PROTON ACCELERATION IN BLAZAR JETS

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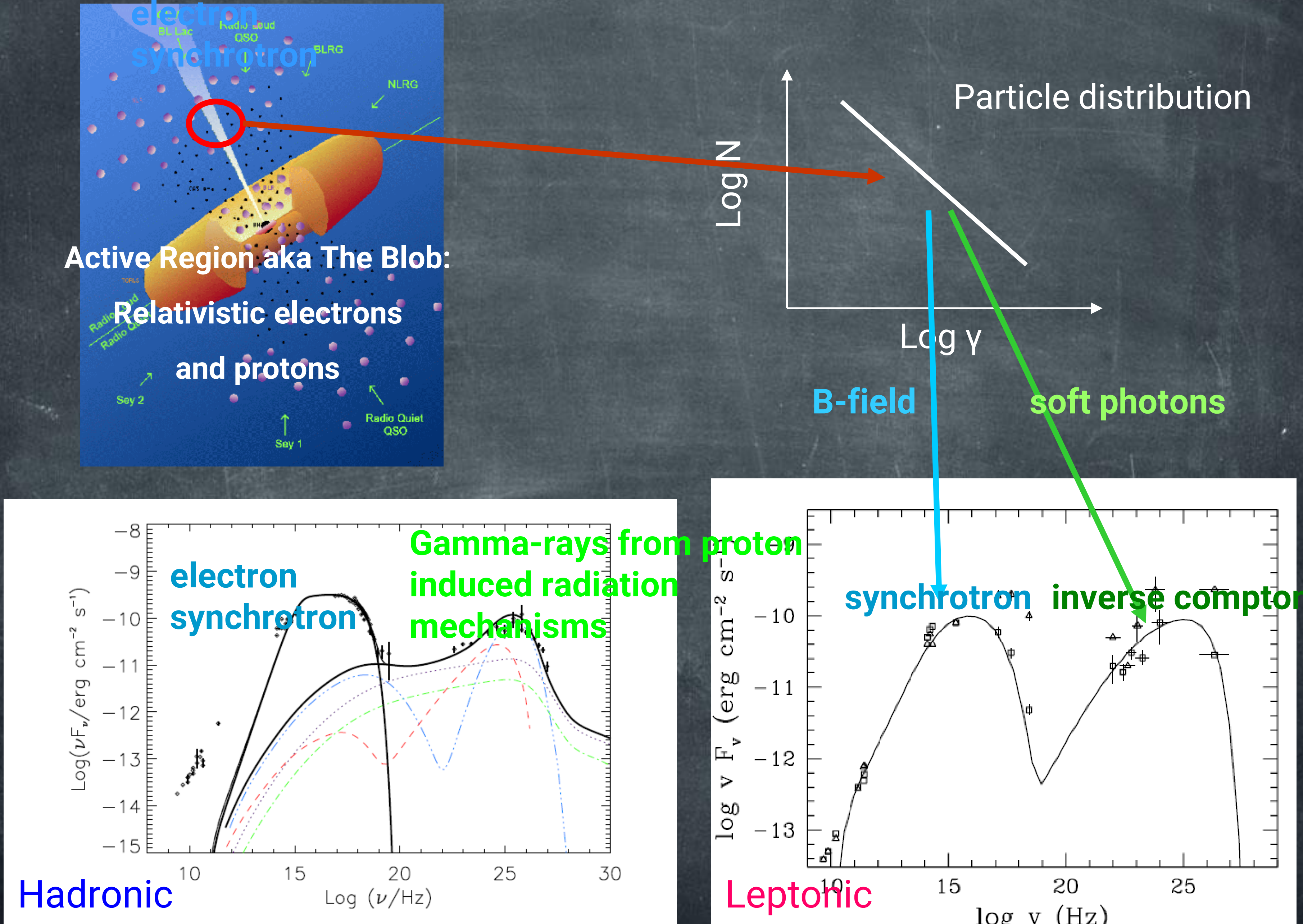
TALK OUTLINE

- Hadronic Models: key ideas and processes
- Multiwavelength fits
- BL Lacs as IceCube neutrino sources
- Jet Energetics
- Box Model for shock acceleration

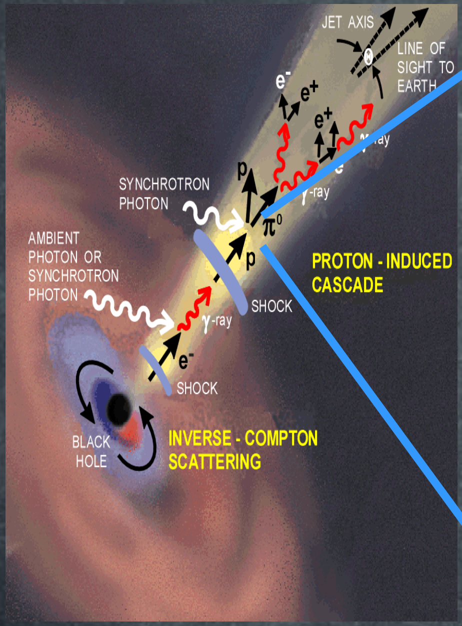
In collaboration with

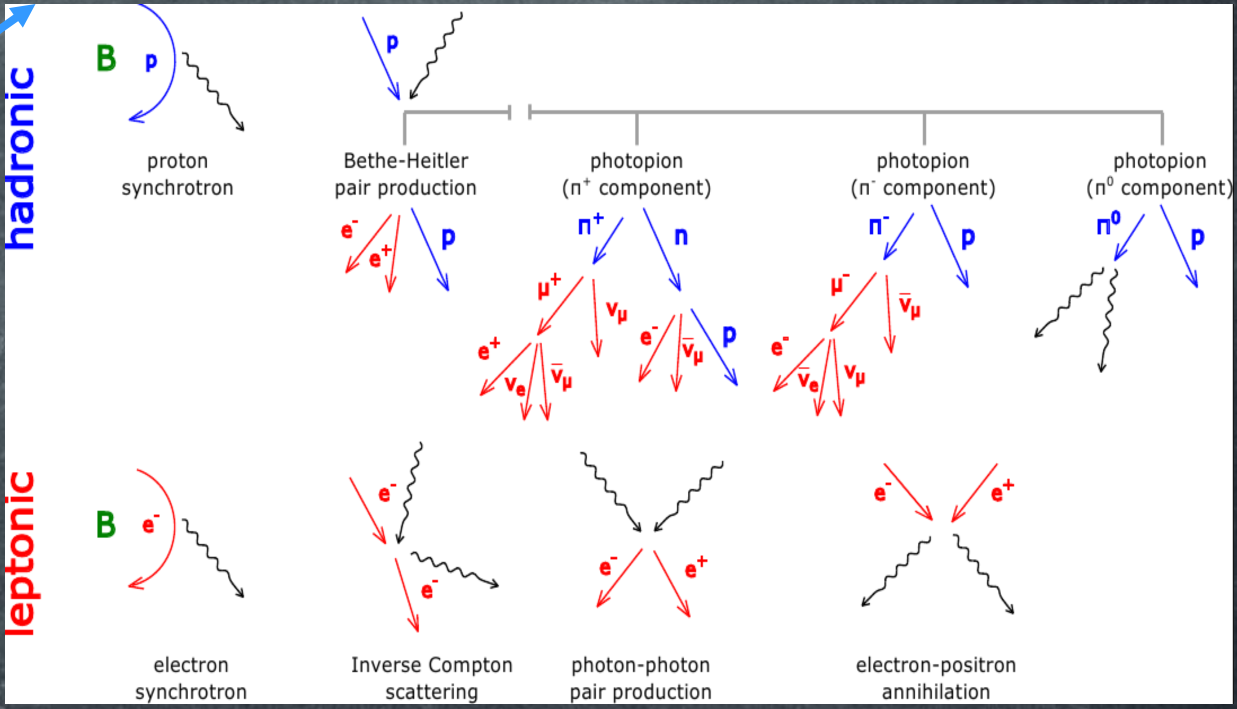
- Maria Petropoulou – *Purdue University (Einstein Fellow)*
- Stavros Dimitrakoudis – *University of Alberta*

MODELS FOR H.E. EMISSION



PHYSICAL PROCESSES





SPECTRAL FORMATION: THREE DIFFERENT APPROACHES

1. Use a 'tailor-made' particle distribution function + textbook emissivities

   - Very good fits

   - Some ad-hoc assumptions (e.g. multiple breaks)

2. Create particle distribution functions from injection rates → kinetic equations

   - Self-consistency (energy conserved)

   - Temporal studies (flaring)

   - Injection rates? (e.g. functional form)

3. Use acceleration scheme → injection rates

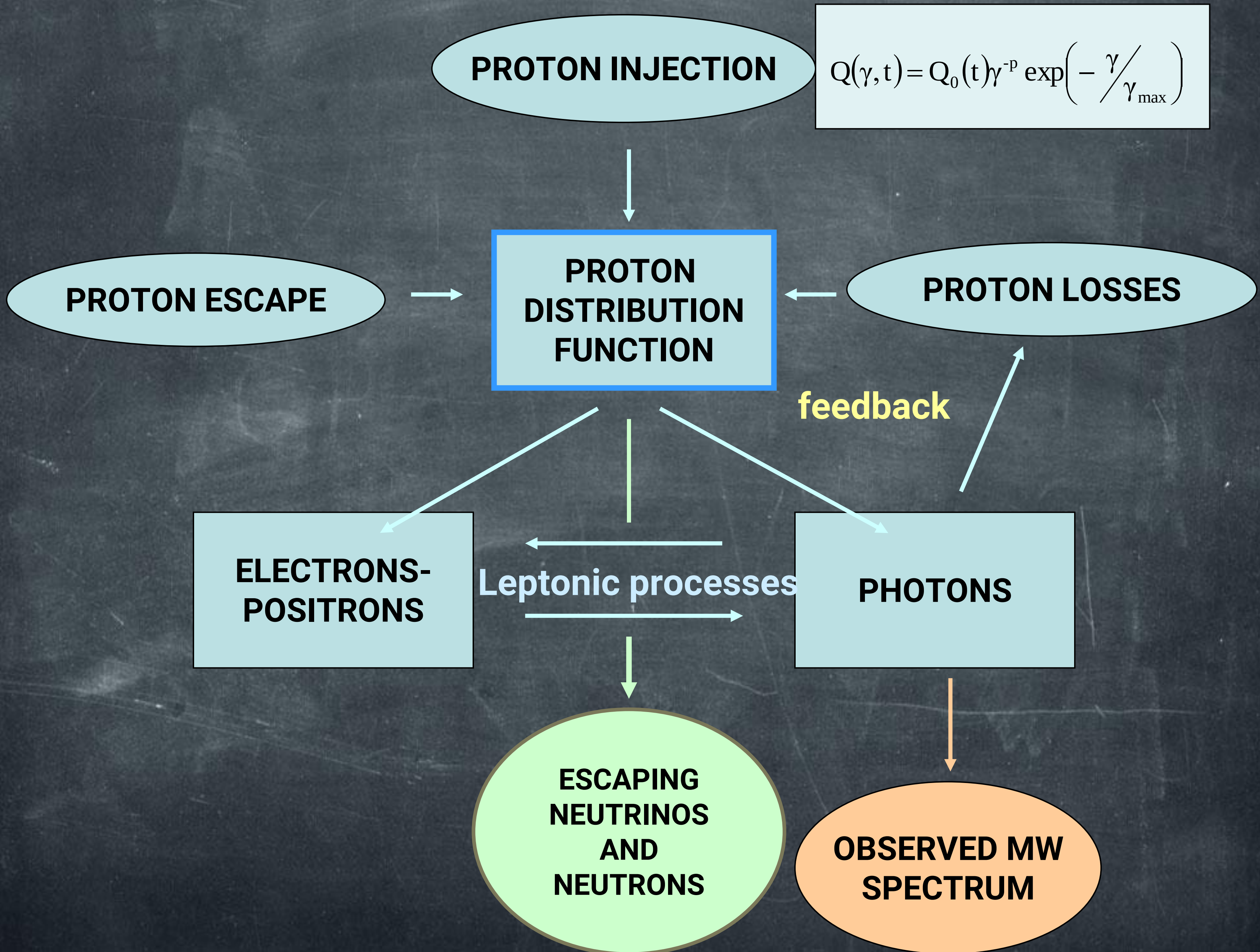
   - More consistency (functional form of injection: power-laws, cutoffs)

   - Simplified acceleration schemes

complexity

Extra complications:

- Radiative transfer?
- Hadronic rates (secondary injection)



PROTON INJECTION
$Q(\gamma,t)=Q_0(t)\gamma^{-p}\exp\left(-\gamma/\gamma_{max}\right)$
PROTON ESCAPE
PROTON DISTRIBUTION FUNCTION
PROTON LOSSES
feedback
ELECTRONS-POSITRONS
Leptonic processes
PHOTONS
ESCAPING NEUTRINOS AND NEUTRONS
OBSERVED MW 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:

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

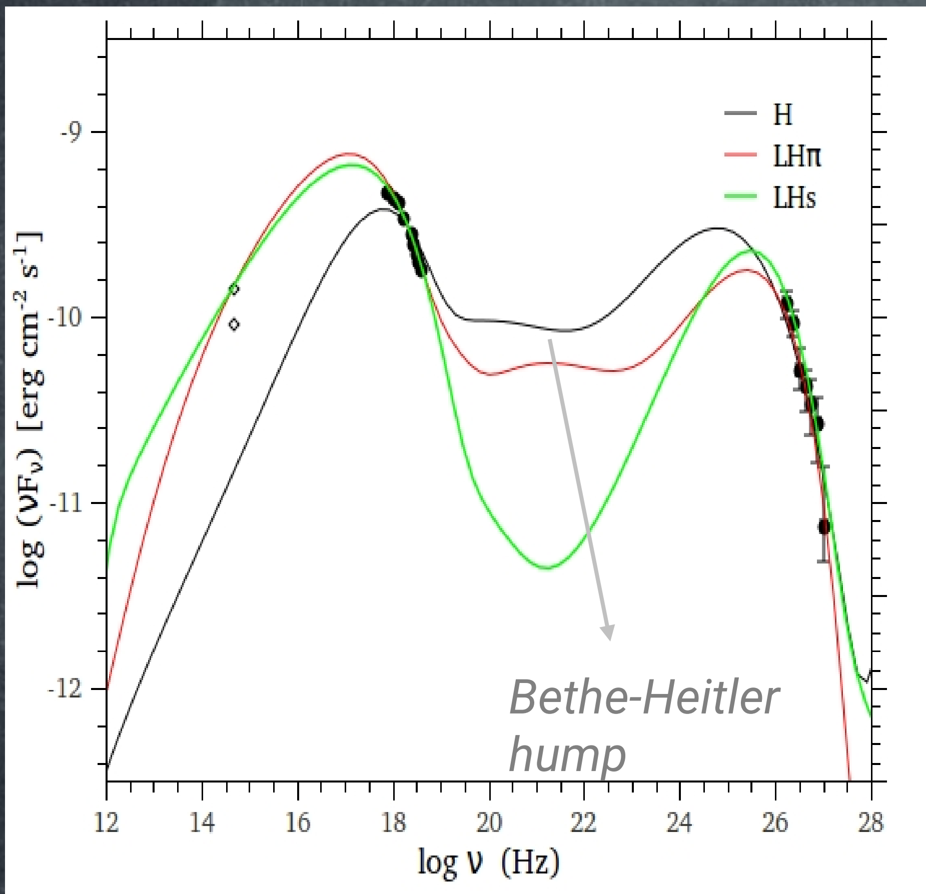
Neutrons:

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

- **Energy conserving scheme**
- **Pion, muon & kaon decay is modeled using results of MC code SOPHIA (Muecke et al. 2000)**
- **Synchrotron cooling of secondaries is also included.**

Dimitrakoudis et al. 2012

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

PHOTOPAIR vs PHOTOPION

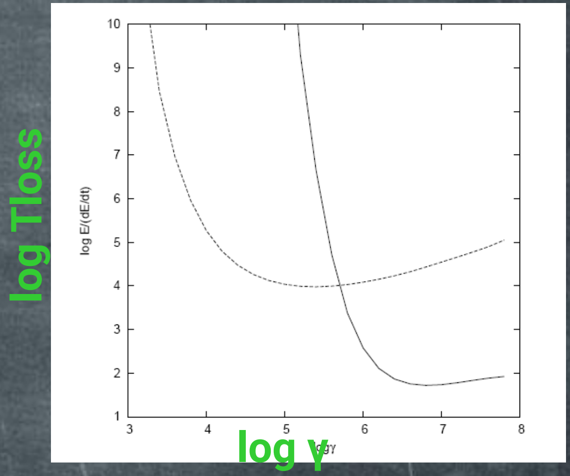
Both processes involve protons and photons

Photopair

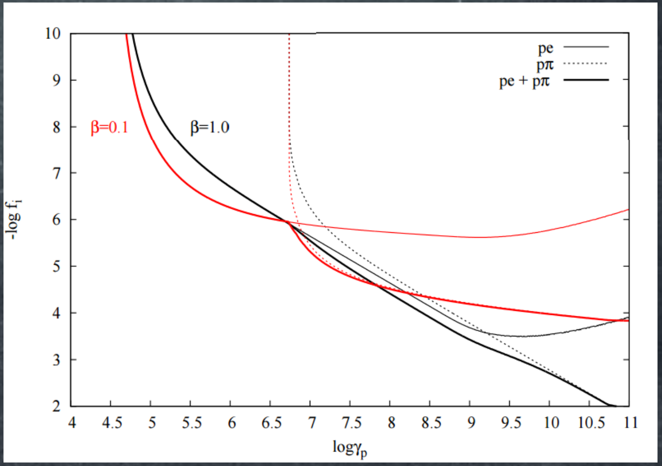
$$N + \gamma_{target} \longrightarrow N + e^{+} + e^{-}$$
$$s^{1/2}_{threshold} = m_p + 2m_e$$

Photopion

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



	photopair	photopion
Threshold (PRF) (MeV)	~1	~140
Cross section (mb)	~10	~0.1
Inelasticity	~0.001	~0.1

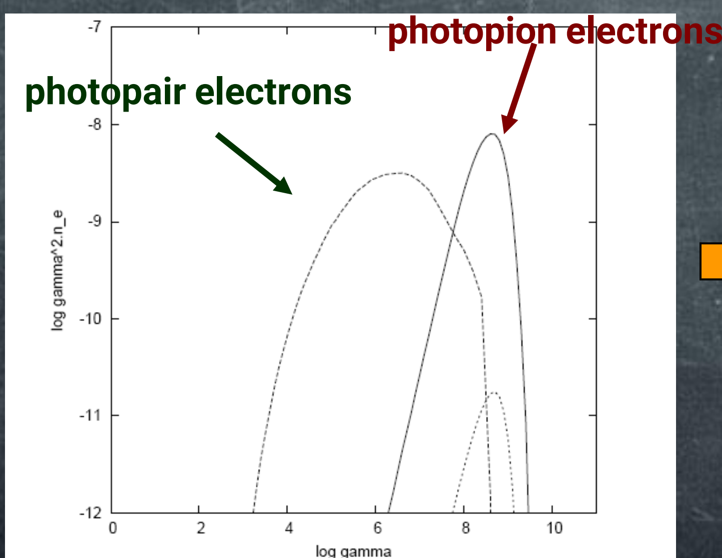


INJECTION OF SECONDARY ELECTRONS - RESULTING PHOTON SPECTRA

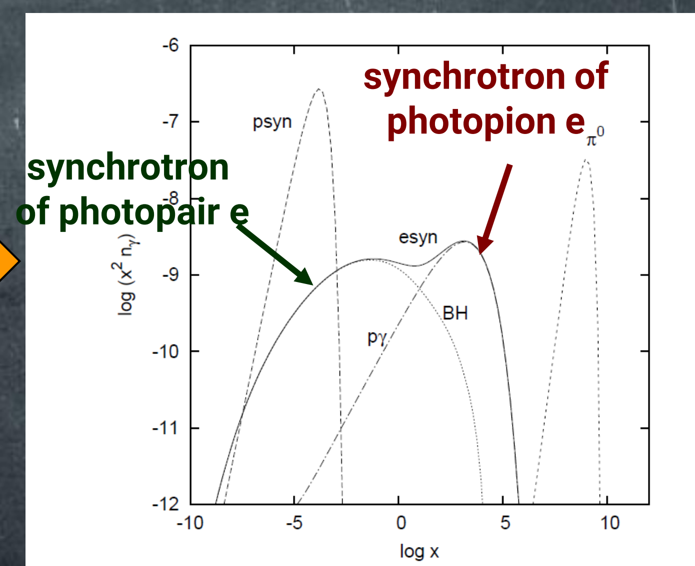
- Energy lost from protons = Energy injected in secondaries
  = Energy radiated in photons
- Photopair injection spectrum different from photopion
  → the two processes have inherently different radiative signatures

A SIMPLE CASE

injected electrons



photons



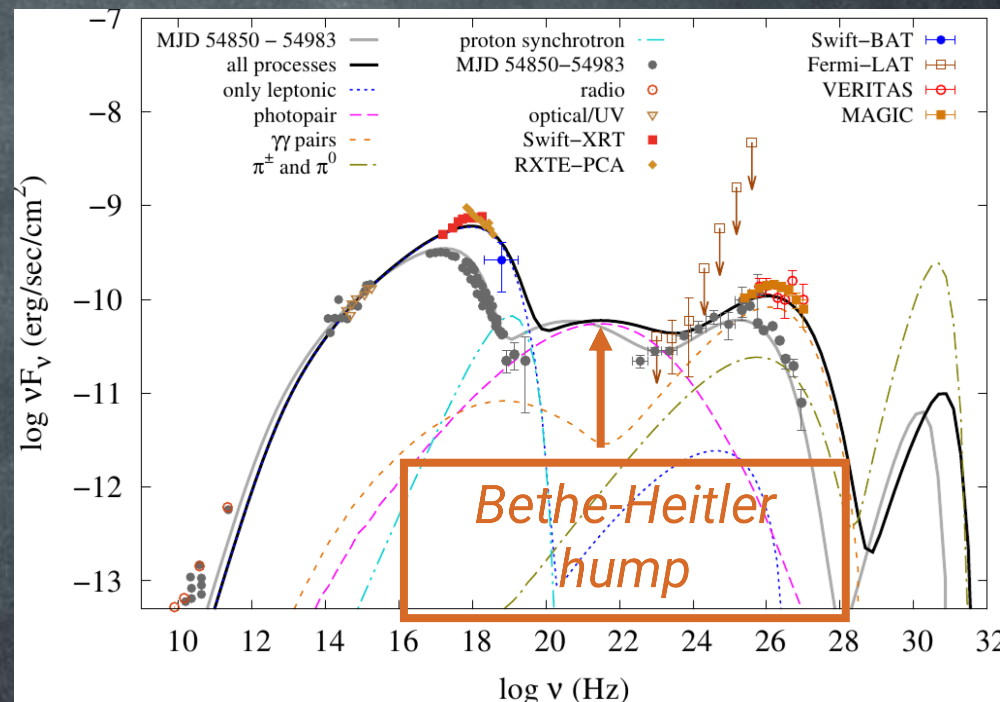
S. Dimitrakoudis et al. 2012

SIGNATURES OF BETHE-HEITLER PAIRS IN MW BLAZAR SPECTRA

LH-π model:
- Radio – X-rays: electrons
- Hard gamma-rays: photopion
- Soft gamma-rays: photopair

If such a feature is ever observed

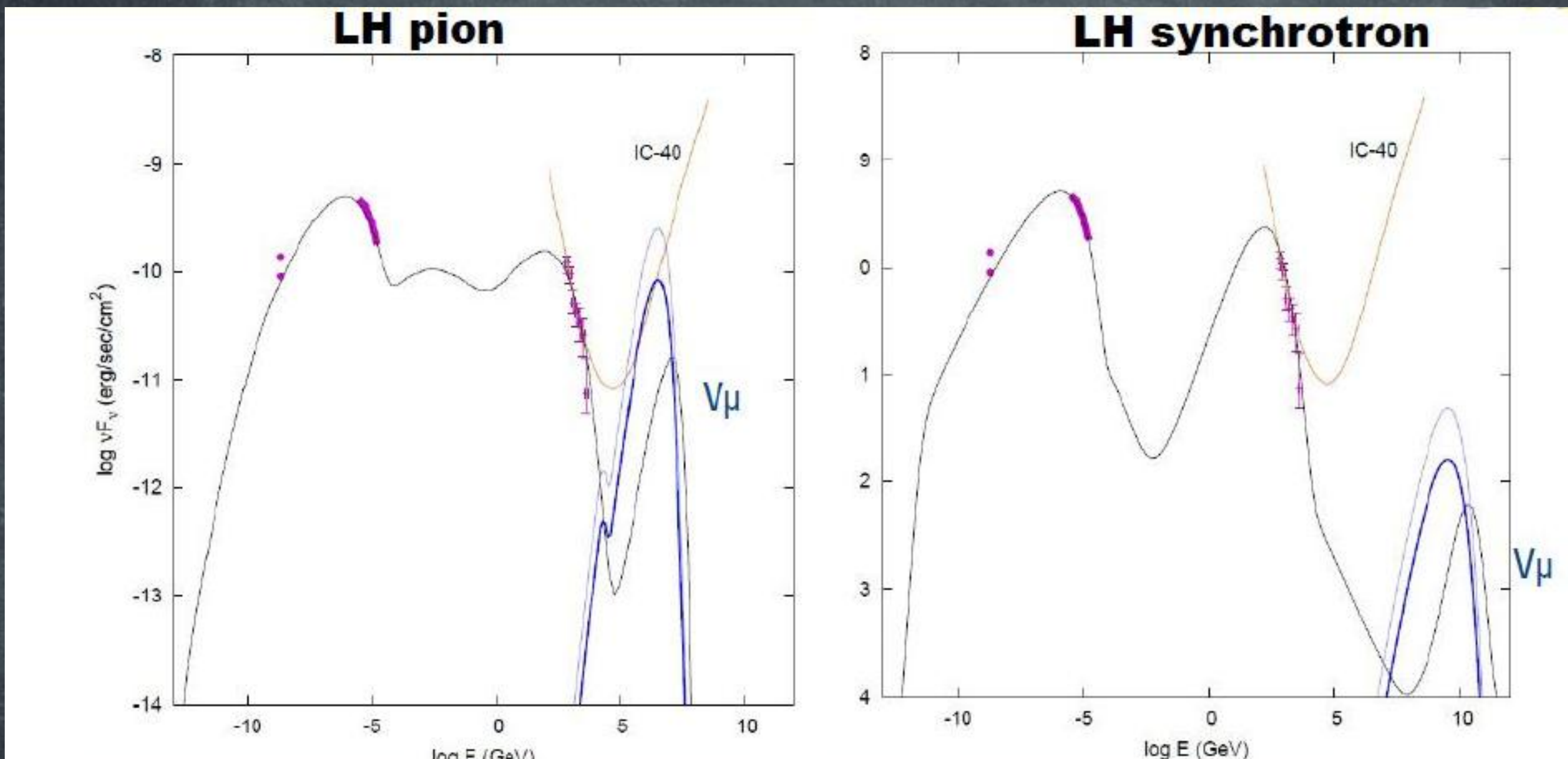
2-20 PeV neutrinos → IceCube



MJD 55265-55277

Petropoulou et al. 2016

MODEL SIGNATURES: NEUTRINO EMISSION



Due to differences in fitting parameters

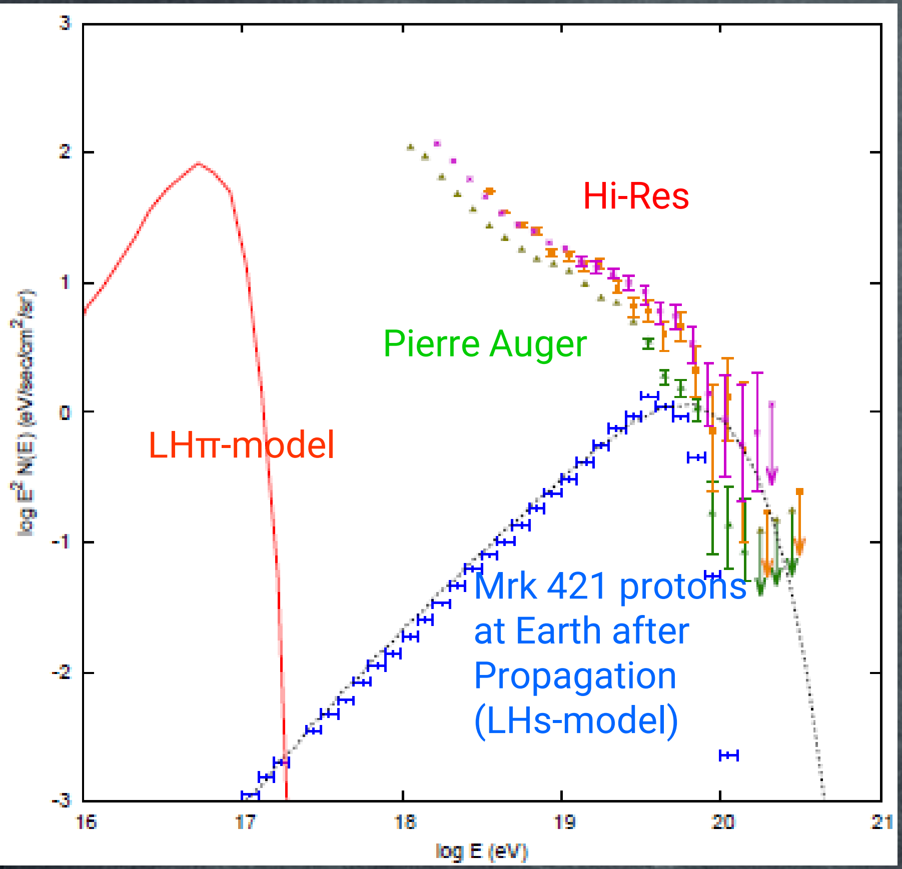
•LHπ model: PeV neutrinos with high flux → **IceCube**

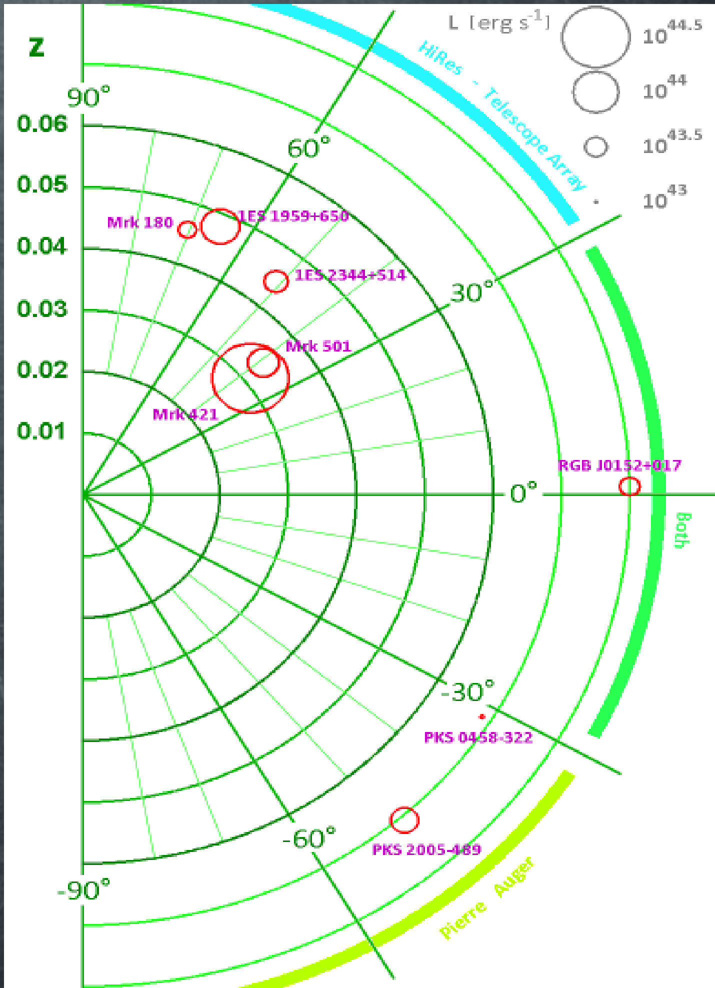
•LHs model: EeV neutrinos with low flux

S. Dimitrakoudis et al. 2014

MODEL SIGNATURES: COSMIC RAYS

Small UHECR contribution from nearby BL Lac objects if similar to Mrk 421
- ➢ Lower luminosities
- ➢ Larger distances





LHs model: Mrk 421 CR peak at ~30 EeV

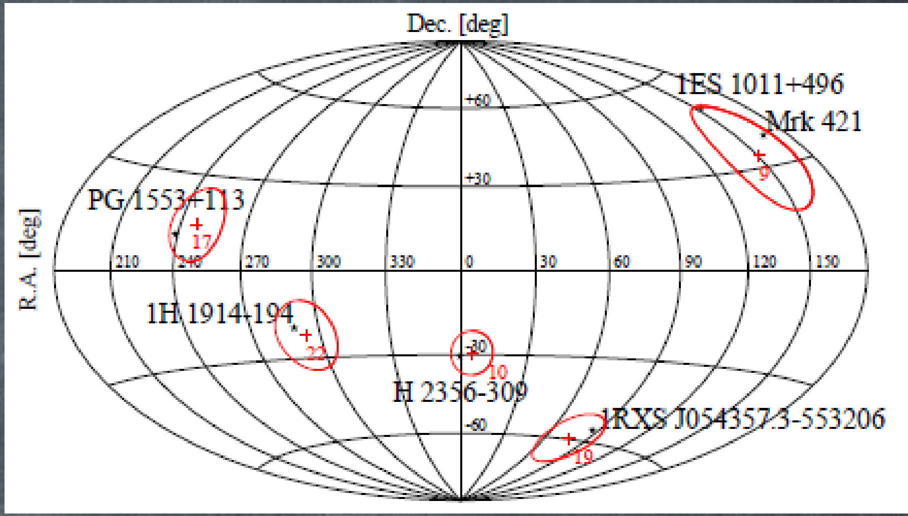
BL Lac – IceCube EVENTS ASSOCIATION?

The facts

- IceCube: 54 events 0.03 – 2 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

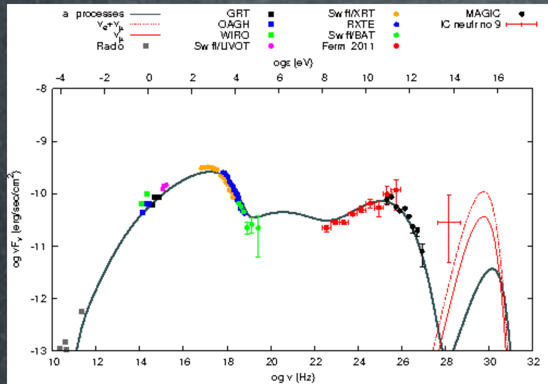
1. Can hadronic models (LHπ) fit the SED of these blazars? *(sources not a-priori selected!)*
2. Is the associated neutrino flux compatible with IceCube detections? *(tailor-made: SED fit → source parameters → neutrino flux)*



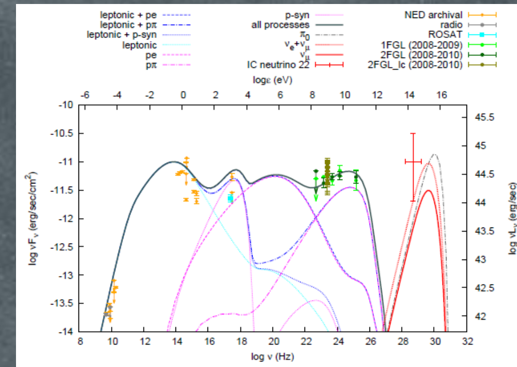
IceCube ID	Counterpart(s)	Class	Catalogue(s)
9	MKN 421	BL Lac (HSP)	TeVCat/WHSP
	1ES 1011+496	BL Lac (HSP)	TeVCat/WHSP
10	H 2356−309	BL Lac (HSP)	TeVCat/WHSP
17	PG 1553+113	BL Lac (HSP)	TeVCat/WHSP
19	1RXS J054357.3−553206	BL Lac (HSP)	WHSP
20	SUMSS J014347−584550	BL Lac (HSP)	WHSP
22	1H 1914−194	BL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

Padovani & Resconi 2014

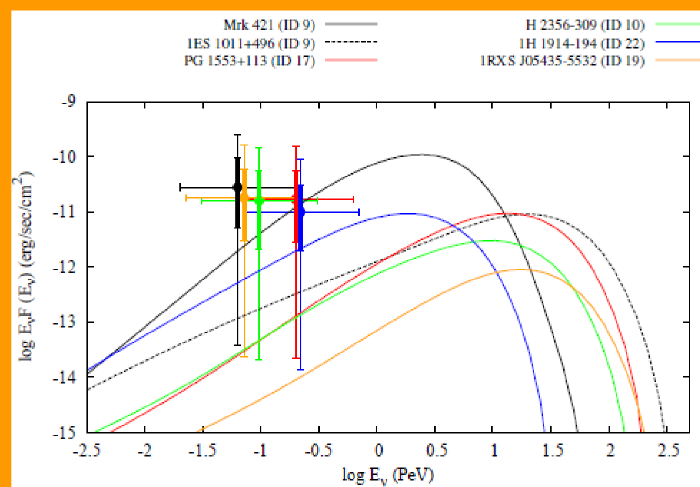
Talk of P. Padovani

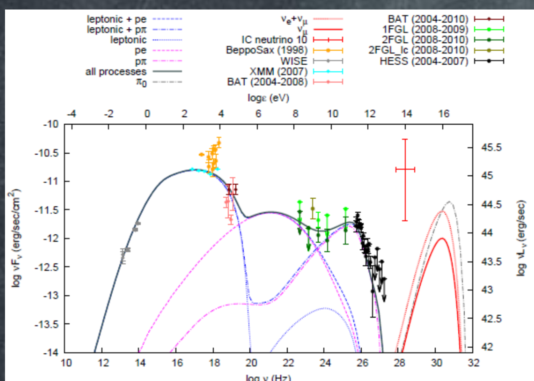


Mrk 421

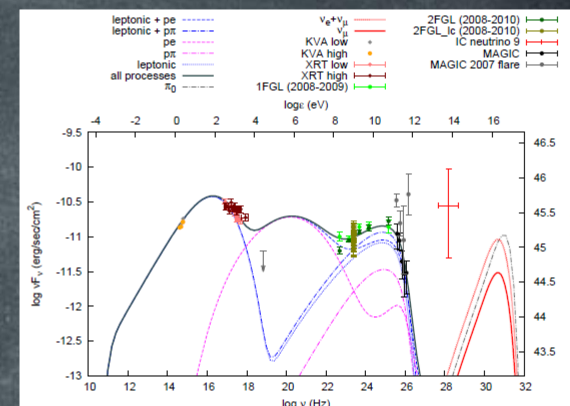


H 1914-194

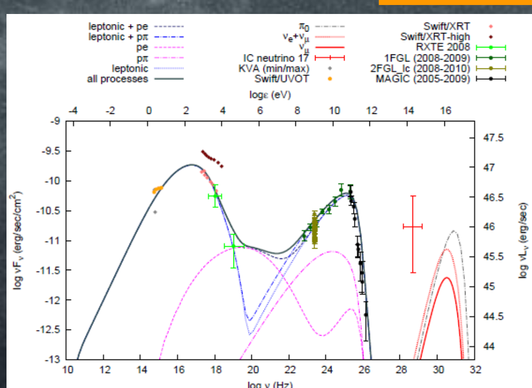




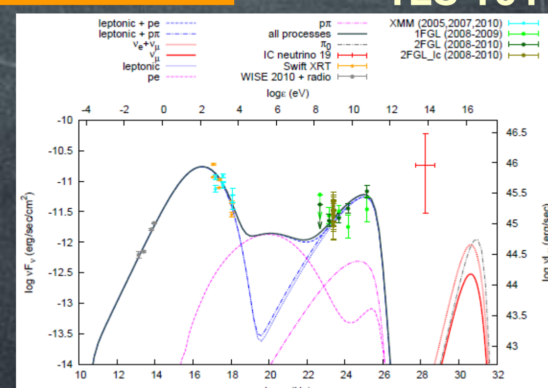
H 2356-309



1ES 1011+496



PG 1553+113



1 RXS J054357.3-553206

Petropoulou et al 2015

OVERALL ENERGETICS

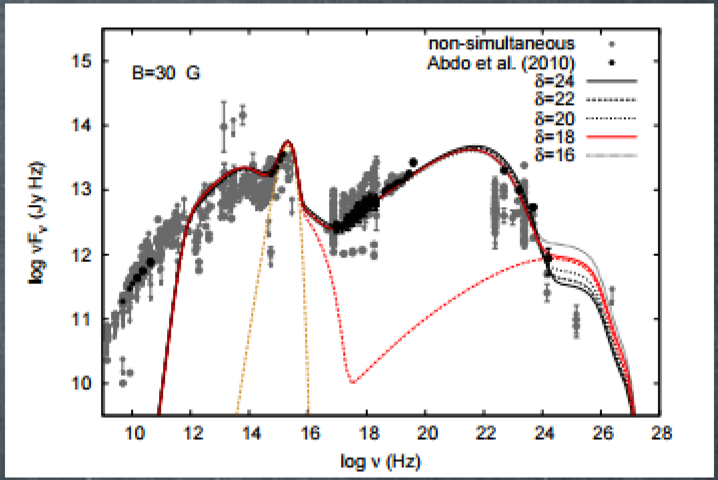
- Simple one-zone synchrotron hadronic fits can be degenerate → different sets of parameters give same fits.
- Minimize the power (similar to equipartition arguments in radio sources with gamma-rays replacing radio and protons replacing electrons) (*Petropoulou & AM 2012*)

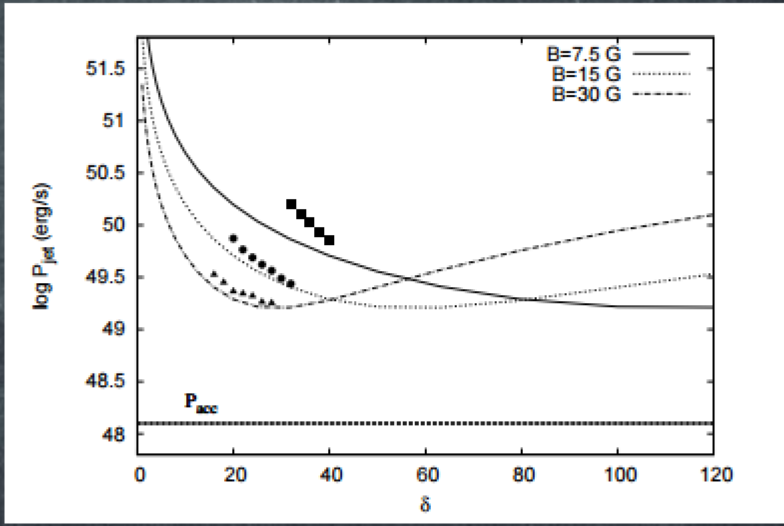
$$P_{jet} \approx \pi R^2 \Gamma^2 c(u_p + u_B)$$

$$P_{jet} \approx \pi R^2 c\left[A(\delta.B)^{-3/2} + \frac{(\delta.B)^2}{8\pi}\right]$$

$$\frac{dP_{jet}}{dB} = 0 \Rightarrow P_{jet,min} \text{ for } \delta.B = C$$

3C273





Petropoulou & Dimitrakoudis 2015

A PARADIGM: BOX-MODEL FOR PARTICLE ACCELERATION

$$\frac{\partial N}{\partial t} + \frac{\partial}{\partial E}\left(r_{acc} E N - \alpha_s E^2 N\right) = Q - r_{esc} N$$

acceleration

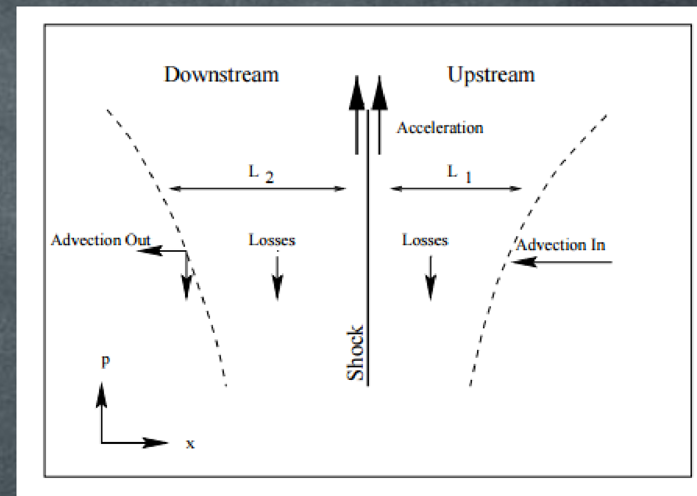
energy loss

escape

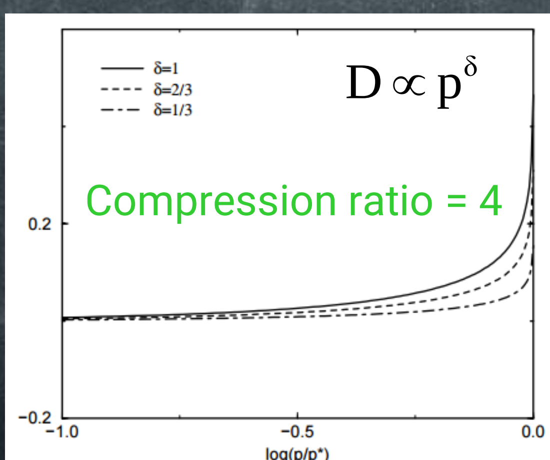
particle injection
at low momenta

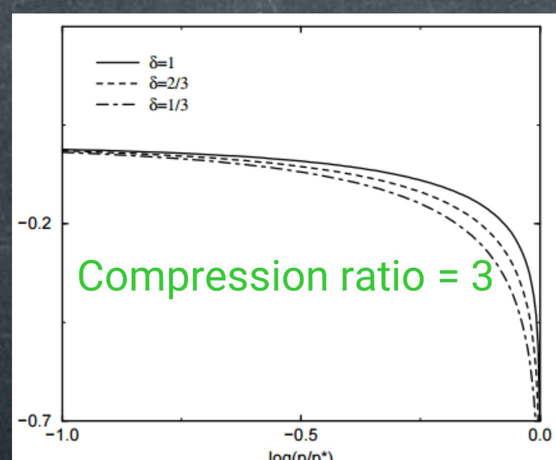
$$r_{acc} = \frac{\vec{n}.\left(\vec{\upsilon}_1 - \vec{\upsilon}_2\right)}{3L}$$

$$r_{esc} = \frac{\vec{n}.\vec{\upsilon}_2}{L}$$



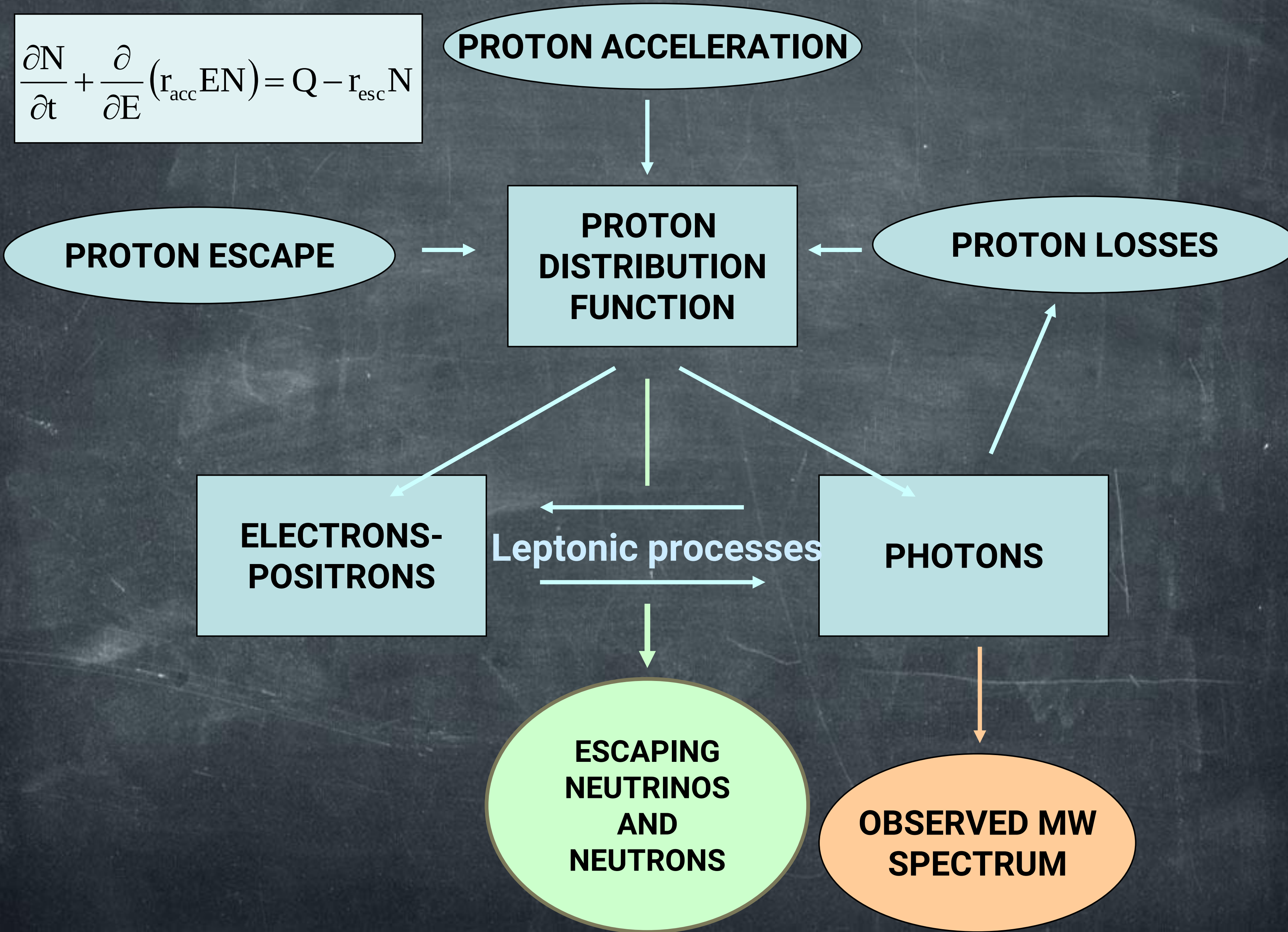
Drury et al. 1999





Particle distribution
up to a max energy
where Tacc=Tloss.
Shape of cutoff
not *a-priori* assumed
(obtained shape
non-trivial, *e.g.* pile-ups)

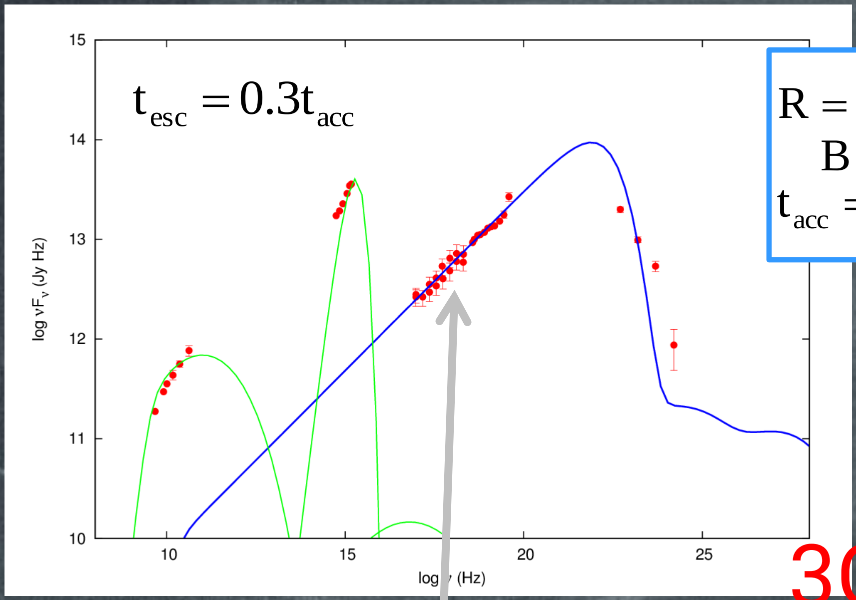
$$\frac{\partial N}{\partial t} + \frac{\partial}{\partial E}\left(r_{acc} E N\right) = Q - r_{esc} N$$

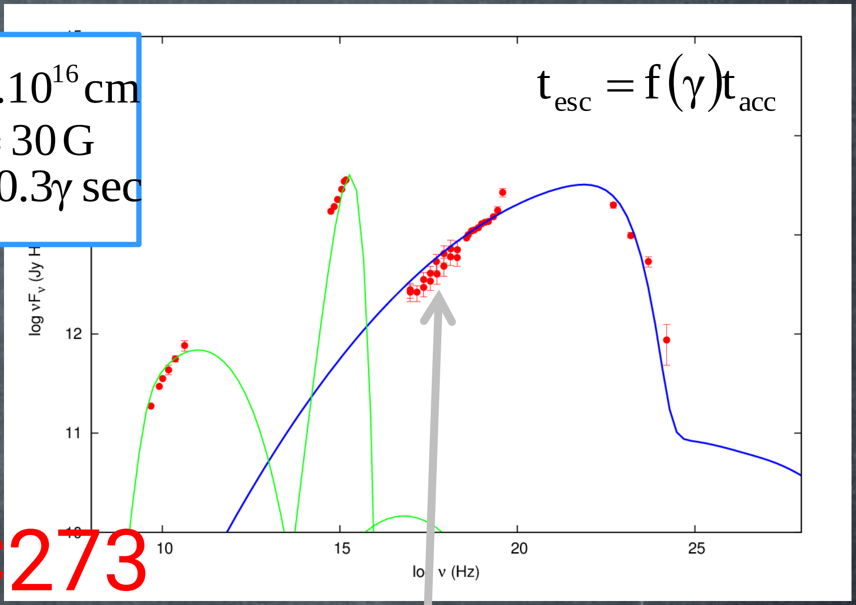


Standard box model

Modified box model

$$R = 3.10^{16}\,\mathrm{cm}$$
$$B = 30\,\mathrm{G}$$
$$t_{acc} = 0.3\gamma\ \mathrm{sec}$$





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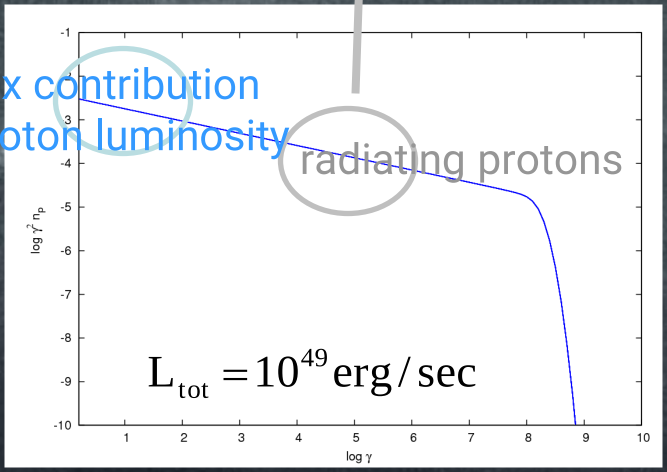
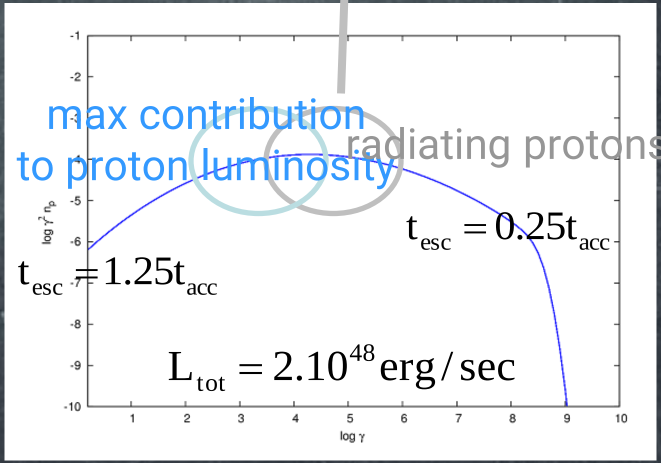




CONCLUSIONS

- One-zone hadronic model
  - Accurate secondary injection (photopion + Bethe Heitler)
  - Time dependent - energy conserving PDE 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 acceleration to higher proton energies)
- Both fit MW equally well – LHπ predicts a Bethe-Heitler hump at MeV energies
- 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
- Overall energetics: High energy requirements somehow relaxed with equipartition

Box model for shock acceleration: Acceptable fits for 'standard' values.

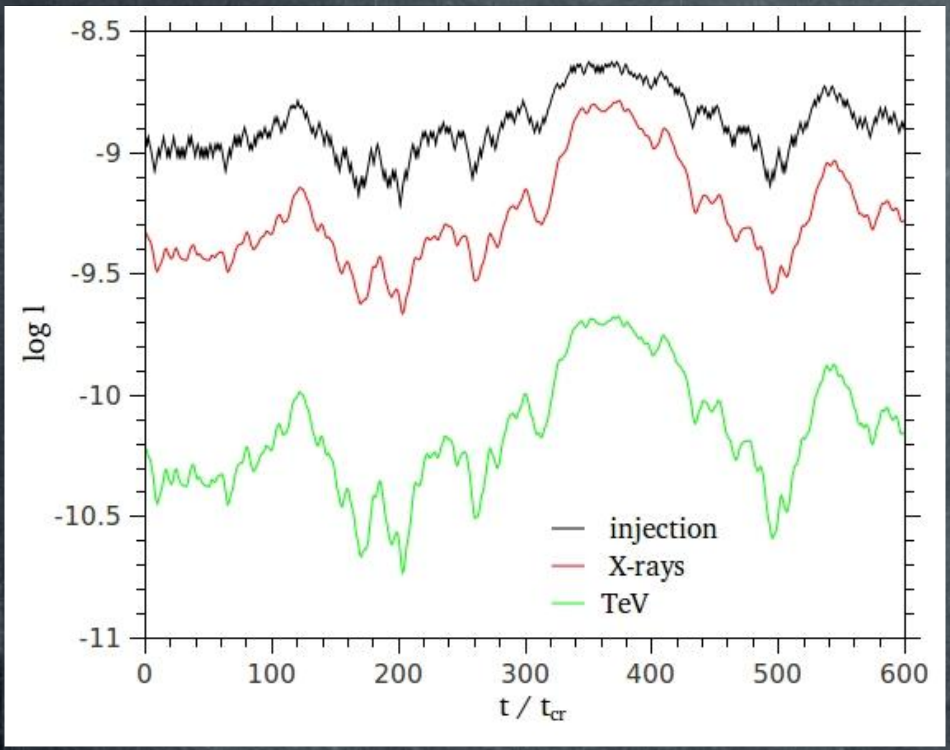
If tacc/tesc not constant but a (weak) function of energy:

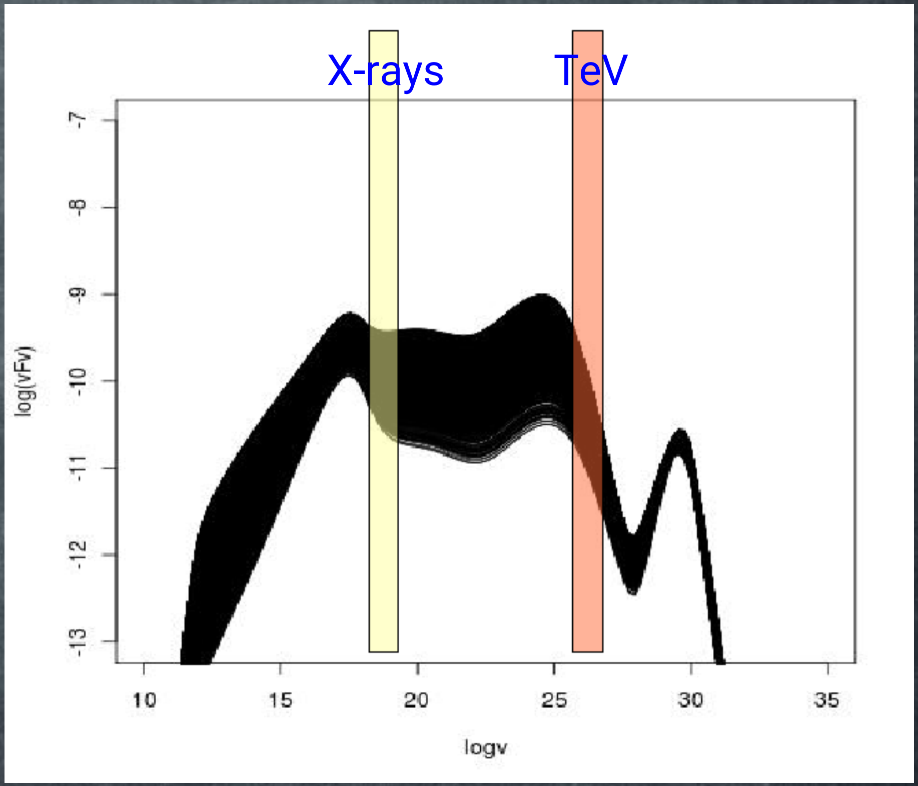
- Good fits to observations + more relaxed energy requirements

BACK UP SLIDES

VARYING THE INJECTION LUMINOSITY

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

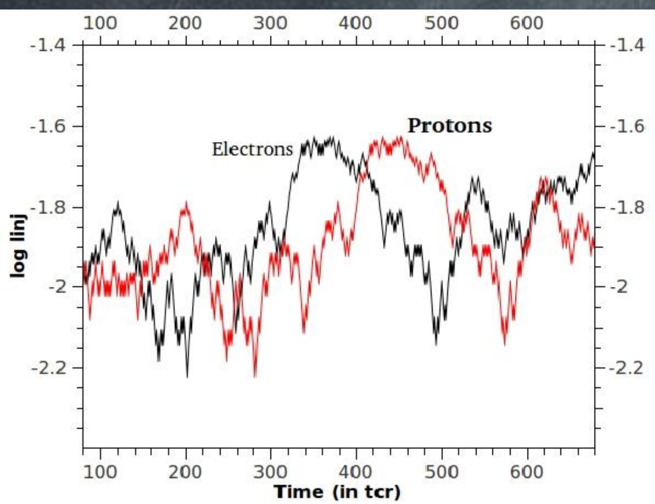


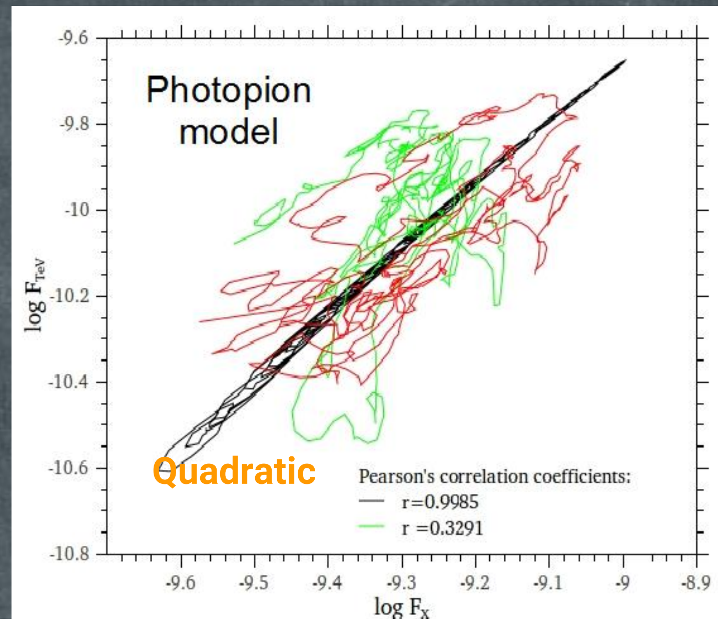


Injection and spectra when p and e totally correlated

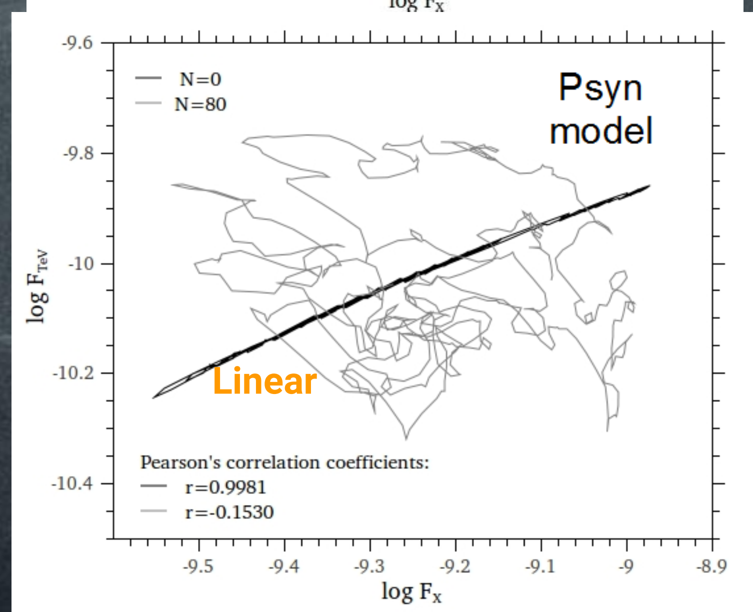
PHOTOPION vs P-SYN: TIME VARIATIONS

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.