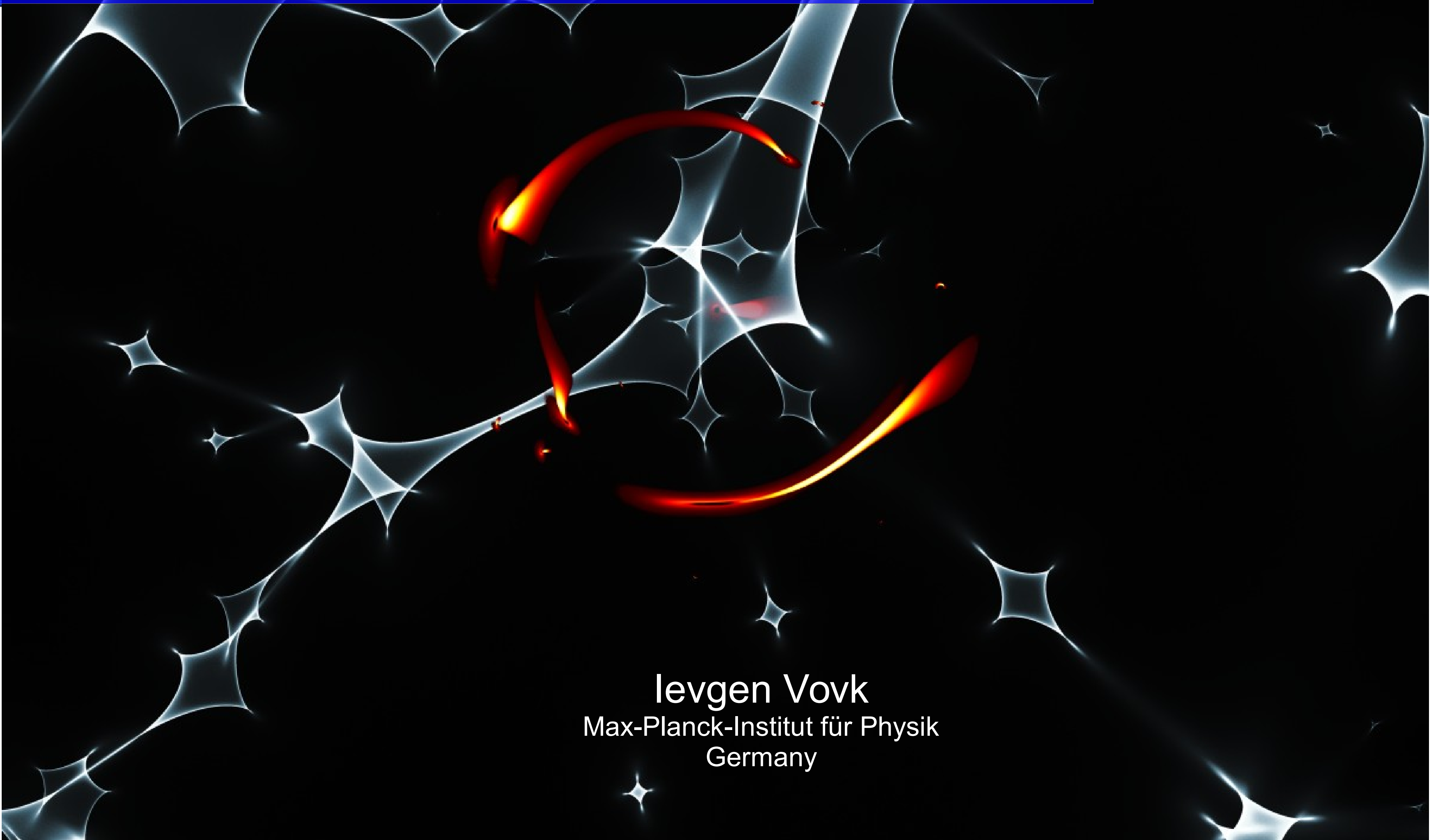
Resolving the blazar gamma-ray emission regions with gravitational microlensing



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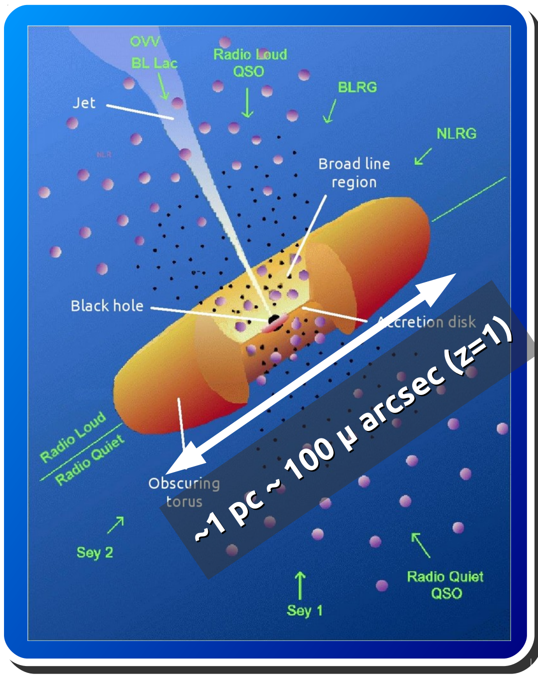
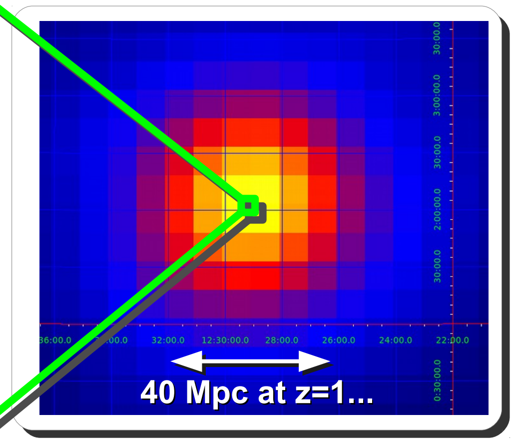
The problem of resolving the AGN „central engine“



Urry & Padovani (1995)

Fermi/LAT image > 1GeV



The apparent size of the central region of an AGN is ~100 μ arcsec at z=1.

The plausible regions of high-energy emission are even smaller – ~1 μ arcsec for accretion disk (10^{-2} pc) and ~0.01 μ arcsec for SMBH (10^{-4} pc).

1 μ arcsec is the size of an ant at the Moon...

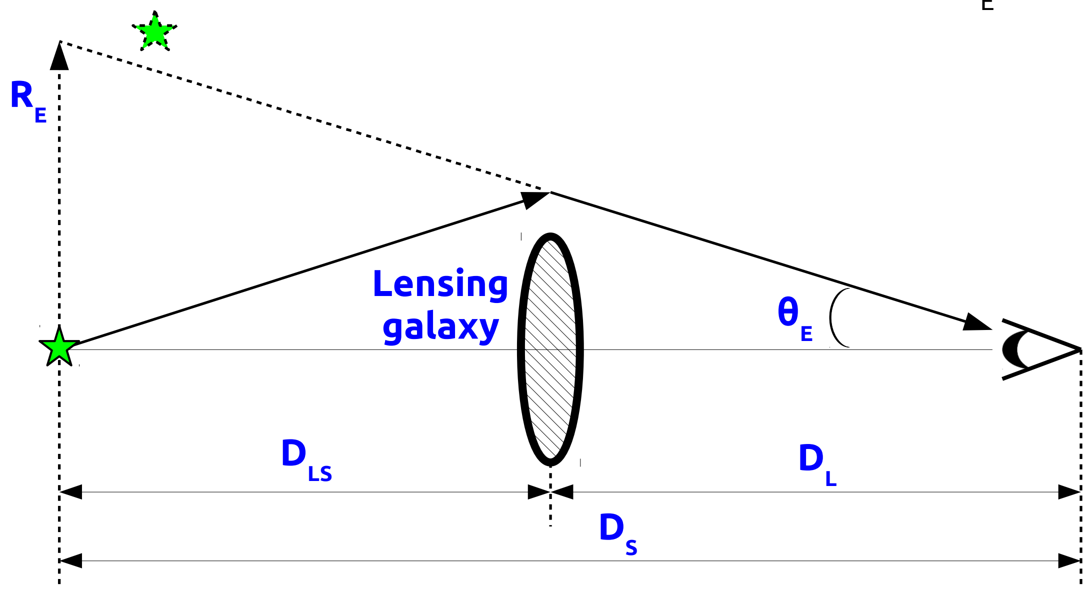
The gamma ray source can not be directly resolved with existing and planned future gamma-ray telescopes.

Towards the resolution of the central engine

To assist our observations we can use the „lenses“ created by the Nature.

This is possible via the effect of the **gravitational (micro)lensing.**

Gravitational lensing leads to creation of several distorted and magnified images of the source.
The characteristic spatial scale of the lensing is set by the Einstein radius R_E.

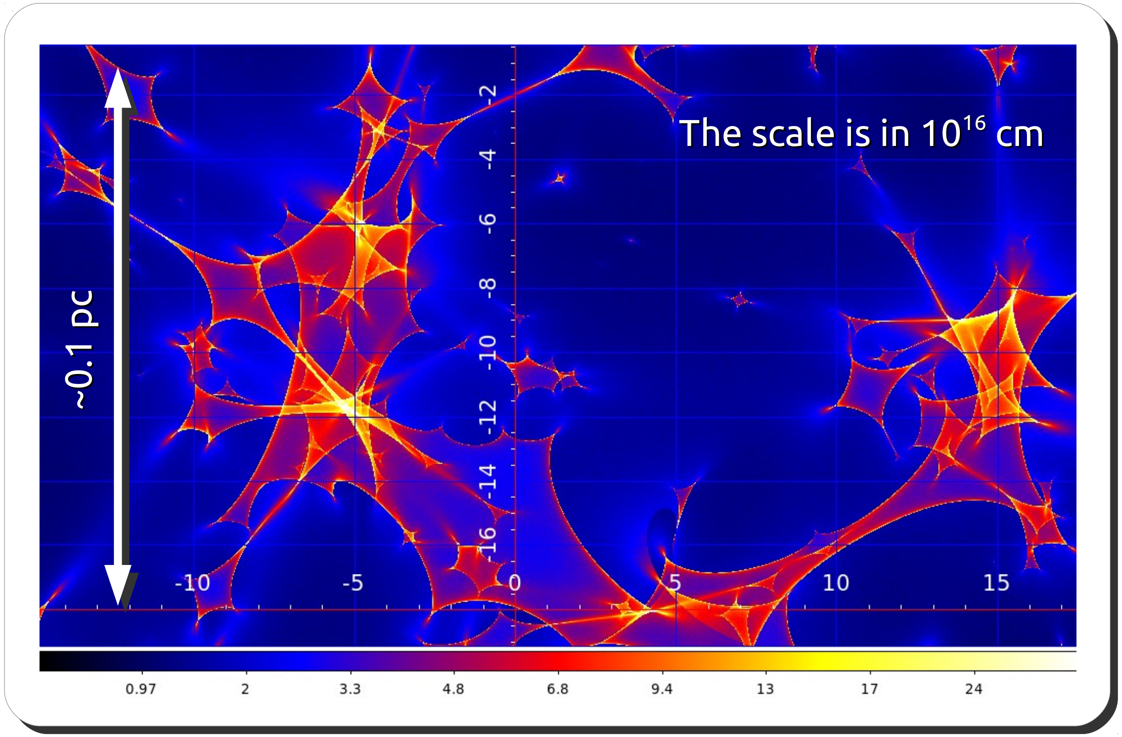


$$\theta_E = [4GM/c^2 * D_{LS}/(D_S D_L)]^{0.5}$$

$$R_E \sim 4 \times 10^{16} (M/M_{Sun})^{0.5} \text{ cm}$$

Gravitational microlensing

Many stars-microlenses → complex magnification pattern



The characteristic scale in the map is set by the Einstein radius $R_E = 4x10^{16} (M/M_{Sun})^{0.5}$ cm of the microlenses

→ sensitive to small sub-structures in the source

The lens and the source are moving with respect to each other at v~1000 km/s, leading to a constant change in magnification.

Magnification amplitude and duration depend on the source size:

$\mu_{micro} \sim (R_E/R)^{0.5}$ and $\Delta t = R/v$

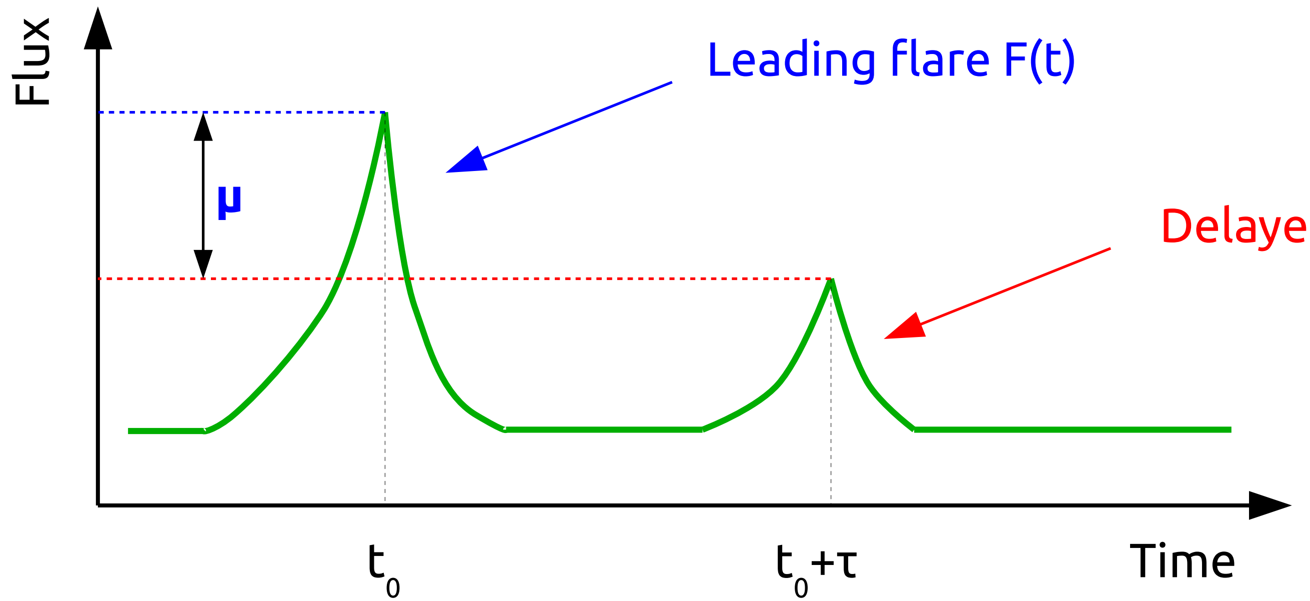
$$\mu \approx 10 \left(\frac{R}{3\,x\,10^{14}\,cm} \right)^{-0.5}$$

$$\Delta t \approx 100 \left(\frac{R}{3\,x\,10^{14}\,cm} \right) \left(\frac{v}{300\,km/s} \right)^{-1} days$$

Microlensing in the gamma-ray band

If we can not resolve separate images (as in gamma rays), we will see only the total flux

$$F_{tot}(t) = \mu F(t)+F(t-\tau)$$



Microlensing acts on top of the normal lensing, leading to variations in range μ/μ_{micro} to $\mu*\mu_{micro}$.

One can search for such variations for the known gravitationaly lensed systems PKS 1830-211 and B0218+357.

Gamma-ray gravitational lenses

There are only two know gravitational lenses: PKS 1830-211 and B0218+357.

In both cases radio observations indicate the presence of two lensed images and an Einstein ring.
Both objects are relatively bright in the GeV band.

PKS 1830-211

Source redshift: z=2.5 (Lidman+ '99)
Lens redshift: z=0.89 (Wiklind & Combes '96) and, possibly z=0.19 (Lovell+ '96)
Gravitational time delay in radio: 26^{+4}_{-5} days (Lovell+ '98)

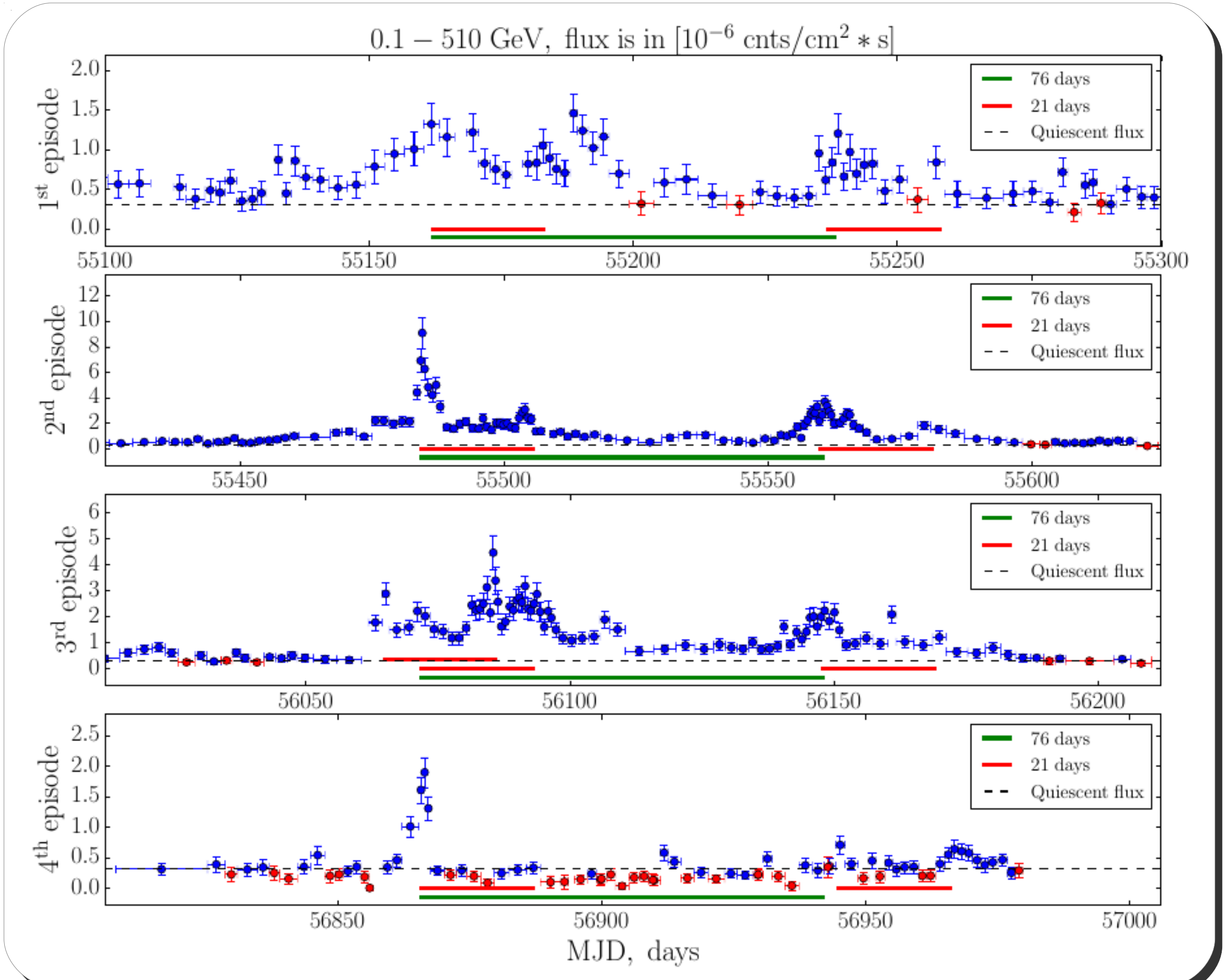
Gravitational time delay in gamma: 21^{+2}_{-2} (Neronov+ '15, Barnacka+ '15)
Magnification ratio in radio: 1.52+/-0.5 (Lovell+ '98)
Magnification ratio in gamma: >6 (Abdo+ '15)

B0218+357

Source redshift: z=0.94 (Cohen+ '03)
Lens redshift: z=0.68 (Browne+ '93)

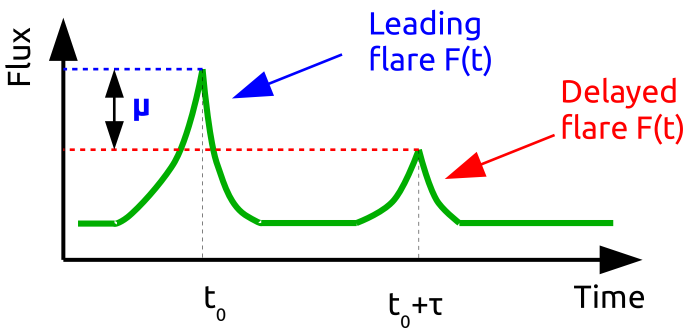
Gravitational time delay in radio: 10.5+/-0.4 d (Biggs+ '99), 10.1+/-1.6 d (Cohen+ '00, Eulares & Magain '11)
Gravitational time delay in gamma: 11.46+/-0.16 d (Cheung+ '14)
Magnification ratio in radio: 3.5-3.7 (Mittal+ '07)
Magnification ratio in gamma: ~1? (Cheung+ '15)

PKS 1830-211: first detection of microlensing in the gamma-ray band

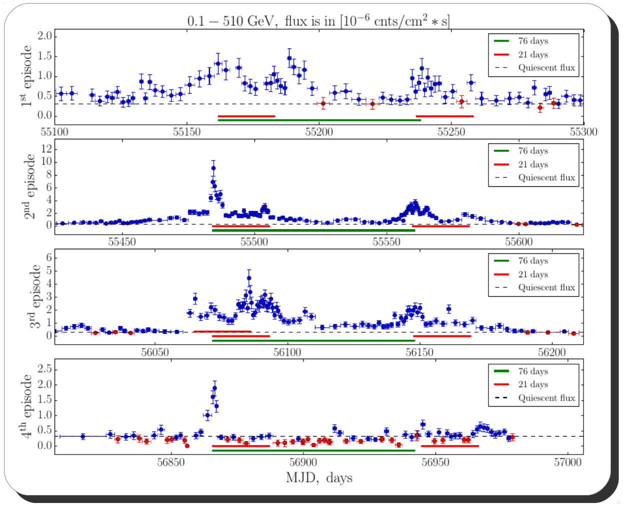


Neronov et al., Nature Physics (2015)

- Duration of observations: ~6 years (Fermi/LAT)
- Magnification in radio: 1.5
- Time delay in gamma: τ_γ =21+/-2 days
- Magnification in gamma-rays: variable, 2-7
- Time scale of variations: $1<\Delta t<75$ days



PKS 1830-211: microlensing constraints on the source size



μ_{micro} = 2-5 $\quad \mu_{micro} \approx 10 \left(\frac{R}{3 \times 10^{14}\, cm} \right)^{-0.5}$ ⇒ $R_\gamma \sim 10^{15}$ cm

1<Δt<75 d $\quad \Delta t \approx 100 \left(\frac{R}{3 \times 10^{14}\, cm} \right) \left(\frac{v}{300\, km/s} \right)^{-1} days$ ⇒ $R_\gamma < 3 \times 10^{15}$ cm

Microlensing

Supplementary

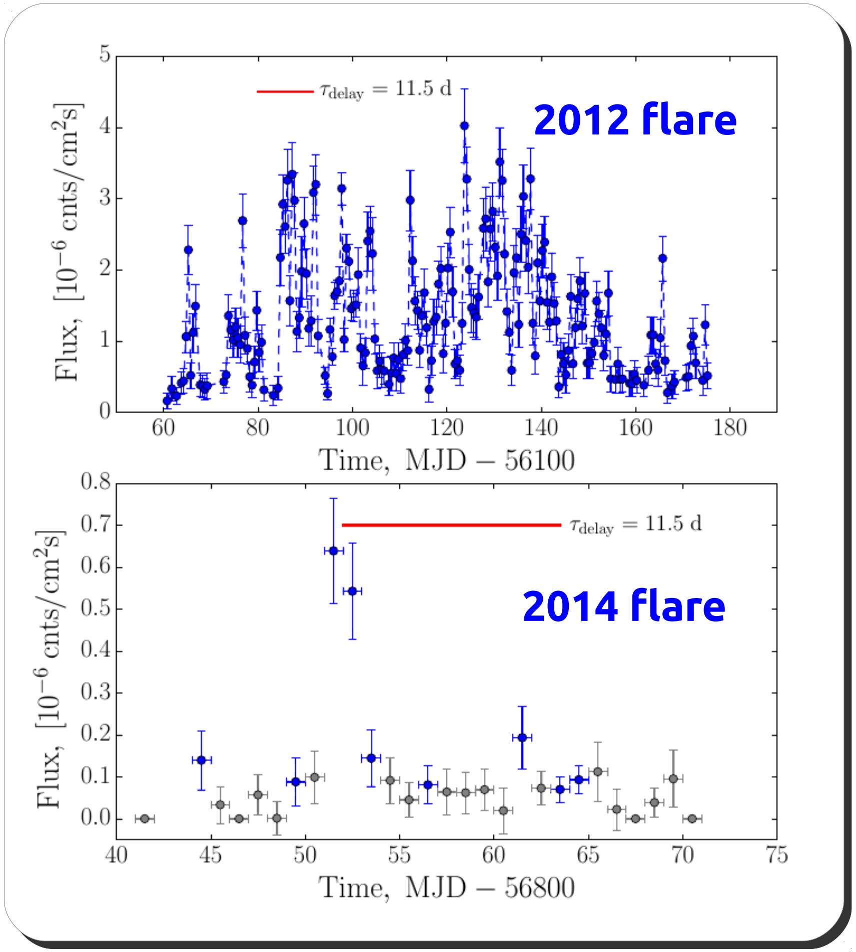
t_{rep} =76 d ⇒ $R_\gamma \sim 10^{15}$ cm

t_{rise} ~ 0.5 d ⇒ $R_\gamma \sim 10^{15}\, \Gamma$ cm

If v>c (superluminal motion) then
$R_\gamma = v * \Delta t > R_E$
and no strong microlensing magnification is possible.

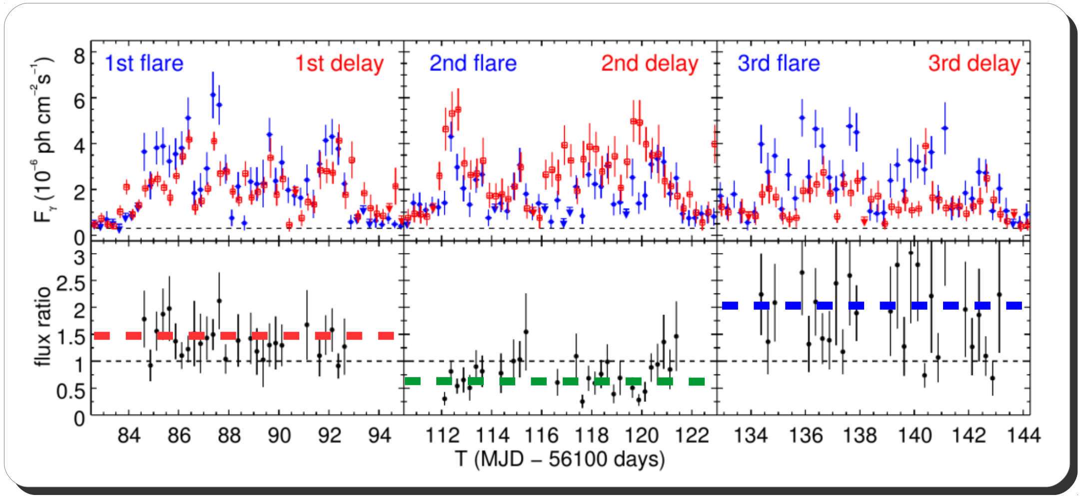
⇒ **The possibility of relativistic motion is disfavoured by the data**

Variability of B0218+357



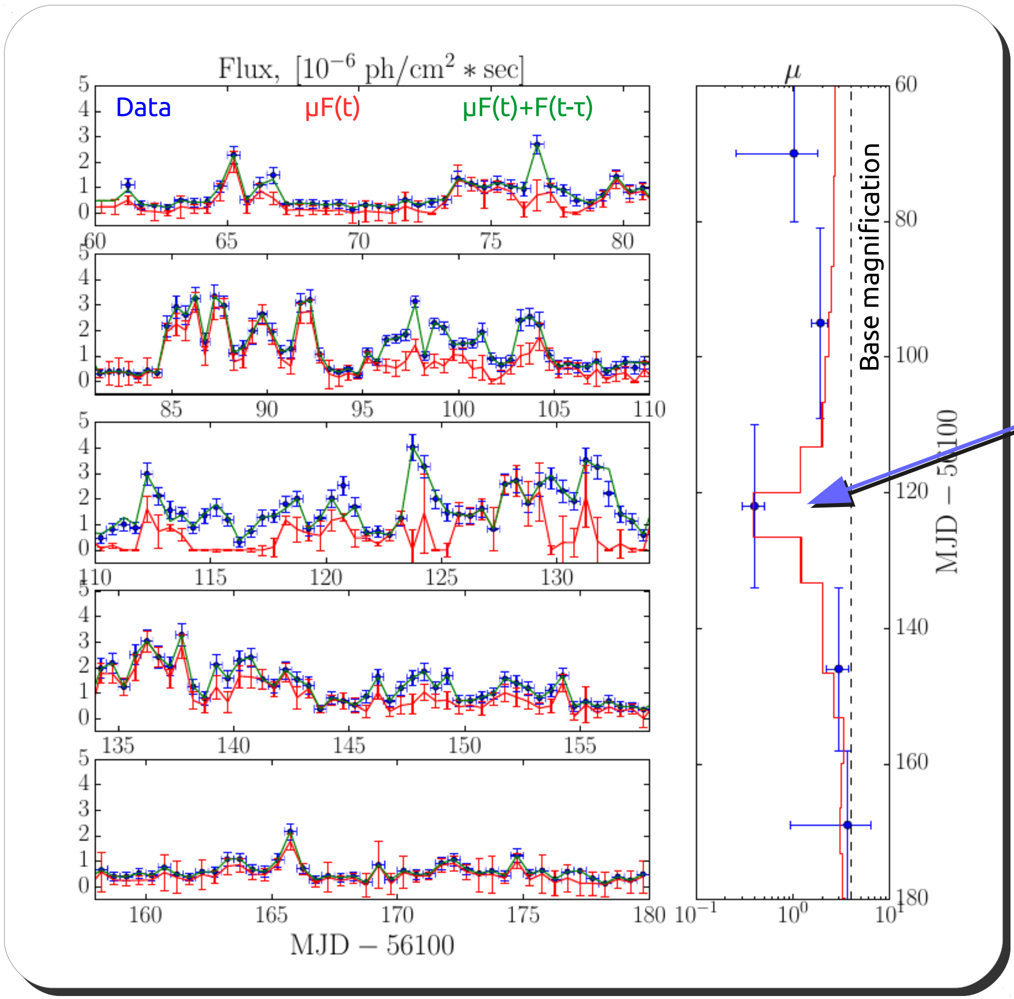
- Two flares in ~6 years of Fermi/LAT observations
- Magnification in radio: ~3.5-3.7 (Mittal+ '07)
- Magnification in gamma-rays: variable ?

A hint of variability can be also seen in the Fermi/LAT light curves over the 2012 flare from Cheung+ 14.



Cheung+ 14

Microlensing caustic crossing caught in action in B0218+357



Vovk & Neronov '15, accepted

In order to find magnification factor μ_γ we solved the equation

$$F_{tot}(t) = \mu F(t)+F(t-\tau)$$

for F(t) and μ, minimizing the intrinsic correlation at time scale τ of the gravitational time delay. The resulting time dependence μ(t) shows a rapid change in magnification over 60-100 days.

A natural explanation for the detected behaviour of μ_γ is found in terms of microlensing – the caustics crossing of a compact source with **R_γ~10^{14}-10^{15} cm**.

This conclusion is supproted by the simulations of caustics maps and provides a self-consistent picture of both 2012 and 2014 flaring episodes.

Microlensing reveils small sizes of gamma-ray sources in AGNs

μ_{micro}

- PKS 1830-211: 2-5
- B0218+357 : 10

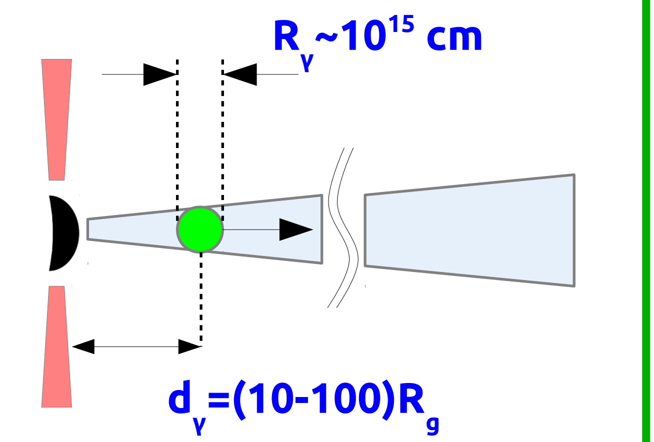
Time scale of variations:

- PKS 1830-211: $1<\Delta t<75$ days
- B0218+357 : ~50 days

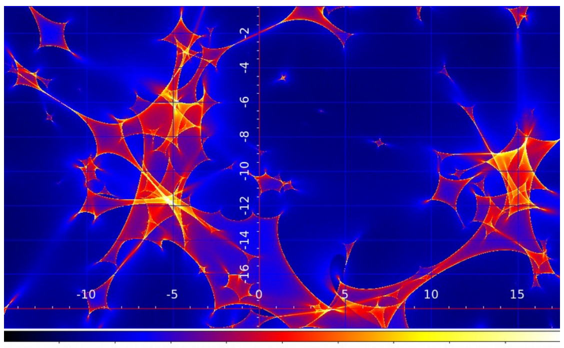
	PKS 1830-211	B0218+357
μ_{micro}	10^{15}-10^{16} cm	10^{14}-10^{15} cm
Duration	10^{14}-10^{15} cm	10^{14}-10^{15} cm
Fast variability	$<10^{16}$ (Γ/10) cm	$<3\times10^{15}$ (Γ/10) cm

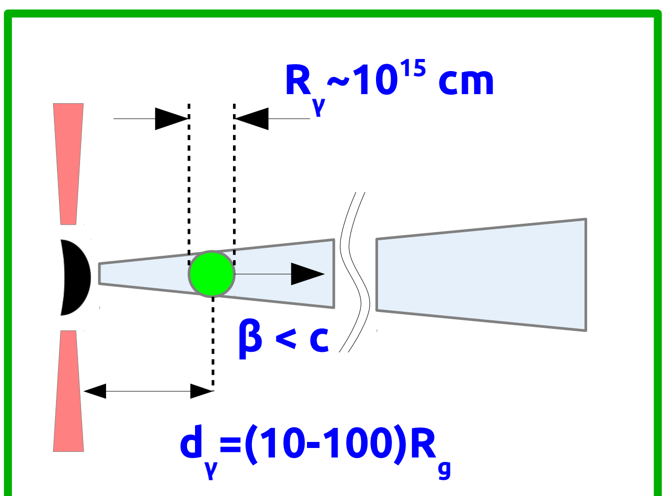
Detection of microlensing suggests that the emitting source is not relativistic.

Microlensing removes the long-standing puzzle of the location of the gamma-ray source in blazars, providing solid arguments in favour of its assosication with the AGN's central black hole.



Potential of microlensing observations





Regular observations of microlensing open a new way to learn about the structure of AGNs:

- ✔ energy dependence of R_γ
- ✔ its variations with time

One of the lenses – B0218+357 – is also detected by MAGIC (ATel #6349) at sub-TeV energies, which allows to study the source size over 3 decades in energy!

Fermi/LAT observations are essential here to detect the flares and measure the magnification ratios in the GeV band.

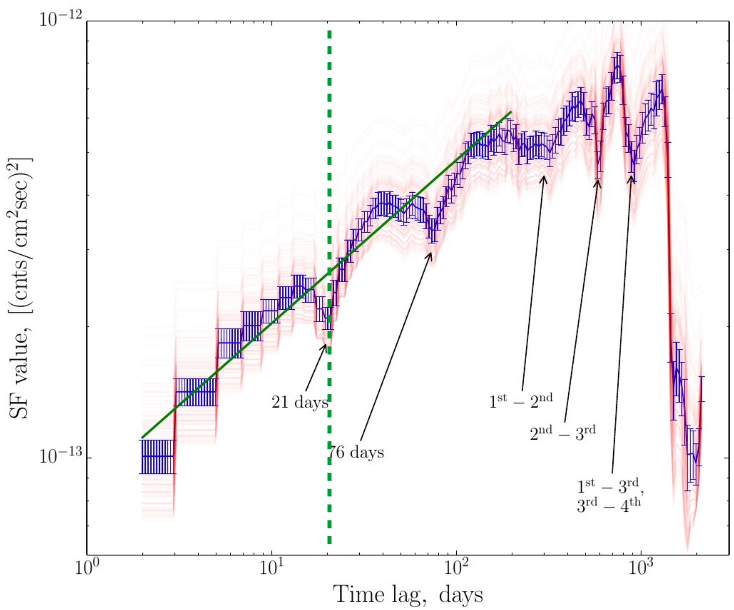
Microlensing provides a unique opotunity to study the details of the structure of the acceleration sites in AGNs, effectively improving the angular resolution of gamma-ray telescopes by 10^{11} times.

Backup slides

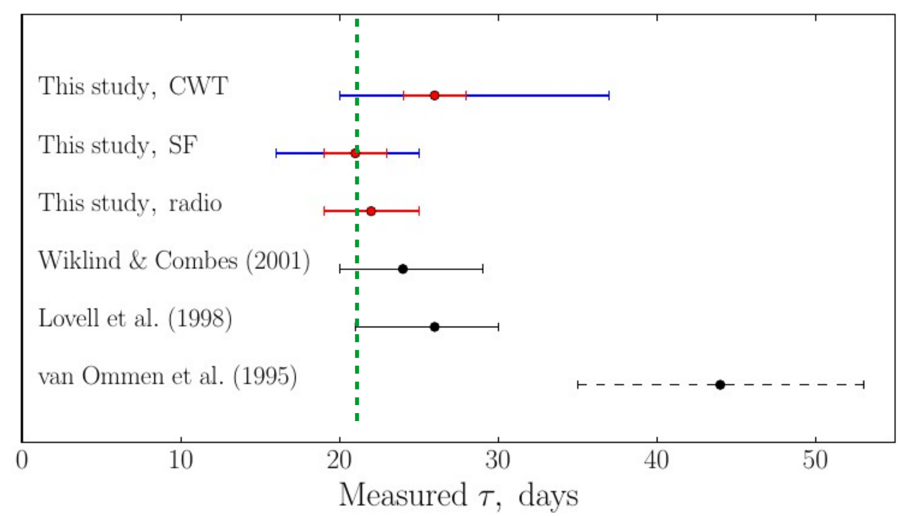
PKS 1830-211: detection of the gravitational time delay in gamma rays

Temporal analysis of the 6 years of Fermi/LAT data: τ_γ =21+/-2 days.

Structure function ($SF=\langle[f(t)-f(t-\tau)]^2\rangle$)



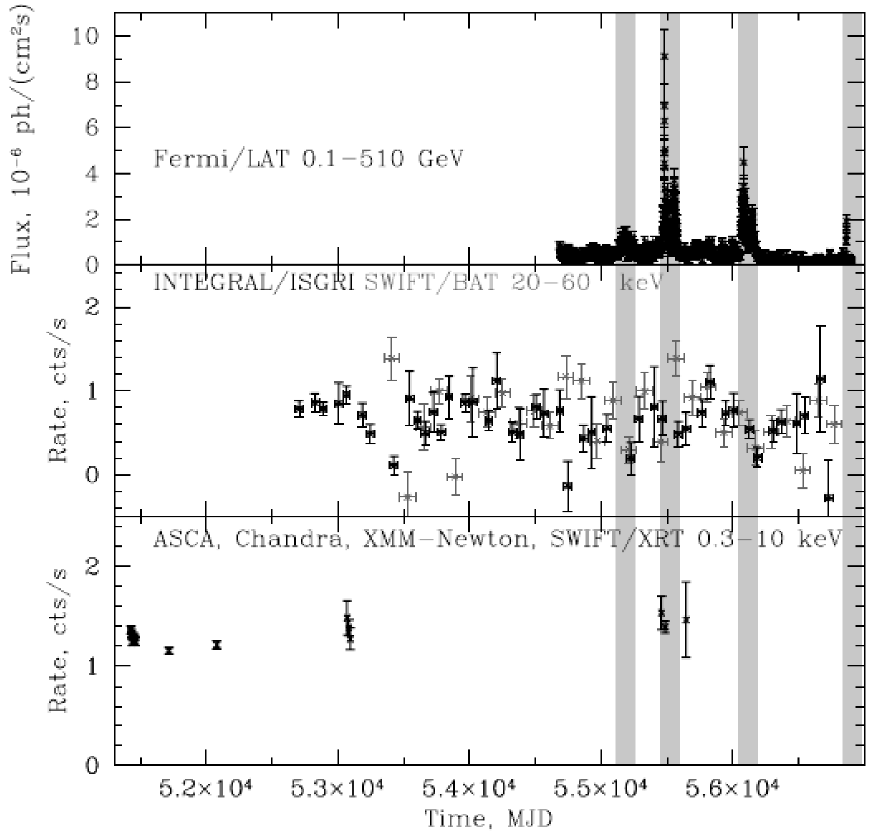
Comparison with other measurements



Neronov+ '15

Consistent estimates from several techniques: autocorrelation, structure function and wavelet analysis.
The estimated delay is consistent with measurements in radio.

PKS 1830-211: γ-γ opacity



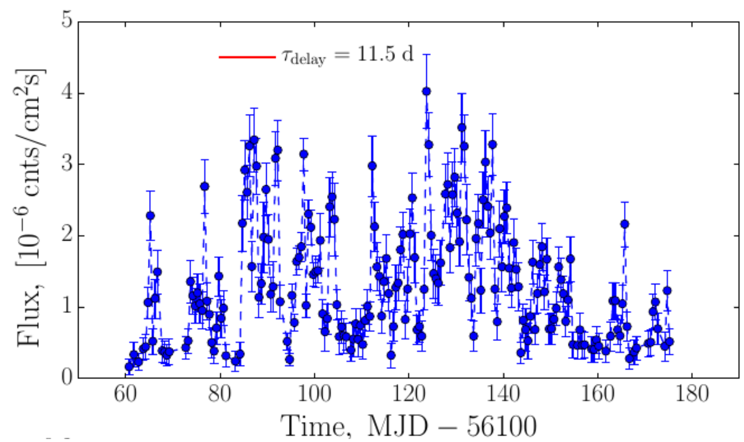
X-ray light curves show variability of only ~10 % during the Fermi flaring episodes.

Microlensing does not affect X-ray emission of the source.

$R_X > R_E$

Opacity τ_γ<3 (or >5%) at 10 GeV, so **the central source is sufficiently transparent to the gamma-ray emission**.

γ-ray magnification factor issue



In 2012 several subsequent, partially overlapping flares were taking place.

$$F_{tot}(t) = \mu F(t)+F(t-\tau)$$

The exact solution can be found in the Fourier space:

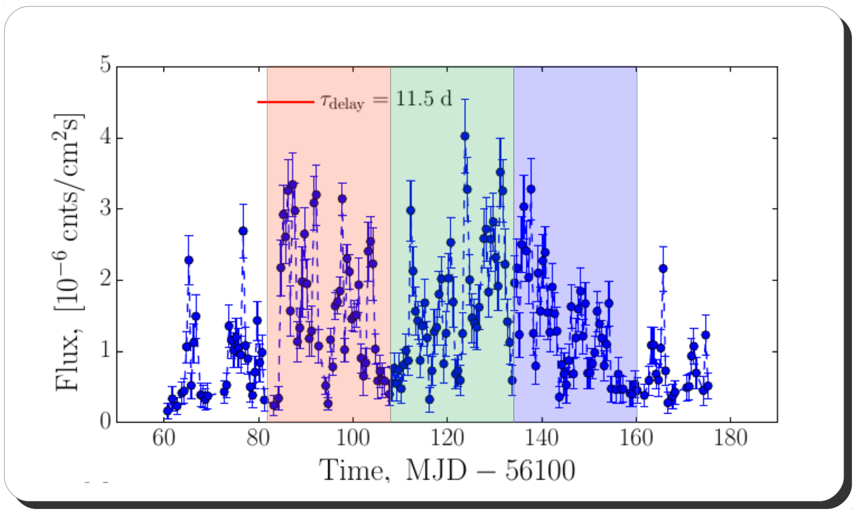
$$F^*_{tot}(\omega) = F^*(\omega)(\mu+e^{-i\omega\tau})$$

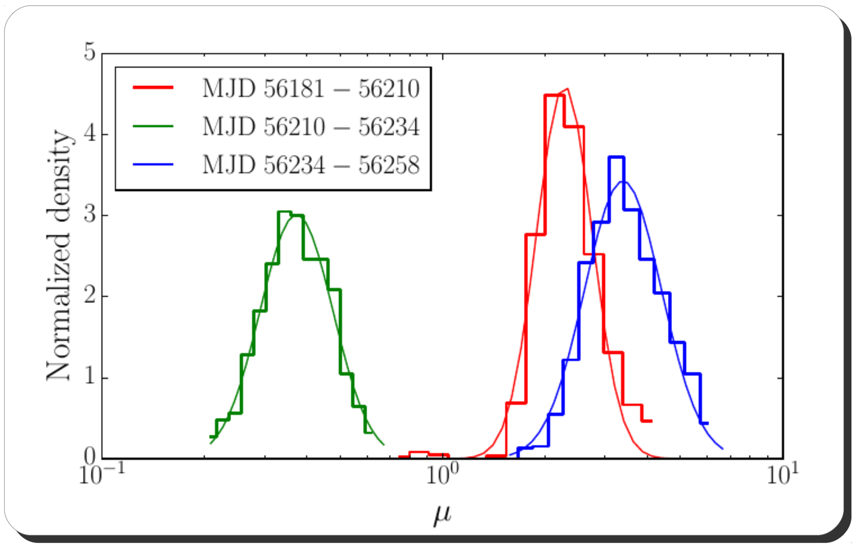
In case of real data – binned and with uncertainties – an approximate solution can be found instead, provided that the time delay **τ** and magnification ratio **μ** are known.

Time delay τ=11.46 days is already known (Cheung+ 14). **However, magnification ratio μ is not.**

Variability of the γ-ray magnification factor in B0218+357

The value of magnification ratio μ_{best} can be found by scanning μ in a certain range and requiring, that the intrinsic light curve F(t) does not contain signatures of the time delay τ=11.46 days.

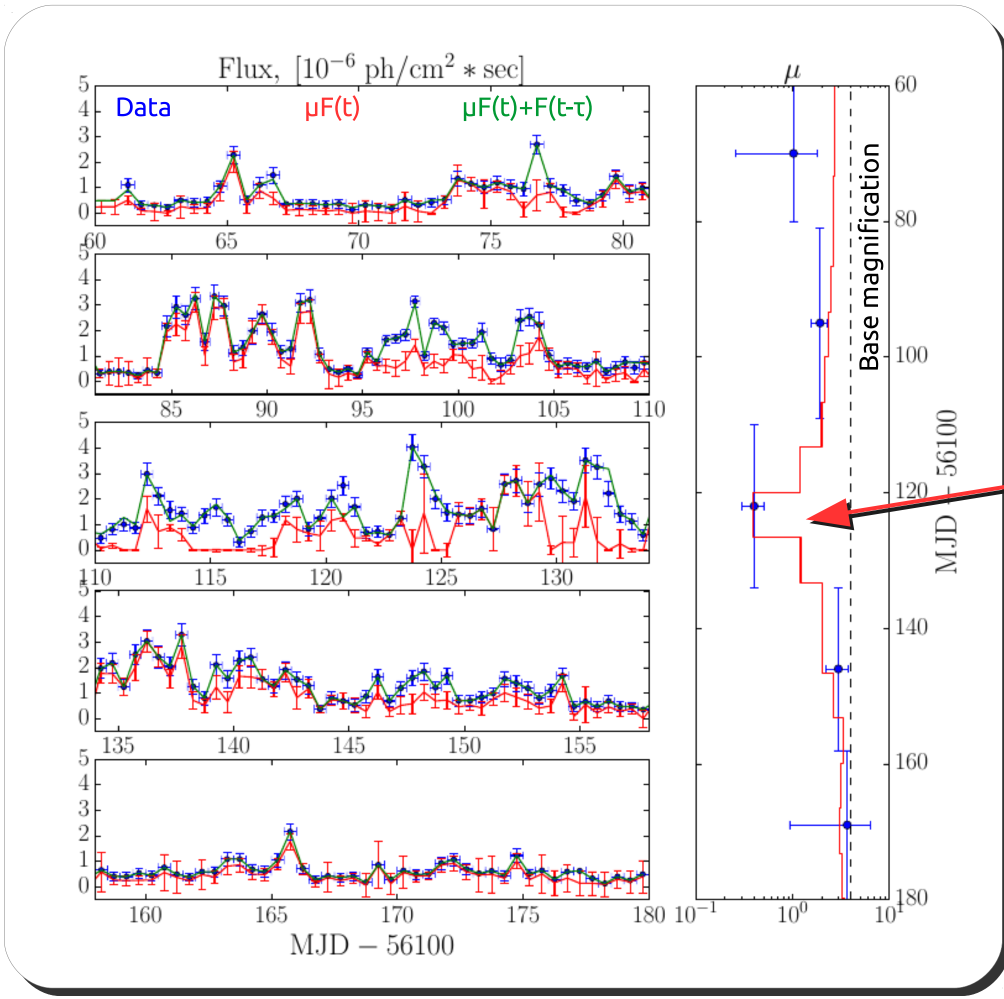




This approach reveals a variation of the magnification factor ratio in range 0.4-4 over the time scale of 100 days.

Taking into account μ_{radio}~4 this implies the presence of microlensing with μ_{micro}~10.

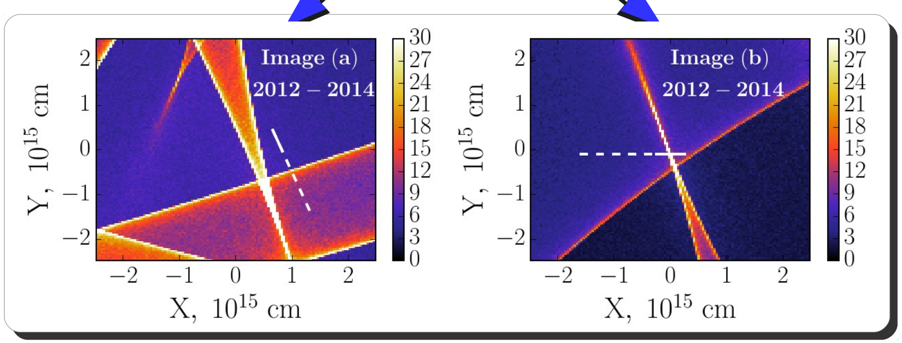
Caustic crossing caught in action in B0218+357



Vovk & Neronov '15

A natural explanation of the detected behaviour of μ_γ is found in terms of microlensing – the caustics crossing by a compact source with $\mathbf{R_\gamma \sim 10^{14}\text{-}10^{15}}$ **cm**.

Events of similar duration and amplitude are not difficult to find in the simulated caustics maps.



This provides a self-consistent picture of both 2012 and 2014 flaring episodes.