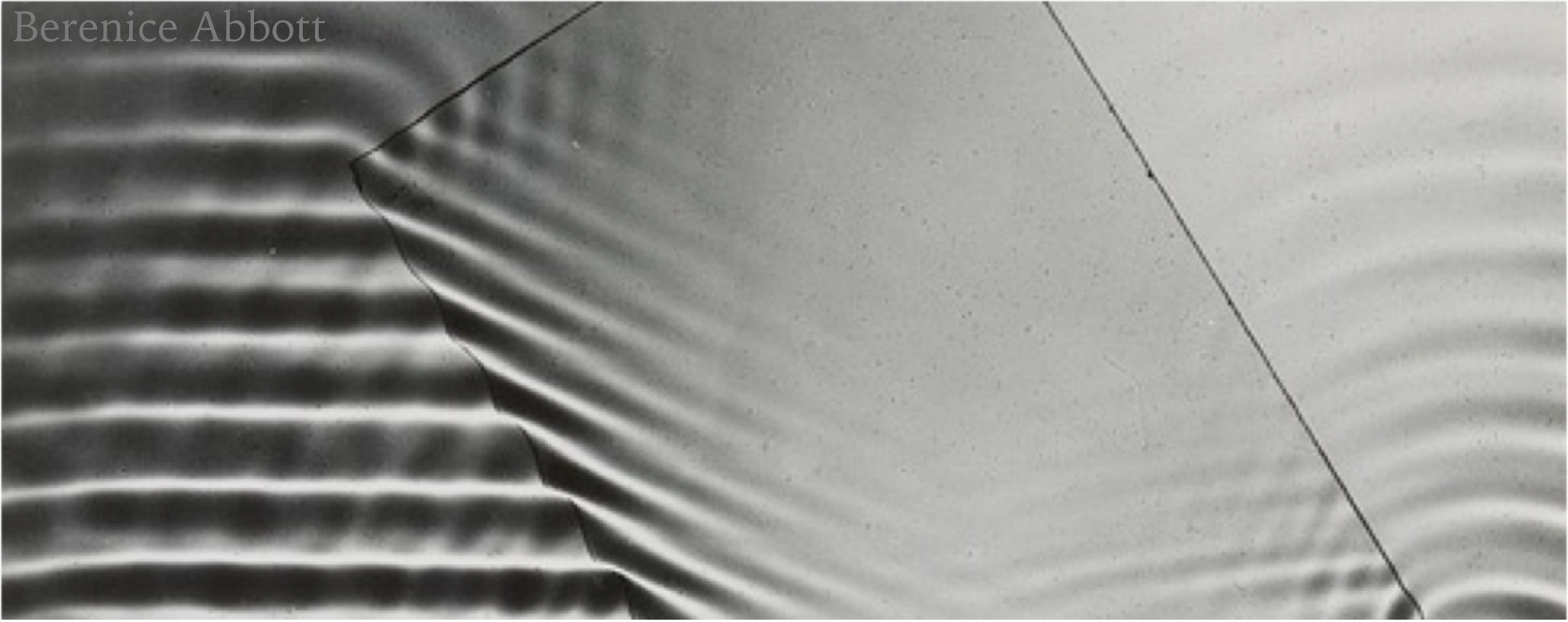


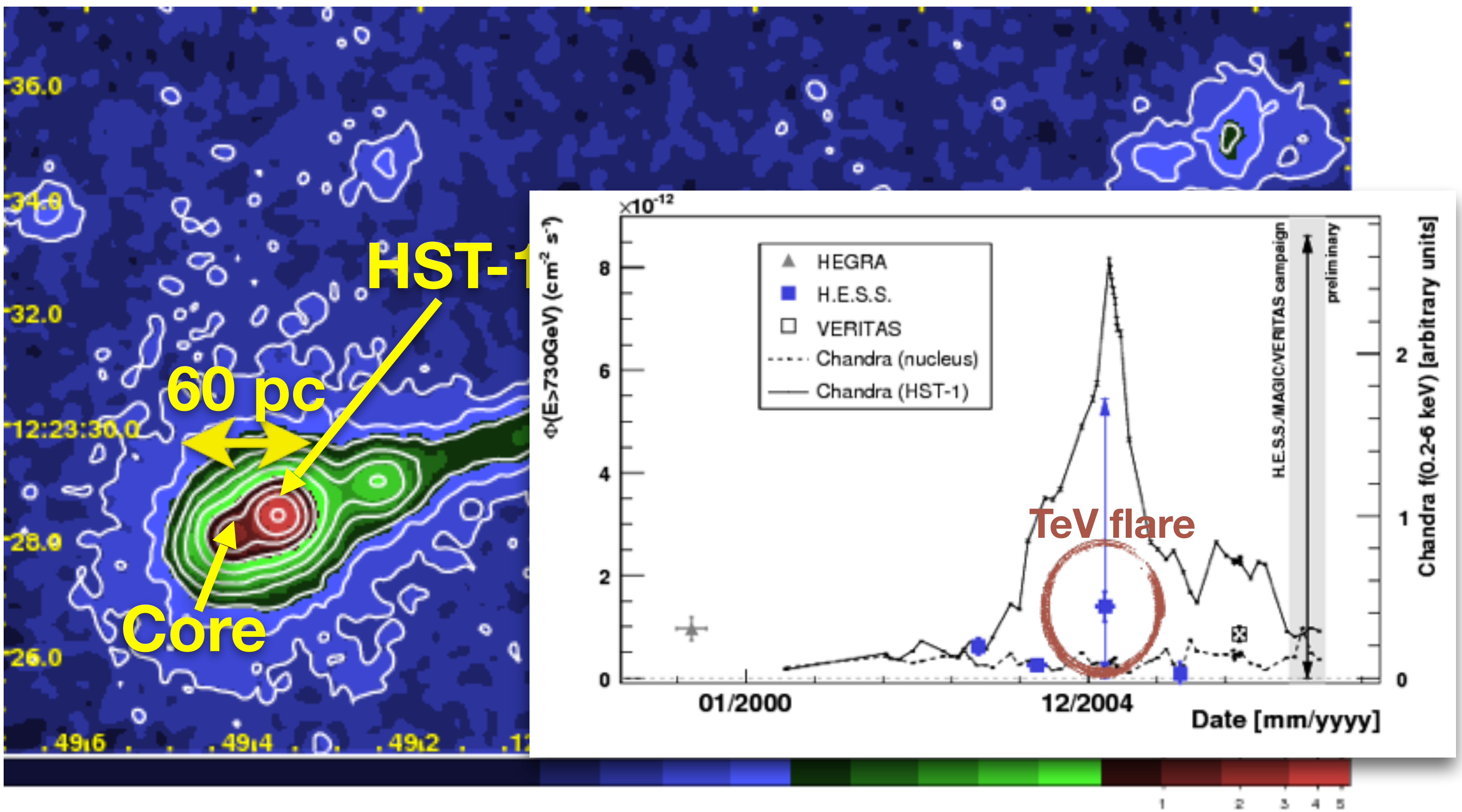

# RESOLVING HIGH ENERGY UNIVERSE USING STRONG GRAVITATIONAL LENSING

Anna Barnacka
Einstein Fellow at Harvard

# 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

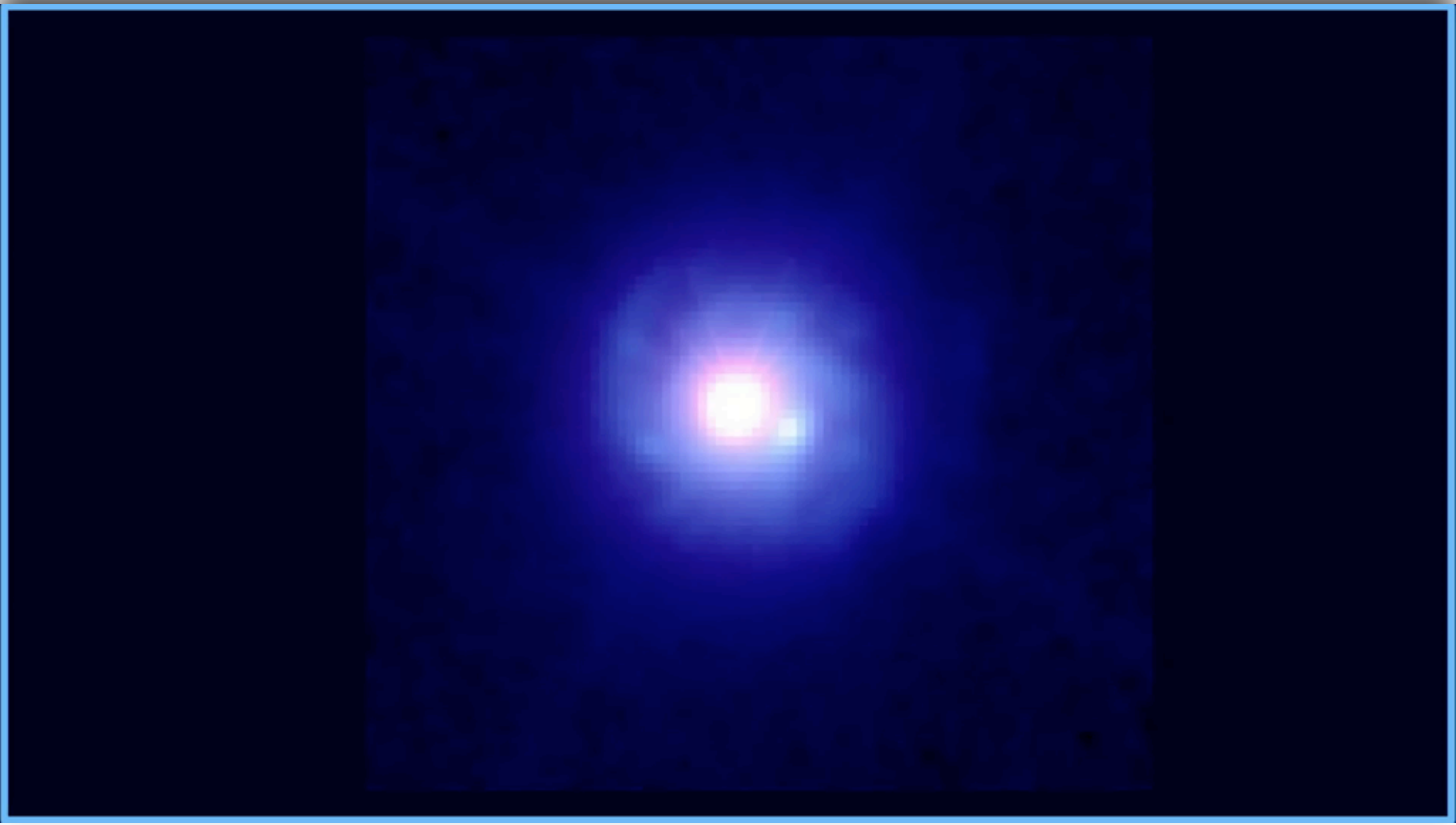



*Flares from knots along the jets*

## SCIENTIFIC CHALLENGES

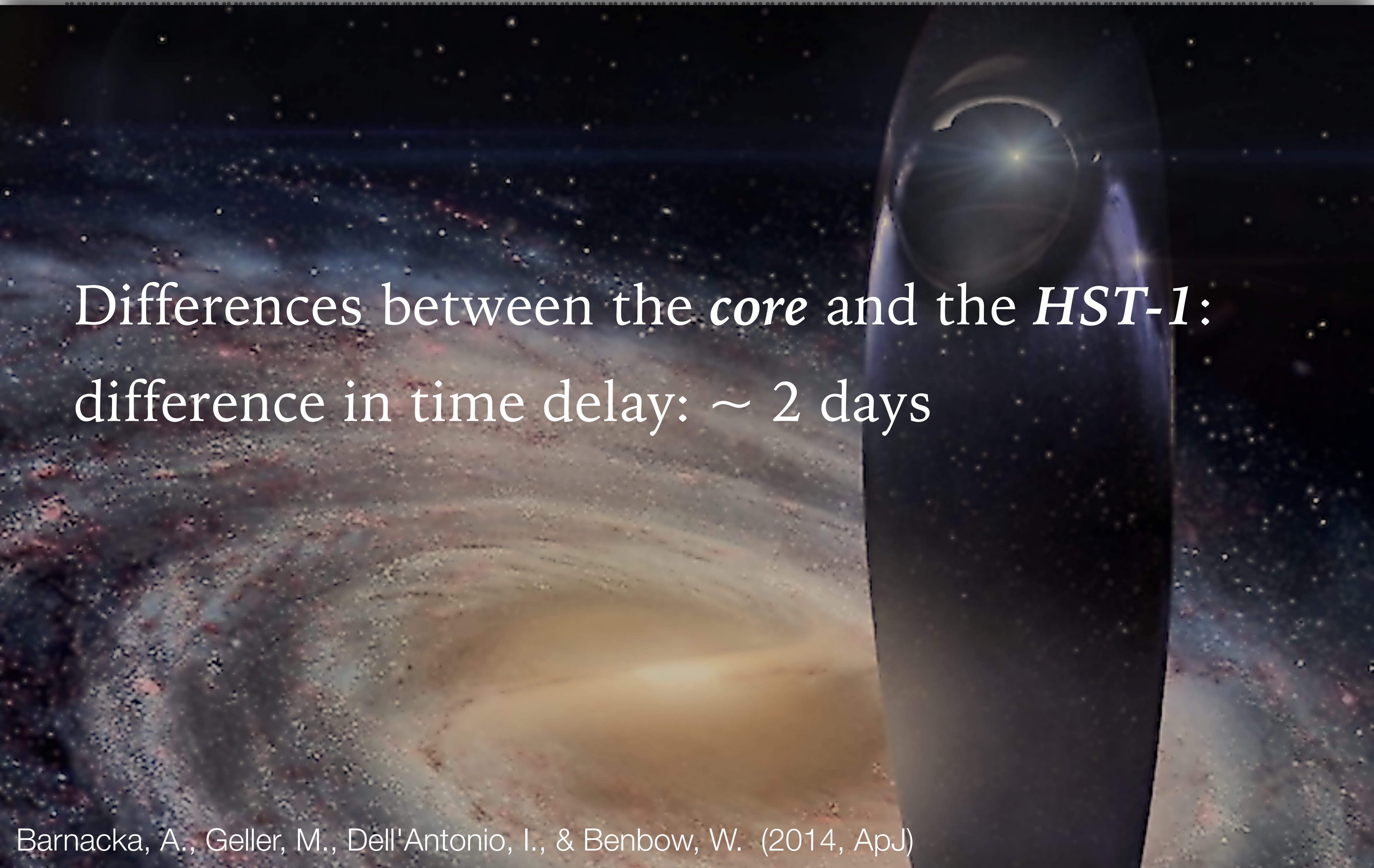
- Frequency of M87-like variability
- Origin of gamma-ray flares

# GRAVITATIONALLY LENSED JETS



Credit: NASA's Goddard Space Flight Center

# IMAGINE M87 AT Z=1

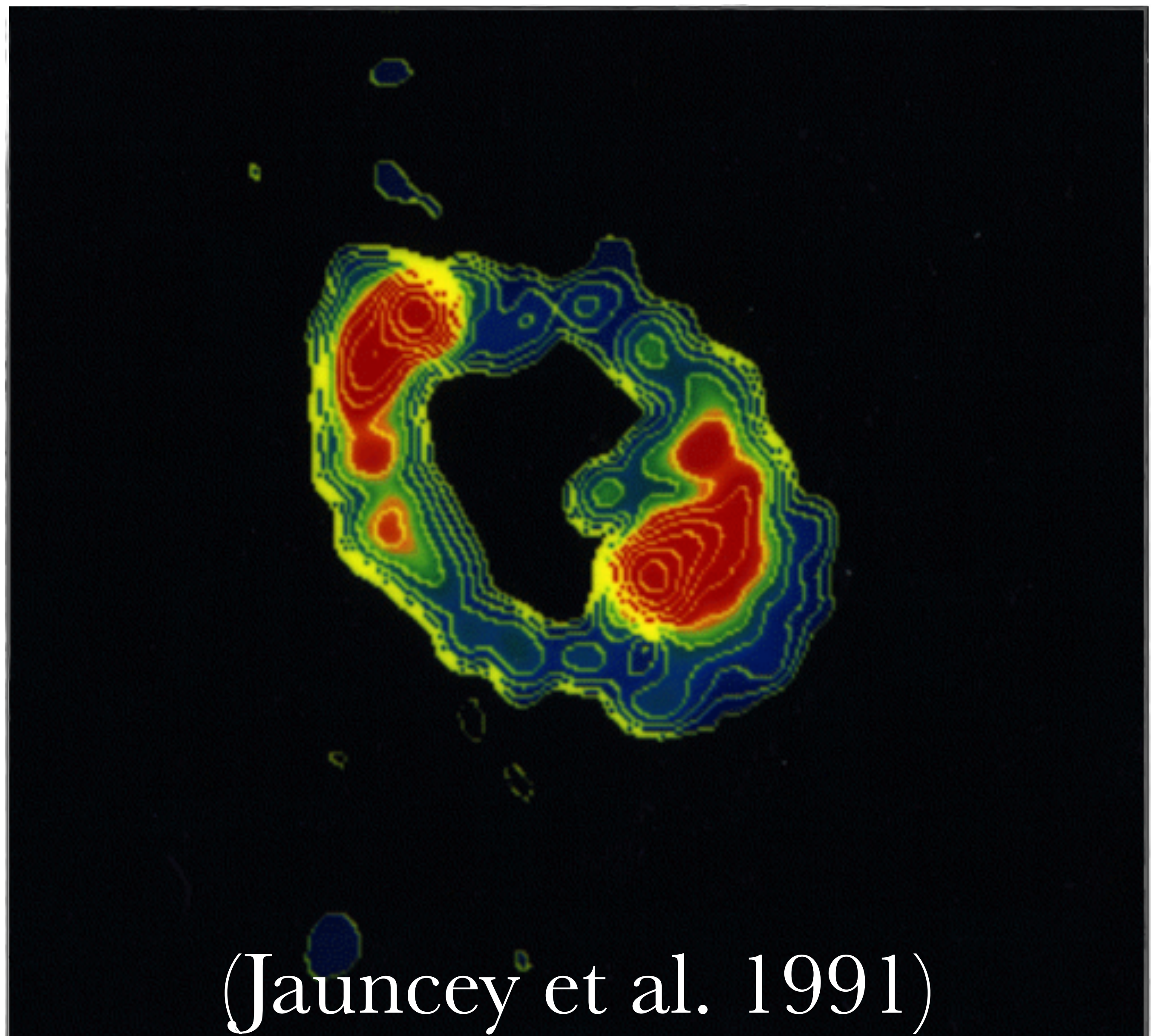


Differences between the *core* and the ***HST-1***:

difference in time delay: ~ 2 days

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

# LENSED GAMMA-RAY JETS: PKS 1830-211



(Jauncey et al. 1991)

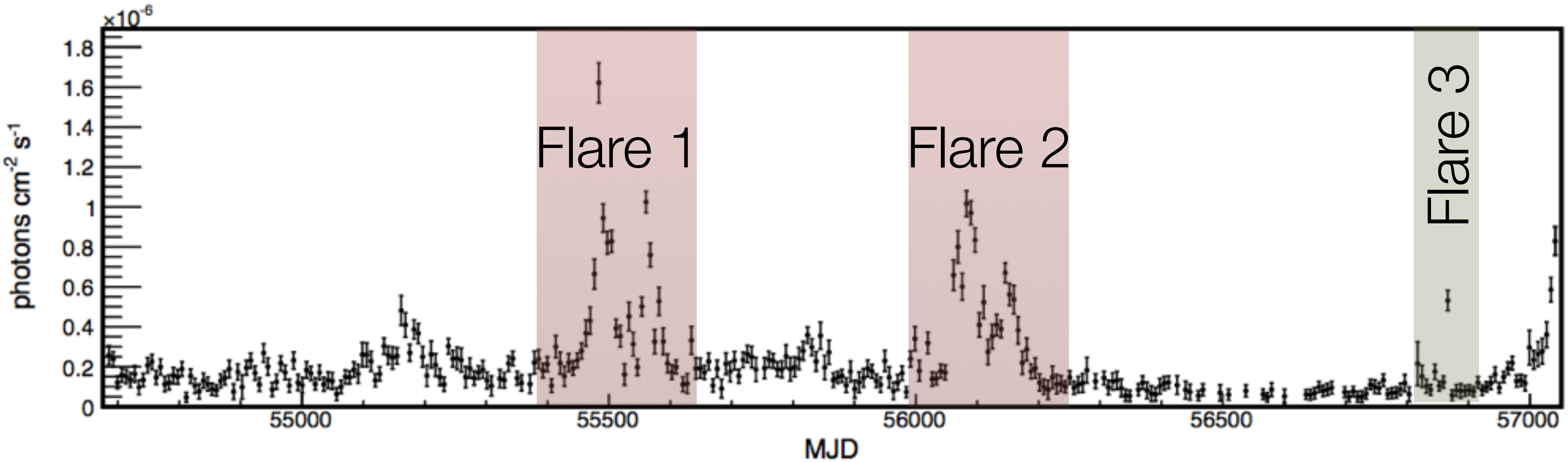
Source z = 2.5,
Lens z = 0.9

Radio Time Delay
26±5 days

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

- **Time Delay = 27±0.5 days**

# GAMMA-RAY FLARES: TIME DELAYS

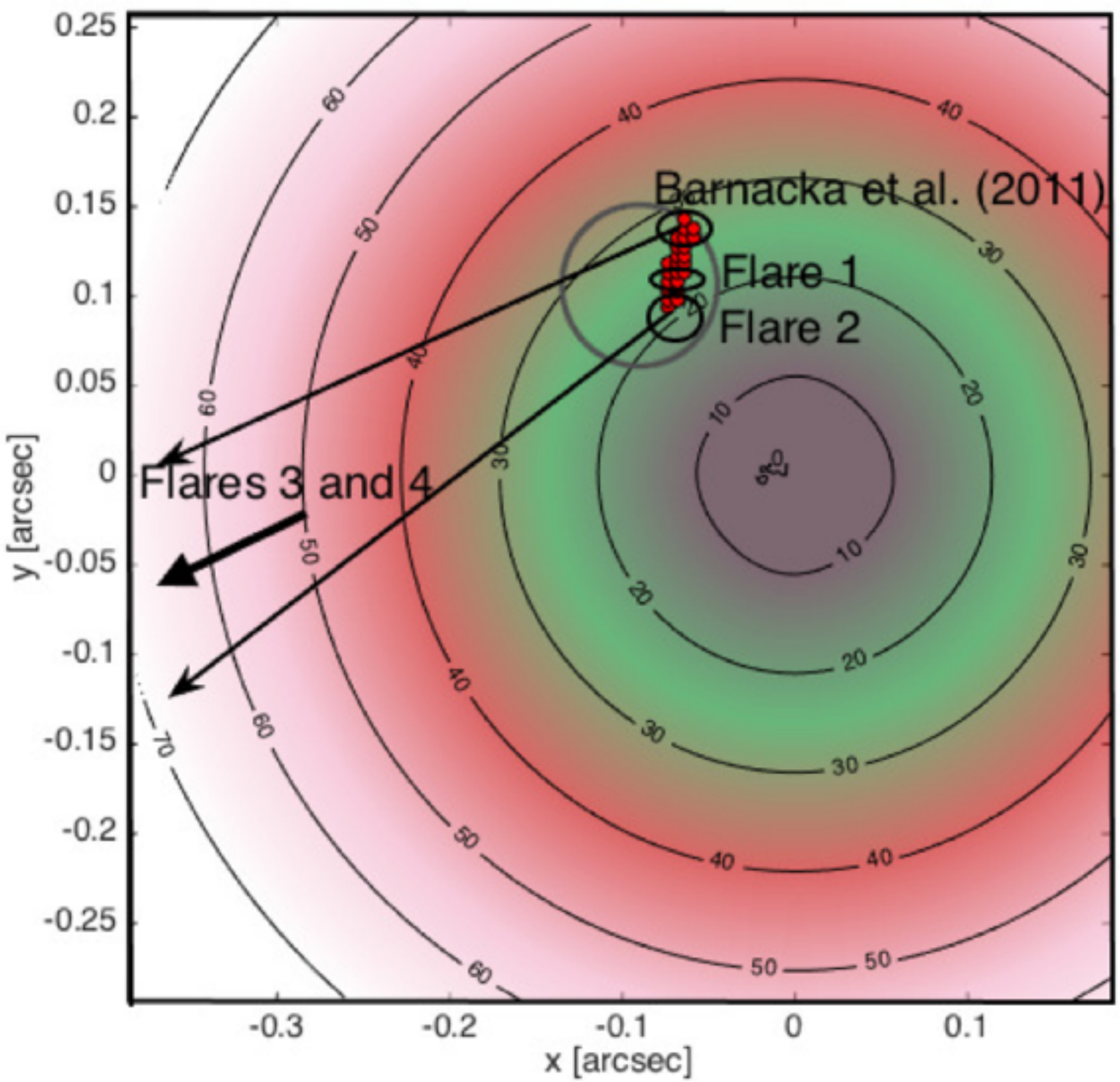



**23±0.5 days** **19±1.2 days** **> 50 days**

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

# SPATIAL ORIGIN OF GAMMA-RAY FLARES

**Time Delay Map**



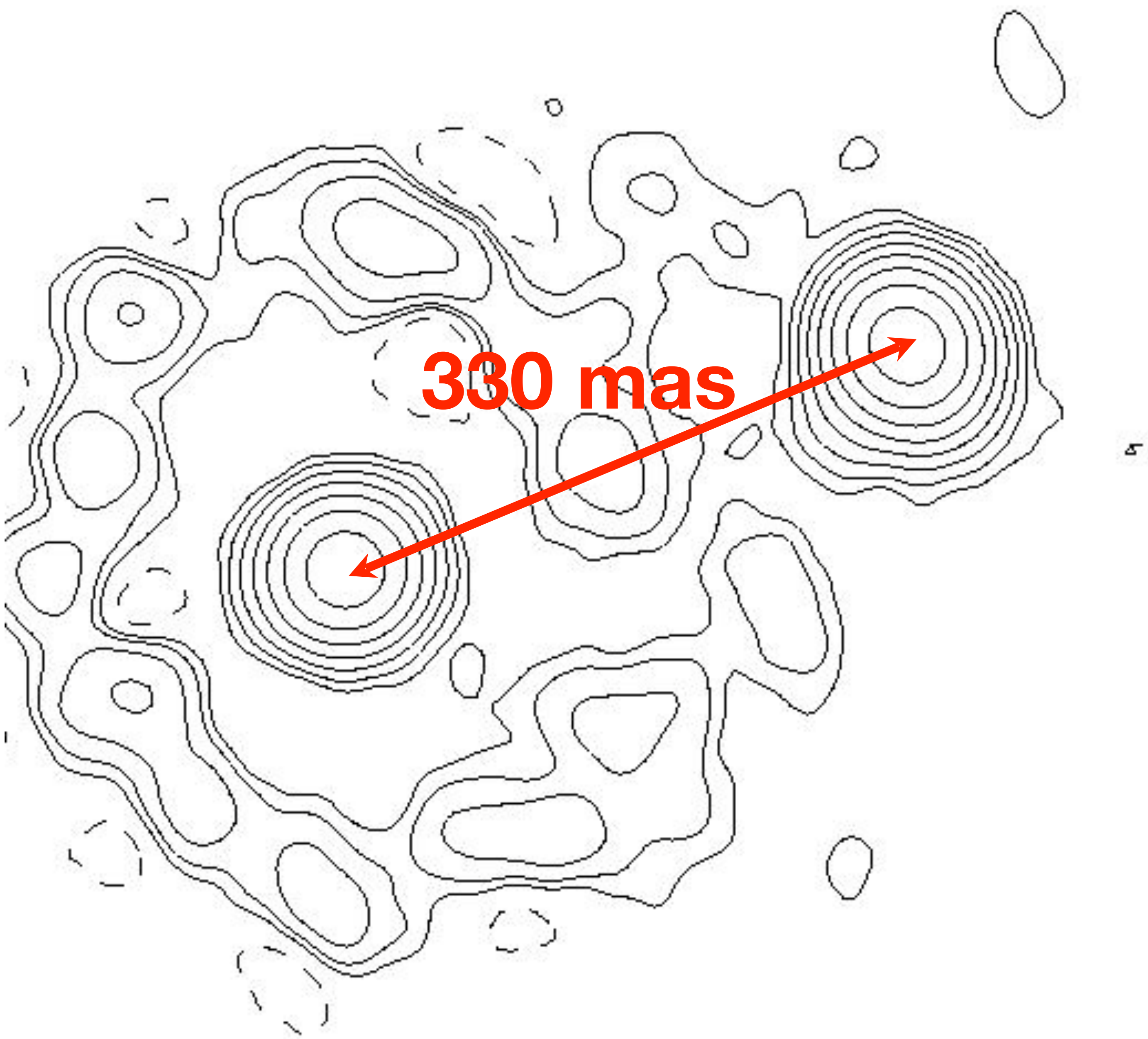

Barnacka, A., Geller, M., Dell'Antonio, I., & Benbow, W. (ApJ,2015)

# GAMMA-RAY SPATIAL RESOLUTION

- **PKS 1830-211**
- Effective Spatial Resolution ~ **0.02”** (~ HST)
  Barnacka, A., et al. (2015, ApJ, 809, 100)

- What if we could resolve emission ~**0.001”**?

# LENSED BLAZAR: B2 0218+35




1.687 GHz, Patnaik et al. (1992)

Source z = 0.944,

Lens z = 0.6847

Radial Jet Projection

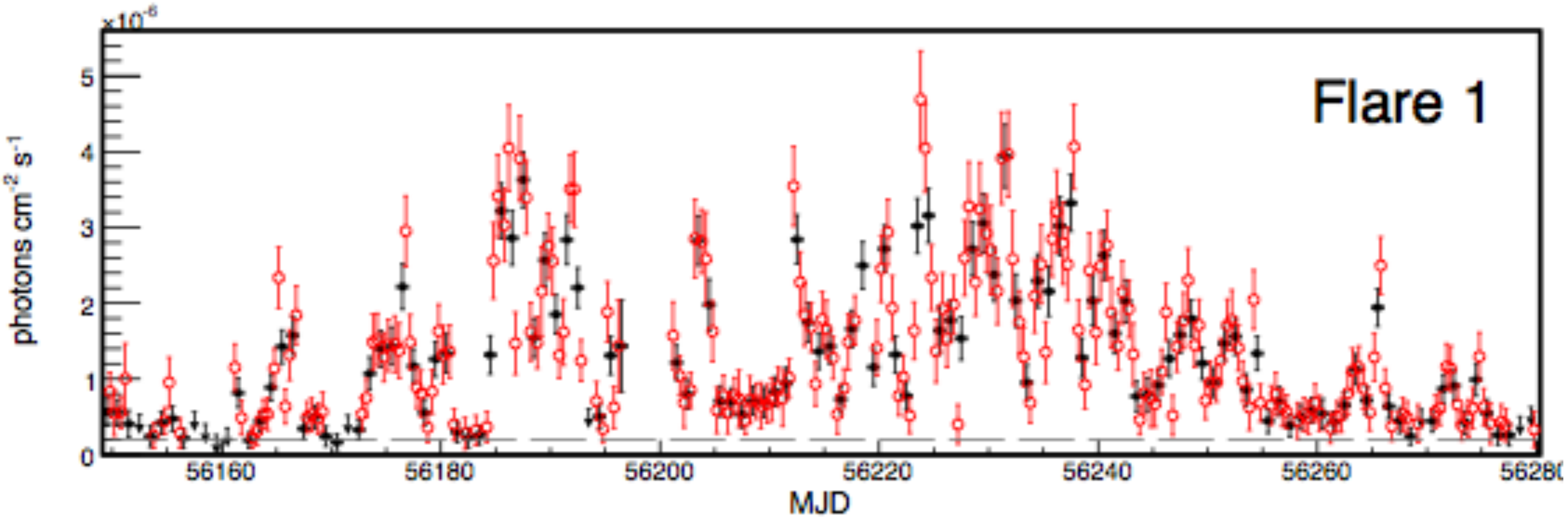
**Reconstruction**

**~ 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

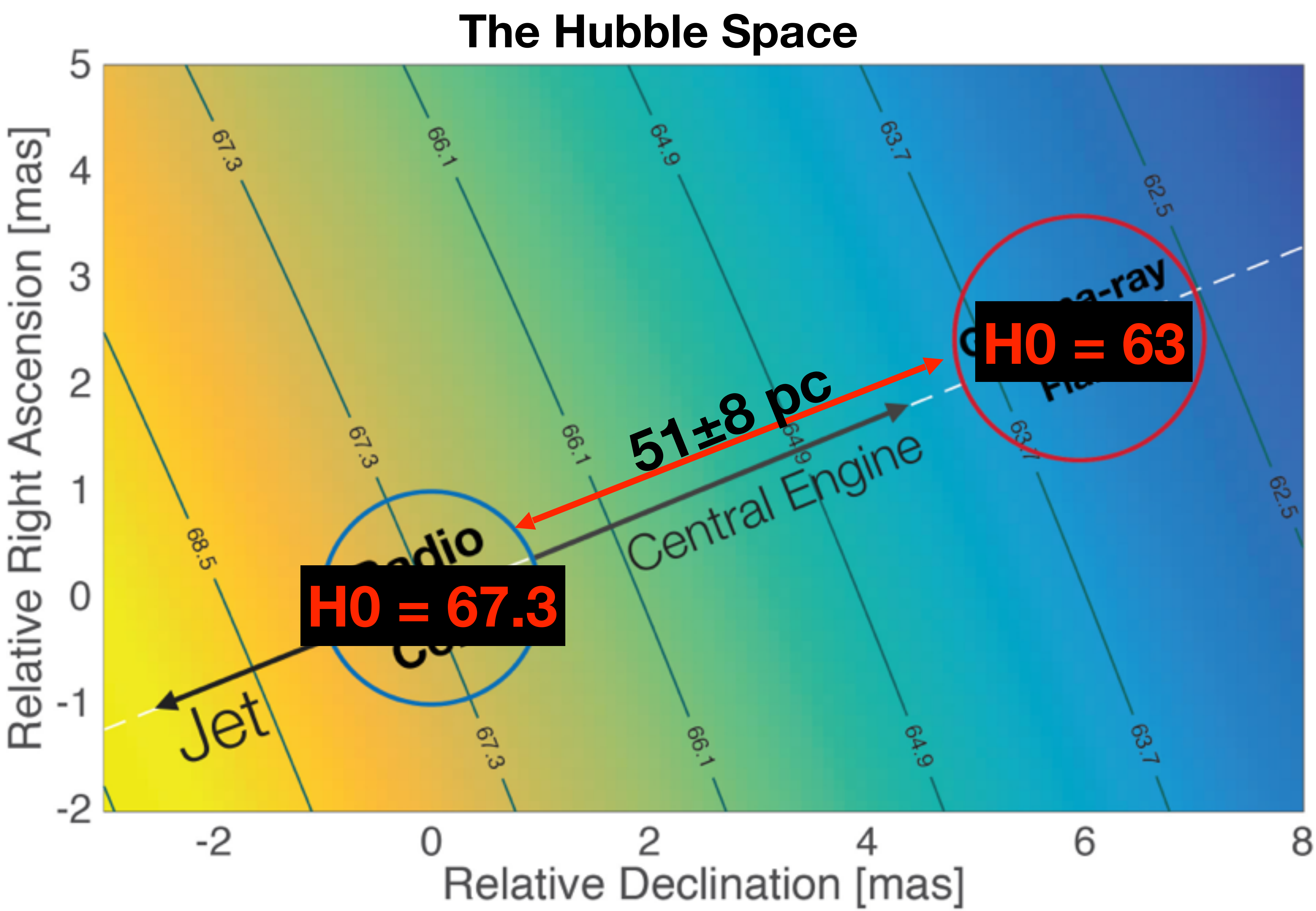
Time Delay + Position of the Images + Lens Model

***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

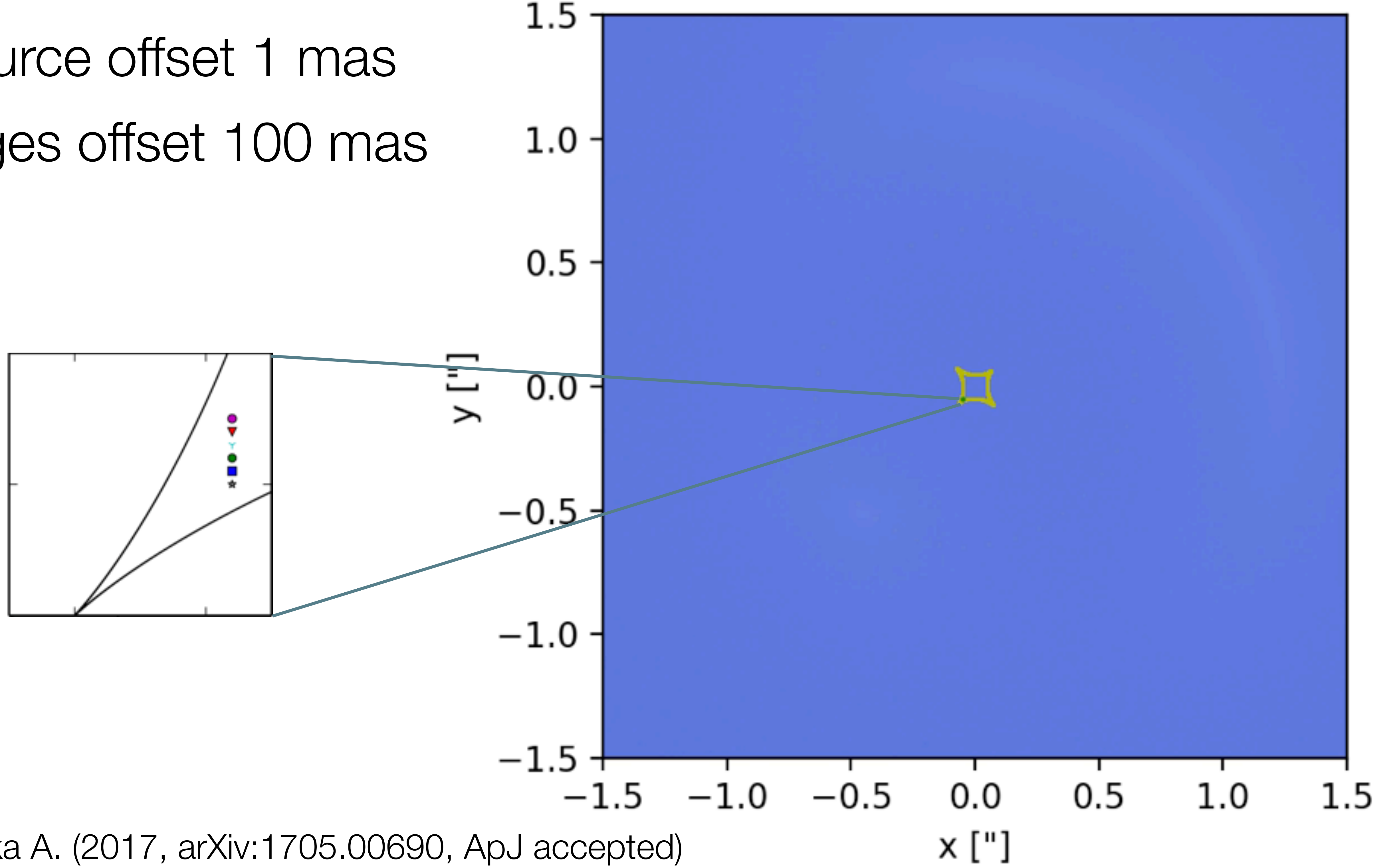



Barnacka et al. 2016, ApJ, 821, 58

# GALAXIES AS HIGH-RESOLUTION TELESCOPES

Source offset 1 mas

Images offset 100 mas



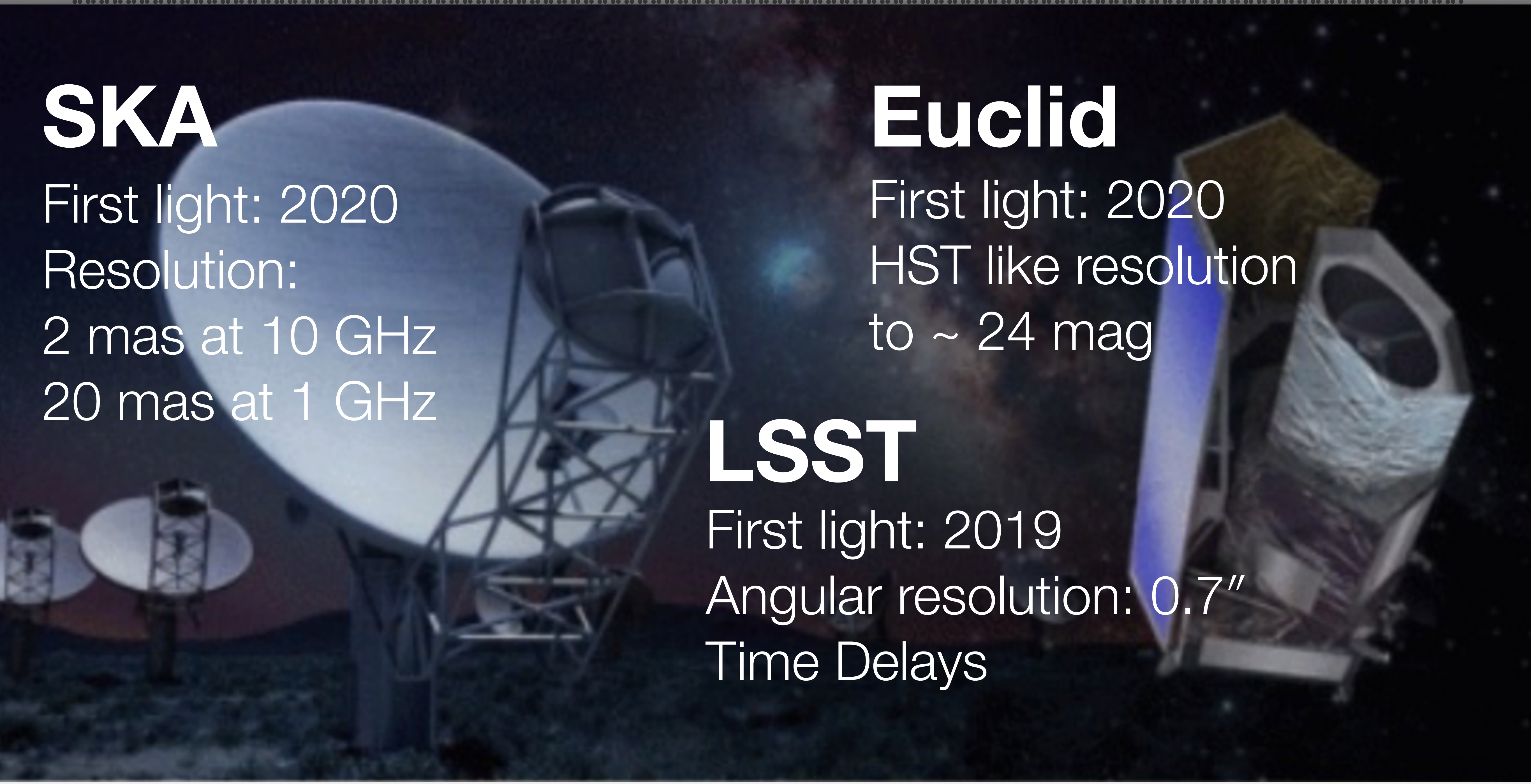

Barnacka A. (2017, arXiv:1705.00690, ApJ accepted)

# LENSED QUASARS IN CAUSTIC CONFIGURATION


**8 out of 20**

JVAS / CLASS

# EUCLID, LSST, AND SKA SYNERGY



## SKA

First light: 2020
Resolution:
2 mas at 10 GHz
20 mas at 1 GHz

## Euclid

First light: 2020
HST like resolution
to ~ 24 mag

## LSST

First light: 2019
Angular resolution: 0.7″
Time Delays

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

# SUMMARY

- Spatial Resolution at Gamma Rays:
    - ~1 milliarcsecond
    - Gamma-ray Flares not always from Radio Core
    - Radio Core not at Central Engine
- Caustic Configuration:
    - >50 x Flux Magnification
    - >50 x Offset Amplification
- Insight into inner parts of active galaxies at high redshifts
- Currently: dozen of sources
- Near future: SKA and Euclid dozen of thousands of sources

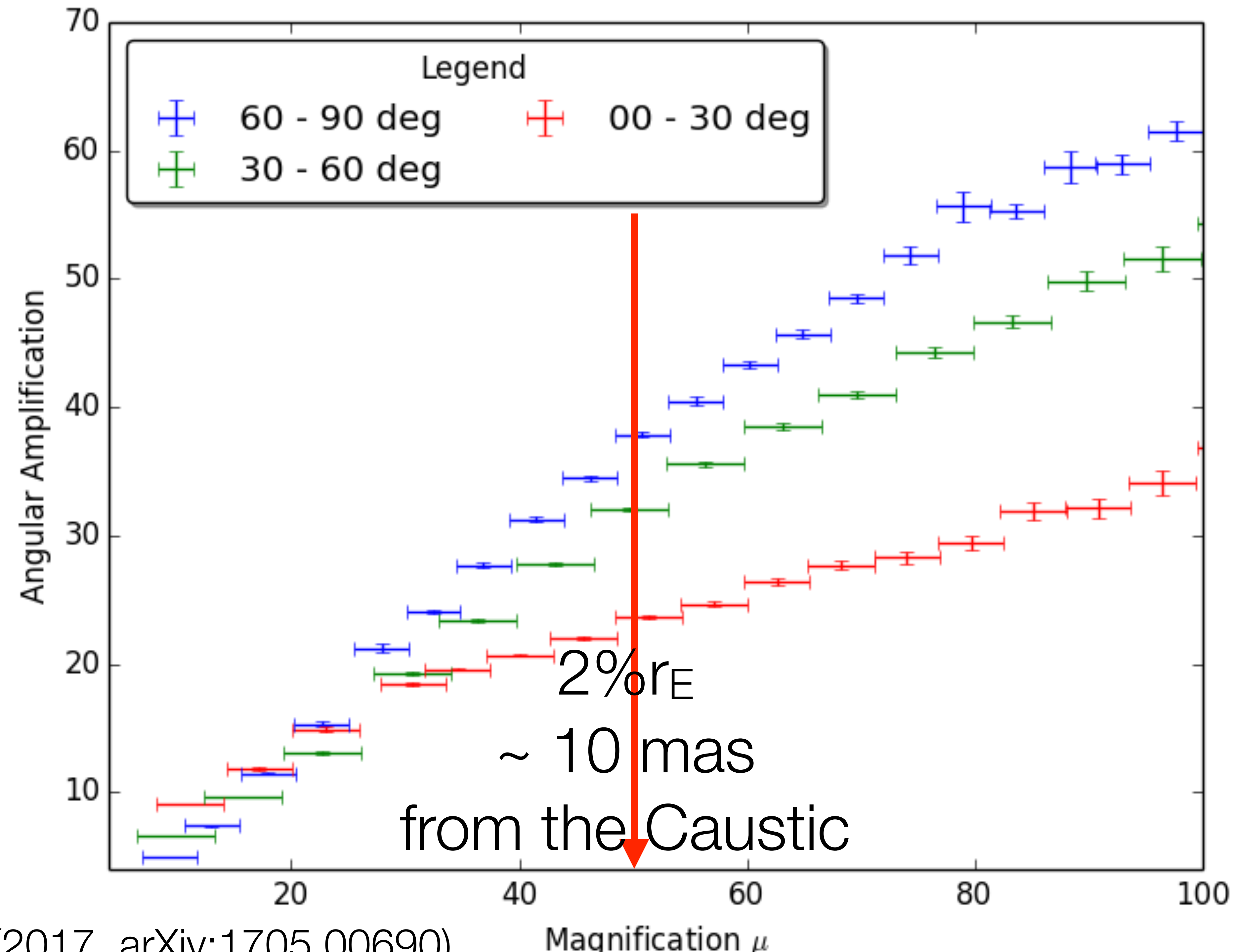
# Backup Slides

Backup Slides

Galaxies as High Resolution Telescopes

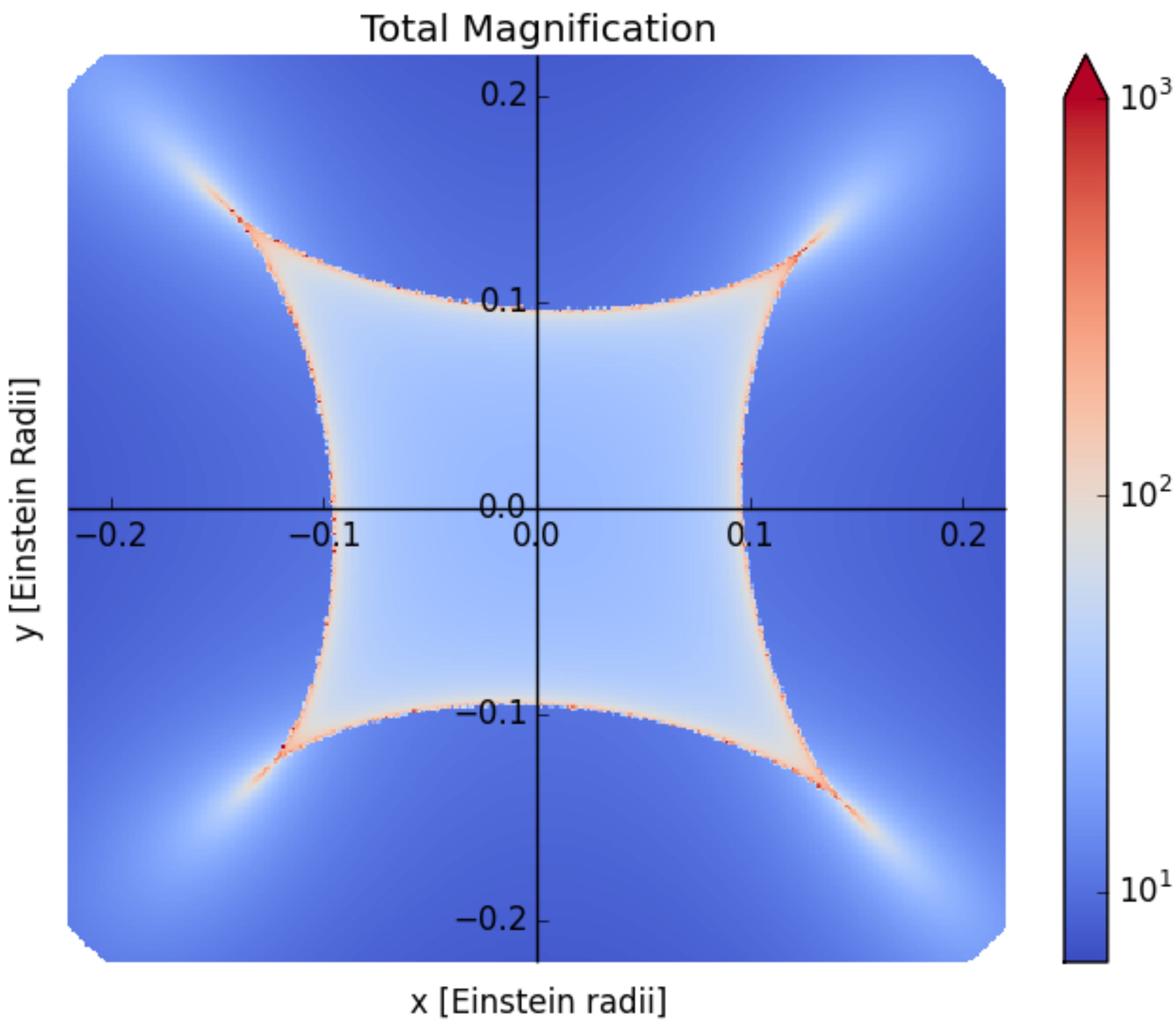
# ANGULAR AMPLIFICATION IN CAUSTIC REGION

Monte Carlo Simulations of $\mathbf{10^6}$ pair of offset sources




Barnacka (2017, arXiv:1705.00690)

# FLUX MAGNIFICATION IN CAUSTIC REGION




Barnacka (2017, arXiv:1705.00690)

Backup Slides

B2 0218+35

# THE HUBBLE PARAMETER TUNING APPROACH

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

$$D \equiv \frac{D_{OL} D_{OS}}{D_{LS}} = \boxed{h} d$$

where :

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

For an Singular Isothermal Sphere gravitational potential :

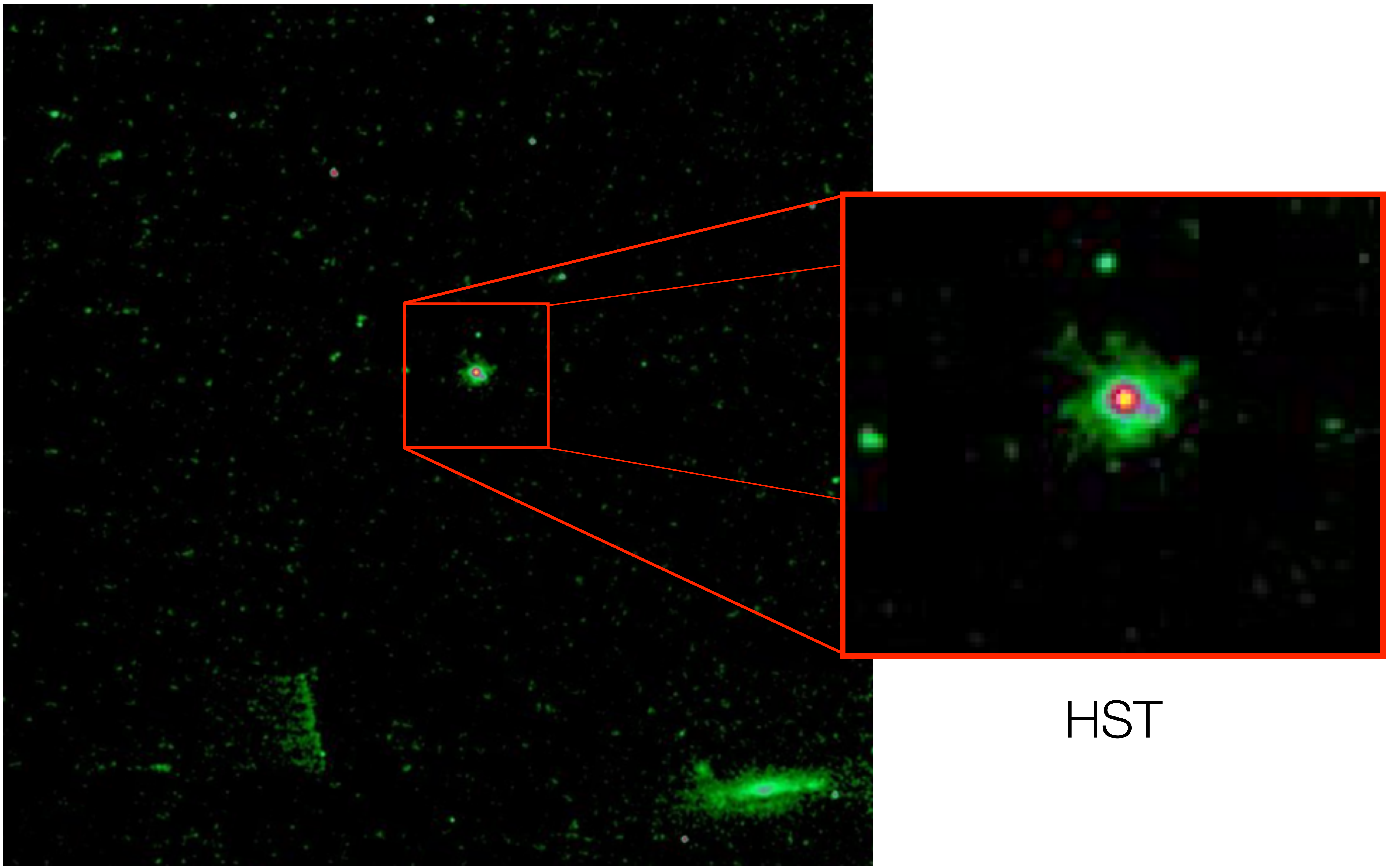
*Mirage Image B*

*Mirage Image A*

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

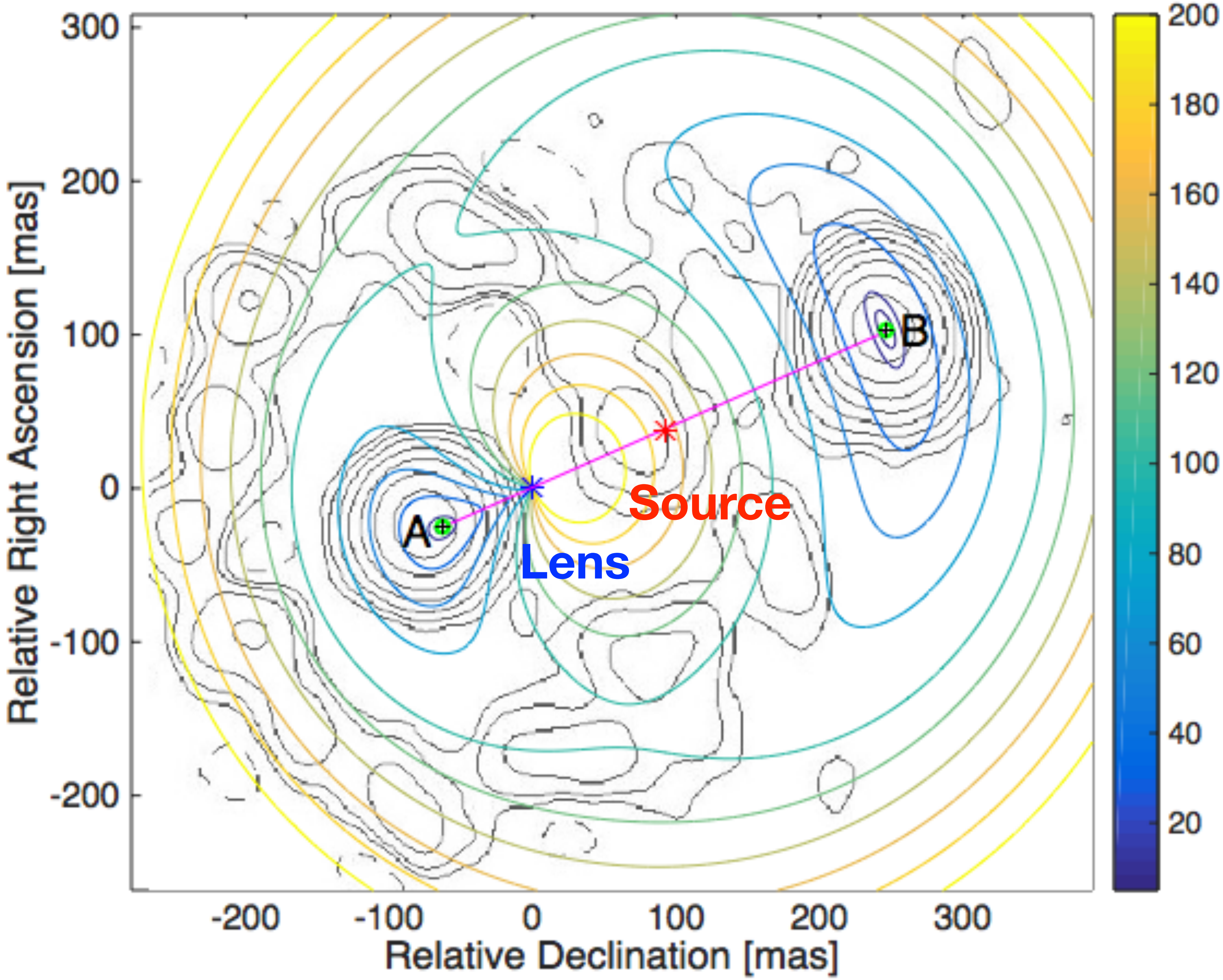
*Time Delay between mirage image A and B*

# OBSERVATIONS: B2 0218+35



HST

# LENS MODELING

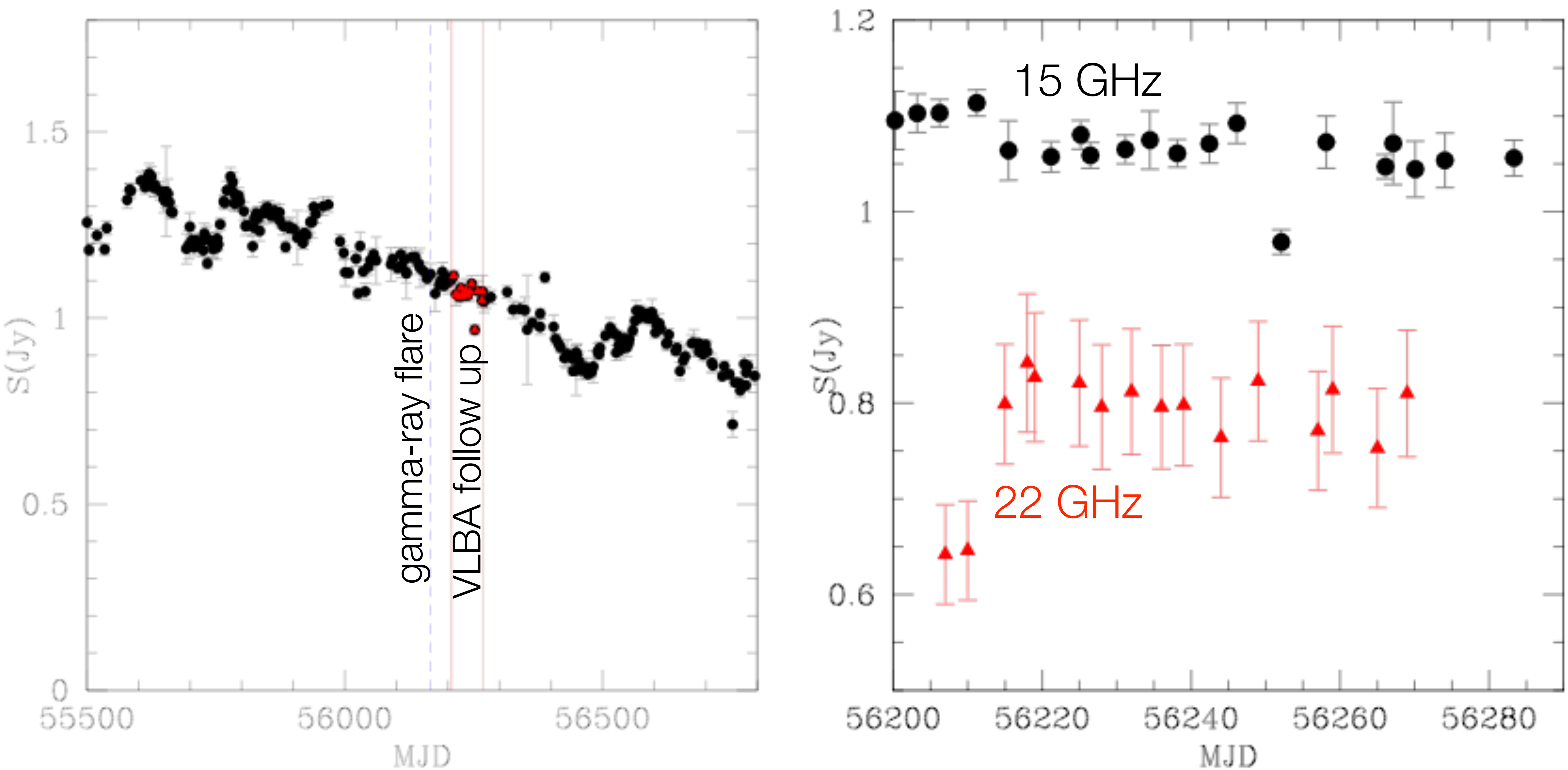



Reconstruction

~ 1 milliarcsecond

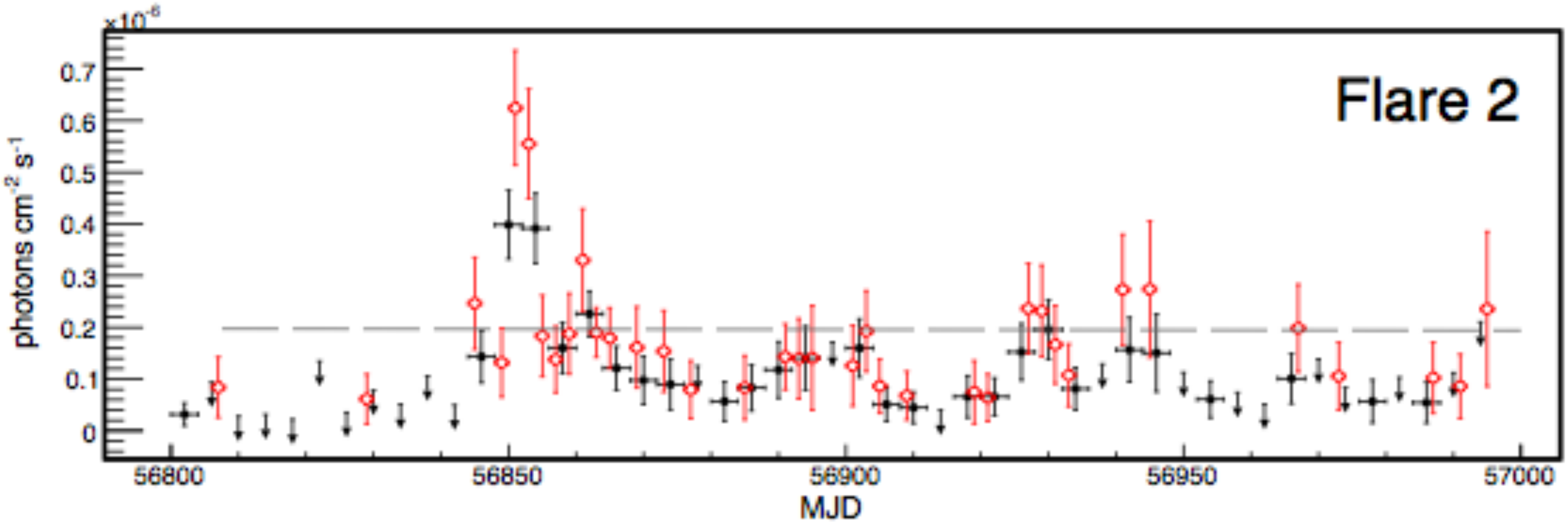
Barnacka et al. 2016, ApJ, 821, 58

# RADIO FOLLOW UP



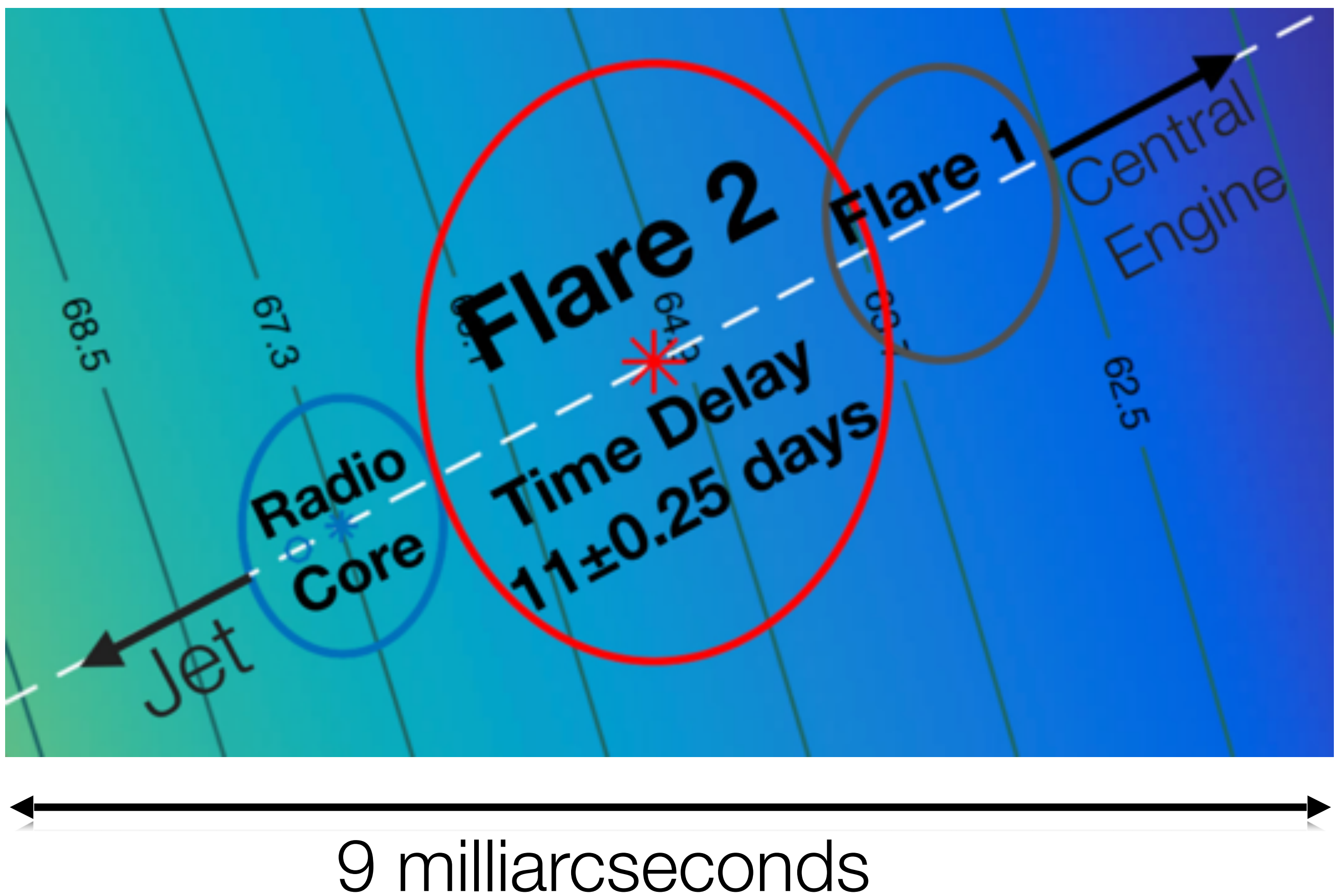

Spingola et al. (2016)

# GAMMA-RAY FLARE 2



# FUTURE FLARES

**If Flare 1 and Flare 2 connected:**




$$\beta_{app} = \frac{D_{projected}(1+z_S)}{c\,\Delta t_{obs}}$$

$$\approx 70 \left(\frac{D_{projected}}{24\,\mathrm{pc}}\right)\left(\frac{\Delta t_{obs}}{690\,\mathrm{days}}\right)$$

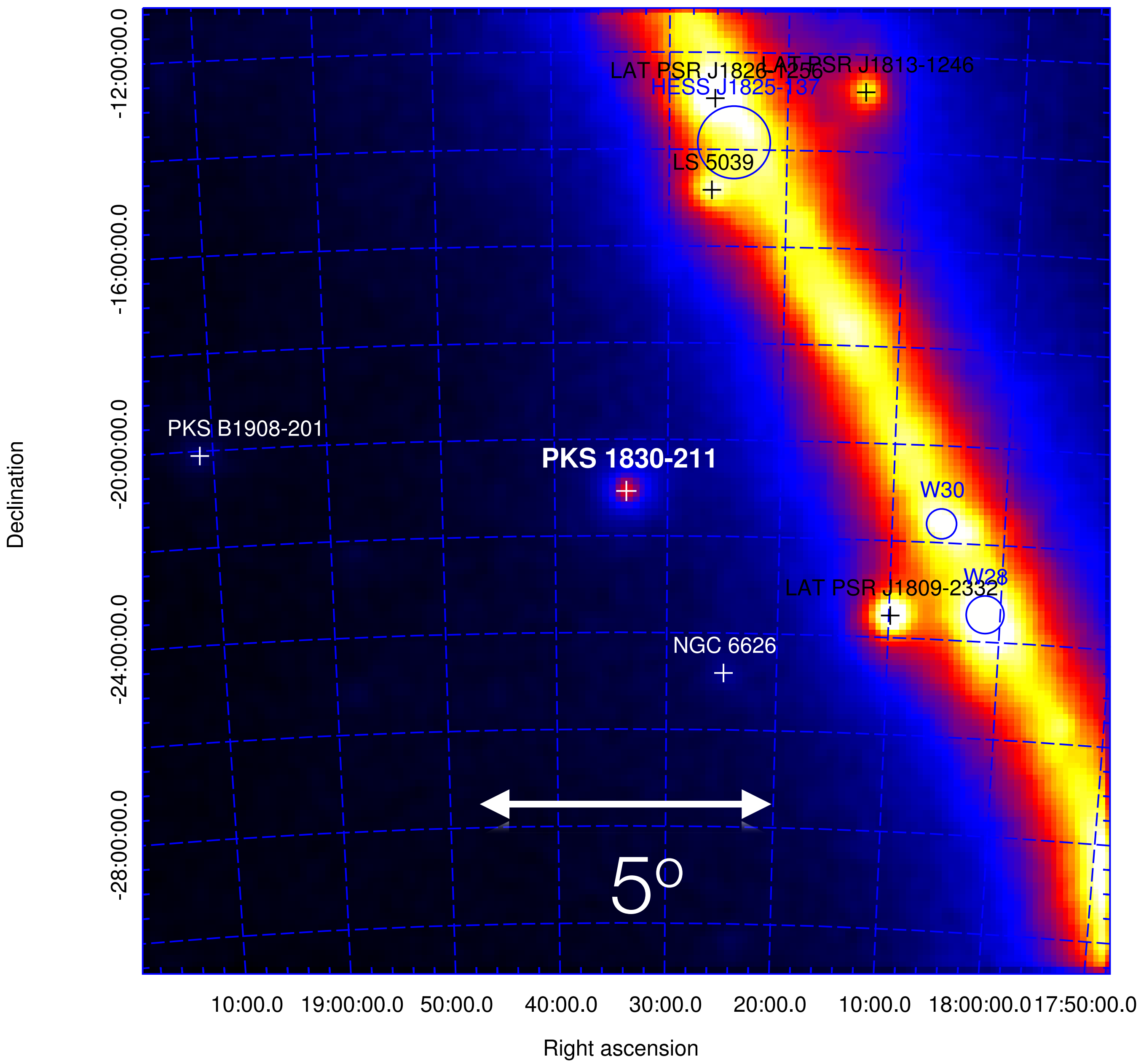
If plasmoid continues its motion:

interaction with radio core ~ **July 2016**

Backup Slides

PKS 1830-211

# Lensed Gamma-Ray Jets: PKS 1830-211

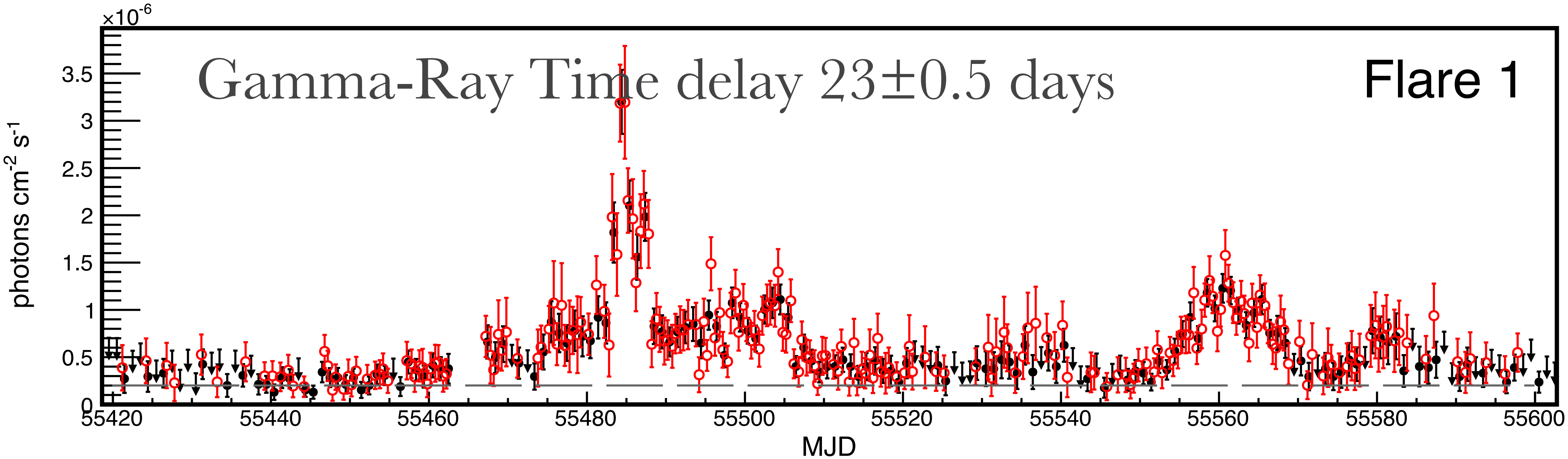


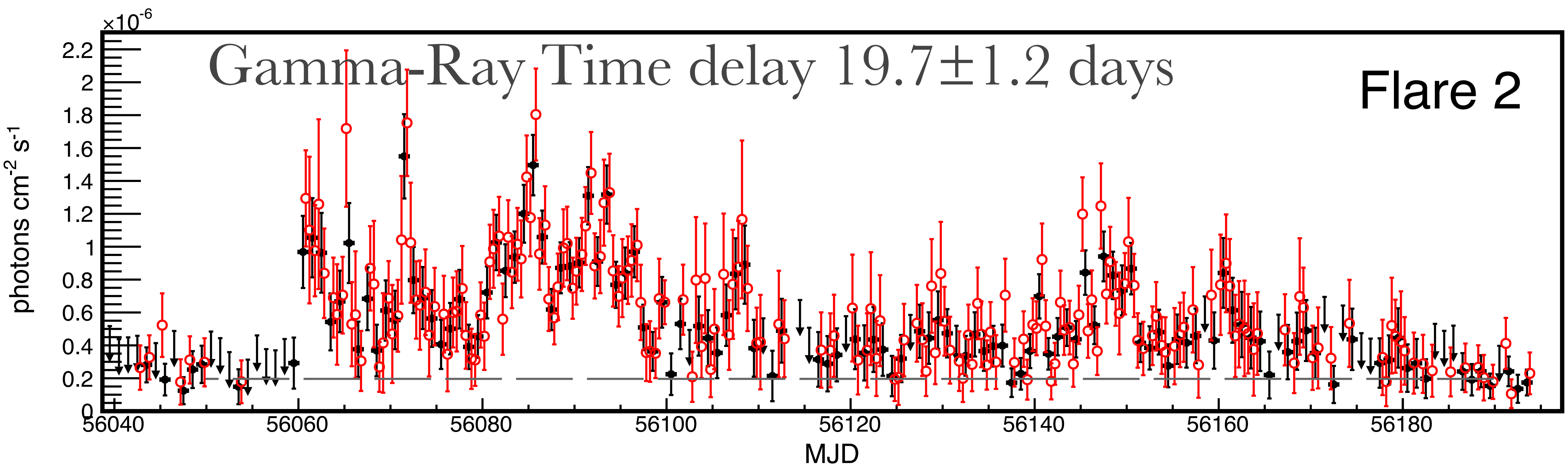

- The first evidence of lensing at gamma-rays (Barnacka et al. 2011)

Gamma-Ray Time delay 27.1±0.45 days

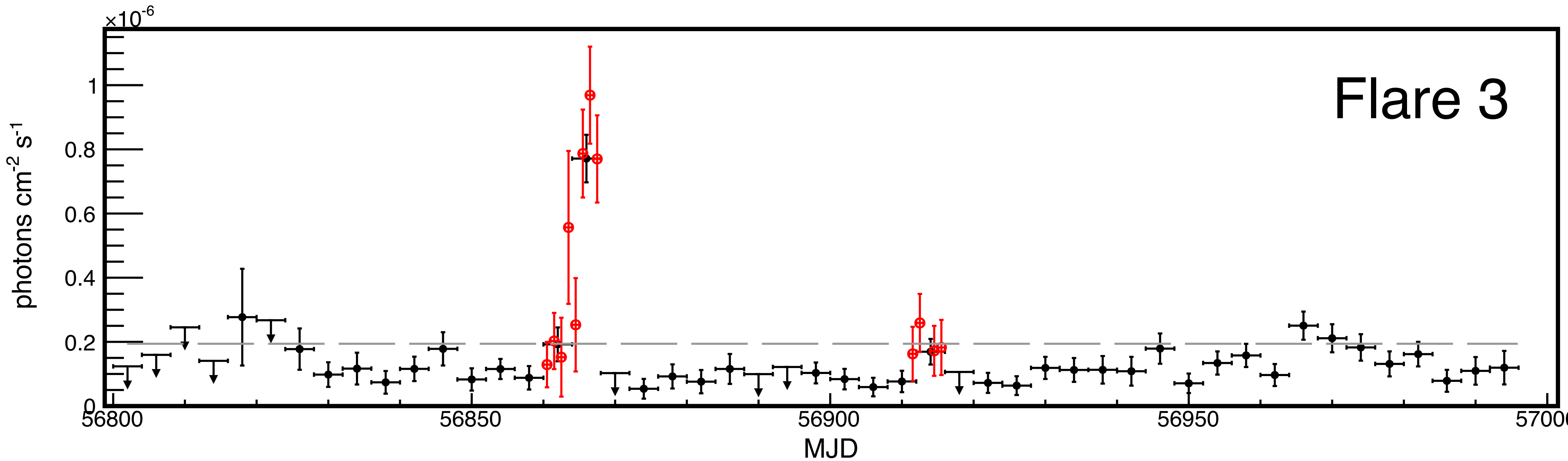
**Gamma-ray Flares Time Delays ?**

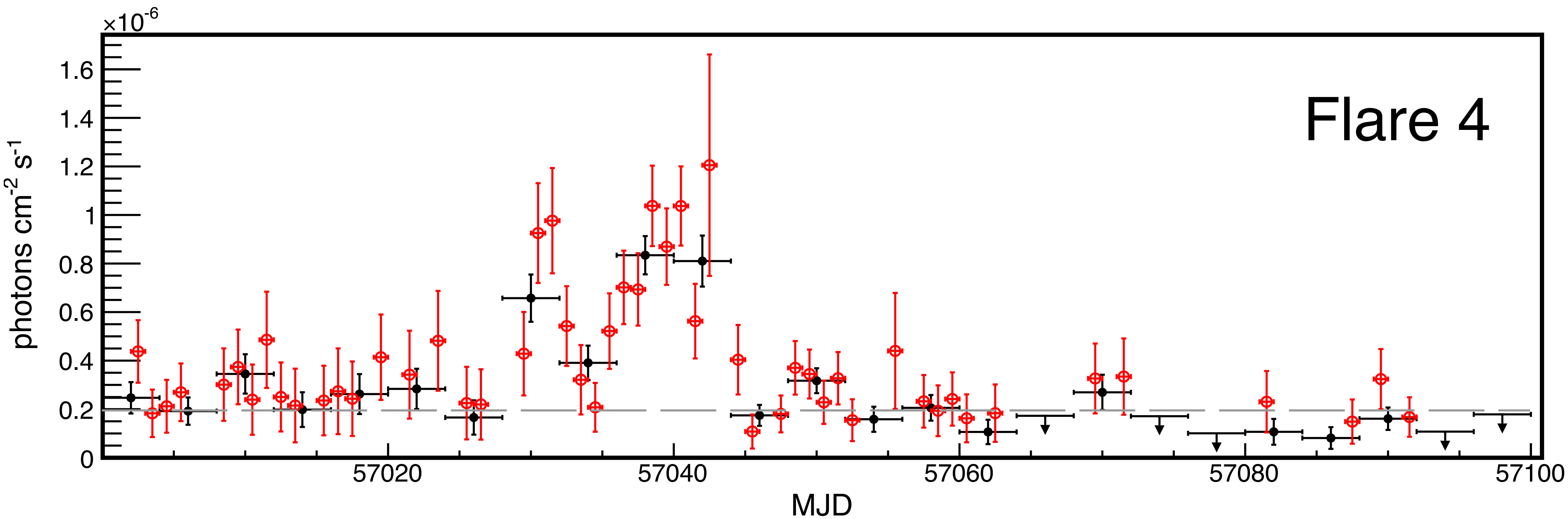
# Gamma-ray Flare 1 and 2: Time Delays



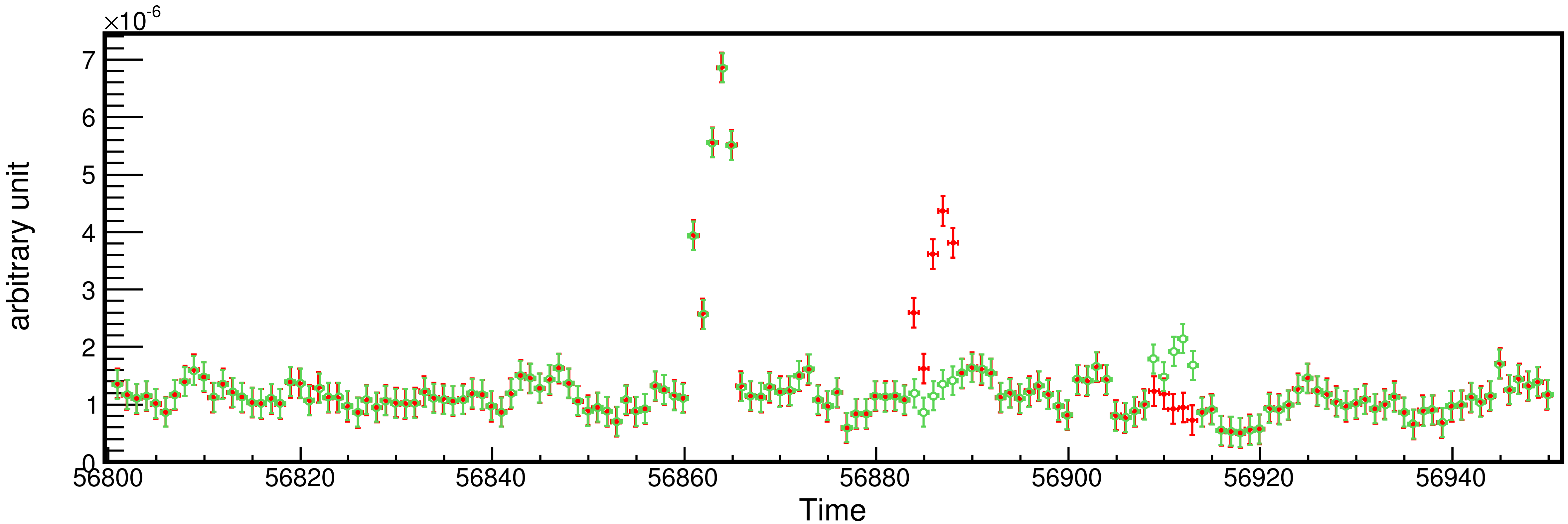
# Gamma-ray Flare 3 and 4: Time Delays



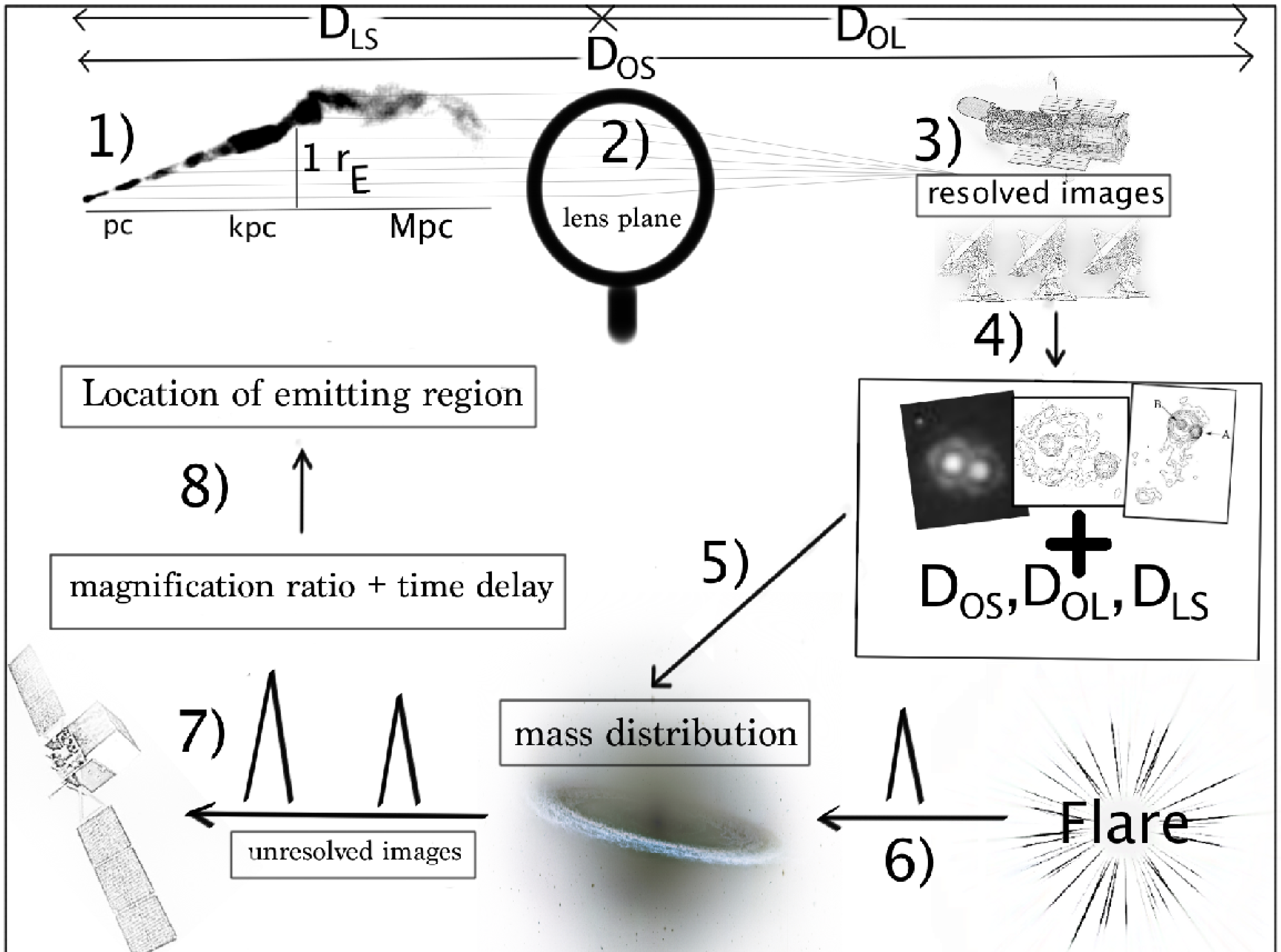




Gamma-Ray Time delay > 50 days

# Monte Carlo Simulations



# Application of strong lensing




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