# *H0LiCOW*

## $H_0$ Lenses in COSMOGRAIL Wellspring

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Galaxies and Cosmology in Light of Strong Lensing
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# H0LiCOWers

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**Tommaso Treu (UCLA)**
**Simona Vegetti (MPA, Garching)**
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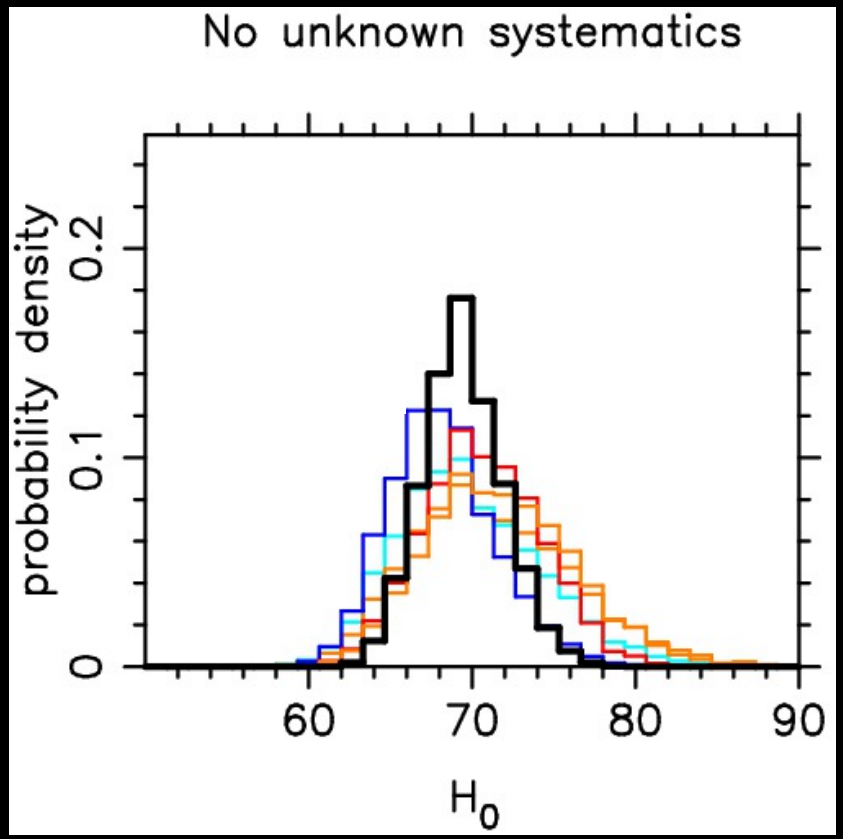
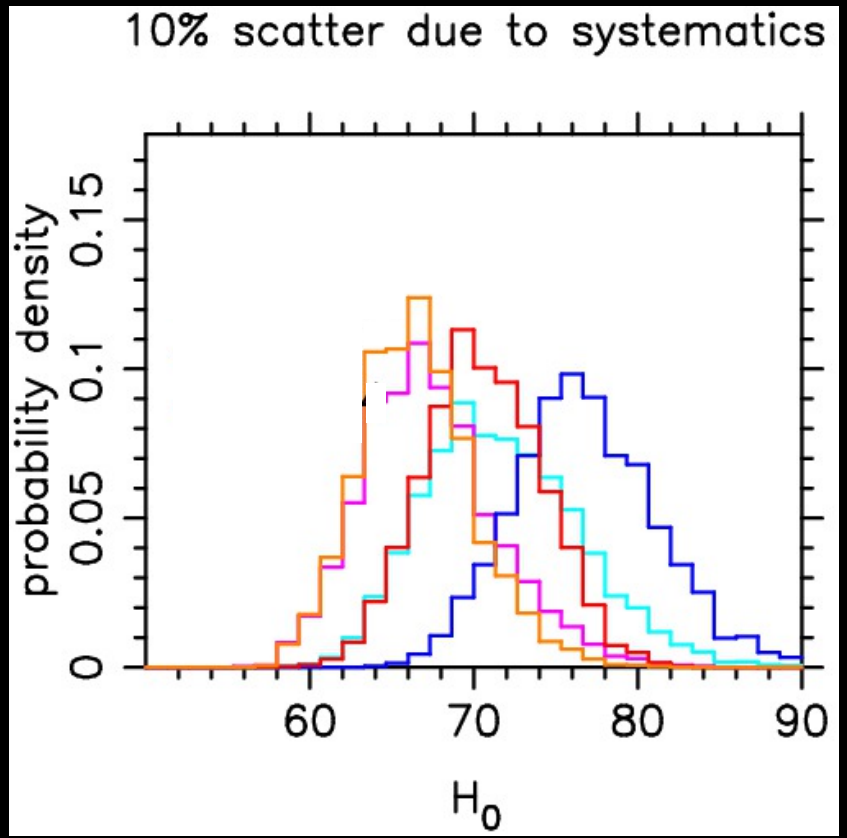
# Goal: $H_0$ with <4% uncertainty

H0LiCOW: Pilot sample of 5 lenses with excellent ancillary data to

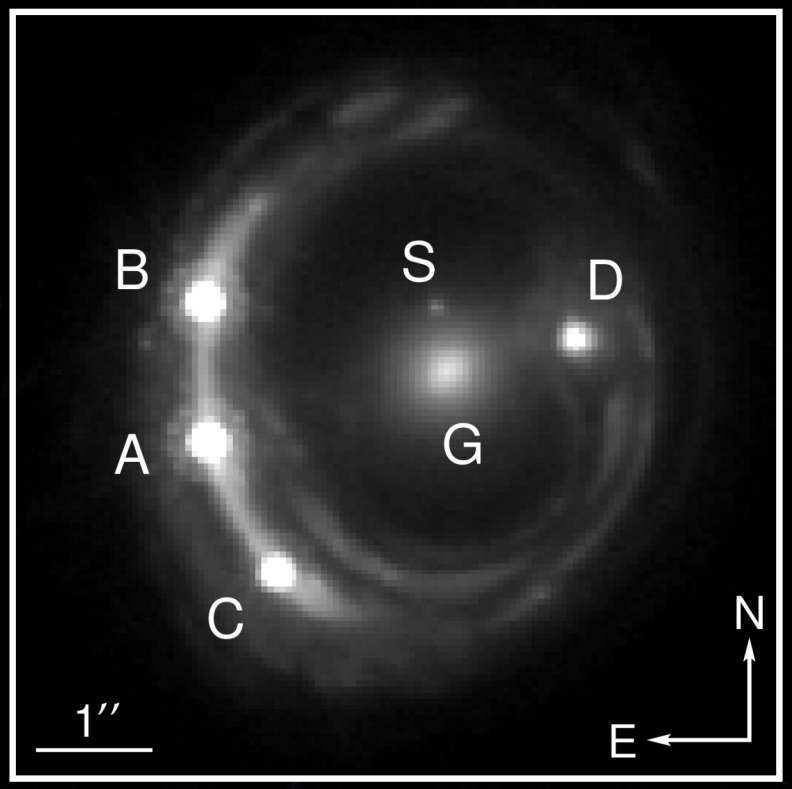
- gain in statistical precision
- test for systematics, particularly the unknown unknowns



# Cosmography with time-delay lenses

RXJ1131-1231




Time delay:

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

Time-delay distance:

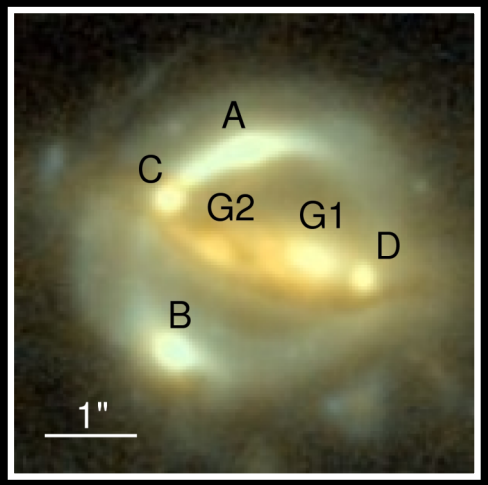
$$D_{\Delta t} \propto \frac{1}{H_0}$$

Obtain from lens mass model

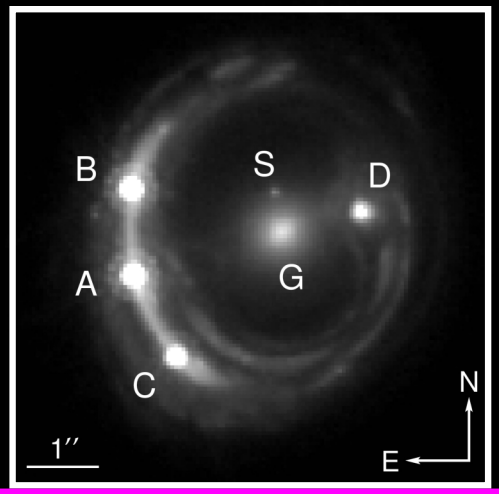
To measure $D_{\Delta t}$, need:
(1) time delays
(2) lens mass model
(3) mass along line of sight

# H0LiCOW Sample

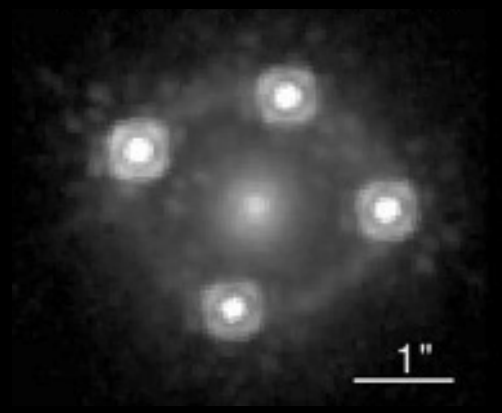
B1608+656

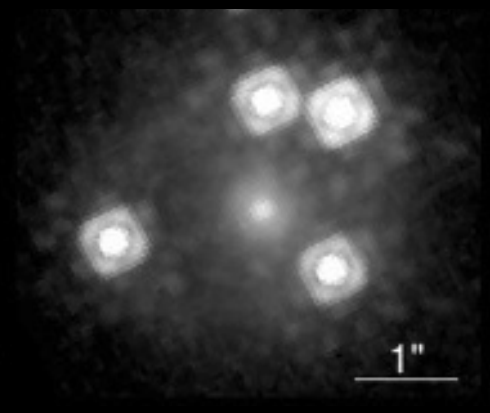


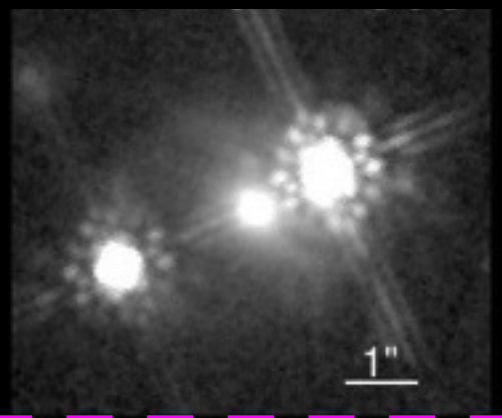

RXJ1131-1231




completed



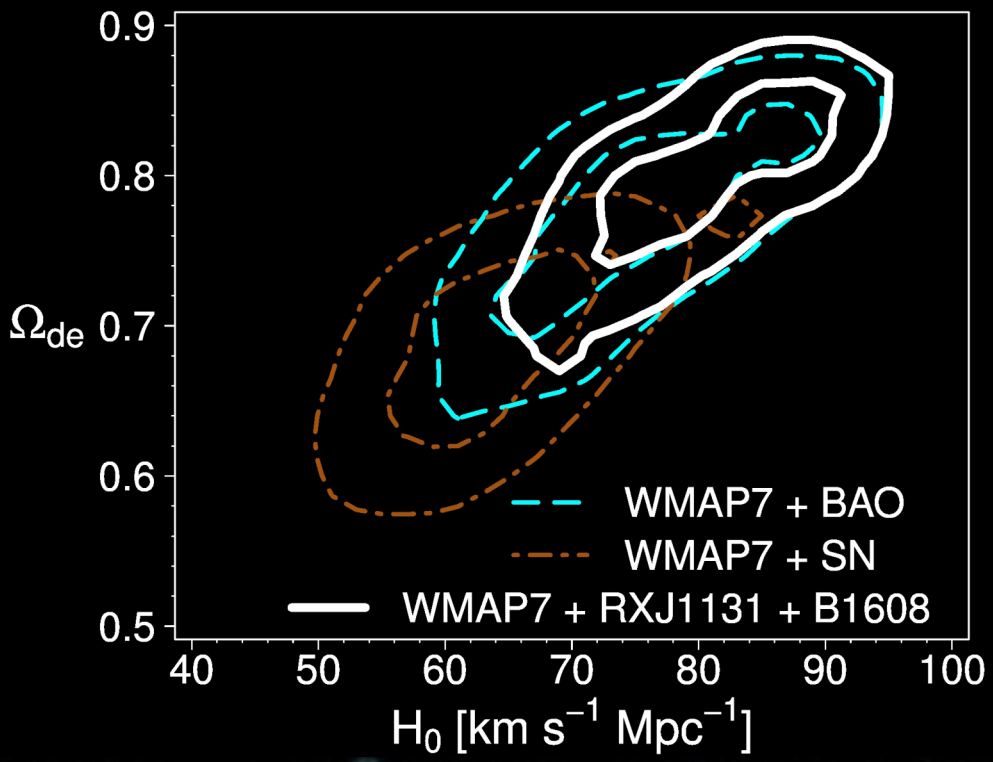



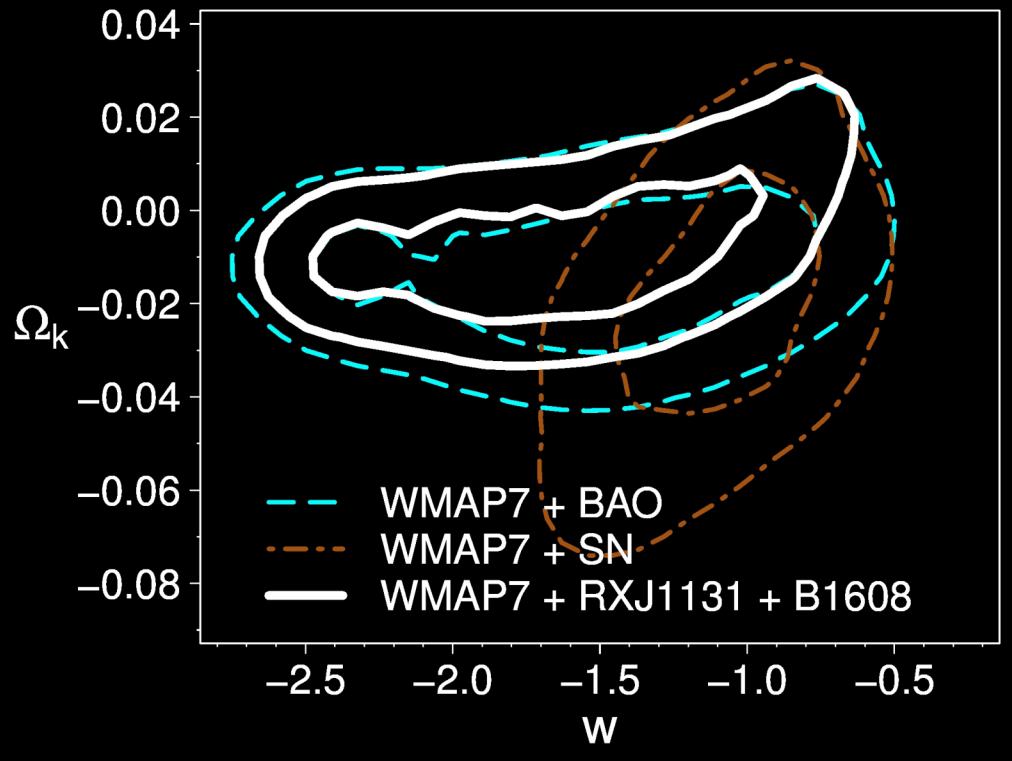

ongoing

# Cosmological Constraints from Two Time-delay Lenses

WMAP7owCDM prior

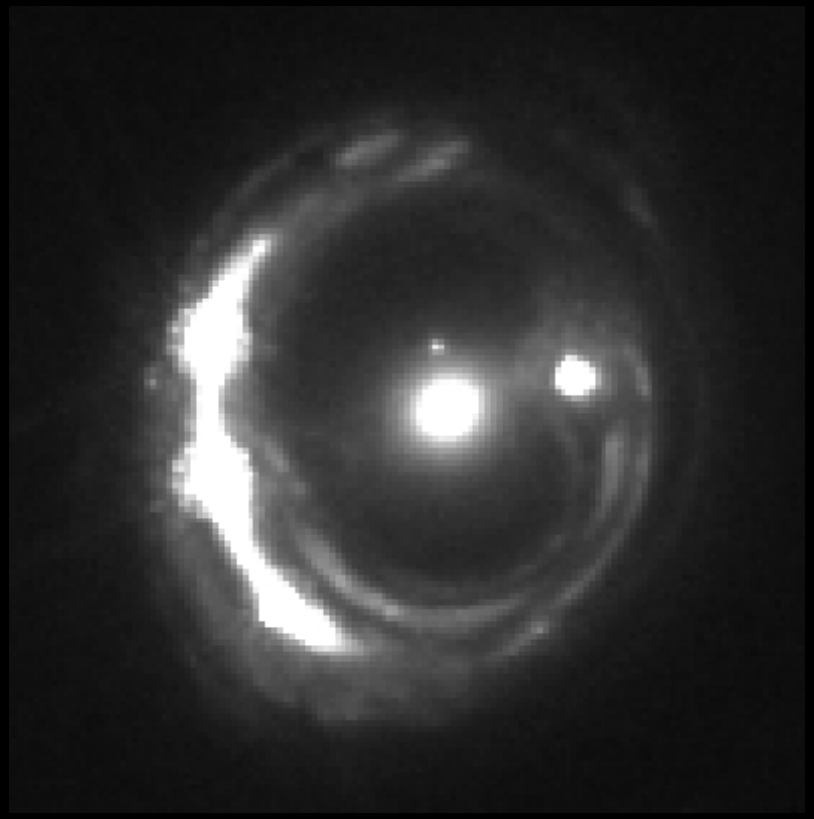
[Suyu et al. 2013]




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

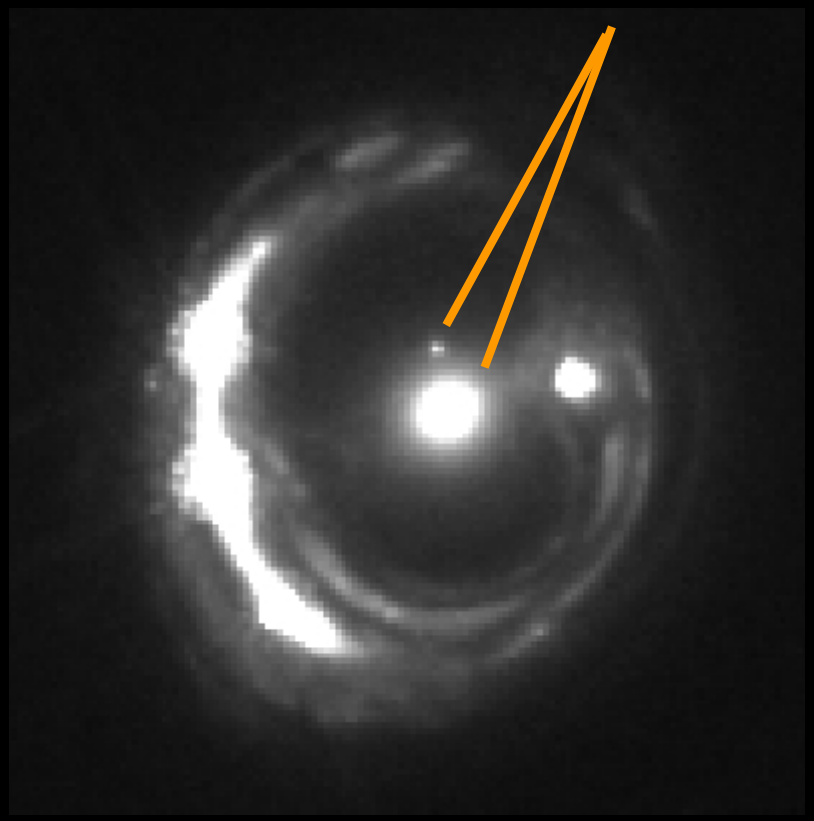
# RXJ1131-1231



Data:

- COSMOGRAIL time delays with 1.5% precision [Tewes et al. 2013]
- HST F814W imaging
- Lens velocity dispersion of 323+/-20 km/s from spectroscopy at Keck
- Relative galaxy number count of 1.4 within 45” from the lens [Fassnacht et al. 2011]

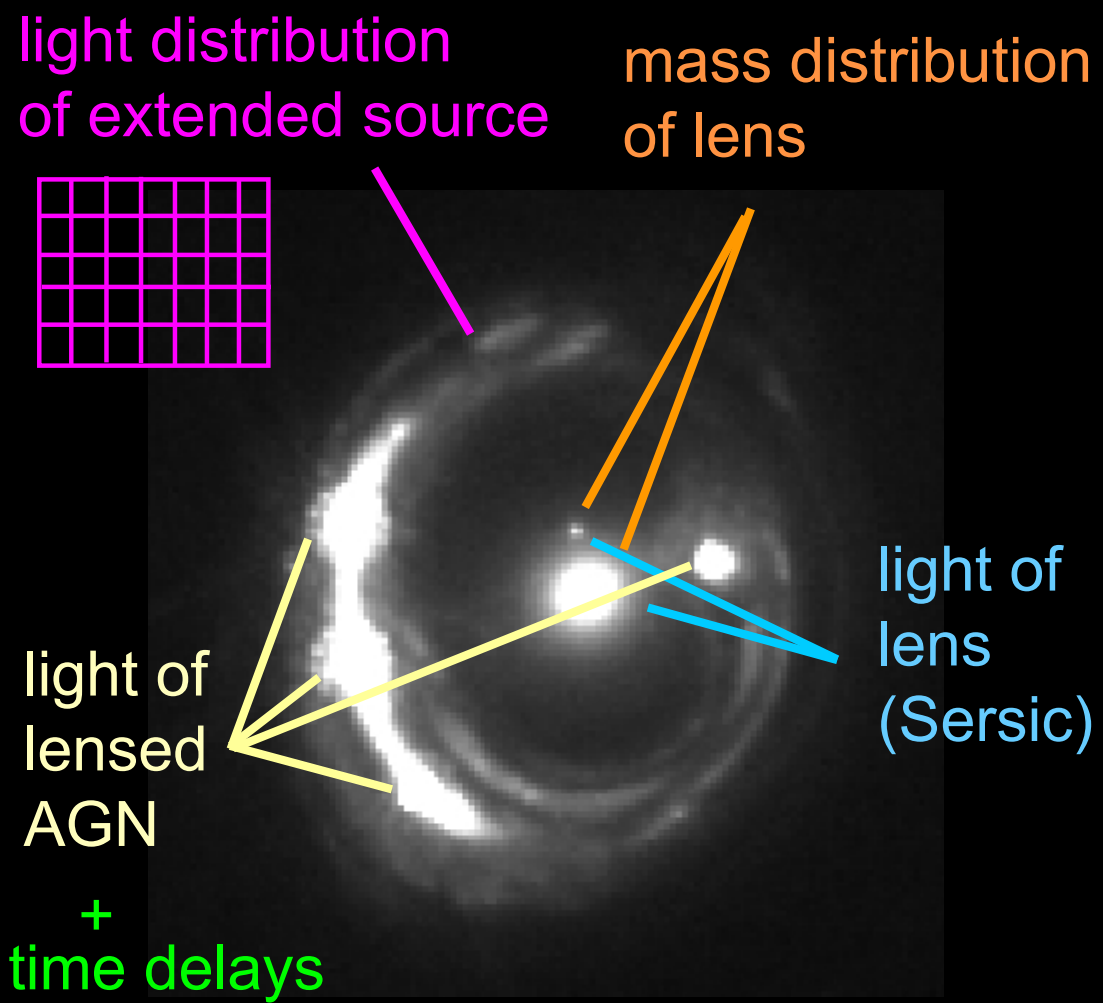
# Lens Mass Model



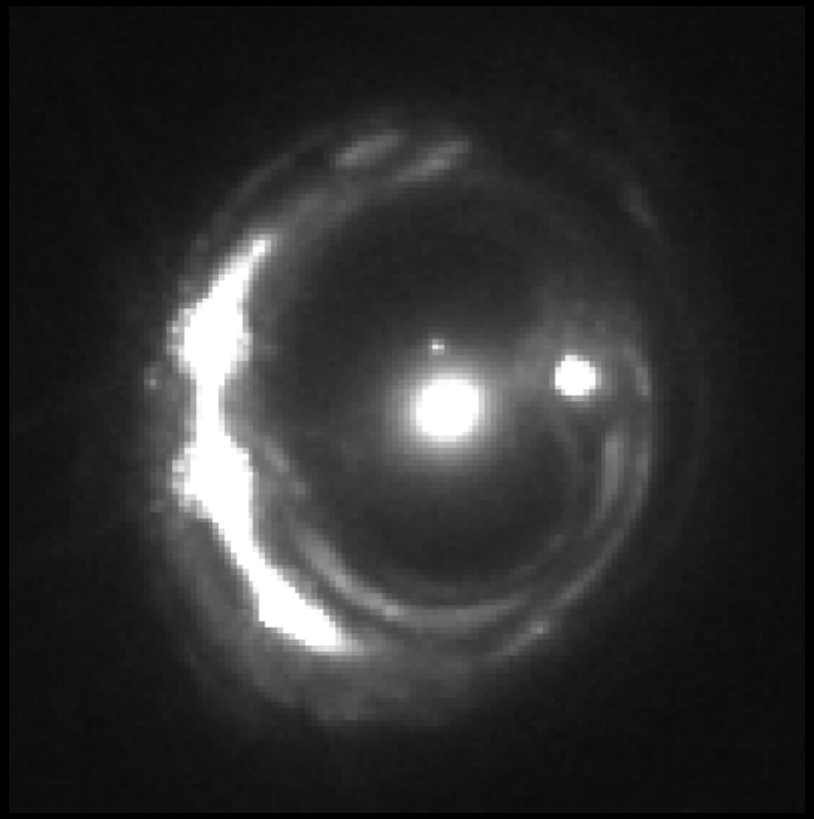

Three lens mass models:
(1) power-law profile
(2) cored power-law profile
(3) composite
- baryons = light x M/L
- dark matter = NFW halo

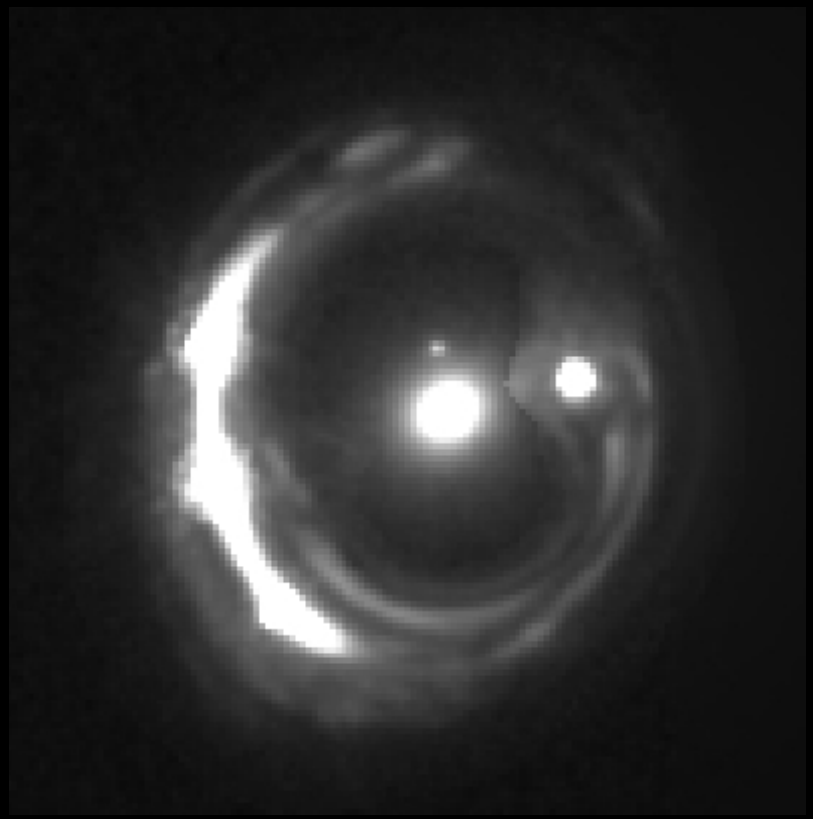
[Suyu et al. 2013, 2014]

# Lens Mass Model



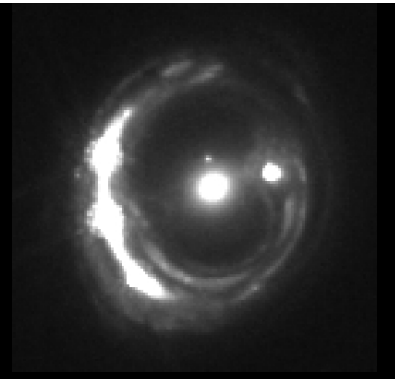
# Lens Mass Model



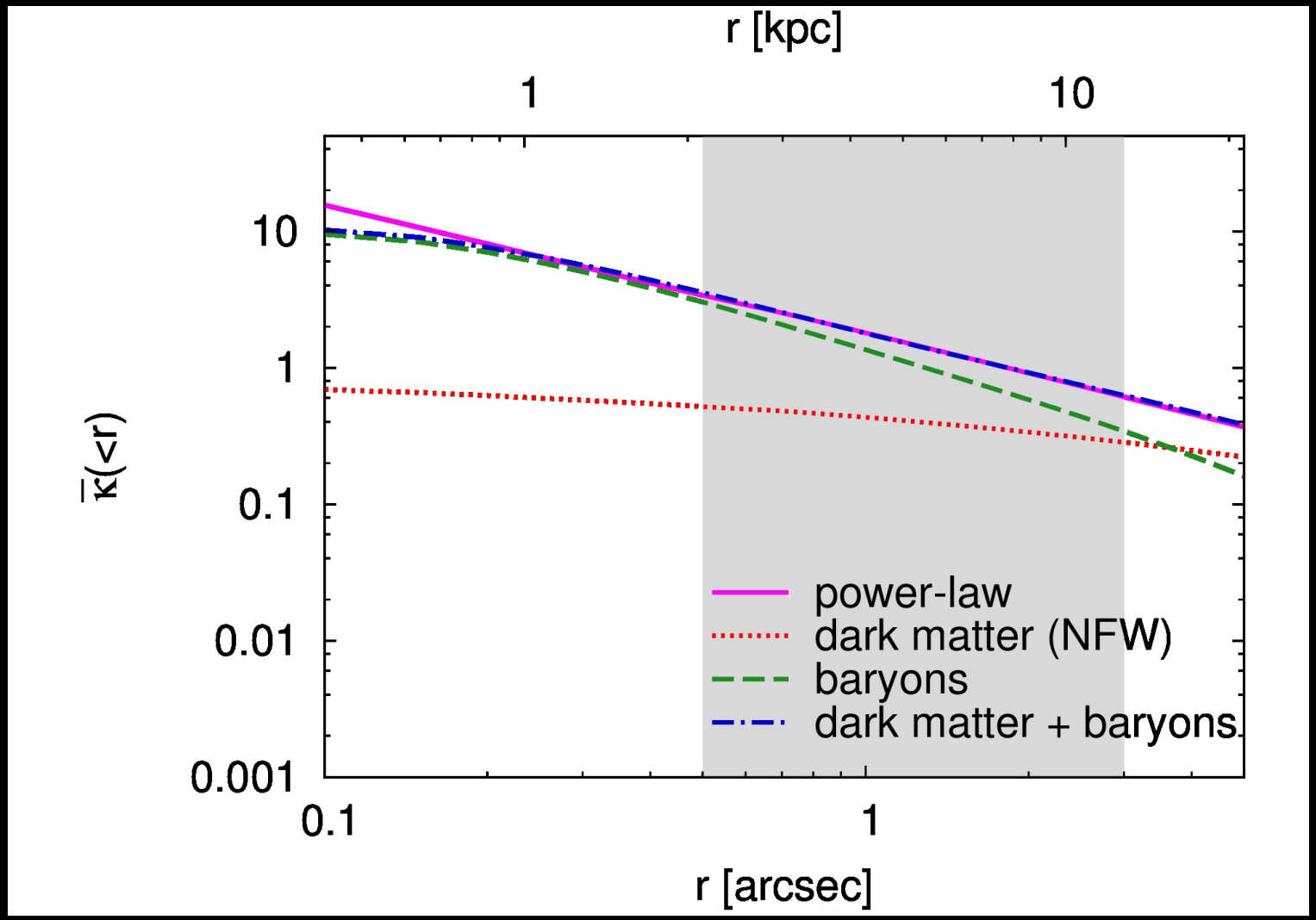


[Suyu et al. 2013]

# Lens mass profiles

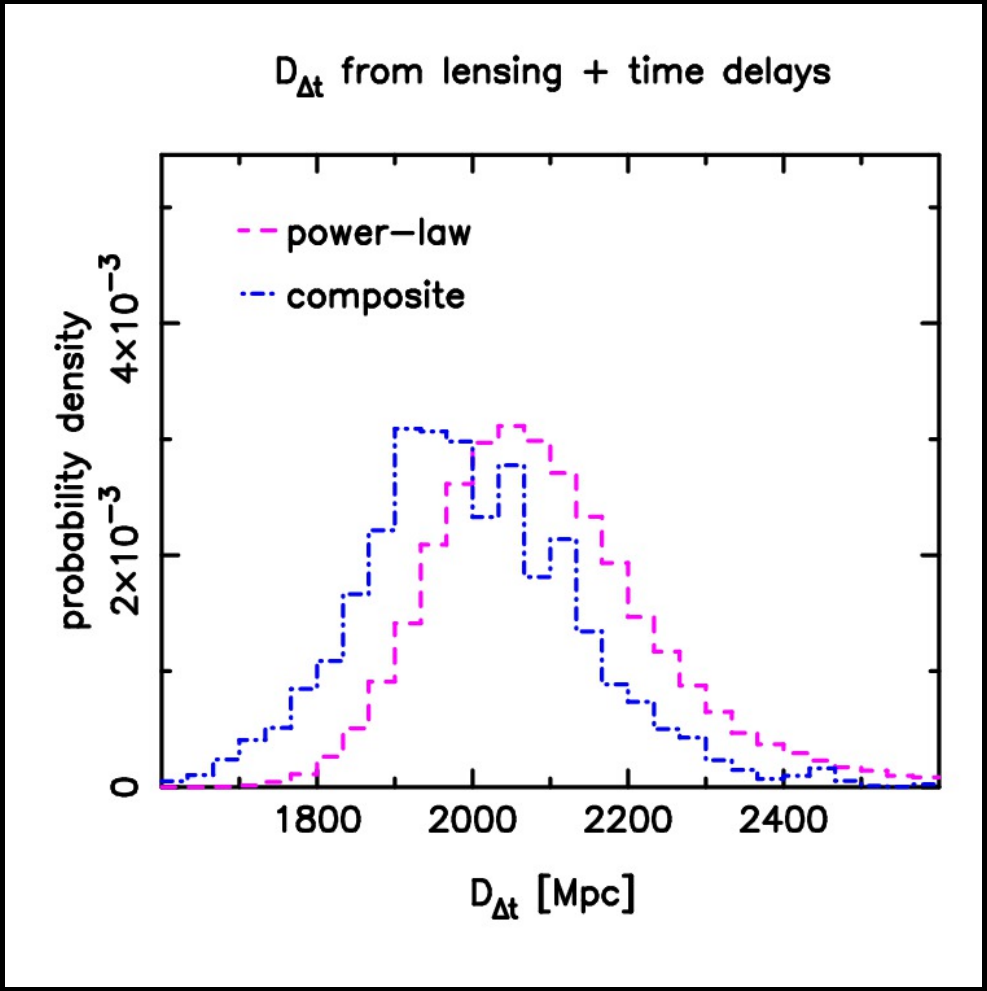


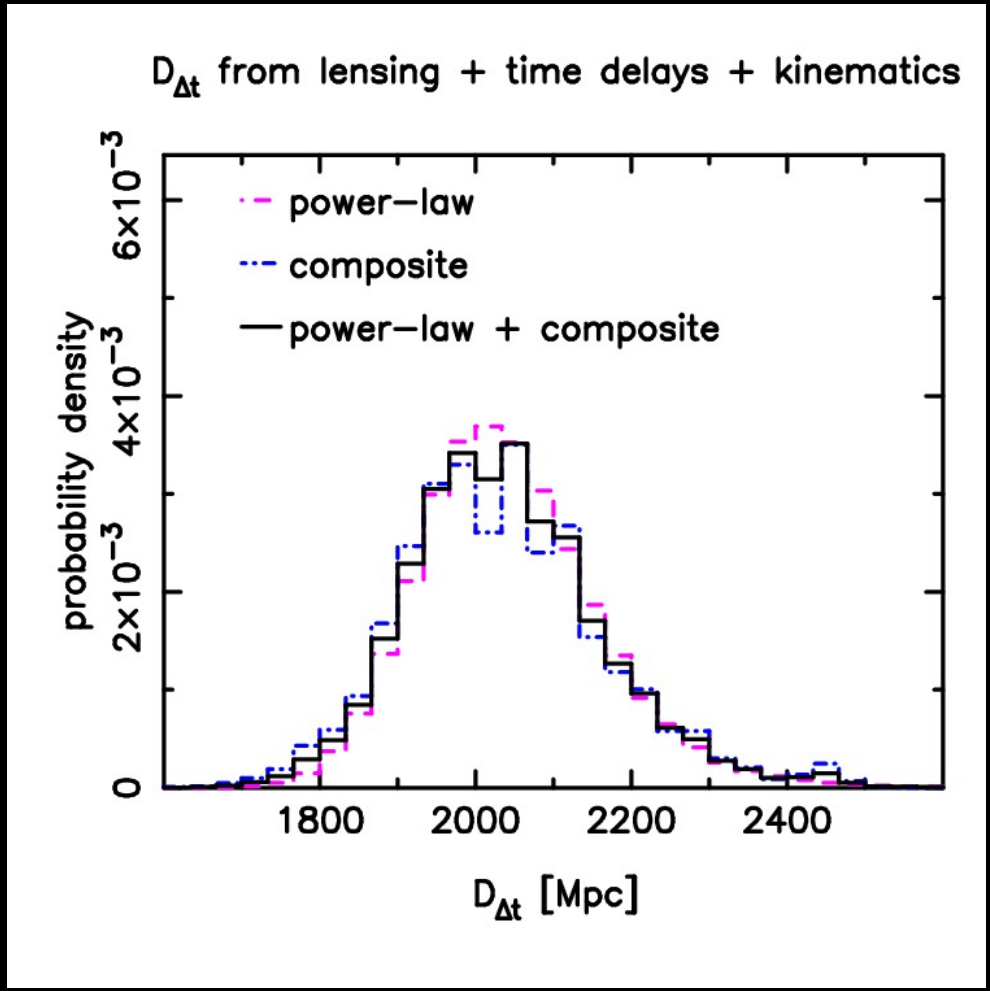
Comparison of power-law and composite model:




[Suyu et al. 2014]

# Power of lensing + kinematics



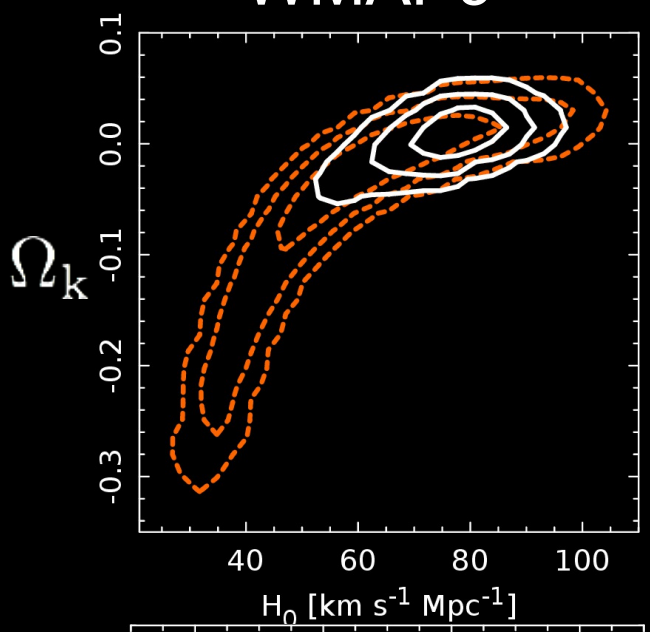

Velocity dispersion of the lens provide substantial information to break lens model degeneracies [Suyu et al. 2014]

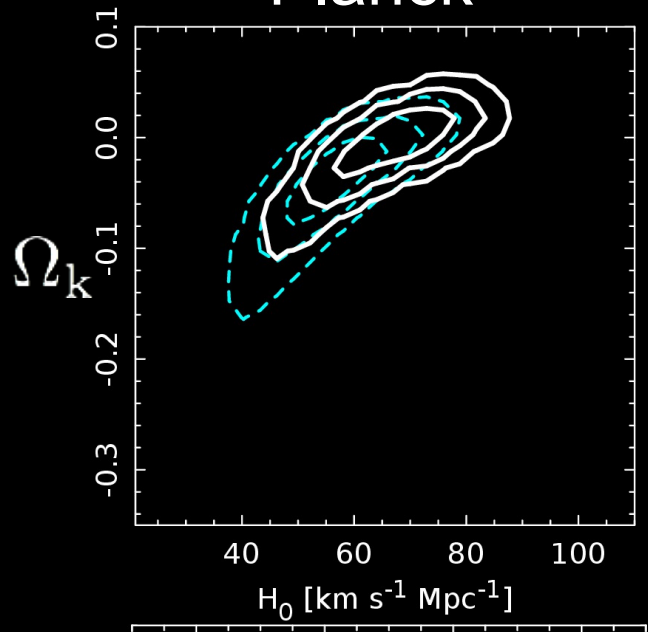
# Update: WMAP9 and Planck

WMAP9

Planck

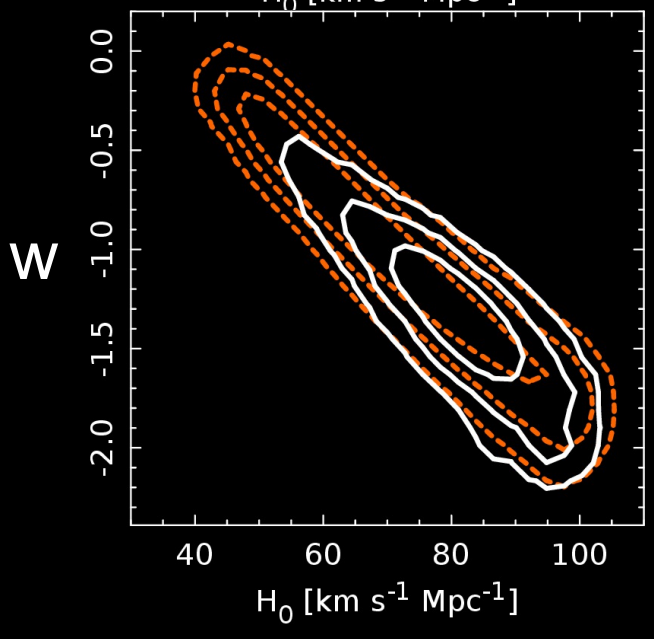
open ΛCDM

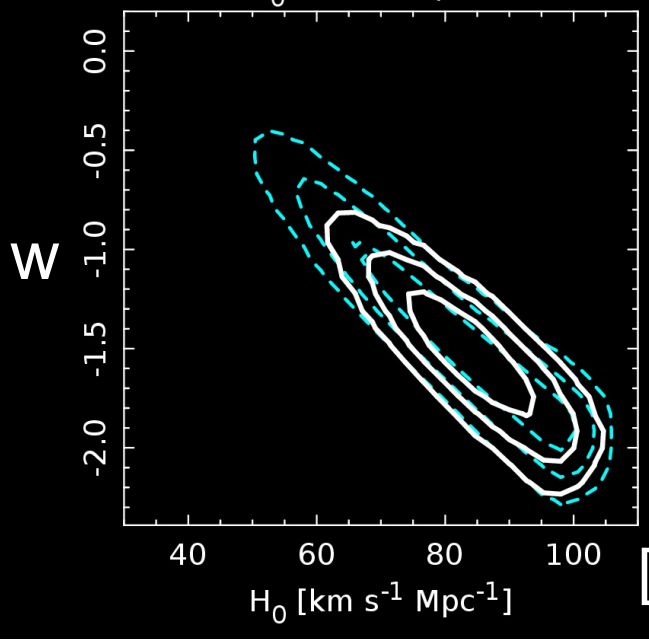



RXJ1131
+
CMB

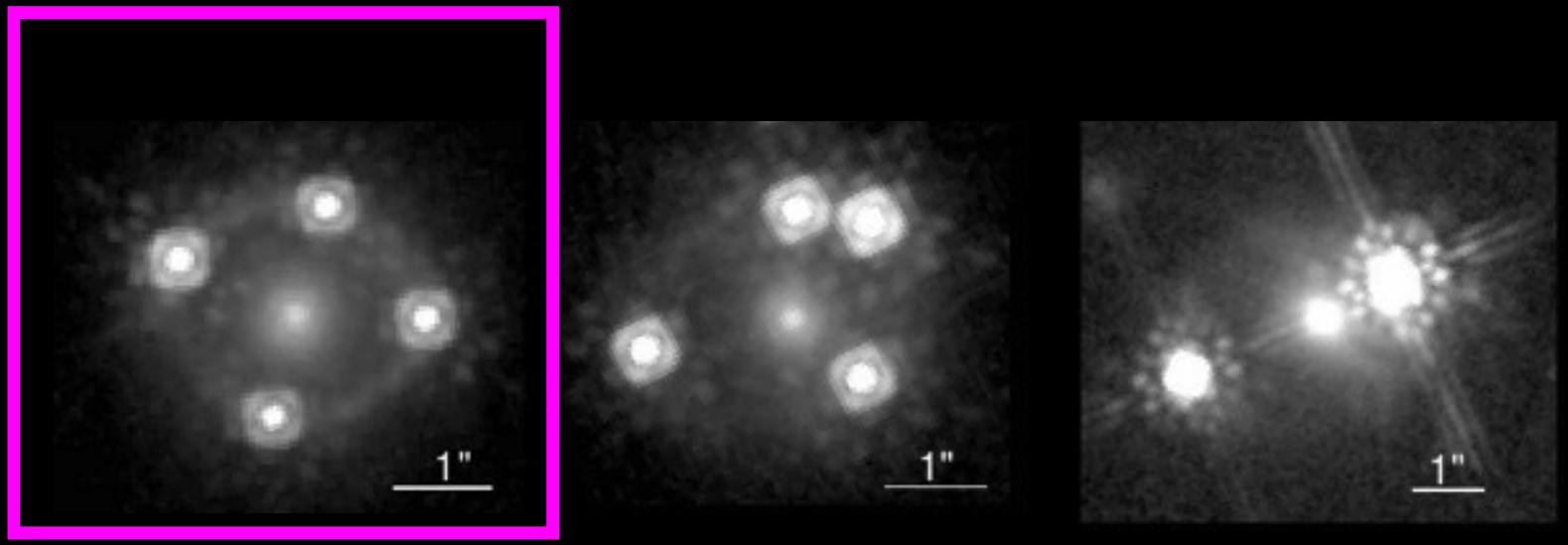
flat wCDM




[Suyu et al. 2014]

# Next 3 H0LiCOW Lenses

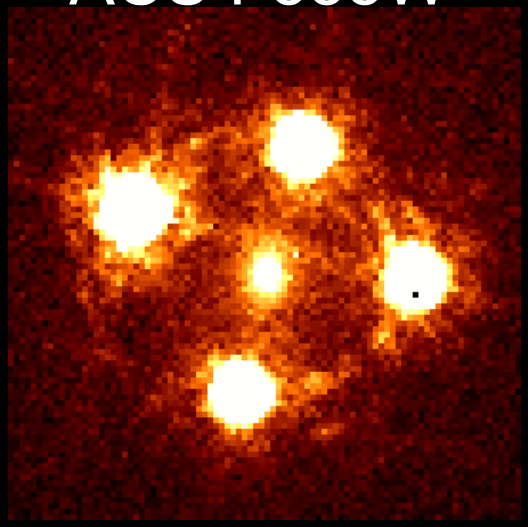



***Follow ups on next 3 lenses***:

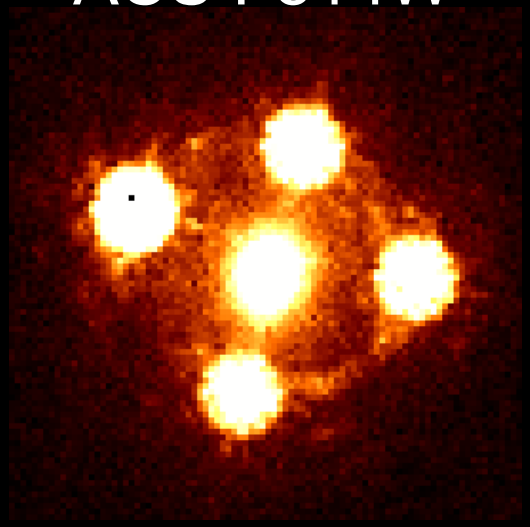
- delays with a few percent uncertainty from COSMOGRAIL
- *HST* deep imaging for modeling
- Lens galaxy spectroscopy pending
- Imaging and spectroscopy of the fields pending

# HE0435: modeling

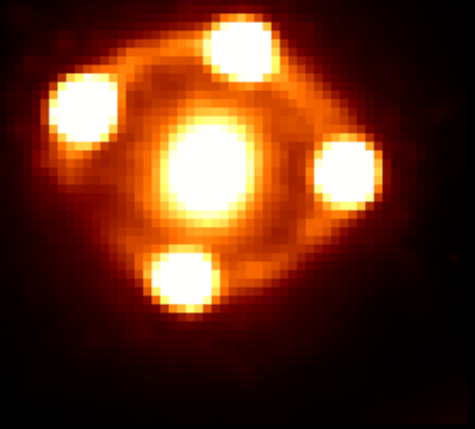
ACS F555W



ACS F814W



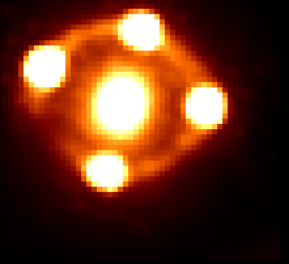
WFC3 F160W



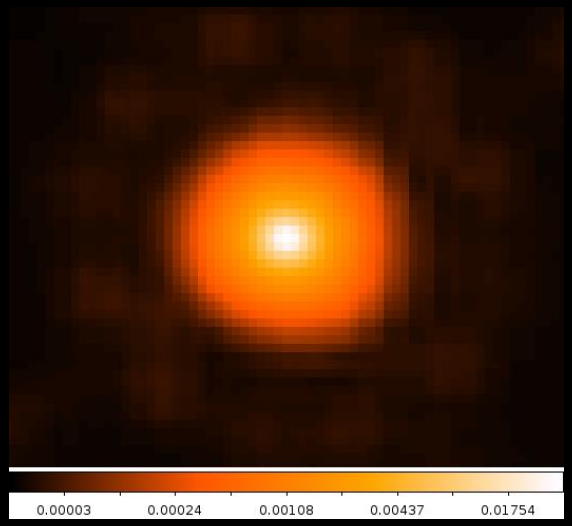
- HST imaging in 3 bands
- Modeling:
  elliptical power-law profile
  and external shear

Ken Wong

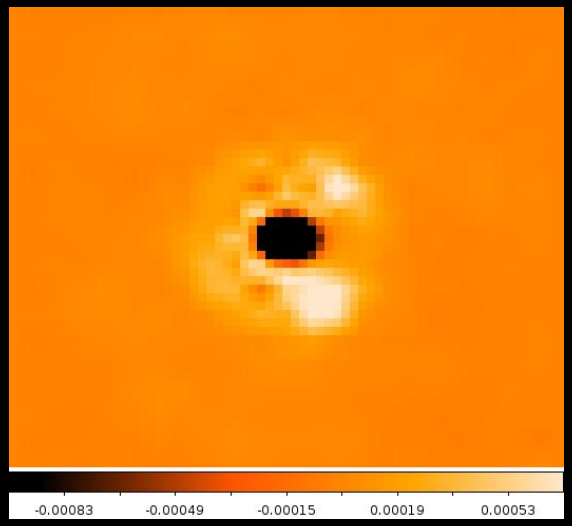
# HE0435: PSF (F160W) [Preliminary]



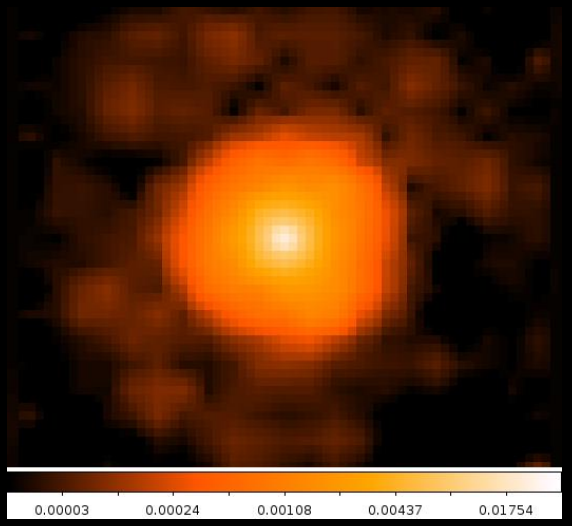
Initial PSF (from stars)




PSF correction (fractional)




Corrected PSF

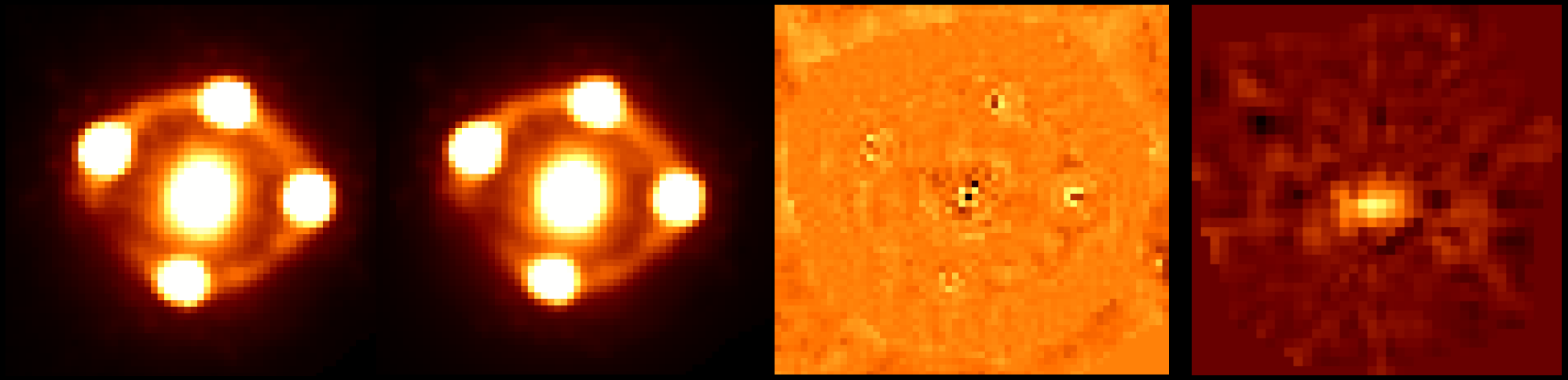



[figure material courtesy of Vivien Bonvin and Ken Wong]

- AGNs are very bright, so need accurate PSF model to extract the ring (of AGN host galaxy) for lens mass modeling
- Initial PSF built from stars in field (by Vivien Bonvin & Frederic Courbin)
- Correct the PSF on a grid of pixels, simultaneously with the ring modeling

# HE0435: image reconstruction (F160W) [Preliminary]

Data Model Residuals Source recon.



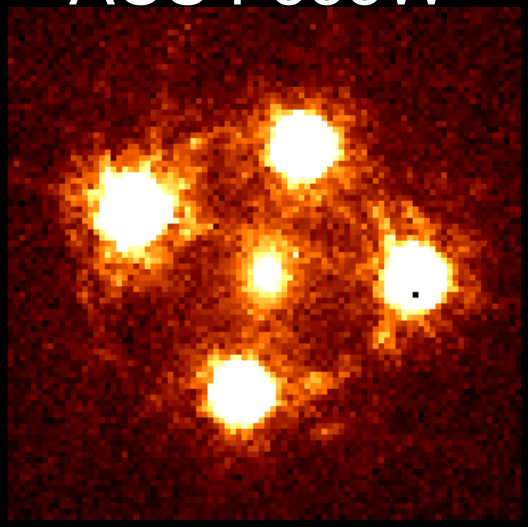
[figure material courtesy of Ken Wong]

Based on:

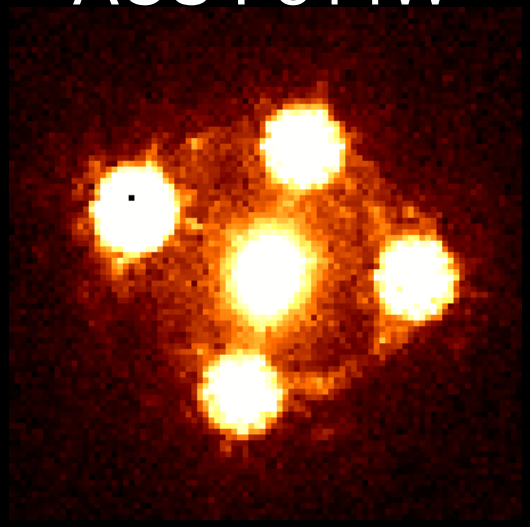
- power-law lens with external shear
- pixelated PSF correction

# HE0435: next steps

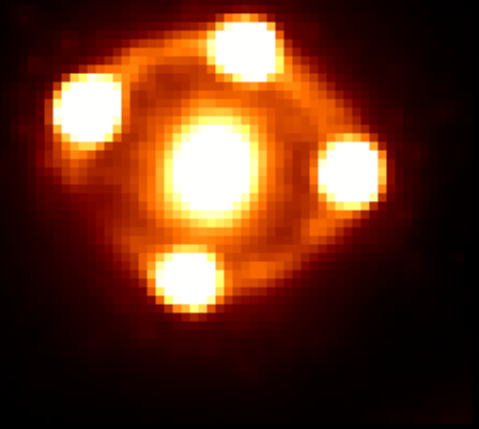
ACS F555W



ACS F814W



WFC3 F160W



- ACS bands modeling (ongoing)
- simultaneous modeling of all 3 bands
- use flexible mass models incorporating nearby perturbers
- characterize mass along the line of sight

# Cosmography and Beyond

- Exquisite imaging and spectroscopic data on H0LiCOW lenses enable a wide range of scientific studies
- Current projects based on H0LiCOW lenses:
  - Cosmography
  - Lens environment studies (number counts, weak lensing, galaxy group identification)
  - Interplay between baryons and dark matter
  - Stellar Initial Mass Function
  - Host galaxies of Active Galactic Nuclei
  - Data Challenge (simulations and real data)

# Summary

- H0LiCOW: pilot sample of 5 time-delay lenses with exquisite data to measure $H_0$ to better than 4% (stat. + sys.)
- 2 lenses analyzed with cosmological results competitive and complementary to other probes
- spatially extended Einstein ring and the multiple time delays provide constraints on the local profile of lens mass distribution in RXJ1131-1231
- velocity dispersion further breaks lens model degeneracies
- analysis of HE0435 ongoing
- H0LiCOW lenses are also great for studying dark matter distributions, stellar IMF and supermassive black holes