Exploring the Dark Universe with Gravitational Lensing

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Outline

• Dark Energy
  Accurate Cosmology from Gravitational Lens Time Delays
  • Motivation and introduction to lensing
  • Gravitational lens B1608+656
  • Measurements of cosmological parameters
  • Future prospects

• Dark Matter
  Baryons and Dark Matter in a Spiral Galaxy
  • Introduction
  • Method for disentangling baryons and dark matter
  • Dark matter halo and stellar IMF of the spiral gravitational lens B1933+503
Accurate Cosmology from Gravitational Lens Time Delays

in collaboration with

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Roger Blandford, Stefan Hilbert (KIPAC)
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Chris Fassnacht (UC Davis)
Malte Tewes, Frédéric Courbin (EPFL)
Cécile Faure, Georges Meylan (EPFL)
Dominique Sluse (AlfA, Bonn)
Motivation

- $H_0$, a key parameter that sets the age, size and critical density of Universe

- $H_0$ is the single most useful complement to the CMB for dark energy studies [e.g. Hu 2005]

Independent methods are needed to overcome systematics (unknown unknowns)

[Riess et al. 2011]
Gravitational Lensing

Galaxy Cluster Abell 1689

SLAC SJ0737+3216

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Lensing probes the Dark Universe

Dimensionless surface mass density:
\[ \kappa(\theta) = \frac{1}{2} \nabla^2 \psi(\theta) \]

\( \checkmark \) Dark matter probe
\( \checkmark \) Cosmographic probe

Time Delay:
\[ t = \frac{1}{c} \frac{D_d D_s}{D_{ds}} (1 + z_d) \left[ \frac{1}{2} (\theta - \beta)^2 - \psi(\theta) \right] \]

Time-delay distance:
\[ D_{\Delta t} \propto \frac{1}{H_0} \phi_{\text{lens}} \]
Gravitational Lens Time Delays

Time delay:
\[ t = \frac{1}{c} D_{\Delta t} \phi_{\text{lens}} \]

Time-delay distance:
\[ D_{\Delta t} \propto \frac{1}{H_0} \]

Obtain from lens mass model

For cosmography, need:
1. time delays
2. lens mass model
3. mass along line of sight

Method proposed in 1964 by Refsdal!
Lens Mass Model

\[ t = \frac{1}{c} D_{\Delta t} \phi_{\text{lens}} \]

Use extended images of AGN host

Used only image positions of AGN (providing few constraints)

[Suyu et al. 2009]
Mass along Line of Sight

\[ t = \frac{1}{c} D_{\Delta t} \phi_{\text{lens}} \]

galaxy number counts + Millennium Simulation

[Suyu et al. 2010]
Results from B1608+656 for flat $\Lambda$CDM

B1608+656 and WMAP5:

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

\[ w = -0.94^{+0.17}_{-0.19} \]
## Constraints on Dark Energy

### Comparison of cosmological probes (68% CL)

<table>
<thead>
<tr>
<th></th>
<th>$H_0/\text{km}\text{s}^{-1}\text{Mpc}^{-1}$</th>
<th>$w$</th>
</tr>
</thead>
<tbody>
<tr>
<td>WMAP5</td>
<td>$74^{+15}_{-14}$</td>
<td>20%</td>
</tr>
<tr>
<td>WMAP5 + HST KP</td>
<td>$72.1^{+7.4}_{-7.6}$</td>
<td>10%</td>
</tr>
<tr>
<td>WMAP5 + SN</td>
<td>$69.4^{+1.6}_{-1.7}$</td>
<td>2.3%</td>
</tr>
<tr>
<td>WMAP5 + BAO</td>
<td>$73.9^{+4.7}_{-4.8}$</td>
<td>6.6%</td>
</tr>
<tr>
<td>WMAP5 + Riess</td>
<td>$74.2 \pm 3.6$</td>
<td>5.0%</td>
</tr>
<tr>
<td>WMAP5 + B1608</td>
<td>$69.7^{+4.9}_{-5.0}$</td>
<td>6.9%</td>
</tr>
</tbody>
</table>

- ~300 orbits
- ~200 orbits

### Notes:
- http://lambda.gsfc.nasa.gov
- Komatsu et al. (2009).
- Freedman et al. (2001).
- Kowalski et al. (2008).
- Percival et al. (2007).
- Riess et al. (2009).
- Not marginalized over other cosmological parameters.

When combined with WMAP5, B1608+656 is
- more informative than the HST Key Project
- comparable to the current BAO data in constraining $H_0$ and $w$
COSMOGRAIL: the COSmological MOnitoring of GRAvItational Lenses

- time delays of lensed quasars from optical monitoring
- expect to have delays with a few percent error for ~20 lenses
Accuracy Test

- a blind analysis of RXJ1131-1231 to test for residual systematics, if any

Blinded: PDF centroids of final (cosmological) parameters hidden
Why use time delays

• each cosmographic probe is sensitive to different combination of cosmological parameters
• a small sample of time-delay lenses is a competitive probe

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Future Prospects

Time-delay lenses with Planck forecast from Zhan et al. (2006)


Time-delay lenses provide an independent and competitive cosmological probe

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Summary on Cosmography

- Time-delay lenses provide measurements of $D_{\Delta t}$, which is primarily sensitive to $H_0$
- In combination with WMAP, B1608+656 is comparable to BAO measurements in constraining $w$ and $\Omega_k$
- A blind analysis of RXJ1131-1231 is under way to test for residual systematics
- Future samples of time-delay lenses provide an independent and competitive probe of cosmology
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Stars and Dark Matter in the Spiral Lens B1933+503
(arXiv:1110.2536)

in collaboration with

Sebastian Hensel (Universität Bonn)
John McKean (ASTRON), Chris Fassnacht (UC Davis)
Tommaso Treu (UCSB), Aleksi Halkola (Excellence Cluster)
Martin Norbury (Las Cumbres Observatory Global Network)
Neal Jackson (University of Manchester)
Peter Schneider (Universität Bonn)
Dave Thompson (Large Binocular Telescope)
Matt Auger (University of Cambridge)
Leon Koopmans (Kapteyn Institute)
Keith Matthews (Caltech)
Motivation

Understanding the relative mass contributions of luminous and dark matter help constrain spiral galaxy formation models

• determine the shape and density profile of dark matter
• measure the M/L ratio of the luminous components
• constrain the stellar initial mass function
How to probe mass

Two methods to measure mass in spiral galaxies:

• Strong lensing ➞ mass enclosed within the Einstein radius
• Rotation curve ➞ mass enclosed within a 3D radius

figure credits: A. Dutton, S. Suyu
Each of the methods is limited by the “disk-halo” degeneracy: large disk + small halo or small disk + large halo can both fit to either of lensing or rotation curve data. A combination of lensing and dynamics helps break the degeneracy since the mass dependence is different in the two methods.

Dutton et al. 2011
B1933+503

global VLBI and MERLIN 1.7-GHz

- Discovered in CLASS [Sykes et al. 1998; Marlow et al. 1999; Biggs et al. 2000]
- Lens $z_l = 0.76$
- Source $z_s = 1.71$
- Lensing and kinematics data on system:
  1) 10 images (2 quads and 1 double) in radio
  2) High-resolution AO K-band imaging (Keck II)
  3) Rotation curve (Keck ESI)
Rotation Curve (Keck ESI)
Mass Model

Assume axisymmetric mass model

1) NFW halo
\[ \rho \propto \frac{1}{(r/r_0)(1 + r/r_0)^2} \]

2) Exponential disk
\[ \kappa = \kappa_0 \exp\left(-\frac{R}{R_d}\right) \]

3) Sersic bulge with n=1

4) External shear
Mass Model

Assume axisymmetric mass model

1) NFW halo
\[ \rho \propto \frac{1}{(r/r_0)(1 + r/r_0)^2} \]

2) Exponential disk
\[ \kappa = \kappa_0 \exp(-R/R_d) \]

3) Point mass bulge

4) External shear

Measure from photometry:

a) galaxy centroid
b) inclination angle
c) PA of disk and bulge
d) orientation of oblate halo
e) scale radii of disk and bulge \( \rightarrow \) small bulge \( (R_{\text{eff}} \sim 0.05'') \)

Remaining unconstrained parameters:

- \( a/c \)
- \( r_0 \)
- \( R_{\text{Ein}} \)
- \( \kappa_0 \)
- \( M_b \)
- \( \gamma^\text{ext}, \phi^\text{ext} \)
Lens Model

\[ \text{source position} = \text{modeled image position} \]

adjust lens mass parameters to “match” modeled and observed image positions

sample posterior PDF using Multinest [Feroz et al. 08, 09]
Rotation curve

displacement [kpc]

line-of-sight velocity [km s⁻¹]

-10  -5  0  5  10

-1.5  -1  -0.5  0  0.5  1  1.5

all  disk  halo  bulge
Lensing and Kinematics

- disk-halo degeneracy mostly broken
- lensed radio images spanning a range of radii provide strong constraints
- disk is marginally submaximal
- halo $a/c = 0.33 \pm 0.07/-0.05$
- lower limit on halo scale radius (95% CL): $r_{h,0} \geq 2.1'' = 16$ kpc
Dark Matter Mass Fraction
Stellar IMF

Compare disk mass lensing + kinematics to stellar mass from stellar population synthesis modeling

- Assume gas contributes 20% +/- 10% to total disk mass from lensing + kinematics

- Chabrier IMF is preferred to Salpeter IMF by probability factor of 7.2

- supports a non-universal IMF for galaxies that is dependent on mass or Hubble type
Future Prospects

The sample of spiral lenses is growing rapidly thanks to dedicated surveys [e.g. Marshall et al. 2009, Sygnet et al. 2010, Treu et al. 2011]

SWELLS Survey:
[Treu et al. 2011]
Summary

• Lensing+kinematics is a powerful dark matter probe
• Decomposed the spiral lens B1933+503 into disk, bulge and halo
• Radio lensing data with images spanning a range of radii provide strong constraints on the mass model
• Dark matter halo is flattened (oblate): a/c~0.3
• Lensing+kinematics probe the inner ~10kpc region of the mass distribution and set lower limit on $r_0$ of 16kpc
• Chabrier IMF is preferred to Salpeter by a probability factor of 7.2