Finding gravitational arcs in real and simulated images

Martín Makler
COSMO - CBPF

Sob o Sol de Sobral
Uma Janela para o Cosmos
27 de Março, 2019
Sobral/CE

CBPF

100 centenário do ECLIPSE DE SOBRAL 1919 - 2019

Mock Córdoba
Galaxy formation for gravity and cosmology

MENU nature Subscribe

NEWS · 08 APRIL 2019

Brazil's government freezes nearly half of its science spending

The decision could derail multi-million-dollar research projects such as the Sirius synchrotron.

Claudio Angelo

RELATED ARTICLES

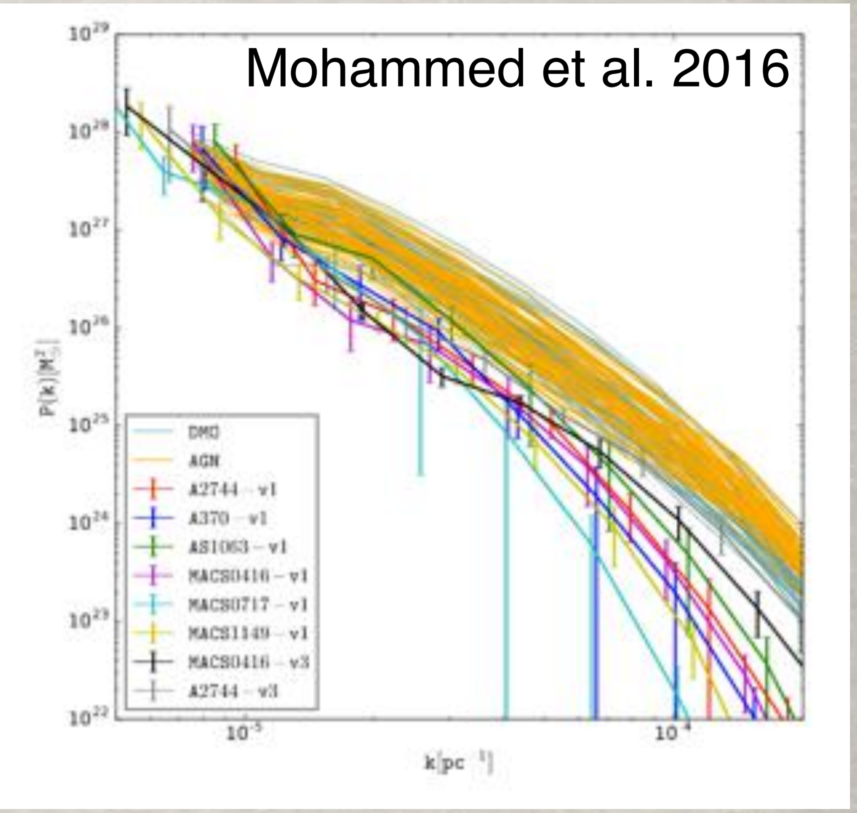
Brazilian scientists reeling as federal funds slashed by nearly half

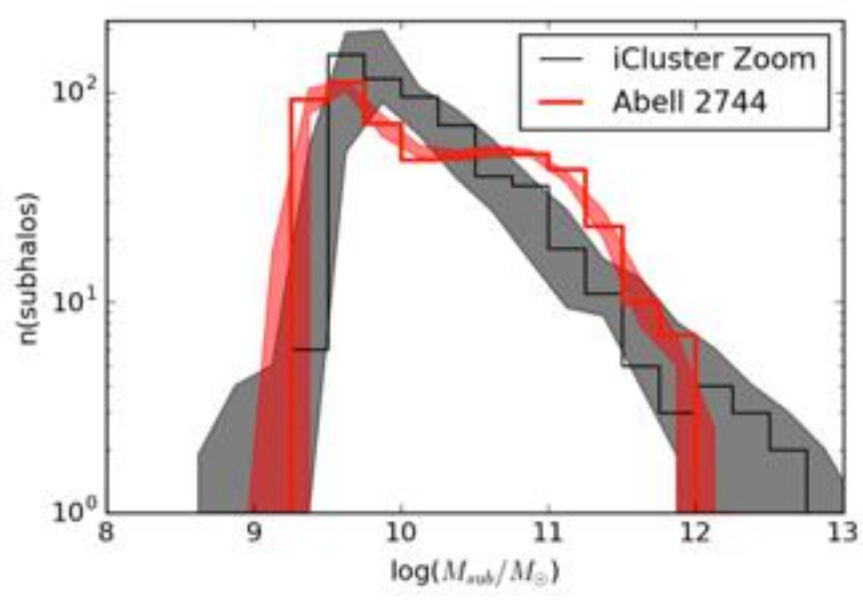
'Tropical Trump' victory in Brazil stuns scientists

Strong Lensing and Cosmology

- Density profiles of galaxies and inner cluster regions:
  - cuspy halo profiles?
  - dark matter interactions
  - baryonic processes: cooling, AGN feedback,…
- Substructure
  - cold, warm, self-interacting?
  - primordial spectrum
- Luminous x Matter
  - e.g. DM cross section

    $\sigma_{DM}/m_{DM} \lesssim 2\,\mathrm{cm}^2/\mathrm{g}$ Wittman et al.
- Modified gravity
- Cosmology (see FoF talk)
- Challenges for using arcs as astrophysical and fundamental physics probes:
  - statistics
  - systematics





Jauzac et al. 1702.04348

Strong lensing and substructures

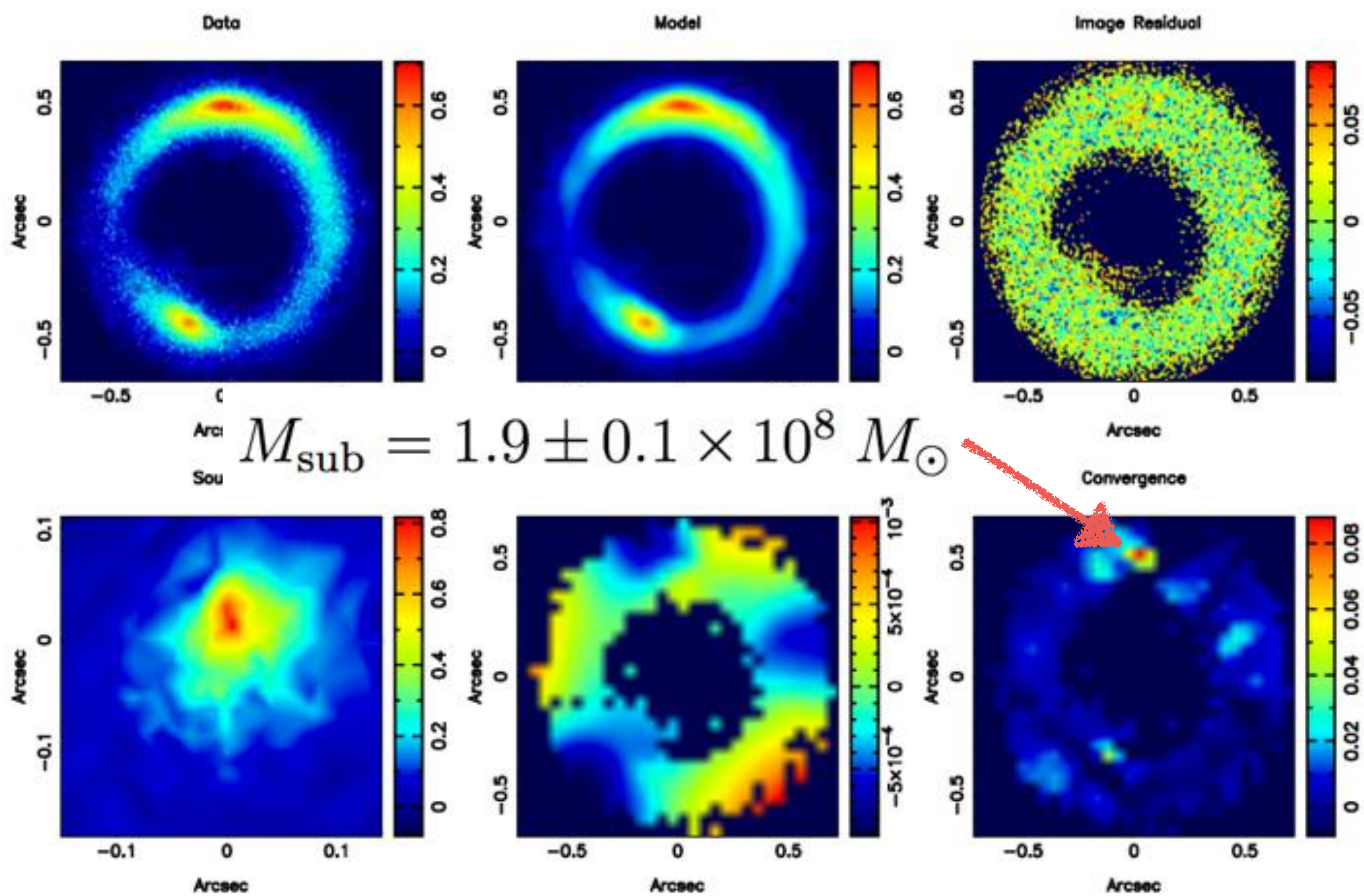
High sensitivity to small perturbations due to the caustic structure

MENU nature

Gravitational detection of a low-mass dark satellite galaxy at cosmological distance

S. Vegetti, D. J. Lagattuta, J. P. McKean,

Nature **481**, 341–343 (19 January 2012)



$$M_{\rm sub} = 1.9 \pm 0.1 \times 10^8\ M_\odot$$

Strong lensing and substructures

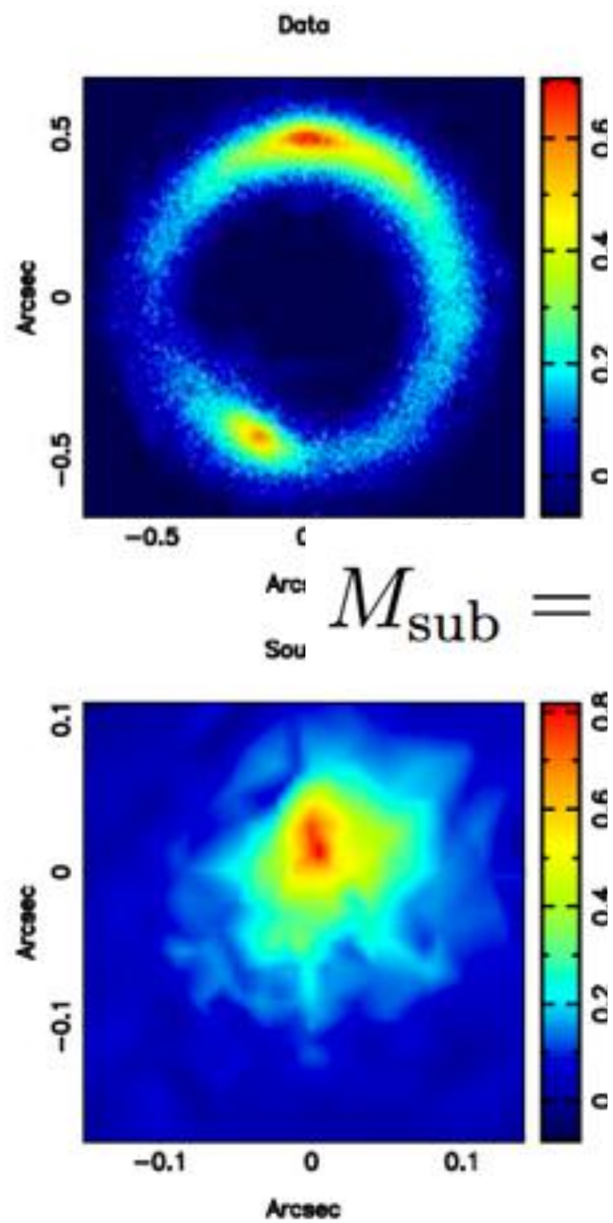
High sensitivity to small perturbations due to the caustic structure

MENU nature

Gravitational detection of a low-mass dark satellite galaxy at cosmological distance

S. Vegetti, D. J. Lagattuta, J. P. McKean,

Nature **481**, 341–343 (19 January 2012)



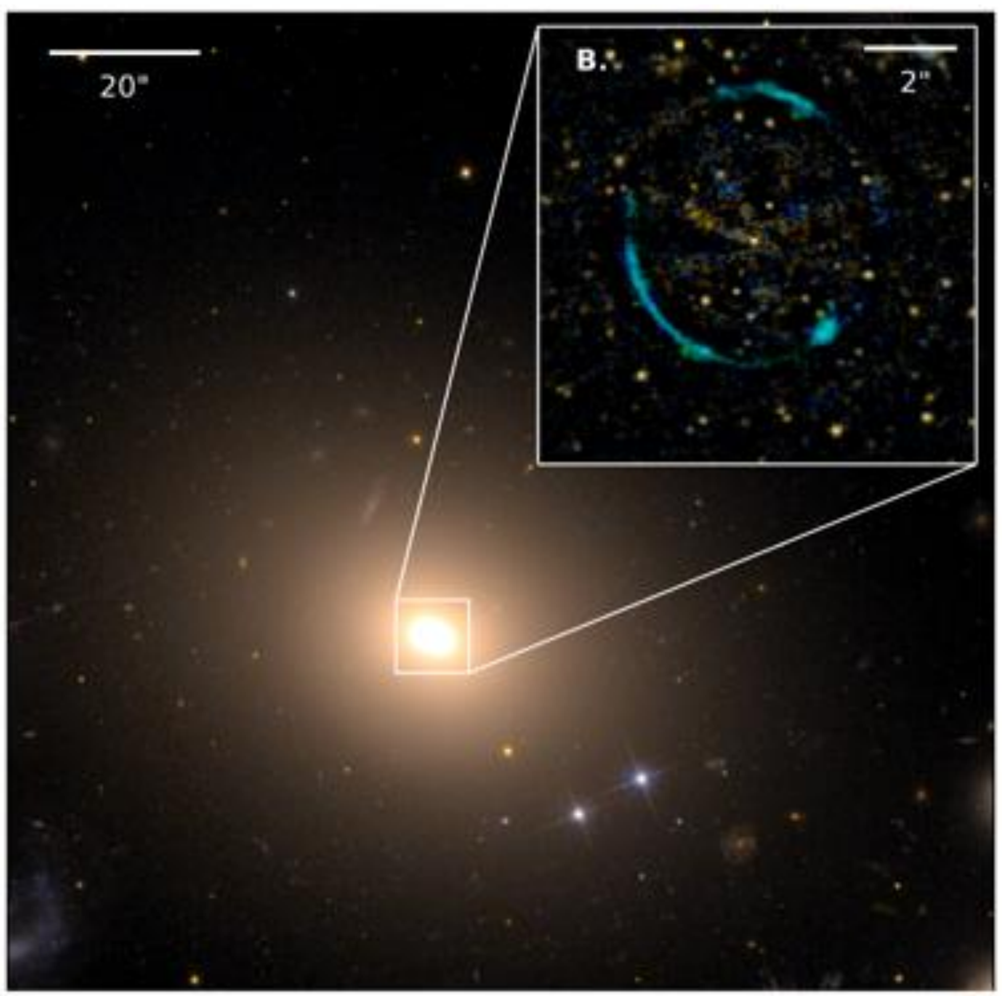
- "Aside from direct or indirect detection of the dark matter particles themselves, Einstein ring systems currently offer the best astrophysical test of the nature of the dark matter" (Li et al. 2016)
- measurements of approximately 100 strong lens systems with a detection limit of $M_{low} = 10^7\ h^{-1}\ M_\odot$ would clearly distinguish CDM from WDM in the case where this consists of 7 keV sterile neutrinos

Testing gravity with Einstein Rings

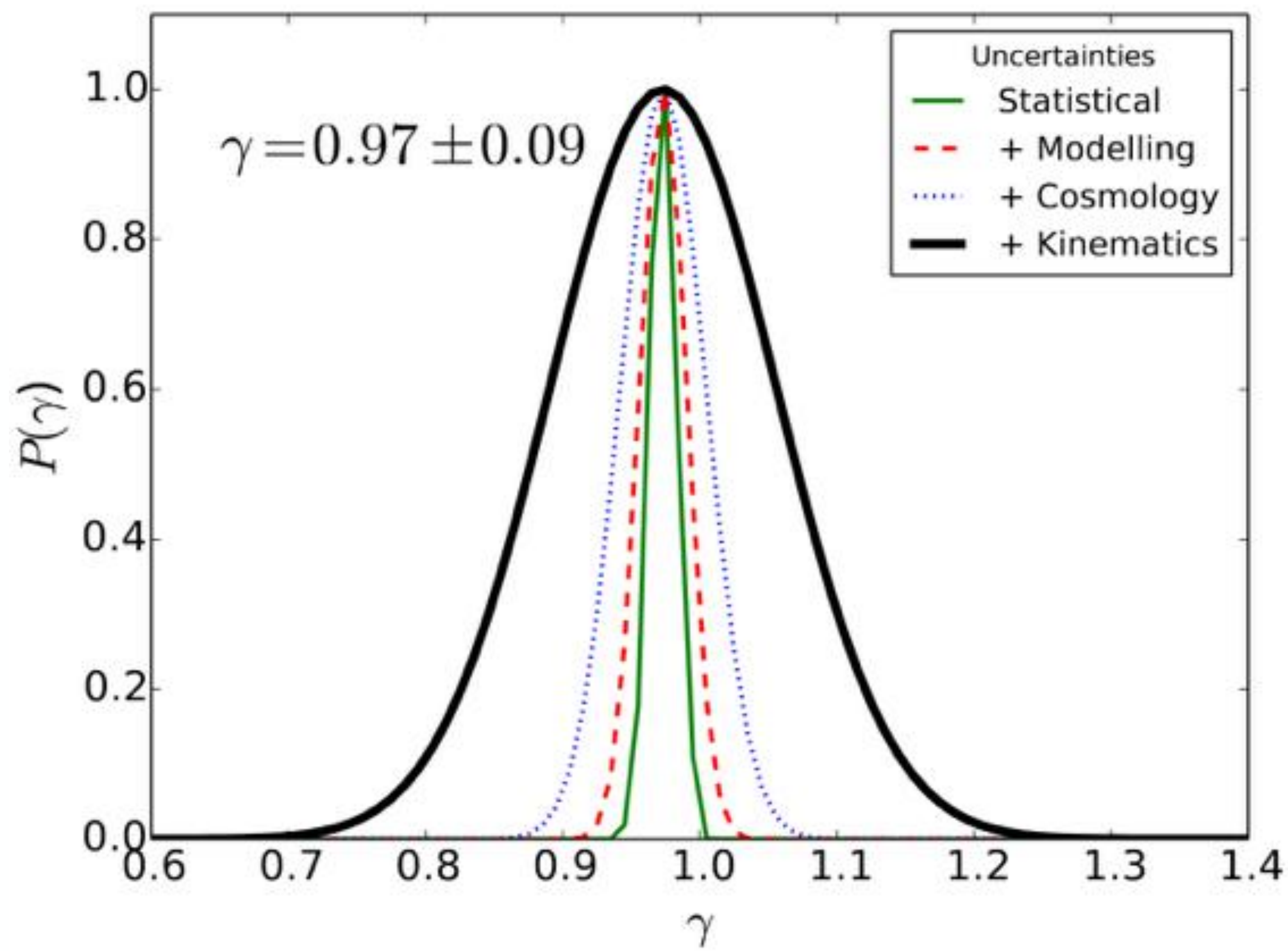
Combining dynamics and lensing

Detailed kinematical analysis

Detailed strong lensing modelling



Einstein Ring ESO 325-G004



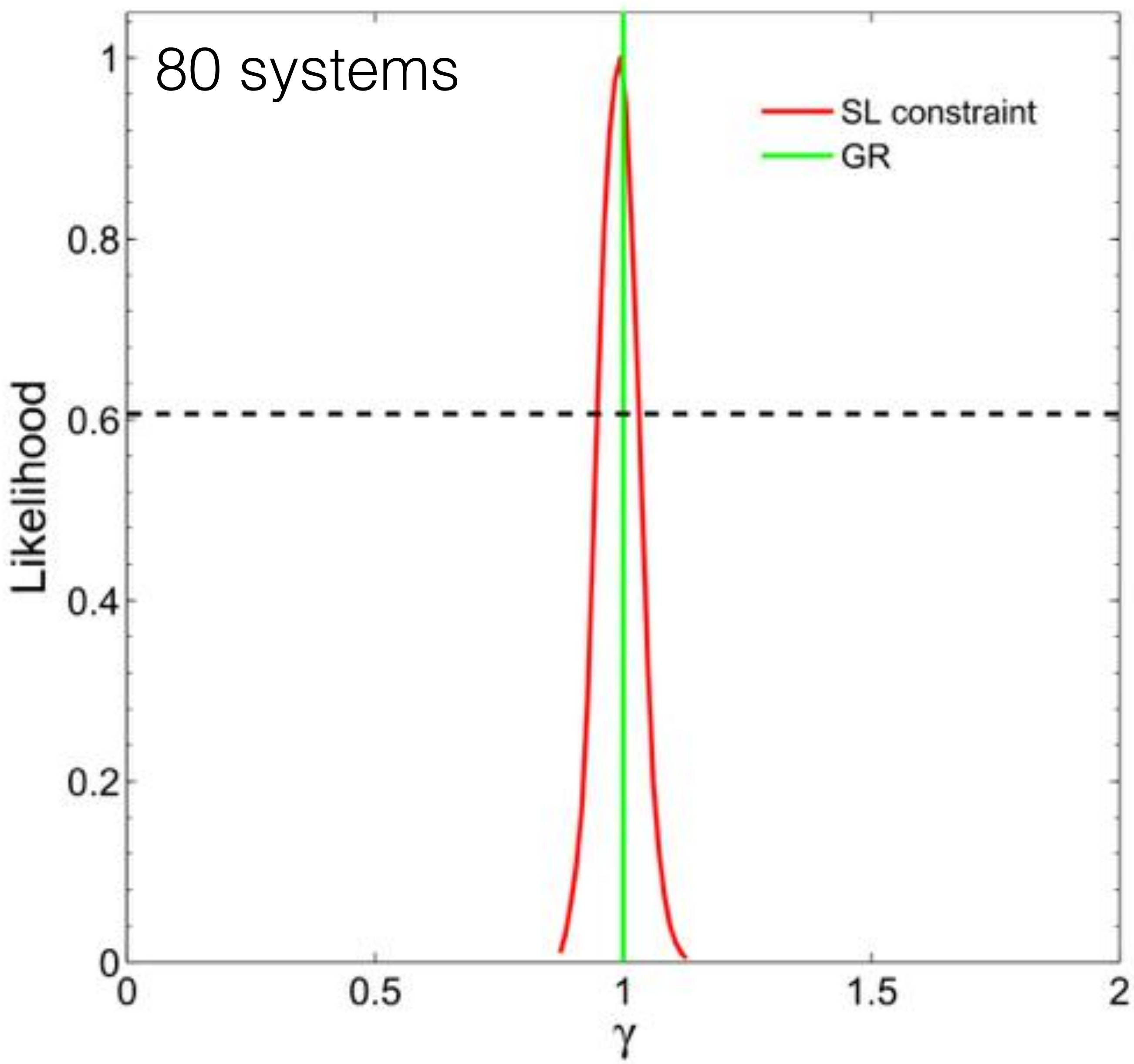
Collet et al, 2018, Science

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 SLACS, BELLS, LSD, LS2S sample



Cao et al. 2017

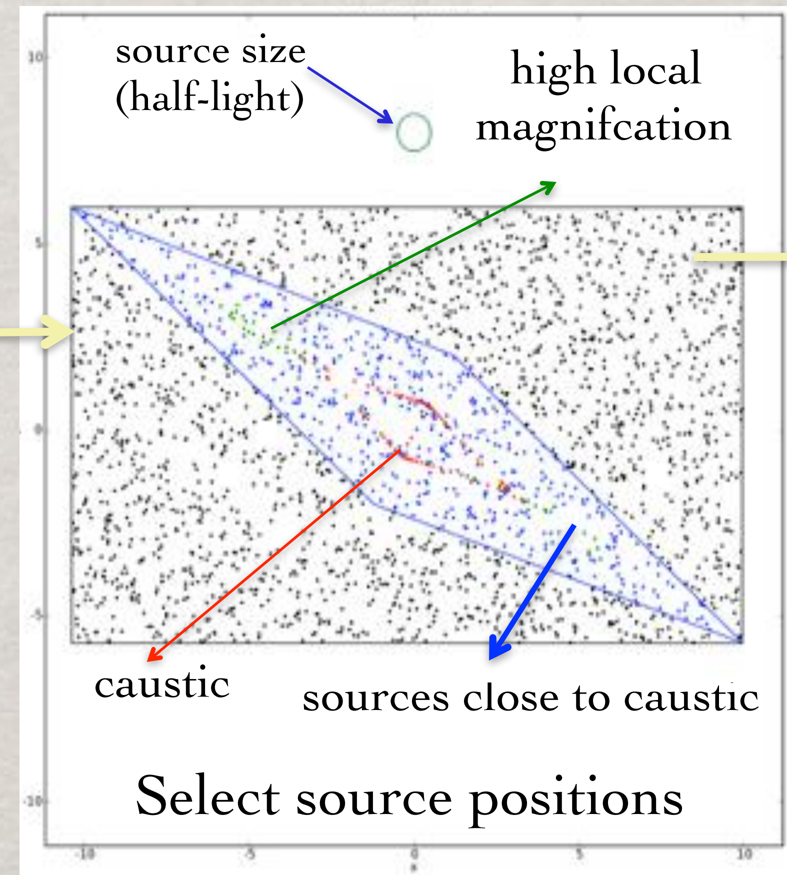
The results are in agreement with GR

Next:

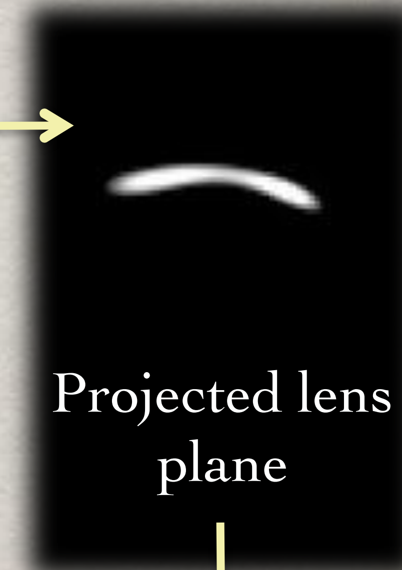
- **study systematics (ellipticity, profiles, substructures...)**
- **Increase sample size**
- **Increase mass and distance range**
- **make detailed analysis**

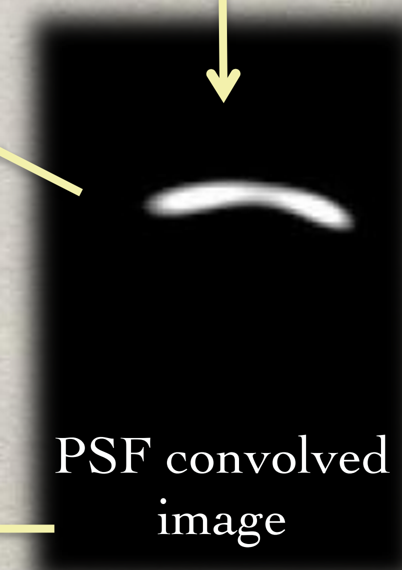
AddArcs

- Selects haloes from catalog
- Slices source plane in redshift bins
- Selects positions and lenses finite sources
- Identifies gravitational arc
- *Adds arc* to image and creates truth table

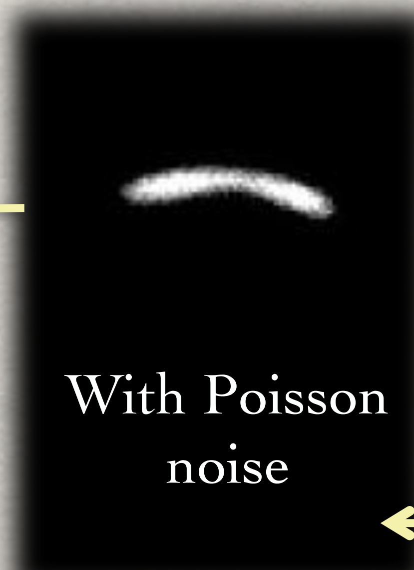


Lens Sersic source from UDF catalog

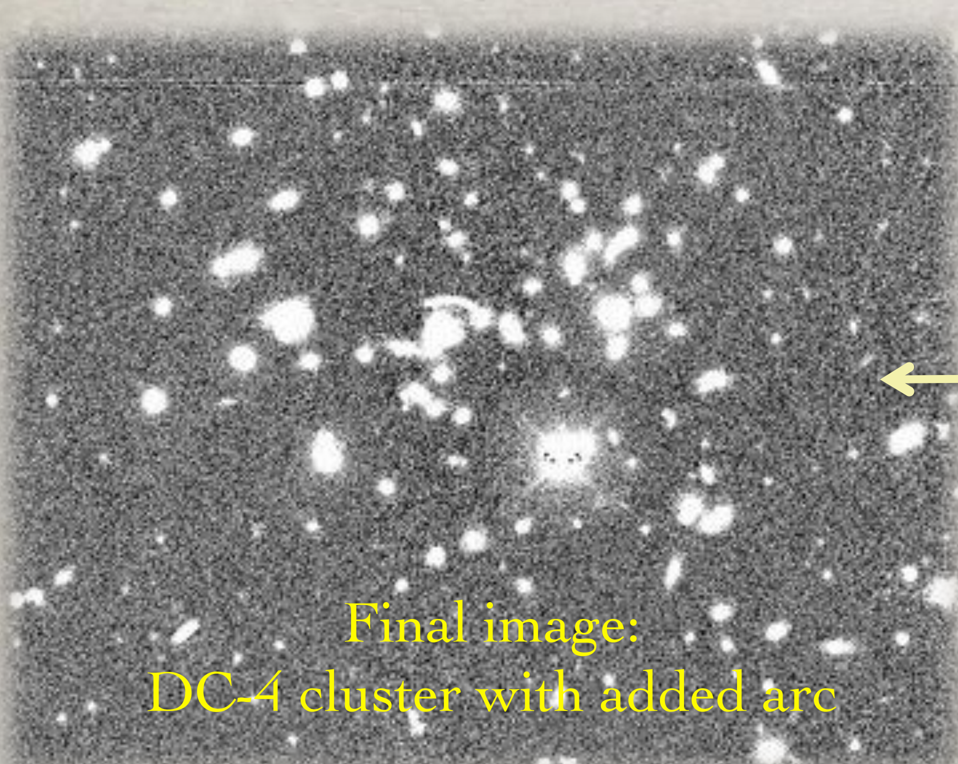




"Sextracted" arc "postage stamp" ➔ arc parameters "truth table"



WCS



Data Challenge (DC) 4 ➔ shapelets for DC-5

PaintArcs

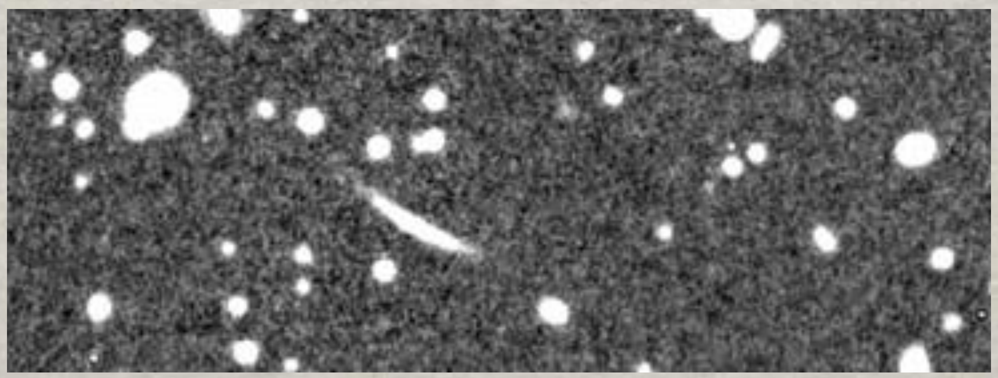
- Quick'n'dirty arc simulator (controlled sample)

- ArcEllipse: simple arc morphology

$$r_\pm = r_c \pm b\sqrt{1-\left[\frac{r_c(\theta_0-\theta)}{a}\right]^2}$$

- Combine with radial profile (e.g. Sérsic)

- Scale counts, convolve with PSF, Poisson sample

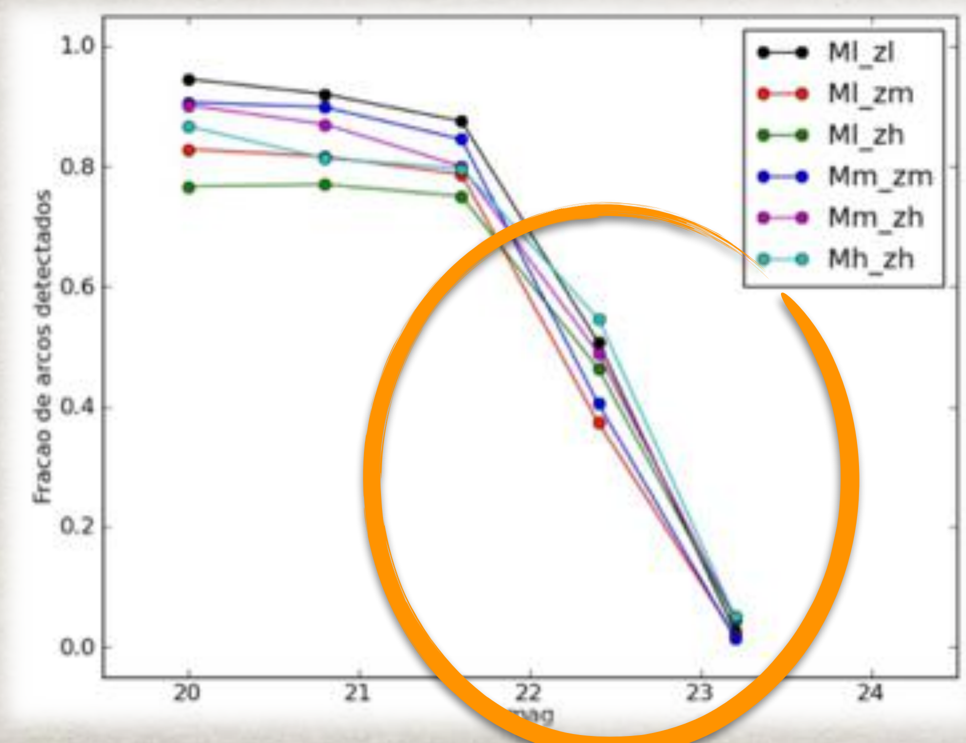


DES DC-6

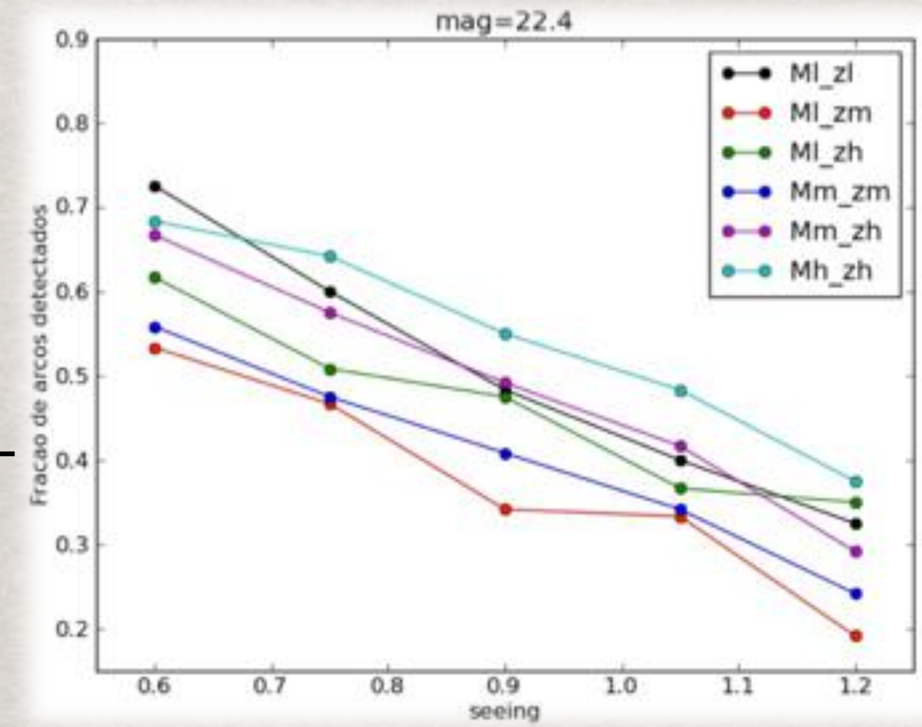
Paint Arcs + Horesh Arcfinder

- Added 3000 arcs in DES simulated cluster images
- Fraction of recovery

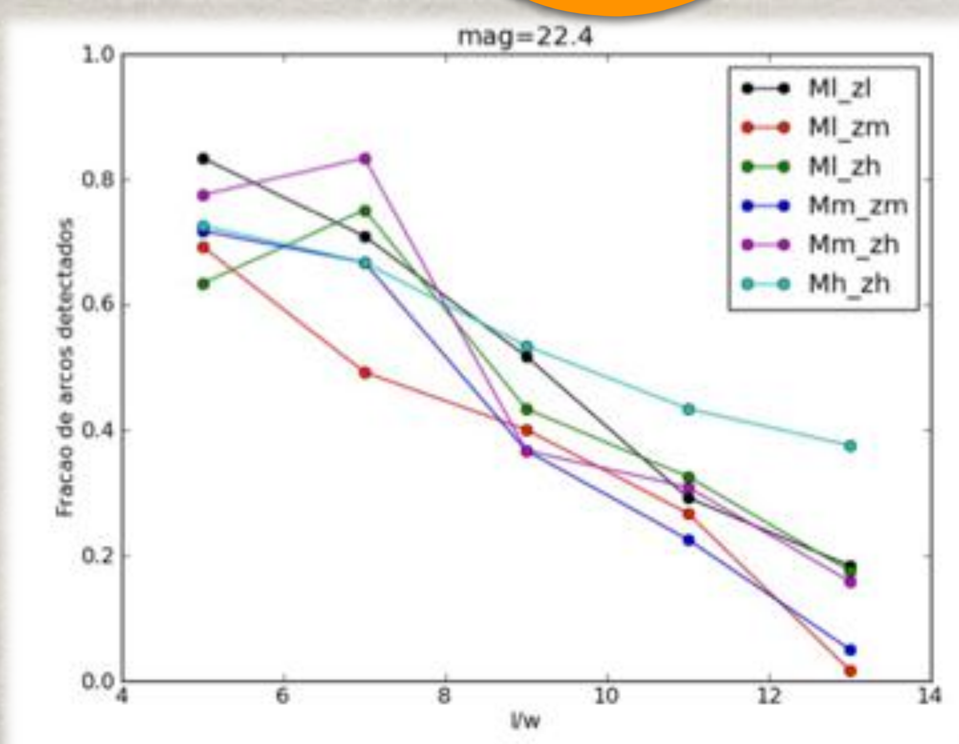
completeness



completeness

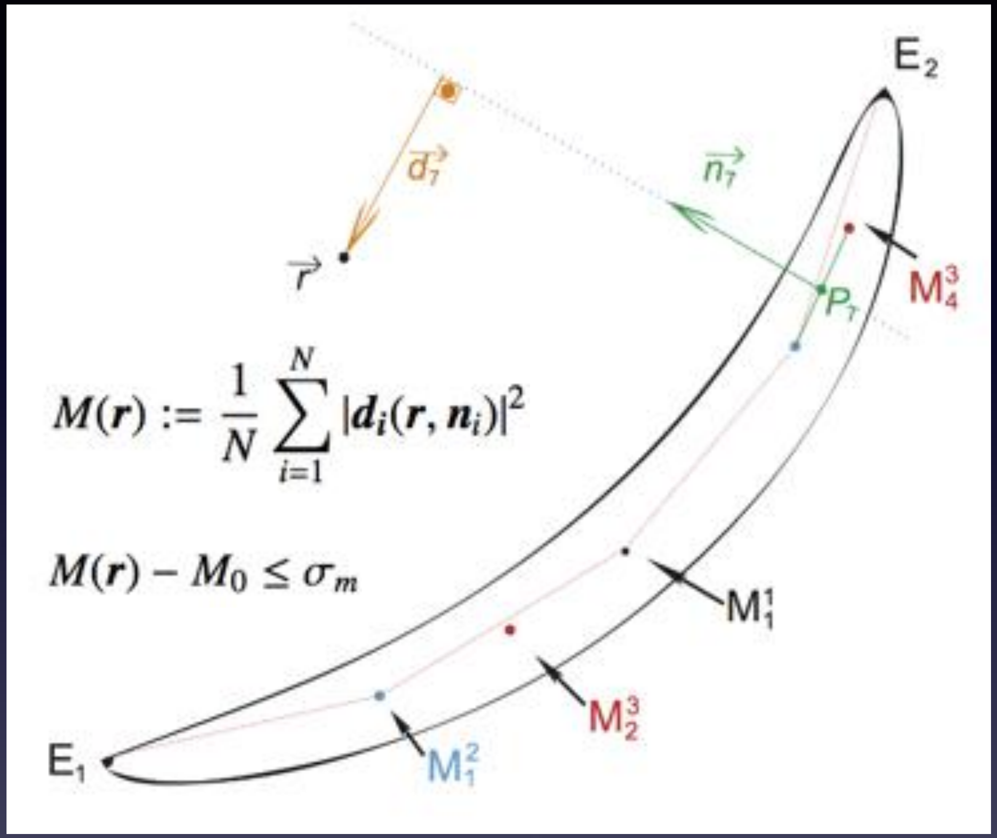


completeness



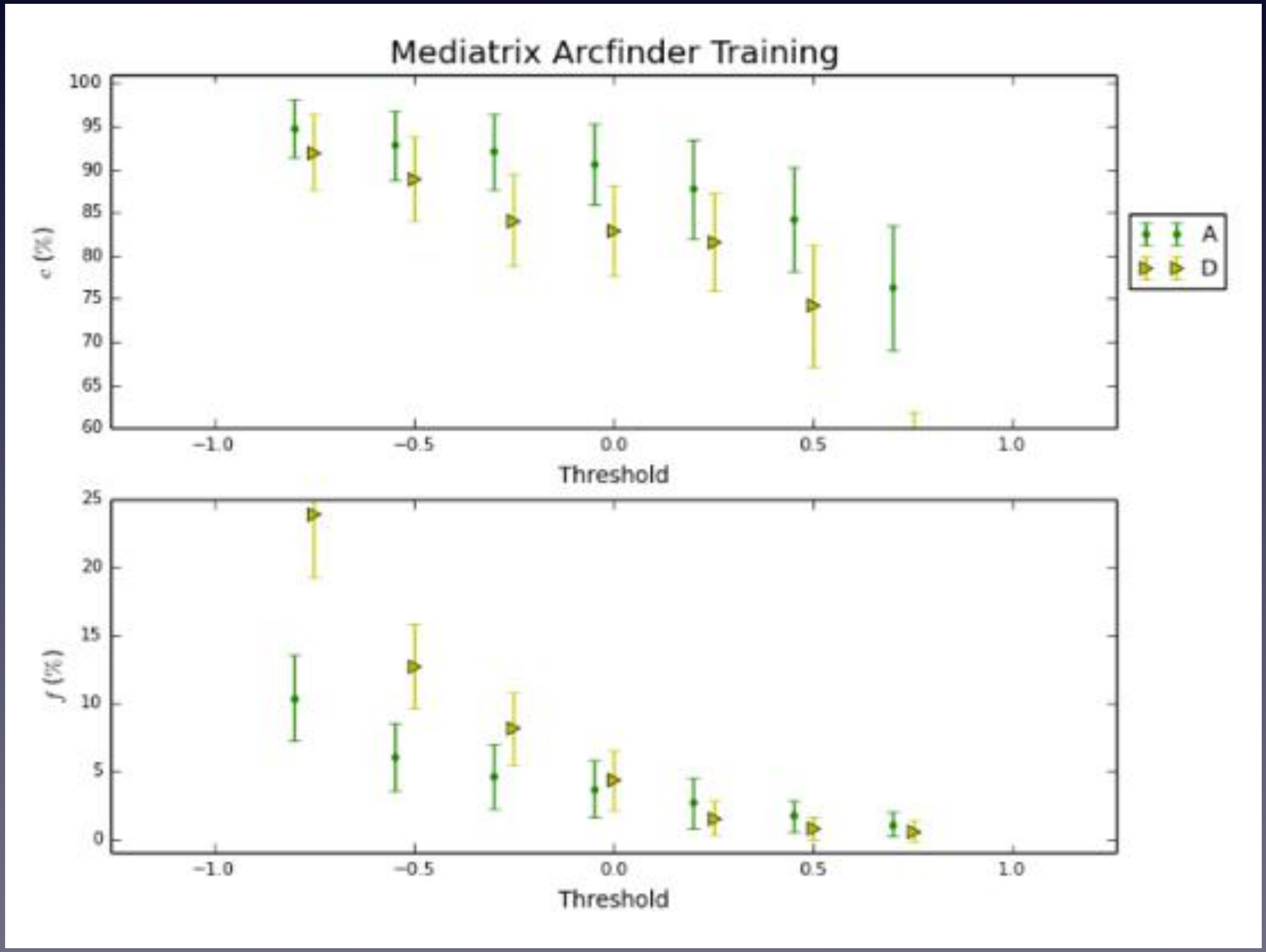
- Problem with fragmentation
- Lower surface brightness systems are not detected

Mediatrix Neural Network Arcfinder



Use Mediatrix (Bom, et al.) method to obtain object parameters. Account for curvature

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



- Trained and validated on AddArcs sample
- Applied to HST data
- Apply to PaintArcs/DES

Obtain completeness and spurious detections

Testing other Arcfinders

Arcfinding steps:

Image pre-processing

Object detection

Object measurement

Arc candidates selection/decision

- Large sample of arcs with controlled properties: PaintArcs

  (Furlanetto et al.)
- Determine selection function
- Effects of PSF, noise, background, blending
- Test and optimize on CS82

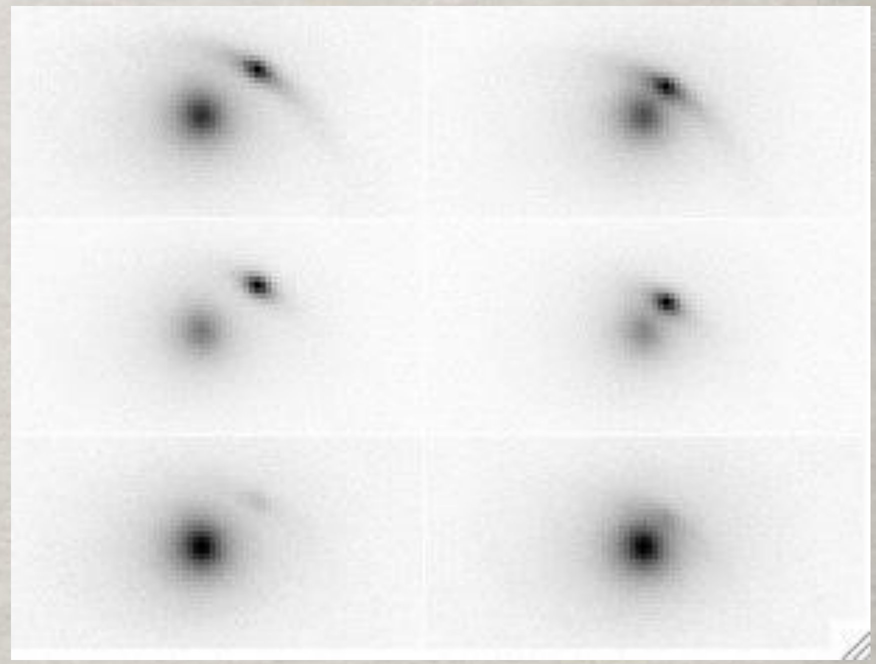
Arcfinders:

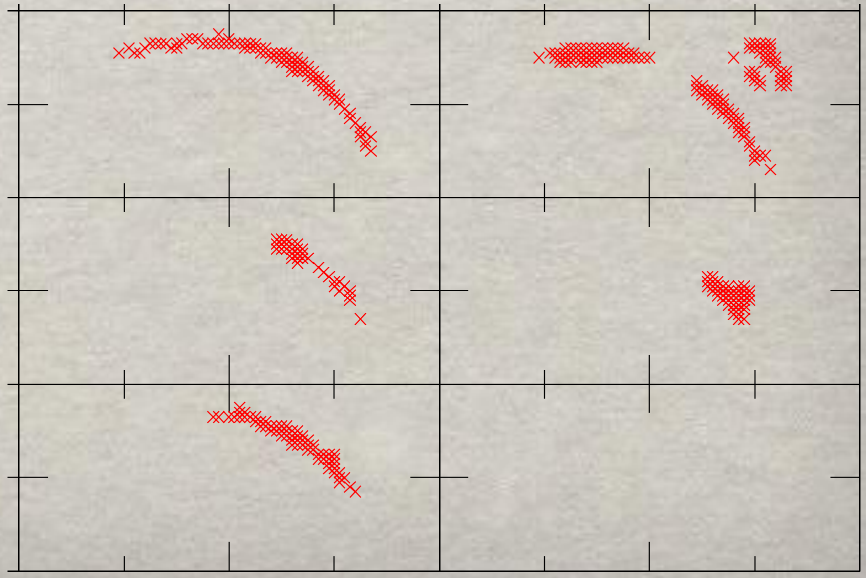
More-Alard

Mediatrix Neural Network (Bom et al. 2017)

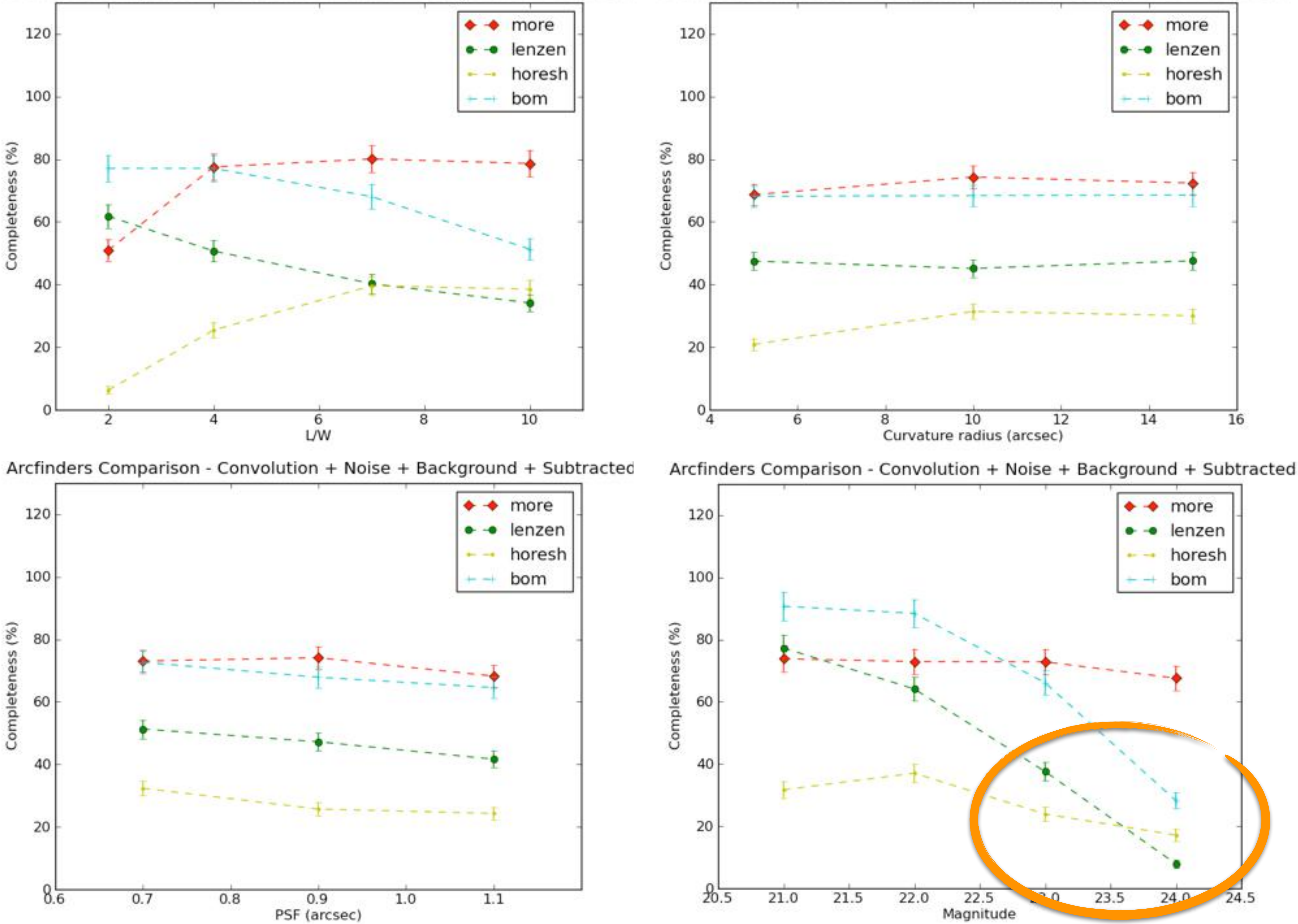
Horesh et al.

Lenzen et al.





Arc finder comparison



Deep Learning and the Challenge

- 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
  - 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)]

Gravitational Lens Finding Challenge

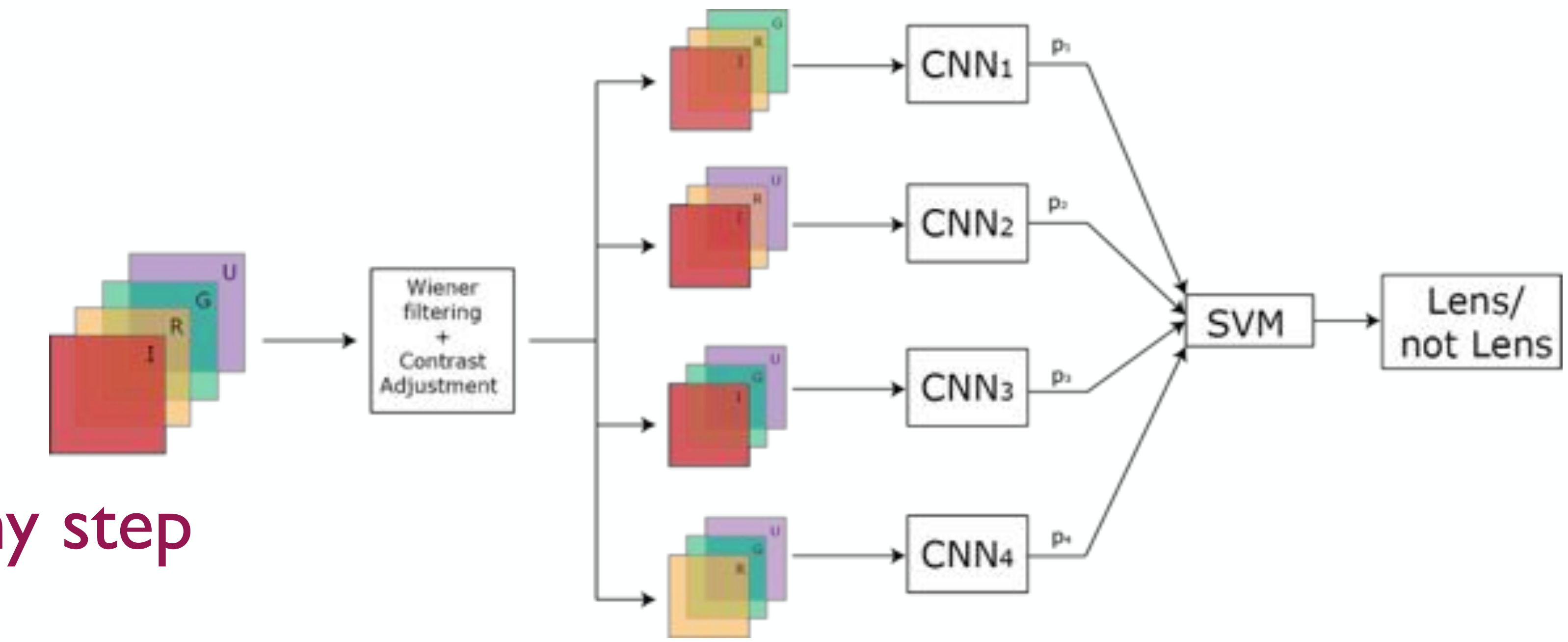
- CAST - CBPF arc search team

Data on 4 filters

Tested combinations

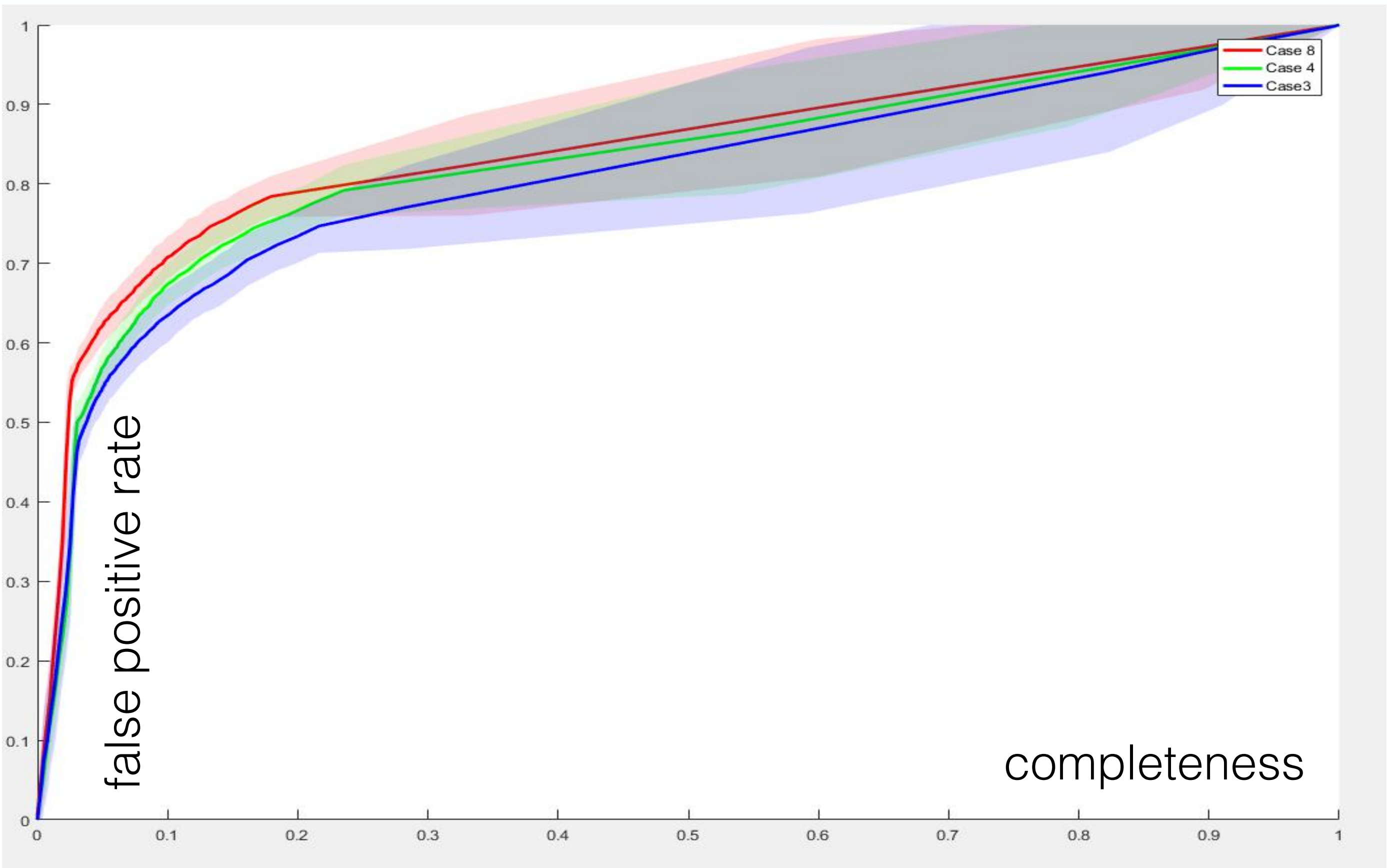
of CNN and SVM

No human intervention in any step



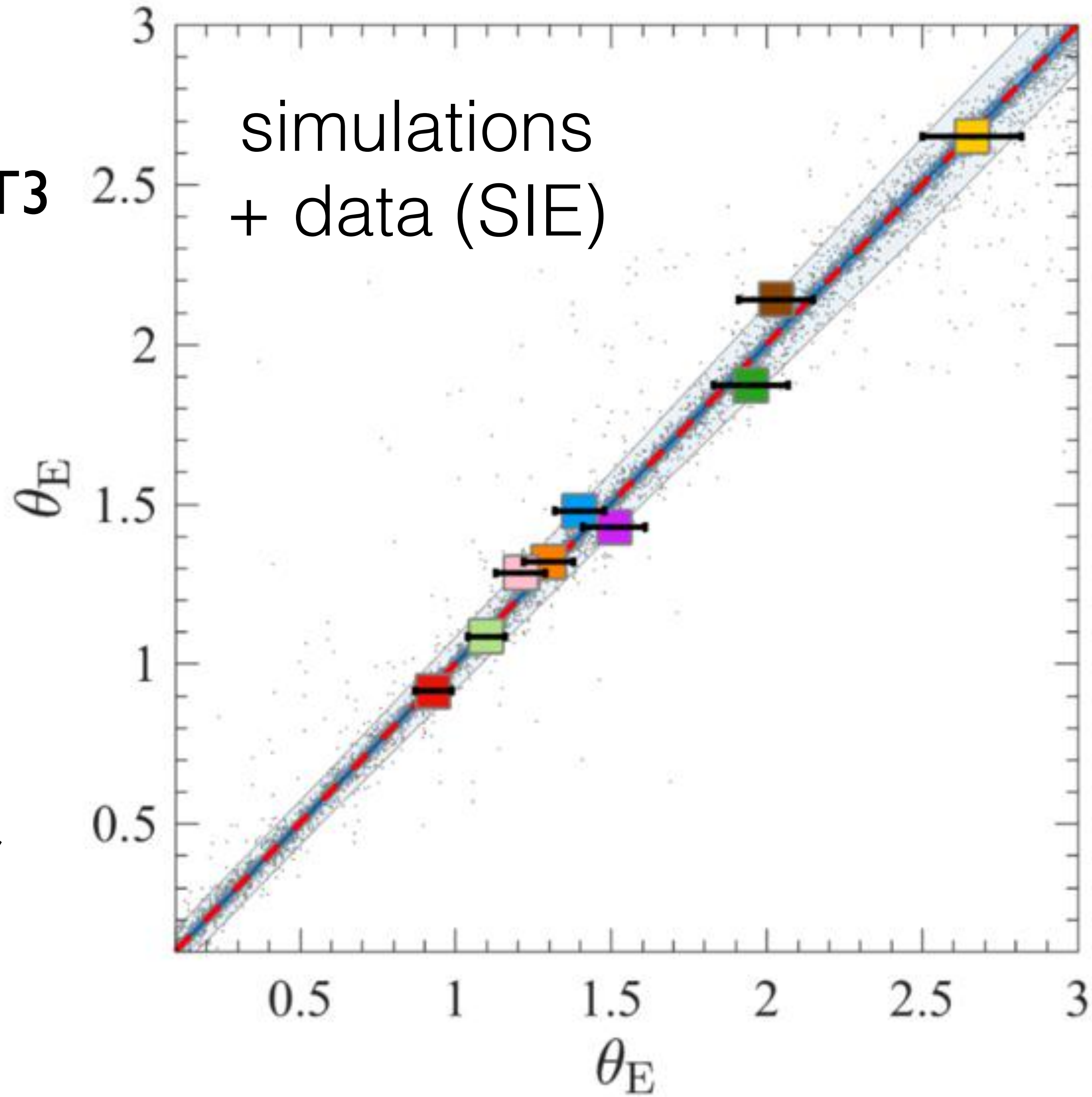
- Case 8: 4 CNNs with combinations of 3 filters + SVN
  - Training time: 680 s
  - Total Processing Time: 2h 30 min (for classifying 100k objects)
  - Area Under ROC: 84.08%
  - Third in the challenge

Metcalf, et al., arXiv:1802.03609



Recovering Einstein Ring Parameters

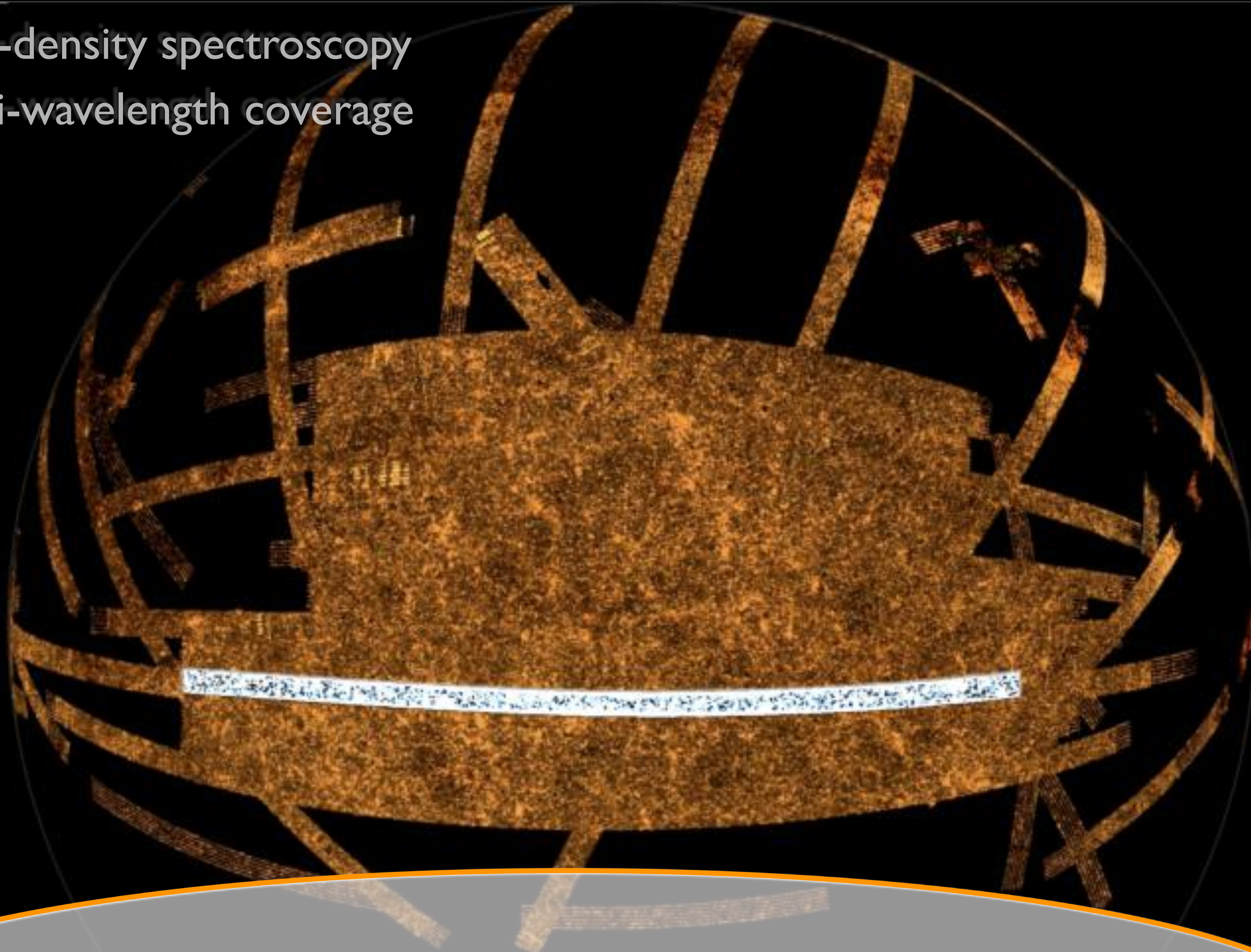
- Automated analysis of large datasets (e.g. LSST, Euclid)
- Sources: GalaxyZoo, GREAT3 + clumpy galaxies
- 500.000 system training set
- ICA to remove the lens galaxy
- Same precision as inverse modelling
- Convolutional Neural Networks (inception-v4 for no ICA)
- 10^8 times faster than ML
- Still need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



Hezaveh, Levasseur, Marshall, 2017, Nature

SDSS Stripe 82

- High-density spectroscopy
- Multi-wavelength coverage



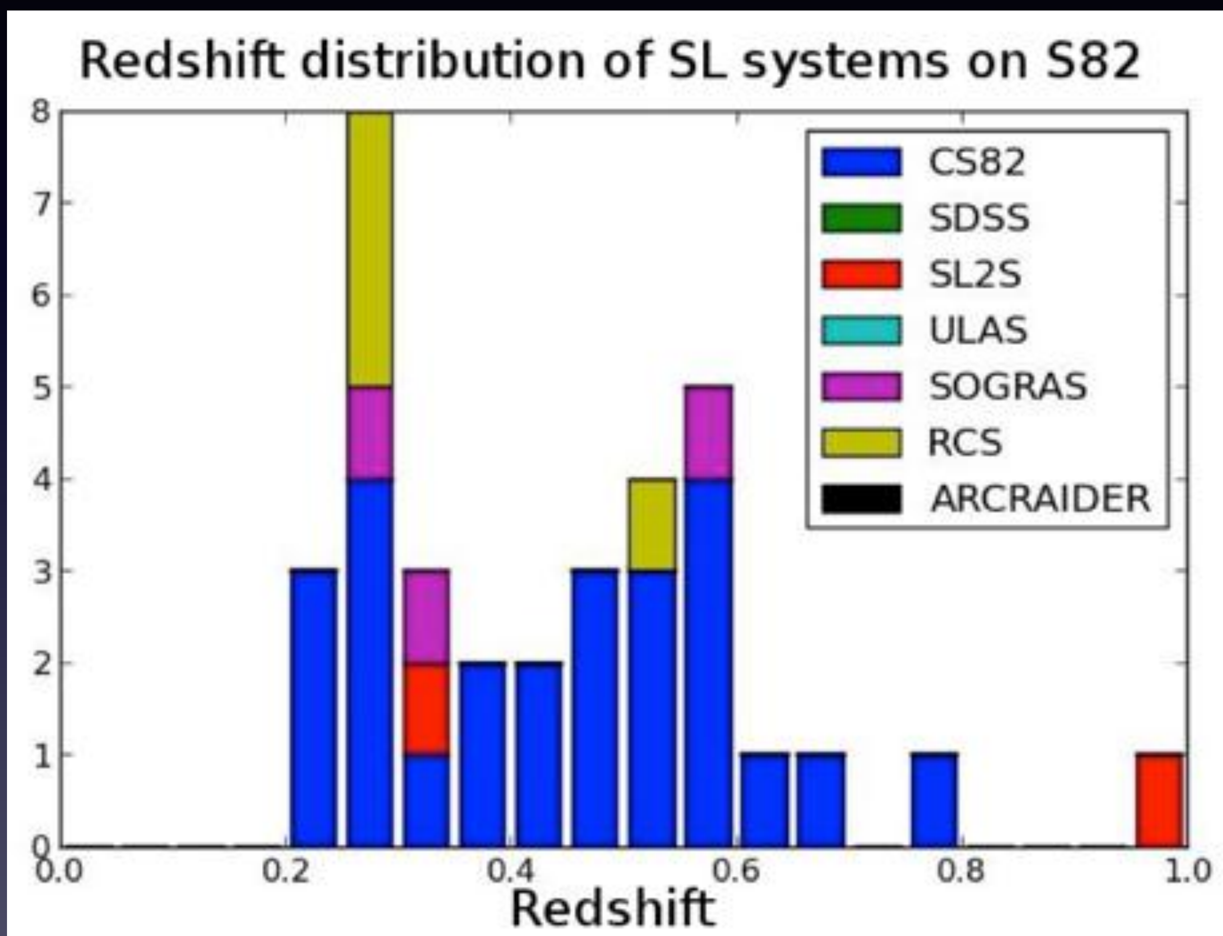
- CFHT Stripe 82 Survey (CS82): The weak lensing survey in S82
  - ✓ 170 deg2, down to i = 24 and superb median seeing of 0.6”

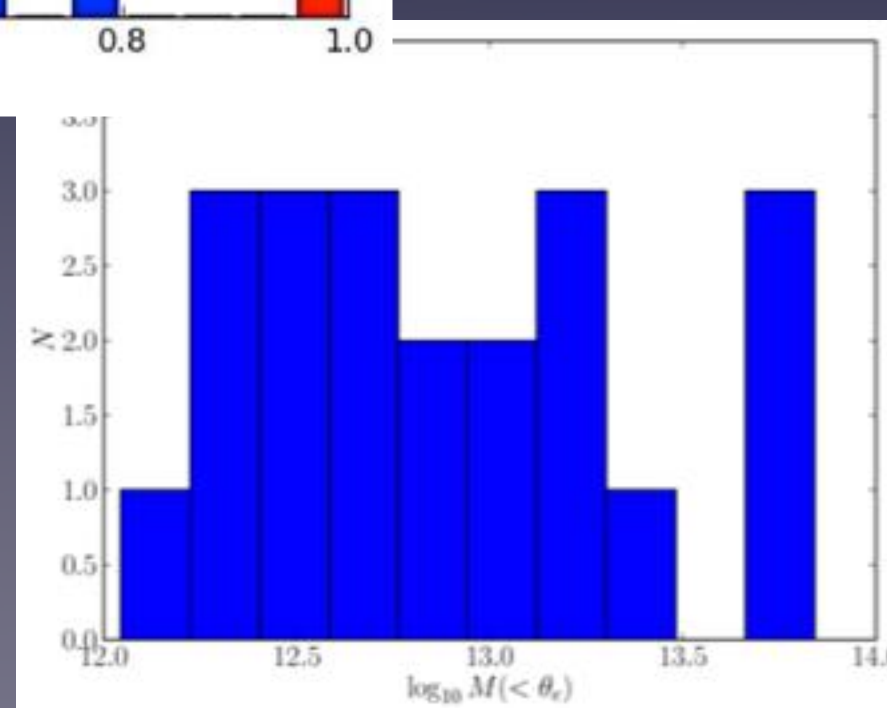
Semi-automated arcfinding

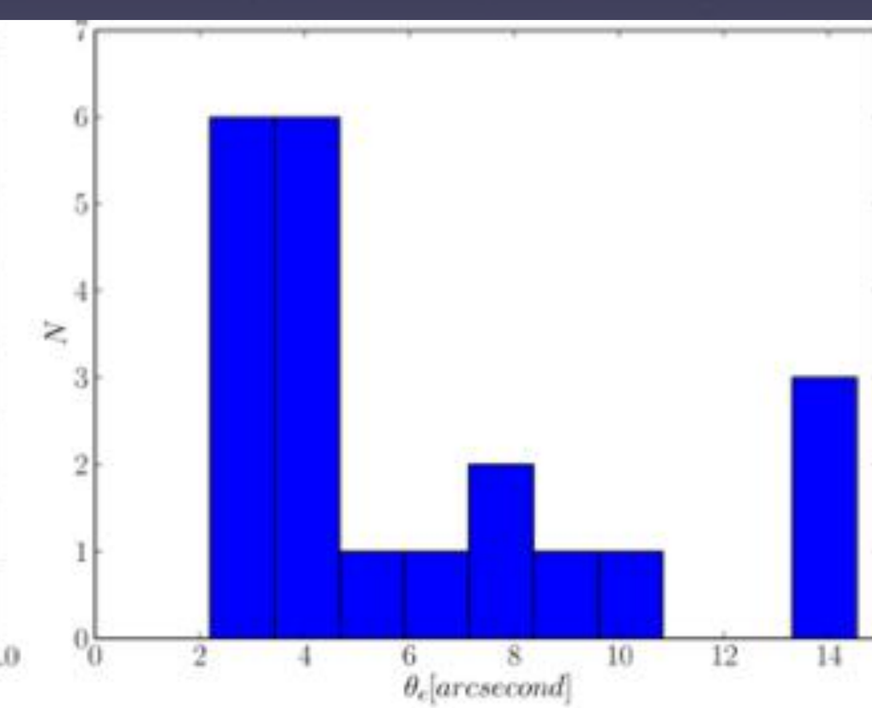
- More-Alard Arcfinder (More et al., arXiv:1109.1821)
- 127000 candidates visually inspected!
- 10 volunteers (every candidate inspected by 2 people)

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

CS82 Arc Candidates

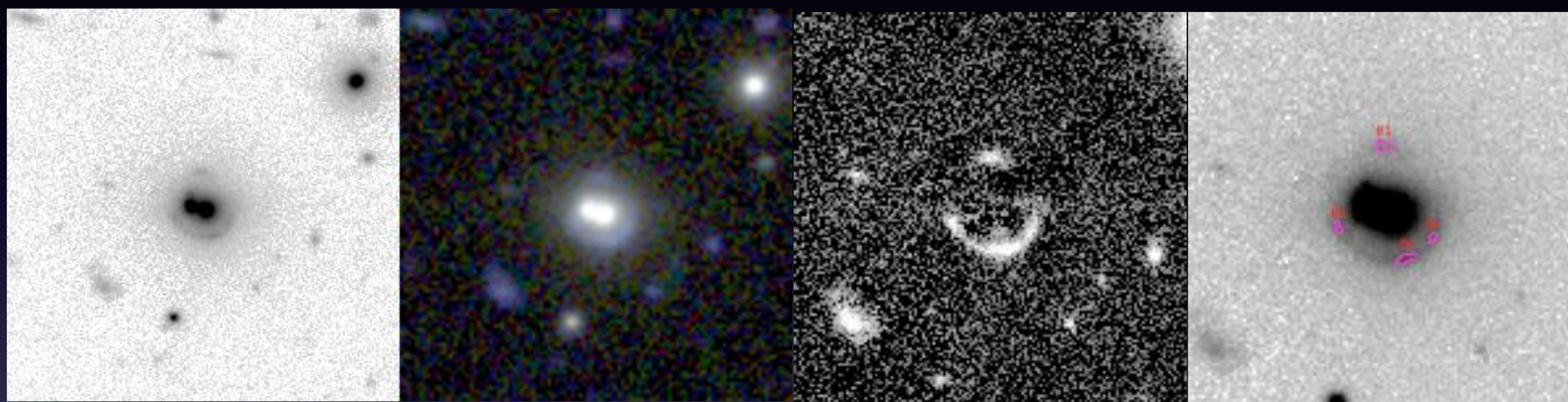






CS82 Einstein Rings

CS82SL01:36



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

Anna Niemiec

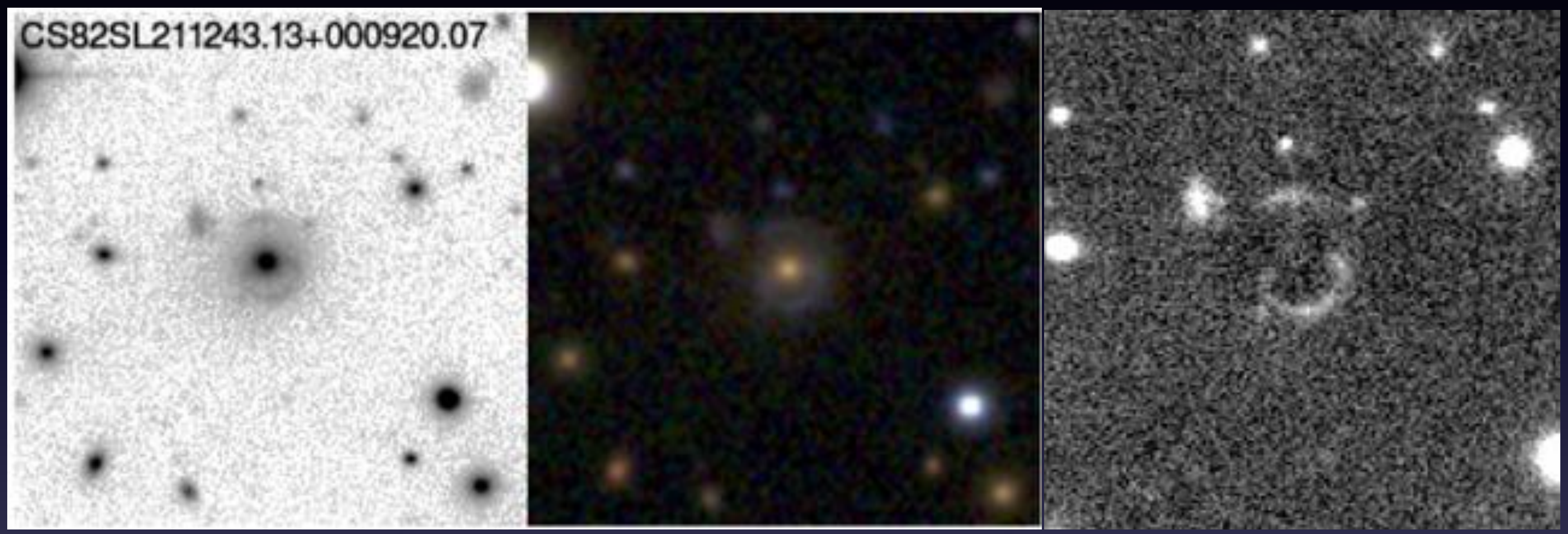
- $z_{spec} = 0.562$,
- $o_E = 2.54$''
- velocity dispersion:

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

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



Anna Niemiec

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

Concluding remarks

- Strong lensing is a useful cosmological and astrophysical observable, allowing one to study 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
- Analyses agree down to ~ 10 kph
- Current simulations seem OK for training arc finders and recovering the global properties of the systems
- Progress on pixel level simulation
- <u>Need reliable lens simulations for WDM, SIDM, MoG</u>
- Can ML measure substructure, constrain WDM, etc.?
- Very happy to collaborate!


Gracias!
Obrigado!