Testing General Relativity at Kiloparsec Scales with Gravitational Lenses

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Reuven Opher Workshop on Challenges of New Physics in Space

ICTP SAIFR International Centre for Theoretical Physics
South American Institute for Fundamental Research

Motivation

- Over two decades after its major discovery, the acceleration of the Universe remains one of the deepest mysteries of cosmology
- Cosmological constant fits most data, but Dark Energy and Modified Gravity are widely studied alternatives
- Modified gravity has a rich behavior: transition from GR on small to acceleration at large scales
- Constrain MoG on kiloparsec scales: strong lensing

One gravitational potential or two? Forecasts and tests

By Edmund Bertschinger*

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

conformal newtonian metric (choices and assumptions):

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

for General Relativity (for *standard* matter components) in general

$$\Phi = \Psi$$

slip parameter

$$\gamma = \frac{\Phi}{\Psi}$$

$\gamma = 1$ compatible with GR

$\gamma \neq 1$ GR ruled out

(see poster/video by D. Rodrigues and J. Toniato)

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geodesics

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

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

on ~ 100 kph galaxy scales

kinematics: Φ

from galaxy velocity dispersion

deflection angle: $\Phi + \Psi$

from strong lensing

Basic picture

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

slip parameter
$$\gamma = \frac{\Phi}{\Psi}$$

Observed stellar velocity dispersion $\sigma_{\rm obs}$ probes Φ

Lensing yields $\sigma^2_{\rm lens}$ from $\Phi + \Psi$: $\sigma^2_{\rm lens} = \left(\frac{1+\gamma}{2}\right)\sigma^2_{\rm obs}$

Einstein radius $\theta_E = 4\pi\sigma^2_{\rm obs}\left(\frac{1+\gamma}{2}\right)\frac{D_{LS}}{D_S}$

Measure velocity dispersion + rings ➔ Limit on gravity

(need z_L and z_S ,which is hard to obtain!)

Real life:

- Non isothermal elliptical models
- Anisotropic velocity dispersion (assumptions)
- Seeing and aperture corrections

State-of-the-art@2021

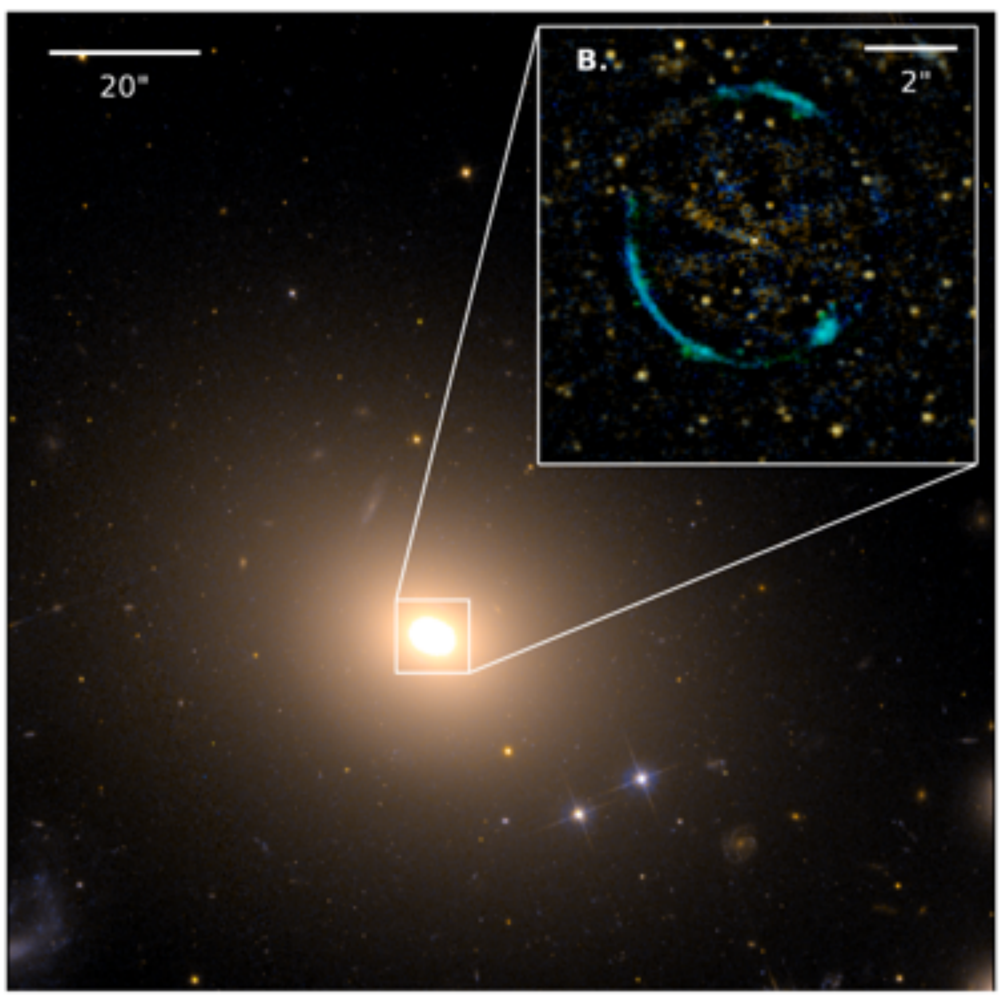
Combining dynamics and lensing

Detailed kinematical analysis: MUSE@VLT

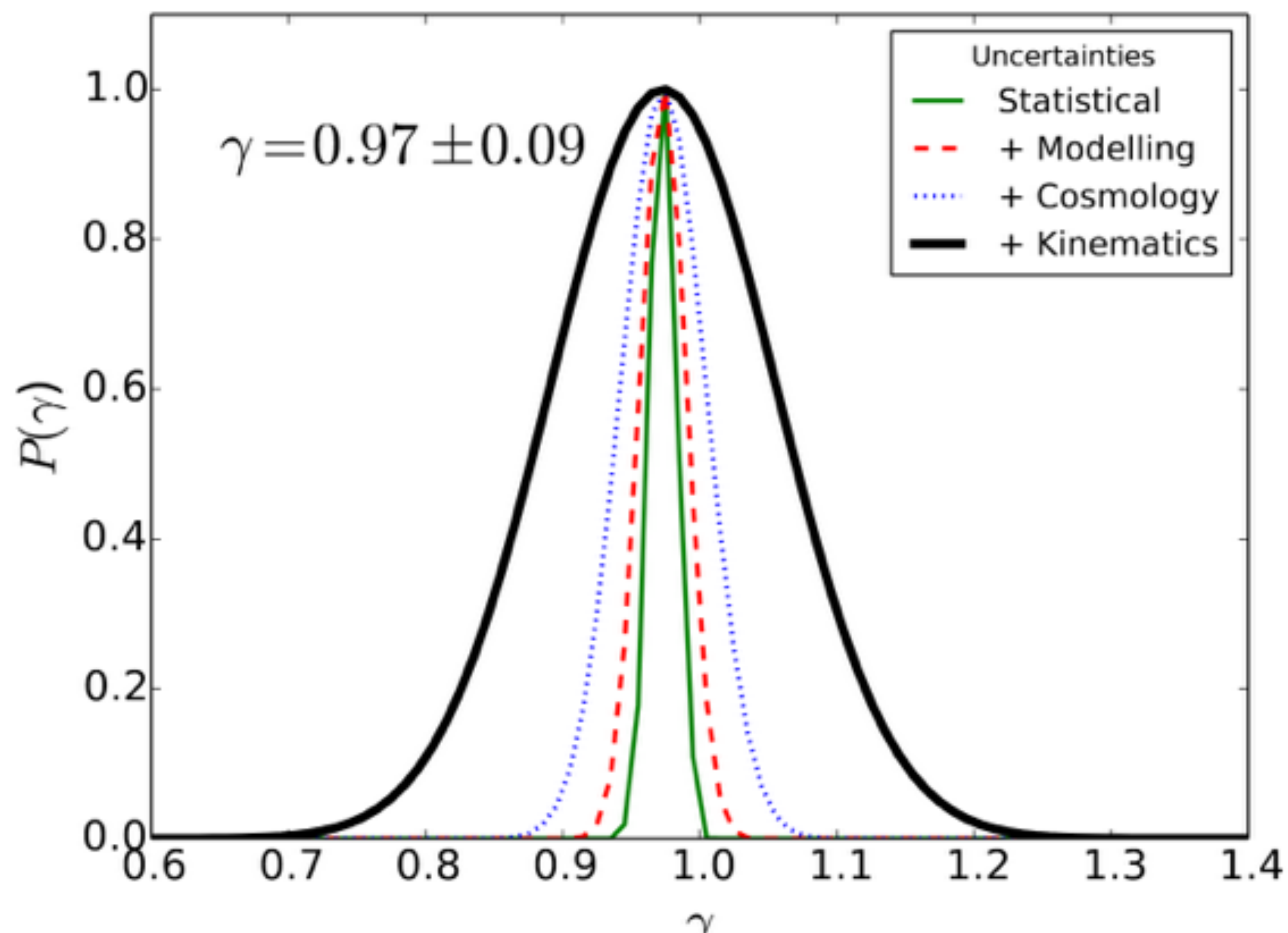
Detailed strong lensing modelling: HST imaging

A single system at low redshift! (z ~ 0.04)

HST+ MUSE



Einstein Ring ESO 325-G004



Collet et al, 2018, Science

State-of-the-art@2021

A single system at low redshift! ($z_L \sim 0.04$)

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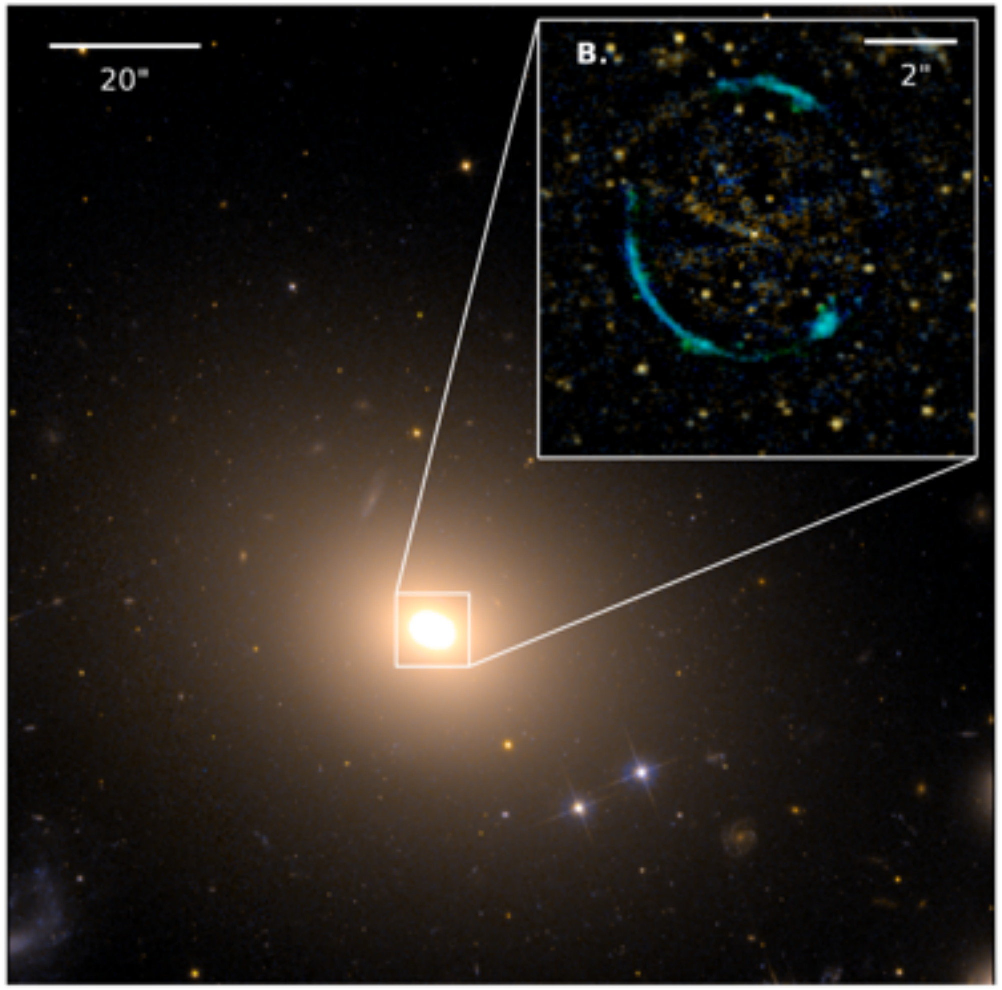


Collet et al, 2018, Science

$\gamma = 0.97 \pm 0.09$

A (heterogeneous) collection of ~ 100 systems ($z_L \sim 0.05$ - 1)

Single value of velocity dispersion

- Averaged within the fiber/slit
- Luminosity and velocity dispersion profiles

$$\rho(r) = \rho_0 \left(\frac{r}{r_0}\right)^{-\alpha}, \quad \nu(r) = \nu_0 \left(\frac{r}{r_0}\right)^{-\delta}$$

$$\beta(r) := 1 - \frac{\sigma_t^2}{\sigma_r^2}$$

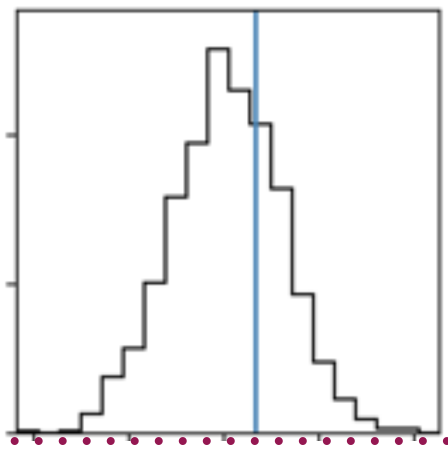
25% systematics!!

Cao et al. 2017

$\gamma = 0.995^{+0.037}_{-0.047}$

Archival Data

Crisnejo et al.



From (beta, public) “masterlens” catalog of 8577 SL systems

Galaxy-Galaxy systems, with known z_L, z_S , σ_v and lens modelling

Restrict to systems with $z_S < 1.5$: total of 110 systems

Run “machinery” (as in Schwab+2010, Cao+2017)

Includes:

- Anisotropic velocity dispersion

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

seeing and fiber/slit

ts

sity profile $\rho(r) \propto r^{-\alpha}$

Priors on $\beta = 0.180^{+0.014}_{-0.014}$ $\alpha = 1.995^{+0.009}_{-0.009}$

- Totally “blind analysis”
- Power *and danger* of “gamma-machine”!
- Prone to *confirmation bias*
- Revisit every single step, from modelling to data, to test for systematics

Slip parameter

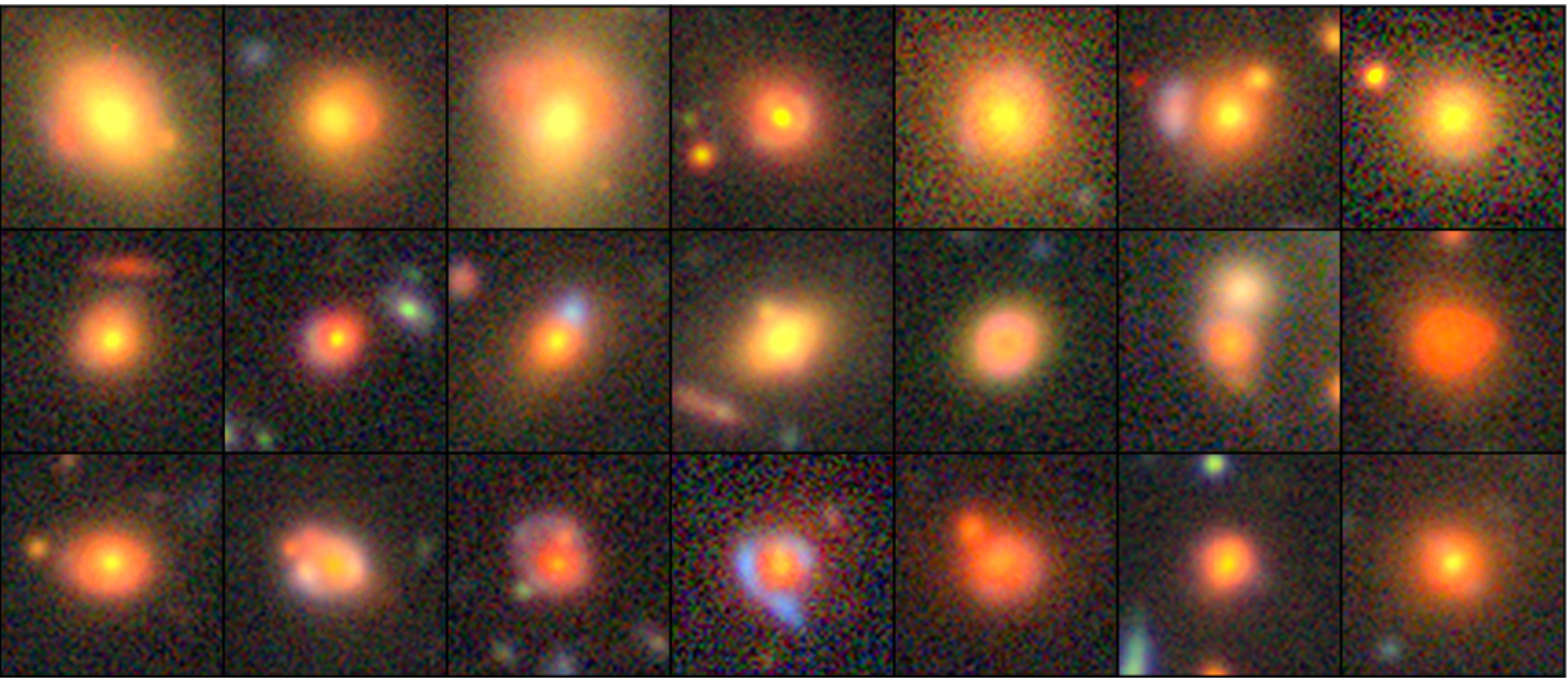
$$\gamma = 1.001^{+0.022}_{-0.023}$$

Improving statistics: finding new systems

Catalog from **S**pectroscopic **I**dentification of **L**ensing **O**bjects (Talbot et al. 2020)
+ Inspection on Hyper Suprime Cam images (+ DES, DECaLS, SDSS)

Found ~ 40 excellent systems, some in SuGOHI sample

Have z_L, z_S , and the coarse σ_v. "Only" needs SL modelling (+galaxy subtraction)



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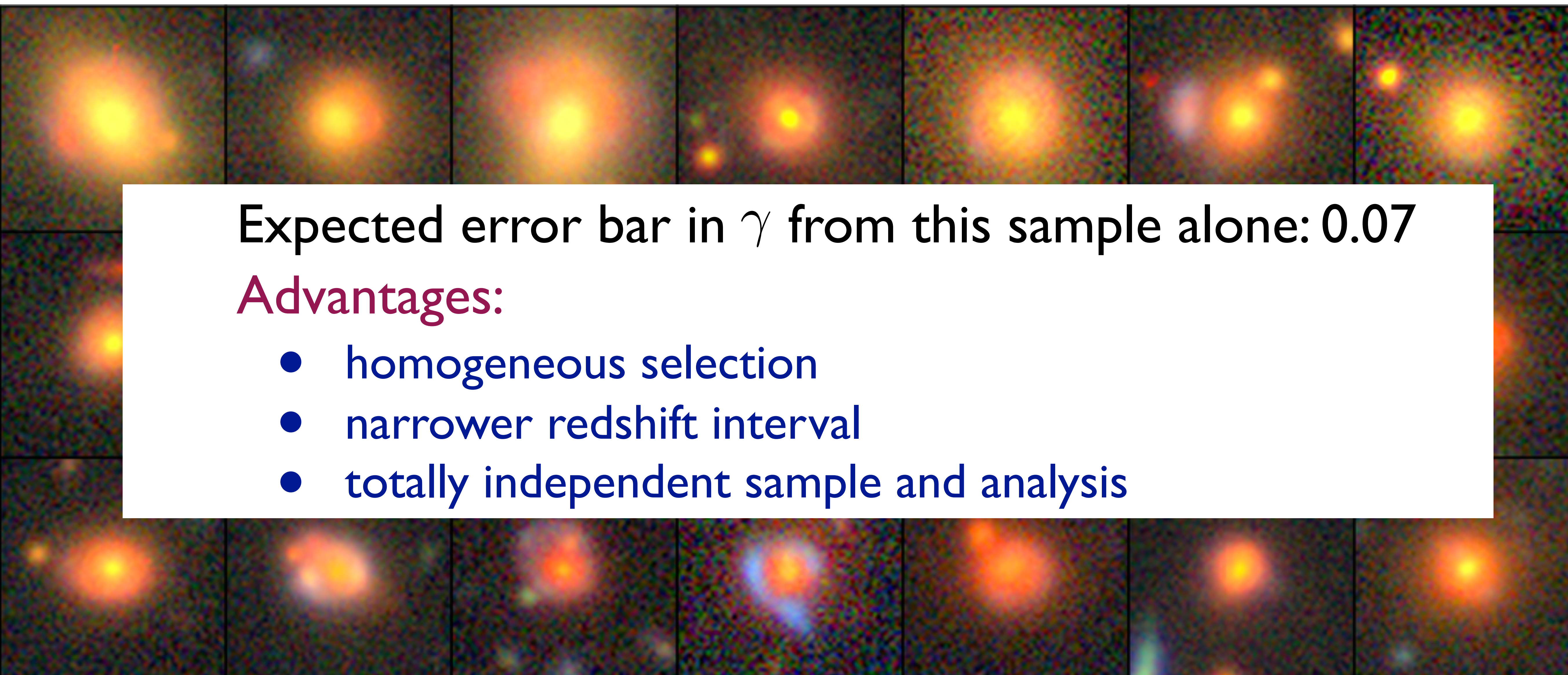


Expected error bar in γ from this sample alone: 0.07

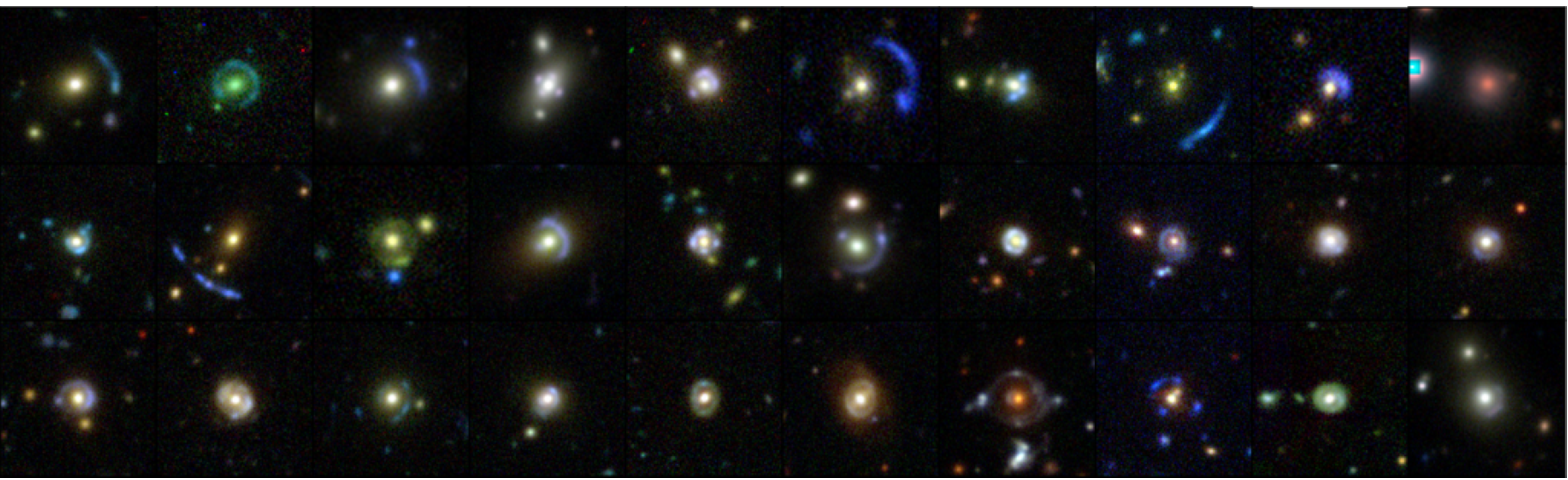
Advantages:

- homogeneous selection
- narrower redshift interval
- totally independent sample and analysis

Improving statistics: finding new systems

Seeking confirmation of Strong Lensing Systems identified in the wide-field imaging surveys (HSC, DES, DECaLS, KiDS, +) [compilation by Alves et al.]

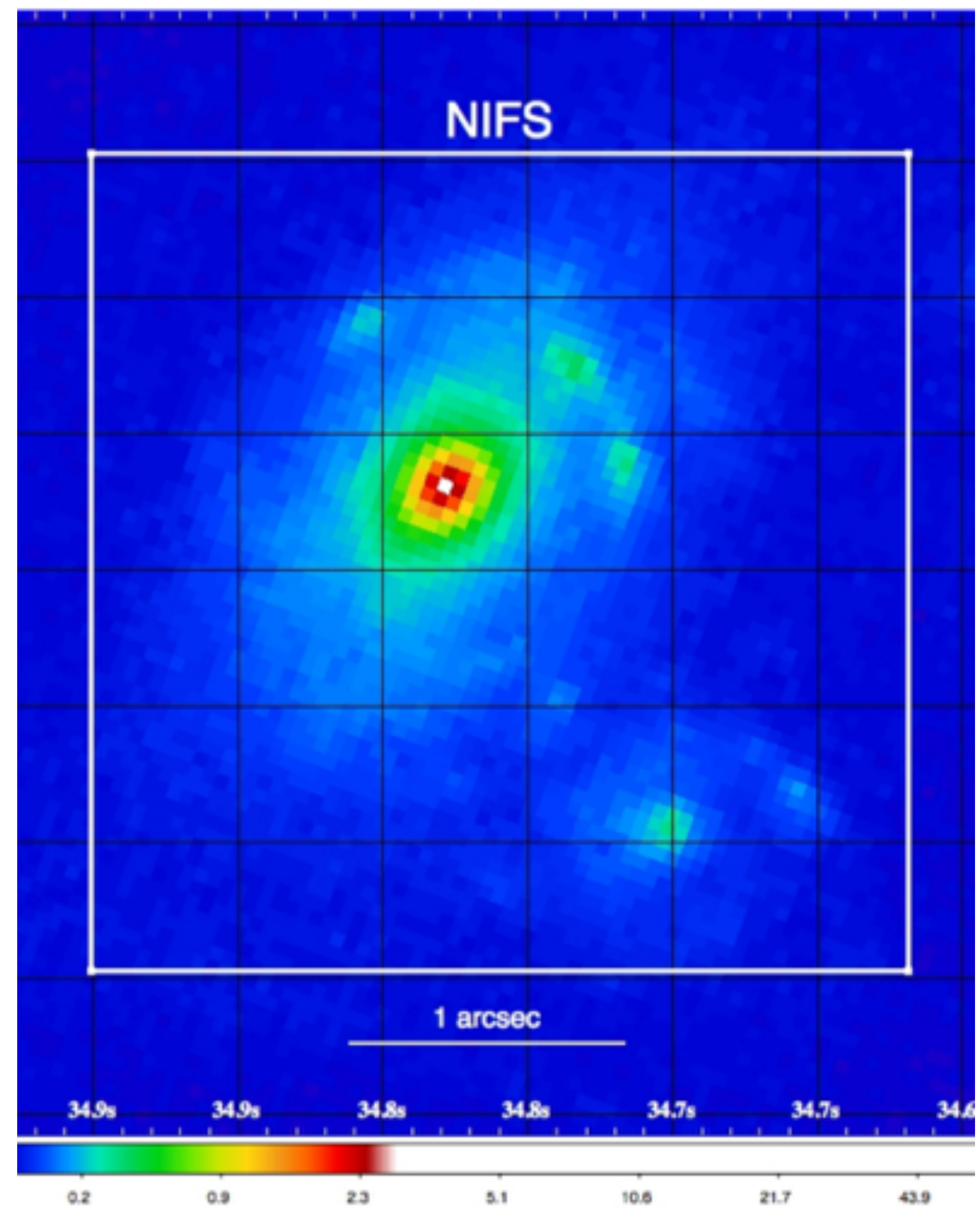
Proposal for CASLEO (2022A):
found ~ 30 excellent systems from their morphology
Seeking to obtain z_S from emission lines



If successful, go to large telescope (e.g. SOAR, Gemini), to obtain σ_v

Improving systematics: resolved kinematics

- More typical system for this analysis:
  lens redshift and Einstein radius x galaxy size
- Pilot program:
  Diffraction limited IFU spectroscopy in the IR with NIFS + ALTAIR LGS @Gemini (GN2021B-010)
- System SDSS J0747+4448
- $z_L \sim 0.4$, $z_S \sim 0.9$
- from BELLS
- HST imaging
- Expected 0.1" FWHM
- Resolve ~ 40 pc at the source!



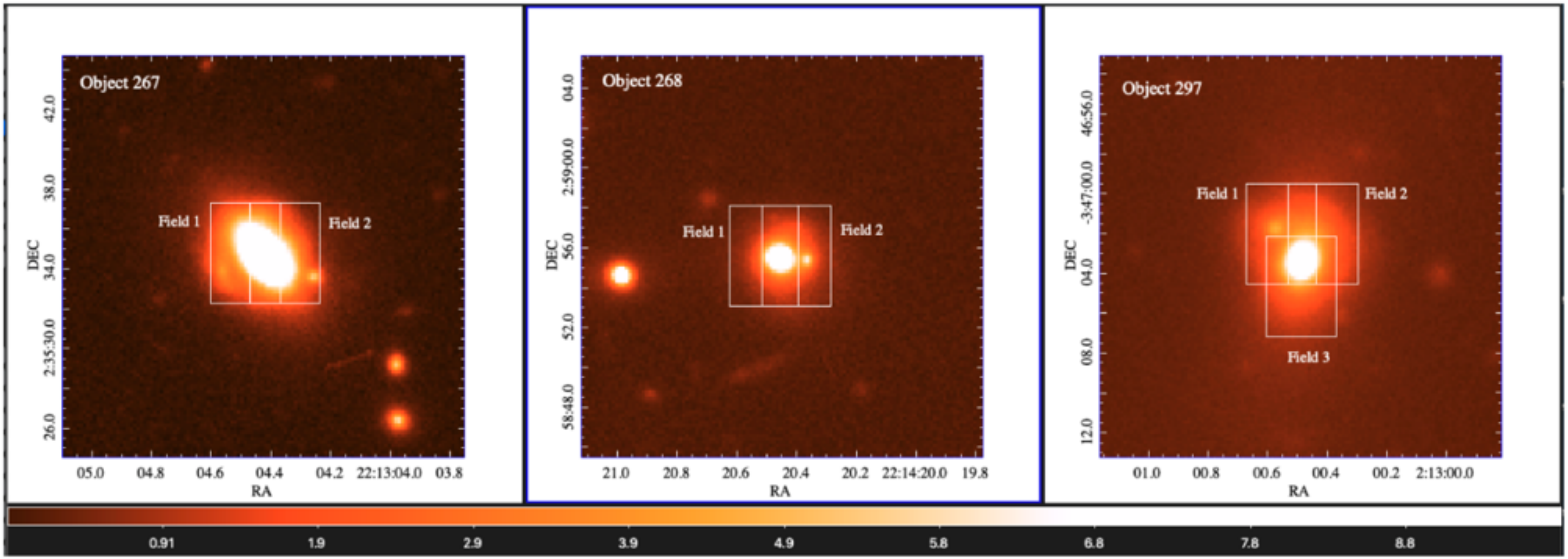
"the cursed proposal"…

A new regime

- Obtain spatially resolved spectral observations for higher redshift systems
  - few arcsec: natural seeing allows for a coarse angular and radial measurement of the velocity dispersion
  - disentangle and improve S/N of source
  - high S/N spectrum of the lens
  - address the systematics on the kinematics
  - improve the strong lensing modelling
- Many objects are perfect for the Gemini GMOS/IFU fov!
  - pilot program for Gemini for 2021B: 3 systems

A new regime

- Obtain spatially resolved spectral observations



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A new regime

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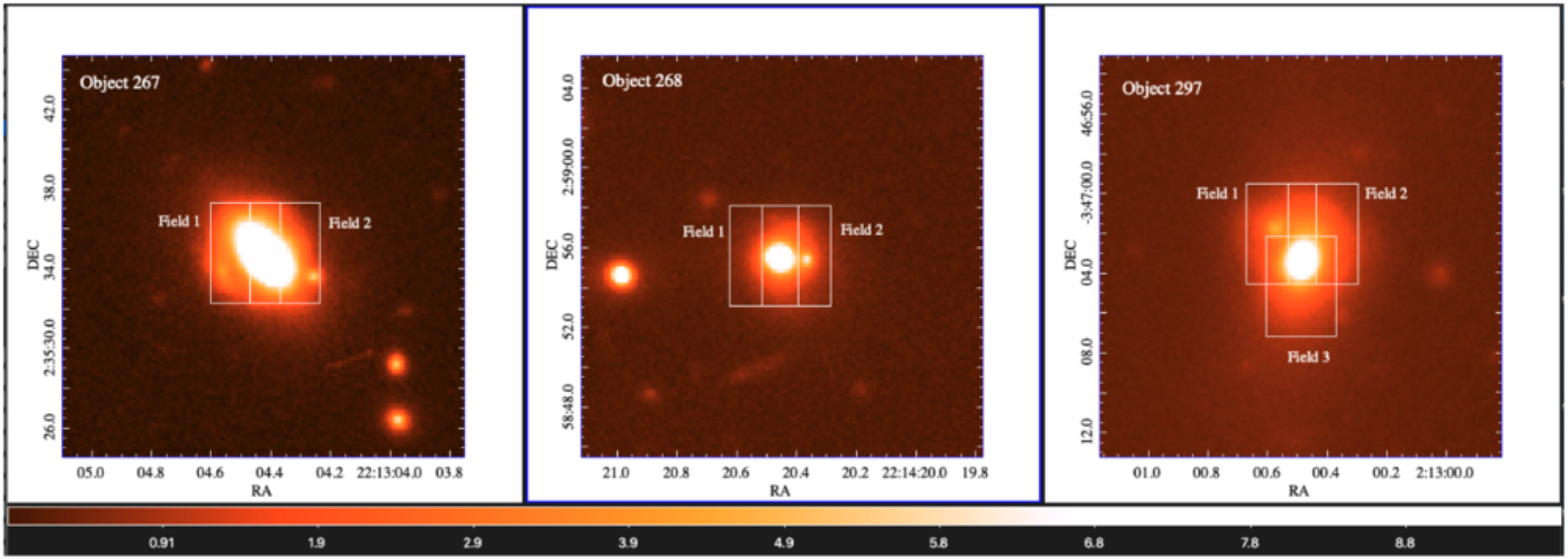


- Expected statistical uncertainty in γ from the 3 systems with the standard analysis: ~ 0.1
  - Most important: study of systematics

Pilot program of the pilot program: in the queue for this month (FT)!

Future surveys (**Rubin**/Roman/Euclid): need automated identification **and** modelling

Gravitational Lens Finding Challenge 2

- Euclid-like simulations
- 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)

Future surveys (**Rubin**/Roman/Euclid): need automated identification **and** modelling

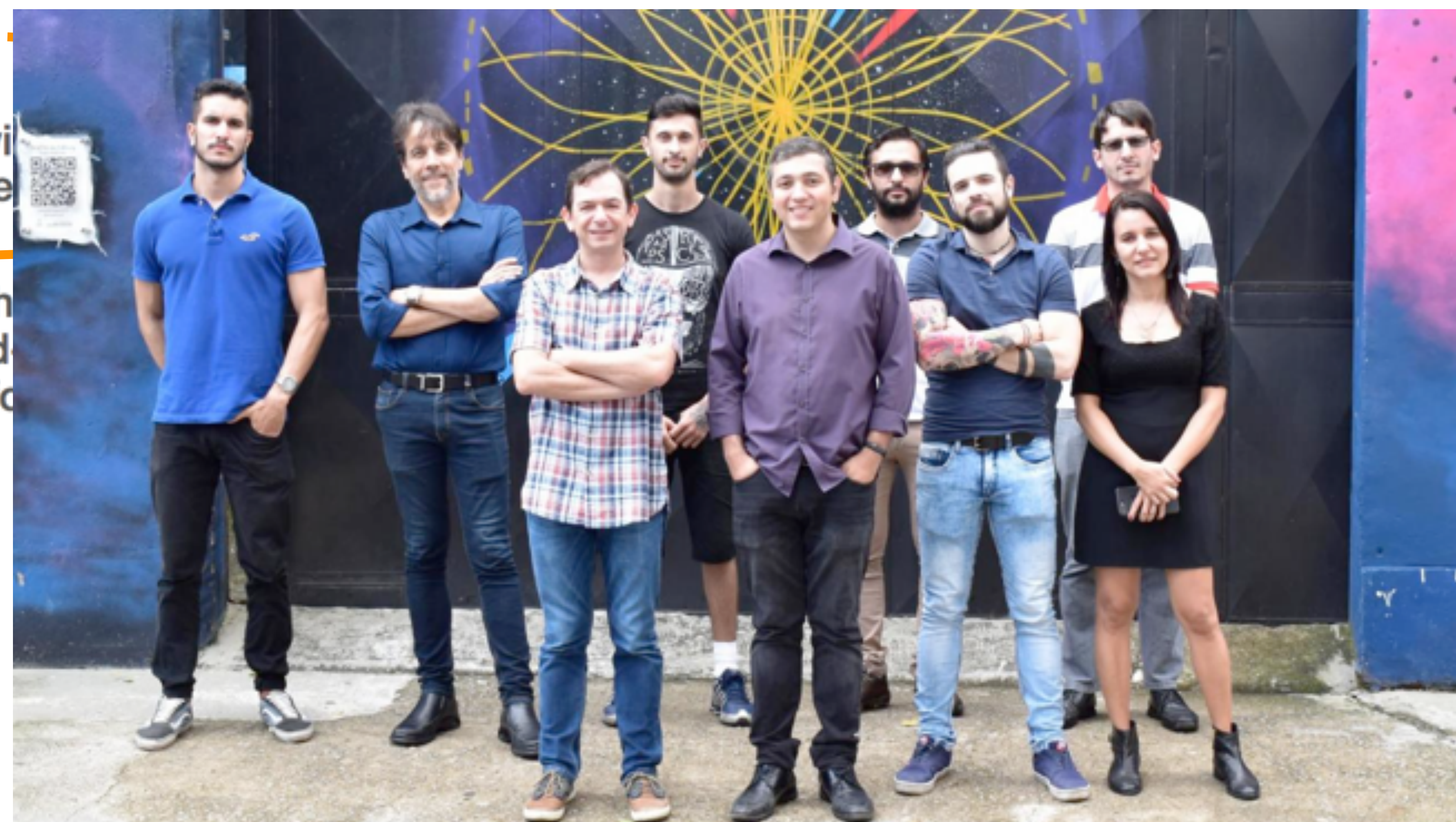
Gravitational Lens Finding Challenge 2

- Euclid-like simulations
- Submitted 4 classification and 2 regression entries (measuring Einstein radius)

Challenge 2.0

Update Feb. 28, 2020 We have a wi
Congratulations to them and everyone
follow...

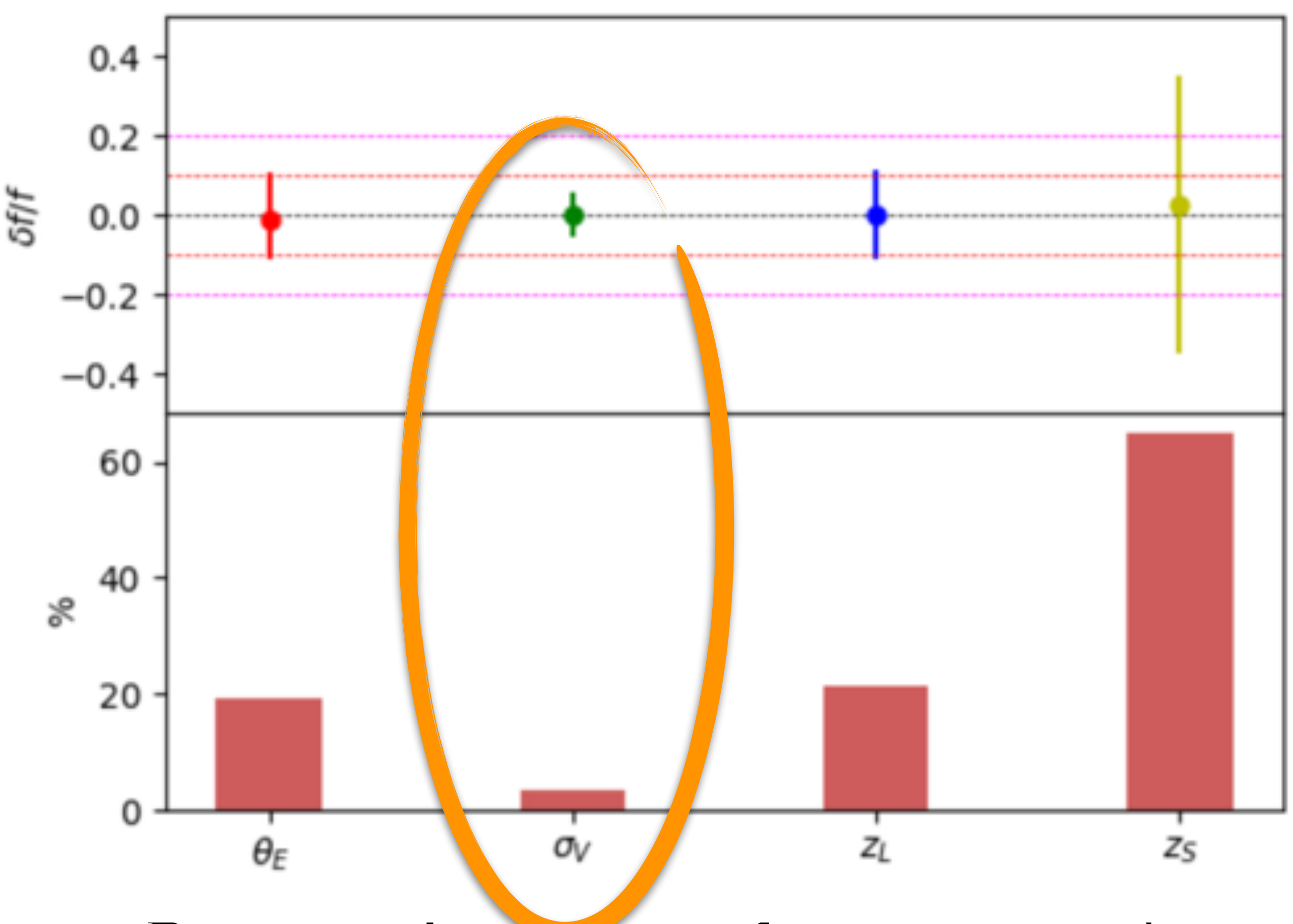
Challenge 2.0 is an improvement in th
challenge concentrates only on Euclid
pixels sizes are 0.1'' for VIS and 0.3'' fo
images in each band.



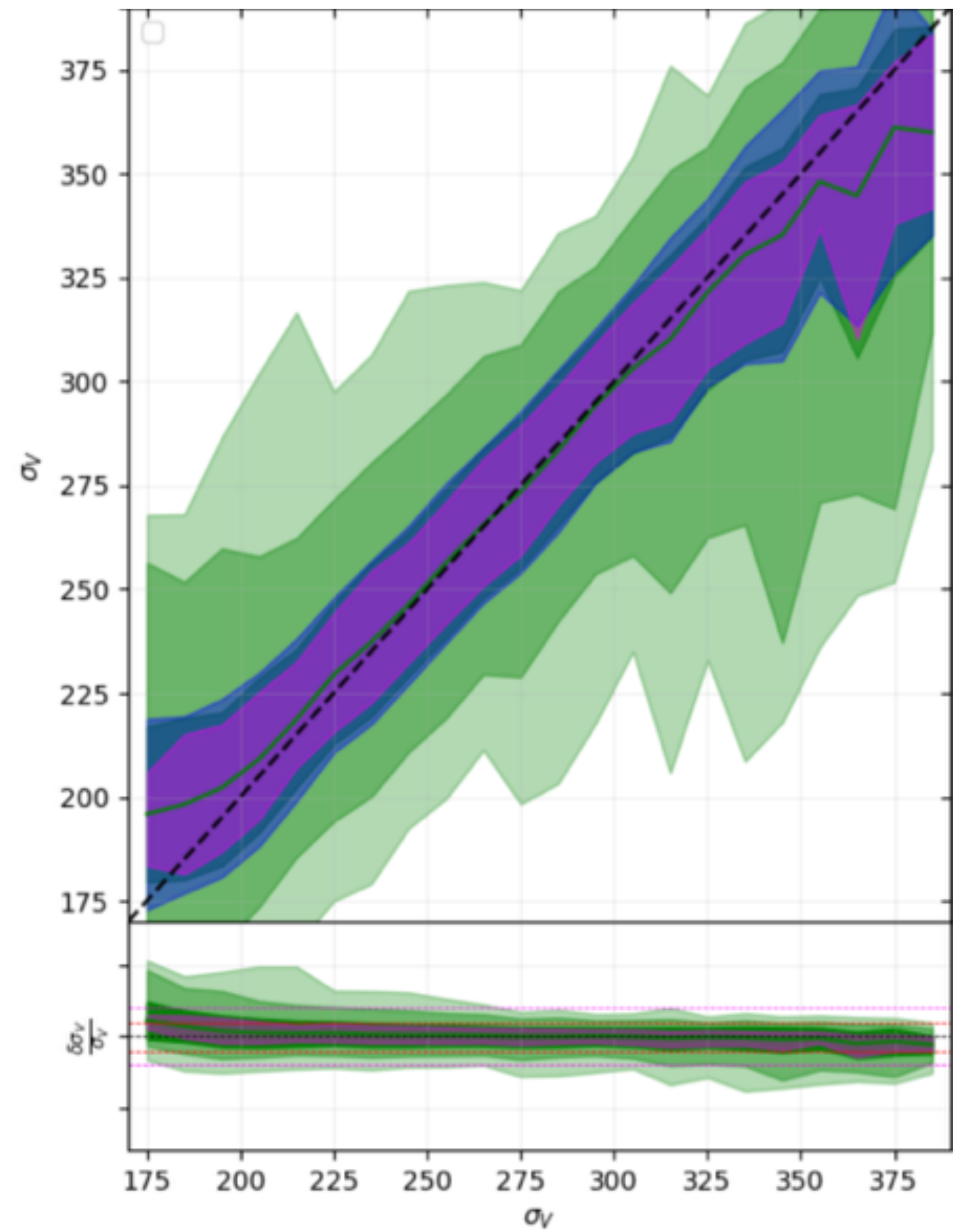
Best result, 4 entries
out of the 6/7 best
Good regression results

Which parameters can we recover with ML?

- Only photometry (3 bands)
- Lenspop (Collet 2015) **simulations**
    - SIE, instrument (DES conditions)
    - ~1860 mock DES-observable systems
- Inception Neural Network



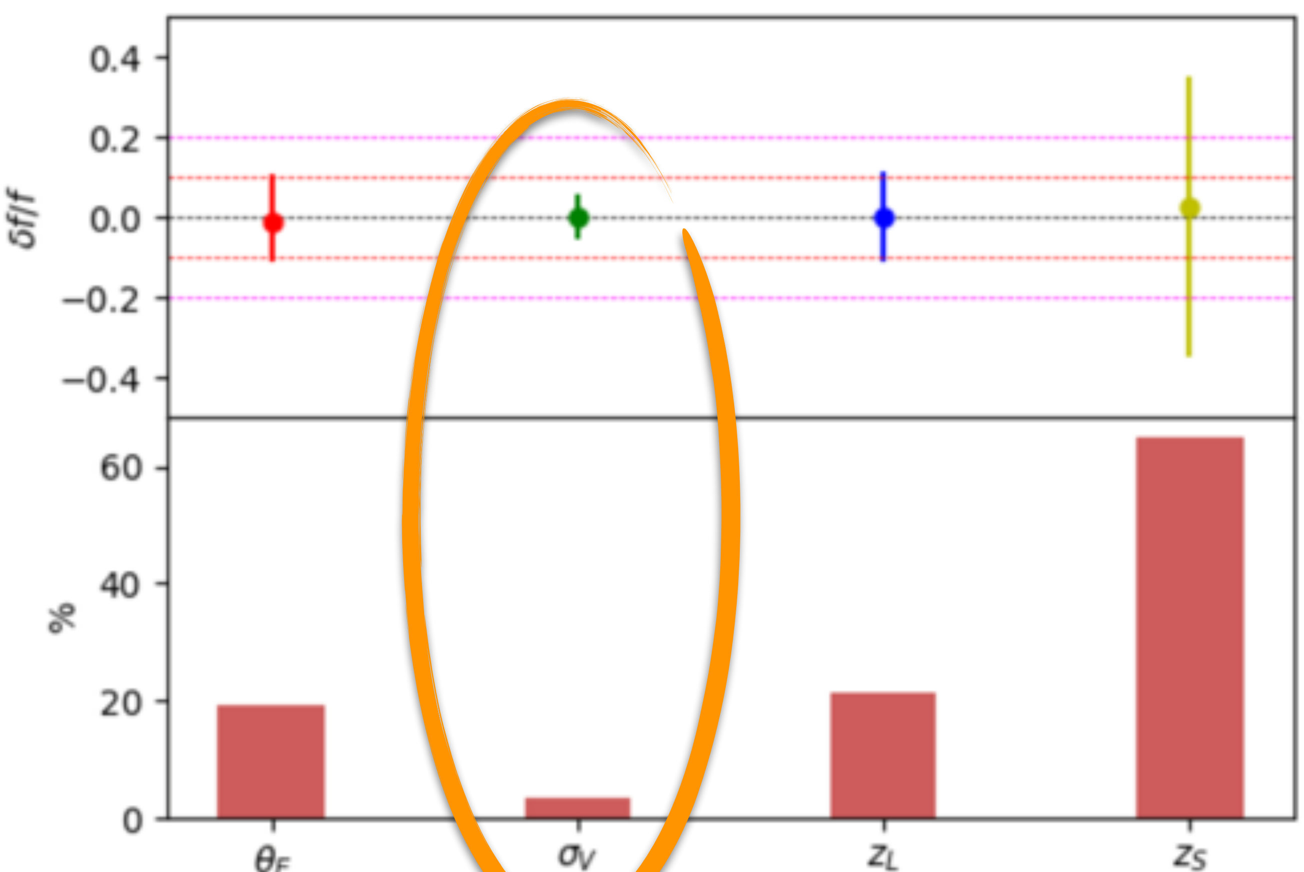
Recover simultaneously $z_L, z_S,$ and σ_v



Bom et al., 2019, arXiv:1911.06341

Can we measure the slip from systems modelled using Machine Learning?

- Only photometry (3 bands)
- Lenspop (Collet 2015) simulations
  - SIE, instrument (DES conditions)
  - run in ~ 1860 mock DES-observable systems
- Inception Neural Network



$0.6 < \theta_E < 3.1$ Bom et al., 2019

Simulated velocity dispersion sample:

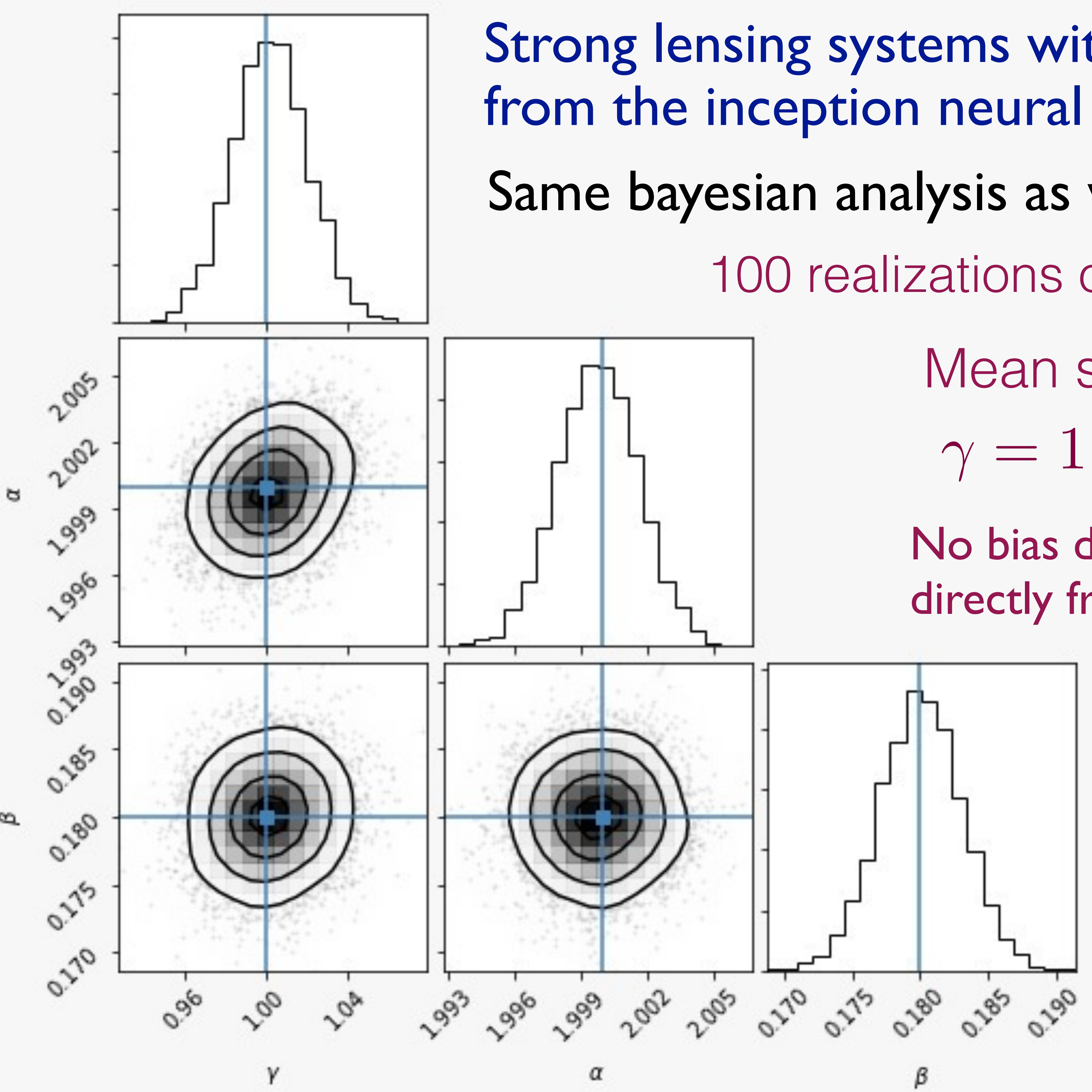
- Assumes $\gamma = 1$
- From true redshifts and Einstein radii generates (fake) velocity dispersion using previous modelling and assuming a Gaussian distribution
- Run for the sample of ~ 1500 simulated arcs with

$$0.8'' < \theta_E < 2.0''$$

- Analyse parameters recovered from the ML (θ_E, z_L and z_S) and the simulated velocity dispersions as data

Results

Crisnejo, MM, Bom, in prep.



Strong lensing systems with parameters recovered from the inception neural network

Same bayesian analysis as with the real data

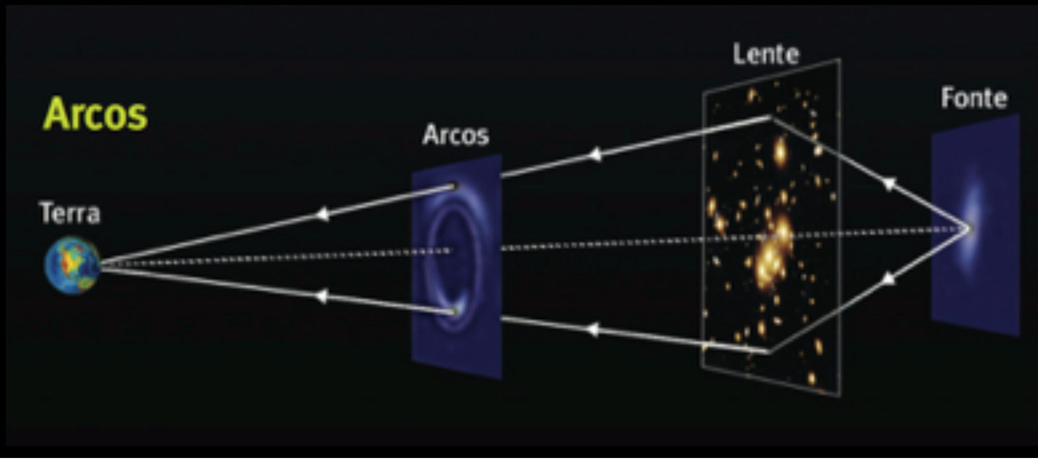
100 realizations of the simulated sample

Mean slip parameter

$$\gamma = 1.003 \pm 0.019$$

No bias despite using (θ_E, z_L and z_S) directly from the ML!

- Constraints on modified gravity from an (almost) end-to-end analysis using Machine Learning
- Towards a fully automated modified gravity test!
- No need of z_S (?!)



Take aways

slip parameter

$$\gamma = \frac{\Phi}{\Psi}$$

- *Galaxy-galaxy SL + stellar kinematics:* testing MoG at ~ 100 kpc
- Measure the slip parameter in 3 regimes:
  - Coarse: systems with a single measurement of velocity dispersion
    - Archival data agrees with current estimates and GR [OK]
    - New confirmed systems [modelling in progress]
    - Compilation of known systems + wide field surveys [observing for z_S]
    - Rubin/Roman/Euclid $O(10^4)$: use DL to find **and** model the systems (+ massive spectroscopy) [promising]
  - Natural seeing IFU data [2022B?]
    - possible for $O(10^2)$ systems
    - better handling of kinematics systematics
    - separation lens/source of spectra
  - IFU + AO, possible for O(10) systems, pathfinder in IR [2021B]
- Towards precise and robust measurements of slip with strong lenses
- Testing other aspects of MoG? Modifications of Jeans equation…


Thank you

Galaxy kinematics

The Jeans equation described the motion of a collection of stars. In spherical symmetry,

$$\frac{d}{dr}\left(\nu(r)\sigma_r^2(r)\right) + \frac{2\beta(r)}{r}\nu(r)\sigma_r^2(r) = \nu(r)\frac{d\Phi}{dr},$$

where

$$\frac{d\Phi}{dr} = \frac{GM(r)}{r^2}, \quad \beta(r) := 1 - \frac{\sigma_t^2}{\sigma_r^2},$$

where $M(r)$ is the total mass inside a sphere of radius r.
For $\beta =$ constant,

$$\sigma_r^2(r) = \frac{G}{r^{2\beta}\nu(r)} \int_r^\infty (r')^{2\beta-2}\nu(r')M(r')dr'.$$

The total mass contained within a sphere with radius r is,

$$M(r) = 4\pi \int_0^r (r')^2 \rho(r')dr' = 4\pi \frac{r^{(3-\alpha)}}{3-\alpha}\frac{\rho_0}{r_0^{-\alpha}}$$

The actual velocity dispersion measured by observations is given by,

$$\bar{\sigma}_*^2 := \frac{\int_0^\infty dR R w(R) \int_{-\infty}^\infty dz \nu(r) \left(1 - \beta \frac{R^2}{r^2}\right) \sigma_r^2(r)}{\int_0^\infty dR R w(R) \int_{-\infty}^\infty dz \nu(r)},$$

where $w(R)$ is the convolution of the atmospheric seeing σ_{atm} and fiber aperture θ_{ap}.

$$\bar{\sigma}_*^2 = \left[\frac{2}{1+\gamma}\frac{c^2}{4}\frac{D_S}{D_{LS}}\theta_E\right]\frac{2}{\sqrt{\pi}}\frac{(2\tilde{\sigma}_{\mathsf{atm}}^2/\theta_E^2)^{1-\alpha/2}}{\xi - 2\beta} \times \left[\frac{\lambda(\xi) - \beta\lambda(\xi+2)}{\lambda(\alpha)\lambda(\delta)}\right]\frac{\Gamma(\frac{3-\xi}{2})}{\Gamma(\frac{3-\delta}{2})},$$

where

$$\tilde{\sigma}_{\mathsf{atm}} \approx \sigma_{\mathsf{atm}}\sqrt{1 + \chi^2/4 + \chi^4/40}, \quad \chi = \theta_{\mathsf{ap}}/\sigma_{\mathsf{atm}}.$$