The effect of leptohadronic feedback processes on high-energy signatures from GRBs

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Gamma-Ray Bursts in the Multi-Messenger Era

Paris, 18th June 2014

What happens if we inject HE protons

in a compact magnetized region

Outline

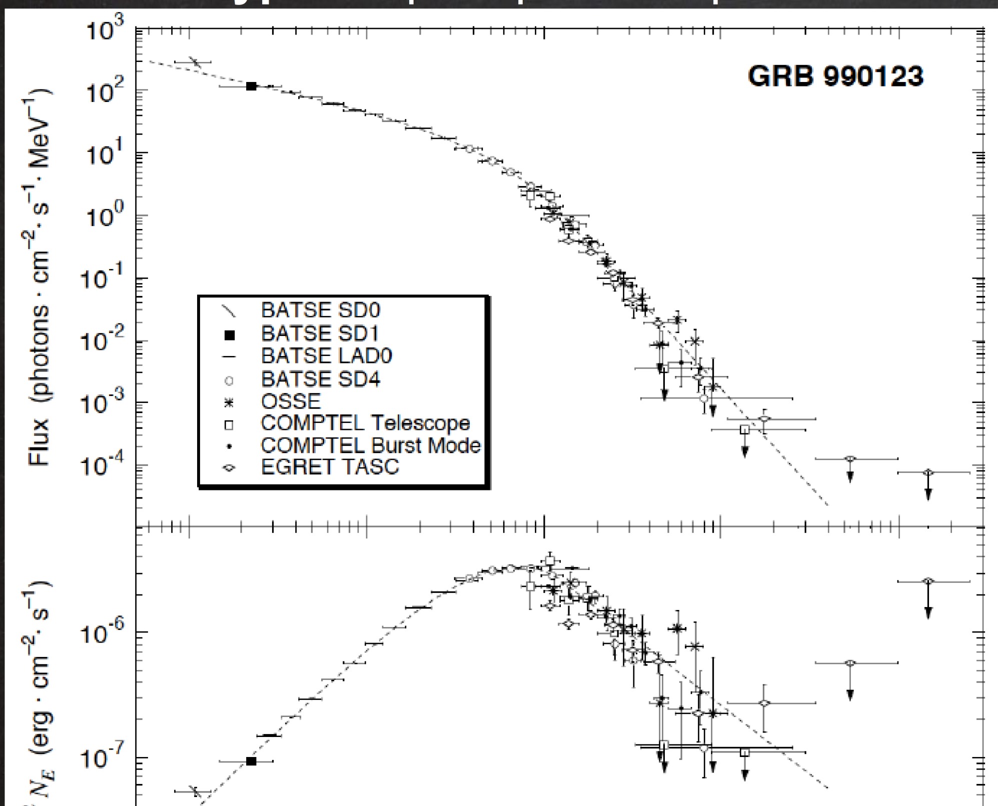
- Introduction: leptonic & hadronic GRB models
- Physical processes in leptohadronic plasmas
- Interlude : spontaneous γ-ray quenching
- Model description & analytical estimates
- First results: spectra & efficiency
- Future aspects

Introduction

Spectral features described by Band function
(Band et al. 1993)

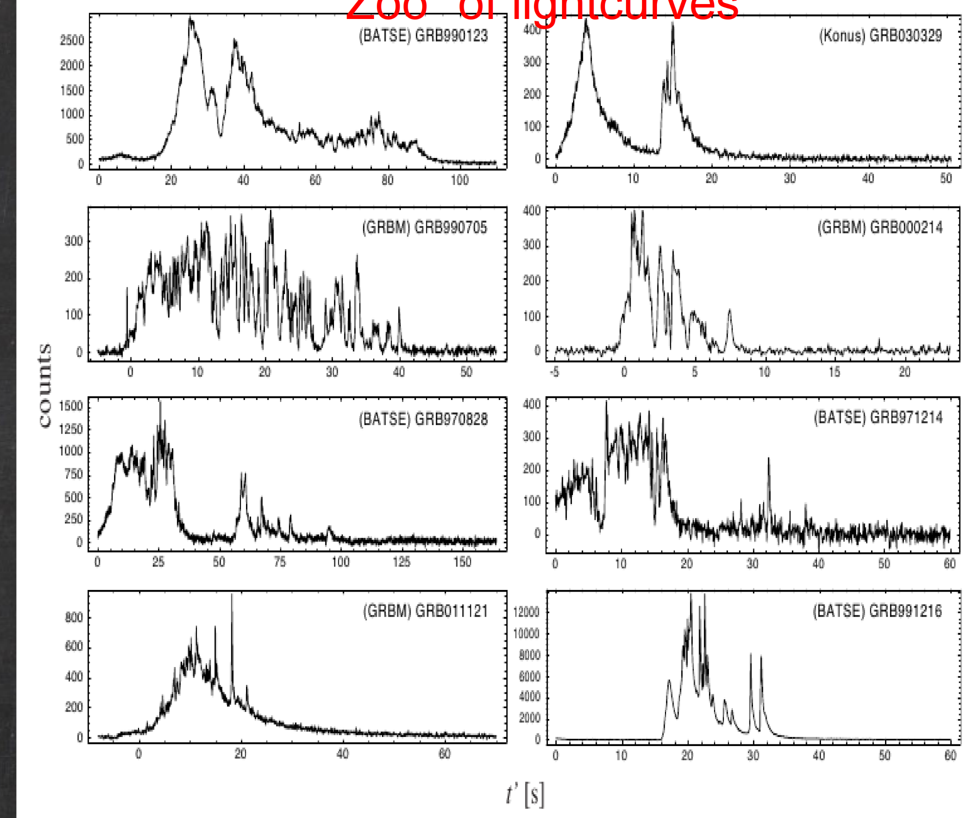
- Non-thermal appearance
- peak at ~0.5-1 MeV
- Photon indices: α ~ 1, β~2.3

"Typical" prompt GRB spectrum

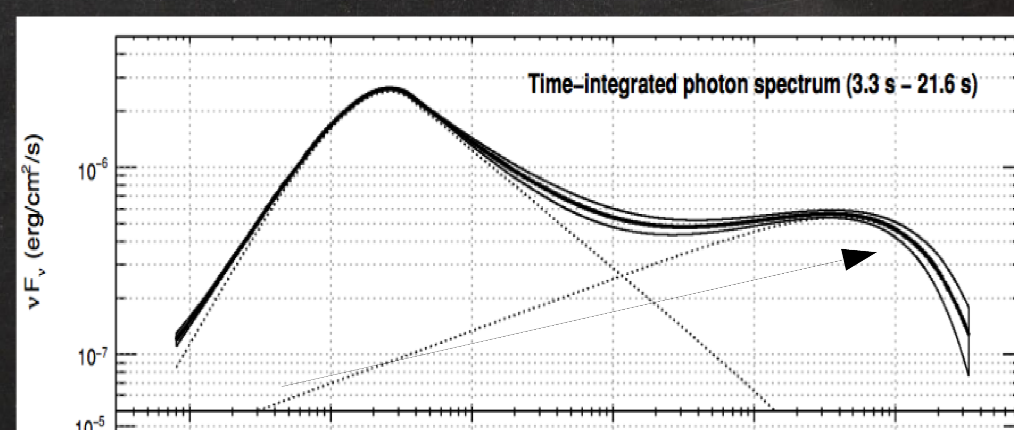


Credit: Briggs et al. 1999, ApJ, 524

"Zoo" of lightcurves



e.g. of a bright Fermi/LAT burst: GRB090926A



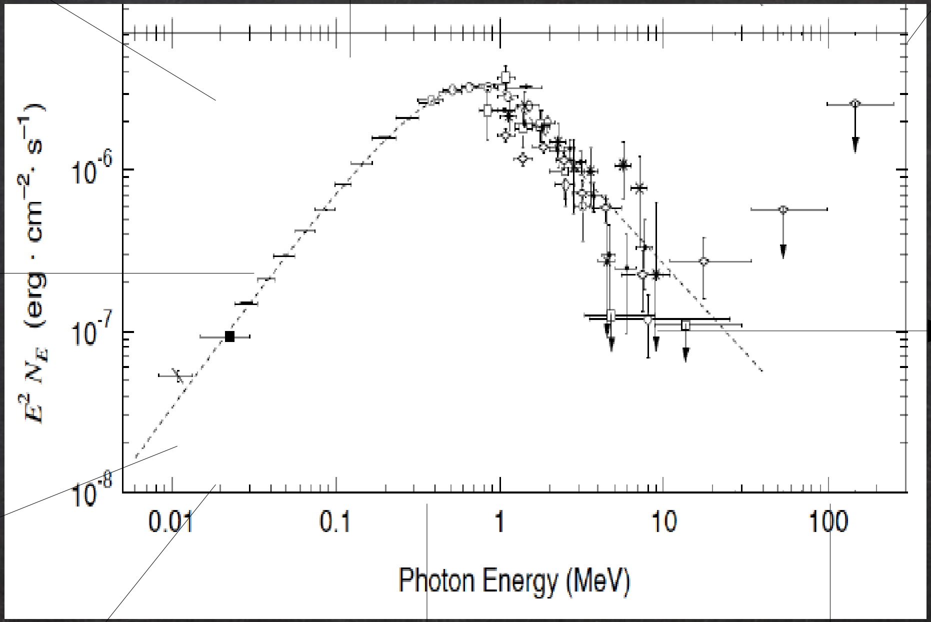
Introduction – leptonic variants

Optically thin synchrotron emission
(e.g. Katz 1994, Sari + 1996, Tavani 1996, …, Beniamini & Piran 2013)

Modifications due to electron cooling in KN regime and adiabatic cooling
(e.g. Derishev + 2001, Wang+2009, Daigne + 2011)

SSC & continuous acceleration of electrons
(Stern & Poutanen 2004)

synchrotron emission & anisotropic pitch angle distribution
(Lloyd & Petrosian 2000)



Comptonization of Quasi-thermal emission In continuous dissipation models
(e.g.Meszaros & Rees 2000, Pe'er et al 2006, Giannios 2010, 2012)

Jitter radiation
(Medvedev 2000)

Synchrotron emission in decaying magnetic fields
(e.g. Pe'er & Zhang 2006)

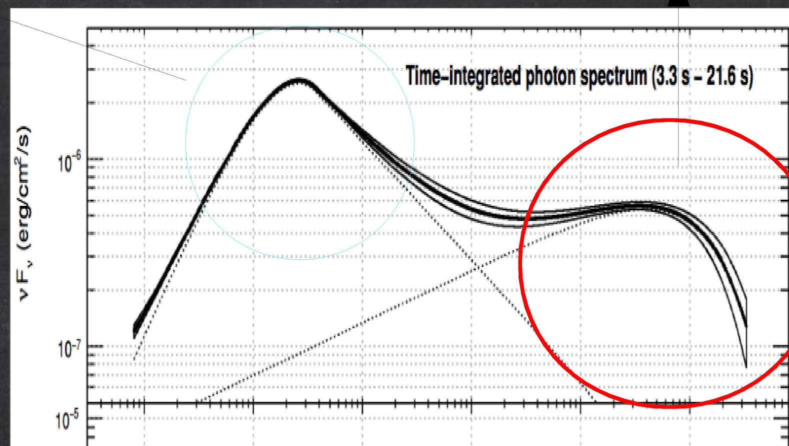
ICS of synchrotron self-absorbed emission
(Panaitescu & Kumar 2000)

Photospheric emission
(e.g. Goodman 1986, Thompson 1994, Beloborodov 2010)

Introduction – hadronic variants

Synchrotron emission of re-accelerated secondary pairs injected by the hadronic cascade
(Murase et al. 2008)

Synchrotron and/or ICS emission from pairs produced through the proton initiated cascade
(e.g. Dermer & Atoyan 2006, Asano & Inoue 2007, Asano et al. 2009, Asano et al. 2010)

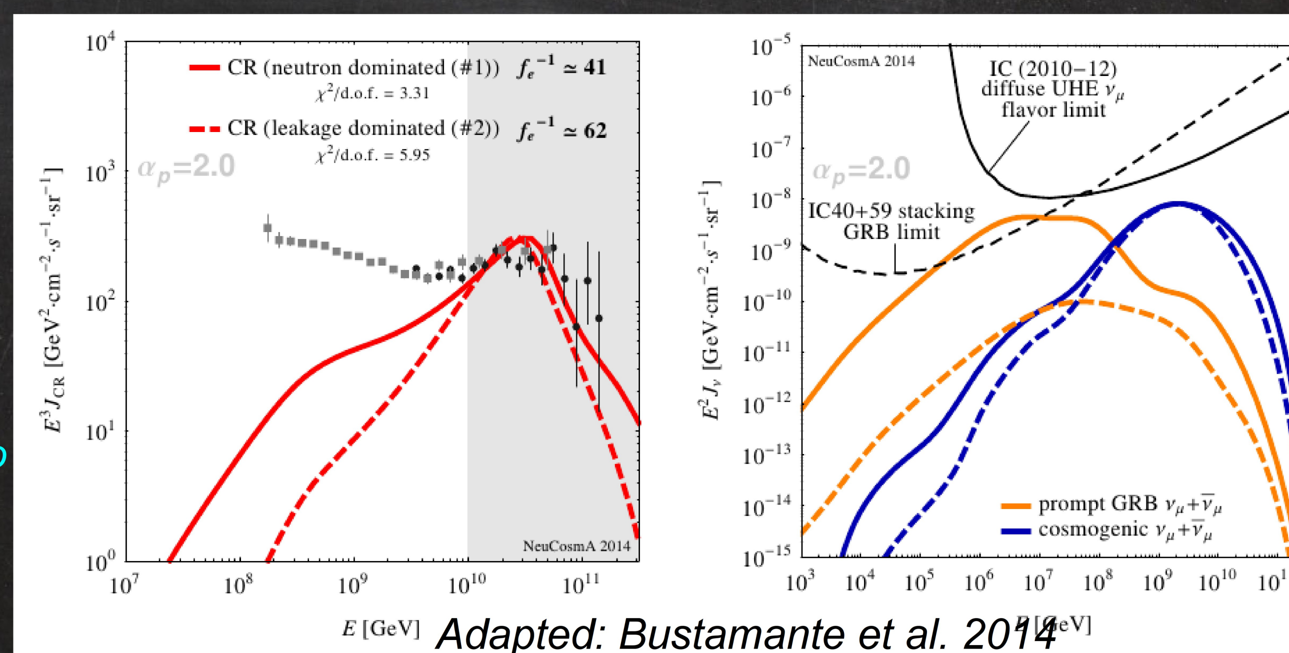


Proton synchrotron emission
(e.g. Vietri 1997, Totani 1998)

BONUS: UHECRs + neutrinos

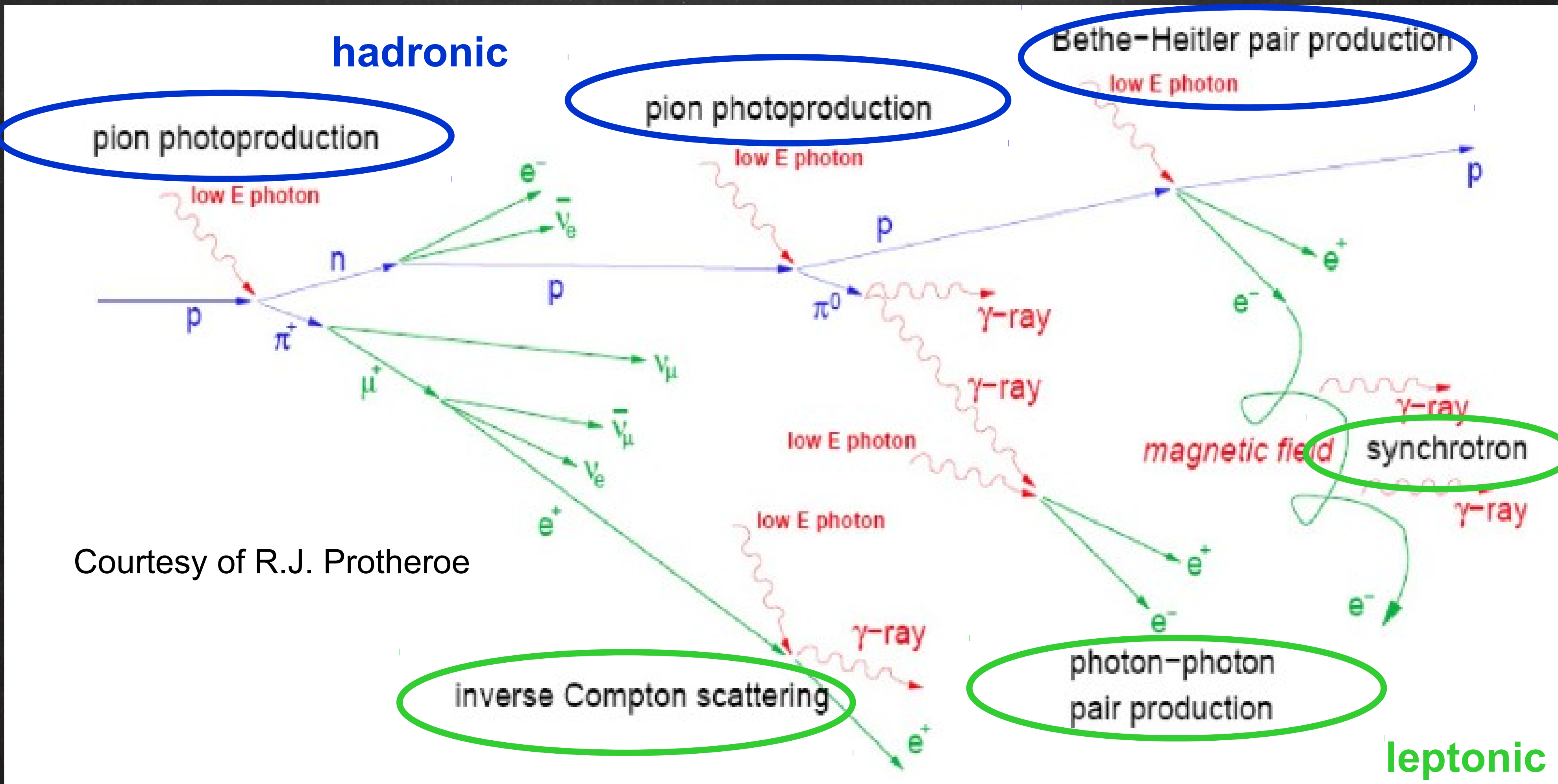
(e.g. Vietri 1995, Waxman 1995, Waxman & Bahcall 1997, Murase & Nagataki 2006, Gao et al. 2012, Baerwald 2014, Reynoso 2014, Petropoulou et al. 2014...)

(talks by S. Inoue, D. Allard, M. Bustamante, K. Murase ...)

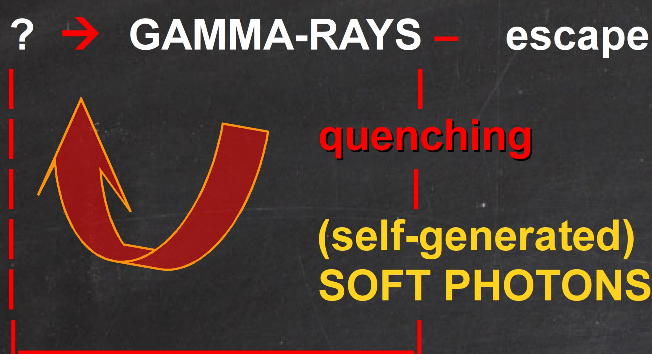


Adapted: Bustamante et al. 2014

Physical processes in a nutshell

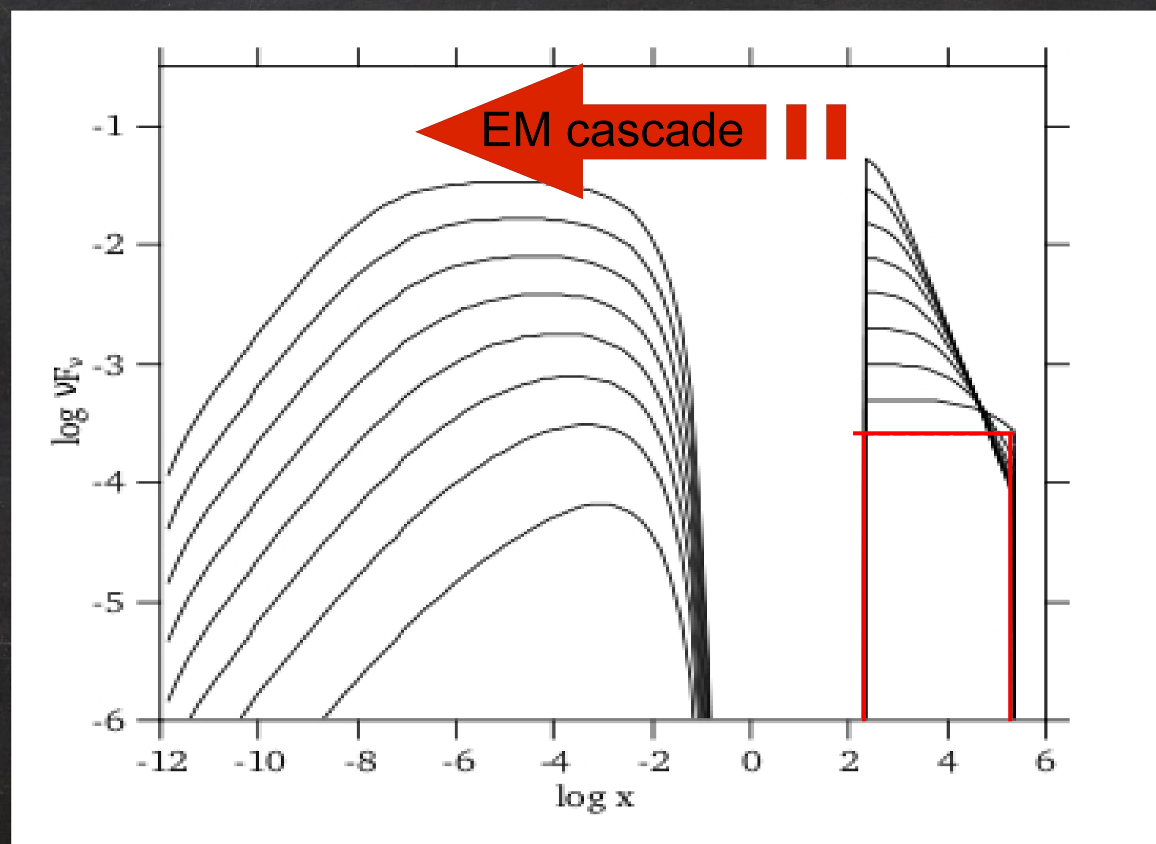


Interlude: Spontaneous γ-ray quenching



γ-ray compactness

$$l_\gamma \propto L_\gamma^{co} / r$$



Gradual increase of γ-ray compactness

Stawarz & Kirk 2007,
Petropoulou & Mastichiadis 2011, Petropoulou et al. 2013

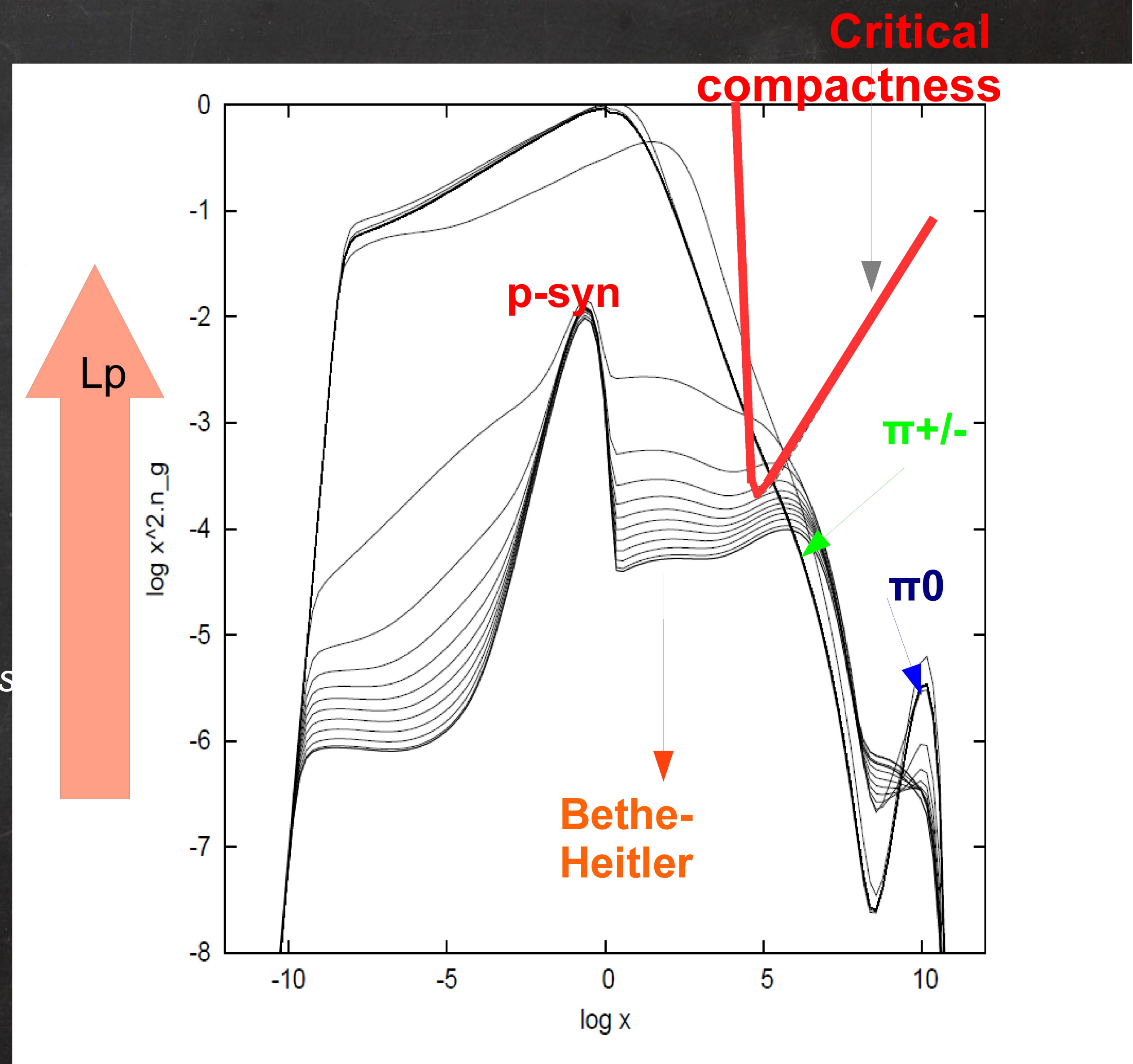
Interlude: γ-ray quenching & other processes

γ-rays are the product of:

Photopion processes (*Stern & Svensson 1991;Petropoulou & Mastichiadis 2012*)

Proton synchrotron radiation

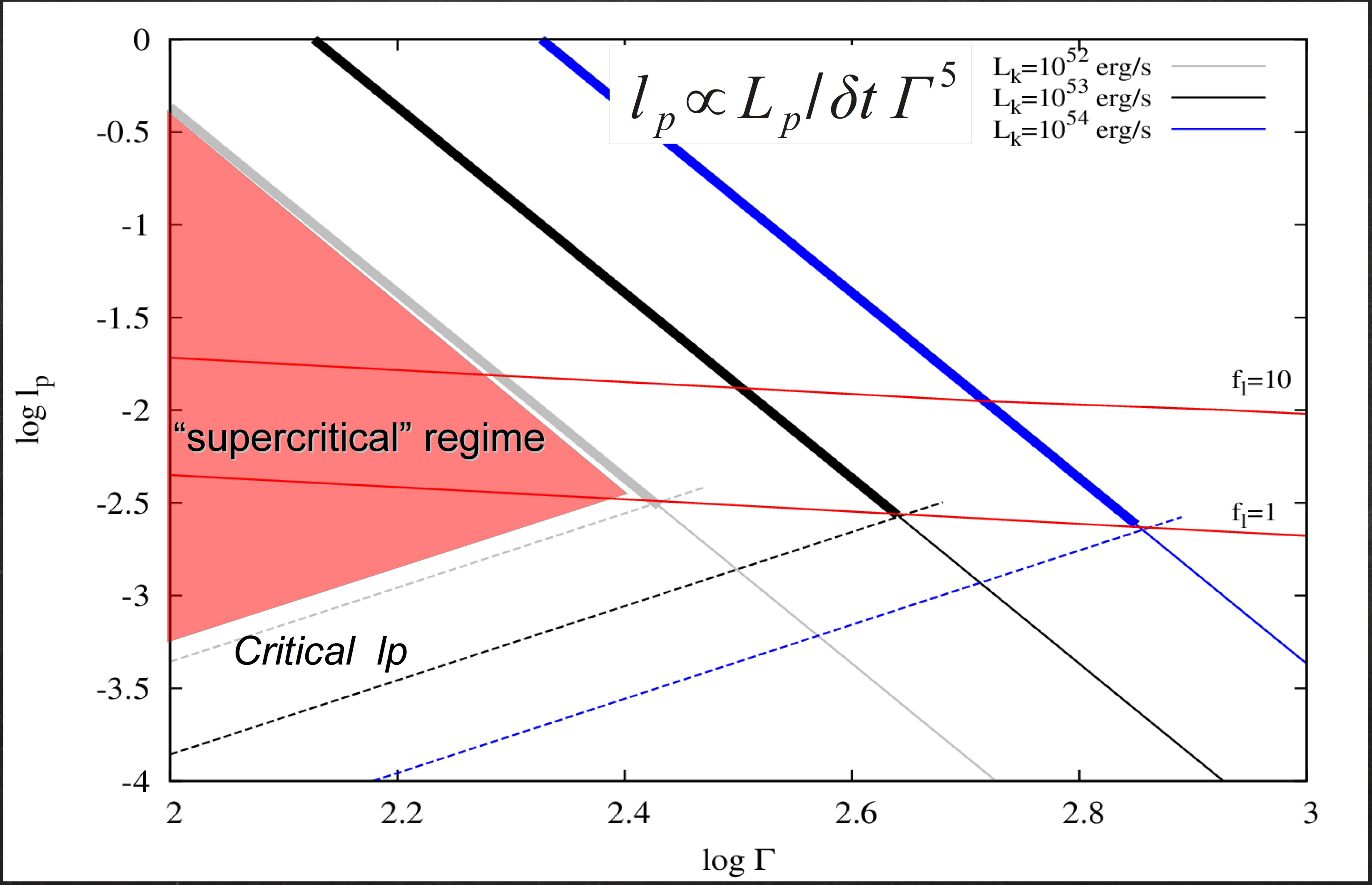
(*Petropoulou & Mastichiadis, 2012*
Petropoulou et al. 2014 submitted MNRAS)



Model description & analytical estimates

Assumptions:

- Acceleration of protons to UHE with power-law distribution (e.g. Ep,max >0.1EeV)
- Injection of protons in an initially *optically thin* region of size r/Γ and variability cδt ~ r/Γ^2
- $L_p = \xi_p * L_k$ and $L_B = \xi_B * L_k$, L_k : kinetic luminosity of the jet
- Band-like photon spectrum not pre-assumed



Numerical code: kinetic equation approach

- Bethe-Heitler pair production
- Proton photon pion production
- Neutron photon pion production
- Proton synchrotron radiation
- Pion, muon, kaon synchrotron radiation
- Electron synchrotron radiation
- Inverse Compton scattering
- Photon photon absorption
- Synchrotron self-absorption
- Pair annihilation
- Photon downscattering on cooled pairs
- Escape /adiabatic cooling

Dimitrakoudis et al. 2012

Protons:

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

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:

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

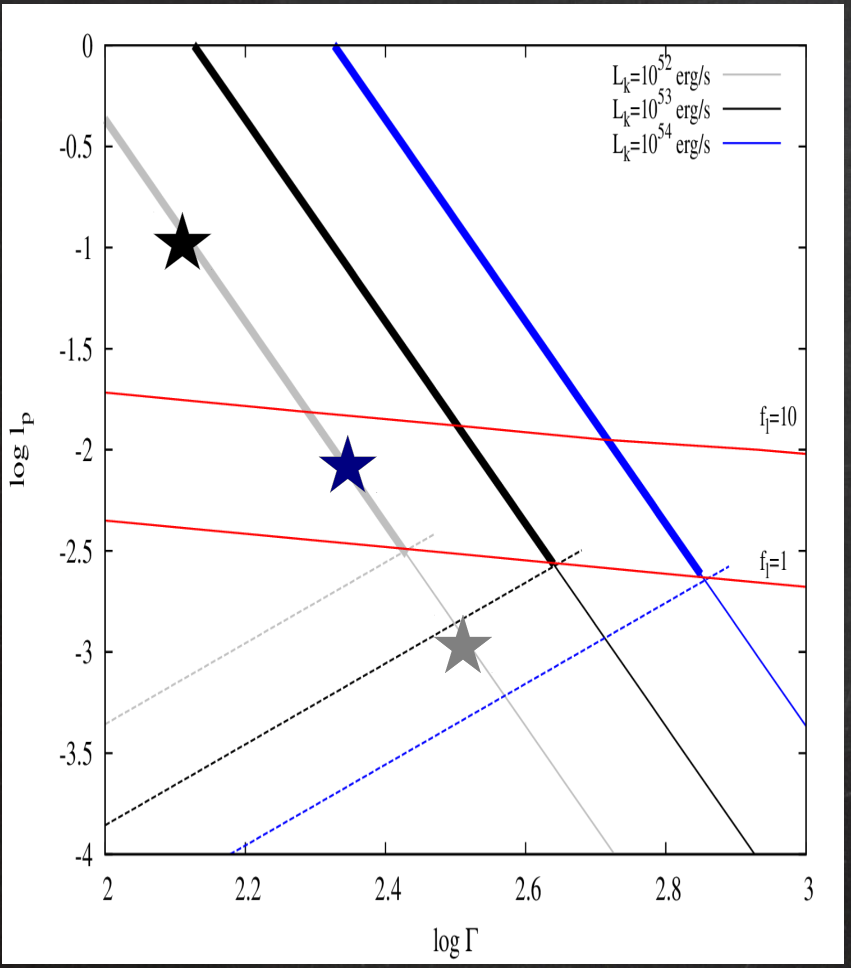
Neutrons:

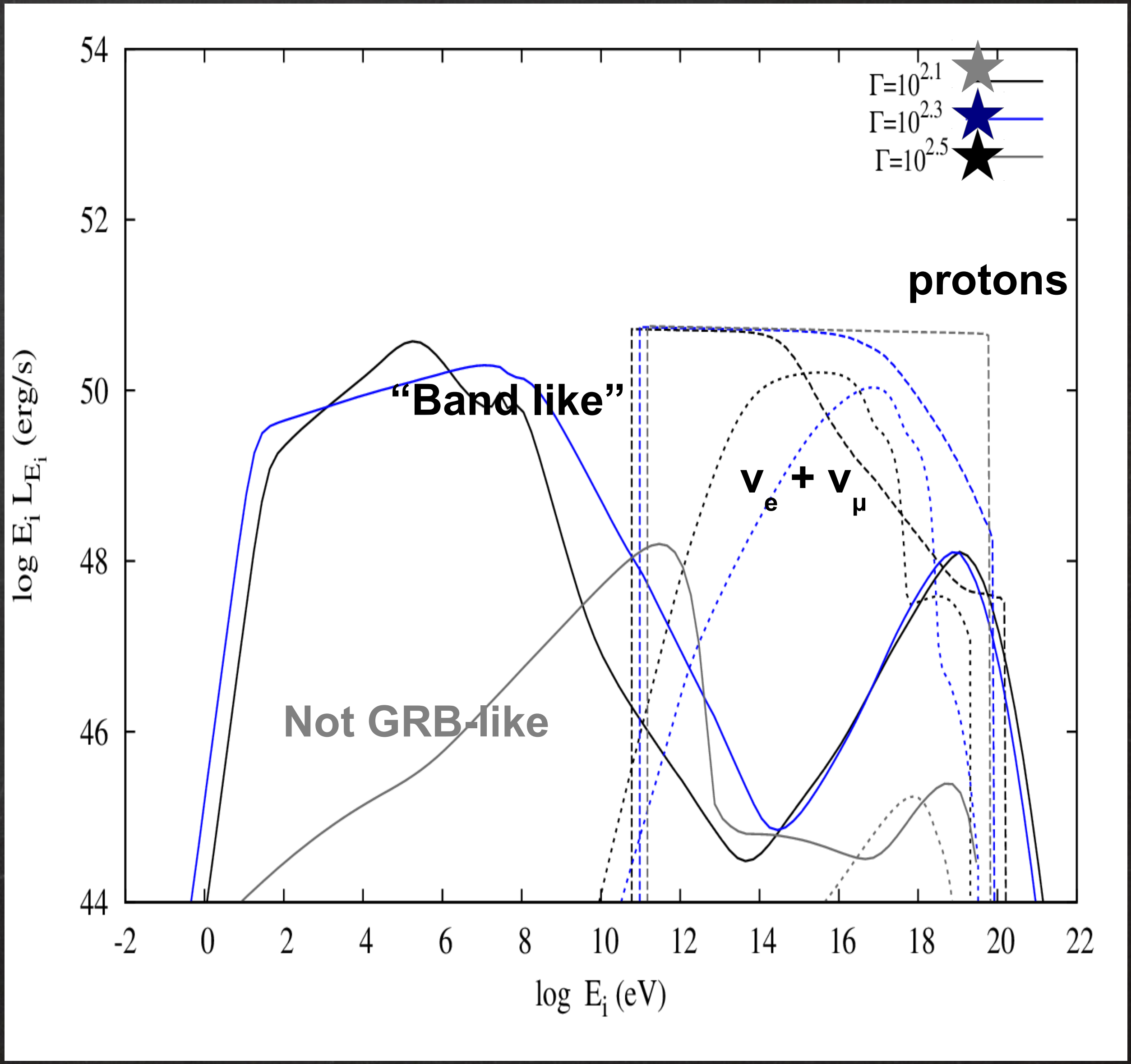
$$\frac{\partial n_{n}}{\partial t} + L_{n}^{\rm photopion} + \frac{n_{n}}{t_{\rm esc}} = Q_{n}^{\rm photopion}$$

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

BH pair production modeled using results by **MC of Protheroe & Johnson (1996)**

Results: Spectra

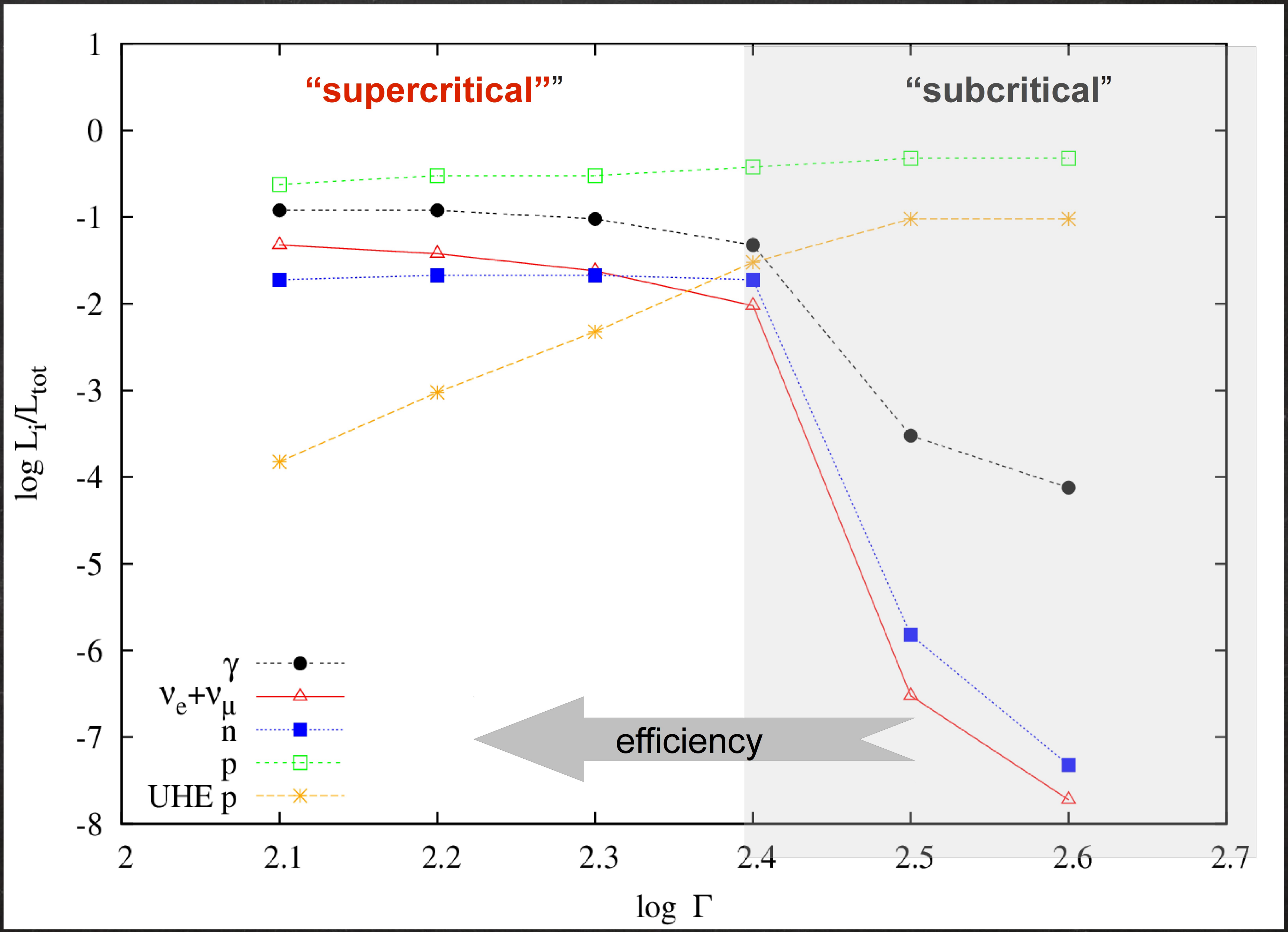




Photon + ν spectra sensitive to the ratio of lp/lp,cr!

Results: Efficiency

Ltot=L_k + L_p + L_B =const & Ep,max=const

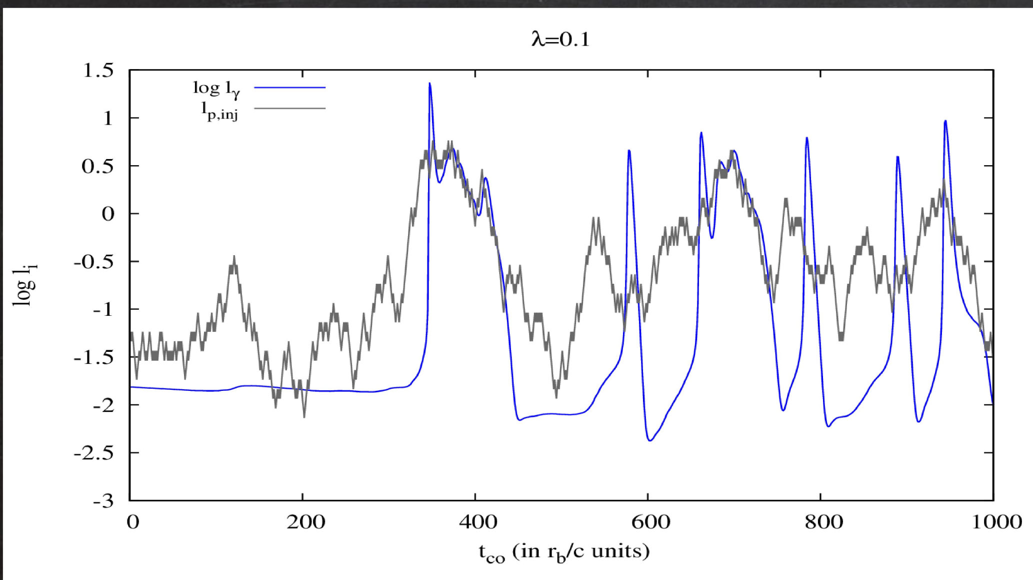


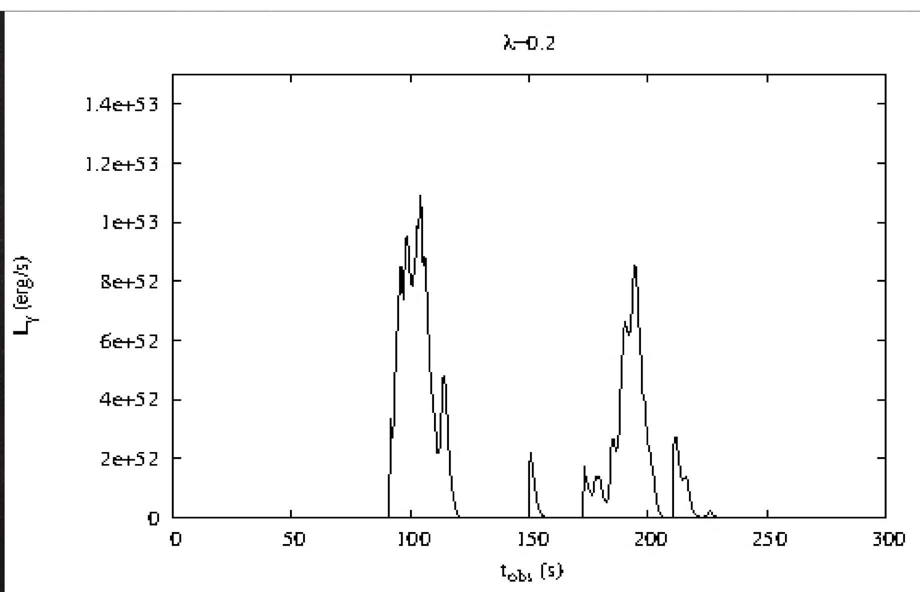
Future aspects: variability

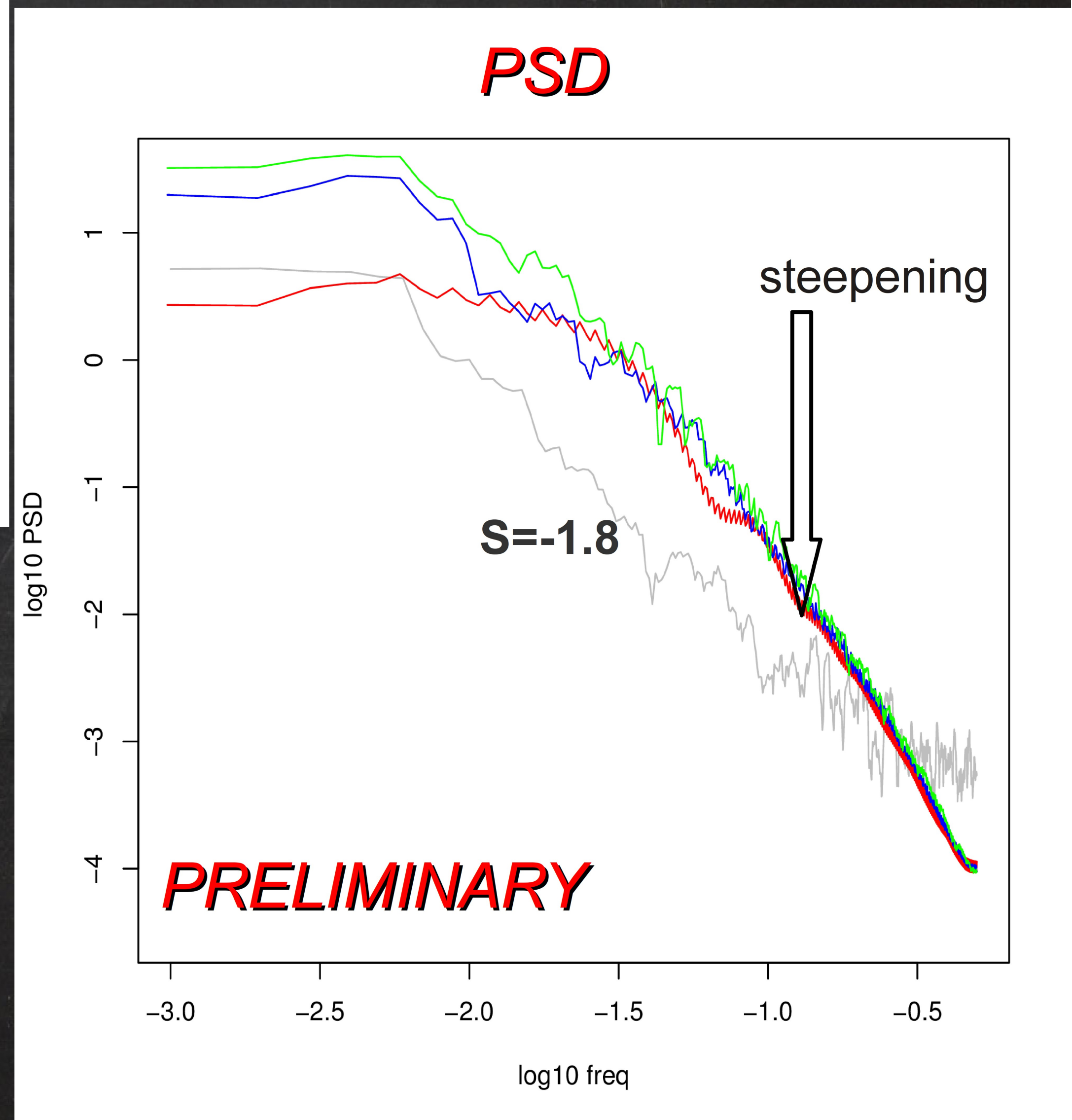
Motivations:

- Emission spectra + efficiency depends sensitively on the ratio lp,inj/lp,cr .
- Power spectral density of γ-ray lightcurves is described by a (broken) power-law
  (e.g. Beloborodov + 2000, ApJ,535 Dichiara + 2013, MNRAS)

See also Poster 3







Summary

Q: What are the main results?
A: Efficient transfer of energy from HE protons (e.g. $E_p>0.1$EeV) to γ-rays, neutrinos and neutrons with a **minimum of free parameters**

Q: When?
A: Whenever the injection proton compactness exceeds a critical value →
e.g. $L_k = L_p \sim 1e52$erg/s & $\Gamma < 250$, $L_k = L_p \sim 1e53$erg/s & $\Gamma < 400$ …

Q: With what assumptions?
A: proton acceleration to HE energies & $B \sim 1000 - 10^6$ G

Q: What else?
A: (1) Time-dependent study of the problem seems promising for γ-ray lightcurves
(2) Time-integrated gamma-ray and neutrino spectra have to be studied
(3) Study the parameter space that leads to Band spectra
(4) Maybe more free parameters needed for addressing the whole GRB phenomenology

Thank you for your attention