAIL: long-term monitoring of time-delay lenses using small (1-m and 2-m) telescopes (Courbin+2011)
- Well-tested algorithms for time-delay measurements (Tewes+2013)
- Time delays of HE0435 from 13 years of monitoring (Bonvin+2017)
  - Long time baselines needed to minimize effects of microlensing



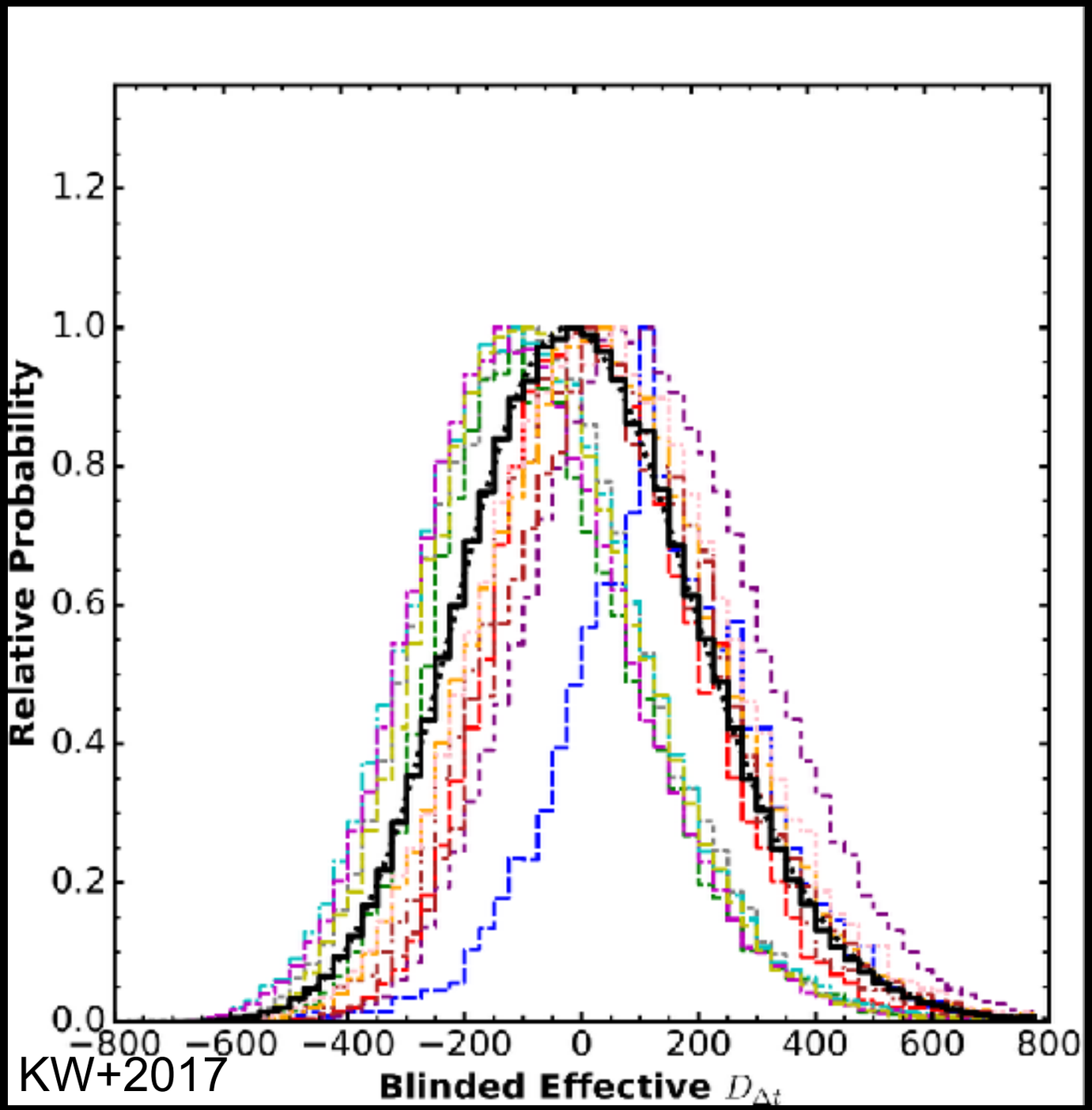
Accurate Lens Model

- Accurate lens model using 3-band of *HST* imaging (KW+2017)
- High-resolution needed to model quasar host galaxy
- Adaptive PSF correction using quasar images (e.g. Chen+2016)
- Account for nearby perturber using multi-plane lensing formalism
- External convergence from weighted galaxy number counts
- Velocity dispersion of lens galaxy from Keck/LRIS spectrum to break model degeneracies



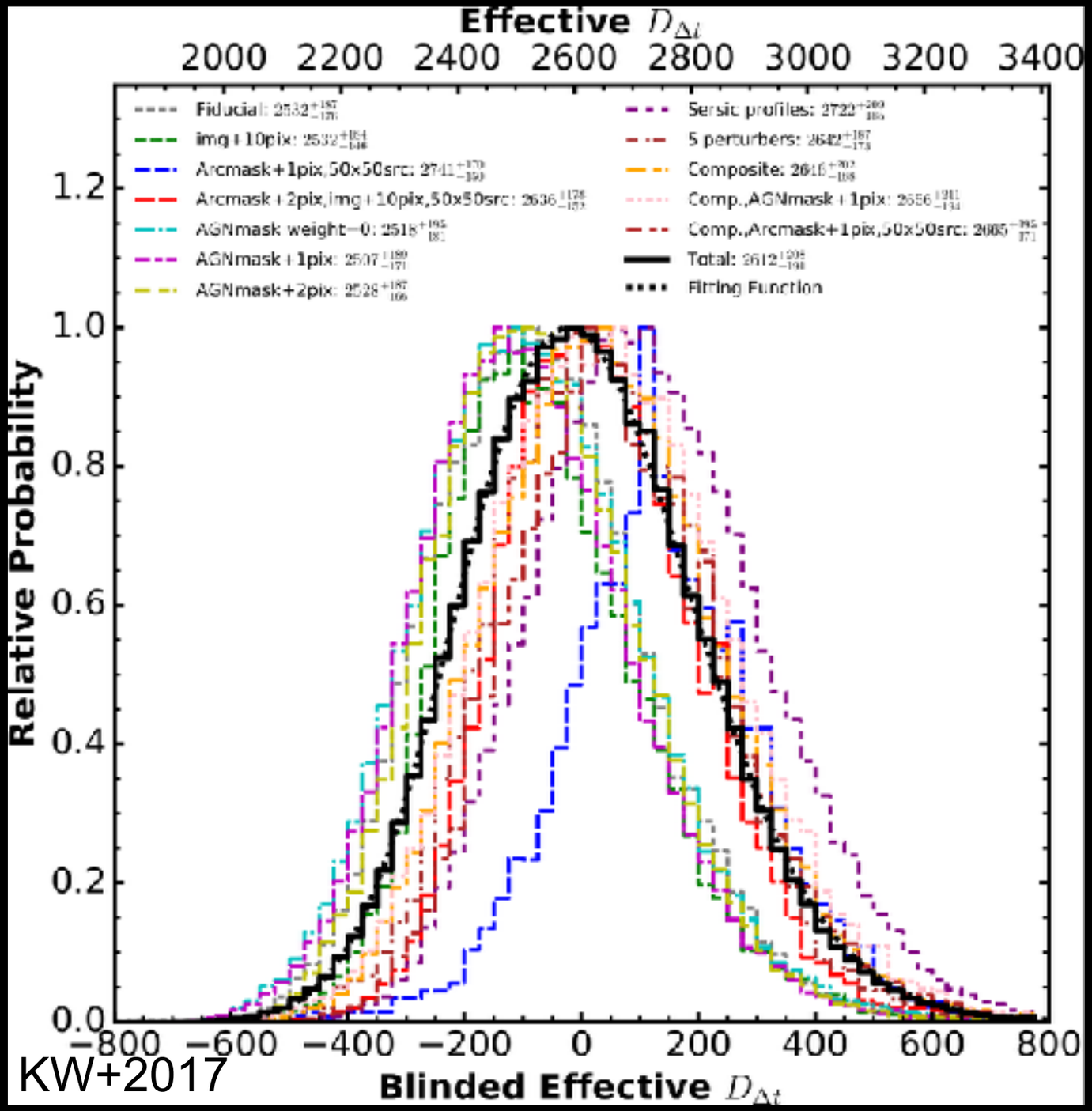
KW+2017

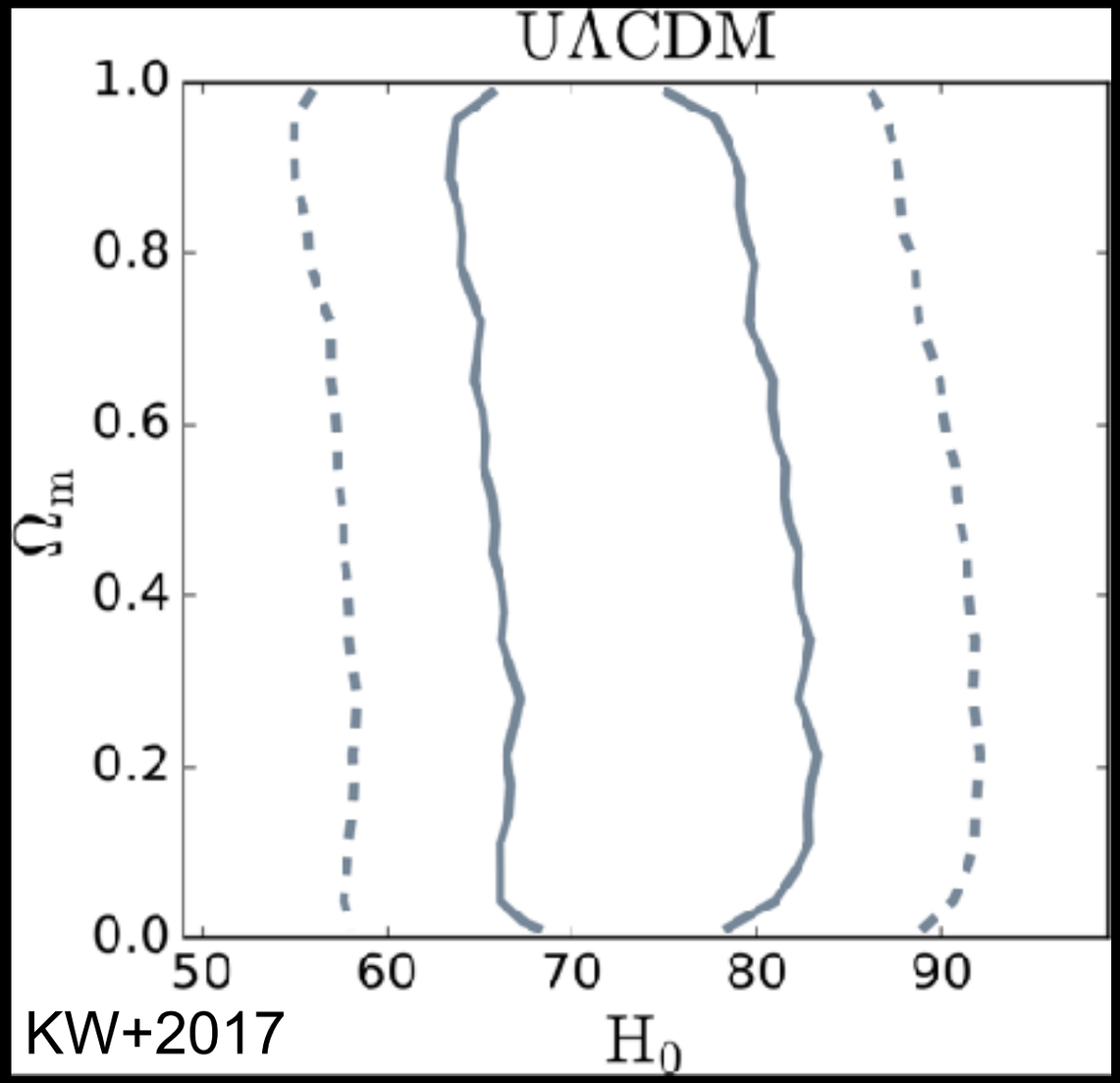
Blind Analysis



KW+2017

Results from HE0435





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

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

for flat ΛCDM cosmology

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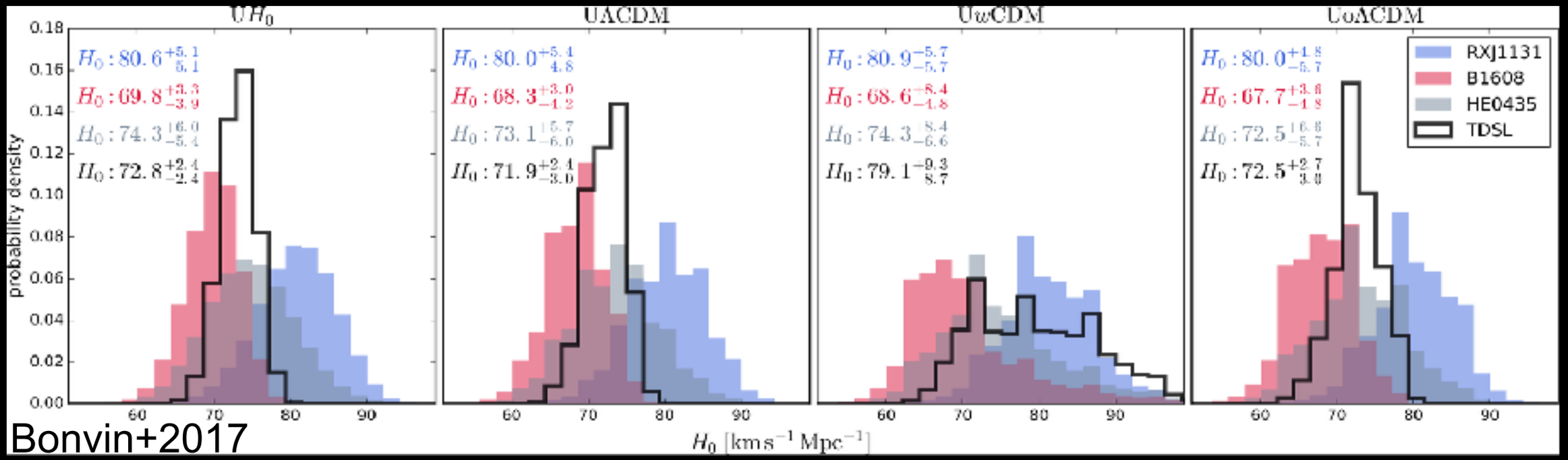
Combined Results from 3 H0LiCOW Lenses

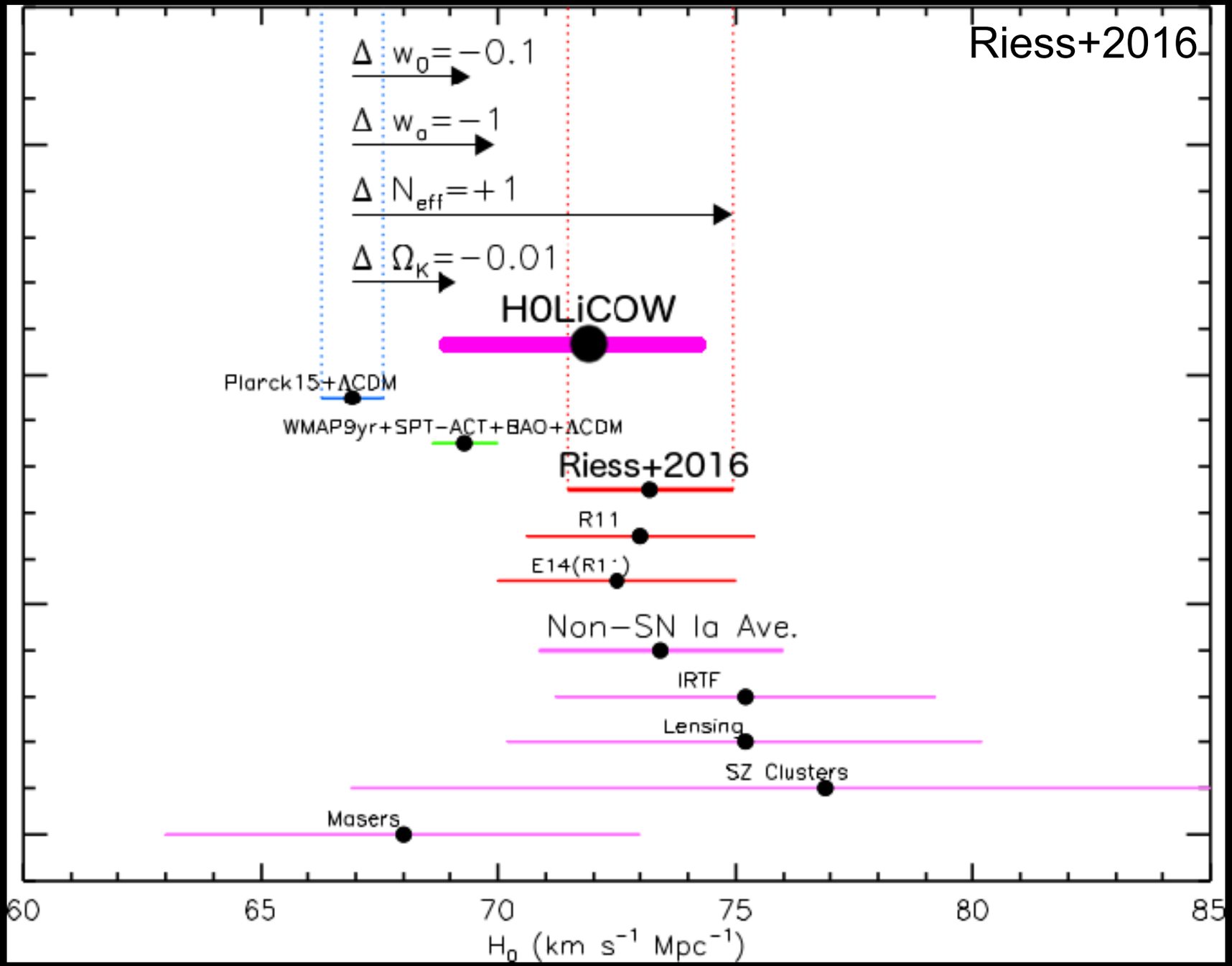


Bonvin+2017

~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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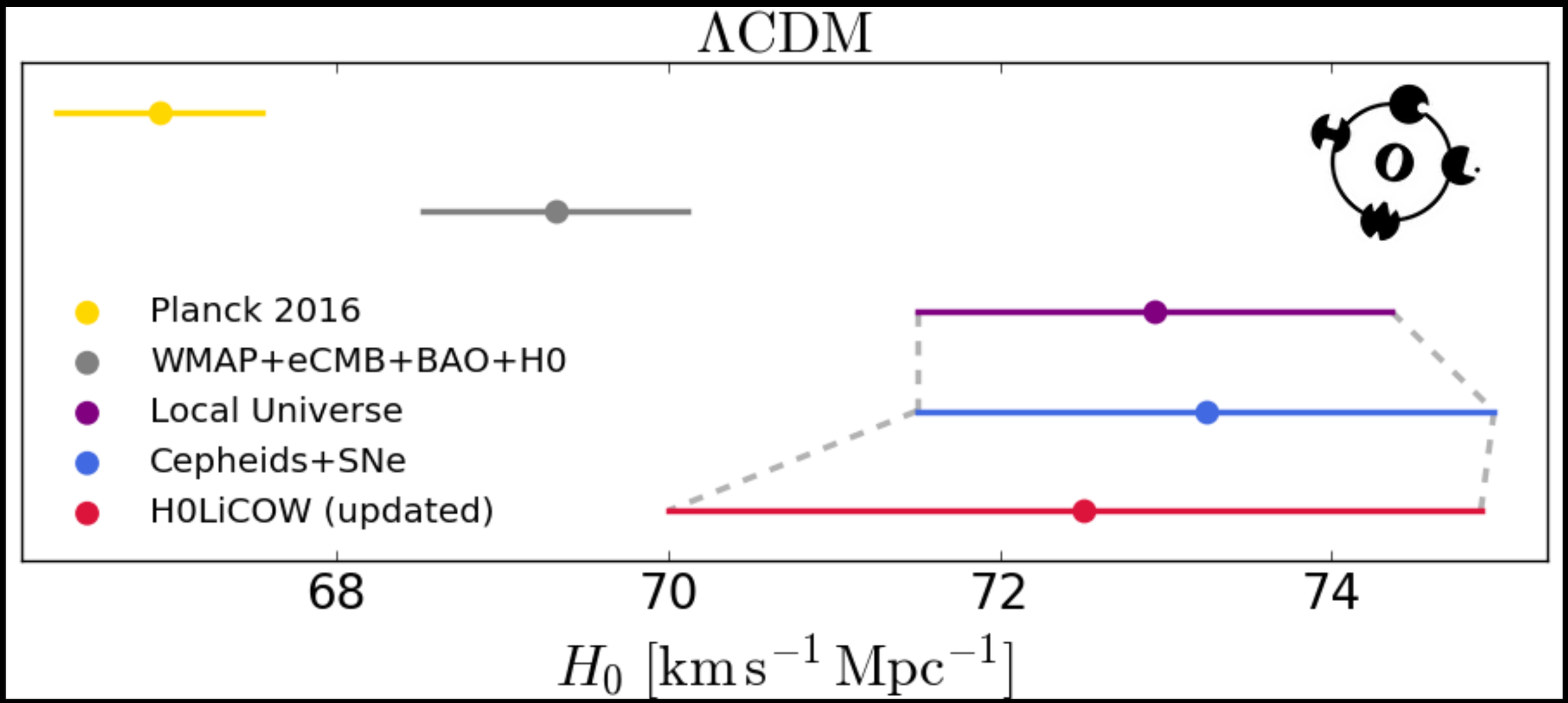
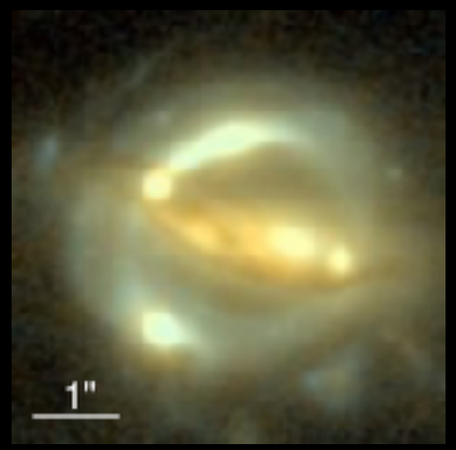


Ongoing Work

- Analysis of WFI2033 in progress, HE1104 to follow
- Four additional lenses with time delays and *HST* data
  - ancillary data (velocity dispersion, LOS spec/photo) in progress
  - full sample of 9 lenses will constrain H_0 to ~2%
- Weak lensing analysis of HE0435 field (Tihhonova+ in prep.)
  - independent test of LOS mass distribution
- AGN host galaxy studies
  - study evolution of BH-bulge relation using lensing magnification (Ding+2017a)
  - application to H0LiCOW data (Ding+ 2017b)



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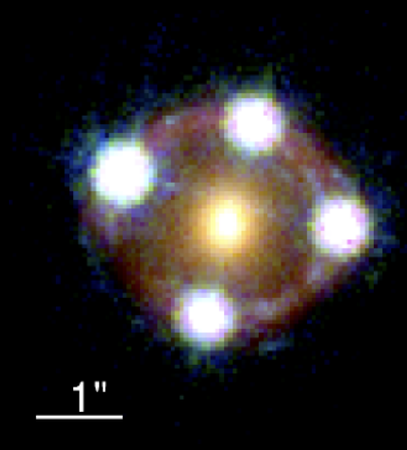

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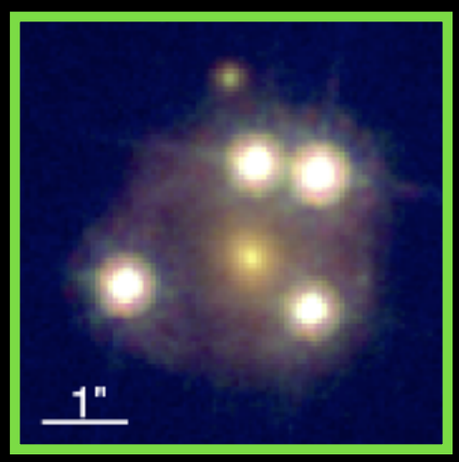

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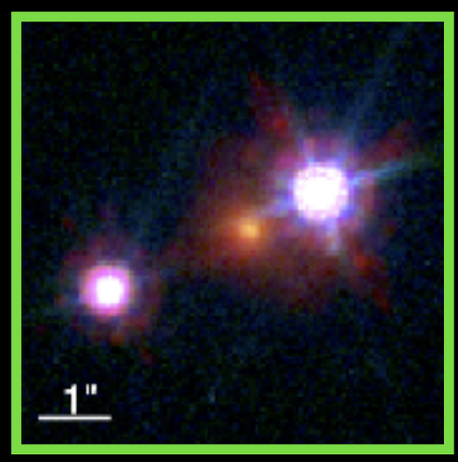

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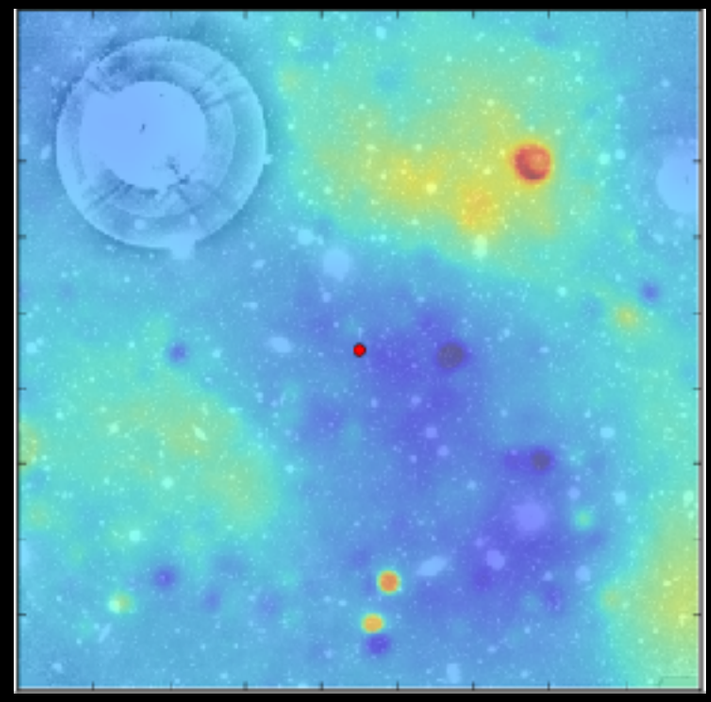

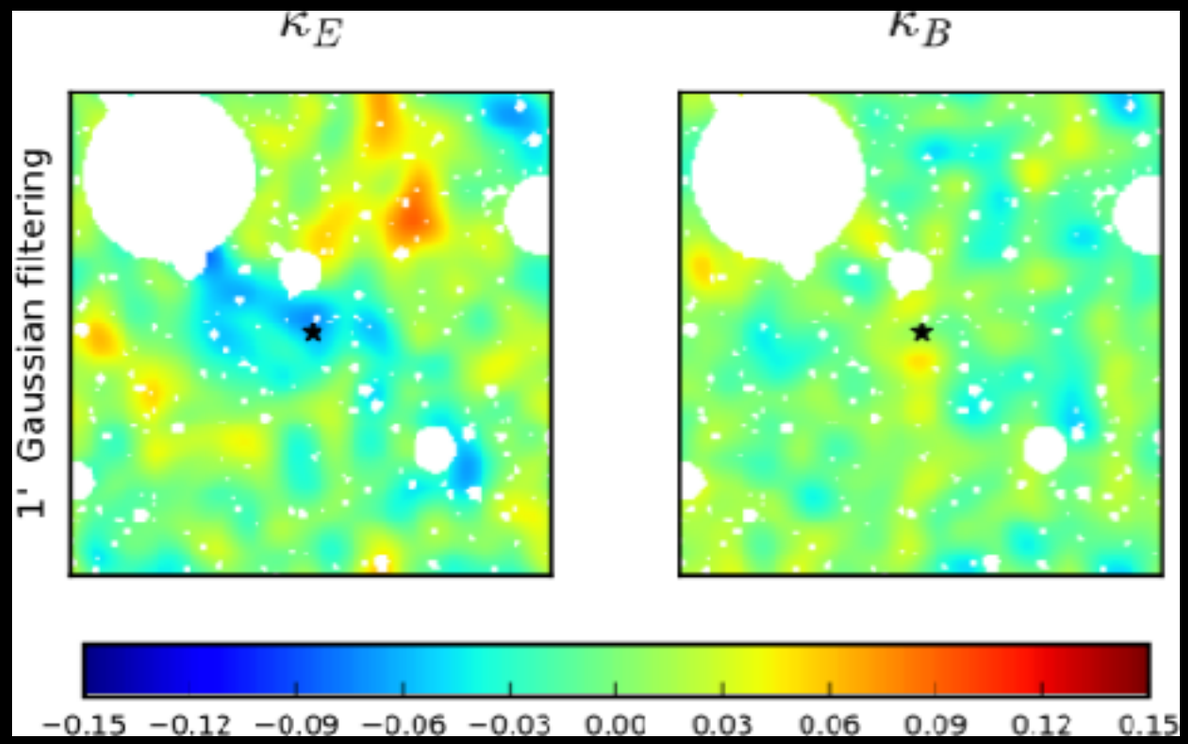

Tihhonova+ in prep.

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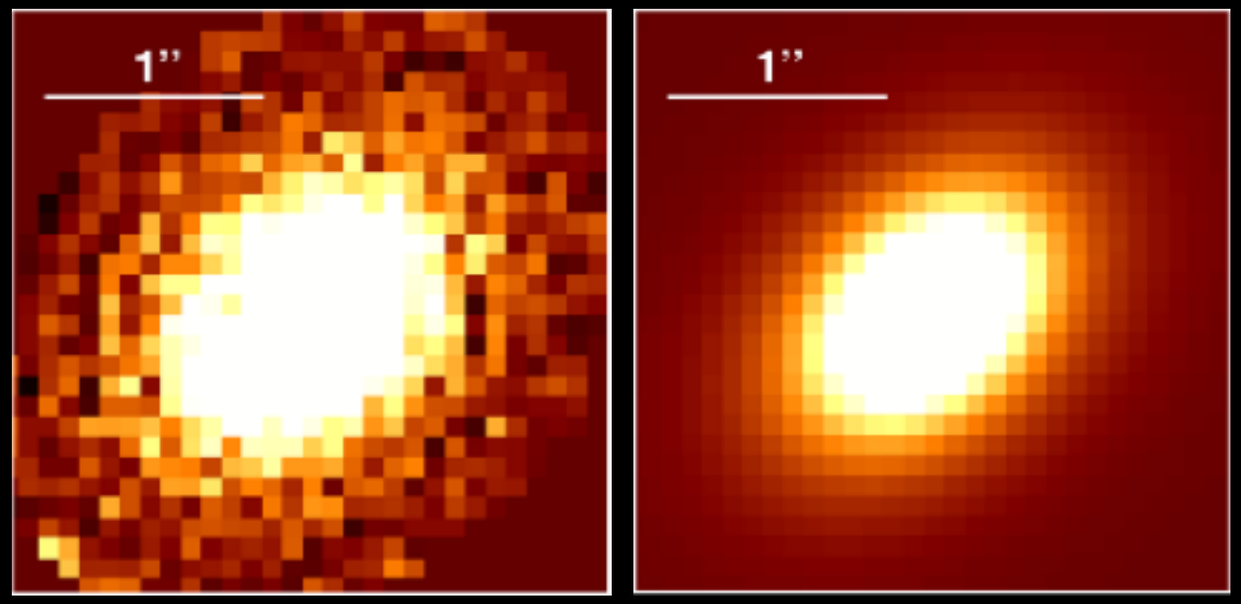
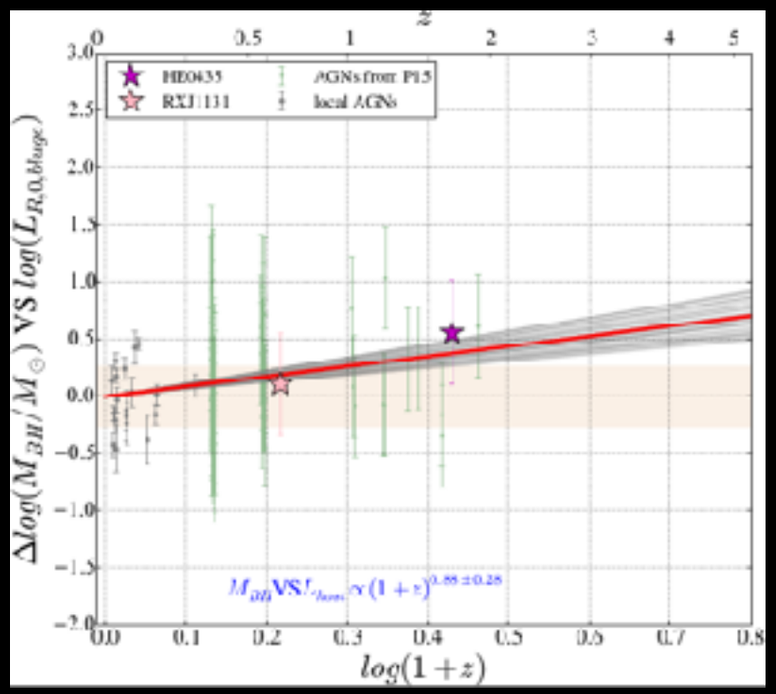


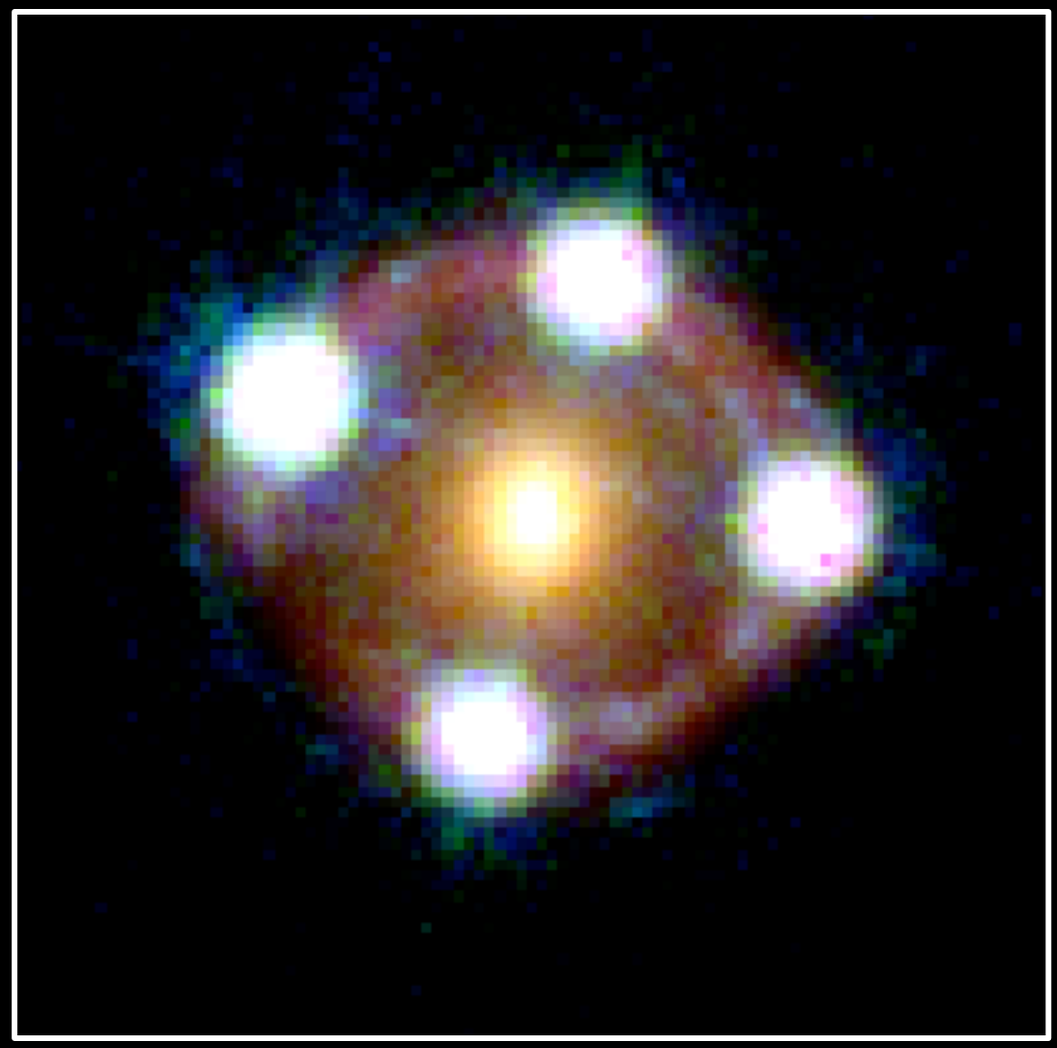
Ding+2017a



Ding+2017b

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 (possibly ~2% precision from 9 lenses)
- Current and future surveys will find thousands of new time-delay lenses, providing competitive probe of cosmology



East Asian Young Astronomer's Meeting (EAYAM) 2017

Postdocs and grad students from East Asia region encouraged to participate

November 13-17, 2017
Ishigaki, Japan

Registration deadline: **July 15**

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http://www-irc.mtk.nao.ac.jp/eayam/2017/

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