TIME-DEPENDENT LEPTOHADRONIC MODELS OF AGN: APPLICATION TO Mrk 421

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- Leptonic models: ~20 yrs old and still going strong (SED, variability)
- Hadronic models: More complicated – less understood
  - Can they fit SEDs?
  - Time variability?
  - Bonus: UHECR and v production
- Judgement Day: MW campaigns, cross-correlations

  Has it started already? See Poster #41

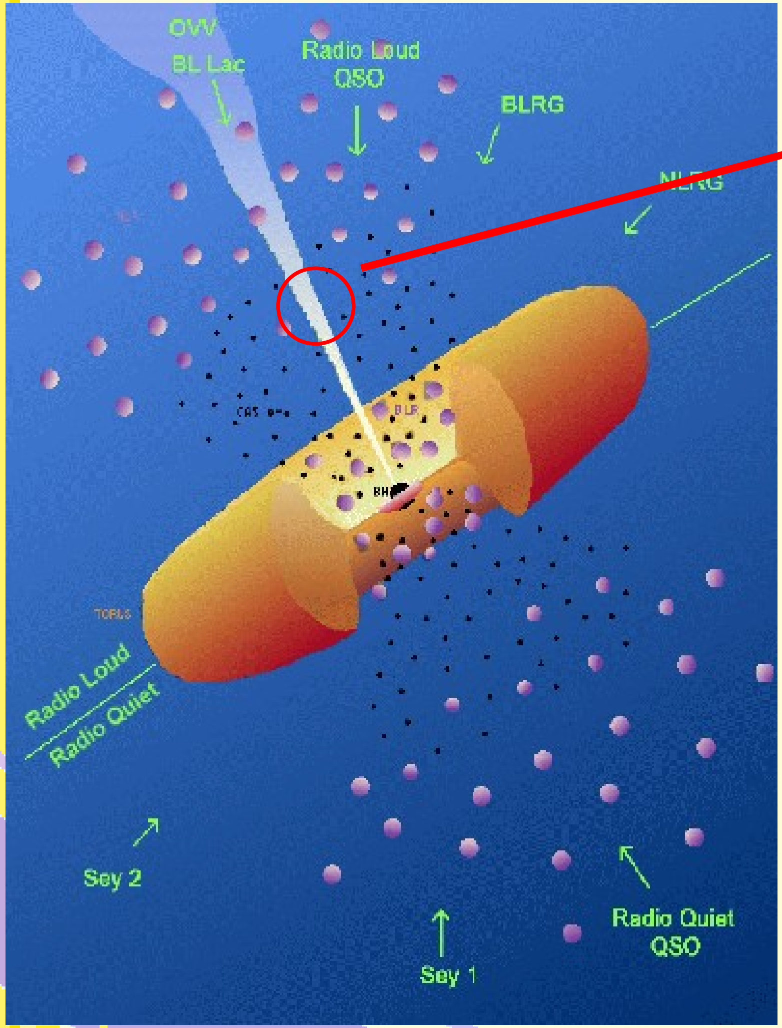
TALK OUTLINE

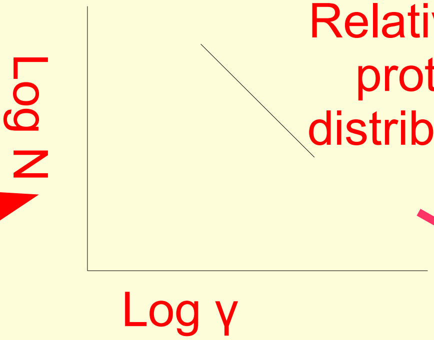
- Leptohadronic Models: key ideas and processes
- Application to Mrk 421
  - SED and variability signatures
  - Neutrino and neutron emission

In collaboration with
Stavros Dimitrakoudis
Maria Petropoulou

SED OF BLAZARS - LEPTOHADRONIC MODELS

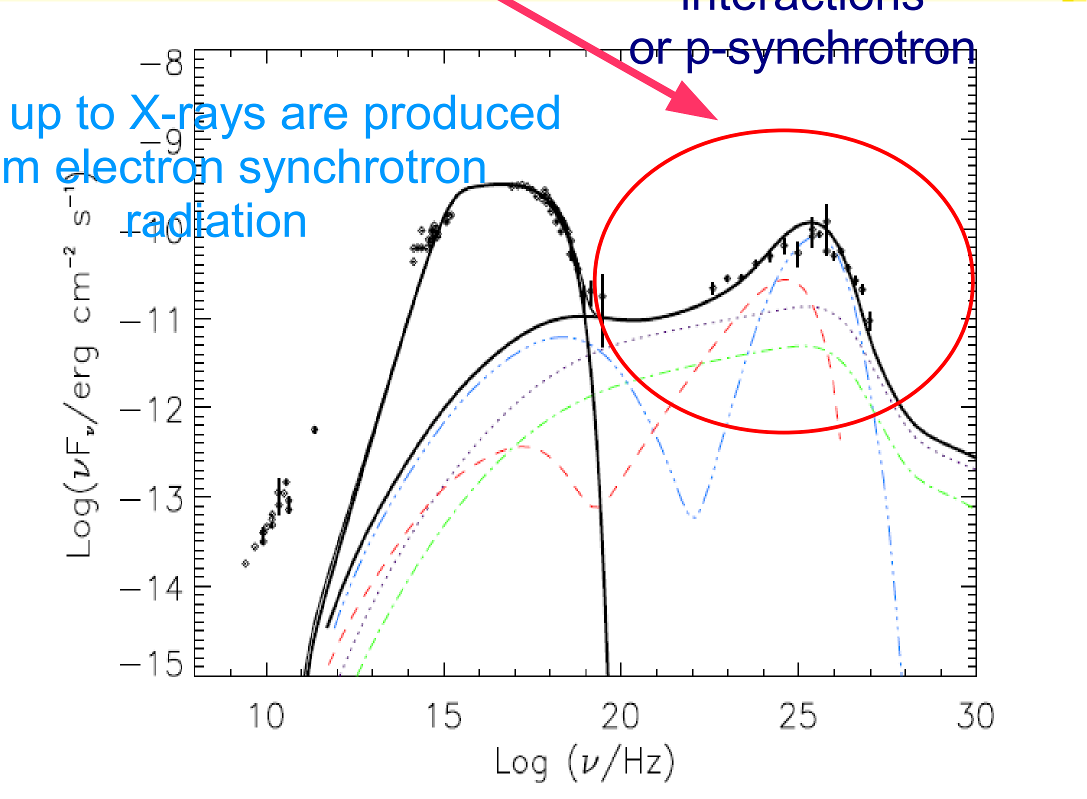
cf. M. Boettcher & M. Weidinger talks





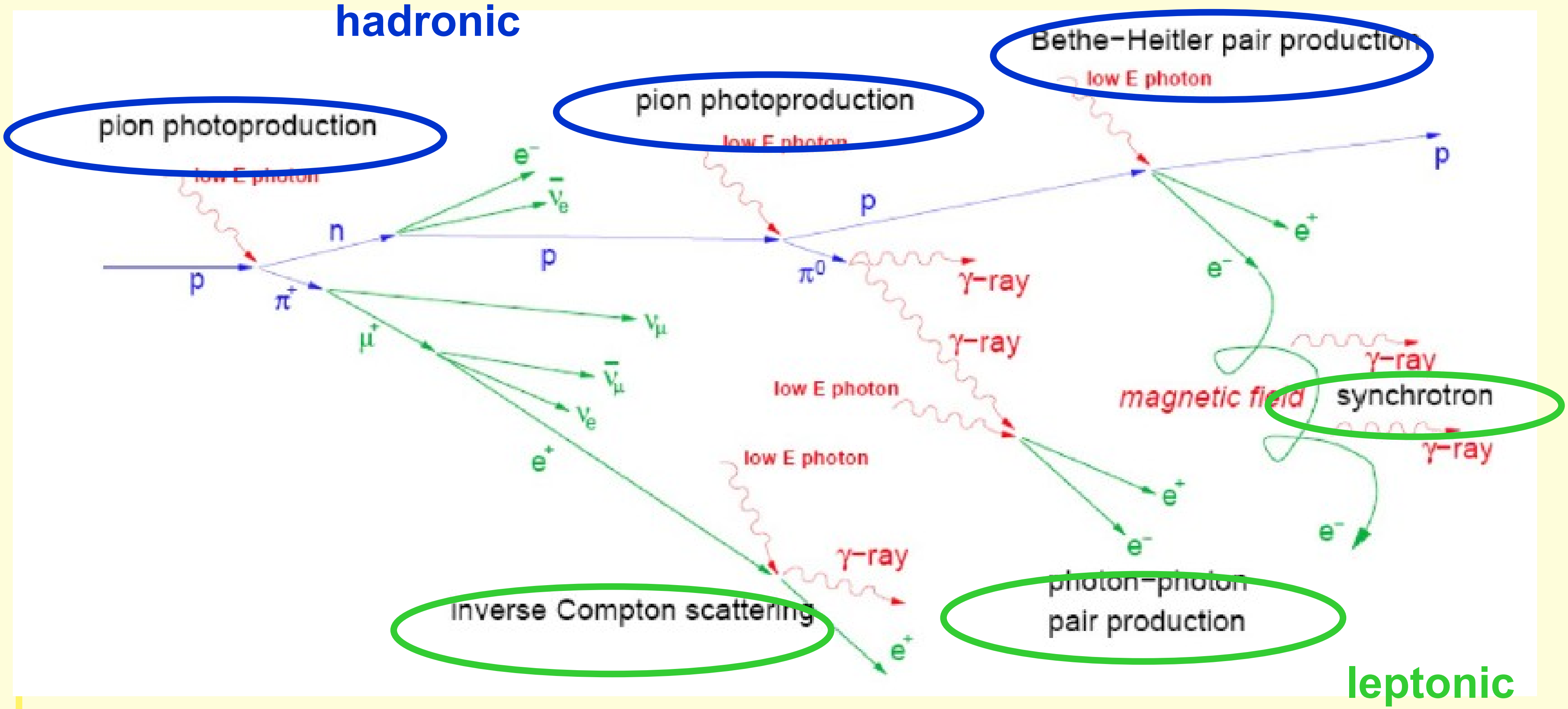
Relativistic proton distribution

Gamma-rays produced from photo-hadronic interactions or p-synchrotron

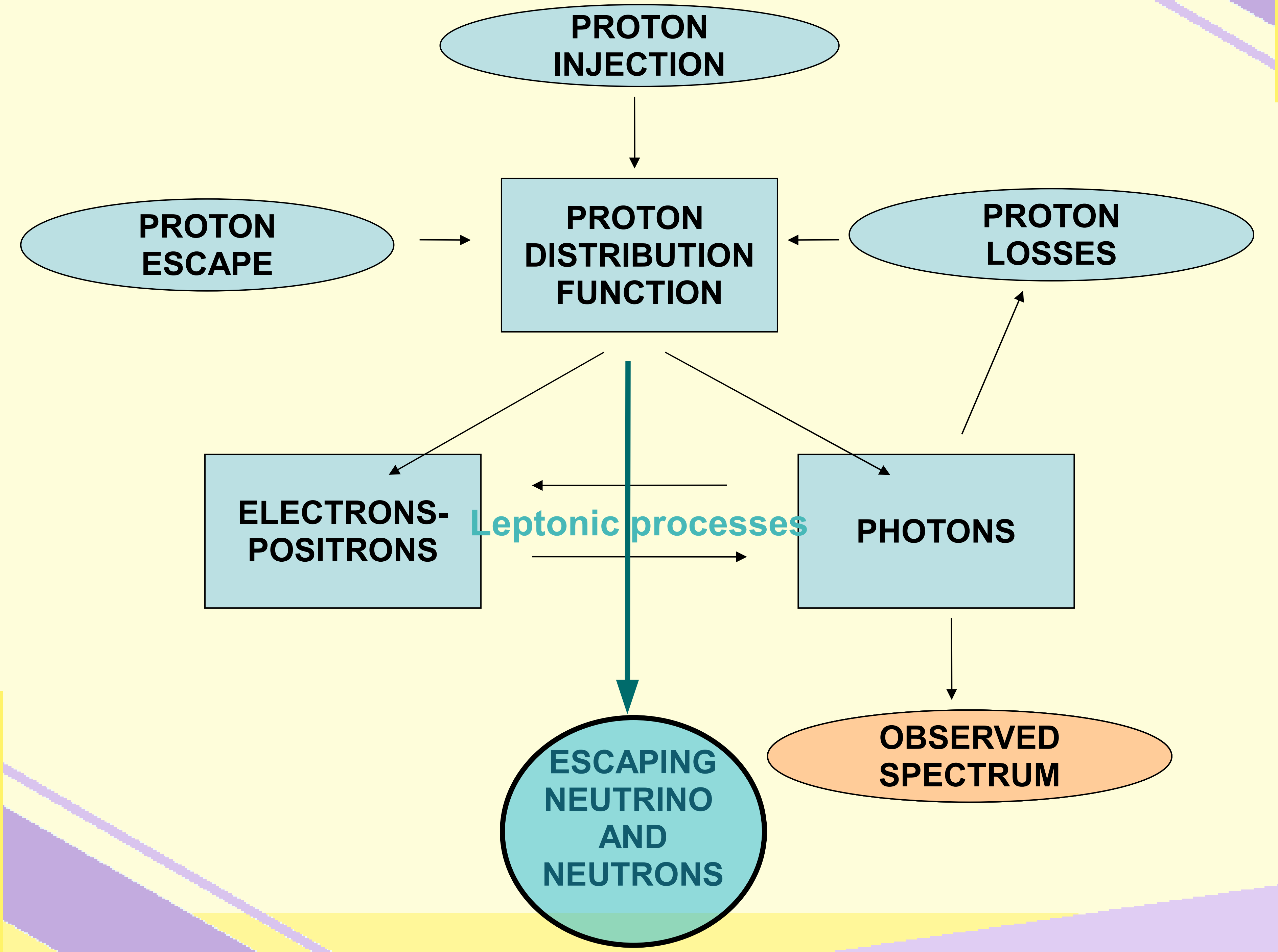


Radio up to X-rays are produced from electron synchrotron radiation

PHYSICAL PROCESSES



Courtesy of R.J. Protheroe



PROTON INJECTION

PROTON ESCAPE

PROTON DISTRIBUTION FUNCTION

PROTON LOSSES

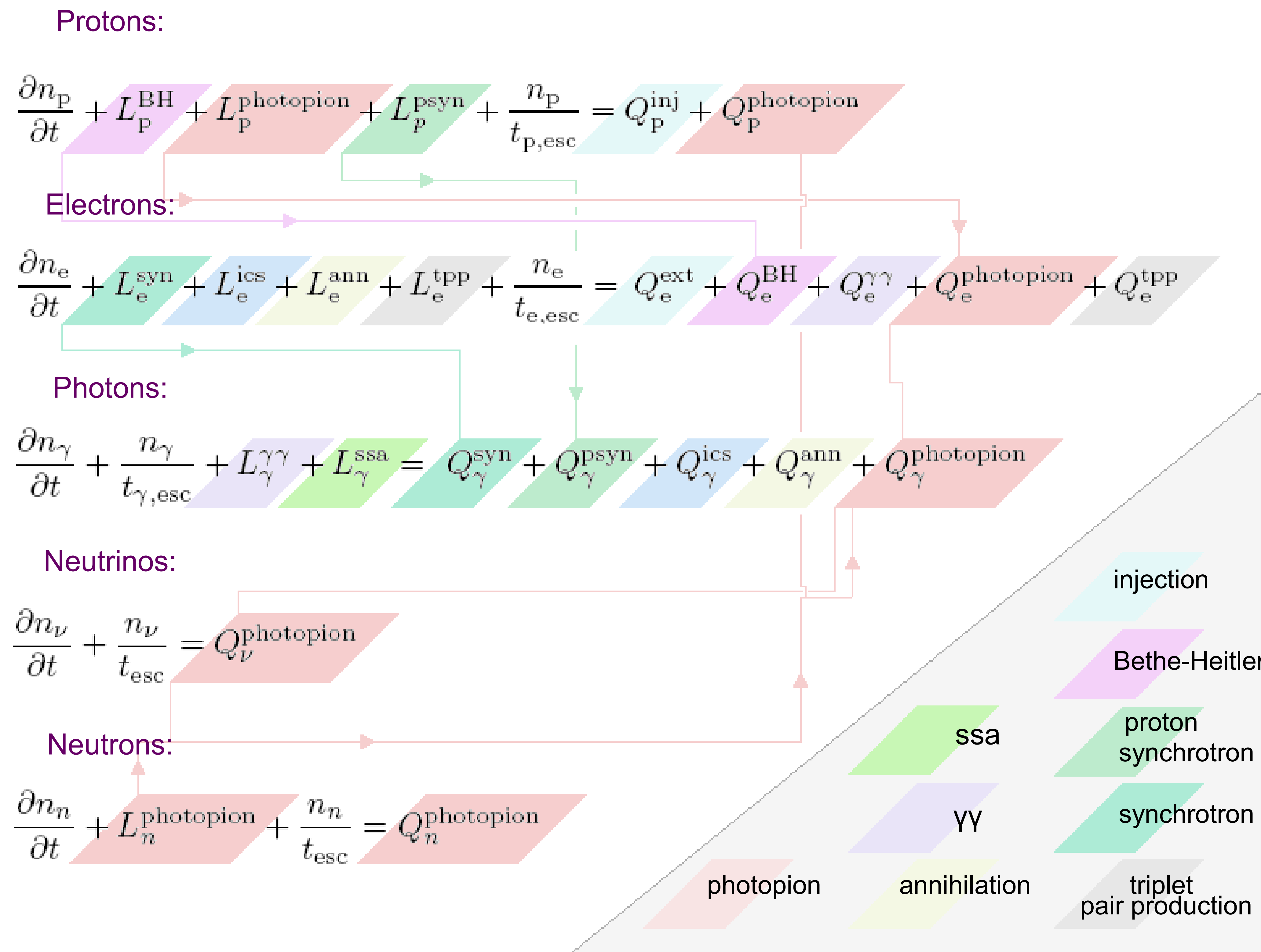
ELECTRONS-POSITRONS

Leptonic processes

PHOTONS

ESCAPING NEUTRINO AND NEUTRONS

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:

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

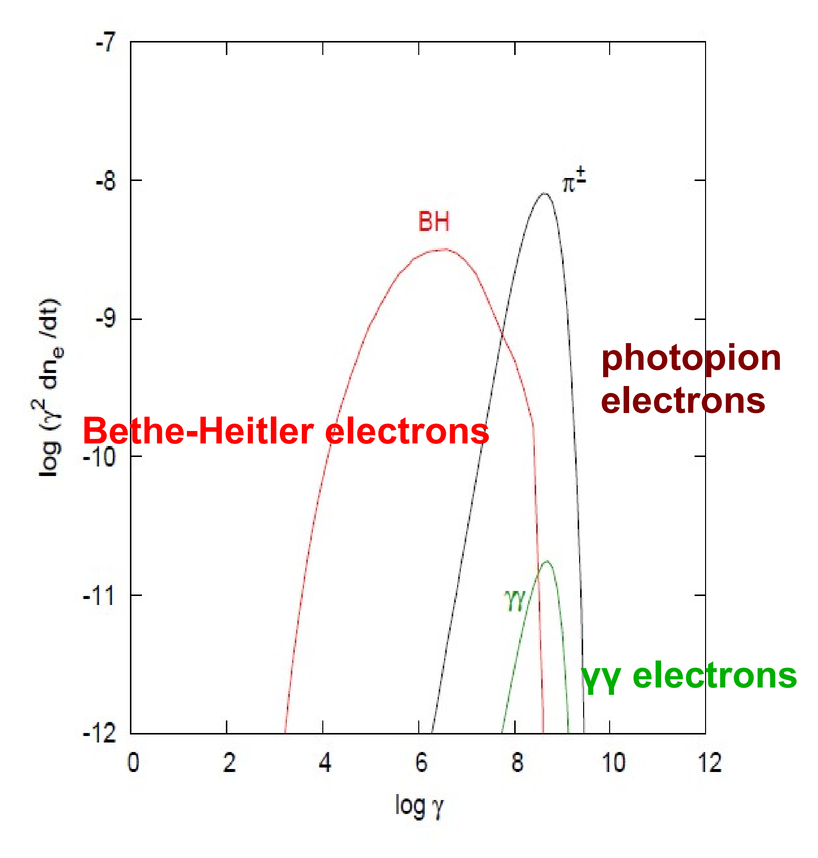
Neutrinos:

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

Neutrons:

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

TEST #1: SECONDARY ELECTRONS AND PHOTONS

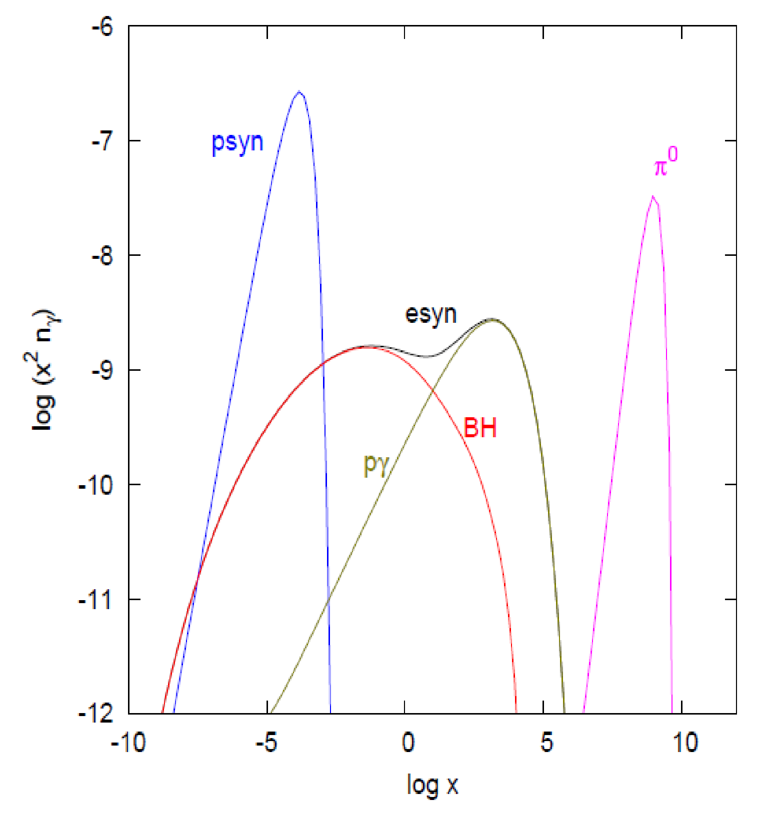


Bethe-Heitler electrons

photopion electrons

γγ electrons

electrons



photons

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

R = 3e16 cm

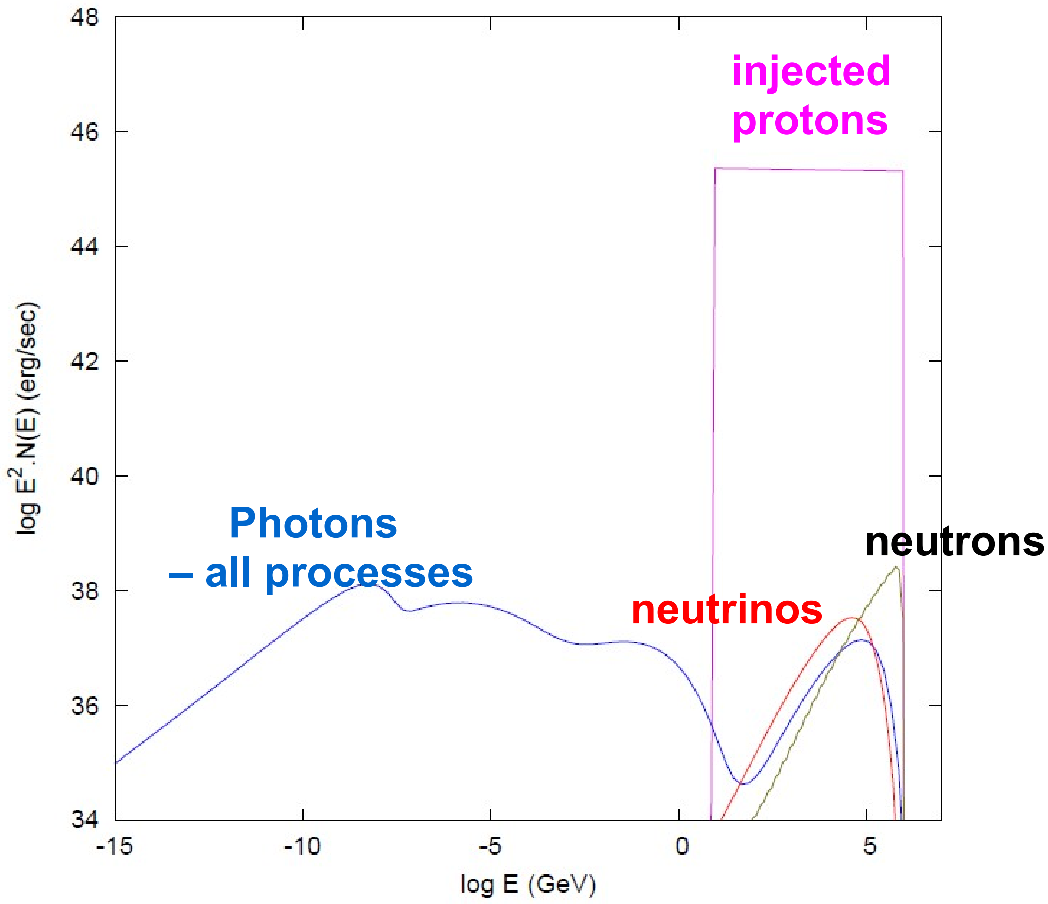
B = 1 G

γ_p = 2e6

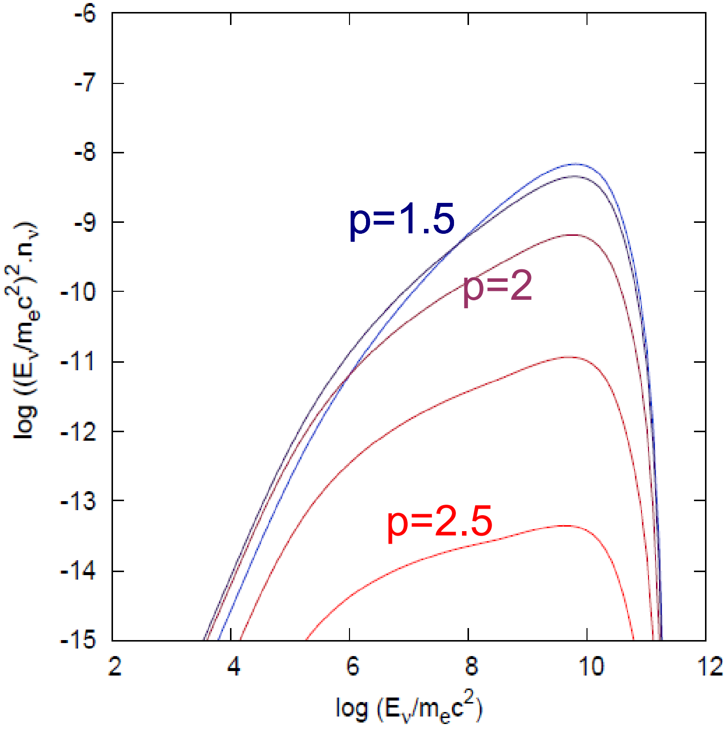
l_p = 0.4

S. Dimitrakoudis et al. (2012)

TEST #2: PROTON INJECTION AND STABLE SECONDARIES

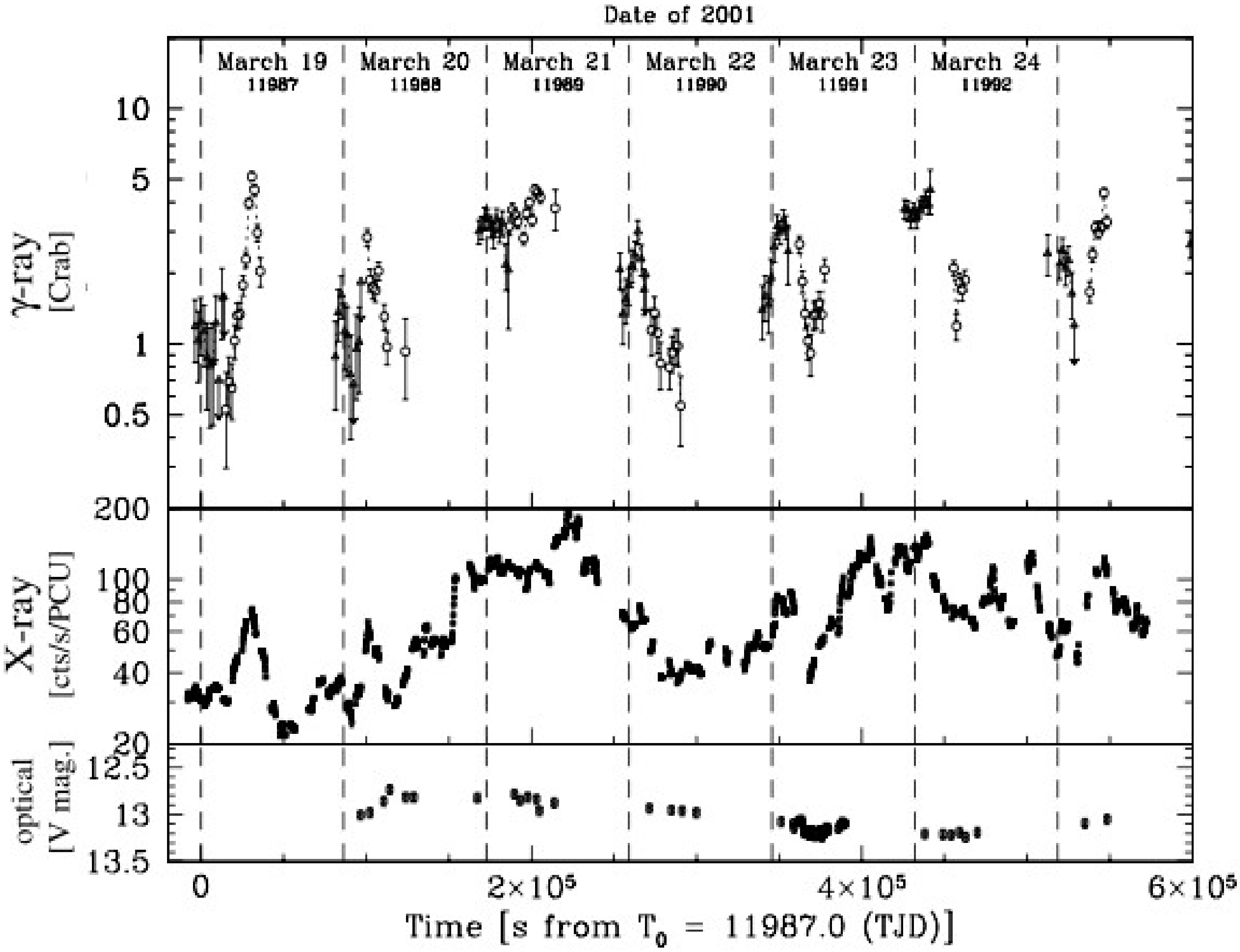


Neutrino spectra - different proton injection indices p

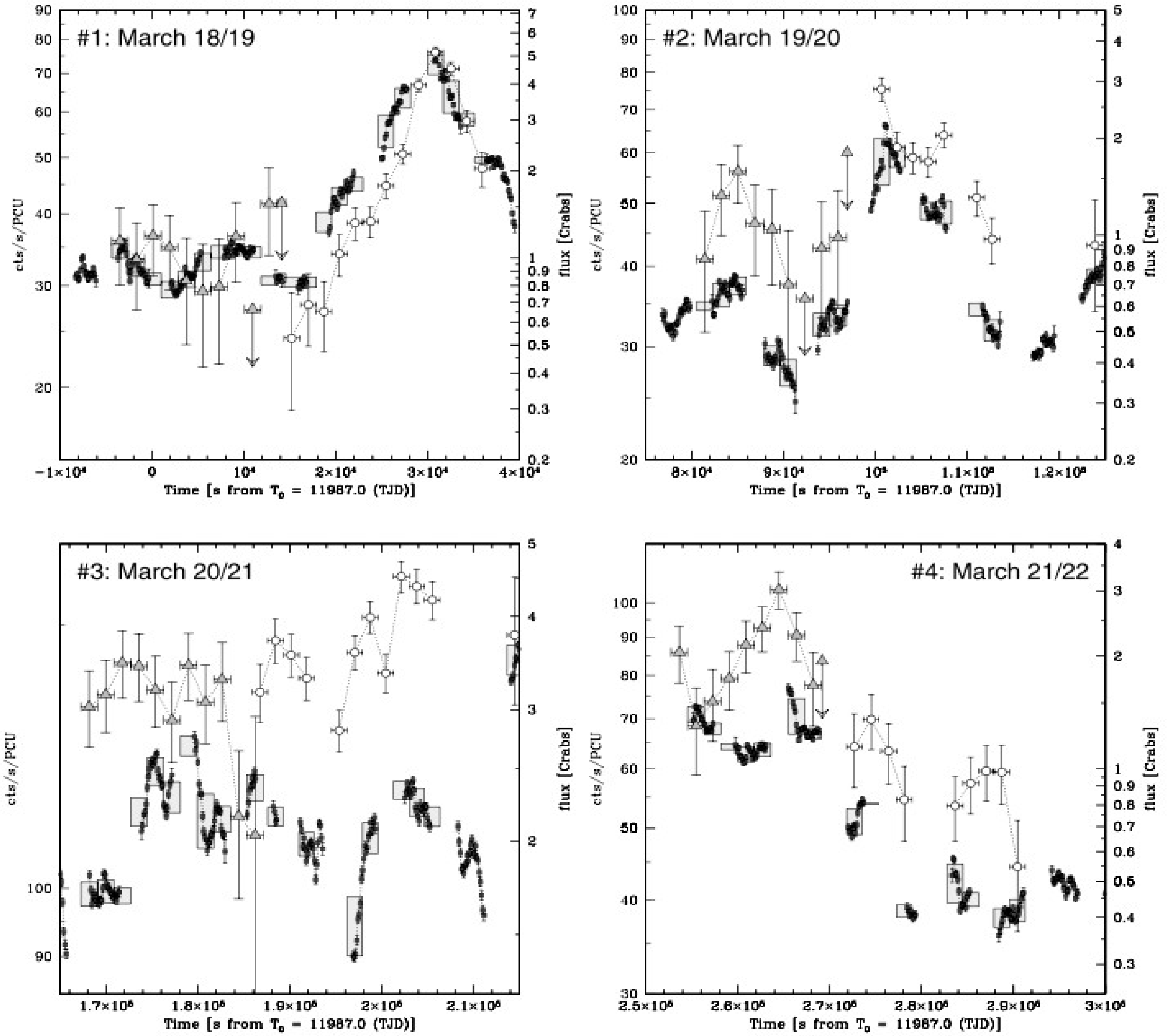


S. Dimitrakoudis et al. (2012)

Mkr 421 2001 MULTIWAVELENGTH CAMPAIGN

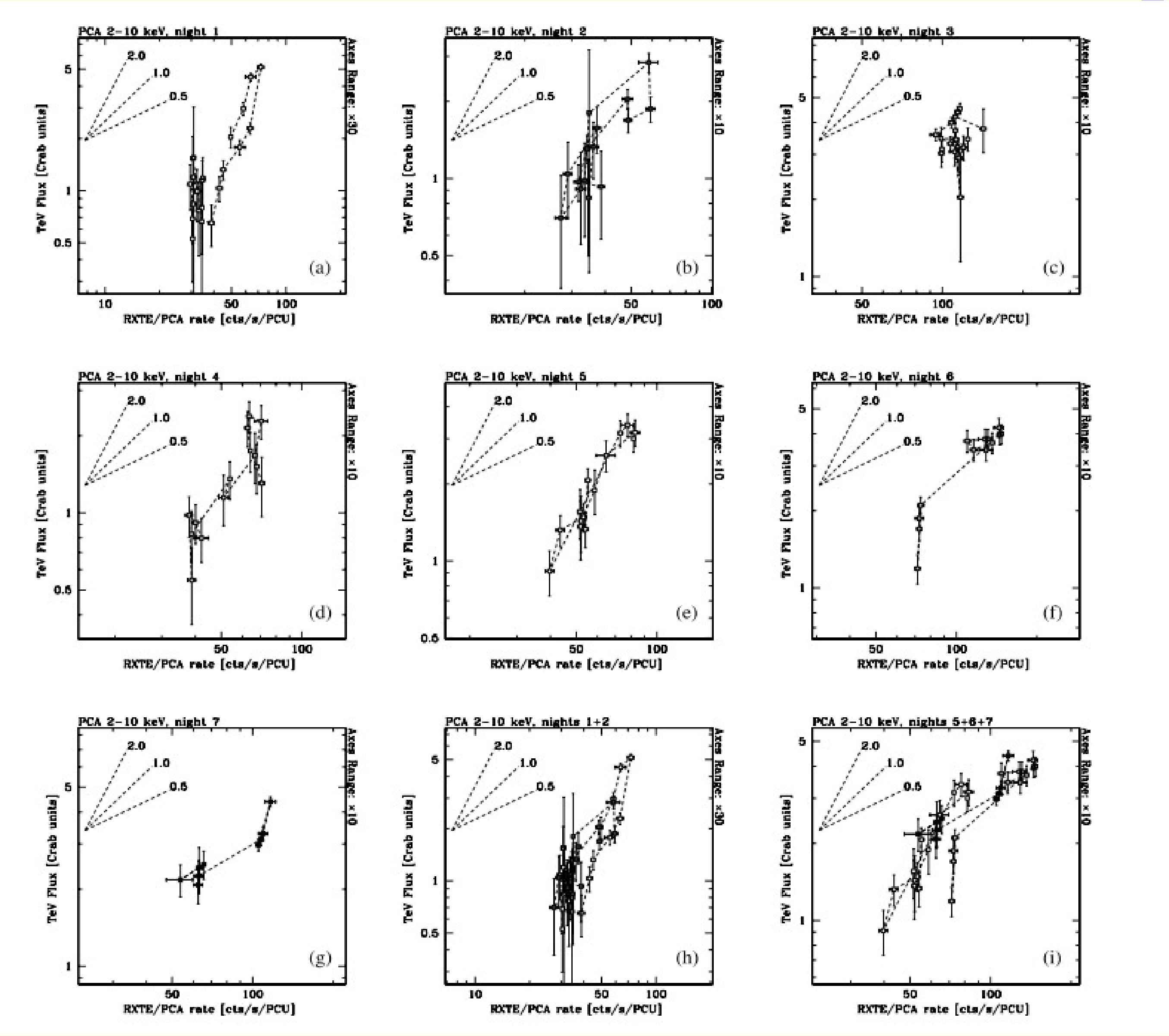


Fossati et al. ,2008, ApJ, ***677,*** *906*



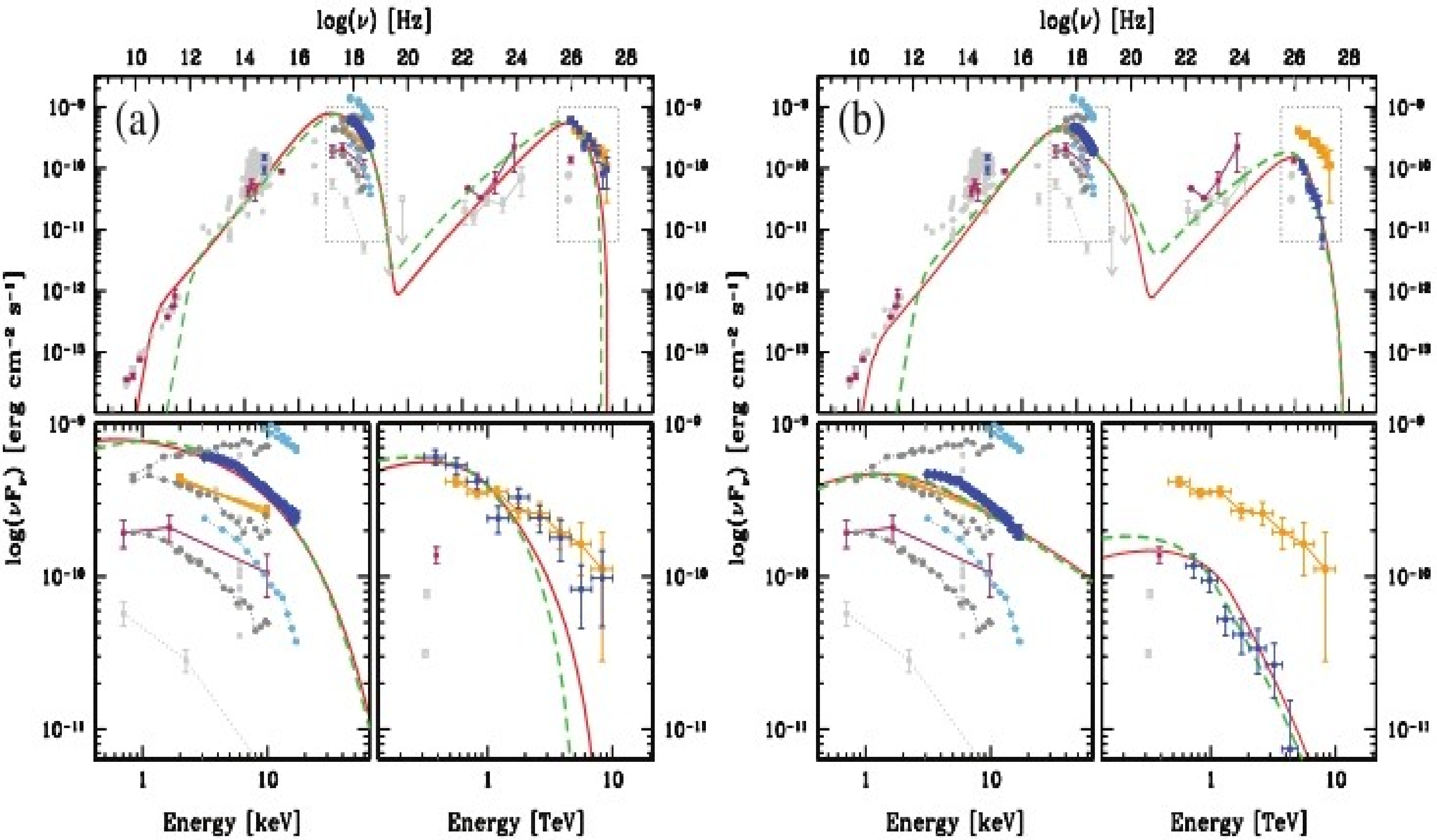
X-rays and γ-rays highly correlated...

Fossati et al. ,2008, ApJ, ***677,*** *906*



...with TeVs increasing more than linearly wrt the X-rays

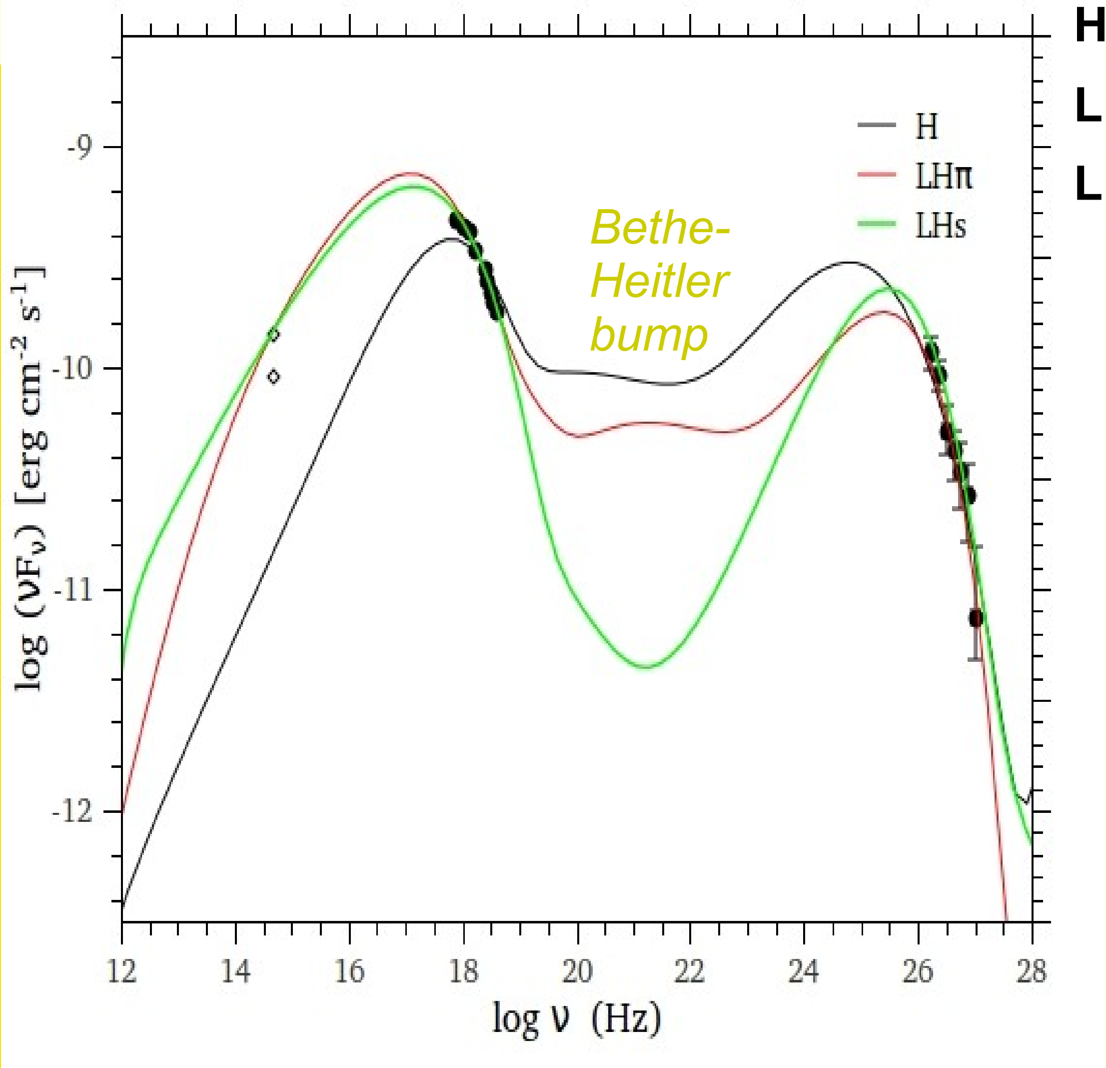
Fossati et al. ,2008, ApJ, ***677,*** *906*



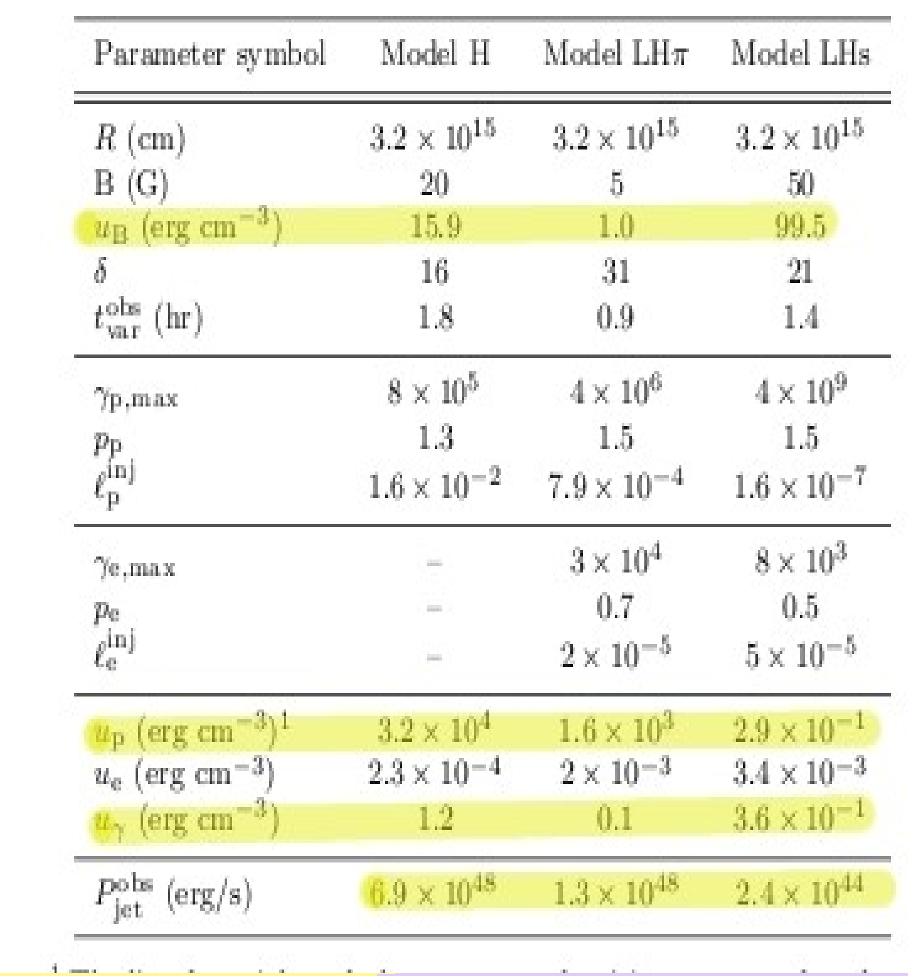
Fossati et al. ,2008, ApJ, ***677,*** *906*

SED OF Mrk 421- LEPTOHADRONIC MODELS

	V - X-rays	γ-rays
H-model	p-syn	photopion
LHπ - model	e-syn	photopion
LHs - model	e-syn	p-syn



Bethe-Heitler bump



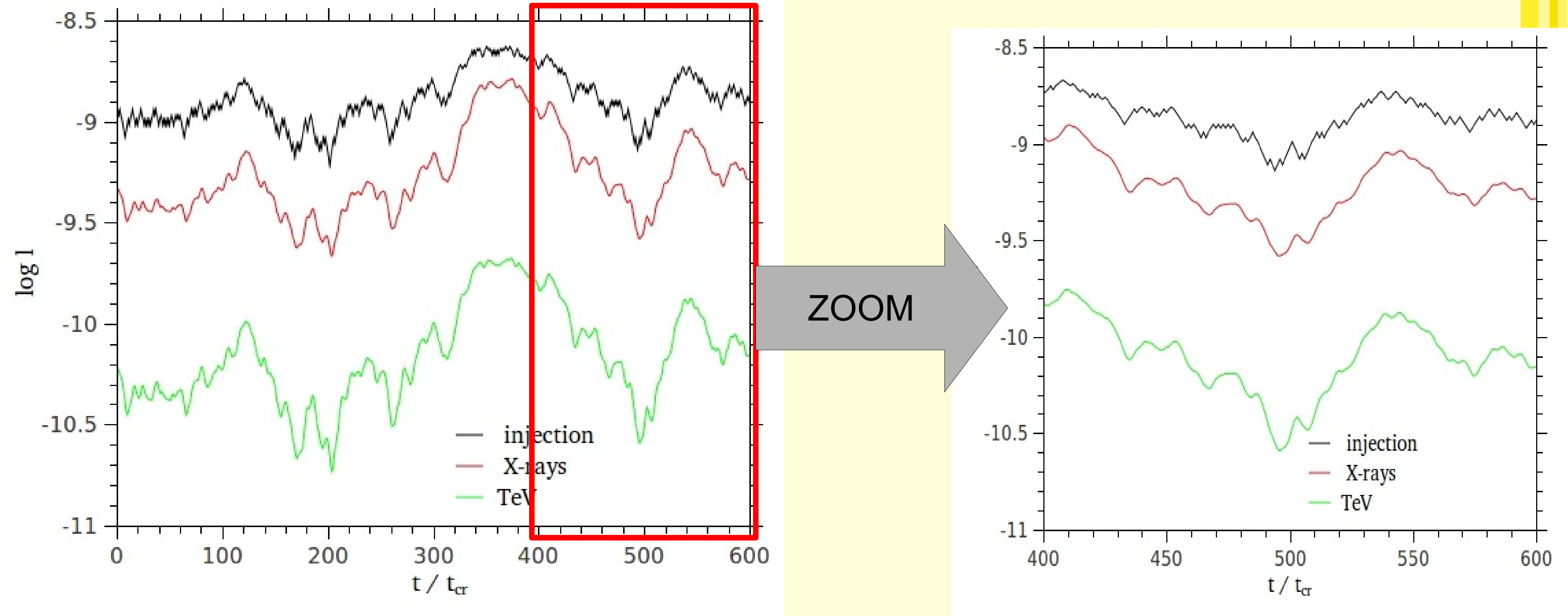
Parameter symbol	Model H	Model LHπ	Model LHs
R (cm)	3.2×10^{15}	3.2×10^{15}	3.2×10^{15}
B (G)	20	5	50
u_B (erg cm^{-3})	15.9	1.0	99.5
δ	16	31	21
$t_{\rm var}^{\rm obs}$ (hr)	1.8	0.9	1.4
$\gamma_{\rm p,max}$	8×10^5	4×10^6	4×10^9
$p_{\rm p}$	1.3	1.5	1.5
$\ell_{\rm p}^{\rm inj}$	1.6×10^{-2}	7.9×10^{-4}	1.6×10^{-7}
$\gamma_{\rm e,max}$	-	3×10^4	8×10^3
$p_{\rm e}$	-	0.7	0.5
$\ell_{\rm e}^{\rm inj}$	-	2×10^{-5}	5×10^{-5}
$u_{\rm p}$ (erg cm^{-3})[1]	3.2×10^4	1.6×10^3	2.9×10^{-1}
$u_{\rm e}$ (erg cm^{-3})	2.3×10^{-4}	2×10^{-3}	3.4×10^{-3}
u_γ (erg cm^{-3})	1.2	0.1	3.6×10^{-1}
$P_{\rm jet}^{\rm obs}$ (erg/s)	6.9×10^{48}	1.3×10^{48}	2.4×10^{44}

Mastichiadis et al. submitted

INDUCING TIME-VARIABILITY

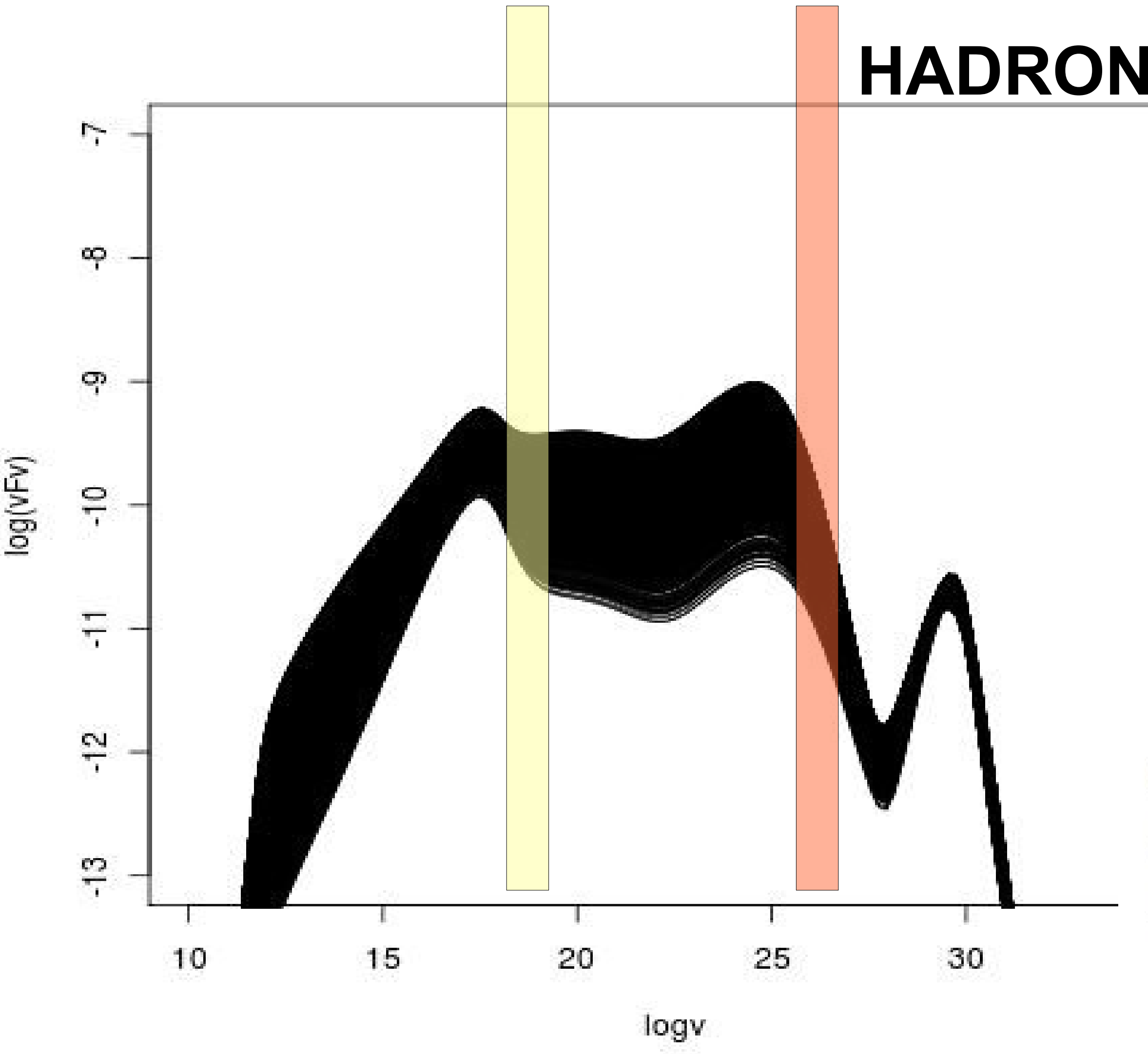
Assume small amplitude random-walk variations in particle injection
Protons and electron injection can have

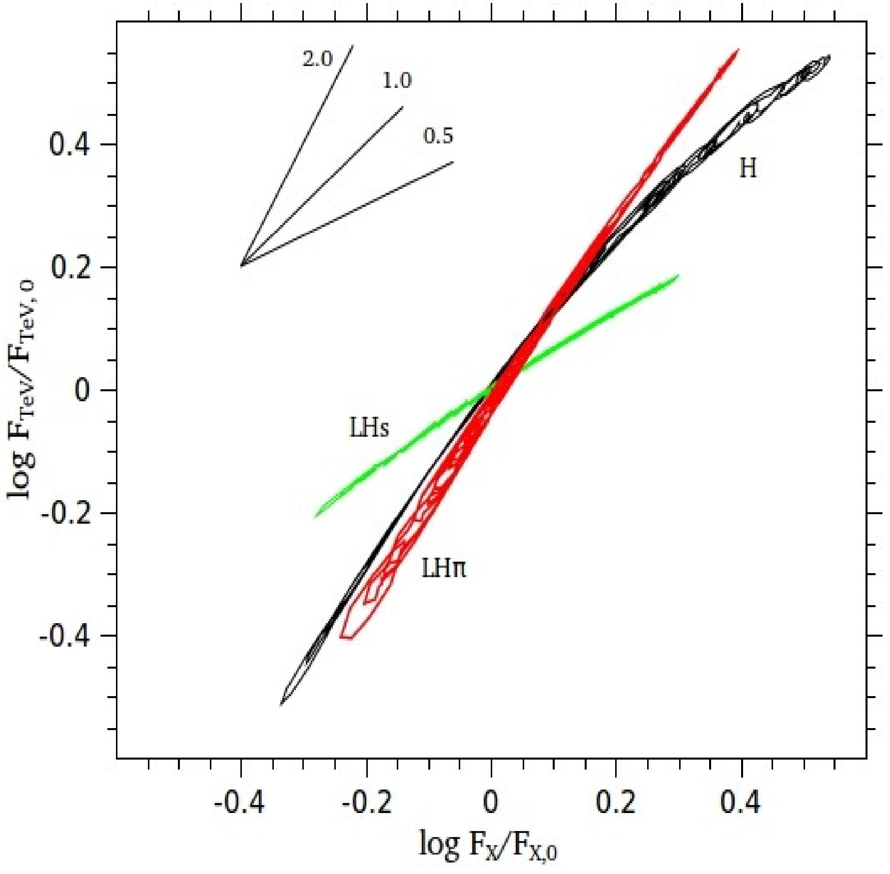
(i) correlated variability without time lag
(ii) correlated variability with time lag
(iii) totally uncorrelated variability



Injection and lightcurves when p and e totally correlated

VARIATIONS OF INJECTION LUMINOSITY (1)

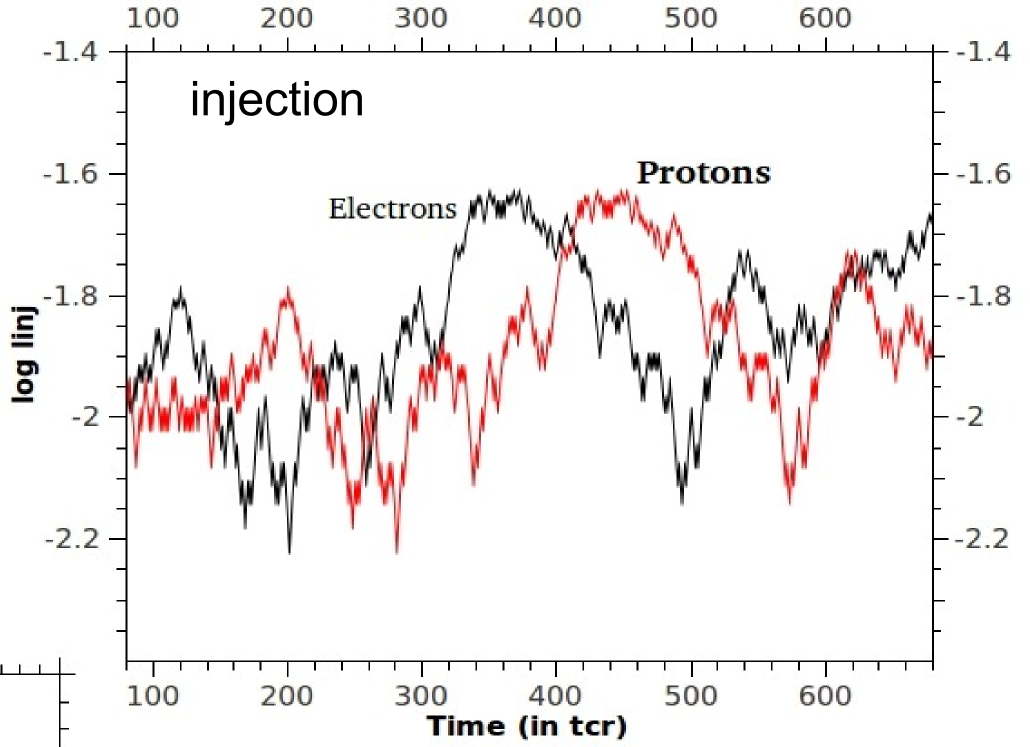


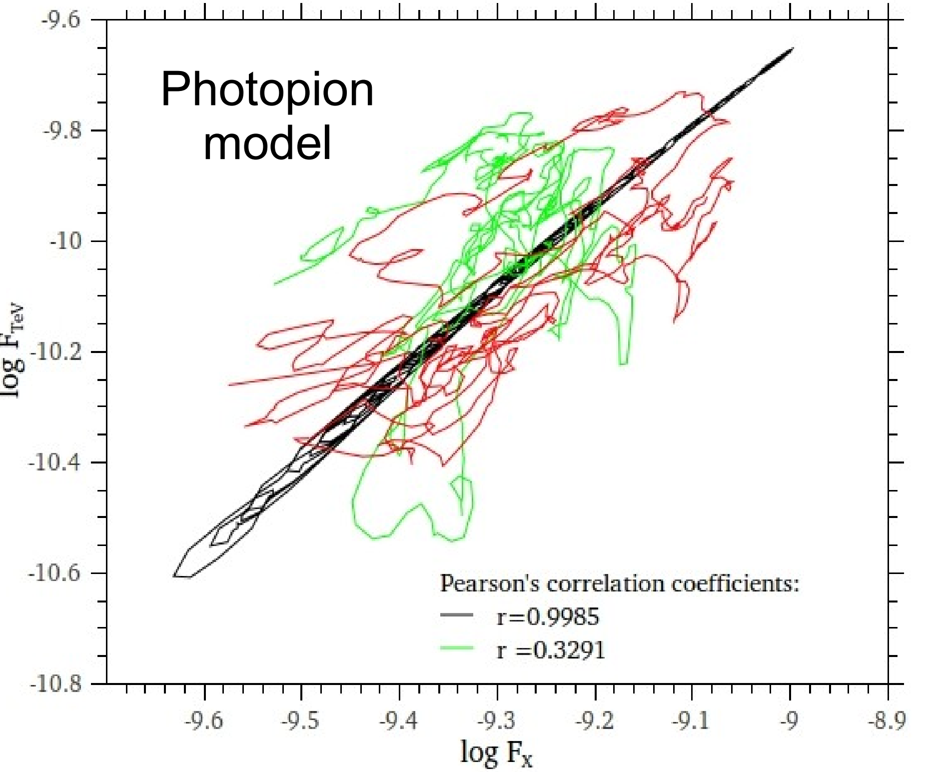


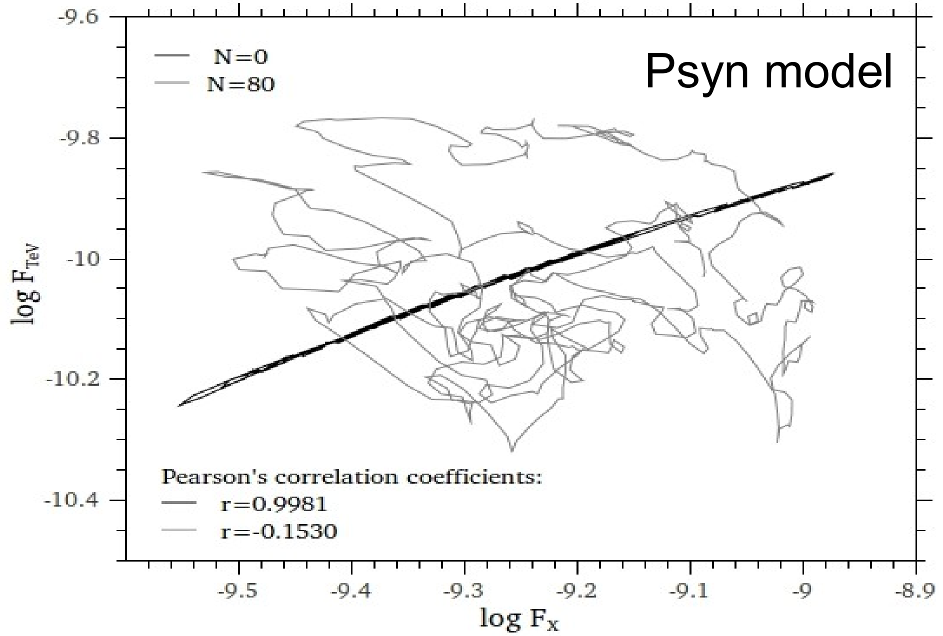
VARIATIONS OF INJECTION LUMINOSITY (2)

Artificially weaken the correlation

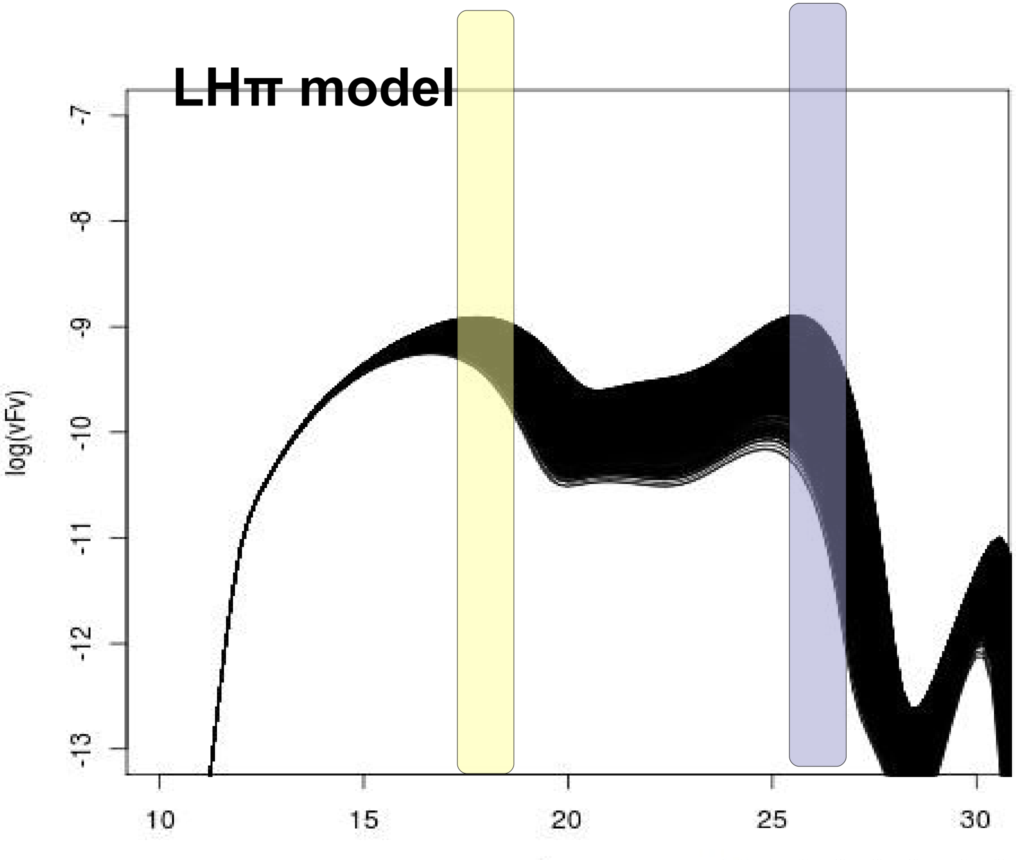
Correlated – no time lag
Correlated – time lag of 80 tcr
Uncorrelated

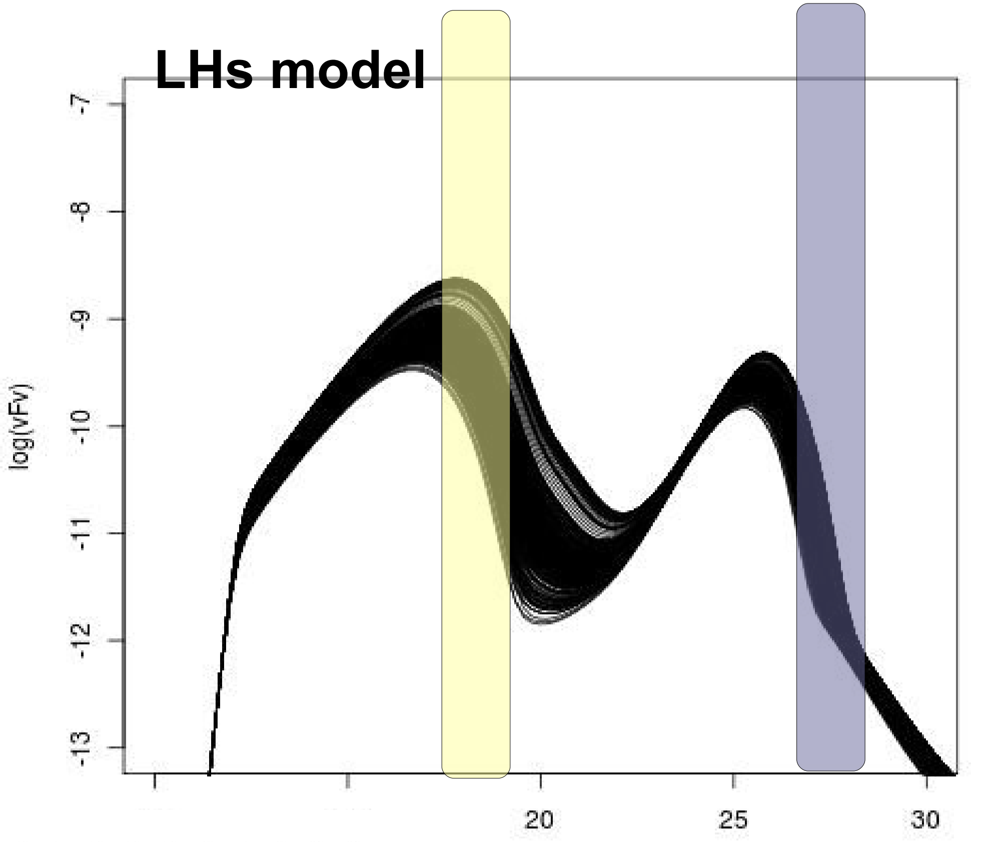


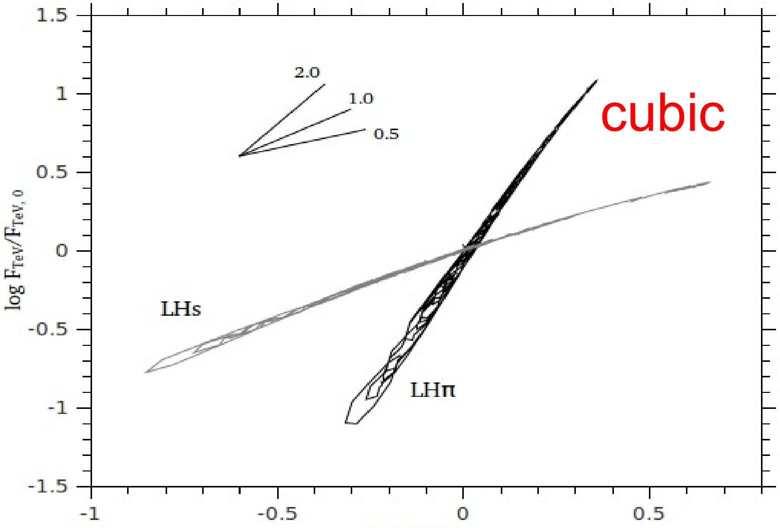




VARIATIONS OF MAXIMUM ENERGY

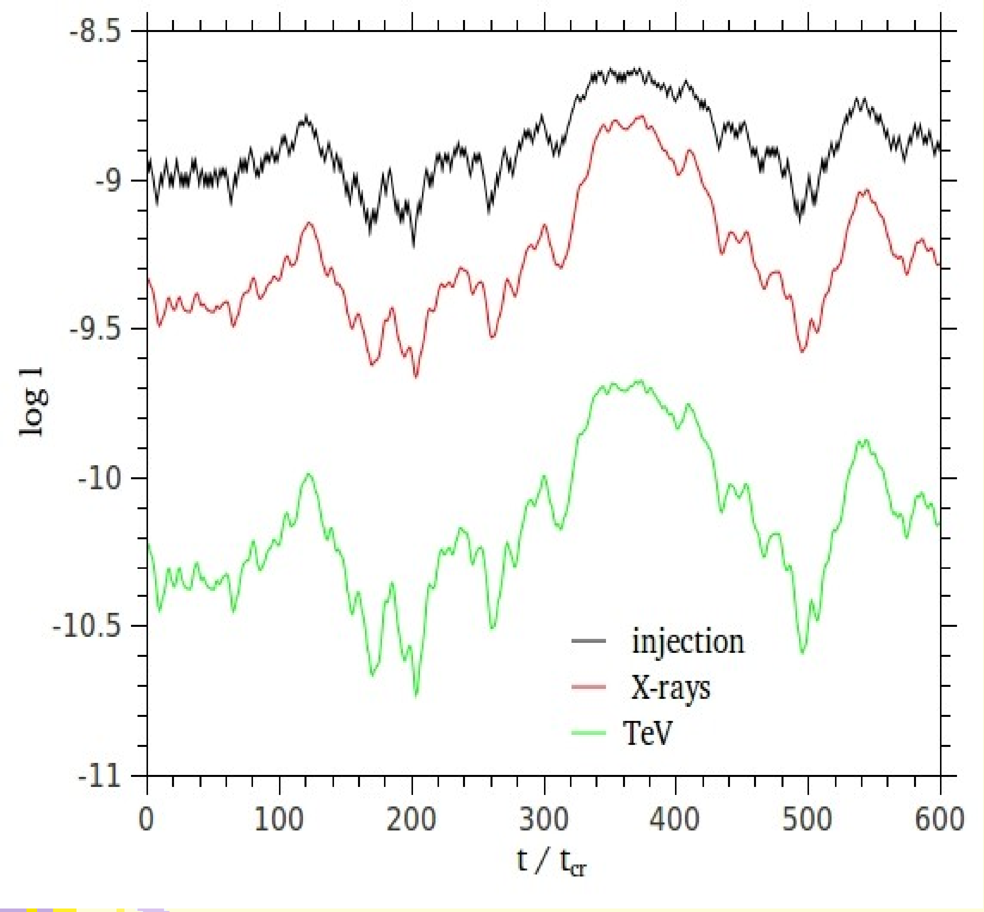




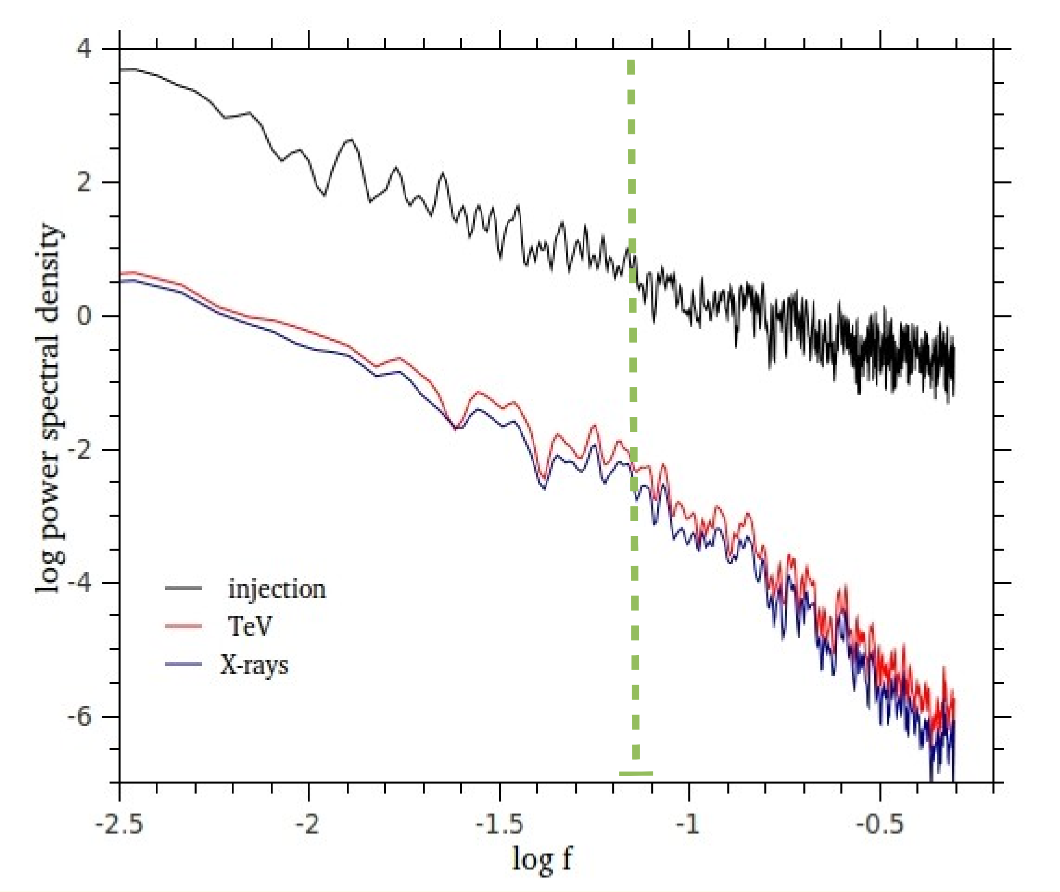


POWER SPECTRAL DENSITY

Time domain

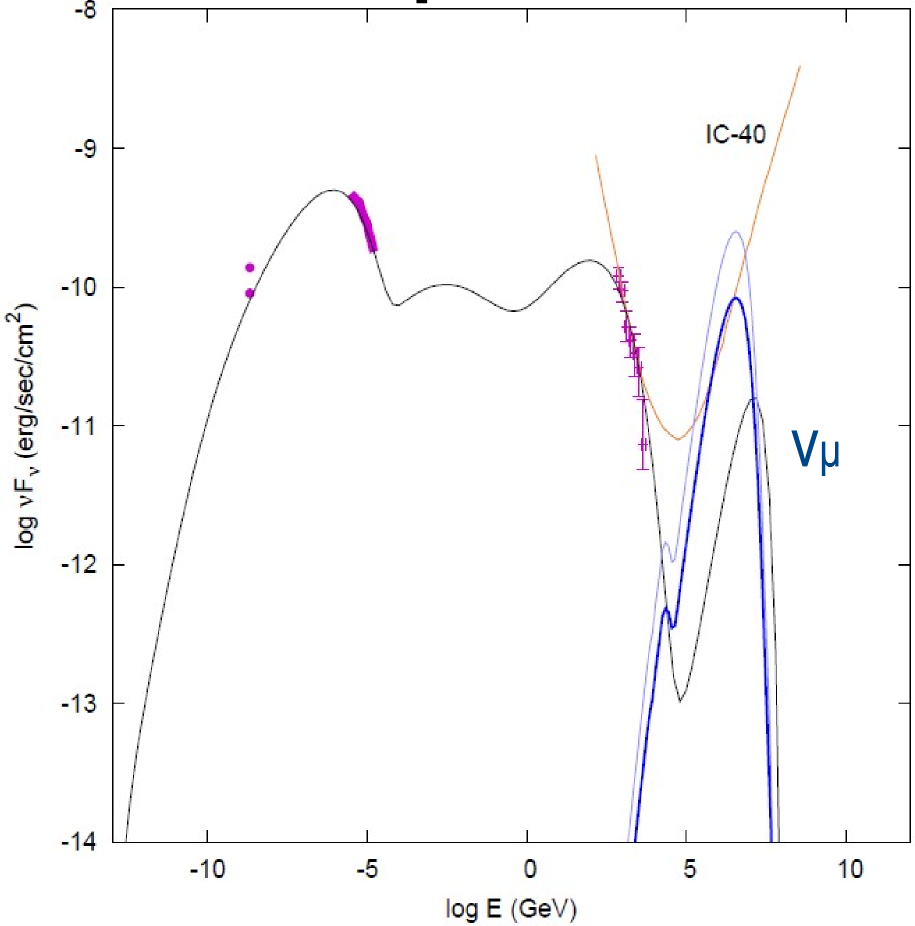


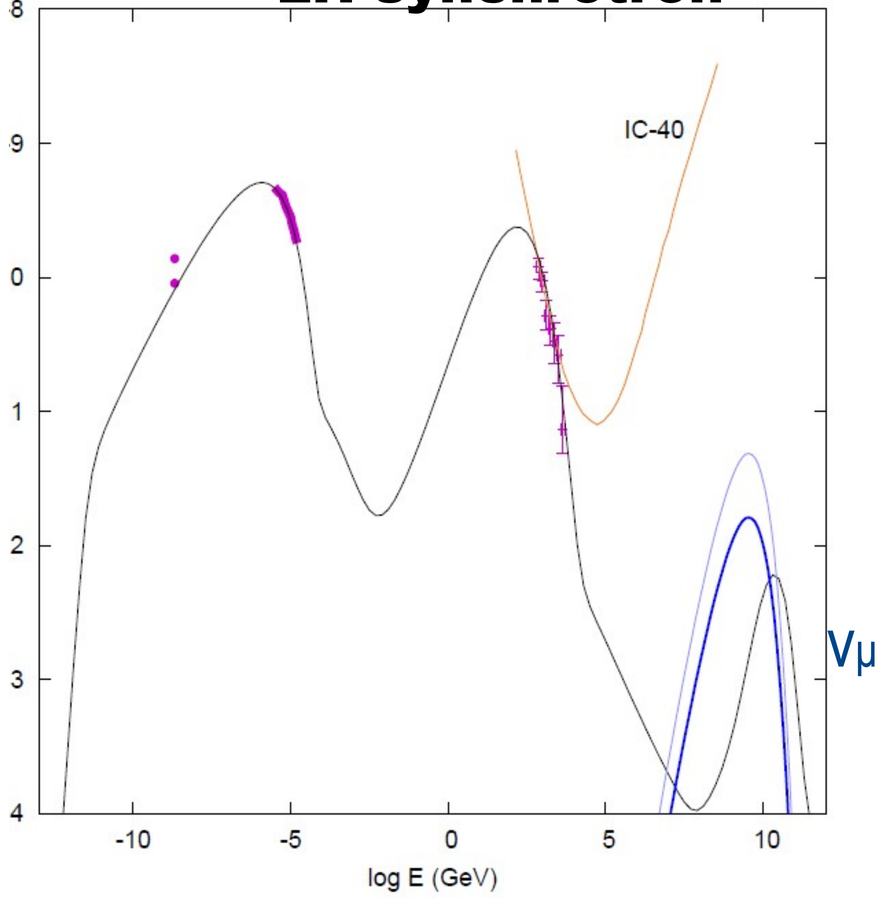
Frequency domain



Break – higher frequencies
(smaller timescales) suppressed

NEUTRINO EMISSION

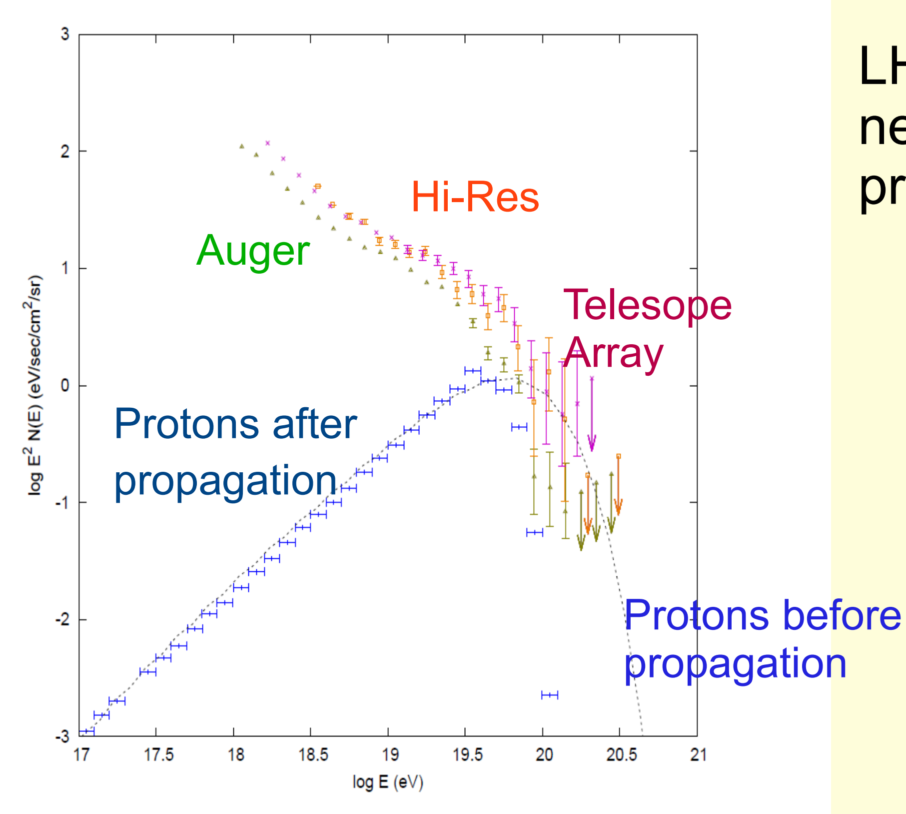

LH pion


LH synchrotron

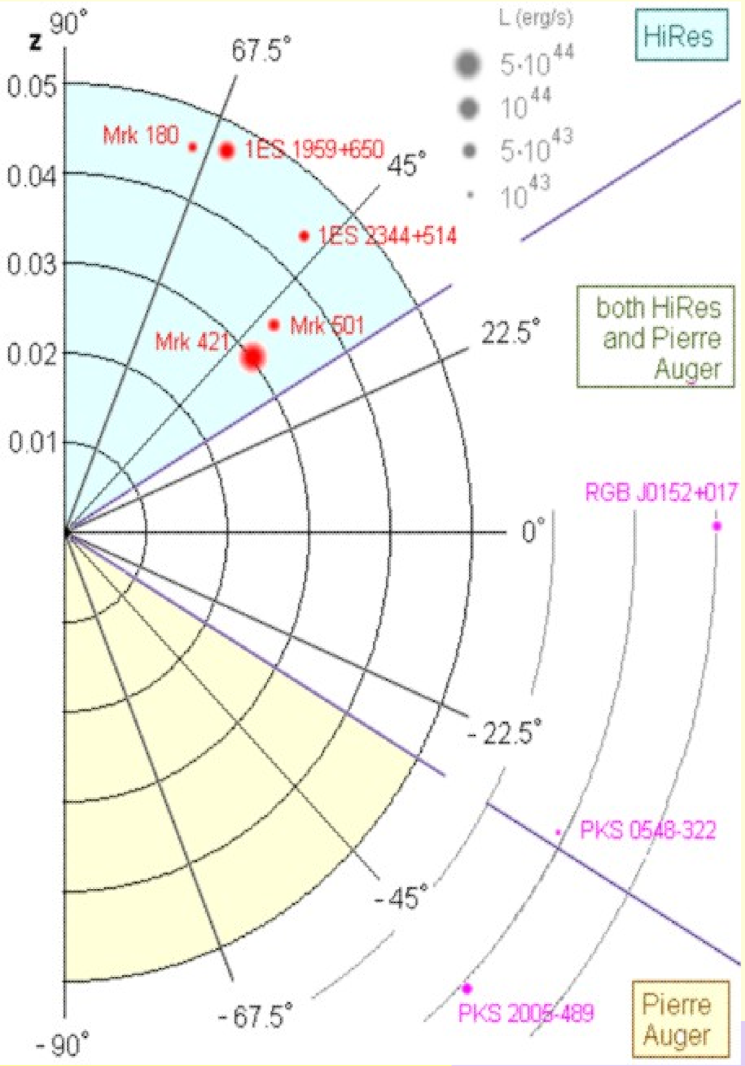
Due to differences in the fiting parameters:
LHπ: PeV neutrinos with high flux → ICE CUBE
LHs: EeV neutrinos with low flux

S. Dimitrakoudis et al submitted

UHECR FROM NEUTRON ESCAPE



LHs model: proton peak (after neutron escape, decay and proton propagation to Earth) ~30 EeV



Small UHECR contribution from nearby BL Lacs if similar to Mrk 421:
- Lower luminosities
- Larger distances

S. Dimitrakoudis et al. submitted

CONCLUSIONS

We have developed a one-zone time-dependent, self-consistent leptohadronic code with state-of-the-art treatment of photopair and photopion interactions (proton losses and secondary injection)

Its application to the contemporaneous SED of Mrk 421 yields two very different fits → further MW observations and temporal correlations are needed.

LH-π model produces neutrino flux very close to the recent Ice-Cube observations.

	LH-π	**LH-s**
Dominant energy density	Protons	B-field
Max proton energy	~PeV	~EeV
TeV/X-ray variations	~quadratic	~linear
Neutrino peak and flux (erg/cm^2/sec)	PeV, 1.e-10	EeV, 1.e-12
Contribution to UHECR flux	None	EeV