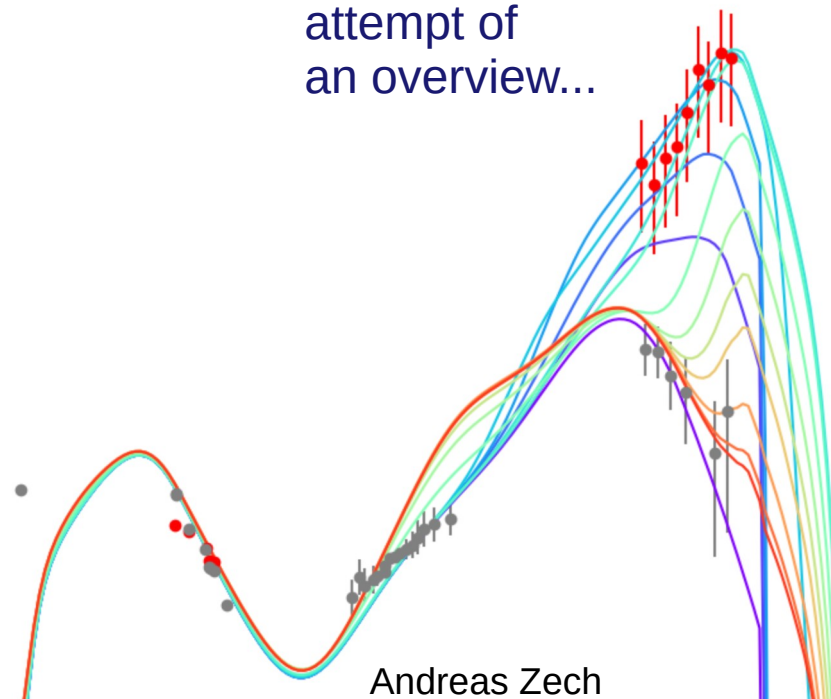
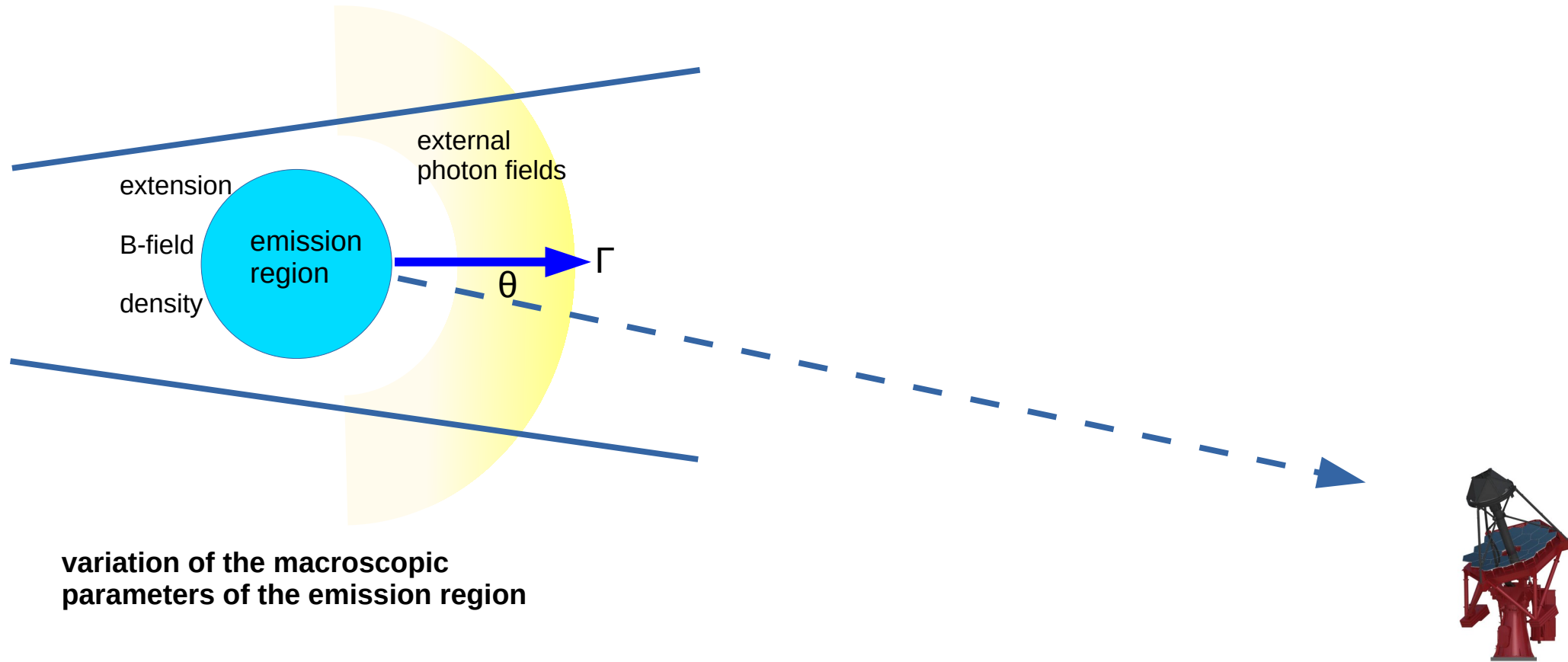


# Radiative models for rapid blazar flares

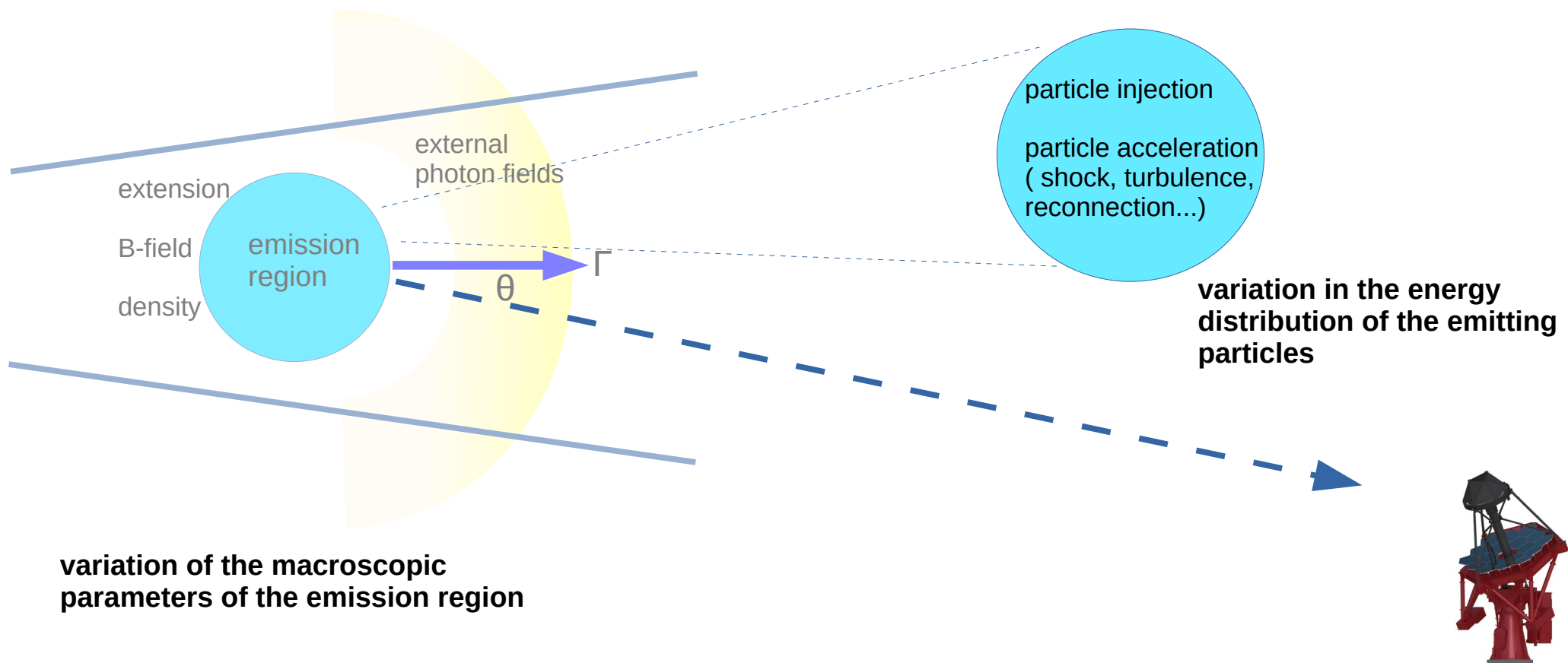


**Illuminating the Active Universe**  
ESO, September 2026

# Origin of blazar flares



# Origin of blazar flares



# Outline

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- Observational clues
- Particle acceleration scenarios
  - shock
  - shock & turbulence
  - magnetic reconnection
- Jet propagation scenarios
- Conclusions

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# Observational clues

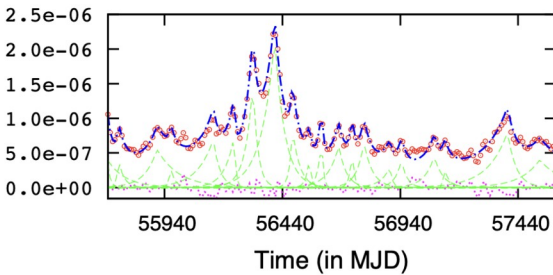
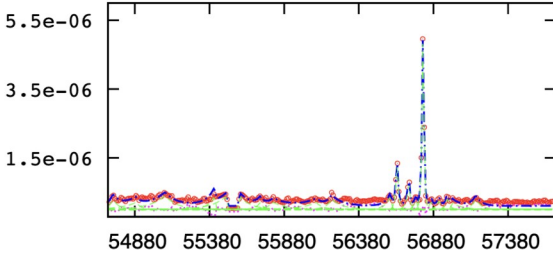
# Some lessons from Fermi-LAT

*Roy et al. 2019 :*

Study of GeV flares in 10 blazars.

→ most **long-term** (~weeks–months)  
**flares** are **symmetric** :  
dominated by the crossing time-scale of a  
**disturbance** ?

→ larger fraction of **short-term** (~hr–d)  
**flares asymmetric** : gradual **acceleration**  
and **cooling** ?



Asymmetry  
parameter  $\xi = \frac{T_d - T_r}{T_d + T_r}$

with rise time  $T_r$   
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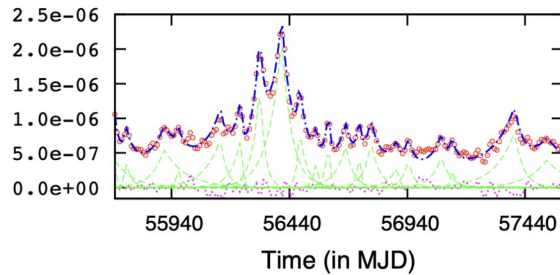
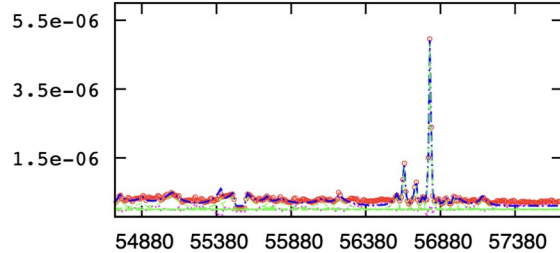
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*Meyer, Scargle, Blandford 2019 :*

Analysis of the brightest γ-ray flares of  
6 FSRQs.

→ did not find same trend as Roy et al.  
→ no signs of intrinsic γ-ray absorption  
→ **γ-rays produced beyond BLR**



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and **cooling** ?

*Cerruti 2025 :*

Study of 732 blazars from LAT light curve  
repository (3 day bins) with ML classification.

→ **Continuous** distribution of **symm. and asymm.**  
and of **achromatic and chromatic** flares.

→ **Shortest** flares show **highest luminosity**  
variation.

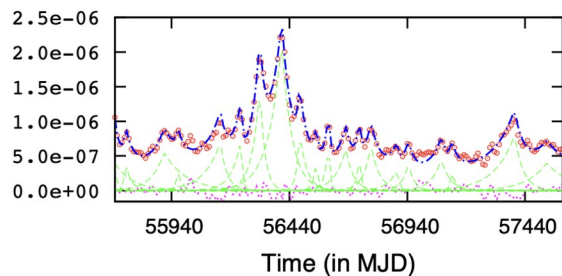
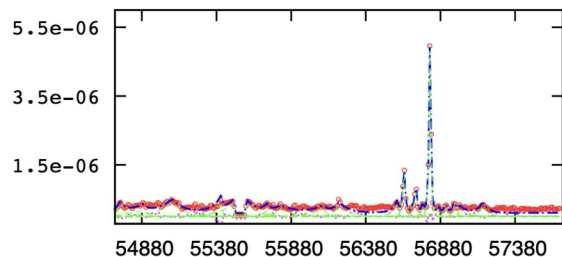
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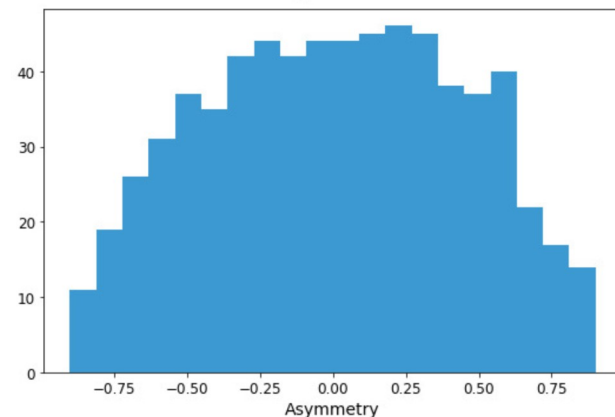
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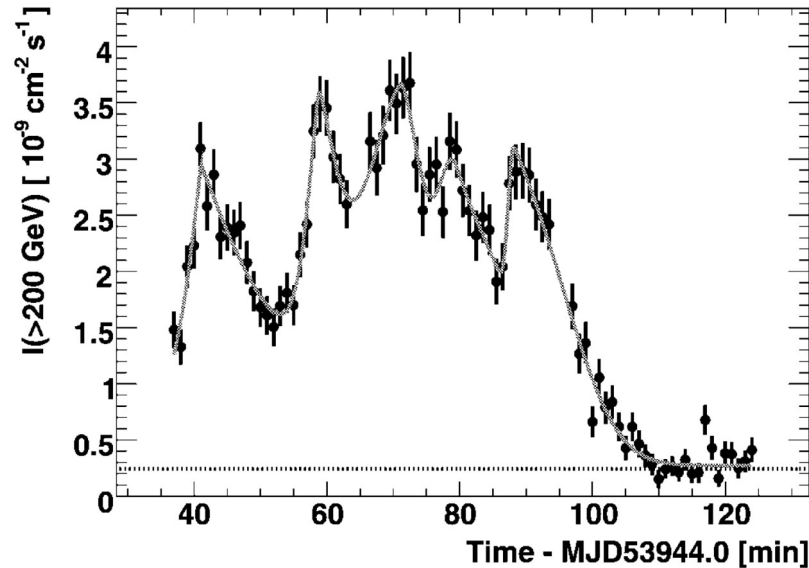
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# Some lessons from the VHE domain

Flares with **minute variability time scales** detected in several blazars (PKS 2155-304, Mrk 501, BL Lac...)

→ **very compact emission regions ( $< r_G$ ) and / or extreme Doppler boosting.**

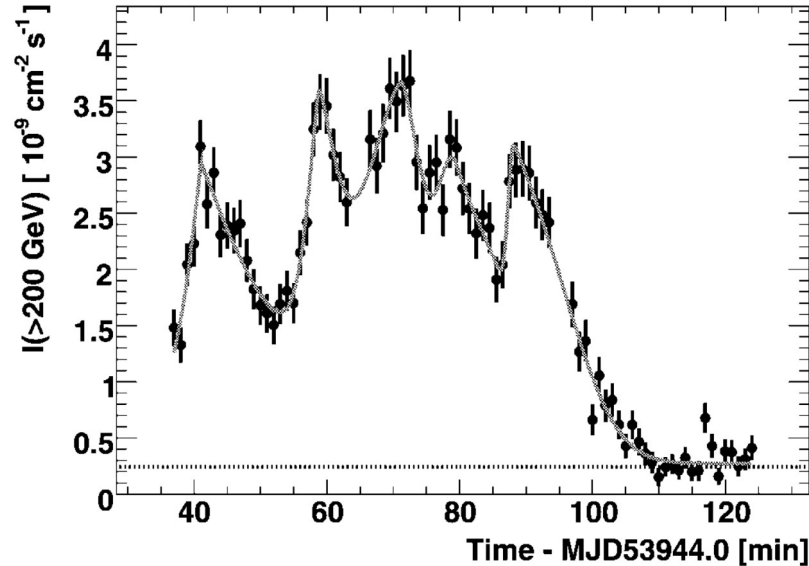


*PKS 2155-304, Aharonian et al. 2007*

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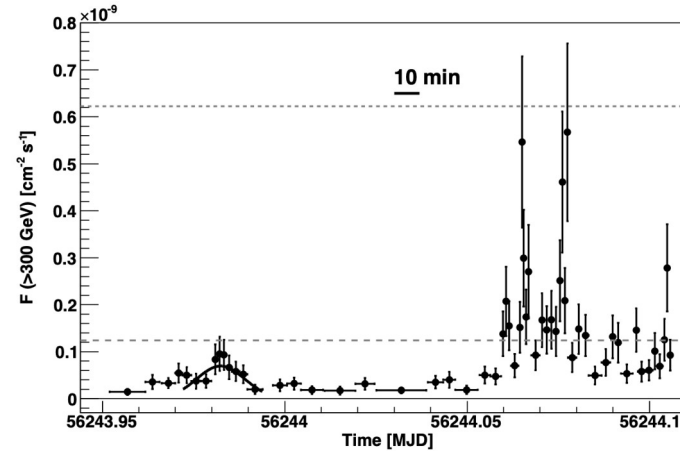
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Very rapid flares also detected from **radio galaxies**, without the benefit of strong Doppler beaming.

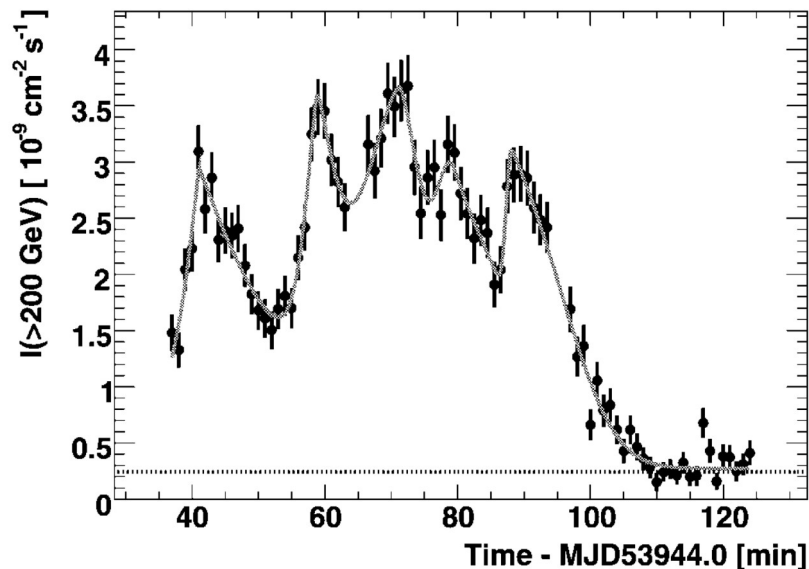


Flare from radio galaxy IC310, Aleksic et al. 2014

# Some lessons from the VHE domain

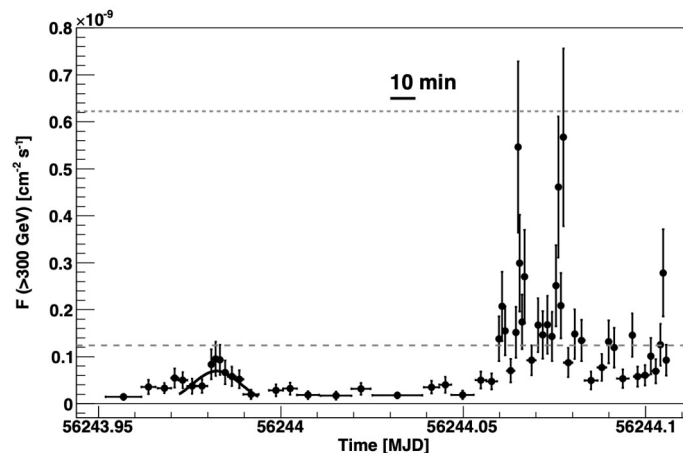
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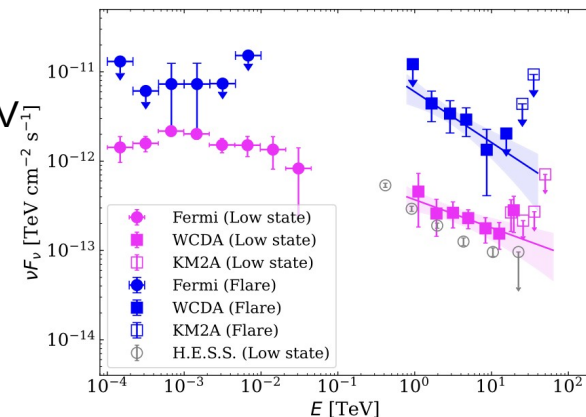


Flare from radio galaxy IC310, Aleksic et al. 2014

Flare spectra from M87 extending beyond 10 TeV energies.

→ **very efficient particle acceleration**

Cao et al. 2024



# MWL time delays in flares

---

*de Jaeger et al. 2023 :*

Correlation of **optical** ASAS-SN and **y-ray** Fermi flares of 1180 blazars using Bayesian Blocks.

- 321 **correlated flares** with average time delays consistent with zero
- 191 optical and 115 y-ray **orphan flares**

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X-ray and γ-ray delays :

- frequent observations of correlation with **zero lag** (e.g. Mrk 421 VHE vs. X)

- **delay of high-energy photons**

up to a few (10) ks in Mrk 421 & *1ES 1218+304* in X-rays (*Zhang et al. 2002; Sato et al. 2008*);

4±1 min in Mrk 501 VHE (*Albert et al. 2007*)

- **delay of low-energy photons**

e.g. Mrk 421 X-ray band (*Ravasio et al. 2004*)

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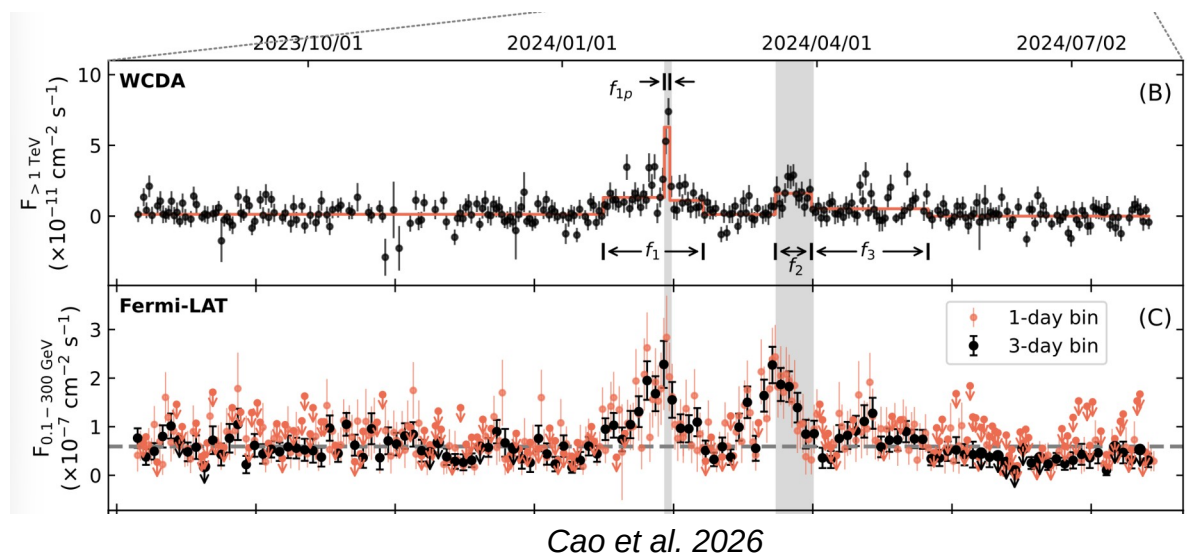
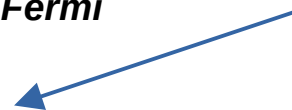
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e.g. Mrk 421 X-ray band (*Ravasio et al. 2004*)

- *1ES 1959+650 TeV flare 5 days delayed wrt Fermi*

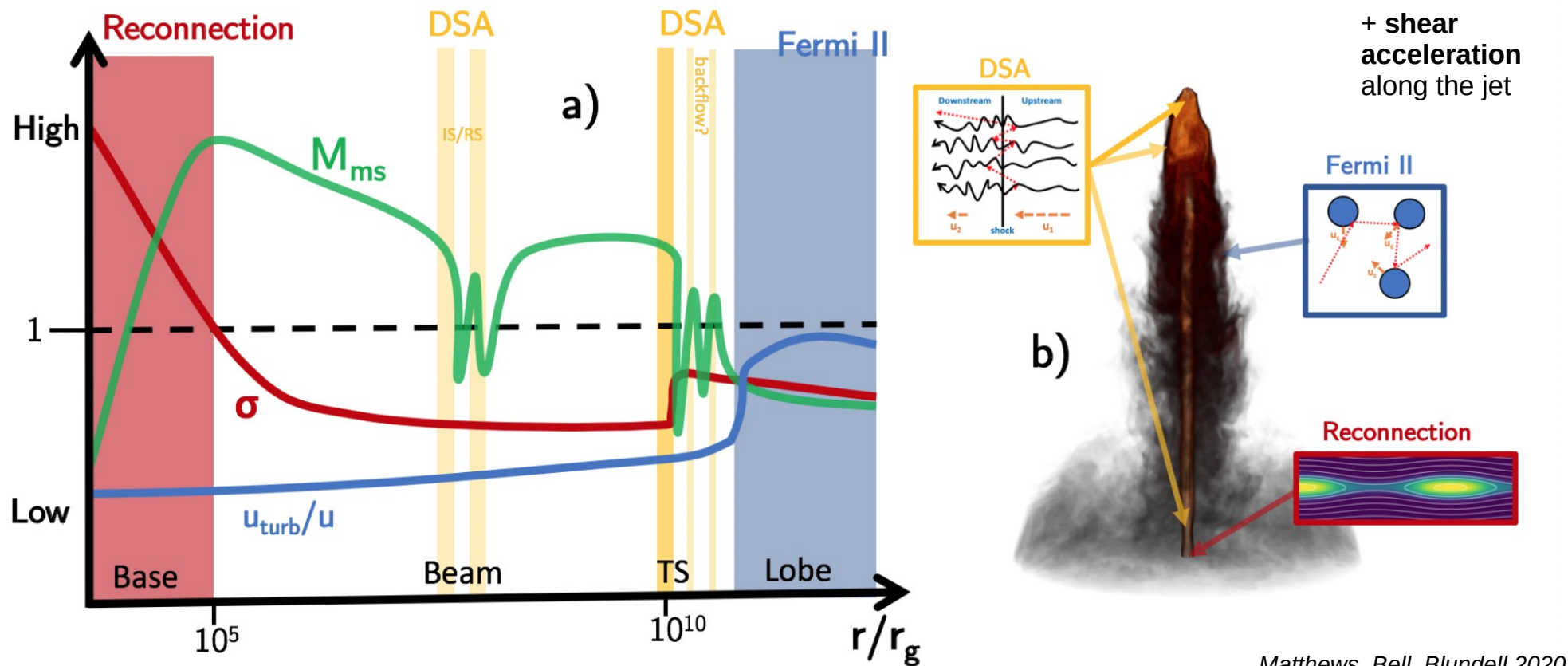


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# Particle acceleration scenarios

# particle acceleration in jets

Several mechanisms seem to contribute in different regions of the jet.

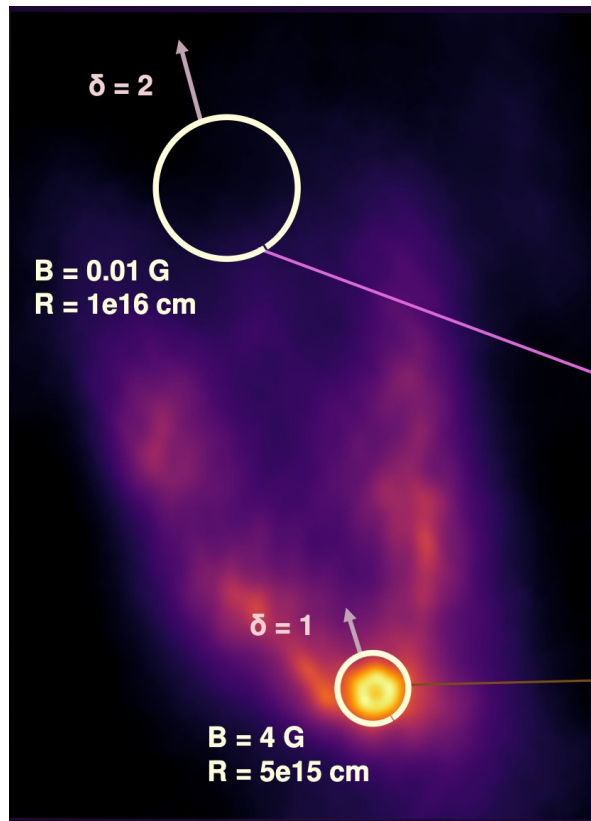


Matthews, Bell, Blundell 2020

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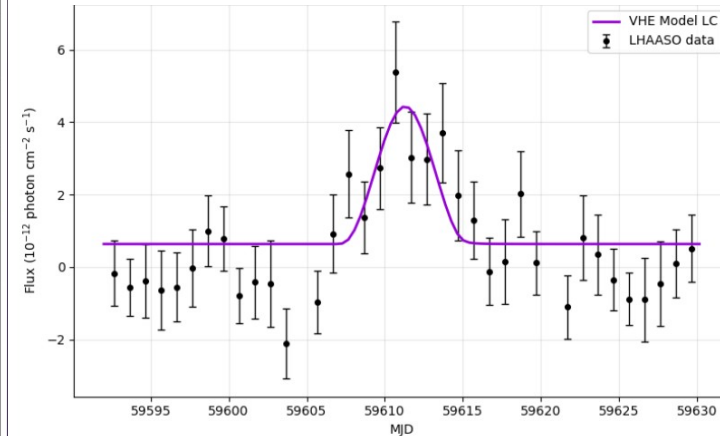
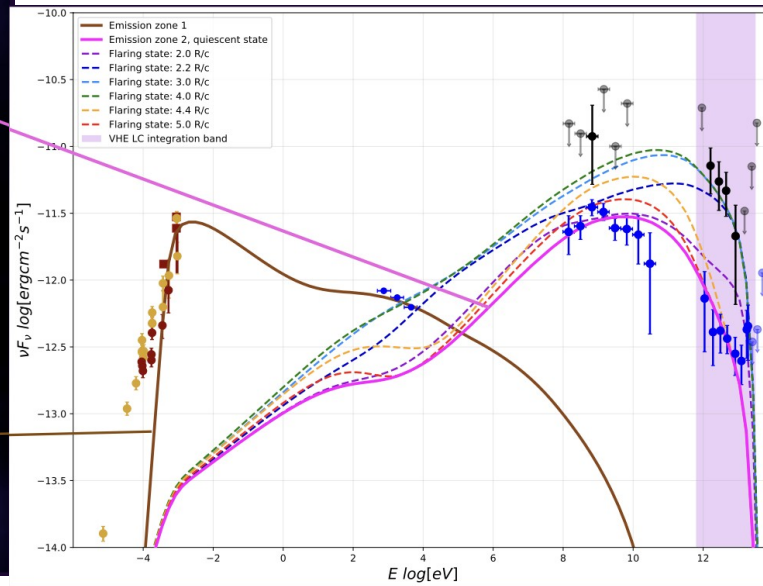
# Particle acceleration scenarios : shock examples

# two-zone models : LHAASO flare from M87



Emission region at **base of jet** (within a few  $10 r_G$  from SMBH) : **radio to X-rays**.  
(high magnetization  $\rightarrow$  reconnection)

More **distant emission region** ( $10^3 - 10^6 r_G$ ) : **y-ray low state and flare**.  
(low magnetization  $\rightarrow$  moving or standing shock)



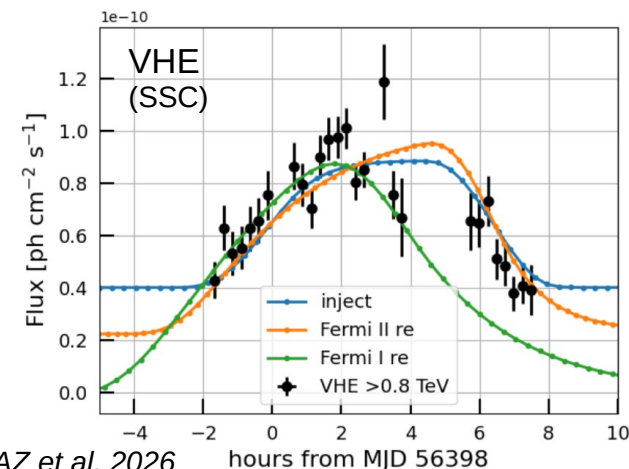
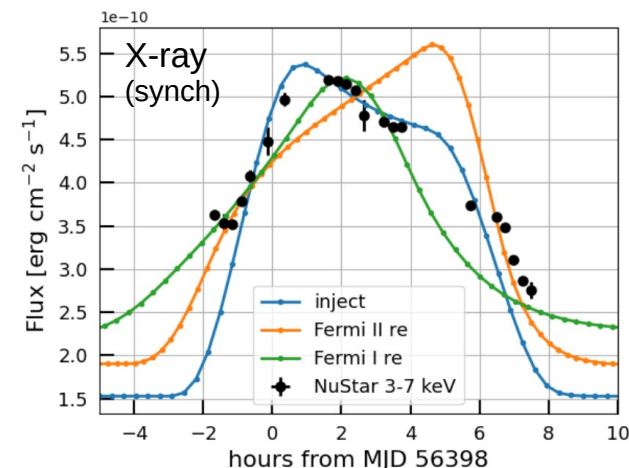
Thevenet, AZ et al.  
Gamma Symposium 2026

# two-zone models : scenarios for a 2013 flare of Mrk 421

- addition of a **baseline flux** to model the unknown continuum flux below the flare → **a single zone is generally not sufficient !**
- for this simplified application, the **injection scenario** (= efficient **shock** acceleration) provides the best representation of the high-energy data.

Distinct flare shapes for other scenarios.

- delays in peaks between bands due to different cooling times

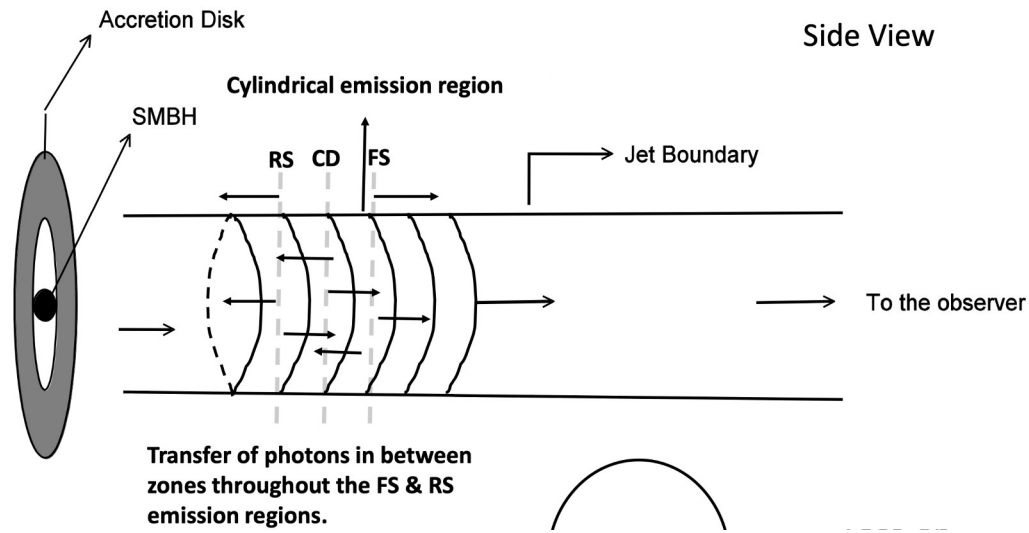


Thevenet, AZ et al. 2026

# multi-zone models : internal shock

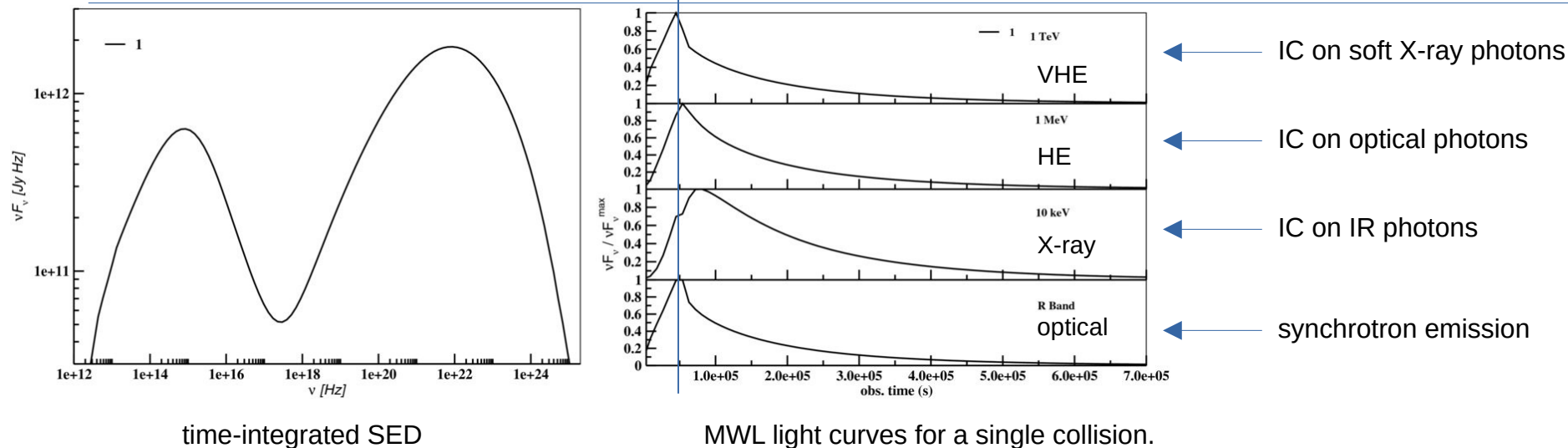
## MUZORF (multi-zone radiation feedback)

- emission of two relativistic plasma shells with different Lorentz factors
- faster inner shell catches up with slower outer shell → inelastic collisions produces **internal shock**
  - particle acceleration on the reverse and forward shock
  - synchrotron and SSC radiation is followed across multiple cylindrical slices



Joshi M. & Boettcher M., 2011

# multi-zone models : internal shock



Joshi M. & Boettcher M., 2011, *ApJ*, 727, 21

**Time delays** of emission from the spatially resolved interactions :

**X-ray flux** : continues to rise even after the shocks exit the emission region

- X-ray photons from up-scattering of IR photons off lower energy electrons  $\rightarrow$  cool slowly
- continued increase of late-arriving photons at the sites of scattering due to the **internal light crossing time effect**.

**VHE photons** : scattering of soft X-ray photons off higher-energy electrons  $\rightarrow$  cool faster

# shock scenarios

---

Efficient relativistic shock acceleration requires **low magnetization** ( $\sigma < \sim 10^{-2}$ ).

→ compatible with **emission region beyond BLR**

→ compatible with high IC dominance seen in several flare data sets ( $u_e / u_B \gg 1$ )

**Spectrum** : spectral index for relativistic shocks  $\sim 2.2 - 2.3$ .

→ hardest observed spectra in extreme blazars require re-acceleration

**Time delays** :

→ **hard lags of a few days** from different contributions of forward / reverse shock ?

**Asymmetric flares** from acc./cooling time scales or by varying shell parameters in internal shock model.

**Polarization** :

→ stratified shock models seem preferred by IXPE observations (e.g. Mrk 421 flare)

Many other models exist :

- Kirk, Rieger, Mastichiadis 1998

- Marscher & Gear, 1985;

- Spada, Ghisellini, Lazzati, & Celotti, 2001

- Błażejowski, Sikora, Moderski, & Madejski, 2000

- Ghisellini, Tavecchio, & Chiaberge, 2005;

- Tavecchio & Ghisellini, 2008

- Boettcher & Baring, 2019

...

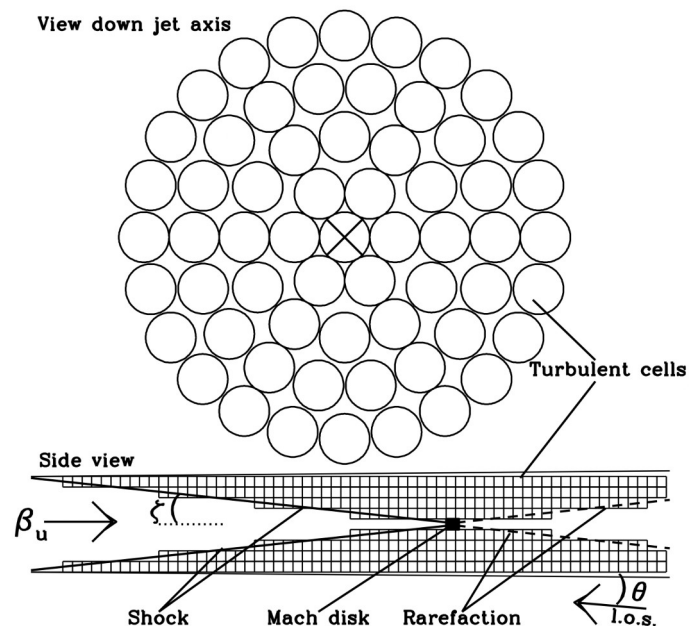
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# Particle acceleration scenarios : shock & turbulence examples

# turbulent plasma and standing shock

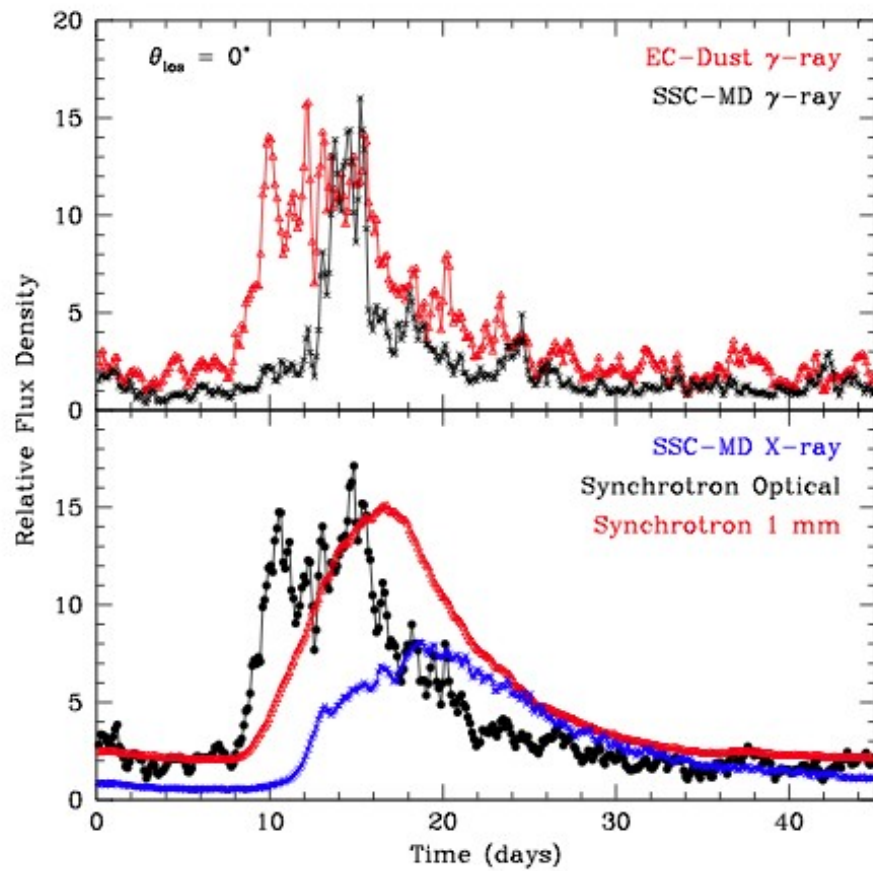
## Turbulent, Extreme Multi-zone model (TEMZ)

- Turbulent plasma flowing down a jet crosses a standing conical shock (e.g. recollimation shock).
- The **shock** compresses the plasma and **accelerates** electrons.
- Emission of **synchrotron** and **EIC** on IR photons from dust torus and **SSC at the Mach disk**.
- Turbulence is approximated as many cells, each with a uniform magnetic field with random direction.
- Density of high-energy electrons in the cells changes randomly with time following the PSD from observations.



Marscher 2014  
Marscher et al. 2017

# turbulent plasma and standing shock



Marscher 2014

**time delays** for a rapid flaring event :

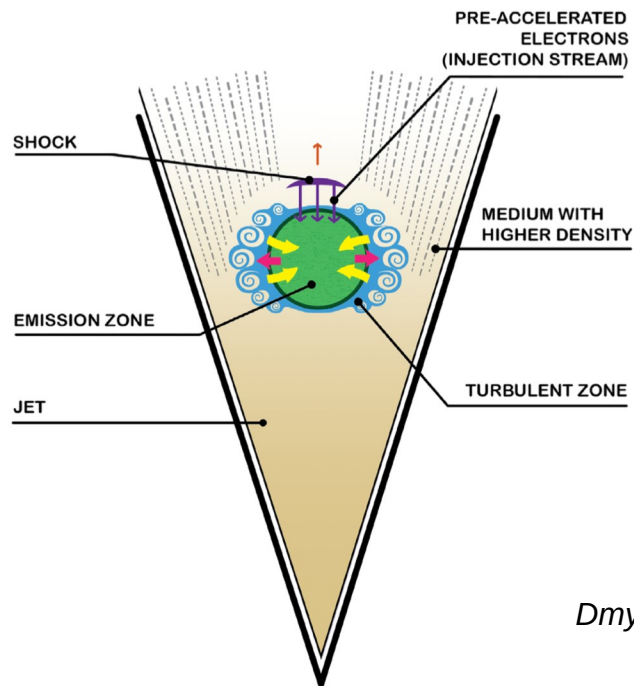
- due to different cooling times of the emitting electrons
- pulse crossing the Mach Disk leads to high synchrotron flux  
→ delayed seed photons for X-ray and  $\gamma$ -ray SSC

# blob moving through turbulent jet region

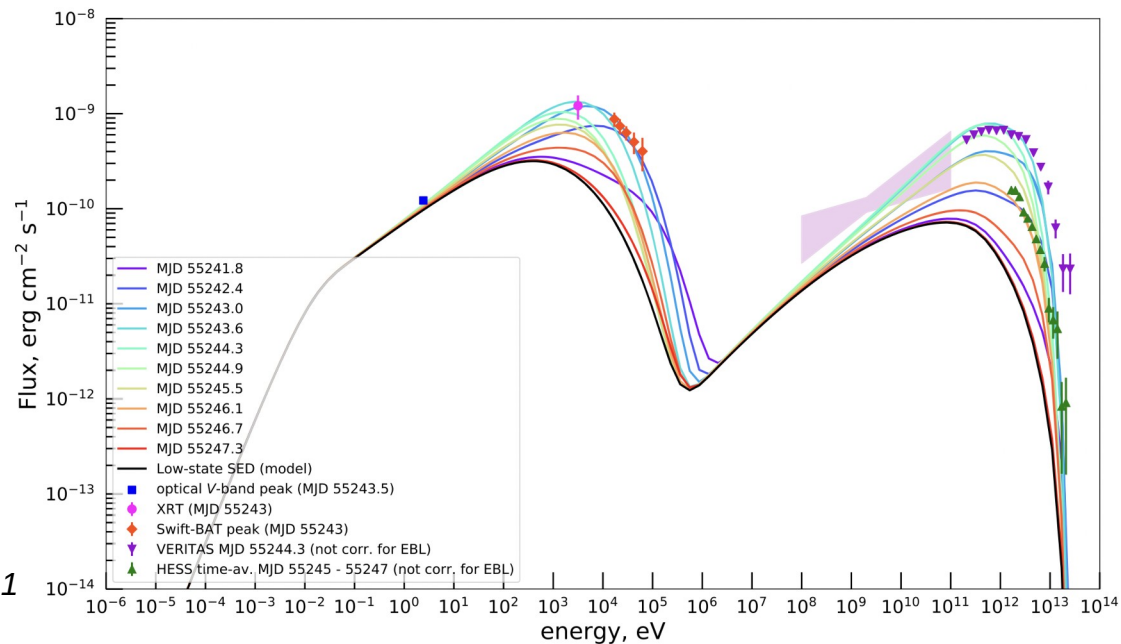
The continuous low-state emission from Mrk 421 is connected with a flare in Feb. 2010 :

- **low state** is modeled with a continuous injection (+ cooling, escape) of electrons accelerated on a **bow shock**
- **Fermi II re-acceleration** from a turbulent emission region surrounding the blob leads to hard flare spectrum.

Modeling based on Fokker-Planck equation. 
$$\frac{\partial N_e(\gamma, t)}{\partial t} = \frac{\partial}{\partial \gamma} \left[ b\gamma^2 + \frac{1}{t_{ad}}\gamma - a\gamma - \frac{2D}{\gamma} N_e(\gamma, t) \right] + \frac{\partial}{\partial \gamma} \left( D \frac{\partial N_e(\gamma, t)}{\partial \gamma} \right) - N_e(\gamma, t) \left( \frac{1}{t_{esc}} - \frac{3}{t_{ad}} \right) - \dot{Q}(\gamma, t)$$



*Dmytriiev, Sol, AZ 2021*



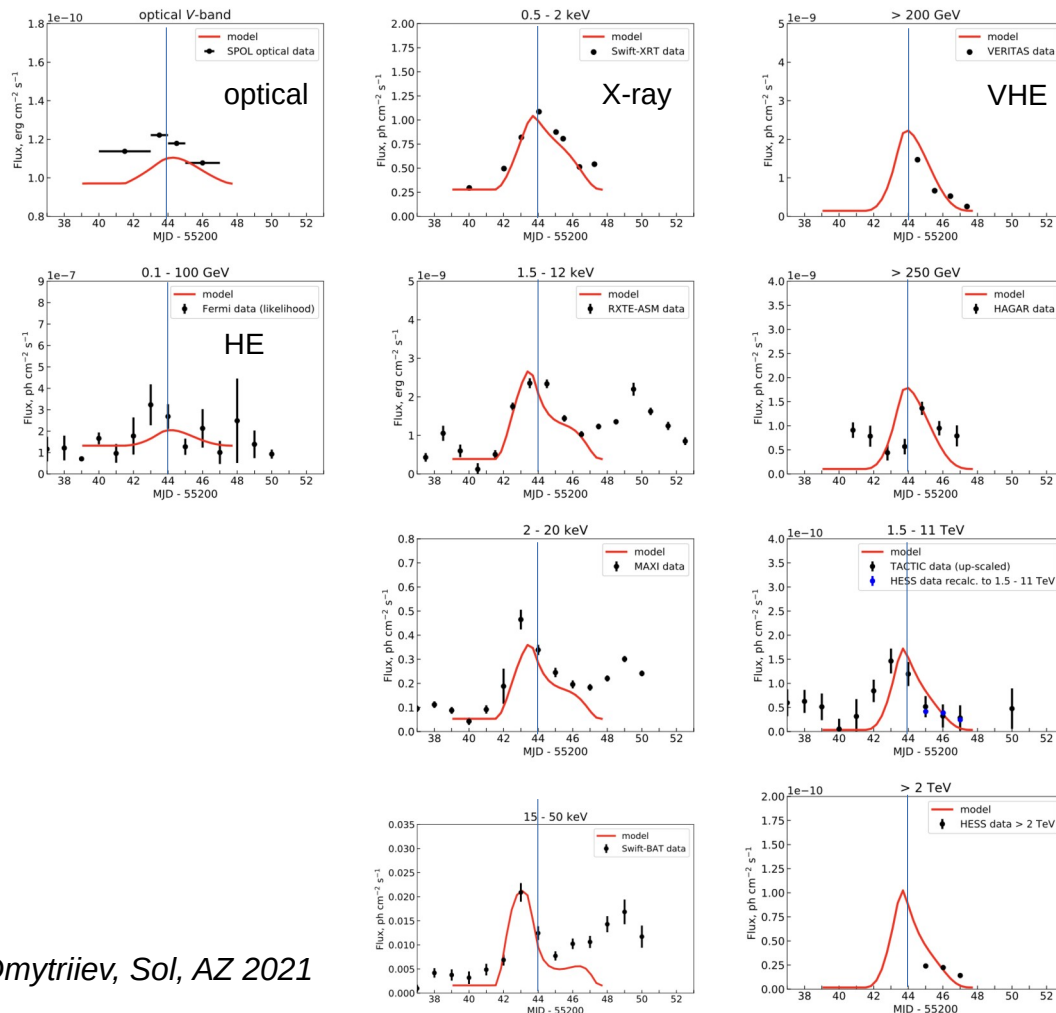
# blob moving through turbulent jet region

## Time delays

**HE band** “synchronized” with **optical** band :  
IC emission off optical photons

**X-ray** bands peak earlier :  
synchrotron emission from high-energy electrons  
with short cooling times

**VHE** bands peak a bit earlier :  
SSC emission



*Dmytriiev, Sol, AZ 2021*

# shock and turbulence models

---

Fermi II acceleration works for low or high magnetization; **high turbulence** level required.

**Spectrum** : spectral shape from Fermi-II acceleration can deviate from power law.  
Hard spectra expected for high  $\sigma$ .

**Time delays** :

→ **hard lags of a few days** possible ?

**Asymmetric flares** possible from acceleration/injection vs. cooling times

**Polarization** : turbulence expected to reduce polarization degree  
Higher polarization closer to the shock front → in agreement with IXPE.

Many other models exist

- *stochastic and shear acceleration in structured jet* : Wang, Rieger, Mizuno 2024
- *relativistic turbulence model* : Narayan & Piran, 2012
- *stochastic SSC flare model* : Tramacere, Massaro, Taylor 2011

...

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# Particle acceleration scenarios : magnetic reconnection examples

# magnetic reconnection in jets

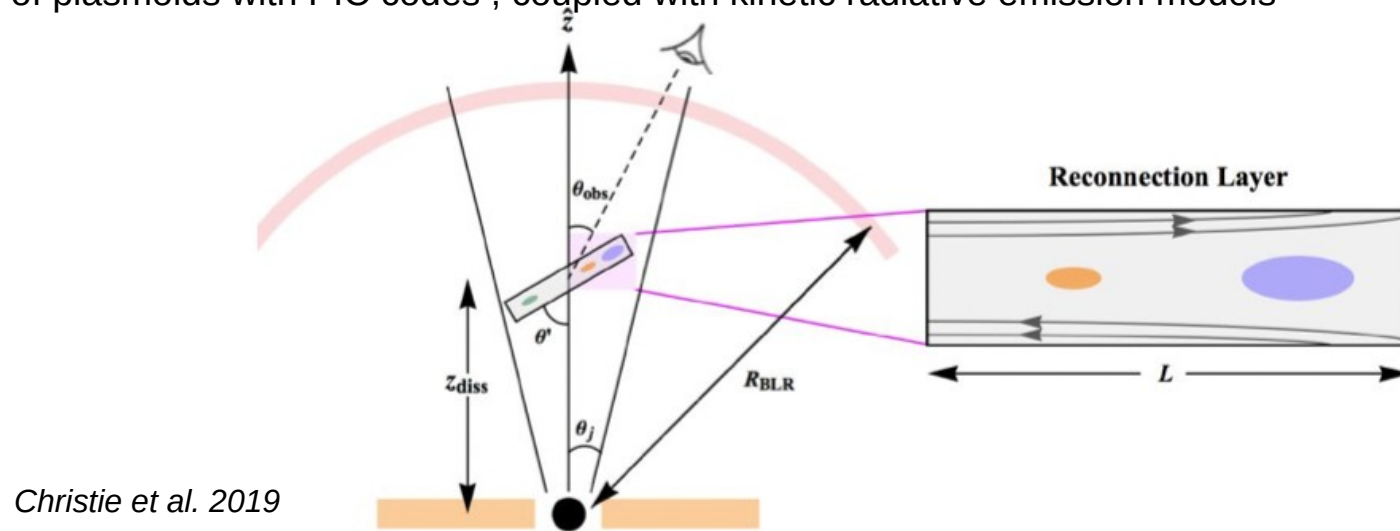
reconnection events occur in **current sheets** that form :

- via **instabilities** (KH, kink) or **turbulence** in the jet
  - current sheets can be smaller than the size of the blazar zone → **very rapid variability** (cf. VHE observations)
- or between oppositely oriented stripes in a “**striped jet**” (*Giannios & Uzdensky 2019*)

reconnection events within the jet lead to particle acceleration and flares

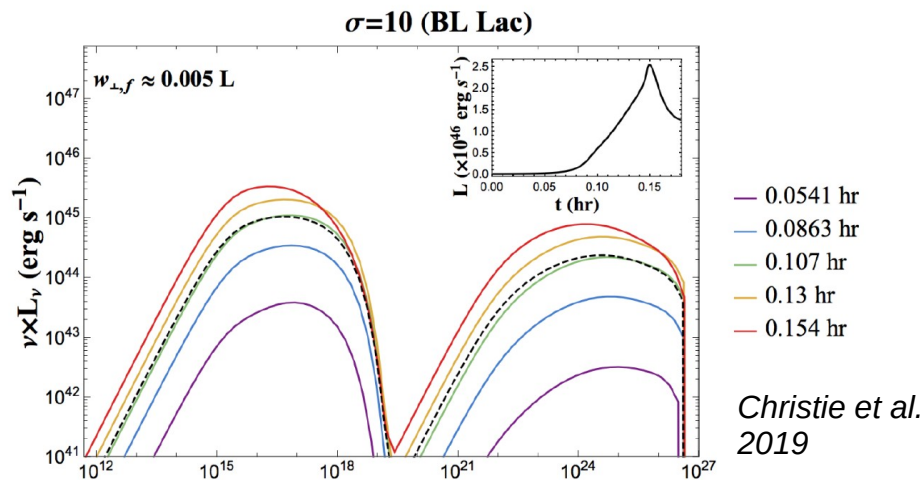
→ requires **high jet magnetization**  $\sigma > 1$

simulation of plasmoids with PIC codes , coupled with kinetic radiative emission models



Christie et al. 2019

# rapid flares from reconnection

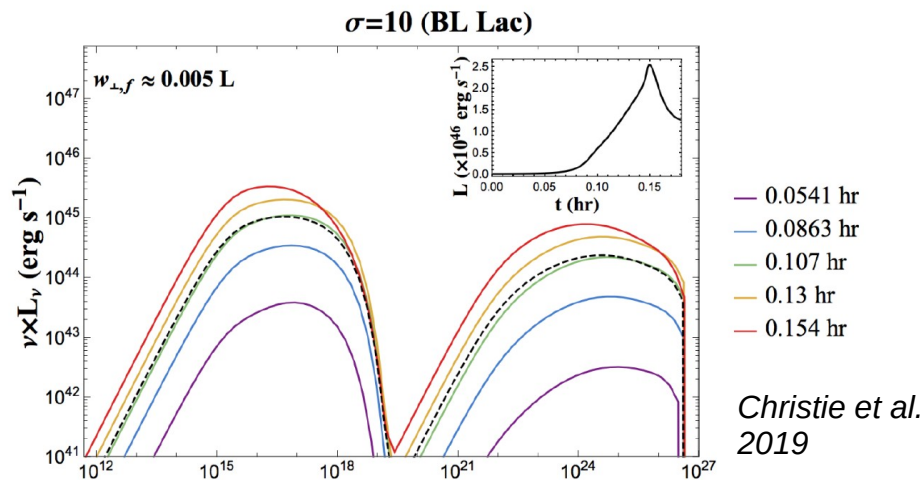


*Petropoulou et al. 2016 :*

→ Correlated synchrotron and SSC flares of several **hours–days** for the **largest and slowest plasmoids**

→ **Smaller and faster plasmoids** produce flares of **sub-hour** duration with **higher peak luminosities**.  
(cf. observations of Fermi flares)

# rapid flares from reconnection



*Petropoulou et al. 2016 :*

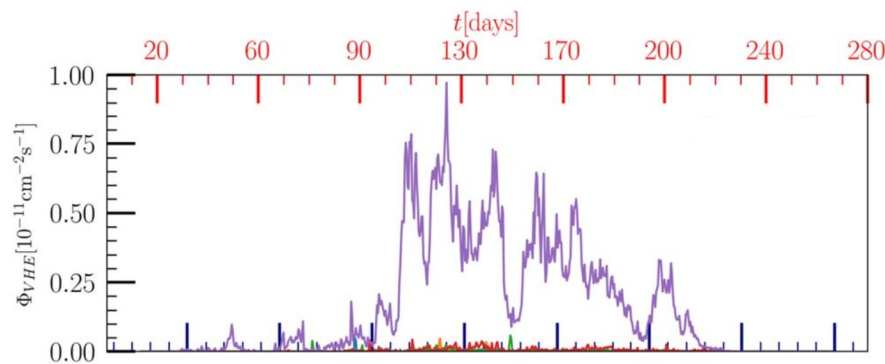
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*Solanki et al. 2025*

GRMHD simulation of VHE flares from current sheets close to **M87\*** (within a few  $r_G$ ), assuming magnetically arrested disk.

→ Flare events extend over  $\sim 100$  days, but subflares of the current sheet can account for **~day flares** in the observer frame.

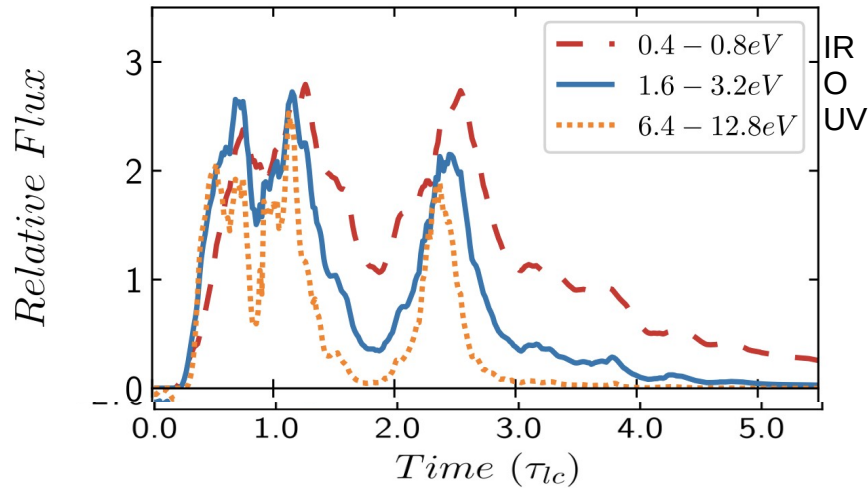
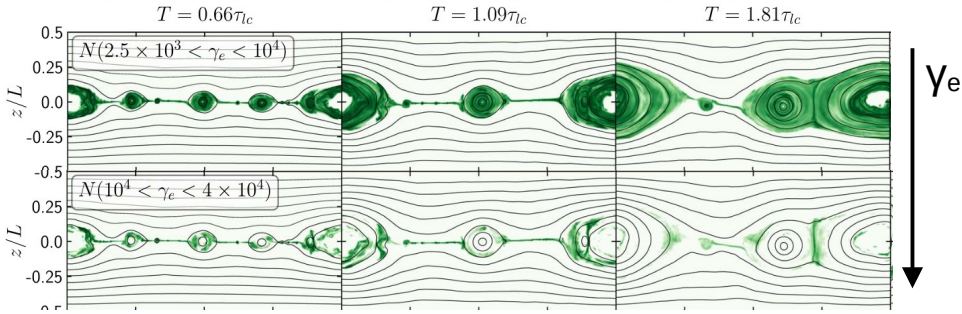


# delays in light curves

*H. Zhang et al. 2020*

Peak of higher-energy particles in the **contact region** of two merging plasmoids, where **acceleration is most efficient**.

As the merging moves **beyond the contact region**, it can no longer accelerate these highest-energy particles.



→ **Higher-energy bands peak earlier** than lower-energy bands.

# magnetic reconnection models

**Spectrum** : power law index depends on magnetization : hard spectra with index  $< 2$  possible for  $\sigma \gg 1$

**Time delays** : higher-energy bands peak earlier in synchrotron component

**Asymmetric flares** possible and **multiple flares** arising from one current sheet.

**Polarization** : high ratio  $\Pi_x / \Pi_o$  might be due to EM field geometry in parabolic magnetized jets (*Bolis et al. 2024*)

Reconnection can explain **very rapid** (min-scale) flares. Can explain **higher variability for shorter flares**.

## Constraints :

- high magnetization required in regions beyond BLR
- difficult to describe the observed high Compton dominance in many flares  
→ turbulent cascade model (*Sobacchi et al. 2023*) ?

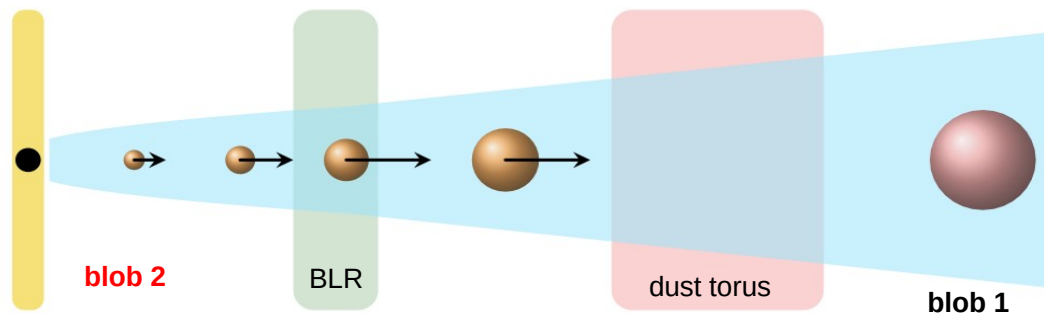
Many other models exist :

- *minijets in jet* : *Giannios, Uzdensky, & Begelman, 2009*
- *reconnection-accelerated pairs from near the event horizon* : *B. Ripperda et al. 2020; A. Chashkina et al. 2021; B. Ripperda et al. 2022; H. Hakobyan et al. 2023b*
- *turbulent reconnection* : *de Gouveia del Pino et al. 2025, Sobacchi et al. 2023*
- *kink instabilities* : *Das et al. 2026* ...

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# Jet propagation scenarios an example

# accelerating blob model



*Le Bihan, Dmytriiev, AZ 2026*

low-state emission from a stationary emission region, e.g. recollimation shock (“**blob 1**”)

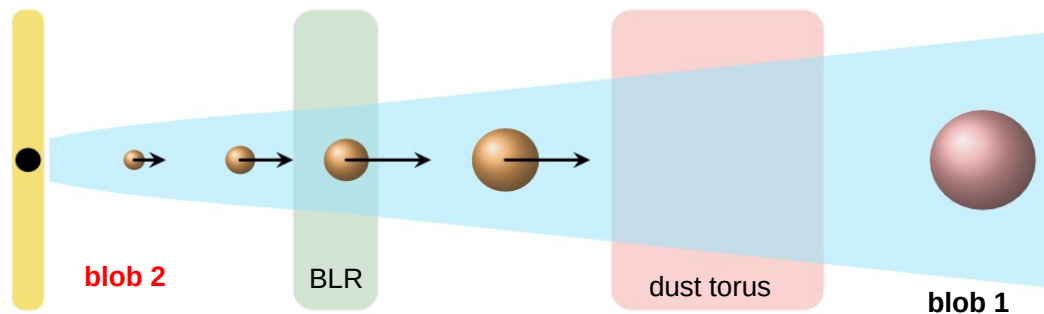
flare is caused by an accelerating, expanding emission region (“**blob 2**”)

→ acceleration through differential collimation up to  $\sim$  BLR

$$\Gamma_{blob} = \min\left(\Gamma_{max}, \sqrt{d/(3R_s)}\right)$$

$$\Gamma_{max} = 30$$

# accelerating blob model



*Le Bihan, Dmytriiev, AZ 2026*

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→ acceleration through differential collimation up to  $\sim \text{BLR}$

$$\Gamma_{\text{blob}} = \min\left(\Gamma_{\text{max}}, \sqrt{d/(3R_s)}\right)$$

$$\Gamma_{\text{max}} = 30$$

- for  $d < R_{\text{BLR}}$ , as blob 2 accelerates :

$$U' \propto d$$

- for  $d > d_{\text{max}}$ , as blob 2 advances at constant velocity :

$$U' \propto d^{-\beta_{\text{BLR}}}$$

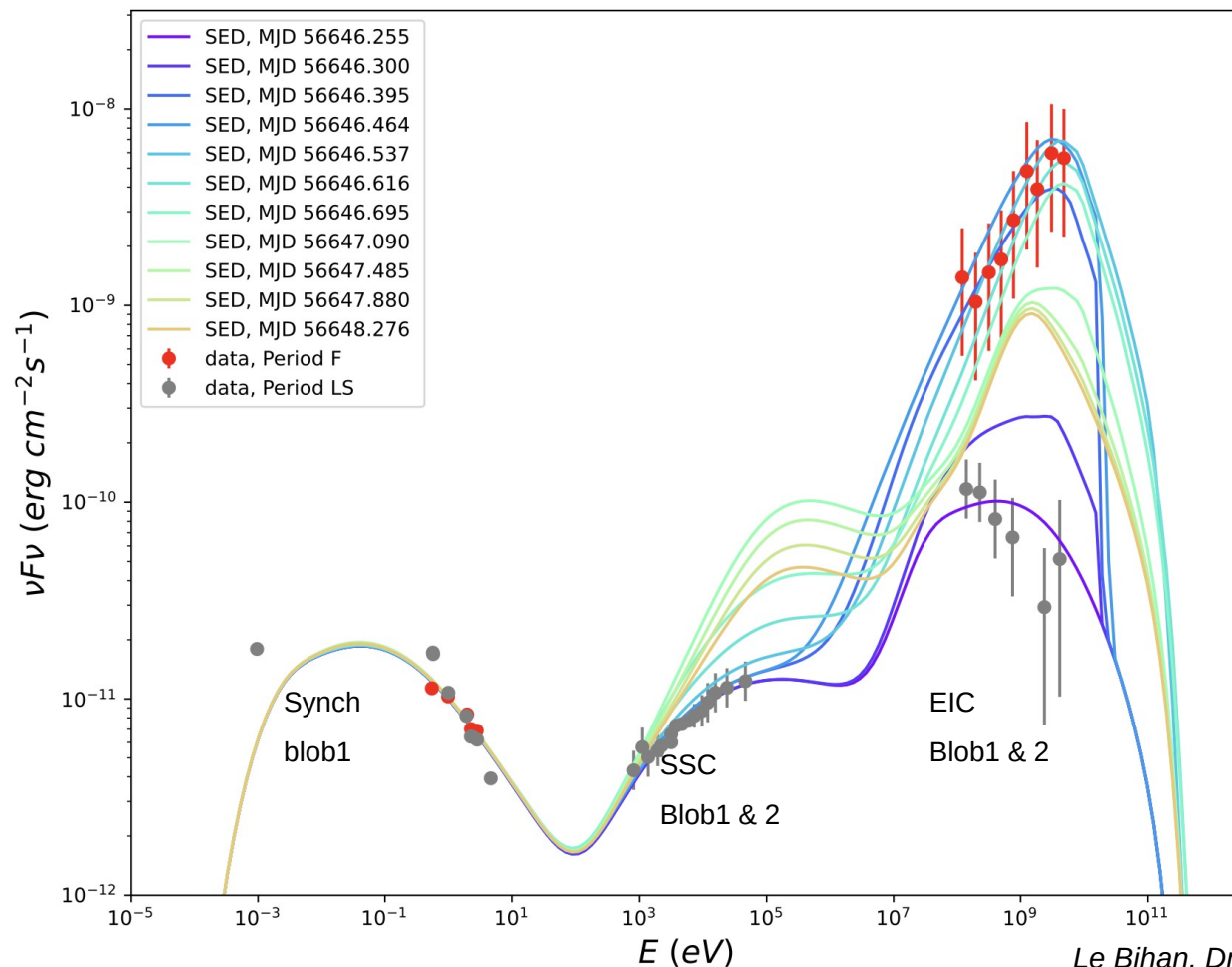
assuming a density profile of the BLR photon field following a power law

# accelerating blob model : SED

Applied to 3C 279  
flare in 2013.

Low-state SED  
from 'blob 1'

Flare is caused  
by 'blob 2'



Le Bihan, Dmytriiev, AZ 2026

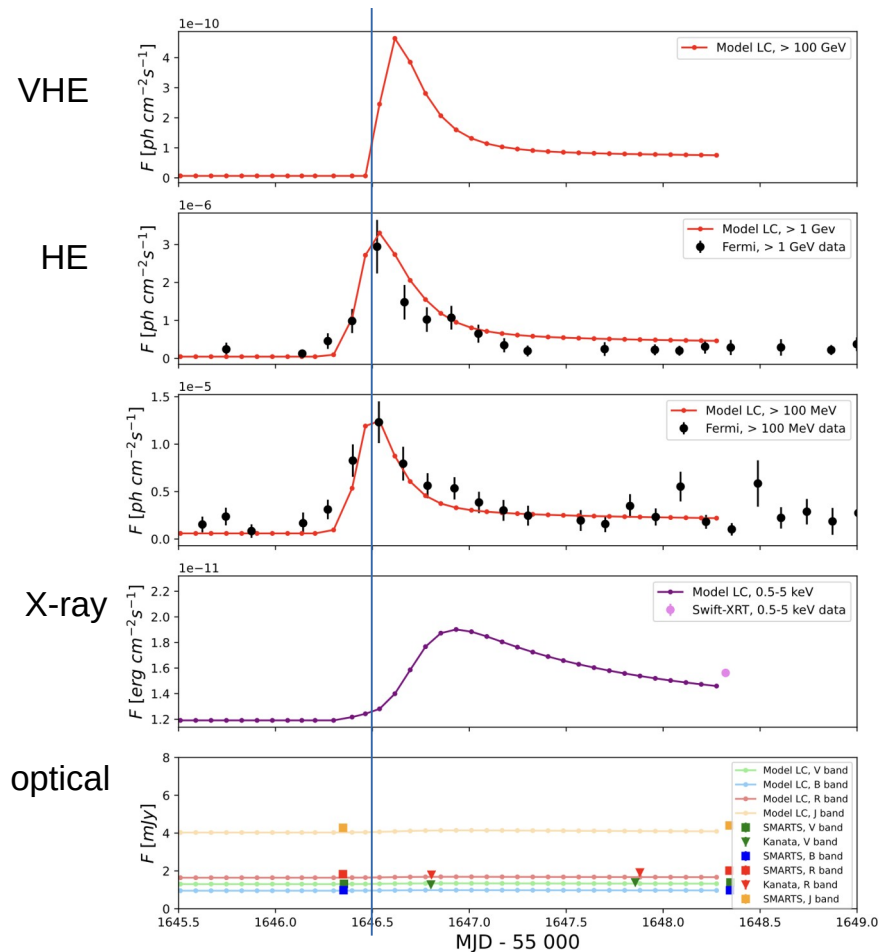
# accelerating blob model : light curves

**VHE band** : delayed wrt HE band due to **yy absorption** on the BLR photons

**X-ray band** : SSC delayed wrt EIC in HE band.  
Before crossing BLR, synchrotron is suppressed by EIC cooling.

**Optical band** : no variation of the optical flux (by design)

→ high-energy “**orphan**” flare



Le Bihan, Dmytriiev, AZ 2026

# jet propagation models

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Other models propose the injection of matter from **clouds and stars crossing the jet** or **helical motion leading to variation of the Doppler factor** of a plasma blob.

**Time delays** e.g. from change in external photon field (absorption, up-scattering)

**Asymmetric flares** possible.

Some cloud/star models produce **very rapid flares in hadronic scenarios**.

Many other models exist :

*stars : Blandford & Königl 1979; Komissarov 1994; Perucho et al. 2014 & 2017; Bosch-Ramon 2015,*

*stars and gas clouds : Araudo et al. 2009; de la Cita et al. 2017, Araudo et al. 2010; Bosch-Ramon et al. 2012, Bosch-Ramon, Perucho, Barkov, A&A (2012), D.V. Khangulyan, M.V. Barkov, V. Bosch-Ramon, F.A. Aharonian, A.V. Dorodnitsyn 2013; M. Zacharias 2017, 2019*

*hadronic model with external fields : M. Zacharias 2023*

*helical motion : Larionov et al. 2016, Schramm et al. 1993*

# Conclusions

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**A large variety of possible scenarios for the emergence of blazar flares**, depending on the location and physical conditions that characterize the acceleration / emission region.

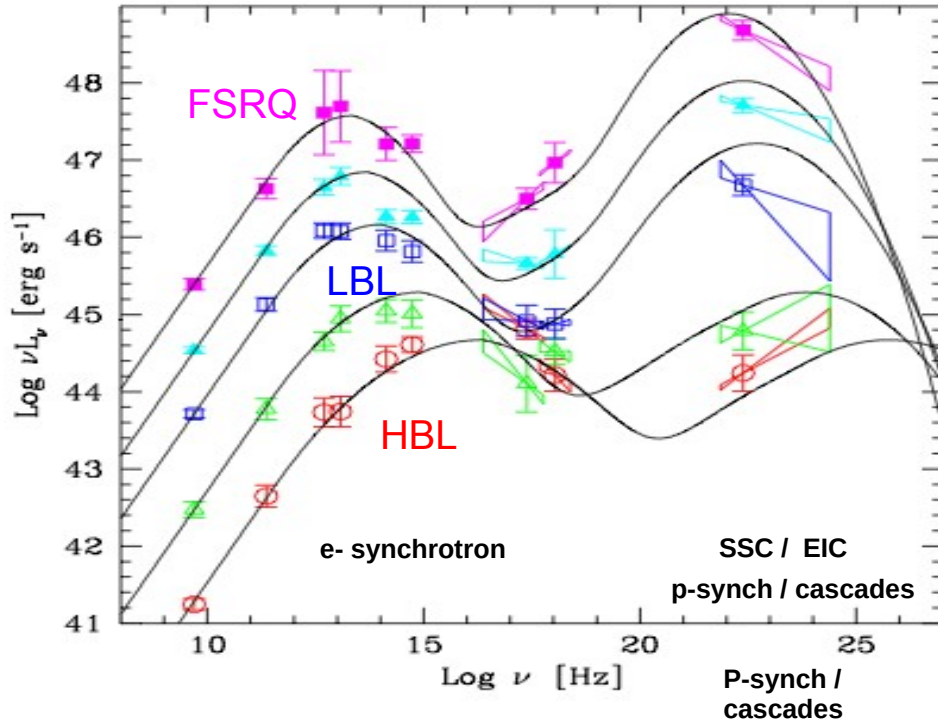
Many more scenarios exist, e.g. emission from BH magnetosphere (gap, centrifugal acceleration) ...

How to advance with modeling ?

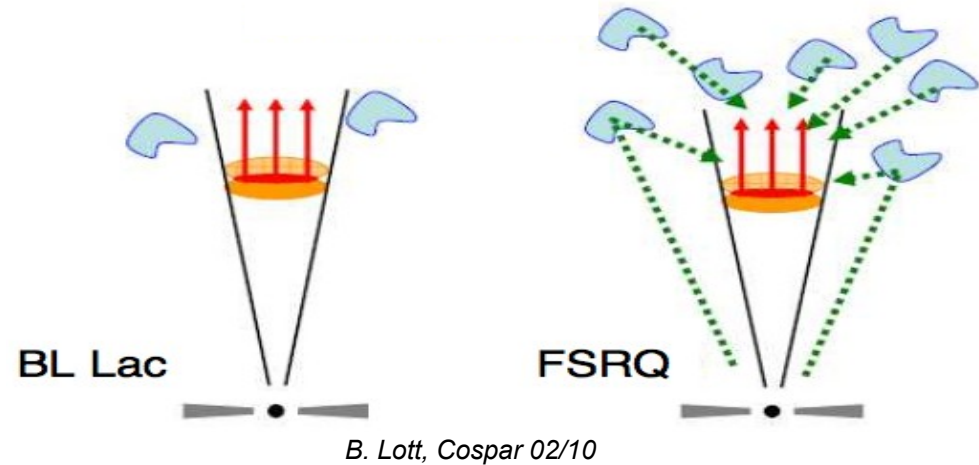
- **well-sampled MWL datasets** of rapid flares are still rare (especially for BL Lacs)
- systematic comparison of **different models** against data is still the exception
- detailed modeling not only of high-state and low-state SEDs, but also **MWL light curves**
  - search for temporal delays, asymmetries, ...
- MWL **polarization** and **neutrino** observations to complete the observables



# emission processes and photon fields



Donato et al. (2002), based on Fossati et al. (1998)



- Disk, Broad Line Region, dust torus emit **weakly**

- leptonic models :  $\gamma$ -rays due to **Synchrotron Self Compton**

- hadronic models : **p-synchrotron** dominated ?

- Disk, Broad Line Region, dust torus emit **strongly**

- leptonic models:  $\gamma$ -rays mostly due to **External Inverse Compton**

- hadronic models : important contribution from p- $\gamma$  triggered **cascades**

# Some lessons from the VHE domain

Study of flares from 7 AGNs seen with the H.E.S.S. Cherenkov telescopes on hours to days scales.

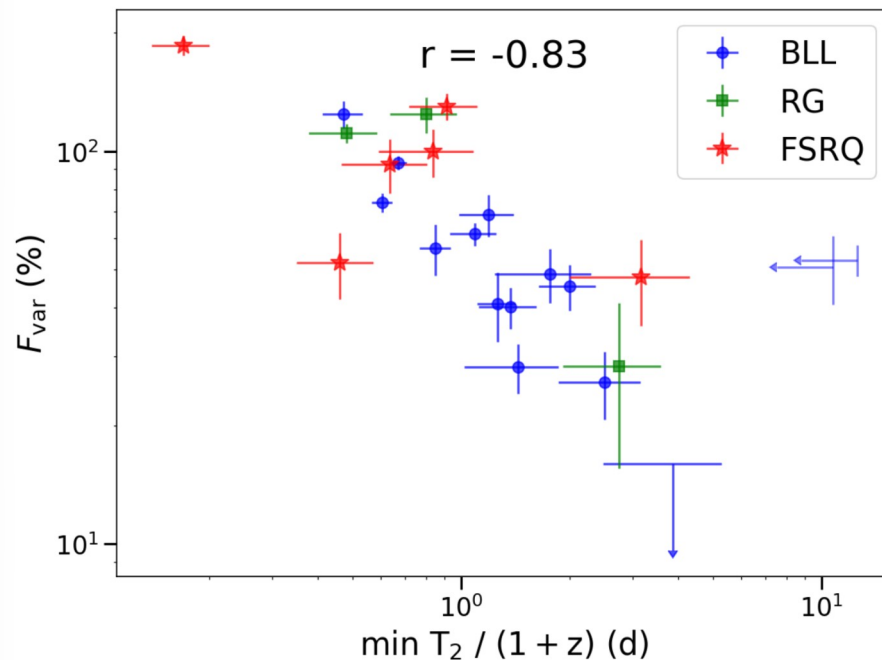
The **shortest flares show the highest variability amplitude**.

$F_{\text{var}}$ : fractional variability amplitude  
([Vaughan et al. 2003](#))

$$F_{\text{var}} = \sqrt{\sigma_{NXS}^2} = \sqrt{\frac{S^2 - \sigma_{\text{err}}^2}{\bar{x}^2}}$$

$T_2$ : minimal flux doubling/halving time ([Zhang et al. 1999](#))  
sets an upper limit to the variability time.

$$T_2^{ij} = \frac{F_i + F_j}{2} \left| \frac{t_j - t_i}{F_j - F_i} \right|$$



Luashvili, Bylund AZ et al., Gamma Symposium 2026

# Some lessons from IXPE

*Abe et al. 2025*

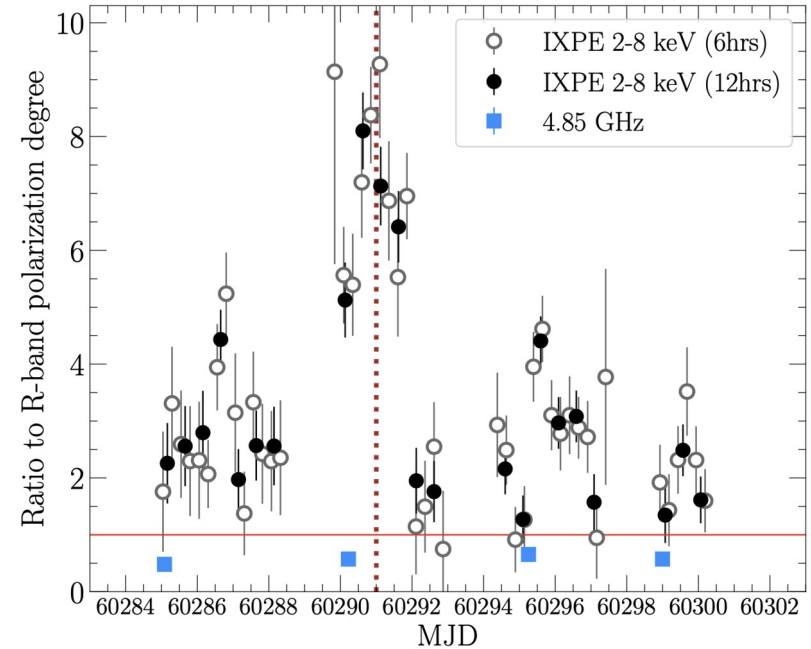
Observation of  $\gamma$ -ray flare from Mrk 421 in 2023 with simultaneous X-ray polarization data.

**X-ray polarization degree in X-rays significantly higher than in the radio and optical band**, similar to previous results on Mrk 421 and other BL Lacs.

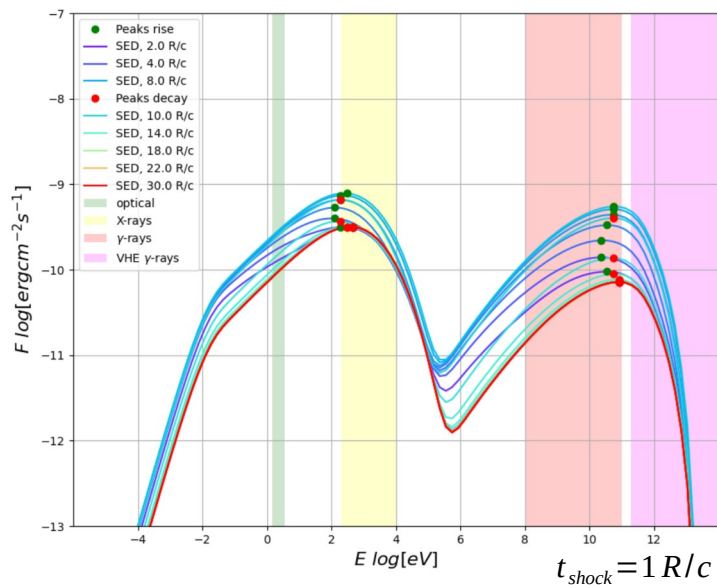
- energy-stratification of the emitting zone ?
- highly turbulent electron-ion plasma crossing a shock front ?

X-ray **polarization angle varies** by  $\sim 100$  deg on time scales of days, while the **average angle remains closely aligned with the jet** and the optical band

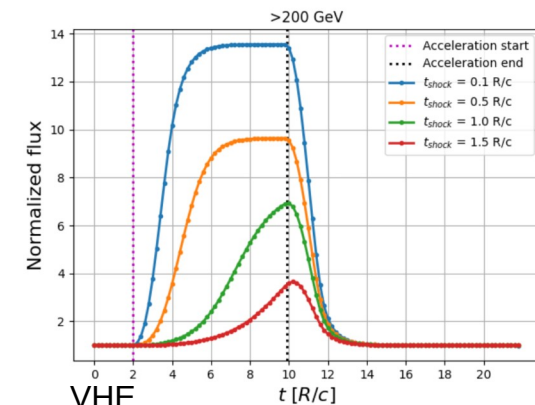
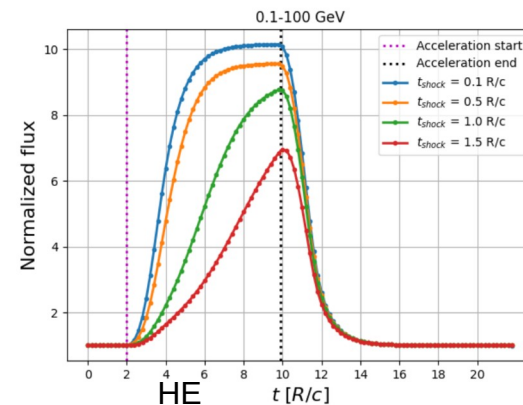
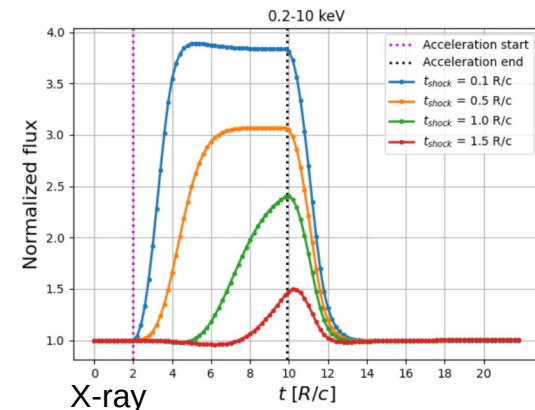
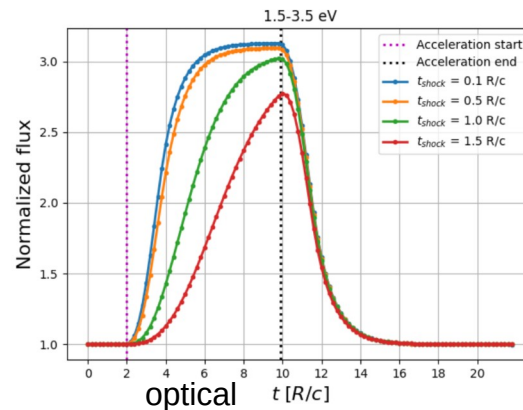
- argument against magnetic reconnection for this flare ?



# single-zone approach

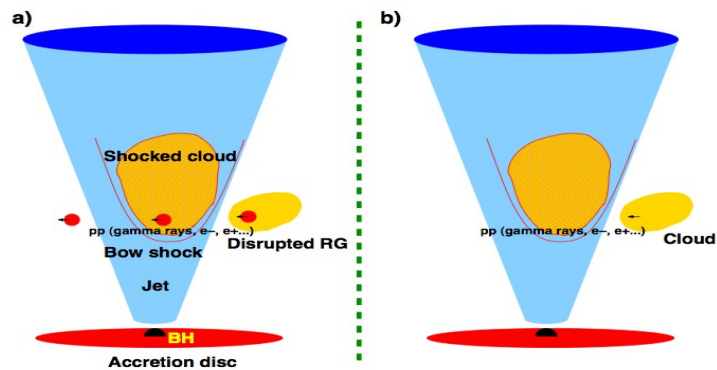


- injection of accelerated particles (power law), here with increasing maximum energy
- flare **onset** shifts between energy bands
- occurrence of a plateau (= high steady-state) only for very rapid  $t_{\text{shock}}$

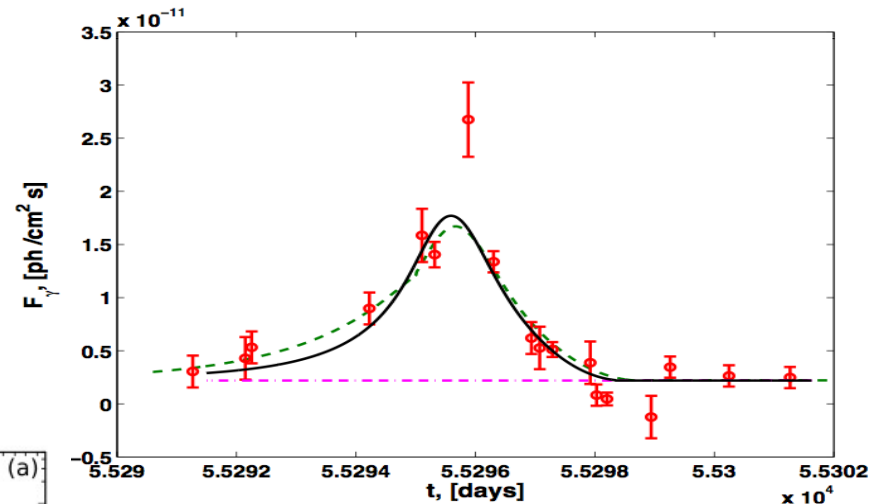


Thevenet, AZ et al. 2026

# clouds or stellar envelopes crossing jet



Bosch-Ramon, Perucho, Barkov, A&A (2012)



VHE flare of M87 in 2010  
Barkov, Bosch-Ramon, Aharonian, ApJ (2012)

very rapid variability possible if relativistic hadrons in the jet interact with stellar envelopes (red giants) or gas clouds (BLR) via p-p, p- $\gamma$  or p-synchrotron.

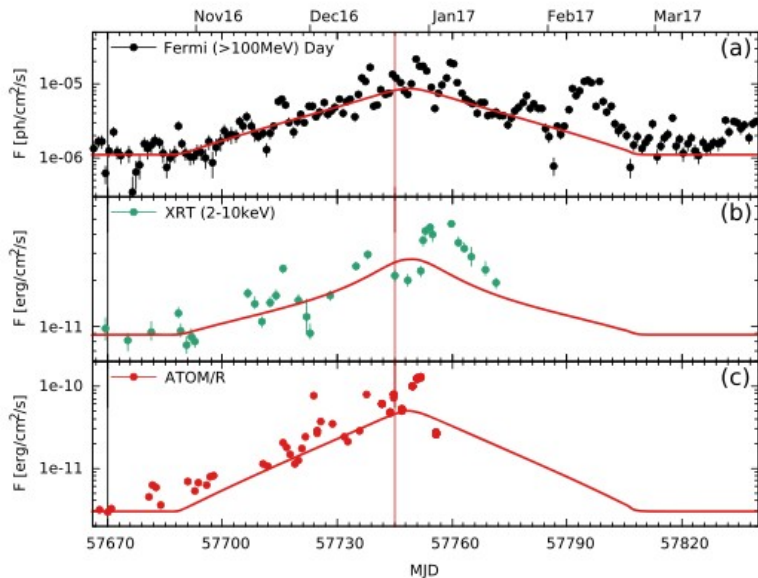
(e.g. D.V. Khangulyan, M.V. Barkov, V. Bosch-Ramon, F.A. Aharonian, A.V. Dorodnitsyn 2013)

Zacharias et al. 2017, 2019

Optical to  $\gamma$ -ray flare of the FSRQ CTA 102 over several months from large gas cloud crossing jet.

→ Variation in particle density reflects the gradual ablation of cloud layers.

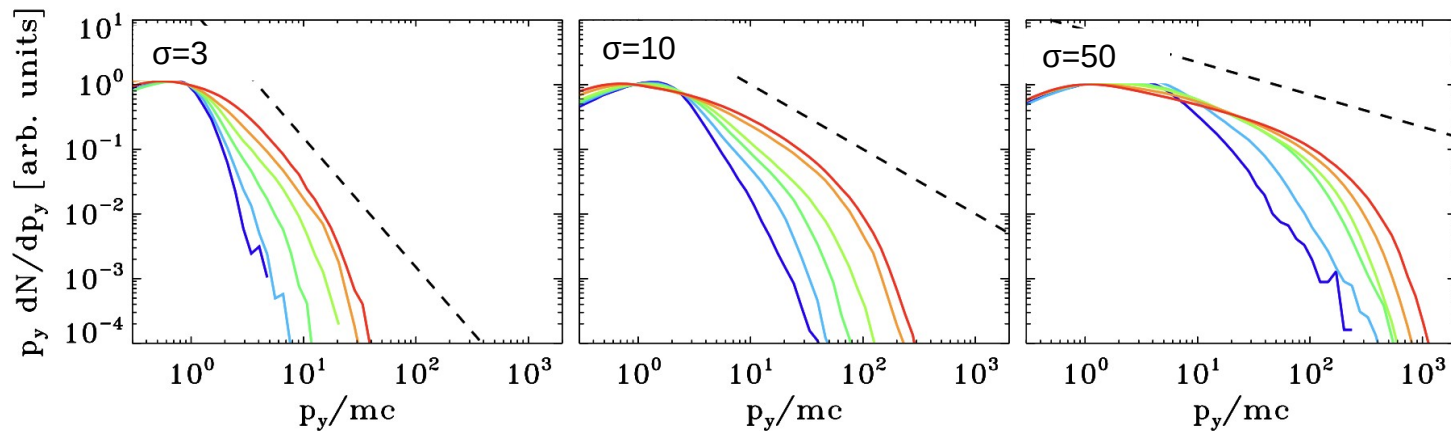
→ acceleration of particles in standing shock



# Particle spectrum from reconnection

*Sironi, Giannios, Petropoulou 2016*

Particle momentum spectra from PIC simulations show a dependence of the spectral slope with magnetisation.



different colours correspond to different plasmoid widths (from blue for small  $w$ , to red for large  $w$ ).

At large plasmoid widths, spectrum approaches a power law, with slope  $s \sim 3$  for  $\sigma = 3$ ,  $s \sim 2$  for  $\sigma = 10$  and  $s \sim 1.5$  for  $\sigma = 50$ .

# particle evolution through injection or acceleration

Particle distribution often described by Fokker-Planck equation (e.g. leptonic EMBLEM code) :

$$\frac{\partial N_e(\gamma, t)}{\partial t} = \underbrace{\frac{\partial}{\partial \gamma} \left[ (b_c(\gamma, t) \gamma^2 + \frac{1}{t_{ad}} \gamma - a(t) \gamma - \frac{2}{\gamma} D_{FII}(\gamma, t)) N_e(\gamma, t) \right]}_{\text{Cooling terms}} + \underbrace{\frac{\partial}{\partial \gamma} \left( D_{FII}(\gamma, t) \frac{\partial N_e(\gamma, t)}{\partial \gamma} \right)}_{\text{Acceleration terms}} - \underbrace{N_e(\gamma, t) \left( \frac{1}{t_{esc}} + \frac{3}{t_{ad}} \right)}_{\text{Injection term}} + \underbrace{\dot{Q}_{inj}(\gamma, t)}_{\text{Injection term}}$$

## Cooling

- Synchrotron and Inverse Compton:  $b_c(\gamma, t) = \frac{4 \sigma_T (u_B + u_{rad})}{3 m_e c}$
- Adiabatic expansion:  $t_{ad}(t) = \frac{R(t)}{\beta_{exp} c}$

## acceleration (of cold electrons)

Fermi I :  $\dot{Q}_{inj}$   
 Fermi II :  $D_{FII} = p^2 / t_{FII}$

## re-acceleration (of relativistic electrons)

Fermi I :  $a = 1 / t_{shock}$   
 Fermi II :  $D_{FII} = p^2 / t_{FII}$

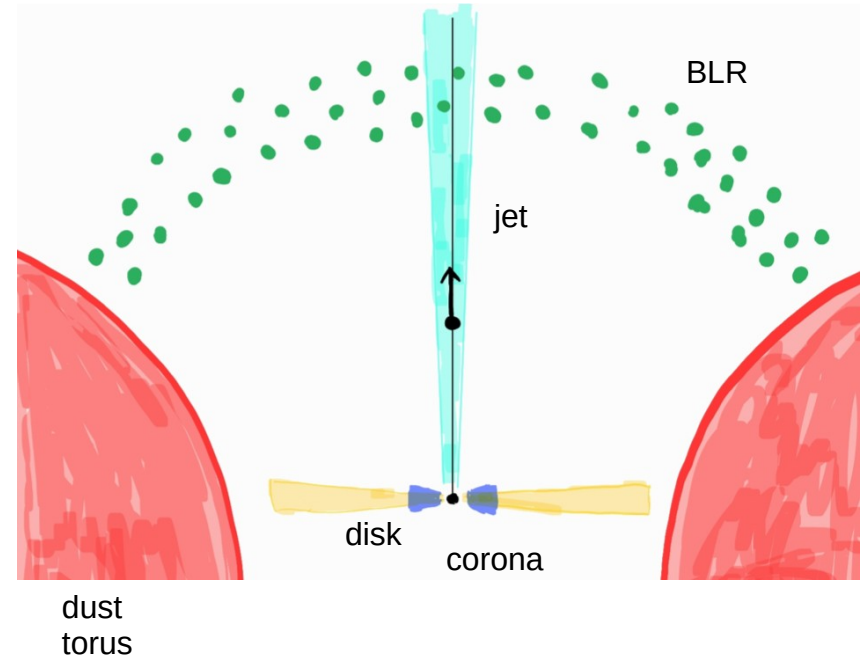
# modeling the photon fields in a FSRQ

- External Compton emission on photon fields from accretion disk, corona, Broad Line Region, dust torus
- In many scenarios, the **BLR** has the most significant contribution (emission region at sub-pc scales):
  - photons from a spectrum of emission lines
  - BLR modeled as a spherical shell with inner radius  $R_{\text{BLR}} \sim 0.1 \text{ pc}$
  - For distance  $d > R_{\text{BLR}}$ , the energy density decreases as :

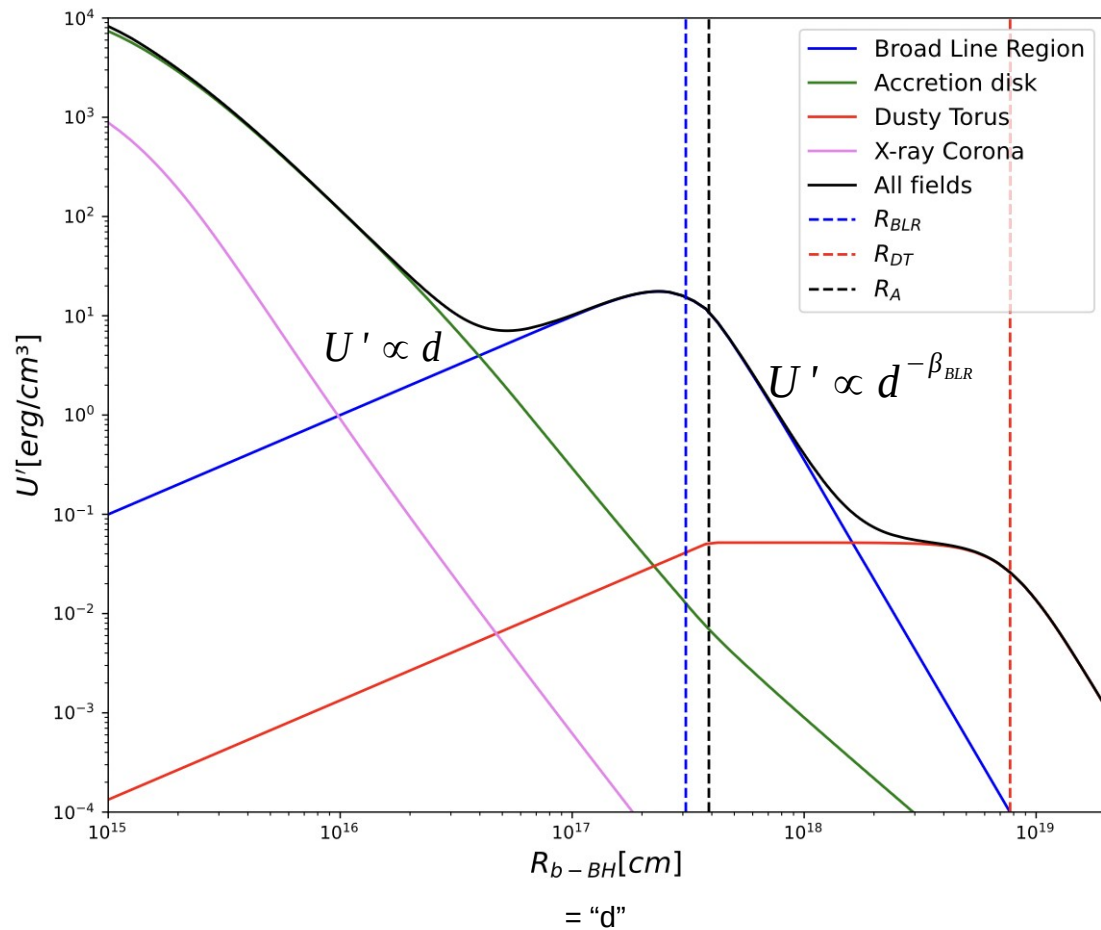
$$U'(\epsilon', d) = \frac{L'_{\text{BLR}}(\epsilon') \Gamma_{\text{blob}}^2}{3 \pi R_{\text{BLR}}^2 c \left(1 + (d/R_{\text{BLR}})^{\beta_{\text{BLR}}}\right)}$$

(Hayashida et al 2012)

- $\gamma$ - $\gamma$  absorption following e.g. *Böttcher & Els (2016)*

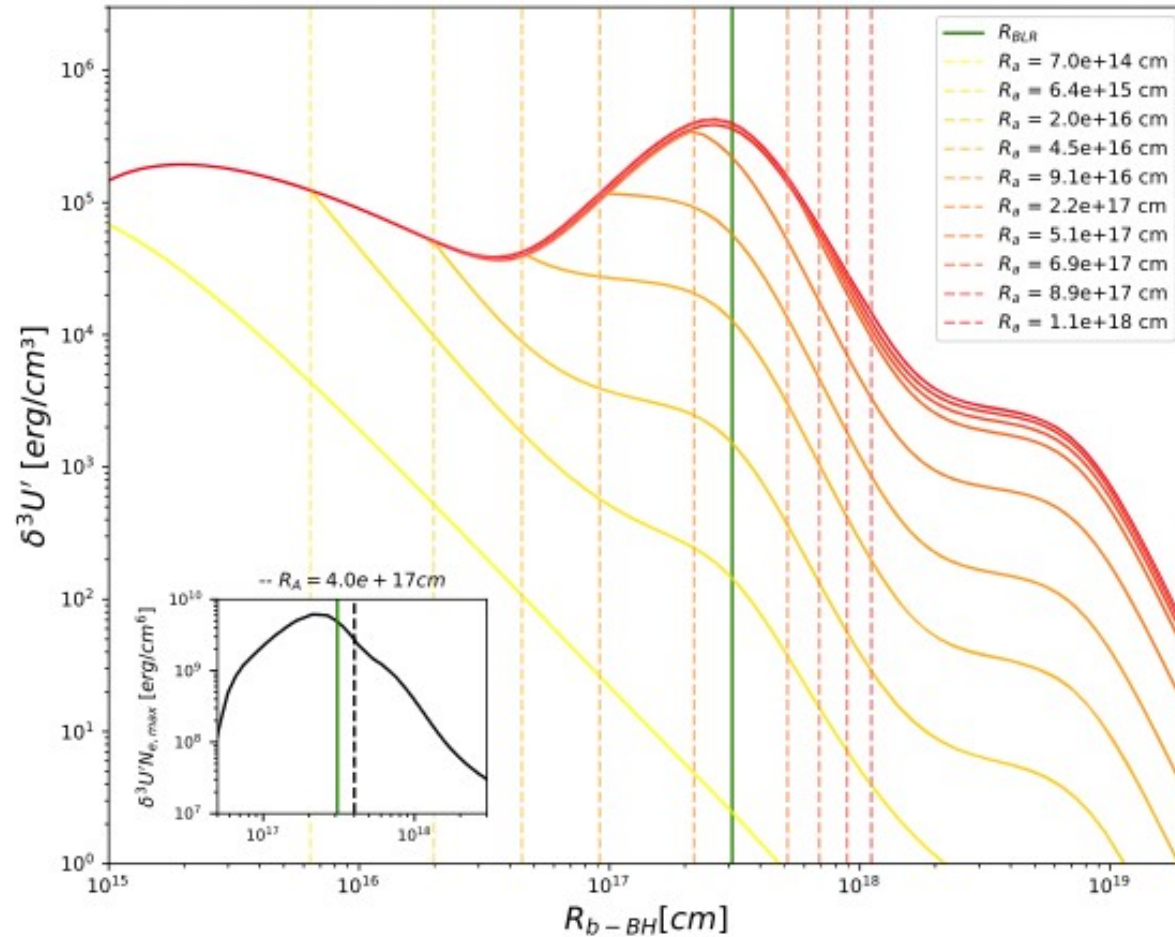


# Photon fields



Photon energy density in the “blob” frame vs. distance from black hole for an accelerating blob.

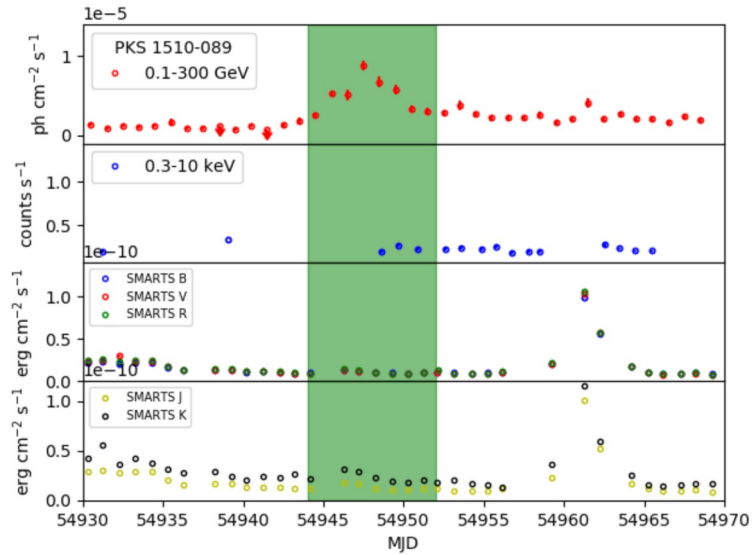
# Accelerating blob, impact of the length of acc. region



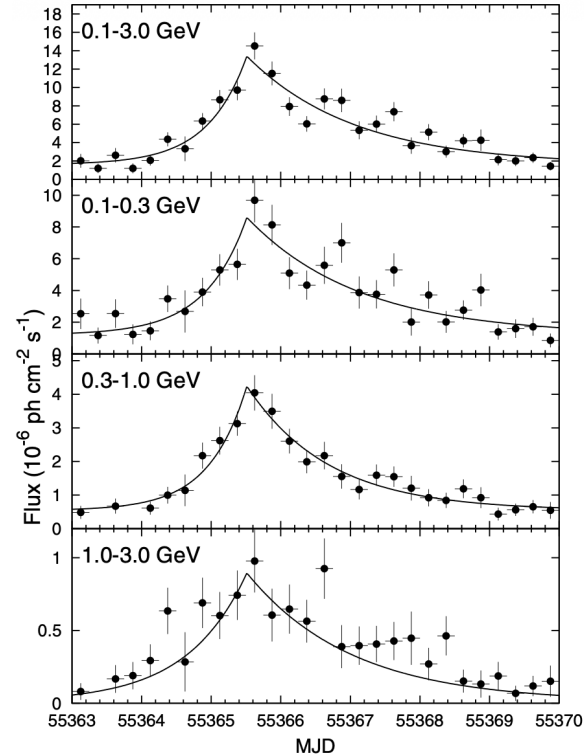
# Accelerating blob, model parameters

| Parameter                        | Blob 1               | Blob 2                      |
|----------------------------------|----------------------|-----------------------------|
| Blob characteristics             |                      |                             |
| Type                             | Stationary           | Accelerating                |
| $B(\text{G})$                    | 0.09                 | [0.03,0.02]                 |
| $R_{b-BH}(\text{cm})$            | $2.0 \times 10^{19}$ | $[0.05, 3] \times 10^{18}$  |
| $R_b(\text{cm})$                 | $5.0 \times 10^{16}$ | $[2.0, 2.9] \times 10^{15}$ |
| Injection spectrum               |                      |                             |
| Type                             | BPL                  | PL                          |
| $N(\text{cm}^{-3}\text{s}^{-1})$ | $3.0 \times 10^{-7}$ | $5.0 \times 10^{-1}$        |
| $\gamma_{\text{pvt}}$            | 215                  | 200                         |
| $\gamma_{\text{brk}}$            | 3000                 | /                           |
| $\alpha_1$                       | -2.5                 | /                           |
| $\alpha_2$                       | -3.5                 | -3.5                        |
| $\gamma_{\text{min}}$            | 200                  | 1300                        |
| $\gamma_{\text{max}}$            | $10^5$               | $10^5$                      |

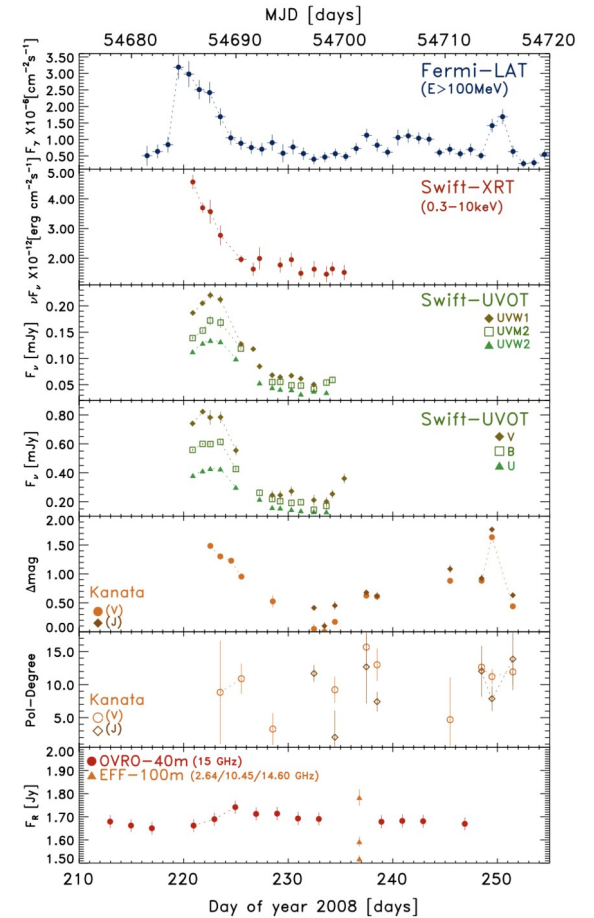
# Application to other sources ?



PKS 1510-089 , *Patel et al. 2021*



PKS 1222+216 ,  
*Kushwaha et al. 2014*



PKS 1502+106 ,  
*Abdo et al. 2010*

# propagating blob model : hadronic vs. leptonic

A plasma blob is moving along the jet with constant velocity.

It is expanding following the constant jet opening angle.  
B-field decreasing (magnetic flux is conserved)

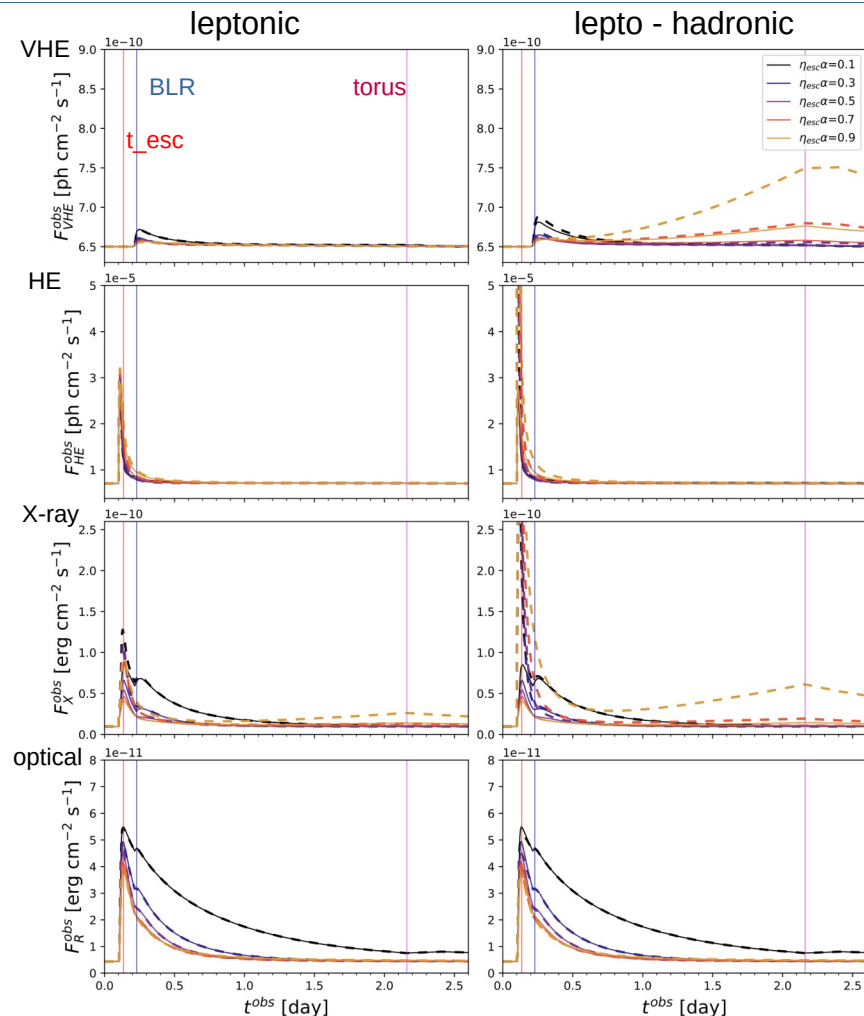
Continuous injection of relativistic particles with constant power.

**VHE band** is fully absorbed at early times due to  $\gamma\gamma$  pair production on photon fields → **delay** wrt other bands !

Effect of **pair production** (dashed lines) :

For large opening angles,  $t_{\text{esc}}$  becomes very large at large distance  
→ **secondary flares** from pair production  
→ more significant for hadronic scenario (secondary particles)

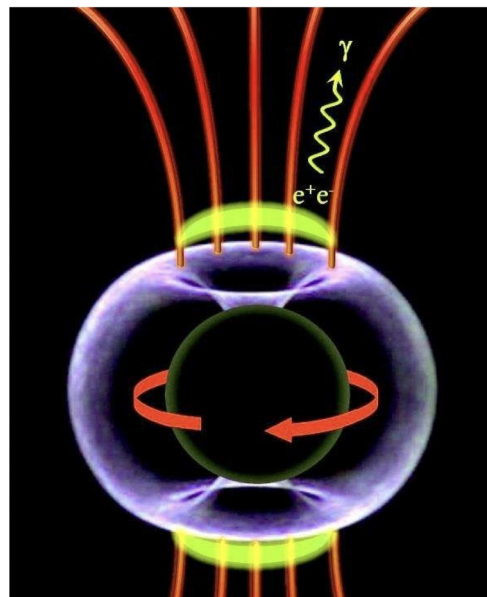
OneHaLe code  
M. Zacharias 2023



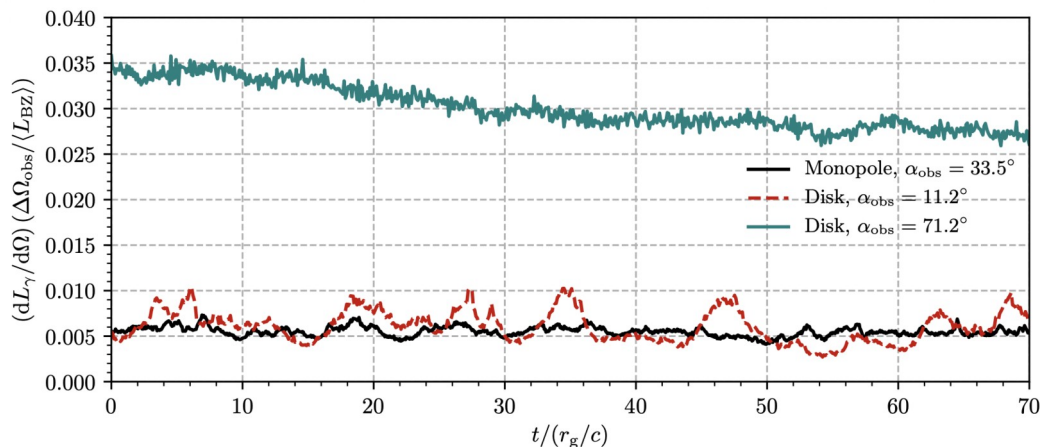
# rapid variability from the BH magnetosphere ?

**Scenarios of pulsar-like particle acceleration** by the electric field across a magnetospheric gap at the base of the radio jet.

- A maximally rotating BH with event horizon  $r_g$  accretes plasma. In the ergosphere extending to  $2r_g$  in the equatorial plane, Poynting flux generated by frame-dragging effect ( $\rightarrow$  Blandford-Znajek)
- The rotation of the BH induces a magnetosphere with polar vacuum gap regions. In the gaps, the **electric field of the magnetosphere has a component parallel to the magnetic field** accelerating particles to ultra-relativistic energies.
- **Inverse-Compton scattering and pair production** due to interactions with low-energy thermal photons from the accretion disk leads to the observed gamma rays.



(Aleksic et al. 2014)

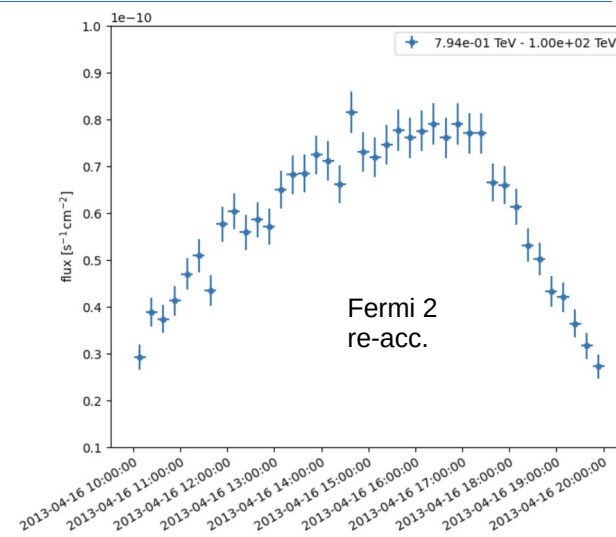
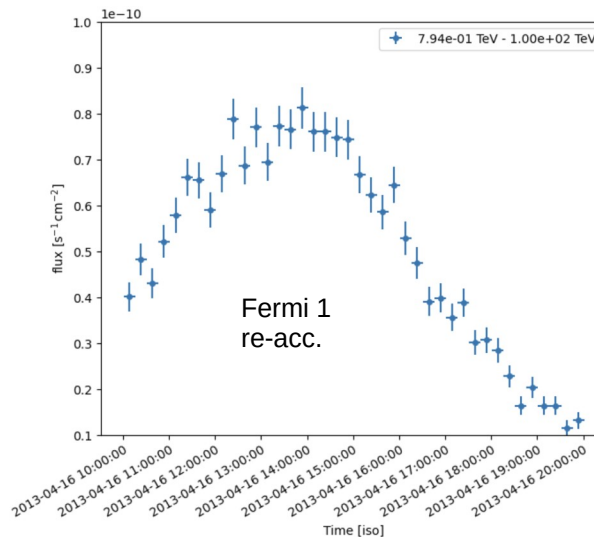
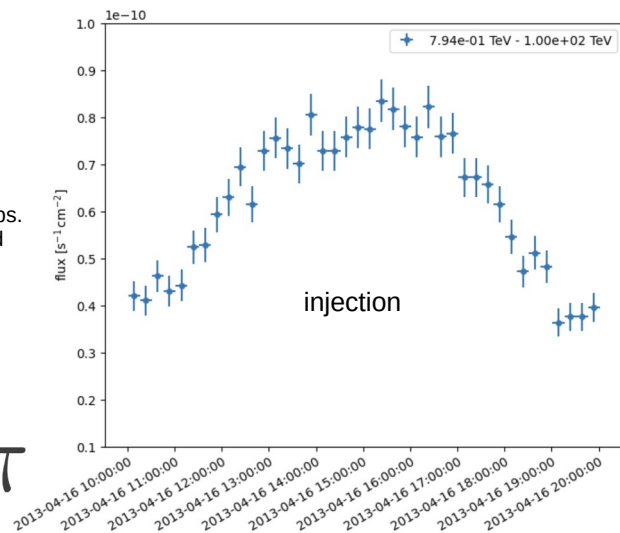


(Crinquand et al. 2021)

# What would CTAO see ?

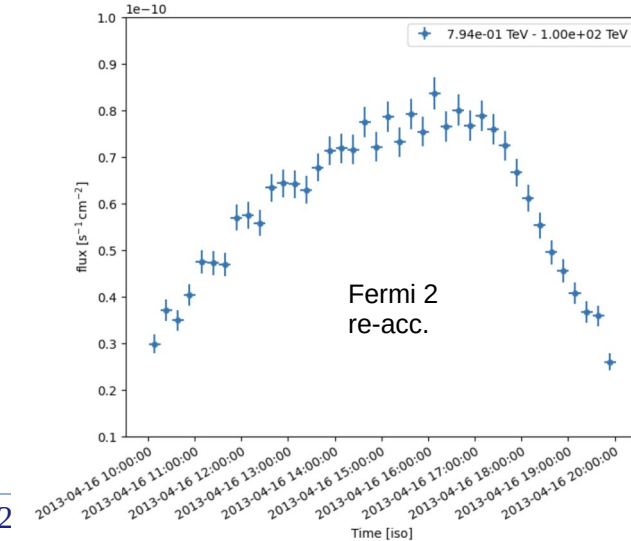
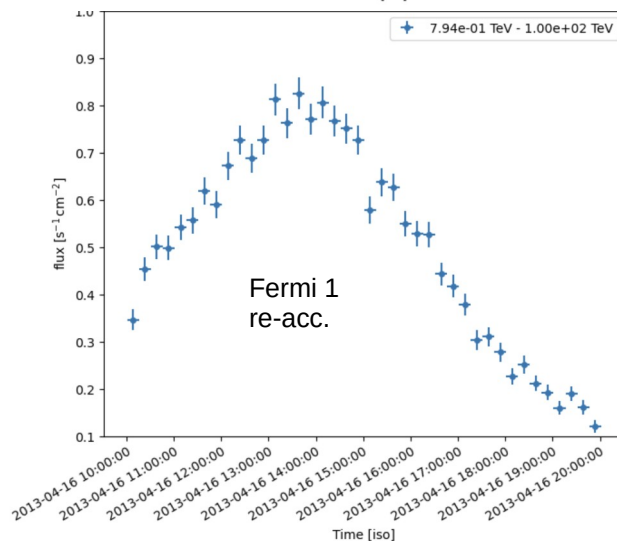
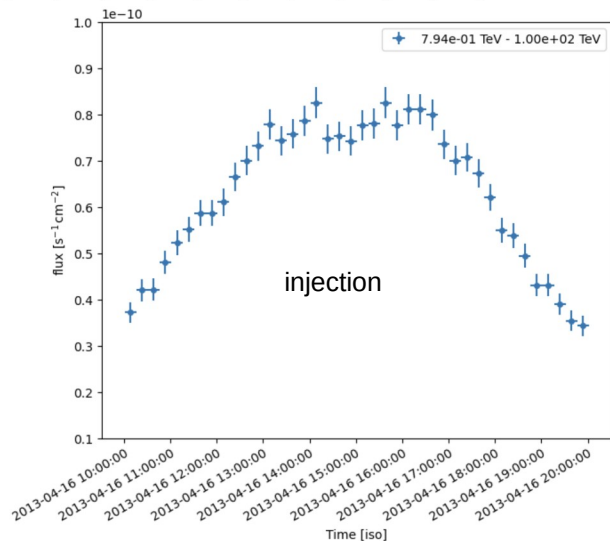
CTAO  
Nord  
(alpha)

Caveat:  
10h of obs.  
assumed

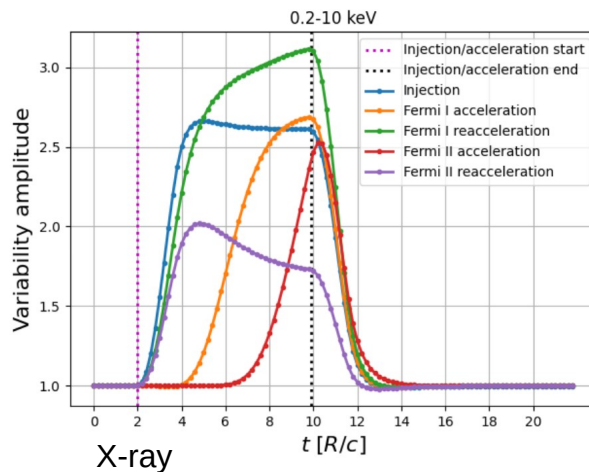
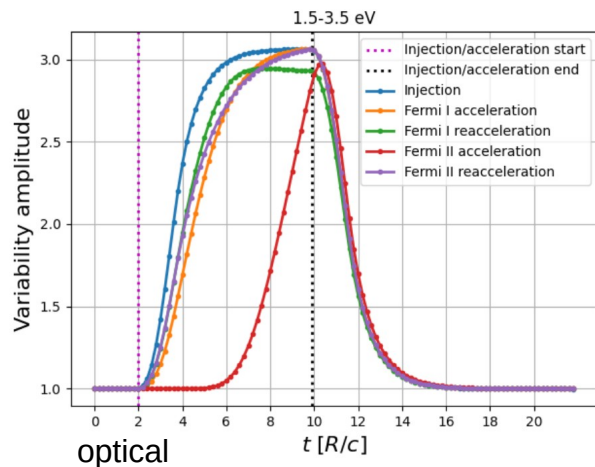


CTAO  
Sud  
(alpha)

Caveat:  
10h of obs.  
assumed



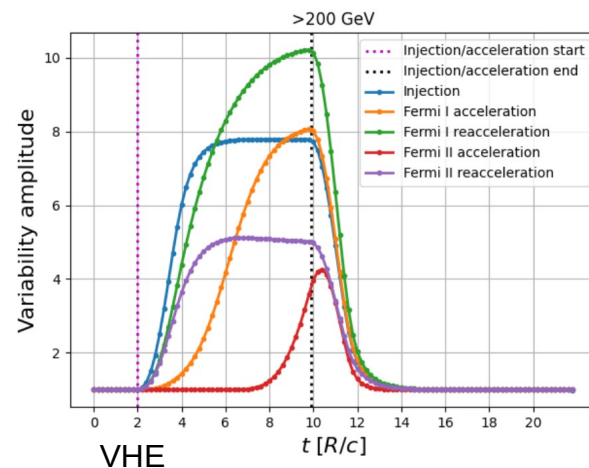
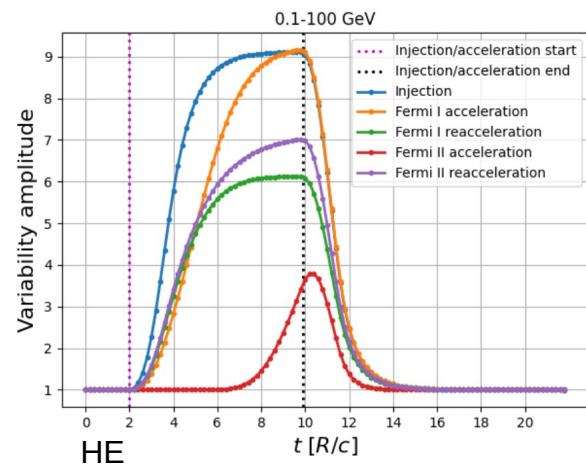
# light-curves for different acceleration mechanisms



Comparison of different scenarios with same optical amplitude

Fermi I acceleration :

Delays between flare onset due to **gradual acceleration**.



Fermi II re-acceleration , Injection :

Flare peaks early in the X-ray band, then **IC cooling** sets in rapidly and leads to a flux decline.

# Acceleration scenarios : parameters

| Parameter                        | Variable                    | Value                  | Unit                          |
|----------------------------------|-----------------------------|------------------------|-------------------------------|
| Source                           |                             |                        |                               |
| Initial magnetic field           | $B_0$                       | 0.04                   | G                             |
| Magnetic field configuration     | $m_B$                       | 1                      | -                             |
| Initial blob radius              | $R_0$                       | $2.8 \times 10^{16}$   | cm                            |
| Blob Doppler factor              | $\delta$                    | 29                     | -                             |
| Redshift                         | $z$                         | 0.0308                 | -                             |
| Angle to observer                | $\theta$                    | {0 ; 1}                | °                             |
| Evolution                        |                             |                        |                               |
| Quiescent injection duration     | $t_{\text{inj}}$            | 30                     | R/c                           |
| Quiescent escape timescale       | $t_{\text{esc}}$            | 1                      | R/c                           |
| Beginning of expansion           | $t_{\text{exp}}$            | 0                      | R/c                           |
| Beginning of flaring             | $t_{\text{flare}}$          | 2                      | R/c                           |
| Duration of flaring              | $t_{\text{dur}}$            | 3                      | days*                         |
| Escape timescale during flaring  | $t_{\text{esc,flare}}$      | 1                      | R/c                           |
| Continuous injection spectrum    |                             |                        |                               |
| Spectrum normalization           | $\dot{N}_{\text{inj}}$      | $1.86 \times 10^{-14}$ | $\text{cm}^{-3}\text{s}^{-1}$ |
| Spectrum slope                   | $\alpha_{\text{inj}}$       | -2.23                  | -                             |
| Pivot Lorentz factor             | $\gamma_{\text{inj,pivot}}$ | $1.0 \times 10^5$      | -                             |
| Cutoff Lorentz factor            | $\gamma_{\text{inj,cut}}$   | $5.8 \times 10^5$      | -                             |
| Minimal injected Lorentz factor  | $\gamma_{\text{inj,min}}$   | 800                    | -                             |
| Flaring injection spectrum       |                             |                        |                               |
| Spectrum normalization           | $\dot{N}_{\text{add}}$      | $4 \times 10^{-14}$    | $\text{cm}^{-3}\text{s}^{-1}$ |
| Spectrum slope                   | $\alpha_{\text{add}}$       | -2.23                  | -                             |
| Pivot Lorentz factor             | $\gamma_{\text{add,pivot}}$ | $1.0 \times 10^5$      | -                             |
| Cutoff Lorentz factor            | $\gamma_{\text{add,cut}}$   | $5.8 \times 10^5$      | -                             |
| Minimal injected Lorentz factor  | $\gamma_{\text{add,min}}$   | 800                    | -                             |
| Particle acceleration            |                             |                        |                               |
| Fermi I reacceleration timescale | $t_{F_I}$                   | [0.7 – 2.0]            | R/c                           |
| Turbulent spectrum slope         | $q$                         | 2                      | -                             |
| Maximum spectrum wavelength      | $\lambda_{\text{max}}$      | [0 – 1]                | R                             |
| Turbulence level                 | $\mathcal{L}_{\text{turb}}$ | [0 – 1]                | -                             |
| Simulation grids                 |                             |                        |                               |
| Minimal electron Lorentz factor  | $\gamma_{\text{min}}$       | 100                    | -                             |
| Maximal electron Lorentz factor  | $\gamma_{\text{max}}$       | $1.0 \times 10^7$      | -                             |
| Lorentz factor grid's points     | $n_\gamma$                  | 200                    | -                             |
| Simulation start time            | $t_{\text{start}}$          | 0                      | R/c                           |
| Simulation end time              | $t_{\text{end}}$            | 30                     | R/c                           |
| Time grid's bins                 | $n_{\text{bins}}$           | 1000                   | -                             |

The parameters for the injection scenario are:  $R = 5.5 \times 10^{15}$  cm,  $B = 0.2$  G,  $\gamma_{\text{min}} = 5 \times 10^3$ ,  $\gamma_{\text{max}} = 8 \times 10^5$ . The same radius was used for the Fermi-I reacceleration scenario, but with a smaller magnetic field of  $B = 0.05$  G and a smaller value of  $\gamma_{\text{max}} = 1.5 \times 10^6$  for the initial electron spectrum. Particle acceleration was achieved with an underlying weak turbulent acceleration ( $\mathcal{L} = 0.4$ ,  $\lambda_{\text{max}} = 0.1$  R) and a dominant shock acceleration with timescale  $t_{F_I} = 1.6$  R/c. The best scenario of Fermi-II reacceleration invoked a smaller radius of  $R = 4.1 \times 10^{15}$  cm, an intermediate magnetic field strength  $B = 0.1$  G,  $\gamma_{\text{min}} = 2 \times 10^3$  and  $\gamma_{\text{max}} = 2 \times 10^6$  for the initial injection. Particle acceleration during the flare was achieved with  $\mathcal{L} = 0.6$  and  $\lambda_{\text{max}} = 0.1$  R.

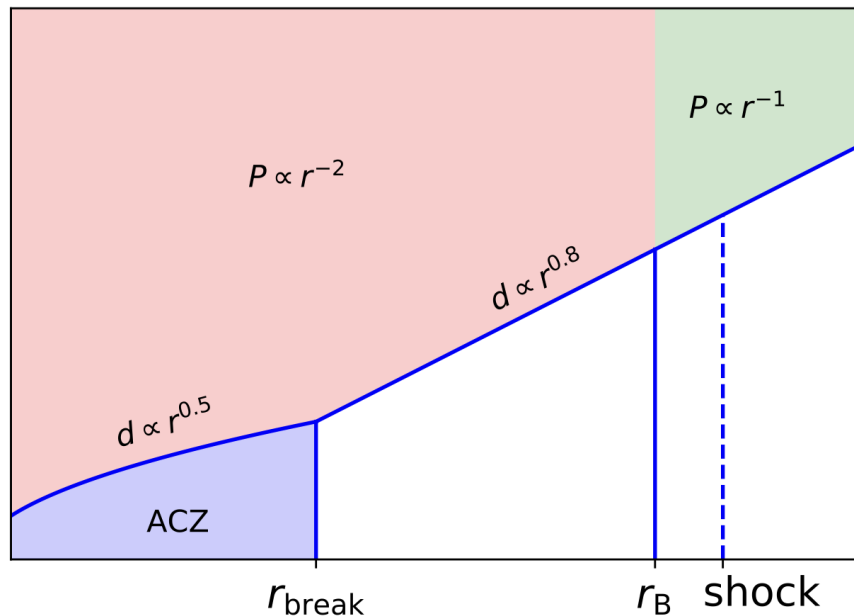


**Figure 8.** A schematic jet boundary shape for an ambient pressure with different profiles, changing at the Bondi radius  $r_B$ . The jet accelerates while sustaining its boundary as a parabola (acceleration and collimation zone, ACZ). After reaching  $\sigma = 1$  at  $r_{\text{break}}$  the jet form becomes almost conical up to the Bondi radius.

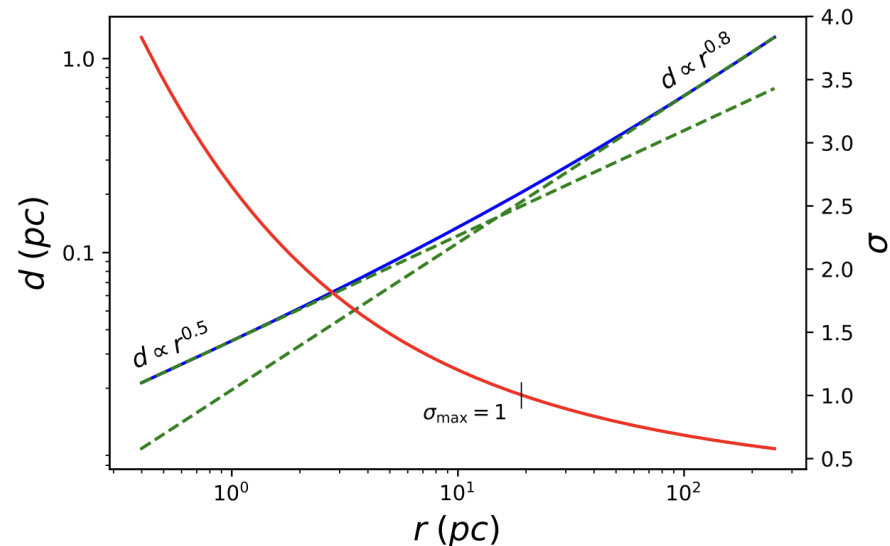


**Figure 7.** An example of a jet boundary shape (blue solid line) for  $\sigma_M = 50$  and  $P_0 = 10^{-6}$  dyn/cm<sup>2</sup> at  $r_0 = 10$  pc. The jet magnetization at a given distance from its base is plotted by a red solid line, with black vertical line marking  $\sigma_{\text{max}} = 1$ . The transition from one power law to the other (green dashed lines) for the jet boundary roughly coincides with the point where the outflow transits from the magnetically dominated to particle dominated (equipartition) regime.

**Table 4.** Derived parameters of the jet shape break for 10 AGN with addition of 0321+340 adopted from [Hada et al. \(2018\)](#) and 1228+126 from [Nokhrina et al. \(2019\)](#). Columns are as follows: (1) source name (B1950); (2) jet width at the break in mas; (3) same as (2) but in pc; (4) projected distance of the break from the apparent core along the jet in mas; (5) projected distance of the break from the BH along the jet in mas; (6) same as (5) but in pc; (7) deprojected distance of the break from the BH along the jet in pc, the parameter uses the estimated viewing angle; (8) presence of a bright low pattern speed feature ([Lister et al. 2019](#)).

| Source   | $d_{\text{break}}$ | $r_{\text{break, app}}^{\text{proj}}$ | $r_{\text{break}}^{\text{proj}}$ | $r_{\text{break}}^{\text{proj}}$ | $r_{\text{break}}^{\text{deproj}}$ | Stationary  |                |
|----------|--------------------|---------------------------------------|----------------------------------|----------------------------------|------------------------------------|-------------|----------------|
| (mas)    | (pc)               | (mas)                                 | (mas)                            | (pc)                             | (pc)                               | jet feature |                |
| (1)      | (2)                | (3)                                   | (4)                              | (5)                              | (6)                                | (7)         | (8)            |
| 0111+021 | $0.30 \pm 0.03$    | $0.28 \pm 0.03$                       | $2.46 \pm 0.27$                  | $2.62 \pm 0.29$                  | $2.38 \pm 0.26$                    | 27.31       | Y              |
| 0238−084 | $0.53 \pm 0.05$    | $0.05 \pm 0.01$                       | $2.93 \pm 0.57$                  | $3.73 \pm 0.65$                  | $0.37 \pm 0.06$                    | 0.49        | Y              |
| 0321+340 | 1                  | 1.16                                  | 10                               | 10.04                            | 11.64                              | 106.07      | Y <sup>a</sup> |
| 0415+379 | $0.78 \pm 0.03$    | $0.74 \pm 0.03$                       | $7.03 \pm 0.50$                  | $7.07 \pm 0.50$                  | $6.72 \pm 0.47$                    | 29.00       | ...            |
| 0430+052 | $0.45 \pm 0.06$    | $0.29 \pm 0.04$                       | $2.67 \pm 0.40$                  | $2.85 \pm 0.41$                  | $1.85 \pm 0.27$                    | 5.77        | ...            |
| 0815−094 | $0.37 \pm 0.05$    | ...                                   | $1.37 \pm 0.30$                  | $1.54 \pm 0.30$                  | ...                                | ...         | ...            |
| 1133+704 | $0.57 \pm 0.02$    | $0.50 \pm 0.02$                       | $1.39 \pm 0.09$                  | $1.46 \pm 0.10$                  | $1.29 \pm 0.09$                    | 14.80       | ...            |
| 1228+126 | $13.00 \pm 0.50$   | $1.20 \pm 0.04$                       | ...                              | $131 \pm 6$                      | $10.50 \pm 0.46$                   | 43.41       | Y <sup>b</sup> |
| 1514+004 | $0.34 \pm 0.02$    | $0.34 \pm 0.02$                       | $3.10 \pm 0.22$                  | $3.39 \pm 0.30$                  | $3.39 \pm 0.30$                    | 13.10       | Y              |
| 1637+826 | $0.32 \pm 0.02$    | $0.16 \pm 0.01$                       | $1.92 \pm 0.26$                  | $2.13 \pm 0.28$                  | $1.02 \pm 0.13$                    | 3.30        | Y              |
| 1807+698 | $0.26 \pm 0.04$    | $0.25 \pm 0.04$                       | $1.53 \pm 0.33$                  | $1.67 \pm 0.34$                  | $1.63 \pm 0.33$                    | 12.83       | Y              |
| 2200+420 | $0.74 \pm 0.03$    | $0.95 \pm 0.04$                       | $2.45 \pm 0.10$                  | $2.52 \pm 0.13$                  | $3.25 \pm 0.16$                    | 24.57       | ...            |

<sup>a</sup>From [Hada et al. \(2018\)](#).

<sup>b</sup>From [Asada & Nakamura \(2012\)](#). This refers to the well-known HST-1 feature ([Chang et al. 2010](#)) which is located too far downstream to be sampled by typical MOJAVE images