Physics of the Universe: Gravitational Lensing

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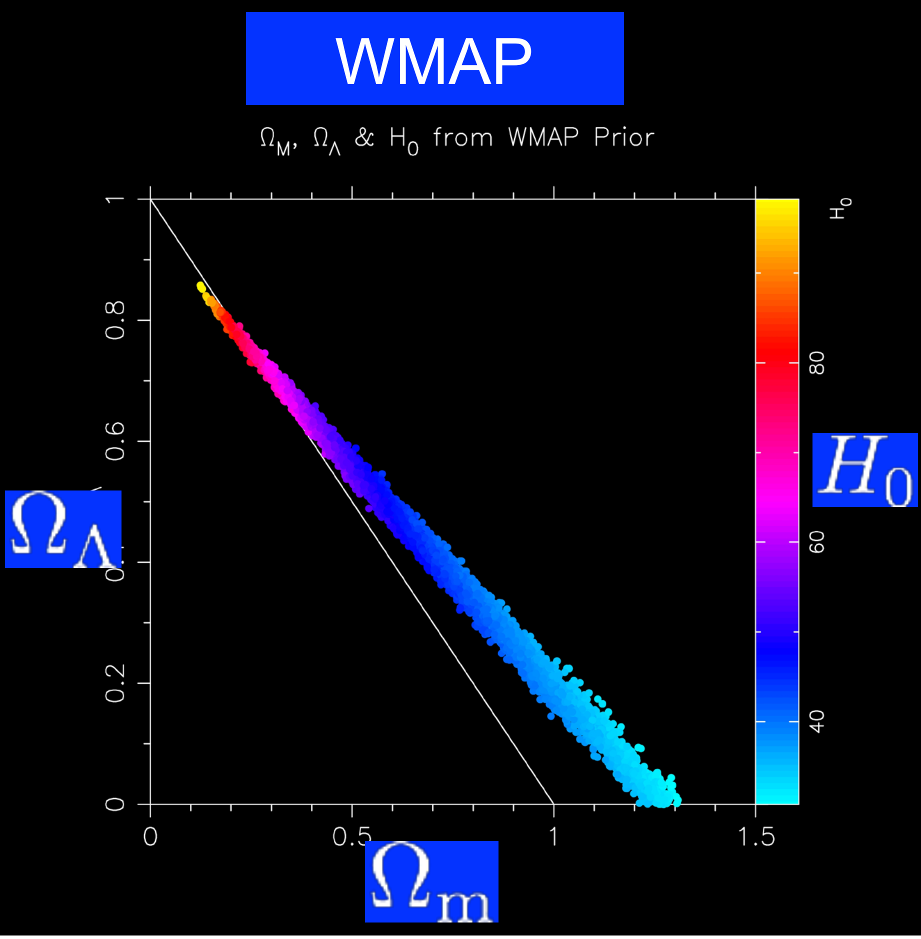
The motivation

- The big question:
  - What is dark energy?
- More specifically
  - Obtain independent measurements of cosmological parameters
- The tools
  - gravitational lensing
  - high resolution imaging

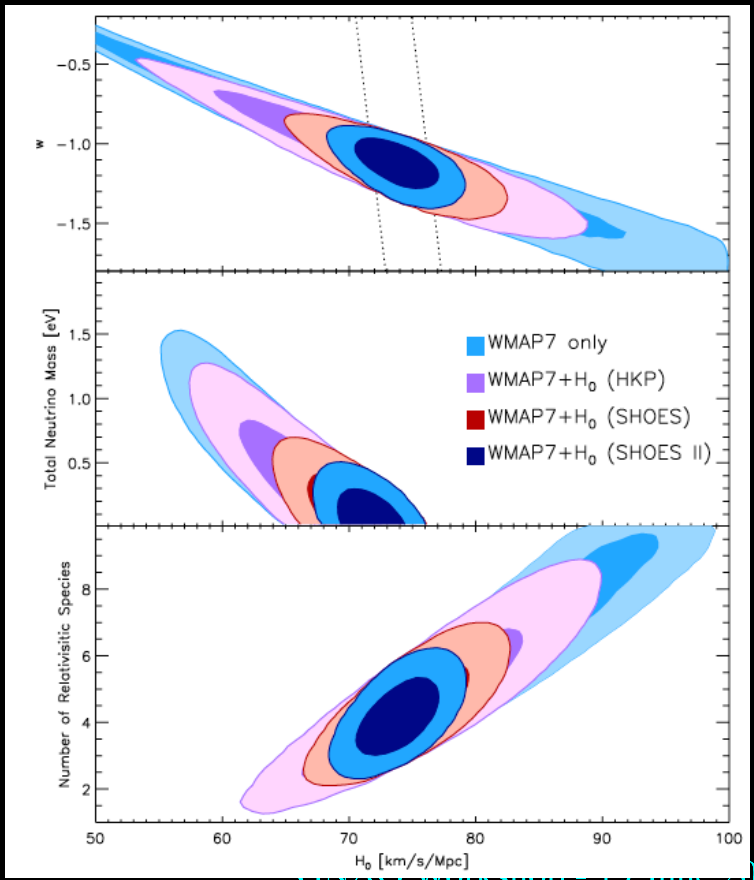
Motivation

Key Question: *What is the nature of dark energy?*

H_0 is the single most useful complement to CMB parameters for dark energy studies [e.g. Hu 2005, Riess et al. 2009, 2011]



Riess et al. 2011



Take-away messages

- A small sample of gravitational lens systems can produce measurements of cosmological parameters with comparable precision to other approaches.
- These lens-based measurements are independent and complementary to the traditional methods.
- The lens-based measurements contain internal checks for systematics
- AO observations are a promising avenue for breaking one of the main degeneracies in the lensing approach

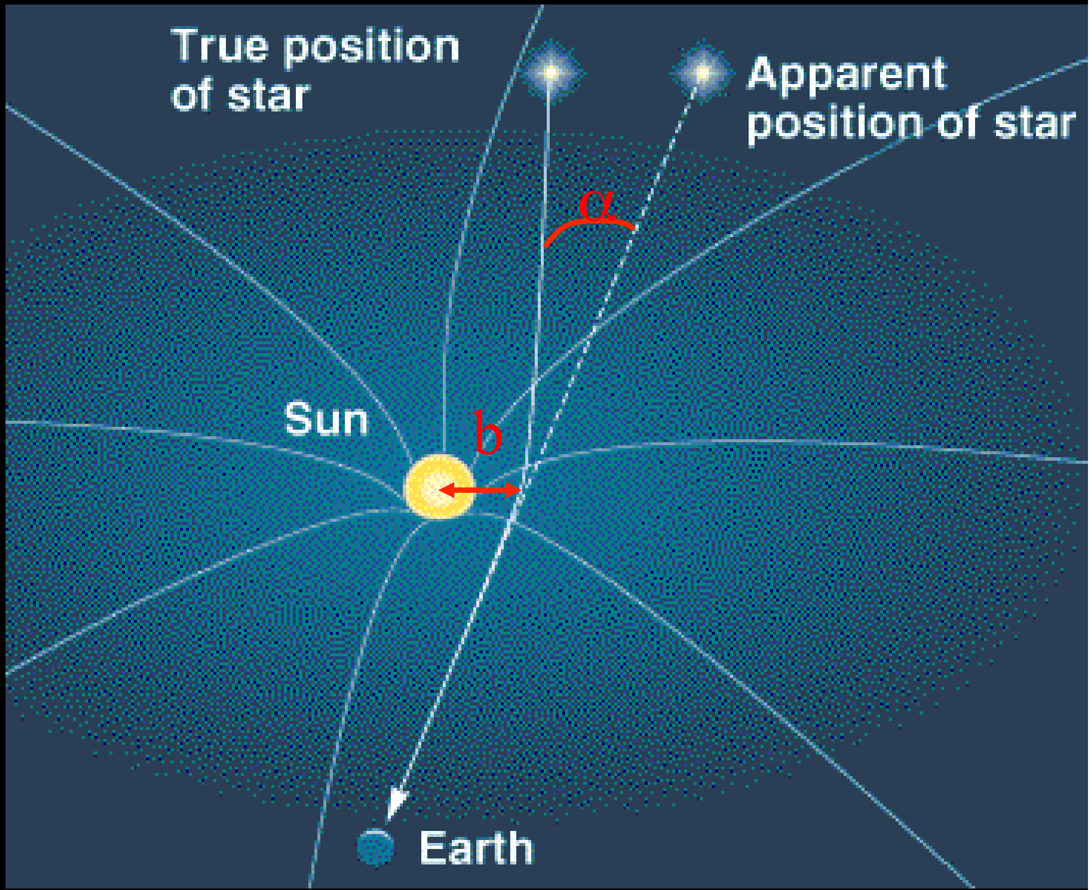
The Tool: Gravitational Lensing

Gravitational Lenses: The Basic Idea

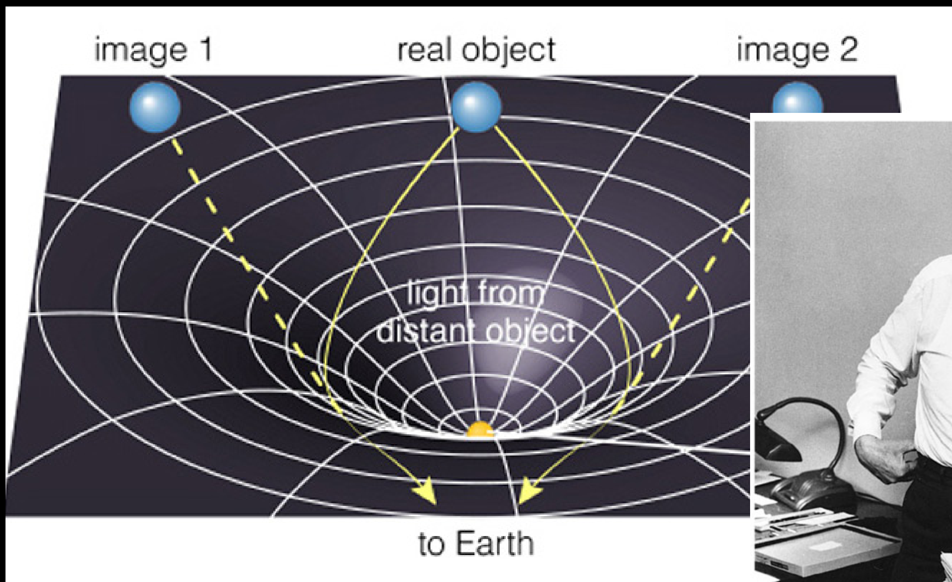
- General relativity: mass can deflect light from its original path

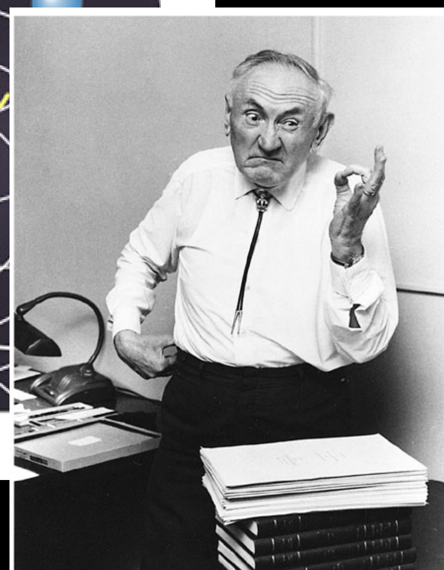
$$\alpha = \frac{4GM}{c^2 b} = \frac{2R_s}{b}$$

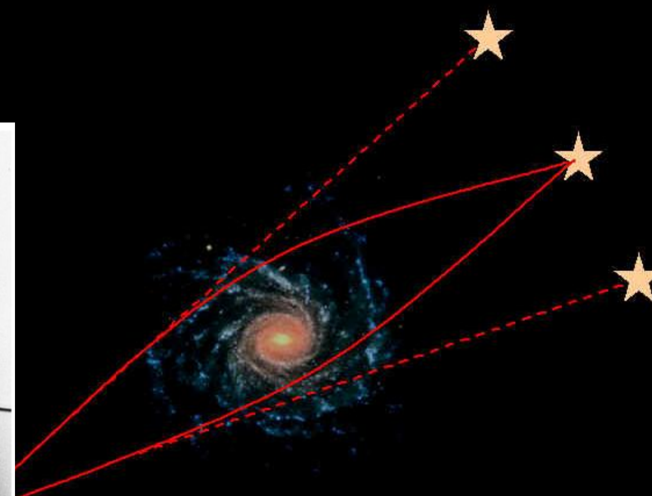
- Images of the background object will be magnified and distorted.



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

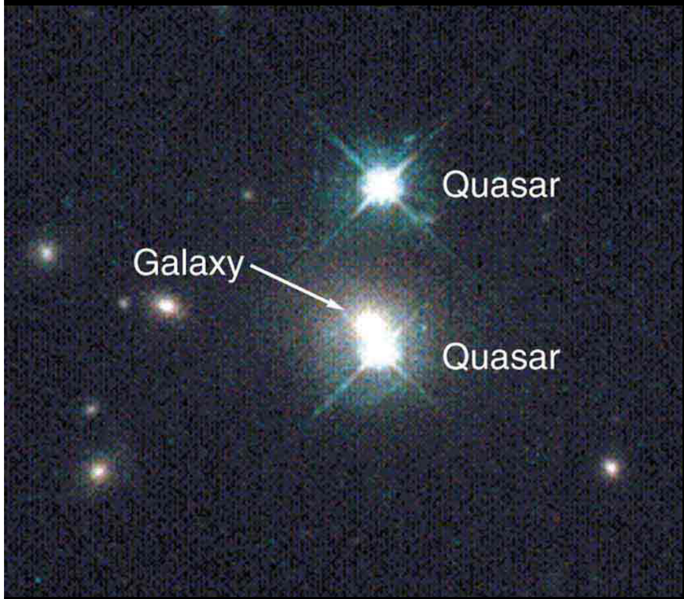




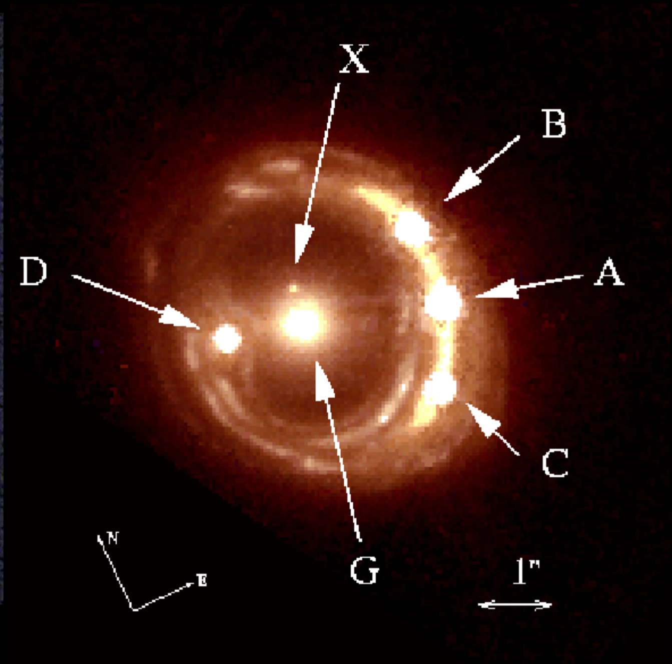


The mass of the lens (roughly) sets the angular separation of the lensed images

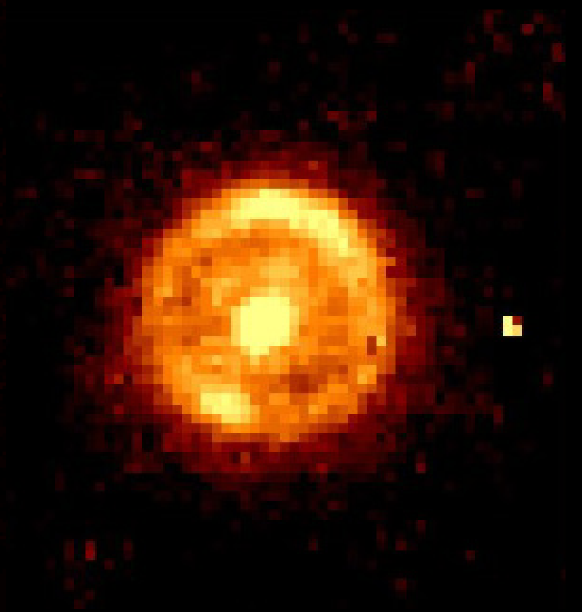
Basic Strong Lensing by Galaxies



2 images

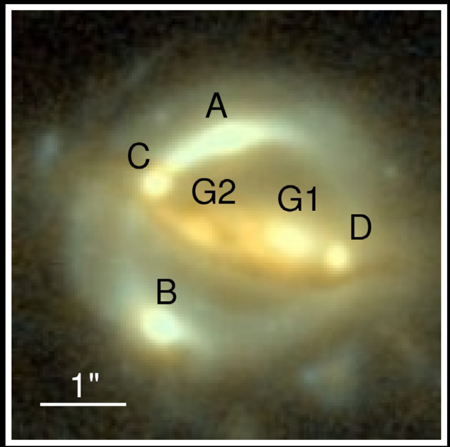


4 images

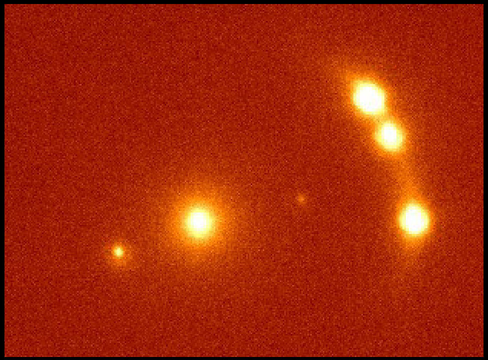


Einstein ring

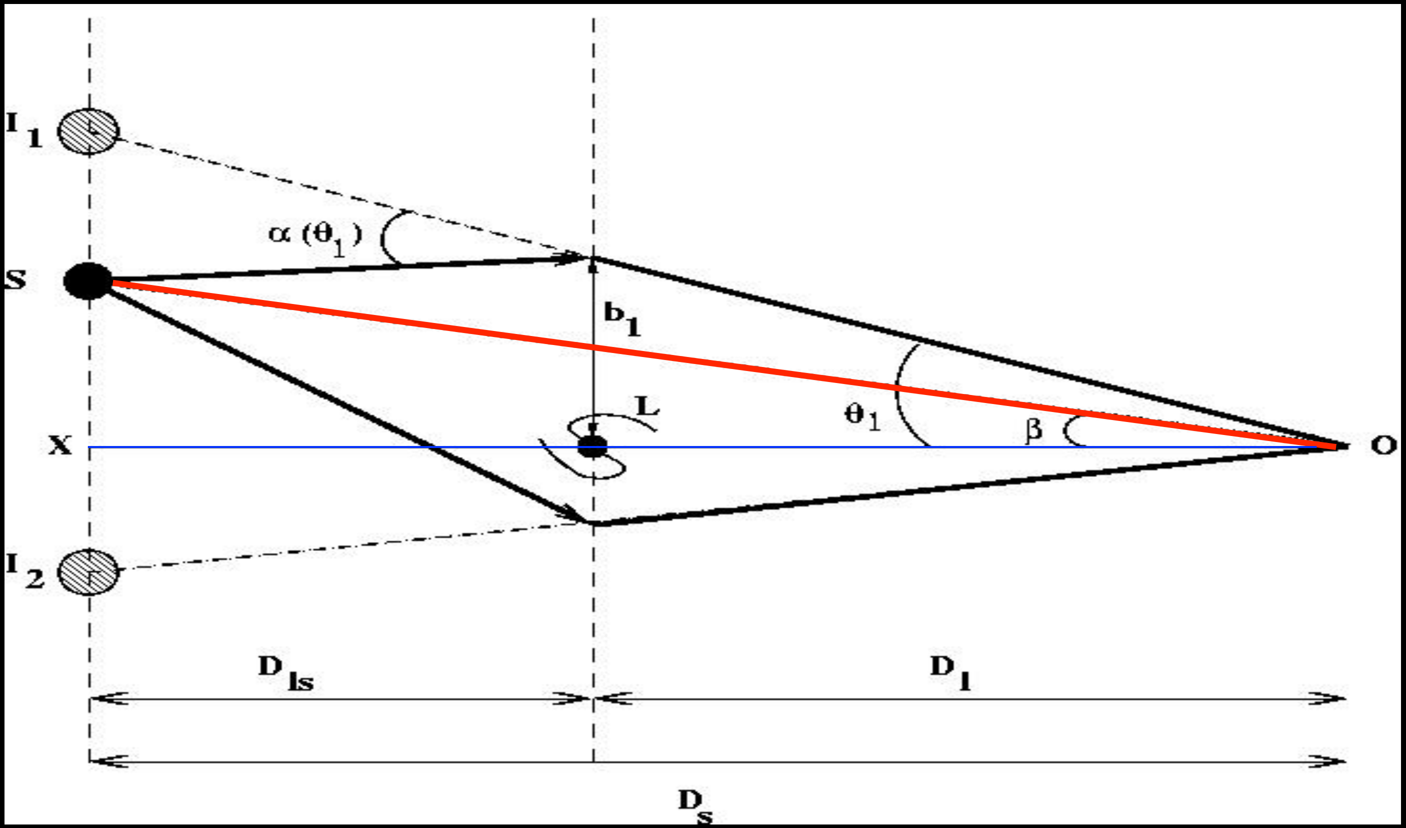
My favorite lens



My 2nd favorite lens



Strong Lensing 101



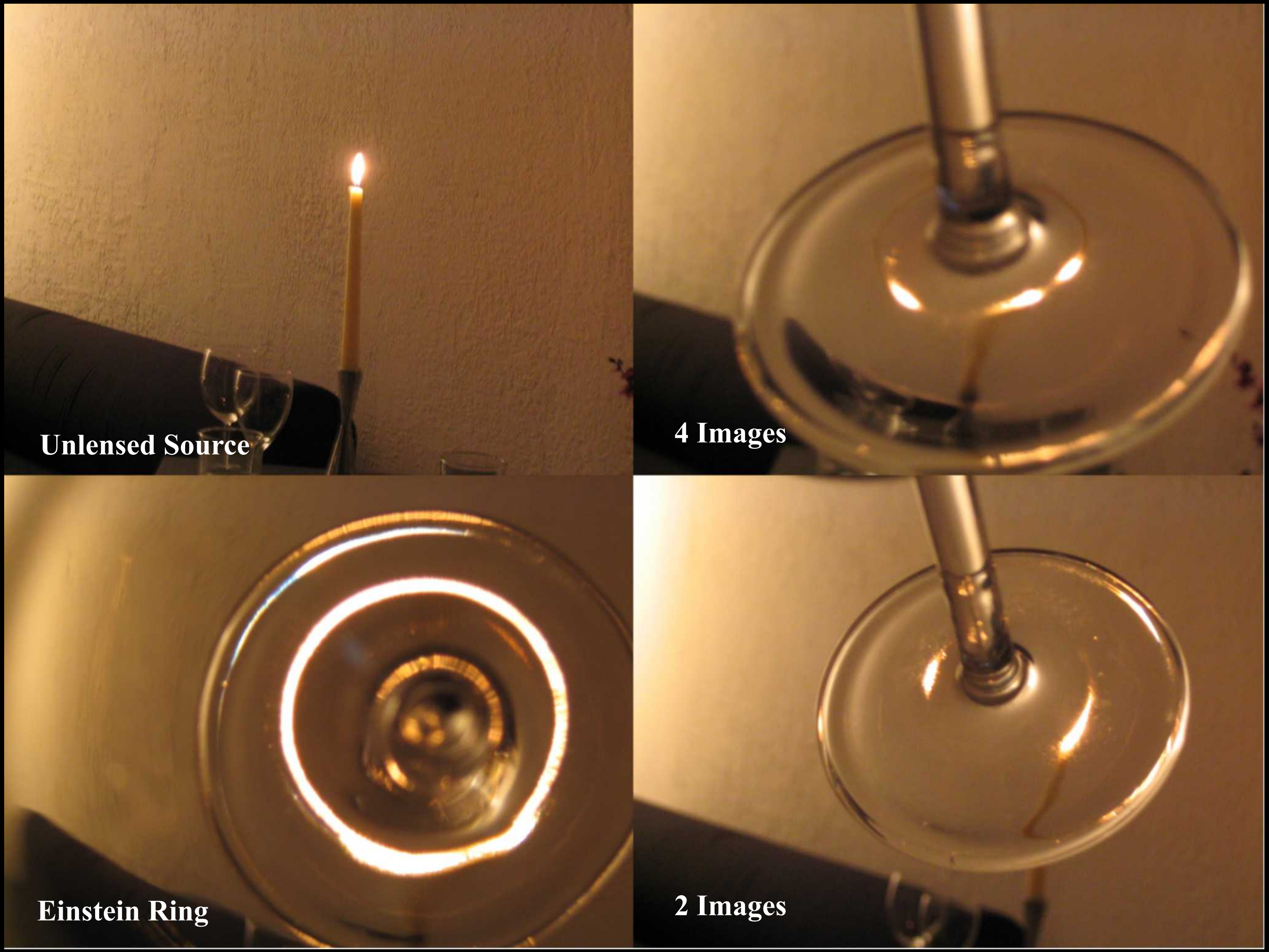
- $\Delta t_{tot} = \Delta t_{geom} + \Delta t_{grav}$
- $\Delta t_i = (D_{\Delta t} / c) \, [(1/2) \, |\theta_i - \beta|^2 - \psi(\theta_i)]$
- $D_{\Delta t} = (1+z_l) \, (D_l \, D_s / D_{ls})$

From time delays to cosmology

$$D_{\Delta t} = \frac{c\Delta t}{\frac{1}{2}(\theta - \beta)^2 - \psi(\theta)}$$

- Observables
  - Δt , θ, z_l, z_s
- Model
  - β, $\psi(\theta)$
- Cosmology
  - $D_{\Delta t} = f(z_l, z_s, H_0, \Omega_M, \Omega_\Lambda, w)$

Everyday analogy of gravitational lensing



Courtesy of Phil Marshall (Oxford)

Motivation, revisited

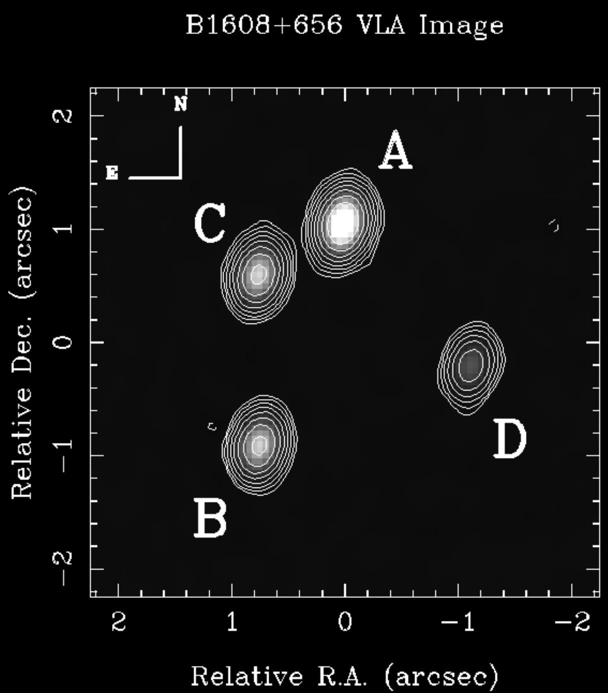
- Several methods to break the degeneracies seen in CMB data alone
  - each provides a big improvement when combined with CMB
  - each has (possibly unknown) systematics
- Obtain high-precision measurements with several *independent* methods to test for systematics and improve accuracy
- Lensing is an important part of this effort

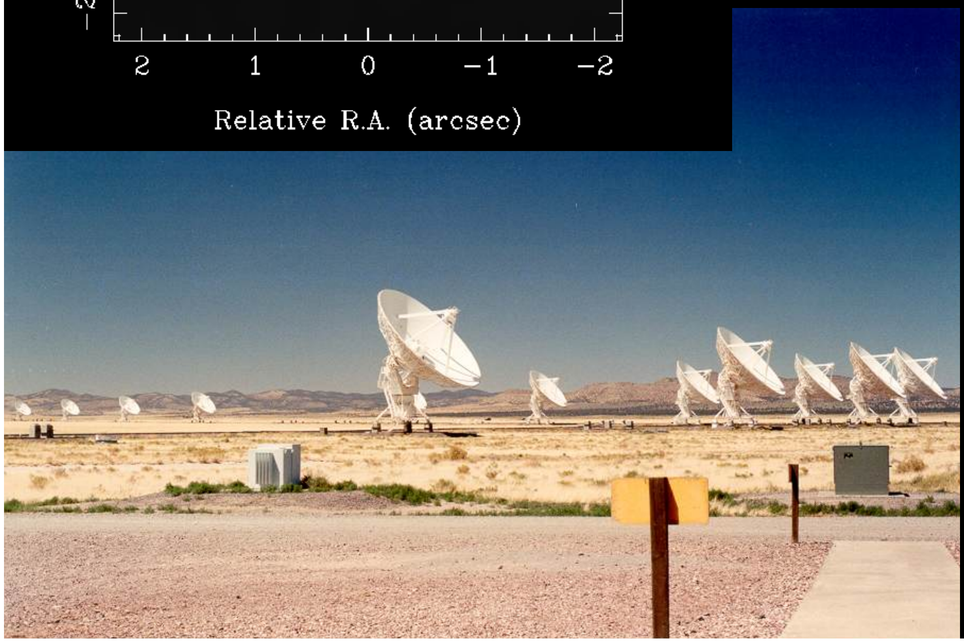
$$D_{\Delta t} = \frac{c\Delta t}{\frac{1}{2}(\theta - \beta)^2 - \psi(\theta)}$$

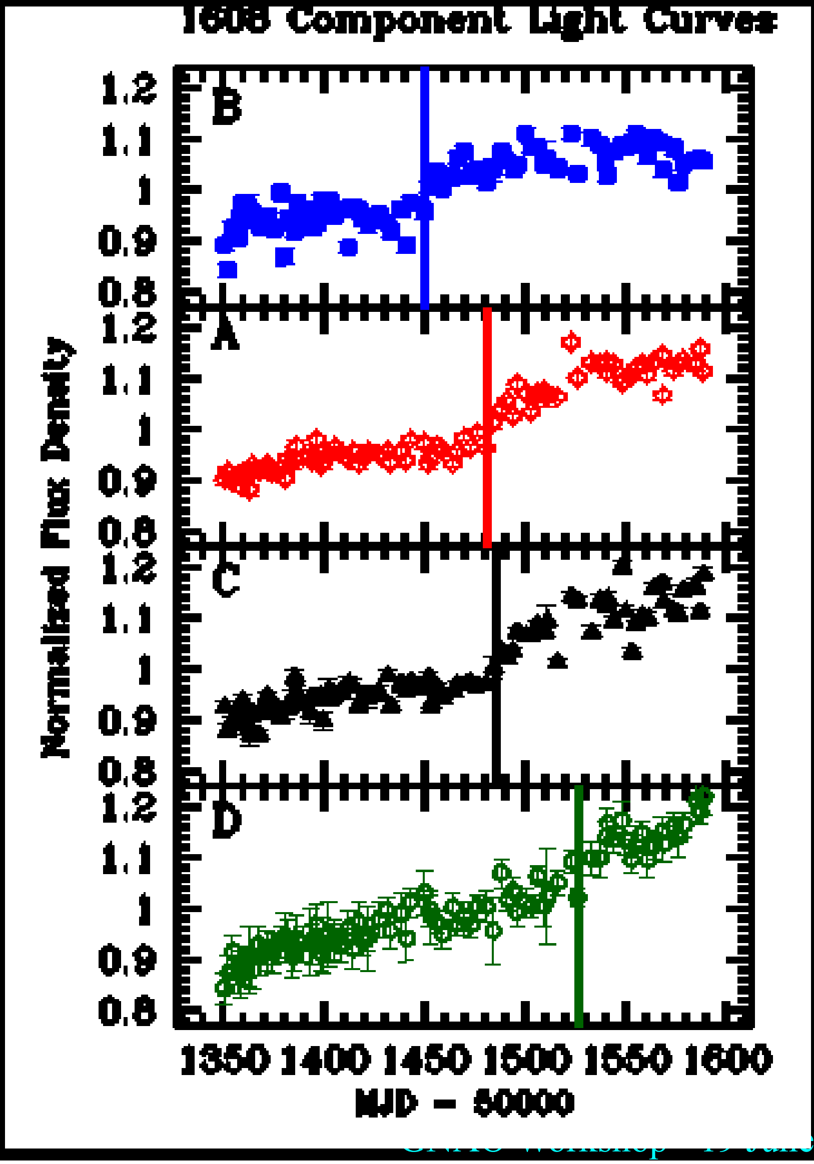
A very brief history of cosmology from lenses

- 1979: First gravitational lens discovered
- 1980s and early 90s:
  - Only a few lenses known.
  - Time delays are very controversial
- Mid 1990s – mid 2000s:
  - Dedicated time delay programs produce high-precision measurements
  - Modeling makes unwarranted assumptions, giving big spread in derived values of H_0
- Late 2000s – today:
  - Improvements in modeling and data lead to first robust high precision measurements
  - Best case so far: B1608+656 (Suyu et al. 2010)

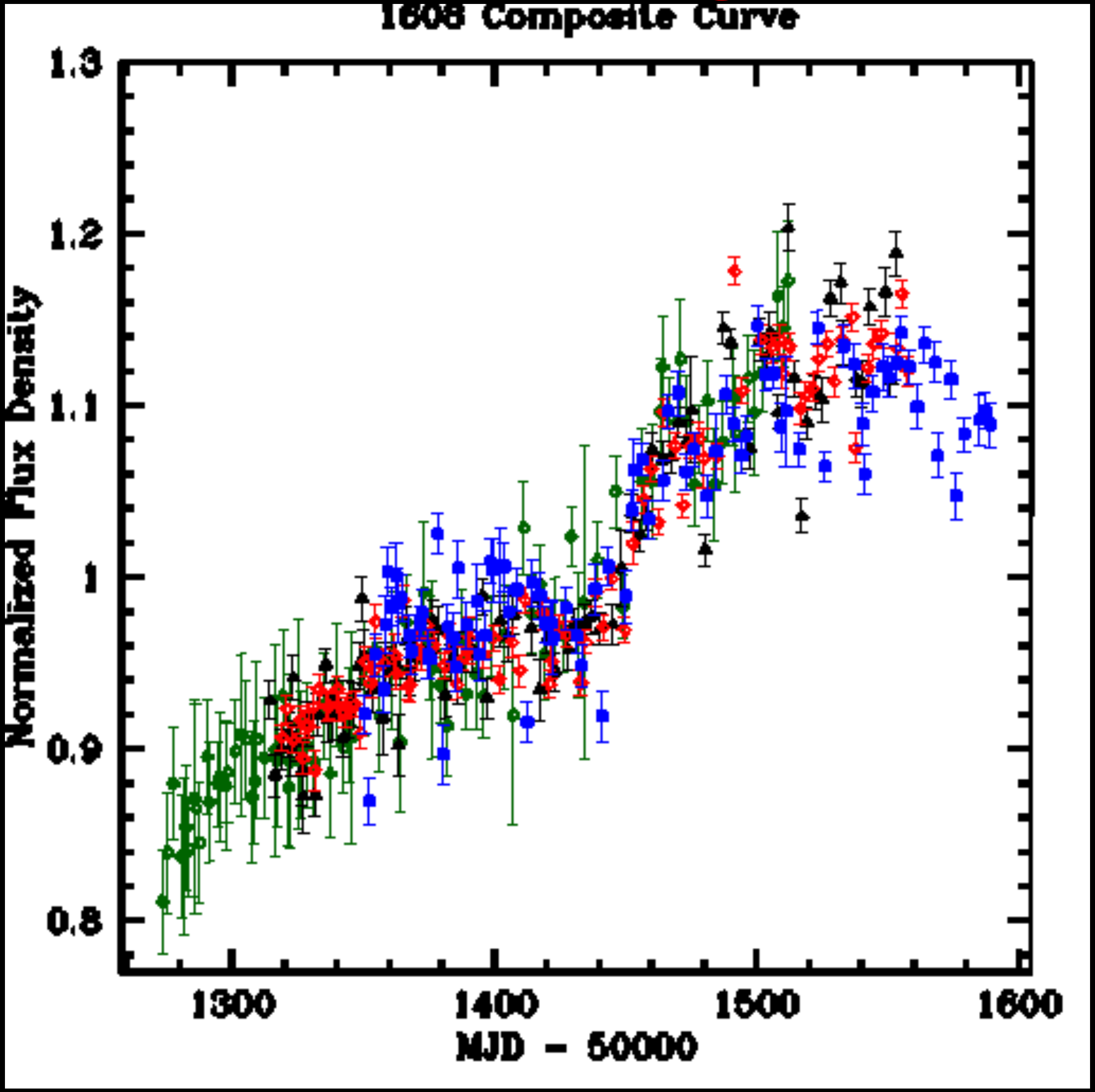
Measuring Δt in B1608+656







Measuring Δt in B1608+656



Fassnacht et al. (2002)

- Relative time delays (Fassnacht et al. 1999, 2002)

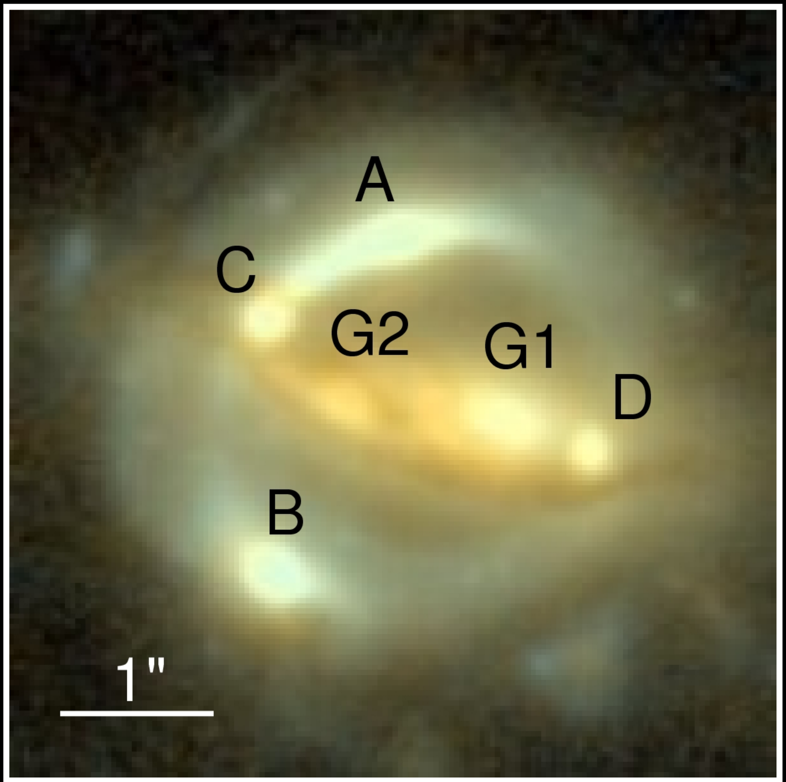
$\Delta t_{AB} = 31.5\ ^{+2.0}_{-1.0}$ days

$\Delta t_{CB} = 36.0 \pm 1.5$days

$\Delta t_{DB} = 77.0\ ^{+2.0}_{-1.0}$ days

B1608+656

z_d = 0.63 (Myers et al. 1995)
z_s = 1.39 (Fassnacht et al. 1996)

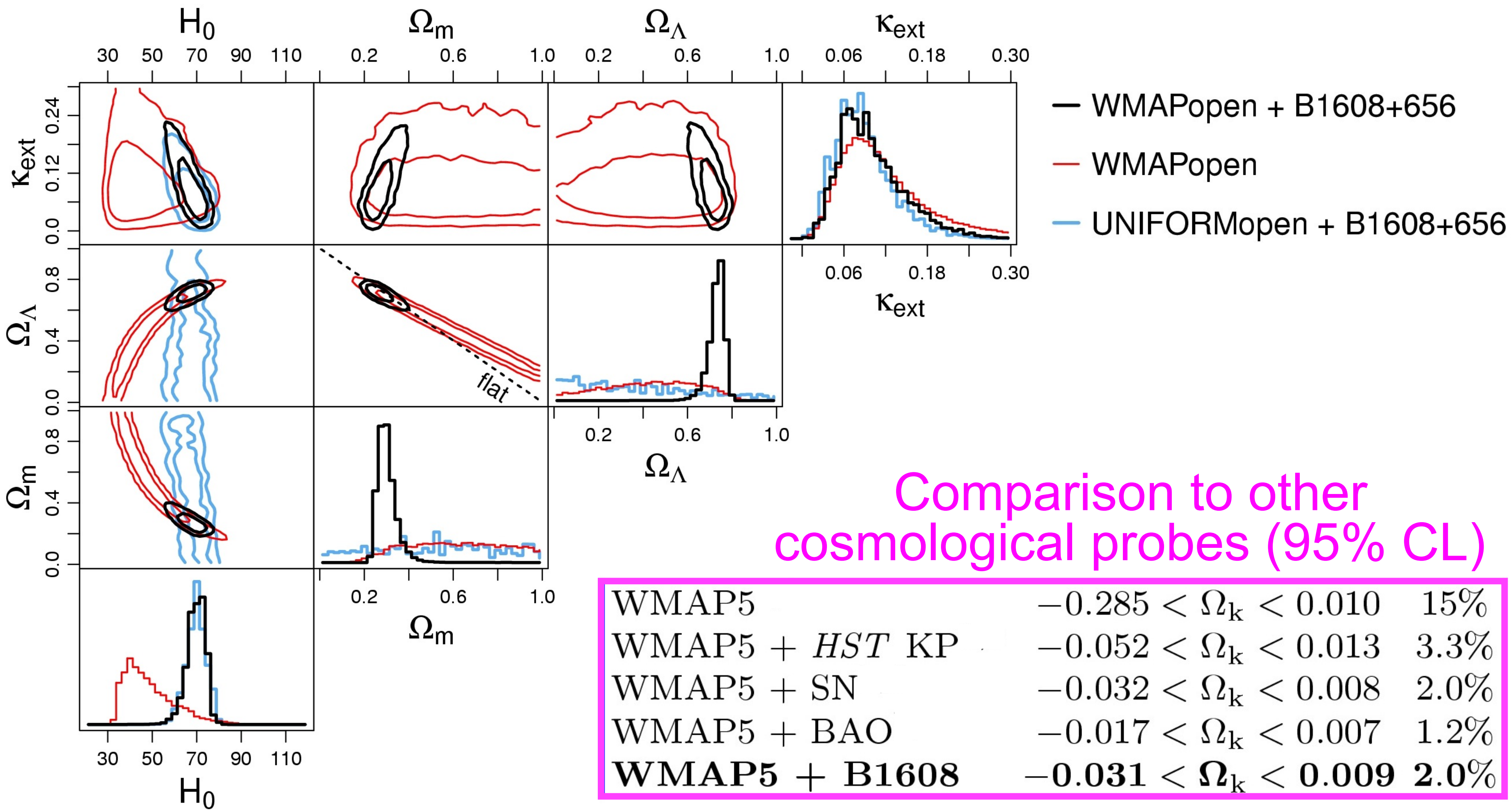


B1608+656 provides a good opportunity to measure $D_{\Delta t}$ with high precision

- One of the biggest systematic errors for lenses: *the mass-slope degeneracy*
- This can be broken with high SNR detections of the lensed extended emission in the Einstein ring
- For B1608+656 we did this through deep (20 orbits) HST/ ACS imaging (PI: Fassnacht)

Constraints on Curvature

assuming w = -1



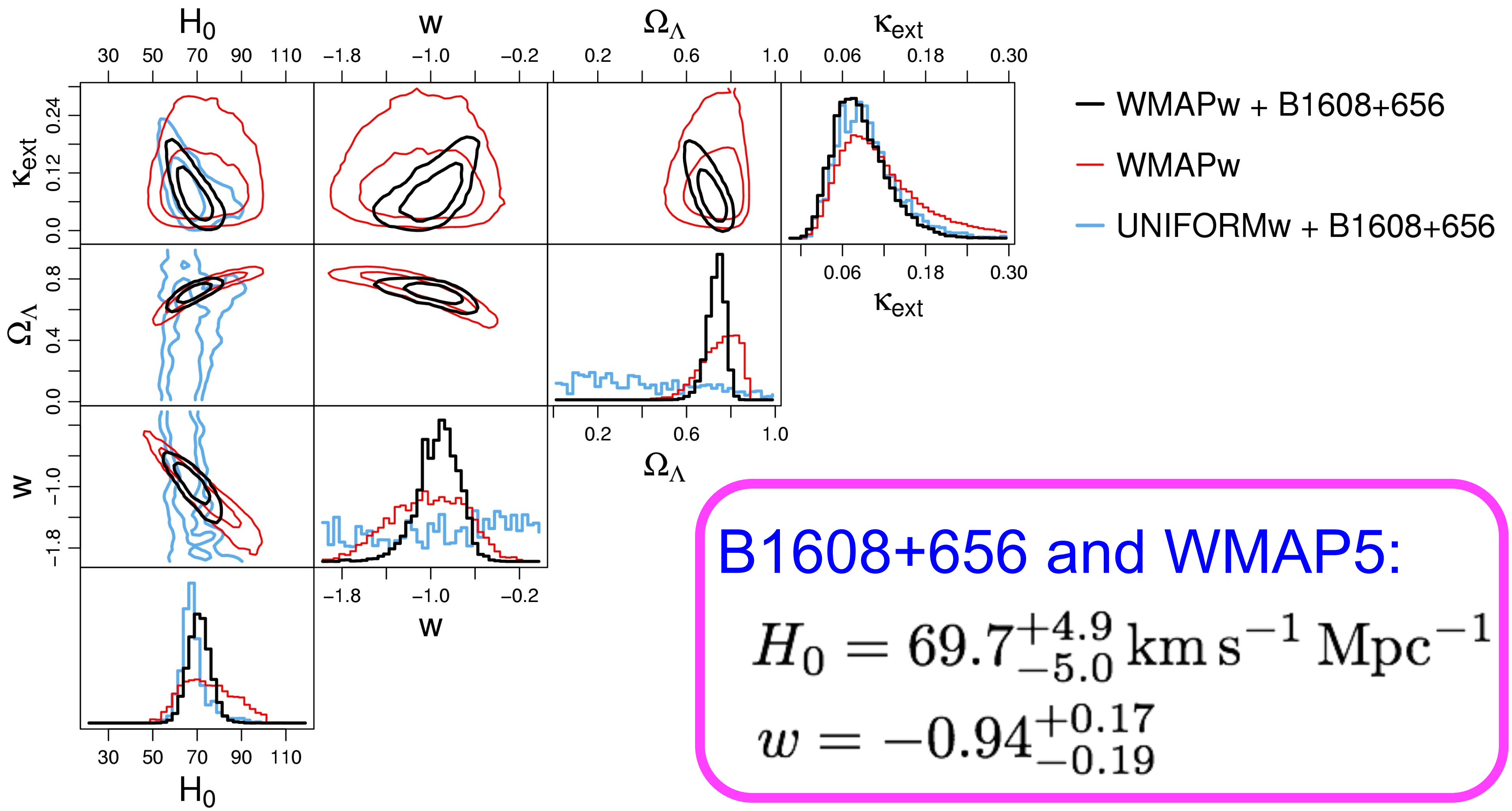
Comparison to other cosmological probes (95% CL)

WMAP5	$-0.285 < \Omega_k < 0.010$	15%
WMAP5 + *HST* KP	$-0.052 < \Omega_k < 0.013$	3.3%
WMAP5 + SN	$-0.032 < \Omega_k < 0.008$	2.0%
WMAP5 + BAO	$-0.017 < \Omega_k < 0.007$	1.2%
WMAP5 + B1608	$\mathbf{-0.031 < \Omega_k < 0.009}$	**2.0%**

Suyu et al. 2010

Constraints on Dark Energy

assuming flatness



B1608+656 and WMAP5:

$$H_0 = 69.7^{+4.9}_{-5.0}\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$$

$$w = -0.94^{+0.17}_{-0.19}$$

Suyu et al. 2010

Future prospects

- Our simulations have shown that, once systematics have been controlled (e.g., mass-slope degeneracy), precision on cosmological parameters improves as ~1/sqrt(N)
  - See also Coe & Moustakas (2009), Dobke et al. (2009)
- Right now B1608+656 is only system with all required data
- Need to increase the sample size of well-measured lenses

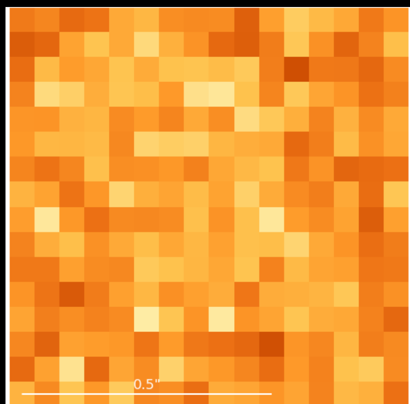
Can AO contribute?

- Quick answer: probably yes
- To break mass-slope degeneracy, need to detect arcs/rings at high SNR and *resolve them in the radial direction*
  - => need excellent angular resolution and sensitivity
- Right now, this is being approached with expensive HST observations
- What can AO do with lenses?

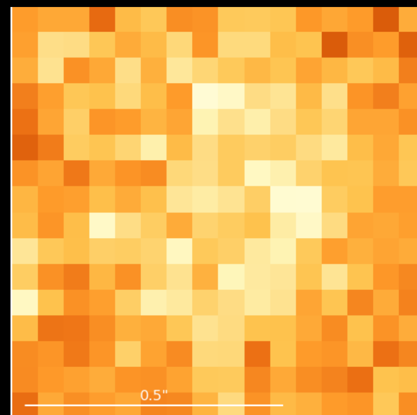
SHARP: The Strong-lensing High Angular Resolution Program

- Collaborators
  - Simona Vegetti (MIT)
  - Dave Lagattuta (Swinburne)
  - Matt Auger (Cambridge)
  - John McKean (ASTRON)
  - Leon Koopmans (Kapteyn)

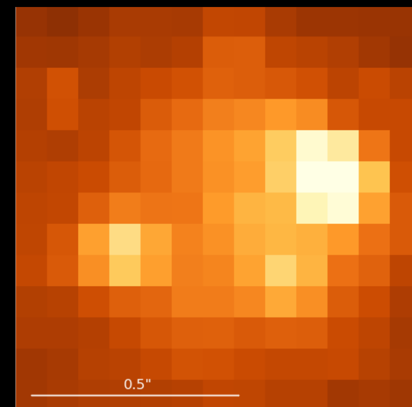
AO vs. Space: B0128+437



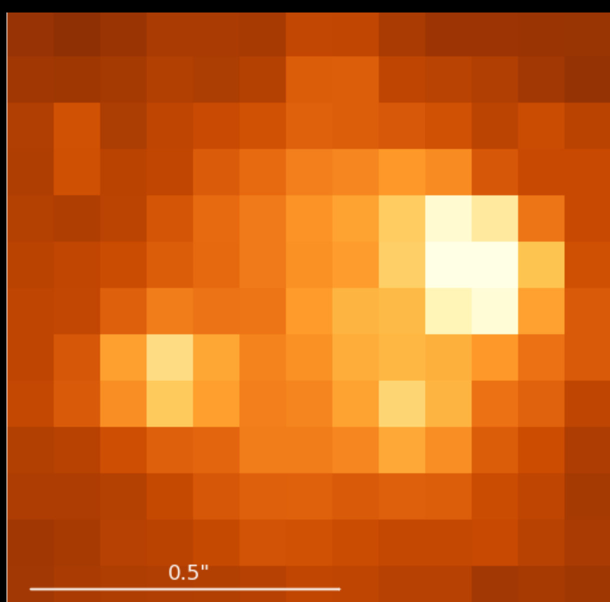
F555W



F814W

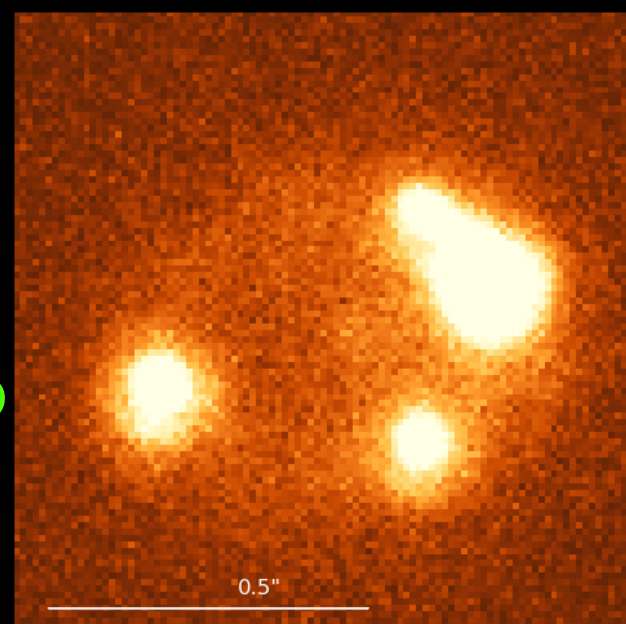


F160W



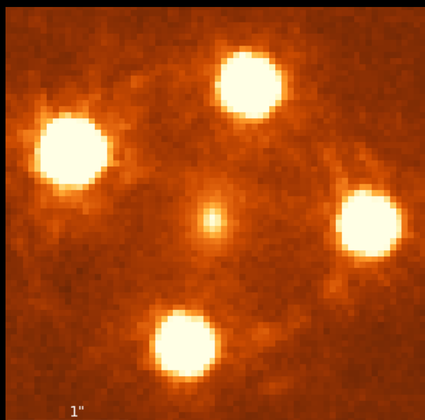
F160W, again

Keck AO K'-band



Lagattuta et al. 2010

AO vs. Space: HE0435-1223



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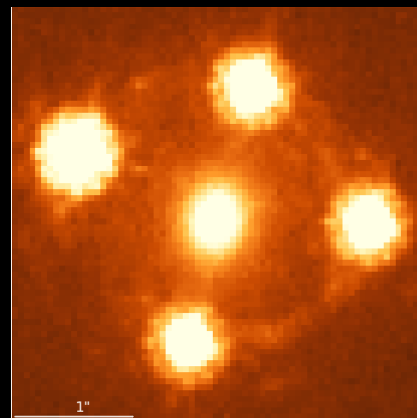

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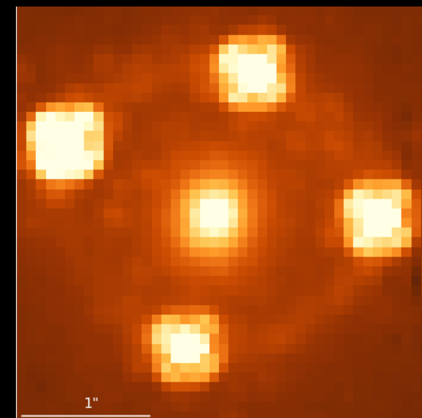

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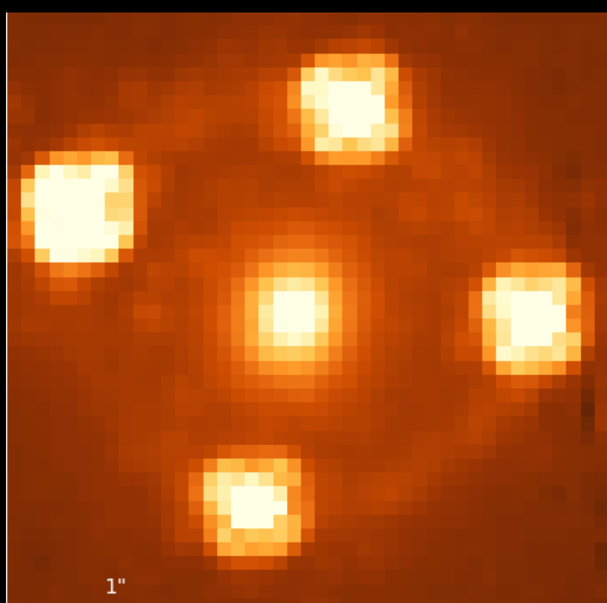
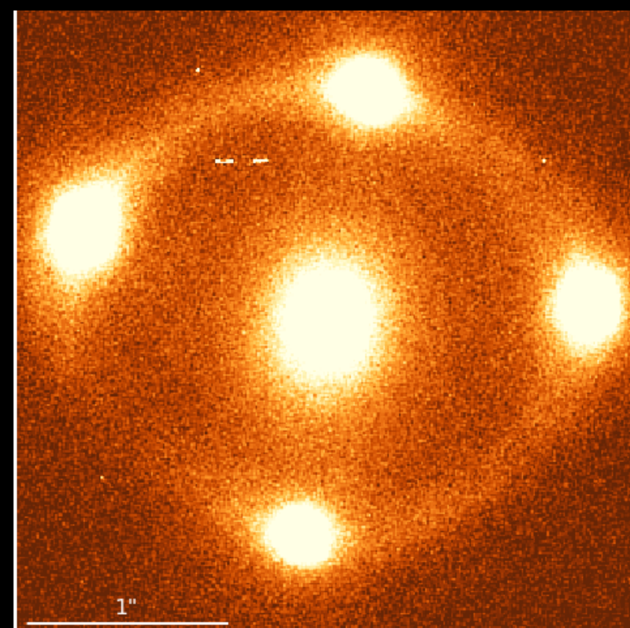


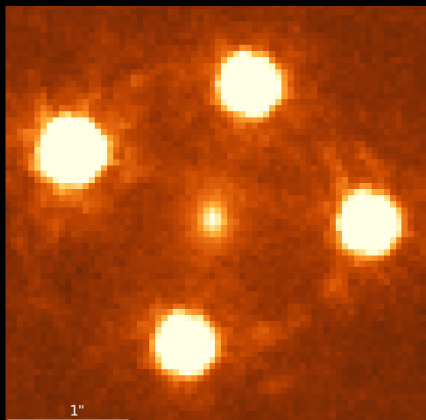
F160W, again

Keck AO K'-band



Fassnacht et al. in prep

AO vs. Space: HE0435-1223



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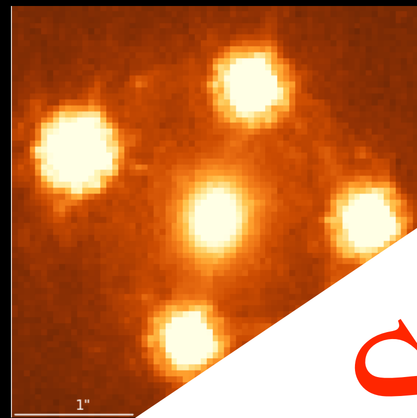
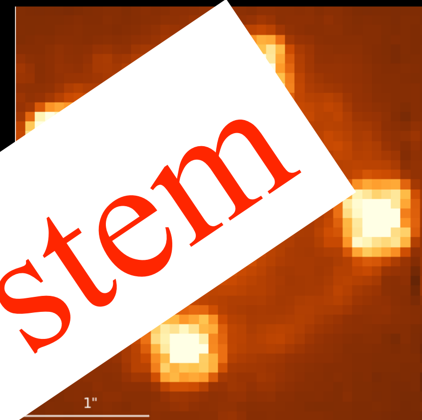
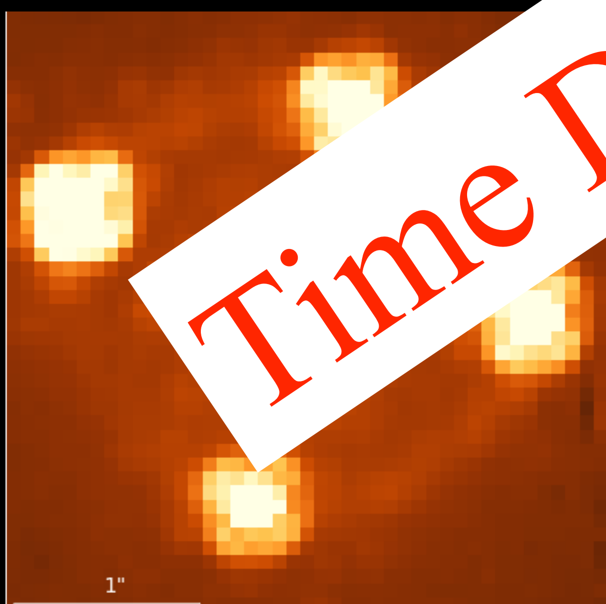




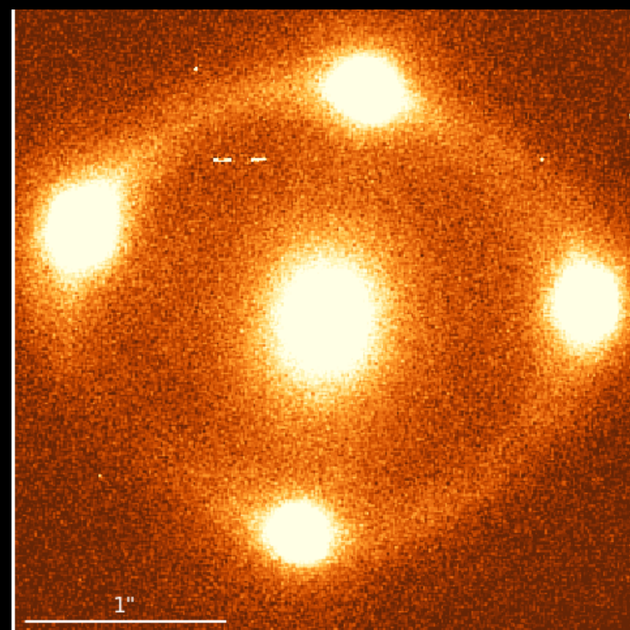
F160W



Time Delay System

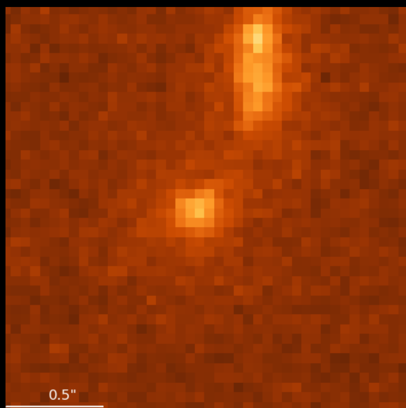
0W,
again

Keck AO
K'-band



Fassnacht et al. in prep

AO vs. Space: B0631+519



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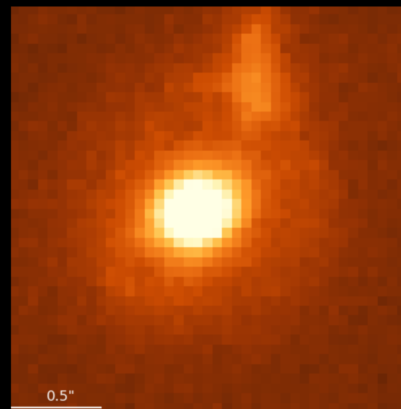

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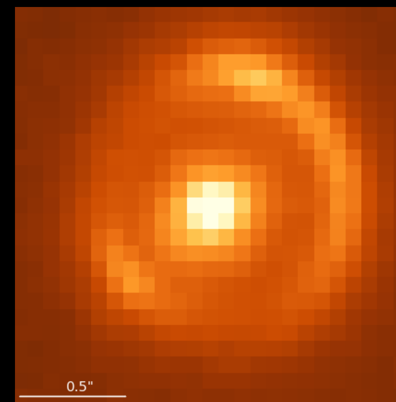

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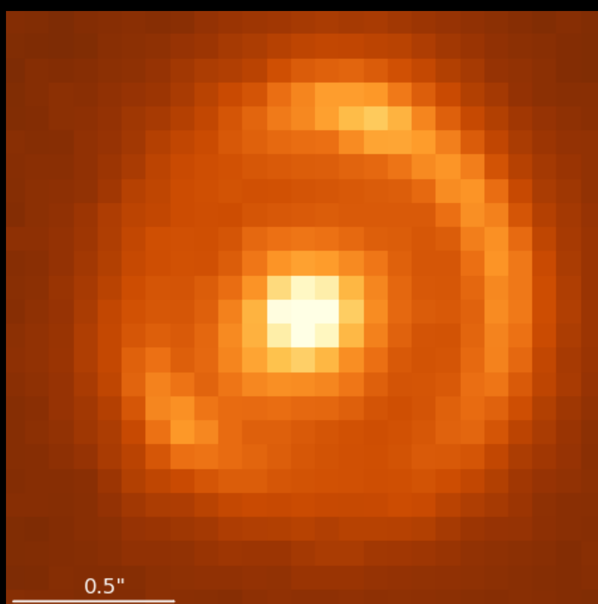
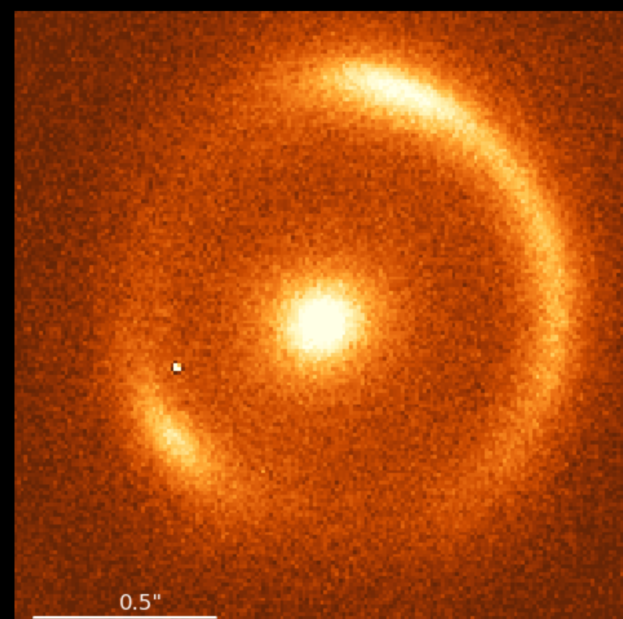


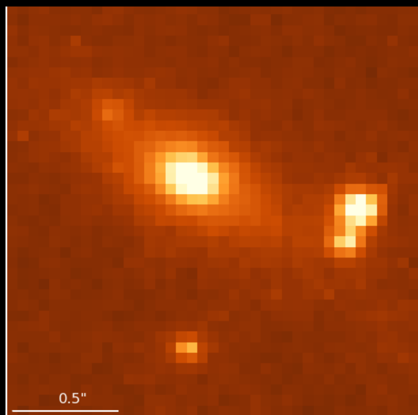
F160W, again

Keck AO K'-band

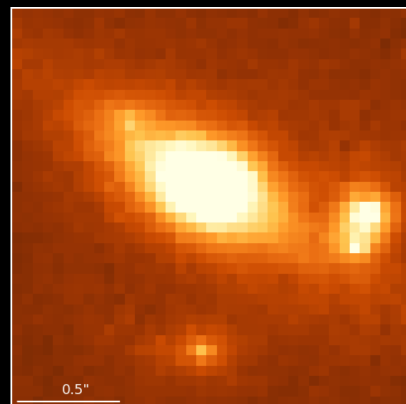


Fassnacht et al. in prep

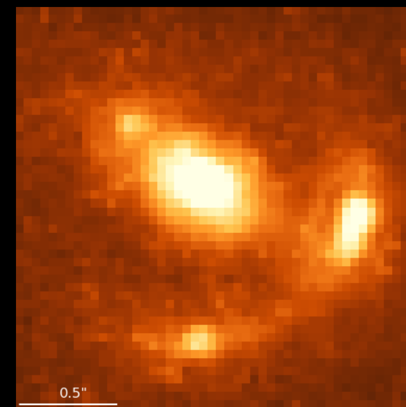
AO vs. Space: B0712+472



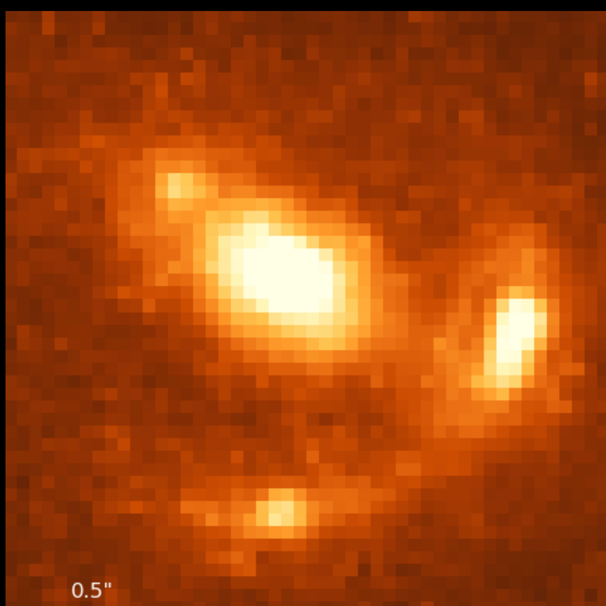
F555W



F814W

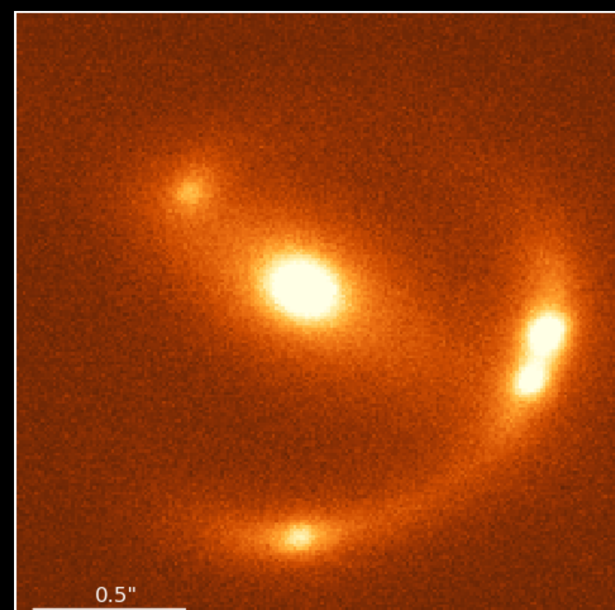


F160W



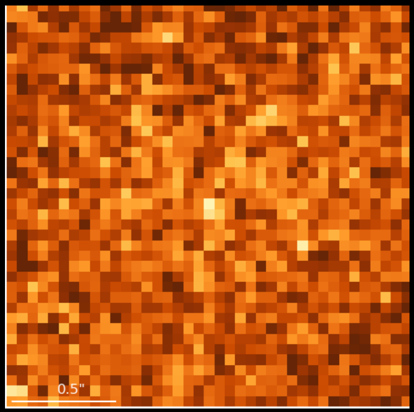
F160W,
again

Keck AO
K'-band

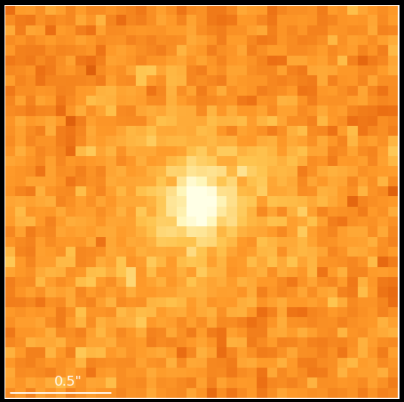


Fassnacht et al. in prep

AO vs. Space: B1938+666



F555W



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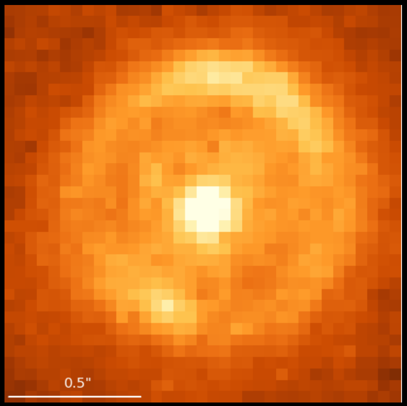
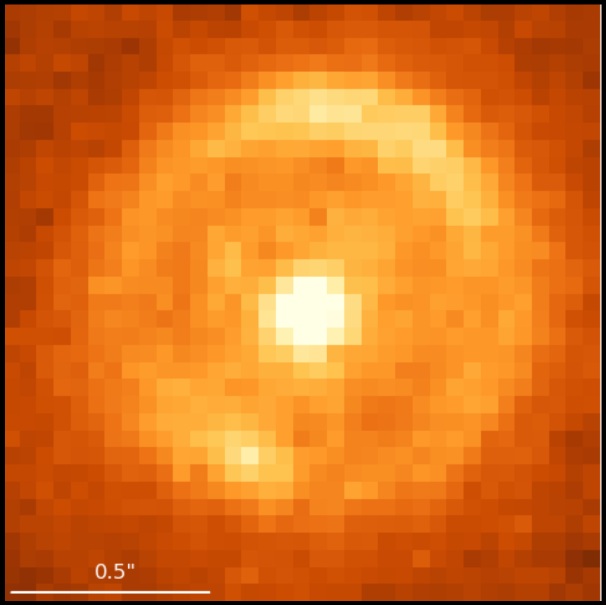
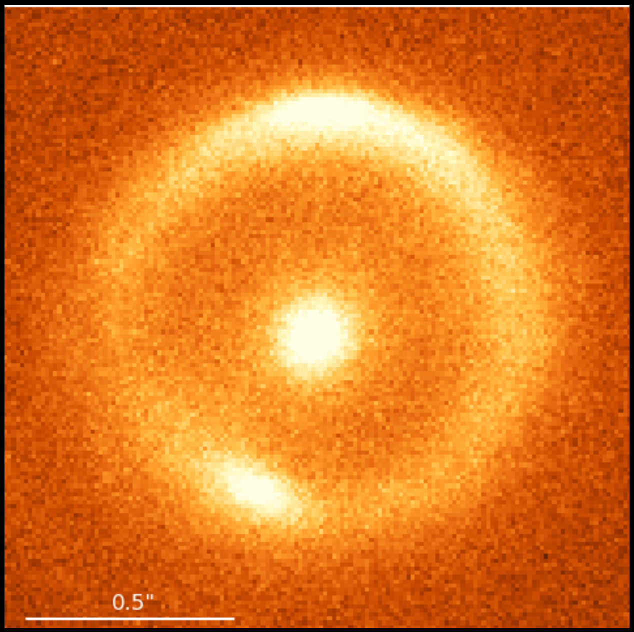


F160W



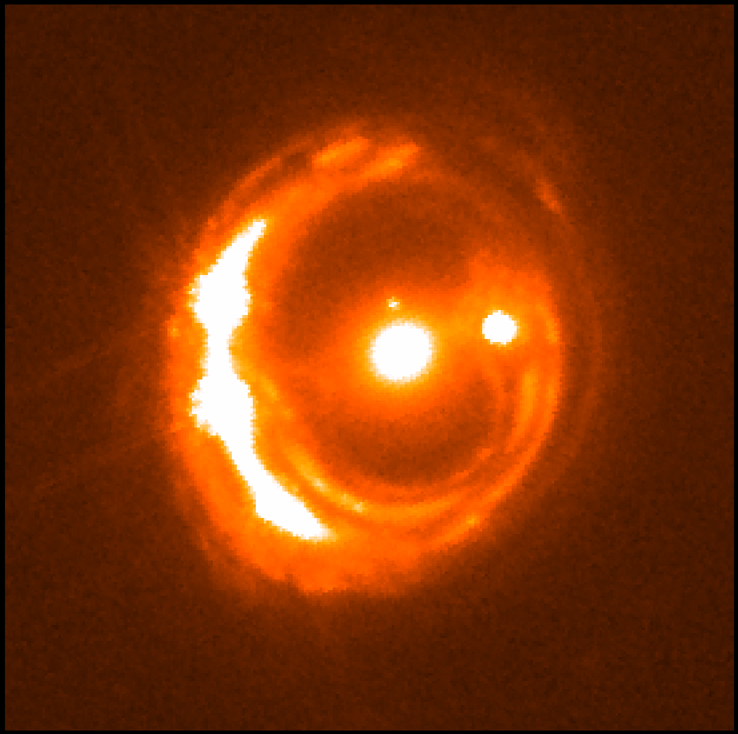
F160W, again

Keck AO K'-band

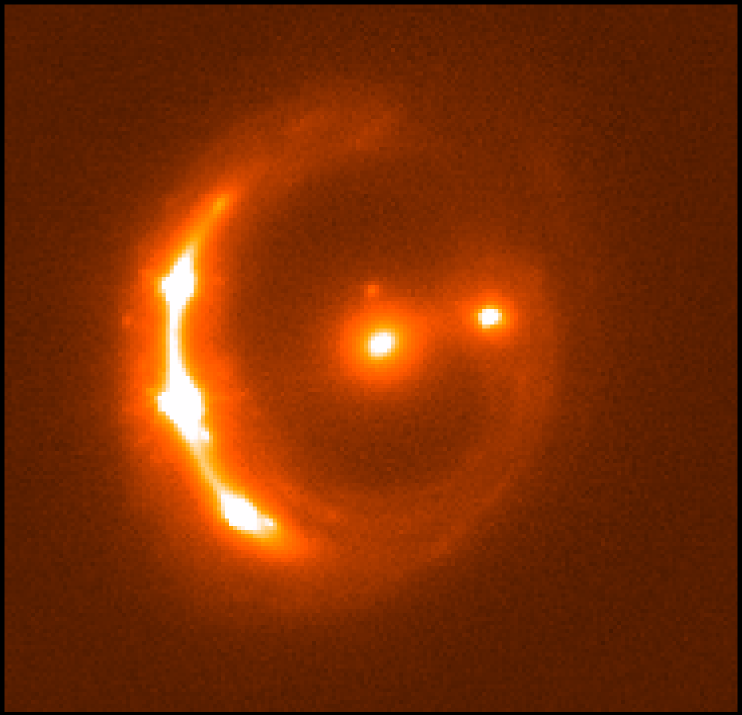


Fassnacht et al. in prep

AO vs. Space: RXJ 1131



HST/ACS F814W



Keck AO Ks

Fassnacht et al. in prep

AO vs. Space: RXJ 1131

Time Delay System

HST/ACS F814W

Keck AO Ks

Fassnacht et al. in prep

Requirements and Wishes

- Diffraction-limited imaging is a must
  - need to resolve the ring in the radial direction
- Must understand the PSF
  - disentangle lens and background source emission
  - We're testing now with Keck AO data, but lack of knowledge of the PSF may be the biggest problem with current data
  - Best if we could reconstruct the PSF from the data
- Small FOV is OK
  - most lens systems are 1-3 arcsec across
  - although bigger FOV can be beneficial if a PSF star is in the field
- We need lots of potential targets, to improve statistics
  - Set by tip-tilt star availability
  - Can we use the quasar images as TT objects?

Summary

- Gravitational lenses provide a powerful probe of cosmology that is independent from more traditional approaches
- AO observations of time delay lenses have the potential to be very important for breaking degeneracies in the modeling.

Spare slides

Constraints on Dark Energy

Comparison to other cosmological probes (68% CL)

NB: All assume flat, with w free but time-independent

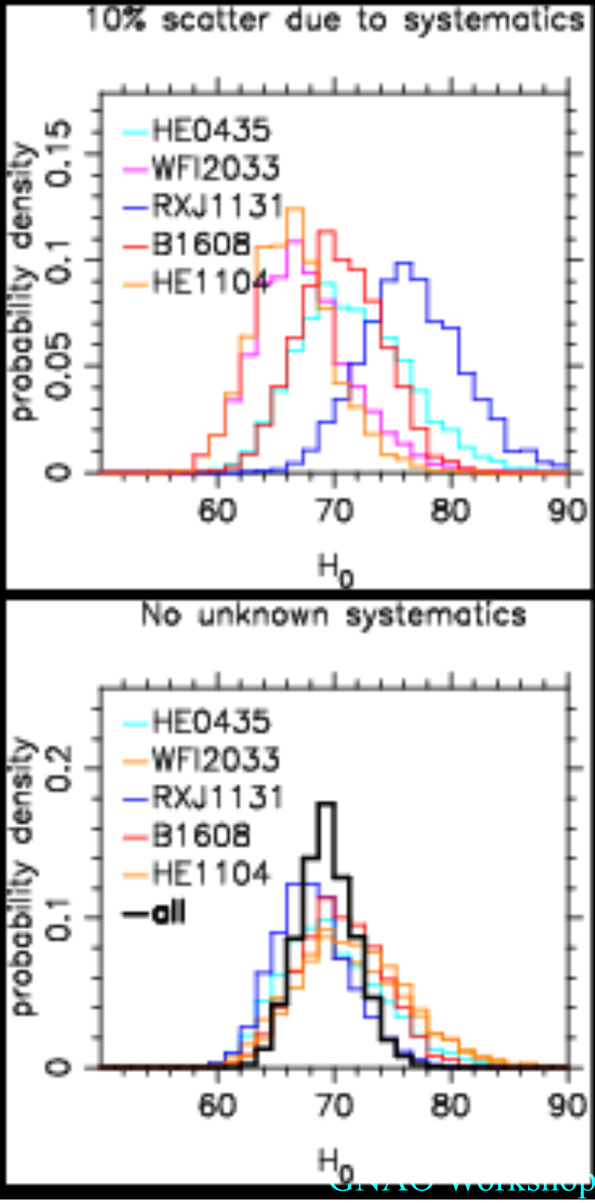
	$H_0/\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$		w	
WMAP5[a,b]	74^{+15}_{-14}	20%	$-1.06^{+0.41}_{-0.42}$	42%
WMAP5+*HST* KP[a,b,c]	$72.1^{+7.4}_{-7.6}$	10%	$-1.01^{+0.23}_{-0.22}$	23%
WMAP5+SN[a,b,d]	$69.4^{+1.6}_{-1.7}$	2.3%	$-0.977^{+0.065}_{-0.064}$	6.5%
WMAP5+BAO[a,b,e]	$73.9^{+4.7}_{-4.8}$	6.6%	$-1.15^{+0.21}_{-0.22}$	22%
WMAP5+Riess[f]	74.2 ± 3.6[g]	5.0%	-1.12 ± 0.12	12%
WMAP5+B1608	$\mathbf{69.7^{+4.9}_{-5.0}}$	**6.9%**	$\mathbf{-0.94^{+0.17}_{-0.19}}$	**18%**

When combined with WMAP5, B1608+656 is

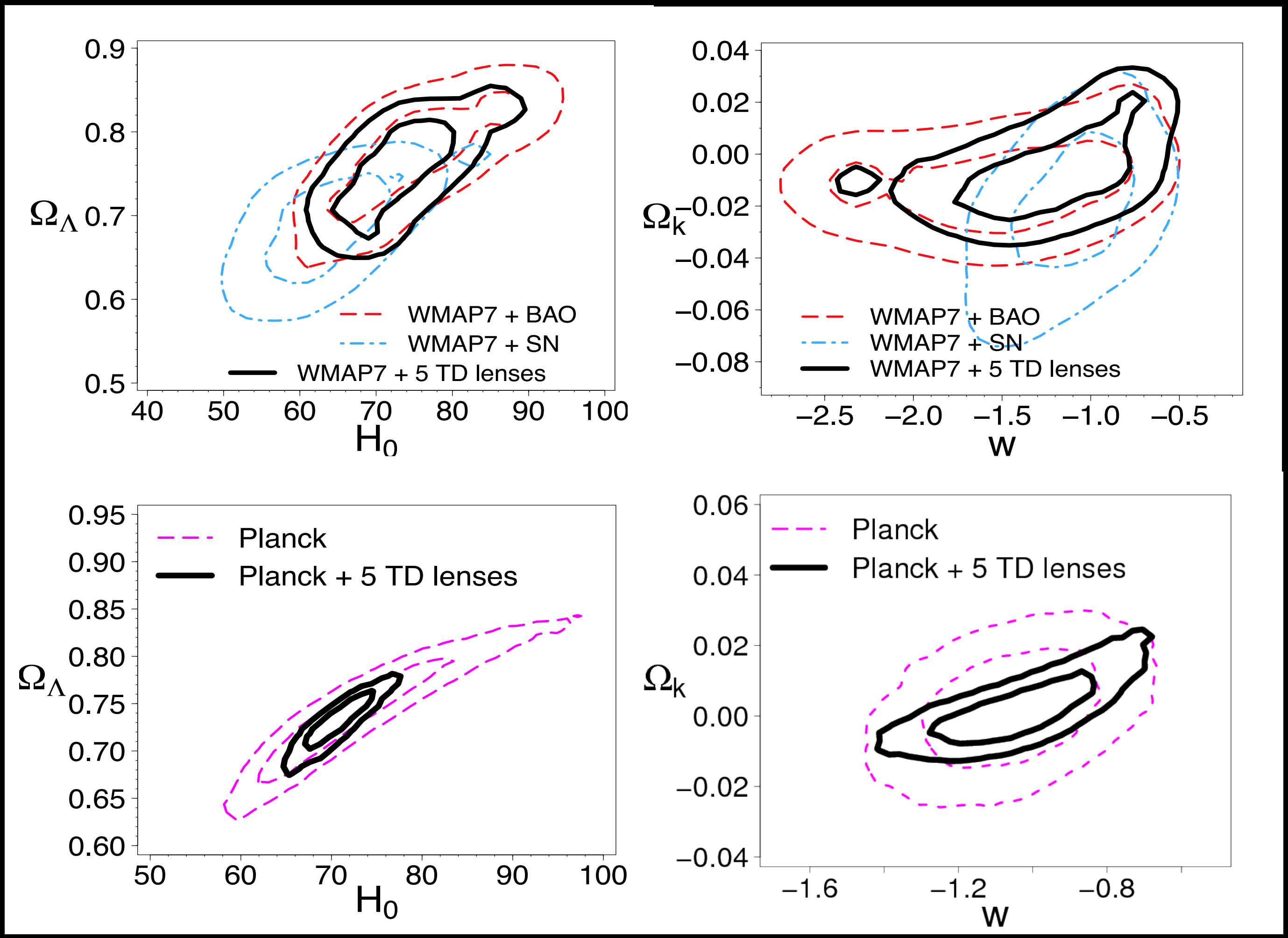
- more informative than the *HST* Key Project
- comparable to the pre-BOSS BAO data in constraining H_0 and w

Near-term future

- There are 4 additional lens systems that nearly have B1608-quality data sets
- We're systematically acquiring data and will do similar analysis
- Each lens provides an independent measurement (unlike, e.g., supernovae) so we can test for internal systematics

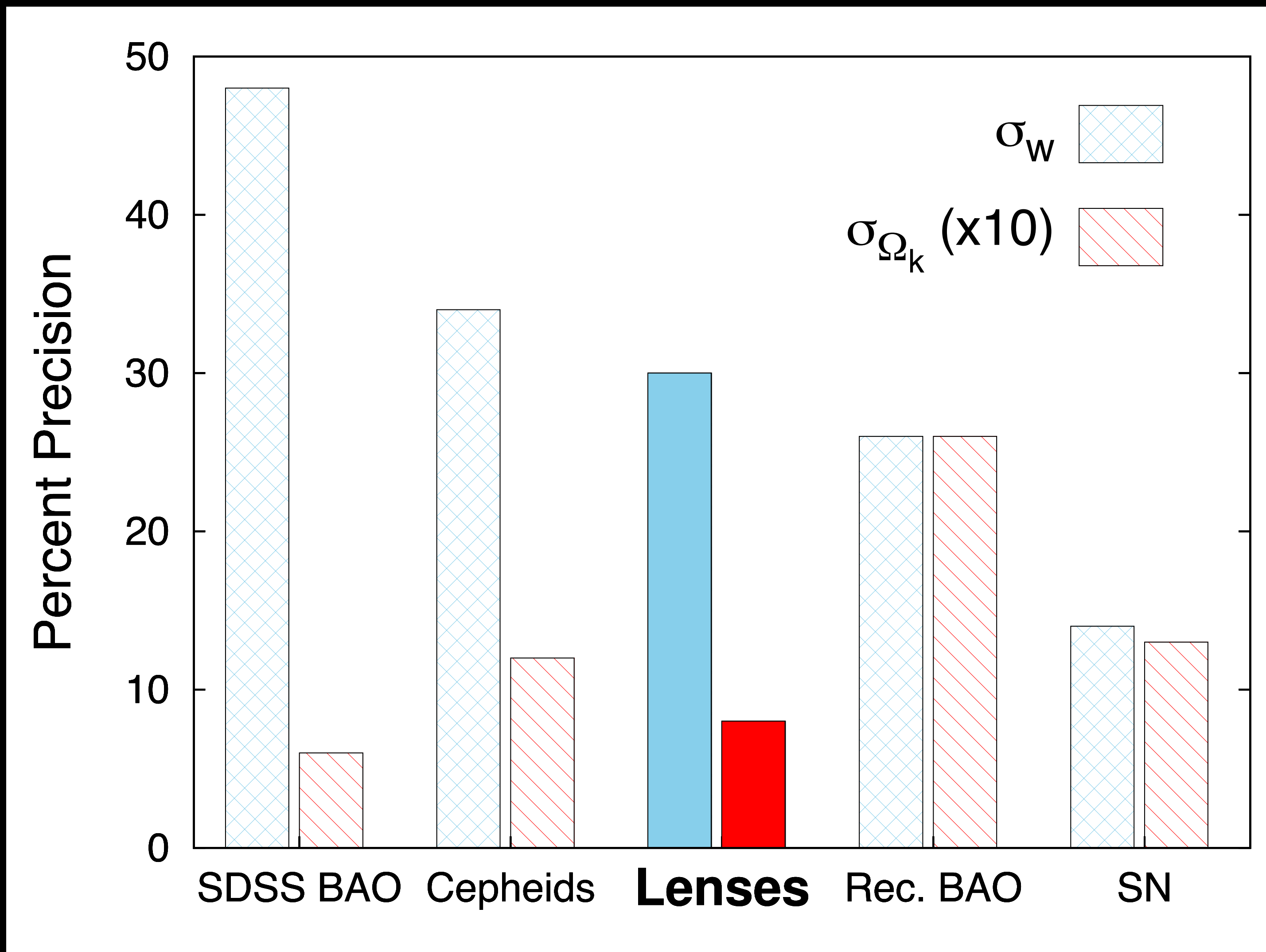


Near-term future



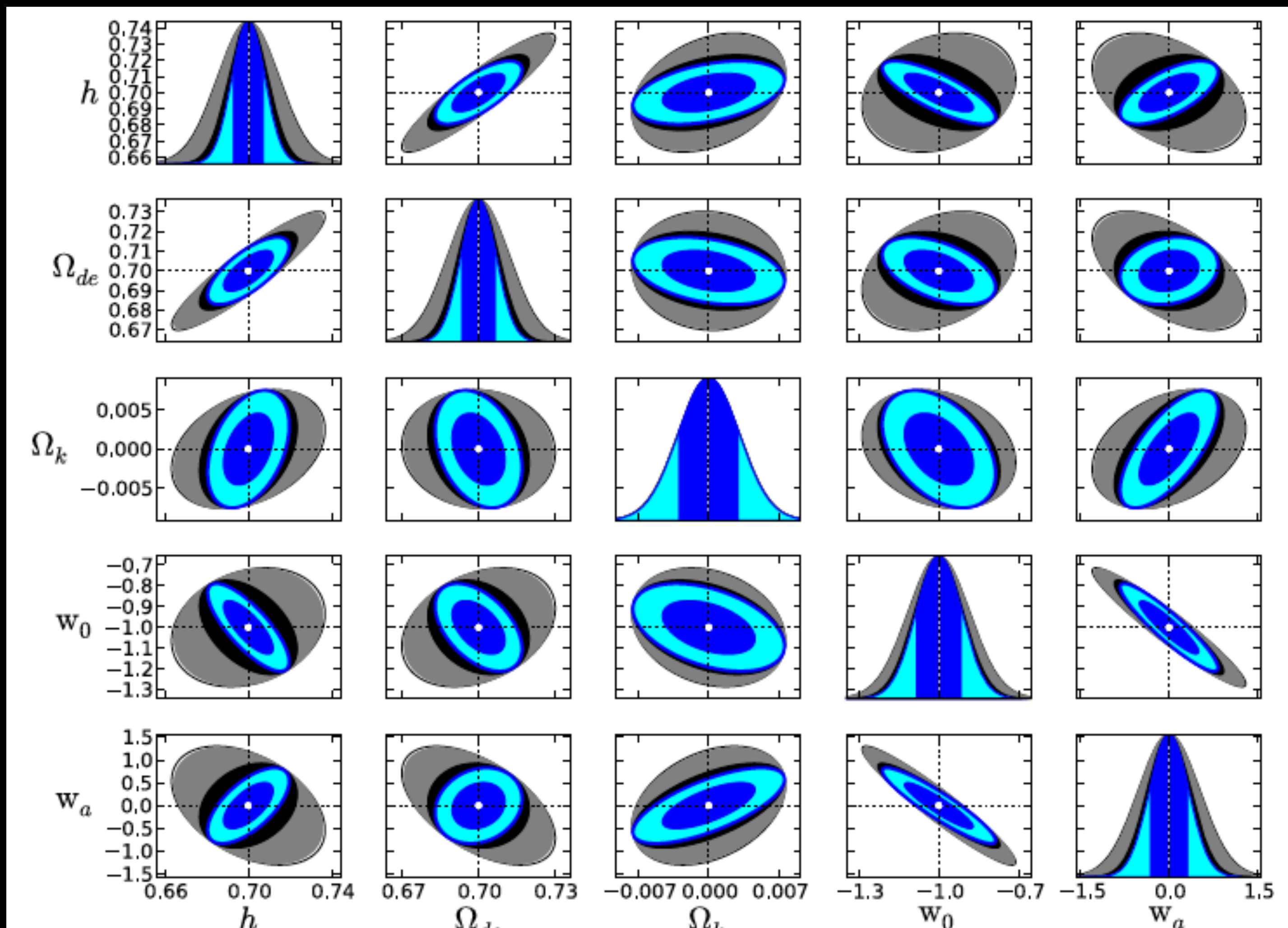
Simulations from Sherry Suyu

Near-term future



Simulations from Sherry Suyu

Mid-to-long-term future



Coe & Moustakas 2009

How to combine multiple data sets

Bayesian Analysis

Denote $\boldsymbol{\pi} = \{H_0, \Omega_{\rm m}, \Omega_\Lambda, w\}$ (cosmological parameters)

$\boldsymbol{\xi} = \{\boldsymbol{\pi}, \boldsymbol{\nu}\}$ (all model parameters)

Posterior Probability Distribution:

$$P(\boldsymbol{\pi}|\boldsymbol{d}_{\rm ACS}, \boldsymbol{\Delta t}, \boldsymbol{\sigma}) = \int {\rm d}\boldsymbol{\nu}\, {\rm P}(\boldsymbol{\xi}|\boldsymbol{d}_{\rm ACS}, \boldsymbol{\Delta t}, \boldsymbol{\sigma})$$

where

$$P(\boldsymbol{\xi}|\boldsymbol{d}_{\rm ACS}, \boldsymbol{\Delta t}, \boldsymbol{\sigma}) \propto \underbrace{P(\boldsymbol{d}_{\rm ACS}|\boldsymbol{\xi})\, P(\boldsymbol{\Delta t}|\boldsymbol{\xi})\, P(\boldsymbol{\sigma}|\boldsymbol{\xi})}_{\text{Likelihood}} \overbrace{P(\boldsymbol{\xi})}^{\text{Prior}}$$

Our new approach for SHARP: Use Keck adaptive optics imaging

- Use Keck adaptive optics imaging of lens systems to search for both luminous and dark substructures
- Get resolution comparable to or better than HST, while using a mirror that has 16 times the collecting area
  - especially good for red objects that are faint at optical wavelengths

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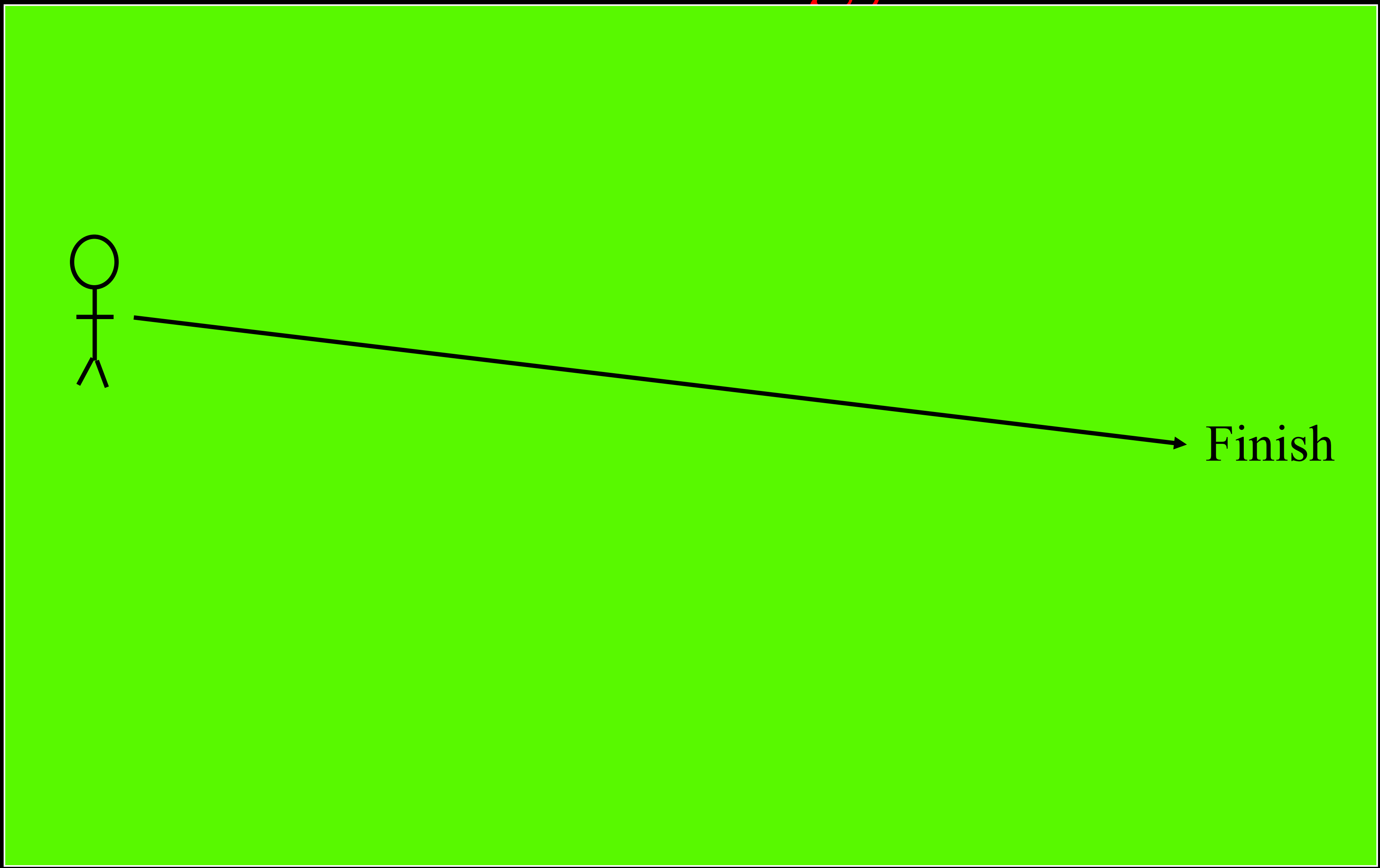
$$\theta \sim \lambda / D$$

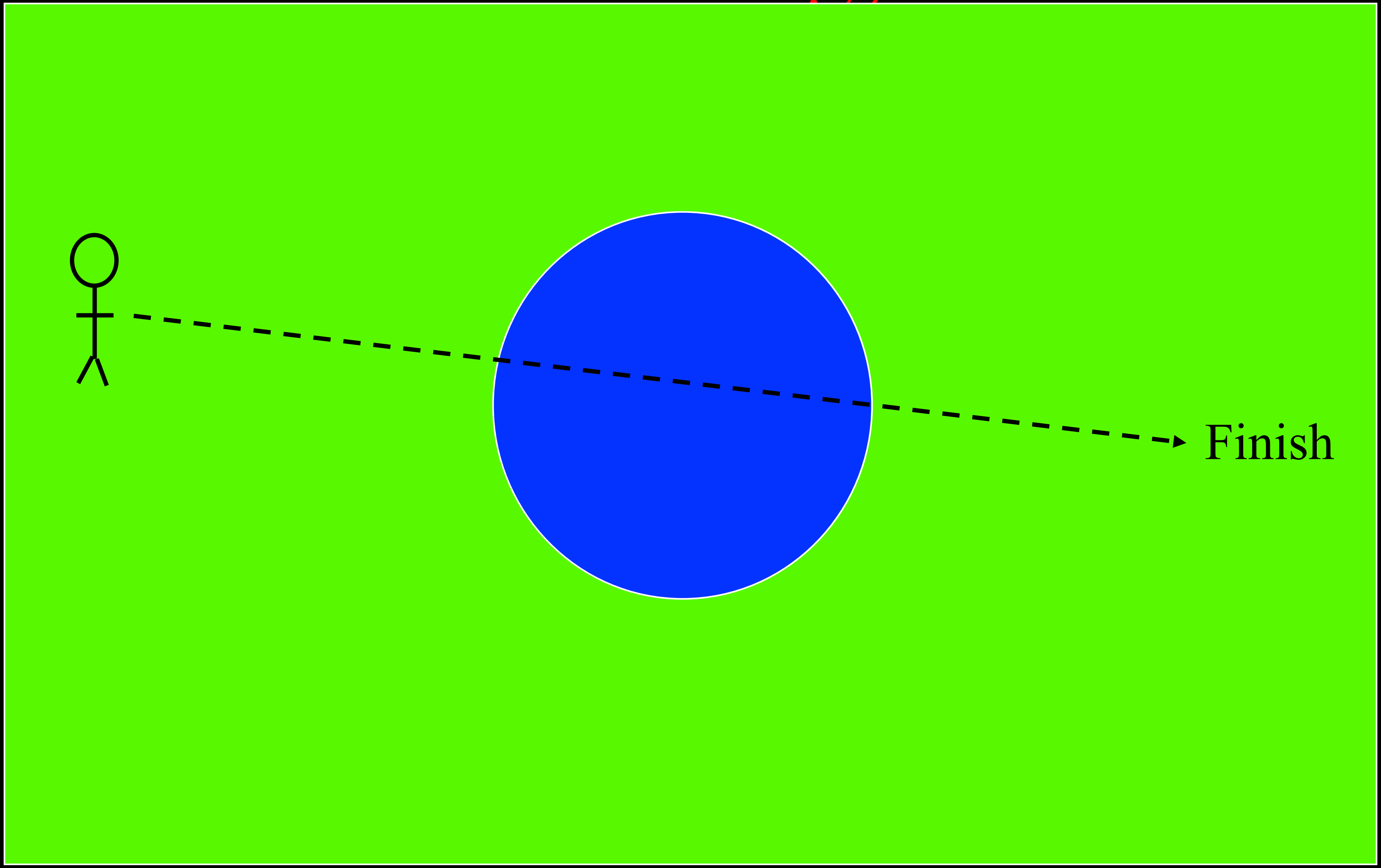
SHARP Logistics

- Focus on systems with 4 lensed images or prominent arcs/rings
- For AO, need bright (R<17) tip-tilt star within ~60 arcsec
  - restricts size of available sample
- Ultimate goal for depth of AO imaging: ~3-4 hours integration time per target
  - enables search for substructure less massive than LMC/SMC
- Goal for sample size: ~20 systems

An analogy



An analogy



An analogy