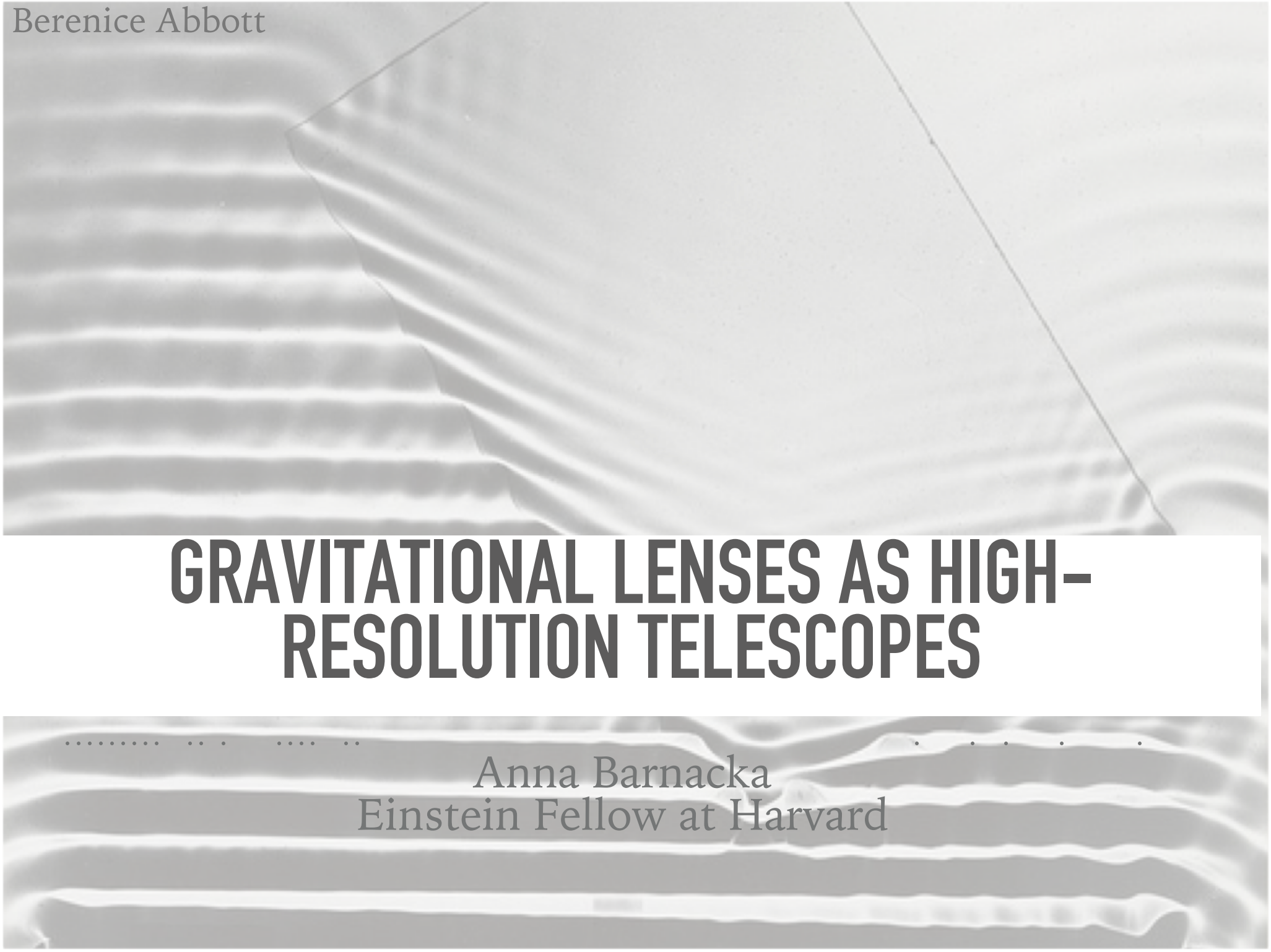
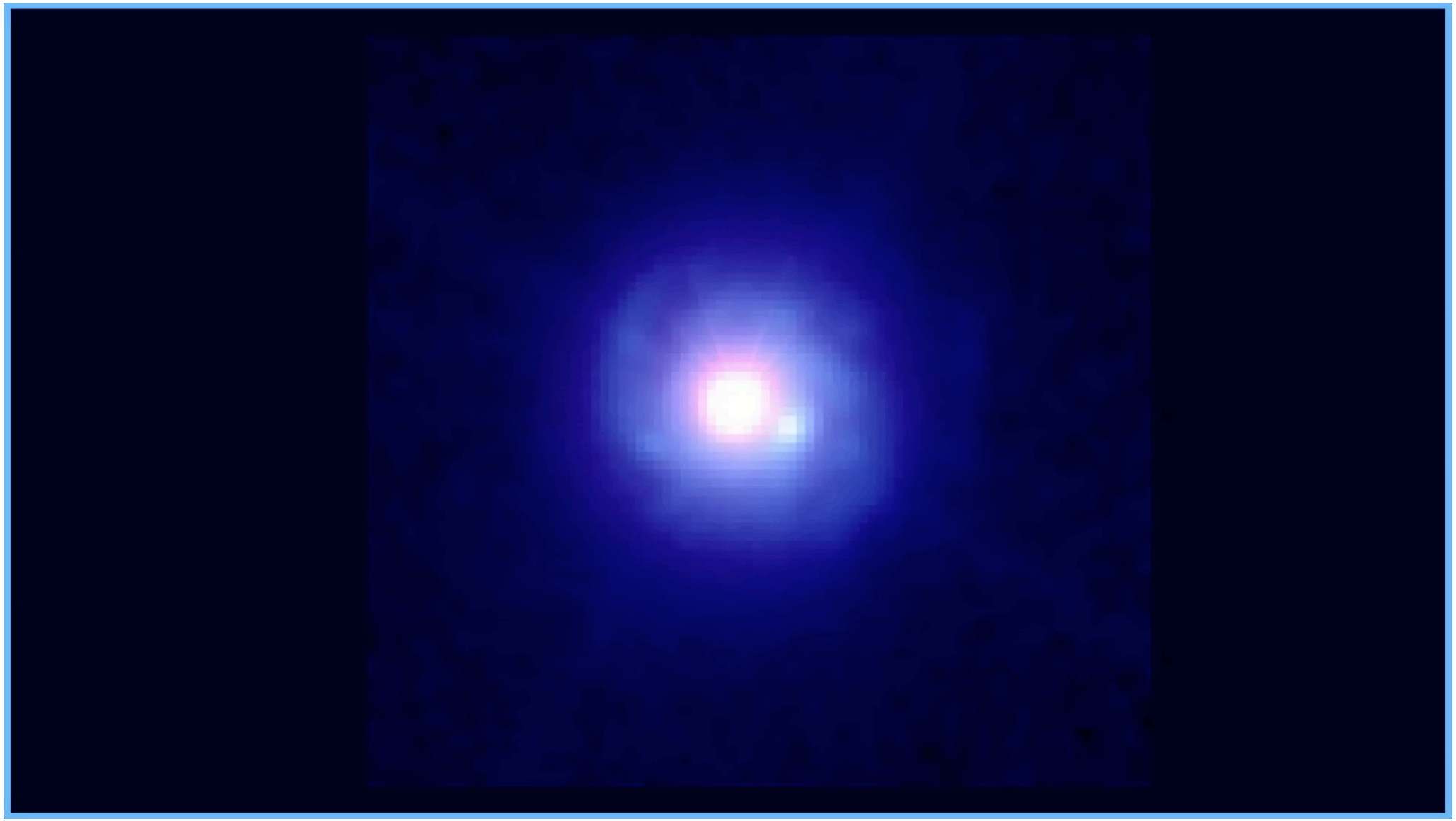


GRAVITATIONAL LENSES AS HIGH-RESOLUTION TELESCOPES

Anna Barnacka
Einstein Fellow at Harvard

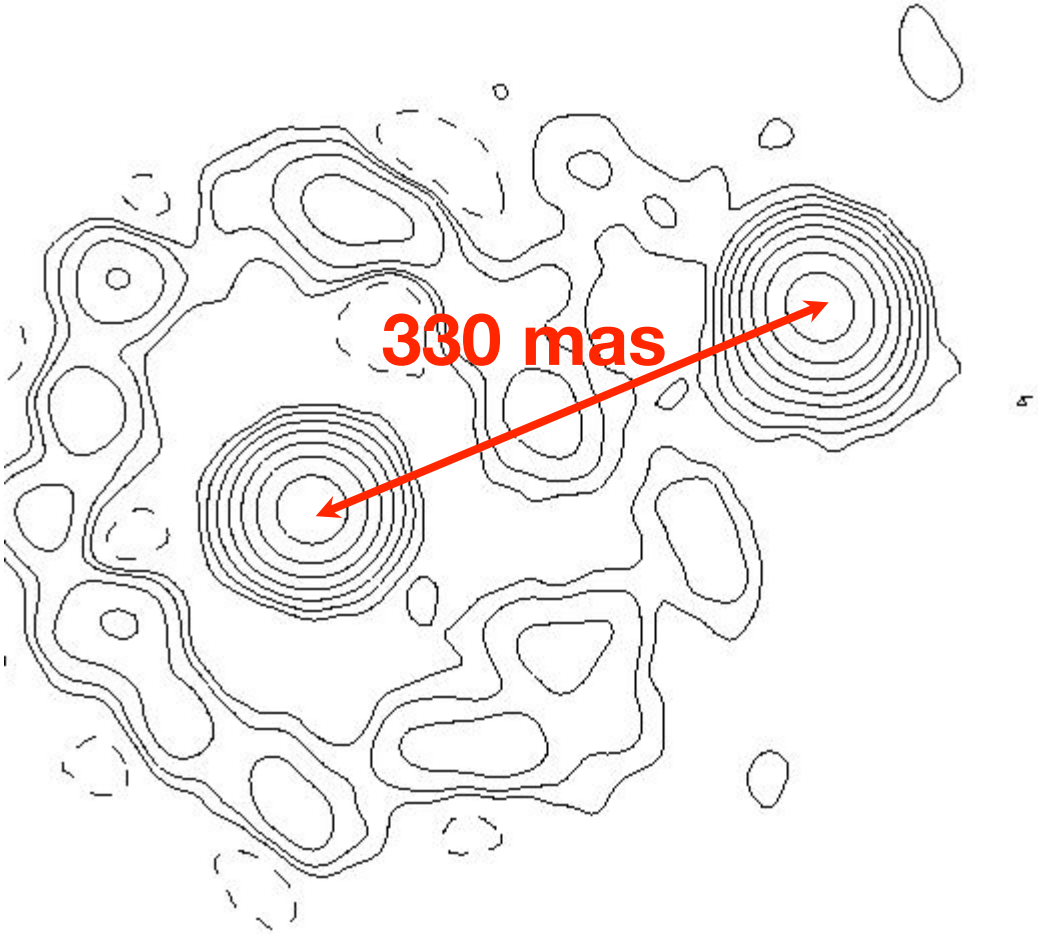
THE INNER REGION OF ACTIVE GALAXIES

GALAXIES AS COSMIC LENSES



Credit: NASA's Goddard Space Flight Center

LENSED BLAZAR: B2 0218+35



1.687 GHz, Patnaik et al. (1992)

Source z = 0.944,

Lens z = 0.6847

Radial Jet Projection

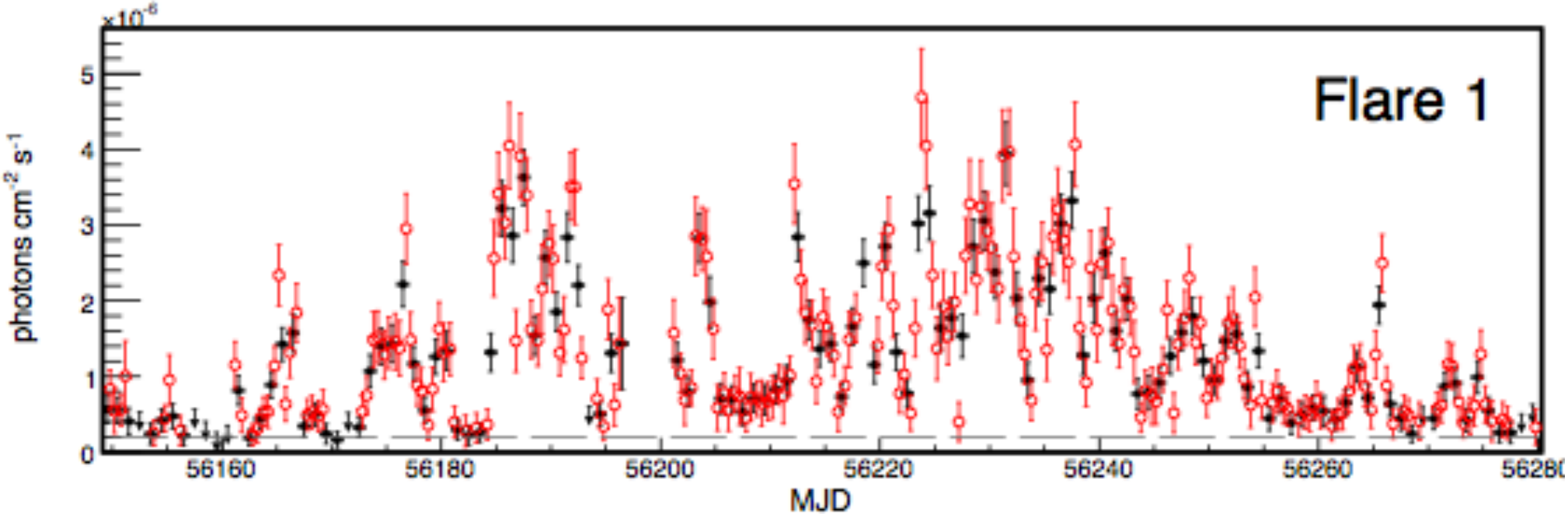
Reconstruction

~ 1 milliarcsecond

Radio Time Delay

10.5±0.5 days

GAMMA-RAY TIME DELAY



Time Delay = 11.38±0.13 days (Barnacka et al.,2016)

Time Delay = 11.46±0.16 days (Cheung et al. 2014)

COSMIC SCALE

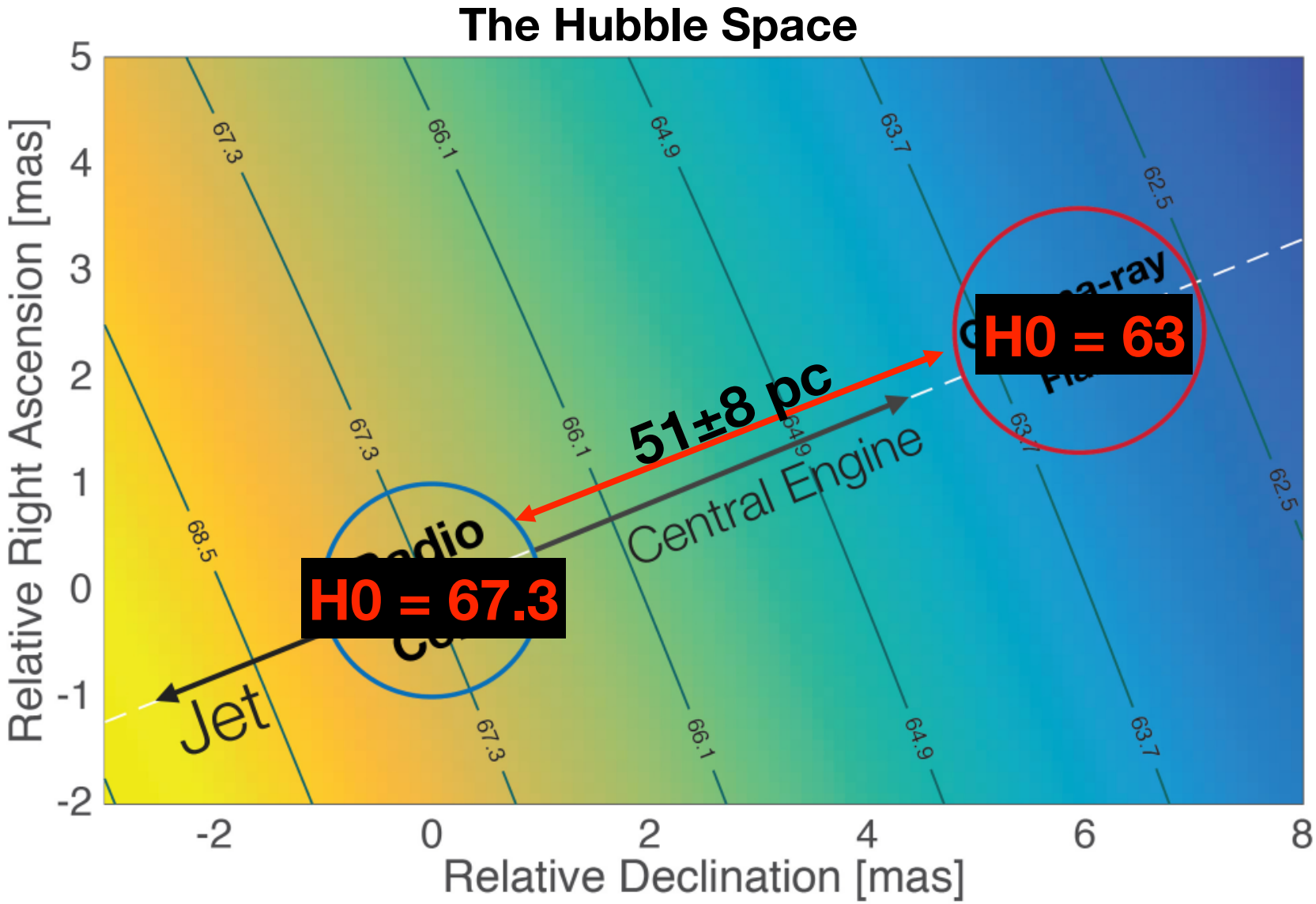
Time Delay + Position of the Images + Lens Model

Cosmic Scale: Hubble Parameter

Offset between the resolved emitting region and the variable emitting region

Barnacka, A., et al. (2015,ApJ,799,48)

HUBBLE CONSTANT & GAMMA-RAY SOURCE CONNECTION



Barnacka et al. 2016, ApJ, 821, 58

GAIA–VLBA OFFSETS

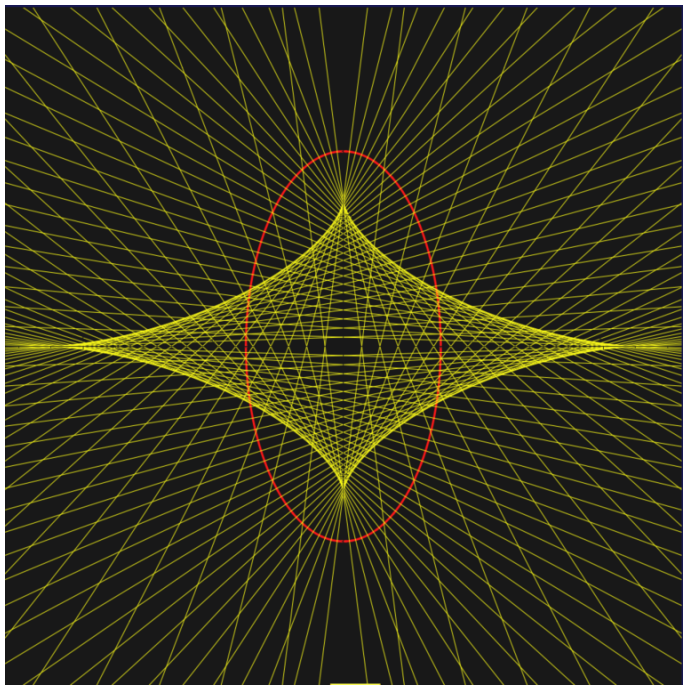
~ 400 VLBI sources with large offsets relative to Gaia

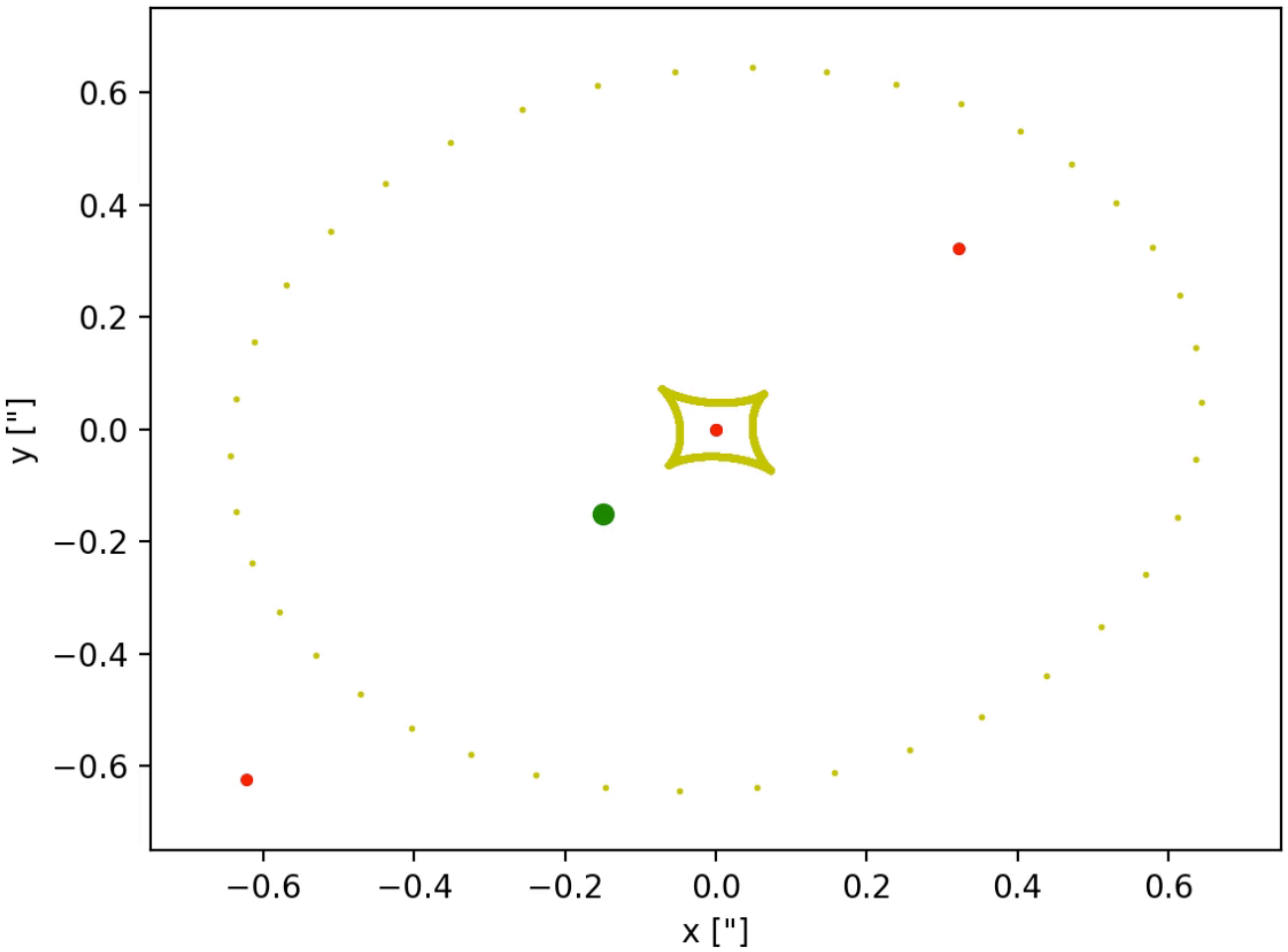
VLBI ID	*Gaia* ID	PFA	RNP	*q*	*dα* (mas)
RFC J0000−3221	*Gaia* 2314315845817748992	4.47×10^{-8}	2.47×10^{-22}	20.78	−6.51
RFC J0004−0802	*Gaia* 2441584492826114432	3.58×10^{-6}	4.14×10^{-03}	4.73	−21.39
RFC J0005+3820	*Gaia* 2880735411259458048	1.98×10^{-7}	5.03×10^{-08}	10.80	5.77
RFC J0008−2339	*Gaia* 2337107759788510464	2.01×10^{-8}	5.84×10^{-06}	8.84	1.17

Table from Petrov & Kovalev (2017)

The first four rows of the table of **384 VLBI/*Gaia*** matches with statistically significant offsets: probability of false association (PFA) less than 0.0002 and the random noise probability (RNP) less than 0.01. The fifth column contains the normalized arc lengths, and two last columns contain positions of *Gaia* minus VLBI over right ascensions, including cos δ factor and declination.

CAUSTIC

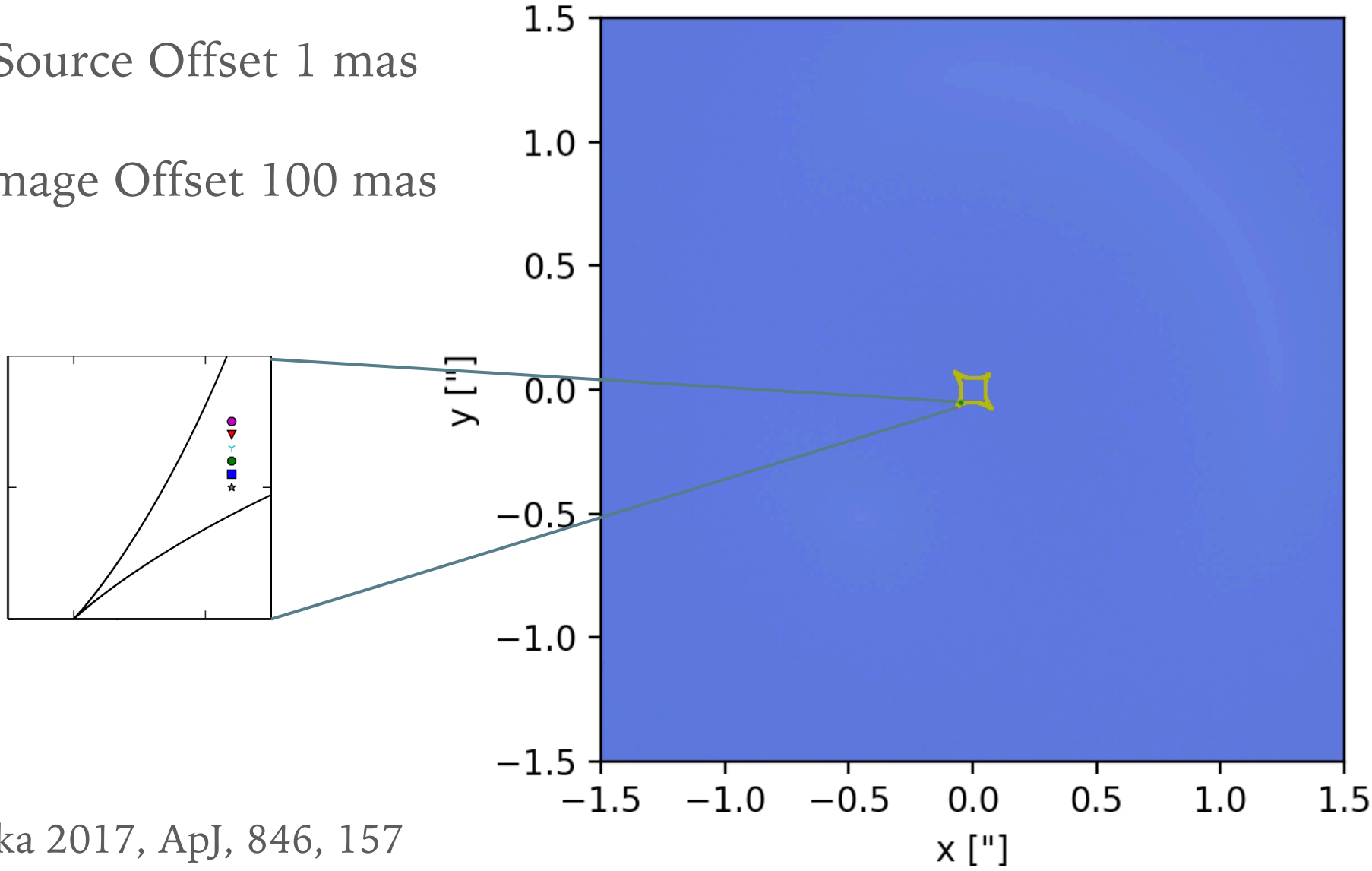




TOY MODEL: SOURCES CLOSE TO THE CAUSTIC

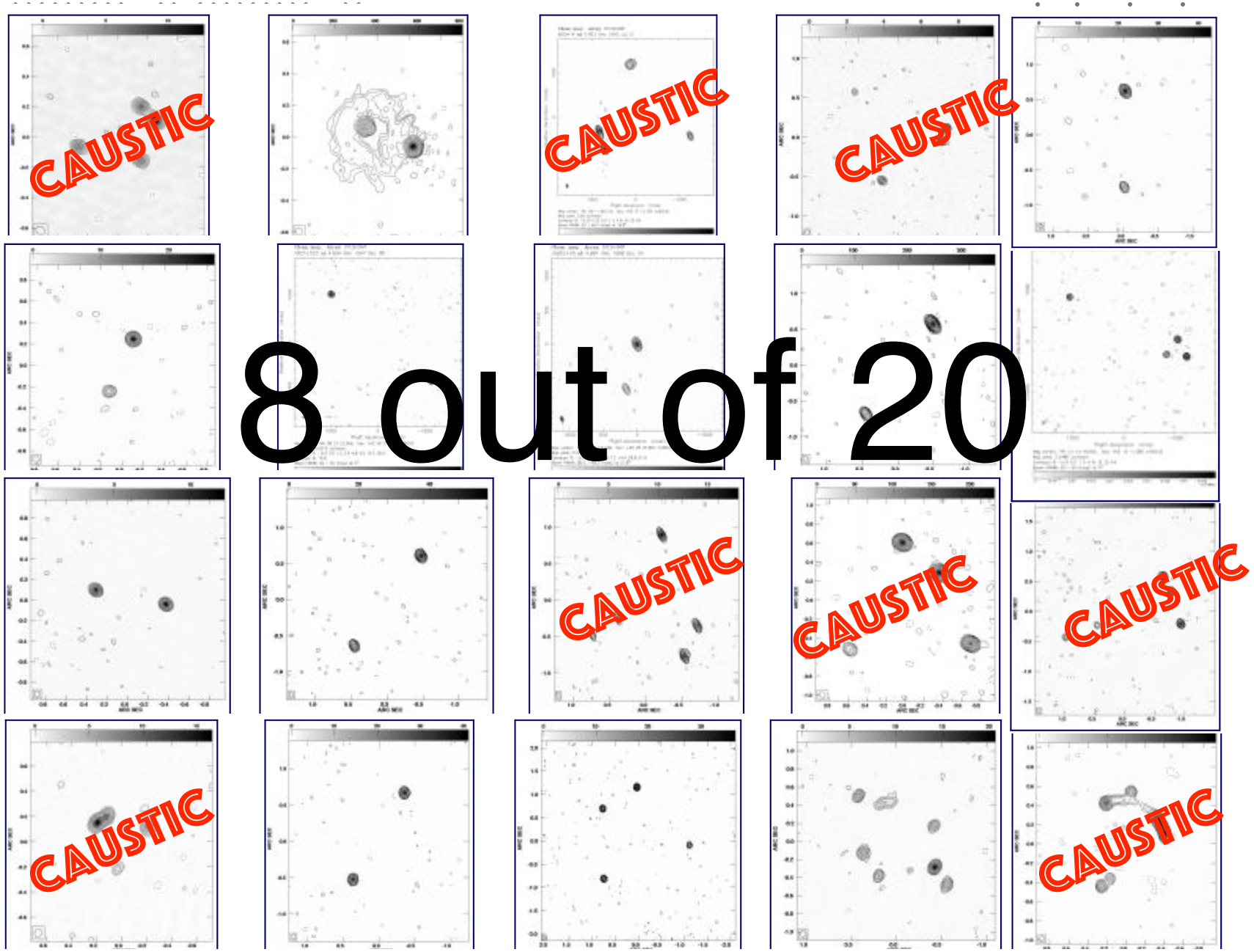
Source Offset 1 mas

Image Offset 100 mas



Barnacka 2017, ApJ, 846, 157

LENSED QUASARS IN CAUSTIC CONFIGURATION



8 out of 20

JVAS/CLASS

EUCLID AND SKY SYNERGY

In near future: observations of more than $\mathbf{10^5}$ strongly lensed flat spectrum radio-loud quasars

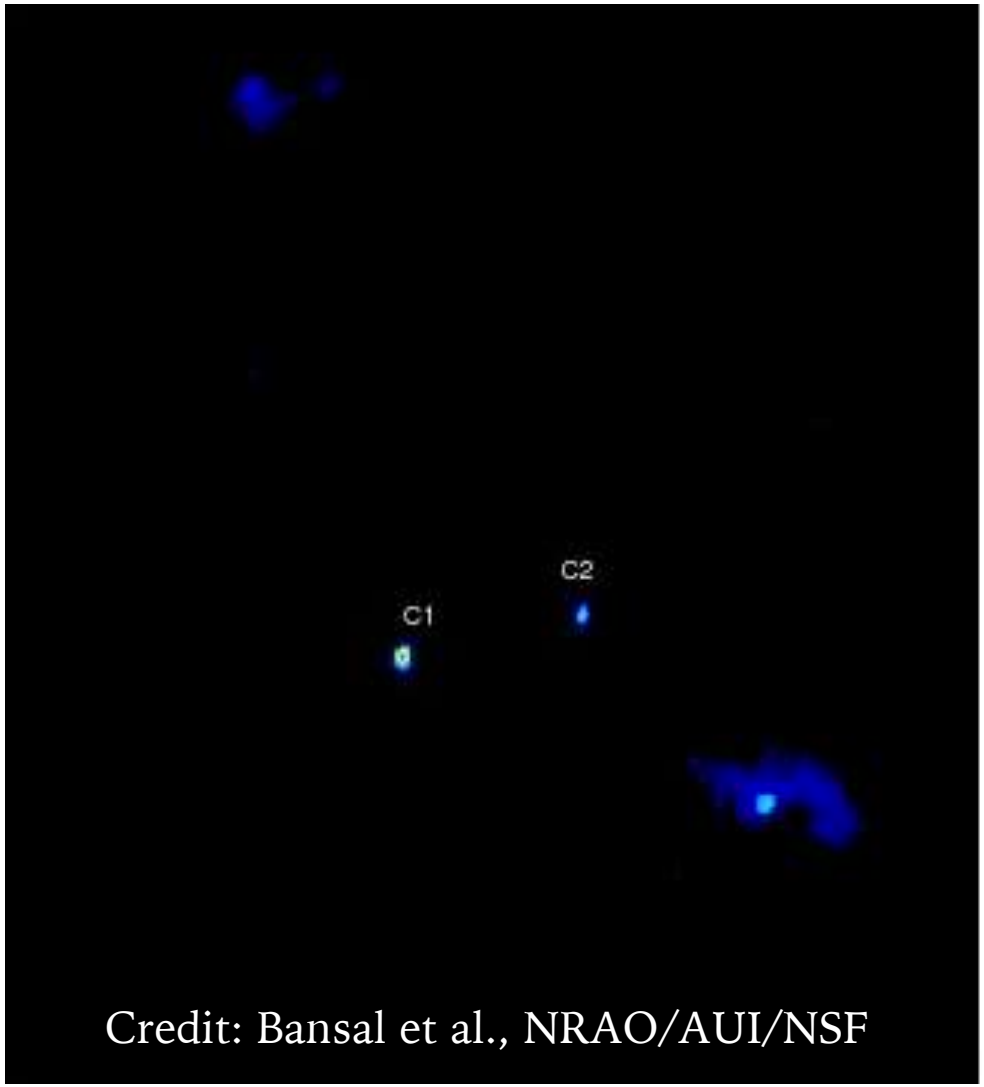
TOY MODEL: SUPERMASSIVE BLACK HOLE BINARY 0402+379

0402+379, z = 0.05

separation ~ 8 pc ~8 mas

If 0402+379 were at z = 2

separation ~ 8 pc ~ 1 mas



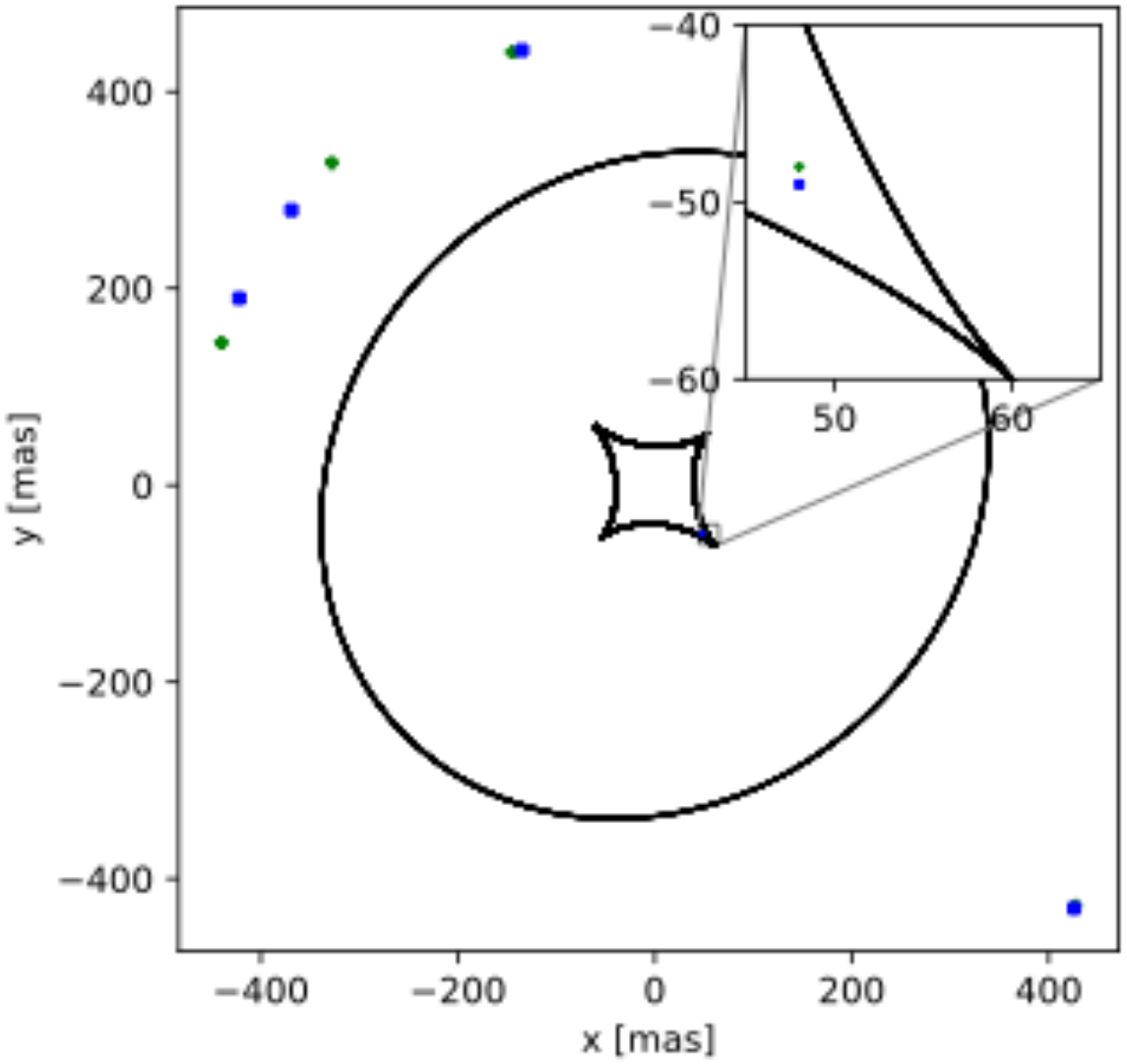
Credit: Bansal et al., NRAO/AUI/NSF

TOY MODEL: 0402+379 AT Z = 2

If 0402+379 were

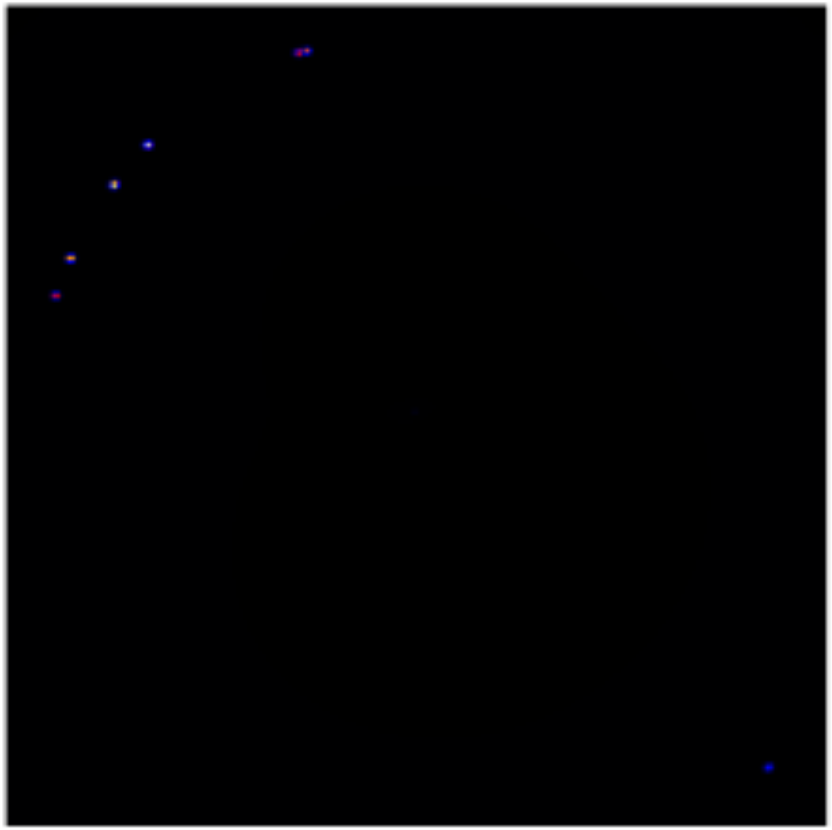
at z = 2

8 pc ~ 1 mas

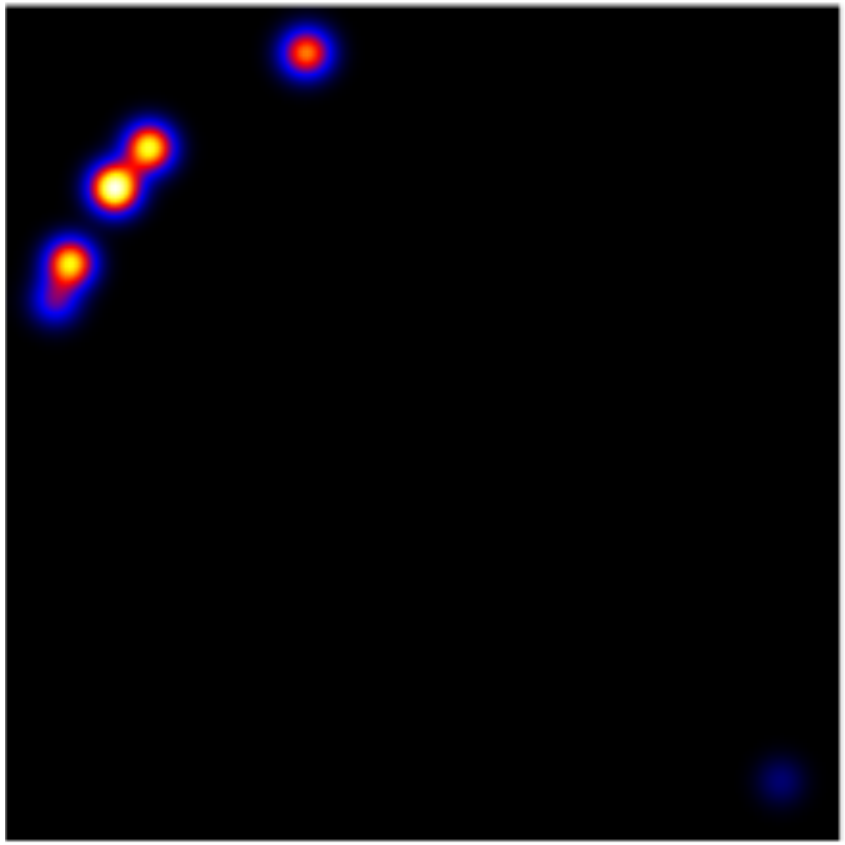


PREDICTION FOR SKA

Resolution: 2 mas



Resolution: 20 mas



SKA can be used to select binary candidates with separation down to **0.2 pc**

VLBI can be used to measure relative motion.

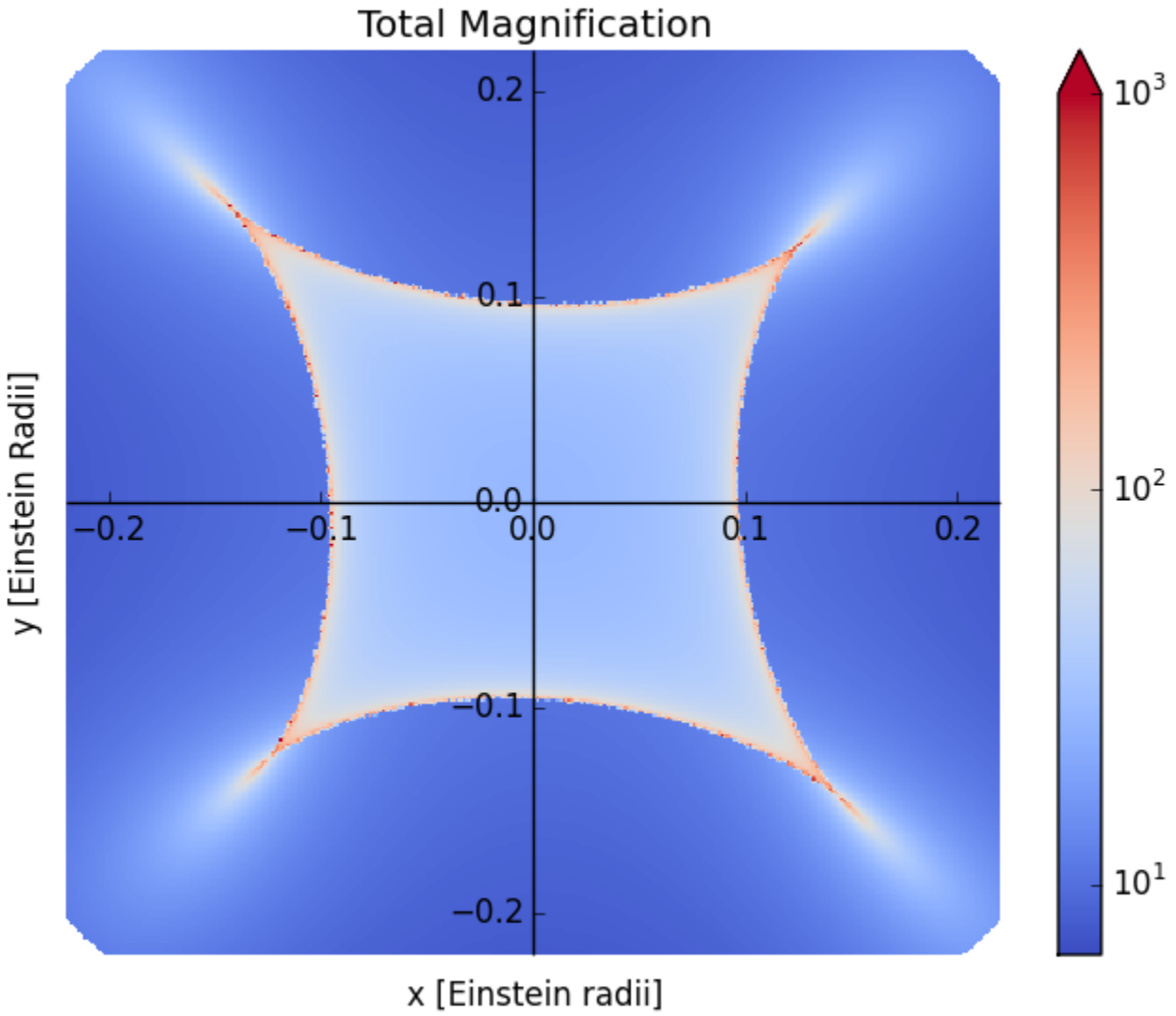
COSMIC LENSES

- Caustic Configuration:
  - >50 x Flux Magnification
  - >50 x Angular Amplification
  - Resolution ~ a few mas
  - Reference Frame for Astrometry
  - Eliminates need for Absolute Astrometry

SUMMARY

- Currently: Dozen of Sources
- Near Future: SKA and Euclid Dozen of Thousands of Sources
- Insight into:
  - Inner Parts of Active Galaxies at High z
  - Identify the Most Distant Quasars
  - Find Binary SMBH Candidates
  - Follow-up Observations with VLBI, JWST or ELT

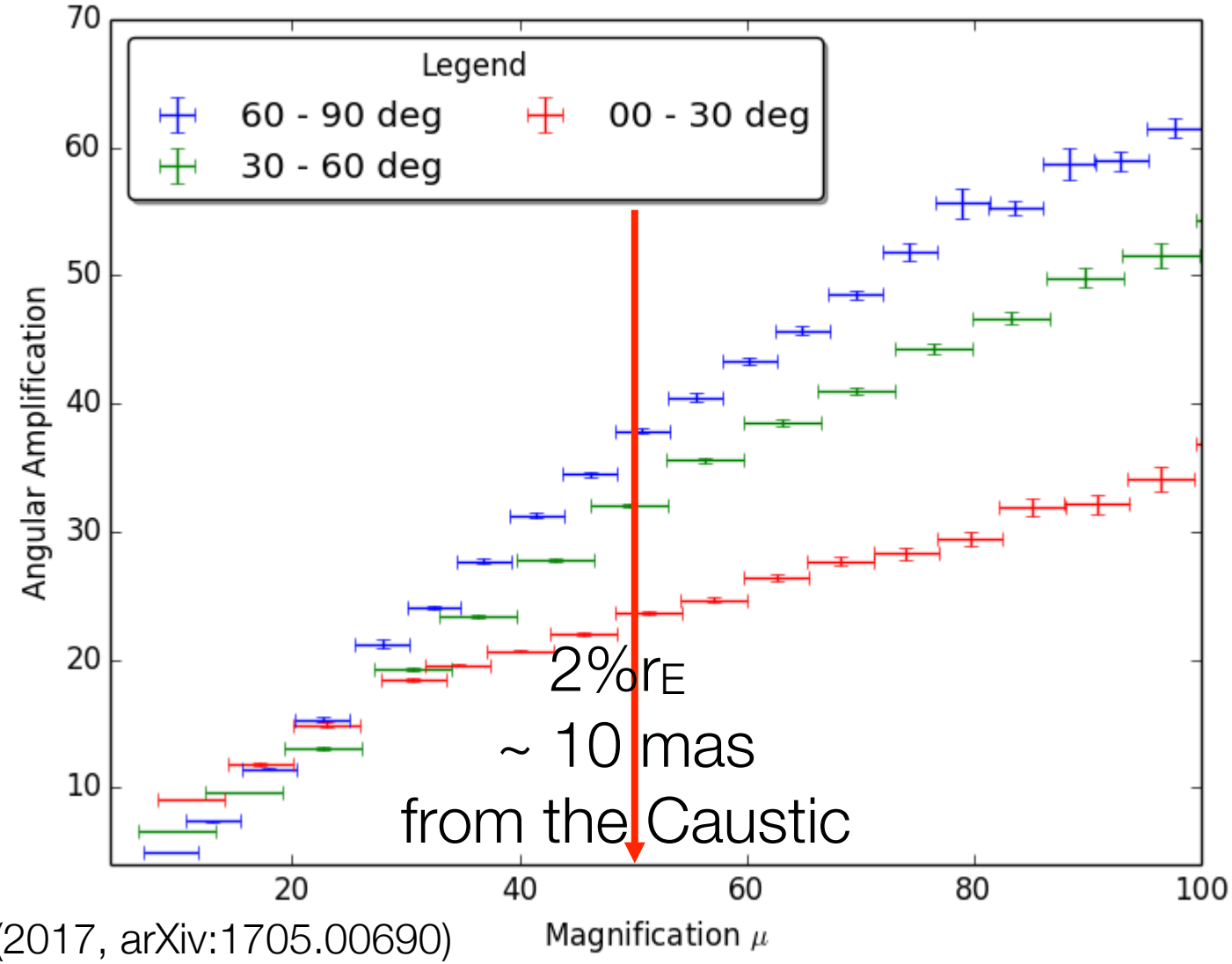
FLUX MAGNIFICATION IN CAUSTIC REGION



Barnacka (2017, ApJ, arXiv:1705.00690)

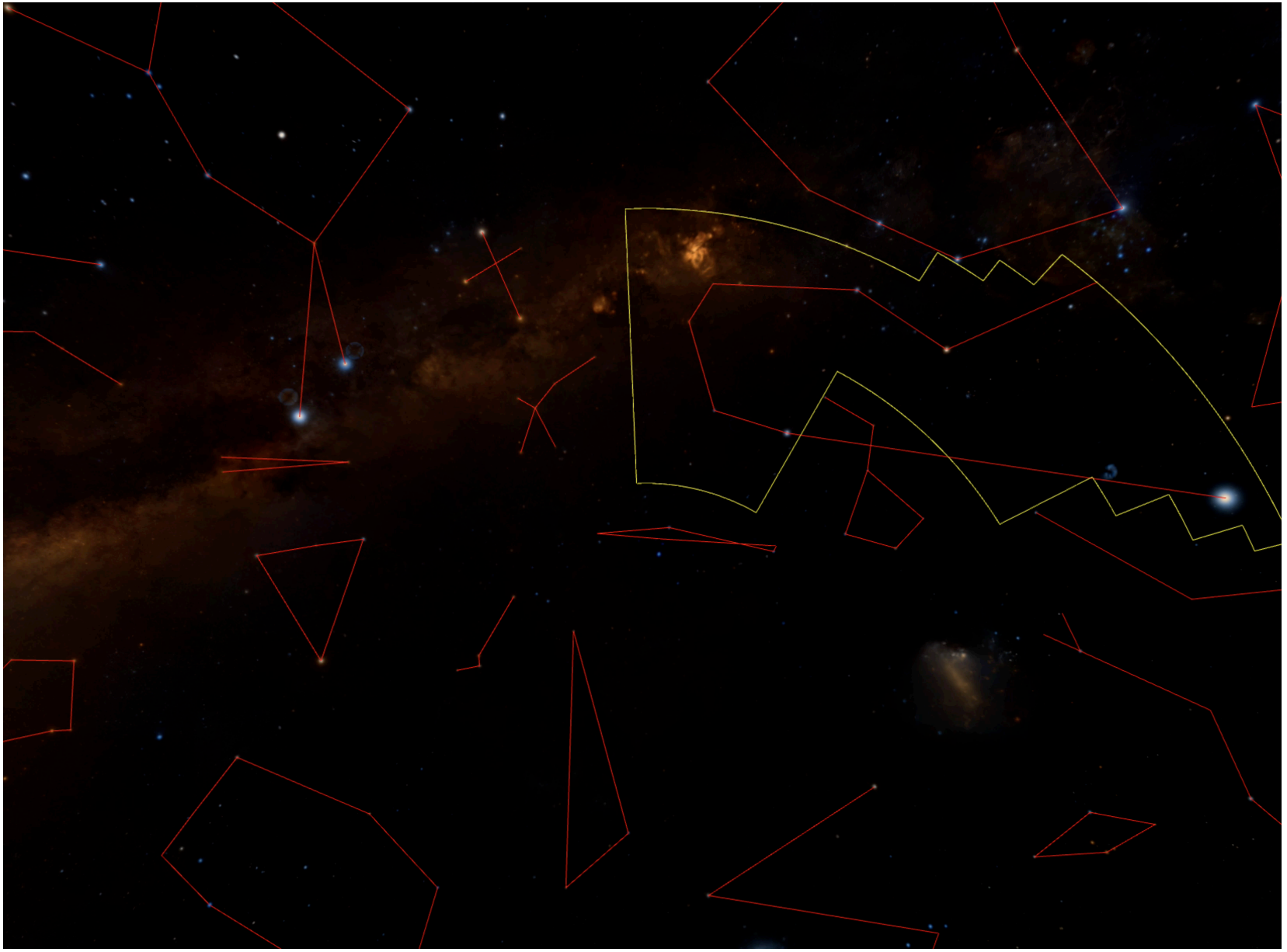
ANGULAR AMPLIFICATION IN CAUSTIC REGION

Monte Carlo Simulations of **10^6** pair of offset sources



Barnacka (2017, arXiv:1705.00690)

JOURNEY TO INNER REGION OF M87



Journey created with **World Wide Telescope**: Special thanks to Philip Rosenfield

GAIA–VLBA OFFSETS

Table from Petrov & Kovalev (2017)

The first four rows of the table of **384 VLBI/*Gaia*** matches with statistically significant offsets: probability of false association (PFA) less than 0.0002 and the random noise probability (RNP) less than 0.01. The fifth column contains the normalized arc lengths, and two last columns contain positions of *Gaia* minus VLBI over right ascensions, including cos δ factor and declination.

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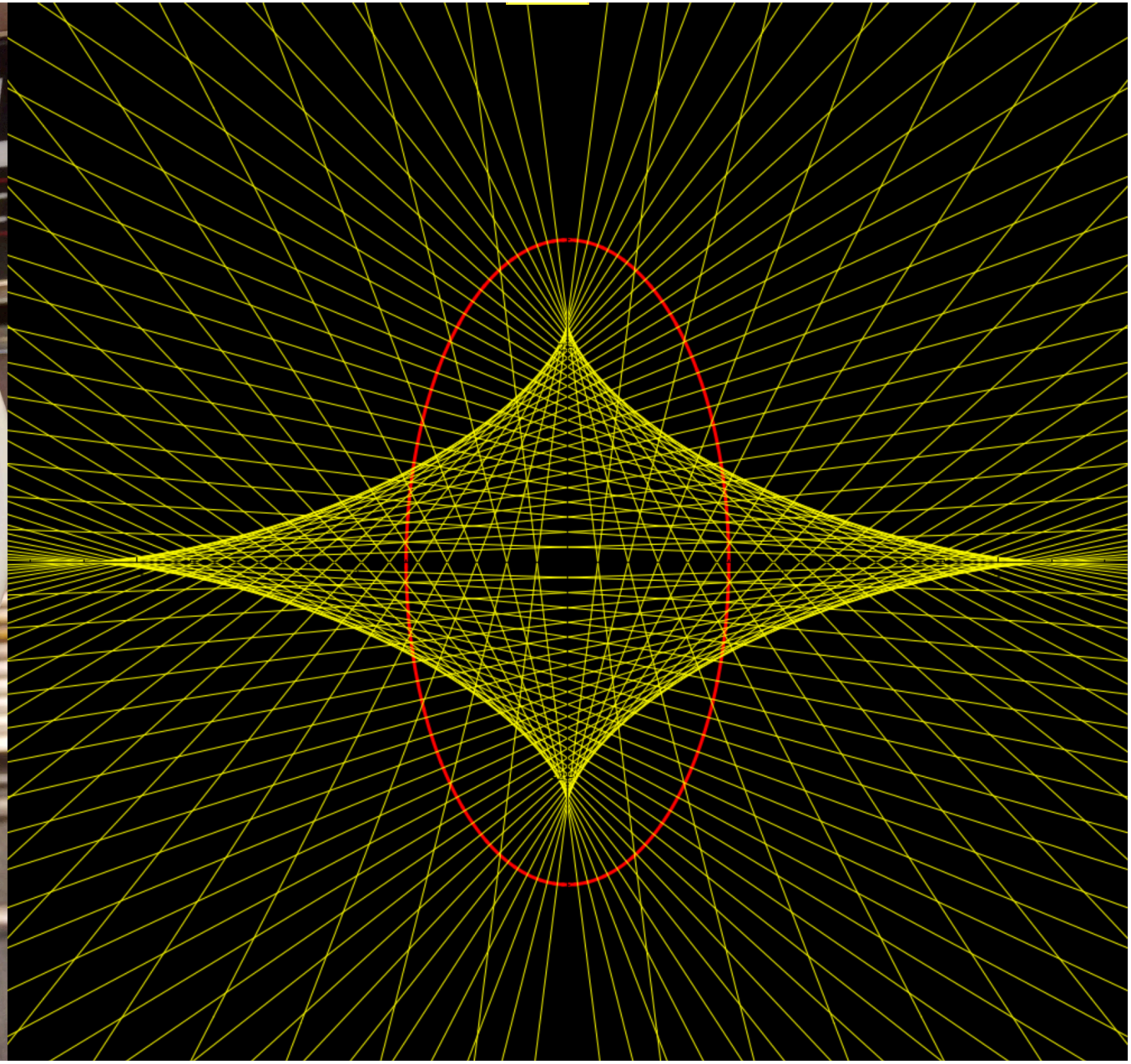
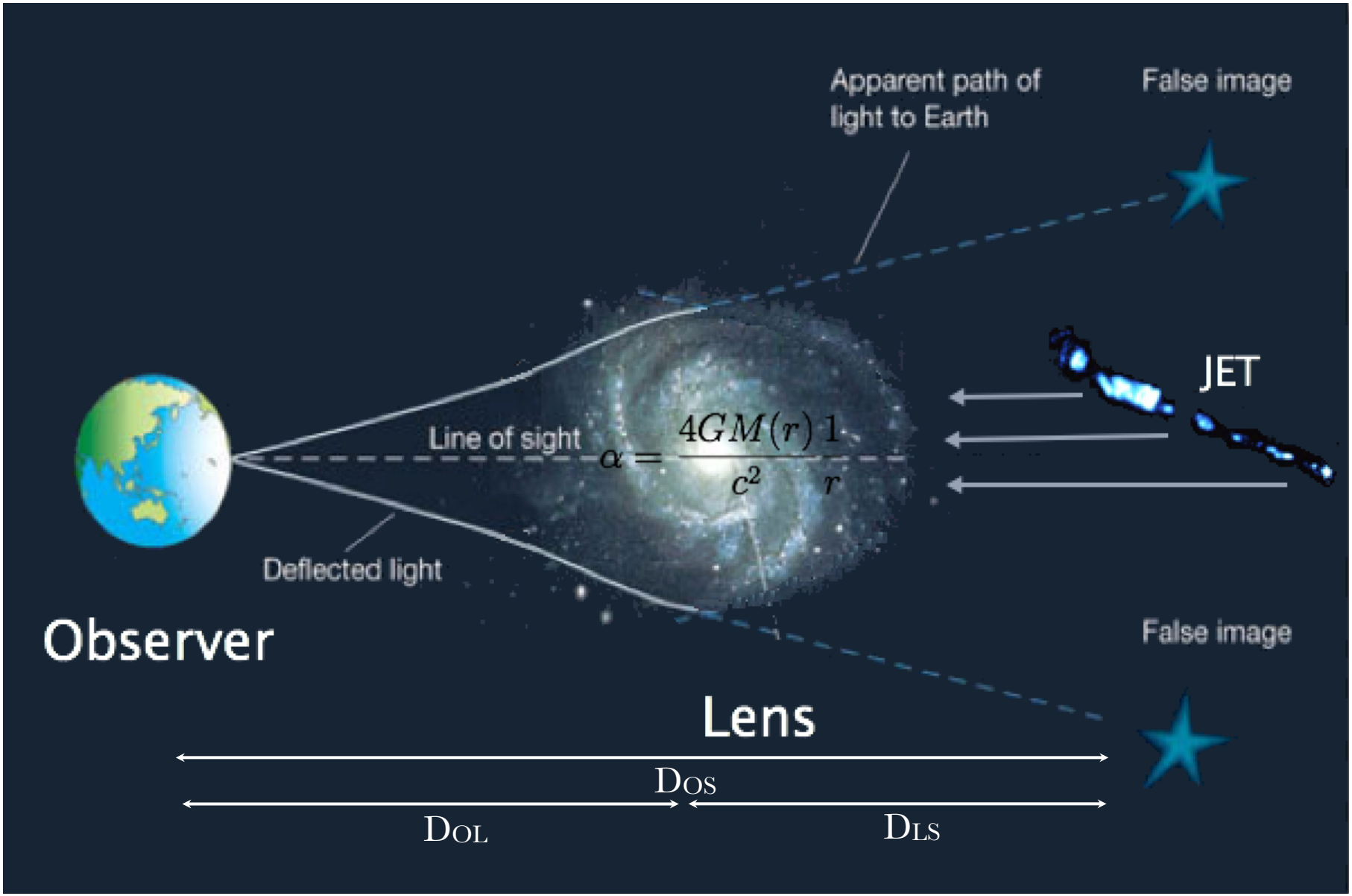
RFC J0008−2339	*Gaia* 2337107759788510464	2.01×10^{-8}	5.84×10^{-06}	8.84	1.17
...					

CAUSTIC OF ELLIPTICAL LENSES

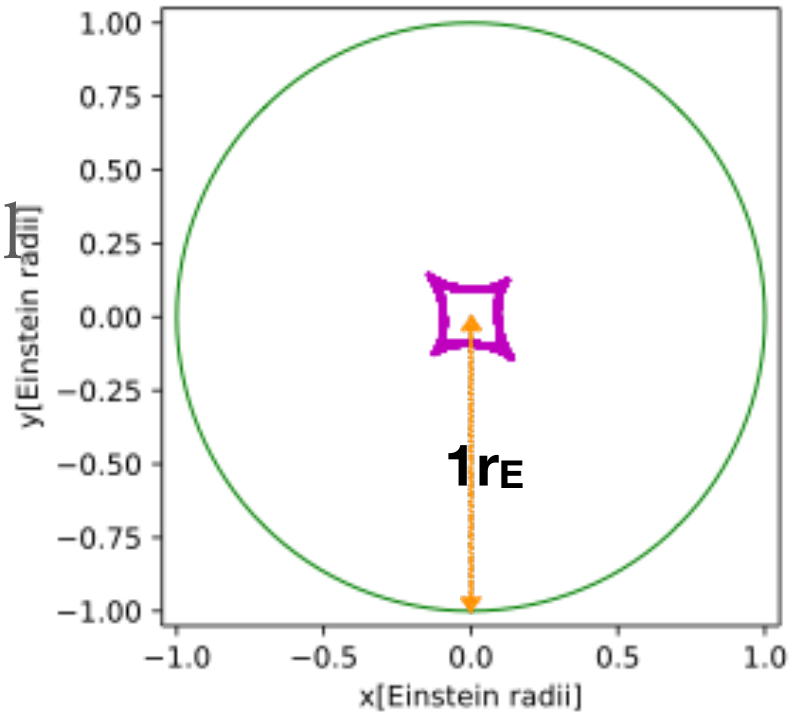


M87 Gravitationally Lensed?

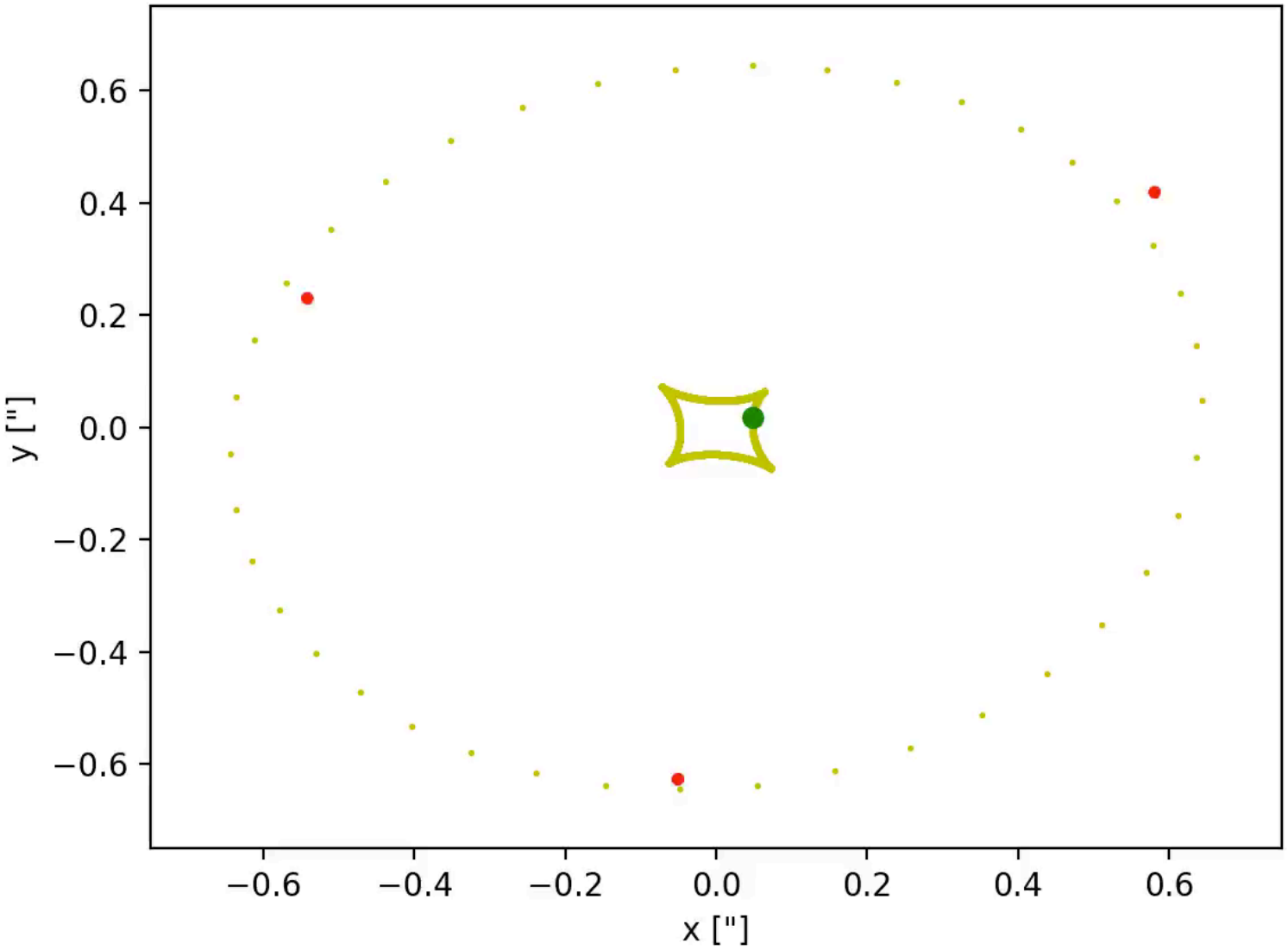


PROBABILITY OF CAUSTIC CONFIGURATION

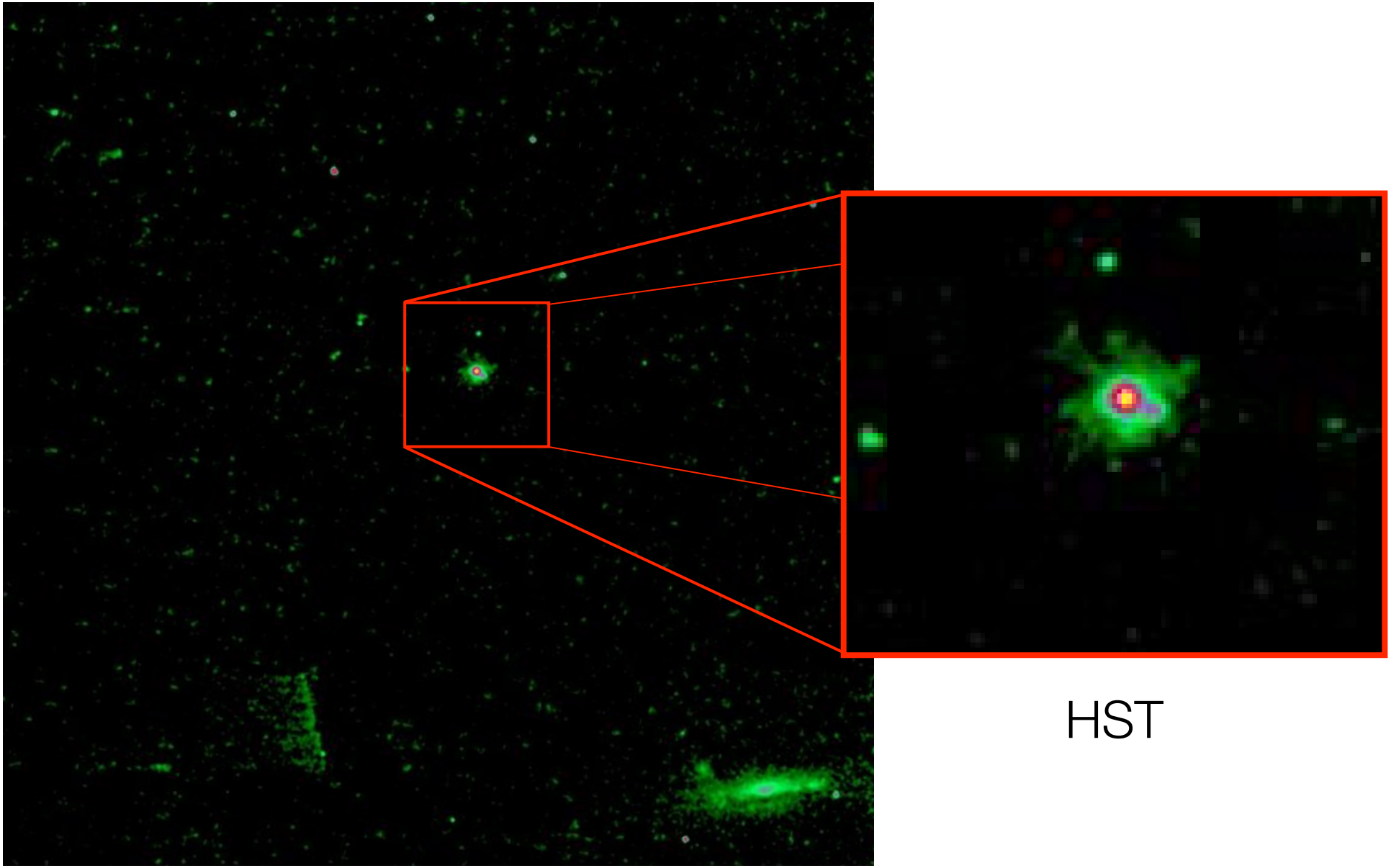
- Elliptical lens e=0.2
  - lens z=0.5, source z=2
- Caustic Length ~2.1 rE
  - Probability that a source will be with 2%rE from the Caustic is ~ **1%**
- Magnification bias
  - Magnification close to the caustic > 50
  - Probability > **8%**



SOURCE CLOSE TO THE CAUSTIC OF THE LENSING GALAXY

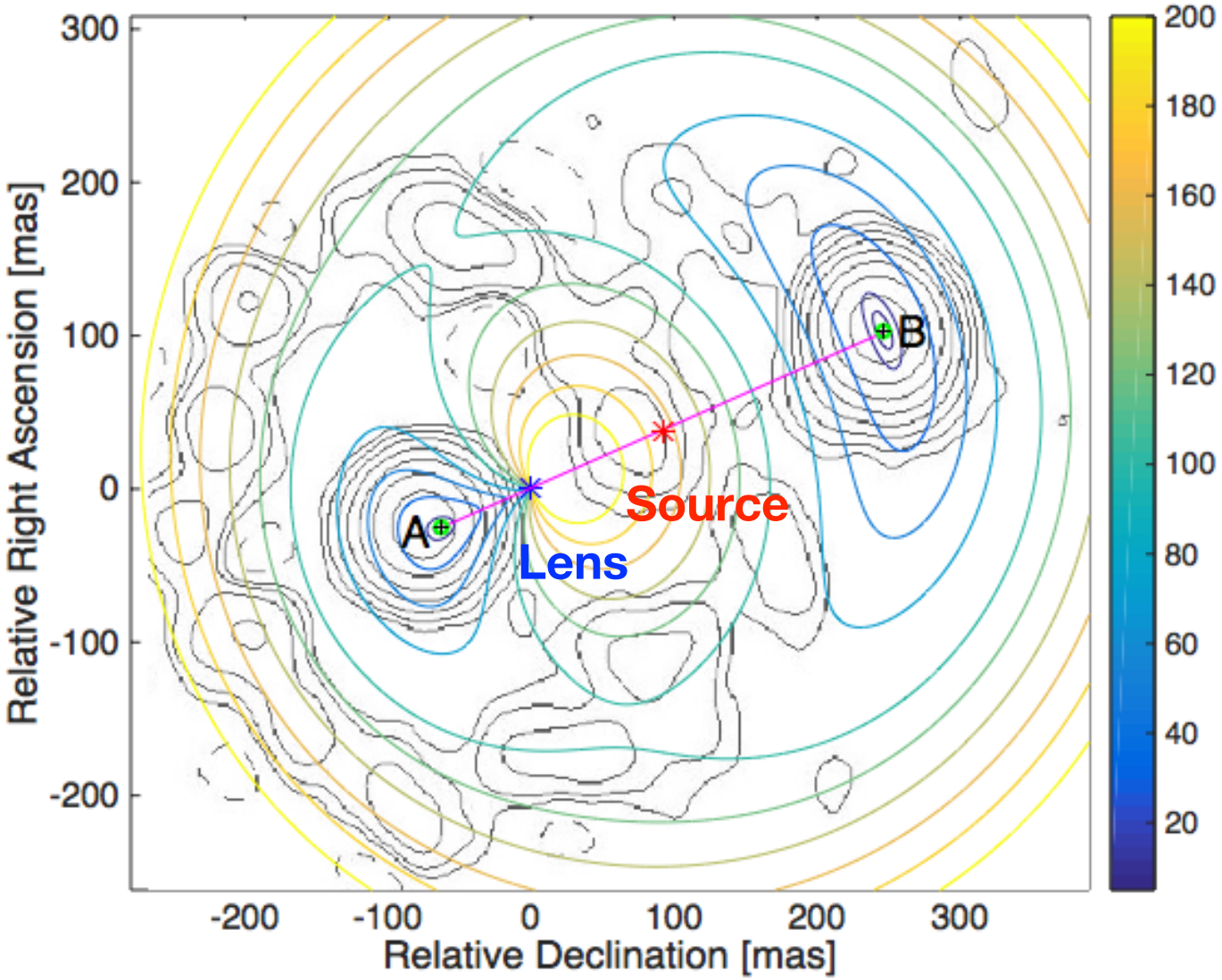


OBSERVATIONS: B2 0218+35



HST

LENS MODELING

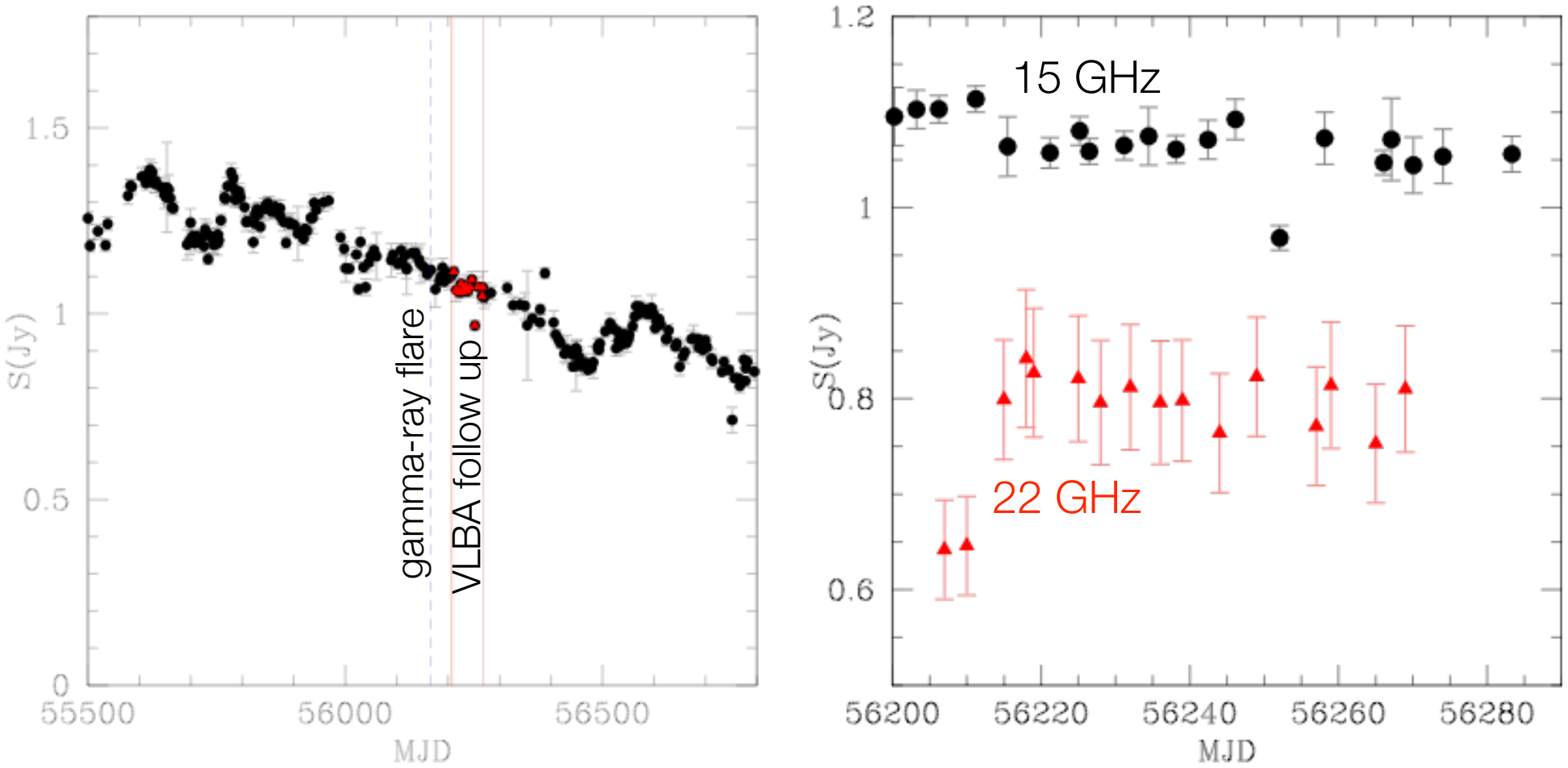


Reconstruction

~ 1 milliarcsecond

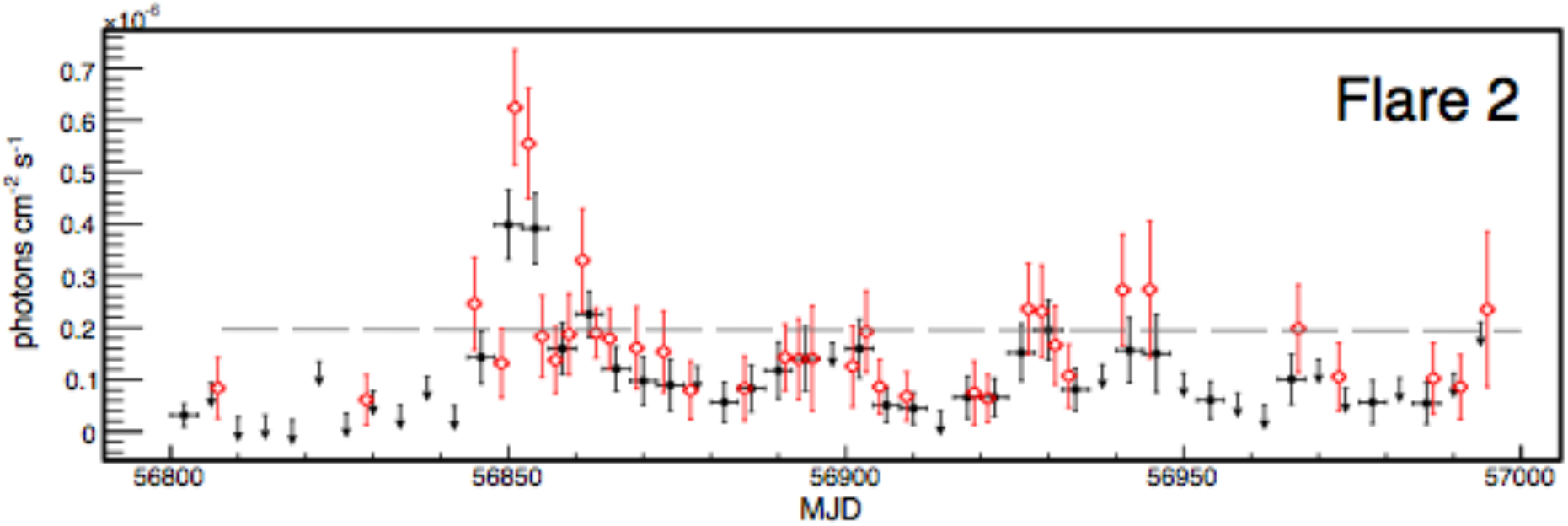
Barnacka et al. 2016, ApJ, 821, 58

RADIO FOLLOW UP

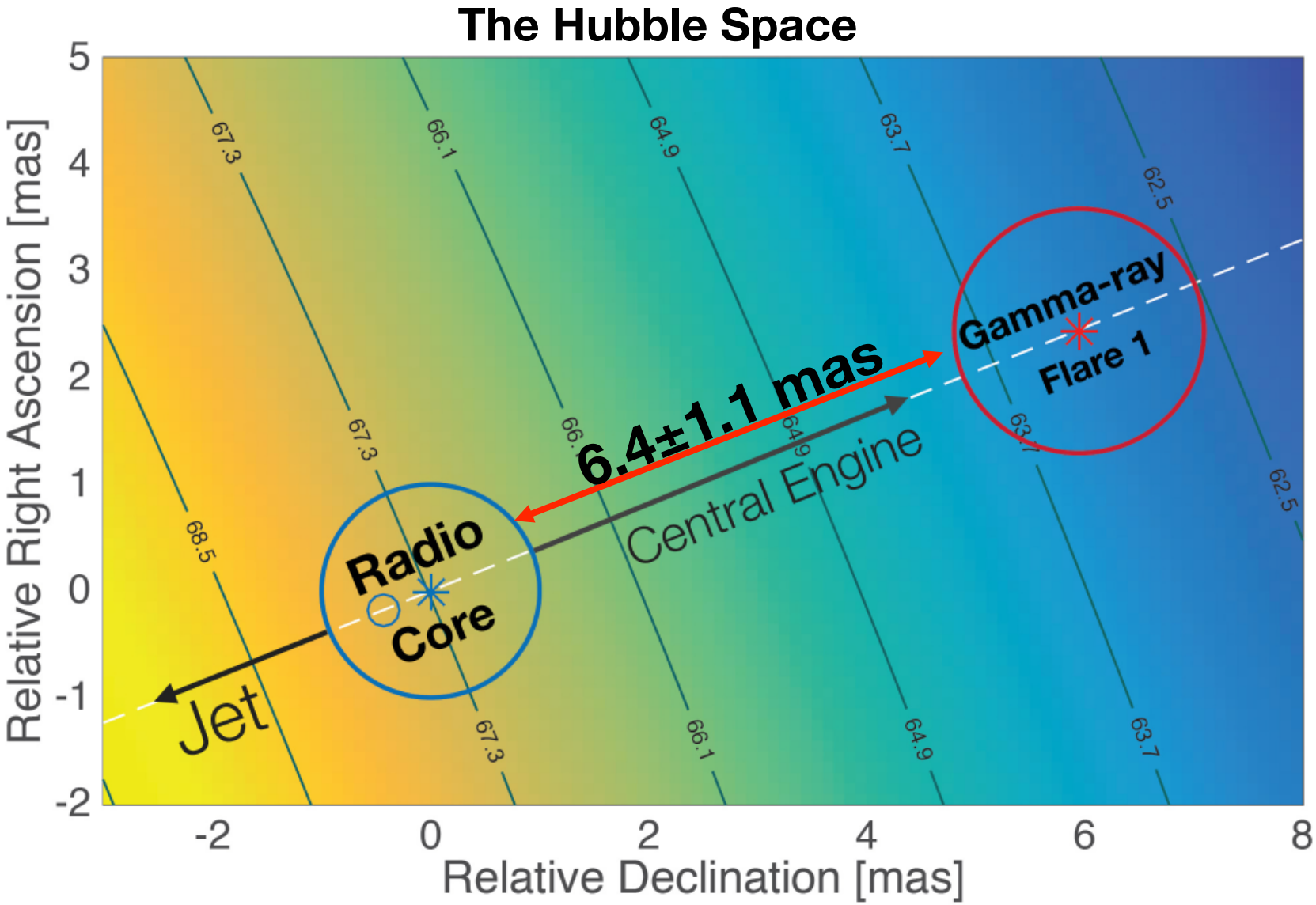


Spingola et al. (2016)

GAMMA-RAY FLARE 2



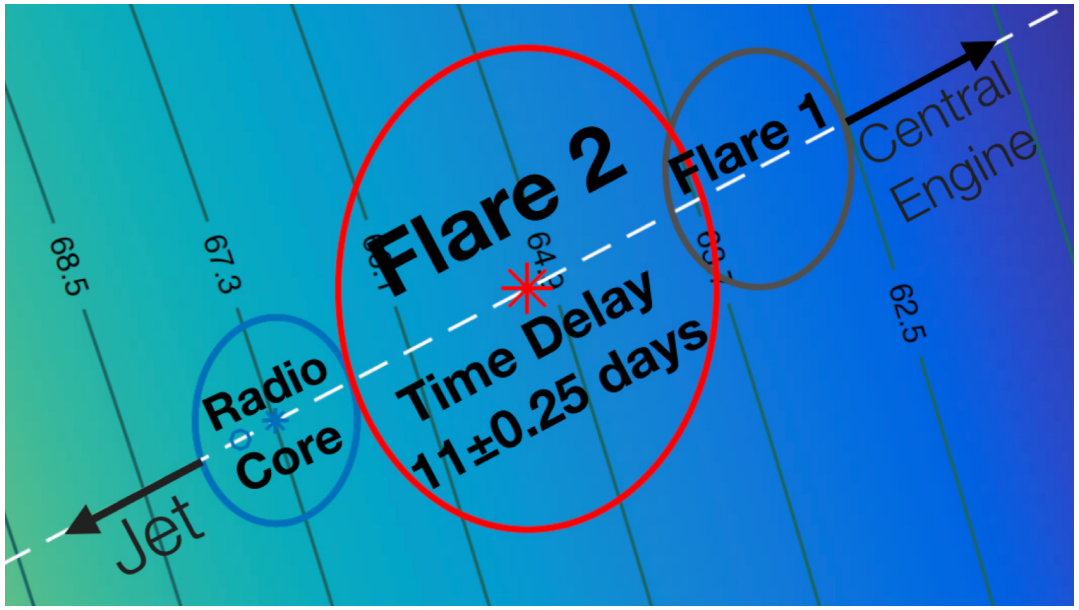
OFFSET: RADIO CORE – SUPERMASSIVE BLACK HOLE



Barnacka et al. 2016, ApJ, 821, 58

FUTURE FLARES

If Flare 1 and Flare 2 connected:



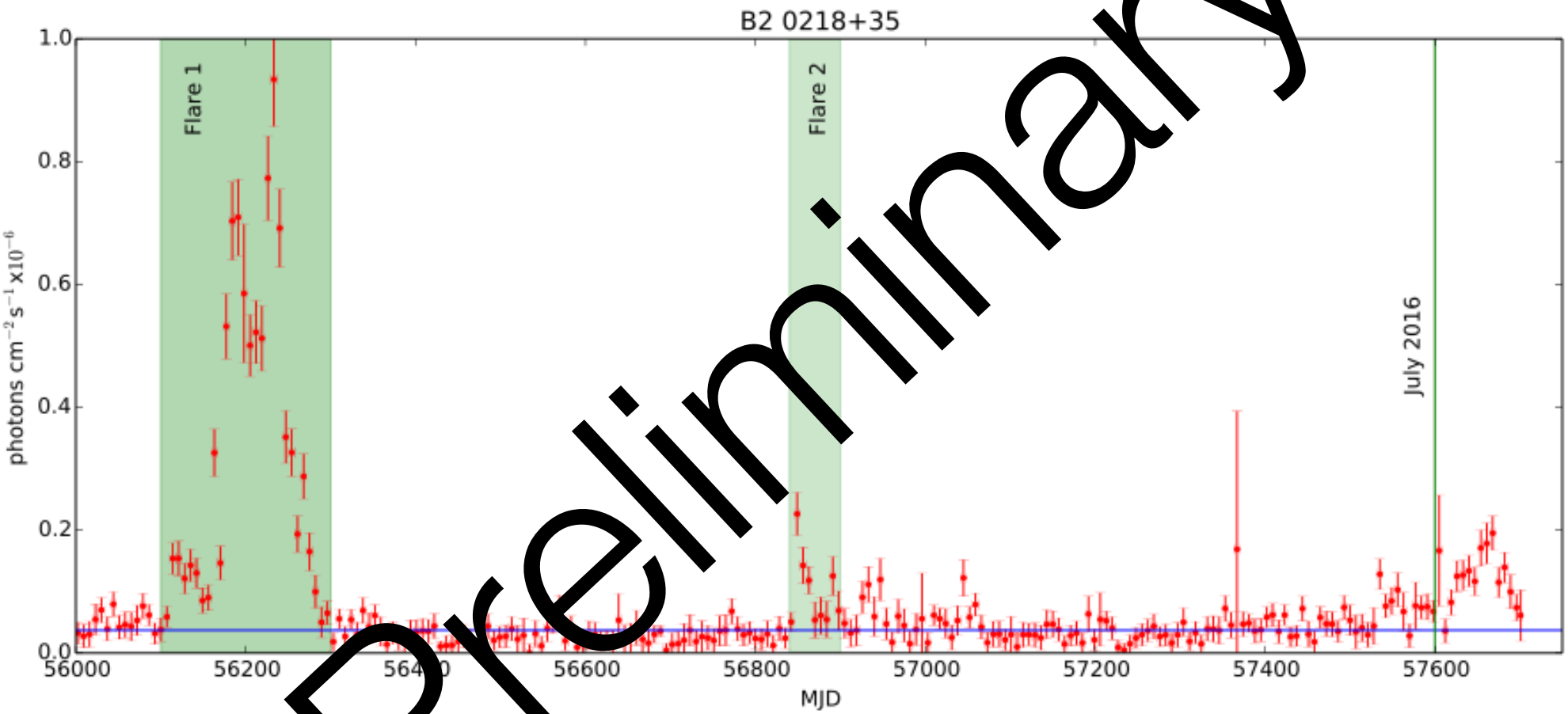
9 milliarcseconds

$$\beta_{app} = \frac{D_{projected}(1+z_S)}{c\,\Delta t_{obs}} \approx 70 \left(\frac{D_{projected}}{24\,\mathrm{pc}}\right)\left(\frac{\Delta t_{obs}}{690\,\mathrm{days}}\right)$$

If plasmoid continues its motion:

interaction with radio core ~ **July 2016**

MONITORING OF B2 0218+35 AT GAMMA RAYS



Preliminary