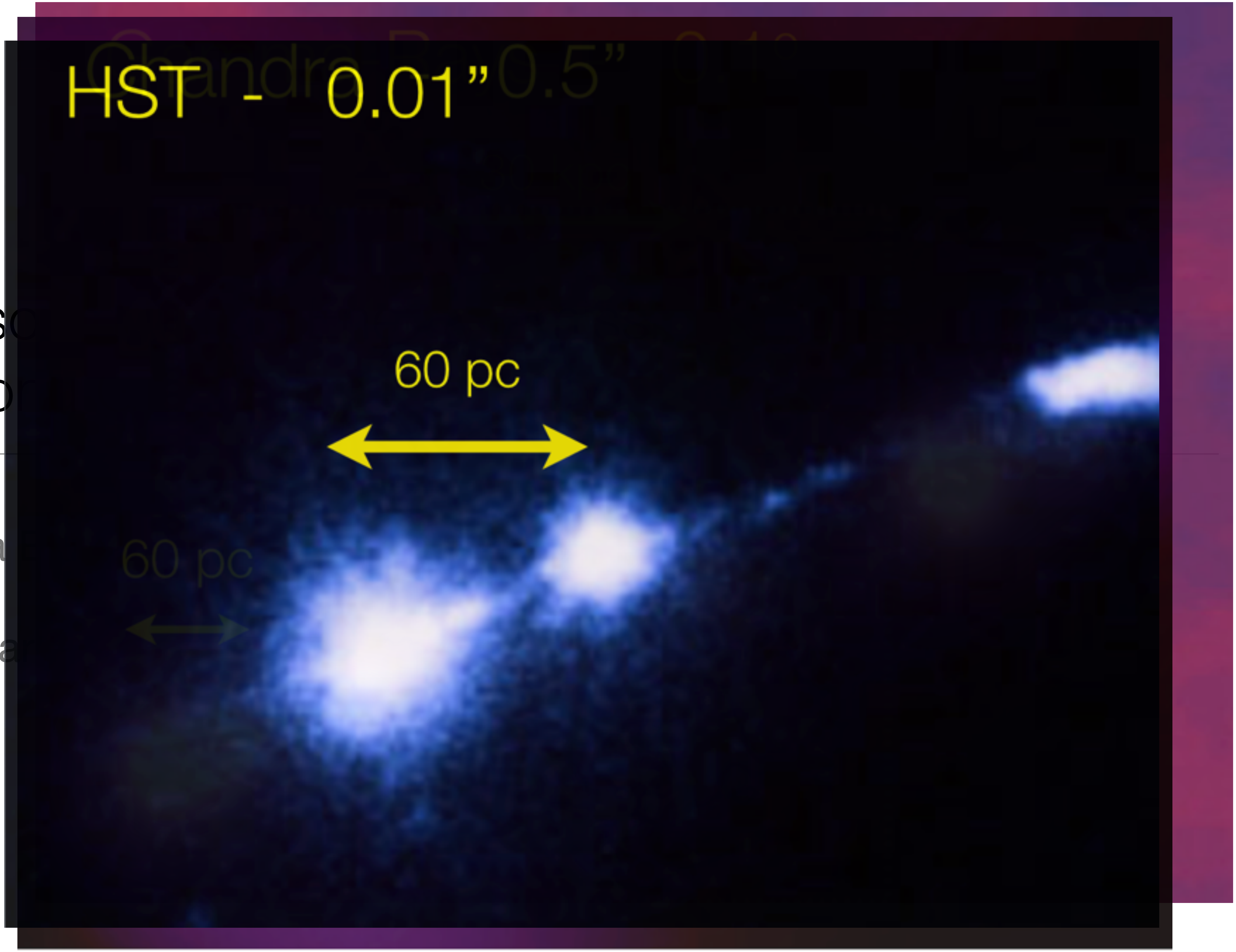
Reso
Stro

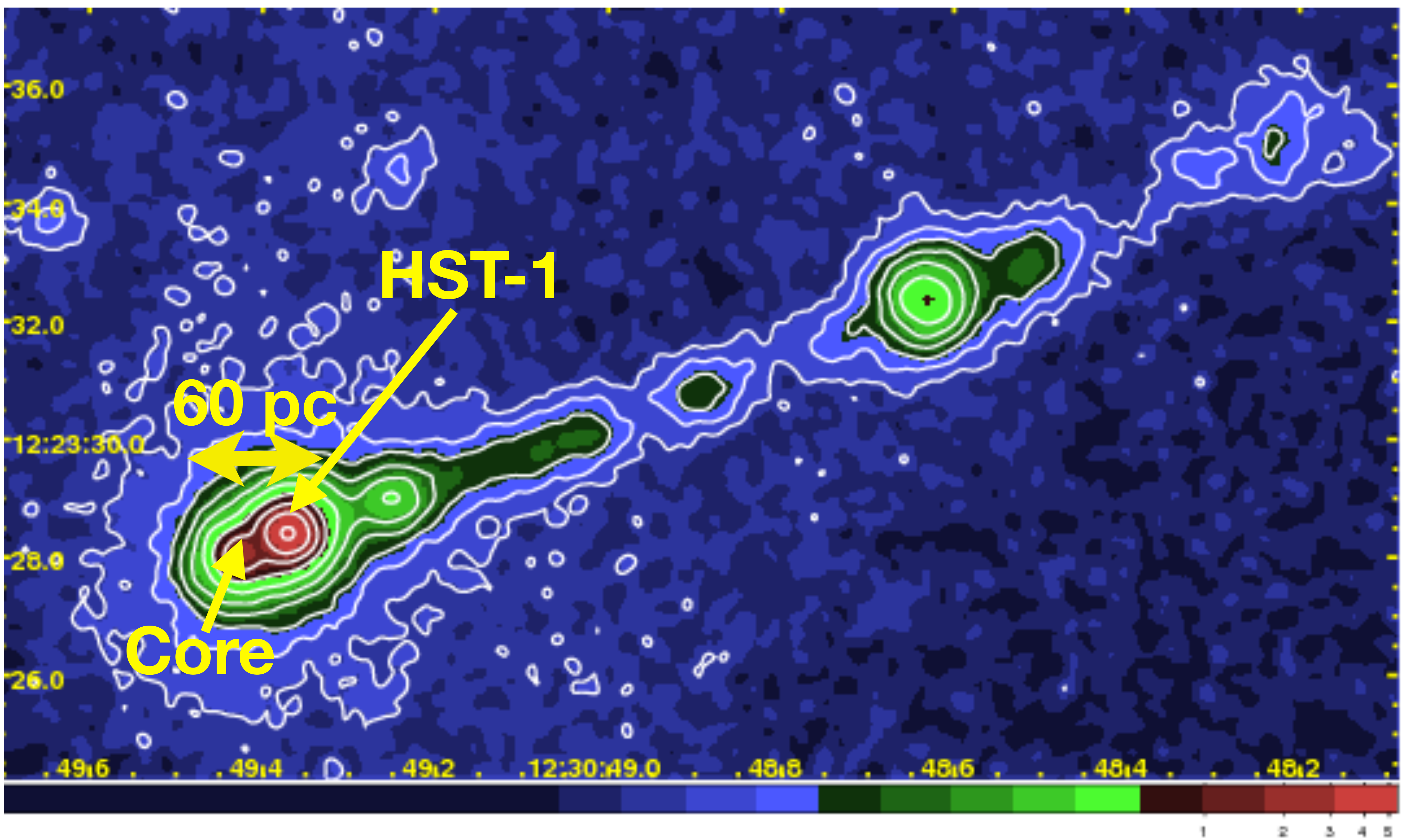
Anna
Harva



X-Ray Jets - Lessons from Chandra

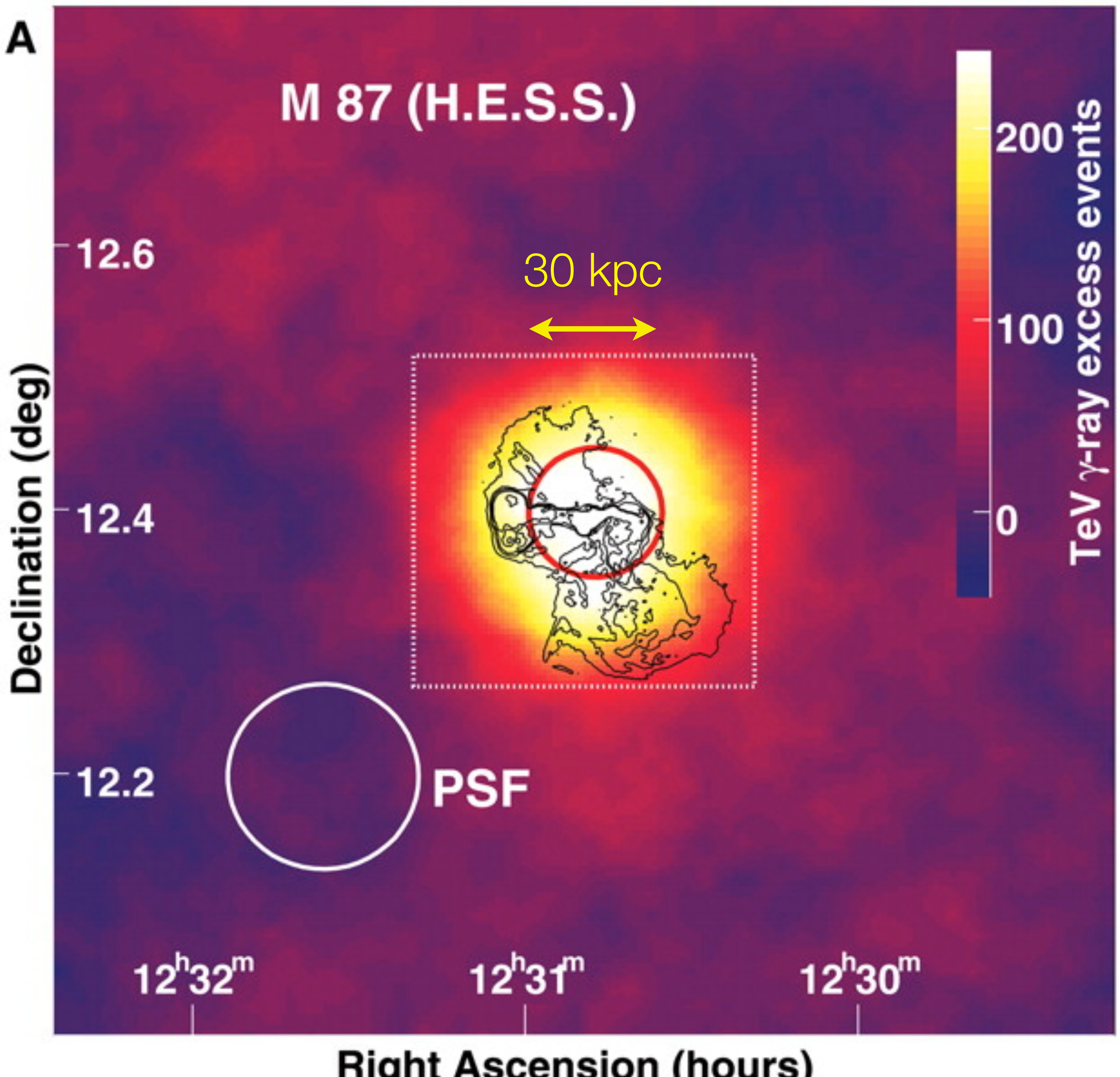
Increased x-ray emission by a factor of 50 from the HST-1 knot (Harris et al. 2006,2009)

Core and HST-1: Separation ~ 60 pc



Flares from knots along the jets

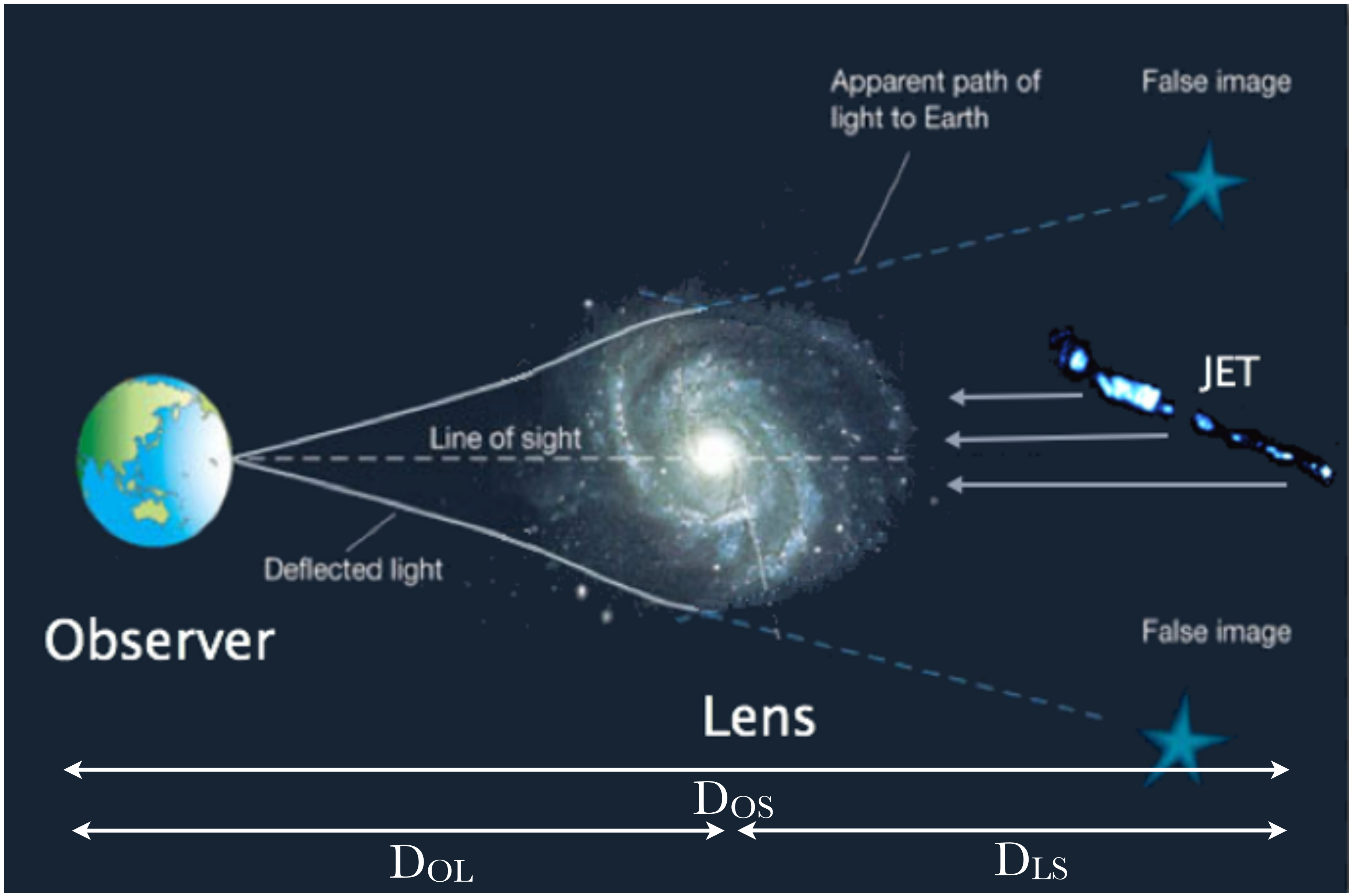
Ambiguity of Gamma-Ray Origin



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

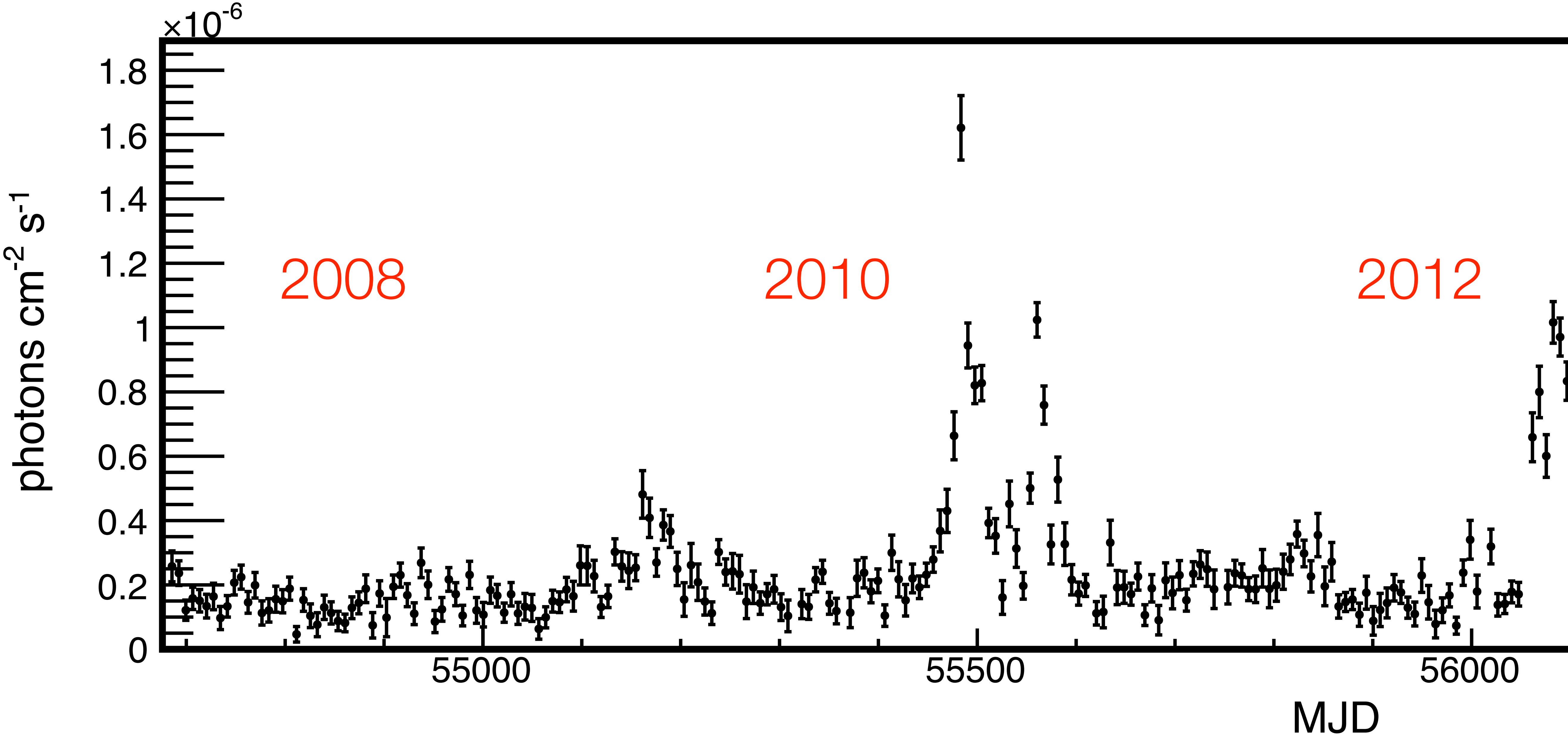
time delay magnification ratio

M87 as a Toy Model

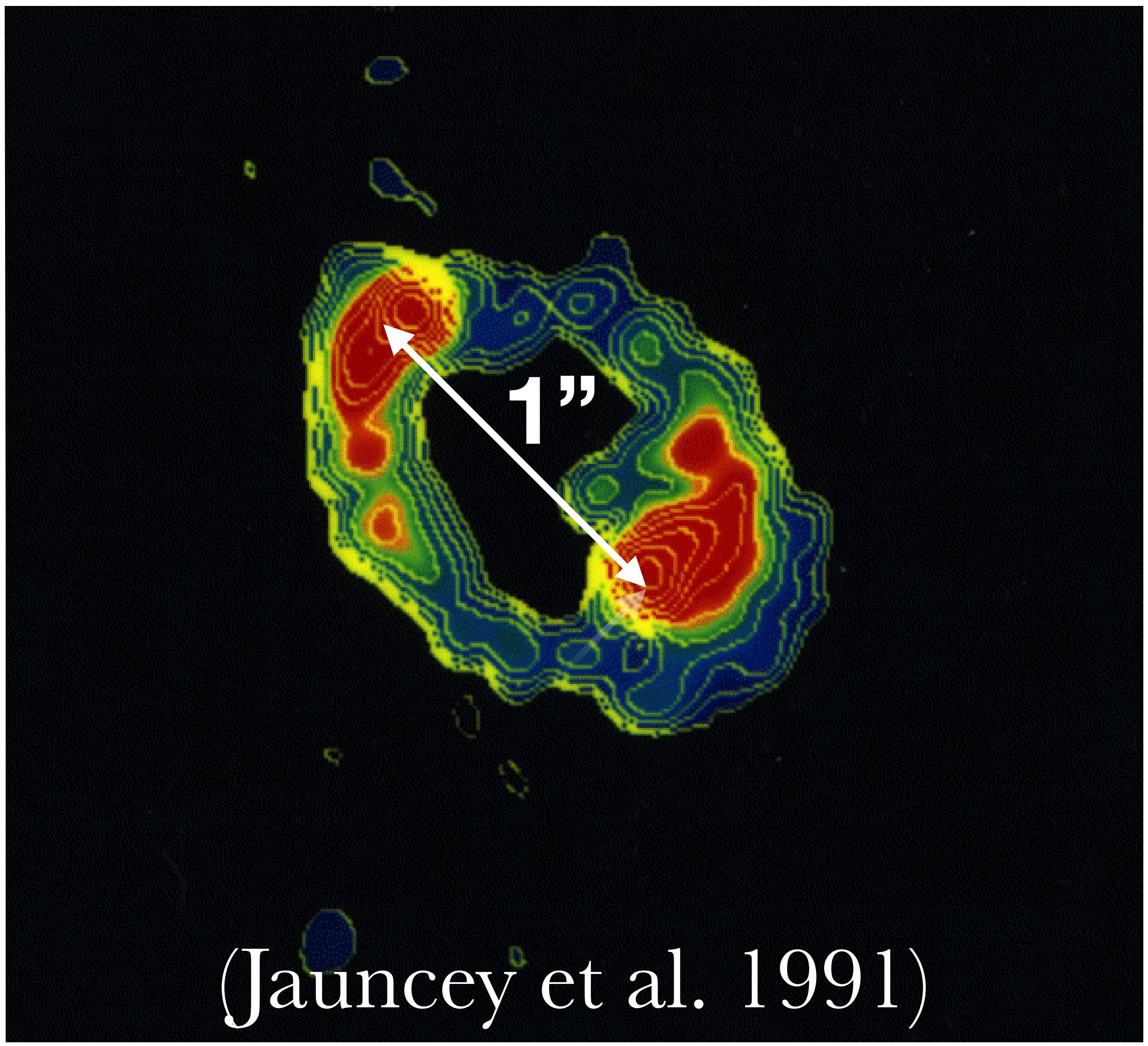
- zs=1, zl = 0.6
- Einstein radius ~ 2.2 kpc (0.45”)
- 60 pc ~ 0.01” ~ 3% Einstein radius
  - Differences between the **core** and the **HST-1**:
    - **difference in time delay: ~ 2 days**
    - **difference in magnification ratio: ~ 0.2**

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

Temporal Resolution at Gamma Rays



Lensed Gamma-Ray Jets: PKS 1830-211



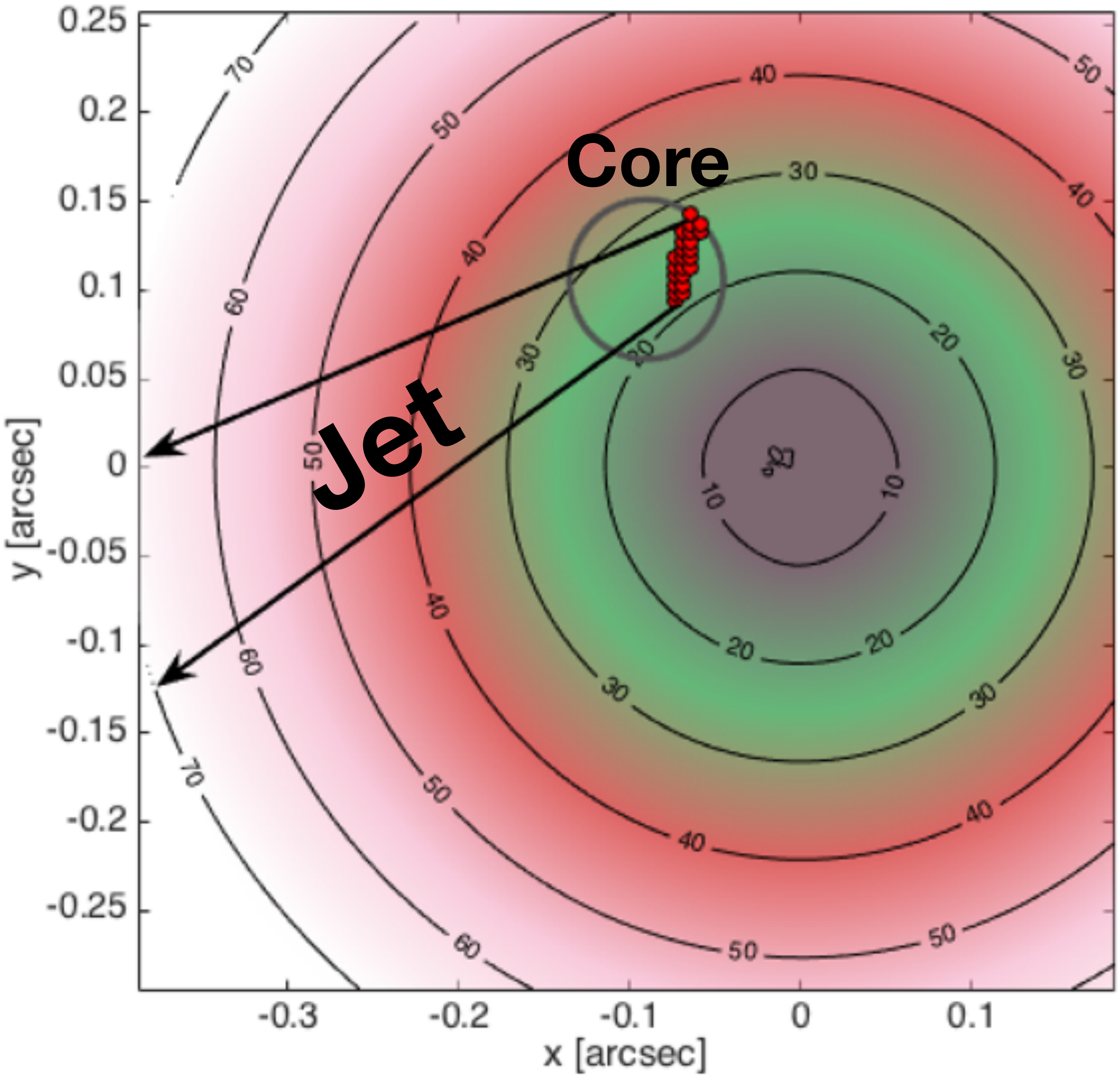
Source z = 2.5,
Lens z = 0.9

Radio Time Delay
26±5 days

Magnification Ratio
1.52±0.05

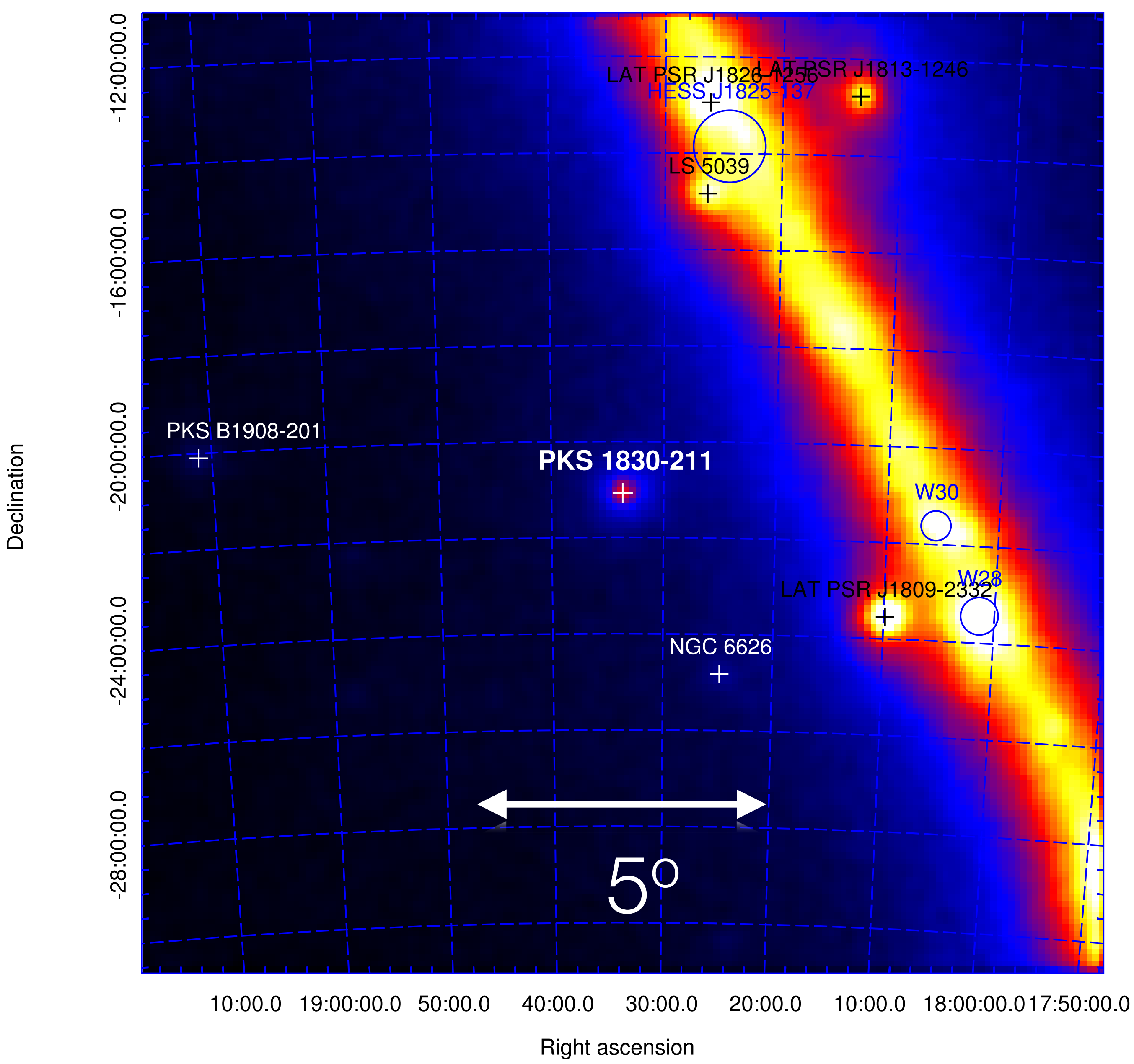
(Lovell et al. 1998)

Properties of the Lensed System



Barnacka, A., et al. (April, 2015: **arXiv:1504.05210**)

Lensed Gamma-Ray Jets: PKS 1830-211

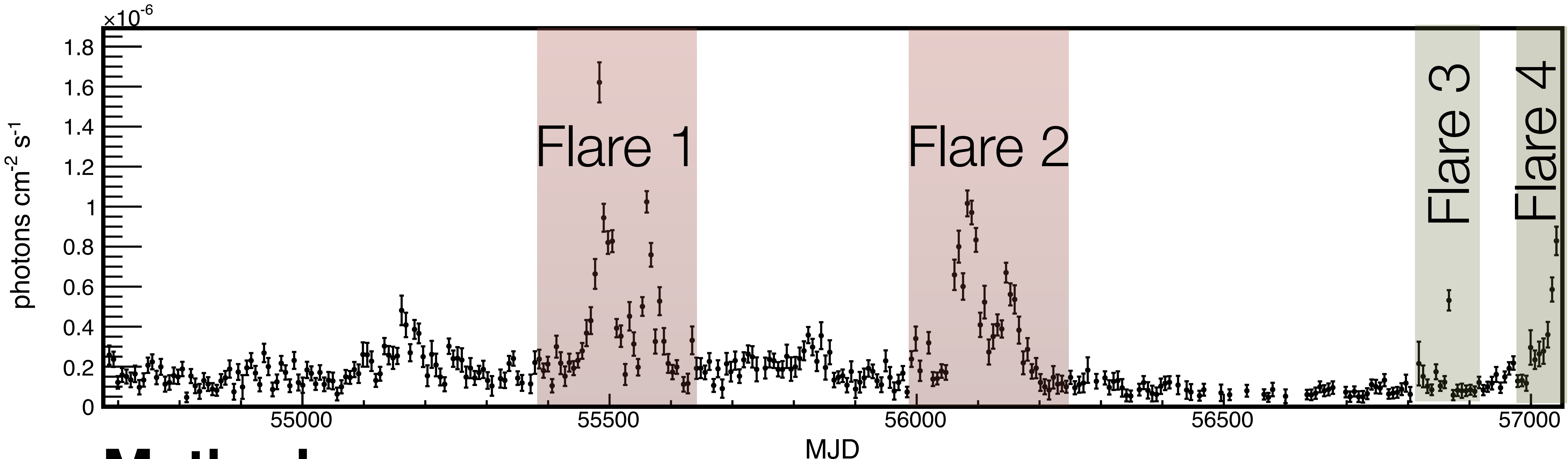


- The first evidence of lensing at gamma-rays (Barnacka et al. 2011)

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

Characteristic of the Signal

Power Law Noise

$$S(f) \propto 1/f^{\alpha}$$

α ~ 2 - Red Noise: Flaring State

α ~ 1 - Pink Noise: Quiescent State

α ~ 0 - White Noise

Double Power Spectrum

a - time delay **b** - magnification ratio

I Fourier Transform

$$\text{f(t)+bf(t+a)} \underset{FT}{\longrightarrow} \tilde{f}(\nu) + b\tilde{f}(\nu)e^{-2\pi i\nu a}$$

$$\tilde{g}(\nu) = \tilde{f}(\nu)(1 + be^{-2\pi i\nu a})$$

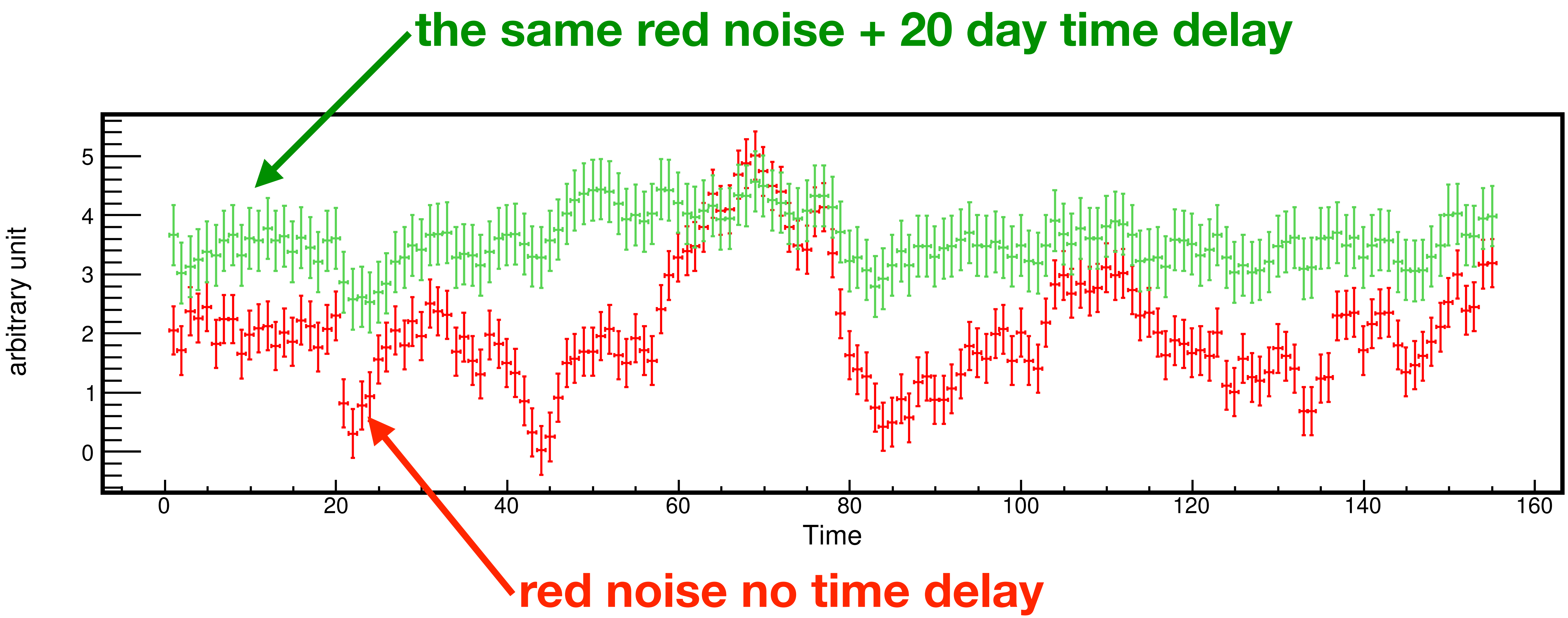
I Power Spectrum

$$P_\nu = |\tilde{g}(\nu)|^2 = |\tilde{f}(\nu)|^2(1 + b^2 + 2bcos(2\pi\nu a))$$

The measured Power Spectrum is the product of the "true" power spectrum of the source times a periodic component with a period equal to the inverse of the relative time delay "a"

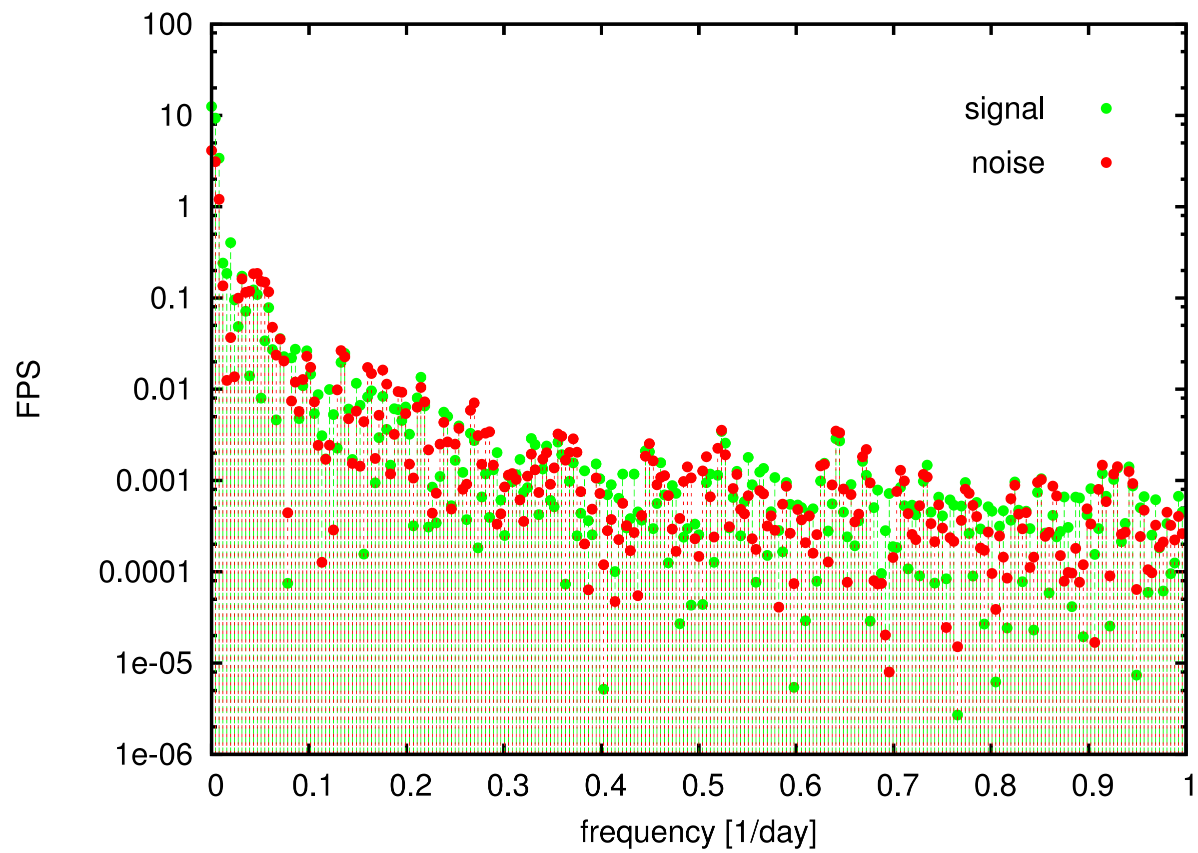
The cepstrum method (Bogert et al. 1963)

Double Power Spectrum - Monte Calo Simulations

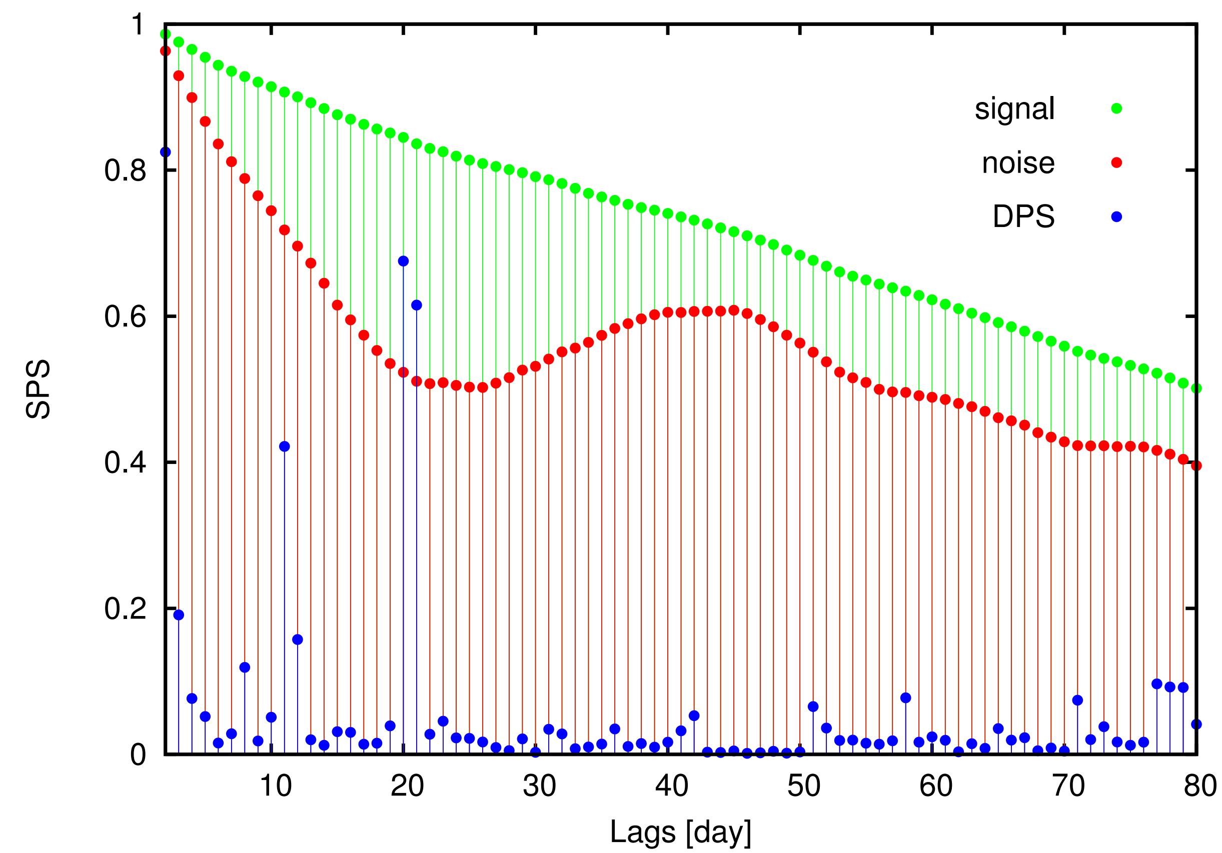


Double Power Spectrum - Monte Calo Simulations

I Power Spectrum



II Power Spectrum



Red - red noise, no time delay simulated, no signal processing

Green - red noise, 20 days time delay, no signal processing

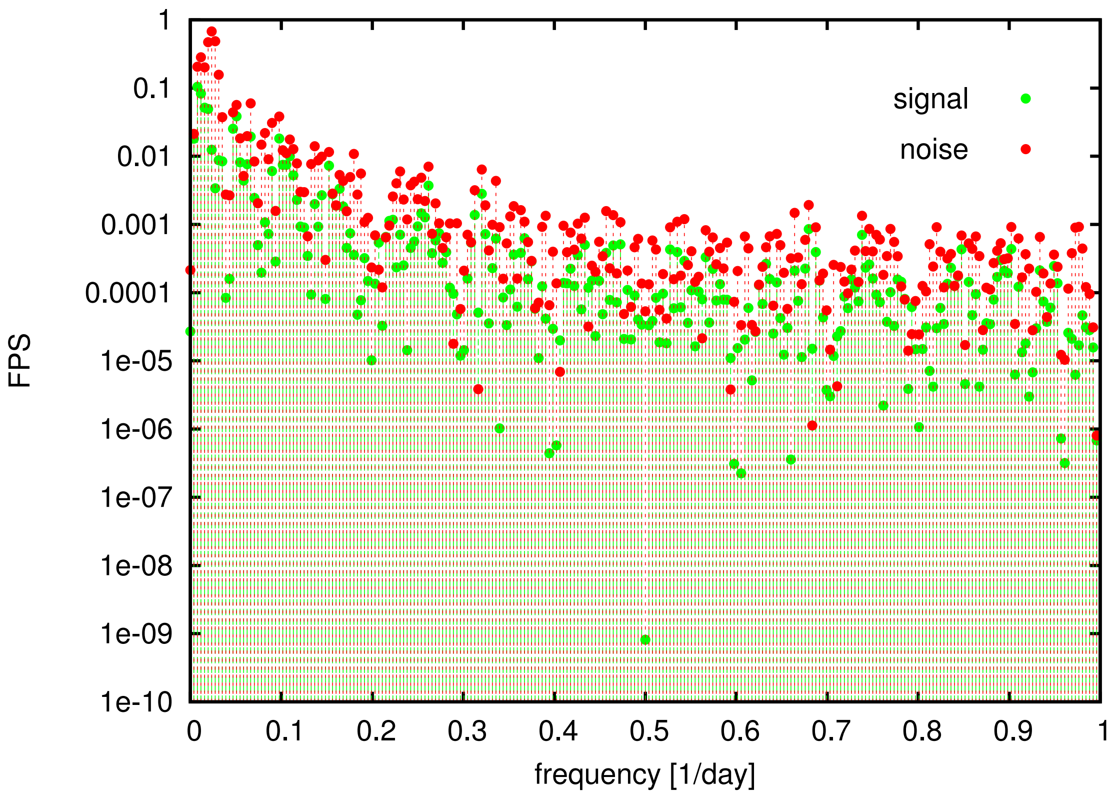
Blue - red noise, 20 days time delay, **after signal processing**

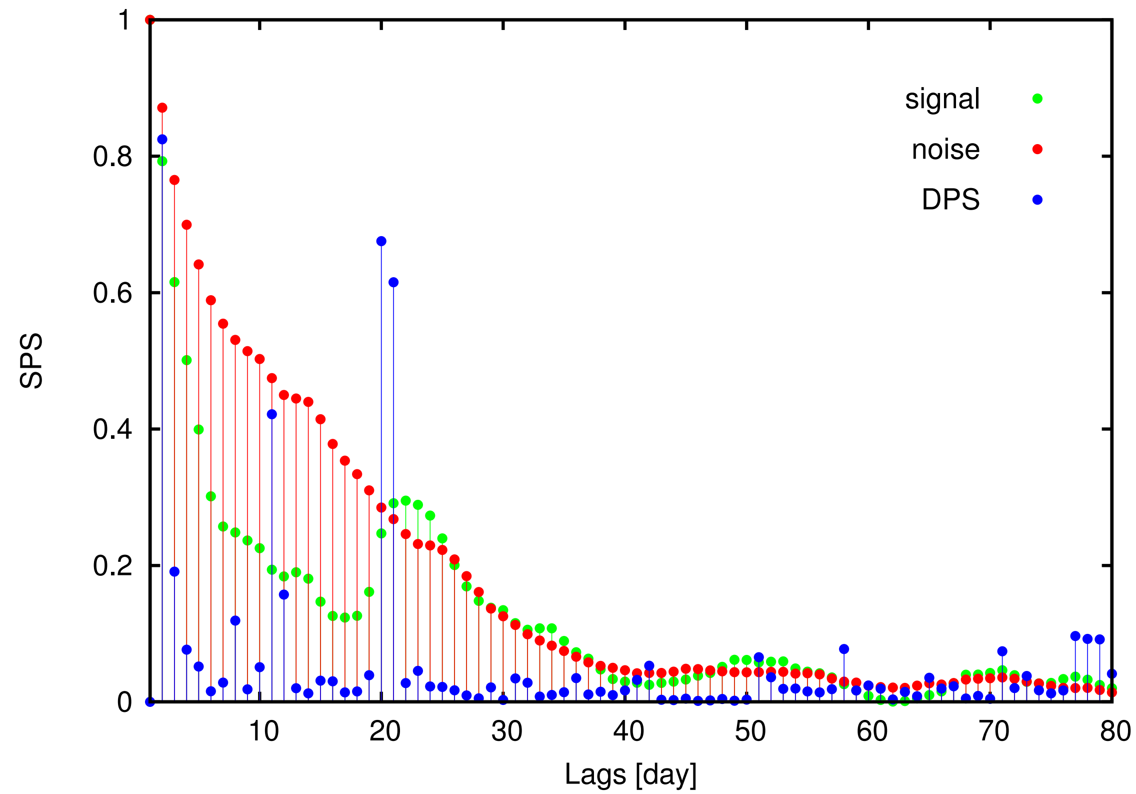
Signal Processing - Step 1

Based on widely used methods: Oppenheimer & Schafer (1975), Brault & White (1971)

Step 1: The First Power Spectrum

Mean Extraction and Windowing, Zero Padding, Doubling the Points

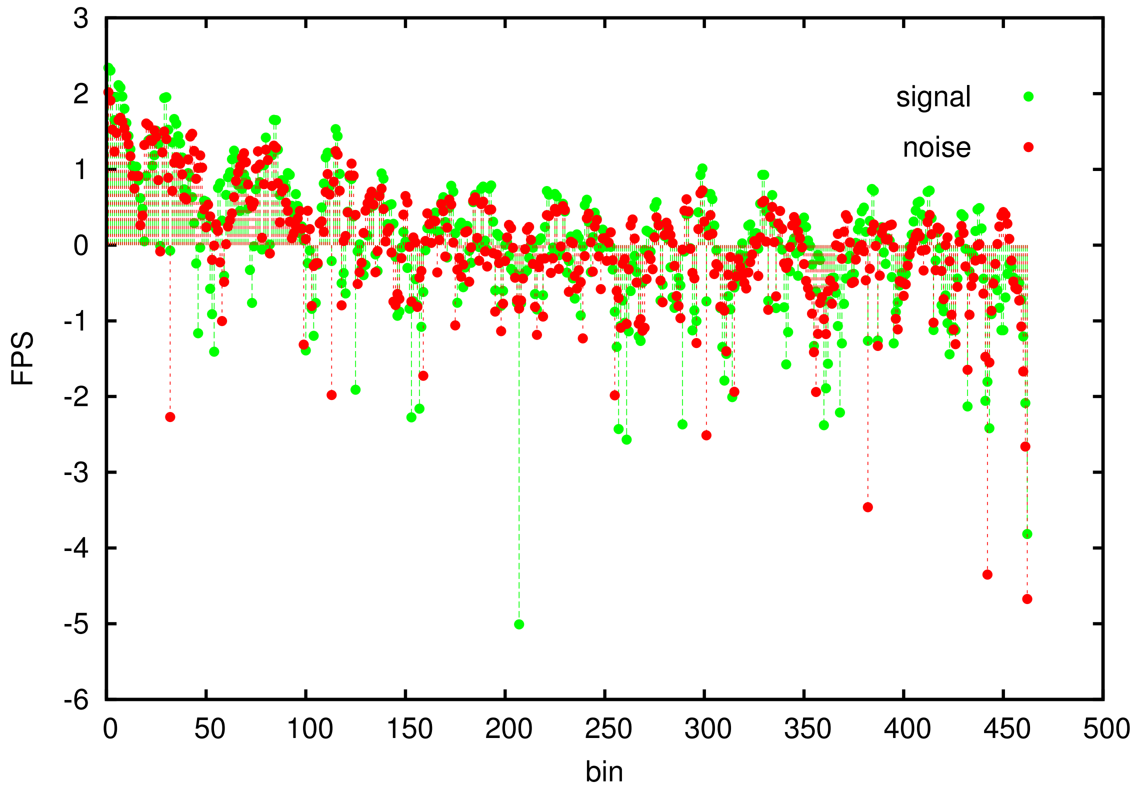


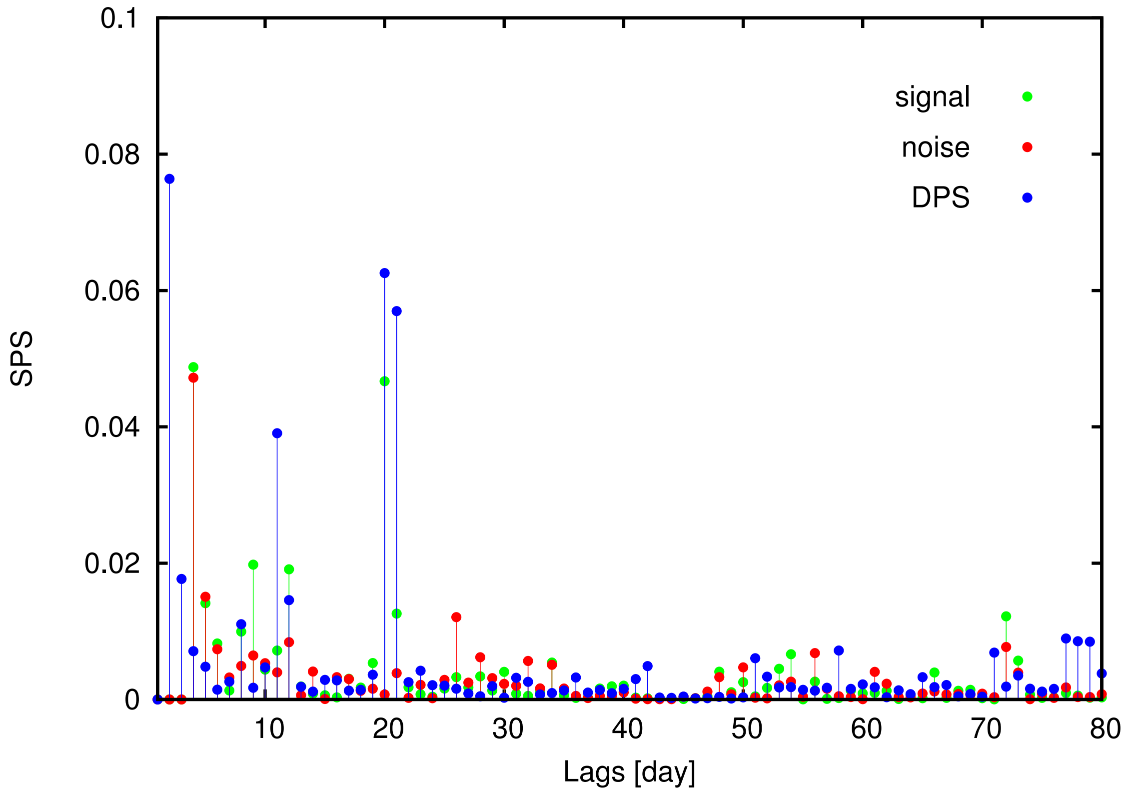


Signal Processing - Step 2

Step 2: The Second Power Spectrum

Flattening and Mean Extraction

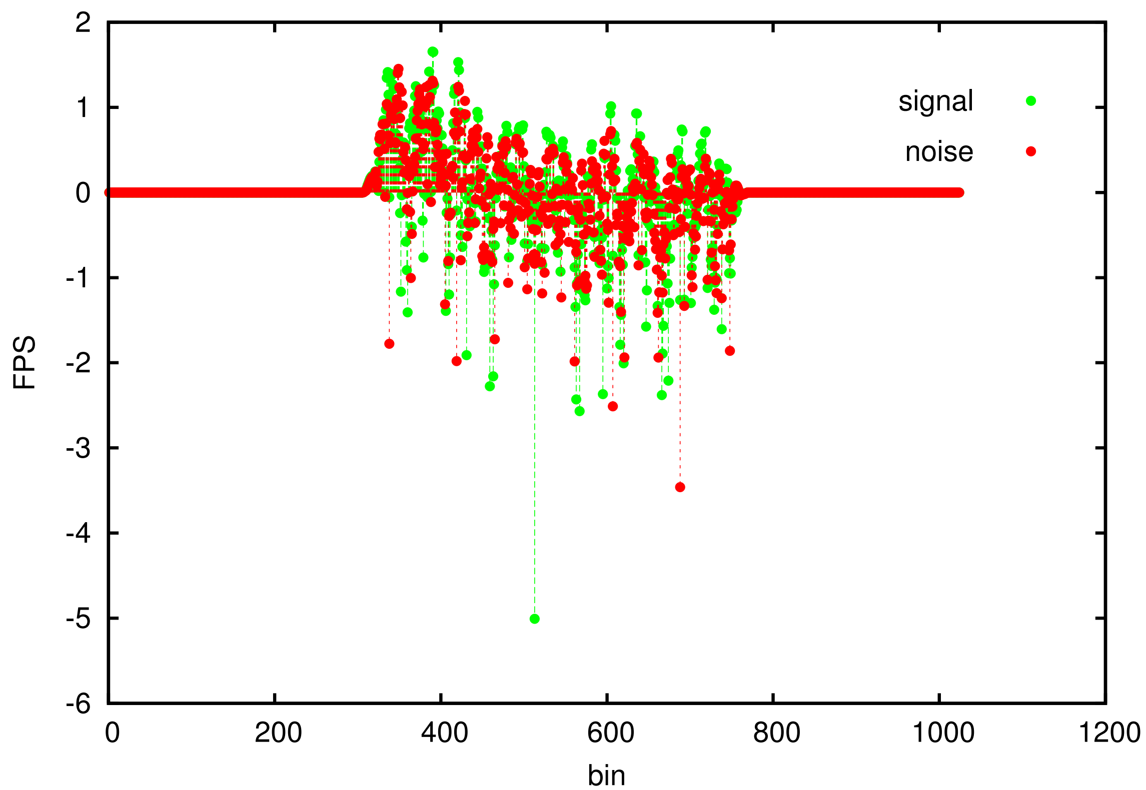


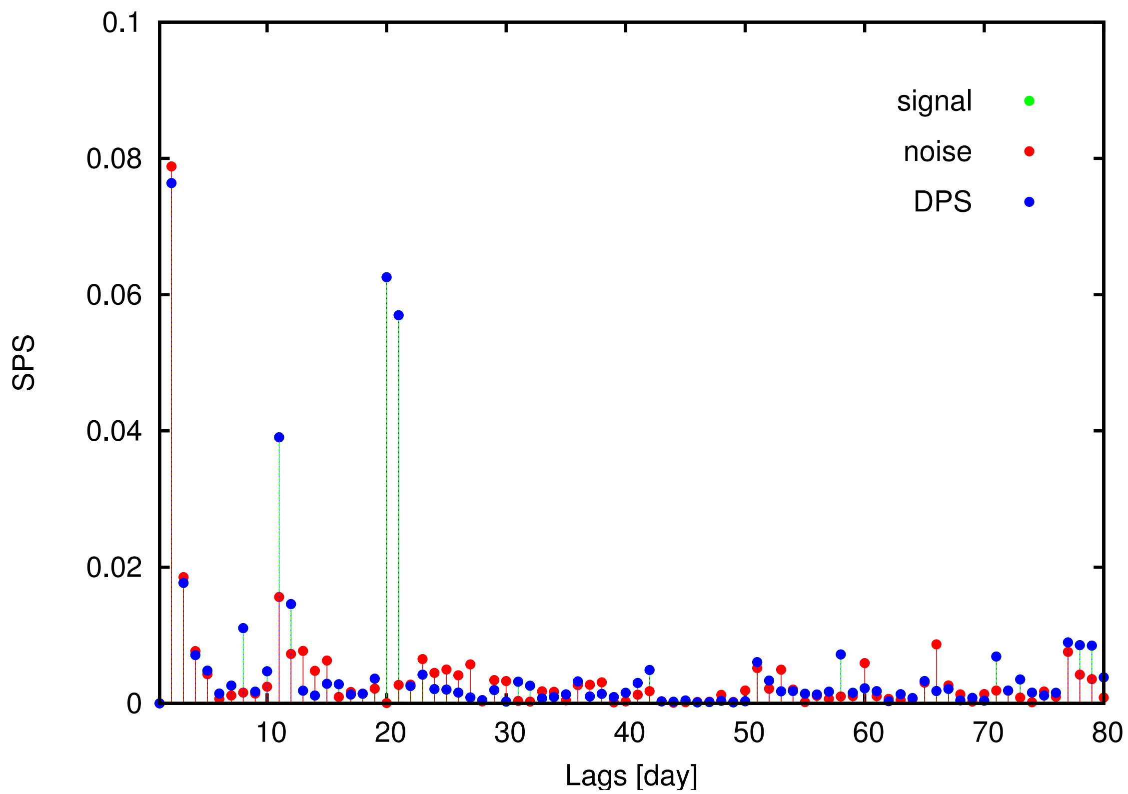


Signal Processing - Step 3

Step 3: The Second Power Spectrum

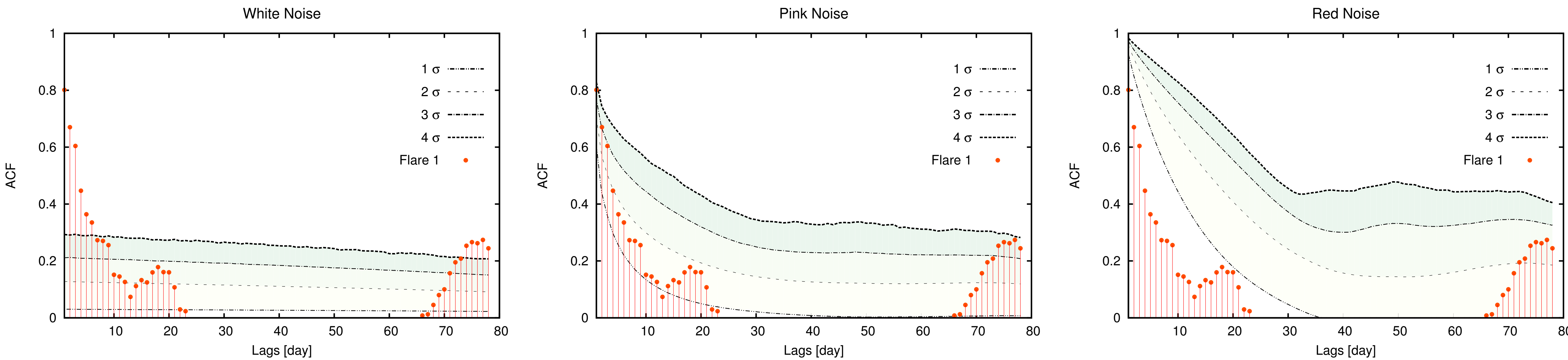
Windowing (Bingham window) and Zero Padding



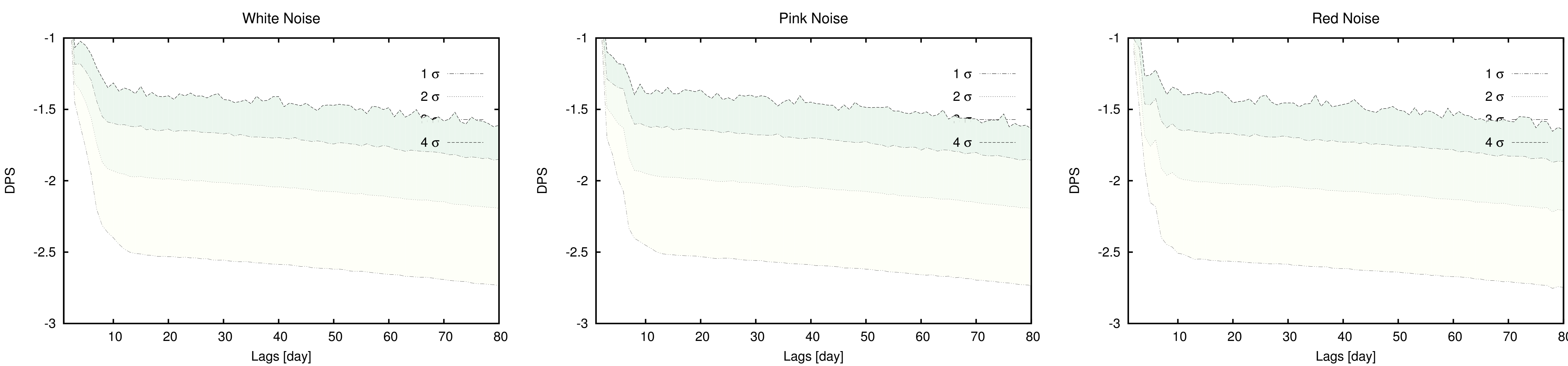


Monte Carlo Simulations - Significance Level

Autocorrelation Function

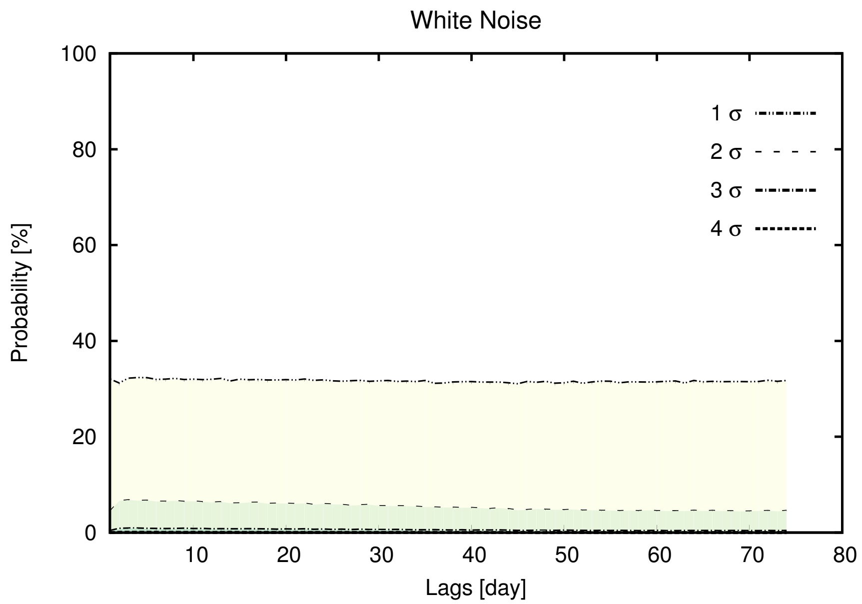


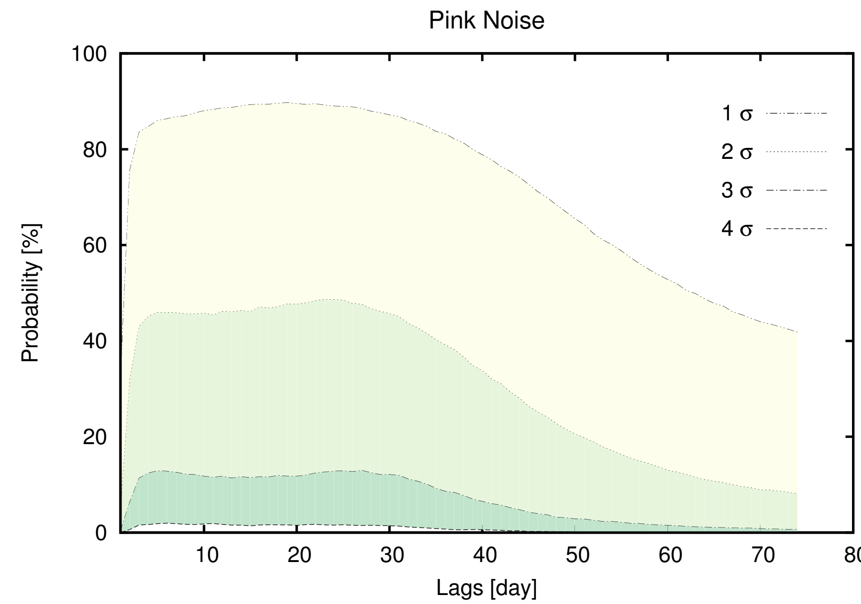
Double Power Spectrum

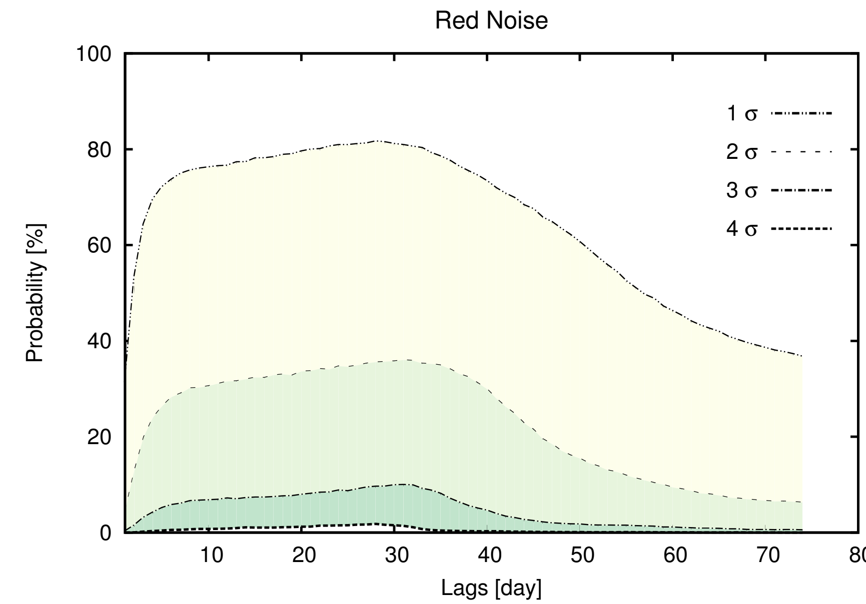


Detectability of the Time Delay

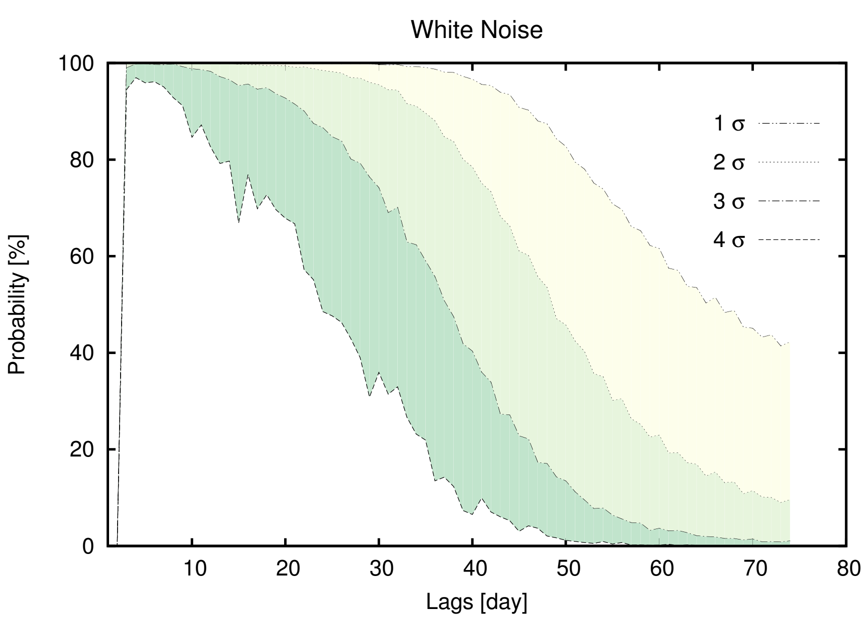
Autocorrelation Function

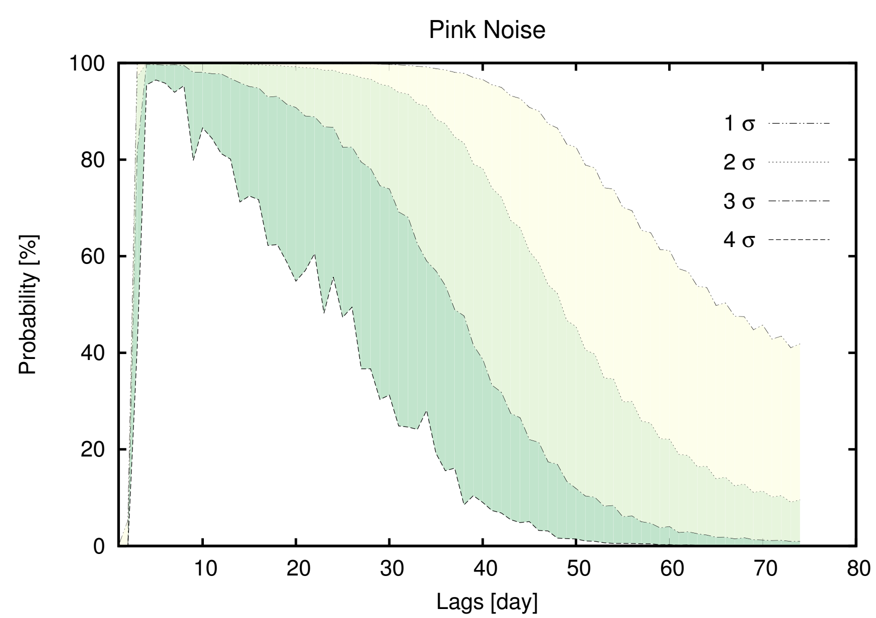


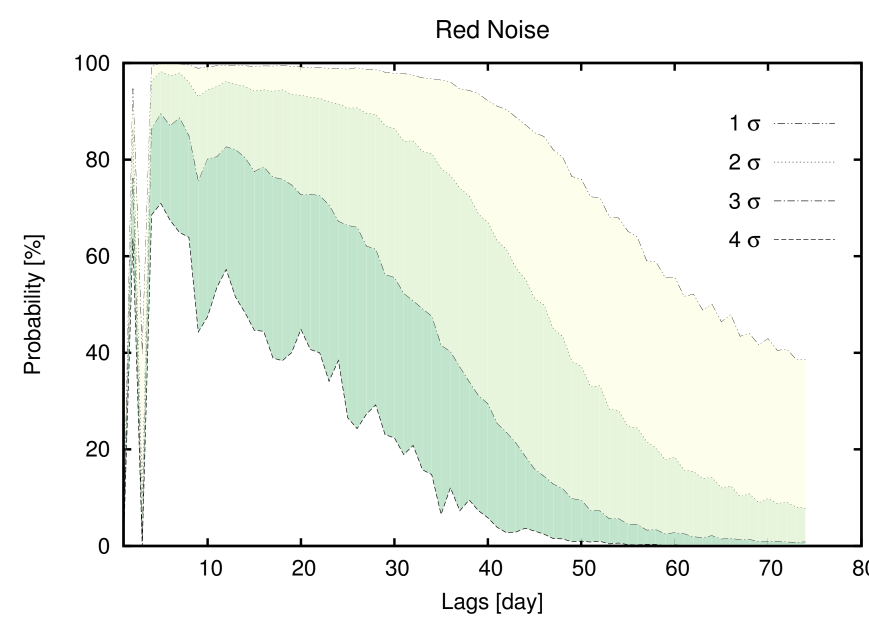




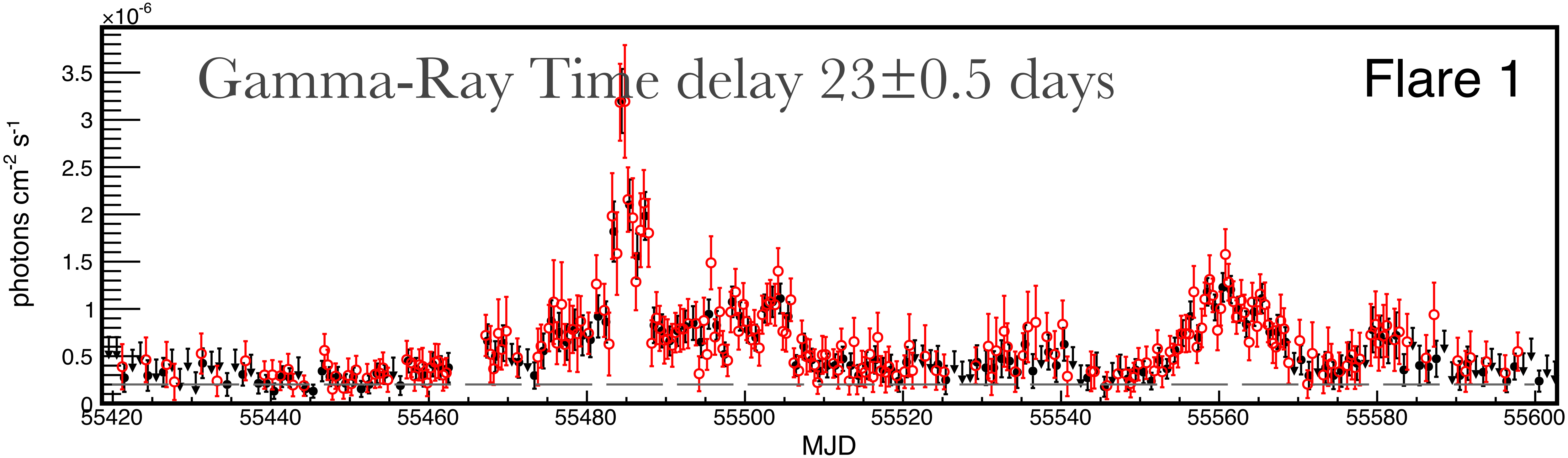
Double Power Spectrum

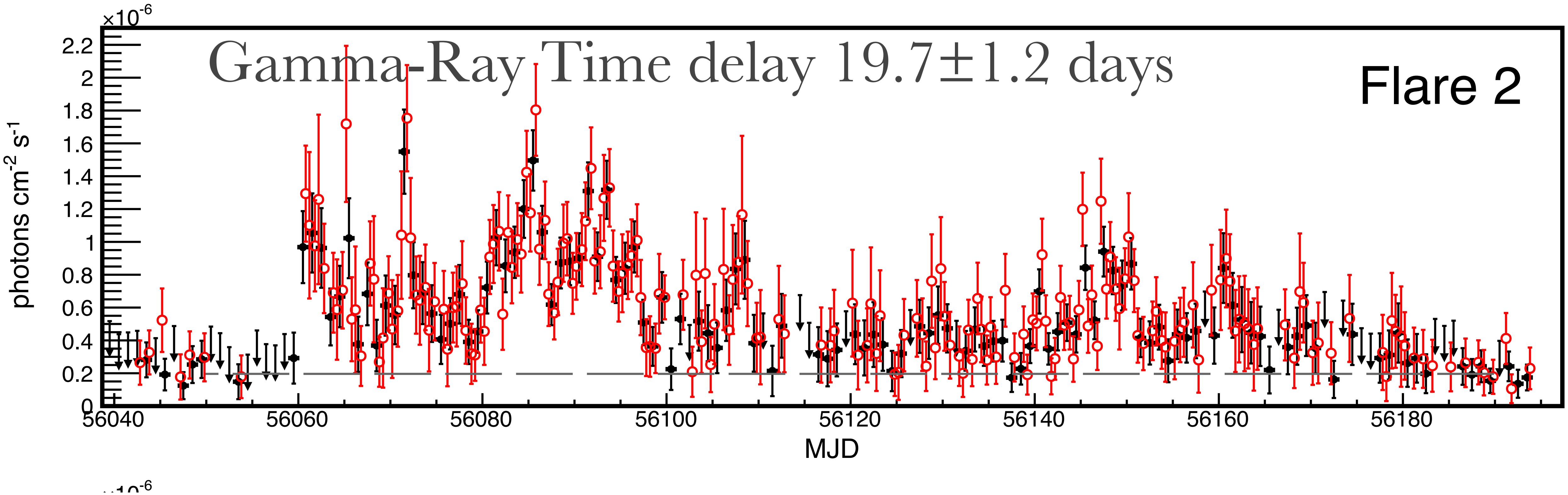






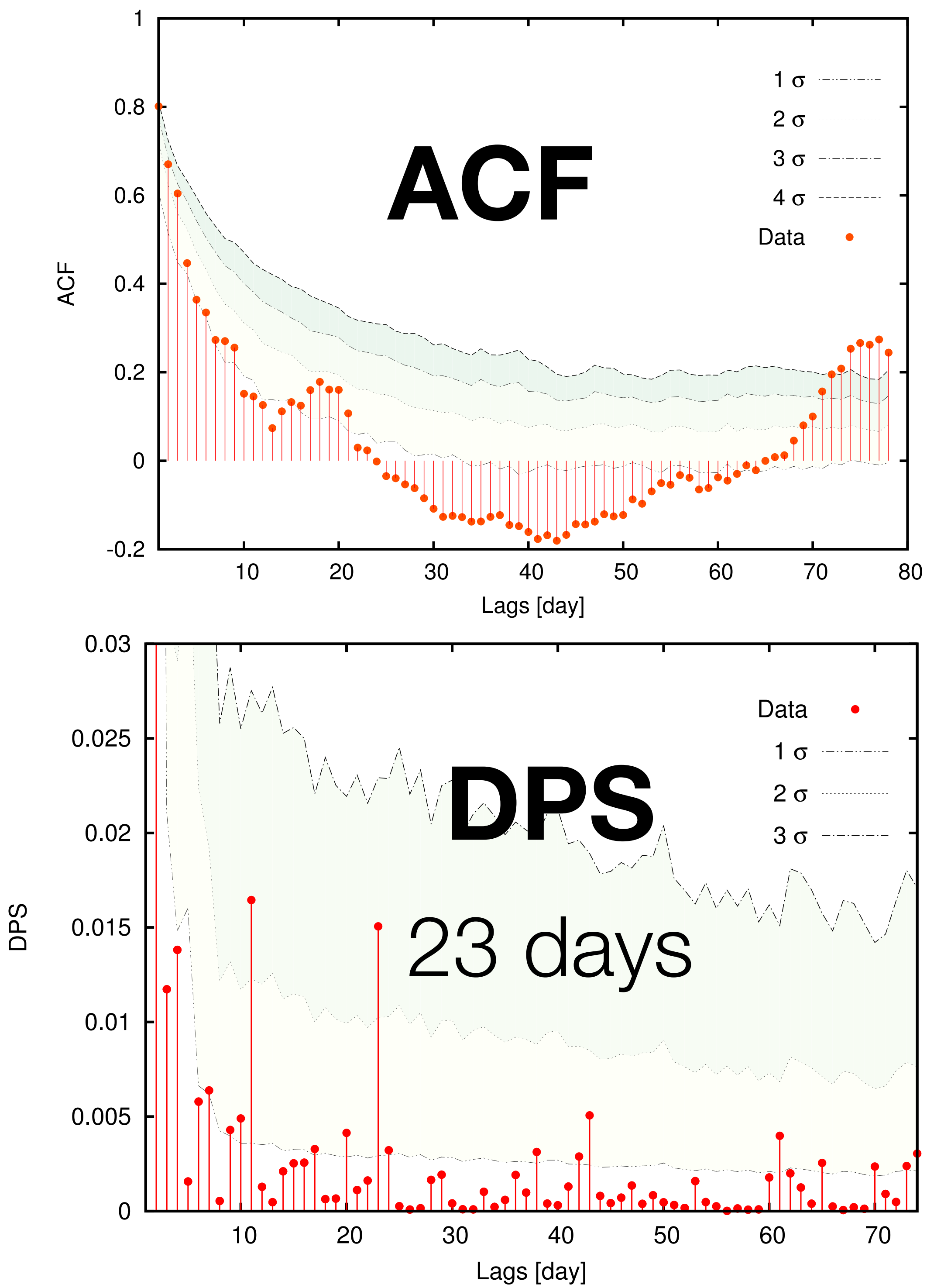
Gamma-ray Flare 1 and 2: Light Curves



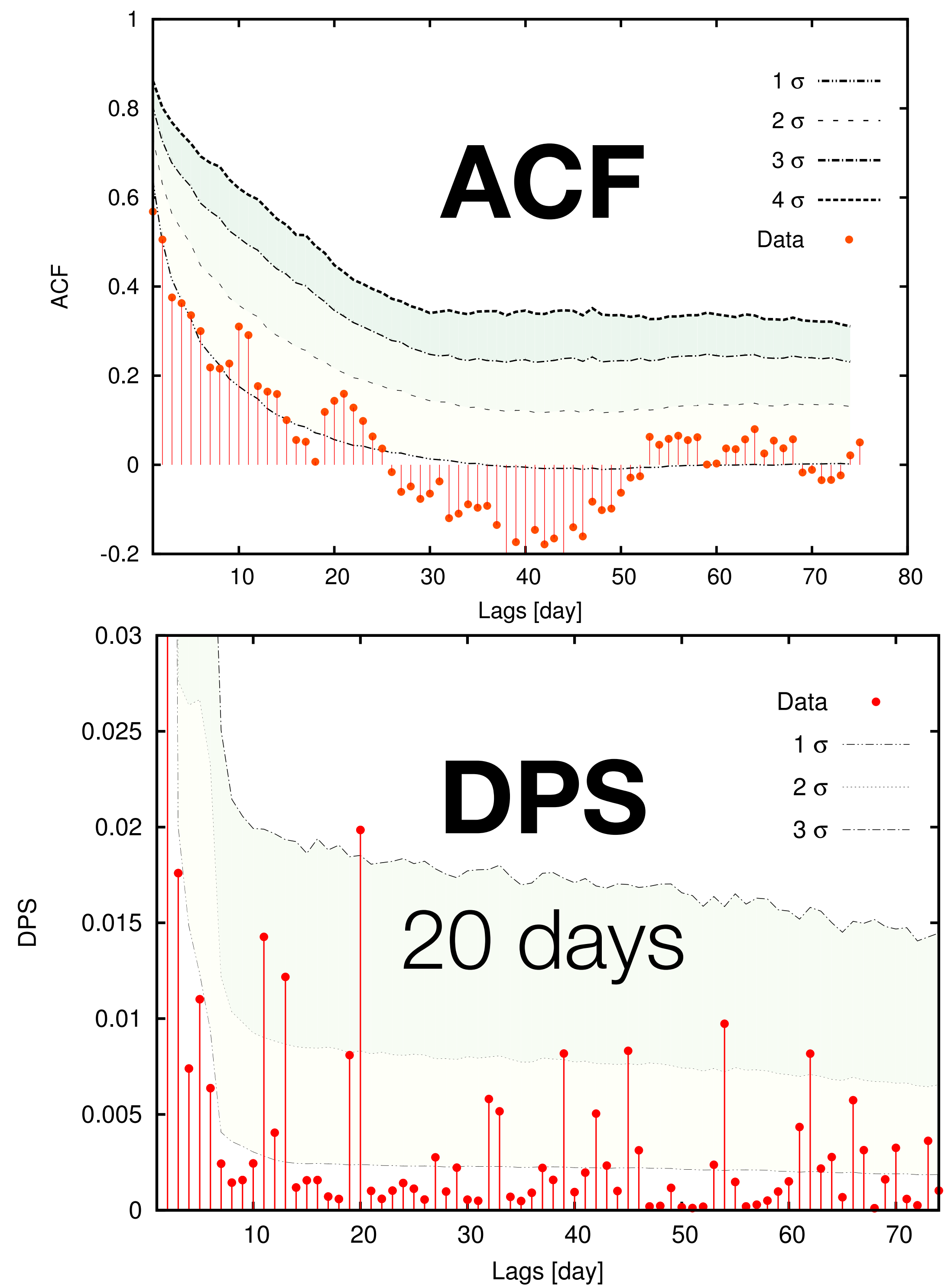


Gamma-ray Flare 1 and 2: Time Delays

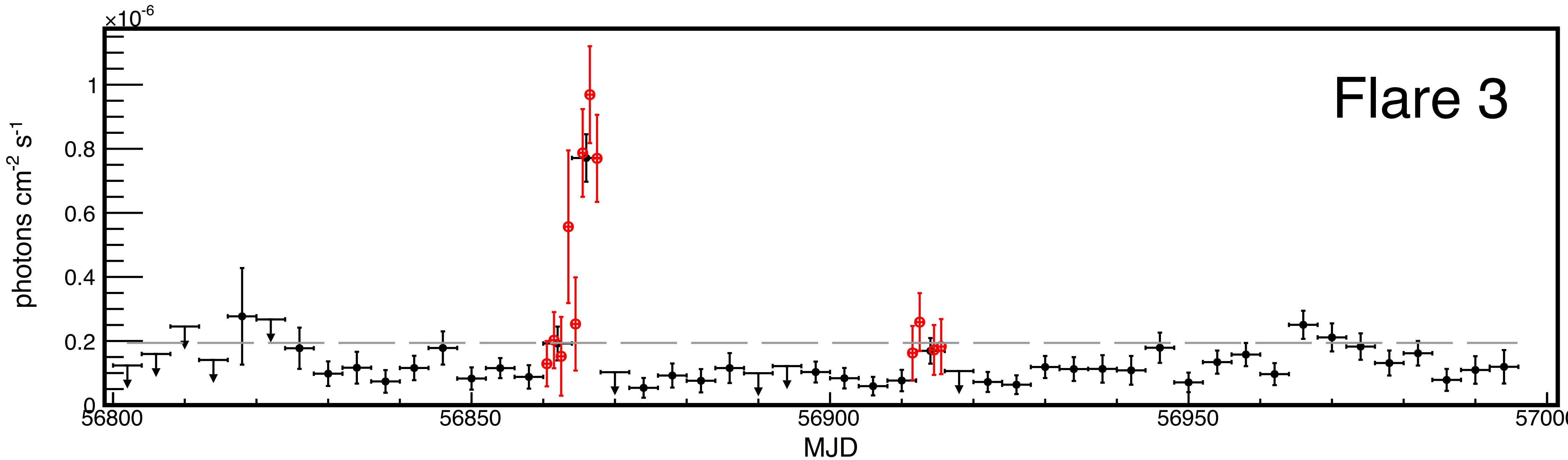
Flare 1

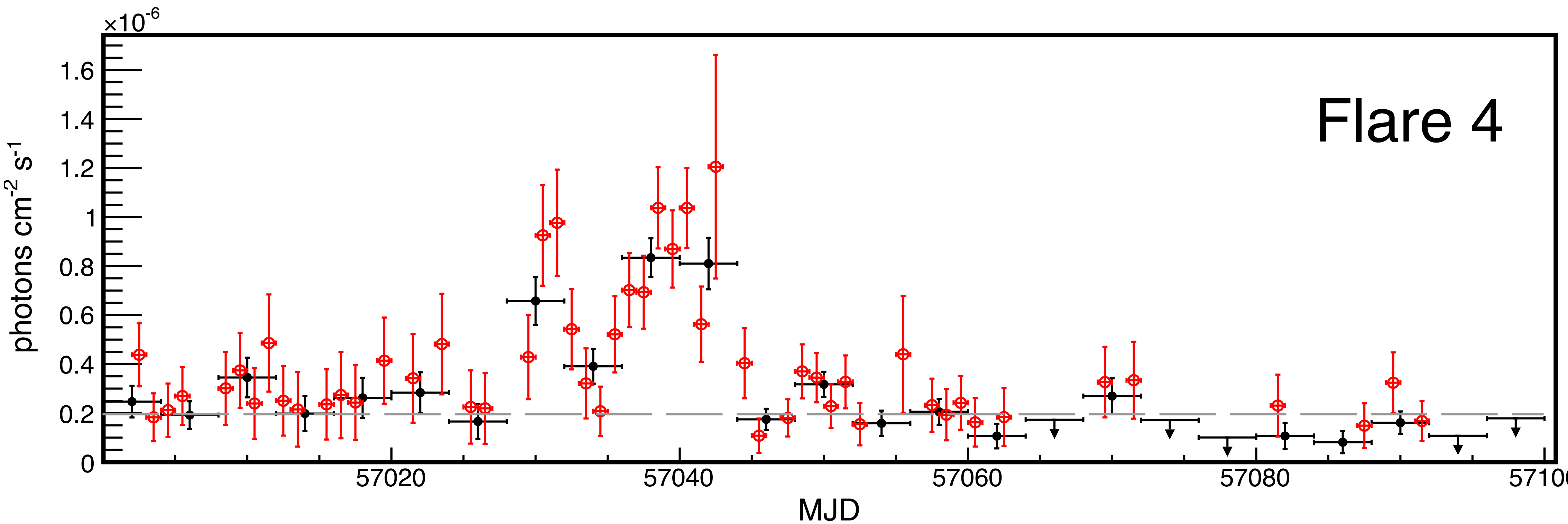


Flare 2

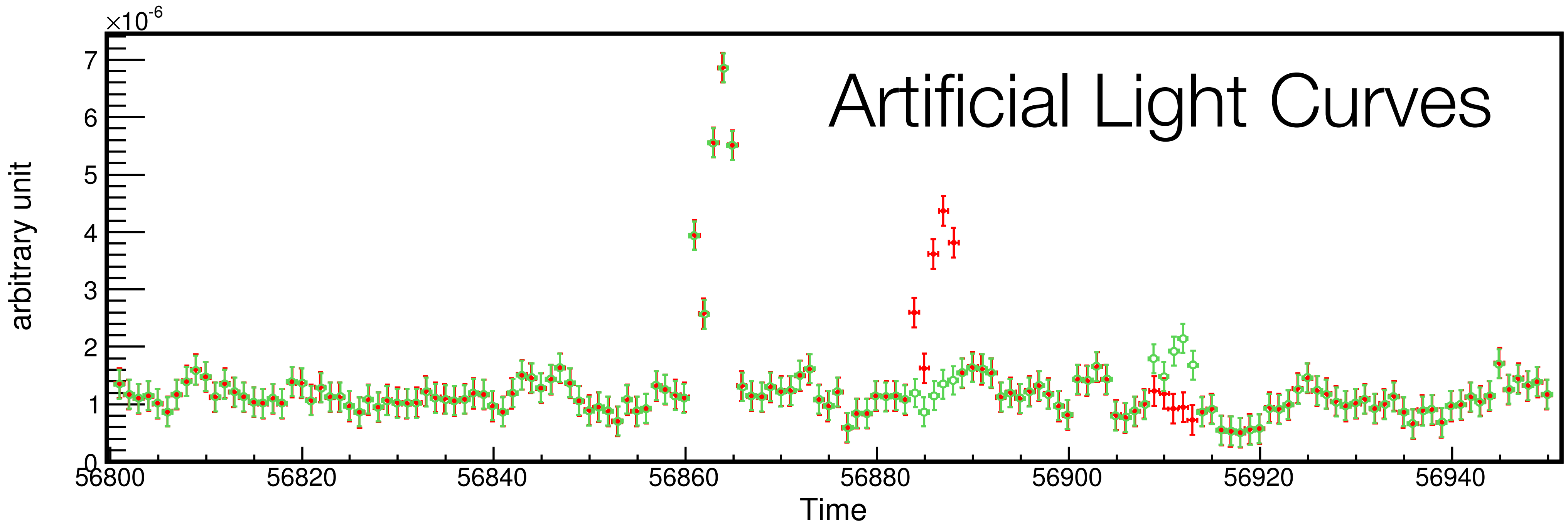


Gamma-Ray Flare 3 & Flare 4

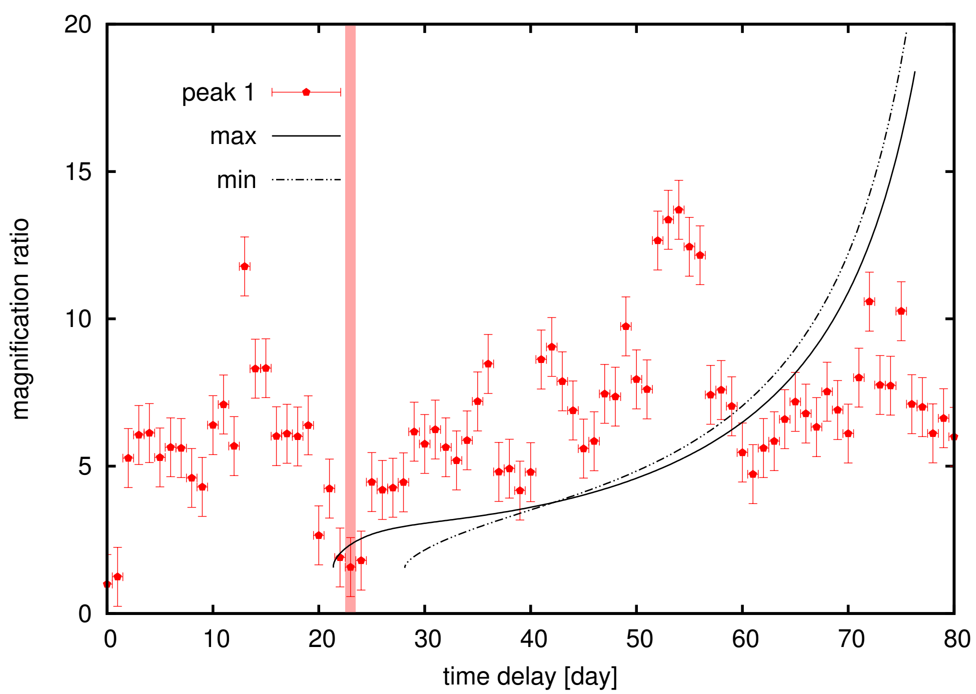




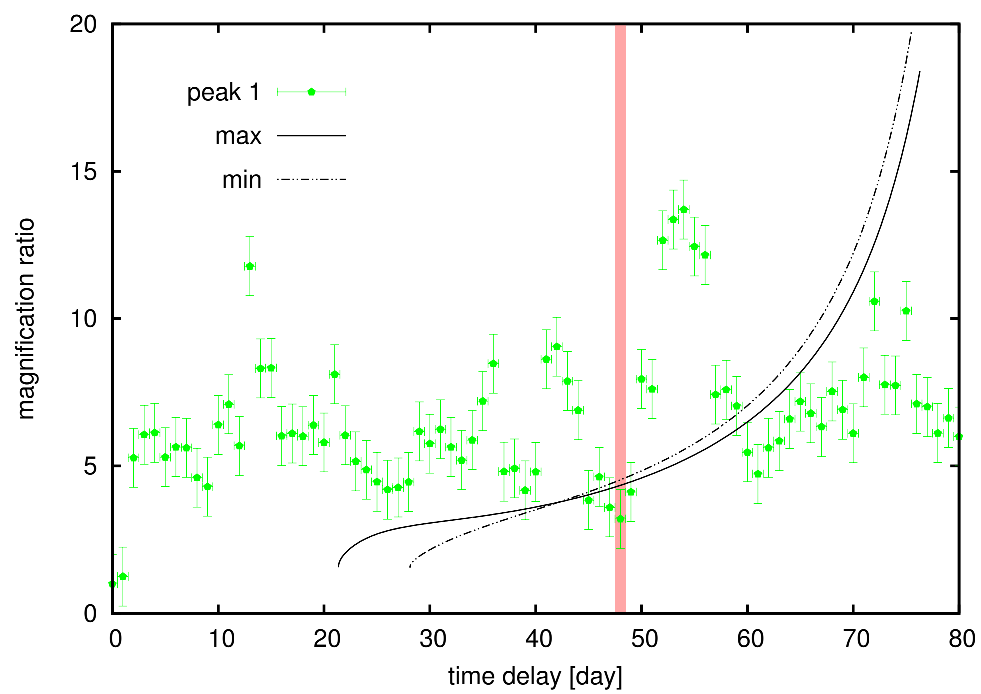
Maximum Peak Method - Monte Carlo



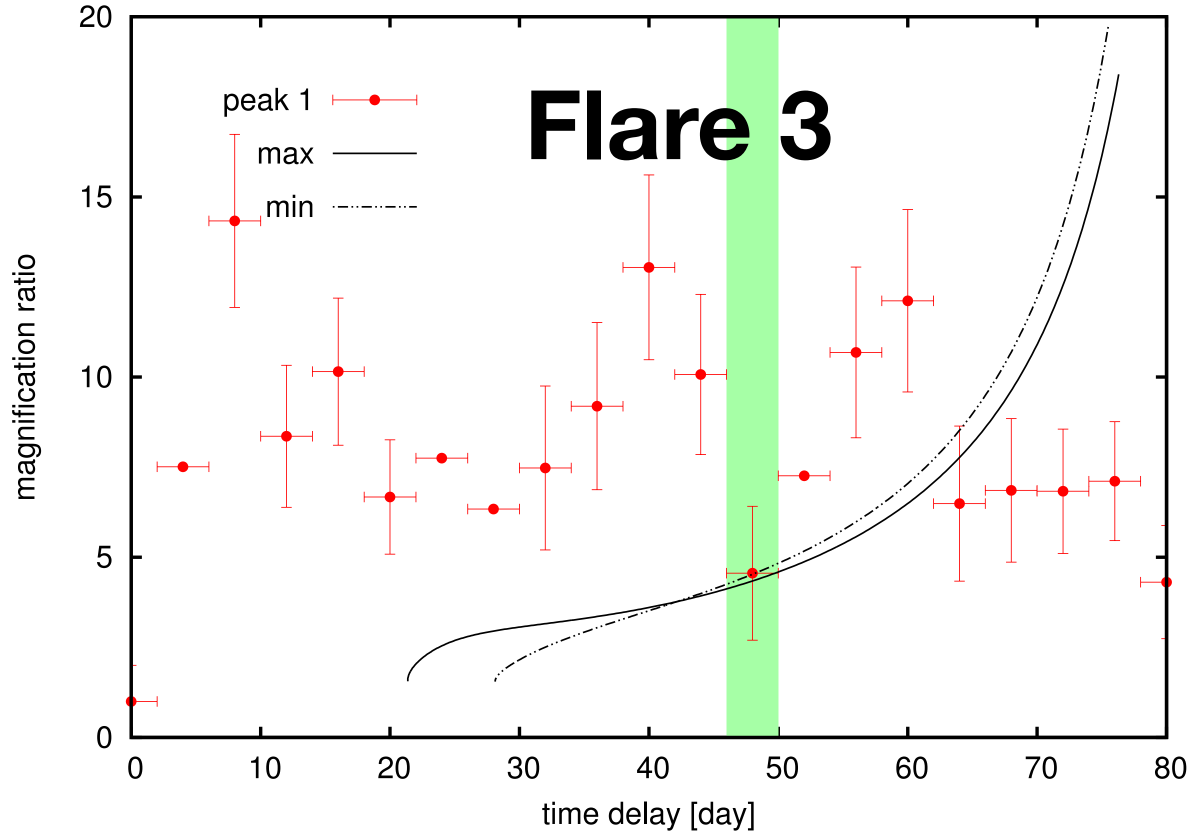
Time Delay ~ 24 days

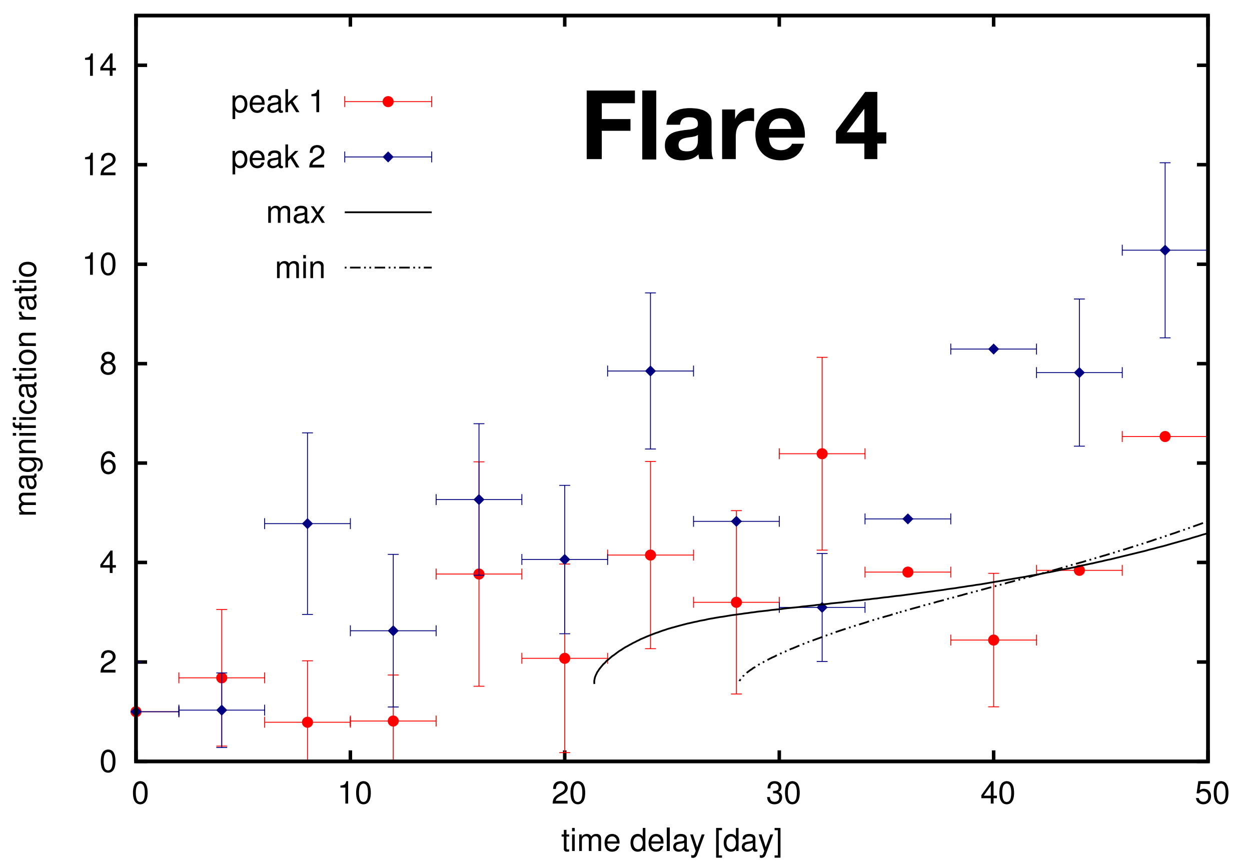


Time Delay ~ 48 days



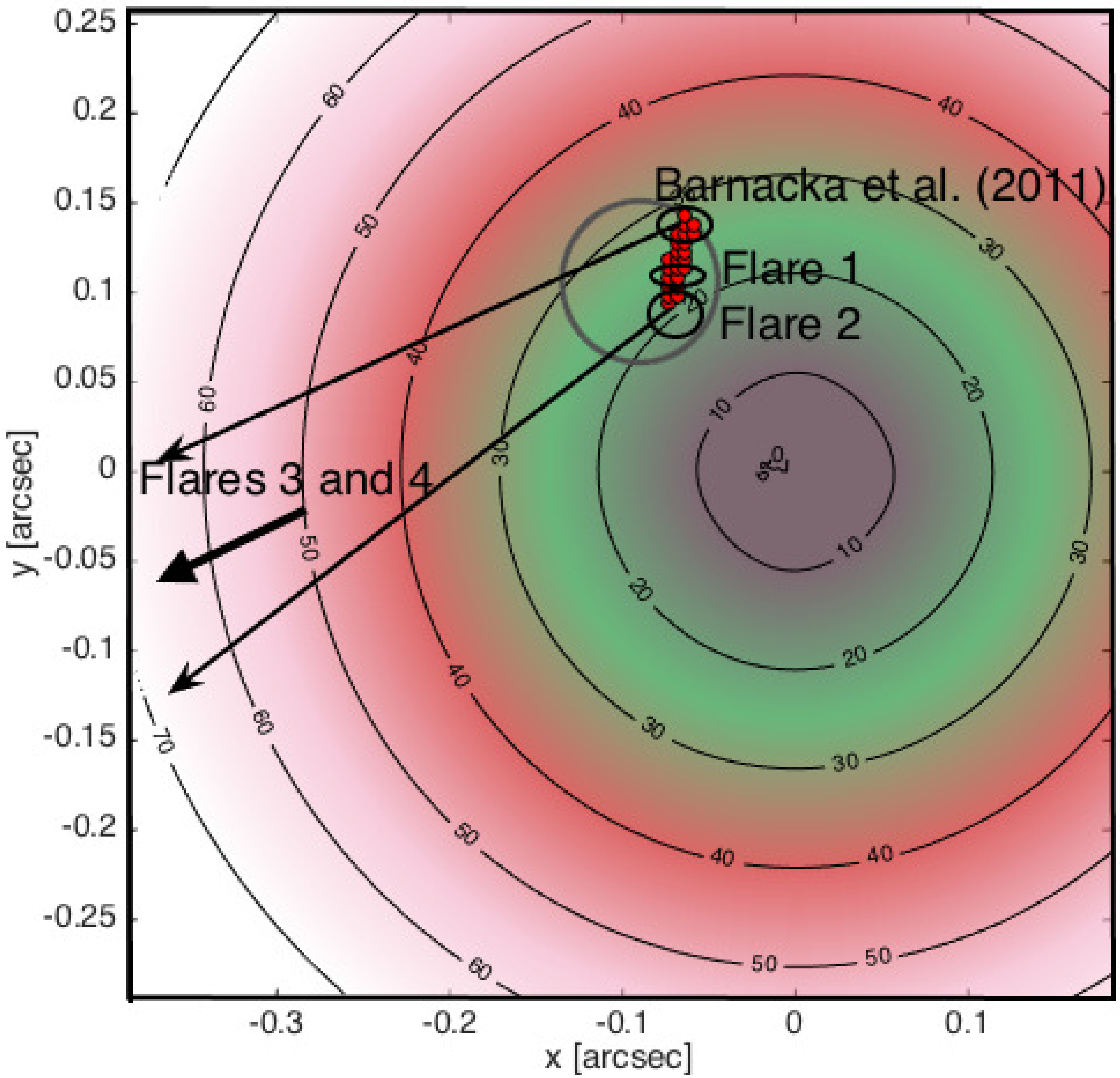
Maximum Peak Method - Data





Time Delay >= 50 days

Spatial Origin of Gamma-ray Flares



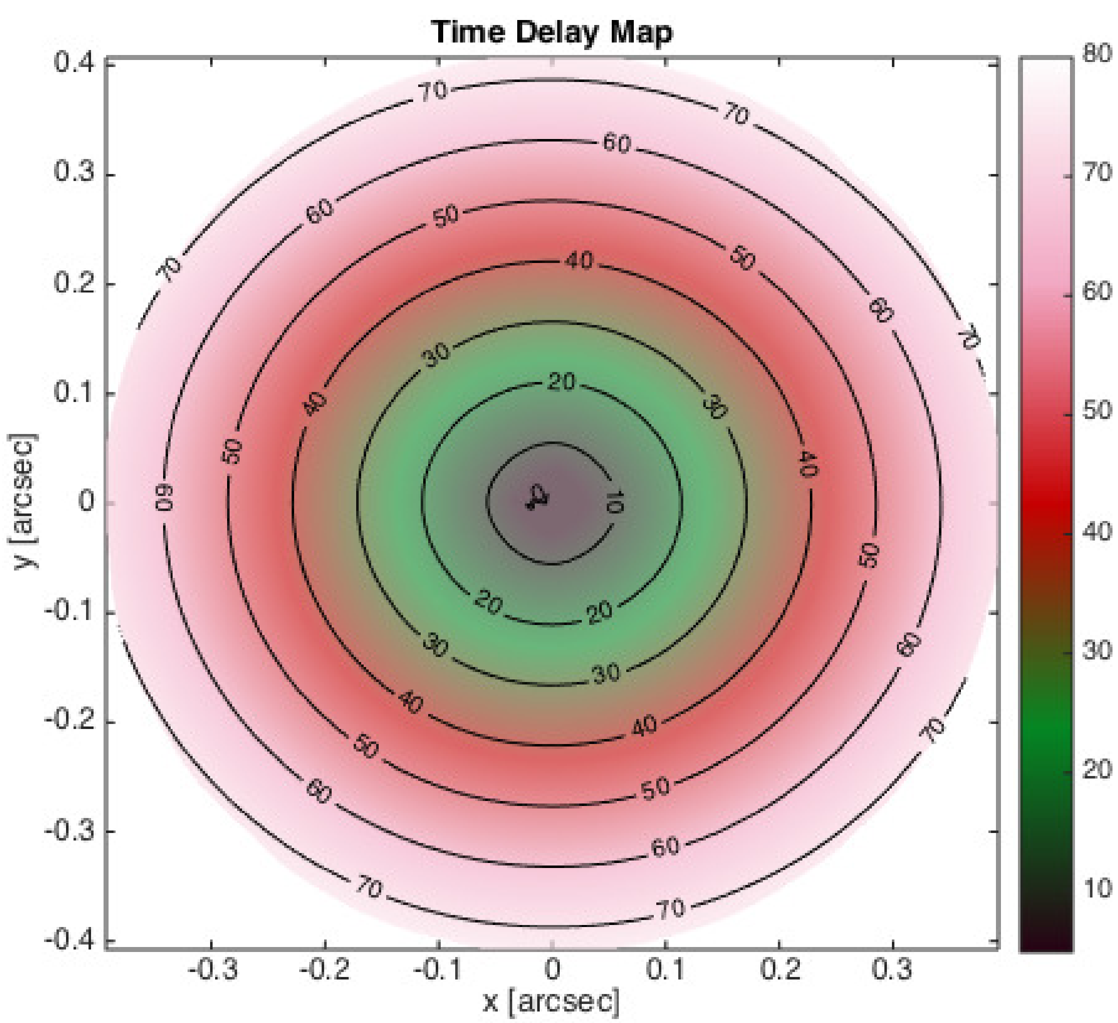
Barnacka, A., et al. (April, 2015: **arXiv:1504.05210**)

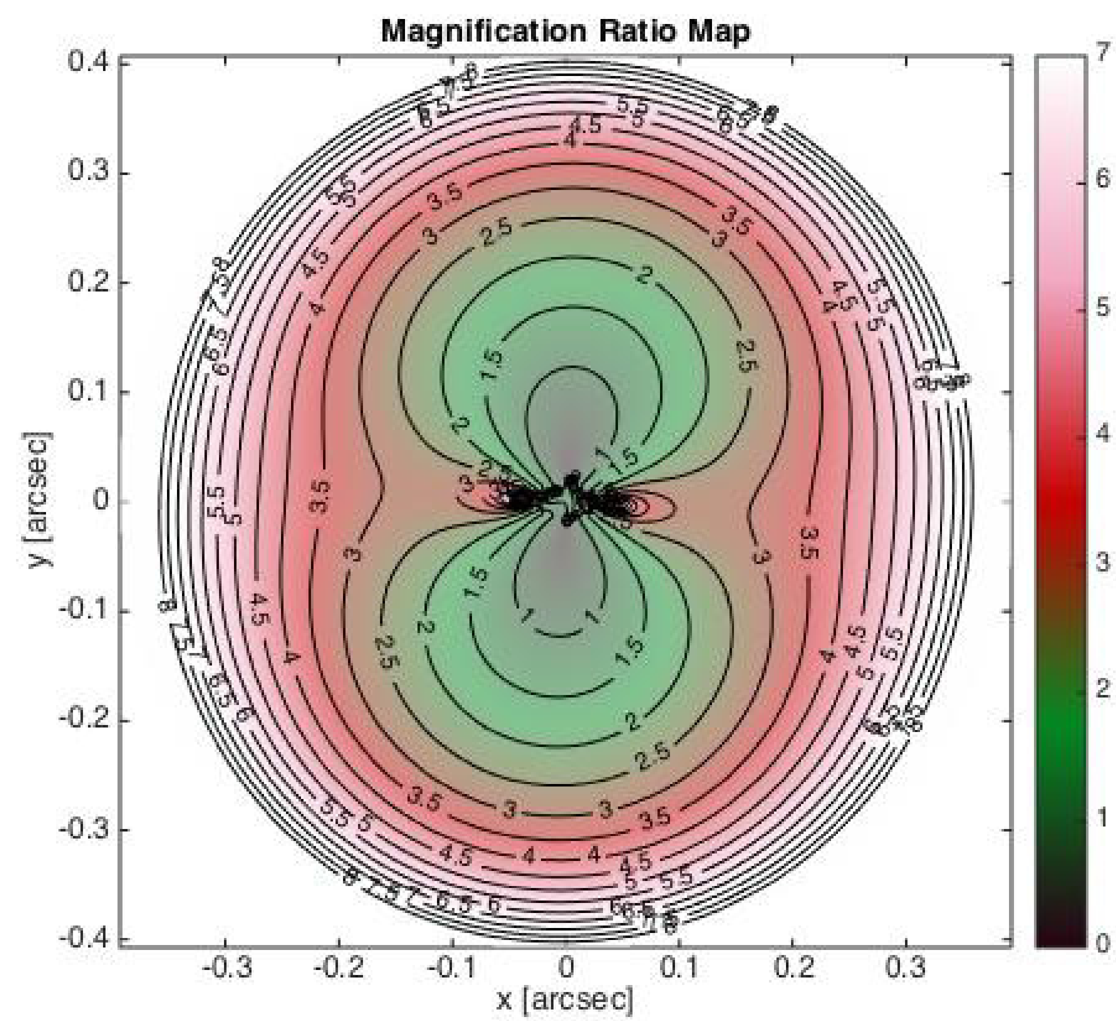
Summary

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

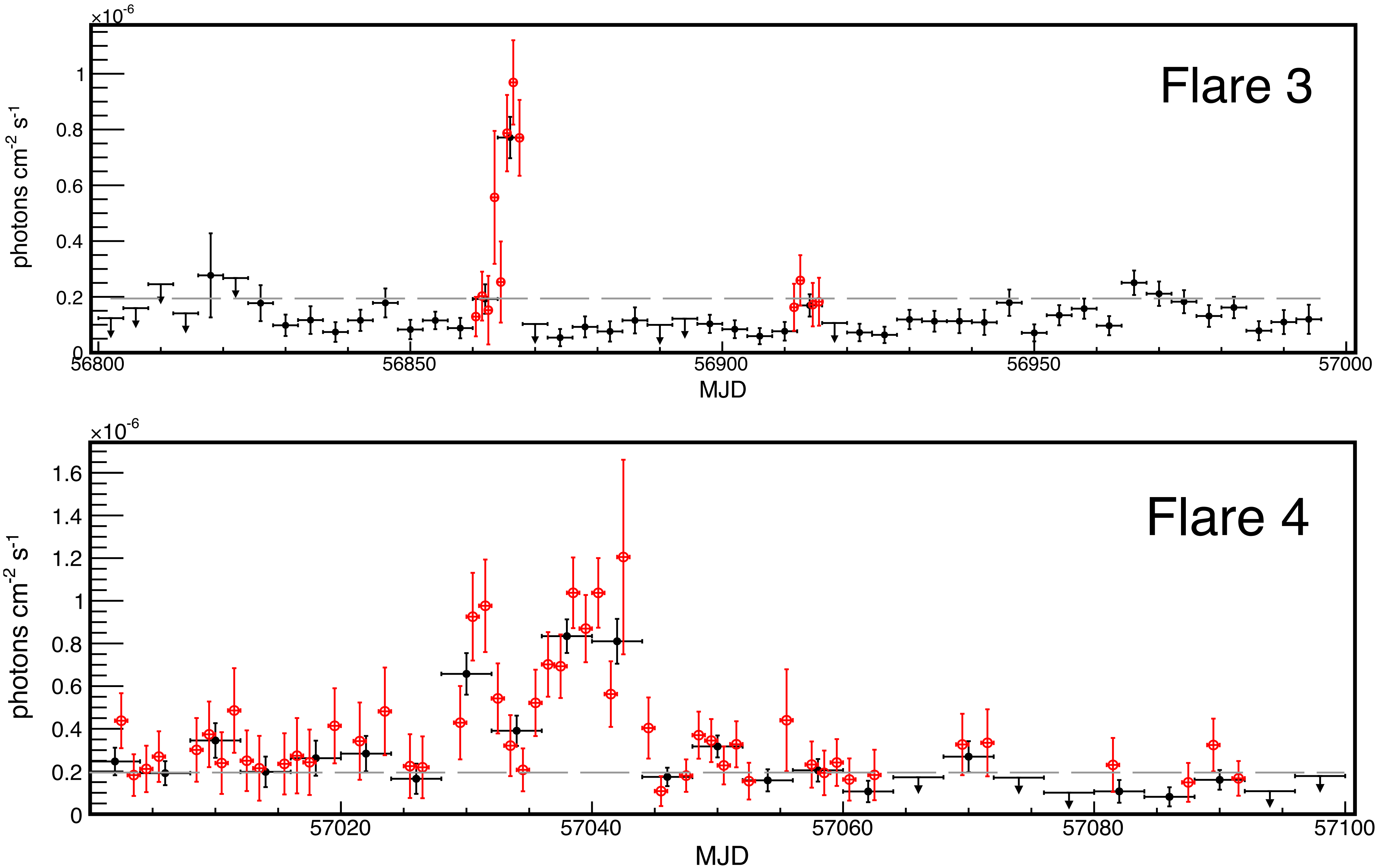
Backup Slides

Lensing Maps



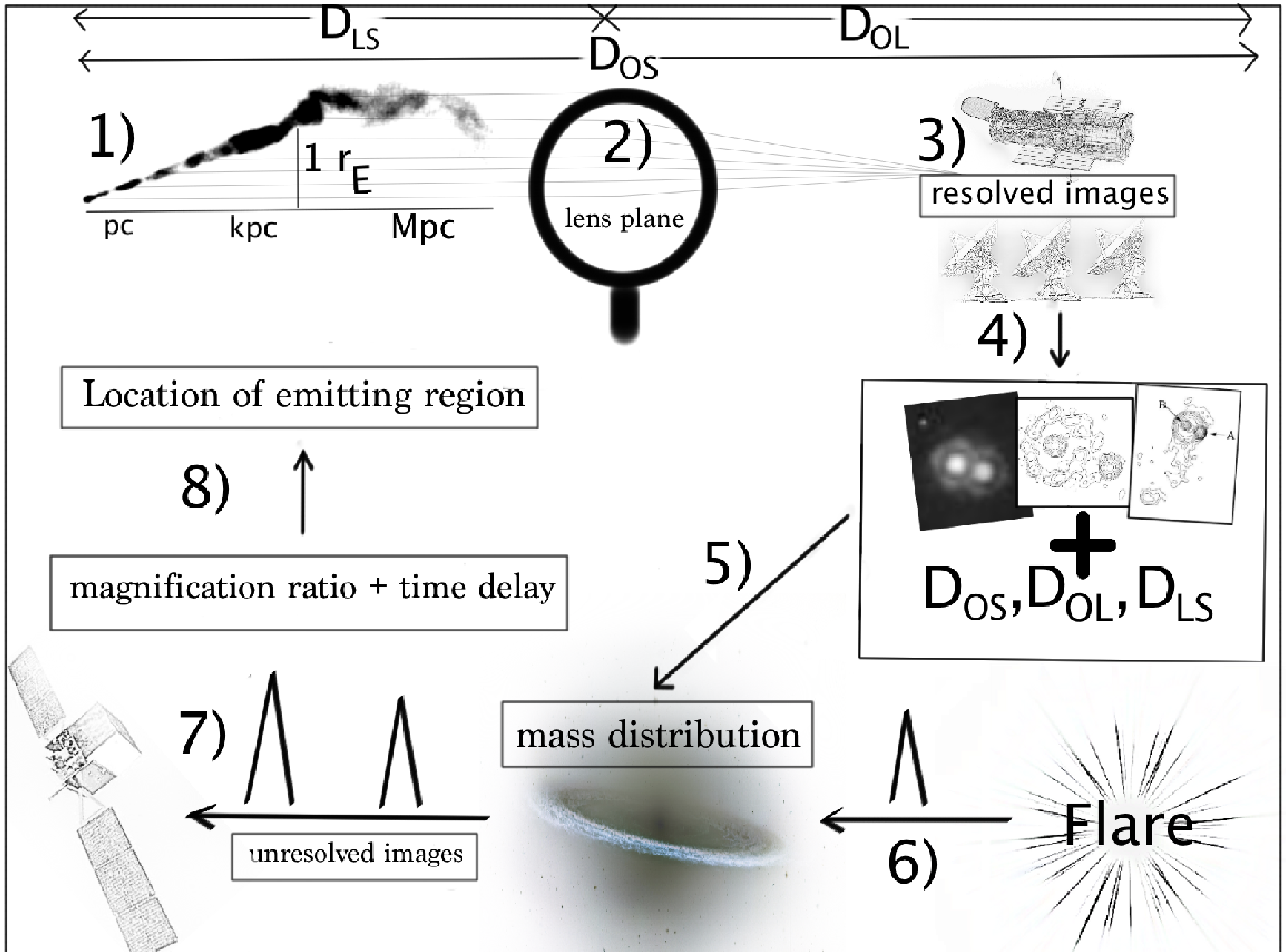


Gamma-ray Flare 3 and 4: Time Delays



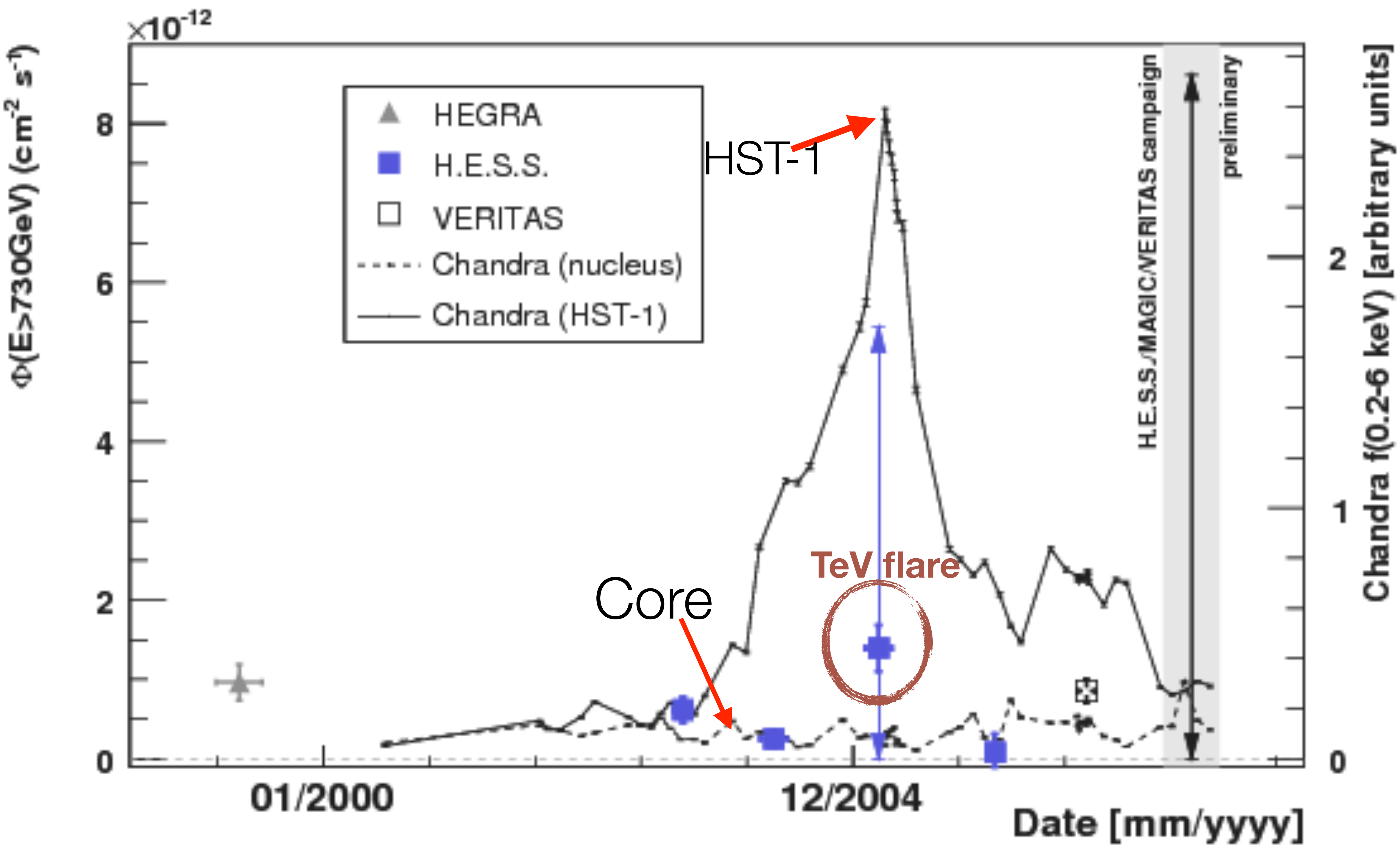
Gamma-Ray Time delay > 50 days

Application of strong lensing



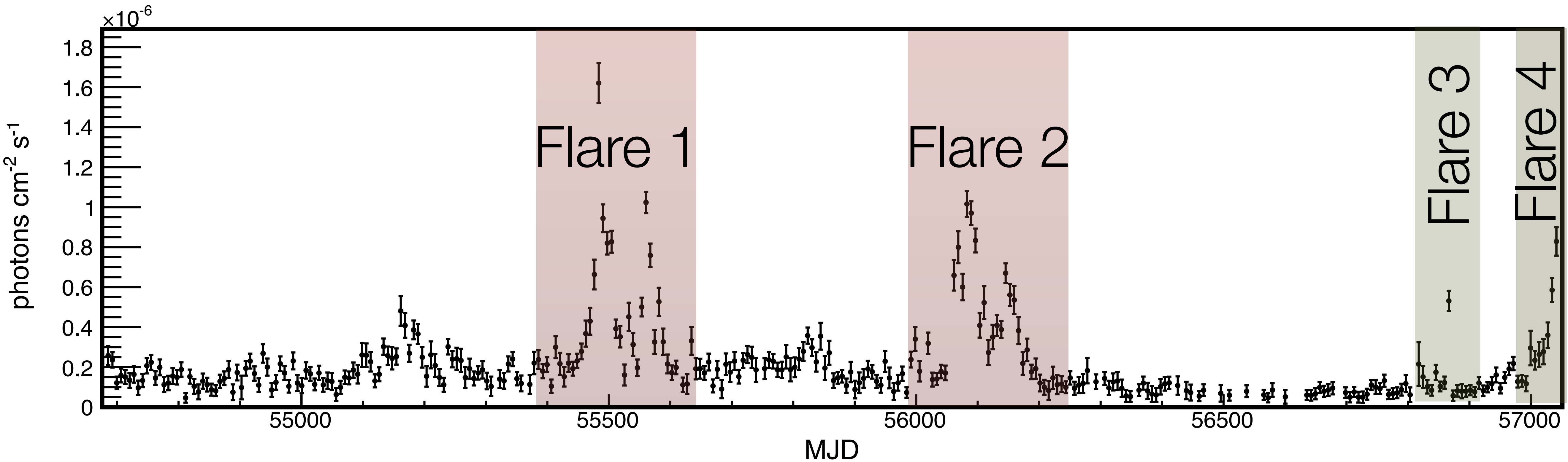
Barnacka, A., Geller, M., Dell'Antonio, I., & Benbow, W. (June 2014, ApJ)

Spatial Origin of Gamma-Ray Flares



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

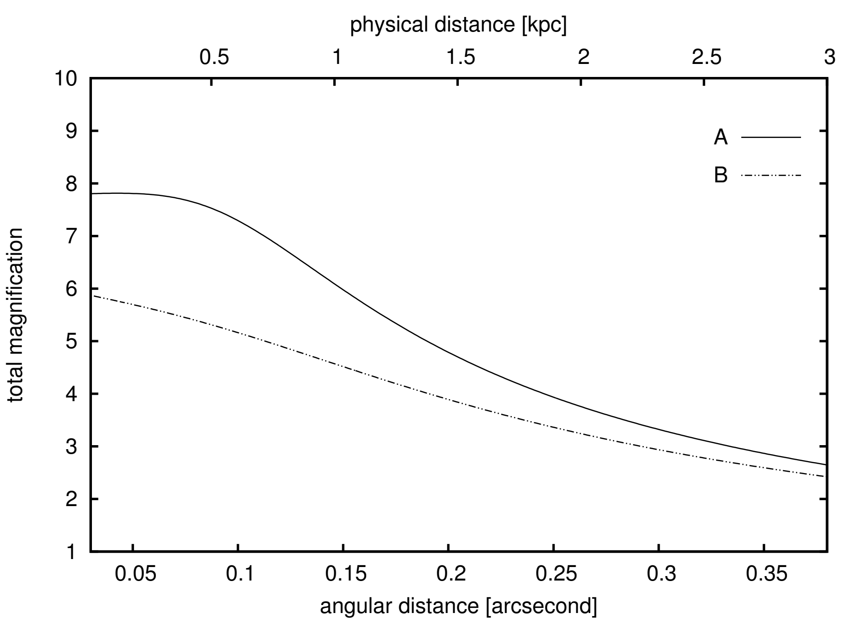
Gamma-ray Flares: Time Delays

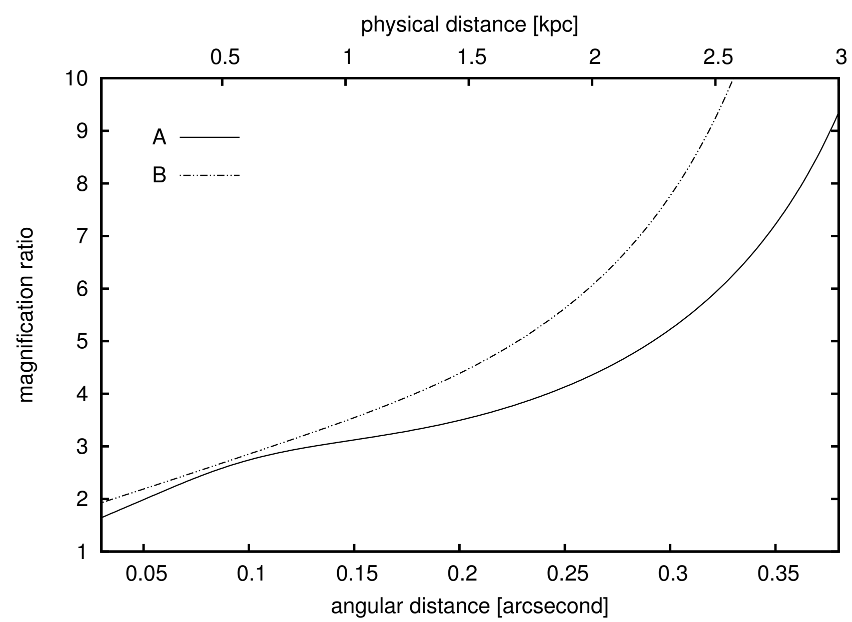


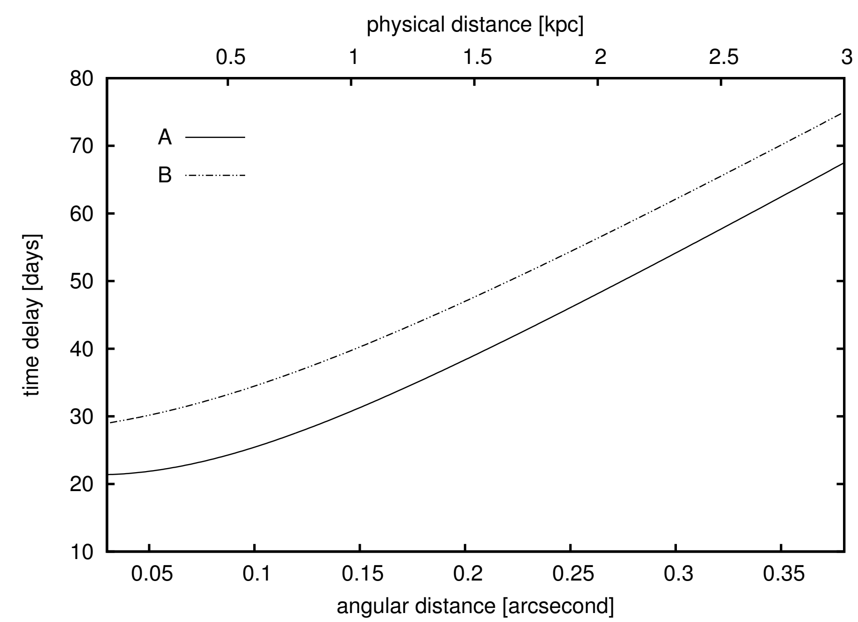
23±0.5 days **19±1.2 days** **> 50 days**

Barnacka, A., et al. (April, 2015: **arXiv:1504.05210**)

Lensing Parameters Along the Jet







Position of the Core