VARIABILITY SIGNATURES OF THE HADRONIC MODEL

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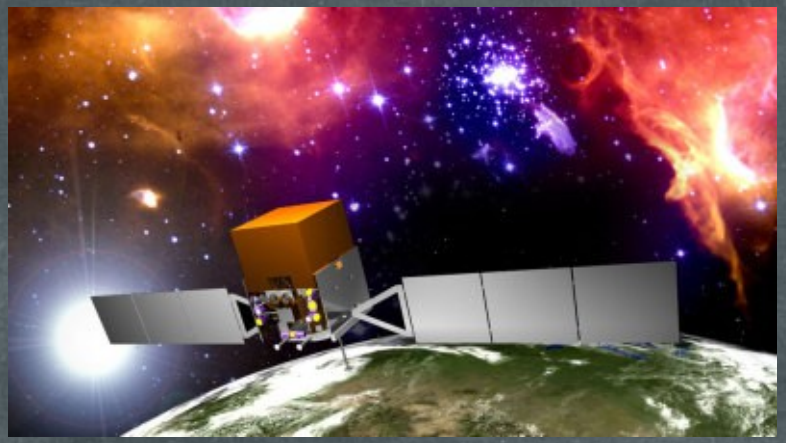
TALK OUTLINE

- Hadronic Models: key ideas and processes
- MW fits and simulated variability of blazars
- Proton supercriticalities: application to GRBs

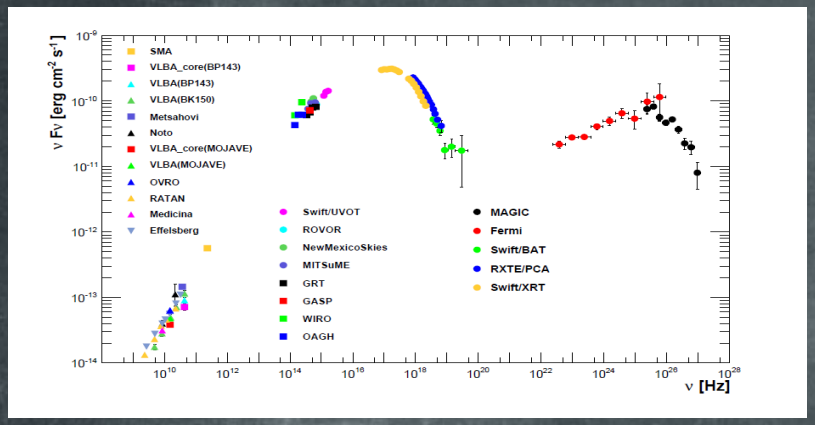
In collaboration with

- Maria Petropoulou
- Stavros Dimitrakoudis
  and
- Georgios Vasilopoulos
- Dimitrios Giannios

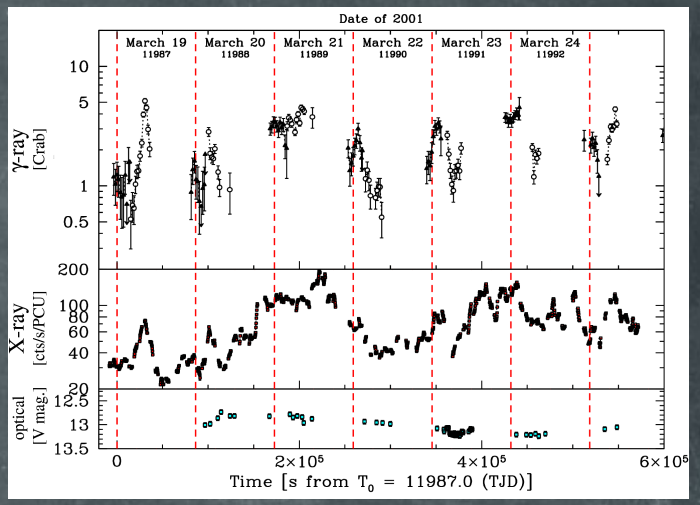
THE MULTI-MESSENGER ERA



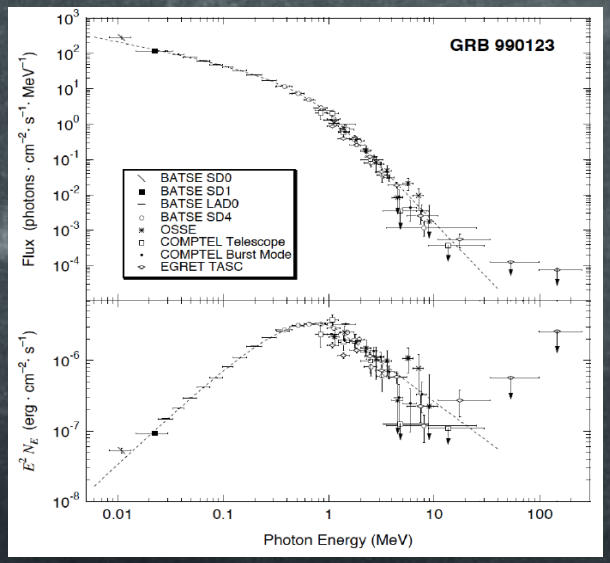
BLAZARS



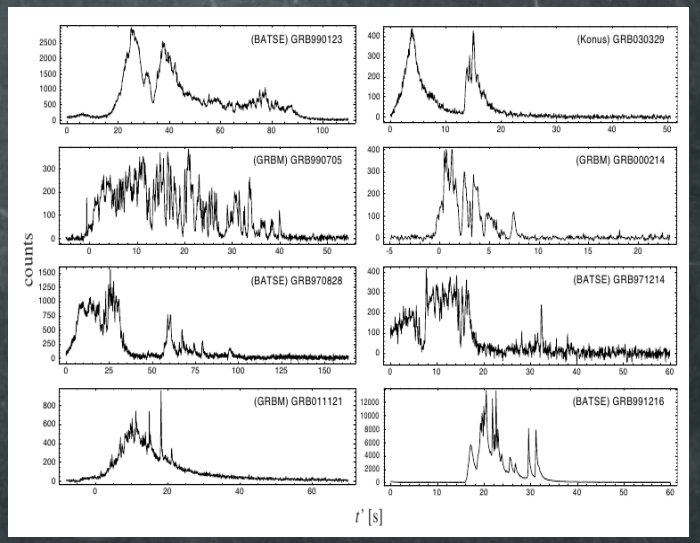
Spectra



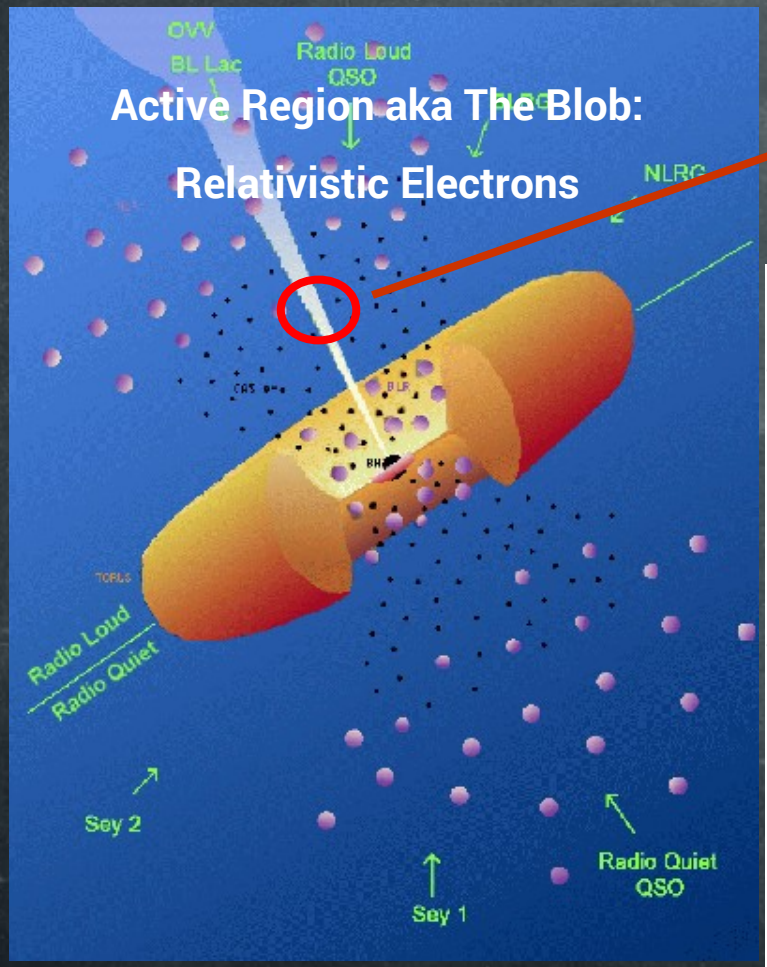
Lightcurves

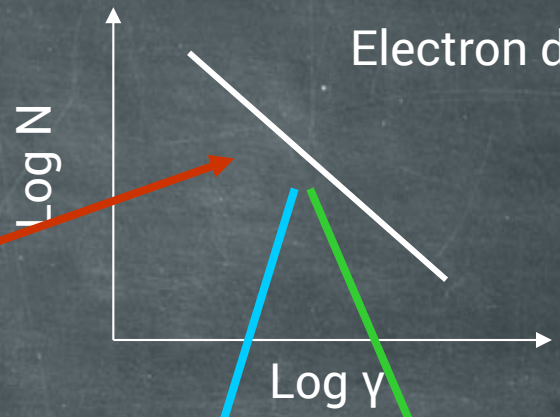


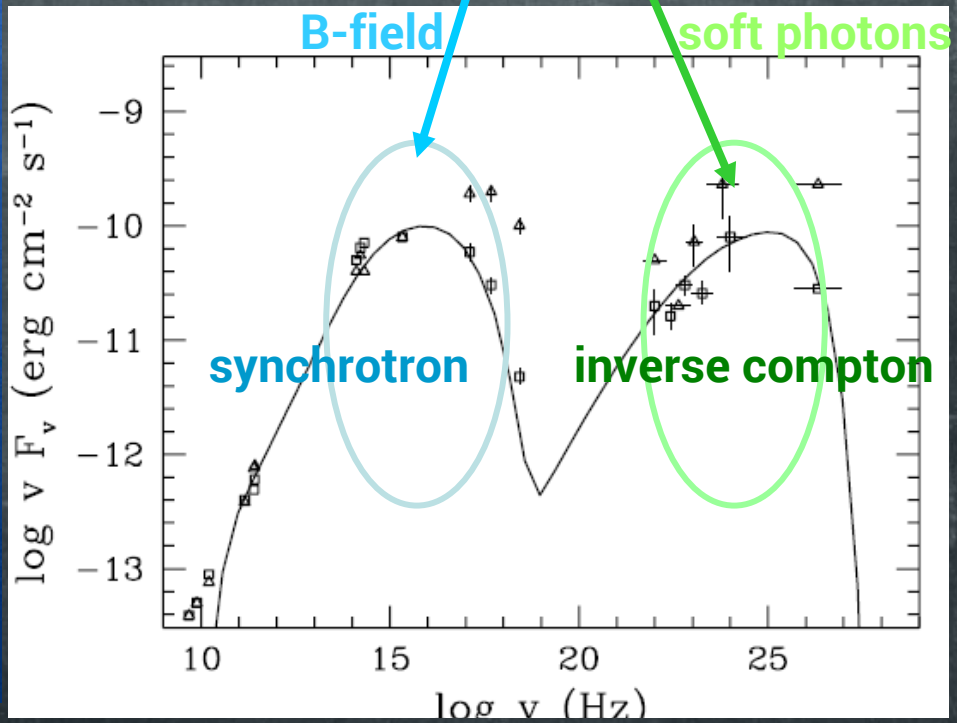
GRBs



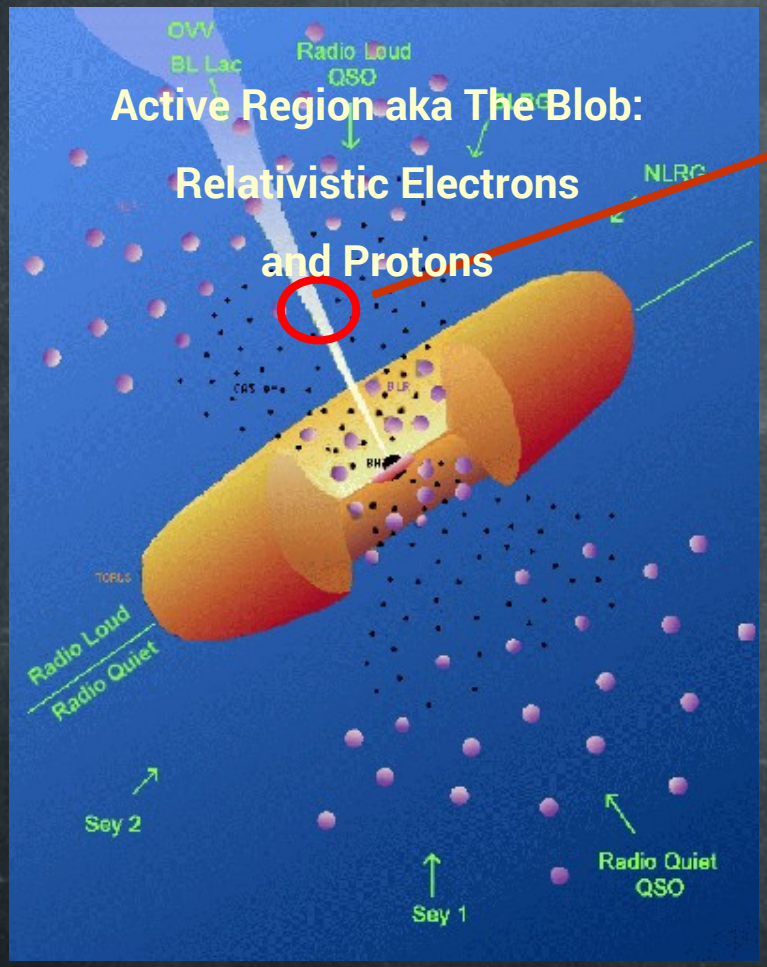
BLAZARS: LEPTONIC MODEL

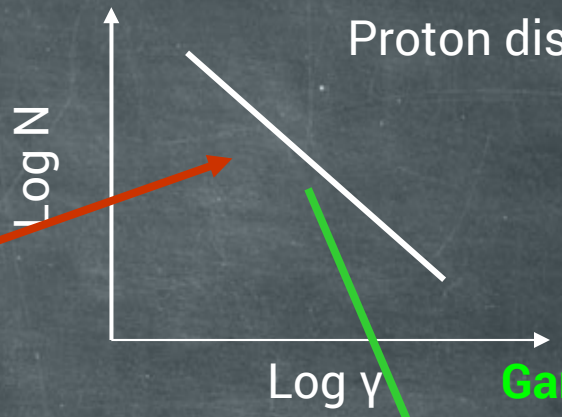




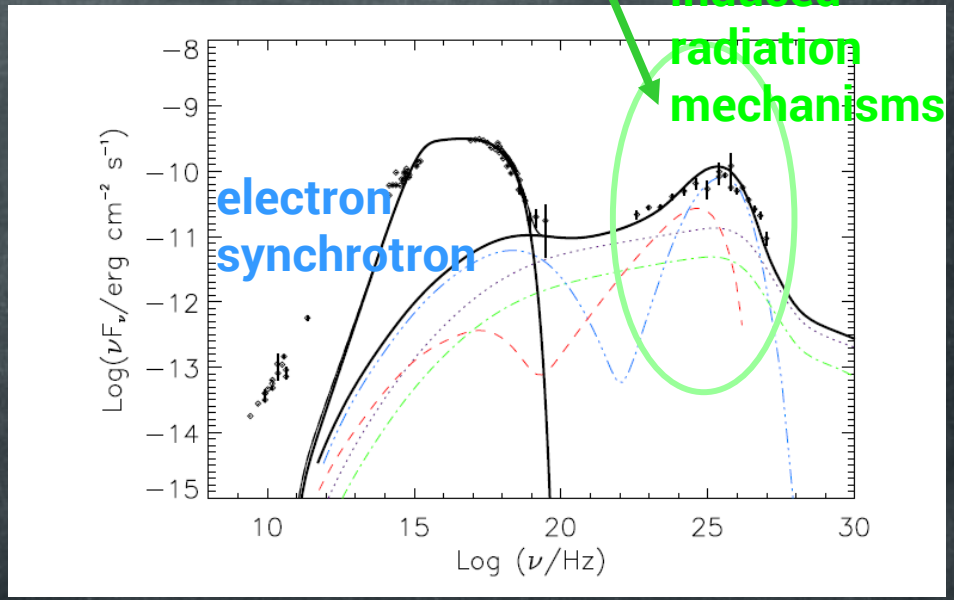


…AND THE HADRONIC MODEL

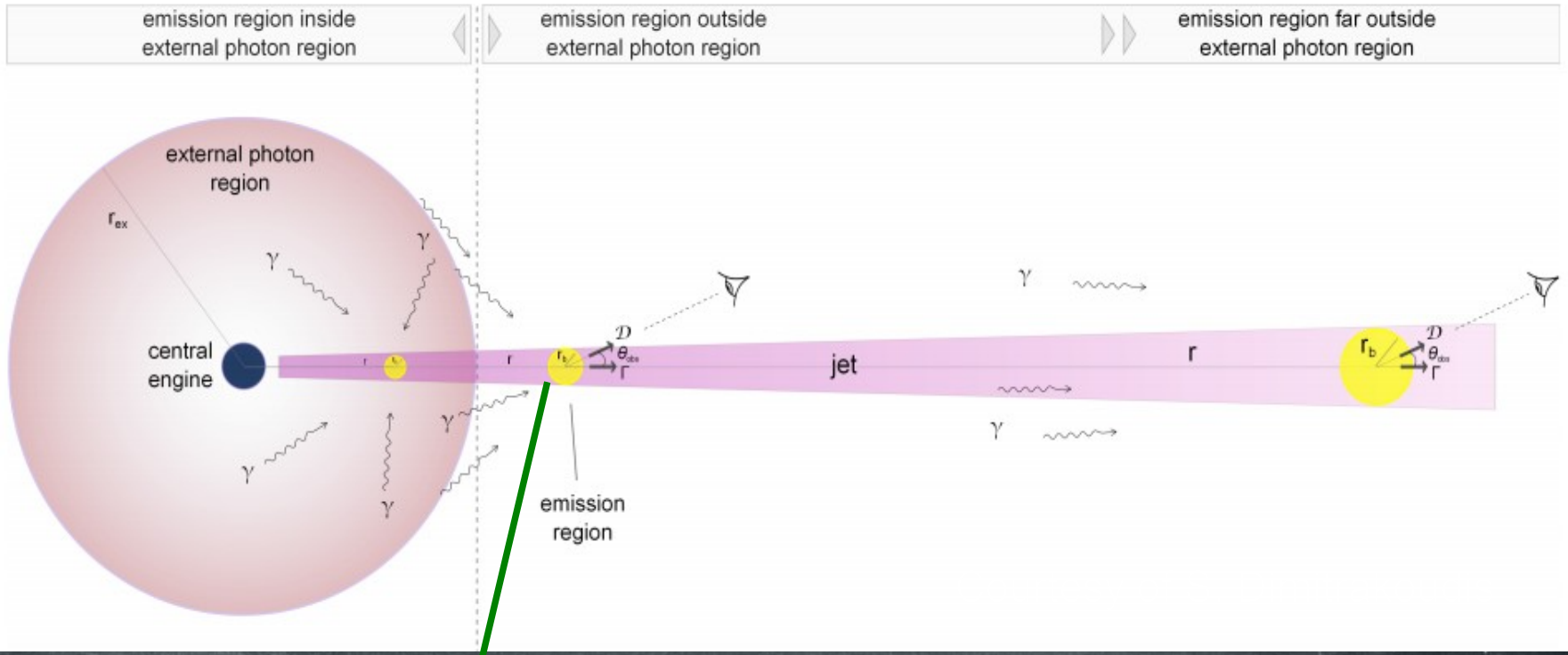


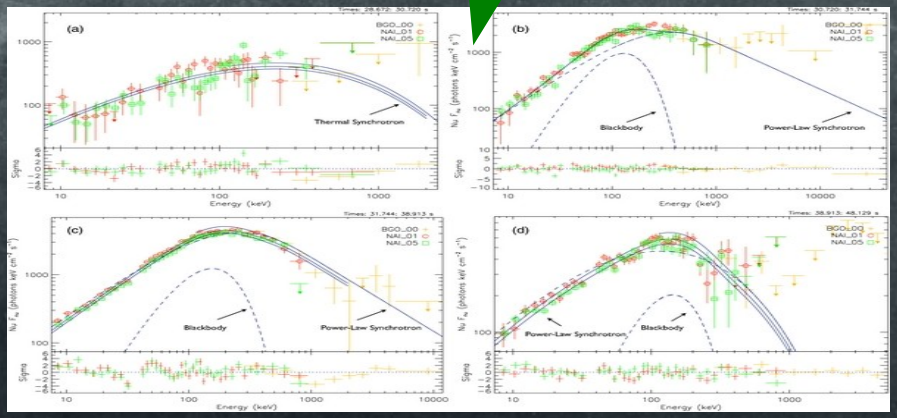


Gamma-rays from proton induced radiation mechanisms



GRBs: LEPTONIC OR HADRONIC





INTERACTION OF NUCLEONS WITH PHOTON FIELDS

photopair production

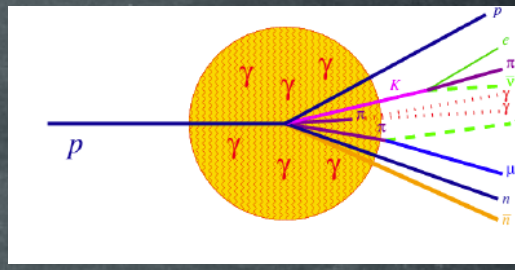
$$N + \gamma_{target} \longrightarrow N + e^+ + e^-$$

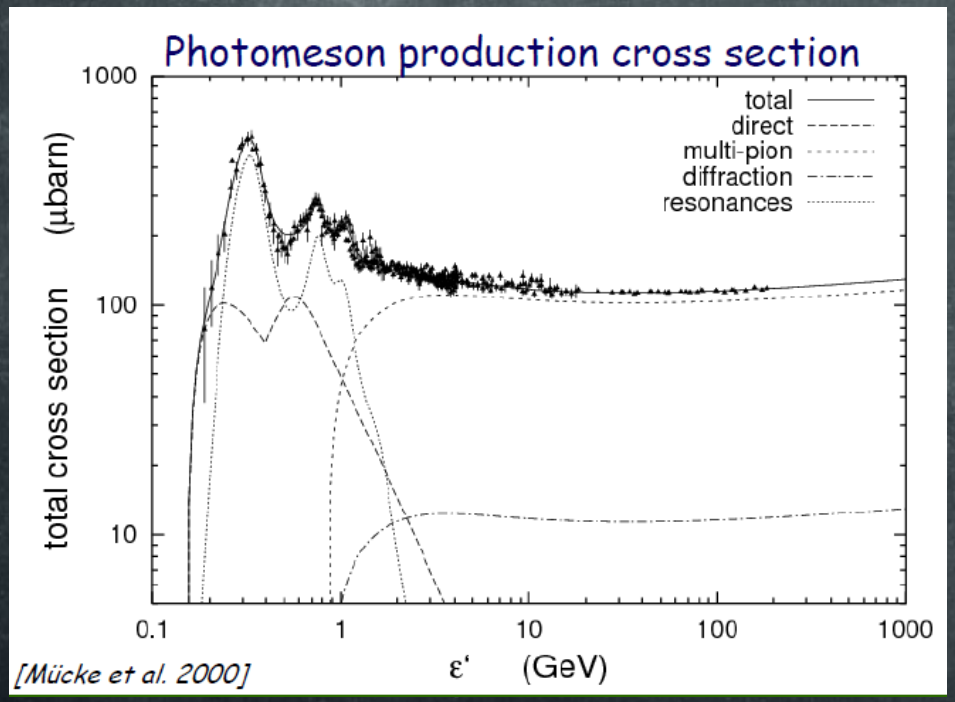
$$s^{1/2}_{threshold} = m_p + 2m_e$$

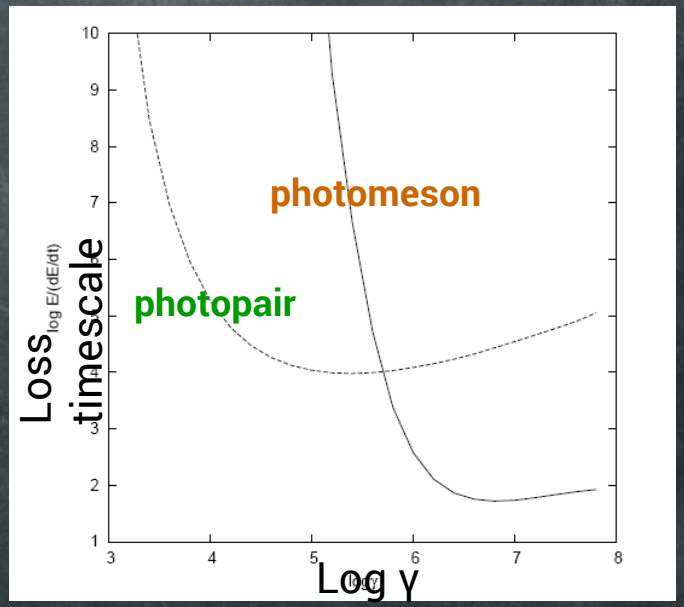
photomeson production

$$N + \gamma_{target} \longrightarrow N + \pi s + \ldots$$

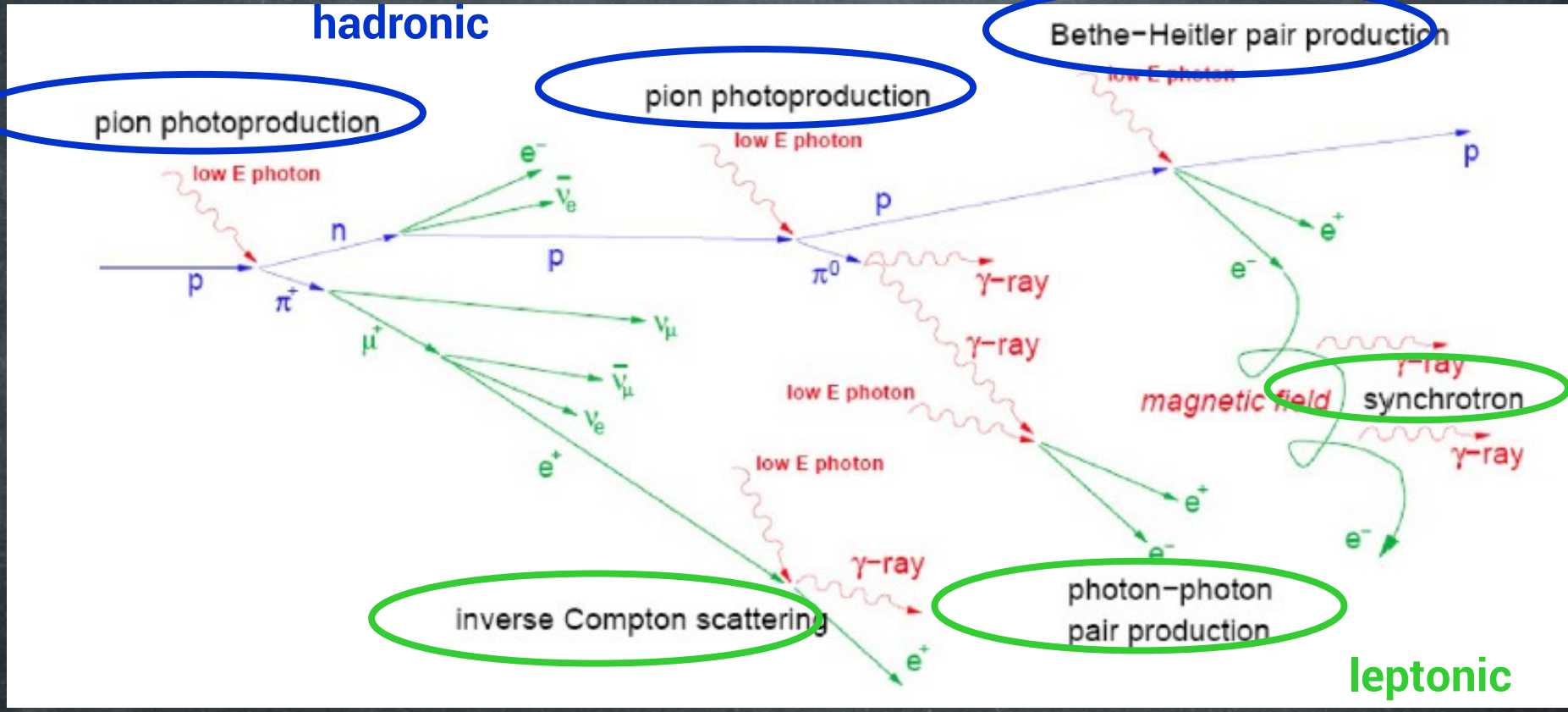
$$s^{1/2}_{threshold} = m_p + m_{\pi 0}$$



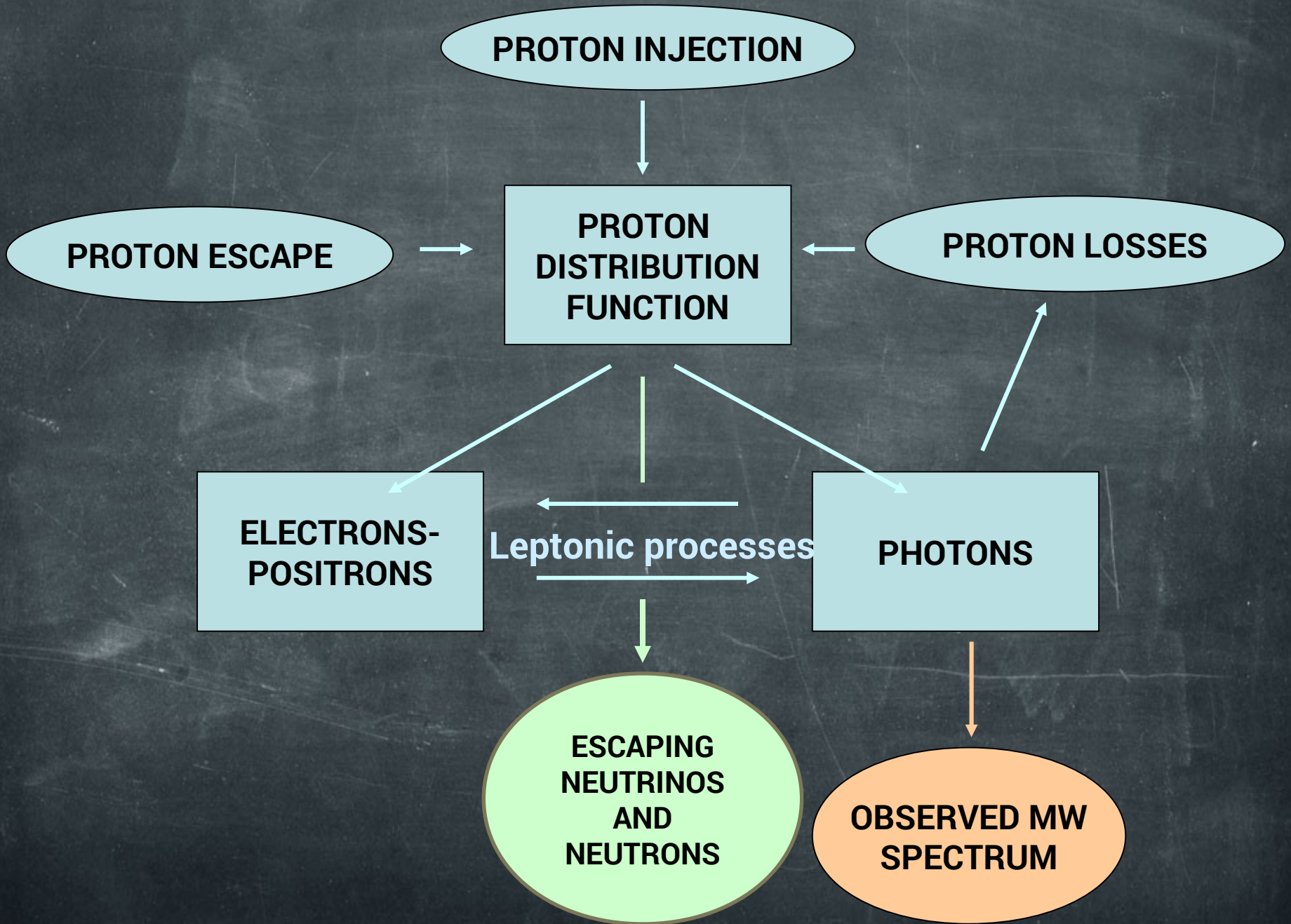




THE HADRONIC MODEL: PHYSICAL PROCESSES

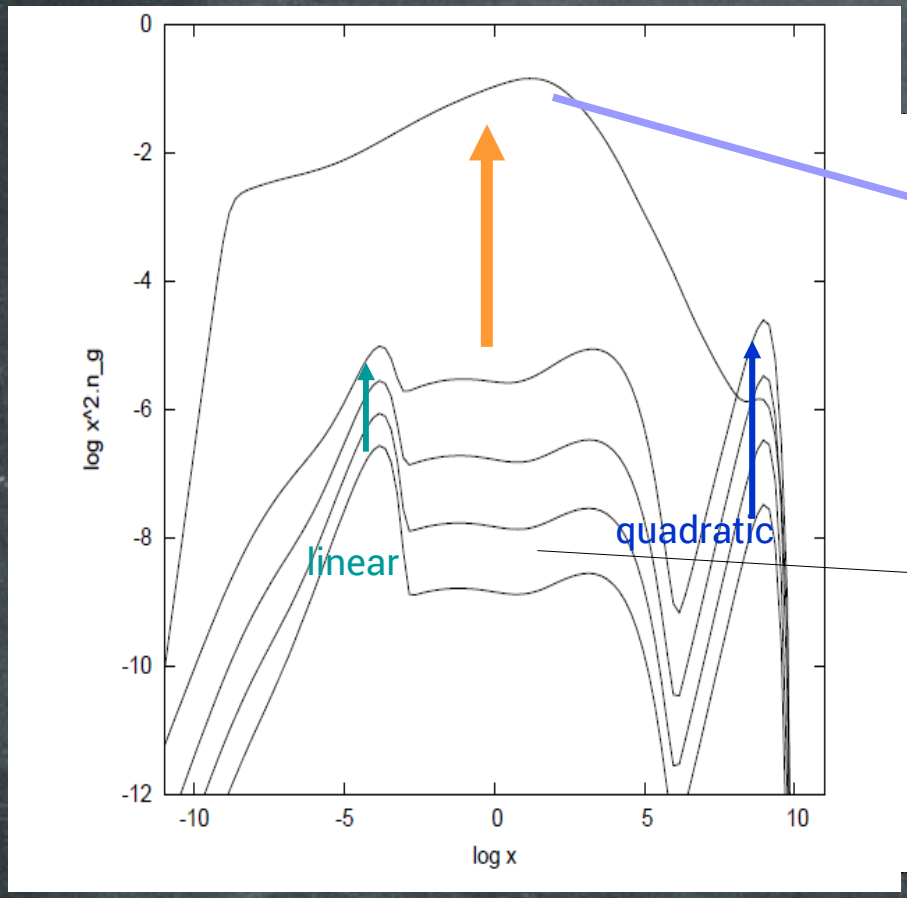


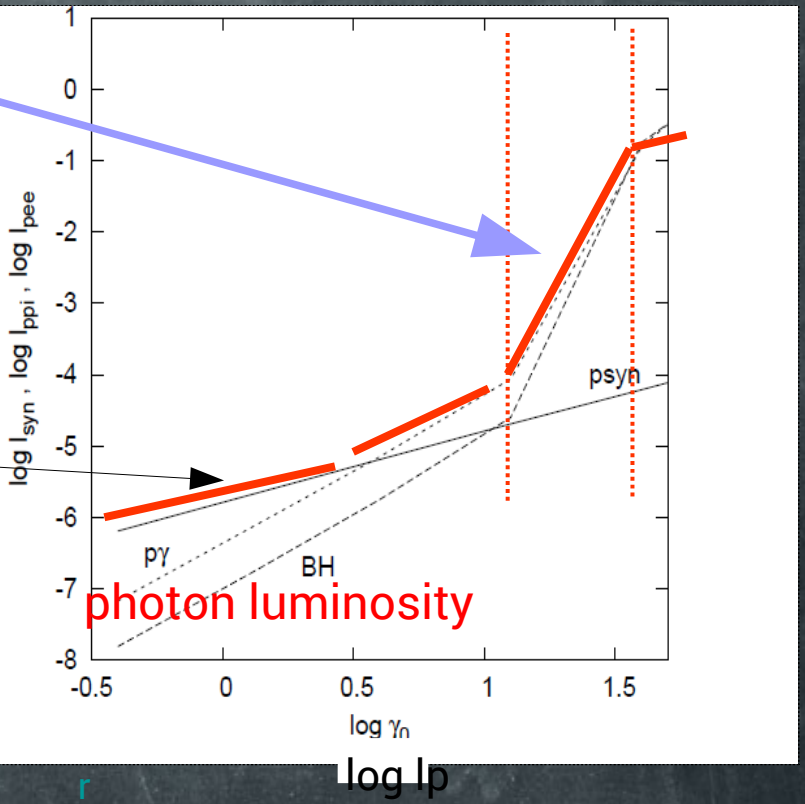
Courtesy of R.J. Protheroe


PROTON INJECTION
PROTON ESCAPE
PROTON DISTRIBUTION FUNCTION
PROTON LOSSES
ELECTRONS-POSITRONS
Leptonic processes
PHOTONS
ESCAPING NEUTRINOS AND NEUTRONS
OBSERVED MW SPECTRUM

INCREASING THE PROTON INJECTED LUMINOSITY

B=1 G R=3e16 cm



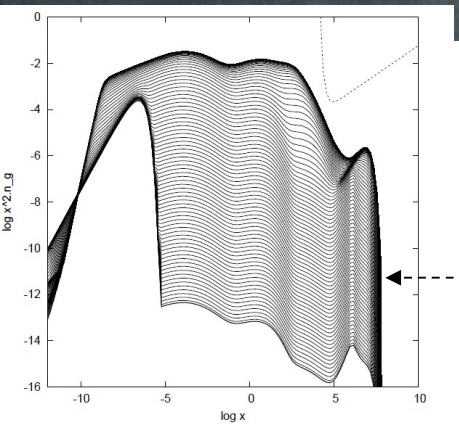


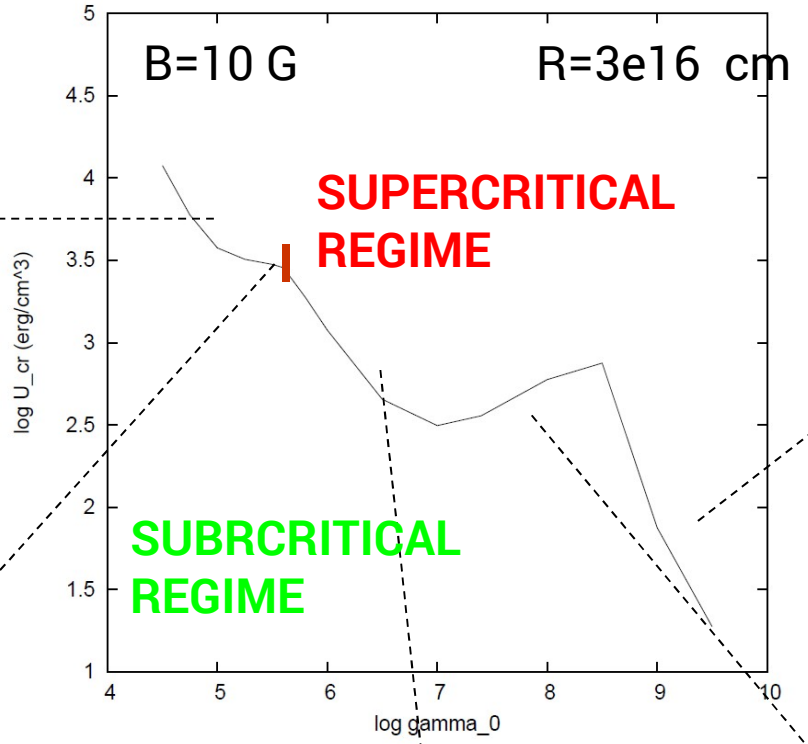
log lp

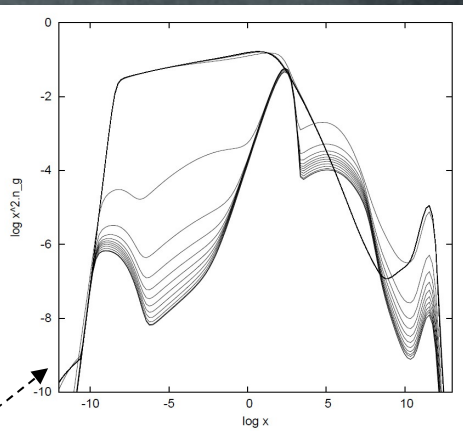
Proton injected luminosity
is increased by a factor 3 --
at some point the system becomes
supercritical

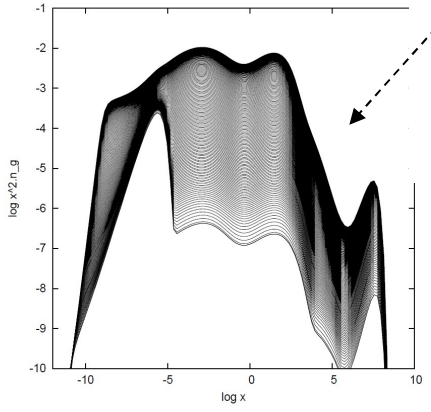
Dimitrakoudis et al. 2012

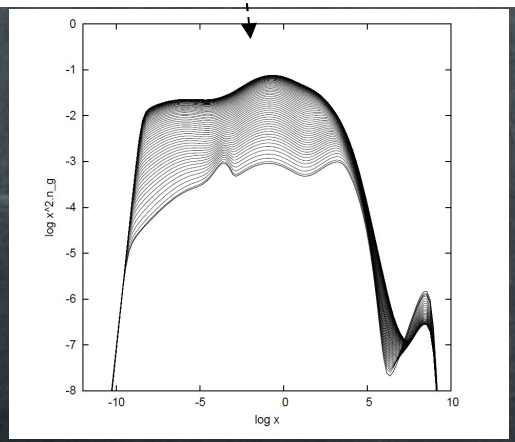
THE STEP TO SUPERCRITICALITY

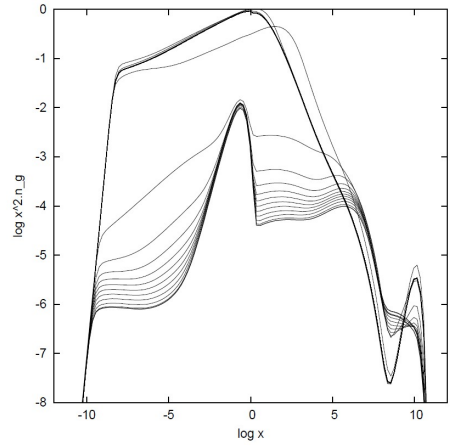












Time-dependent transition of photon spectra from the subcritical to the supercritical regime

In all cases the proton injection luminosity is increased by **1.25** **->** corresponding photons increase by **several orders of magnitude**

A PROTON SUPERCRITICALITY 'ZOO'

PROTONS → BETHE-HEITLER PAIRS

SYNCHROTRON PHOTONS

ESCAPE

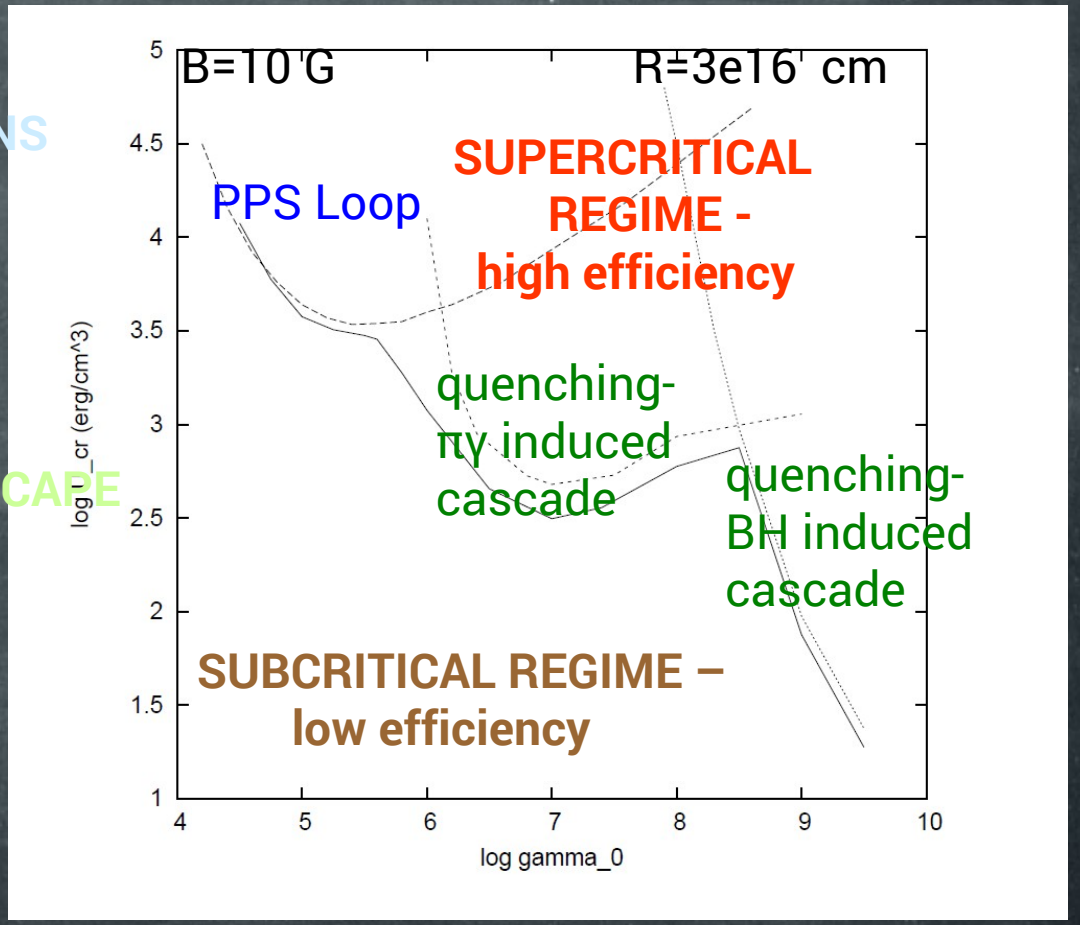
Kirk & AM 1992

PROTONS → GAMMA-RAYS → ESCAPE

AUTOMATICALLY GENERATED SOFT PHOTONS

ESCAPE

Stawarz & Kirk 2007
Petropoulou & AM 2012



Loops are a way of extracting efficiently energy stored in protons

HADRONIC MODELS AS DYNAMICAL SYSTEMS

protons

'hard' photons

'soft' photons

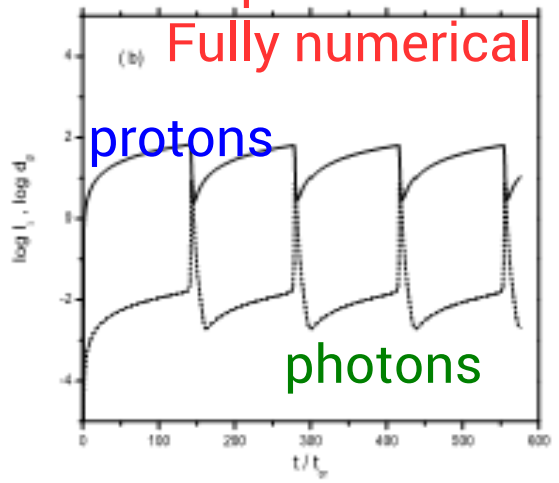
$$\dot{n}_p = -\frac{n_p}{\tau_p} - An_{ex}n_p - Bn_s n_p + Q_o$$

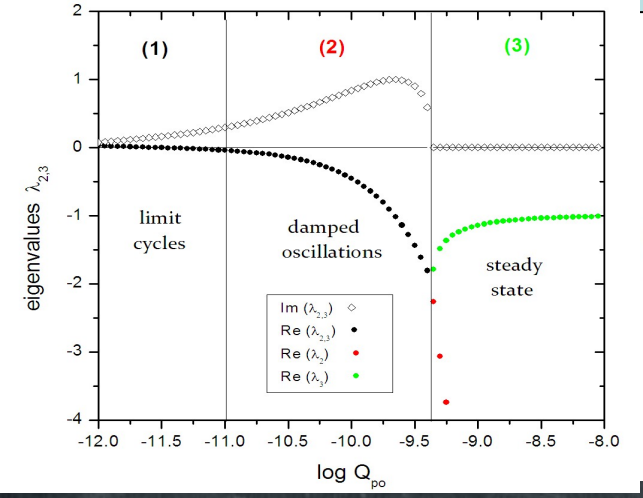
$$\dot{n}_h = -n_h + \tilde{A}n_{ex}n_p + \tilde{B}n_s n_p - Cn_s n_h$$

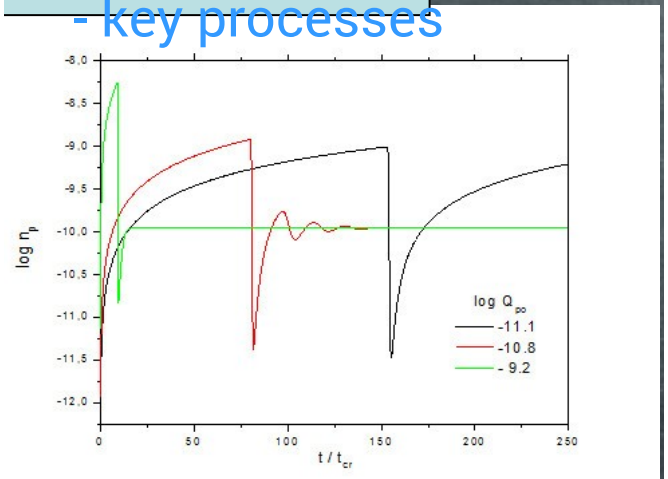
$$\dot{n}_s = -n_s + \tilde{C}n_s n_h$$

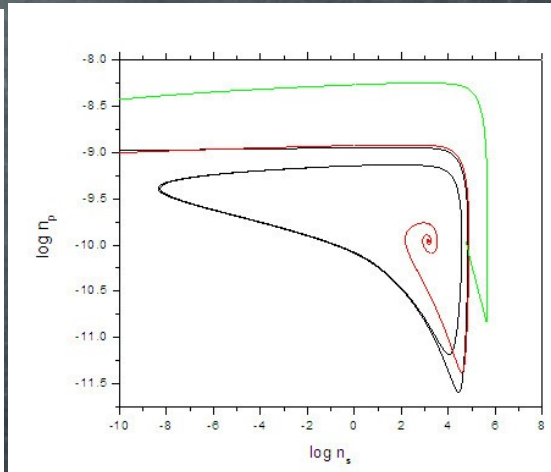
Simplified system - key processes

All processes- Fully numerical







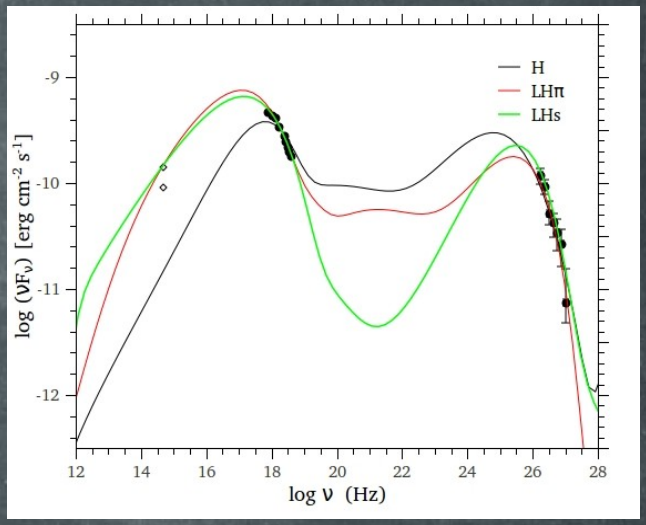


When supercritical, depending on the (constant) proton injection rate, the system goes from limit cycle behavior to damped oscillations to steady state

M. Petropoulou & AM 2012

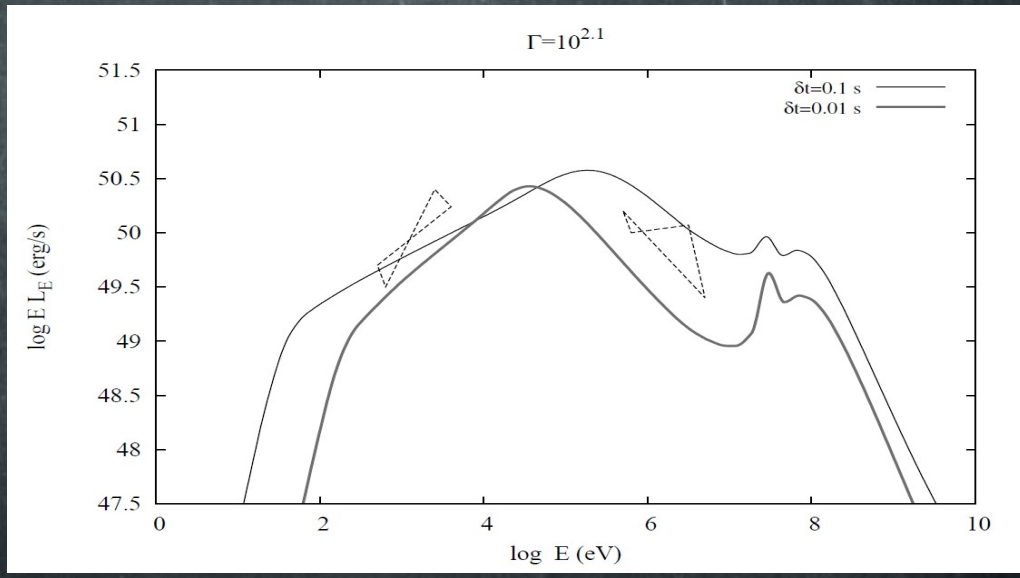
HADRONIC MODELS: SPECTRAL SIGNATURES

When system subcritical → Blazars



AM, M. Petropoulou, S. Dimitrakoudis 2013

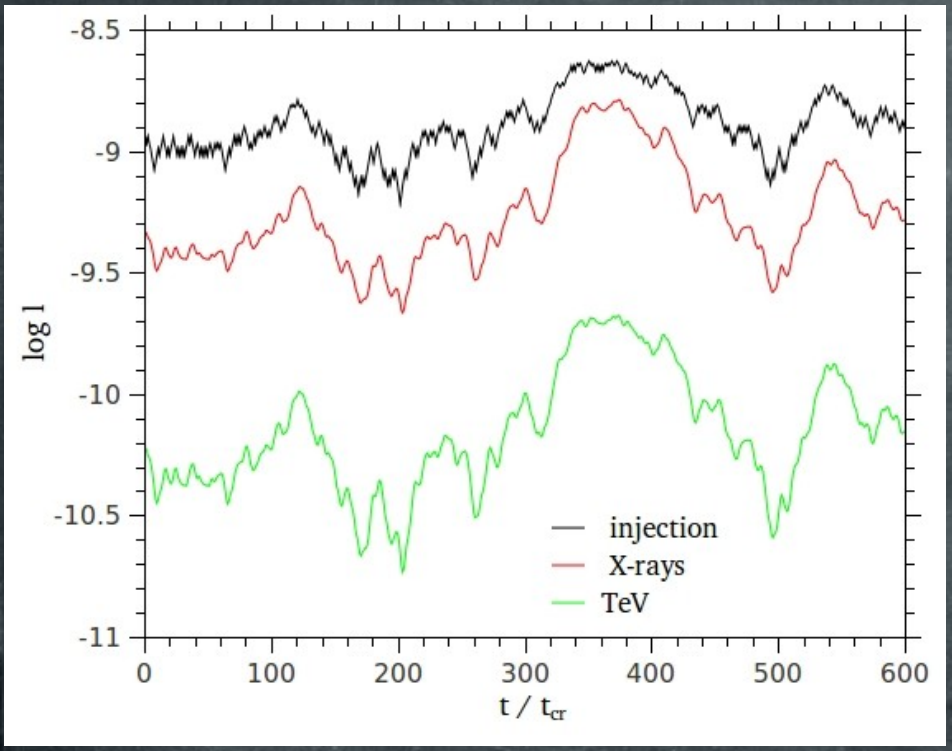
When system supercritical → GRBs

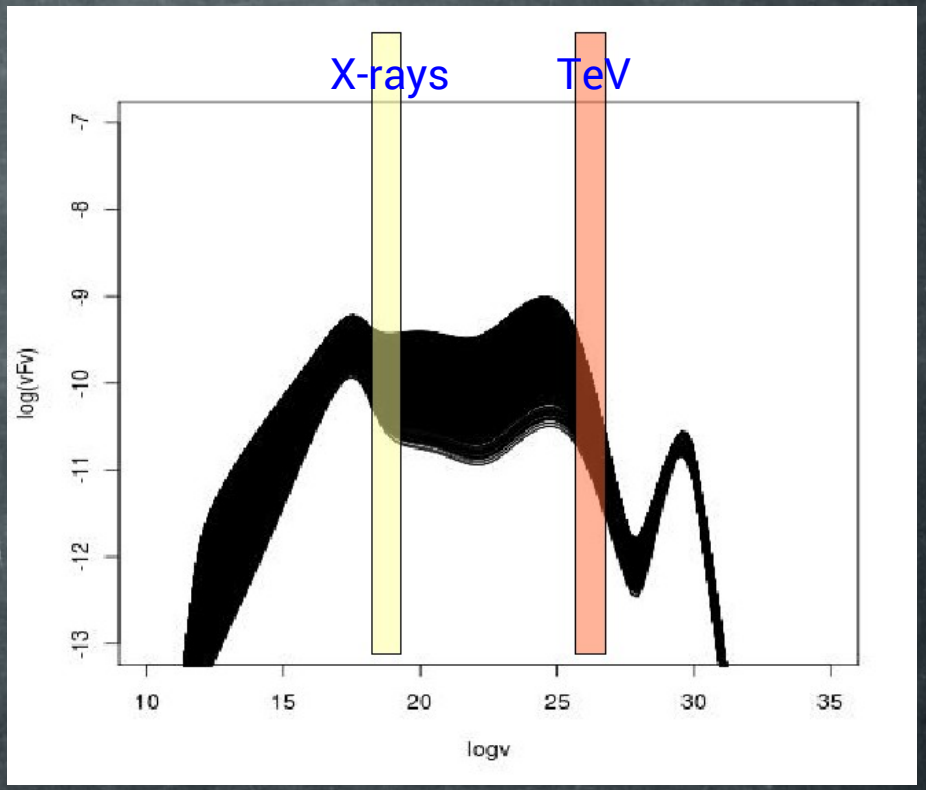


M. Petropoulou, S. Dimitrakoudis, AM, D. Giannios 2013

VARIABILITY IN THE SUBCRITICAL REGIME

Assume small amplitude random-walk variations in proton and electron injection

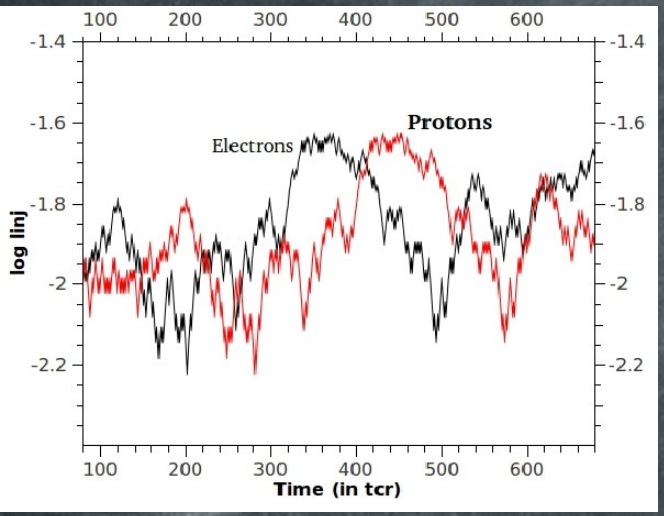


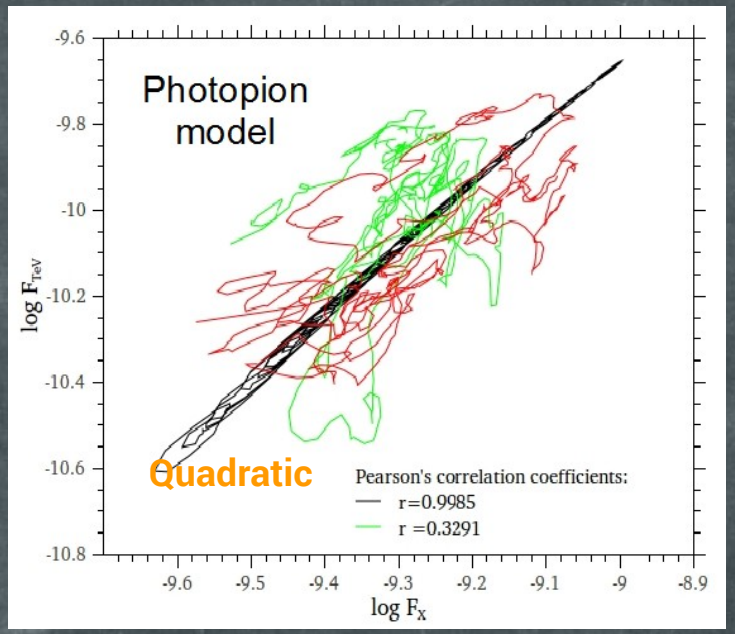


Injection and spectra when p and e totally correlated

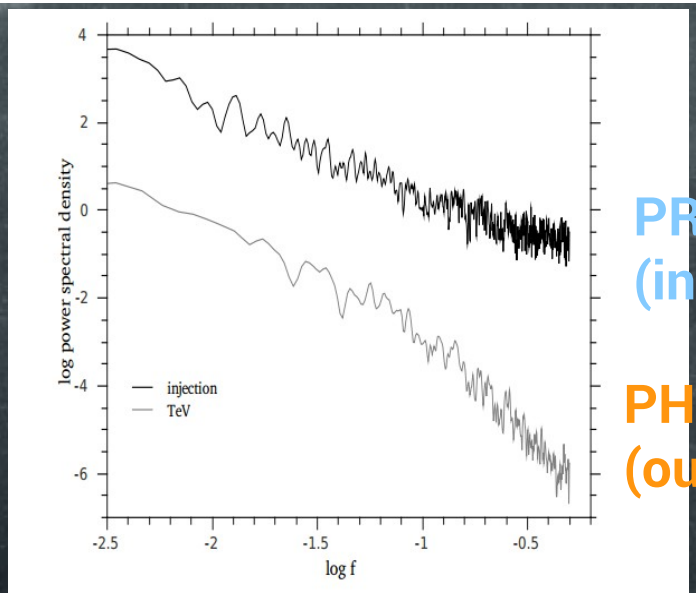
SUBCRITICAL (AGN) REGIME

Correlated: no time lag
Correlated: time lag of 80 tcr
Uncorrelated





When electrons-protons are correlated, TeV (hadronic) and X-rays (leptonic) vary quadratically
Even when electrons-protons totally uncorrelated,
X and TeV
retain some correlation

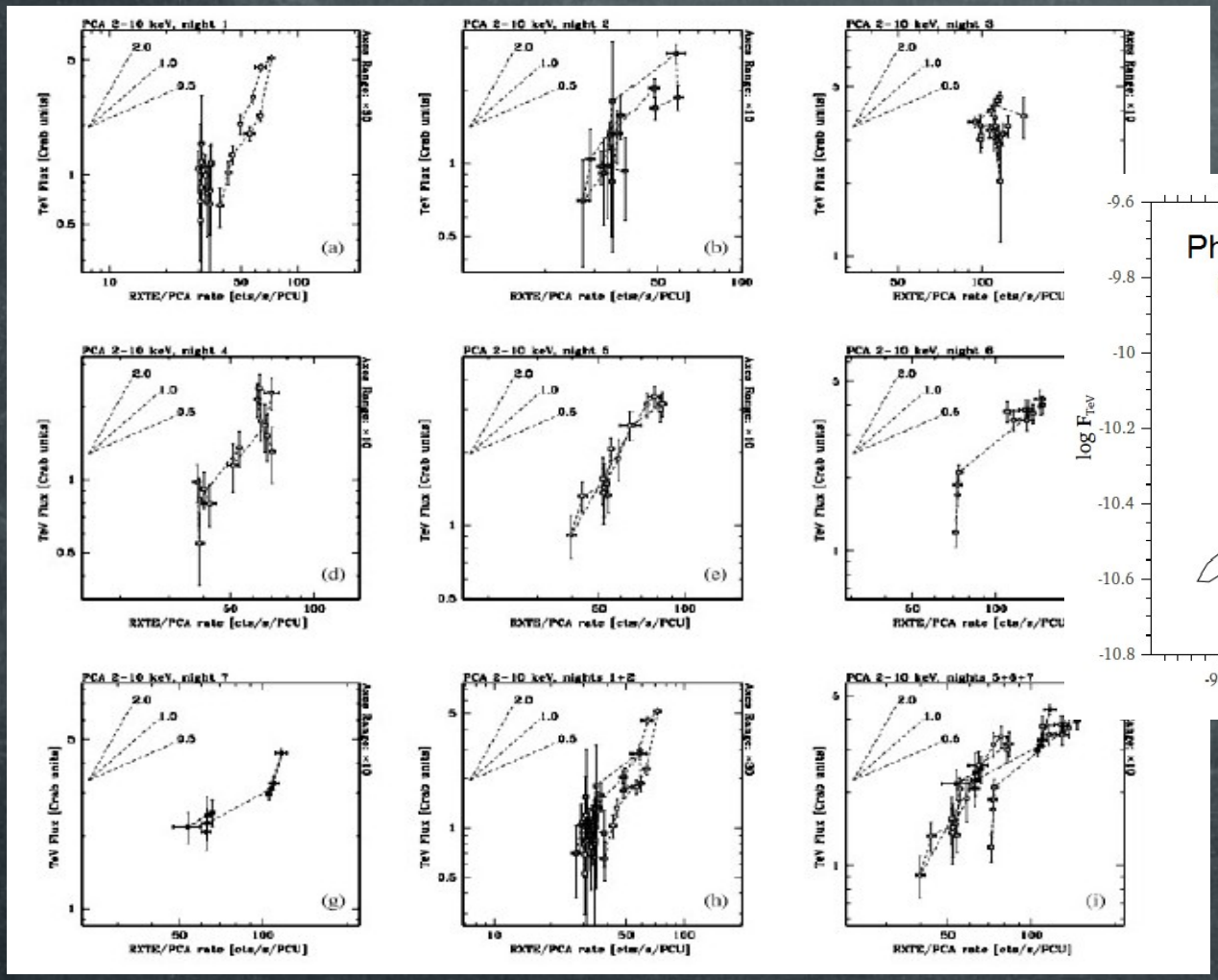


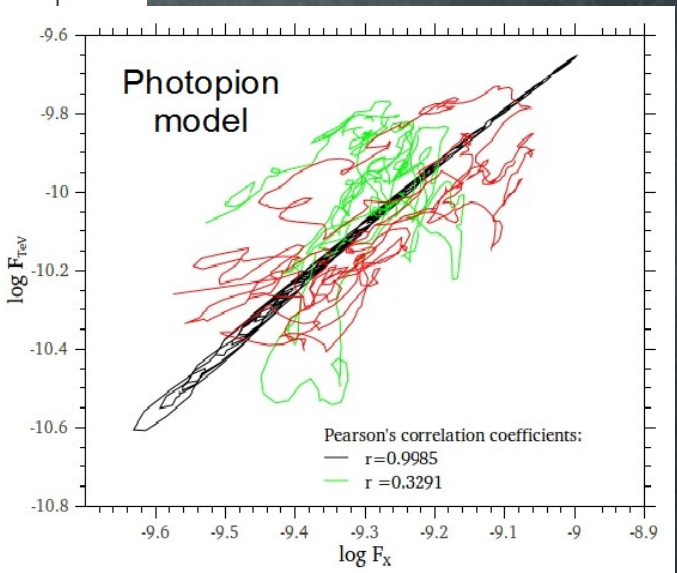
Power-spectra

PROTONS (input)

PHOTONS (output)

BLAZAR Mrk 421: X-TeV CORRELATIONS

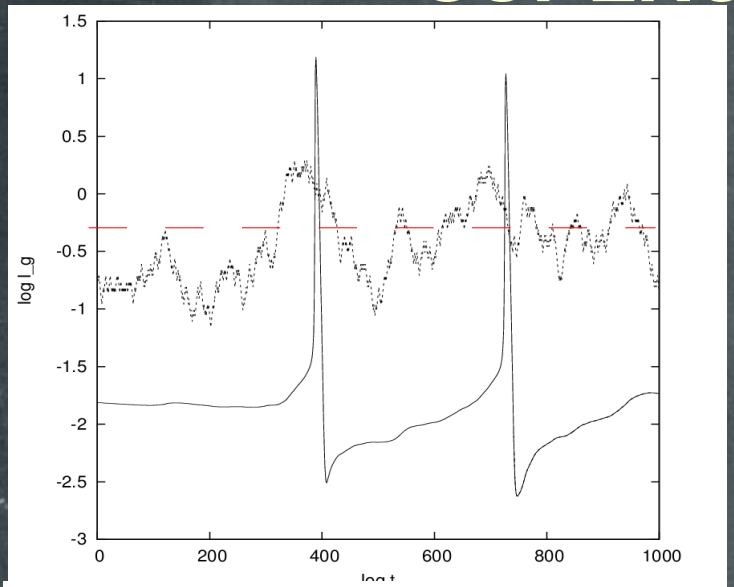


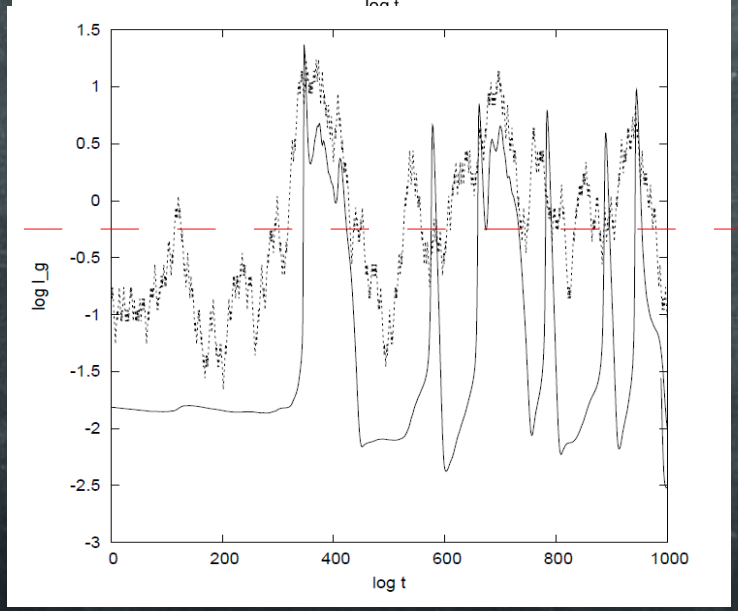


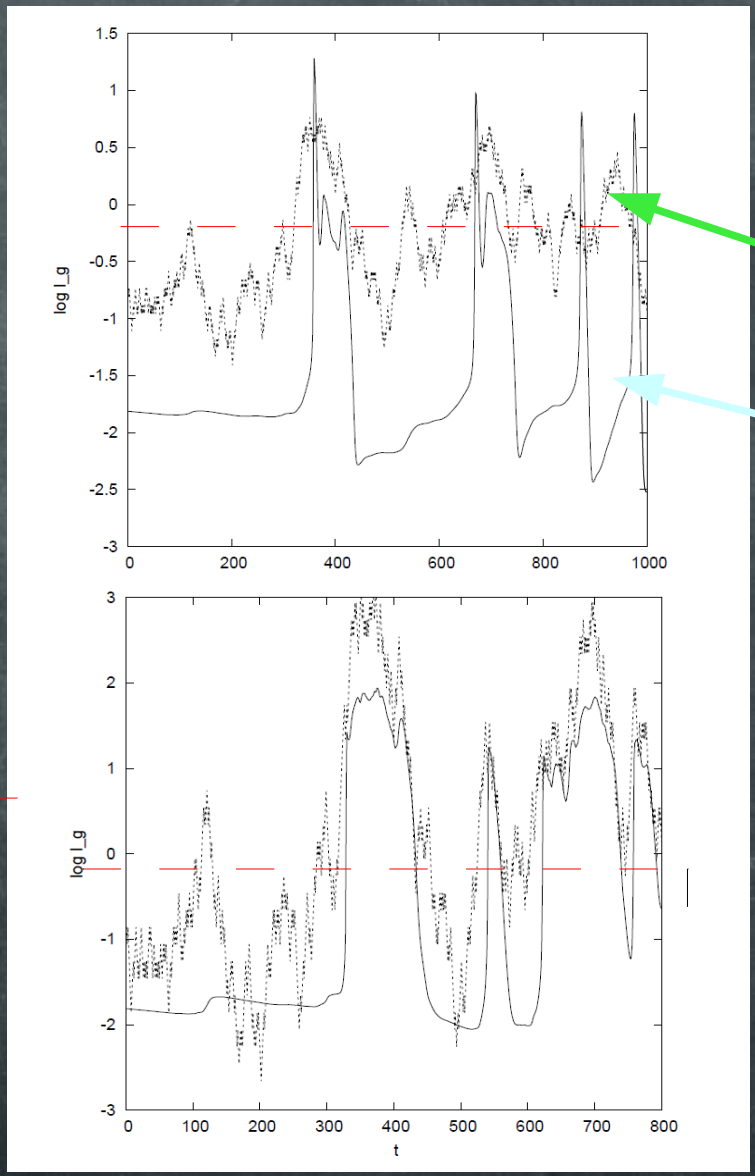
Fossati et al 2008

...

VARIABILITY IN SUPERCRITICAL REGIME



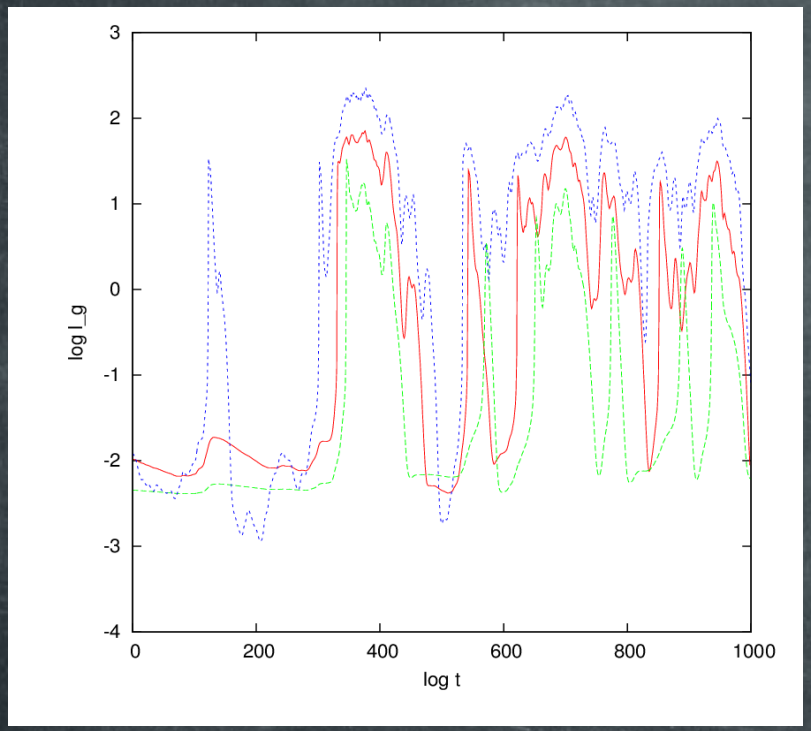


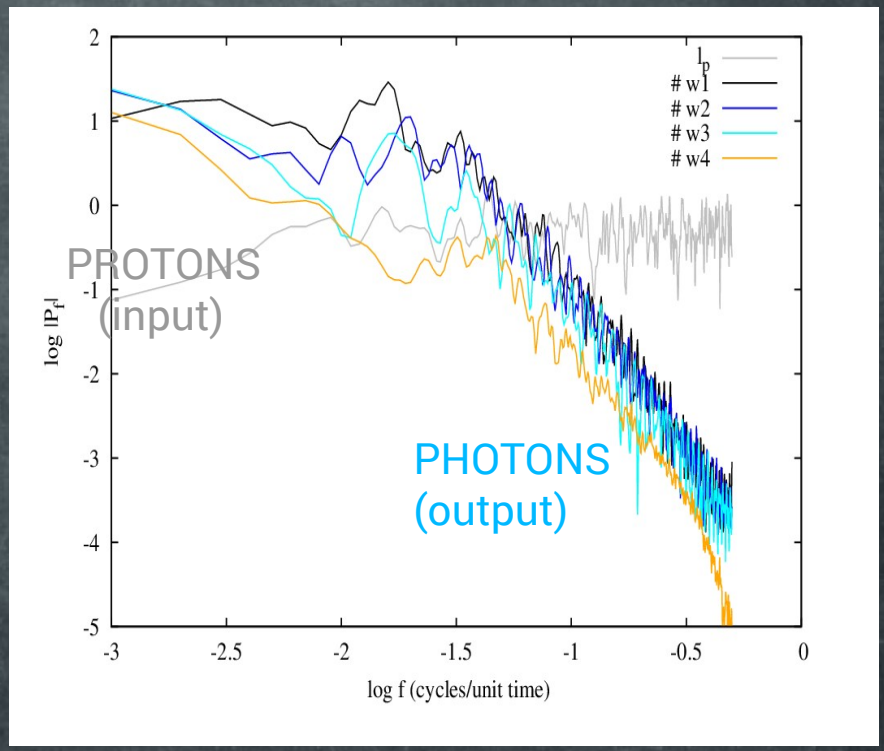


protons

photons

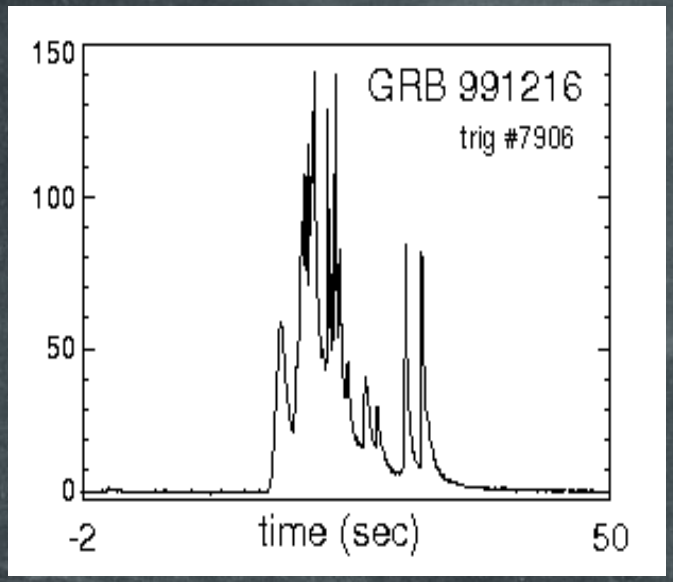
SUPERCRITICAL VARIABILITY: POWER-SPECTRA

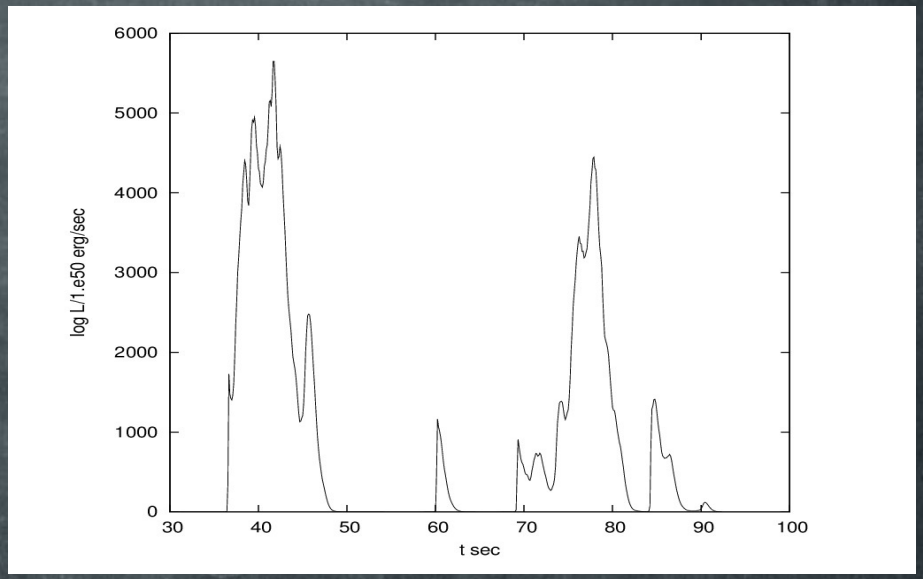




M.Petropoulou , G.Vasilopoulos, AM (in prep)

COMPARING...





Observed GRB lightcurves

Synthetic lightcurves

CONCLUSIONS

- One-zone hadronic model
  - Accurate secondary injection (photopion + Bethe Heitler)
  - Time dependent - energy conserving PDE schme

•Two modes:

• Subcritical (linear) regime

Spectrum: fits to blazar spectra (X-rays from electron synchrotron – γ-rays from secondary pion cascades)

Variability: TeV – X-rays quadratic – as (mostly) observed in blazars

• Supercritical (nonlinear) regime

Spectrum: Optically thick ($\tau \gg 1$) emission – large proton energy content turned into radiation

Variability: Burst-type of behavior if proton injection close to the threshold for supecriticality

Can these be a basis for a viable hadronic GRB model?