Strong Gravitational-Lens Modeling

The Structure & Evolution of Early-type Galaxies to z=1 and beyond...

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WARNING!

This talk will be an eclectic collection of old and new ideas, results, and some background behind the modeling of extended-image strong lenses combined with galaxy dynamics to coherently model early-type galaxies...

More details in talks by e.g. Barnabè, Bolton, Treu, Vegetti,
Short Outline

• Galaxy Structure, Formation & Evolution 101
• Integrated approach to lensing & dynamics
• A new Differential Lens Equation (DLE)
• Grid-based Strong Lensing
• The future
Only several “self-consistent” simulations have been done with DM and baryons.

1. Galaxies can contract with time: radial density profile changes
2. Galaxies shapes can change with time.
3. Galaxies grow more massive with time.
4. Substructure + evolution.

Meza et al. 2003
Galaxy Structure Formation & Formation 101

(1) *Galaxy formation* models predict distinct DM density profiles (e.g. NFW97, Moore et al. 98)

(2) DM density profiles are modified by collisional and/or gravitational processes of baryons & stars.

(3) Hierarchical models predict abundant CDM mass substructure (Moore et al. 1999), not (yet) found.

(4) Strong scaling relations (FP/TF) are observed (e.g. Dressler et al. 1987; Djorgovski & Davis 1987).

(5) Independent stellar M/L ratios/Stellar populations

The baryonic & DM mass distribution and their evolution are a direct measure of the (hierarchical) galaxy formation process, in particular for early-type galaxies (i.e. merger remnants).
Integrated Approach

Why lensing should be combined with other methods to make the results more robust...
**Integrated Approach**

**Strong Lensing**
- Baryonic + Dark Matter around the Einstein Radius
- CDM Substructure
- Grid-based methods

**Weak Lensing**
- Environment & Outer DM halo
- Grid-based methods

**Stellar Dynamics**
- Baryonic + Dark Matter around the effective radius
- Phase-space density
- Grid-based methods

**Slac(s)ers:**
- Leon Koopmans
- Tommaso Treu
- Adam Bolton
- Scott Burles
- Lexi Moustakas
- Oliver Czoske
- Matteo Barnabè
- Simona Vegetti
- Raphael Gavazzi
- plus friends ...

**LSD Survey**
- HST V, I, H
- Keck ESI

**SLACS Survey**
- HST B/V, I, H
- VLT VIMOS-IFU
- Keck LRIS
- Gemini/Magellan
- VLT X-shooter
- Chandra ?

**Breaking Degeneracies**
- (mass-anisotropy, mass-sheet, inclination)
# Integrated Approach to Gravitational Lens Modeling

The Sloan-Lens ACS Survey

<table>
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<tr>
<th>HST Program</th>
<th>VLT-IFU Program + Keck Spectroscopy</th>
<th>Models + Theory</th>
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<tr>
<td>• Lensed Images</td>
<td>• 2D Stellar Kinematics</td>
<td>• Grid-based Lens Modeling</td>
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<td>• Galaxy Surface Brightness</td>
<td>• Stellar populations</td>
<td>• Combined Lensing &amp; Stellar Dynamics</td>
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<td>• Optical/IR Colors</td>
<td>• Source kinematics?</td>
<td>• Strong &amp; Weak Lensing</td>
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<td>• Weak Lensing</td>
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*e.g. Bolton et al. 2005/6/7; Treu et al. 2006/8; Koopmans et al. 2006/8; Gavazzi et al. 2007/8; Bolton et al. 2008a&b; Barnabè & Koopmans 2007; Czoske et al. 2008; Vegetti & Koopmans, 2008, ...*
HST Follow-up of SDSS-spectroscopically selected lens candidates
(talk Bolton)

Cycle - 13:
SNAP-10174 (PI: Koopmans): Snapshot imaging F435W/F814W -
39/49 Orbits, ACS

Cycle - 14:
GO-10494 (PI: Koopmans): Single-orbit multi color follow-up -
45 orbits, ACS+NIC
SNAP-10587 (PI: Bolton): Snapshot imaging F814W -
55/118 Orbits, ACS

Cycle - 15:
GO-10798 (PI: Koopmans): Single-orbit multi color follow-up -
60 orbits, ACS/WFPC2+NIC
GO-10886 (PI: Bolton): Single-orbit multi color follow-up -
60 orbits, ACS/WFPC2

Cycle - 16:
GO-11202 (PI: Koopmans): Single-orbit multi color follow-up -
159 orbits, WFPC2+NIC
SLACS Survey

Image credit: A. Becker (UC Berkeley) for the SLACS team and HEAVY/EA
VLT VIMOS-IFU Large Program -
Resolved Stellar Kinematics at z=0.08-0.35

- VLT VIMOS IFU Large program (77.A-0682): 14 lenses, observations spread over two semesters (HR-orange) plus 3 lenses in pilot program (HR-blue); Observing time 128 hrs (PI: Koopmans) -> Analysis: Czoske

- Keck LRIS (long-slit/pseudo-IFU): 13 additional targets were scheduled; Observing time 5 nights (PI: Treu)

**GOAL:** Spatially resolved VLT/Keck kinematics data to be combined with HST gravitational-lensing data.

**TOOL:** Full Bayesian (ultra-fast; few seconds) non-parametric axisym. 2-Integral $f(E,L_z)$ dynamical code to model these data iteratively, self-consistently with lensing data (grid-based).

See Barnabè & Koopmans (2007) for details and Czoske et al. (2008) for first results.
### VLT VIMOS-IFU Large Program

**PI: Koopmans/Czoske**

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</table>
Integrated Approach

With detailed multi-color HST images of the lens galaxies, SDSS, Keck and VLT-IFU spectra in hand, what can we do?

• Galaxy structure (lensing & dynamics)
• Spatially resolved stellar populations.
• Scaling relations
• Weak lensing/Environmental studies
• Source structure (de-lensing)
• Etc...
A Little Background on Lensing

Which lensing feature contains information about the density profile...
Methodology: Gravitational lensing

Galaxy mass distorts space → Multiple images form of a background object

Source of light → Observer

Reconstruct galaxy mass ← Extract information from the multiple images
Deflection Angle and Density profiles

Deflection angle of a power-law density profile

\[ \alpha(\theta) = b \left( \frac{\theta}{b} \right)^{2-n} \]

Radial Magnification

\[
\frac{\theta_1(\beta + \Delta \beta) - \theta_1(\beta)}{\Delta \beta} \approx \frac{d\theta}{d\beta} = \left( 1 - \frac{d\alpha}{d\theta} \right)^{-1}
\]

Kochanek, Schneider & Wambsganss 2004
Defection Angle and Density profiles

Kochanek, Schneider & Wambsganss 2004
Example: B0218+357

Radio jet lensed by spiral galaxy at $z=0.9$

Note the very similar radial stretching of the lensed images compared to the source

$\gamma' \propto r^{-1.96 \pm 0.02}$

Wucknitz et al 2002
Background on Lensing & Dynamics

The ideas behind it...
Combining Lensing & Dynamics

Why?

• Degeneracies are nearly orthogonal.

• Both methods are only based on gravity (i.e. no (g)astrophysical assumptions).

• Most lens galaxies are bright E/S0 galaxies that can be studied to $z \sim 1$.

• Individual systems can be studied (opposed to weak lensing)
Scale-free toy model

Let us assume that the density and luminosity densities are scale-free power-law distributions

\[
\begin{align*}
\rho(r) &= \rho_0 \times r^{-\gamma'} \\
\nu(r) &= \nu_0 \times r^{-\delta} \\
\beta(r) &= \text{constant} \\
M_E &= M(< R_E)
\end{align*}
\]

And that the (an)isotropy is constant as function of radius to first approximation
Scale-free toy model

The spherical Jeans equation can analytically be solved:

\[
\langle v^2 \rangle (R) = \frac{1}{\pi} \left[ \frac{G M_E}{R_E} \right] \left( \frac{\xi - 3}{\delta - 3} \right) f(\gamma', \delta, \beta) \times \left( \frac{R}{R_E} \right)^{2-\gamma'}
\]

Or averaged inside an aperture:

Koopmans 2004
Scale-free toy model

With

\[
    f(\gamma', \delta, \beta) = 2\sqrt{\pi} \left( \frac{\delta - 3}{(\xi - 3)(\xi - 2\beta)} \right) \times \left\{ \frac{\Gamma[(\xi - 1)/2]}{\Gamma[\xi/2]} - \beta \frac{\Gamma[(\xi + 1)/2]}{\Gamma[(\xi + 2)/2]} \right\} \times \left\{ \frac{\Gamma[\delta/2]\Gamma[\gamma'/2]}{\Gamma[(\delta - 1)/2]\Gamma[(\gamma' - 1)/2]} \right\}
\]

Koopmans 2004
Scale-free toy model

What does this equation tell us?

- If $\gamma' = 2$, the dispersion independent of radius in these scale-free models. A “flattish” dispersion profile hints at a density profile with $\rho \propto r^{-2}$.
- If $\gamma' = \delta = \xi = 2$ and $\beta = 0$ then we recover the well-known SIS with

$$\langle v_{||} \rangle^2(R) = \frac{1}{\pi} \left[ \frac{GM_E}{R_E} \right].$$

- For $\delta = 3$, $f(\gamma', 3, \beta)$ is independent of $\beta$.

Note that for SLACS $<\delta> \approx 2.4$

(Adam Bolton, private communication)
Scale-free toy model

Dependences of \( f(\gamma, \delta, \beta) \)

(Left) Value of \( f(\gamma', \delta, \beta = 0) \) for \( \gamma' \in (1.5, 2.5) \) and \( \delta \in (1.5, 2.5) \).

(Right) Value of \( f(\gamma', \delta = 2, \beta) \) for \( \gamma' \in (1.5, 2.5) \) and \( \beta \in (-0.5, 0.5) \).
Scale-free toy model

The error on the stellar velocity dispersion becomes:

\[ \frac{\delta v_{||}}{v_{||}} (\leq R_A) = \frac{1}{2} \frac{\delta M_E}{M_E} + \frac{1}{2} \left( \frac{\partial \log f}{\partial \log \gamma'} - \gamma' \log \left[ \frac{R_A}{R_E} \right] \right) \cdot \frac{\delta \gamma'}{\gamma'} \]

\[ \equiv \frac{1}{2} \left( \frac{\delta M_E}{M_E} + \alpha_g \frac{\delta \gamma'}{\gamma'} \right), \]

or

\[ \langle \delta_{\gamma'}^2 \rangle = \alpha_g^{-2} \left\{ \langle \delta_{M_E}^2 \rangle + 4 \langle \delta_{\sigma_{||}}^2 \rangle \right\} \]

The typical errors are < few % and < 5 % on the lens mass and stellar velocity dispersion, respectively.
Illustration: mock lens

Constant $M/L$ model versus SIS

$R^{1/4}$ constant $M/L$ density profile

Lensing mass is the same

SIS density profile with stellar $M/L=0$
Does it also work at $z=1$?

LSD Survey: MG2016+112 ($z_{\text{lens}}=1.01$)

- Constant $M/L$ models fail dramatically to match the observed velocity dispersion.

- An isothermal density profile for stars+DM fits the stellar velocity dispersion.

(e.g. Koopmans & Treu 2002; Treu & Koopmans 2002)
Two-component (DM+Star) mass models result in the same conclusion: Galaxy is isothermal and DM halo contributes ~75% of mass inside $R_E$ 

(e.g. Koopmans & Treu 2002; Treu & Koopmans 2002)
Early-type Lens Galaxy Density Profiles

Density slope, correlations and evolution...
The structure of E/S0 galaxies

Analysis of full HST-ACS sample (58 systems)

Koopmans et al. 2008 (in prep)
The structure of E/S0 galaxies

No correlations with anything whatsoever?

Analysis of the SLACS-ACS sample with good lensing & kinematic data shows no dependence of the slope on (i) galaxy properties, (ii) redshift or (iii) environment

1. $\gamma' = (2.06 \pm 0.19) - (0.3 \pm 7.3) \times 10^{-4} \sigma_{\text{SIE}}$
2. $\gamma' = (2.06 \pm 0.05) - (0.3 \pm 1.3) \times 10^{-3} M_{\text{eff}}$
3. $\gamma' = (1.95 \pm 0.09) + (0.17 \pm 0.14)(R_{\text{einst}}/R_{\text{eff}})$
4. $\gamma' = (2.05 \pm 0.08) - (0.23 \pm 3.8) \times 10^{-1} z$
The logarithmic (total) density slope of SLACS+LSD E/S0 galaxies between $z=0.08 - 1.01$

$$d\gamma'/dz = -0.23 \pm 0.16$$ (isotropic models)

(Koopmans et al. 2006)
The structure of E/S0 galaxies

Dark matter inside one effective radius (stellar M/L ~ constant)

DM mass fraction increases dramatically from <L* to >L* (up to 50% for σ~350 km/s) (if the IMF does not change strongly with galaxy mass)

Koopmans et al. 2008 (in prep)
Stellar Populations in Early-type Lens Galaxies

Independent constraints on what mass-fraction is luminous/dark?
Example: HST & IFS of J2321-097

HST F435W

HST F814W

Czoske et al. 2008

HST B/V& I imaging

VLT VIMOS-IFU luminosity-weighted spectrum

Obtain Lick Indices
Stellar populations of E/S0 galaxies

Stellar populations of SLACS lenses span a range in age and metallicity.

Preliminary results!
The stellar M/L of E/S0 galaxies

Age & metallicity are anti-correlated

Preliminary results!
The stellar M/L of E/S0 galaxies

Czoske, Trager, Koopmans et al.

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<th>System</th>
<th>M/L(_B)</th>
<th>(e_{M/LB})</th>
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Preliminary results!

Single-age, single-metallicity populations might not be right, but can be tested.
Grid-based Strong Lensing

How to approach the modeling of complex lenses with extended sources w/o simply parameterized source and lens models.

Going from smooth to clumpy models...
Grid-based Lensing

Simulated Massive Galaxy

Observed Massive Galaxy

Smooth Dark Matter

Clumpy Dark Matter

Stars

Modeling must be more sophisticated than simply parameterized!
Smooth mass model: Lensed images correlate strongly
Clumpy mass model: Lensed images correlate less.

Exploit this to detect (DM) clumps (talk Vegetti)

(e.g. Warren & Dye 2003, Koopmans 2005,
Brewer & Lewis 2005; Suyu & Blandford 2006a&b, Vegetti & Koopmans 2008)
A Differential-Lens Equation

To solve for (i) the source brightness distribution and (ii) the potential, using

\[ S_x(\vec{x}) = S_y(\vec{y}, \psi(\vec{x})) \]

with

\[ \vec{y} = \vec{x} - \nabla \psi(\vec{x}) \]

Conservation of source surface brightness

The usual lens equation

Koopmans (2008), in prep.
A Differential-Lens Equation

Solving for $S(x)$ is simple and leads to a linear equation (e.g. Warren & Dye 2003)

\[ S_y(\vec{y}) = S_x(\vec{x}) \]

or

\[ L(\psi) \vec{s} = \vec{d} \]

(e.g. Koopmans 2005; Suyu et al. 2006/8; Brewer & Lewis 2005; Vegetti & Koopmans 2008; talk Vegetti)
Linearizing the DLE

Solving the DLE in actual practice so far...
Linearized Differential Equation

Assume that the "best lens model" still gives image residuals compared with the data:

\[
\delta d(\vec{x}) = s(\vec{y} + \delta \vec{y}) - s(\vec{y}) \approx \nabla_y s(\vec{y}) \cdot \delta \vec{y}
\]

Since:

\[
\vec{y} + \delta \vec{y} = \vec{x} - \nabla_x (\psi(\vec{x}) + \delta \psi(\vec{x}))
\]

\[
\delta \vec{y} = -\nabla_x \delta \psi(\vec{x})
\]

one finds the relation:

\[
\delta d(\vec{x}) \approx -\nabla_y s(\vec{y}) \cdot \nabla_x \delta \psi(\vec{x})
\]

Between source SB, potential and image residuals
Linearized Differential Equation

In algebraic form this reads:

\[
B[L(\vec{\psi}) | - D_s(\vec{s}) D_x] \left( \begin{array}{c}
\delta \vec{s} \\
\delta \vec{\psi}
\end{array} \right) = \vec{d} - BL(\vec{\psi}) \vec{s} = \delta \vec{d}.
\]

Koopmans et al 2005; Suyu et al. 2006/8; Vegetti & Koopmans 2008)

This linear algebraic equation can be solved using a Bayesian penalty function for the residuals and standard Cholesky/gradient methods.

This is what we have used so far with great success (see talks Vegetti/Barnabe)
Example: CDM Substructure

Strong image distortion

Simulation of lens system: SIE + SIS

SIE: $10^{11}$ solar mass

SIS substructure of $10^{8}$ solar mass

Koopmans 2005
Example:

CDM Substructure

Potential Correction

Koopmans 2005

Best Smooth Model Residuals

Reconstruction: SIS substructure of $\sim 10^8$ solar mass
The End?
Next Steps - The Future for Strong Galaxy-Galaxy Lensing

- **VLT X-shooter:**
  UV-IR Spectroscopy of massive lenses to assess their “true” stellar M/L to $z=1$ (22hrs GTO time; PI. Koopmans)

- **ELT, OPTIMOS (ESO Phase-A study since Sept. 2008):**
  Spatially-resolved kinematics and stellar population of E/S0 galaxies at $z \geq 1$ (co-I).

- **SKA, LSST, Pan-STARRS, follow-up w/JDEM, JWST, ALMA etc.:**
  Large all-sky surveys to discover 1000s of new lenses (e.g. Koopmans, Jackson & Browne 2004)

- **Other ongoing surveys e.g.:**
  COSMOS (Faure et al. 2008), CFHT (Cabanac et al. 2007), GOODS (Moustakas et al. 2006), HAGLeS (Marshall et al.), SLQS (Gavazzi et al.), etc ...
**General Conclusions**

- *(Strong)* Gravitational Lensing provides a unique tool to measure the mass structure of galaxies to $z=1$

- Combined Lensing & Dynamics breaks mass model degeneracies (mass-sheet & mass-anisotropy)

- Grid-based lensing can detect mass structure in the range of $10^7$ solar mass and up

- The key all these studies and results has been to **combine** gravitational lensing with other techniques!