A Century of Gravitational Lensing: Introduction and overview

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Contents of this talk

- Where we come from: brief early history & the mid-1980s
- Strong lensing by galaxies, including MSD and substructure
- Gravitational telescopes and microscopes
- Galactic microlensing
- Weak gravitational lensing

Disclaimer: This is not intended as a (fair) review of the field.
Early days; expectations

1915/19 GR; Light deflection at Sun, ‘factor 2’ verified

1919 Lodge used ‘lens’ for deflector

1920 Eddington: possible occurrence of multiple images

1924 Chwolson predicted ring-like images (‘Einstein rings’)

1936 Einstein studied properties of point-mass lenses, but argued that phenomenon is unobservable

1937 Zwicky’s visions: gravitational lensing

- allows direct mass estimates of ‘extragalactic nebulae’ (galaxies)
- allows a deeper view into the Universe (through magnification)
- probability of observing lensing phenomenon is ‘a certainty’.

1964Refsdal: determination of Hubble constant from time delay measurements

1979 First GL system, the ‘double quasar’ Q0957+561
~ 30 years ago

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  – Einstein rings (Hewitt et al. 1988; Langston et al. 1989)
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- **Visions**
  
  - Galactic microlensing as search for MACHOs (Paczyński 1986)
  - AGN microlensing (Paczyński 1986; Kayser et al. 1986; Schneider & Weiss 1987; earlier: Chang & Refsdal 1979)
  - Galaxy-galaxy lensing (Tyson et al. 1984)

- **Theoretical developments**
  
  - Mass-sheet degeneracy (Falco et al. 1985)
Early developments in weak lensing

- Cluster mass reconstruction (Tyson et al. 1990; Kaiser & Squires 1993)
- Galaxy-galaxy lensing (Brainerd et al. 1996)
Strong lensing by galaxies

Selection of candidate lens systems mainly by:

- Image configuration (multiple images, arcs, rings), in optical or radio surveys
- Spectroscopy: Two redshifts in a single spectrum (e.g., SLACS)
- Extreme apparent luminosity

Selected applications and results:

- Slope of the mass profile (why so close to isothermal?)
  contribution of DM to the mass inside $\theta_E$
- $M/L$ for the stellar components – clues to IMF
- Ellipticity/orientation of the mass distribution – follows light?
- Independent determination of $H_0$, from time delays in multiple image systems
Suyu et al. (2011); obtained from the spiral lens system B1933+503

Bolton et al. (2012) from SLACS & BELLS samples
Mass profiles and dark matter-fraction of galaxies in the Illustris simulation:

Xu et al. (2016)
Health warning: The mass-sheet degeneracy

Mass models are not unique – for a given source and lens redshift:

The mass distributions \( \kappa(\theta) \) and, for all \( \lambda \),

\[
\kappa_\lambda(\theta) := \lambda \kappa(\theta) + (1 - \lambda)
\]

yield **the same** image configurations, magnification ratios, image shapes!

Magnification depends on \( \lambda \), \( \mu_\lambda = \mu / \lambda^2 \) – but unmeasurable without information about the source (or source population)

Time-delay and radial profile affected, \( (H_0 \Delta t)_\lambda = \lambda (H_0 \Delta t) \)

Invariant: (Mass inside) Einstein radius, angular structure (e.g., ellipticity)

**Thus:** To determine slope of mass profile, absolute masses (away from the Einstein radius), Hubble constant, mass-sheet degeneracy must first be broken!!

**Note:** \( 1 - \lambda \neq \kappa_{\text{ext}} \) ! Vastly different scales.

Source position transformation: a more general near-degeneracy.
How to break the mass-sheet degeneracy

- Assume a parametrized mass model (e.g., power law, or NFW, for $\kappa$)
- Use independent mass probes – e.g., stellar dynamics in galaxies
- Assume $\kappa \rightarrow 0$ (or $\kappa \rightarrow \kappa_{NFW}$) for large separation from lens center (WL)
- Assume ‘mass follows light’ on average, for clusters
- Have independent information about source size or luminosity (e.g., fundamental plane)
- Employ statistical distribution of source properties (e.g., number counts for large-scale cluster lensing)
- MSD partly broken if sources at vastly different (and known) redshifts are lensed by the same mass concentration (e.g., multiple arc systems in clusters)

These methods are ‘more or less’ successful ...

MSD remains the largest obstacle for model-independent accurate results.

For galaxy lenses, stellar dynamical techniques have been most successful.
Mass substructure in (lens) galaxies

CDM model predicts more subhalos in galaxies than observed satellite galaxies. Whereas astrometry of quad lenses is well reproduced by ‘simple’ mass models, flux ratios are not; magnification can be altered by substructure in mass distribution. Are these two issues related?

• Predictions from numerical simulations difficult (resolution/smoothing, effects of baryons, survival of subhalos in the inner region)

• (High-mass) substructure in some cases directly seen (e.g., MG2016+112; MG0414+0534)

• Astrometric search for substructure using extended sources (e.g., with ALMA)
Gravitational telescopes & magnification bias

- ‘bright’ flux-limited samples of distant objects contain higher fraction of lensed sources (best example: sub-mm sources)

Negrello et al. (2010)
Gravitational telescopes & magnification bias

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• the apparently most luminous \( (L = 4\pi D_L^2 S) \) sources (typically) are strongly lensed: apparently most luminous QSOs, sub-mm sources, LBGs, ...
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Kneib et al. (2004)
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- employ high fluxes and large spatial resolution for physical studies of high-$z$ objects (detailed spectroscopy/internal structure/QSO hosts)
Galactic microlensing

- First discoveries 1993 towards LMC and Galactic bulge
- Up to today, $\geq 10^4$ microlensing events found
- Significant contribution of MACHOs to the dark matter in our Galaxy can be ruled out ($f \lesssim 10\%$);
- Planets (= binaries with extreme mass ratio) detected, as short-term perturbations of standard single-mass light curve;
- Detection of free-floating planets?
- Structure of the inner Milky Way
- Spin-off of microlensing surveys (e.g., variable stars, AGN, ...)

An ongoing success story!
Gravitational microscopes

Stellar graininess of mass distribution cause microcaustics; provided source component \( \lesssim \) Einstein radius of stars, significant magnification variation can occur.

Magnification pattern and caustics from microlensing

Witt et al. (1992)
Gravitational microscopes

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- caustics generated by AGN microlensing resolve innermost source components
- size (and brightness distribution) of accretion disk, broad line region & X-ray emitting region

Mosquera et al. (2013) left: 2237+0305
Gravitational microscopes

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- caustics generated by AGN microlensing resolve innermost source components
- size (and brightness distribution) of accretion disk, broad line region & X-ray emitting region
- standard thin accretion disk model viable?
- AGN microlensing may affect time delay measurements
Weak gravitational lensing

Shear effect: \( \epsilon \approx \epsilon^s + \gamma \) and \( \langle \epsilon^s \rangle = 0 \) \( \Rightarrow \) \( \langle \epsilon \rangle = g = \frac{\gamma}{(1 - \kappa)} \).

Magnification effect: \( n(> S) = \frac{1}{\mu} n_0 \left( > \frac{S}{\mu} \right) \).

Main applications:

- Mass reconstruction of galaxy clusters (also in combination with strong lensing)
- (Model-dependent) mass calibration of clusters
- Galaxy-galaxy (\& group-galaxy) lensing: mean mass properties of galaxies \& groups; biasing properties; \( M_*/M_{\text{tot}} \)
- Lensing by the LSS (cosmic shear) – cosmological parameters; testing gravity theory
- Lensing of the CMB – sensitive test of gravitational instability model for structure growth; breaking degeneracies in CMB measurements.
Weak lensing by clusters

- Parameter-free mass reconstructions; e.g., ‘bullet clusters’, filaments between cluster pairs, mass vs. light distribution, mass substructure
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Dietrich et al. (2012)
Weak lensing by clusters

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- Radial mass profile of clusters – do they follow the universal DM profile?

Umetsu et al. (2011)
Weak lensing by clusters

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- NFW-profile fits remarkably well! Too well?
- Mean concentration parameter is $c \approx 7.7$, slightly higher than expected in 3-D, from DM-only simulations
- $c$ biased high due to strong lensing selection

Umetsu et al. (2011)
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- Uniqueness of mass profiles?

Projected enclosed mass in A2261 for different methods to get mass model

(Coe et al. 2012)
Weak lensing by clusters

- Parameter-free mass reconstructions; e.g., ‘bullet clusters’, filaments between cluster pairs, mass vs. light distribution, mass substructure
- Radial mass profile of clusters – do they follow the universal DM profile?
- Uniqueness of mass profiles?
- $M_{200}$ determination through NFW fit – mass calibration of clusters, important input for cluster cosmology (mass-observable relations)
Cosmic shear

- Probing cosmological parameters with shear-shear correlations
  (and other statistics: higher-order shear correlations; shear peak statistics)
- Currently determined best: banana-like confidence regions in $\Omega_m-\sigma_8$ plane. Discrepancy with Planck-CMB results?

CFHTLenS tomographic cosmic shear (re-)analysis

Joudaki et al. (2016)
Cosmic shear

- Probing cosmological parameters with shear-shear correlations (and other statistics: higher-order shear correlations; shear peak statistics)
- Currently determined best: banana-like confidence regions in $\Omega_m$-$\sigma_8$ plane. Discrepancy with Planck-CMB results?
- Major ongoing surveys: KiDS/VIKING, DES, HSC
- The future: Euclid, LSST, WFIRST, SKA $\rightarrow$ probing e.o.s. of Dark Energy
Cosmic shear issues

The statistical power of future experiments much larger than for current surveys; this requires **much** better control of systematic effects, such as:

- Unbiased shear estimates from faint, PSF-convolved, pixelized & noisy images
- Knowledge of photometric redshift properties
- Intrinsic alignment effects
- Theoretical predictions – impact of baryonic physics
- Covariance estimates
Conclusions

• We’ve come a long way ... from first ideas, to visions, discoveries, and quantitative results

• Gravitational lensing is a powerful tool for many fields of astrophysics, e.g. planets, stars, low- and high-z galaxies, AGN, galaxy evolution, groups & clusters, large-scale structure and galaxy biasing, cosmology, dark matter & dark energy, gravity theory

• Future facilities (e.g., JWST, 4MOST, DESI, Euclid, LSST, WFIRST, SKA) will open new fascinating opportunities, as we will hear this week