THE TIME-DEPENDENT ONE-ZONE HADRONIC MODEL:
Some preliminary results

A. Mastichiadis

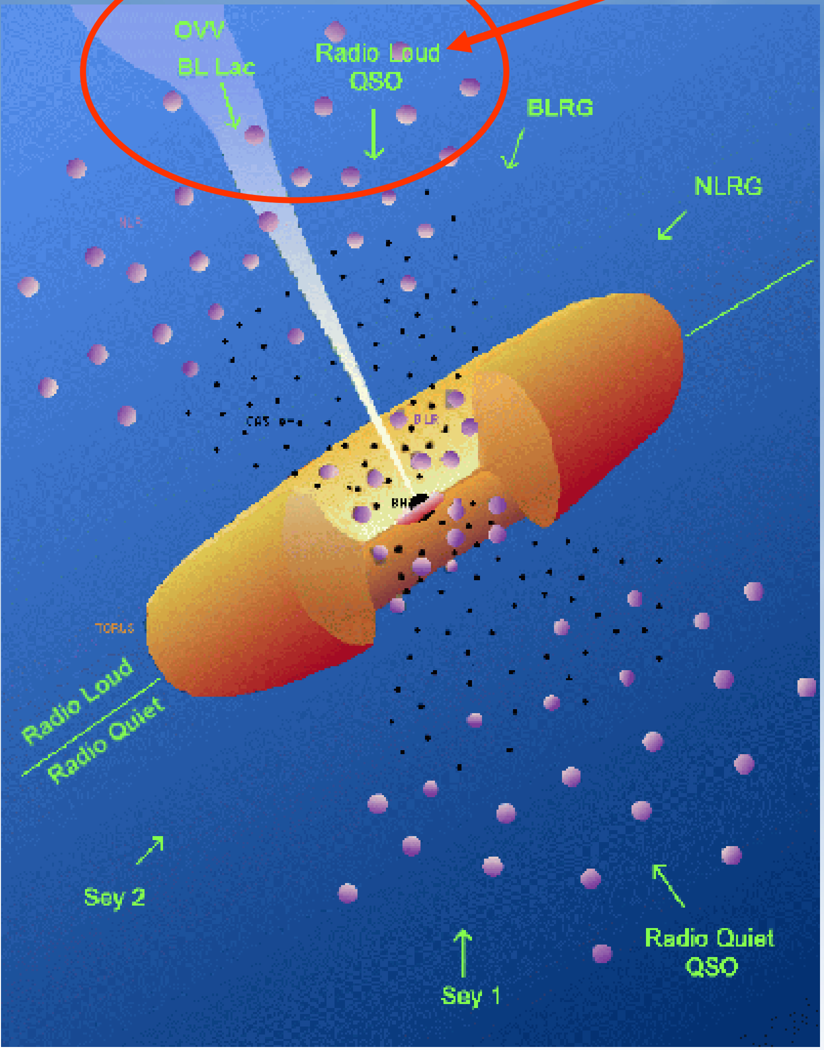
University of Athens

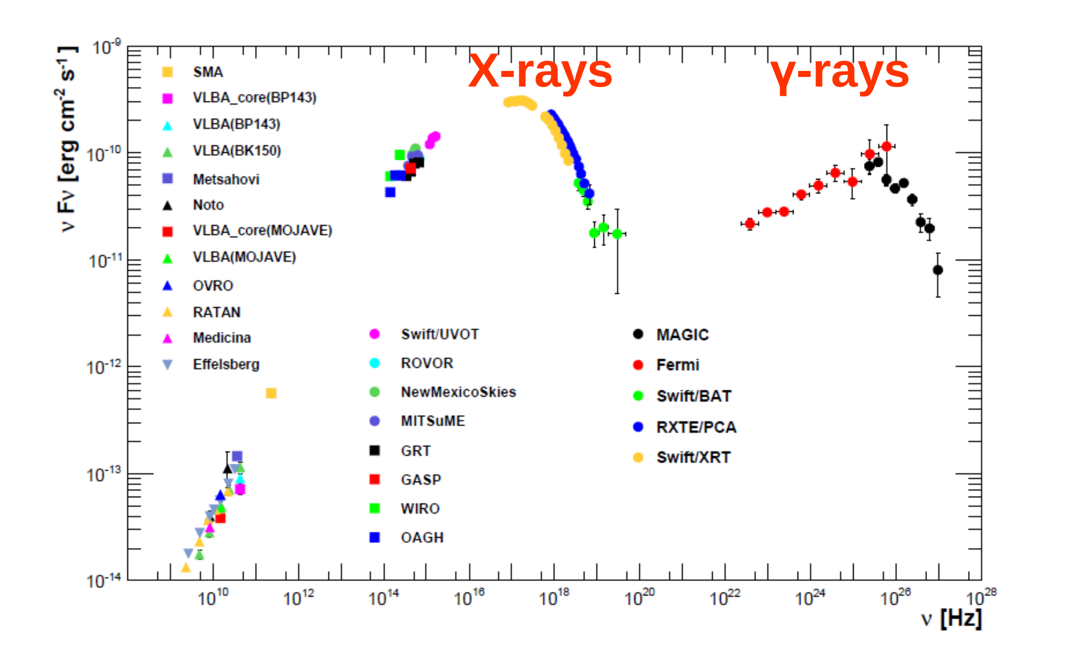
...in collaboration with

- Stavros Dimitrakoudis – *UoA*
- Maria Petropoulou – *UoA*
- Ray Protheroe – *University of Adelaide*
- Anita Reimer – *University of Innsbruck*

ACTIVE GALACTIC NUCLEI

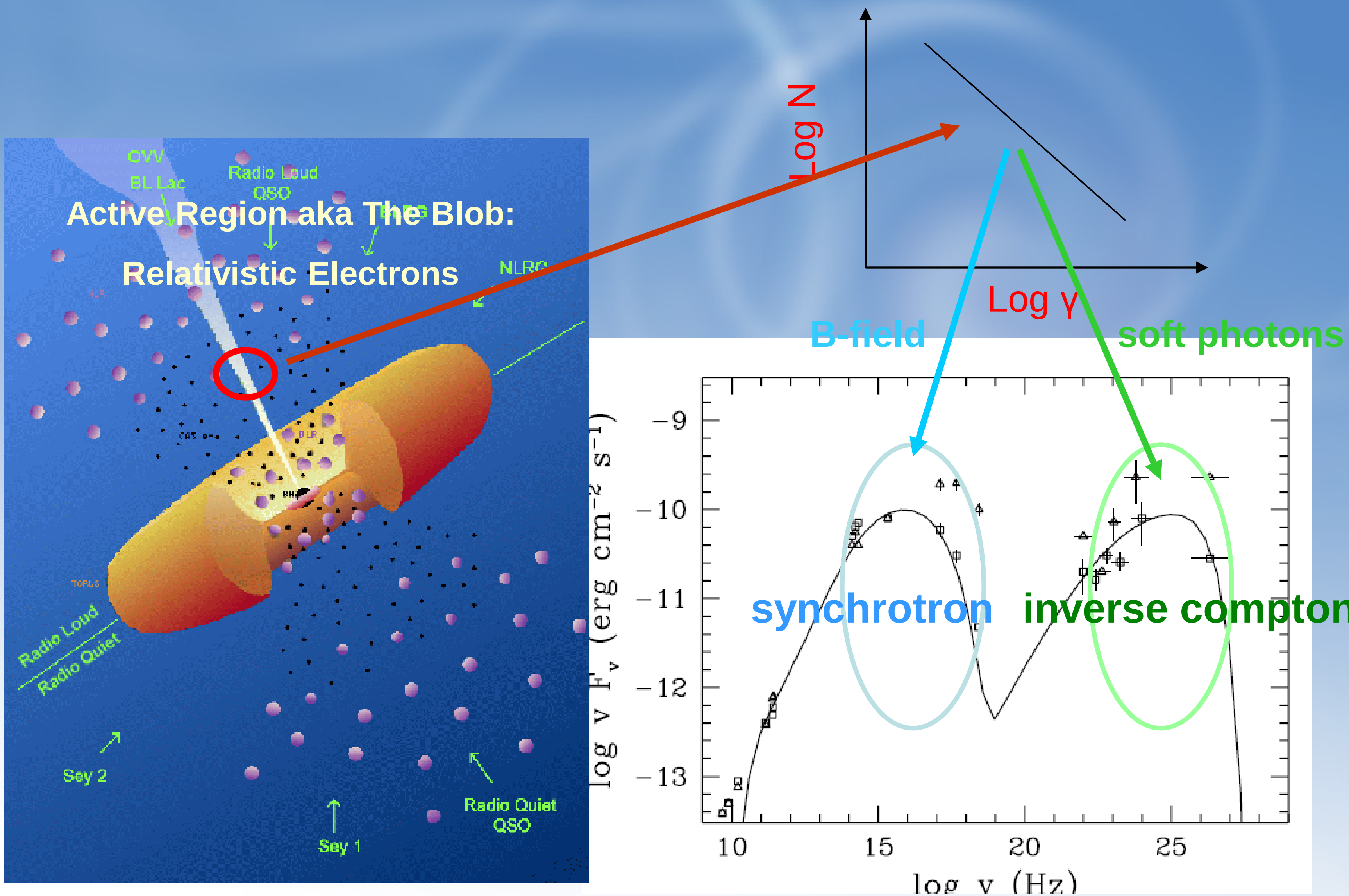
Blazars



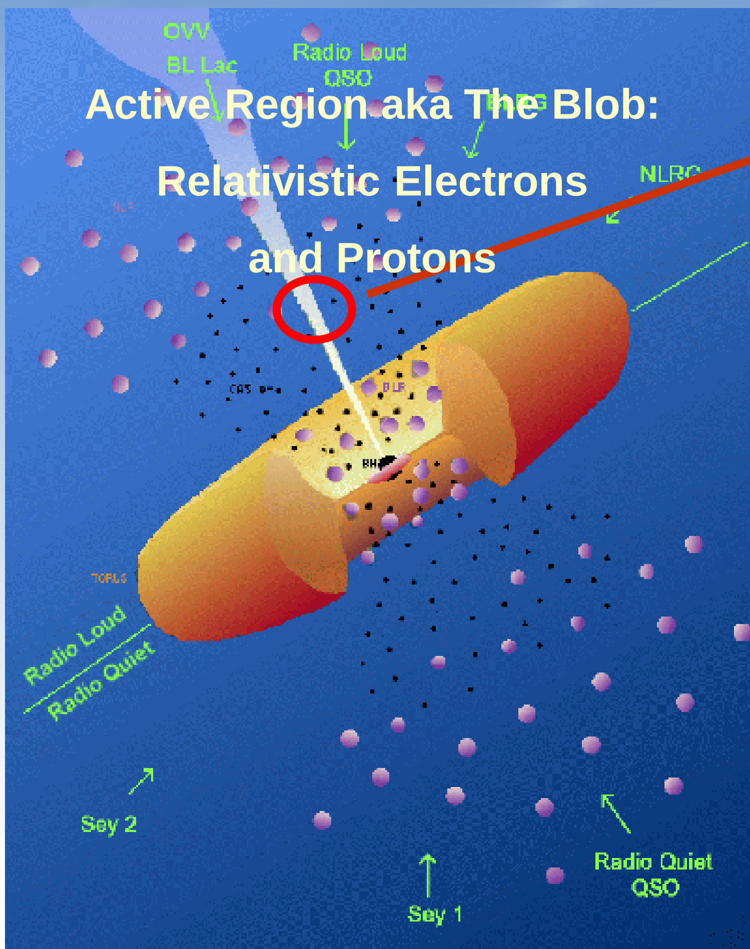


Blazar MW spectrum

LEPTONIC MODEL FOR H.E. EMISSION



…AND THE HADRONIC MODEL

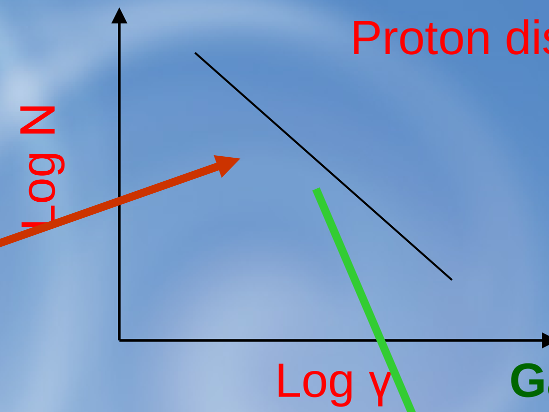


Active Region aka The Blob:

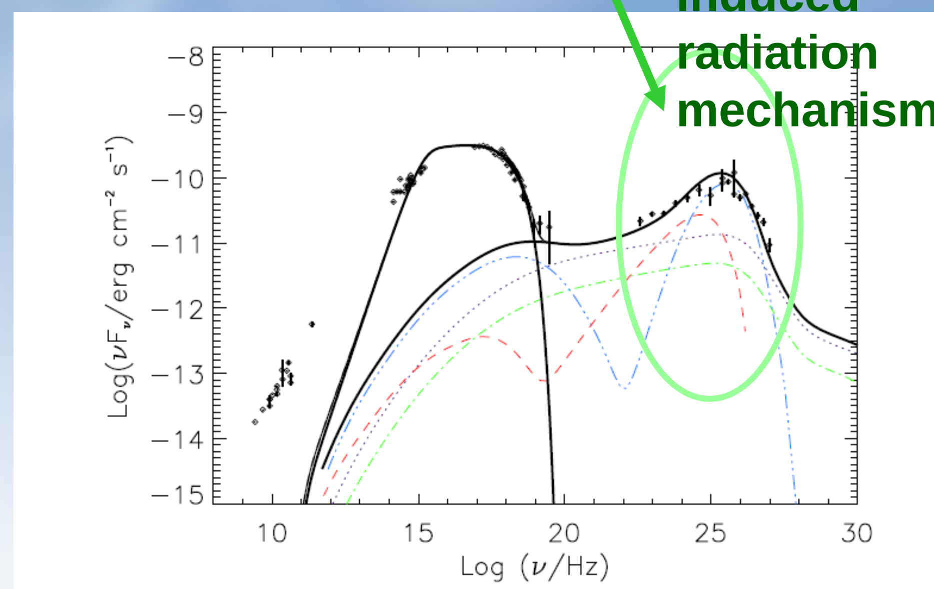
Relativistic Electrons

and Protons

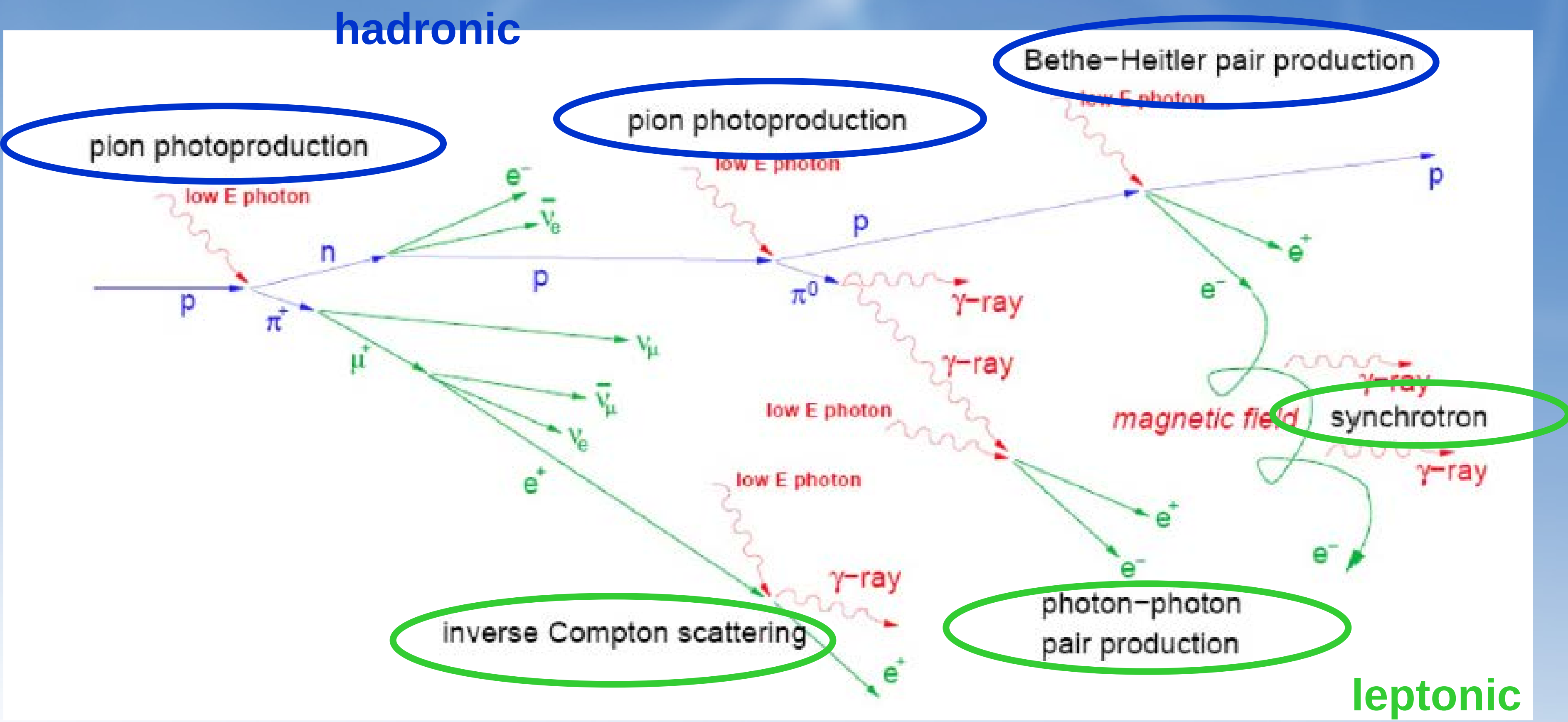
Proton distribution



Gamma-rays from proton induced radiation mechanisms



THE HADRONIC MODEL: PHYSICAL PROCESSES



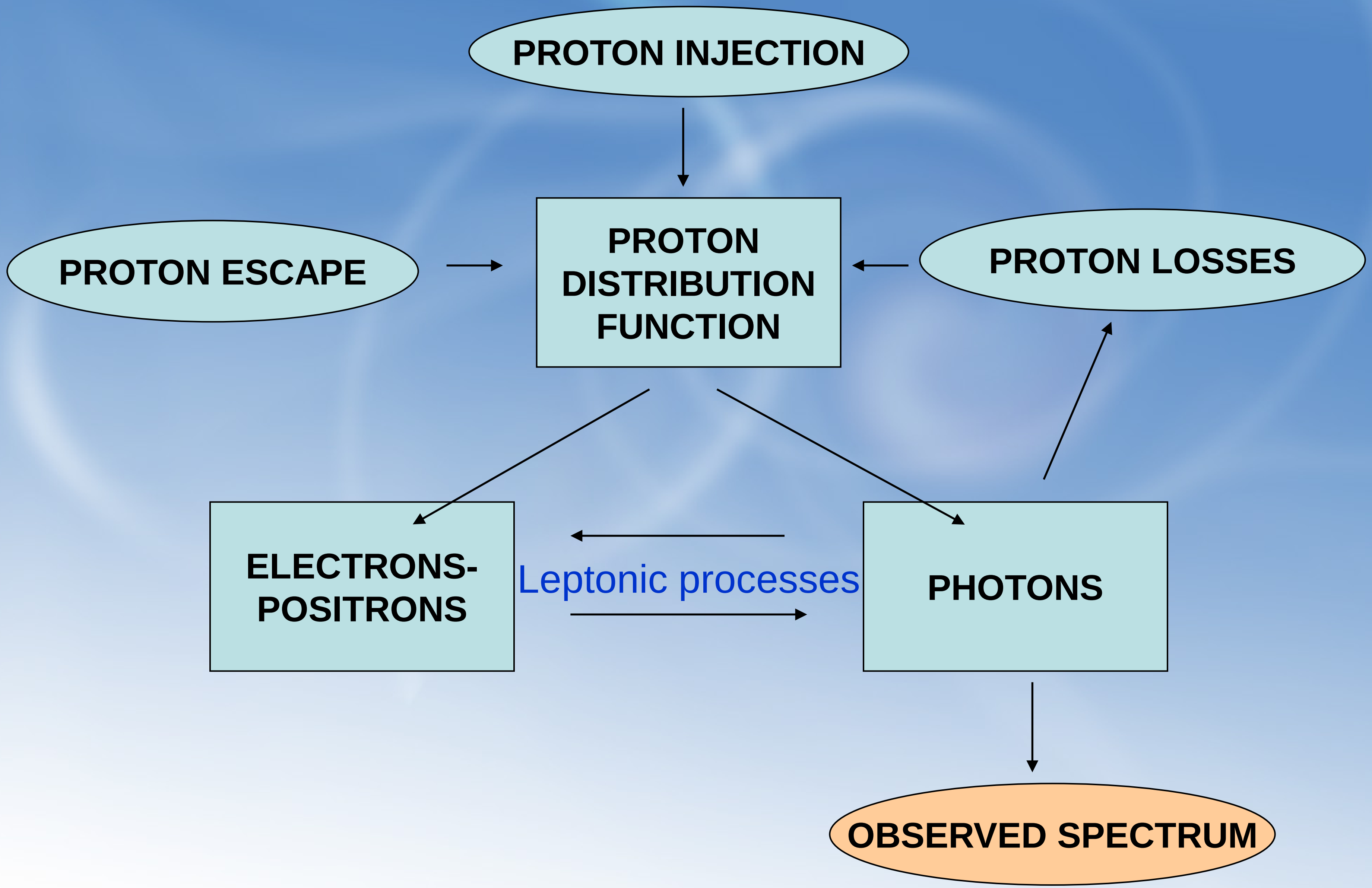
Courtesy of R.J. Protheroe

KEY IDEAS AND ASSUMPTIONS

- Injection of high energy protons – proton energy and luminosity are free parameters.
- Protons cool by (i) synchrotron
  (ii) photopair (Bethe-Heitler)
  (iii) photopion (neutral/charged)
- Model (ii) from MC results of Protheroe & Johnson (1996)
  (iii) from SOPHIA code (Stanev et al 2000).
- Study the simultaneous evolution of protons and secondaries through time-dependent, energy conserving kinetic equations.
- No external photons / no electron injection (pure hadronic model).
  → keep free parameters to a minimum (R, B, γ_p, L_p)

AIMS

1. Study photon spectral formation simultaneously with neutrino spectra.
2. Calculate efficiencies (e.g. photon luminosity/proton luminosity)
3. Study expected time signatures (as in leptonic models).
4. Study potential supercriticalites (Stern et al. 1995, Kirk & AM 1992) Self consistent approach allows it while they go unnoticed when different approaches are employed (e.g. ‘ready’ proton distribution function).


PROTON INJECTION
PROTON ESCAPE
PROTON DISTRIBUTION FUNCTION
PROTON LOSSES
ELECTRONS-POSITRONS
Leptonic processes
PHOTONS
OBSERVED SPECTRUM

Protons:

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

Electrons:

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

Photons:

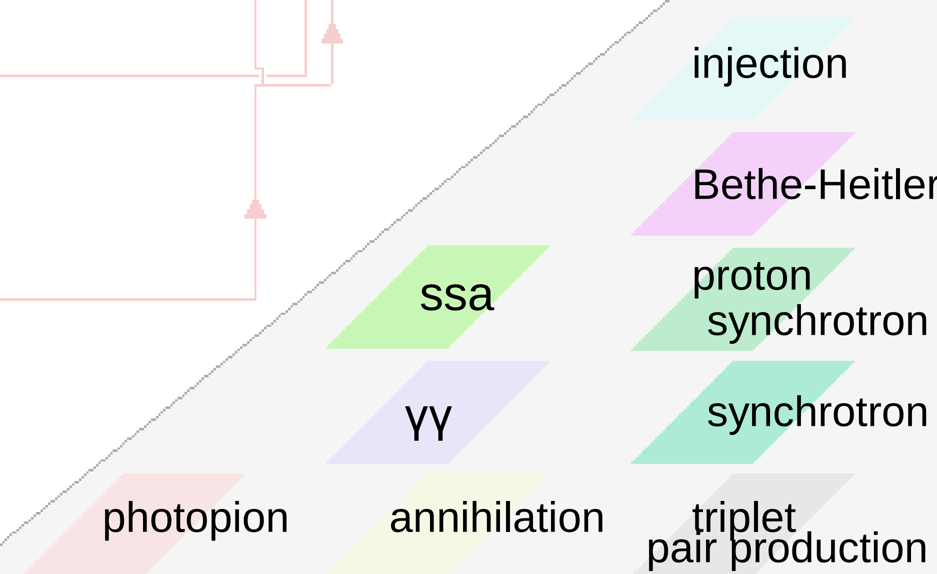
$$\frac{\partial n_{\gamma}}{\partial t} + \frac{n_{\gamma}}{t_{\gamma,\mathrm{esc}}} + L_{\gamma}^{\gamma\gamma} + L_{\gamma}^{\mathrm{ssa}} = Q_{\gamma}^{\mathrm{syn}} + Q_{\gamma}^{\mathrm{psyn}} + Q_{\gamma}^{\mathrm{ics}} + Q_{\gamma}^{\mathrm{ann}} + Q_{\gamma}^{\mathrm{photopion}}$$

Neutrinos:

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

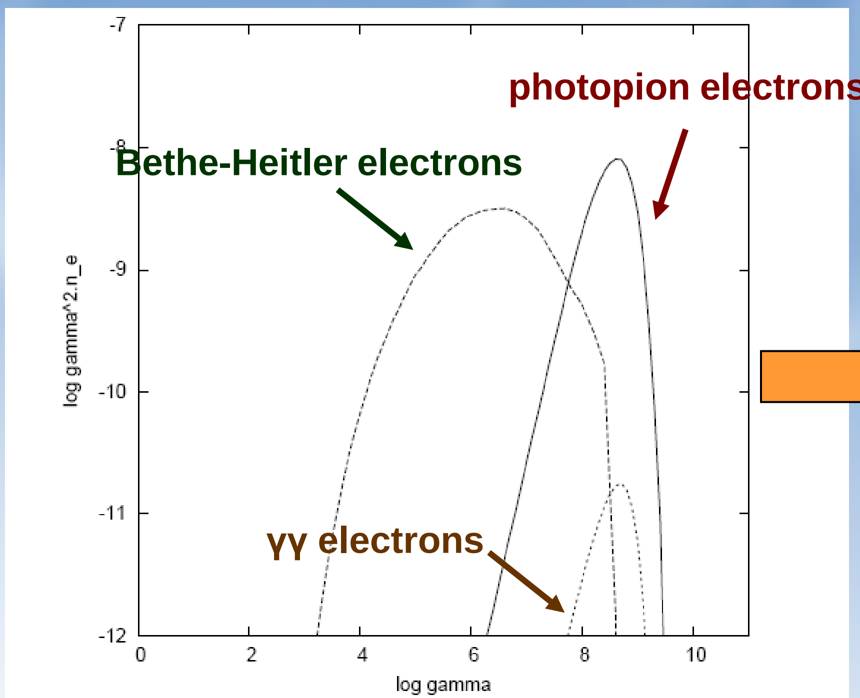
Neutrons:

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

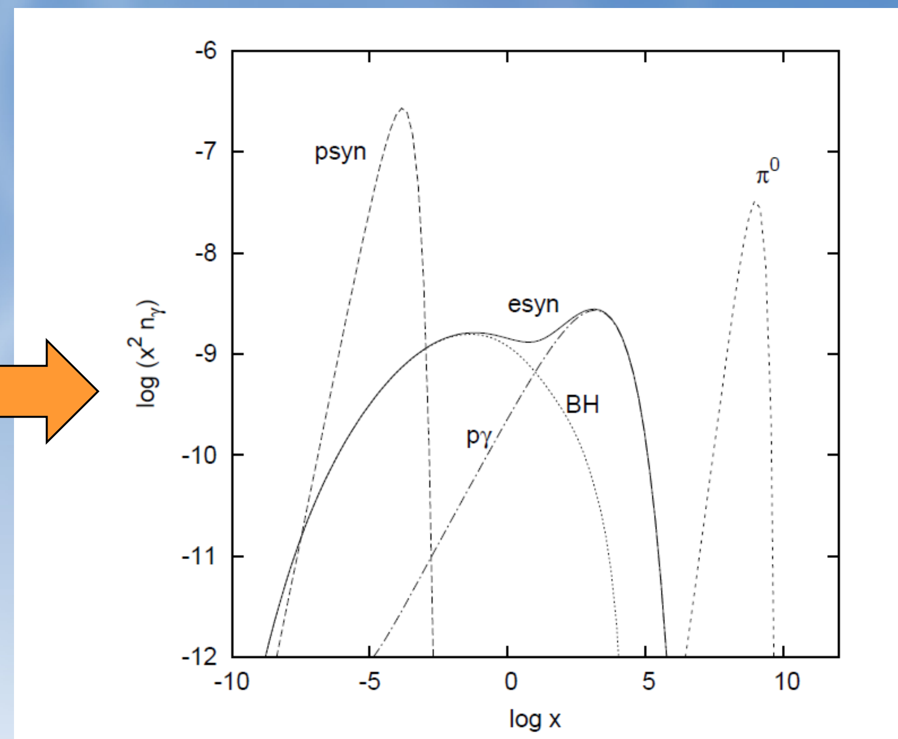


INJECTION OF SECONDARY ELECTRONS - RESULTING PHOTON SPECTRA

electrons



photons



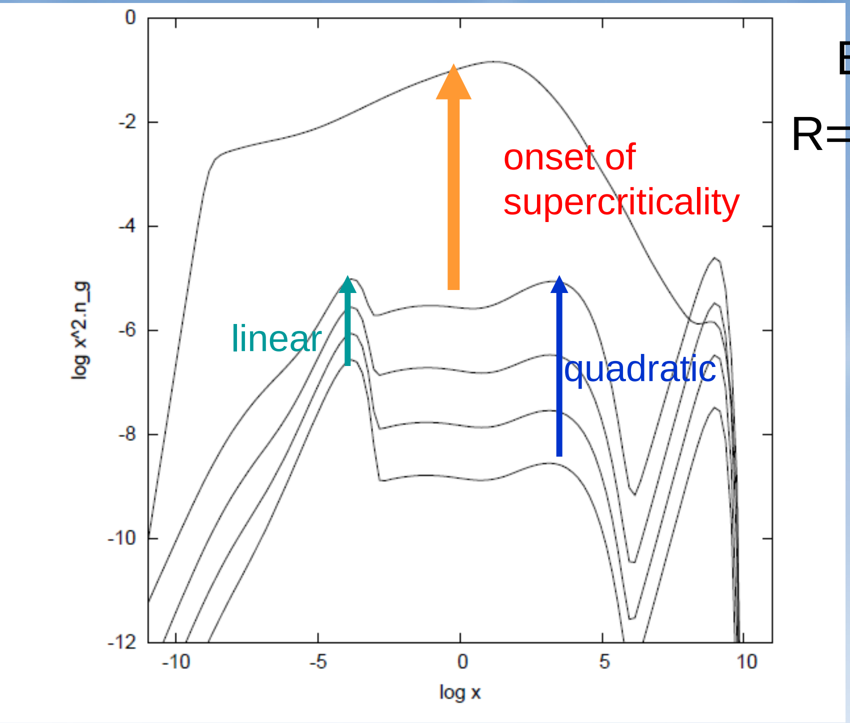
R = 3e16 cm γ_p = 2e6

B = 1 G l_p = 0.4

$$L_p = \frac{4\pi R m_p c^3}{\sigma_T} \ell_p.$$

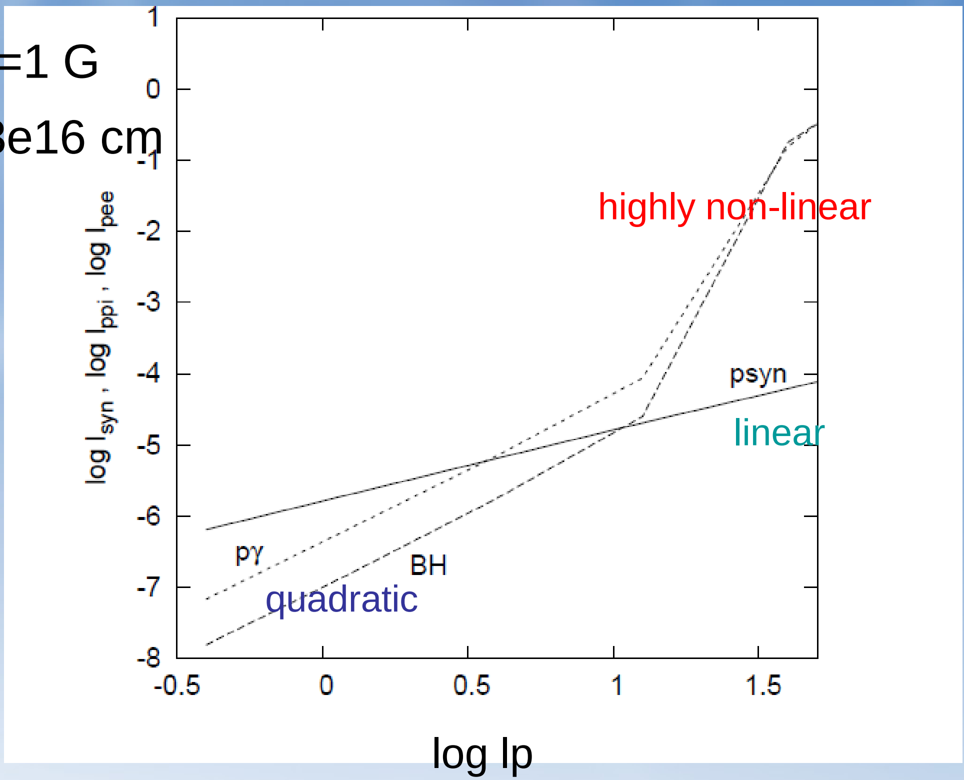
S. Dimitrakoudis et al., in preparation

INCREASING THE PROTON INJECTED LUMINOSITY



B=1 G

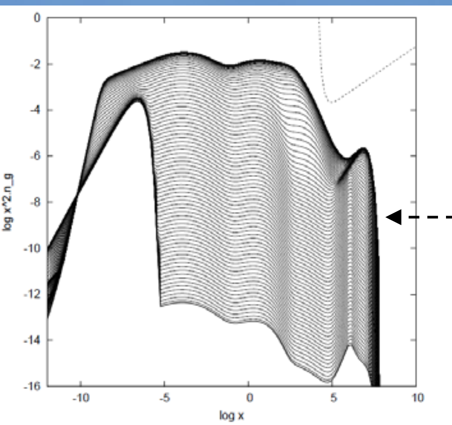
R=3e16 cm

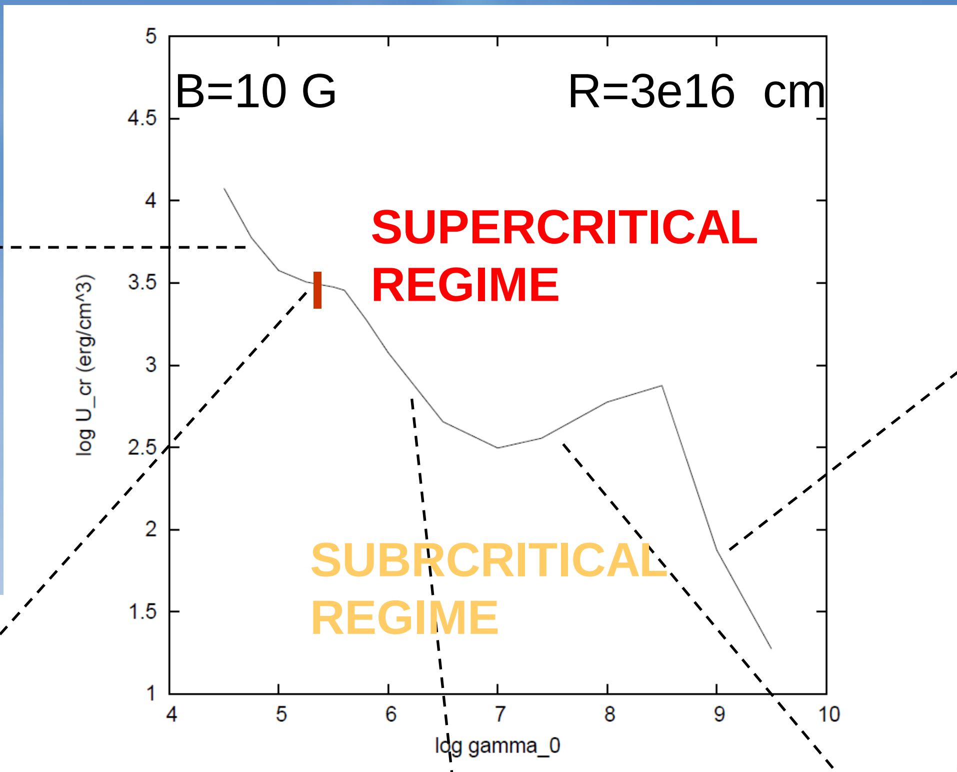


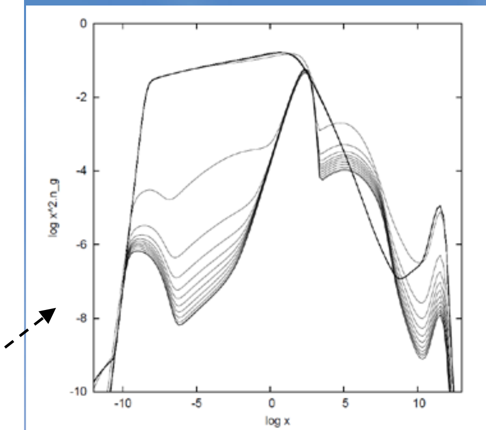
Proton injected luminosity
is increased by a factor 3

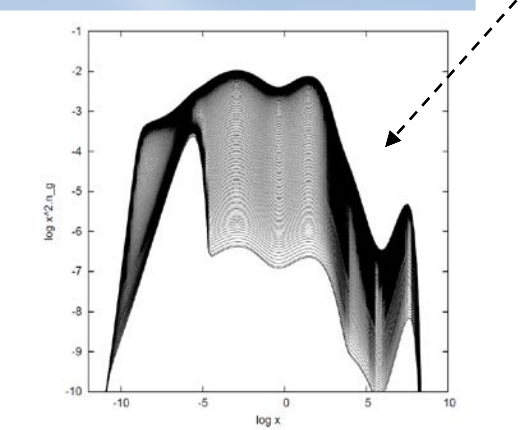
$$L_p = \frac{4\pi R m_p c^3}{\sigma_T}\ell_p.$$

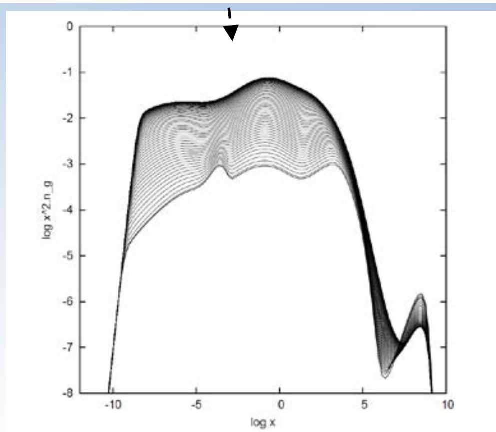
THE STEP TO SUPERCRITICALITY

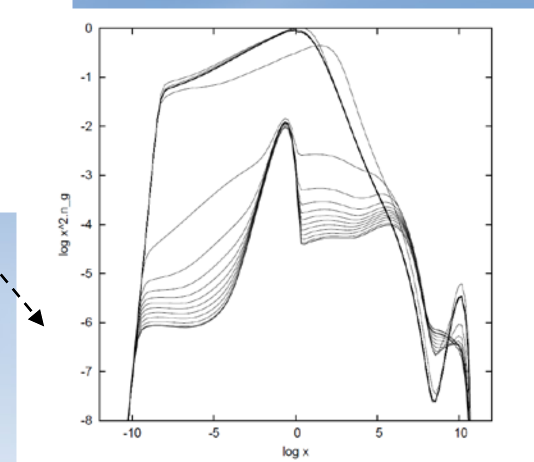












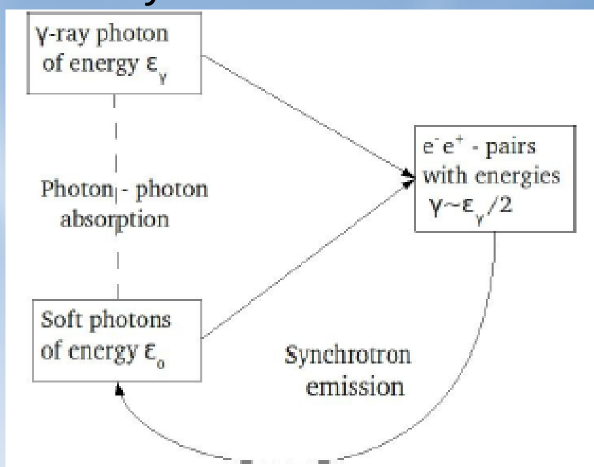
Time-dependent transition of photon spectra from the subcritical to the supercritical regime

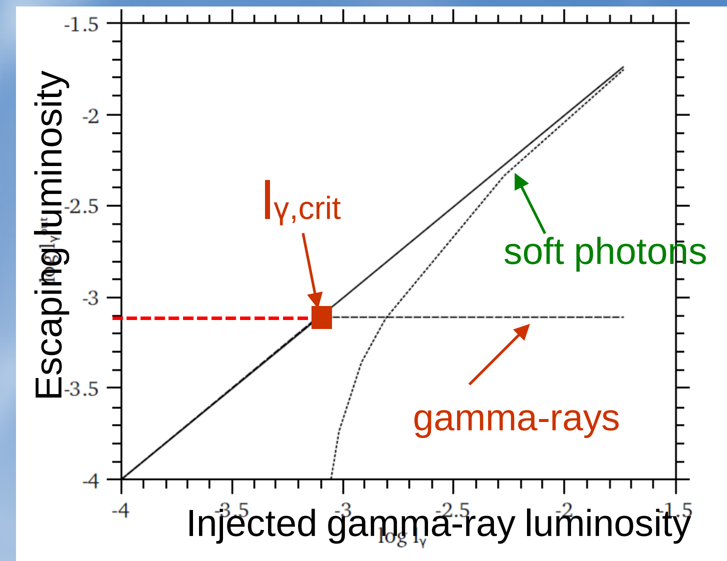
In all cases the proton injection luminosity is increased by **1.25**
→ corresponding photons increase by **several orders of magnitude**

AUTOMATIC PHOTON QUENCHING

Stawarz & Kirk 2007
Petropoulou & AM 2011

Gamma-rays can be self-quenched:
Non-linear network of
• photon-photon annihilation
• electron synchrotron radiation
Operates **independently** of soft photons
Poses a strong limit on the gamma-ray luminosity of a source

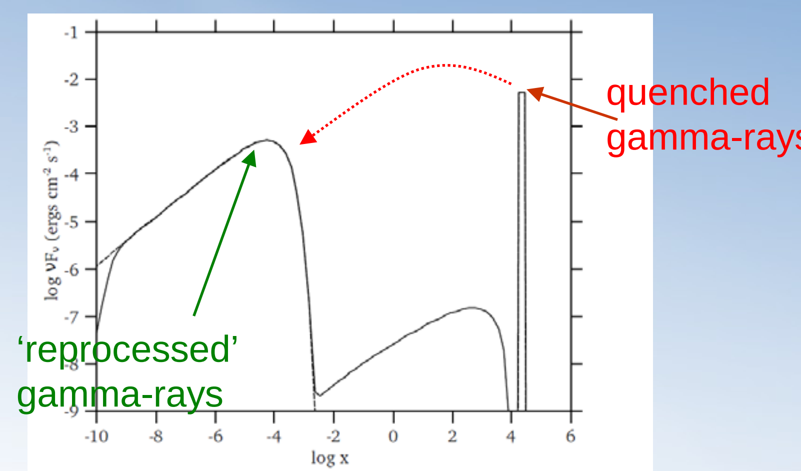




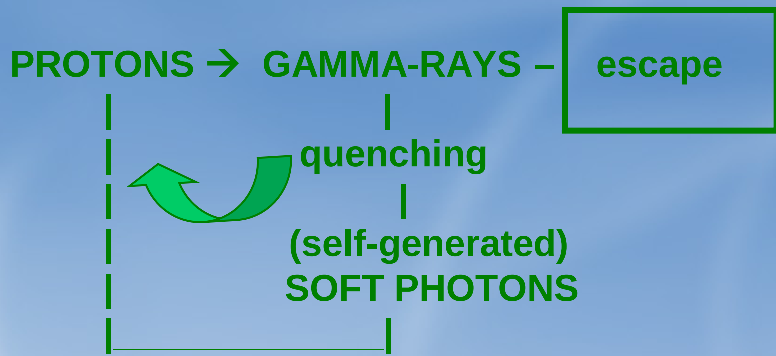
$$\frac{\partial n'}{\partial \tau} = -n' - \frac{2}{3}\frac{n'_0 \bar{n}}{\epsilon_\gamma}\delta(\epsilon_\gamma - 2\gamma)$$

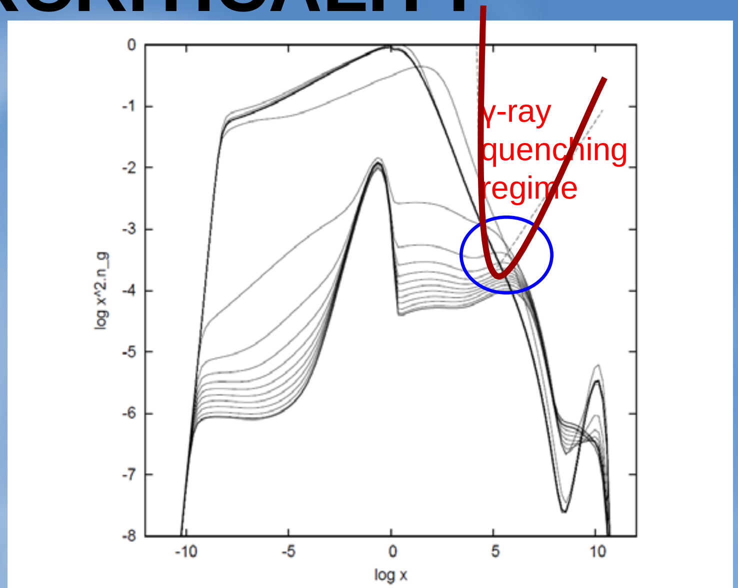
$$\frac{\partial n'_0}{\partial \tau} = -n'_0 + \frac{2}{3} l_B b^{-3/2} x^{-1/2} n'_e$$

$$\frac{\partial n'_e}{\partial \tau} = +\frac{4}{3}\frac{n'_0 \bar{n}}{\epsilon_\gamma}\delta(\gamma - \epsilon_\gamma/2) + \frac{4}{3} l_B \frac{\partial}{\partial \gamma}\left(\gamma^2 n'_e\right).$$



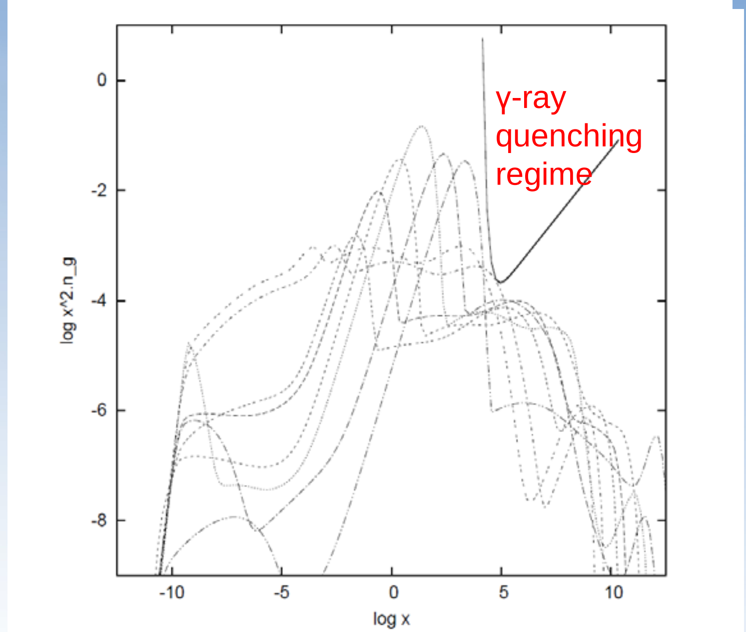
PHOTON QUENCHING
AND PROTON SUPERCRITICALITY





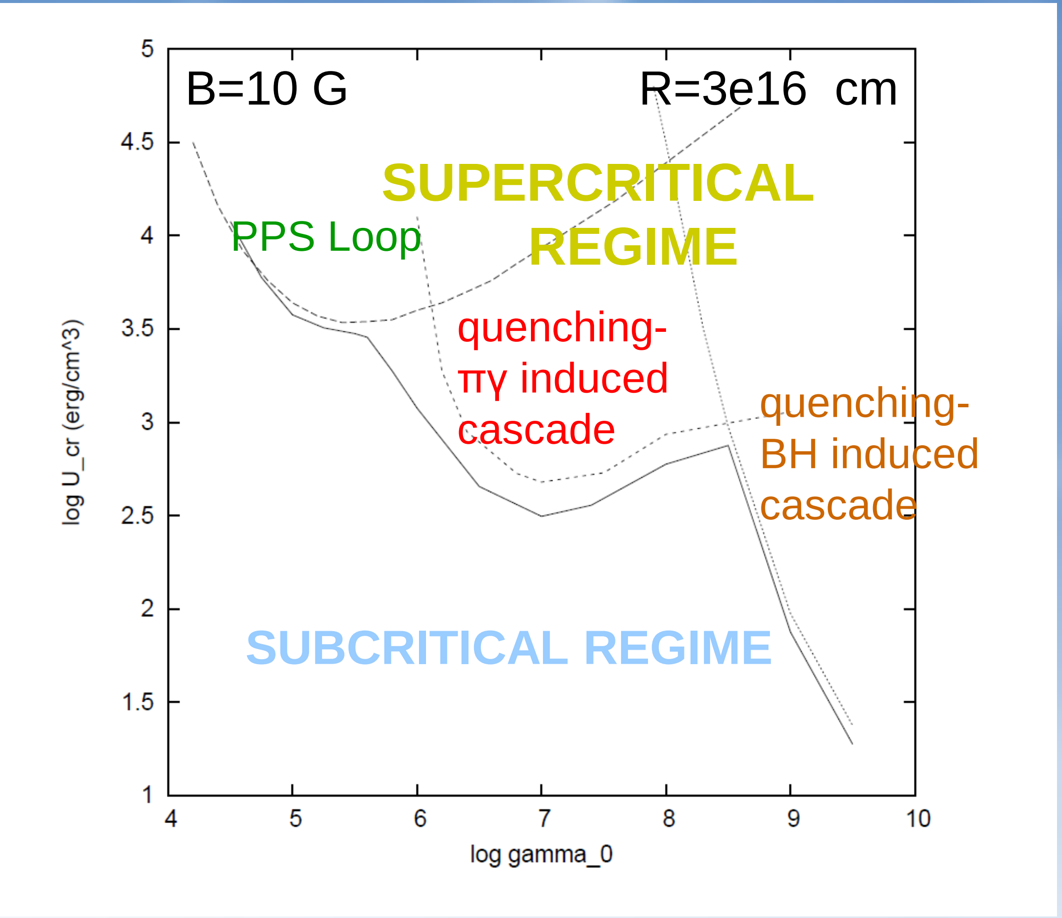
Soft photons from γ-ray quenching pump proton energy → proton losses → more secondaries → more γ-rays

Exponentiation starts when γ-rays enter the quenching regime.

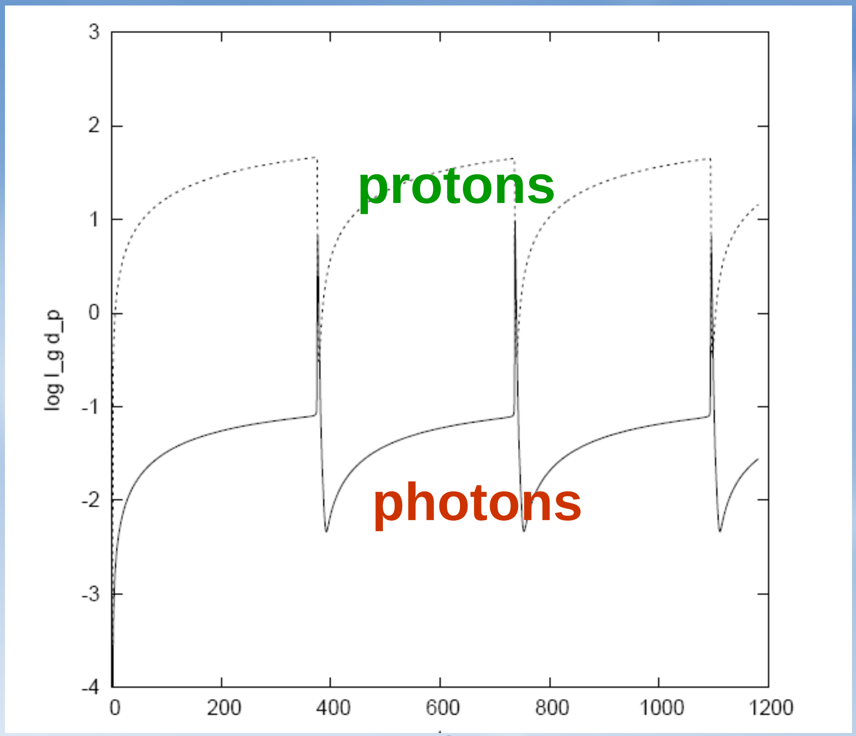


Photon spectra for various monoenergetic proton injection energies just before supercriticality

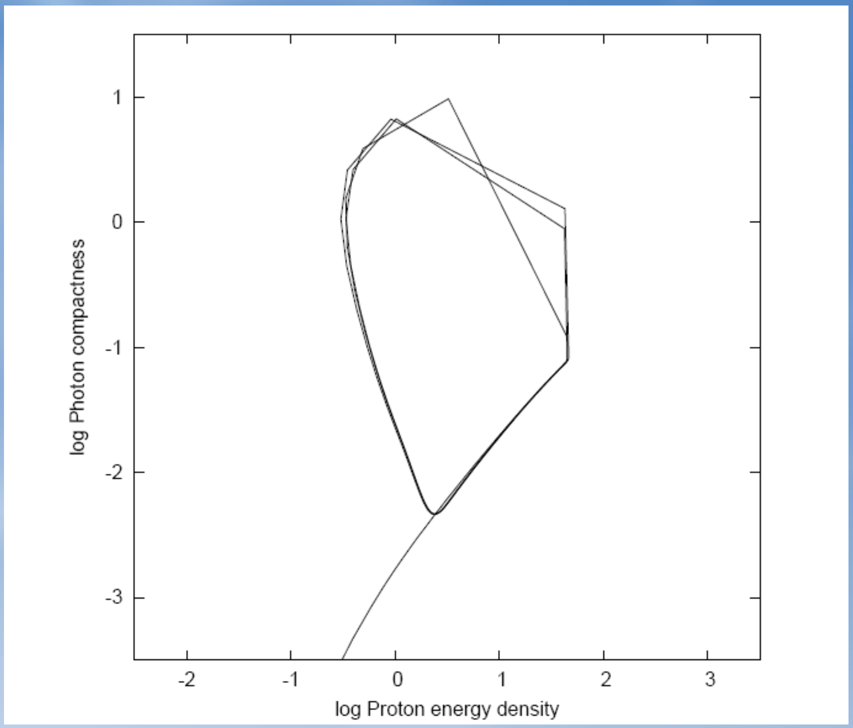
A MAP OF PROTON SUPERCRITICALITIES



DYNAMICAL BEHAVIOUR



time



As the protons enter the supercritical regime → limit cycles

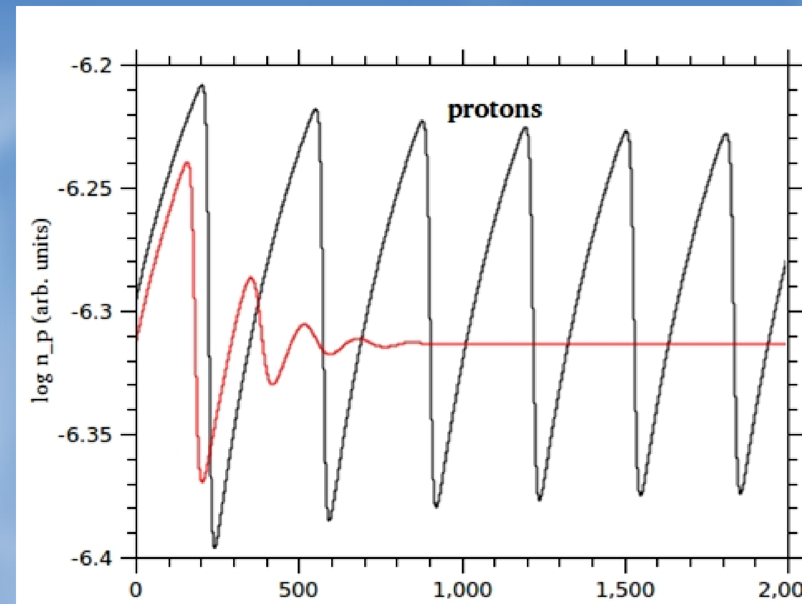
Simplified equations

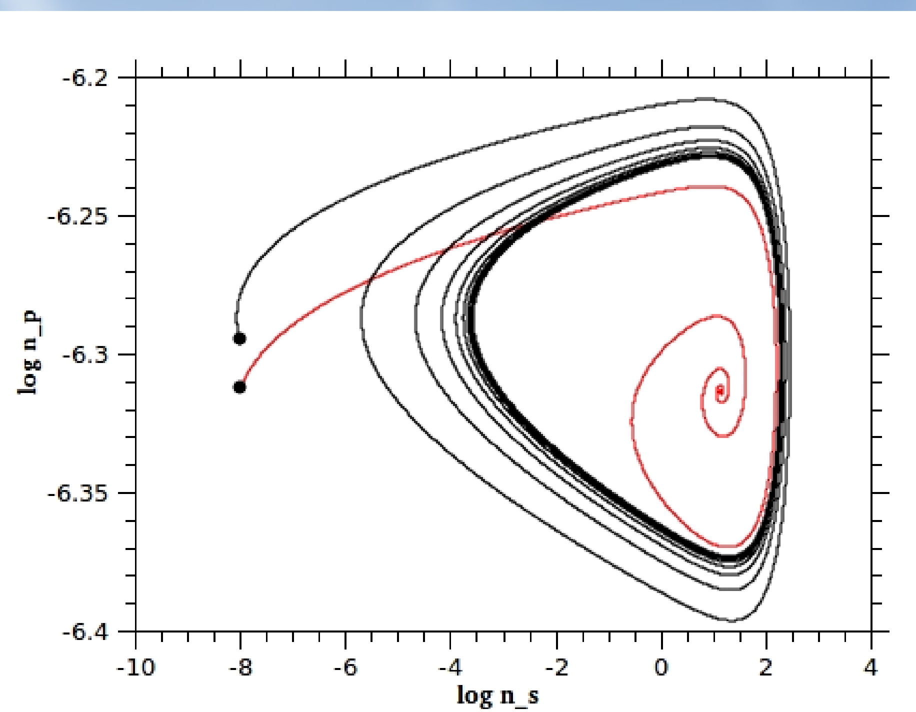
M. Petropoulou & A.M., in preparation

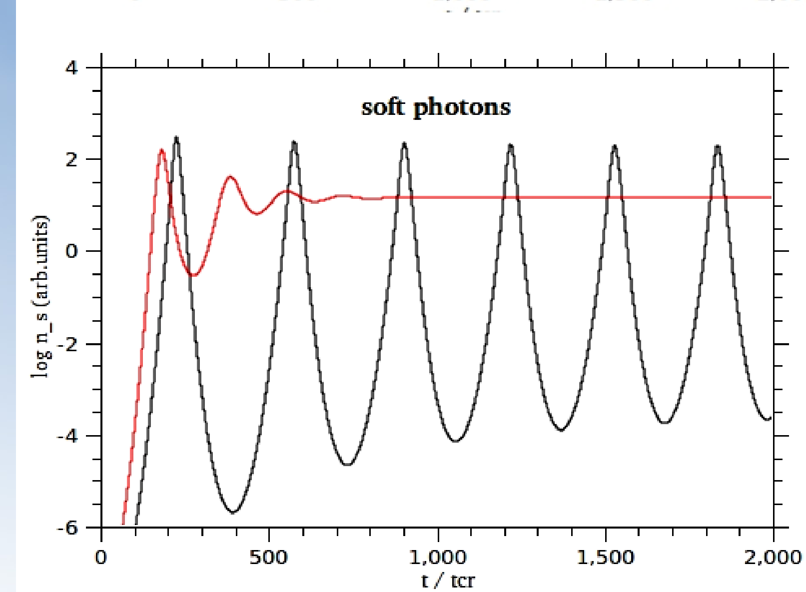
$$\dot{n}_p = -\frac{n_p}{\tau_p} - \boxed{A n_{ex} n_p} - \boxed{B n_s n_p} + Q_o$$

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

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







CONCLUSIONS

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

- Five non-linear PIDE – c.f. leptonic models have only two
- First results for pure hadronic injection

  - Low efficiencies
  - γ-rays steeper than neutrino spectra
  - Quadratic time-behaviour of radiation from secondaries (similar to synchrotron – SSC relation of leptonic models)
  - Inherently non-linear (c.f. 'Compton catastrophe' in leptonic models)
  - Strong supercriticalities exclude sections of parameter-space used for modeling AGNs