The role of hadronic cascades in GRB models of efficient neutrino production

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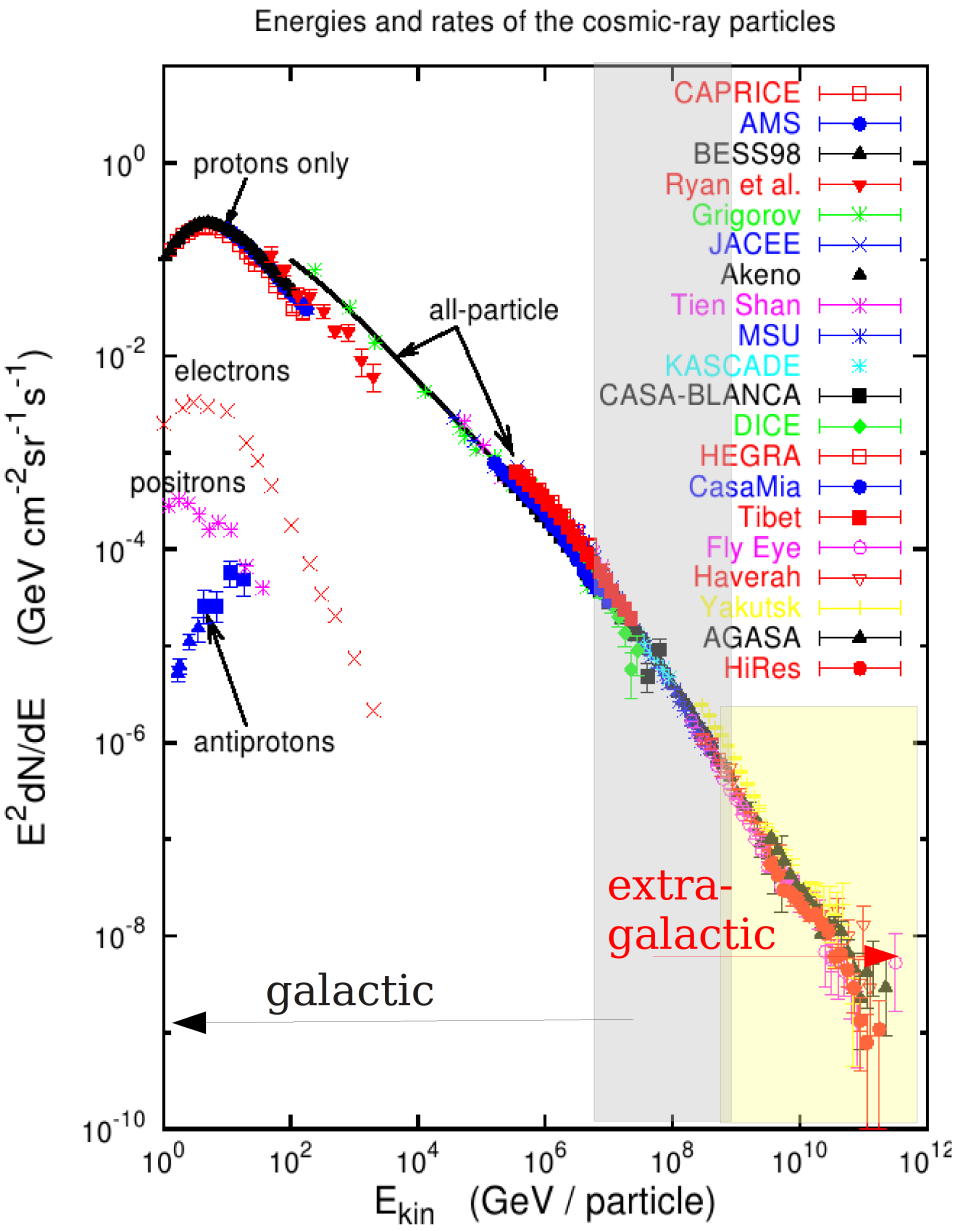
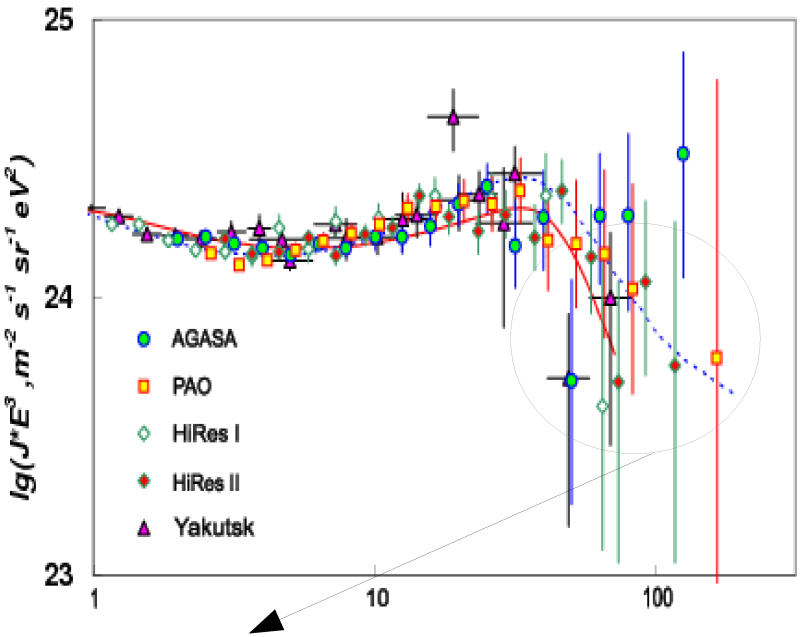
Outline

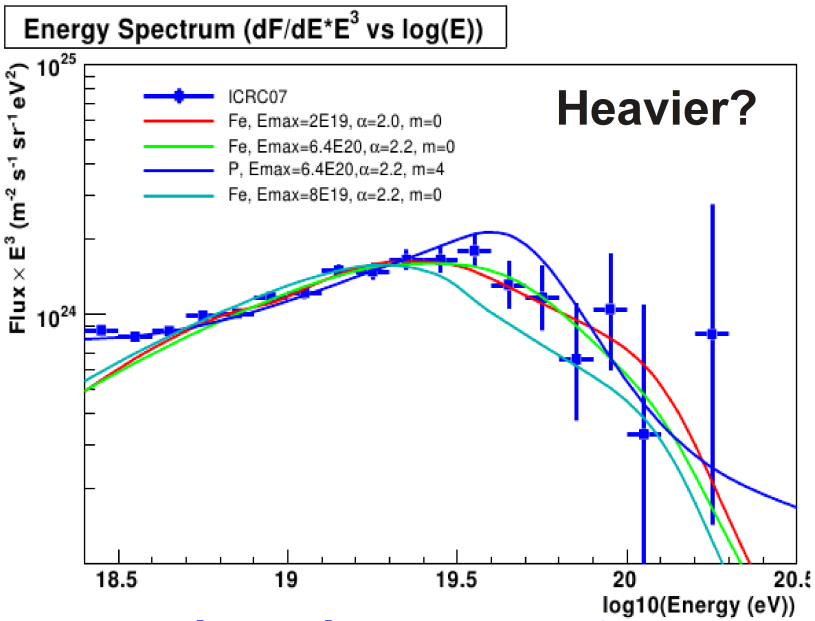
- Introduction : UHECRs and neutrinos
- Motivation and goals
- Method
- Results & implications for GRB models



UHECRs



Evidence of GZK cutoff *E, EeV*



Arisaka et al. 2007, JCAP, 12

e.g. talks: E. Kido, H. Takami, F. Oikonomou

Neutrino production connected with UHECRs

UHECR source - a simple scenario:
only p+ only pγ interactions + neutron escape

At Δ-resonance $p+\gamma \rightarrow \pi^0 + p$ 2/3 cases

$p+\gamma \rightarrow \pi^+ + n$ 1/3 cases

$\pi^0 \rightarrow \gamma+\gamma$

$\pi^+ \rightarrow \mu^+ + \nu_\mu$

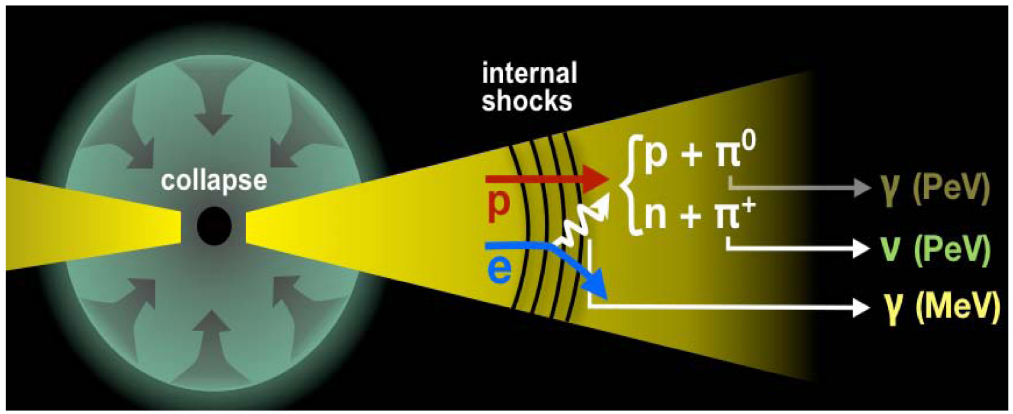
$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$

Neutron decay $n \rightarrow p + e^- + \bar{\nu}_e$

$(\nu_e : \nu_\mu : \nu_\tau) = (1:2:0)$

$p + CMB \rightarrow \ldots\ cosmogenic\ \nu$

GRBs: a good candidate



(1) $t_{acc} \leq min(t_{loss}, t_{dyn})$

$t_{acc} \approx k\ E / ZeBc$

(2) local injection rate at

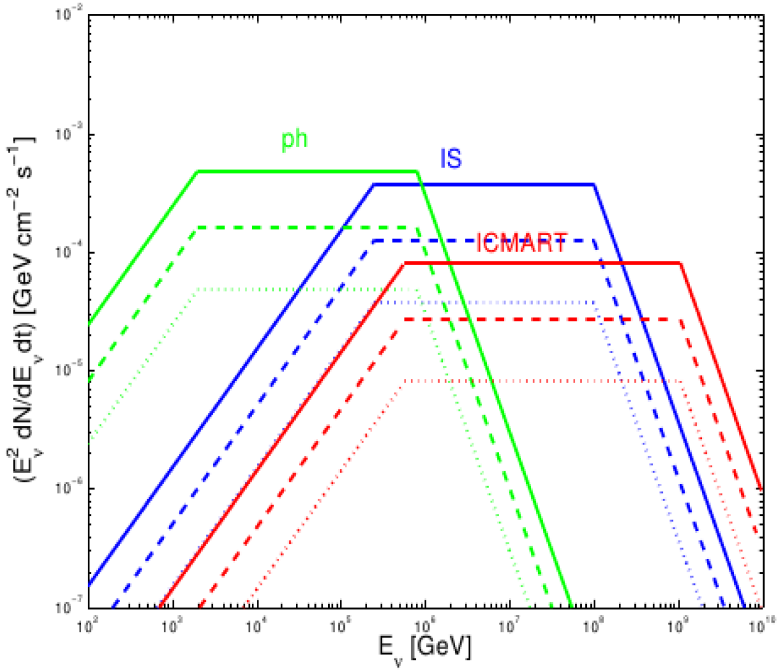
$10^{19} - 10^{21}\ eV$

$E_{CR} \frac{d\dot{N}_{CR}}{dE_{CR}} \approx 10^{44} \frac{erg}{Mpc^3\ yr}$

Two main approaches

- Use: “fixed” photon targets (MeV)
- Focus on: ν emission
- Neglect: emission from cascade

(e.g. Guetta et al. 2004, Abbasi et al. 2010, Zhang & Kumar 2013)

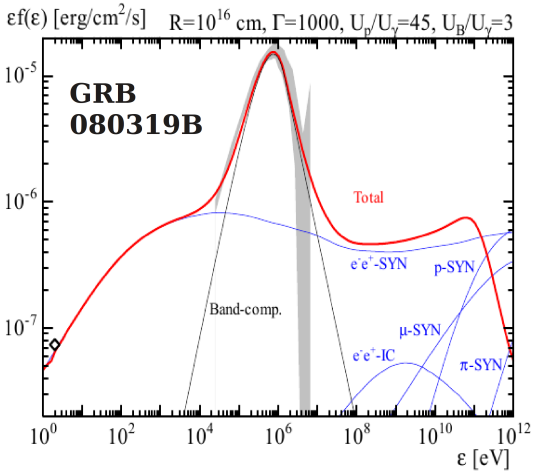


Credit: Zhang & Kumar 2013, PhRvL, 110

- Use: “fixed” photon targets (MeV)
- Focus on: emission from the cascade

(e.g. Boettcher & Dermer 1998, Dermer & Atoyan 1996, Asano & Inoue 2007, Asano & Meszaros 2014)

Right:
Asano+2010, ApJ, 725
Bottom:
Murase+ 2012, ApJ, 746



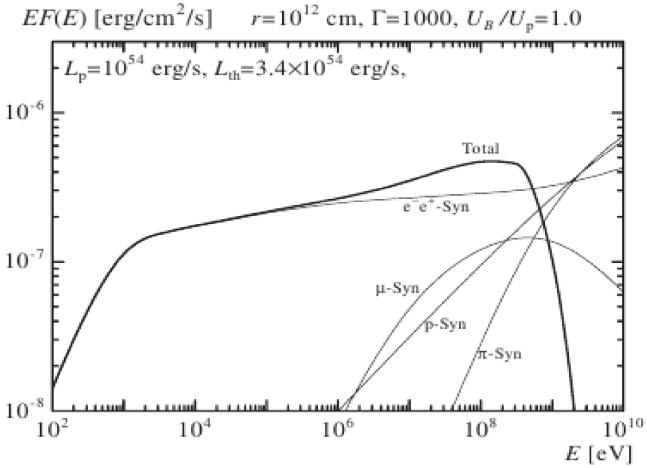
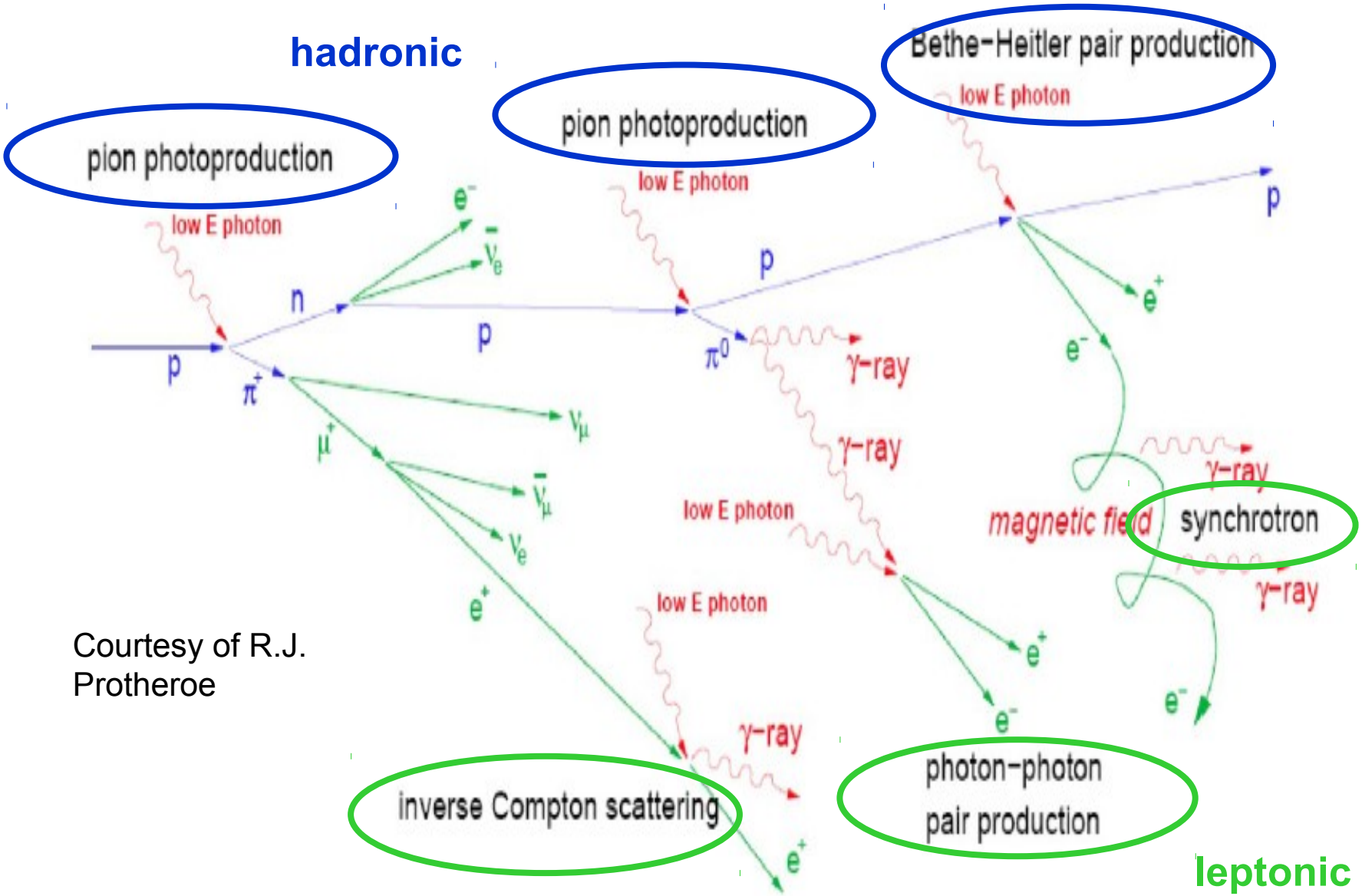


Illustration of a hadronic cascade



Courtesy of R.J. Protheroe

Motivation: Try to combine both approaches

Goals:

- Find a generic framework
- Find the parameter space where:
  the contribution of the hadronic cascade (HC) to the “fixed” photon field is important
- Derive a maximum value of the “p/γ” ratio (e.g. η=Lp/Lγ)
- Derive the ν production efficiency for this maximum η.
- Compare with results from the literature

What follows can be found in:
Petropoulou, 2014, accepted by MNRAS (arXiv:1405.7669)

I assume:

- a “fixed” photon field for MeV emission (Band-function)
- proton acceleration to UHE with power-law distribution of slope p=2
- injection of protons in a region of size $R_b \sim r/\Gamma$ with magnetic field B

Point of differentiation:
Use as main parameters the photon and proton **compactnesses**

$$l_\gamma = \frac{\sigma_T L_\gamma}{4\pi R_b \Gamma^4 m_e c^3}$$

$$l_p = \frac{\sigma_T L_p}{4\pi R_b \Gamma^4 m_p c^3}$$

- Intrinsic quantities for the description of a leptohadronic system
- The efficiency, the cooling etc depend on them
- Different combinations of observables in GRB models lead to the same lγ, lp

Numerical method: Kinetic equation approach

(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:

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

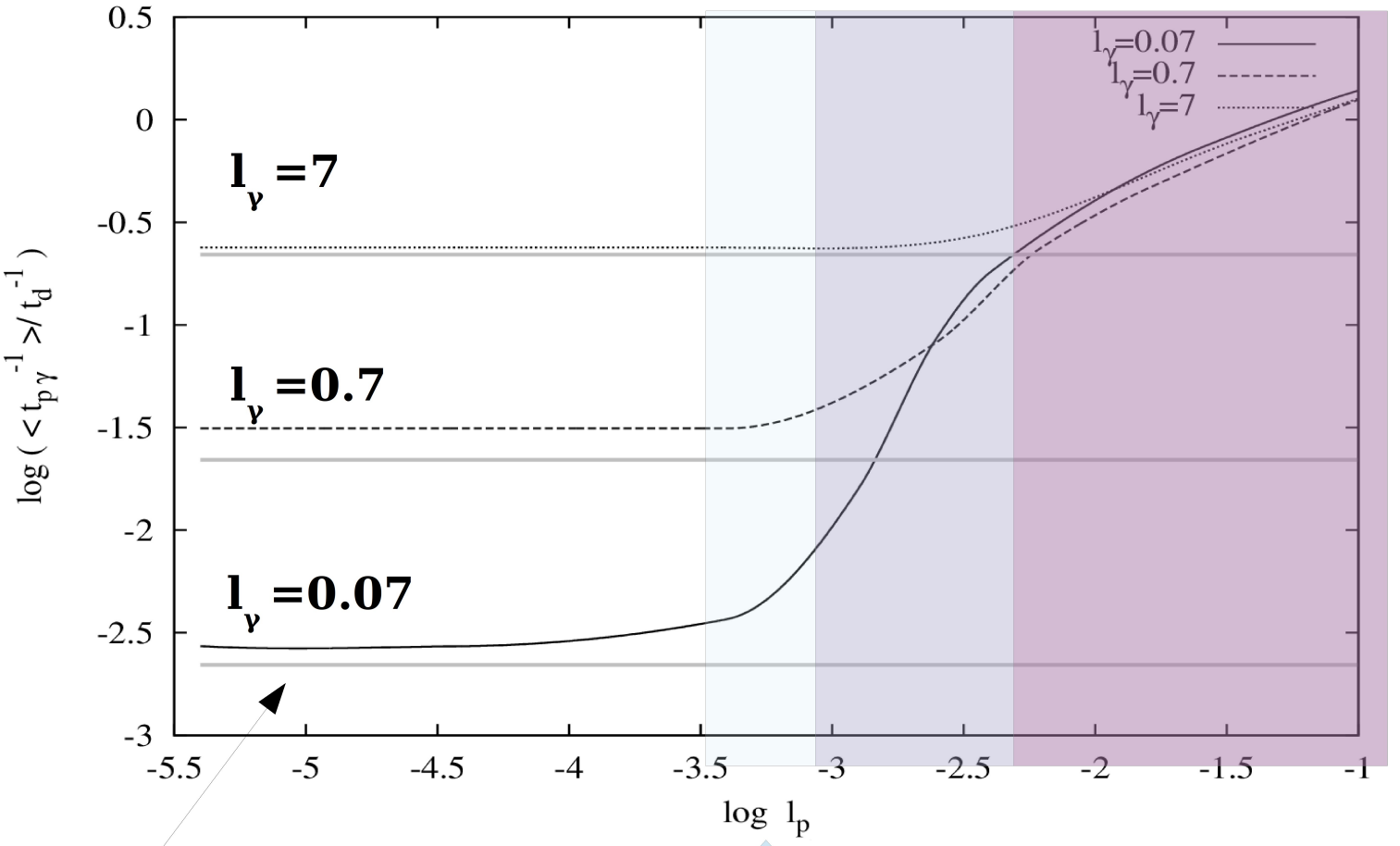
Courtesy of S. Dimitrakoudis

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

Synchrotron cooling of the above is also included.

Indirect manifestation of hadronic cascade

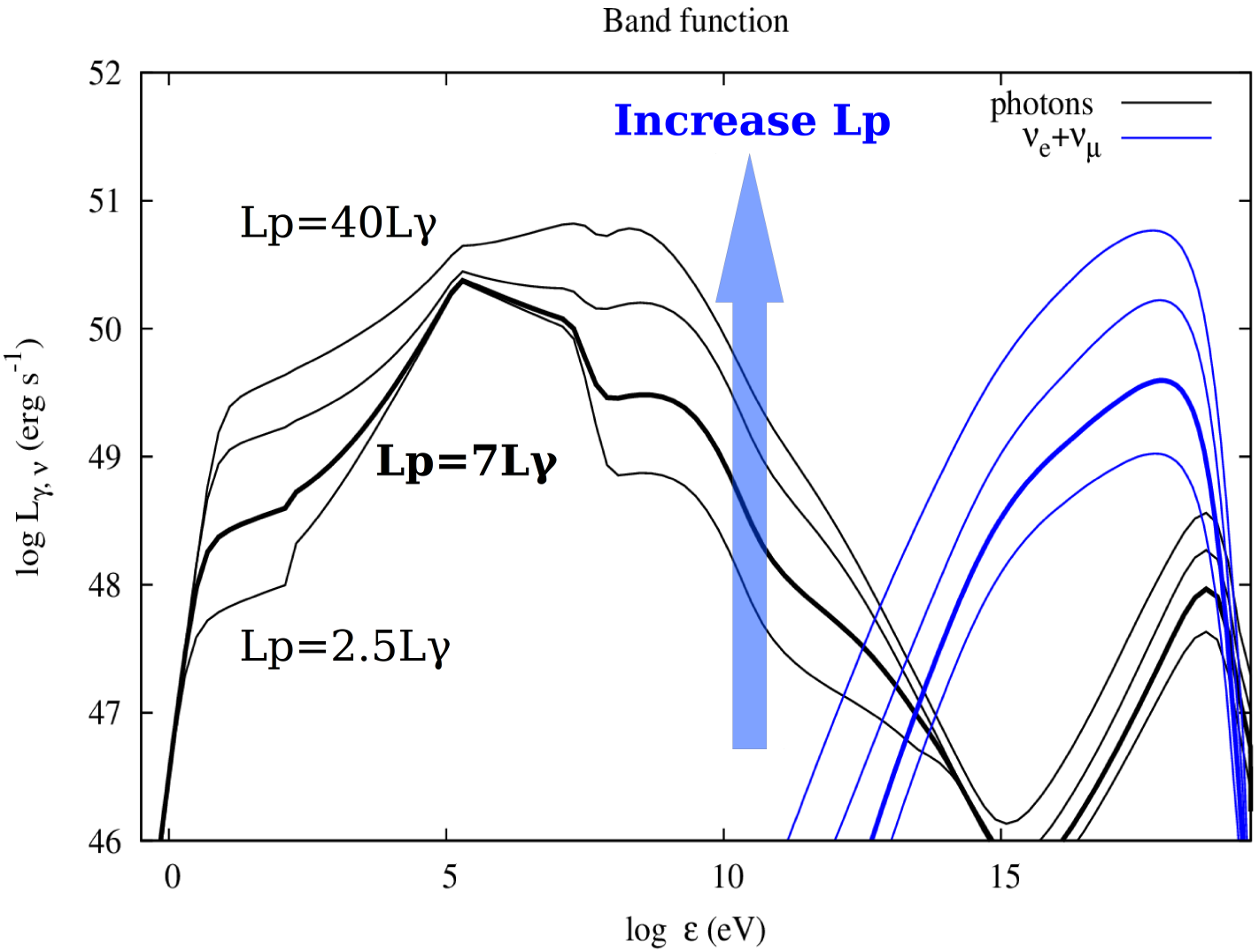
Proton cooling rate due to pγ interactions



Analytical expression – neglecting HC emission

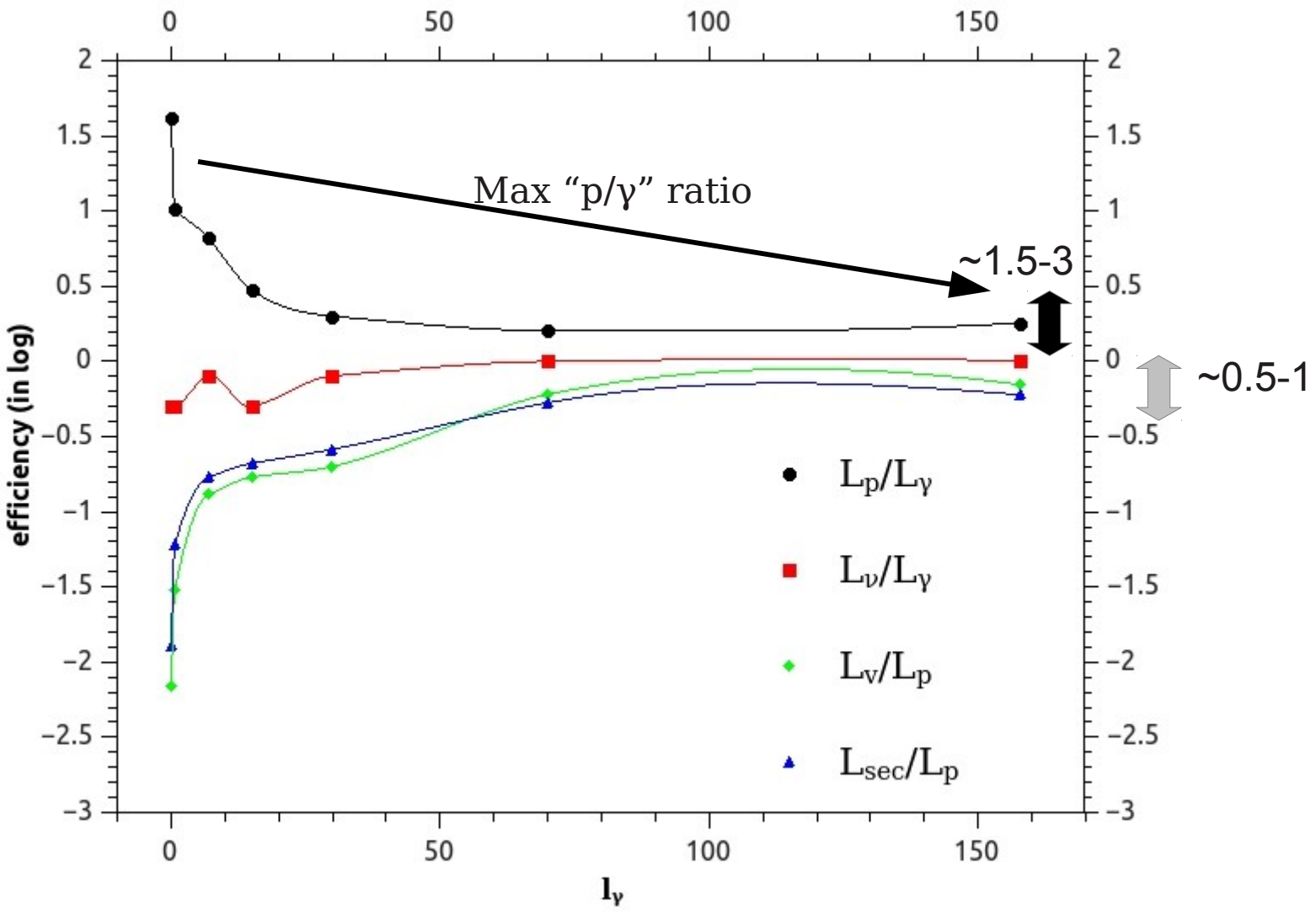
Set up of cascade emission

Direct manifestation of hadronic cascade



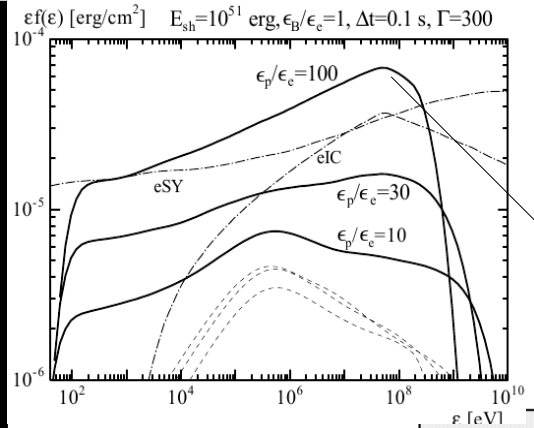
lγ=0.7, Lγ=1e51 erg/s (Γ=225, B=960G, R_b=1e12cm)

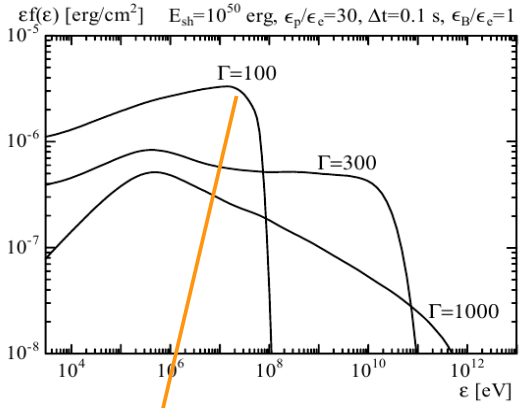
Maximum Efficiencies: Just before the HC dominance

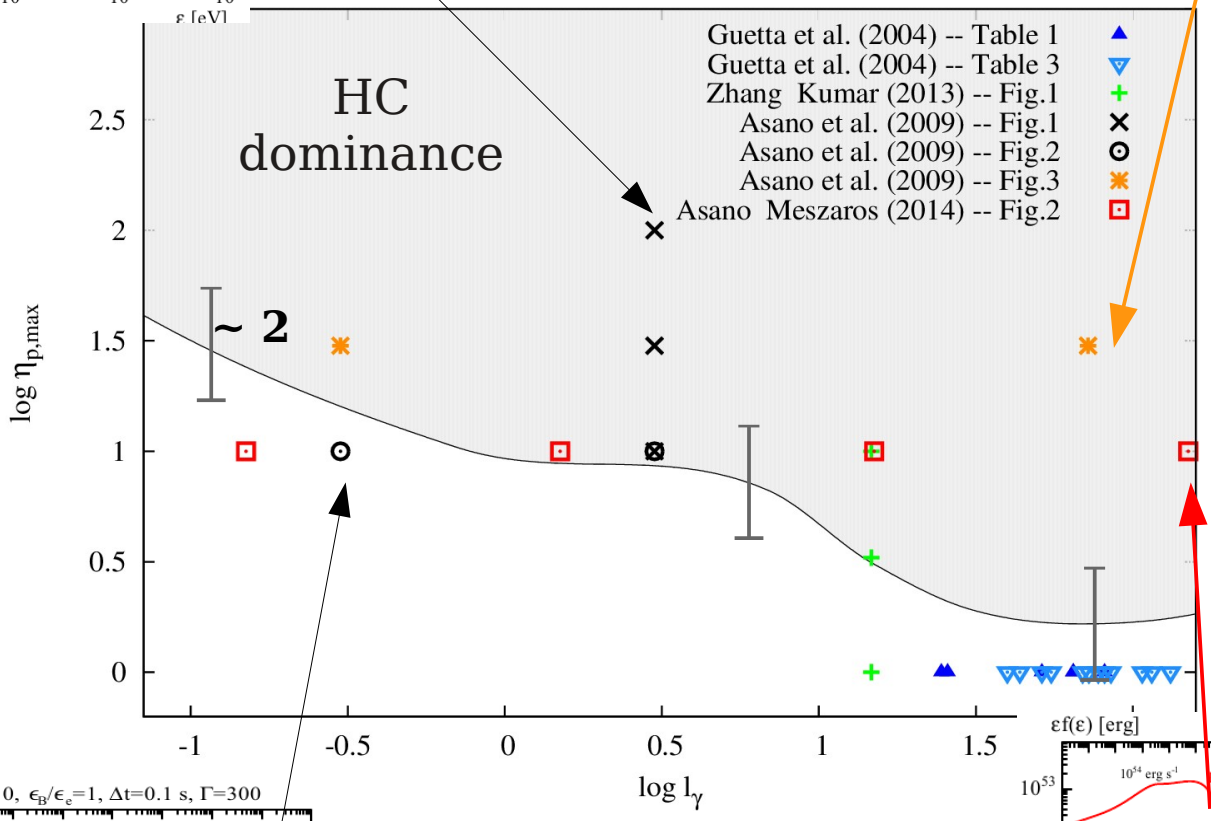


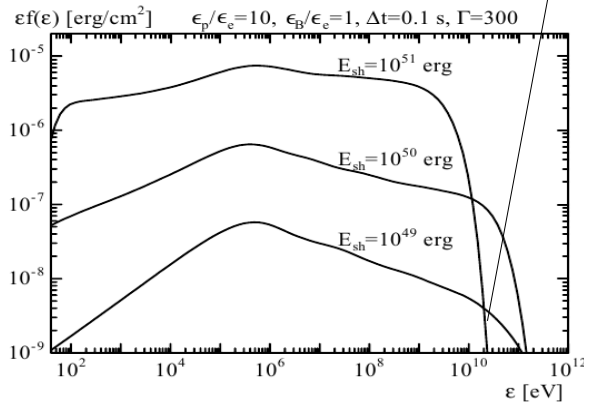
The $\eta_{p,max}$ – l_γ plane

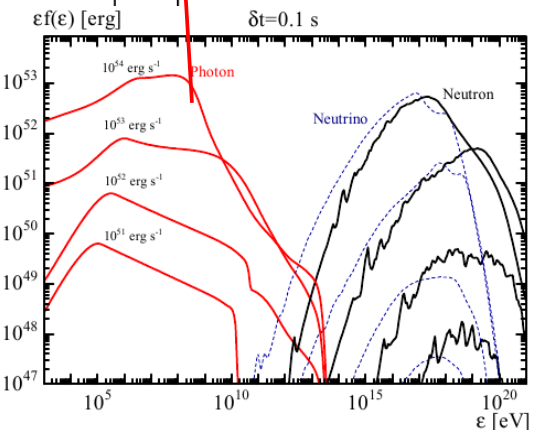
comparison with other works



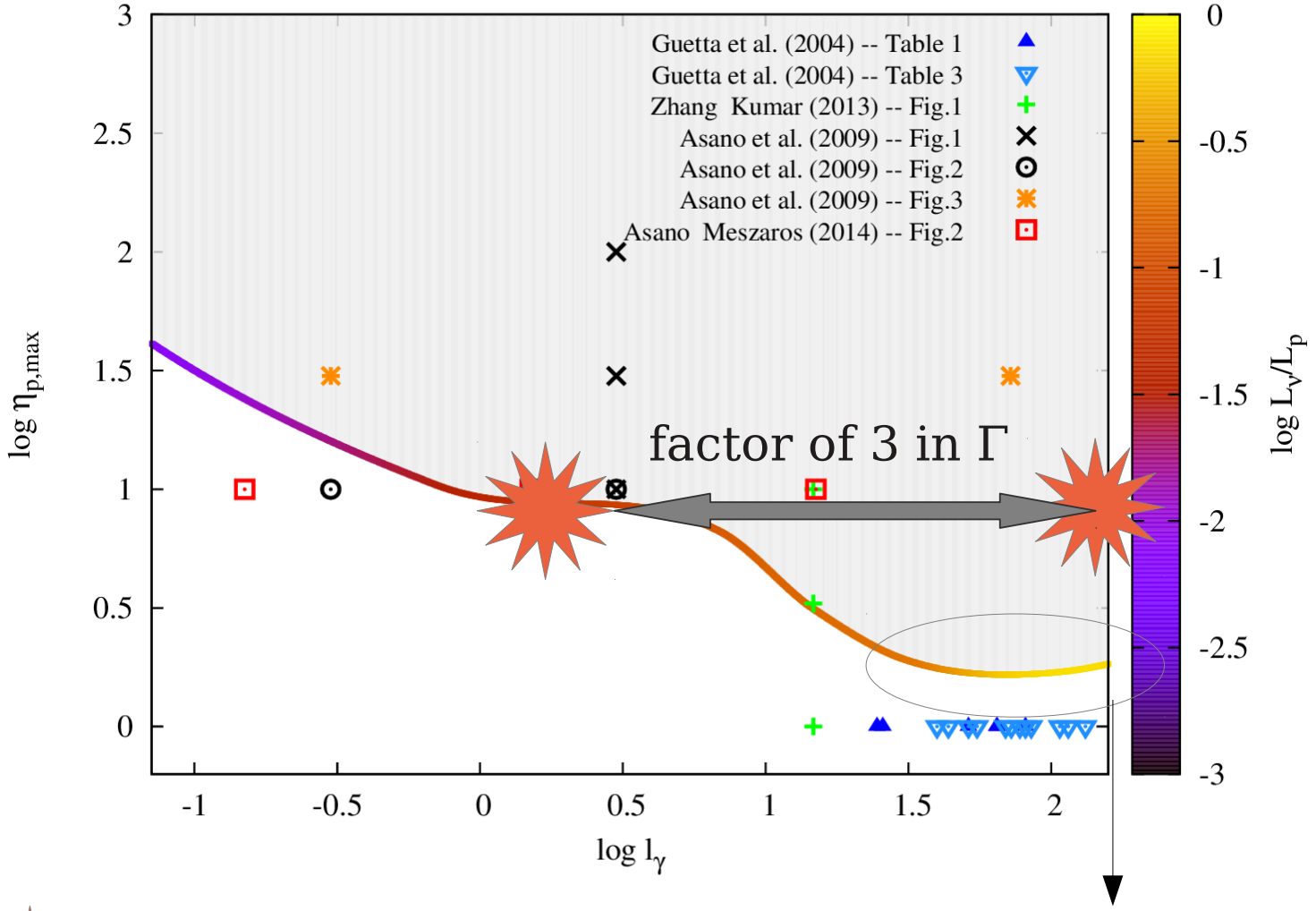








The $\eta_{p,max}$ – l_γ plane
ν efficiency



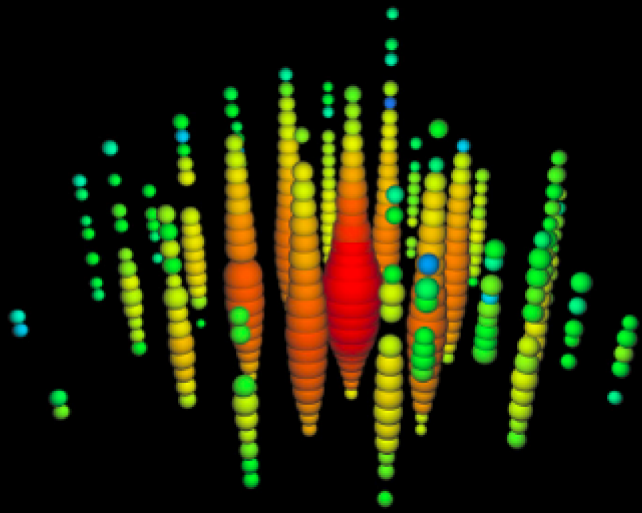
: bright burst Lγ=1.e54 erg/s, for Γ=316 and 1000

Still high efficiency

Summary

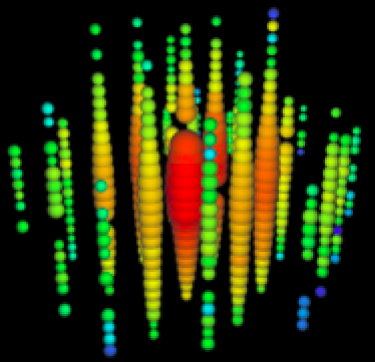
- Hadronic cascade (HC) becomes dominant for high enough Lp/Lγ and modifies the *pre-assumed* GRB photon emission

- The γ-ray and proton compactnesses are *key* parameters of the study



- Different combination of GRB observables lead to the same γ- and p-compactnesses

- The maximum "p/γ" ratio ($\eta_{p,max}$) is a decreasing function of the γ-ray compactness



- Even for the maximum "p/γ" ratio the ν efficiency may reach ~60% (for high l_{γ})

- The plane $\eta_{p,max}$ – l_{γ} is a useful tool for studying HC in GRB emission