Gravitational arcs as cosmological and astrophysical probes: the case of Stripe 82

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IATE

GRAVITATIONAL ARCS AS COSMOLOGICAL PROBES

+ STRIPE 82 PUBLICITY

MARTÍN MAKLER

COSMO - CBPF

CBPF

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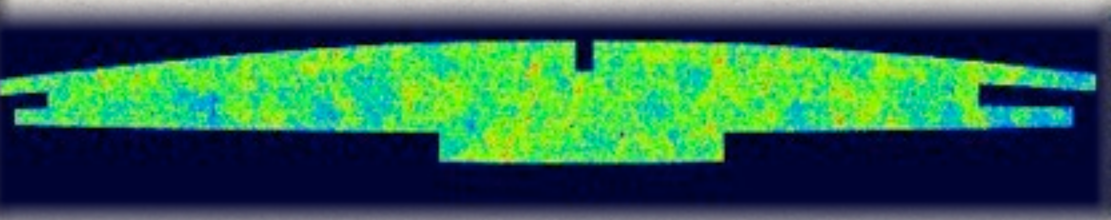
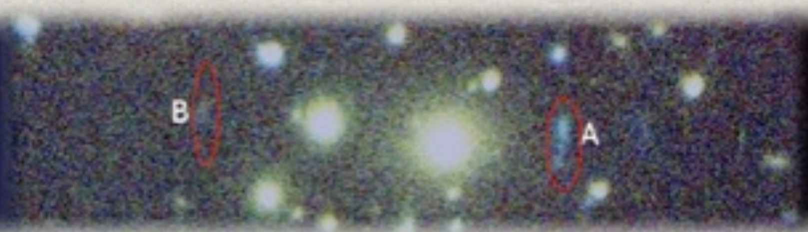
IATE

OUTLINE

- Introduction to Strong Lensing
- Strong lensing and cosmology
  - Cluster scales and cosmology
  - Einstein Rings and modified gravity
- Einstein Rings in the CS82 Survey
- Automated arc finding



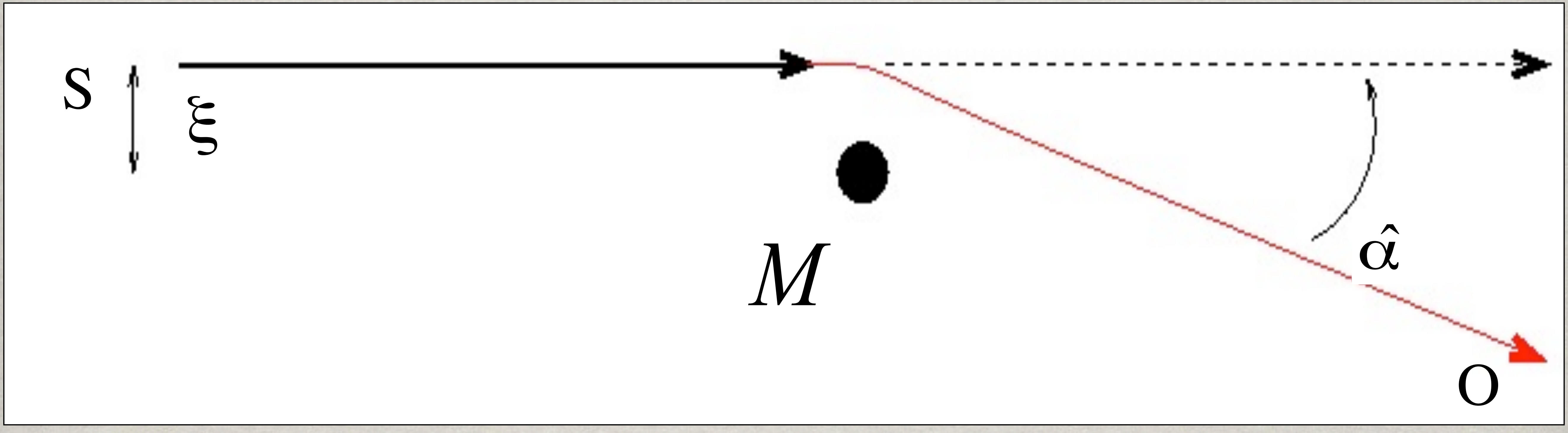


BENDING OF LIGHT BY GRAVITY

Null geodesic,
Fermat principle

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

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

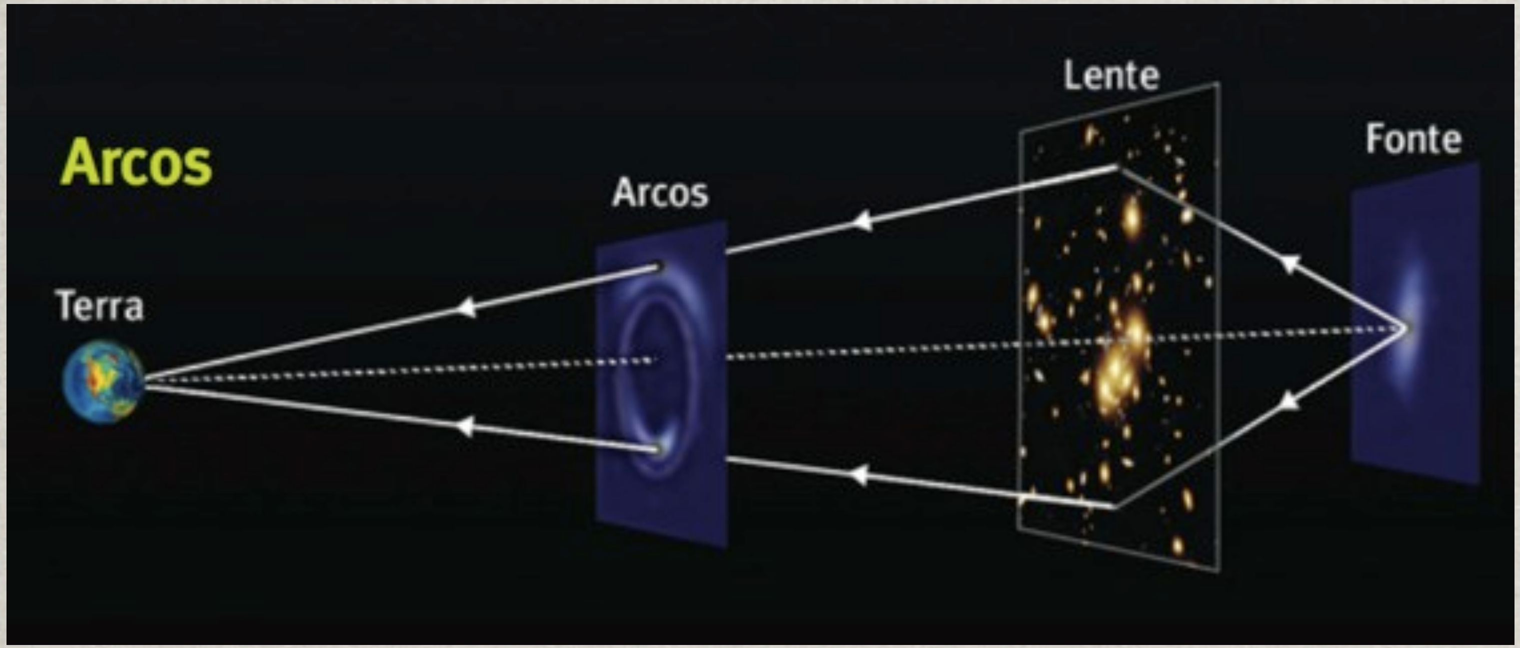


Deflection angle (point source) $\hat{\alpha} = \frac{4GM}{c^2}\frac{1}{\xi}$

STRONG LENSING

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

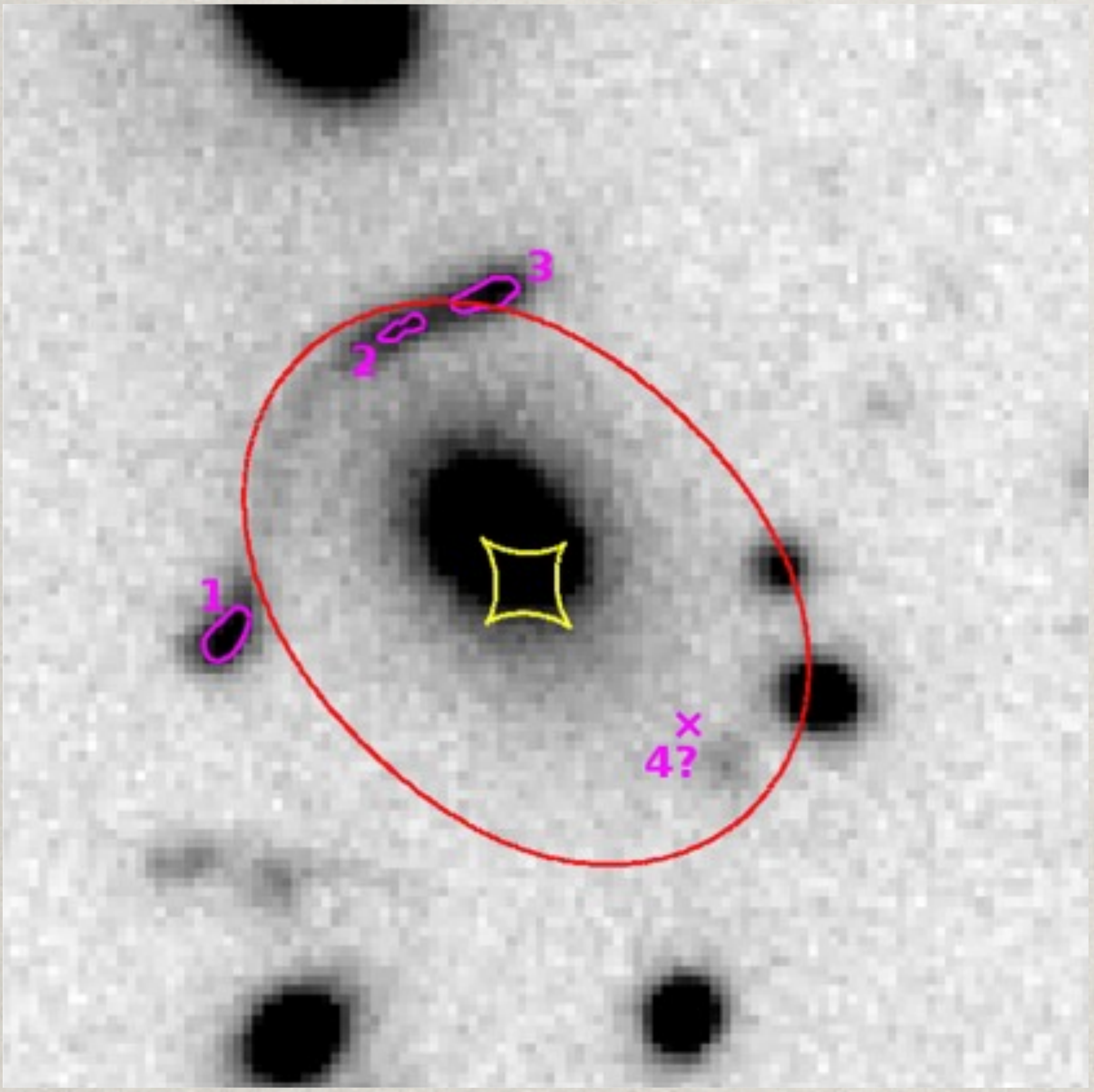
  } → Gravitational telescopes
  - Unique probe of inner structure of galaxy clusters ➔ DM, *b*
  - Provide complementary cosmological probes and tests of gravity



strong lensing, **weak gravity**

Gravitational arcs

INVERSE MODELING: MAPPING THE MASS



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

Methods: parametric (often "mass traces light"), free form

The more multiple images, the more constrains

- Combination with independent mass constraints (e.g., x-ray, Sunyaev Zel'dovich, velocity dispersions) yields limits on cosmology or gravity

Strong Lensing

- Lens potential: Mass distribution
  - Dark Matter properties
  - Modified Gravity
  - Cluster and galaxy evolution
- Gravitational telescope
  - z ~ 2 – details of highly magnified galaxies (resolved!)
  - z ~ 6 – galaxy abundance at high-z
  - z ~12 – find the next highest-z record holder
- Geometry
  - Cosmology
- Need a good mass model for all applications!
- Multi-wavelength data: astrophysics
- Need follow-up data: IFU, high-quality deep imaging

GALAXY CLUSTER SCALE
COSMOLOGICAL CONSTRAINTS AND MORE

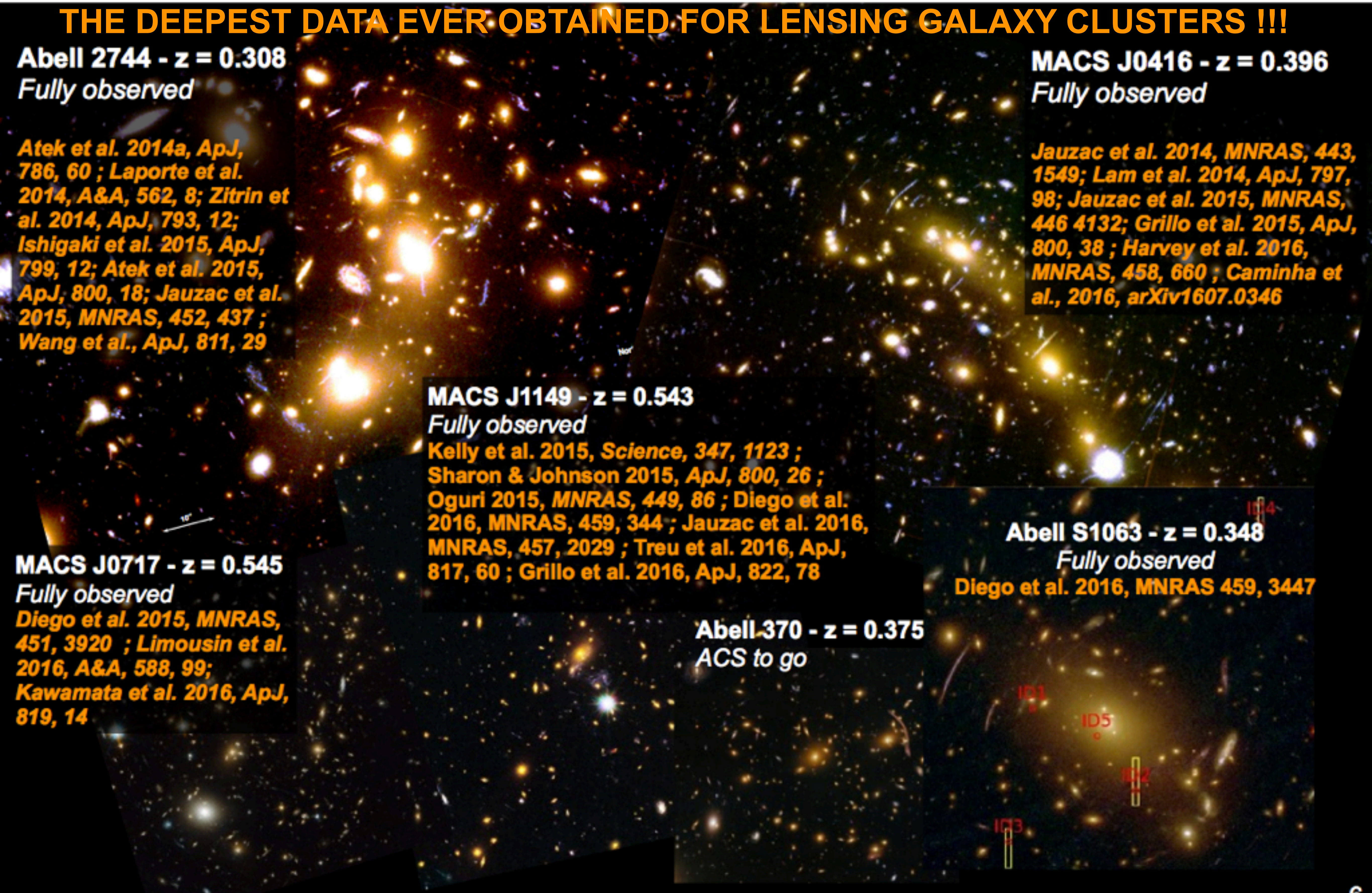
Families of images with sources at different *redshifts*
☑ constraints on cosmology, in addition to the matter distribution

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

$$\Xi(z_1, z_{s1}, z_{s2}; \Omega_M, \Omega_X, w_X) = \frac{D(z_1, z_{s1})}{D(0, z_{s1})} \frac{D(0, z_{s2})}{D(z_1, z_{s2})}$$

☑ 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
☑ Magaña, Motta, Cárdenas, Verdugo, Jullo, 2015

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

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

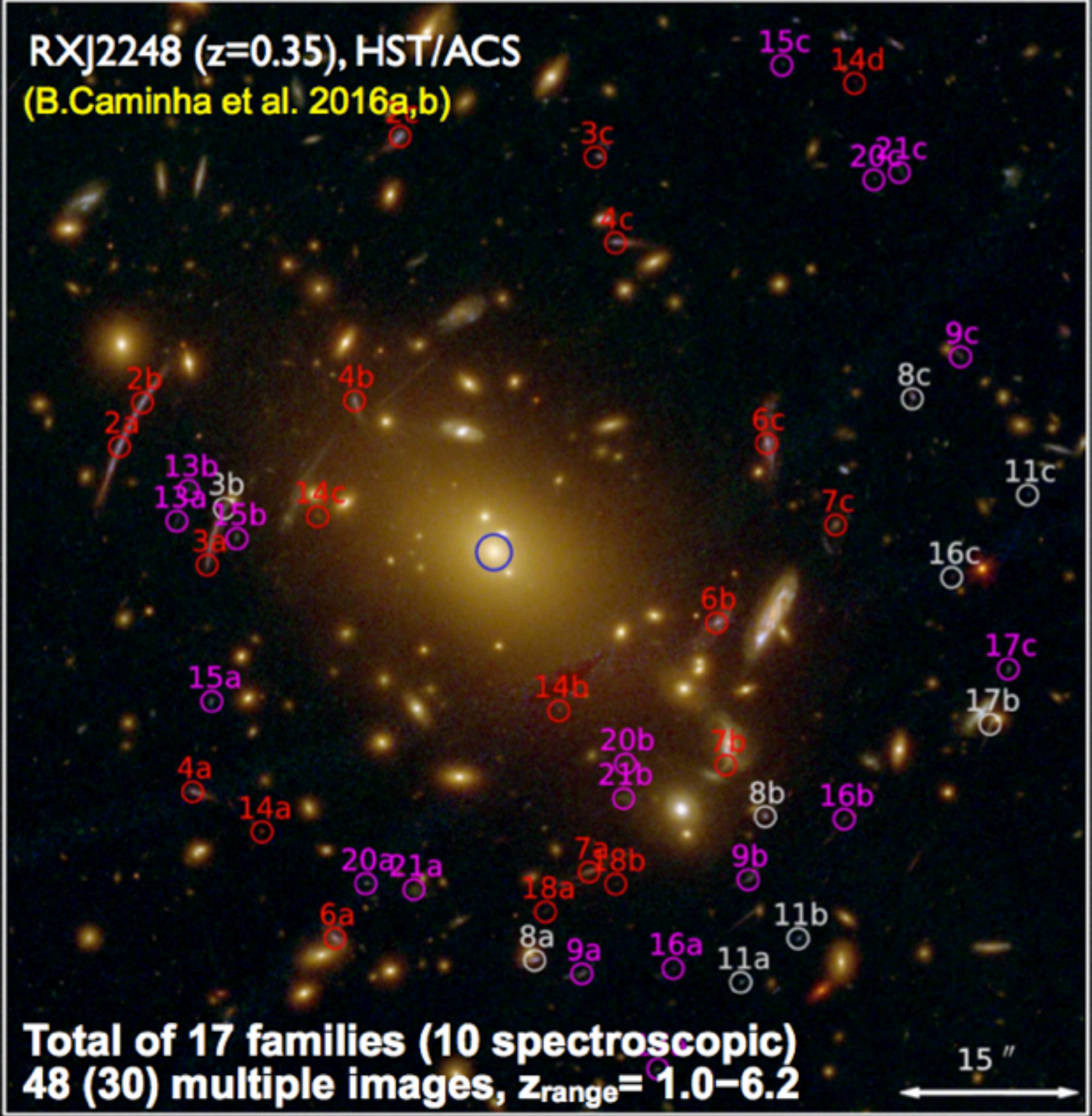
Abell 370 - $z = 0.375$
ACS to go

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

COSMOLOGICAL CONSTRAINTS

Caminha et al., 2016

Frontier Field Cluster AS1063 (aka RXJ2248)

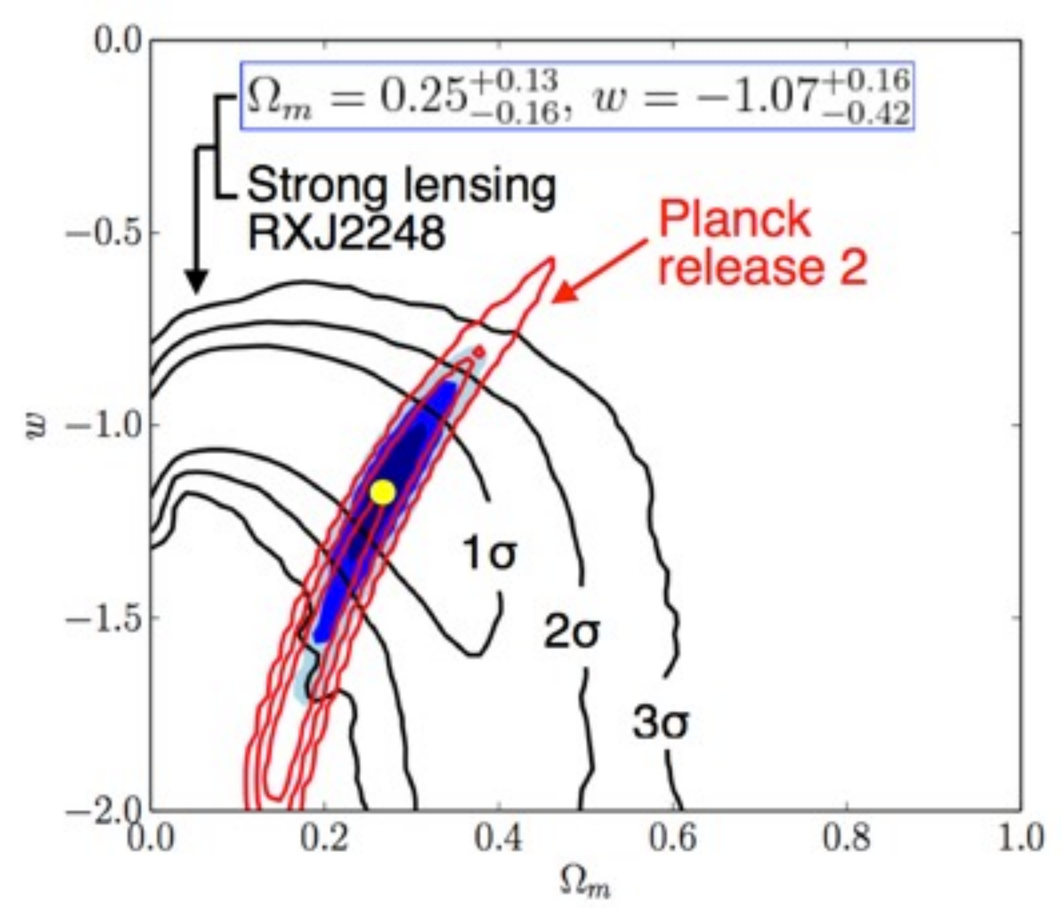


RXJ2248 (z=0.35), HST/ACS

(B.Caminha et al. 2016a,b)

Total of 17 families (10 spectroscopic)
48 (30) multiple images, z_{range}= 1.0–6.2

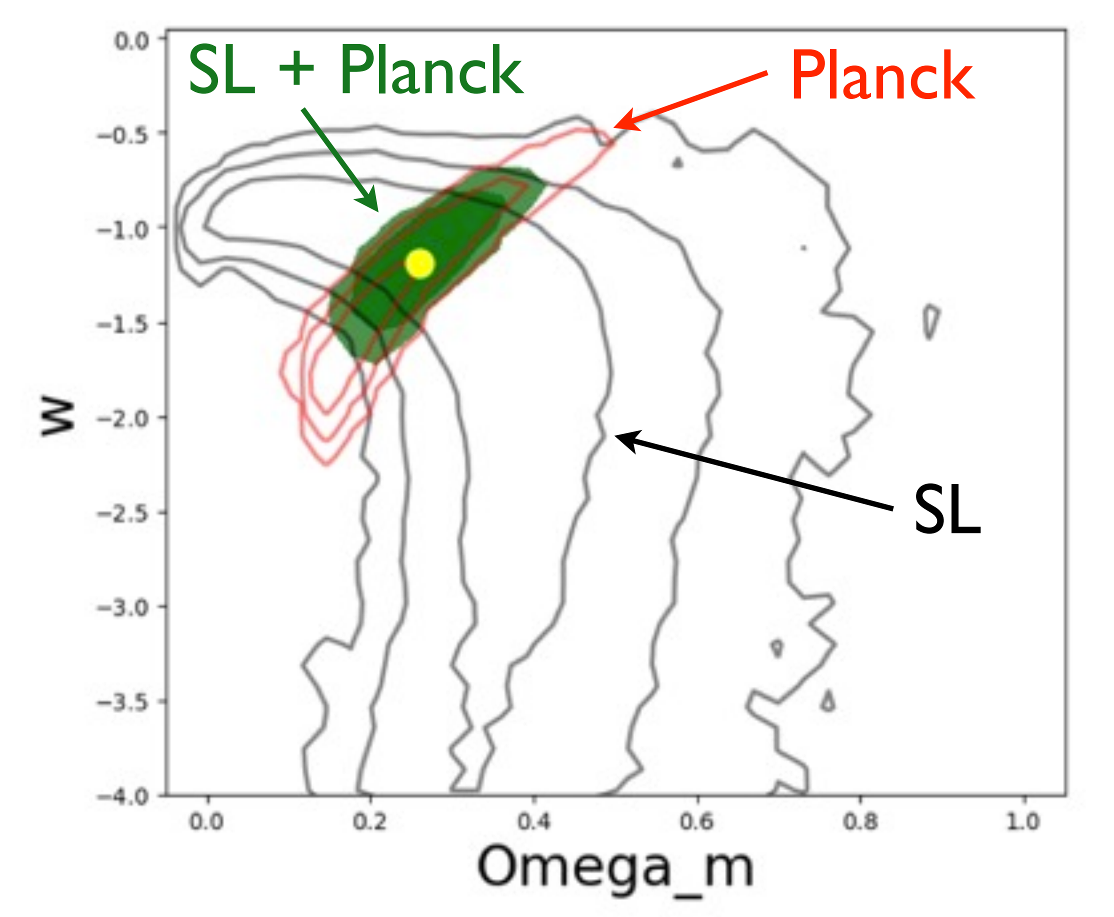
MUSE SV programme + GO (PI: K.Caputi)
(Karman et al. 2015)
(W.Karman et al. 2016, arXiv/160601471)



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

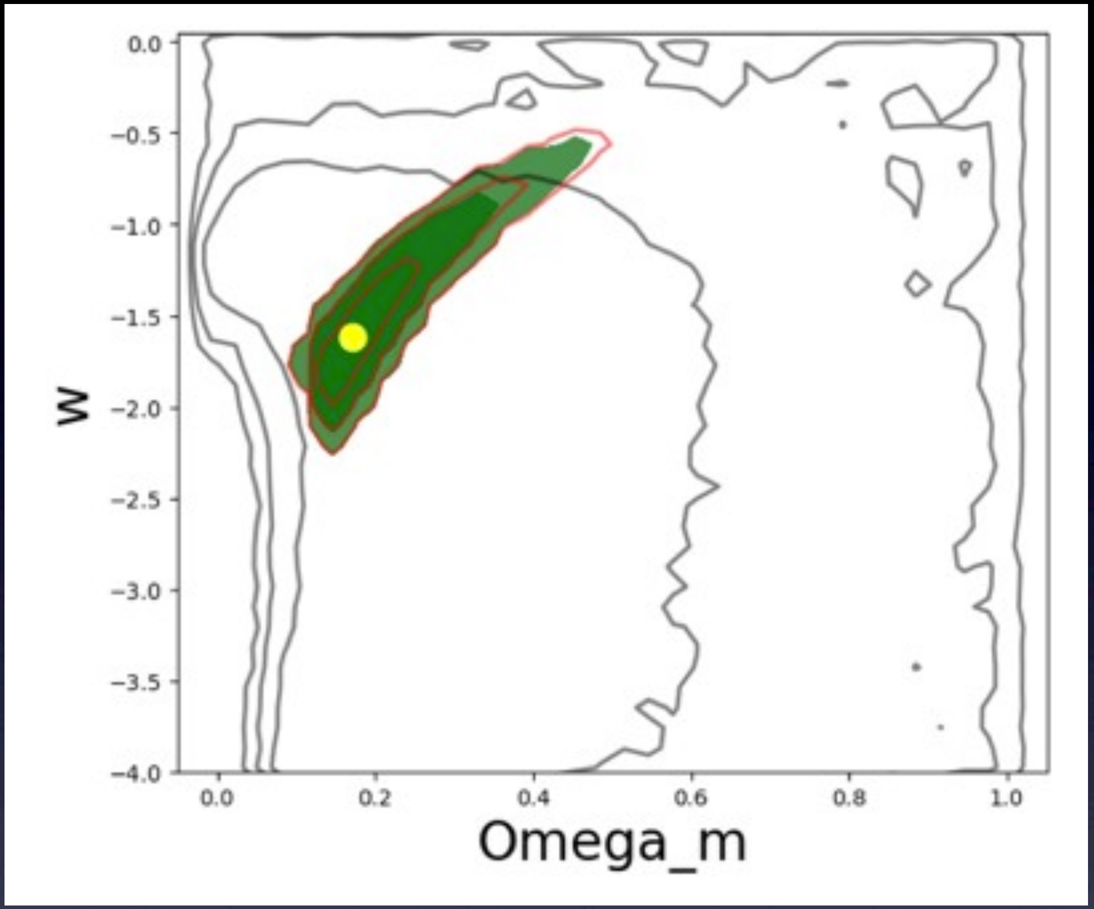
Distance ratios from the ground?

Example: RXC J2248.7−4431



C. Bom, G. Caminha, MM, 2017

HFF: magAB ~ 29, 7 filters + MUSE



C. Bom, G. Caminha, MM

HFF degraded to FWHM = 0.6”, mag = 25 (7 families, 17 multiple images), assuming known redshifts

- ~ 20 systems would yield the same constraints
- Better for systematics and comparison to simulations

Light-Matter Offsets

Smoking gun for self-interacting dark matter

- Williams and Saha (2011): kpc offsets in Abell 3827 from Free form modeling [Can also do "blobology" using parametric models (Jauzac)]
- If interpreted solely as evidence for self-interacting dark matter:

$$\sigma/m \gtrsim 8 \times 10^{-31} \left(t/10^{10} yr\right)^{-2} cm^2 GeV^{-1}$$

- Schaller (2015): tension with CDM, Kahlhoefer (2015) different value
- Mohamed et al. (2014): Abell 3827 and also Abell 2218, no LoS
- Interacting systems. Not seen in field galaxies and relaxed clusters
- Not seen in MACS-J0416.1-2403 but not enough resolution (Sebesta et al. 2016)
- Not in contradiction with small offsets in Bullet Cluster (Robertson et al. 2017), using sims with self interaction.
- Alternative explanations: dynamical friction...

Constraints on Warm Dark Matter

- WDM produces a cutoff in the matter power spectrum (Bode et al. 2001) and thus on the halo mass function
- Gravitational telescopes: luminosity function of ultra-fraint UV galaxies at high-redshift

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]

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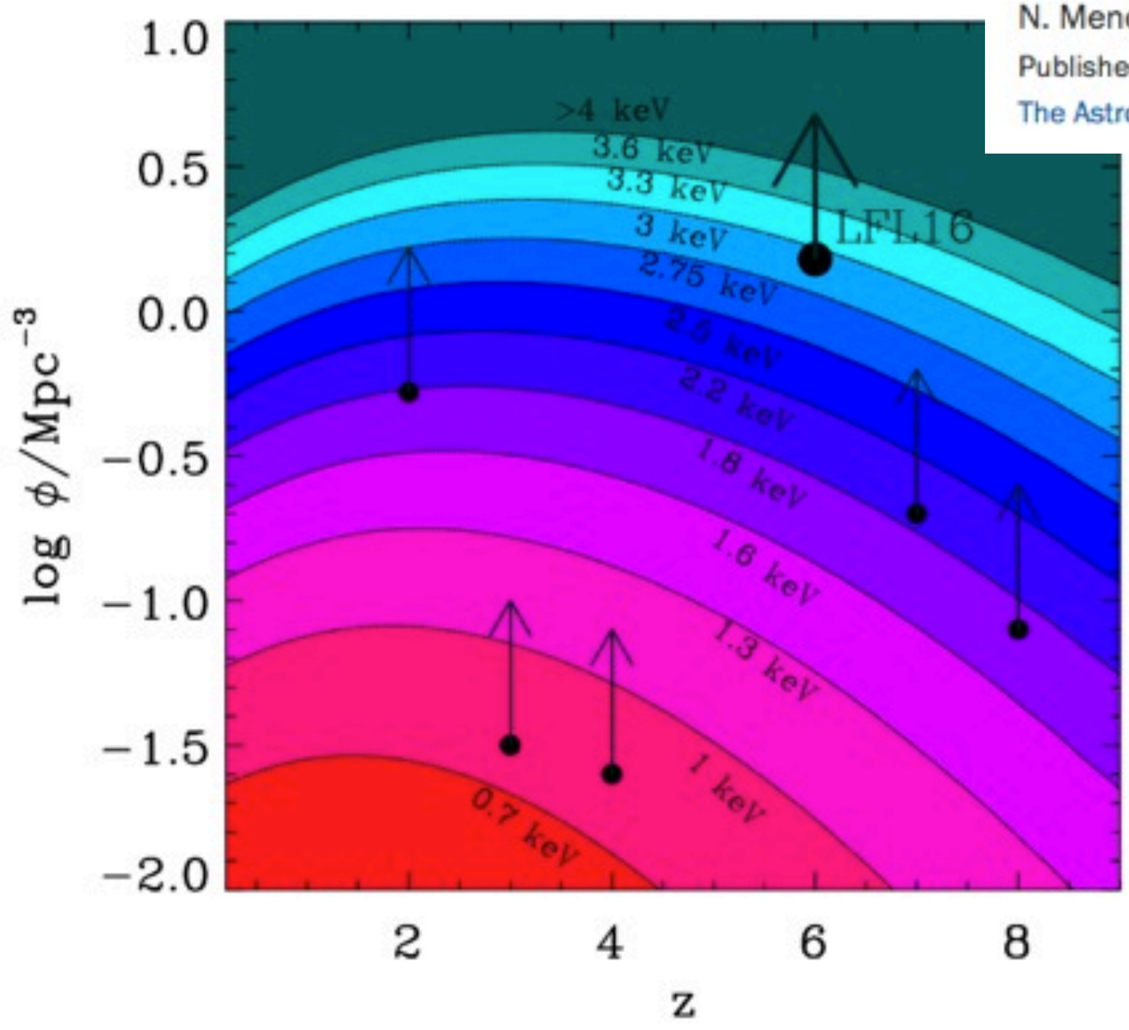
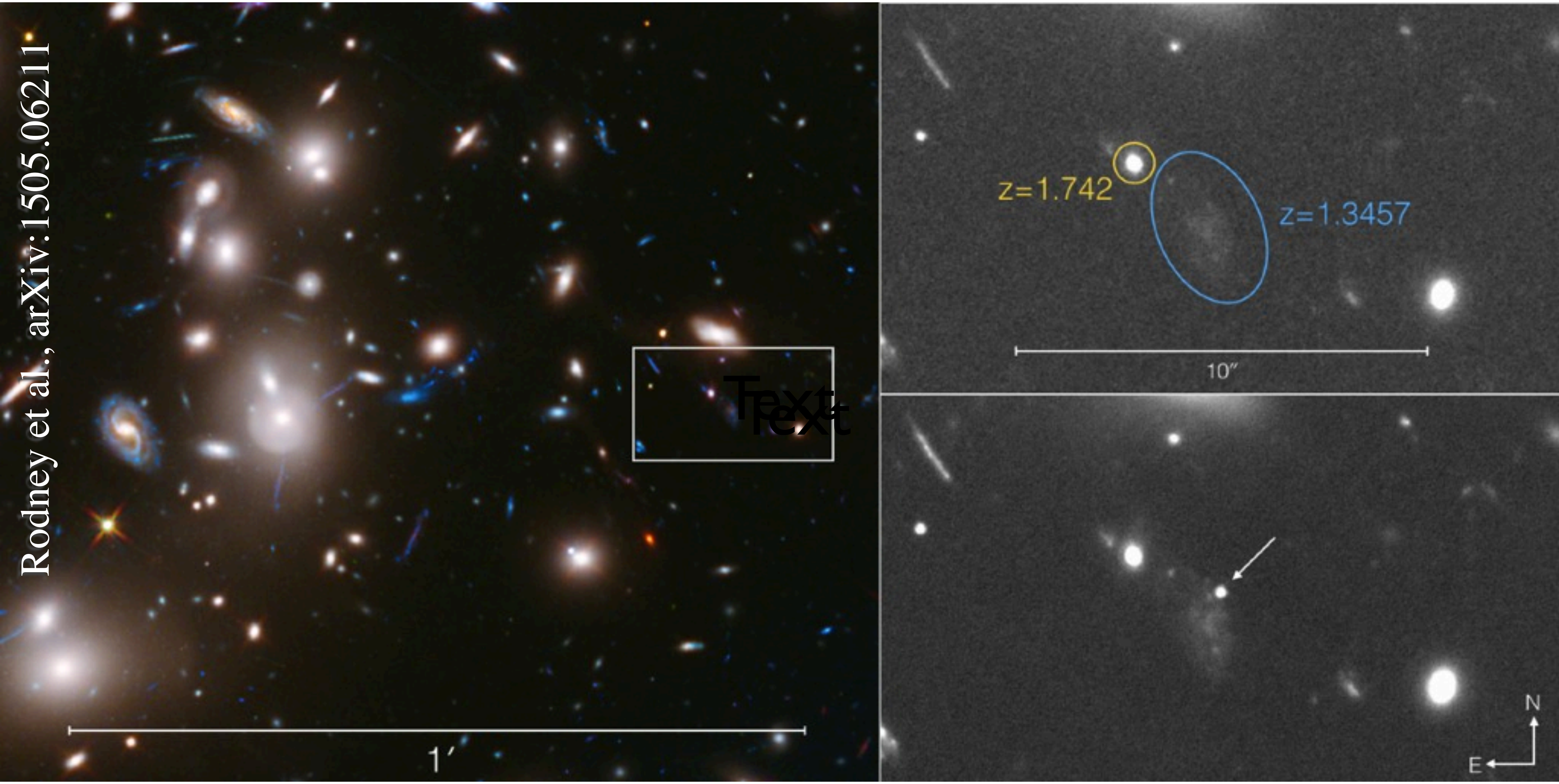
The Astrophysical Journal Letters, Volume 825, Number 1



Mass of thermal relic WDM particles $m_X \geq 2.1$ keV at 3σ.

Ia supernovae in Abell 2744 (FF)



Rodney et al., arXiv:1505.06211

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

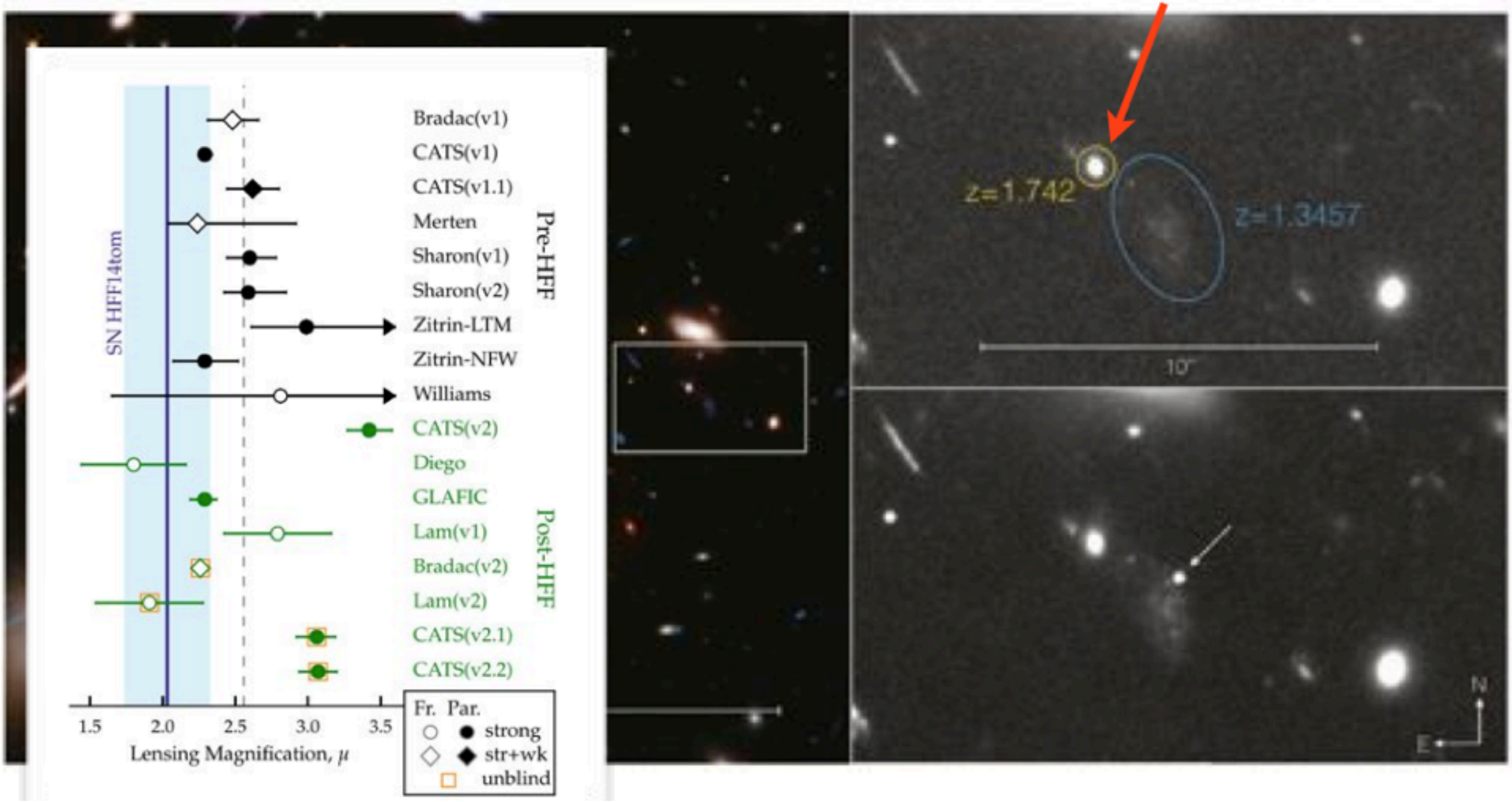
Testing models and inversion codes and constraints for new analyses

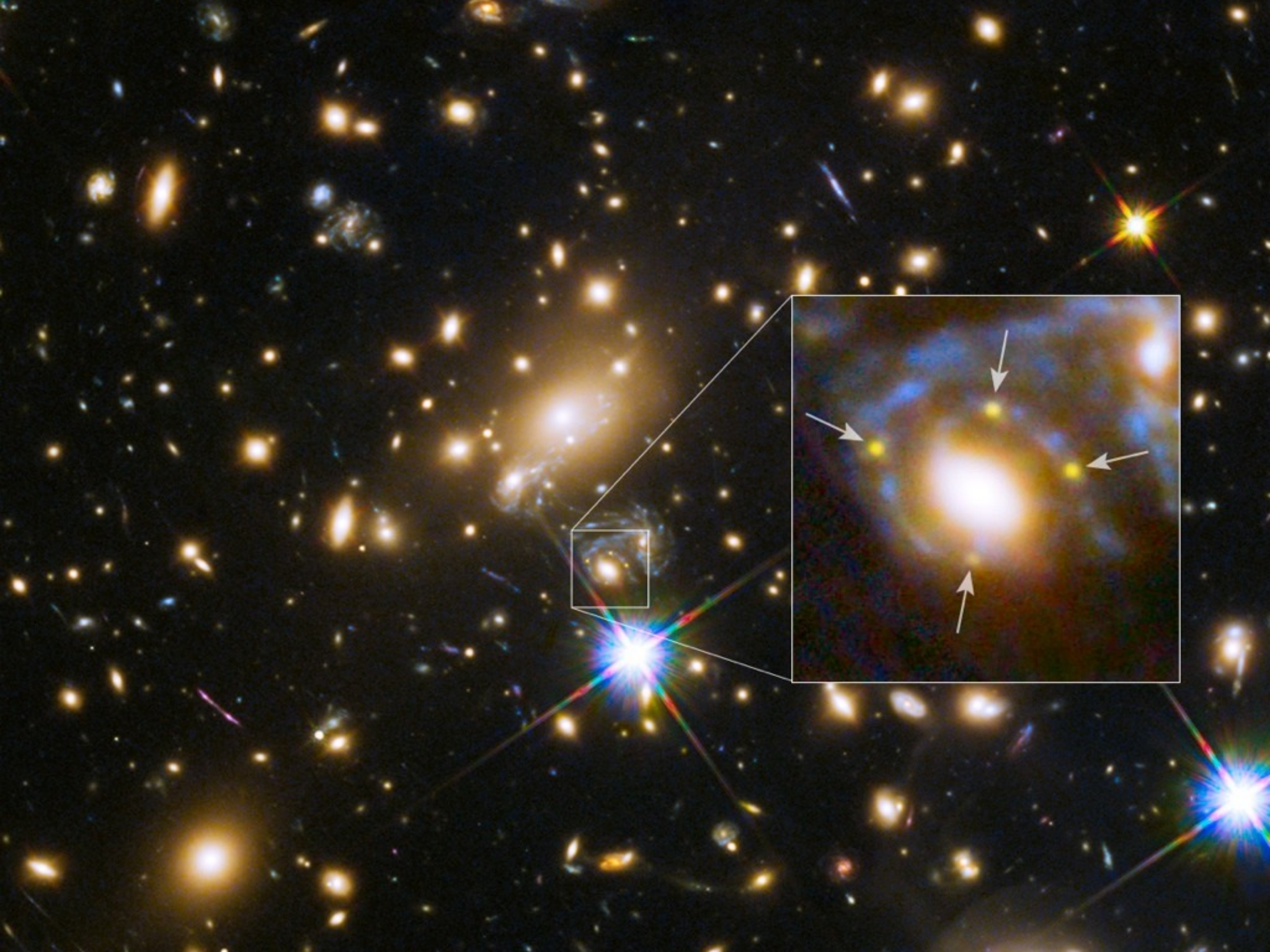
Use measured magnification to test model predictions

- Model assumptions

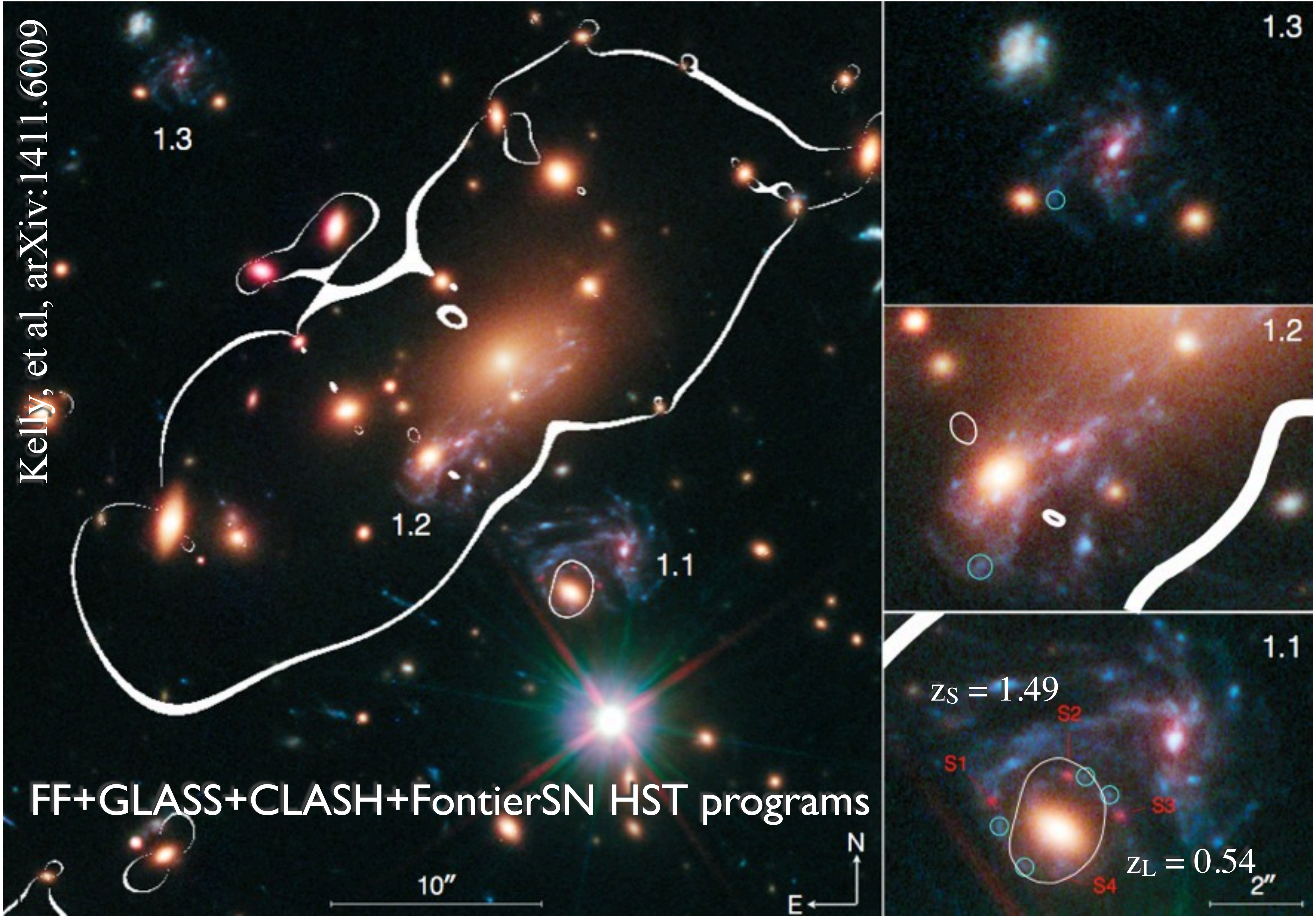
Rodney+15 ApJ

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


SN "Tomas"



Supernovae in MACS J1149.6+2223

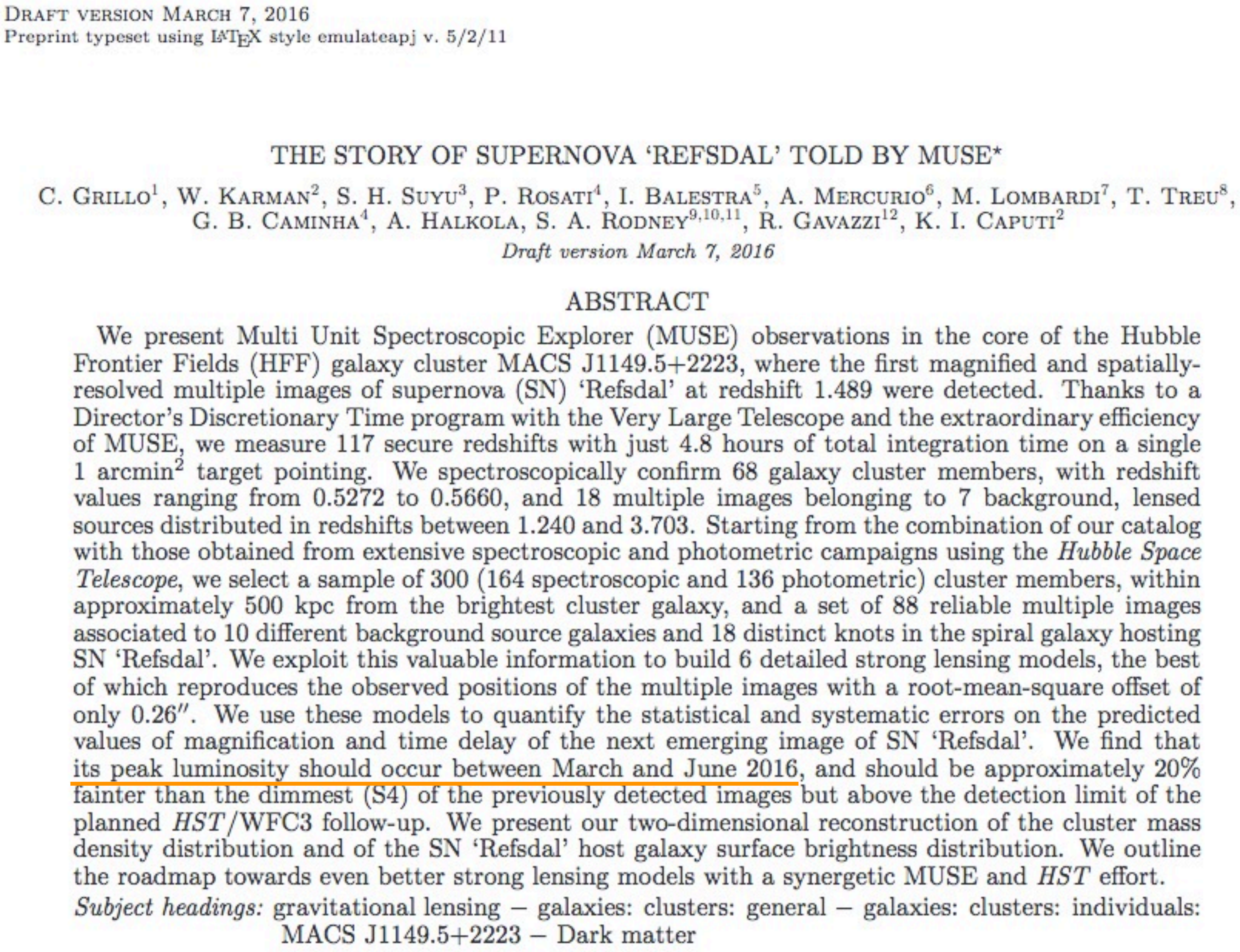


Kelly, et al, arXiv:1411.6009

FF+GLASS+CLASH+FontierSN HST programs

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

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,
K. Sharon[12], A. Zitrin[13,29] Show full author list

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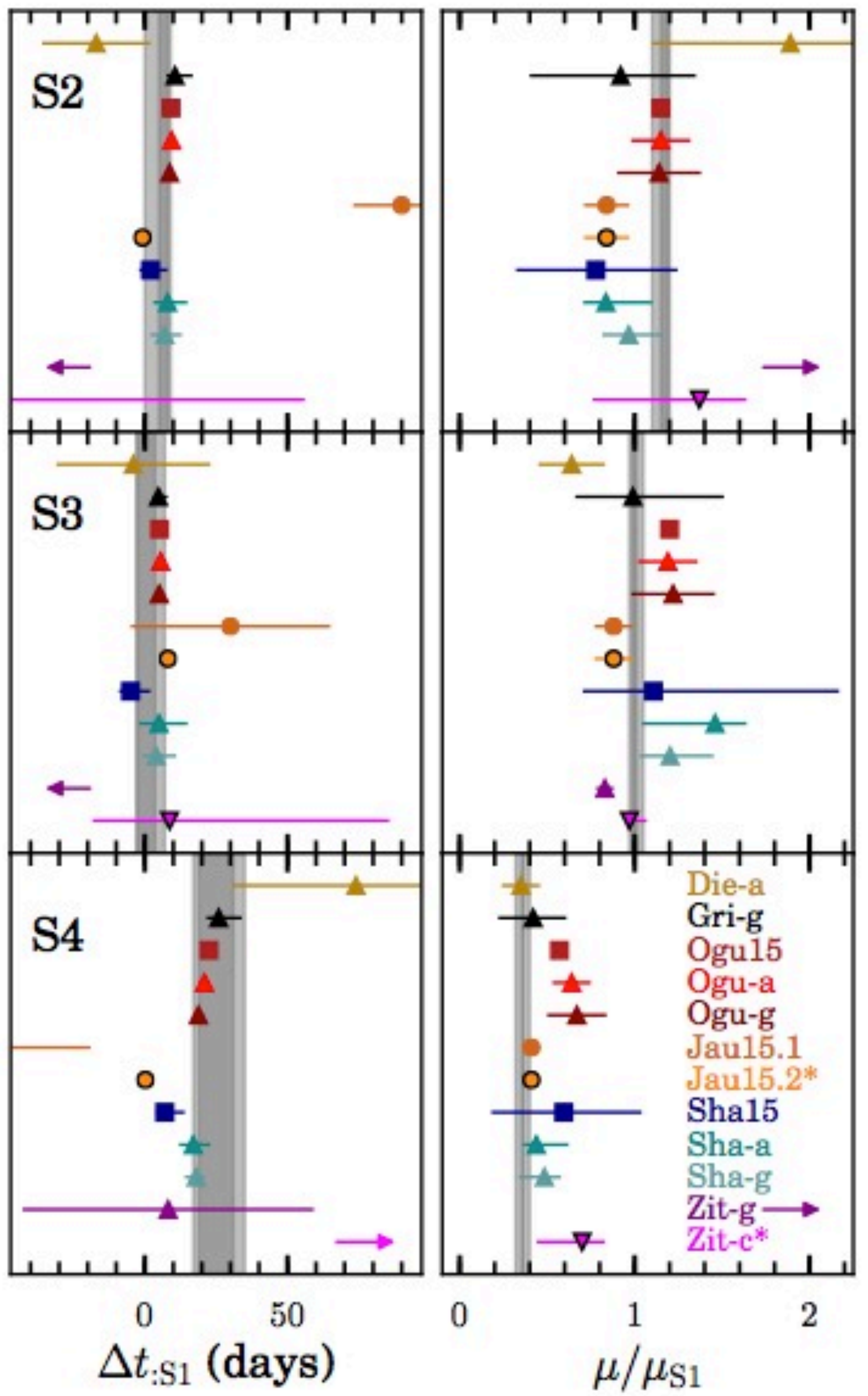
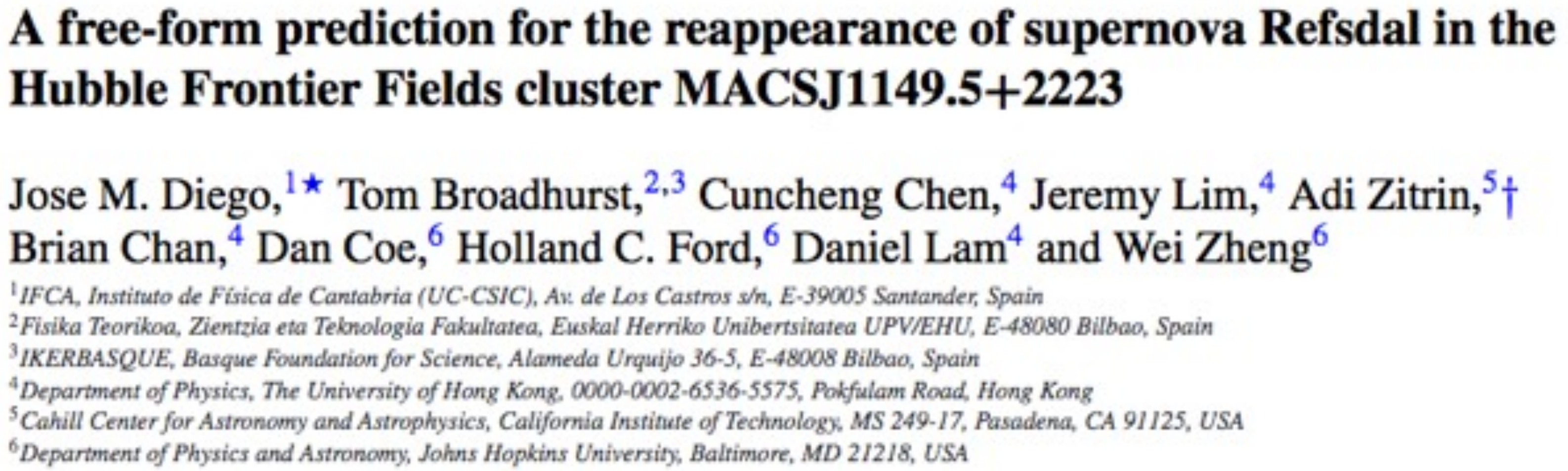
The Astrophysical Journal, Volume 817, Number 1





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]

[1] *IFCA, Instituto de Física de Cantabria (UC-CSIC), Av. de Los Castros s/n, E-39005 Santander, Spain*
[2] *Fisika Teorikoa, Zientzia eta Teknologia Fakultatea, Euskal Herriko Unibertsitatea UPV/EHU, E-48080 Bilbao, Spain*
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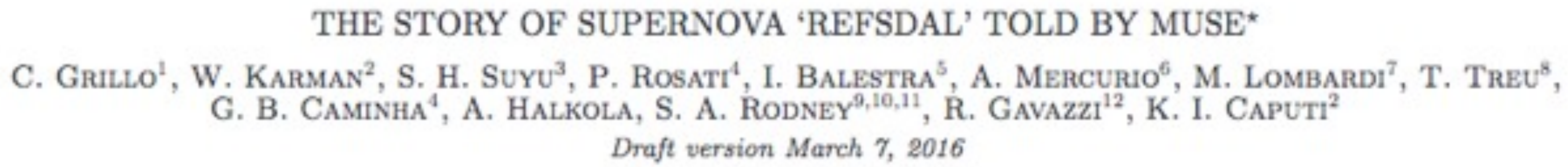
[5] *Cahill Center for Astronomy and Astrophysics, California Institute of Technology, MS 249-17, Pasadena, CA 91125, USA*
[6] *Department of Physics and Astronomy, Johns Hopkins University, Baltimore, MD 21218, USA*



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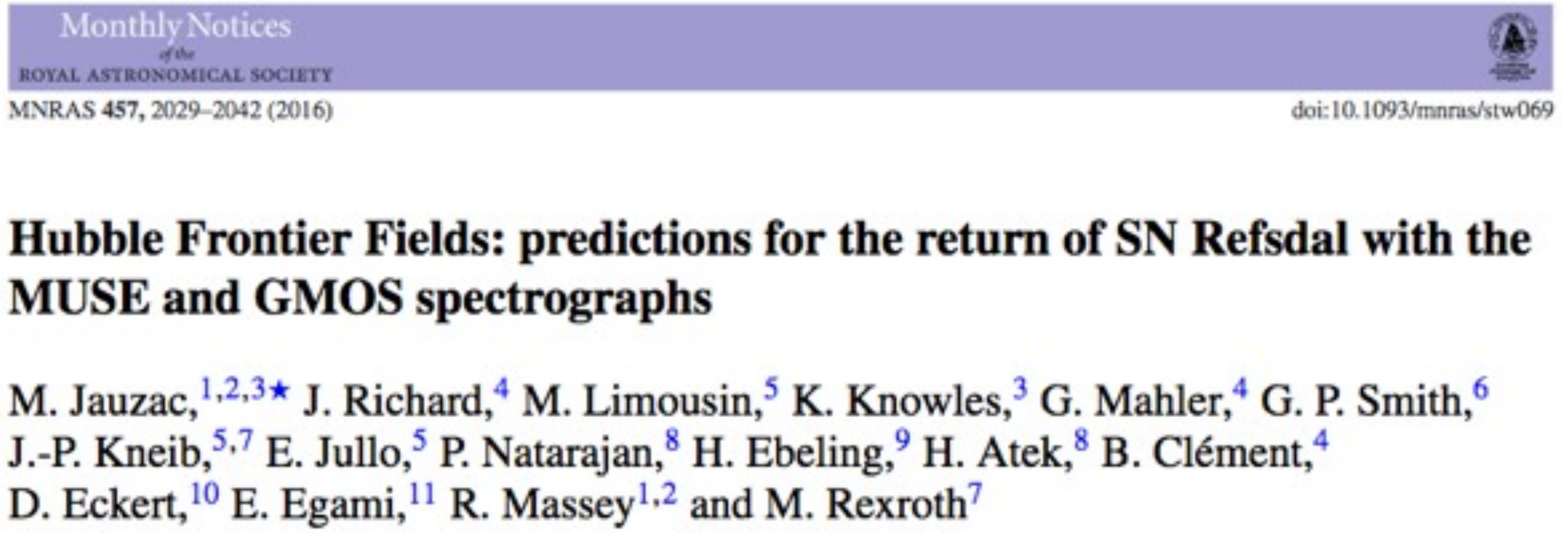
Draft version March 7, 2016

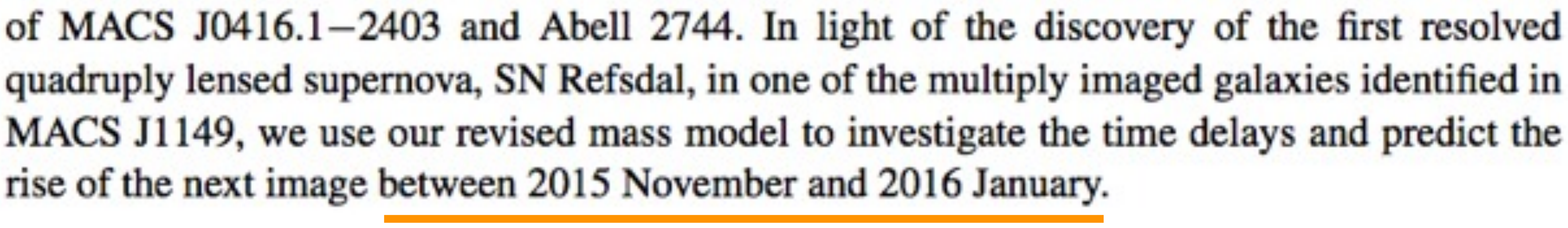


Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY

MNRAS **457**, 2029–2042 (2016) doi:10.1093/mnras/stw069

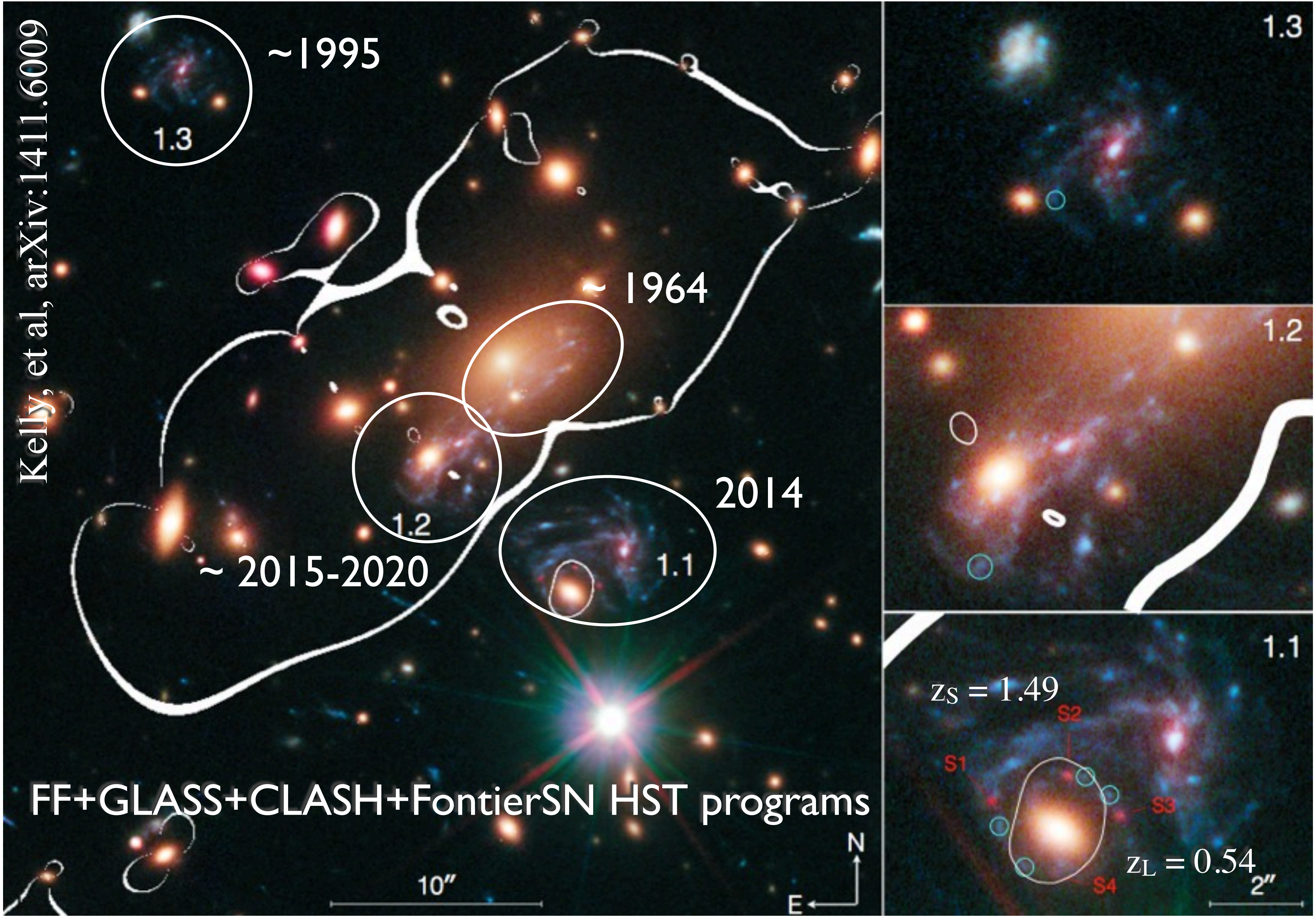
Hubble Frontier Fields: predictions for the return of SN Refsdal with the MUSE and GMOS spectrographs

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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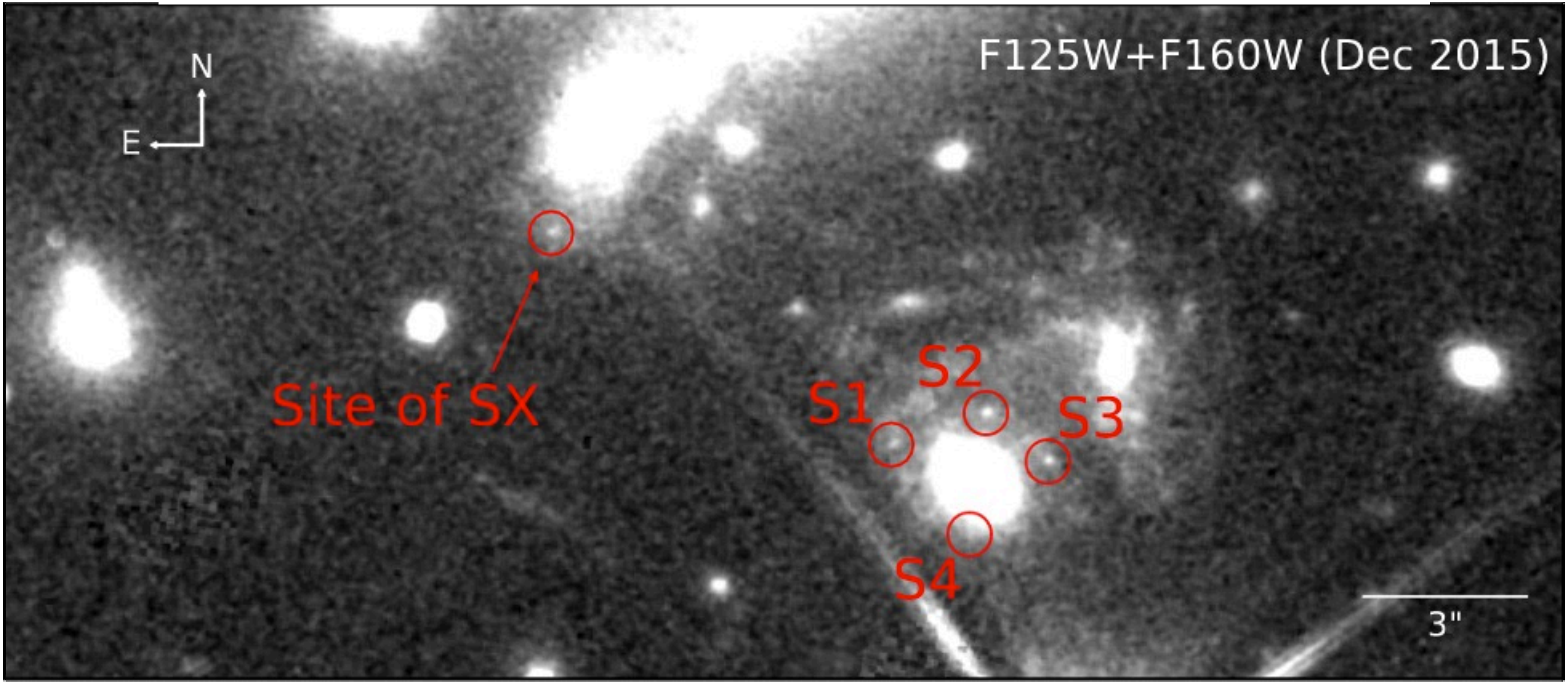
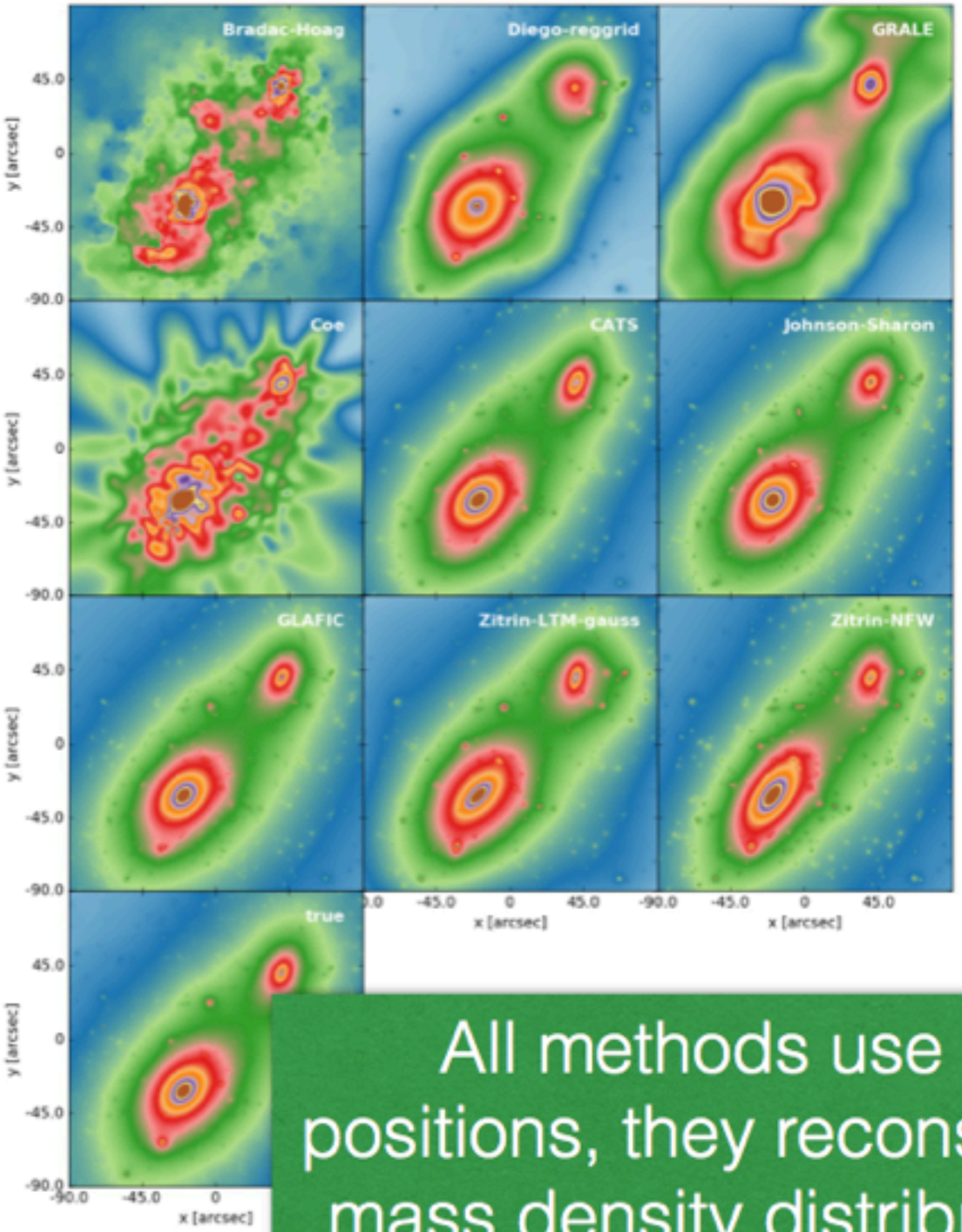
The Astrophysical Journal Letters, Volume 819, Number 1



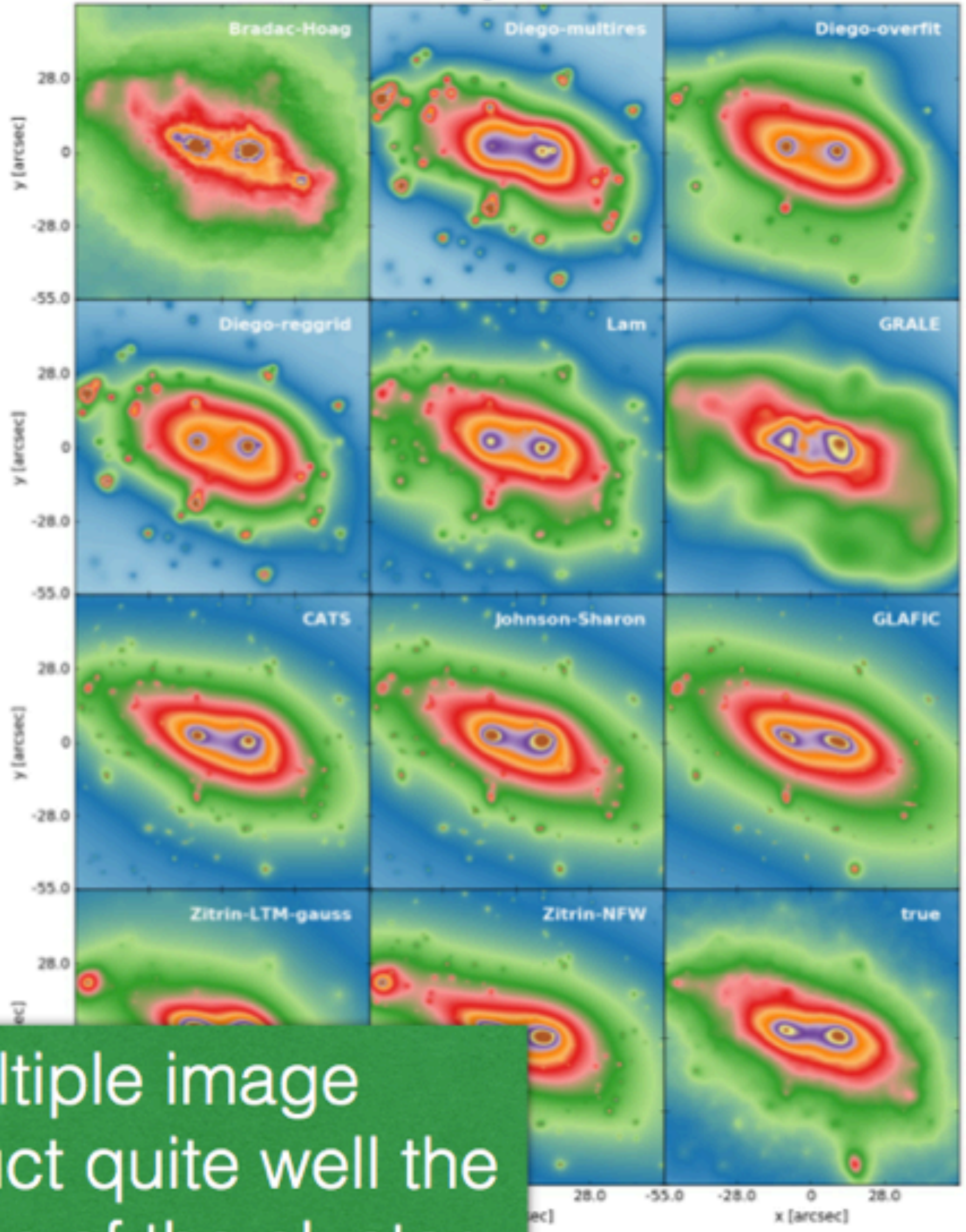
FF Lens Modeling Comparison Project

Use simulated clusters to test different model reconstructions

MOKA cluster



N-Body cluster



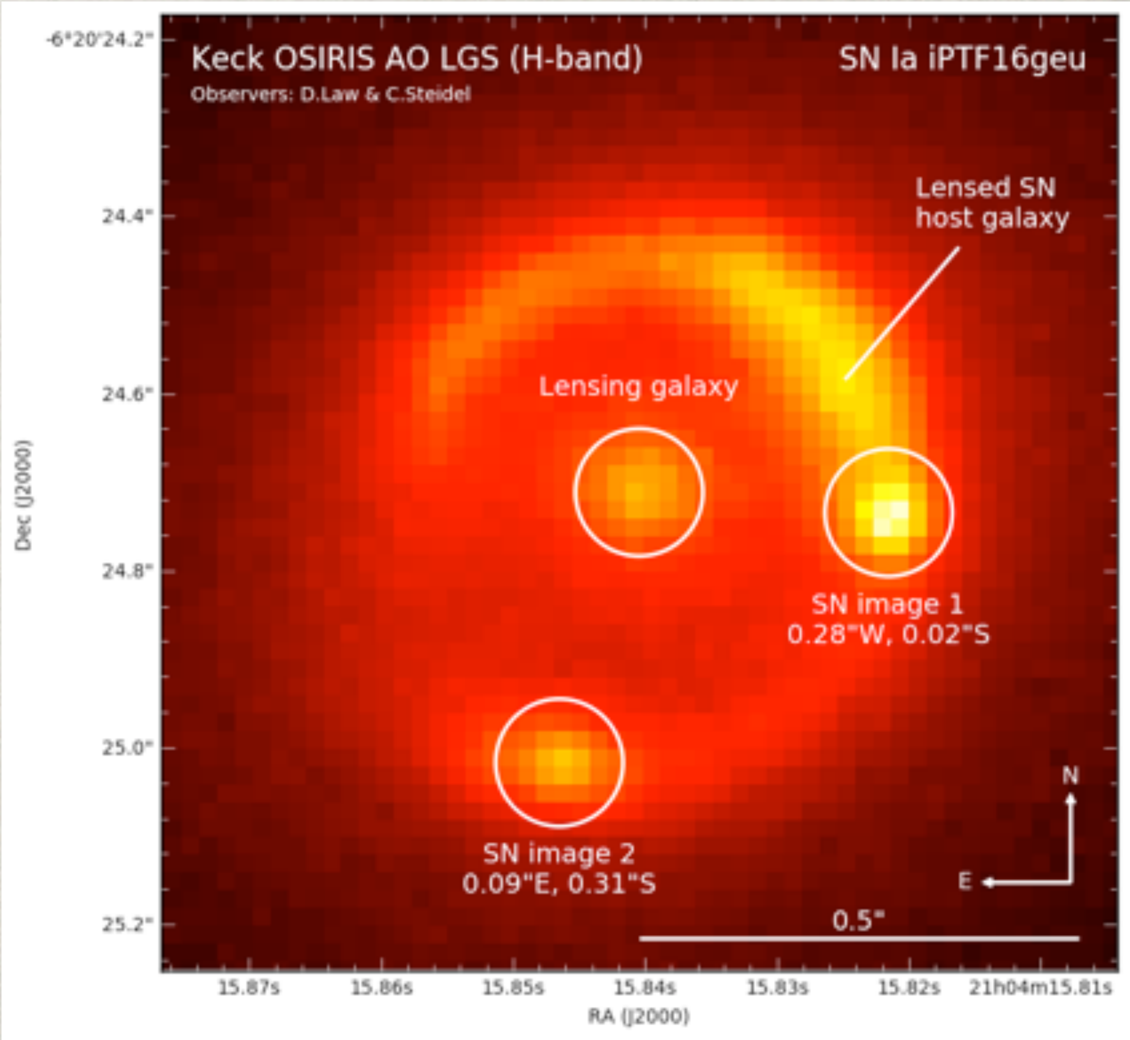
All methods use multiple image positions, they reconstruct quite well the mass density distribution of the cluster and the location of the critical lines.

Meneghetti+16

GALAXY SCALE LENSES

- Einstein rings
  - Probing mass profiles
  - Substructures
  - Modified gravity
  - HST (SLACS/BOSS), CFHTLS (+CS82, etc.)
- Time delays
  - H_0, time delay distance
  - Angular diameter distance
  - HST mass models
  - QSO and...

Supernovae!



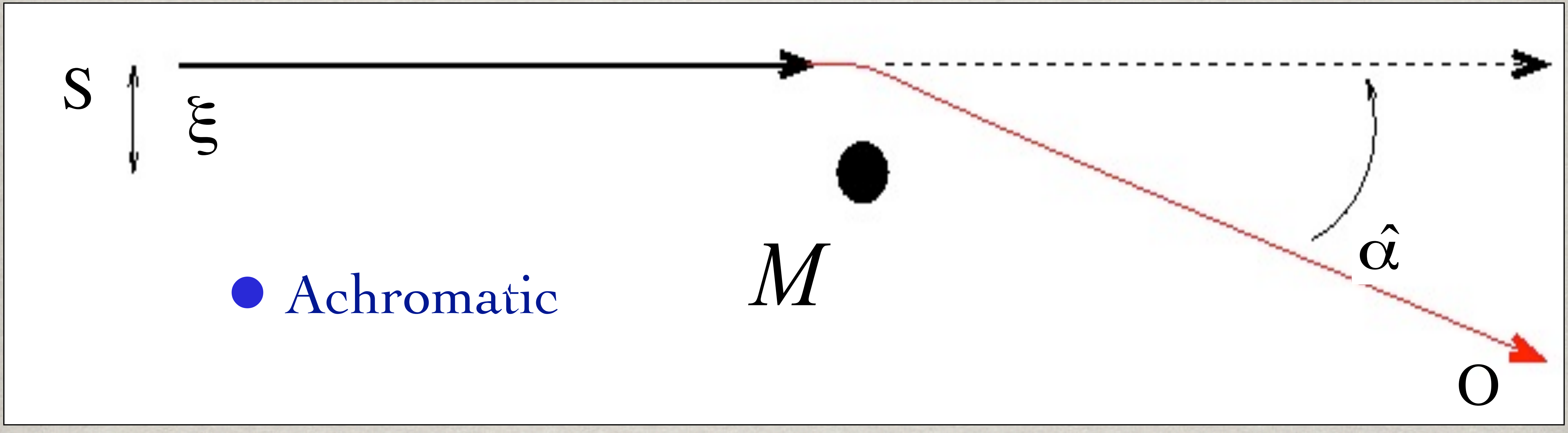
Goobar et al., The discovery of the multiply-imaged lensed Type Ia supernova iPTF16geu, arXiv:1611.00014

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

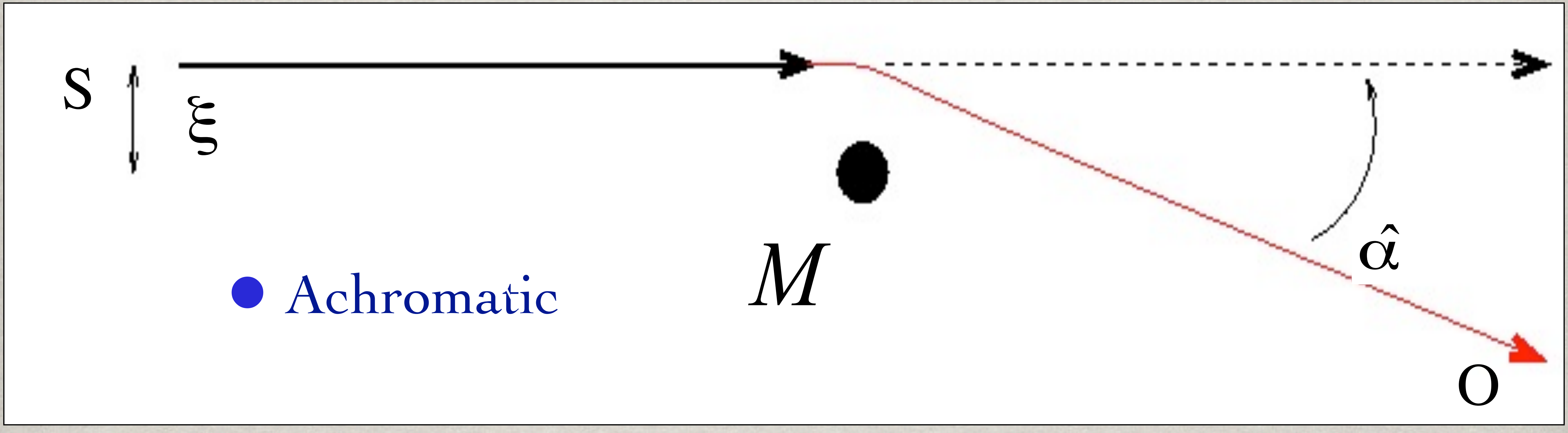
Deflection angle (point source) $\hat{\alpha} = \frac{4GM}{c^2}\frac{1}{\xi}$

BENDING OF LIGHT BY (MODIFIED) GRAVITY

Null geodesic,
Fermat principle

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

peculiar gravitational potentials
(in GR $\psi = \phi$)



- Achromatic

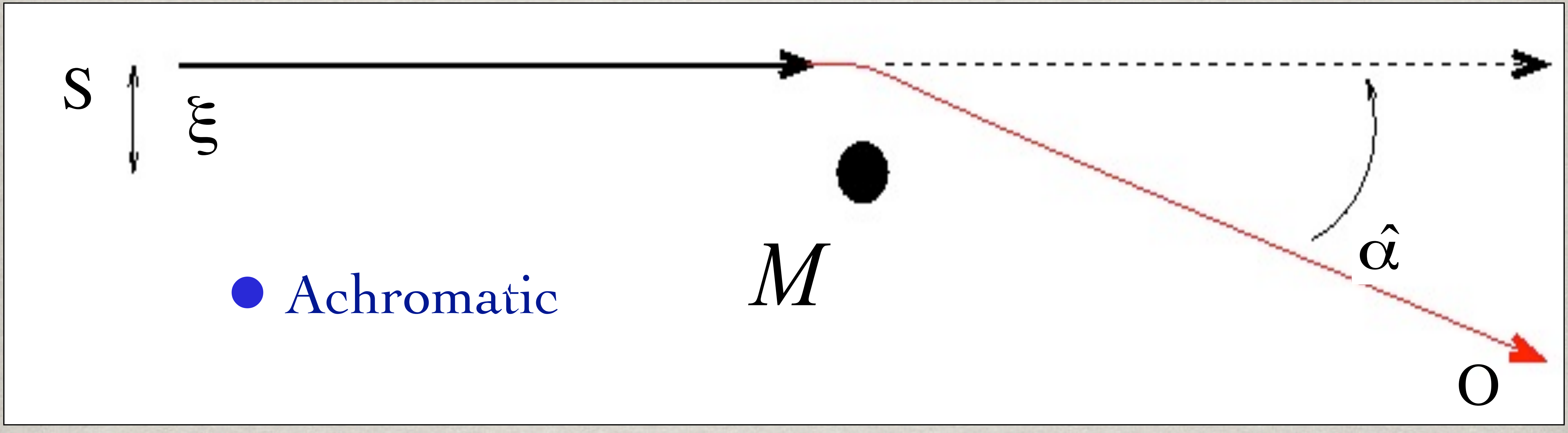
BENDING OF LIGHT BY (MODIFIED) GRAVITY

Null geodesic,
Fermat principle

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

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

$$\frac{\phi}{\psi} = \gamma$$



- Achromatic

Dynamical mass obtained from

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

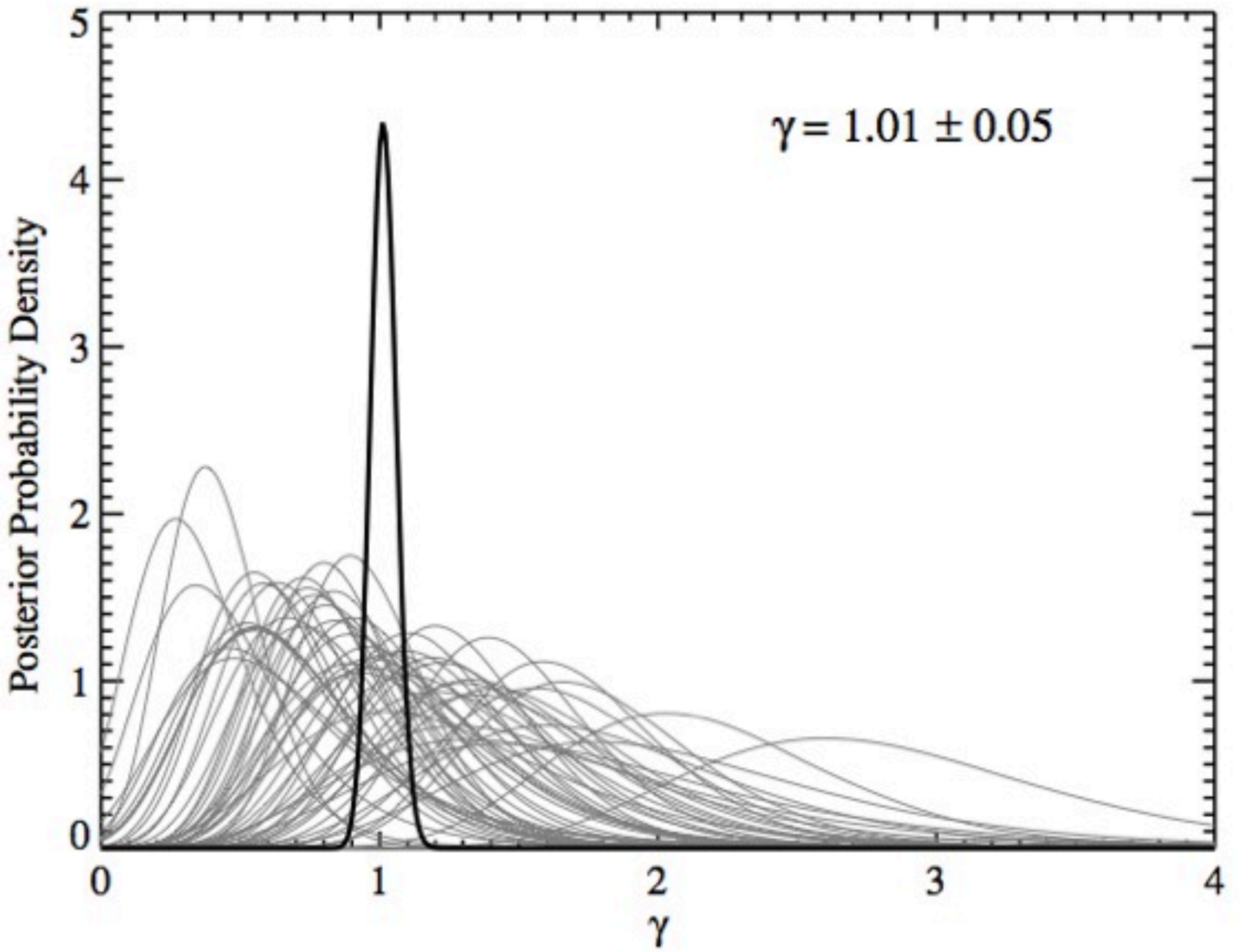
Use combination of lensing + dynamics to test gravity

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

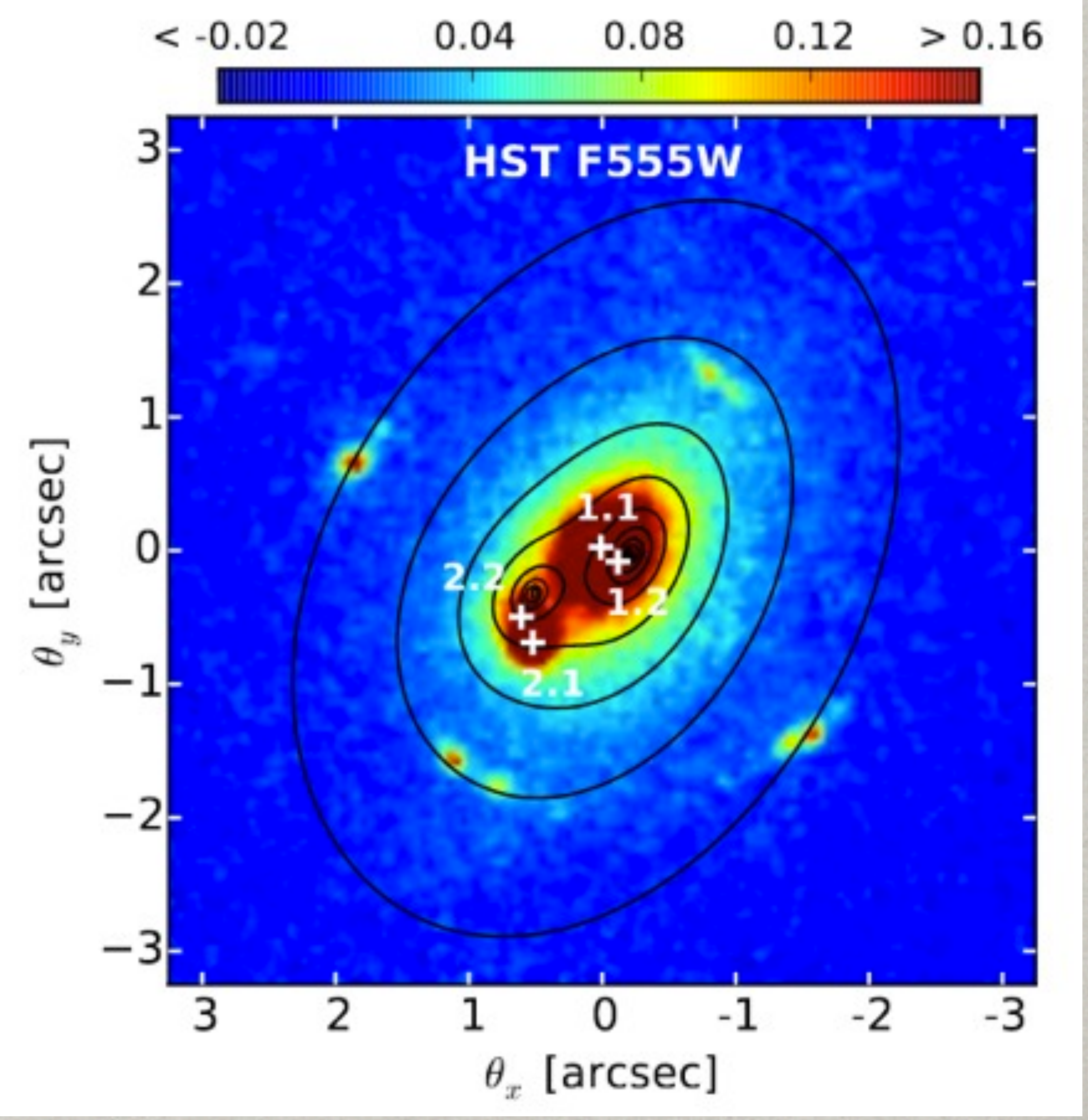
GALAXY SCALE LENSES

- Self-Intercting Dark-Matter predicts offsets between luminous and dark matter in dense regions
  - Seen in clusters, e.g., Harvey et al., 2015, *The nongravitational interactions of dark matter in colliding galaxy clusters*, Science, 347, 1462 (2015); arXiv: 1503.07675
- offsets found in a galaxy scale system
  - Interacting systems
  - kpc offsets in SDSS J1011+0143

    (Shu et al. 2015)
  - If interpreted solely as evidence for self-interacting dark matter:

$$\sigma_{\mathrm{DM}}/m \sim (1.7 \pm 0.7) \times 10^{-4}\ \mathrm{cm}^2\ \mathrm{g}^{-1} \times (t_{\mathrm{infall}}/10^9\ \mathrm{yr})^{-2}$$

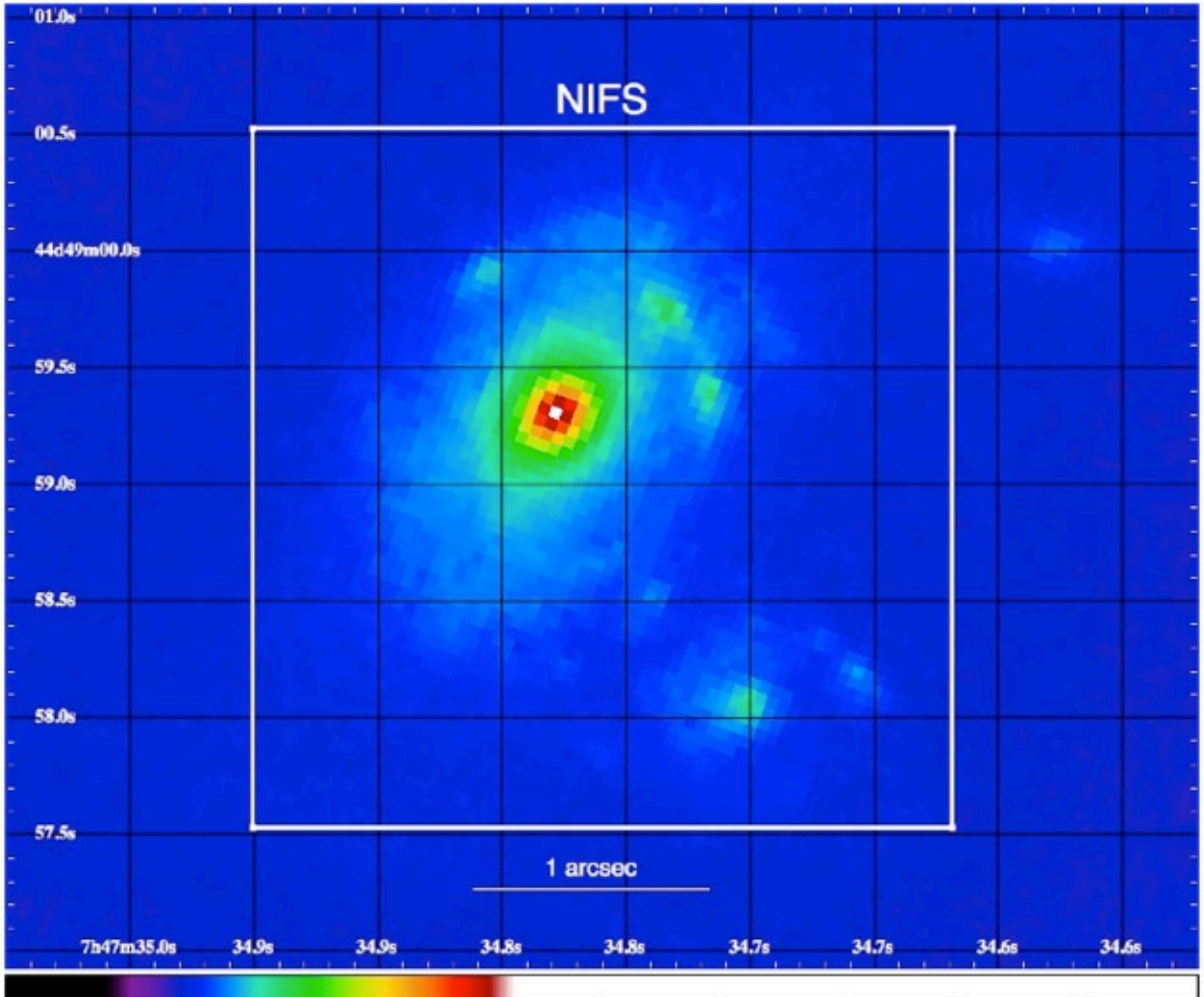
  - only SDSS spectroscopy



2D Kinematics

Detailed "3D" modeling of systems with IFU. Source and lens redshifts, new images. Control astrophysics systematics, velocity dispersion maps.

Example: follow-up of SDSS J0747+4448 with NIFS + Altair LGS



One spectra per pixel

Lens $z = 0.4366 \pm 0.0001$

Souce $z = 0.897 \pm 0.001$

Einstein Radius

$(0.610 \pm 0.001)''$

Magnification $\mu = 39.72$

NIFS resolution:

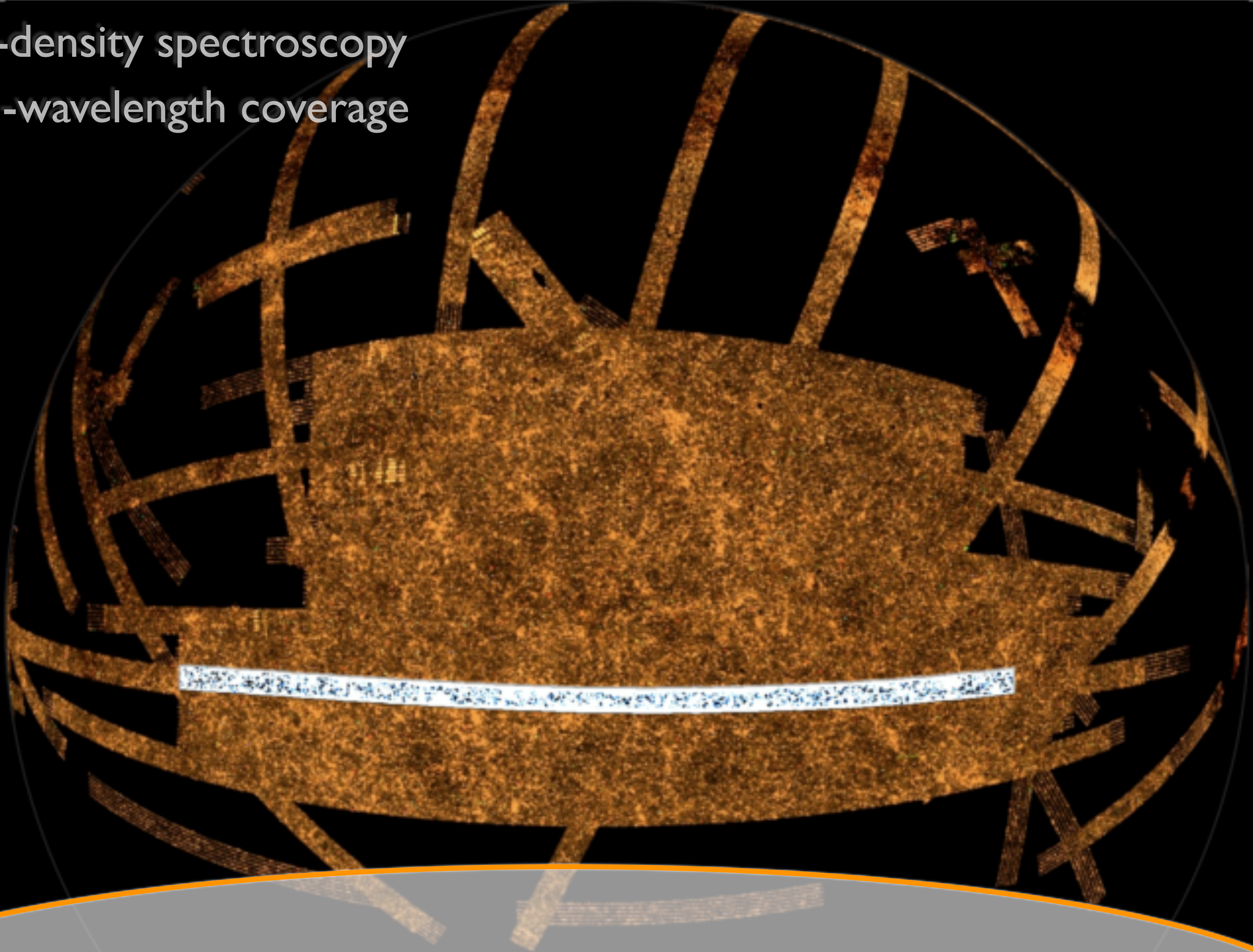
$0.2''/\mathrm{spaxel}$

In the source plane

$\sim 0.01'' \quad \sim 40\ \mathrm{pc}$

SDSS Stripe 82

- High-density spectroscopy
- Multi-wavelength coverage



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

Finding arcs in CS82

Multiple target selection and inspections

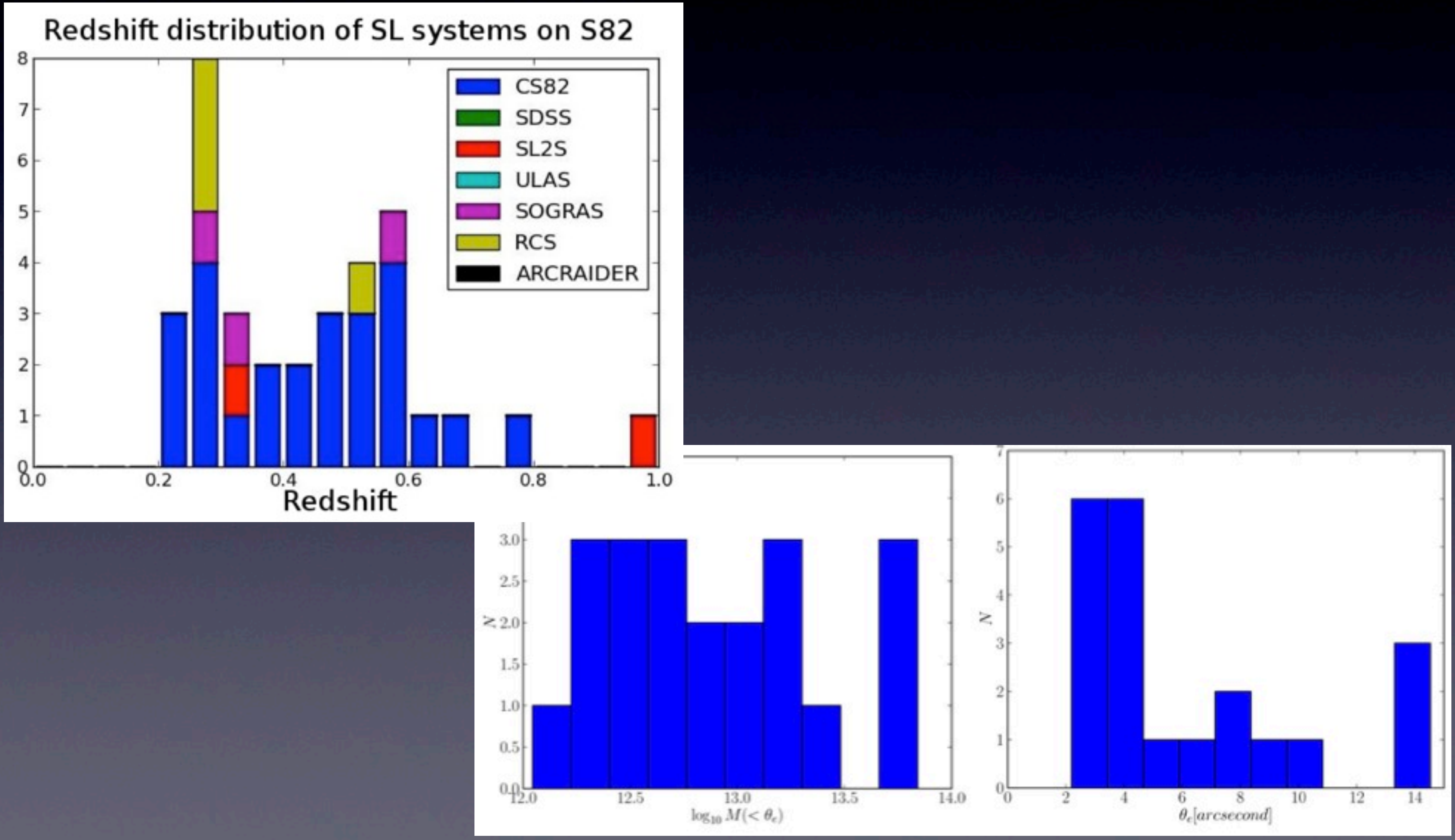
- More et al. arc finder (127.000 inspections!)
- Optical cluster catalogs
- x-ray (S82X, XCS, RASS-BSC), SZE (Planck, ACT)
- Weak Lensing Peaks (new!)
- Luminous Red Galaxies

> Additional 20 candidates and counting...

- + VICS82 (SpaceWarps)

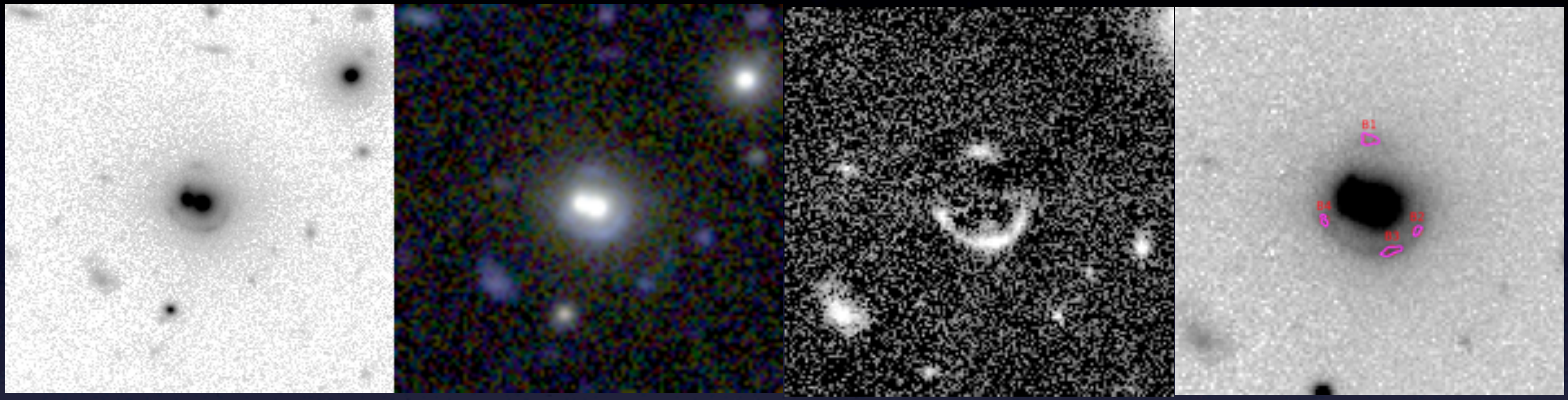
Need multiple search criteria

CS82 Arc Candidates



CS82 Einstein Rings

CS82SL01:36:39+00:08:18



Anna Niemiec

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

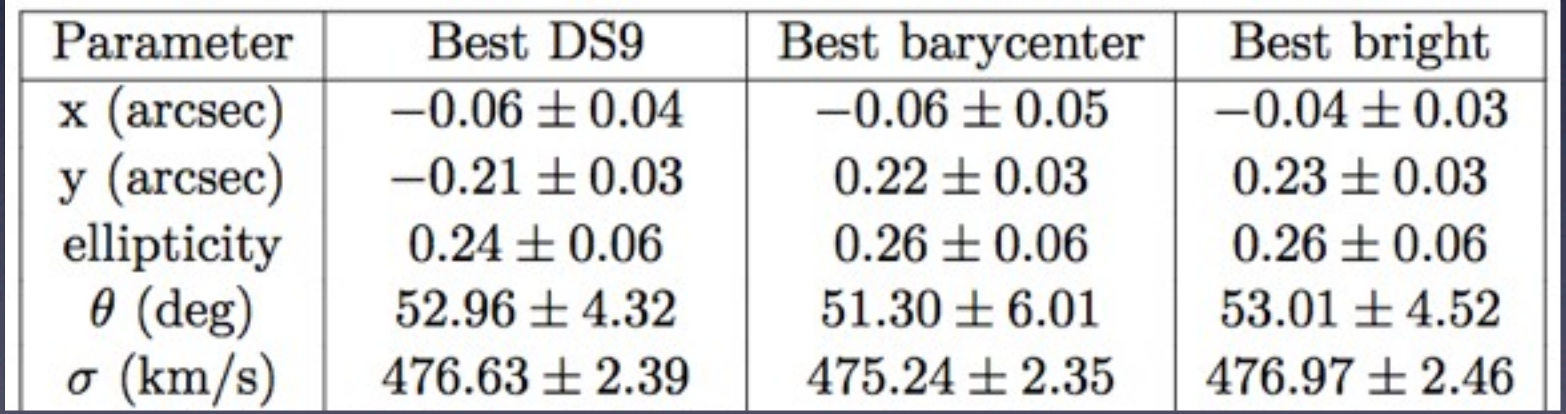
CS82 Einstein Rings

CS82SL21:15:27-00:38:17

Anna Niemiec

- z_{spec} = 0.562,
- O_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

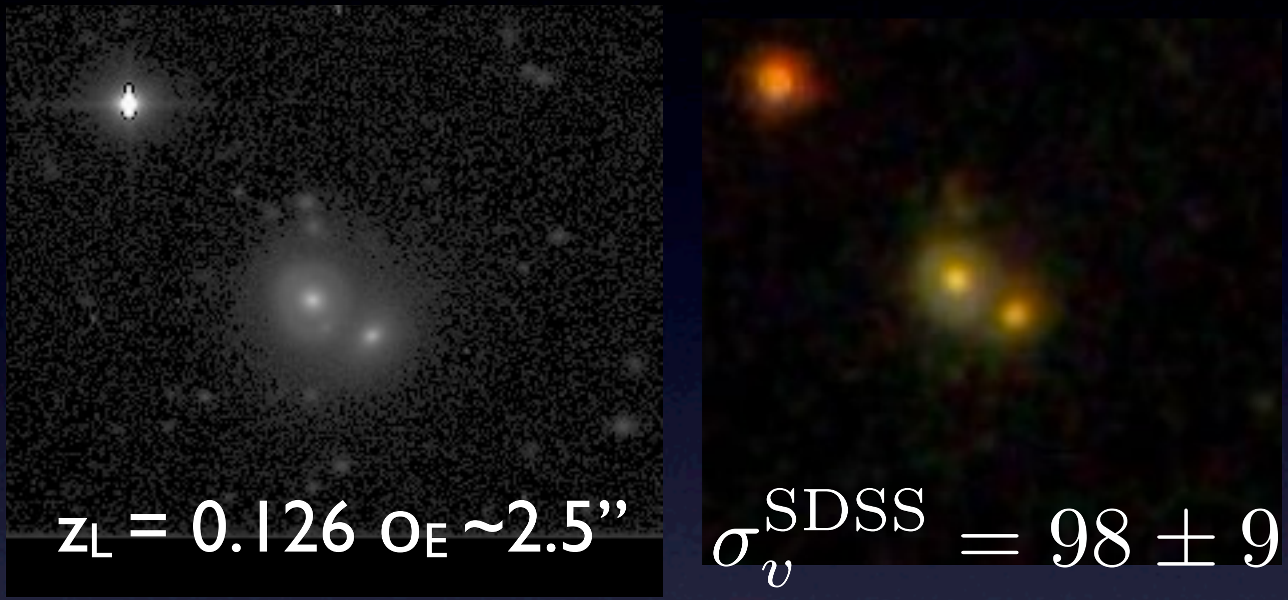
- $z_{spec} = 0.445$, $\sigma_v^{\mathrm{SDSS}} = 224 \pm 30$
- $o_E = 3.33''$

Einstein Rings or Ring Galaxies?

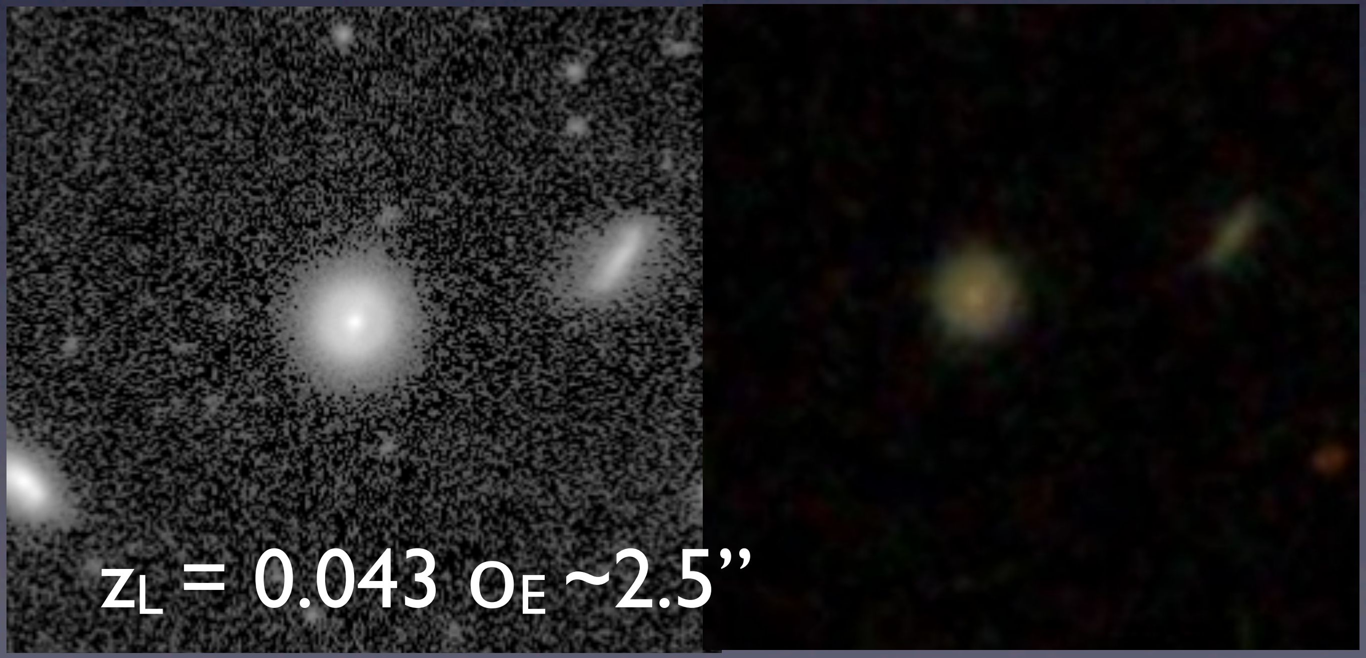
CS82SL23:27:42+00:17:46

$z_L = 0.217$ $\theta_E \sim 2.15''$

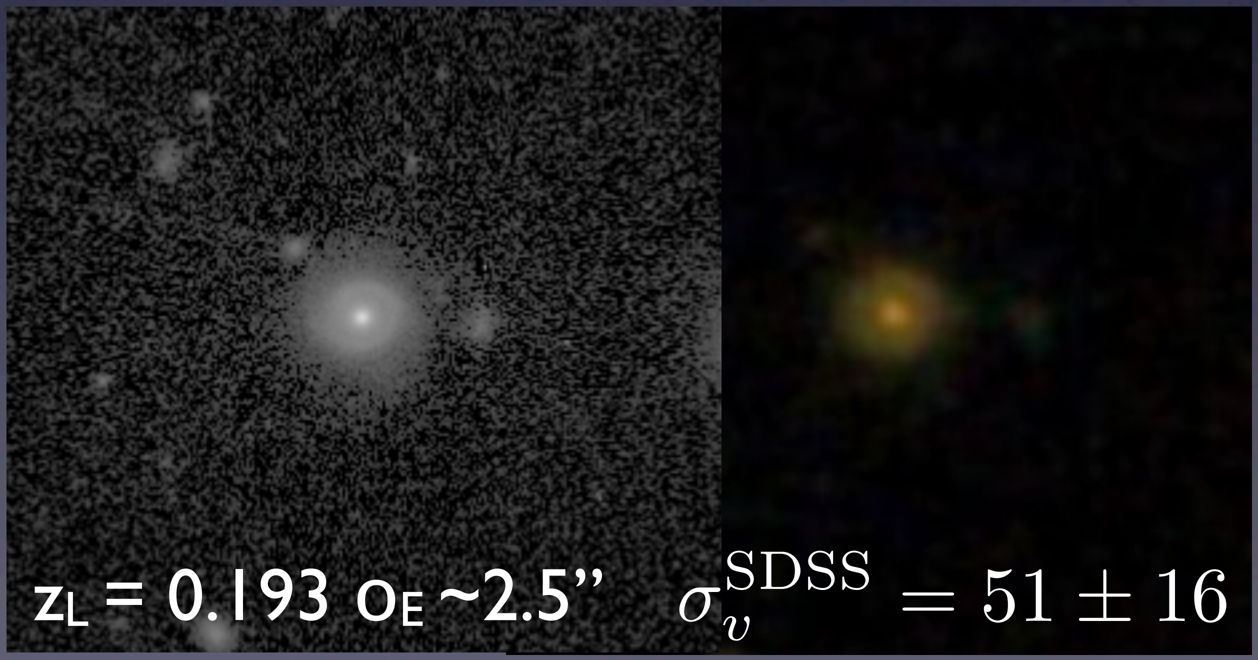
Ring galaxies from scanning of LRGs?



$z_L = 0.126$ $\theta_E \sim 2.5''$ $\sigma_v^{\mathrm{SDSS}} = 98 \pm 9$



$z_L = 0.043$ $\theta_E \sim 2.5''$



$z_L = 0.193$ $\theta_E \sim 2.5''$ $\sigma_v^{\mathrm{SDSS}} = 51 \pm 16$

Alice Candeias

Multi-wavelength information

Of the 38 lens candidates:

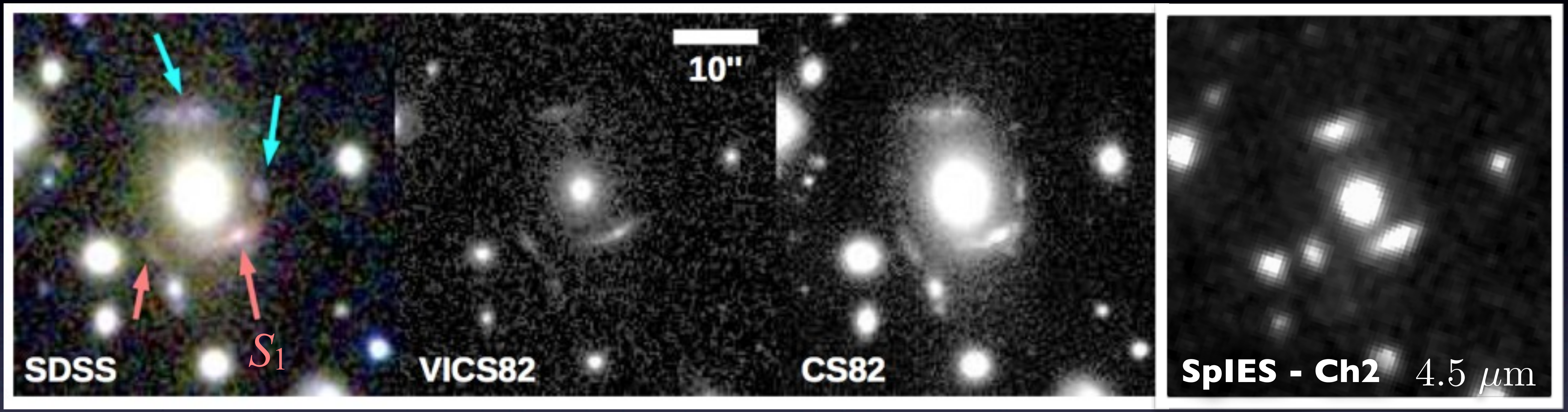
- 32 have SDSS spectroscopy
- 15 are in optical clusters/groups
- NIR: 16 in 2MASS, most in VICS82 (VISTA+CFHT) [2017]
- IR: 30 in WISE, 9 in SpIES [2016] + 4 in SHELA
- 4 in VLA-FIRST, 2 in VLA-Stripe 82, 1 in ACT
- 1 in XMM [2016], 2 in Galex

Arc candidates:

- 9 in VICS82, 7 in SpIES

Multi-wavelength data

CS82SL00:44:37-00:55:20

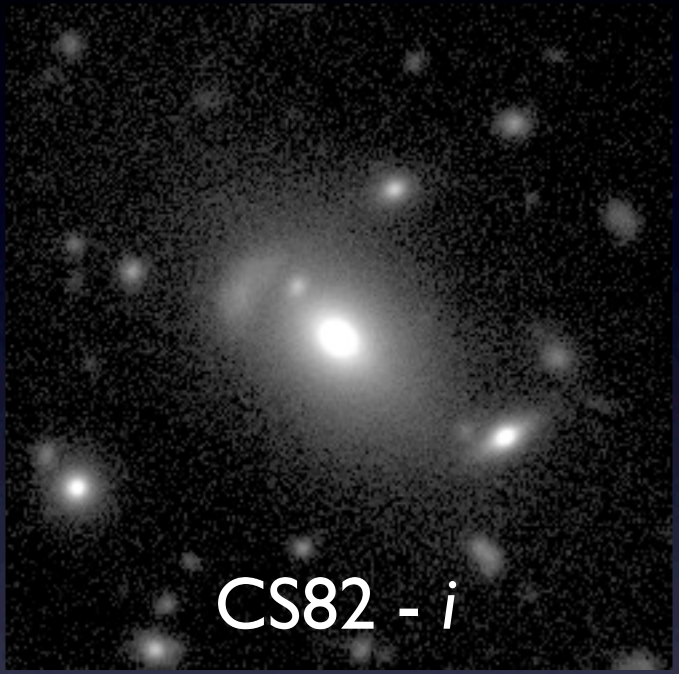


$$z_L = 0.201, \quad z_{S_1}^{\rm phot} = 0.55 \pm 0.06, \quad \sigma_v^{\rm SDSS} = (278 \pm 14)\,{\rm Km/s}$$

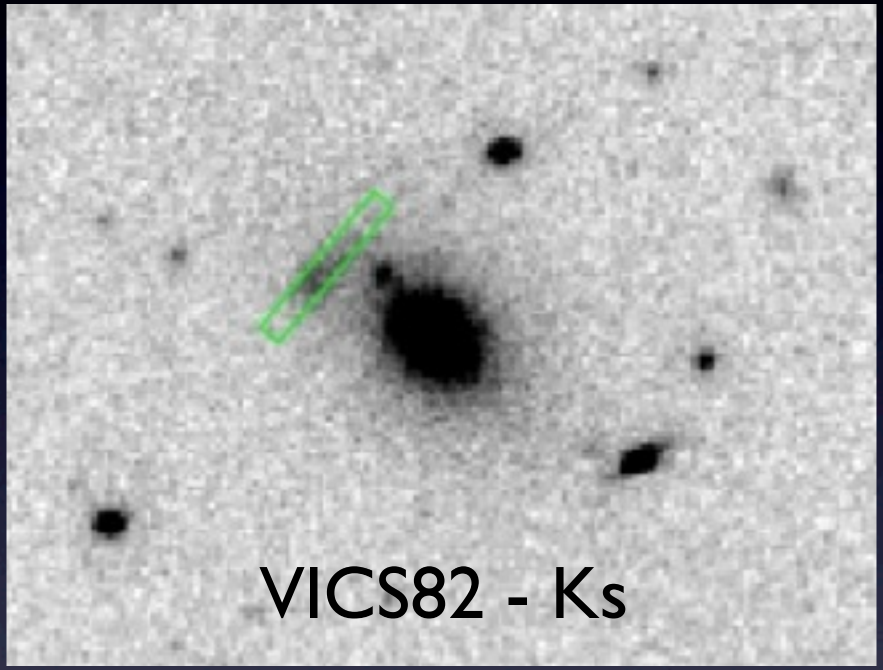
- System found in CS82 has clear IR emission
- Gemini approved for AO follow-up, but no suitable star
- Carry out systematic search

Multi-wavelength data

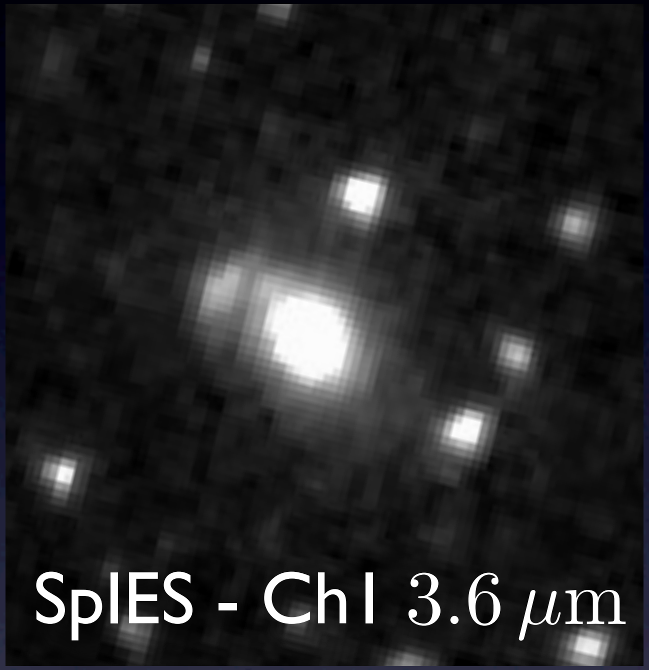
CS82SL02:20:32+00:28:03



CS82 - *i*



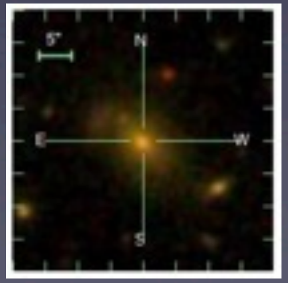
VICS82 - Ks



SpIES - Ch1 $3.6\,\mu\mathrm{m}$

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

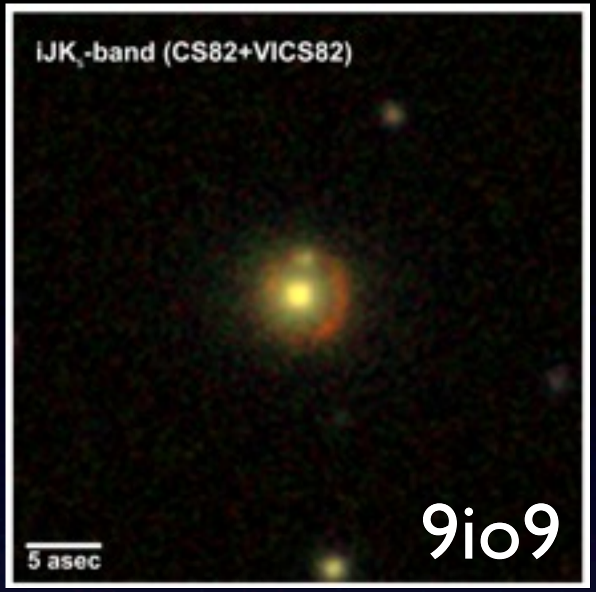
- Build SED
- Estimate magnification
- Work in progress....



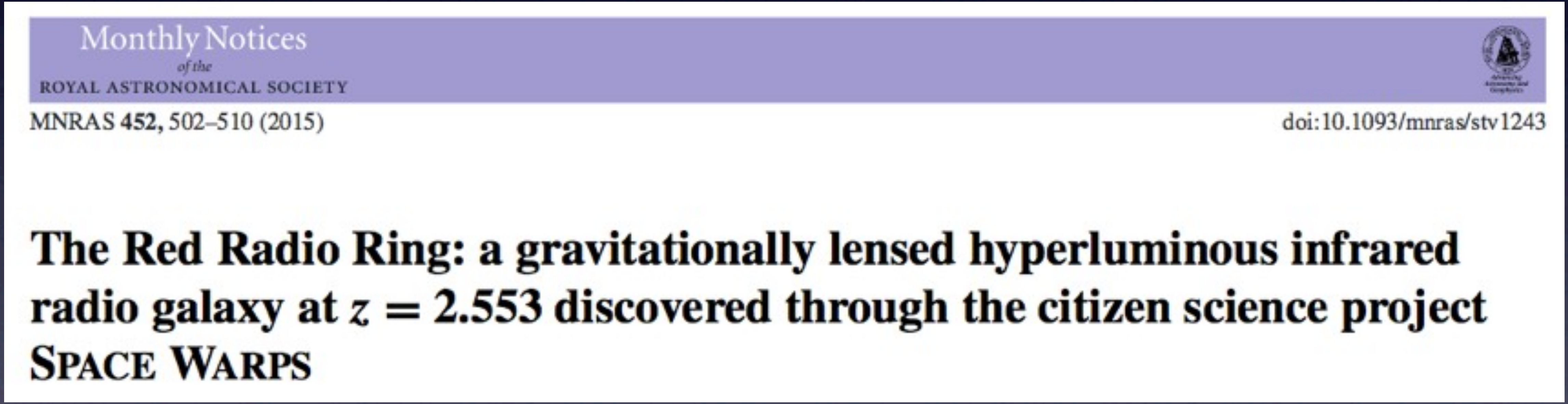
~ 1 arcmin

Lobes only seen in VLA-Stripe82 resolution

SpaceWarps Einstein Ring



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



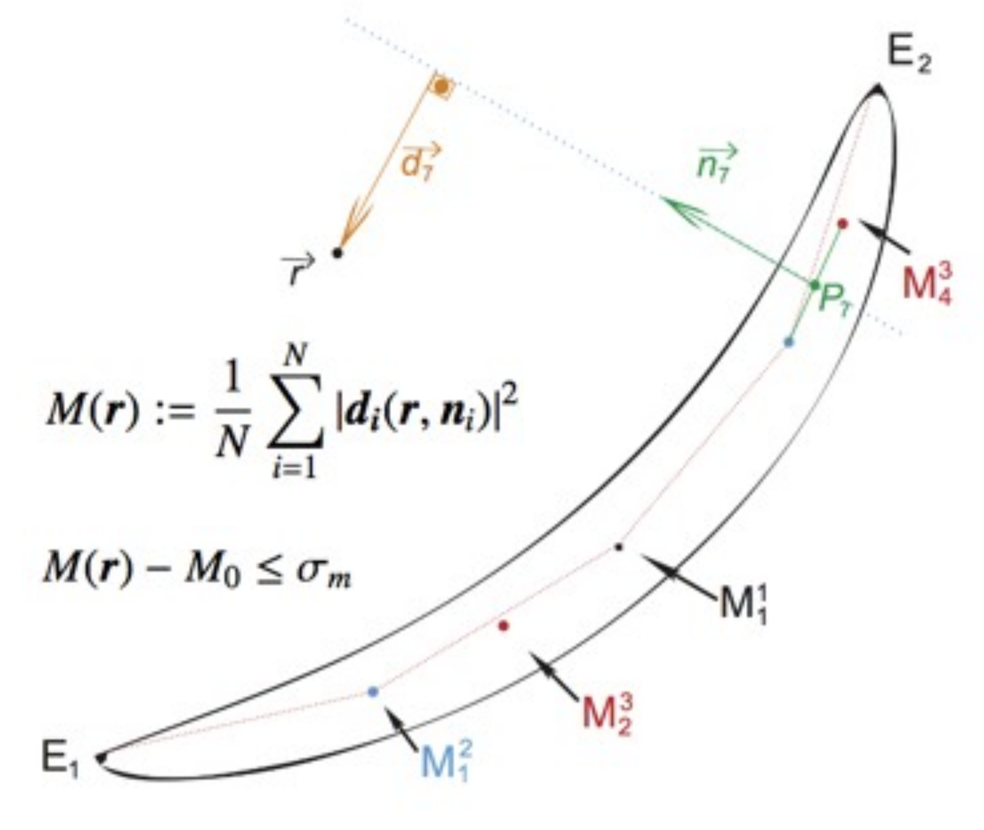
Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY

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

- New samples of Einstein rings from the ground will improve the MoG constraints
- Need redshifts
- IFU improves the modeling (both lens inversion and lens dynamics)
- Constraints on substructure from SB fluctuations

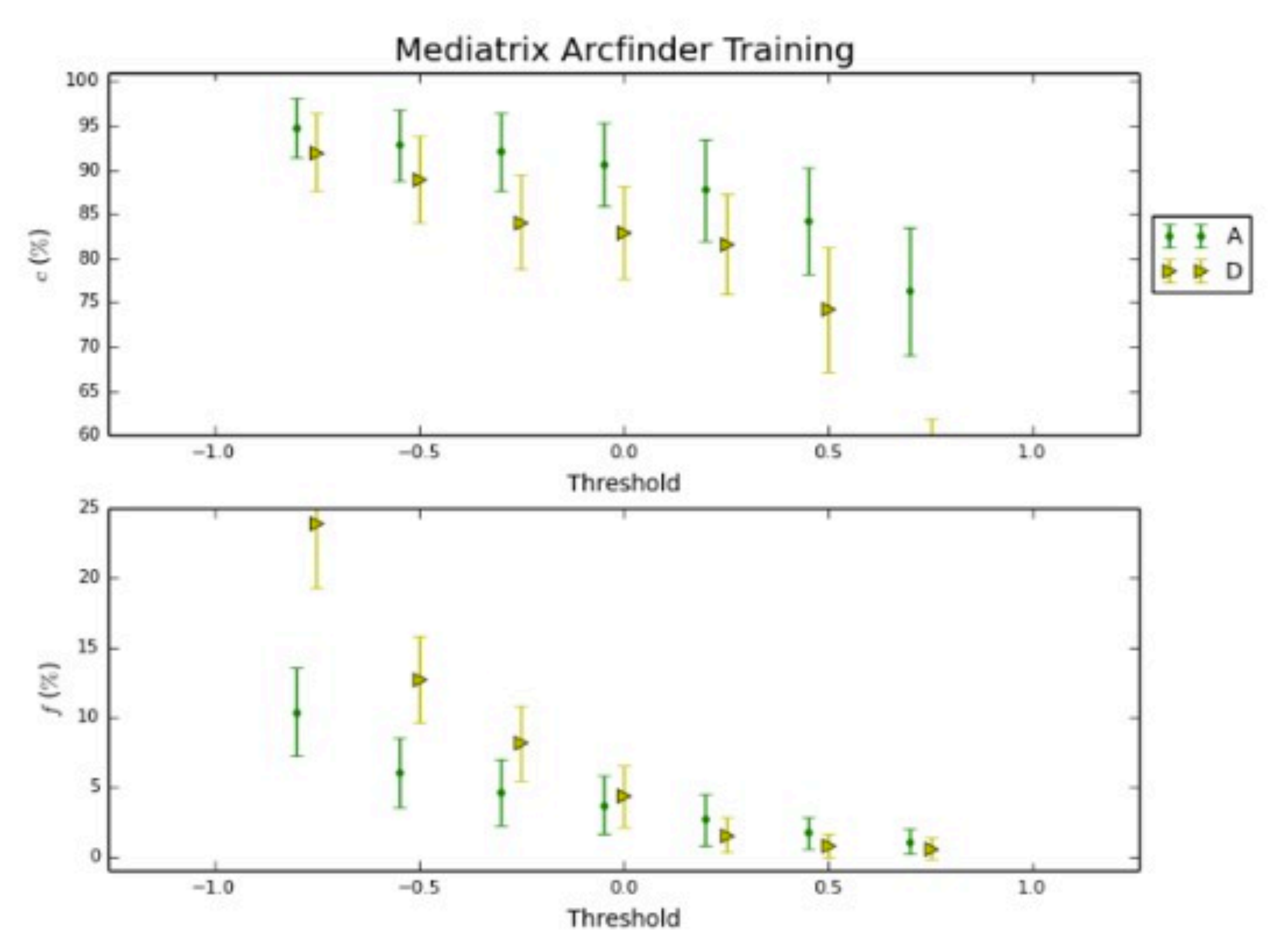
Mediatrix Neural Network Arcfinder



- Applied to HST data
- Apply to wide-field data
  - Parallelization
  - Masks
  - Genetic optimization
  - Model subtraction

Use Mediatrix (Bom, et al. 2016a), a novel method to obtain object parameters

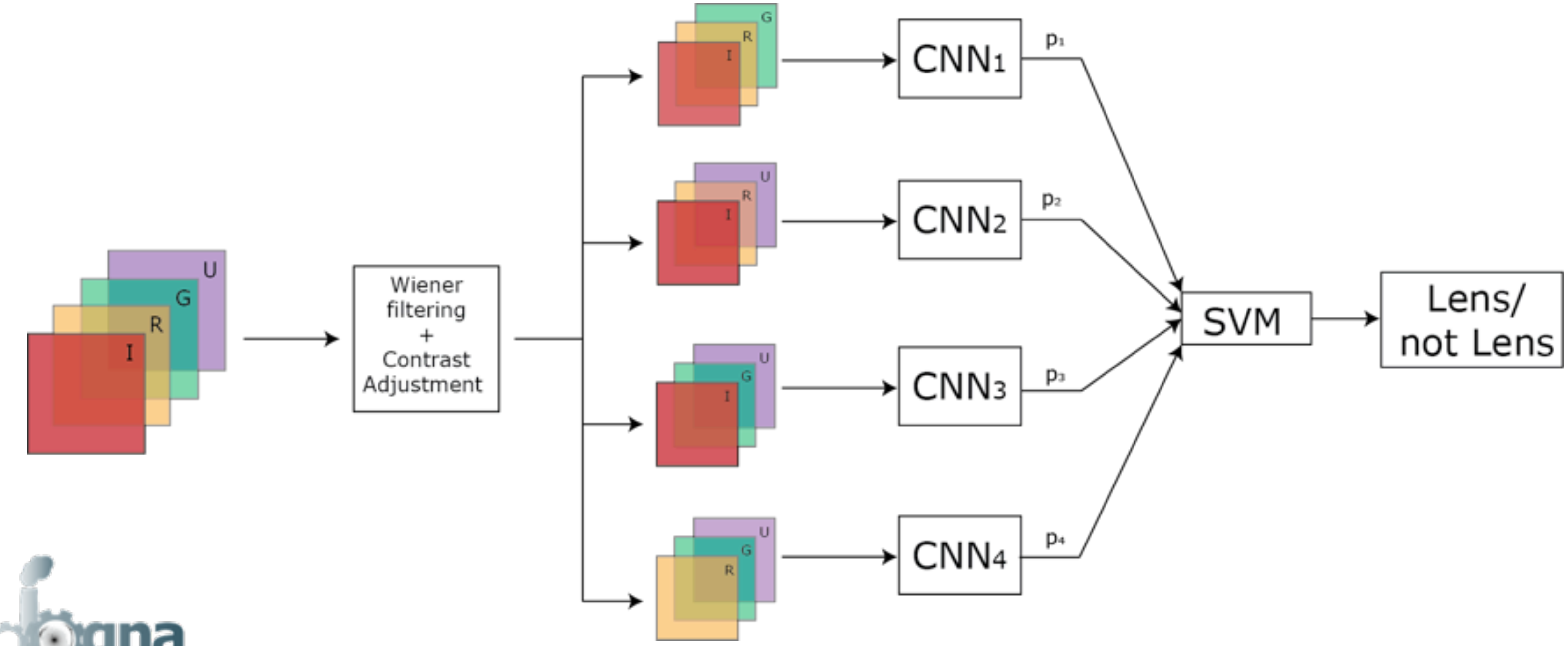
Use simulations (AddArcs) to train an Artificial Neural Network (Bom, et al. 2016b)



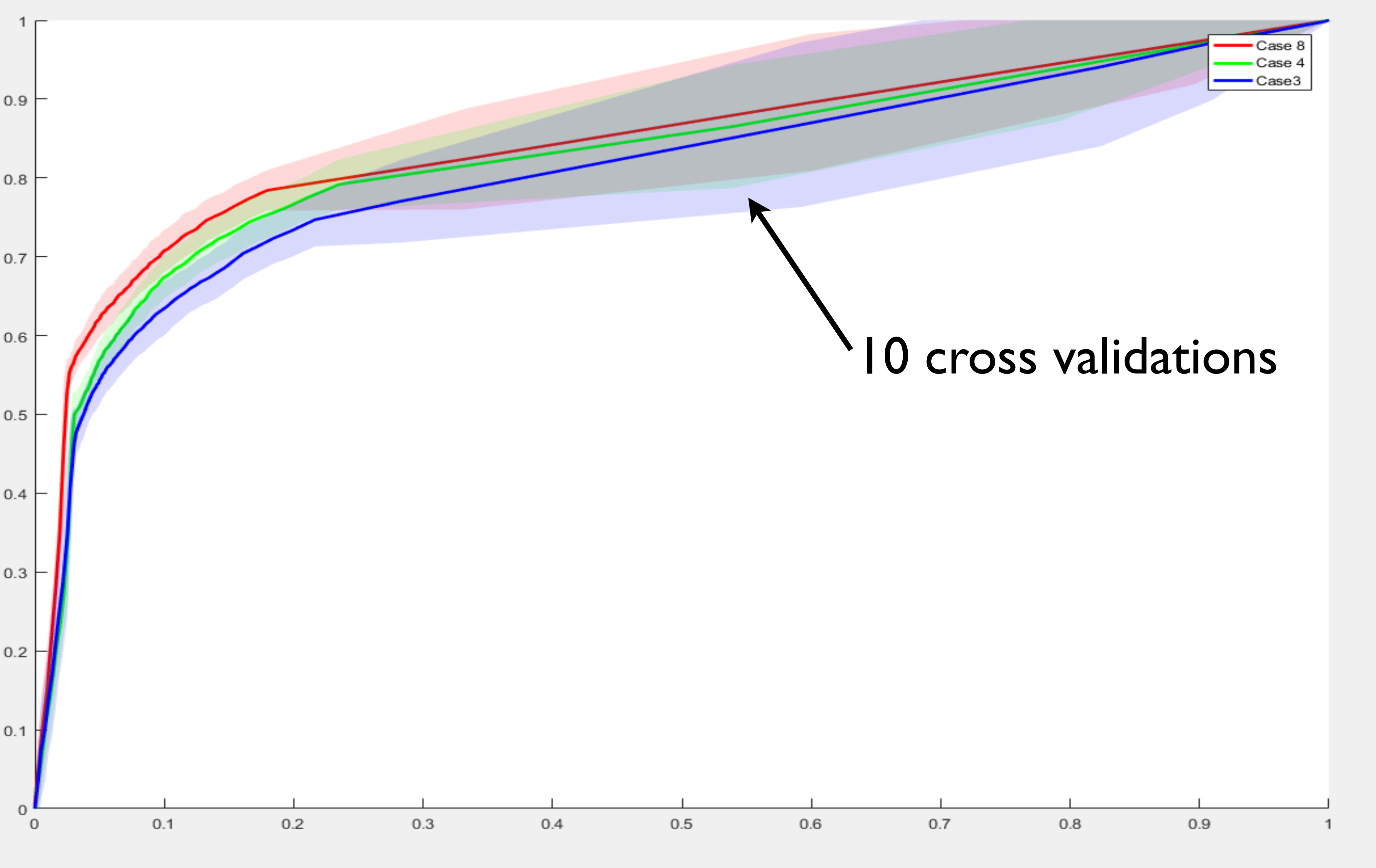
Obtain completeness and spurious detections

Gravitational Lens Finding Challenge

- Data on 4 filters
- Tested combinations of CNN and SVM
- No human intervention in any step
- Execution times range from ~ 1 to 2.5 hr (for 10 x 20k images, training + validation)



CNN + SVM



10 cross validations

- Case 8: 4 CNNs with combinations of 3 filters + SVN
  - Training time: 680 s
  - Total Processing Time: 2h 30 min (for classifying 100k objects)
  - Area Under ROC: 84.08%

Concluding remarks

- Strong lensing has become a useful cosmological and astrophysical observable, fulfilling its promises for studying the lenses, the sources, and the large-scale geometry of the Universe
  - Unique for modified gravity and DM properties
  - Unique for inner cluster regions and inner ETG slope
  - Resolving ~ 10-100 pc @ z ~ 1
- Statistics: arcfinders
- As in any other modern astrophysical and cosmological setting, results are being dominated by systematics
  - Models good down to ~ 10 kpc
  - Explore implications for DM: WDM and SIDM
  - Use data (“golden lenses”) and end-to-end simulations

Concluding remarks

- Strong lensing has become a useful cosmological and astrophysical observable, fulfilling its promises for studying the lenses, the sources, and the large-scale geometry of the Universe
  - Unique for modified gravity and DM properties
  - Unique for inner cluster regions and inner ETG slope
  - Resolving ~ 10-100 pc @ z ~ 1
- 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 wide-field surveys
- Lots of excellent data to come in the near future!
- Very happy to collaborate!

Thank You

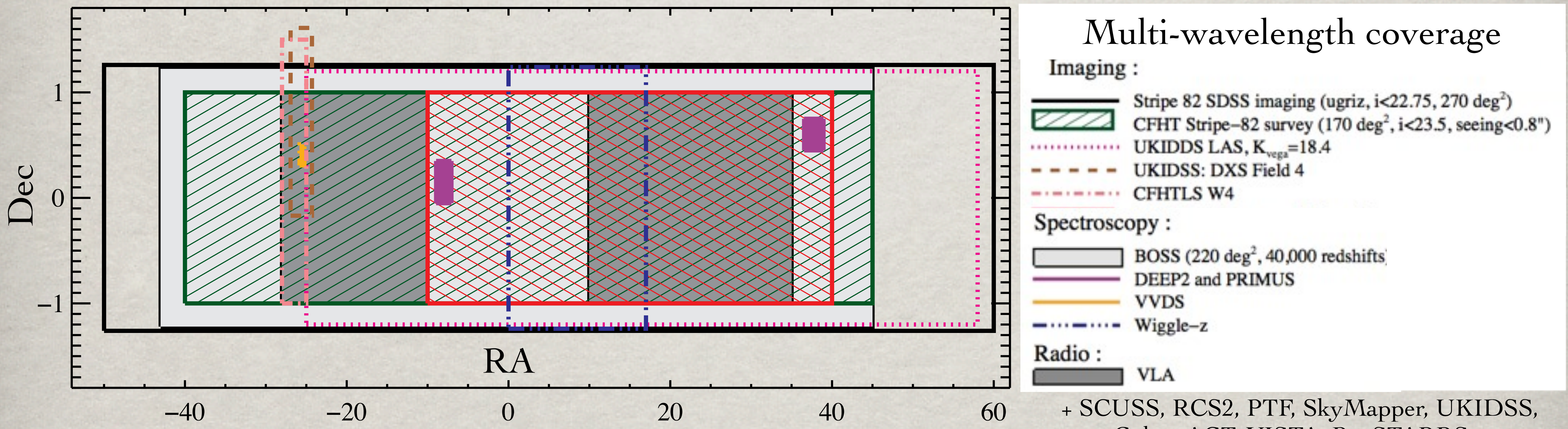
M C

#VoltaMCTI

T I

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,...)

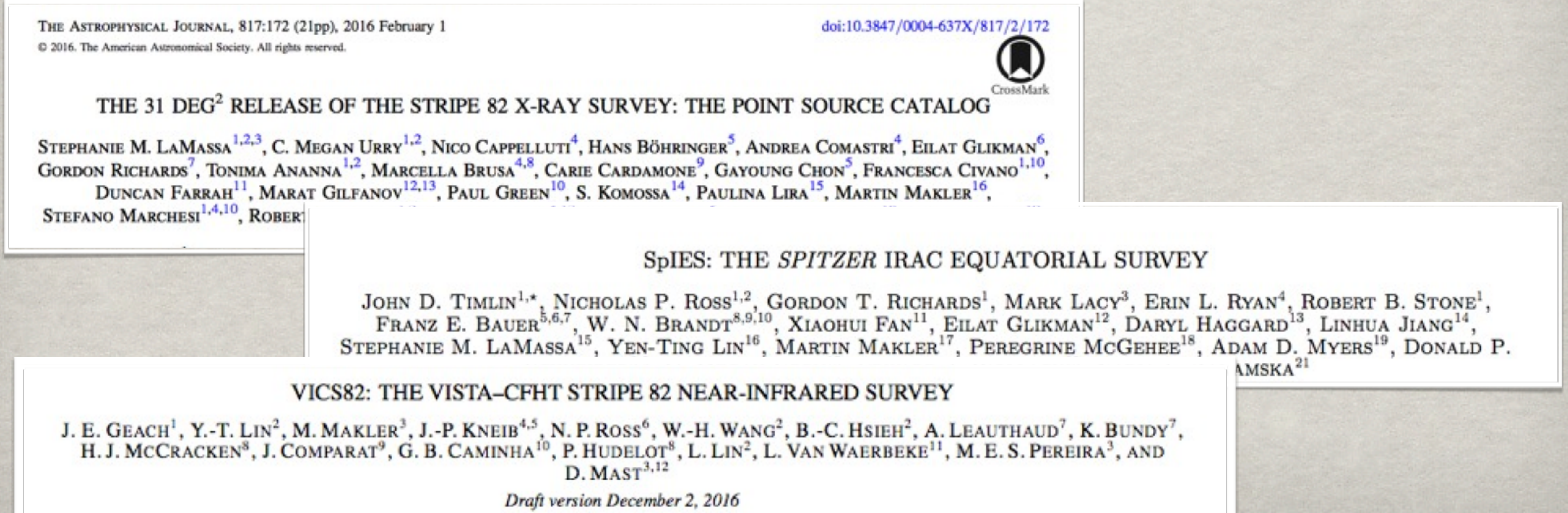


+ SCUSS, RCS2, PTF, SkyMapper, UKIDSS, Galex, ACT, VISTA, PanSTARRS...

- SOAR Gravitational Arc Survey (SOGRAS)
    - ✓ 47 clusters selected from S82 coadd
- CFHT Stripe 82 Survey (CS82): The weak lensing survey in S82
    - ✓ 170 deg2, down to i = 24 and superb median seeing of 0.6”

Stripe 82 @ 2017

- 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], Rober

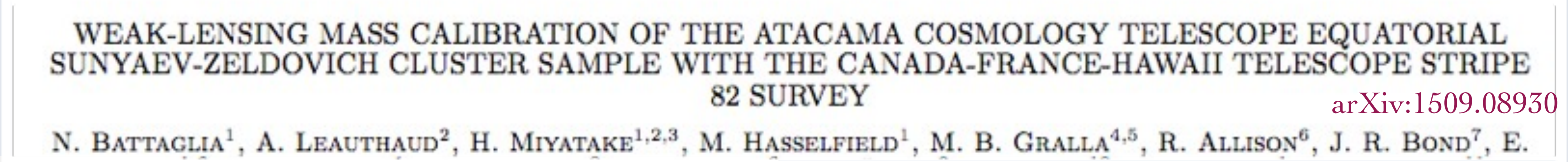
SpIES: THE *SPITZER* IRAC EQUATORIAL SURVEY

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.
AMSKA[21]

VICS82: THE VISTA–CFHT STRIPE 82 NEAR-INFRARED SURVEY

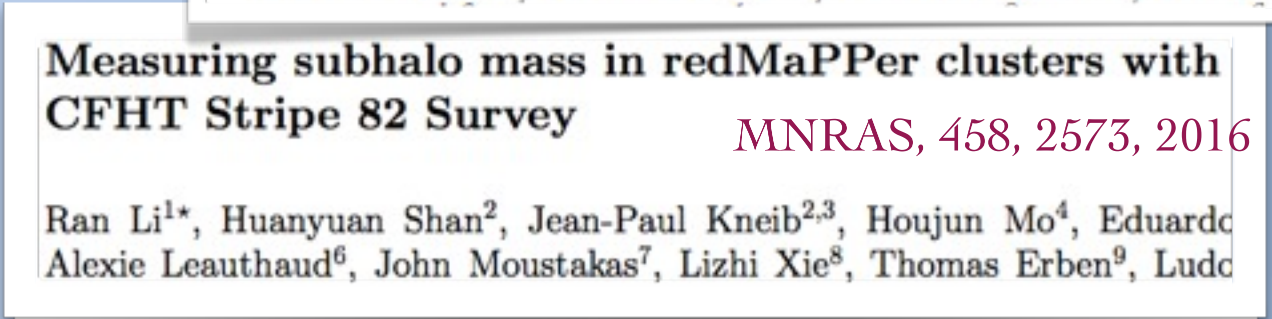
J. E. Geach[1], Y.-T. Lin[2], M. Makler[3], J.-P. Kneib[4,5], N. P. Ross[6], W.-H. Wang[2], B.-C. Hsieh[2], A. Leauthaud[7], K. Bundy[7],
H. J. McCracken[8], J. Comparat[9], G. B. Caminha[10], P. Hudelot[8], L. Lin[2], L. Van Waerbeke[11], M. E. S. Pereira[3], and
D. Mast[3,12]

Draft version December 2, 2016


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

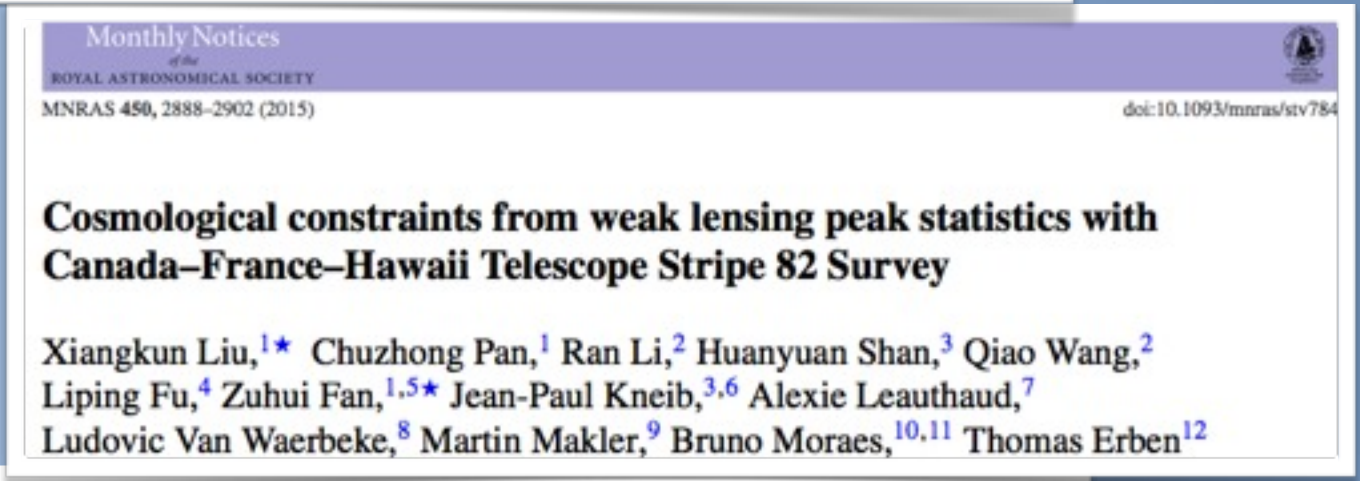
N. Battaglia[1], A. Leauthaud[2], H. Miyatake[1,2,3], M. Hasselfield[1], M. B. Gralla[4,5], R. Allison[6], J. R. Bond[7], E.


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], Eduard
Alexie Leauthaud[6], John Moustakas[7], Lizhi Xie[8], Thomas Erben[9], Lud

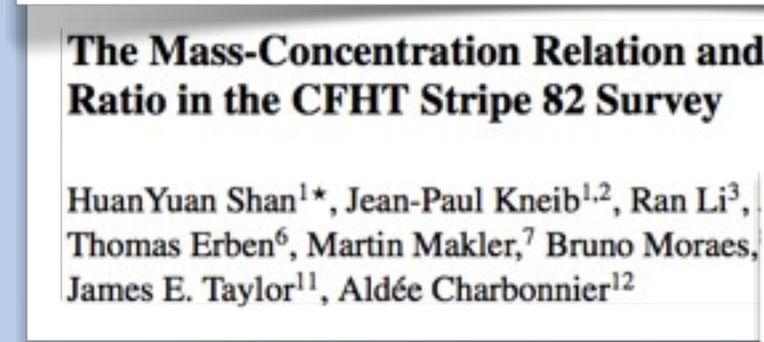
---


Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY

MNRAS 450, 2888–2902 (2015) doi:10.1093/mnras/stv784

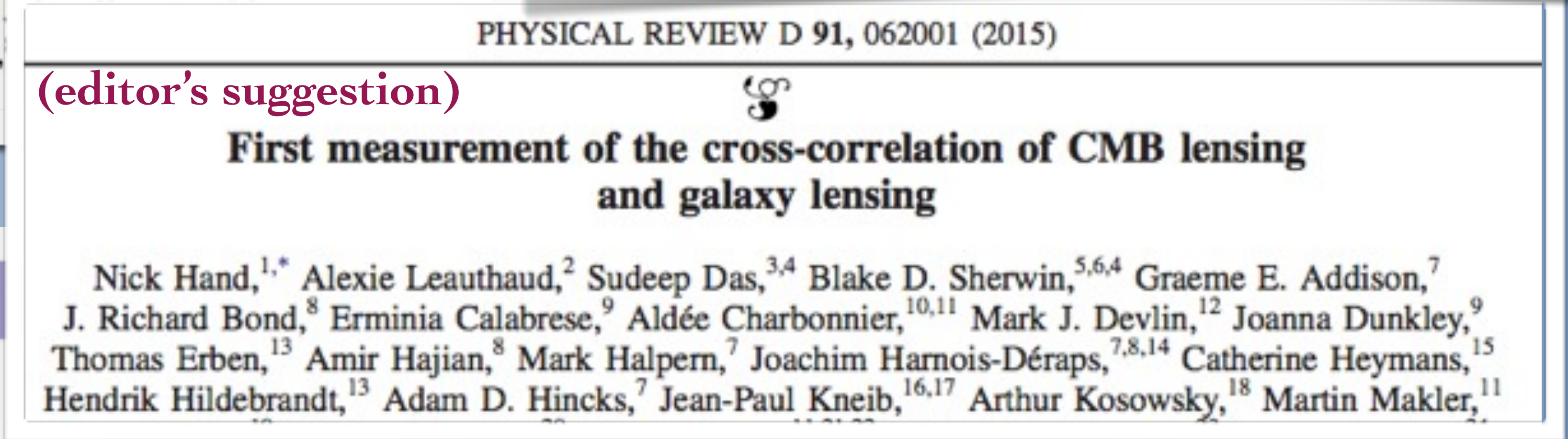
Cosmological constraints from weak lensing peak statistics with Canada–France–Hawaii Telescope Stripe 82 Survey

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

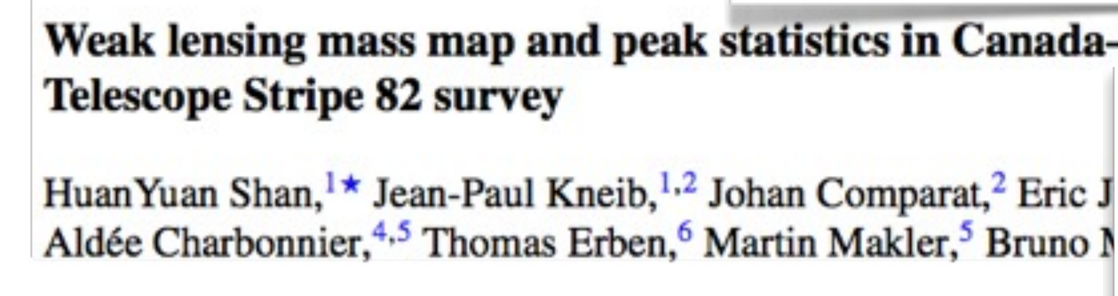
HuanYuan Shan[1*], Jean-Paul Kneib[1,2], Ran Li[3],
Thomas Erben[6], Martin Makler,[7] Bruno Moraes,
James E. Taylor[11], Aldée Charbonnier[12]


PHYSICAL REVIEW D **91**, 062001 (2015)

(editor's suggestion)

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

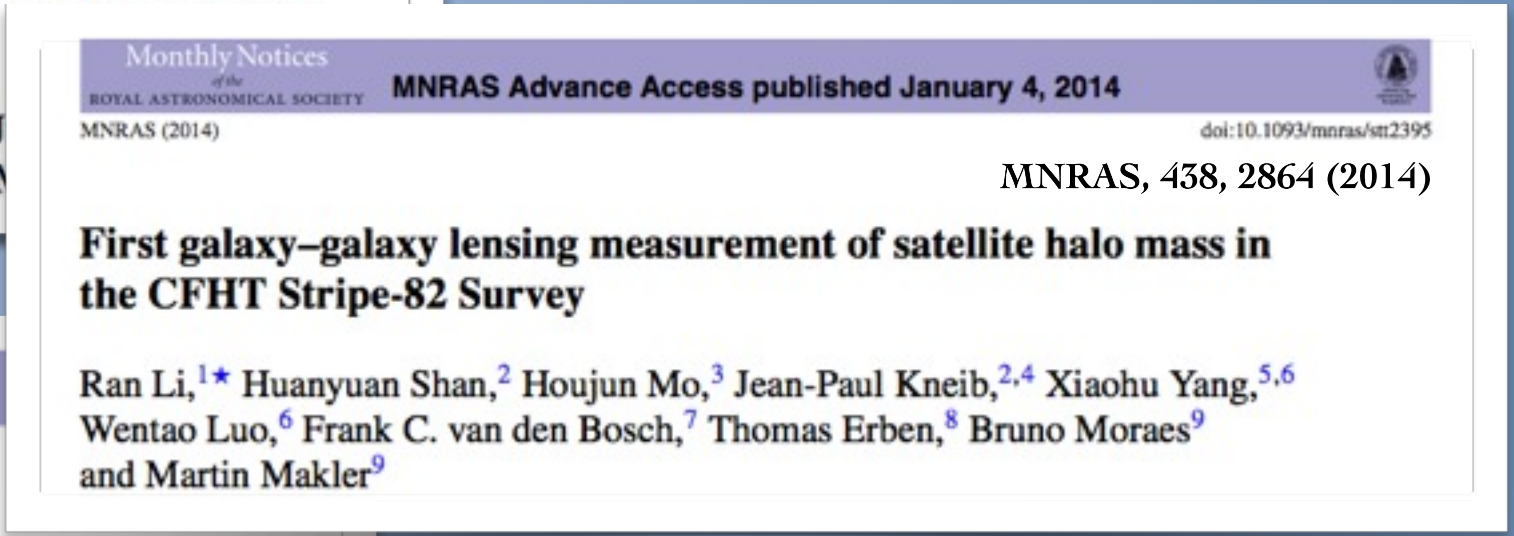
Nick Hand,[1,*] Alexie Leauthaud,[2] Sudeep Das,[3,4] Blake D. Sherwin,[5,6,4] Graeme E. Addison,[7]
J. Richard Bond,[8] Erminia Calabrese,[9] Aldée Charbonnier,[10,11] Mark J. Devlin,[12] Joanna Dunkley,[9]
Thomas Erben,[13] Amir Hajian,[8] Mark Halpern,[7] Joachim Harnois-Déraps,[7,8,14] Catherine 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

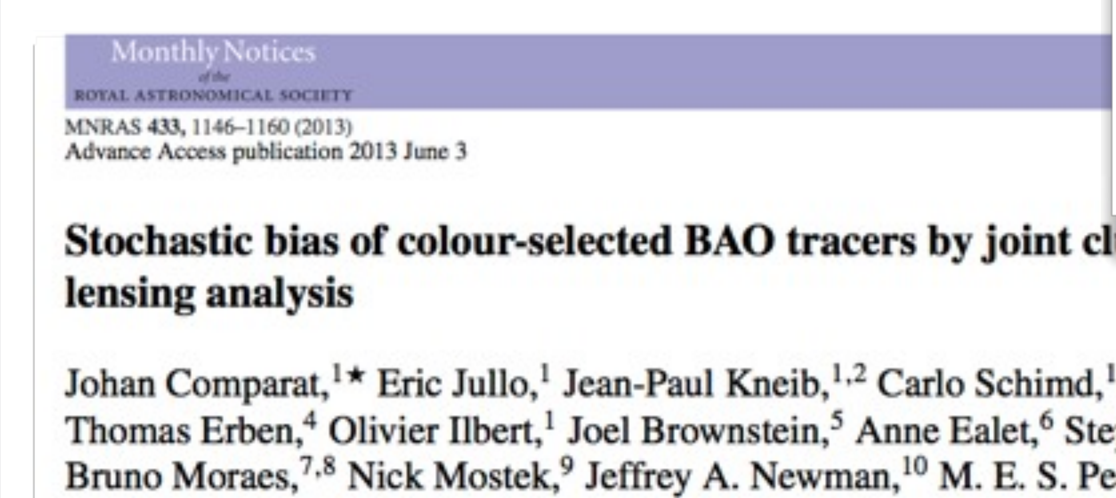
MNRAS Advance Access published January 4, 2014

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

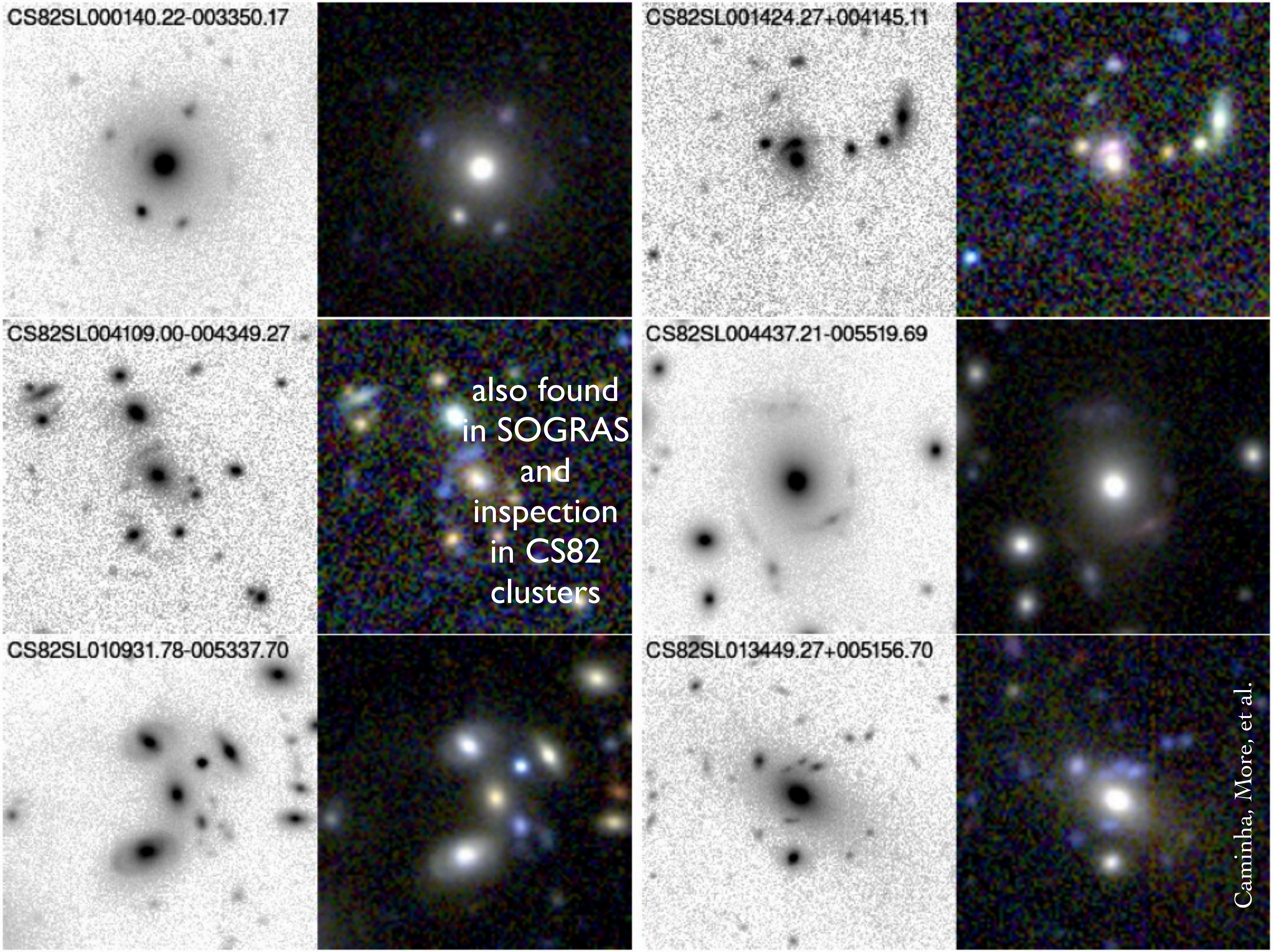
Johan Comparat,[1★] Eric Jullo,[1] Jean-Paul Kneib,[1,2] Carlo Schimd,[1] HuanYuan Shan,[2,3]
Thomas Erben,[4] Olivier Ilbert,[1] Joel Brownstein,[5] Anne Ealet,[6] Stephanie Escoffier,[6]
Bruno Moraes,[7,8] Nick Mostek,[9] Jeffrey A. Newman,[10] M. E. S. Pereira,[7,8]

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

Semi-automated arcfinding

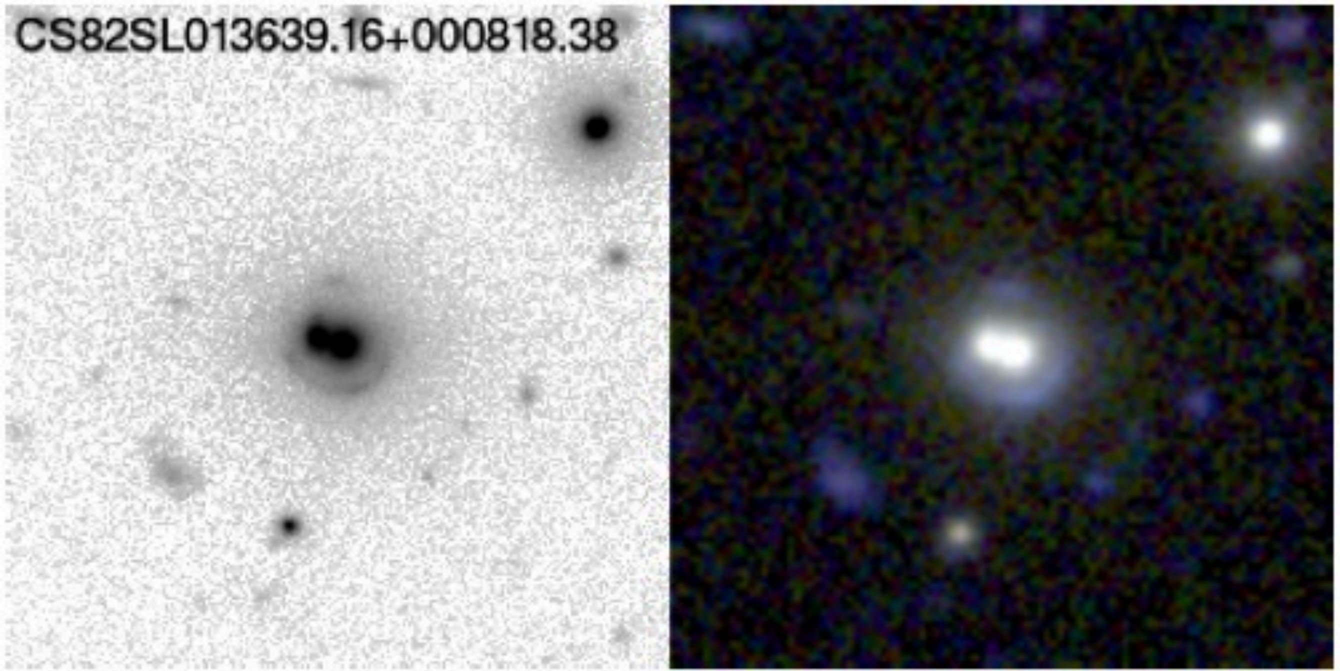
- More-Alard Arcfinder (More et al., arXiv:1109.1821)
- 127000 candidates visually inspected!
- 10 volunteers (every candidate inspected by 2 people)

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



also found in SOGRAS and inspection in CS82 clusters

Caminha, More, et al.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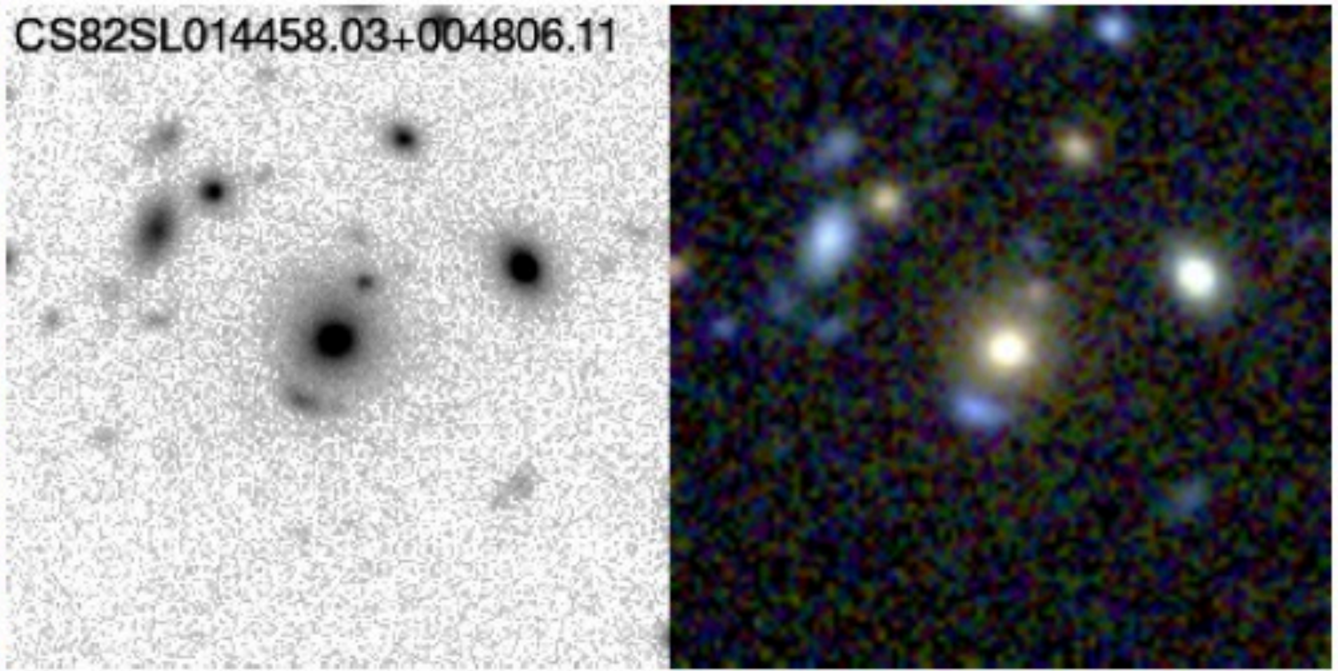
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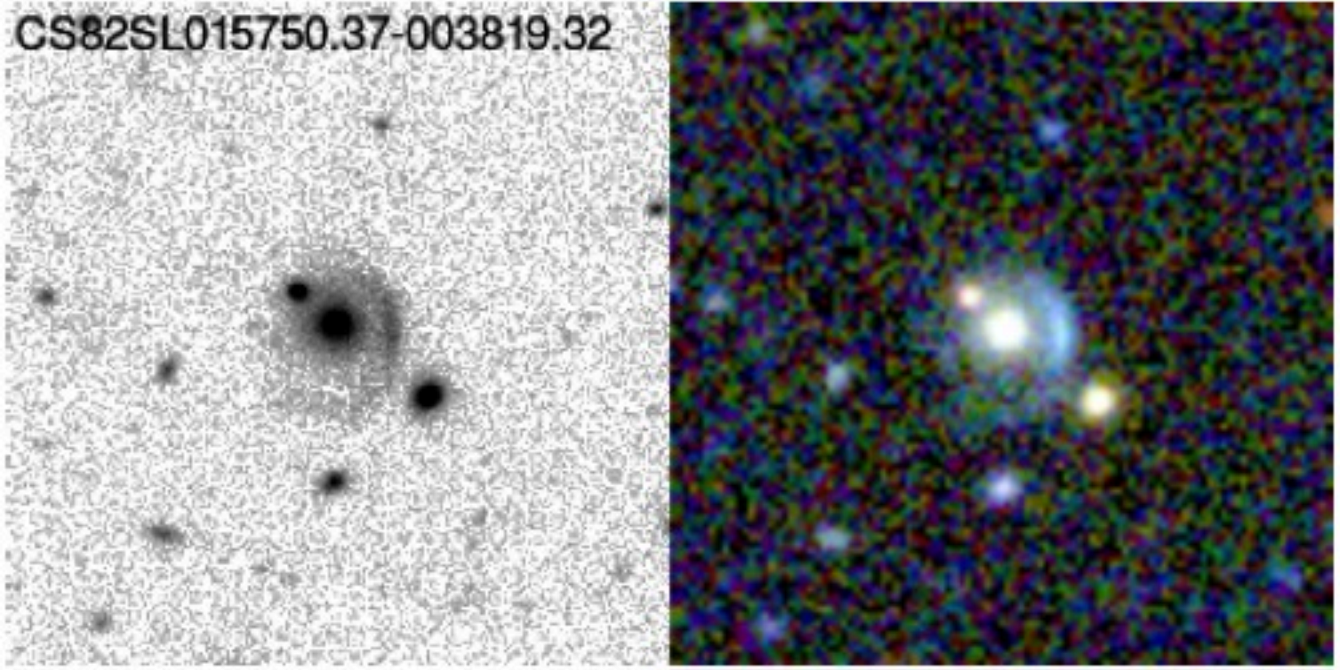
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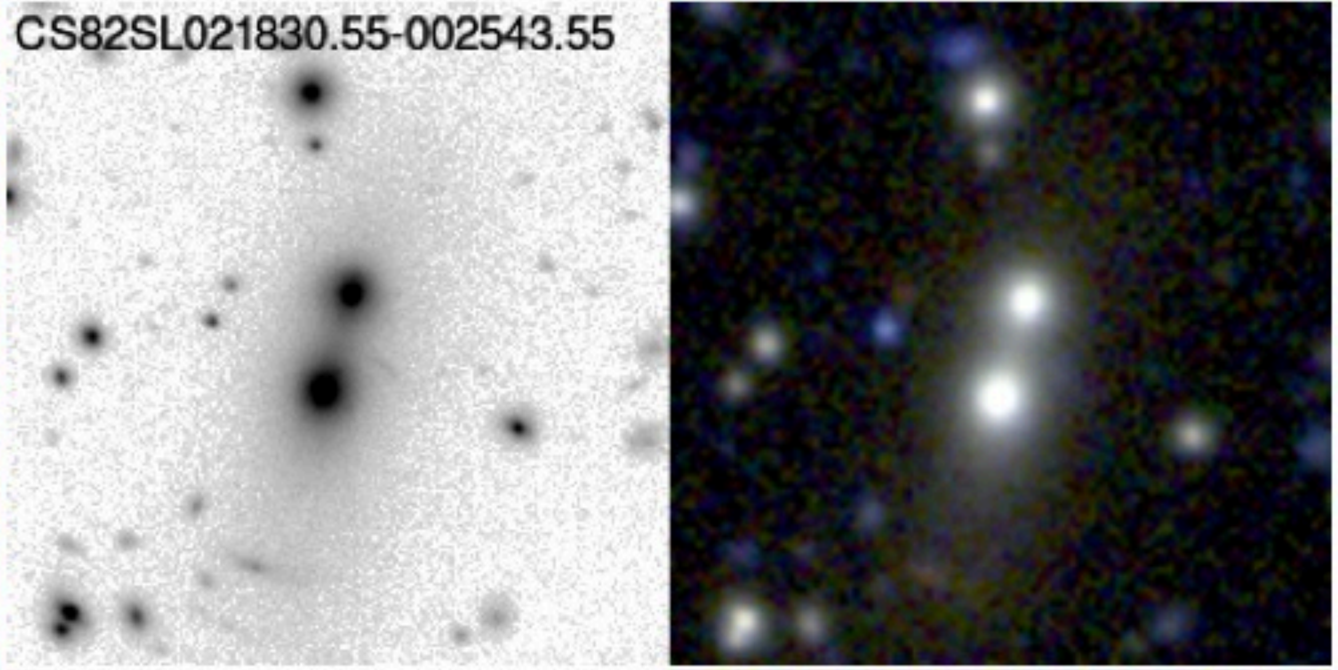
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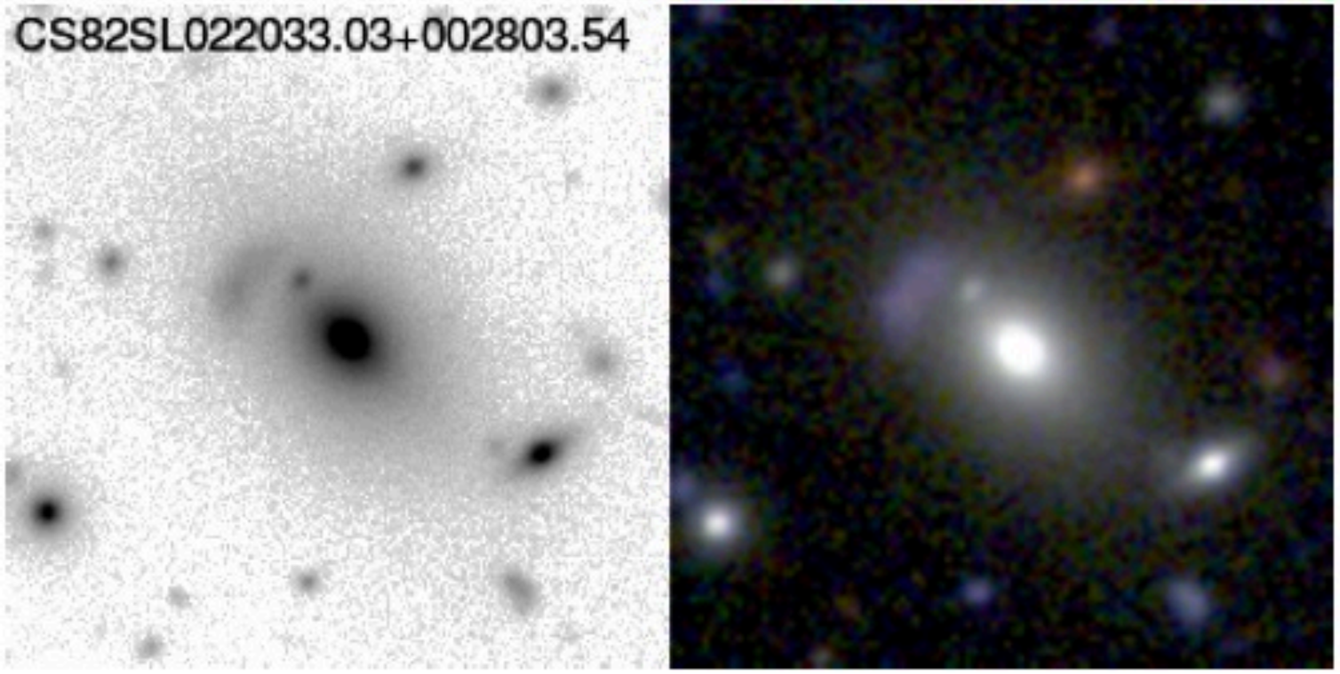
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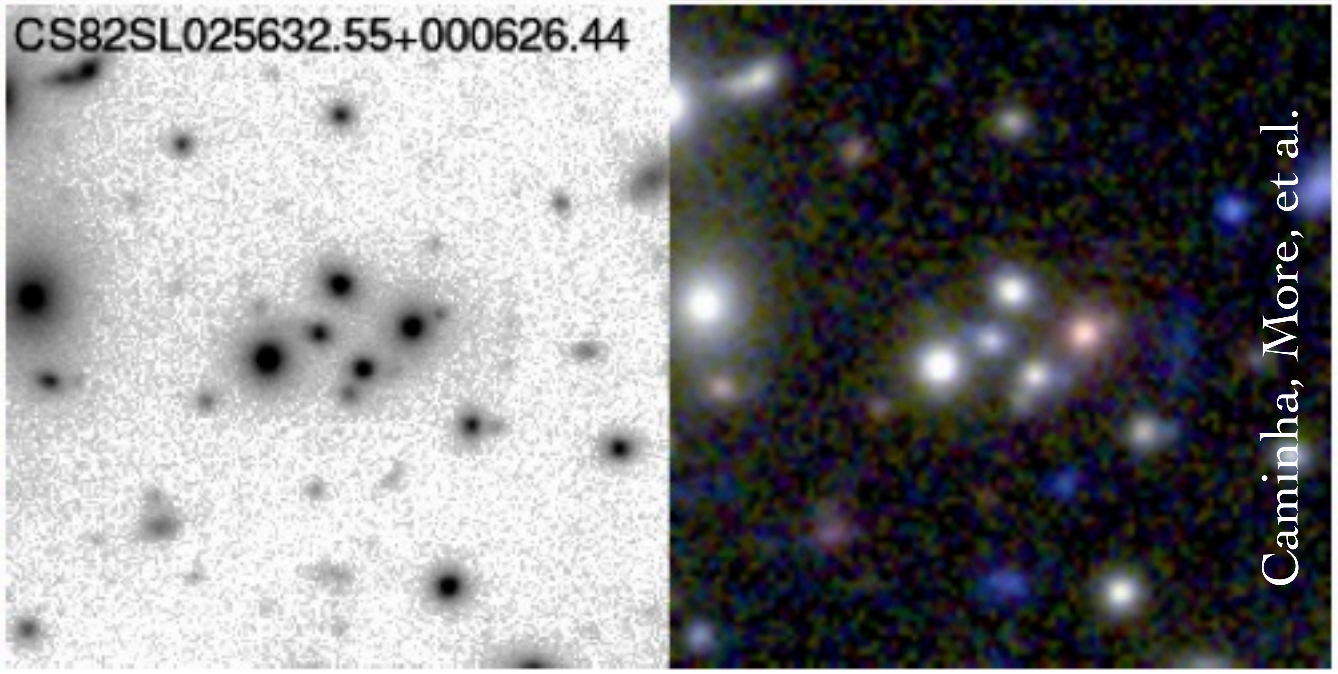
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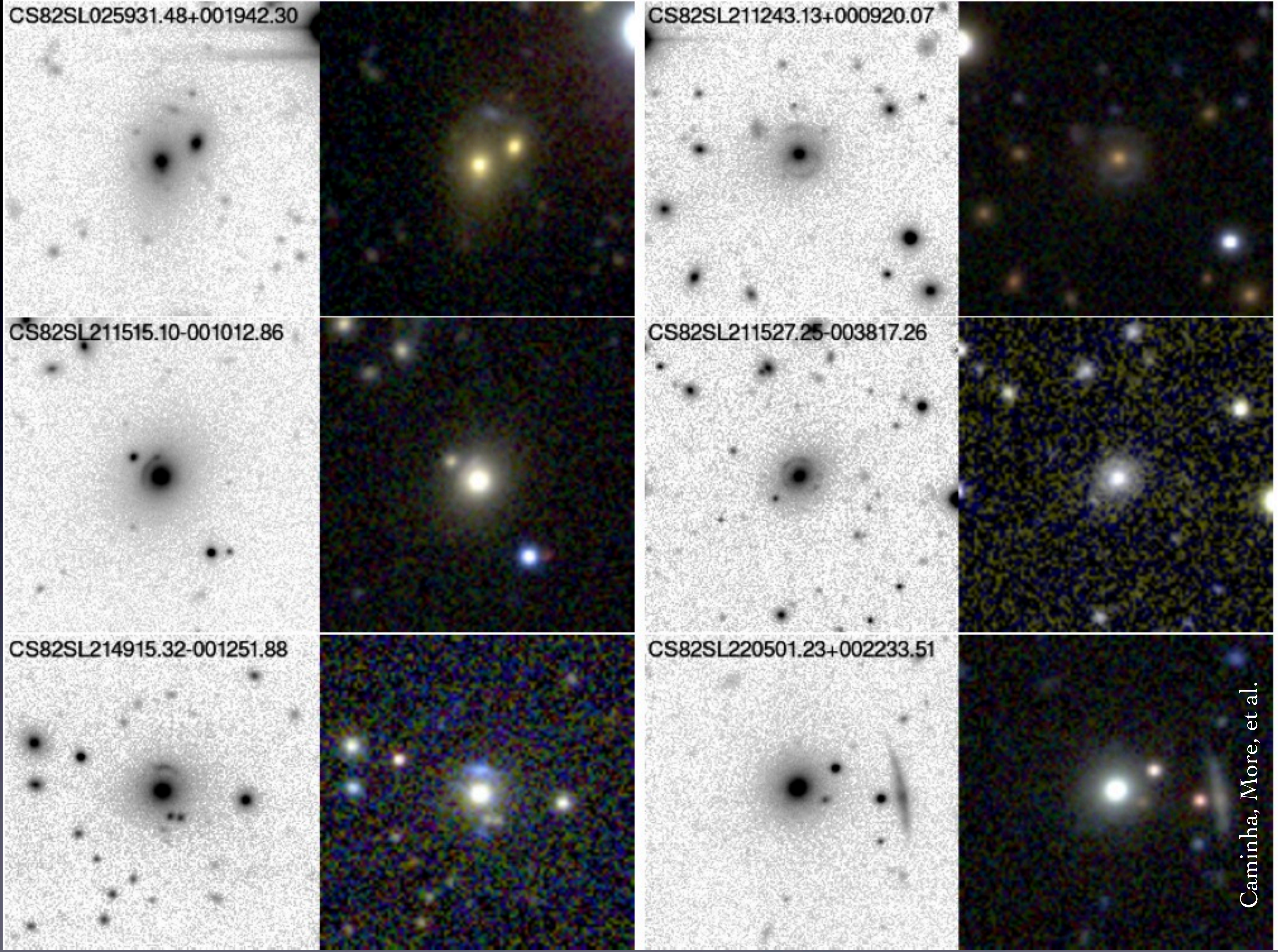
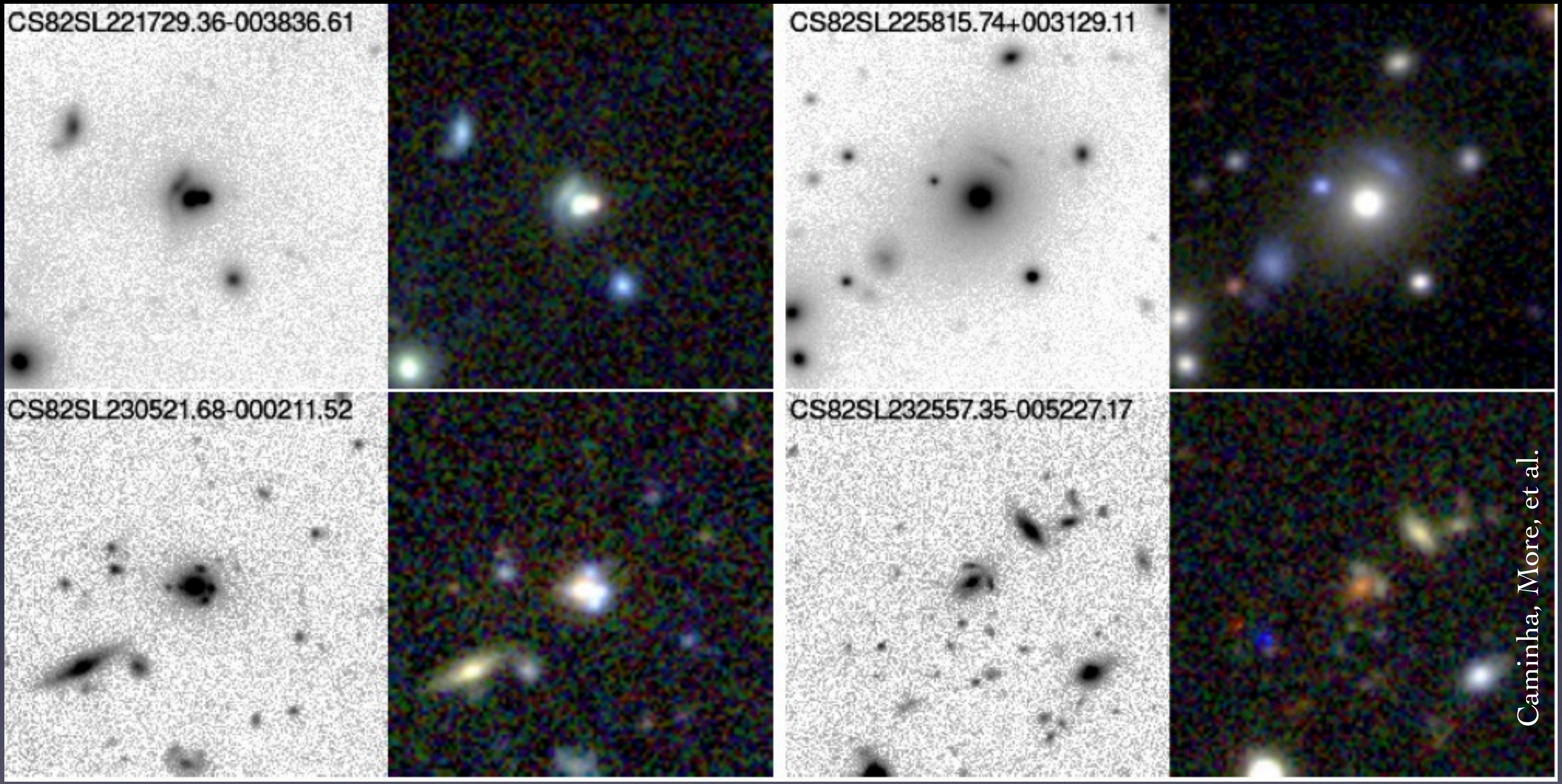


Caminha, More, et al.



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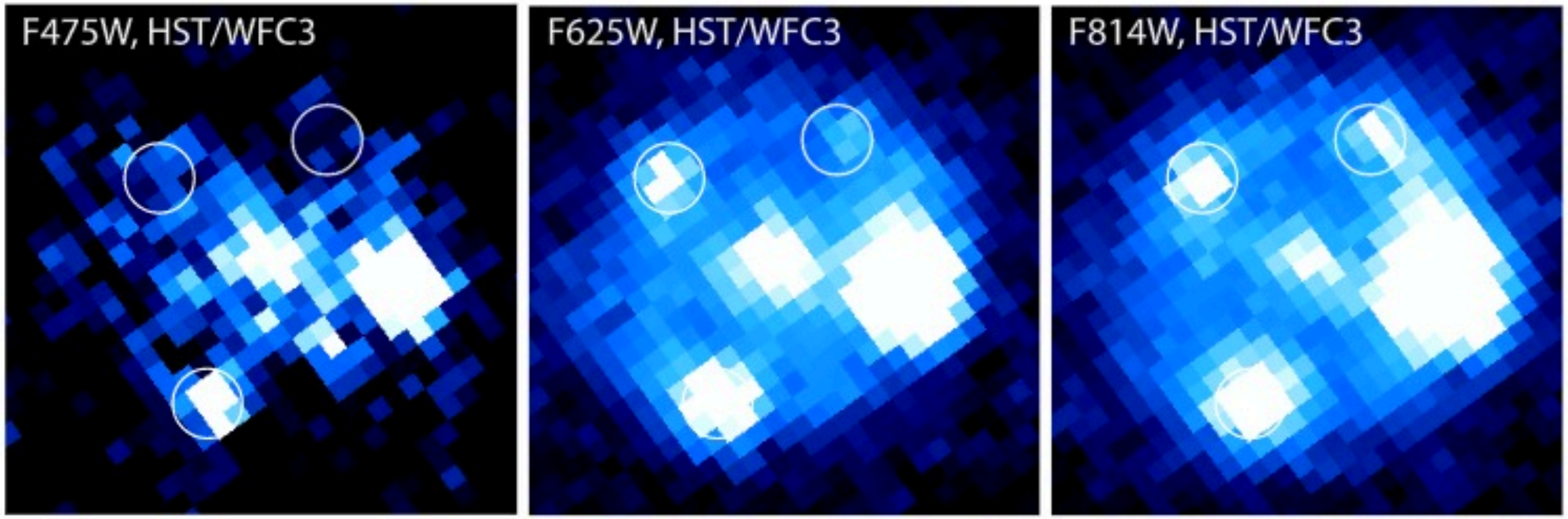
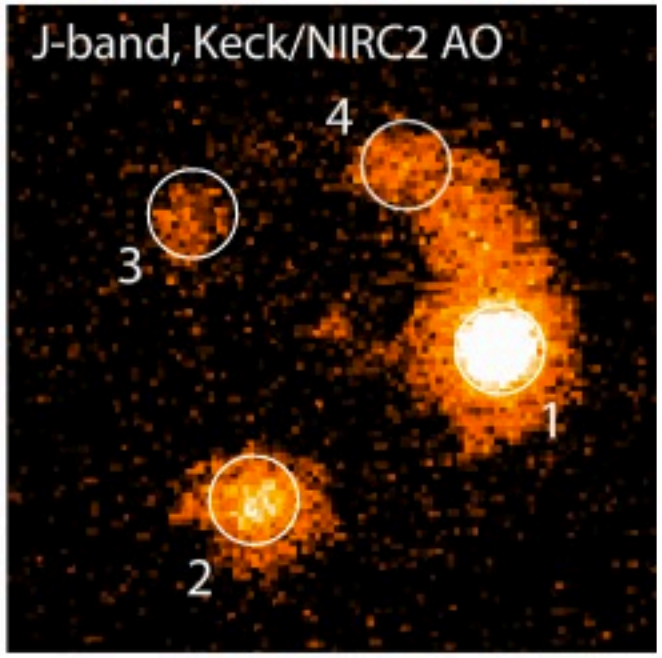
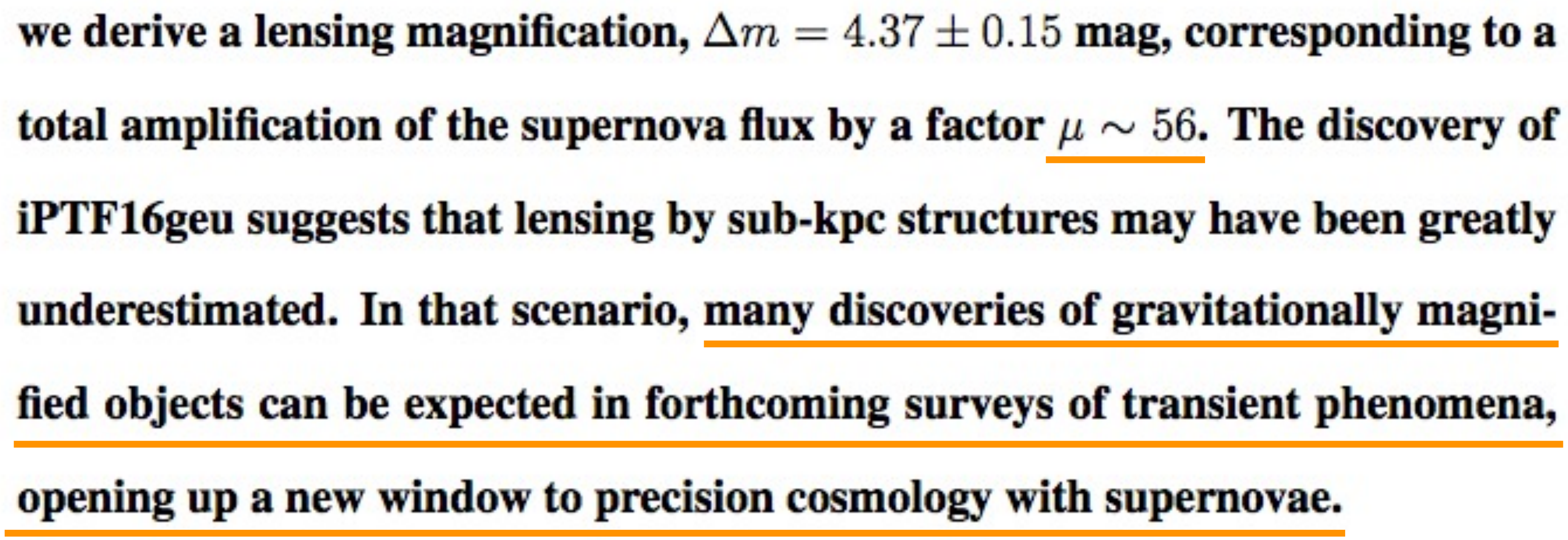
First Type Ia Supernovae with Multiple Images







we derive a lensing magnification, $\Delta m = 4.37 \pm 0.15$ mag, corresponding to a total amplification of the supernova flux by a factor $\mu \sim 56$. The discovery of iPTF16geu suggests that lensing by sub-kpc structures may have been greatly underestimated. In that scenario, many discoveries of gravitationally magnified objects can be expected in forthcoming surveys of transient phenomena, opening up a new window to precision cosmology with supernovae.

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A SPECTROSCOPICALLY CONFIRMED DOUBLE SOURCE PLANE LENS SYSTEM IN THE HYPER SUPRIME-CAM SUBARU STRATEGIC PROGRAM

Masayuki Tanaka[1], Kenneth Wong[1], Anupreeta More[2], Arsha Dezuka[3], Eiichi Egami[4], Masamune Oguri[2,5,6], Sherry H. Suyu[7,8], Alessandro Sonnenfeld[2], Ryou Higuchi[9], Yutaka Komiyama[1], Satoshi Miyazaki[1,10], Masafusa Onoue[10,1], Shuri Oyamada[11], Yousuke Utsumi[12]

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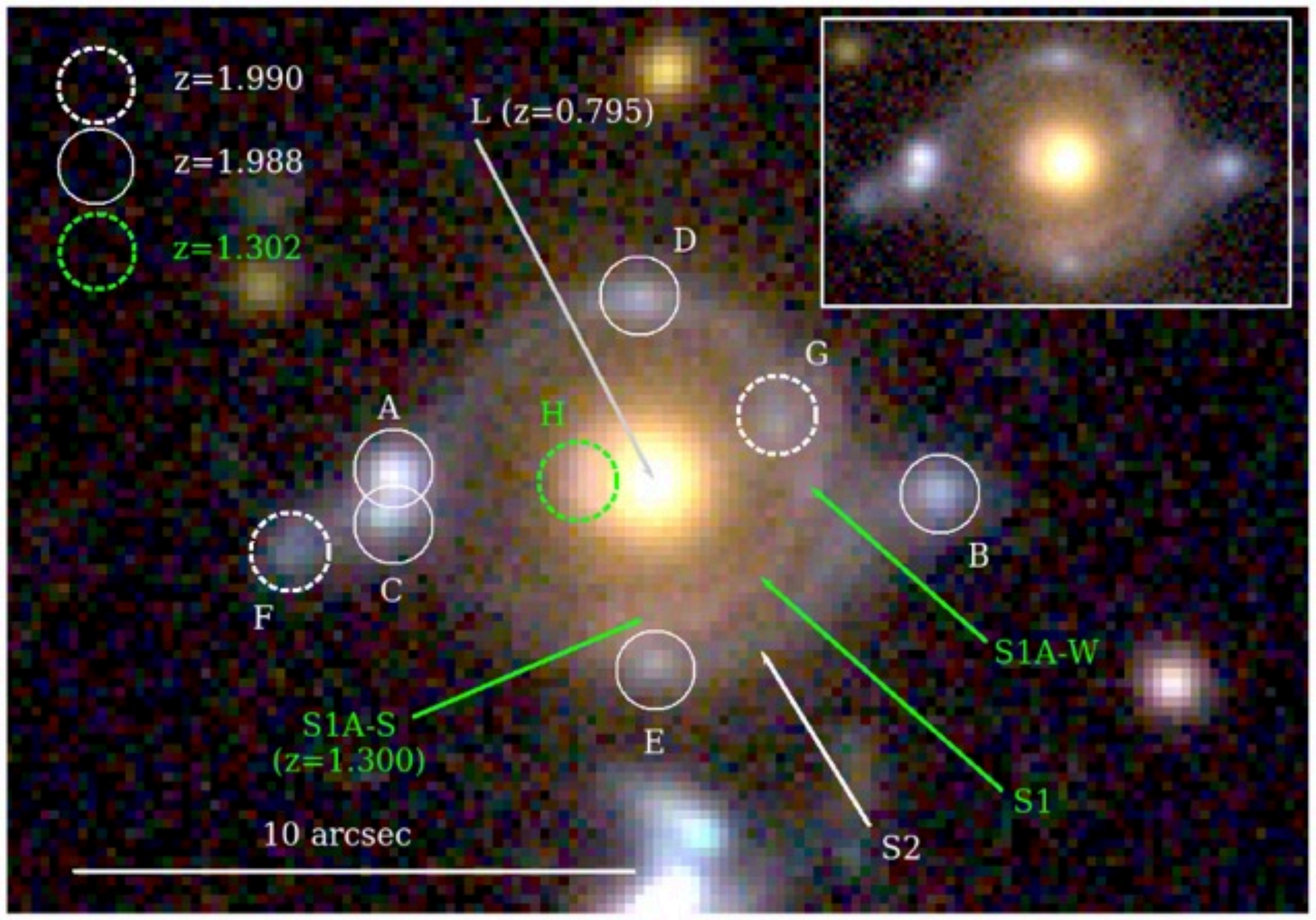

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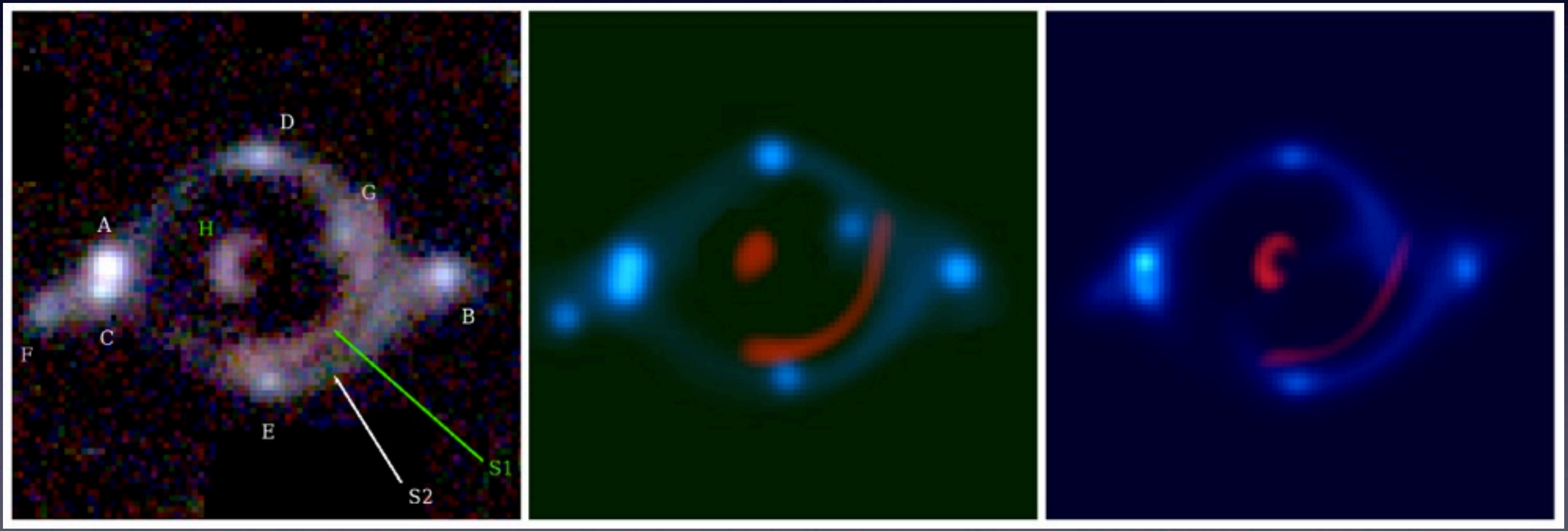

OBSERVATION AND CONFIRMATION OF SIX STRONG-LENSING SYSTEMS IN THE DARK ENERGY SURVEY SCIENCE VERIFICATION DATA*

B. Nord[1], E. Buckley-Geer[1], H. Lin[1], H. T. Diehl[1], J. Helsby[2], N. Kuropatkin[1], A. Amara[3], T. Collett[4], S. Allam[1], G. B. Caminha[5,6], C. De Bom[5,7], S. Desai[8,9], H. Dúmet-Montoya[10], M. Elidaiana da S. Pereira[5], D. A. Finley[1], B. Flaugher[1], C. Furlanetto[11], H. Gaitsch[1], M. Gill[12], K. W. Merritt[1], A. More[13], D. Tucker[1], A. Saro[14], E. S. Rykoff[12,15], E. Rozo[16], S. Birrer[3], F. B. Abdalla[17,18], A. Agnello[19], M. Auger[20], R. J. Brunner[21,22], M. Carrasco Kind[21,22], F. J. Castander[23], C. E. Cunha[15], L. N. da Costa[24,25], R. J. Foley[21,26], D. W. Gerdes[27], K. Glazebrook[28], J. Gschwend[24,25], W. Hartley[3], R. Kessler[2], D. Lagattuta[29], G. Lewis[30], M. A. G. Maia[24,25], M. Makler[5], F. Menanteau[21,22], A. Niernberg[31], D. Scolnic[2], J. D. Vieira[21,22,26], R. Gramillano[21], T. M. C. Abbott[32], M. Banerji[20,33], A. Benoit-Lévy[17,34,35], D. Brooks[17], D. L. Burke[12,15], D. Capozzi[4], A. Carnero Rosell[24,25], J. Carretero[23,36], C. B. D'Andrea[4,37], J. P. Dietrich[8,9], P. Doel[17], A. E. Evrard[27,38], J. Frieman[1,2], E. Gaztanaga[23], D. Gruen[39,40], K. Honscheid[31,41], D. J. James[32], K. Kuehn[42], T. S. Li[43], M. Lima[24,44], J. L. Marshall[43], P. Martini[31,45], P. Melchior[31,41,46], R. Miquel[36,47], E. Neilsen[1], R. C. Nichol[4], R. Ogando[24,25], A. A. Plazas[48], A. K. Romer[49], M. Sako[50], E. Sanchez[51], V. Scarpine[1], M. Schubnell[27], I. Sevilla-Noarbe[21,51], R. C. Smith[32], M. Soares-Santos[1], F. Sobreira[1,24], E. Suchyta[50], M. E. C. Swanson[22], G. Tarle[27], J. Thaler[26], A. R. Walker[32], W. Wester[1], Y. Zhang[27] (The DES Collaboration) Hide full author list

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