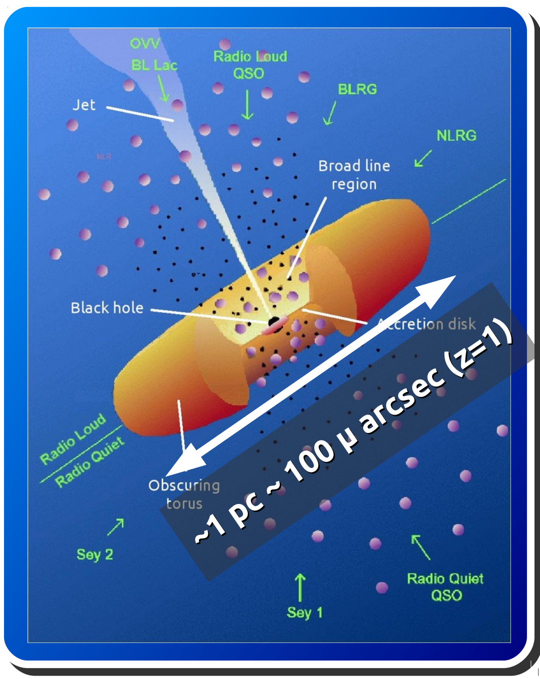
Resolving the blazar gamma-ray emission regions with gravitational microlensing

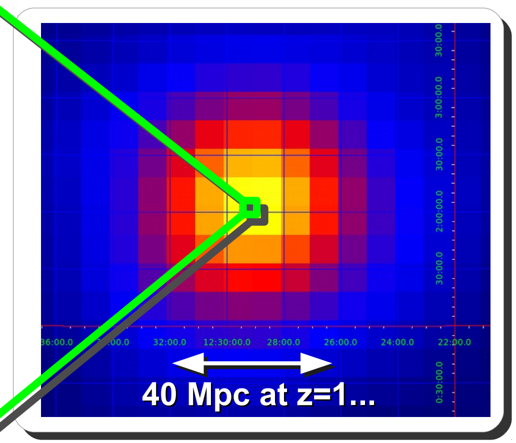
Ievgen Vovk
Max-Planck-Institut für Physik

The problem of resolving the AGN „central engine“



Urry & Padovani (1995)

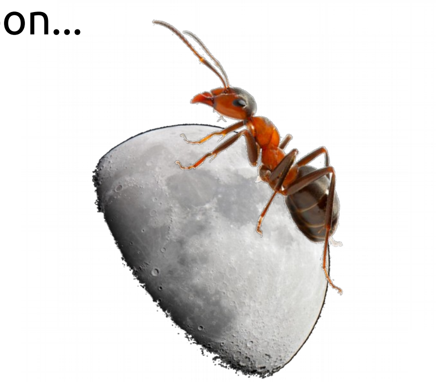
Fermi/LAT image > 1GeV



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...



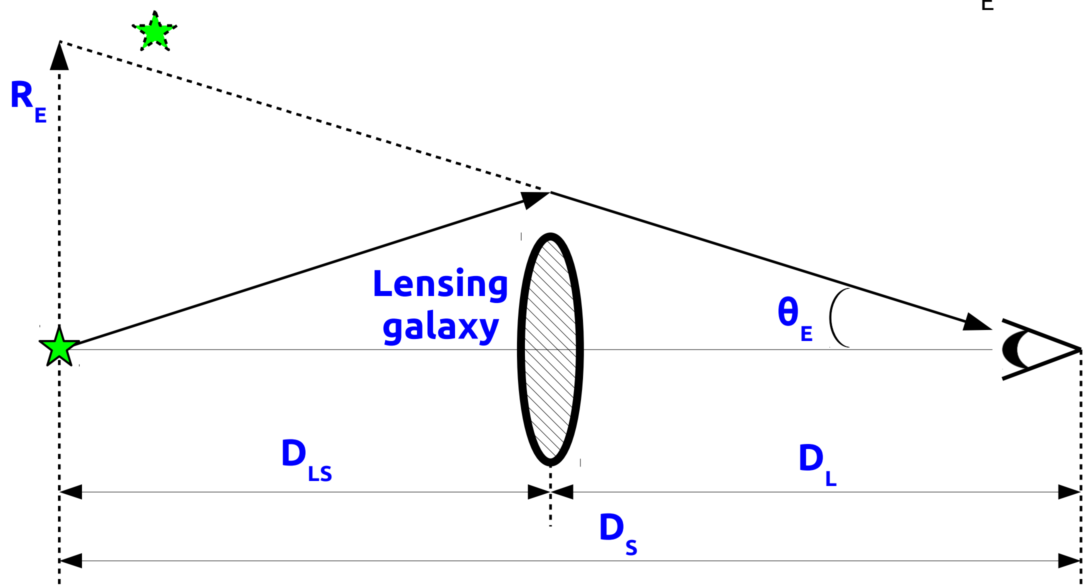
The gamma ray source can not be directly resolved with existing and even planned future gamma-ray telescopes.

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.

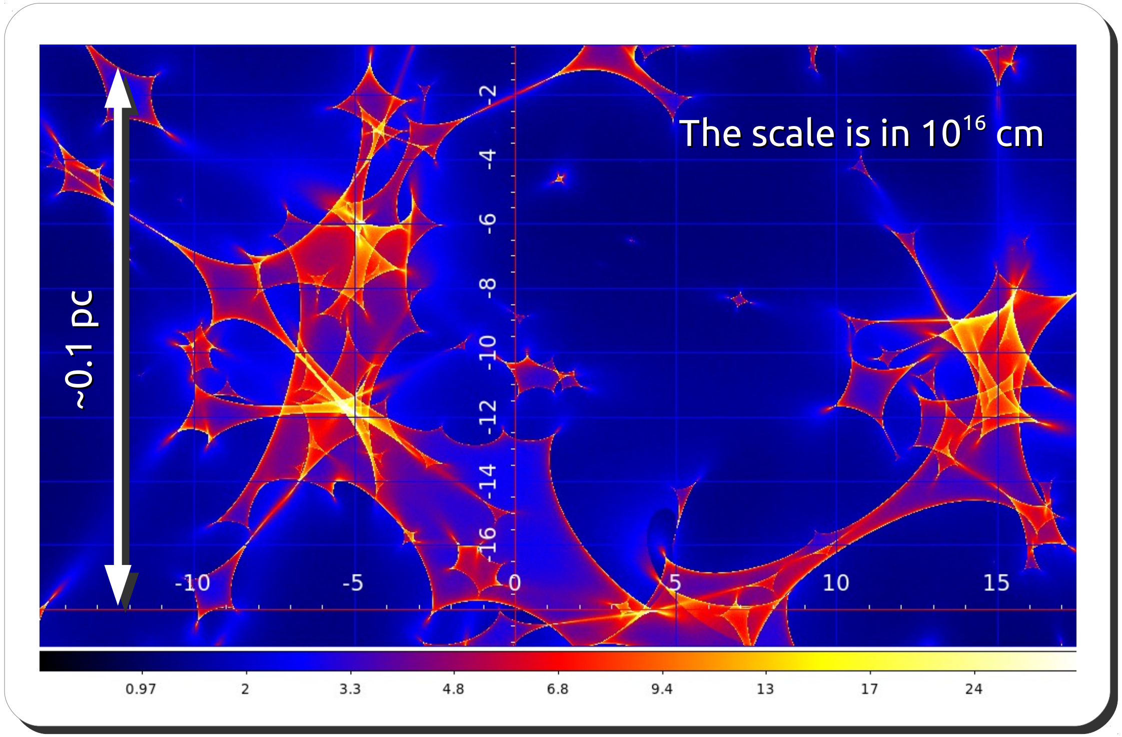


$$\theta_E = [4GM/c^2 * D_{LS}/(D_S D_L)]^{0.5}$$

$$R_E \sim 4\times10^{16} (M/M_{Sun})^{0.5} \text{ cm}$$

Gravitational microlensing

Many stars-microlenses ➡ complicated magnification pattern



The characteristic scale in the map is set by the Einstein radius
$R_E = 4 \times 10^{16} (M/M_{Sun})^{0.5}$ 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 depends on the source size:
$\mu_{micro} \sim (R_E/R)^{0.5}$ and $\Delta t = R/v$

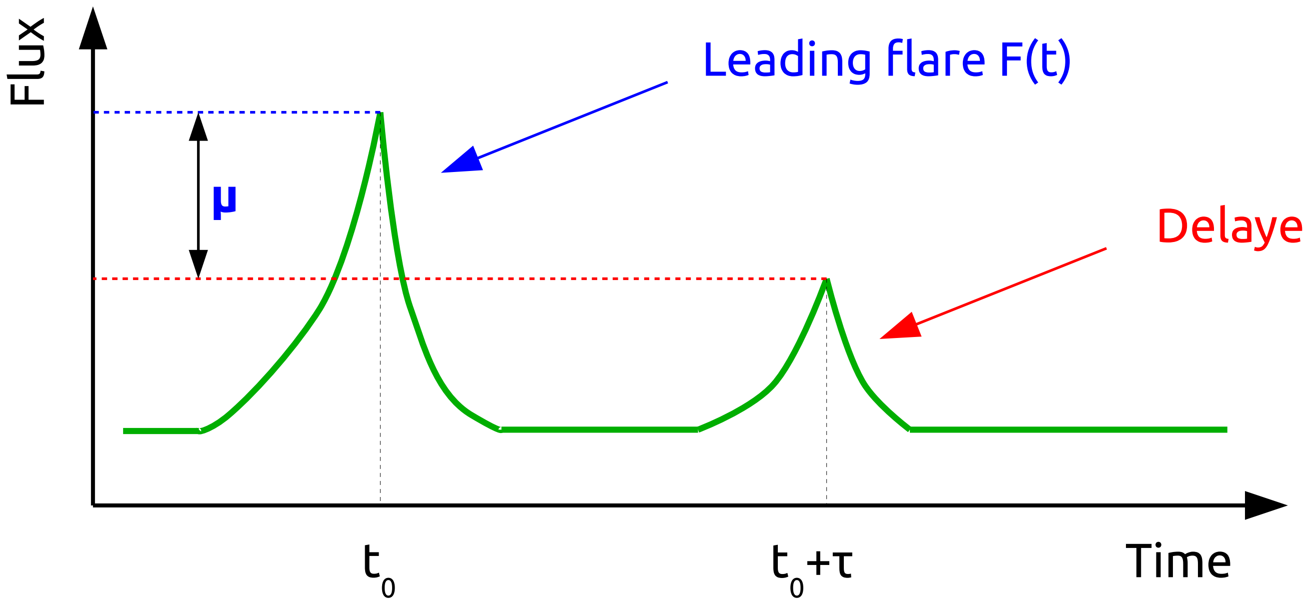
$$\mu \approx 10 \left(\frac{R}{3\,x\,10^{14}\,cm} \right)^{-0.5}$$

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

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)

Magnification factor in radio: 1.52+/-0.5 (Lovell+ '98)
Magnification factor in gamma: >6 (Abdo+ '15)

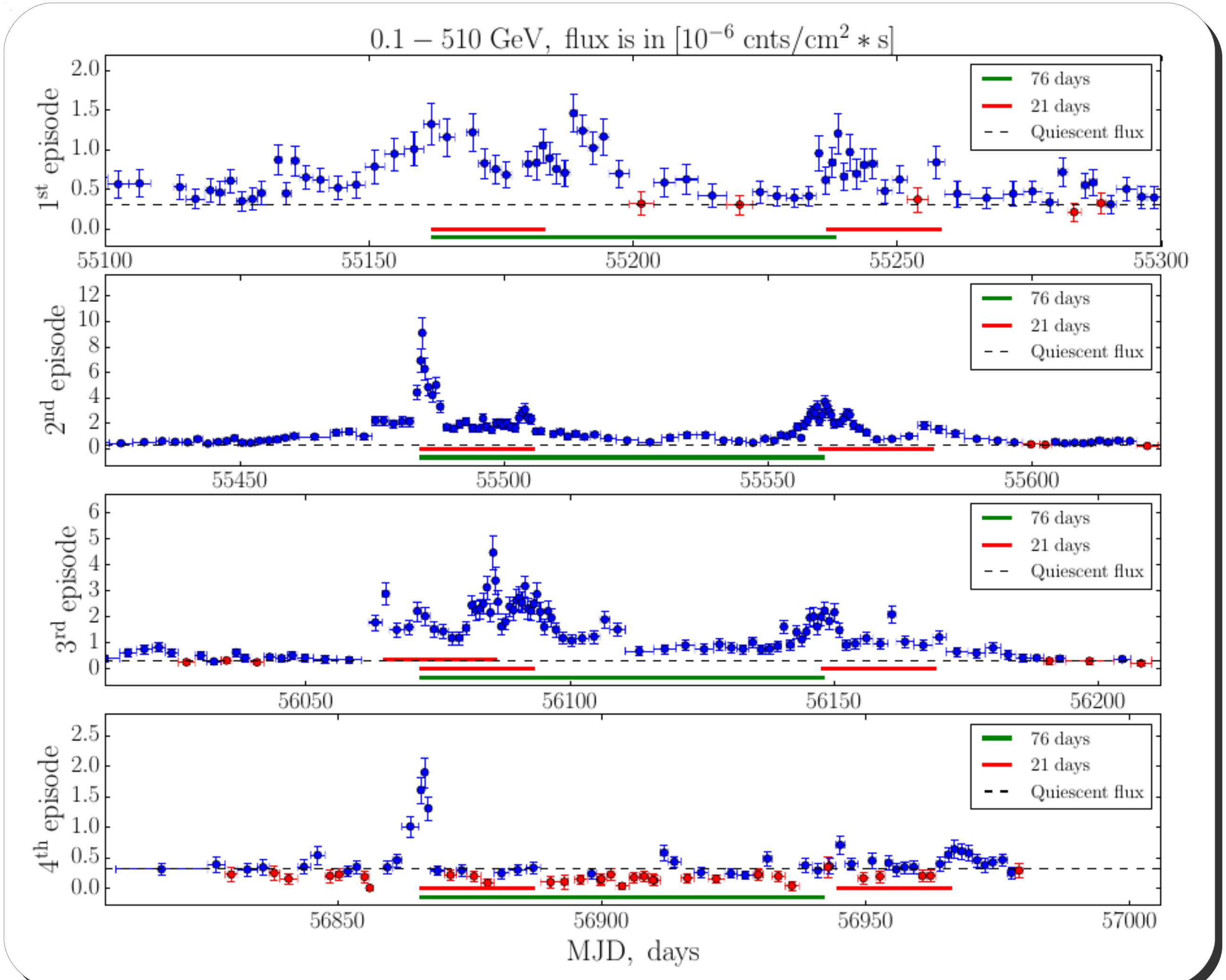
B0218+357

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)

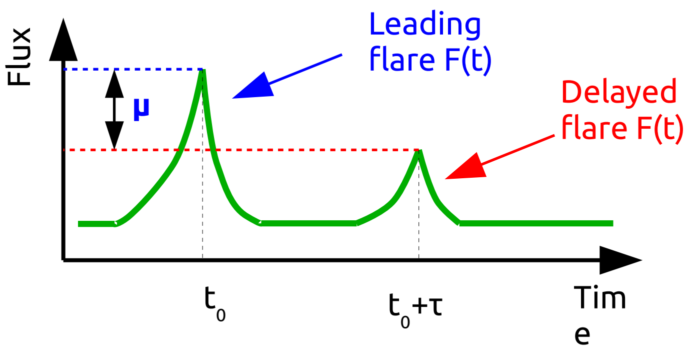
Magnification factor in radio: 3.5-3.7 (Mittal+ '07)
Magnification factor in gamma: ~1? (Cheung+ '15)

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

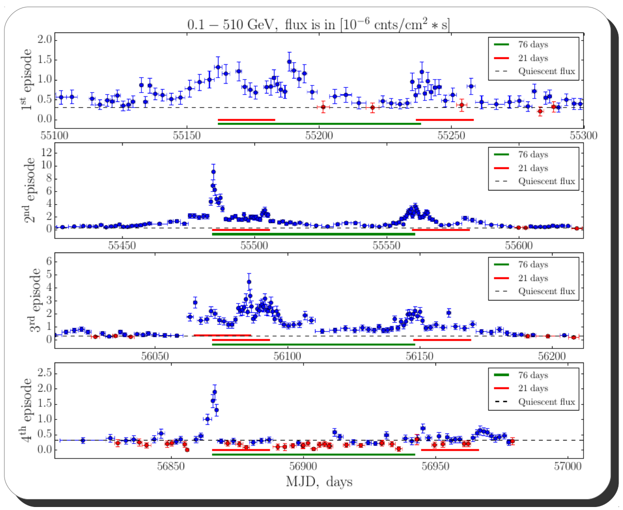


Neronov et al., Nature Physics (2015)

- 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<Δt<75 days



PKS 1830-211: microlensing constraints on the source size



μ_{micro} = 2-5 $\quad \mu_{micro} \approx 10 \left(\frac{R}{3\,x\,10^{14}\,cm} \right)^{-0.5}$ → **R_γ~10^{15} cm**

1<Δt<75 d $\quad \Delta t \approx 100 \left(\frac{R}{3\,x\,10^{14}\,cm} \right) \left(\frac{v}{300\,km/s} \right)^{-1} days$ → **R_γ<3x10^{15} cm**

Microlensing

t_{rep} =76 d → **R_γ~10^{15} cm**

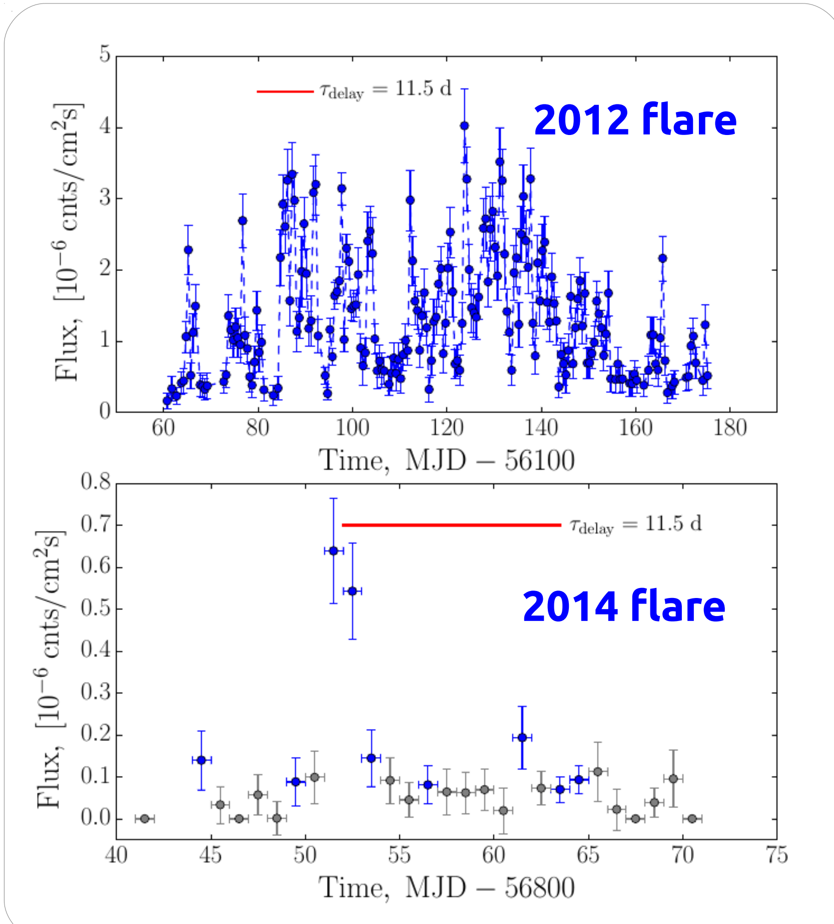
t_{rise} ~ 0.5 d → **R_γ~10^{15} Γ cm**

Supplementary

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

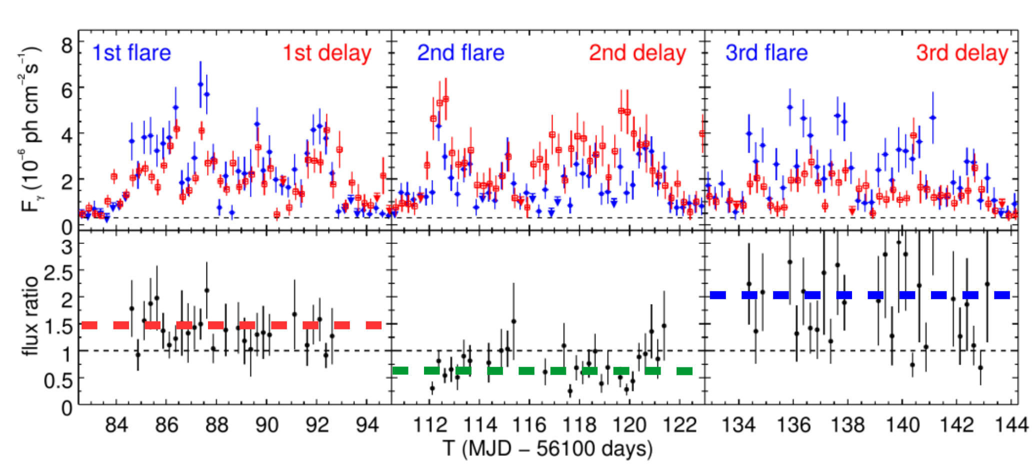
→ **The possibility of relativistic motion is disfavoured by the data**

Variability of B0218+357



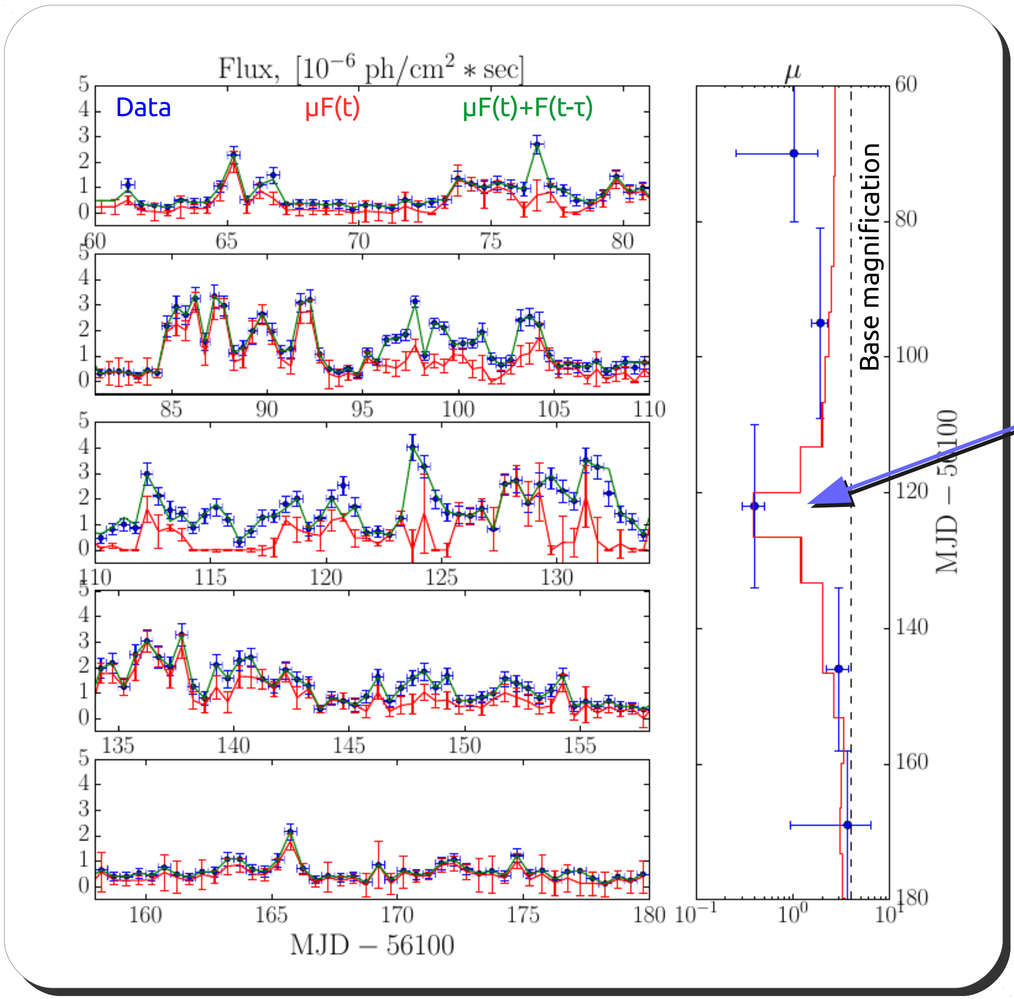
- Two flares in ~6 years of Fermi/LAT observations
- Magnification in radio: ~3.5-3.7 (Mittal+ '07)
- Magnification in gamma-rays: variable ?

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



Cheung+ 14

Caustic crossing caught in action in B0218+357



Vovk & Neronov '15

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 of the detected behaviour of μ_γ is found in terms of microlensing – the caustics crossing by 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

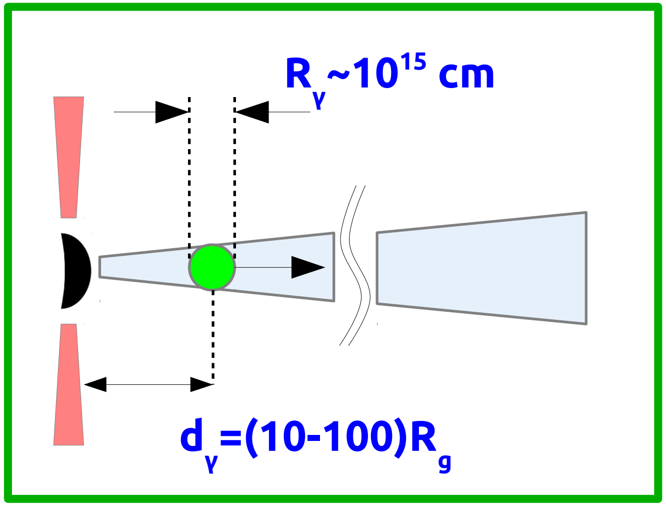
Time scale of variations:

- PKS 1830-211: 1<Δt<75 days
- B0218+357 : ~50 days

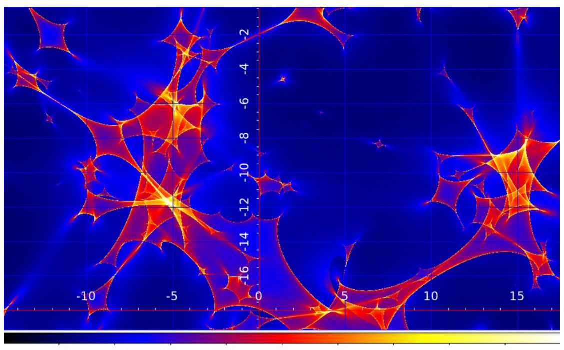
	PKS 1830-211	B0218+357
μ_{micro}	10^{15}-10^{16} cm	10^{14}-10^{15} cm
Duration	10^{14}-10^{15} cm	10^{14}-10^{15} cm
Fast variability	$<10^{16}$ (Γ/10) cm	$<3 \times 10^{15}$ (Γ/10) cm

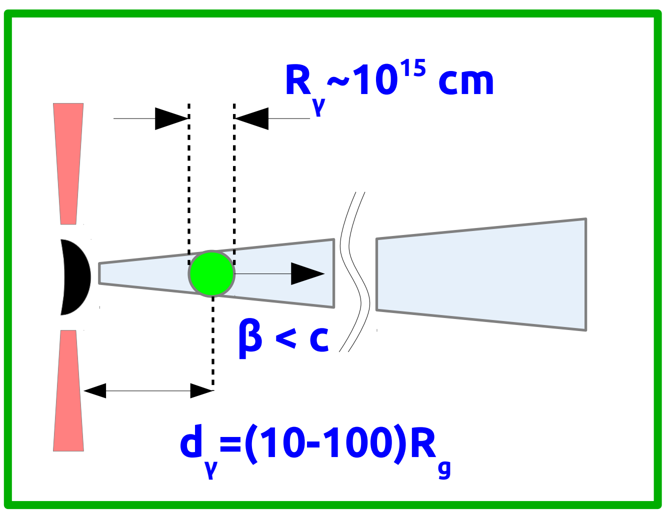
Detection of microlensing suggests that the emitting source is not relativistic.

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





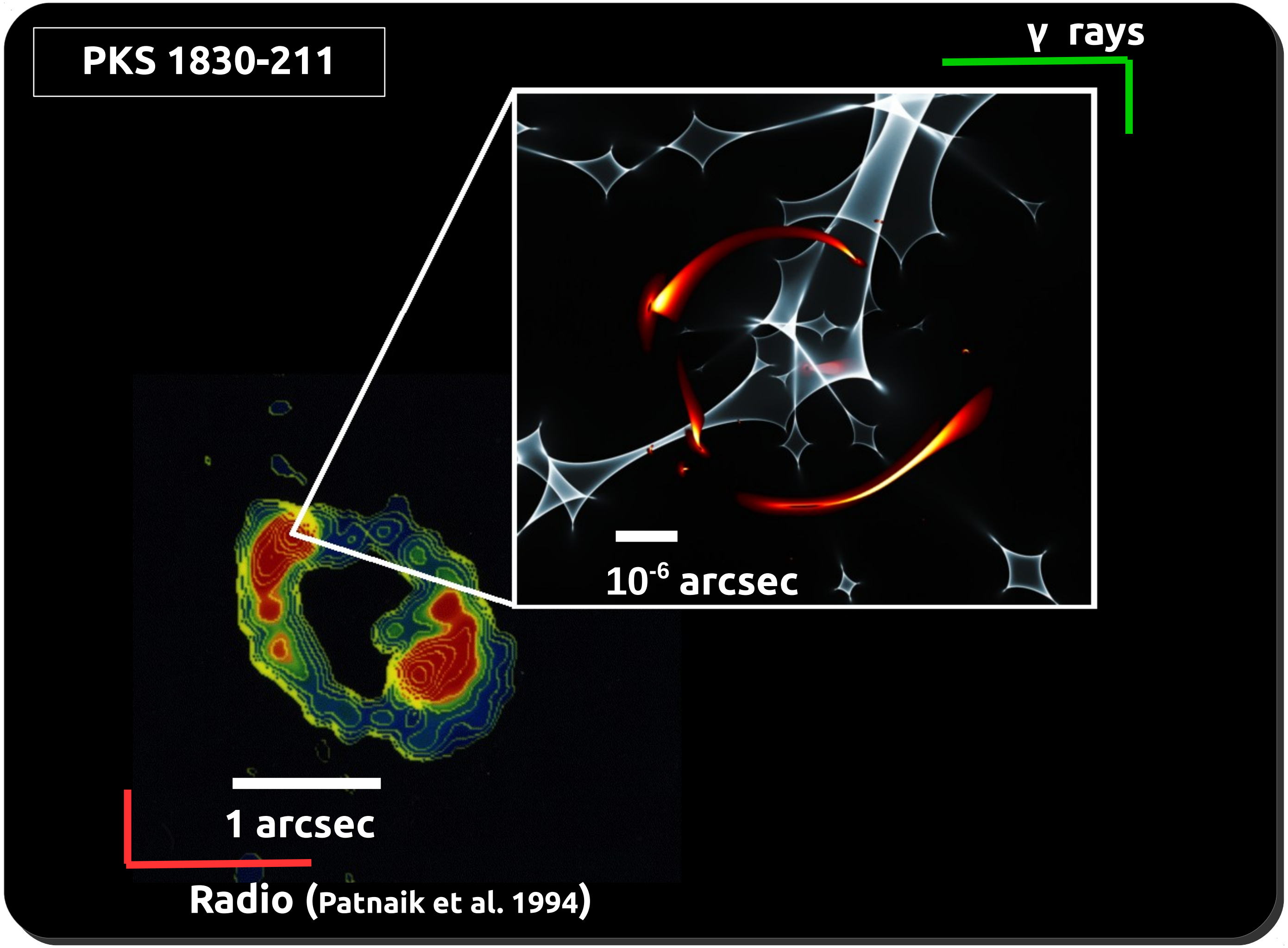
Regular observations of microlensing opens a new way to learn about the nature of AGNs:

- ✔ energy dependence of R_γ
- ✔ its variations with time
- ✔ gamma vs radio location estimates

This gives a completely 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

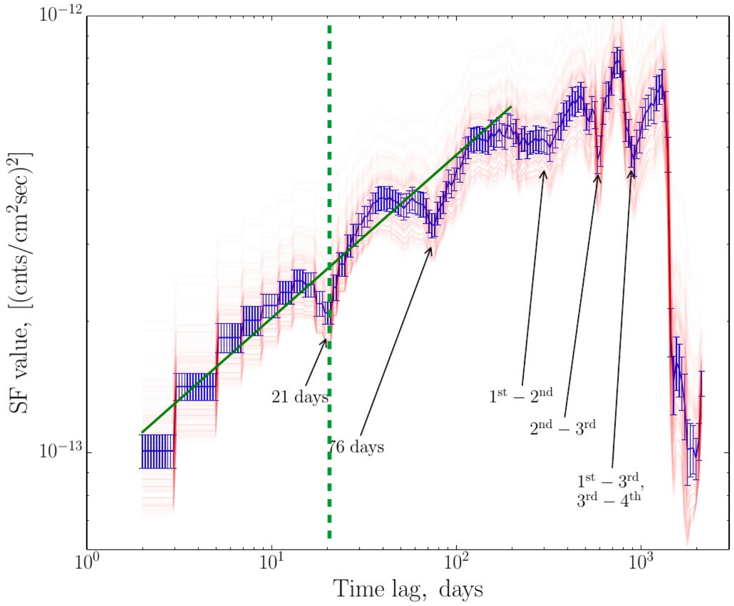
Gravitational magnifying glass



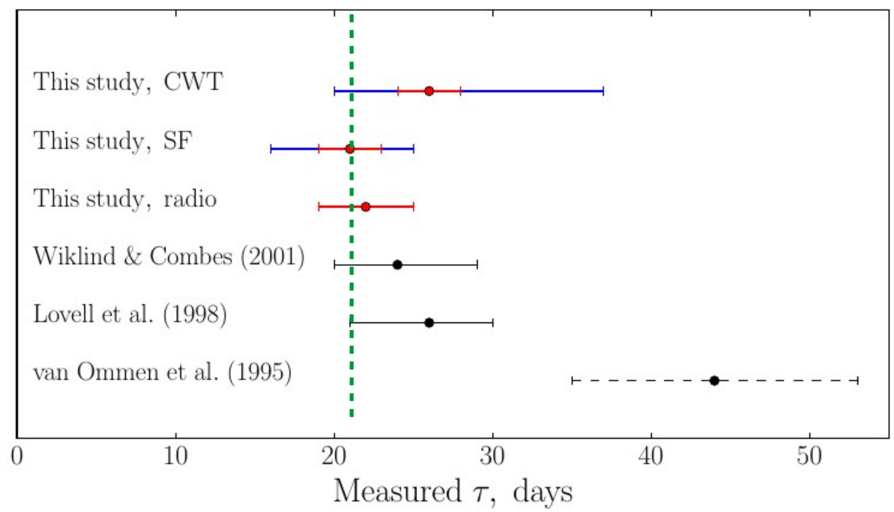
PKS 1830-211: detection of the gravitational time delay in gamma rays

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

Structure function (SF=<[f(t)-f(t-τ)]^2>)



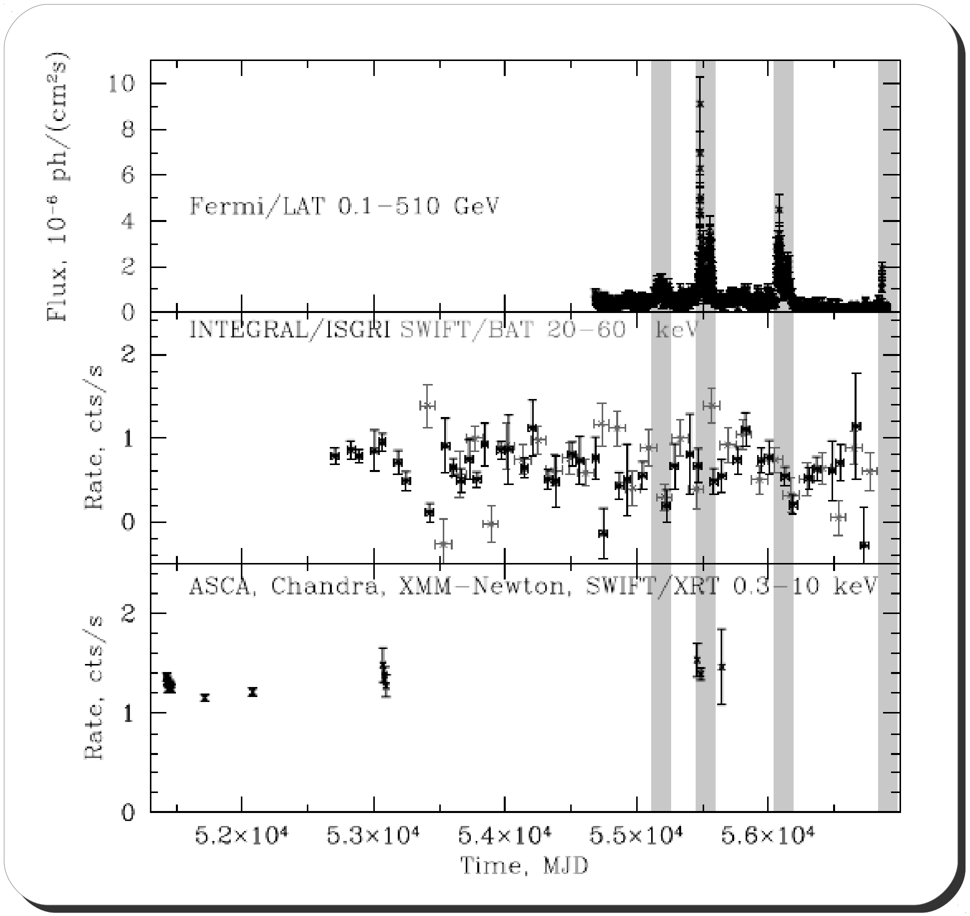
Comparison with other measurements



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



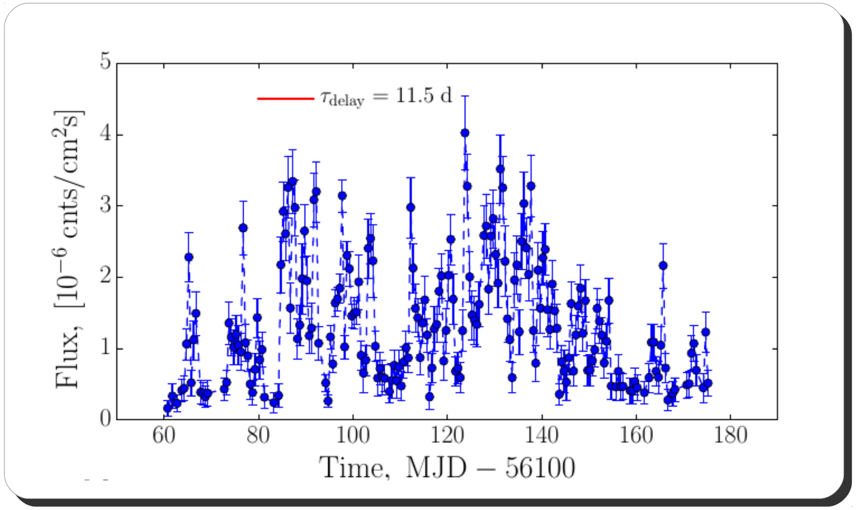
X-ray light curves show variability of only ~10 % during the Fermi flaring episodes.

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:

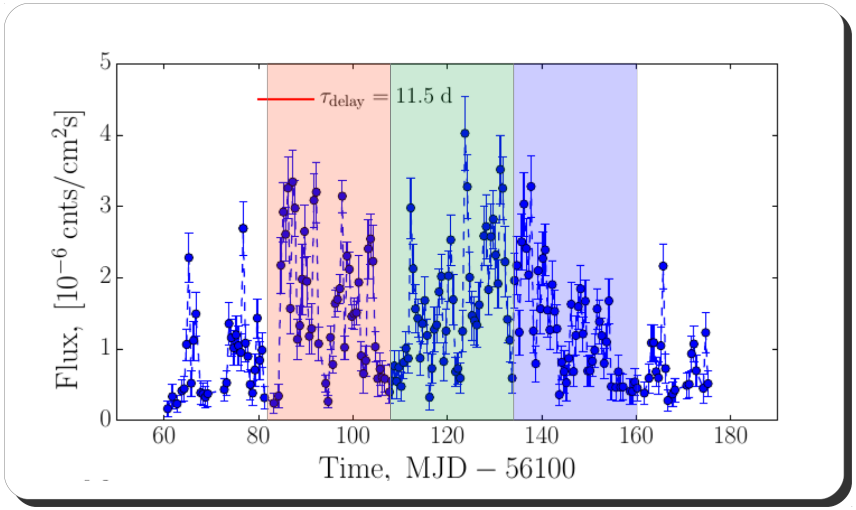
$$F^*_{tot}(\omega) = F^*(\omega)(\mu+e^{-i\omega\tau})$$

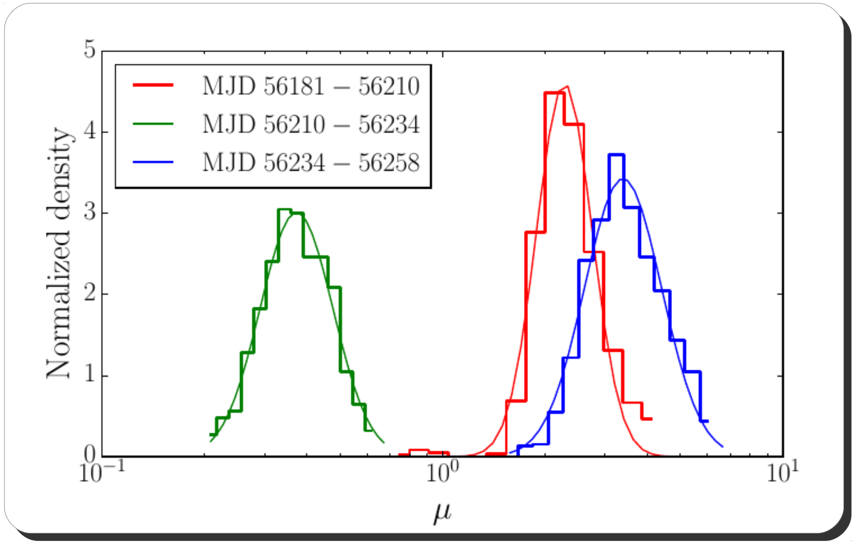
In case of real data – binned and with uncertainties – an approximate solution can be found instead, provided that the time delay **τ** and magnification ratio **μ** are known.

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.

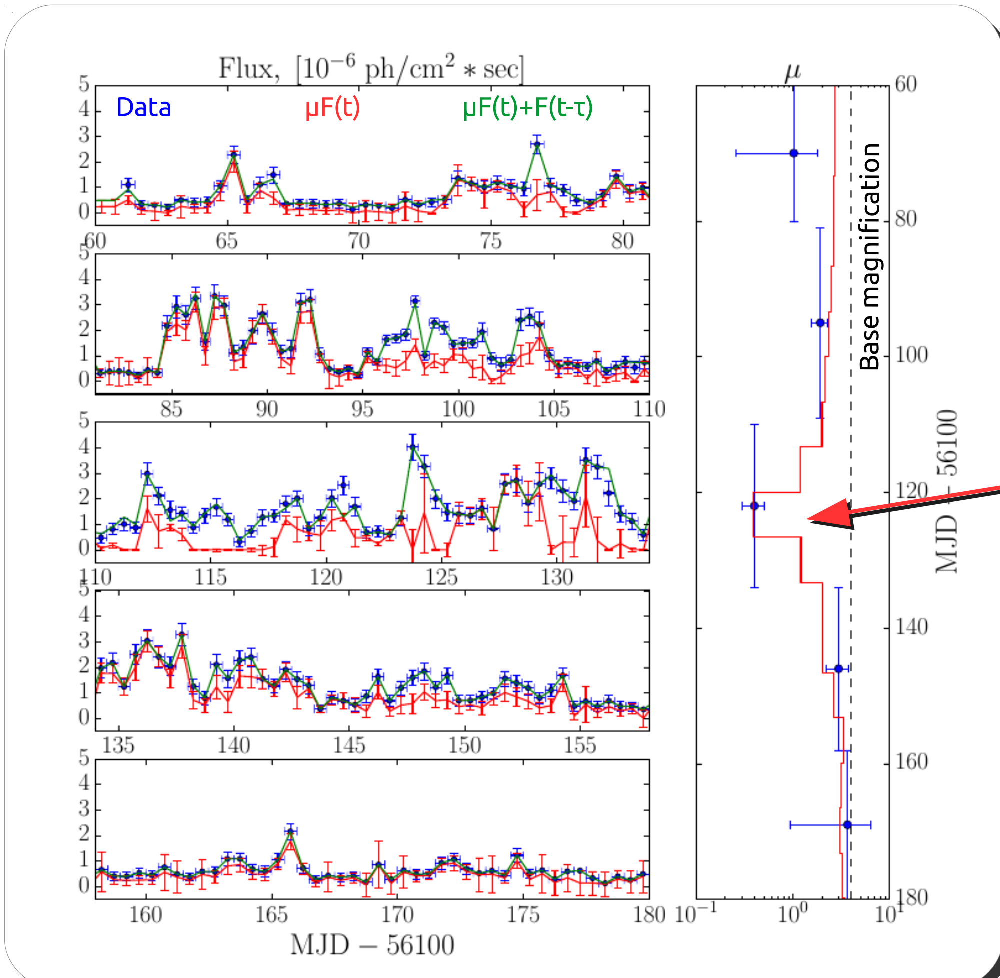




This approach reveals a variation of the magnification factor ratio in range 0.4-4 over the time scale of 100 days.

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

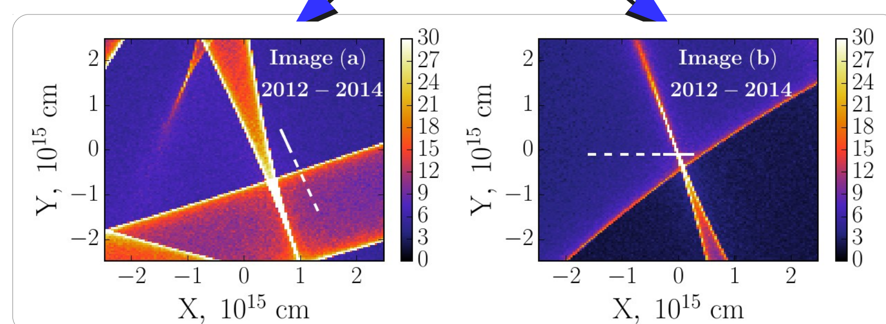
Caustic crossing caught in action in B0218+357



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 **R_γ~10^{14}-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.