Exploring the properties of leptohadronic plasmas: from theory to observations

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Talk outline

- Introduction
- Motivation & goals of my PhD research
- What is “hadronic supercriticality” ?

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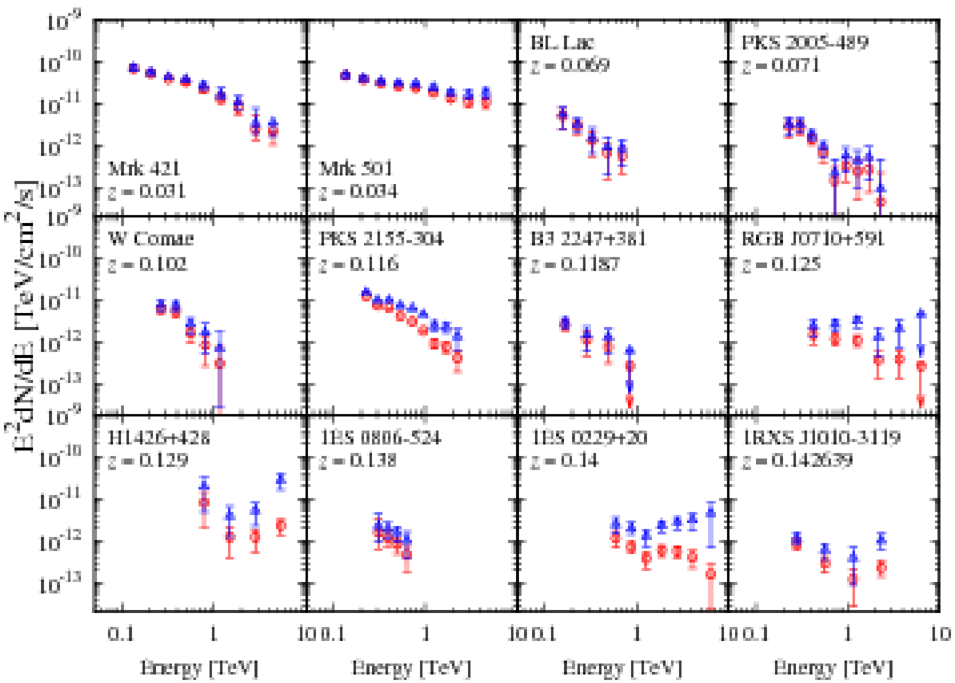
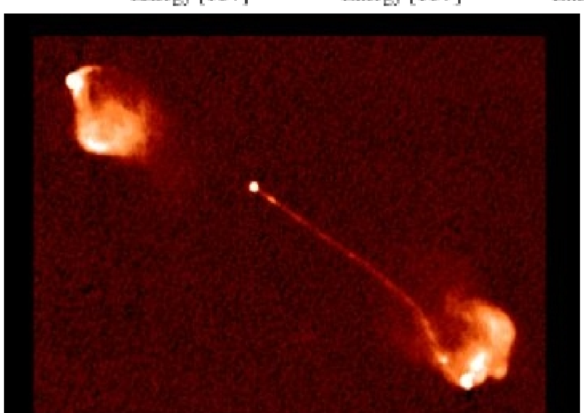
- Introduction
- Motivation & goals of my PhD research
- What is “hadronic supercriticality” ?
- Hadronic supercriticality as a trigger for Gamma-Ray Burst (GRB) prompt emission
- Leptohadronic models for Active Galactic Nuclei (AGN)
- Predictions of neutrino emission from AGN

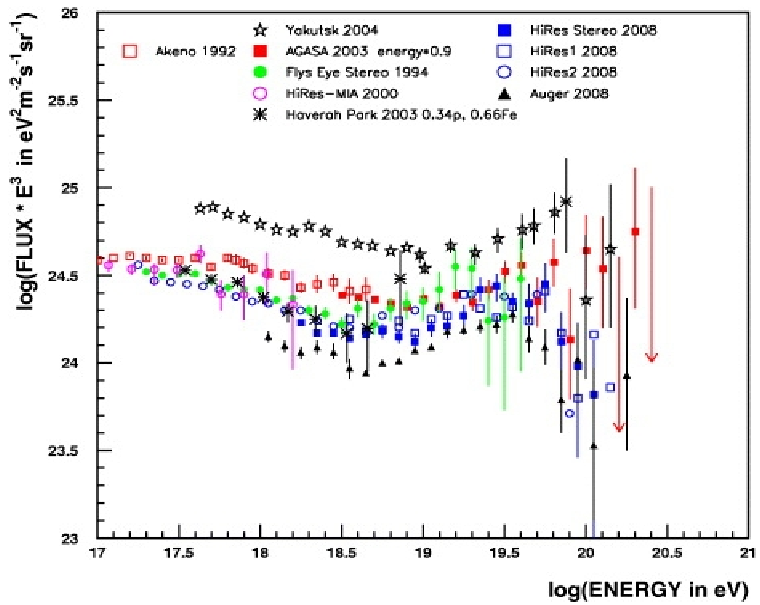
Introduction

Evidence of particle acceleration in AGN, GRBs etc




FR Class II source: quasar 3C175

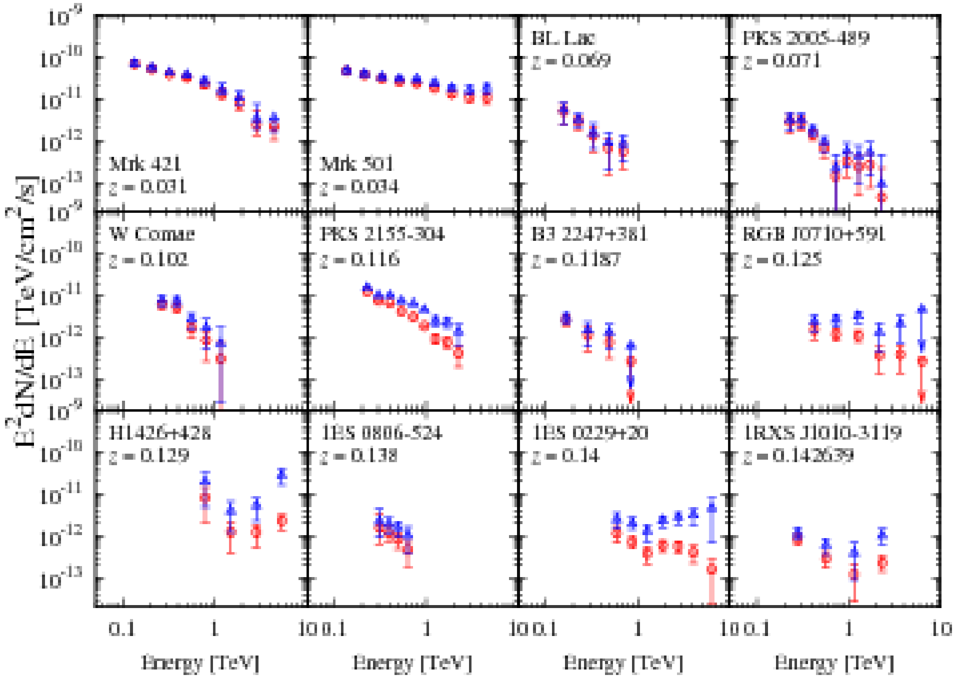
Detections of ultra-high energy cosmic-rays (UHECR) up to ~10^{20} eV

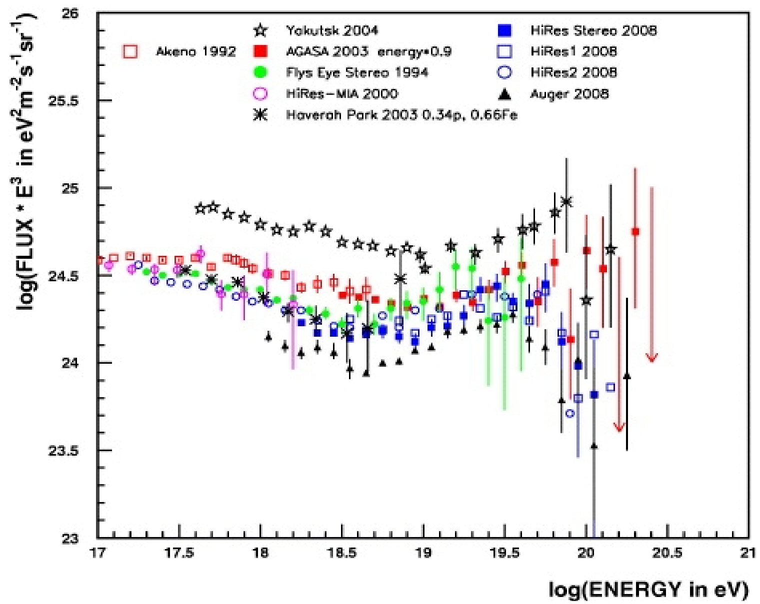


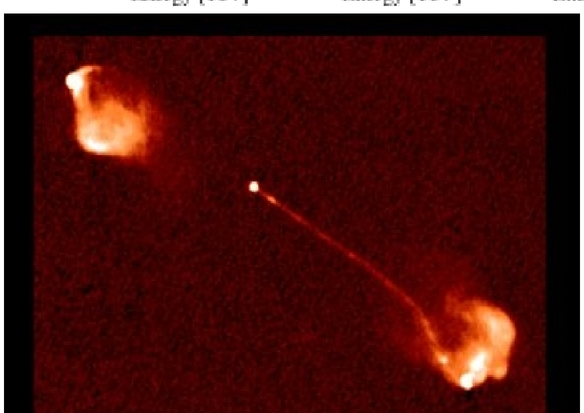
Hints of high-energy (~10^{15} eV) neutrinos

Evidence of particle acceleration in AGN, GRBs etc

Detections of ultra-high energy cosmic-rays (UHECR) up to ~10^{20} eV

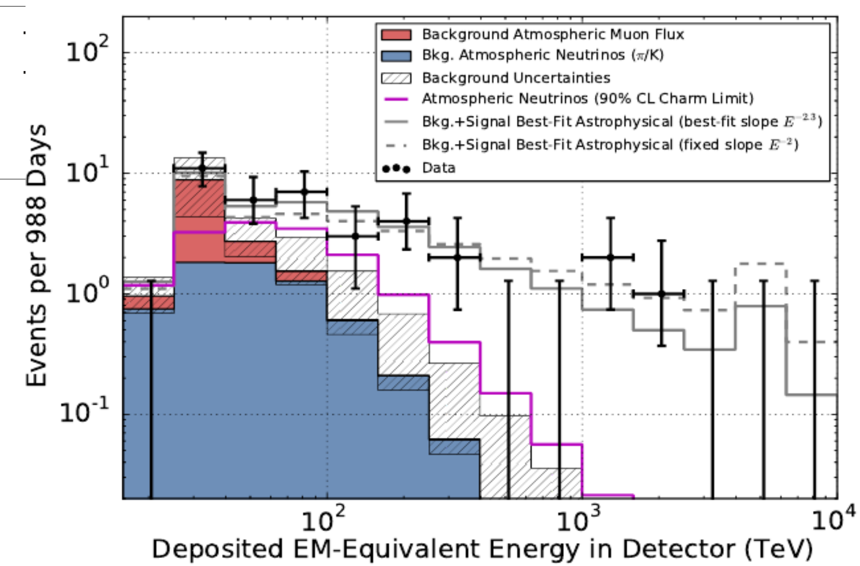






FR Class II source: quasar 3C175

Detections



Introduction

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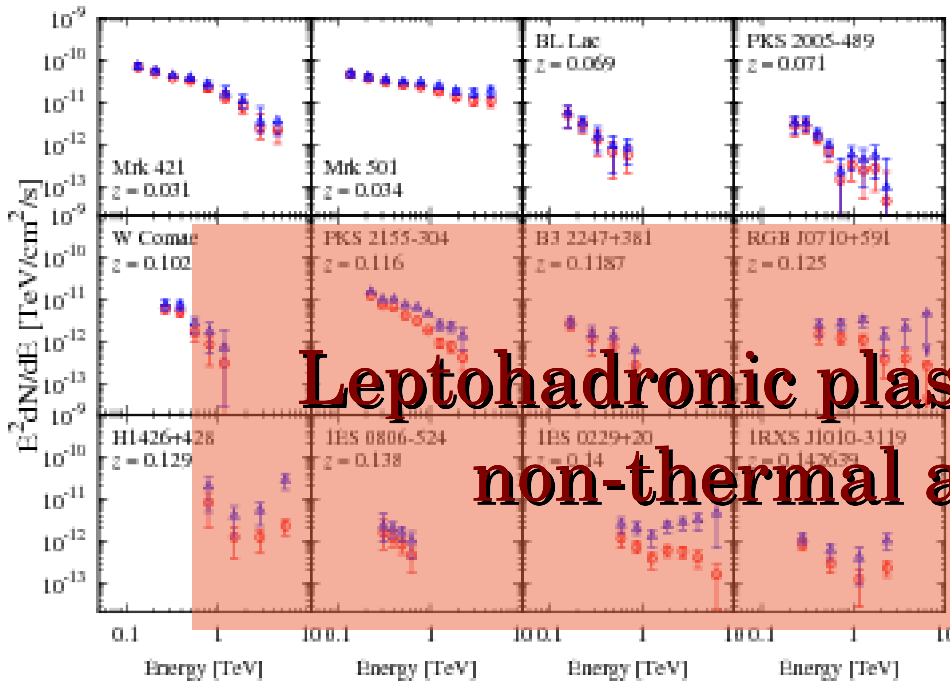
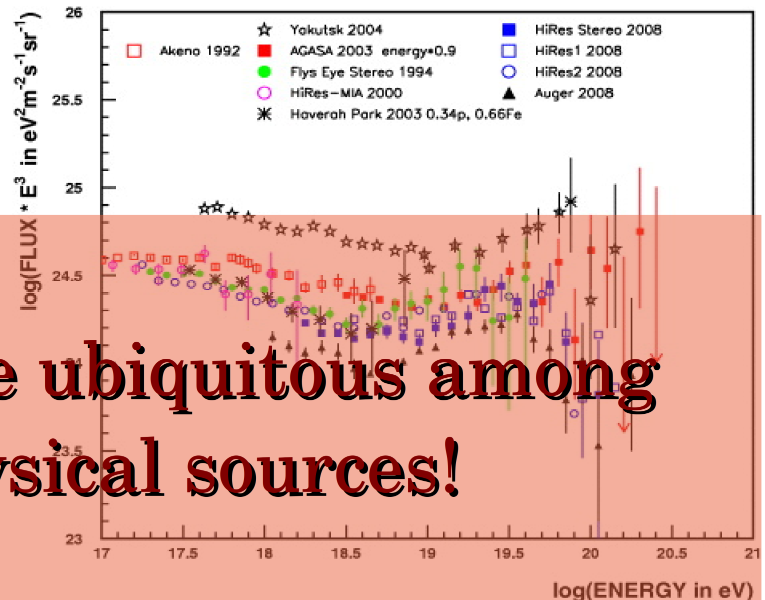
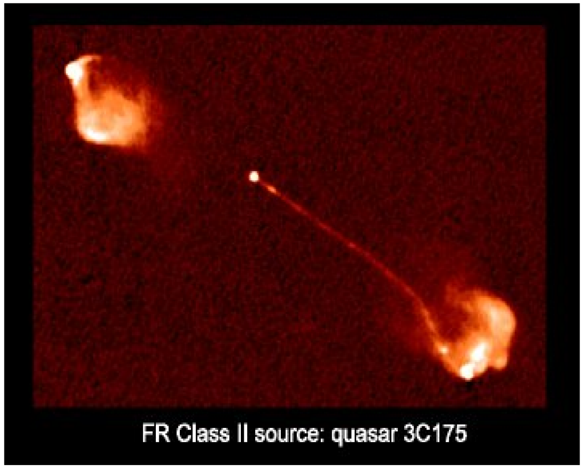
Detections of ultra-high energy cosmic-rays (UHECR) up to ~10^{20} eV

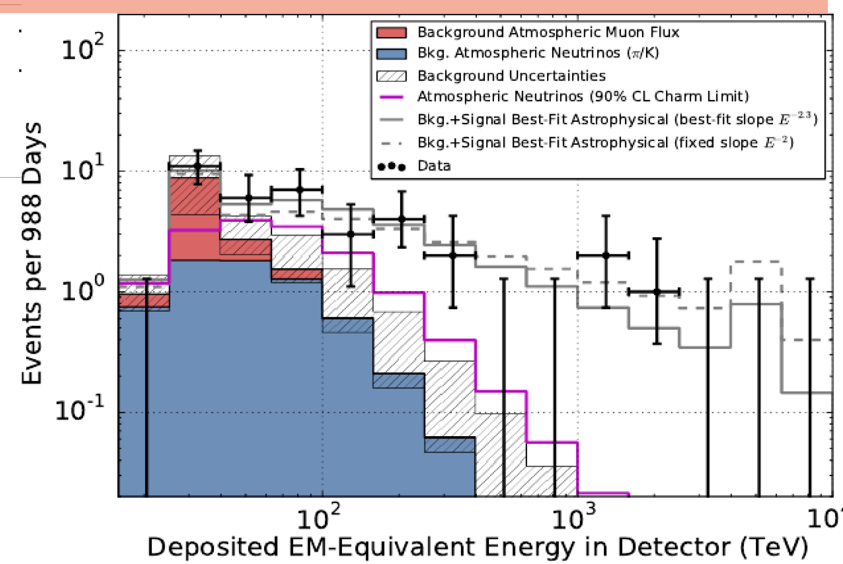




Leptohadronic plasmas are ubiquitous among non-thermal astrophysical sources!



Detections



Motivation

Leptohadronic plasma in a magnetized source

B+relativistic electrons/protons/neutrons +photons+ neutrinos

A system of coupled integro-differential equations

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

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

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

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

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

Courtesy of S. Dimitrakoudis

Motivation

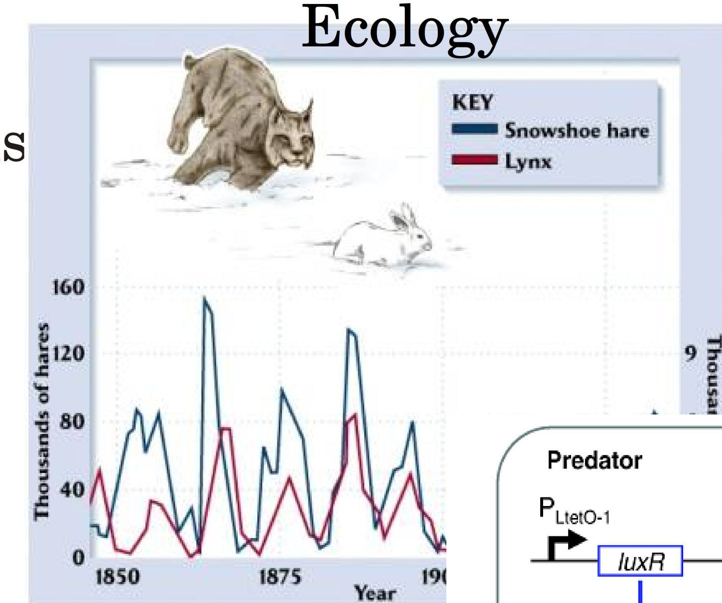
What are the temporal properties of a leptohadronic system?
After all... prey-predator systems are everywhere.

Leptohadronic plasma in a magnetized source

B+relativistic electrons/protons/neutrons +photons+ neutrinos

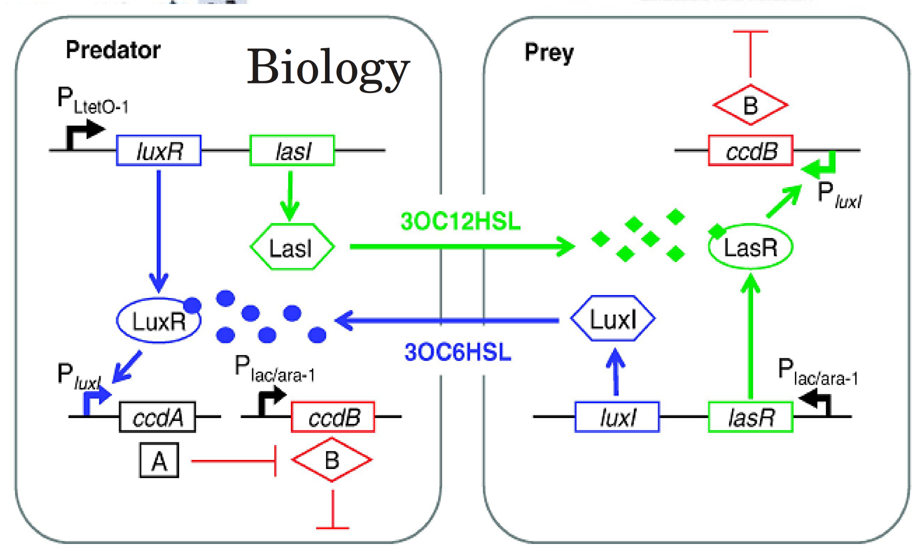
A system of coupled integro-differential equations

Ecology



Popular culture

Biology



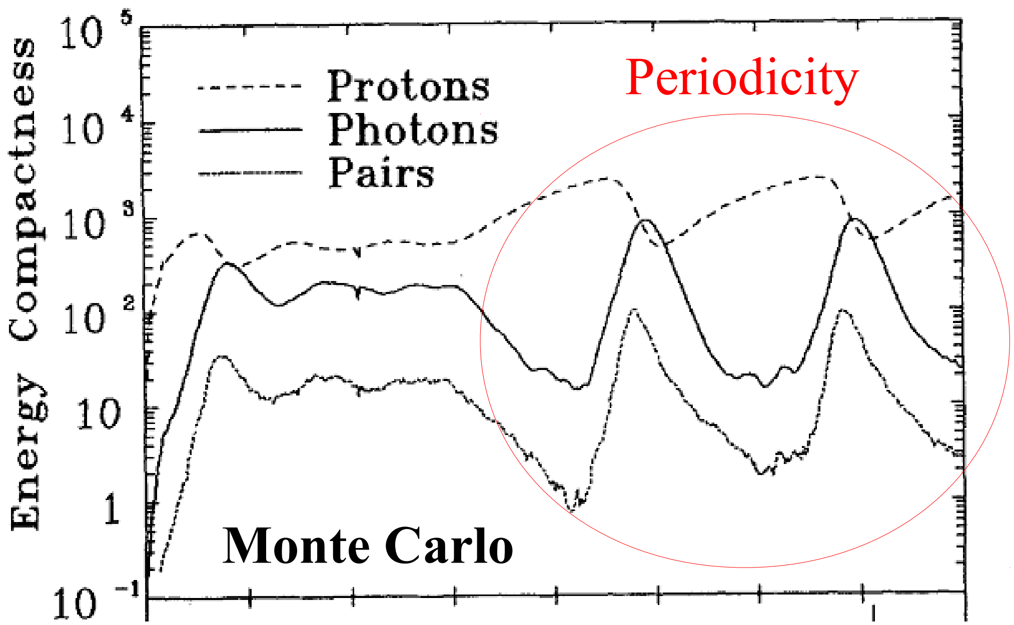
Goals

Limit Cycles in Electromagnetic Cascades in Compact Objects

(1991)

Boris Stern [1], Roland Svensson [2]

Abstract: Electromagnetic cascades possibly occurring near accreting compact objects have been discovered to show limit cycle behaviour. The power from accelerated protons gets converted by the cascade into soft radiation (X-rays and below) if the photon compactness is sufficiently large. Then the proton-photon system may develop limit cycles much like a prey-predator system with each component interchangebly dominating. This causes periodic large amplitude short time variability of the nonthermal luminosity from a compact object even if the acceleration or injection process is completely steady. Results both from detailed Monte Carlo simulations and from a simple phenomenological model are presented.

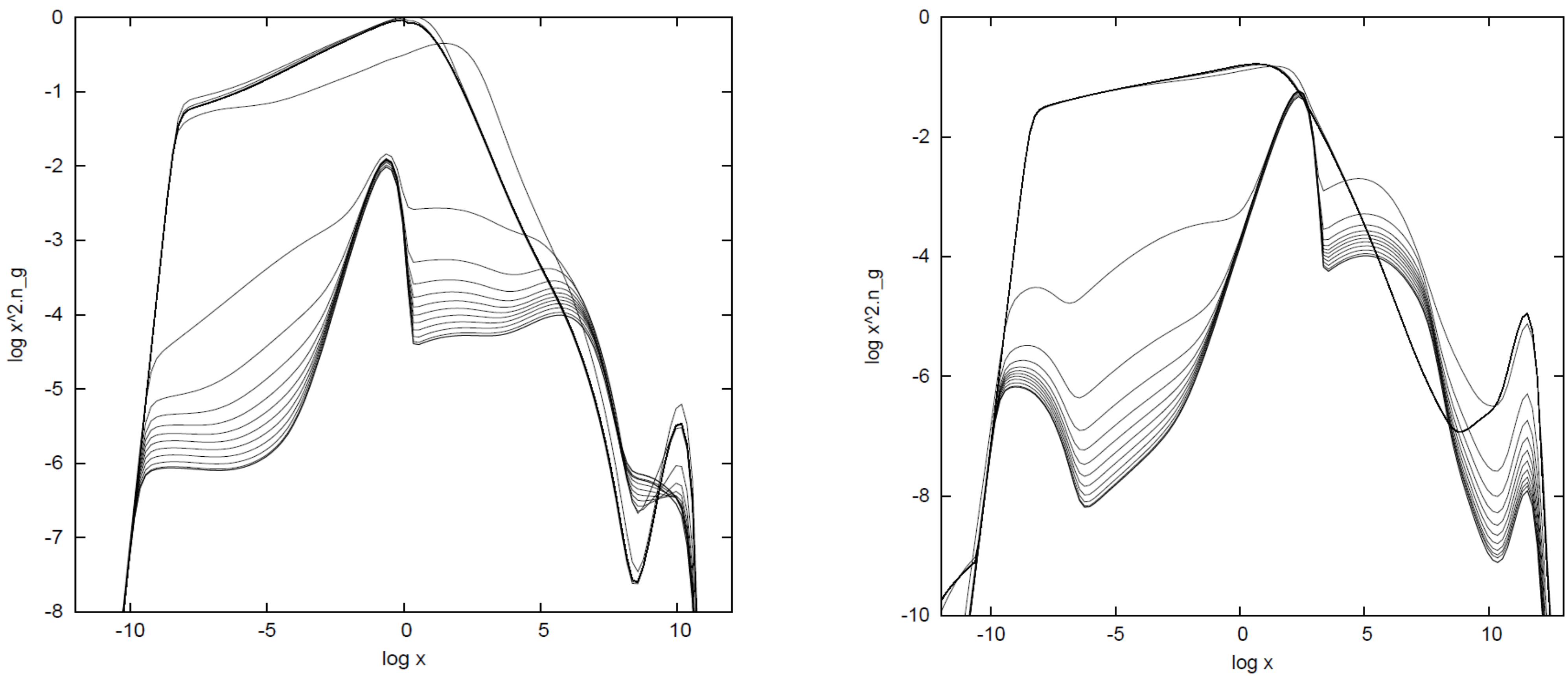


- What causes this limit cycle behaviour?
- For what parameters does the system exhibit this temporal behaviour?

Goals

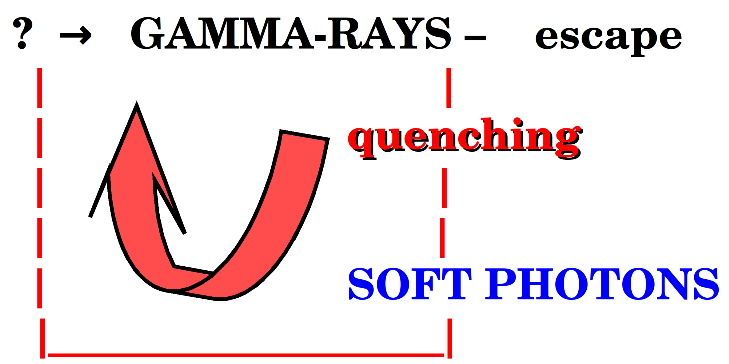
Examples of multi-wavelength photon spectra within the leptohadronic model

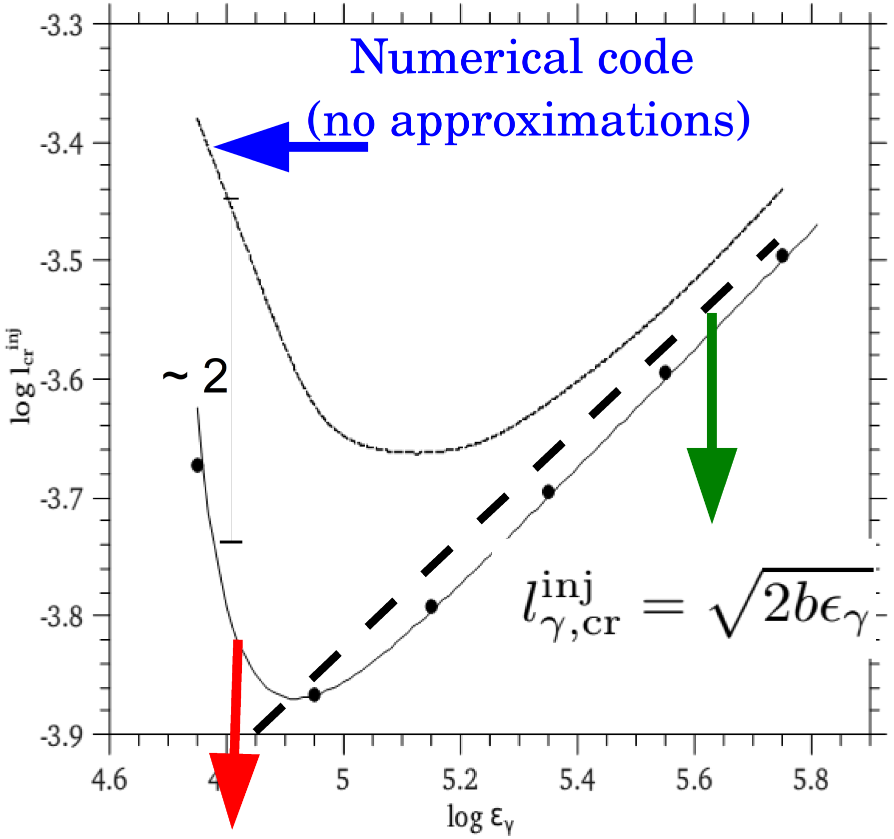
(Numerical calculations are performed with the code described in Dimitrakoudis et al. 2012, A&A)

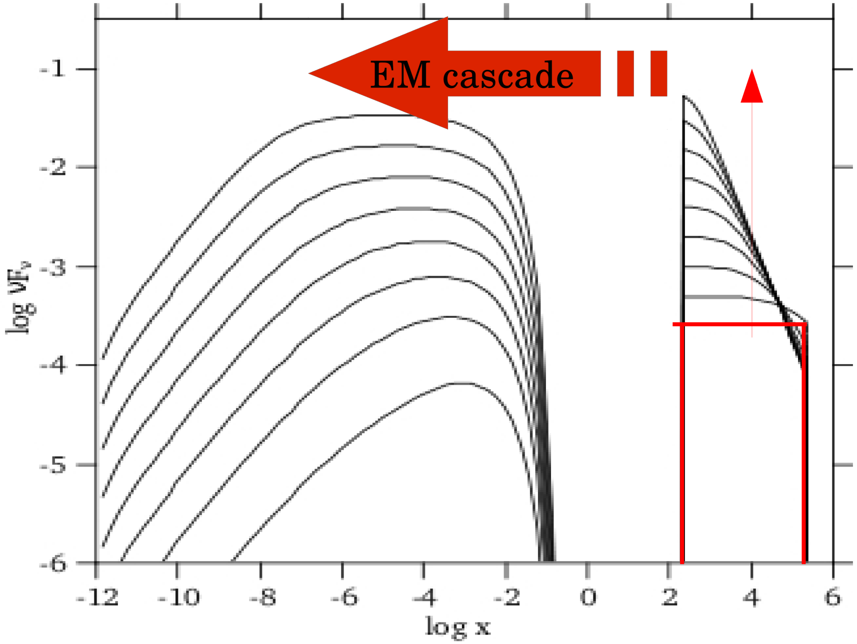


- **Is the abrupt spectral and flux change a numerical artifact?**
- **If not, what are the underlying physics of this transition?**

Interlude: Spontaneous γ-ray quenching





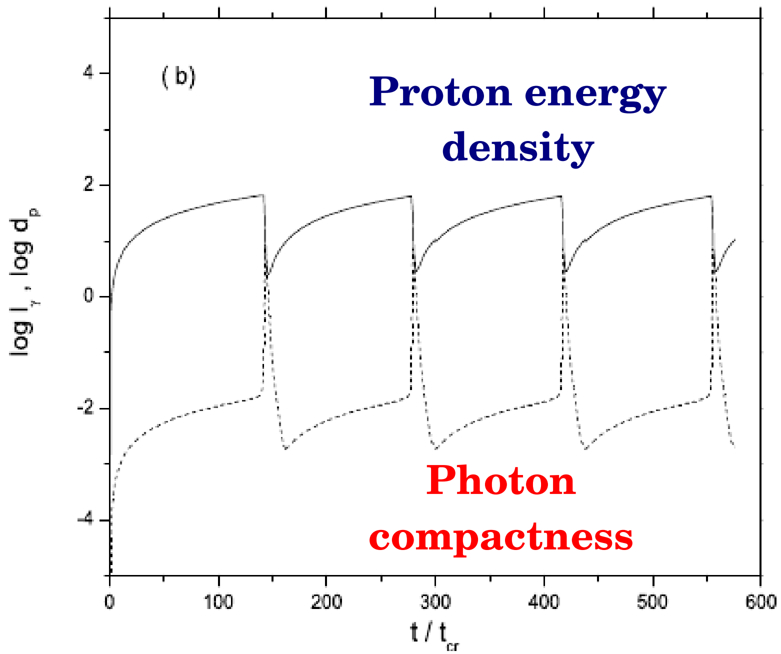


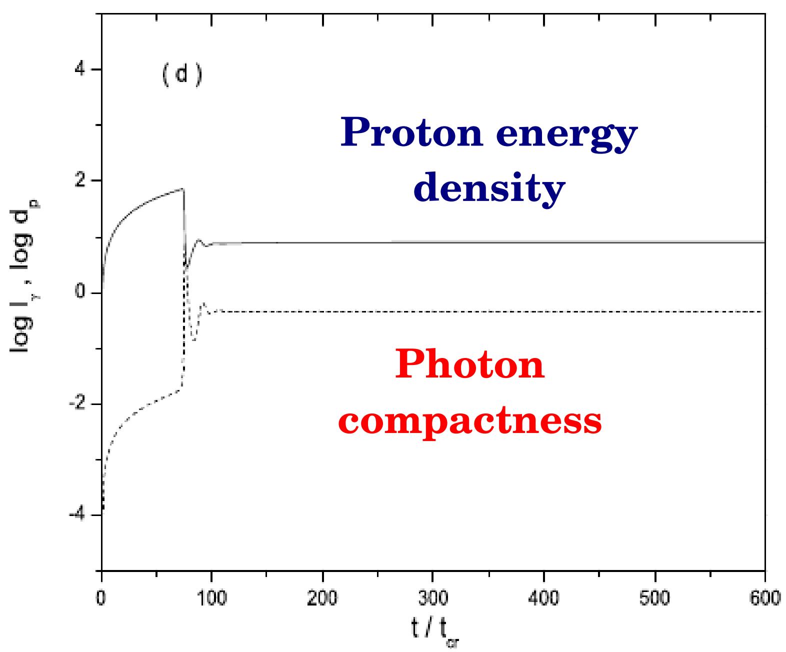
Gradual increase of γ-ray compactness

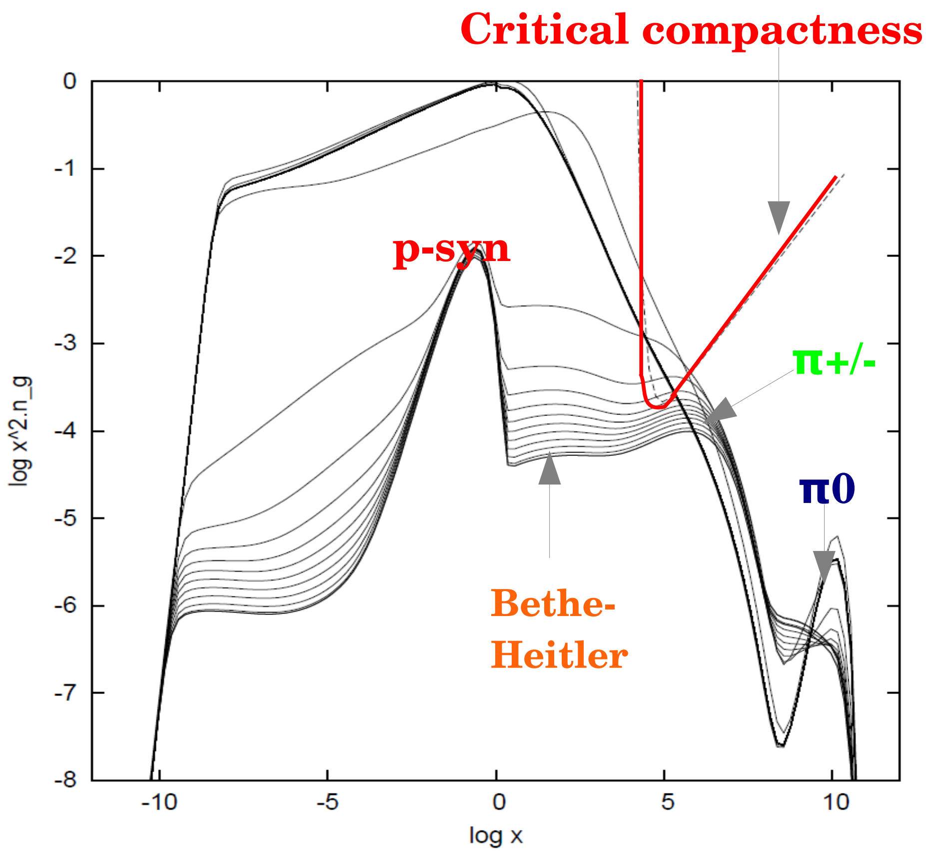
$$l^{\rm inj}_{\gamma,\rm cr} = \frac{b^2\epsilon_\gamma^2}{2\sigma_0}\left[\left(\frac{b\epsilon_\gamma}{2}\right)^{3/2} - \frac{8}{\epsilon_\gamma^3}\right]^{-1}$$

Stawarz & Kirk 2007, ApJ, 661L; Petropoulou & Mastichiadis 2011, A&A, 532; Petropoulou et al. 2013, A&A, 557

Hadronic supercriticality (in a nutshell)



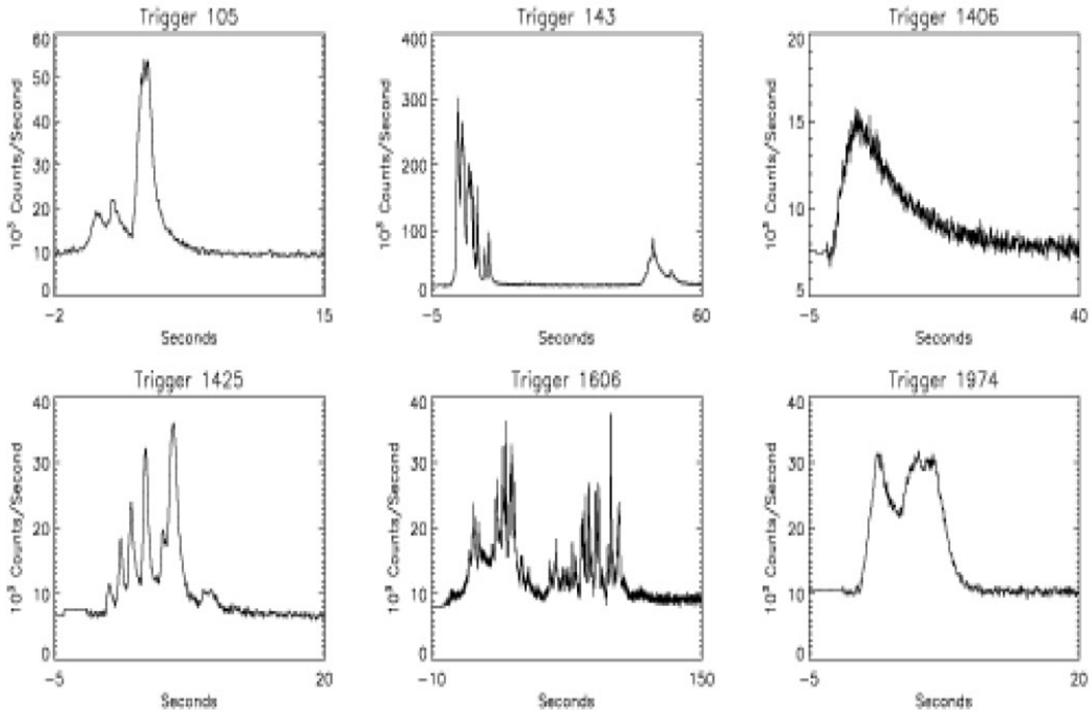




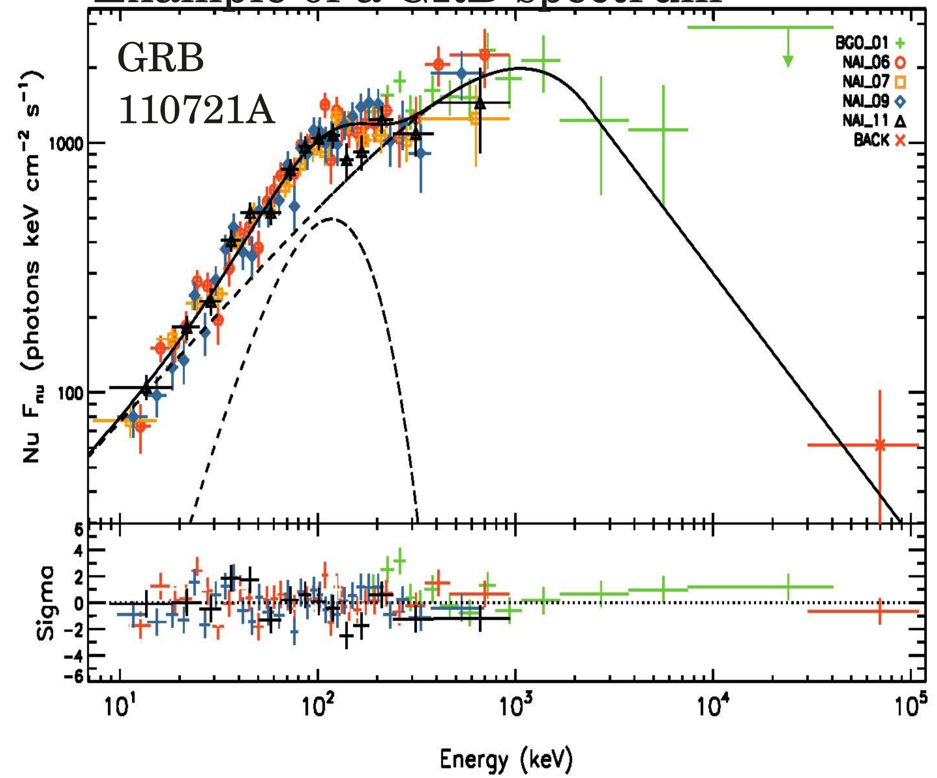
Petropoulou & Mastichiadis, 2012, MNRAS, 421

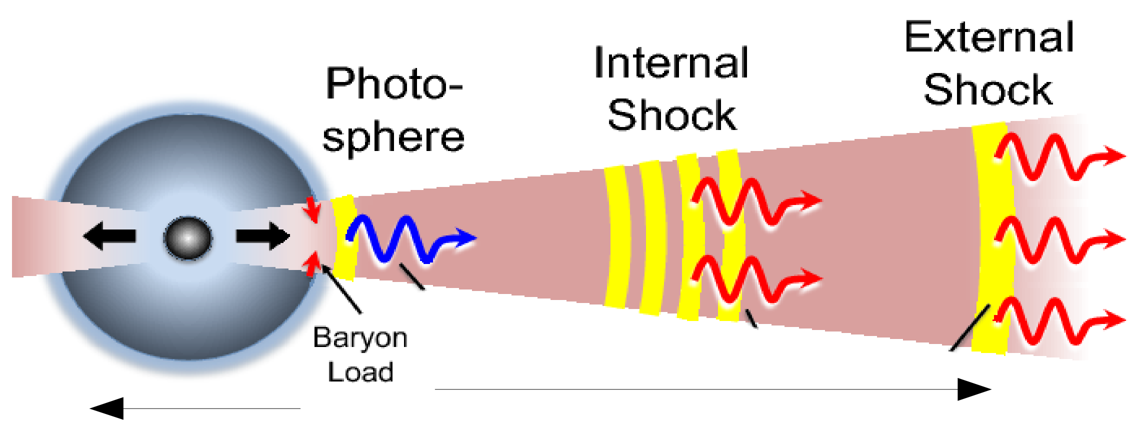
Hadronic supercriticality & GRB emission

A variety of GRB light curves



Example of a GRB spectrum



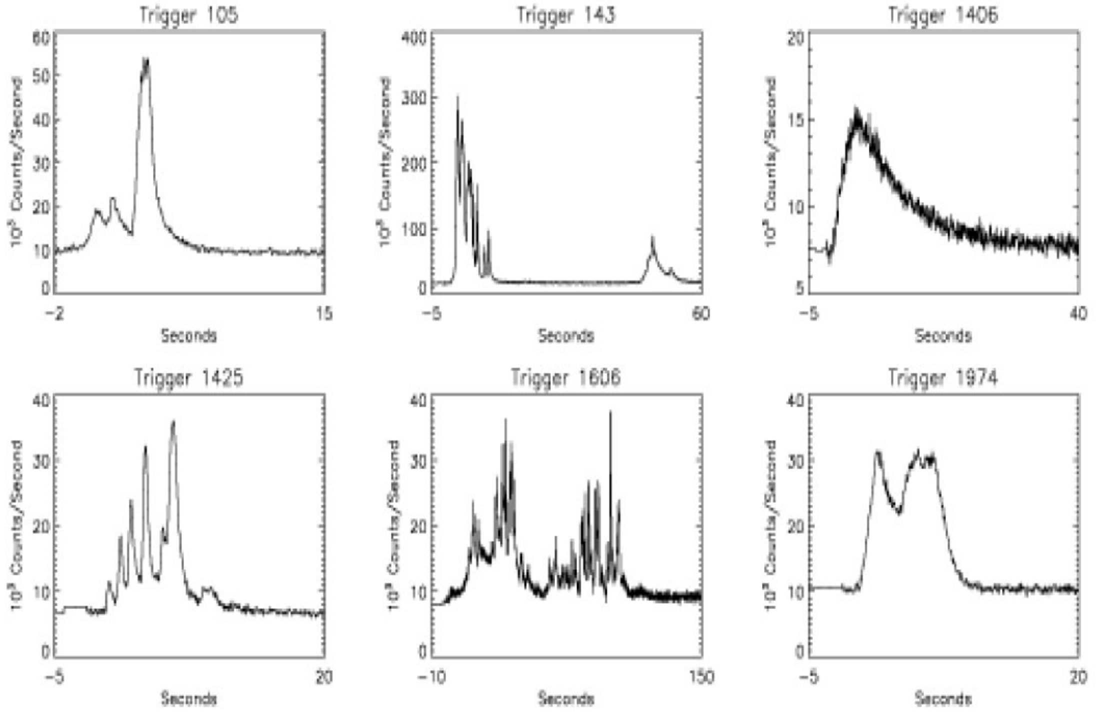


Optically thick

Optically thin

Hadronic supercriticality & GRB emission

A variety of GRB light curves



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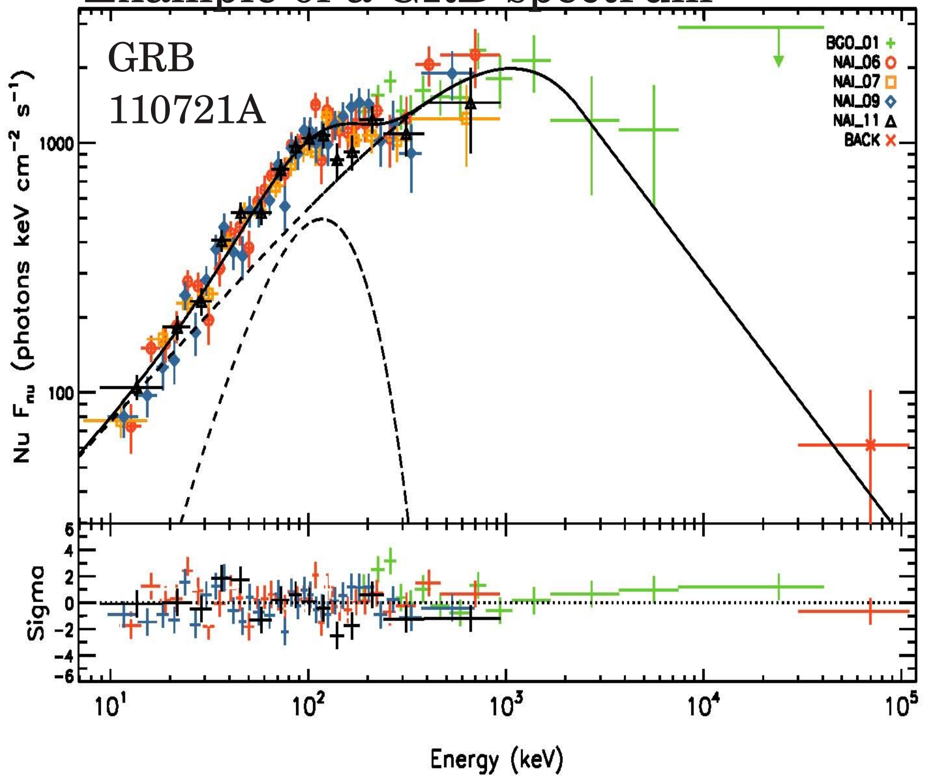
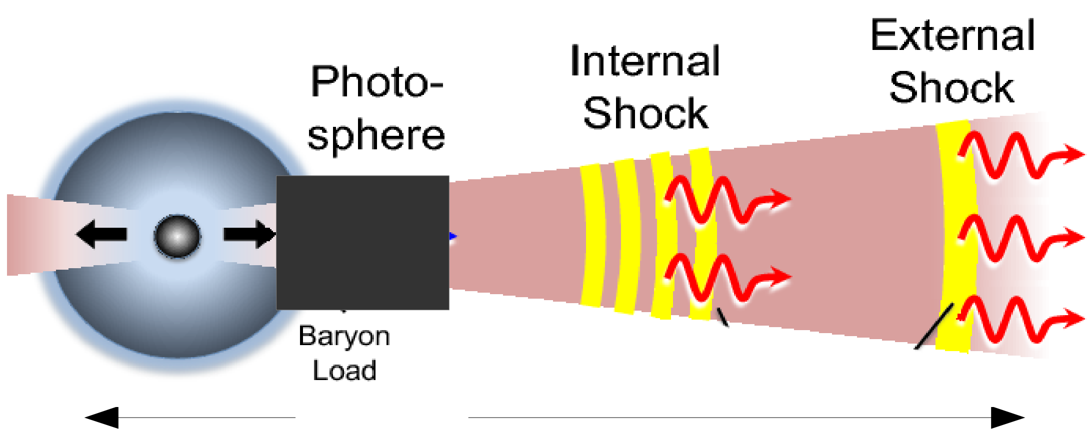


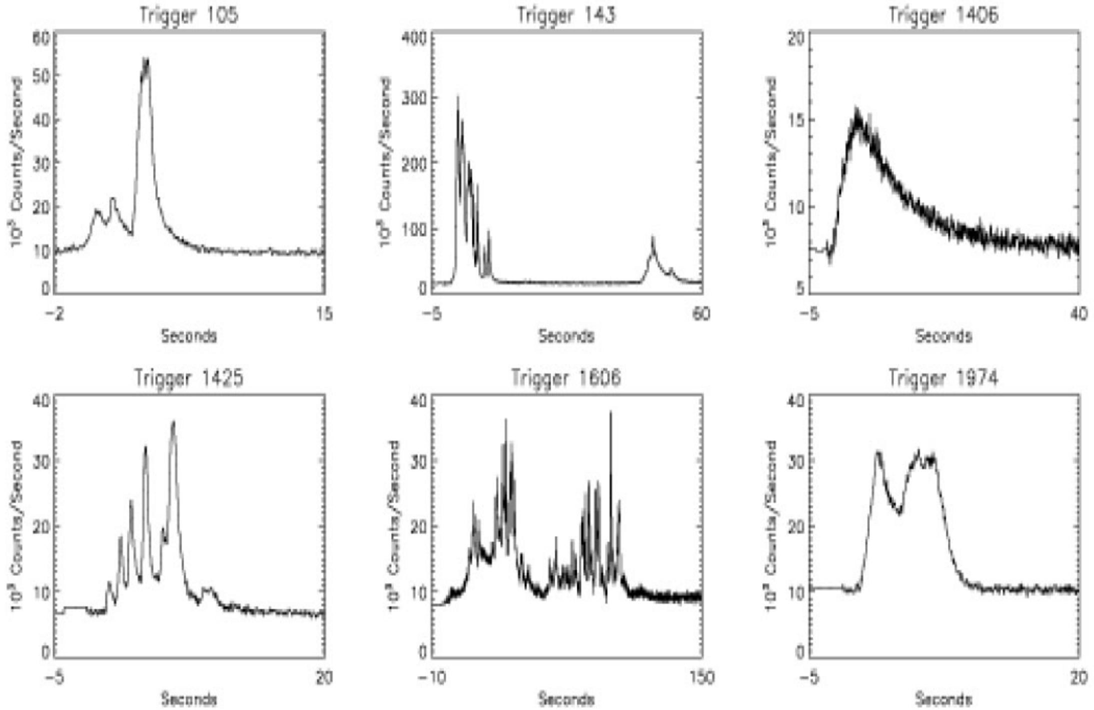


Optically thick

Optically thick conditions at large radii (>10^{14} cm)?

Hadronic supercriticality & GRB emission

A variety of GRB light curves



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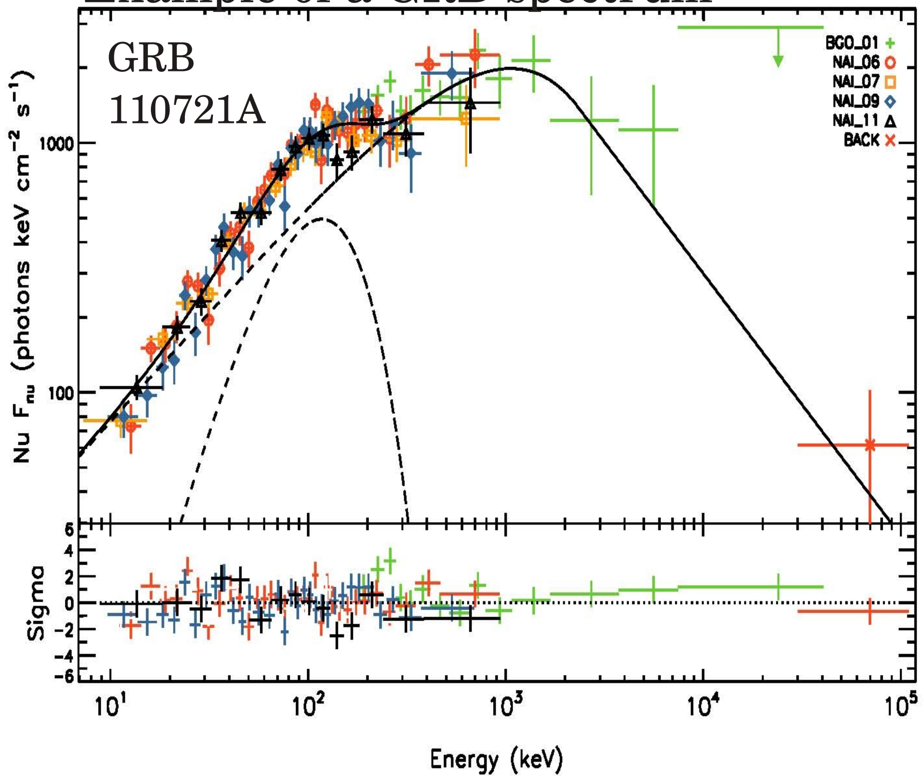
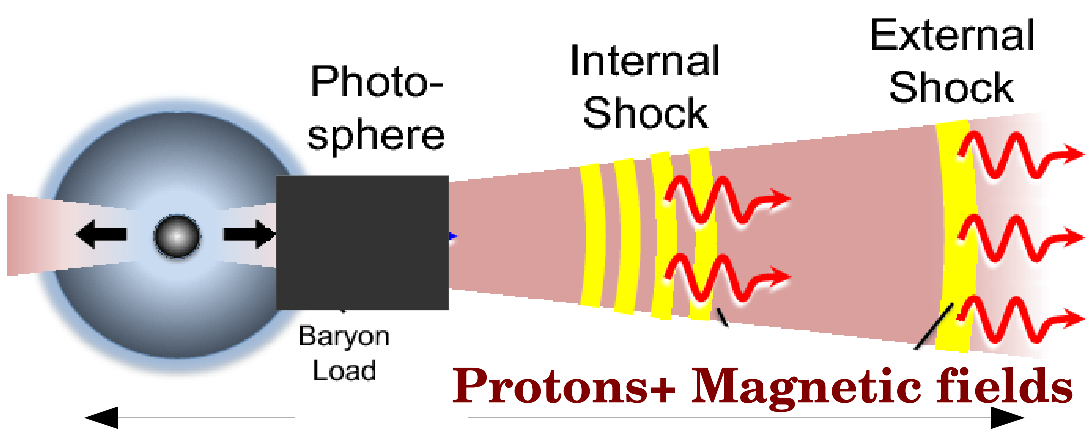
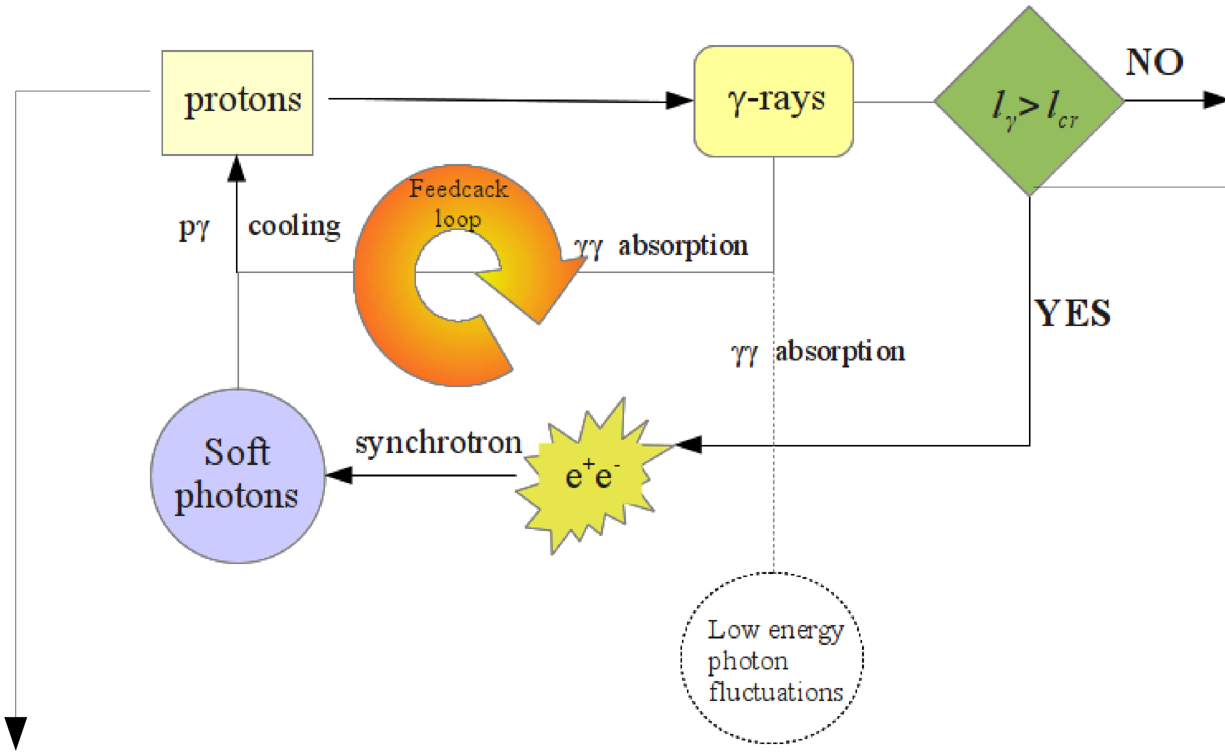




Optically thick

Optically thick conditions at large radii ($>10^{14}$ cm)?

Sketch of the coupling between protons, electrons and photons



Proton injection compactness

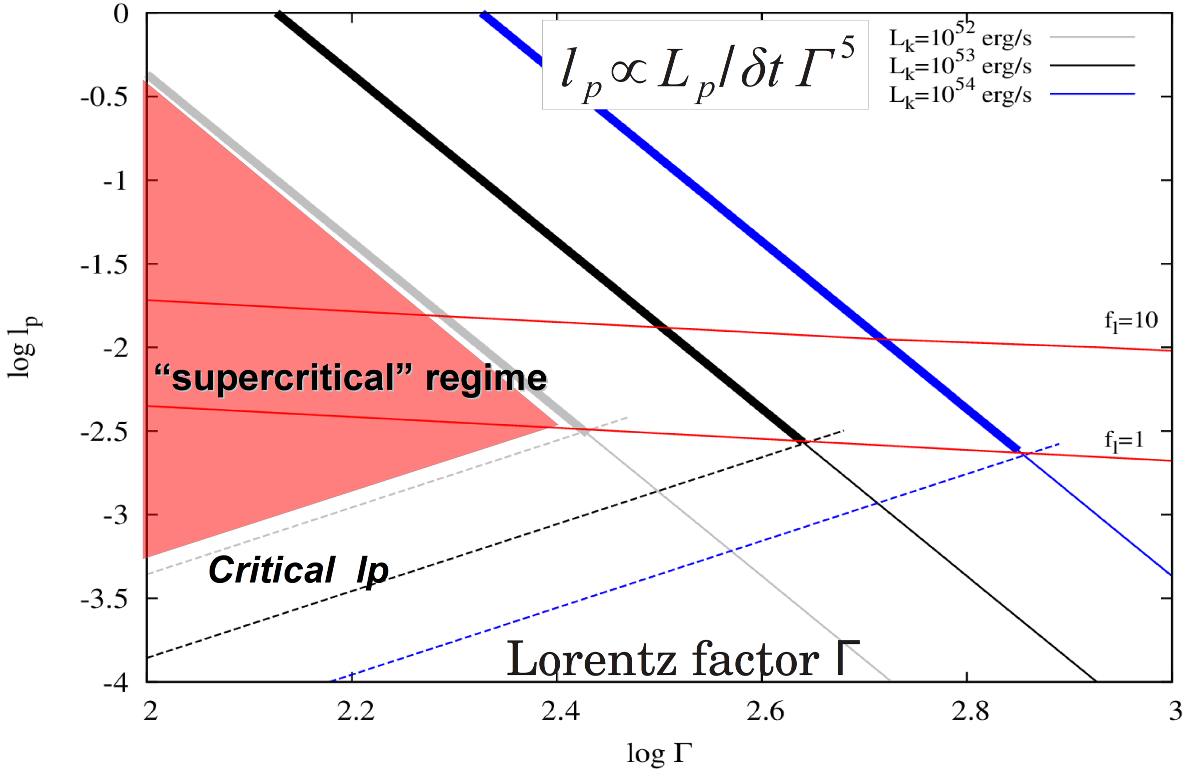
$$\ell_{\mathrm{p}}^{\mathrm{inj}} = \frac{\epsilon_{\mathrm{p}} L_{\mathrm{k}} \sigma_{\mathrm{T}}}{4\pi m_{\mathrm{p}} c^4 \delta t \Gamma^5} = 0.43 \frac{\epsilon_{\mathrm{p},0} L_{\mathrm{k},52}}{\delta t_{-1} \Gamma_2^5}$$

Proton **critical** compactness

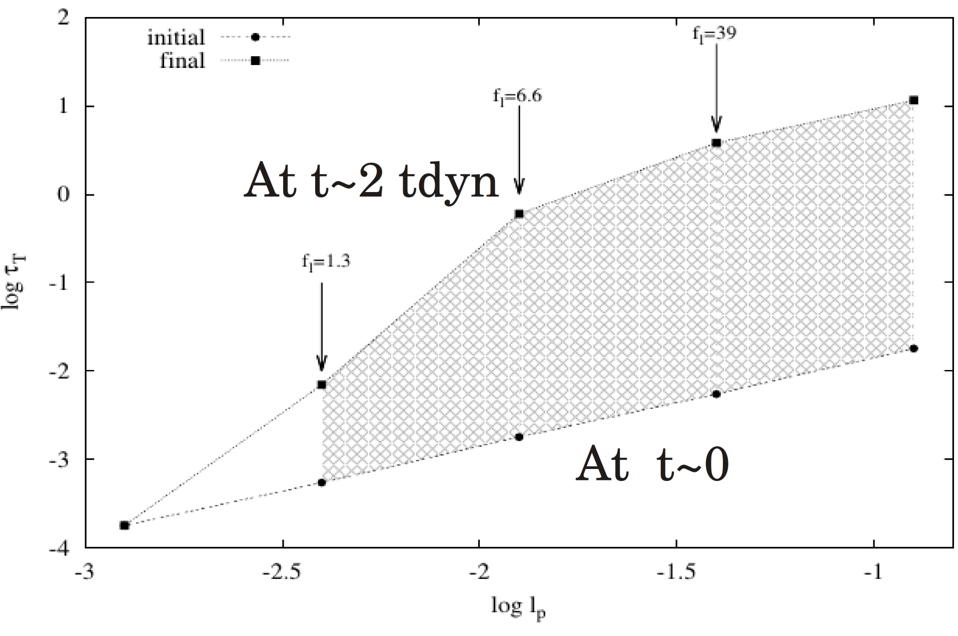
$$\ell_{\mathrm{p,cr}} = 4 \times 10^{-4} \Gamma_2^2 \epsilon_{\mathrm{B},-1}^{-1/2} L_{\mathrm{k},52}^{-1/2}$$

Petropoulou, Dimitrakoudis, Mastichiadis, Giannios. 2014, MNRAS, 444

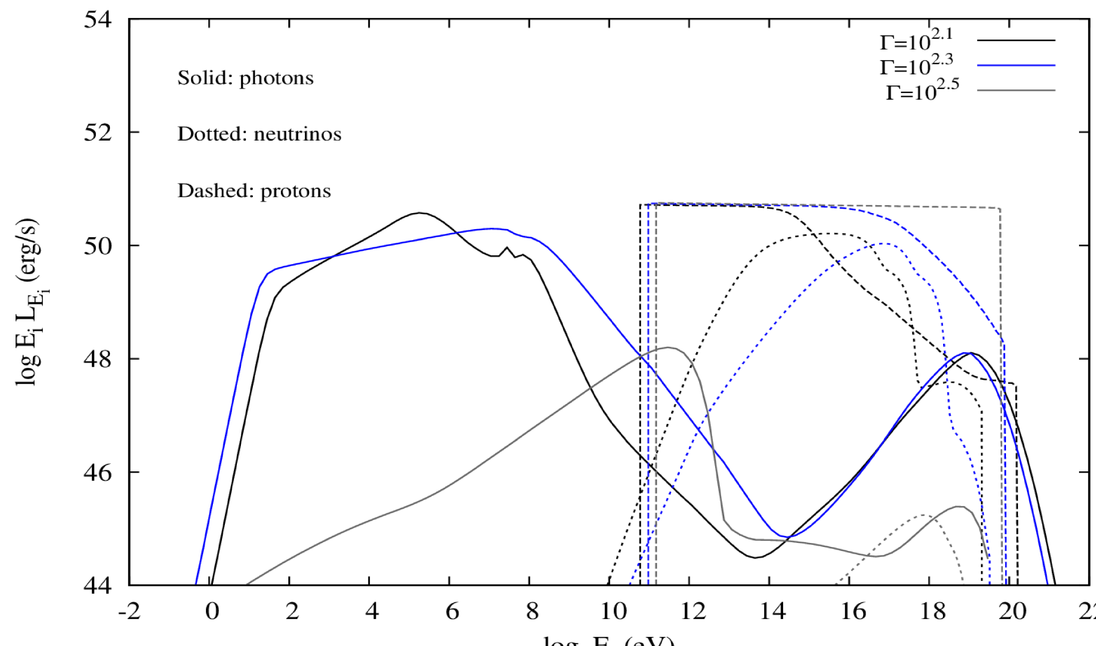
Hadronic supercriticality & GRB emission



Thomson optical depth



Emission spectra

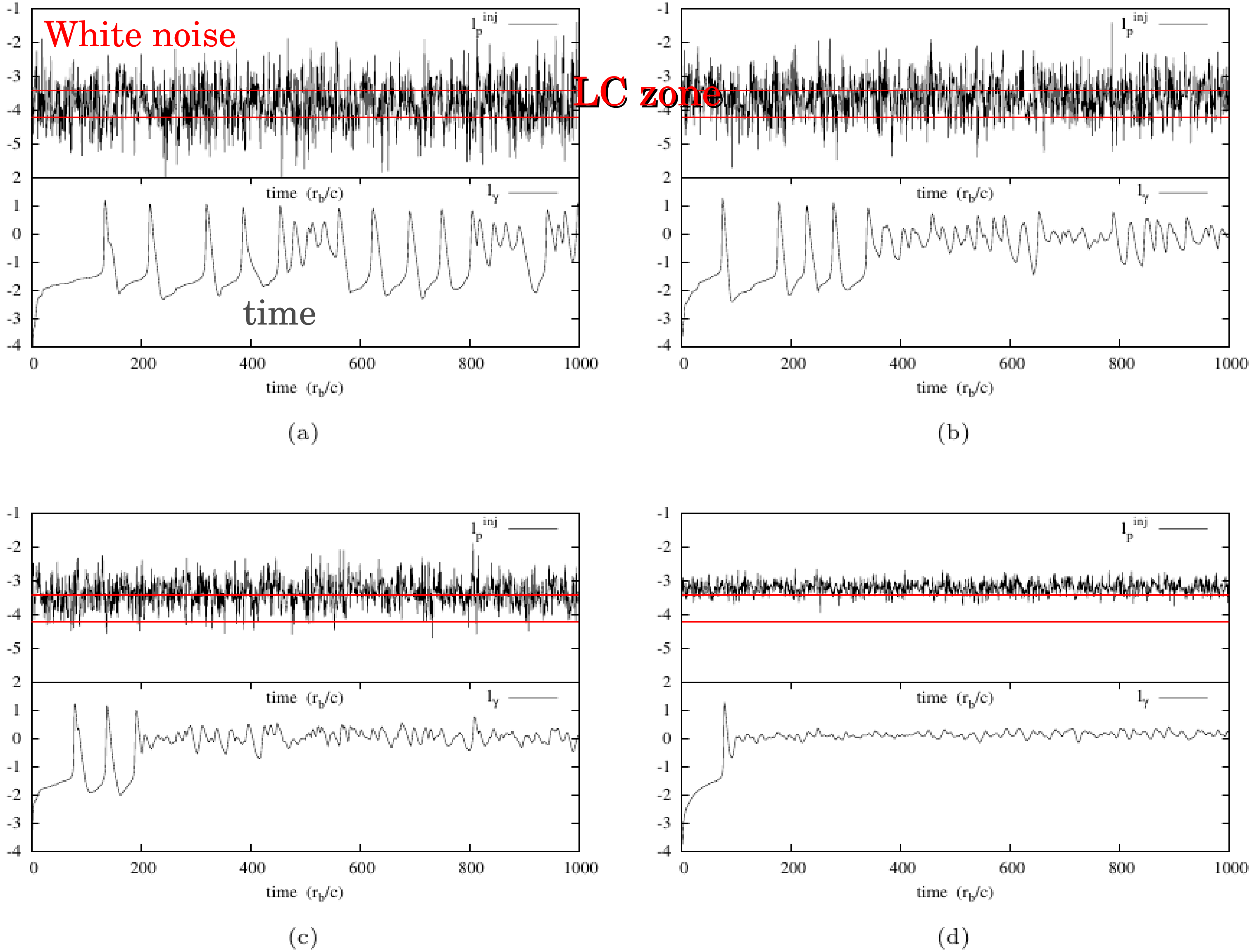


Hadronic supercriticality & GRB emission

White noise

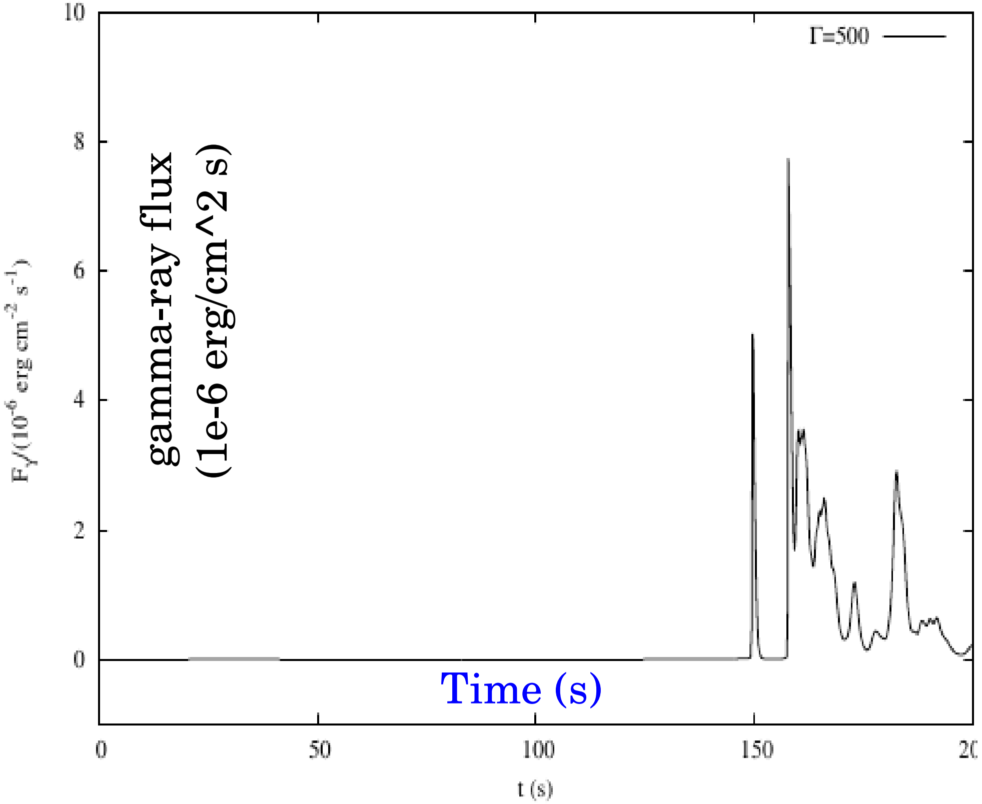
proton
luminosity

photon
luminosity

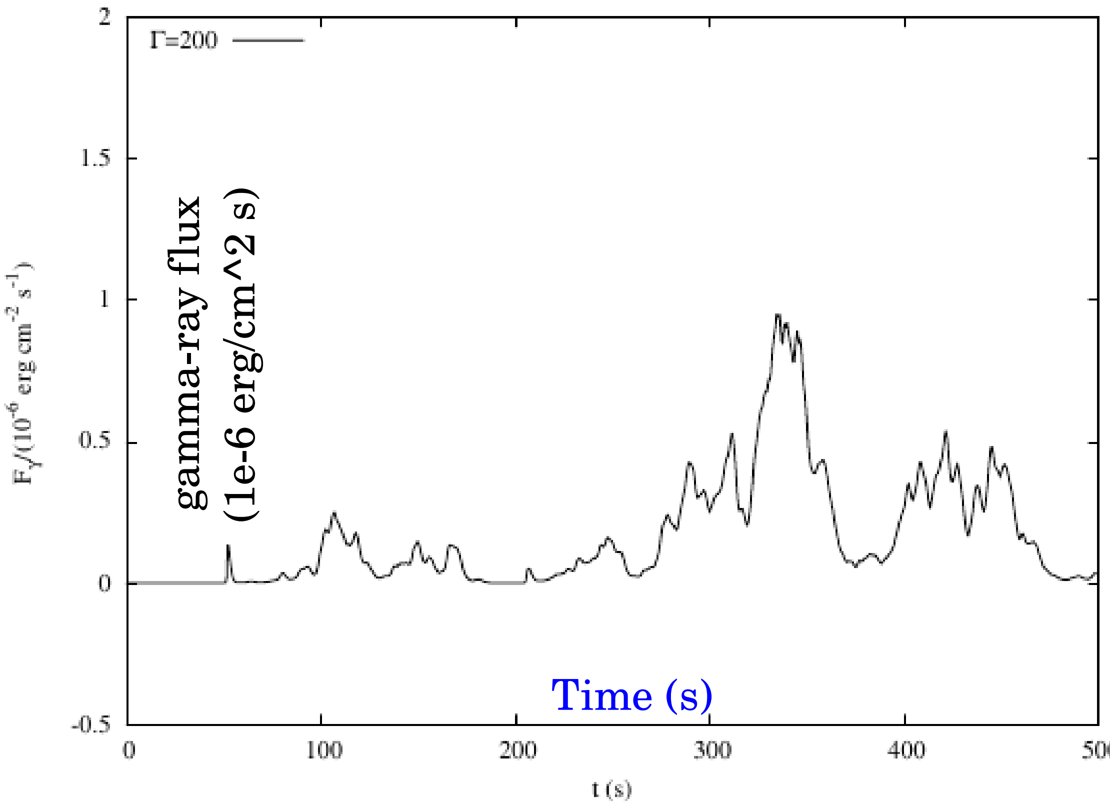


Petropoulou, Vasilopoulos, Mastichiadis (in prep)

Hadronic supercriticality & GRB emission

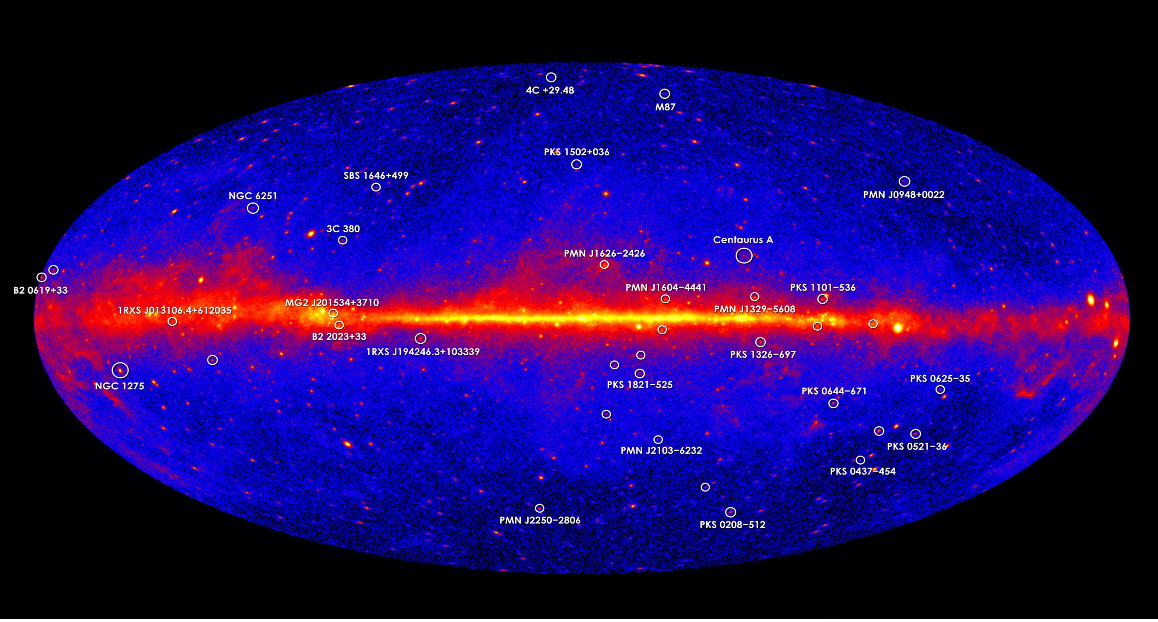


Examples of model light curves for variable proton injection (red noise)



Petropoulou, Vasilopoulos, Mastichiadis (in prep)

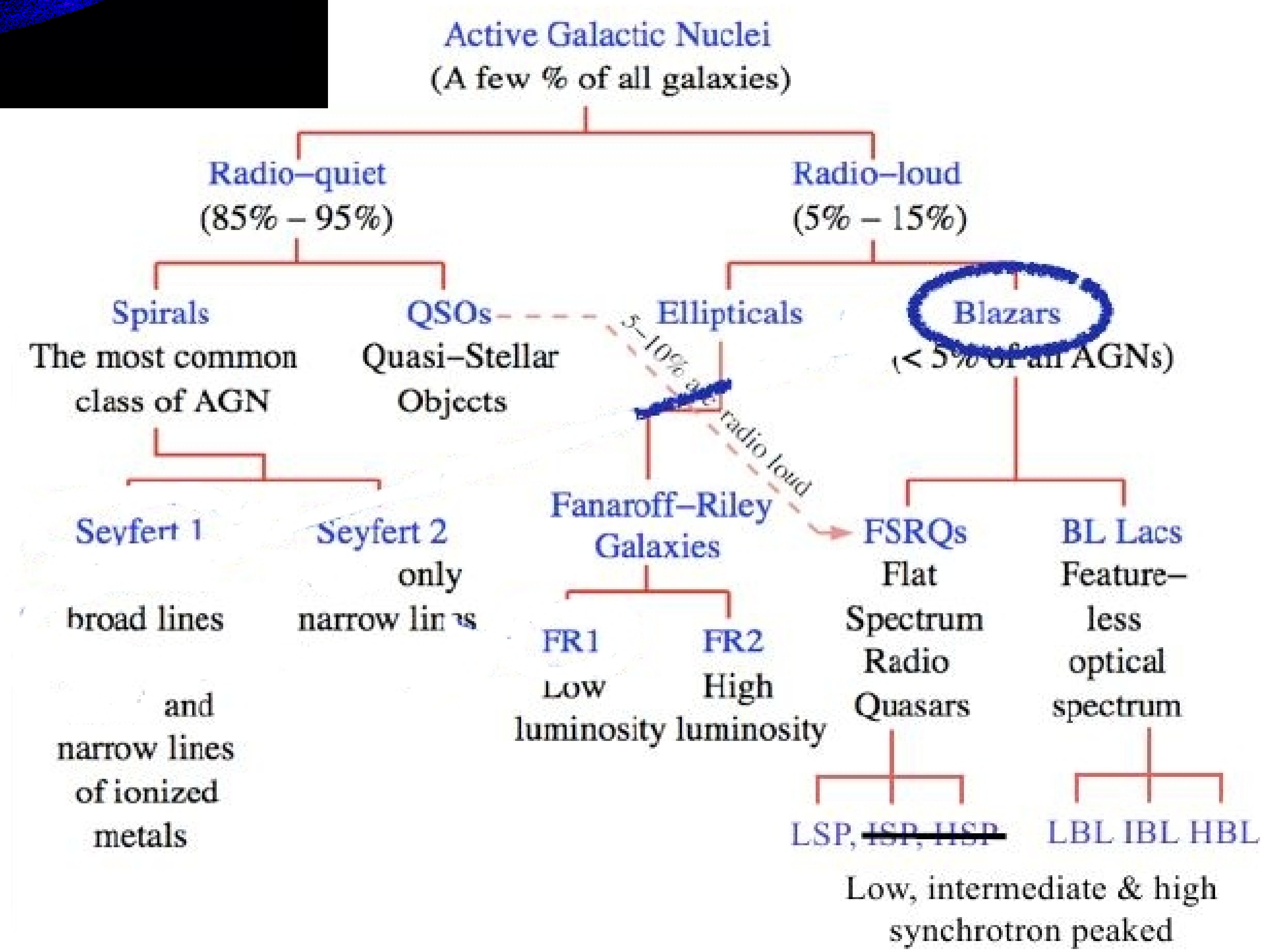
Blazar emission



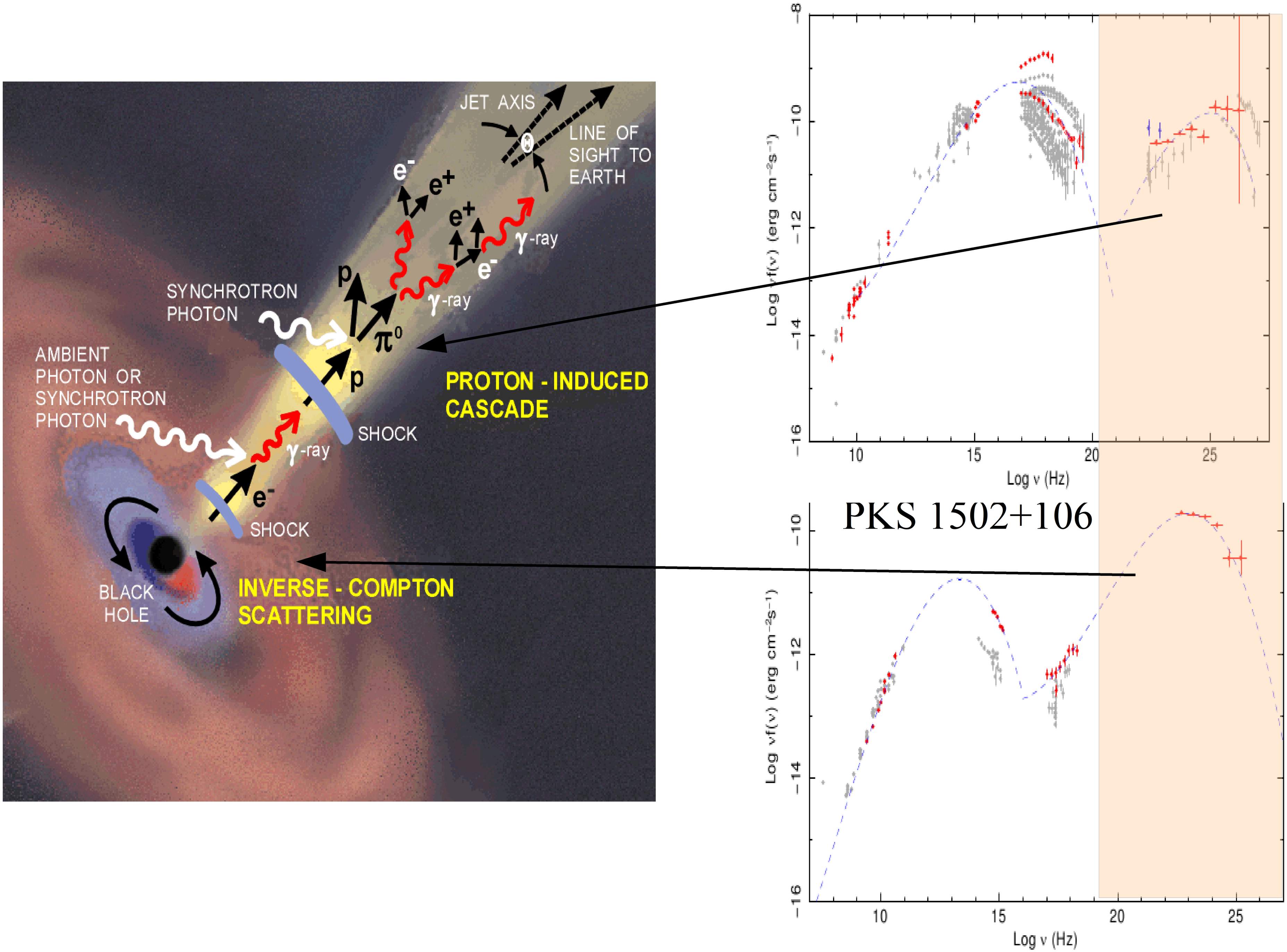
The 3rd Fermi-LAT catalog
for AGN(>100 MeV): 1591 sources

- 632 BL Lacs
- 467 FSRQs
- 460 blazars unknown type
- 32 non-blazar AGN

Ackermann et al. 2015, arXiv:1501.06054

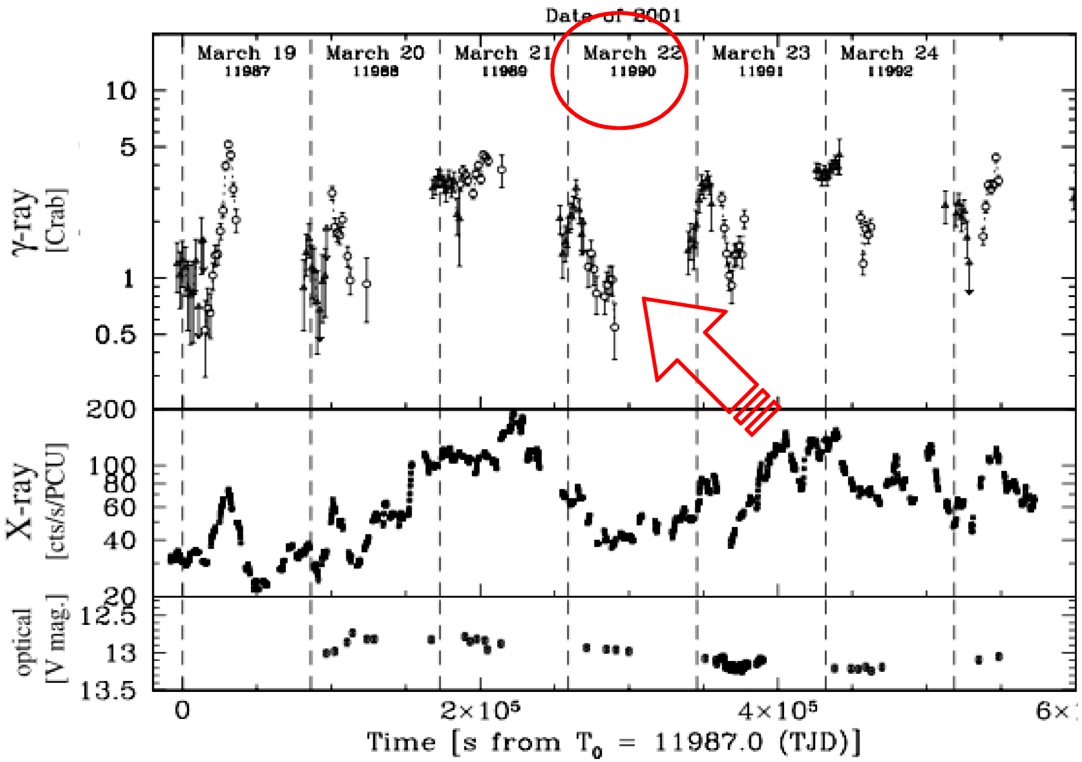


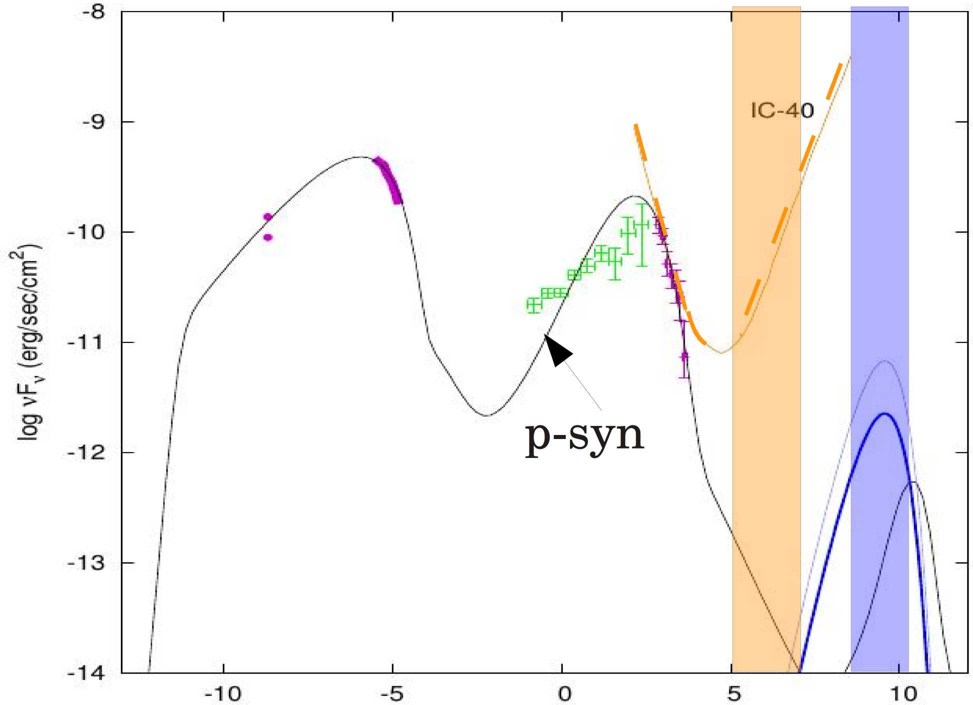
Leptohadronic models for blazar emission



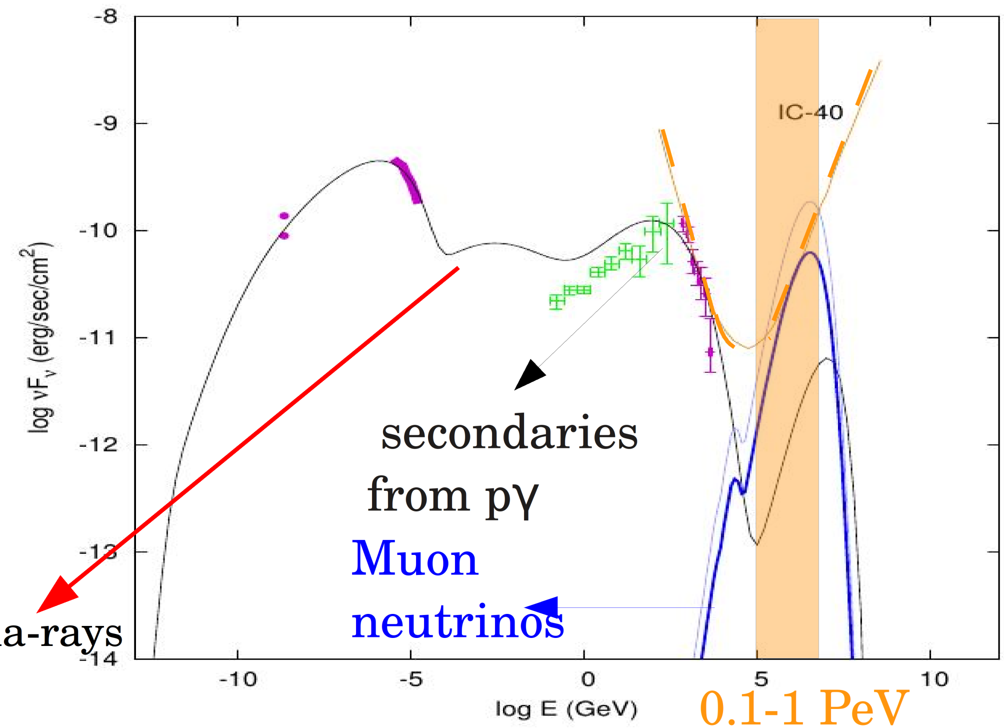
The case of Mrk 421

The 2001 MW campaign (Fossati et al. 2008, ApJ, 677)





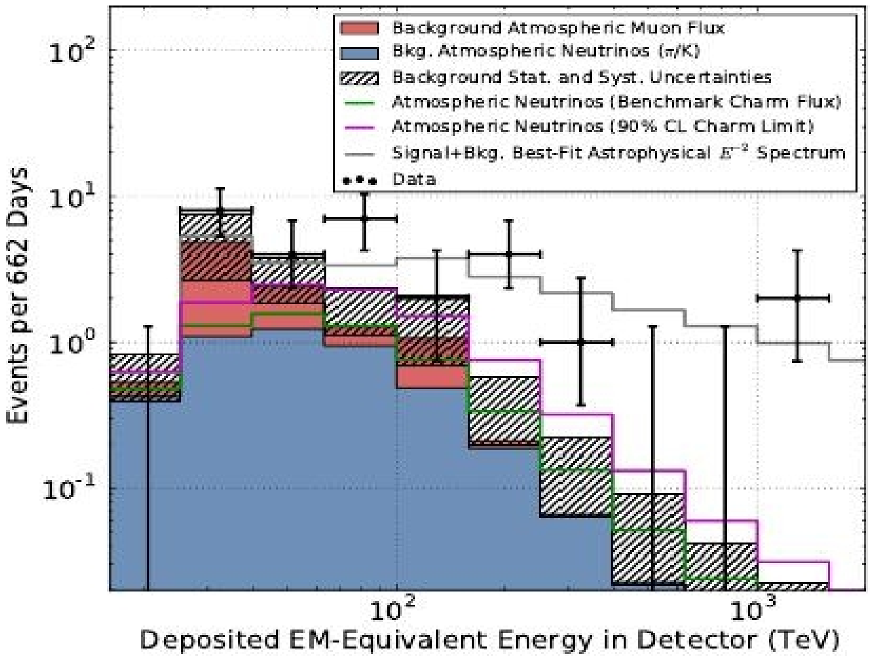
Dimitrakoudis et al., 2014, Aph, 54

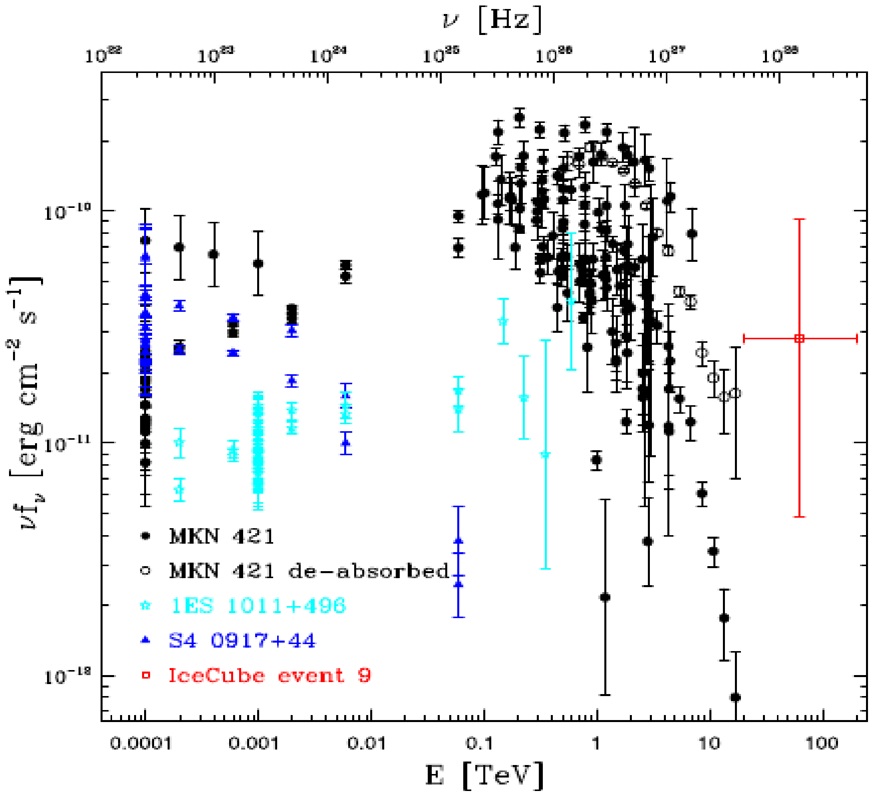


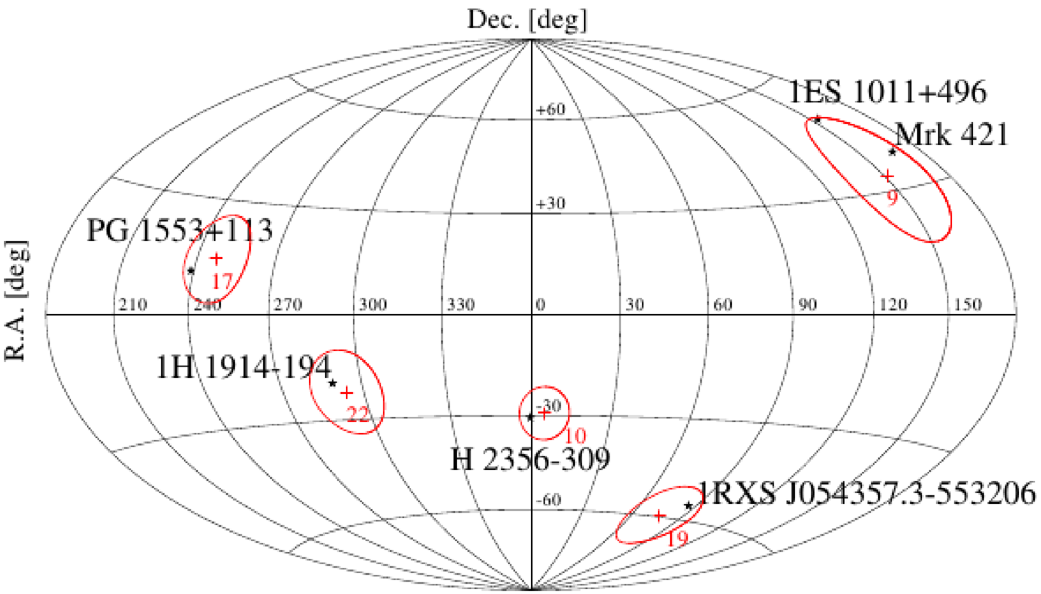
“Bethe-Heitler” component: a third hump in soft gamma-rays (Petropoulou & Mastichiadis 2015, MNRAS, 447)

BL Lacs as counterparts of IceCube neutrinos

(The IceCube collaboration,2014, Phys.Rev.Lett)





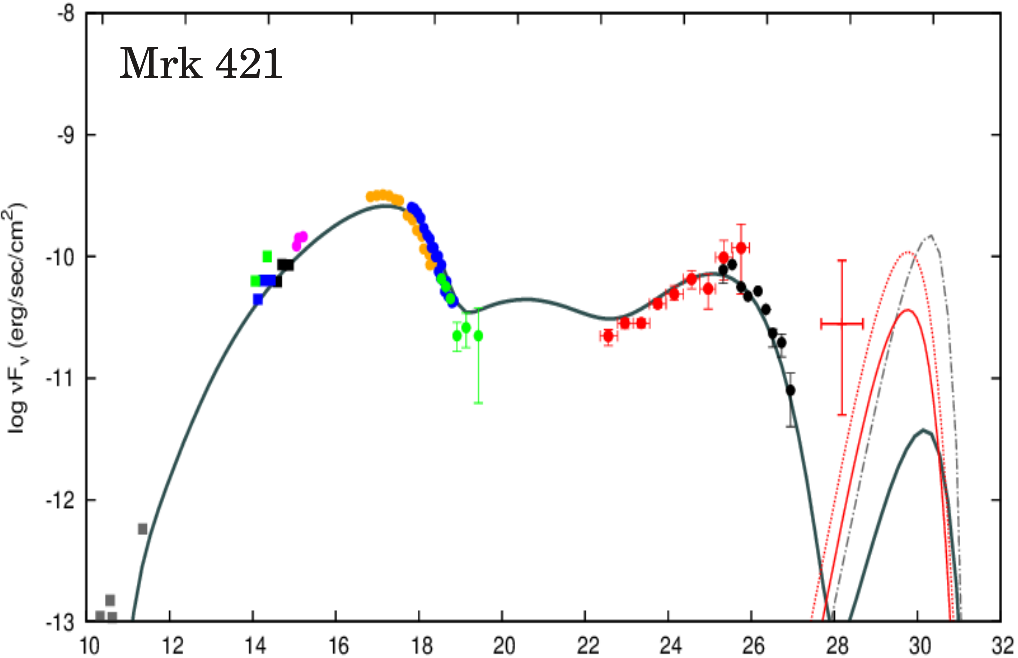


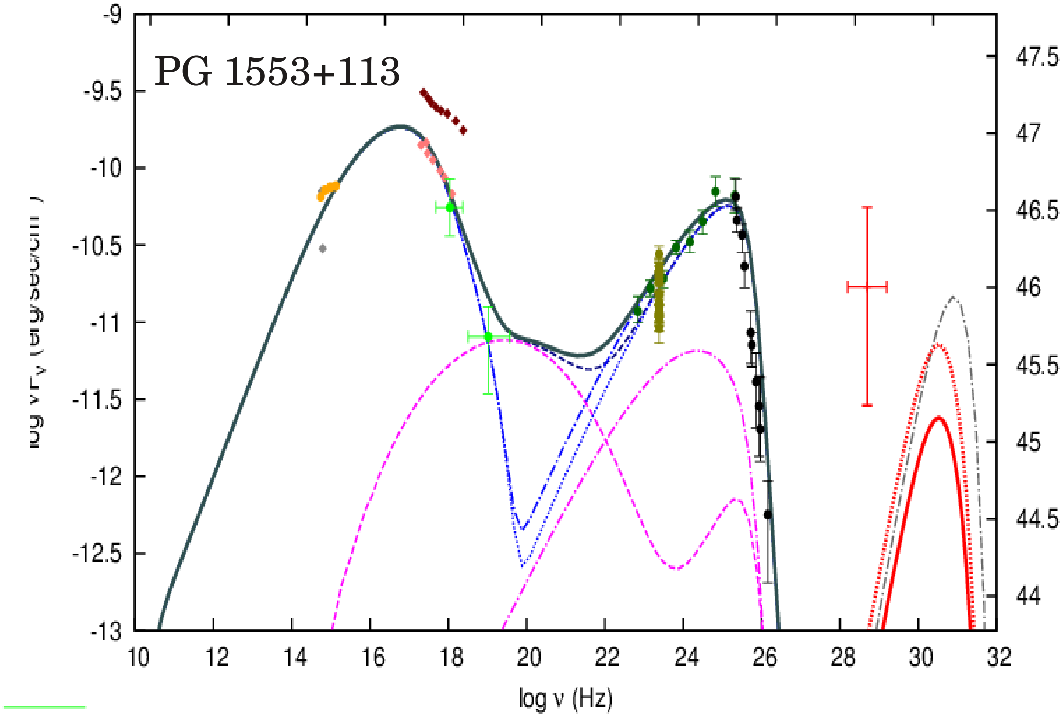
Top left: muon ν spectrum (28 events)

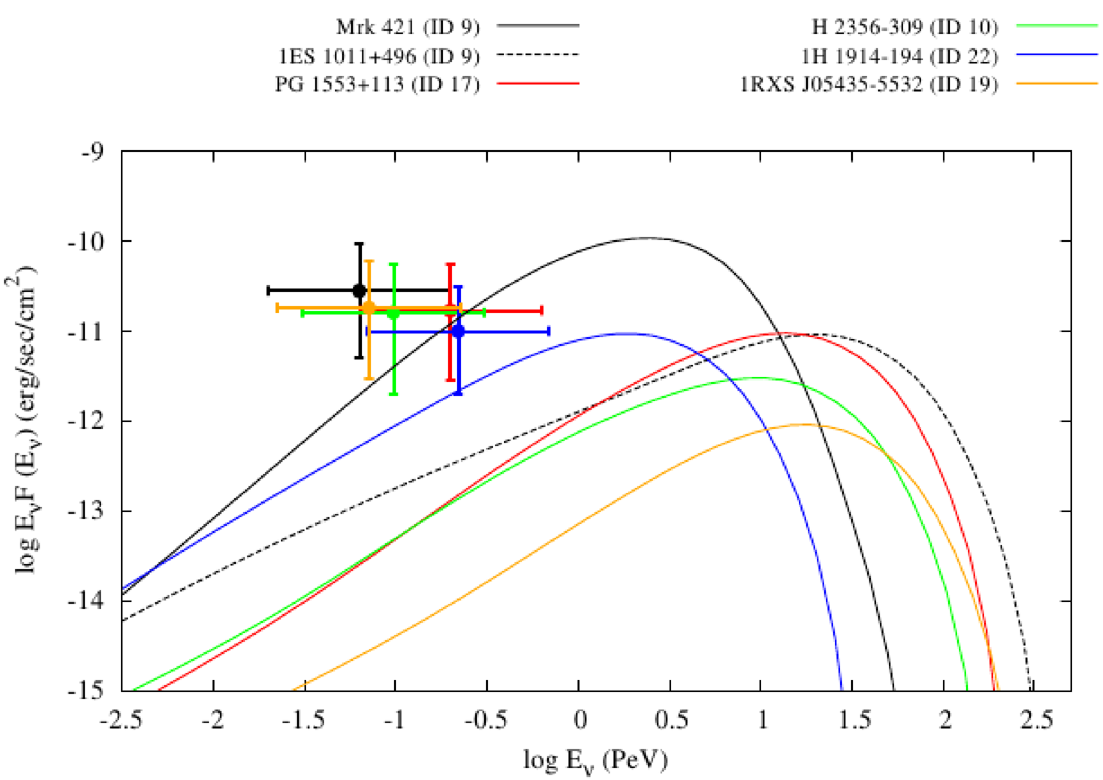
Top right: “hybrid SED” from Padovani & Resconi, 2014, MNRAS, 443

Bottom left: Sky map of 5 neutrino events and BL Lac counterparts from Petropoulou et al. 2015, MNRAS, 448

Neutrino emission from individual BL Lacs





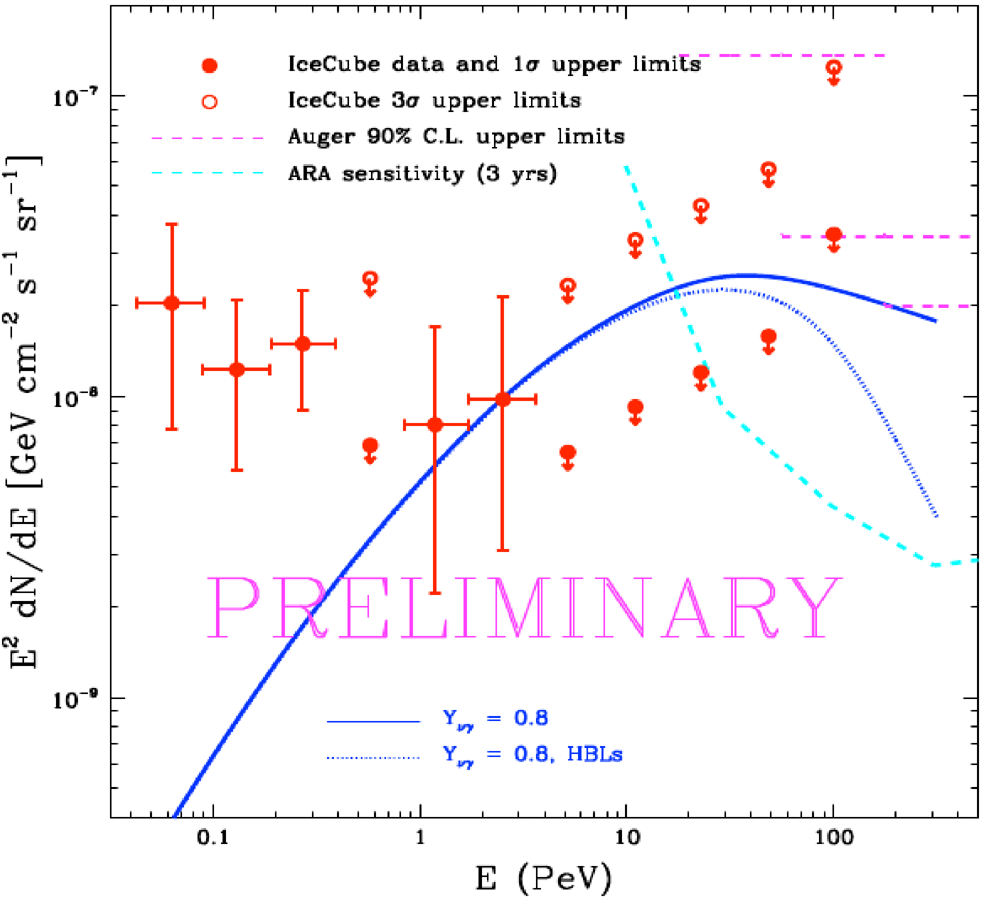


Mrk 421: possible positive detection of neutrinos might be achievable with some confidence (~3σ level) using preliminary discovery potentials based on 6 years IceCube life time

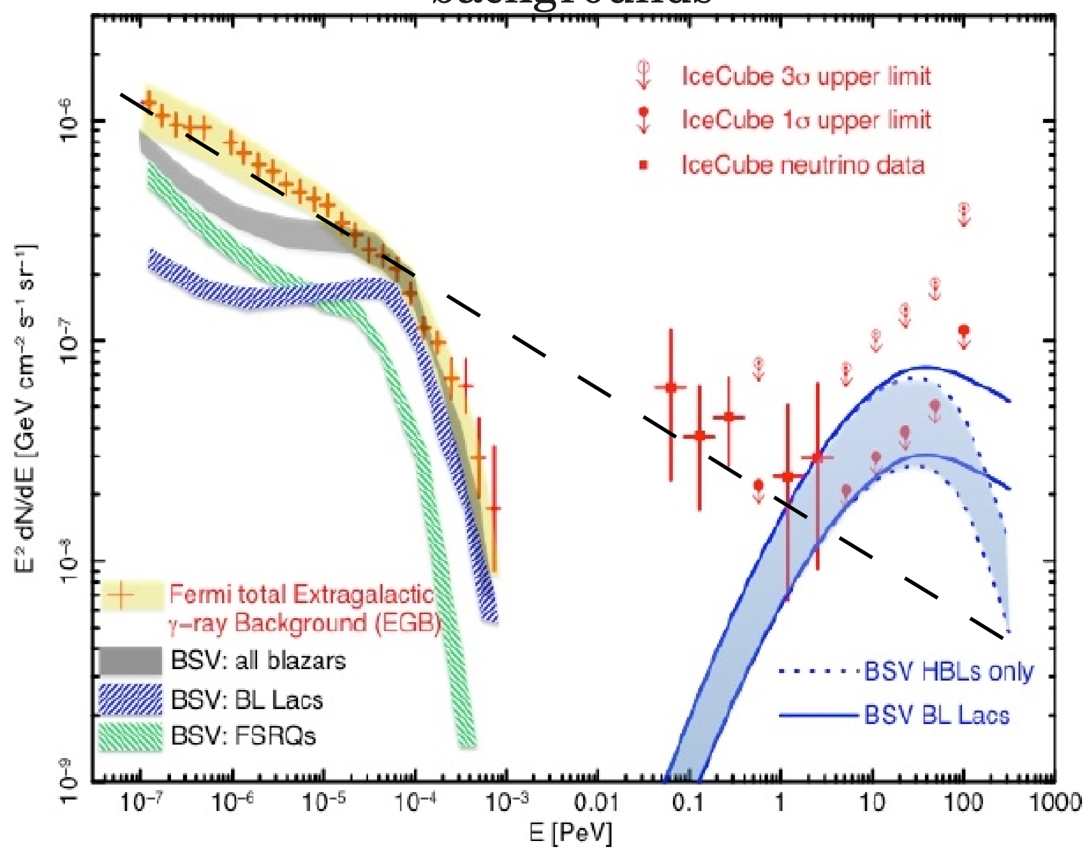
PG 1553+113: model prediction is much below the 3σ error bars. Gamma-ray emission mostly from SSC

Petropoulou et al. 2015, MNRAS, 448

Neutrino emission from *all* BL Lacs



The extragalactic γ-ray and neutrino backgrounds



Padovani et al. 2015, submitted in MNRAS

Summary

Leptohadronic plasmas are dynamical systems with interesting properties:

– for constant injection they reach steady state or show limit cycle behavior of a prey-predator type; gradual accumulation of proton energy → explosive release
– for variable injection in and out from the supercritical regime → series of randomly distributed outbursts – more GRB-like behaviour than AGN
– hadronic supercriticality → high radiative efficiency and GRB-like spectra

Two variants of leptohadronic models for AGN MW emission:

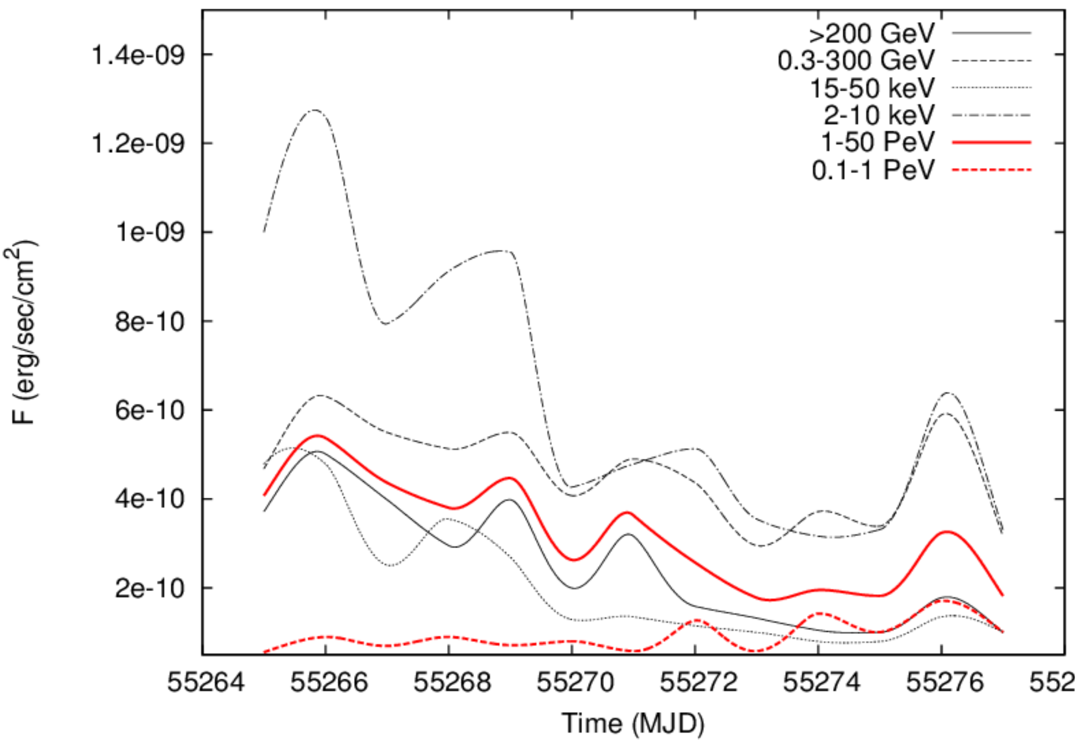
- LHπ : γ-rays from photopion + EM cascade (more energetically demanding)
- LHs : γ-rays from proton synchrotron (requires higher proton energies
  – both fit equally well the MW spectra
  – the LHπ predicts a Bethe-Heitler hump at MeV energies
  – the LHπ model predicts neutrinos at ~2-20 PeV

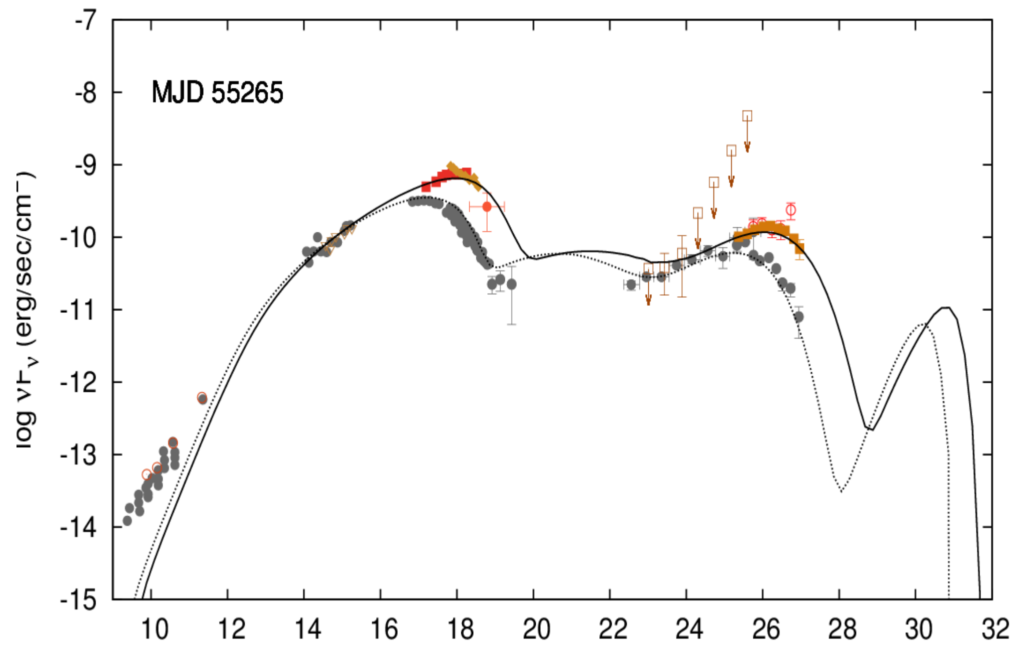
BL Lac - IceCube neutrino events correlations:
– successful MW fits using the LHπ model of 6 sources
– Mrk 421 potential point source of neutrinos
– the NBG from BL Lacs explains the 1-2 PeV flux but requires another population for the sub-PeV neutrino flux

Thank you

Back up slides

Time-dependent ν emission from Mrk 421





Top left: photon and neutrino light curves (MJD 55265-5527)

Top right: model SED and observations for MJD 55265

Bottom right:
Neutrino event rate (in 0.01/yr) within a window of 90%

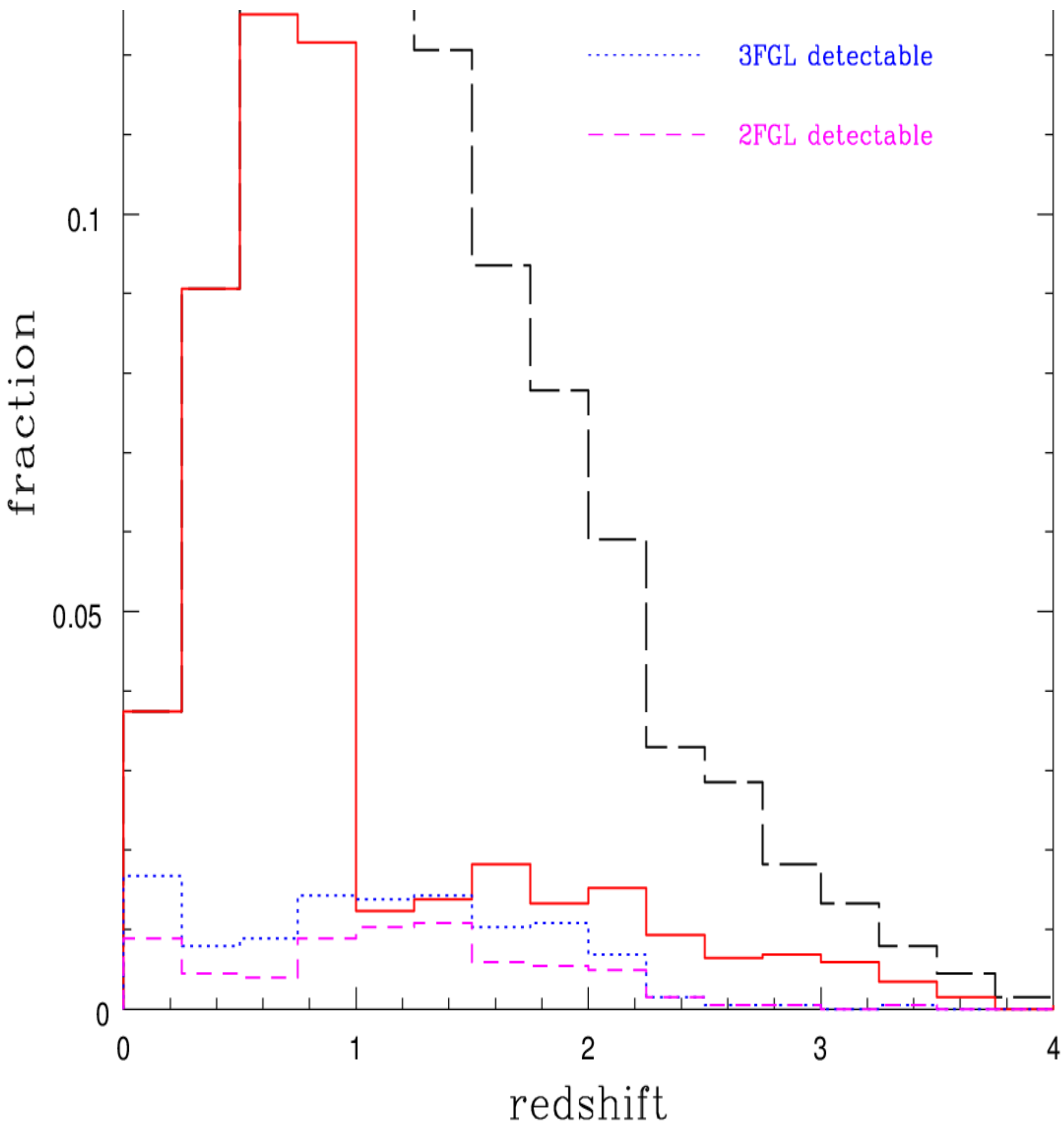
# of events

	100GeV to 10TeV ($\Delta\Psi < 0.37°$)	10TeV to 1PeV ($\Delta\Psi < 0.20°$)	1PeV to 100PeV ($\Delta\Psi < 0.16°$)
atmospheric[a]	1333.	7.054	7.516e-5
diffuse[a]	0.374	0.251	3.569e-3
54850-54983	0.023	30.02	28.85
55265	0.016	17.61	25.98
55266	0.025	27.75	39.60
55267	0.023	21.84	31.93
55268	0.027	28.29	35.02
55269	0.020	22.06	32.92
55270	0.035	25.21	28.80
55271	0.021	17.66	27.81
55272	0.055	39.88	35.47
55273	0.024	18.19	20.71
55274	0.090	47.54	33.53
55275	0.061	33.60	27.80
55276	0.053	37.64	32.24
55277			
Σ 12 day flare	0.036	28.25	30.82

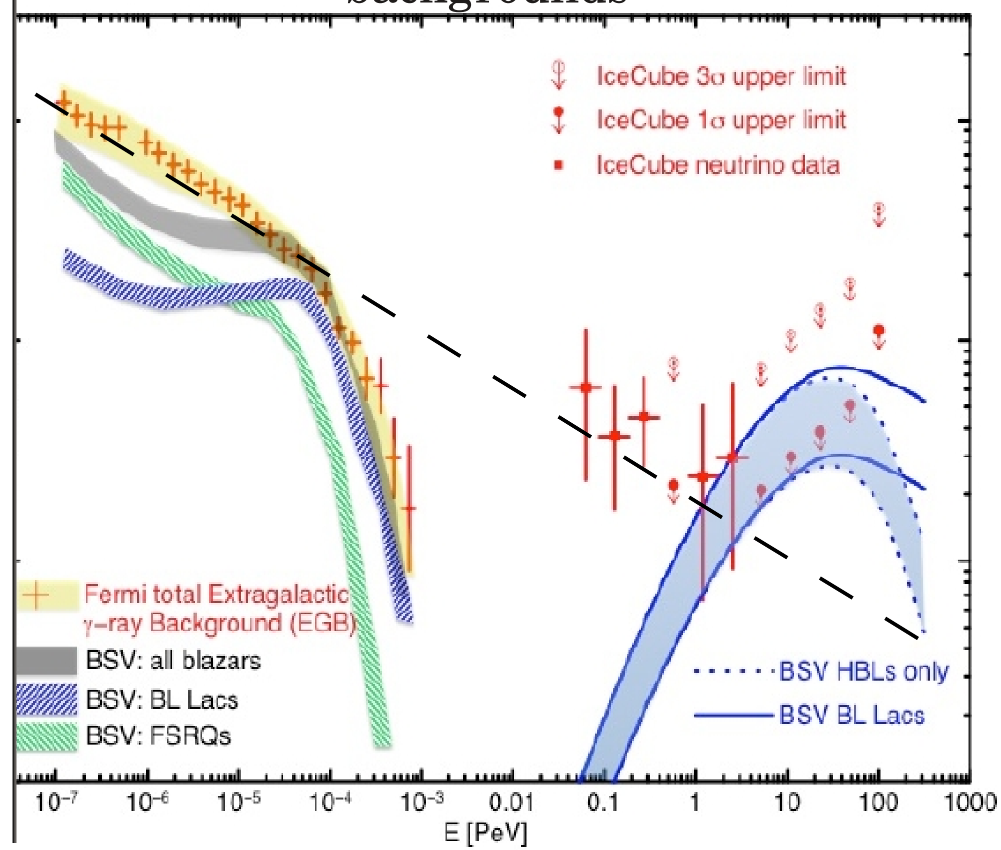
Petropoulou, Coenders et al., in prep

What are the sources of NBG?

Redshift distribution of sources ~95% of NBG

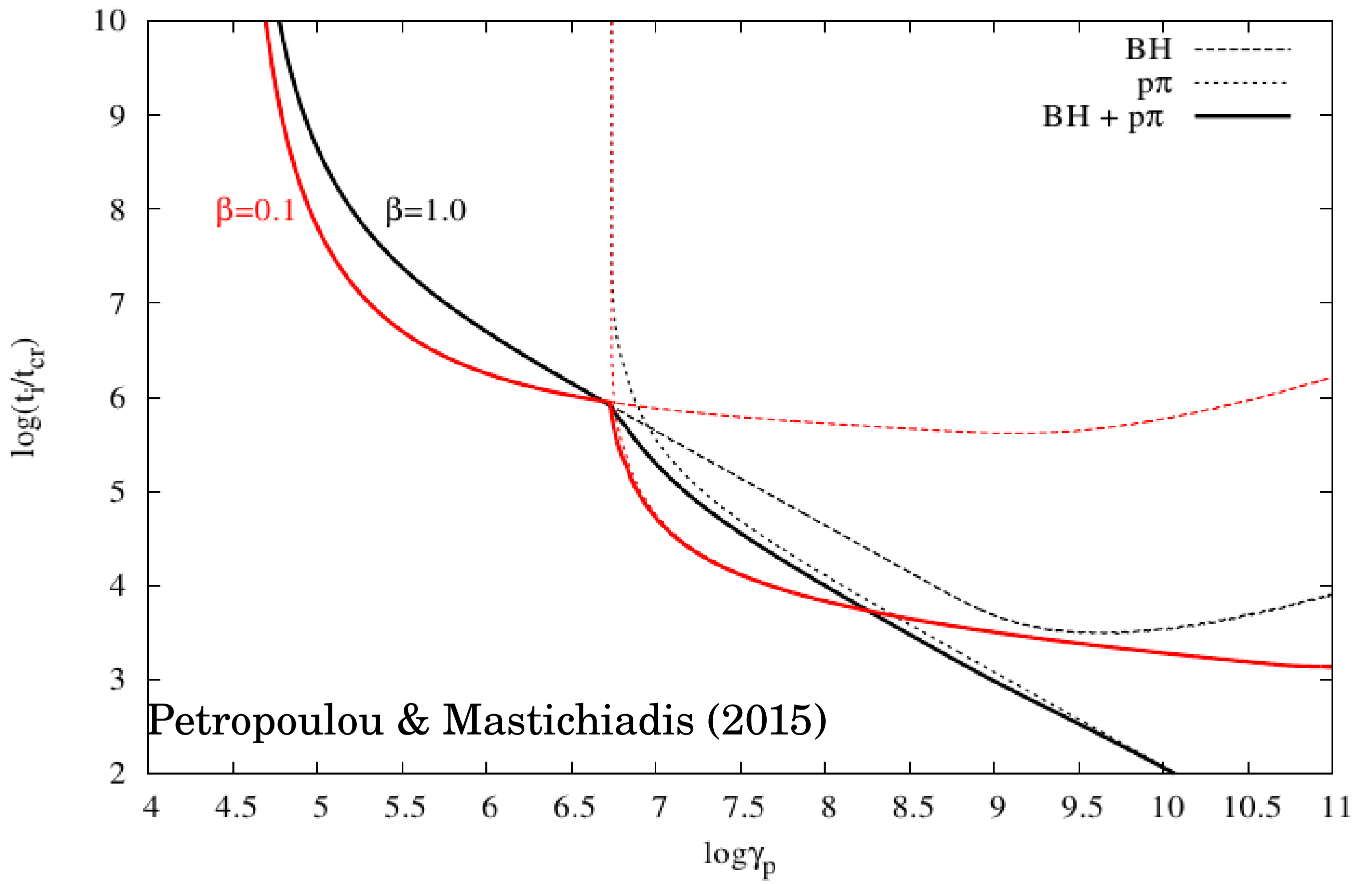


The extragalactic γ-ray and neutrino backgrounds



Padovani et al. 2015, submitted in MNRAS

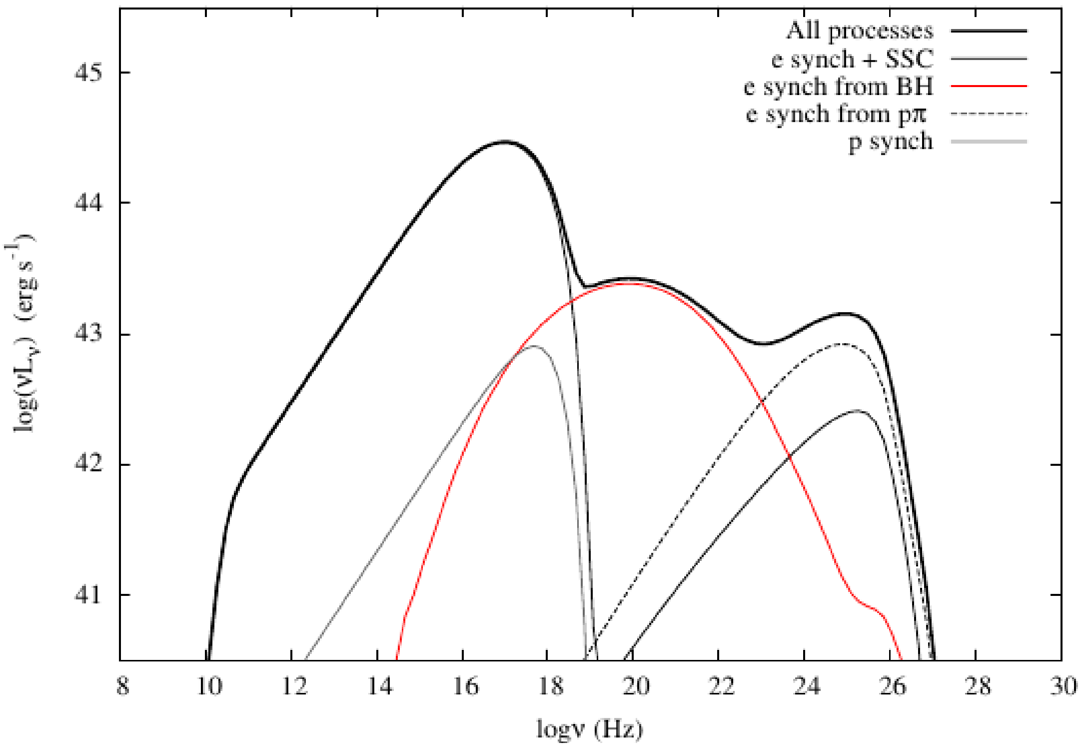
The “Bethe-Heitler” hump: pγ vs. pe timescales

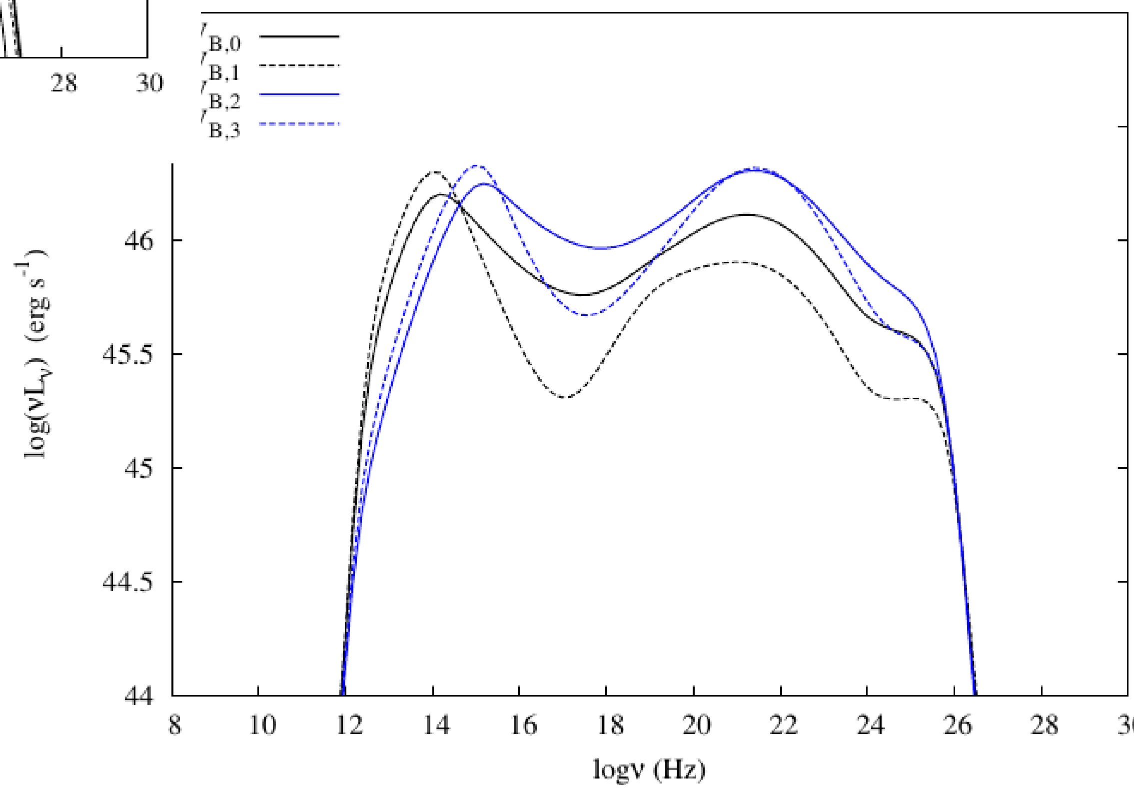


$$f_{p\pi}(\xi_{p\pi}) \simeq 22 \frac{L_{\mathrm{syn},45}\lambda(\beta,\epsilon_{\mathrm{s}})}{r_{\mathrm{b},15}\delta^3\nu_{\mathrm{s},16}(1+z)} \begin{cases} \xi_{p\pi}^{\beta}, & \xi_{p\pi} < \frac{\epsilon_{\mathrm{s}}}{\epsilon_{\mathrm{min}}} \\ \left(\frac{\epsilon_{\mathrm{s}}}{\epsilon_{\mathrm{min}}}\right)^{\beta}, & \xi_{p\pi} > \frac{\epsilon_{\mathrm{s}}}{\epsilon_{\mathrm{min}}} \end{cases}$$

$$f_{\mathrm{pe}}(\xi_{\mathrm{BH}}) \simeq 0.06 \frac{L_{\mathrm{syn},45}\beta(\beta+2)\lambda(\beta,\epsilon_{\mathrm{s}})}{r_{\mathrm{b},15}\delta^3\nu_{\mathrm{s},16}(1+z)}\xi_{\mathrm{BH}}^{\beta} I(\gamma_{\mathrm{p}},\beta)$$

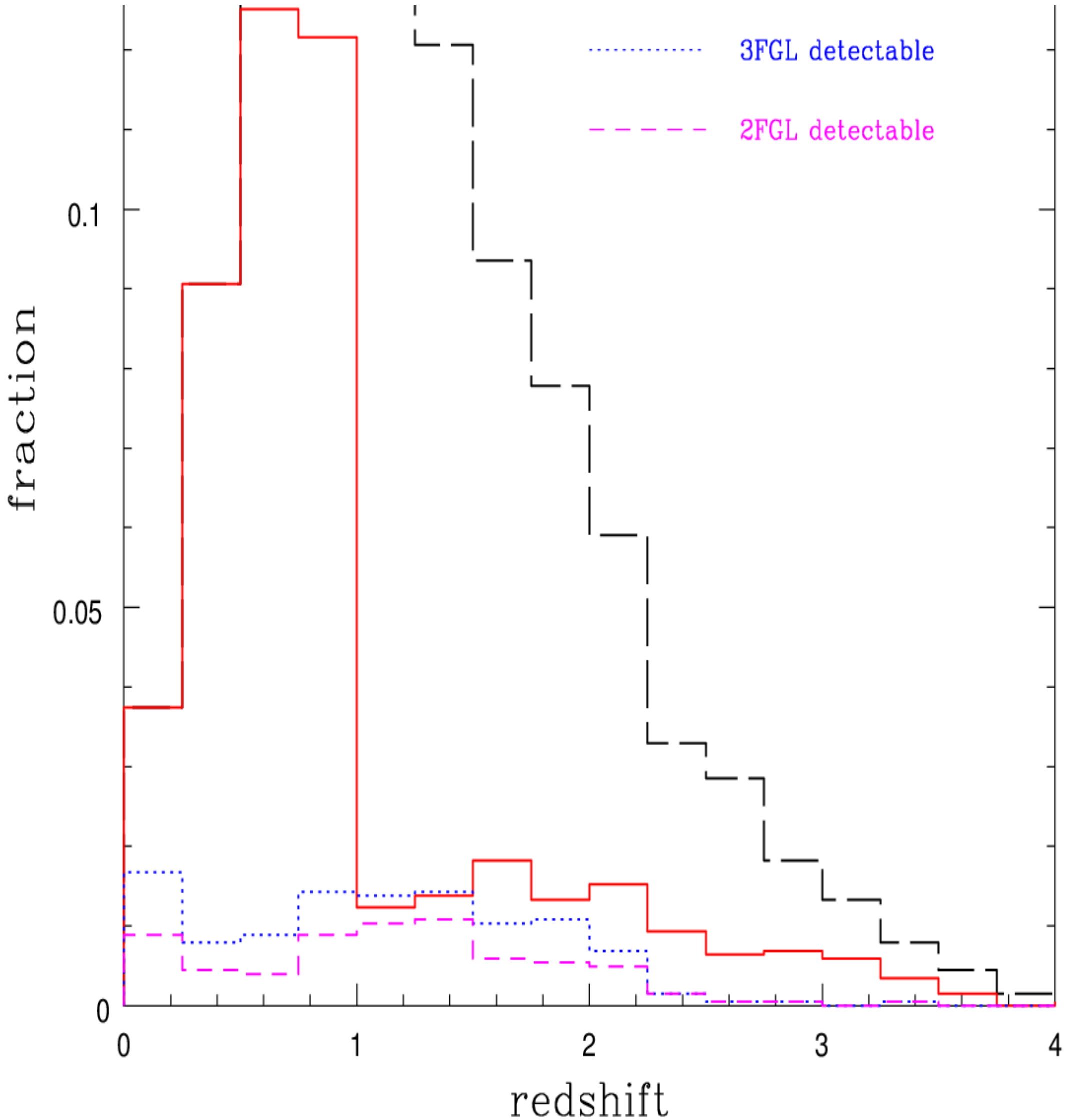
The “Bethe-Heitler” hump: generic SEDs



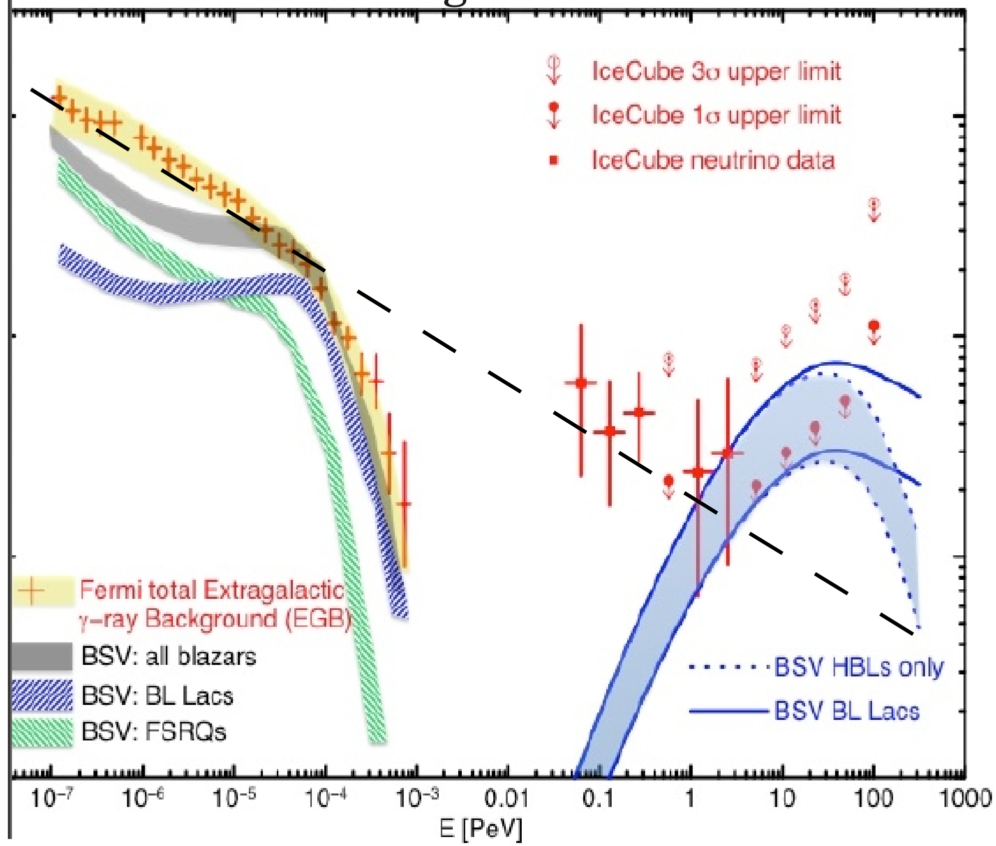


Back-up slides

Redshift distribution of sources ~95% of NBG



The extragalactic γ-ray and neutrino backgrounds



Padovani et al. 2015, submitted in MNRAS