Lentes gravitacionales en astrofísica y cosmología

Semana - 9

Parte II: lentes por galáxias y cúmulos de galáxias

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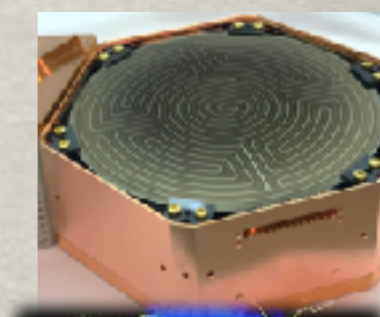
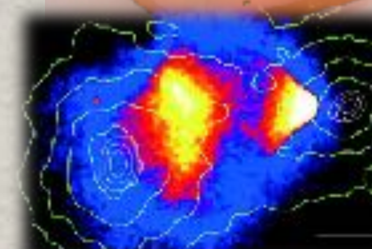
CBPF

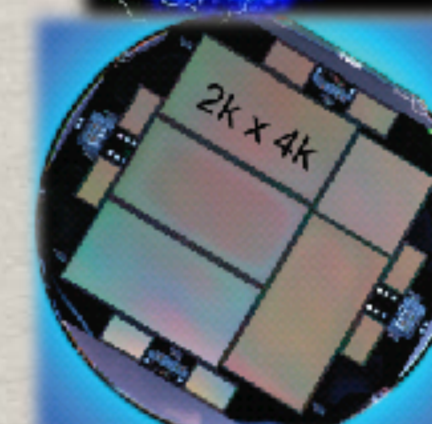
Instituto de Tecnología SABATO 30 años

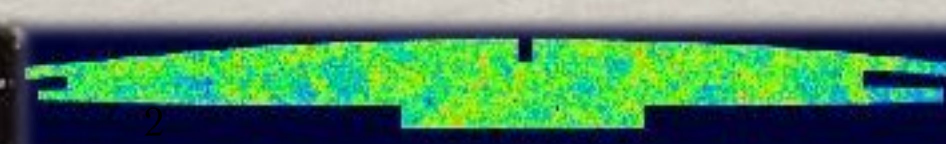
Plan de la Parte II

- [x] Redshift y expansión del Universo
- [x] Dinámica y parámetros cosmológicos
- [x] Métrica y distancias
- [x] Energía oscura
- [x] Propagación de la luz y ecuación de la lente
- [x] Lentes extendidas
- [x] Jacobiana de la transformación: cáusticas y curvas críticas
- [ ] Modelos de lentes extendidas y aplicaciones
- [ ] Retraso temporal y aplicaciones
- [ ] Efecto débil de lentes

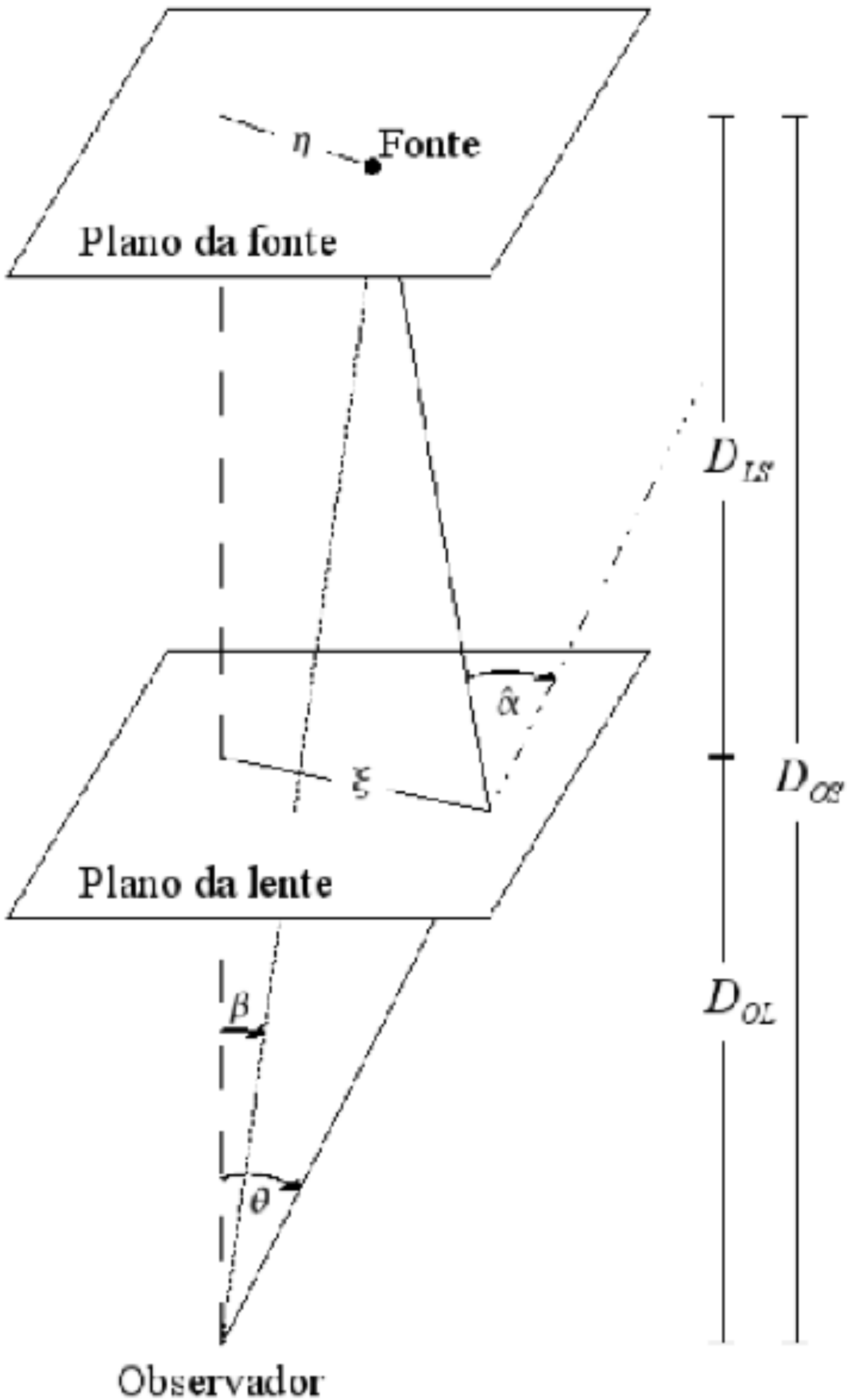








Summary



Lens equation $$\vec{\beta} = \vec{\theta} - \vec{\alpha}\left(\vec{\theta}\right) = \vec{\theta} - \vec{\nabla}_\theta \Psi\left(\vec{\theta}\right)$$

Lens potential $$\Psi(\vec{x}) \equiv \frac{2}{c^2}\frac{D_{LS}}{D_{OS}D_{OL}}\psi$$

Deflection angle
$$\hat{\vec{\alpha}} = \frac{4G}{c^2}\int d^2\xi' \Sigma\left(\vec{\xi'}\right)\frac{\vec{\xi} - \vec{\xi'}}{|\vec{\xi} - \vec{\xi'}|^2}$$

Multiple images, magnification,
Einstein rings, arcs
Examples: point mass, SIS

Jacobiana de la transformación

$$\vec{\beta} = \vec{\theta} - \vec{\nabla}_\theta \Psi\left(\vec{\theta}\right)$$

$$J_{ij} = \left(\frac{\partial \vec{\beta}}{\partial \vec{\theta}}\right)_{ij} = \delta_{ij} - \frac{\partial^2 \Psi}{\partial \theta_i \partial \theta_j},$$ definiendo $\Psi_{ij} = \dfrac{\partial^2 \Psi}{\partial \theta_i \partial \theta_j}$

tenemos $\mathbf{J} = \begin{pmatrix} 1 - \Psi_{11} & -\Psi_{12} \\ -\Psi_{21} & 1 - \Psi_{22} \end{pmatrix}$

como $\nabla_\theta^2 \Psi = \Psi_{11} + \Psi_{22} = 2\kappa$ Recordar que $\kappa\left(\vec{\theta}\right) = \dfrac{\Sigma\left(\vec{\theta}\right)}{\Sigma_{\mathrm{crit}}}$

$$\mathbf{J} = (1-\kappa)\mathbf{I} - \begin{pmatrix} \frac{1}{2}\left(\Psi_{11} - \Psi_{22}\right) & \Psi_{12} \\ \Psi_{21} & -\frac{1}{2}\left(\Psi_{11} - \Psi_{22}\right) \end{pmatrix}$$

Cizalladura

$$\mathbf{J} = (1-\kappa)\mathbf{I} - \begin{pmatrix} \frac{1}{2}\left(\Psi_{11} - \Psi_{22}\right) & \Psi_{12} \\ \Psi_{21} & -\frac{1}{2}\left(\Psi_{11} - \Psi_{22}\right) \end{pmatrix}$$

Cizalladura:

$$\gamma_1(\vec{\theta}) = \frac{1}{2}(\Psi_{11} - \Psi_{22})$$

$$\gamma_2(\vec{\theta}) = \Psi_{12} = \Psi_{21}$$

$$\gamma = \sqrt{\gamma_1^2 + \gamma_2^2}$$

Em términos de la cizalladura y la convergencia tenemos

$$\mathbf{J} = (1-\kappa)\mathbf{I} + \begin{pmatrix} -\gamma_1 & -\gamma_2 \\ -\gamma_2 & \gamma_1 \end{pmatrix}$$

Autovalores de $\mathbf{J}^{-1}$

$$\mu_1 = \frac{1}{1-\kappa-\gamma}, \quad \mu_2 = \frac{1}{1-\kappa+\gamma}$$

Modelos de Lentes

Dos caminos

Ecuación de la lente $\vec{\beta} = \vec{\theta} - \vec{\alpha}\left(\vec{\theta}\right) = \vec{\theta} - \vec{\nabla}_\theta \Psi \left(\vec{\theta}\right)$

⇨ Obtener $\vec{\alpha}\left(\vec{\theta}\right)$ o $\Psi\left(\vec{\theta}\right)$

⇨ Solución de la ecuación de la lente y jacobiana

$$\hat{\vec{\alpha}} = \frac{4G}{c^2} \int d^2\xi' \Sigma\left(\vec{\xi'}\right) \frac{\vec{\xi} - \vec{\xi'}}{|\vec{\xi} - \vec{\xi'}|^2}.$$

$$\psi\left(\vec{\xi}\right) = 2G \int d^2\xi' \Sigma\left(\vec{\xi'}\right) \ln|\xi - \xi'|$$

Camino I: Elegir $\Sigma\left(\vec{\xi}\right)$ o $\rho\left(\vec{r}\right)$

Camino II: Modelo para $\Psi\left(\vec{\theta}\right)$

Modelos de potencial

Esfera isotérmica singular $\Psi = \theta_E \left|\vec{\theta}\right|$

Esfera isotérmica com "caroço" $\Psi = \theta_0 \sqrt{\theta^2 + \theta_c^2}$

Convergência $\kappa = \theta_0 \dfrac{\theta^2 + 2\theta_c^2}{2\left(\theta^2 + \theta_c^2\right)^{3/2}}$

Perfil de densidade

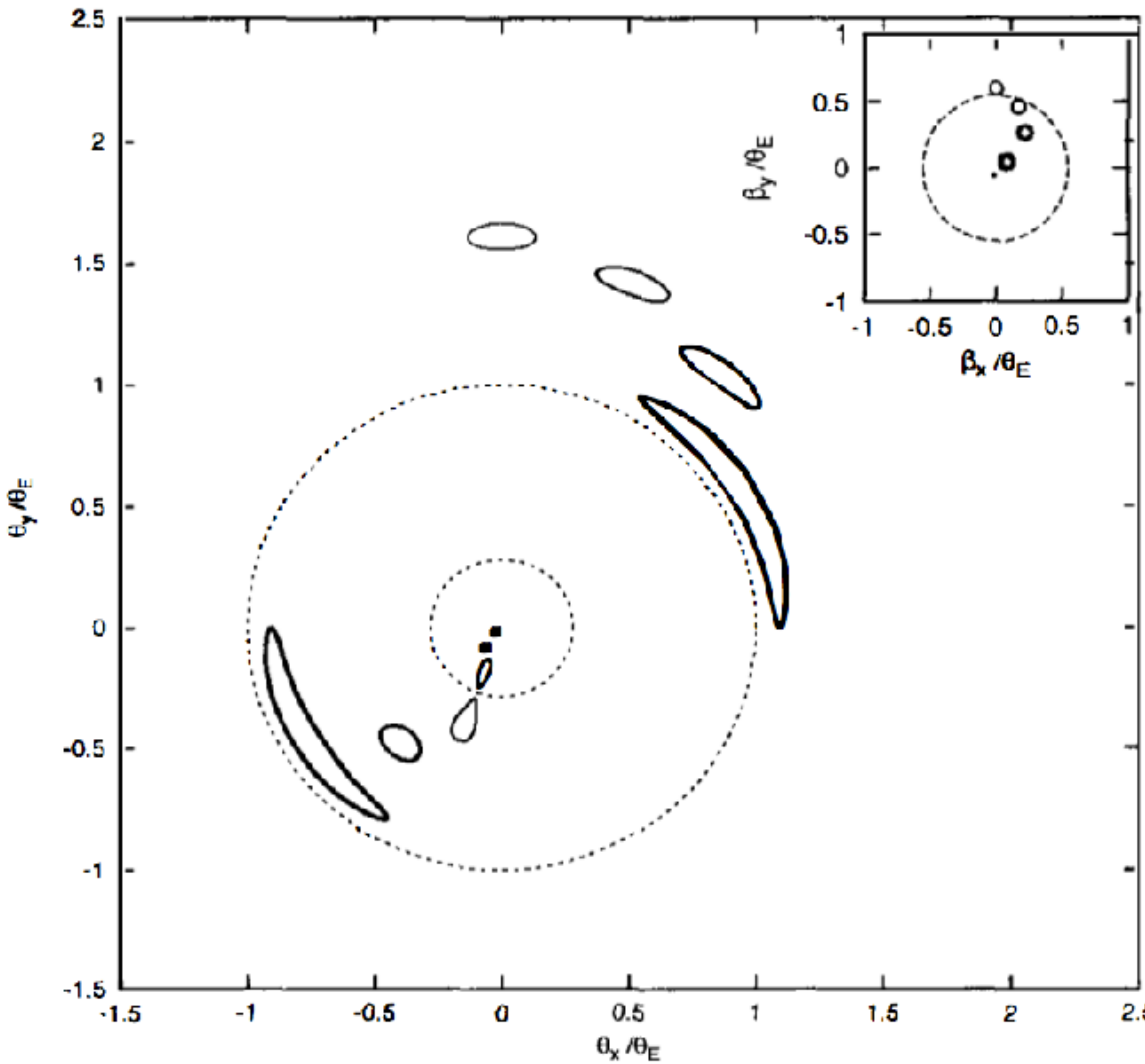
Esfera isotérmica suavizada $$\rho(r) = \frac{\sigma^2}{2\pi G(r^2 + r_c^2)}$$

Densidade projetada $$\Sigma(\theta) = \frac{\sigma^2}{2GD_{OL}} \frac{1}{\sqrt{\theta^2 + \theta_c^2}}$$

Potencial de lente

$$\Psi(\vec{\theta}) = \theta_0 \left[\sqrt{\theta^2 + \theta_c^2} - \theta_c \ln\left(\sqrt{\theta^2 + \theta_c^2} + \theta_c\right)\right]$$

Modelo axial não singular



Modelo Navarro-Frenk-White

Simulaciones computacionales de *N-cuerpos* en un contexto cosmológico

Densidad media radial: $\rho(r) = \dfrac{\rho_s}{(r/r_s)(1 + r/r_s)^2}$

Universalidad de los perfiles de materia oscura!

El perfil de Navarro-Frenk-White

https://wwwmpa.mpa-garching.mpg.de/~swhite/pictures/NFW_profile1.jpg


LOS SIMULADORES

Modelo Navarro-Frenk-White

Densidade média radial: $$\rho(r) = \frac{\rho_s}{(r/r_s)(1+r/r_s)^2}$$

Convergência:

$$\kappa(x) = 2\kappa_s \frac{1-F(x)}{x^2-1}, \qquad x = \frac{\xi}{r_s} \quad \text{e} \quad k_s = \frac{\rho_s r_s}{\Sigma_{cr}}$$

$$F(x) = \begin{cases} \frac{\mathrm{ArcTan}\left(\sqrt{x^2-1}\right)}{\sqrt{x^2-1}} & , \quad x > 1 \\ 1 & , \quad x = 1 \\ \frac{\mathrm{ArcTanh}\left(\sqrt{1-x^2}\right)}{\sqrt{1-x^2}} & , \quad x < 1 \end{cases},$$

Potencial de lente:

$$\Psi(x) = 2\kappa_s r_s^2 \left[\ln^2 \frac{x}{2} - \mathrm{ArcTanh}^2 \sqrt{1-x^2}\right]$$

Potencial mais suave que o da Esfera Isotérmica:
curvas críticas menores, maior amplificação, menor separação angular

Other lens models

Implemented in *gravlens* and several public codes (+ Sérsic, Einasto, etc.)

Model	N_r	Density $\rho(r)$	Surface Density $\kappa(r)$
Point mass	0	$\delta(\mathbf{x})$	$\delta(\mathbf{x})$
Power law or α-models	2	$\left(s^2+r^2\right)^{(\alpha-3)/2}$	$\left(s^2+r^2\right)^{(\alpha-2)/2}$
Isothermal ($\alpha=1$)	1	$\left(s^2+r^2\right)^{-1}$	$\left(s^2+r^2\right)^{-1/2}$
$\alpha=-1$	1	$\left(s^2+r^2\right)^{-2}$	$\left(s^2+r^2\right)^{-3/2}$
Pseudo-Jaffe	2	$\left(s^2+r^2\right)^{-1}\left(a^2+r^2\right)^{-1}$	$\left(s^2+r^2\right)^{-1/2}-\left(a^2+r^2\right)^{-1/2}$
King (approximate)	1	$\cdots$	$2.12\left(0.75r_s^2+r^2\right)^{-1/2}$ $-1.75\left(2.99r_s^2+r^2\right)^{-1/2}$
de Vaucouleurs	1	$\cdots$	$\exp\left[-7.67(r/R_e)^{1/4}\right]$
Hernquist	1	$r^{-1}\left(r_s+r\right)^{-3}$	see eq. (47)
NFW	1	$r^{-1}\left(r_s+r\right)^{-2}$	see eq. (53)
Cuspy NFW	2	$r^{-\gamma}\left(r_s+r\right)^{\gamma-3}$	see eq. (57)
Cusp	3	$r^{-\gamma}\left(r_s^2+r^2\right)^{(\gamma-n)/2}$	see eq. (64)
Nuker	4	$\cdots$	see eq. (71)
Exponential disk	1	$\cdots$	$\exp[-r/R_d]$
Kuzmin disk	1	$\cdots$	$\left(r_s^2+r^2\right)^{-3/2}$

Modelos Elípticos y Pseudo-Elípticos

Modelos elípticos

Sustituir $\theta \rightarrow \sqrt{q_1\theta_1^2 + q_2\theta_2^2}$

- en el potencial (modelos pseudo-elípticos)
- en la densidad proyectada (modelos elípticos)

Ejemplo: Esfera isotérmica com *core* pseudo-elíptico

$$\Psi(\theta_1,\theta_2) = \frac{\Psi_0}{\theta_c}\sqrt{(1-\epsilon)\theta_1^2 + (1+\epsilon)\theta_2^2 + \theta_c^2}$$

Elipticidad en la densidad proyectada

Ejemplo: Esfera isoterma elíptica con *core*

$$\Sigma(\theta_1, \theta_2) = \frac{\Sigma_0 \theta_c}{\sqrt{(1-\epsilon)\theta_1^2 + (1+\epsilon)\theta_2^2 + \theta_c^2}}$$

Solución para modelos elípticos

$$\begin{aligned}
\phi(x,y) &= \frac{q}{2}\, I(x,y) \\
\phi_{,x}(x,y) &= q\, x\, J_0(x,y) \\
\phi_{,y}(x,y) &= q\, y\, J_1(x,y) \\
\phi_{,xx}(x,y) &= 2\, q\, x^2\, K_0(x,y) + q\, J_0(x,y) \\
\phi_{,yy}(x,y) &= 2\, q\, y^2\, K_2(x,y) + q\, J_1(x,y) \\
\phi_{,xy}(x,y) &= 2\, q\, x\, y\, K_1(x,y)
\end{aligned}$$

$$\begin{aligned}
I(x,y) &= \int_0^1 \frac{\xi}{u}\, \frac{\phi_{,r}\left(\xi(u)\right)}{\left[1-(1-q^2)u\right]^{1/2}}\, du \\
J_n(x,y) &= \int_0^1 \frac{\kappa\left(\xi(u)^2\right)}{\left[1-(1-q^2)u\right]^{n+1/2}}\, du \\
K_n(x,y) &= \int_0^1 \frac{u\, \kappa'\left(\xi(u)^2\right)}{\left[1-(1-q^2)u\right]^{n+1/2}}\, du \\
\xi(u)^2 &= u\left(x^2 + \frac{y^2}{1-(1-q^2)u}\right)
\end{aligned}$$

Campos externos

Expansión hasta segundo ordem del potencial

$$\Psi(\theta_1,\theta_2) = \frac{\kappa}{2}\left(\theta_1^2+\theta_2^2\right) + \frac{\gamma_1}{2}\left(\theta_1^2-\theta_2^2\right) + \gamma_2\theta_1\theta_2$$

Model for the source

Surface brightness distribution of the source

Example: Sérsic profile

$$\boxed{I(R) = I_0 \exp\left\{ -b_n \left(\frac{R}{R_e} \right)^{1/n} \right\}}$$

Elliptical brightness distribution

source centered at (S_1, S_2)

$$\begin{aligned} R^2 = &(1-\varepsilon_S)[(\beta_1 - S_1)\cos\phi_e + (\beta_2 - S_2)\sin\phi_e]^2 \\ &+(1+\varepsilon_S)[(\beta_2 - S_2)\cos\phi_e - (\beta_1 - S_1)\sin\phi_e]^2 \end{aligned}$$

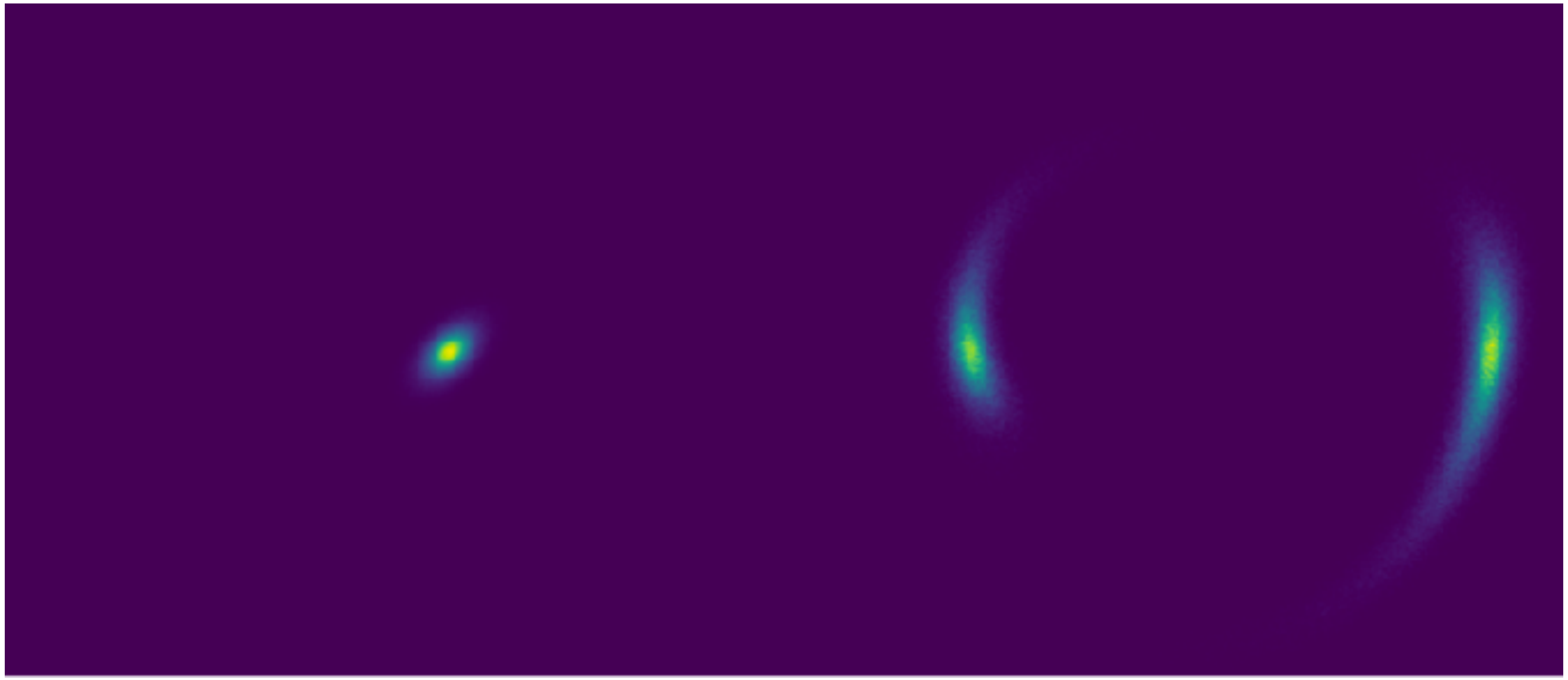
Simulating Strong Lensing Images

Map the brightness distribution of the source to the lens plane

$$I(R) = I\left(\vec{\beta}\right) = I\left(\vec{\beta}\left(\vec{\theta}\right)\right)$$

Use the lens equation (no need to solve it!)

Add PSF and noise




AddArcs v2.0
SIE
Actividad Práctica 7

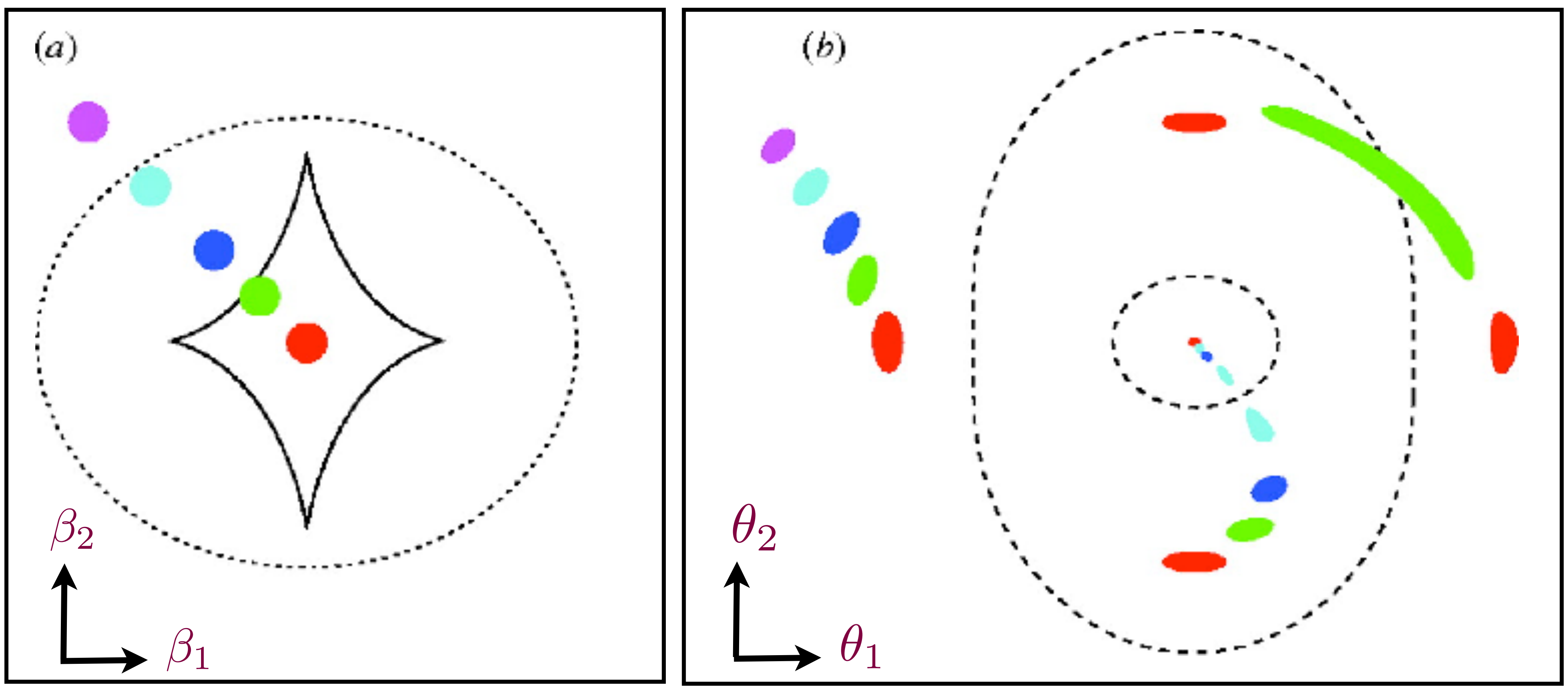
Lensing Mapping

- image → source mapping:

$$\frac{\partial \beta_i}{\partial \theta_j} = \delta_{ij} - \frac{\partial^2 \Psi(\vec{\theta})}{\partial \theta_i \partial \theta_j}$$

- eigenvalues:

$$\mu_1 = \frac{1}{1-\kappa+\gamma}, \mu_2 = \frac{1}{1-\kappa-\gamma}$$



Source plane

Lens/image

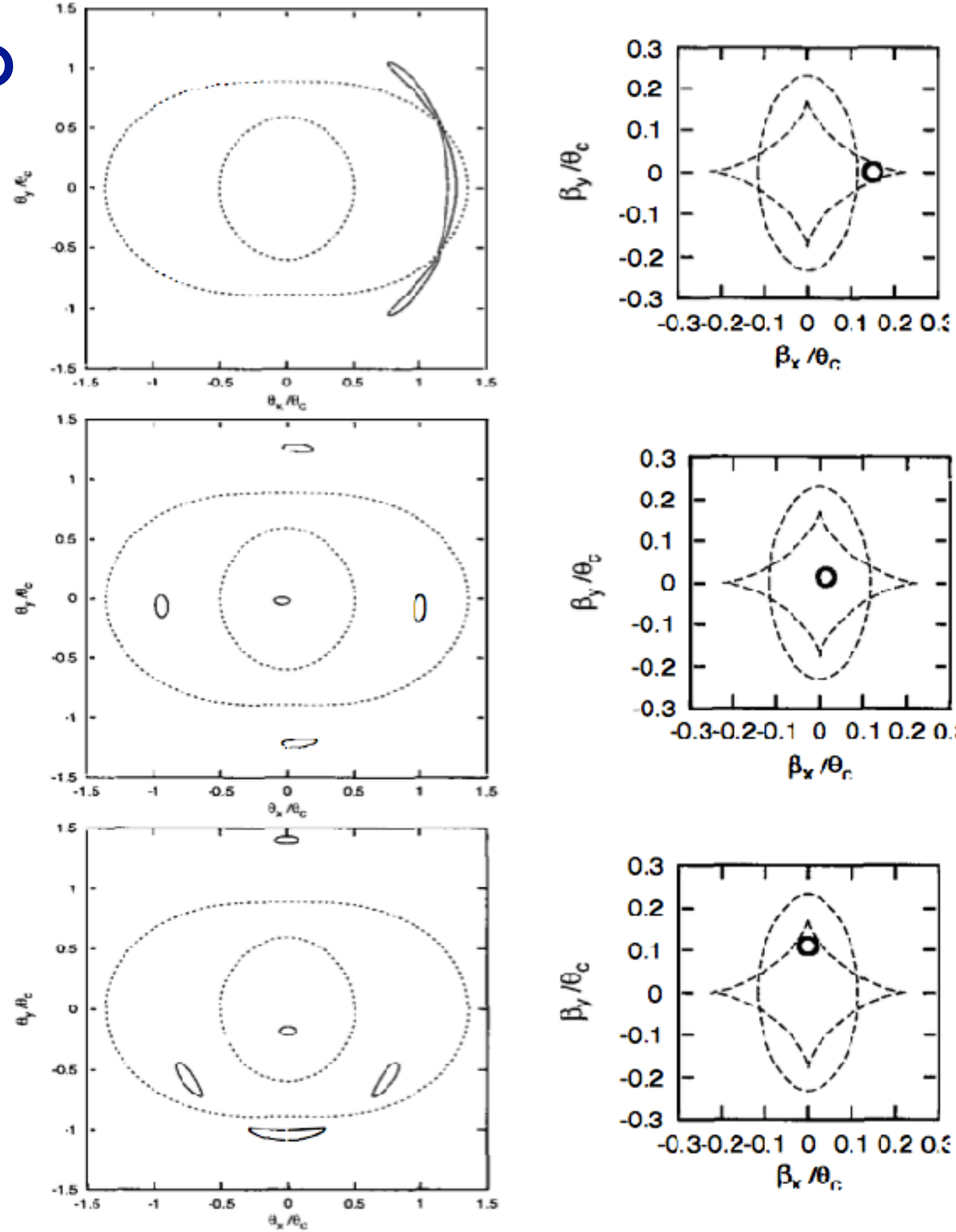
Comportamento geral

Cáusticas:

- tangencial: astróides com cúspides
- radial: "oval"

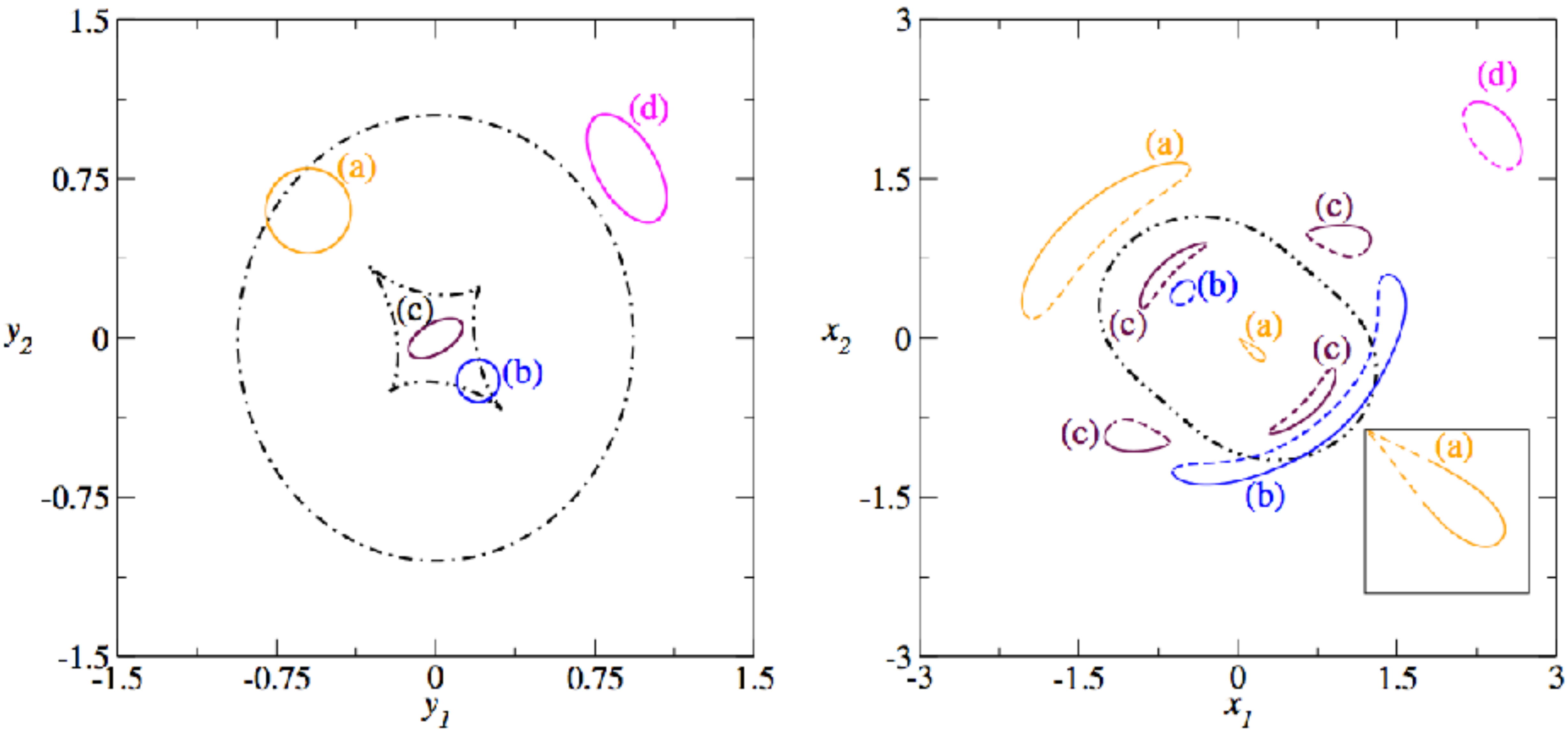
Curvas críticas:

- tangencial: "oval"
- radial: "circular"



Arcos em modelos elípticos

Soluções analíticas para esfera isotérmica elíptica e pseudo-elíptica com campos externos e fontes elípticas



Dúmet-Montoya & Makler in prep.

Reconstrucción de la distribución de materia en la lente

Inverse Modeling

Use systems of multiple images to determine the lensing potential

$$\chi^2_{\mathrm{lente}} := \sum_i \left(\frac{\vec{\theta}_i^{\mathrm{obs}} - \vec{\theta}^{\mathrm{mod}} \left(\vec{\beta}, \vec{\Pi} \right)}{\sigma_i^{\mathrm{obs}}} \right)^2$$

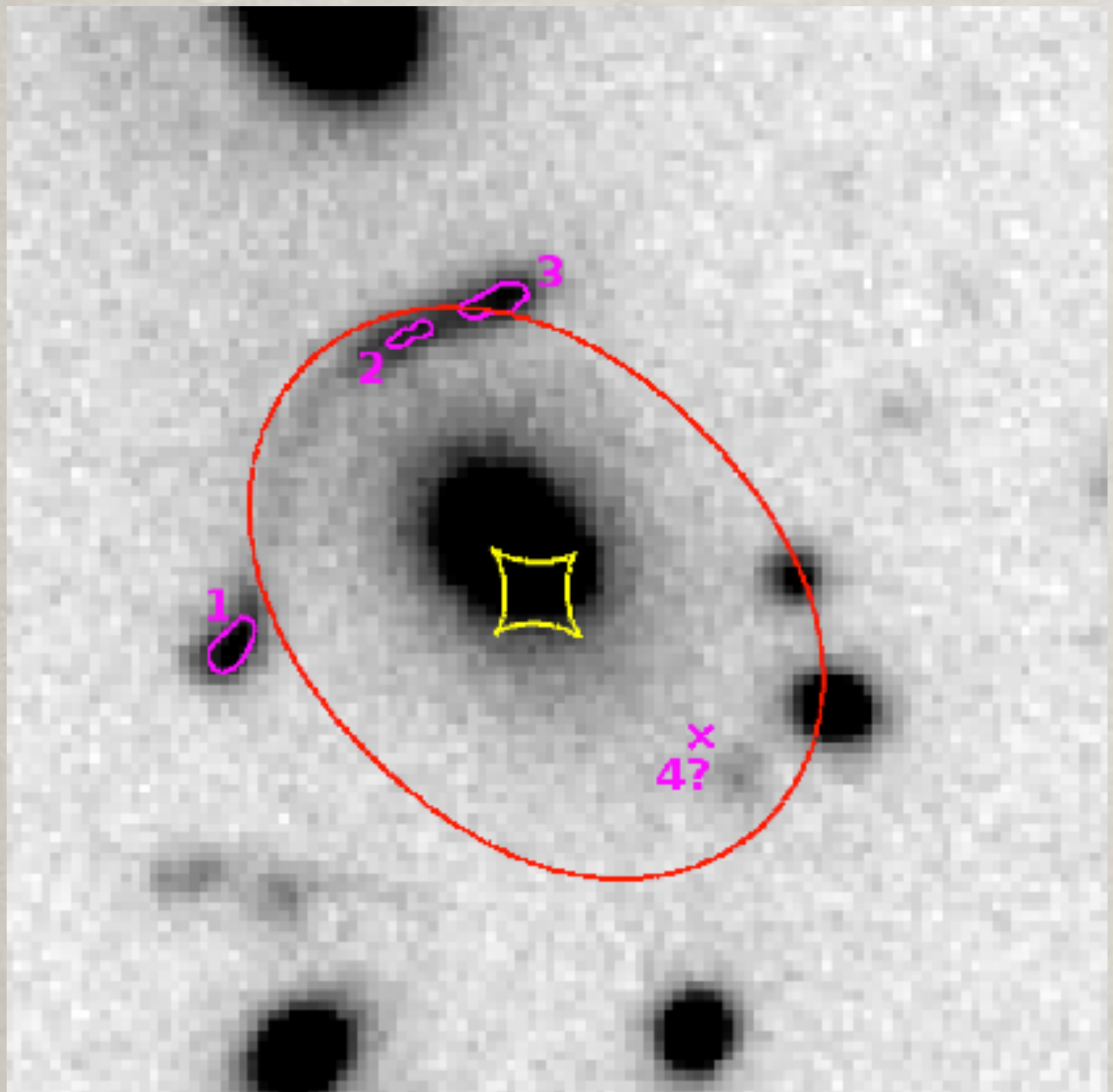
Position of the multiple images

Uncertainty on the image positions

Available codes: *lenstool*, *gravlens*, *glafic*, etc. + “home-made”

- Parameters that minimize this function (or maximize the likelihood) are the best fitting lens model
- Combination with independent mass constraints (e.g., x-ray, Sunyaev Zel’dovich, velocity dispersions) yields limits on cosmology or gravity

Inverse Modeling: Mapping the Mass



Use systems of multiple images to determine the lensing potential

$$\chi^2_{\mathrm{lente}} := \sum_i \left(\frac{\vec{\theta}_i^{\mathrm{obs}} - \vec{\theta}_i^{\mathrm{mod}}\left(\vec{\beta}, \vec{\Pi}\right)}{\sigma_i^{\mathrm{obs}}} \right)^2$$

Multiple image positions

Error on image positions

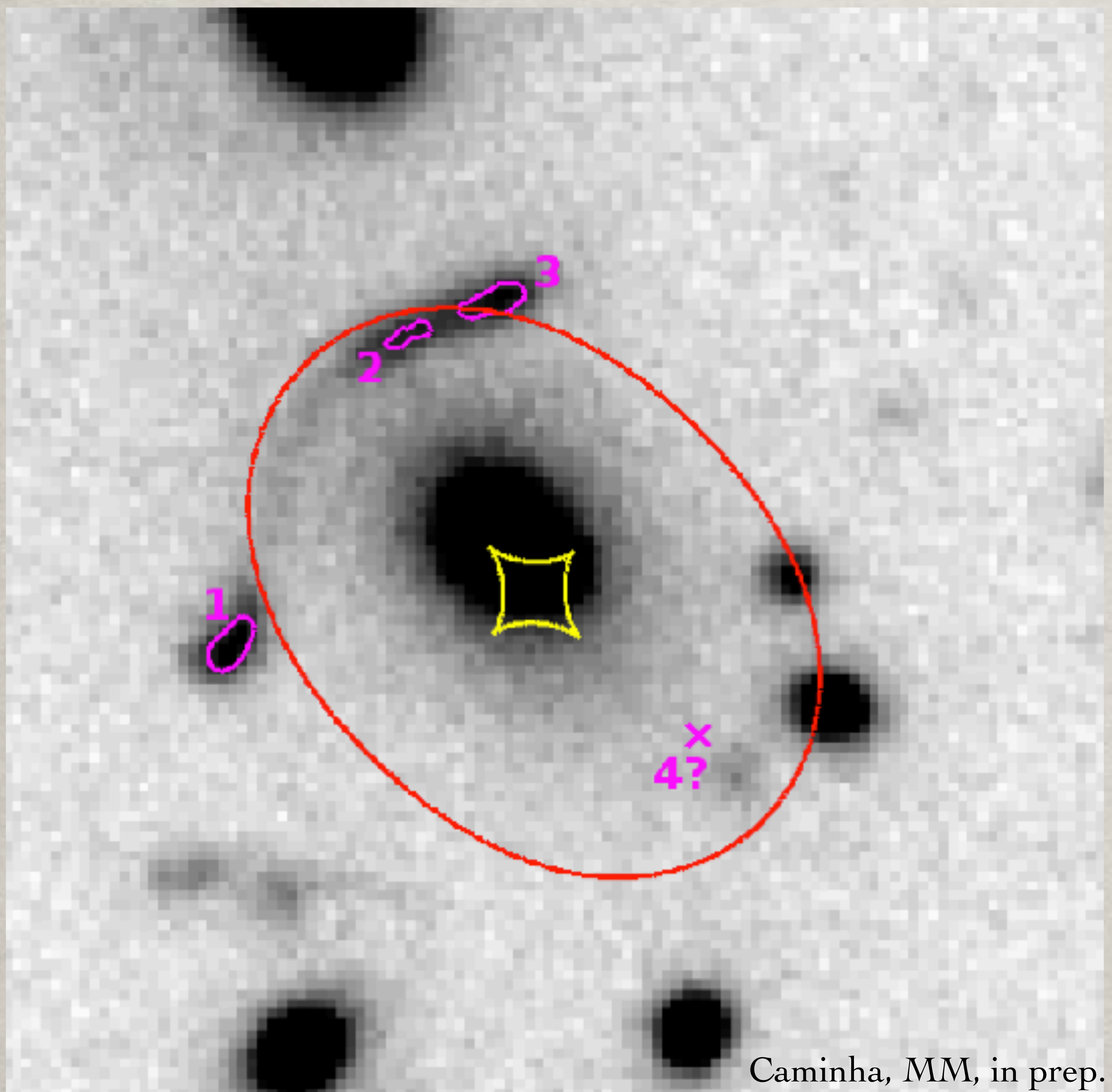
Methods: parametric (often “mass traces light”), free form

The more multiple images, the more constrains

Cluster x Galaxy scales

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

Inverse Modeling for system SOGRAS0041-0043



$$2.35^{+0.03}_{-0.14} \times 10^{14} M_{\odot}$$

Modelling with lenstool (Jullo, Kneib)

Fit 1: 3 images
Fit 2: 4 images

	Fit 1	Fit 2
$\sigma_v[km/s]$	622^{-11}_{-13}	642^{+3}_{-3}
$\theta_{or}[°]$	$135.2^{+0.7}_{-0.8}$	$135.2^{+1.5}_{-1.3}$
$x_{lente}['']$	$0.50^{+0.2}_{-0.2}$	$0.50^{+0.05}_{-0.06}$
$y_{lente}['']$	$-0.76^{+0.17}_{-0.15}$	$-0.86^{-0.06}_{-0.03}$
ε	—	$0.13^{+0.02}_{-0.03}$

~ 0.9" displacement between central galaxy and center of mass distribution (*Zitrin et al. 2012*)

Error estimate from simulations (Caminha et al. in prep.):

~ 8% bias in mass

~ 5% statistical errors

Modeling the full light distribution of the images

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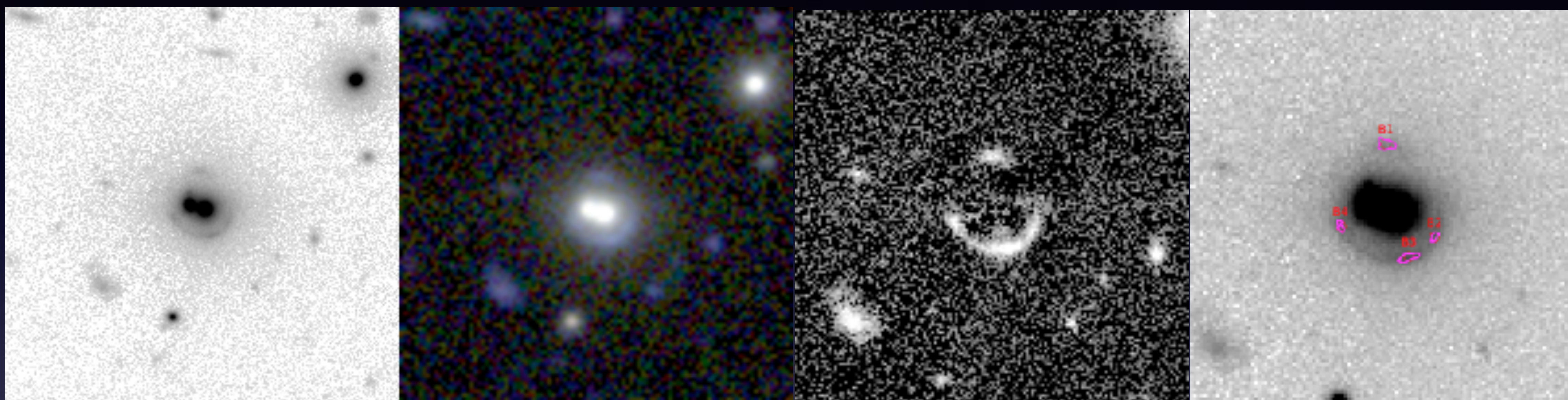
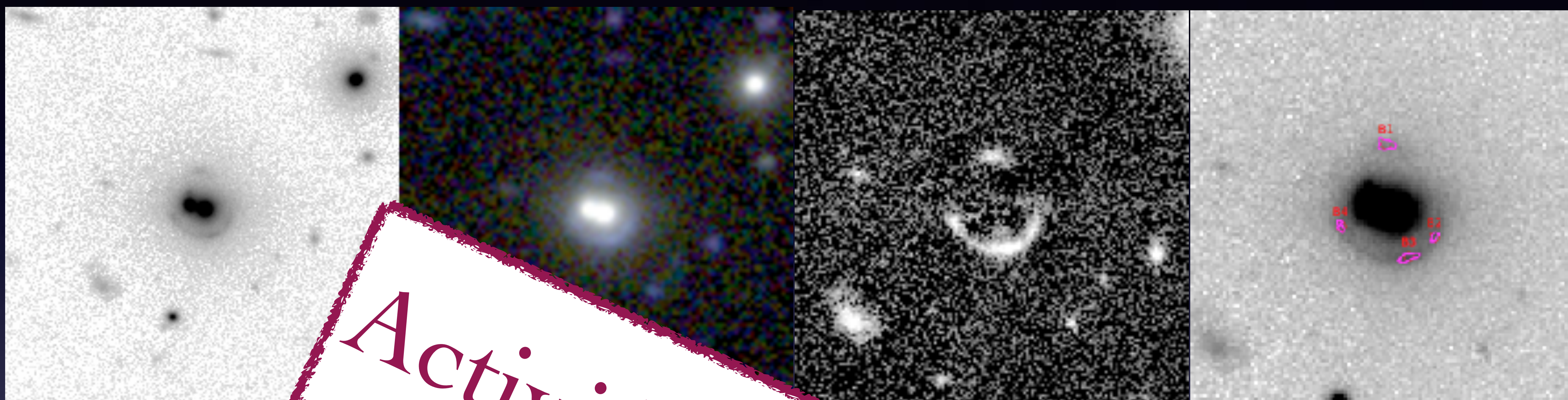


Anna Niemiec

- Instead of peak/multiple images, use the full information of the images
- Allows one to reconstruct source properties (often parametrically)
- Remove contamination from lens galaxy (with galfit) and mask other objects

Modeling the full light distribution of the images

CS82SL01:36:39+00:08:18



Anna Niemiec

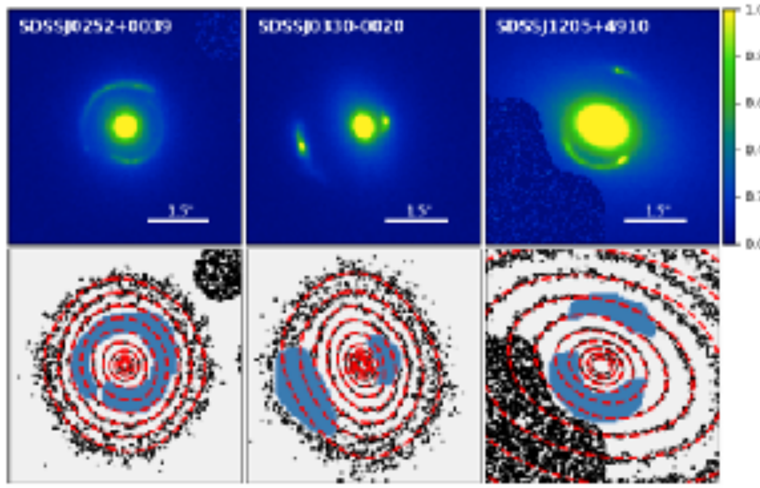
Actividad Práctica 7

- Instead of pea... use the full information of the im...
- Allows one to reconstruct so... erties (often parametrically)
- Remove contamination from lens galaxy (with galfit) and mask other objects

Inverse modeling with extended sources

Example code: PyAutoLens

Parametric light distribution for lenses



$$I_{\Gamma}(R,\theta) = \sum_{j=1}^{N} I_j \cdot \mathrm{Exp}\left(-\frac{R_i^2(x,y)}{2\sigma_i^2}\right)$$

$$R_i(x,y) = \sqrt{x'^2 + \left(\frac{y'}{q_i}\right)^2}$$

Elliptical Power-Law (EPL) projected mass density

$$k_{\alpha}(x,y) = \frac{\Sigma(\xi)}{\Sigma_{\mathrm{crit}}} = \frac{3-\alpha}{1+q}\left(\frac{b}{\xi}\right)^{\alpha-1}$$

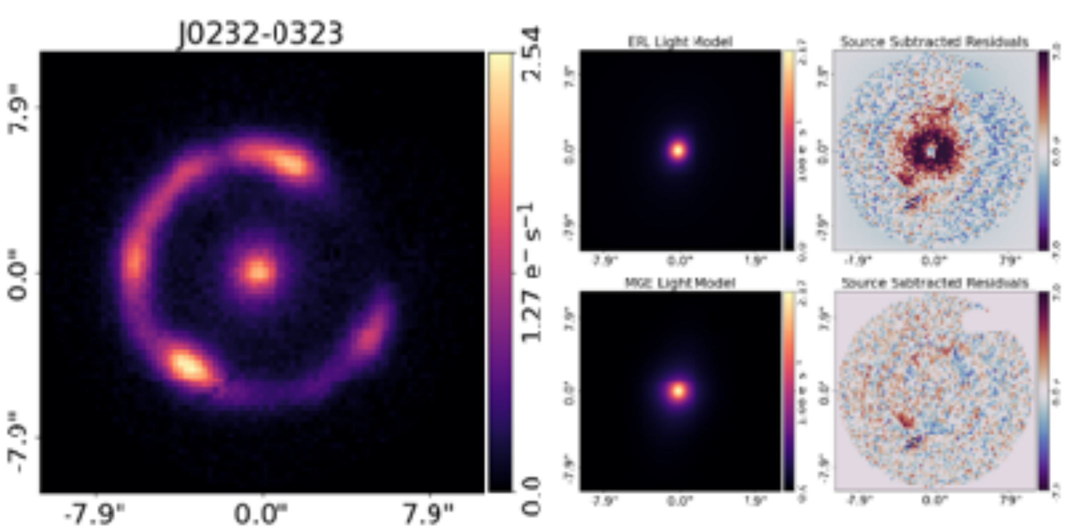
External shear

$$\gamma_1 = \frac{1}{2}\left(\frac{\partial^2\psi}{\partial\theta_1^2} - \frac{\partial^2\psi}{\partial\theta_2^2}\right)$$

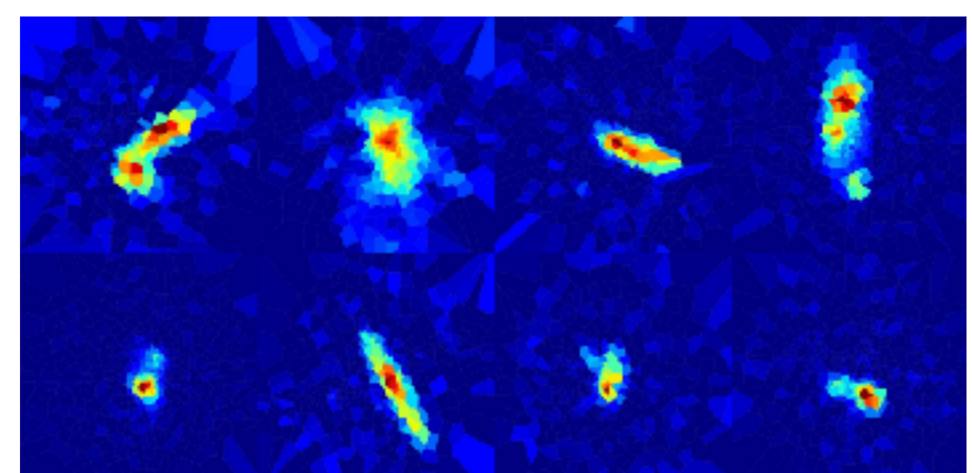
$$\gamma_2 = \frac{\partial^2\psi}{\partial\theta_1\partial\theta_2}$$

Total mass model is the sum of the two

MGE vs EPL on Lens light fitting on ground-based image modeling



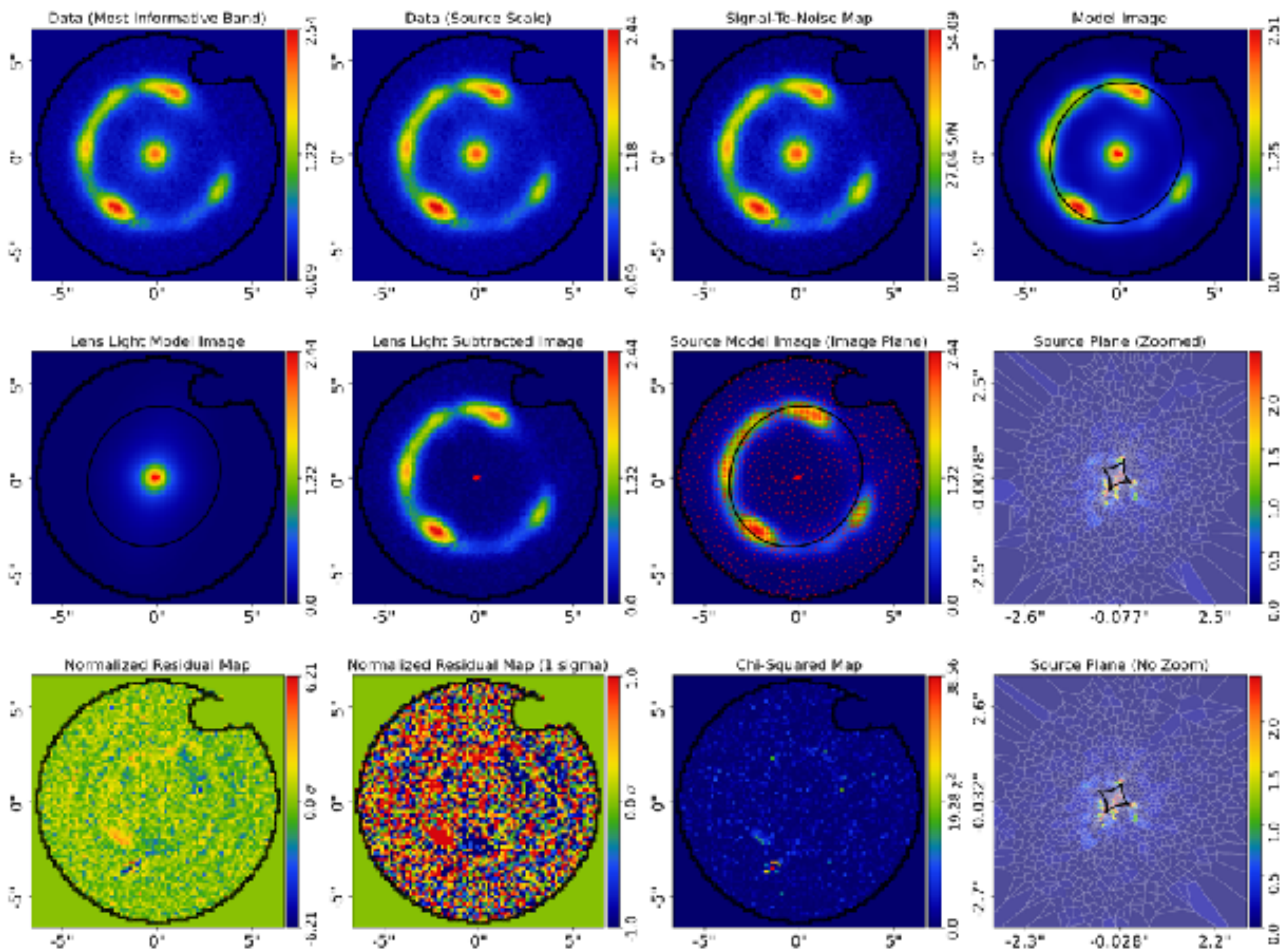
Voronoi adaptive pixelization for sources



Galan+; *arxiv:***2012.02802**

Source Lens and Mass (SLaM) pipelines

with PyAutoLens



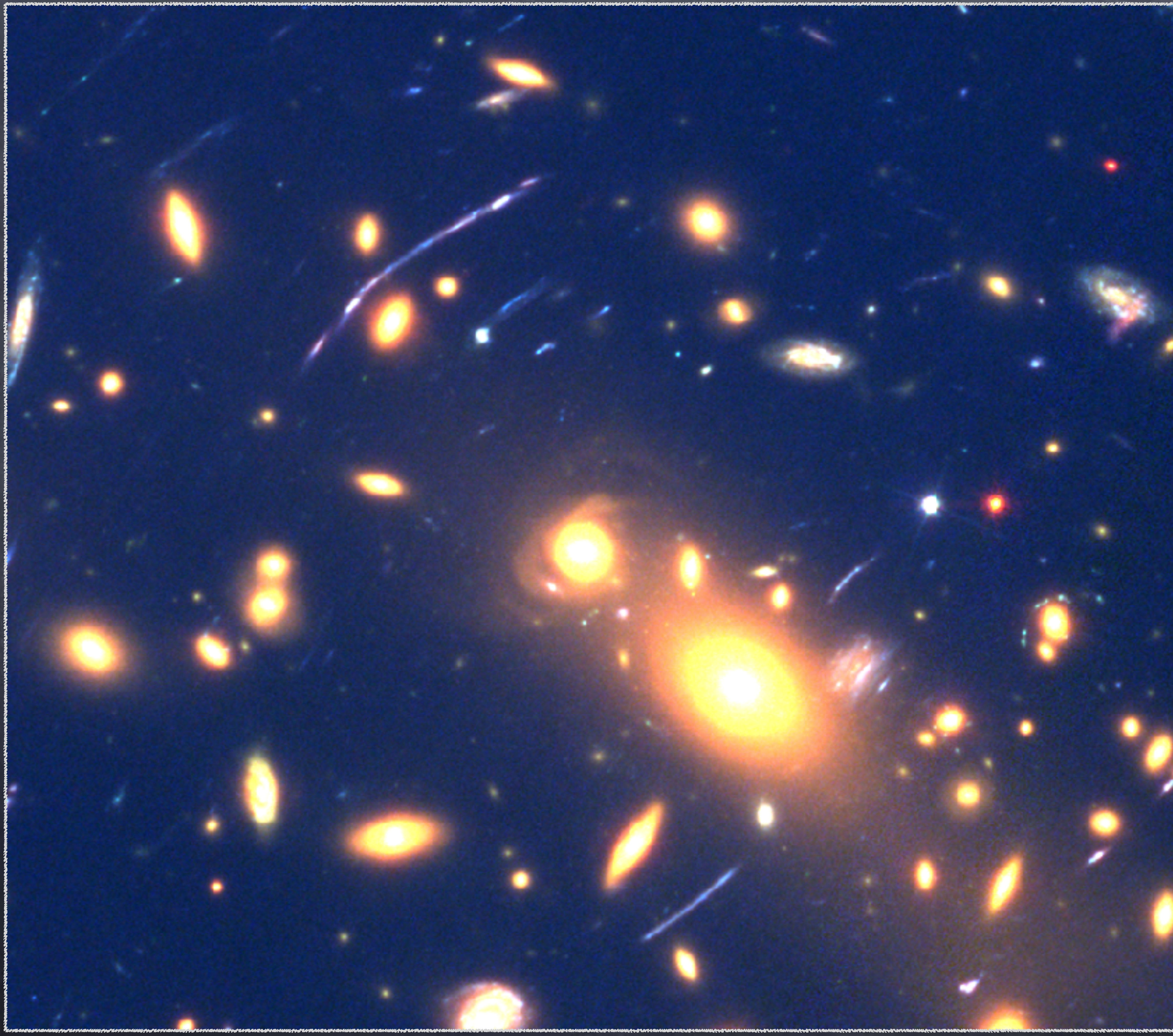
Session	Phase	Component	Model	Prior info
Source parametric	SP	Lens mass	SIE+Shear	-
		Lens light	MGE	-
		Source light	MGE	-
Source Inversion	SI1	Lens mass	SIE+Shear	SP
		Lens light	MGE	SP
		Source light	MPR	-
	SI2	Lens mass	SIE+Shear	SI1
		Lens light	MGE	SP
		Source light	BPR	-
Light Parametric	LP	Lens mass	SIE+Shear	SI1
		Lens light	MGE	SP
		Source light	BPR	SI2
Mass Total	MT	Lens mass	EPL+Shear	SI1
		Lens light	MGE	SP
		Source light	BPR	SI2

Regimes and Challenges

- Galaxy cluster scale
  - Complex mass models, but many families of multiple images
  - HST Data: Frontier Fields, CLASH, RELICS, etc.
  - + Massive spectroscopic follow-up (IFU/MUSE)
  - Cosmology from single systems + high-z sources
  - Limited to very massive lenses and few systems
  - Promising for particle DM properties!
- Galaxy scale systems
  - Simple mass modes, but few constraints
  - Also HST imaging, but few IFU data (e.g. Gemini/NIFS)
  - Promising for Modified Gravity!
- Statistics
  - Spin-off from cosmological surveys:

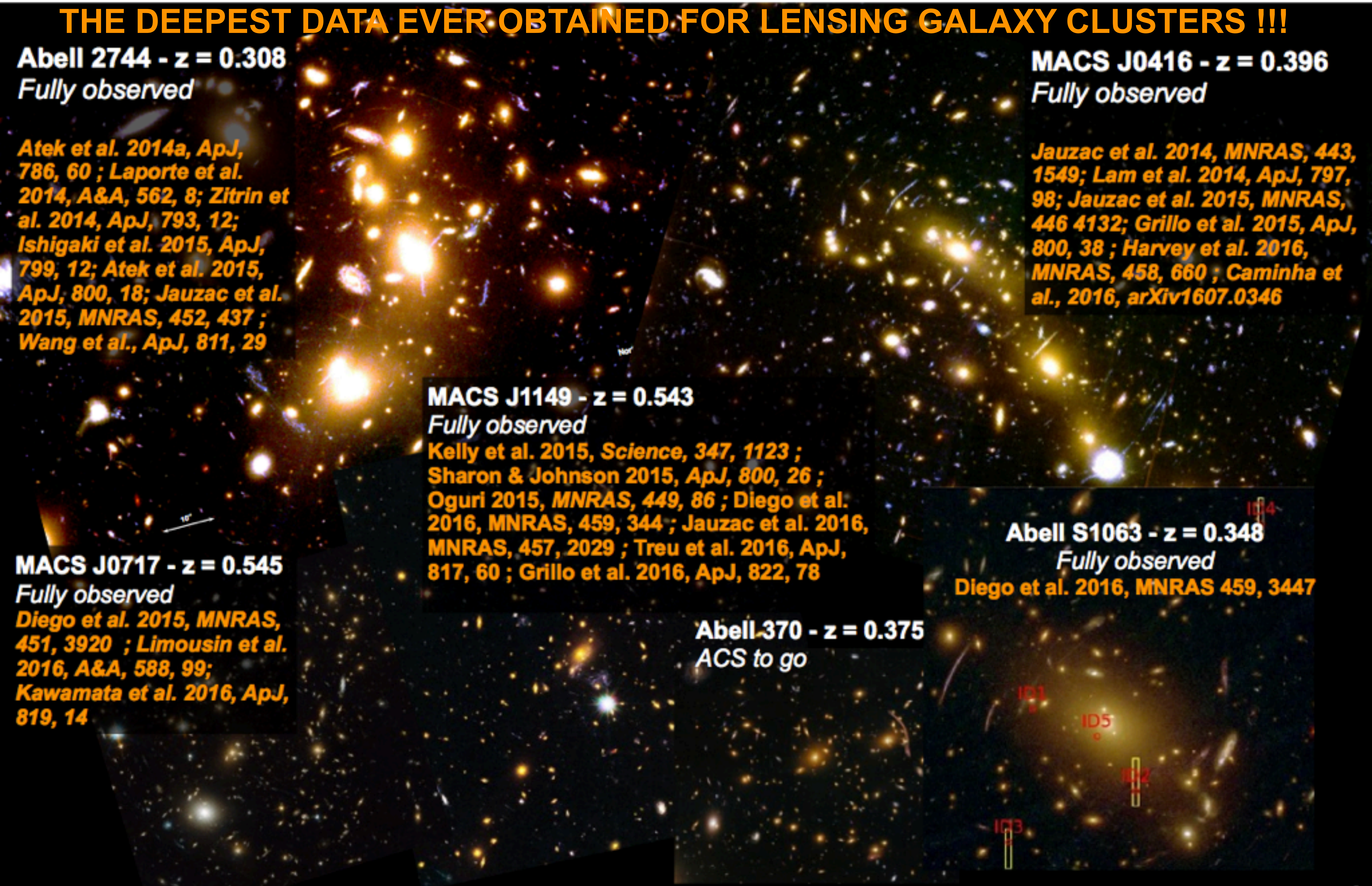
    $\mathcal{O}(10^{1\text{-}2}) \rightarrow \mathcal{O}(10^{3\text{-}5})$
  - Need to find these systems!
    - Automated arc finders
  - Understand selection function.
    - Use simulations
  - Need to automate analyses!
- Challenge: Systematics
  - Use simulations ➔ end-to-end approach
  - Test modeling at the data level. Independent tests: predictions x SN!
  - Improve models from data: LSS/los, IFU, etc.

Cúmulos de galaxias



THE *HST* FRONTIER FIELDS

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

¿Cómo se arma un modelo de cúmulos de galaxias?

- Modelos paramétricos: distribución de masa compuesta de
  - Uno o más halos de materia oscura para el cúmulo
  - Un halo para cada galáxia con relaciones empíricas de escaleo (exponente, radio de corte, etc.) $M = M_c(L/L_\star)^\gamma$
- Datos: posiciones de las imágenes múltiples (más parámetros: posiciones de las fuentes), o distribución de brillo superficial
- Hoy: datos de HST para los cúmulos más masivos, $\mathscr{O}(10)$ sistemas + JWST
- Futuro/actualidad: Euclid, Roman + ULTRASET, CSST, CASTOR
- Software: LensPerfect, LensTool, GLAFIC, Gravlens, Glee, HERCULENS…

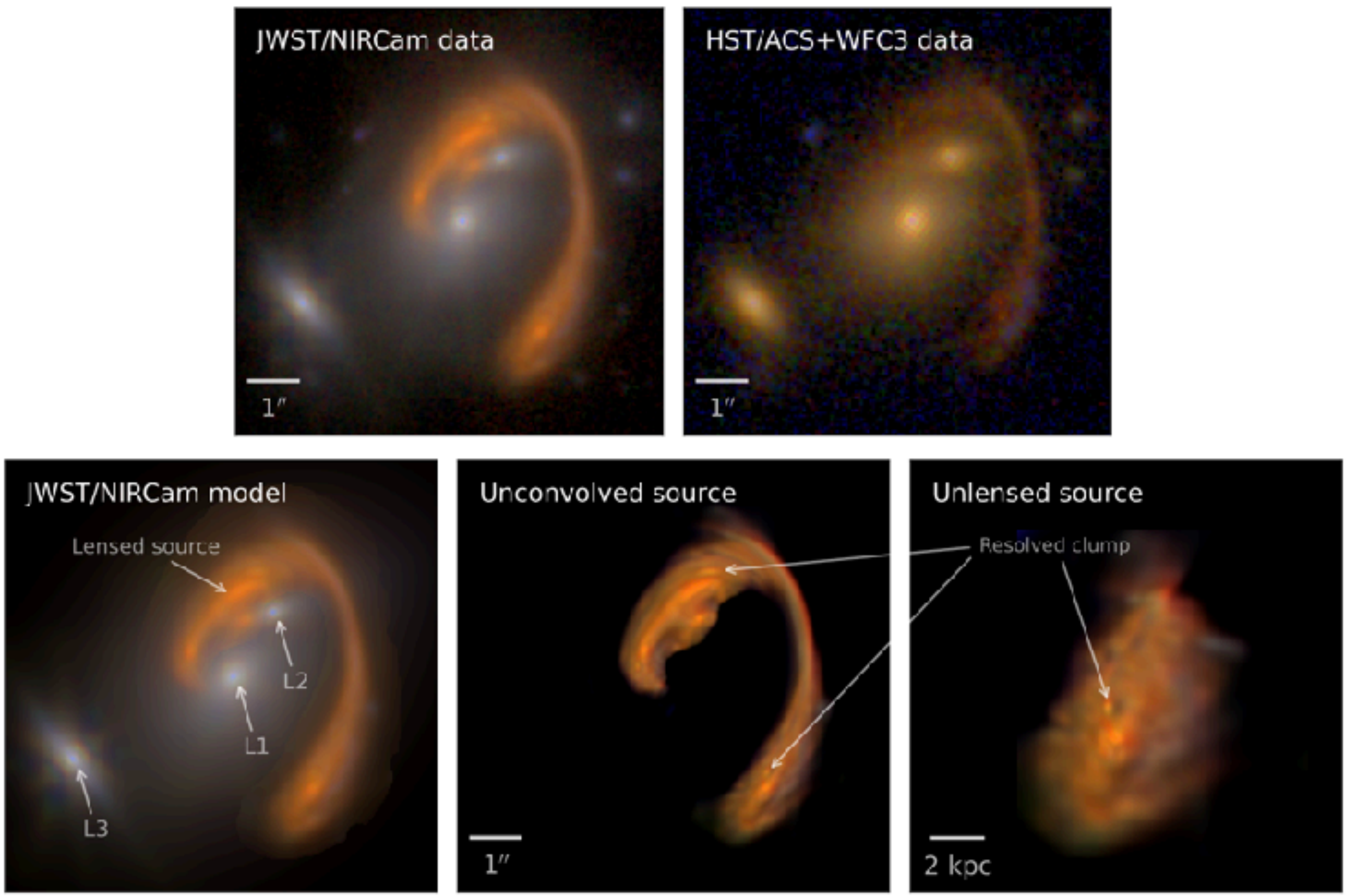

Cúmulo de galaxias El Gordo (ACT-CL J0102-4915, SPT-CL J0102-4915) observado con el JWST

A&A, 689, A304 (2024)
https://doi.org/10.1051/0004-6361/202449876

Astronomy & Astrophysics

El Gordo needs El Anzuelo: Probing the structure of cluster members with multi-band extended arcs in JWST data

A. Galan[1,2,⋆], G. B. Caminha[1,2], J. Knollmüller[1,3,4], J. Roth[5,2,6], and S. H. Suyu[1,2]



Reconstrucción de la fuente usando el modelo de lente

Dark Energy from Families of Multiple Images

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

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

☑ 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), 17 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

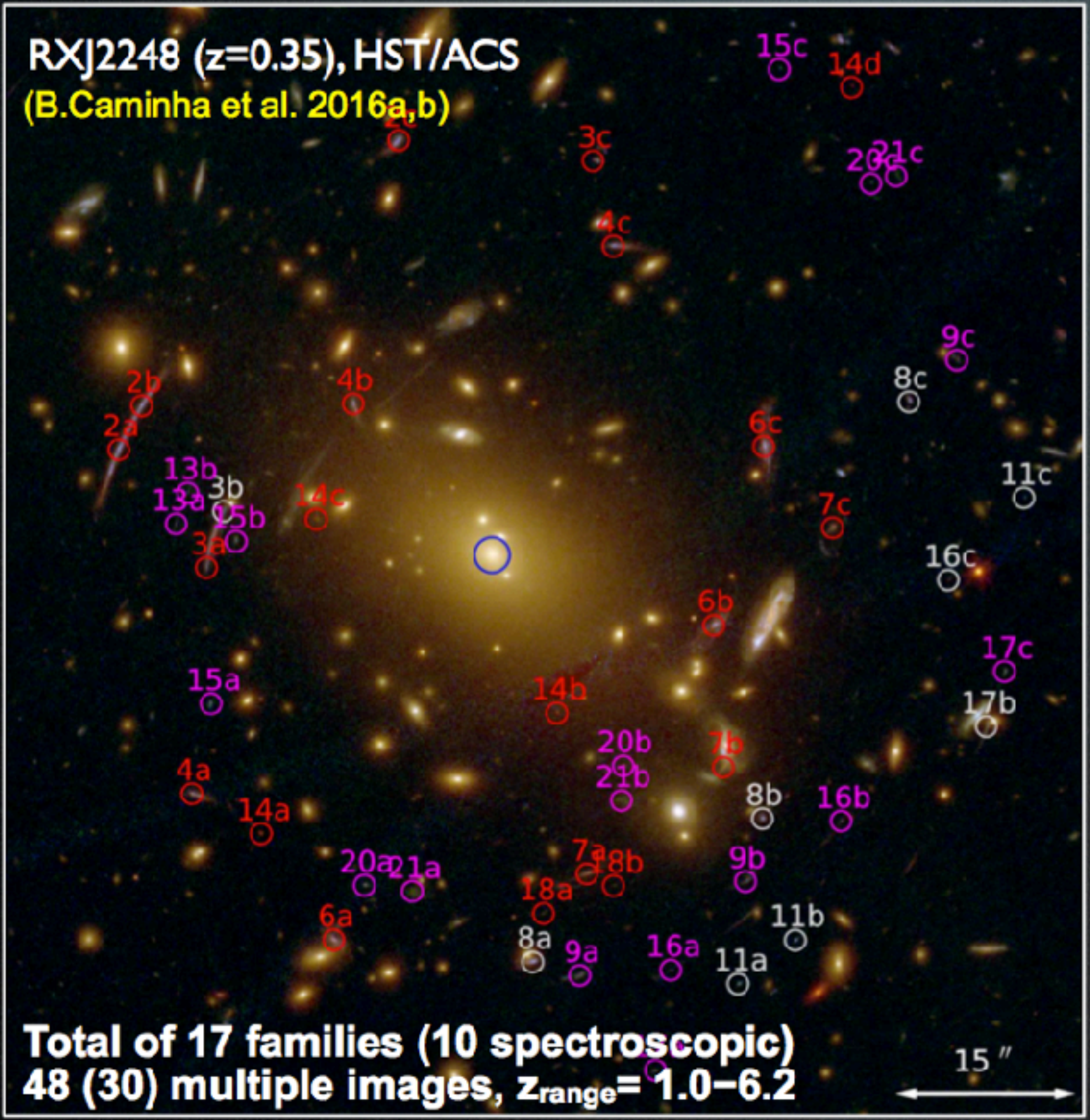
$$D_A\left(z_1, z_2\right) = \frac{\left(1+z_2\right)^{-1}}{H_0}\int_{z_1}^{z_2}\frac{dz'}{\sqrt{\Omega_M(1+z')^3 + \left(1-\Omega_M\right)\left(1+z'\right)^{3(1+w)}}}$$

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

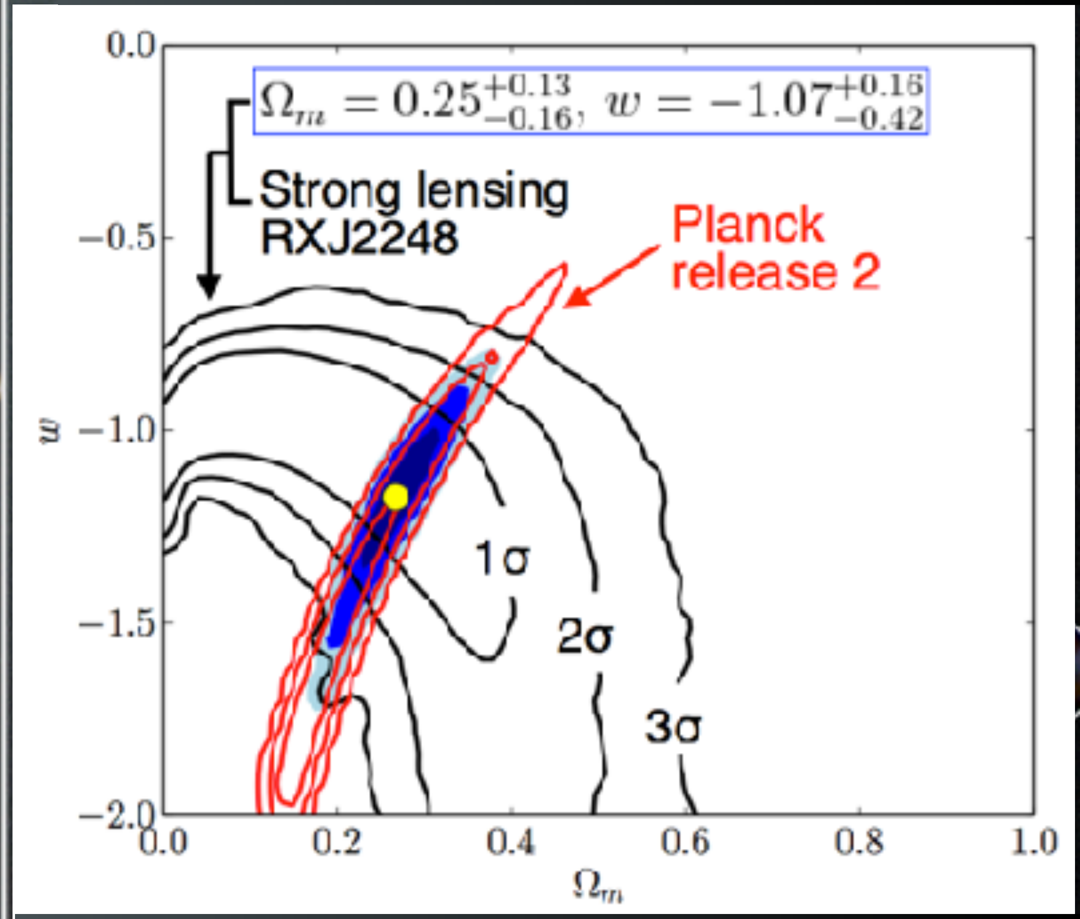
Cosmological Constraints

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)

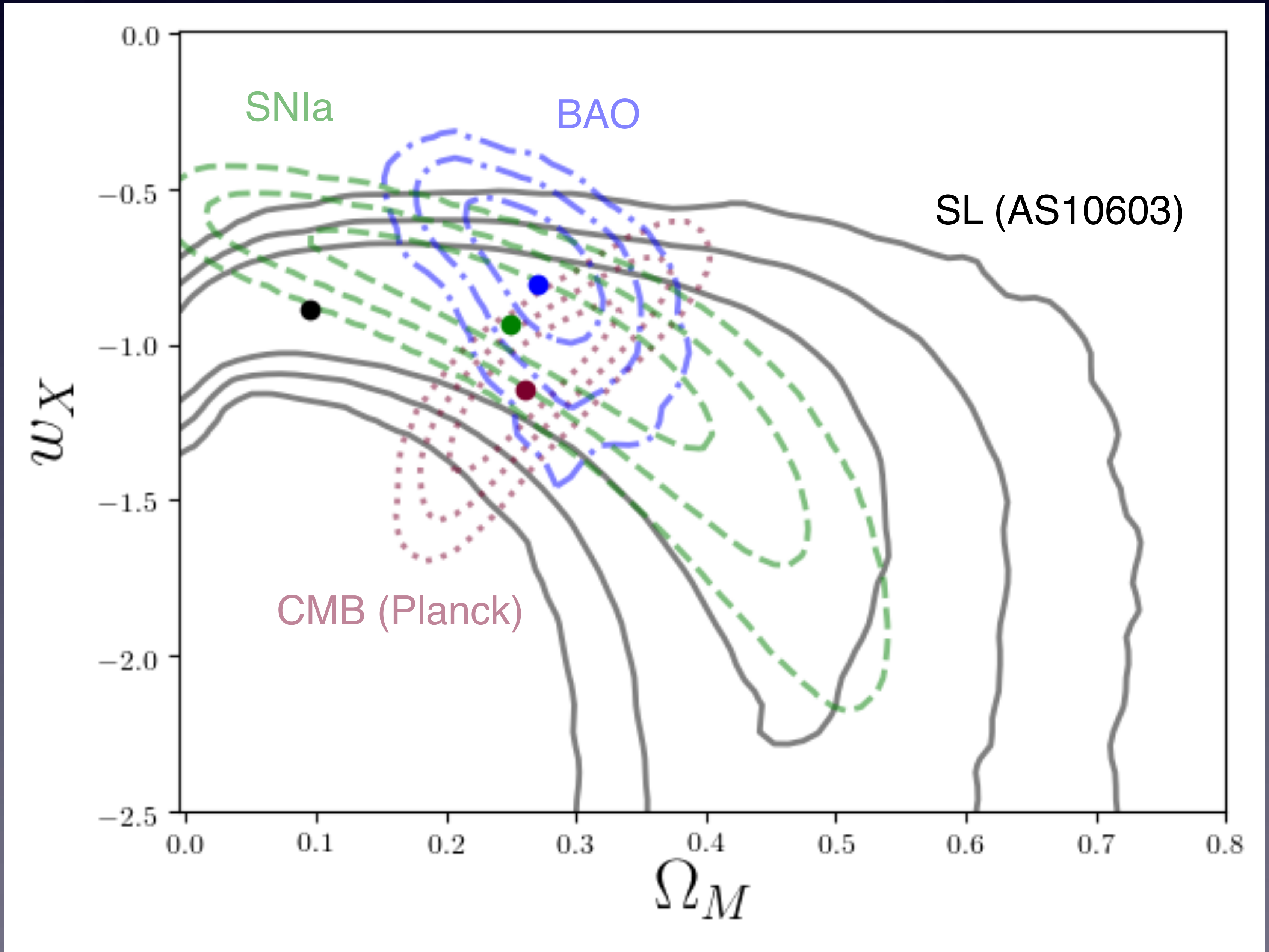


1 arcmin² FoV
2.6 Å resolution (4800-9300 Å)
0.2 arcsec/pxl
Exp. = 5 hrs

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 (2022, in prep.)



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 %