Detailed and Spatially Resolved Modelling of Blazar Emissions

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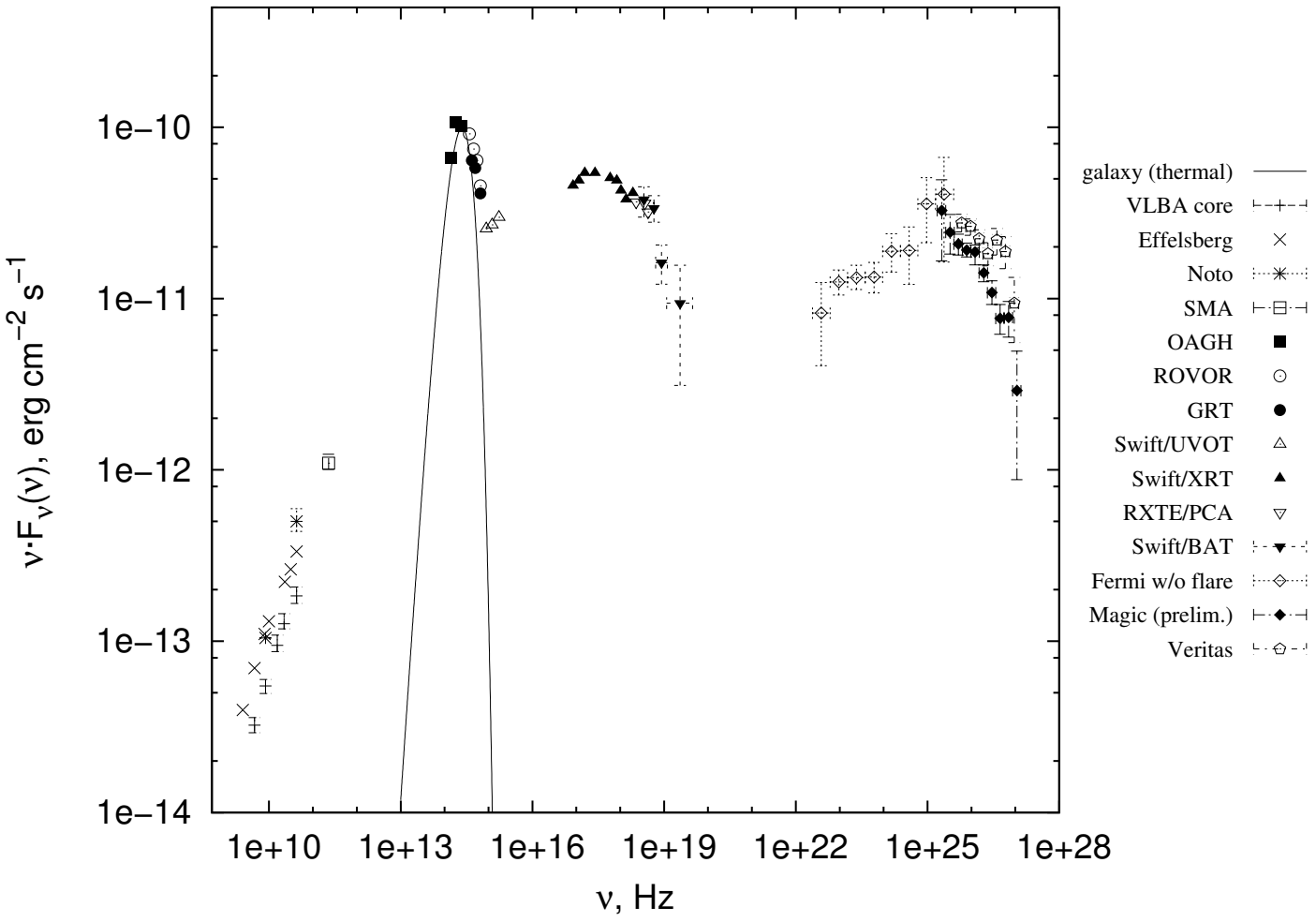
Outline

1. What we can do
   - Homogenous models
   - A self-consistent model
   - A spatially resolved model
   - SSC and photo hadronics
2. What we try to do
   - Variability and steady state
   - Distinguish leptonic and hadronic
   - More physics, less numerics
   - Understand the radio emission
3. What we can't do (yet)
   - Microphysics
   - VLBI - blob connection
   - Polarisation and EVPA

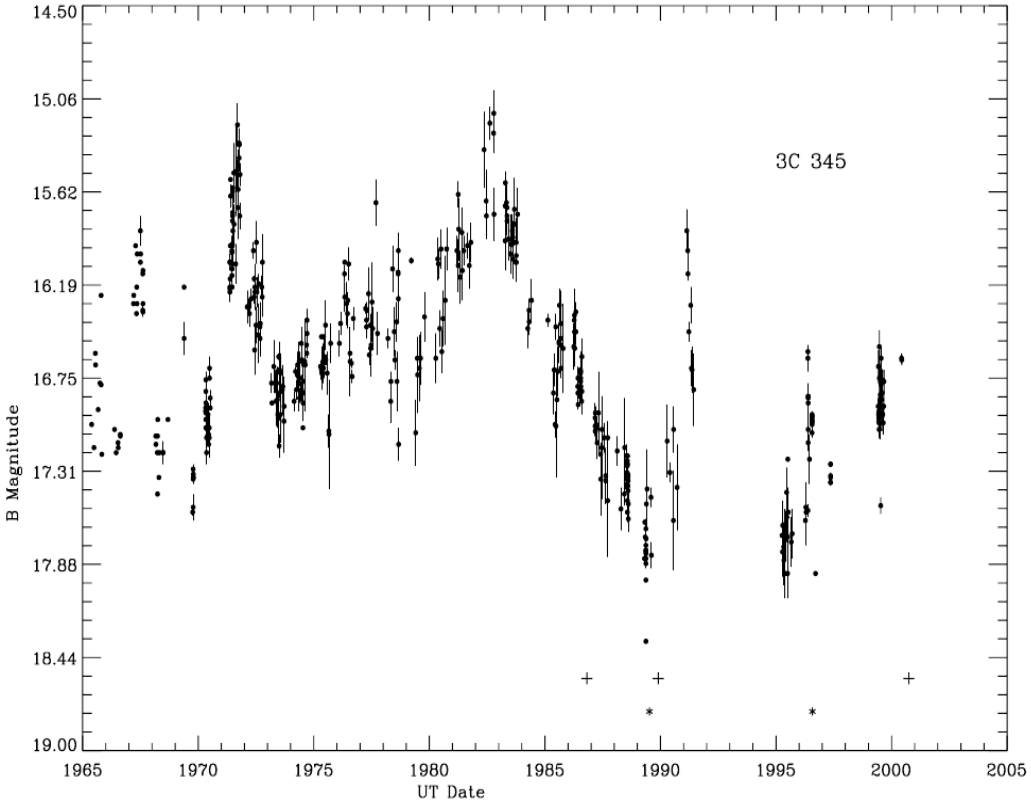
The objects in question

. . . show a wide, mostly featureless spectrum, from (self absorbed) radio frequencies, to the VHE γ-rays (example of *Markarian501*):



The objects in question

. . . show strong variability in most parts of the spectrum, from years to minutes



from Howard et al. (2004)

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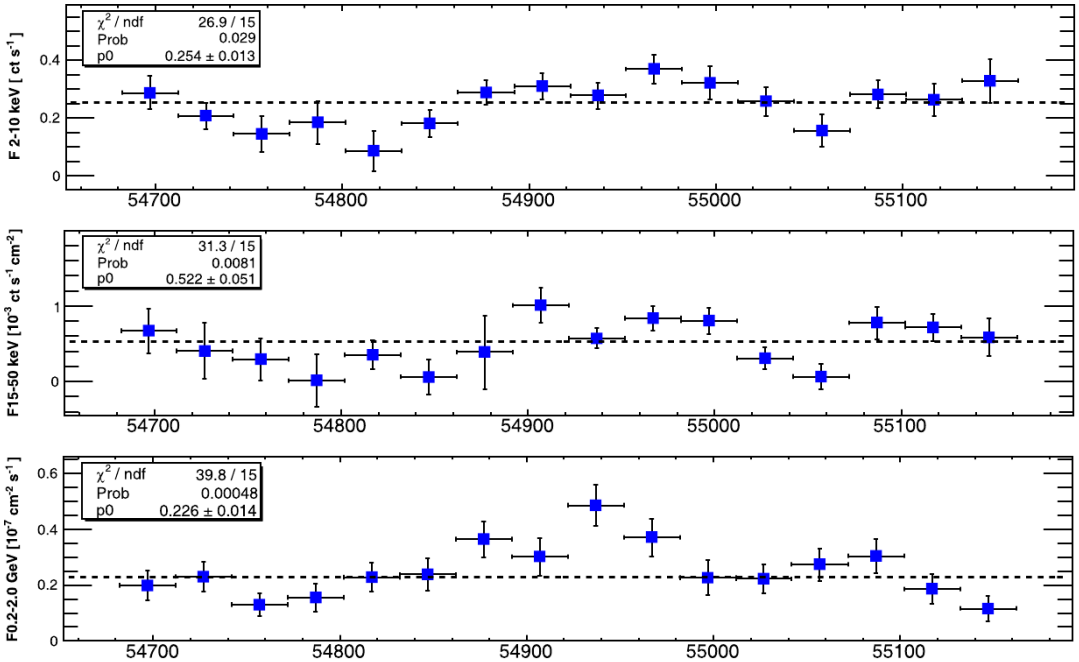

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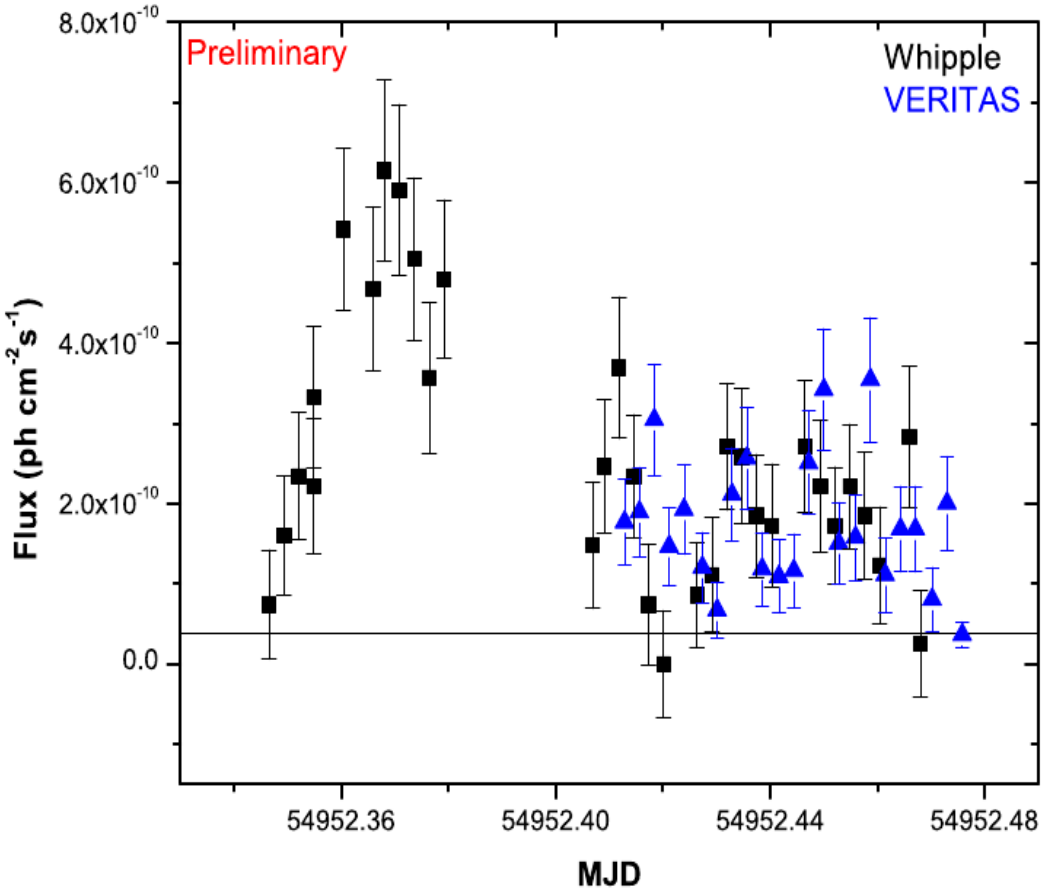
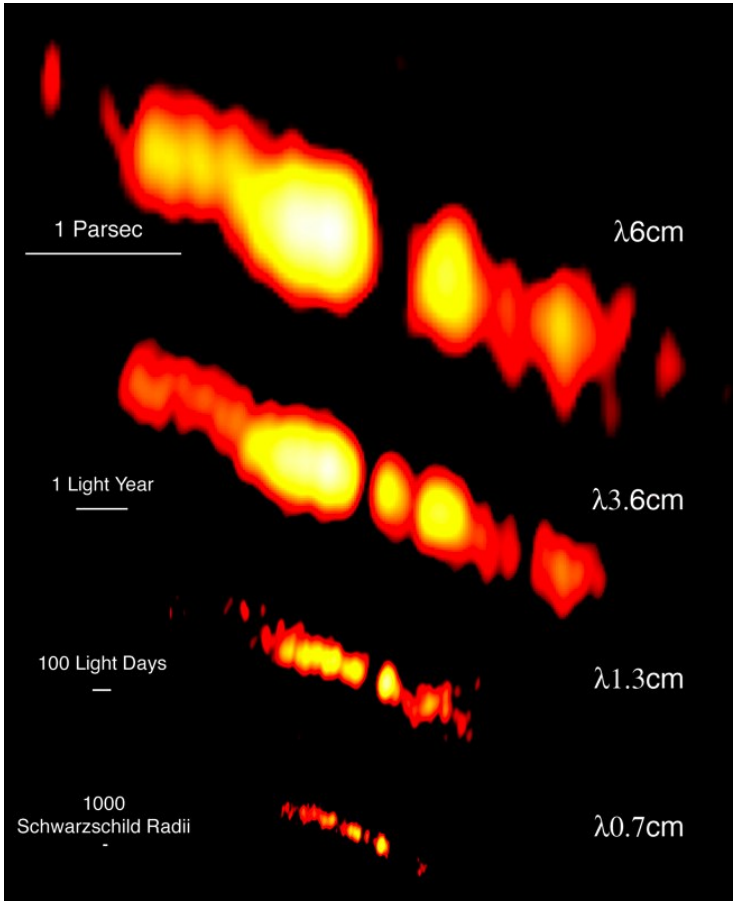


from Pichel and Paneque (2011)

The objects in question

. . . look like this (best picture we can get via VLBI):



VLBI image of the jet of NGC1052; M. Kadler, Universität Wuerzburg

What we can do

Homogenous, steady state, powerlaw SSC

properties

- homogenous, constant electron distribution $\Rightarrow$ photon distribution $\Rightarrow$ flux
- $n_{el}(\gamma)$ is some (multiple) broken powerlaw
- parameters are γ_{max},γ_{min},γ^i_{break},s^i
- physical parameters are R, B, δ, n_{el} – normalisation

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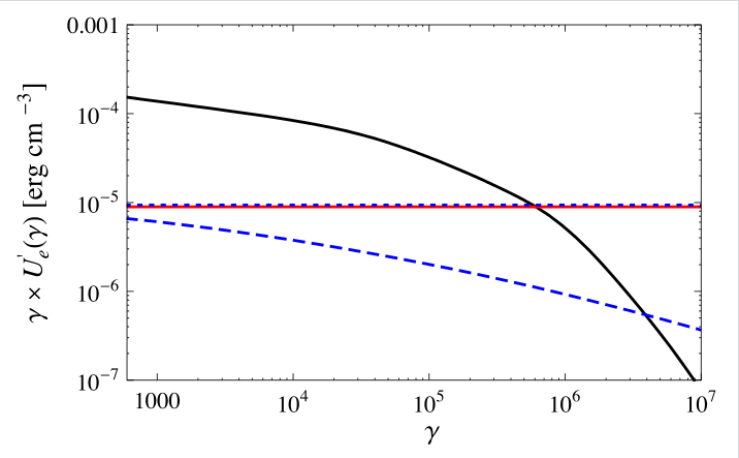
problems

- not time dependent
- physics of spectral indices, breaks, ...
- $\gamma_{max}(B, t_{acc})$, $s(t_{acc}, t_{esc})$, $\gamma_{break}(B, t_{esc})$, $B(B)$ $\Rightarrow$overdetermined



Homogenous, powerlaw SSC

- takes less than a second to compute $\Rightarrow$ do this often, get time variability
- BUT: what is the time evolution (and the physics behind it) from one electron distribution to the other?
- need for a model, that computes particle acceleration in a time dependent, selfconsistent way
- since lightcurves are usually available, one should try to explain any data with more advanced models

Homogenous, selfconsistent SSC

properties

- homogenous, time dependent electron distribution $\Rightarrow$ time dependent flux $\Rightarrow$ lightcurves
- $n_{el}(\gamma)$ evolves selfconsistently
- parameters are γ_{inject} - delta injection; physical parameters are $R, B, \delta, Q_{inject} = Q_0 \cdot \delta(\gamma - \gamma_0), t_{acc}$, Fermi-I to Fermi-II ratio

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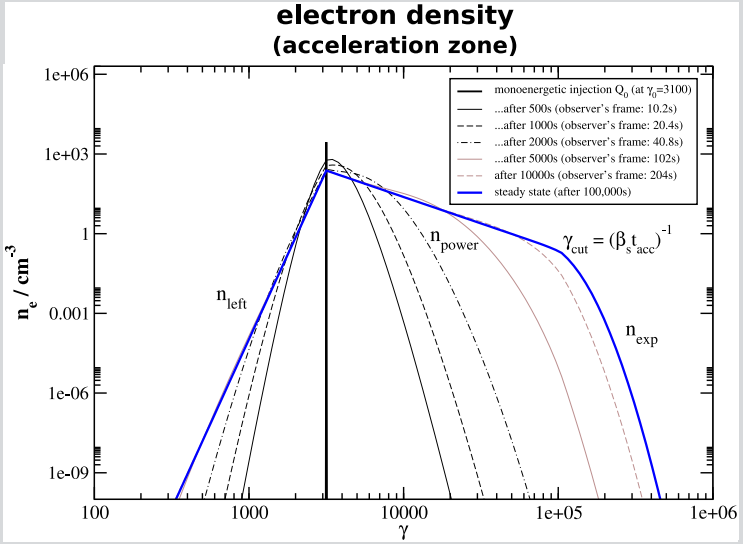
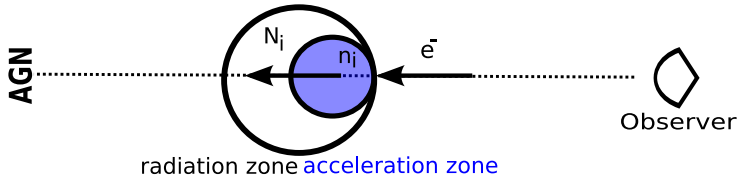
issues

- one gets lightcurves
- single run takes $\sim$ 5 minutes $\Rightarrow$ reasonable fit after one hour
- less parameters
- more physical parameters



COJONES - SSC part

Assume spherical emission and acceleration region containing isotropic particle distributions and randomly orientated magnetic field in a nested setup:



see Weidinger et al. 2010 for details

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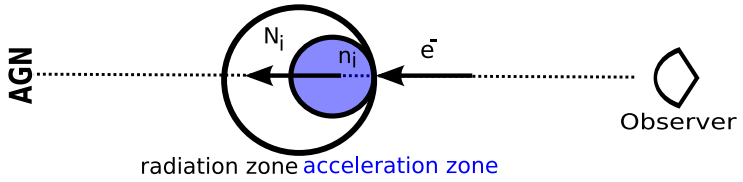

Kinetic equation: acceleration zone

$$\partial_t n_e = \partial_\gamma \left[(\beta_s \gamma^2 - t_{\mathrm{acc}}^{-1} \gamma) \cdot n_e \right] + \partial_\gamma \left[[(a+2) t_{\mathrm{acc}}]^{-1} \gamma^2 \partial_\gamma n_e \right] + Q_0 - t_{\mathrm{esc}}^{-1} n_e$$

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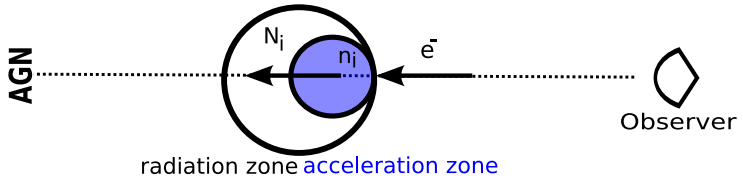

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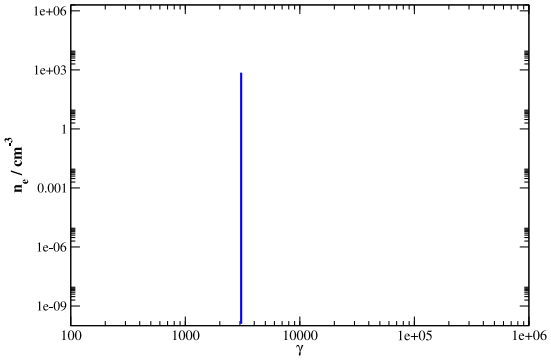

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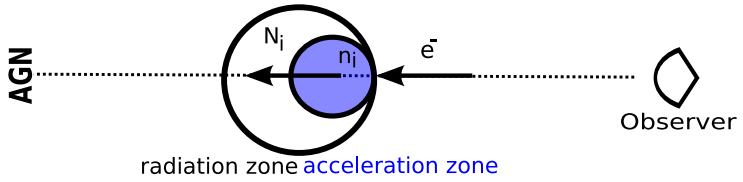

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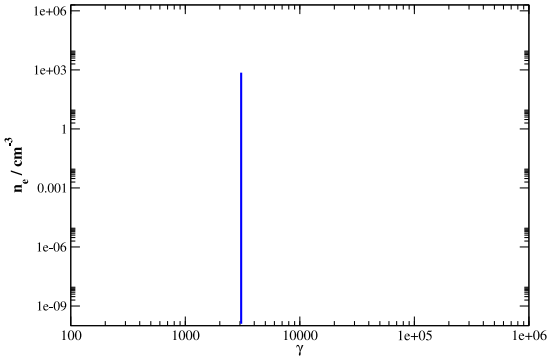

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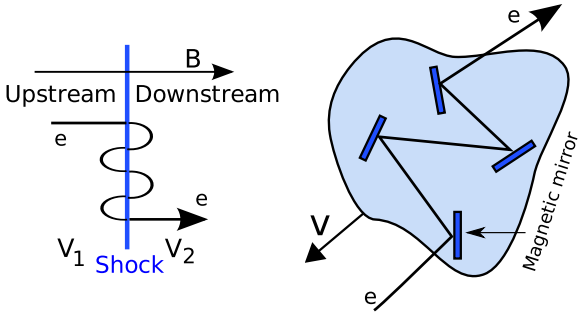

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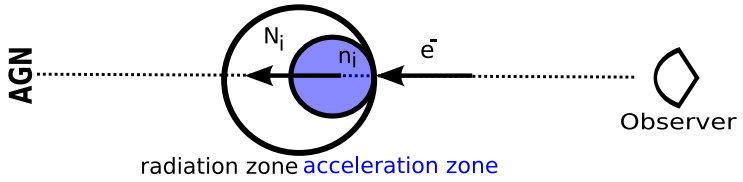

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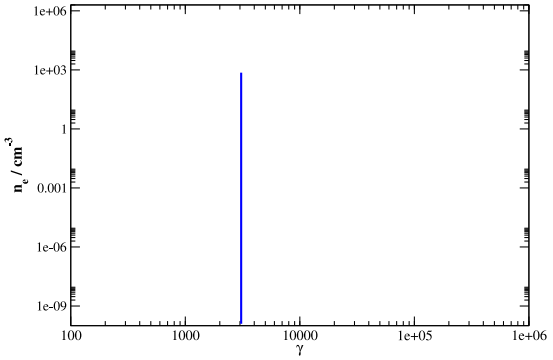

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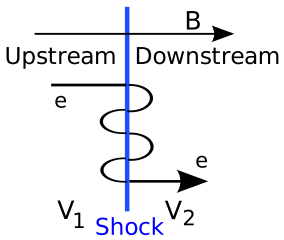

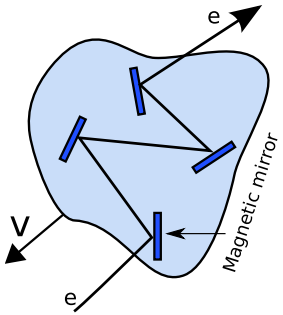

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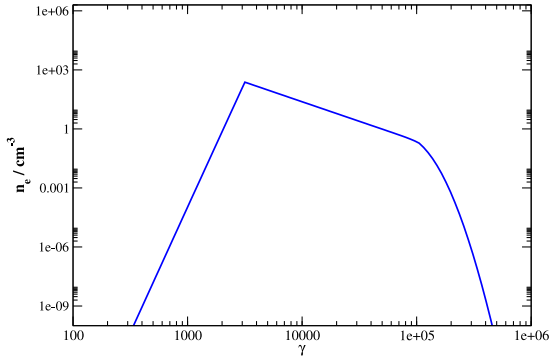

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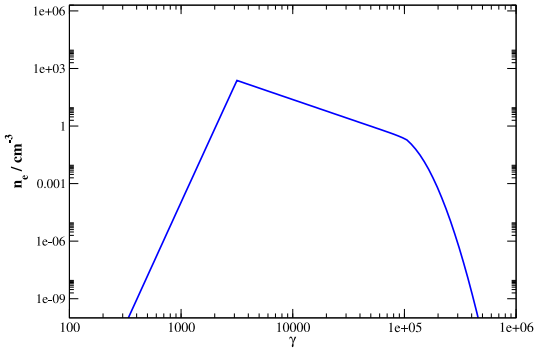

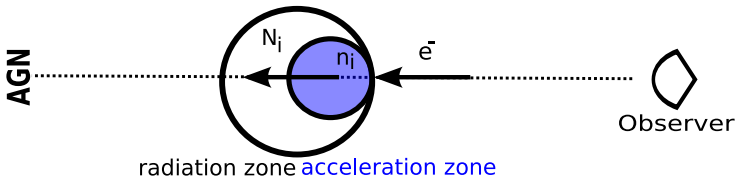

Kinetic equation: radiation zone

$$\partial_t N_e = \partial_\gamma \left[(\beta_s \gamma^2 + \dot{\gamma}_{\mathrm{IC}}) \cdot N_e \right] + t_{\mathrm{esc}}^{-1} n_e - t_{\mathrm{esc,N}}^{-1} N_e$$

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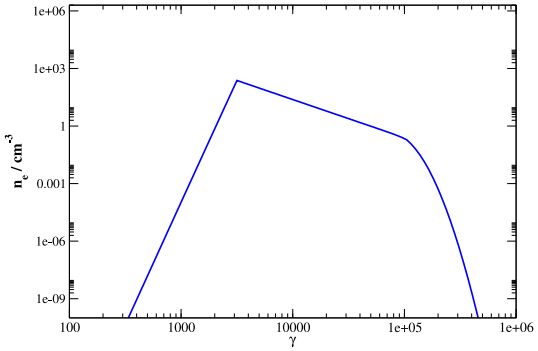

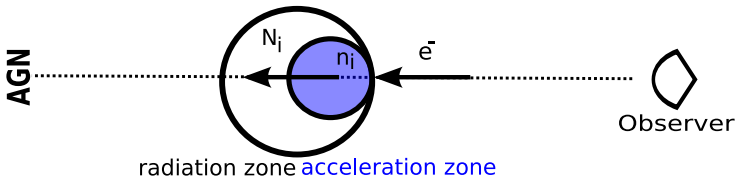

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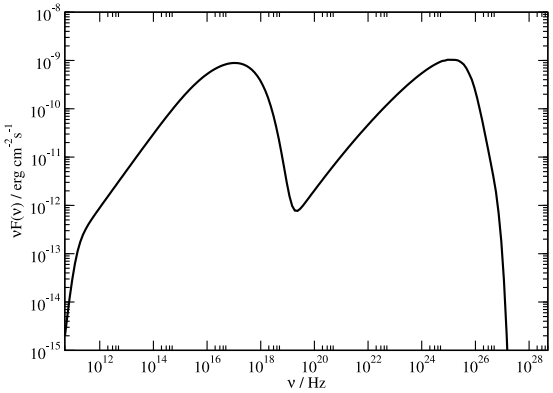
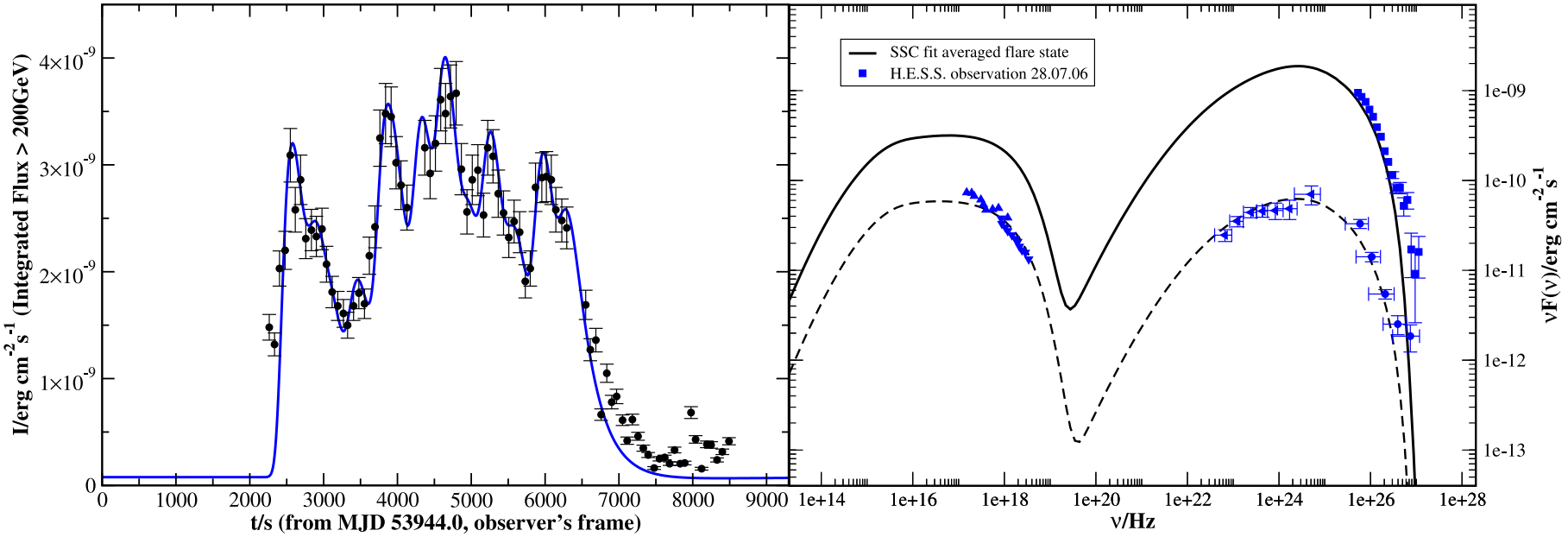
Photon distribution

$$\partial_t N_{\mathrm{ph}} = R_{\mathrm{syn}} + R_{\mathrm{IC}} - c\alpha_{\mathrm{SSA}} N_{\mathrm{ph}} - t_{\mathrm{esc,ph}}^{-1} N_{\mathrm{ph}}$$



Homogenous, selfconsistent SSC

- model flares due to changes in $Q_{inject}, B, t_{acc}, (\delta)$
- validate steady state fit with lightcurves

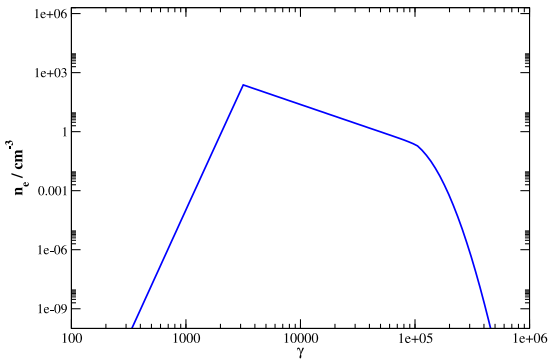


spatially resolved SSC

Motivation

- acceleration due to Fermi I happens at finite size shock
  $\Rightarrow \quad R_{acc} \ll R_{rad}$
- acceleration efficiency should depend on distance to shock
- for energies with $t_{cool} < lct$ the blob simply isn't homogenous
  - example values from Abdo et al. (2011):
    $B = 0.015\,\mathrm{G},\ R = 1.3 \cdot 10^{17}\,\mathrm{cm},\ \gamma_{max} = 1.5 \cdot 10^{7}$
  - $t_{cool} = 5.7 \cdot 10^{4}\,\mathrm{s} \ll t_{esc} = 4.3 \cdot 10^{6}\,\mathrm{s}$
- compute *multiple shock*-scenarios
- homogenous modells constrain time variability to $\Delta t > R_{rad}/c \Rightarrow$ inhomogenous models allow shorter timescales while preserving causality

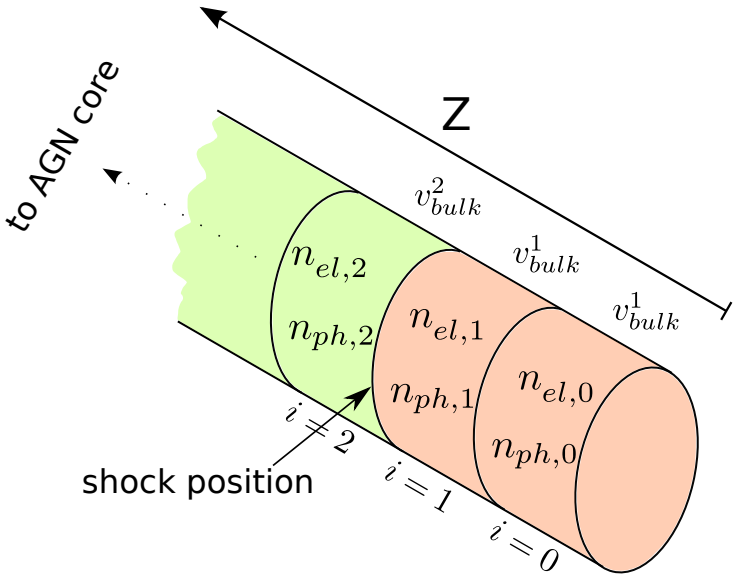
Unicorn



expand two-zone-model to N-zone-model

⇓ ⇓

move from nested to aligned setup



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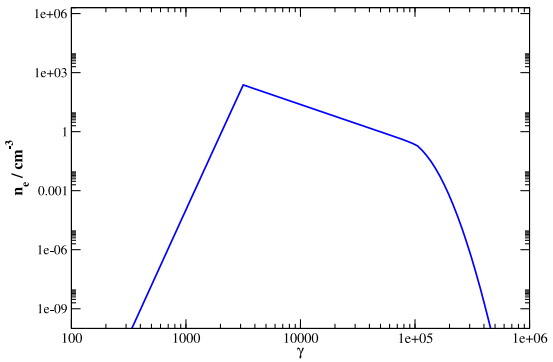

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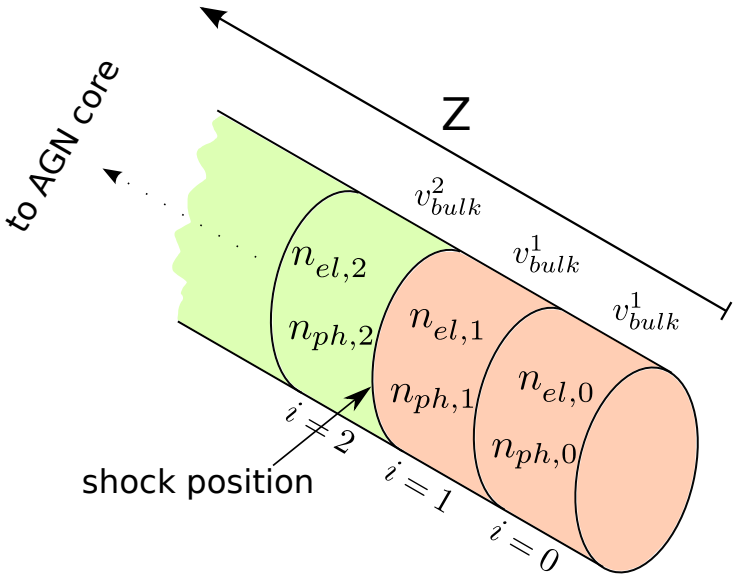
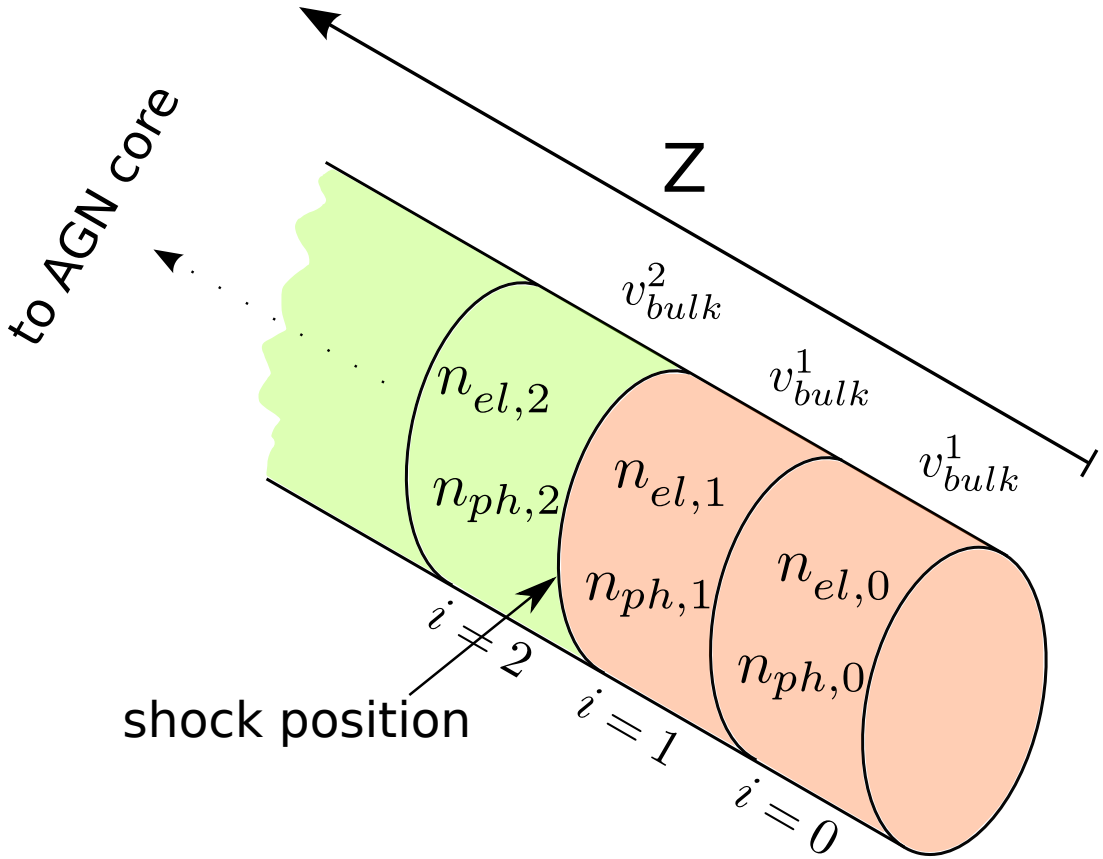


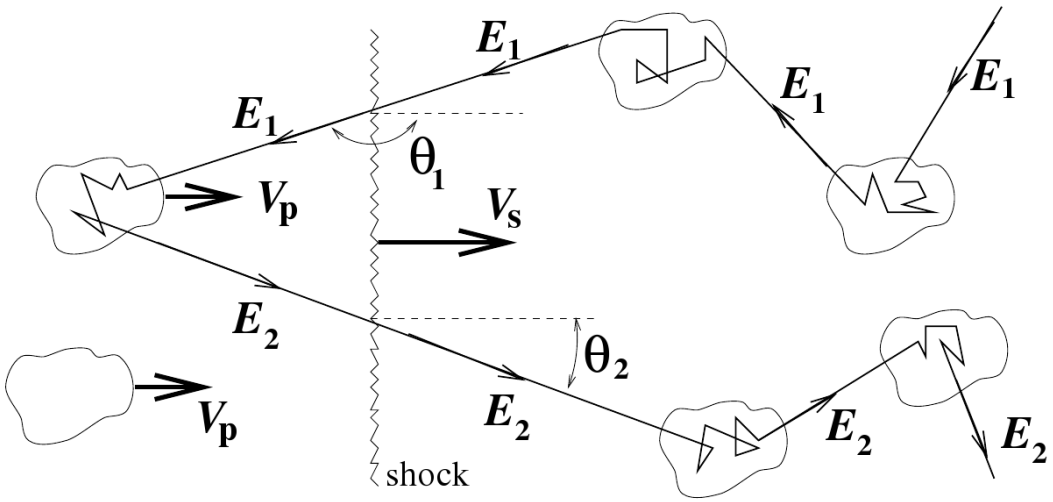
Not a multi
component model!

Unicorn - model geometry

- divide simulation region into N slices along the direction parallel to shock normal
- each slice has local bulk speed, electron density, photon density (, magnetic field, radius)

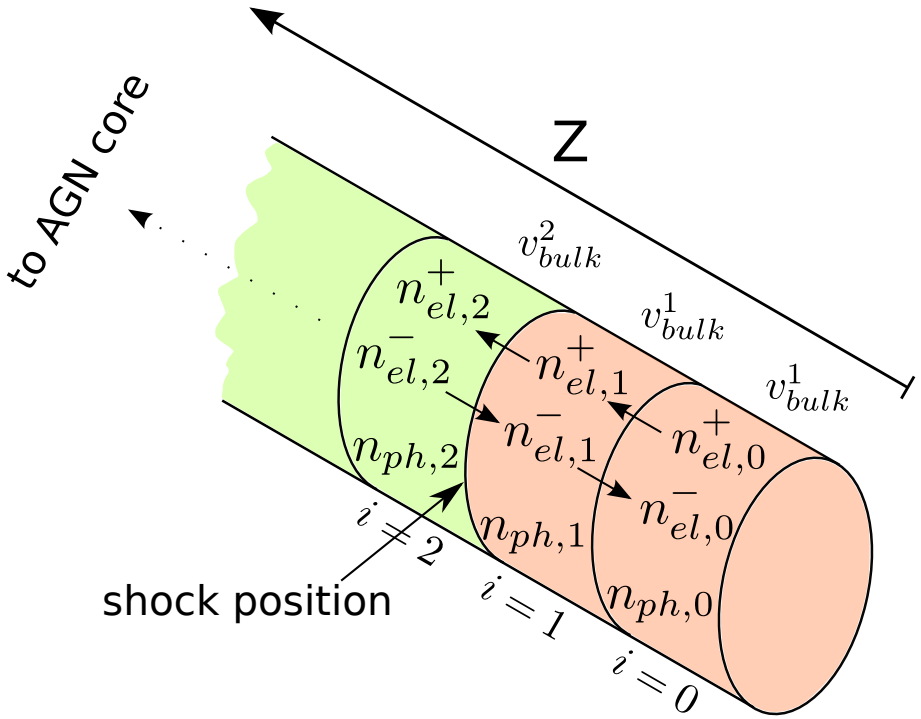


Unicorn - acceleration



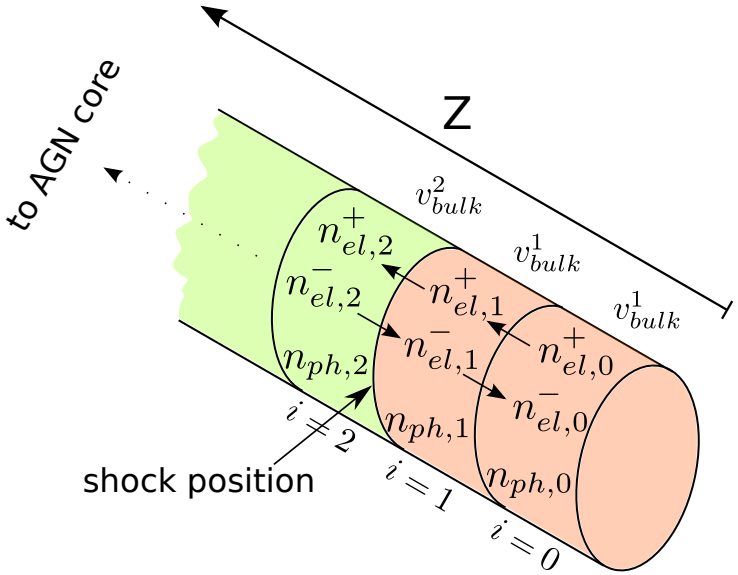
- multiple scattering on both sides of a shock
- scattering is elastic in plasma frame
- when particles cross the shock, the boost into the bulk frame distorts the isotropy of the target distribution
- hence head on collisions are more likely and acceleration becomes more efficient

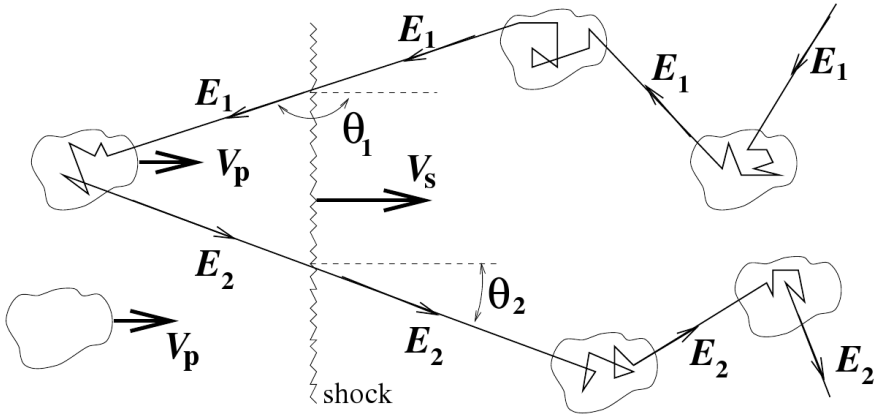
Unicorn - acceleration



- split electron population into two half spheres; one moving downstream (n^+), the other moving upstream (n^-)
- connecting the slices via advection of electrons between them
- shock is represented by jump in bulk velocity u between neighboured zones

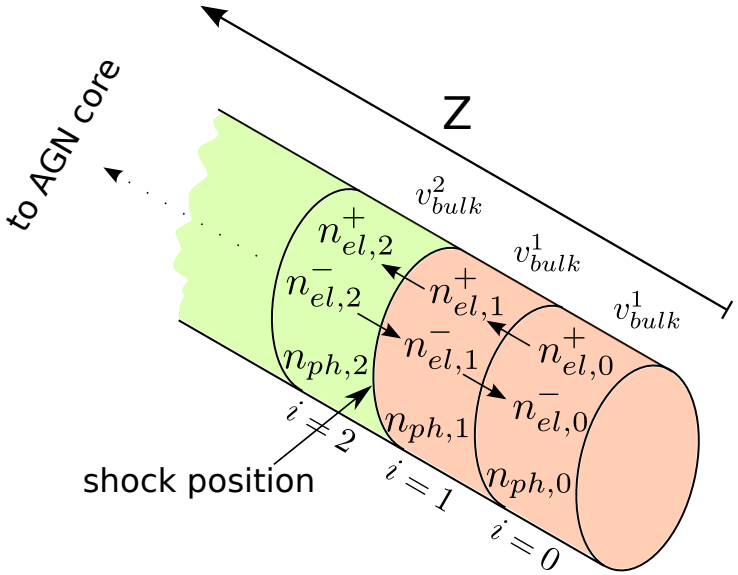
Unicorn - acceleration

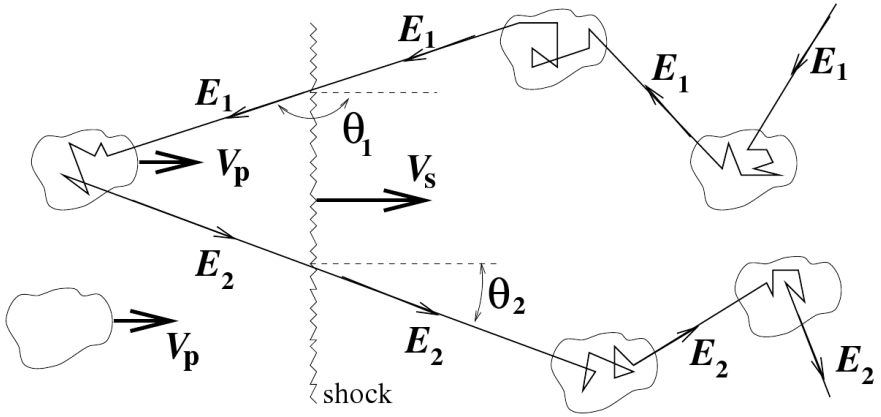




- in shock frame: $v^1_{bulk} = u_u = -V_S$, $v^2_{bulk} = u_d = V_P - V_S$, $R = \frac{u_u}{u_d}$
- relativistic treatment yields $V_P = \frac{V_S(R-1)}{R-V_S^2}$

Unicorn - acceleration





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- relativistic treatment yields $V_P = \frac{V_S(R-1)}{R-V_S^2}$
- scattering is controlled via the probability for an electron to change its propagation direction (including the boost into the new frame of reference)

Unicorn - acceleration

- stochastic acceleration independent of presence of shock
- repeated scattering of relativistic particles leads to acceleration second order in bulk velocity
- included in model as diffusion in momentum space

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kinetic equation including Fermi-II acceleration

$$\frac{\partial F}{\partial t} = \frac{1}{p^2}\frac{\partial}{\partial p}\left[p^2 \cdot \left(\langle \dot{p}_{FII} \rangle \frac{\partial F}{\partial p} + \dot{p}_{cool} \cdot F\right)\right] + S(\mathrm{x}, \mathrm{p}, t)$$

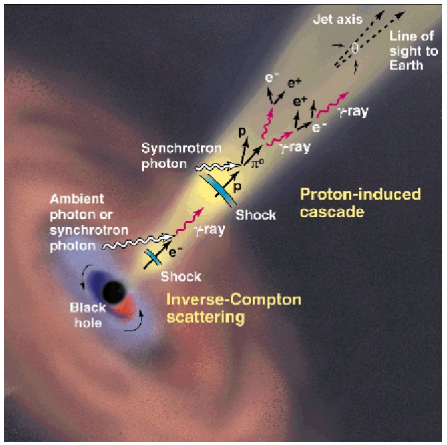
$$\text{with } \langle \dot{p}_{FII} \rangle = p^2 \frac{V_A^2}{9\kappa_{\|}} = p^2 D$$

V_A ... Alfvén velocity; $\kappa_{\|}$ ... parallel diffusion coefficient

COJONES - add photo hadronics

Photo-Meson production:

- $p + \gamma \rightarrow p + n_0\pi^0 + n_+\pi^+ + n_-\pi^-$
- $\pi^\pm \rightarrow \mu^\pm + \nu_\mu/\bar{\nu}_\mu$
- $\pi^0 \rightarrow \gamma + \gamma$
- $\mu^\pm \rightarrow e^\pm + \nu_e/\bar{\nu}_e + \bar{\nu}_\mu/\nu_\mu$



Resulting γ-radiation above $\approx 10^{28}$ Hz will be opaque to

$$\gamma + \gamma \rightarrow e^+ + e^-$$

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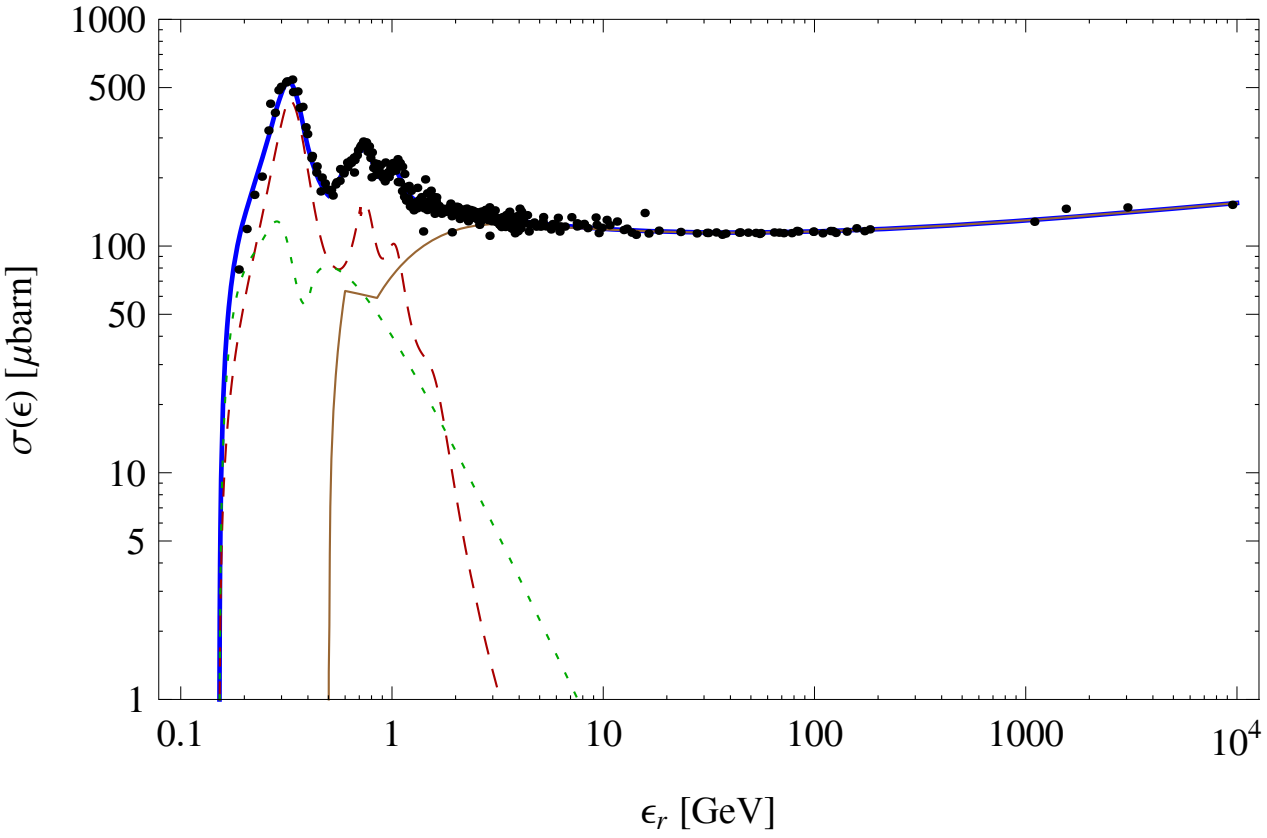

⇒ pair induced cascades and cascade radiation will emerge in jets with non-thermal p^+ present.

COJONES - add photo hadronics

Now there are 4 **non-linear coupled** equations in the radiation zone:

Kinetic equations: radiation zone

$$\partial_t N_{p^+} = \partial_\gamma \left[\beta_p \gamma^2 \cdot N_{p^+}\right] + b^3 t_{\mathrm{esc,p}}^{-1} n_{p^+} - t_{\mathrm{esc,p,N}}^{-1} N_{p^+}$$

$$\partial_t N_{e^-} = \partial_\gamma \left[(\beta_e \gamma^2 + \dot{\gamma}_{\mathrm{IC}}) \cdot N_{e^-}\right] + b^3 t_{\mathrm{esc,e}}^{-1} n_{e^-} + Q_{\mathrm{pp}} + Q_{\mathrm{p}\gamma^-} - t_{\mathrm{esc,e,N}}^{-1} N_{e^-}$$

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Photon distribution

$$\partial_t N_{\mathrm{ph}} = R_{\mathrm{syn}} + R_{\mathrm{IC}} + R_{\pi^0} - c\left(\alpha_{\mathrm{SSA}} + \alpha_{\mathrm{pp}}\right) N_{\mathrm{ph}} - t_{\mathrm{esc,ph}}^{-1} N_{\mathrm{ph}}$$

COJONES - add photo hadronics

Now there are 4 **non-linear coupled** equations in the radiation zone:

Kinetic equations: radiation zone

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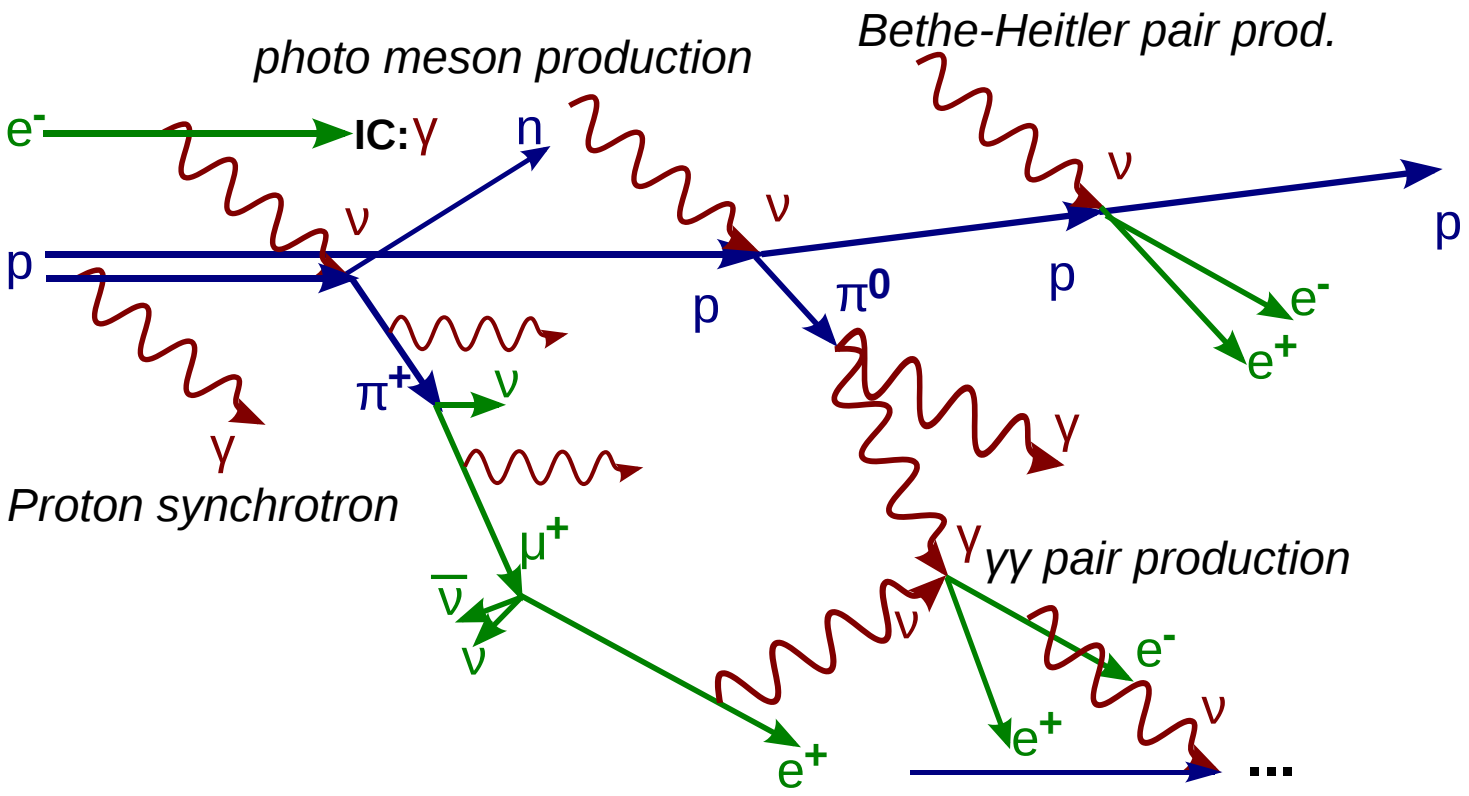
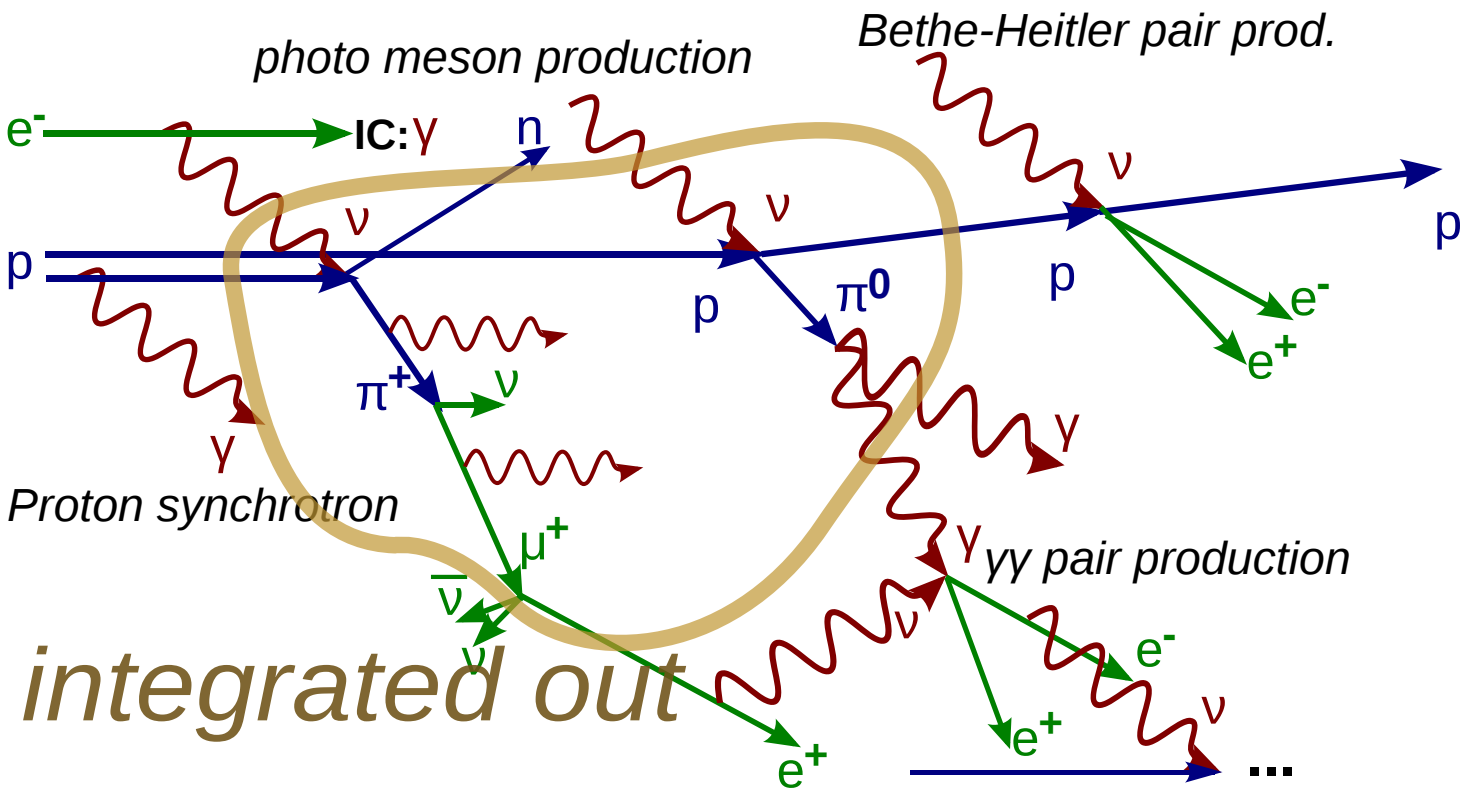
- Cascades will emerge in the optically thick regime $> 10^{28}$ Hz

Unicorn - add photo hadronics



schematic of the dominant photohadronic processes [from: Weidinger 2012]

Unicorn - add photo hadronics



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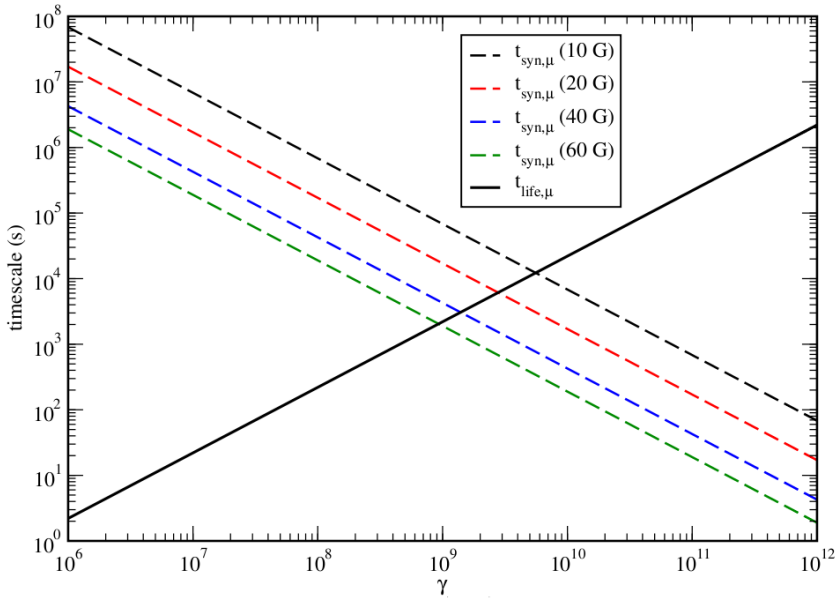
Unicorn - add photo hadronics

- cooling (and possibly acceleration) of intermediates is relevant in AGNs
- ⇒ using model by Hümmer et al. 2010
- How does this influence resulting SEDs and variation timescales?
- calculation of realistic, flavour splitted neutrino spectra



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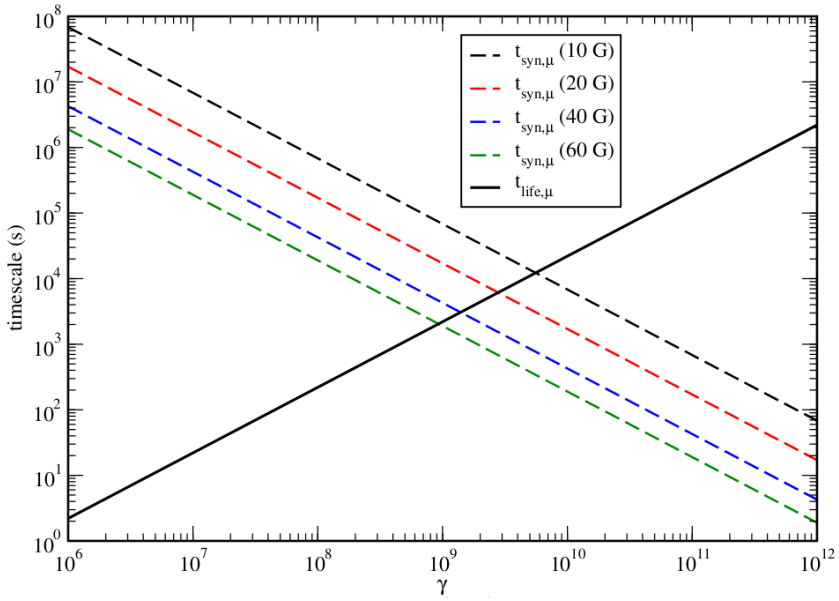

Muon lifetime vs. dominant cooling process [from: Weidinger 2012]

status

- arbitrary combinations of particle species and all relevant processes implemented in *Unicorn*
- todo: numerics of cascades and large differences in timescales

What we try to do

Variability and steady state

observed lightcurves, especially in sources with short variability timescales, are constraining steady state fits

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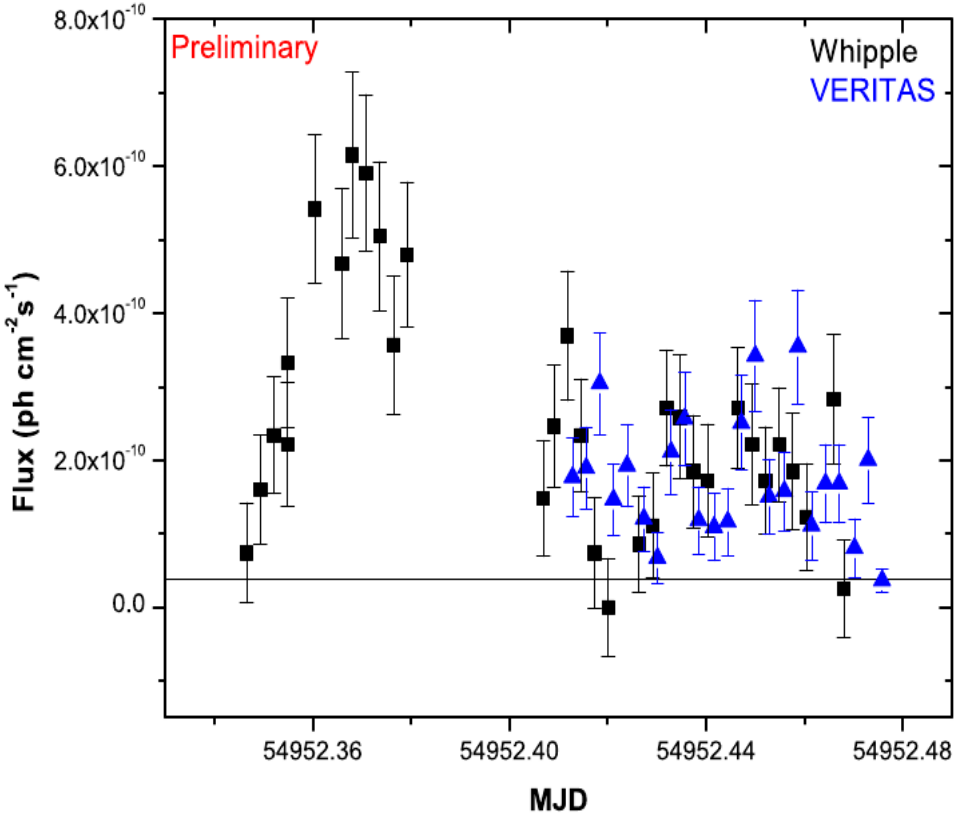
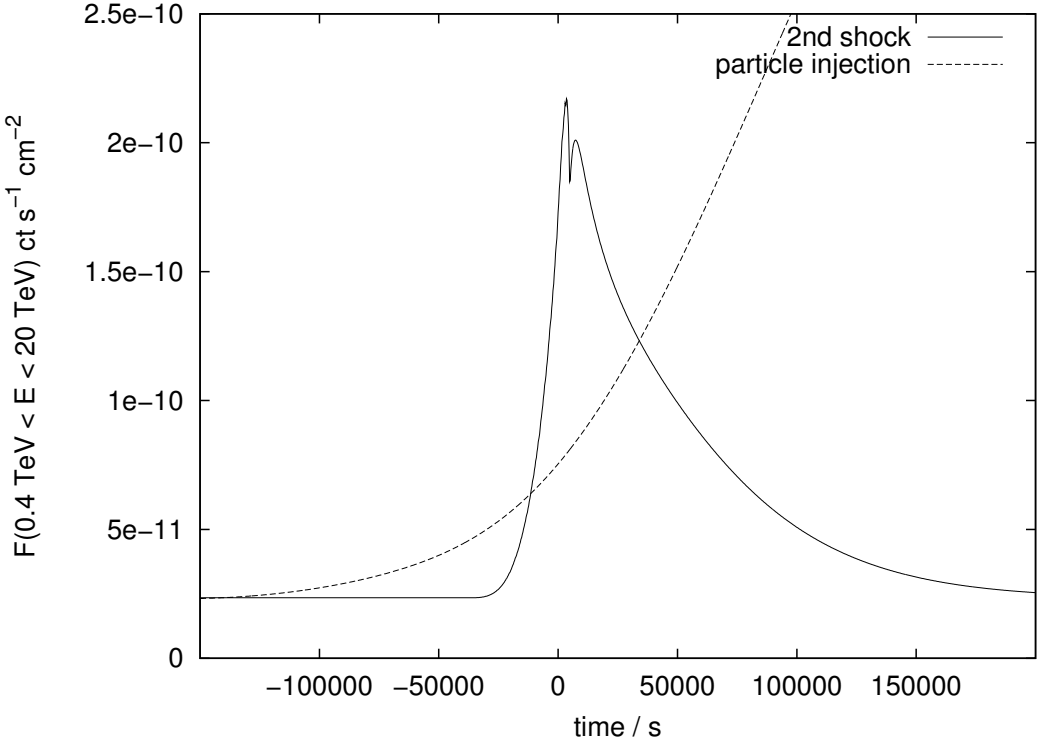


from Pichel and Paneque (2011)

- 6 times the flux in less than 2000 seconds
- steady state fit from Abdo et al. (2011): $R = 1.3 \cdot 10^{17}$ cm, $\delta = 12 \Rightarrow t_{lc}^{obs} = 3.6 \cdot 10^5$ s
- even with a 100 times smaller region with instanteneous acceleration it would be hard to explain this

Variability and steady state

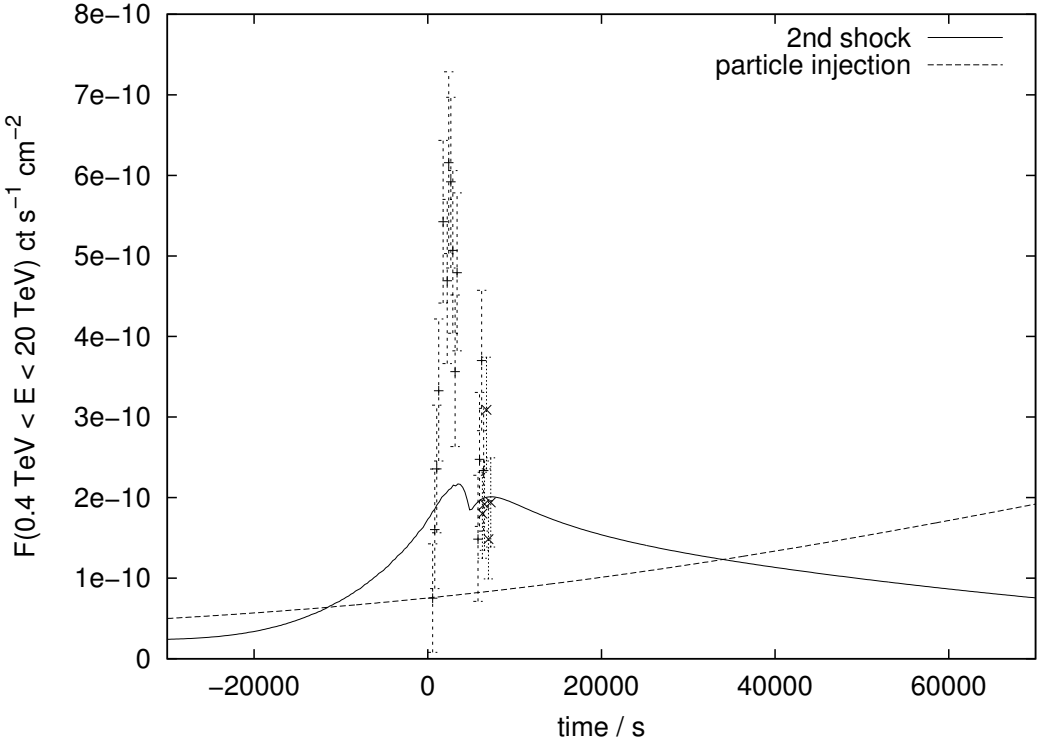
reacceleration in a small part of the emission region?



better, but....

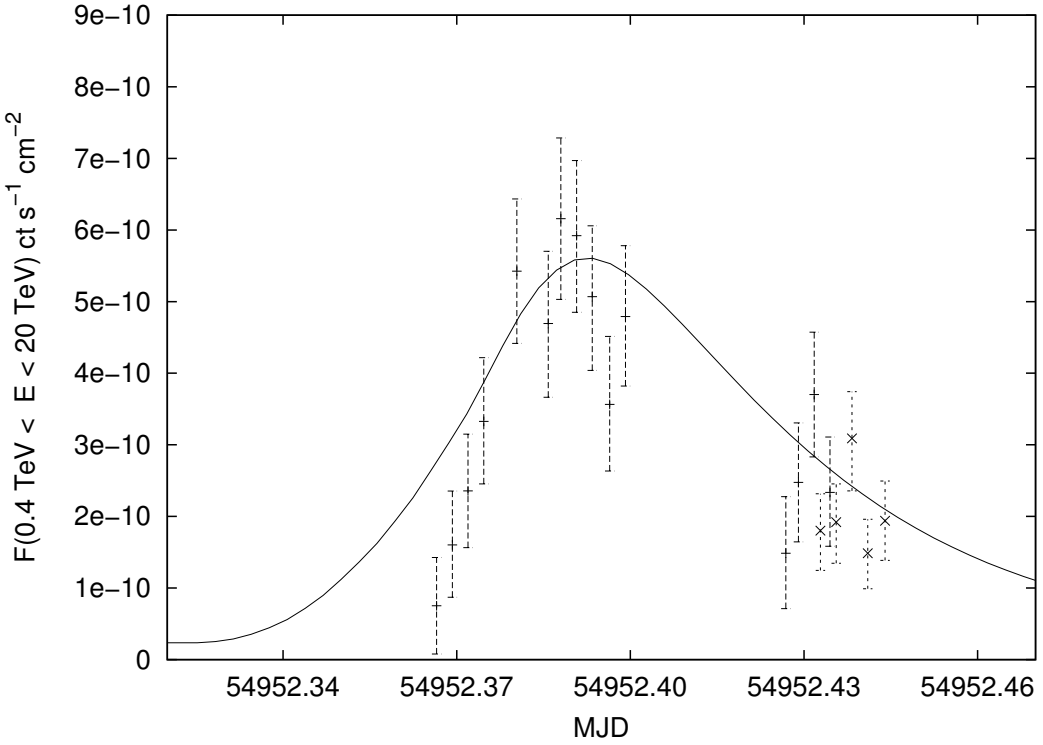
Variability and steady state

..not good enough:



in general: we need better ideas for flare scenarios, to be computed selfconsistently

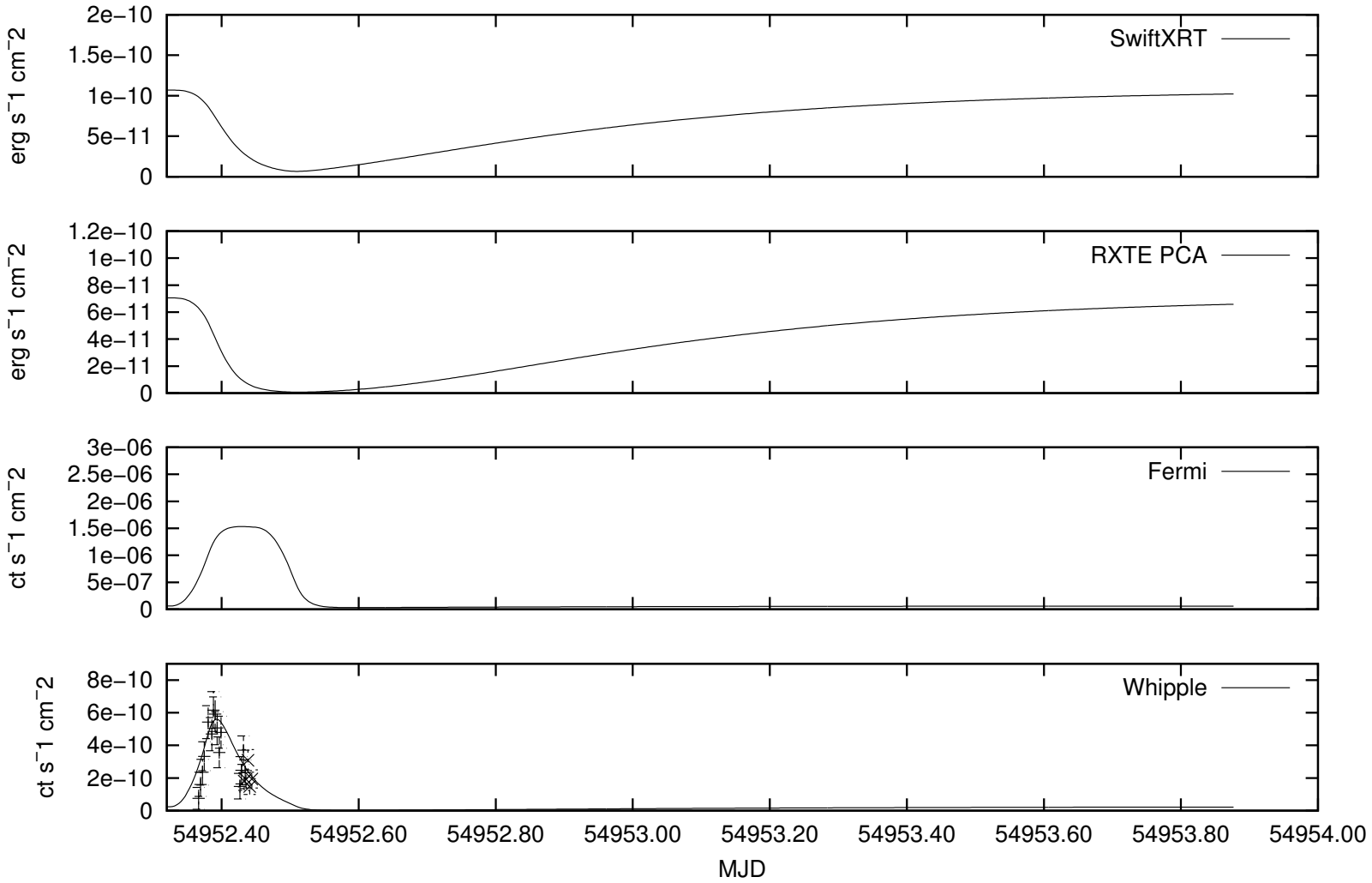
Variability and steady state



- injection of a *Melrose*-spectrum [Brown et al. (1983)] photon distribution ($\nu_{cut} = 10^{14}$ Hz, $n(\nu_{cut}) = 3 \cdot 10^{-5}\,\mathrm{cm}^{-3}$)
- details soon in [Richter and Spanier (in prep.)]

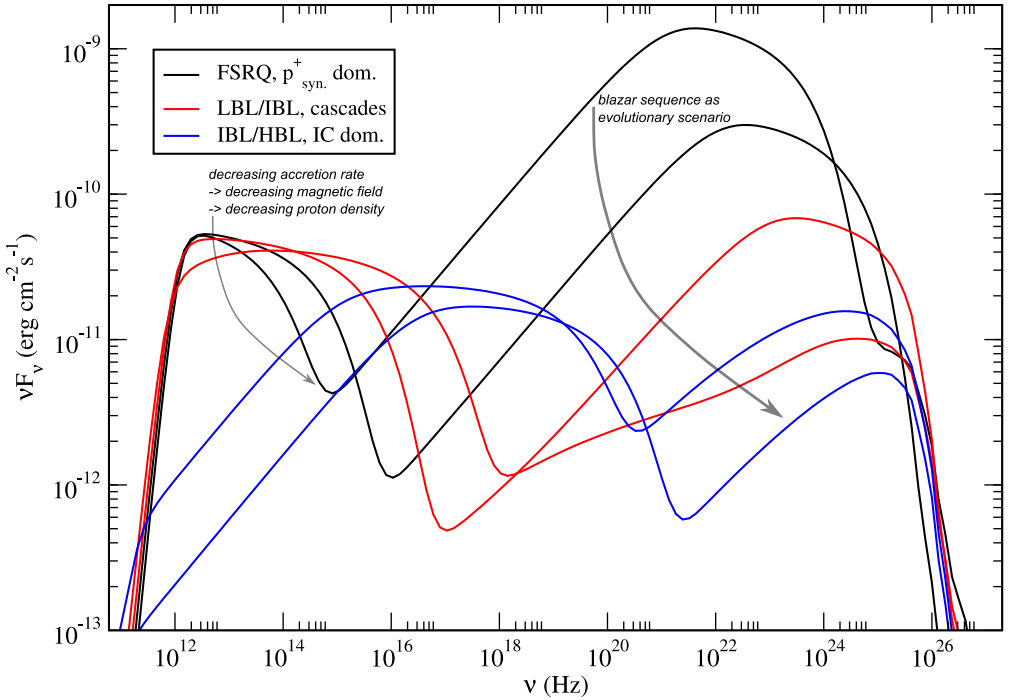
Variability and steady state

usually the multitude of bands makes such models falsifiable



Distinguish leptonic and hadronic

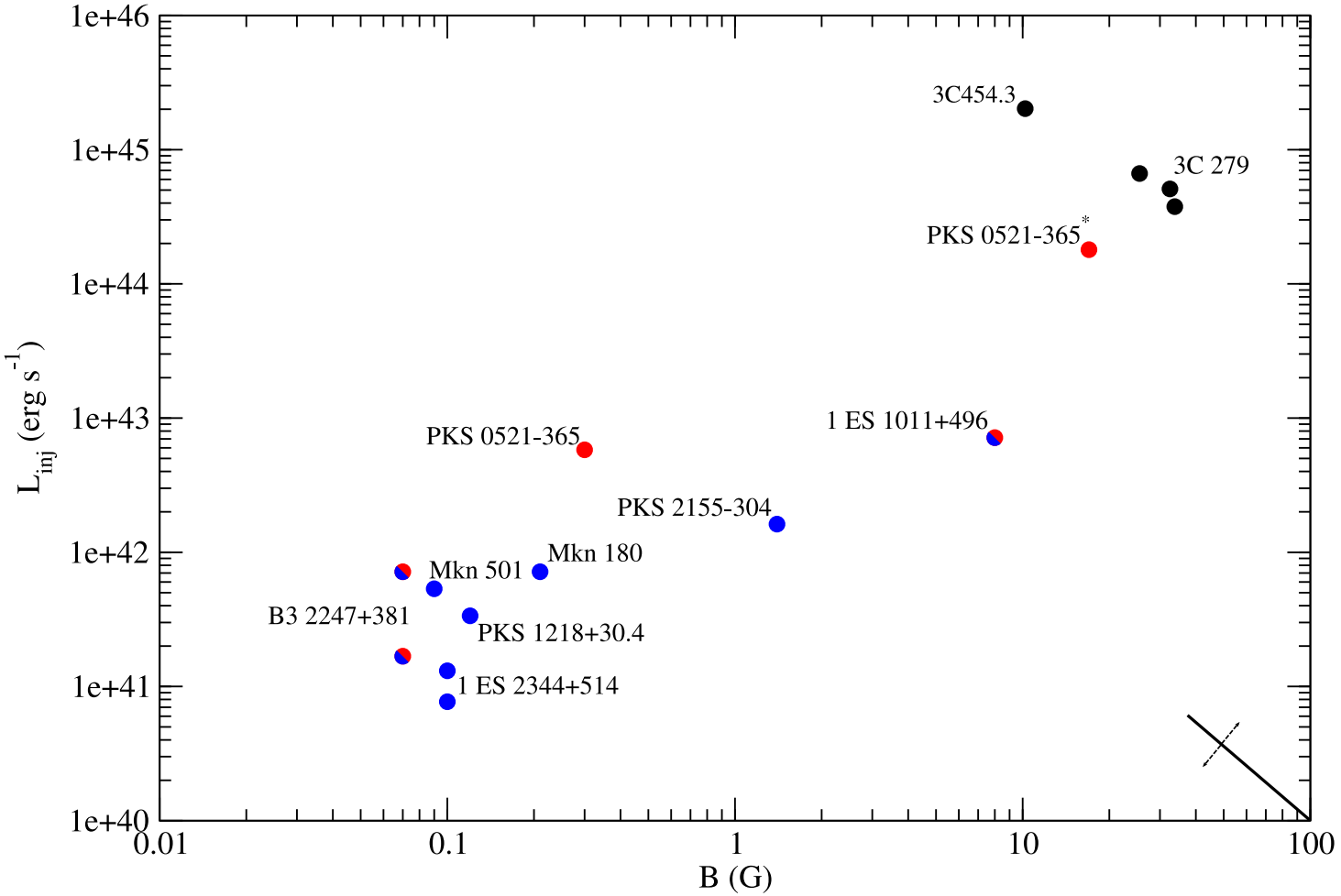
to discover the leptonic vs hadronic character of sources is quite important (consequences for jet formation, contribution of AGN to cosmic ray spectrum,. . .)



from [Weidinger (2012)]

- modeling of various sources with a hybrid model indicates connection to the blazar sequence (if it exists)
- increasing magnetic field resembles transition from *IC*, via *cascade* to p^+-*synchrotron* dominated sources

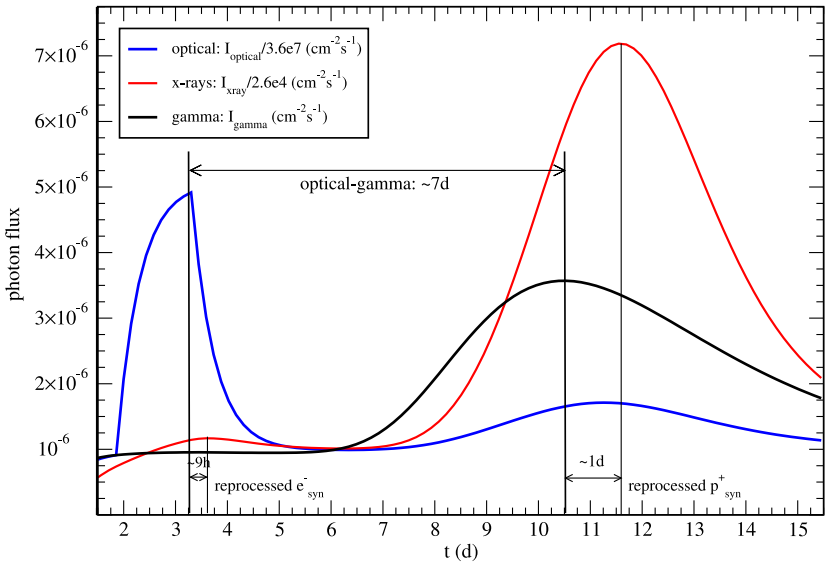
Distinguish leptonic and hadronic

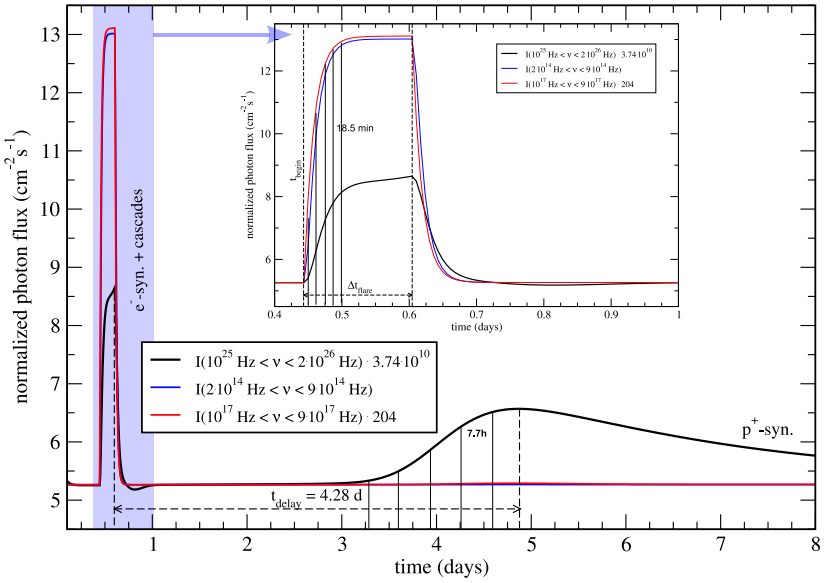


from [Weidinger (2012)]

Distinguish leptonic and hadronic

time evolution of flares contains much information about the dominant physical processes



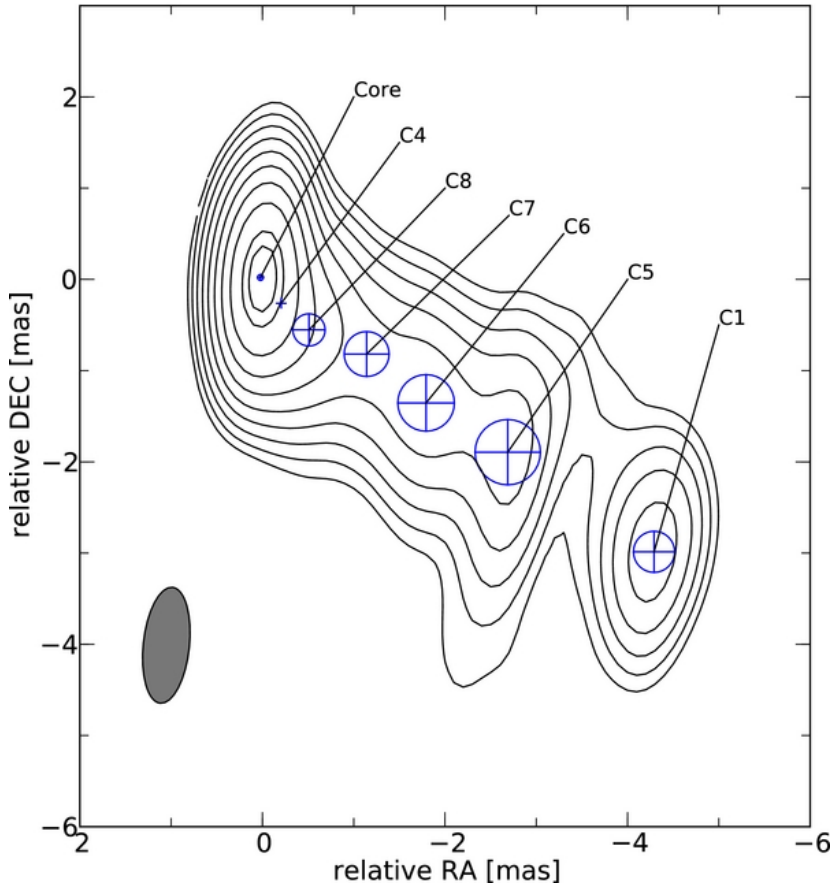


hybrid models for *3C279* and *1ES1011+496* from [Weidinger (2012)]

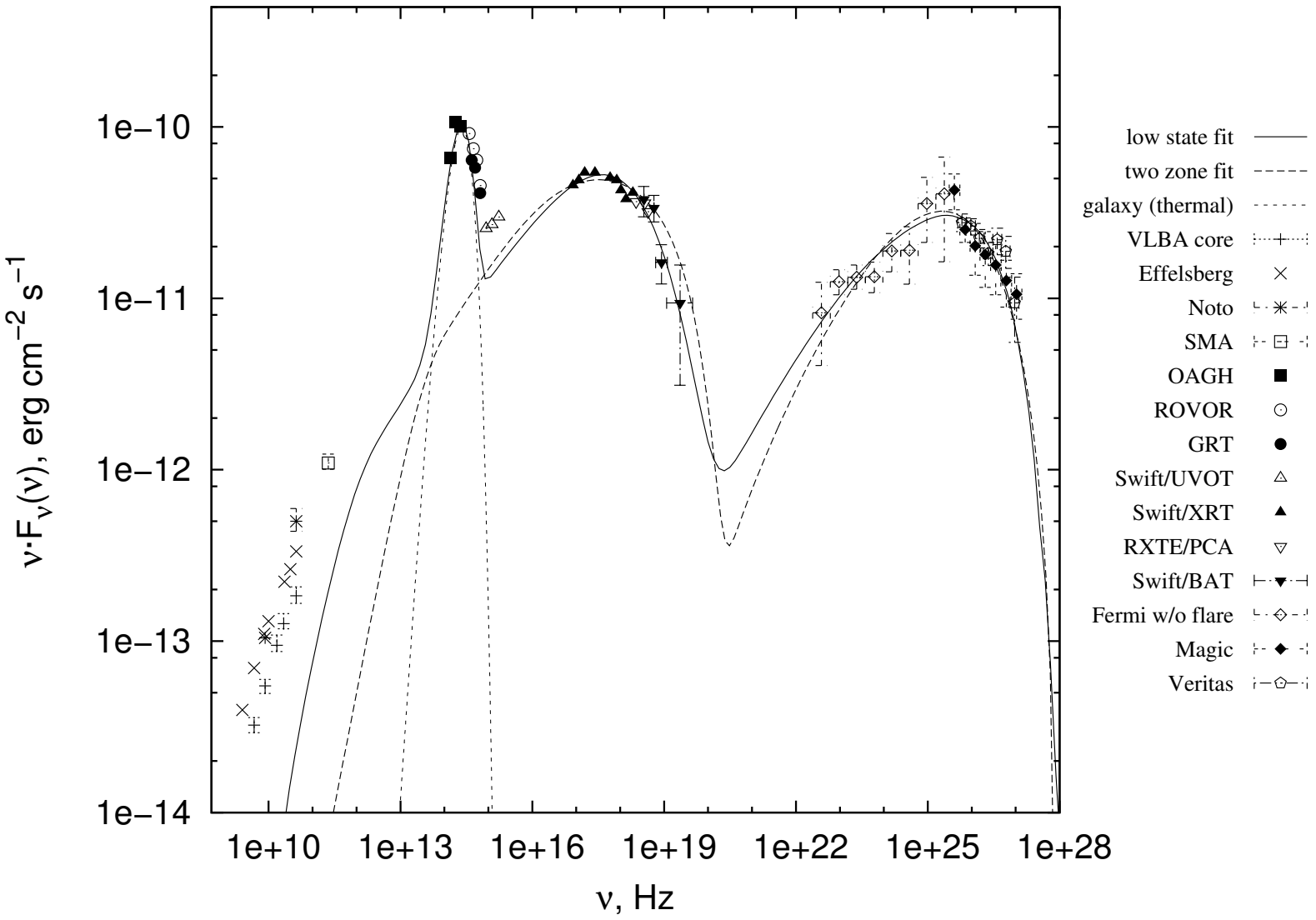
More physics, less numerics

What are the (physical) boundary conditions of a blob?

- we see (in the radio) structures larger than the (numerical) emission region
- we see variability shorter than the simulated size predicts
- how can we close the gap between overall SED and radio spectra/morphology?
- can we learn something about the magnetic field structure from that?



radio spectrum



radio spectrum

synchrotron self absorption by a powerlaw distribution

equivalence of brightness and kinetic temperature leads to a flux

$$F_\nu \propto \nu^{\frac{5}{2}}$$

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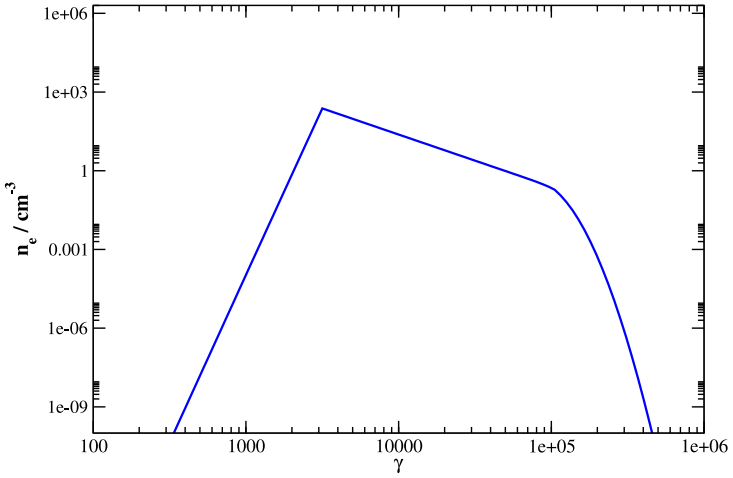
usual approach:
increase γ_{min} or γ_{inject}, respectively



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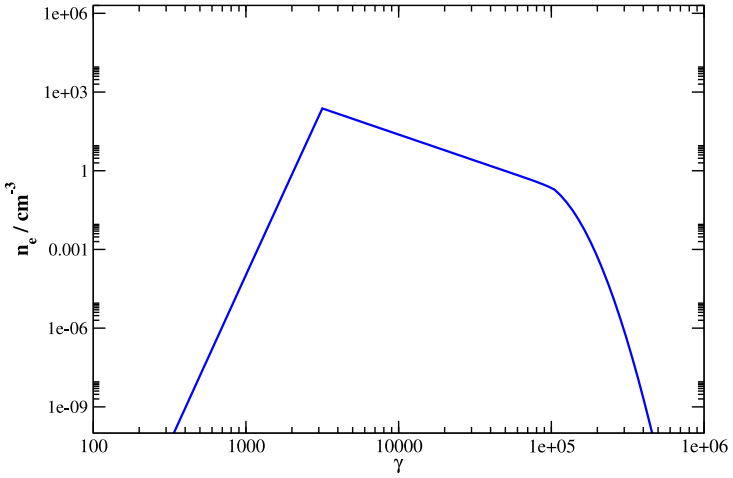
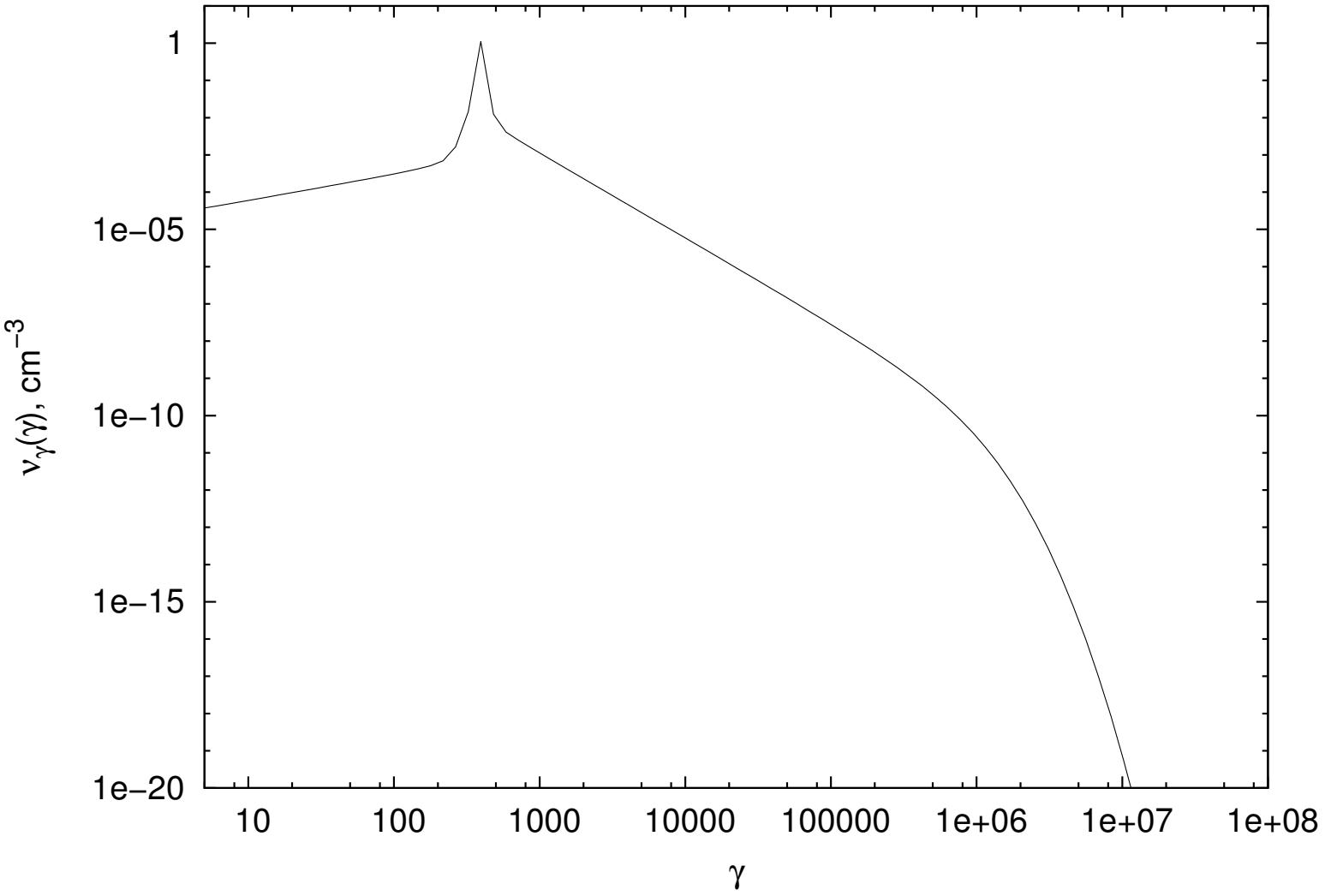


synchrotron radiation of a single electron

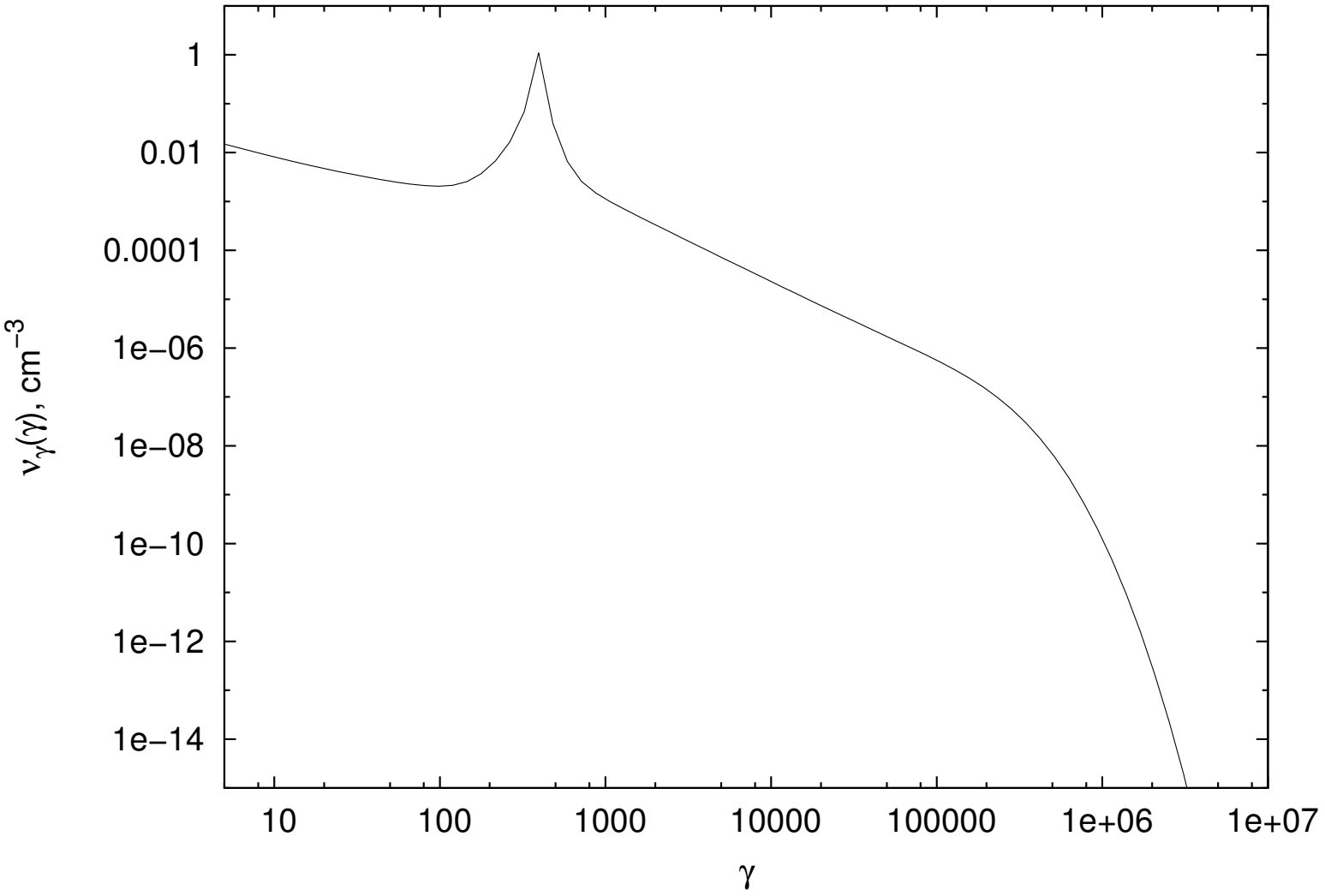
$$P_\nu(\gamma,\nu) = \frac{\sqrt{3}\ q^3 B}{m\ c^2} \cdot \frac{\nu}{\nu_c} \int_{\frac{\nu}{\nu_c}}^{\infty} \mathrm{d}\eta\ K_{\frac{5}{3}}(\eta) \overset{\text{small } \nu}{\propto} \nu^{\frac{1}{3}}$$

electron distribution development



Electron distribution at different distances to the shock.

electron distribution development



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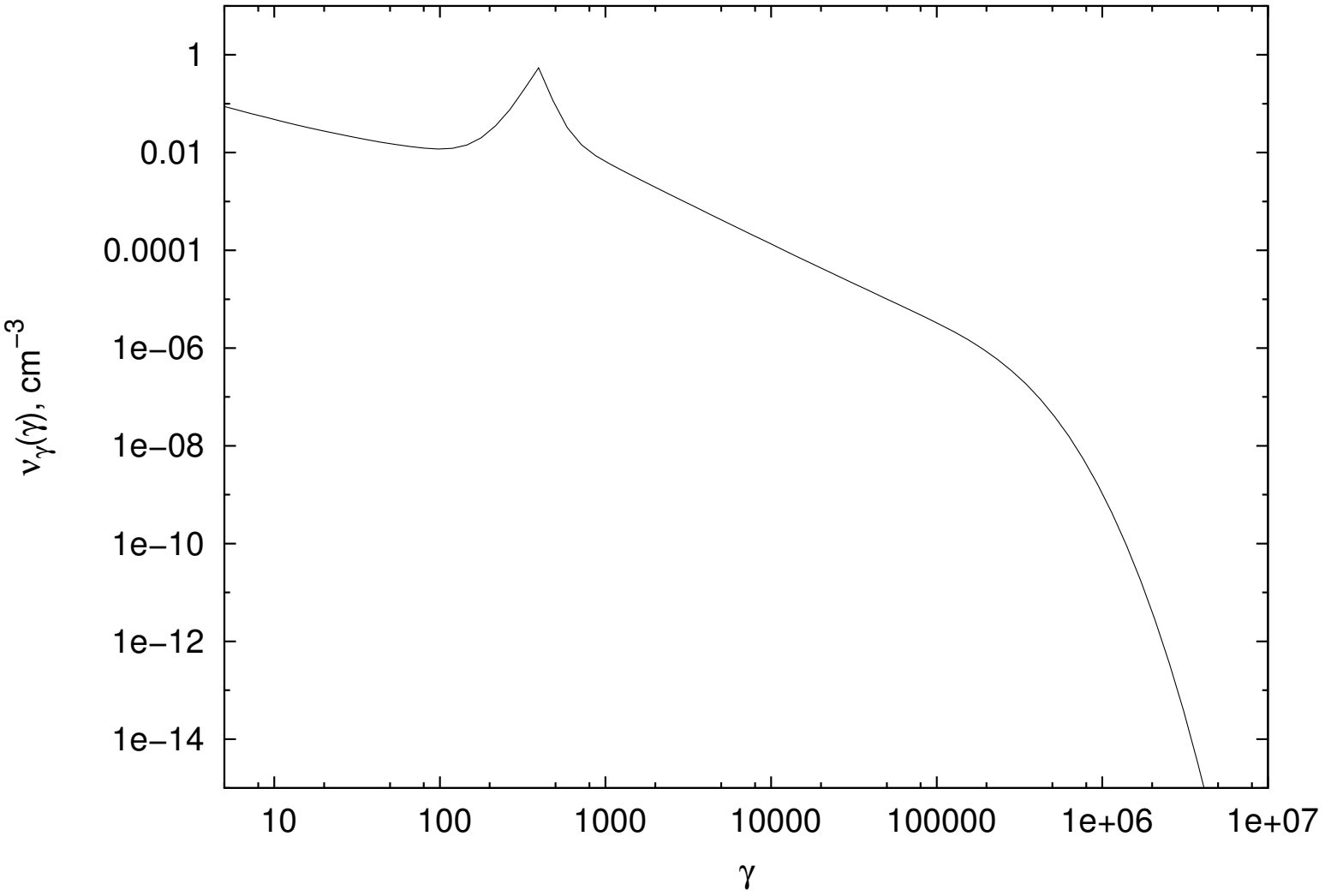

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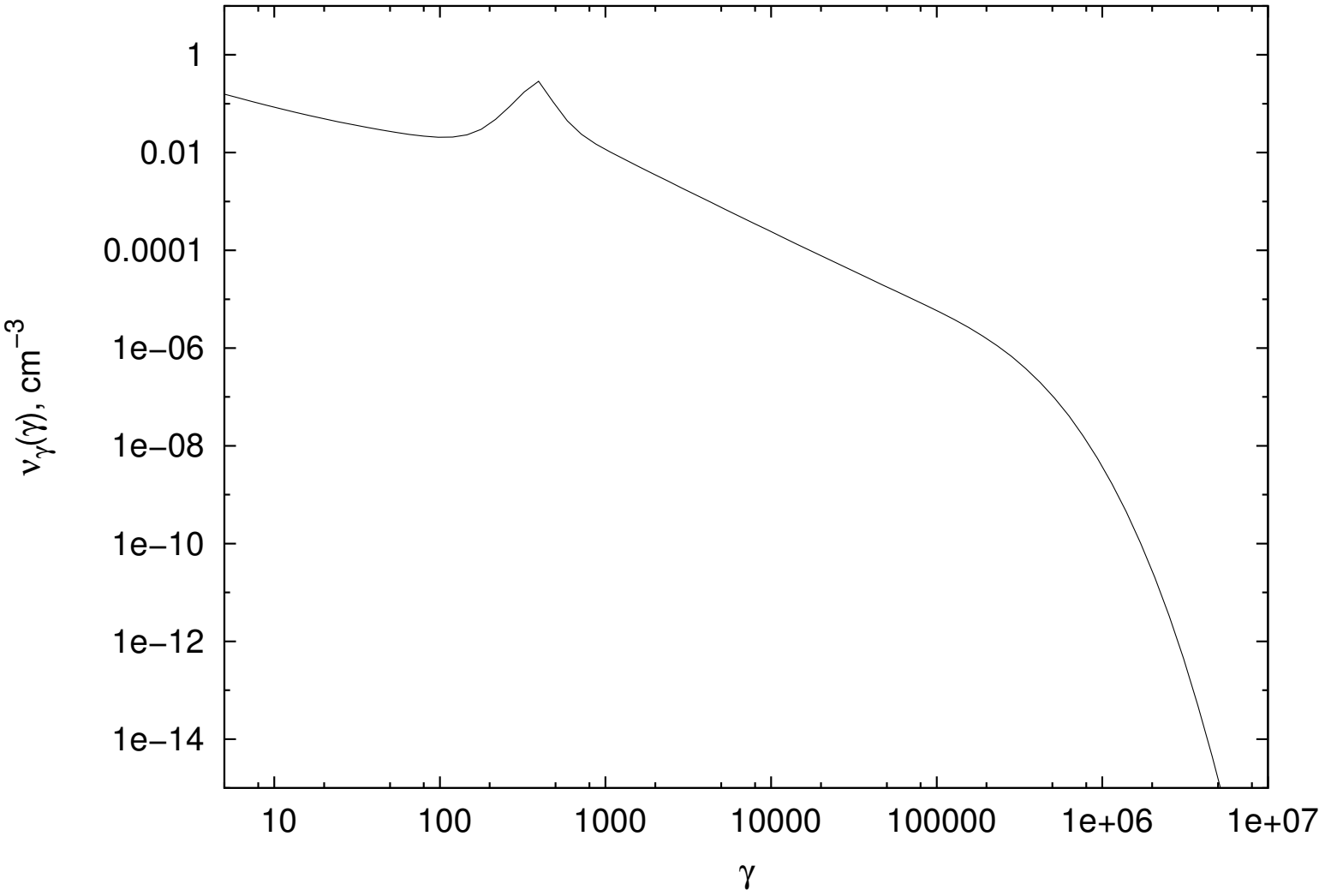

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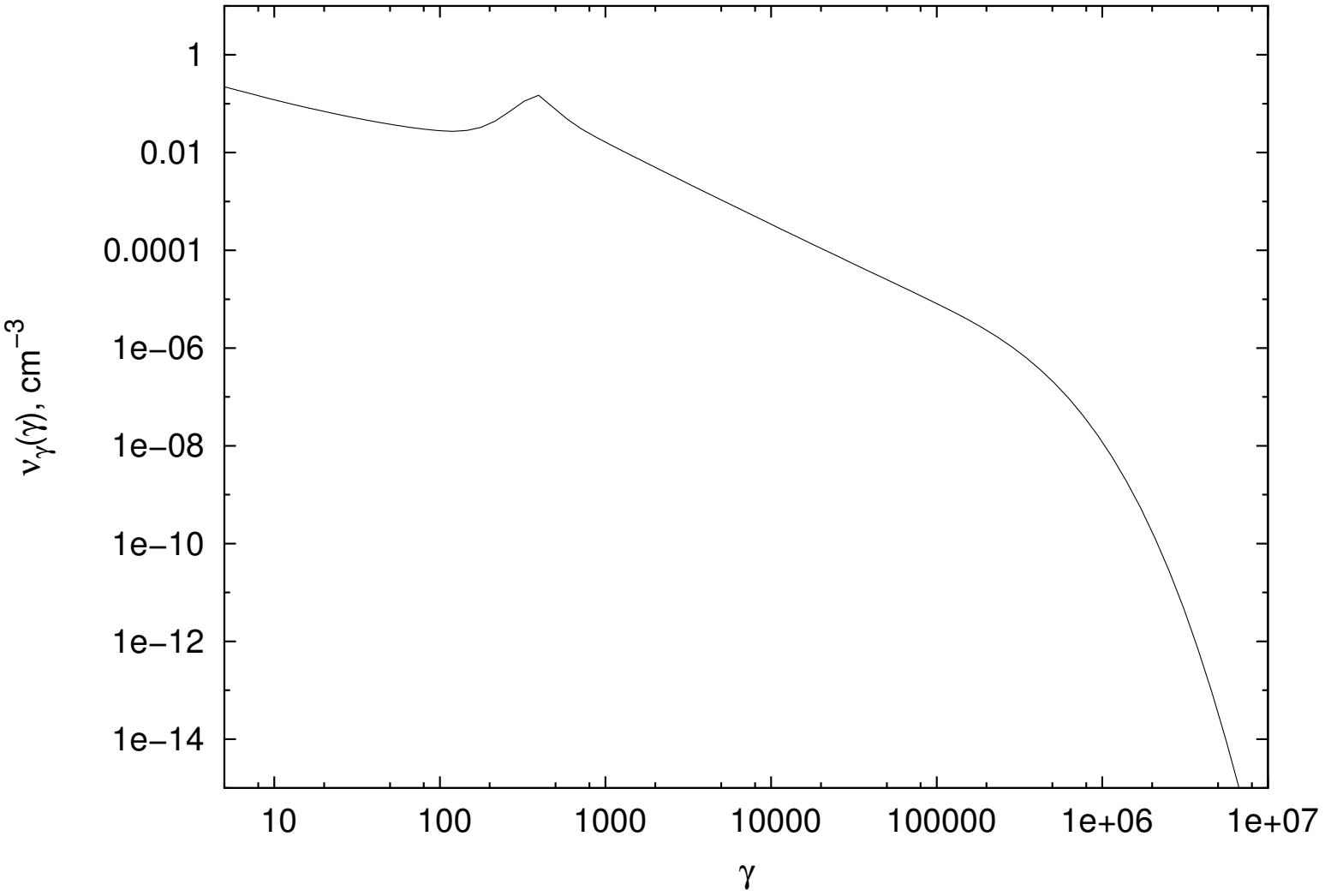

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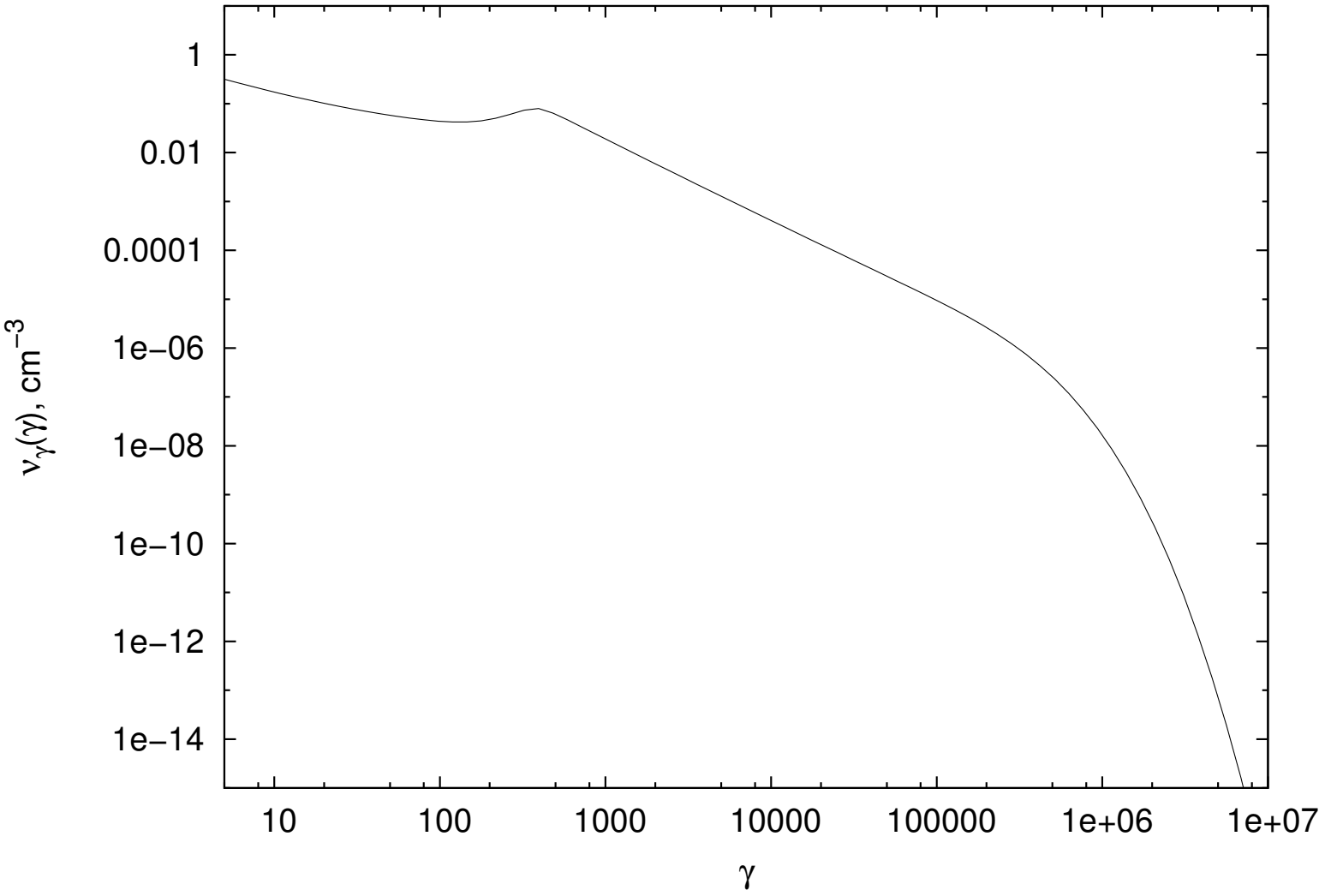

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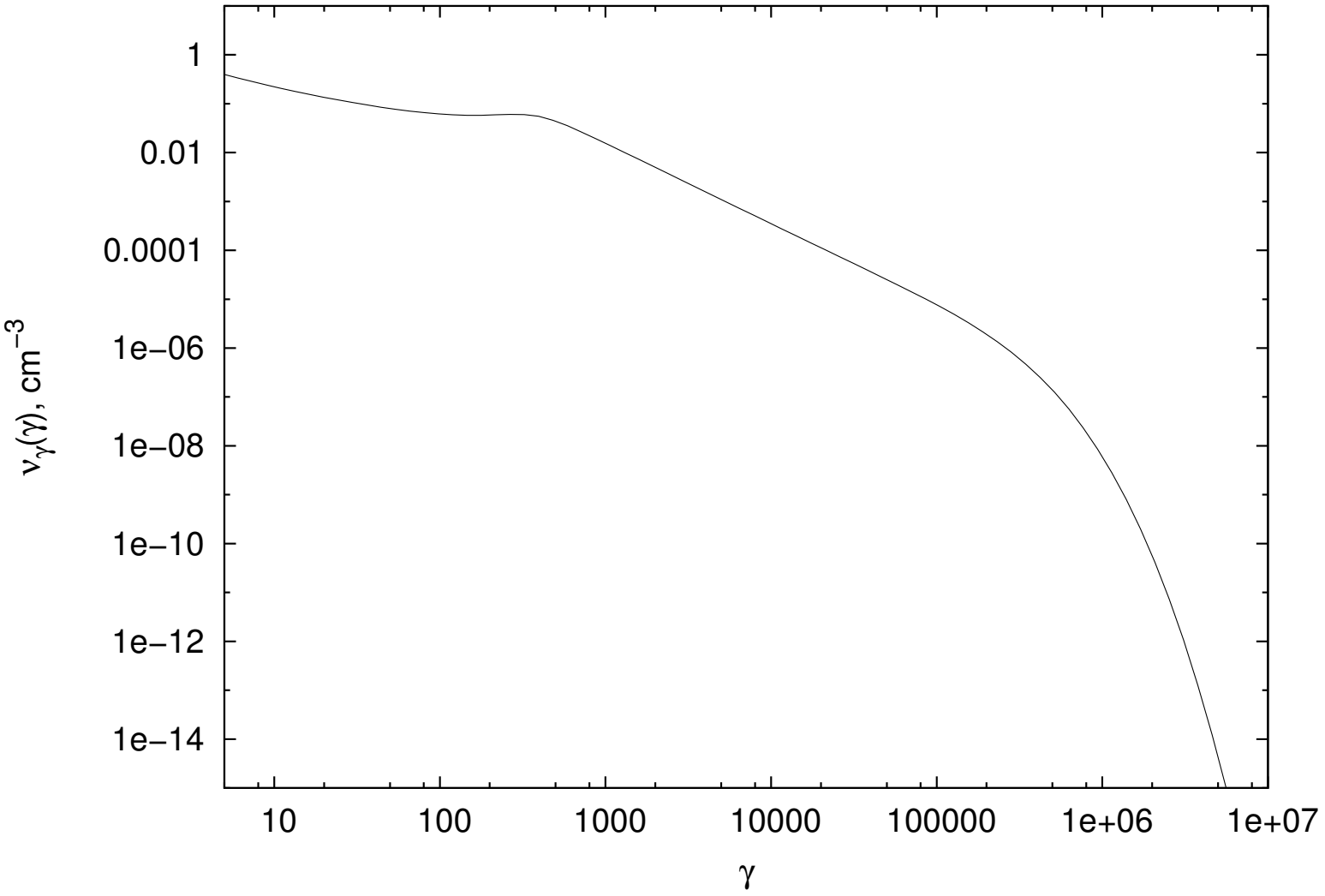

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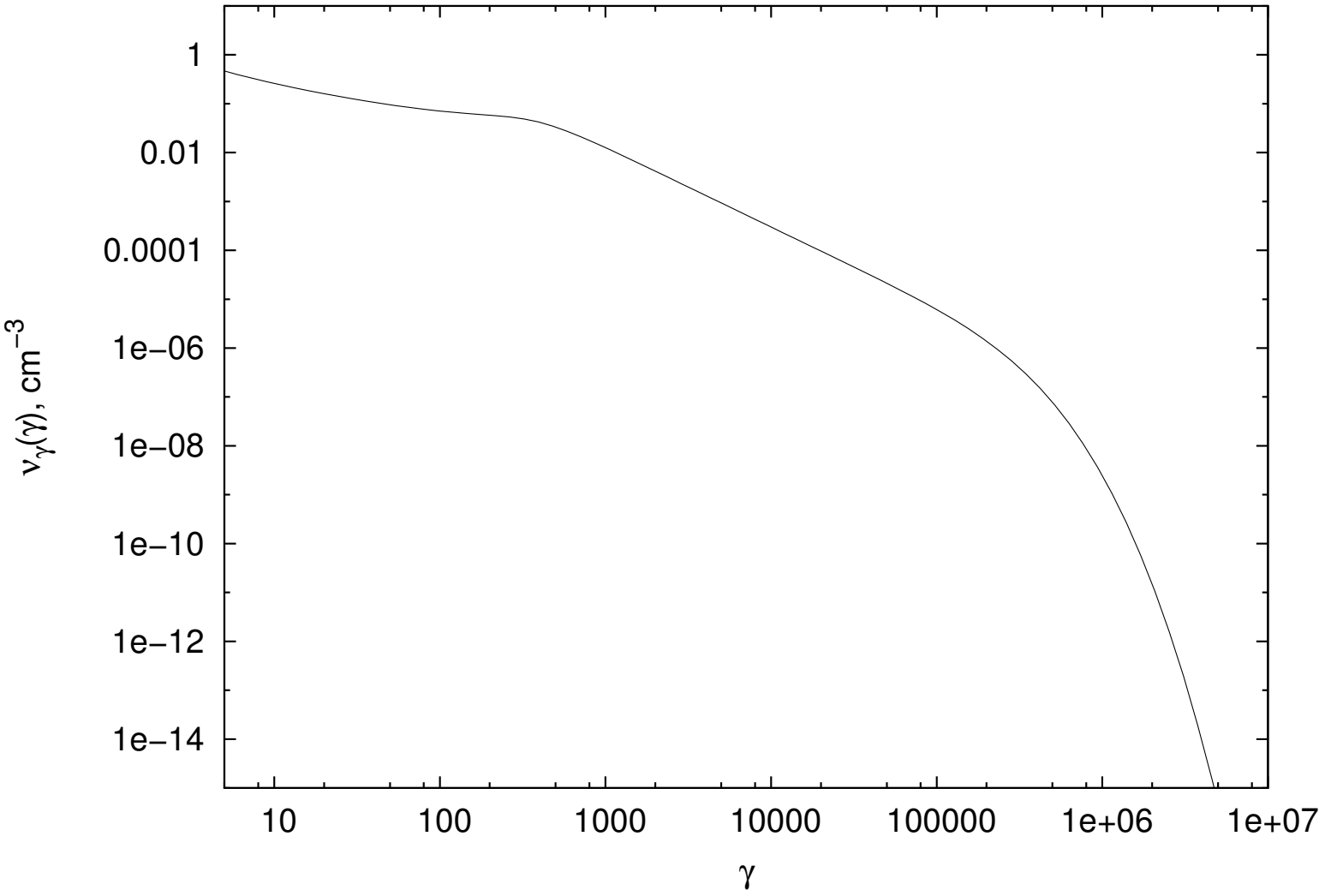

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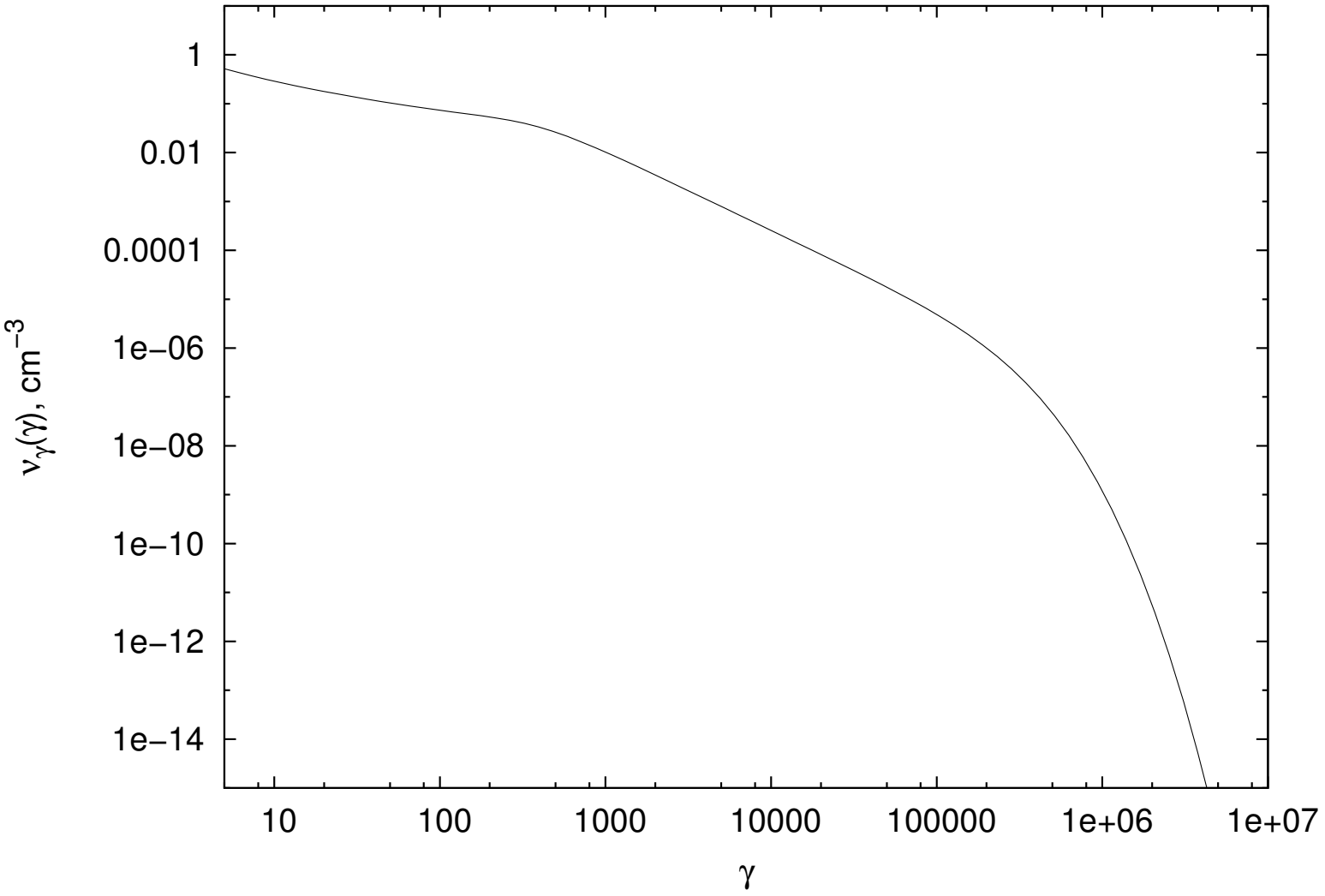

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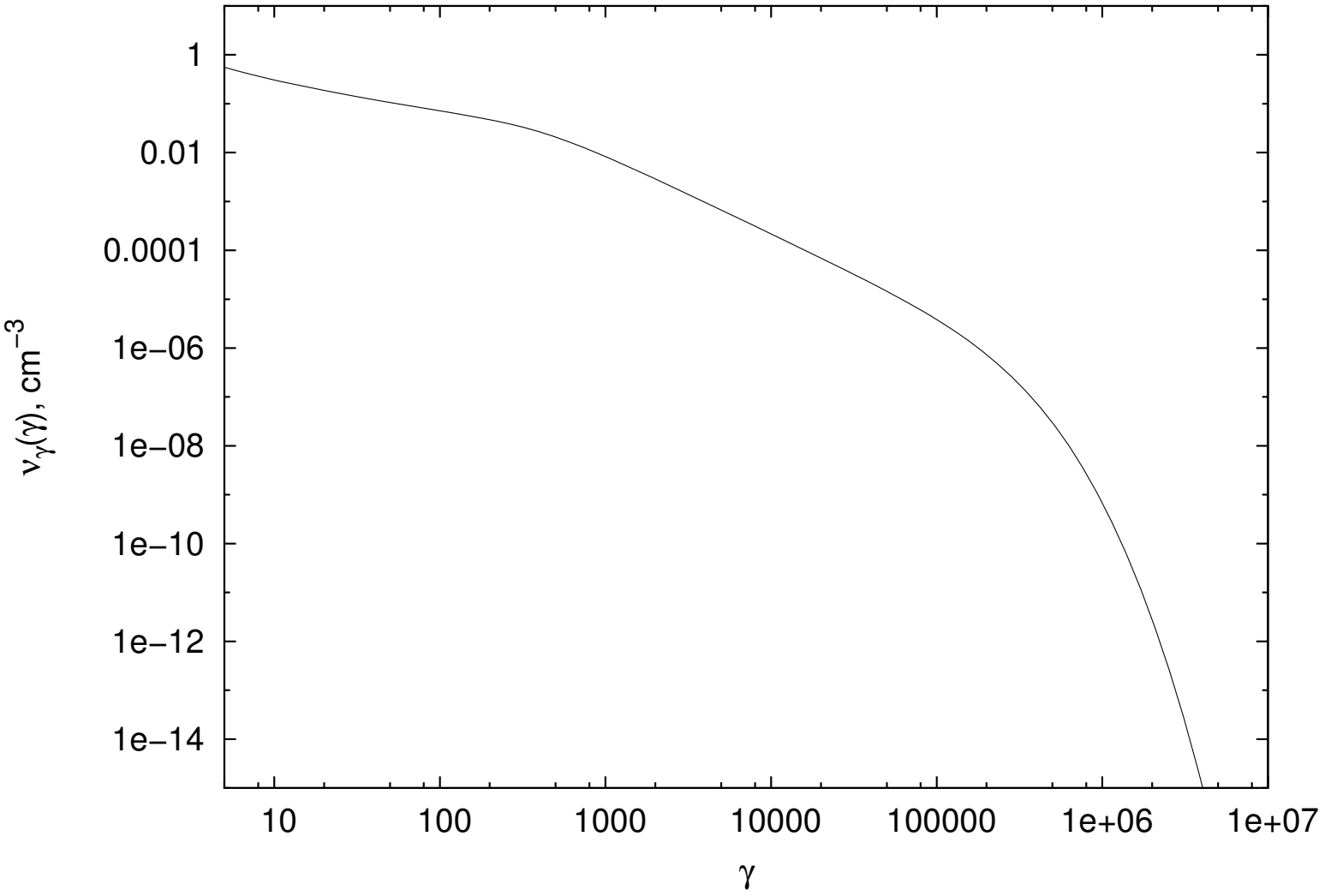

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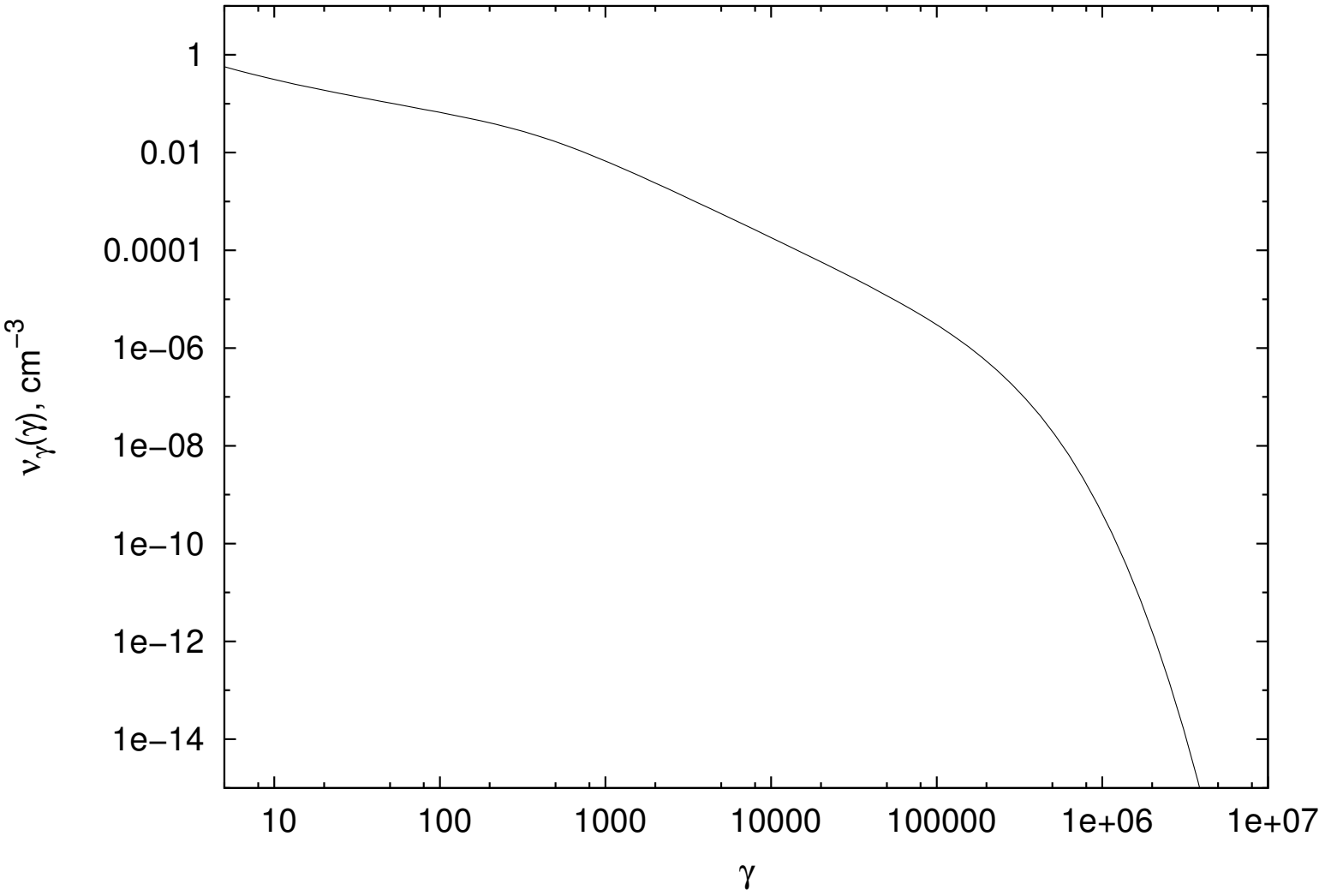

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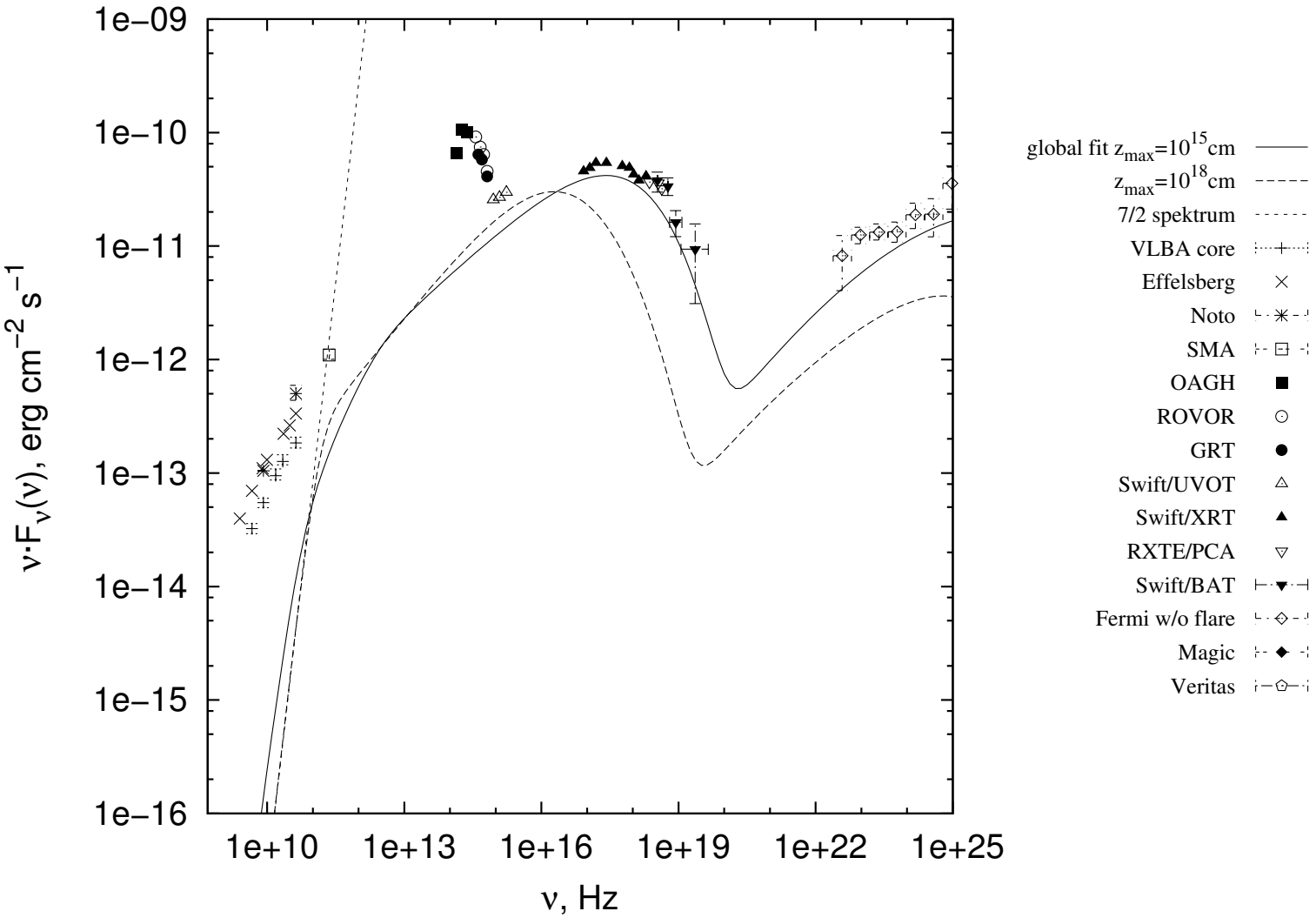
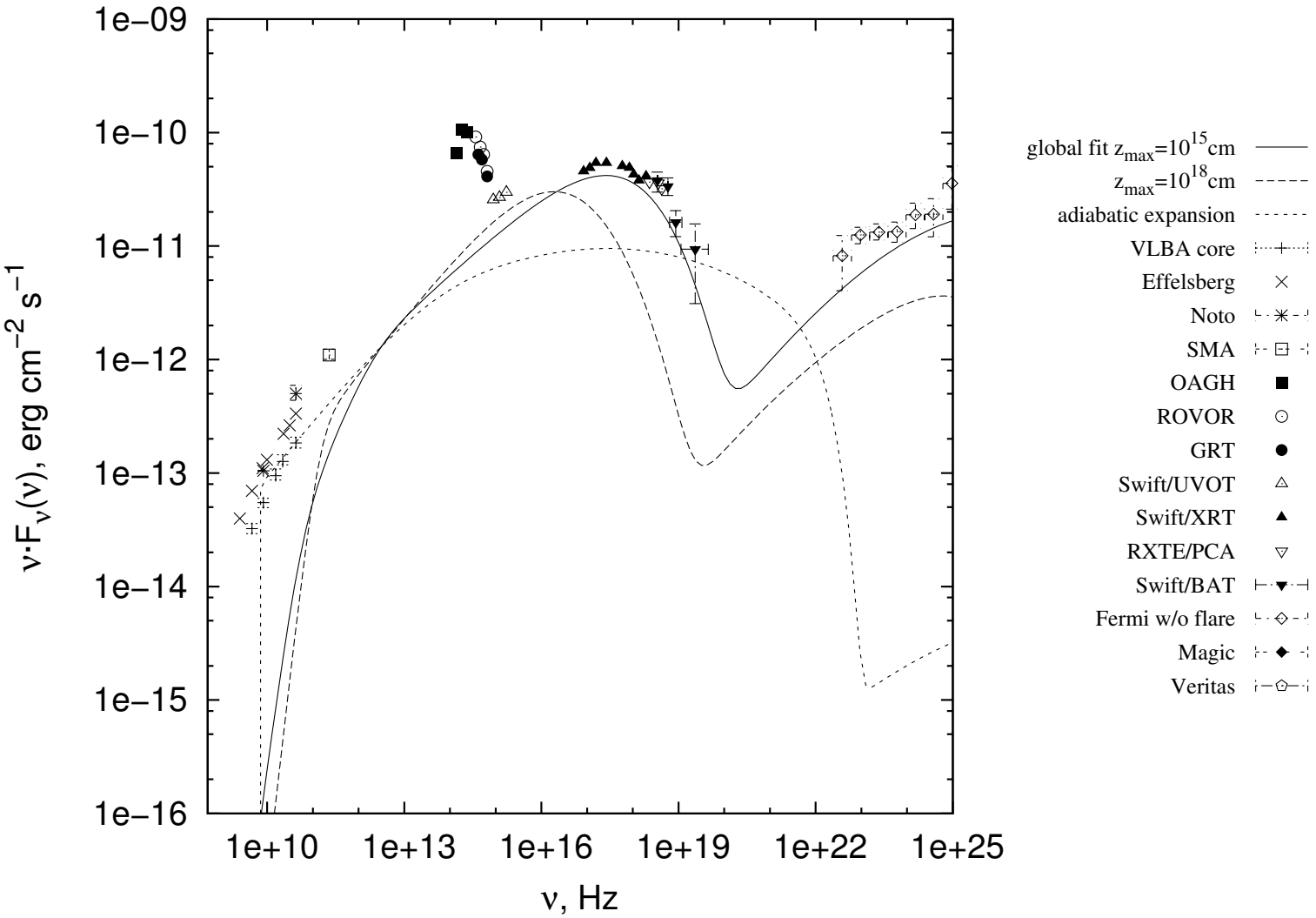
radio spectrum



Effect of significant larger simulation region.

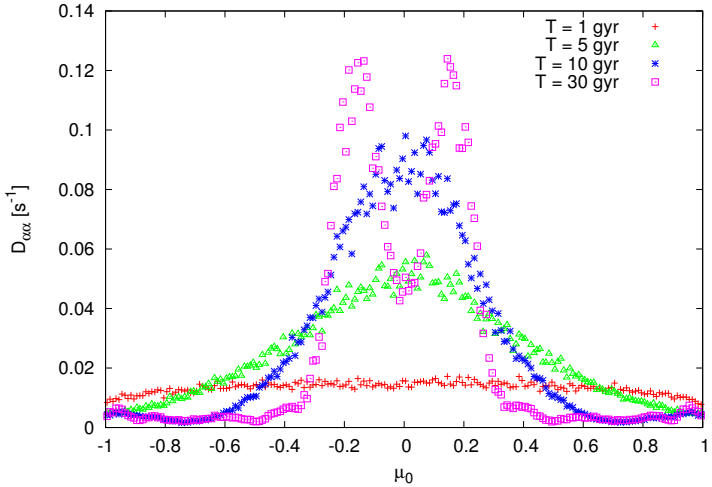
adiabatic expansion



Effect of additional adiabatic expansion.

What we can't do (yet)

Microphysics



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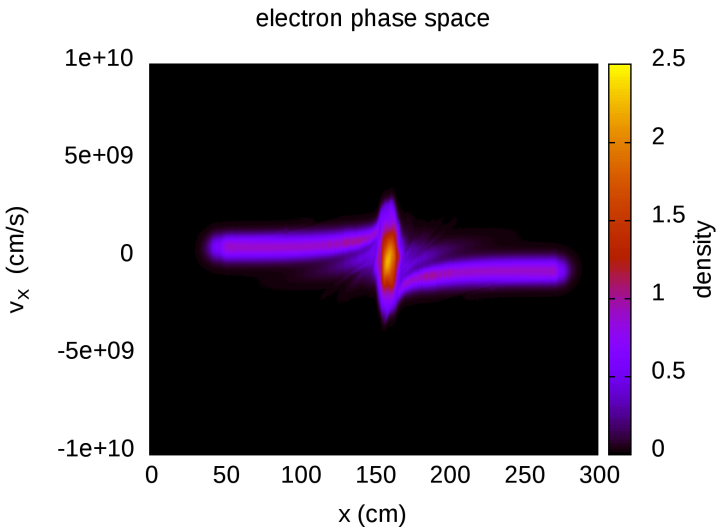
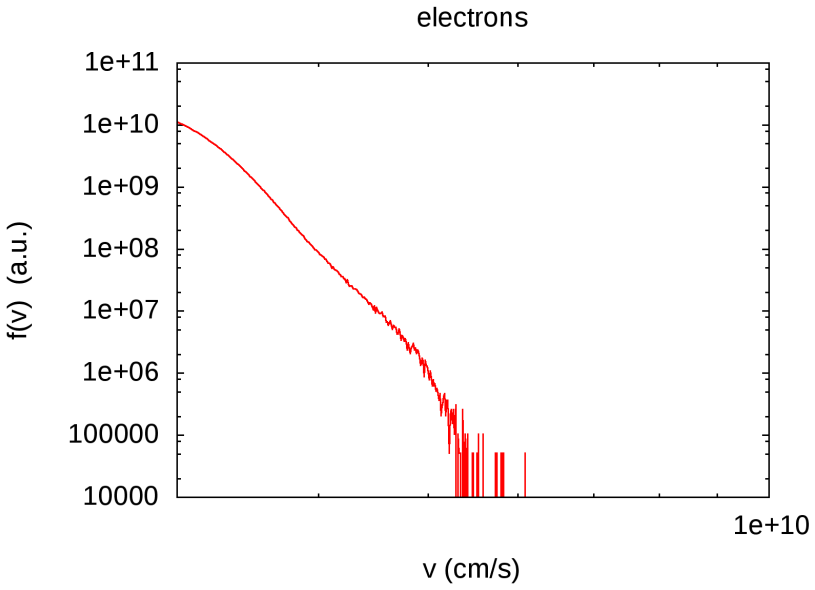


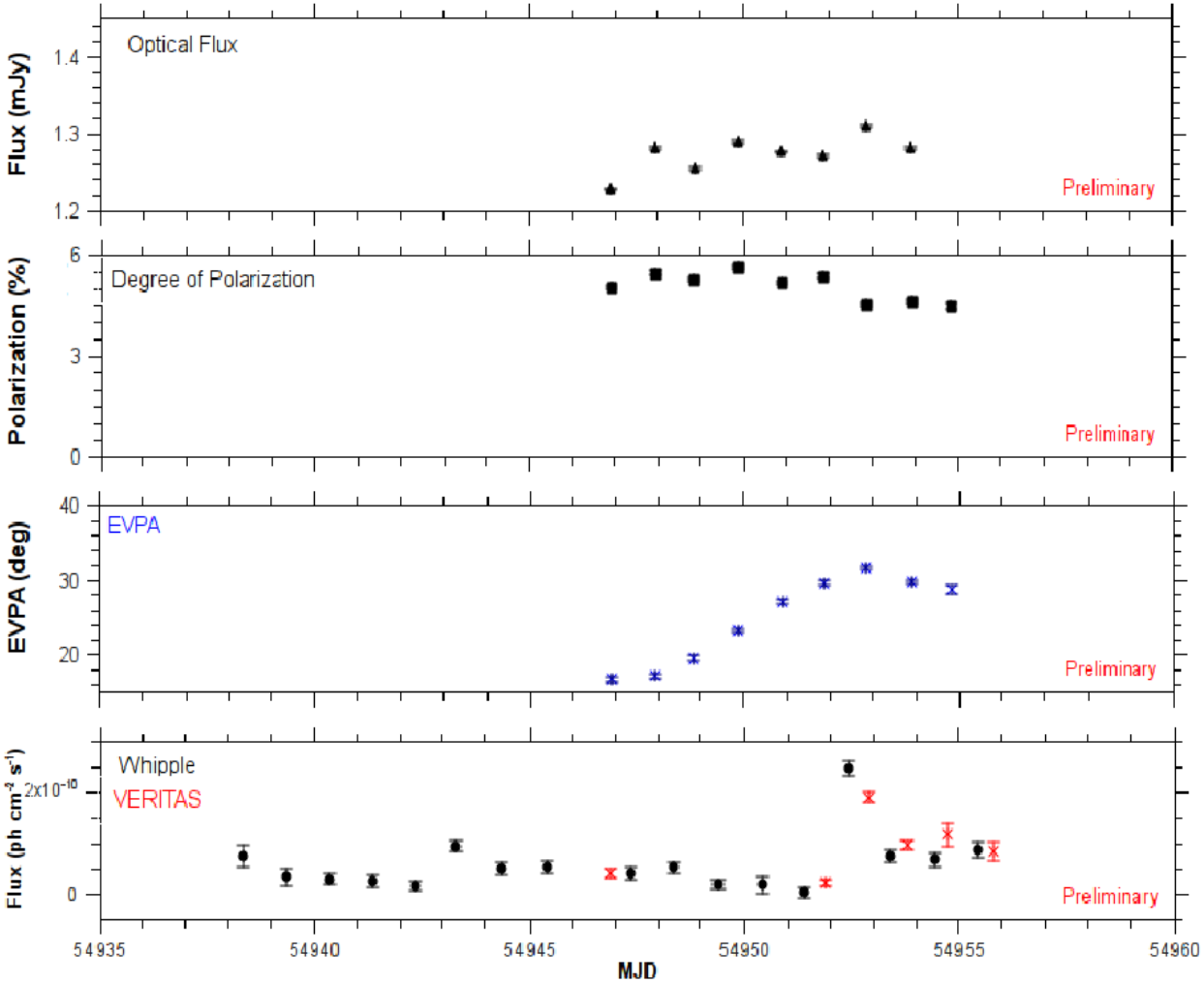
- in principle closed chain from MHD, via PiC, to power law spectra
- but scales of extraglactic accelerators are not achievable: 10^{42} a für 10^{21} eV cosmic rays
- since processes seem to be nice, extrapolation might not be too ridiculous



VLBI - blob connection

- VHE emission length scale $\sim 10^{15}$ cm (max)
- known radio morphology scale is $\sim 10^{19}$ cm
- consistent simulations of the complete system does not exist (as far as I know)
- moving to (2D) large scale simulations on super computers this should, in principle be possible

Polarisation and EVPA



Polarisation - flare correlation [Pichel and Paneque (2011)].

Conclusion

- although blazars are extreme and almost violent objects, many aspects can be explained quite beautifully
- more and more simultaneous multi-frequency data will help to increase our understanding of these objects
- time dependent hadronic simulations offer a whole new parameter space to test against that data
- detailed observation often challenges established models
- additional channels (polarisation, maybe neutrinos some day) need completly new modelling approaches

Thank you

Bibliography I

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