Strong Gravitational Lensing

Overview, Status and Opportunities

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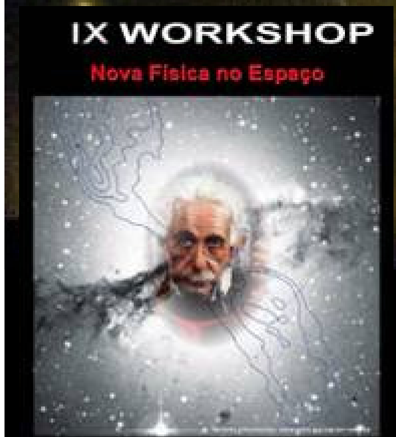
IAG-USP



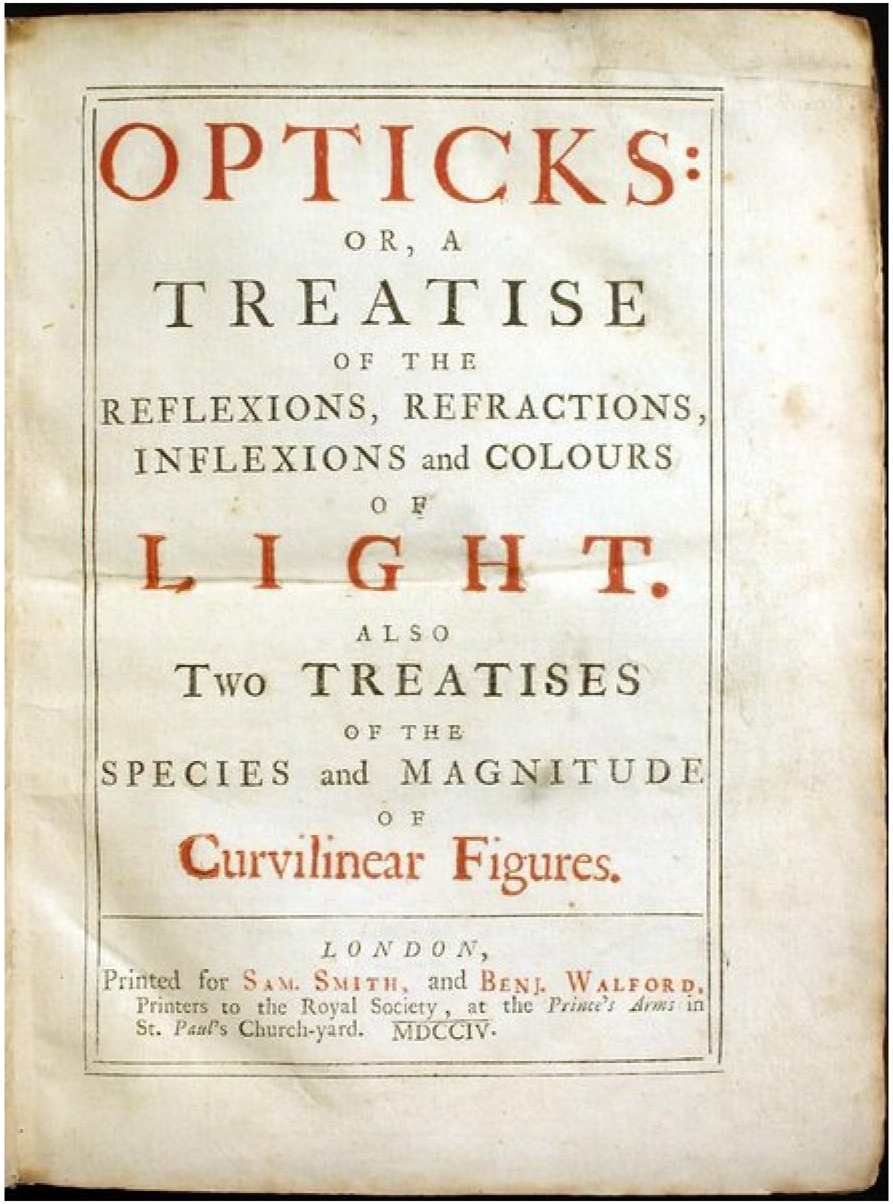
Campos do Jordão, March/2010

Roteiro da apresentação

- fundamentos de lentes fortes

- observações: passado, presente e futuro

- fenomenologia e ciência com lentes fortes


OPTICKS:

OR, A

TREATISE

OF THE

REFLEXIONS, REFRACTIONS, INFLEXIONS and COLOURS

OF

LIGHT.

ALSO

Two TREATISES

OF THE

SPECIES and MAGNITUDE

OF

Curvilinear Figures.

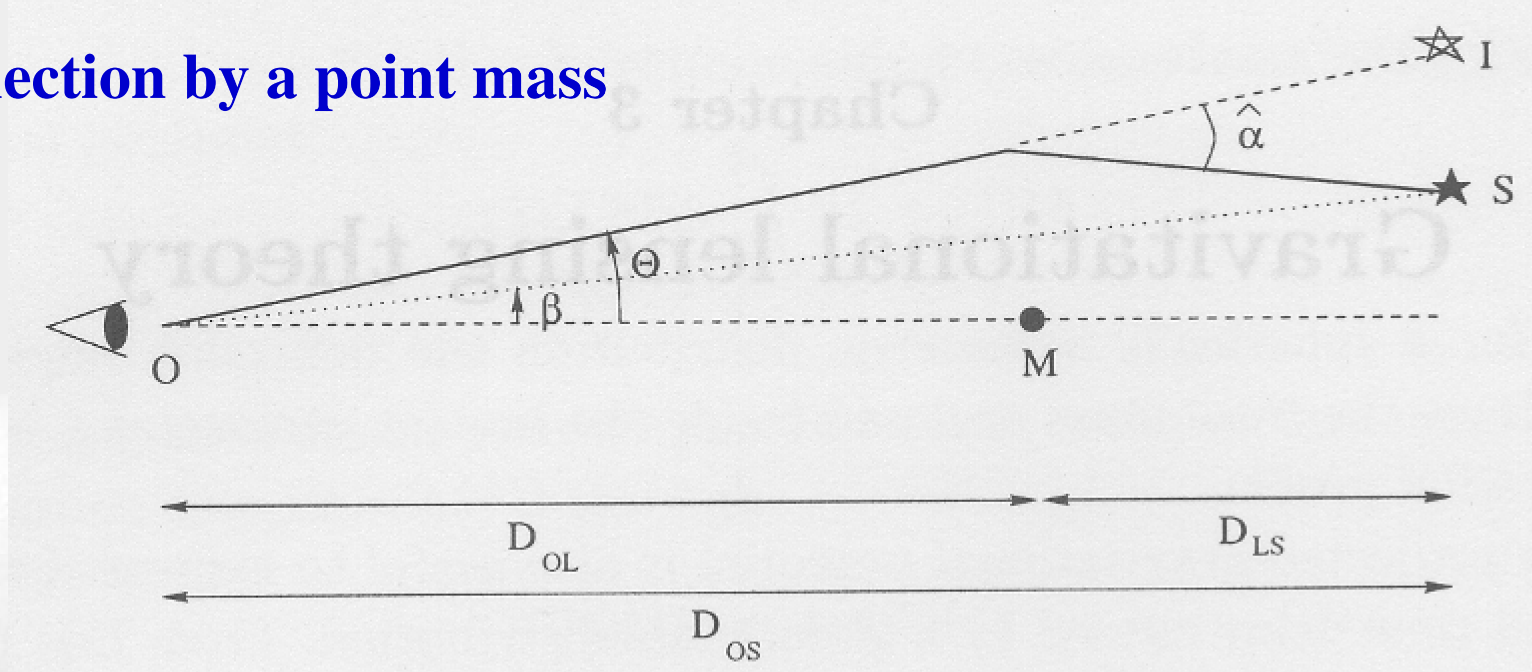
LONDON,

Printed for SAM. SMITH, and BENJ. WALFORD, Printers to the Royal Society, at the *Prince's Arms* in St. *Paul's* Church-yard. MDCCIV.

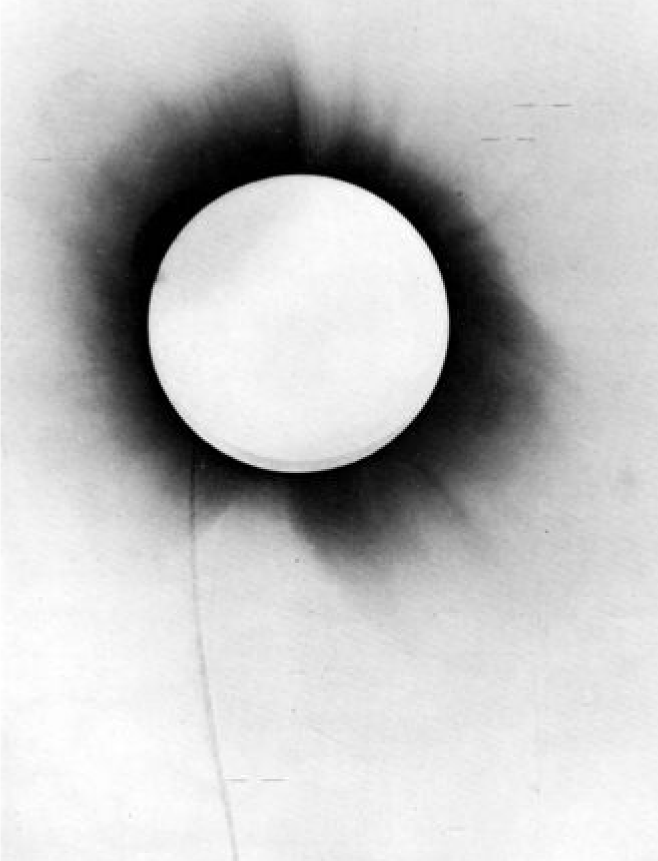
"Do not Bodies act upon Light at a distance, and by their action bend its Rays; and is not this action strongest at the least distance?"

Sir Isaac Newton, *Opticks*, 1704

light deflection by a point mass



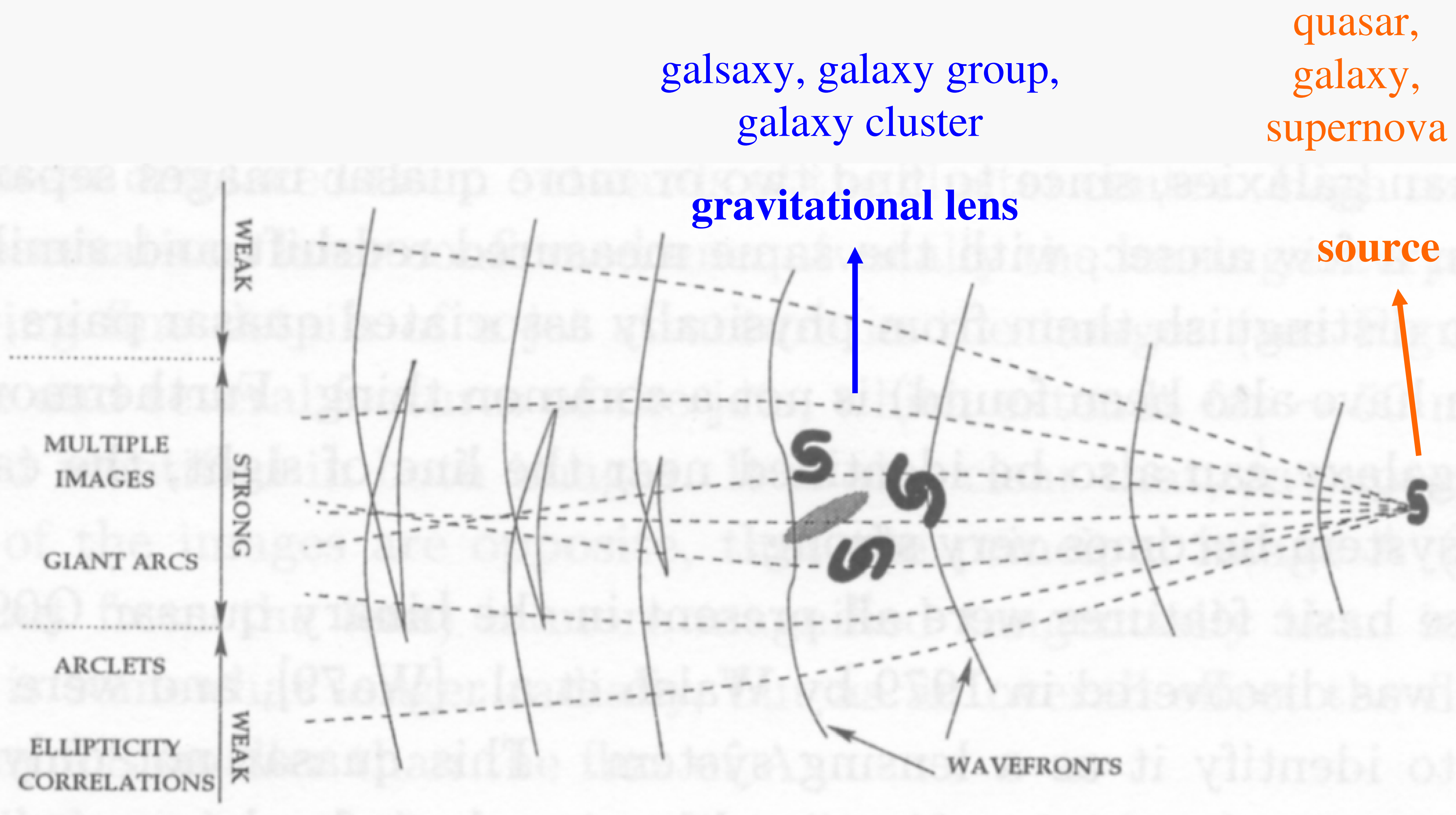
1916: General Theory of Relativity, Einstein derives the **correct** deflection angle:



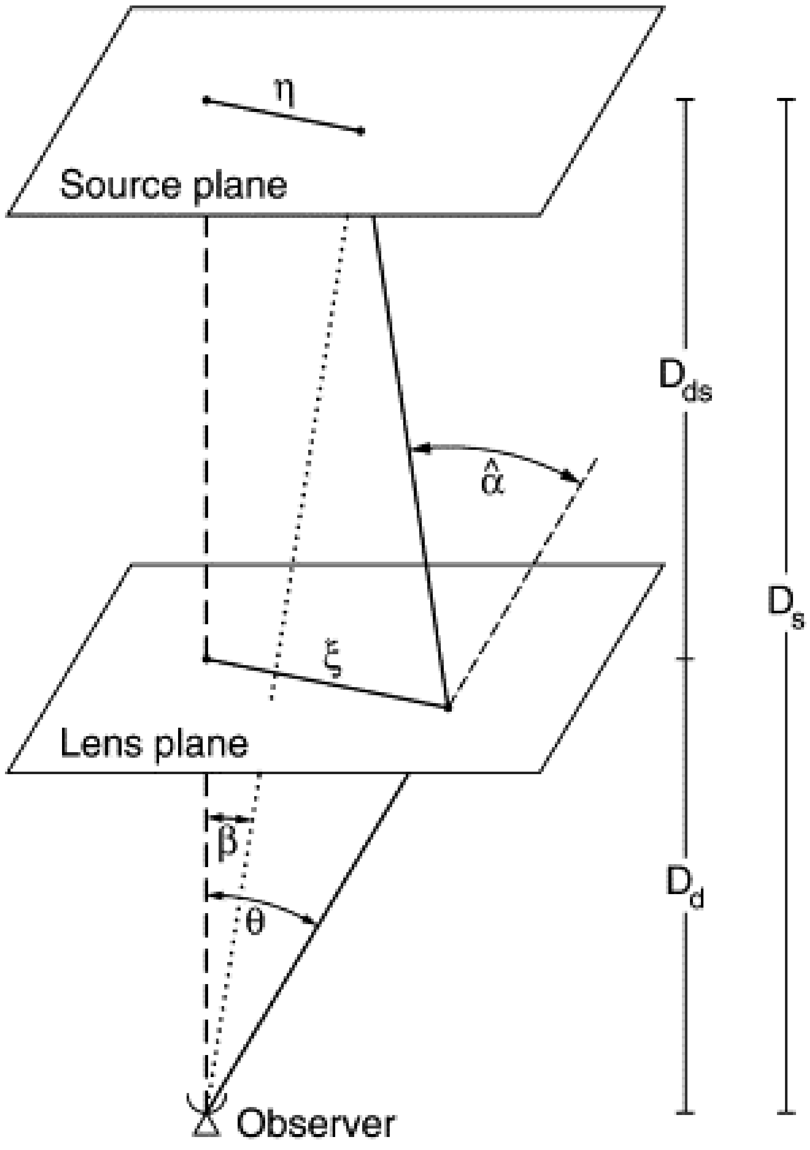
$$\tilde{\alpha}_\odot = \frac{4GM_\odot}{c^2}\frac{1}{R_\odot} = 1.74 \text{ arcsec}$$

1919: Arthur Eddington and his group confirms the GR prediction for the light deflection by the Sun.

SOBRAL = 1,98" PRÍNCIPE = 1,60"



Mollerach & Roulet 2002



Lens Equation

- coordinates $\vec{\theta}$ for the image(s) and $\vec{\beta}$ for the source(s) are related by

$$D_s\vec{\beta} = D_s\vec{\theta} - D_{ls}\hat{\vec{\alpha}}$$

- *reduced* deflection angle

$$\vec{\alpha} \equiv \frac{D_{ls}}{D_s}\hat{\vec{\alpha}}$$

- gives *lens equation*

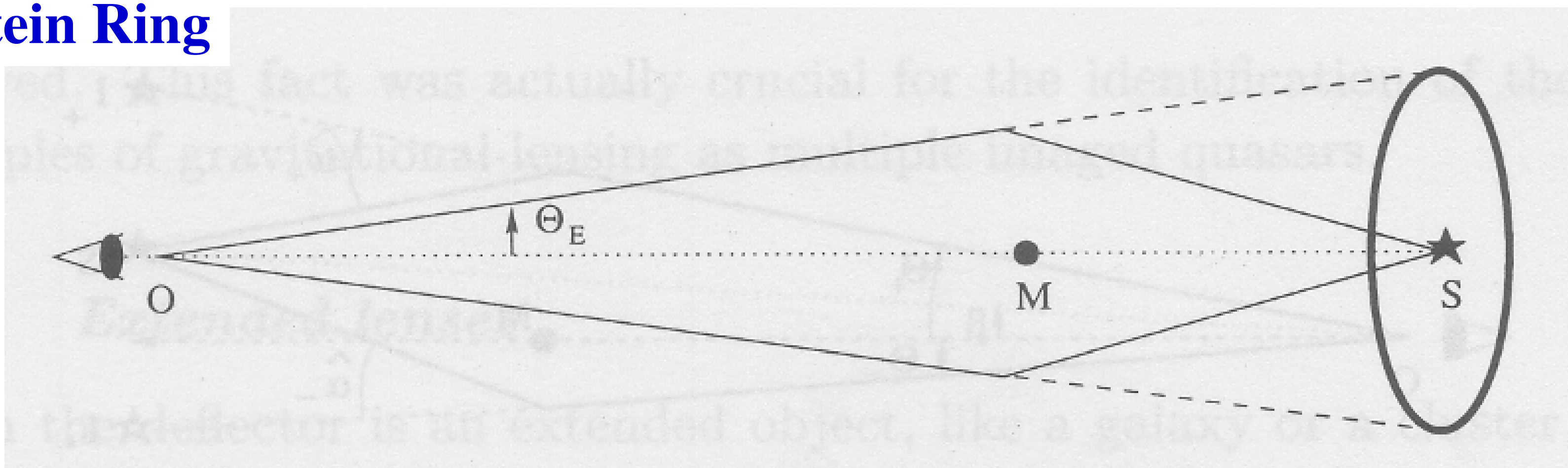
$$\vec{\beta} = \vec{\theta} - \vec{\alpha}$$

true position = apparent position – deflection

$$\vec{\alpha}(\vec{\theta}) = \vec{\nabla}\psi$$

$$\psi(\vec{\theta}) = \frac{D_{LS}}{D_L D_S}\frac{2}{c^2}\int \Phi(\vec{\theta}, z)dz$$

Einstein Ring



point mass

- deflection angle is

$$\hat{\alpha} = \frac{4GM}{c^2\, b} = \frac{4GM}{c^2\, D_l \theta}$$

- lens equation becomes

$$\beta = \theta - \frac{4GM}{c^2\, D_l \theta} \frac{D_{ls}}{D_s}$$

- introducing Einstein angle

$$\theta_E \equiv \left(\frac{4GM}{c^2} \frac{D_{ls}}{D_l D_s} \right)^{1/2}$$

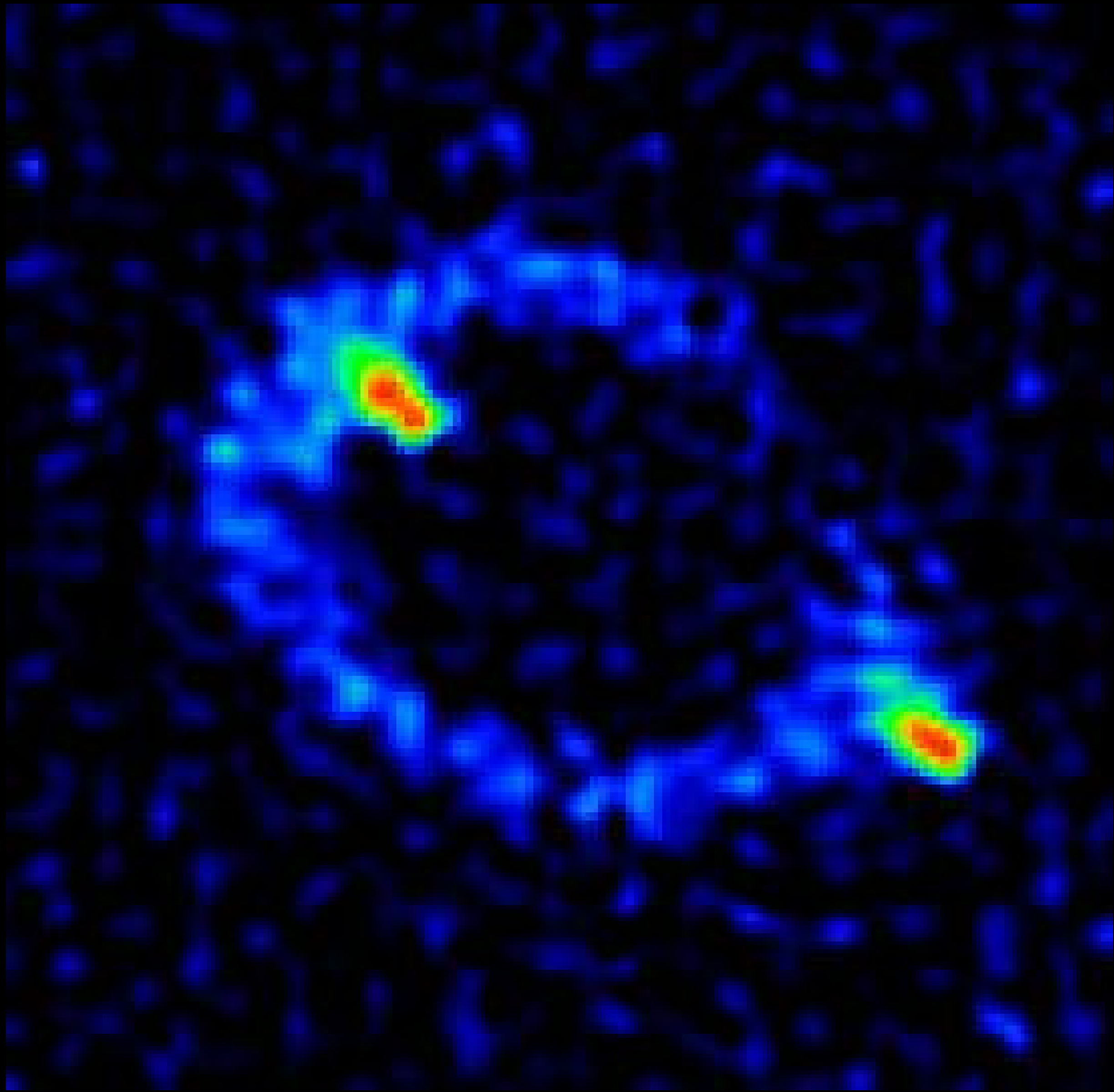
- always two solutions of the lens equation:

$$\theta_\pm = \frac{1}{2} \left[\beta \pm \left(\beta^2 + 4\theta_E^2 \right)^{1/2} \right]$$

- if $\beta = 0$, $\theta_\pm = \pm\theta_E$
- let $D \equiv (D_l D_s / D_{ls})$, then

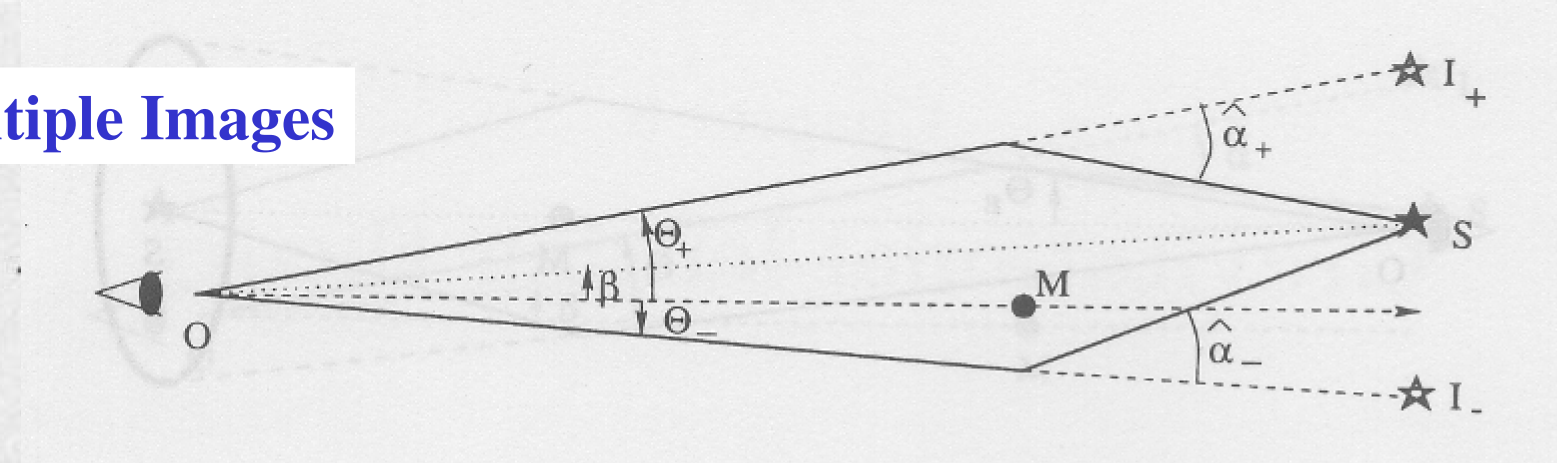
$$\theta_E \approx (10^{-3})'' \left(\frac{M}{M_\odot} \right)^{1/2} \left(\frac{D}{\mathrm{kpc}} \right)^{-1/2}$$

$$\approx 1'' \left(\frac{M}{10^{12} M_\odot} \right)^{1/2} \left(\frac{D}{\mathrm{Gpc}} \right)^{-1/2}$$



1987: The First Einstein Ring
MG1131+0456: VLA, quasar radio emission lensed by a galaxy

Multiple Images



1979: The First Gravitational Lens

0957+561A,B: D. Walsh, R. F. Carswell & R. J. Weymann

$$\theta_{\pm} = \frac{1}{2}\left[\beta \pm \left(\beta^2 + 4\theta_E^2\right)^{1/2}\right]$$

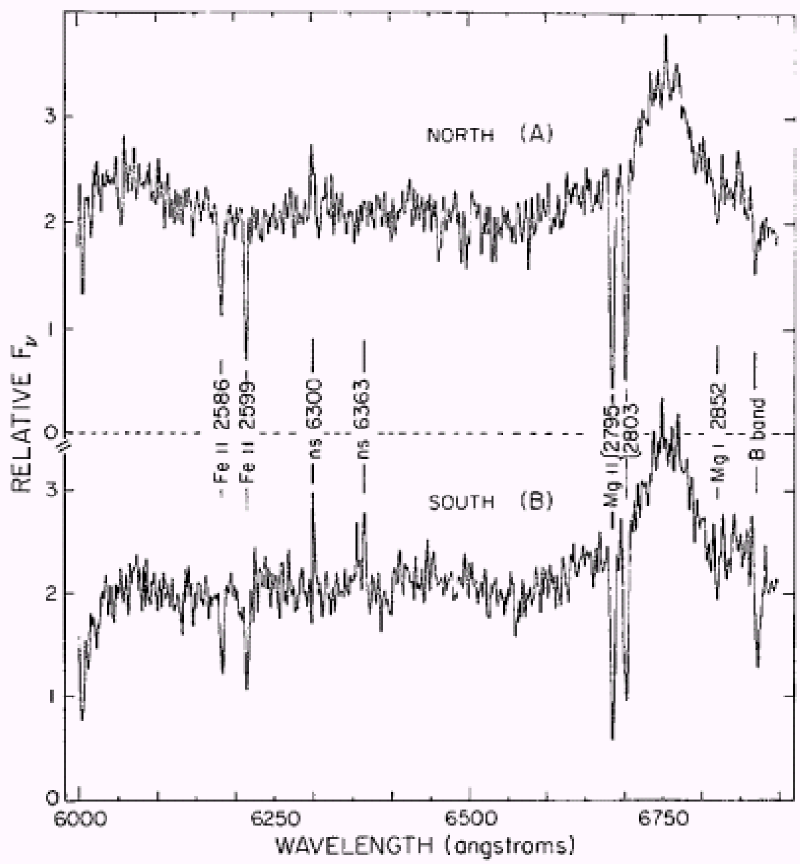
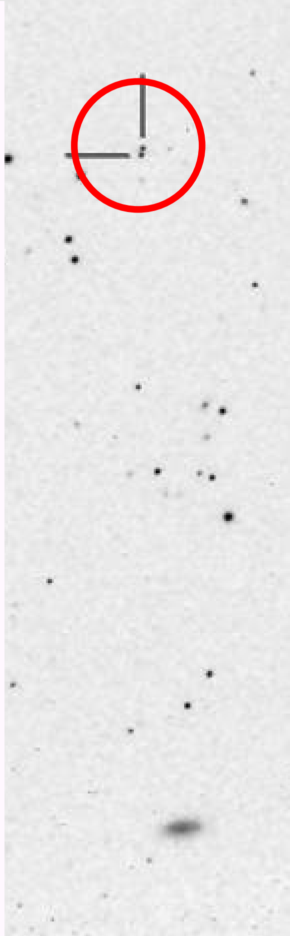
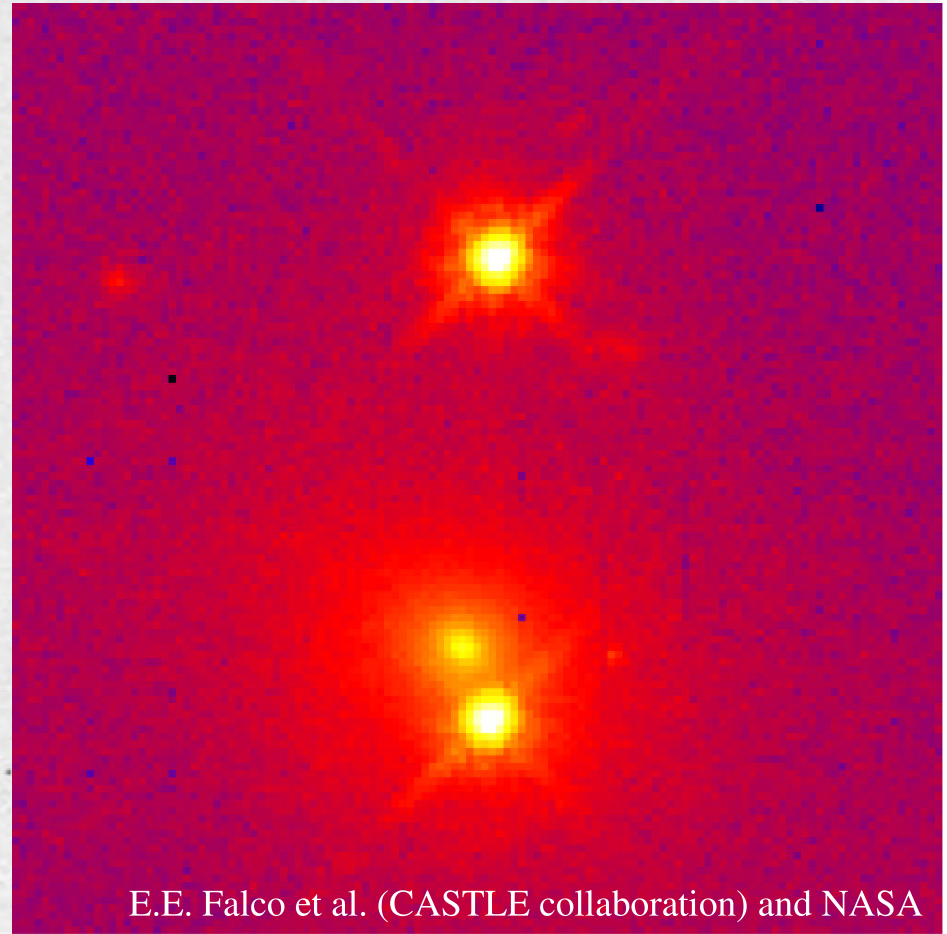
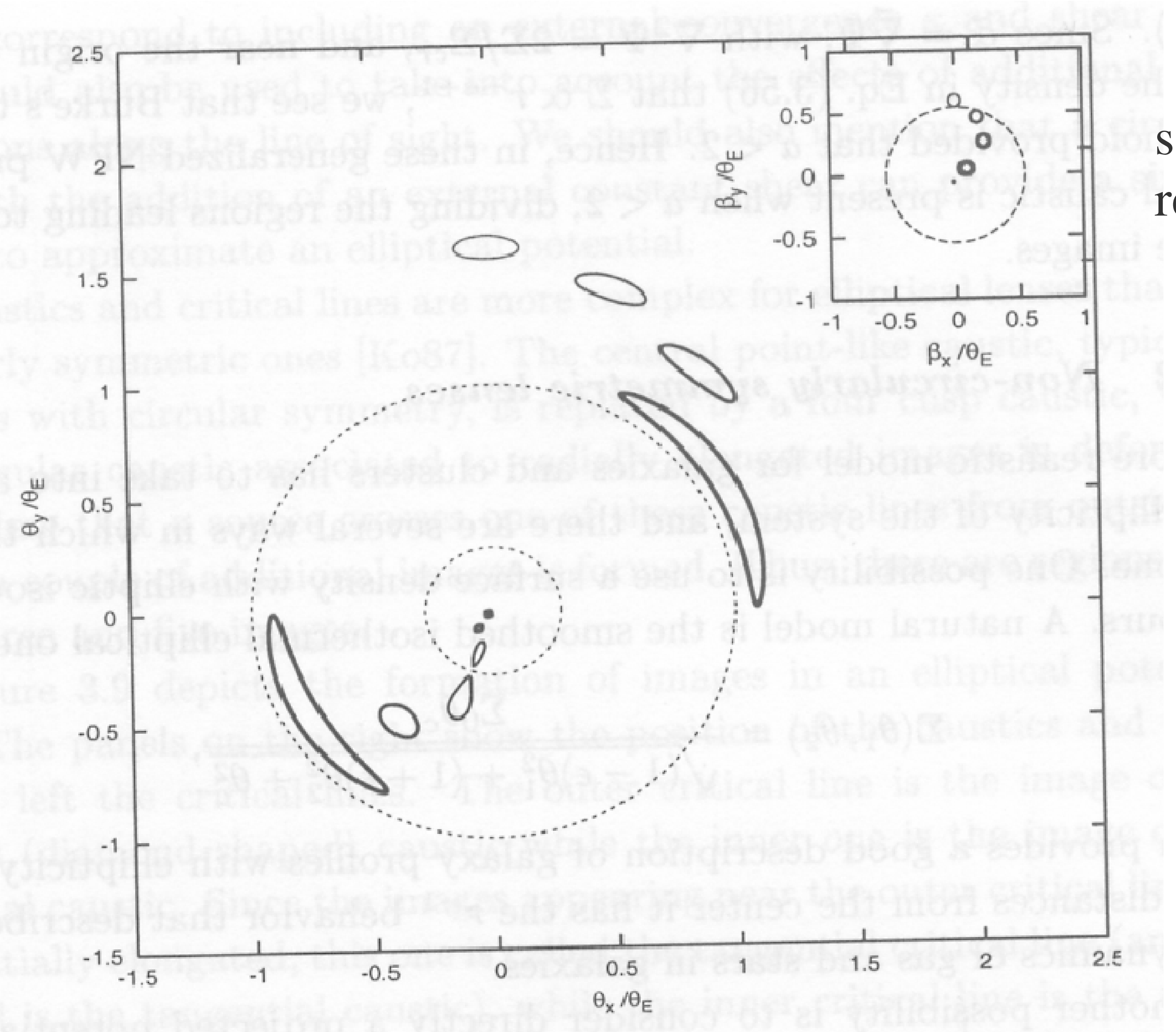


FIG. 1.—Spectra of the two QSOs 0957+561 A, B obtained





Circular Lens



source
real position

image

Mollerach & Roulet 2002

Non-Circular Lens (elliptical)

critical lines & caustics

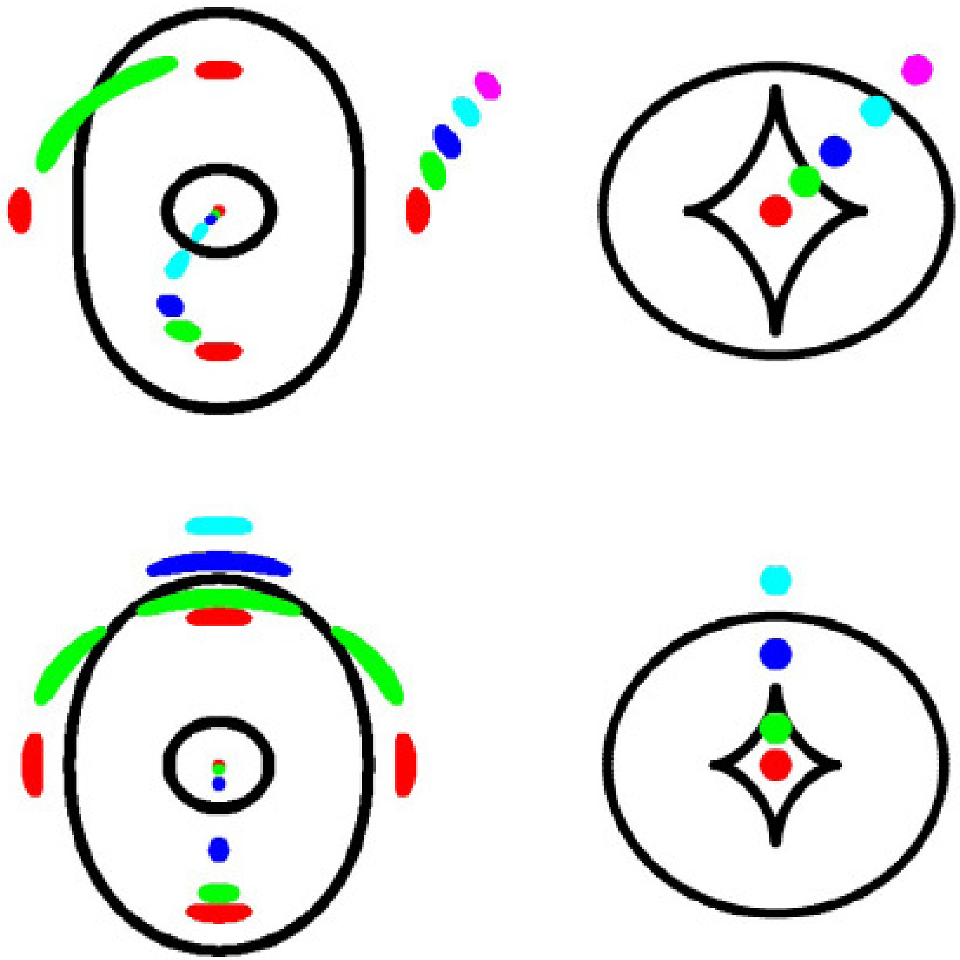
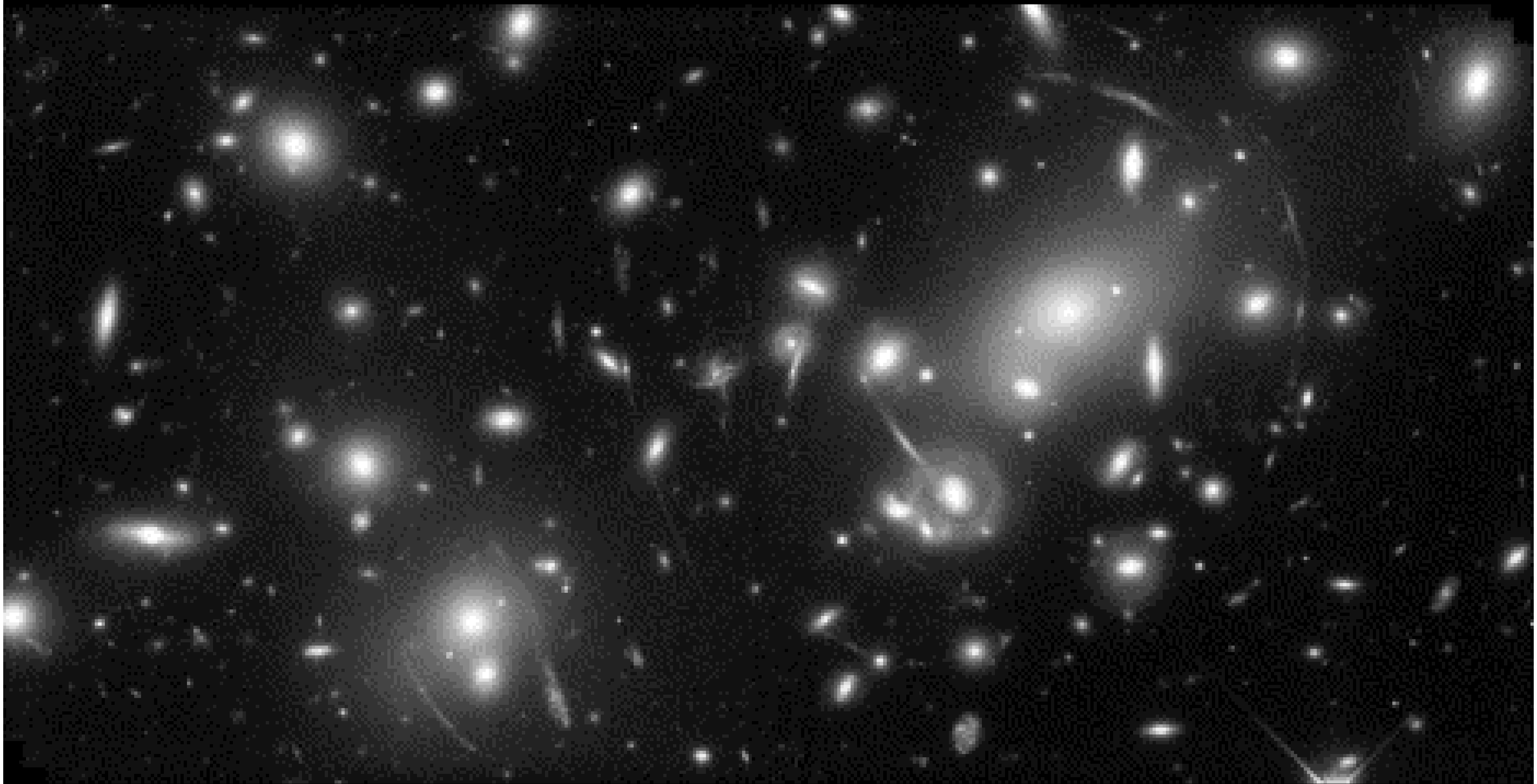


image source real position

Bartelmann

1985: Q2237+0305, Einstein Cross, Huchra et al.

Giant Arcs



Abell 2218 , HST

Strong Gravitational Lensing Observational Status

~ 200 galaxy-scale lenses

Major past and present surveys

- CLASS: 22 lenses, radio source-selected
  (JVAS, Browne et al 2003)
- SLACS: ~100 galaxy lenses, lens-selected, spectroscopy
  (SDSS, Bolton et al 2006)
- SQLS: >25 quasar lenses, source-selected, spectroscopy
  (SDSS, Oguri et al 2007)
- SL2S: >20 galaxy lenses, lens-selected
  (CFHTLS, Cabanac et al 2007)
- COSMOS: ~20 galaxy lenses, lens-selected, optical imaging
  (COSMOS, Faure et al 2008)

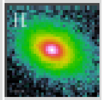
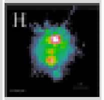
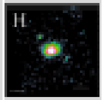
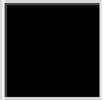
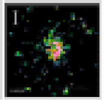
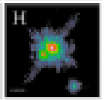
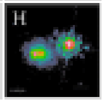
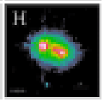
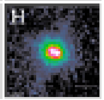
Marshall 2009

CASTLES Survey (~ 100 lenses)

(CfA-Arizona Space Telescope LEns Survey of gravitational lenses)

Complete survey of all them known galaxy-mass gravitational lens systems (those with image separations of less than 10 arcseconds)

http://www.cfa.harvard.edu/castles/

#	Image	Lens Name	G	z_s	z_l	RA (J2000)	Dec (J2000)	E(B-V)	m_s (mag)	m_l (mag)	F_{GHz} (mJy)	N_{im}	size (")	dt (days)	sigma (km/s)
1		Q0047-2808	A	3.60	0.48	00:49:41.89	-27:52:25.7	0.016		I=20.05		4ER	2.7		229±15
2		HE0047-1756	A	1.66	0.41	00:50:27.83	-17:40:8.8	0.022	I=16.52/2	I=18.96		2	1.44		
3		HST01247+0352	C			01:24:44.4	+03:52:00	0.029	I=24.13/2	I=21.86		2	2.20		
4		HST01248+0351	C			01:24:45.6	+03:51:06	0.029				2	0.74		
5		B0128+437	B	3.124		01:31:13.405	+43:58:13.14	0.082			$F_5=48$	4	0.55		
6		PMNJ0134-0931	A	2.216	0.77	01:34:35.67	-09:31:02.9	0.031	I=18.96/4	I=19.31	$F_5=529$	5R	0.73		
7		Q0142-100	A	2.72	0.49	01:45:16.5	-09:45:17	0.031	I=16.47/2	I=18.72	$F_5\sim1$	2	2.24		
8		QJ0158-4325	A	1.29	0.317	01:58:41.44	-43:25:04.20	0.015	I=17.39/2	I=18.91	$F_8<0.2$	2	1.22		
9		B0218+357	A	0.96	0.68	02:21:05.483	+35:56:13.78	0.068	I=19.28/2	I=20.06	$F_5=1209$	2ER	0.34	10.5±0.4	

redshift

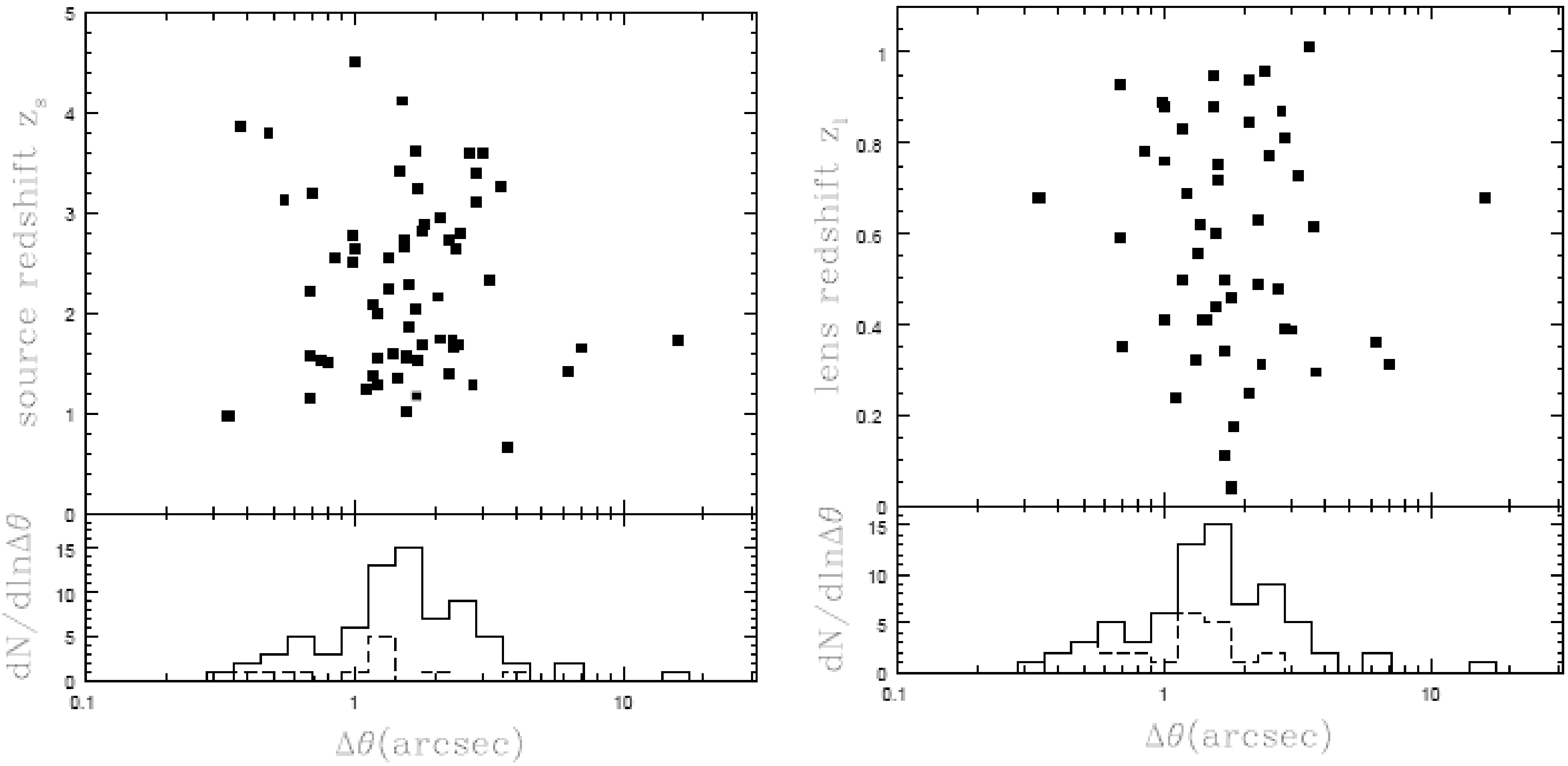


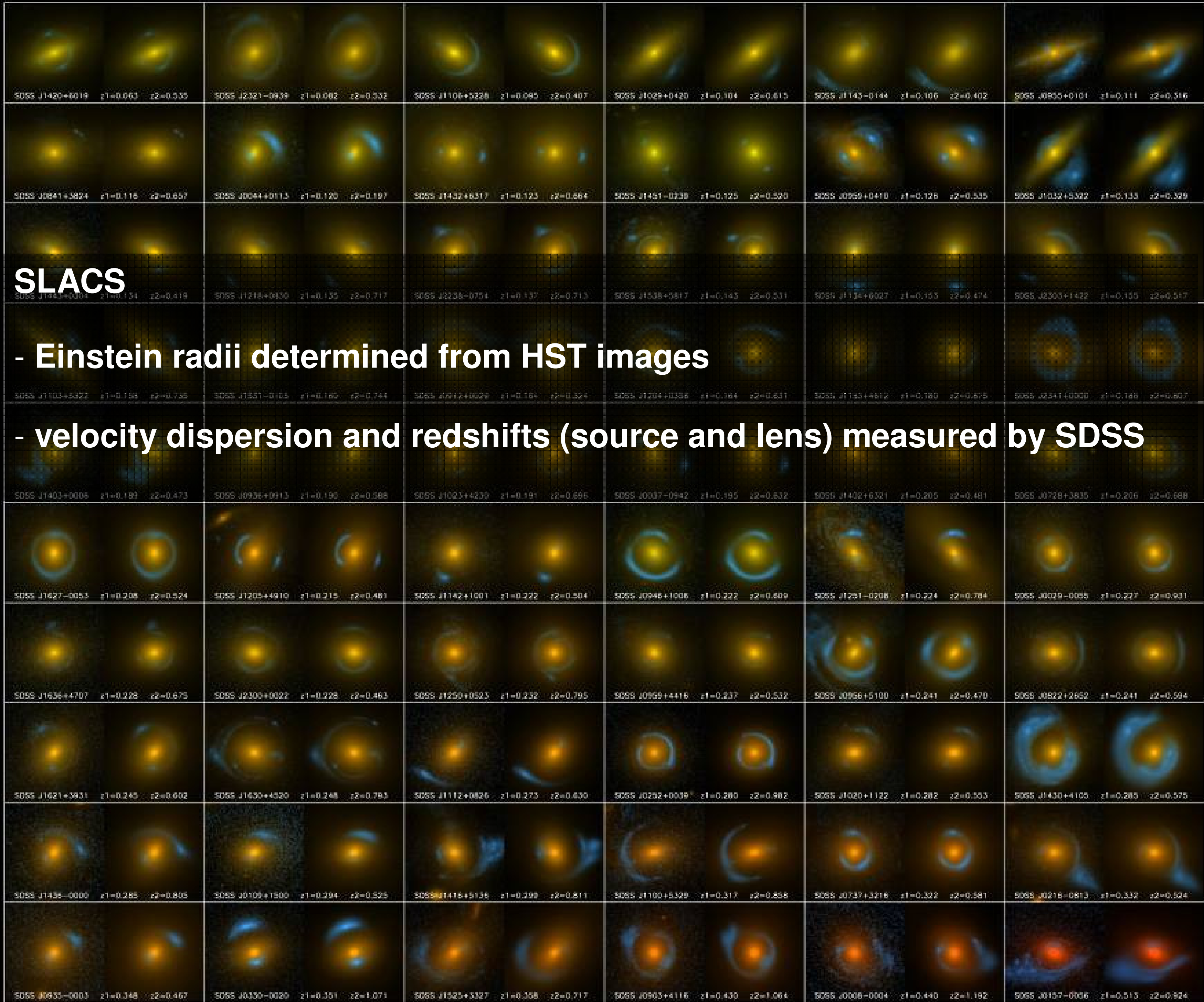
image separation

Kochanek 2004

SLACS

- Einstein radii determined from HST images

- velocity dispersion and redshifts (source and lens) measured by SDSS



SLACS: The Sloan Lens ACS Survey www.SLACS.org

A. Bolton (U. Hawai'i IfA), L. Koopmans (Kapteyn), T. Treu (UCSB), R. Gavazzi (IAP Paris), L. Moustakas (JPL/Caltech), S. Burles (MIT)

Image credit: A. Bolton, for the SLACS team and NASA/ESA

Current and Future Surveys

Plenty of lenses

Survey	Depth	Res	Area	Gal	QSO	Sn
SL2S	25	0.9	130	30	10	-
SDSS	21	1.5	8000	30	100	-
HST	26	0.1	3	30	1	-
PS1	22.5	1.0	30000	300	2000	20
DES	25	0.9	5000	1000	100	1
LSST	24	0.6	20000	10000	10000	600
SNAP-WL	27	0.1	1000	20000	300	-
SNAP-SN	29	0.1	10	300	3	200

Marshall, 2008, private communication

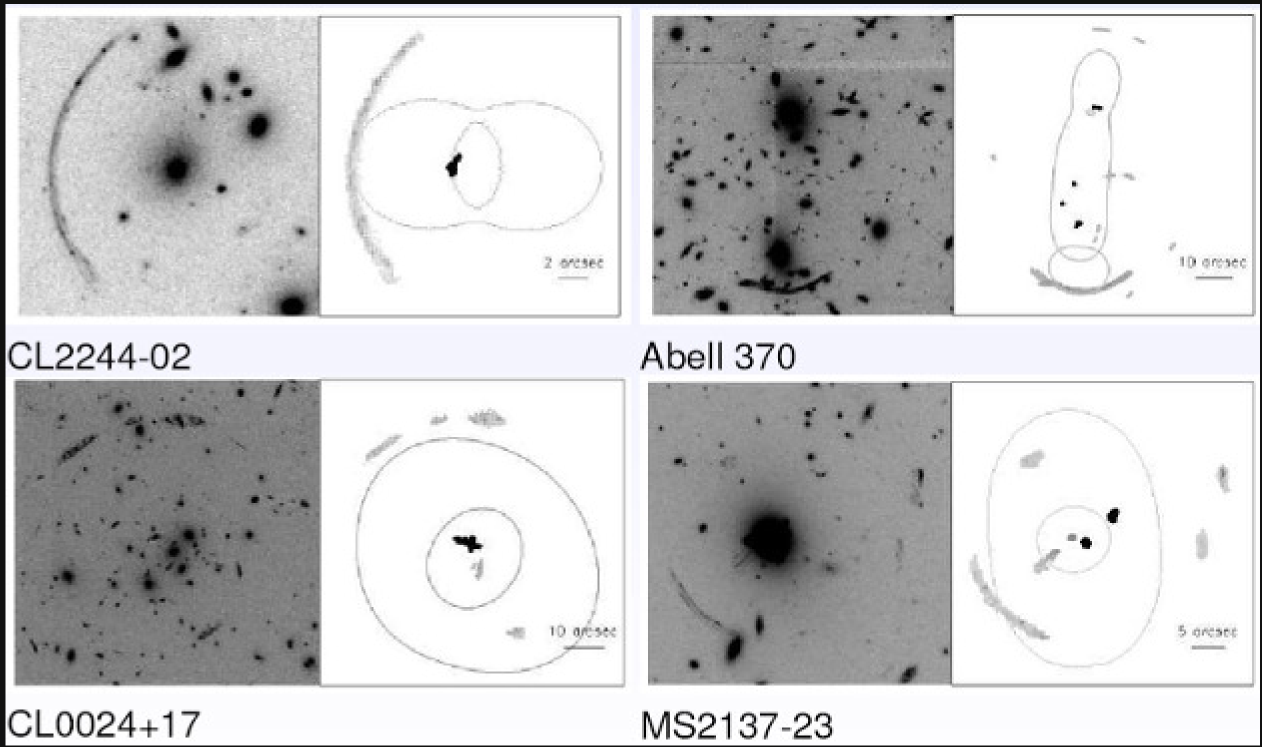
AND RADIO WILL PROVIDE A LOT OF LENSES TOO!

Science with Strong Lenses

Lens (galaxy, group, cluster) Modeling

- the image positions and relative fluxes can be used to constrain

    - mass
    - profile
    - shape
    - substructure

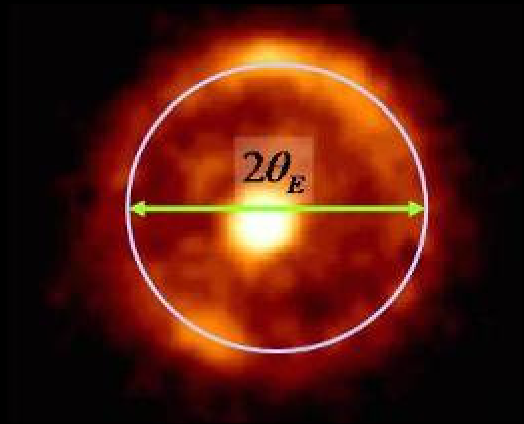


Comerford et al. 2006

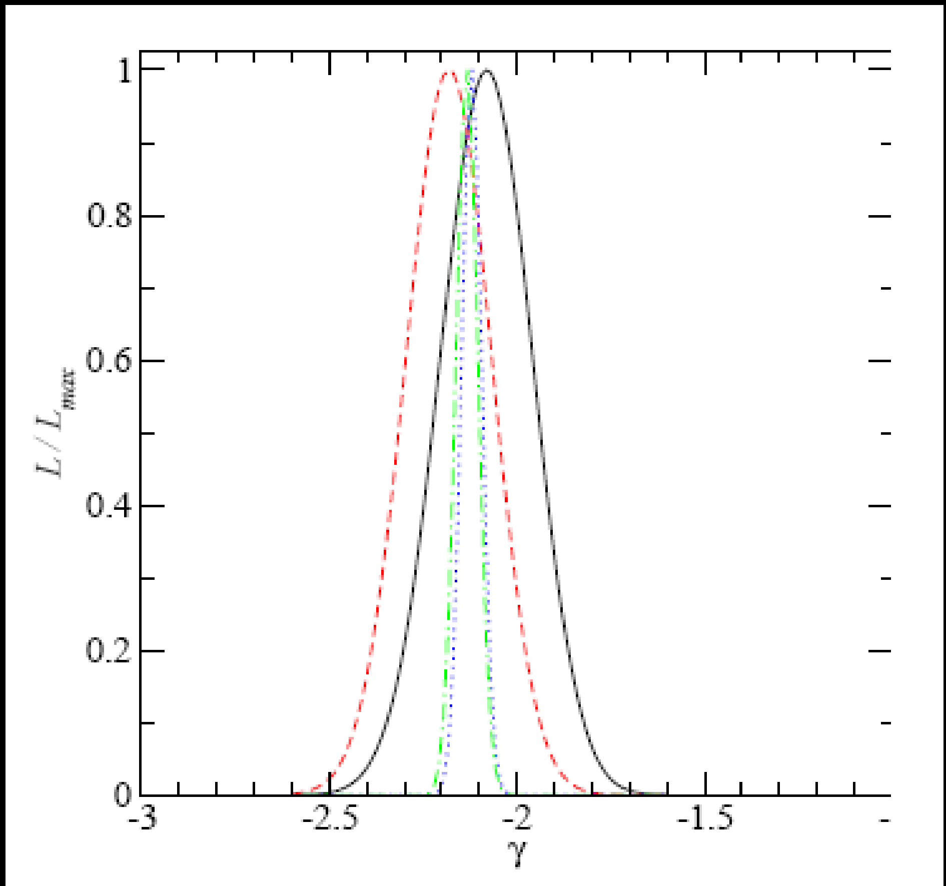
Stellar Dynamics and Lensing

spherical Jeans equation

$$\frac{1}{\nu}\frac{d\nu\sigma_r^2}{dr} + \frac{2\beta(r)}{r}\sigma_r^2 = -\frac{GM(r)}{r^2}$$



$$M_L = \frac{c^2}{4G}\frac{D_l D_s}{D_{ls}}\theta_E^2$$



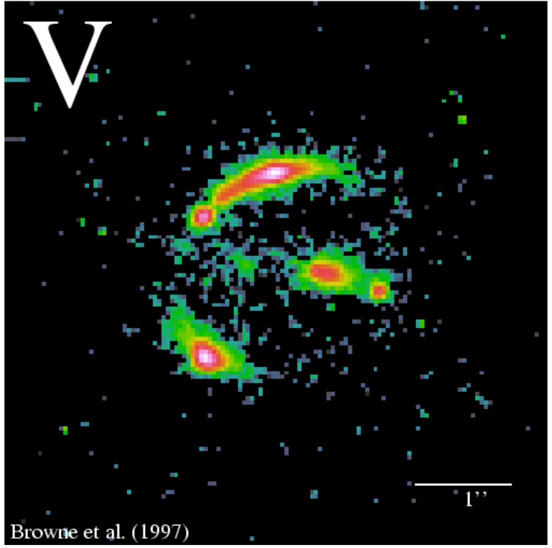
density profile slope

$$\rho(r) \propto r^{\gamma}$$

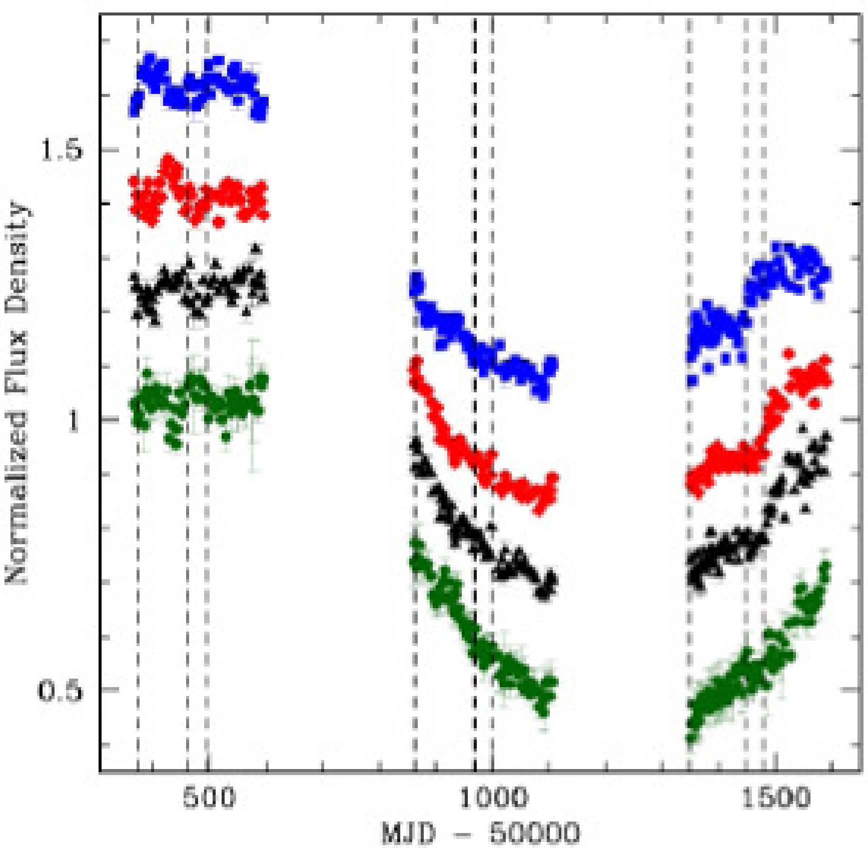
58 strong lensing events from SLACS
Sloan velocity dispersions

Guimarães & Sodré 2009

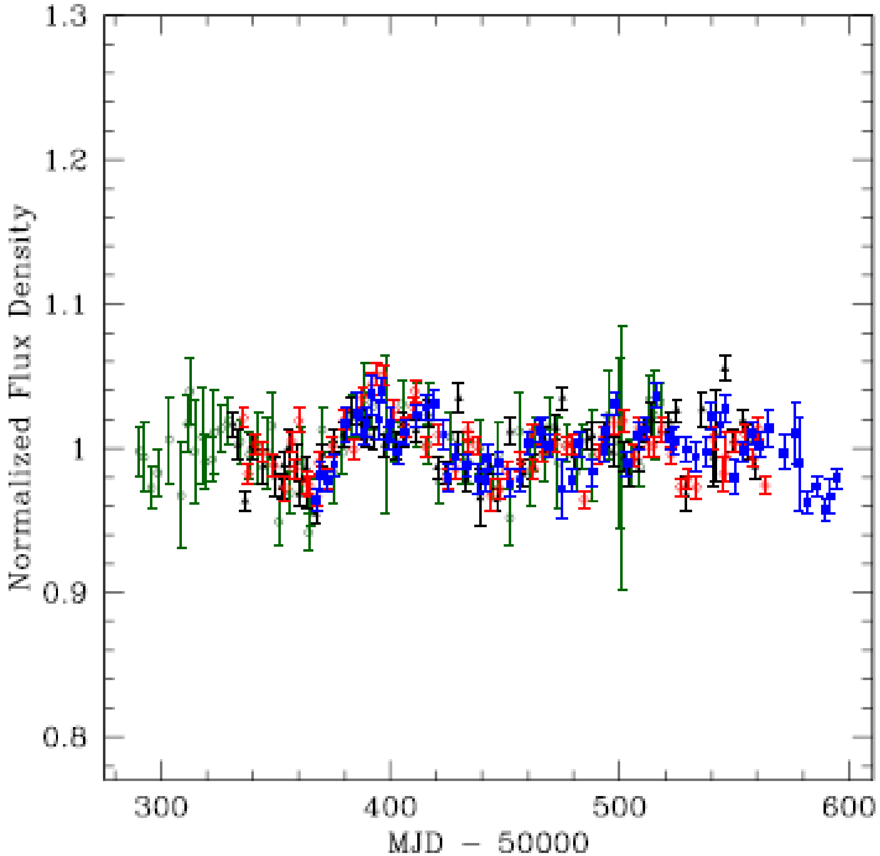
B1608+656 (Fassnacht et al. 2002)



Time Delay



time delays and magnifications
adjusted image fluxes



time (days)

Time Delay

light **travel time** for each image relative to a fiducial unperturbed ray

$$\tau(\theta) = \frac{D_d D_s}{c D_{ds}} \left[\frac{1}{2} (\theta - \beta)^2 - \Psi(\theta) \right]$$

time delay between two images, assuming a lens model (SIS), $\Psi = b\theta$

$$\Delta t_{SIS} = \tau_B - \tau_A = \frac{1}{2} \frac{D_d D_s}{c D_{ds}} (\theta_A^2 - \theta_B^2)$$

The time scales as H_0^{-1}

because of the scalings of the distances

HUBBLE CONSTANT FROM EACH LENS SYSTEM

Lens Name	h (1 σ Range)
B0218+357	0.21 (. . .)
HE 0435−1223	1.02 (0.70–1.39)
RX J0911+0551	0.96 (0.75–1.21)
SBS 0909+532	0.84 (0.47–)
FBQ 0951+2635	0.67 (0.56–0.81)
Q0957+561	0.99 (0.82–1.17)
HE 1104−1805	1.04 (0.92–1.22)
PG 1115+080	0.66 (0.49–0.84)
RX J1131−1231	0.79 (0.59–1.03)
B1422+231	0.16 (–0.36)
SBS 1520+530	0.53 (0.46–0.61)
B1600+434	0.65 (0.54–0.77)
B1608+656	0.89 (0.77–1.20)
SDSS J1650+4251	0.53 (0.44–0.63)
PKS 1830−211	0.88 (0.58–)
HE 2149−2745	0.69 (0.57–0.82)
All	0.70 (0.68–0.73)

Oguri et al. 2007

method advantages:

- measures expansion rate directly at high redshifts (negligeble peculiar velocities)
- does not depend on distance ladders nor standard candle

disadvantage: needs lens model

Statistical Lensing

Observables:

- lens number (relates to cosmological volume and structure formation)
- image separation distribution (relates to halo mass function)

Defining quantities:

- lens cross section

$$\sigma = \pi(Einstein\ radius)^2$$

- optical depth (probability that a source bean hits a lens)

$$d\tau = n_l \sigma \frac{cdt}{dz_l} dz_l$$

$$\tau = \frac{3}{2}\Omega_L \frac{H_0}{c} \int \frac{D_l D_{ls}}{D_s} \frac{(1-z_l)^2}{H(z_l)} dz_l$$

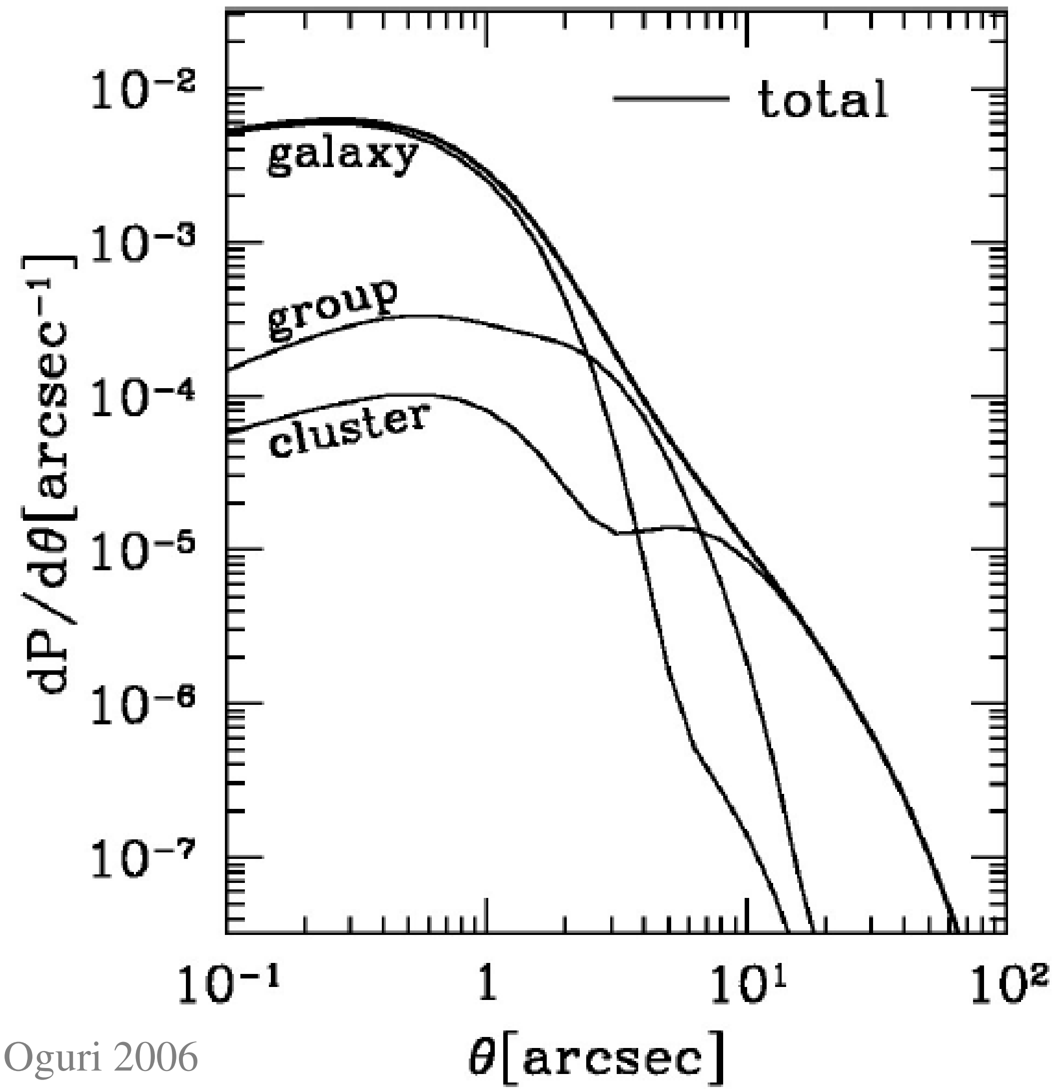
comoving density of lenses

lens density parameter

cosmological dependence

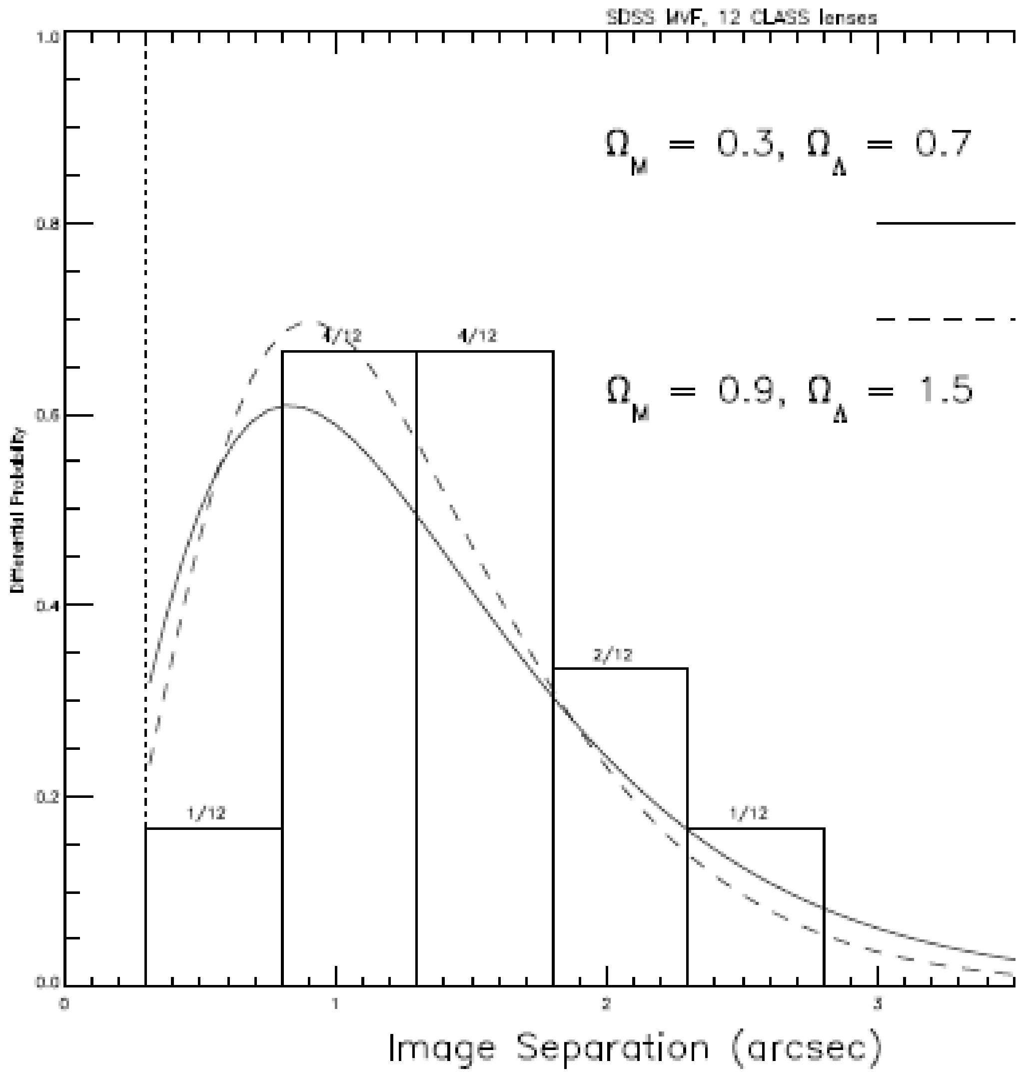
Distribution of lens image separations

predicted (using halo model)



Oguri 2006

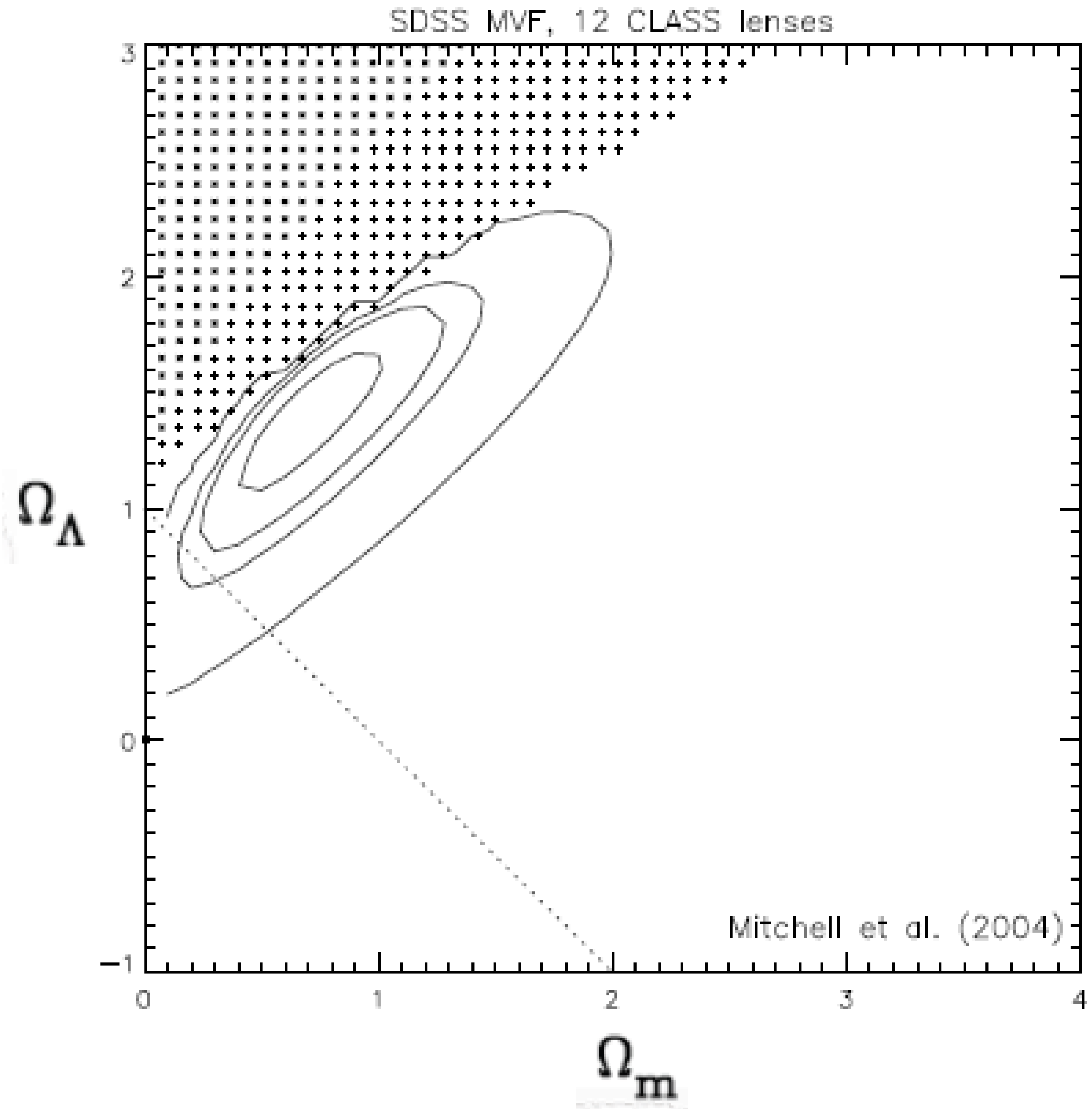
measured (12 CLASS lenses)



Mitchell et al. 2004

⟶ maps halo mass function

Cosmography

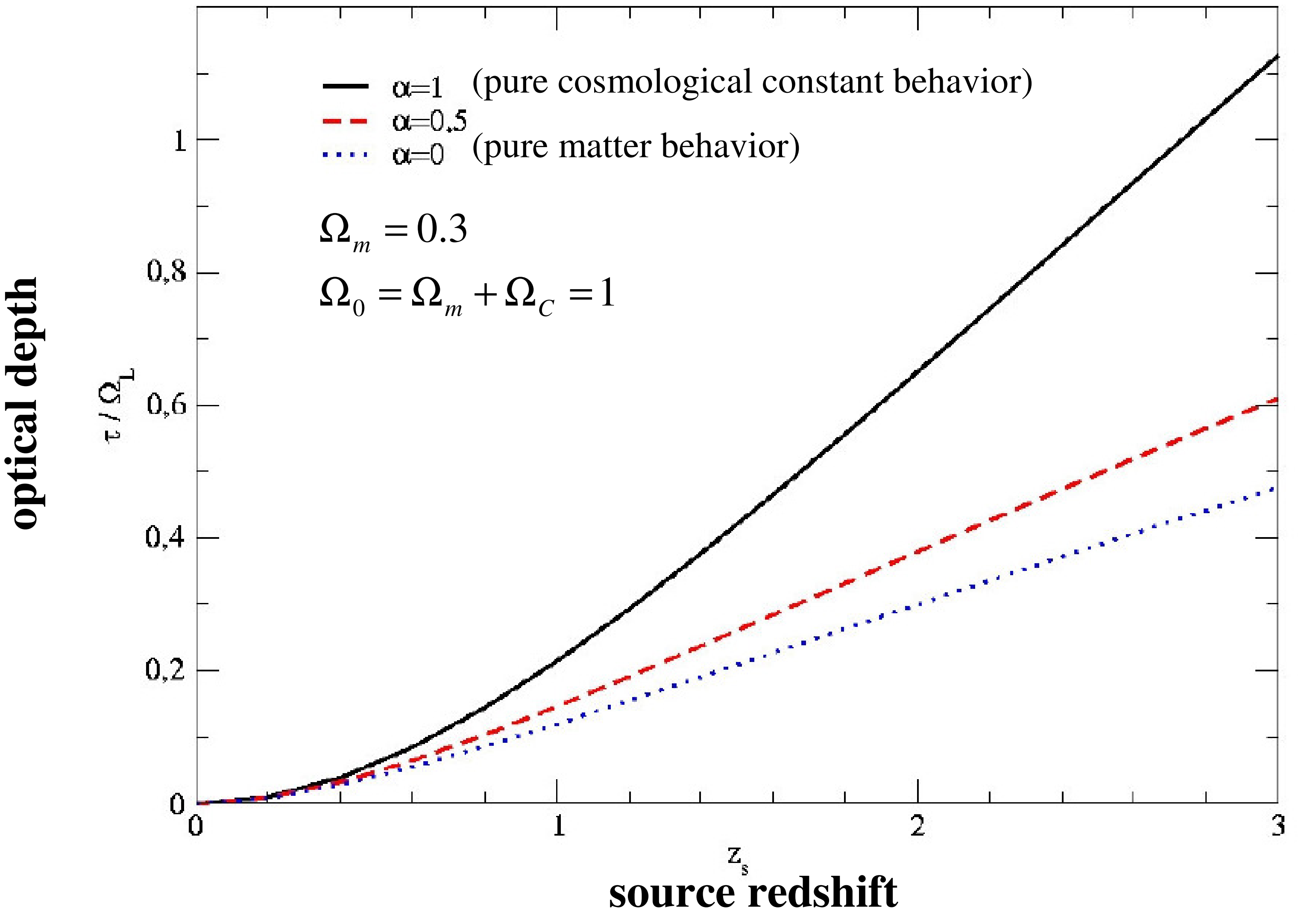


Likelihood functions for the cosmological model using the velocity function of galaxies measured from the SDSS survey and a sample of 12 CLASS lenses. The contours show the 68, 90, 95 and 99% confidence intervals on the cosmological model. In the shaded regions the cosmological distances either become imaginary or there is no big bang

Optical Depth for a Chaplygin gas model

$$\begin{cases} p_C = -\alpha \rho_{C0} \left(\dfrac{\rho_{C0}}{\rho_C} \right)^{\alpha} \\ \rho_C = \rho_{C0} \left[\alpha + (1-\alpha)\, a^{-3(1+\alpha)} \right]^{1/(1+\alpha)} \end{cases}$$

$$H(a) = H_0 \left\{ \Omega_m a^{-3} + (1-\Omega_m) \left[\alpha + (1-\alpha) a^{-3(1+\alpha)} \right]^{1/(1+\alpha)} \right\}^{1/2}$$



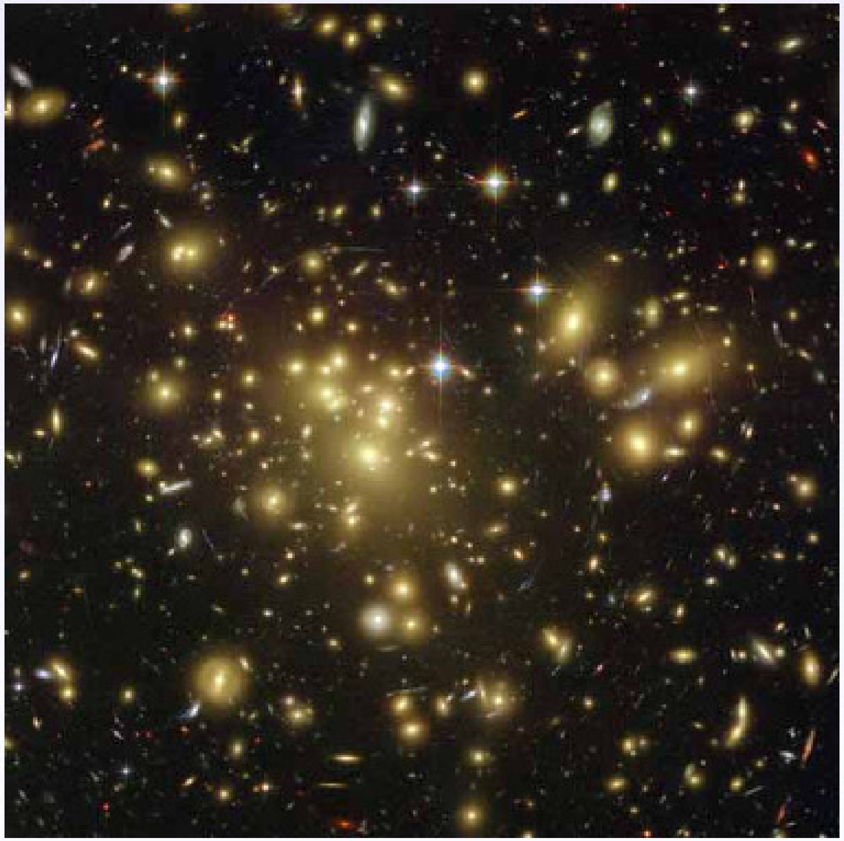
Guimarães & Lima

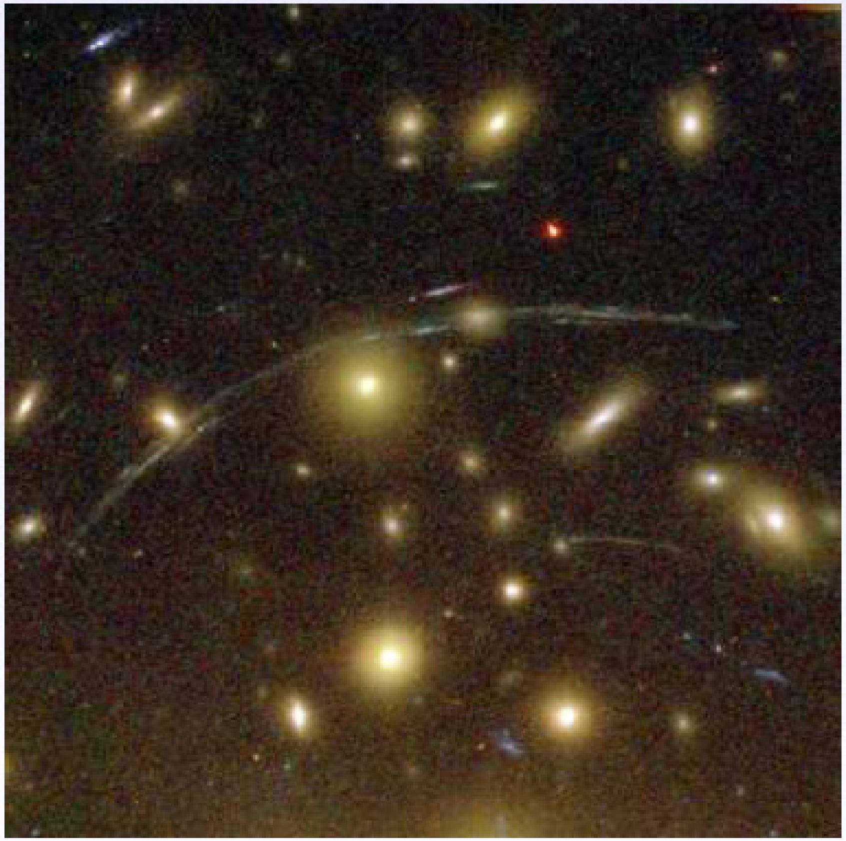
Other areas of application (non exhaustive)

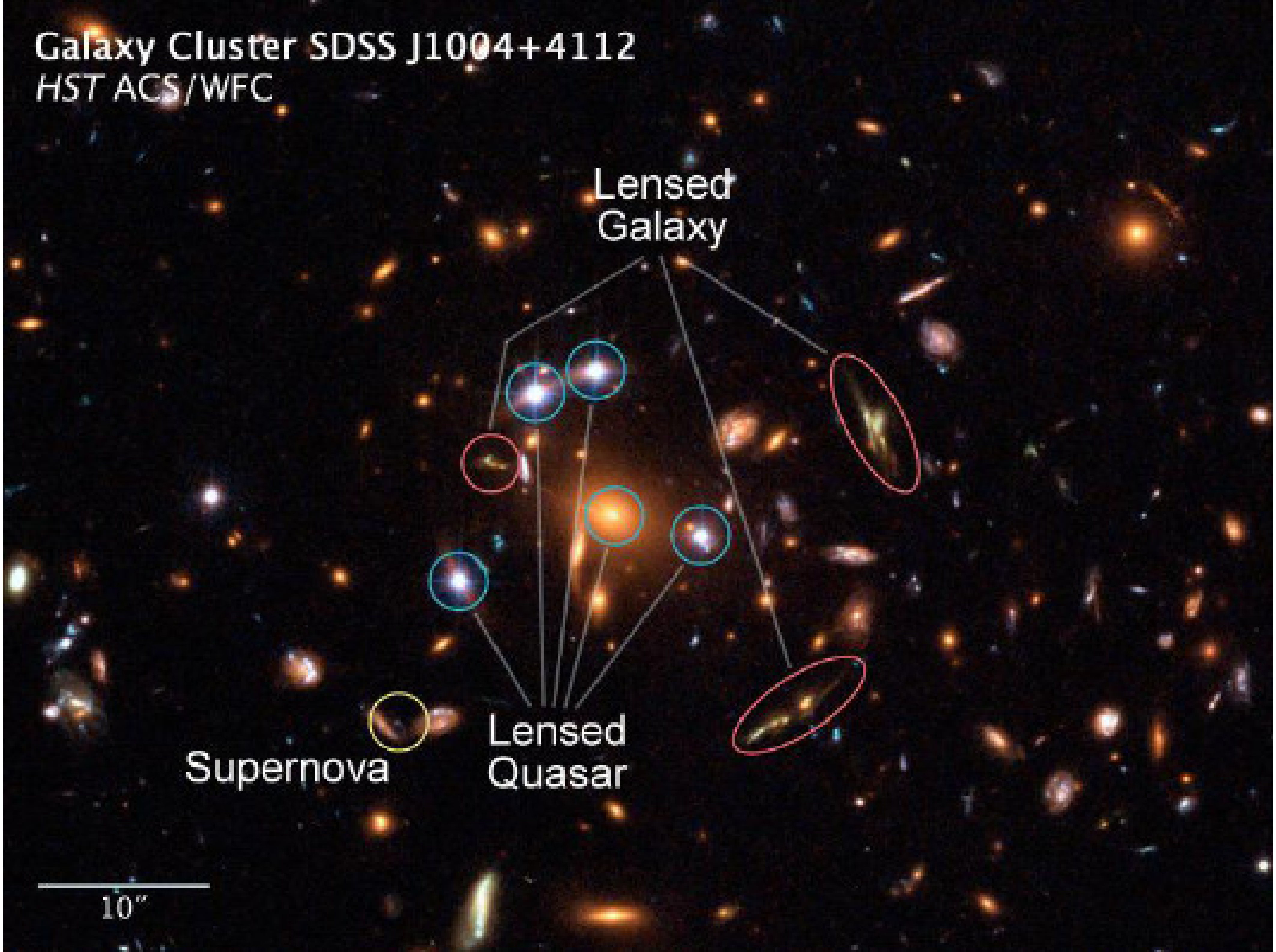
- cluster lensing (giant arcs statistics, gravitational telescopes)

- supernovae lensing

- microlensing (planetary discovery, galactic substructure, MACHOS)






Galaxy Cluster SDSS J1004+4112
HST ACS/WFC
Lensed
Galaxy
Lensed
Quasar
Supernova
10″