PROBING THE DARK UNIVERSE WITH GRAVITATIONAL LENSING

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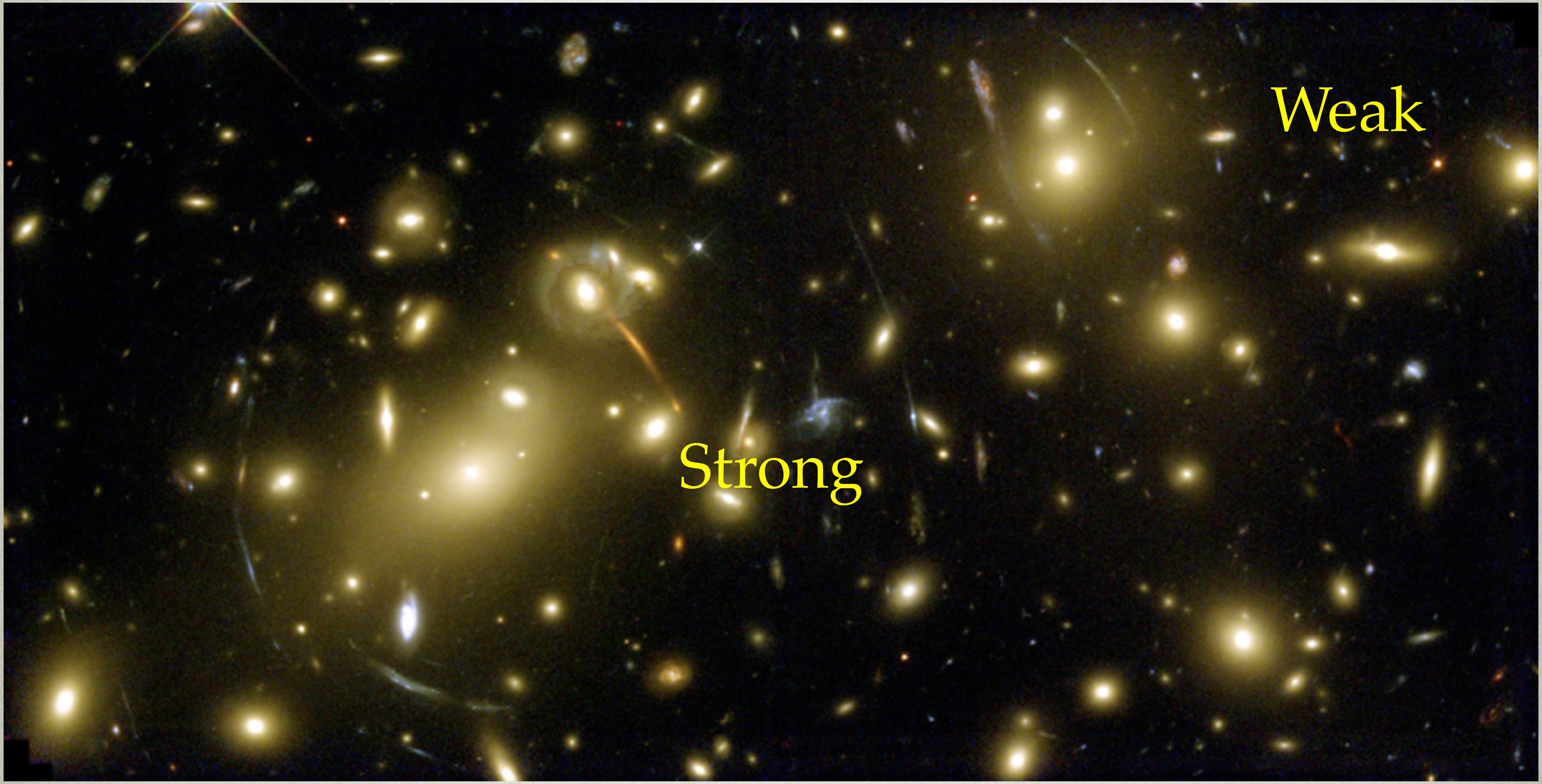
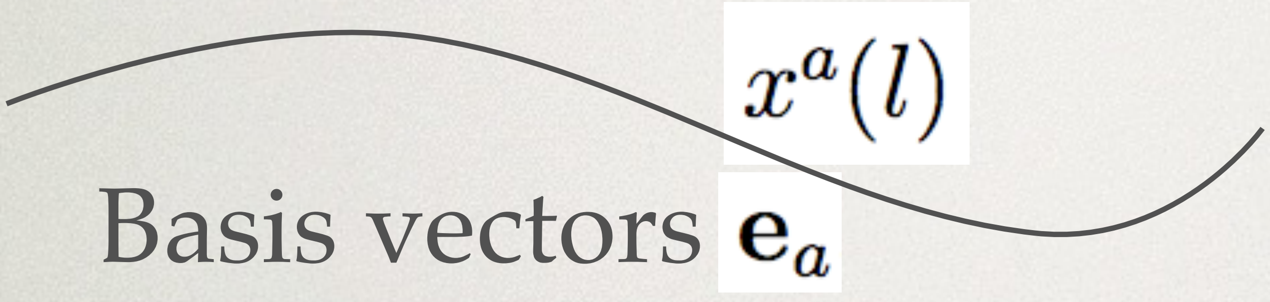
GRAVITATIONAL LENSING



Abell 2218 (Draco)
Cluster of galaxies 2 billion light years away,
background galaxies 6 billion light years away

Geodesic equation

Ray:



$x^a(l)$

Basis vectors $\mathbf{e}_a$

Tangent vector

$$\mathbf{t} = \frac{dx^a}{dl}\mathbf{e}_a$$

This is parallel transported along ray, so

$$\frac{dt_a}{dl} - \Gamma^b_{ac} t_b \frac{dx^c}{dl} = 0$$

We can rewrite this as

$$\boxed{\frac{dt_a}{dl} = \frac{1}{2} g_{cd,a} t^c t^d}$$

c.f. geometrical optics:

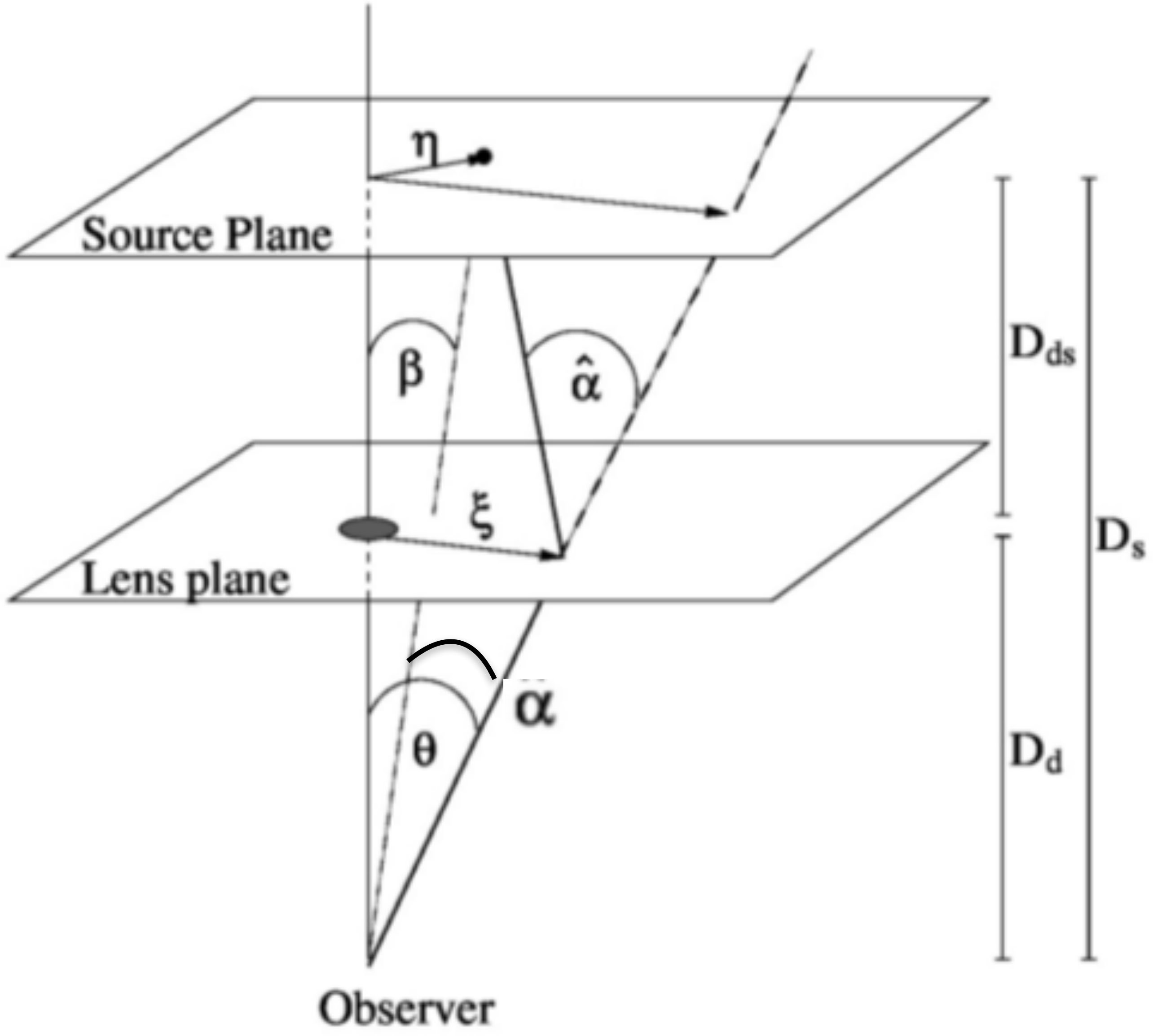
$$\frac{d\mathbf{t}}{dl} = \frac{\nabla_\perp n}{n}$$

or $\Psi+\Phi$

Perturbed FRW:

$$\boxed{n = 1 - \frac{2\Phi}{c^2}}$$

Lens geometry



[Schneider et al. 2006]

$$ds^2 = -(1+2\Psi)dt^2 + (1+2\Phi)a^2\delta_{ij}dx^i dx^j$$

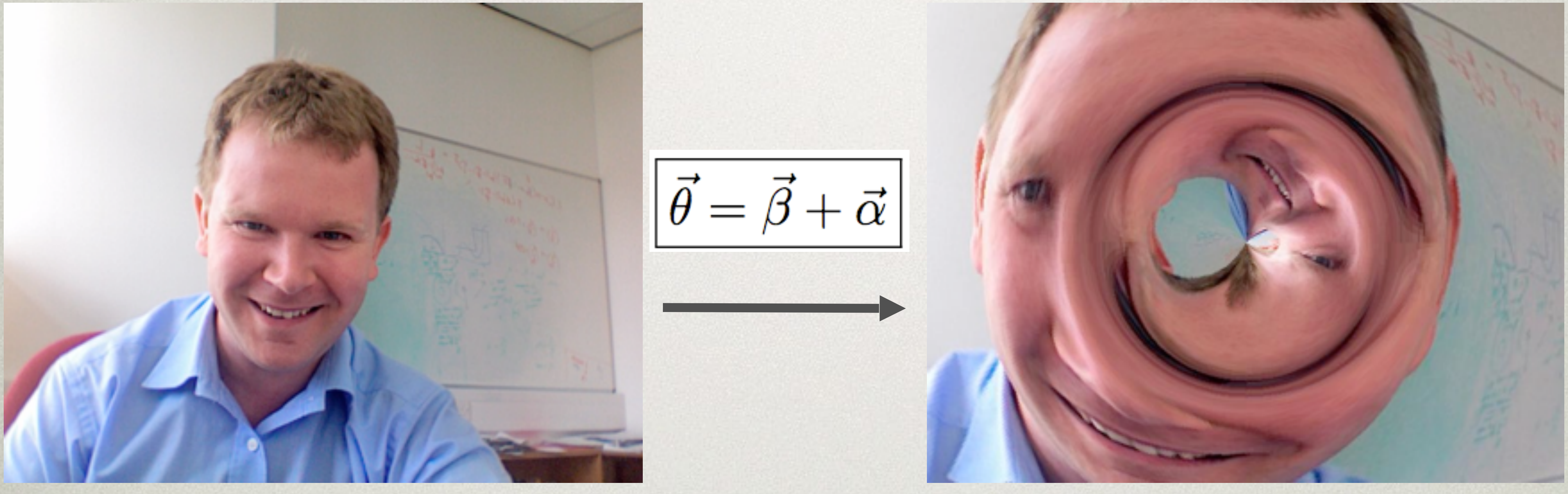
For perturbed FRW, plus Born approximation,

$$\hat{\boldsymbol{\alpha}}(\boldsymbol{\xi}) = \frac{4G}{c^2}\int \mathrm{d}^2\xi' \underbrace{\int \mathrm{d}r_3'\,\rho(\xi_1',\xi_2',r_3')}_{\Sigma(\boldsymbol{\xi}')}\frac{\boldsymbol{\xi}-\boldsymbol{\xi}'}{|\boldsymbol{\xi}-\boldsymbol{\xi}'|^2}$$

$$\boxed{\boxed{\vec{\theta} = \vec{\beta} + \vec{\alpha}}}$$

Lens equation

RAYTRACING



$$\boxed{\vec{\theta} = \vec{\beta} + \vec{\alpha}}$$

Bend angle varies from place to place

→ gradient of angle gives distortions

STRONG LENSING

Jacobian matrix:

$$\mathcal{A}_{ij} = \frac{\partial \beta_i}{\partial \theta_j}$$

Source plane

Image plane

Magnification factor:

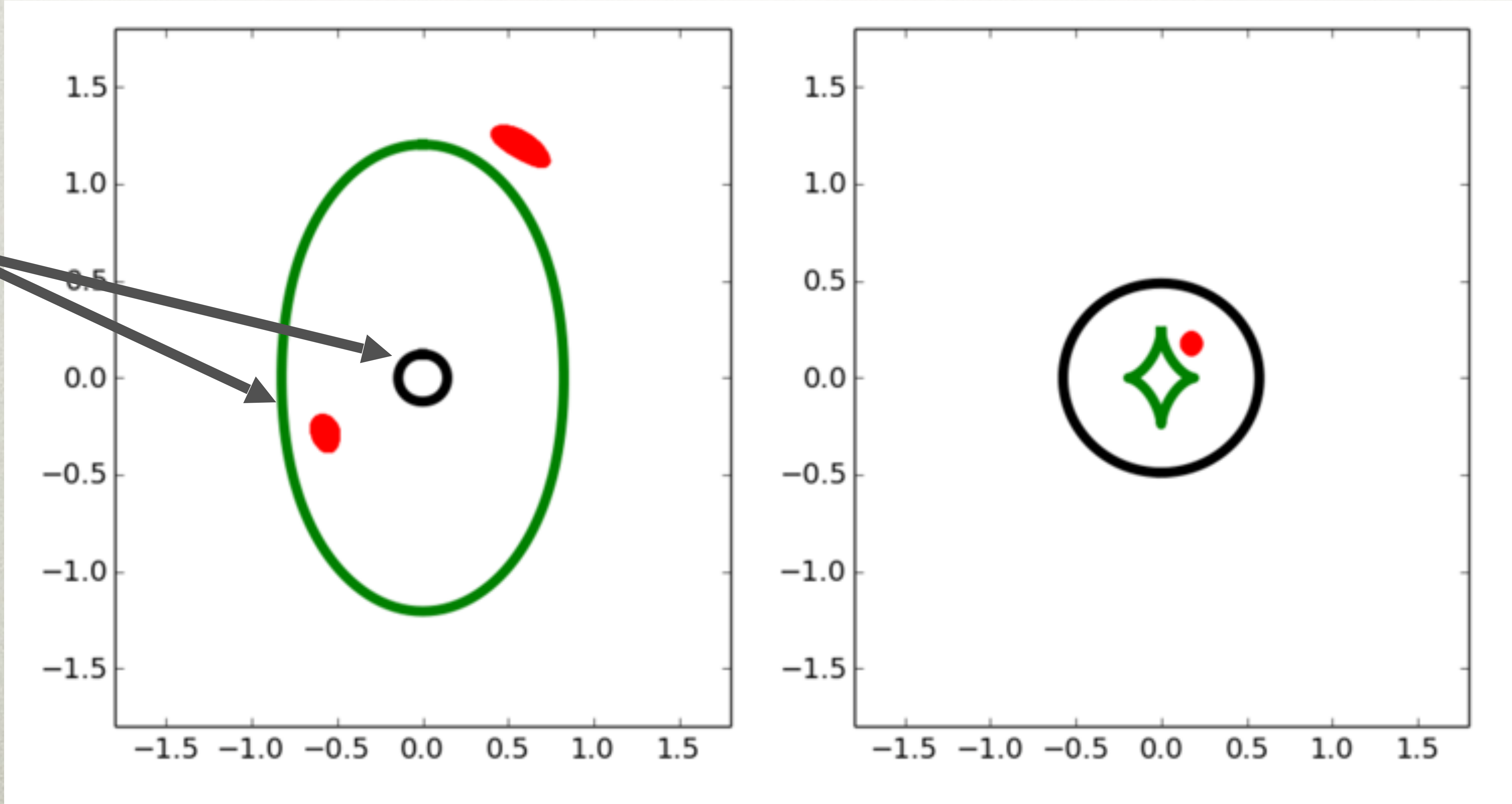
$$\mu(\boldsymbol{\theta}) = \frac{1}{\det \mathcal{A}(\boldsymbol{\theta})}$$

So det A = 0 gives critical curves of high magnification

MULTIPLE IMAGES

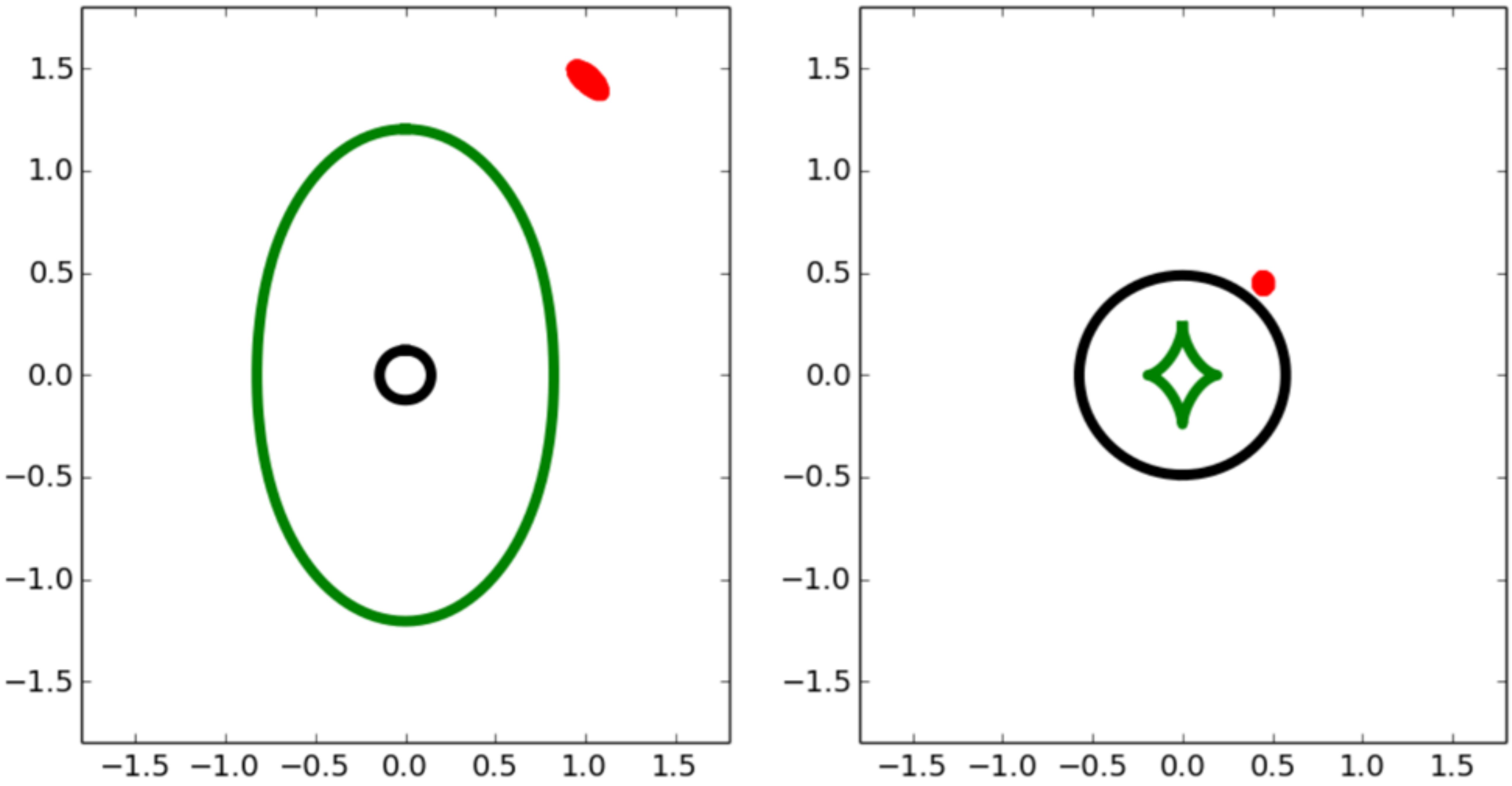
e.g. Isothermal ellipsoid:

$$\kappa_{\text{lens}}(\boldsymbol{x}) = \frac{2-\eta}{2}\left(\frac{\theta_E}{qx_1^2 + x_2^2/q}\right)^{\eta}$$



det A = 0

from Tom Collett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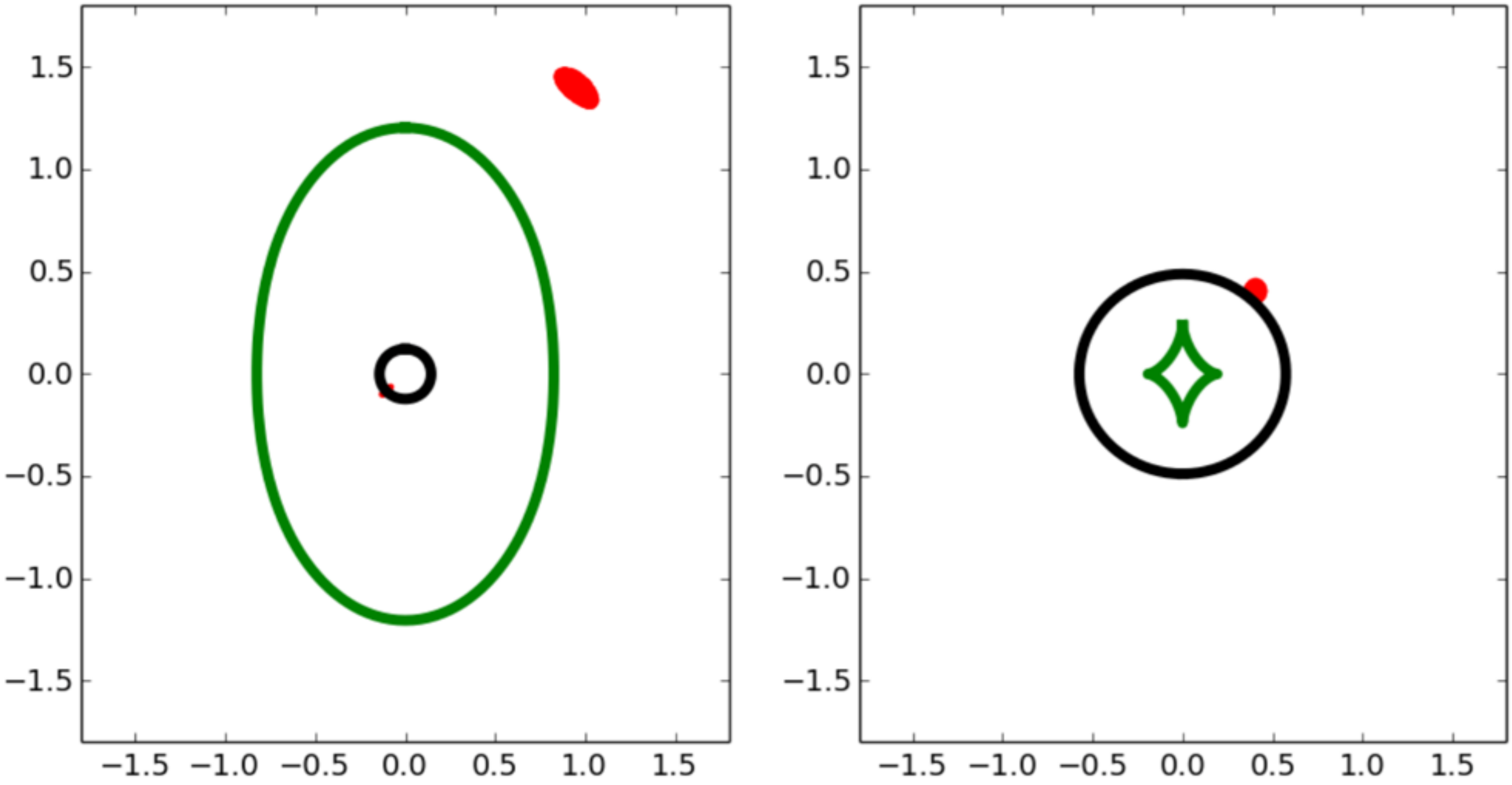
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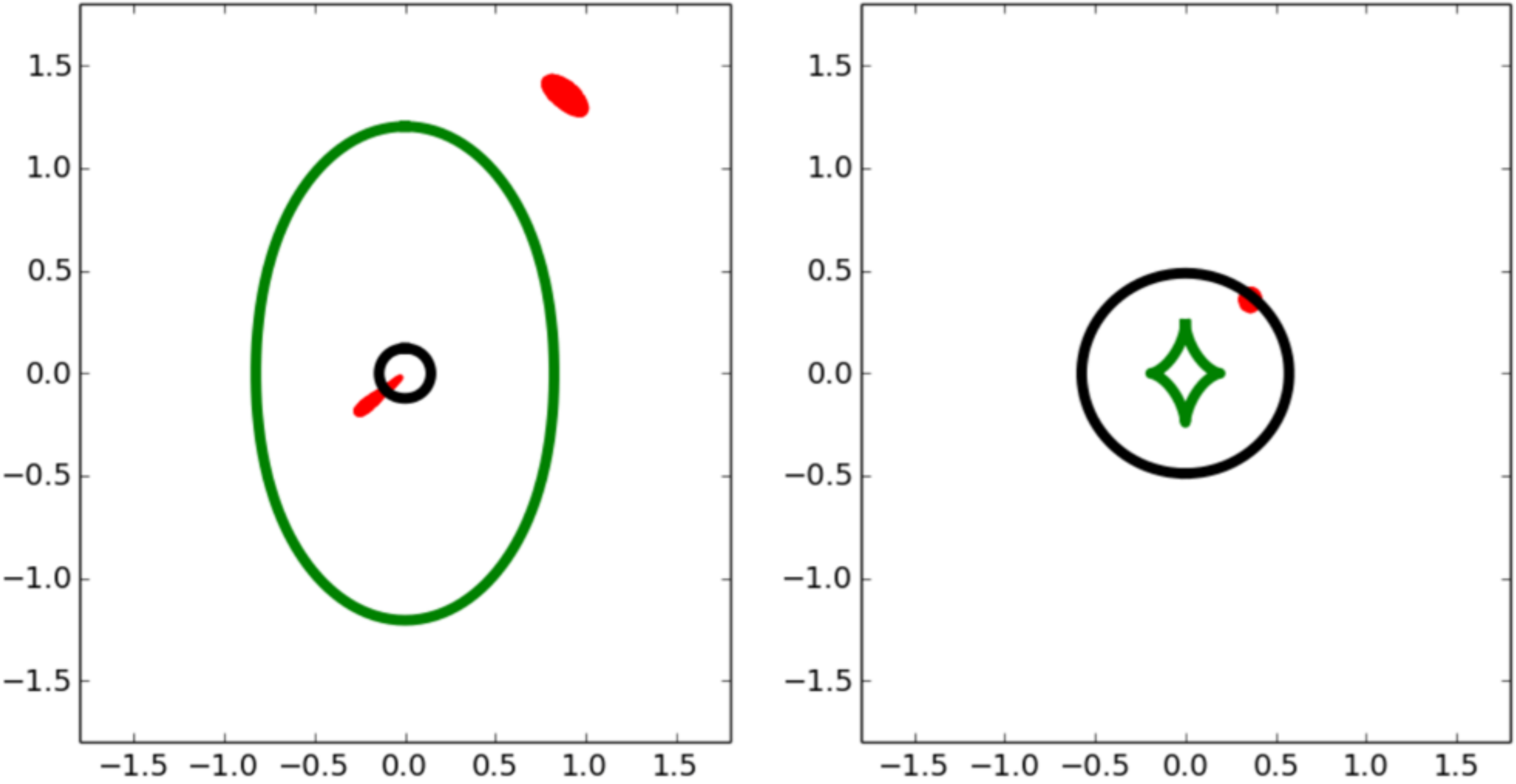
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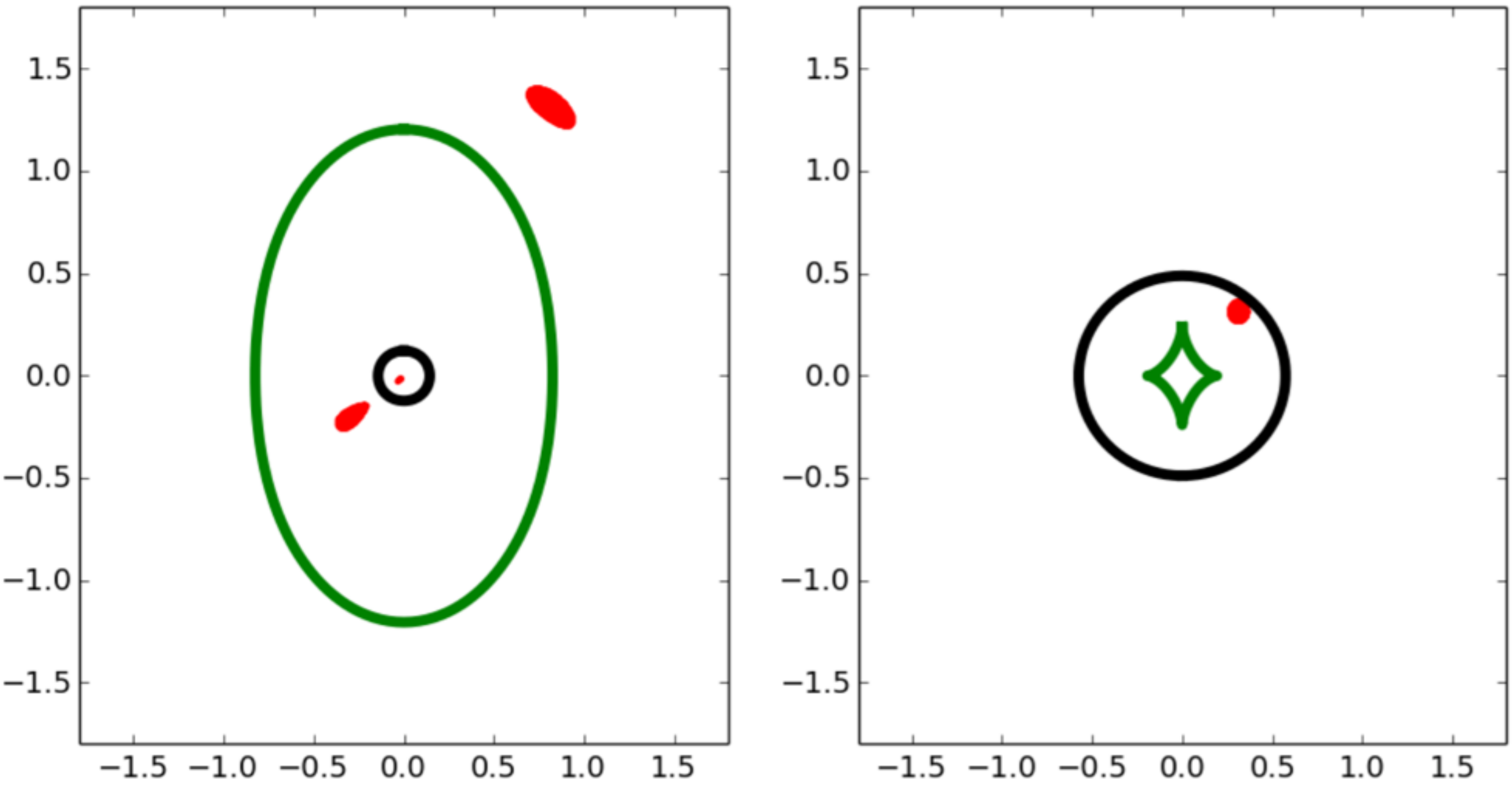
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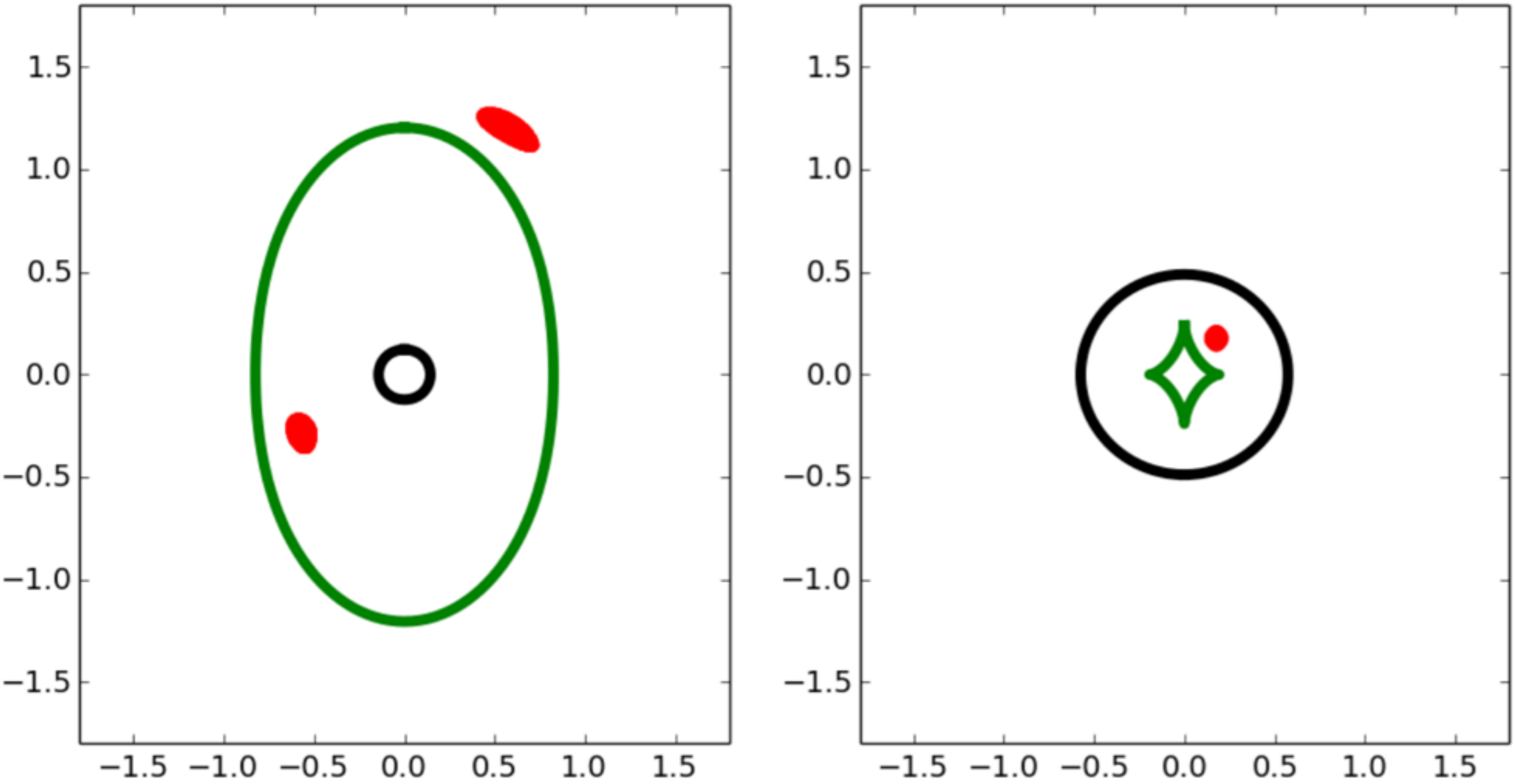
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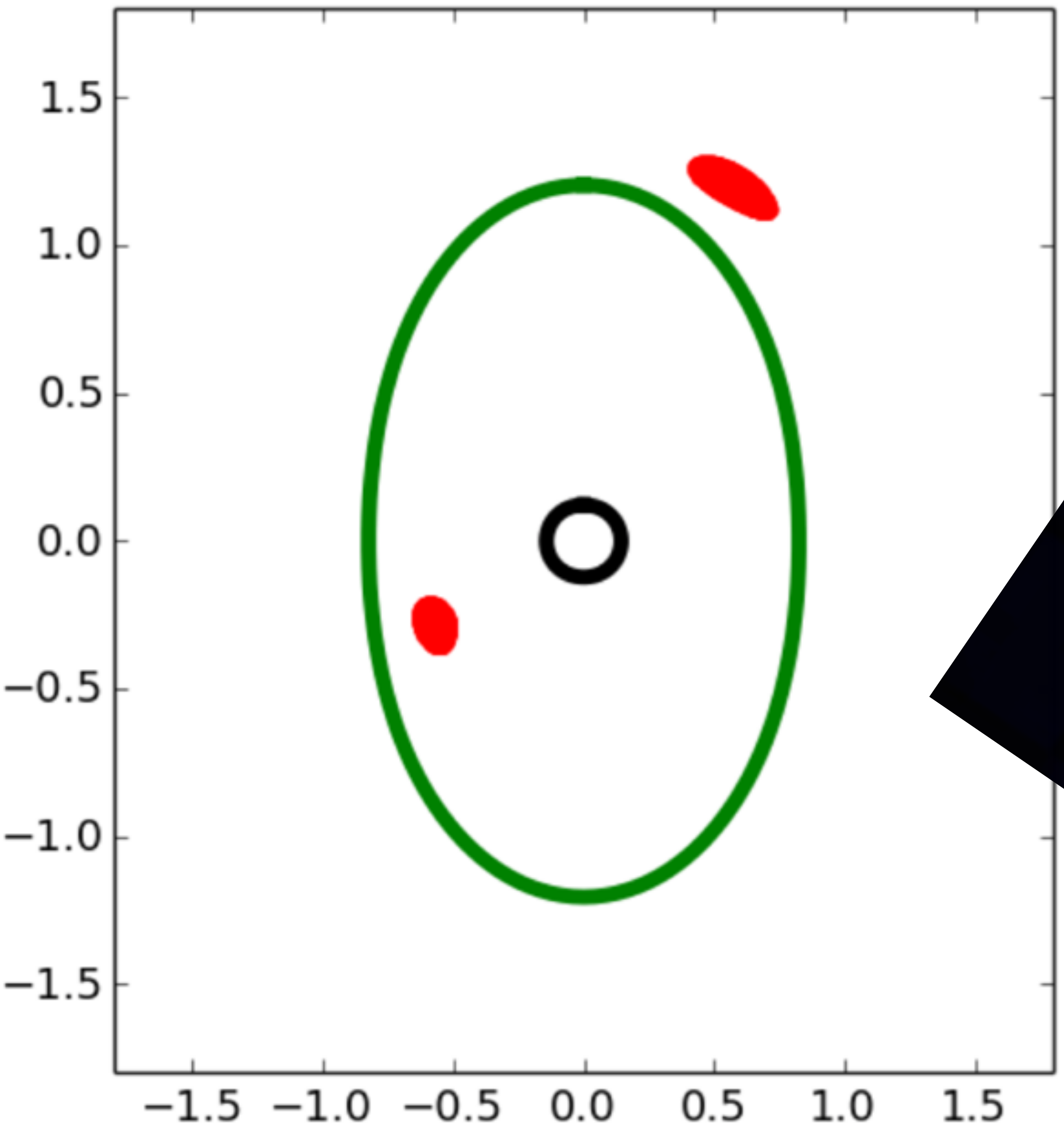
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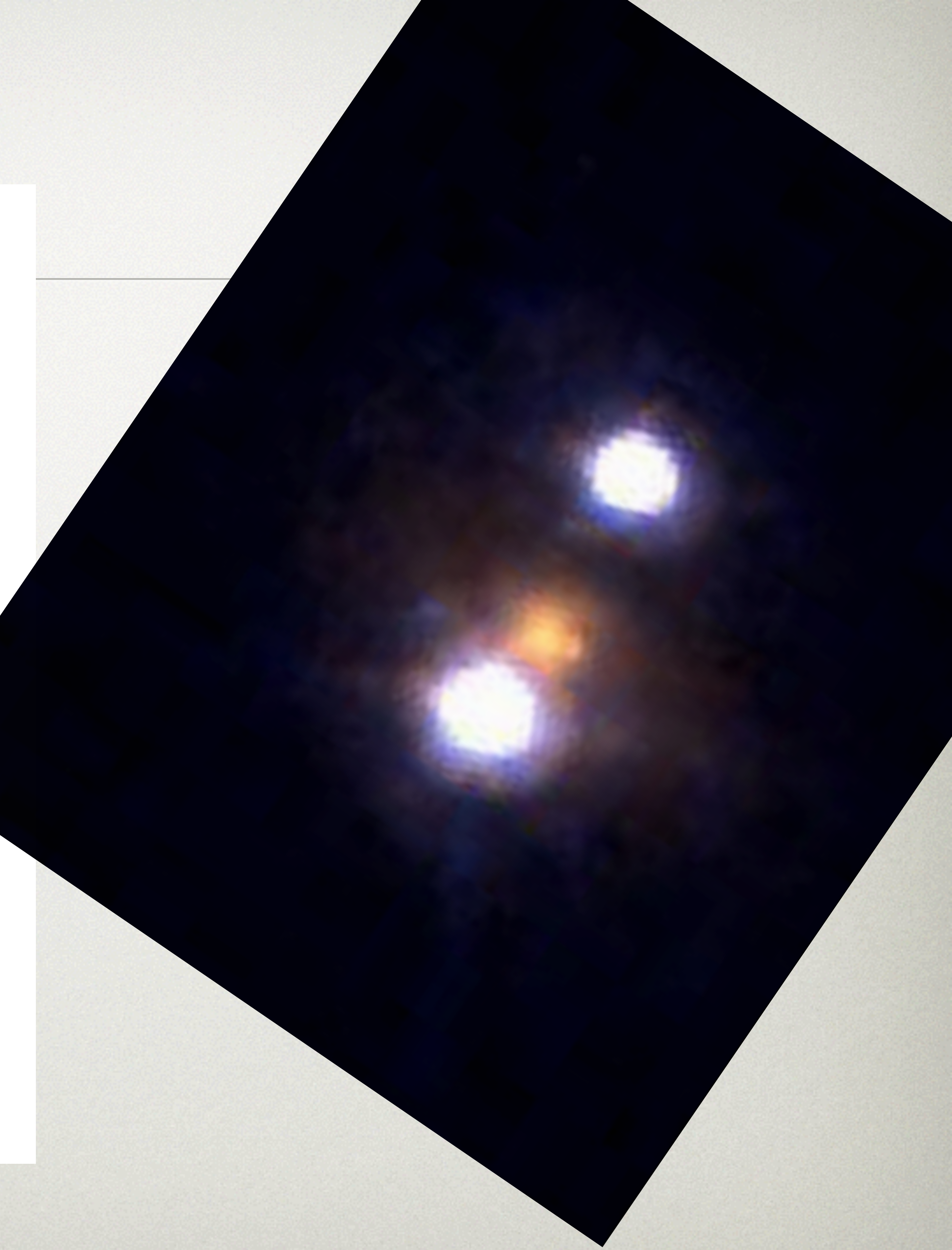

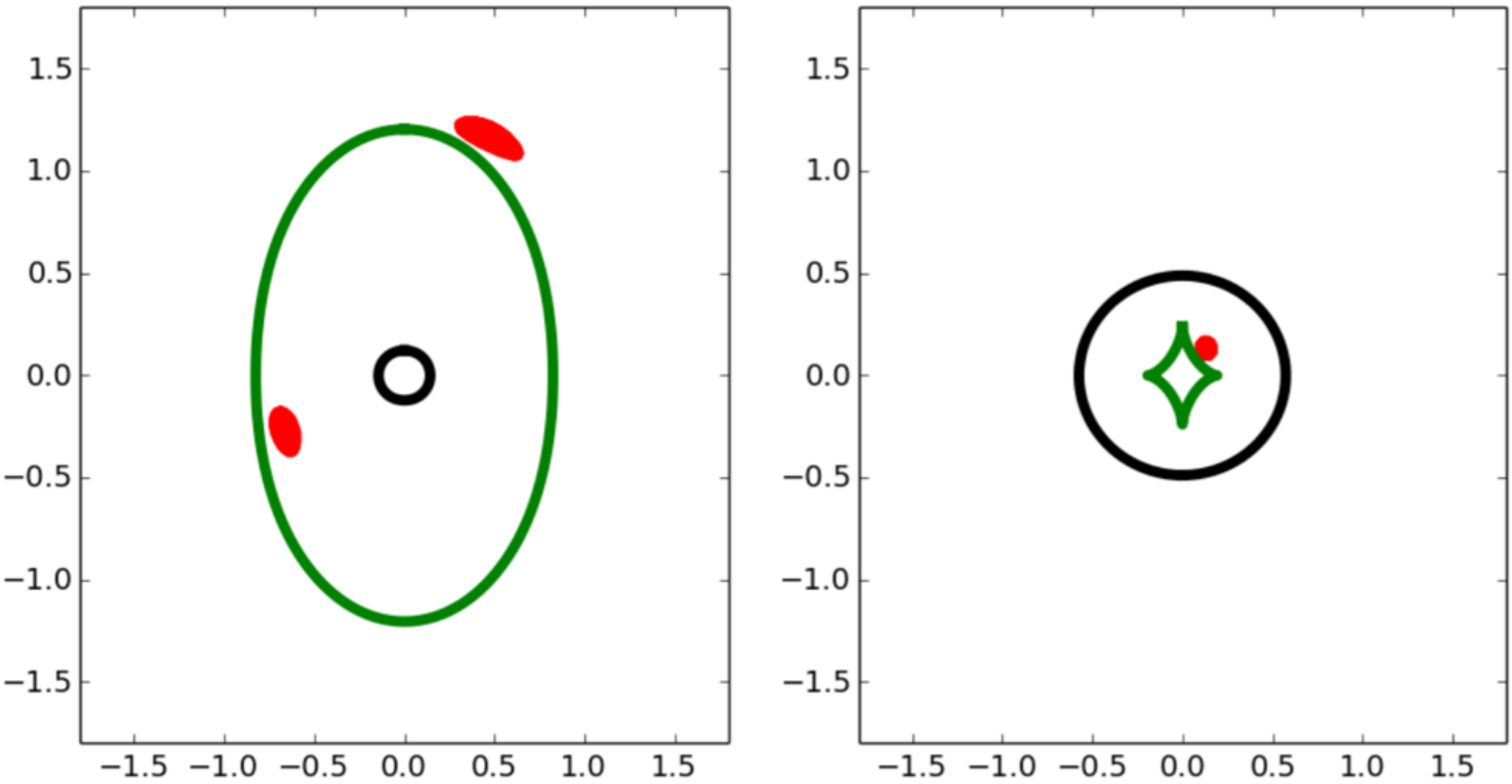
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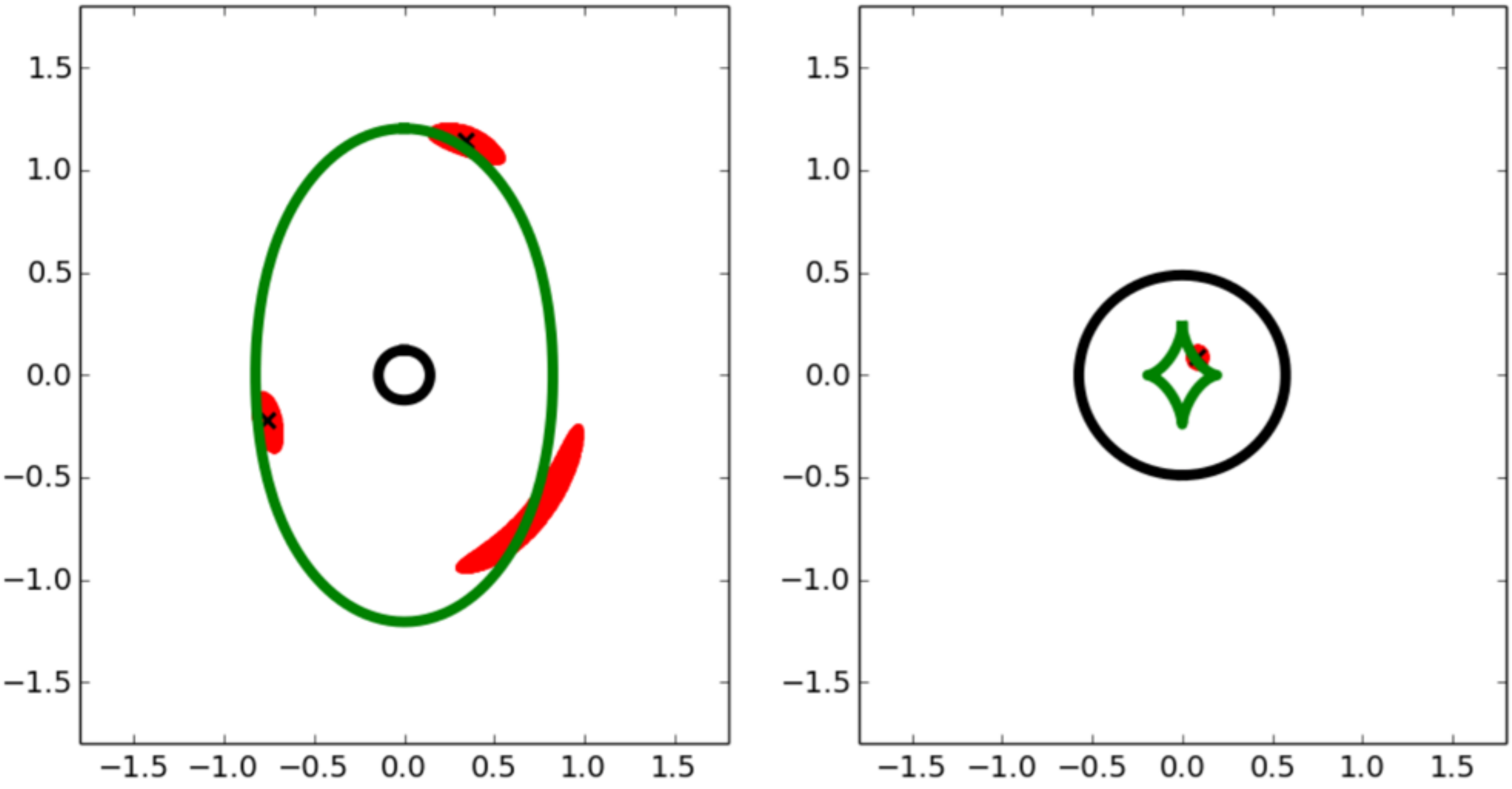
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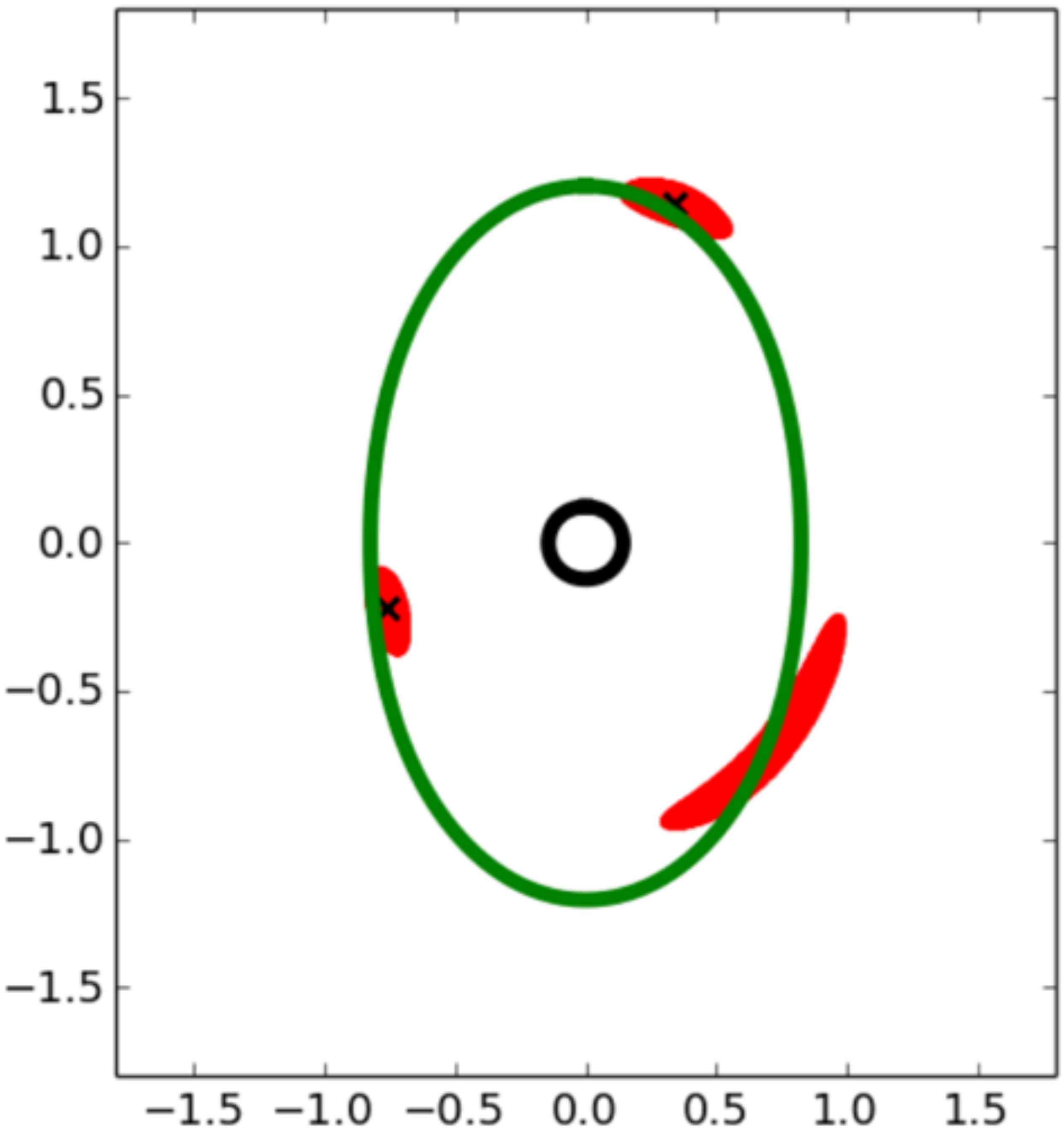
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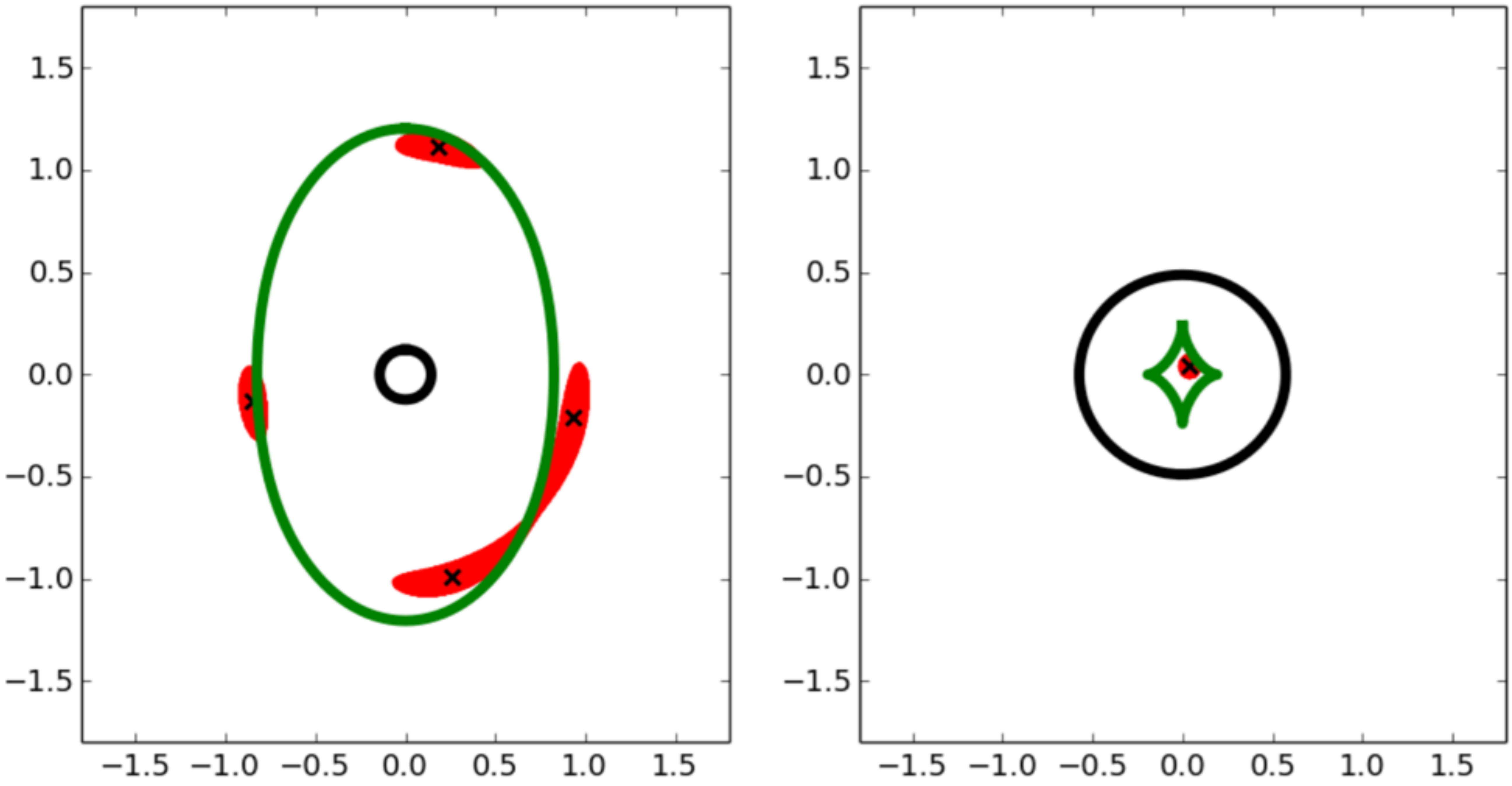
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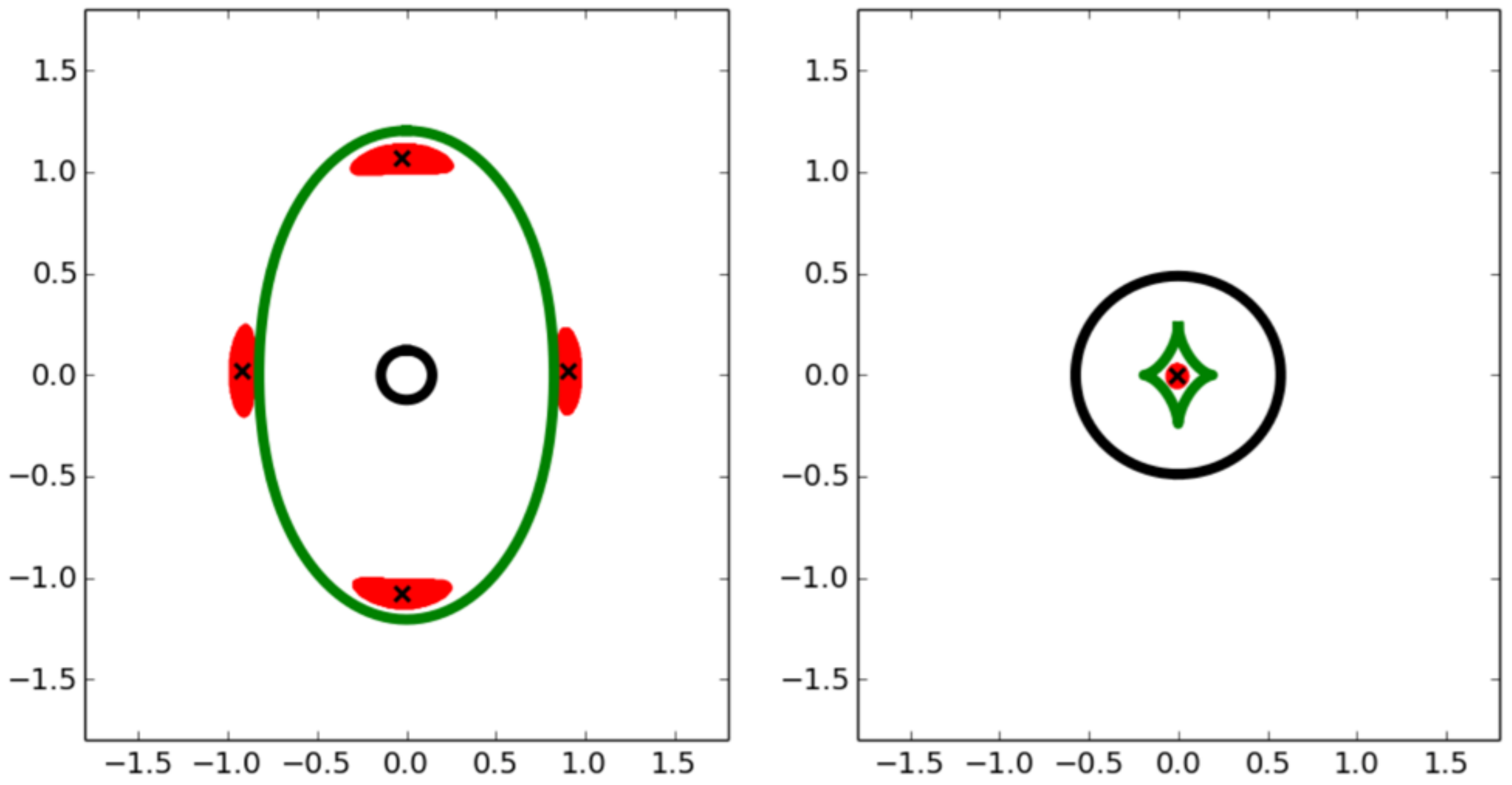
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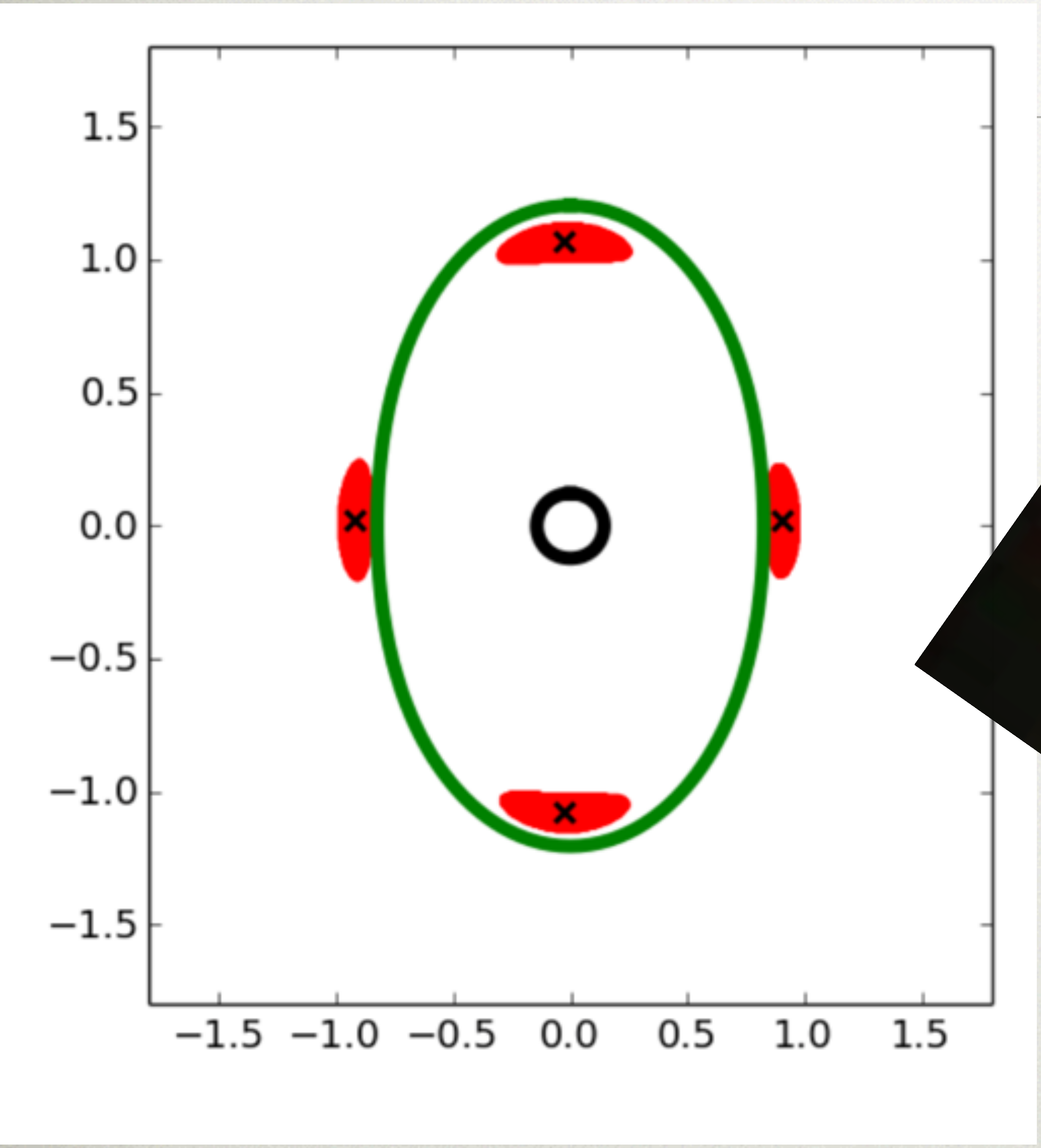
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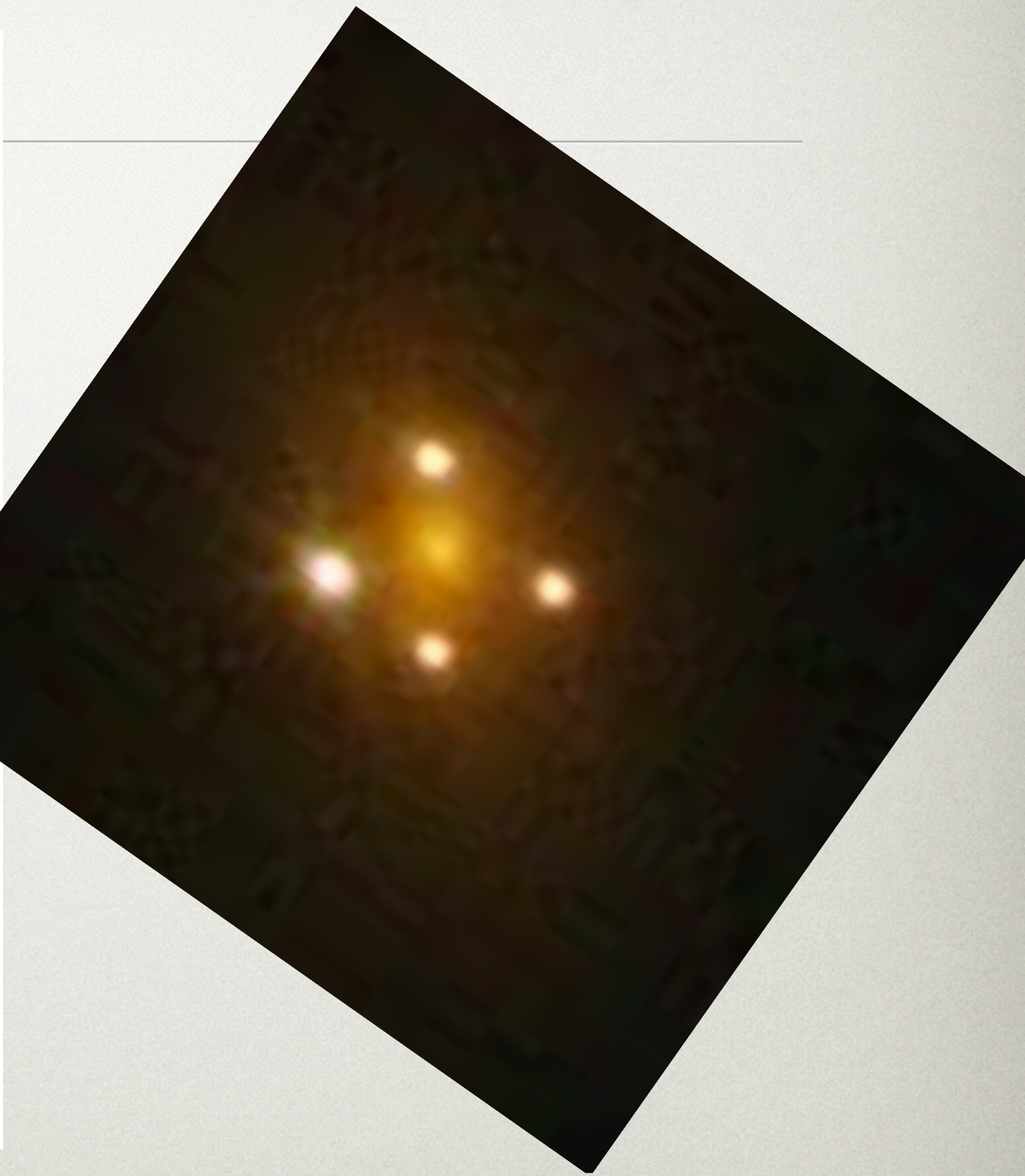

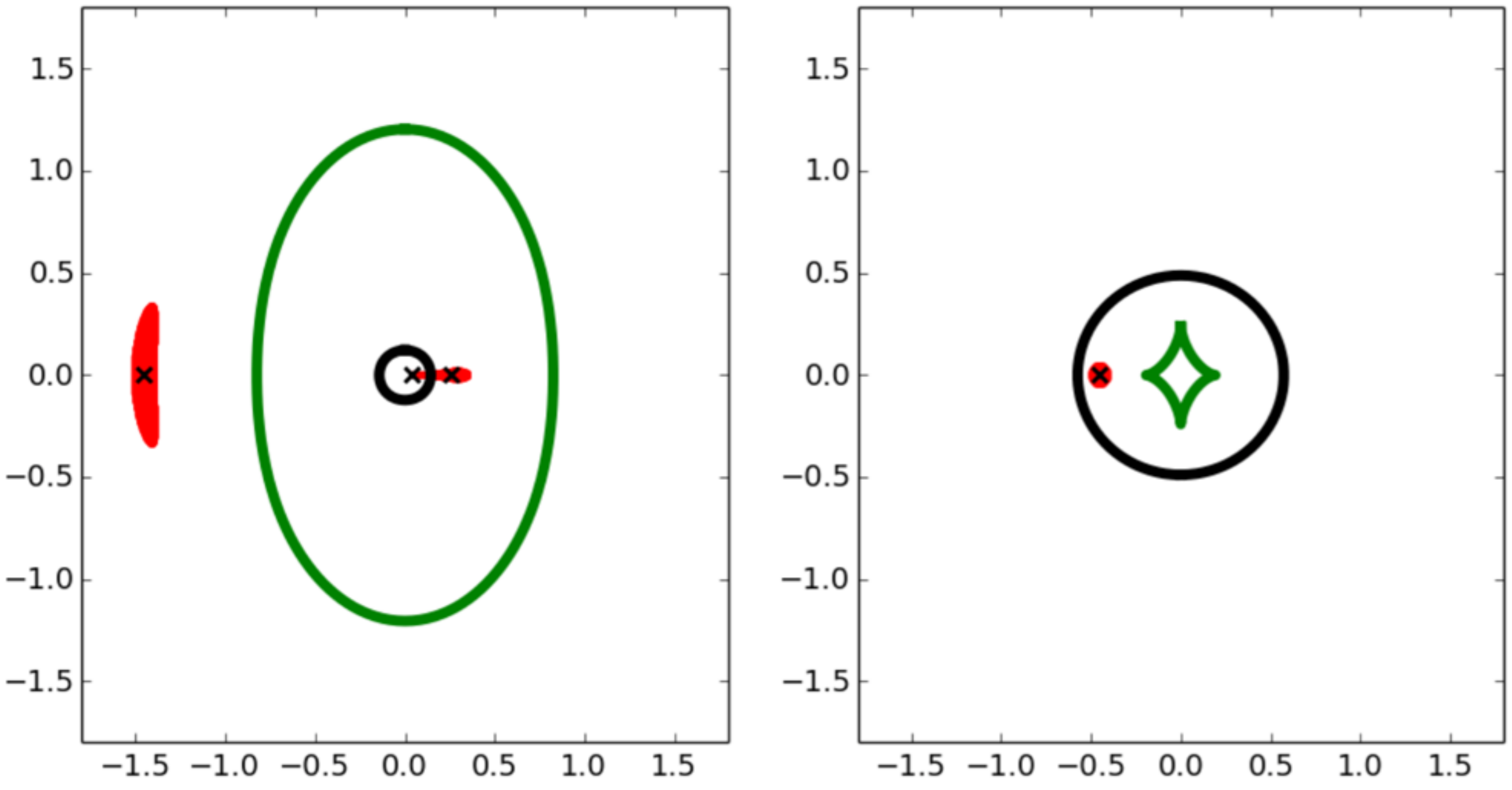
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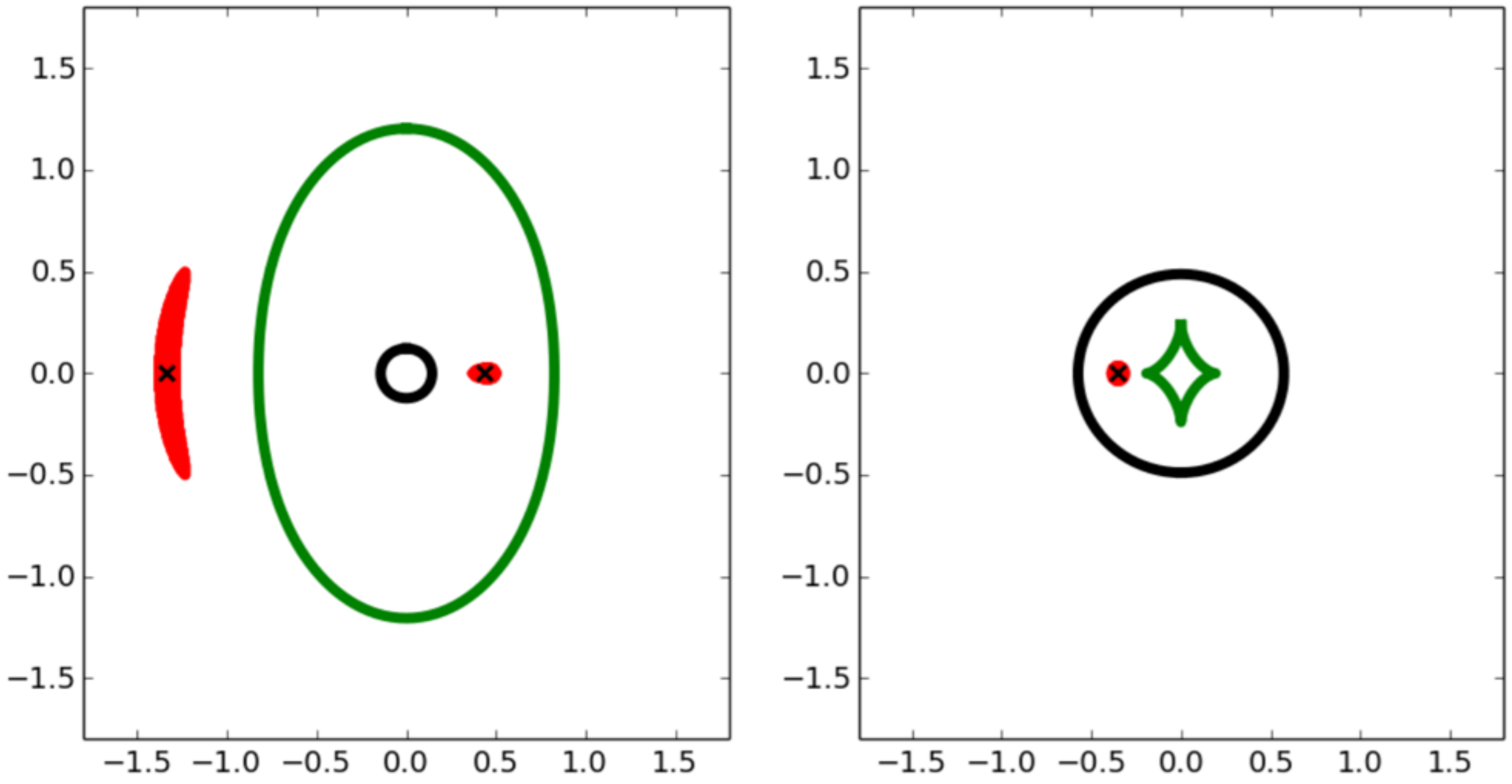
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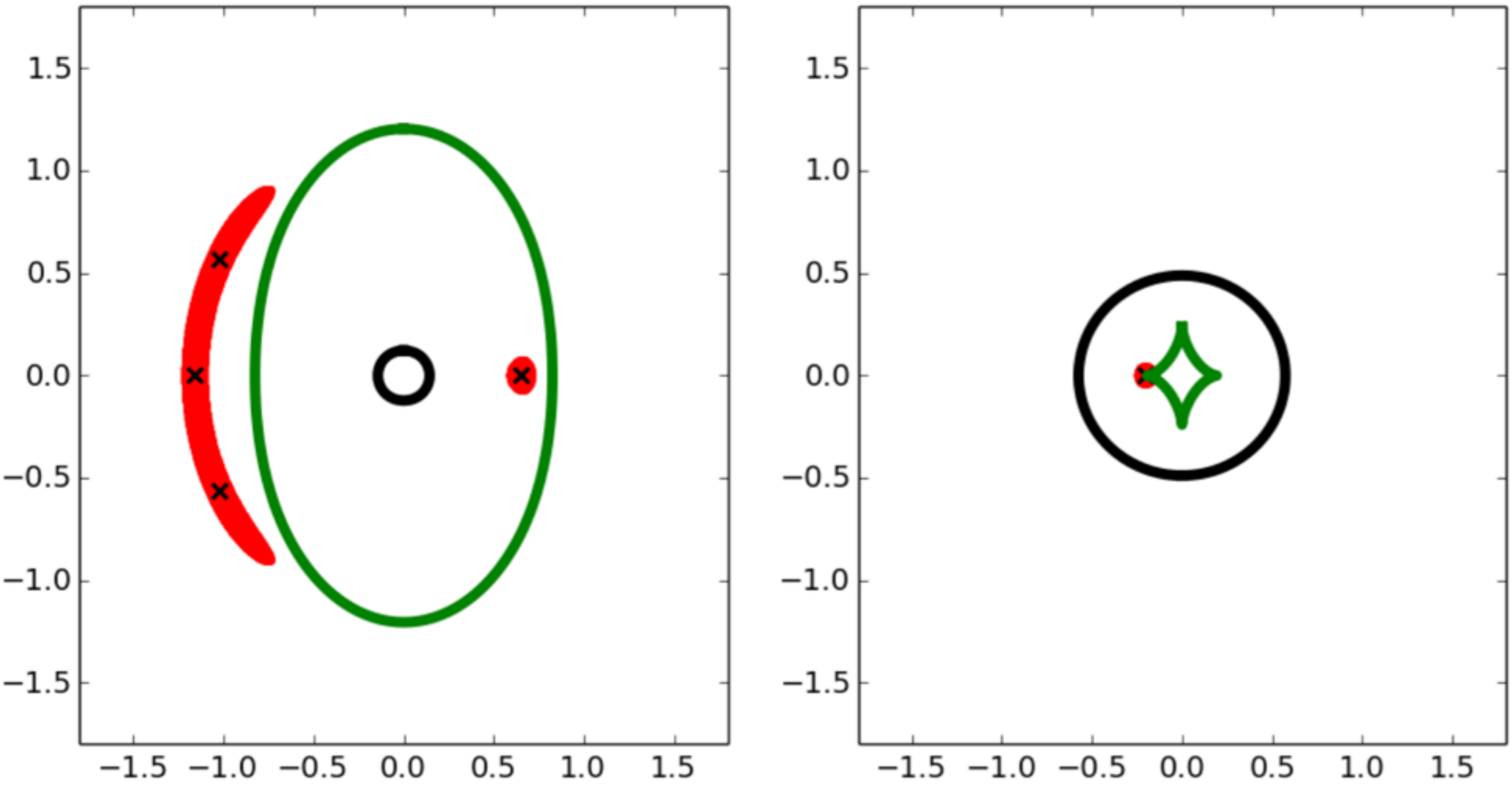
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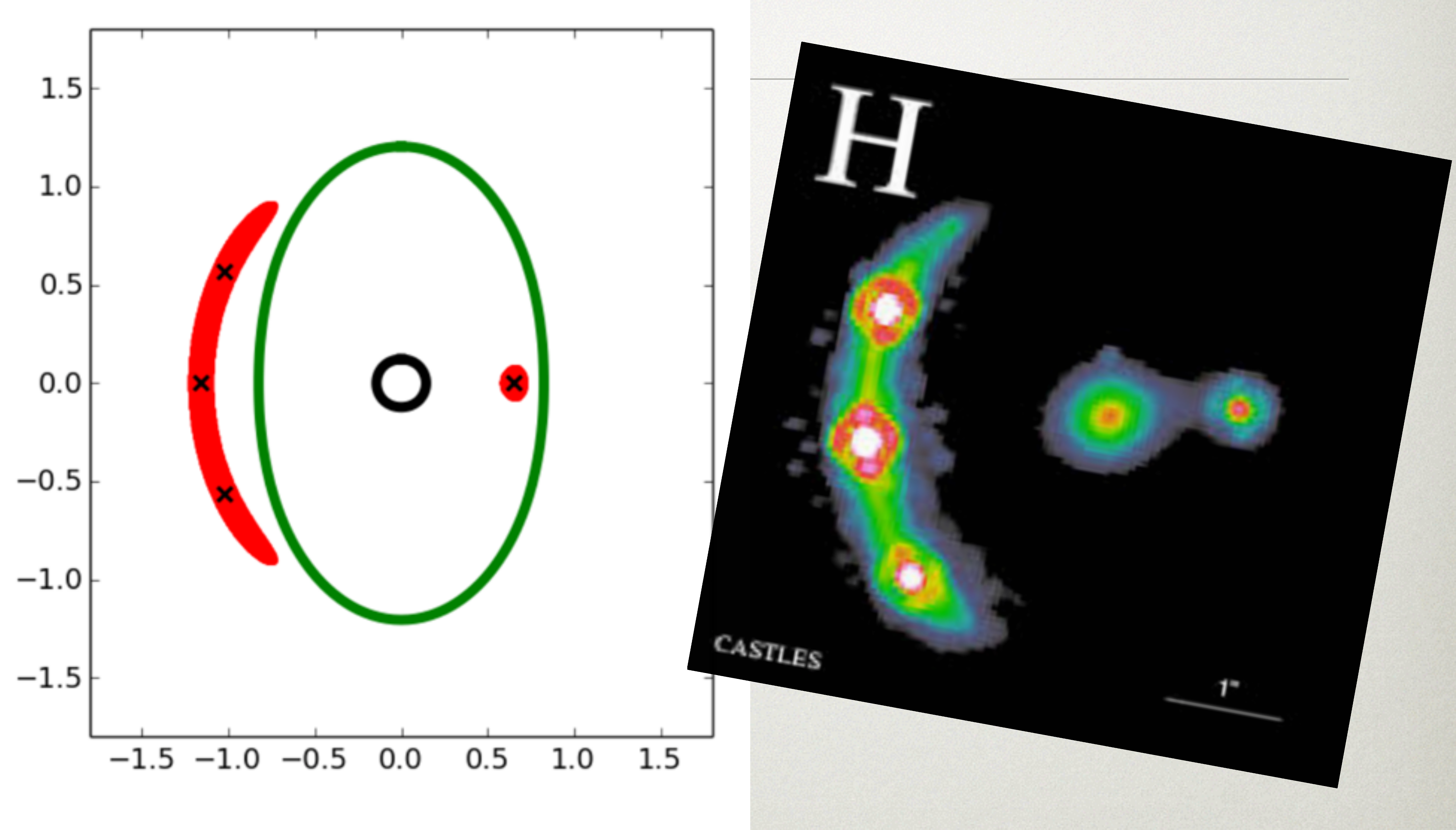
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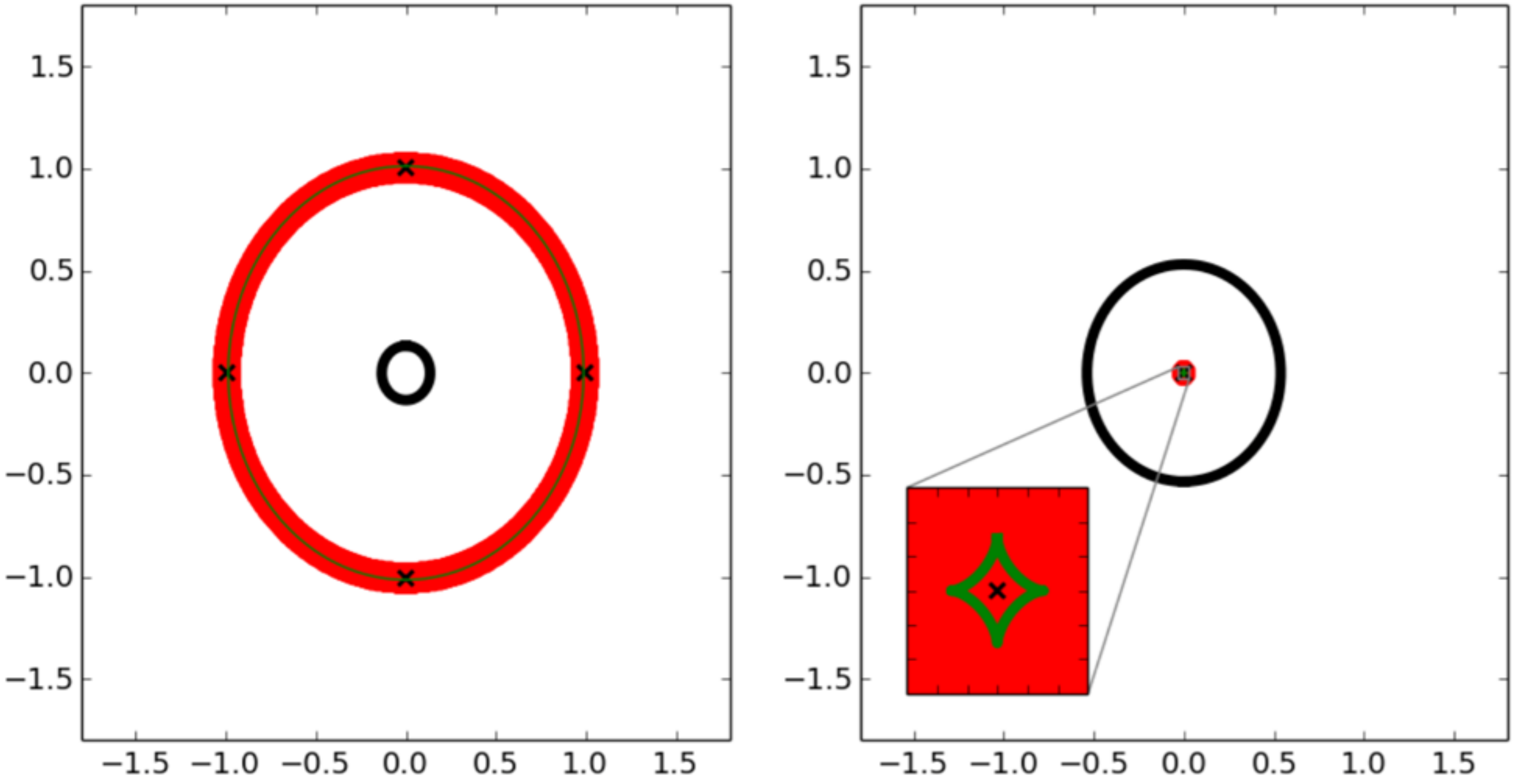
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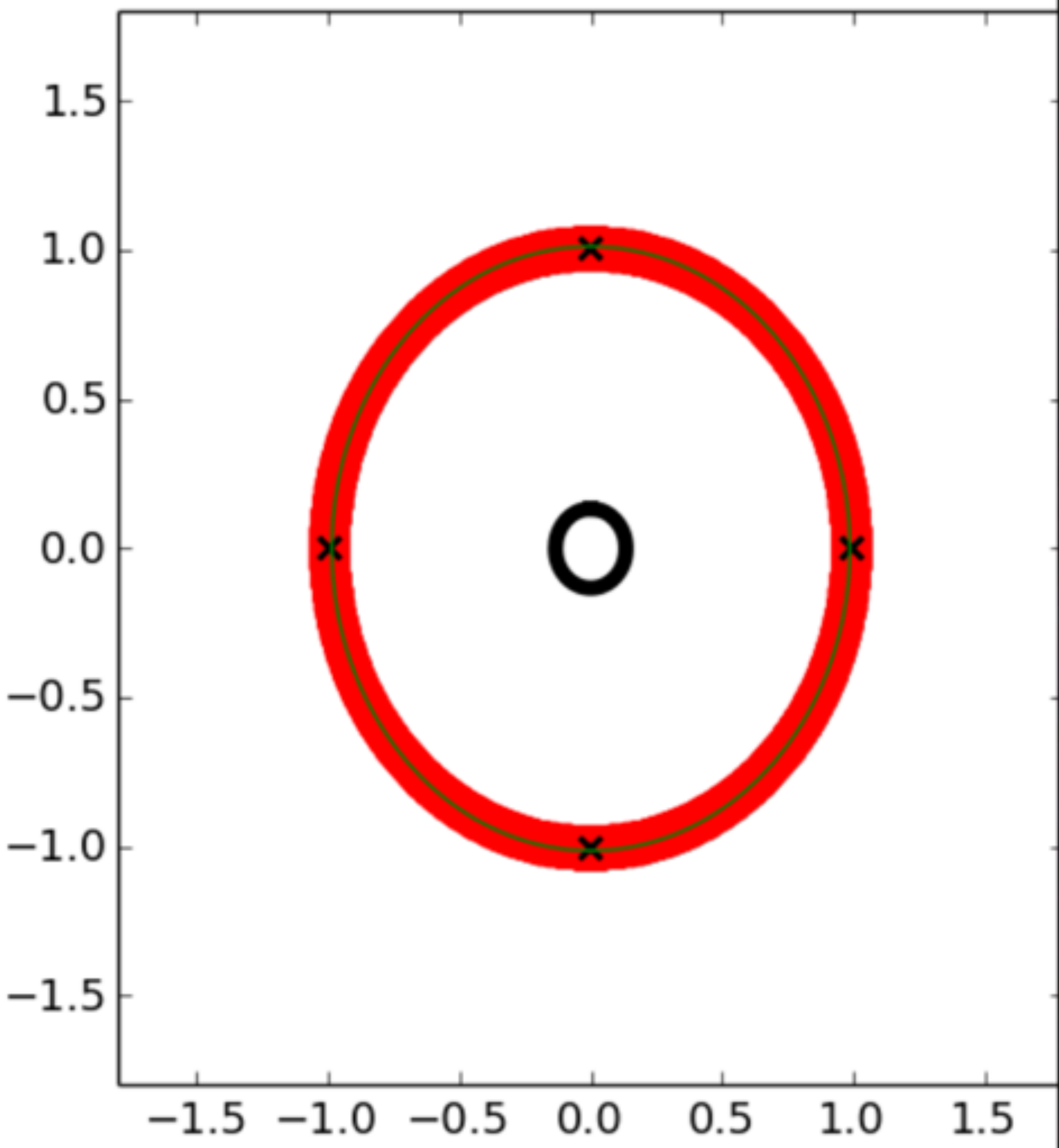
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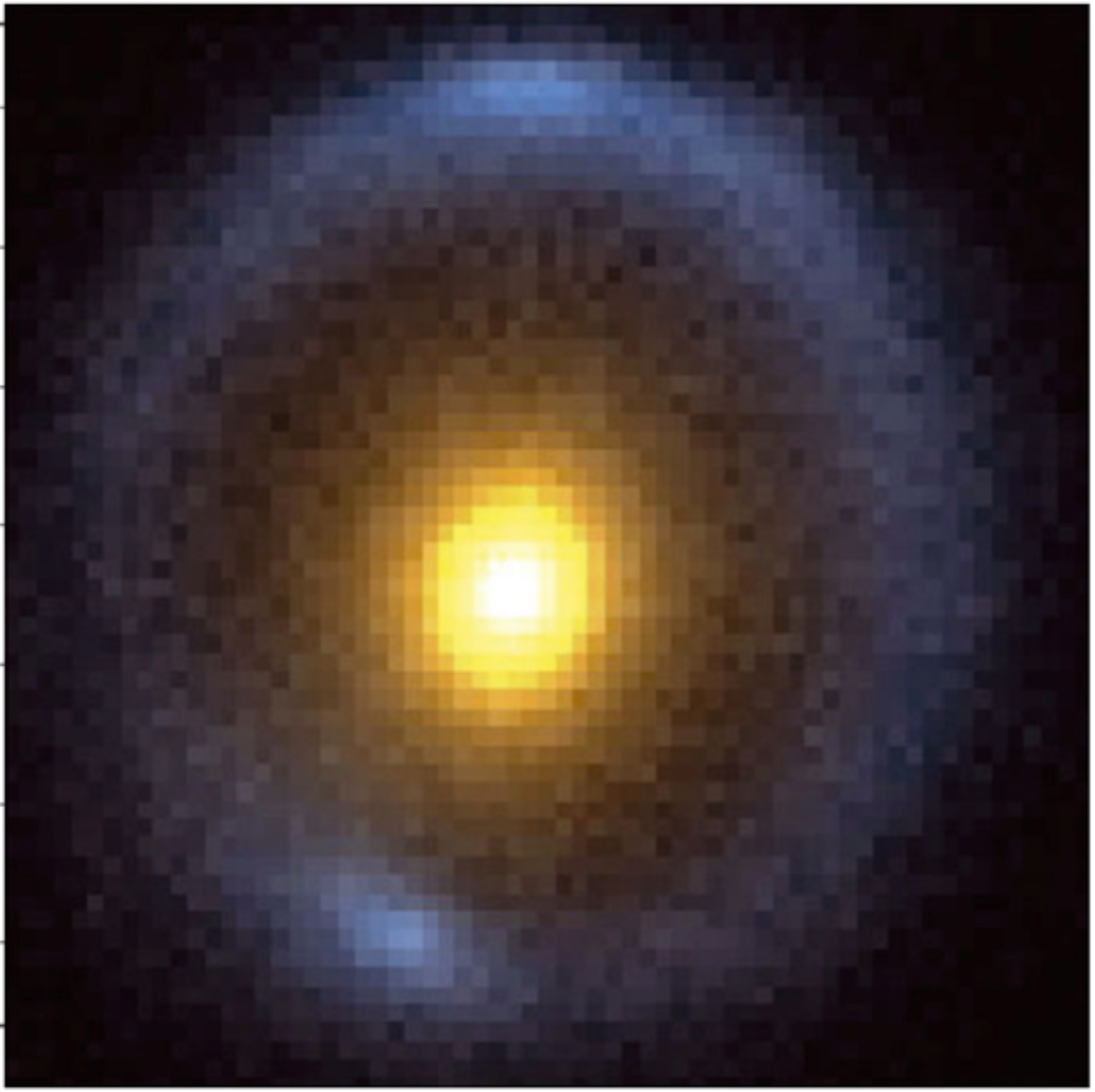
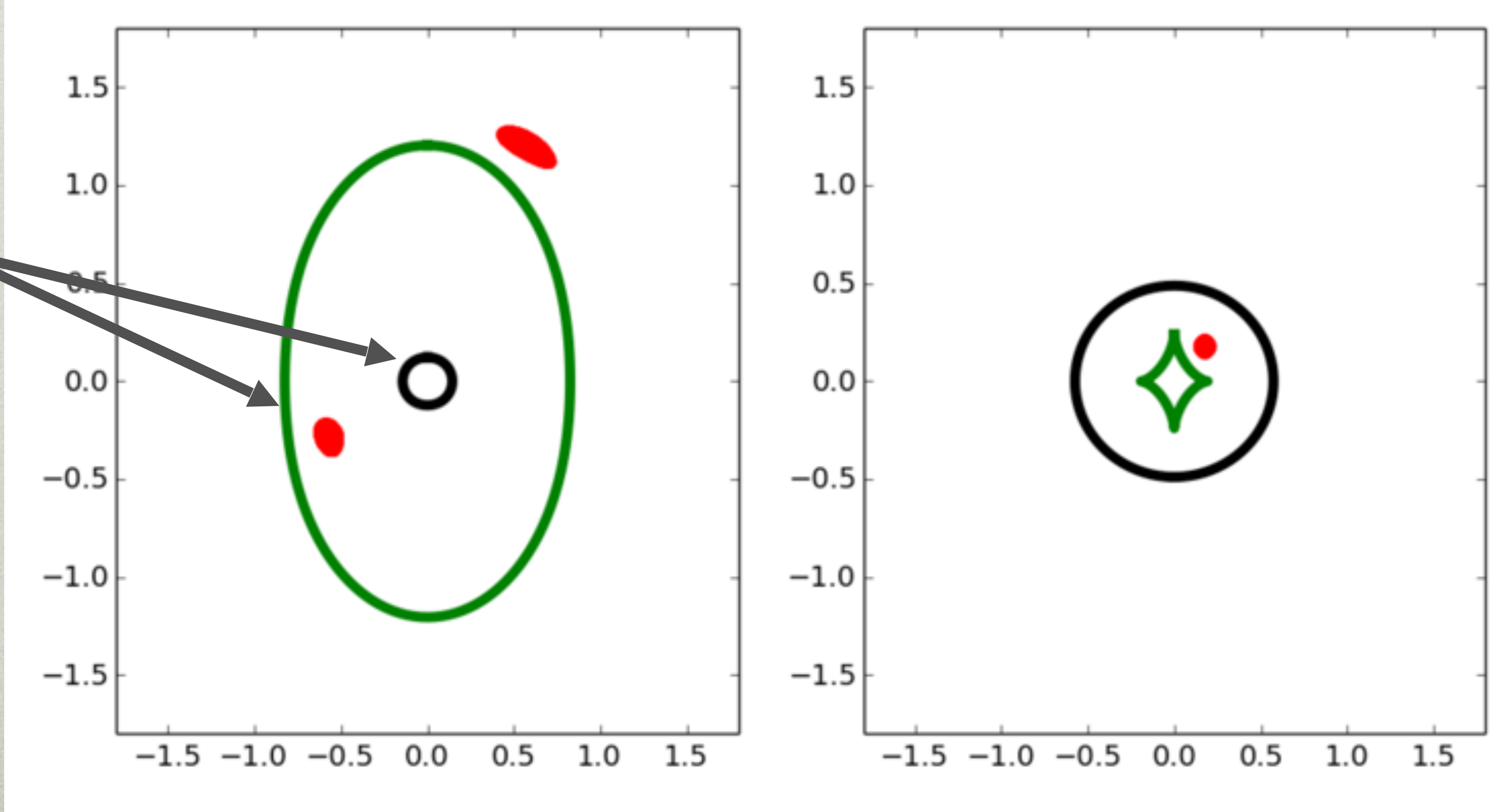


MULTIPLE IMAGES

e.g. Isothermal ellipsoid:

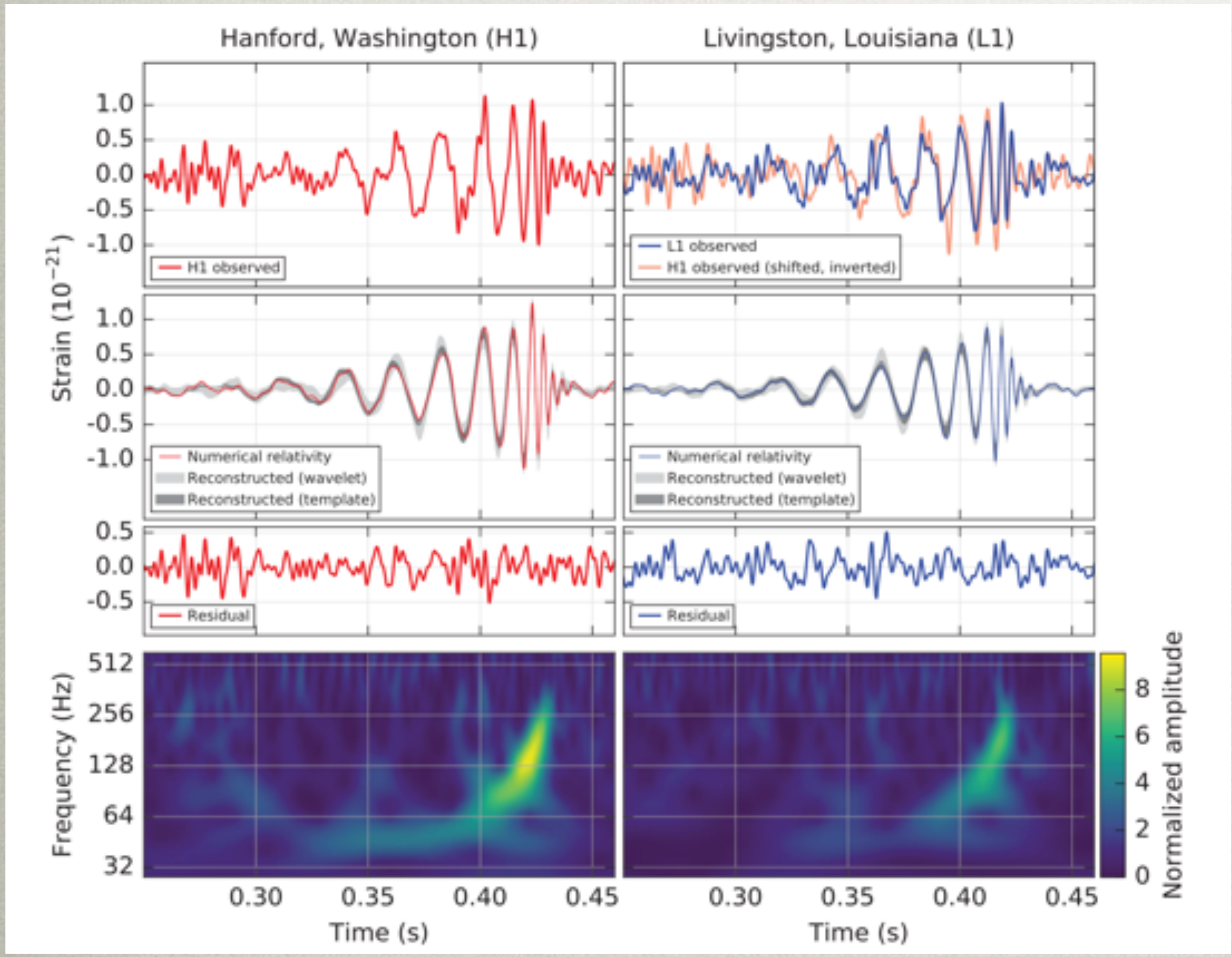
$$\kappa_{\rm lens}(\boldsymbol{x}) = \frac{2-\eta}{2}\left(\frac{\theta_E}{qx_1^2 + x_2^2/q}\right)^{\eta}$$

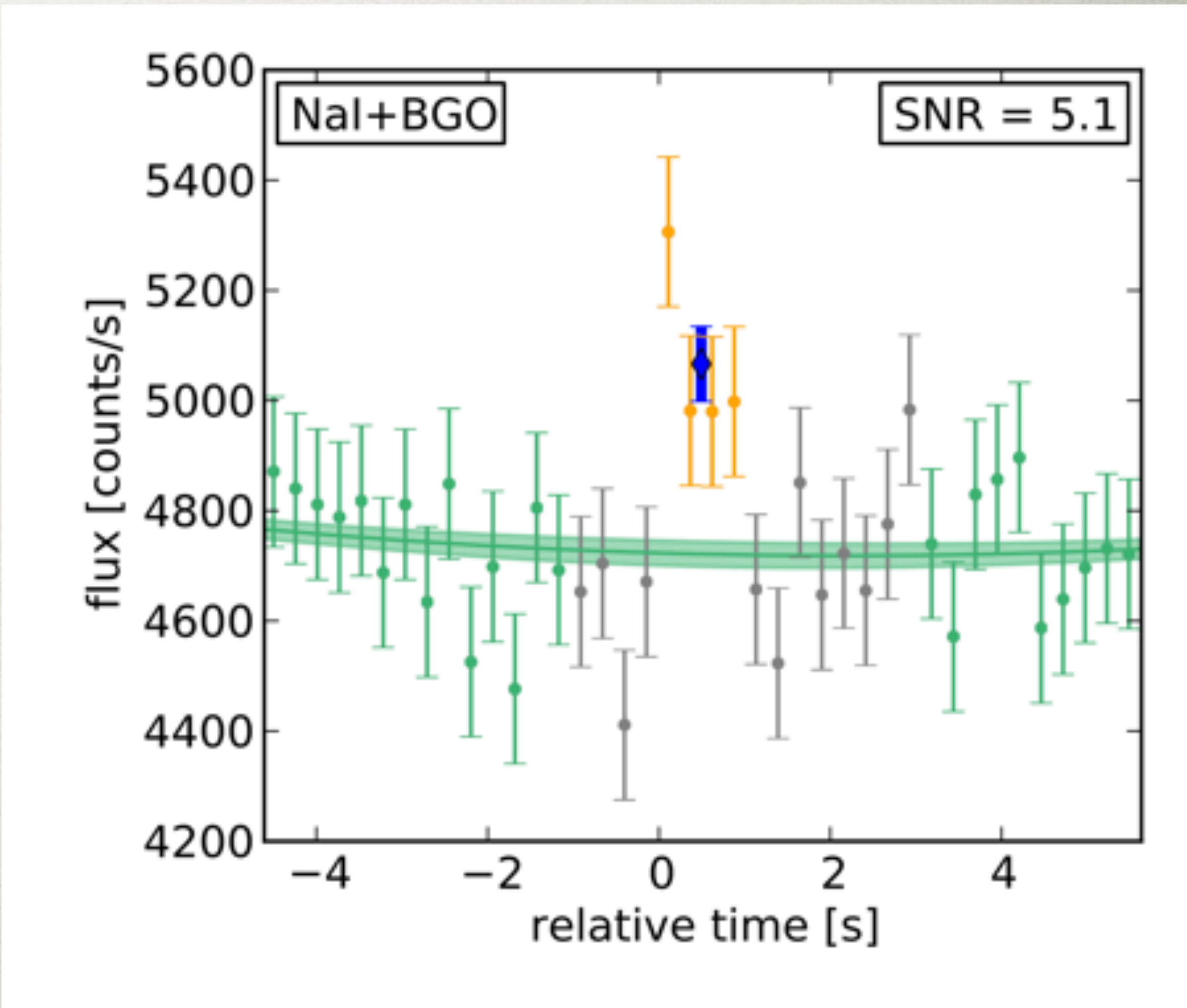
det A = 0



from Tom Collett

TEST FOR SPEED OF GRAVITATIONAL WAVES





Abbott et al 16, LIGO

Connaughton et al 16, Fermi

TEST FOR SPEED OF GRAVITATIONAL WAVES

Collett & Bacon 16:

Suppose photon signal after GW signal is associated with same event (now or future obs).

If emitted at same (or nearby) point in space-time, we get a constraint on ratio of speeds.

$$n_g = \frac{c_{\mathrm{GW}}}{c_\gamma}$$

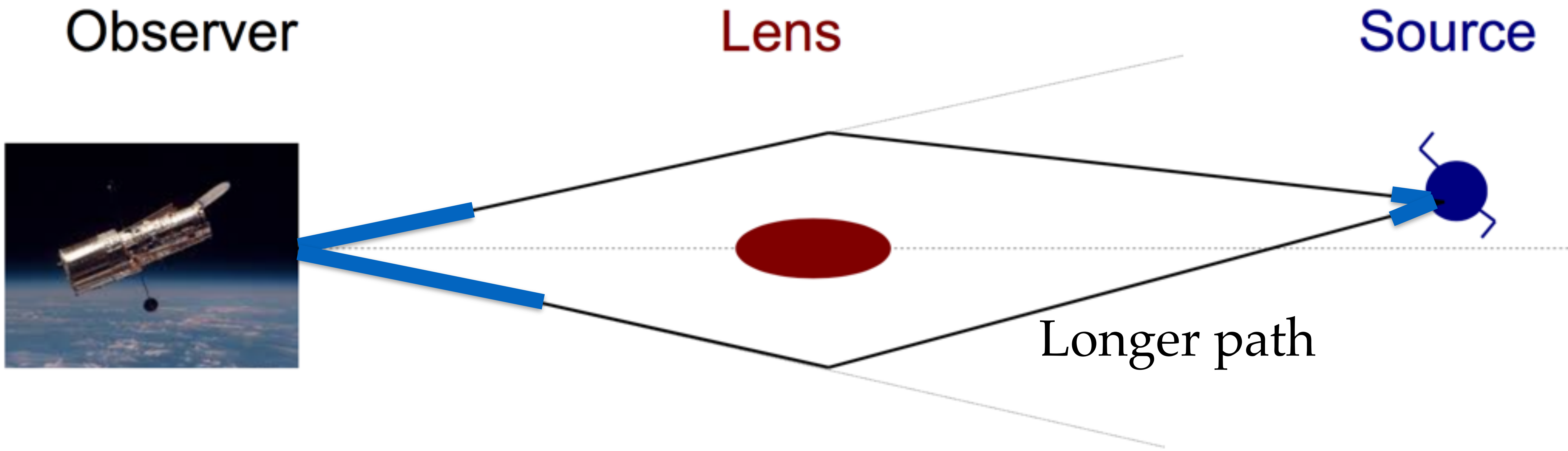
$$1 - {n_g}^{-1} = 1.0^{+1.9}_{-0.8} \times 10^{-17}.$$

But that assumes a lot. Rather, if multiply imaged: signals arrive at different times, having traversed different path lengths. Measure if time difference is same in each case.

$$\frac{c_{\mathrm{GW}}}{c_\gamma} = \frac{t_2 - t_0}{t_3 - t_1}$$

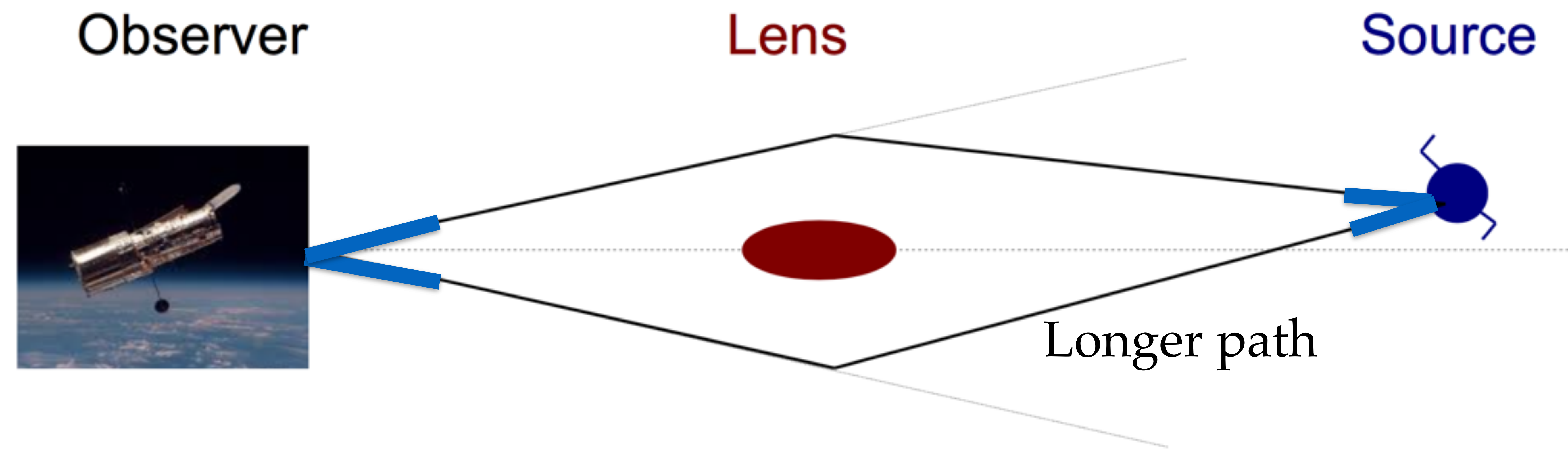
TEST FOR SPEED OF GRAVITATIONAL WAVES

If GW speed is not equal to speed of light:

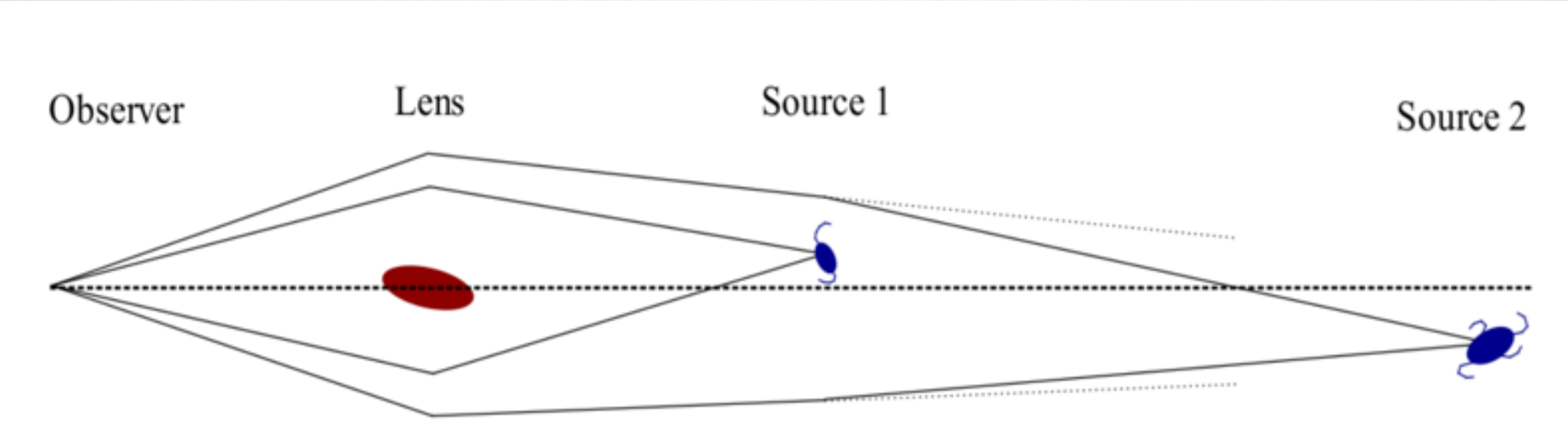


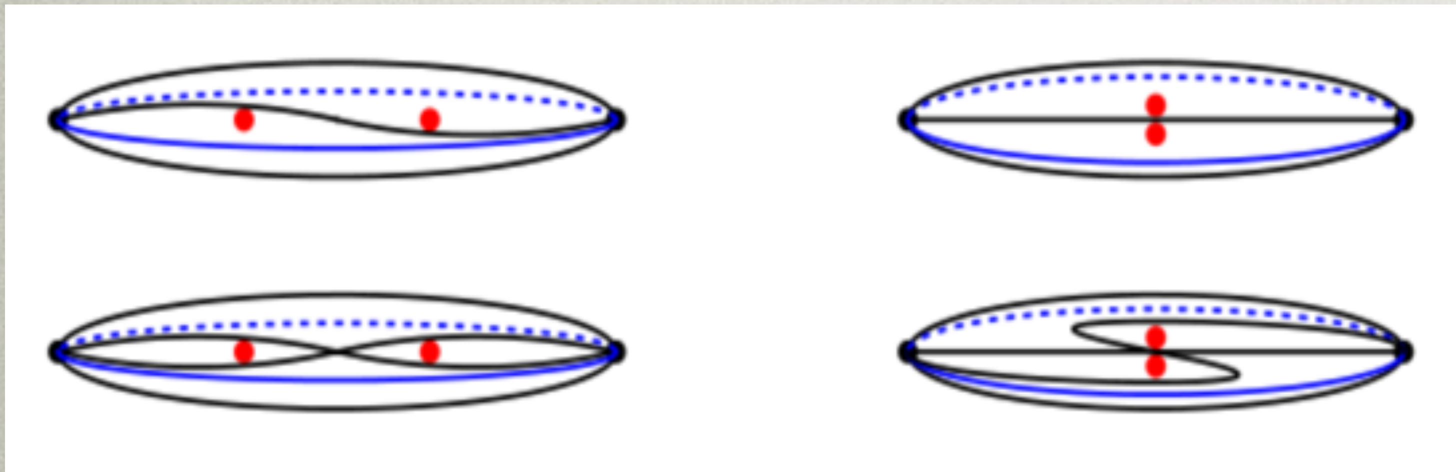
TEST FOR SPEED OF GRAVITATIONAL WAVES

If GW speed *is* equal to speed of light:



Compound Lensing





$$\boldsymbol{x}_\nu = \boldsymbol{x}_1 - \sum_{\mu=1}^{\nu-1} \beta_{\mu\nu} \boldsymbol{\alpha}_\mu(\boldsymbol{x}_\mu),$$

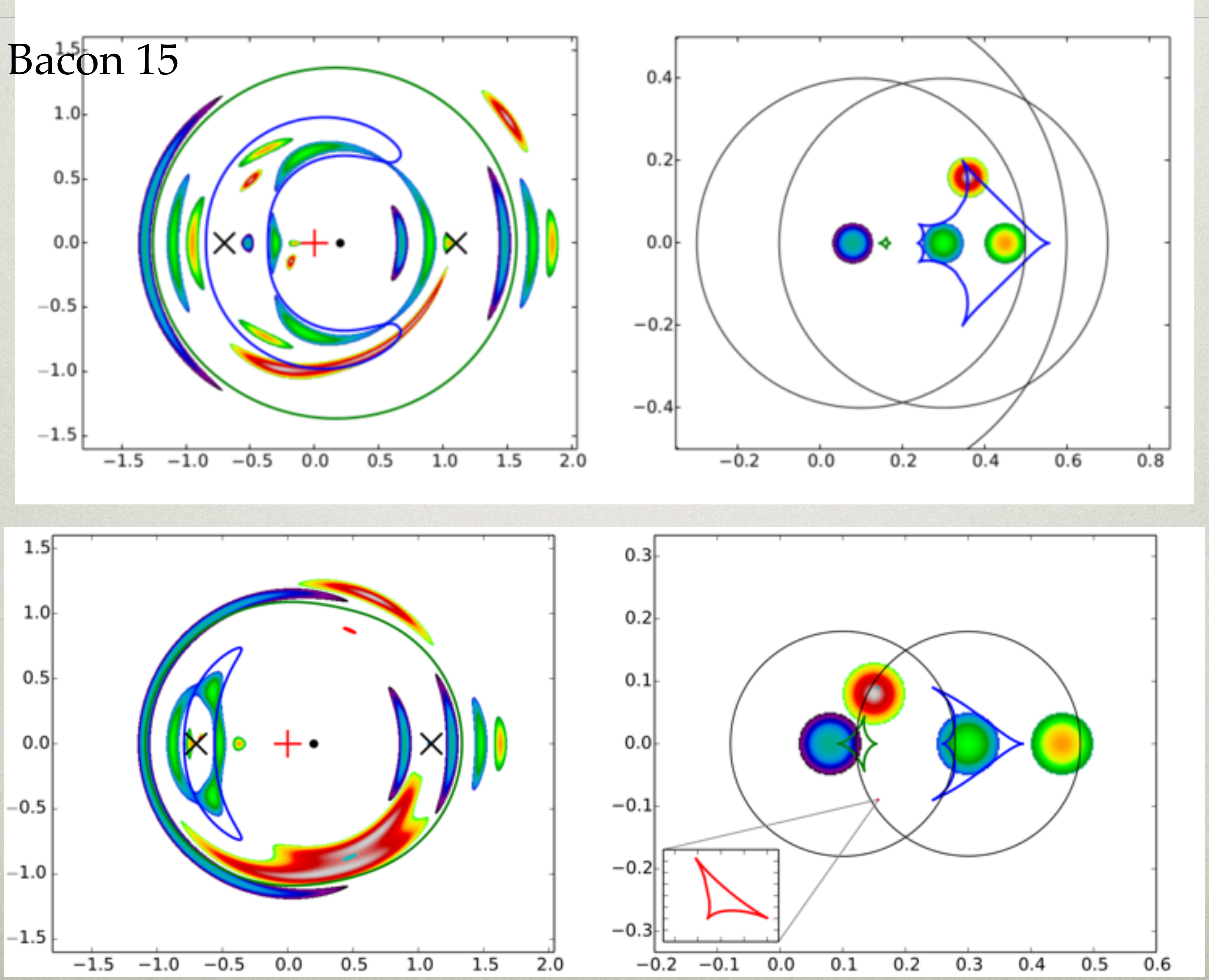
$$\beta_{\mu\nu} \equiv \frac{D_{\mu\nu} D_s}{D_\nu D_{\mu s}}.$$

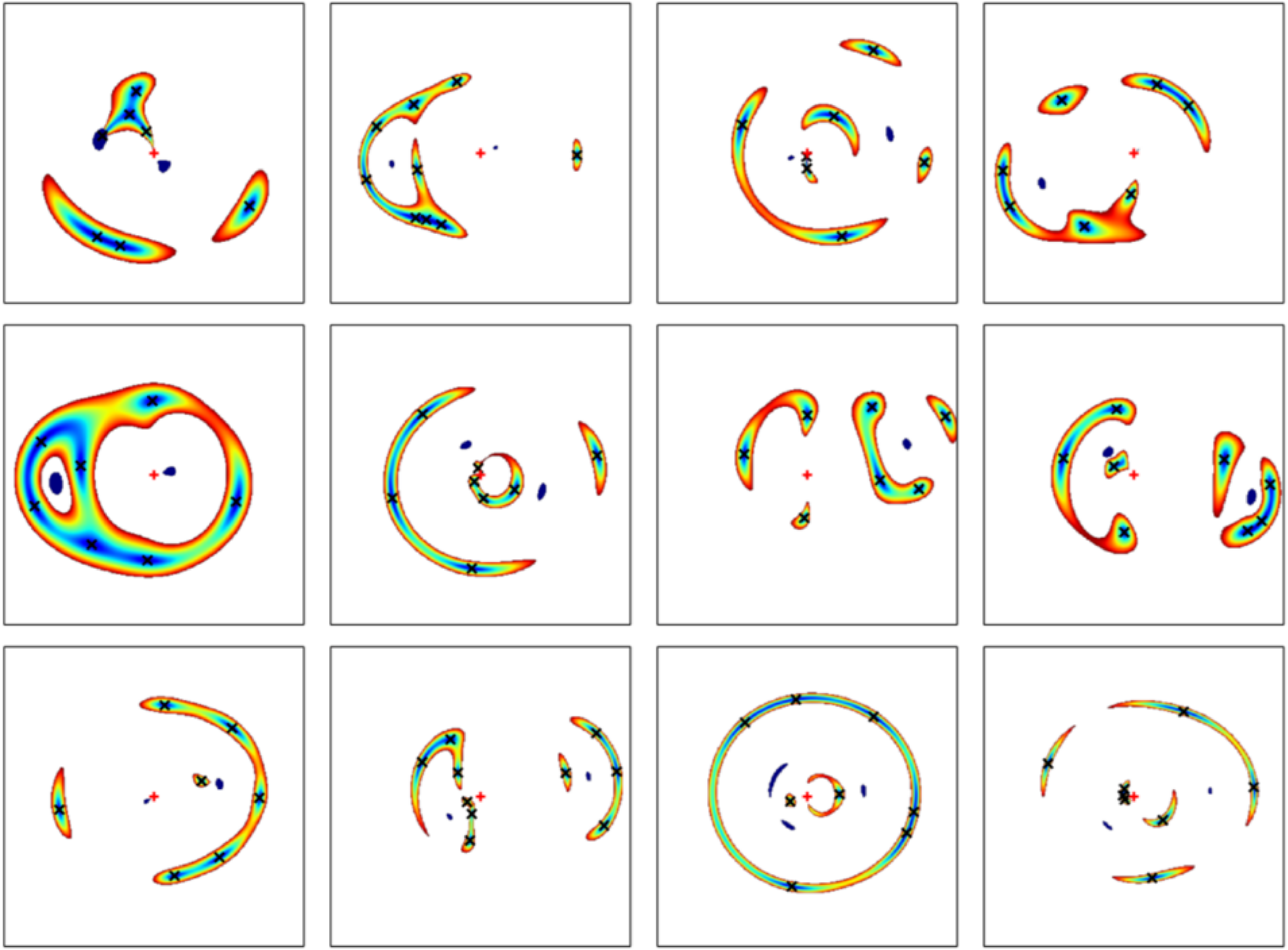
Collett & Bacon 15

NB sensitive to geometry

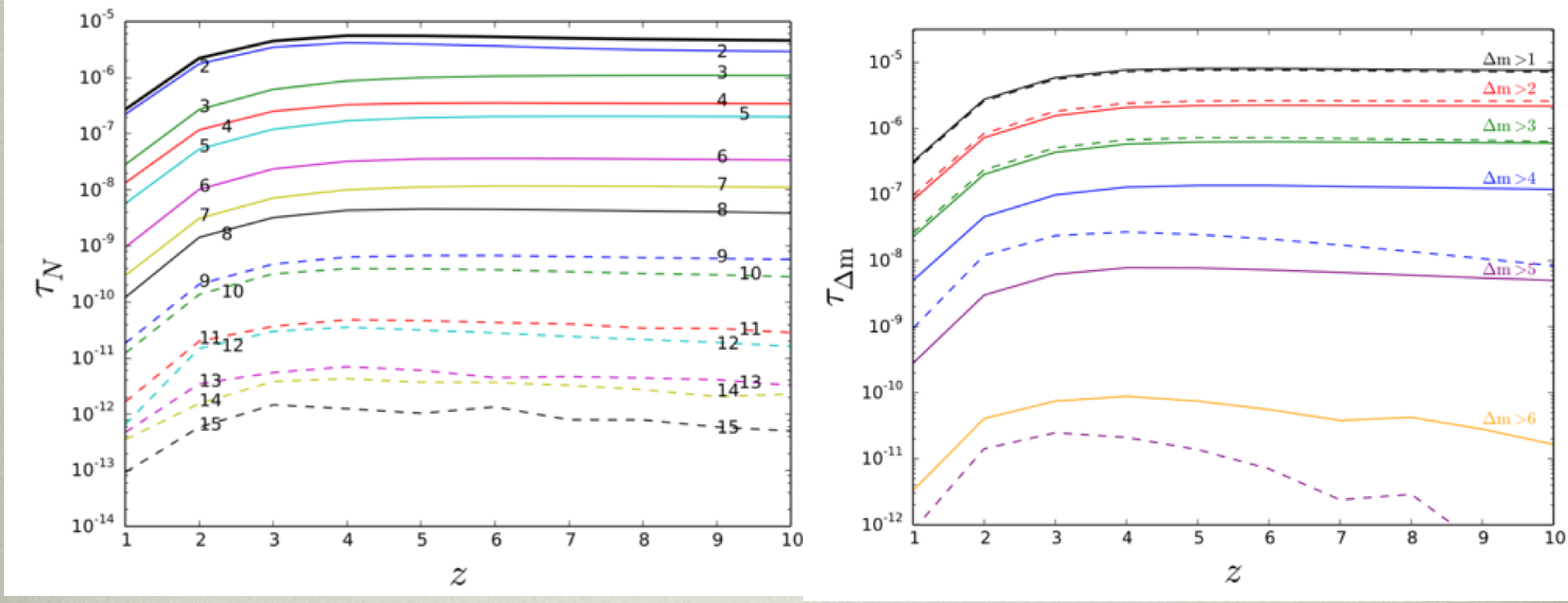
COMPOUND LENSING

Collett & Bacon 15



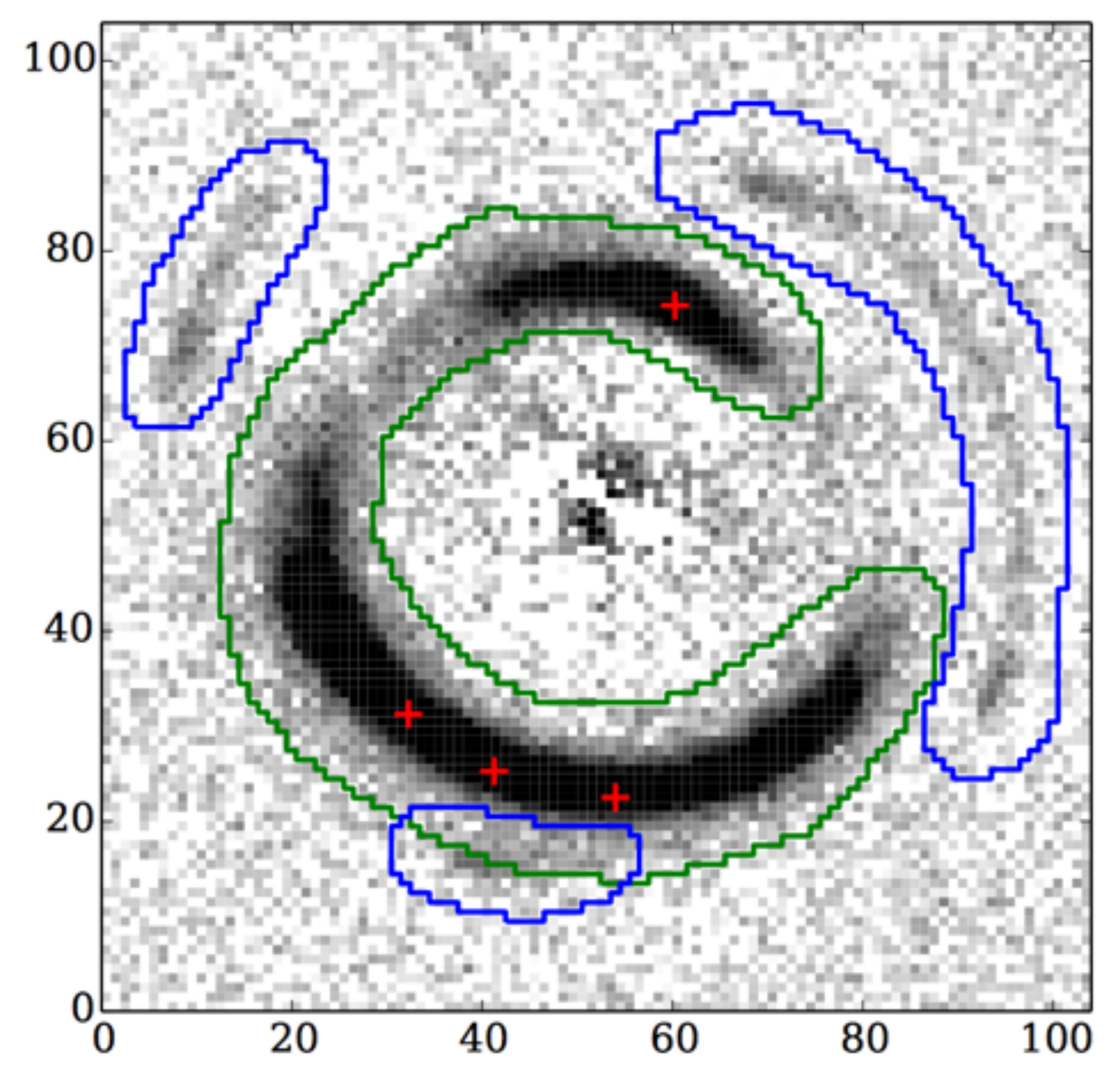


Cross-section



Collett & Bacon 15

With one compound lens...



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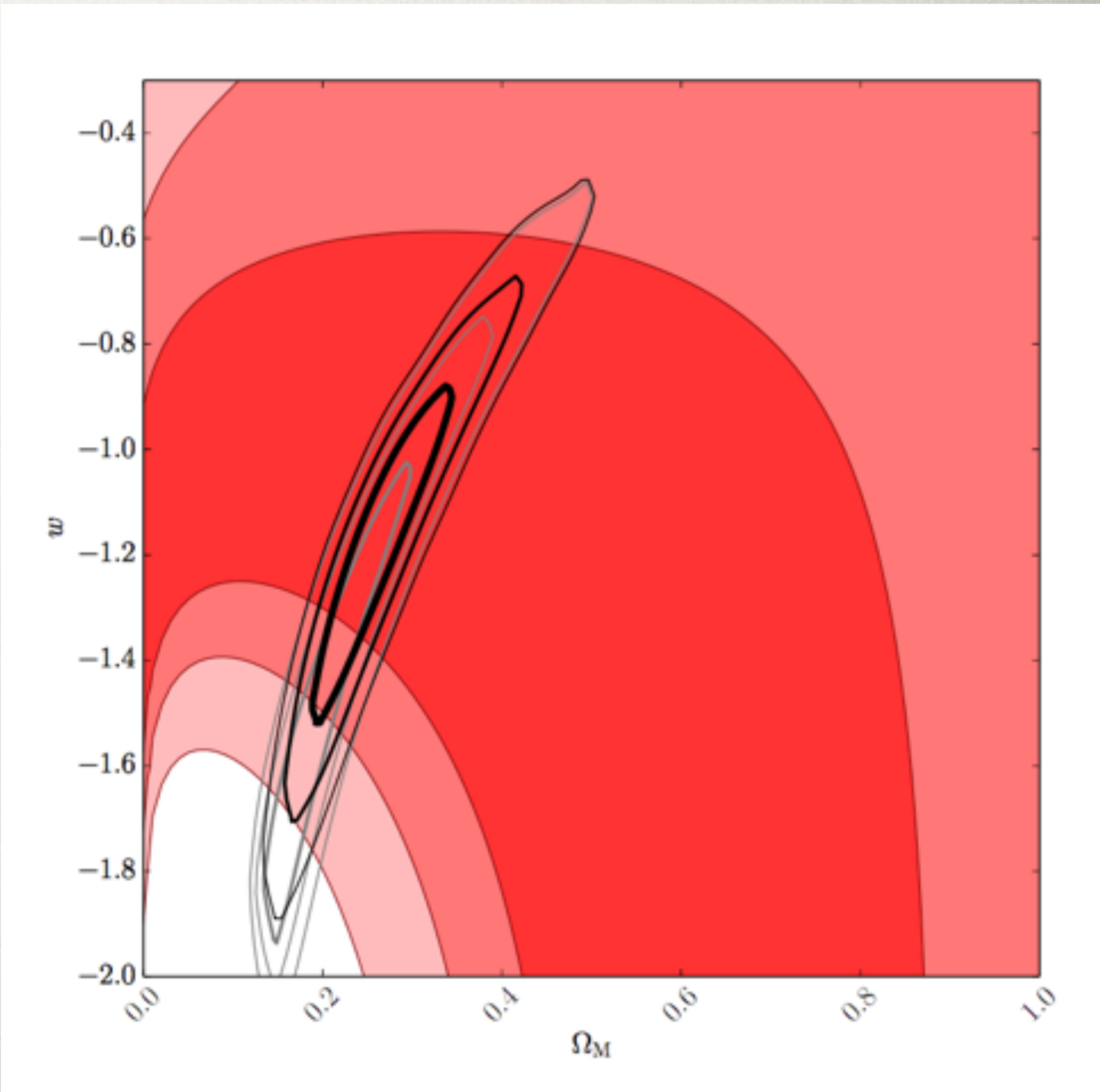
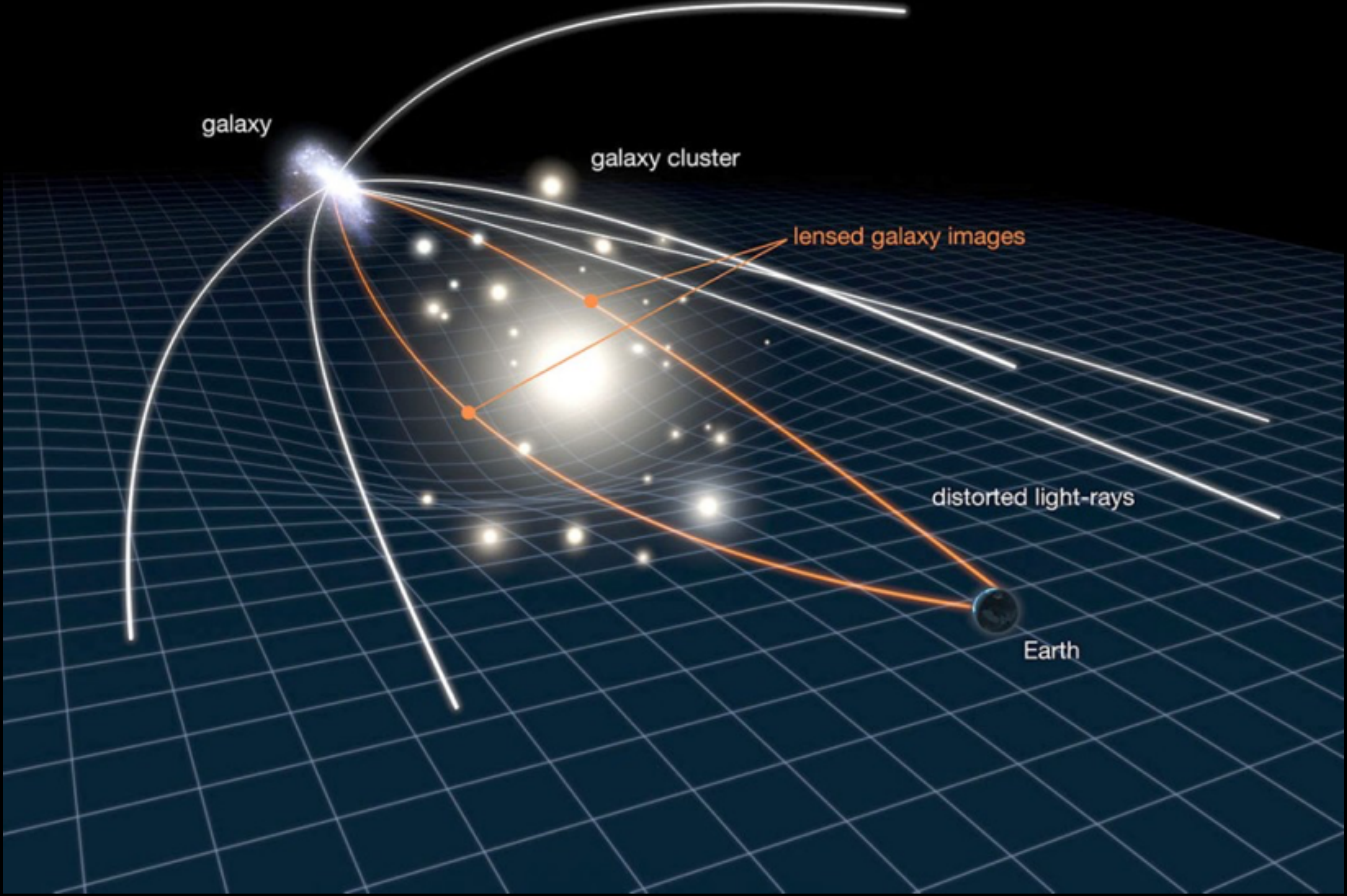


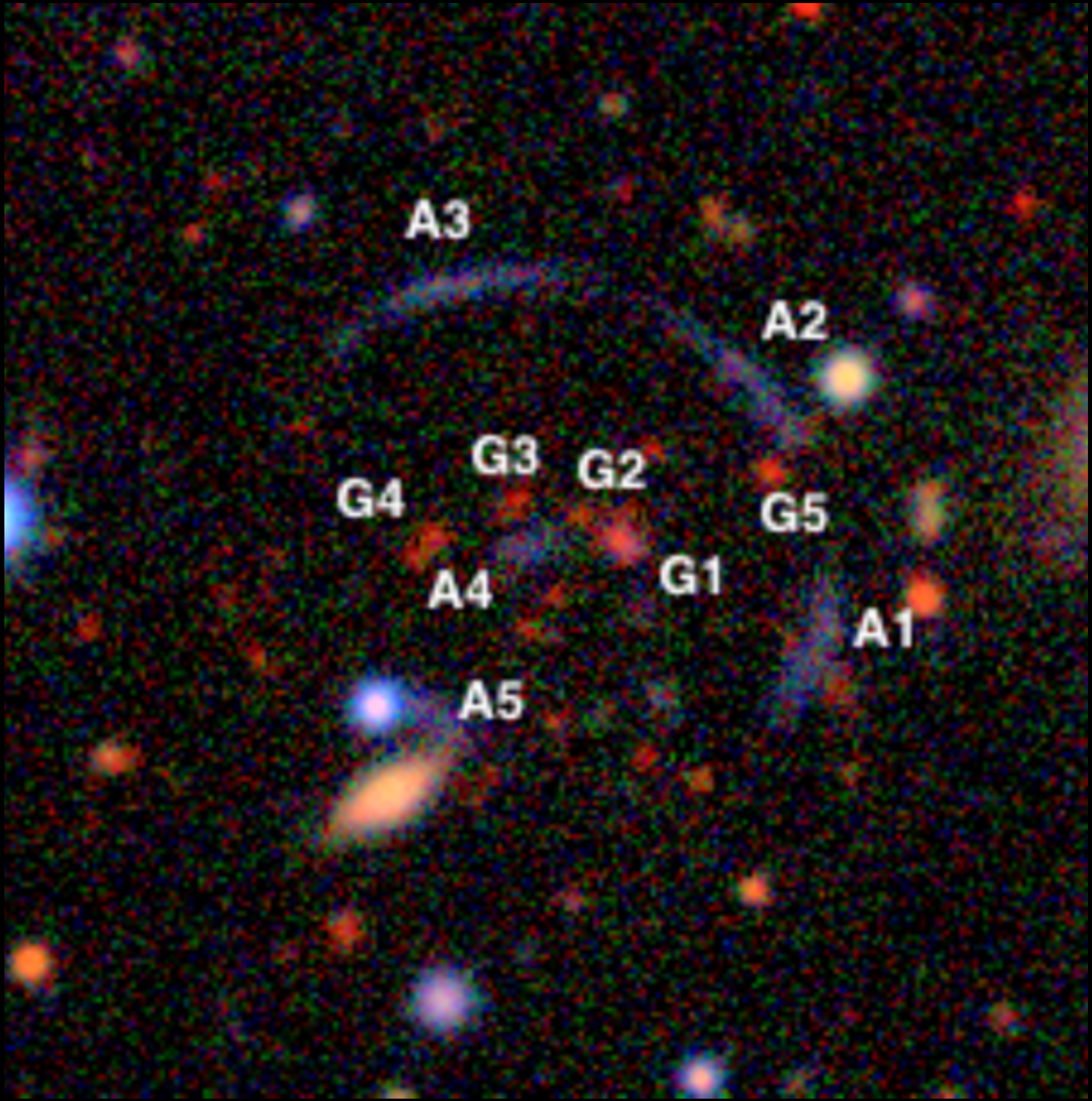
Collett & Auger 14

STRONG LENSING AROUND CLUSTER



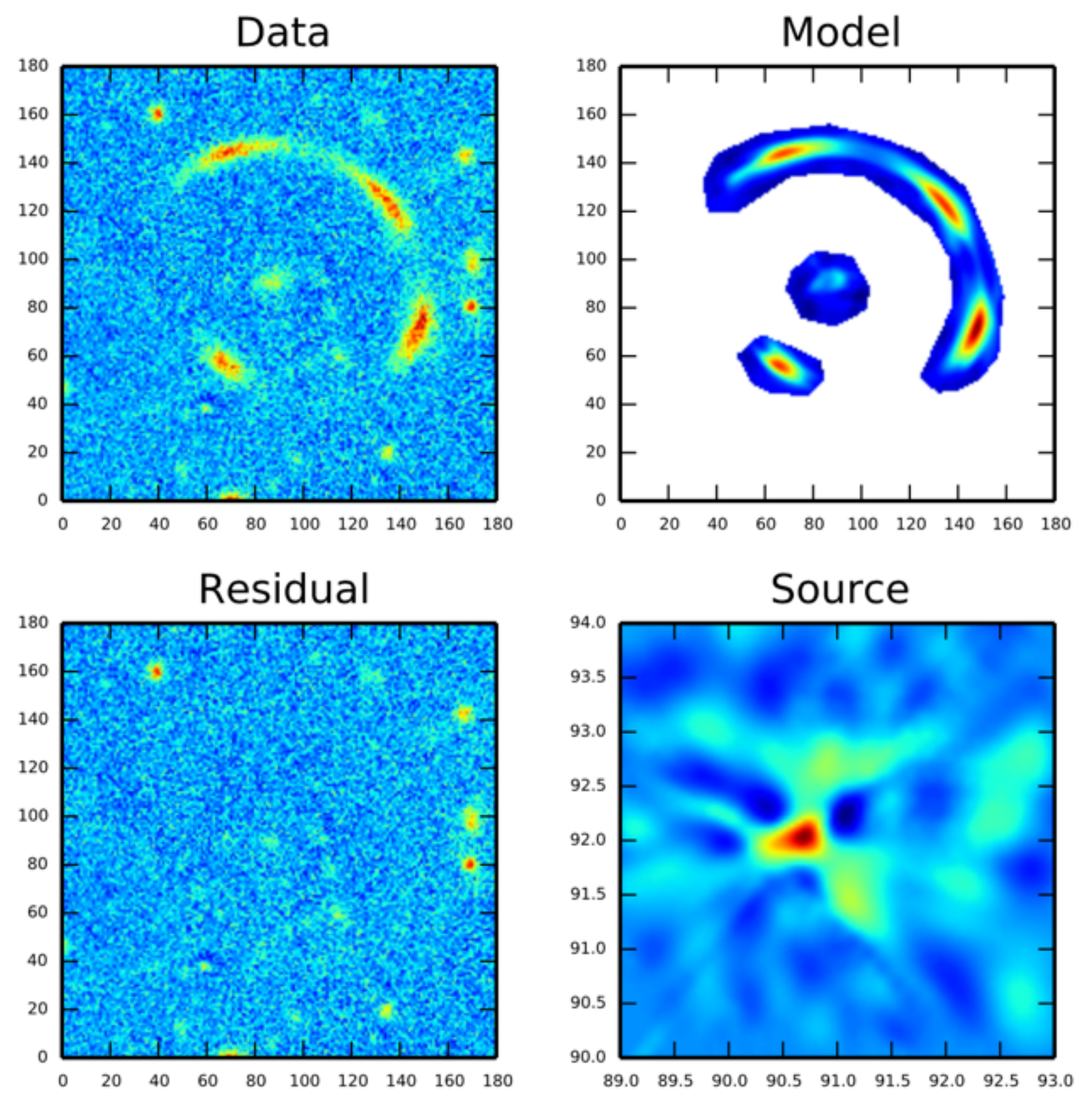
ESA/NASA

STRONG GRAVITATIONAL LENSING



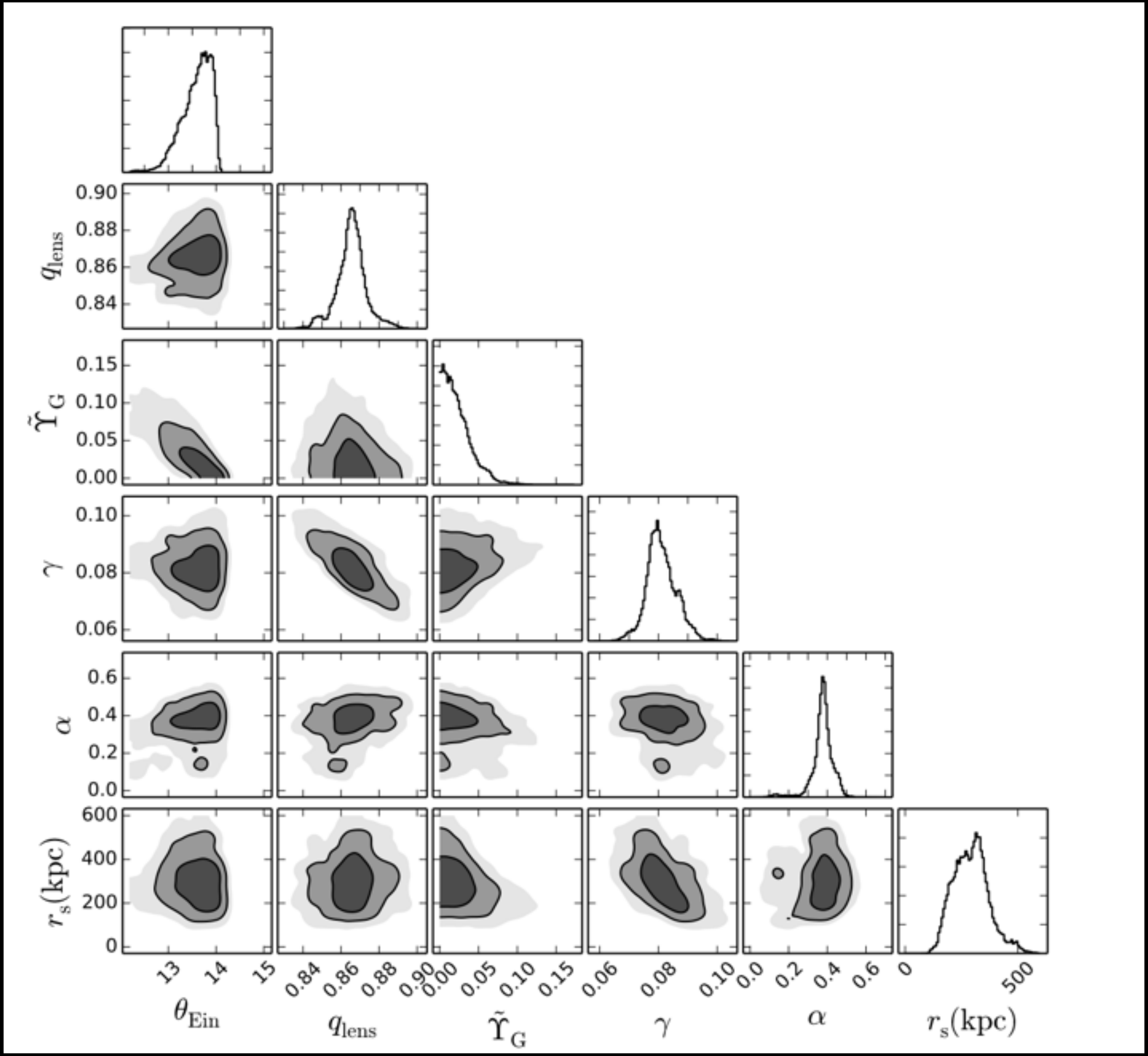
Collett et al 17

MODELLING



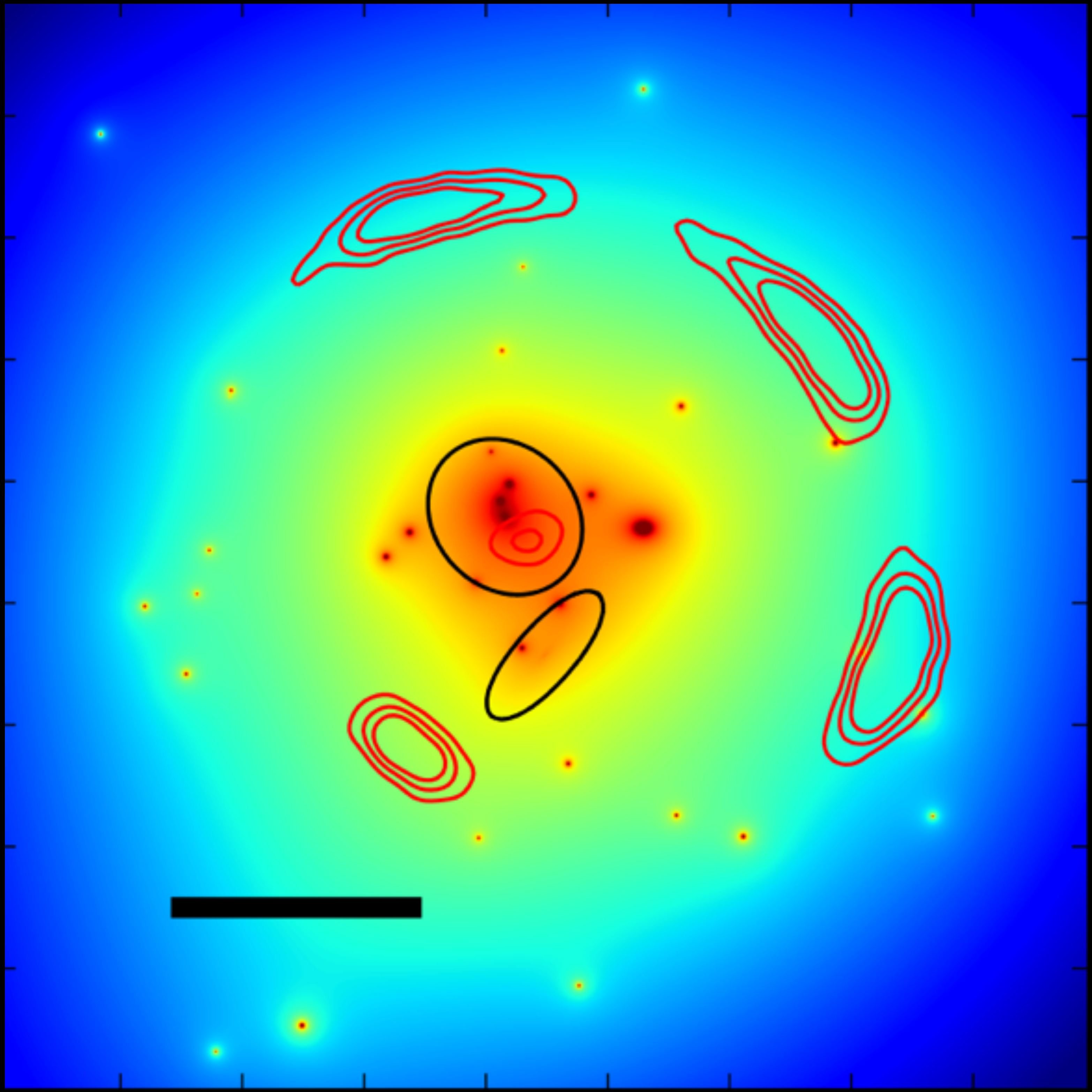
Collett et al 17

MODEL PARAMETERS



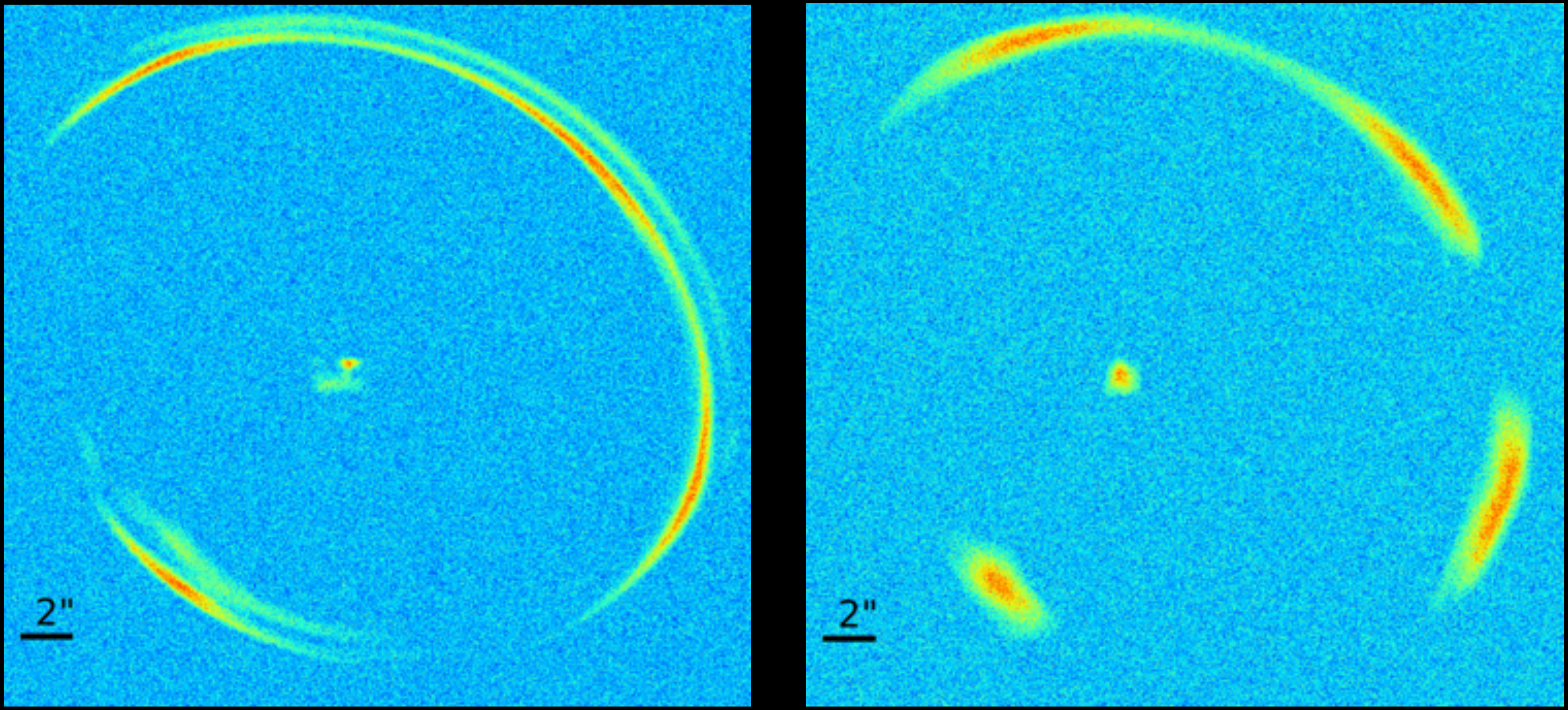
Collett
et al 17

STRONG GRAVITATIONAL LENSING



Collett et al 17

PREDICTIONS



Collett et al 17

WEAK DISTORTIONS

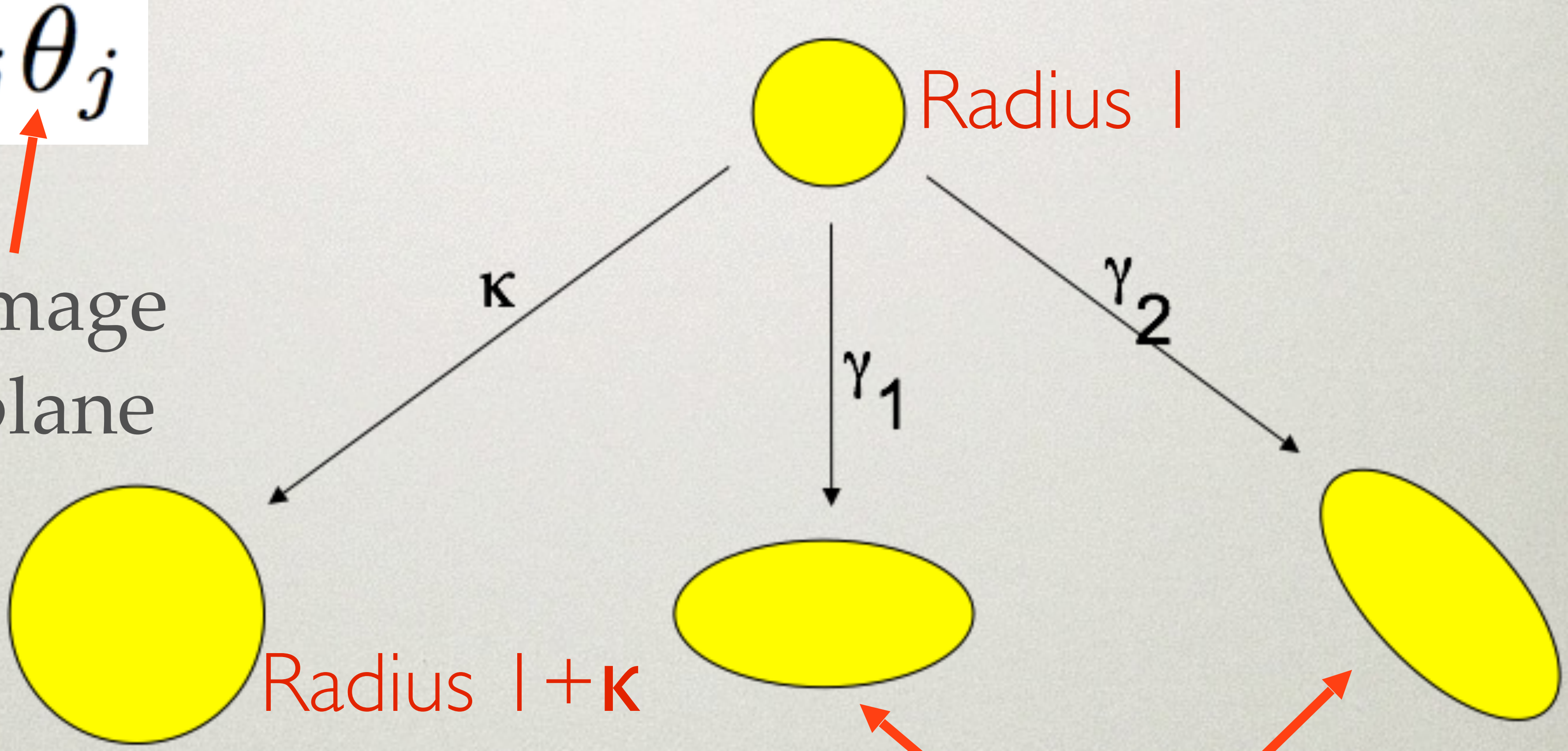
Linearise so that across a galaxy,

$$\beta_i = A_{ij}\theta_j$$

Source plane

Image plane

$$A = \begin{pmatrix} 1-\kappa & 0 \\ 0 & 1-\kappa \end{pmatrix} + \begin{pmatrix} -\gamma_1 & -\gamma_2 \\ -\gamma_2 & \gamma_1 \end{pmatrix}$$



Convergence

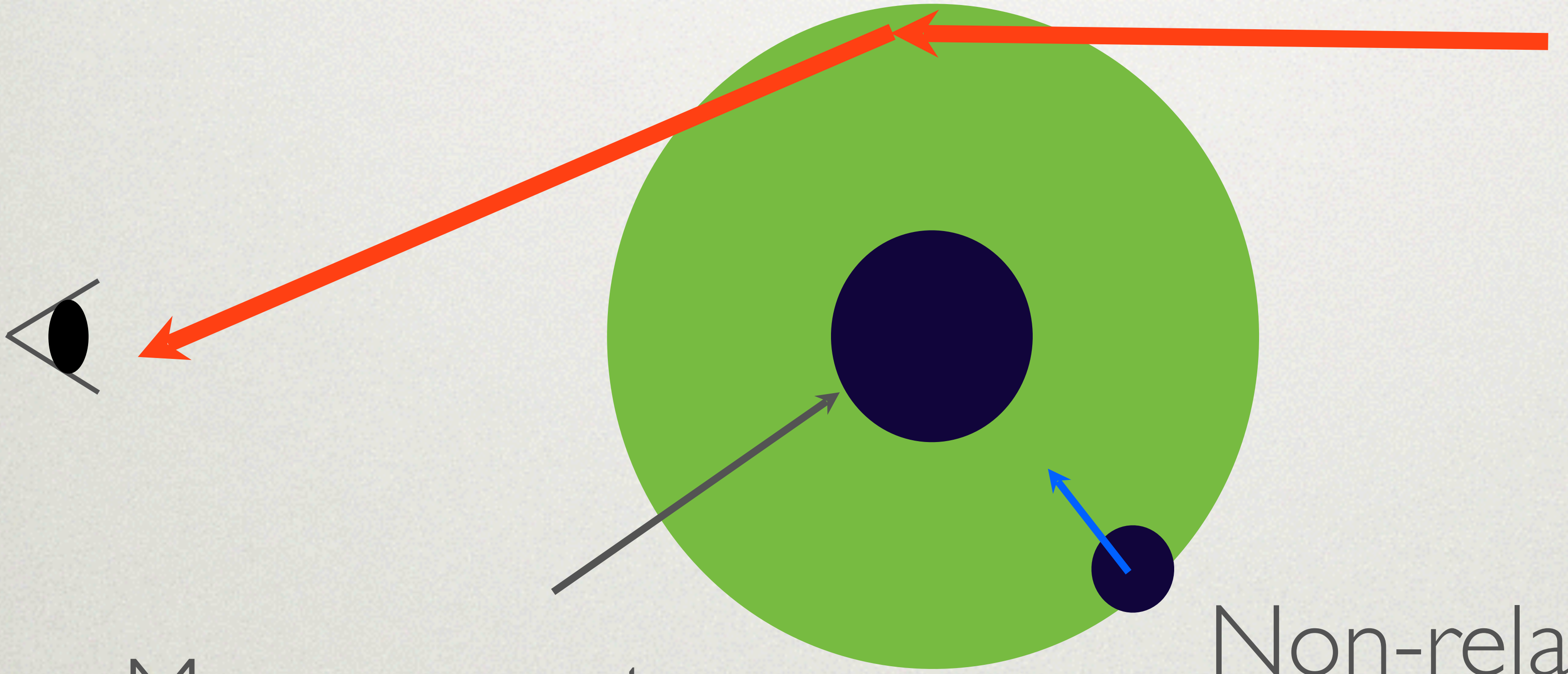
Shear

$$\gamma = \gamma_1 + i\gamma_2 = \frac{1}{2}\partial\partial\psi$$

Gravity Tests

$$ds^2 = -(1+2\Psi)dt^2 + (1+2\Phi)a^2\delta_{ij}dx^i dx^j$$

Newtonian guage



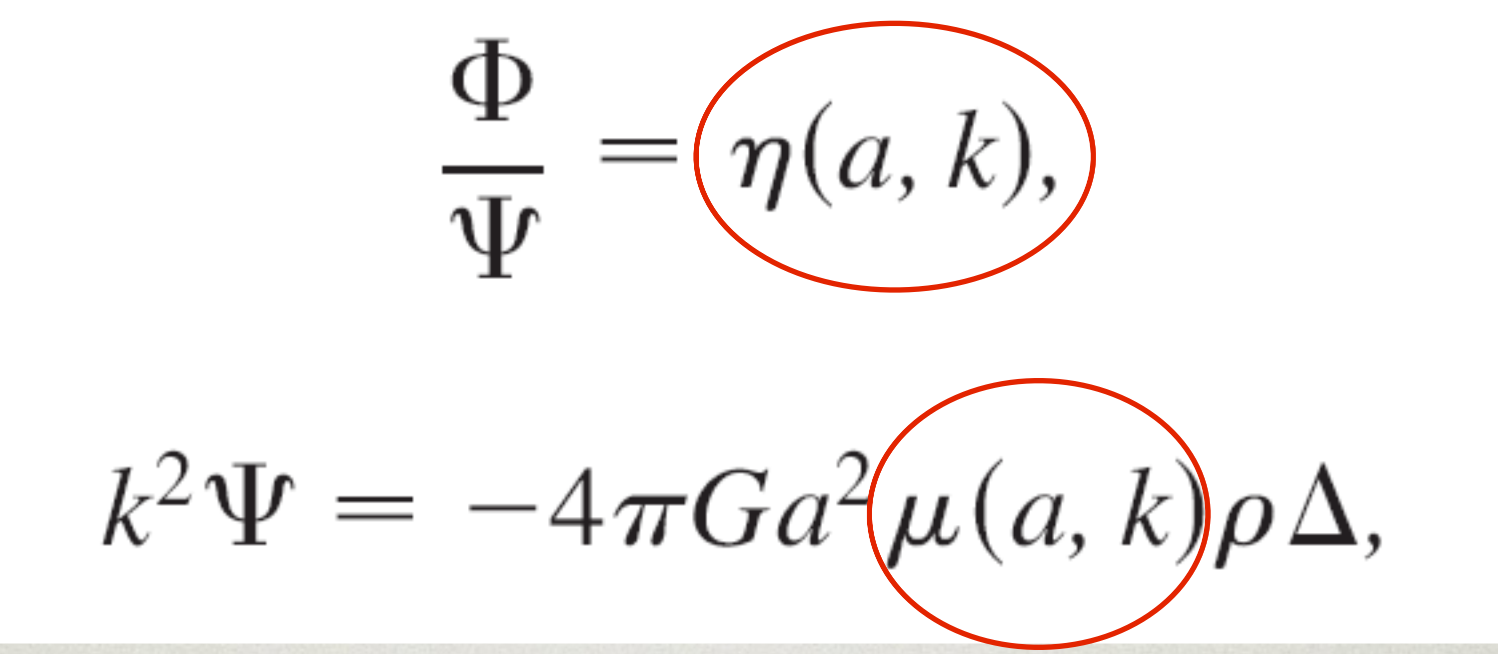
Lensing feels Ψ+Φ

Mass generates potential Ψ (Poisson)

Non-relativistic objects respond to Ψ

TESTING GENERAL RELATIVITY

We can examine



$$\frac{\Phi}{\Psi} = \eta(a, k),$$

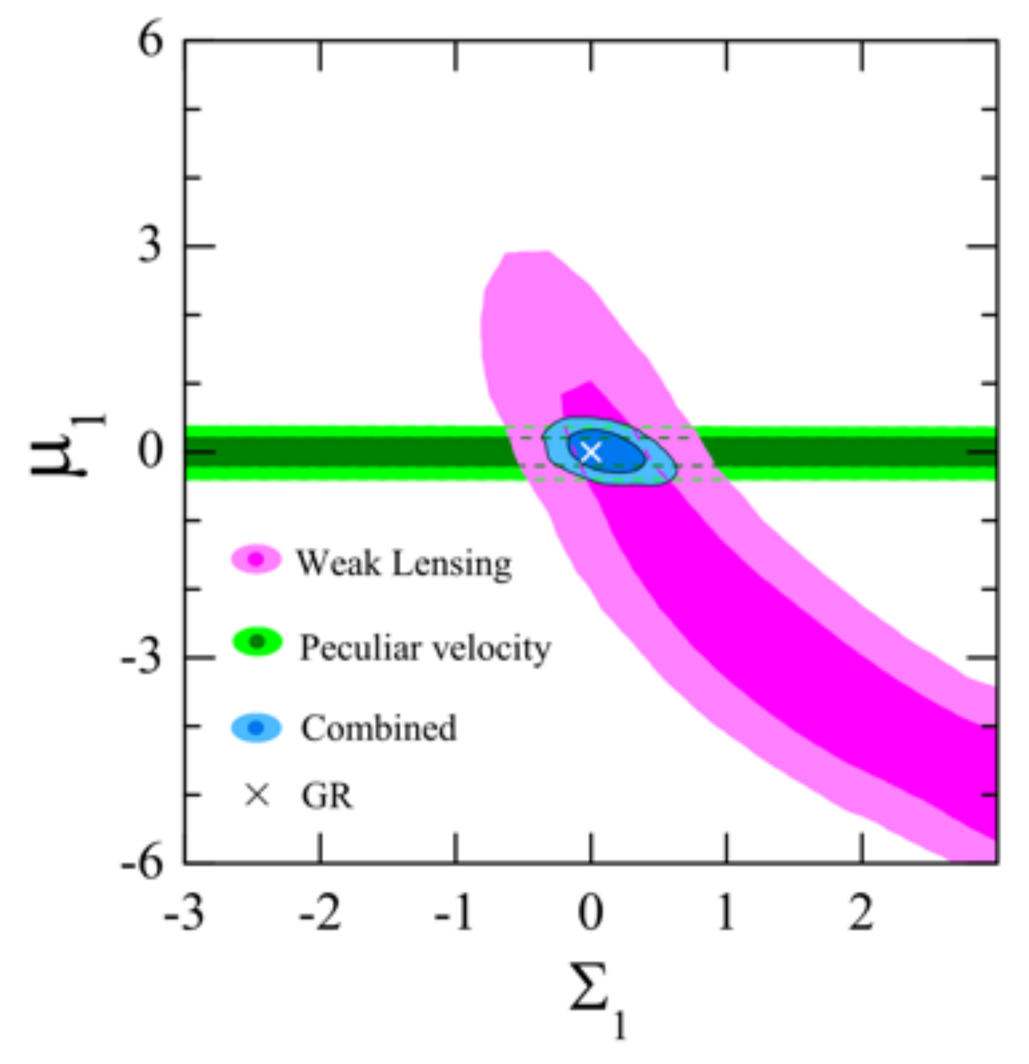
$$k^2\Psi = -4\pi G a^2 \mu(a, k) \rho \Delta,$$

Calculate lensing and RSD models with corresponding modified expansion and growth.

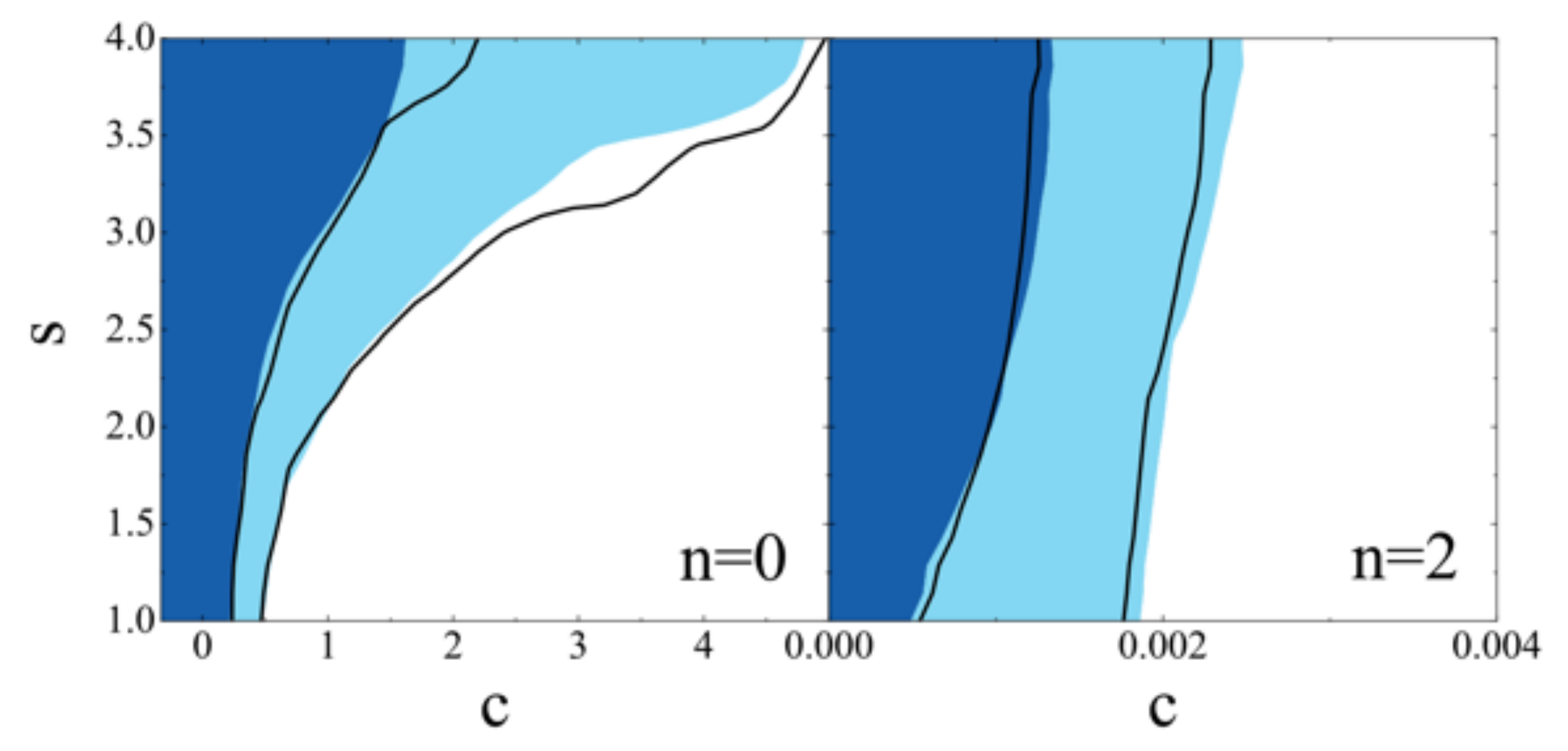
GRAVITY CONSTRAINTS

CFHTLens + SDSS DR7

Song et al 11



Zhao et al 12



$$\mu = 1 + \frac{c a^s k_H^n}{1 + 3 c a^s k_H^n}$$

$$\begin{aligned} k^2\Psi &= -4\pi G a^2 \mu(k,a)\rho\delta, \\ k^2(\Phi - \Psi) &= 8\pi G a^2 \Sigma(k,a)\rho\delta, \end{aligned}$$

TESTING GRAVITY WITH CLUSTERS:

Chameleon mechanism: fifth force is screened in dense environments.

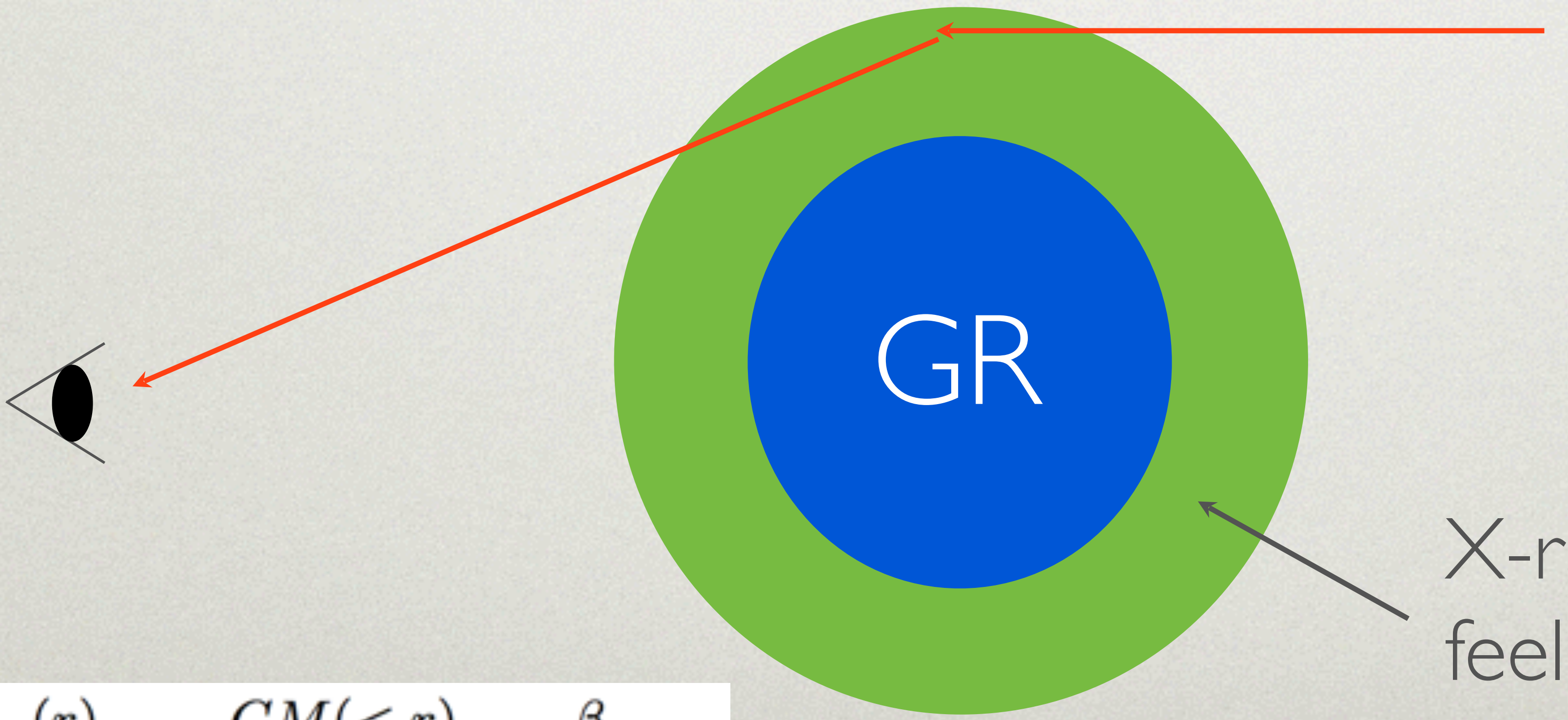
$$\nabla^2\phi = V_{,\phi} + \frac{\beta}{M_{\rm Pl}}\rho,$$

$$F_\phi = -\frac{\beta}{M_{\rm Pl}}\nabla\phi.$$

f(R) exhibit this with

$$\beta = \sqrt{1/6}$$

Khoury & Weltman 04



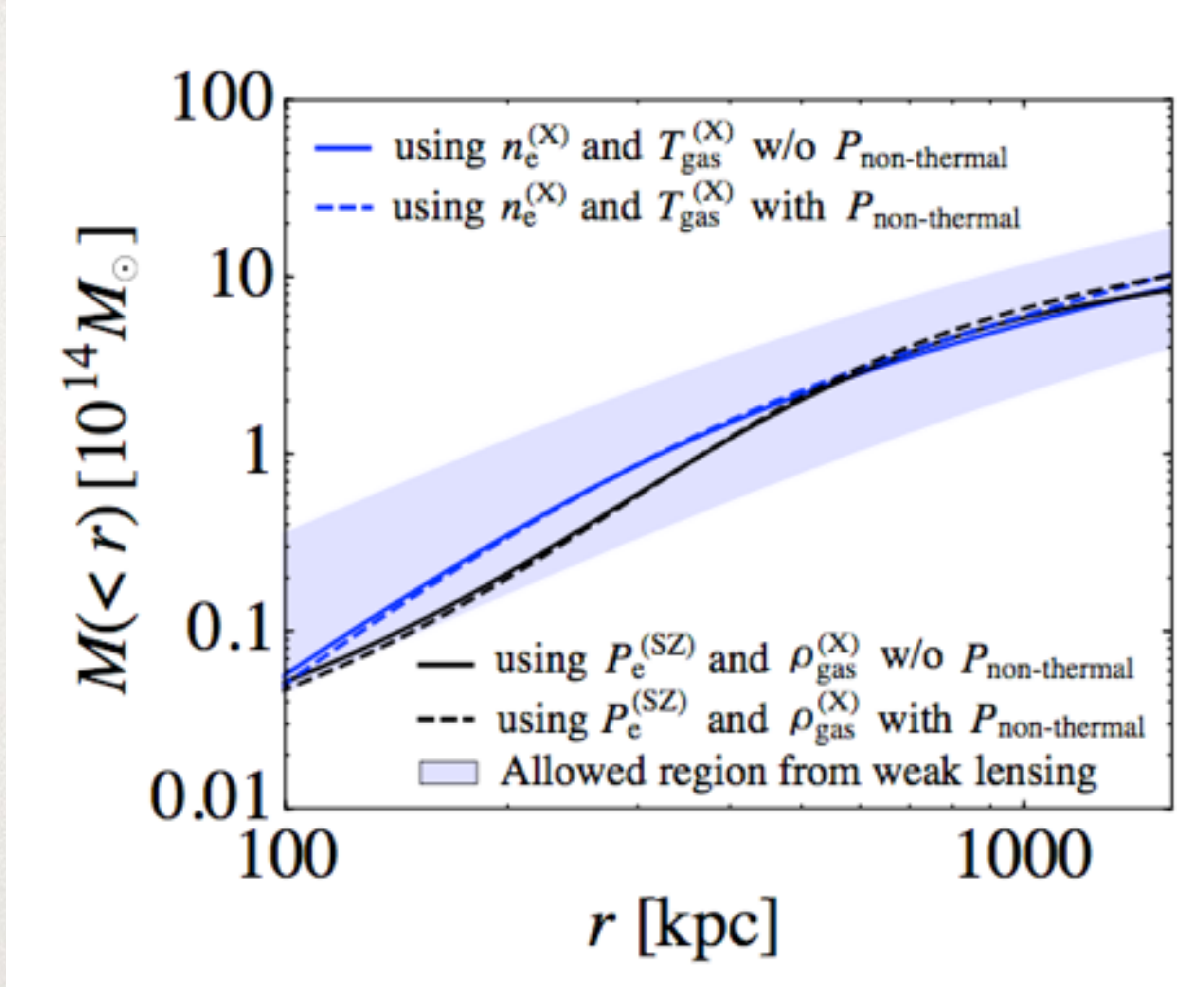
Lensing doesn’t feel fifth force

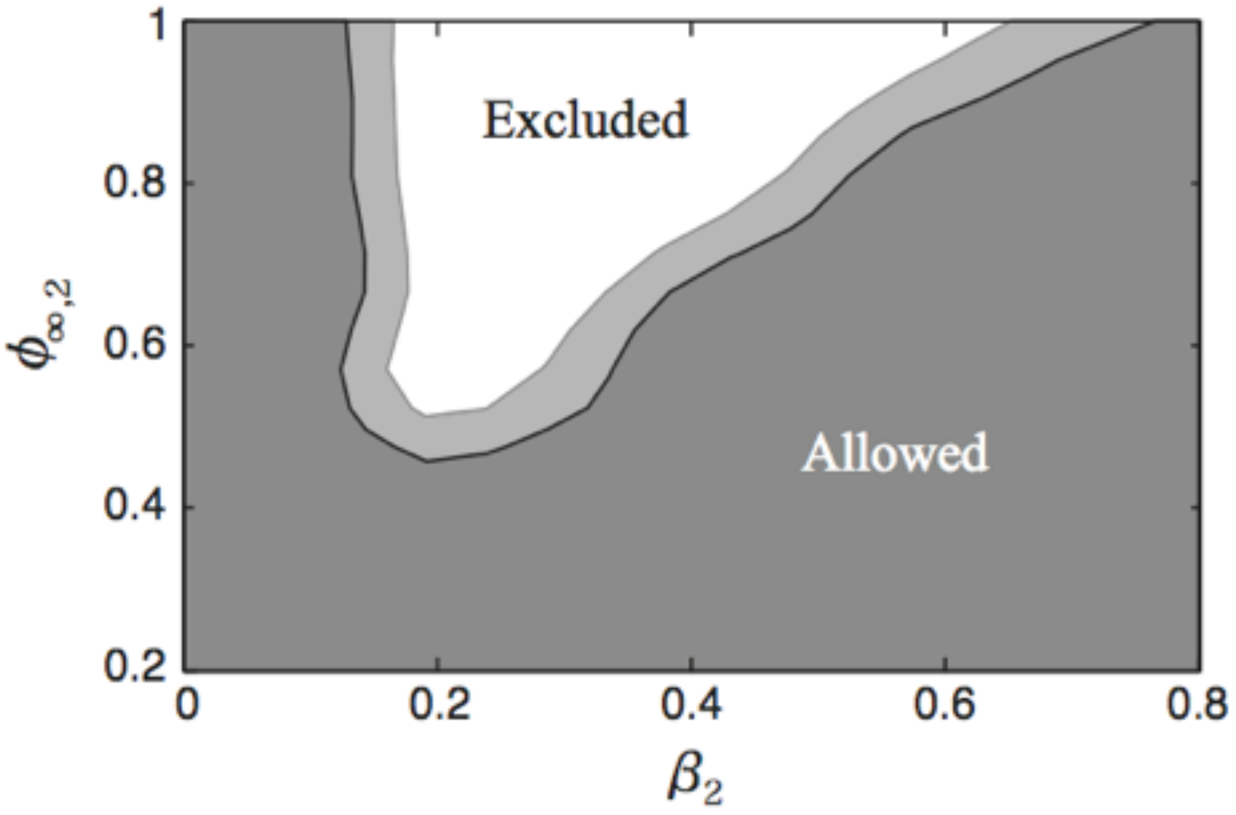
X-ray emitting gas feels fifth force here

$$\frac{1}{\rho_{\rm gas}(r)}\frac{dP_{\rm gas}(r)}{dr} = -\frac{GM(<r)}{r^2} - \frac{\beta}{M_{\rm Pl}}\nabla\phi$$

CHAMELEON TESTS WITH COMA

Adam Block





β is 5th force strength

ϕ∞ is screening efficiency

Terukina et al 2014

CHAMELEON WITH XMM CLUSTERS

Lensing data from CFHTLens wide; median $z=0.75$

X-ray data from XMMLSS survey

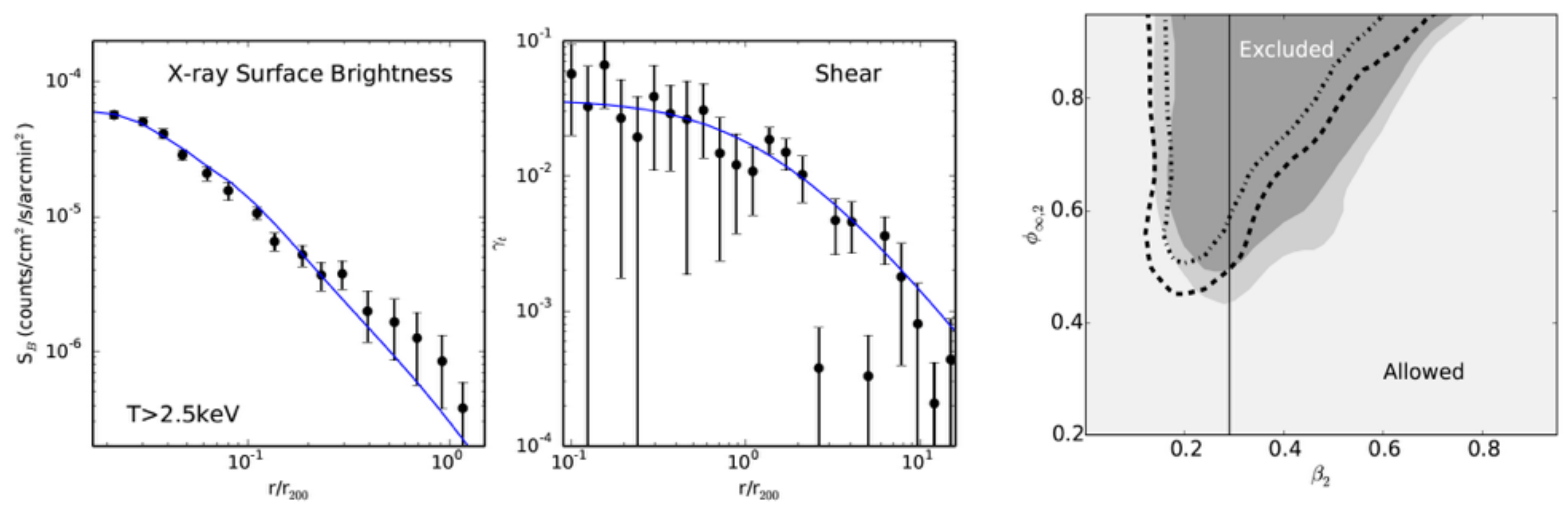
52 clusters detected in both datasets; $0.1<z<0.8$, $0.3<T_X(\mathrm{keV}) < 11$

Make X-ray temperature bins (2 or 3)

Stacked profiles made on X-ray centroids, removing 4 sigma outliers in X-ray surface brightness images.

CHAMELEON WITH XMM CLUSTERS

Wilcox et al 2015



$f_{\rm R} = {\rm d}f/{\rm d}R$

$|f_{\rm R0}| < 6 \times 10^{-5}$ 95%CL

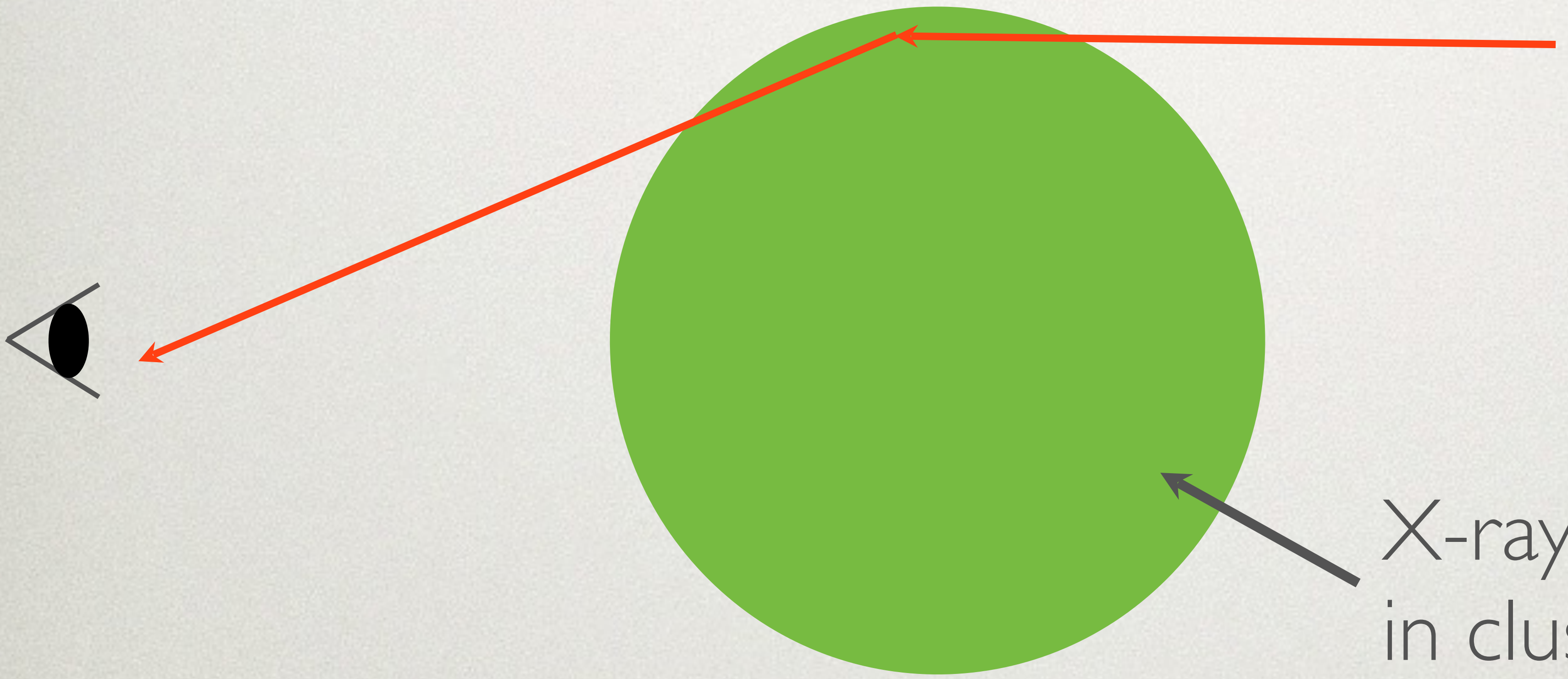
Next: Dark Energy Survey - 4 times as many clusters with X-ray data in SV alone.

"BEYOND HORNDESKI" GRAVITY

Very general, well-behaved theory of gravity

One extra field

BEYOND HORNDESKI



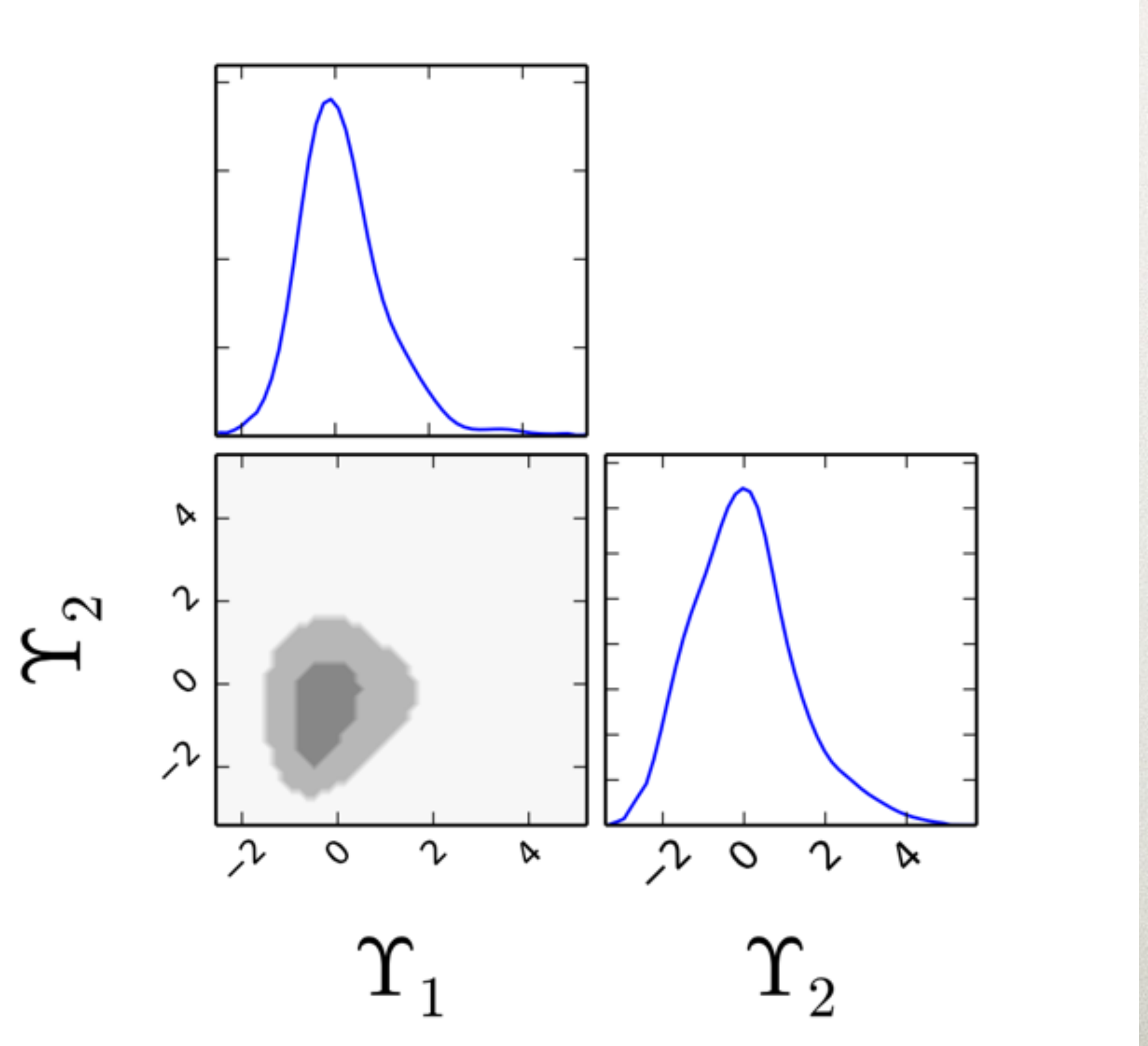
Lensing modified in cluster Υ_2

X-ray emission modified in cluster Υ_1

$$\frac{\mathrm{d}\Phi}{\mathrm{d}r} = \frac{GM(r)}{r^2} + \frac{\Upsilon_1 G}{4}\frac{\mathrm{d}^2 M(r)}{\mathrm{d}r^2}$$
$$\frac{\mathrm{d}\Psi}{\mathrm{d}r} = \frac{GM(r)}{r^2} - \frac{5\Upsilon_2 G}{4r}\frac{\mathrm{d}M(r)}{\mathrm{d}r}.$$

Wilcox et al 16

FIRST CONSTRAINT ON Υ_2



Wilcox et al 16

As before, fit X-ray and lensing profiles for different values of Υ_1 and Υ_2

SUMMARY

Lensing probes a combination of the matter distribution and geometry.

Strong lensing can

- constrain gravitational wave speed,
- make precise constraints of dark energy,
- probe dark matter physics;

Weak lensing can

- make useful maps of projected total matter density,
- measure cosmological parameters using shear statistics,
- constrain gravity properties;

Amongst other things!