Cosmology with Strong Lenses

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PPGCosmo Workshop on Astrophysics, Cosmology and Gravitation

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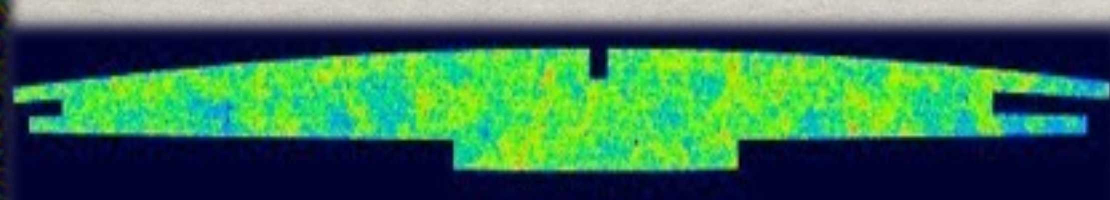
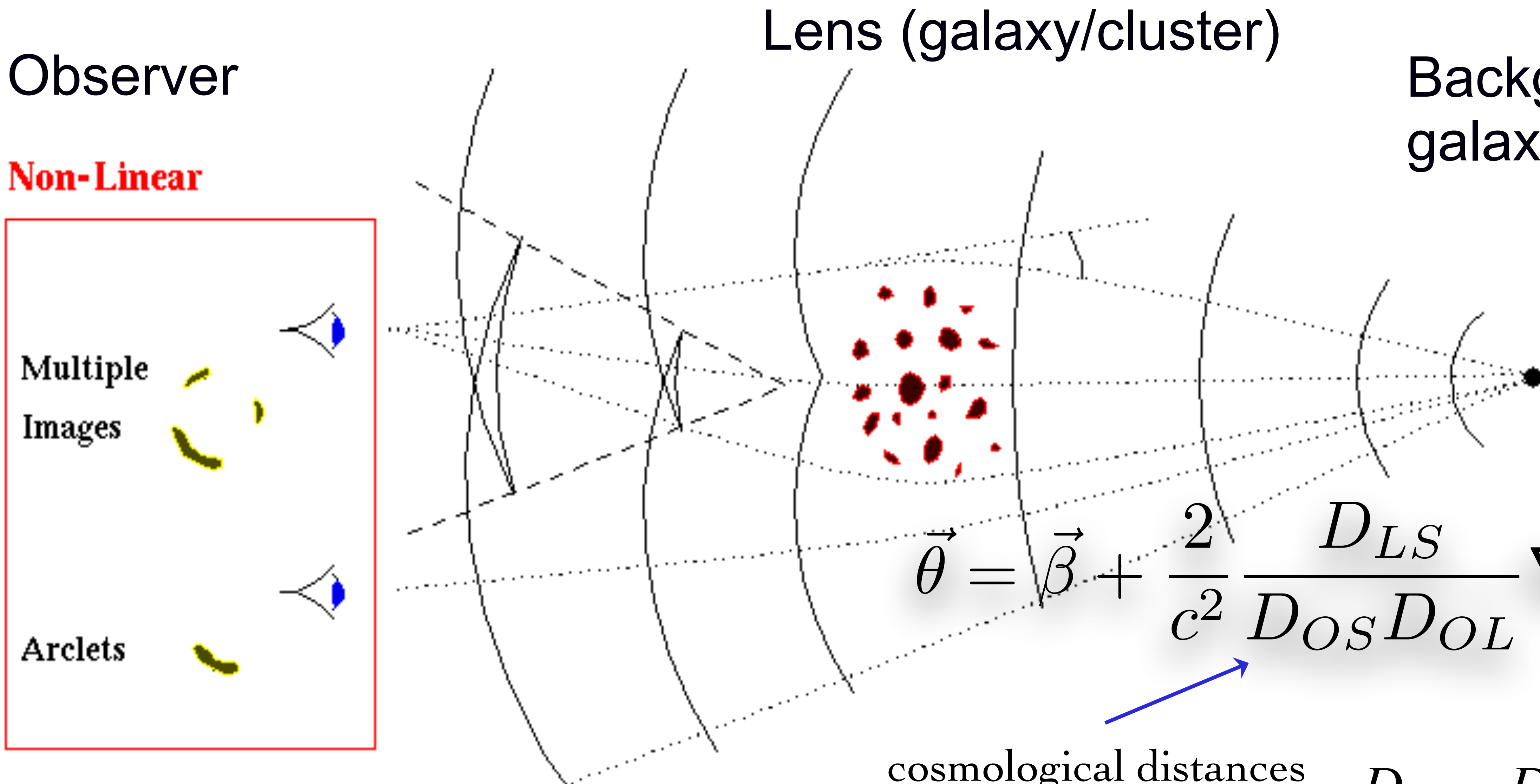
CAPES

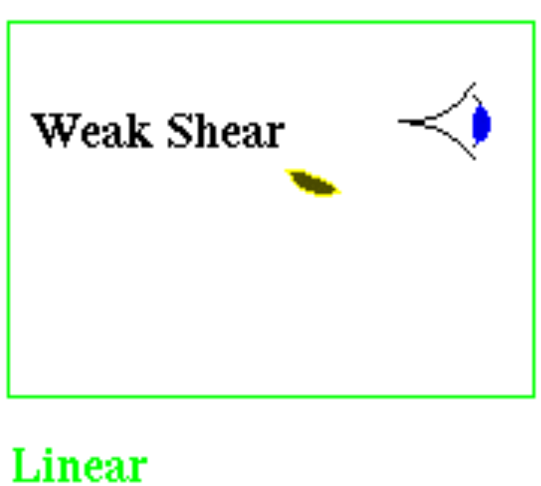
Outline

- Strong (macro) lensing
- Cluster Strong Lensing and Cosmology
- Einstein rings and modified gravity
- Machine learning: finding and measuring SL systems
- Concluding remarks



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)

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

Light deflection by gravity:

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

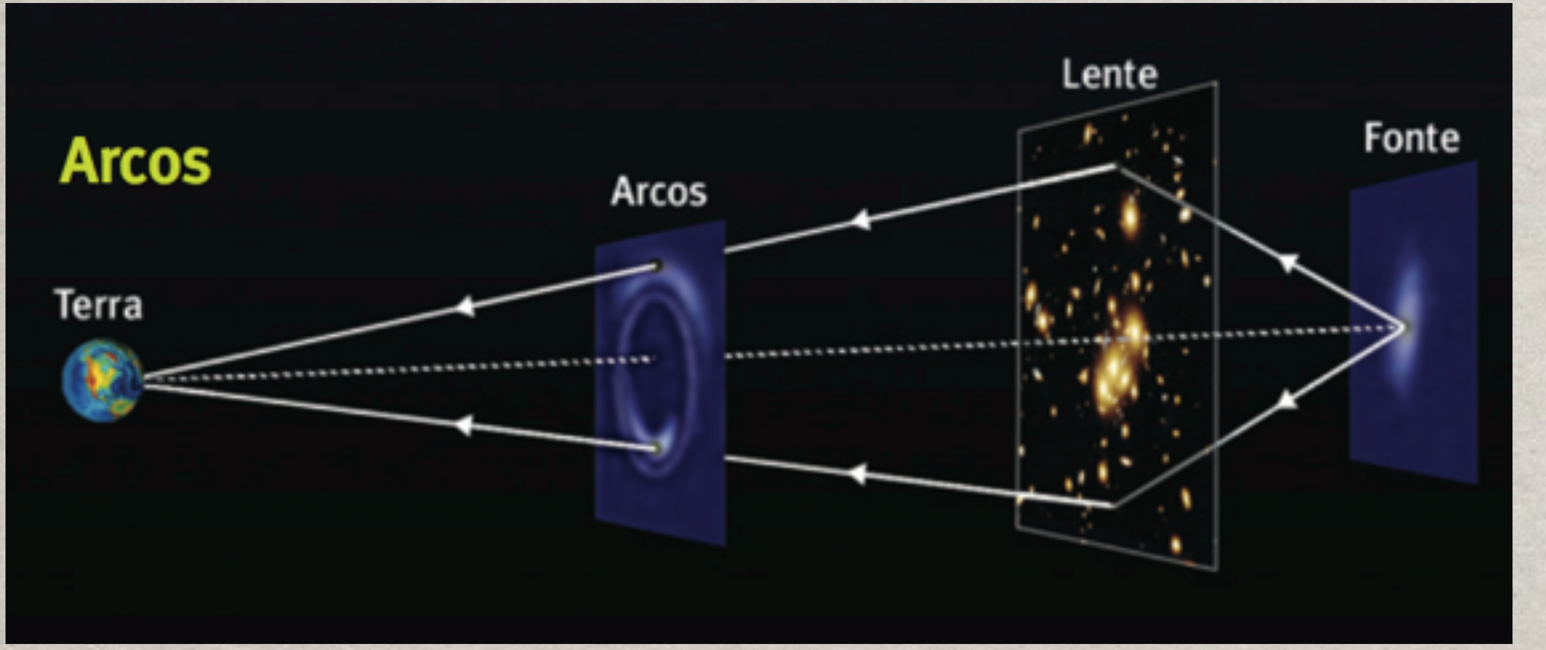
$$\psi = \int_0^{r_{\rm source}} \phi(\xi, r)\,dr$$

gravitational potential
(astrophysics)

Strong Lensing

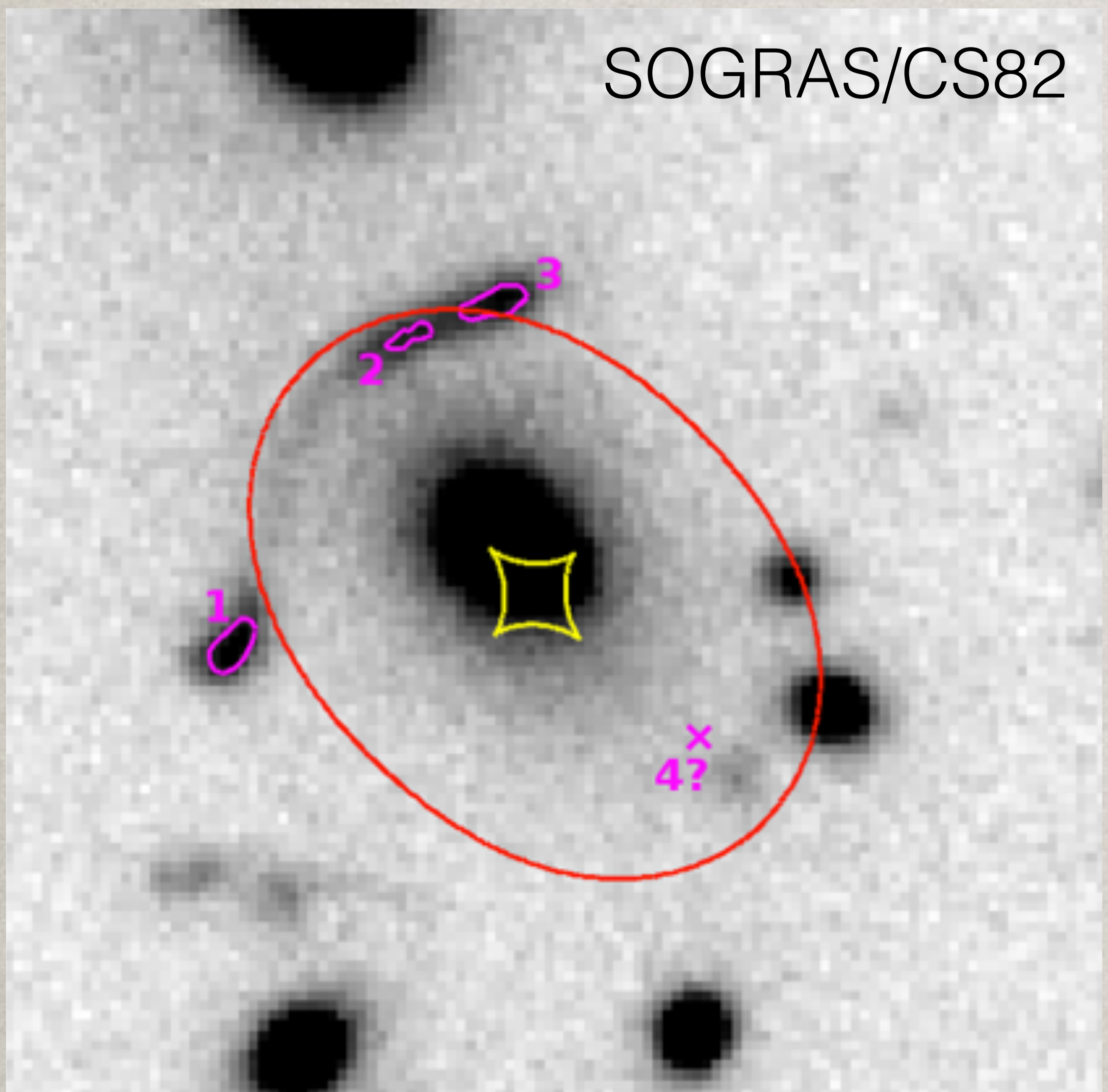
- Multiple images, strong distortions, large magnifications, time delays
- Null geodesics
  - surface brightness conservation
  - achromatic

  } → Gravitational telescopes
  - Unique probe of the mass distribution in galaxies and clusters → DM, *b*
  - Provide complementary cosmological probes and tests of gravity



strong lensing, **weak gravity**

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

$\vec{\Pi}$: parameters of the mass distribution and cosmological parameters

The more multiple images, the more constrains

Cluster x Galaxy scales

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

Two Regimes

- Targeted observations of the systems
  - High-resolution imaging (HST, adaptive optics, interferometry)
  - Redshifts for the lens and the sources (MOS, IFU)
  - Cosmology from single systems + high-z sources
  - Detailed modelling of the mass distribution
  - Dark Matter, Dark Energy, Modified Gravity, etc.
  - Limited to few systems
- Systems from wide-field surveys
  - Broad features (e.g. Einstein radius, magnification)
  - Single redshifts or estimated from multi-band data
  - Background cosmology
  - Constraints on modified gravity
  - Statistics (number counts: cross sections)
  - Need automated arcfinding (and modelling)

Galaxy Cluster Scale
Cosmological Constraints and more

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

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

$$\Xi(z_{\mathrm{l}}, z_{\mathrm{s1}}, z_{\mathrm{s2}}; \Omega_{\mathrm{M}}, \Omega_{\mathrm{X}}, w_{\mathrm{X}}) = \frac{D(z_{\mathrm{l}}, z_{\mathrm{s1}})}{D(0, z_{\mathrm{s1}})} \frac{D(0, z_{\mathrm{s2}})}{D(z_{\mathrm{l}}, z_{\mathrm{s2}})}$$

☑ 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: Dark Energy models

Reminder: Angular Diameter Distance

In the wCDM model

$$p = w\rho$$

$$H^2(a) = H_0^2 \left[\Omega_r a^{-4} + \Omega_M a^{-3} + \Omega_k a^{-2} + \Omega_{DE} a^{-3(1+w)}\right]$$

In the flat case

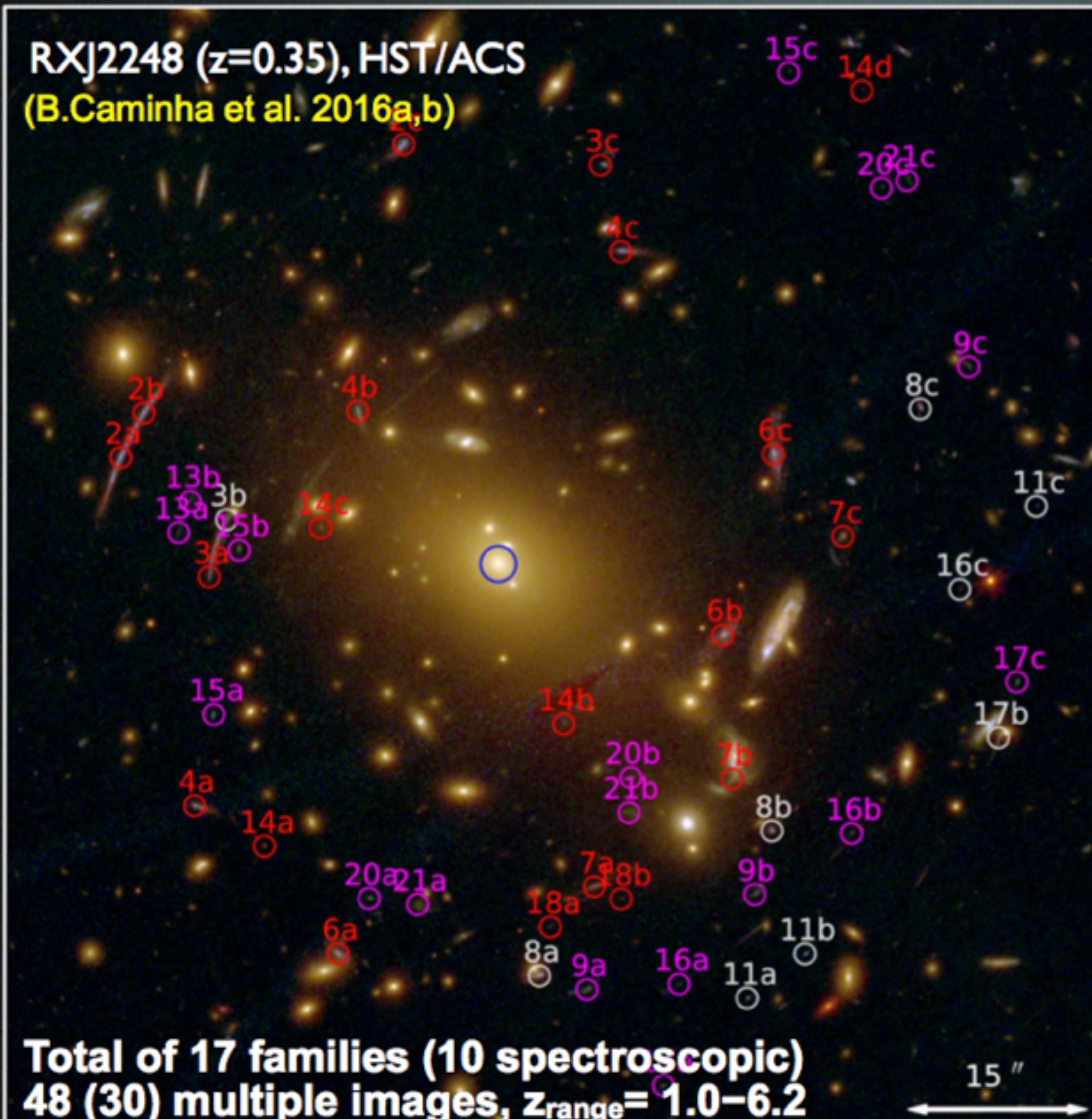
$$D_A\left(z_1, z_2\right) = \frac{\left(1+z_2\right)^{-1}}{H_0} \int_{z_1}^{z_2} \frac{dz'}{\sqrt{\Omega_M (1+z')^3 + \left(1-\Omega_M\right)\left(1+z'\right)^{3(1+w)}}}$$

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

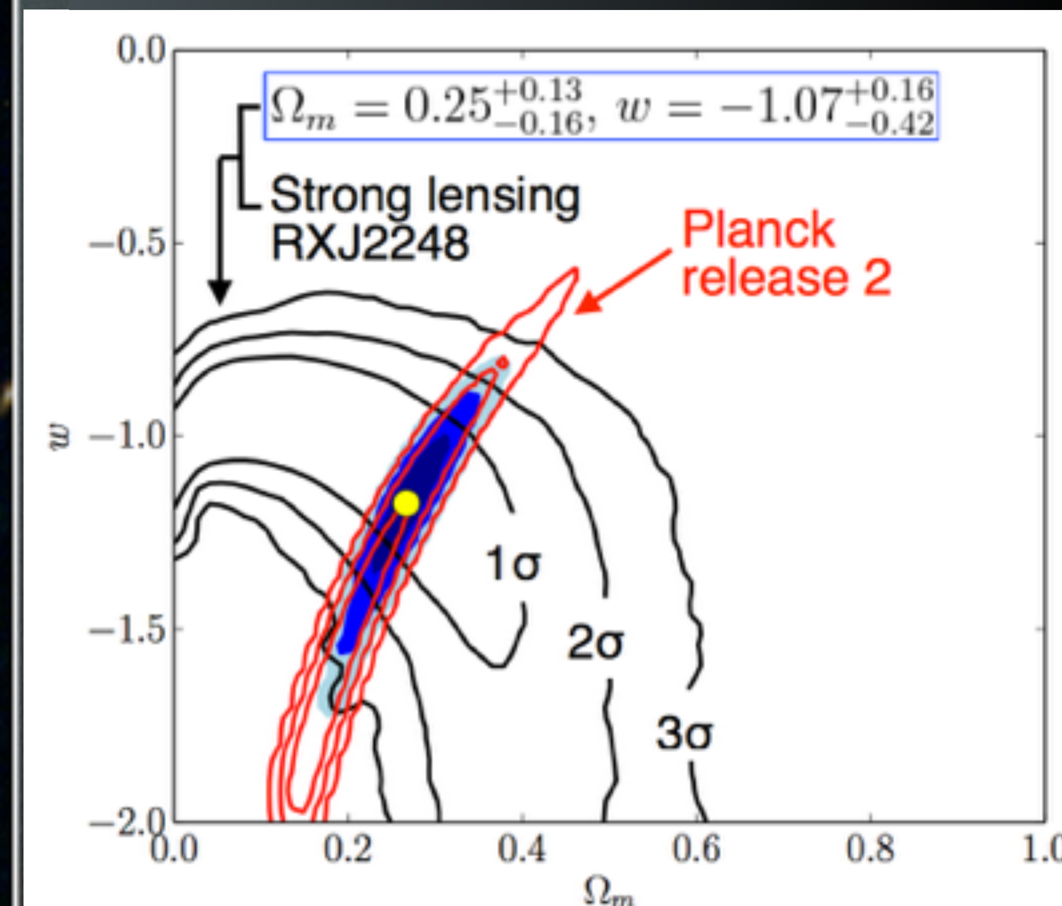
Cosmological Constraints

Caminha et al., 2016

Frontier Field Cluster AS1063 (aka RXJ2248)



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

New constraints from Abell S1063

- **Doubling the number of families of multiple images**
- **Comparison and combination with other observables**

Bom, MM, Caminha, Vitenti, Penna-Lima (2020, in prep.)

- Consistency test
- Now: running blindly in several clusters
- Independent tests and stronger constraints
- Large datasets
  - What if no MUSE?
  - From the ground?

Limits from Strong Lensing only:

$$\Omega_M = 0.422^{+0.062}_{-0.274}$$

$$w = -0.911^{+0.030}_{-1.356}$$

Single system!

Improvement by combining with SL over each probe alone:

Probe	$\Delta\sigma_w$	$\Delta\sigma_{\Omega_M}$	ΔA_σ
SNIa	27%	23 %	31 %
BAO	29%	17%	28 %
CMB	44%	37%	36 %

Constraints from galaxy scale systems (aka Einstein Rings)

Cosmological focus (large scales)

- H_0 from QSO time delays and D_L
- Dark energy models

Science   Contents   News   Careers   Journals

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RESEARCH ARTICLE

A measurement of the Hubble constant from angular diameter distances to two gravitational lenses

Inh Jee[1,*], Sherry H. Suyu[1,2,3,*], Eiichiro Komatsu[1,4], Christopher D. Fassnacht[5], Stefan Hilbert[6,7], Léon V. E. Koopmans[8]

+ See all authors and affiliations

Science 13 Sep 2019:
Vol. 365, Issue 6458, pp. 1134-1138
DOI: 10.1126/science.aat7371

One gravitational potential or two? Forecasts and tests

Phil. Trans. R. Soc. A (2011) **369**, 4947–4961
doi:10.1098/rsta.2011.0369

BY EDMUND BERTSCHINGER*

conformal newtonian metric (choices and assumptions):

$$ds^2 = a^2(\tau)[-(1+2\Phi)\,d\tau^2 + (1-2\Psi)\gamma_{ij}\,dx^i\,dx^j]$$

geodesics

$$\frac{1}{a}\frac{d(a\boldsymbol{v})}{d\tau} = -\boldsymbol{\nabla}\Phi, \quad v^2 \ll 1 \text{ (CDM)} \longrightarrow \text{Jean's equation}$$

$$\frac{d\boldsymbol{v}}{d\tau} = -\boldsymbol{\nabla}_\perp(\Phi + \Psi), \quad v^2 = 1 \text{ (photons)} \longrightarrow \text{lensing}$$

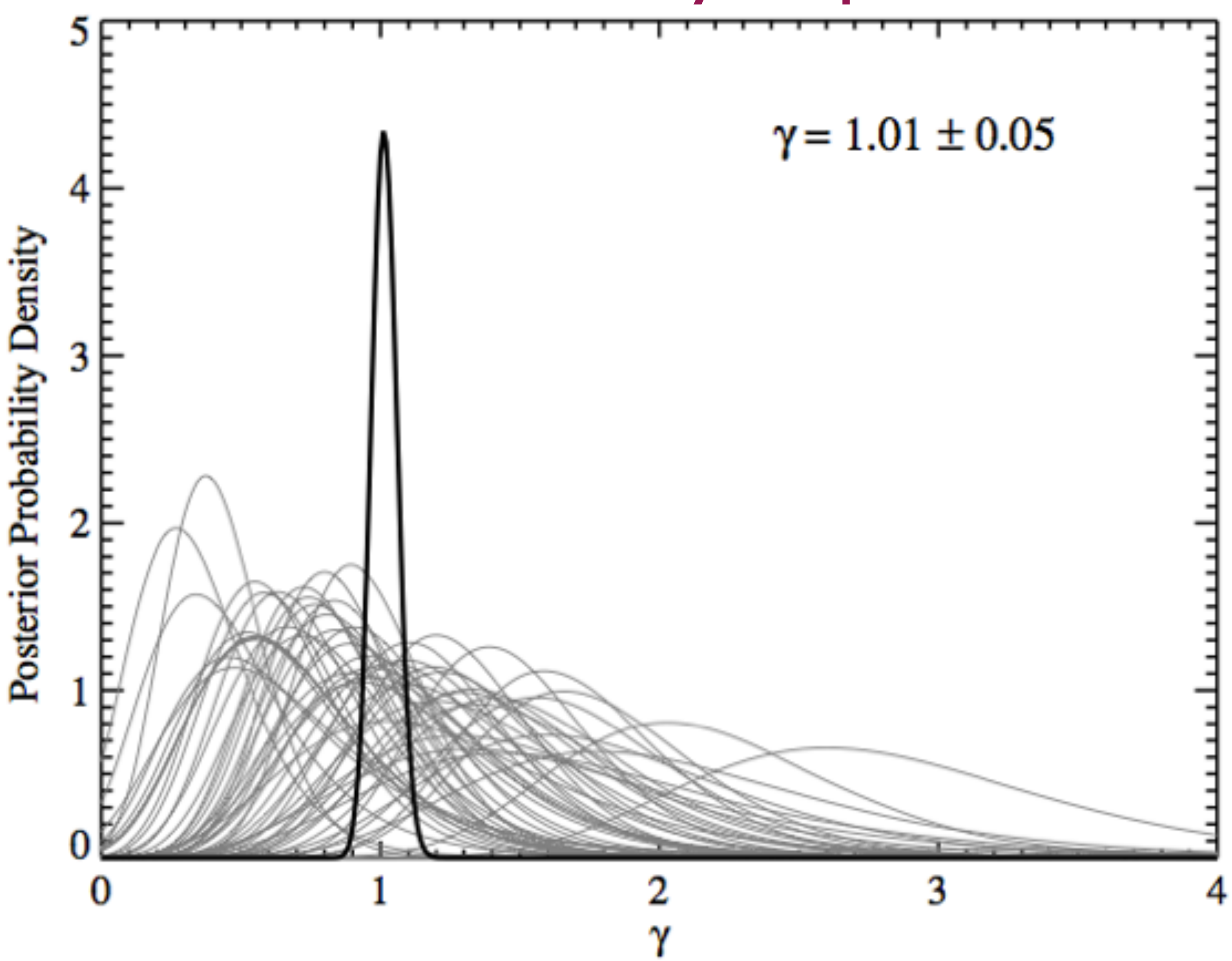
kinematics: Φ deflection angle: $\Phi + \Psi$

Einstein Rings

Singular Isothermal Sphere: $\rho(r) = \frac{\sigma_v^2}{2\pi G r^2}$

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

Measure velocity dispersion ➔ Limit on gravity



Schwab, Bolton, Rappaport, arXiv:0907.4992

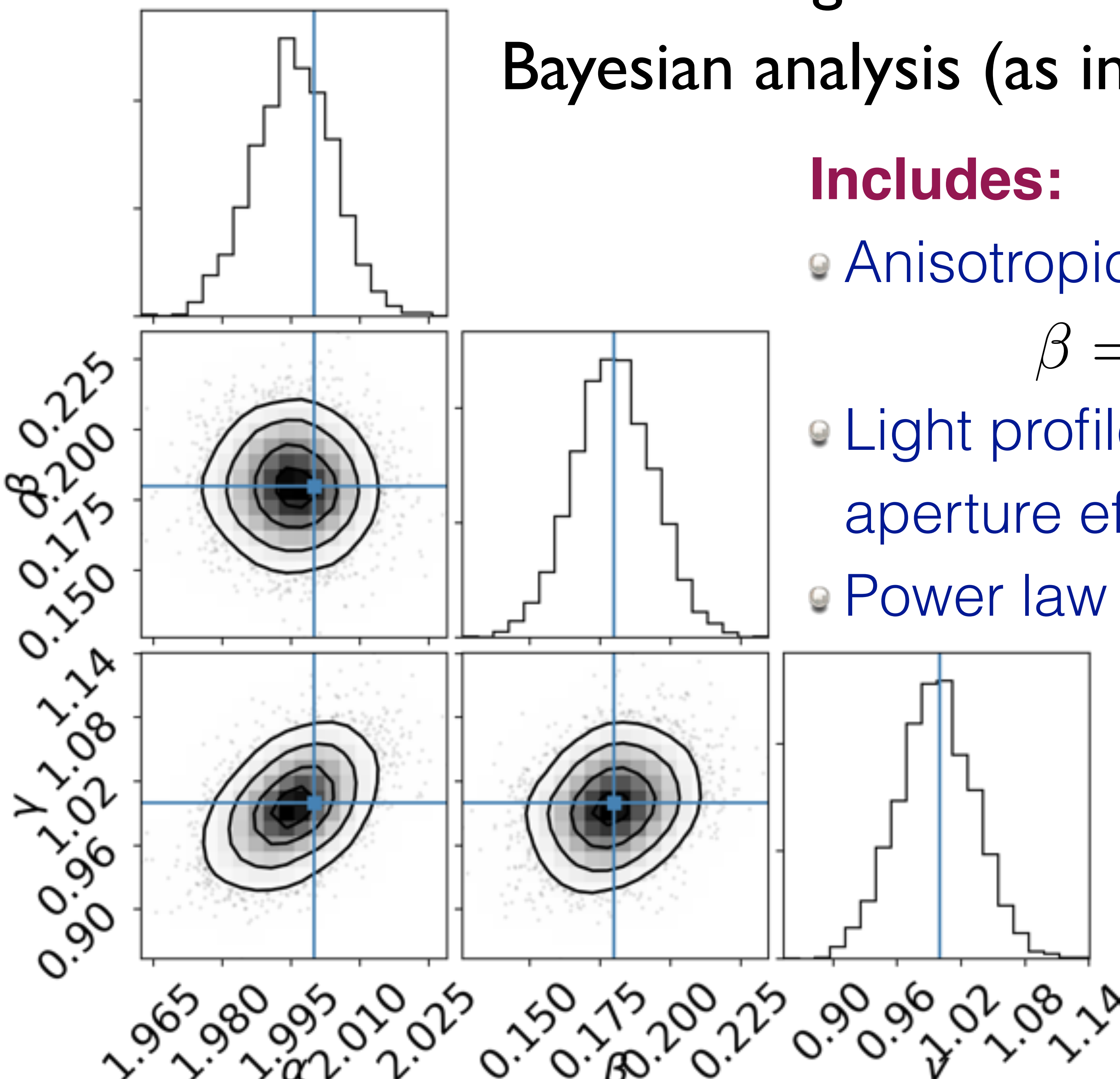
Current results are in agreement with GR

Real life:

- Velocity dispersion in appertures
- Anisotropic velocity dispersion (assumptions)
- Measure and/or learn from simulations
- Other systematics?

Current Results

Crisnejo et al.



Einstein rings in SLACS, BELLS, LSD, LS2S sample

Bayesian analysis (as in Cao et al. 2017)

Includes:

- Anisotropic velocity dispersion

$$\beta = 1 - \sigma_t^2/\sigma_r^2$$

- Light profiles, seeing and fiber/slit aperture effects
- Power law density profile $\rho(r) \propto r^{-\alpha}$
- Priors on $\beta = 0.180^{+0.014}_{-0.014}$ $\alpha = 1.995^{+0.009}_{-0.009}$

Slip parameter

$$\gamma = 0.996^{+0.037}_{-0.035}$$

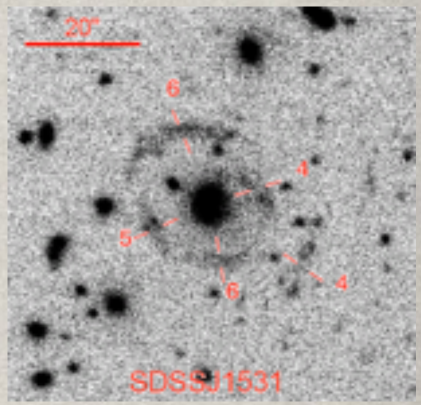
Does ellipticity bias the results?

- Elliptical lens with elliptical source and external fields
- Solution at the perturbative level

$$x_{\mathrm{E}} = 1 - \frac{\epsilon_\ell}{6}\cos 2\phi + s\cos\left(\phi - \phi_0\right) + \gamma\cos 2\left(\phi - \phi_\gamma\right)$$

- Mean Einstein radius equivalent to SIS
- Mass parameter estimate is unbiassed

Statistics: Wide-Field Surveys



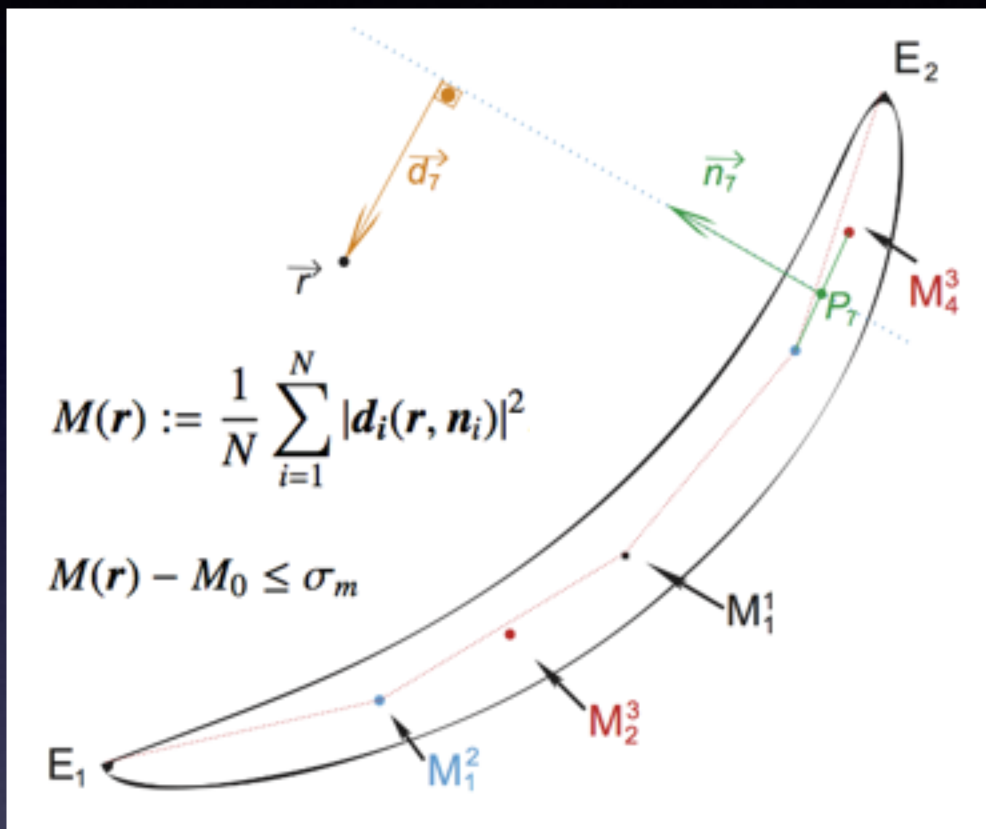
Homogeneous Strong Lensing Samples (arcs)

- 1986-2016: $\mathcal{O}(10^2)$ systems
  - Spectroscopy + HST: SLACS, BELLS
  - $\mathcal{O}(10^2)$ deg^2 surveys: CFHTLS/SL2S, SOGRAS, CS82
- 2016-2020: $\mathcal{O}(10^3)$ systems
  - $\mathcal{O}(10^3)$ deg^2 surveys: KiDS, RCSLens, DES, HSC
- > 2020: $\mathcal{O}(10^4 - 10^5)$ systems
  - LSST, EUCLID, WFIRST
  - DESI, Subaru PFS/SUMIRE

Challenges

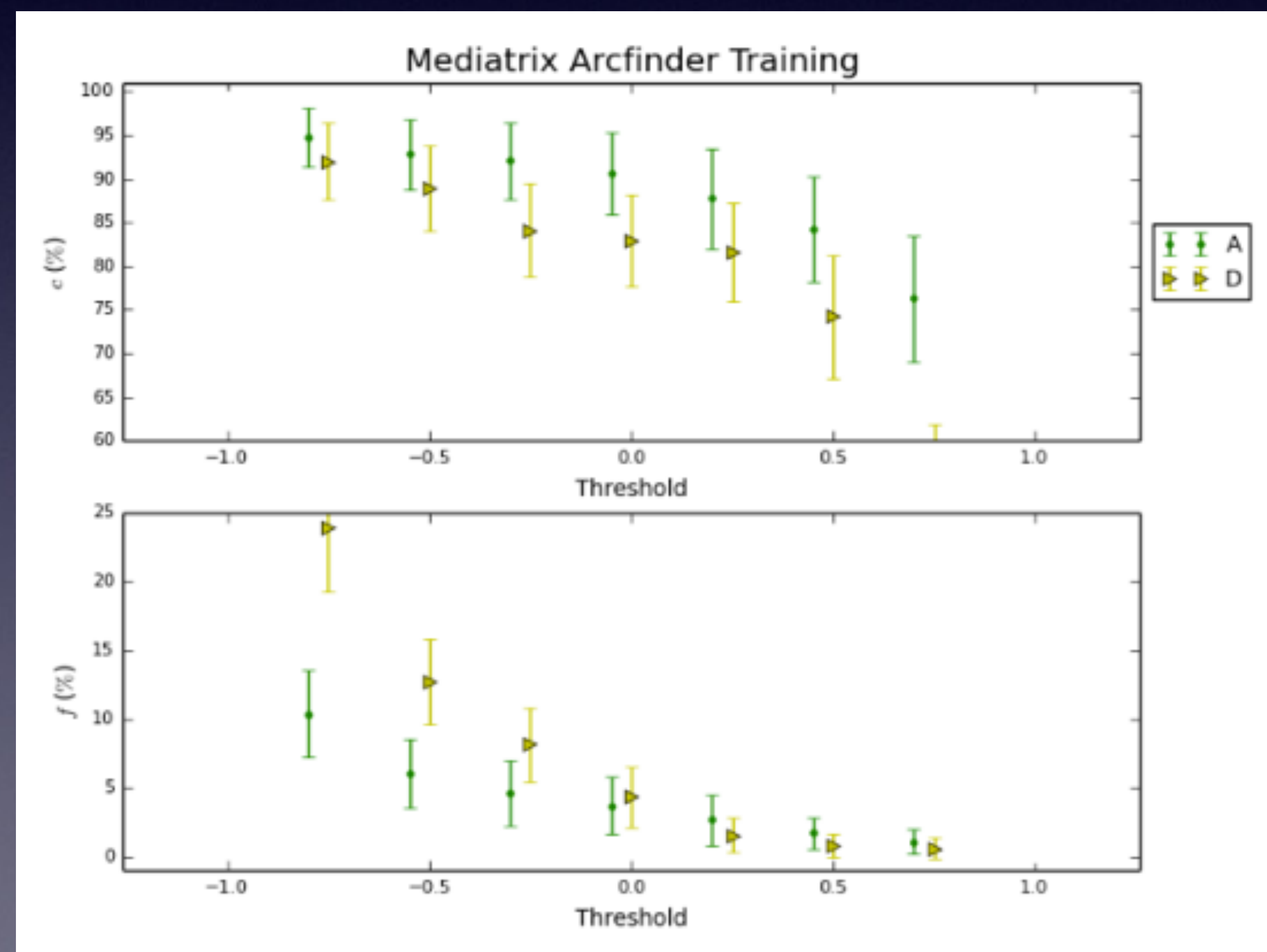
- arcfinding codes: completeness and purity
- automated analyses (including z)
- Systematics (modelling and data)
- ☑ Simulations + arcfinders + inverse modelling

Mediatrix Neural Network Arcfinder



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

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

Deep Learning and the Challenge

- Gravitational Lens Finding Challenge
  - Foreground galaxies: Millenium + SAM (Guo et al. 2011)
  - GALMER code: NFW + stellar mass model, 20 lens planes
  - 33 source planes, "noise free" UDF sources
  - ground based images (4 bands) [10 codes]
  - space based (single band) [14 codes (9 using CNN)]
- Issue with NN on object features: do not detect lower surface brightness systems that are clearly visible to the eye
- Work directly at the image level
  - Computer vision, Deep Learning
  - Convolutional Neural Networks

Gravitational Lens Finding Challenge

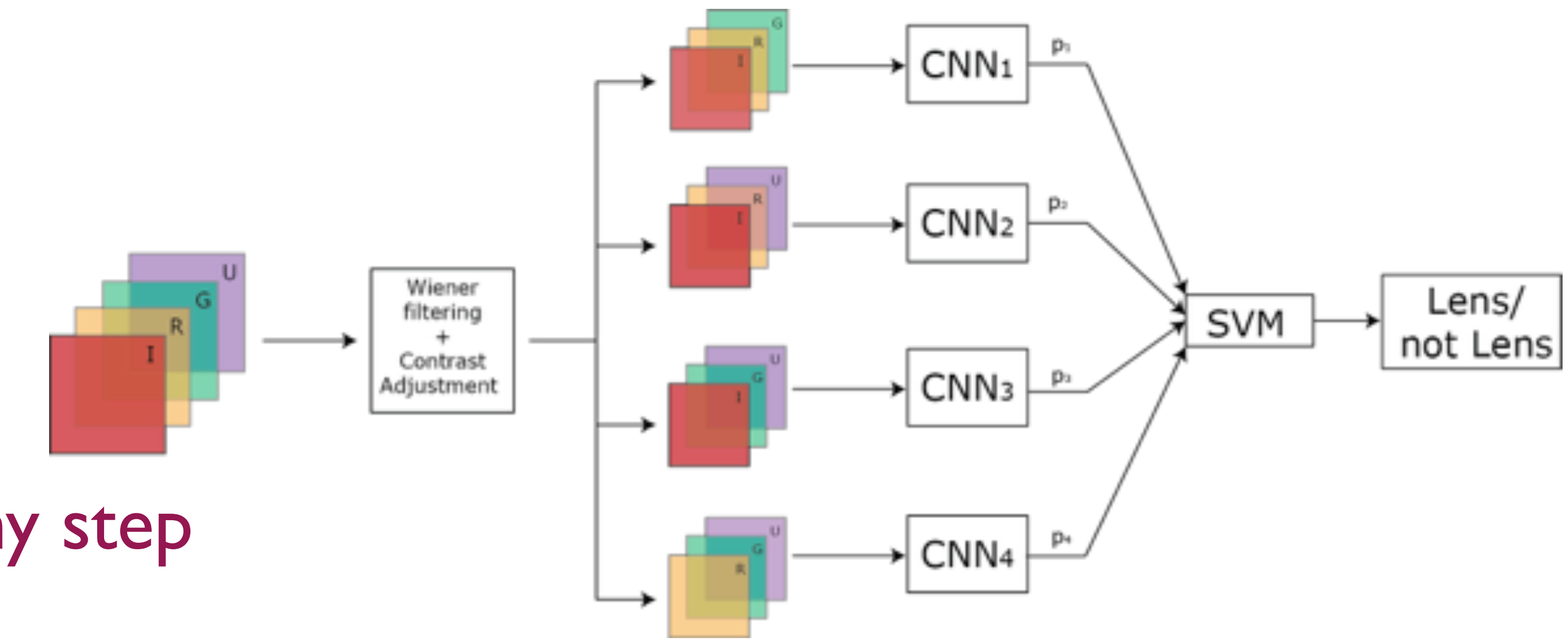
- CAST - CBPF arc search team

Data on 4 filters

Tested combinations

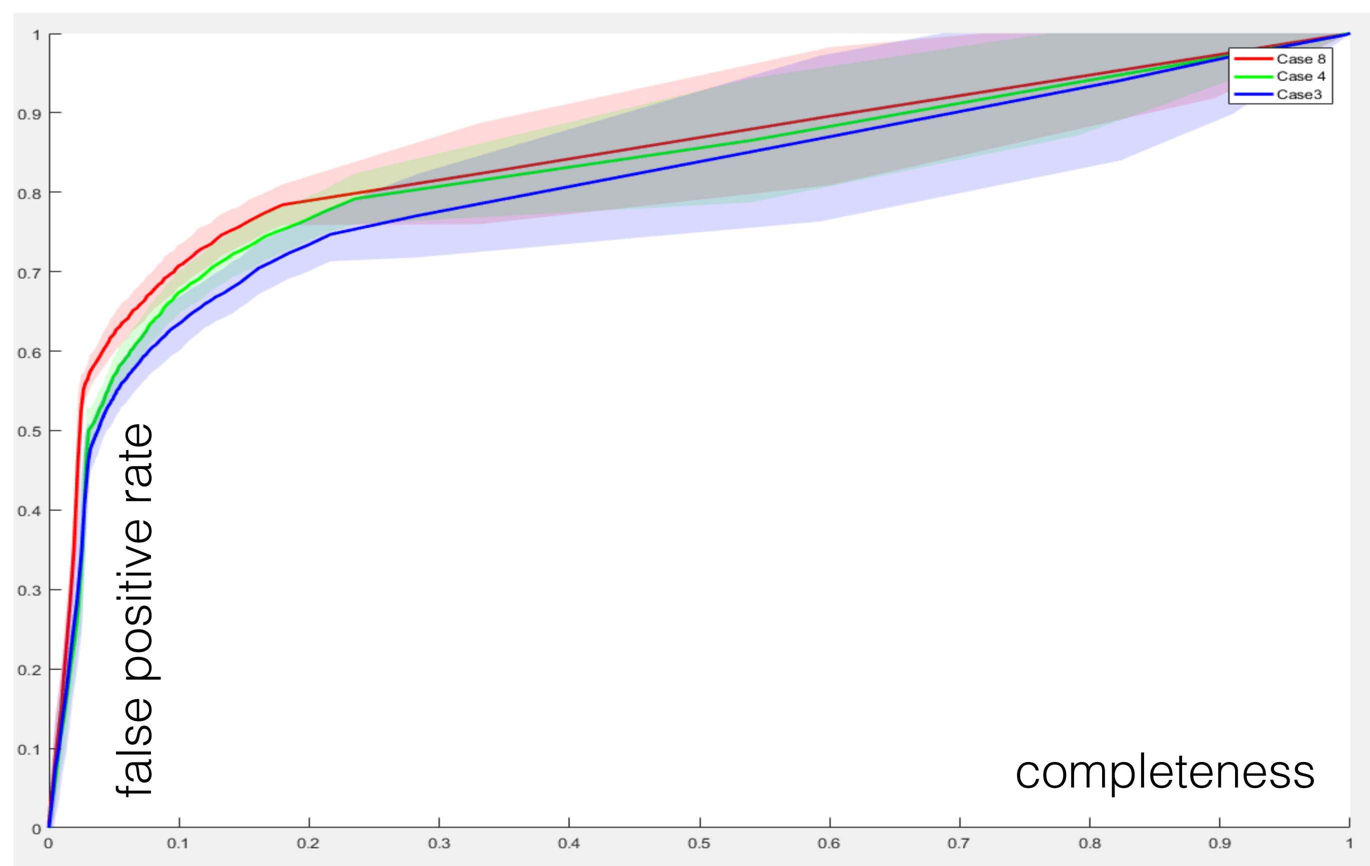
of CNN and SVM

No human intervention in any step



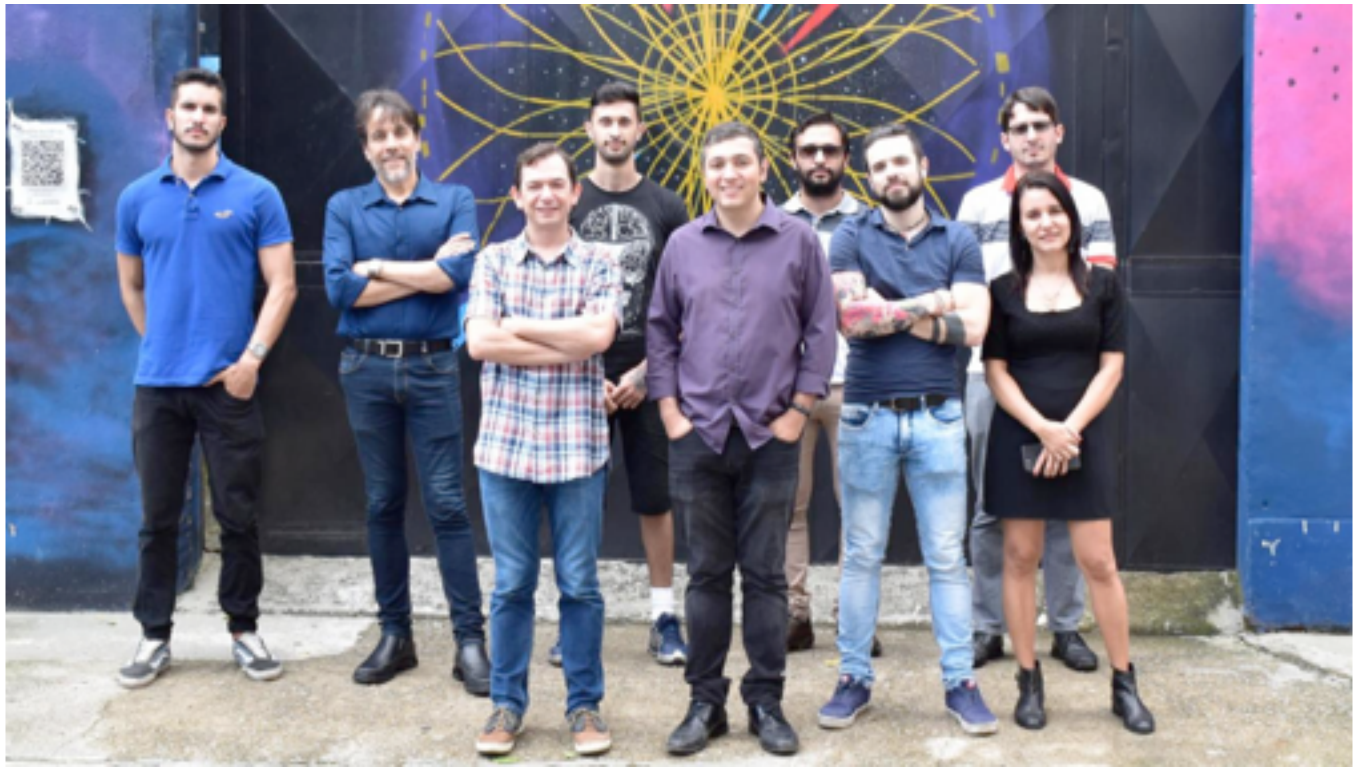
- Case 8: 4 CNNs with combinations of 4 filters + SVN
  - Training time: 680 s
  - Total Processing Time: 2h 30 min (for classifying 100k objects)
  - Area Under ROC: 84.08%
  - Third in the challenge

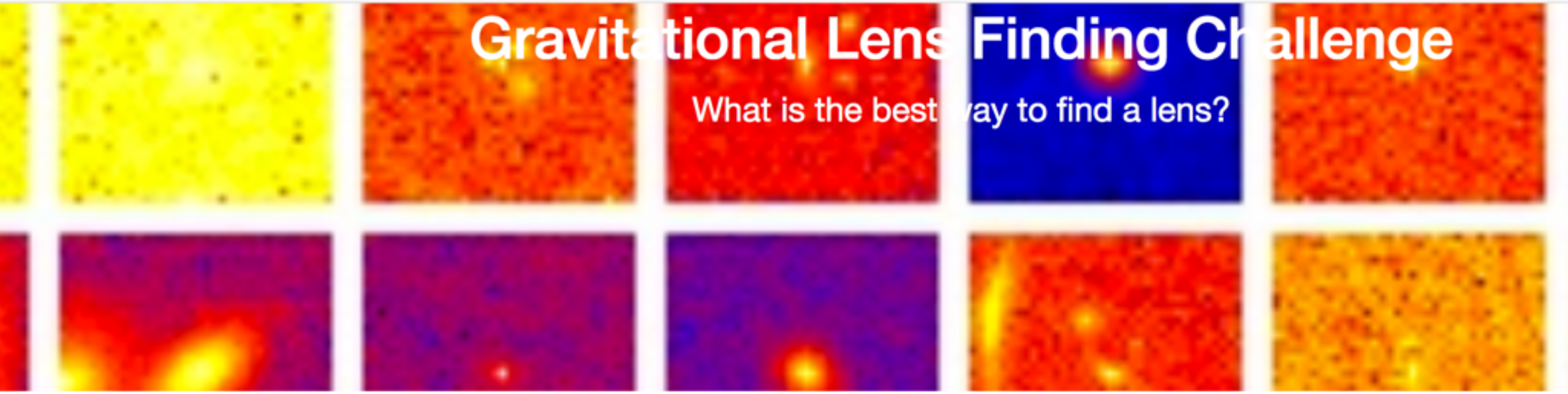
Metcalf, et al., 2019



Gravitational Lens Finding Challenge 2

- Euclid-like simulations (several issues)
- Many many tests:
  - architectures (CMU, ResNet, efficientNet, etc.) and configurations (metrics, optimizers, etc.)
  - data sets (visual and IR bands, different resolution)
  - processing (subtract rotated images, filters, etc.)
- Submitted 4 classification entries and 2 regression entries (measuring Einstein radius)
- Hardware effort (GPU farms @ CBPF)
- Large team working over the (Brazilian) summer (vacation)





Introduction

Finding strong gravitational lenses in the current imaging surveys is difficult. Future surveys will have orders of magnitude more data and more lenses to find. It will become impossible for a single human being to find them by inspection. In addition, to properly interpret the science coming out of strong lens samples it is necessary to accurately quantify the detection efficiency and bias of automated lens detectors. These open challenges are designed as a friendly way of stimulating activity and helping to quantify results in this regard.

Challenges

Challenge 2.0

Update Feb. 28, 2020 We have a winner!! C. Bom, et al. 's "Cast_efficient_auc" entry has won.

Best result, 4 entries out of the 6/7 best
Good regression results (comparison ongoing)

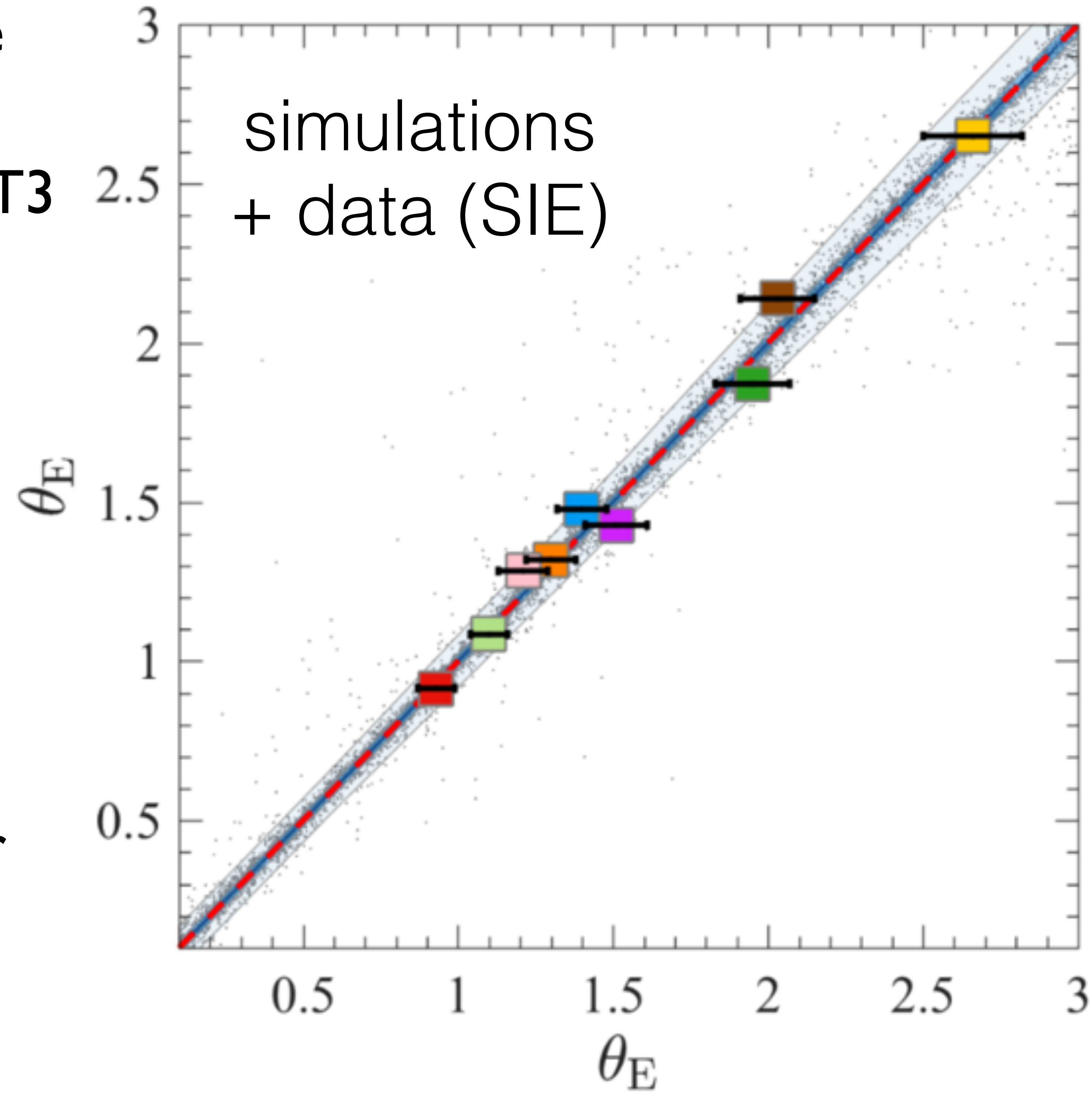
People

Funding

This pro
Europea
research
under
Program
n. 25934

Recovering Einstein Ring Parameters

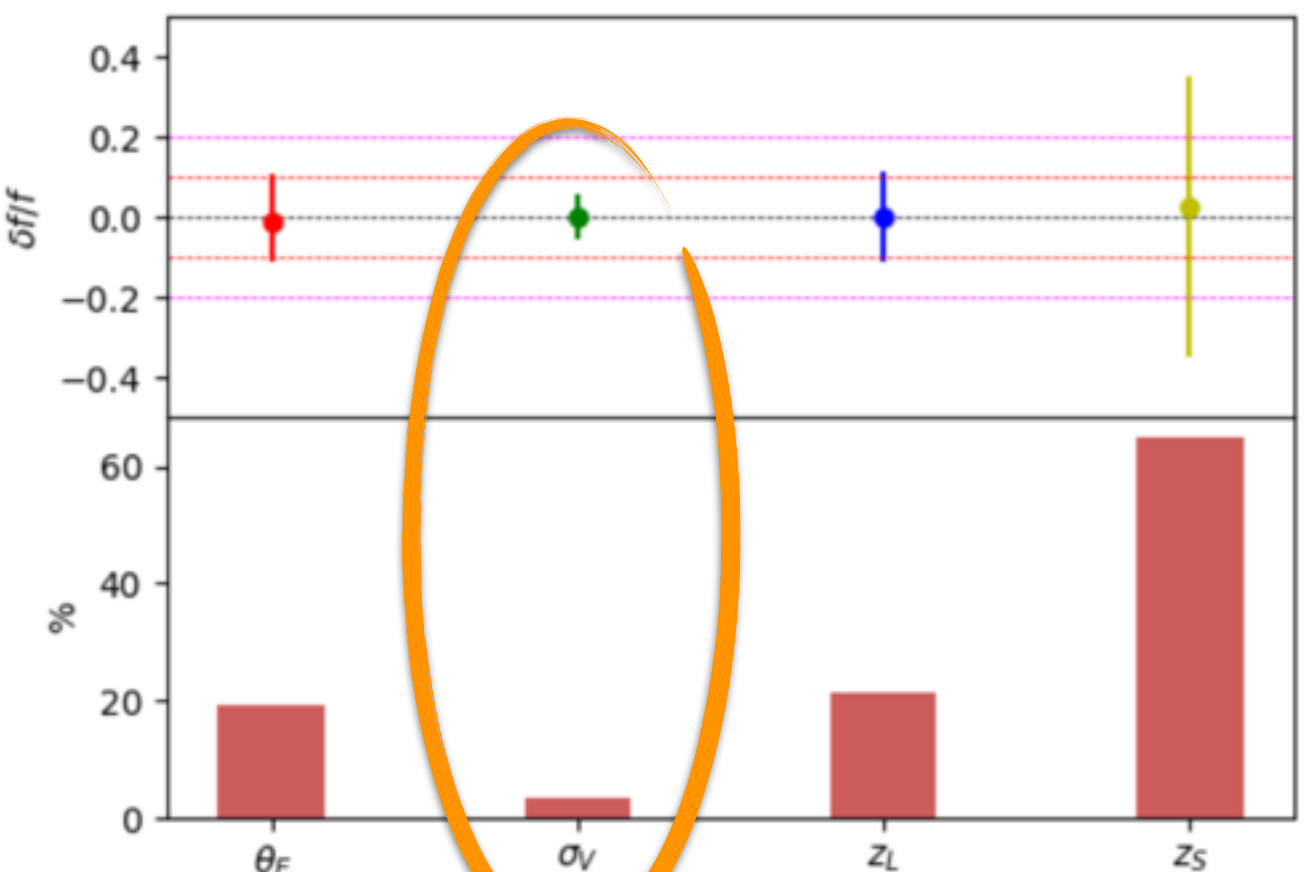
- Automated analysis of large datasets (e.g. LSST, Euclid)
- Sources: GalaxyZoo, GREAT3 + clumpy galaxies
- 500.000 system training set
- ICA to remove the lens galaxy
- Same precision as inverse modelling
- Convolutional Neural Networks (inception-v4 for no ICA)
- 10^8 times faster than ML
- Still need redshifts

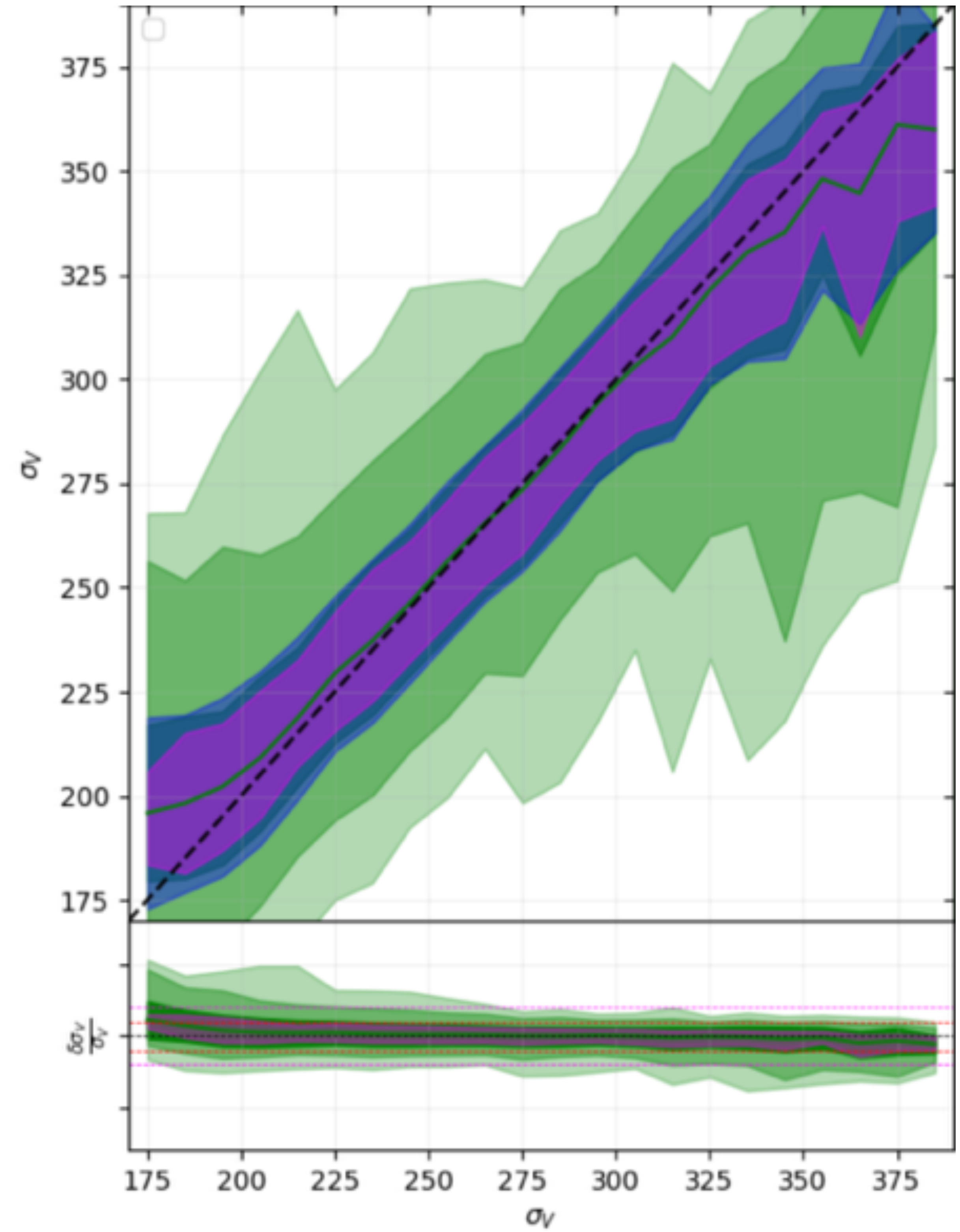


Hezaveh, Levasseur, Marshall, 2017, Nature

Recovering physical parameters

- Only photometry (3 bands)
- Lenspop (Collet 2015) simulations
  - SIE, instrument (DES conditions)
  - 18,600 mock DES-observable systems
- Inception Neural Network





Bom et al., 2019.

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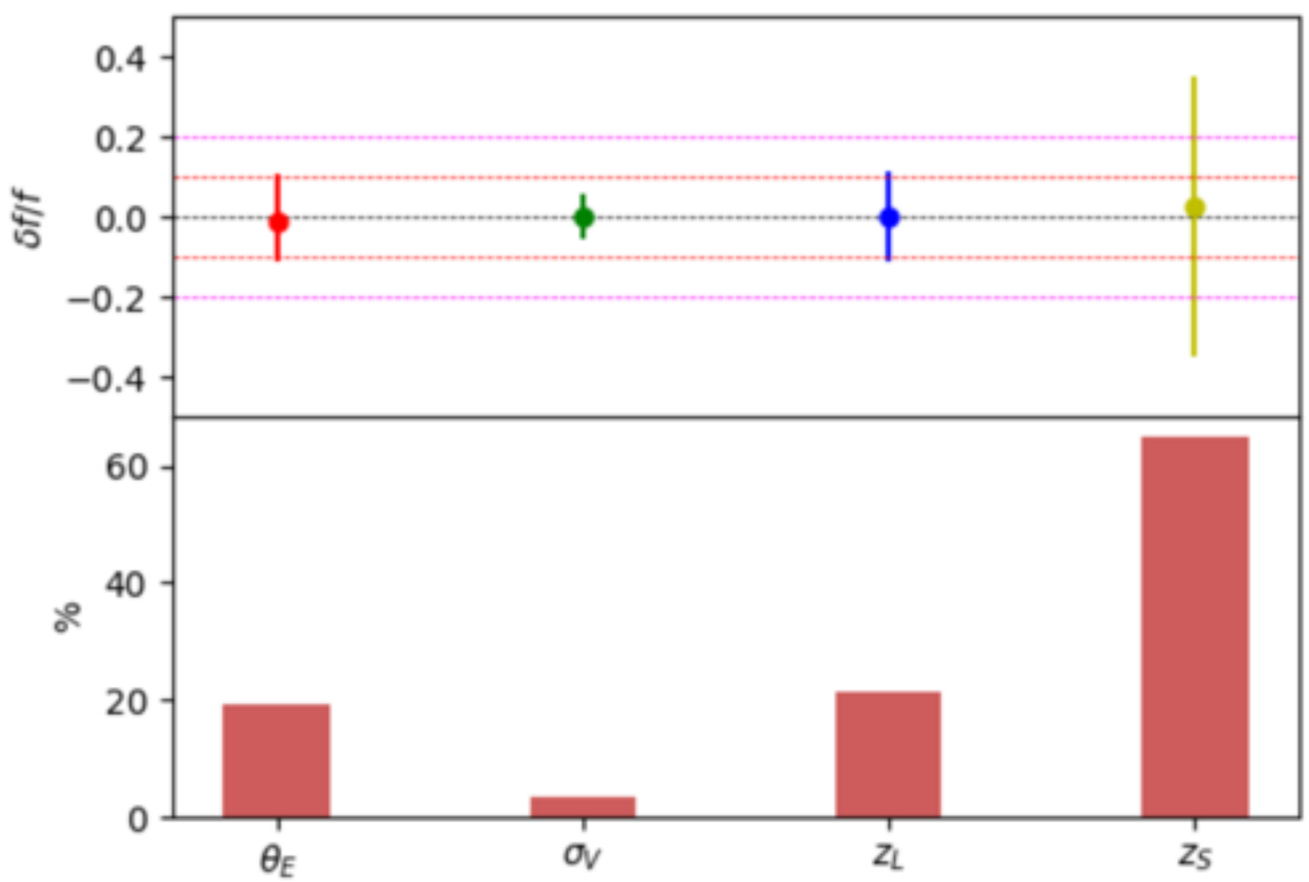

- Challenge
  - Derive constraints on cosmology and MoG from an end-to-end analysis using Machine Learning
  - Towards a fully automated modified gravity test!
  - Ongoing today!

Bom et al., 2019

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
  - Complementary cosmological probe for DE and DM
  - Unique for modified gravity and DM properties
- Interdisciplinary field involving from fundamental physics to data reduction, including image processing, statistics, simulations, theory and semi-analytic modelling
- As any other field, need to improve the statistics and systematics (modeling, simulation, data)
- Data available from CS82, Blink, S-PLUS (+ DES/DECaLS, KiDS, HST) and lots of excellent data to come in the near future!
- @CBPF/PPGCosmo: surveys, arc finding, simulations, modelling, and cosmology; interested in MoG and DM
- Very happy to collaborate!


Thanks