Ultrafast VHE Gamma-Ray Flares of AGN

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Stanislav R. Kelner
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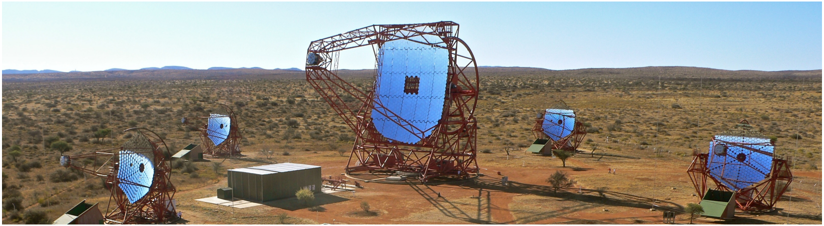
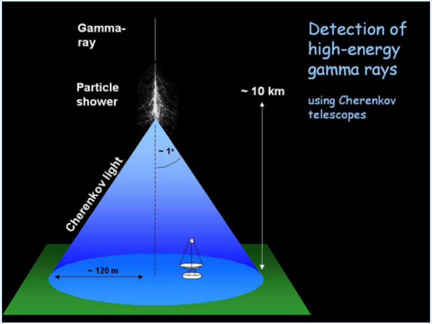
Manel Perucho

Outline



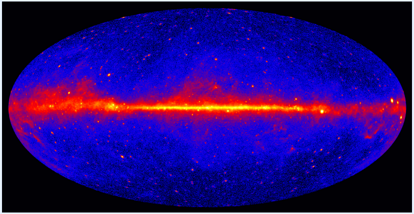
Cherenkov Technique



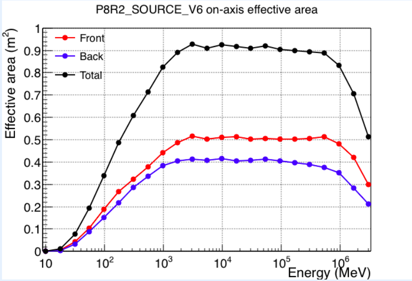
HESS Location

Fermi Gamma-Ray Space Telescope (NASA)

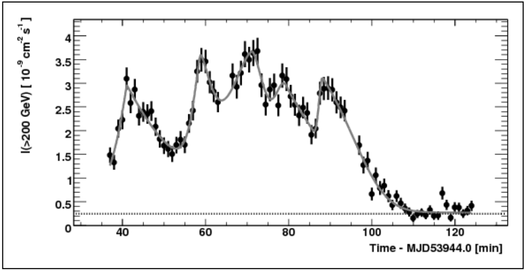
GeV Sky

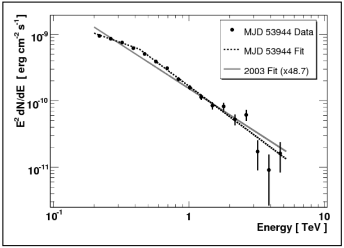


LAT collection area



PKS 2155–304 observations (the First)





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

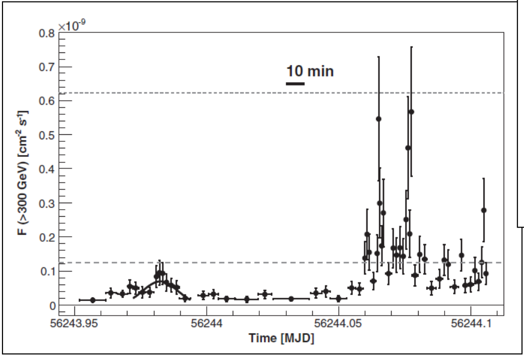
$$L_\gamma \approx 10^{47} \text{erg s}^{-1}$$

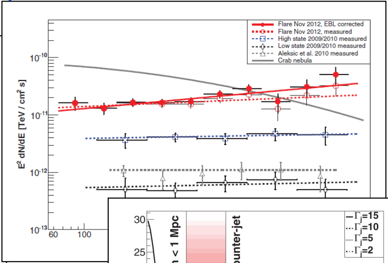
$$t_{\rm var} \approx 200\ \text{s} \sim 0.04 r_{\rm g}/c$$

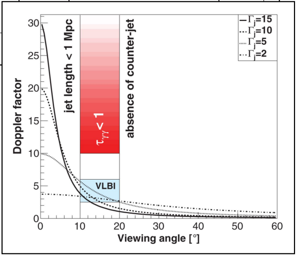
$$L_X \sim 10^{46} \text{erg s}^{-1}$$

(Aharonian et al 2007)

TeV Flare in IC310 (Misaligned)







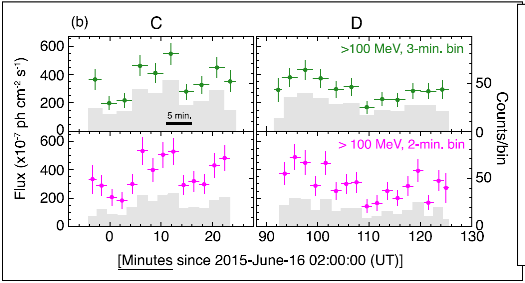
The observed parameters of the IC310 TeV flares (MAGIC data)

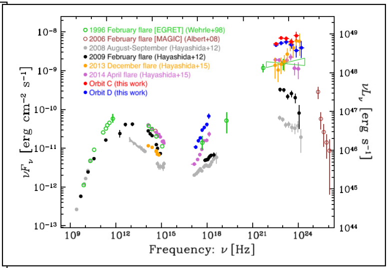
$$L_\gamma \approx 2 \times 10^{44} \mathrm{erg\ s}^{-1}$$

$$t_{\mathrm{var}} \approx 4.8\,\mathrm{min} \sim 0.2 r_{\mathrm{g}}/c$$

Aleksic et al (2014)

GeV Flare in 3C279 (Bright)





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

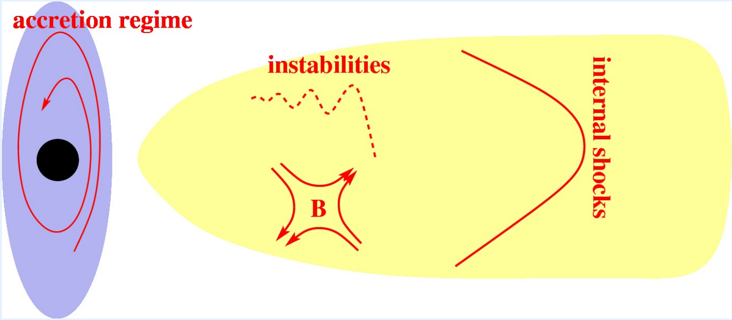
$$L_\gamma \approx 10^{49} \mathrm{erg\ s}^{-1}$$

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

Ackermann et al (2016)

Where is the source of the variability?

There are a lot of hypothetical sites



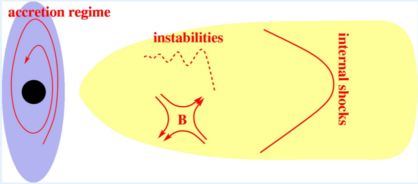
Internal Shocks, Magnetic Reconnection, Change in Accretion, Magnetospheric Gap, Instabilities....

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
  $\lambda \ll 1 \quad \Gamma_{\mathrm{emj}} \sim \Gamma_{\mathrm{j}} \sim 1$
- Relativistically Moving Blobs (jet-in-jet)
  $\lambda \sim 1 \quad \Gamma_{\mathrm{em}} \gg \Gamma_{\mathrm{j}} \gg 1$
- Cloud/Star in jet model
  $\lambda \ll 1 \quad \Gamma_{\mathrm{em}} \sim \Gamma_{\mathrm{j}} \gg 1$

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

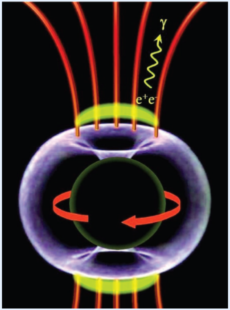
The Black Hole Magnetospheric Model

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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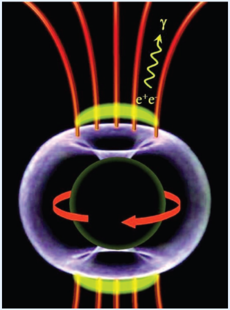

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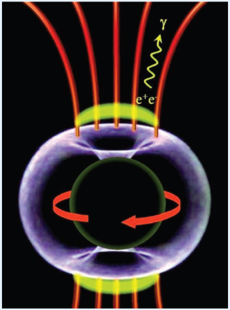

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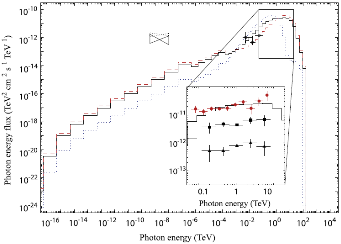
- $L_{\gamma,\rm IC310} \gg L_{\gamma,ms}$

Black Hole Magnetosphere

Aleksic et al (2014)

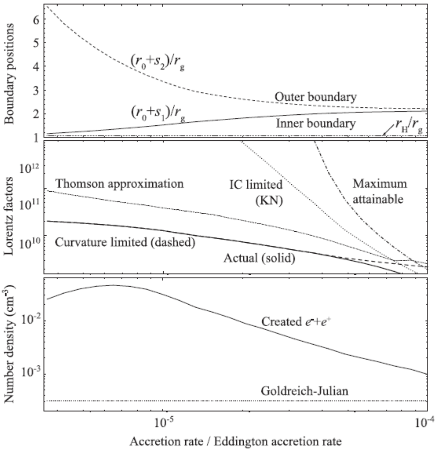
Black Hole Magnetospheric Model:



Payback for the model:

- The thickness of the Gap not consistent with the variability time.
- $B_{\mathrm{BH}} = 10^4$ G with $\dot{m} = 8 \times 10^{-6}$.
- The effectiveness of accretion >10 000 % !!!

Numerical gap properties:



Hirotani&Pu (2016)

Relativistically Moving Blobs (jet-in-jet)

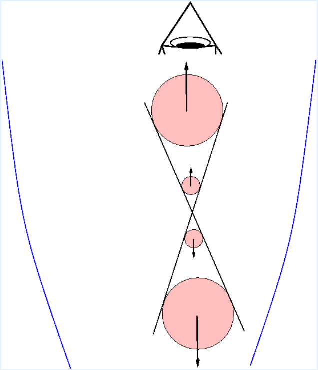
Relativistically Moving Blobs (jet-in-jet):

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: $\tilde{l}_{em} = c\Delta t\Gamma_{em}$, here $\Gamma_{em} = 2\Gamma_j\Gamma_{co}/(1+\alpha^2)$ and $\alpha = \theta\Gamma_j$
- $L_j = 1.4\times10^{-5} L_\gamma \left(\frac{1+\alpha^2}{4}\right)^6 \frac{r_2^2 M_8^2}{\Gamma_{co,1}^6 \Gamma_{j,1}^6 \xi_{-1} t_{var,5}^2}$.

idea from Giannios (2009,2009)

Lucky Jet-in-Jet



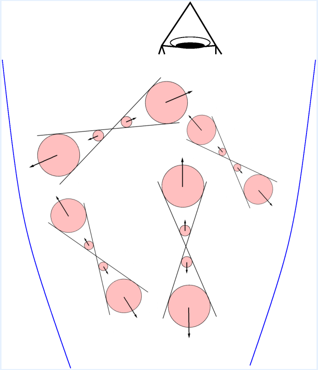
Relativistically Moving Blobs (jet-in-jet):

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 (2009,2009)

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

Cloud-Jet interaction (Numerical results)

Uniform cloud

(Bosch-Ramon et al 2012)

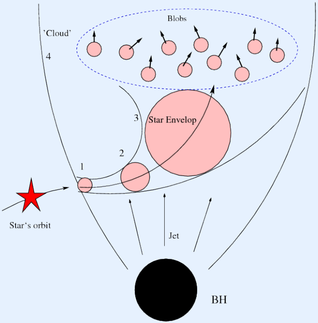
Cloud/Star in jet model:

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



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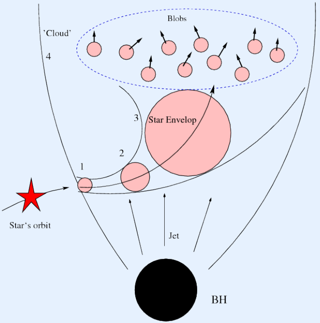


Summary

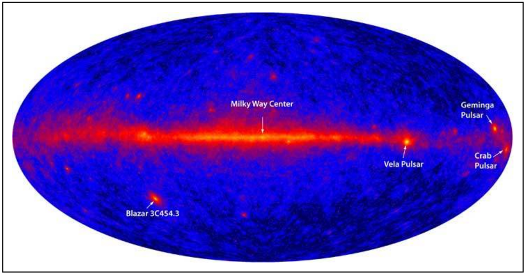
Comparison of models for different sources

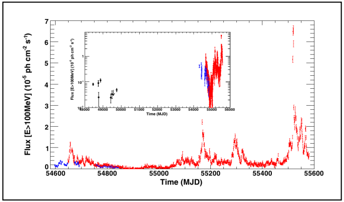
Source	IC 310	M87	3C454.3	3C 279	PKS 2155−304
$M_{\mathrm{BH},8}$	3	60	10	5	3
t_5	1	175	54	1	0.6
τ	0.2	2	3	0.1	0.04
L_γ, $\mathrm{erg/cm^2 s}$	2×10^{44}	10^{42}	2×10^{50}	10^{49}	10^{47}
Φ	0.1	0.3	0.7	0.3	0.7
Γ_{j}	10	10	20	20	20
Γ_{co}	10	10	10	10	10
α	2	2	0	0	0
$L_\gamma/L_{\gamma,ms}$	10	5×10^{-4}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

Table : Where $M_{\mathrm{BH},8} = M_{\mathrm{BH}}/10^8 M_\odot$ 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, $\alpha = \theta/\Gamma_{\mathrm{j}}$ is normalized viewing angle, $L_{\gamma,ms}$ is upper limit of γ-ray luminosity for magnetospheric model, $L_{\mathrm{j,jj}}$ is minimal jet power for jet-in-jet model, $L_{\mathrm{j,cj}}$ is minimum jet power for cloud-jet model.

Fast variability in GeV blazars (3C454.3)

3C454.3 observations





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

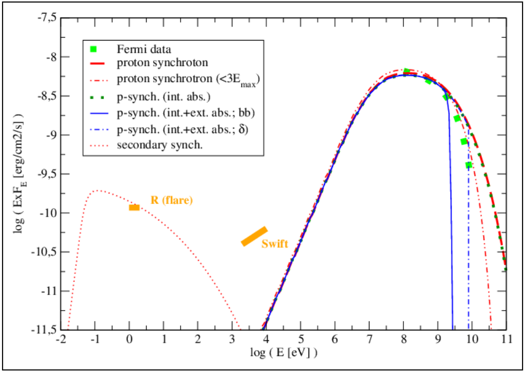
$$L_\gamma \approx 2 \times 10^{50} \mathrm{erg\,s}^{-1}$$

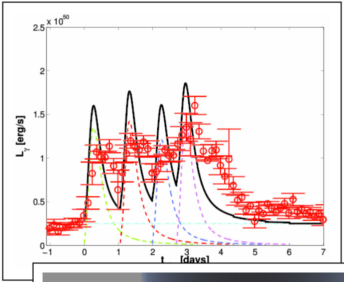
$$\tau_{\mathrm{r}} \approx 4.5\,\mathrm{h}$$

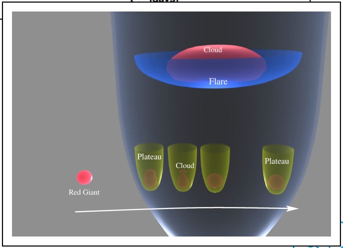
$$L_X \sim 5 \times 10^{47} \mathrm{erg\,s}^{-1}$$

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

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



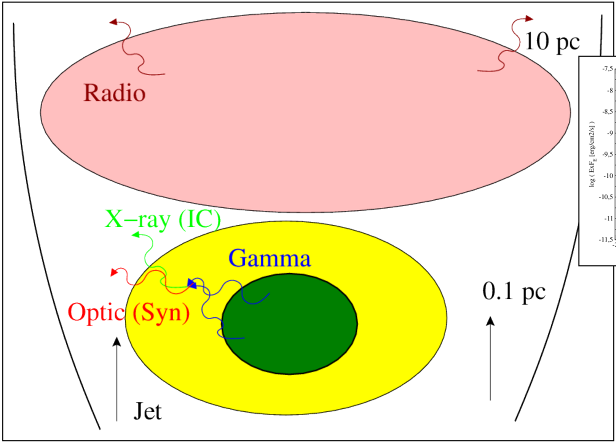


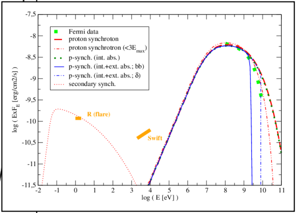


$$t_{acc}/(2\Gamma_b^2) \approx 5 \text{ h.}$$

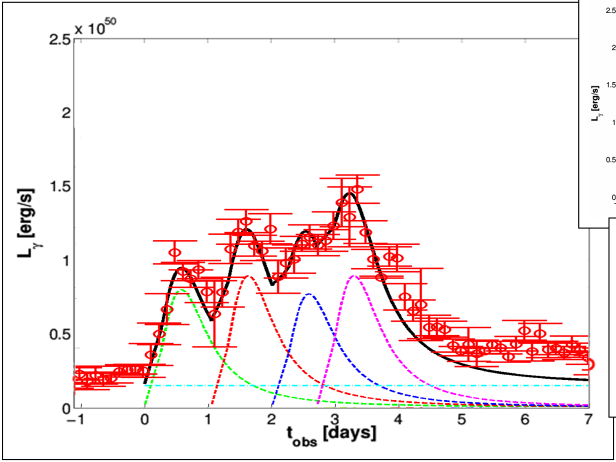
Khangulyan et al (2013)

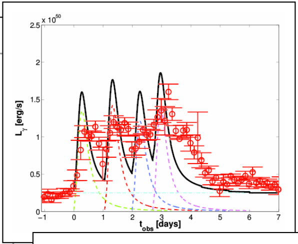
Radiation Model: Geometry

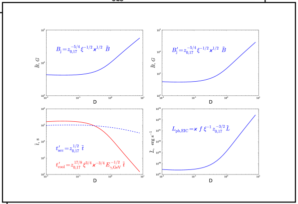




Radiation Model: Dynamical light curve + cooling time







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.
- 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

Thank you!!!

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:

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

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 $\bar{\rho} = 10^6 M_{\odot}\text{pc}^{-3}$ and $a = 1/2$ for $\bar{\rho} = 10^8 M_{\odot}\text{pc}^{-3}$

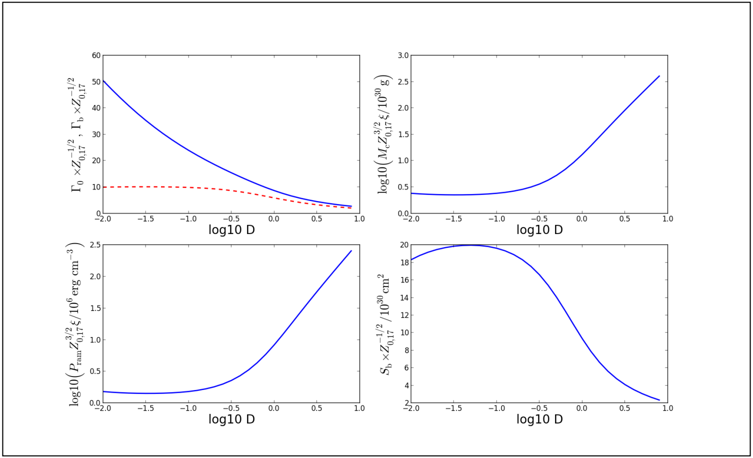
Mass injection appears to depend very weakly on a

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

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

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

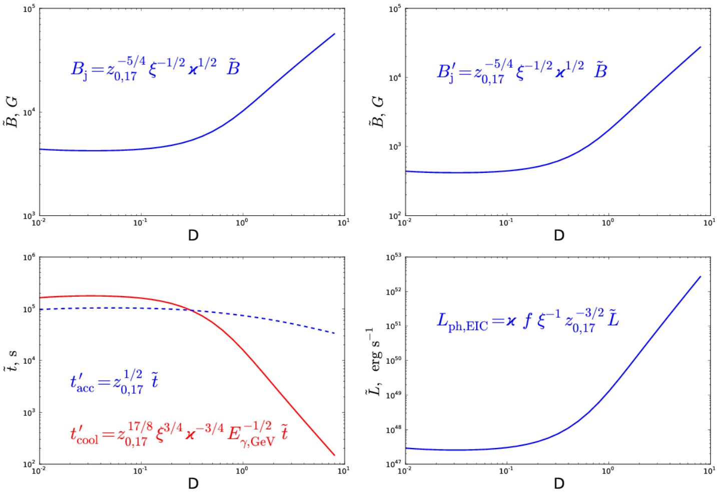
The Model Solution for the Main Flare



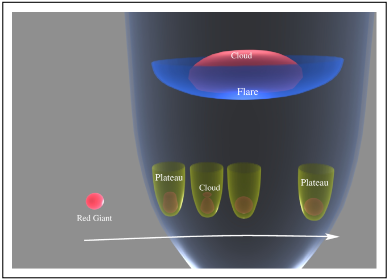
$$D \equiv \frac{L_j r_c^2}{4\theta^2 \Gamma_j^3 z_0 c^3 M_c} \qquad L_j \geq 10^{48} \quad \mathrm{erg\ s}^{-1}$$

$$M_{BH} \approx 10^9 M_\odot \qquad \delta_b \approx 20$$

Radiation Model: limitations



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

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