# Gravitational lensing in the era of brokers

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CBPF

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ICIFI-ECYT_UNSAM-CONICET

Fink-Brazil Workshop

FINK BRAZIL

# Outline

- Gravitational lensing in a nutshell

LSST
Discovery Alliance

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- Transients from microlensing

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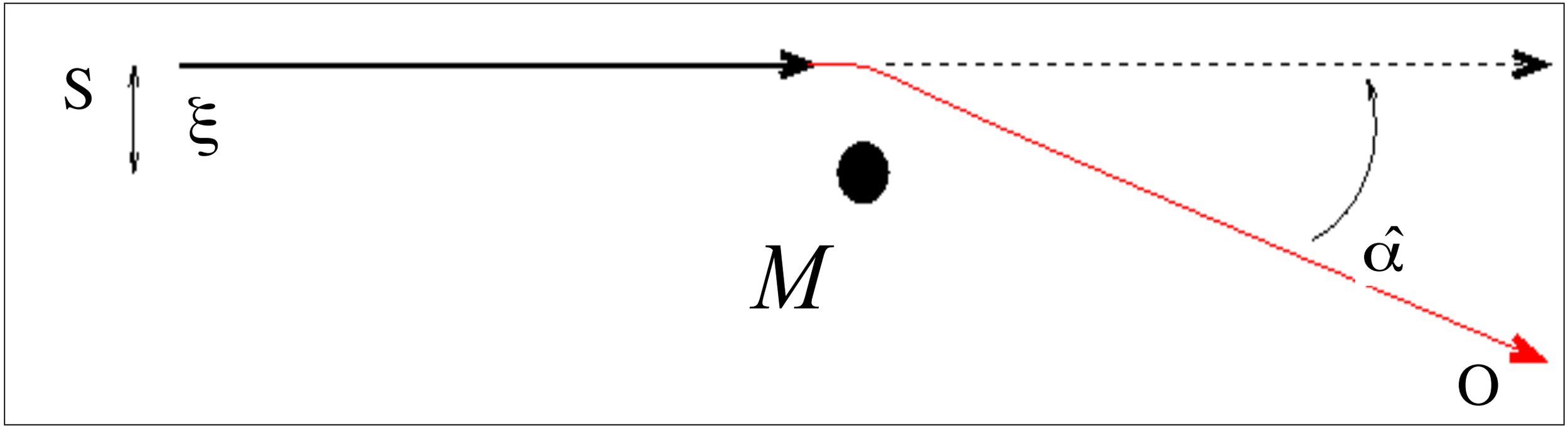
- Transients from microlensing
- Strong lensing of transients (SNe)
- Strong lensing without optical counterparts (GW)

LSST Discovery Alliance

# Bending of light by gravity

Null geodesic,
Fermat principle

$$ds^2 = \left(1 + \frac{2\phi}{c^2}\right) c^2 dt^2 - \left(1 - \frac{2\phi}{c^2}\right) d\sigma^2$$



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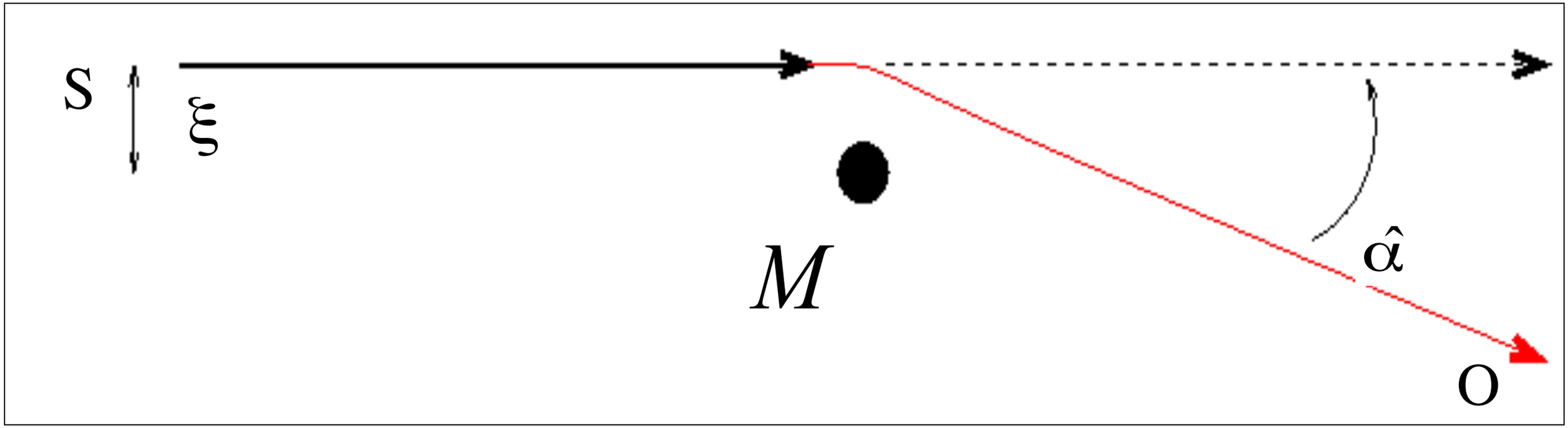

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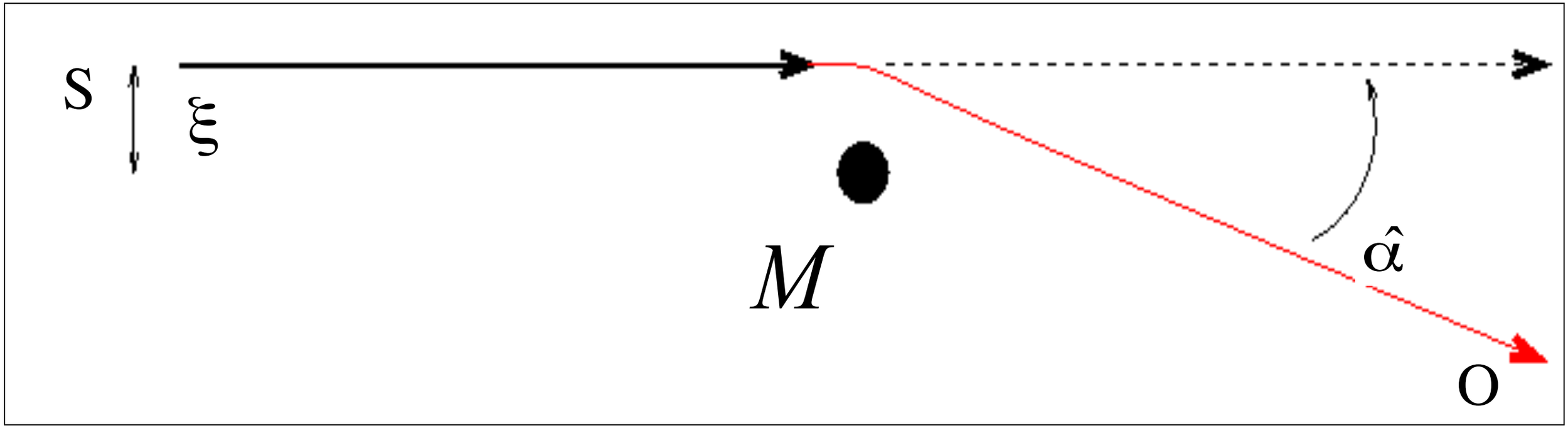


Deflection angle: $\hat{\alpha} = \frac{4GM}{c^2}\frac{1}{\xi}$

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- Strong lensing
  - Strong magnifications
  - Multiple images
  - Distortions
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- Micro-lensing
  - MACHOS
  - Planetary search
- Micro and mili-lensing
  - Quasars
- "Macro-lensing"
  - Galaxies
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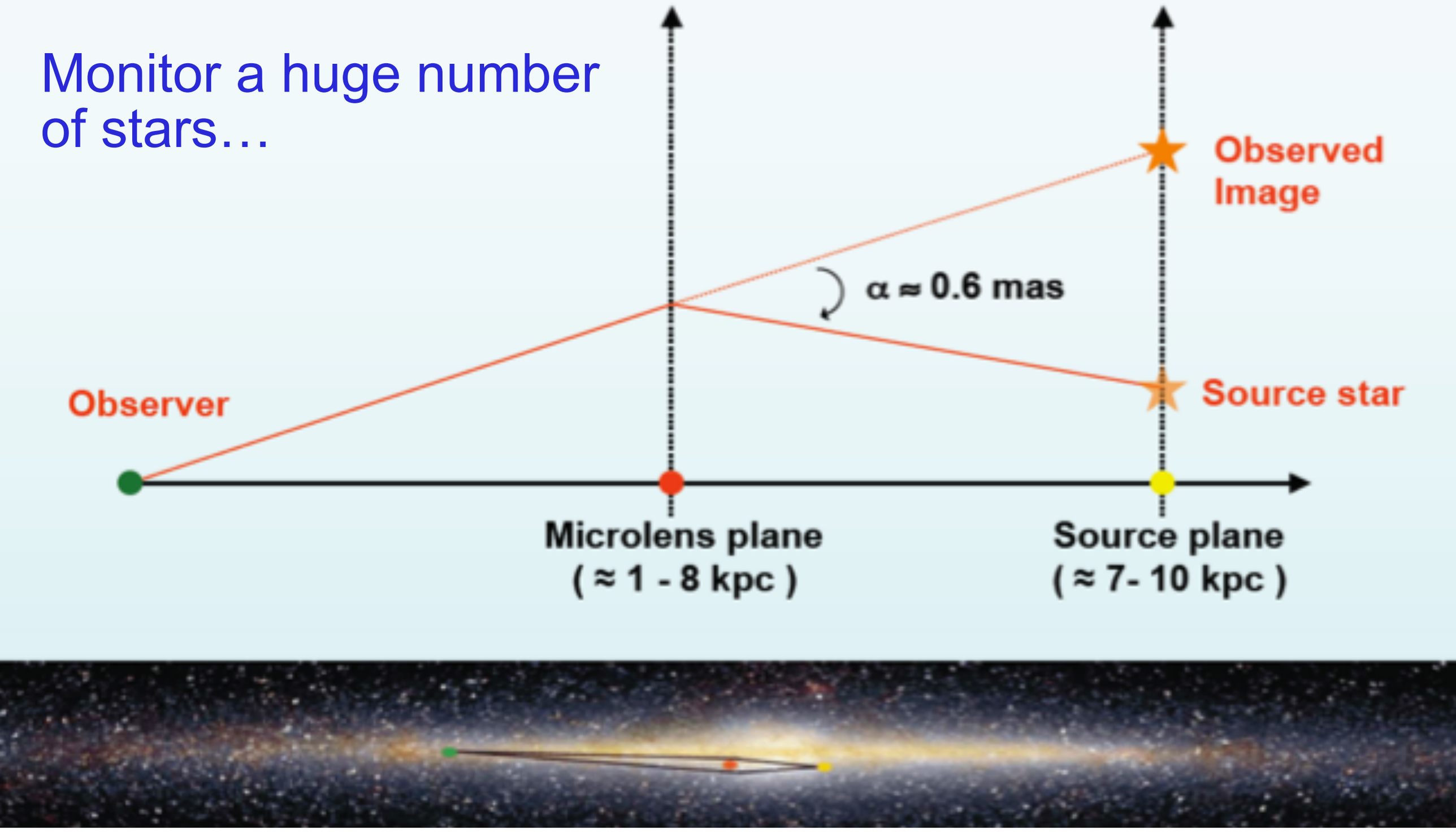
**Gravitational Lensing is everywhere**

+ astrometric microlensing, black-hole shadows, retrolensing, femtolensing, lensing of gravitational waves….

# Galactic microlensing

Monitor a huge number of stars…



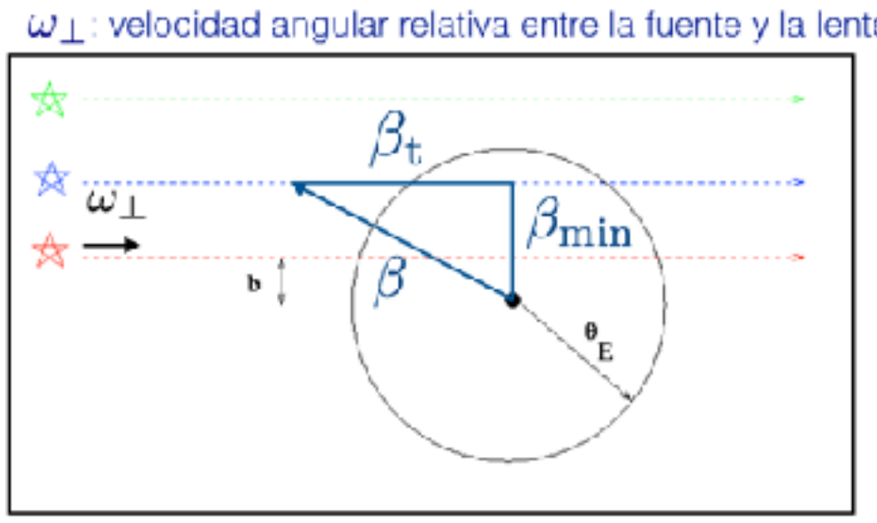

*Arnaud Cassan ARI/ZAH, Heidelberg University, talk @ Institut d'Astrophysique de Paris, Jan. 11, 2008*

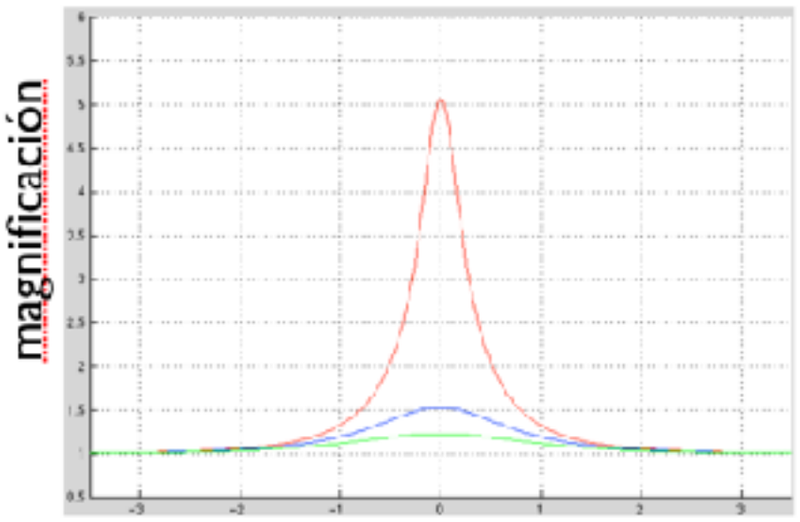
# (Galactic) Microlensing

$$\mu = \frac{u^2+2}{u\sqrt{u^2+4}} \qquad u = \beta/\theta_E$$

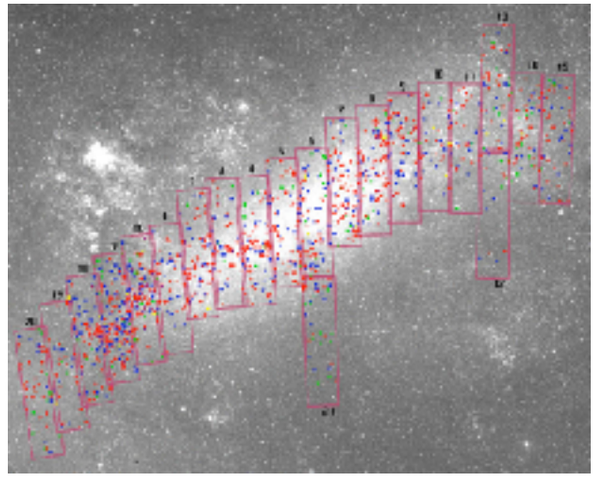
Einstein Angle $$\theta_E = \sqrt{\frac{D_{LS}}{D_{OS}D_{OL}}\frac{4GM}{c^2}}$$

- Light magnification of a star produced by the strong lensing effect of a closer condensed object




- Relative motion causes a variation in the magnification
- Need to monitor a large number of stars (Einstein though this effect was undetectable)



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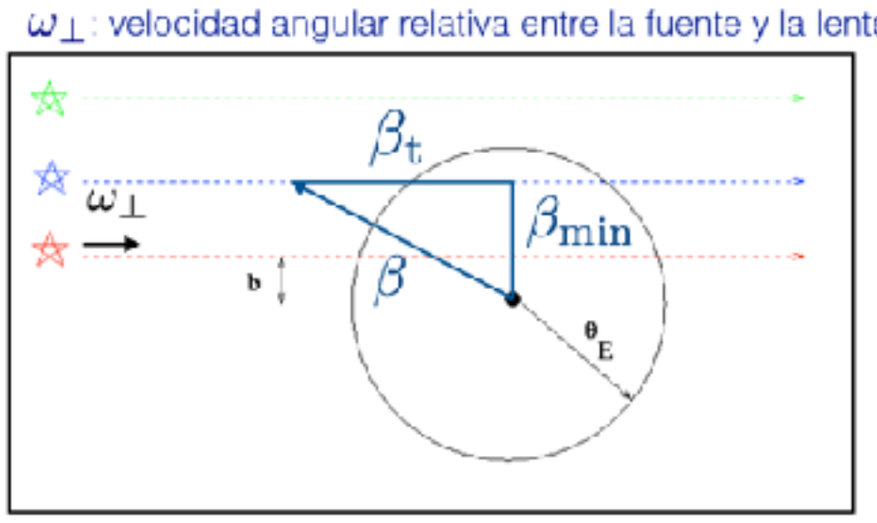


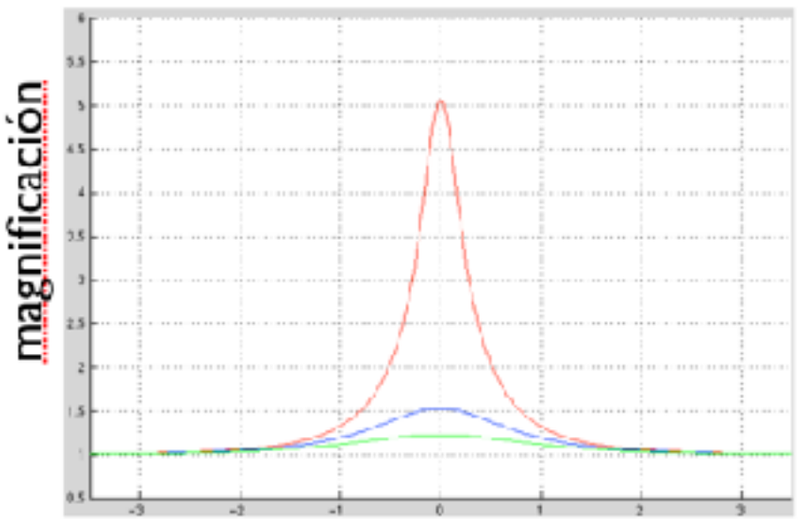


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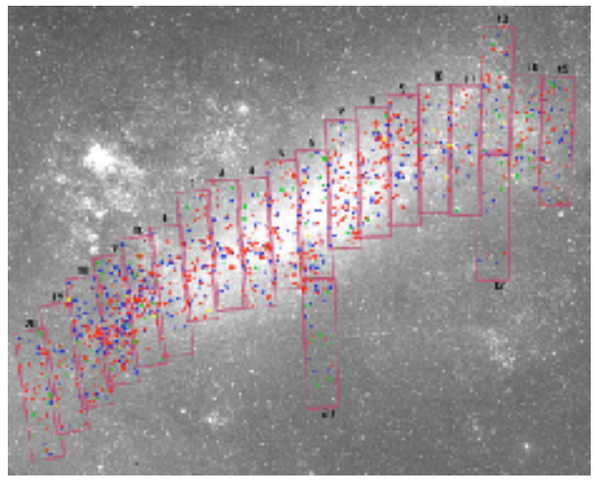

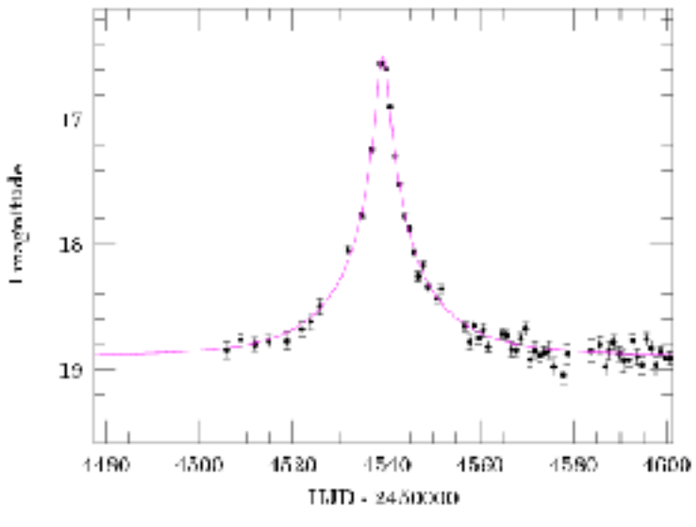

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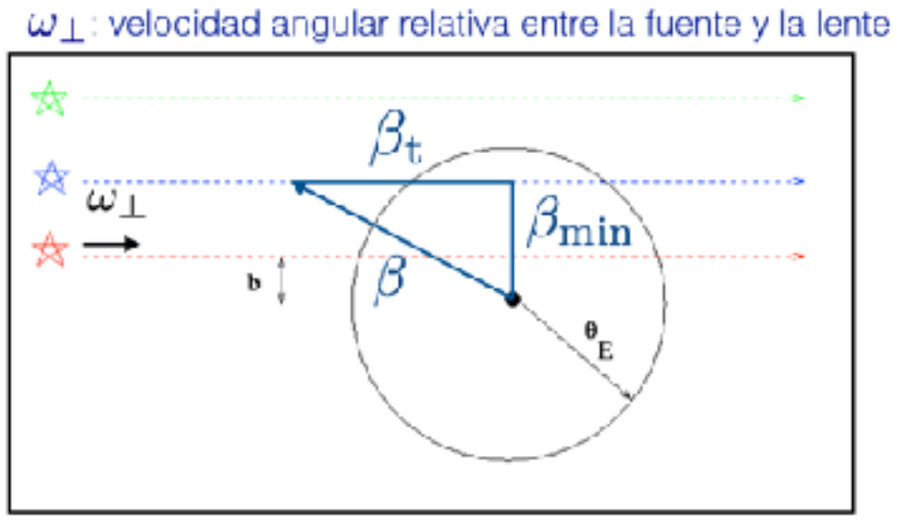


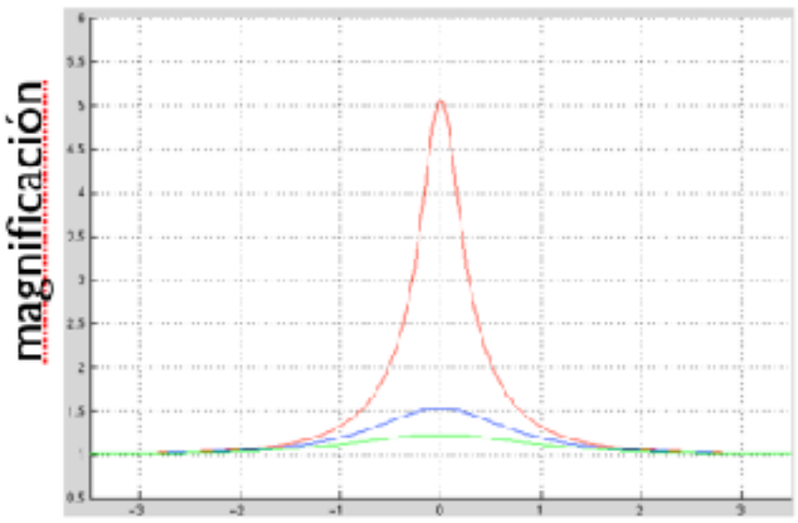


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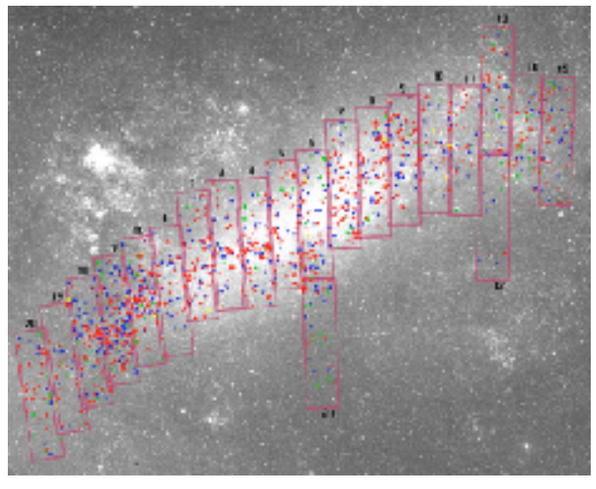
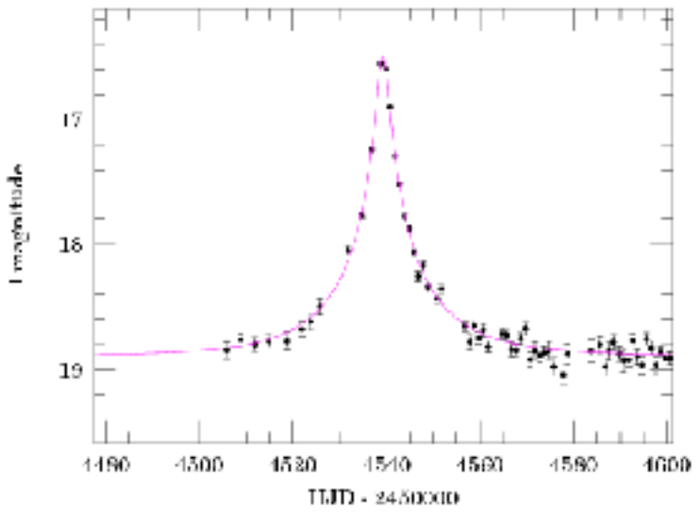
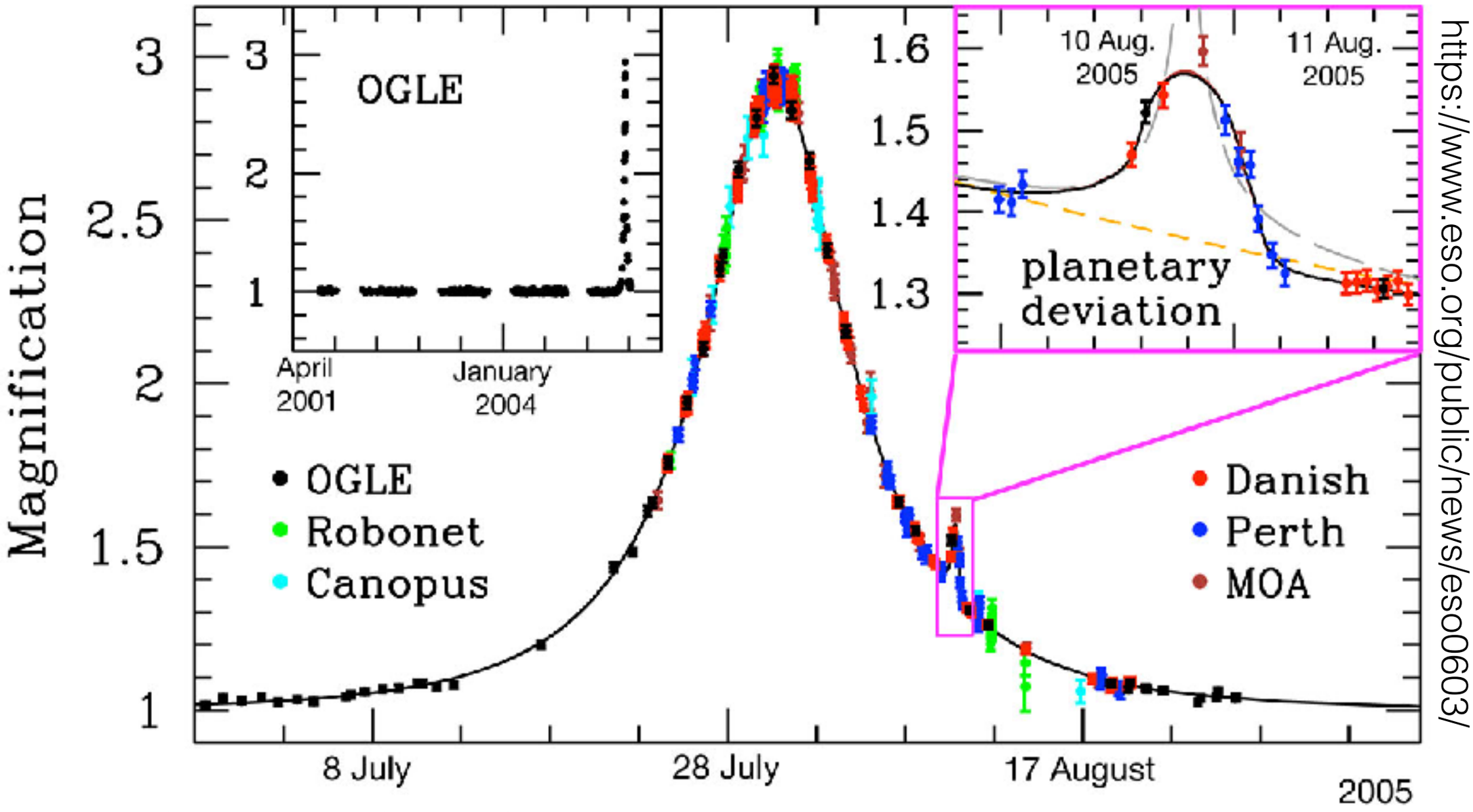





Also microlensing of QSO and SN by stars in lens galaxies

# Exoplanets

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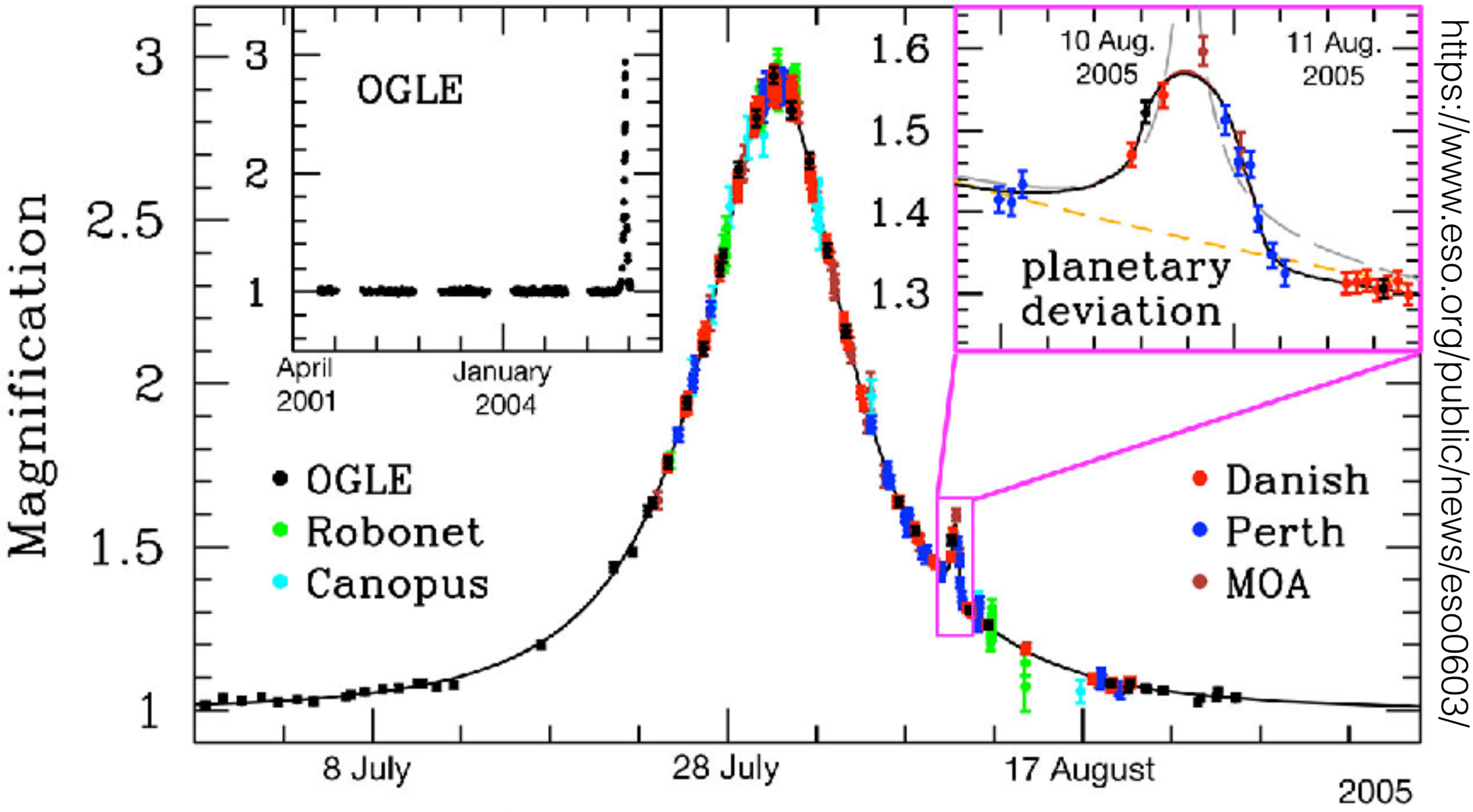


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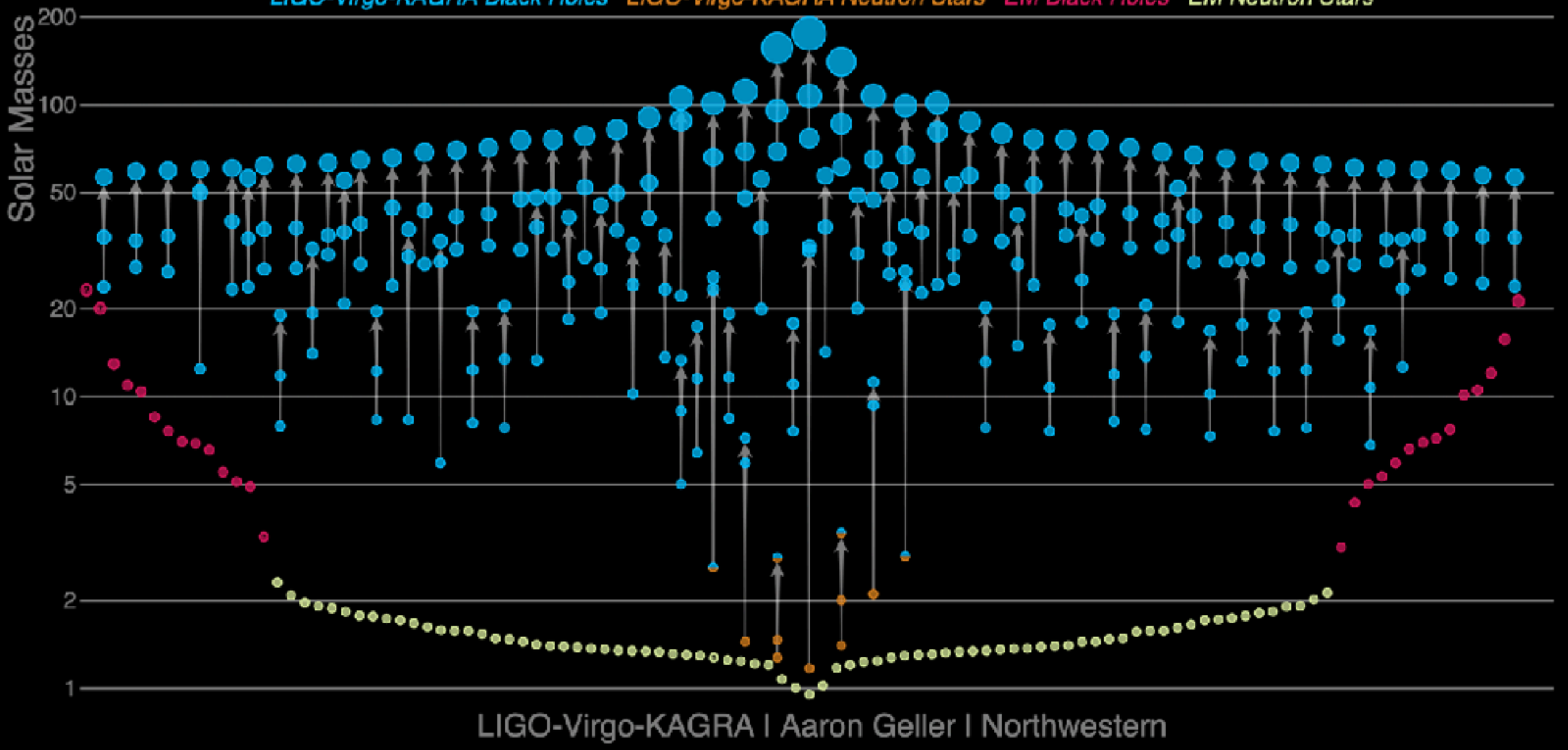
**See Leandro Almeida's talk**

https://ligo.northwestern.edu/media/mass-plot/index.html

# Masses in the Stellar Graveyard



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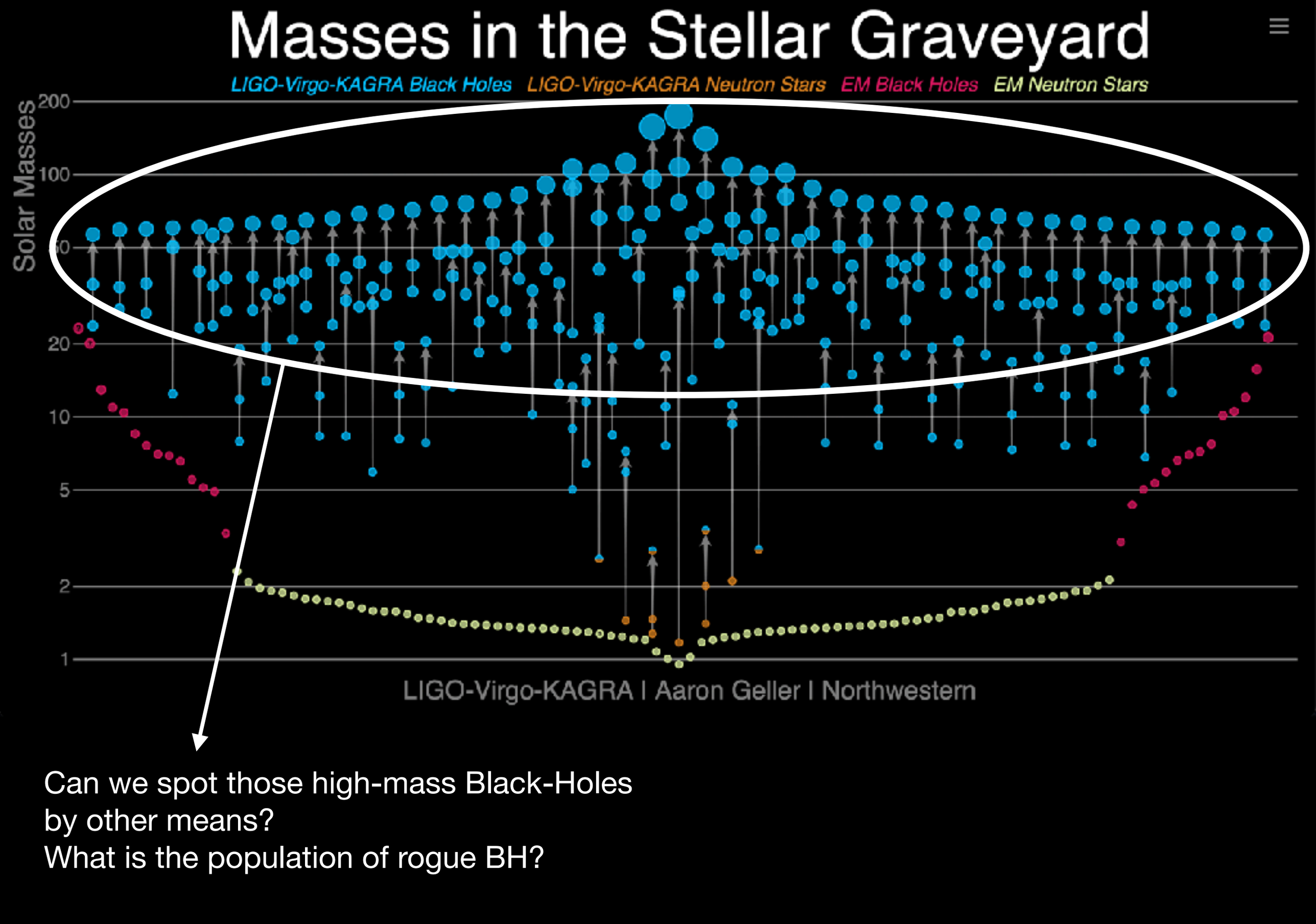


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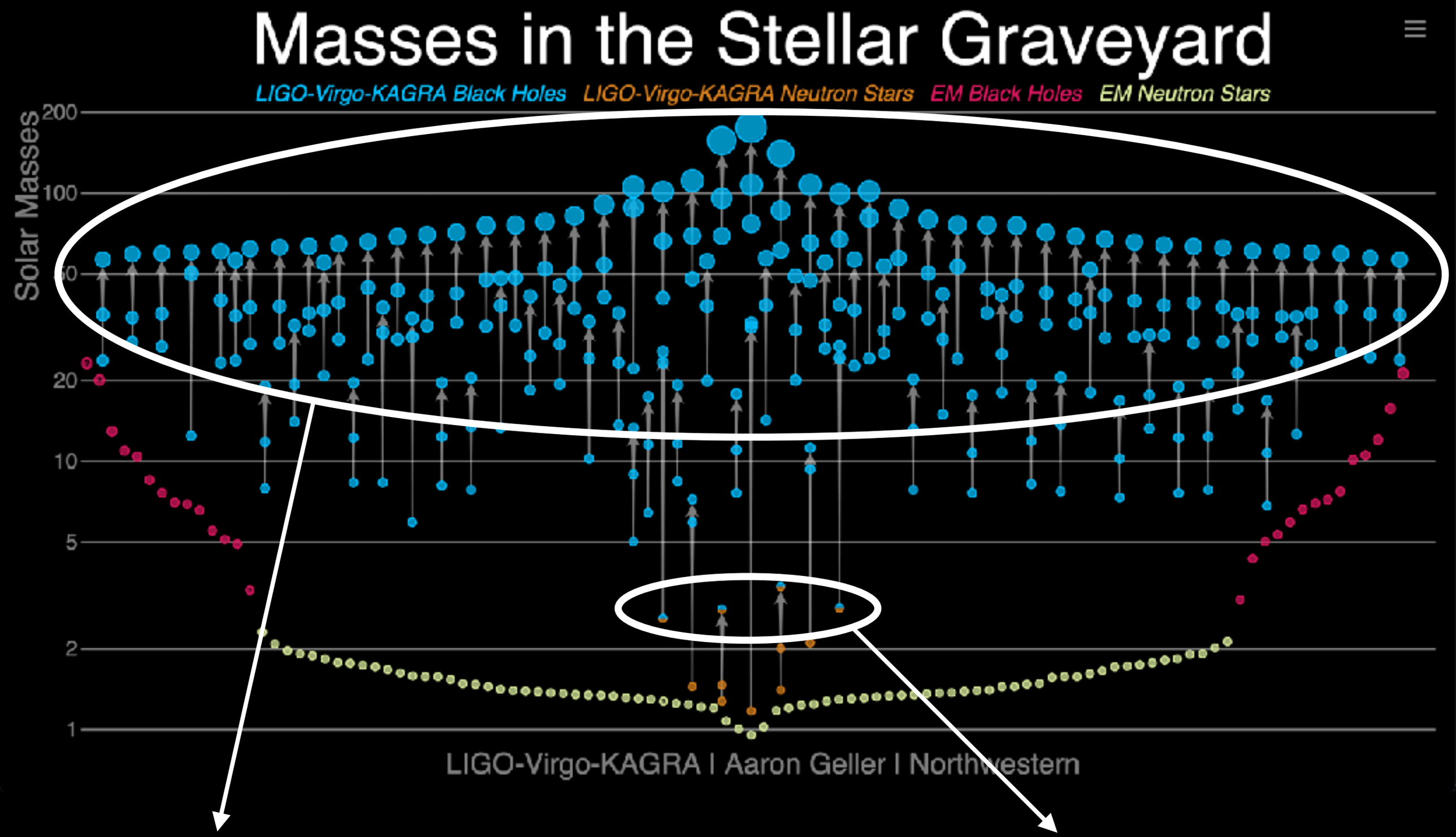


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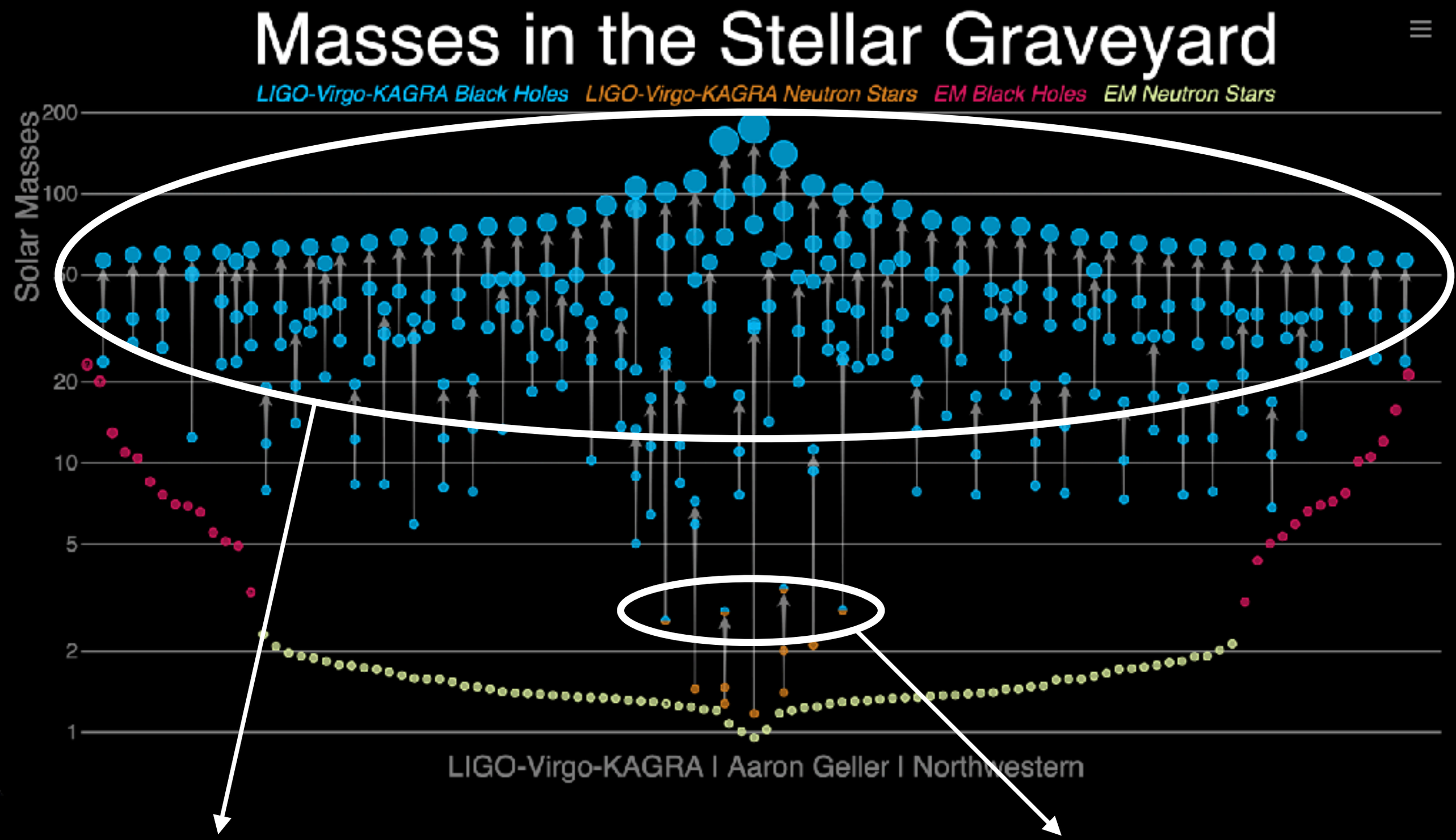


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**Microlensing can help us build a more complete census of compact objects**

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## State-of-the art for imaging astronomy with natural seeing

- Brand new observatory in Cerro Pachón, Chile (alongside Gemini and SOAR)
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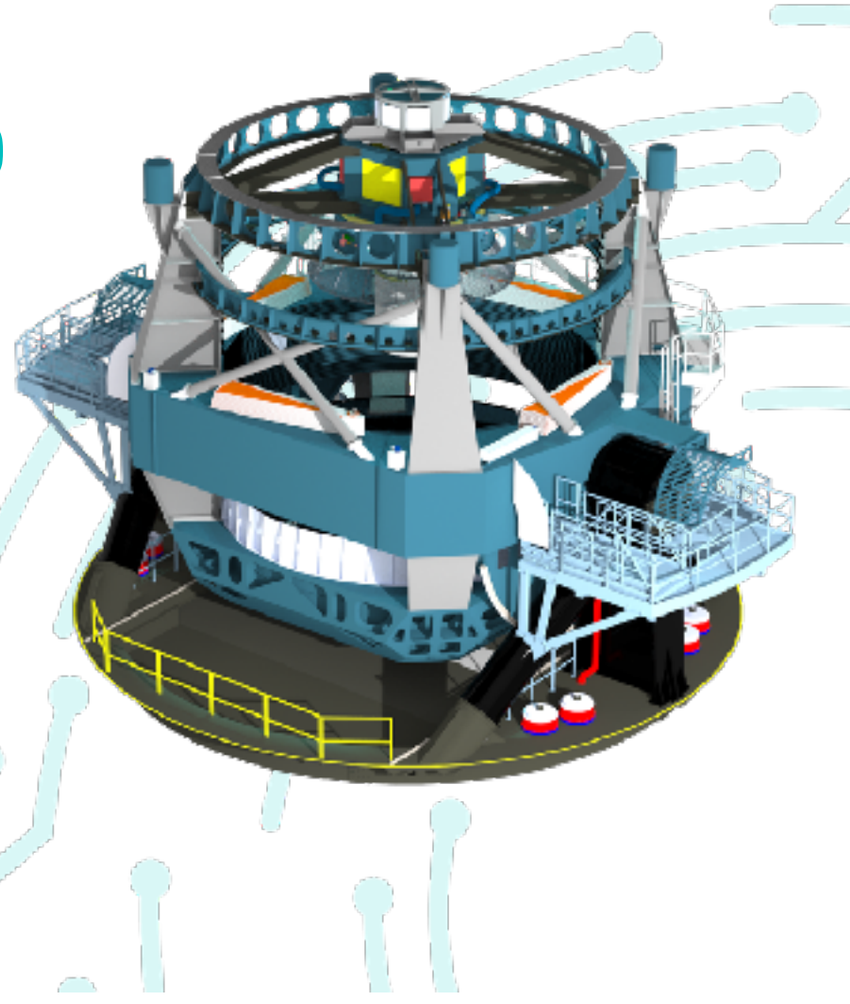

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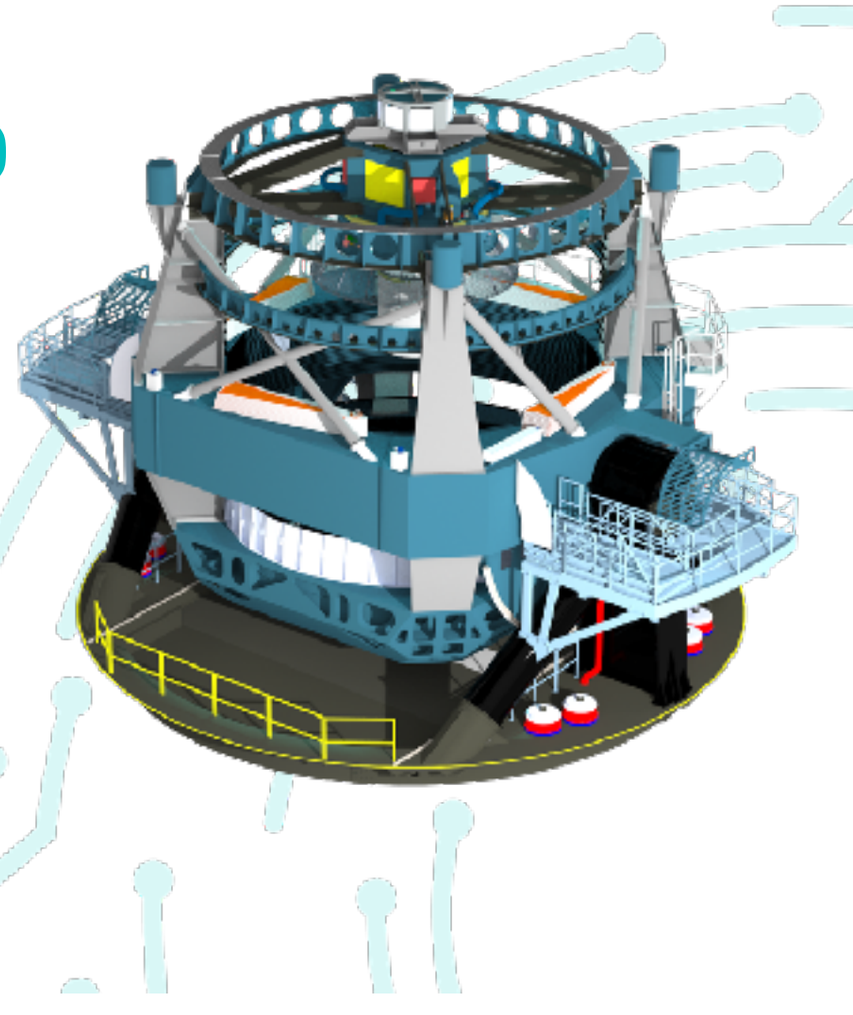

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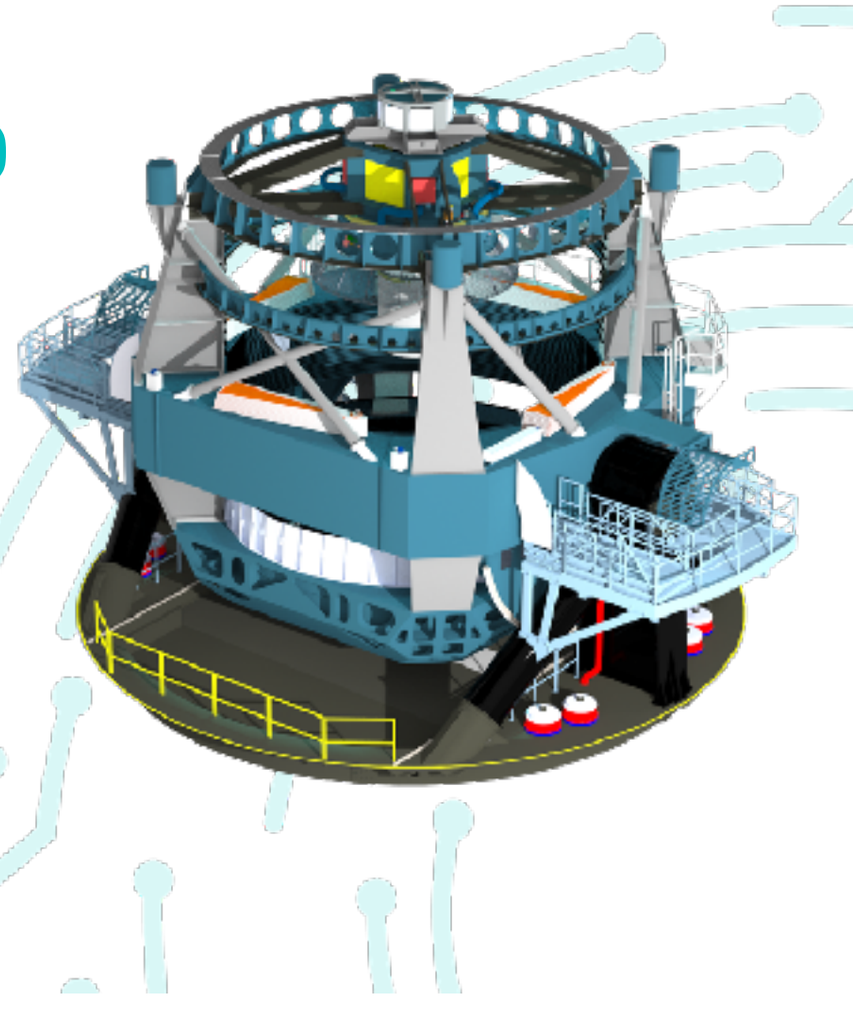

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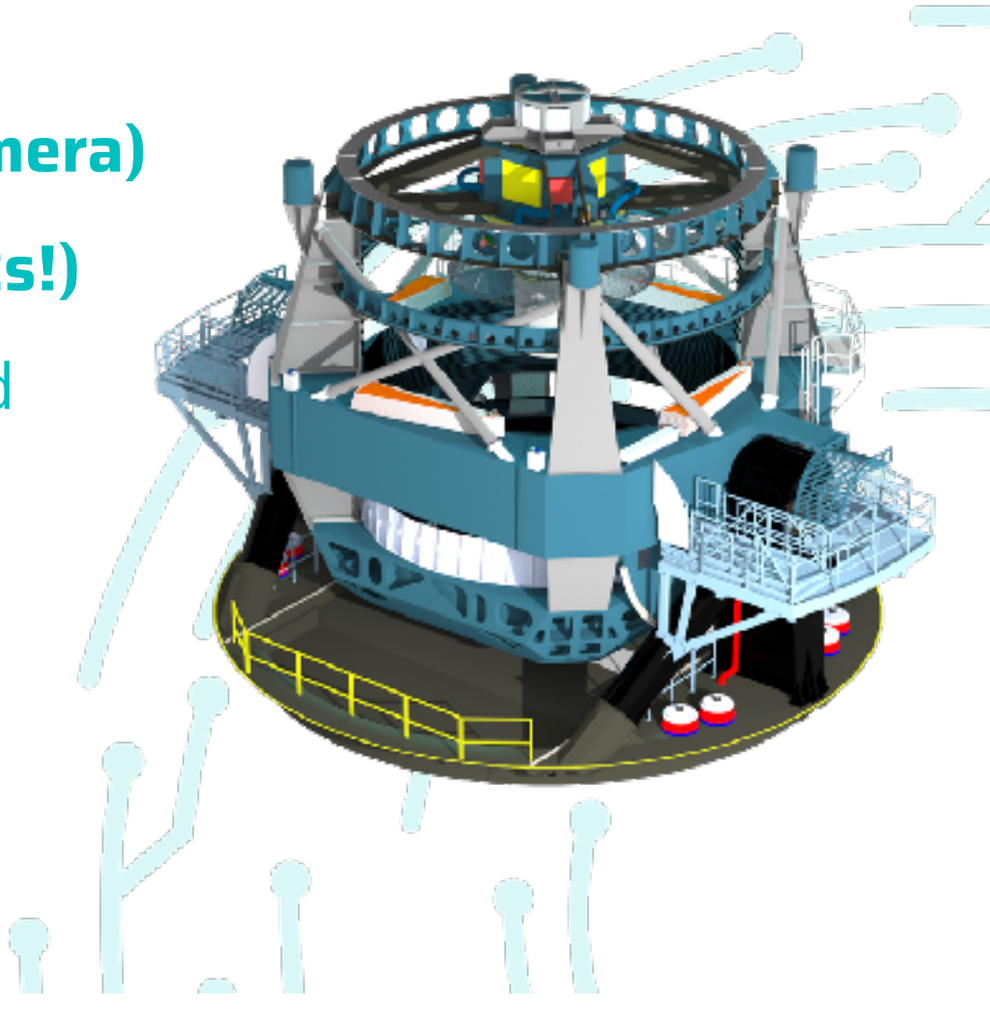

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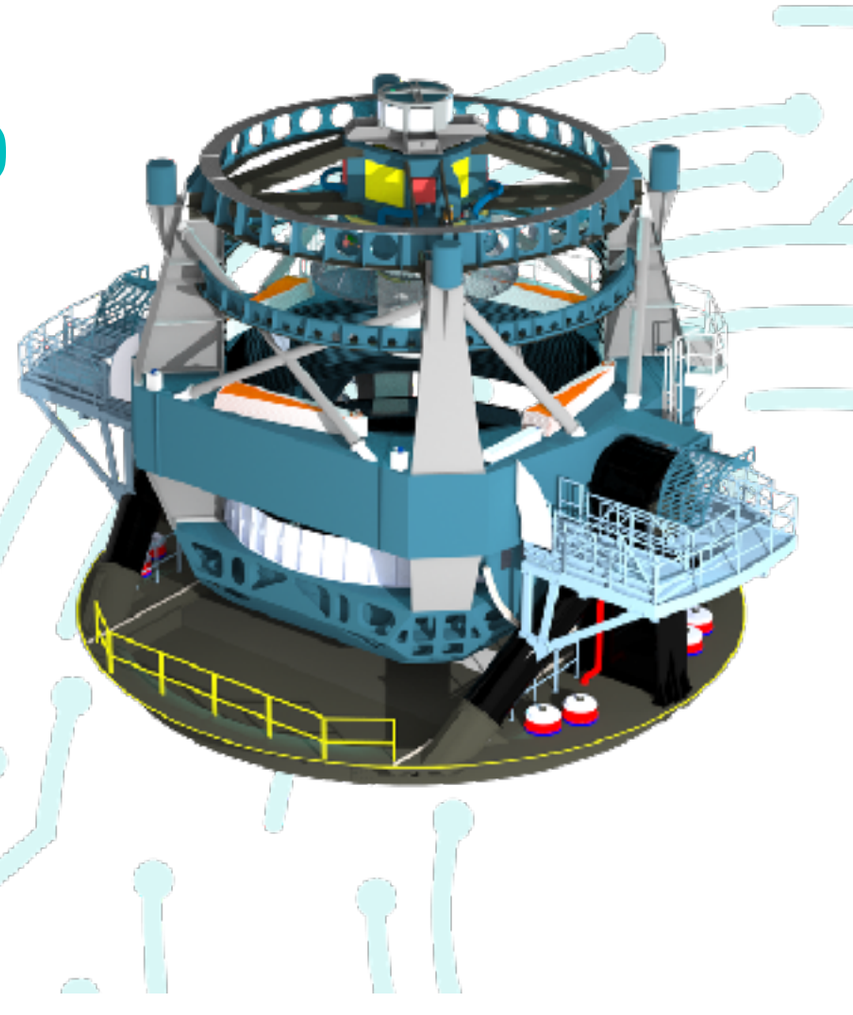

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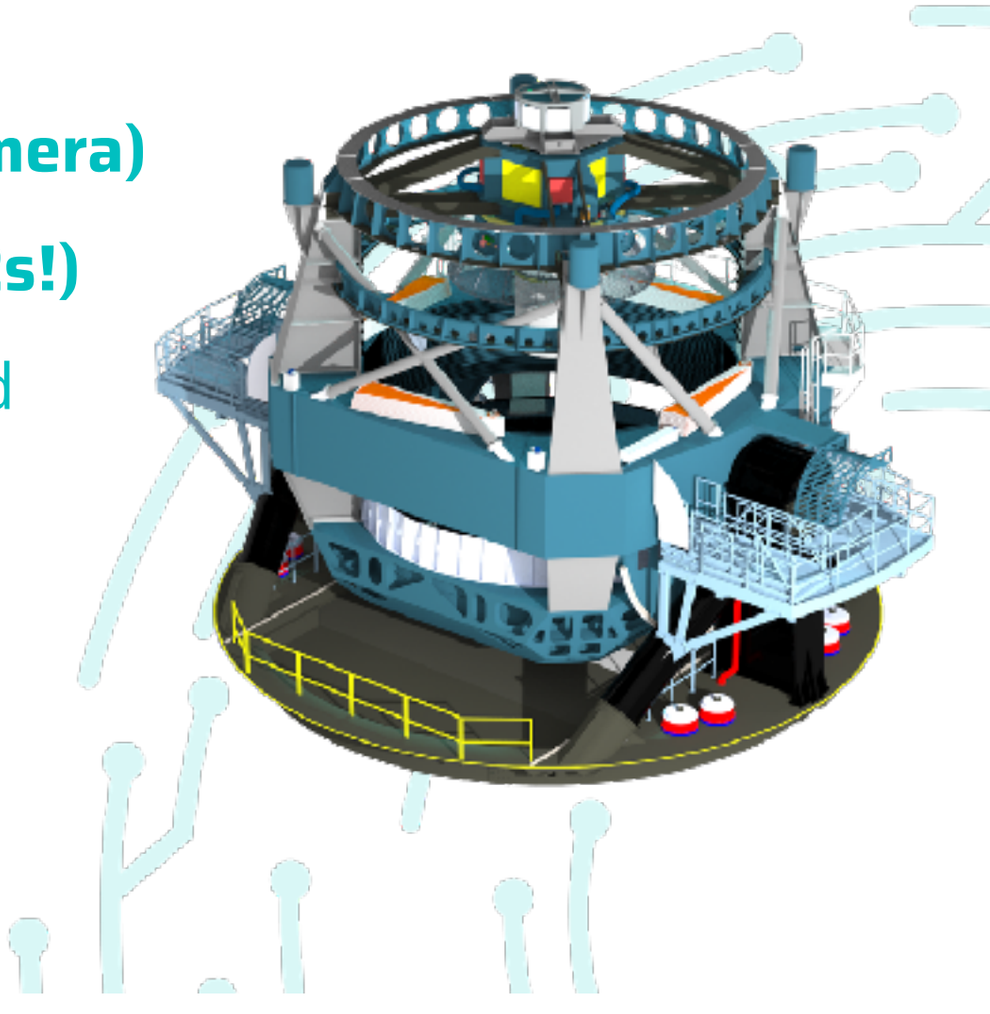

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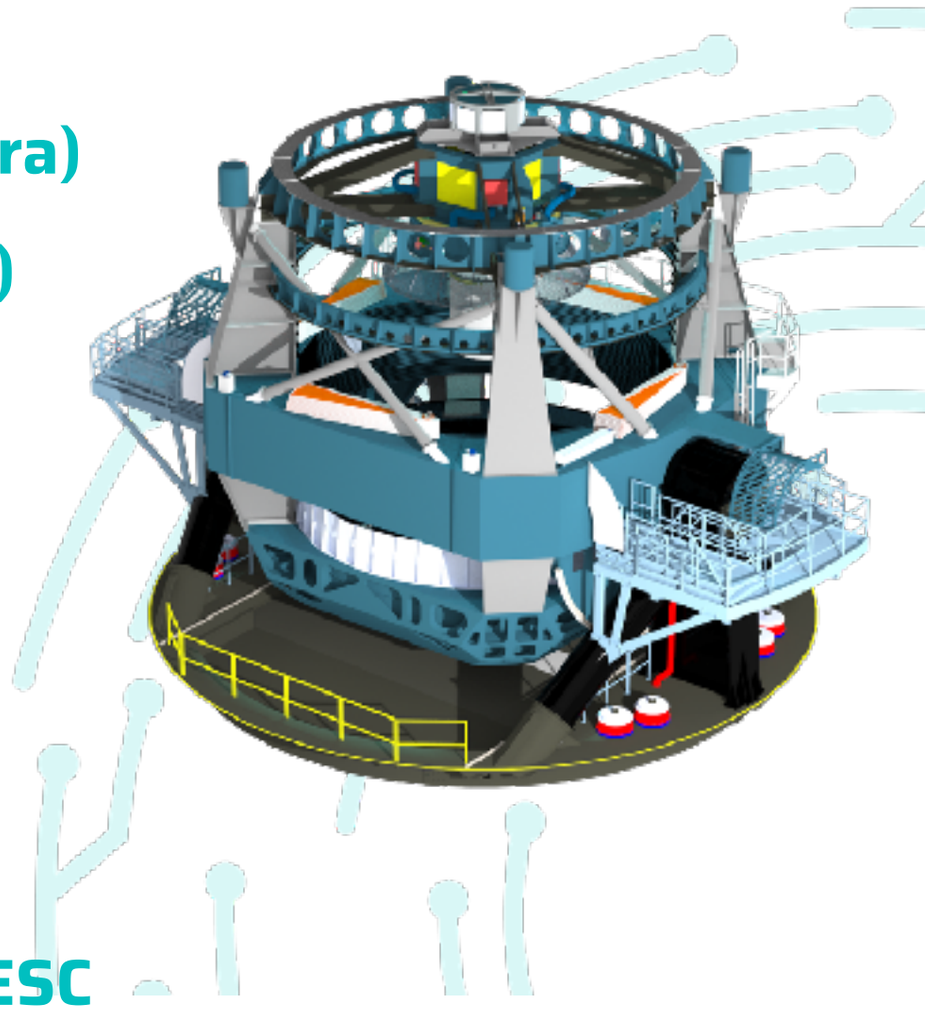

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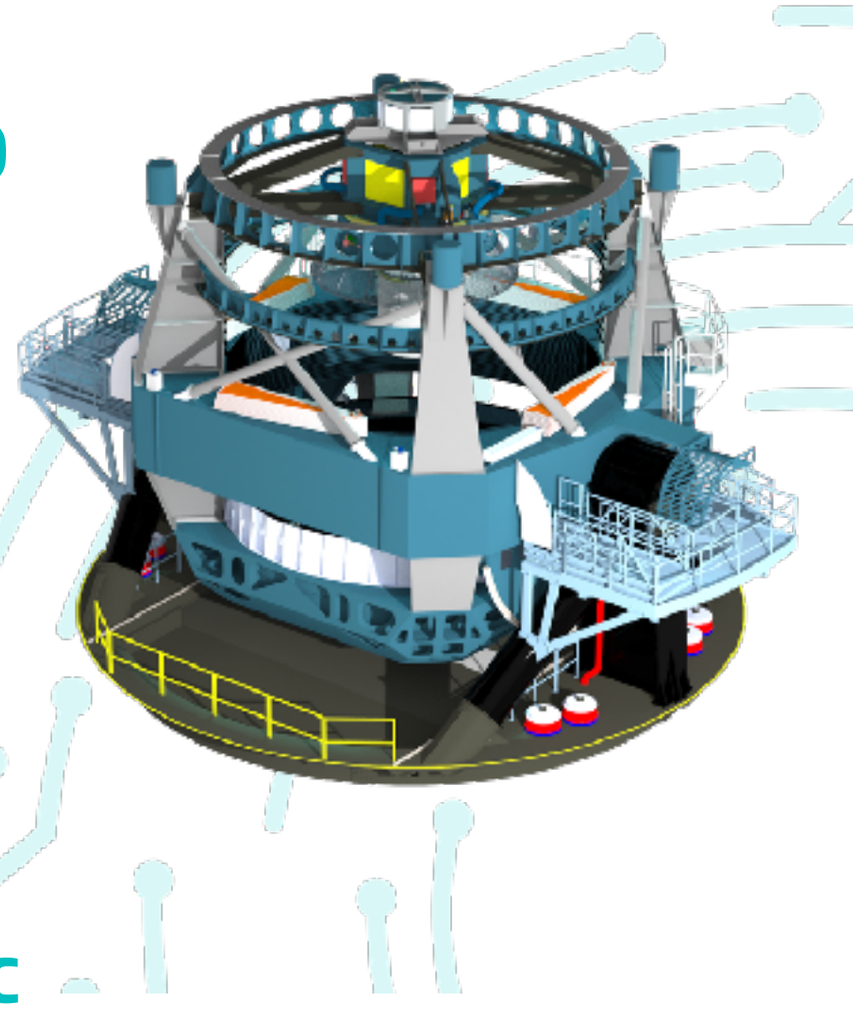

- **Argentina, Brazil (in-kind contributors) and Chile (site) are members**

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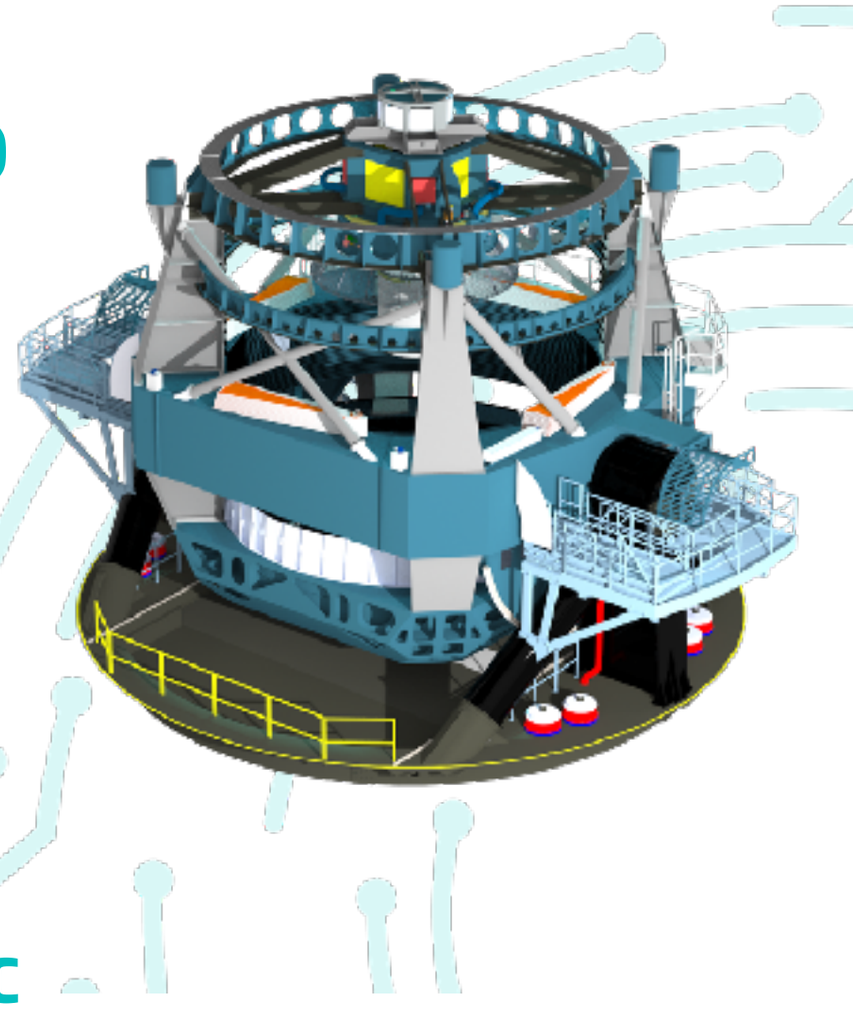

- **Argentina, Brazil (in-kind contributors) and Chile (site) are members**

See overview by Mariana Penna-Lima

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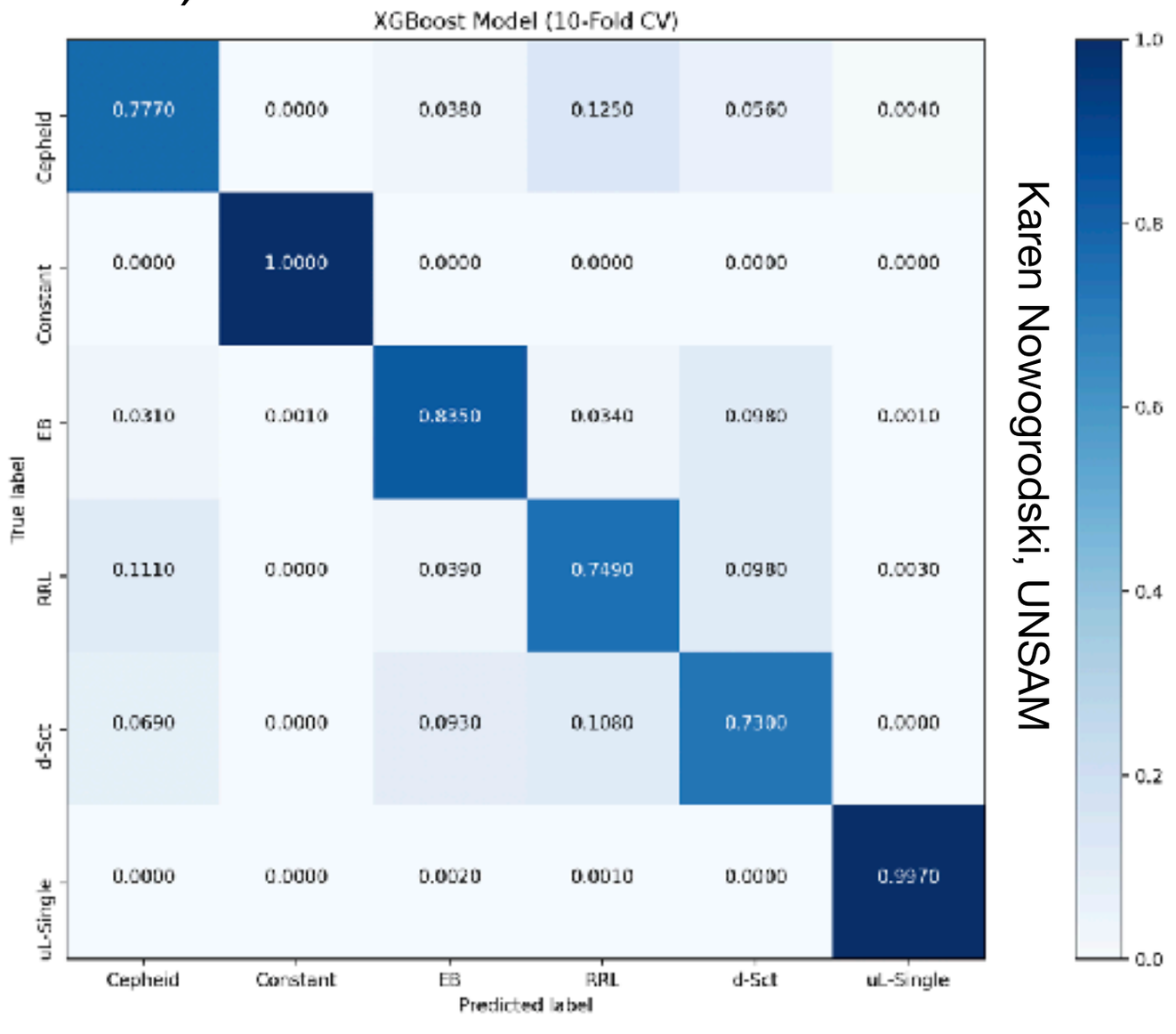


Karen Nowogrodski, UNSAM

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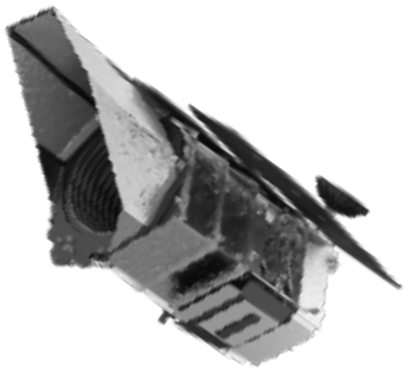

- Free-floating plants, binary lenses, Black Holes
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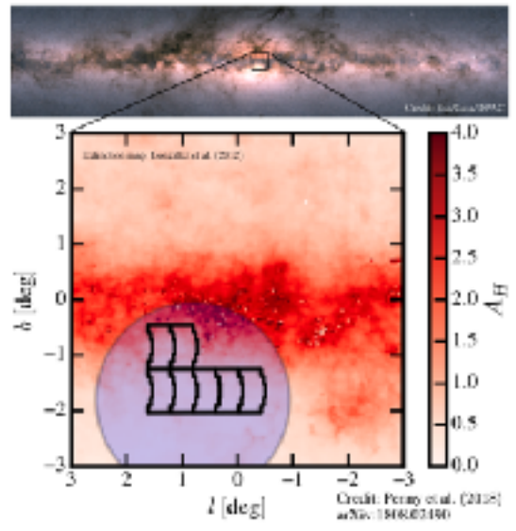

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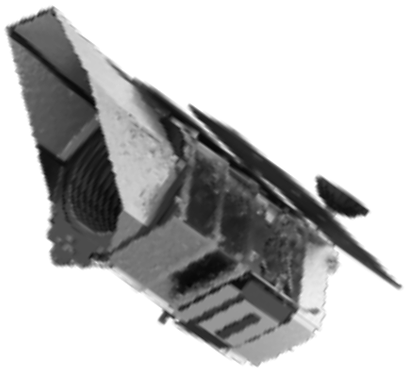

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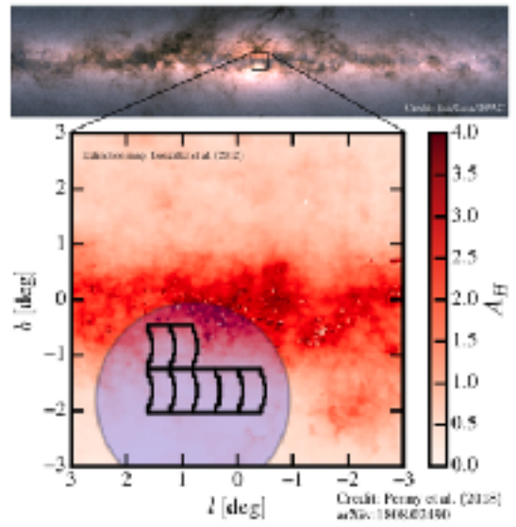


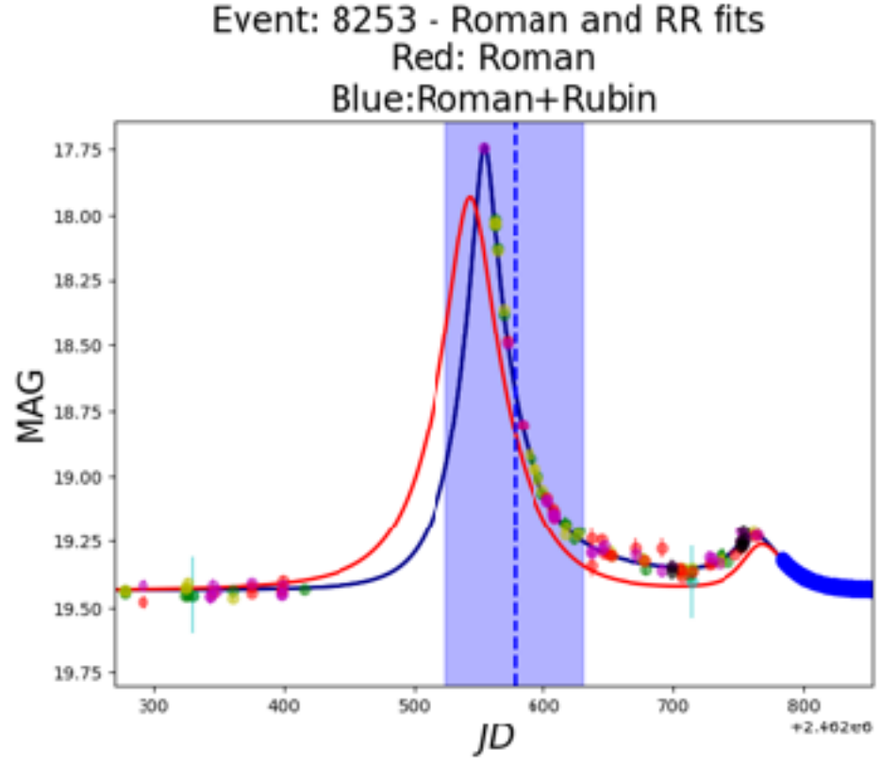


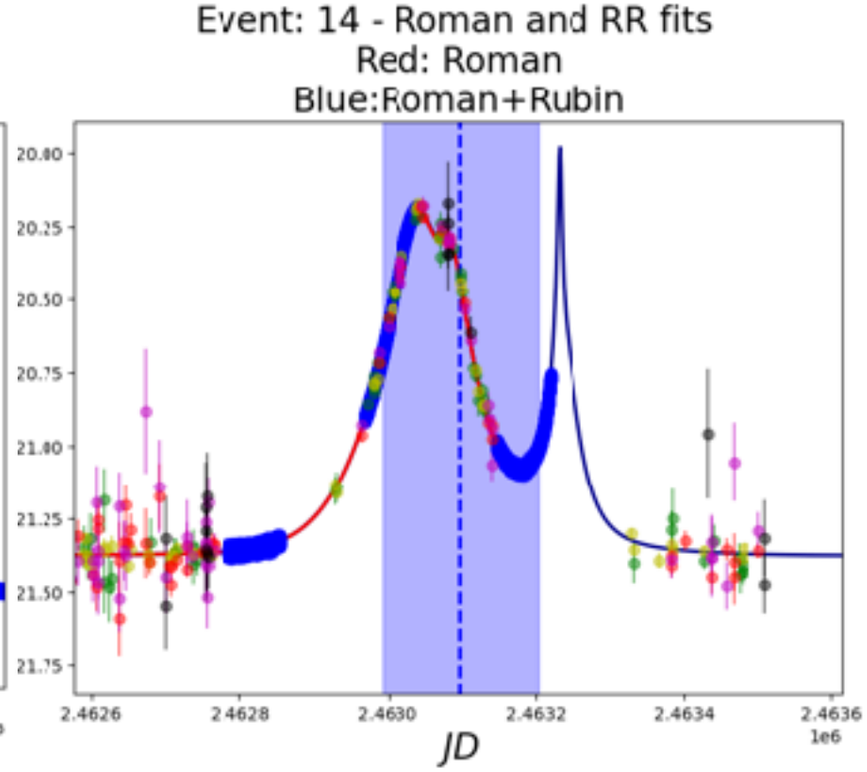


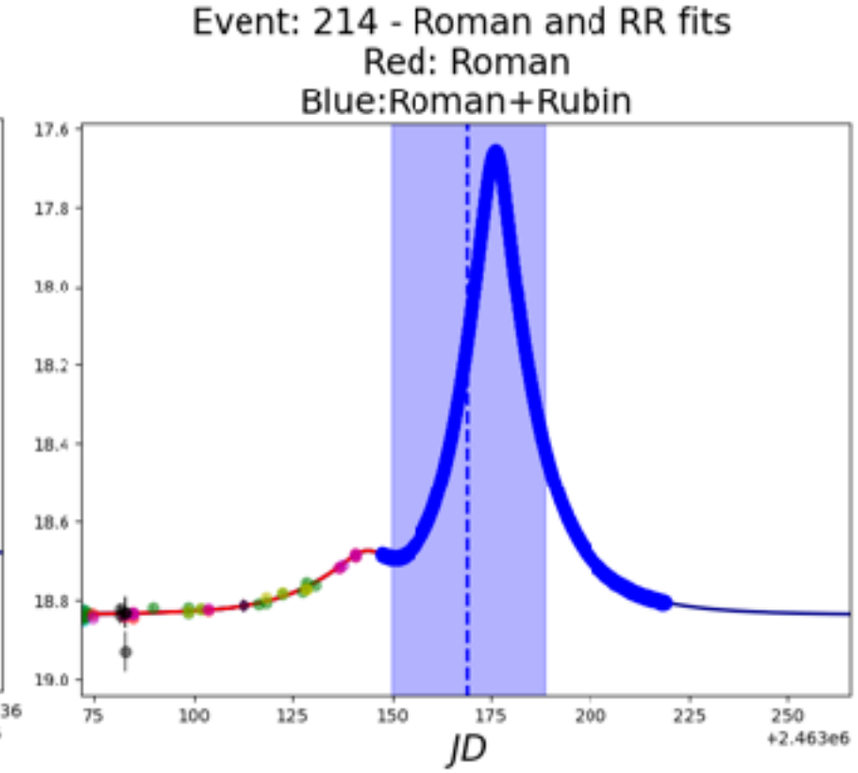


Anibal Varela, UNSAM

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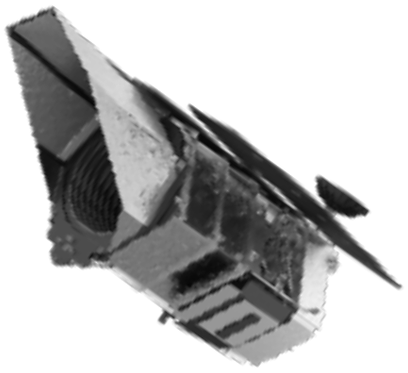

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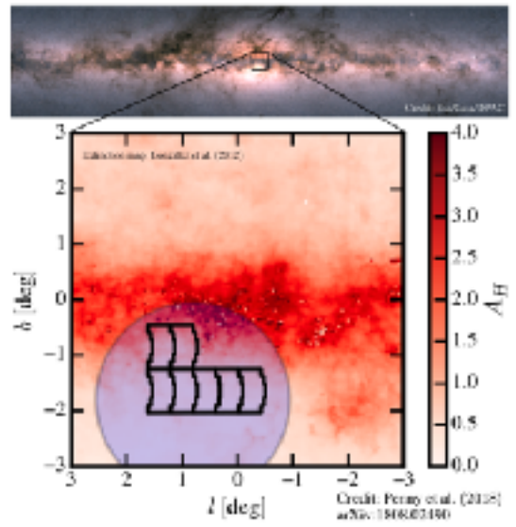


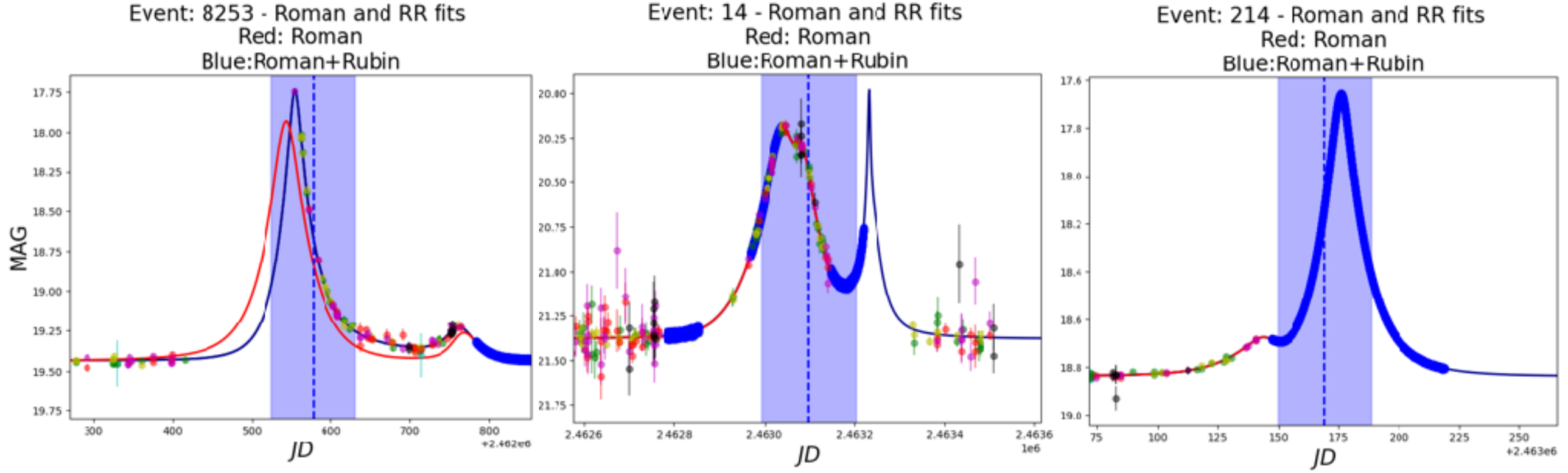


## Case for Rubin-Roman coordination

arXiv:2306.13792

Anibal Varela, UNSAM

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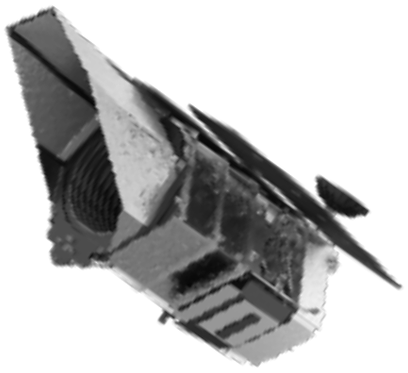

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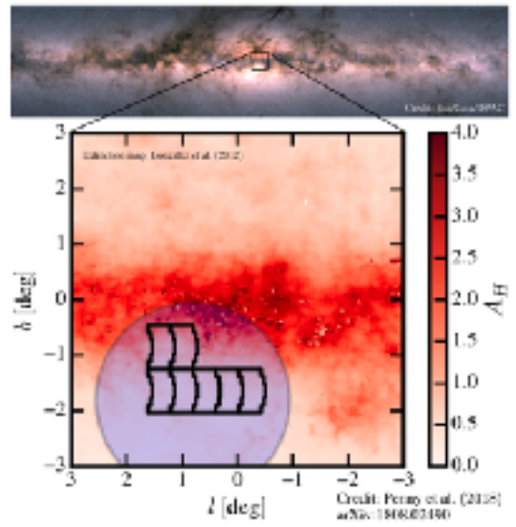
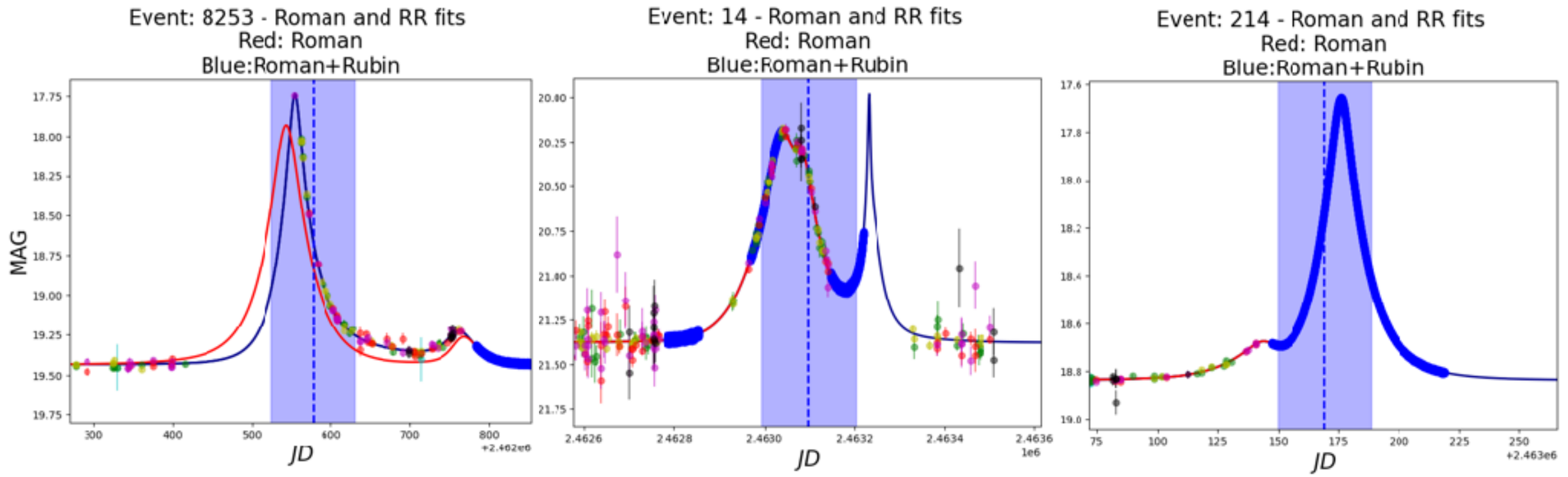



## Case for Rubin-Roman coordination

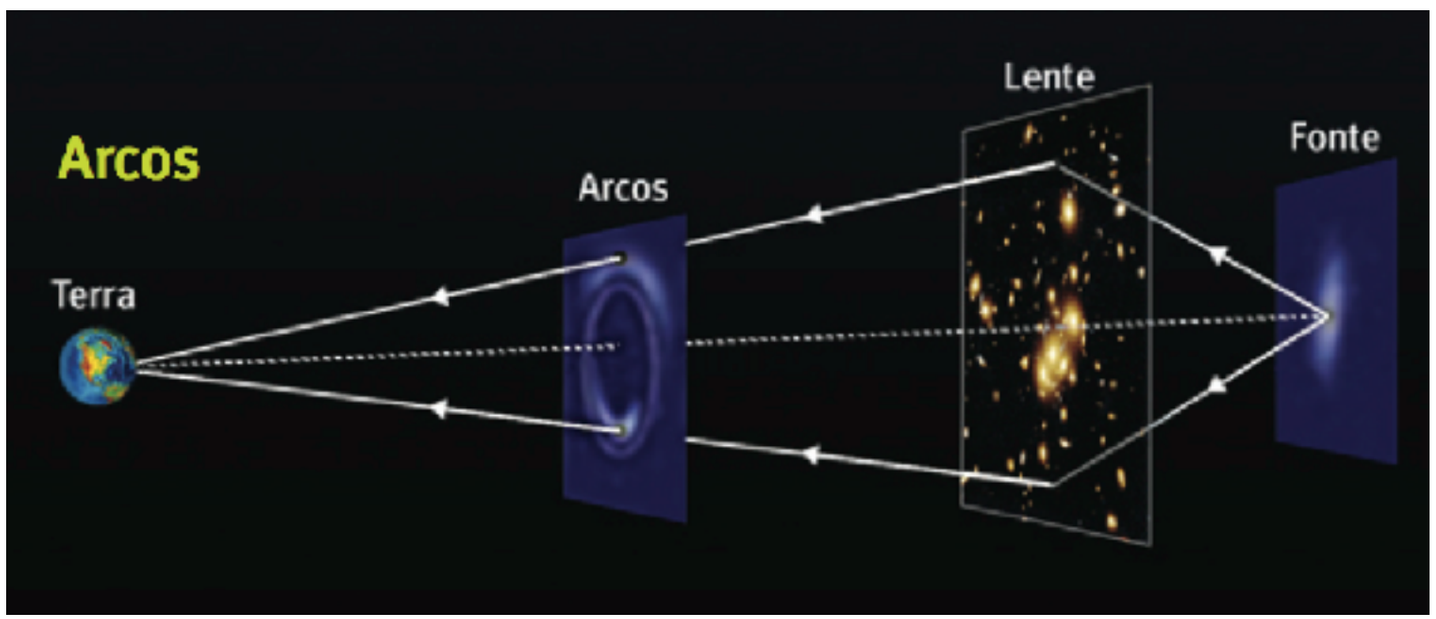
arXiv:2306.13792

- Provide baseline for Roman
- Fill the gaps of Roman observations
- Determine parallax for a fraction of the events

Anibal Varela, UNSAM

# Strong Lensing (macrolensing)

- Gravitational lensing (geometrical optics): null geodesics
  - Surface brightness conservation + achromatic: gravitational telescope
  - Unique probe of the mass distribution in galaxies and clusters ➔ DM, *b*
  - Sensitive on cosmological distances (cosmological model/parameters)
  - Probes gravitational potentials in a different way from dynamics
- Strong Lensing: multiple images, strong distortions, large magnifications, time delays

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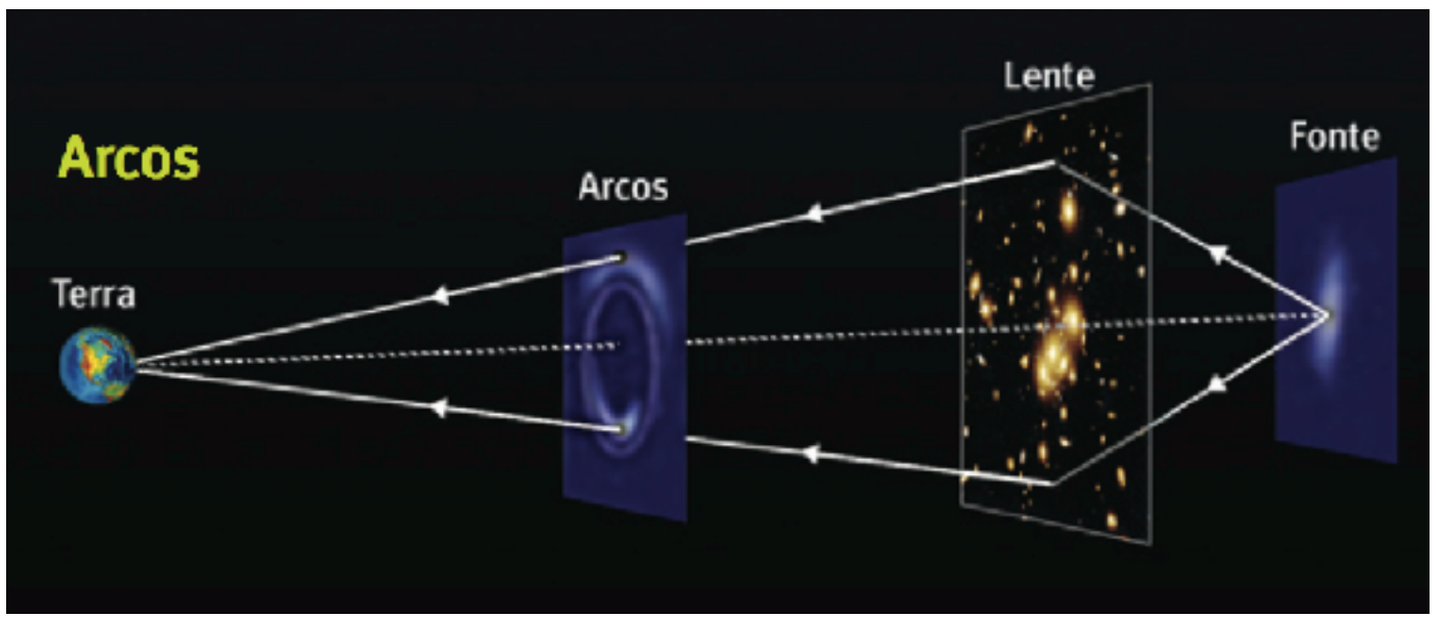


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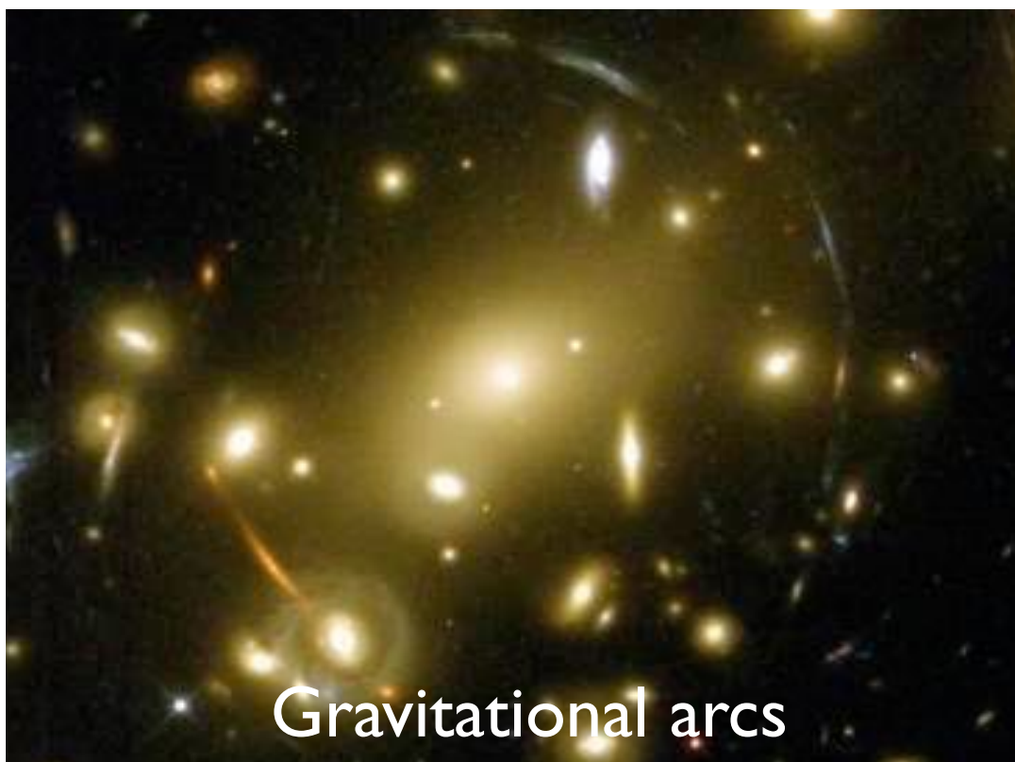

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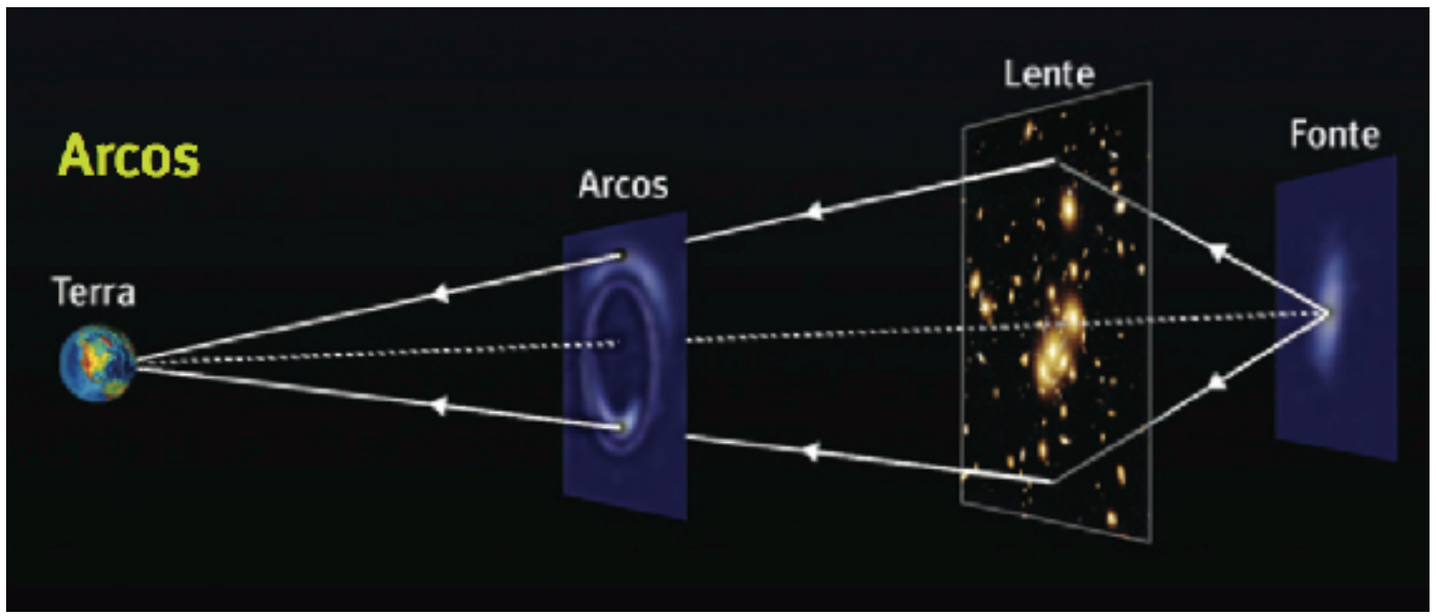


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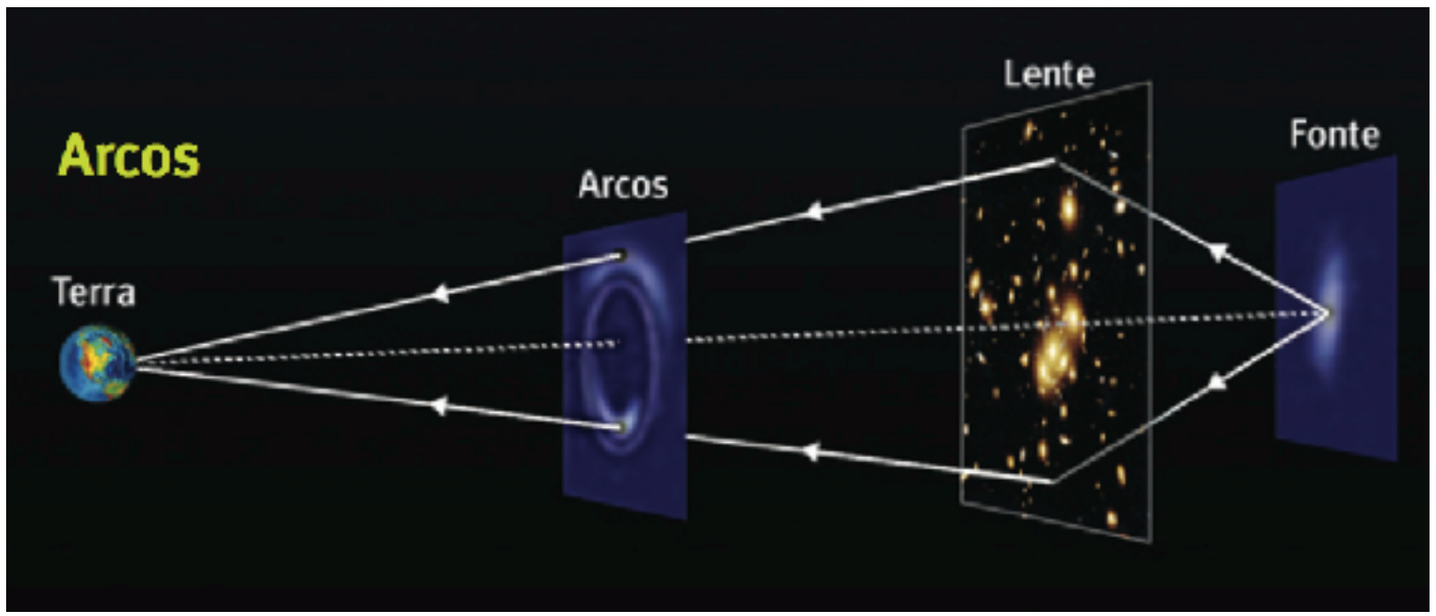
(arc finding is a challenge, see Clecio's talk)

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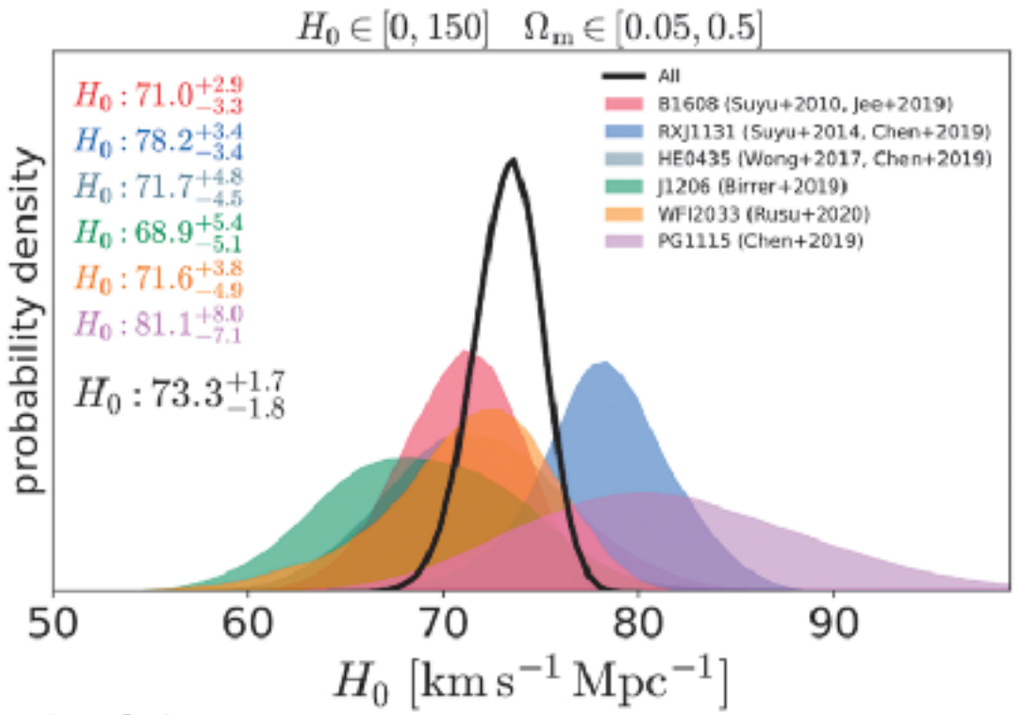
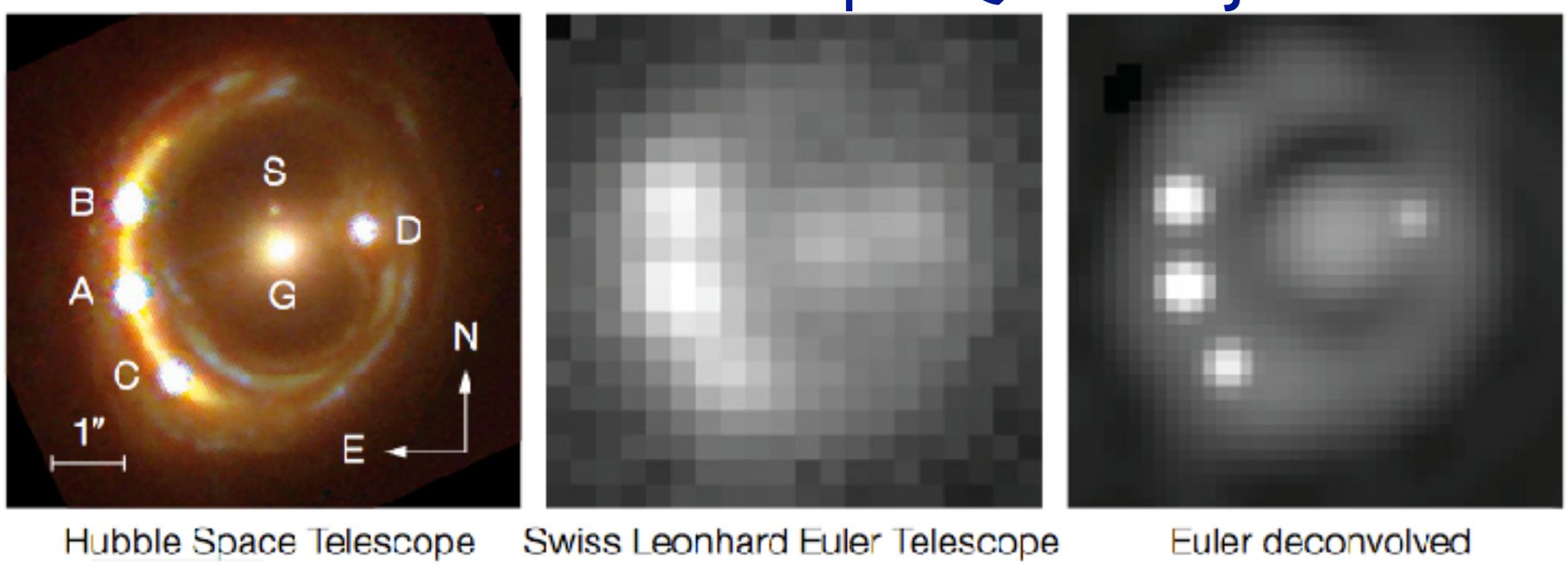
# Strong Lensing in the Time Domain

- Arcs, multiple images
- Mass reconstruction
- Cosmology
- Time delays
- Different physical dependence!
- See talks by João França and Stefan Schuldt




## Exemple: QSO RX J1131−1231



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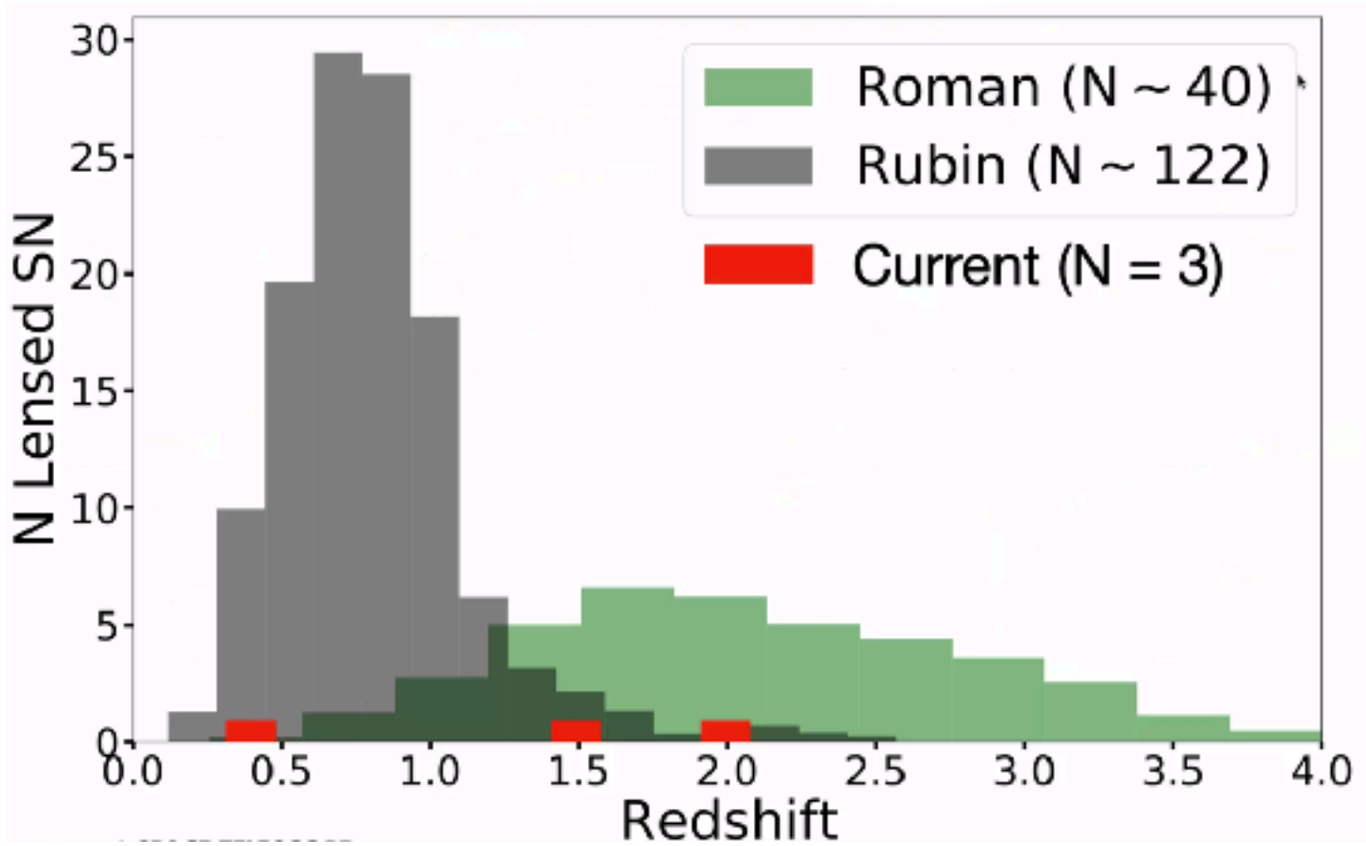

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(3/4 doubles, 1/4 quads)
golden sample: 13
[Arendse++, arXiv:2312.04621]

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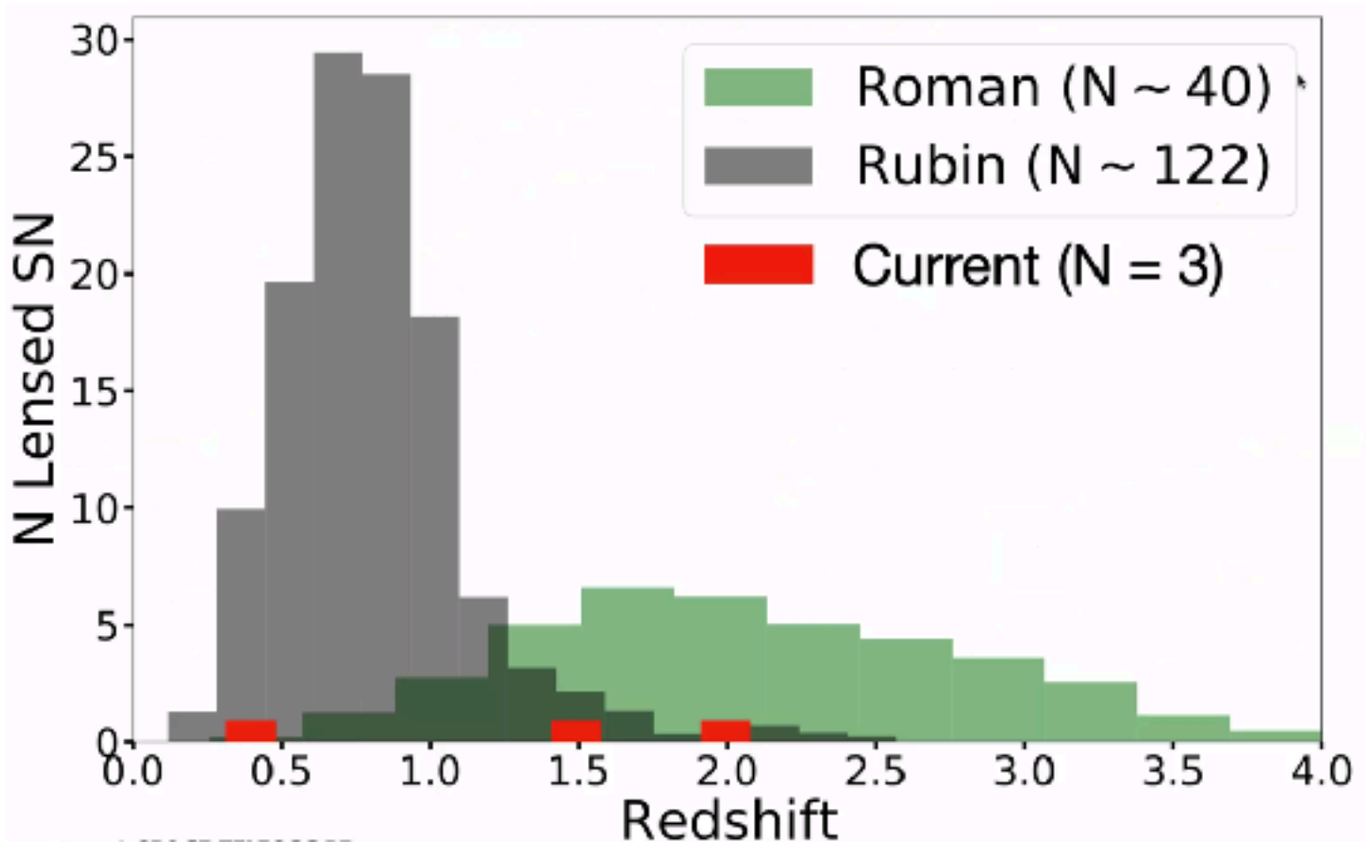

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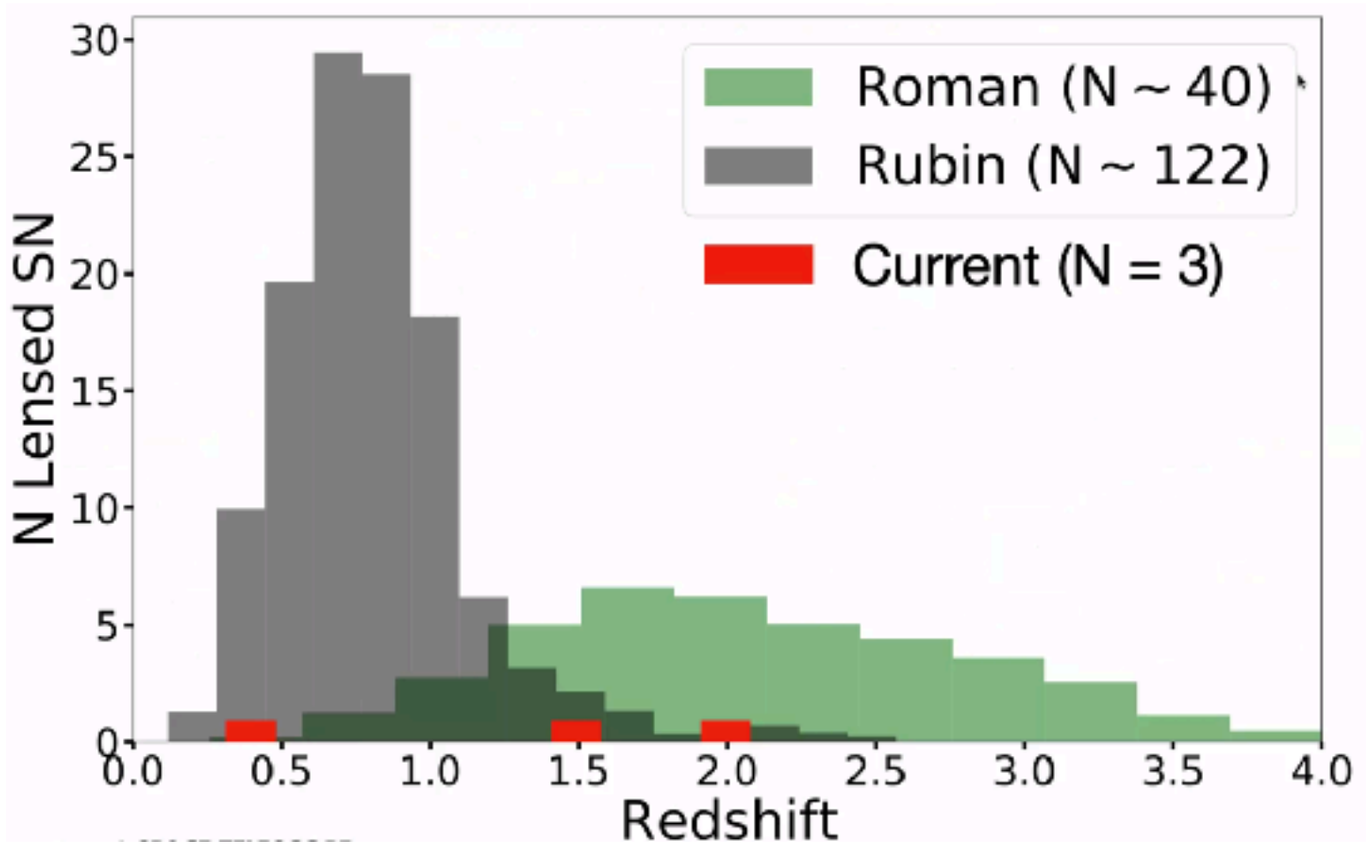


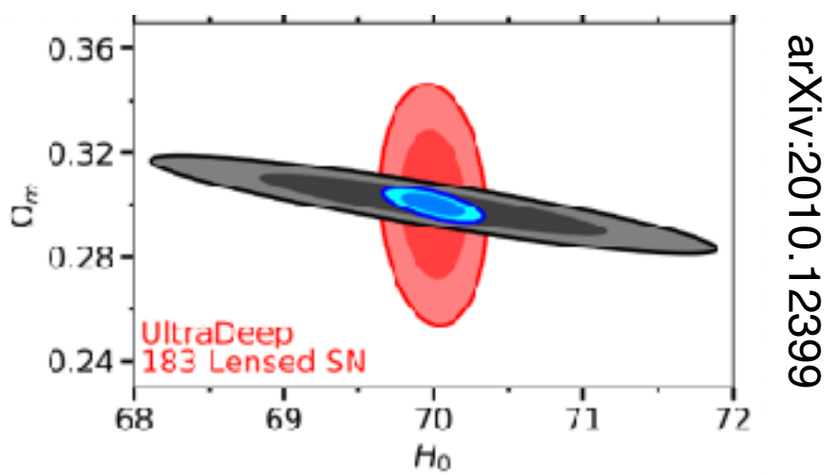


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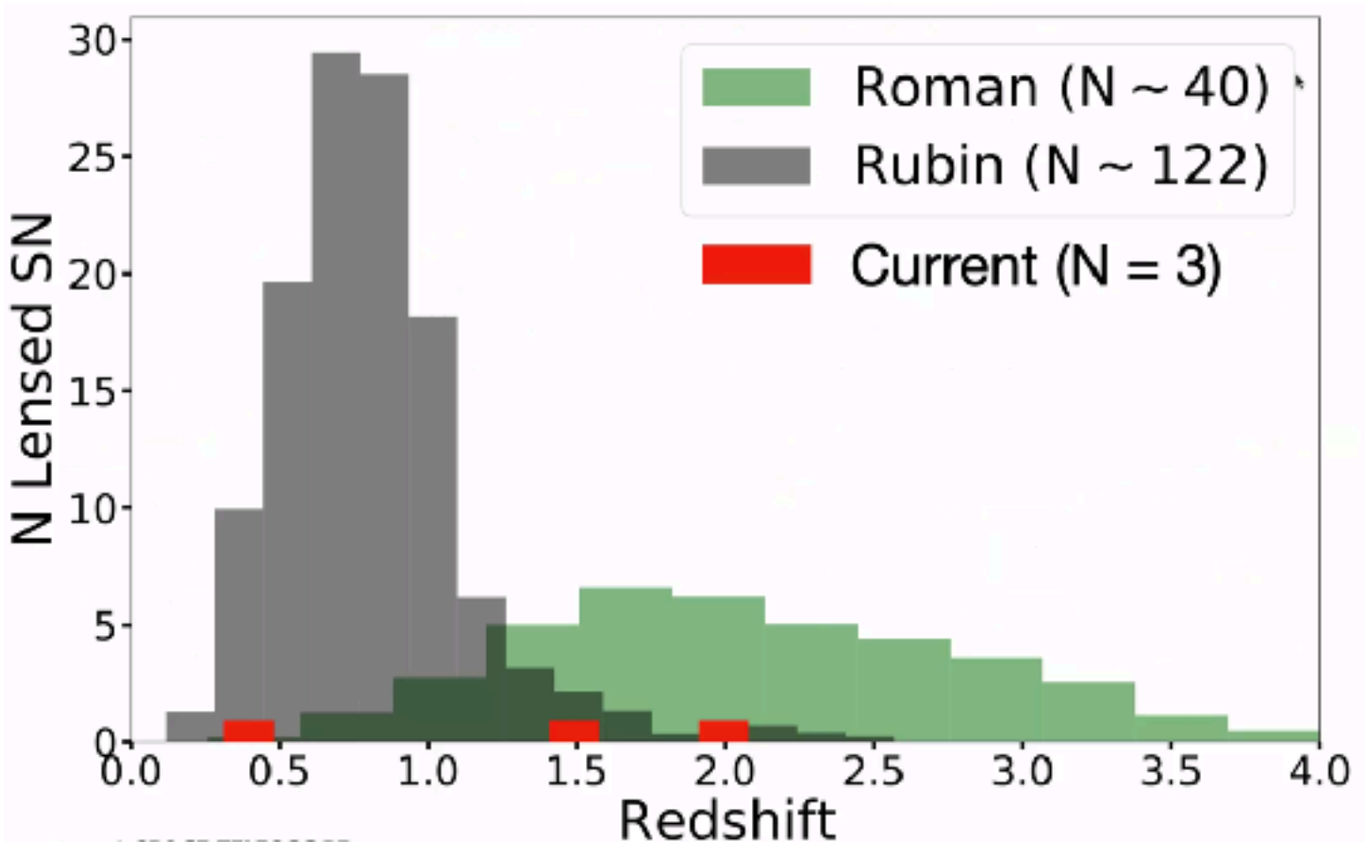
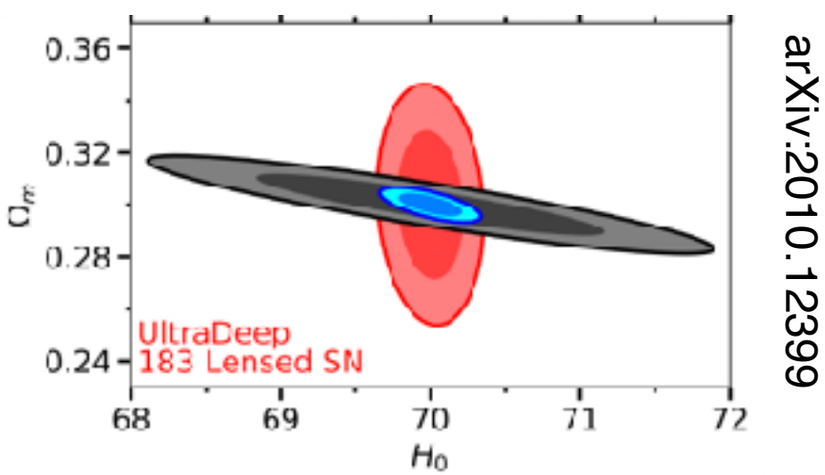
- Need to find these systems in real time!

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- Prepare for LSST:
  - Build up a sample before pixel data is available, before arc finders can be run, before modeling is run, and before data goes public

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- More on João França's talk

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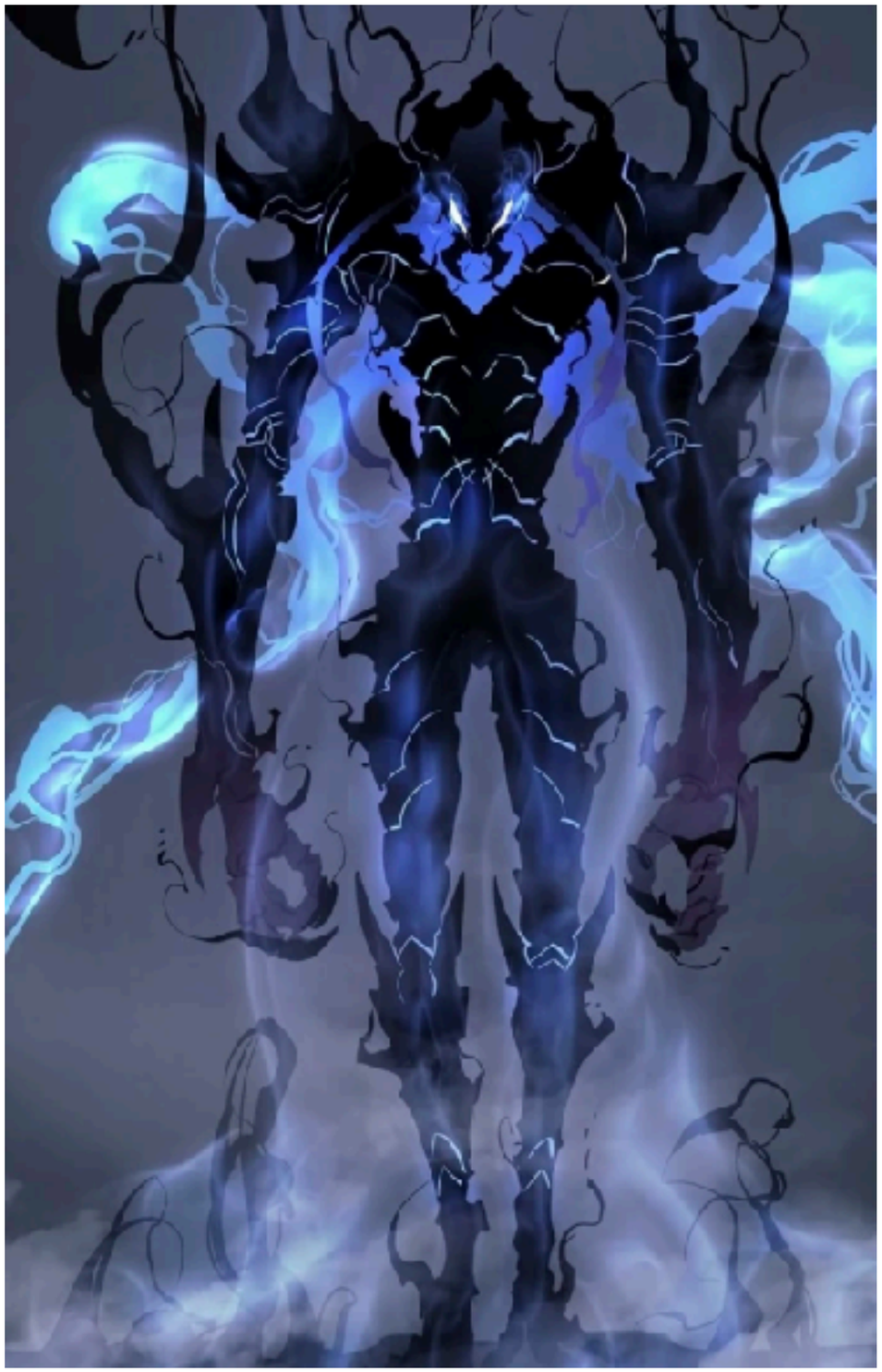
# LaStBeRu

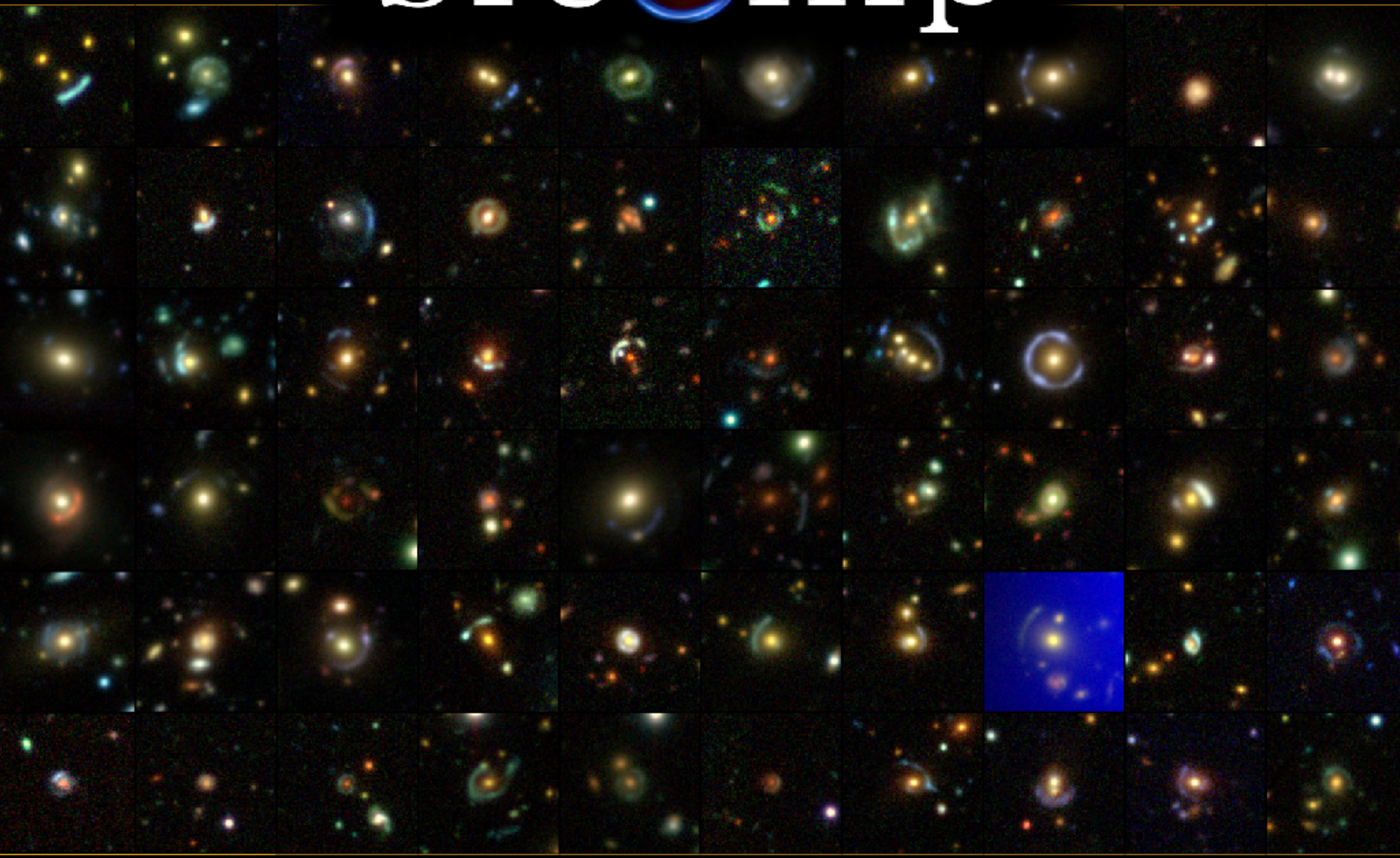


Groovy, cool, or otherwise something good or favored


Renan Alves, UFES

# slcomp

Some systems….



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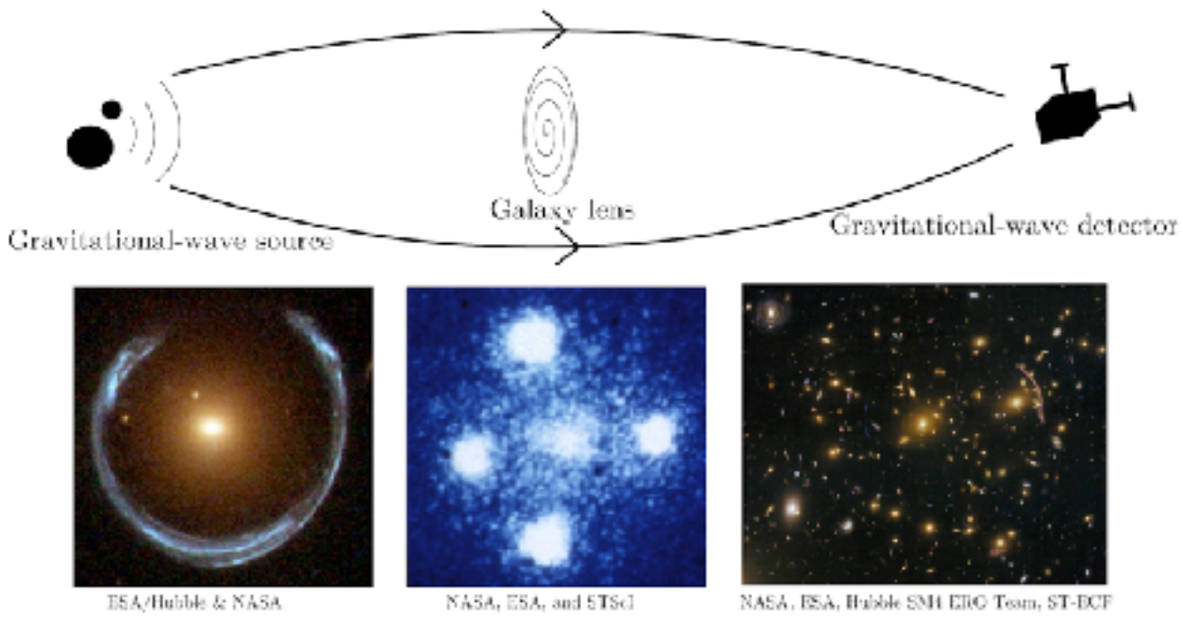


https://www.ligo.org/science/Publication-O3aLensing/images/O3aLensing-Fig1.png

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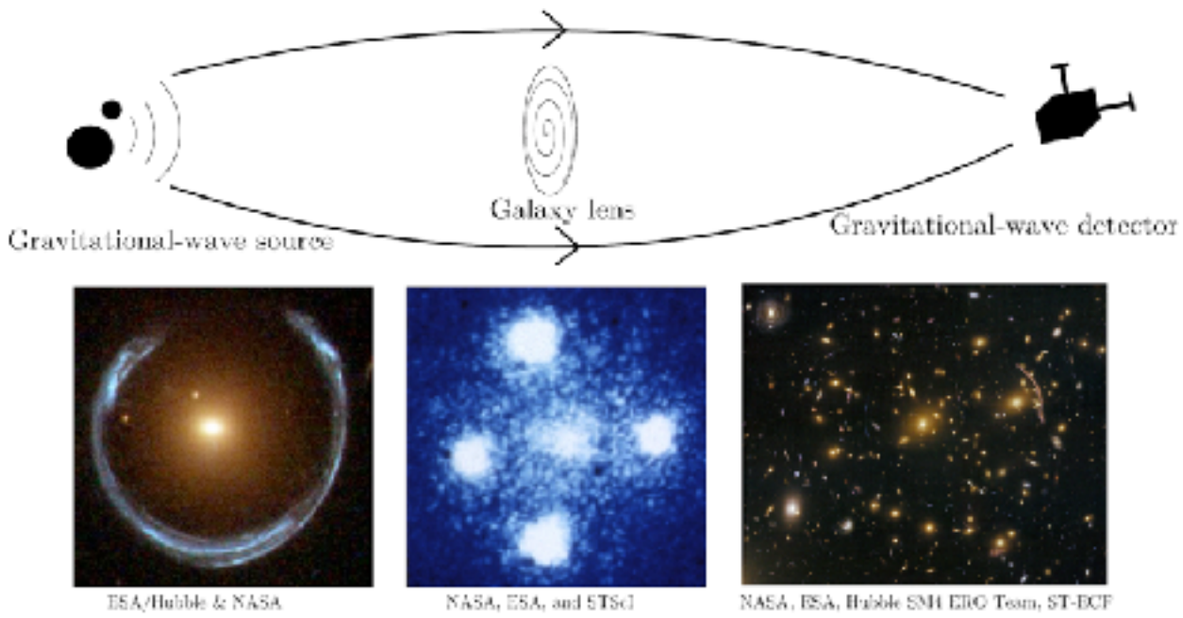


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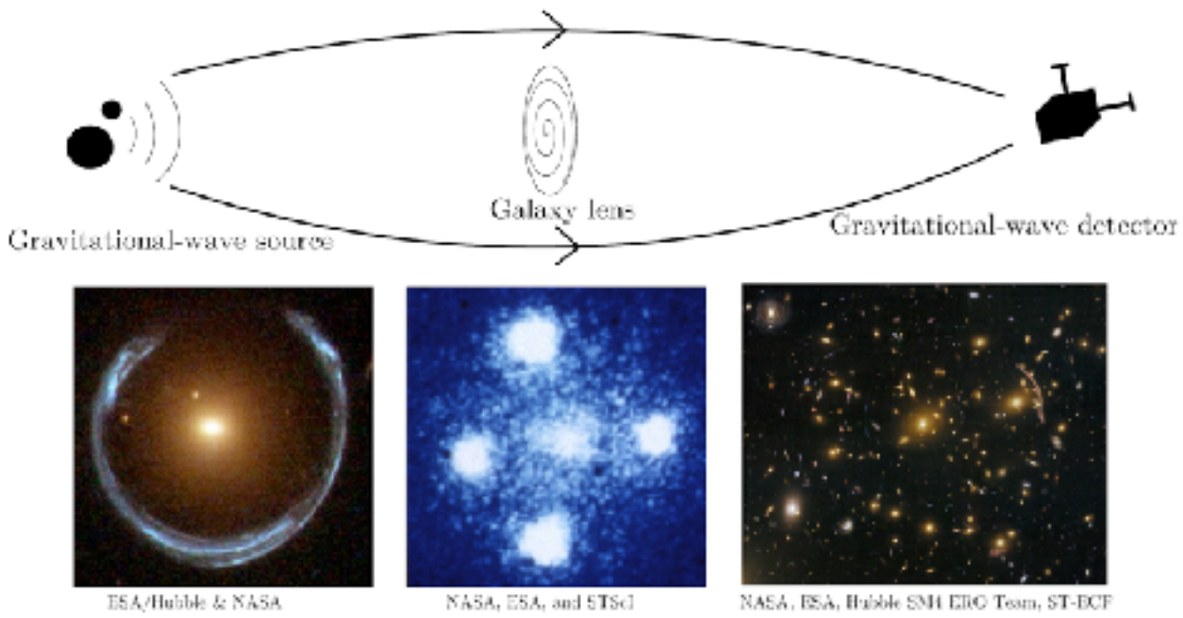


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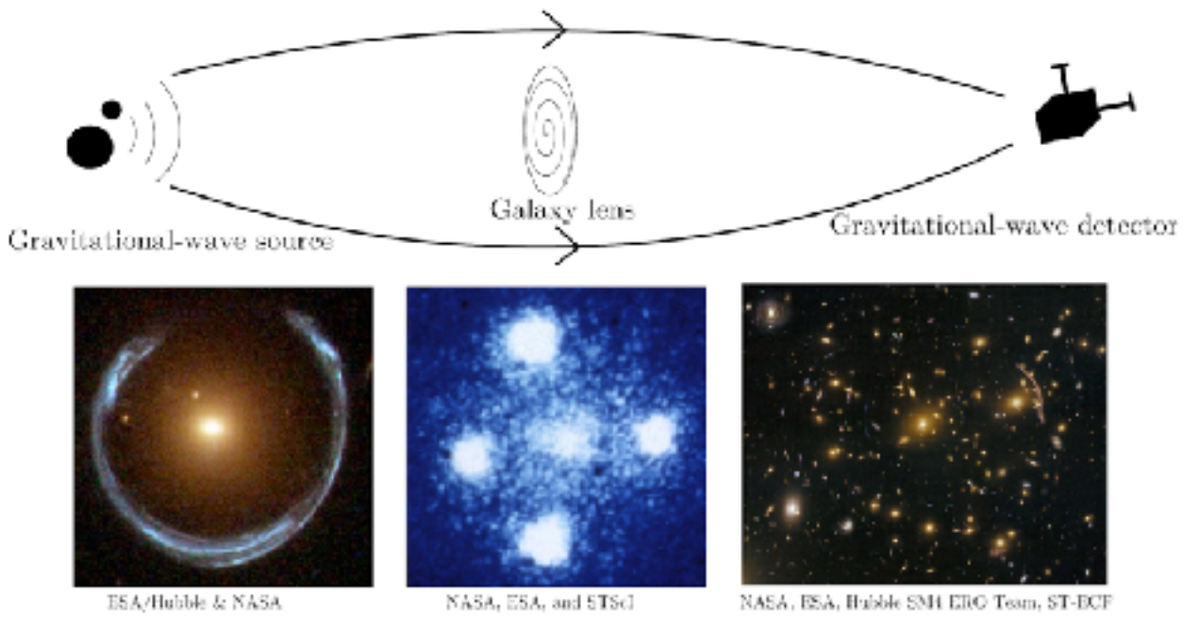


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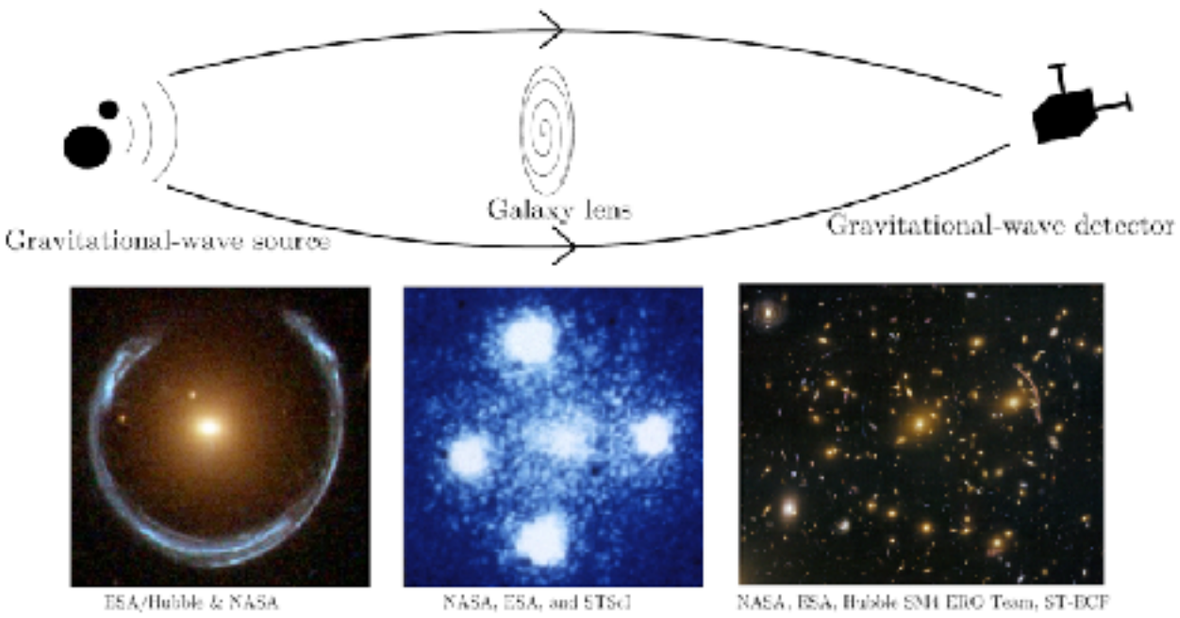


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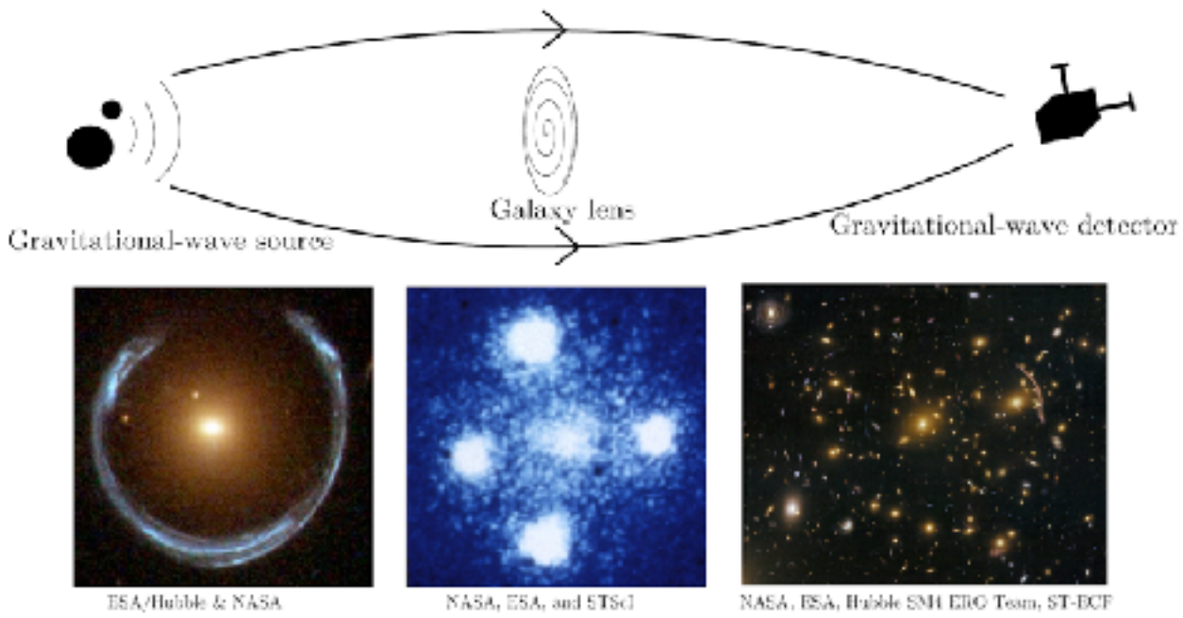


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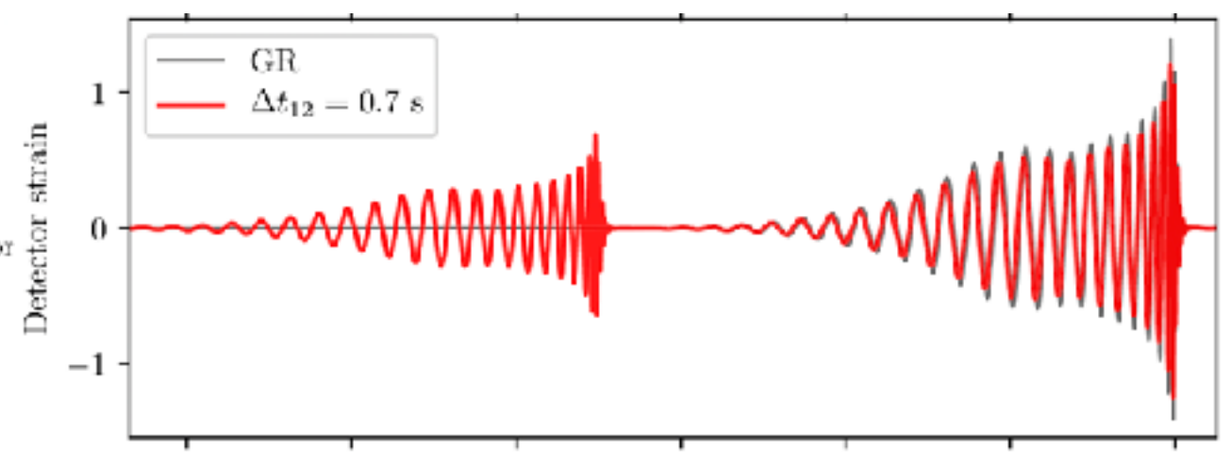


Ezquiaga & Zumalacárregui, PRD 102, 124048 (2020)

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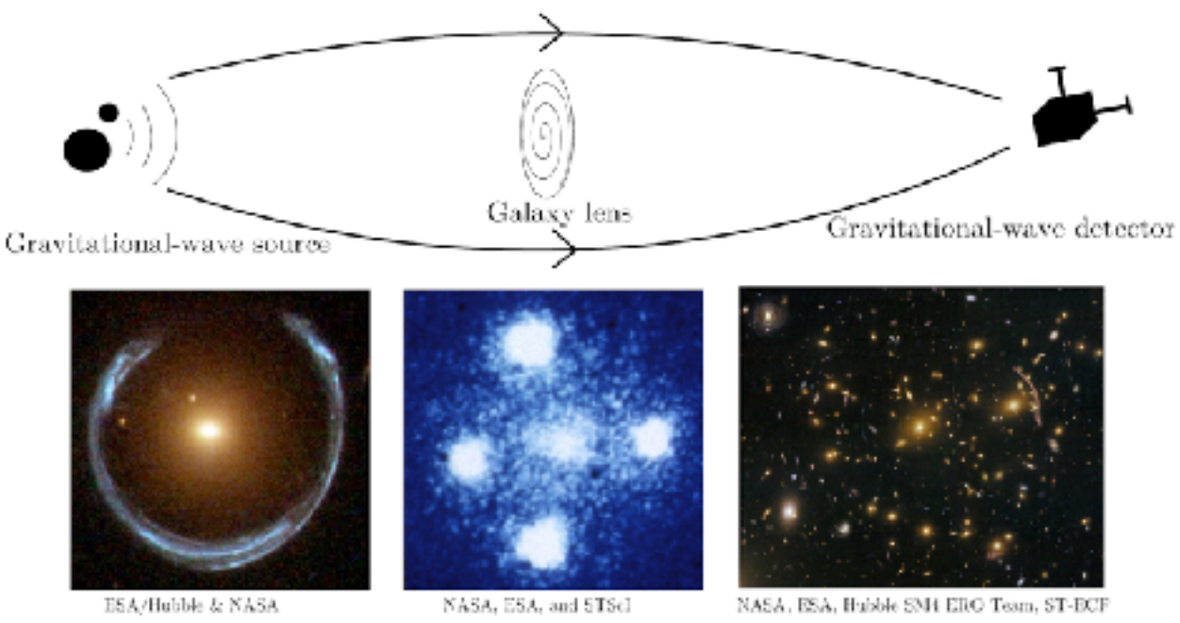


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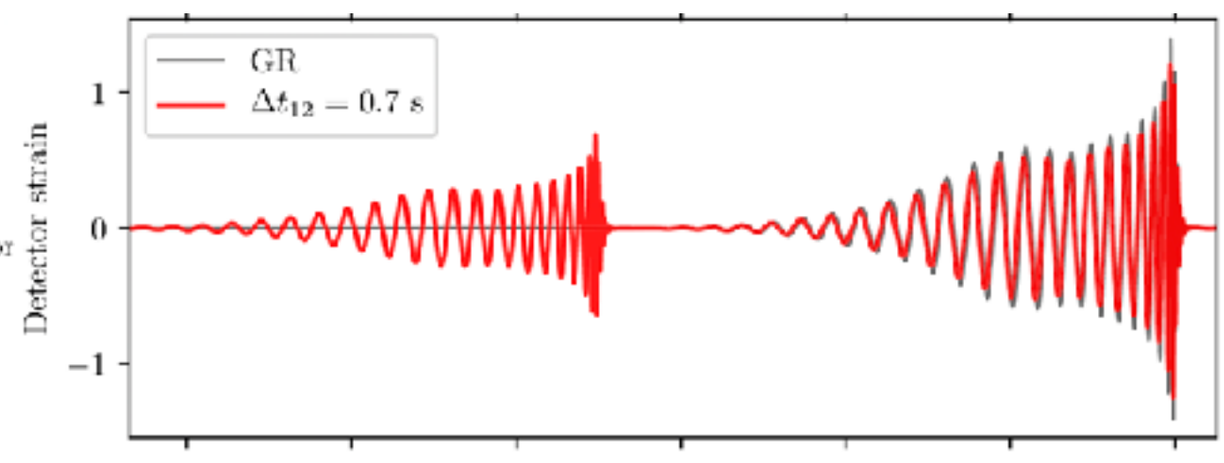


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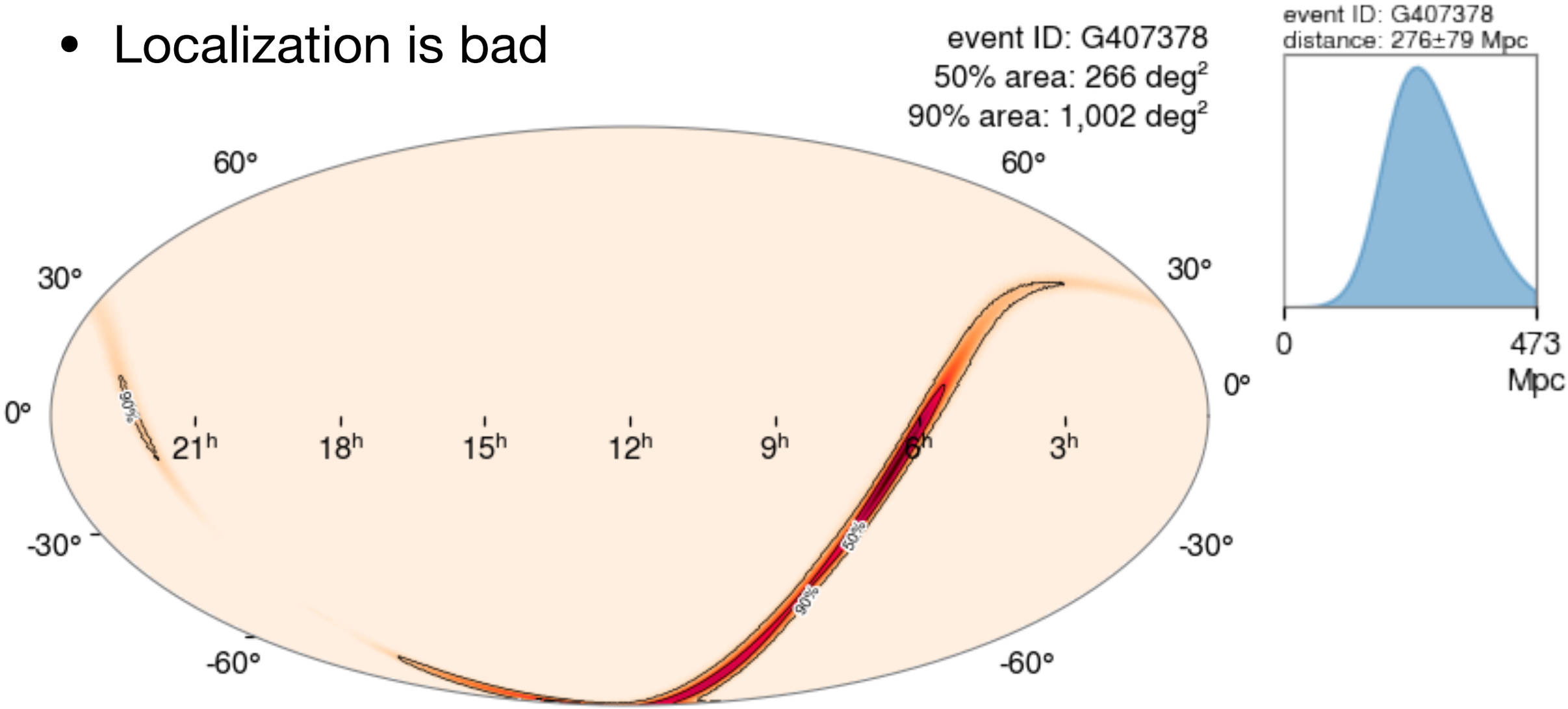


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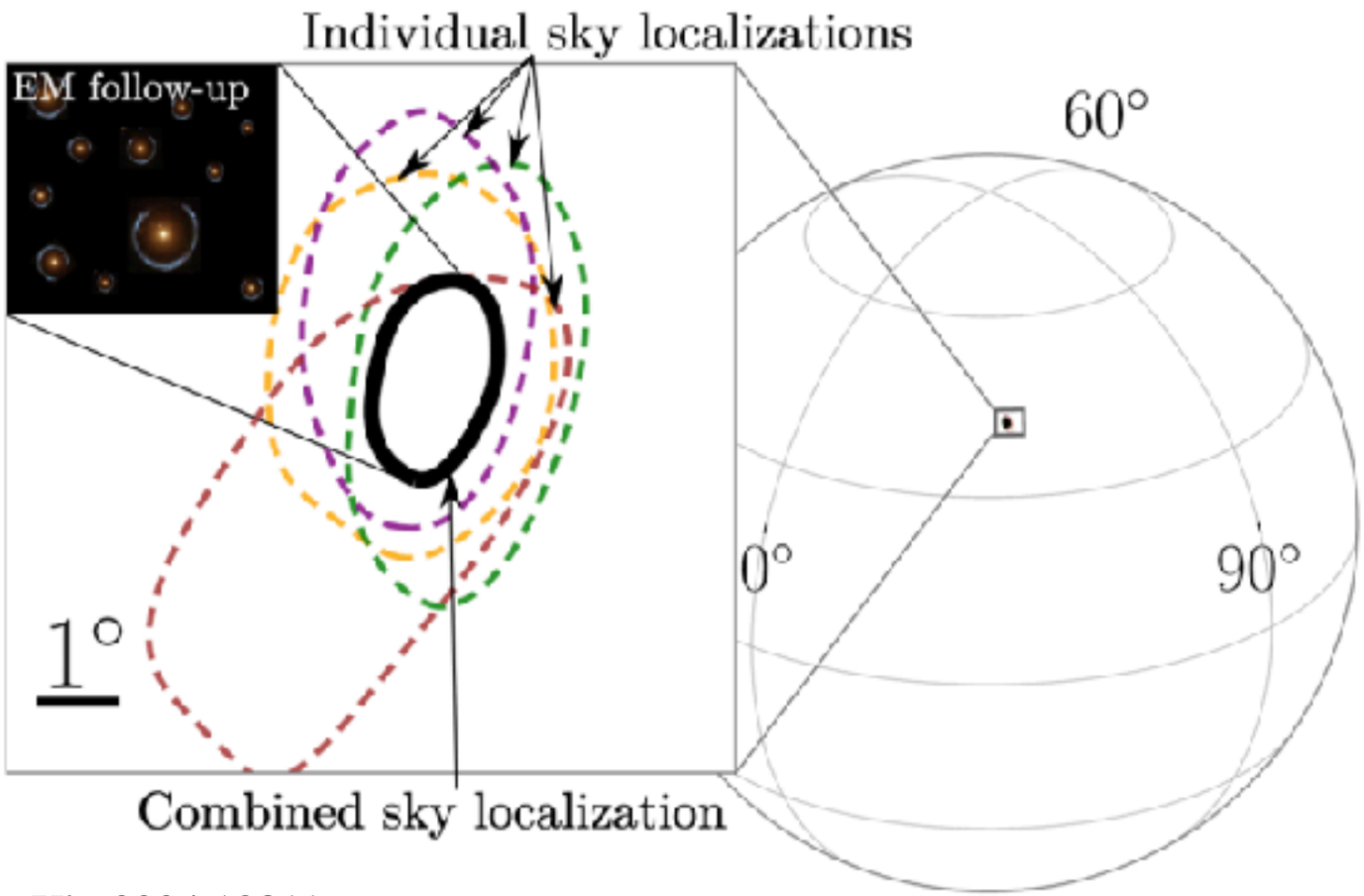


arXiv:2004.13811

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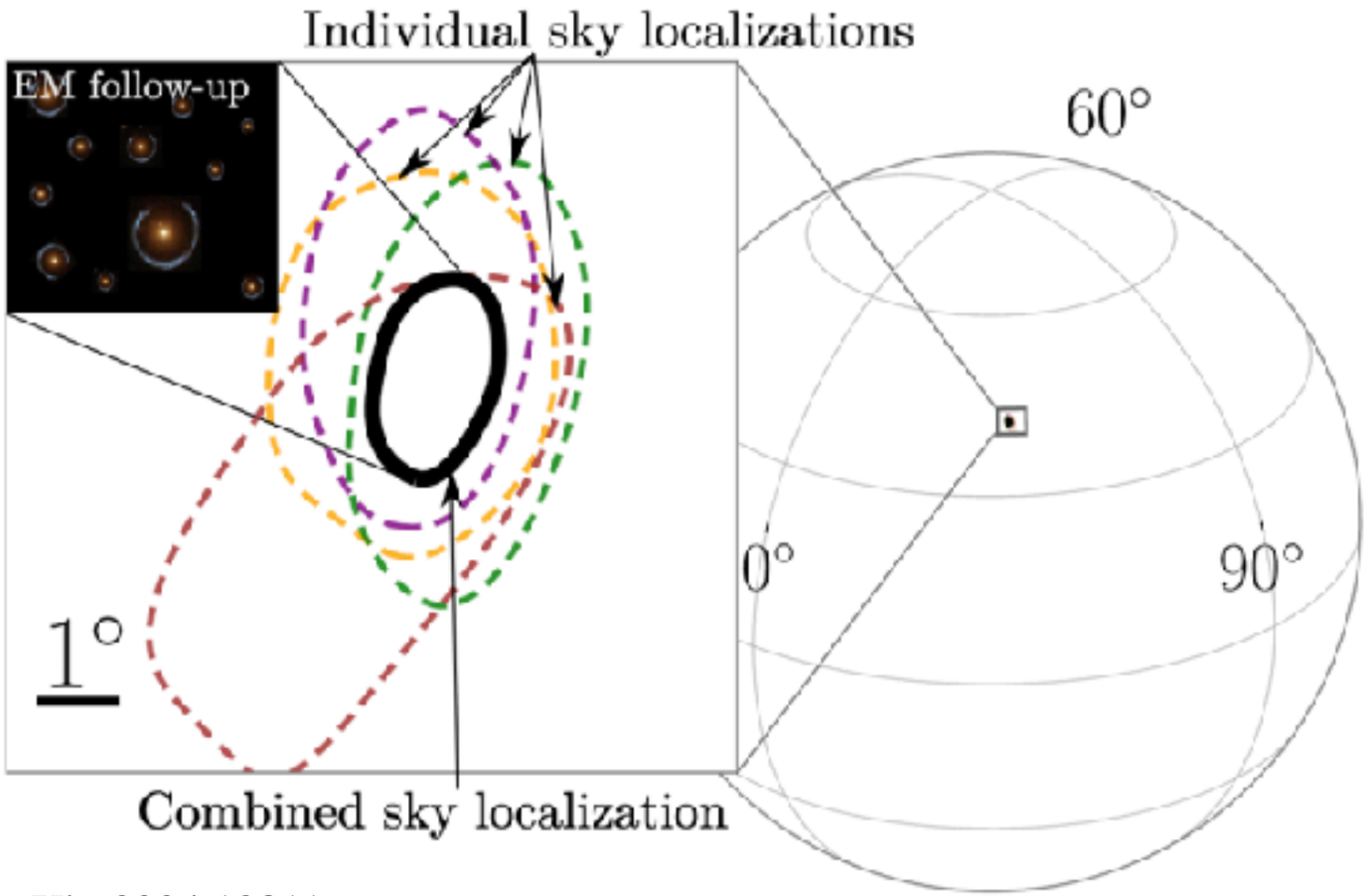


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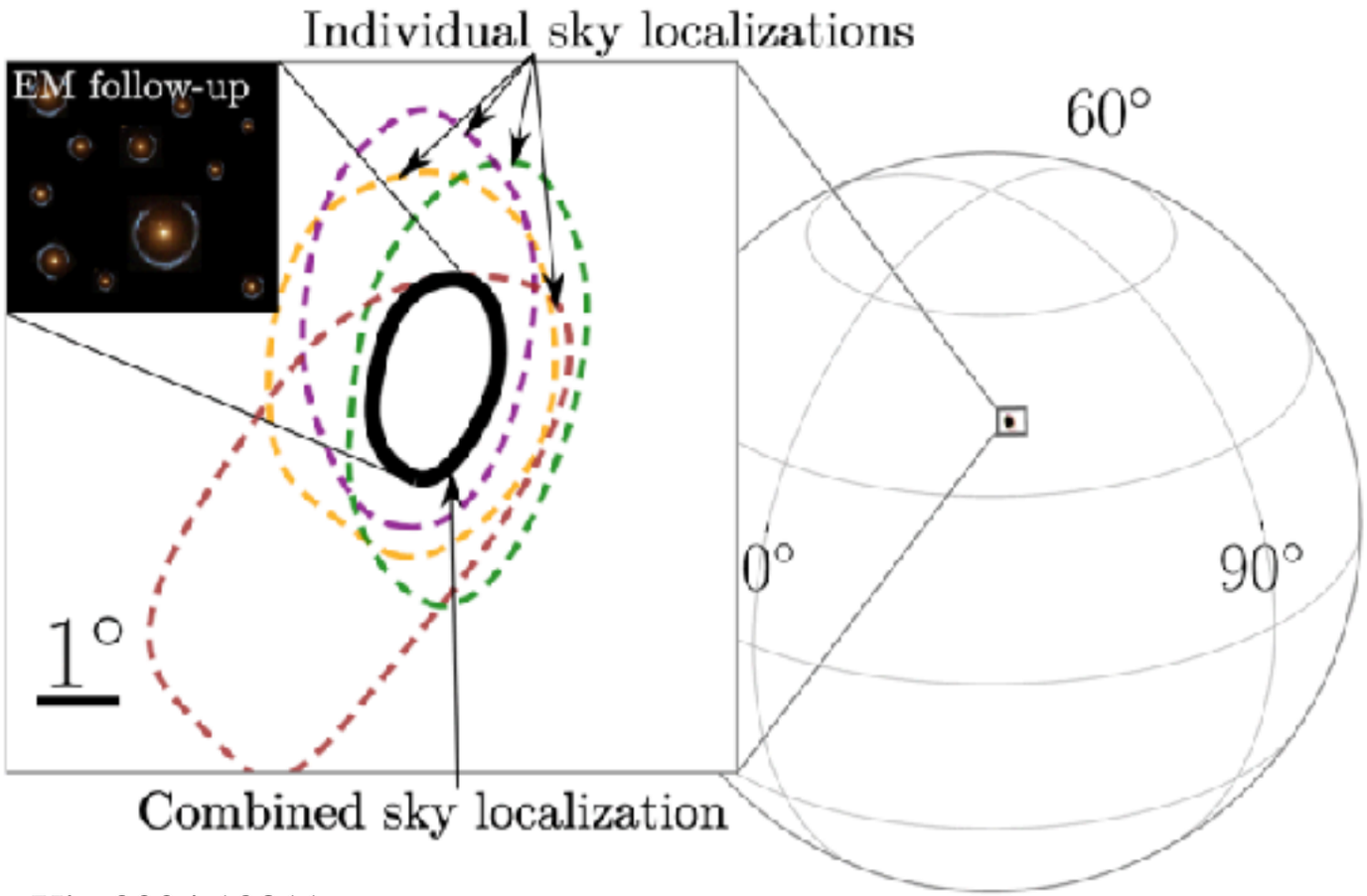


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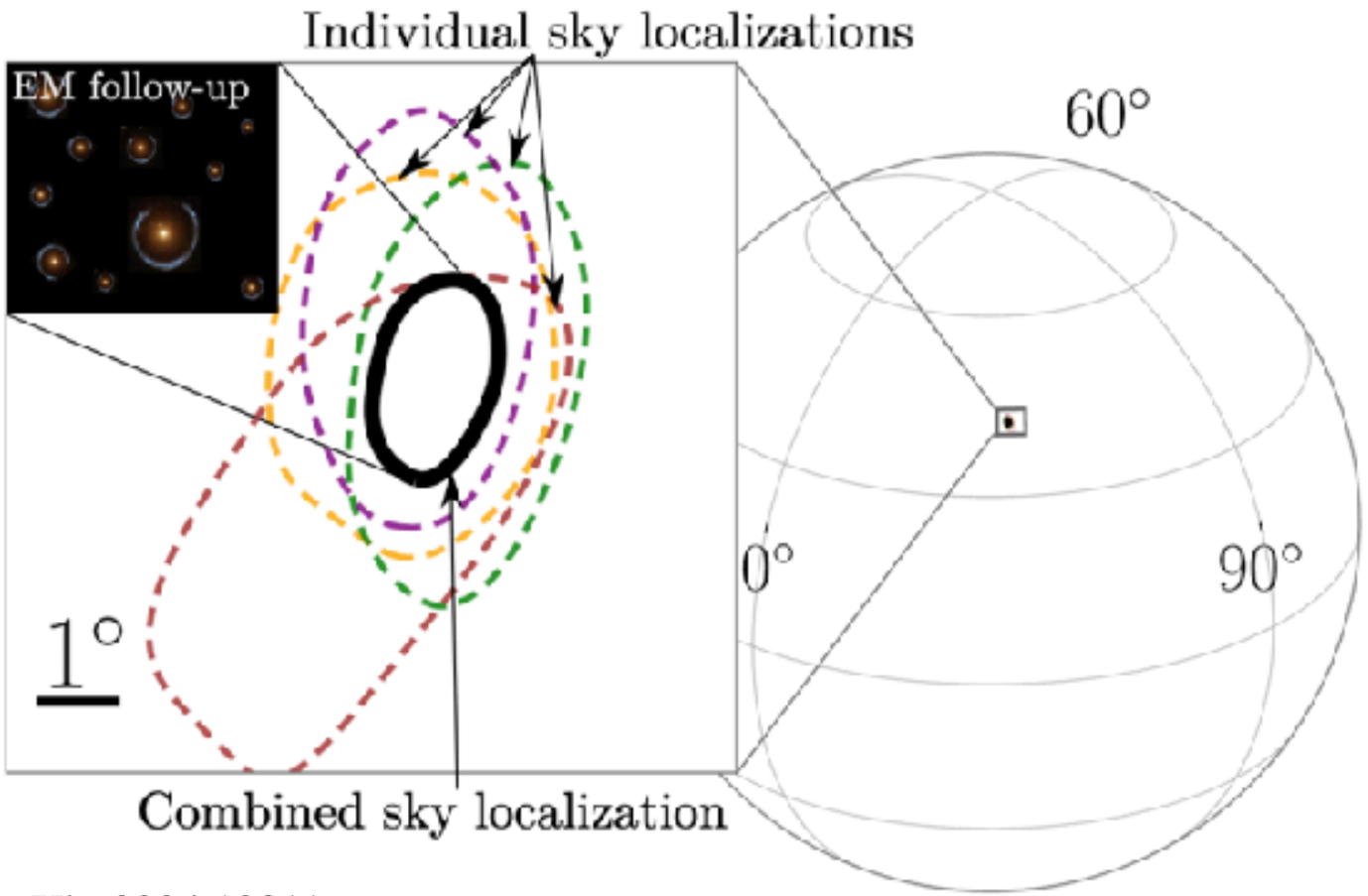


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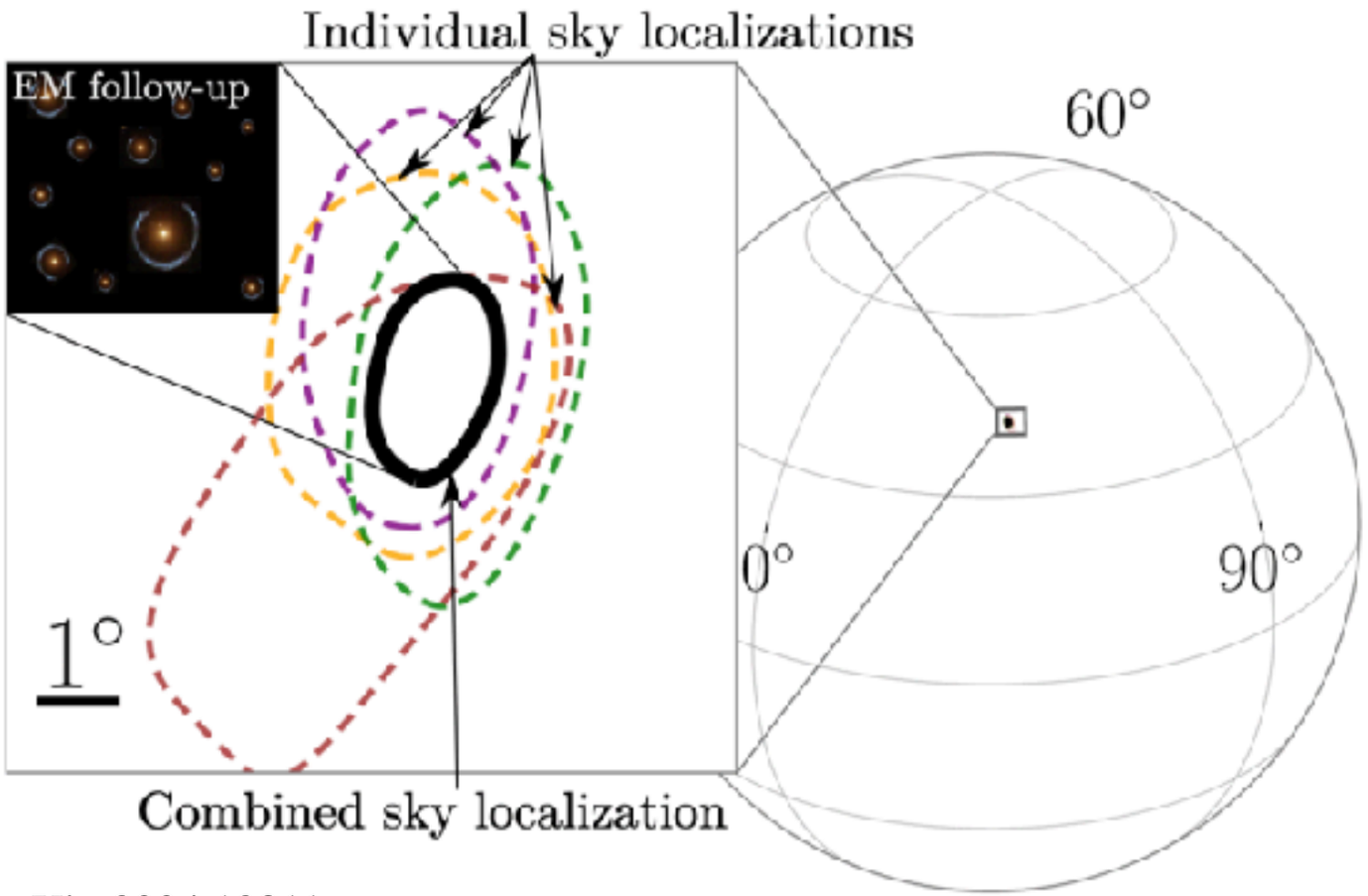


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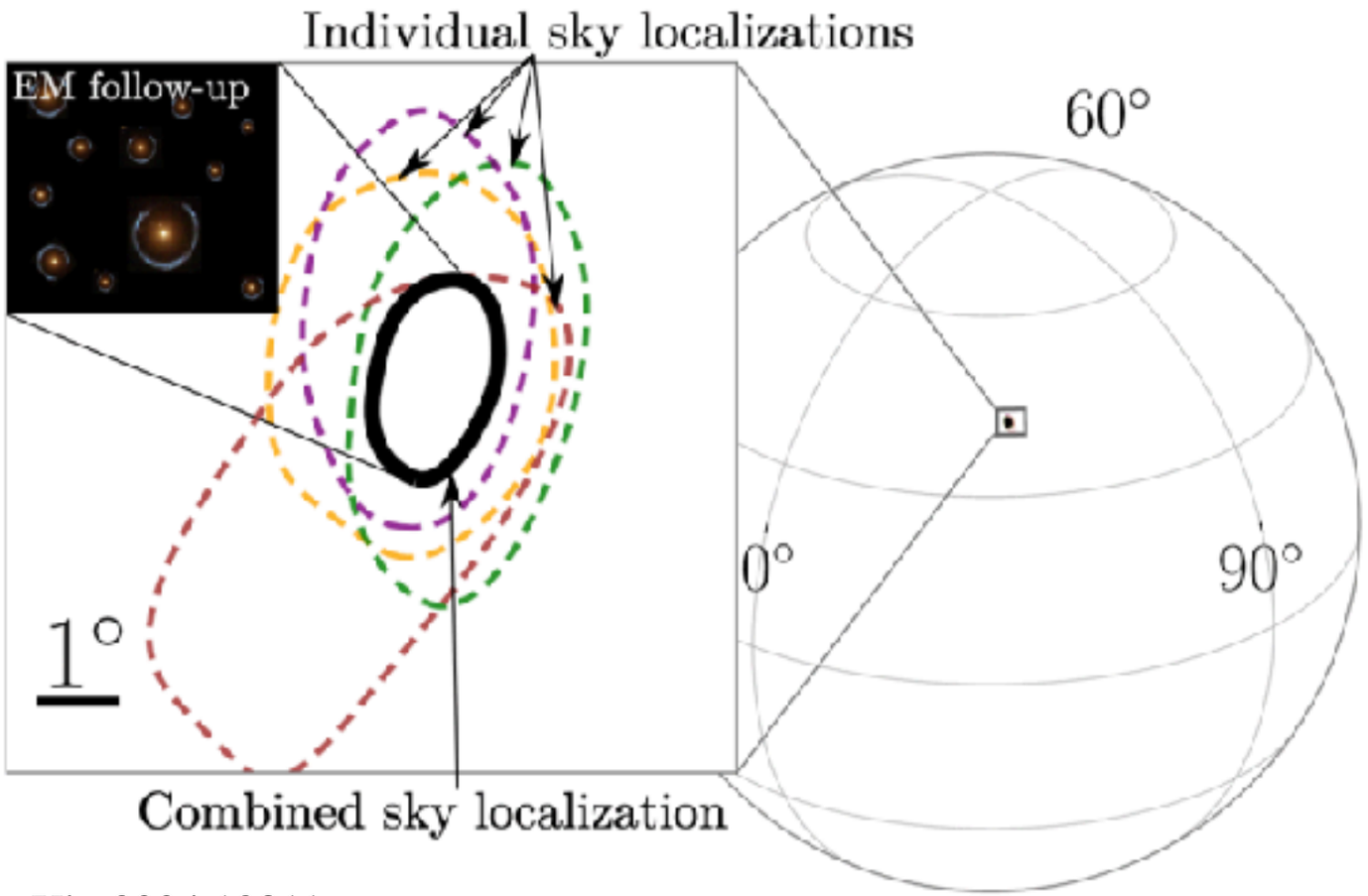


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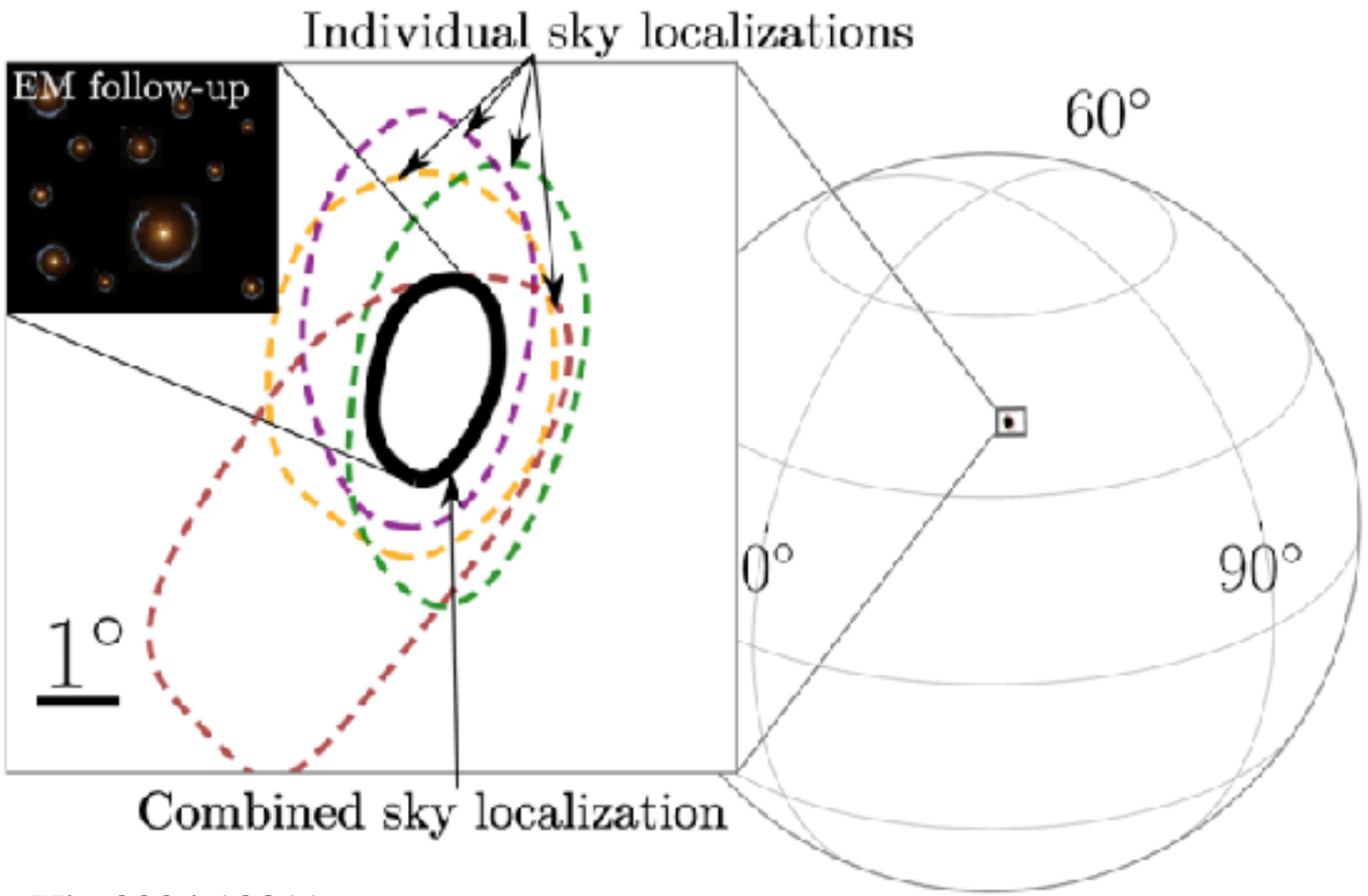


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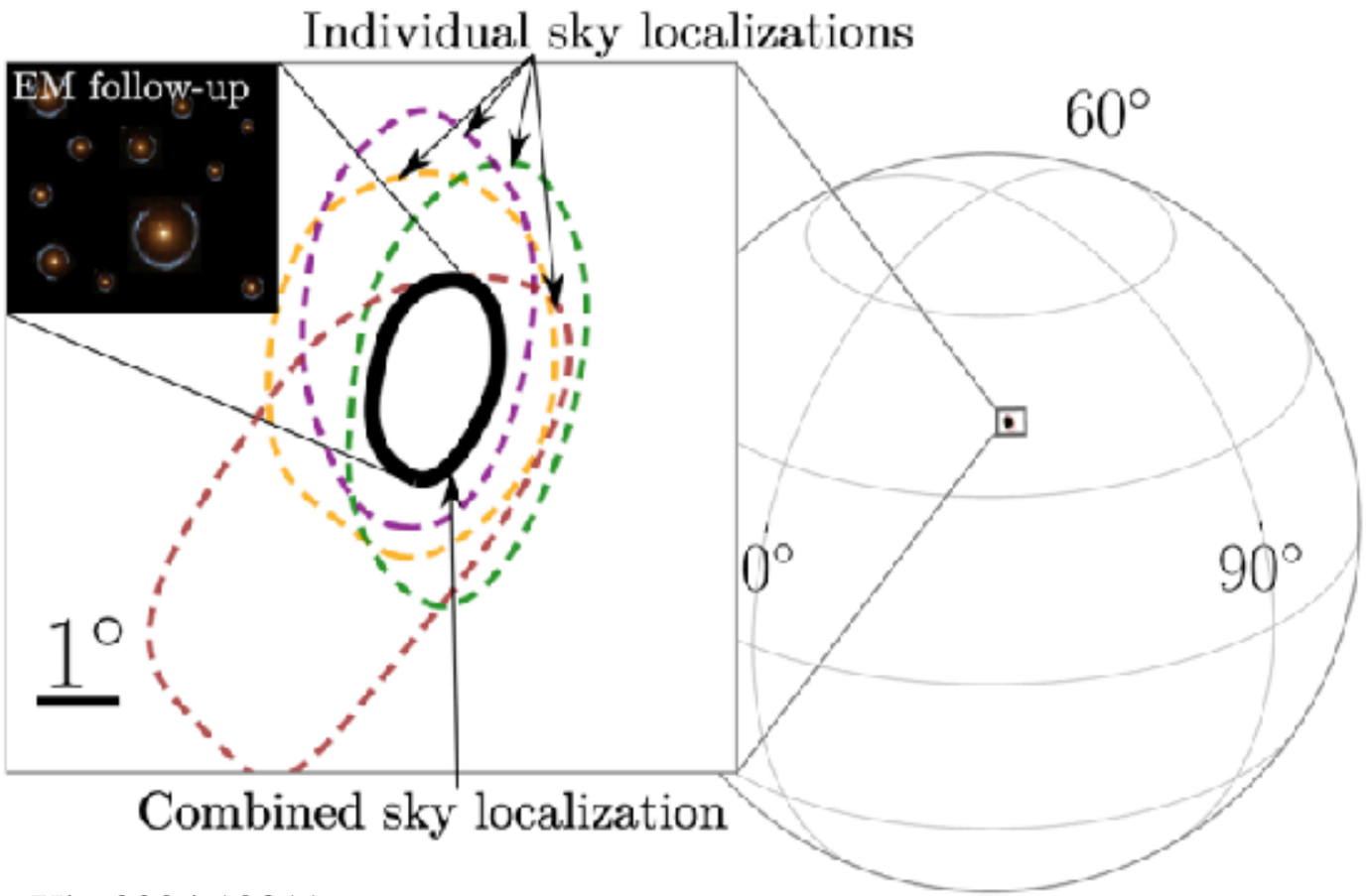


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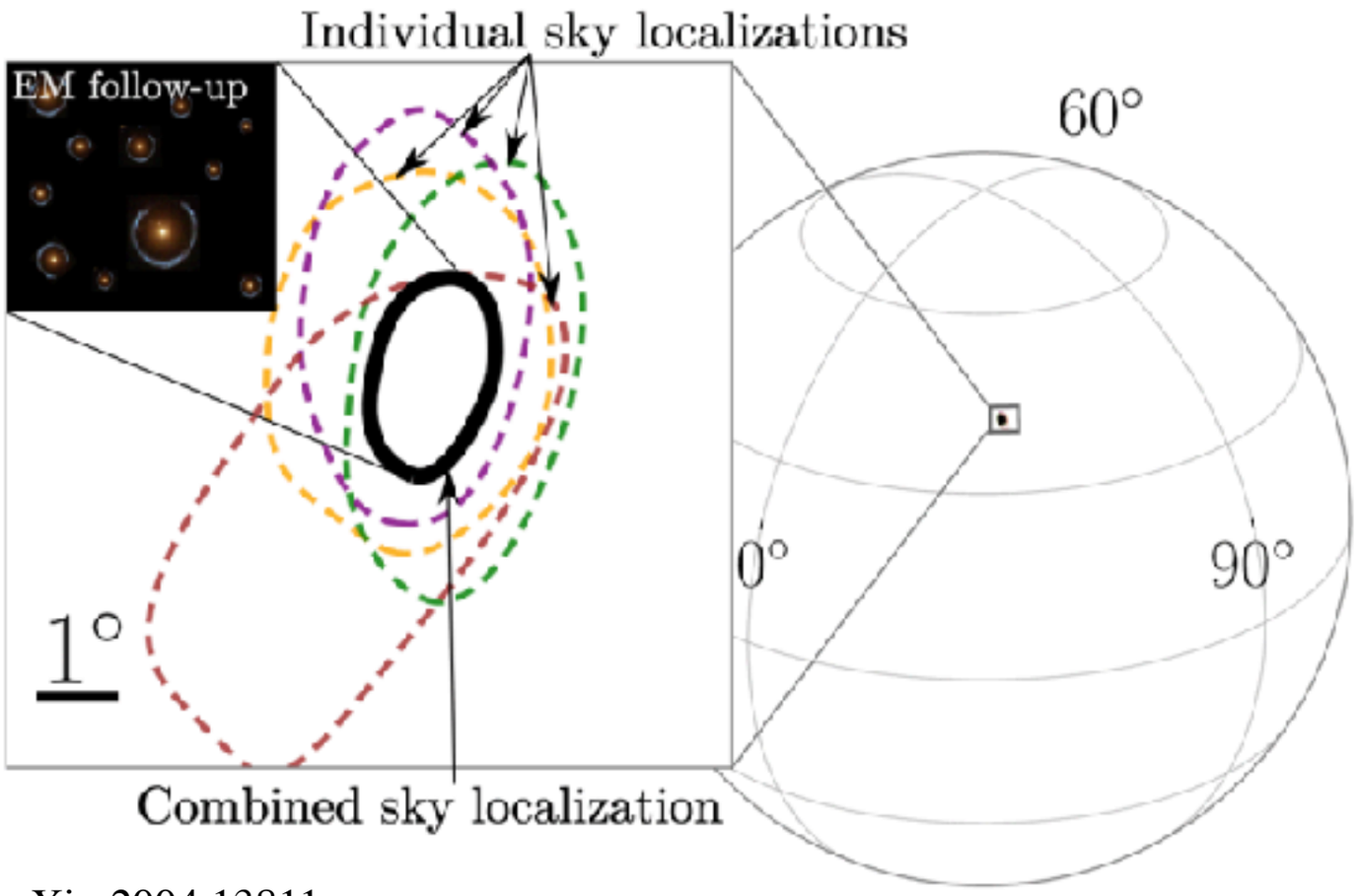


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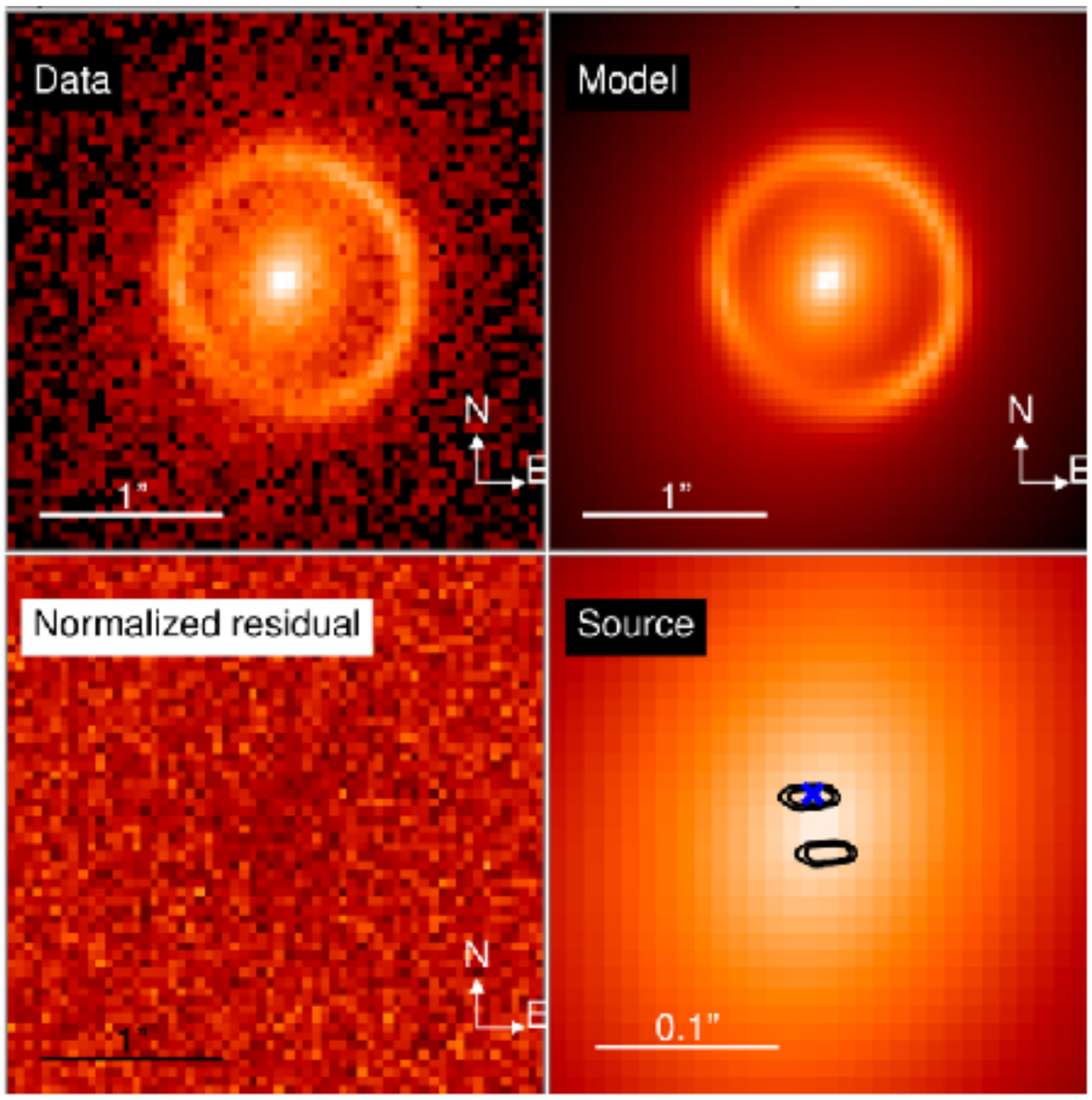


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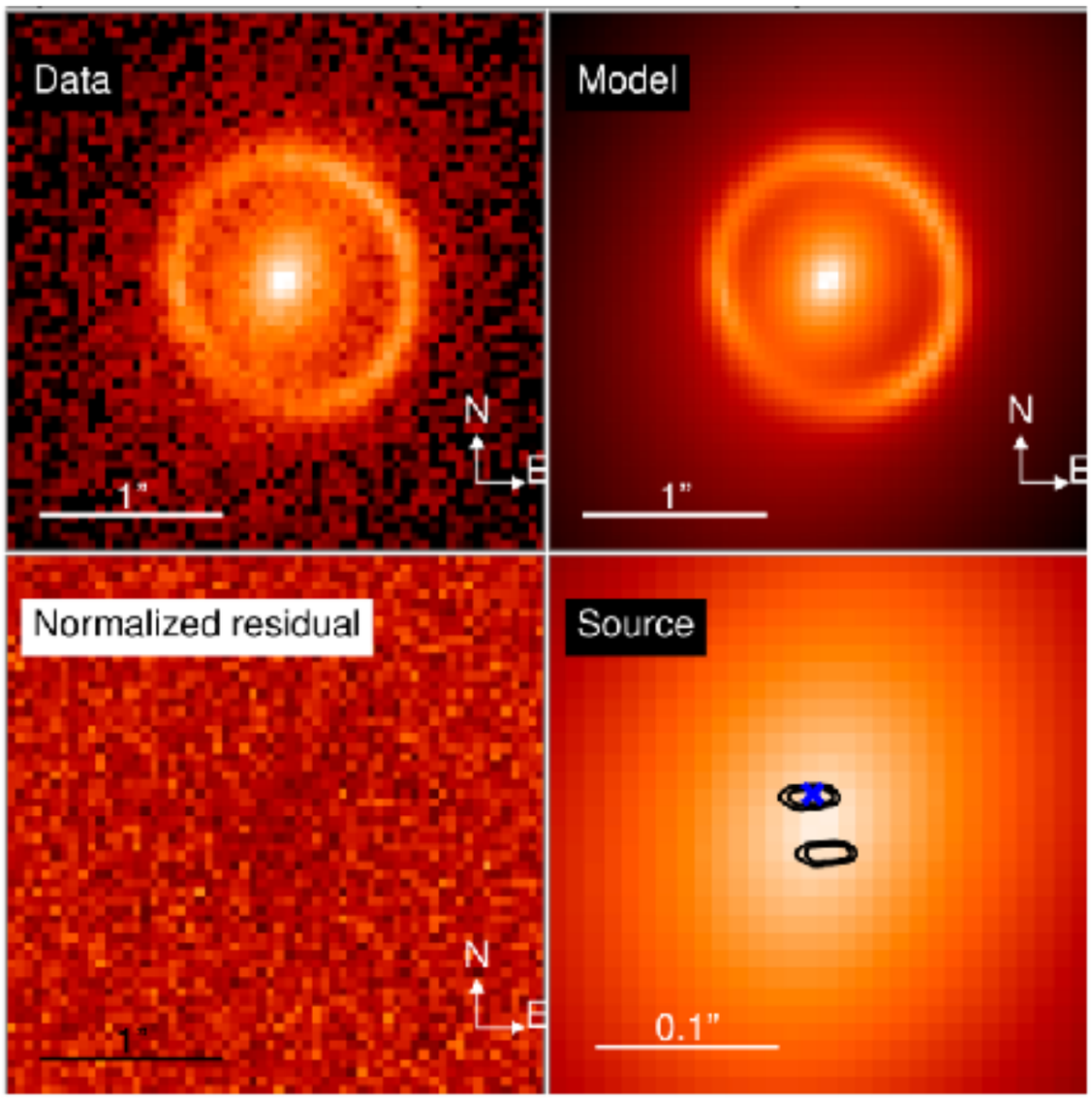


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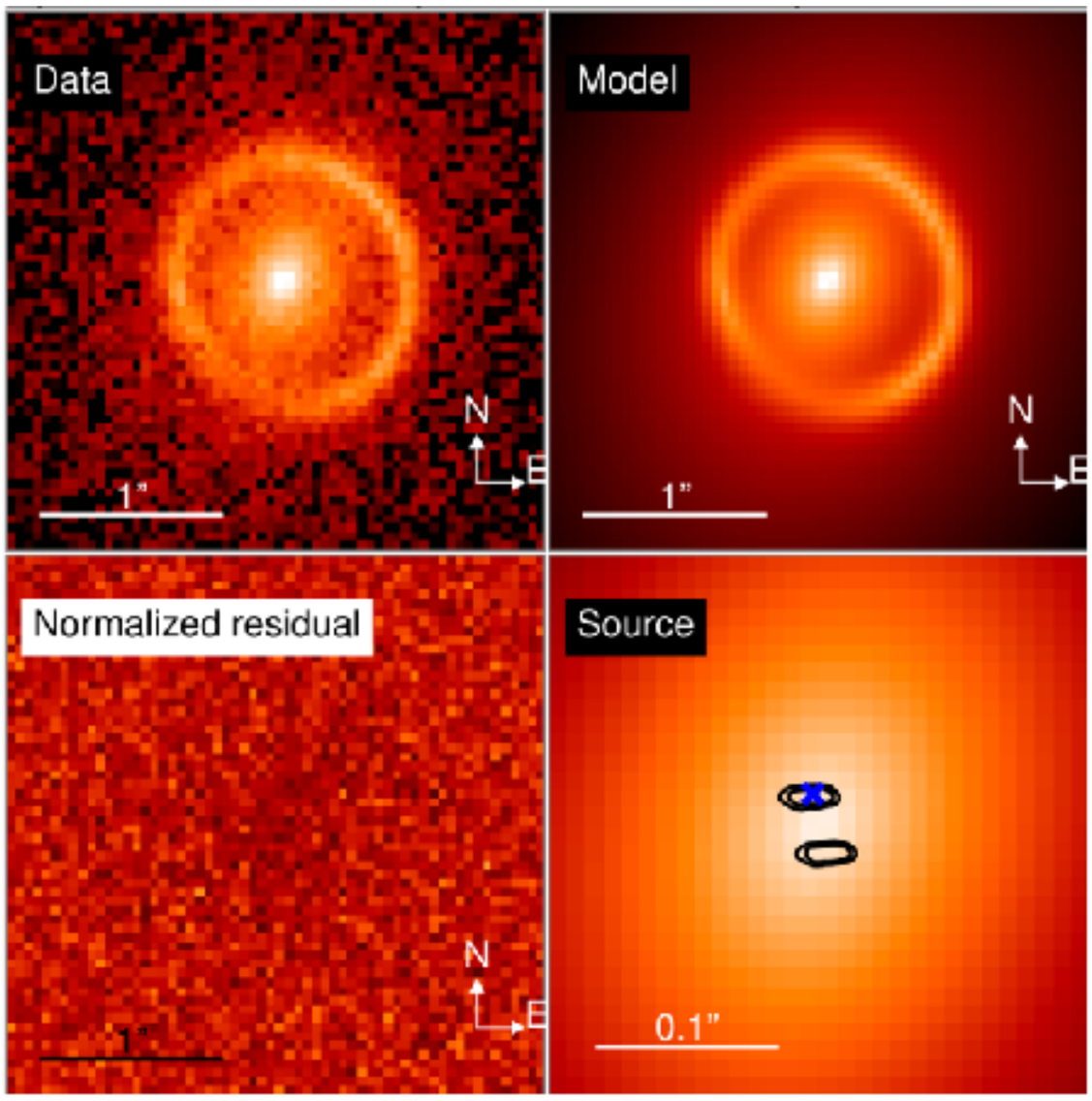


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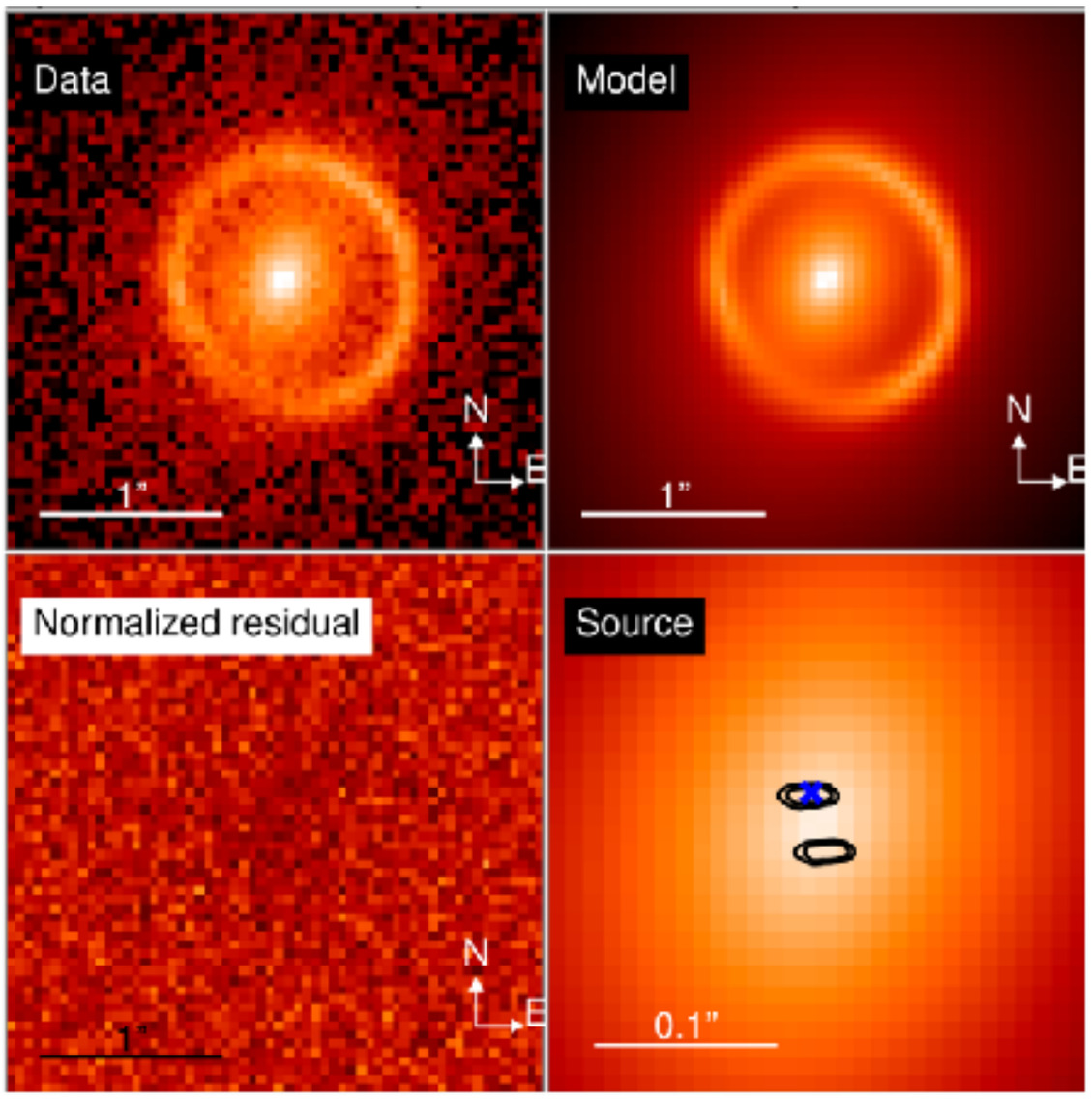


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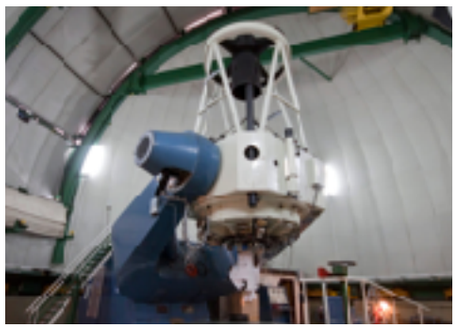

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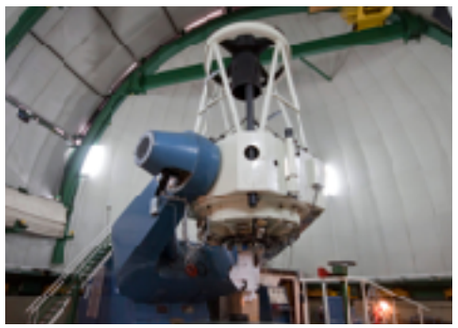

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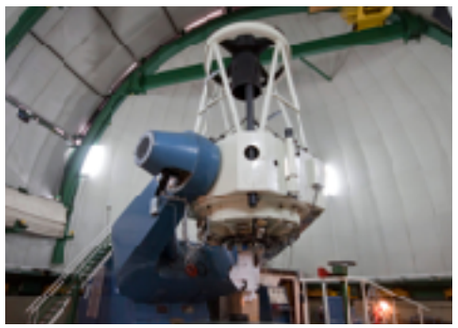

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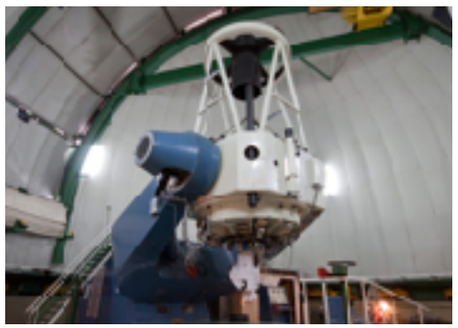

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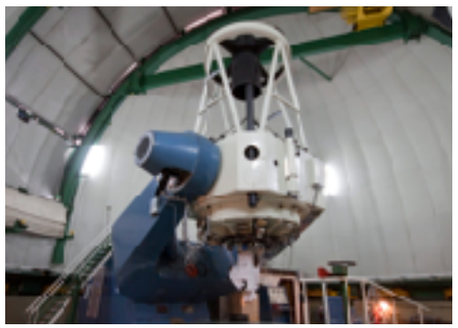

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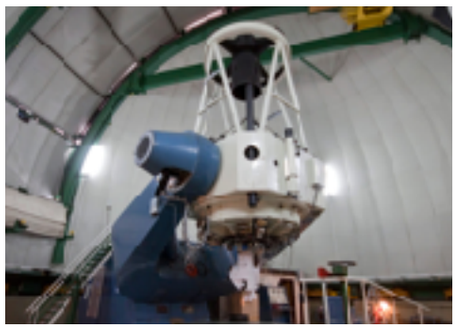

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