Gravitational Lensing

Y. Mellier - IAP
Gravitational deflection of light

- **Source**
- **Lens**
- **Observer**

- **DLS**: Distance between the Source and the Lens
- **DOS**: Distance between the Source and the Observer
- **DOL**: Distance between the Observer and the Lens

**Diagram Details**:
- Blue Galaxy
- Line of sight
- Dark Matter
- Cluster of Galaxies
- Light bent by gravity
- Light's normal path
Gravitational deflection of light

Projected gravitational potential

\[ \vec{\alpha} = \frac{2}{c^2} \frac{D_{LS}}{D_{OS}} \nabla \theta_i \phi_N \]

Angular distances:
- Redshifts \( z_S, z_L \)
- Cosmology

Source → Observer

Lens

Gravitational Lensing

ESO@50, Garching 3-7 September 2012

Tony Tyson, Greg Kochanski and Jon Dell'Antonio
Frank O'Connell and Jim McManus/ The New York Times
Gravitational lensing effects
on lensed sources

Mellier 1999
Gravitational lensing effects on lensed sources

- Image multiplication
  → image parity, time delay, flux ratios
- Magnification (size)
- Image distortion (shear)

Mellier 1999
Astrophysics with gravitational lenses

- **Properties of Halos:**
  - Total mass, mass profile, mass function, internal structures, clustering and evolution with redshifts of:
    - galaxies, groups, clusters of galaxies, superclusters, filaments.
  - Relation(s) between baryonic and dark matters in structure formation processes, biasing;

- **Cosmology:**
  - Expansion rate and growth rate of structure in the Universe
  - Test dark matter, dark energy, gravity models
  - Measure $H_0$ with time delays in multiply imaged sources

- **Gravitational telescope - High- z universe:** magnified sources

- **Exoplanets** with micro-lensing
50 yrs of gravitational lensing@ESO: some highlights
ESO Key Programmes: finding « golden » lenses:
Multiply imaged QSOs for time delays/Ho/mass models of galaxy-scale lenses

1988 ESO 2.2 m: discovery of the quadrupled imaged quasar
ESO GL2 « Cloverleaf »=H1413+117

1988 ESO 3.60 m/EFOSC: confirmation that spectra are identical → same QSO with 4 lensed images.
Giant gravitational arcs

Soucail et al 1988

6 Sept. 1985 - A370 arc discovery
Very 1st image at CFHT Cass. focus
RCA 512x320 CCD 0.8”/pixel,
10mn R-band, seeing 0.8"

- Space telescope best for imaging
- Ground based facilities
  - NIR imaging follow up (AO)
  - VIS/NIR spectroscopy follow up (AO)
  - Statistics: wide field
The birth of gravitational distortion astrophysics

ESO 1987: first demonstration of the gravitational lensing nature of giant arcs

ESO 1987 A370:
spectrum of the giant arc with the MOS PUMA2-v1.0 punching machine on 3.60m/EFOCS1

\( z_{A30} = 0.374 \)

\( z_{\text{arc}} = 0.724 \)
ESO/EOSC1 pioneered deep spectroscopic observations of very high-z lensed galaxies

1987-1988: ESO 3.60m/EOSC1: redshift of the giant arc Cl2244-02

ESO 1998: Giant arc in Cl2244-02: UT1/ISAAC in Ks + (V,R) with VLT test camera
Cosmic shear@ESO $\rightarrow$ service mode with the VLT for imaging with critical IQ requirements

Maoli et al (2000, 2001)

- VLT/FORS Large Programme on Cosmic Shear

- A different approach: many small independent «empty» fields with FORS randomly selected over the whole sky

- A use case for service mode: superb seeing sample
ESO spectroscopy: whatever the lens and lensing configurations

Redshifts of sources and lenses are needed

Galaxy halos  Clusters of galaxies  Filaments between clusters  Cosmic shear

\[ \vec{\alpha} = \frac{2}{c^2} \frac{D_{LS}}{D_{OS}} \vec{\nabla}_I \phi^2_N \]
ESO spectroscopic surveys for weak lensing surveys

- **CFHTLS : VVDS** with VMOS,
  - 32,000 redshifts to $I=22.5$ over $\sim15$ deg$^2$, (Garilli et al 2008)
  - 15,000 to $I=24$ over $\sim1$ deg$^2$ (Le Fèvre et al 2005)
  - 1000 redshifts $23<I<24.75$ over 0.15 deg$^2$ (Le Fèvre et al 2012)

- **CFHTLS : VIPERS** with VMOS:
  - $\sim100,000$ redshifts to $I=22.5$ over 25 deg$^2$ (Guzzo et al 2012)

- **COSMOS : z-Cosmos** with VMOS:
  - $\sim20,000$ redshifts to $I=22.5$ over 1.7 deg$^2$ (Lilly et al 2009)
  - $\sim10,000$ redshifts $B<25.25$ color selected, over 0.9 deg$^2$

2000-2012 VLT/VMOS: weak lensing analysis of CFHTLS and COSMOS fields impossible without these data.

ESO PR, Le Fèvre et al 2006
Microlensing by moving sources

The EROS collaboration

Gravitational Lensing
1990-1997: ESO as support to a major micro-lensing project:
La Silla facilities to the EROS collaboration

- 380 photographic B,R plates from the 1.0m ESO Schmidt telescope
- Installation of the Marly telescope at La Silla
The future of gravitational lensing@ESO
The future for gravitational lensing@ESO in the context of JWST, Euclid: resolution, sensitivity, multiplex
The future for gravitational lensing@ESO in the context of JWST, Euclid: resolution, sensitivity, multiplex

- **Very high redshift Universe**: faint/ultra-faint sources, high spatial resolution, mid-spectral resolution (AO+IFU+NIR – SINFONI, MUSE, ALMA, E-ELT)
- **Sub-halos**: modelling lenses/ sources (VLT, E-ELT)
- **Redshift of faint/ultra-faint arcs/rings** and lenses: scale total mass (VLT, ELT): magnified and also *demagnified* images

- **Wide field for cosmic shear**: wide field faint spectroscopic surveys → VMOS/PILMOS, 4 MOST, MOONS

- **Time domain**: mu-lens, exoplanets, times delays: Danish VST, ESO 4-m class telescopes (?)
The future for gravitational lensing@ESO in the context of JWST, Euclid: **resolution, sensitivity, multiplex**

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Magnification: the high-z universe with gravitational telescopes

A spiral structure resolved at z=0.724

Stretched rotation curved resolved at z=0.724
Constraining mass model of lenses and model of lensed sources with IFU observations of arcs

Narasimha & Chitre 1993

\[ z_{\text{cl}} = 0.56, \quad z_{\text{arc}} = 1.116 \]

Gravitational arc in the cluster Cl2236-04:

- Discovery: Melnick et al. (1993) with ESO 3.60m /EFOSC1.
- Redshift measured by Kneib et al. (1994) with ESO/NTT/EMMI

Narasimha and Chitre in 1993:
Use together high resolution imaging (HST) and observation of magnified rotation curve of the source to constrain models of lens/source.
Gravitational magnification + ALMA
understanding the dynamics and halos properties of high-z galaxies

Swinbank et al 2011

MACS J2135-0102: the Cosmic Eyelash
$z_{cl}=0.325$, $z_{SMM2125}=2.3$

HST + IRAM + EVLA
Gravitational magnification + ALMA
dissecting the content and physical properties of gas in high-z galaxies

Swinbank et al. 2011: « Only ALMA will be capable of verifying the true pressure-induced offsets in distant forming galaxies by probing scales < 100pc.... This will be possible for strongly lensed starburst systems such as SMM J2135, allowing an unprecedented insight into key quantities characterising the turbulent molecular gas in star forming systems at high redshifts. »

M(H2)-R2 relation. The molecular star forming regions in SMM J2135 lie on a line corresponding to very high turbulent pressure.
Gravitational magnification of SMM J2135 + ALMA
dissecting content and physical properties of gas in high-z galaxies

The promise of ALMA on test data: spectrum of SMM J2135.

- Left: emission lines J=7-6 of carbon monoxide and fine structure of atomic carbon
- Impossible to observe without magnification + capabilities of ALMA

http://www.almaobservatory.org/visuals/images
Gravitational magnification + ESO AO spectro-imaging
dissecting the content, physical properties and dynamics of high-z galaxies

**Observational Parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spectral range (simultaneous)</td>
<td>0.465-0.93 µm</td>
</tr>
<tr>
<td>Resolving power</td>
<td>2000@0.46 µm</td>
</tr>
<tr>
<td>Resolving power</td>
<td>4000@0.93 µm</td>
</tr>
</tbody>
</table>

**Wide Field Mode (WFM)**

- Field of view: 1x1 arcmin²
- Spatial sampling: 0.2x0.2 arcsec²
- Spatial resolution (FWHM): 0.3-0.4 arcsec
- Gain in ensquared energy within one pixel with respect to seeing: 2
- Condition of operation with AO: 70%-ile
- Sky coverage with AO: 70% at Galactic Pole
- Limiting magnitude in 80h: $I_{AB} = 25.0$ (R=3500), $I_{AB} = 26.7$ (R=180)
- Limiting Flux in 80h: $3.9 \times 10^{-19}$ erg s⁻¹ cm⁻²

**Narrow Field Mode (NFM)**

- Field of view: 7.5x7.5 arcsec²
- Spatial sampling: 0.025x0.025 arcsec²
- Spatial resolution (FWHM): 0.030-0.050 arcsec
- Strehl ratio: 10-30%
- Limiting Flux in 1h: $2.3 \times 10^{-18}$ erg s⁻¹ cm⁻²
- Limiting magnitude in 1h: $R_{AB} = 22.3$
- Limiting surface brightness in 1h: $R_{AB} = 17.3$ arcsec⁻²

Synergy HST/JWST with ground based AO+IFU (SINFONI / MUSE):

Dissecting high-z magnified galaxies with MUSE+Galacsi

A370, HST/ACS ; NASA/ESA
Gravitational magnification + ESO AO spectro-imaging

Exploring sub-halos with lensing models coupled with MUSE or ALMA

Models are now so accurate that properties of bright/dark halos can be derived from anomalies to predictions of simple models:


→ « milli-lensing » effects can be detected - perturbations to large halo models:
  • Change flux ratios
  • Change source/lenses image positions
  • May create extra-images
  • Change time delays

Bright halos: AO/IFU is a tool to constrain mass/size of visible halos
Dark halos: probed by lensing effects
Gravitational magnification + ESO AO spectro-imaging

Exploring sub-halos with lensing models coupled with MUSE or ALMA

Synergy HST/JWST with ground based facilities:

- AO+IFU + deep AO NIR:
  - Dynamical properties of magnified galaxy halos with MUSE+Galacsi
  - Monitoring time delays in lensed galaxies/QSOs with multiple images

Abell 370, HST/ACS; credit NASA/ESA

Richard et al 2010
The future for gravitational lensing@ESO in the context of JWST, Euclid: resolution, sensitivity, multiplex

- Very high redshift Universe: faint/ultra-faint sources, high spatial resolution, mid-spectral resolution (AO+IFU+NIR – SINFONI, MUSE, ALMA, E-ELT)
- Sub-halos: modelling lenses/sources (VLT, E-ELT)
- Redshift of faint/ultra-faint arcs/rings and lenses: scale total mass (VLT, ELT)

- **Wide field for cosmic shear**: KIDS/VIKING, wide field faint spectroscopic surveys → VMOS/PILMOS, 4 MOST, MOONS

- **Time domain**: mu-lens, exoplanets, times delays: Danish, VST, ESO 4-m class telescopes (?)
ESO and wide fields weak lensing surveys

VST / VISTA – KIDS / VIKING

- 9-band u-K survey with VST+VISTA (photo-z)
- 1500 deg$^2$ (CFHTLS = 150 deg$^2$)
- 2 mag. deeper than SDSS, but x2 sharper
- 1 mag. shallower than CFHTLS: spectro follow up easier
- Started Oct. 15, 2011

VST
- 2.6m telescope
- 1 sq.deg. optical camera (OmegaCAM)
- 32 2kx4k detectors
- 0.21" pixels

VISTA
- 4m telescope
- 0.6 sq.deg. InfraRed camera
- 16 2kx2k detectors
- 0.35" pixels

PI: K. Kuijken

250 nights: VIKING
(Pi: Will Sutherland)

440 nights: KIDS
(Pi: K. Kuijken)

Courtesy: K. Kuijken
**ESA/ESO synergy: Euclid**

Weak Lensing and BAO surveys to probe dark energy

<table>
<thead>
<tr>
<th>Euclid: ESA mission</th>
<th>Launch date: 2020</th>
<th>Survey: 6 yrs</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Description</td>
<td></td>
</tr>
<tr>
<td><strong>Wide Survey</strong></td>
<td>15,000 deg$^2$</td>
<td>Step and stare with 4 dither pointings per step.</td>
</tr>
<tr>
<td><strong>Deep Survey</strong></td>
<td>40 deg$^2$</td>
<td>In at least 2 patches of $&gt;10$ deg$^2$ 2 magnitudes deeper than wide survey</td>
</tr>
</tbody>
</table>

**PAYLOAD**

<table>
<thead>
<tr>
<th>Telescope</th>
<th>VIS</th>
<th>NISP</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.2 m Korsch, 3 mirror anastigmat, f=24.5 m</td>
<td>0.787×0.709 deg$^2$</td>
<td>0.763×0.722 deg$^2$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Capability</th>
<th>VIS</th>
<th>NIR Imaging Photometry</th>
<th>NIR Spectroscopy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Visual Imaging</td>
<td>Y (920-1146nm), J (1146-1372 nm), H (1372-2000nm)</td>
<td>1100-2000 nm</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Wavelength range</th>
<th>Sensitivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>550–900 nm</td>
<td>24.5 mag 10σ extended source</td>
</tr>
<tr>
<td></td>
<td>24 mag 5σ point source</td>
</tr>
<tr>
<td></td>
<td>24 mag 5σ point source</td>
</tr>
<tr>
<td></td>
<td>24 mag 5σ point source</td>
</tr>
<tr>
<td></td>
<td>3 $10^{-16}$ erg cm-2 s-1</td>
</tr>
<tr>
<td></td>
<td>3.5σ unresolved line flux</td>
</tr>
</tbody>
</table>

Shapes + Photo-z of $n = 1.5 \times 10^9$ galaxies

Euclid : $\sim 300,000$ strong galaxy lensing, $\sim 5000$ giant arcs, $\sim 30$ z=8 QSOS
ESA/ESO synergy: Euclid and ESO

• Ground based visible (u-band) imaging for Euclid photo-z: VST? (no next gen. wide field visible imaging at ESO ?)

• Need for spectroscopic follow up of Euclid galaxies:
  • $10^5$ redshifts to $I_{AB}=24.5$:
    • Shear galaxy sample, control completeness, calibration of photo-z of galaxies used for shape measurement.
    • BAO (emission line) galaxy redshift samples: very high completeness, purity well understood, high uniformity

→ Wide field and ultra-deep spectroscopic surveys: ESO next generation wide field faint MOS/high multiplex is needed.

→ Euclid deep field: E-ELT spectroscopic follow up of Euclid discoveries: very high-z galaxies, $z\sim 8$ QSOs, cool stars
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- **Time domain**: mu-lens, exoplanets, times delays: Danish, VST, ESO 4-m class telescopes (?), E-ELT spectro follow up.
2002-2012: La Silla as support to the micro-lensing PLANET collaboration (an example of planetary research project reported by Alvio)

A 5.5 Earth mass cool planet

Beaulieu et al 2006

Source: European Southern Observatory (ESO), Astronomer Uffe G. Joergensen, Microlensing Observations in Astrophysics

Graphic: Elisabeth Nielsen, Isabel Sondgaard

Times brighter than normal shine

1. First observed change of light was the passing of the front star.
2. The way the distant star’s light changed again, betrays the Earth-like planet’s presence.
3. Computer analysis calculates planet’s size and likely characteristics:
   - Size: Only five times as massive as Earth
   - Surface: Likely to be rocky/icy
   - Atmosphere: Likely to have a thin atmosphere
   - Temperature: Its relative cool parent star implies a surface temperature of -364°F (-220°C)

A 5.5 Earth mass cool planet

- ESO facilities for detecting/monitoring mu-lens events and
- VLT, E-ELT for follow up
So… ESO and gravitational lensing?.

• Major impacts on (S+W) lensing, mu-lensed QSOs and exo-planets

• Considerable contribution on spectro weak lensing surveys
  • CFHTLS and COSMOS, (KIDS/VIKING)
  • Lensing clusters surveys (VLT-CLASH)
• Imaging: VST/VISTA (Collaboration with non-ESO visible surveys?)

• E-ELT: spectra very-high-z magnified (z> 8) + demagnified images

• Space/Ground synergy obvious on
  • Magnified sources: HST/JWST $\rightarrow$ AO/IFU on VLT/E-ELT
  • Euclid: VLT (MOS wide field) and E-ELT follow up

• Exoplanets: detection and follow up a niche for E-ELT
So... ESO and gravitational lensing?.

- Major impacts on (S+W) lensing, mu-lensed QSOs and exo-planets
- Considerable contributions on spectro-weak lensing surveys
  - CFHTLS
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...the next review will be interesting...