Strong Gravitational lensing

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Gravitational lensing



Deflection of light in the vicinity of a massive object due to gravity

Main observables are: image positions, magnifications and time delays

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Magnification







Relative time delays measure Hubble constant

$$\Delta \tau_{ij} = \frac{(1+z_d)}{c} \frac{D_d D_s}{D_{ds}} \left[\phi \left(\boldsymbol{\theta}_i, \boldsymbol{\beta} \right) - \phi \left(\boldsymbol{\theta}_j, \boldsymbol{\beta} \right) \right]$$

$$\frac{D_d D_s}{D_{ds}} \propto \frac{1}{H_0}$$

Effect observable for variable sources only.

Unperturbed path length to the source is unknown. Hence, only relative time delays of the lensed images comprise the observables.





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Time delay surface

Images form at

d

 $\nabla \tau(\boldsymbol{\theta}; \boldsymbol{\beta}) = 0$

rent cantly magnified a sources which are located well outside the 1) Example do the sents (14)_macc_M $= \frac{1}{2} + \frac$ $\frac{1}{2} \frac{1}{2} \frac{1}$ y singet needay x) and compological distance with the mass densitand source position st the following Euclidean, the (16)separation, to illustrative example, we genuider (θ) one find by (15)tōr $_1$ ỹ hịch $M \sim M_{\odot}$ HOnkass, lenst elepsing by a galaxy I as contoidereal distance with c. The corresponding Kinstein radio and Ha acetimes. How sealed Deflection watrop: R - Ker Examples, My consu uation_must of sing present the state of the second state of D₁g₁cognological dista (12) $D \sim 1$ Gpc. The corresponding Minstein radio and 4GM D_{LS} ezmass density frens equation DDD_L Ŋ*₽*′ s equation: 4GMFor a point mas 200 kopcewr Wencen prm $\alpha(\theta)$ $\theta_E =$ 467M Einstein Radius _ (θ') 23 Credit: C/Fassnacht / UCDavis naging by a D_{LS} $4GM^2$ Gpc (21)at is, $\beta \propto \theta$. **De(\theta_{1})** define trnass lens in the form the lens equation in the form $\mathbf{2}2)$ $4GM D_{LS}$ (23)Thyaging by a Point Mass Lens *þ*θ±² $(24\theta_{\rm E}^2)$ (24), $\hat{\alpha} = \frac{1}{2}$, $\frac{1}{2}$, with one image inside the Elipten ring and the other outside. As the source moves away28rom the lens (i.e.465M3 the eases), 20ne of the images approaches the lens and becomes very faint, while This other images in the source and tends to the true position of the source and tends toward e is imaged twice by the source, the two images are on either side of the source, a magnification of unity. $C^2 D_s D_L$ image inside the Einstein ring and the other outside As the source moves away from type a gravitational lens, if ring and the other outside $A = \frac{1}{2} + \frac{1}{2} +$ (24)For the integration of the inte

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Extended mass lens

Singular Isothermal sphere

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Most frequently seen lenses are early-type galaxies

Narayan and Bartelmann 1996

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 $\det \mathcal{A}(\boldsymbol{\theta}) = 0 \quad \mu = 1/\det \mathcal{A}$

correspond to critical curves (image plane) and caustics (source plane)

Wambsganss 1998

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Lens Search Methods

Lensing Search Algorithms

Source properties

- Galaxies
 - Extended, bluish ring/arc-like morphology e.g. SL2S (CFHTLS), SuGOHI (HSC)
 - Spectroscopic selection e.g. SLACS (SDSS), BELLS (BOSS)
- Quasars/AGNs
 - radio multi-band compact sources e.g. CLASS (NVSS,GB6)
 - color-color + point-like morphology e.g. STRIDES (DES)
 - spectroscopic survey e.g. SLQS (SDSS), BLQS (BOSS)
- Supernovae
 - Transient surveys Difference imaging, color-mag, photo-z
 - Follow-up monitoring of known lenses (gals/clusters)

Lensing Search Algorithms

Lens properties

- Galaxies
 - Massive early type galaxies (photometric selection)
 - Spiral galaxies (spectroscopic selection) e.g. SWELLS
- Clusters
 - Serendipity/Visual inspection
 - Cluster-finding algorithm
 - optical richness e.g. SuGOHI-c (HSC), SGAS (SDSS)
 - X-ray e.g. MACS
 - Sunyaev Zeldovich e.g. SPT
 - Arc-finding algorithm e.g. SL2S (CFHTLS)

Lensing Search Algorithms

- Space Warps (<u>spacewarps.org</u>) Citizen Science (*Supervised learning*) since 2013
 - pure visual inspection CFHTLS
 - targeted searches CS82, HSC and DES
- Machine learning algorithms (since 2017)
 - CNNs on Multi-band (color) images e.g. KiDS, CFHTLS, SuGOHI (HSC), DES
 - 1D CNN on Light curves e.g. lensed Supernovae
 - others?

Applications

• Mass (or

Mass distribution

Constraining density profiles of a population of galaxies Koopmans et al. 2009

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Mass distribution of a galaxy cluster using presence of the oddth image of a lensed quasar

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 $\beta = +0.50$ Mass distribution θ |arcsec| Constraining density profiles of a 10 100 projected mass $M_{\text{proj}}(< r) \, [h^{-1}M_{\odot}]$ population of galaxies 1015 Koopmans et al. 2009 SDSS J1004+4112 014 1013 lens (total) 1.5 2 lens (DM) $\gamma' \equiv -dlog(\rho)/dlog(r)$ X-ray 0.1 Ein 012 Total 10 100 0.01 SLACS r [h⁻¹kpc] SIS SARCS dP/dθ arcsec-1 10⁻⁵ 10⁻⁶ MACS Mass distribution of a galaxy cluster using presence of the oddth image of a lensed quasar NFW 10-5

10-7

10-8

0.1

z_s=2.0

10

Image separation θ (arcsec)

100

Statistical constraint on density profiles of galaxy groups AM et al. 2012

15

10

5

0

2.5

Number

 $\mid \beta = -0.25$

Oguri 2010

Anomalies in the flux ratios of lensed quasars to test LCDM predictions about subhalos (Dalal & Kochanek 2002)

1

High resolution imaging can constrain small scale perturbations from subhalos AM et al. 2009, Hezaveh et al. 2016

Anomalies in the flux ratios of lensed quasars to test LCDM predictions about subhalos (Dalal & Kochanek 2002)

1

 Test of CDM (cosmological) model using subhalo/substructure mass function

Mapping the DM subhalo mass function with strong lensing to test LCDM predictions Natarajan et al. 2017

Source: Galaxies

• Stellar population (bulk) properties: luminosity, stellar mass, velocity dispersion, star-formation rate, clump sizes, metallicity

RCSGA 032727-132609: Reconstructed source (inset) Sharon et al. 2012

Source redshift z = 1.70

 $\begin{array}{c} \text{magnification} \\ 42.2\pm5.5 \end{array}$

 $\begin{array}{c} \text{Giant arc} \\ \sim \ 38'' \ \log \end{array}$

Source is part triply imaged and part quintuply imaged

Source: Galaxies

 Stellar population (bulk) properties: luminosity, stellar mass, velocity dispersion, star-formation rate, clump sizes, metallicity

Wuyts et al. 2013

SDSS J1226+2149, galaxy cluster at 6.3 billion light-years Credit: ESA/Webb, NASA & CSA, J. Rigby and HST

Source: Quasars

credit: Surhud More

 Hubble Constant using time delays between multiply lensed SNe (Refsdal 1964)

credit: Surhud More

 Hubble Constant using time delays between multiply lensed SNe (Refsdal 1964)

- Lensed Quasars have been used hitherto for H0 (Suyu 2012, Bonvin et al. 2017, Birrer et al. 2020 COSMOGRAIL, H0LiCoW and TDCOSMO collaborations)
- Pros: Much more abundant than lensed SNe; Cons: Painstakingly long monitoring observations spanning decades

SN Refsdal (Kelly et al. 2015)

Discovery of iPTF16geu (Goobar et al. 2017), Microlensing (AM et al. 2017)

SN Requiem in MACS J0138.0-2155 d (Rodney et al. 2021)

Lensed SN in Abell 370

(Chen et al. 2022)

SN 2022qmx ("Zwicky") HST WFC3/UVIS: F814W F625W F475W 1″ www.lenswatch.org

SN Zwicky (Goobar et al. 2022)

- Upcoming Surveys like LSST, Euclid will find several dozens of lensed SNe
- Pros: Standard candles absolute magnification; transient - host only emission, monitoring easier
- Cons: Microlensing or mass distribution complex ; follow-up obs. essential

Source: Supernovae

Different progenitor models

- Different progenitor models —> differences in light curves
- Lensed SNe
 - Higher redshifts
 - Long time delays —> accurate early predictions
 - Lower lensing systematics (e.g. microlensing) if in clusters

Expected detections in LSST survey per year Goldstein et al. 2019

Lensed Gravitational Waves

to the accuracy of time-delay distance measurement			
	$\delta \Delta t$	δΔψ	δLOS
Lensed GW + EM	0%	0.6%	1%
Lensed quasar	3%	3%	1%

- Uncertainty on the lensing potential
 lower for lensed transients
- Uncertainty on the time delay negligible SNe results
- EM identification necessary

Image: NASA/ESA

 $N_{
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m CDM}) \ . \end{cases}$

Abundance of giant arcs in clusters to constrain cosmological parameters such as Dark Energy (Bartelmann 1998)

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m OCDM}) \ 280 \ (\Lambda {
m CDM}) \ 36 \ ({
m S}/ au {
m CDM}) \end{cases}$

Statistical samples of lensed quasars to constrain Dark Energy Oguri et al. 2012

Abundance of giant arcs in clusters to constrain cosmological parameters such as Dark Energy (Bartelmann 1998)

Collet et al. 2012

No dependence on Hubble constant

Complementarity with other cosmological probes e.g. Cosmic Microwave Background

0.2 0.4 0.6 0.8 Ω_M

References

- Material on lensing basics taken from multiple sources (Lectures from Pritchard, Suyu, Wambsganss, Narayan, Bartelmann, Blandford)
- Saas Fee Lectures by Schneider, Kochanek and Wambsganss
- Lens modelling software: Lensmodel/gravlens by Keeton and Glafic by Oguri