Resolving the High Energy Universe with Strong Gravitational Lensing

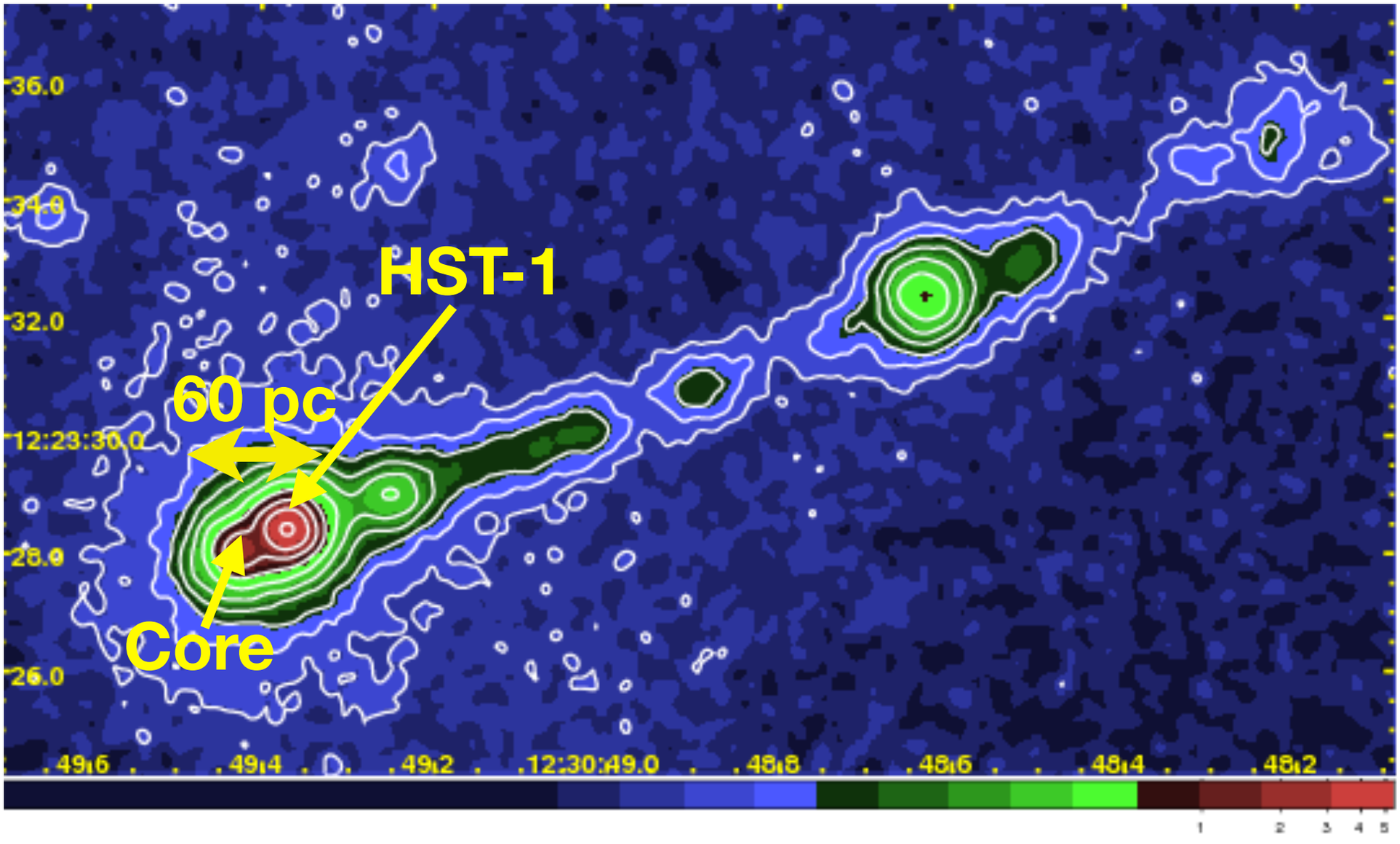
Anna Barnacka

Harvard

X-Ray Jets - Lessons from Chandra

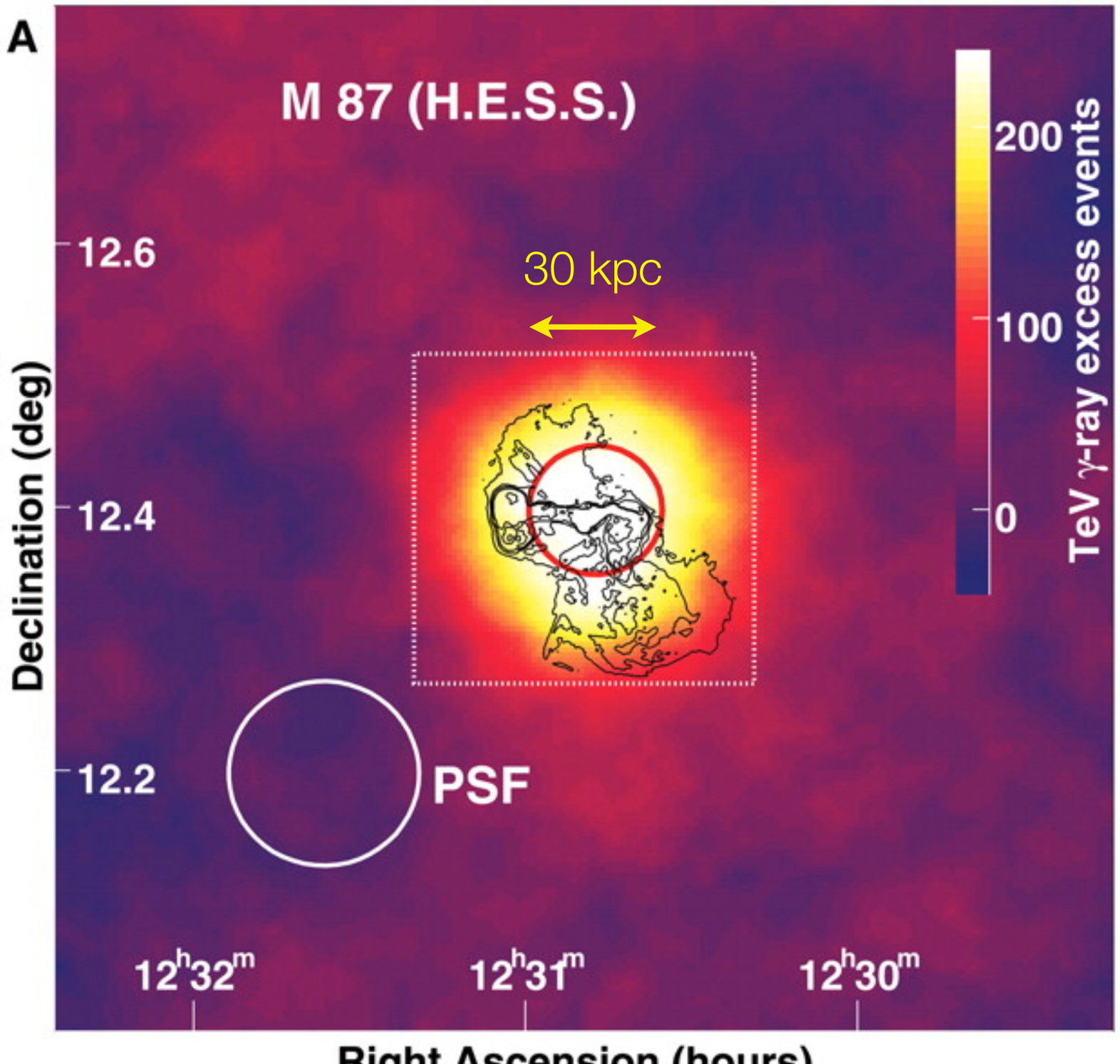
Increased x-ray emission by a factor of 50 from the HST-1 knot (Harris et al. 2006,2009)

Core and HST-1: Separation ~ 60 pc



Flares from knots along the jets

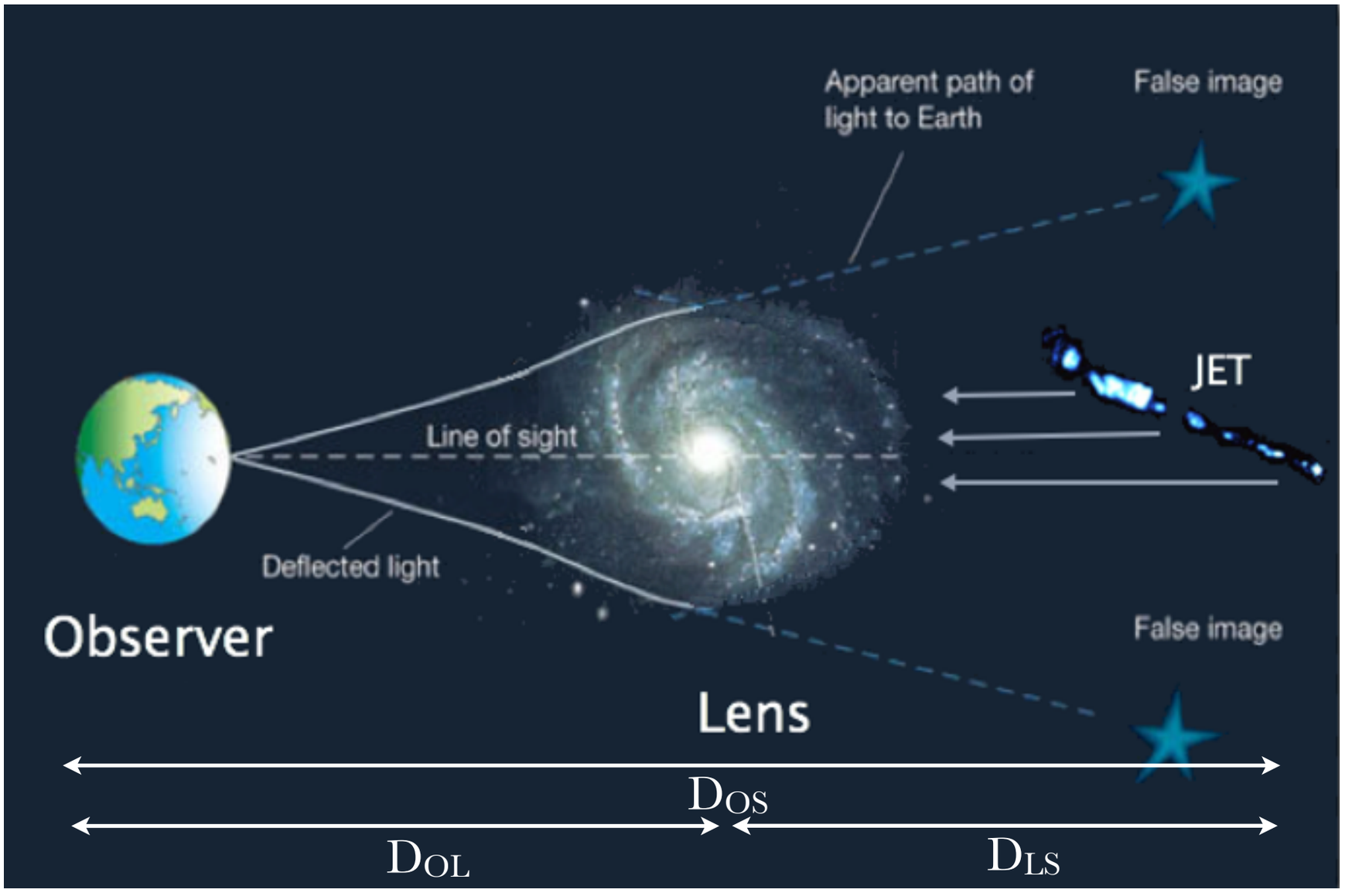
Ambiguity of Gamma-Ray Origin



Scientific Issues

- Frequency of M87-like variability
- Structure of gamma-ray jets
- Spatial origin of gamma-ray flares

M87 Gravitationally Lensed?



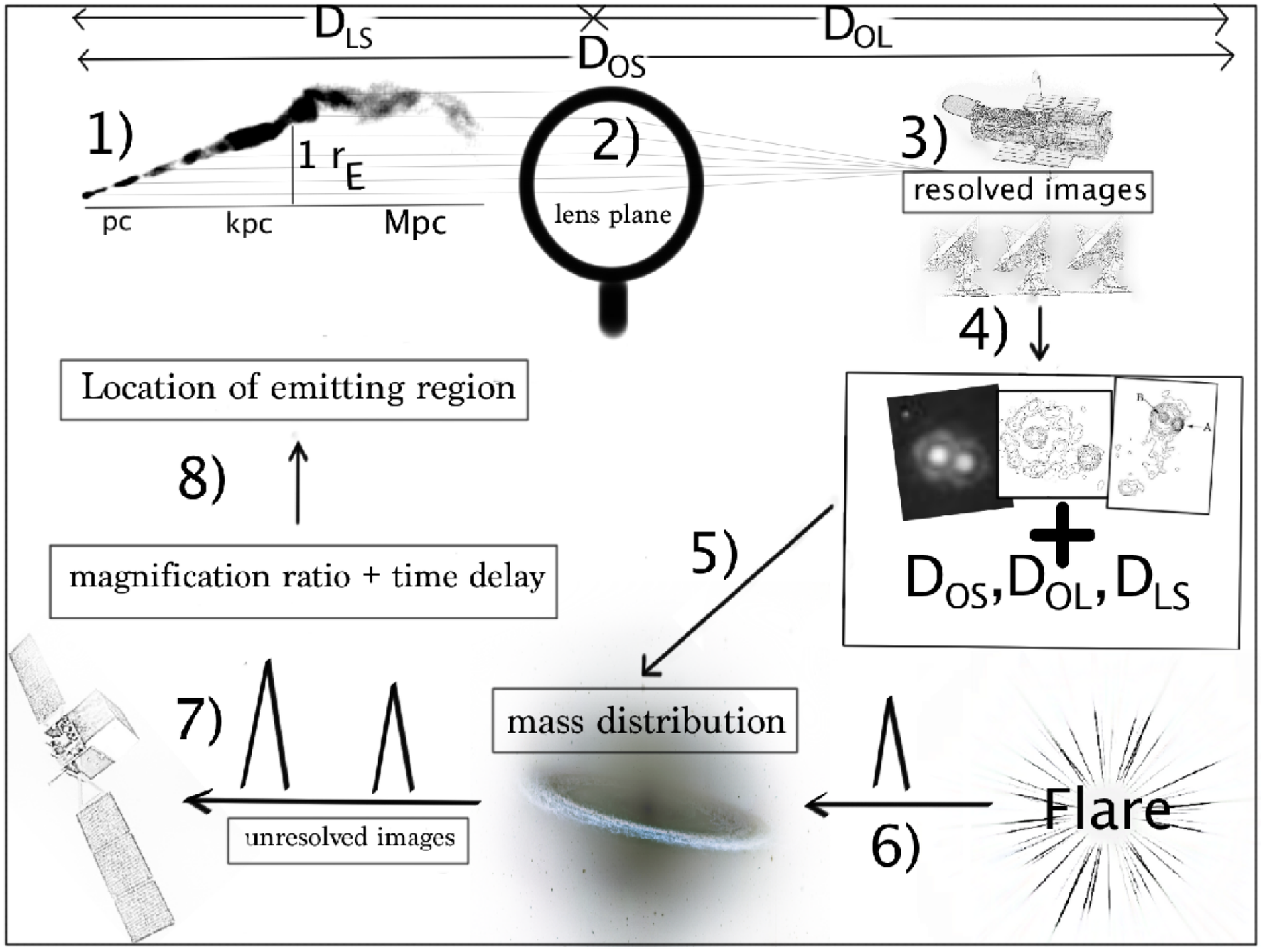
Deflection angle:

$$\alpha = \frac{4GM(r)}{c^2}\frac{1}{r}$$

Images separation - a few arcseconds

time delay magnification ratio

Application of strong lensing



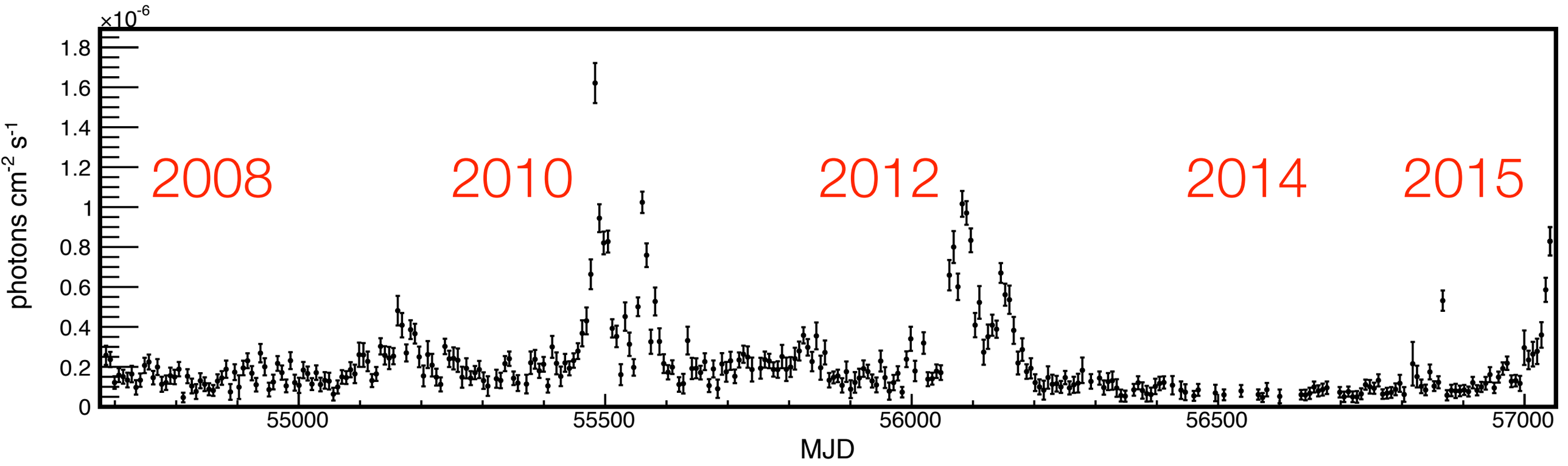
Barnacka, A., Geller, M., Dell'Antonio, I., & Benbow, W. (June 2014, ApJ)

M87 as a Toy Model

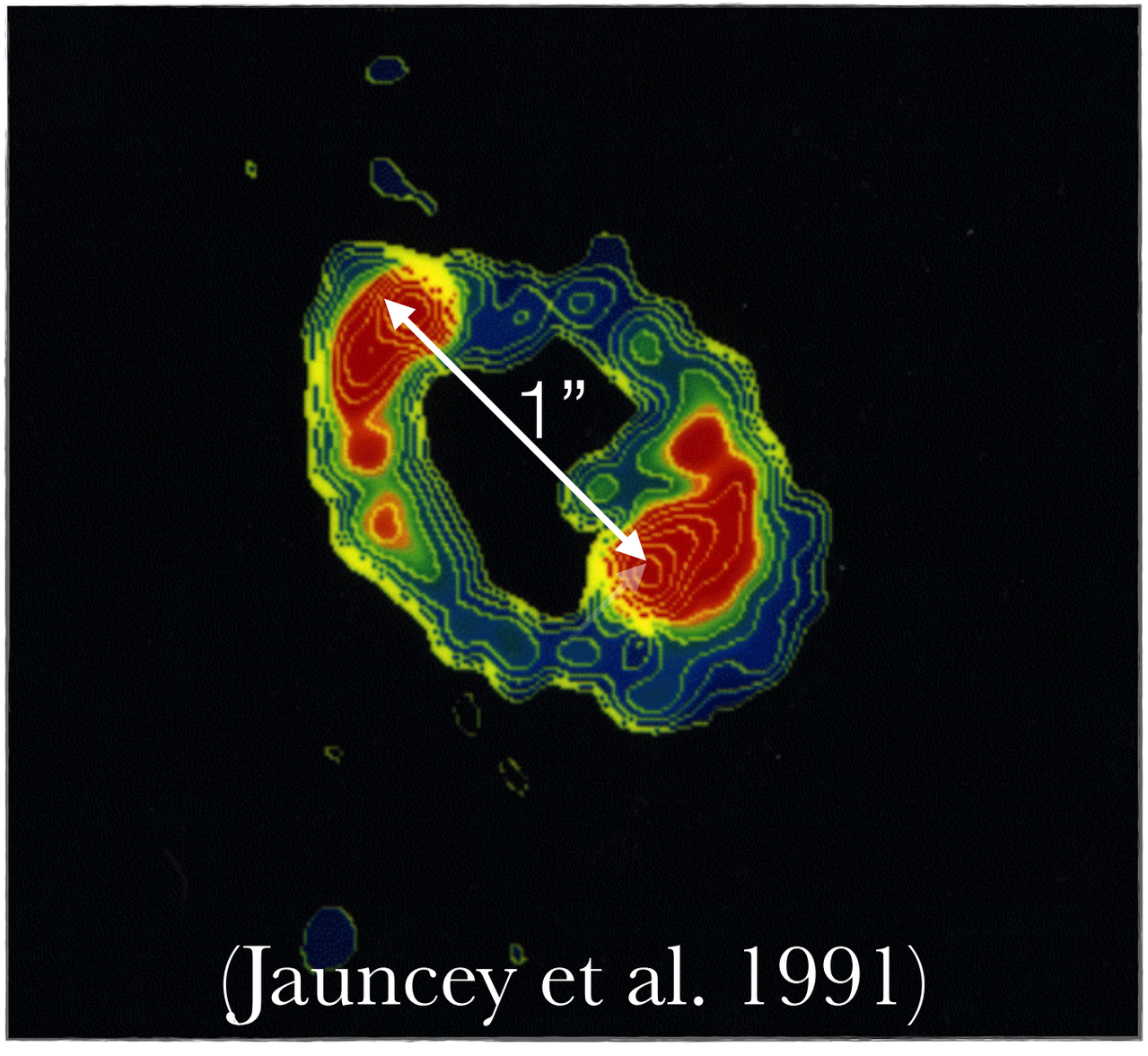
- zs=1, zl = 0.6
- Einstein radius ~ 2.2 kpc (0.45”)
- 60 pc ~ 0.01” ~ 3% Einstein radius
- Differences between the **core** and the **HST-1**:
  - **difference in time delay: ~ 2 days**
  - **difference in magnification ratio: ~ 0.2**

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

Temporal Resolution at Gamma Rays



Lensed Gamma-Ray Jets: PKS 1830-211

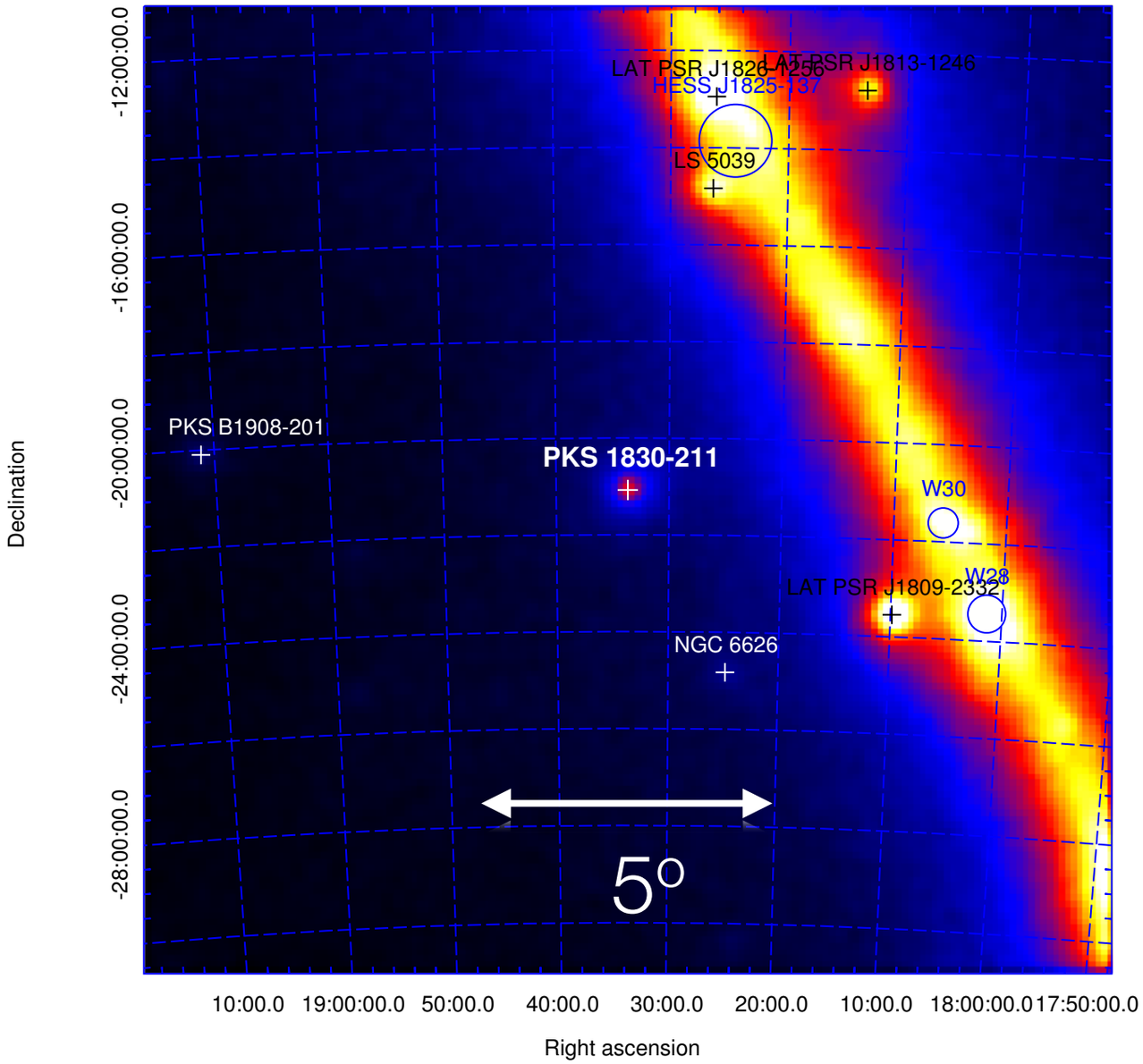


Source z = 2.5,
Lens z = 0.9

Radio Time Delay
26±5 days

Magnification Ratio
1.5±0.2

Lensed Gamma-Ray Jets: PKS 1830-211

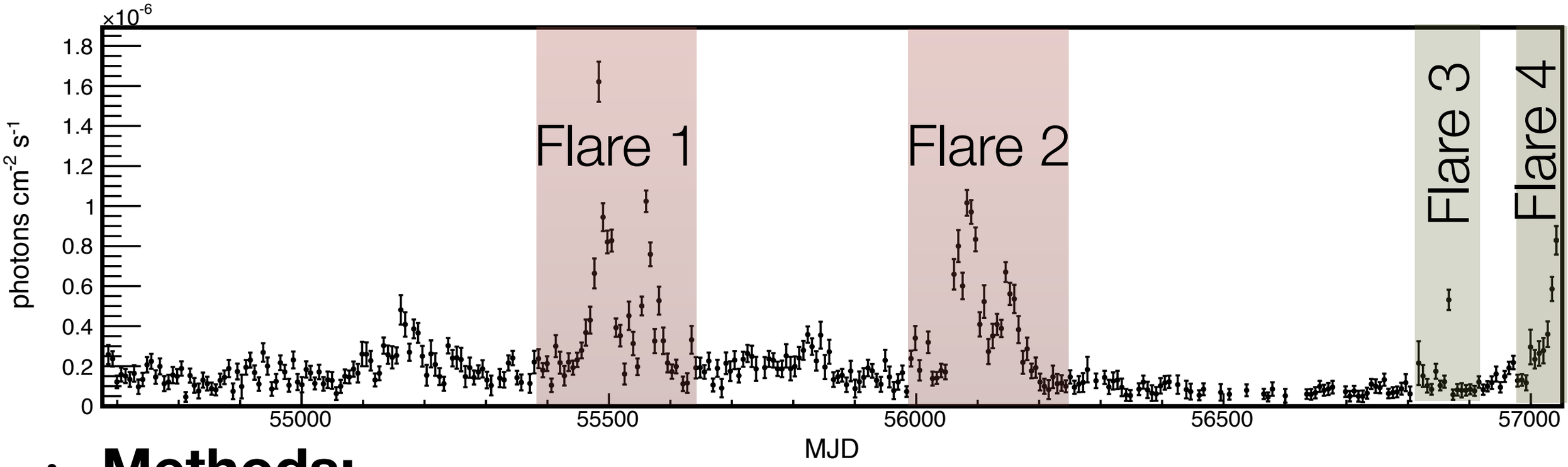


- The first evidence of lensing at gamma-rays (Barnacka et al. 2011)

Gamma-Ray Time delay 27.1±0.45 days

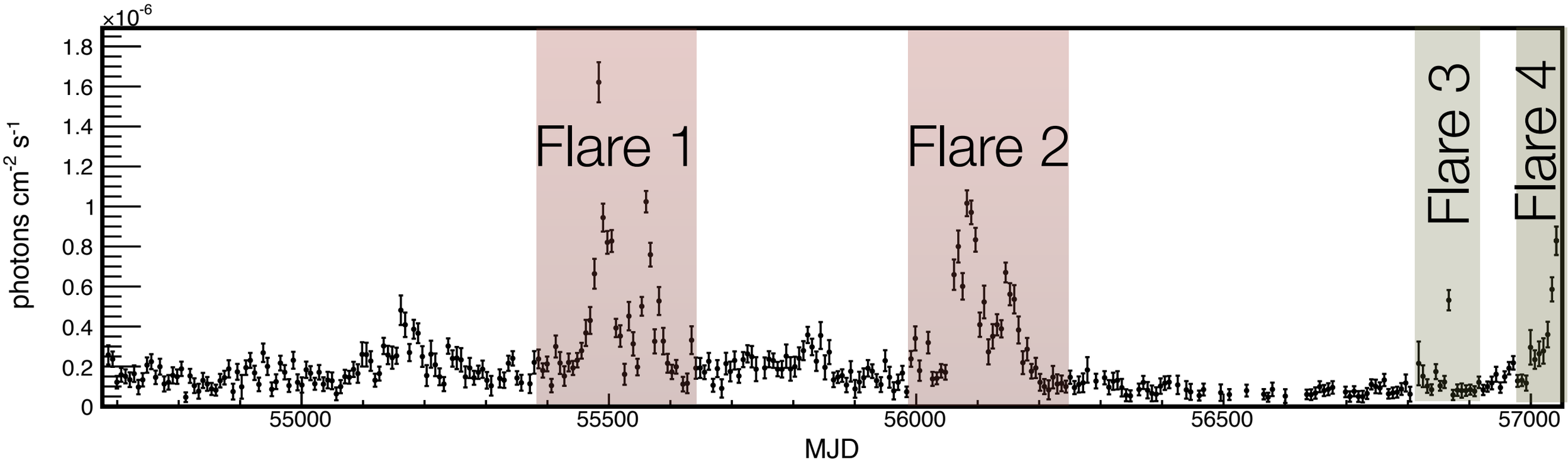
Gamma-ray Flares Time Delays ?

Gamma-ray Flares: Time Delays



- **Methods:**
  - The Autocorrelation Function
  - The Double Power Spectrum
  - The Maximum Peak Method

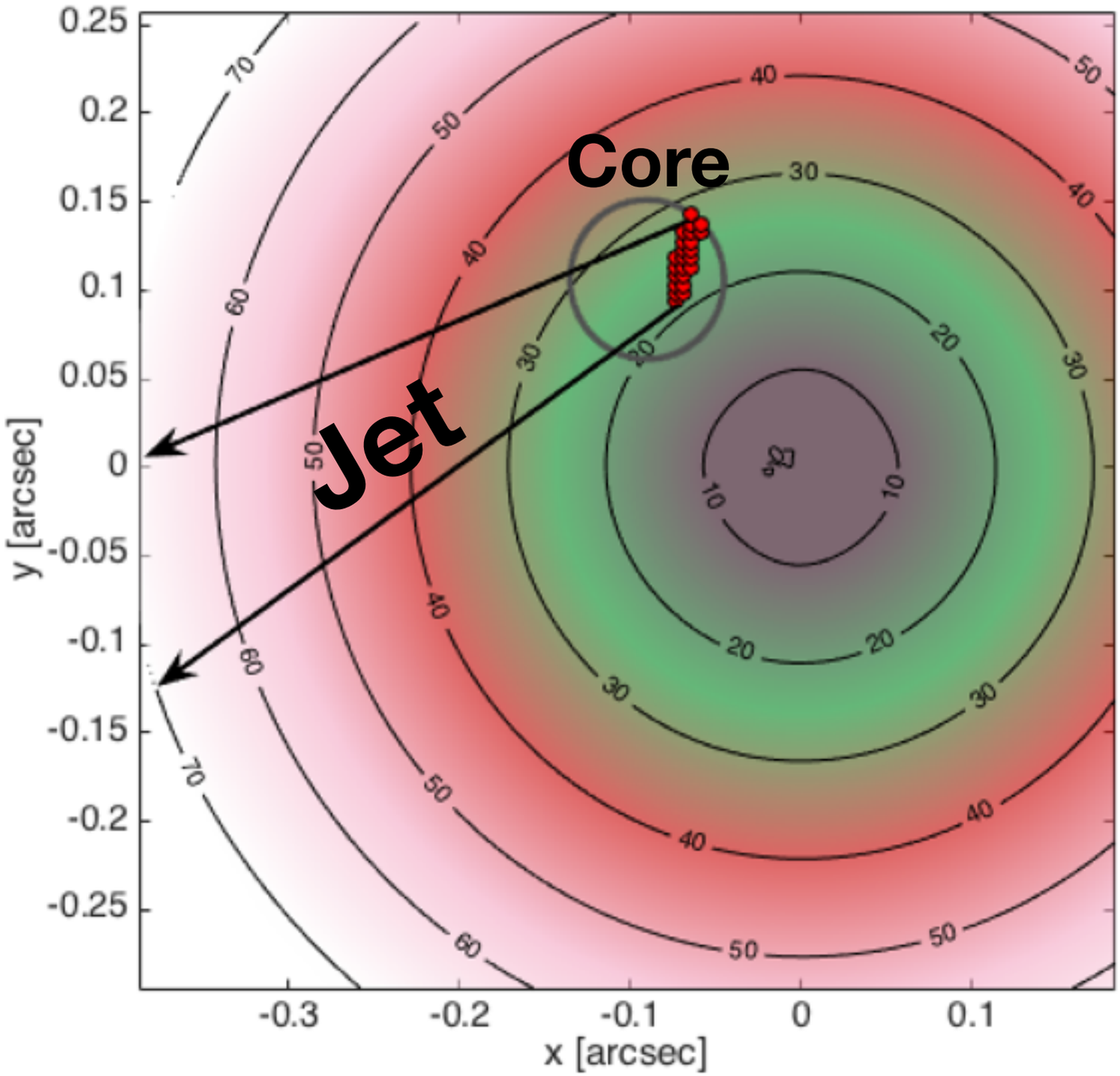
Gamma-ray Flares: Time Delays



23±0.5 days **19±1.2 days** **> 50 days**

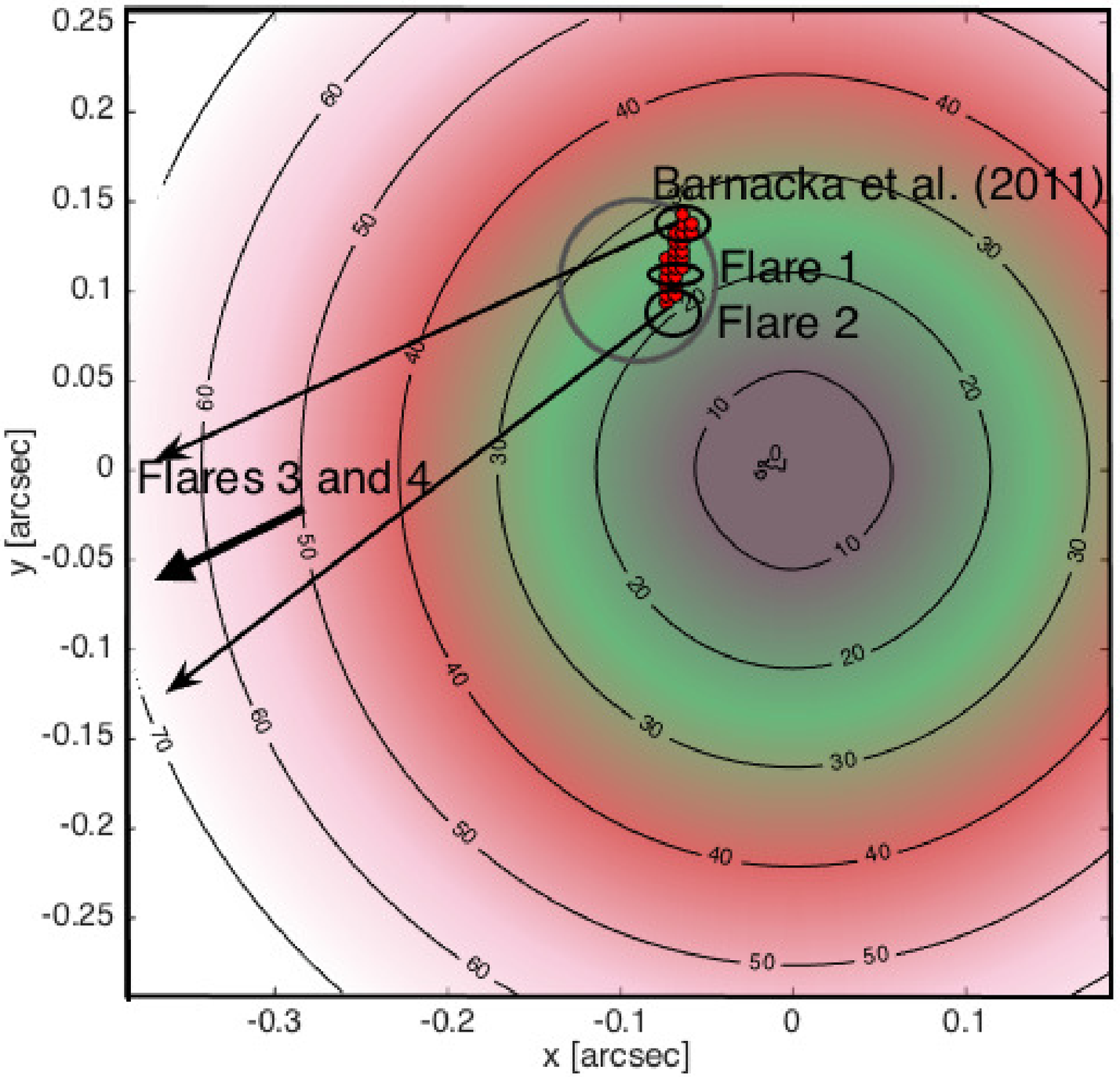
Barnacka, A., Geller, M., Dell'Antonio, I., & Benbow, W. (2015)

Properties of the Lensed System



Barnacka, A., Geller, M., Dell'Antonio, I., & Benbow, W. (2015)

Spatial Origin of Gamma-ray Flares



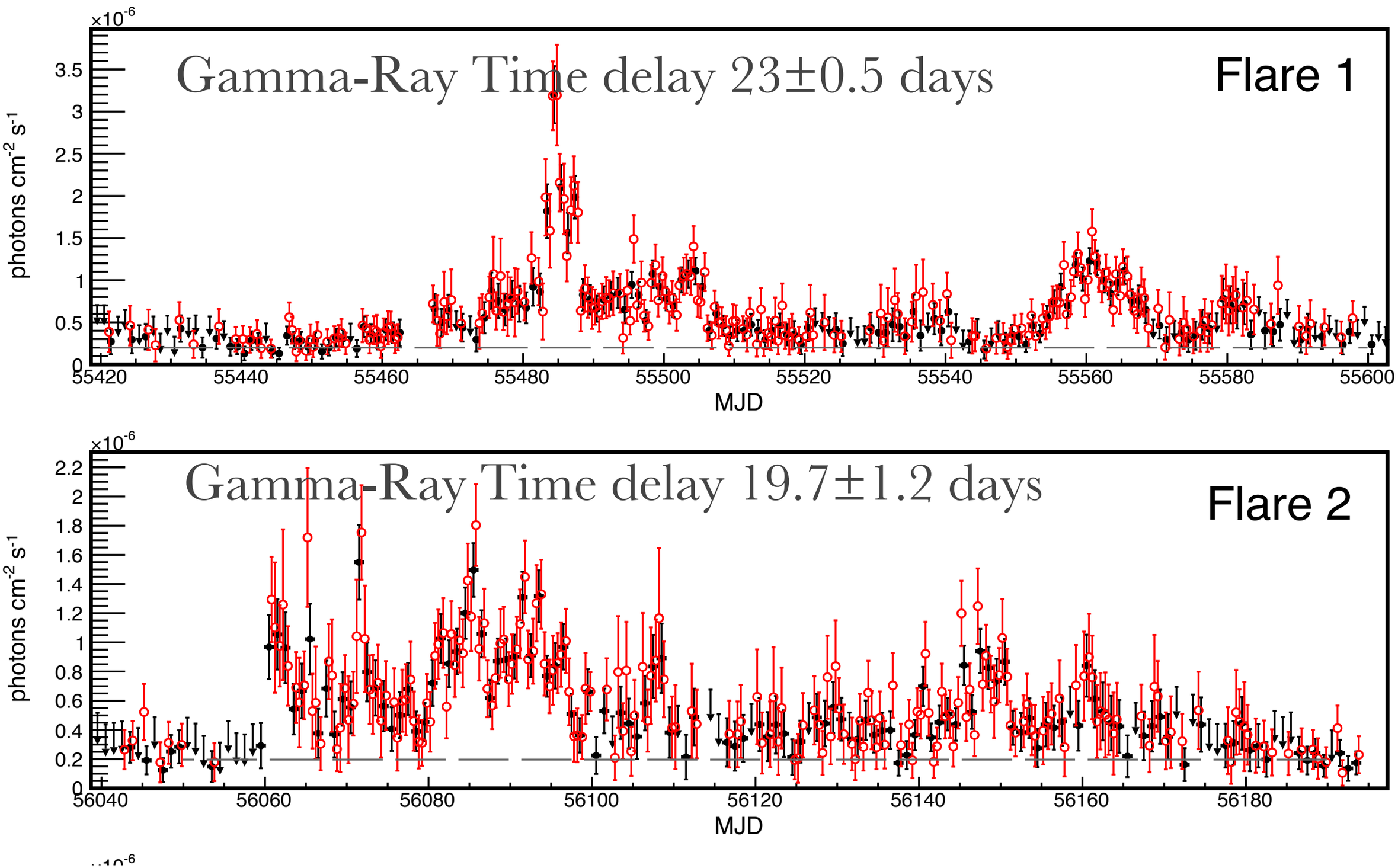
Barnacka, A., Geller, M., Dell'Antonio, I., & Benbow, W. (2015)

Summary

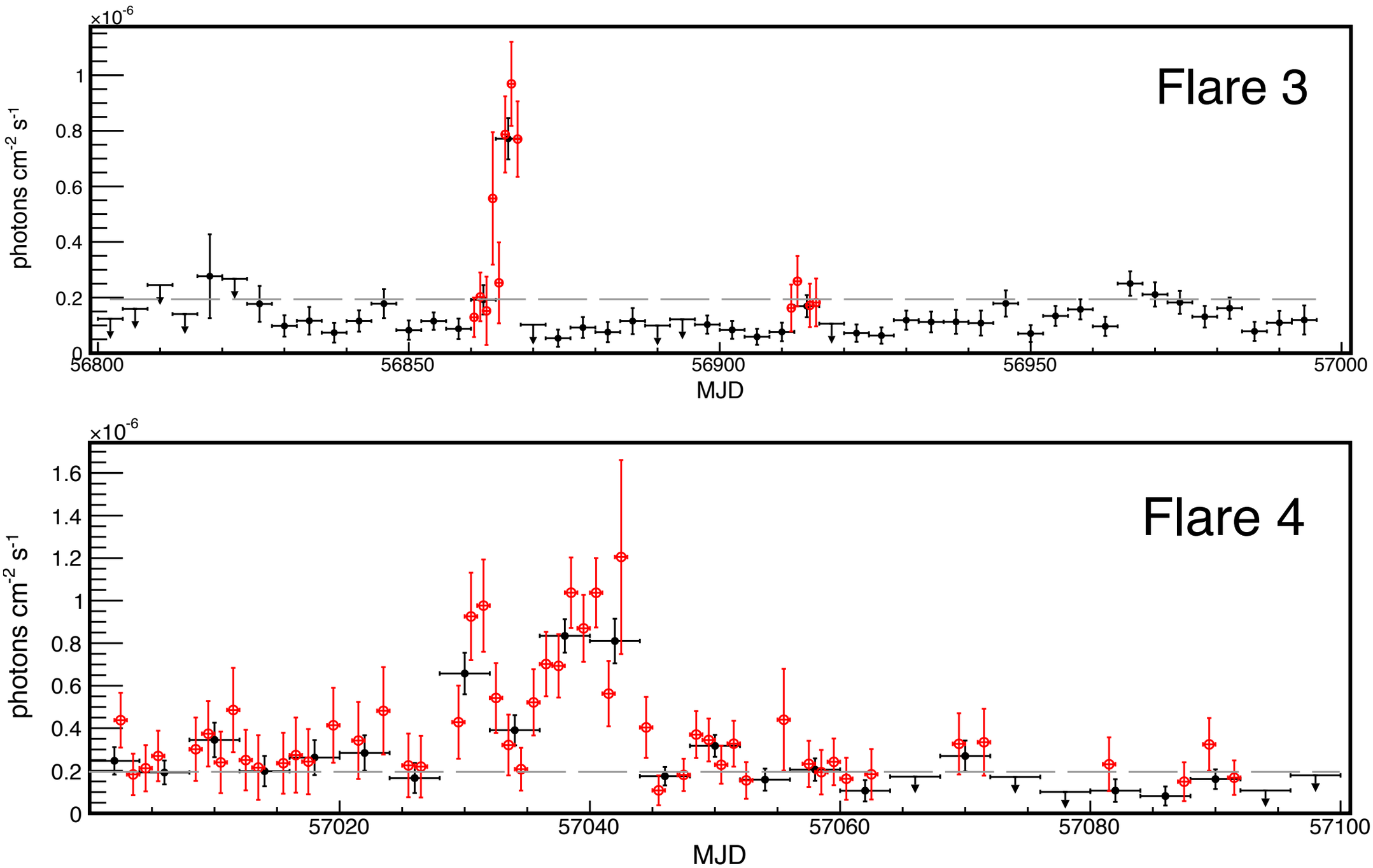
- **Strong Lensing:**
  - **Powerful Tool to Resolve High Energy Universe**
  - **Effective Spatial Resolution ~ 0.02” - improvement x 10,000**

Backup Slides

Gamma-ray Flare 1 and 2: Time Delays

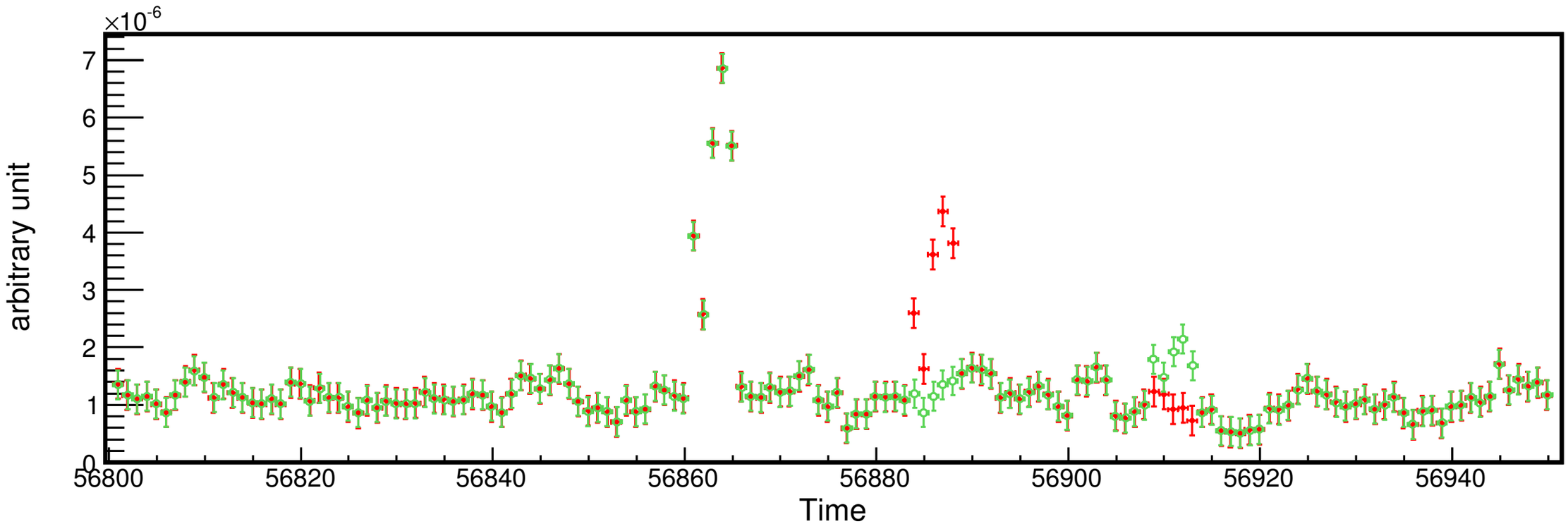


Gamma-ray Flare 3 and 4: Time Delays

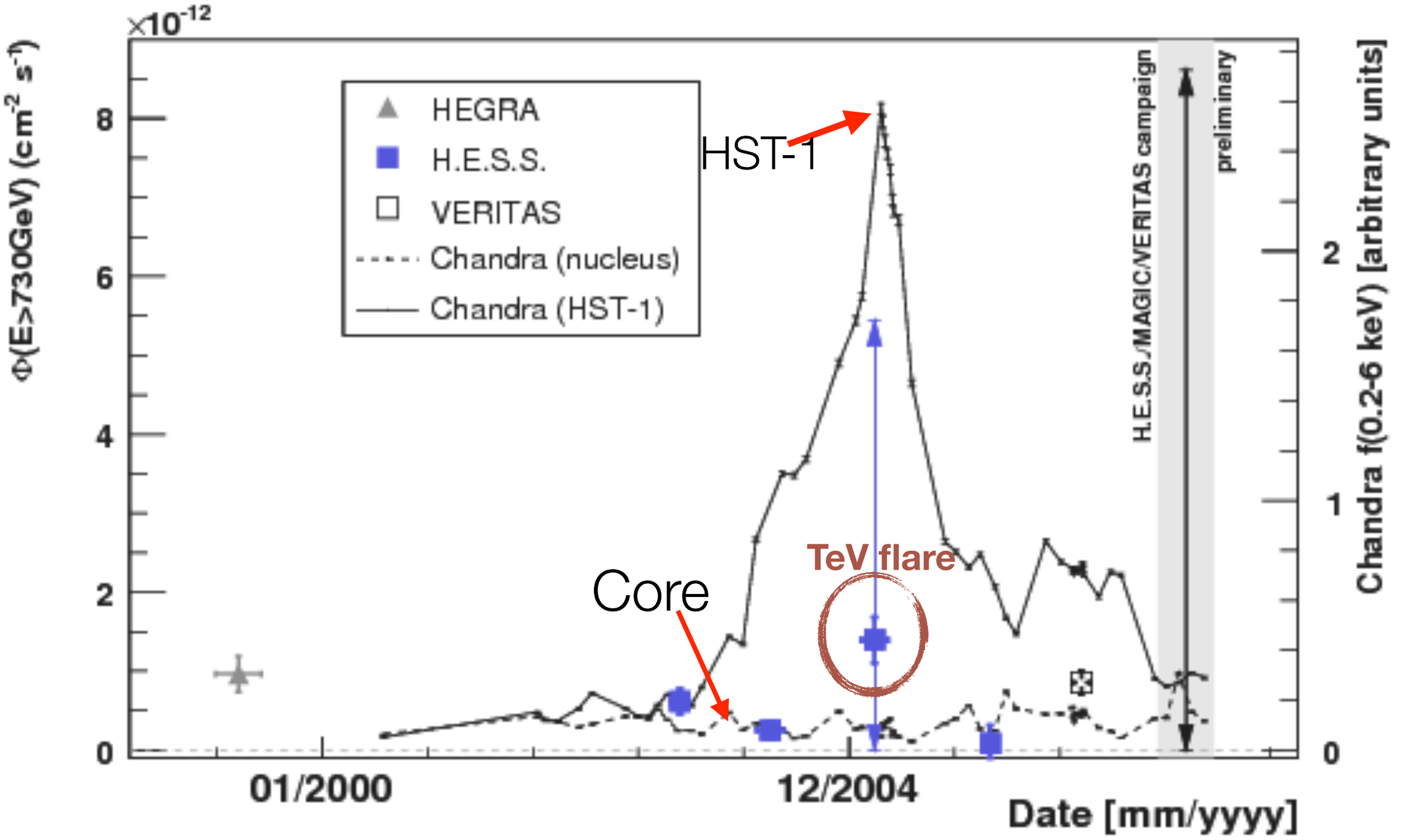


Gamma-Ray Time delay > 50 days

Monte Carlo Simulations

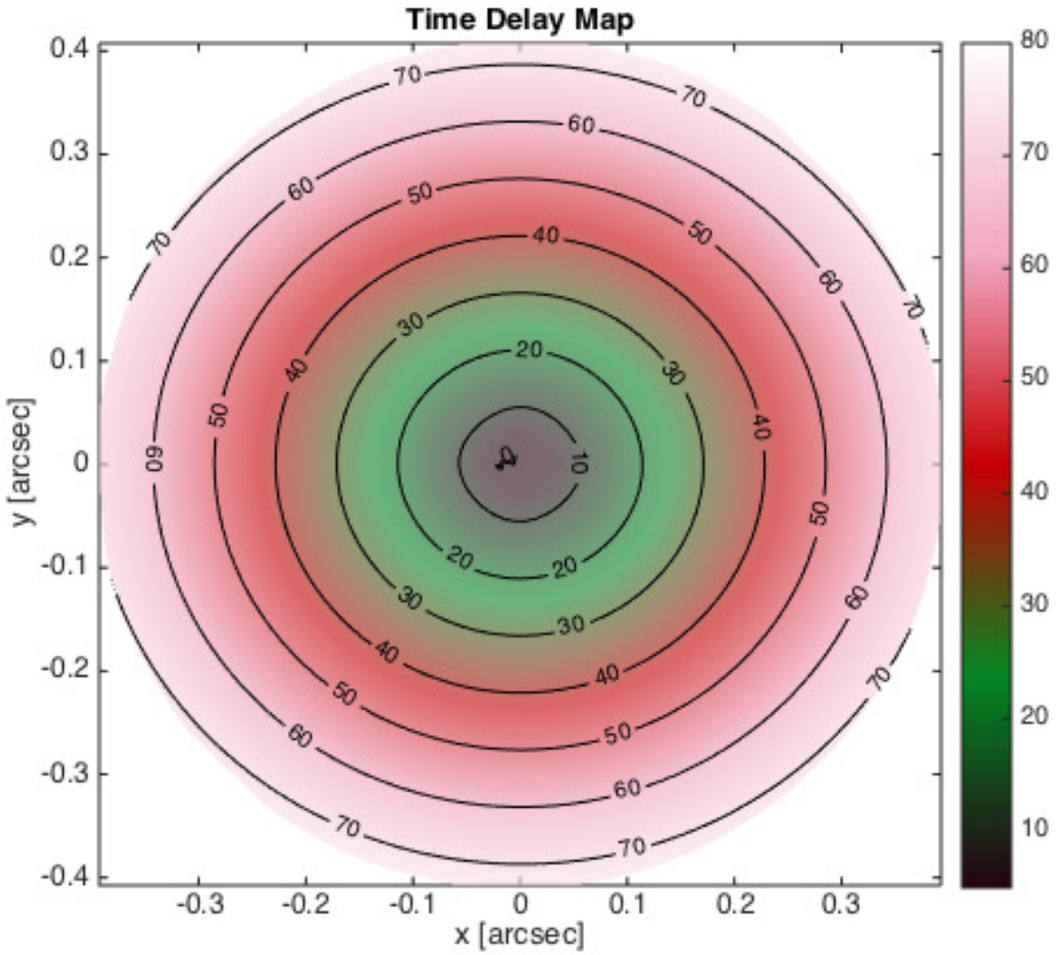


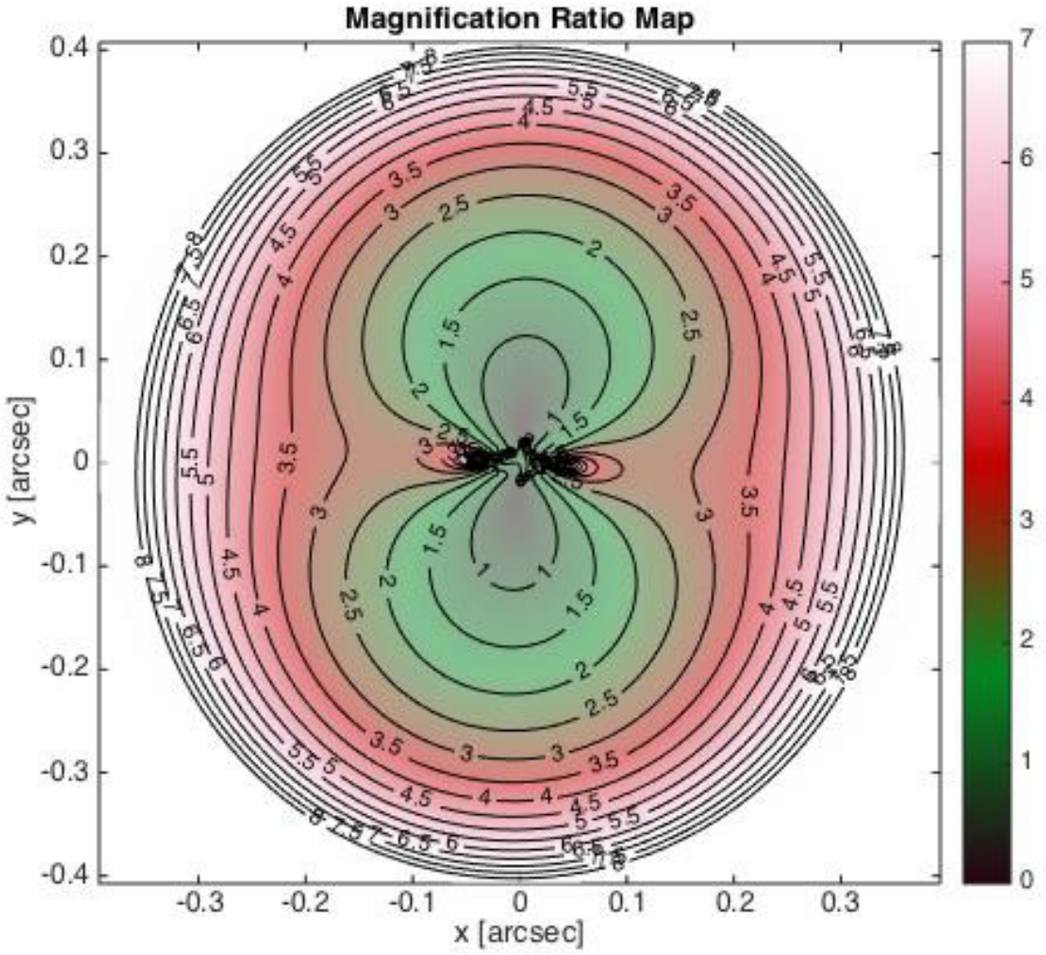
Spatial Origin of Gamma-Ray Flares



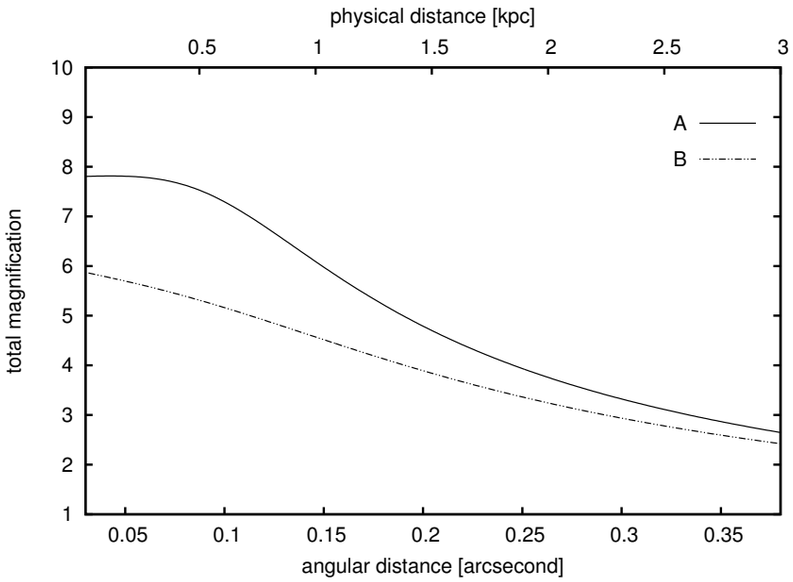
Credit: MAGIC and VERTIAS and H.E.S.S. Collaborations (2009)

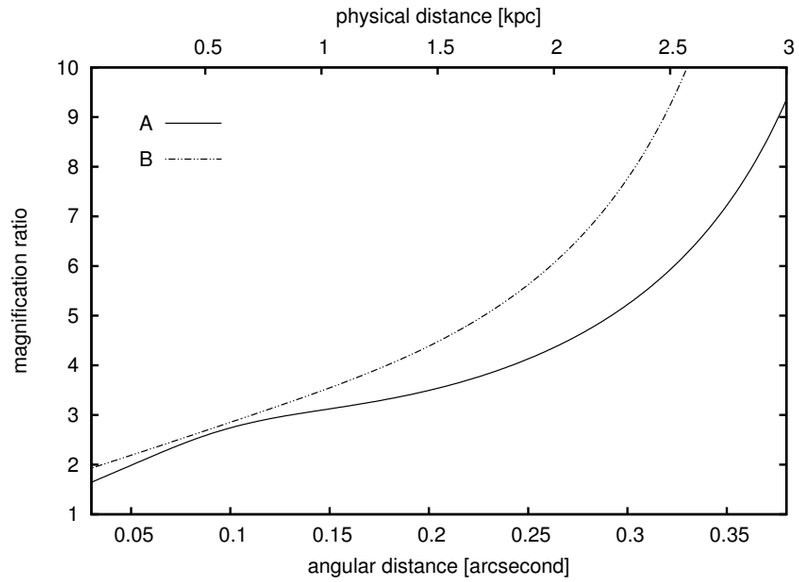
Lensing Maps

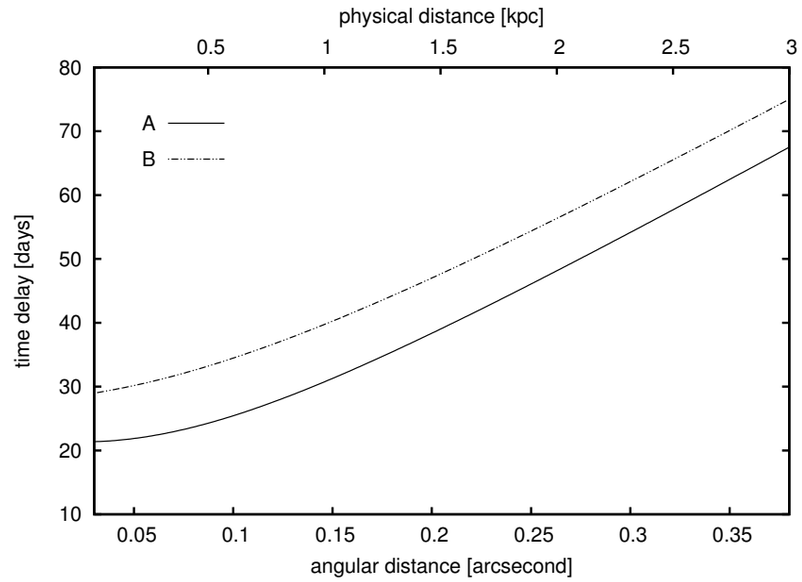




Lensing Parameters Along the Jet







Position of the Core