Cosmological Parameters from Strong Gravitational Lenses

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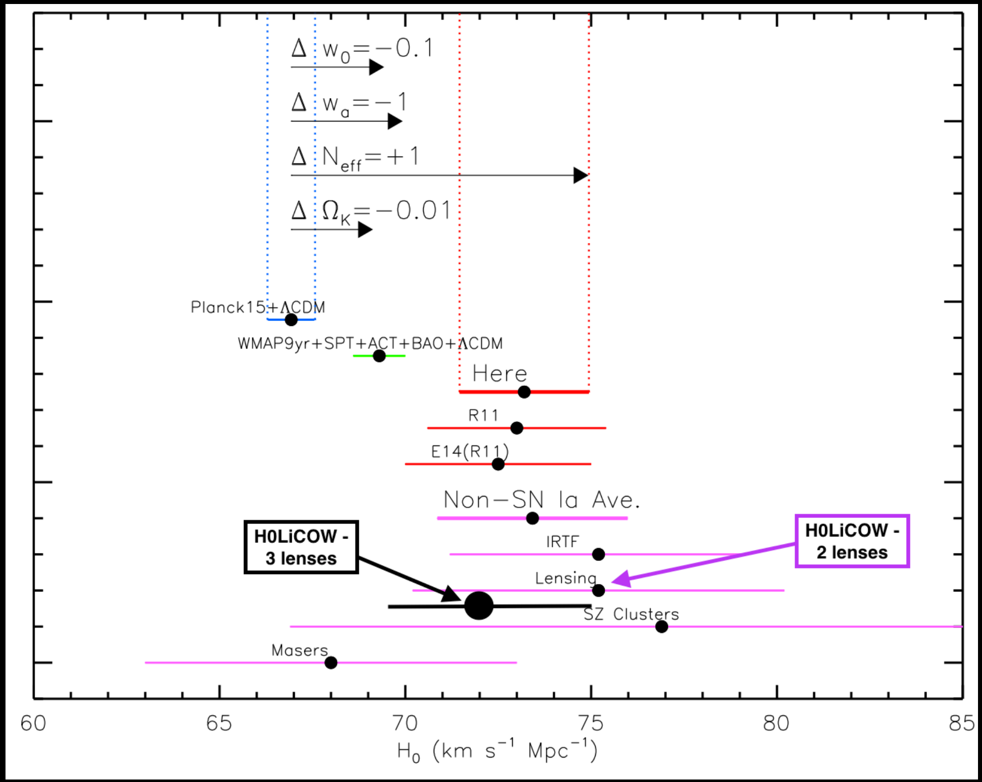
Motivation

- H_0 measurements in combination with CMB parameters are a powerful probe of dark energy
- CMB analysis assumes flat ΛCDM ("standard model")
- Indications of new physics will come from combination of CMB and lower-z probes
- Tension (3.8σ) between CMB and distance ladder / SNae ("Here" in the figure)
  - Note: Gaia results don't resolve the tension
- Need independent techniques to test for possible unknown systematics



Modified from Riess et al. (2016)

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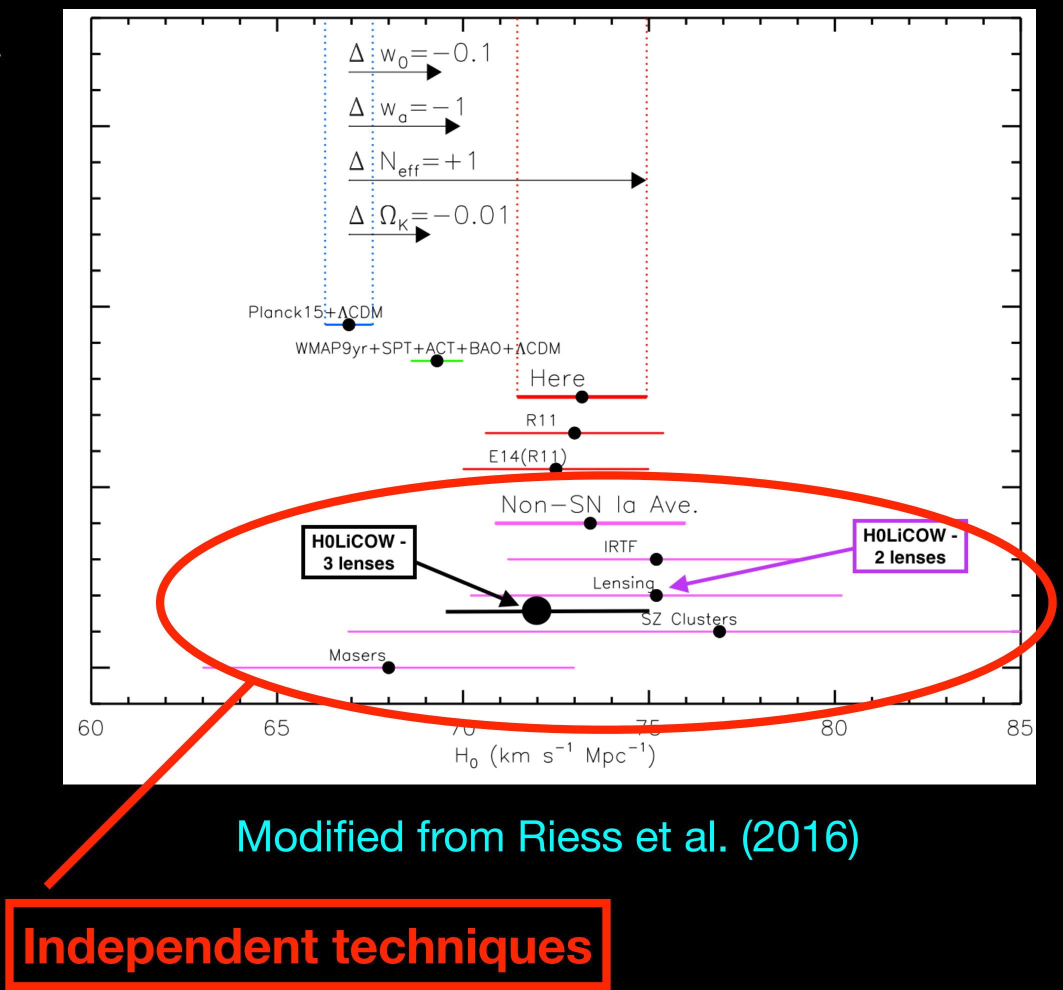
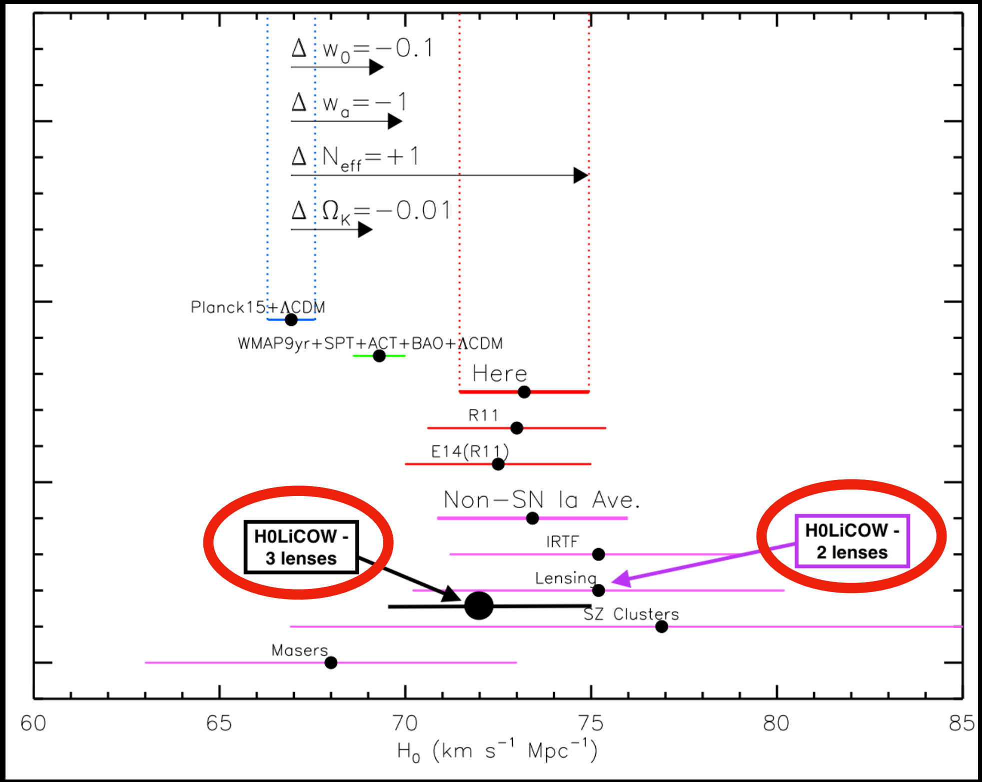


Modified from Riess et al. (2016)

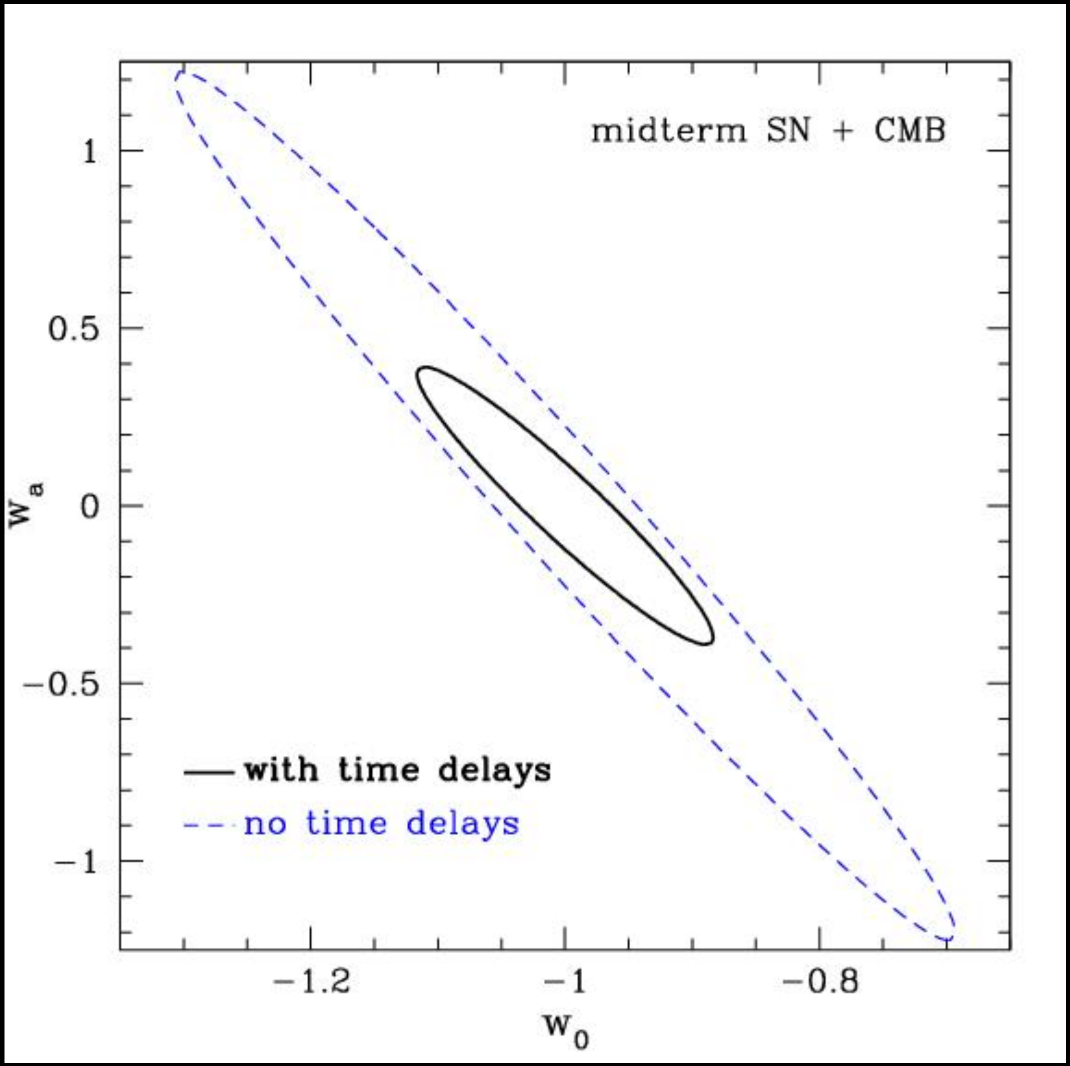
Motivation

- Time delay lenses are completely independent of distance ladder techniques
- Each well-constrained system provides a relatively precise and independent measurement of H_0 (6-10%)
- This can lead to a roughly sqrt(N) improvement in the uncertainties from time delay lensing (see plot)
- New large sky surveys (DES, HSC, LSST, Euclid, etc.) should provide thousands of new lensed quasar systems



Modified from Riess et al. (2016)

The Motivation: Combining probes



Linder 2011

- Confidence regions from different cosmology probes will not fully overlap in parameter space
- => More informative constraints by combining probes
- e.g., adding 150 time-delay lenses to SN + CMB can improve dark energy figure of merit by a factor of ~5 (Linder 2011)

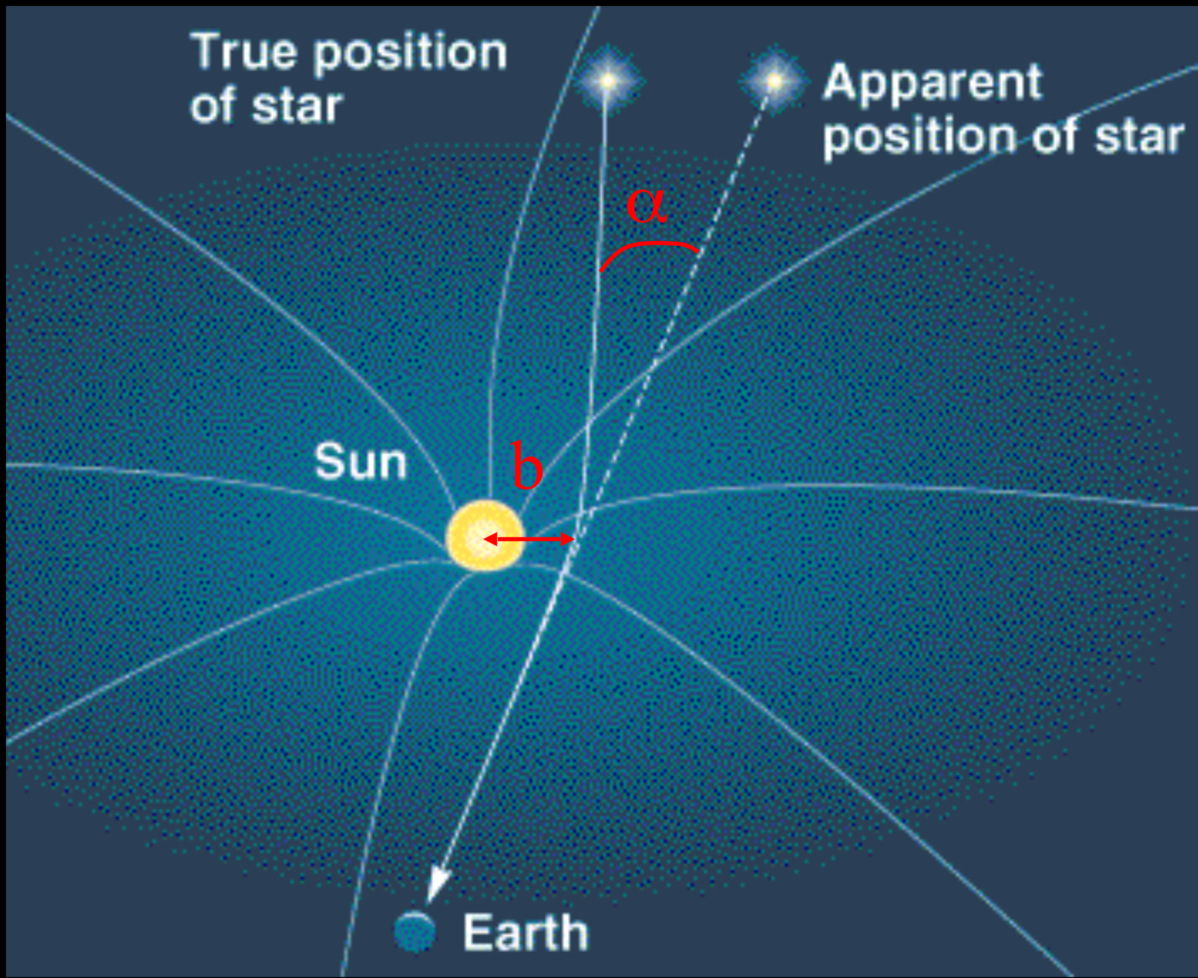
The Technique

Gravitational Lenses: The Basic Idea

- General relativity: mass can deflect light from its original path

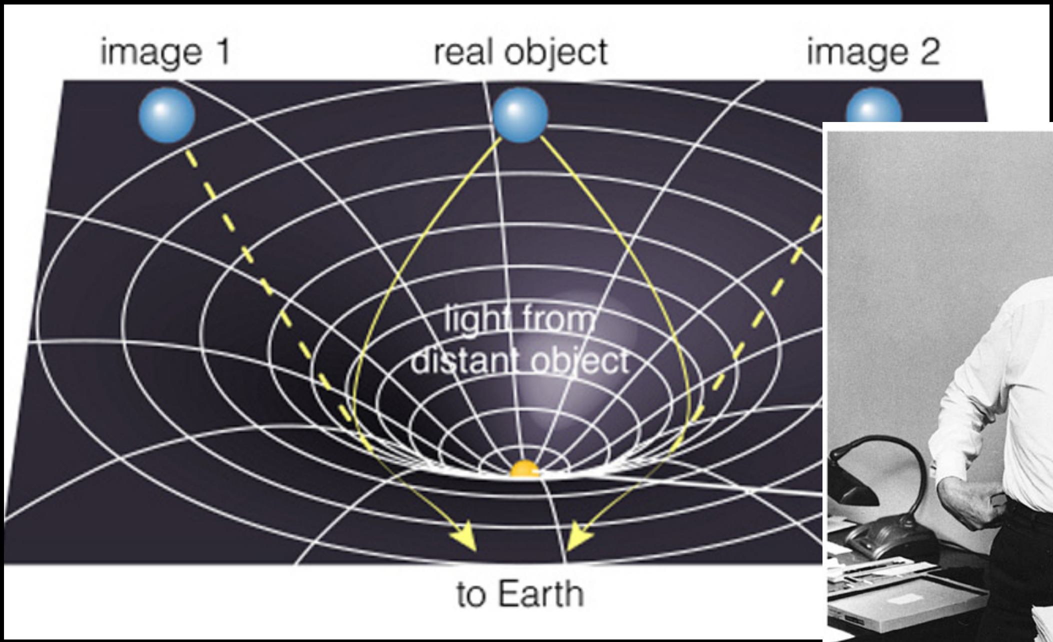
$$\alpha = \frac{4GM}{c^2 b} = \frac{2R_s}{b}$$

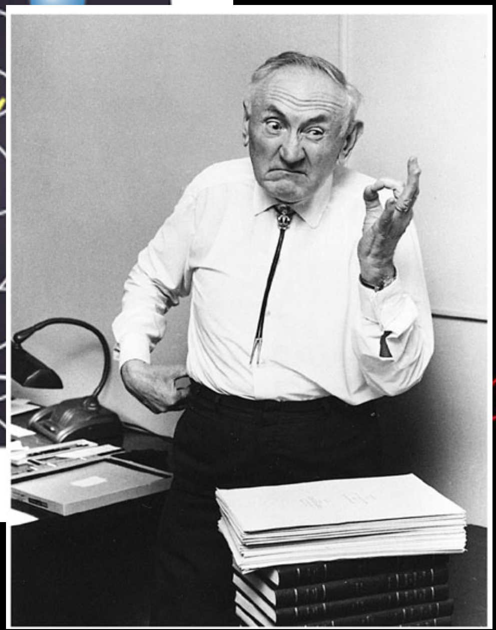
- Images of the background object will be magnified and distorted.

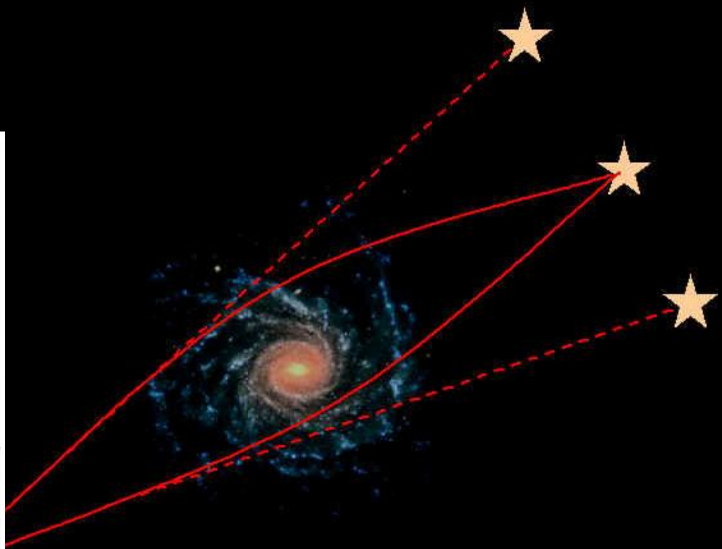


This is for a point mass, for extended masses need to account for full distribution

A high degree of alignment leads to multiple images (strong lensing)

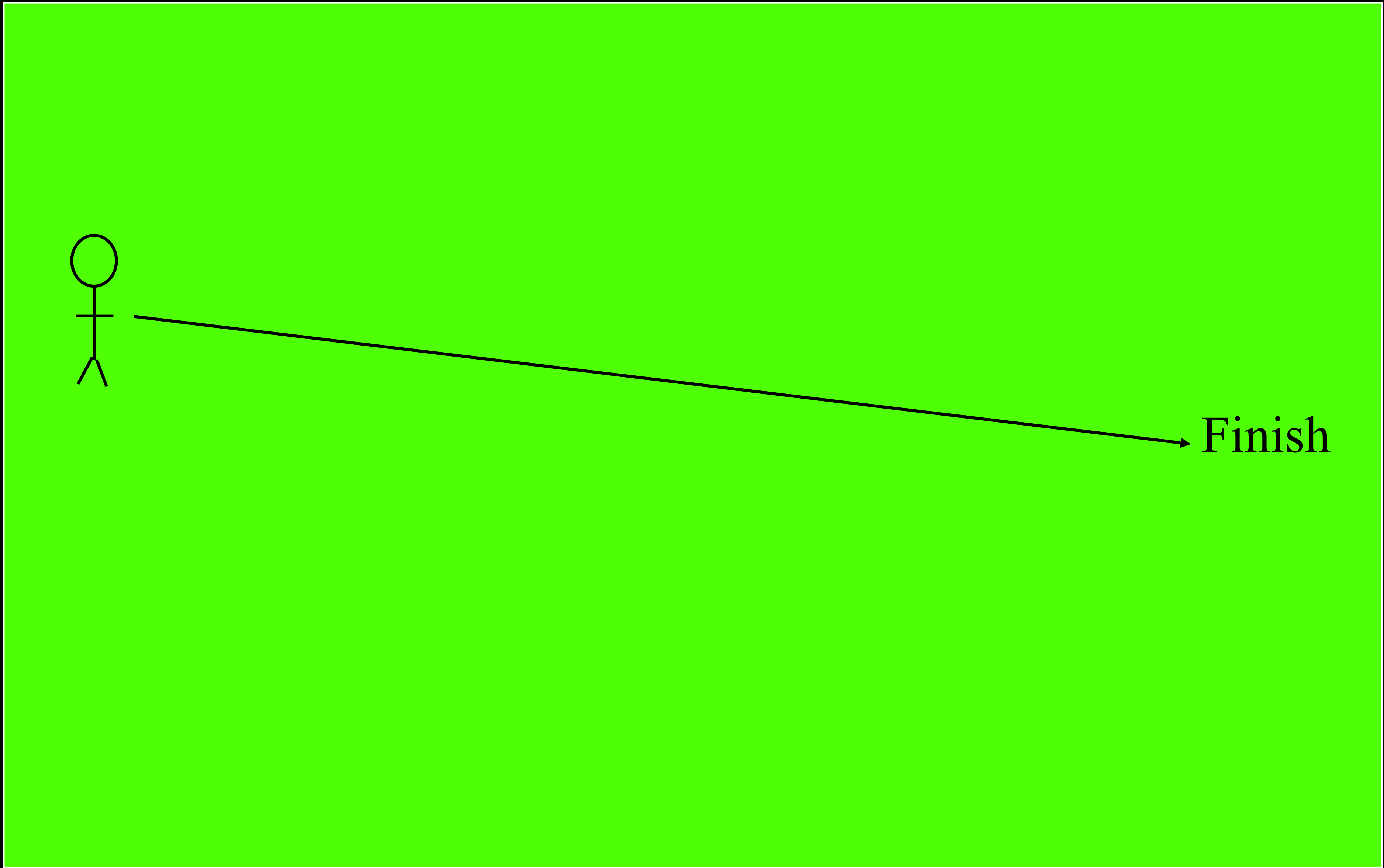




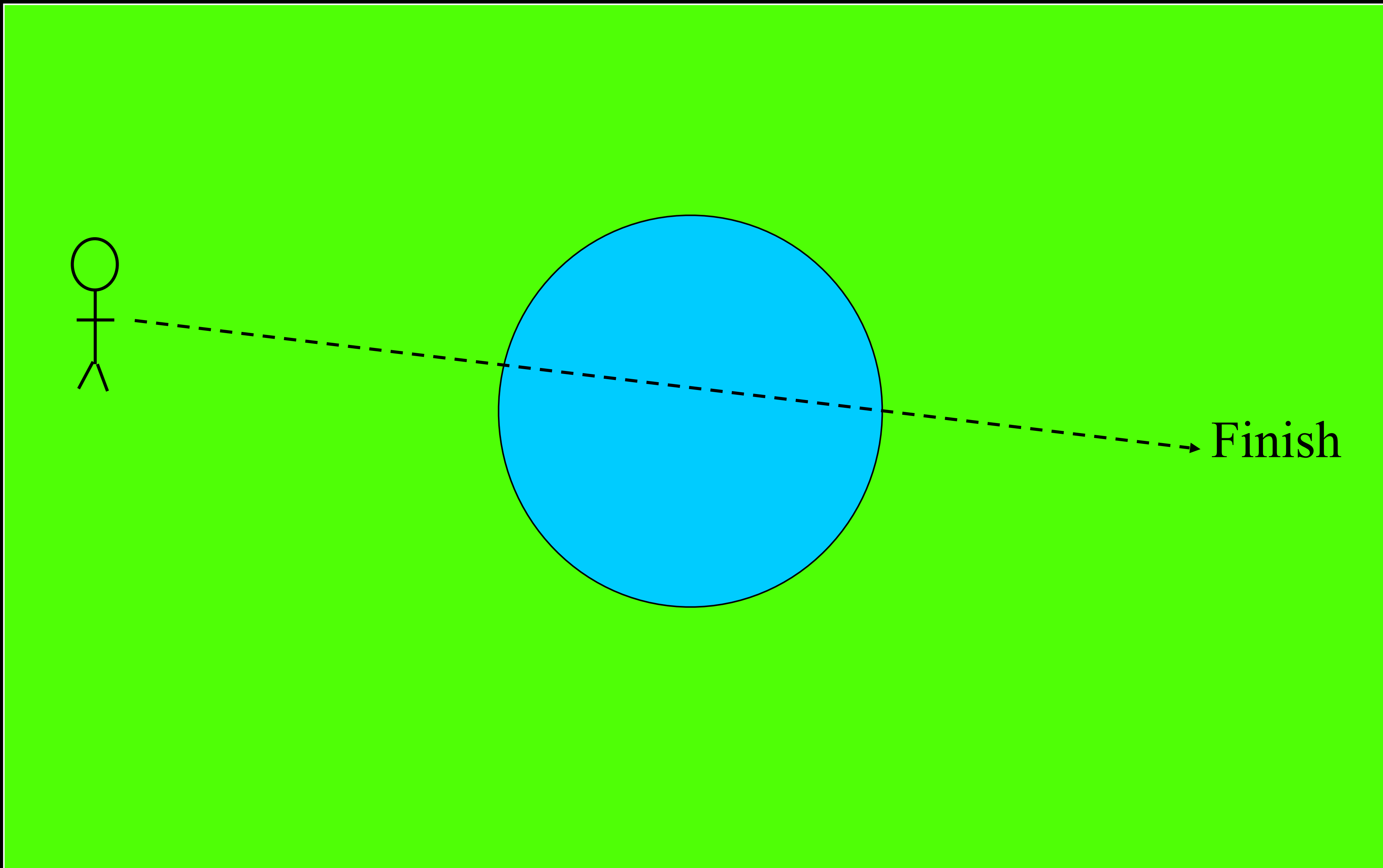


The mass of the lens (roughly) sets the angular separation of the lensed images

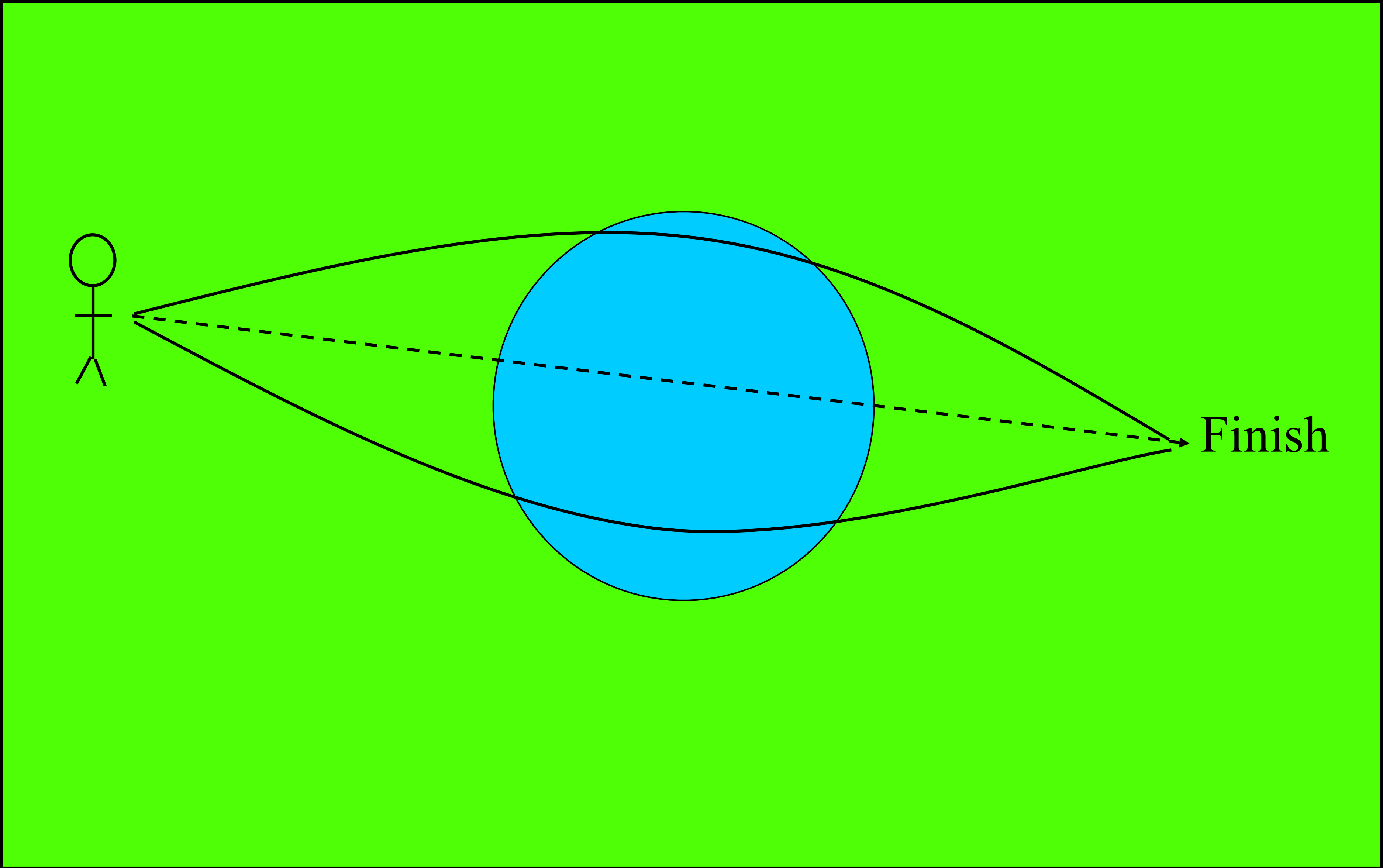
An analogy



An analogy

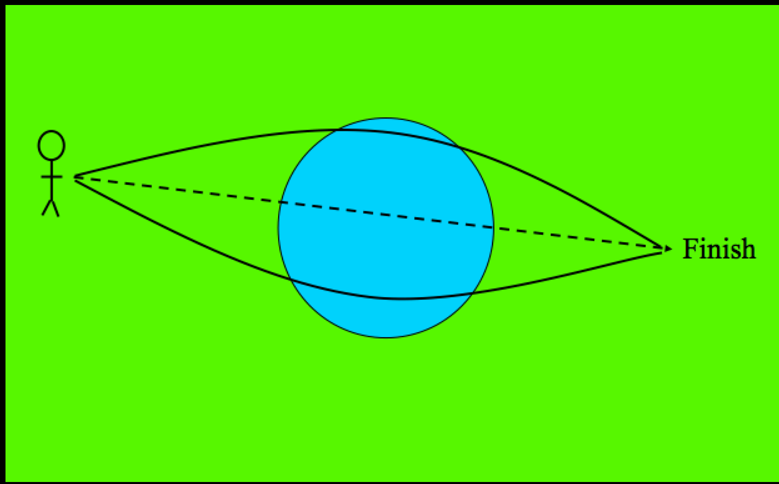


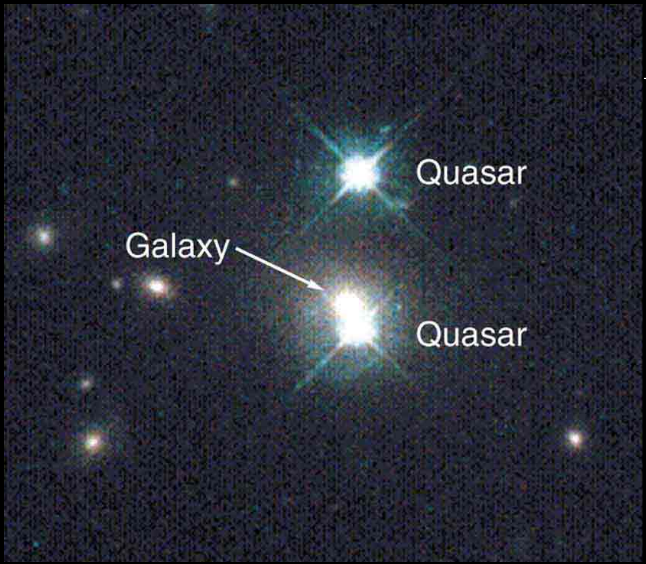
An analogy



Where the images appear depends on the mass distribution

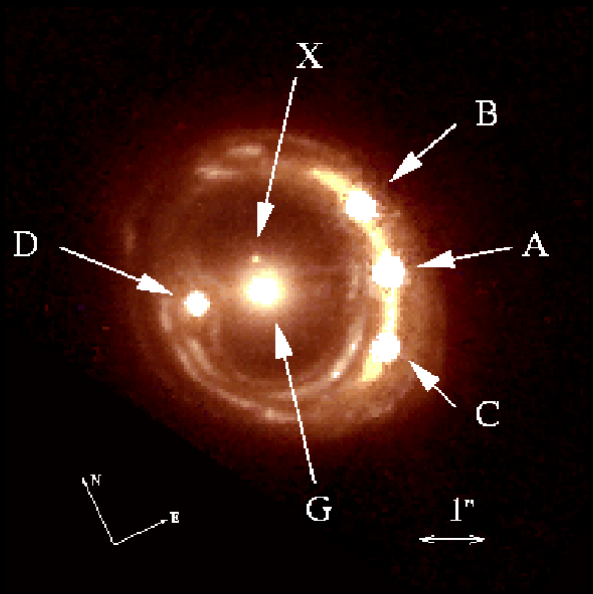
- The more lensed emission you have, the easier it is to constrain the mass distribution of the lensing object



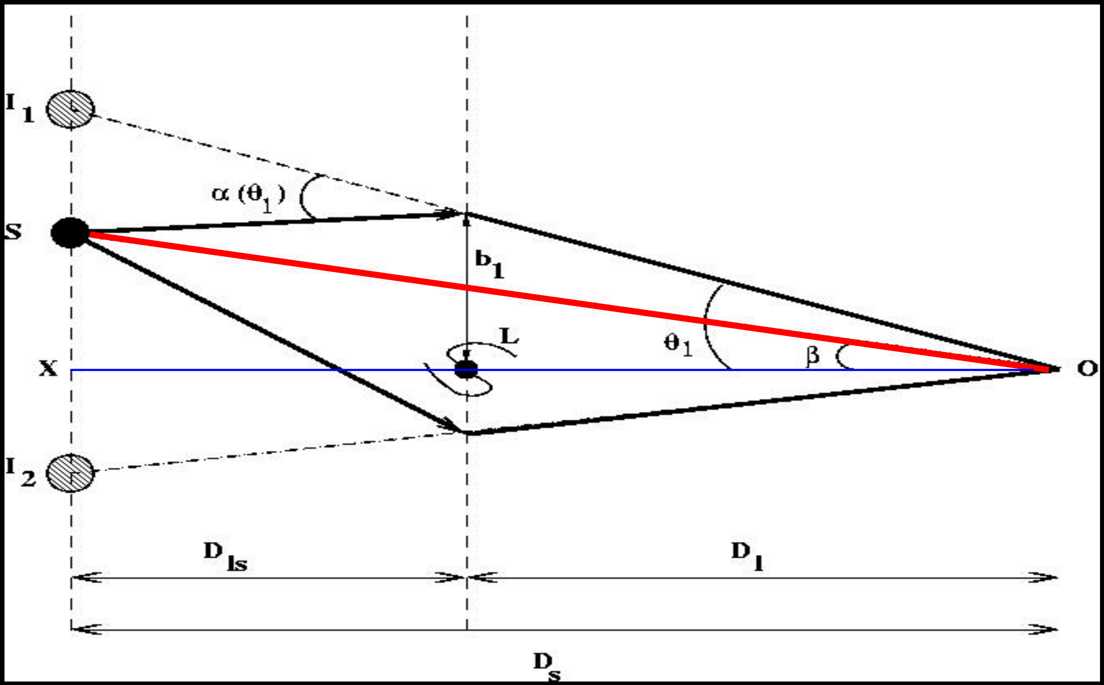


Not much info

Lots of info



Strong lensing in the time domain



- $\Delta t_{tot} = \Delta t_{geom} + \Delta t_{grav}$
- $\Delta t(\theta_i) = (D_{\Delta t} / c) \; [(1/2) \, |\theta_i - \beta|^2 - \psi(\theta_i) \,]$
- Images form where $d(\Delta t)/d\theta = 0$
- Measure time delays through variability
- $D_{\Delta t} = (1+z_l) \, (D_l \, D_s / \, D_{ls})$

From measurements to cosmology

$$D_{\Delta t} = \left(\frac{1}{1-\kappa_{\rm ext}}\right) \frac{c\,\Delta t}{\frac{1}{2}(\theta-\beta)^2 - \psi(\theta)}$$

- Observables
  - Δt , θ, z_l, z_s
- Model of the mass distribution in the lens
  - β, $\psi(\theta)$
- Characterize the line-of-sight structure
  - κ_{ext}
- Cosmology
  - $D_{\Delta t} = f(z_l, z_s, H_0, \Omega_M, \Omega_\Lambda, w)$

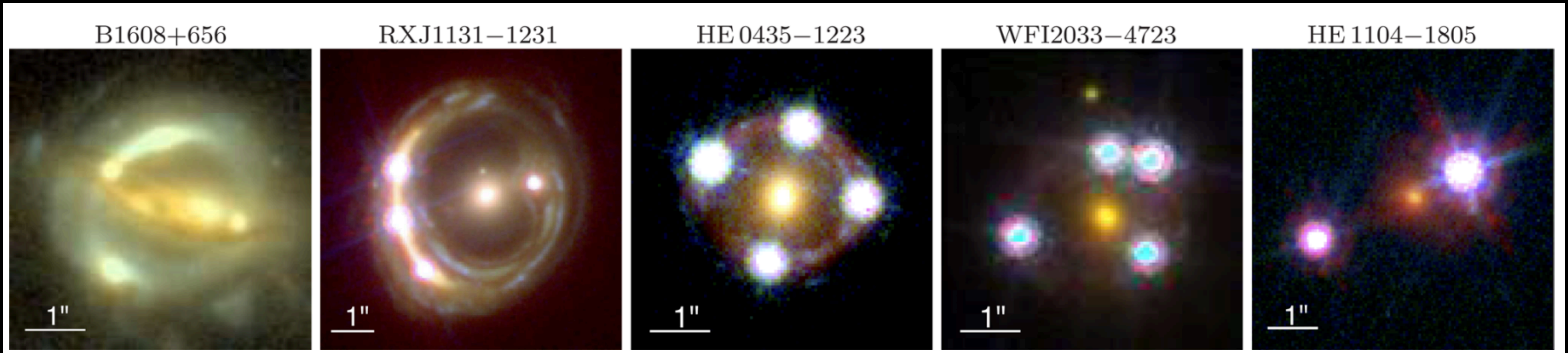
$$D_A = \frac{c}{H_0(1+z_2)} \int_{z1}^{z2} \frac{dz}{\sqrt{\Omega_M(1+z)^3 + \Omega_{\rm DE}^{3(1+w)}}} \quad (\text{for } \Omega_k = 0)$$

Where are we now?

A very brief history of cosmology from lenses

- 1979: First gravitational lens discovered
- 1980s and early 90s
  - Only a few gravitational lenses known
  - Time delays are very controversial
- Mid 1990s - mid 2000s
  - Dedicated monitoring programs produce high-precision time delay measurements
  - Modeling makes unwarranted assumptions, leading to large spreads in derived values of H_0
- Mid 2000s - today
  - Improvements in time-delay measurements and modeling lead to first high-precision H_0 measurements
  - H0licow program starts: 3 high-precision measurements so far (Suyu et al. 2010, 2013, 2014; Bonvin et al. 2017)

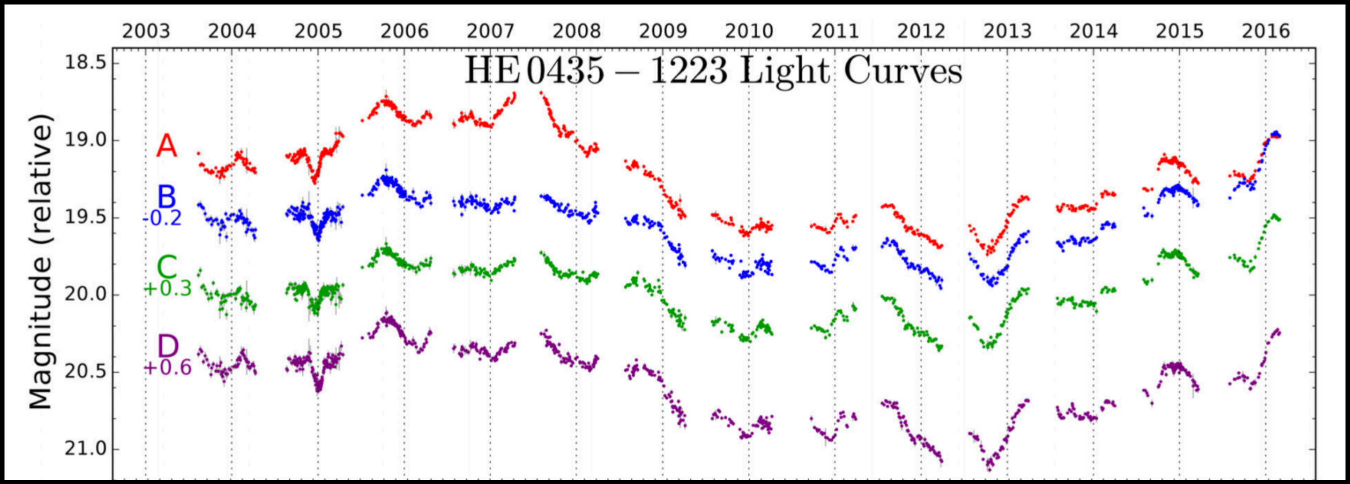
The H0licow program



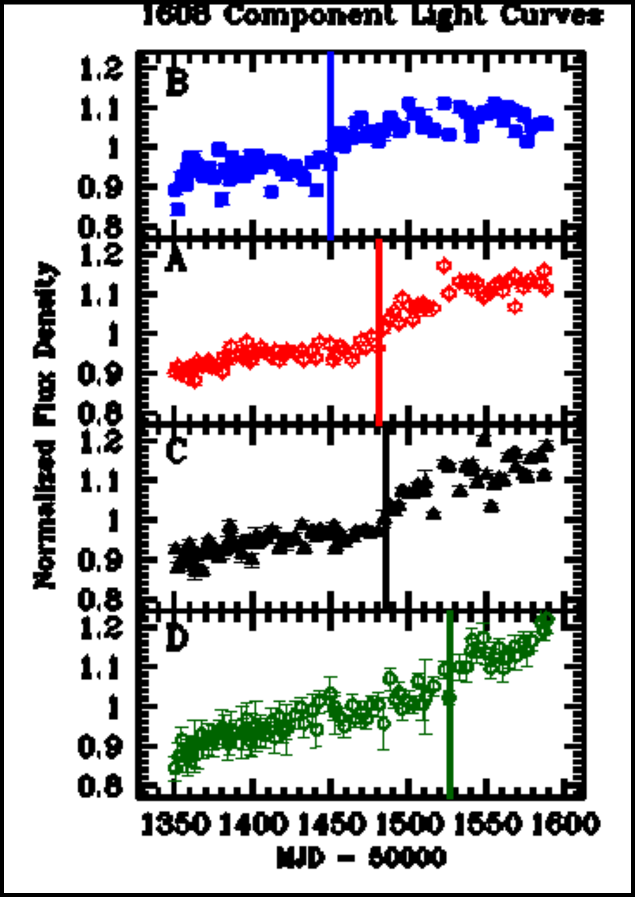
- Dedicated effort to use strongly-lensed quasars to make cosmological inferences, using a sample of five systems
  - Team unites several previously competing groups
- Employ latest modeling techniques, utilizing sensitive high-resolution imaging from HST
- Time delays from dedicated monitoring programs
  - COSMOGRAIL (4 of 5 systems) or at radio wavelengths (1 of 5)
- Incorporate line-of-sight information based on deep imaging and spectroscopy
- Full analysis complete for 3 systems: B1608, RXJ1131, and HE0435

Time delay measurements

- Dedicated lens monitoring campaigns can measure delays to a few percent or better
- Optical (1-2m class telescopes) or radio (VLA)
- Cadences: every 3-5 days



Optical: Bonvin et al. 2017

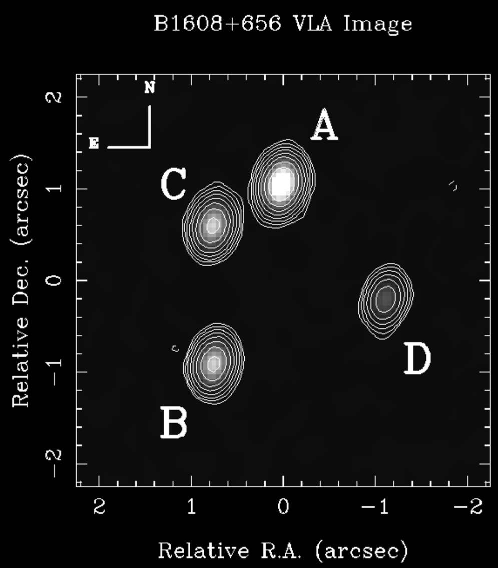


Radio: Fassnacht et al. 2002

Modeling the lens galaxy: Imaging

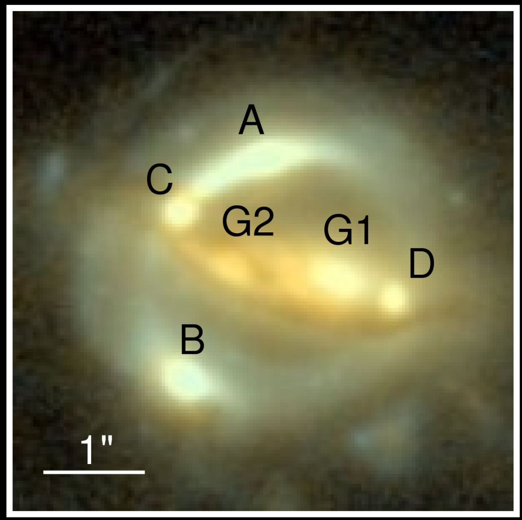
- Old days: only had positions and possibly fluxes of lensed AGN
- Huge flexibility in possible mass models

- Now: include lensed AGN host galaxy
- Breaks (mostly) the slope-H_0 degeneracy
- Gives few % uncertainties
- Requires sensitive high resolution imaging



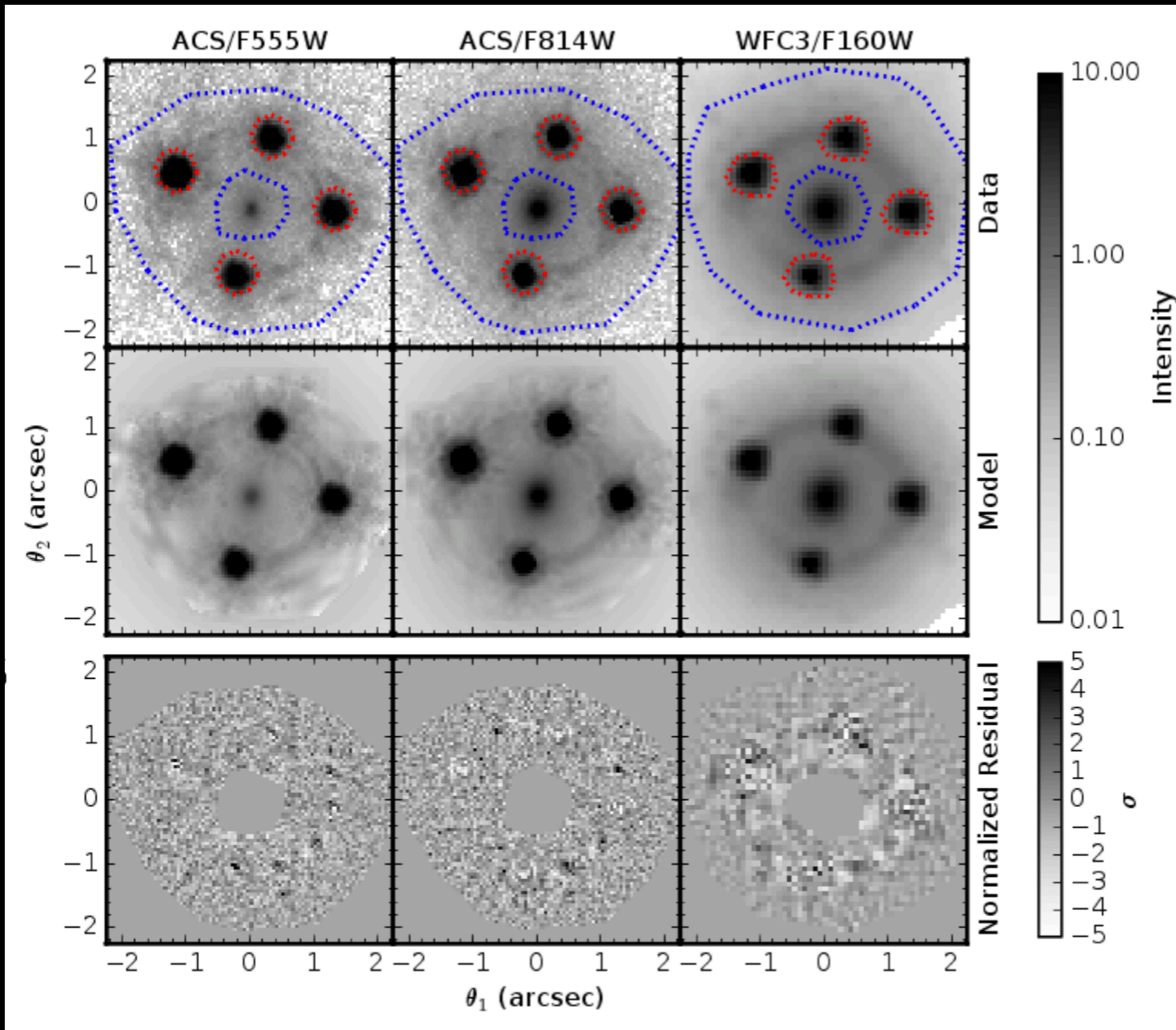
Only a few constraints

Same lens system (radio vs. optical)



1000s of constraints: pixel values

Lens modeling in action

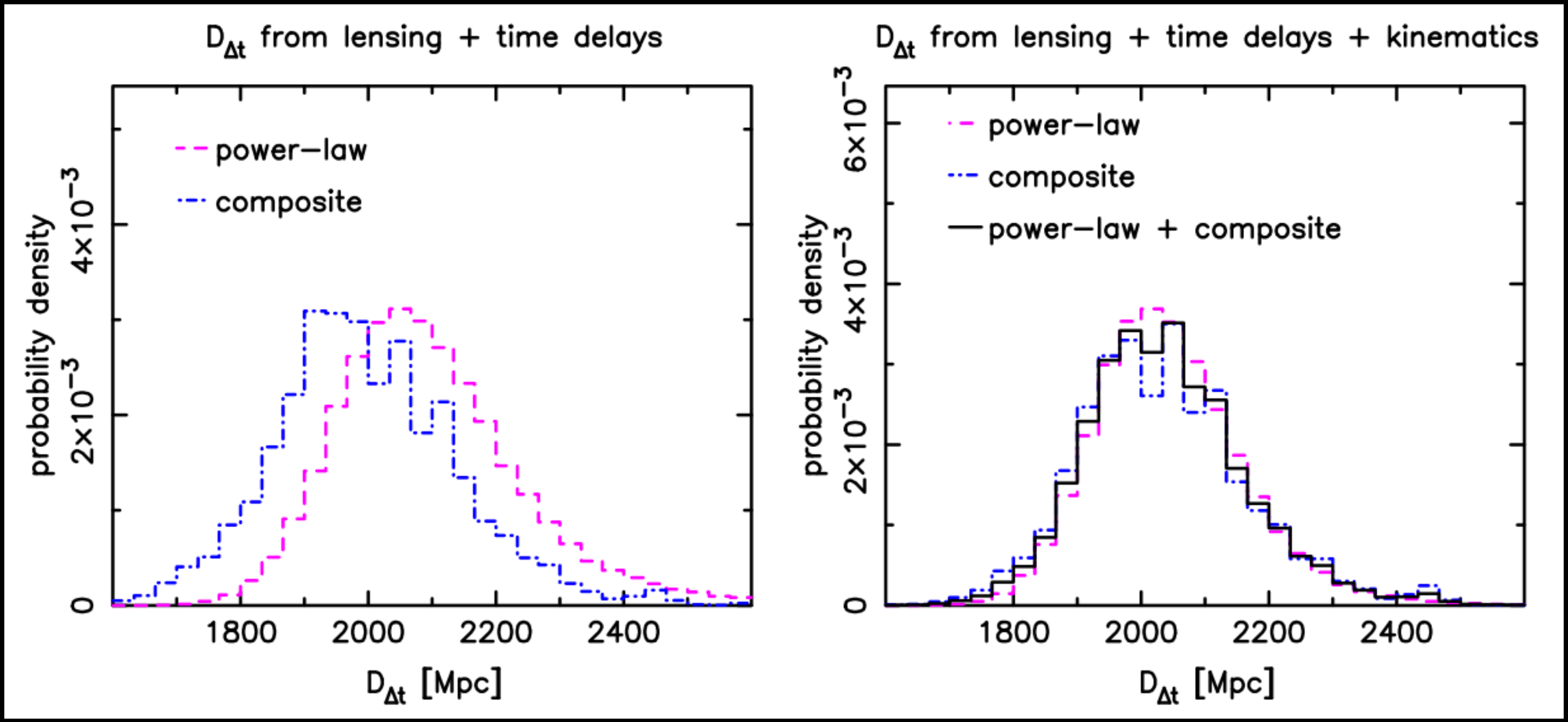


HE0435-1223

(Wong et al 2017)

Modeling the lensing galaxy: Spectroscopy

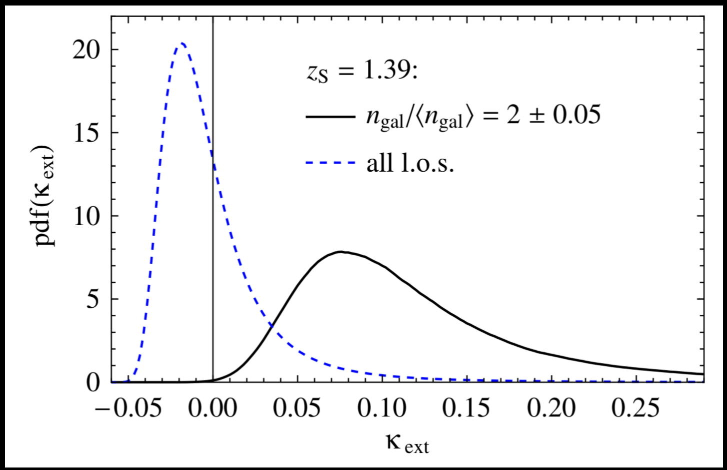
- Stellar velocity dispersion of lensing galaxy breaks additional degeneracies
- e.g., when comparing a simple power-law mass model with a more complex NFW+stellar composite model



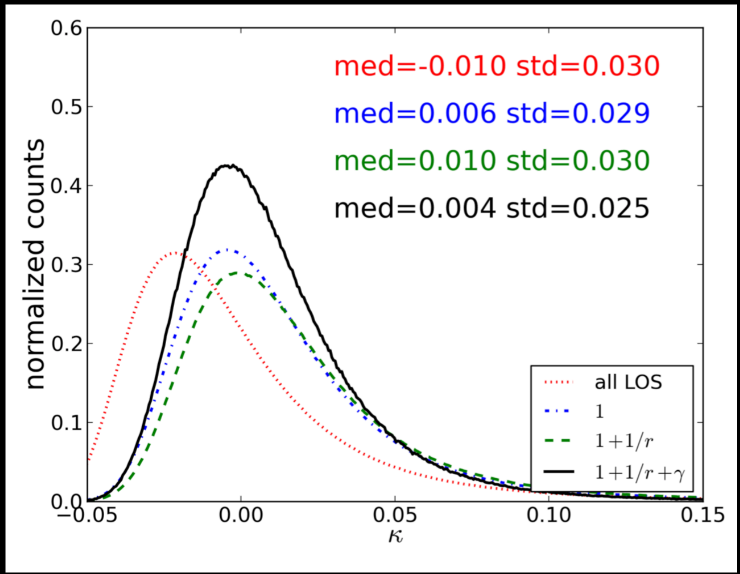
Suyu et al. 2014

Line-of-sight contribution

- Old days: assume that the LOS to each lens system had the average density in the Universe ($\kappa_{ext} = 0$)
- Now: use imaging and spectroscopy of the field to assess galaxy over/under-densities compared to a sample average
- Combine with ray-tracing through cosmological simulations to place priors on κ_{ext} for each system
- Uncertainties of a few to <~ 10%



Suyu et al. 2013



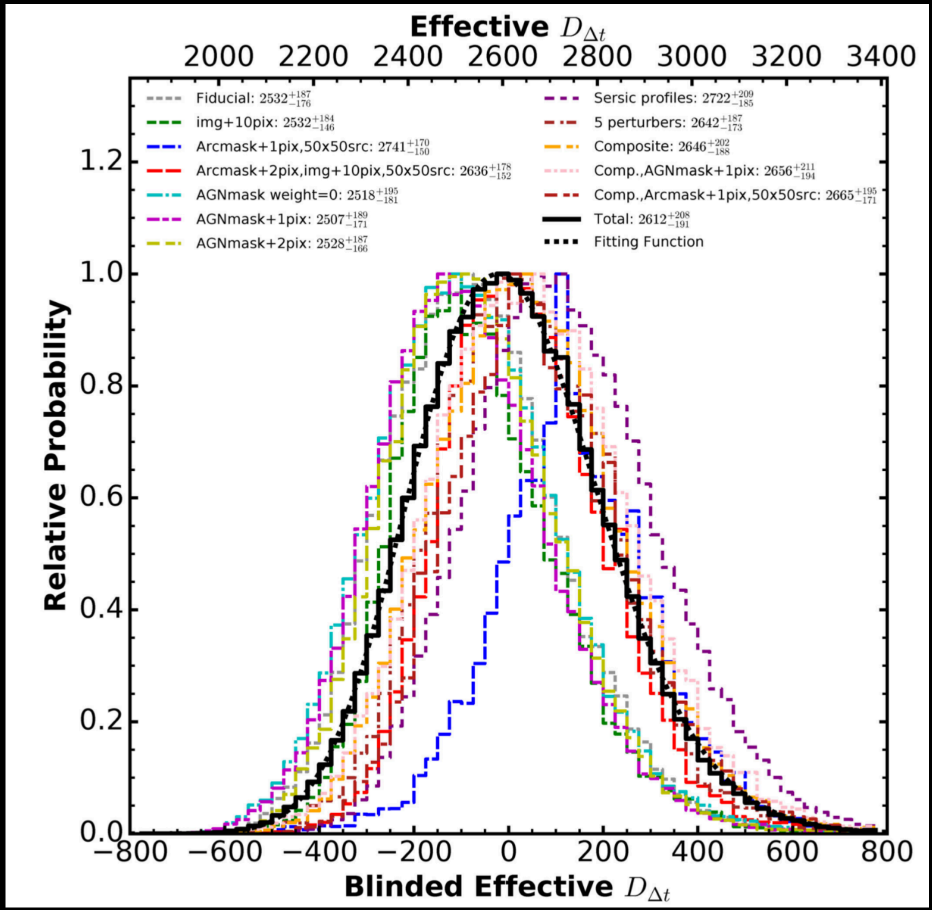
Rusu et al. 2017

End result: A $D_{\Delta t}$ distribution

$$D_{\Delta t} = \left(\frac{1}{1-\kappa_{\rm ext}}\right) \frac{c\,\Delta t}{\frac{1}{2}(\theta-\beta)^2 - \psi(\theta)}$$

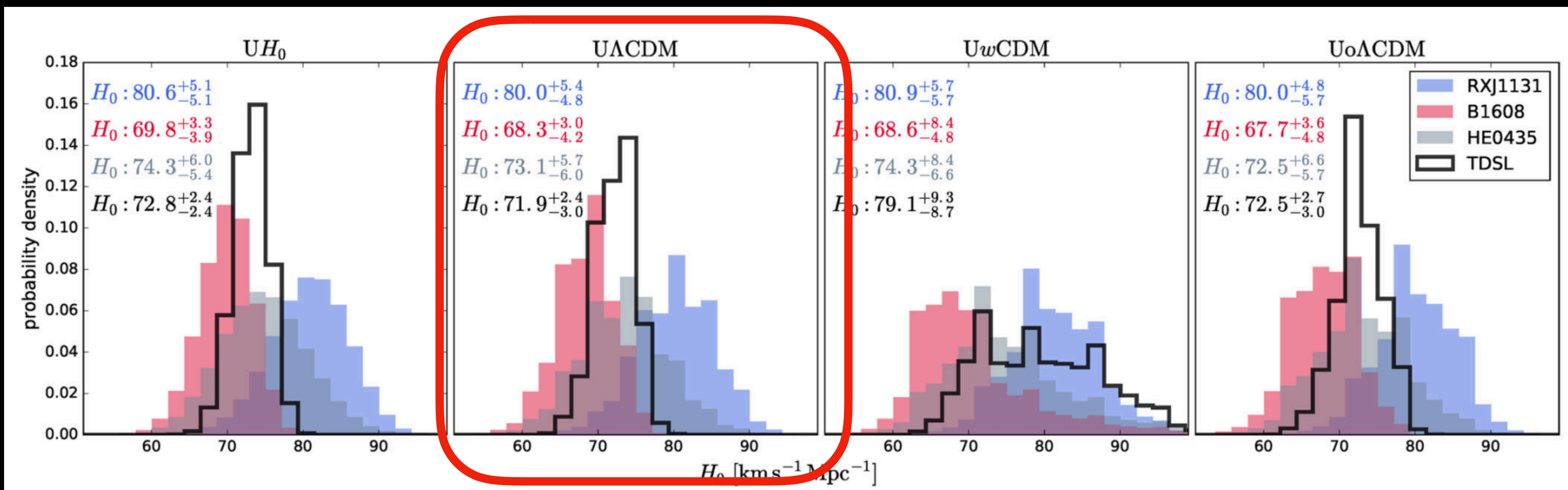
- Combine time delay measurements with lens models and line-of-sight information to get final PDF for $D_{\Delta t}$
  - Include investigation of potential systematic effects
- Provide an analytic function fit to the PDF to make it more useful for combination with other techniques

$$P(D_{\Delta t}) = \frac{1}{\sqrt{2\pi}(x-\lambda_D)\sigma_D} \exp\left[-\frac{(\ln(x-\lambda_D)-\mu_D)^2}{2\sigma_D^2}\right]$$



HE0435: Wong et al. 2017

H_0 from 3 H0licow lenses



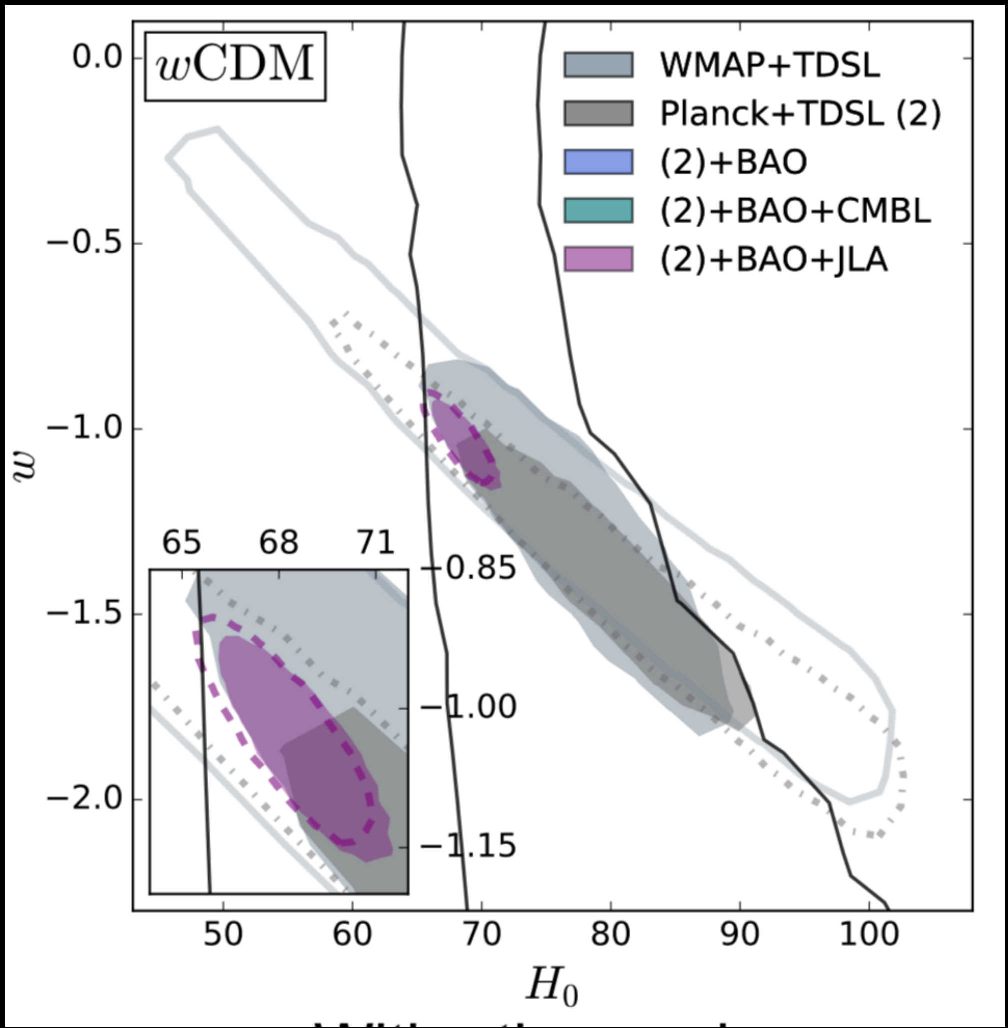
- Bayesian analysis incorporates time-delay and mass modeling uncertainties, a prior on κ_{ext}, and various cosmological priors
- For flat ΛCDM with free Ω_M and Ω_Λ — UΛCDM in plot — we find H_0=71.9 +2.4/-3.0
- Can also combine our $D_{\Delta t}$ with CMB data to obtain improved constraints on other parameters in more general cosmologies

Priors used for analysis steps

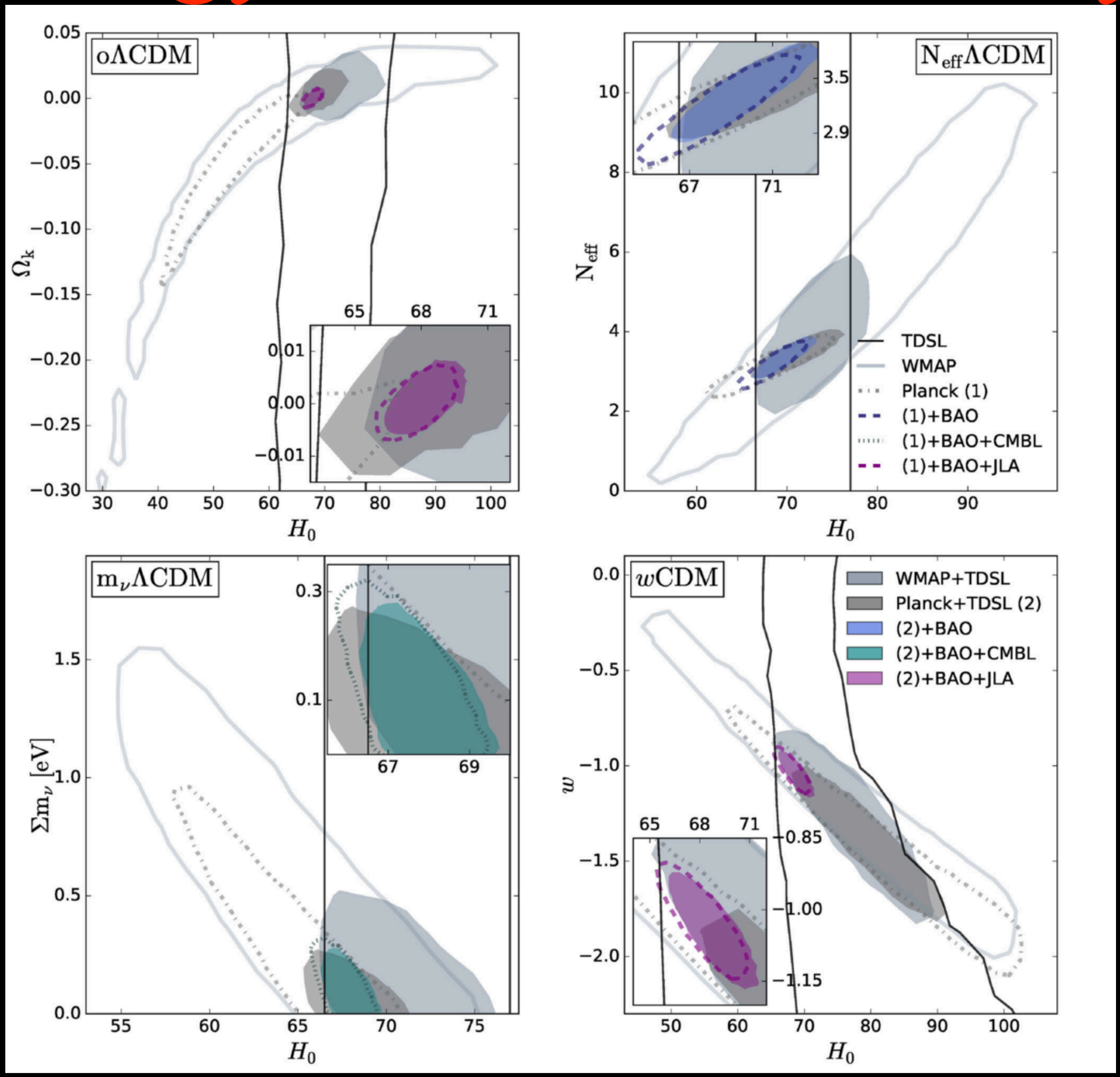
Model name	Description
UH_0	Flat − Λ CDM cosmology $\Omega_m = 1 - \Omega_\Lambda = 0.32$ H_0 uniform in [0, 150]
UΛCDM	Flat − Λ CDM cosmology $\Omega_m = 1 - \Omega_\Lambda$ H_0 uniform in [0, 150] Ω_m uniform in [0, 1]
UwCDM	Flat − wCDM cosmology H_0 uniform in [0, 150] Ω_{de} uniform in [0, 1] w uniform in [−2.5, 0.5]
UoΛCDM	Non − flat − Λ CDM cosmology $\Omega_m = 1 - \Omega_\Lambda - \Omega_k > 0$ H_0 uniform in [0, 150] Ω_Λ uniform in [0, 1] Ω_k uniform in [−0.5, 0.5]
oΛCDM	Non − flat − Λ CDM cosmology *WMAP*/Planck for $\{H_0, \Omega_\Lambda, \Omega_m\}$ $\Omega_k = 1 - \Omega_\Lambda - \Omega_m$
N_{eff}ΛCDM	Flat − Λ CDM cosmology *WMAP*/Planck for $\{H_0, \Omega_\Lambda, N_{eff}\}$
m_νΛCDM	Flat − Λ CDM cosmology *WMAP*/Planck for $\{H_0, \Omega_\Lambda, \Sigma m_\nu\}$
wCDM	Flat − wCDM cosmology Planck for $\{H_0, w, \Omega_{de}\}$
$N_{eff} m_\nu$ΛCDM	Flat − Λ CDM cosmology Planck for $\{H_0, \Omega_\Lambda, \Sigma m_\nu, N_{eff}\}$
owCDM	Open Λ CDM cosmology Planck for $\{H_0, \Omega_{de}, \Omega_k, w\}$

Current H0licow status: Cosmology with 3 time-delay lenses

- We have completed the joint analysis of the first 3 H0licow lens systems
  - Bonvin et al. 2017
- In plots, our results are designated TDSL
  - Time Delay Strong Lensing
- By combining $D_{\Delta t}$ / H_0 results from lensing with Planck chains, we place constraints on further cosmological parameters
  - Further improvement via combinations with additional probes of cosmology



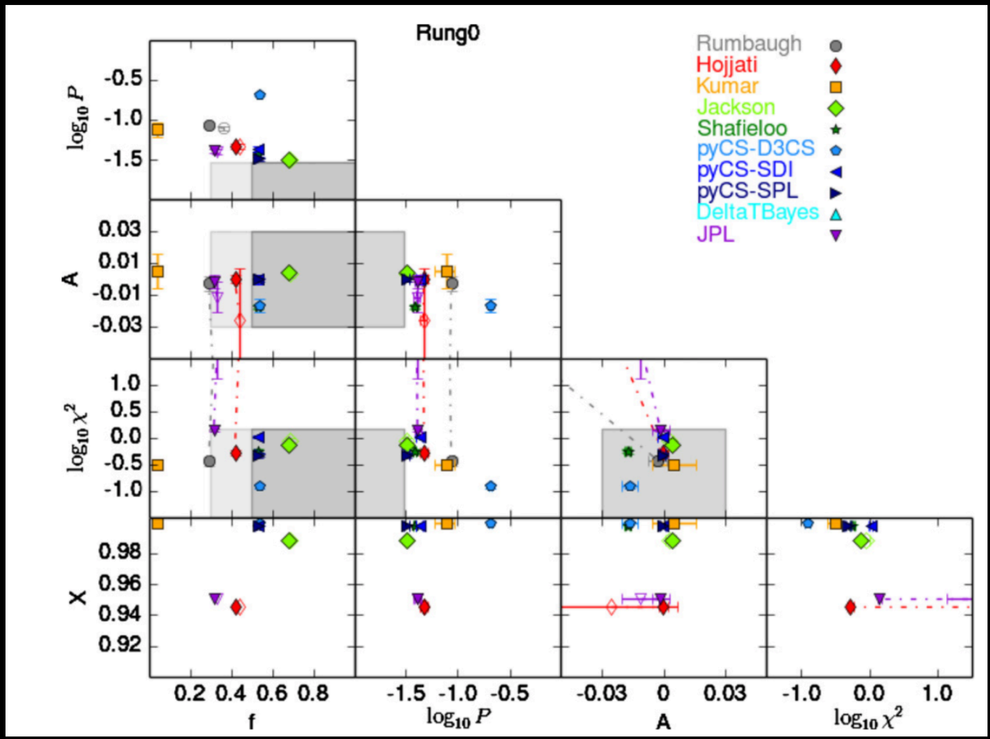
Cosmology with 3 time-delay lenses



1-parameter extensions to standard cosmological model (Bonvin et al. 2017)

Testing for systematics

- Each lens system provides high enough precision to give an internal systematics check
- All analyses after the first H0licow system are blinded w/r.t. cosmological parameter values
- Data challenges to test for systematics in the analysis techniques
  - Time-delay challenge 1 (completed)
  - Time-delay challenge 2 (under development)
  - Lens modeling challenge (ongoing)



TDC1 results; Liao et al. 2015

$$P = \frac{1}{fN} \sum_i \left(\frac{\delta_i}{\Delta t_i} \right);$$

$$A = \frac{1}{fN} \sum_i \frac{\tilde{\Delta t}_i - \Delta t_i}{\Delta t_i}.$$

What are the next steps?

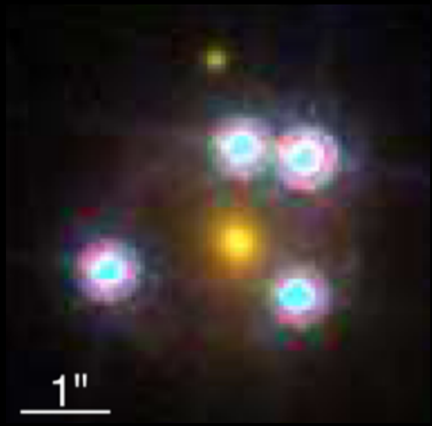
Toward higher precision with TDSL

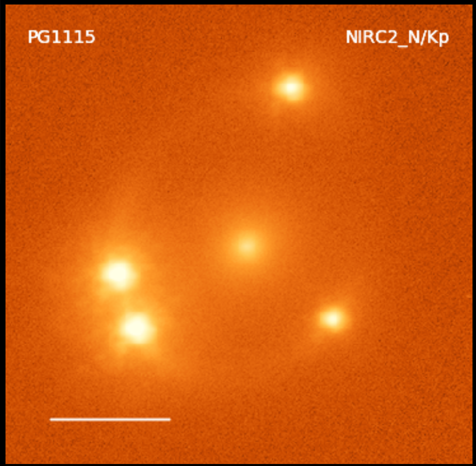
- The obvious step forward is to increase the sample of high-quality lenses beyond the current sample of 3
- How large does the sample need to be?
  - Depends on the precision of the individual measurements
- Right now we are getting ~6-7% precision per lens system
- With more precise individual measurements, the final sample can be smaller for the desired cosmological inference
  - e.g., a ~100 lens sample with current precisions can become a ~40 lens sample with improved precisions (e.g., Shajib et al. 2018)
- Therefore, work on increasing both sample size and precision

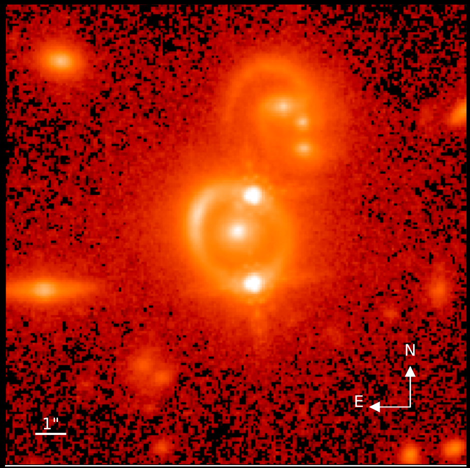
First approach:
Increasing the sample size

Near-term future (2018)

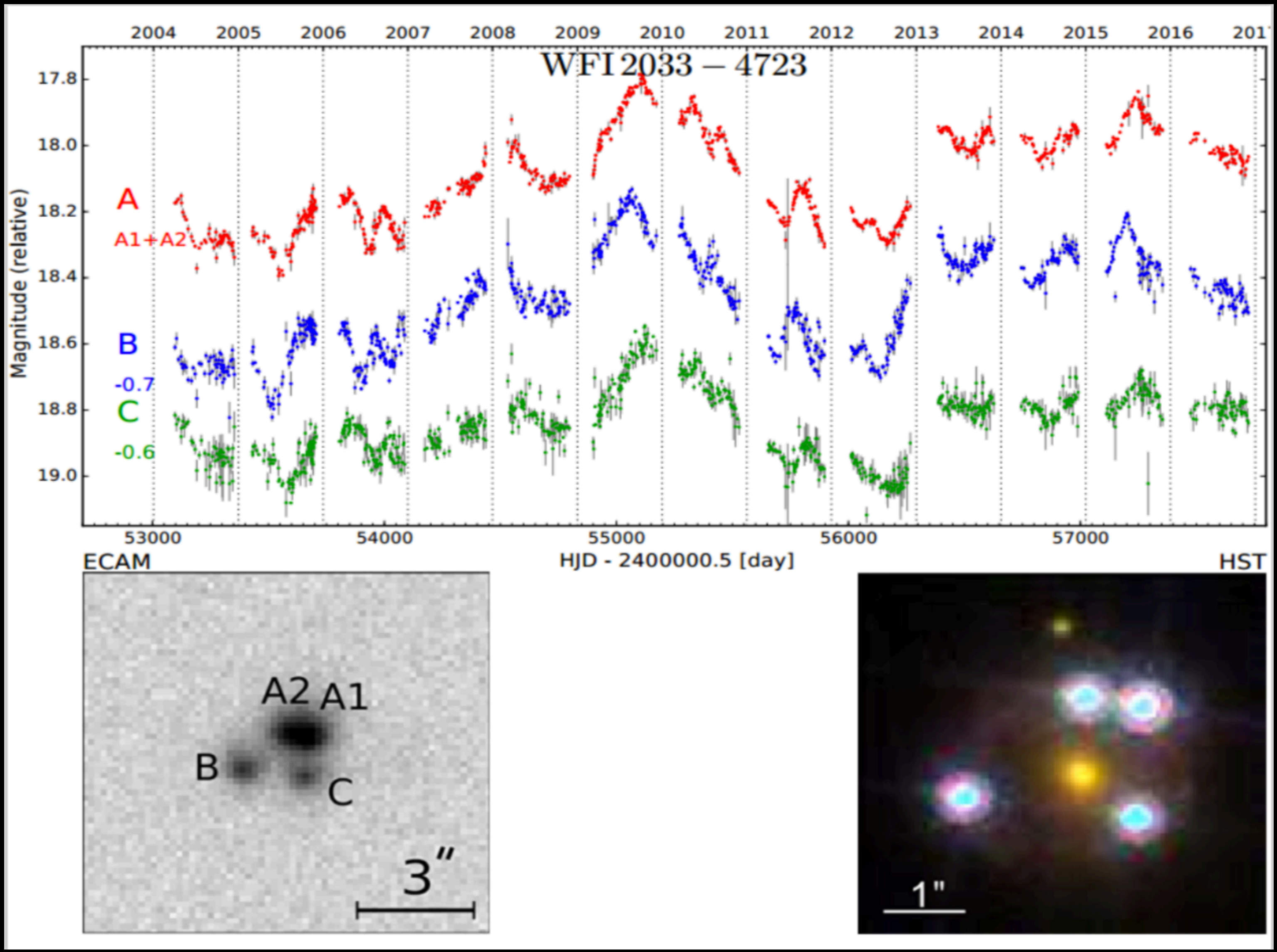
- Results from three new high-quality lens systems will soon be published
  - If systematics are under control, this could lead to as much as a sqrt(2) improvement in precision of global H_0 measurement
- One systems is formally part of H0licow (WFI2033), while two more are outside the H0licow sample but being analyzed in the same fashion
  - WFI2033-4723
  - PG1115+080 (Using adaptive optics imaging)
  - SDSS J1206+4332
- Right now all results are blinded





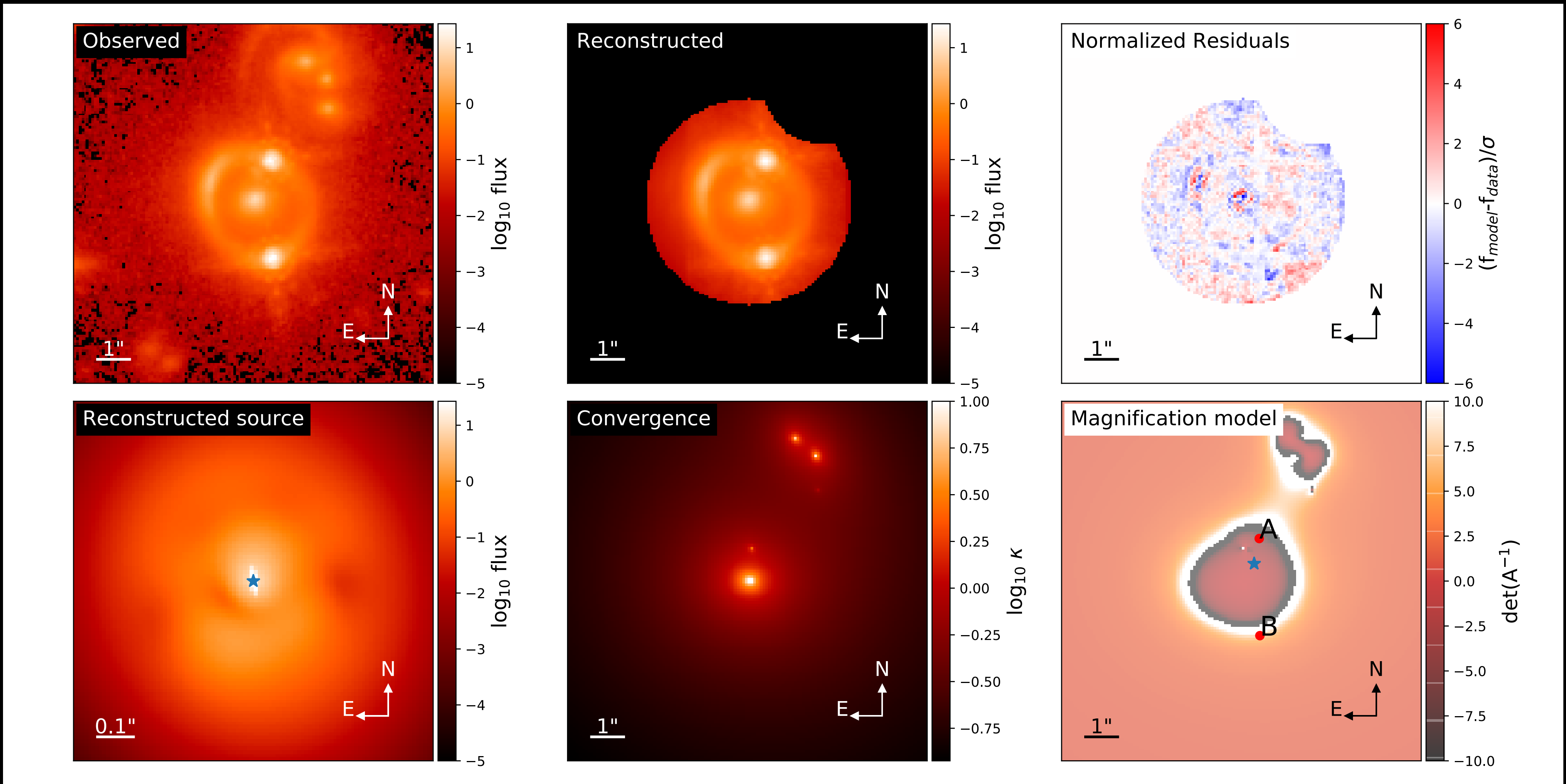


H0licow #4: WFI 2033-4723



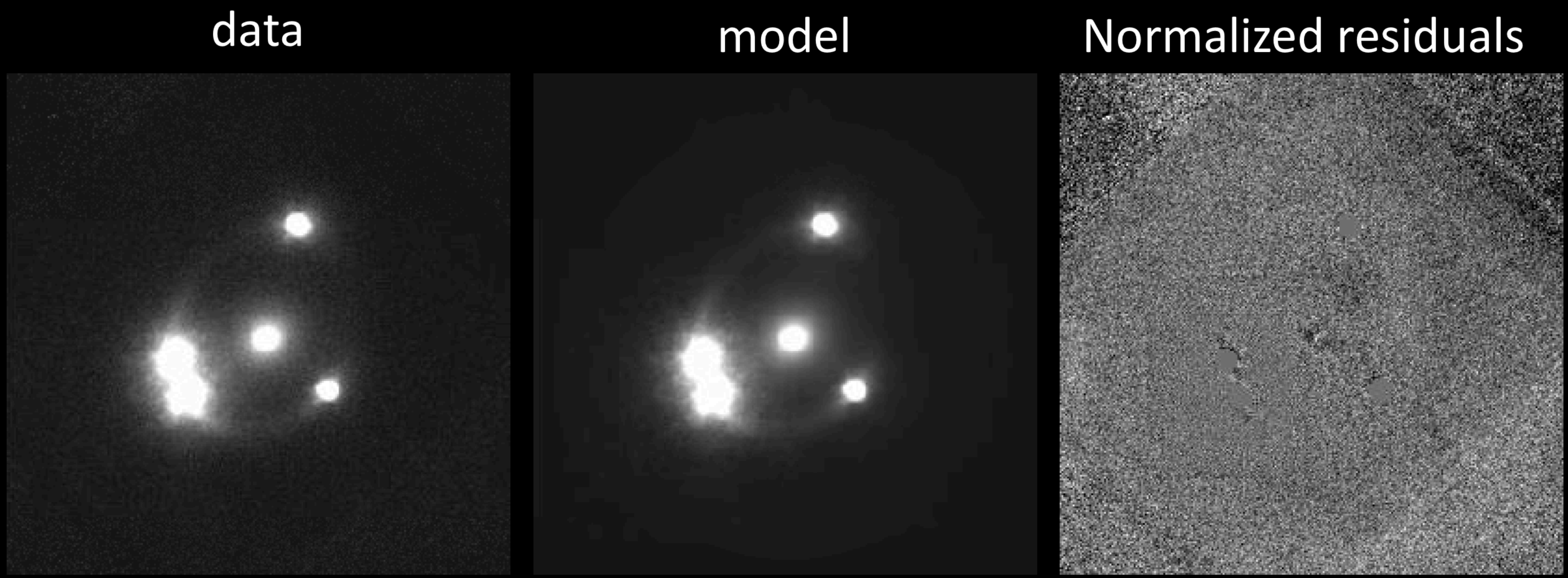
Bonvin et al., in prep; Rusu et al. in prep

Post-H0licow: J1206



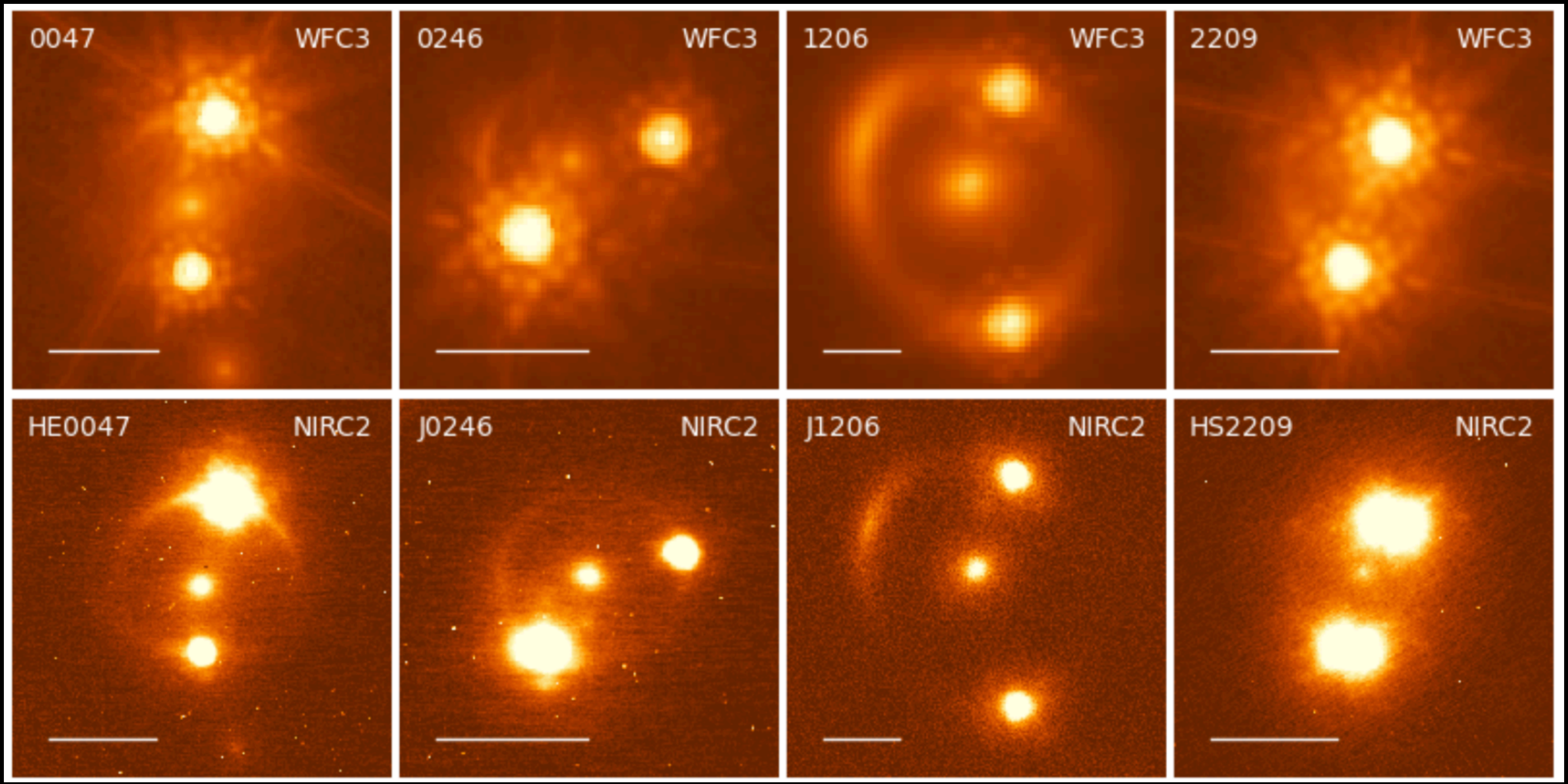
Birrer et al., in prep

Post-H0licow: PG1115+080



- Input data for modeling are from Keck adaptive optics (AO) imaging
- Cosmological inference will also include results from AO data on two H0licow systems, RXJ1131 and HE0435
  - Gives some systematics checks
- Chen et al., in prep.

Next H0licow-like step



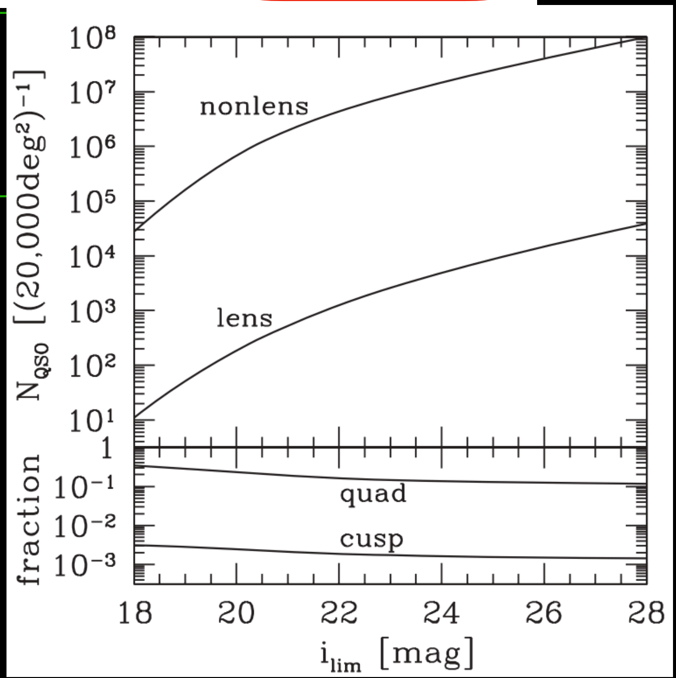
- Three additional lensed quasars with nearly all of the required input data (J1206 analysis is effectively finished)
- With 8-9 systems we hope to achieve ~2% precision on H_0

Searches for new lensed quasars

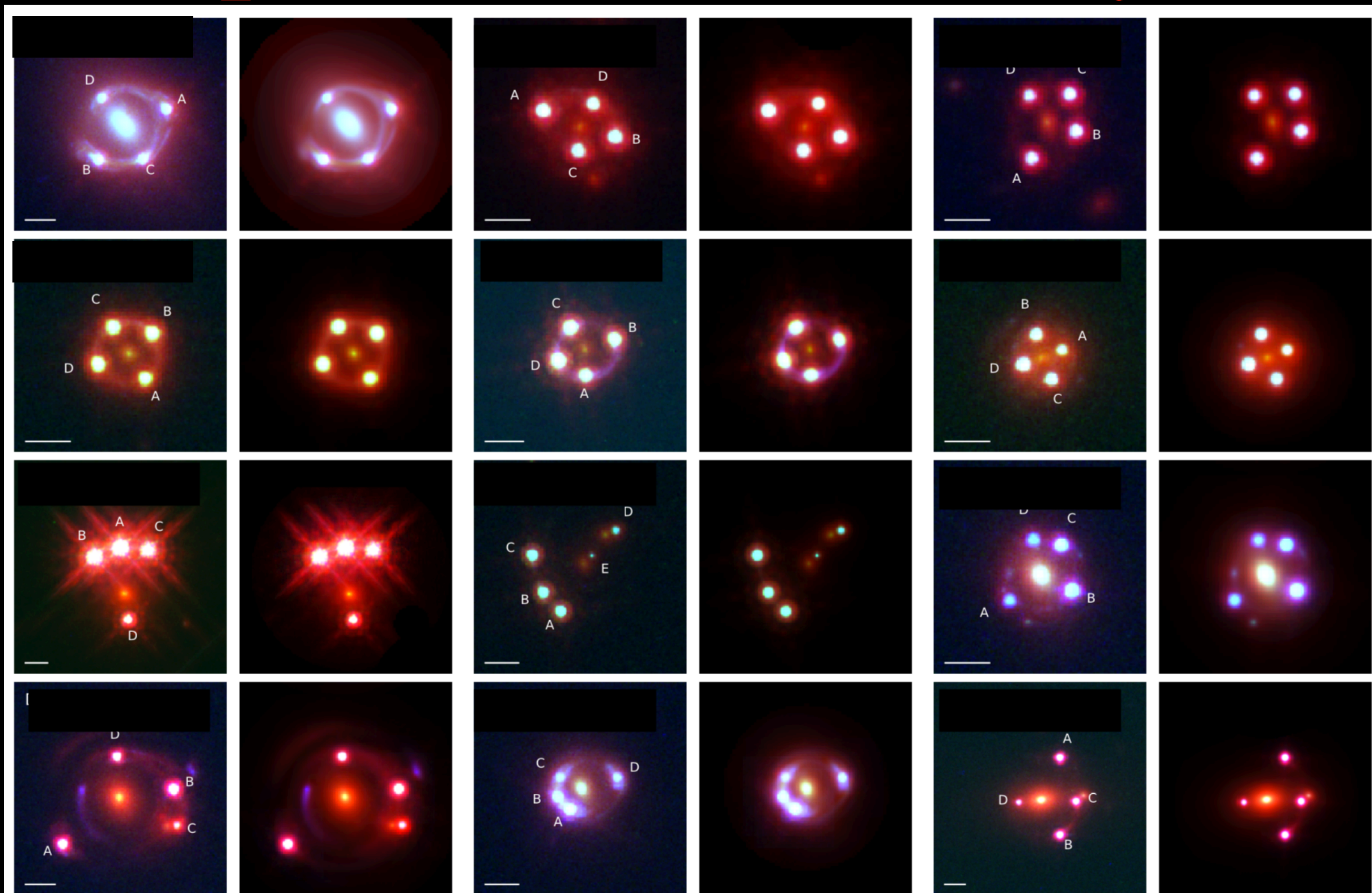
- Forecasts are that we need at least 40 new systems for desired ~1% precision on H_0
- Search for lensed quasars in new large sky surveys
  - DES, HSC, SDSS, ATLAS, Gaia, etc.
- Good testbed for developing methods for LSST and Euclid that should produce thousands of lensed quasars
- Already finding new systems in the current surveys
  - e.g., Agnello et al. 2015, 2017, 2018ab, Lin et al. 2017, Ostrovski et al. 2017, 2018

Survey	QSO (detected) $N_{\text{non-lens}}$	N_{lens}
SDSS-II	1.18×10^5	26.3 (15 per cent)
SNLS	9.23×10^3	3.2 (12 per cent)
PS1/3π	7.52×10^6	1963 (16 per cent)
PS1/MDS	9.55×10^4	30.3 (13 per cent)
DES/wide	3.68×10^6	1146 (14 per cent)
DES/deep	1.26×10^4	4.4 (12 per cent)
HSC/wide	1.76×10^6	614 (13 per cent)
HSC/deep	7.96×10^4	29.7 (12 per cent)
JDEM/SNAP	5.00×10^4	21.8 (12 per cent)
LSST	2.35×10^7	8191 (13 per cent)

Predictions from Oguri & Marshall 2010



Examples of new lens systems



HST imaging and (relatively) automated lens modeling from Shajib et al., in prep

Second approach: Improving the precision for each lens system

TDSL Error Budget

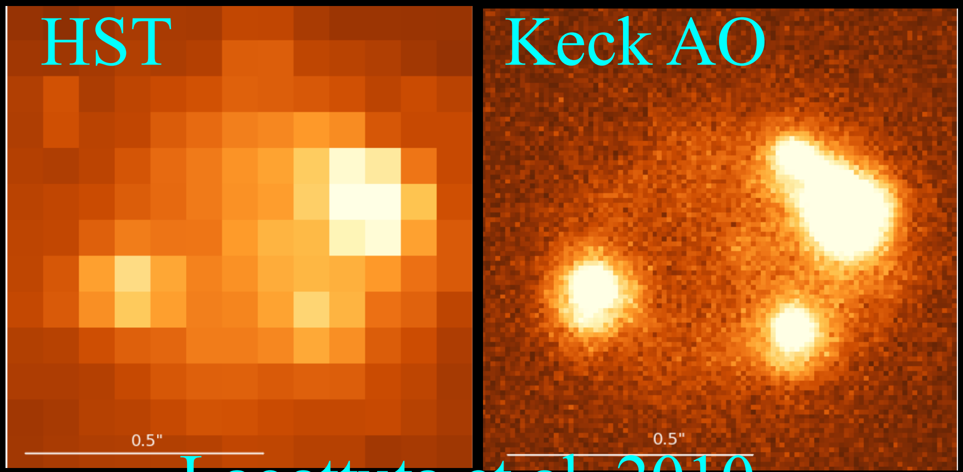
- Three main contributions, all at roughly the same level (a few percent from each)
  - Time delay measurements (Δt)
  - Mass distribution in the primary lensing galaxy and its immediate environment (ψ)
  - Line-of-sight mass distribution (κ_{ext})
- NOTE: ψ and κ_{ext} used to be systematic effects
  - Now they are incorporated into the Bayesian analysis and are statistical
- What are the scenarios for improvement as we move into the medium-term future?

Δt: Time delay possibilities

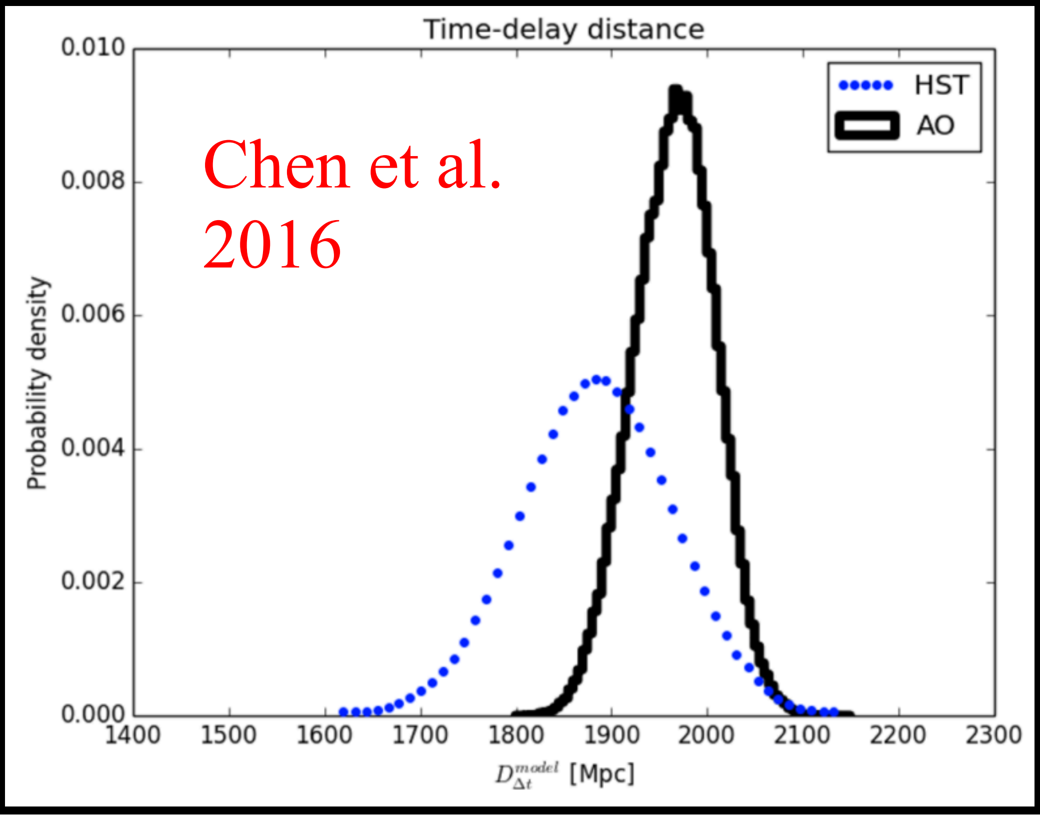
- Continuation of monitoring programs with 1-2m class telescopes
  - Including purchasing of telescope time explicitly for monitoring
  - Requires several years of data to overcome microlensing
- Intensive short-term monitoring with 8-10m class telescopes
- LSST provides 10 years of lensed quasar monitoring “for free”
  - Time delay challenges to see how cadence and multiple filters impact the ability to measure delays at high enough precision

ψ: Improving lens modeling precision

- Resolving the lensed AGN host galaxy in the radial direction is a key to improving the lens modeling
- Keck AO vs. HST has shown clear improvements in modeling precision
  - Lagattuta et al. 2010, Vegetti et al. 2012, Chen et al. 2016
- Can expect similar improvements in resolution with ELTs vs. JWST
- Caveat: Requires an extremely well characterized PSF

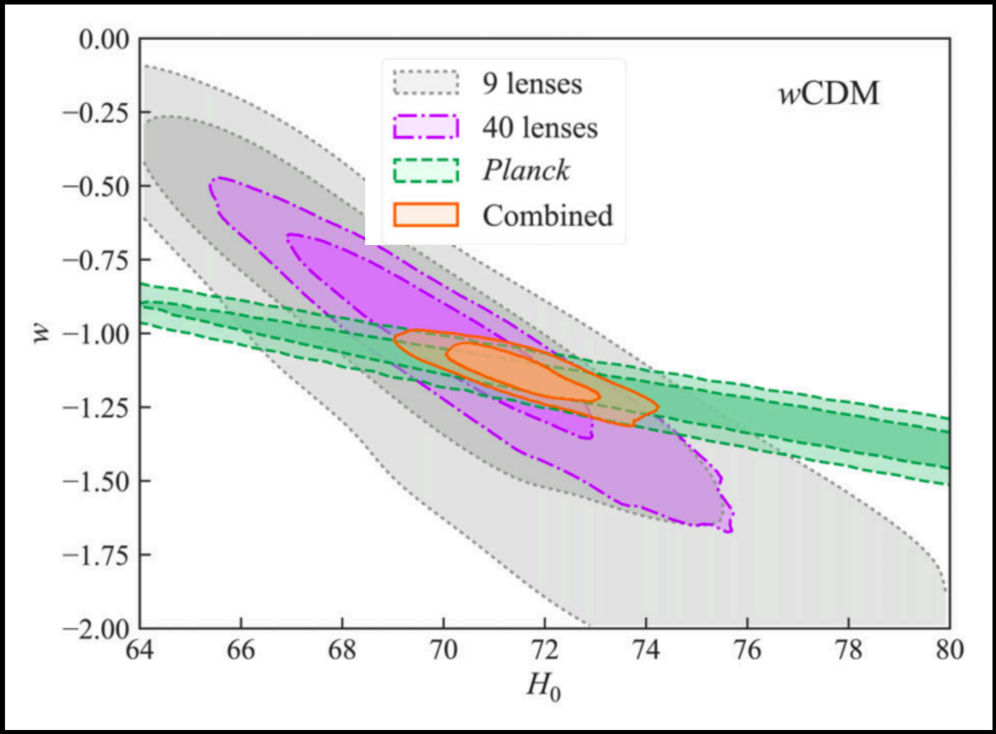


Lagattuta et al. 2010



ψ: Improving lens modeling precision

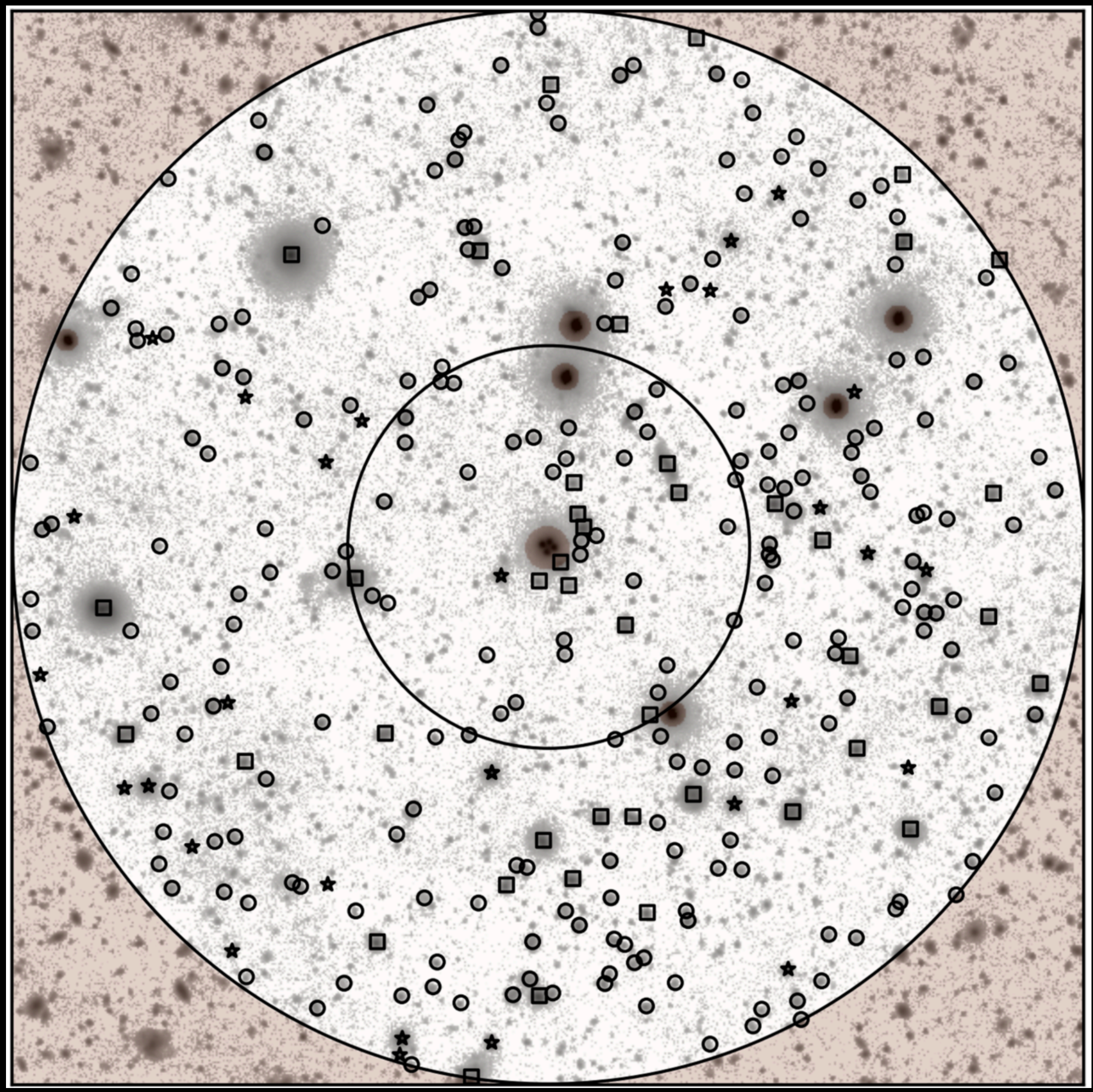
- The inclusion of resolved 2-d kinematic information for the lensing galaxy can provide a big improvement in the precision of the lens modeling
- Observations are challenging on a 8-10m class ground-based telescope, so here an ELT is a game changer



Shajib et al. 2018

κ_{ext}: Improving the LOS constraints

- Wide field and deep imaging from current and upcoming sky surveys (e.g., HSC, LSST, possibly DES) will provide the requisite photometric data
- Multiplexing spectroscopic follow-up with ELTs could improve the mass estimates of the galaxies and galaxy groups/ clusters along the LOS
- Employ more sophisticated analysis techniques
  - e.g., McCully et al. 2014



Subaru imaging of HE0435 field; Rusu et al 2017

Summary

- Current 3-lens H0licow sample already gives better than 4% precision on H_0
- With ELTs, advances in modeling and analysis, and larger sample sizes from new sky surveys, we can aim for ~1% precision (or better?) on H_0
- This will really test the standard ΛCDM model, in an independent fashion from other distance-scale techniques