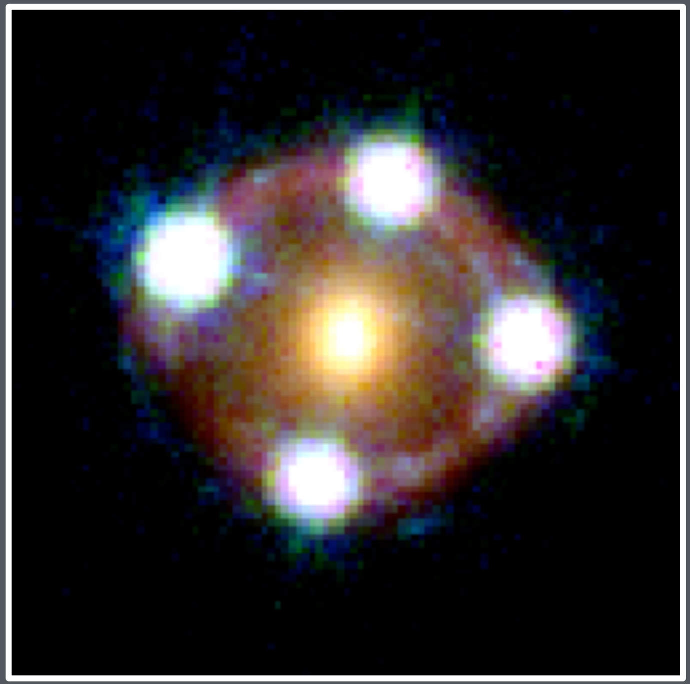
Cosmology from Gravitational Lens Time Delays



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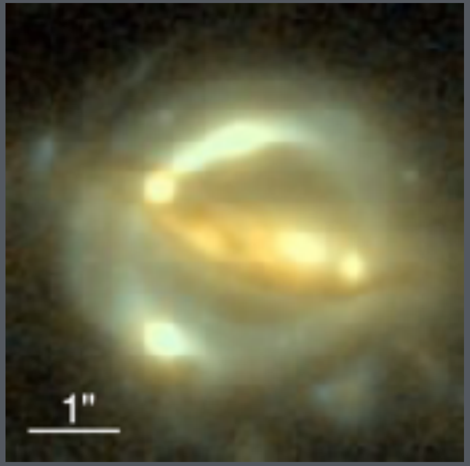
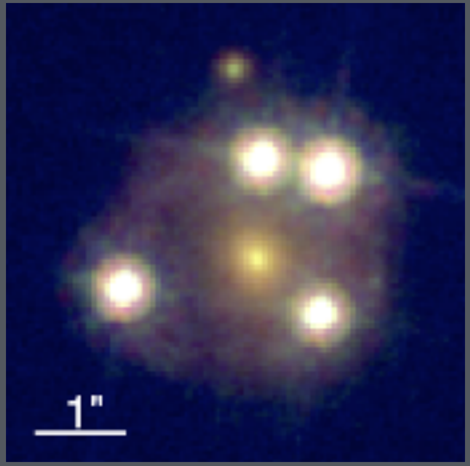
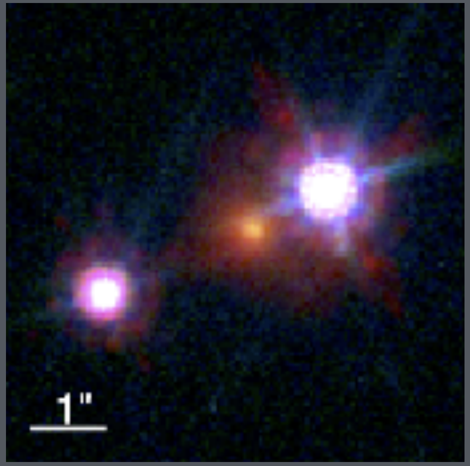
East Asia Young Astronomers Meeting 2017
November 15, 2017







国立天文台 NAOJ National Astronomical Observatory of Japan

EACOA East Asia Core Observatories Association

The Standard Model of Cosmology

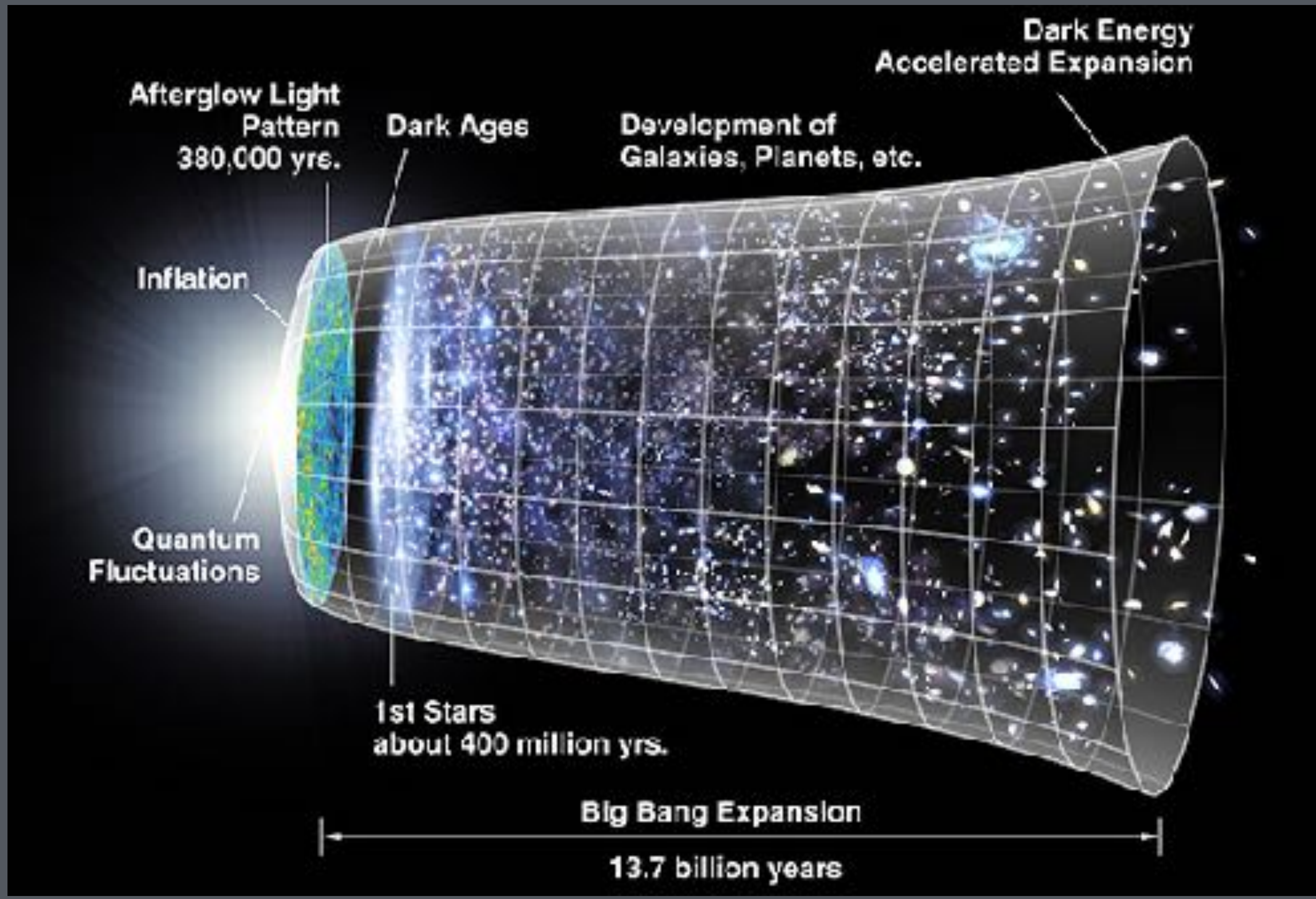
<u>**Important Parameters**</u>

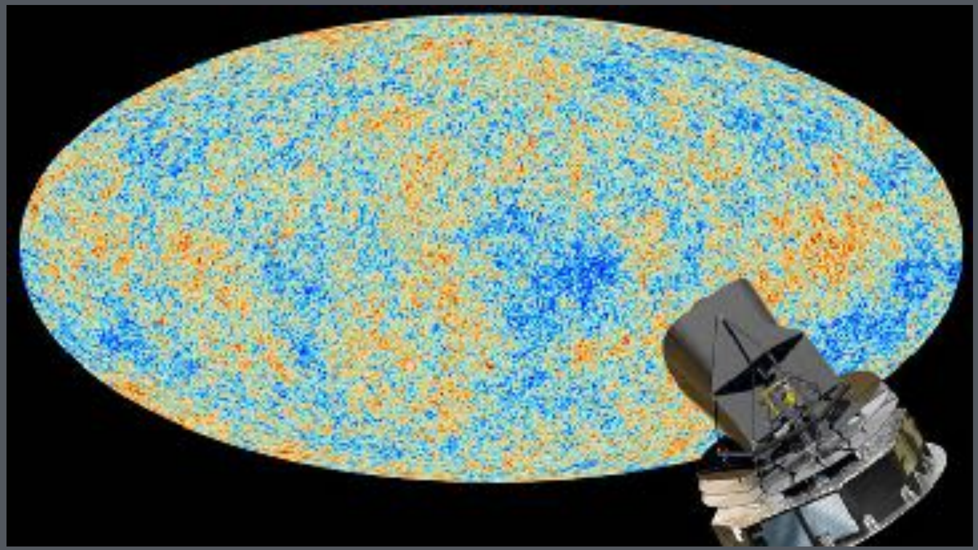
H_0 - sets expansion rate of universe
Ω_m - matter density
Ω_Λ - dark energy density
Ω_k - curvature
w - dark energy equation of state parameter

Standard model is the "flat ΛCDM" cosmology, where $\Omega_k = 1-\Omega_m-\Omega_\Lambda = 0$, $w = -1$

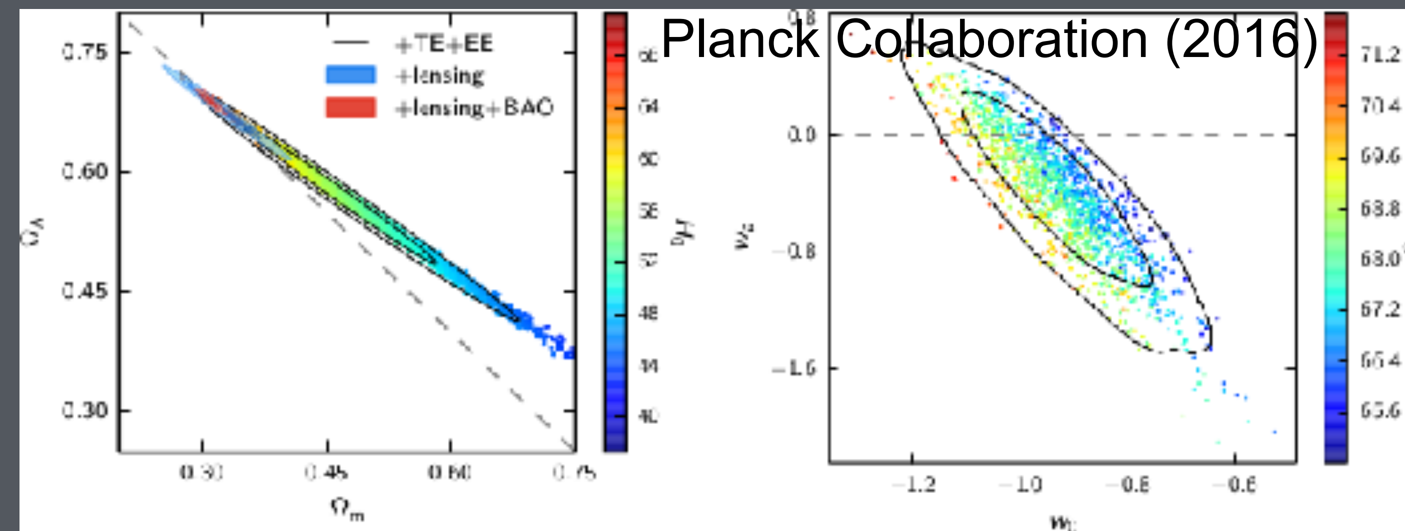
Extensions to flat ΛCDM include nonzero curvature, $w \neq -1$, time-varying w, different number of relativistic neutrino species, etc.

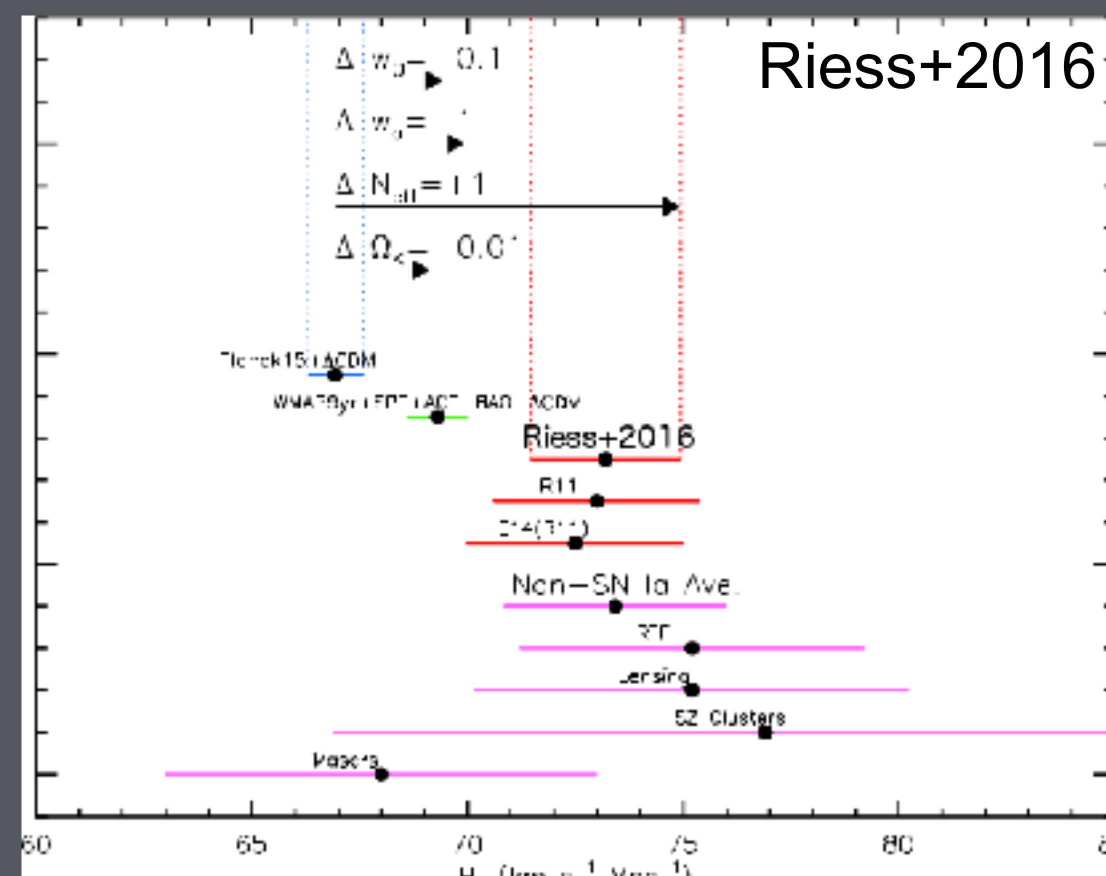
Planck mission measures cosmological parameters by observing the cosmic microwave background (CMB)





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
- What can we learn about lens and source?
  - Total mass (within Einstein radius)
  - Mass profile slope
  - Ellipticity/orientation
  - Intrinsic (unlensed) source flux
  - Can detect/resolve source features by taking advantage of magnification
  - **Cosmology!**

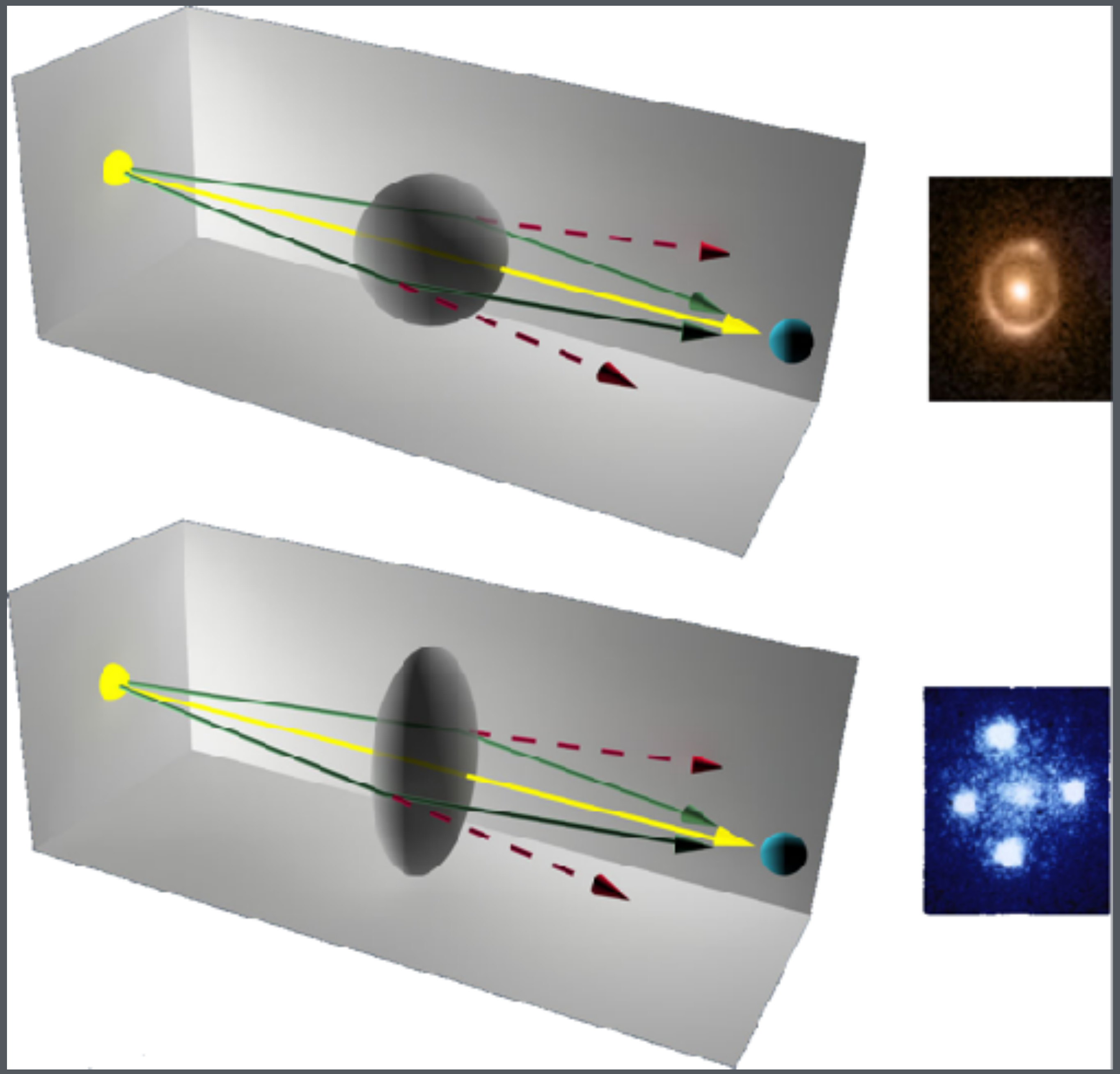
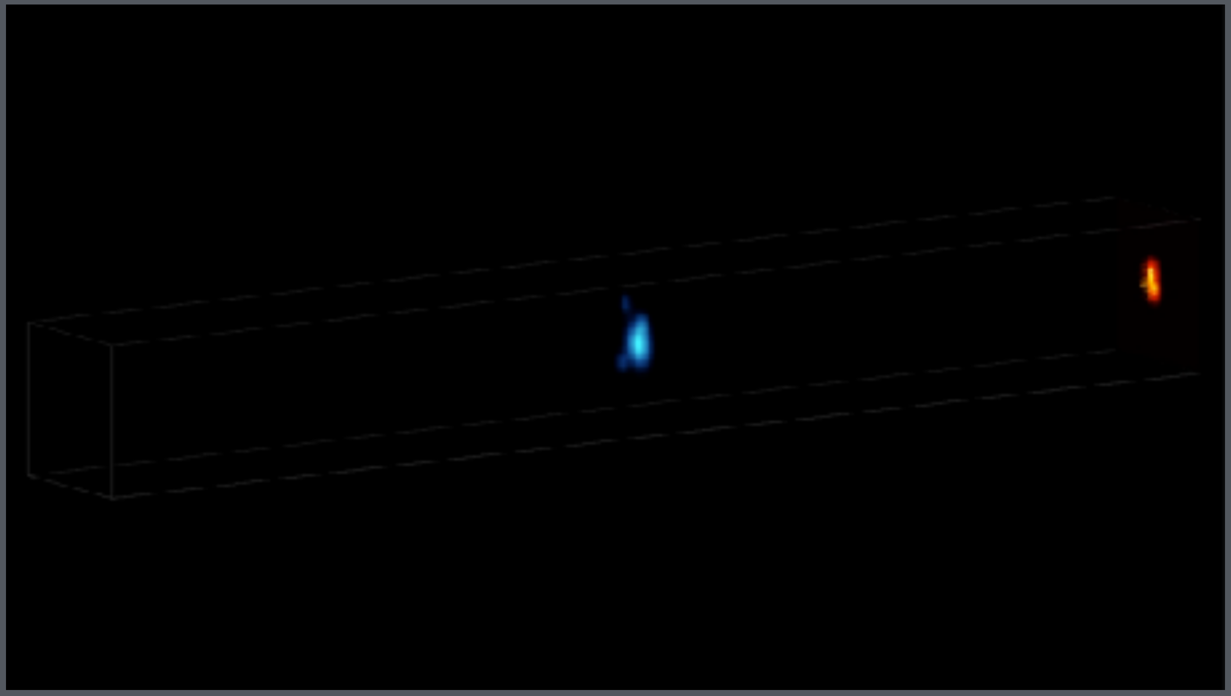


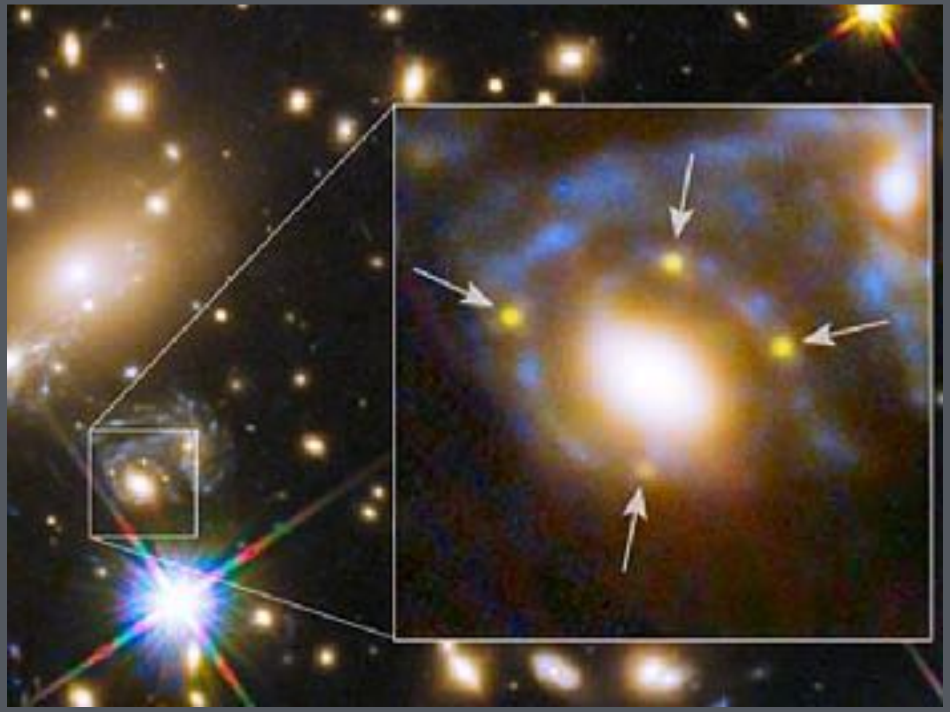
Image credit: ASIAA EPO



Movie credit: Y. Hezaveh

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 CMB and distance ladder*
- e.g., lensed supernovae (e.g. Kelly+2015, Goobar+2016), but very rare!



SNe "Refsdal"

Time delay   Lens potential (from mass model)

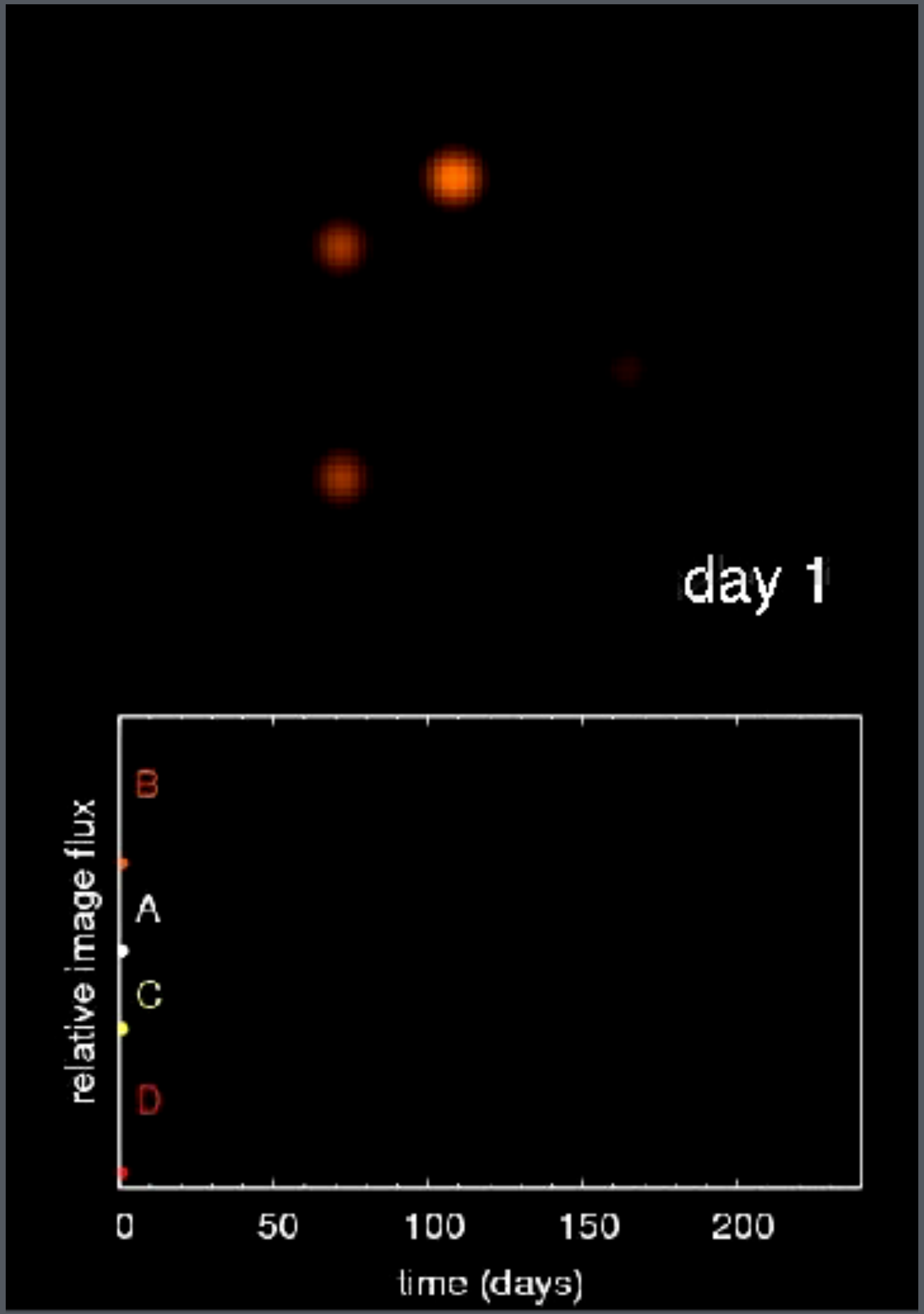
$$\Delta t = \frac{1}{c} D_{\Delta t} \phi_{lens}$$

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
- To constrain H_0, need:
  - Measured time delay
  - Accurate lens model
  - Estimate of mass along line of sight (LOS)



Time delay

Lens potential (from mass model)

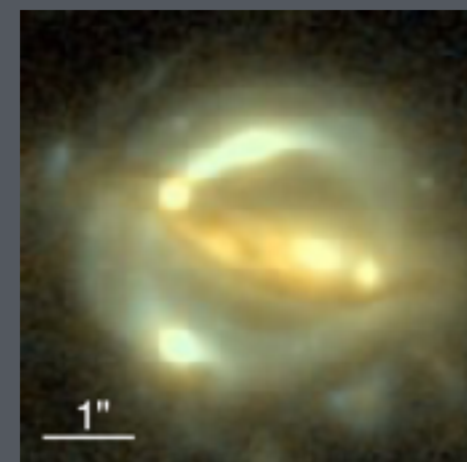
$$\Delta t = \frac{1}{c} D_{\Delta t} \phi_{lens}$$

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+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
- Four additional lenses tentatively will be added to sample (~2% precision on H_0)
- First two lenses previously analyzed (Suyu+2010, 2013), latest results on 3rd lens, HE 0435-1223



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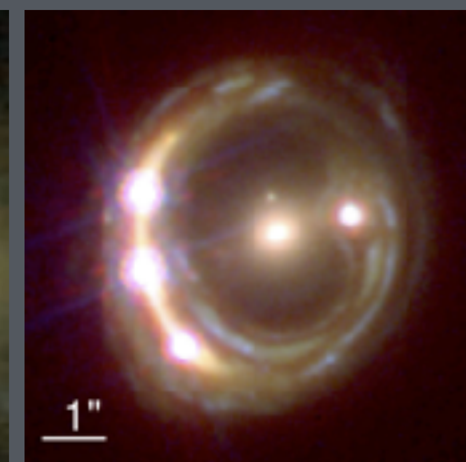
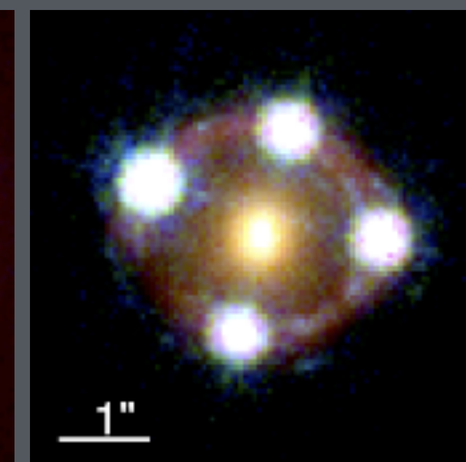
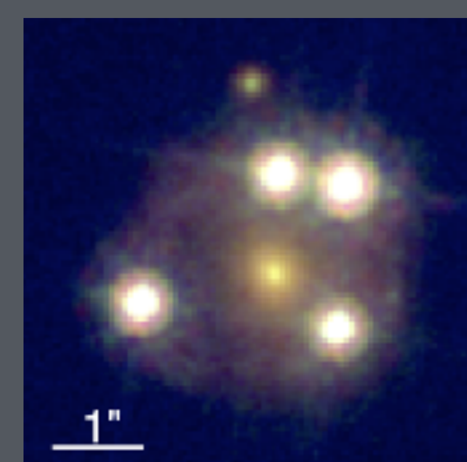


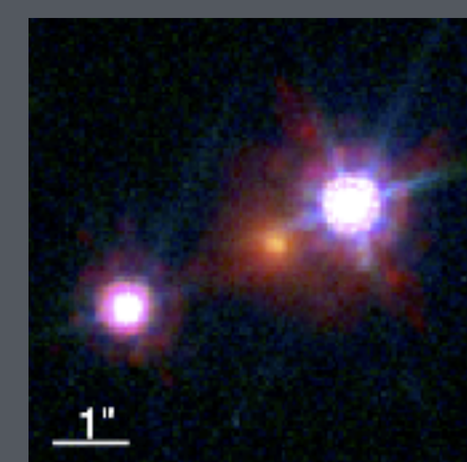
RXJ1131-1231



HE 0435-1223



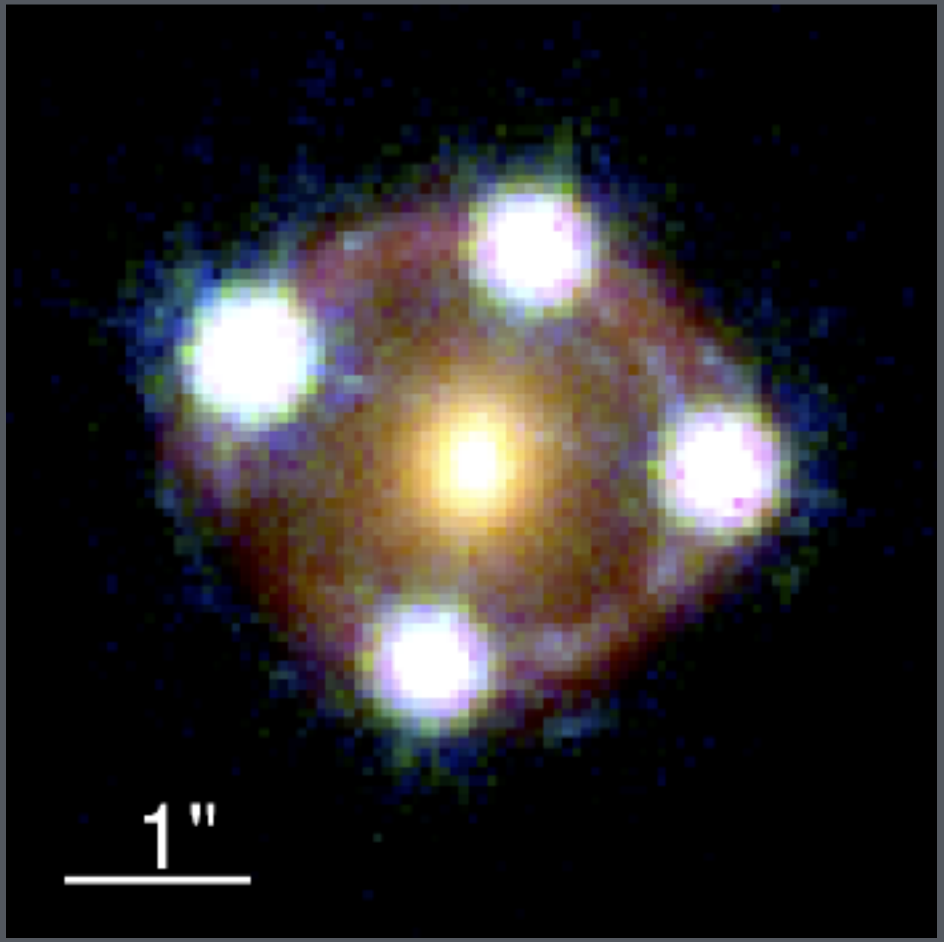
WFI2033-4723



HE 1104-1805

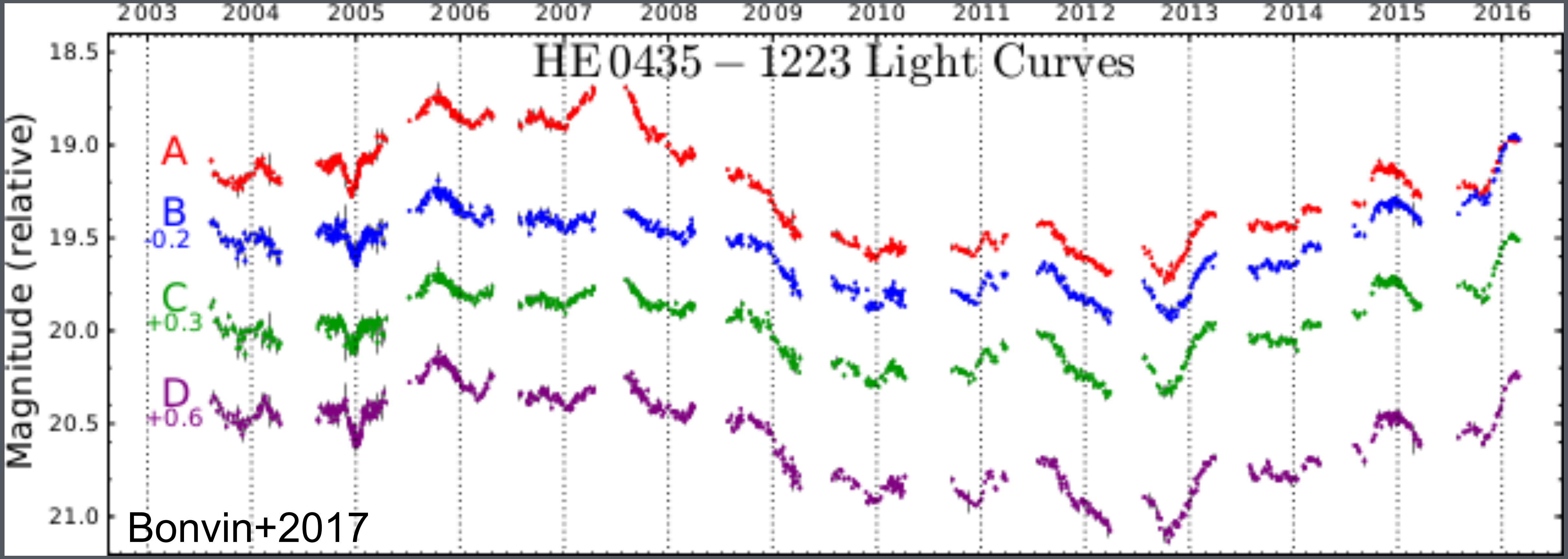
Latest Results from HE0435

- 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 to mitigate lens model degeneracies
  - Spectroscopic data on LOS galaxies to get perturber redshifts
  - Multiband photometry to get photo-zs and stellar masses of LOS galaxies
- 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

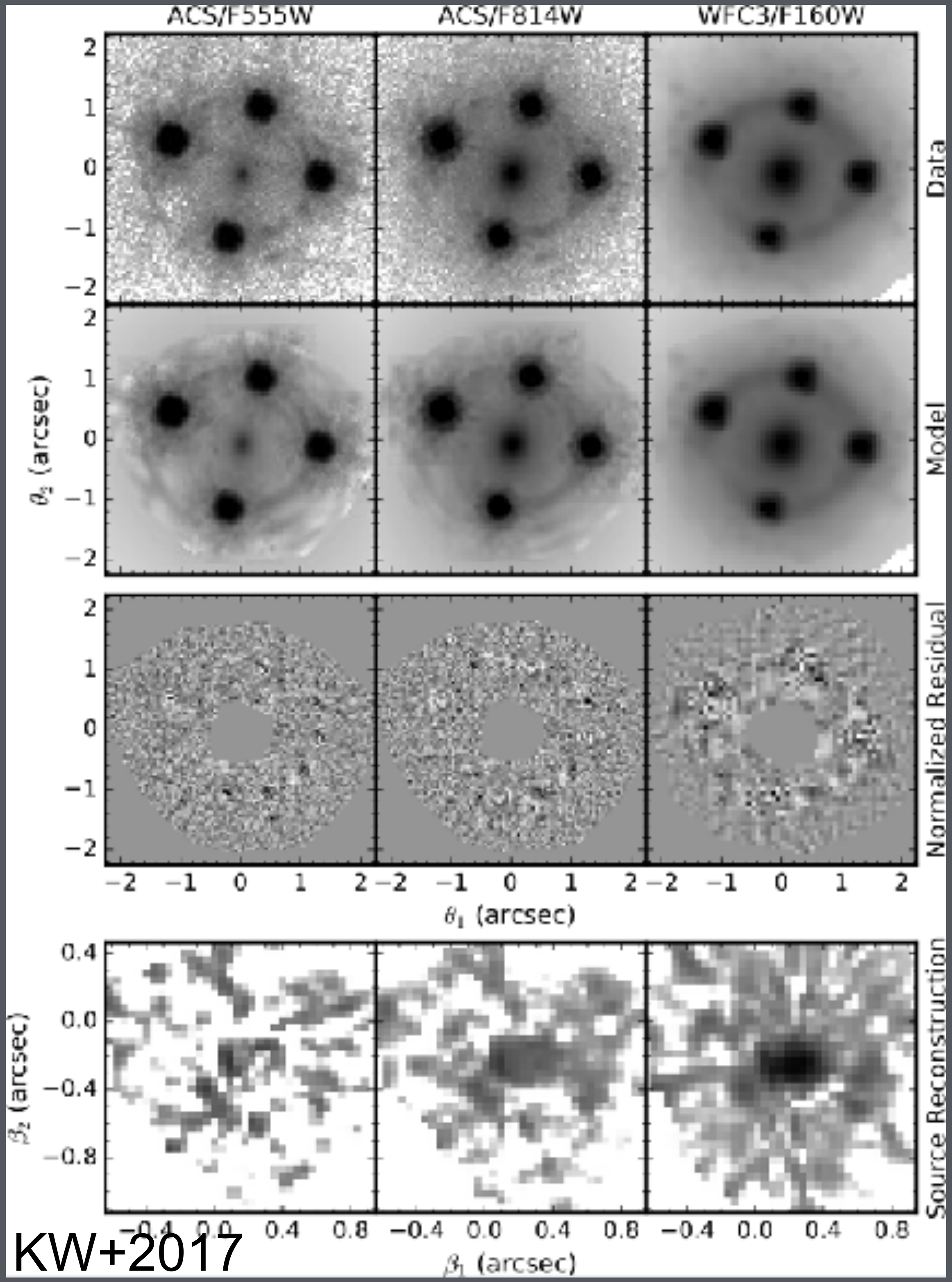
- COSMOGRAIL: long-term monitoring of time-delay lenses using small (1-m and 2-m) telescopes (Courbin+2011)
- Well-tested algorithms for time-delay measurements (Tewes+2013)
- Time delays of HE0435 from 13 years of monitoring (Bonvin+2017)
  - Long time baselines needed to minimize effects of microlensing



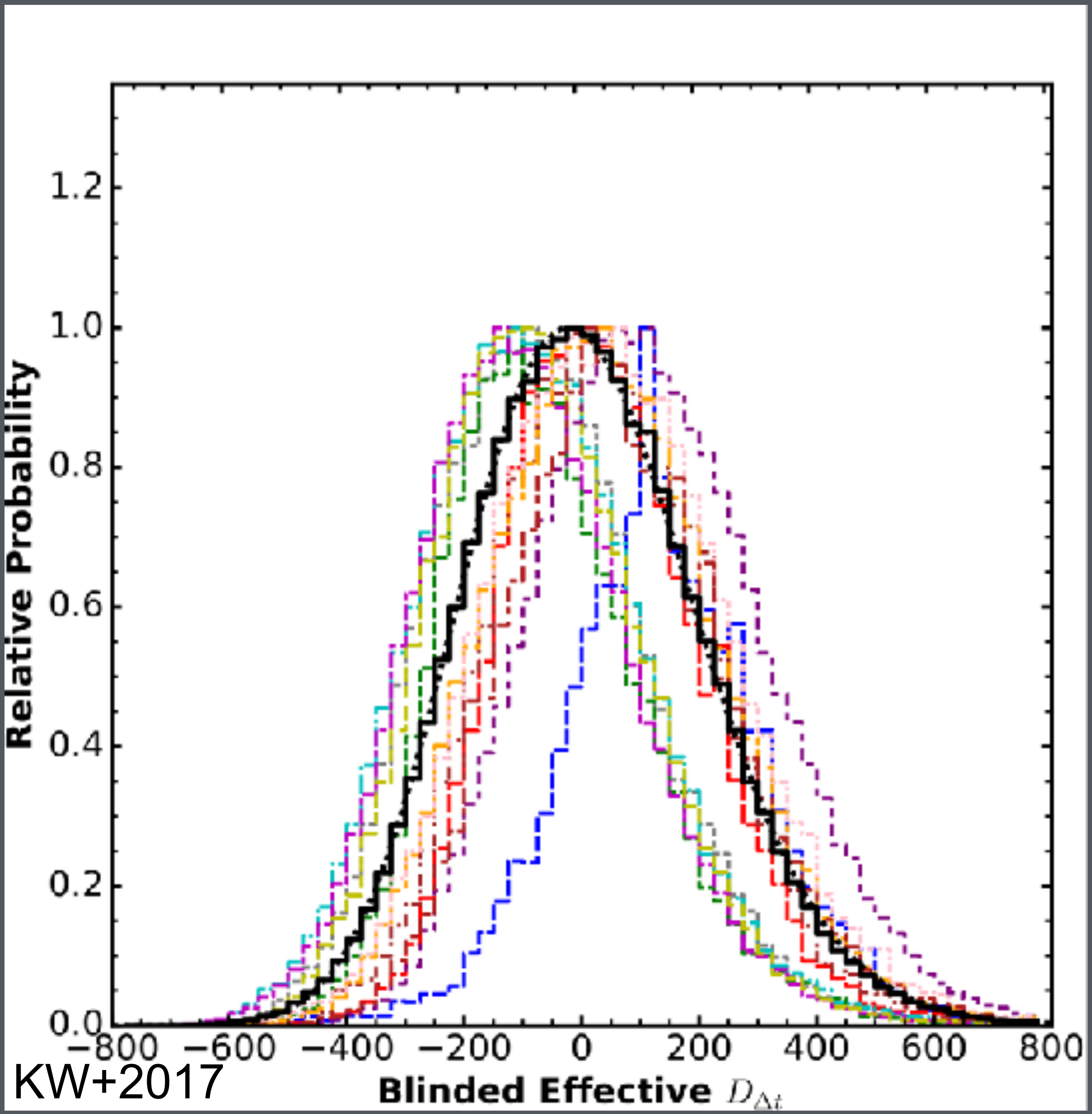
Bonvin+2017

Lens Model

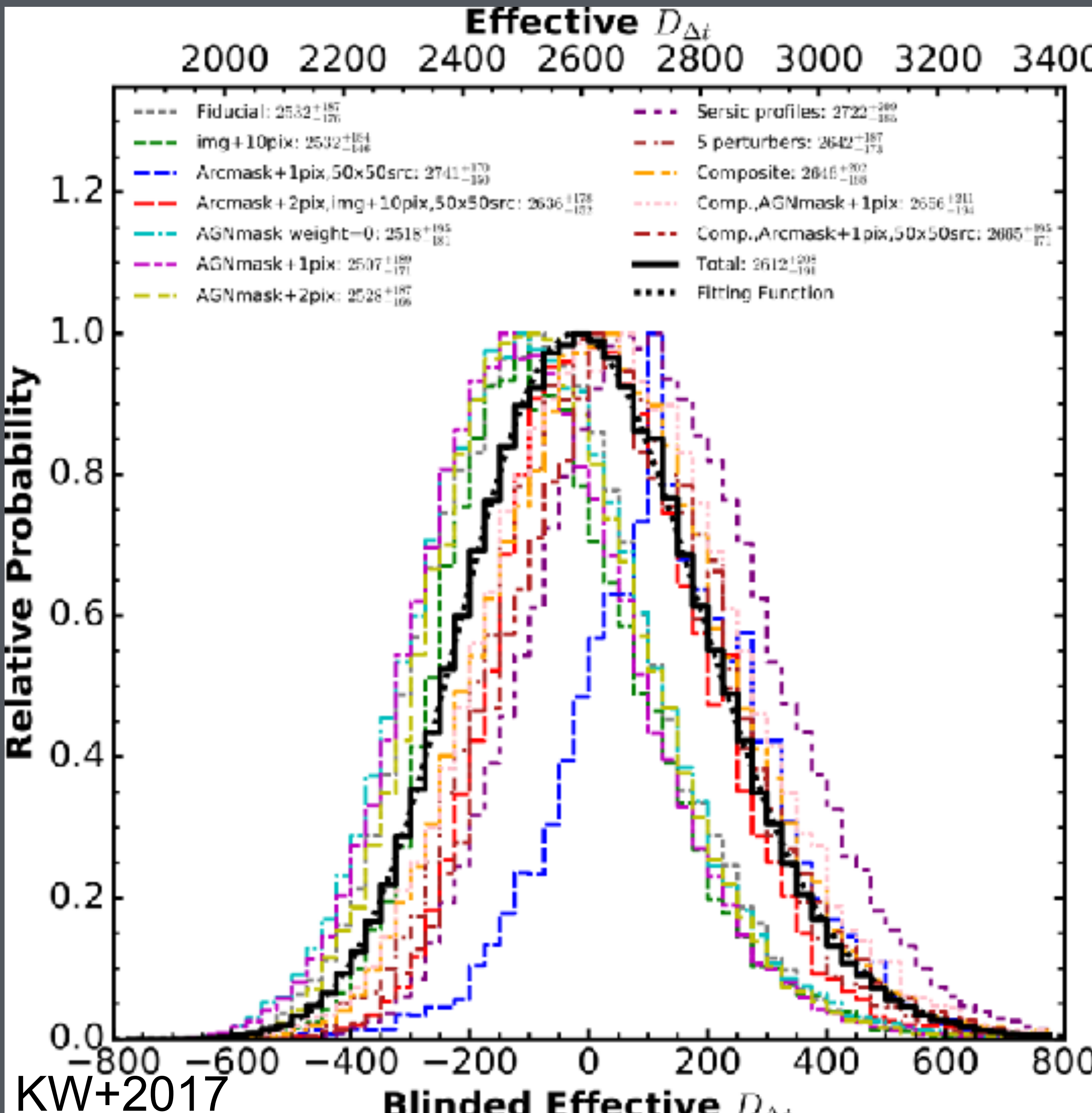
- Accurate lens model using 3-band of *HST* imaging (KW+2017)
- High-resolution needed to model quasar host galaxy
- Account for nearby perturber using multi-plane lensing formalism
- Influence of LOS perturbations from weighted galaxy number counts (Rusu+2017)
- Velocity dispersion of lens galaxy from Keck/LRIS spectrum to break model degeneracies

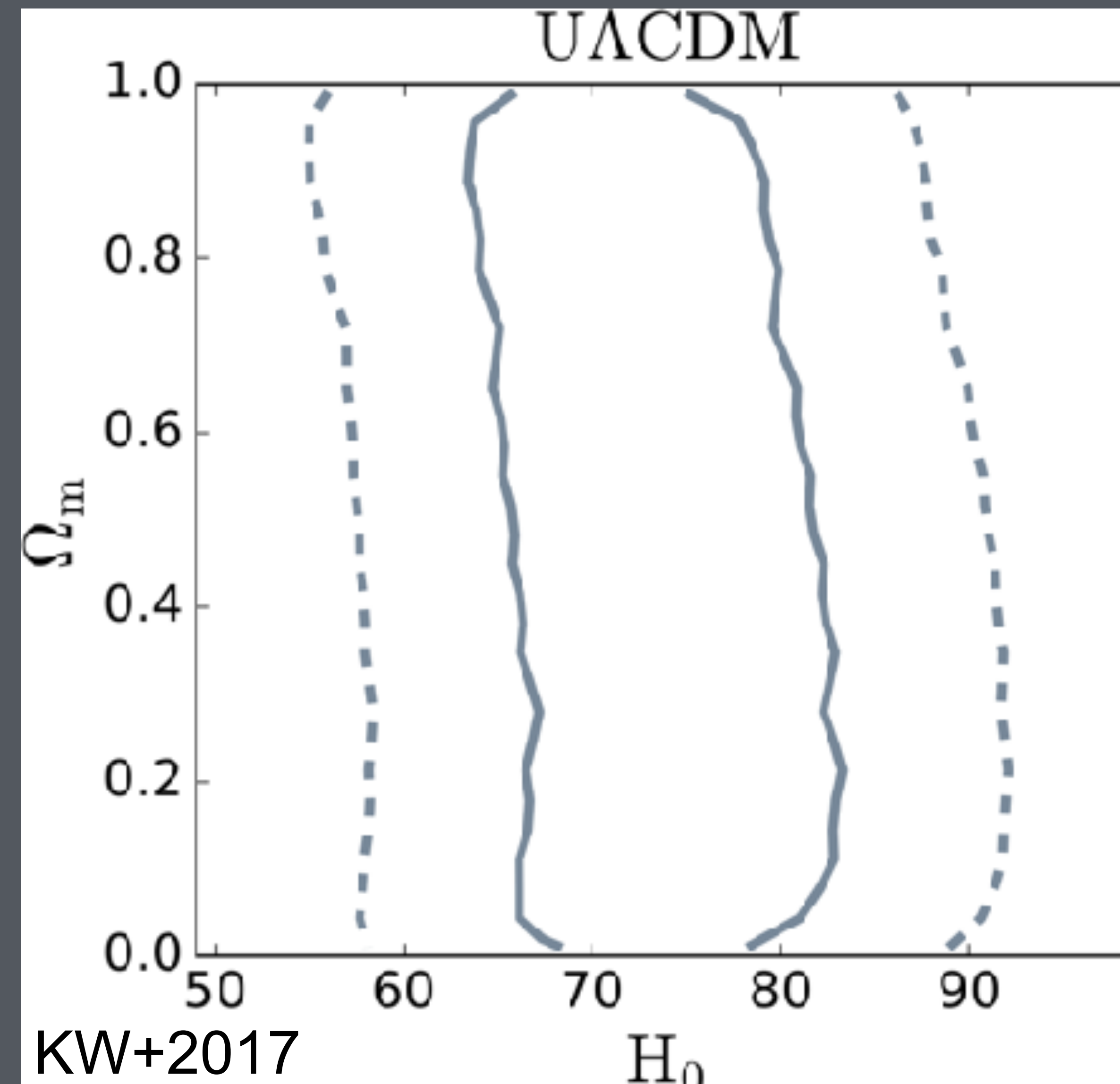


Blind Analysis



Results from HE0435



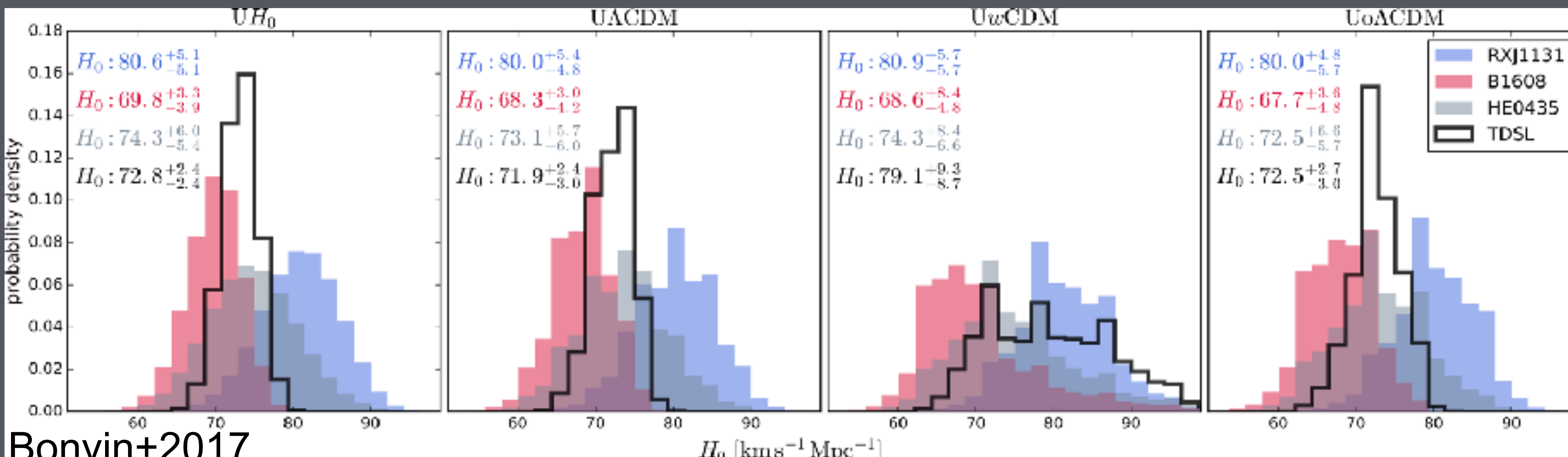


~8% constraint on $D_{\Delta t}$
$H_0 = 73.1^{+5.7}_{-6.0}$ km/s/Mpc
for flat ΛCDM cosmology

EAYAM
11/15/2017

Kenneth Wong (NAOJ)

Combined Results from 3 H0LiCOW Lenses

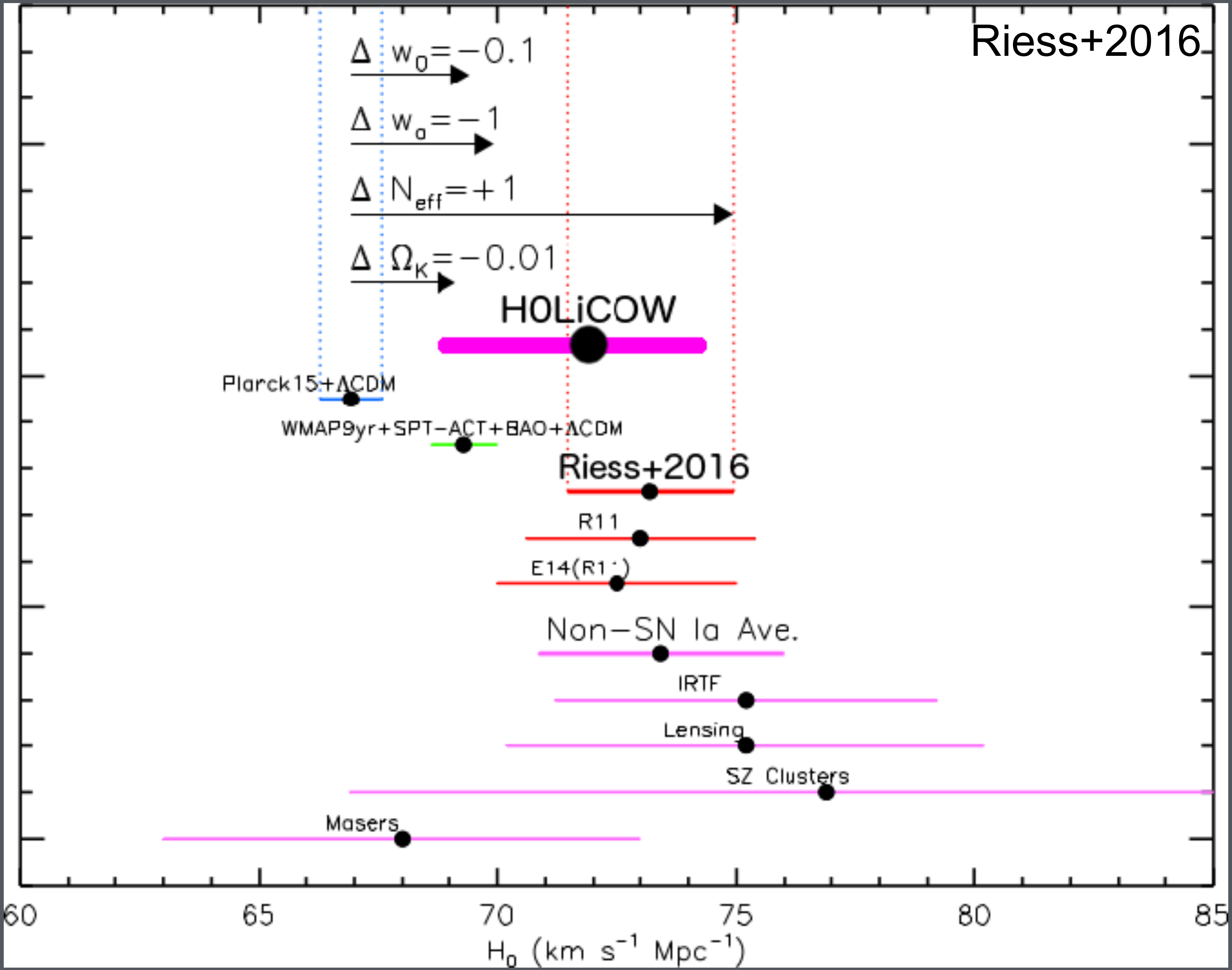


Bonvin+2017

~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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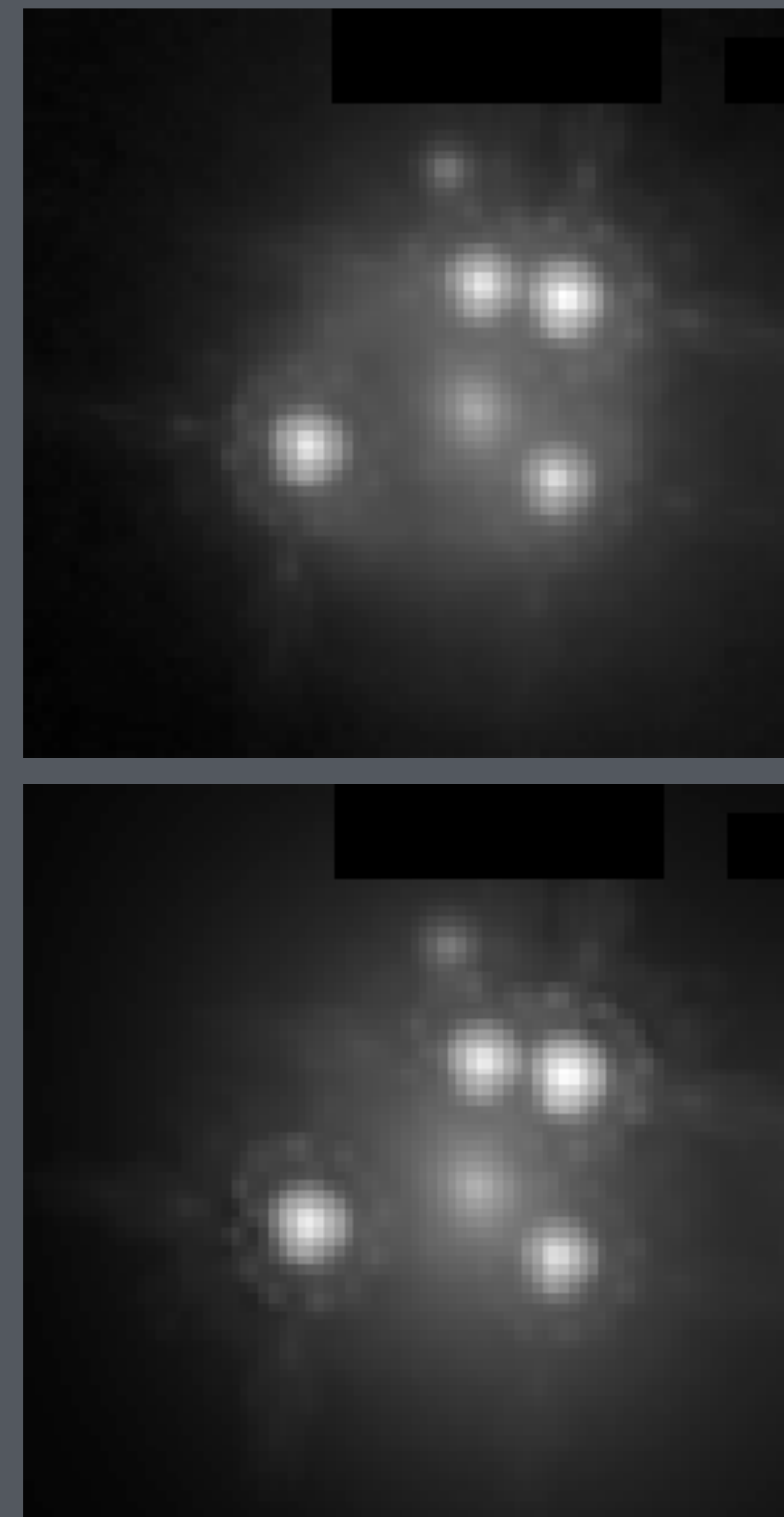
Ongoing/Future Work

- Analysis of WFI2033 ongoing, 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%

WFI2033-4723



Data

Model

Ongoing/Future Work

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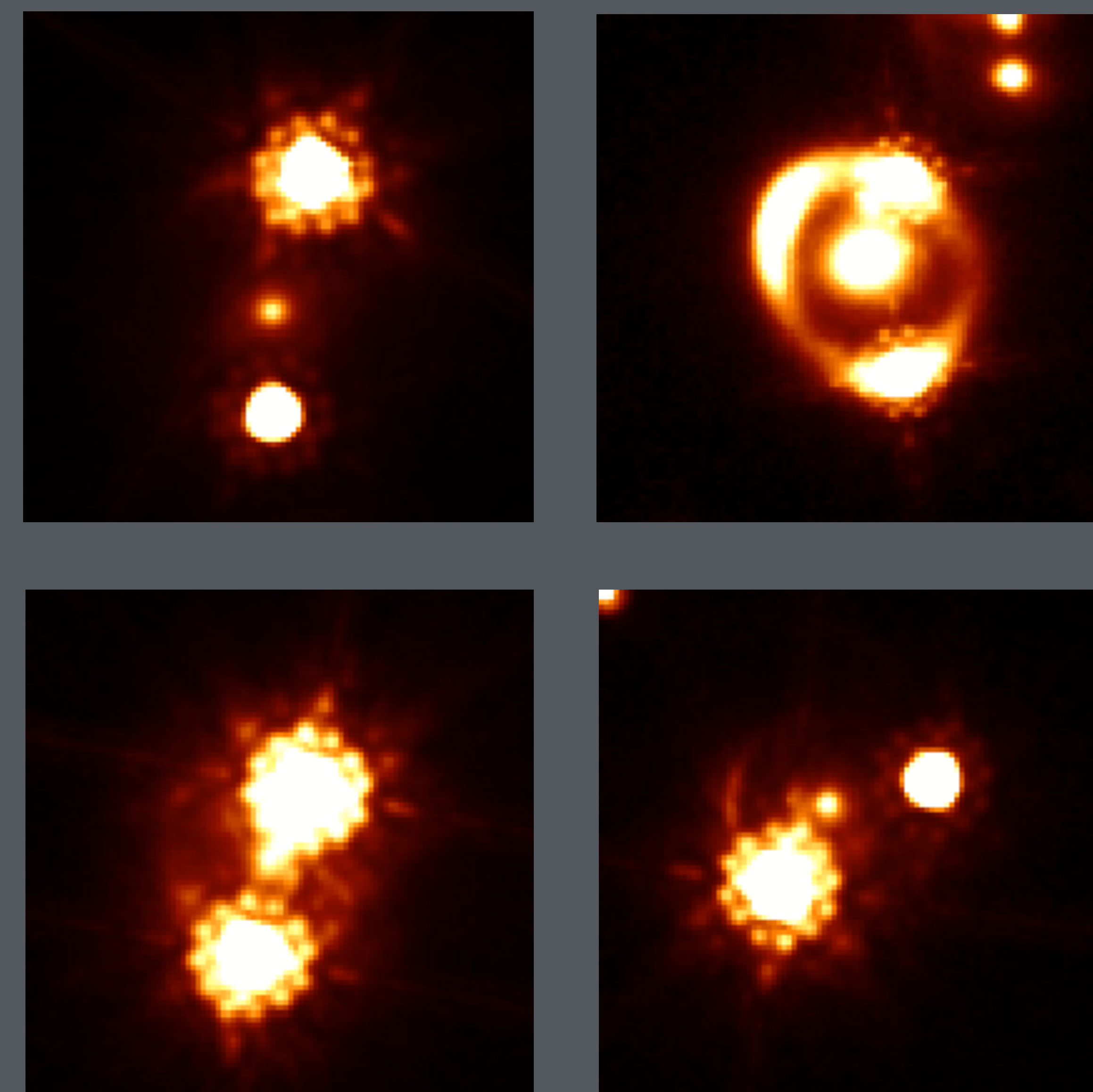
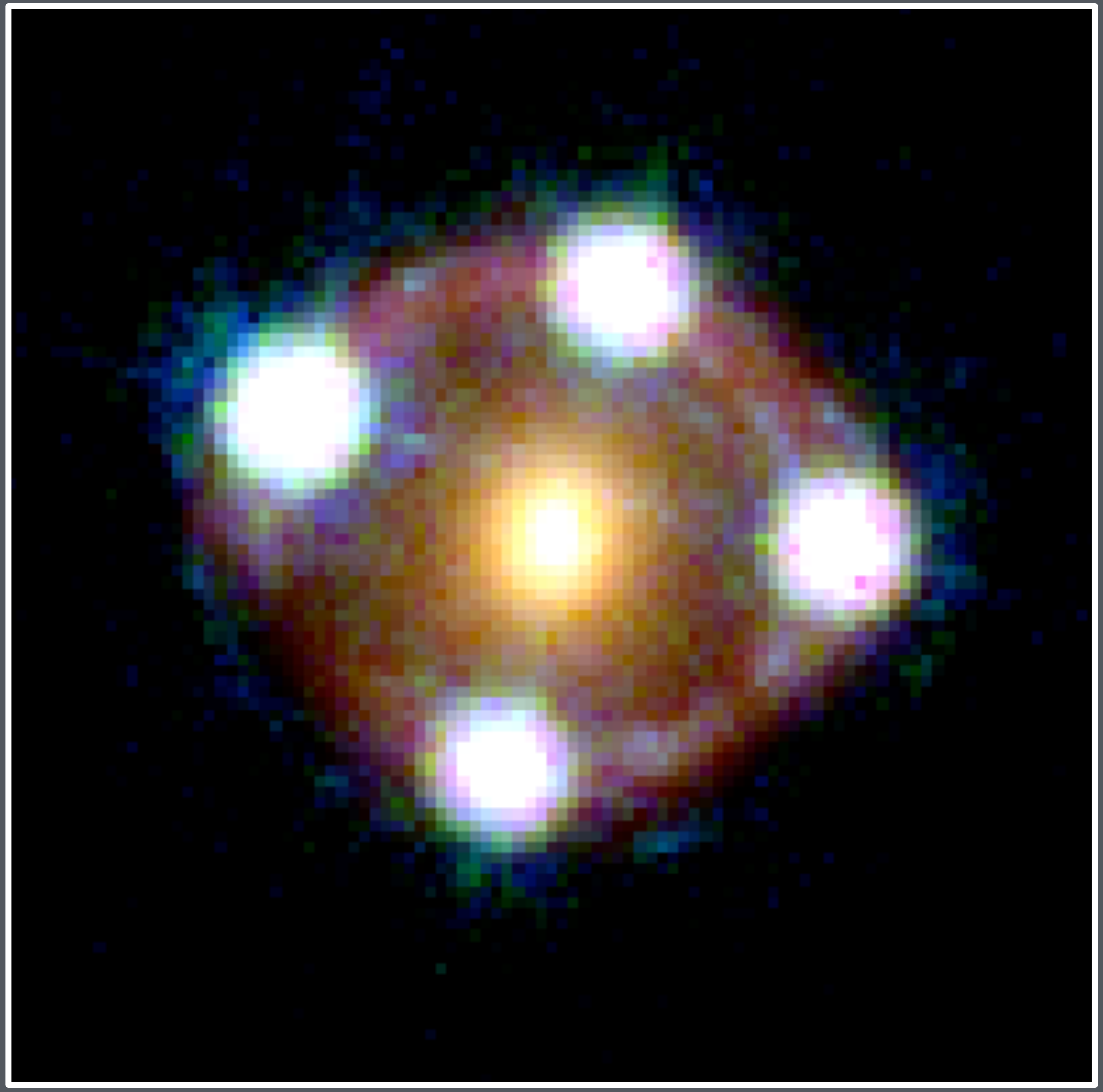


Summary

- Time-delay lenses are a one-step probe of H_0, independent of the CMB and the distance ladder
- 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



H0LiCOW Collaboration

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*bold/underlined: attending this conference

H0LiCOW Publications

Paper I - Suyu et al. 2017, MNRAS, 468, 2590
Paper II - Sluse et al. 2017, MNRAS, 470, 4838
Paper III - Rusu et al. 2017, MNRAS, 467, 4220
Paper IV - Wong et al. 2017, MNRAS, 465, 4895
Paper V - Bonvin et al. 2017, MNRAS, 465, 4914
Paper VI - Ding et al. 2017a, MNRAS, 465, 4634
Paper VII - Ding et al. 2017b, MNRAS, 472, 90
Paper VIII - Tihhonova et al. in preparation

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http://www.h0licow.org