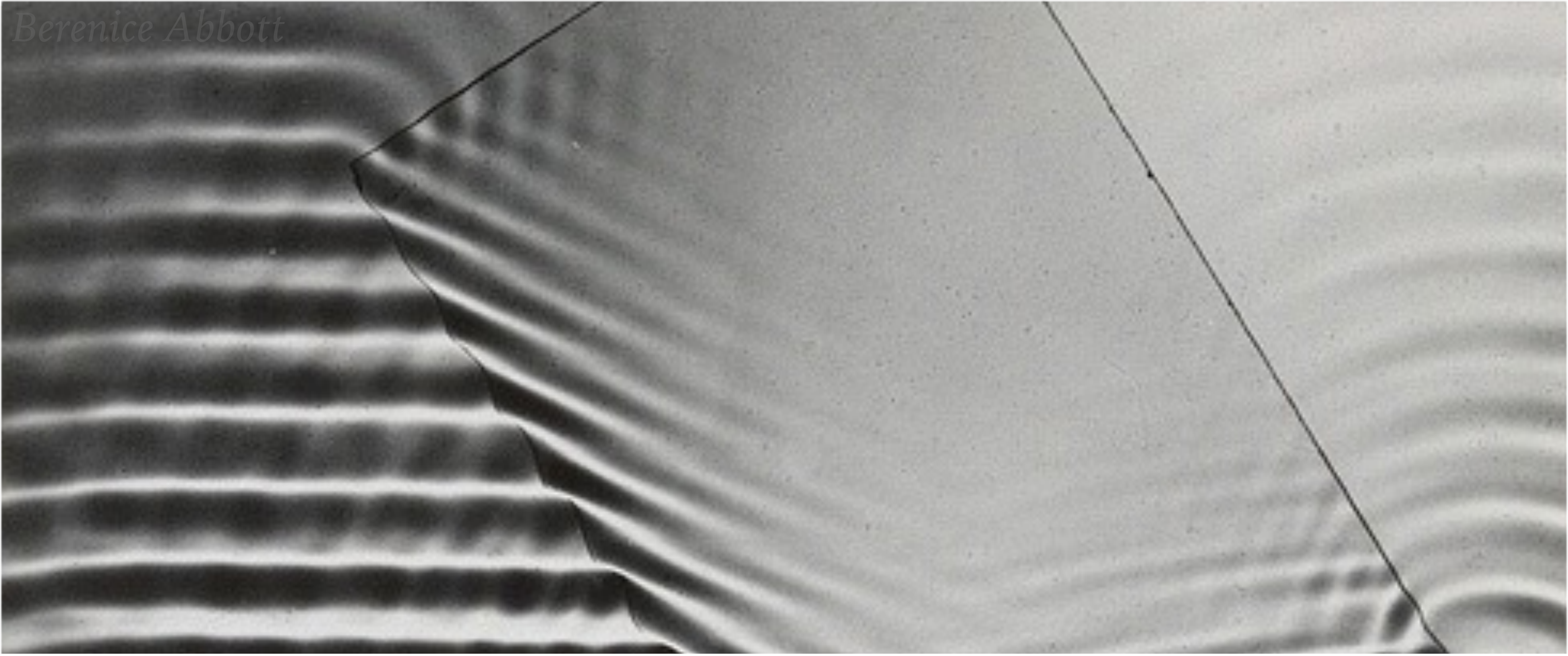
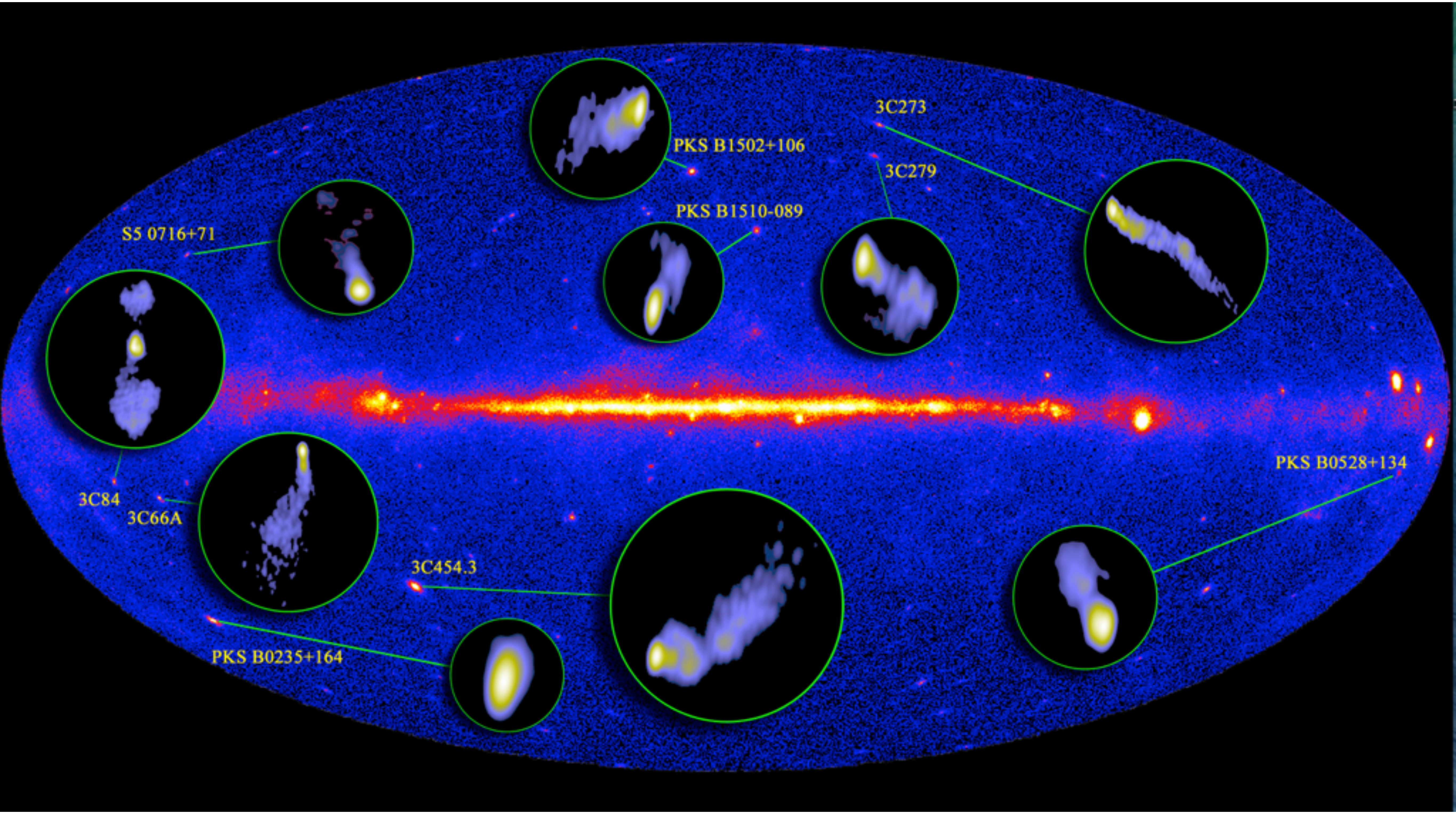


RESOLVING HIGH ENERGY UNIVERSE USING STRONG GRAVITATIONAL LENSING

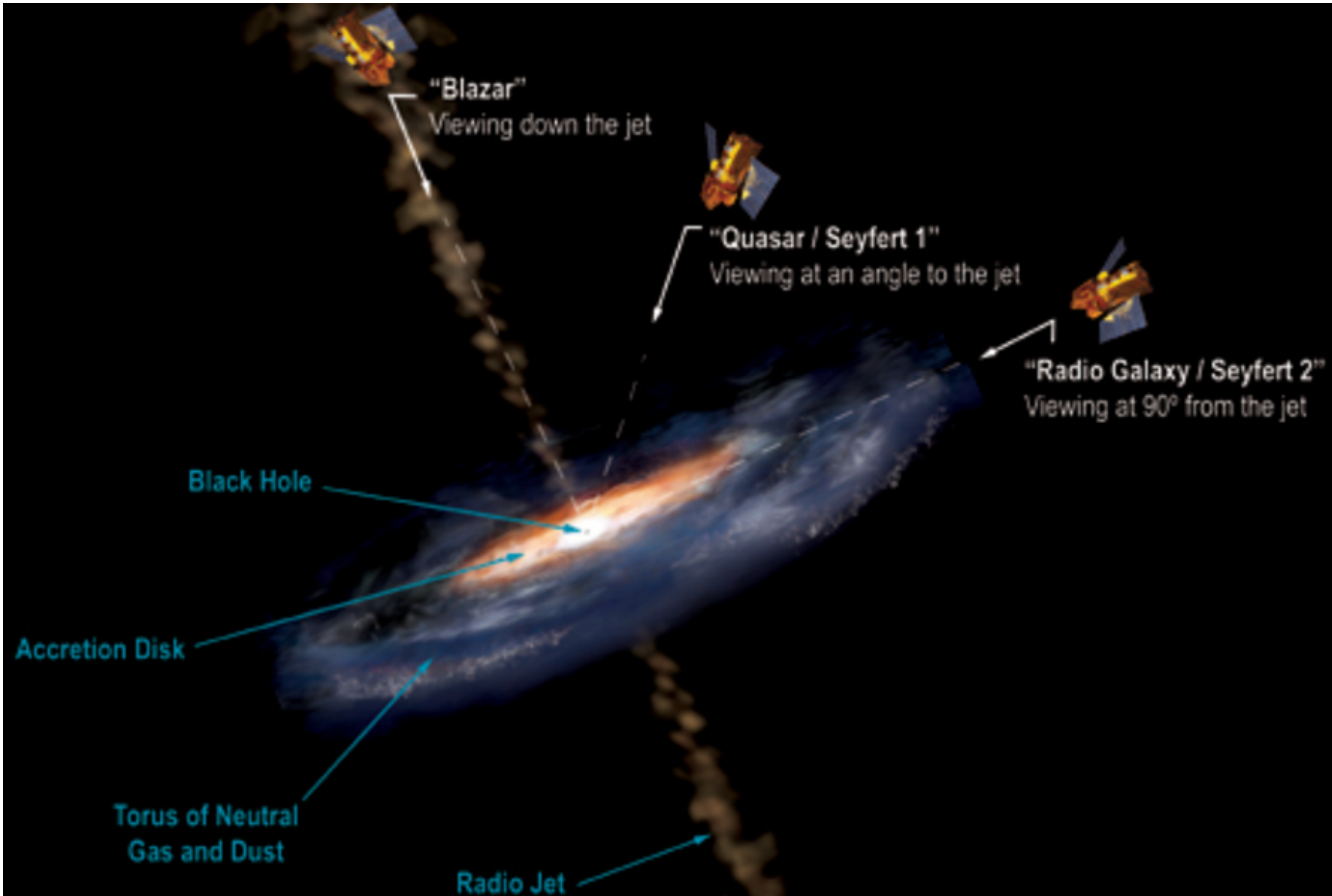
Anna Barnacka
Einstein Fellow at Harvard

GAMMA-RAY SKY

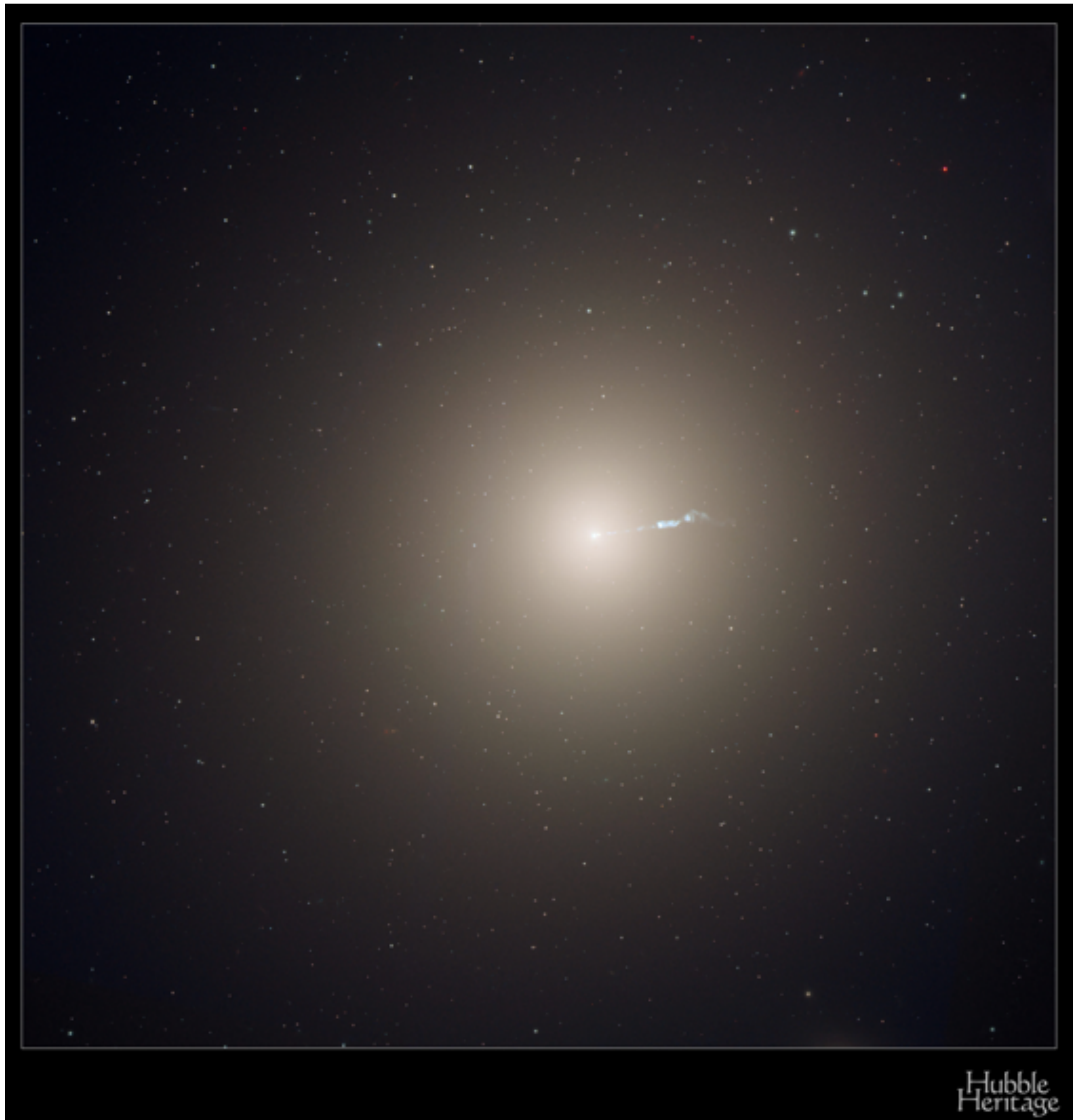


Credit: NASA/DOE/Fermi LAT Collaboration and NRAO/AUI/MOJAVE Team/M. Kadler

BLAZERS, QUASARS AND EXTRAGALACTIC JETS



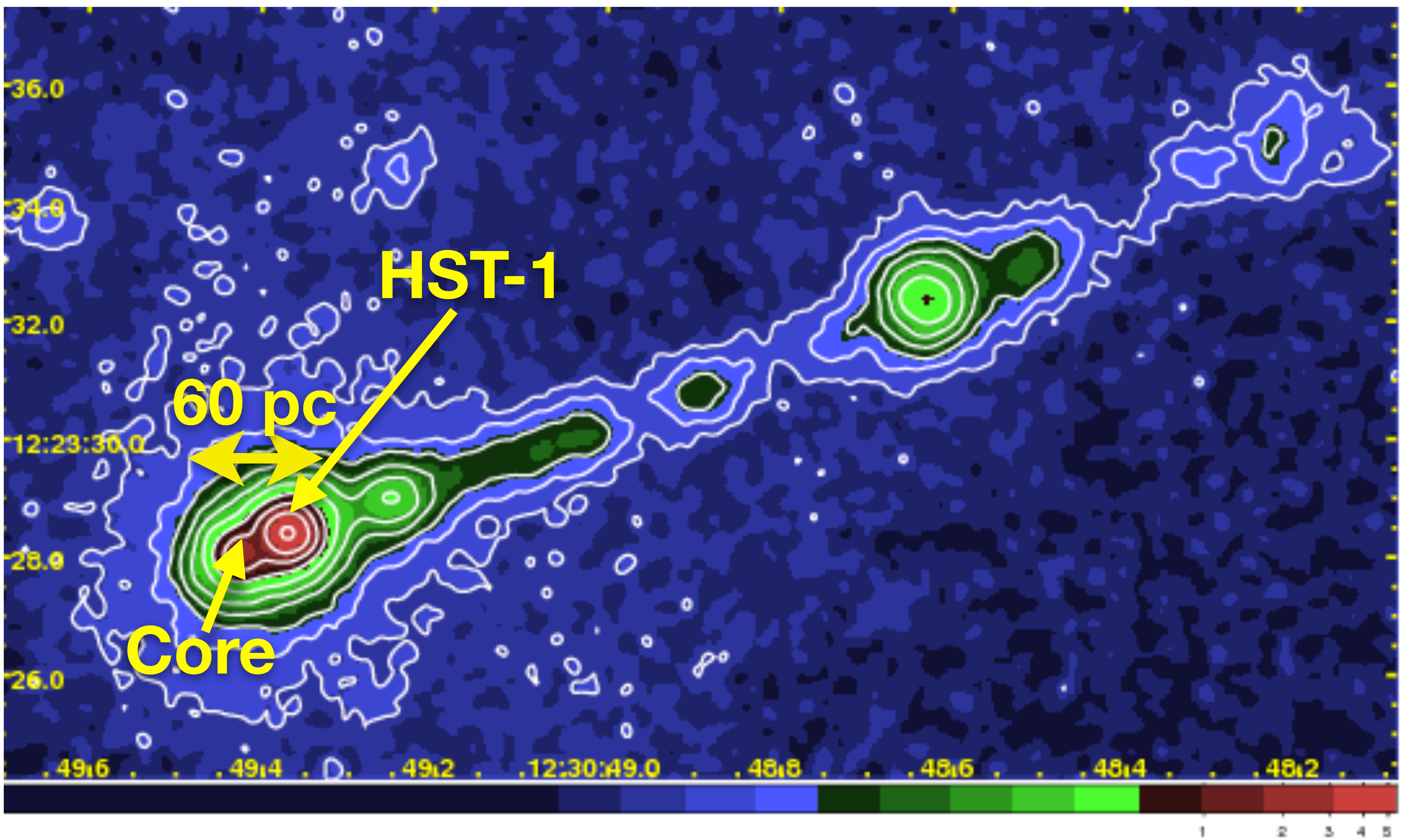
ELLIPTICAL GALAXY M87 – THE NEAREST EXTRAGALACTIC JET



EXTRAGALACTIC JETS – M87

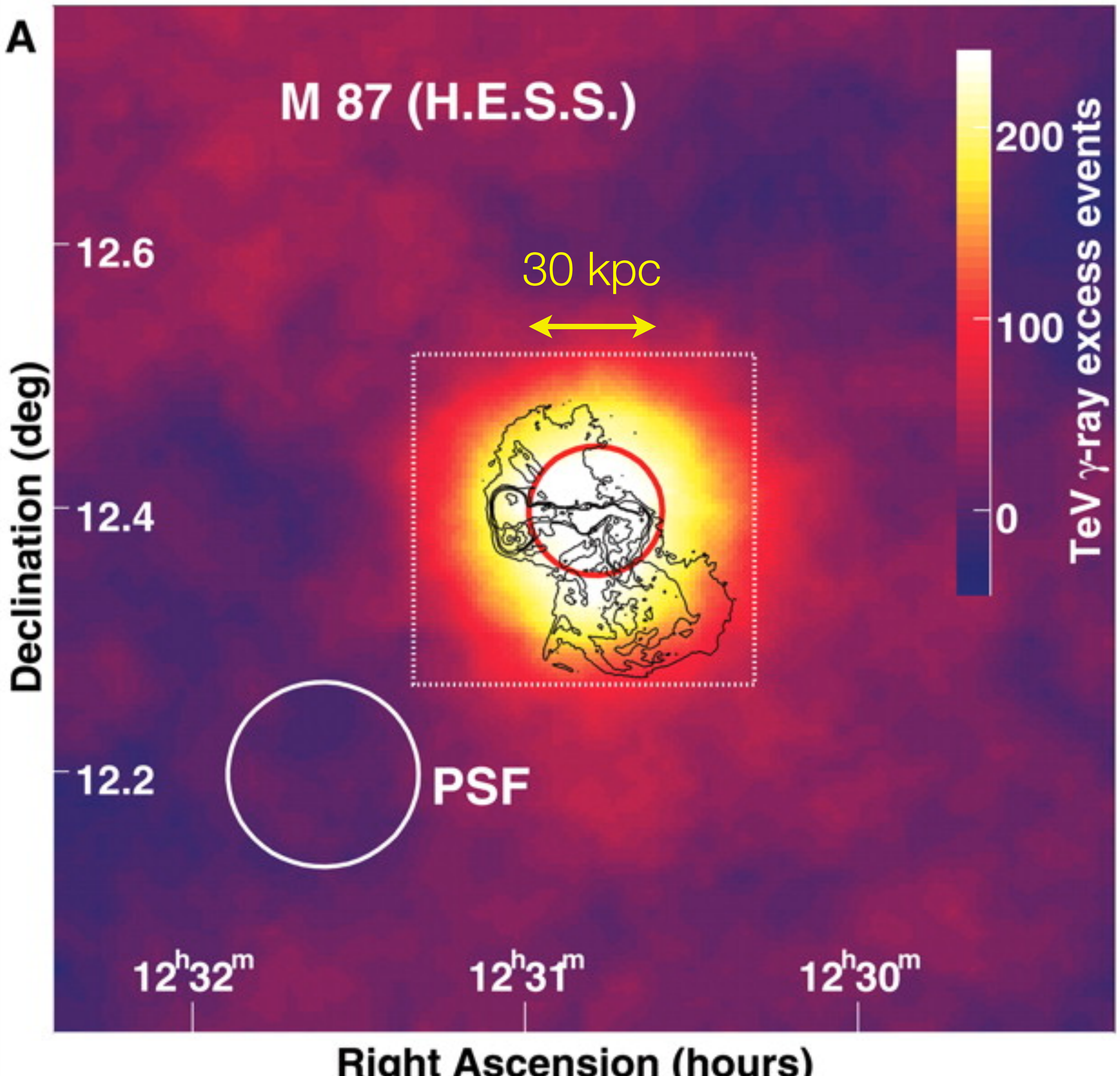
Increased x-ray emission by a factor of 50 from the HST-1 knot (Harris et al. 2006,2009)

Core and HST-1: Separation ~ 60 pc



Flares from knots along the jets

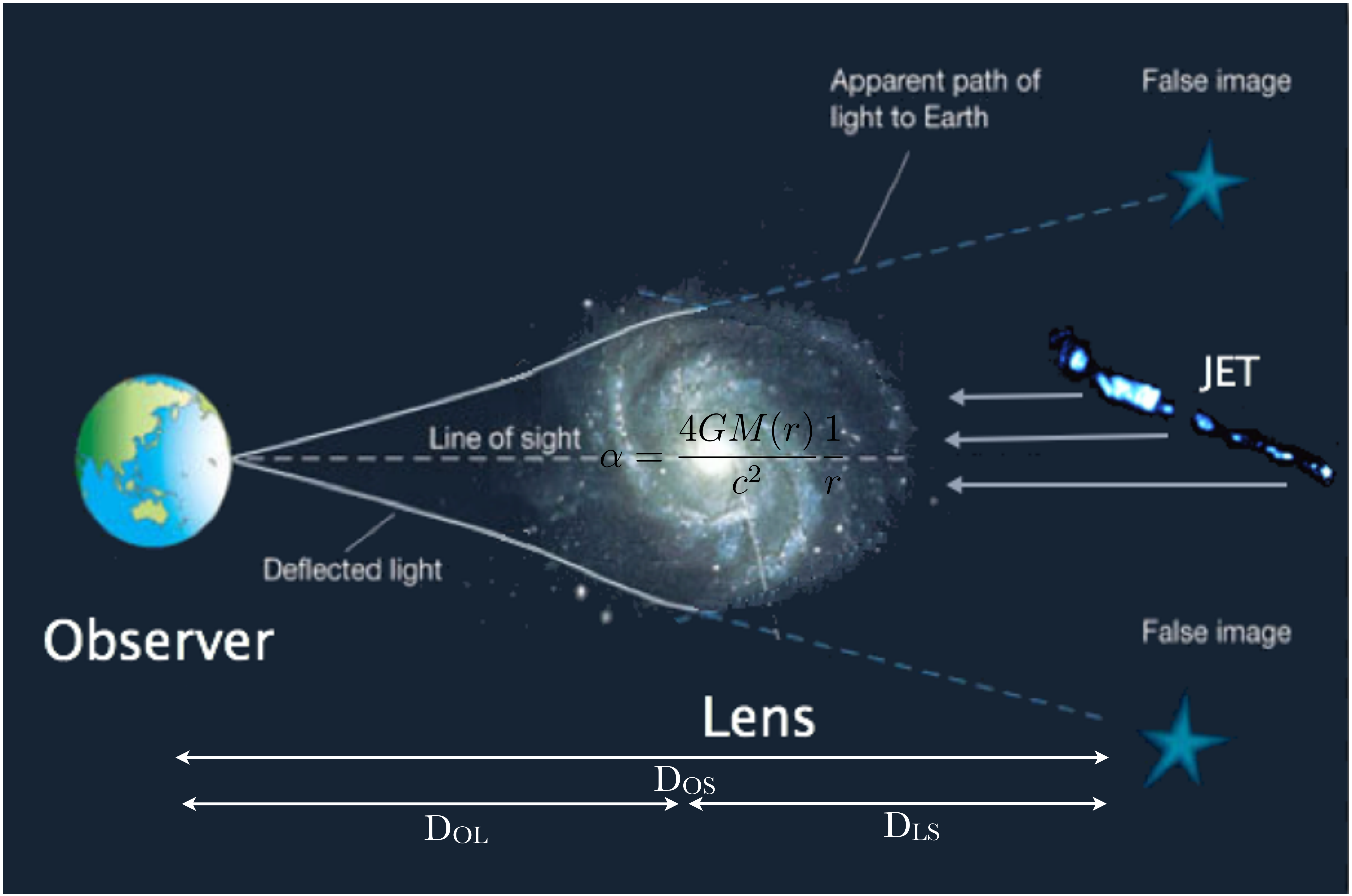
AMBIGUITY OF GAMMA-RAY ORIGIN



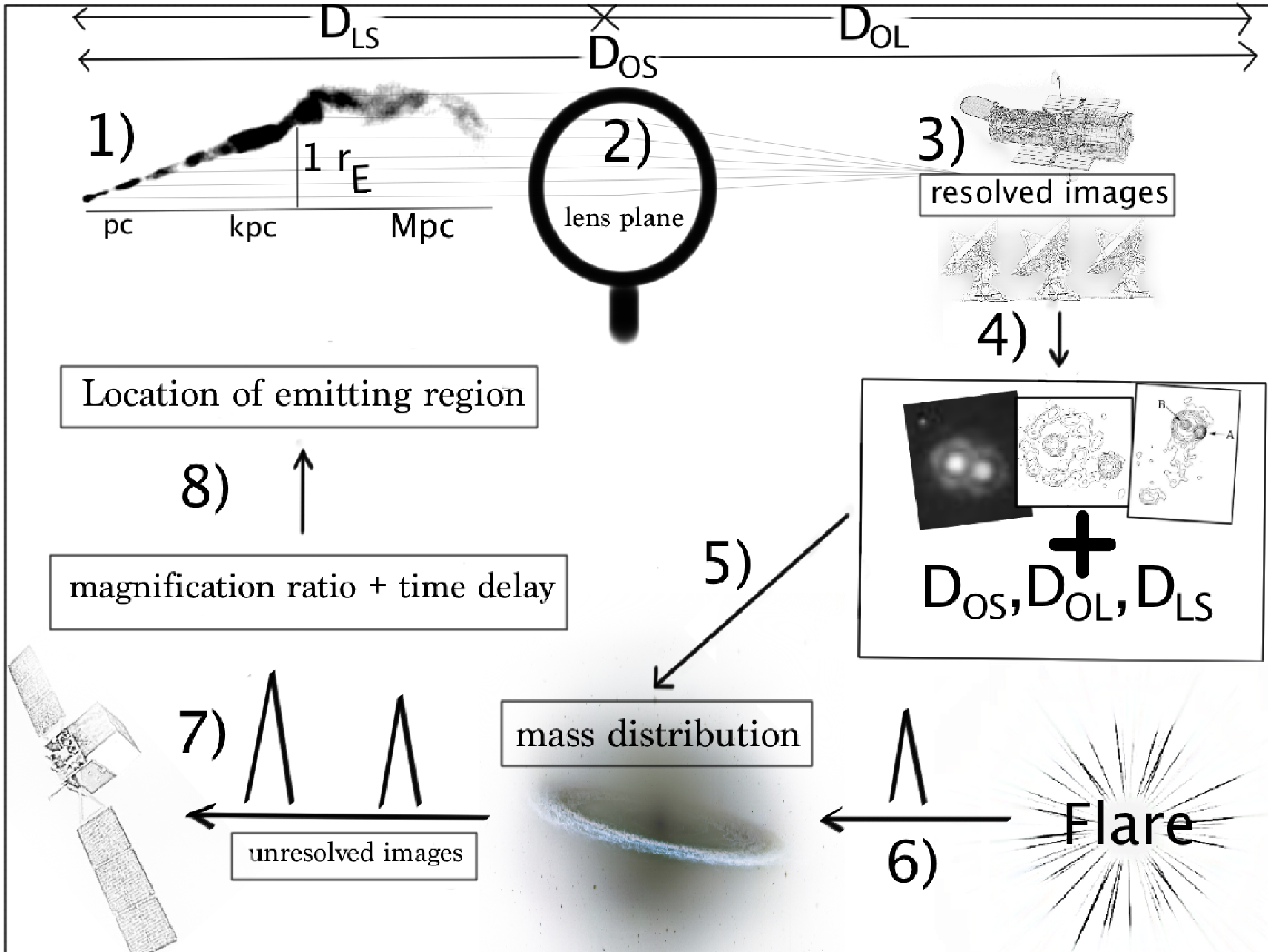
SCIENTIFIC CHALLENGES

- Frequency of M87-like variability
- Origin of gamma-ray flares

M87 Gravitationally Lensed?



APPLICATION OF STRONG GRAVITATIONAL LENSING



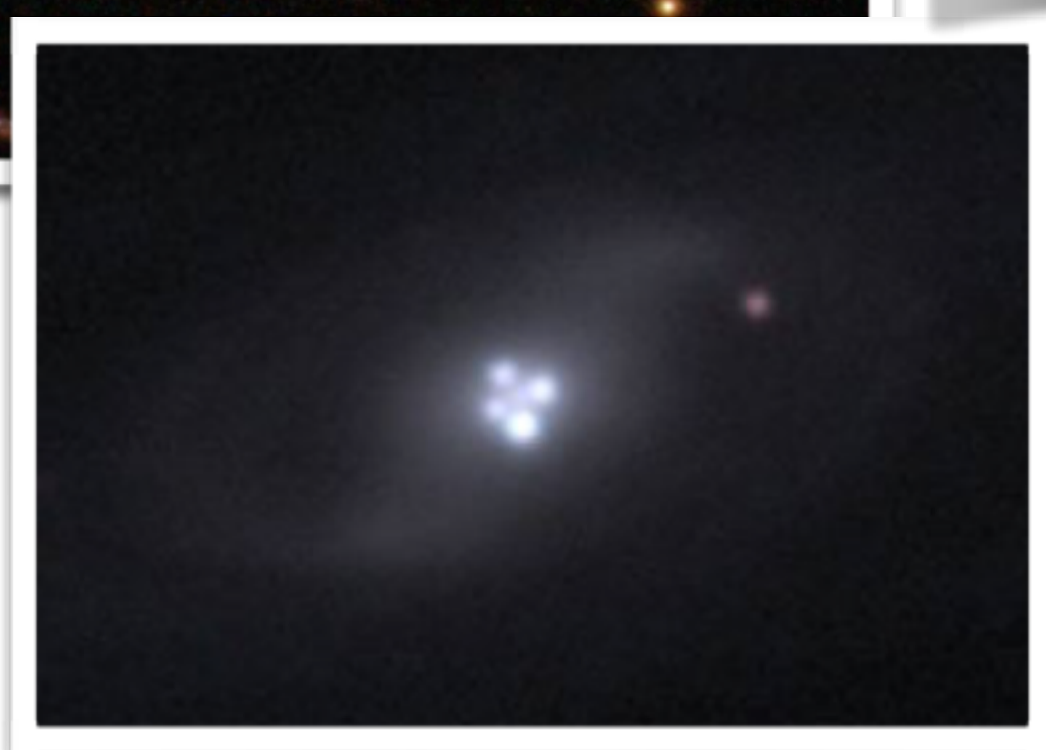
Barnacka, A., Geller, M., Dell'Antonio, I., & Benbow, W. (June 2014, ApJ)

M87 AT Z=1

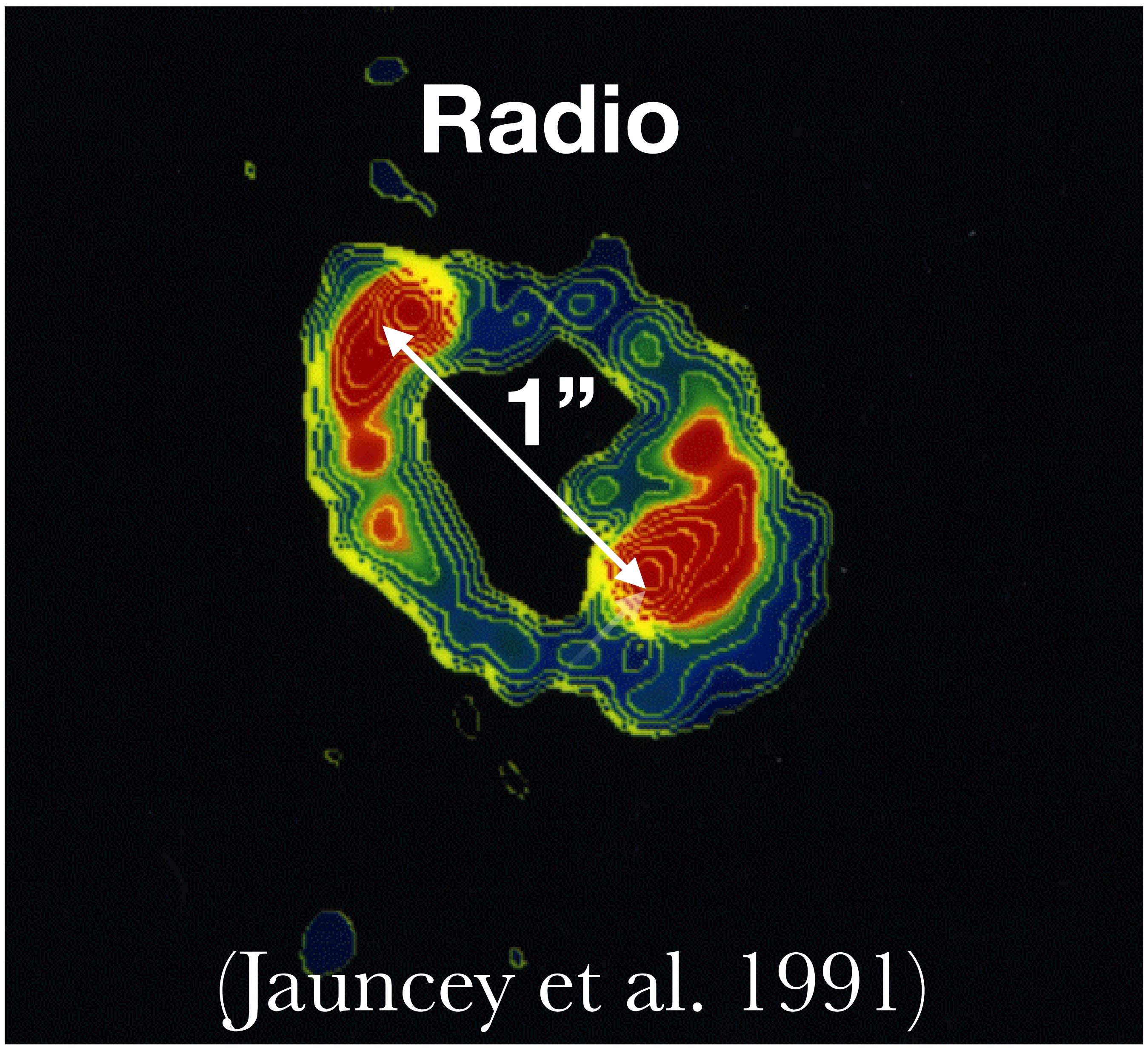
Differences between the ***core*** *and the* ***HST-1****:*

difference in time delay: ~ 2 days

Gravitational Lensing: Examples



Lensed Radio Jet: PKS 1830-211



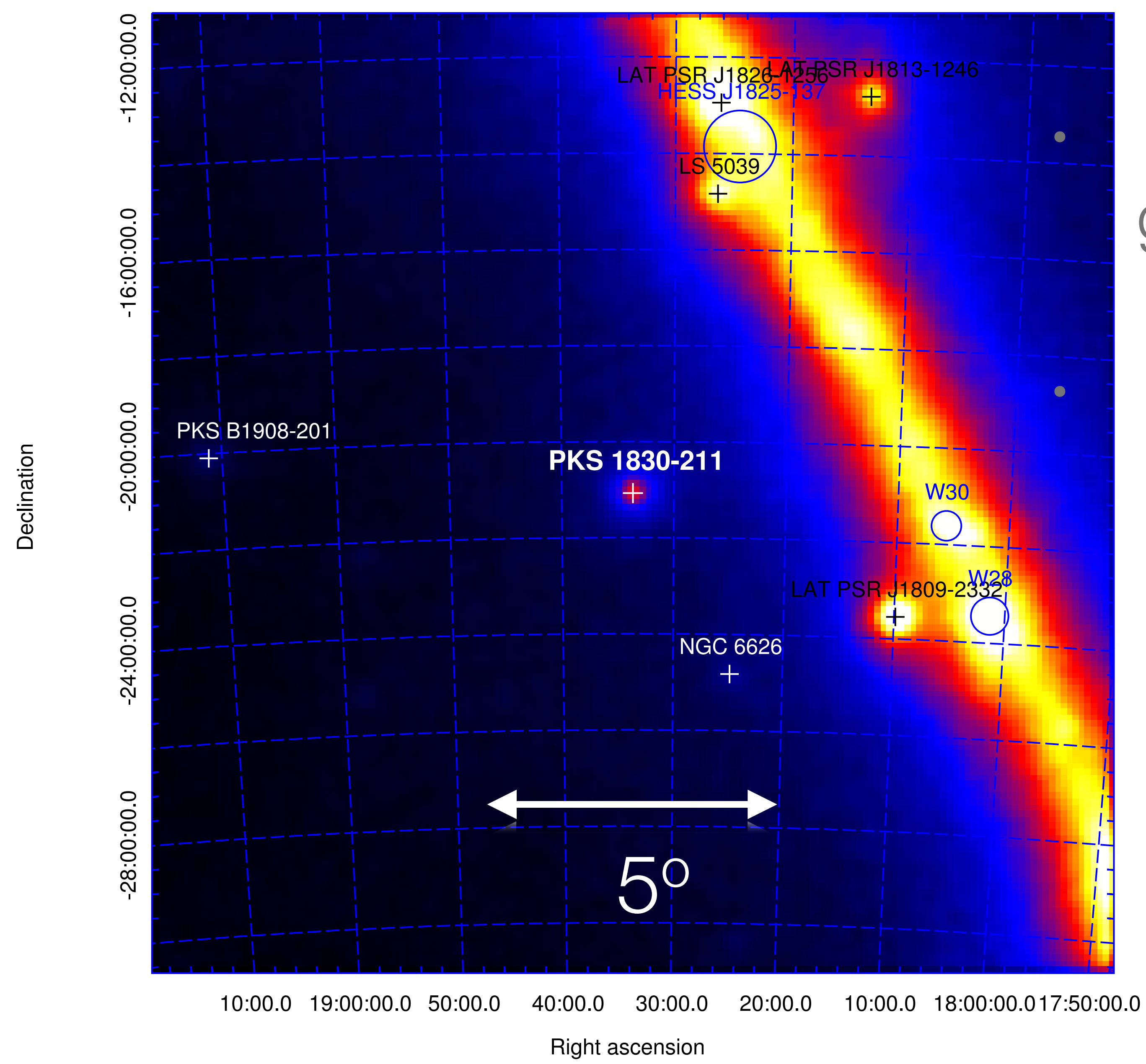
Source z = 2.5,
Lens z = 0.9

Radio Time Delay
26±5 days

Magnification Ratio
1.52±0.05

(Lovell et al. 1998)

Lensed Gamma-Ray Jet: PKS 1830-211

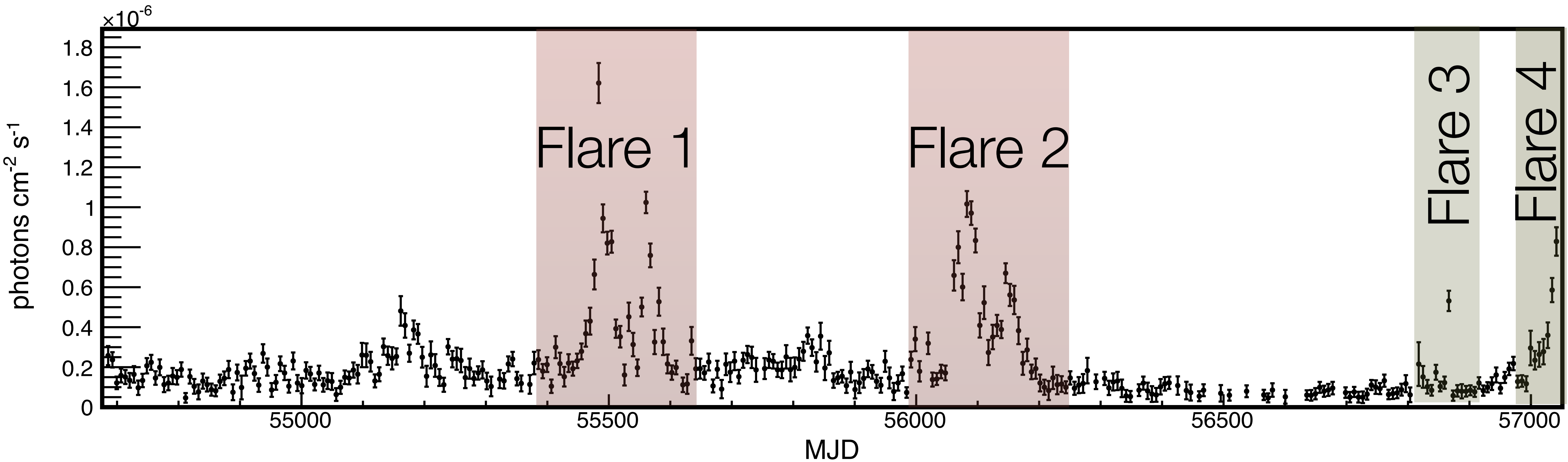


The first evidence of lensing at gamma-rays (Barnacka et al. 2011)

Time Delay = 27±0.5 days

Gamma-ray Flares
Time Delays ?

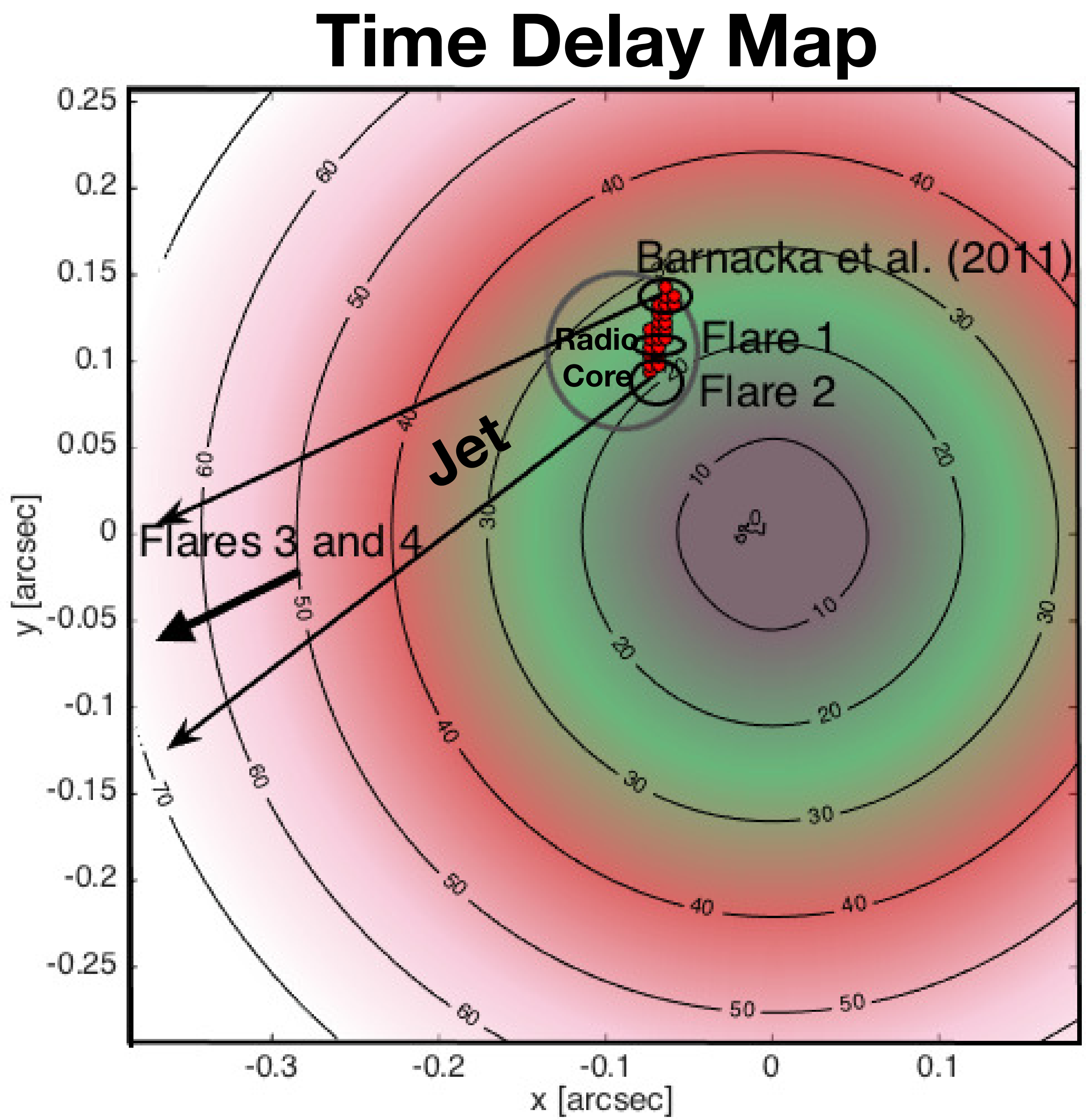
Gamma-ray Flares: Time Delays



23±0.5 days 19.7±1.2 days > 50 days

Barnacka, A., et al. (2015, ApJ, 809, 100)

Spatial Origin of Gamma-ray Flares

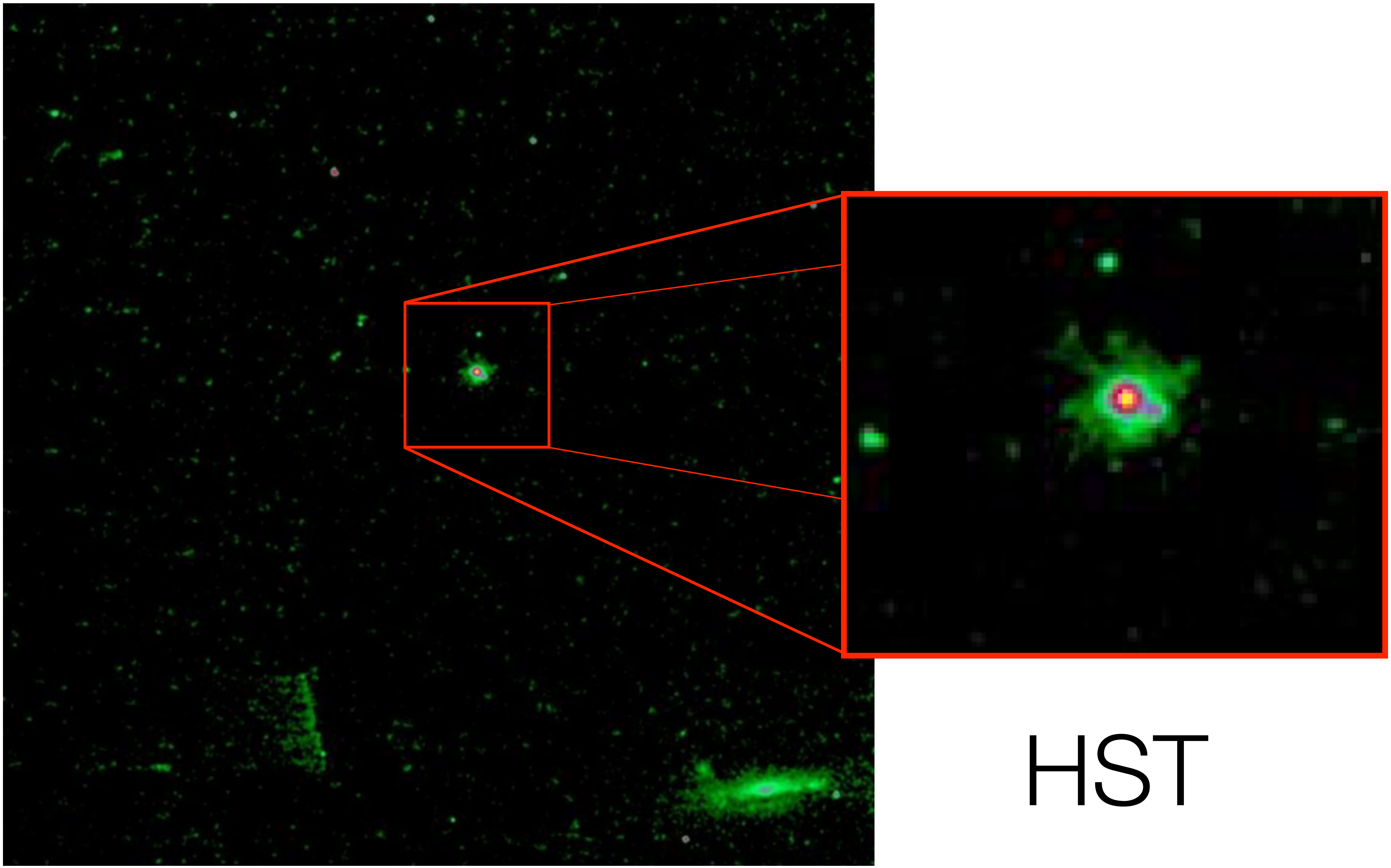


Barnacka, A., et al. (2015, ApJ, 809, 100)

Gamma-ray Spatial Resolution

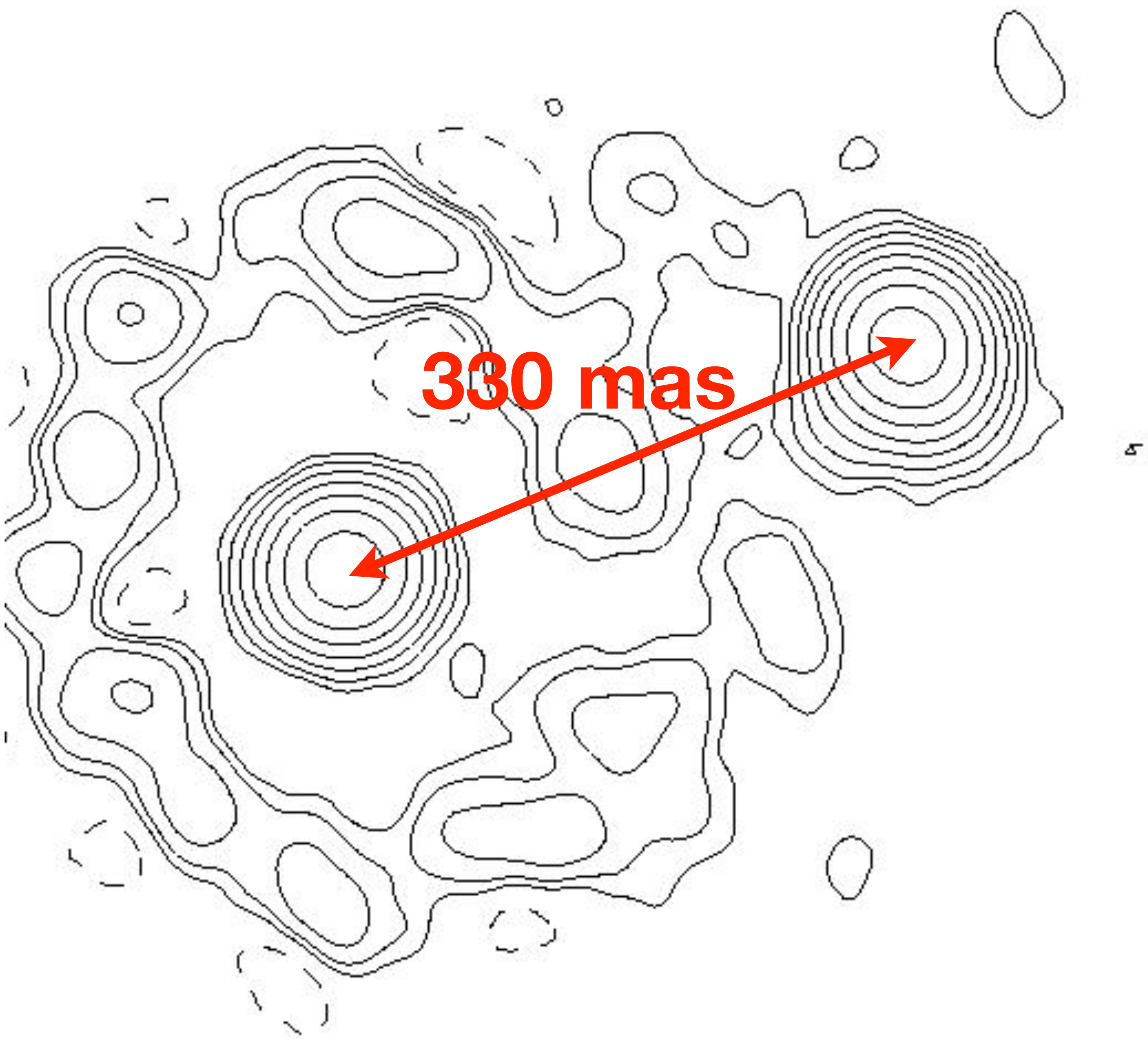
- **PKS 1830-211: Effective Spatial Resolution ~ 0.02” (~ HST)**
- **What if we could resolve gamma-ray emission with resolution of radio telescopes: ~0.001”?**

OBSERVATIONS: B2 0218+35



HST

LENSED BLAZAR: B2 0218+35



1.687 GHz, Patnaik et al. (1992)

Source z = 0.944,

Lens z = 0.6847

Radio Time Delay

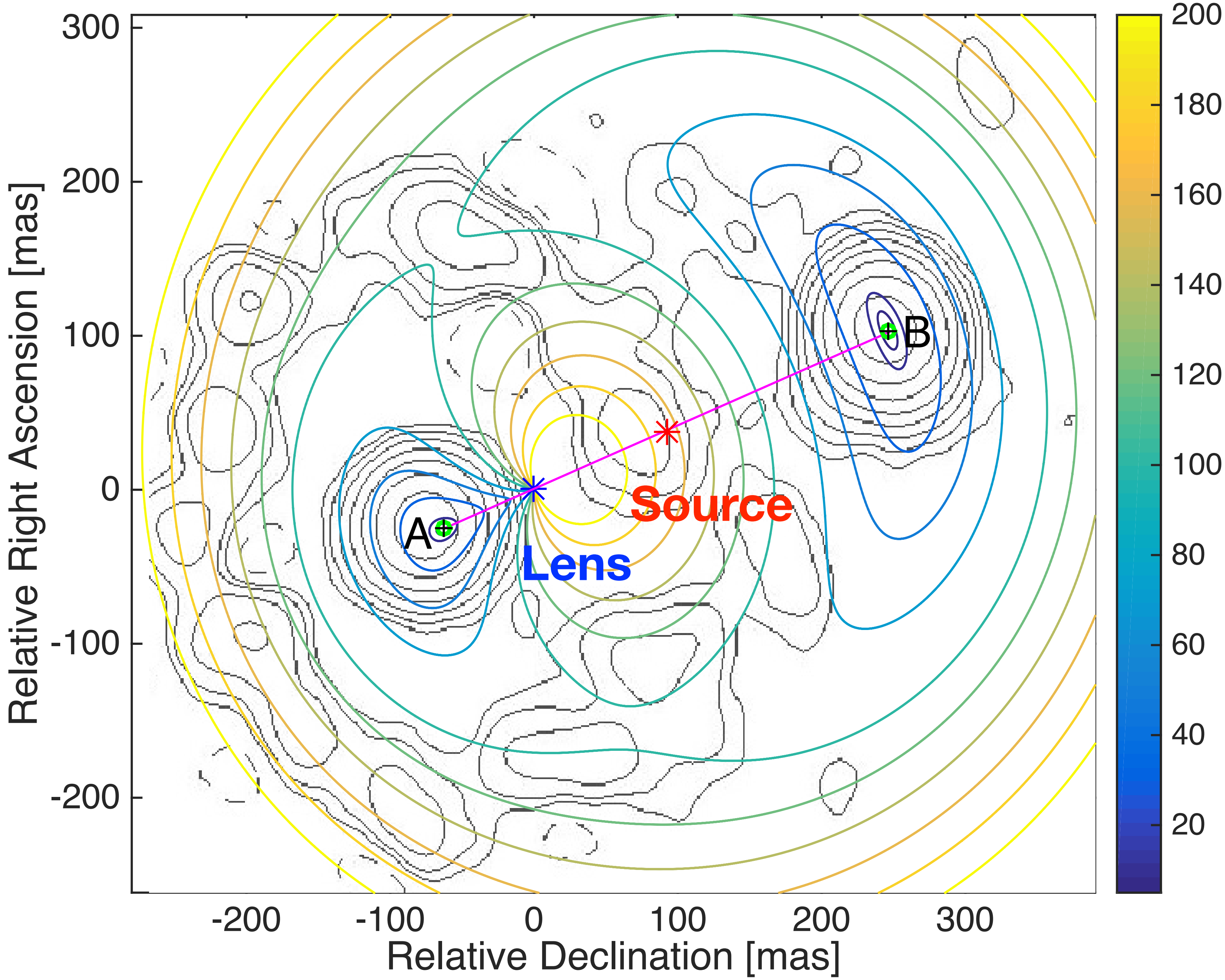
10.5±0.5 days

Magnification Ratio

3.62±0.06

Radial Jet Projection

LENS MODELING

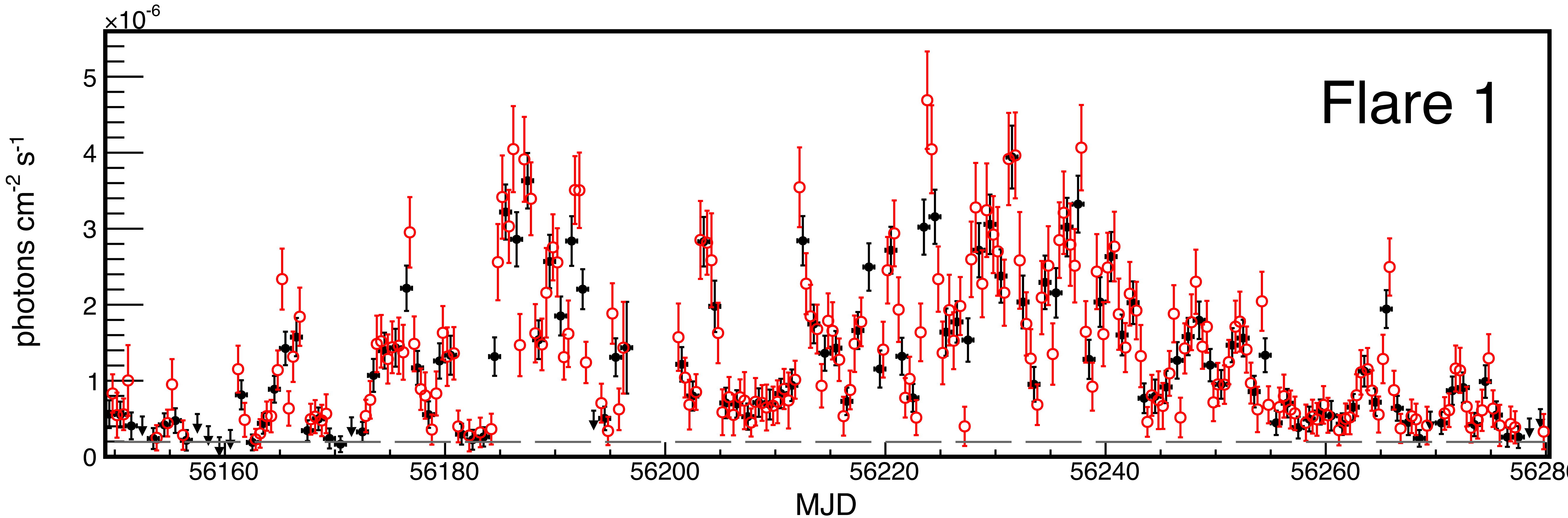


Reconstruction

~ 1 milliarcsecond

Barnacka et al. 2016, ApJ, 821, 58

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., Geller, M., Dell'Antonio, I., & Benbow, W. (2015,ApJ,799,48)

THE HUBBLE PARAMETER TUNING APPROACH

The Hubble parameter enters into distance ratio in the time delay calculation:

$$D \equiv \frac{D_{OL} D_{OS}}{D_{LS}} = hd$$

where: $\mathrm{H}_0 = h \times 100\,\mathrm{km\,s^{-1}Mpc^{-1}}$

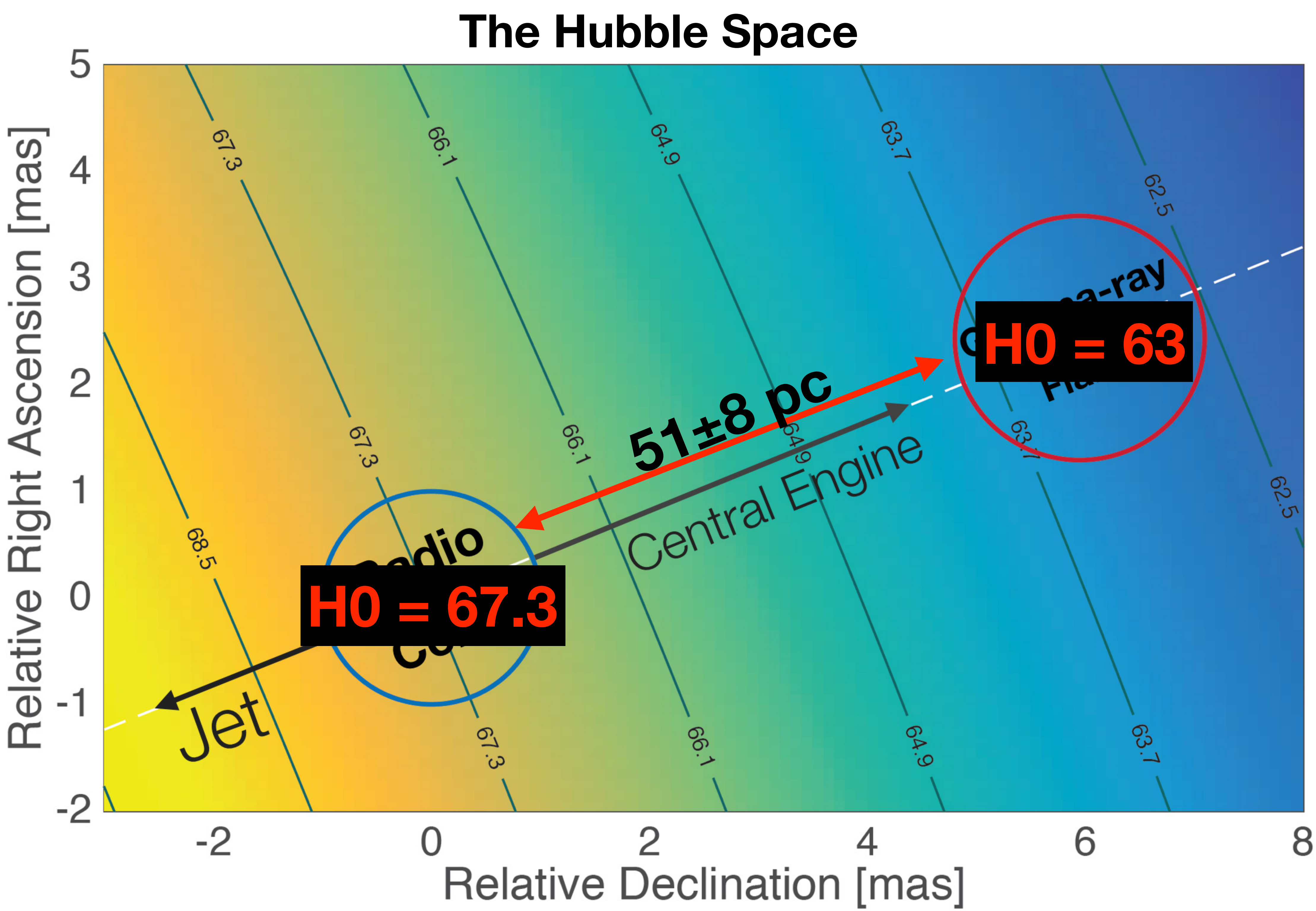
For an Singular Isothermal Sphere gravitational potential :

Mirage Image B *Mirage Image A*

$$h = \frac{d(1+z_L)(\theta_B^2 - \theta_A^2)}{2c\,\Delta t}$$

Time Delay between mirage image A and B

HUBBLE CONSTANT & GAMMA-RAY SOURCE CONNECTION



Barnacka et al. 2016, ApJ, 821, 58

THE TOOLS

- Radio:
  - Excellent Angular Resolution
- Gamma Rays:
  - Excellent Temporal Resolution
- Hubble Parameter:
  - Cosmic Scale
- Gravitational Lensing:
  - **Combines the Above**

THE RESULTS

- Multiple Time Delays from single source
- Spatial Resolution at Gamma Rays:
  - ~1 milliarcsecond
- Gamma-ray Flares not from Radio Core
- Radio Core not at Supermassive Black Hole
- Future: LSST, SKA, Euclid