THE HADRONIC MODEL OF ACTIVE GALACTIC NUCLEI

A. Mastichiadis

University of Athens

TALK OUTLINE

- High Energy Emission from Active Galactic Nuclei
- Hadronic Models: key ideas and processes
- MW fits and simulated variability of Mrk 421
- BL Lacs as IceCube neutrino sources
- Proton supercriticalities: revisiting a long-standing issue

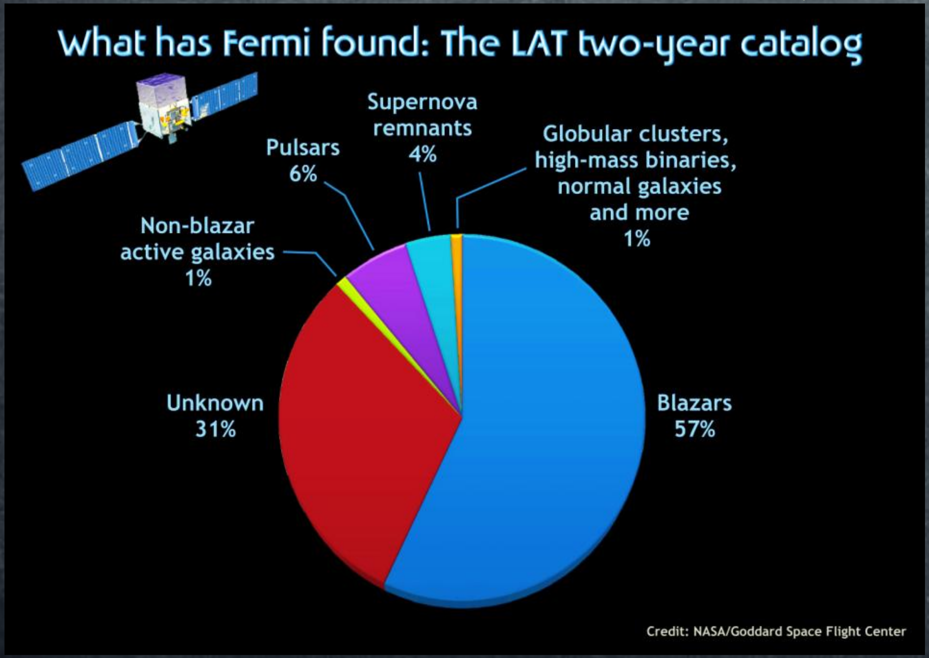
In collaboration with

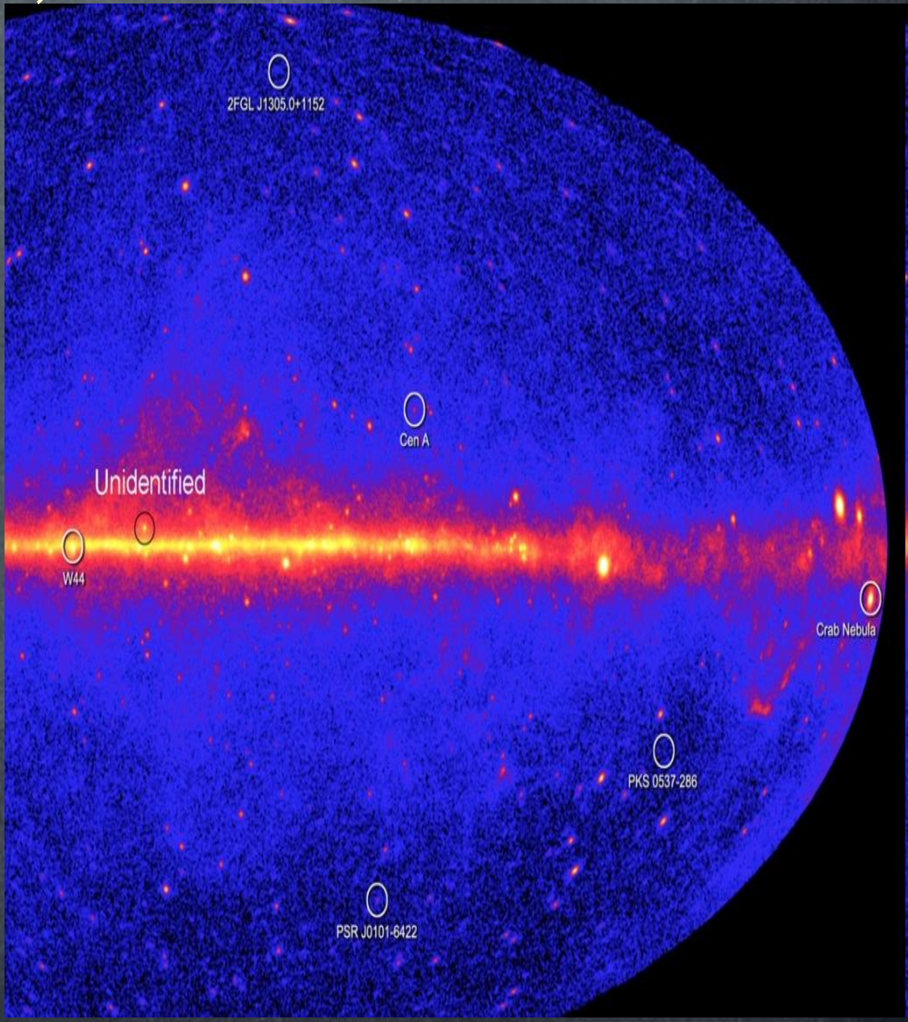
- Maria Petropoulou
- Stavros Dimitrakoudis

GAMMA-RAYS AND AGN

Fermi gamma-ray detector
2nd LAT AGN catalog: 1016 sources (2011)
• 395 BL Lac objects
• 315 FSRQs
• 156 blazars of unknown type

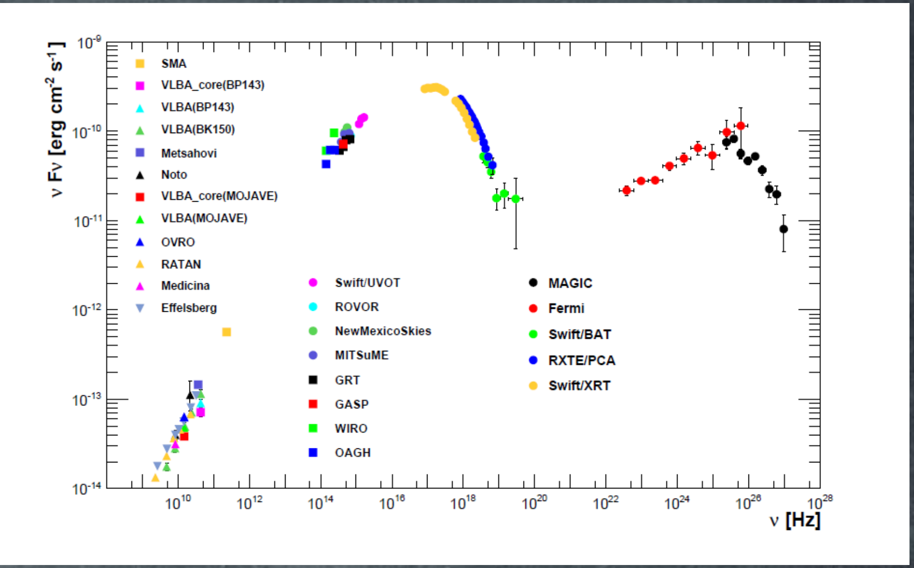
c.f. EGRET catalog: 66 AGN (1995)
COS-B catalog: 1 AGN (1983)

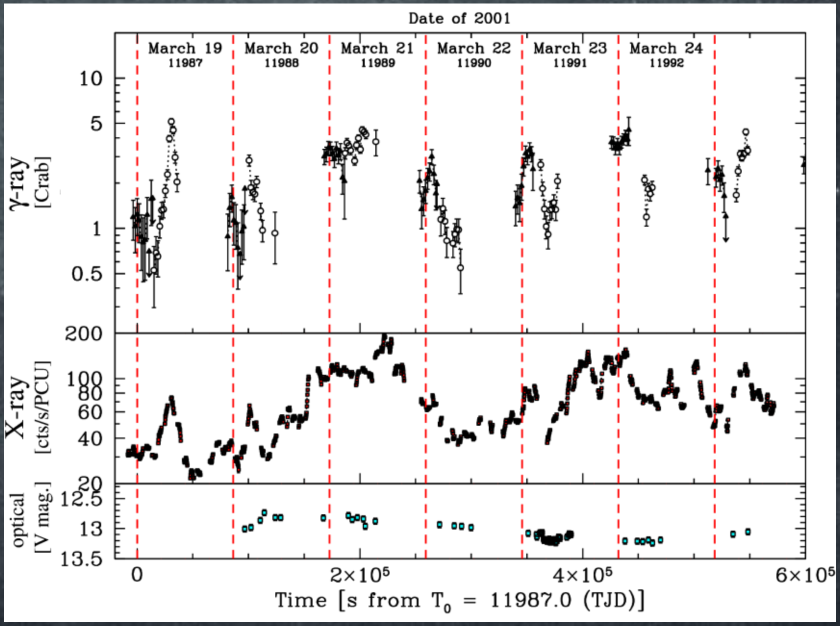




BLAZAR PROPERTIES

- Compact , flat spectrum radio sources.
- Broad (radio-γ) non-thermal continuum.
- Variable at all energies – correlations!
- Superluminal motion → beaming → emission from inside the jet.
- Short variability → emission from a localized region.



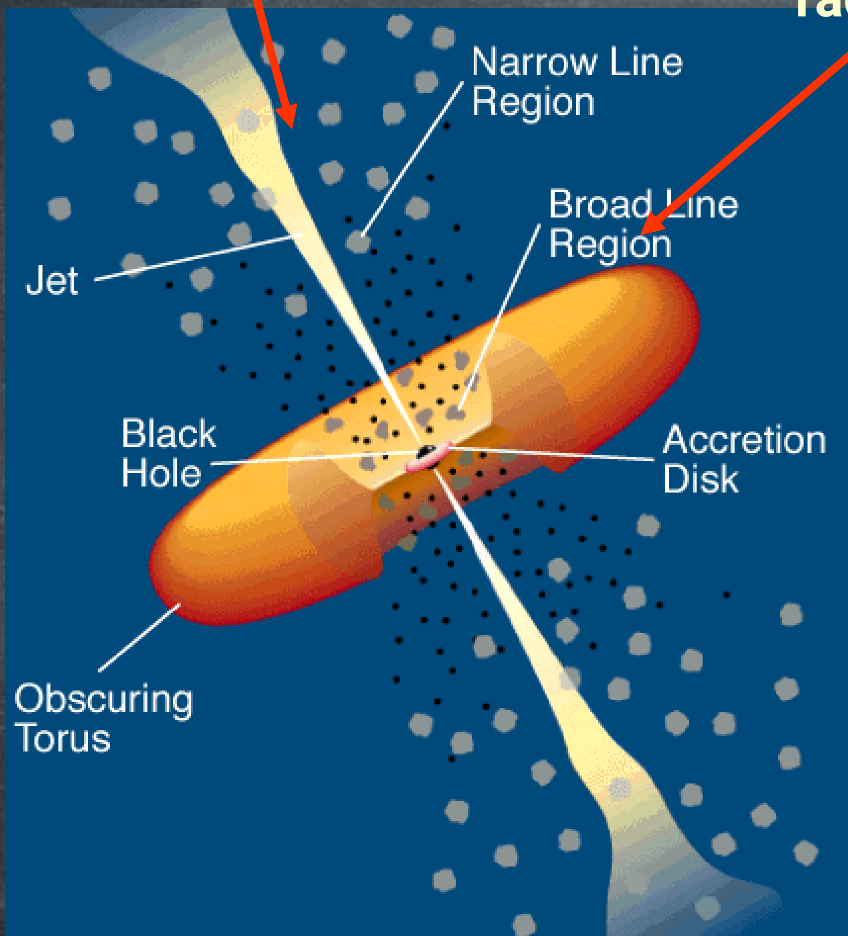


Fosatti et al 2008

RADIO-LOUD AGN

Blazar (BL Lac + Quasars)

radiogalaxy



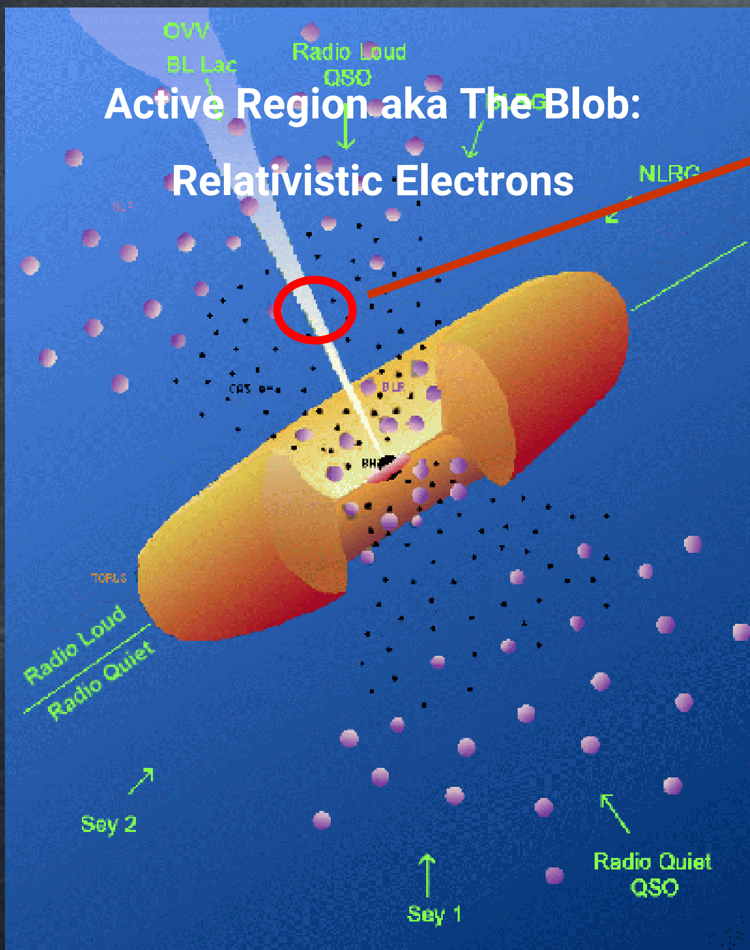
Open questions:

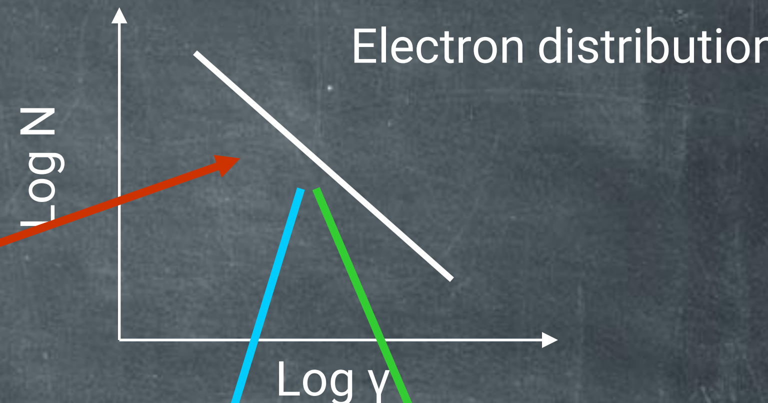
• Emission mechanism (leptonic or hadronic)

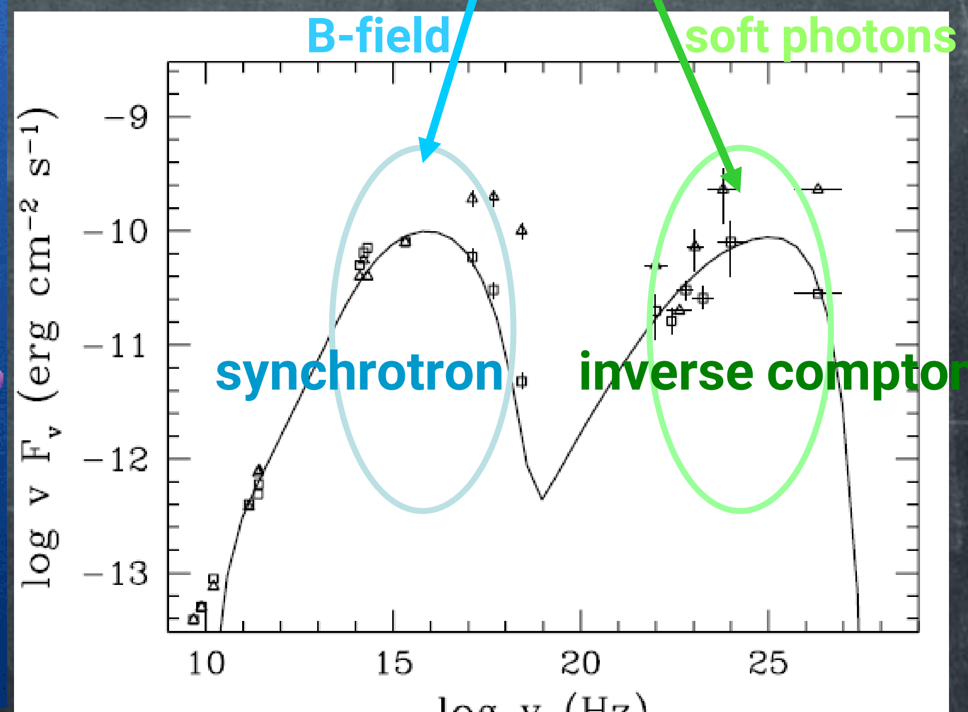
• Jet composition (electron-proton; electron-positron, B)

• Emission zone – location of energy dissipation

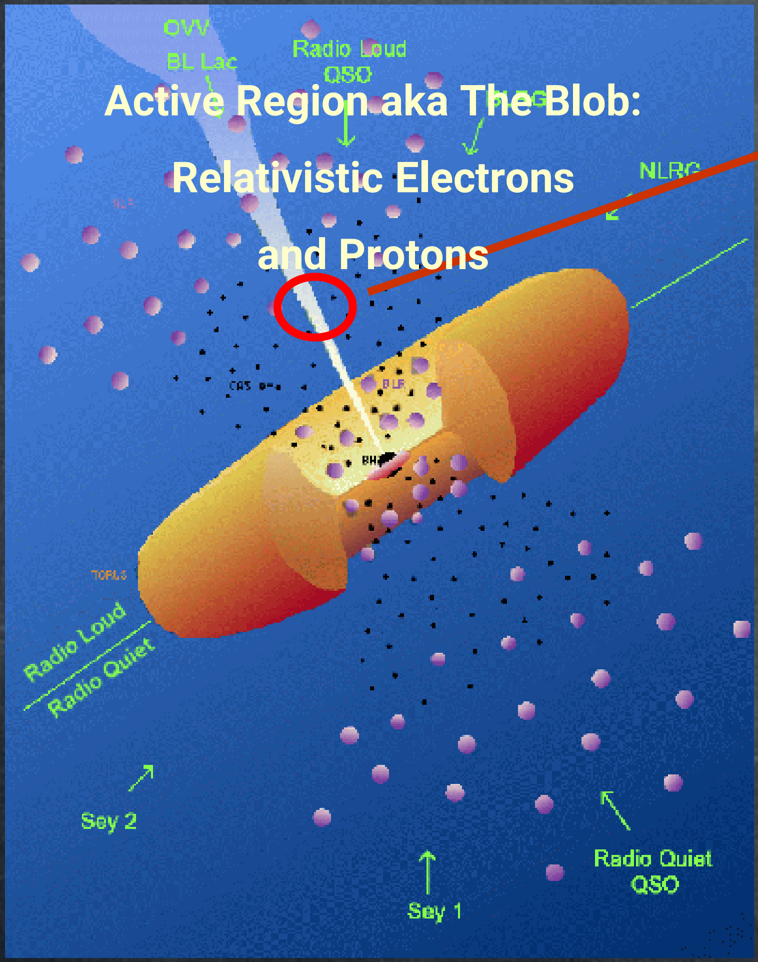
LEPTONIC MODEL FOR H.E. EMISSION







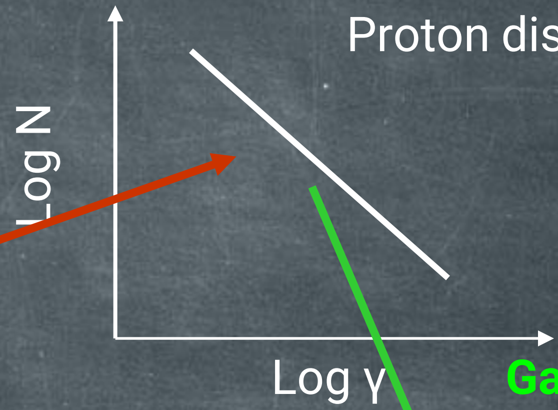
...AND THE HADRONIC MODEL



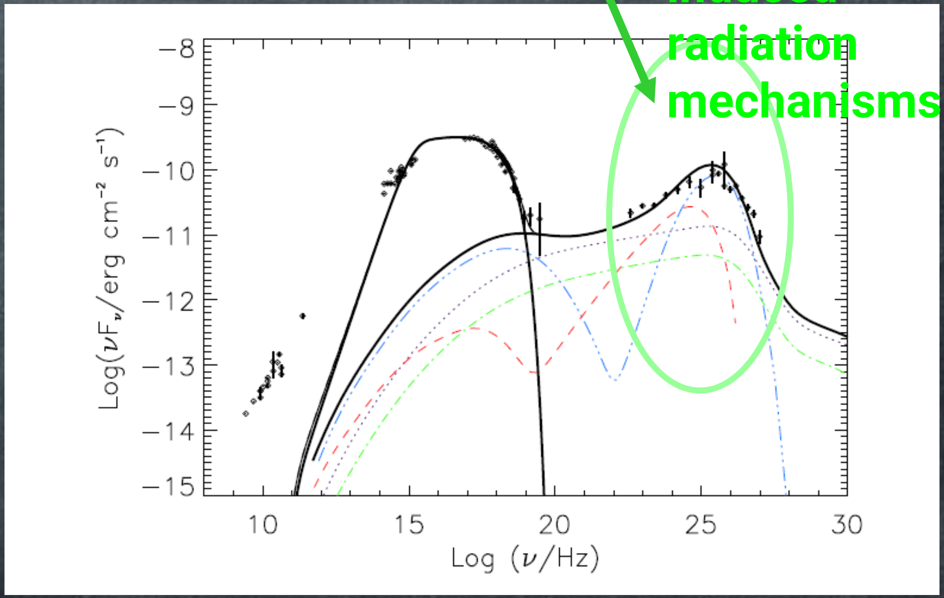
Active Region aka The Blob:

Relativistic Electrons

and Protons



Gamma-rays from proton induced radiation mechanisms



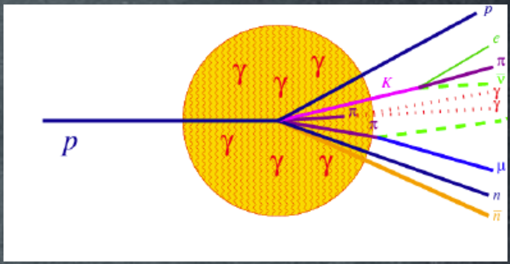
INTERACTION OF NUCLEONS WITH PHOTON FIELDS

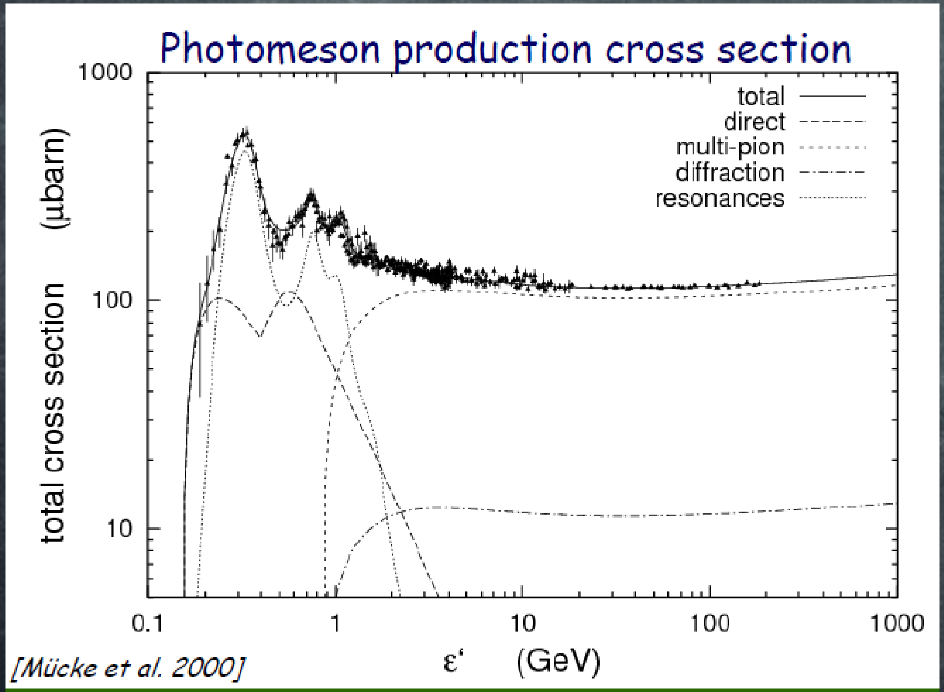
photopair production

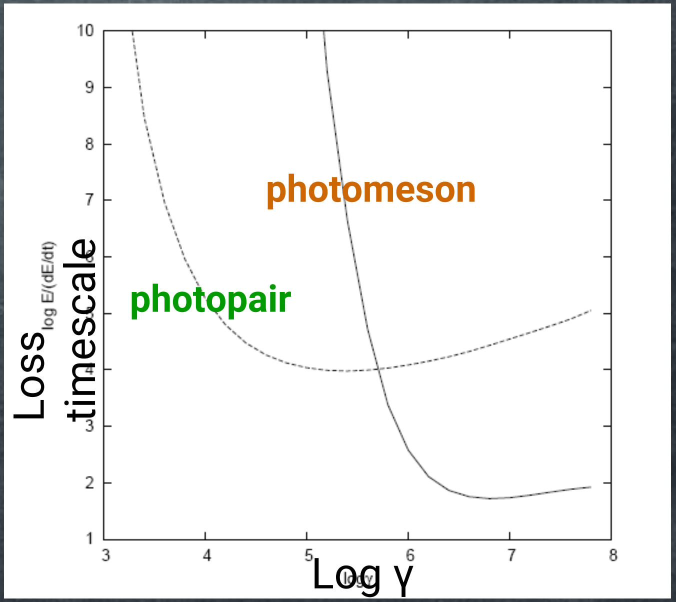
$$N + \gamma_{target} \longrightarrow N + e^{+} + e^{-}$$
$$s^{1/2}_{threshold} = m_p + 2m_e$$

photomeson production

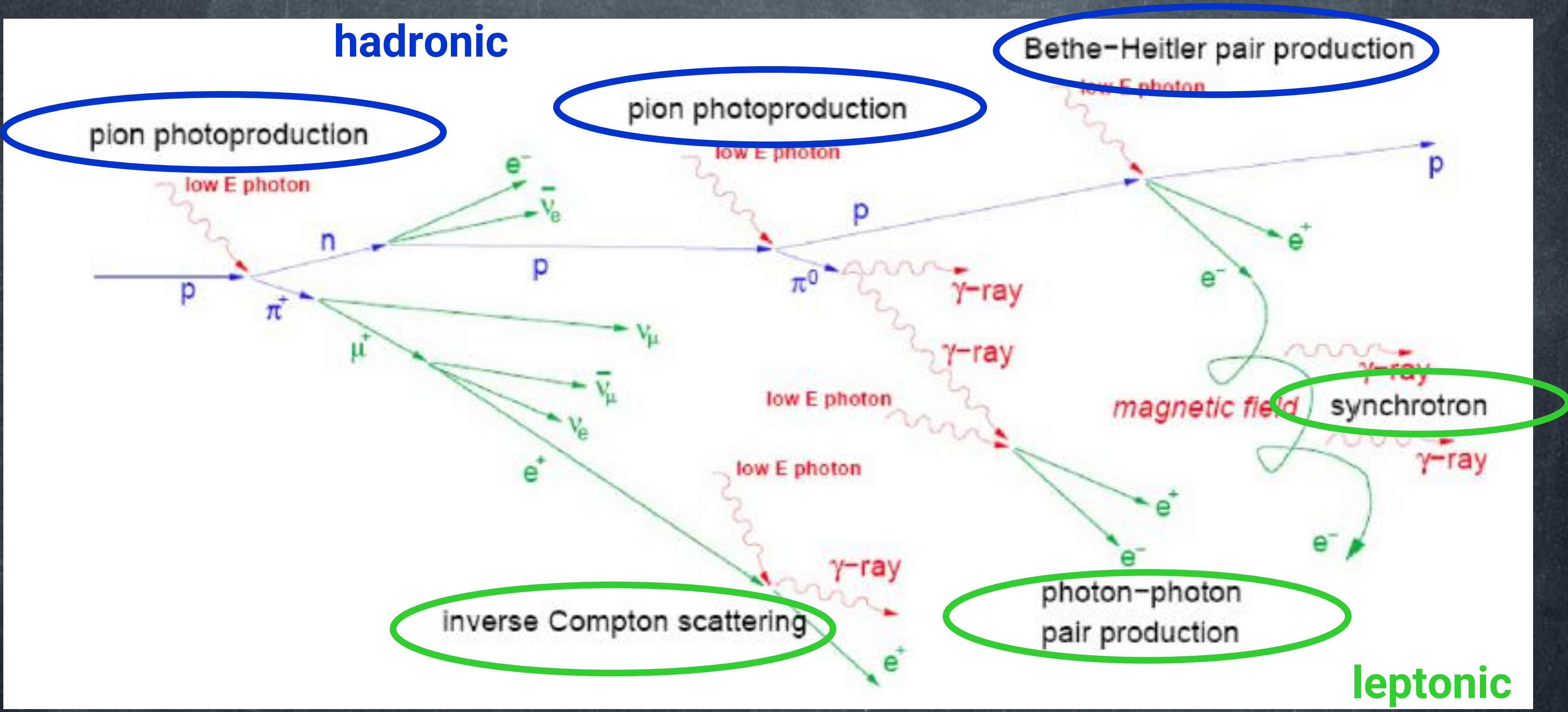
$$N + \gamma_{target} \longrightarrow N + \pi s + \ldots$$
$$s^{1/2}_{threshold} = m_p + m_{\pi 0}$$



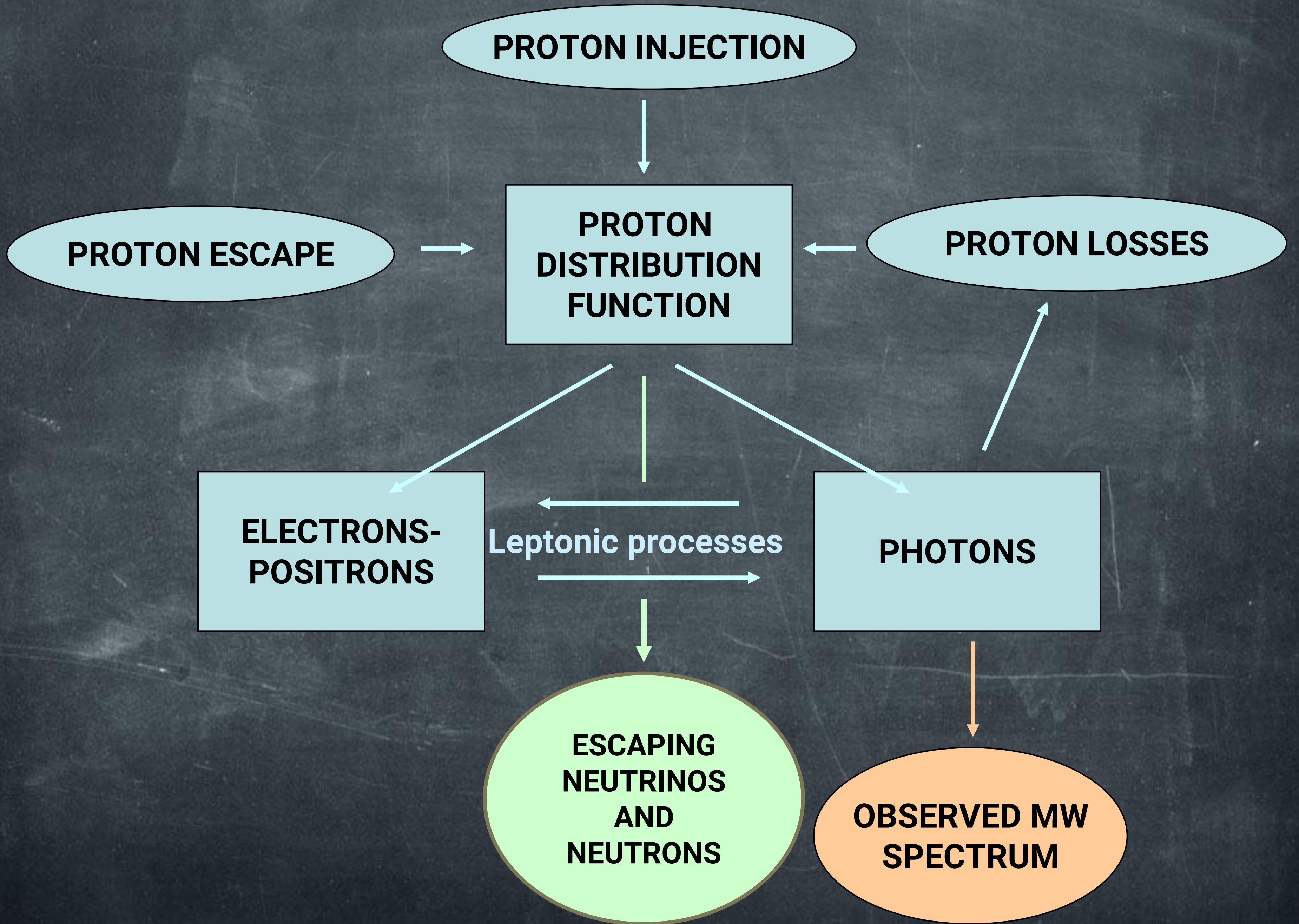




THE HADRONIC MODEL: PHYSICAL PROCESSES



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

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:

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

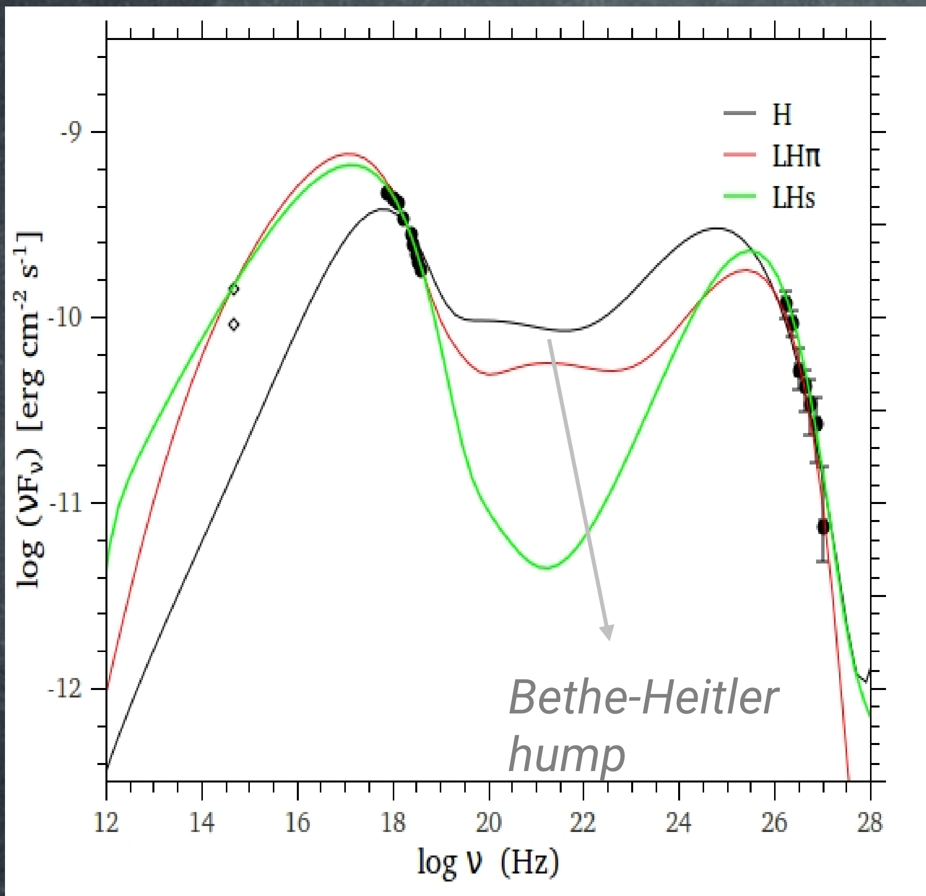
Dimitrakoudis et al. 2012

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

Synchrotron cooling of secondaries is also included.

(1) Mrk 421 : SPECTRAL FITS AND TEMPORAL BEHAVIOR

SED OF Mrk 421: LEPTO-HADRONIC MODELS



AM, M. Petropoulou, S. Dimitrakoudis 2013

	V-Xrays	γ-rays
LH-π model	e-syn	photopion
LH-s model	e-syn	p-syn

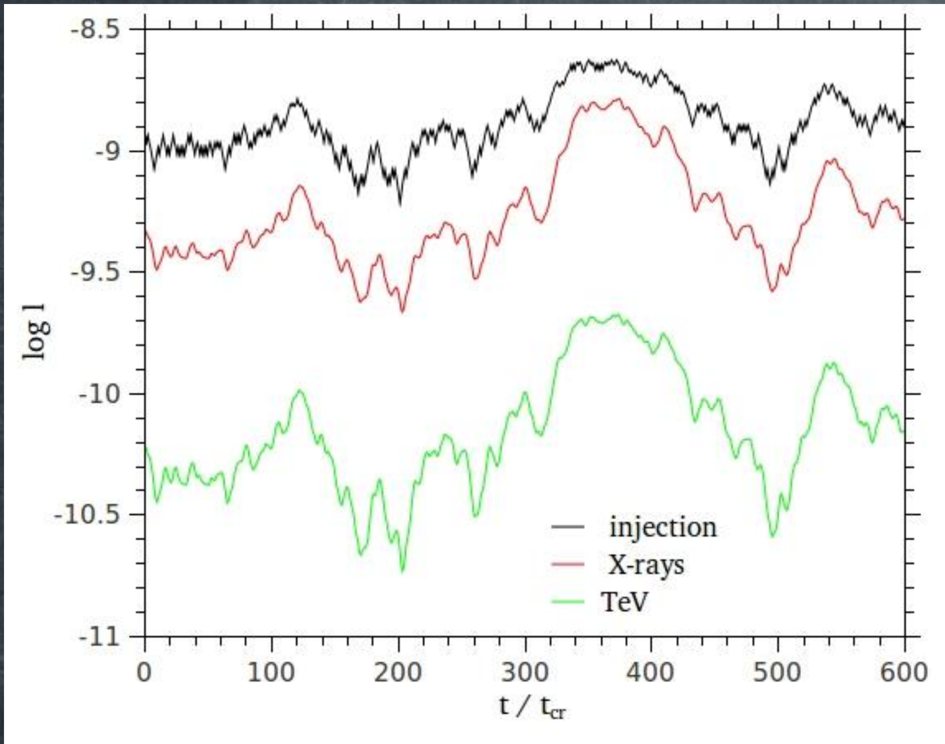
	LH-π	LH-s
Dominant energy density	Protons	B-field
Maximum proton energy	~PeV	~EeV

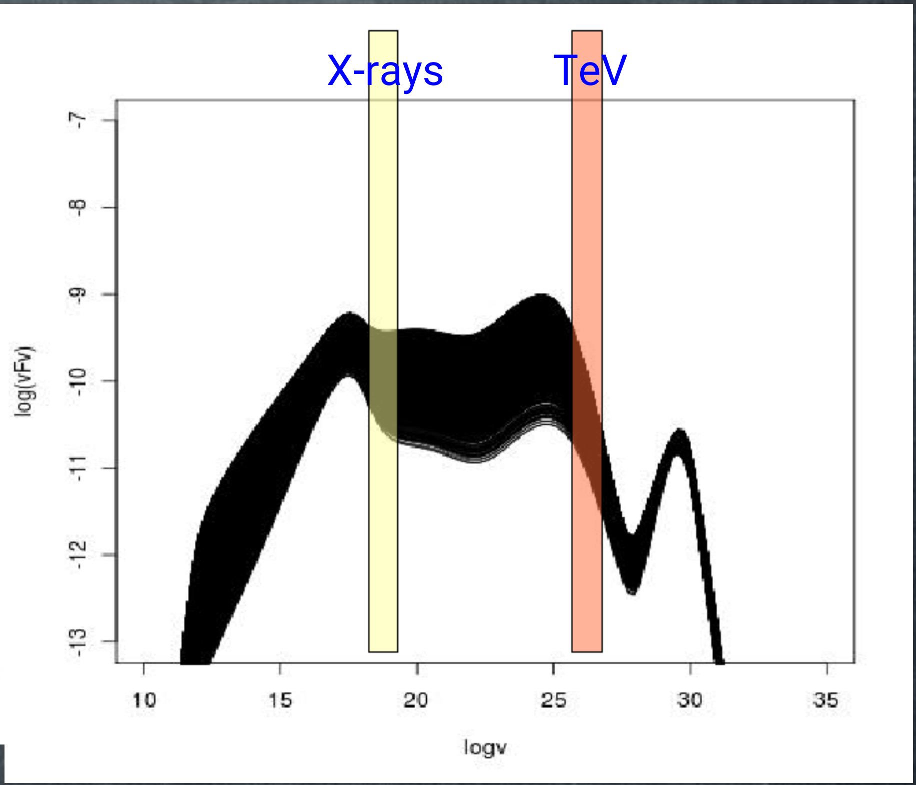
Bethe-Heitler pair-production hump is an unavoidable consequence of the LH-π model (Petropoulou + AM 2015)

See Poster #63

VARYING THE INJECTION LUMINOSITY

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

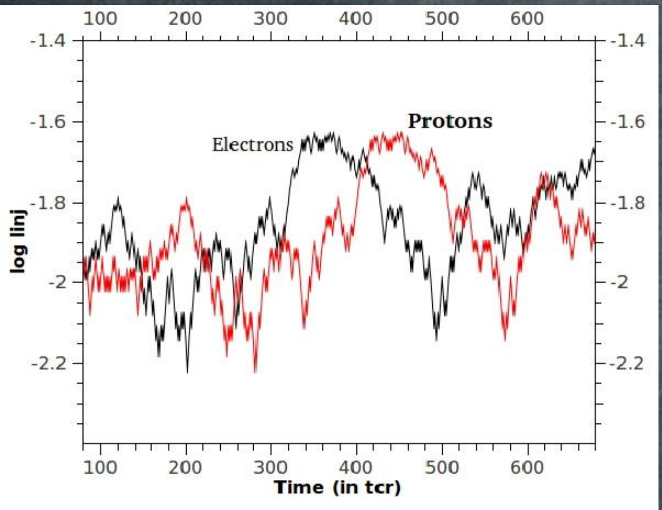


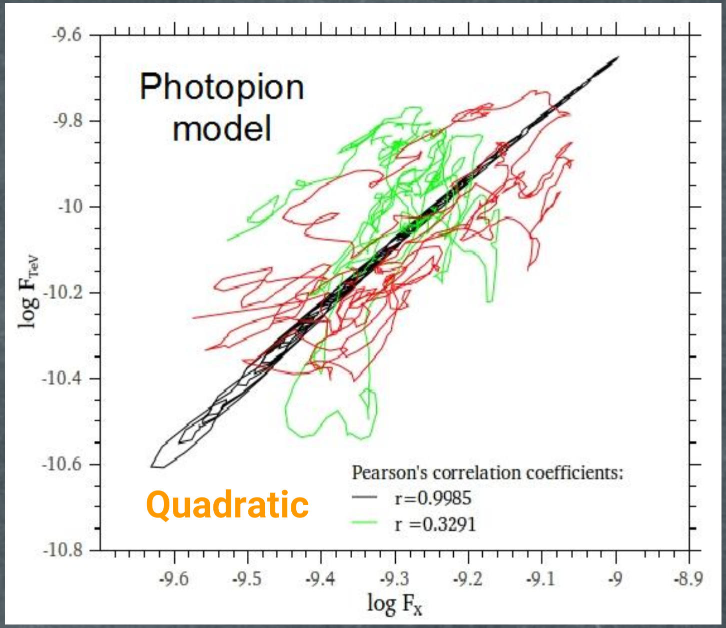


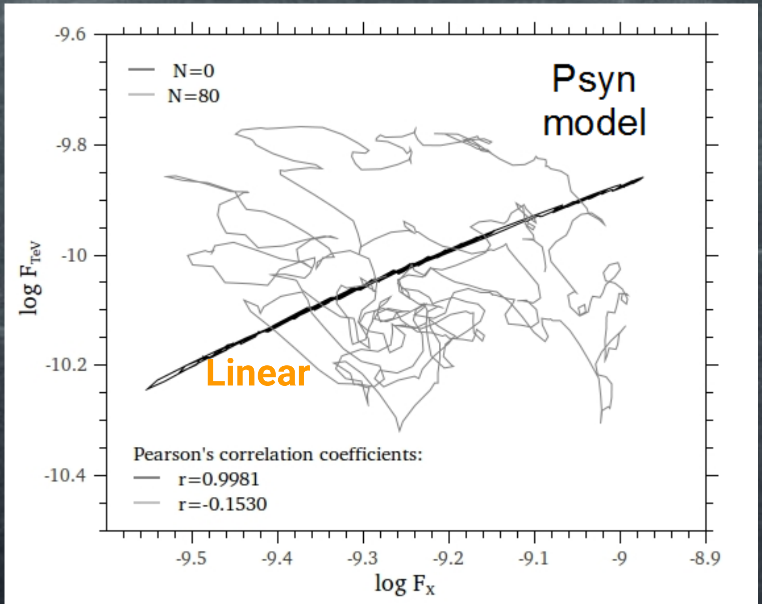
Injection and spectra when p and e totally correlated

PHOTOPION vs P-SYN: TIME VARIATIONS

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





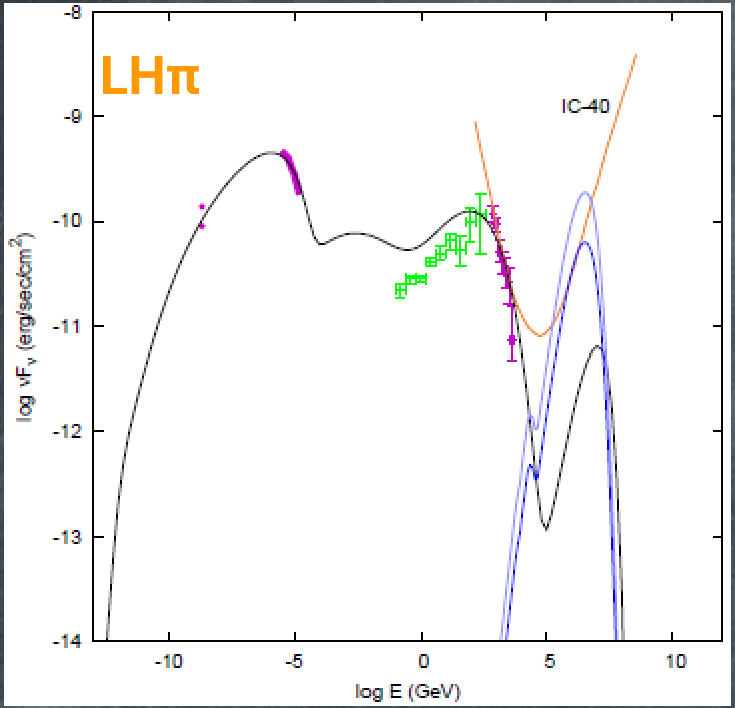


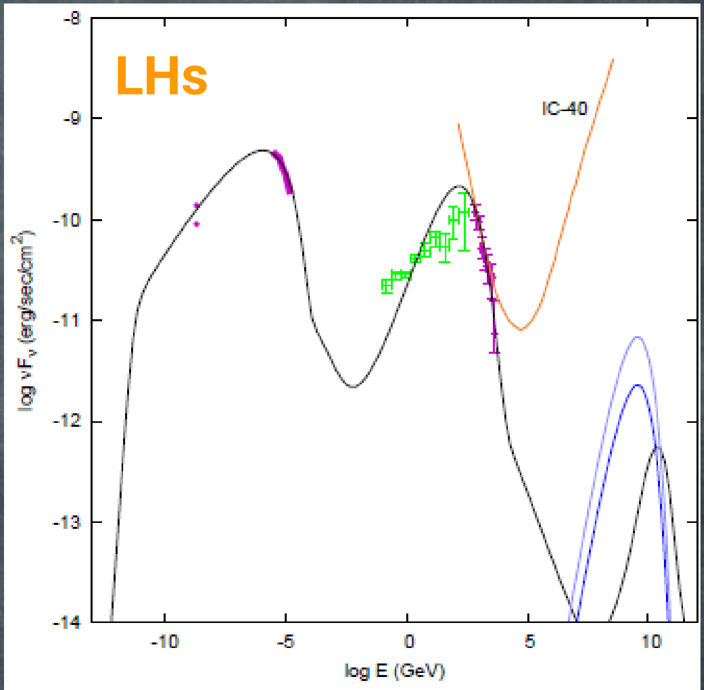
Photopion:
When electrons-protons are correlated, TeV (hadronic) and X-rays (leptonic) vary quadratically
Even when electrons-protons totally uncorrelated,
X and TeV
retain some correlation

P-syn:
When electrons-protons totally correlated,
X and TeV
linear. When uncorrelated, all X-TeV correlation is lost.

(2) BLAZARS AS NEUTRINO AND COSMIC-RAY SOURCES

THE 'SMOKING GUN': NEUTRINO EMISSION





Due to differences in fitting parameters

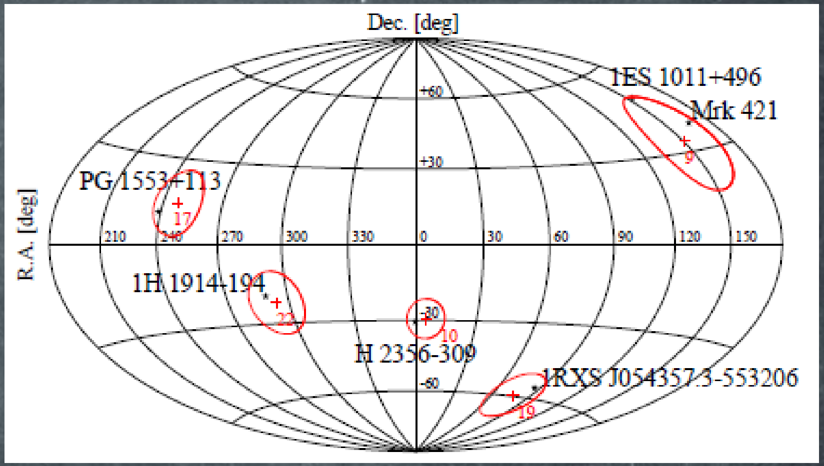
- LHπ model: PeV neutrinos with high flux → **IceCube**
- LHs model: EeV neutrinos with low flux

S. Dimitrakoudis et al. 2014

BL Lac – IceCube EVENTS ASSOCIATION?

The facts

- IceCube: 37 events 0.1 – 1 PeV *(Aartsen et al 2013,2014)*
- Background or point sources?
- 8 possible associations between Bl Lac – IceCube events *(Padovani & Resconi 2014)*
- 6 (out of 8) BLLacs with good quality observations

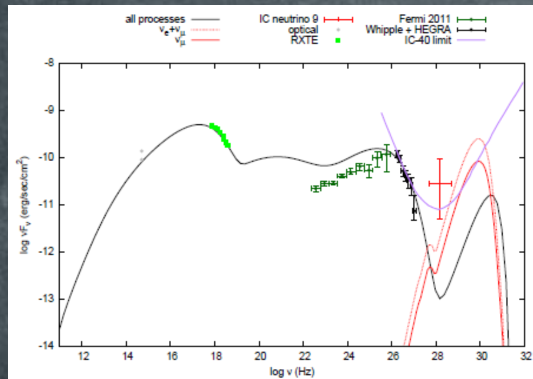


The challenges

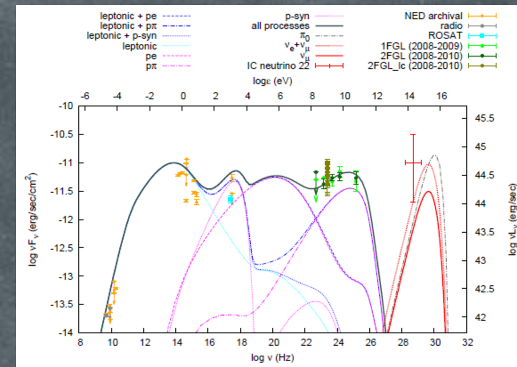
1. Can hadronic models (LHπ) fit the SED of these blazars? *(sources not a-priori selected!)*
2. Is the associated neutrino flux compatible with IceCube detections? *(tailor-made: SED fit → source parameters → neutrino flux)*

IceCube ID	Counterpart(s)	Class	Catalogue(s)
9	MKN 421	BL Lac (HSP)	TeVCat/WHSP
	1ES 1011+496	BL Lac (HSP)	TeVCat/WHSP
10	H 2356−309	BL Lac (HSP)	TeVCat/WHSP
17	PG 1553+113	BL Lac (HSP)	TeVCat/WHSP
19	1RXS J054357.3−553206	BL Lac (HSP)	WHSP
20	SUMSS J014347−584550	BL Lac (HSP)	WHSP
22	1H 1914−194	BL Lac (HSP)	WHSP
27	PMN J0816−1311	BL Lac (HSP)	WHSP

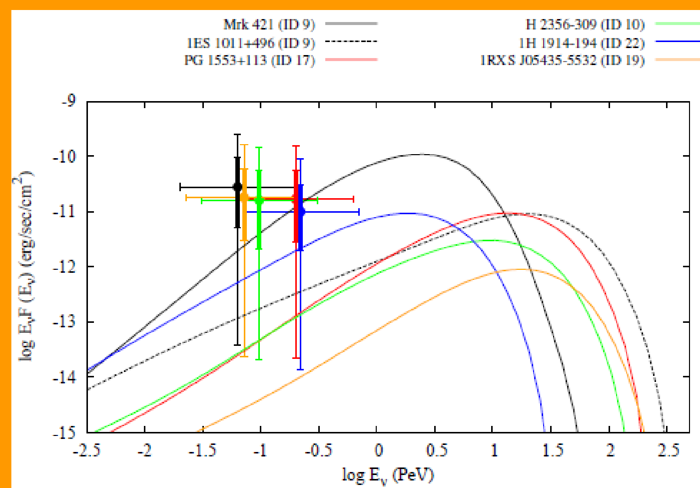
Padovani & Resconi 2014

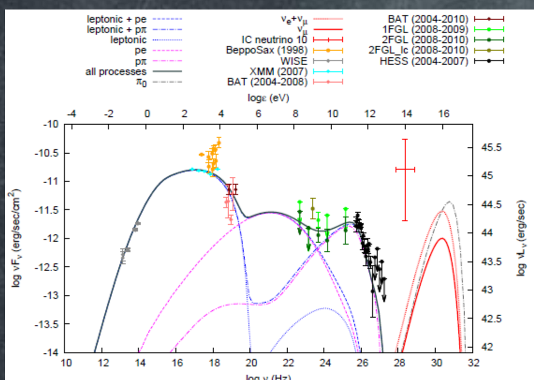


Mrk 421

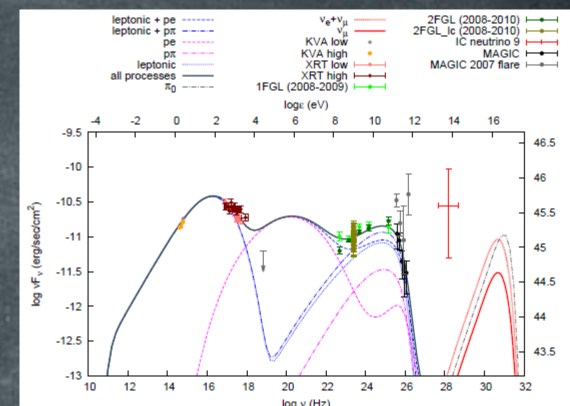


H 1914-194

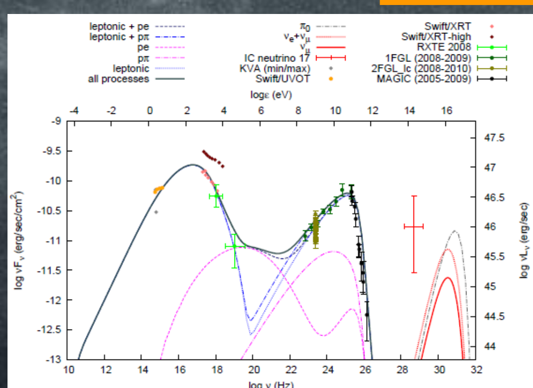




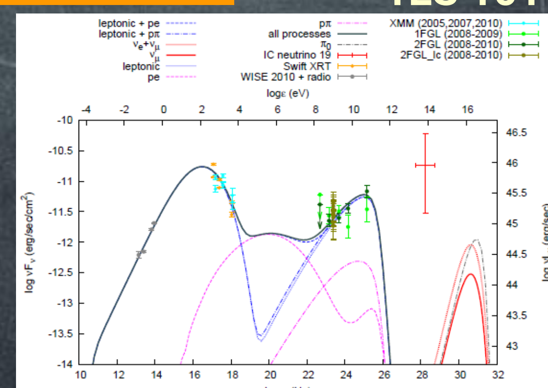
H 2356-309



1ES 1011+496



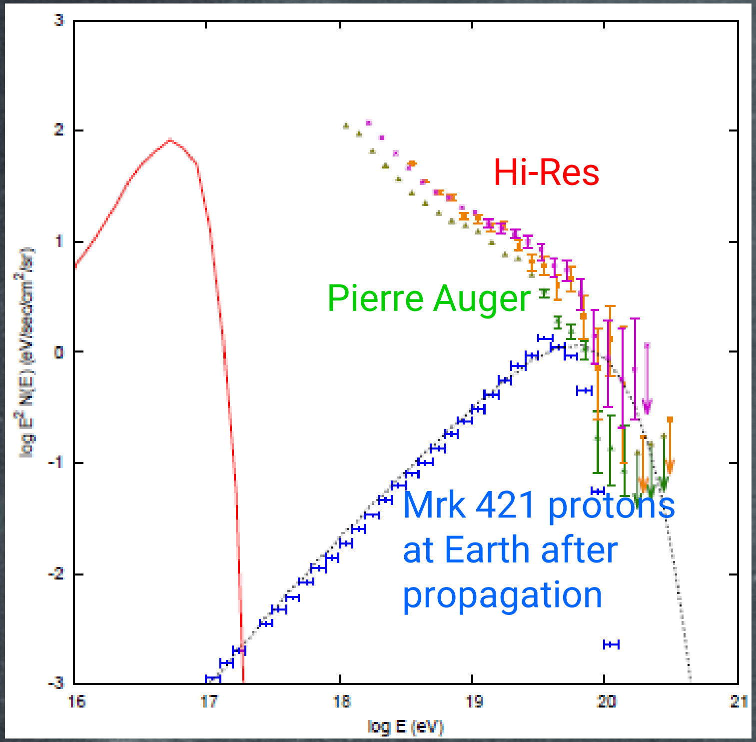
PG 1553+113



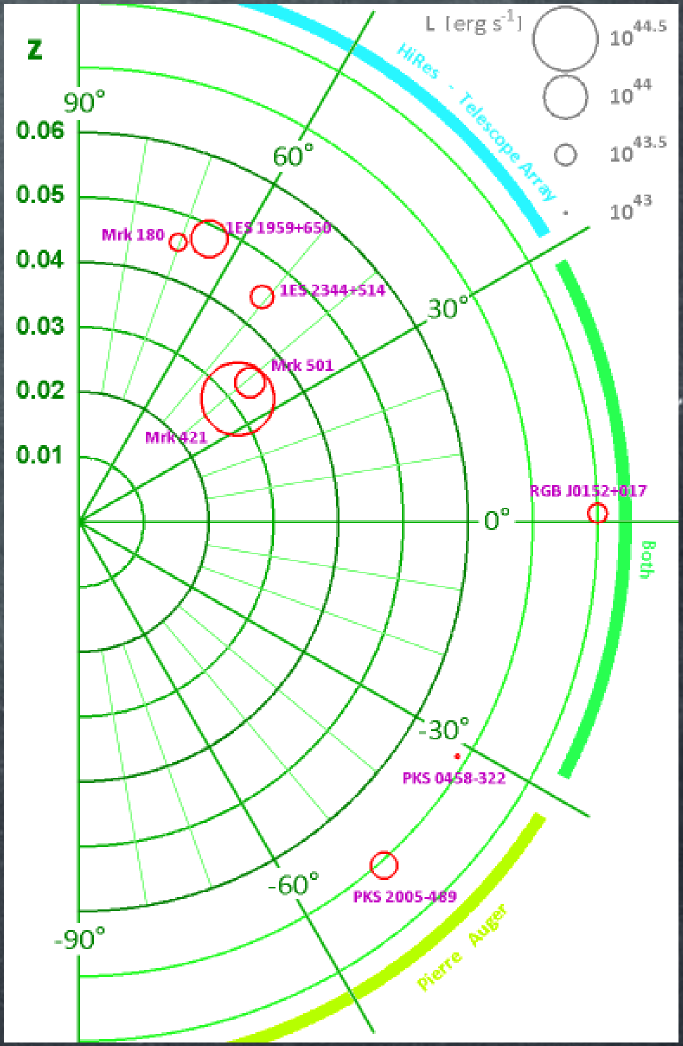
1 RXS J054357.3-553206

Petropoulou et al 2015

UHECR FROM NEUTRON ESCAPE



LHs model: Mrk 421 CR peak at ~30 EeV

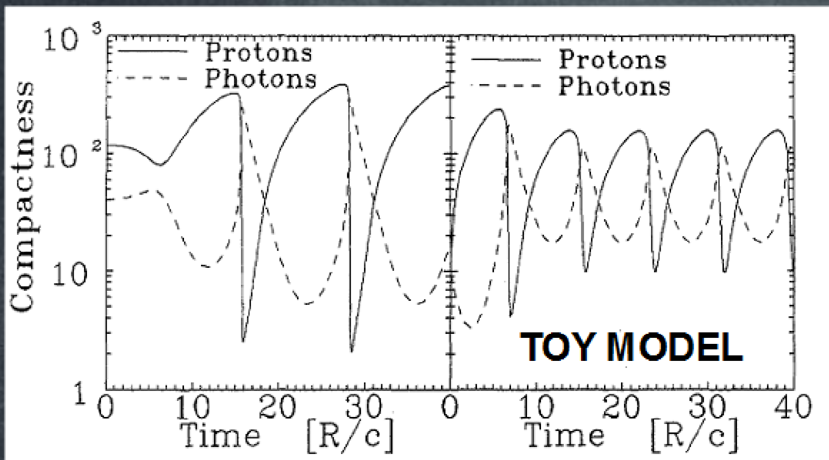


Small UHECR contribution from nearby BL Lac objects if similar to Mrk 421

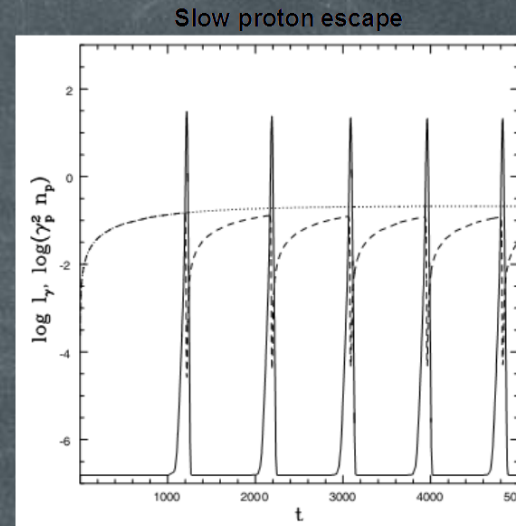
- Lower luminosities
- Larger distances

(3) A THEORETICAL ISSUE: HADRON SUPERCRITICALITIES

PROTON SUPERCRITICALITIES: THE EARLY DAYS

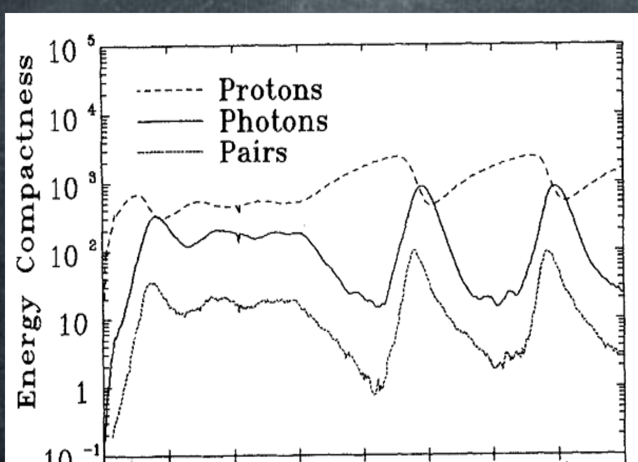


Stern & Svensson 1991

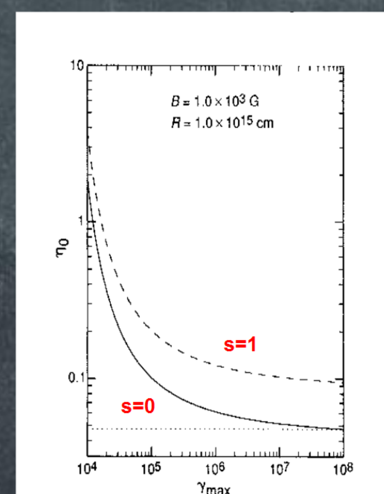


Kinetic equations

AM, Protheroe, Kirk 2005



Monte-Carlo

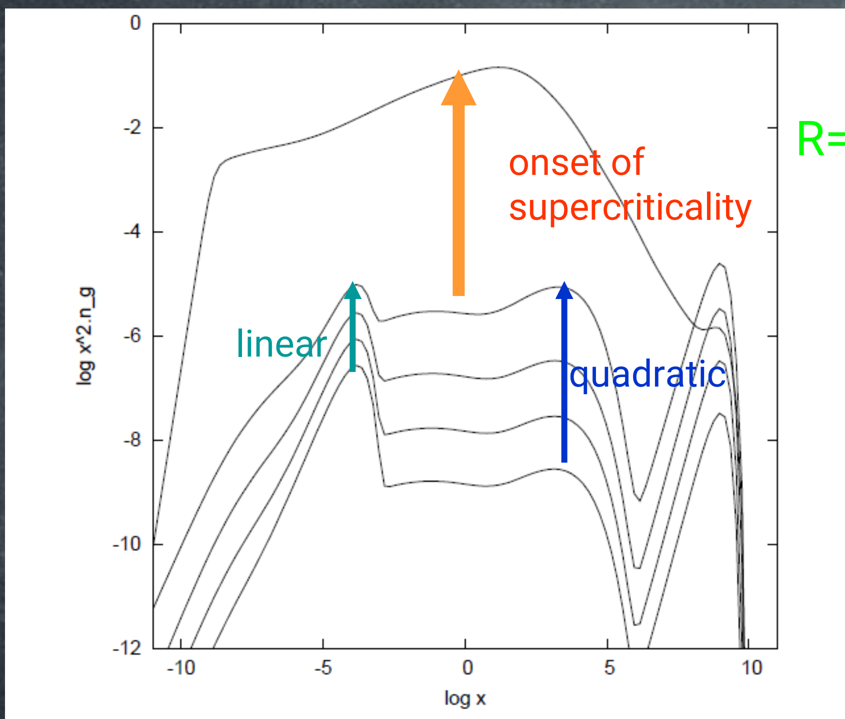


Stability criteria
- analytical

$$n_{p,0} > n_{crit} \left(\frac{2\beta}{3} - 1\right) b^{1-\beta/3} \times \left[\int_0^{b\gamma^2_{p,max}} dy\, y^{-1-\beta/3} \sigma_{p\gamma}(y)\right]^{-1} / (\sigma_T R)$$

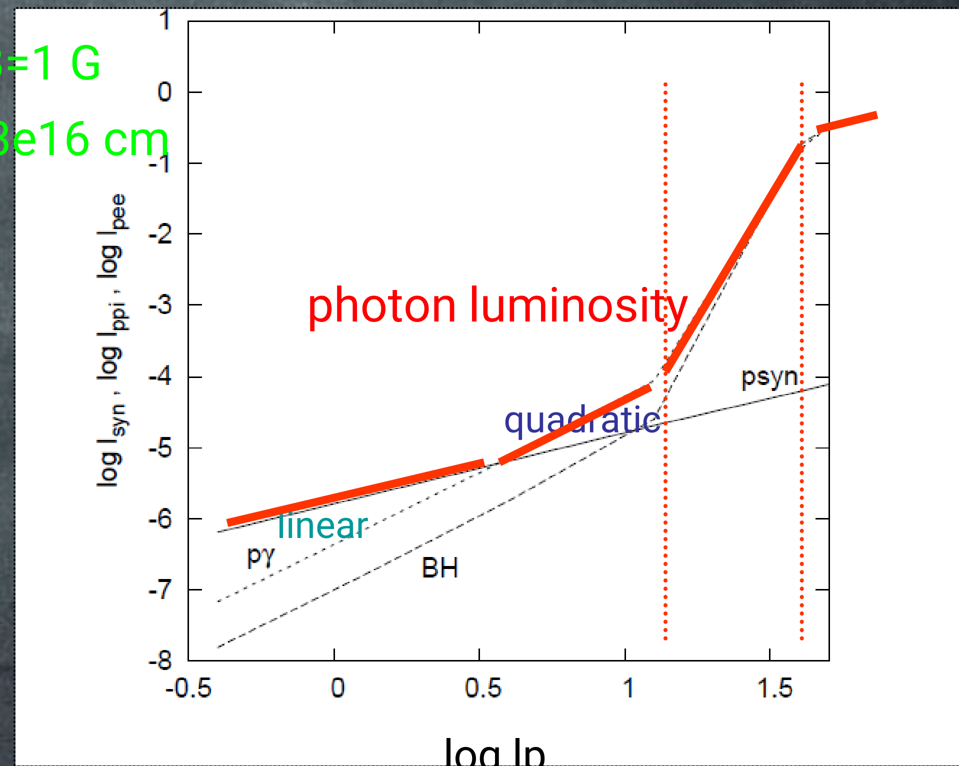
Kirk & AM 1992

INCREASING THE PROTON INJECTED LUMINOSITY



B=1 G

R=3e16 cm

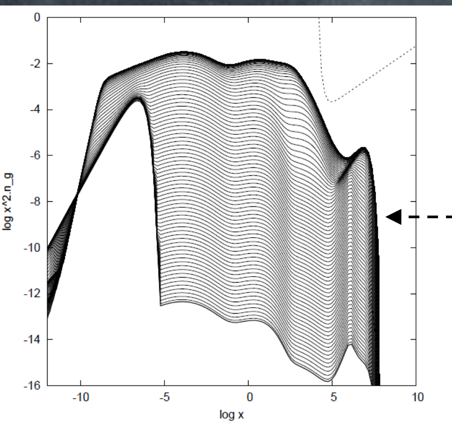


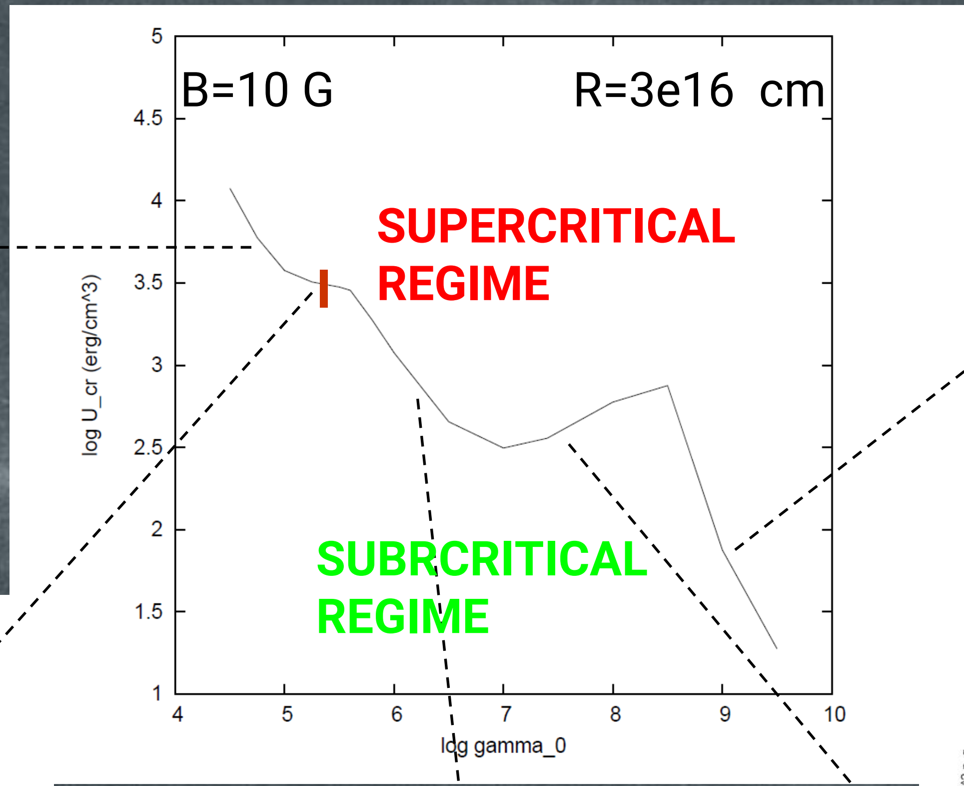
Proton injected luminosity
is increased by a factor 3

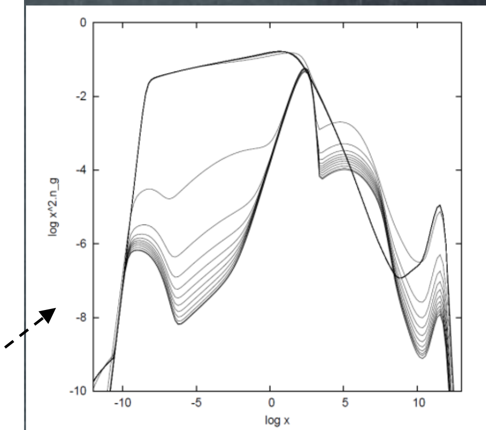
$$L_p = \frac{4\pi R m_p c^3}{\sigma_T}\ell_p.$$

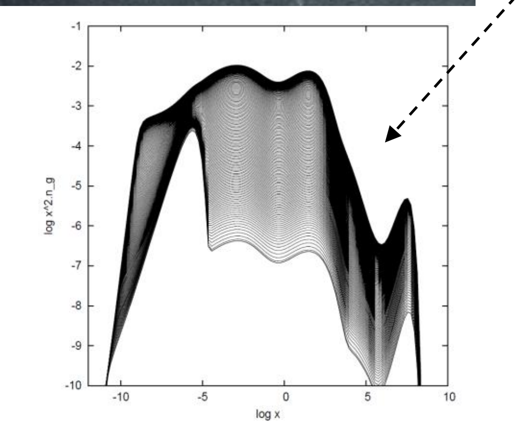
Dimitrakoudis et al. 2012

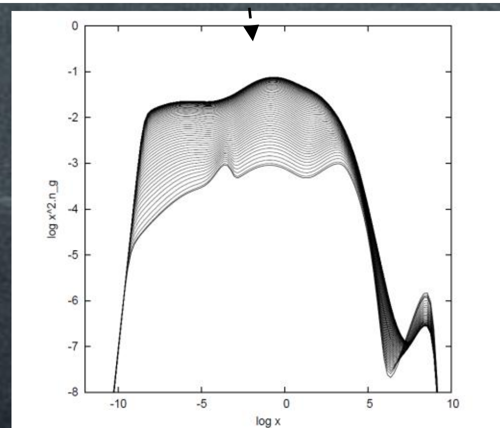
THE STEP TO SUPERCRITICALITY

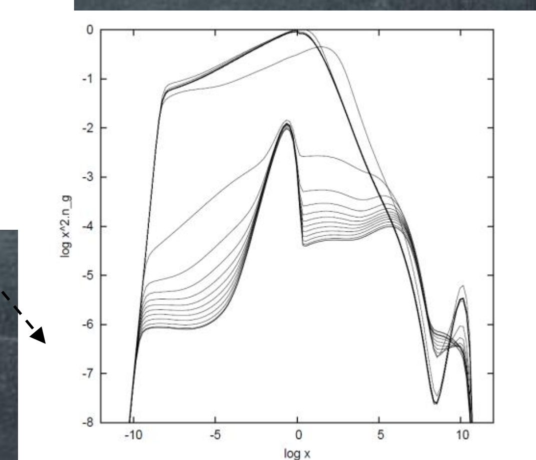












Time-dependent transition of photon spectra from the subcritical to the supercritical regime

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

(Small **Δl→** steady-state to steady-state)

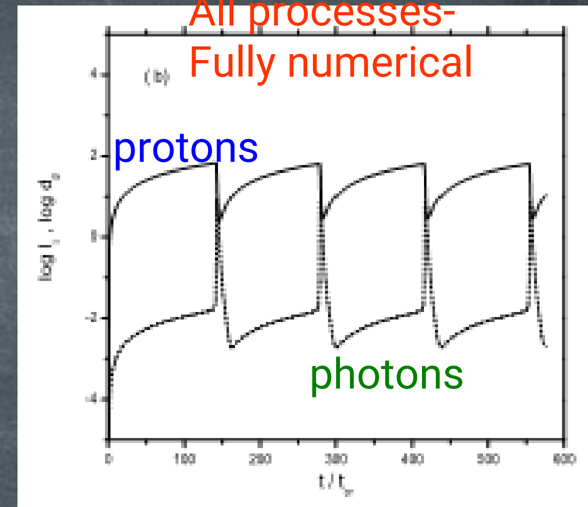
HADRONIC MODELS AS DYNAMICAL SYSTEMS

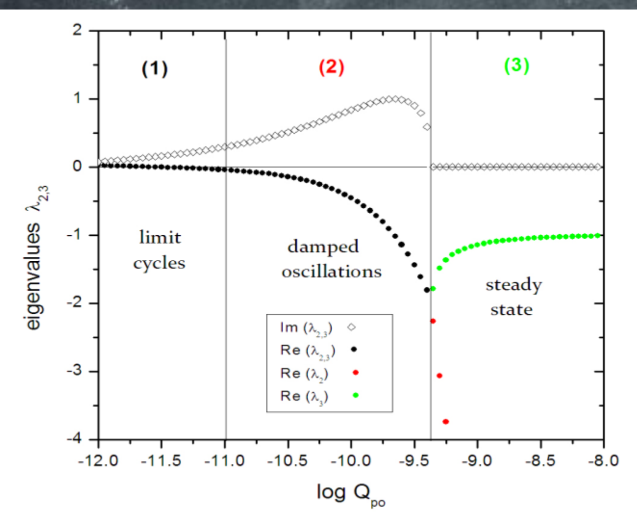
protons
$$\dot{n}_p = -\frac{n_p}{\tau_p} - A n_{ex} n_p - B n_s n_p + Q_o$$

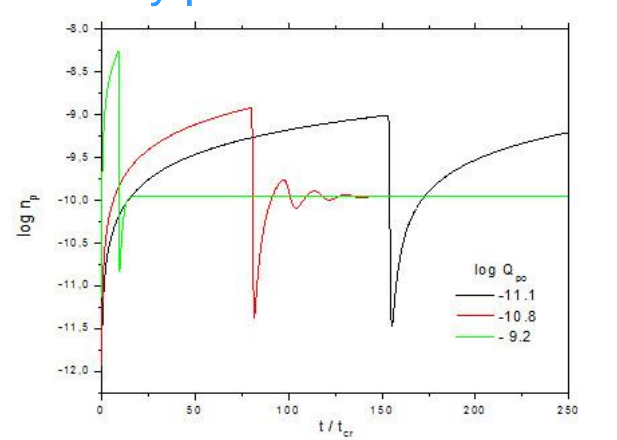
'hard' photons
$$\dot{n}_h = -n_h + \tilde{A} n_{ex} n_p + \tilde{B} n_s n_p - C n_s n_h$$

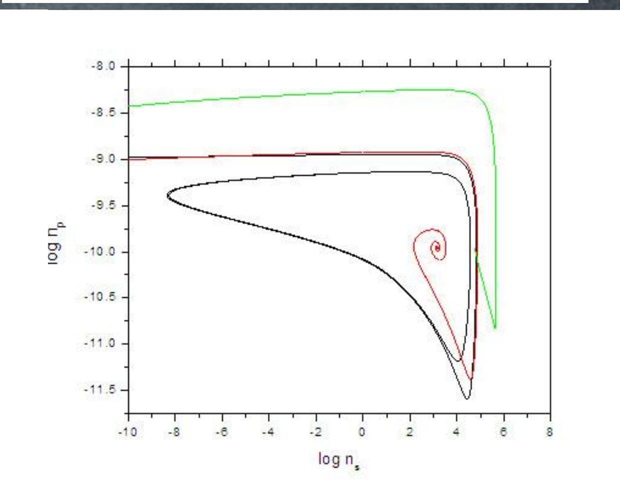
'soft' photons
$$\dot{n}_s = -n_s + \tilde{C} n_s n_h$$

Simplified system - key processes









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

A PROTON SUPERCRITICALITY 'ZOO'

PROTONS → BETHE-HEITLER PAIRS

SYNCHROTRON PHOTONS

ESCAPE

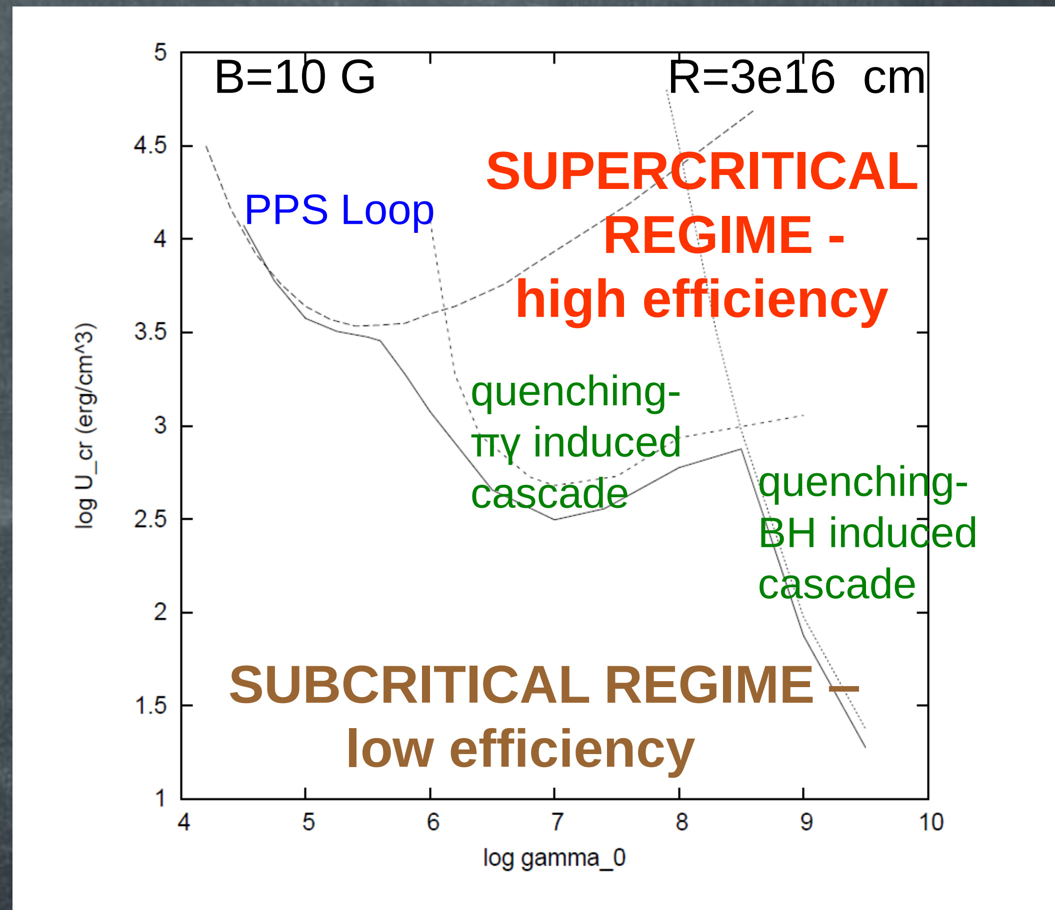
Kirk & AM 1992

PROTONS → GAMMA-RAYS → ESCAPE

AUTOMATICALLY GENERATED SOFT PHOTONS

ESCAPE

Stawarz & Kirk 2007
Petropoulou & AM 2012

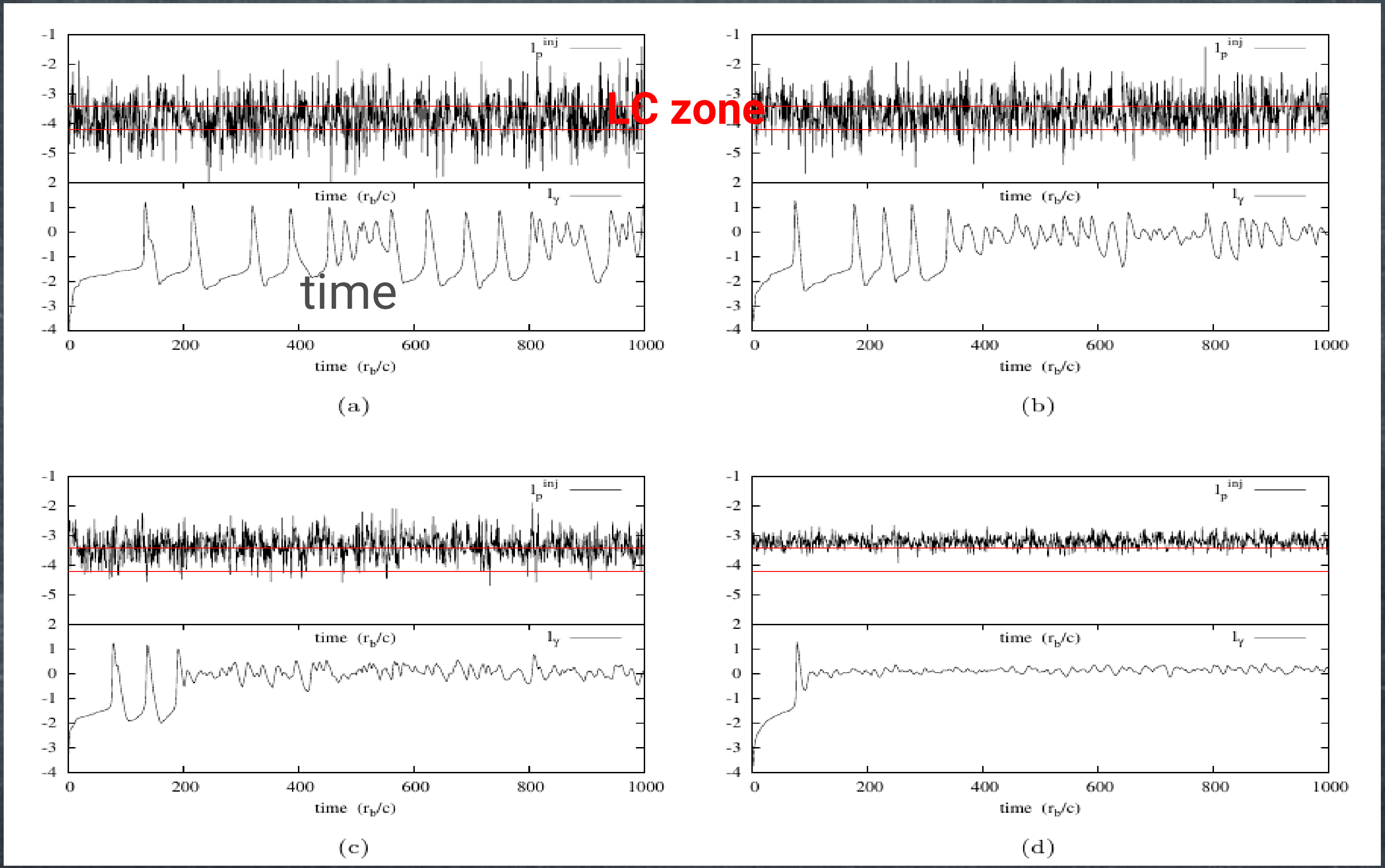


Loops are a way of extracting efficiently energy stored in protons

VARIABLE PROTON INJECTION: FROM SUB-TO SUPER-CRITICAL

proton luminosity

photon luminosity



M. Petropoulou et al. in preparation

CONCLUSIONS

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

Two brands of hadronic 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 MW equally well – LHπ predicts a Bethe-Heitler hump at MeV energies
- Time-variations favour LHπ → X-ray – TeV correlations more natural
- BL Lac - IceCube neutrino events correlations: successful MW fits using the LHπ model of 6 sources → neutrino flux and energy very close to the one measured

• Hadronic systems are dynamical systems → for constant injection either they reach steady state or they show limit cycle behavior of a prey-preadator type (gradual accumulation + explosive release)

• When supercritical → highly efficient

• If varying injection in and out from the supercritical regime→ series of strong, randomly distributed outbursts – more GRB-like behavior than AGN.

HADRONIC MODELS: MYTHS AND FACTS

Myth: Hadronic models are inefficient

Fact: Not always. When in supercritical regime, their efficiency approaches ~1

Myth: Bethe-Heitler pair production can 'safely' be neglected

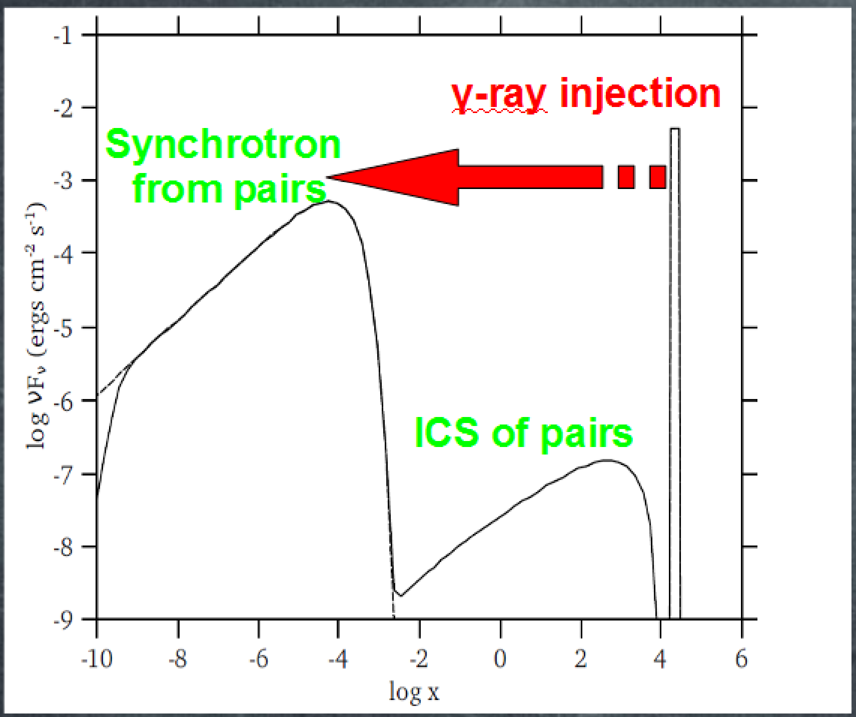
Fact: Even if BH causes smaller losses than photopion, the radiative signature of the pairs appear in distinct spectral regime of the SED.

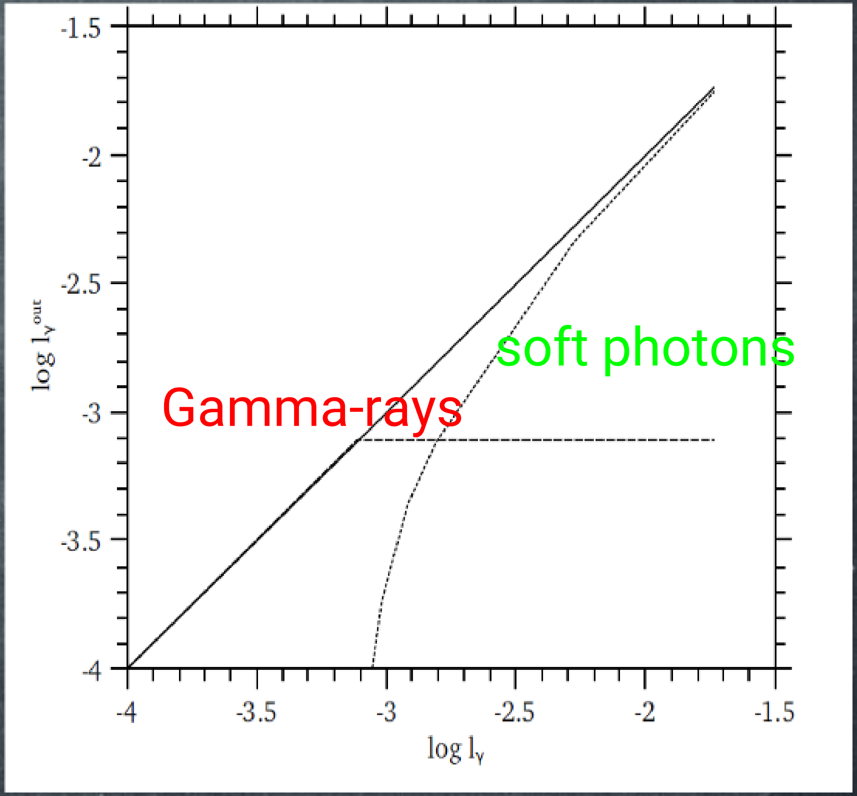
Myth: Use of a 'ready' relativistic proton distribution function to obtain a radiated photon spectrum → SED.

Fact: This approach misses entirely the feedback loops and therefore can lead to erroneous results.

AUTOMATIC GAMMA-RAY QUENCHING

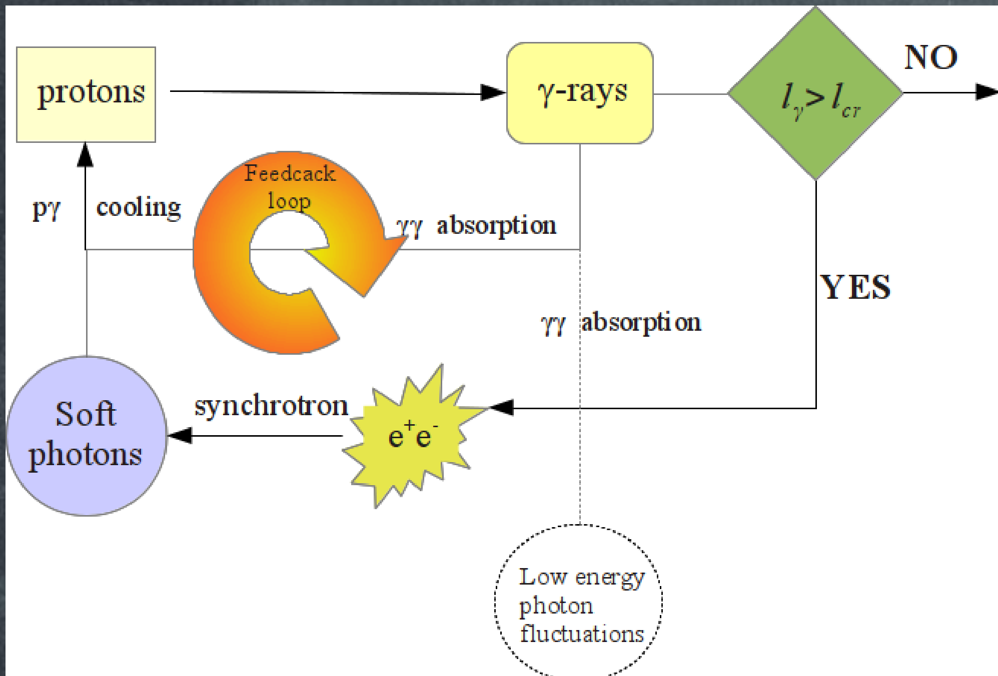
Stawarz & Kirk 2007

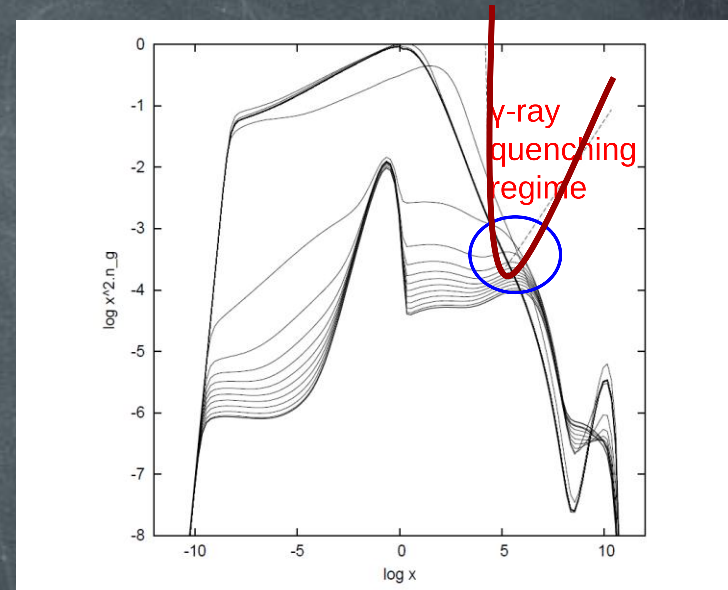


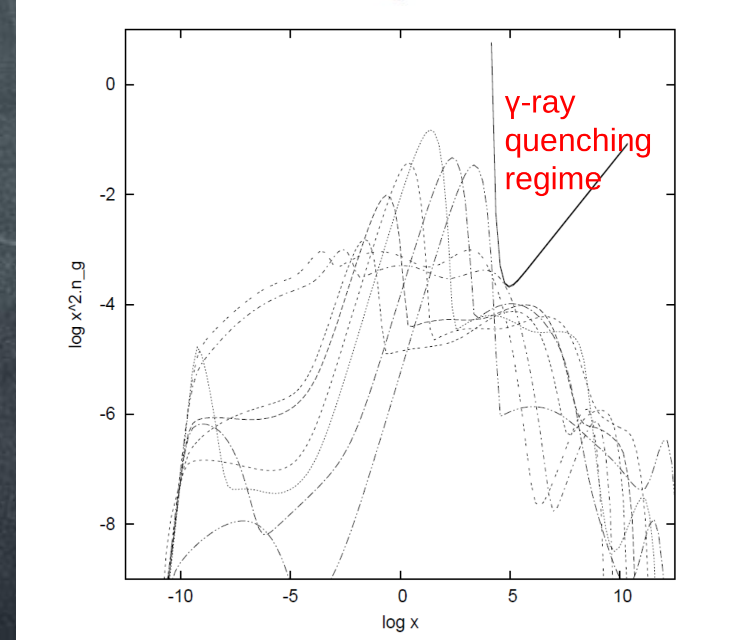


M. Petropoulou & AM 2011

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