Strong Lensing and the Dark Sector

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The Dark Sector of the Universe

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Pedra Azul - Domingos Martins, ES, Brazil. September 25-30, 2016

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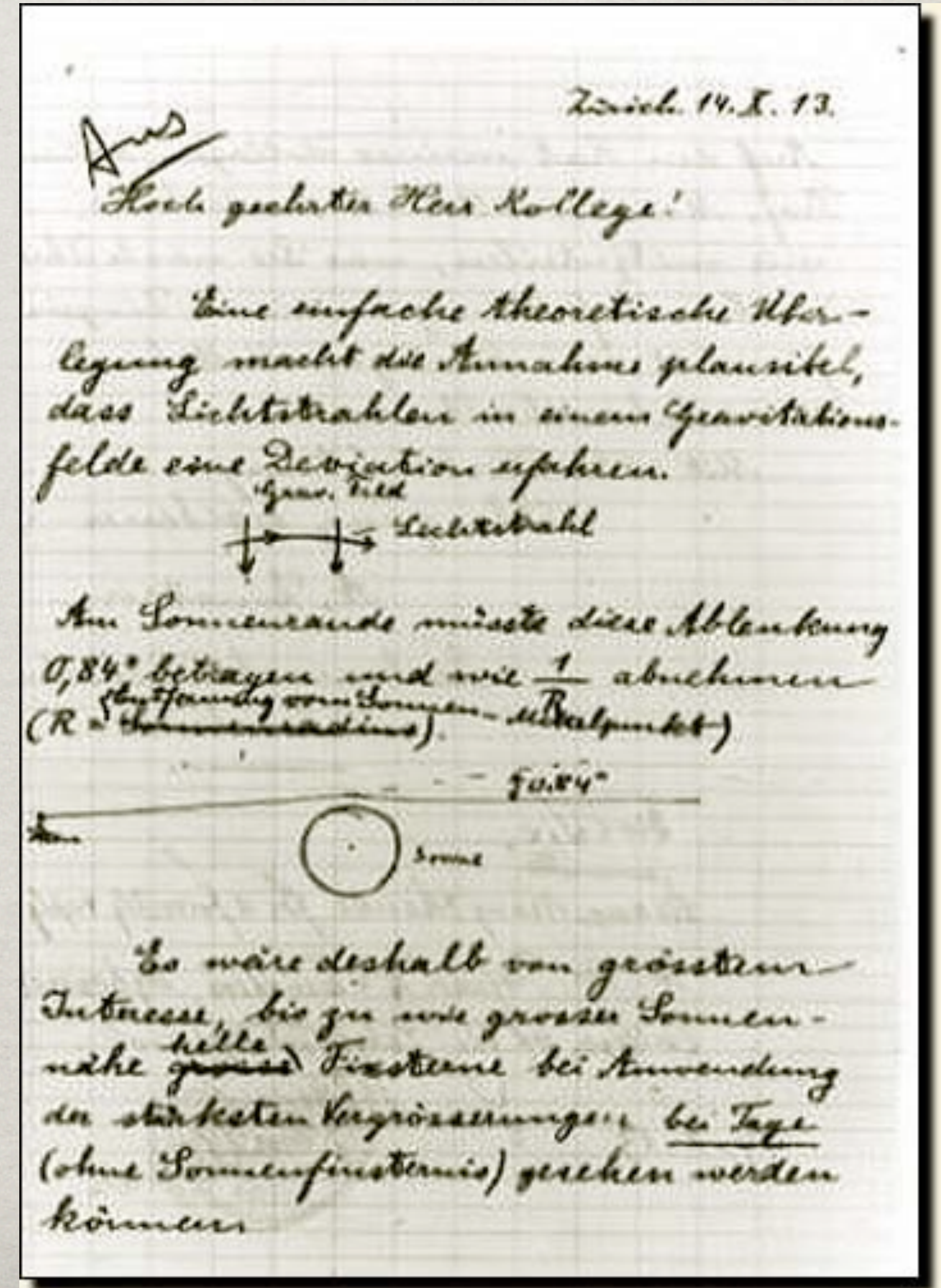
#FicaMCTI

T I

Detection of Light Deflection by Gravity

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

  Urges observational tests



Zürich. 14. X. 13.

Ans

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

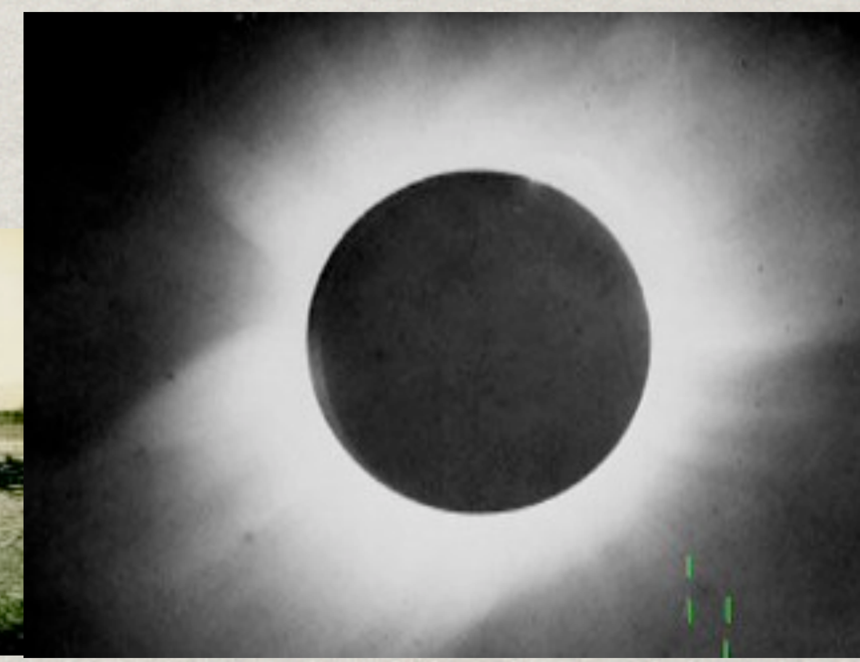
Es wäre deshalb von grösstem Interesse, bis zu wie grosser Sonnennähe ~~grosse~~ helle Fixsterne bei Anwendung der stärksten Vergrösserungen bei Tage (ohne Sonnenfinsternis) gesehen werden können.

Detection of Light Deflection by Gravity

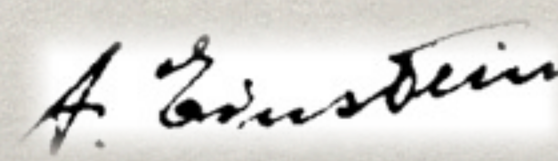
- 1912: Argentinean expedition to observe solar eclipse in Brazil
  - Got rained out

Detection of Light Deflection by Gravity

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



“The question that my mind formulated was answered by the sunny sky of Brazil”



Discoveries

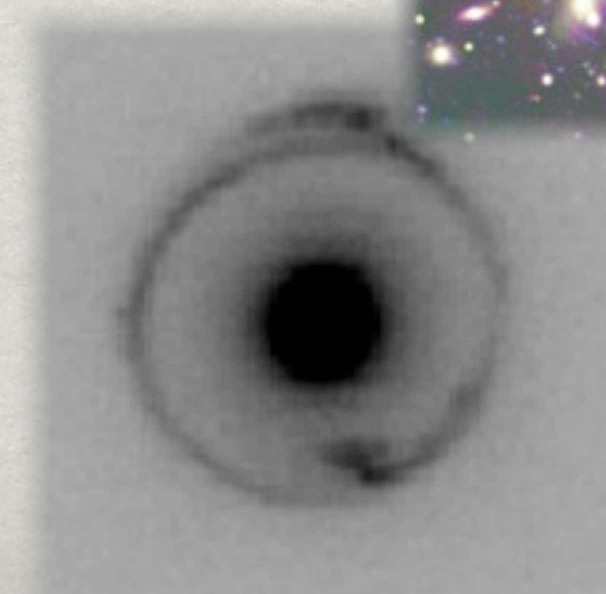
- Sobral 1919: light deflection
- Walsh, Carswell, Weymann 1979: first lensed quasar (double image of QSO 0957+561)
- Roger Lynds e Vahe Petrosian 1986, Soucail, Fort, & Picat 1987: discovery of gravitational arcs

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

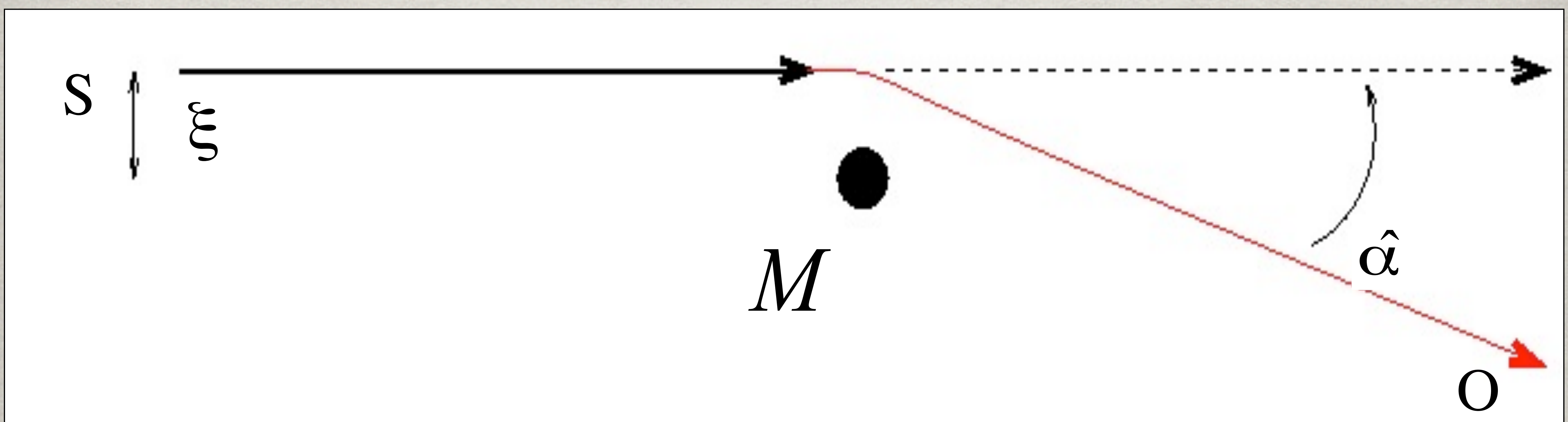


Bending of light by gravity

Null geodesic,
Fermat principle

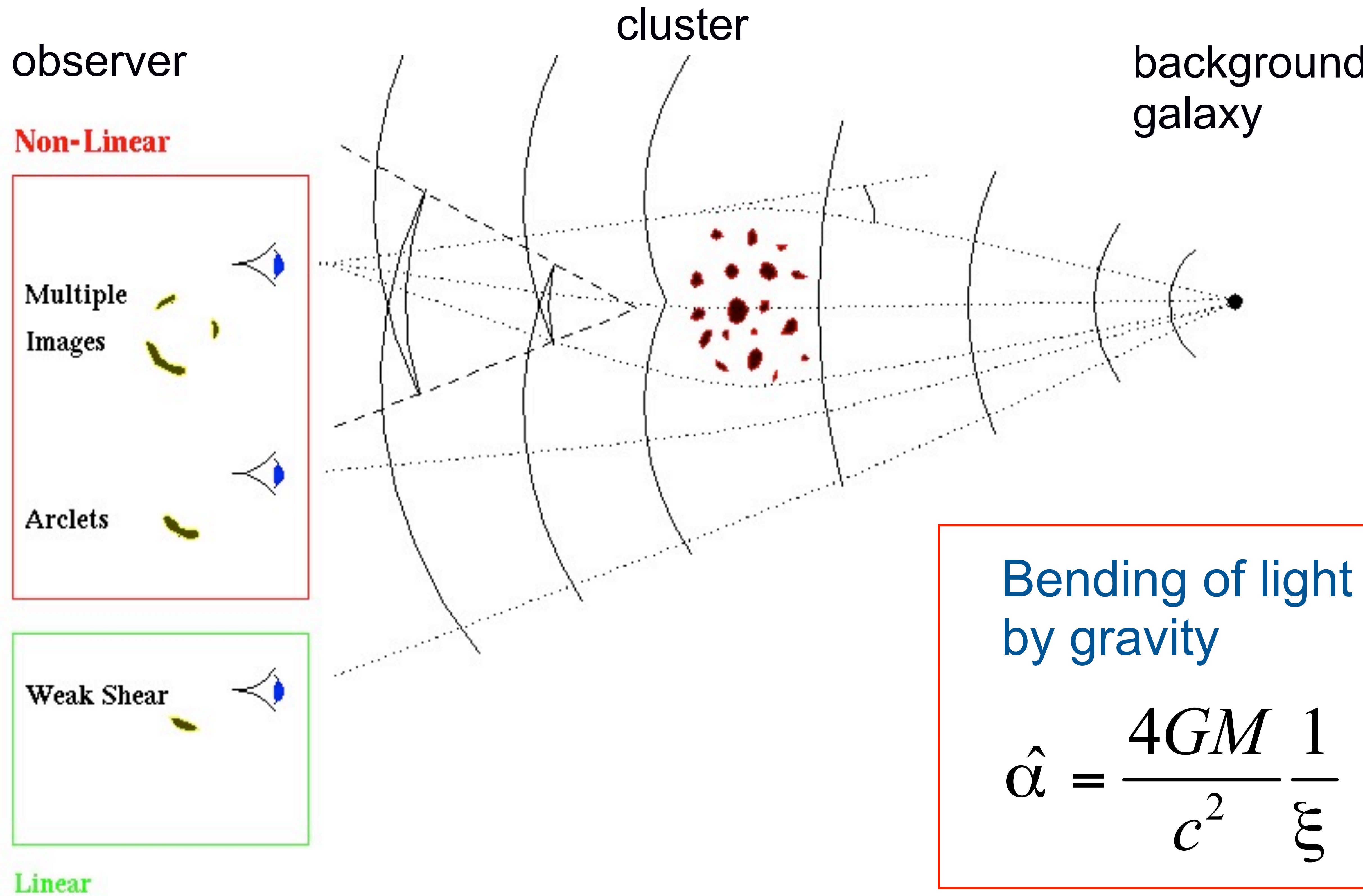
$$ds^2 = \left(1 + \frac{2\phi}{c^2}\right) c^2 dt^2 - \left(1 - \frac{2\phi}{c^2}\right) d\sigma^2$$

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



Deflection angle (point source) $\hat{\alpha} = \frac{4GM}{c^2}\frac{1}{\xi}$ Achromatic

Weak and Strong Lensing Effects



Bending of light by gravity

$$\hat{\alpha} = \frac{4GM}{c^2}\frac{1}{\xi}$$

A plethora of phenomena

<u>Strength</u>

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

<u>Angular scale</u>

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

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:

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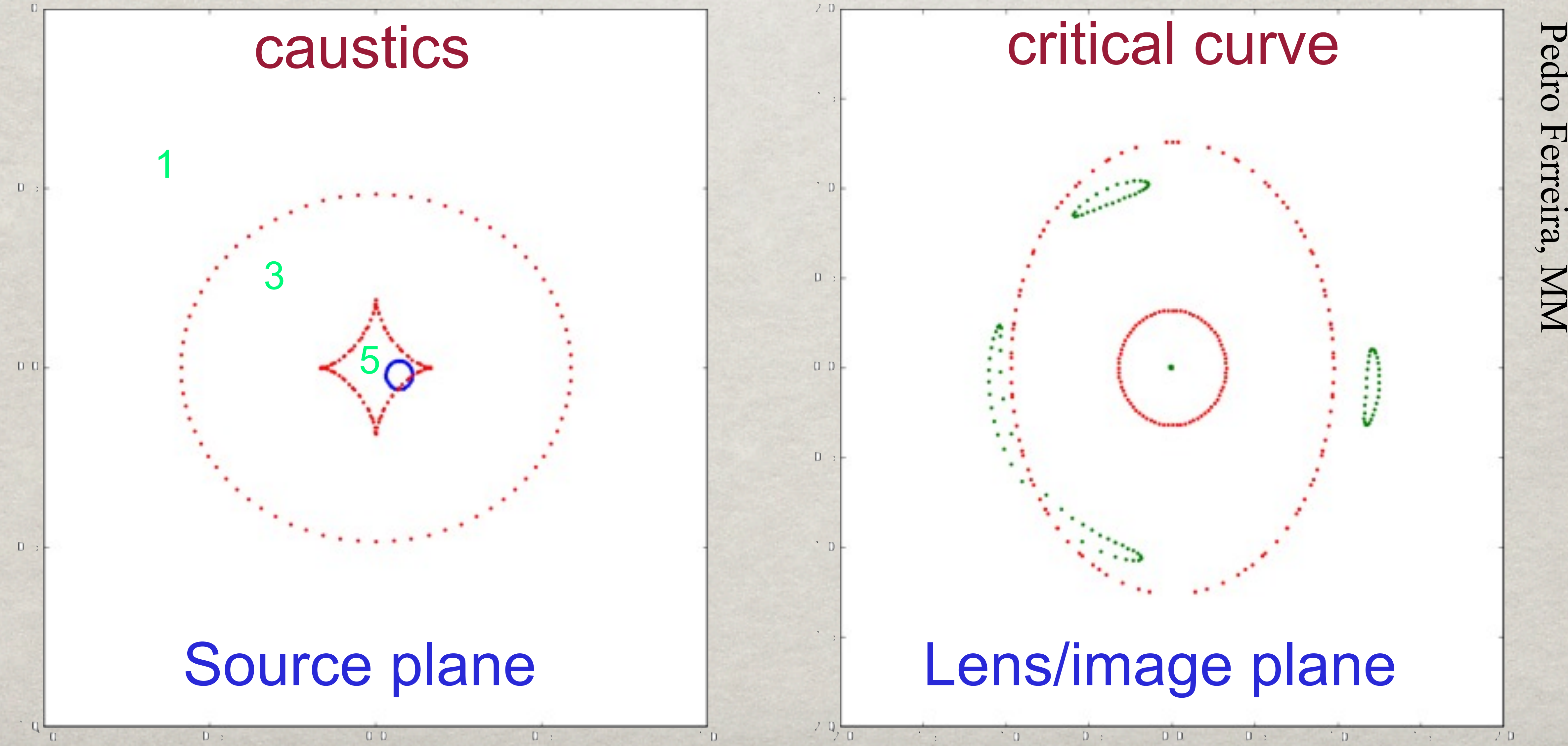
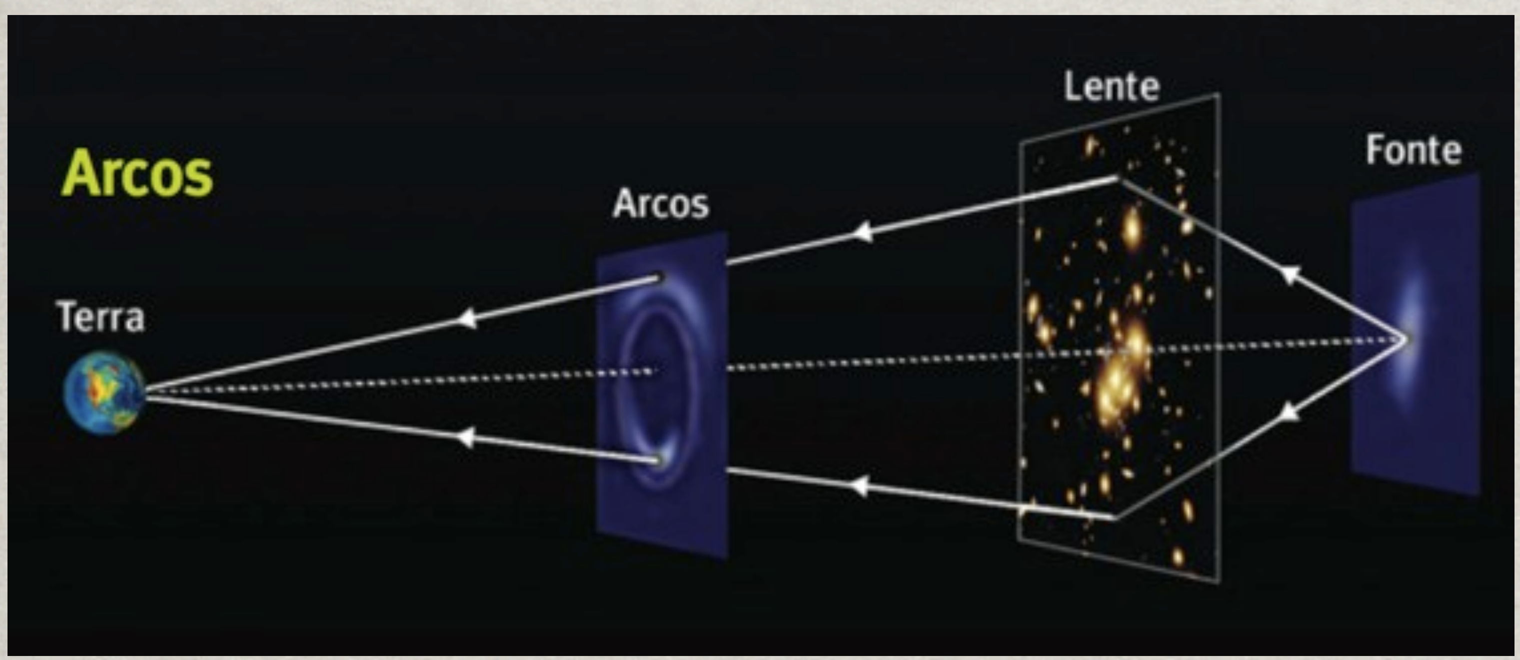


Strong Lensing

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

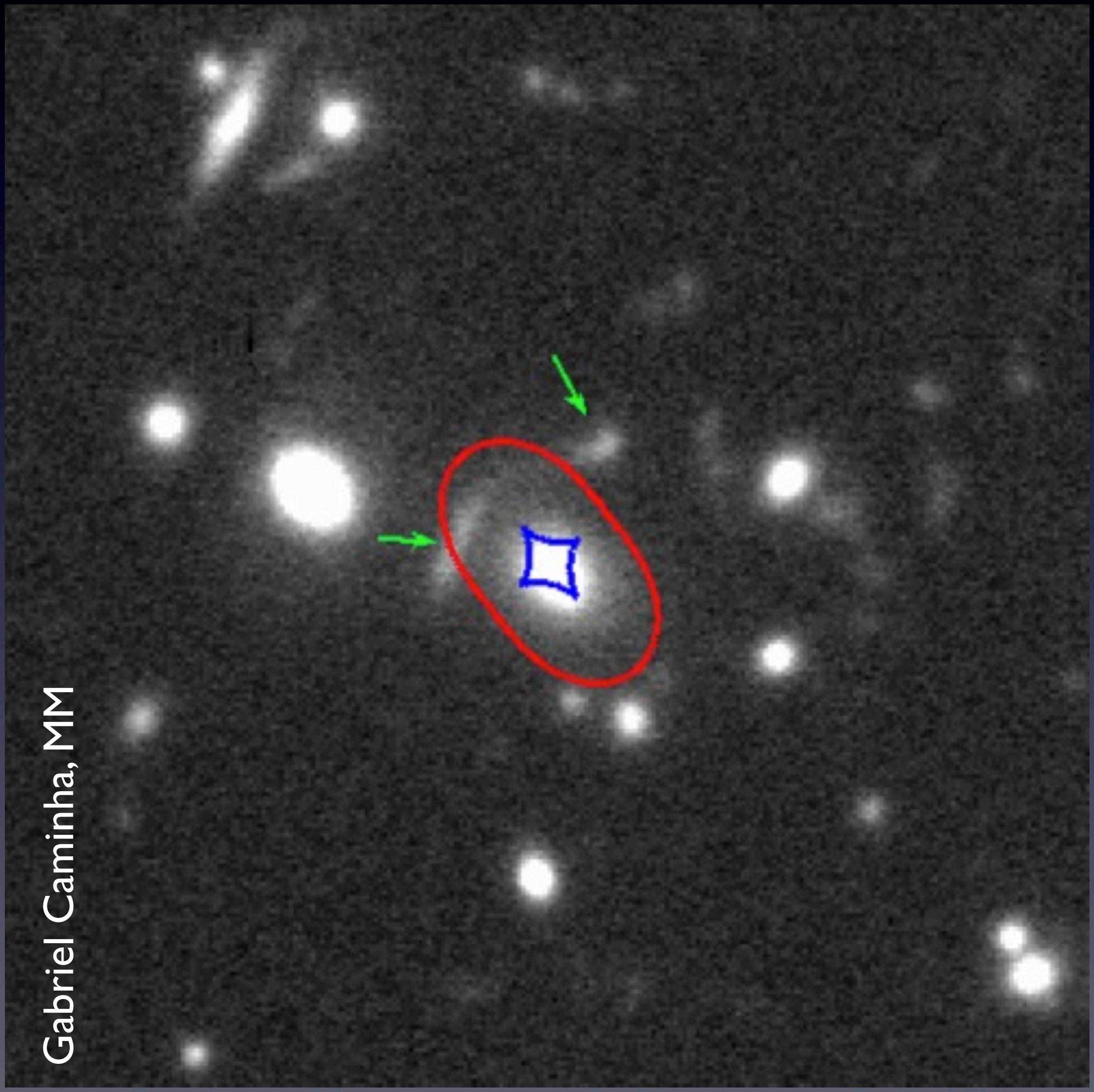
  } → Gravitational telescopes
  - Unique probe of inner structure of galaxy clusters ➔ DM, b
  - Provide complementary cosmological probes and tests of gravity



strong lensing, **weak gravity**


Gravitational arcs

Mapping the lens mass



Arcs and multiple images

Parameters of the mass distribution

- ✓ Density profiles in the galaxy cluster inner regions
- ✓ Substructure

Sensitivity to cosmology

Source reconstruction

Challenges to using arcs as probes of the dark sector

- statistics
- systematics

Inverse Modeling

Use systems of multiple images to determine the lensing potential

$$\chi^2_{\mathrm{lente}} := \sum_i \left(\frac{\vec{\theta}_i^{\mathrm{obs}} - \vec{\theta}^{\mathrm{mod}}\left(\vec{\beta}, \vec{\Pi}\right)}{\sigma_i^{\mathrm{obs}}} \right)^2$$

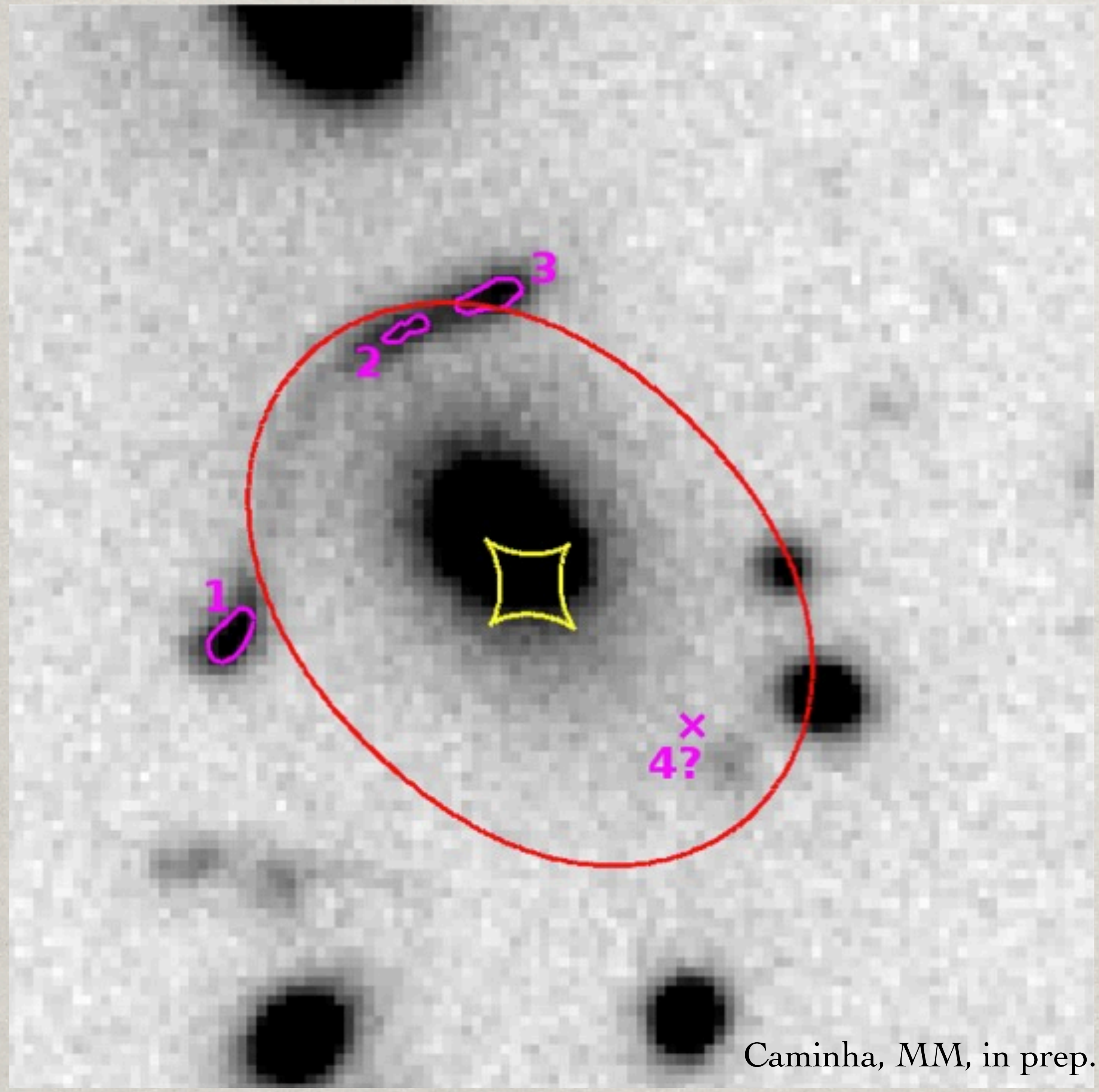
Multiple image positions

Error on image positions

Available codes: *lenstool*, *gravlens*, *glafic*, etc. + "home-made"

- Parameters that minimize this function (or maximize the likelihood) are the best fitting lens model
- Combination with independent mass constraints (e.g., x-ray, Sunyaev Zel'dovich, velocity dispersions) yields limits on cosmology or gravity

Inverse Modeling for system SOGRAS0041-0043



$$2.35^{+0.03}_{-0.14} \times 10^{14} M_{\odot}$$

Modelling with lenstool (Jullo, Kneib)

Fit 1: 3 images
Fit 2: 4 images

	Fit 1	Fit 2
$\sigma_v[km/s]$	622^{+11}_{-13}	642^{+3}_{-3}
$\theta_{\rm or}[°]$	$135.2^{+0.7}_{-0.8}$	$135.2^{+1.5}_{-1.3}$
$x_{\rm lente}['']$	$0.50^{+0.2}_{-0.2}$	$0.50^{+0.05}_{-0.06}$
$y_{\rm lente}['']$	$-0.76^{+0.17}_{-0.15}$	$-0.86^{+0.06}_{-0.03}$
ε	—	$0.13^{+0.02}_{-0.03}$

~ 0.9" displacement between central galaxy and center of mass distribution (*Zitrin et al. 2012*)

Error estimate from simulations (Caminha et al. in prep.):

~ 8% bias in mass

~ 5% statistical errors

Lens Mass Distribution and Dark Matter

Strong Lensing and Dark Matter

- Density profiles of galaxies and inner cluster regions:
  - cuspy halo profiles? $\rho(r) \propto r^{-\gamma} \quad \gamma \sim 1$ Bartelmann, astro-ph/0207032
  - dark matter interactions
  - baryonic processes: cooling, AGN feedback,… Mead et al. 1001.2281
- Substructure Moustakas et al. 0902.3219, Koopmans et al. 0902.3186
  - overabundance of satellites
  - primordial spectrum
- Luminous x Matter
  - e.g. DM cross section Williams and Saha, 1102.3943

    $\sigma/m \gtrsim 8 \times 10^{-31} \left(t/10^{10} yr\right)^{-2} cm^2 GeV^{-1}$
- Challenges for using arcs as astrophysical and fundamental physics probes:
  - statistics
  - systematics

Dark Energy from Families of Multiple Images

Galaxy Clusters

Families of images with sources at different *redshifts*

☑ constraints on cosmology, in addition to the matter distribution

The ratio of angular diameter distances for 2 (or more) images with sources at different redshifts defines a ratio of families

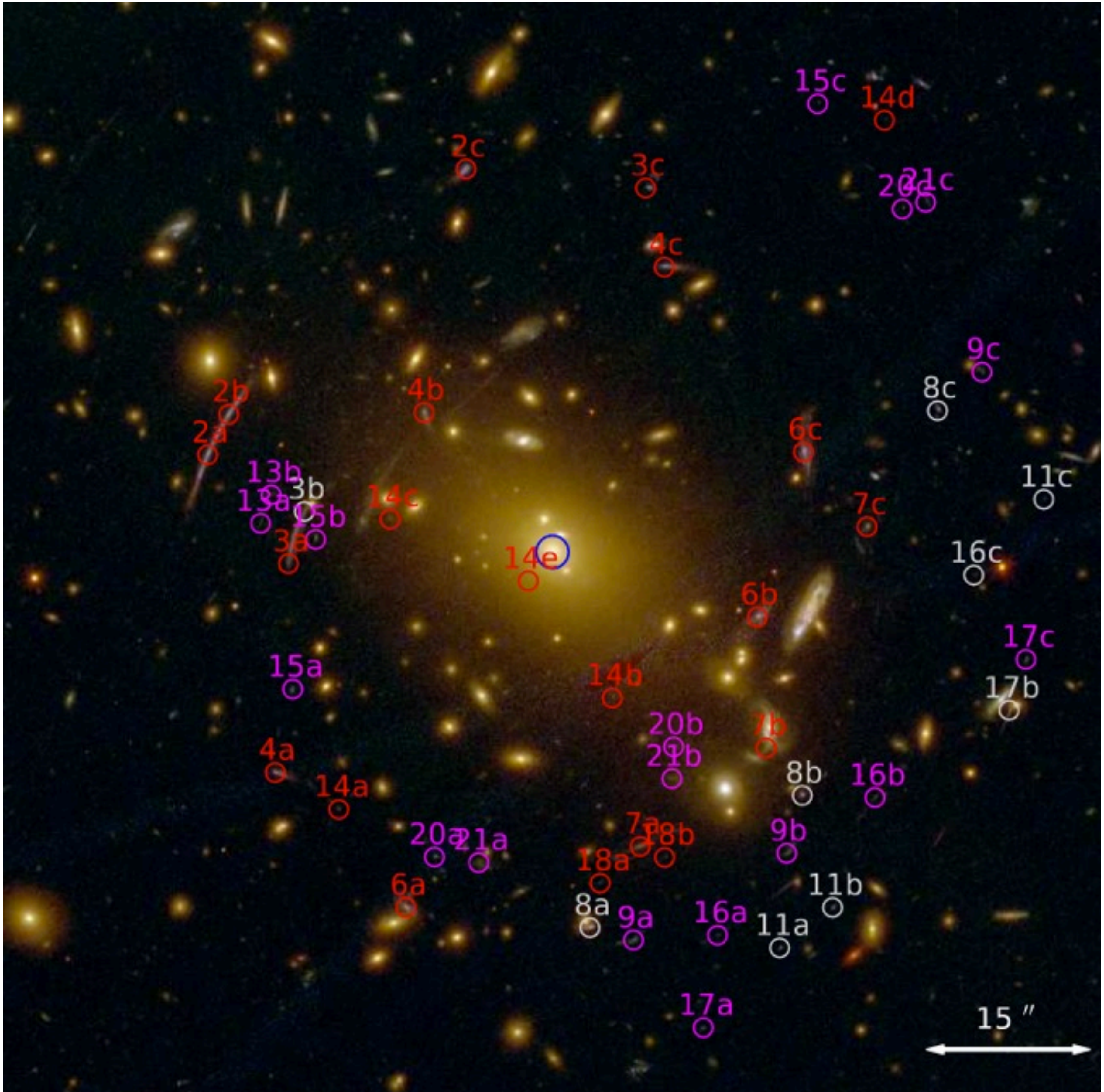
$$\Xi(z_l, z_{s1}, z_{s2}; \Omega_M, \Omega_X, w_X) = \frac{D(z_l, z_{s1})}{D(0, z_{s1})} \frac{D(0, z_{s2})}{D(z_l, z_{s2})}$$

☑ Jullo et al. 2010, Science: example of competitive limits in cosmological parameters fom the Abell 1689 system

☑ **8** families of sources with z = 1.15 to 4.86

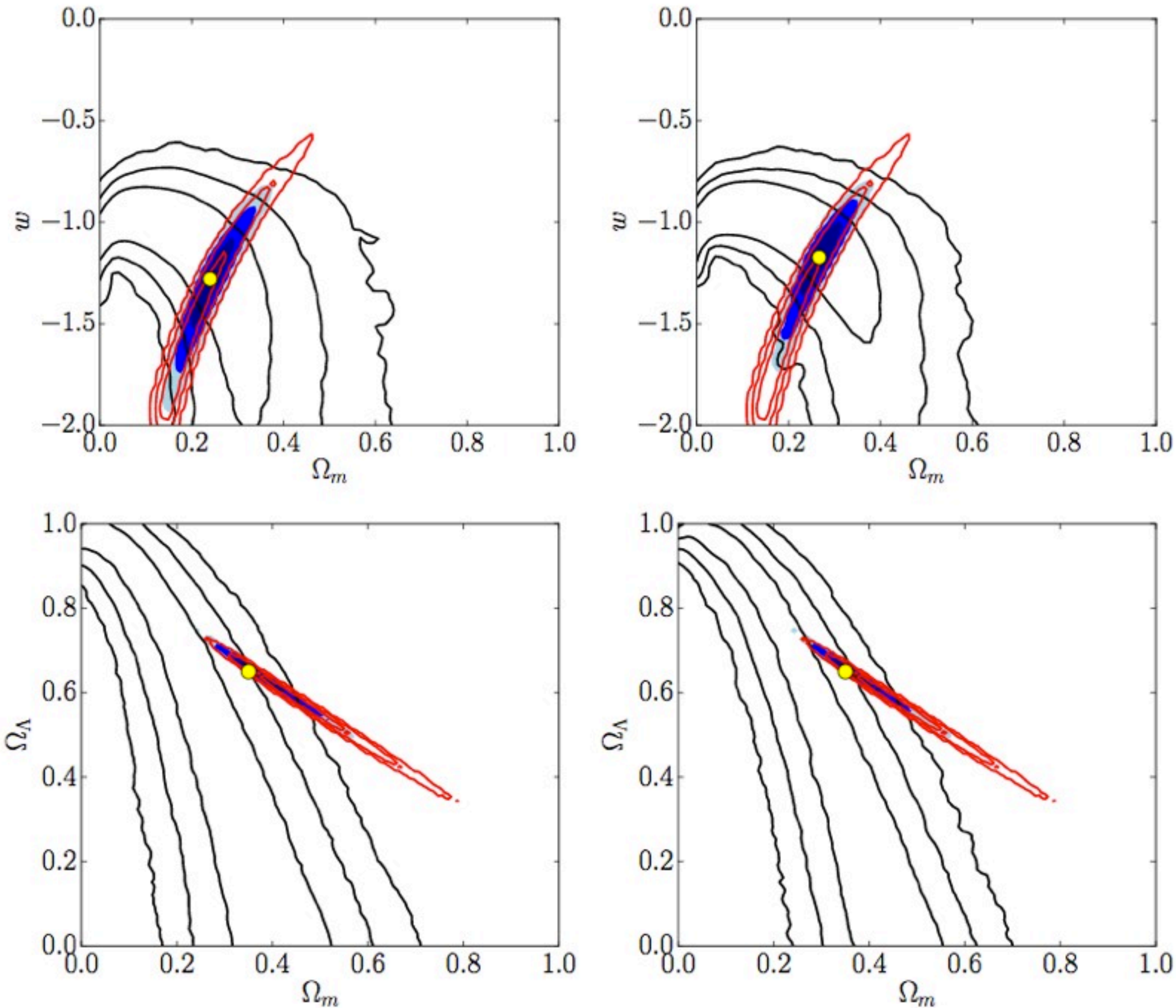
☑ Caminha et al. 2016: RXC J2248.7-4431 (Abell S1063), 16 sources, 47 images

Cluster CLASH RXC J2248.7-4431



Caminha et al. 2016

Cluster CLASH RXC J2248.7-4431



Caminha et al. 2016

Time Delays and Cosmology

Time Delay

$$\Delta t_{ij} = \frac{D_\Delta}{c}\left(\frac{1}{2}(\vec{\theta_i} - \vec{\beta})^2 - \Psi(\theta_i) - \frac{1}{2}(\vec{\theta_j} - \vec{\beta})^2 + \Psi(\theta_j)\right)$$

Where $D_\Delta = (1 + z_L)\frac{D_{OS}D_{OL}}{D_{LS}}$

inverse modeling (multiple images)

"time delay distance"

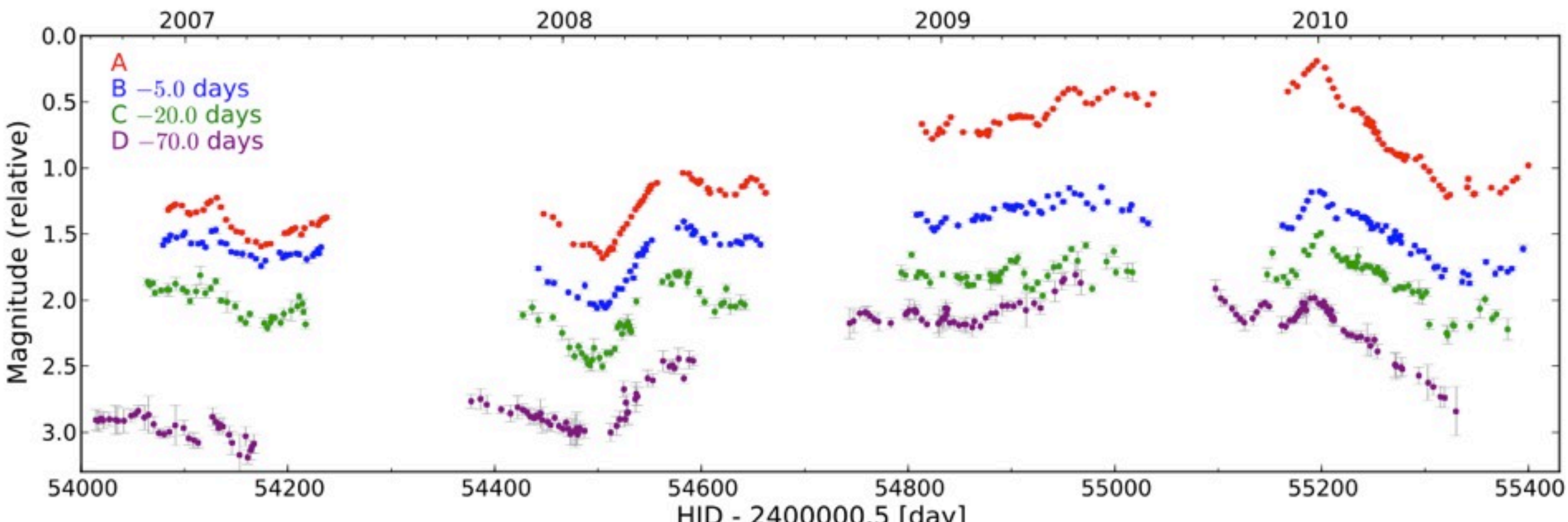
Main cosmological dependence $\propto H_0^{-1}$

Quasar light-curves

Time delay between images

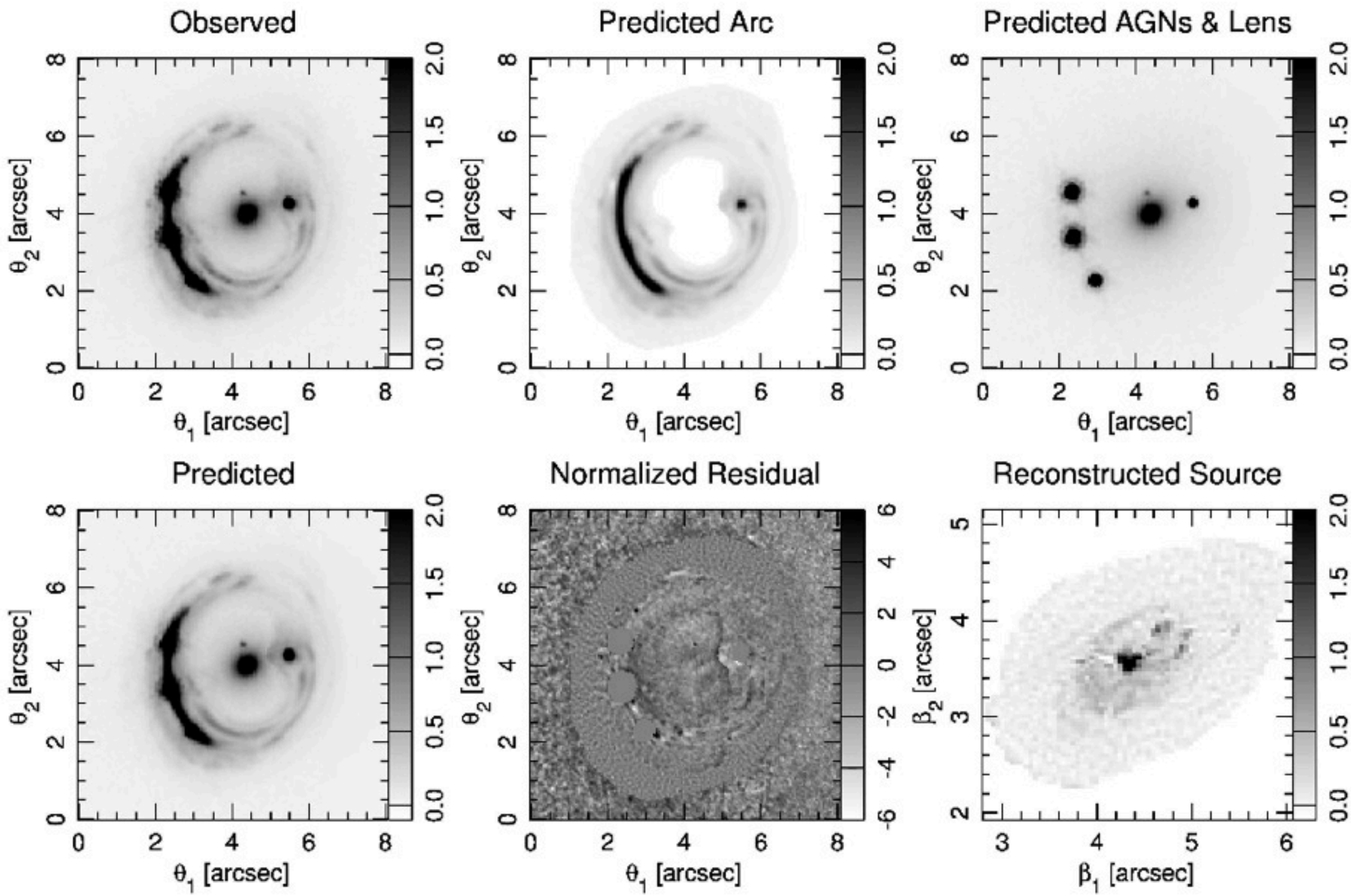
$$\Delta t_{ij} = \delta t\left(\vec{\theta}_i, \vec{\beta}\right) - \delta t\left(\vec{\theta}_j, \vec{\beta}\right)$$

$$= (1+z_L)\frac{D_{OS}D_{OL}}{cD_{LS}}\left(\frac{1}{2}(\vec{\theta_i} - \vec{\beta})^2 - \Psi(\theta_i) - \frac{1}{2}(\vec{\theta_j} - \vec{\beta})^2 + \Psi(\theta_j)\right)$$



Tewes et al.: COSMOGRAIL XI

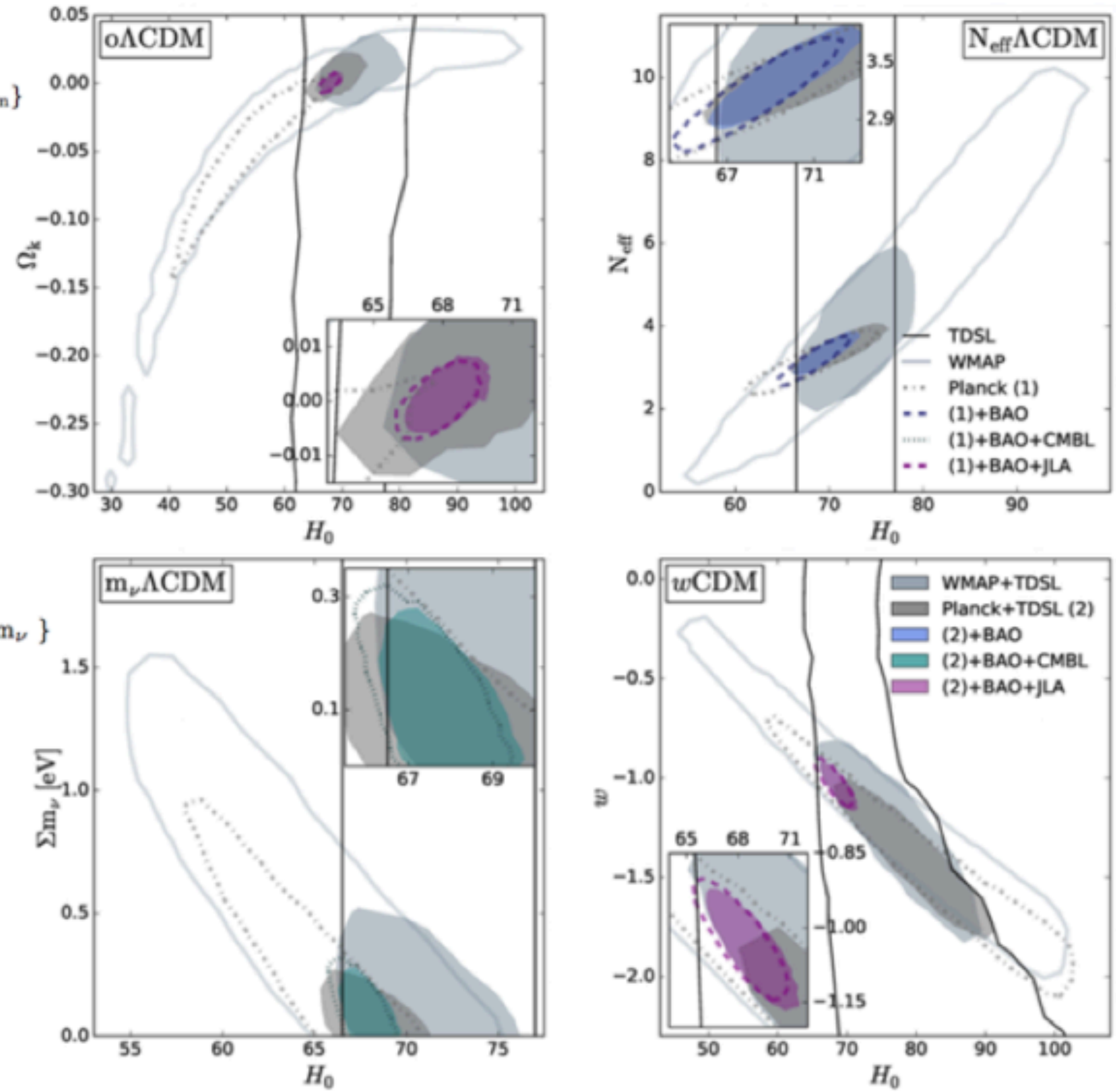
Modeling of RX J1131−1231



Cosmology Results

Non-flat ΛCDM cosmology
WMAP/Planck for $\{H_0, \Omega_\Lambda, \Omega_m\}$
$\Omega_k = 1 - \Omega_\Lambda - \Omega_m$

Flat ΛCDM cosmology
WMAP/Planck for $\{H_0, \Omega_\Lambda, N_{eff}\}$

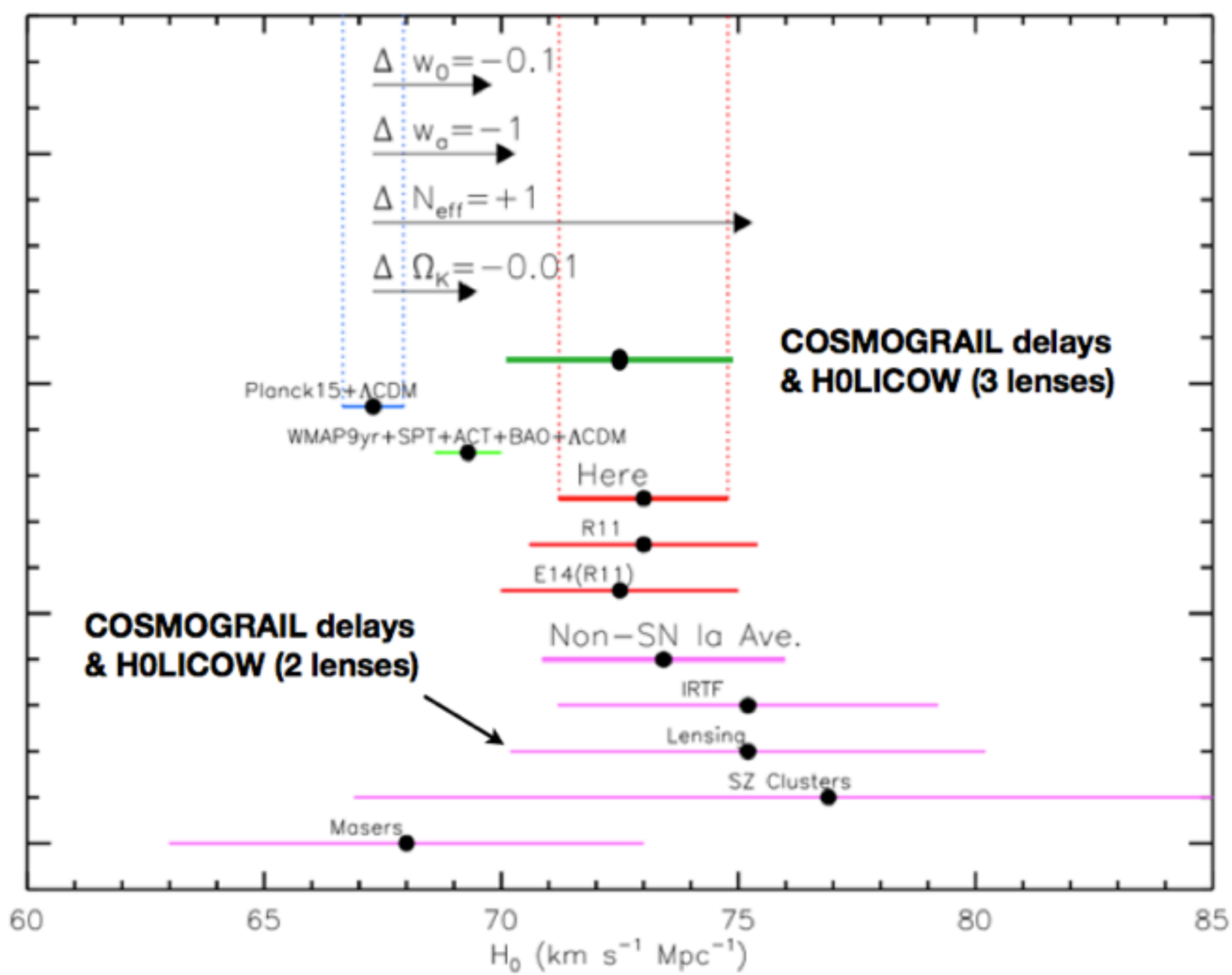


Flat ΛCDM cosmology
WMAP/Planck for $\{H_0, \Omega_\Lambda, \Sigma m_\nu\}$

Flat wCDM cosmology
Planck for $\{H_0, w, \Omega_{de}\}$

Bonvin et al. 2016
(Paper V; arXiv:1607.01790)
Cosmology results for 3 lenses

Comparison with other Cosmological Probes



Adapted From Riess et al. (2016)

Strong Lensing and Modified Gravity

Modifications of GR

Weak-field metric in the conformal Newtonian gauge

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

peculiar gravitational potentials

(in GR $\psi = \phi$)

homogeneous and isotropic line element

Conditions:

- Light follows null geodesics (*valid even for nonmetric theories of gravity*)
- Metric can be split into a homogeneous part and linear scalar perturbations

Can be extended for inhomogeneous models, such as LTB

Strong Lensing is a probe of:

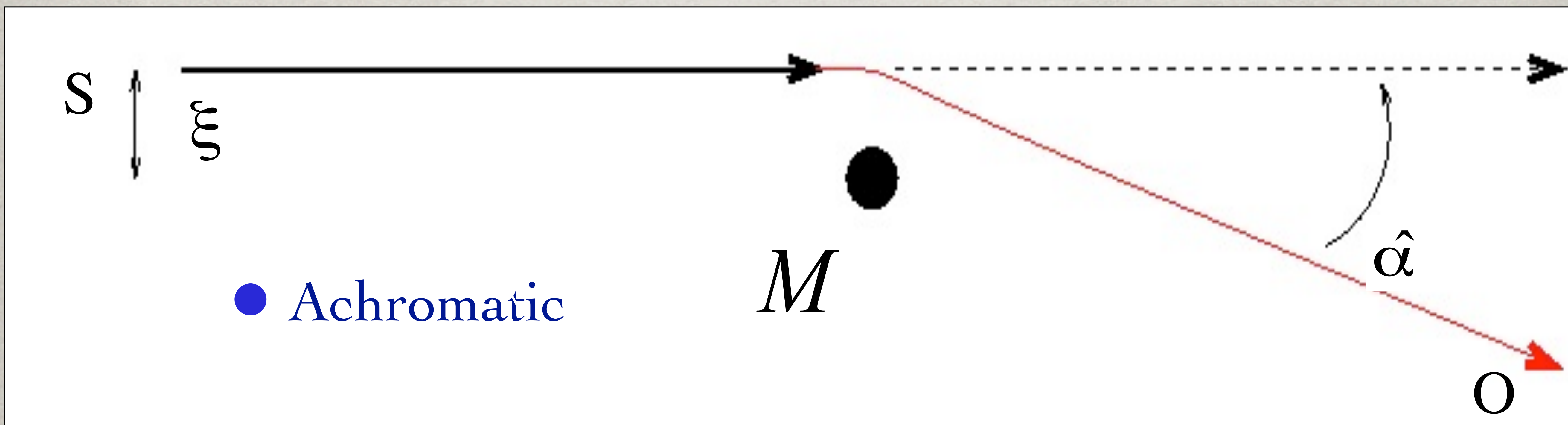
- Small scales: testing gravity on kiloparsec scales
- Cosmological distances: large-scale modifications of gravity

Bending of light by gravity

Null geodesic,
Fermat principle

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

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



- Achromatic

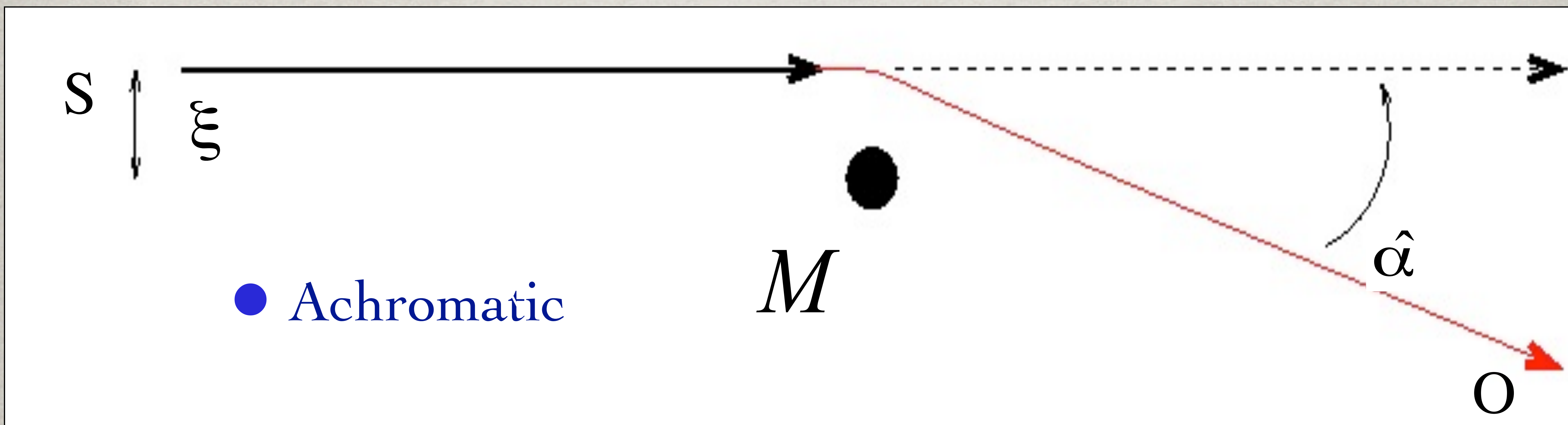
Deflection angle (point source) $\hat{\alpha} = \frac{4GM}{c^2}\frac{1}{\xi}$

Bending of light by (modified) gravity

Null geodesic,
Fermat principle

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

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



- Achromatic

Lensing potential:

$$\Psi = \frac{1}{c^2} \frac{D_{\rm LS}}{D_{\rm OS} D_{\rm OL}} \int (\psi + \phi)\, d\chi$$

Modifications of GR

Weak-field metric in the conformal Newtonian gauge

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

Generic parameterization

$$\frac{1}{2}\nabla^2 (\psi + \phi) = 4\pi\mu G\rho \qquad \frac{\phi}{\psi} = \gamma$$

γ_{PPN} e μ may vary in space, time, density, photon energy, etc.

Examples: scalar-tensor, *f(R)*

Deflexion angle

$$\hat{\alpha} = \int (\psi + \phi)\, dl$$

Dynamical mass obtained from

$$\nabla^2 \psi = 4\pi G\rho$$

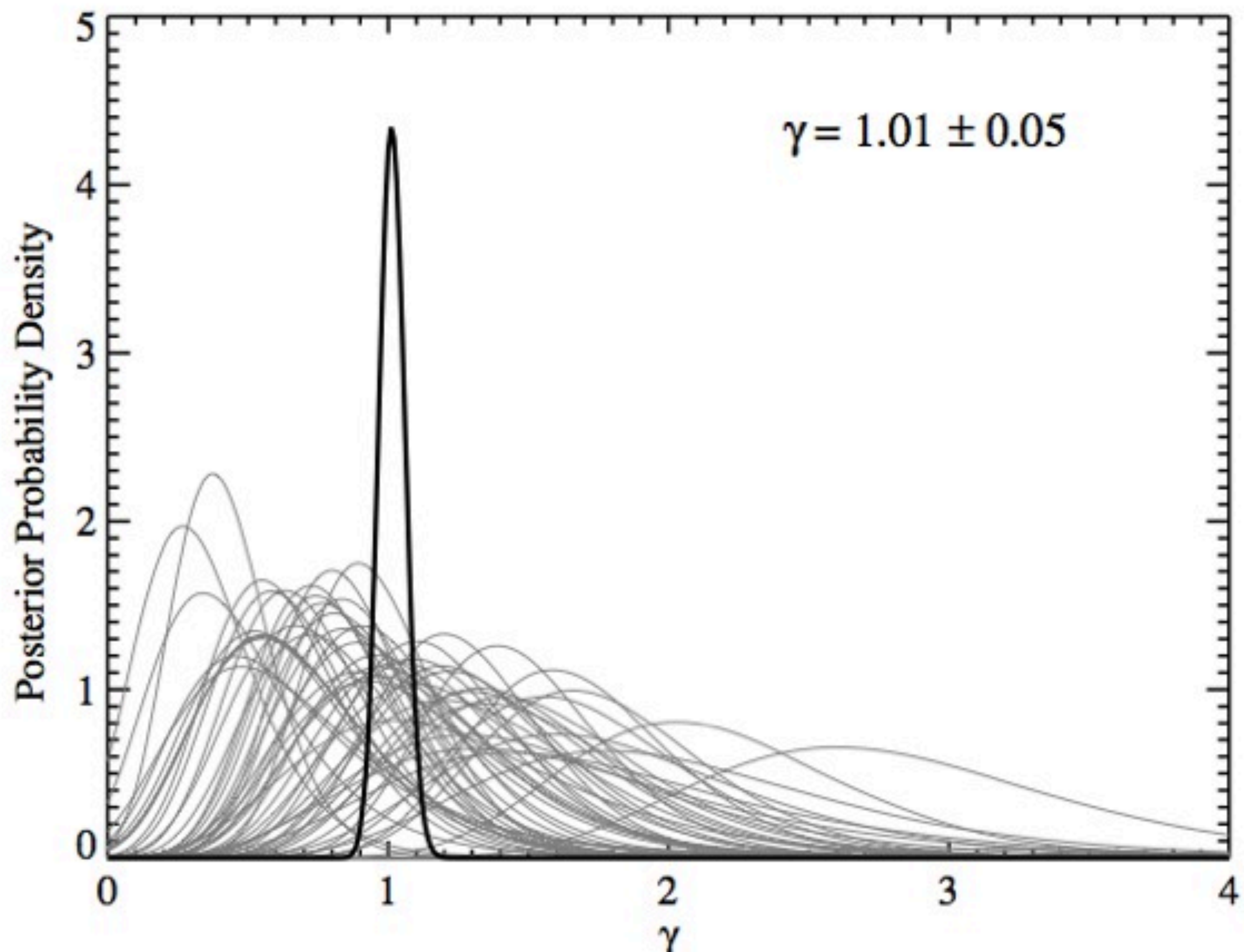
Need combination of lensing + dynamics, e.g., spectra

Einstein Rings

Einstein Ring $R_E = 4\pi\sigma_{\rm obs}^2 \left(\frac{1+\gamma_{\rm PPN}}{2}\right)\frac{D_L D_{LS}}{D_S}$

Measure velocity dispersion -> Limit on gravity

Einstein rings in the SLACS sample



Smith, arXiv:0907.4829;
Schwab, Bolton, Rappaport, arXiv:0907.4992

The results are in agreement with GR

Frontiers and Challenges

Frontiers and Challenges

- Detailed observations of selected fields
  - Space-based observations (HST)
  - Frontier Fields, CLASH, RELICS, etc.
  - Massive spectroscopic follow-up (IFU/MUSE)
  - Cosmology from single systems + high-z sources
  - Limited to very massive lenses and few systems
- Wide-field surveys
  - High statistics: discovery of thousands of systems
  - Probe wide mass range
  - Few constraints
  - Spin-off from cosmological surveys
- Different Challenges and Systematics

THE *HST* FRONTIER FIELDS TARGETS

THE DEEPEST DATA EVER OBTAINED FOR LENSING GALAXY CLUSTERS !!!

Abell 2744 - z = 0.308
Fully observed

Atek et al. 2014a, ApJ, 786, 60 ; Laporte et al. 2014, A&A, 562, 8; Zitrin et al. 2014, ApJ, 793, 12; Ishigaki et al. 2015, ApJ, 799, 12; Atek et al. 2015, ApJ, 800, 18; Jauzac et al. 2015, MNRAS, 452, 437 ; Wang et al., ApJ, 811, 29

MACS J0416 - z = 0.396
Fully observed

Jauzac et al. 2014, MNRAS, 443, 1549; Lam et al. 2014, ApJ, 797, 98; Jauzac et al. 2015, MNRAS, 446 4132; Grillo et al. 2015, ApJ, 800, 38 ; Harvey et al. 2016, MNRAS, 458, 660 ; Caminha et al., 2016, arXiv1607.0346

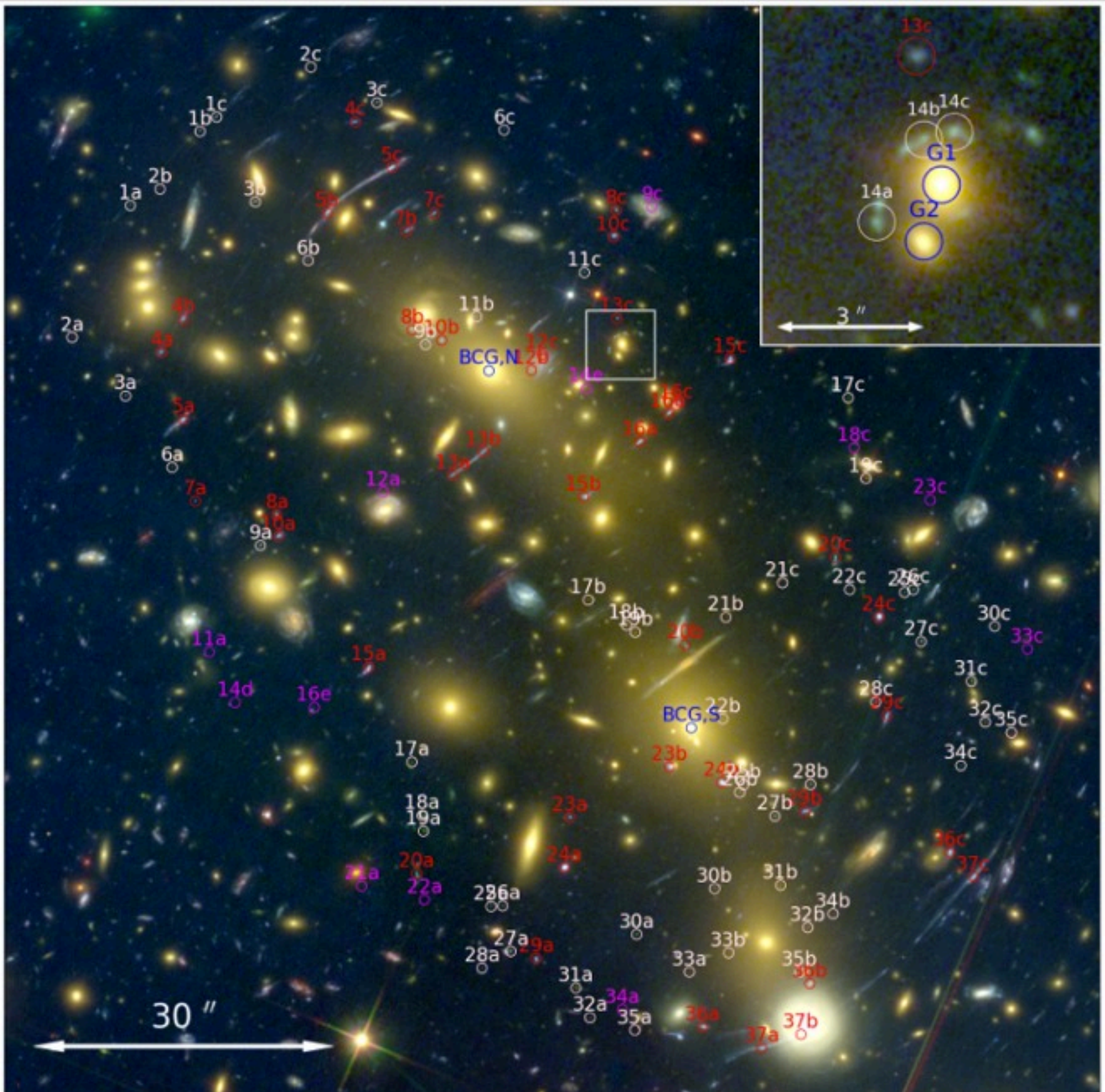
MACS J1149 - z = 0.543
Fully observed
Kelly et al. 2015, *Science, 347, 1123* ; Sharon & Johnson 2015, *ApJ, 800, 26* ; Oguri 2015, *MNRAS, 449, 86* ; Diego et al. 2016, MNRAS, 459, 344 ; Jauzac et al. 2016, MNRAS, 457, 2029 ; Treu et al. 2016, ApJ, 817, 60 ; Grillo et al. 2016, ApJ, 822, 78

Abell S1063 - z = 0.348
Fully observed
Diego et al. 2016, MNRAS 459, 3447

MACS J0717 - z = 0.545
Fully observed
Diego et al. 2015, MNRAS, 451, 3920 ; Limousin et al. 2016, A&A, 588, 99; Kawamata et al. 2016, ApJ, 819, 14

Abell 370 - z = 0.375
ACS to go

Example MACS J0416.1-2403

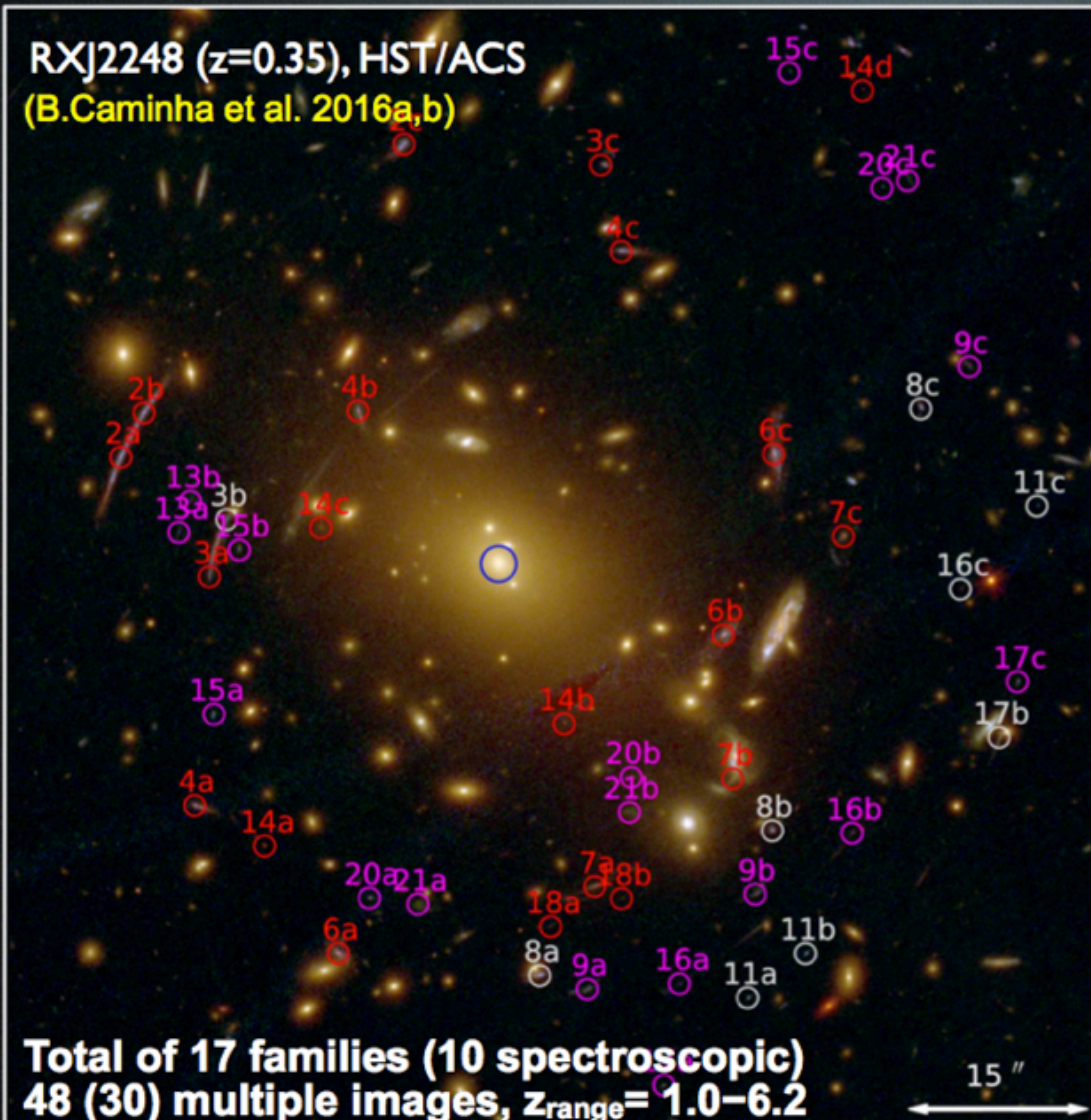


Caminha et al. 2016

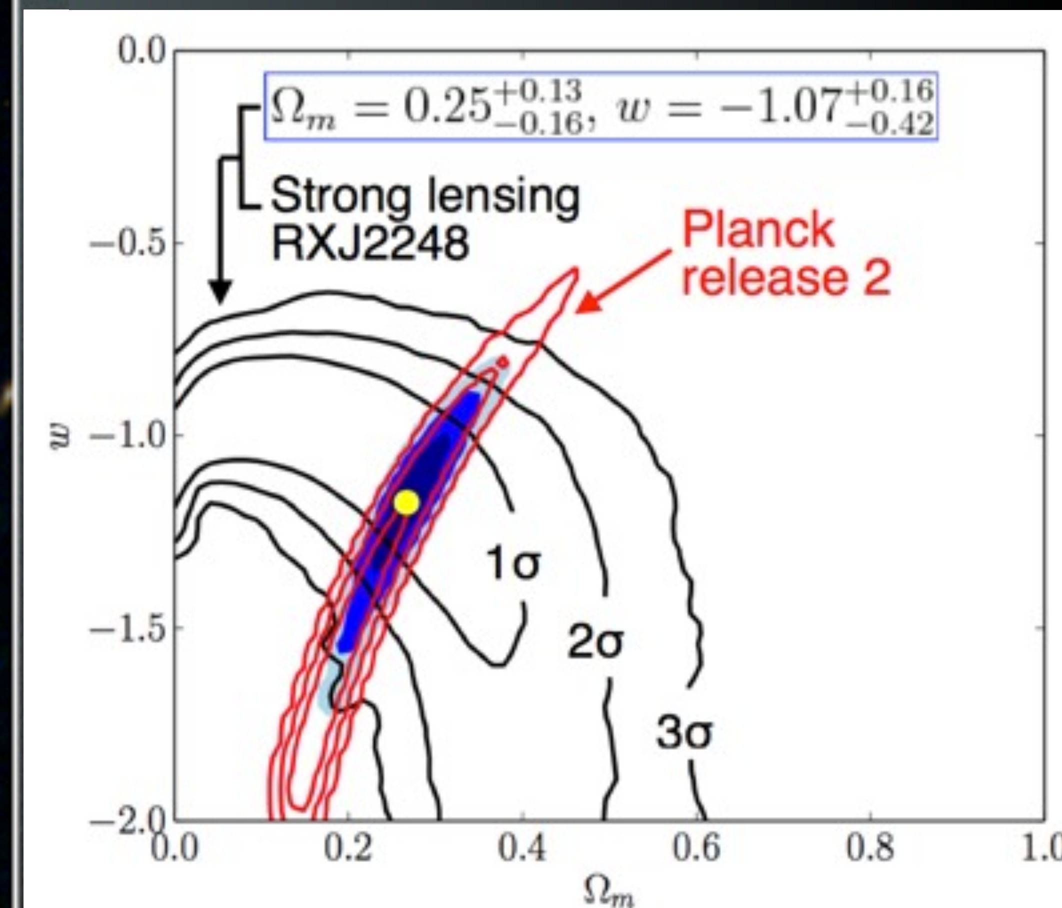
- HST + MUSE IFU
- 102 multiple images!
- Discovery of new systems in the data cube
- Robust determination of projected mass
- Cosmological constraints
- Available redshifts and shear and convergence maps

Frontier Field Cluster AS1063 (aka RXJ2248)

Caminha et al., 2016



MUSE SV programme + GO (PI: K.Caputi)
(Karman et al. 2015)
(W.Karman et al. 2016, arXiv/160601471)

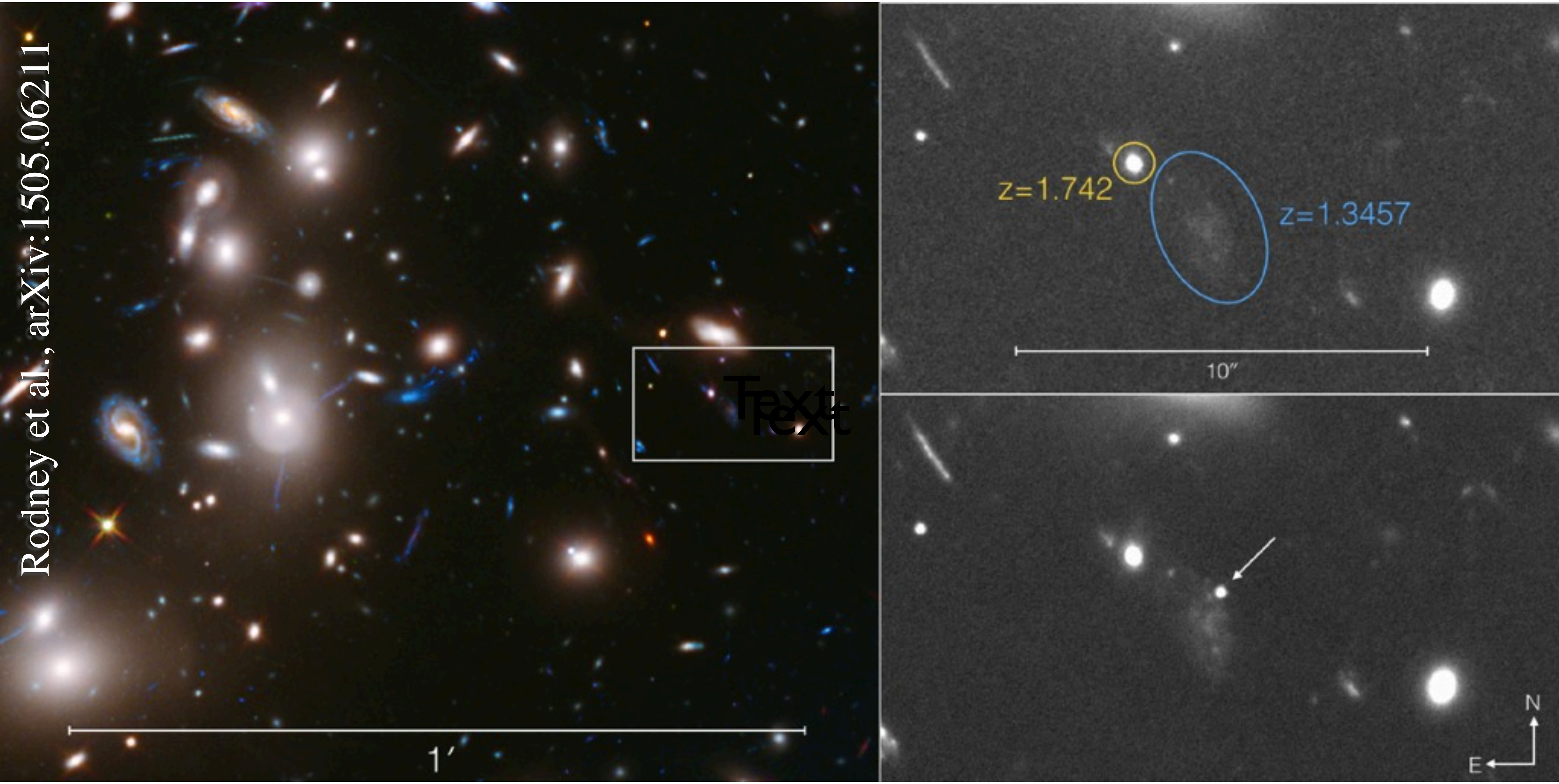


1 arcmin² FoV
2.6 Å resolution (4800-9300 Å)
0.2 arcsec/pxl
Exp. = 5 hrs

Controlling Systematics

- Inverse modeling: ill-posed problem!
    - Check which quantities can be robustly predicted
    - Check robustness with respect to models and data
- Sources of systematics
    - Structure along the line of sight
    - Substructure / correlated mass
    - Mass traces light
    - Which images to choose
- Can be tested with observations and simulations!
    - Project images
    - Additional data (e.g. magnification)
    - Degrading high-quality data
    - Use detailed simulations and test codes and results

Ia supernovae in Abell 2744 (FF)



SNIa with measured light curve: $\mu_{obs} = 2.03 \pm 0.29$

Testing models and inversion codes and constraints for new analyses

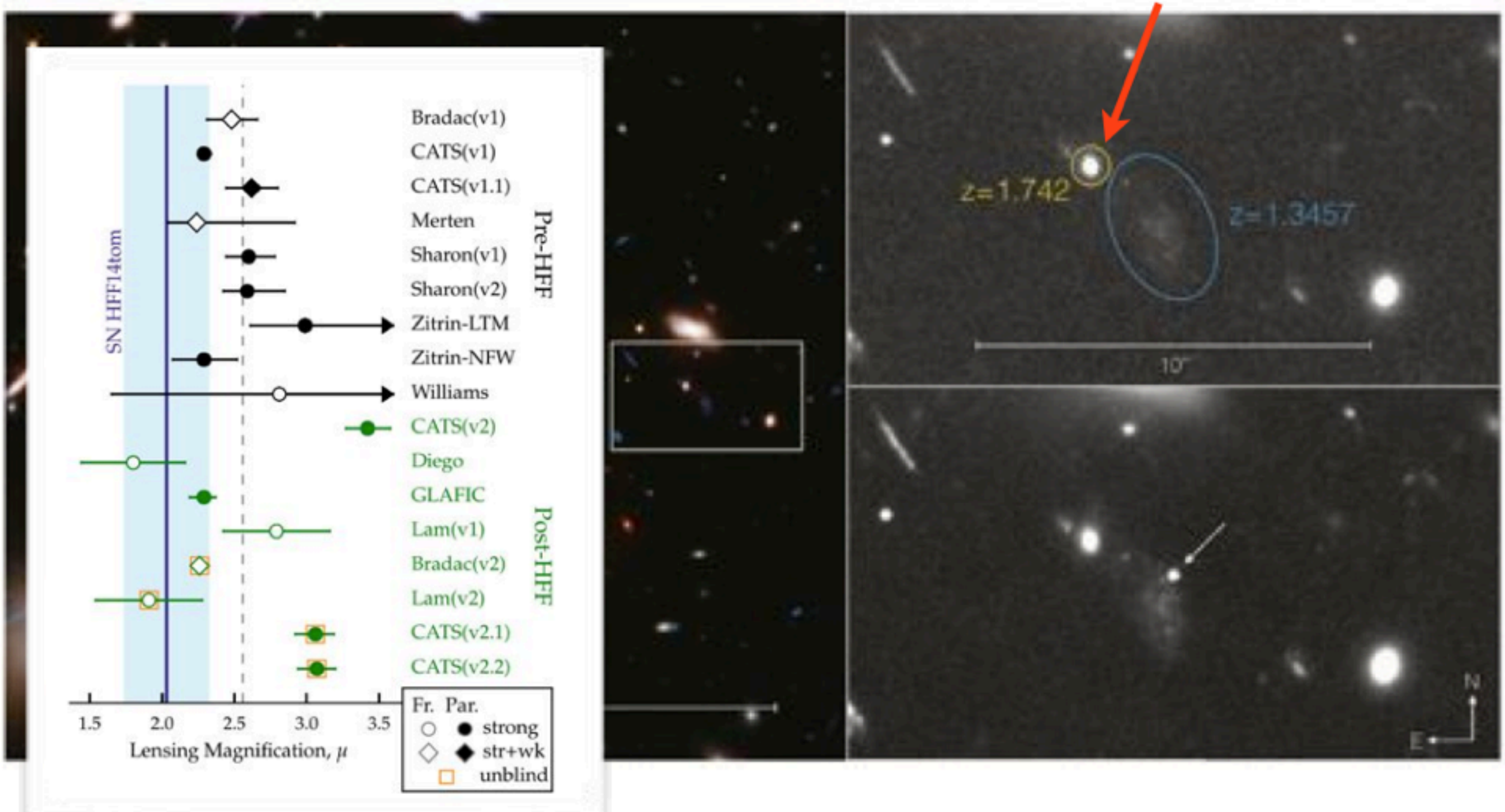
Use measured magnification to test model predictions

- Model assumptions

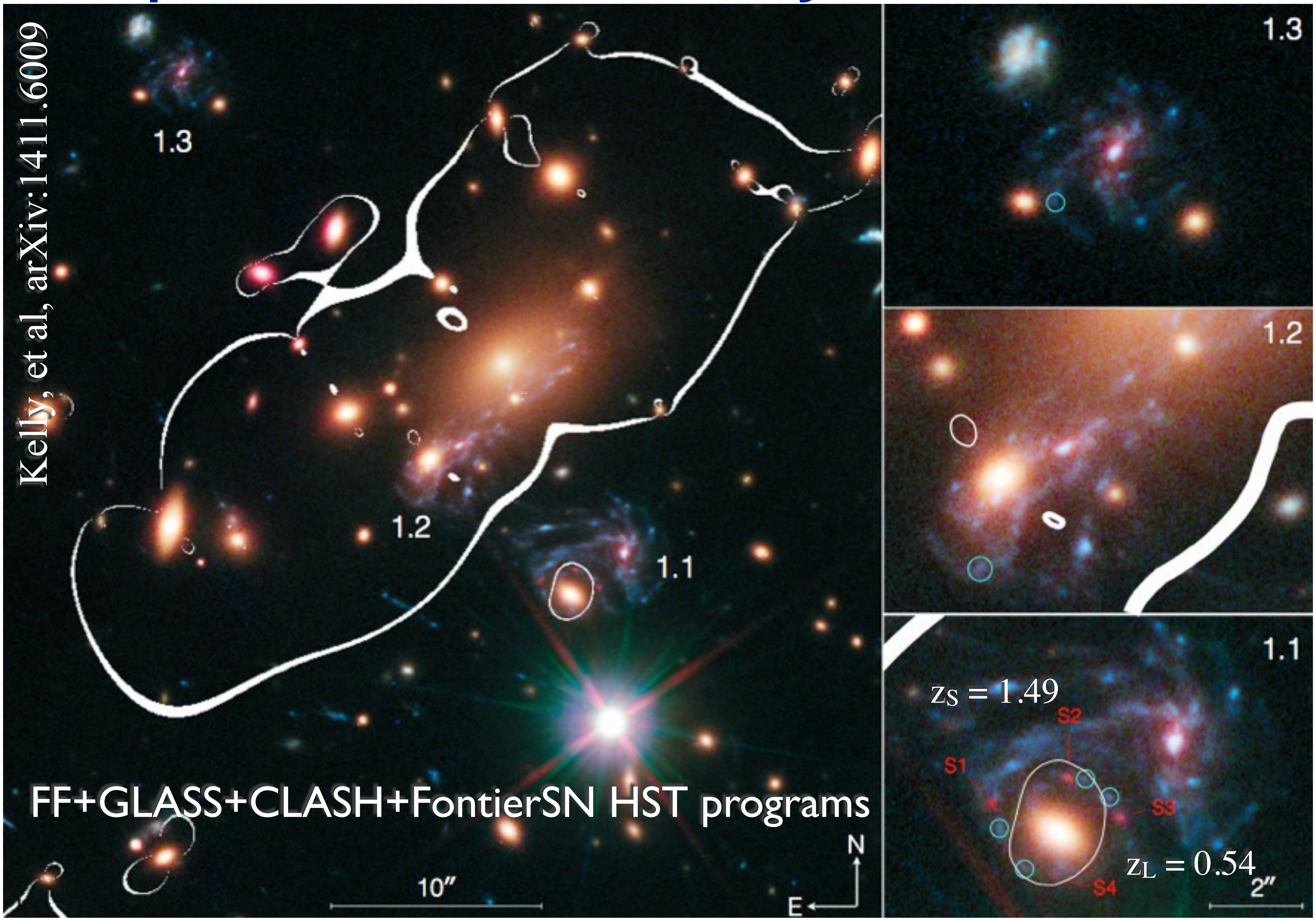
Rodney+15 ApJ

Illuminating a Dark Lens : A Type Ia Supernova Magnified by the Frontier Fields Galaxv Cluster Abell 2744

SN “Tomas”

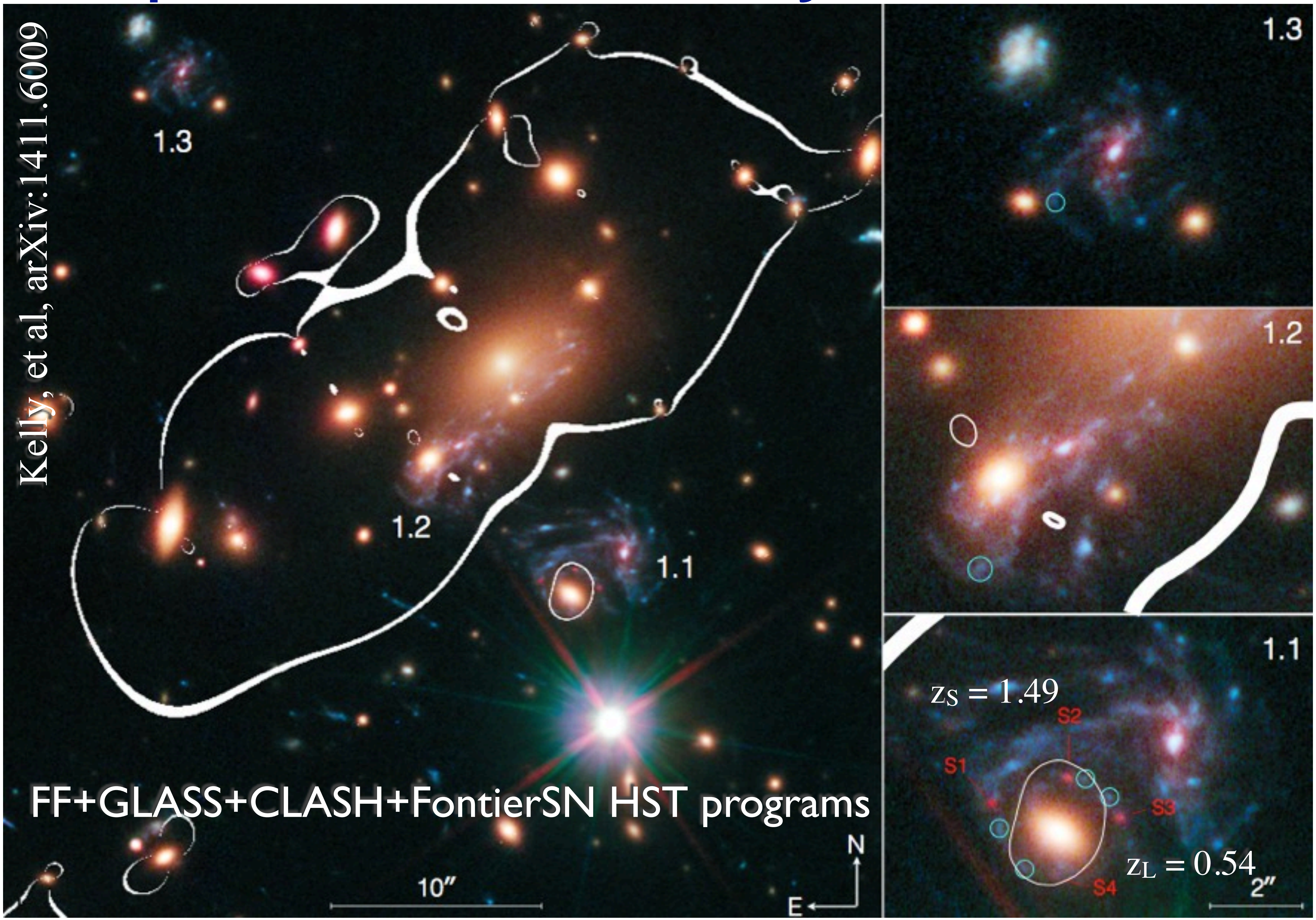


Supernovae in MACS J1149.6+2223



Multiply imaged by an individual galaxy and
+ global potential of the cluster (past/future)

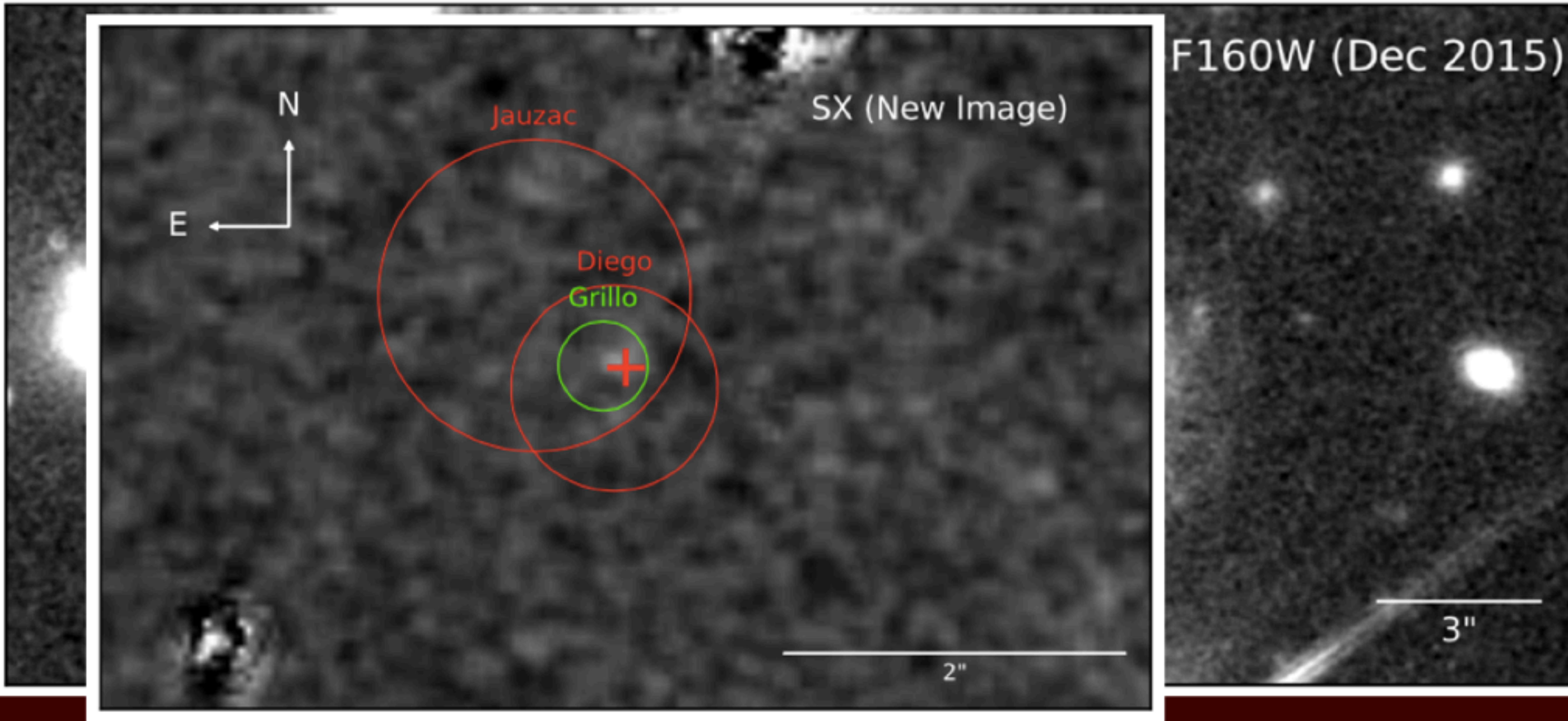
Supernovae in MACS J1149.6+2223



Use prediction for the appearance of multiple images of the SN to test the models

When Refsdal meets Popper!

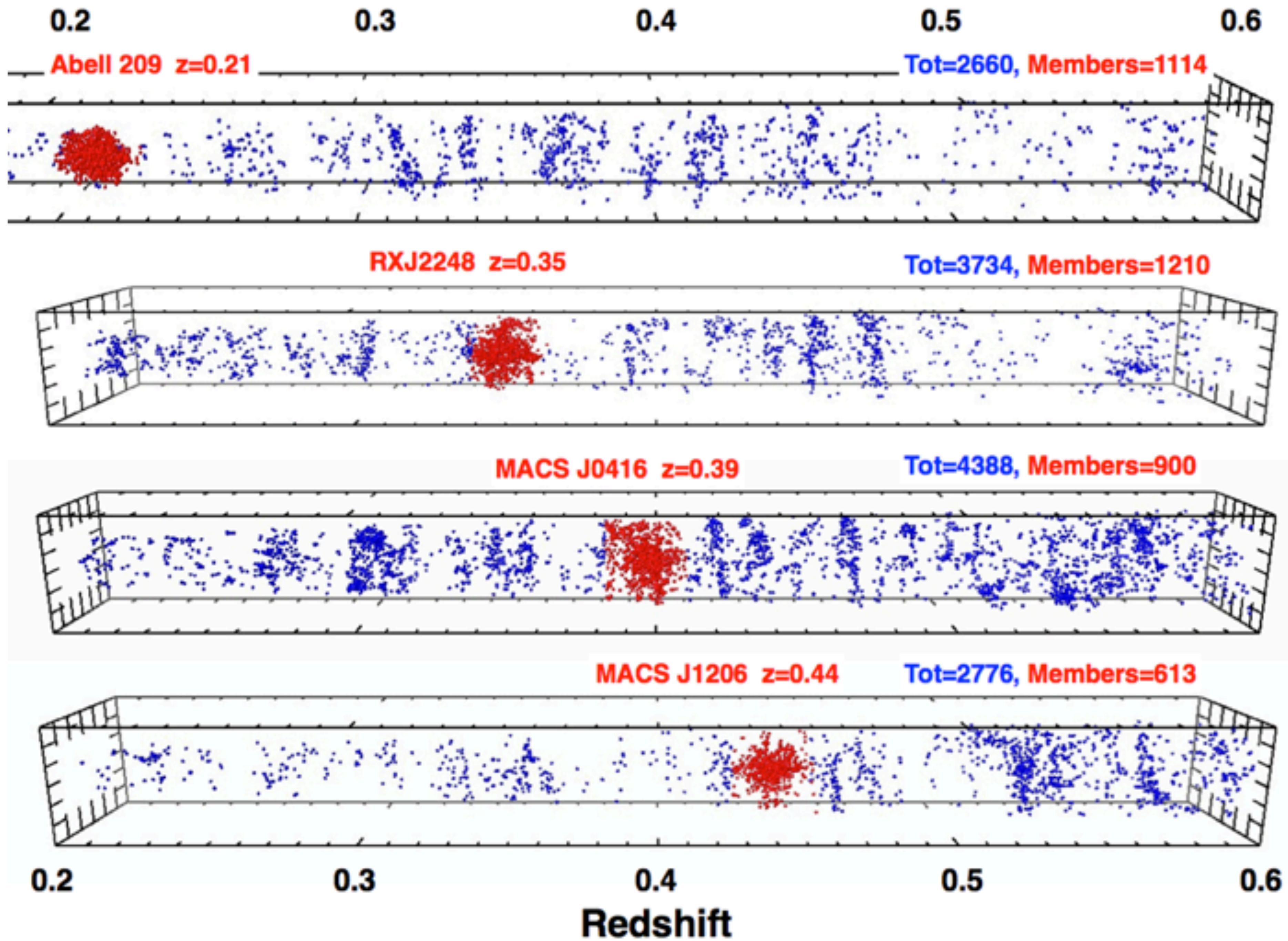
Refsdal returns!



Kelly, Rodney, Treu et al. 2016

Structure along the line of sight

Can be measured from the data and taken into account!

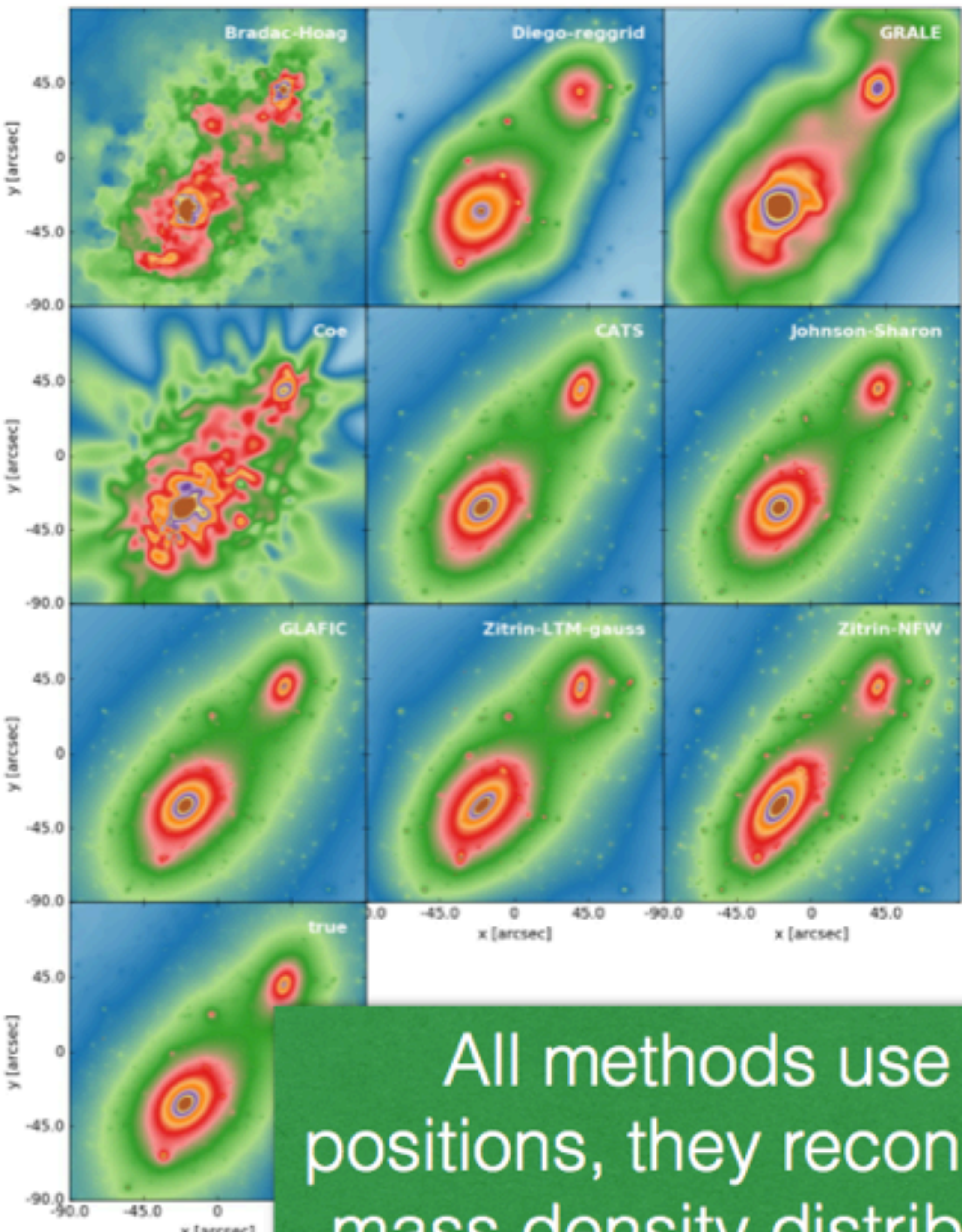


Same for correlated structures close to the lens

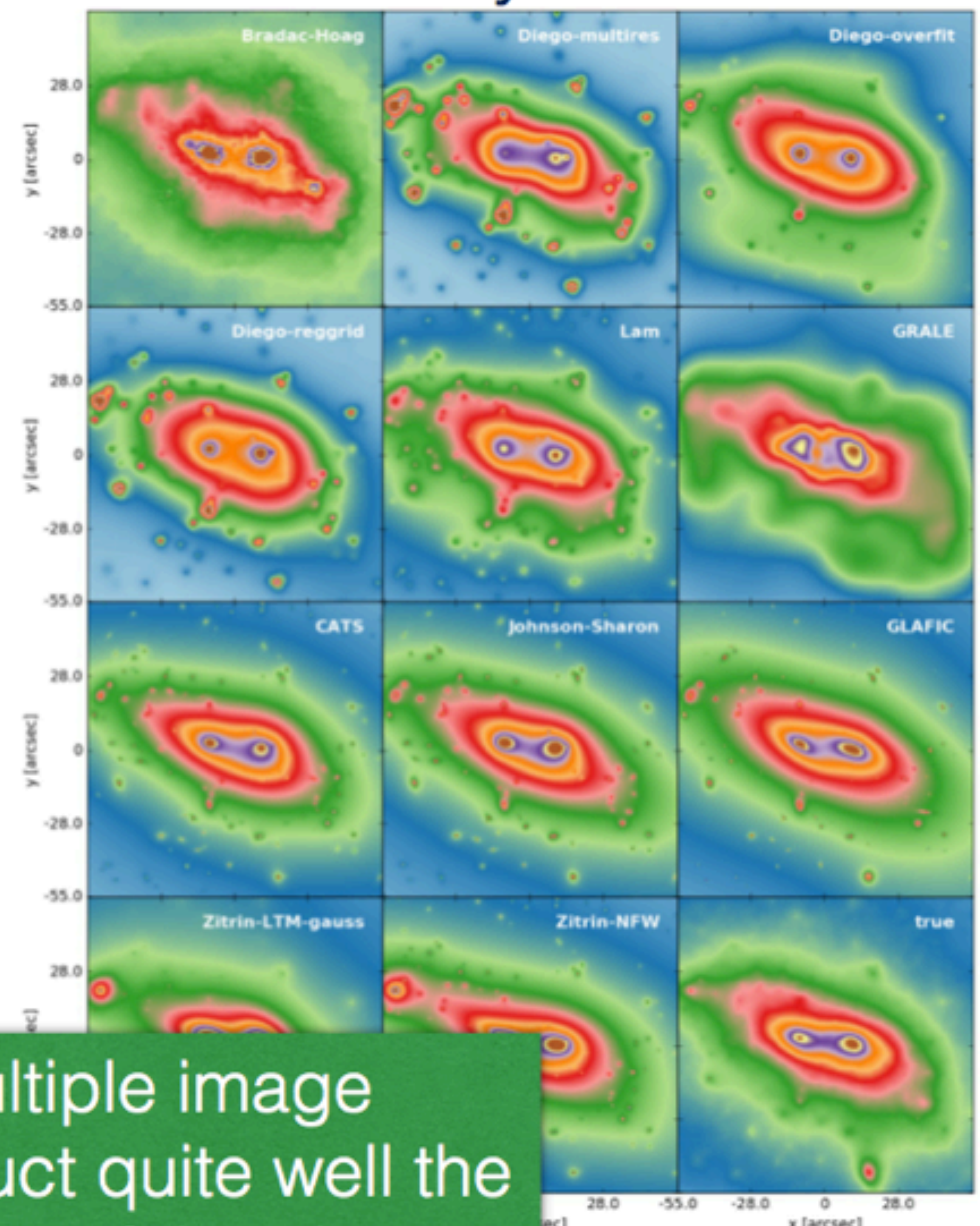
FF Lens Modeling Comparison Project

Use simulated clusters to test different model reconstructions

MOKA cluster



N-Body cluster



All methods use multiple image positions, they reconstruct quite well the mass density distribution of the cluster and the location of the critical lines.

Meneghetti+16

Additional constraints on cosmology

- Gravitational telescopes: luminosity function of ultra-fraint UV galaxies at z ~ 6

A STRINGENT LIMIT ON THE WARM DARK MATTER PARTICLE MASSES FROM THE ABUNDANCE OF $z = 6$ GALAXIES IN THE HUBBLE FRONTIER FIELDS

N. Menci[1], A. Grazian[1,2], M. Castellano[1], and N. G. Sanchez[3]

Published 2016 June 23 •

The Astrophysical Journal Letters, Volume 825, Number 1

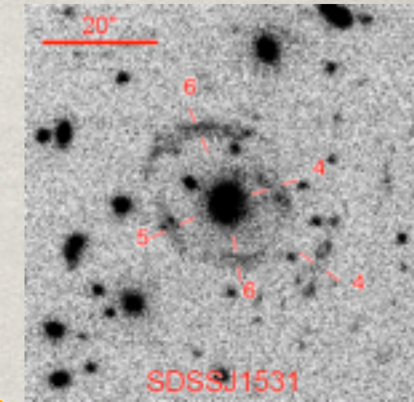
- Mass of thermal relic WDM particles $m_{\mathrm{X}} \geq 2.1$ keV at 3σ.

- If sterile neutrinos are responsible for the 3.5 keV line reported in observations of X-ray clusters, m_{sterile} 6.1 keV (neutrinos produced via the Shi–Fuller mechanism)

- Time delays + mass model + lens dynamics:

$\rightarrow D_A(0, z_L)$ (Jee, I.; Komatsu, E.; Suyu, S. H., JCAP, 2015)

STATISTICS: WIDE-FIELD SURVEYS



Homogeneous Strong Lensing Samples (arcs)

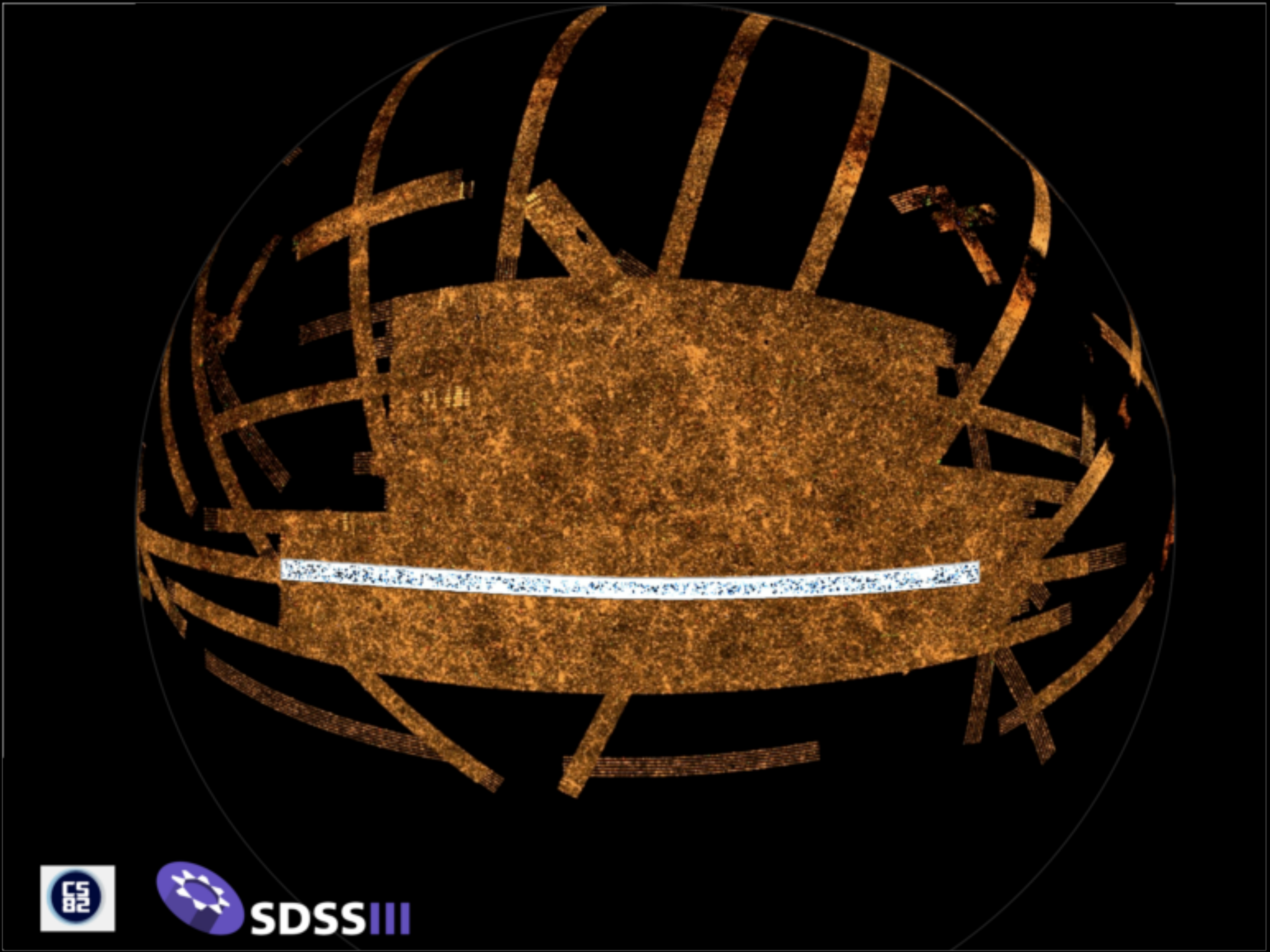
- until now: $\mathcal{O}(10^2)$ systems
  - Spectroscopy + HST: SLACS, BELLS
  - $\mathcal{O}(10^2)$ deg^2 surveys: CFHTLS/SL2S, SOGRAS, CS82
- 2016-2018: $\mathcal{O}(10^3)$ systems
  - $\mathcal{O}(10^3)$ deg^2 surveys: KiDS, DECaLS, RCSLens, DES
- $>$ 2020: $\mathcal{O}(10^4 - 10^5)$ systems
  - LSST, WFIRST, EUCLID
  - DESI, Subaru PFS/SUMIRE

DARK ENERGY SURVEY

Challenges

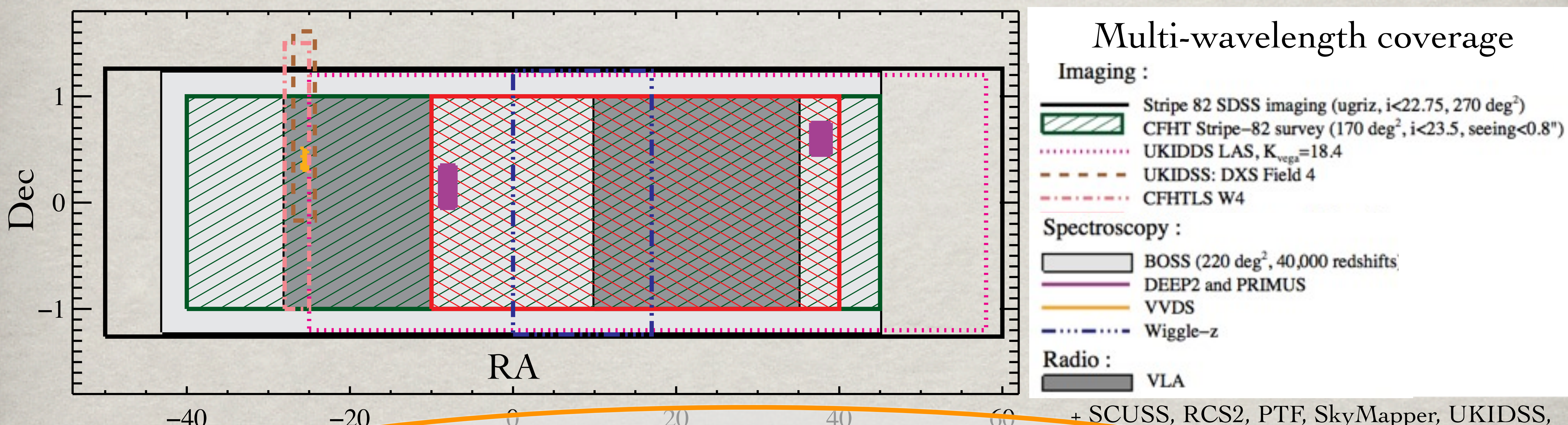
- arcfinding codes: completeness and purity
- automated analyses (including z)
- ☑ Simulations + arcfinders + inverse modelling

SDSS Stripe 82



Stripe 82 @ 2011

- SDSS repeated imaging, coadds 2 mag deeper
- Photo-z and cluster catalogs form SDSS coadds
- Spectroscopy from SDSS-I/II (Wiggle-z and deep fields)
- Emerging multi-wavelength coverage (UKIDSS, VLA)



+ SCUSS, RCS2, PTF, SkyMapper, UKIDSS, Galex, ACT, VISTA, PanSTARRS...

- CFHT Stripe 82 Survey (CS82): The weak lensing survey in S82
  - ✓ 170 deg2, down to i = 24 and superb median seeing of 0.6”

WEAK-LENSING MASS CALIBRATION OF THE ATACAMA COSMOLOGY TELESCOPE EQUATORIAL SUNYAEV-ZELDOVICH CLUSTER SAMPLE WITH THE CANADA-FRANCE-HAWAII TELESCOPE STRIPE 82 SURVEY

arXiv:1509.08930

N. Battaglia[1], A. Leauthaud[2], H. Miyatake[1,2,3], M. Hasselfield[1], M. B. Gralla[4,5], R. Allison[6], J. R. Bond[7], E.

Measuring subhalo mass in redMaPPer clusters with CFHT Stripe 82 Survey

MNRAS, 458, 2573, 2016

Ran Li[1⋆], Huanyuan Shan[2], Jean-Paul Kneib[2,3], Houjun Mo[4], Eduardo
Alexie Leauthaud[6], John Moustakas[7], Lizhi Xie[8], Thomas Erben[9], Ludo

Monthly Notices of the Royal Astronomical Society
MNRAS 450, 2888–2902 (2015) doi:10.1093/mnras/stv784

Cosmological constraints from weak lensing peak statistics with Canada–France–Hawaii Telescope Stripe 82 Survey

Xiangkun Liu,[1⋆] Chuzhong Pan,[1] Ran Li,[2] Huanyuan Shan,[3] Qiao Wang,[2]
Liping Fu,[4] Zuhui Fan,[1,5⋆] Jean-Paul Kneib,[3,6] Alexie Leauthaud,[7]
Ludovic Van Waerbeke,[8] Martin Makler,[9] Bruno Moraes,[10,11] Thomas Erben[12]

The Mass-Concentration Relation and the Stellar-to-Halo Mass Ratio in the CFHT Stripe 82 Survey

arXiv:1502.00313

HuanYuan Shan[1⋆], Jean-Paul Kneib[1,2], Ran Li[3],
Thomas Erben[6], Martin Makler,[7] Bruno Moraes,
James E. Taylor[11], Aldée Charbonnier[12]

PHYSICAL REVIEW D 91, 062001 (2015)

(editor's suggestion)

First measurement of the cross-correlation of CMB lensing and galaxy lensing

Nick Hand,[1,*] Alexie Leauthaud,[2] Sudeep Das,[3,4] Blake D. Sherwin,[5,6,4] Graeme E. Addison,[7]
J. Richard Bond,[8] Erminia Calabrese,[9] Aldée Charbonnier,[10,11] Mark J. Devlin,[12] Joanna Dunkley,[9]
Thomas Erben,[13] Amir Hajian,[8] Mark Halpern,[7] Joachim Harnois-Déraps,[7,8,14] Catherine Heymans,[15]
Hendrik Hildebrandt,[13] Adam D. Hincks,[7] Jean-Paul Kneib,[16,17] Arthur Kosowsky,[18] Martin Makler,[11]

Monthly Notices of the Royal Astronomical Society
MNRAS 442, 2534–2542 (2014)

Weak lensing mass map and peak statistics in Canada–France–Hawaii Telescope Stripe 82 survey

HuanYuan Shan,[1⋆] Jean-Paul Kneib,[1,2] Johan Comparat,[2] Eric J
Aldée Charbonnier,[4,5] Thomas Erben,[6] Martin Makler,[5] Bruno M

Monthly Notices of the Royal Astronomical Society
MNRAS Advance Access published January 4, 2014
MNRAS (2014) doi:10.1093/mnras/stt2395

MNRAS, 438, 2864 (2014)

First galaxy–galaxy lensing measurement of satellite halo mass in the CFHT Stripe-82 Survey

Ran Li,[1⋆] Huanyuan Shan,[2] Houjun Mo,[3] Jean-Paul Kneib,[2,4] Xiaohu Yang,[5,6]
Wentao Luo,[6] Frank C. van den Bosch,[7] Thomas Erben,[8] Bruno Moraes[9]
and Martin Makler[9]

Monthly Notices of the Royal Astronomical Society
MNRAS 433, 1146–1160 (2013)
Advance Access publication 2013 June 3

Stochastic bias of colour-selected BAO tracers by joint clustering–weak lensing analysis

Johan Comparat,[1⋆] Eric Jullo,[1] Jean-Paul Kneib,[1,2] Carlo Schimd,[1] HuanYuan Shan,[2,3]
Thomas Erben,[4] Olivier Ilbert,[1] Joel Brownstein,[5] Anne Ealet,[6] Stephanie Escoffier,[6]
Bruno Moraes,[7,8] Nick Mostek,[9] Jeffrey A. Newman,[10] M. E. S. Pereira,[7,8]

+ fossil groups; compact galaxies;
VT clusters; BOSS galaxies; satellites...

Stripe 82 @ 2016

- SDSS repeated imaging, coadds 2 mag deeper
- Photo-z and cluster catalogs form SDSS coadds
- Spectroscopy from SDSS-I/II (Wiggle-z and deep fields)
- Emerging multi-wavelength coverage (UKIDSS, VLA Stripe 82)
- Increased spectroscopic coverage from BOSS and eBOSS
- VISTA-CFHT Stripe 82 survey (VICS82) in J and Ks, 140 sq-deg (+VHS-DES)
- The Spitzer-IRAC Equatorial Survey (SpIES), 115 sq-deg
- Stripe 82 X-ray Survey (S82X), 31 sq-deg
- Herschel HerMES Large Mode Survey (HeLMS)

The Astrophysical Journal, 817:172 (21pp), 2016 February 1
doi:10.3847/0004-637X/817/2/172

CrossMark

THE 31 DEG^2 RELEASE OF THE STRIPE 82 X-RAY SURVEY: THE POINT SOURCE CATALOG

Stephanie M. LaMassa[1,2,3], C. Megan Urry[1,2], Nico Cappelluti[4], Hans Böhringer[5], Andrea Comastri[4], Eilat Glikman[6], Gordon Richards[7], Tonima Ananna[1,2], Marcella Brusa[4,8], Carie Cardamone[9], Gayoung Chon[5], Francesca Civano[1,10], Duncan Farrah[11], Marat Gilfanov[12,13], Paul Green[10], S. Komossa[14], Paulina Lira[15], Martin Makler[16], Stefano Marchesi[1,4,10], Robert Pecoraro[1,2], Piero Ranalli[4,17], Mara Salvato[5], Kevin Schawinski[18], Daniel Stern[19], Ezequiel Treister[20], and Marco Viero[21,22]

SpIES: THE *SPITZER* IRAC EQUATORIAL SURVEY

John D. Timlin[1,*], Nicholas P. Ross[1,2], Gordon T. Richards[1], Mark Lacy[3], Erin L. Ryan[4], Robert B. Stone[1], Franz E. Bauer[5,6,7], W. N. Brandt[8,9,10], Xiaohui Fan[11], Eilat Glikman[12], Daryl Haggard[13], Linhua Jiang[14], Stephanie M. LaMassa[15], Yen-Ting Lin[16], Martin Makler[17], Peregrine McGehee[18], Adam D. Myers[19], Donald P. Schneider[8,9], C. Megan Urry[15], Edward J. Wollack[20], Nadia L. Zakamska[21]

Stripe 82 @ 2016

- SDSS repeated imaging, coadds 2 mag deeper
- Photo-z and cluster catalogs form SDSS coadds
- Spectroscopy from SDSS-I/II (Wiggle-z and deep fields)
- Emerging multi-wavelength coverage (UKIDSS, VLA Stripe 82)
- Increased spectroscopic coverage from BOSS and eBOSS
- VISTA-CFHT Stripe 82 survey (VICS82) in J and Ks, 140 sq-deg (+VHS-DES)
- The Spitzer-IRAC Equatorial Survey (SpIES), 115 sq-deg
- Stripe 82 X-ray Survey (S82X), 31 sq-deg
- Herschel HerMES Large Mode Survey (HeLMS)
- \+ DES, HSC, J-PAS

....

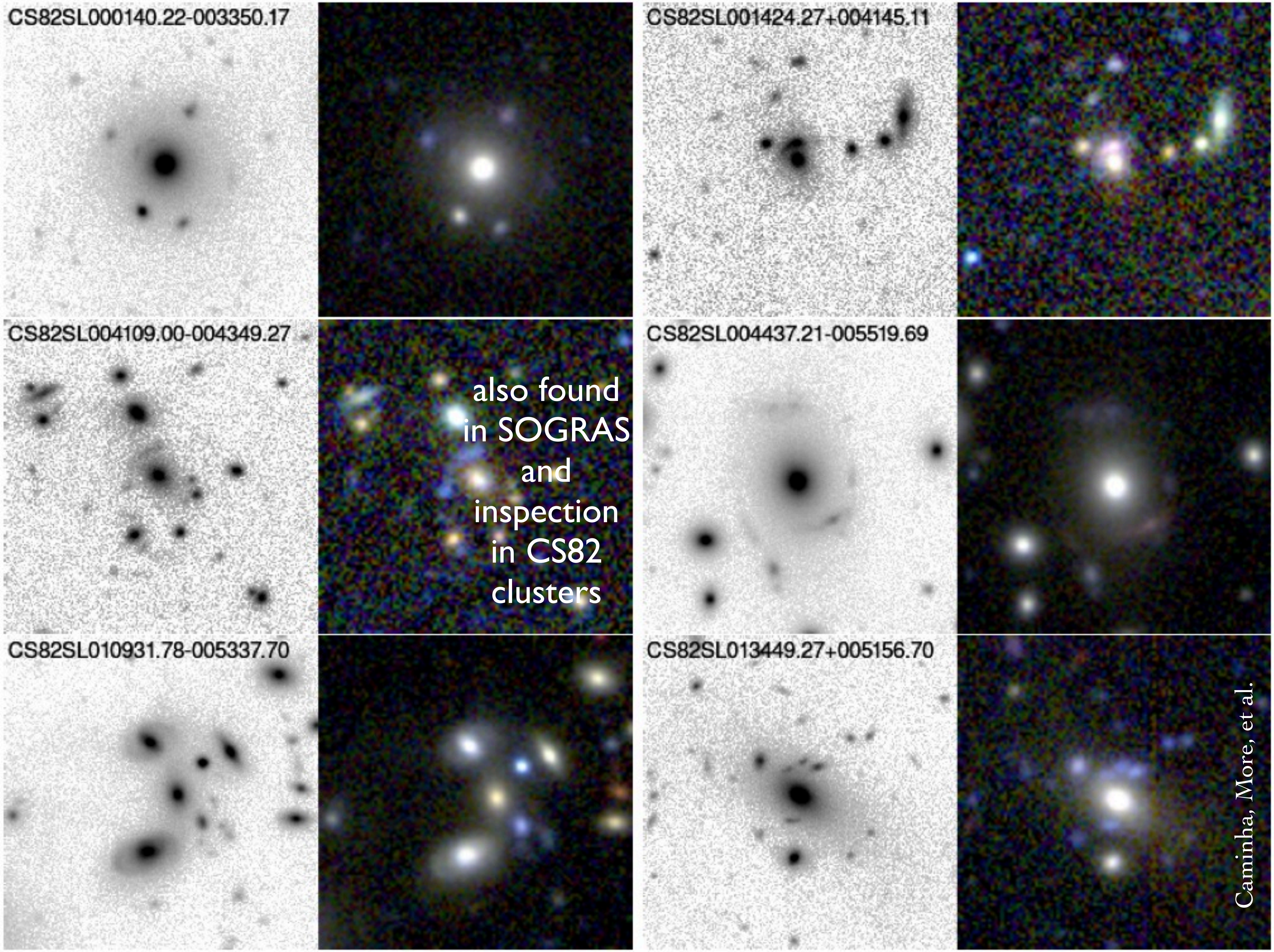
~ KiDS/GAMA

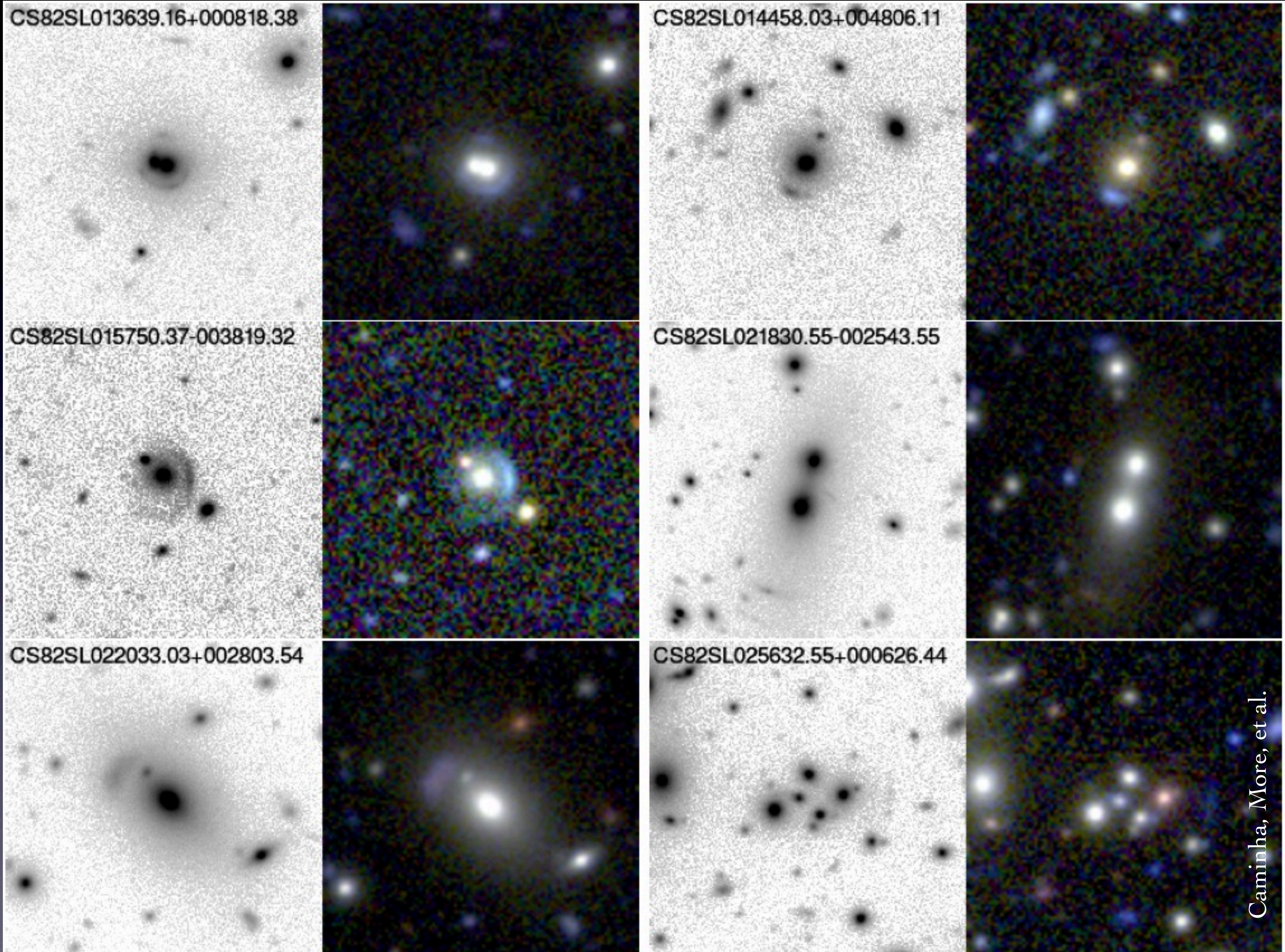
Gravitational arcs: finding and modeling

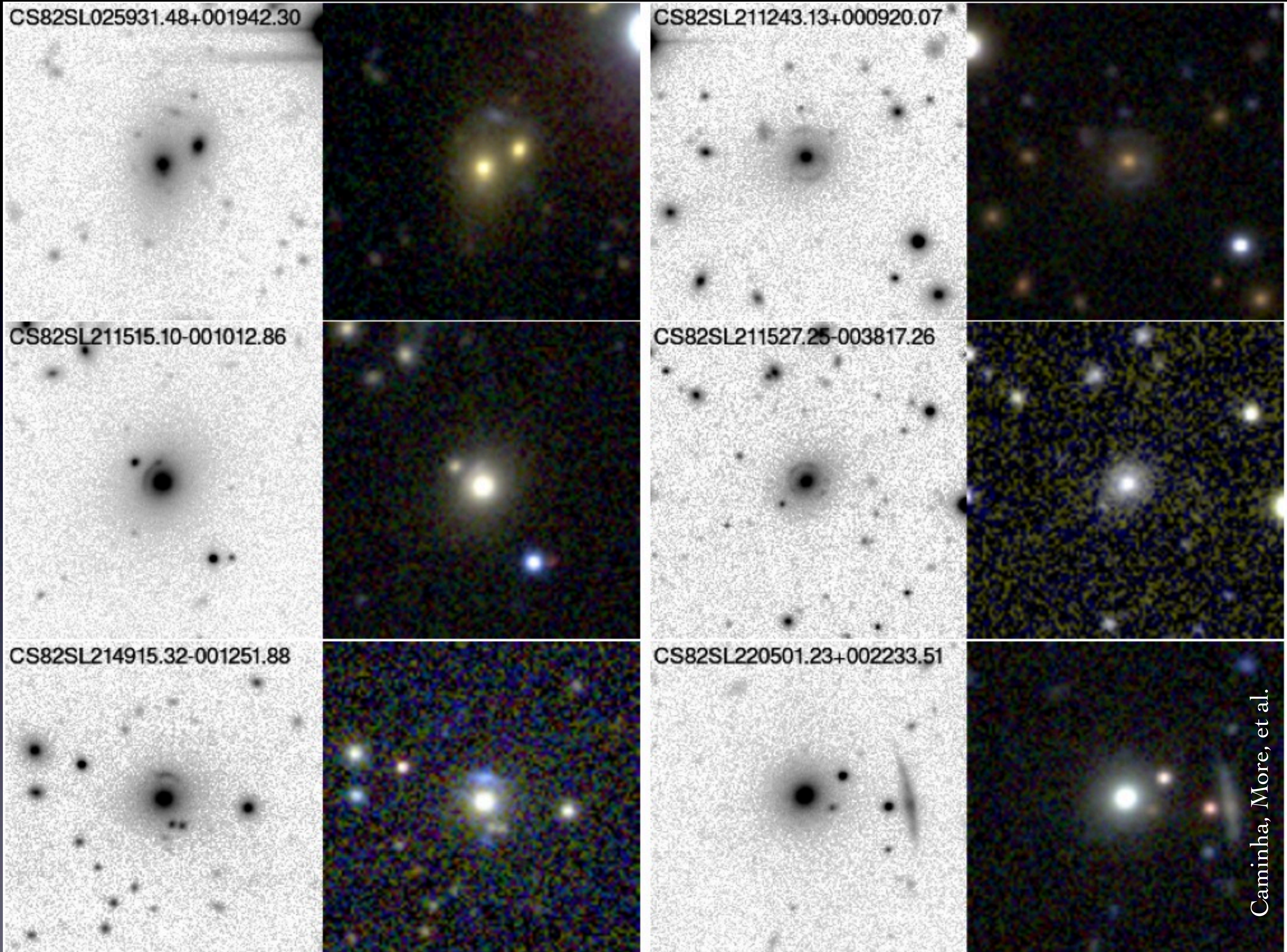
Semi-automated arcfinding

- More-Alard Arcfinder (More et al., arXiv:1109.1821)
- 127000 candidates visually inspected!
- 10 volunteers (every candidate inspected by 2 people)

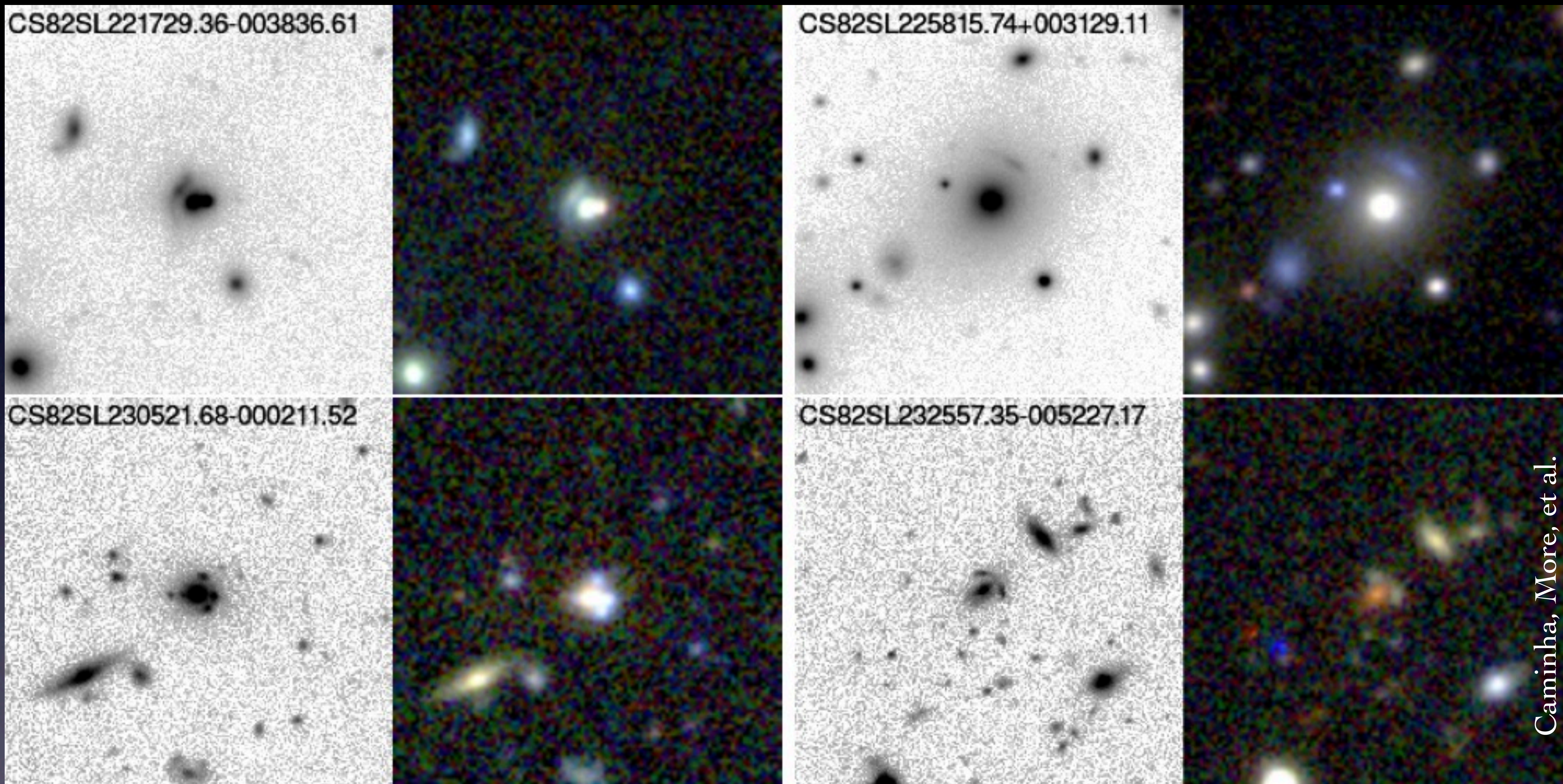
  + java applet (More et al.) for quick view
- 18 excellent candidates


CS82SL000140.22-003350.17
CS82SL001424.27+004145.11
CS82SL004109.00-004349.27
also found in SOGRAS and inspection in CS82 clusters
CS82SL004437.21-005519.69
CS82SL010931.78-005337.70
CS82SL013449.27+005156.70
Caminha, More, et al.


CS82SL013639.16+000818.38
CS82SL014458.03+004806.11
CS82SL015750.37-003819.32
CS82SL021830.55-002543.55
CS82SL022033.03+002803.54
CS82SL025632.55+000626.44
Caminha, More, et al.

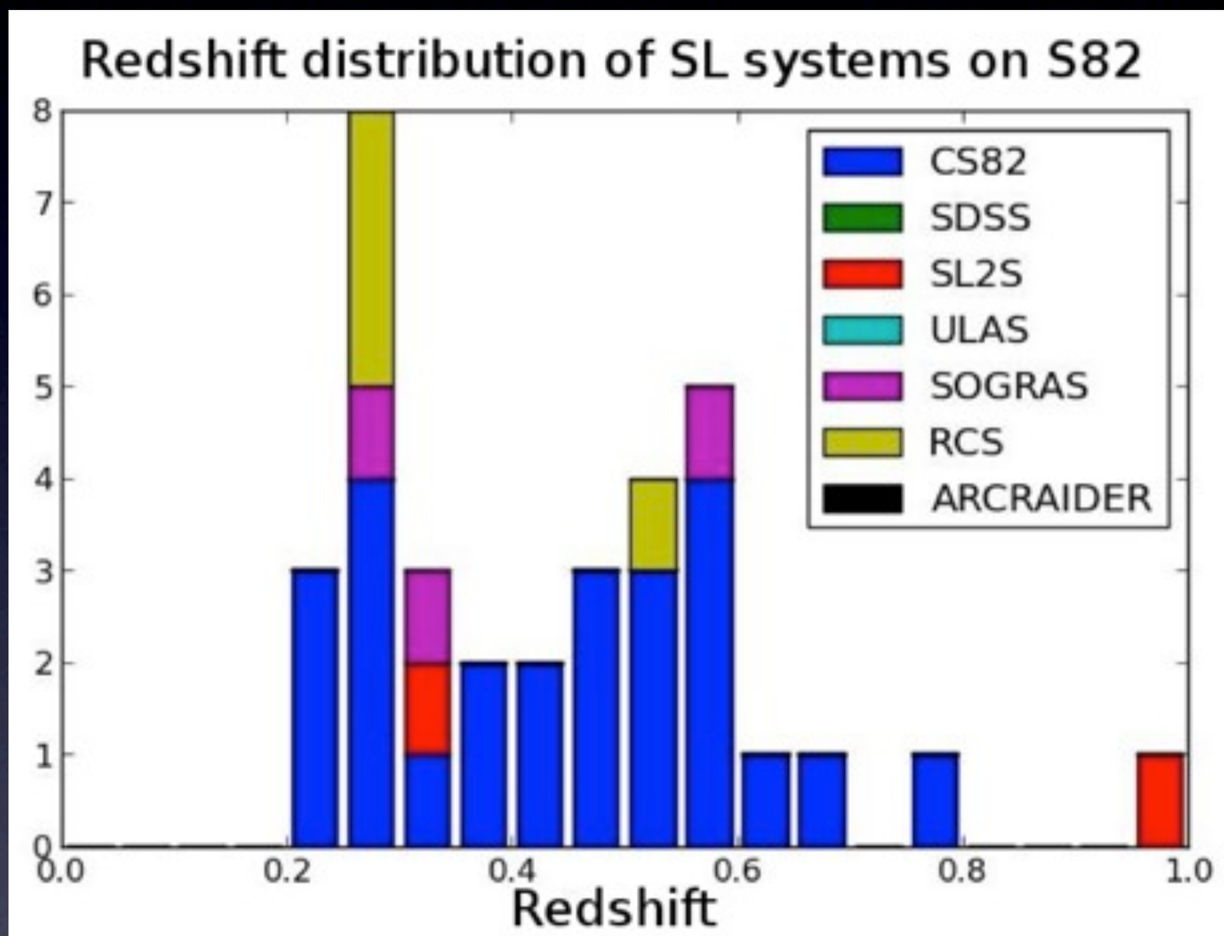


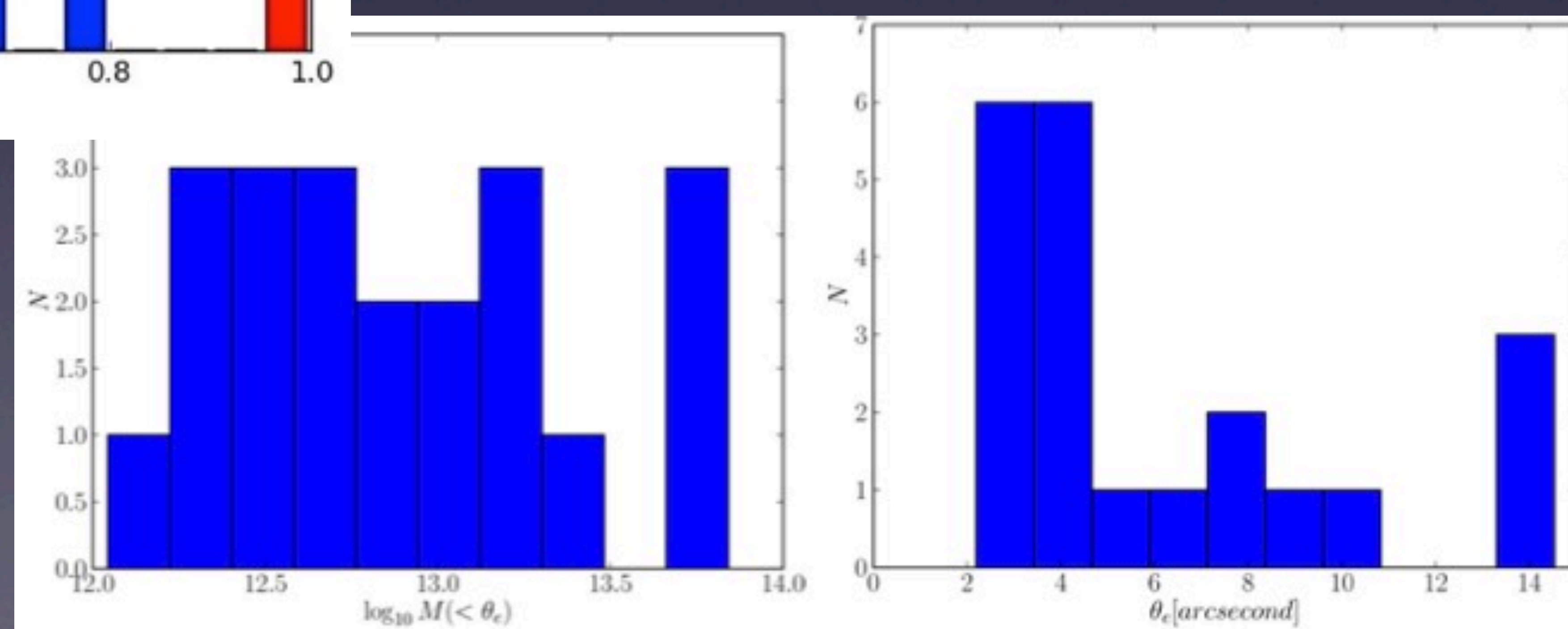
Caminha, More, et al.



Caminha, More, et al.

CS82 Arc Candidates





Search in selected fields

Multiple target selection and inspections

- Optical cluster catalogs
- x-ray (S82X, XCS, RASS-BSC), SZE (Planck, ACT)
- Weak Lensing Peaks (new!)
- Luminous Red Galaxies

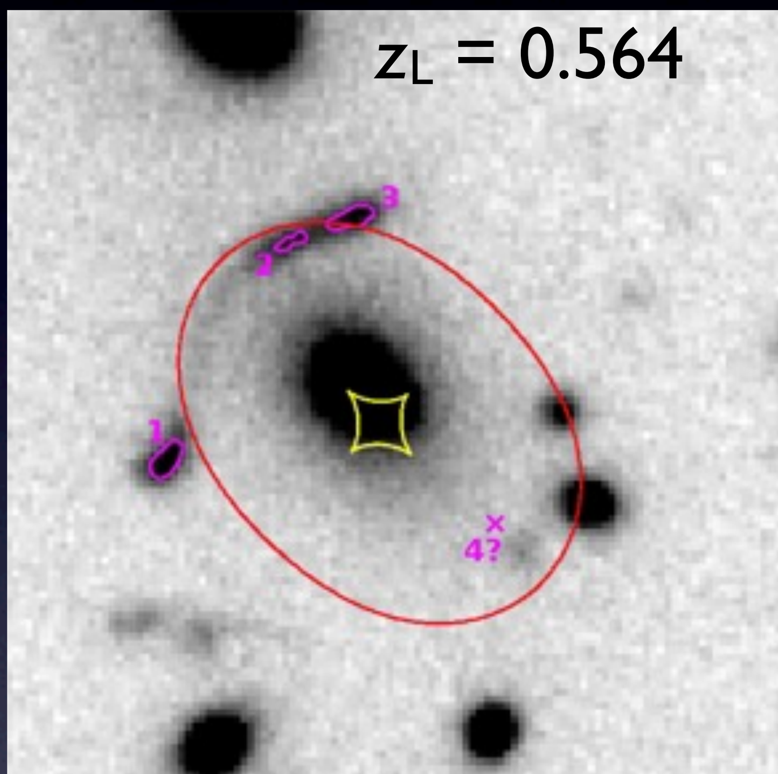
> Additional 20 candidates and counting...

- + VICS82 (SpaceWarps)

Need multiple search criteria

Inverse Modelling

CS82SL00:41:09-00:43:49



Modelling with lenstool (Jullo, Kneib)

Fit 1: 3 images

Fit 2: 4 images

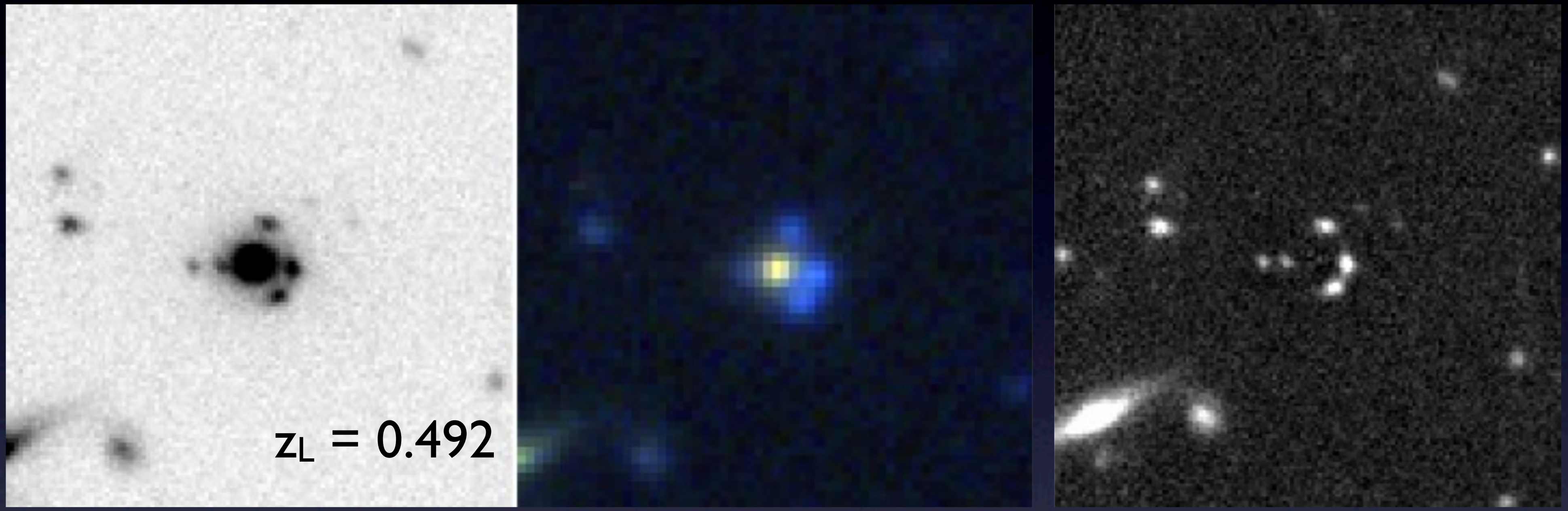
	Fit 1	Fit 2
$\sigma_v[km/s]$	622^{+11}_{-13}	642^{+3}_{-3}
$\theta_{or}[°]$	$135.2^{+0.7}_{-0.8}$	$135.2^{+1.5}_{-1.3}$
$x_{lente}['']$	$0.50^{+0.2}_{-0.2}$	$0.50^{+0.05}_{-0.06}$
$y_{lente}['']$	$-0.76^{+0.17}_{-0.15}$	$-0.86^{+0.06}_{-0.03}$
ε	—	$0.13^{+0.02}_{-0.03}$
χ^2/dof	0.25	0.22

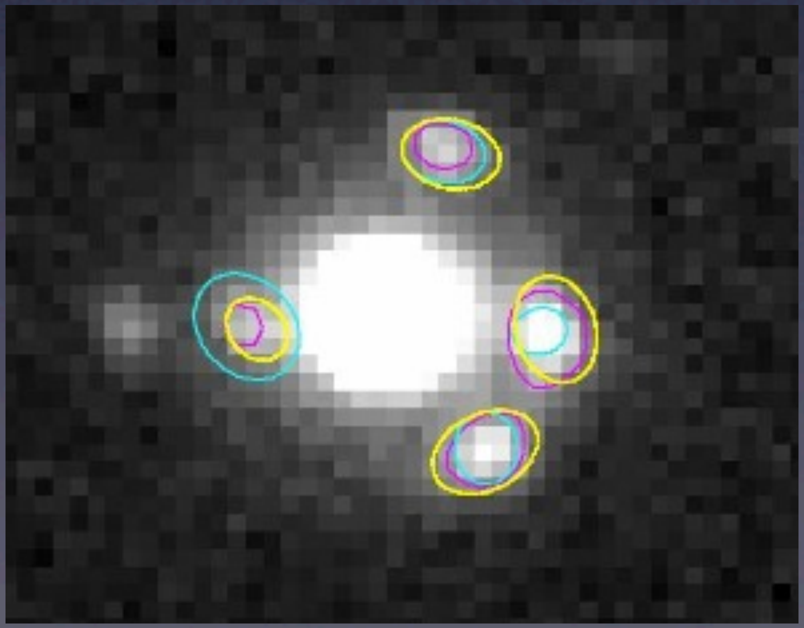
BCG Spectrum in SDSS $\sigma_v^{\mathrm{BCG}} = 312 \pm 46$

Detected in VICS82 $z_S^{\mathrm{phot}} = 1.27$

Towards automation

CS82SL23:05:21-00:02:11



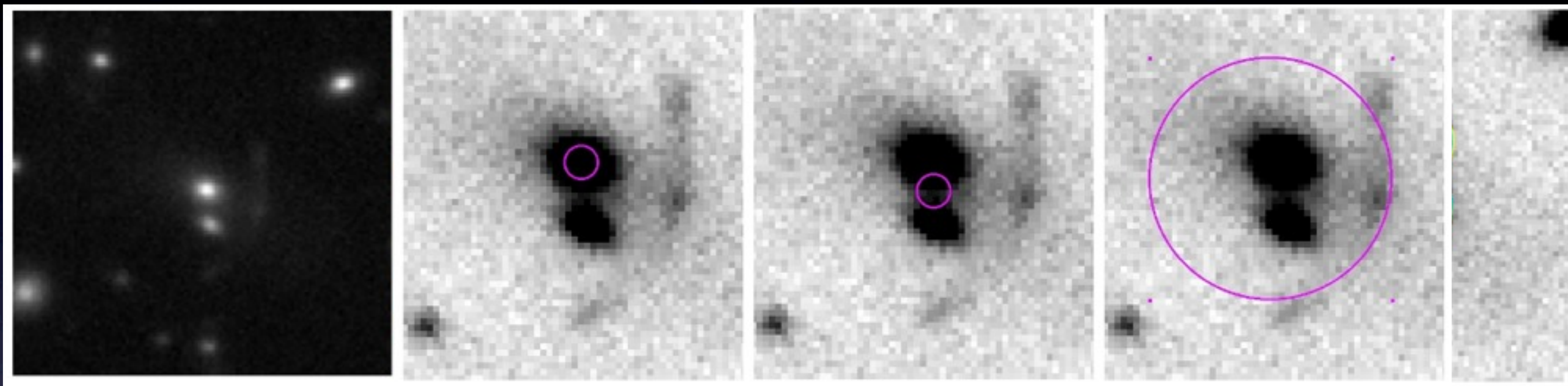


Testing schemes to determine the peaks

Parameter	Best DS9	Best barycenter	Best bright
x (arcsec)	-0.21 ± 0.04	-0.24 ± 0.05	0.05 ± 0.06
y (arcsec)	0.06 ± 0.03	0.05 ± 0.03	0.03 ± 0.03
ellipticity	0.44 ± 0.04	0.47 ± 0.04	0.26 ± 0.07
θ (deg)	5.85 ± 15.91	7.24 ± 11.36	3.51 ± 14.46
σ (km/s)	390.63 ± 2.51	384.11 ± 2.62	381.19 ± 2.76

Robustness of inversion

CS82SL01:58:24-0:40:00



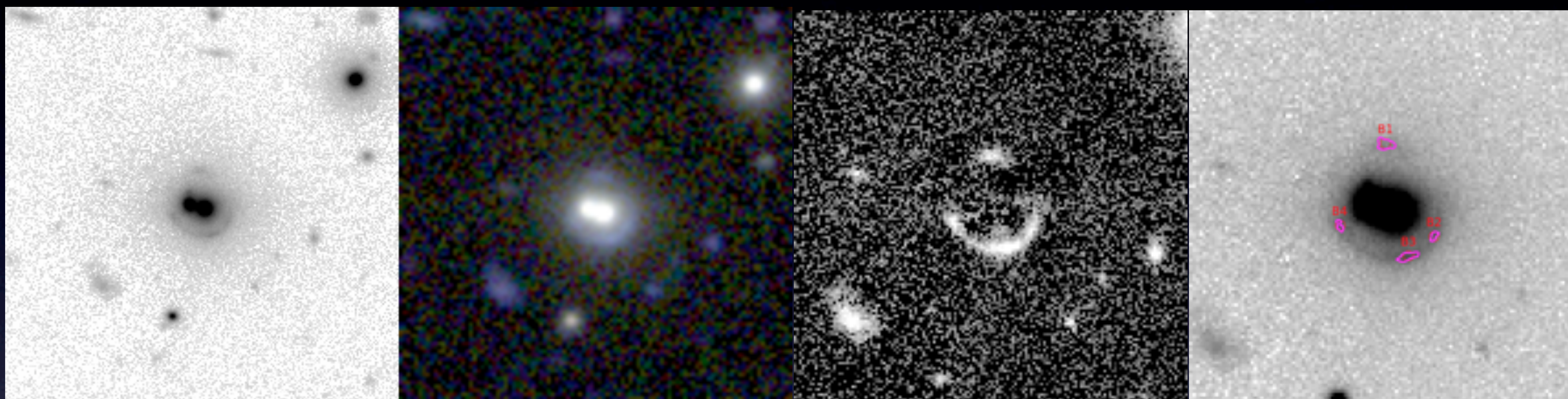
Niemiec, Caminha

- Brightest galaxy: z_L = 0.597, $\sigma_v^{\mathrm{SDSS}} = 535 \pm 133$
- Subtracting lens galaxies with galfit
- Lens center:

	Brightest galaxy			Two galaxies			Center of curvature		
	DS9	Bary	Bright	DS9	Bary	Bright	DS9	Bary	Bright
e	0.51	0.51	0.51 ± 0.012	0.60	0.60	0.09 ± 0.16	0.59	0.60	0.60 ± 0.05
θ	164.1	164.	163.3 ± 0.4	162.4	162.5	153.4 ± 5.4	160.7	160.7	159.4 ± 0.5
σ	524	525	529 ± 1	507	507	522 ± 4	527	527	530 ± 2

CS82 Einstein Rings

CS82SL01:36:39+00:08:18

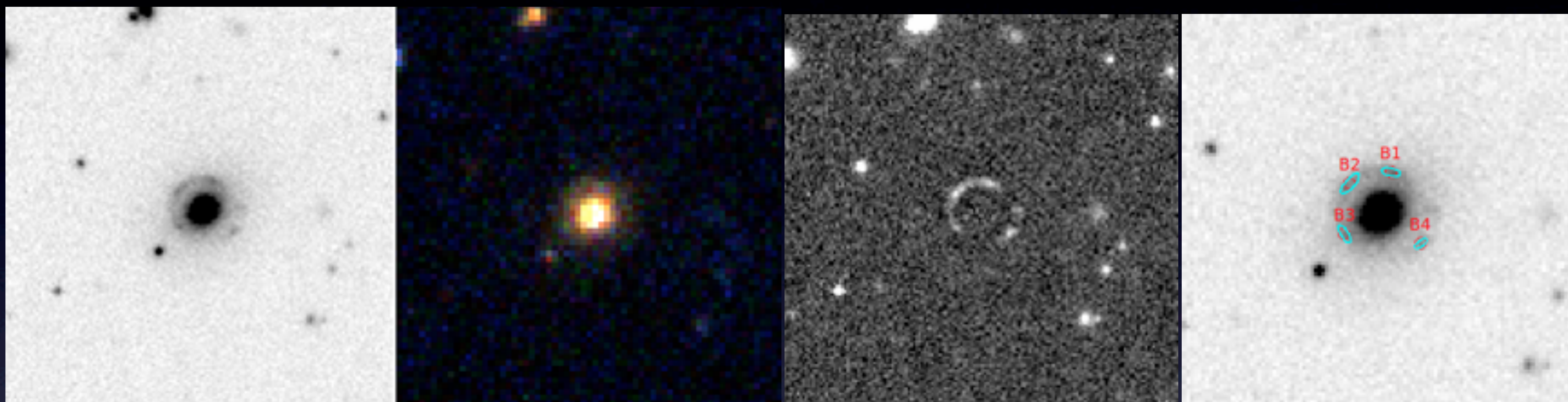


Anna Niemiec

- o_E = 3.51”
- SDSS (right component), z_{spec} = 0.344, $\sigma_v^{\mathrm{BCG}} = 372 \pm 29$
- Fits with a single and two mass components: evidence for single potential -> “bullet cluster like”?
- velocity dispersion (from SL): 440 km/s

CS82 Einstein Rings

CS82SL21:15:27-00:38:17



Anna Niemiec

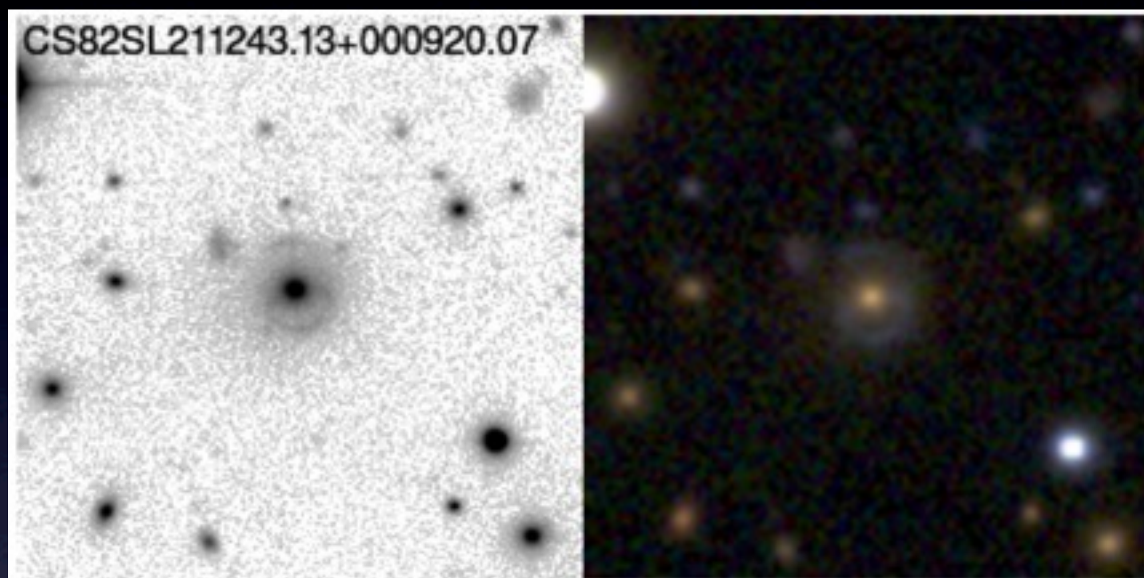
- z_{spec} = 0.562,
- θ_E = 2.54''
- velocity dispersion:

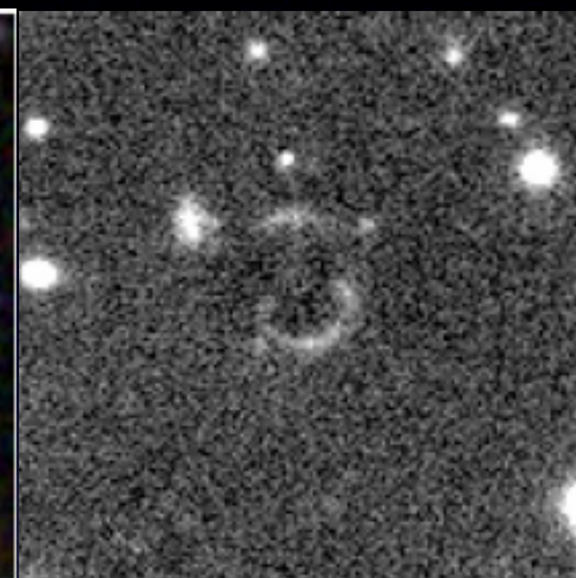
$$\sigma_v^{\mathrm{SDSS}} = 310 \pm 47$$

Parameter	Best DS9	Best barycenter	Best bright
x (arcsec)	-0.06 ± 0.04	-0.06 ± 0.05	-0.04 ± 0.03
y (arcsec)	-0.21 ± 0.03	0.22 ± 0.03	0.23 ± 0.03
ellipticity	0.24 ± 0.06	0.26 ± 0.06	0.26 ± 0.06
θ (deg)	52.96 ± 4.32	51.30 ± 6.01	53.01 ± 4.52
σ (km/s)	476.63 ± 2.39	475.24 ± 2.35	476.97 ± 2.46

CS82 Einstein Rings

CS82SL21:12:43+00:09:20





Anna Niemiec

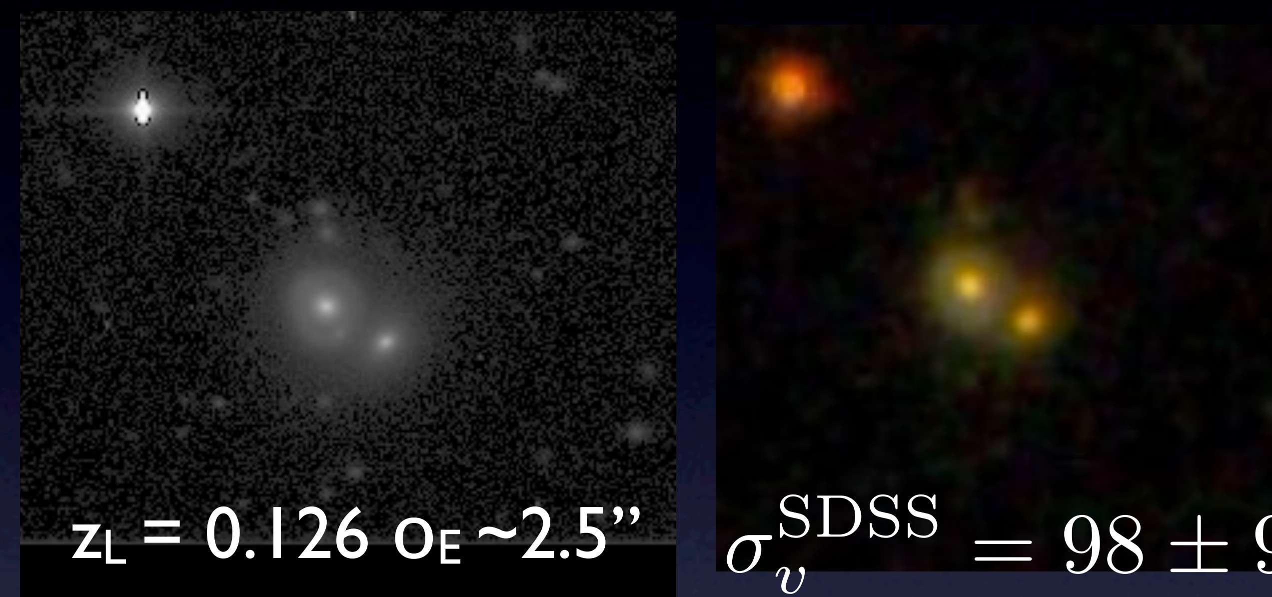
- z_{spec} = 0.445, $\sigma_v^{\mathrm{SDSS}} = 224 \pm 30$
- o_E = 3.33”

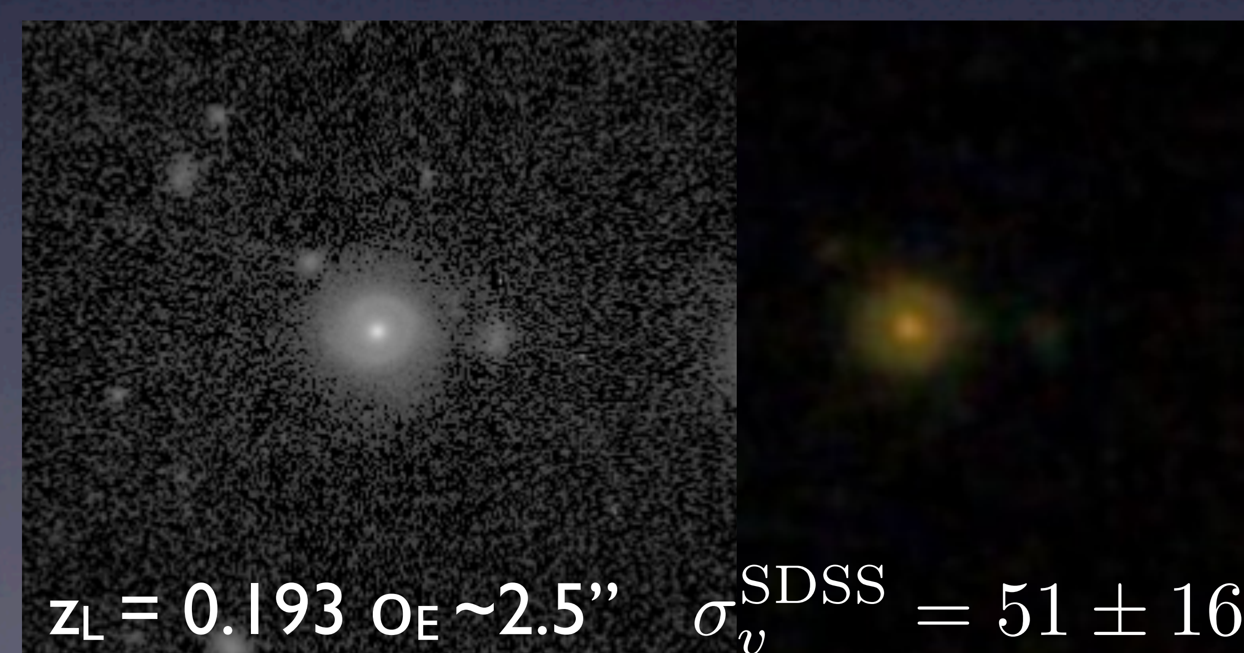
Einstein Rings or Ring Galaxies?

CS82SL23:27:42+00:17:46

$$M(<\theta_E) = (6 \pm 1) \times 10^{11} M_{\rm sol}$$

Ring galaxies from scanning of LRGs?





Alice Candeias

Multi-wavelength information

Of the 38 lens candidates:

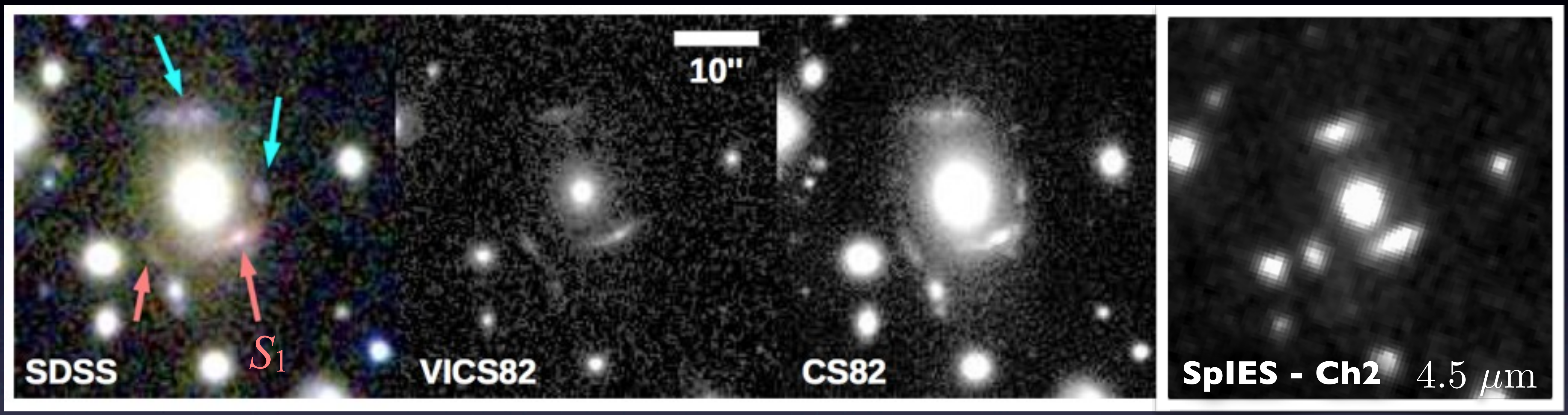
- 32 have SDSS spectroscopy
- 15 are in optical clusters/groups
- NIR: 16 in 2MASS, most in VICS82
- IR: 30 in WISE, 9 in SpIES + 4 in SHELA
- 4 in VLA-FIRST, 2 in VLA-Stripe 82, 1 in ACT
- 1 in XMM, 2 in Galex

Arc candidates:

- 9 in VICS82, 7 in SpIES

Multi-wavelength data

CS82SL00:44:37-00:55:20

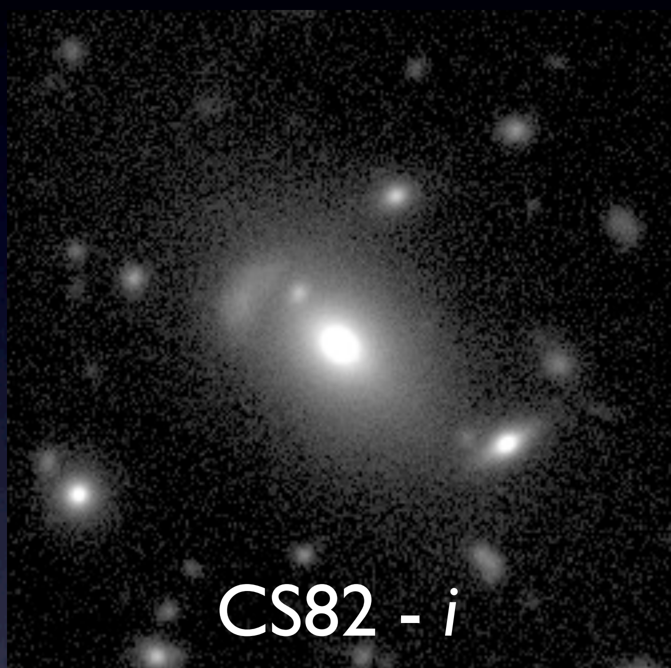


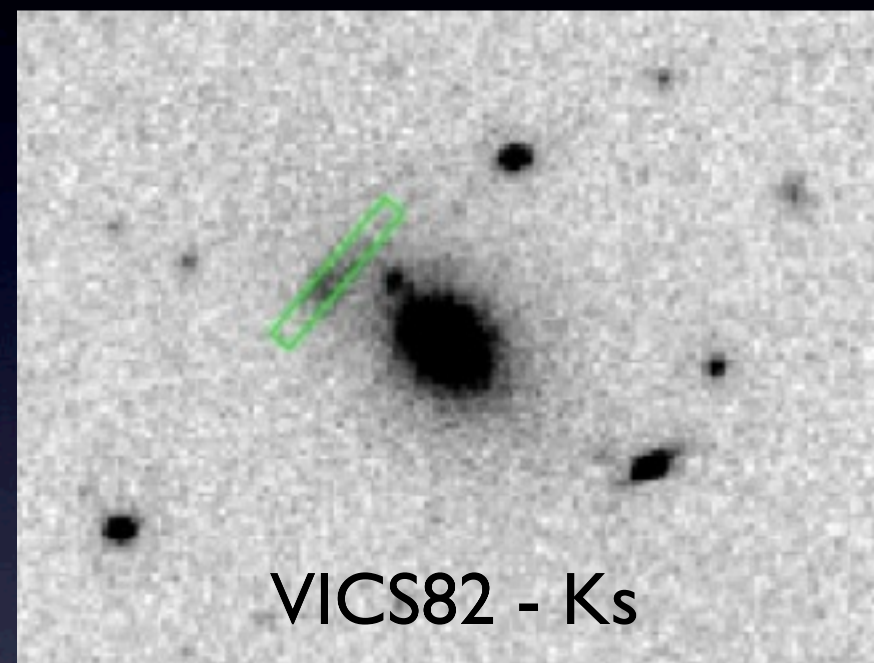
$$z_L = 0.201, \quad z_{S_1}^{\rm phot} = 0.55 \pm 0.06, \quad \sigma_v^{\rm SDSS} = (278 \pm 14)\,{\rm Km/s}$$

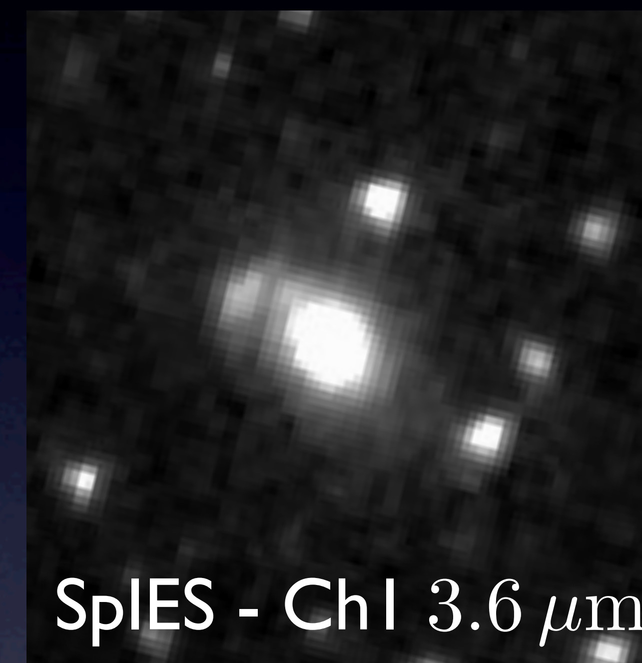
- System found in CS82 has clear IR emission
- Gemini approved for AO follow-up, but no suitable star
- Carry out systematic search

Multi-wavelength data

CS82SL02:20:32+00:28:03







$$z_L = 0.272, \quad z_S^{\mathrm{phot}} = 0.63 \pm 0.14, \quad \sigma_v^{\mathrm{SDSS}} = (320 \pm 8)\,\mathrm{Km/s}$$

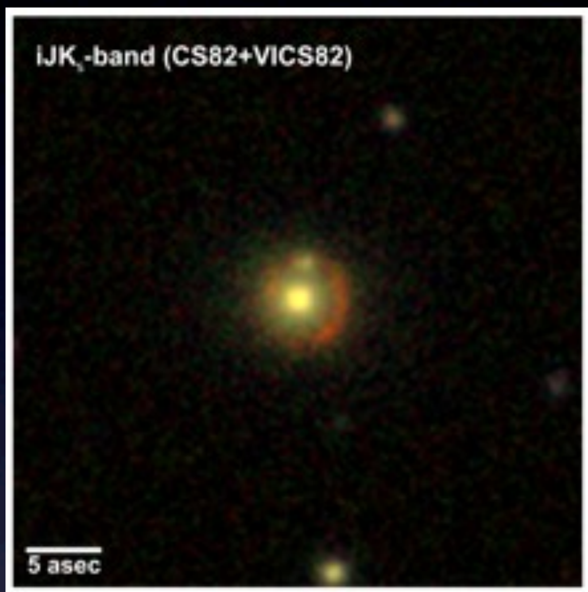
- Build SED
- Estimate magnification
- Work in progress....

~ 1 arcmin

Lobes only seen in VLA-Stripe82 resolution

SpaceWarps Einstein Ring

9io9



- $z_L = 0.2$ ($z_S = 2.553$)
- o_E ~3”
- velocity dispersion: 476.6 ± 2.4 km/s

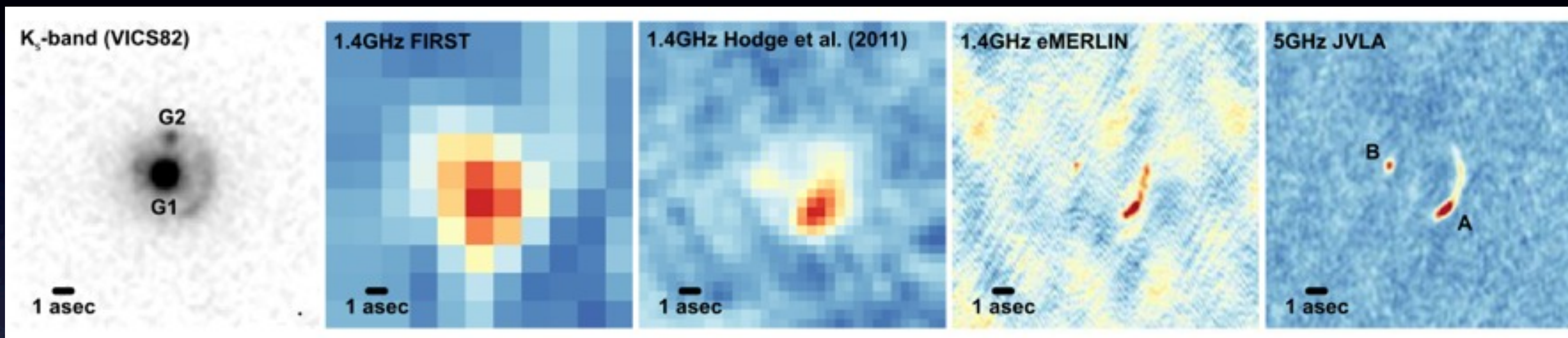
Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY

MNRAS **452**, 502–510 (2015) doi:10.1093/mnras/stv1243

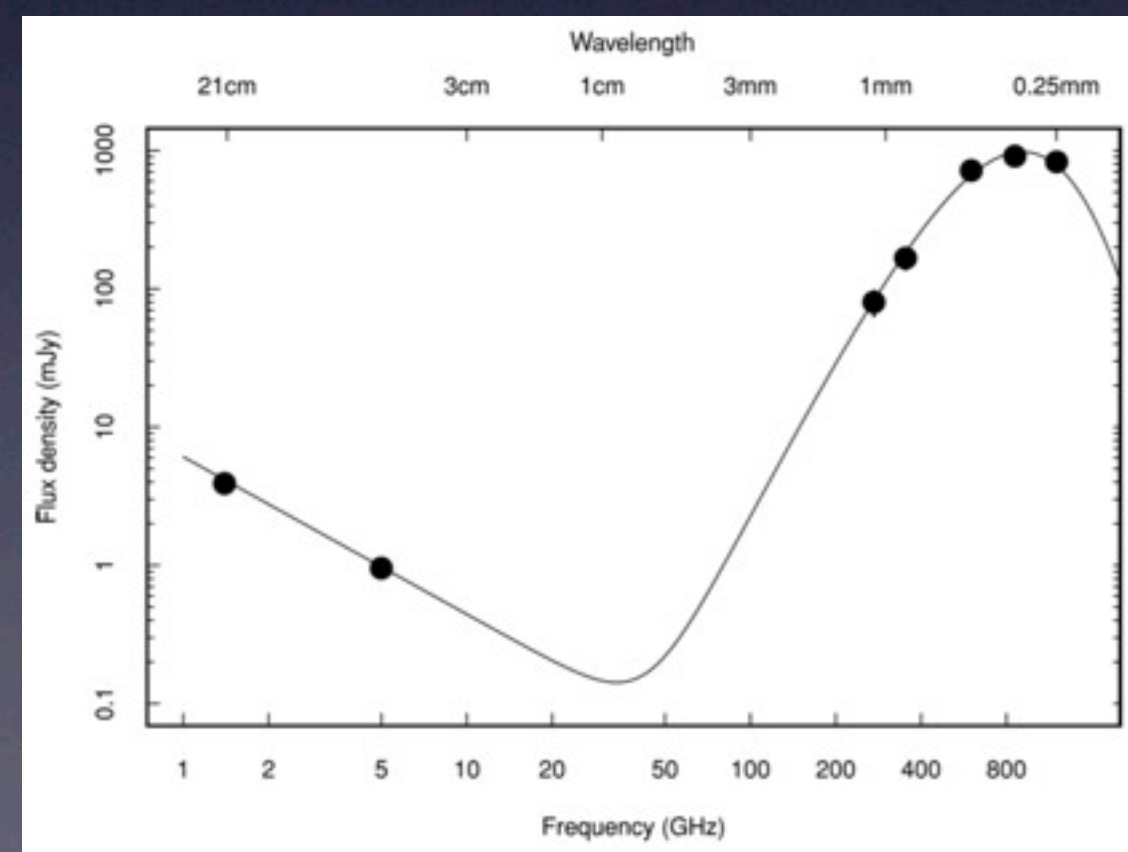
The Red Radio Ring: a gravitationally lensed hyperluminous infrared radio galaxy at $z = 2.553$ discovered through the citizen science project Space Warps

Best candidate: 9io9

- $z_{lens} = 0.2$, $z_{source} \sim 2.5$, Perhaps more distant known Einstein ring



- eMERLIN imaging
- Very bright sub-mm source (Herschel HerS e ACT)
- SED from multi-wavelength data
- High-z galaxy with dust and star formation



Concluding remarks

- After 30 years of the first discoveries (and 100 of GR), gravitational lensing has become a useful cosmological and astrophysical observable
    - Observables are multiple images, gravitational arcs, magnification, and time delays
    - SL is fulfilling its promises for studying the lenses, the sources, and the large-scale geometry of the Universe
    - Strong interplay between cosmology and astrophysics
- Cosmology needs multiple sources or complementary information on the lens (astrophysics)
- Different methods and applications for galaxy and cluster scales
- As in any other modern astrophysical and cosmological setting, results are being dominated by systematics

Concluding remarks

- Addressing systematics
  - End-to-end approaches using simulations to test everything from finding to modeling arc systems
  - Use “golden lenses” (SN + HST + IFU)
- Synergy between wide-field studies and targeted observations
- Interdisciplinary field involving from fundamental physics to data reduction, including image processing, statistics, simulations, theory and semi-analytic modeling
- CS82 is an excellent playground for SL in the ongoing and future wide-field surveys from the ground
- Lots of excellent data to come in the near future!


BARYONIC P-ROCESSES
DENSITY PROFILES AND CONCEN-TRATION
LENS MASS DISTRIBUTI-ON
COSMOLOGIC-AL DISTANC-ES
TIME DELAYS AND-HUBBLE CO-NSTANT
DARK MATTER SELF-INTER-ACTION
STRONG LENSING
DARK ENERG-Y PARAMETE-RS
MASS CALLI-BRATION
MODIFIED GRAVITY
MASS LUMIN-OSITY RATI-OS
GRAVITATIO-NAL TELESC-OPES
HIGH REDSH-IFT UNIVER-SE
DARK MATTER MASS
BARYON - DARK - MATTER INT-ERACTION


Thank You!