Physics of the Universe:
Gravitational Lensing

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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]
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

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

- 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

My favorite lens

4 images

My 2nd favorite lens

Einstein ring
\( \Delta t_{tot} = \Delta t_{geom} + \Delta t_{grav} \)

\( \Delta t_i = \left( \frac{D_{\Delta t}}{c} \right) \left[ \frac{1}{2} |\theta_i - \beta|^2 - \psi(\theta_i) \right] \)

\( D_{\Delta t} = (1+z_l) \left( \frac{D_1 D_s}{D_{ls}} \right) \)

**Strong Lensing 101**

GNAO Workshop - 19 June 2012
From time delays to cosmology

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

- **Observables**
  - \( \Delta t, \theta, z_l, z_s \)
- **Model**
  - \( \beta, \psi(\theta) \)
- **Cosmology**
  - \( D_{\Delta t} = f(z_l, z_s, H_0, \Omega_M, \Omega_\Lambda, w) \)
Everyday analogy of gravitational lensing

Unlensed Source

4 Images

Einstein Ring

2 Images

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 $\Delta t$ in B1608+656
Measuring $\Delta t$ in B1608+656

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

$$\Delta t_{AB} = 31.5 \pm 1.0 \text{ days}$$
$$\Delta t_{CB} = 36.0 \pm 1.5 \text{ days}$$
$$\Delta t_{DB} = 77.0 \pm 2.0 \pm 1.0 \text{ days}$$
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)

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

$z_d = 0.63$ (Myers et al. 1995)

$z_s = 1.39$ (Fassnacht et al. 1996)
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: $-0.031 < \Omega_k < 0.009$ (2.0%)

Suyu et al. 2010
Constraints on Dark Energy
assuming flatness

B1608+656 and WMAP5:

\[ H_0 = 69.7^{+4.9}_{-5.0} \text{ km s}^{-1} \text{ Mpc}^{-1} \]
\[ w = -0.94^{+0.17}_{-0.19} \]

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 $\sim 1/\sqrt{N}$
  - 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

F555W

F814W

F160W

F160W, again

Keck AO K’-band

Fassnacht et al. in prep

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AO vs. Space: HE0435-1223

Fassnacht et al. in prep

F555W

F160W

Keck AO K’-band

Time Delay System

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AO vs. Space: B0631+519

F555W

F814W

F160W

F160W, again

Keck AO K’-band

Fassnacht et al. in prep

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AO vs. Space: B0712+472

F555W
F814W
F160W

F160W, again
Keck AO K'-band

Fassnacht et al. in prep

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AO vs. Space: B1938+666

F555W

F814W

F160W

F160W, again

Keck AO K’-band

Fassnacht et al. in prep

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AO vs. Space: RXJ 1131

HST/ACS F814W

Keck AO Ks

Fassnacht et al. in prep
AO vs. Space: RXJ 1131

HST/ACS F814W

Keck AO Ks

Fassnacht et al. in prep

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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

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<th>$H_0$/ km s$^{-1}$ Mpc$^{-1}$</th>
<th>$w$</th>
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<tbody>
<tr>
<td>WMAP5$^{a,b}$</td>
<td>$74^{+15}_{-14}$</td>
<td>20% $-1.06^{+0.41}_{-0.42}$</td>
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<tr>
<td>WMAP5+$HST$ KP$^{a,b,c}$</td>
<td>$72.1^{+7.4}_{-7.6}$</td>
<td>10% $-1.01^{+0.23}_{-0.22}$</td>
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<tr>
<td>WMAP5+SN$^{a,b,d}$</td>
<td>$69.4^{+1.6}_{-1.7}$</td>
<td>2.3% $-0.977^{+0.065}_{-0.064}$</td>
</tr>
<tr>
<td>WMAP5+BAO$^{a,b,e}$</td>
<td>$73.9^{+4.7}_{-4.8}$</td>
<td>6.6% $-1.15^{+0.21}_{-0.22}$</td>
</tr>
<tr>
<td>WMAP5+Riess$^{f}$</td>
<td>$74.2 \pm 3.6^{g}$</td>
<td>5.0% $-1.12 \pm 0.12$</td>
</tr>
<tr>
<td>WMAP5+B1608</td>
<td>$69.7^{+4.9}_{-5.0}$</td>
<td>6.9% $-0.94^{+0.17}_{-0.19}$</td>
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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 $\pi = \{H_0, \Omega_m, \Omega_\Lambda, w\}$ (cosmological parameters)

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

Posterior Probability Distribution:

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

where

$$P(\xi | d_{ACS}, \Delta t, \sigma) \propto P(d_{ACS} | \xi) P(\Delta t | \xi) P(\sigma | \xi) P(\xi)$$

Prior

Likelihood
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

$\theta \sim \frac{\lambda}{D}$
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

Finish
An analogy
An analogy