Superfast AGN variability

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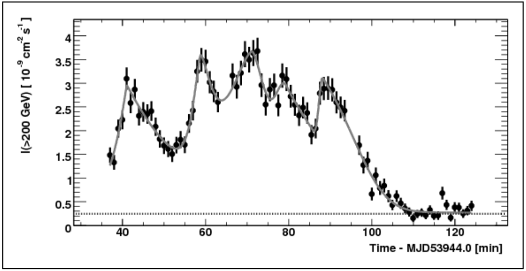
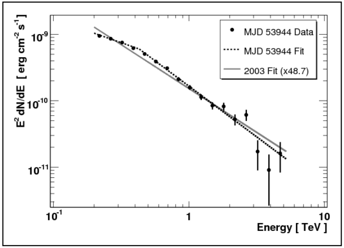
Outline

PKS 2155–304 observations (the First)





The observed parameters of the PKS 2155−304 flares (H.E.S.S. data)

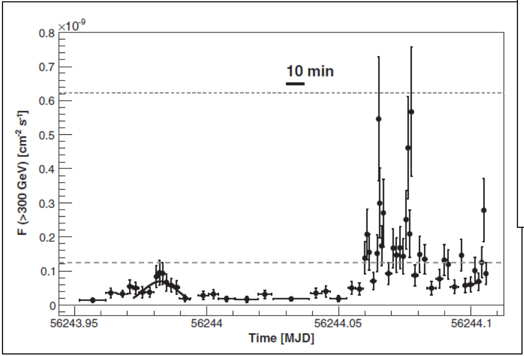
$$L_\gamma \approx 10^{47} \text{erg s}^{-1}$$

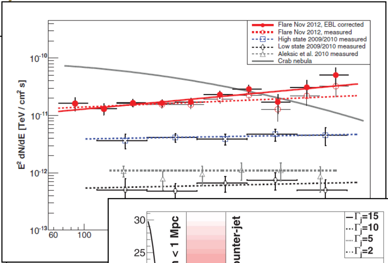
$$t_{\text{var}} \approx 200 \text{ s} \sim 0.04 r_g/c$$

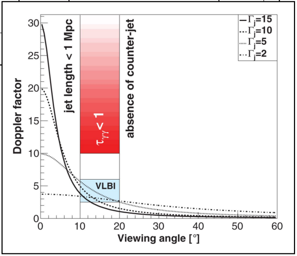
$$L_X \sim 10^{46} \text{erg s}^{-1}$$

(Aharonian et al 2007)

TeV Flare in IC310 (Misaligned)







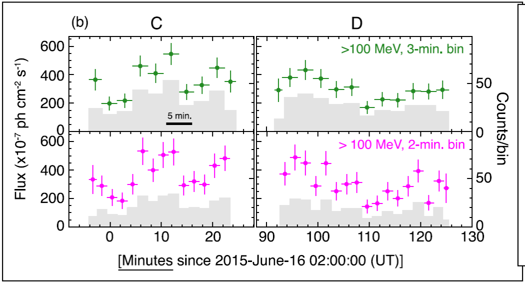
The observed parameters of the IC310 TeV flares (MAGIC data)

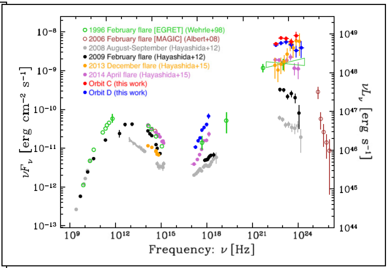
$$L_\gamma \approx 2 \times 10^{44} \mathrm{erg\ s}^{-1}$$

$$t_{\mathrm{var}} \approx 4.8\ \mathrm{min} \sim 0.2 r_g / c$$

Aleksic et al (2014)

GeV Flare in 3C279 (Bright)





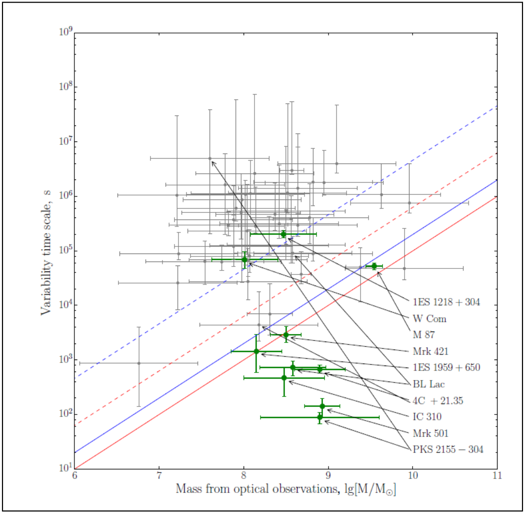
The observed parameters of the 3C279 GeV flares (*Fermi*/LAT data)

$$L_\gamma \approx 10^{49} \mathrm{erg\,s}^{-1}$$

$$t_{\mathrm{var}} \approx 5\,\mathrm{min} \sim 0.1 r_{\mathrm{g}}/c$$

Ackermann et al (2016)

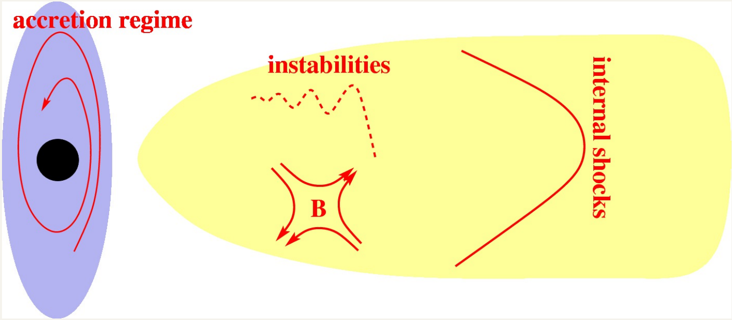
Very fast variability in AGNs



Vovk & Babic (2016)

Where is the source of the variability?

There are a lot of hypothetical sites



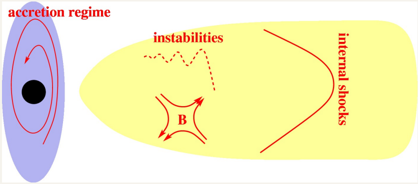
Internal Shocks, Magnetic Reconnection, Change in Accretion, Magnetospheric Gap, Instabilities....

The problem of the fast variability:

BH light crossing time

It is straightforward to compare these timescales with the minimum time that characterizes a black hole system as an emitter, namely, the light crossing time of the gravitational radius of the black hole:

$$\tau_0 = r_g/c \approx 5 \times 10^2 M_8 \,\mathrm{s}.$$



Limitation:

Let us present the proper size of the production region as $R' = \lambda \Gamma_j r_g$, where λ is a dimensionless parameter, which corresponds to the ratio of the production region size in the laboratory frame to the gravitational radius.

The causality condition provides a limitation on the variability timescale:

$$\frac{t_{var}}{\tau_0} \geq \frac{\lambda \Gamma_j}{\Gamma_{em}}.$$

Three models of VHE fast variability

- The Black Hole Magnetospheric Model
  $\lambda \ll 1 \quad \Gamma_{\rm emj} \sim \Gamma_{\rm j} \sim 1$
- Relativistically Moving Blobs (jet-in-jet)
  $\lambda \sim 1 \quad \Gamma_{\rm em} \gg \Gamma_{\rm j} \gg 1$
- Cloud/Star in jet model
  $\lambda \ll 1 \quad \Gamma_{\rm em} \sim \Gamma_{\rm j} \gg 1$

$$\frac{t_{\rm var}}{\tau_0} \geq \frac{\lambda \Gamma_{\rm j}}{\Gamma_{\rm em}}.$$

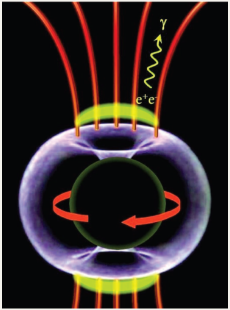
The Black Hole Magnetospheric Model

Black Hole Magnetospheric Model:

Optimistic Total Energetic Budget

- $\Delta V \lesssim hB_{\rm bh}\frac{R\Omega_{\rm F}\sin\theta}{c}, \quad \frac{\Omega_{\rm F}}{c} \simeq \frac{1}{4r_g}$
- $L_{\gamma,ms} < 4\pi R^2 c\kappa\rho_{\rm GJ}\Delta V, \quad \rho_{\rm GJ} = \Omega_{\rm F} B_{\rm bh}\sin\theta/(2\pi c)$
- $L_{\gamma,ms} < \frac{1}{8}\kappa B_{\rm bh}^2 r_{\rm g} hc\sin^2\theta$ (2x larger compare to Balandford-Znajek, 1/100 compare to Levinson&Rieger 2011)
- $\dot{m} < 10^{-2}\alpha_{\rm SS}\eta\beta_{\rm m}^{1/7}M_8^{-1/7}$ the maximum accretion rate compatible with vacuum gap (generalized results of Levinson&Rieger 2011)
- $B_{\rm d} = \sqrt{8\pi\beta_{\rm m}p_g}, \quad h = 10^{13}t_{\rm var,5}\,{\rm cm}$
- $L_{\gamma,ms} < 2\times10^{43}\frac{\beta_{\rm m}^{8/7}\kappa t_{var,5}\sin^2\theta}{M_{\rm BH,8}^{1/7}}$ erg s^{-1}
- $L_{\gamma,\rm IC310} \approx 2\times10^{44}$erg s^{-1}

Black Hole Magnetosphere



Aleksic et al (2014)

idea Neronov& Aharonian (2007)

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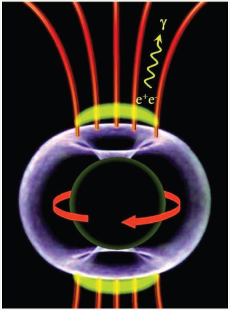

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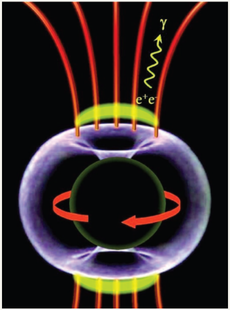

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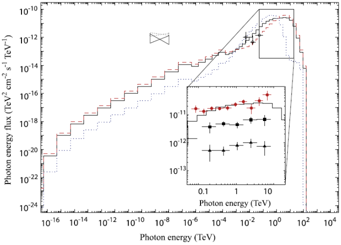
- $L_{\gamma,\rm IC310} \approx 2 \times 10^{44}$erg s^{-1}
- $L_{\gamma,\rm IC310} \gg L_{\gamma,ms}$

Black Hole Magnetosphere

Aleksic et al (2014)

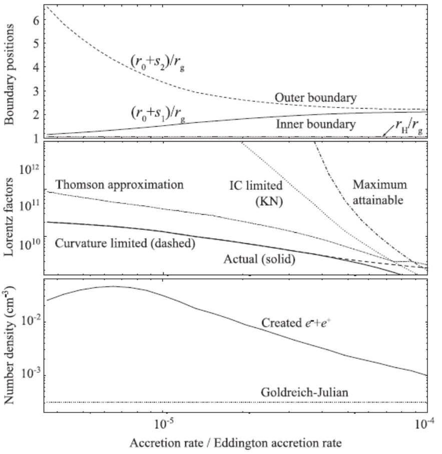
Black Hole Magnetospheric Model:



Payback for the model:

- The thickness of the Gap is inconsistent with the variability time.
- $B_{BH} = 10^4$ G with $\dot{m} = 8 \times 10^{-6}$.
- The effectiveness of accretion > 10000 % !!!
- 3D GRMHD models show the effectiveness < 300 %

Numerical propertiesof the gap:



Hirotani&Pu (2016)

Relativistically Moving Blobs (jet-in-jet)

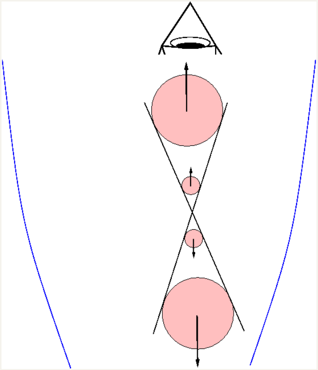
Relativistically Moving Blobs (jet-in-jet):

Energy Budget for single flare

- The magnetic field reconnection in a highly magnetized jet can form relativistically moving blob in the jet reference frame.
- Variability time-scale determines size of the production region: $\tilde{l}_{\rm em} = c\Delta t \Gamma_{\rm em}$, here $\Gamma_{\rm em} = 2\Gamma_{\rm j}\Gamma_{\rm co}/(1+\alpha^2)$ and $\alpha = \theta\Gamma_{\rm j}$
- $L_{\rm j} = 1.4 \times 10^{-5} L_\gamma \left(\frac{1+\alpha^2}{4}\right)^6 \frac{r_2^2 M_8^2}{\Gamma_{\rm co,1}^6 \Gamma_{\rm j,1}^6 \xi_{-1} t_{\rm var,5}^2}$.

idea from Giannios (2009,2010)

Lucky Jet-in-Jet



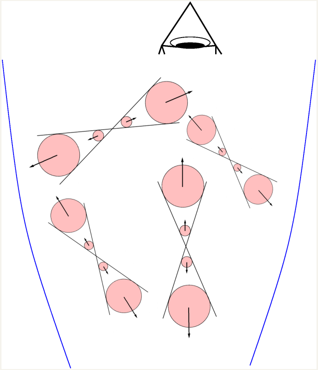
Relativistically Moving Blobs (jet-in-jet):

Energy Budget for multiple flares

- The probability for an observer to be in the mini-jet beaming cone is: $P \simeq (2\Gamma_{co})^{-2}$
- The total number of mini-jets during flaring episode can be estimated as $N \approx \Phi T / P t_{var}$
- The total dissipated energy for the flare should be smaller than the energy that is contained in the dissipation region
- $L_j > 0.006\Phi\left(1+\alpha^2\right)^4 \Gamma_{j,1}^{-2} L_\gamma \xi_{-1}^{-1}$

idea from Giannios (2009,2010)

Isotropic Jets-in-Jet



Cloud/Star in Jet Model

Cloud/Star in Jet Model

External origin of the blobs:

- If blobs have external origin, they can be **very small** as compared to the hydrodynamical scale of the jet....
- External blobs contain **no energy** (as compared to the jet)
- I.e. external blobs must be able to **trigger an intensive interaction**. To be heavy?
- Compact and heavy, i.e **DENSE:** stars, BLR clouds?

Specific realization of such blob formation:

Jet-Red Giant Interaction Scenario

Main Ingredients

AGN jet

- Relativistic outflow ($\Gamma_{\rm bulk} \sim 10 - 100$, likely depends on the distance)
- Narrow: typically one adopts $\theta \simeq \Gamma^{-1}$, i.e.,
- Cross section:

$$\omega \simeq 10^{17} \Gamma_{1.5}^{-1} R_{\rm pc} {\rm cm}$$

Stars around BH

- Moves with Keplerian velocity:

$$V_* \simeq 600 M_{\rm BH}^{1/2} R_{\rm pc}^{-1/2} {\rm km/s}$$

- Density (quite uncertain): $\rho_* \simeq \rho_0 R^{-a}$

Mass injection between 10^{-2} and 10^{-1} pc:

$$\dot{M}_* \simeq 2 \times 10^{-5} \frac{\rho_0 M_{\rm BH,8}^{1/2}}{\Gamma_{1.5}} \int\limits_{0.01}^{0.1} x^{1/2-a} dx \; [{\rm pc}^3\, {\rm yr}^{-1}] \,,$$

Probability to get a star to a jet

Murphy et al. 1991

- it was revealed that "*a*" spans a quite broad range depending on the mass accumulated in the central parsec
- It was obtained that $a = 7/2$ for $\bar{\rho} = 10^6 M_\odot \mathrm{pc}^{-3}$ and $a = 1/2$ for $\bar{\rho} = 10^8 M_\odot \mathrm{pc}^{-3}$

Mass injection appears to depend very weakly on *a*

$$\dot{M}_* \simeq 2 \times 10^2 M_{\mathrm{BH},8}^{1/2} M_\odot \Gamma_{1.5}^{-1} \mathrm{yr}^{-1}$$

for $10^{-2} < R_{\mathrm{pc}} < 0.1$

One can expect HUNDREDS of stars entering per year which can contain a few Red Giants or young stars per year...

Cloud-Jet interaction (Numerical results)

Uniform cloud

(Bosch-Ramon et al 2012)

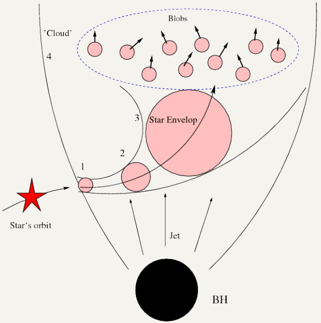
Cloud/Star in jet model:

Optimistic Energetic Constraint

- maximal observed energy to one blob: $E_\gamma \simeq \xi M_c c^2 \delta_j^3$
- The variability time scale: $t_{var} \simeq \frac{4 c M_c \Gamma_j^2}{P_j \pi R_c^2 \delta_j}$
- $L_j > 0.025 \left(1+\alpha^2\right)^4 \Gamma_{j,1}^{-2} L_\gamma \xi_{-1}^{-1}$
- Jet power in star-jet model is only a factor of $4/\Phi$ larger than the estimate for the jet-in-jet scenario

idea from Barkov et al (2012)

Cloud/Star-jet interaction



Summary

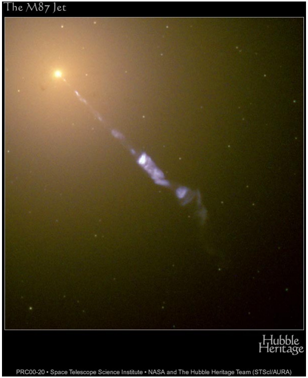
Comparison of models for different sources

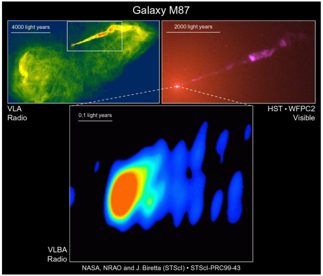
Source	IC 310	M87	3C454.3	3C 279	PKS 2155−304
$M_{BH,8}$	3	60	10	5	3
t_5	1	175	54	1	0.6
τ	0.2	2	3	0.1	0.04
L_γ, erg/cm^{2}s	2×10^{44}	10^{42}	2×10^{50}	10^{49}	10^{47}
Φ	0.1	0.3	0.7	0.3	0.7
Γ_j	10	10	20	20	20
Γ_{co}	10	10	10	10	10
α	2	2	0	0	0
$L_\gamma/L_{\gamma,ms}$	10	5×10^{-4}	3×10^{5}	5×10^{5}	10^{4}
$L_{j,jj}$	10^{44}	10^{42}	2×10^{47}	4×10^{45}	10^{44}
$L_{j,cj}$	3×10^{45}	2×10^{43}	10^{48}	5×10^{46}	6×10^{44}

Table: Where $M_{BH,8} = M_{BH}/10^8 M_\odot$ is SMBH mass, $t_5 = t/300$ s variability time, $\tau = tc/r_g$ non-dimensional variability time in units of gravitation radius light crossing time, L_γ maximum luminosity in γ-rays, Γ_j is jet Lorentz factor, Γ_{co} is Lorentz factor of mini-jet, $\alpha = \theta/\Gamma_j$ is normalized viewing angle, $L_{\gamma,ms}$ is upper limit of γ-ray luminosity for magnetospheric model, $L_{j,jj}$ is minimal jet power for jet-in-jet model, $L_{j,cj}$ is minimum jet power for cloud-jet model.

VHE variability in M87

M87 observations





The parameters of the M87 BH and Jet

$$M_{BH} \simeq 6.4 \times 10^9 M_\odot$$

$$L_{jet} \simeq (1-5) \times 10^{44} \text{ergs s}^{-1}$$

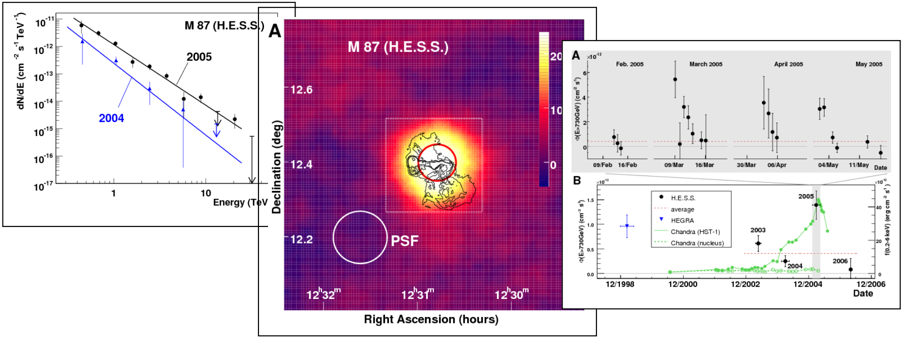
$$\text{radiative active region (in radio) } r \lesssim 10^{17} \text{cm}$$

H.E.S.S., MAGIC, VERITAS observations of M87

Several flashes were observed in 2006, 2008, 2010.

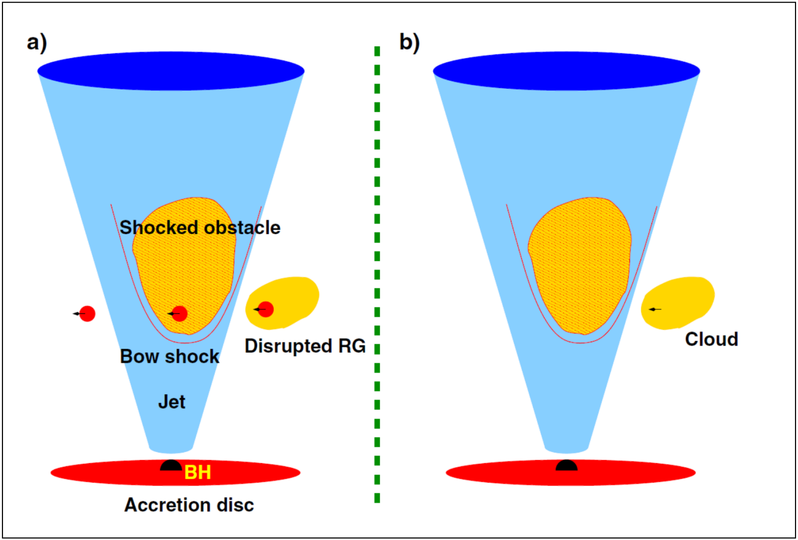
Variability on scales $t \sim 1$day

The flux $L_\gamma \sim 10^{42}$ergs s^{-1} $\qquad E_{\gamma,max} \simeq 20$TeV.



(Aharonian et al 2006; Abramowski et al. 2011; Aliu et al. 2011)

Cloud/Star — Jet interaction

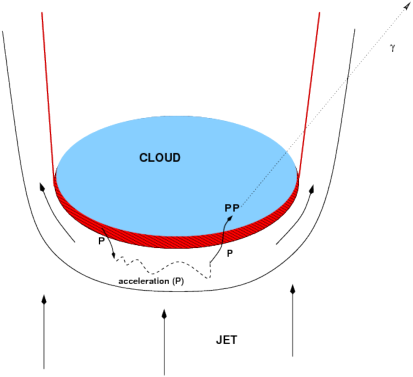


(Barkov et al 2010, 2012b)

p-p interaction

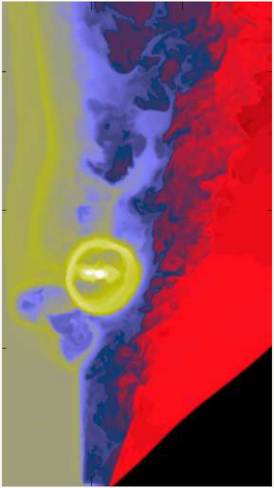
The cloud density can be very high making the *pp* interactions to be the most plausible mechanism for the gamma-ray production in the RG-jet interaction scenario: in this case the characteristic cooling time for *pp* collisions is

$$t_{pp} \approx \frac{10^{15}}{c_f n_c} = 10^5\, n_{c,10}^{-1} c_f^{-1}\, \mathrm{s} \qquad \chi \equiv E_\gamma / E_p = 0.17\,[2 - \exp(-t_v/t_{pp})]$$



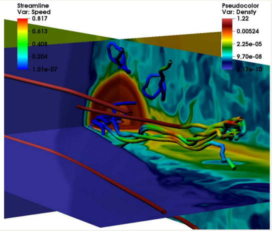
Star envelop evolution (Numerical results)

3D density

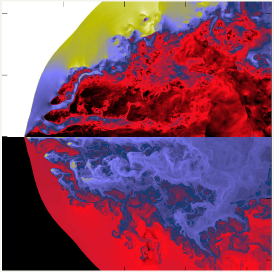


Perucho,Bosch-Ramon and BMV 2017

3D stream lines

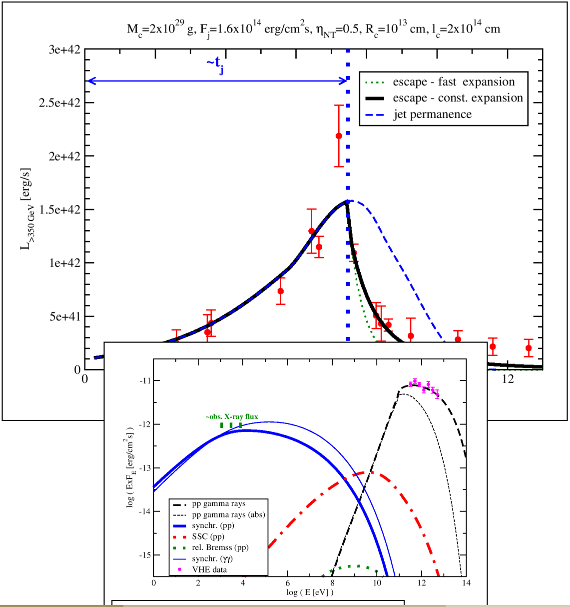


2D density and pressure



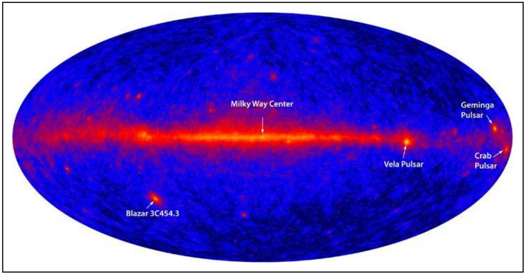
VHE light curves and spectra (Numerical model)

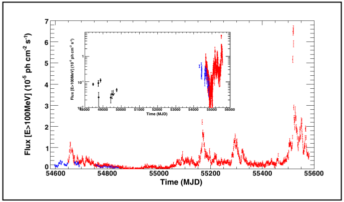
$\xi = 0.5$ and $Q_p(E) \propto E^{-2}$



Fast variability in GeV blazars (3C454.3)

3C454.3 observations





The observed parameters of the 3C454.3 flares (*Fermi* data)

$$L_\gamma \approx 2 \times 10^{50} \mathrm{erg\,s}^{-1}$$

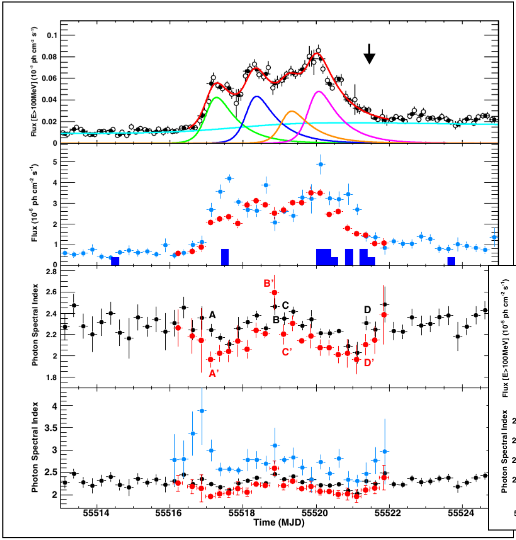
$$\tau_\mathrm{r} \approx 4.5\,\mathrm{h}$$

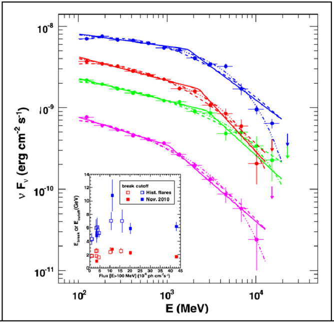
$$L_X \sim 5 \times 10^{47} \mathrm{erg\,s}^{-1}$$

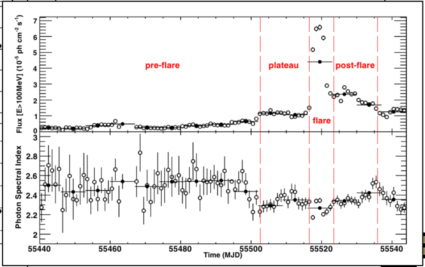
(Abdo et al. 2011; Vercellone et al. 2011)

3C454.3 observations (2010 November)

(Abdo et al 2011)



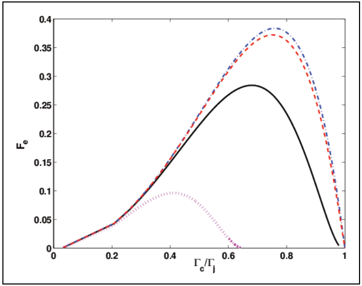


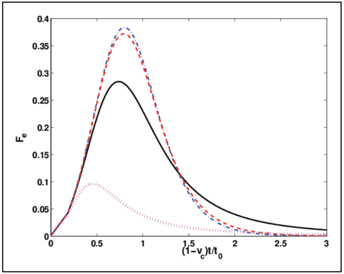


Relativistic Stage

At the relativistic stage, the dynamics of the cloud is described by the following equation:

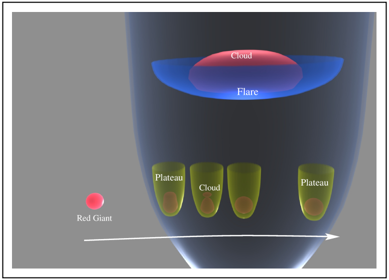
$$\frac{dg}{dy} = \left(\frac{1}{g^2} - g^2\right)\frac{D}{y^2}, \quad D \equiv \frac{L_{\rm j} r_{\rm c}^2}{4\theta^2\Gamma_{\rm j}^3 z_0 c^3 M_{\rm c}}, \quad g \equiv \frac{\Gamma_c}{\Gamma_j}, \quad y \equiv \frac{z}{z_0}.$$





Solutions of the equation shown as $F_e \equiv L/L_{max}$ vs Lorentz factor of the cloud and as L/L_{max} vs the observed time ($t_0 = z_0/2D\Gamma_j^2 c$): $D = 100$, 10, 1 and 0.1. (Barkov et al 2012a)

Sketch and Plateau model



$$\dot{M}_* \approx 10^{24} L_{\gamma,49} \xi_{-1}^{-1} \Gamma_{j,1.5}^{-3} \text{ g/s.}$$

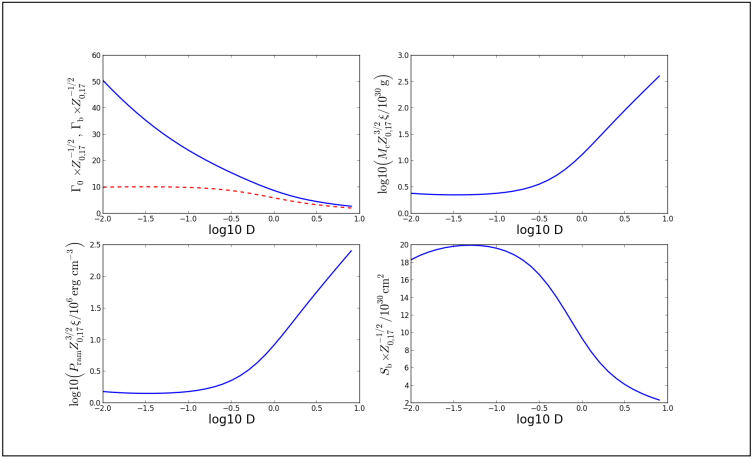
The cosmic ray/X-ray excite stellar wind (Basko et al. 1973; Dorodnitsyn et al. 2008),

$$\dot{M} \approx 10^{24} \alpha_{-12} R_{*,2}^{5/2} M_{*,0}^{-1/2} \chi P_{0,6} \, \text{g s}^{-1}$$

which providing limitations on the stellar radius

$$R_{*,2} \gtrsim \left(\frac{2\bar{F}_e M_{0,*}^{1/2}}{\alpha_{-12}\chi} \right)^{2/5} .$$

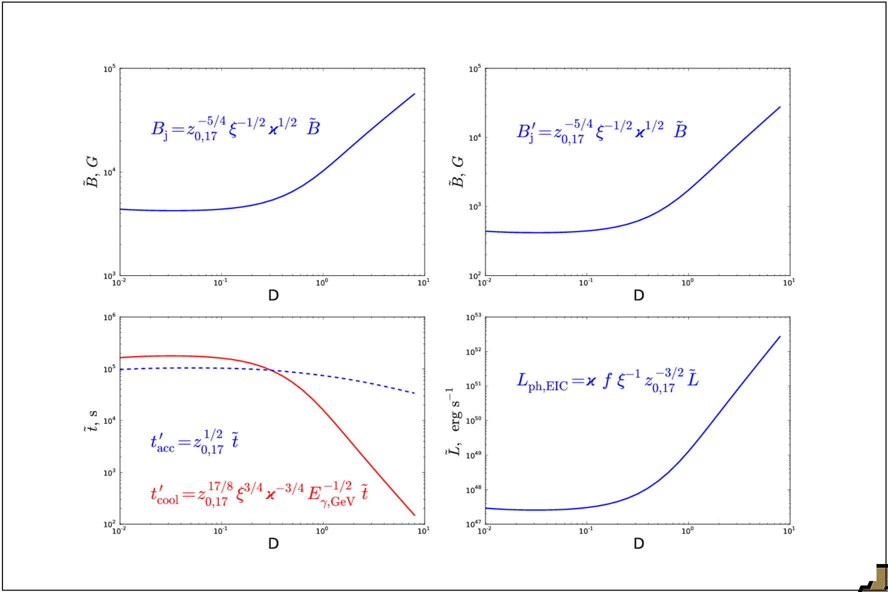
The Model Solution for the Main Flare



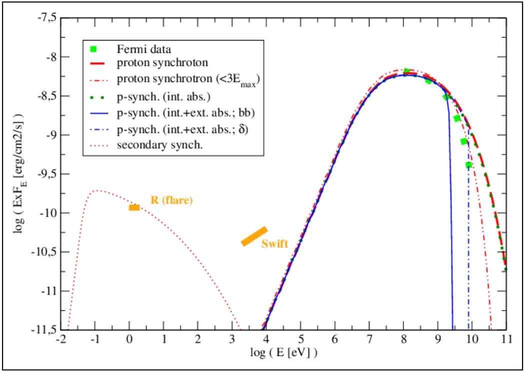
$$D \equiv \frac{L_\mathrm{j} r_\mathrm{c}^2}{4\theta^2 \Gamma_\mathrm{j}^3 z_0 c^3 M_\mathrm{c}} \qquad L_\mathrm{j} \geq 10^{48} \quad \mathrm{erg\ s}^{-1}$$

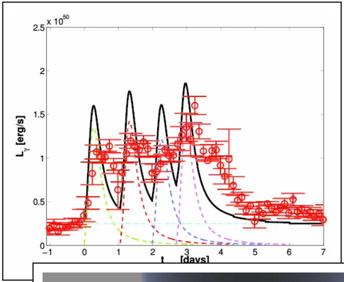
$$M_\mathrm{BH} \approx 10^9 M_\odot \qquad \delta_\mathrm{b} \approx 20$$

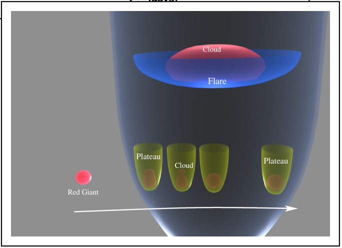
Radiation Model: limitations



Dynamical light curve + Radiation spectra: Proton synchrotron and secondary synchrotron



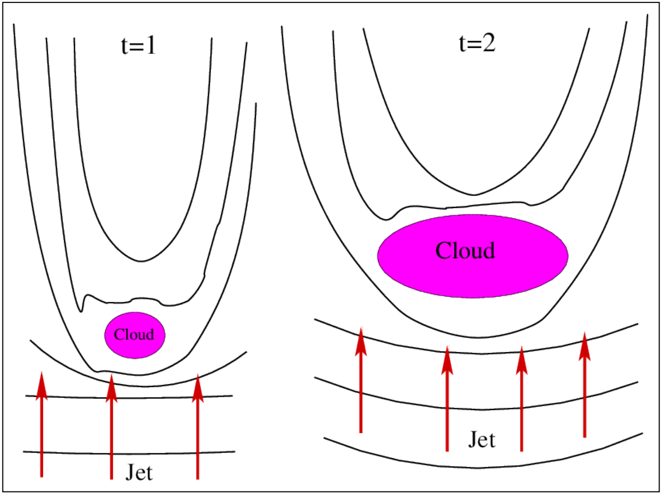




$$t_{\text{acc}}/(2\Gamma_b^2) \approx 5 \text{ h.}$$

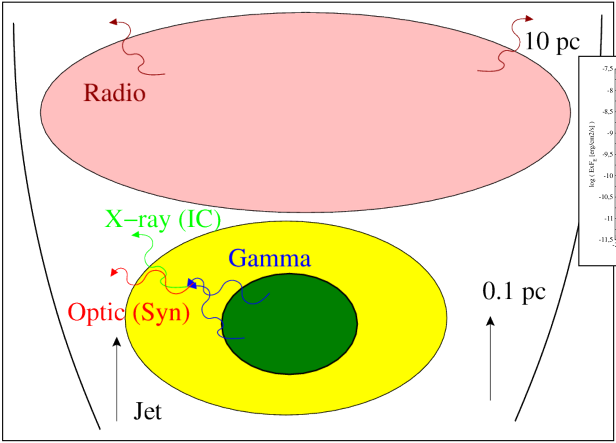
Khangulyan et al (2013)

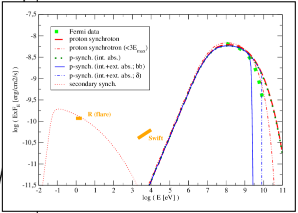
The magnetic field shielding



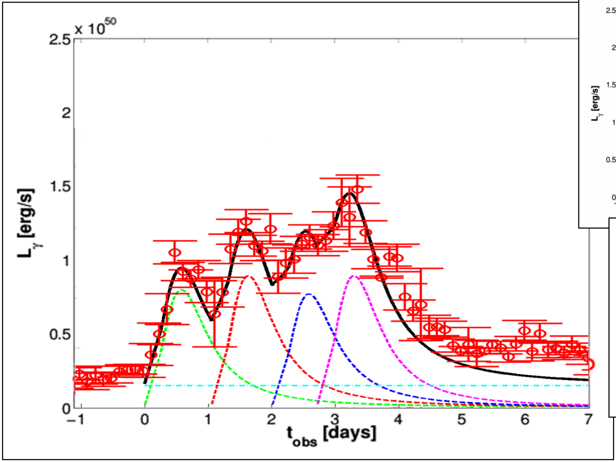
In the framework of JRGI scenario the magnetic field shielding allows to magnetic field remain low inside the blob (Barkov et al. 2012b).
$B_c \ll B_j$

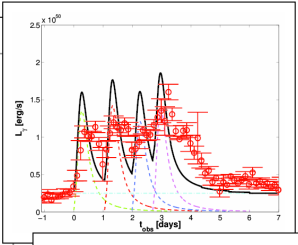
Radiation Model: Geometry

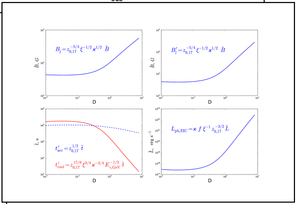




Radiation Model: Dynamical light curve + cooling time







Conclusions

- Jet-in Jet model and Cloud/Star-Jet model can explain VHE fast variability in AGNs and revile comparable limitations for the jet power. Cloud/Star-Jet scenario triggers Jet in Jet model?
- In the cases of VHE fast variability magnetospheric model do not work.
- The process can render suitable conditions for energy dissipation and proton acceleration, which could explain the detected day-scale TeV flares in 2010 from M87 via proton-proton collisions.
- In the case of 3C454.3 the radiation in the GeV energy range can be effectively produced through proton synchrotron radiation, Jitter or EIC in the Thompson regime.

Based on:

- MVB, F.A. Aharonian and V. Bosch-Ramon, (M87); ApJ (2010) 724, 1517
- MVB, F.A. Aharonian, S.V. Bogovalov, S.R. Kelner and D.V. Khangulyan, (PKS 2155−304); ApJ (2012) 749, 119
- V. Bosch-Ramon, M. Perucho and MVB, (M87); A&A (2012) 539, 69
- MVB, V. Bosch-Ramon and F.A. Aharonian, (M87); ApJ (2012) 755, 170
- D.V. Khangulyan, MVB, V. Bosch-Ramon, F.A. Aharonian and A. Dorodnitsyn, (3C454.3) ApJ (2013) 774, 113
- F.A. Aharonian, MVB, and D.V. Khangulyan, (IC 310) ApJ (2017) 841, 61
- M. Perucho, V. Bosch-Ramon and MVB, A&A (2017), v.606, id.A40, 14

Thank you!!!