Strong Lensing and the Dark Sector

Martín Makler

III José Plínio Baptista School of Cosmology
The Dark Sector of the Universe
Strong Lensing and the Dark Sector

III José Plínio Baptista School of Cosmology
Detection of Light Deflection by Gravity

- 1911-1912: Einstein predicts light deflection and gravitational lensing effects
  Urges observational tests
1912: Argentinean expedition to observe solar eclipse in Brazil

- Got rained out
Detection of Light Deflection by Gravity

- 1912: Argentinean expedition to observe solar eclipse in Brazil
  - Got rained out
- 1914: Erwin Freundlich’s expedition to observe an eclipse in Crimea (Russia)
  - Detained because WWI break up
- 1919: Sobral (Brazil)
  - Detection of the bending of light
    (better weather than Prince Island)

“The question that my mind formulated was answered by the sunny sky of Brazil”
Discoveries

- Sobral 1919: light deflection
- Walsh, Carswell, Weymann 1979: first lensed quasar (double image of QSO 0957+561)
- Roger Lynds e Vahe Petrosian 1986, Soucail, Fort, & Picat 1987: discovery of gravitational arcs
  arcs in A370, A2218, CL2244-02, not clearly predicted...
- Irwin et al. 1989: Quasar microlensing
- EROS & MACHO collaborations, 1993: first stellar microlensing
- Bond et al., 2003: first planet detection
  - ~2 Jupiter mass planets @ ~3 AU
Bending of light by gravity

Null geodesic, Fermat principle

\[ ds^2 = \left(1 + \frac{2\phi}{c^2}\right) c^2 dt^2 - \left(1 - \frac{2\phi}{c^2}\right) d\sigma^2 \]

\[ \frac{d\sigma}{dt} := c' = \sqrt{\frac{1 + 2\phi/c^2}{1 - 2\phi/c^2}} \simeq c(1 + 2\phi/c^2) \]

Deflection angle (point source)

\[ \hat{\alpha} = \frac{4GM}{c^2} \frac{1}{\xi} \]

Achromatic
Weak and Strong Lensing Effects

Bending of light by gravity

\[ \hat{\alpha} = \frac{4GM}{c^2} \frac{1}{\xi} \]
A plethora of phenomena

**Strength**
- Strong lensing
  - Strong magnifications
  - Multiple images
  - Distortions
    - Rings
    - Arcs
- Weak Lensing
  - Small twist
  - Small magnification
  - Detected statistically

**Angular scale**
- Micro-lensing
  - MACHOS
  - Planetary search
- Micro and mili-lensing
  - Quasars
- “Macro-lensing”
  - Galaxies
  - Clusters
  - Large-scale structure
Lensing Mapping

- **image → source mapping:**
  \[ \frac{\partial \beta_i}{\partial \theta_j} = \delta_{ij} - \frac{\partial^2 \Psi (\theta)}{\partial \theta_i \partial \theta_j} \]

- **single plane lensing**
  \[ \Psi = \frac{2}{c^2} \frac{D_{LS}}{D_{OS} D_{OL}} \int \phi (\xi, z) dz \]

  - Gravitational potential (astrophysics)
  - Cosmological distances (cosmology)
  \[ D_{LS} = D_A (z_L, z_S) \ldots \]

- **eigenvalues:**
  \[ \mu_1 = \frac{1}{1 - \kappa + \gamma}, \mu_2 = \frac{1}{1 - \kappa - \gamma} \]

- **local magnification and axial ratio:**
  \[ \mu = \mu_1 \mu_2 \]
  \[ r = \begin{vmatrix} \mu_1 \\ \mu_2 \end{vmatrix} \]
Lensing Mapping

- Image source mapping:
  \[
  \frac{\partial \beta_i}{\partial \theta_j} = \delta_{ij} - \frac{\partial^2 \Psi (\vec{\theta})}{\partial \theta_i \partial \theta_j}
  \]

- Eigenvalues:
  \[
  \mu_1 = \frac{1}{1 - \kappa + \gamma}, \quad \mu_2 = \frac{1}{1 - \kappa - \gamma}
  \]

Caustics

Source plane

Critical curve

Lens/image plane
**Strong Lensing**

- Multiple images, strong distortions, large magnifications, time delays
- Null geodesics
  - surface brightness conservation
  - achromatic
- Unique probe of inner structure of galaxy clusters → DM, \(b\)
- Provide complementary cosmological probes and tests of gravity

\[\text{Gravitational telescopes}\]

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**Strong lensing, weak gravity**

Gravitational arcs
Mapping the lens mass

Acs and multiple images
Parameters of the mass distribution
✓ Density profiles in the galaxy cluster inner regions
✓ Substructure
Sensitivity to cosmology
Source reconstruction

Challenges to using arcs as probes of the dark sector
✓ statistics
✓ systematics
Inverse Modeling

Use systems of multiple images to determine the lensing potential

\[ \chi^2_{\text{lente}} := \sum_i \left( \frac{\theta_i^{\text{obs}} - \theta_i^{\text{mod}}(\beta_i, \Pi)}{\sigma_i^{\text{obs}}} \right)^2 \]

Multiple image positions

Error on image positions

Available codes: lenstool, gravlens, glafic, etc. + “home-made”

Parameters that minimize this function (or maximize the likelihood) are the best fitting lens model

Combination with independent mass constraints (e.g., x-ray, Sunyaev Zel’dovich, velocity dispersions) yields limits on cosmology or gravity
**Inverse Modeling for System SOGRAS0041-0043**

Modelling with lenstool (Jullo, Kneib)

Fit 1: 3 images  
Fit 2: 4 images

\[ \begin{array}{|c|c|c|} 
\hline
& \text{Fit 1} & \text{Fit 2} \\
\hline
\sigma_v [\text{km/s}] & 622^{\pm 11}_{-13} & 642^{\pm 3}_{-3} \\
\theta_{or} [^\circ] & 135.2^{+0.7}_{-0.8} & 135.2^{+1.5}_{-1.3} \\
x_{lente} [^\prime \prime] & 0.50^{+0.2}_{-0.2} & 0.50^{+0.05}_{-0.06} \\
y_{lente} [^\prime \prime] & -0.76^{+0.17}_{-0.15} & -0.86^{+0.06}_{-0.03} \\
\varepsilon & - & 0.13^{+0.02}_{-0.03} \\
\hline
\end{array} \]

~ 0.9” displacement between central galaxy and center of mass distribution (Zitrin et al. 2012)

Error estimate from simulations (Caminha et al. in prep.):

~ 8% bias in mass  
~ 5% statistical errors

2.35^{+0.03}_{-0.14} \times 10^{14} M_{\odot}
Lens Mass Distribution and Dark Matter
Density profiles of galaxies and inner cluster regions:

- *cuspy halo profiles?* $\rho(r) \propto r^{-\gamma}$ $\gamma \sim 1$  
  Bartelmann, astro-ph/0207032

- dark matter interactions

- *baryonic processes: cooling, AGN feedback,…*  
  Mead et al. 1001.2281

Substructure

- *overabundance of satellites*

- *primordial spectrum*

Luminous x Matter

- *e.g. DM cross section*  
  Williams and Saha, 1102.3943

\[
\frac{\sigma}{m} \gtrsim 8 \times 10^{-31} \left( \frac{t}{10^{10} \text{yr}} \right)^{-2} \text{cm}^2 \text{GeV}^{-1}
\]

Challenges for using arcs as astrophysical and fundamental physics probes:

- statistics

- systematics
Dark Energy from Families of Multiple Images
Galaxy Clusters

Families of images with sources at different redshifts

Constraints on cosmology, in addition to the matter distribution

The ratio of angular diameter distances for 2 (or more) images with sources at different redshifts defines a ratio of families

$$\Xi(z_1, z_{s1}, z_{s2}; \Omega_M, \Omega_X, w_X) = \frac{D(z_1, z_{s1})}{D(0, z_{s1})} \frac{D(0, z_{s2})}{D(z_1, z_{s2})}$$

Jullo et al. 2010, Science: example of competitive limits in cosmological parameters from the Abell 1689 system

8 families of sources with $z = 1.15$ to 4.86

Caminha et al. 2016: RXC J2248.7-4431 (Abell S1063), 16 sources, 47 images
Cluster CLASH RXC J2248.7-4431

Caminha et al. 2016
Cluster CLASH RXC J2248.7-4431

Caminha et al. 2016
Time Delays and Cosmology
\[ \Delta t_{ij} = \frac{D_\Delta}{c} \left( \frac{1}{2}(\vec{\theta}_i - \vec{\beta})^2 - \Psi(\theta_i) - \frac{1}{2}(\vec{\theta}_j - \vec{\beta})^2 + \Psi(\theta_j) \right) \]

Where \[ D_\Delta = (1 + z_L) \frac{D_{OS}D_{OL}}{D_{LS}} \]

“time delay distance”

Main cosmological dependence \( \propto H_0^{-1} \)
Quasar light-curves

Time delay between images

\[ \Delta t_{ij} = \delta t \left( \vec{\theta}_i, \bar{\beta} \right) - \delta t \left( \vec{\theta}_j, \bar{\beta} \right) \]

\[ = (1 + z_L) \frac{D_{OS} D_{OL}}{c D_{LS}} \left( \frac{1}{2} \left( \vec{\theta}_i - \bar{\beta} \right)^2 - \Psi(\theta_i) - \frac{1}{2} \left( \vec{\theta}_j - \bar{\beta} \right)^2 + \Psi(\theta_j) \right) \]
Modeling of RX J1131−1231
Cosmology Results

Non-flat $\Lambda$CDM cosmology
WMAP/Planck for \( \{H_0, \Omega_\Lambda, \Omega_m\} \)
\( \Omega_k = 1 - \Omega_\Lambda - \Omega_m \)

Flat $\Lambda$CDM cosmology
WMAP/Planck for \( \{H_0, \Omega_\Lambda, N_{\text{eff}}\} \)

Flat $\Lambda$CDM cosmology
WMAP/Planck for \( \{H_0, \Omega_\Lambda, \Sigma m_\nu\} \)

Flat $w$CDM cosmology
Planck for \( \{H_0, w, \Omega_{\text{de}}\} \)

Bonvin et al. 2016
(Paper V; arXiv:1607.01790)
Cosmology results for 3 lenses
Comparison with other Cosmological Probes

Adapted From Riess et al. (2016)
Strong Lensing and Modified Gravity
Modifications of GR

Weak-field metric in the conformal Newtonian gauge

\[ ds^2 = \left( 1 + \frac{2\psi}{c^2} \right) c^2 dt^2 - \left( 1 - \frac{2\phi}{c^2} \right) d\sigma^2 \]

peculiar gravitational potentials
(in GR \( \psi = \phi \))

homogeneous and isotropic line element

Conditions:

• Light follows null geodesics (valid even for nonmetric theories of gravity)

• Metric can be split into a homogeneous part and linear scalar perturbations

Can be extended for inhomogeneous models, such as LTB

Strong Lensing is a probe of:

• Small scales: testing gravity on kiloparsec scales

• Cosmological distances: large-scale modifications of gravity
Bending of light by gravity

Null geodesic, Fermat principle

\[ ds^2 = \left( 1 + \frac{2\phi}{c^2} \right) c^2 dt^2 - \left( 1 - \frac{2\phi}{c^2} \right) d\sigma^2 \]

\[ \frac{d\sigma}{dt} := c' = \sqrt{\frac{1 + 2\phi/c^2}{1 - 2\phi/c^2}} \simeq c(1 + 2\phi/c^2) \]

Deflection angle (point source)

\[ \hat{\alpha} = \frac{4GM}{c^2} \frac{1}{\xi} \]
BENDING OF LIGHT BY (MODIFIED) GRAVITY

Null geodesic, Fermat principle

$$ds^2 = \left(1 + \frac{2\psi}{c^2}\right) c^2 dt^2 - \left(1 - \frac{2\phi}{c^2}\right) d\sigma^2$$

$$\frac{d\sigma}{dt} = c' = c \sqrt{\frac{1 + \frac{2\psi}{c^2}}{1 - \frac{2\phi}{c^2}}} \approx c \left(1 + \frac{\psi + \phi}{c^2}\right)$$

Lensing potential:

$$\Psi = \frac{1}{c^2} \frac{D_{LS}}{D_{OS} D_{OL}} \int (\psi + \phi) \, d\chi$$
Modifications of GR

Weak-field metric in the conformal Newtonian gauge

\[ ds^2 = \left( 1 + \frac{2\psi}{c^2} \right) c^2 dt^2 - \left( 1 - \frac{2\phi}{c^2} \right) d\sigma^2 \]

Generic parameterization

\[ \frac{1}{2} \nabla^2 (\psi + \phi) = 4\pi \mu G \rho \quad \frac{\phi}{\psi} = \gamma \]

\[ \gamma_{PPN} \text{ and } \mu \text{ may vary in space, time, density, photon energy, etc.} \]

Examples: scalar-tensor, \( f(R) \)

Deflexion angle

\[ \hat{\alpha} = \int (\psi + \phi) \, dl \]

Dynamical mass obtained from

\[ \nabla^2 \psi = 4\pi G \rho \]

Need combination of lensing + dynamics, e.g., spectra
Einstein Rings

Einstein Ring

\[ R_E = 4\pi \sigma_{\text{obs}}^2 \left( \frac{1 + \gamma_{\text{PPN}}}{2} \right) \frac{D_L D_{LS}}{D_S} \]

Measure velocity dispersion -> Limit on gravity

Einstein rings in the SLACS sample

The results are in agreement with GR
Frontiers and Challenges
Frontiers and Challenges

- Detailed observations of selected fields
  - Space-based observations (HST)
  - Frontier Fields, CLASH, RELICS, etc.
  - Massive spectroscopic follow-up (IFU/MUSE)
  - Cosmology from single systems + high-z sources
  - Limited to very massive lenses and few systems

- Wide-field surveys
  - High statistics: discovery of thousands of systems
  - Probe wide mass range
  - Few constraints
  - Spin-off from cosmological surveys

- Different Challenges and Systematics
THE DEEPEST DATA EVER OBTAINED FOR LENSING GALAXY CLUSTERS !!!

**Abell 2744 - z = 0.308**
*Fully observed*


**MACS J0416 - z = 0.396**
*Fully observed*


**MACS J1149 - z = 0.543**
*Fully observed*


**MACS J0717 - z = 0.545**
*Fully observed*


**Abell S1063 - z = 0.348**
*Fully observed*


**Abell 370 - z = 0.375**
*ACs to go*
Example MACS J0416.1-2403

- HST + MUSE IFU
- 102 multiple images!
- Discovery of new systems in the data cube
- Robust determination of projected mass
- Cosmological constraints
- Available redshifts and shear and convergence maps

Caminha et al. 2016
Frontier Field Cluster AS1063 (aka RXJ2248)

RXJ2248 ($z=0.35$), HST/ACS
(B.Caminha et al. 2016a,b)

Total of 17 families (10 spectroscopic)
48 (30) multiple images, $z_{\text{range}}=1.0-6.2$

MUSE SV programme + GO (Pl: K.Caputi)
(Karman et al. 2015)
(W.Karman et al. 2016, arXiv/160601471)

1 arcmin$^2$ FoV
2.6 Å resolution (4800-9300 Å)
0.2 arcsec/pixel
Exp. = 5 hrs
Controlling Systematics

• **Inverse modeling: ill-posed problem!**
  - Check which quantities can be robustly predicted
  - Check robustness with respect to models and data

• **Sources of systematics**
  - Structure along the line of sight
  - Substructure / correlated mass
  - Mass traces light
  - Which images to choose

• **Can be tested with observations and simulations!**
  - Project images
  - Additional data (e.g. magnification)
  - Degrading high-quality data
  - Use detailed simulations and test codes and results
SN Ia with measured light curve: $\mu_{\text{obs}} = 2.03 \pm 0.29$

Testing models and inversion codes and constraints for new analyses
Use measured magnification to test model predictions

Model assumptions

Rodney+15 ApJ
Illuminating a Dark Lens: A Type Ia Supernova Magnified by the Frontier Fields Galaxy Cluster Abell 2744

SN “Tomas”

Keren Sharon • High-z Universe, highly magnified • Leiden • GravLens2016
Supernovae in MACS J1149.6+2223

Multiply imaged by an individual galaxy and + global potential of the cluster (past/future)
Use prediction for the appearance of multiple images of the SN to test the models

When Refsdal meets Popper!
Refsdal returns!

Kelly, Rodney, Treu et al. 2016

Steve Rodney (USC)
Structure along the line of sight

Can be measured from the data and taken into account!

Same for correlated structures close to the lens
FF Lens Modeling Comparison Project

Use simulated clusters to test different model reconstructions

MOKA cluster

N-Body cluster

All methods use multiple image positions, they reconstruct quite well the mass density distribution of the cluster and the location of the critical lines.

Meneghetti +16
Additional constraints on cosmology

- **Gravitational telescopes:** luminosity function of ultra-faint UV galaxies at $z \sim 6$

- Mass of thermal relic WDM particles $m_X \geq 2.1$ keV at 3σ.

- If sterile neutrinos are responsible for the 3.5 keV line reported in observations of X-ray clusters, $m_{\text{sterile}} \approx 6.1$ keV (neutrinos produced via the Shi–Fuller mechanism)

- **Time delays + mass model + lens dynamics:**
  \[ \rightarrow D_A(0, z_L) \]
  (Jee, I.; Komatsu, E.; Suyu, S. H., JCAP, 2015)
Homogeneous Strong Lensing Samples (arcs)

- until now: $O(10^2)$ systems
  - Spectroscopy + HST: SLACS, BELLS
  - $O(10^2)$ deg$^2$ surveys: CFHTLS/SL2S, SOGRAS, CS82
- 2016-2018: $O(10^3)$ systems
  - $O(10^3)$ deg$^2$ surveys: KiDS, DECaLS, RCSLens, DES
- > 2020: $O(10^4$ - $10^5)$ systems
  - LSST, WFIRST, EUCLID
  - DESI, Subaru PFS/SUMIRE

Challenges

- arcfinding codes: completeness and purity
- automated analyses (including $z$)
- Simulations + arcfinders + inverse modelling
SDSS Stripe 82
CFHT Stripe 82 Survey (CS82): The weak lensing survey in S82
- 170 deg², down to $i = 24$ and superb median seeing of 0.6”

- SDSS repeated imaging, coadds 2 mag deeper
- Photo-z and cluster catalogs form SDSS coadds
- Spectroscopy from SDSS-I/II (Wiggle-z and deep fields)
- Emerging multi-wavelength coverage (UKIDSS, VLA)
Measuring subhalo mass in redMaPPer clusters with CFHT Stripe 82 Survey

Ran Li1, Huiyuan Shan2, Jean-Paul Kneib1,2, Houjun Mo4, Eduard Axelle Leauthaud6, John Moustakas7, Lizhi Xie8, Thomas Erben9, Lucien Van Waerbeke, Bruno Moraes10,11, Thomas Erben12

The Mass-Concentration Relation and the Stellar-to-Halo Mass Ratio in the CFHT Stripe 82 Survey

HuanYuan Shan1, Jean-Paul Kneib1,2, Ran Li3, Thomas Erben6, Martin Makler7, Bruno Moraes10,11, Aldée Charbonnier12

Weak lensing mass map and peak statistics in Canada–France–Hawaii Telescope Stripe 82 survey

HuanYuan Shan1, Jean-Paul Kneib1,2, Johan Comparat2, Eric Juszkiewicz3,4,5, Aldée Charbonnier4,5, Thomas Erben6, Martin Makler7, Bruno Moraes10,11

Stochastic bias of colour-selected BAO tracers by joint clustering–weak lensing analysis

Johan Comparat1, Eric Julio1, Jean-Paul Kneib1,2, Carlo Schindler, HuanYuan Shan2,3, Thomas Erben4, Olivier Ilbert5, Joel Brownstein5, Anne Ealet6, Stephanie Escoffier6, Bruno Moraes7,8, Nick Mostek9, Jeffrey A. Newman10, M. E. S. Pereira7,8,9, and Martin Makler11

Cosmological constraints from weak lensing peak statistics with Canada–France–Hawaii Telescope Stripe 82 Survey

Xiangkun Liu1, Chu Zhong Pan, Ran Li2, Huiyuan Shan, Qiao Wang2, Liping Fu, Zuhui Fan1, Jean-Paul Kneib3, Alexie Leauthaud7, Ludovic Van Waerbeke8, Martin Makler9, Bruno Moraes10,11, Thomas Erben12

First measurement of the cross-correlation of CMB lensing and galaxy lensing

Nick Hand,2 Alexie Leauthaud,2 Sudeep Das, Blake D. Sherwin, Graeme E. Addison, J. Richard Bond, Erminia Calabrese, Aldée Charbonnier, Thomas Erben, Amir Hajian, Mark Halpern, Joachim Harnois-Déraps, Catherine Heymans, Hendrik Hildebrandt, Adam D. Hincks, Jean-Paul Kneib, Arthur Kosowsky, Martin Makler, and Bruno Moraes

First galaxy–galaxy lensing measurement of satellite halo mass in the CFHT Stripe-82 Survey

Ran Li, Huiyuan Shan, Houjun Mo, Jean-Paul Kneib, Xiaohu Yang, Wentao Luo, Frank C. van den Bosch, Thomas Erben, Bruno Moraes, and Martin Makler

+ fossil groups; compact galaxies; VT clusters; BOSS galaxies; satellites...
Stripe 82 @ 2016

- SDSS repeated imaging, coadds 2 mag deeper
- Photo-z and cluster catalogs form SDSS coadds
- Spectroscopy from SDSS-I/II (Wiggle-z and deep fields)
- Emerging multi-wavelength coverage (UKIDSS, VLA Stripe 82)
- Increased spectroscopic coverage from BOSS and eBOSS
- VISTA-CFHT Stripe 82 survey (VICS82) in J and Ks, 140 sq-deg (+VHS-DES)
- The Spitzer-IRAC Equatorial Survey (SpIES), 115 sq-deg
- Stripe 82 X-ray Survey (S82X), 31 sq-deg
- Herschel HerMES Large Mode Survey (HeLMS)
Stripe 82 @ 2016

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- Stripe 82 X-ray Survey (S82X), 31 sq-deg
- Herschel HerMES Large Mode Survey (HeLMS)
- + DES, HSC, J-PAS

....

~ KiDS/GAMA

Gravitational arcs: finding and modeling
Semi-automated arcfinding

- More-Alard Arcfinder (More et al., arXiv:1109.1821)
- 127000 candidates visually inspected!
- 10 volunteers (every candidate inspected by 2 people)
  + java applet (More et al.) for quick view
- 18 excellent candidates
also found in SOGRAS and inspection in CS82 clusters
CS82 Arc Candidates

Redshift distribution of SL systems on S82

- CS82
- SDSS
- SL2S
- ULAS
- SOGRAS
- RCS
- ARCRAIDER

Redshift

3.0
2.5
2.0
1.5
1.0
0.5
0.0
12.0 12.5 13.0 13.5 14.0

$\log_{10} M(< \theta_*)$

N

0 1 2 3 4 5 6

$\theta_*$ (arcsecond)

0 2 4 6 8 10 12 14

$\log_{10} M(< \theta_*)$
Search in selected fields

Multiple target selection and inspections

- Optical cluster catalogs
- x-ray (S82X, XCS, RASS-BSC), SZE (Planck, ACT)
- Weak Lensing Peaks (new!)
- Luminous Red Galaxies
- Additional 20 candidates and counting...
- + VICS82 (SpaceWarps)

Need multiple search criteria
Inverse Modelling

Modelling with lenstool (Jullo, Kneib)

Fit 1: 3 images
Fit 2: 4 images

\[ z_L = 0.564 \]

<table>
<thead>
<tr>
<th></th>
<th>Fit 1</th>
<th>Fit 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \sigma_v [km/s] )</td>
<td>622^{+11}_{-13}</td>
<td>642^{+3}_{-3}</td>
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<td>( \varepsilon )</td>
<td>—</td>
<td>0.13^{+0.02}_{-0.03}</td>
</tr>
<tr>
<td>( \chi^2/\text{dof} )</td>
<td>0.25</td>
<td>0.22</td>
</tr>
</tbody>
</table>

BCG Spectrum in SDSS

Detected in VICS82

\[ \sigma_v^{\text{BCG}} = 312 \pm 46 \]

\[ z_S^{\text{phot}} = 1.27 \]
Towards automation

Testing schemes to determine the peaks

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Best DS9</th>
<th>Best barycenter</th>
<th>Best bright</th>
</tr>
</thead>
<tbody>
<tr>
<td>x (arcsec)</td>
<td>$-0.21 \pm 0.04$</td>
<td>$-0.24 \pm 0.05$</td>
<td>$0.05 \pm 0.06$</td>
</tr>
<tr>
<td>y (arcsec)</td>
<td>$0.06 \pm 0.03$</td>
<td>$0.05 \pm 0.03$</td>
<td>$0.03 \pm 0.03$</td>
</tr>
<tr>
<td>ellipticity</td>
<td>$0.44 \pm 0.04$</td>
<td>$0.47 \pm 0.04$</td>
<td>$0.26 \pm 0.07$</td>
</tr>
<tr>
<td>$\theta$ (deg)</td>
<td>$5.85 \pm 15.91$</td>
<td>$7.24 \pm 11.36$</td>
<td>$3.51 \pm 14.46$</td>
</tr>
<tr>
<td>$\sigma$ (km/s)</td>
<td>$390.63 \pm 2.51$</td>
<td>$384.11 \pm 2.62$</td>
<td>$381.19 \pm 2.76$</td>
</tr>
</tbody>
</table>
Robustness of inversion

CS82SL01:58:24-0:40:00

- Brightest galaxy: \( z_L = 0.597, \quad \sigma_{v}^{\text{SDSS}} = 535 \pm 133 \)
- Subtracting lens galaxies with galfit
- Lens center:

<table>
<thead>
<tr>
<th></th>
<th>Brightest galaxy</th>
<th>Two galaxies</th>
<th>Center of curvature</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>DS9</td>
<td>Bary</td>
<td>Bright</td>
</tr>
<tr>
<td>( e )</td>
<td>0.51</td>
<td>0.51</td>
<td>0.51 ± 0.012</td>
</tr>
<tr>
<td>( \theta )</td>
<td>164.1</td>
<td>164.</td>
<td>163.3 ± 0.4</td>
</tr>
<tr>
<td>( \sigma )</td>
<td>524</td>
<td>525</td>
<td>529 ± 1</td>
</tr>
</tbody>
</table>
CS82 Einstein Rings

CS82SL01:36:39+00:08:18

- $\theta_E = 3.51"$
- SDSS (right component), $z_{\text{spec}} = 0.344$, $\sigma_{v}^{\text{BCG}} = 372 \pm 29$
- Fits with a single and two mass components: evidence for single potential -> “bullet cluster like”?
- velocity dispersion (from SL): 440 km/s
CS82 Einstein Rings

- $z_{\text{spec}} = 0.562,$
- $\theta_E = 2.54^\prime$
- velocity dispersion:
  \[ \sigma_{v,\text{SDSS}} = 310 \pm 47 \]
CS82 Einstein Rings

\begin{itemize}
  \item $z_{\text{spec}} = 0.445$, $\sigma_{\text{SDSS}} = 224 \pm 30$
  \item $o_E = 3.33''$
\end{itemize}
Einstein Rings or Ring Galaxies?

CS82SL23:27:42+00:17:46

Ring galaxies from scanning of LRGs?

$z_L = 0.1 \, \Omega_E \sim 2.15''$

$z_L = 0.126 \, \Omega_E \sim 2.5''$

$M(< \theta_E) = (6 \pm 1) \times 10^{11} M_{\text{sol}}$

$\sigma_{SDSS}^{\text{SDSS}} = 98 \pm 9$

$z_L = 0.043 \, \Omega_E \sim 2.5''$

$z_L = 0.193 \, \Omega_E \sim 2.5''$

$\sigma_{SDSS}^{SDSS} = 51 \pm 16$

Alice Candeias
Multi-wavelength information

Of the 38 lens candidates:

• 32 have SDSS spectroscopy
• 15 are in optical clusters/groups
• NIR: 16 in 2MASS, most in VICS82
• IR: 30 in WISE, 9 in SpIES + 4 in SHELA
• 4 in VLA-FIRST, 2 in VLA-Stripe 82, 1 in ACT
• 1 in XMM, 2 in Galex

Arc candidates:

• 9 in VICS82, 7 in SpIES
Multi-wavelength data

CS82SL00:44:37-00:55:20

\[ z_L = 0.201, \quad z_{S_1}^{\text{phot}} = 0.55 \pm 0.06, \quad \sigma_{v}^{\text{SDSS}} = (278 \pm 14) \text{Km/s} \]

- System found in CS82 has clear IR emission
- Gemini approved for AO follow-up, but no suitable star
- Carry out systematic search
Multi-wavelength data

CS82SL02:20:32+00:28:03

$z_L = 0.272$, $z_S^{\text{phot}} = 0.63 \pm 0.14$, $\sigma_v^{\text{SDSS}} = (320 \pm 8) \text{ Km/s}$

- Build SED
- Estimate magnification
- Work in progress....
SpaceWarps Einstein Ring

• \( z_L = 0.2 \ (z_S = 2.553) \)
• \( O_E \sim 3'' \)
• velocity dispersion: \( 476.6 \pm 2.4 \text{ km/s} \)

The Red Radio Ring: a gravitationally lensed hyperluminous infrared radio galaxy at \( z = 2.553 \) discovered through the citizen science project SPACE WARPS
Best candidate: 9io9

- $z_{\text{lens}} = 0.2$, $z_{\text{source}} \sim 2.5$, Perhaps more distant known Einstein ring

- eMERLIN imaging
- Very bright sub-mm source (Herschel HerS e ACT)
- SED from multi-wavelength data
- High-z galaxy with dust and star formation
Concluding remarks

• After 30 years of the first discoveries (and 100 of GR), gravitational lensing has become a useful cosmological and astrophysical observable

• Observables are multiple images, gravitational arcs, magnification, and time delays

• SL is fulfilling its promises for studying the lenses, the sources, and the large-scale geometry of the Universe

• Strong interplay between cosmology and astrophysics

• Cosmology needs multiple sources or complementary information on the lens (astrophysics)

• Different methods and applications for galaxy and cluster scales

• As in any other modern astrophysical and cosmological setting, results are being dominated by systematics
Concluding remarks

• Addressing systematics

• End-to-end approaches using simulations to test everything from finding to modeling arc systems

• Use “golden lenses” (SN + HST + IFU)

• Synergy between wide-field studies and targeted observations

• Interdisciplinary field involving from fundamental physics to data reduction, including image processing, statistics, simulations, theory and semi-analytic modeling

• CS82 is an excellent playground for SL in the ongoing and future wide-field surveys from the ground

• Lots of excellent data to come in the near future!
Thank You!