ORPHAN GAMMA-RAY FLARES FROM RELATIVISTIC BLOBS COMPTONIZING RADIATION OF LUMINOUS STARS IN JETS OF AGNs

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Stellar clusters around SMBHs in AGNs

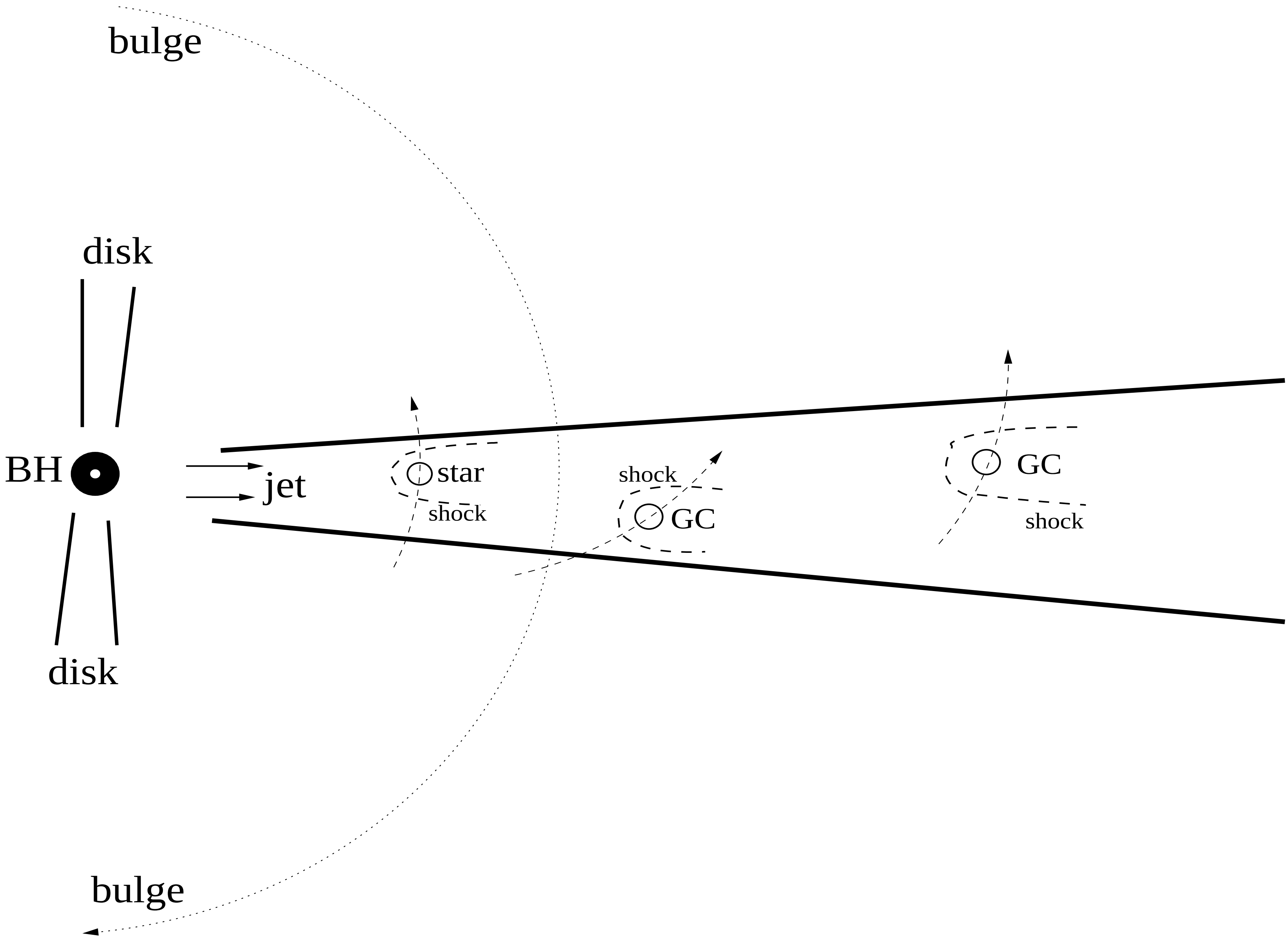
The example of nearby radio galaxy: Centaurs A

- Galactic Bulge: stars in the jet $\sim 8 \times 10^8$ (Wykes et al. 2014),
  if 10^{-3} of them Red Giants $\approx 10^6$ Red Giants within the jet.
- Nuclear stellar cluster: $(6 - 12) \times 10^7\ M_\odot$ in young stars (Wykes et al. 2014),
  ~ 100 massive (O and WR type) stars within the jet.
- Globular clusters:
  $\sim$1550 GC around Cen A (Gültekin et al. 2009),
  $\sim$13000 GC around M87 (McLaughlin et al. 1994),

$$\Downarrow$$

a few to several GCs within a jet

Collision scenario: a star (stellar cluster) within the jet



Collisions of compact objects with the jet plasma in AGNs

High energy radiation models

- Collision of jet plasma with massive star wind (scenario I)

  e.g. Bednarek & Protheroe (1997), Araudo et al. (2013), Bosch-Ramon (2015), de la Cita et al. (2016), ...

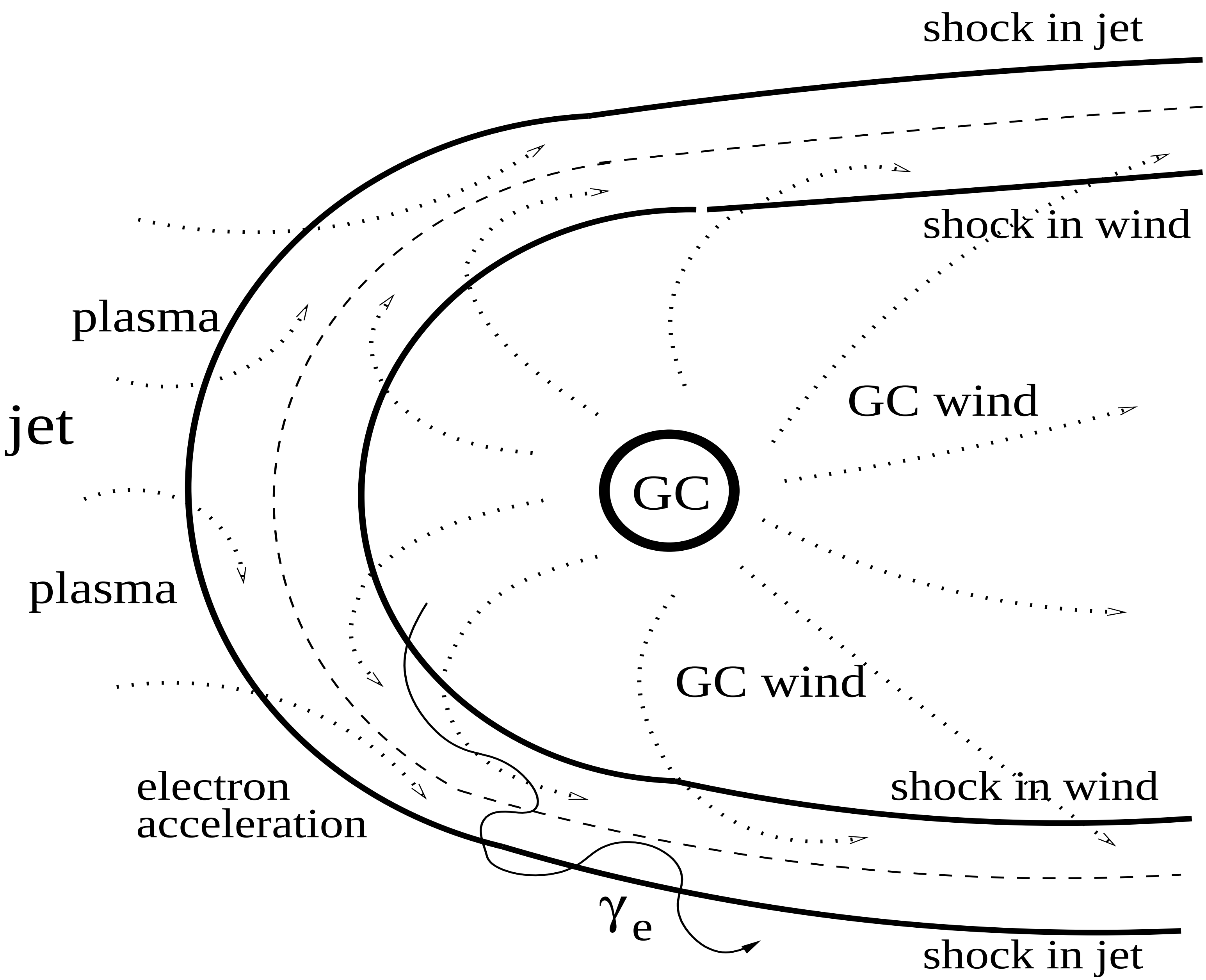
- Collision of jet plasma directly with stellar surface - disruption of star (scenario II) e.g. Barkov et al. (2010), Bosch-Ramon et al. (2012), ...

- Collisions of jet plasma with clouds of matter
  (and also globular clusters, supernova remnants, ... ?)

  e.g. Dar & Laor (1997), Beall & Bednarek (1999), Torres & Reimer (2011), Bednarek & Banasiński (2015, GC), ...

- Interaction of relativistic blob of particles in the jet with stellar radiation (scenario III) (Banasiński, Bednarek, Sitarek 2016)

Collision of jet plasma with massive star wind



Shock localization - different scenarios

- Distance of the shock from stellar surface (Bednarek & Protheroe 1997):

$$R^{\star}_{\rm sh} \approx 6\times 10^{12}(M_{-5}v_3)^{1/2}\theta_{-1}l_{-1}/L^{1/2}_{46}\ {\rm cm},$$

where $\dot{M} = 10^{-5}M_{-5}M_{\odot}$ and $v = 10^3 v_3$ km s^{-1} are the mass loss rate and the velocity of the stellar wind, and $L_{\rm b} = 10^{46}L_{46}$ erg s^{-1} is the power of the blob in the observer's frame, $\theta = 0.1\theta_{-1}$ rad is the jet opening angle, and $l = 0.1 l_{-1}$ pc is the distance of the star from the base of the jet.

- If $R_{\rm sh} >> R_{\star}$: Shock around star accelerates particles (I)

  (strong stellar winds)

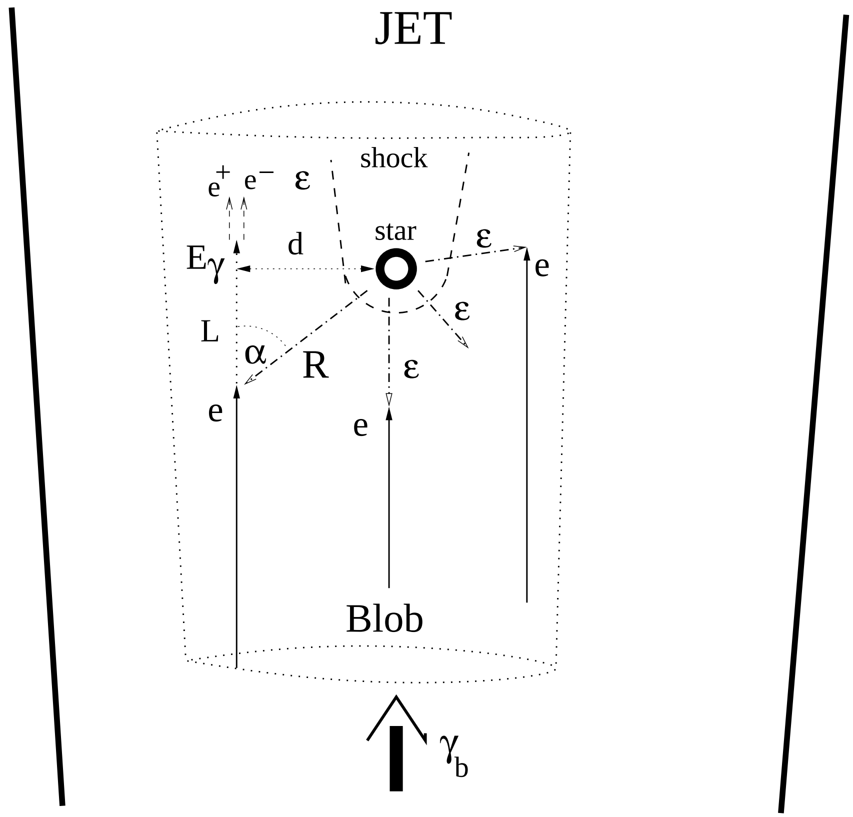
- If $R_{\rm sh} < R_{\star}$: Jet collides with the stellar surface (II)

  (powerful jets, close to the jet base)

- If $R_{\rm sh} >< R_{\star}$: Jet particles interact with stellar radiation (III)

  (moderate winds, everywhere in the jet)

A star colliding with the blob in jet of AGN (Banasiński et al. 2016):



- Relativistic electrons in the blob, moving with the Lorentz factor $\gamma_{\rm b}$, suffer strong energy losses on comptonization of radiation coming from a single star.
- Electrons are injected isotropically into the blob with a power law spectrum to TeV energies.
- Electrons scatter stellar radiation to γ-rays.
- γ-ray photons initiate IC $e^{\pm}$ pair cascade.
- γ-ray spectrum from IC $e^{\pm}$ pair cascade is calculated.

Optical depths for gamma-rays and electrons in stellar radiation

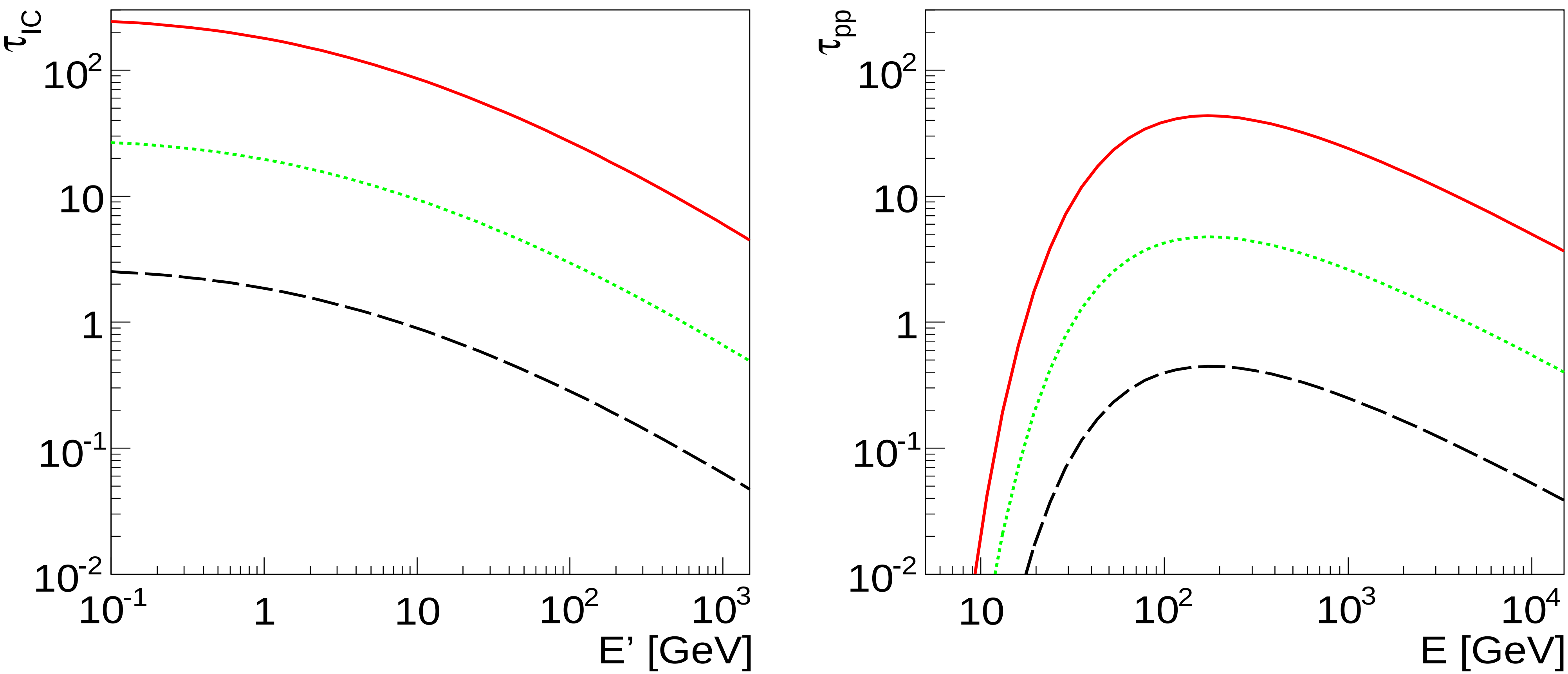


Figure 1: Optical depth for the inverse Compton scattering of the stellar radiation (O type star: $T = 3 \times 10^4$ K, $R = 10^{12}$ cm) by electrons in the blob (on the left) and for absorption of produced γ-rays in this stellar radiation (on the right) as the function of the energy (measured in the reference frame of the blob with $\gamma_b = 10$ for the electrons and in the reference frame of the star for the γ-rays). The impact distance, d, is equal to $1.1\,R_\star$ (red, solid lines), $10\,R_\star$ (green dotted) and $100\,R_\star$ (black dashed).

Gamma-ray spectra from star-blob encounter (specific impacts)

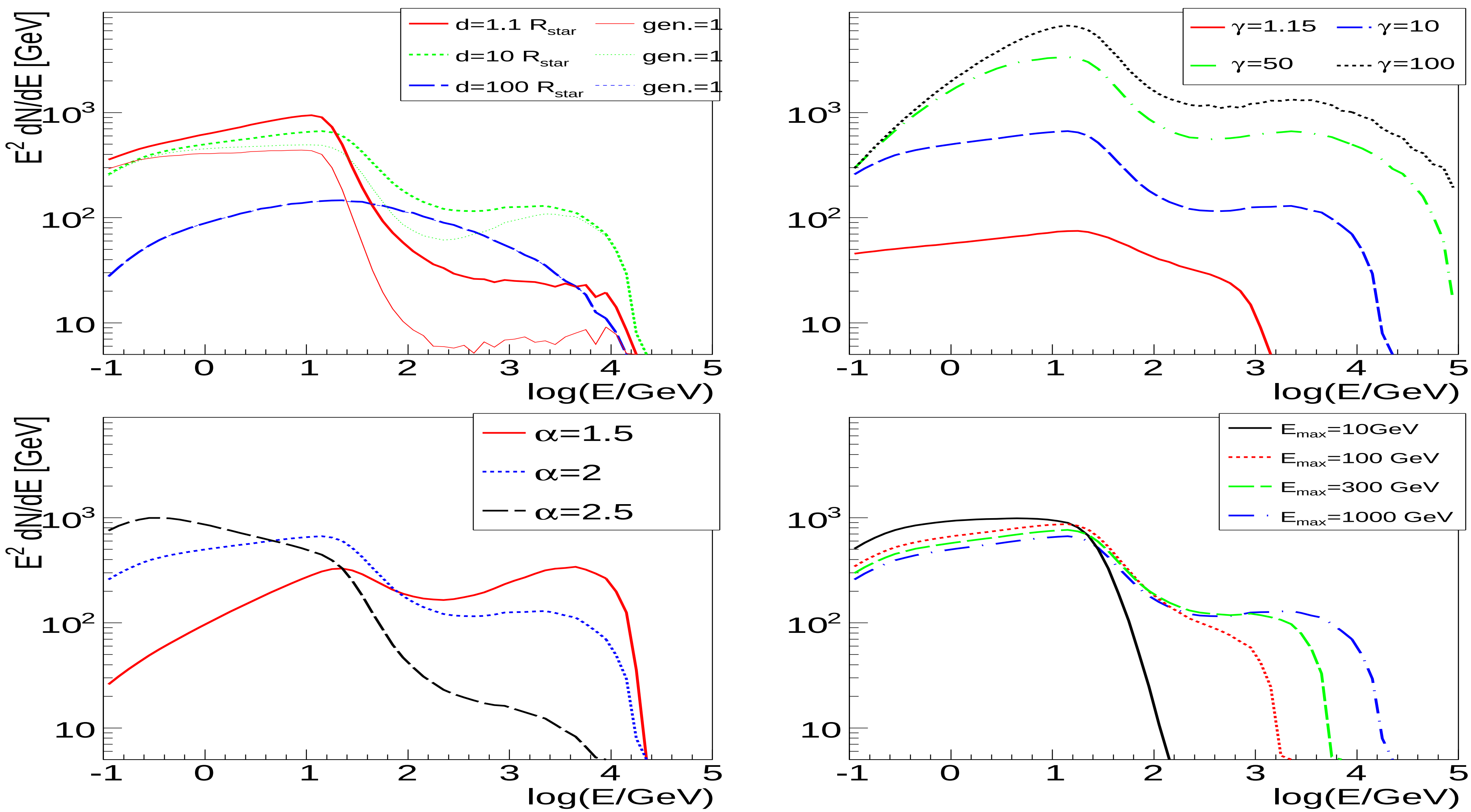


Figure 2: SED of the γ-ray spectrum for a power law differential spectrum of electrons with an spectral index of α between 0.1 GeV and $E'_{\rm max}$ for fixed impact distance of electrons. Top left panel: dependence on impact distance d, thick lines show the spectra from the full cascade, thin lines the spectra escaping from the first generation of photons. Top right panel: dependence on the Lorentz factor of the blob γ_b. Bottom left panel: dependence on the spectral index of electrons α. Bottom right panel: dependence on the maximum energy of the electrons (measured in the blob's frame): $E'_{\rm max}$. Unless specified otherwise $\gamma_b = 10$, $d = 10\,R_\star$, $\alpha = 2$, $E'_{\rm max} = 1\,$TeV. The spectra are normalised to 1 erg of injected electron energy in the blob's frame of reference.

Gamma-ray spectra from star-blob encounter (the whole blob)

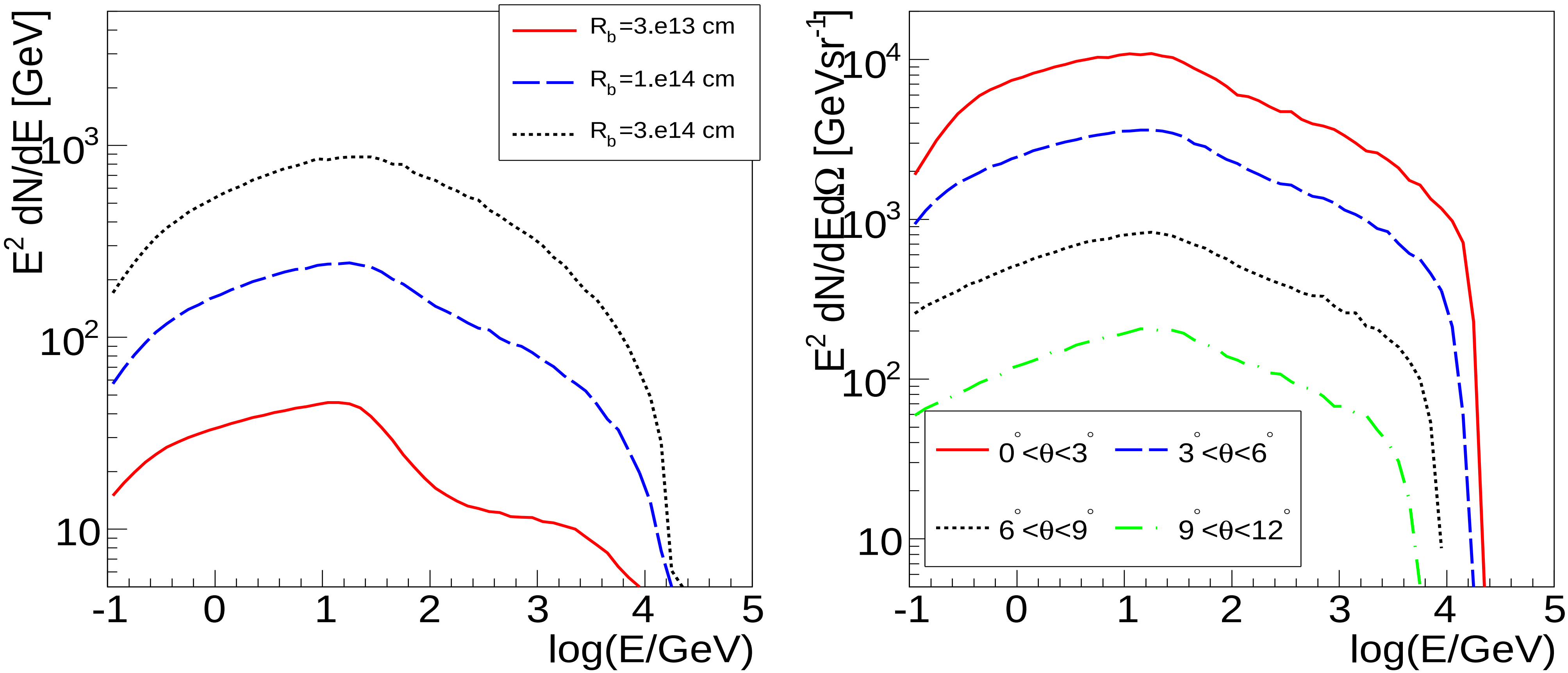


Figure 3: SED from a cylindrical blob filled homogeneously with electrons with a power law energy distribution between 0.1 and 1000 GeV and a spectral index of 2. The total energy in the electron spectrum is normalised to 1 erg per $\pi(10^{14}\,\mathrm{cm})^2$ cross section of the blob. The blob is moving with $\gamma_b = 10$. Left figure: γ-ray spectra for different radii of the blob: 3×10^{13} cm (red, solid), 10^{14} cm (blue, dashed), 3×10^{14} cm (black, dotted). Right figure: spectra emitted within the solid angle observed at different range of observation angles $0° - 3°$ (red solid), $3° - 6°$ (blue dashed), $6° - 9°$ (black dotted), $9° - 12°$ (green dot-dashed). The radius of the blob is equal to 10^{14} cm.

The extreme gamma-ray blazar PKS 1222+21

- FSRQ PKS 1222+21 at $z = 0.432$;
- Relativistic jet with superluminal motion ($\beta_{\rm app} > 10$) (Hooimeyer et al. 1992);
- Detected by *Fermi*-LAT with the flat spectrum (-2) below a few GeV Tanaka et al. 2011, Ackermann et al. 2014);
- Short flare, with rapid variability (∼10 min), between 70-400 GeV (index -3.75), observed by MAGIC (Aleksić et al. 2011);
- Isotropic GeV power: $L_\gamma \approx 7 \times 10^{47}$ erg s^{-1};
- Black hole mass: $(6-8) \times 10^8$ $M_\odot$ (Farina et al. 2012);
- Low energy emission does not change significantly during γ-ray flare (Ackermann et al. 2014):

Orphan γ-ray flare ?

As an example, we interpret PKS 1222+21 in terms of our model:

Interpretation of the extreme blazar PKS 1222+21: spectrum

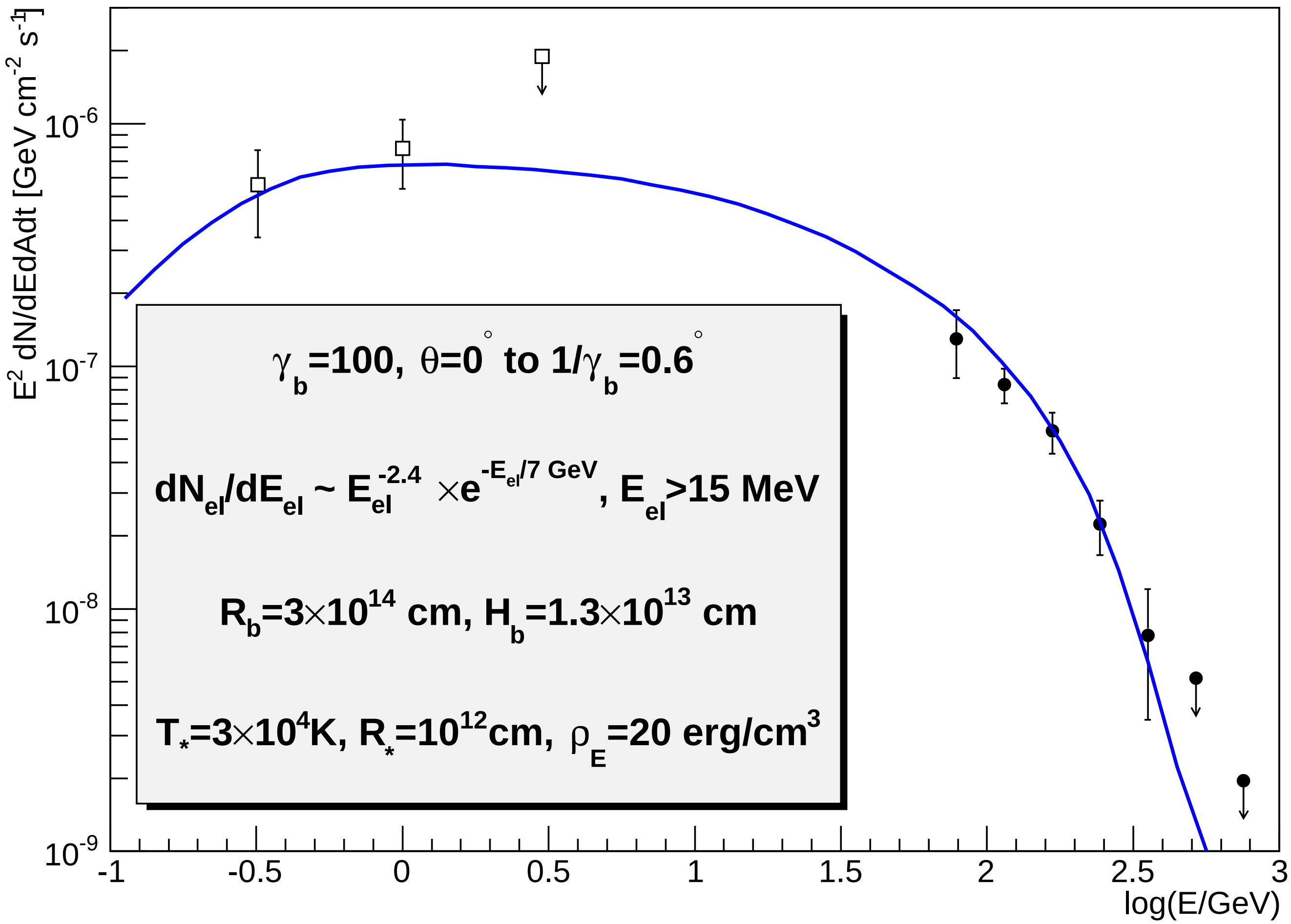


Figure 4: Interpretation of the γ-ray emission (SED) observed during the flare from the FSRQ PKS 1222+21 in June 2010 by *Fermi*-LAT (empty squares) and MAGIC (full circles). A blob has the radius $d = 3 \times 10^{14}$ cm and a Gaussian longitudinal spread with a standard deviation of $H_\mathrm{b} = 1.3 \times 10^{13}$ cm (the reference frame of the observer), and moves with $\gamma_\mathrm{b} = 100$ encountering the O type star ($T_\star = 3 \times 10^4$ K and $R_\star = 10^{12}$ cm). The electrons are injected with a power law spectrum (index -2.5 between 10 MeV and 10 GeV, total energy density of $\rho_E = 24\,\mathrm{erg\,cm^{-3}}$ (in the blob's frame of reference). The γ-ray emission is averaged over the observation angle $0 - 1/\gamma_\mathrm{b}$ rad. The absorption in the Extragalactic Background Light is taken into account according to Dominguez et al. (2011) model.

Interpretation of the extreme blazar PKS 1222+21: light curve

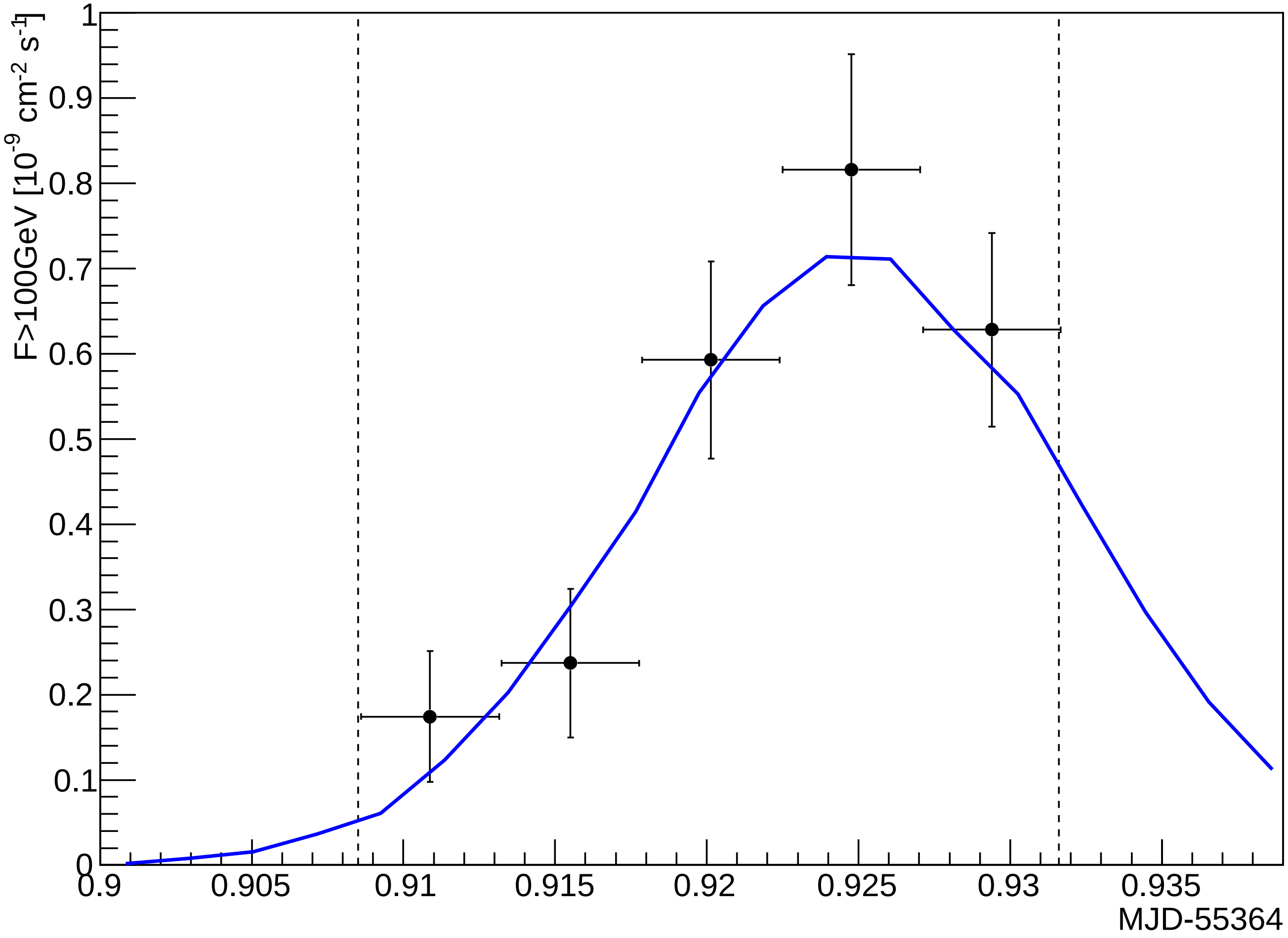


Figure 5: Interpretation of the γ-ray light curve during the flare above 100 GeV from PKS 1222+21 observed by MAGIC (Aleksić et al. 2011). The dashed vertical lines are the time range from which the SED is computed.

Discussion

- We test our model applicability to extreme FSRQ (PKS 1222+21):
- In order to fit the observations we require the following parameters:

  Cylindrical blob with radius $R_{\mathrm{b}} = 3 \times 10^{14}$ cm,

  Longitudinal distribution of electrons with hight $H_{\mathrm{b}} = 1.3 \times 10^{13}$ cm,

  The blob moves with the Lorentz factor $\gamma_{\mathrm{b}} = 100$,

  Relativistic electron energy density $\rho_{\mathrm{b}} = 20$ erg cm^{-3}.

- The power of the blob in the observer's frame:

$$L_\gamma = \pi R_{\mathrm{b}}^2 c \rho_{\mathrm{b}} \gamma_{\mathrm{b}}^2 \approx 1.7 \times 10^{45} \text{ erg s}^{-1};$$

- Eddington luminosity of the SMBH in PKS 1222+21 is:

$$L_{\mathrm{Edd}} = (8 - 10) \times 10^{46} \text{ erg s}^{-1};$$

- **$\sim$2% L_{Edd} in the blob seems not excluded in the inner jet.**