Does General Relativity hold in galactic scales? A test at a z~0.3 elliptical lens galaxy

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01
The goal

Test GR predictions on galactic scales

02
How do we do that?

Measuring the galaxy mass through strong gravitational lensing and galactic dynamics. At the same time!

03
What have we concluded?

GR still holds!

Some of the GR tests so far

- Deflection of light by the Sun - (e.g. Dyson; Eddington; Davidson 1920)
- Time delay using Cassini spacecraft - (Bertotti; Iess; Tortora 2003)
- The Cosmic Microwave Background - (e.g. Planck Collaboration et al. 2014)
- Event Horizon Telescope - (Event Horizon Telescope Collaboration et al. 2019)
- … - (e.g. Baker; Psaltis; Skordis, 2015)

- Lensing + Kinematics - (e.g. Schwab et al. 2010; Cao et al. 2017; Yang et al. 2020)
- Lensing + Spatially resolved kinematics - (Collett et al. 2018)
- Lensing + Galaxy cluster kinematics - (Pizzuti et al. 2016)

Linearly perturbed cosmological *metric*

$$dS^2 = -(1 + 2\frac{\Phi}{c^2})c^2dt^2 + (1 - 2\frac{\Psi}{c^2})h_{ij}dx^i dx^j$$

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

GR
+
Vanish anisotropic stress tensor

$$\eta = 1$$

Assumptions

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

1. The space-time metric is given by the linearly perturbed line element, which is in the Newtonian gauge and considers only scalar perturbations;
2. There is a well-defined Newtonian limit, where the potentials Φ and Ψ still follow the Poisson equation;
3. The gravitational slip parameter is constant on the relevant scales being studied;

How we measure the slip parameter?

Constrained by gravitational lensing and sensitive to Newtonian and Curvature potentials.

$$M_{\rm dyn} = \frac{1+\eta}{2} M_{\rm lens}^{\rm GR}$$

Constrained by the stellar motion, and only sensible to the Newtonian potential.

Ingredients

Jeans Equations
- Collisionless system
- Steady-state
- Axisymmetric configuration

Lens Equation
- Thin lens approximation

$$\overline{v_z^2} = \frac{1}{\nu(R,z)} \int_z^{\infty} dz' \, \nu(R,z') \frac{\partial \Phi(R,z')}{dz'}$$

$$\overline{v_\phi^2} = \overline{v_R^2} + \frac{R}{\nu} \frac{\partial(\nu(R,z)\,\overline{v_R^2})}{\partial R} + R \frac{\partial \Phi(R,z)}{dR}$$

$$\beta = \theta - \alpha(\theta)$$

$$\alpha(\theta) \equiv \frac{D_{LS}}{D_S} \tilde{\alpha}(D_L \theta)$$

$$\tilde{\alpha}(\xi) = (1+\eta) \frac{2GM}{c^2} \frac{\hat{\xi}}{\xi}$$

Multi-Gaussian Expansion (MGE) Formalism

(Emsellem, Monnet & Bacon 1994; Cappellari 2002)

- Surface brightness profile

$$I(x',y') = \sum_{j=1}^{N} \frac{L_j}{2\pi\sigma_j^2 q'_j} \exp\left[-\frac{1}{2\pi\sigma_j^2}\left(x_j'^2 + \frac{y_j'^2}{q_j'^2}\right)\right]$$

$\Upsilon_j = \frac{M_j}{L_j}$

- Projected mass profile

$$\Sigma(x',y') = \sum_{j=1}^{N} \frac{M_j}{2\pi\sigma_j^2 q'_j} \exp\left[-\frac{1}{2\pi\sigma_j^2}\left(x_j'^2 + \frac{y_j'^2}{q_j'^2}\right)\right]$$

Deprojection

- Mass density profile
  - Stellar
  - Dark Matter

$$\rho(R,z) = \sum_{j=1}^{N+M} \frac{M_j}{(2\pi)^{3/2}\sigma_j^3 q_j} \exp\left[-\frac{1}{2\pi\sigma_j^2}\left(R^2 + \frac{z^2}{q_j^2}\right)\right]$$

Ingredients

Fiducial Mass Model

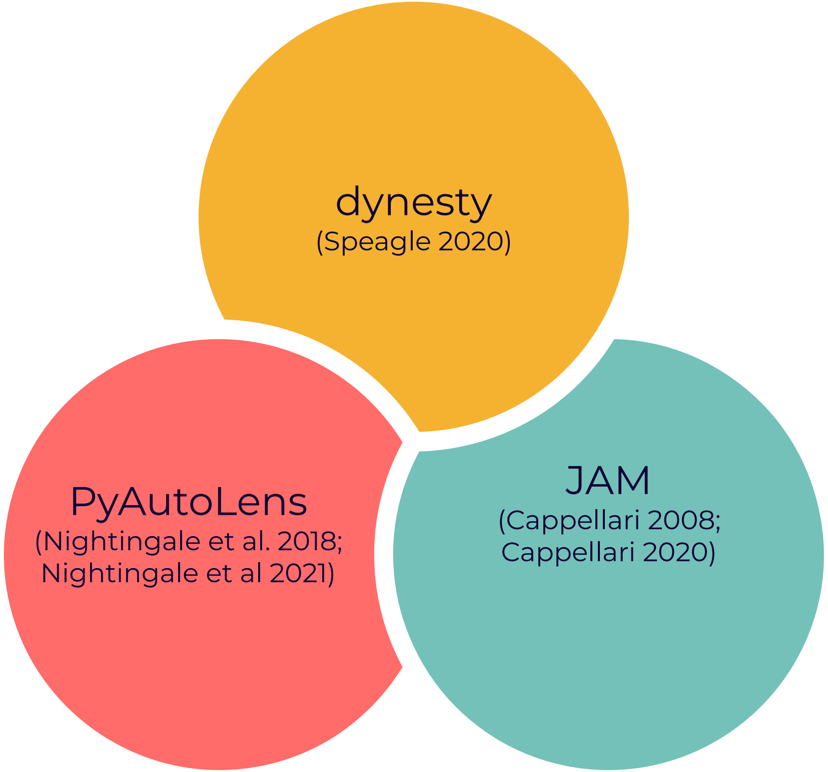
- **Self-consistent model (Lens + Kinematics) - MGE**
  - Stellar component - converting the surface brightness profile
  - Dark Matter Component - represented by an elliptical NFW

Parameter	Prior	Description	Physical Unit
Υ_0	$\mathcal{U}[1.0, 15.0]$	Central M/L	$M_\odot/L_\odot$
υ_0	$\mathcal{U}[0.0, 1.0]$	Lower value of M/L	-
δ	$\mathcal{U}[0.1, 2.0]$	Smoothness of the M/L profile	arcsec^{-1}
β_z	$\mathcal{U}[-1.0, 0.5]$	Anisotropy	-
i	$\mathcal{U}[68.18, 90.0]^a$	Galaxy inclination	degree
κ_s	$\mathcal{U}[0.0, 2.0]$	Scale factor of dark matter halo	-
r_s	Fixed in 10 R_{eff}	Scale radius of dark matter halo	arcsec
q_{DM}	$\mathcal{U}[0.4, 1.0]$	Axial ratio of dark matter halo	-
shear_{mag}	$\mathcal{U}[0.0, 0.1]$	Shear magnitude	-
shear_ϕ	$\mathcal{U}[0.0, 180.0]$	Shear angle counterclockwise from x'−axis	degree
η	$\mathcal{N}[1, 0.09]$	Slip parameter	-

Bayesian inference

$$\mathcal{P}(\mathbf{\Theta}_{\rm M}) = \frac{\mathcal{L}(\mathbf{\Theta}_{\rm M})\pi(\mathbf{\Theta}_{\rm M})}{\mathcal{Z}_{\rm M}}$$

$$\mathcal{L}_{\rm Model} \equiv \mathcal{L}_{\rm Lens} \times \mathcal{L}_{\rm Dyn}$$



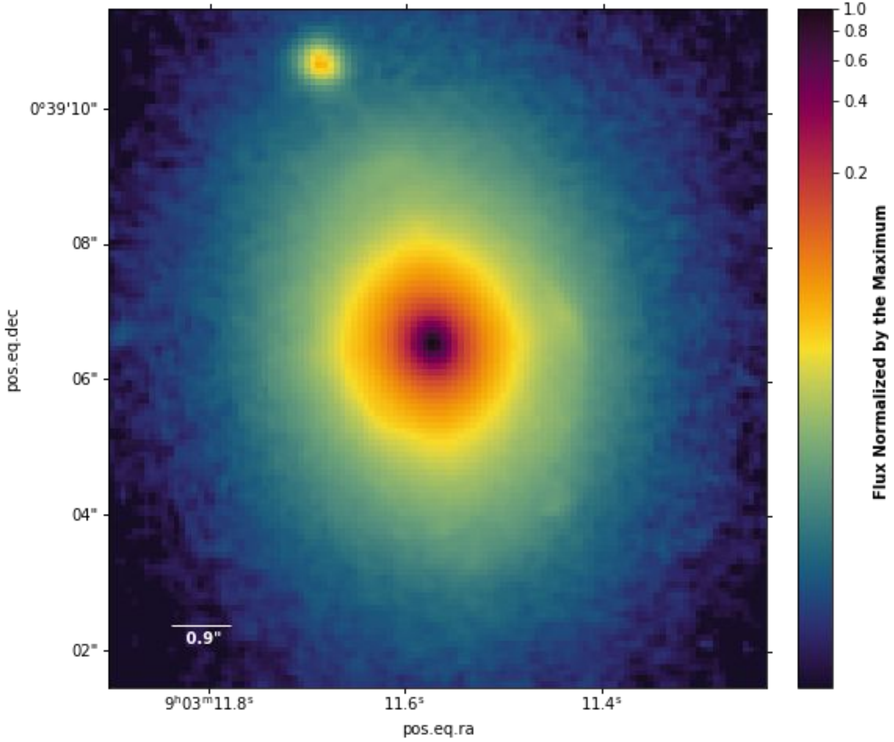
SDP.81

$$z_l = 0.299$$

$$z_s = 3.042$$

Credit: BBC Science Focus Magazine

HST/WFC3 F160W



Data

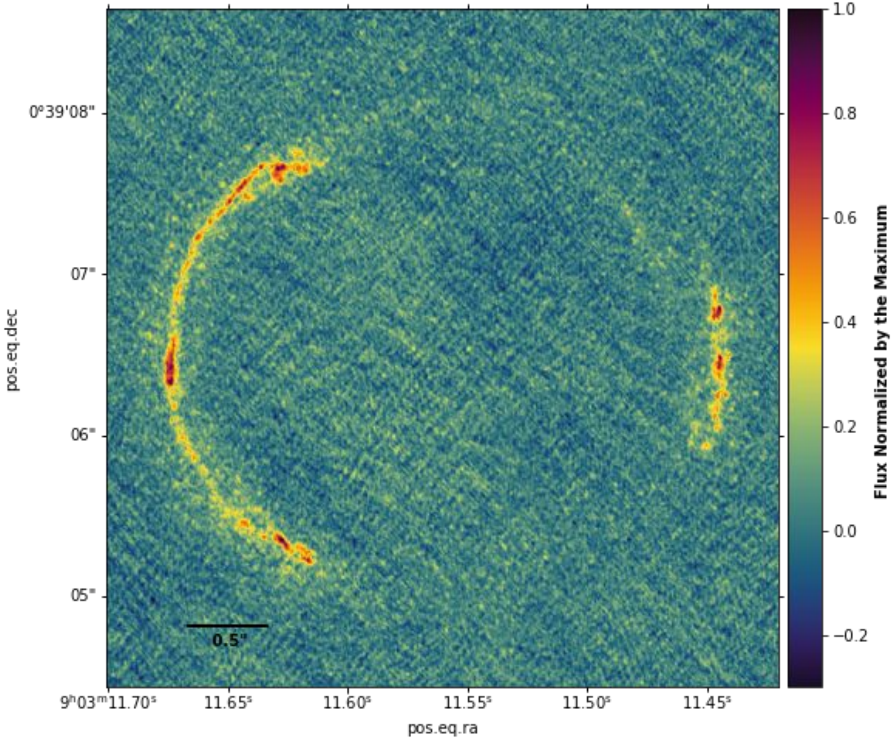
SDP.81

$$z_l = 0.299$$

$$z_s = 3.042$$

Credit: eso.org

ALMA band 7



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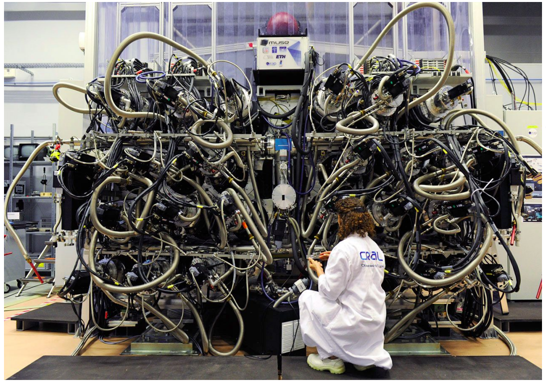
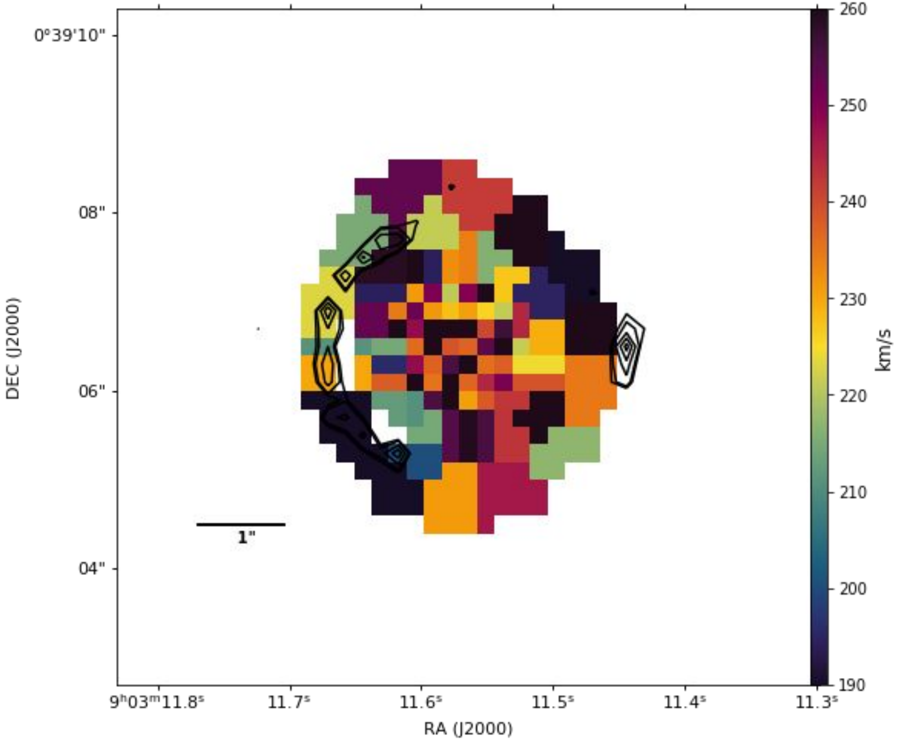


Credit: eso.org

Velocity dispersion map



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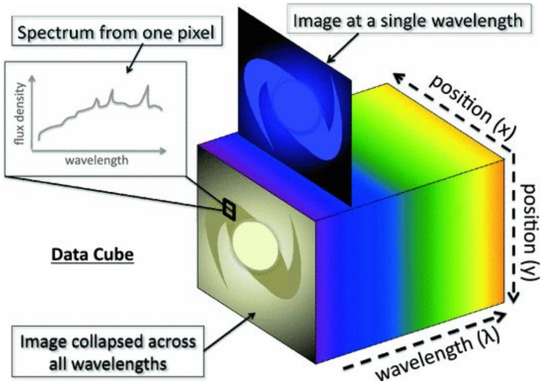
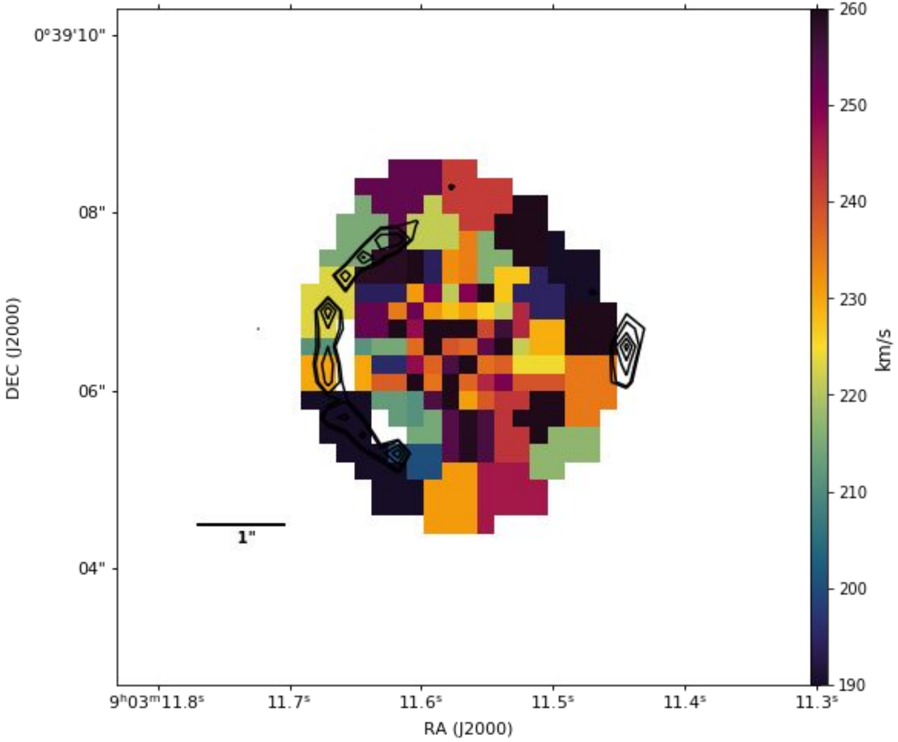


Harrison, C.M. (2016). Integral Field Spectroscopy and Spectral Energy Distributions.

Velocity dispersion map



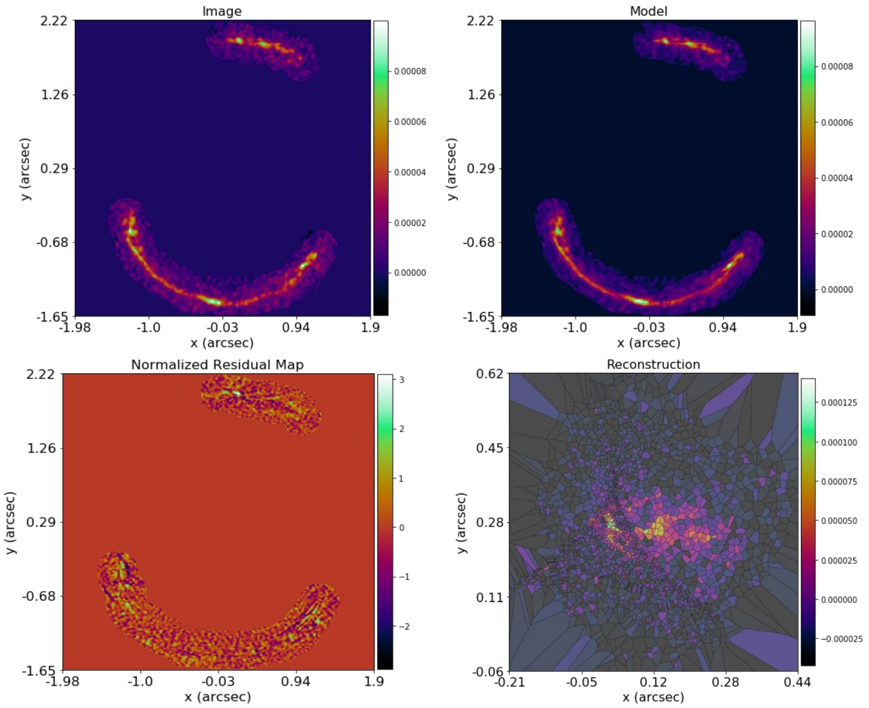
Results

- **Einstein ring ~ 1.61''**
  - Consistent with previous works - (e.g., Dye et al. 2014; Vlahakis et al. 2015; Wong et al. 2015)
- **Mass-to-light ratio ~ 4.51 M⊙/L⊙**
  - On average inside the Einstein ring
  - Relatively higher than expected - (e.g Wong et al. 2015; Tamura et al. 2015)
  - Possible gradient in the M/L
- **Dark matter fraction ~ 35%**
  - Inside the Einstein ring
  - Baryonic dominated in the inner regions
  - Consistent with galaxies at similar redshift - (e.g. Auger et al. 2010; Sonnenfeld et al. 2015)

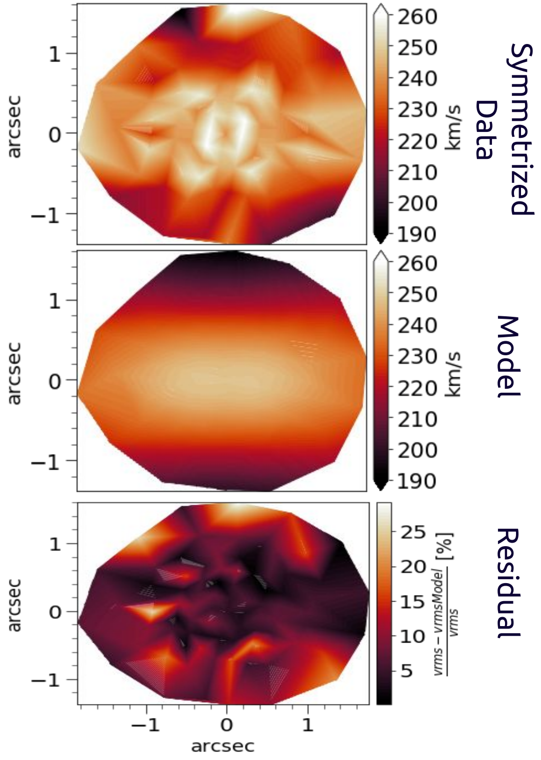
Parameter	MP_5	Physical Units
Υ_0	$4.62^{+0.06}_{-0.09}$	$M_\odot/L_\odot$
δ	$1.48^{+0.1}_{-0.09}$	$arcsec^{-1}$
υ_0	$0.88^{+0.07}_{-0.05}$	-
i	83^{+3}_{-4}	degree
β_z	$-0.52^{+0.03}_{-0.04}$	-
κ_s	$0.086^{+0.003}_{-0.003}$	-
q_{DM}	$0.49^{+0.02}_{-0.01}$	-
η	$1.13^{+0.04}_{-0.03}$	-
$shear_{mag}$	$0.023^{+0.001}_{-0.001}$	-
$shear_{\phi}$	54^{+2}_{-4}	degree

Results

Lens modelling



Dynamical modelling



* all data rotated by the position angle

Results

- **Einstein ring ∼ 1.61''**
  - Consistent with previous works - (e.g., Dye et al. 2014; Vlahakis et al. 2015; Wong et al. 2015)
- **Mass-to-light ratio ∼ 4.51 M⊙/L⊙**
  - On av[illegible]
  - Relat[illegible] Wong[illegible]
  - Possi[illegible]
- **Dark matter fraction ∼ 35%**
  - Inside the Einstein ring
  - Baryonic dominated in the inner regions
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υ_0	$0.88^{+0.07}_{-0.05}$	-
i	83^{+3}_{-4}	degree
[illegible]	[illegible]	-
[illegible]	[illegible]	-
q_{DM}	[illegible]	-
η	$1.13^{+0.04}_{-0.03}$	-
$\mathrm{shear_{mag}}$	$0.023^{+0.001}_{-0.001}$	-
shear_{ϕ}	54^{+2}_{-4}	degree

η $1.13^{+0.04}_{-0.03}$ -

Impact of the choice of the mass profile

- **Alternative 1**
  - No dark matter contribution.
  - Total mass represented only by a stellar component.

$$\eta = 1.52^{+0.01}_{-0.01}$$

- **Alternative 2**
  - Similar to Wong et al. (2015) configuration for SDP.81.
  - Spherical dark matter halo.
  - Inclusion of a supermassive black hole at galaxy center.
  - Constant mass-to-light ratio.

$$\eta = 1.14^{+0.02}_{-0.03}$$

- **Alternative 3**
  - Similar to fiducial model.
  - Dark matter scale radius as a free parameter.

$$\eta = 1.15^{+0.02}_{-0.01}$$

Impact of the choice of the mass profile

- **Alternative 1**
  - No dark matter contribution.
  - Total mass represented only by a stellar component.

$$\eta = 1.52^{+0.01}_{-0.01}$$

- **Altern**
  - Sim
  - Sph
  - Inclusion of a supermassive black hole at galaxy center.
  - Constant mass-to-light ratio.

$$\eta = 1.13^{+0.04}_{-0.03} \pm (0.18)^{\mathrm{mass}}$$

$$4^{+0.02}_{-0.03}$$

- **Alternative 3**
  - Similar to fiducial model.
  - Dark matter scale radius as a free parameter.

$$\eta = 1.15^{+0.02}_{-0.01}$$

Impact of the choice of the stellar library

- **Medium resolution INT Library of Empirical Spectra (MILES)**
  - Vazdekis et al. (2010)
  - Systematically smaller by 2.9%.

- **X-Shooter Spectral Library (XSL)**
  - Gonneau et al. (2020)
  - Systematically higher by 3.9%.

Impact of the choice of the stellar library

- **Medium resolution INT Library of Empirical Spectr**
  - Vazd
  - Syst

$$\eta = 1.13^{+0.04}_{-0.03} \pm 0.19\,(\mathrm{sys})^{\mathrm{kin}}$$

- **X-Shooter Spectral Library (XSL)**
  - Gonneau et al. (2020)
  - Systematically higher by 3.9%.

Final Inference

- **Statistical uncertainty**
  - ~0.04 due to the sampling

- **Systematic uncertainties**
  - 0.18 due to different mass profiles
  - 0.19 due to different stellar libraries
    - 0.26 (in quadrature)

$$\eta = 1.13^{+0.04}_{-0.03} \pm 0.26(\mathrm{sys})$$

Final remarks

- We test GR on galactic scales using gravitational lensing and galactic dynamics
- We extend this class of tests to an intermediate redshift ($z \sim 0.3$)
- The fiducial model considers the contribution of a stellar mass component and a dark matter mass component
- We infer a slip gravitational parameter in accordance with GR within 1σ confidence level

Future work

- Get better spectroscopic data (maybe JWST?)
- Extend this test class to other systems (different redshifts and different scales)
- Relax some of the assumptions (e.g. slip parameter no longer constant)

Thanks!

Any questions?

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- carlos.melo@ufrgs.br

slidesgo
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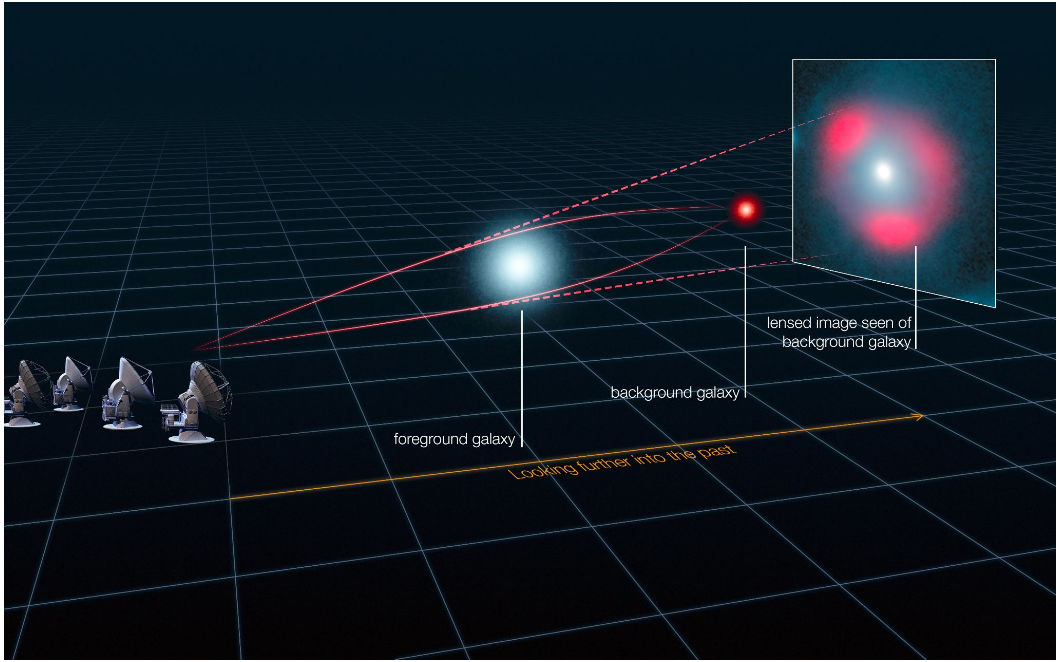
EXTRAS

Strong gravitational lensing

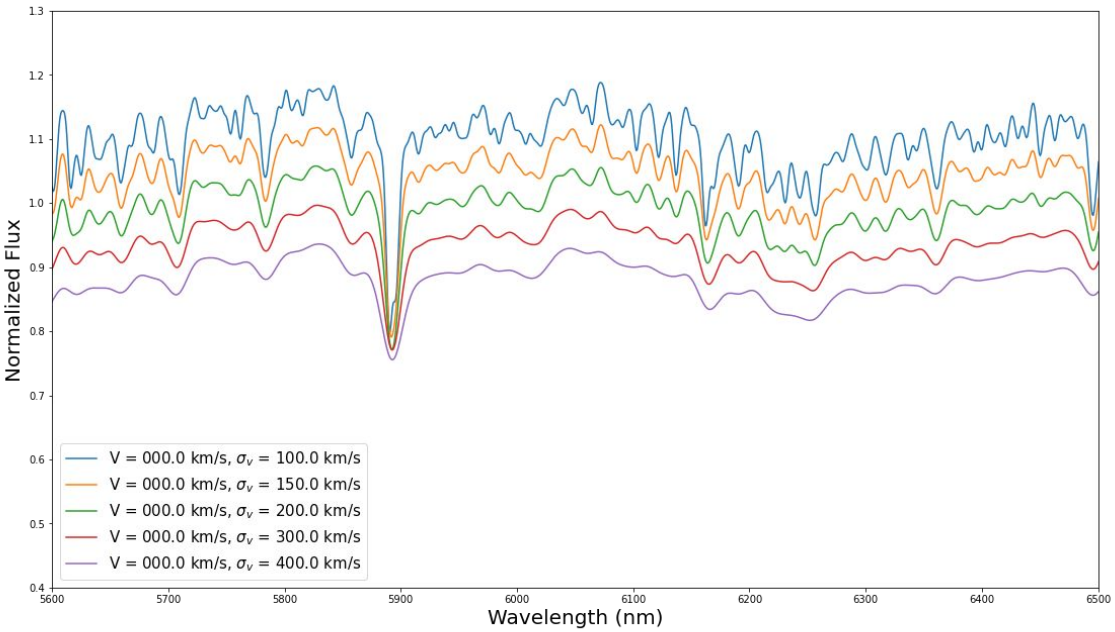


Credit: ALMA (ESO/NRAO/NAOJ), L. Calçada (ESO), Y. Hezaveh et al.

Stellar kinematics

pPXF

(Cappellari 2012)



The pipeline

Phase1

Parametric Source, Lens + Dynamical modelling

Broad priors

Avoids under/over-magnified (non-physical) solutions

→

Phase2

Adaptive Pixelization and Hyperparameters

Fixed Phase1 mass model

Adaptive grid

Constant regularization

→

Phase3

Model Refinement I

Fixed Phase2 hyperparameters

Update the priors: MP_1 ±20% or $MP_1 \pm 1\sigma$, whichever defines a larger interval

→

Phase4

Adaptive Brightness-based Pixelization and Hyperparameters

Fixed Phase3 mass model

Brightness-based grid

Constant regularization

→

Phase5

Model Refinement II

Fixed Phase4 hyperparameters

Update the piors: MP_3 ±10% or $MP_3 \pm 1\sigma$, whichever defines a larger interval

But... what if we change the prior?

Parameter	Prior	Description	Physical Unit
Υ_0	$\mathcal{U}[1.0, 15.0]$	Central M/L	$M_\odot/L_\odot$
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shear_{ϕ}	$\mathcal{U}[0.0, 180.0]$	Shear angle counterclockwise from x'−axis	degree
η	$\mathcal{U}[-10, 10]$	Slip parameter	-

Parameter	**MP$_5$**	Physical Units
Υ_0	$4.59^{+0.07}_{-0.07}$	$M_\odot/L_\odot$
δ	$0.89^{+0.12}_{-0.08}$	arcsec^{-1}
υ_0	$0.90^{+0.06}_{-0.07}$	-
i	80^{+5}_{-5}	degree
β_z	$-0.16^{+0.02}_{-0.01}$	-
κ_s	$0.056^{+0.003}_{-0.004}$	-
q_{DM}	$0.39^{+0.05}_{-0.05}$	-
η	$1.42^{+0.05}_{-0.05}$	-
$\mathrm{shear}_{\mathrm{mag}}$	$0.034^{+0.003}_{-0.002}$	-
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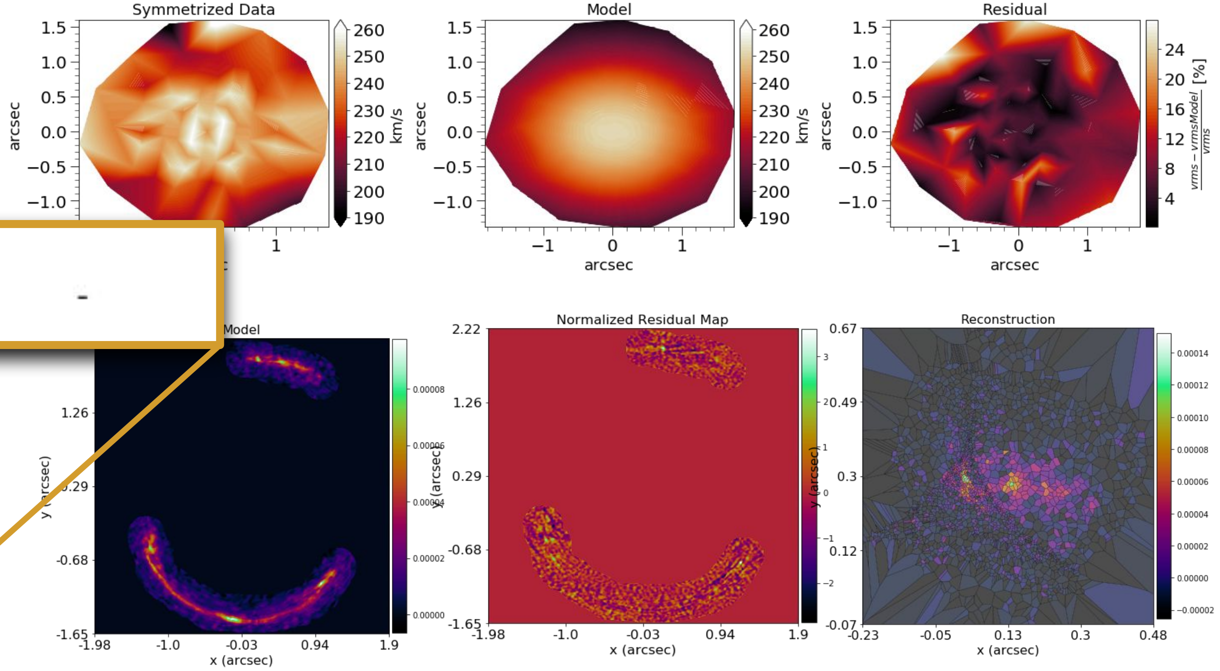

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Higher bayesian evidence!