Gravitational Lensing: from Planets to the Large Scale Structure of the Universe

Martín Makler
ICAS/IFICI/CONICET&UNSAM & CBPF

+ Renan Alves, João França, Elizabeth Gonzalez, Arthur Mesquita, Giulya Souza, Eduardo Valadão, Anibal Varela

FOF 2022

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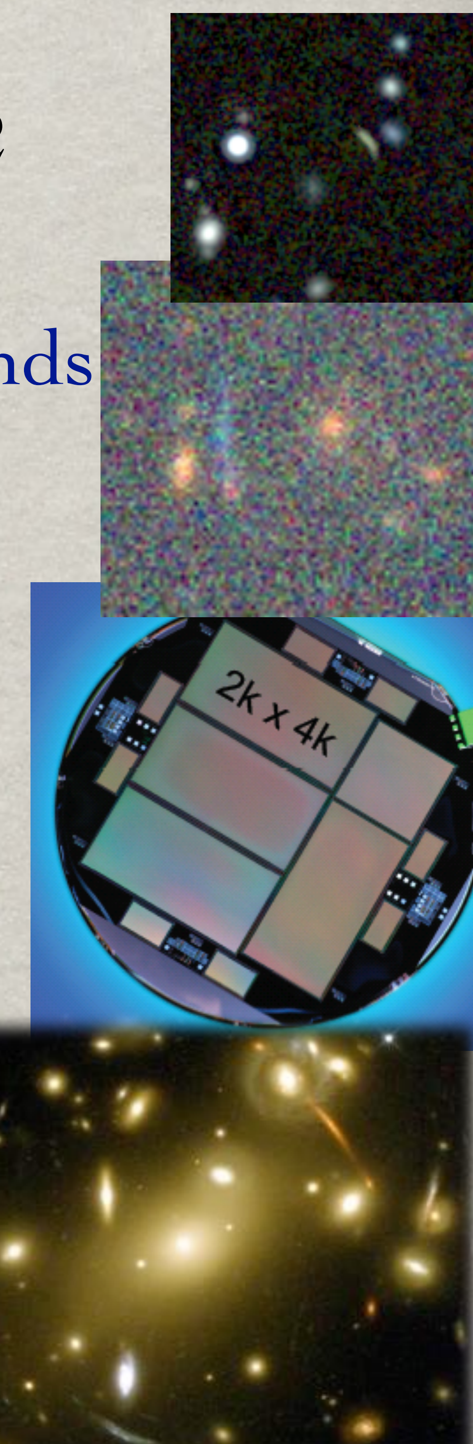
OAC Observatorio Astronómico de Córdoba

UNC Universidad Nacional de Córdoba

IATE

Outline

- Part I: Tuesday, April 19th, 14:30-15:15
  - Introduction to gravitational lensing and basic formalism
  - getting set with https://github.com/CosmoObs/FoF_lensing_2022
- Part II: 15:20 - 16:20
  - Microlensing: from planet detection to Dark Matter bounds
  - Light Curve, MuLensModel, and Anibal/DM notebooks
- Part III: Wednesday, April 20th, 14:30-15:15
  - Strong Lensing
  - PaintArcs, Lenstronomy and PyAutoLens notebooks
- Part IV: 15:20 - 16:20
  - Weak lensing
  - Collosus cluster profile fitting notebook



Part I
Introduction to Gravitational Lensing

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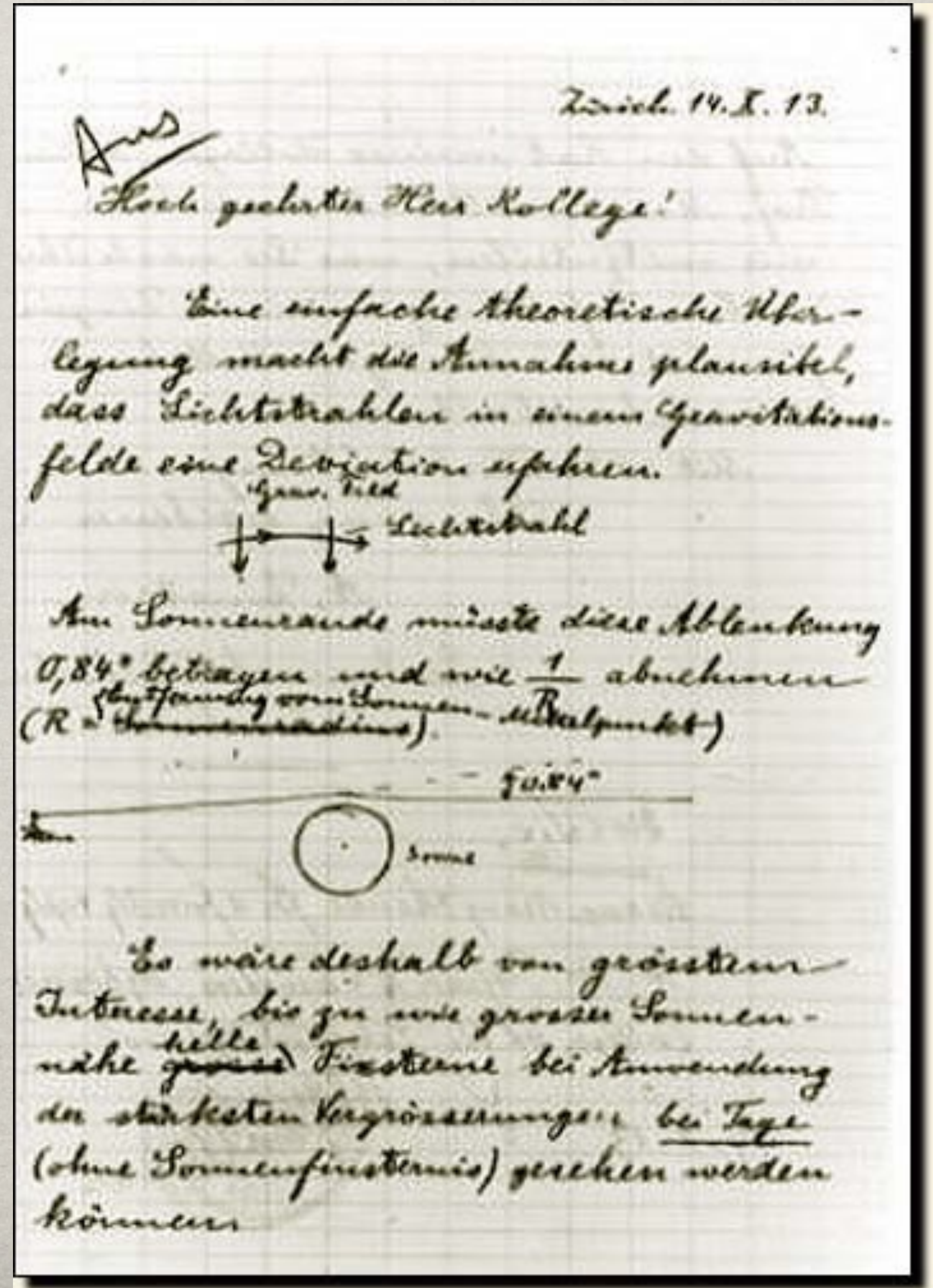
IATE

Detection of Light Deflection by Gravity

- 1907: equivalence principle

- 1911-1912: Einstein predicts light deflection and gravitational lensing effects

  Urges observational tests



Ans

Zürich. 14.X.13.

Hoch geehrter Herr Kollege!

Eine einfache theoretische Überlegung macht die Annahme plausibel, dass Lichtstrahlen in einem Gravitationsfelde eine Deviation erfahren.

Grav. Feld

Lichtstrahl

Am Sonnenrande müsste diese Ablenkung 0,84" betragen und wie $\frac{1}{R}$ abnehmen (R = ~~Sonnenradius~~ Entfernung vom Sonnen-Mittelpunkt).

0,84"

Sonne

Es wäre deshalb von grösstem Interesse, bis zu wie grosser Sonnennähe ~~grosse~~ helle Fixsterne bei Anwendung der stärksten Vergrösserungen bei Tage (ohne Sonnenfinsternis) gesehen werden können.

Zürich. 14. X. 13.

Aus

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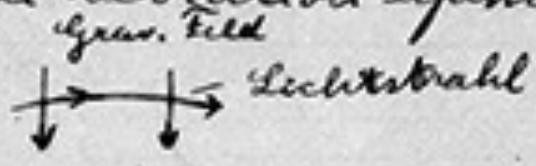

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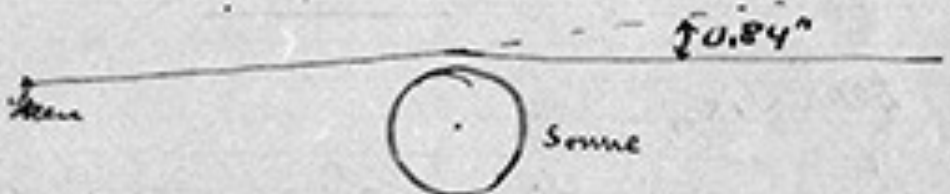


Es wäre deshalb von grösstem Interesse, bis zu wie grosser Sonnennähe ~~grosse~~ helle Fixsterne bei Anwendung der stärksten Vergrösserungen bei Tage (ohne Sonnenfinsternis) gesehen werden können.

Auf den Rat meines Kollegen, d. Herrn Prof. Maurer bitte ich Sie deshalb, mir mitzuteilen, was Sie nach Ihrer reichen Erfahrung in diesen Dingen für mit den heutigen Mitteln erreichbar halten.

Mit aller Hochachtung

Ihr ganz ergebener

A. Einstein

Technische Hochschule Zürich.

Dear Sir,

Many, many thanks for a friendly reply to Mr Professor Dr Einstein, my honorable Collegue of the Polytechnical School.

Yours truly

Maurer

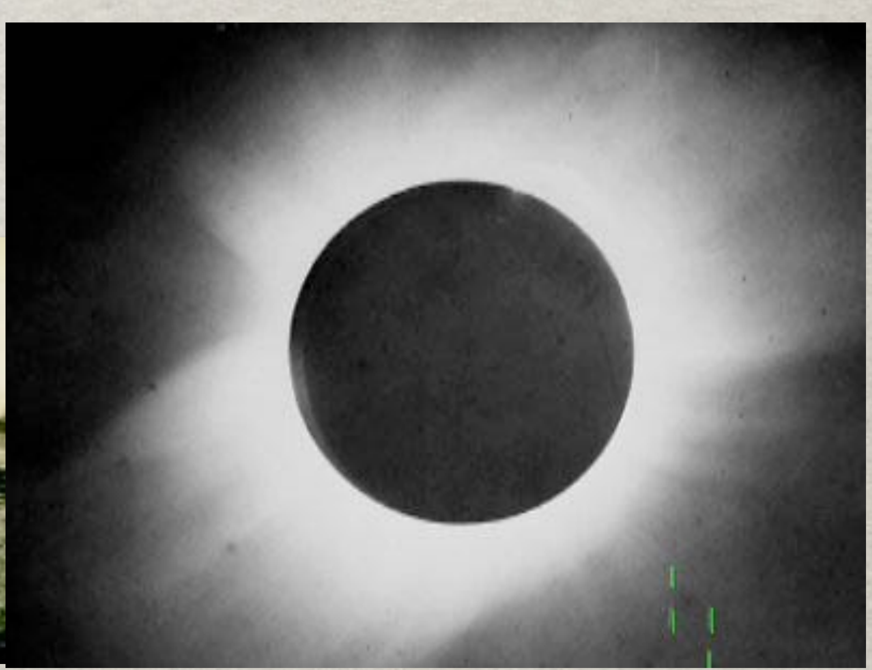
14. X. 13

Detection of Light Deflection by Gravity

- 1912: Argentinean expedition to observe solar eclipse in Brazil
  - Got rained out

Detection of Light Deflection by Gravity

- 1912: OAC expedition to observe solar eclipse in Brazil
  - Got rained out
- 1914: Erwin Freundlich's expedition to observe an eclipse in Crimea
  - Detained because WWI break up
- 1919: Sobral (Brazil)
  - Detection of the bending of light (better than Prince Island)



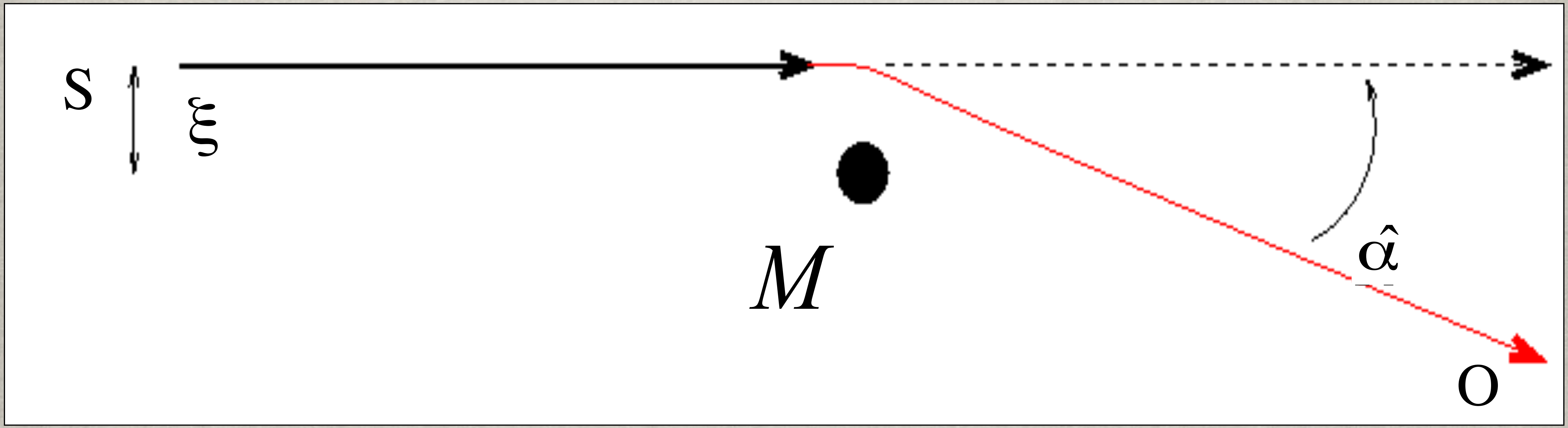
“[illegible] by
[illegible] sky of Brazil”

Bending of light by gravity

Null geodesic,
Fermat principle

$$ds^2 = \left(1 + \frac{2\phi}{c^2}\right) c^2 dt^2 - \left(1 - \frac{2\phi}{c^2}\right) d\sigma^2$$

$$\frac{d\sigma}{dt} := c' = \sqrt{\frac{1 + 2\phi/c^2}{1 - 2\phi/c^2}} \simeq c\left(1 + \frac{2\phi}{c^2}\right)$$



Deflection angle (point source): $\hat{\alpha} = \frac{4\,G\,M}{c^2\,\xi}$ $\left(\hat{\alpha}_N = \frac{2\,G\,M}{c^2\,\xi}\right)$

Achromatic

Brief History

- Einstein 1911-12: Einstein's predictions and the first intent of observation
- Sobral 1919: light deflection by gravity
- Chwolson 1924: first paper on gravitational lensing
- Einstein 1936: lensing by stars

"Of course, there is not much hope of observing this phenomenon directly"

Therefore, there is no great chance of observing this phenomenon, even if dazzling by the light of the much nearer star B is disregarded. This apparent amplification of q by the lens-like action of the star B is a most curious effect, not so much for its becoming infinite, with x vanishing, but since with increasing distance D of the observer not only does it not decrease, but even increases proportionally to $\sqrt{D}$.

ALBERT EINSTEIN

INSTITUTE FOR ADVANCED STUDY,
PRINCETON, N. J.

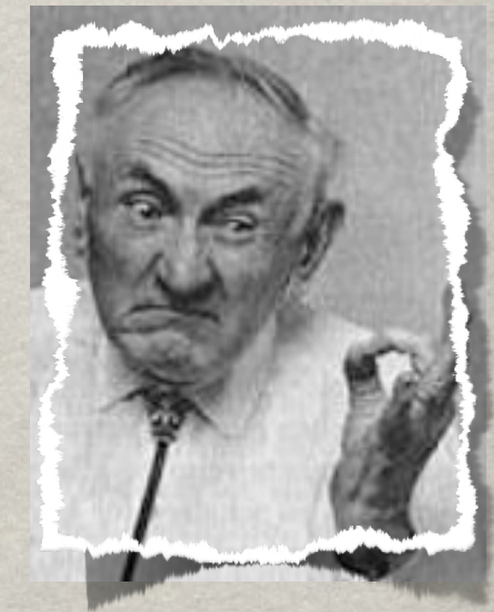
Brief History

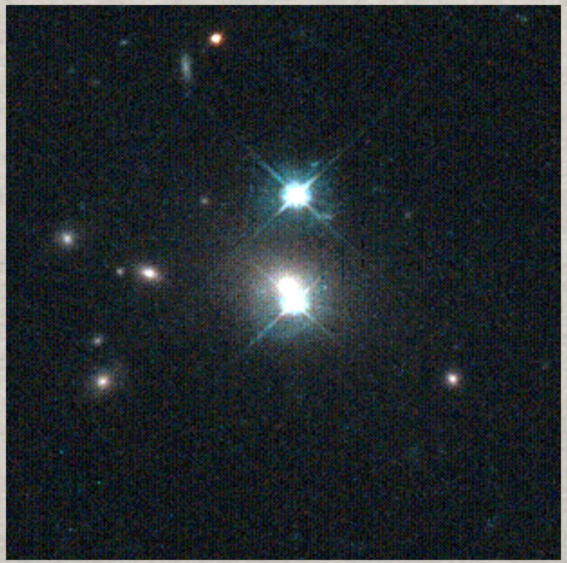
- Einstein 1911-12: Einstein's predictions and the first intent of observation
- Sobral 1919: light deflection by gravity
- Chwolson 1924: first paper on gravitational lensing
- Einstein 1936: lensing by stars

"Of course, there is not much hope of observing this phenomenon directly"

- Zwicky 1937: optimistic

"The probability that nebulae which act as gravitational lenses will be found becomes practically a certainty"





- Walsh, Carswell, Weymann 1979: discovery of the first lensed quasar (double image of QSO 0957+561)

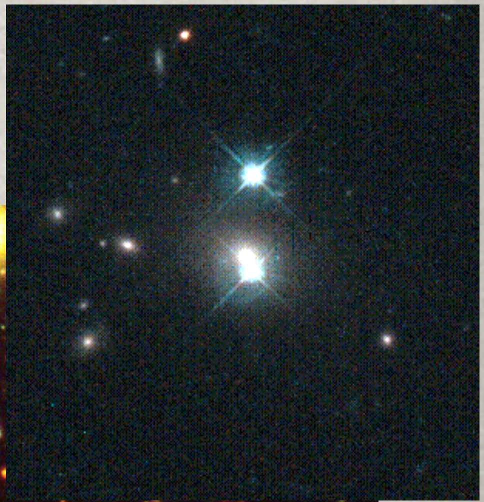
Discoveries

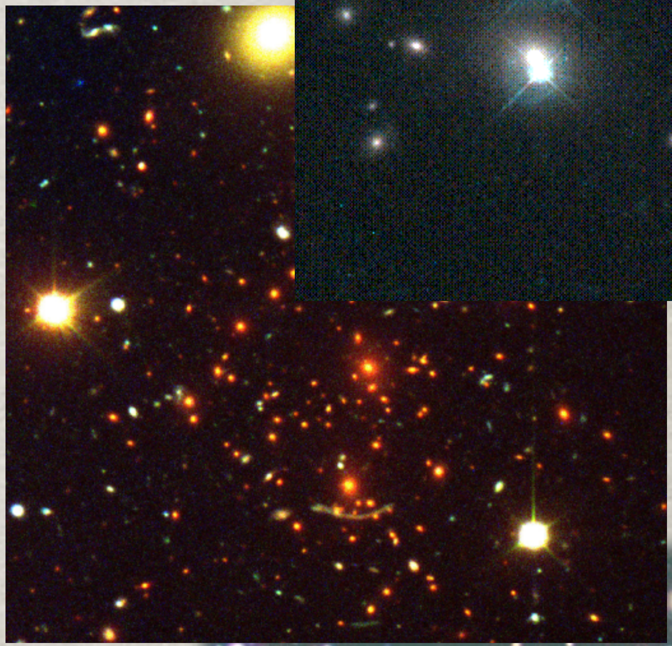
- Sobral 1919: light deflection
- Walsh, Carswell, Weymann 1979: first lensed quasar (double image of QSO 0957+561)
- Roger Lynds e Vahe Petrosian 1986, Soucail, Fort, & Picat 1987: discovery of gravitational arcs

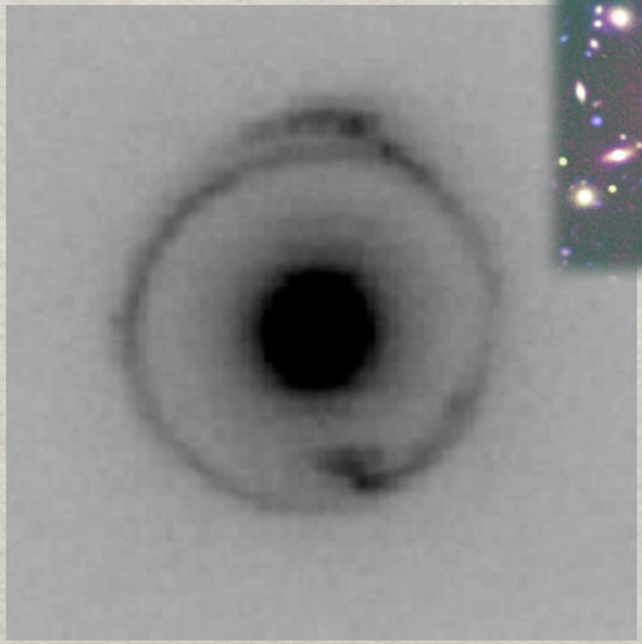
arcs in A370, A2218, CL2244-02,

not clearly predicted...

- Hewitt, et al. 1988: Einstein ring (radio)
- Irwin et al. 1989: Quasar microlensing
- EROS & MACHO collaborations, 1993:
  first stellar microlensing
- Bond et al., 2003: first planet detection
  - ~2 Jupiter mass planets @ ~3 AU
- 21st century: weak lensing in all scales
- lensing of supernovae, individual stars in galaxies, etc.



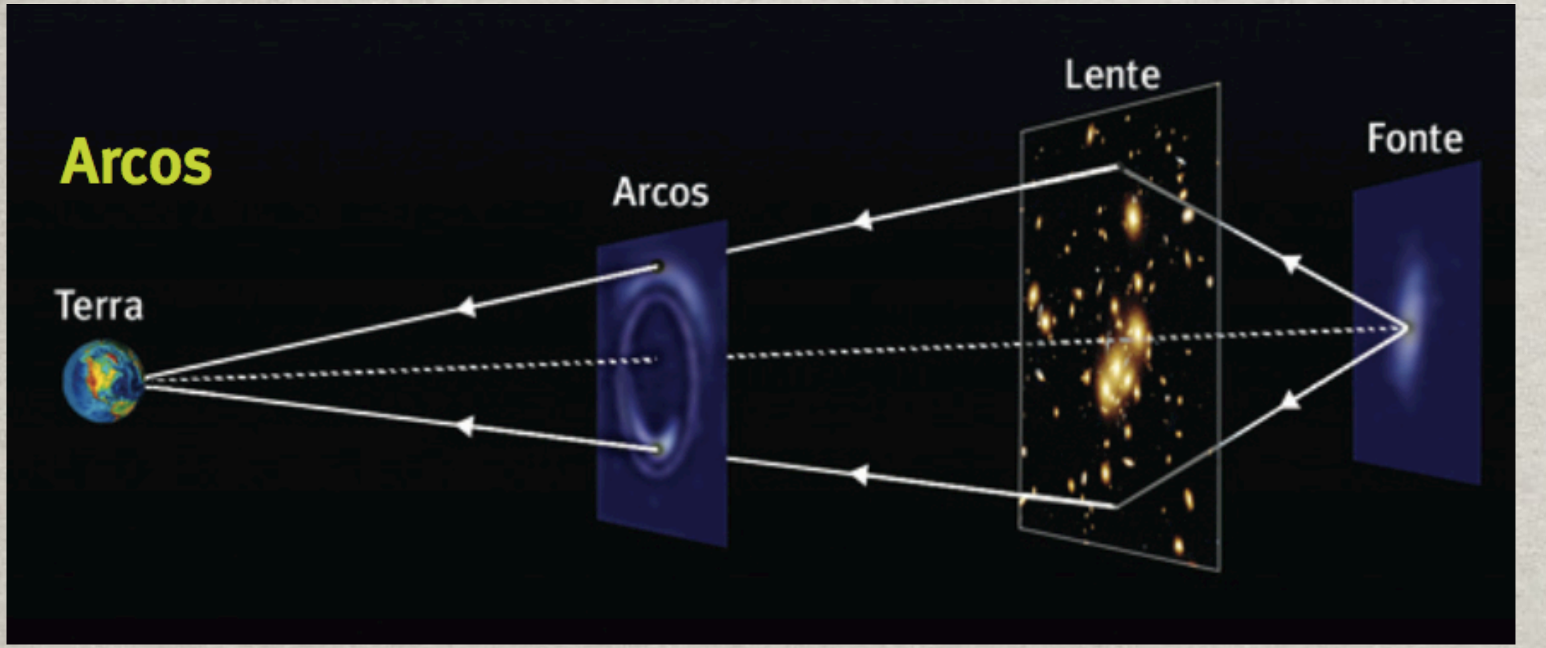




Gravitational Lensing Effects

- Multiple images, distortions, magnifications, time delays
- Null geodesics
  - surface brightness conservation
  - achromatic

  → Gravitational telescopes
  - Sensitive to all matter: planets, dark matter
    unique probe of structure in the universe, from galaxies to LSS
  - Provide complementary cosmological probes and tests of gravity

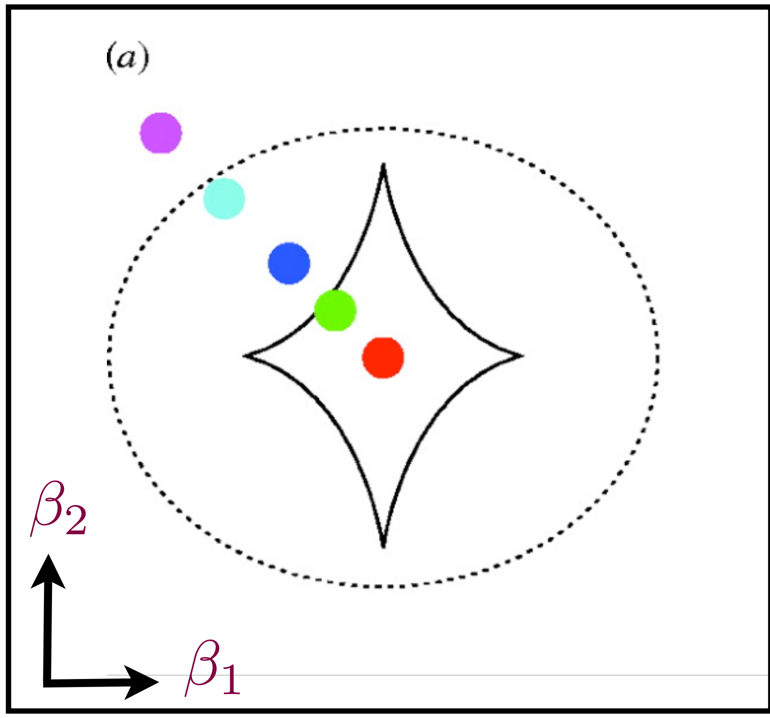


strong lensing, **weak gravity**

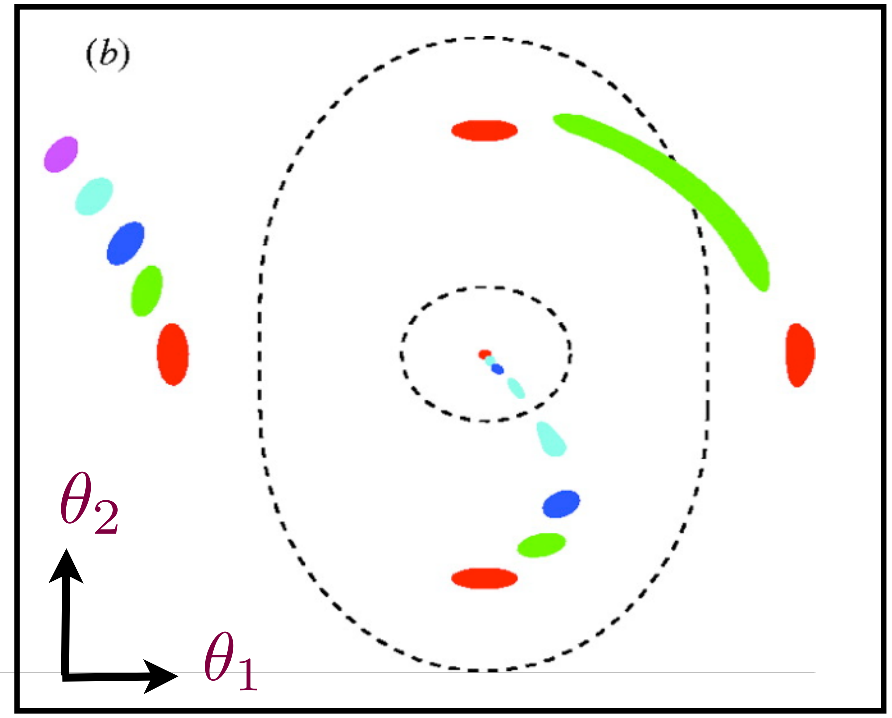
Gravitational arcs

Geometry of lensing by a single plane

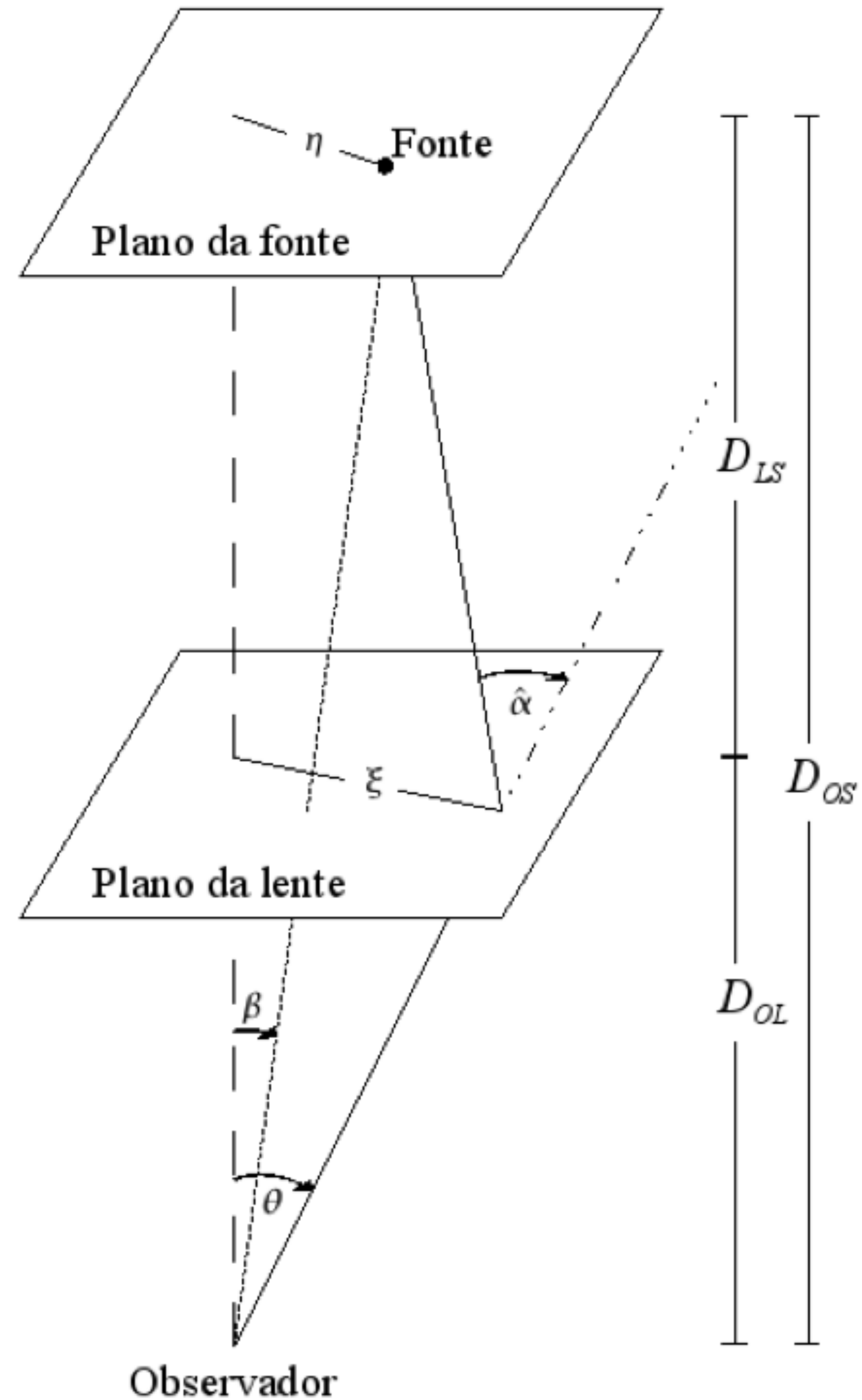
(assumptions: weak field, single plane, geometrical optics)



Source plane

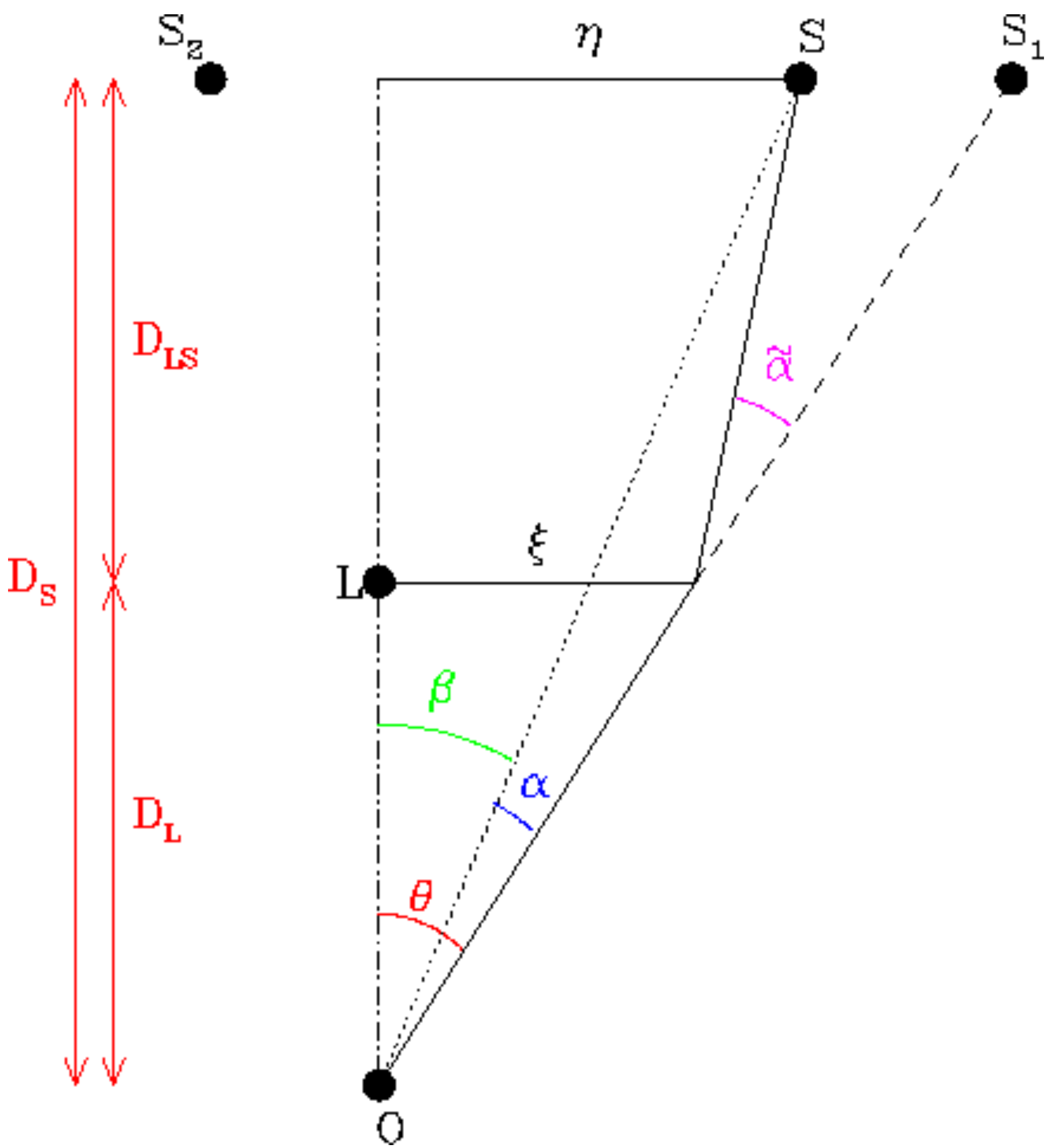


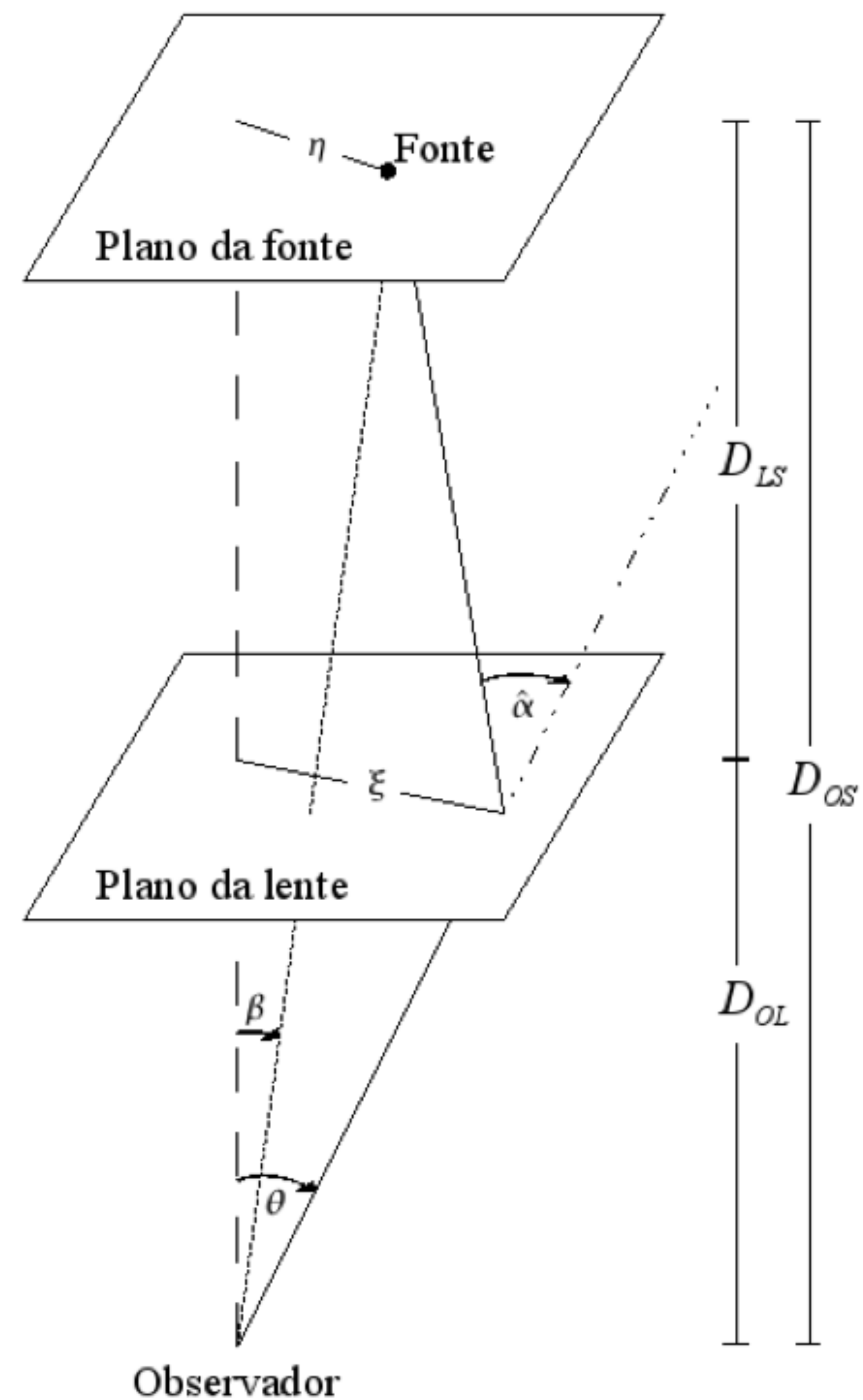
Lens plane



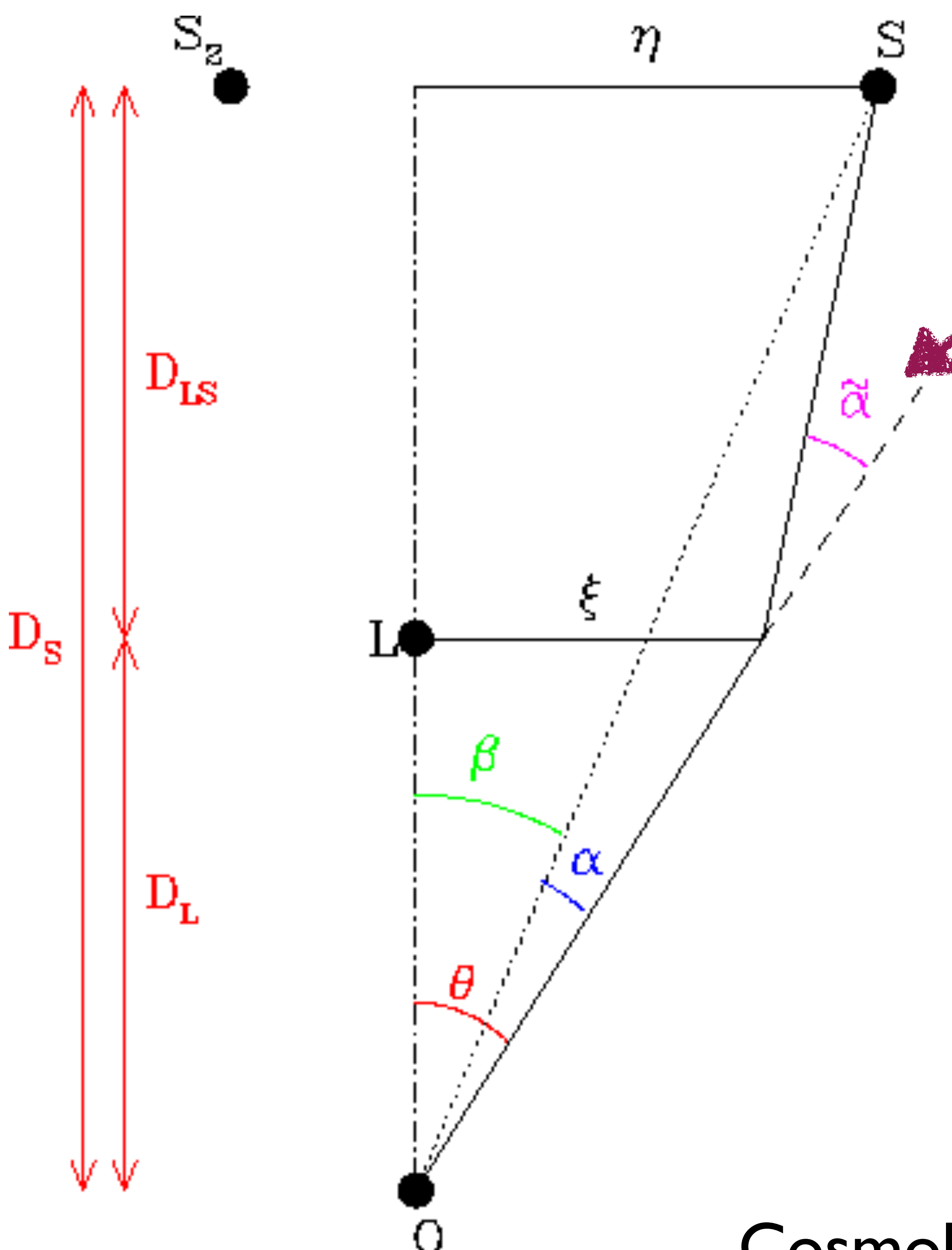
Physical coordinates (distance)	η	ξ
Angular coordinates	β	θ
dimensionless coordinates	y	x

Geometry of lensing by a single plane





The Lens Equation



The physics is in here

$$\vec{\beta} D_{OS} = \vec{\theta} D_{OS} - \hat{\vec{\alpha}} D_{LS} \left(\vec{\theta} \right)$$

Reduced deflection angle

$$\vec{\alpha} = \hat{\vec{\alpha}} \frac{D_{LS}}{D_{OS}}$$

Lens equation

$$\vec{\beta} = \vec{\theta} - \vec{\alpha} \left(\vec{\theta} \right)$$

Cosmology: angular diameter distances

Lensing Mapping

- image → source mapping:

$$\frac{\partial \beta_i}{\partial \theta_j} = \delta_{ij} - \frac{\partial^2 \Psi(\vec{\theta})}{\partial \theta_i \partial \theta_j}$$

- single plane lensing

$$\Psi = \frac{2}{c^2} \frac{D_{LS}}{D_{OS} D_{OL}} \int \phi(\xi, z) dz$$

gravitational potential
(astrophysics)

cosmological distances
(cosmology)

$$D_{LS} = D_A(z_L, z_S)\ldots$$

- eigenvalues:

$$\mu_1 = \frac{1}{1-\kappa+\gamma}, \mu_2 = \frac{1}{1-\kappa-\gamma}$$

- local magnification and axial ratio:

$$\mu = \mu_1 \, \mu_2$$

$$r = \left| \frac{\mu_1}{\mu_2} \right|$$

Lensing Mapping

- image → source mapping:

$$\frac{\partial\beta_i}{\partial\theta_j} = \delta_{ij} - \frac{\partial^2\Psi(\vec{\theta})}{\partial\theta_i\partial\theta_j}$$

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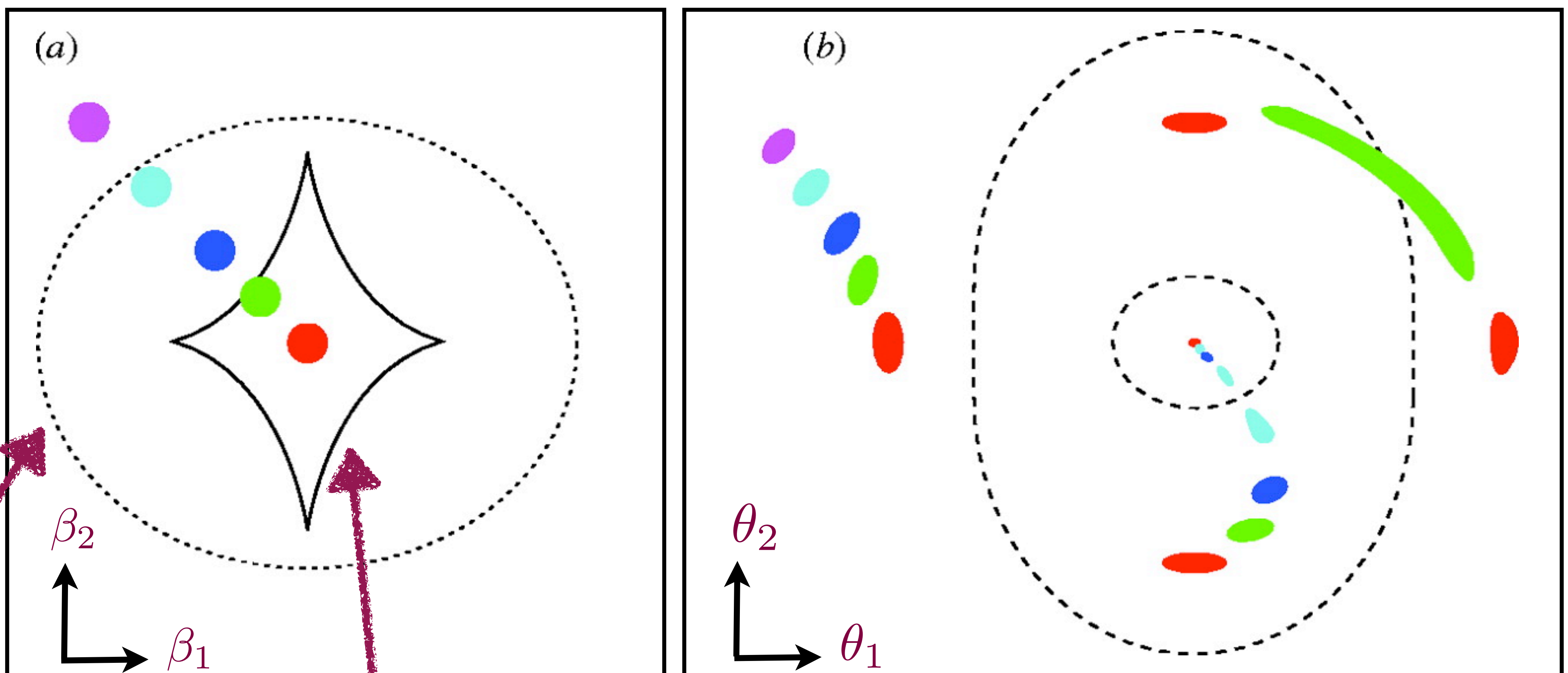
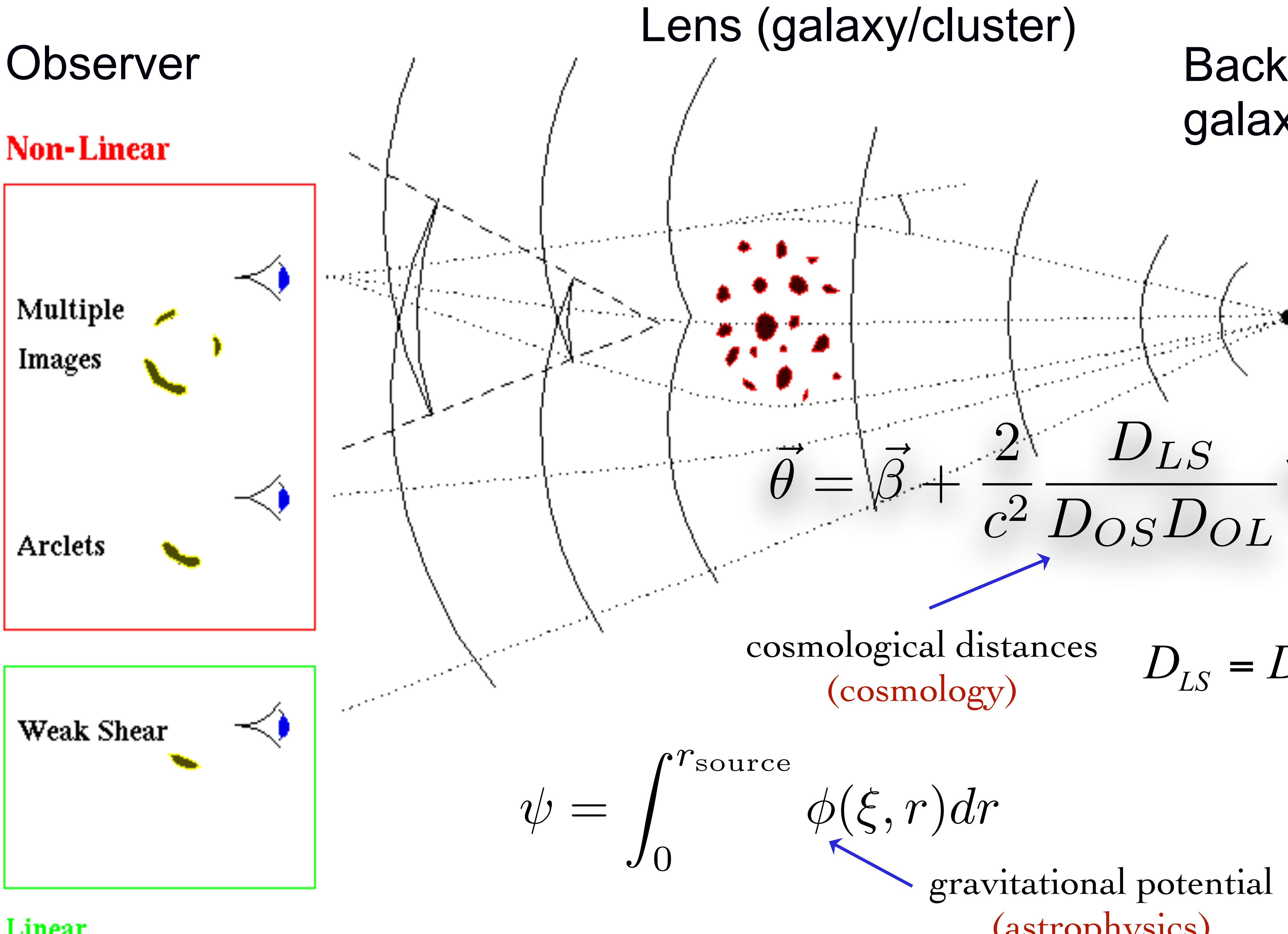


caustics: infinite magnification

Lens/image

Weak and Strong Lensing Effects



$$\vec{\theta} = \vec{\beta} + \frac{2}{c^2}\frac{D_{LS}}{D_{OS}D_{OL}}\nabla_\theta \psi\left(\vec{\theta}\right)$$

cosmological distances
(cosmology)

$$D_{LS} = D_A\left(z_L, z_S\right)\ldots$$

$$\psi = \int_0^{r_{\rm source}} \phi(\xi, r)dr$$

gravitational potential
(astrophysics)

A plethora of Lensing phenomena

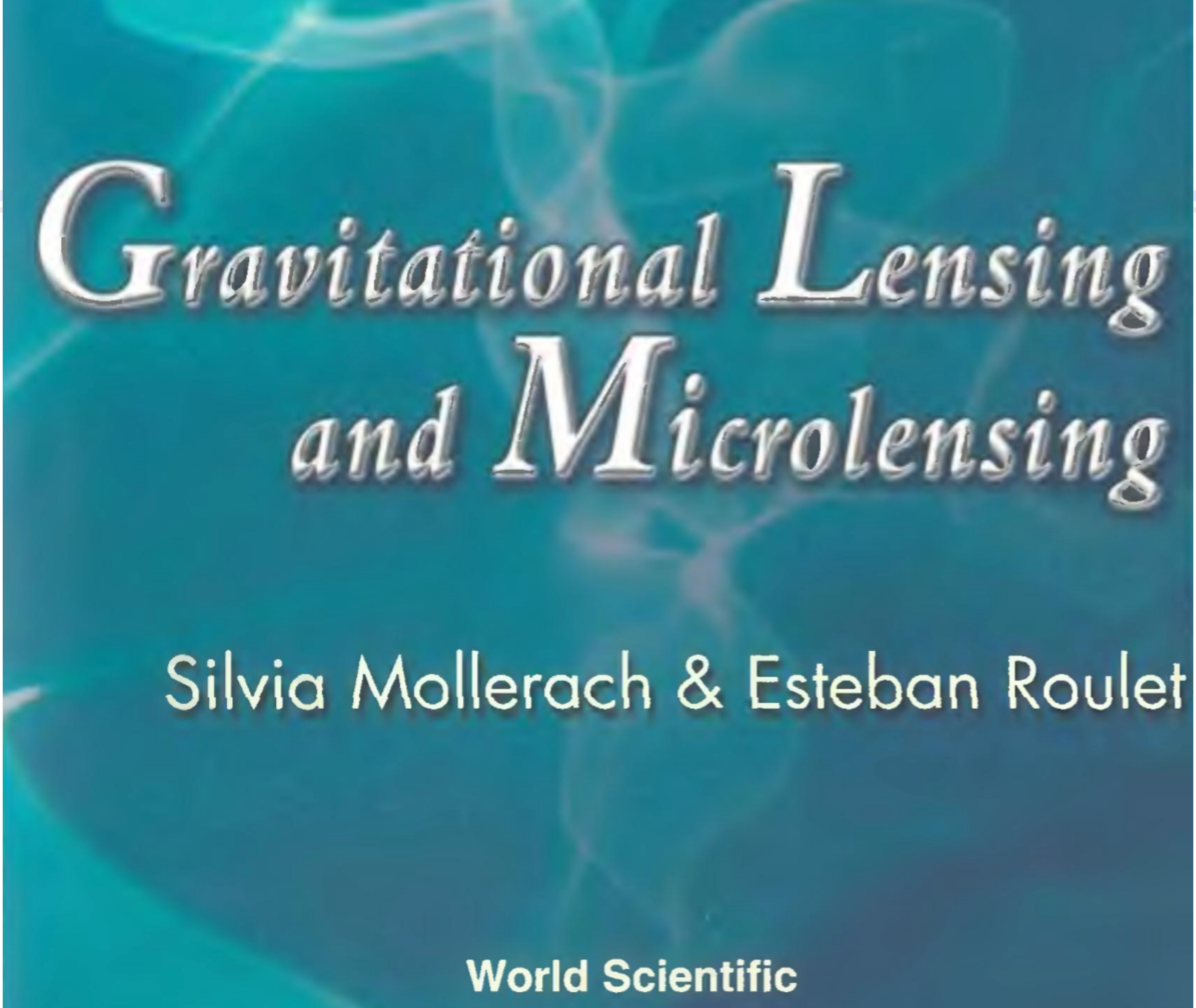
Strength

- Strong lensing
  - Strong magnifications
  - Multiple images
  - Distortions
    - Arcs, Rings
- Weak Lensing
  - Small twist
  - Small magnification
  - Detected statistically

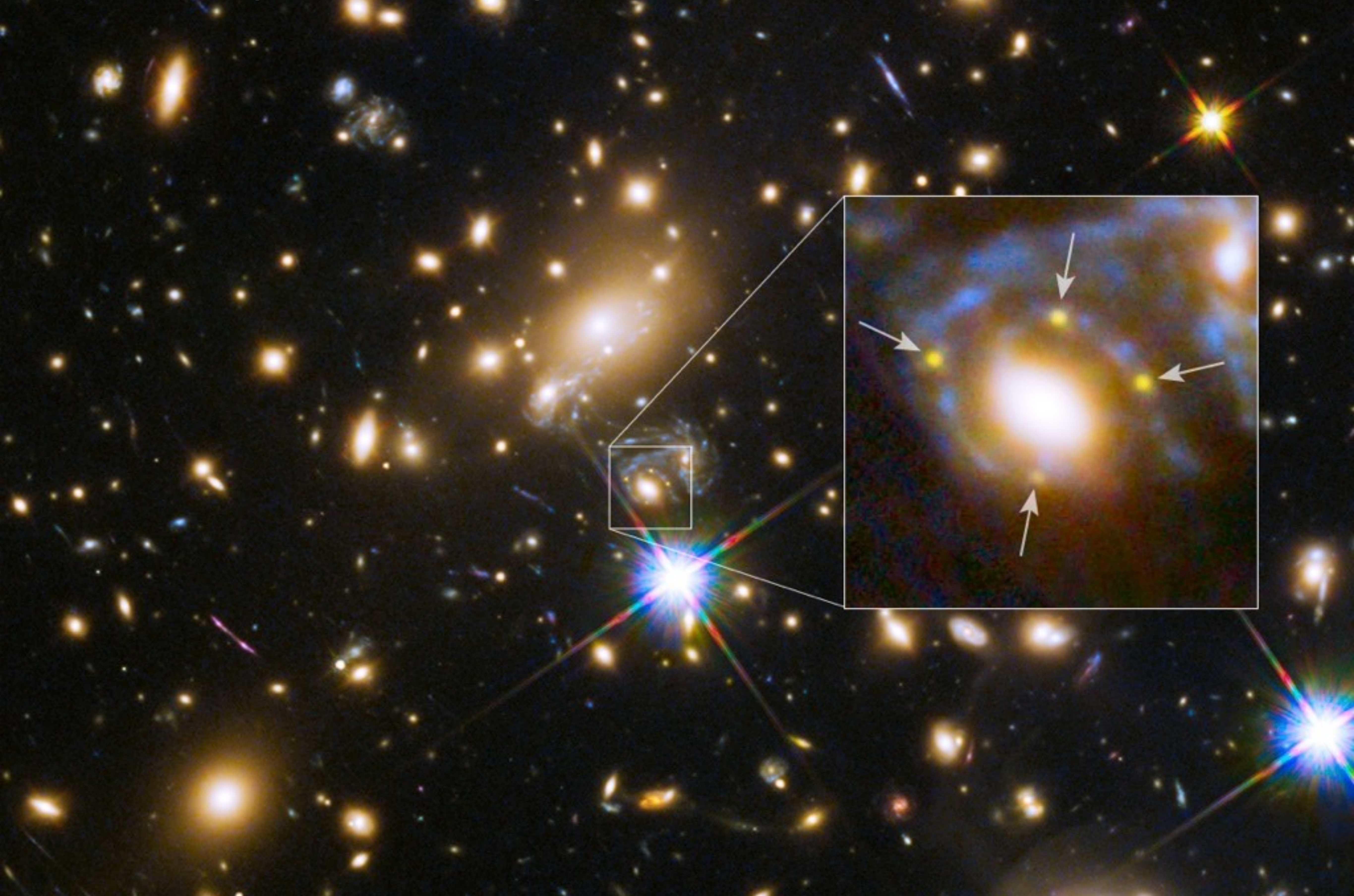
Angular scale

- Micro-lensing
  - MACHOS
  - Planetary search
- Micro and mili-lensing
  - Quasars
- “Macro-lensing”
  - Galaxies
  - Clusters
  - Large-scale structure

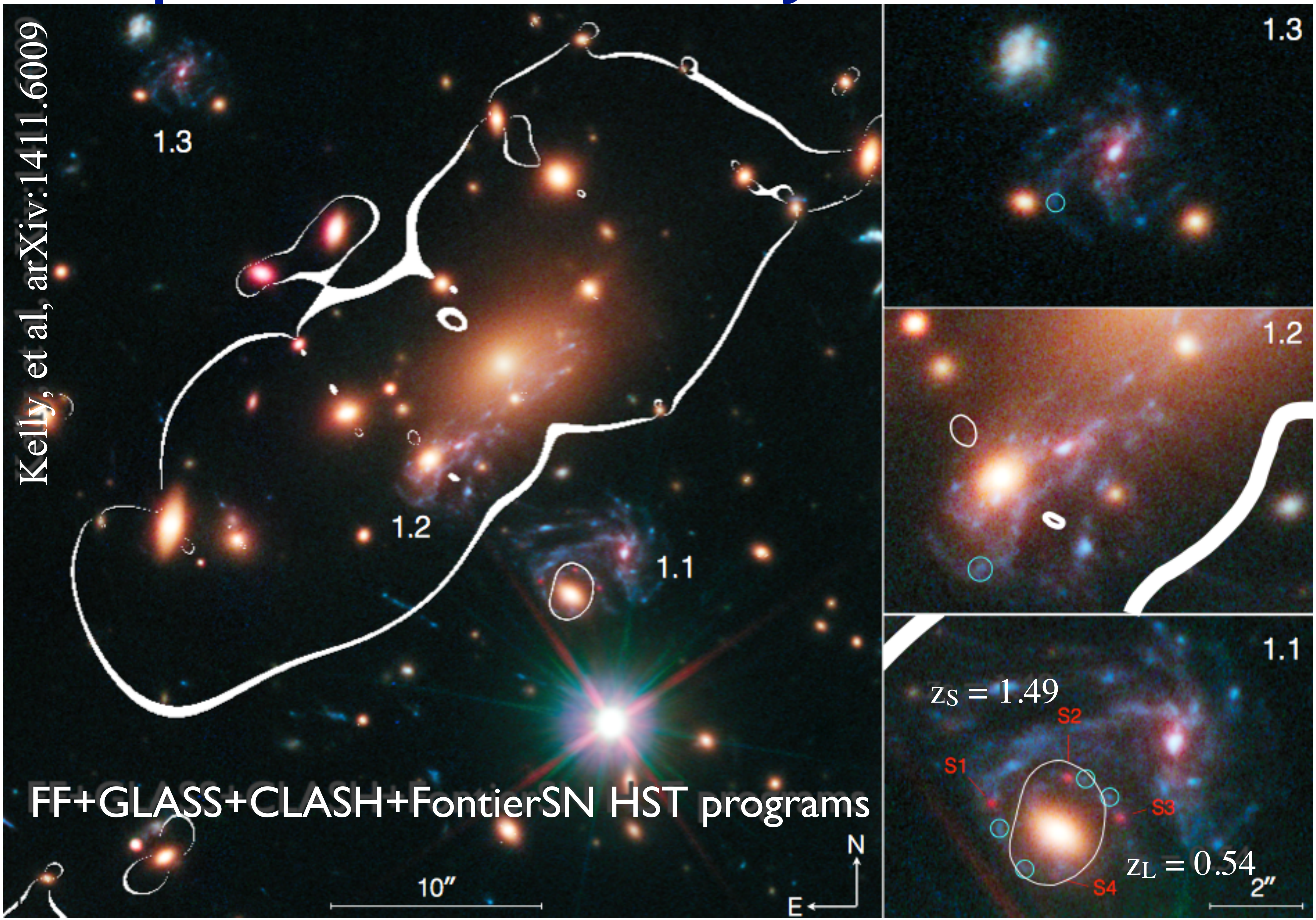
+ astrometric microlensing, black-hole shadows, retrolensing, femtolensing, lensing of gravitational waves….


Gravitational Lensing
and Microlensing
Silvia Mollerach & Esteban Roulet
World Scientific

Strong Lensing and Scientific Method



Supernova in MACS J1149.6+2223



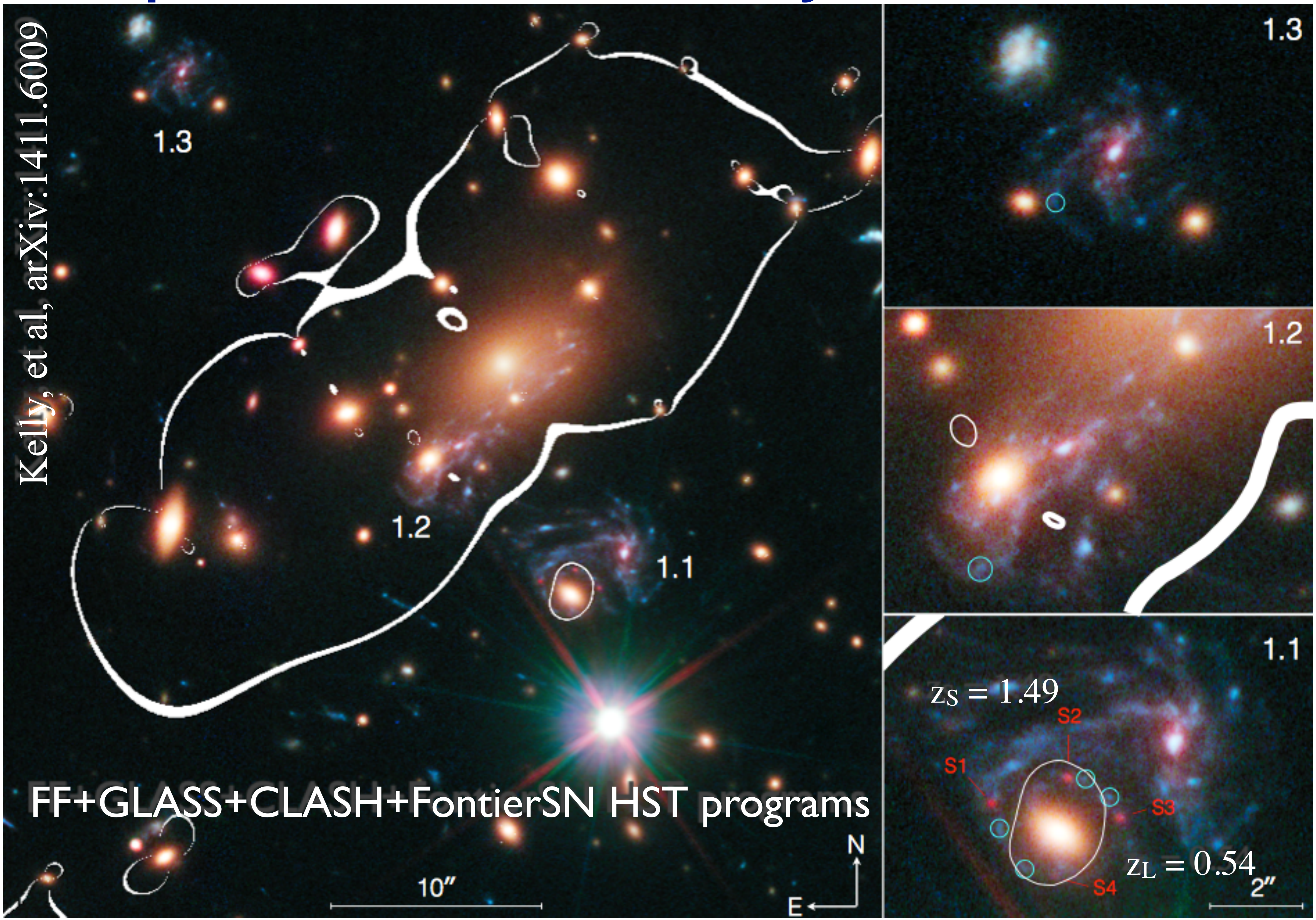
Multiple images by a galaxy cluster member + overall cluster potential

Can be modeled with many degrees of freedom

Modeling Strong Lensing Clusters

- Use positions of multiple images/arcs
  - possibly: surface light distribution, relative fluxes
- Use positions and properties of the cluster galaxies
- Free parameters: 2D mass distribution!
- Parametric approach:
  - Dark matter halos: mass, shapes, number
  - Scaling relations for light - mass
- Can derive a lot of information
- But does it make sense?

Supernova em MACS J1149.6+2223



Use prediction for the appearance of multiple images to test the model

When Refsdal meets Popper!

DRAFT VERSION MARCH 7, 2016
Preprint typeset using LaTeX style emulateapj v. 5/2/11

THE STORY OF SUPERNOVA 'REFSDAL' TOLD BY MUSE*

C. GRILLO[1], W. KARMAN[2], S. H. SUYU[3], P. ROSATI[4], I. BALESTRA[5], A. MERCURIO[6], M. LOMBARDI[7], T. TREU[8], G. B. CAMINHA[4], A. HALKOLA, S. A. RODNEY[9,10,11], R. GAVAZZI[12], K. I. CAPUTI[2]

Draft version March 7, 2016

ABSTRACT

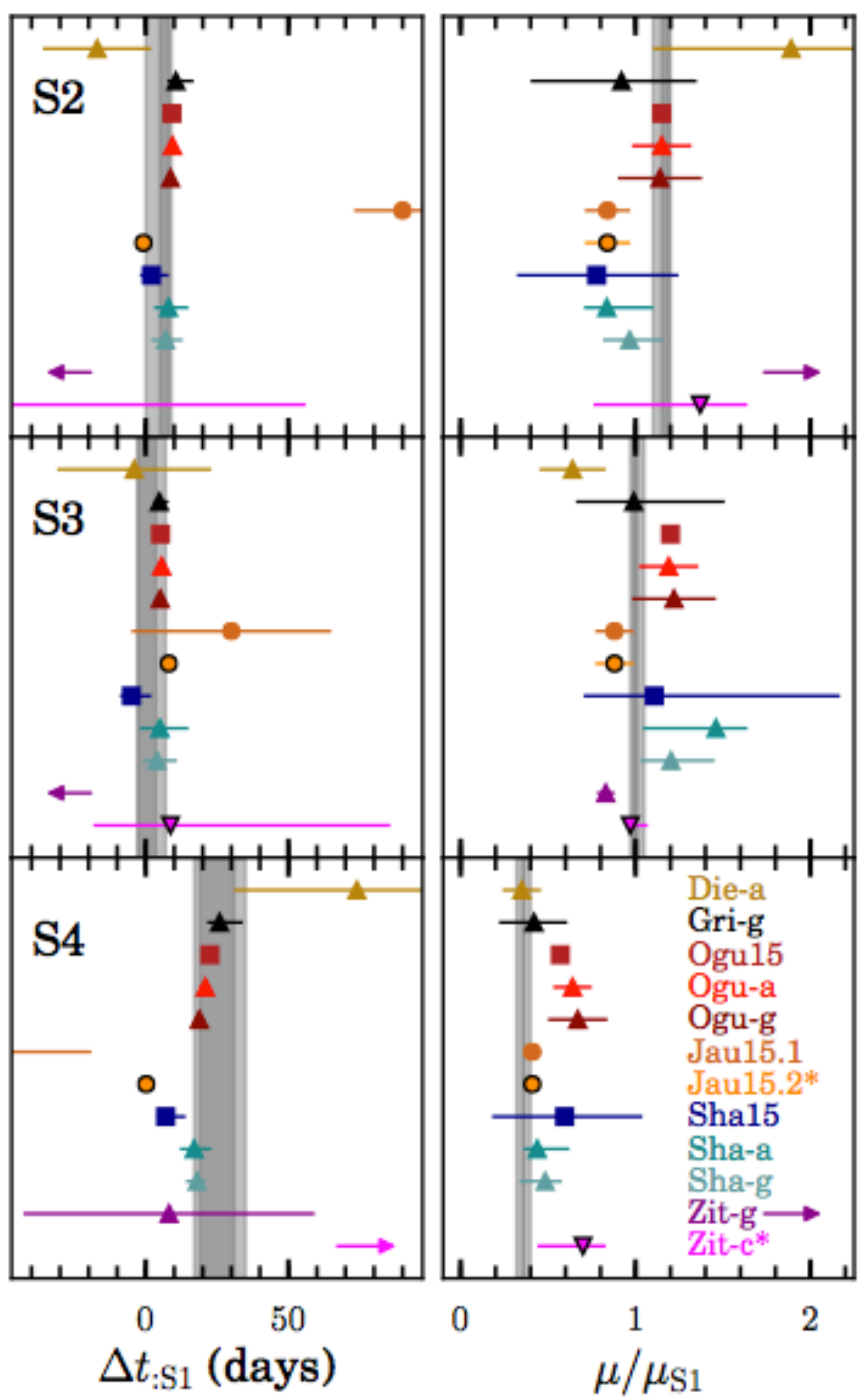
We present Multi Unit Spectroscopic Explorer (MUSE) observations in the core of the Hubble Frontier Fields (HFF) galaxy cluster MACS J1149.5+2223, where the first magnified and spatially-resolved multiple images of supernova (SN) 'Refsdal' at redshift 1.489 were detected. Thanks to a Director's Discretionary Time program with the Very Large Telescope and the extraordinary efficiency of MUSE, we measure 117 secure redshifts with just 4.8 hours of total integration time on a single 1 arcmin^2 target pointing. We spectroscopically confirm 68 galaxy cluster members, with redshift values ranging from 0.5272 to 0.5660, and 18 multiple images belonging to 7 background, lensed sources distributed in redshifts between 1.240 and 3.703. Starting from the combination of our catalog with those obtained from extensive spectroscopic and photometric campaigns using the *Hubble Space Telescope*, we select a sample of 300 (164 spectroscopic and 136 photometric) cluster members, within approximately 500 kpc from the brightest cluster galaxy, and a set of 88 reliable multiple images associated to 10 different background source galaxies and 18 distinct knots in the spiral galaxy hosting SN 'Refsdal'. We exploit this valuable information to build 6 detailed strong lensing models, the best of which reproduces the observed positions of the multiple images with a root-mean-square offset of only 0.26″. We use these models to quantify the statistical and systematic errors on the predicted values of magnification and time delay of the next emerging image of SN 'Refsdal'. We find that its peak luminosity should occur between March and June 2016, and should be approximately 20% fainter than the dimmest (S4) of the previously detected images but above the detection limit of the planned *HST*/WFC3 follow-up. We present our two-dimensional reconstruction of the cluster mass density distribution and of the SN 'Refsdal' host galaxy surface brightness distribution. We outline the roadmap towards even better strong lensing models with a synergetic MUSE and *HST* effort.

Subject headings: gravitational lensing – galaxies: clusters: general – galaxies: clusters: individuals: MACS J1149.5+2223 – Dark matter

"REFSDAL" MEETS POPPER: COMPARING PREDICTIONS OF THE RE-APPEARANCE OF THE MULTIPLY IMAGED SUPERNOVA BEHIND MACSJ1149.5+2223

T. Treu[1,28], G. Brammer[2], J. M. Diego[3], C. Grillo[4], P. L. Kelly[5], M. Oguri[6,7,8
K. Sharon[12], A. Zitrin[13,29] Show full author list

The Astrophysical Journal, Volume 817, Number 1



A free-form prediction for the reappearance of supernova Refsdal in the Hubble Frontier Fields cluster MACSJ1149.5+2223

Jose M. Diego,[1★] Tom Broadhurst,[2,3] Cuncheng Chen,[4] Jeremy Lim,[4] Adi Zitrin,[5†]
Brian Chan,[4] Dan Coe,[6] Holland C. Ford,[6] Daniel Lam[4] and Wei Zheng[6]

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[6]*Department of Physics and Astronomy, Johns Hopkins University, Baltimore, MD 21218, USA*

THE STORY OF SUPERNOVA 'REFSDAL' TOLD BY MUSE*

C. Grillo[1], W. Karman[2], S. H. Suyu[3], P. Rosati[4], I. Balestra[5], A. Mercurio[6], M. Lombardi[7], T. Treu[8], G. B. Caminha[4], A. Halkola, S. A. Rodney[9,10,11], R. Gavazzi[12], K. I. Caputi[2]
Draft version March 7, 2016

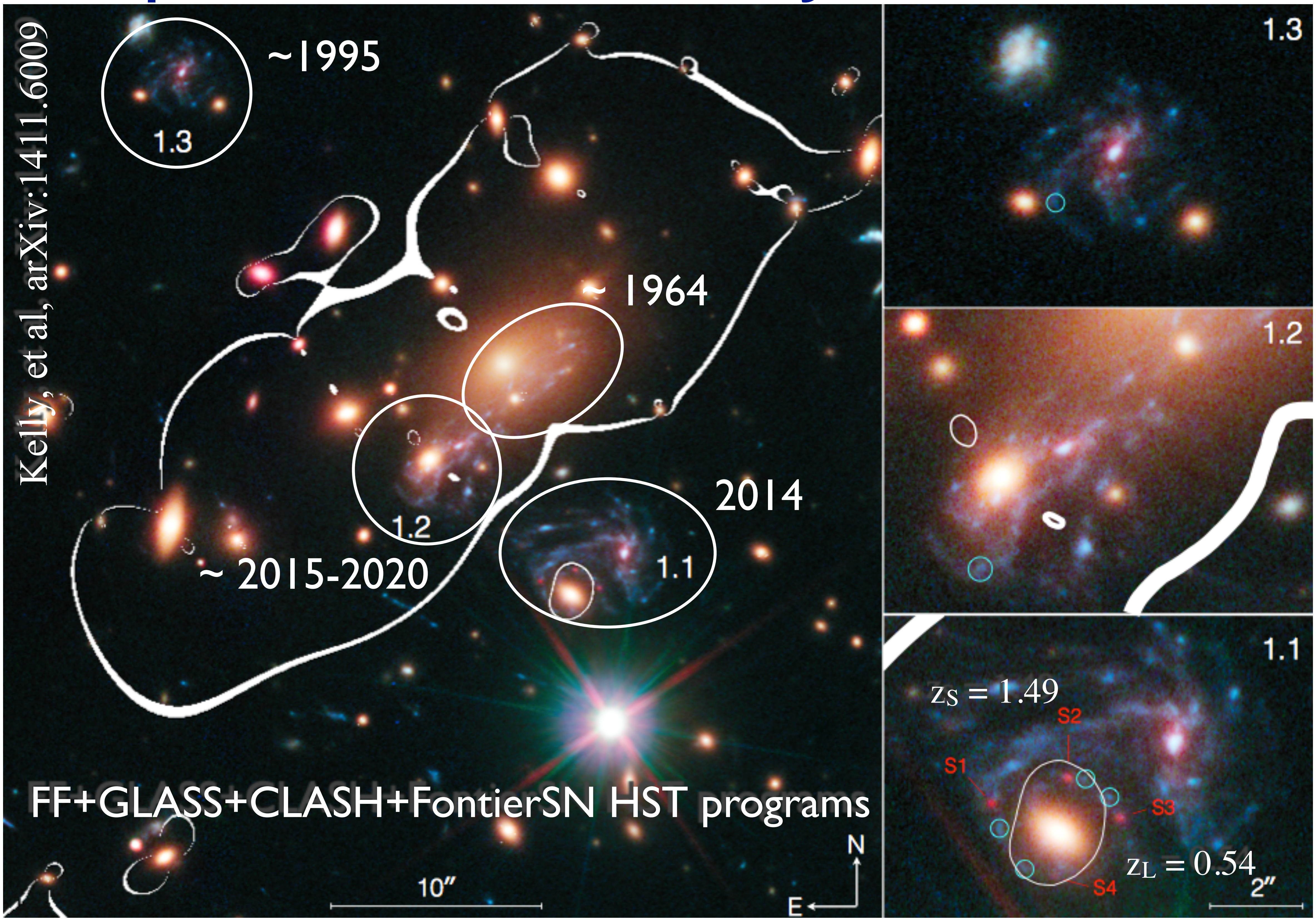
Monthly Notices of the Royal Astronomical Society
MNRAS 457, 2029–2042 (2016) doi:10.1093/mnras/stw069

Hubble Frontier Fields: predictions for the return of SN Refsdal with the MUSE and GMOS spectrographs

M. Jauzac,[1,2,3★] J. Richard,[4] M. Limousin,[5] K. Knowles,[3] G. Mahler,[4] G. P. Smith,[6]
J.-P. Kneib,[5,7] E. Jullo,[5] P. Natarajan,[8] H. Ebeling,[9] H. Atek,[8] B. Clément,[4]
D. Eckert,[10] E. Egami,[11] R. Massey[1,2] and M. Rexroth[7]

of MACS J0416.1−2403 and Abell 2744. In light of the discovery of the first resolved quadruply lensed supernova, SN Refsdal, in one of the multiply imaged galaxies identified in MACS J1149, we use our revised mass model to investigate the time delays and predict the rise of the next image between 2015 November and 2016 January.

Supernova em MACS J1149.6+2223



DEJA VU ALL OVER AGAIN: THE REAPPEARANCE OF SUPERNOVA REFSDAL

P. L. Kelly[1], S. A. Rodney[2], T. Treu[3,3], L.-G. Strolger[4], R. J. Foley[5,6], S. W. Jha[7], J. Selsing[8], G. Brammer[4], M. Bradač[9], S. B. Cenko[10,11] Show full author list

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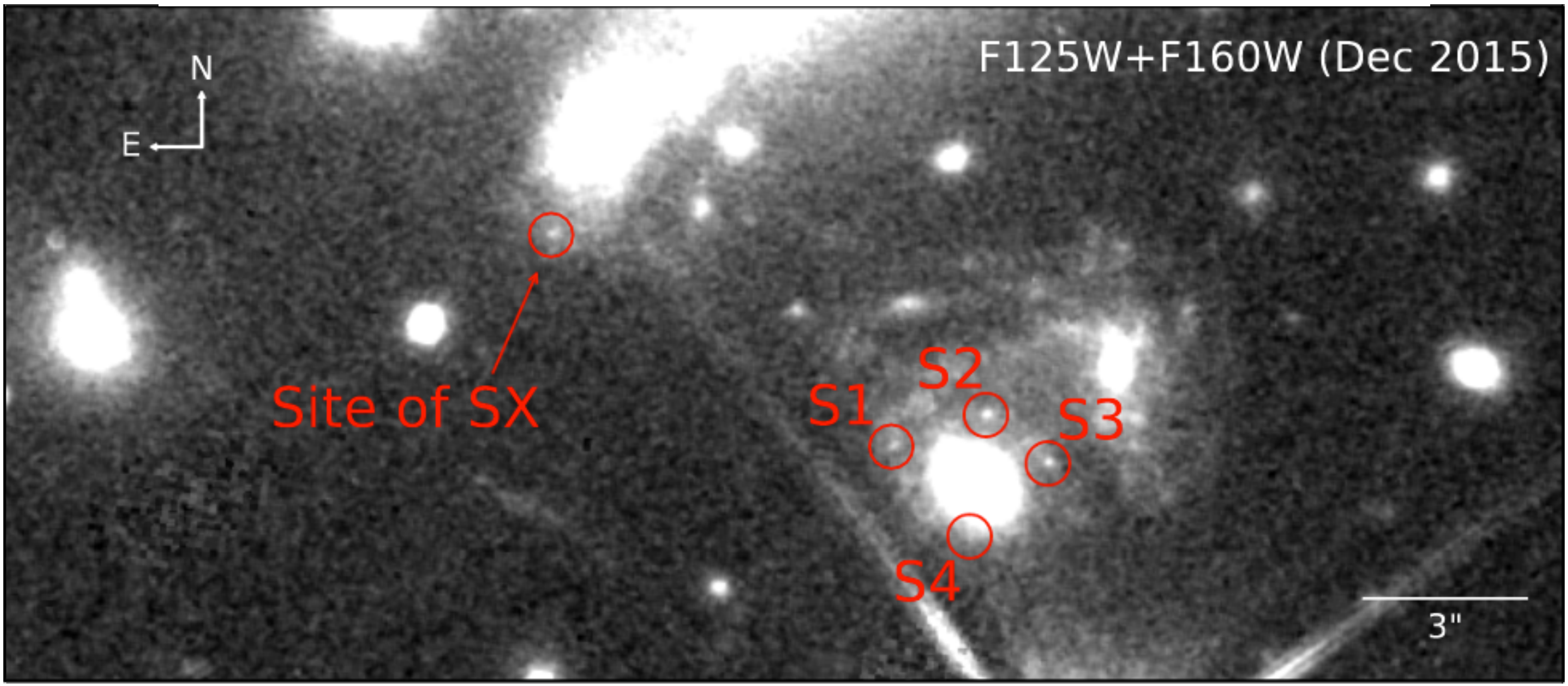

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