First evidence of a gravitational lensing-induced echo in gamma rays with FERMI LAT

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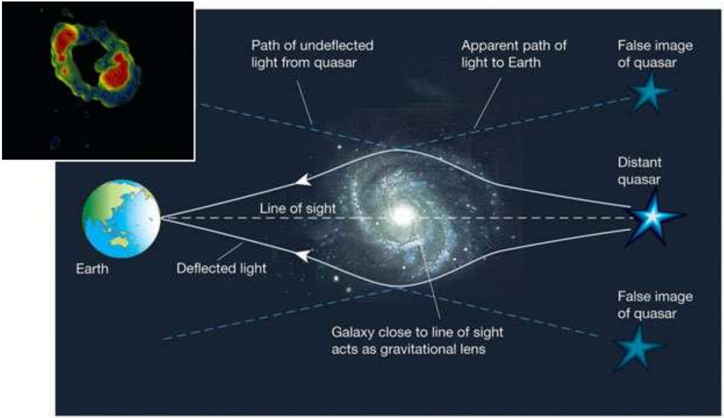


a - time delay

b - magnification ratio

Images separation - a few arcseconds

Calculation of lensing optical depths

- Lensing **optical depth** τ: lensing probability towards a given AGN
- Calculated following the analysis of Fukugita et al, ApJ. 393, 3 (1992)

Optical depth

$$d\tau = n_0(1+z_L)^3\sigma\frac{cdt}{dz_L}dz_L$$
$$= F(1+z_L)^3\left(\frac{D_{OL}D_{LS}}{R_0 D_{OS}}\right)^2\frac{1}{R_0}\frac{cdt}{dz_L}dz_L$$

where:

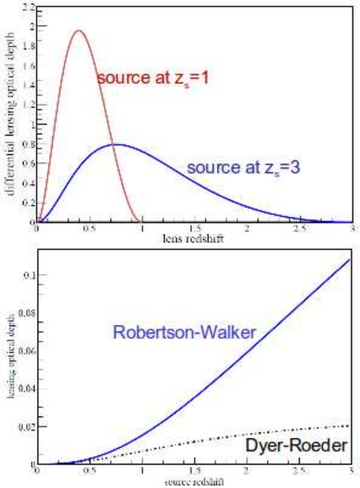
$$\frac{cdt}{dz_L} = \frac{R_0}{1+z_L}\frac{1}{\sqrt{\Omega_0(1+z_L)^3+(1-\Omega_0-\lambda_0)(1+z_L)^2+\lambda_0}}$$

Optical depth

z_l, z_s lens redshift
$n_0$lens density
R_0Hubble constant
D_{OS}: angular distance Observer-Lens
D_{LS}: angular distance Source-Lens

- depends on the cosmological parameters $\Omega_0, \lambda_0 (assumed \Omega_0 = 0.3, \lambda_0 = 0.7)$
- F depends on lenses (assumed Singular Isothermal Spheres = Galaxies)
- Angular distances D_{OL}, D_{OS}, D_{LS} calculated with 2 different assumptions:
  - Homogeneous Robertson-Walker universe
  - "Swiss-Cheese" Dyer-Roeder model

Lensing optical depth versus source and lens redshift



Differential lensing optical depth
$d\tau/dz_l$ (normalized to 1)
Robertson-Walker model

Total lensing optical depth
$\tau(z_s)$

Expected number of lenses

Uses AGN from 1^{st} **Fermi catalog**

- **FRSQ objects** (296 sources)
- expected number of lenses (Robertson-Walker): 8
- expected number of lenses (Dyer-Roeder model): 2.6

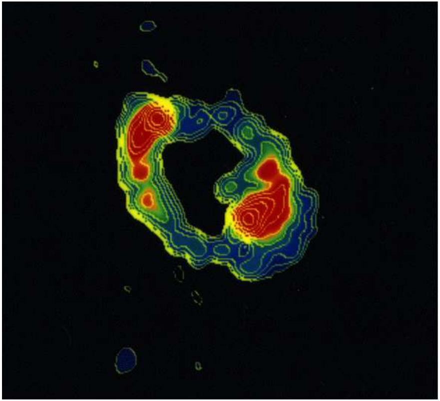
- **BL Lac** objects (300 sources)
- expected number of lenses (Robertson-Walker): 0.8
- expected number of lenses (Dyer-Roeder model): 0.4

Possible magnification biases in the observed redshift distribution not taken into account

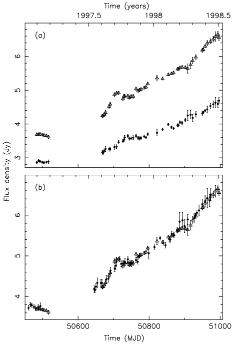
PKS 1830-211

- **PKS 1830-211** - gravitationally lensed blazar z=2.507 (Lidman 1999)
- **Lens** - spiral galaxy z=0.89 (Wiklind & Combes)
- 0.“97 angular distance between the images

(Jauncey et al. 1991)



A standard method for estimating the time delay



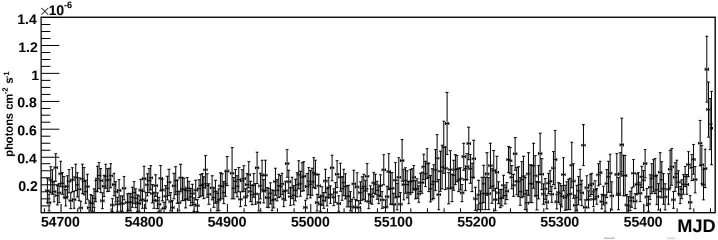
PKS 1830-211

(J.E.J. Lovell et. all, 1998)

- Traditional methods for estimating time delays based on the cross-correlation of the light curves from individual images.
- Disadvantages and limitations:
  - unevenly spaced data
  - need features like flares
  - requires very good angular resolution
- Results for PKS 1830-211 obtained by Lovell et. all:
  - Time Delay $a = 26^{+4}_{-5}$
  - Magnification Ratio $\mathbf{b} = 1.52 \pm 0.05$

PKS 1830-211 observations with FERMI satellite

- Detection $\sim 6.5\sigma$ (Abdo et al. 2010)
- Energy Range from 300 MeV to 100 GeV
- Bin size = 2 days
- Light curve from 4.08.2008 to 13.10.2010
- Average number of photones = 2.6 photon/day
- Analysis Method: Aperture Photometry



FERMI observations and gravitational lensing

Gravitational Lensing

- Maximum separation of images can reach at best 100 arcseconds (Paczyński & Górski 1981)
- $\longmapsto$ observed light curve = the superposition of individual image light curves
  $g(t) = f(t) + bf(t+a)$

FERMI Observations

- Angular resolution 1^o for 1 GeV
- The observation strategy: surveys the whole sky in 190 minutes $\longmapsto$ regular sampling with a period of a few hours
- Since the launch of the Fermi satellite, the LAT instrument has been collecting high energy photons for more than 800 days $\longmapsto$ long time series.
- Very low photon noise

Double Power Spectrum Method

I Fourier Transform

- $f(t) + bf(t+a) \underset{FT}{\rightarrow} \tilde{f}(\nu) + b\tilde{f}(\nu)e^{-2\pi i\nu a}$
- $\tilde{g}(\nu) = \tilde{f}(\nu)(1 + be^{-2\pi i\nu a})$

I Power Spectrum

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

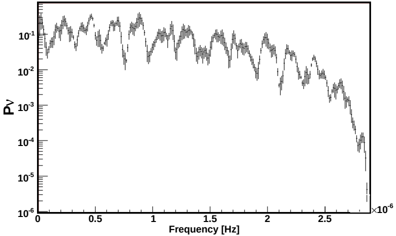
The measured Power Spectrum is the product of the “true” power spectrum of the source times a periodic component with a period equel to the inverse of the relative time delay “a”

Monte Carlo Simulations

Light Curve:**white noise**, $\mathbf{a = 28}$, $\mathbf{b = 1.5}$

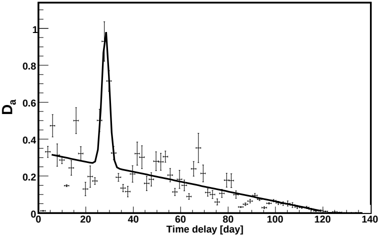
I Power Spectrum

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



II Power Spectrum

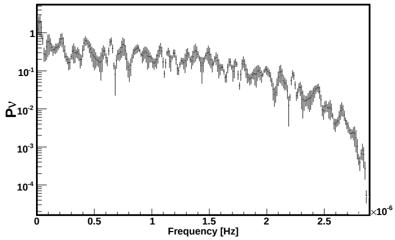
Time delay $\mathbf{a} = 28.56 \pm 0.52$
Significance of the peak $= 10\ \sigma$
Fit: linear+gauss



PKS 1830-211

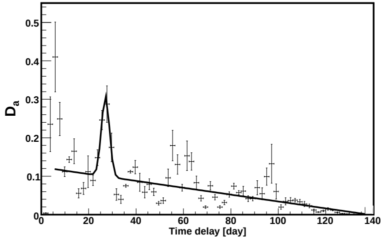
I Power Spectrum

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



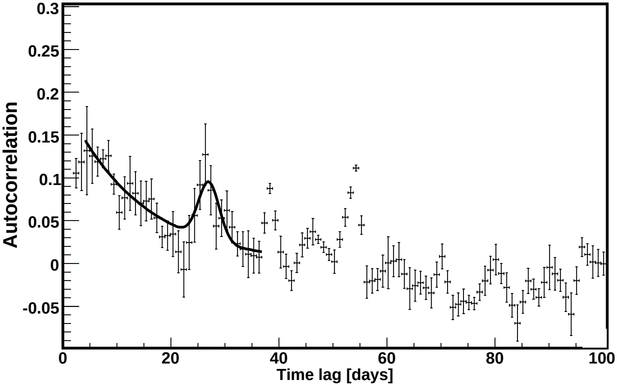
II Power Spectrum

Time delay **a** $= 27.1 \pm 0.6$
Significance of the peak$= 4.2\ \sigma$
Fit: linear+gauss



Autocorrelation function

Time delay **a** $= 27.1 \pm 0.45$
Significance of the peak$= 1.1\ \sigma$
Fit: exp+gauss



Summary

- Precise estimation of the time delay between components of lensed AGN is crucial for modeling the lensed system.
  Time delay:
  26^{+4}_{-5} days Lovel et al.(1998)
  24^{+5}_{-4} days Wiklind & Combes (2001)
  27.1 ± 0.6 days Barnacka et al. (2011)
- Thanks to the uniform light curve sampling provided by the Fermi LAT instrument, it is not necessary to identify features on the light curve to apply Fourier transform methods.
- Possible extensions of the present work are: search for multiple time delays in complicated lens systems or looking for unknown lensing systems in the FERMI catalog of AGN's