High-Energy Signatures from Leptohadronic Interactions in GRB Models

Maria Petropoulou[1]

In collaboration with
D. Giannios[1]
S. Dimitrakoudis[2]
A. Mastichiadis[3]

[1] Department of Physics & Astronomy, Purdue University, USA
[2] Institute for Astronomy, Astrophysics, Space Applications & Remote Sensing, National Observatory of Athens, Greece
[3] Department of Physics, University of Athens, Greece

Einstein Fellows Symposium 2014
Boston, October 28

Outline

- Introduction: leptohadronic processes in a nutshell

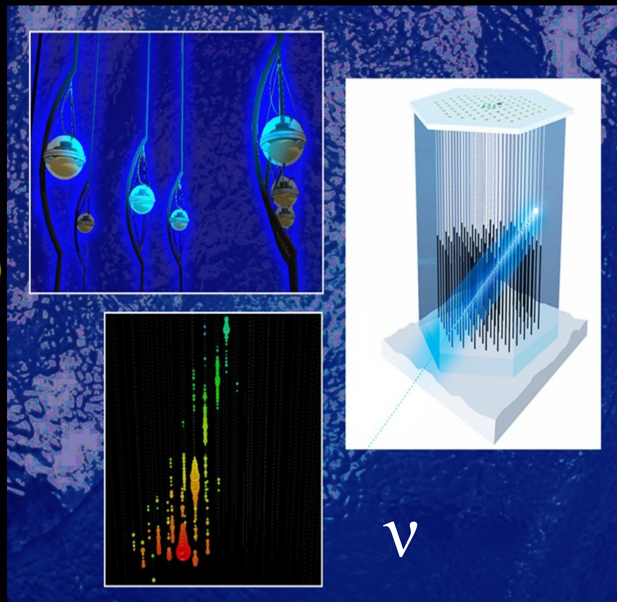
- Recent results:

  1) A PeV cutoff of the IceCube neutrino spectrum and a possible meaning for GRB models
  (Petropoulou, Giannios, Dimitrakoudis, 2014, MNRAS, 445, 570 ,arXiv:1405.2091)

  2) Non-linear feedback in hadronic models as a trigger for GRB emission
  (Petropoulou et al. 2014, MNRAS, 444, 2186 , arXiv:1407.2915)

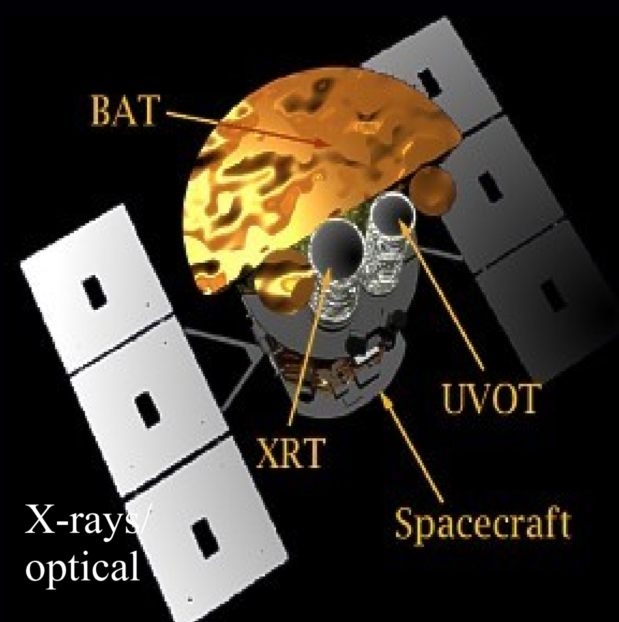
- (Future aspects)

Introduction

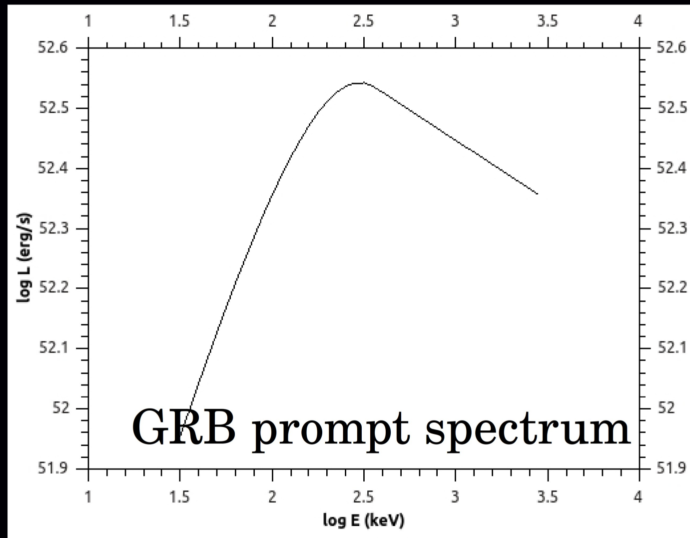


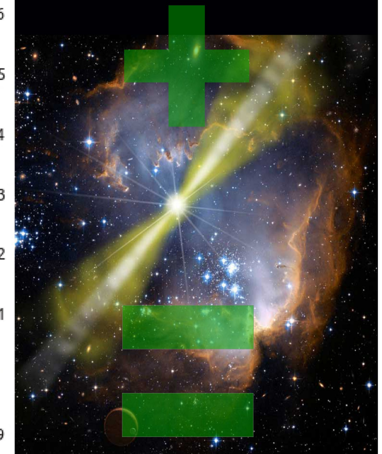
GRBs

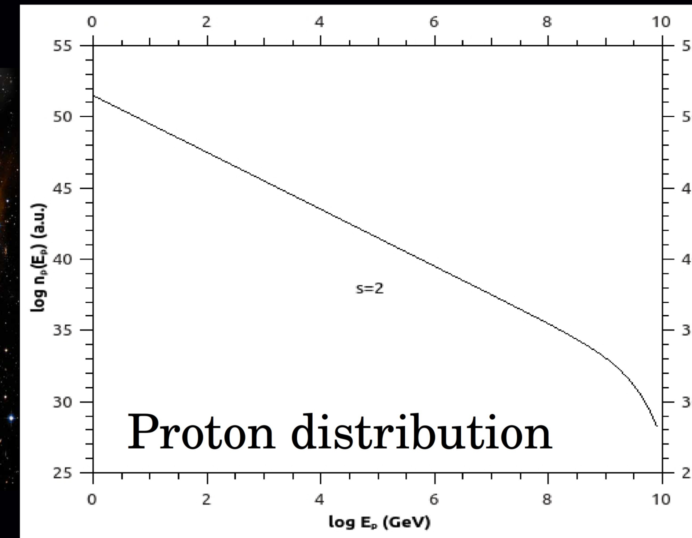
Multi-messenger Astronomy

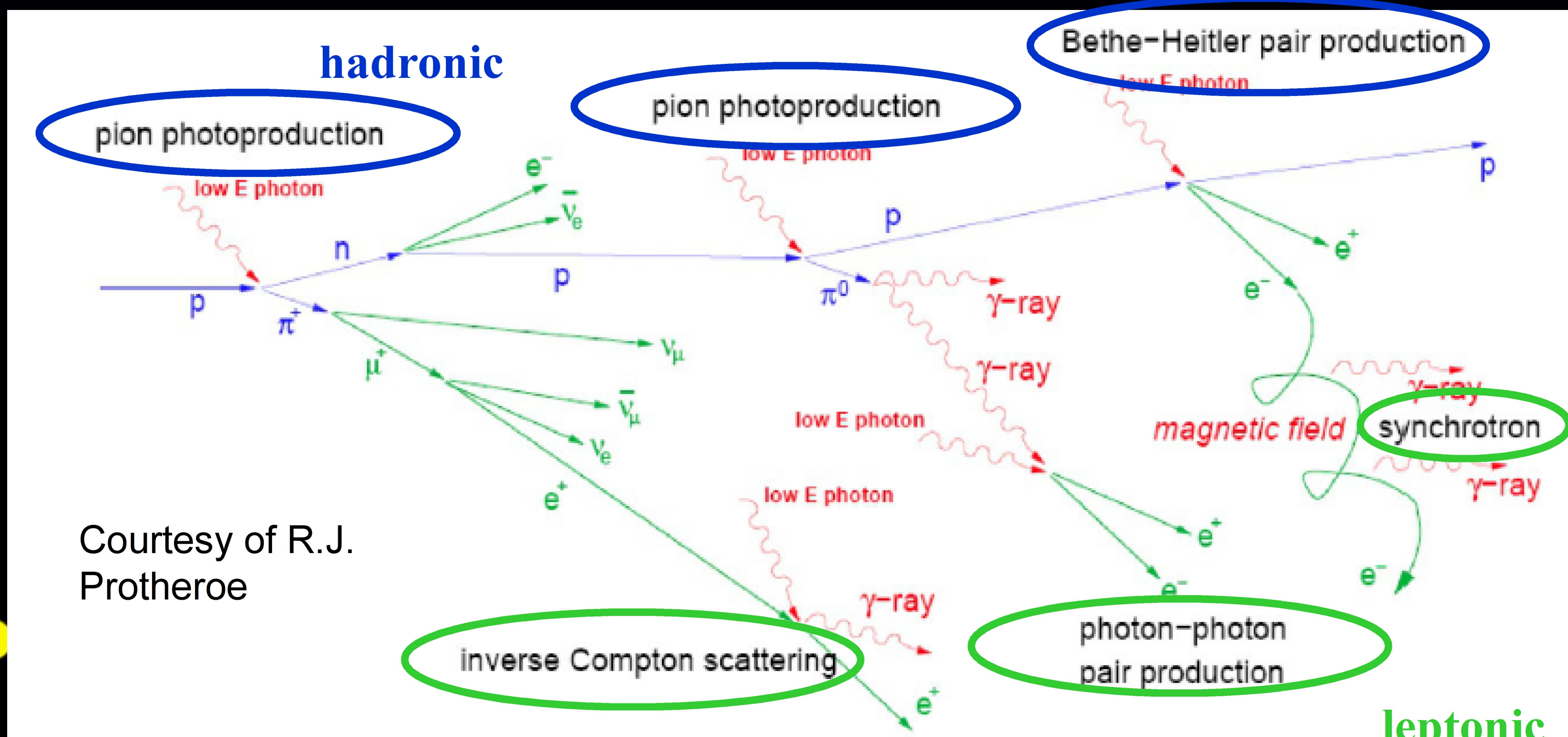


Photohadronic interactions in a nutshell









Numerical method: PDE solver

(Dimitrakoudis et al. 2012)

Protons:

$$\frac{\partial n_{\rm p}}{\partial t} + L_{\rm p}^{\rm BH} + L_{\rm p}^{\rm photopion} + L_{p}^{\rm psyn} + \frac{n_{\rm p}}{t_{\rm p,esc}} = Q_{\rm p}^{\rm inj} + Q_{\rm p}^{\rm photopion}$$

Electrons:

$$\frac{\partial n_{\rm e}}{\partial t} + L_{\rm e}^{\rm syn} + L_{\rm e}^{\rm ics} + L_{\rm e}^{\rm ann} + L_{\rm e}^{\rm tpp} + \frac{n_{\rm e}}{t_{\rm e,esc}} = Q_{\rm e}^{\rm ext} + Q_{\rm e}^{\rm BH} + Q_{\rm e}^{\gamma\gamma} + Q_{\rm e}^{\rm photopion} + Q_{\rm e}^{\rm tpp}$$

Photons:

$$\frac{\partial n_{\gamma}}{\partial t} + \frac{n_{\gamma}}{t_{\gamma,\rm esc}} + L_{\gamma}^{\gamma\gamma} + L_{\gamma}^{\rm ssa} = Q_{\gamma}^{\rm syn} + Q_{\gamma}^{\rm psyn} + Q_{\gamma}^{\rm ics} + Q_{\gamma}^{\rm ann} + Q_{\gamma}^{\rm photopion}$$

Neutrinos:

$$\frac{\partial n_{\nu}}{\partial t} + \frac{n_{\nu}}{t_{\rm esc}} = Q_{\nu}^{\rm photopion}$$

Neutrons:

$$\frac{\partial n_{n}}{\partial t} + L_{n}^{\rm photopion} + \frac{n_{n}}{t_{\rm esc}} = Q_{n}^{\rm photopion}$$

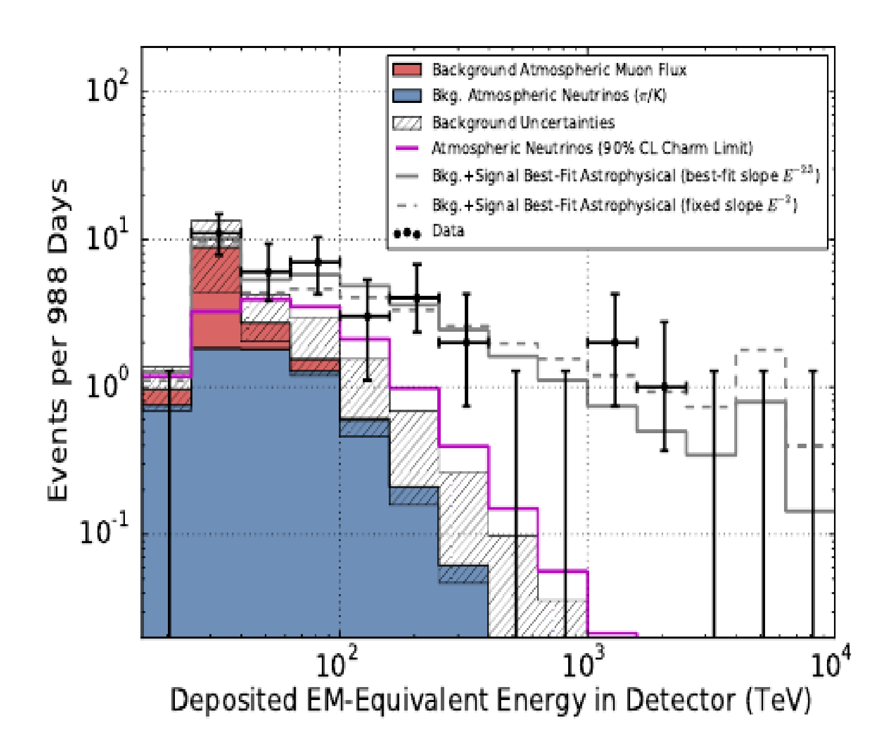
Pion, muon & kaon decay is modeled using results of MC code SOPHIA (Muecke et al. 2000)

Synchrotron cooling of the above is also included.

Courtesy of S. Dimitrakoudis

PeV neutrino emission from GRBs (1)

Aartsen et al. 2014, PhRvL, 113, 10,1101



Flux per flavor:

$$E_\nu^2 \Phi(E_\nu) = (0.95 \pm 0.3) \times 10^{-8}\, GeV\, cm^{-2}\, s^{-1}\, sr^{-1}$$

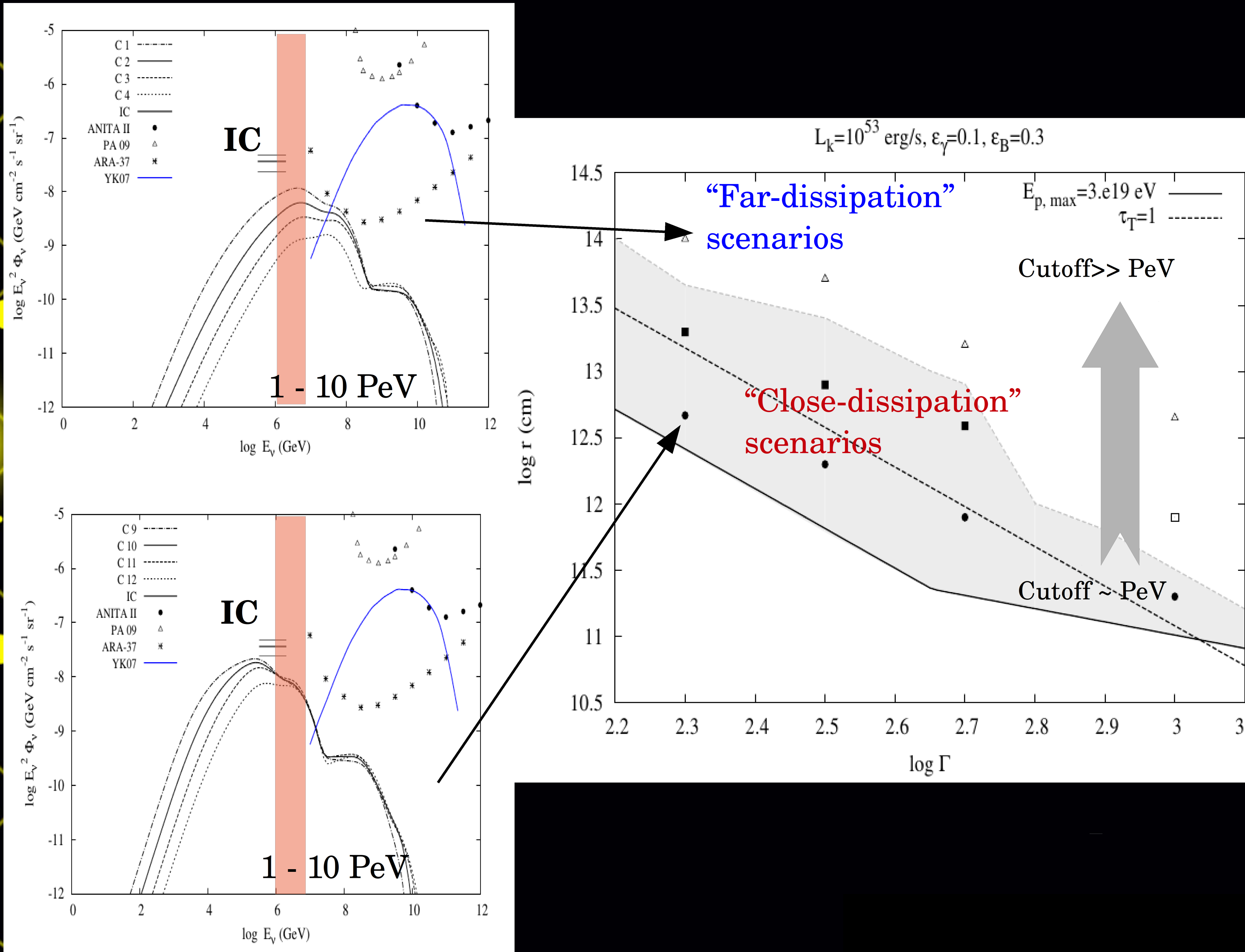
(i) possible cutoff at 2-3PeV
(ii) steepening of the spectrum

Motivation:
A PeV cutoff of the IceCube neutrino spectrum and possible meaning for GRB models

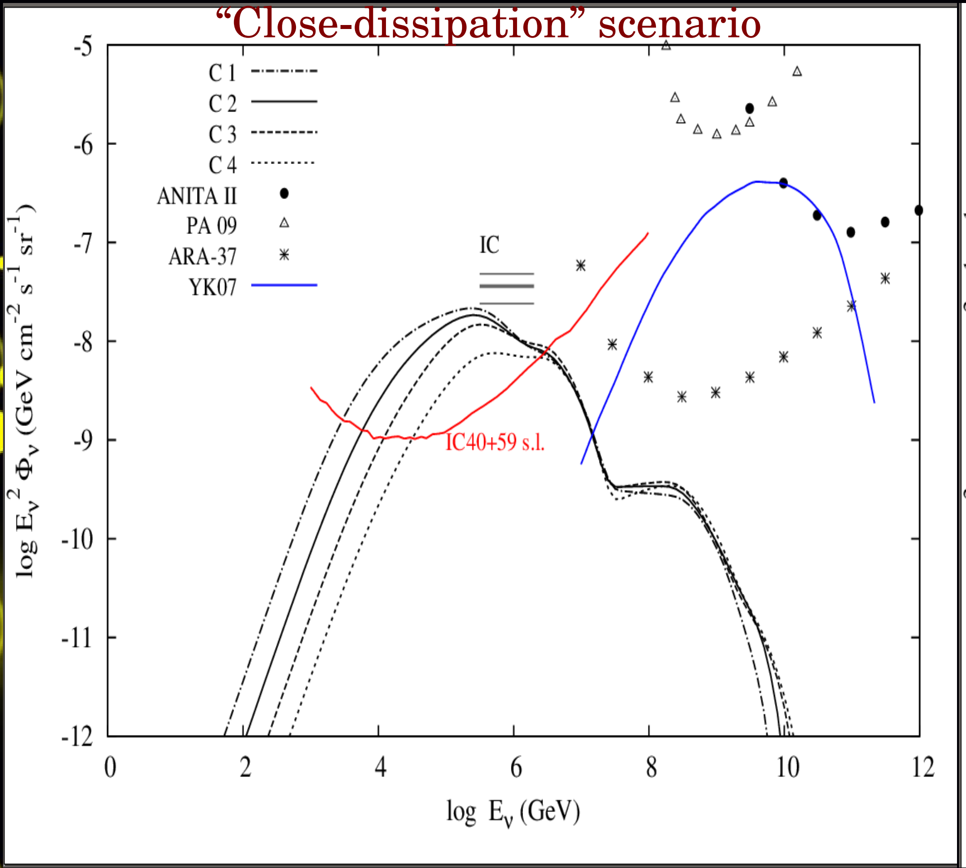
Assumptions:
(i) GRBs are UHECR accelerators

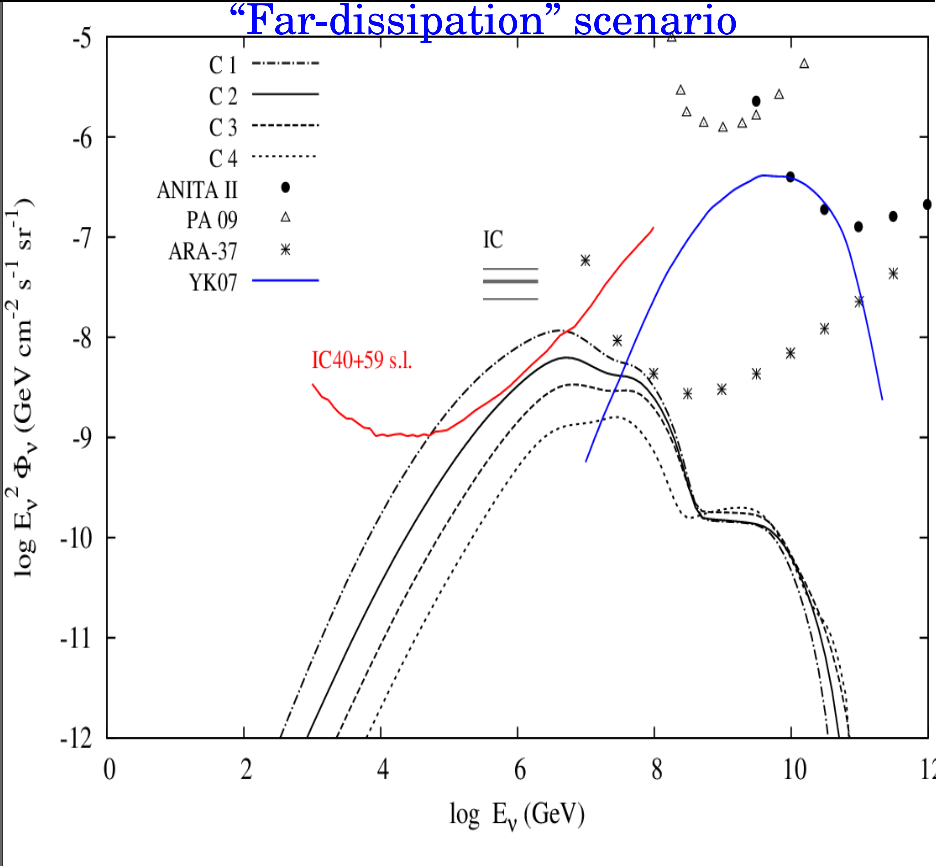
(ii) IceCube flux = diffuse ν flux from GRBs

PeV neutrino emission from GRBs (2)



PeV neutrino emission from GRBs (3)





Conclusions:

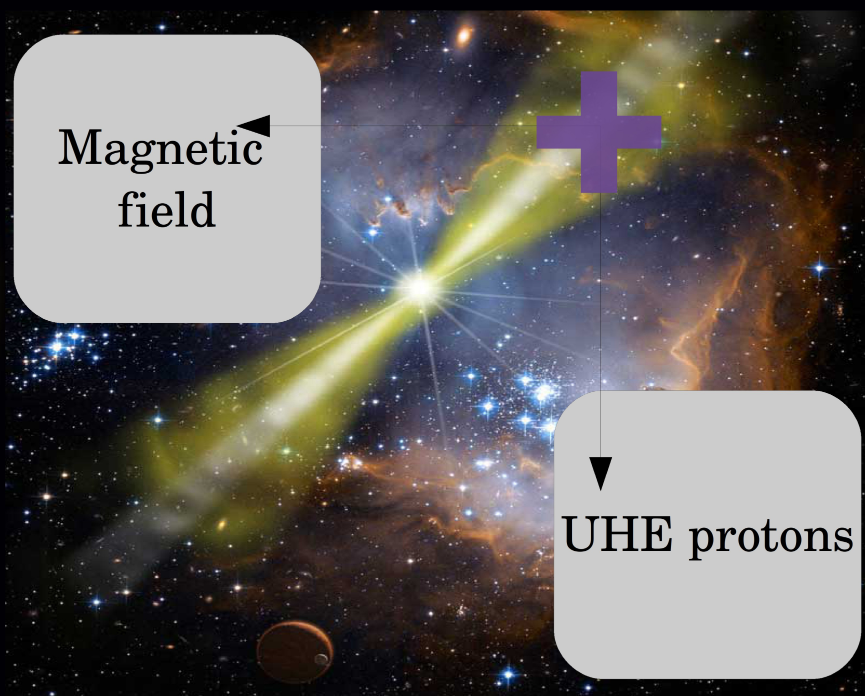
1) If GRBs are UHECR accelerators then far-dissipation scenarios with low pπ efficiency are favored; ν spectral cutoff at >> PeV

2) If dissipation occurs at small distances, the fraction of injected luminosity in UHECRs is << 1

Proton-photon feedback & GRB emission (1)

Motivation:

Efficient and fast transfer of energy from protons to photons due to feedback processes (e.g. *Stern & Svensson 1991, Kirk & Mastichiadis 1992, Petropoulou & Mastichiadis 2012*)

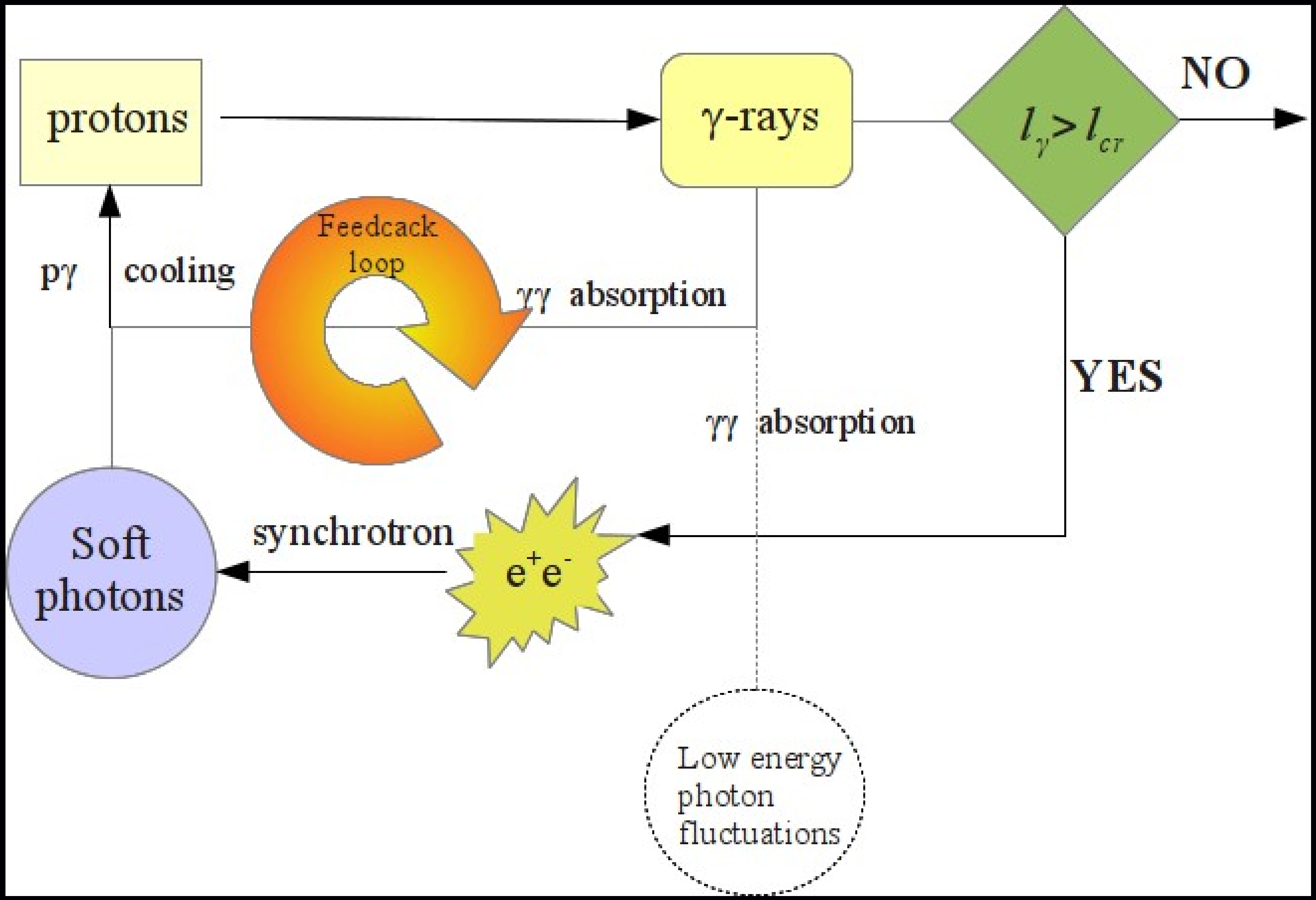


Goals: Answer to the (deceptively) simple question

“ What happens if high-energy protons are injected into a magnetized region?”

Interlude: spontaneous γ-ray quenching

(Stawarz & Kirk, 2007, ApJ, 661, 17; Petropoulou & Mastichiadis, 2011, A&A,532, 11)



Gamma-ray production by:

(1) Photopion processes: *Stern & Svensson 1991; Petropoulou & Mastichiadis 2012,MNRAS, 421, 2325)*

(2) Proton synchrotron radiation: *Petropoulou & Mastichiadis, 2012, MNRAS, 426, 462, Petropoulou et al. 2014 , MNRAS, 444, 2186*

Proton-photon feedback & GRB emission (2)

ASSUMPTIONS

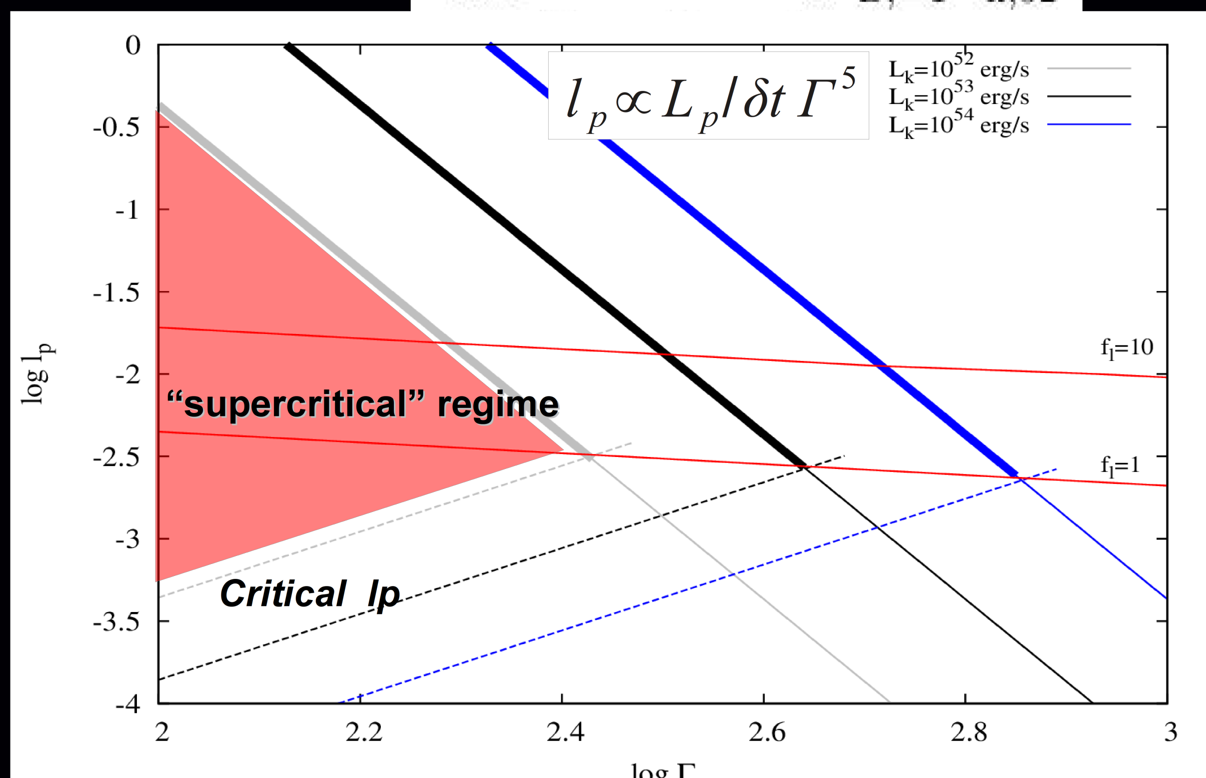
(1) Acceleration of protons to UHE (e.g. Ep,max >0.1EeV) with power-law distribution

(2) Band-like photon spectrum not assumed *a priori*

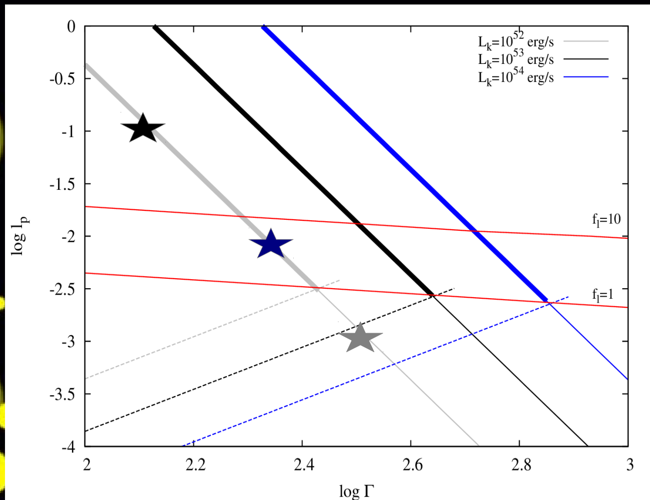
★ Proton injection compactness $\ell_{\rm p}^{\rm inj} = \frac{\epsilon_{\rm p} L_{\rm k} \sigma_{\rm T}}{4\pi m_{\rm p} c^4 \delta t \Gamma^5} = 0.43 \frac{\epsilon_{\rm p,0} L_{\rm k,52}}{\delta t_{-1} \Gamma_2^5}$

★ Proton critical compactness $\ell_{\rm p,cr} = 4 \times 10^{-4} \Gamma_2^2 \epsilon_{\rm B,-1}^{-1/2} L_{\rm k,52}^{-1/2}$! ! !

} Basic quantities



Proton-photon feedback & GRB emission (3)



Subcritical:

proton synchrotron γ-ray emission – low efficiency – not GRB like

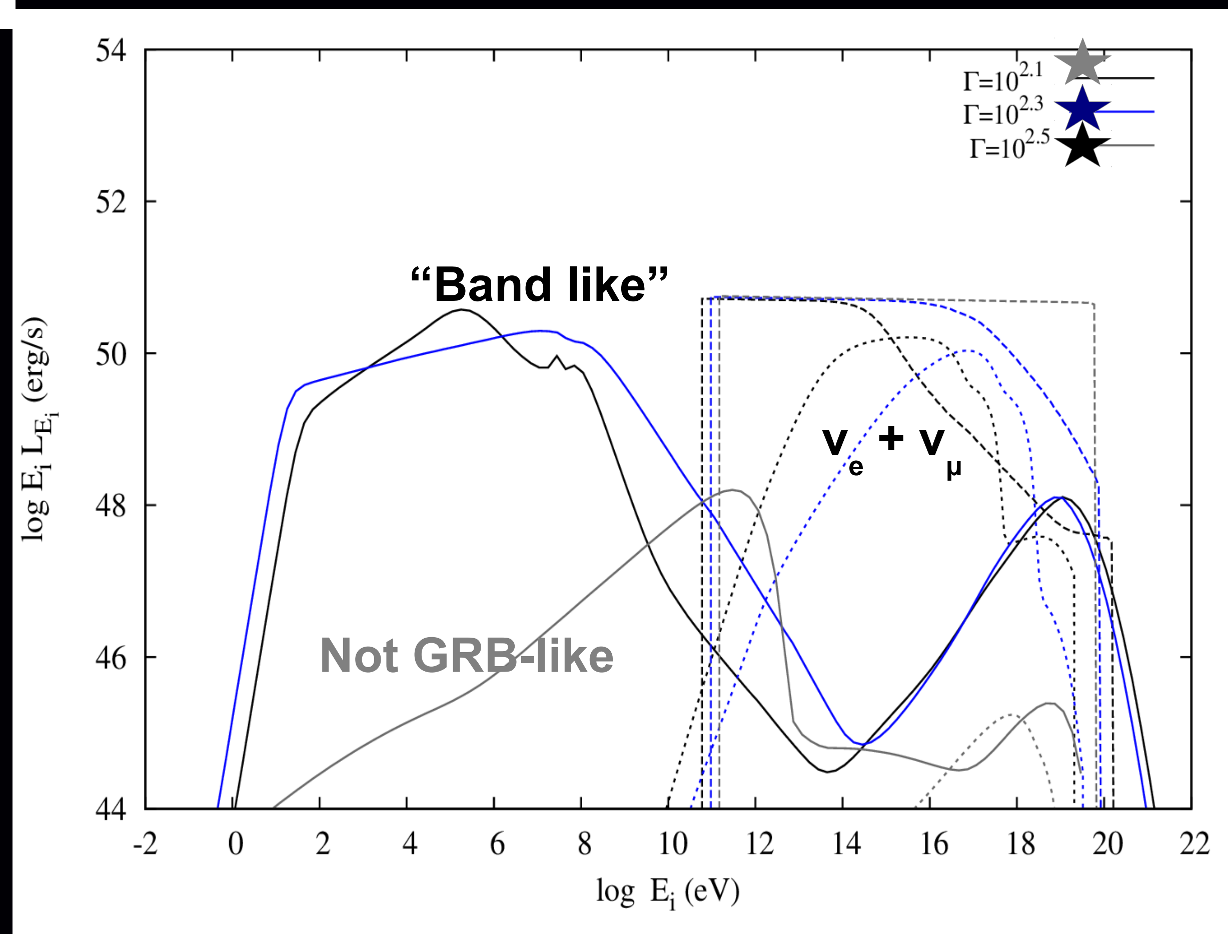
Supercritical:

Photopion efficiency rises → neutrino production; number of cooled pairs increases → γ-ray spectrum shaped by leptonic processes between photons and cold electrons – GRB like

Conclusions

1) Efficient transfer of energy from UHE protons to photons & neutrinos

2) Creation of a “Band-like” photon spectrum from first principles



Thank you

Additional slides

Comparison of MonteCarlo and PDE solver codes for neutrino production

MC codes

(e.g. Asano et al. 2009, ApJ, 699, 953; Huemmer et al. 2010, ApJ, 721, 630, Baerwald et al. 2011, PhRvD, 83, 067303)

Pros:

1) detailed physics of hadronic interactions

2) efficient: good for wide parameter space searches – bounds from stacking analyses – model fits

Cons:

1) steady-state approach: time-dependency cannot be resolved – feedback effects on the proton or/and photon distribution cannot be taken into account

PDE solver code DMPR12

(Dimitrakoudis et al. 2012, A&A, 546, A120)

Pros:

1) detailed physics of hadronic interactions from SOPHIA MC code

2) time-dependent code

3) treats feedback effects

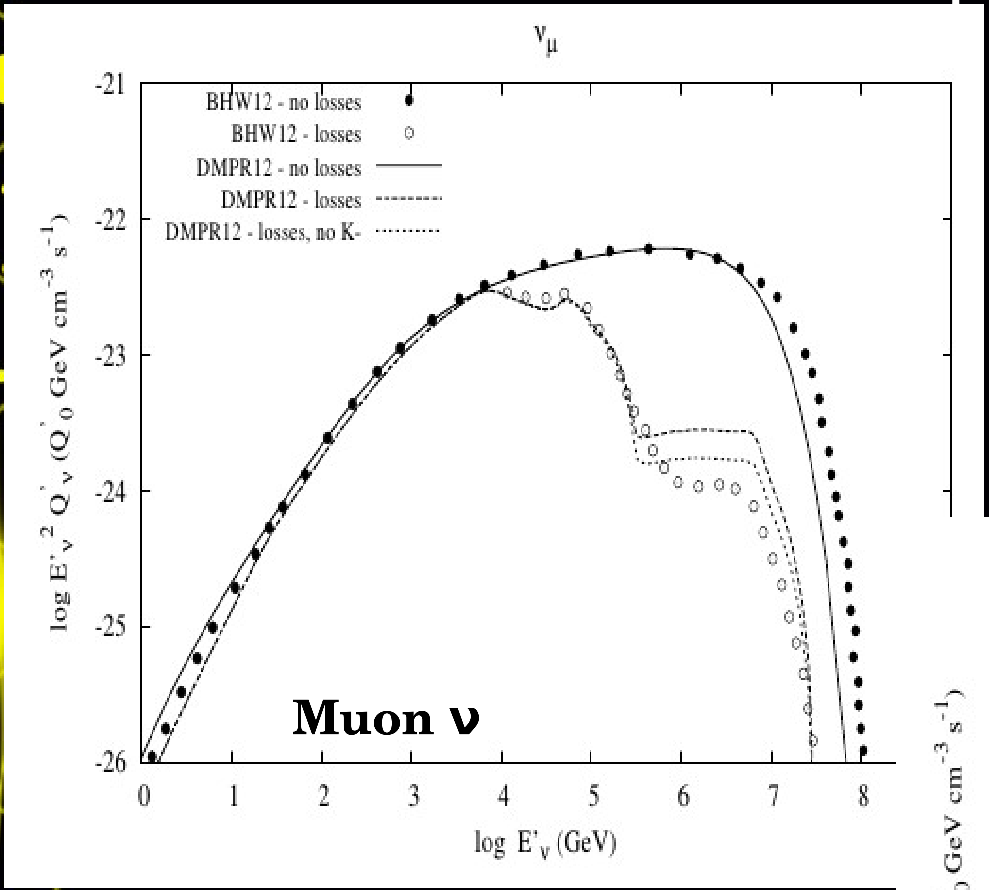
4) energy conserving scheme

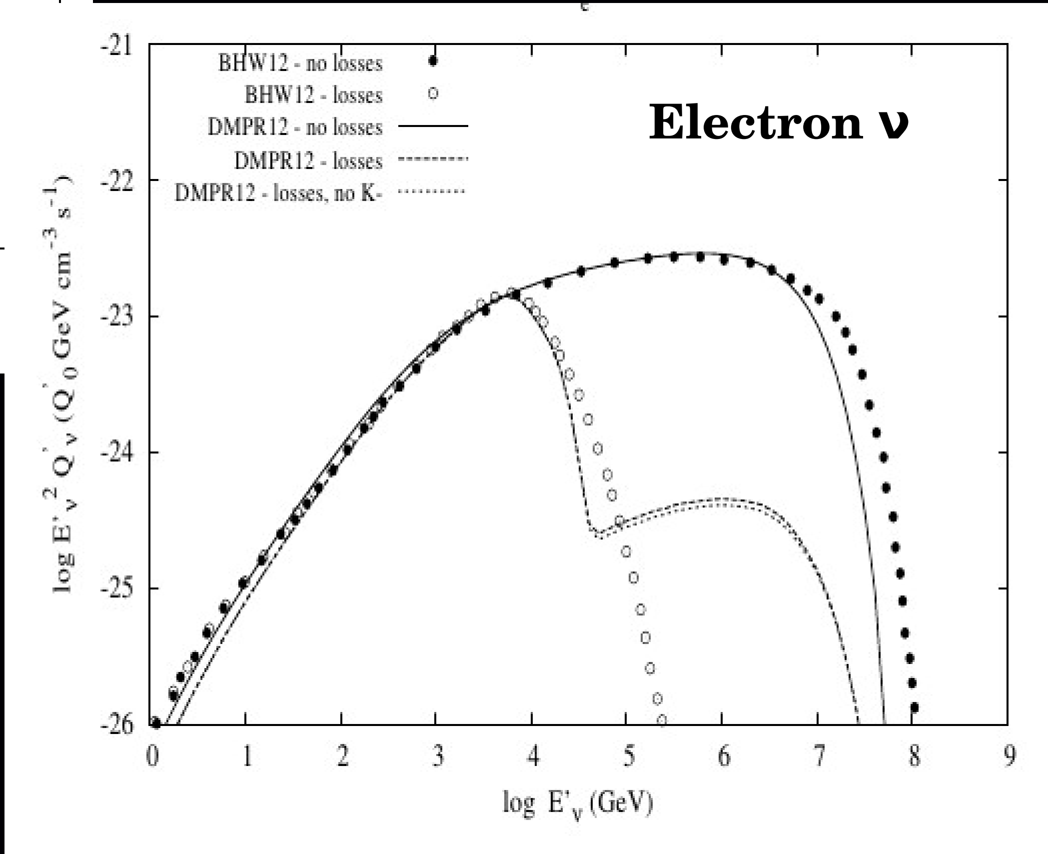
Cons:

1) time-consuming: not designed for parameter space studies

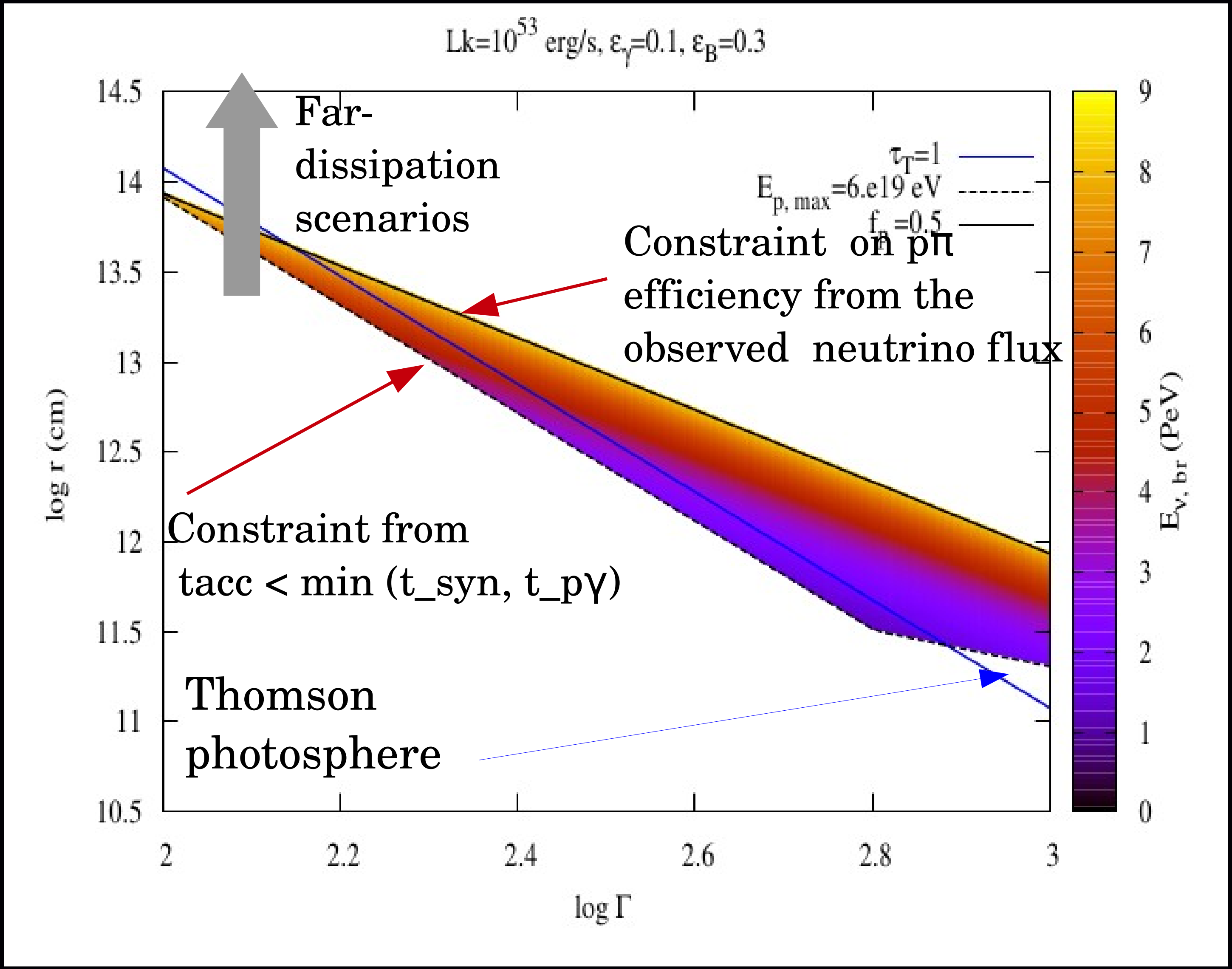
2) cannot isolate the contribution of neutral kaons

Comparison of MonteCarlo and PDE solver codes for neutrino production





PeV neutrino emission from GRBs



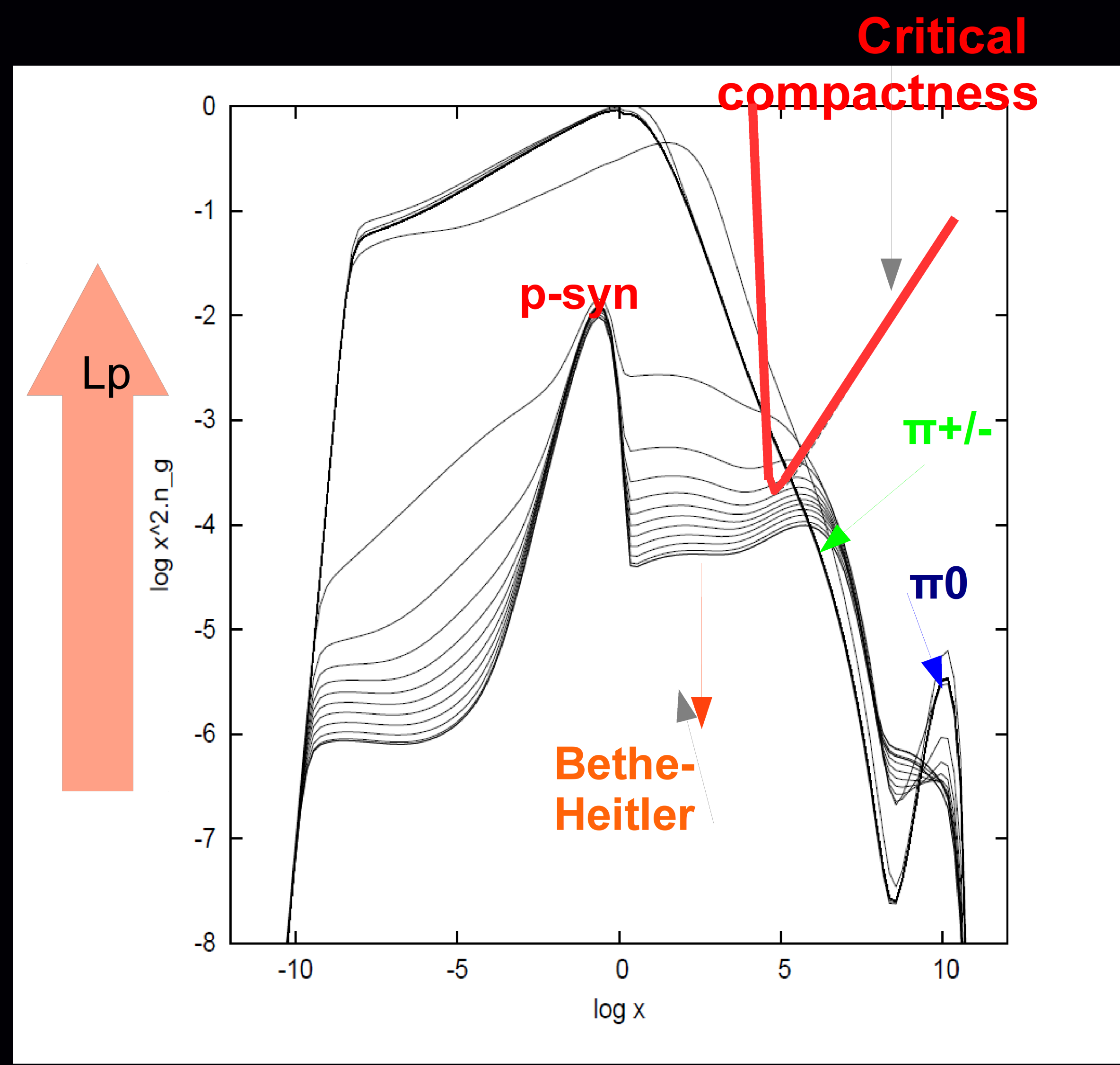
In close-dissipation scenarios → prediction of PeV cutoff !

Interlude: spontaneous γ-ray quenching

PROTONS → GAMMA-RAYS – escape

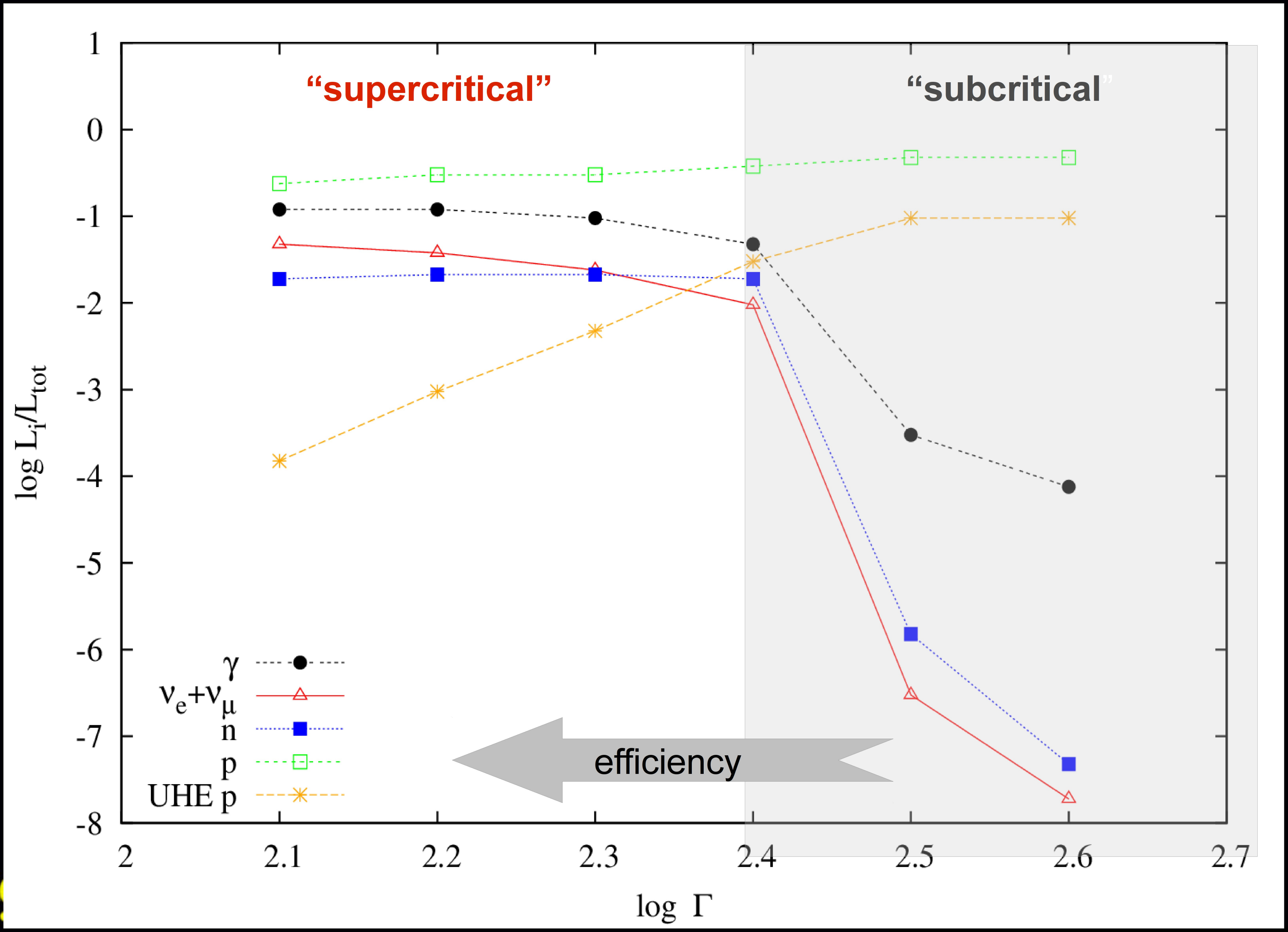
quenching

(self-generated) SOFT PHOTONS



Efficiency

$L_{tot} = L_k + L_p + L_B = const$ & $E_{p,max} = const$



Future aspects: variability

Motivations:

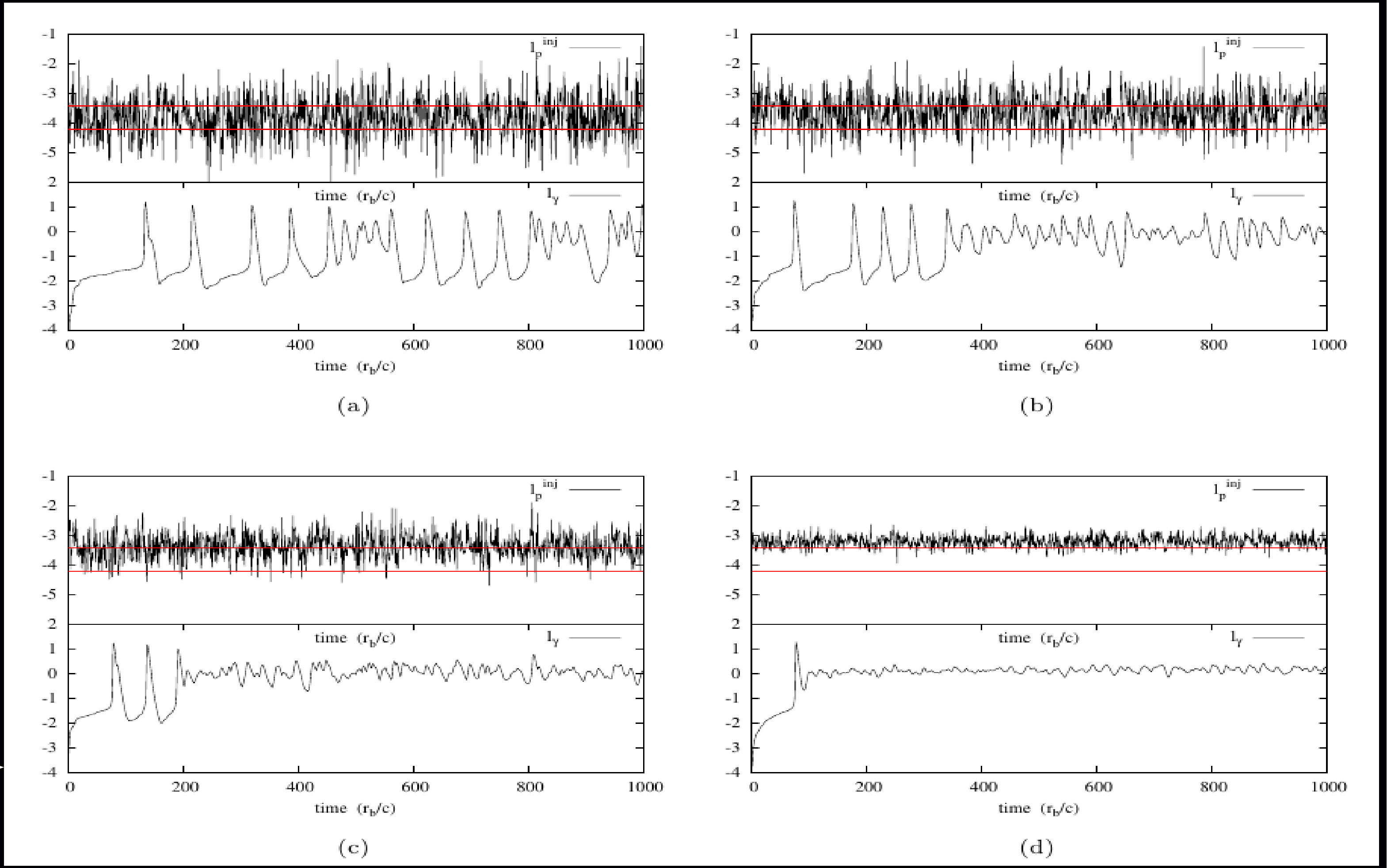
(1) Emission spectra + efficiency depends sensitively on the ratio lp,inj/lp,cr

(2) Power spectral density of γ-ray lightcurves is described by a (broken) power-law

(e.g. Beloborodov + 2000, ApJ, 535; Dichiara + 2013, MNRAS)

Lp(t) →

Lph(t) →



Future aspects: variability