BLAZARS: A LAB FOR HIGH ENERGY ASTROPHYSICS

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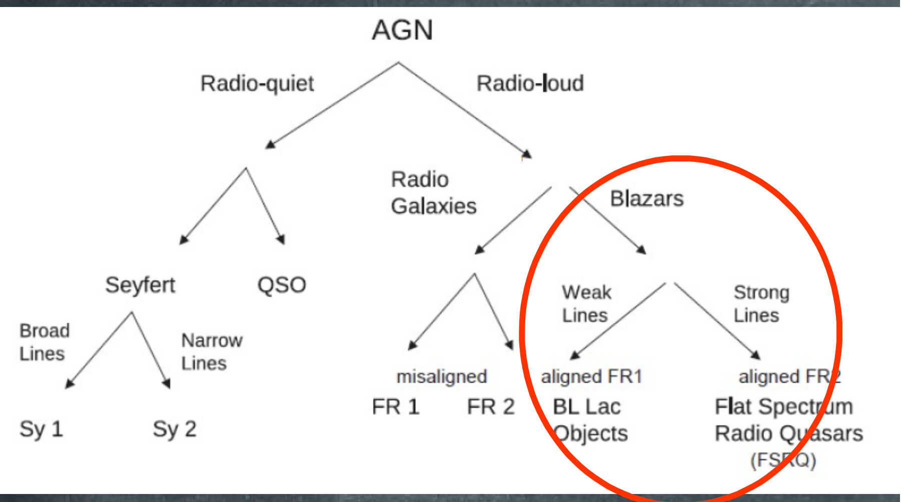
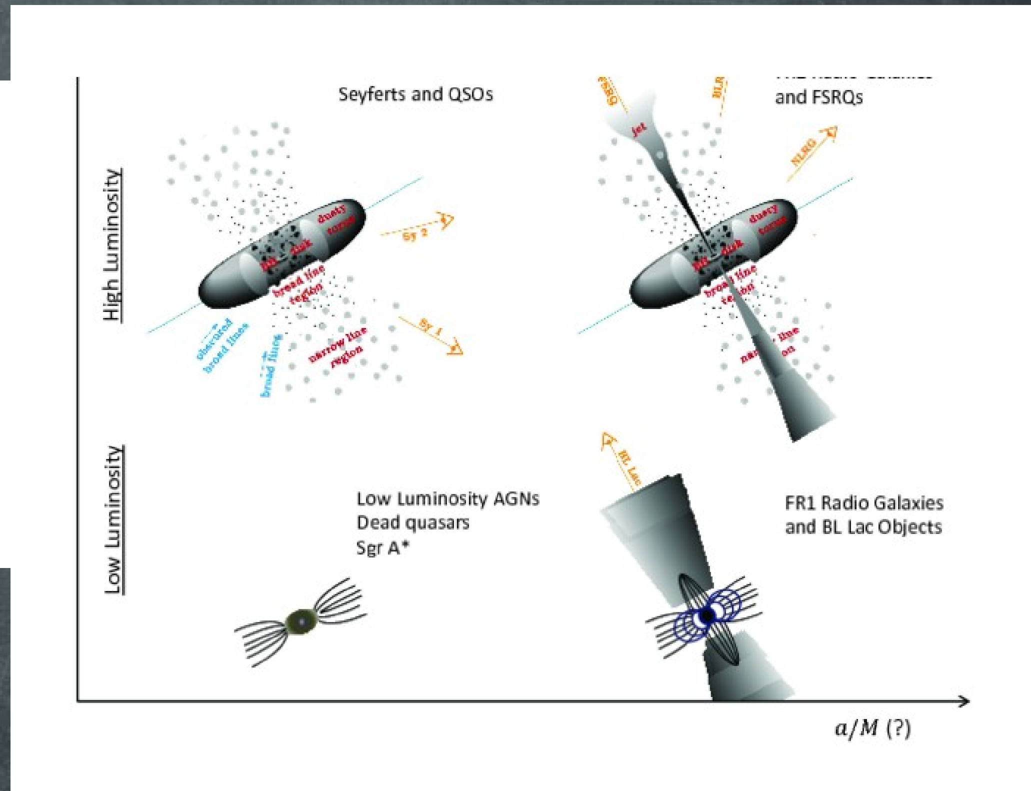
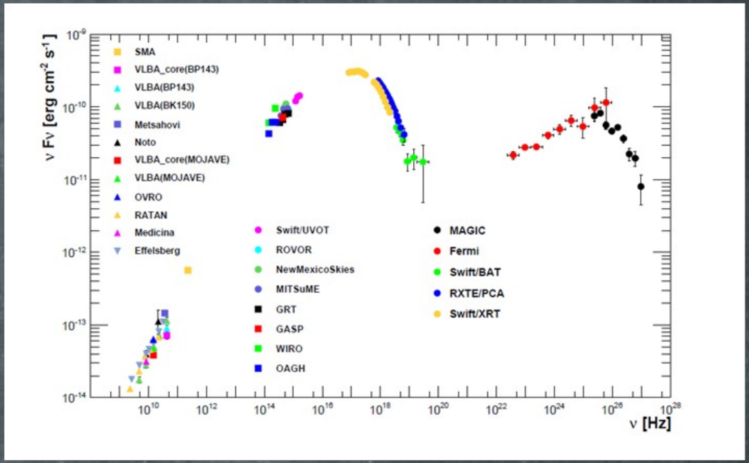
AGN TAXONOMY

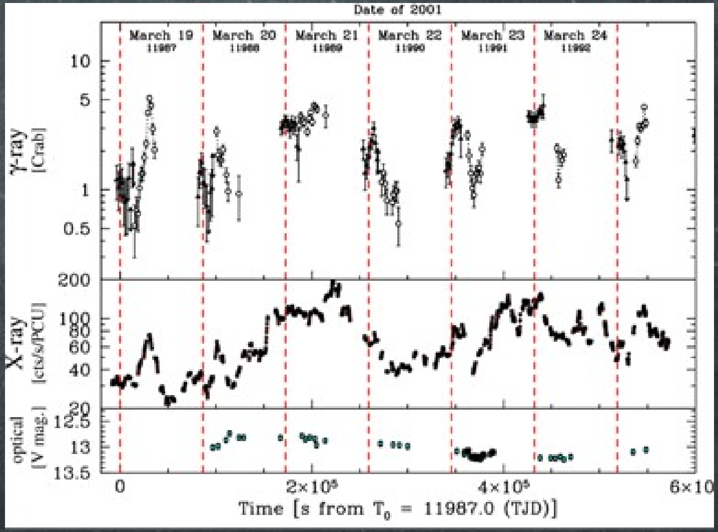




BLAZARS

- Few (~5% of all AGN)
- Compact , flat spectrum radio sources
- Broad (radio-gamma) non-thermal continuum : 'Double hump' spectrum
- Variable at all energies: short – large amplitude variability + correlations
- Superluminal motion



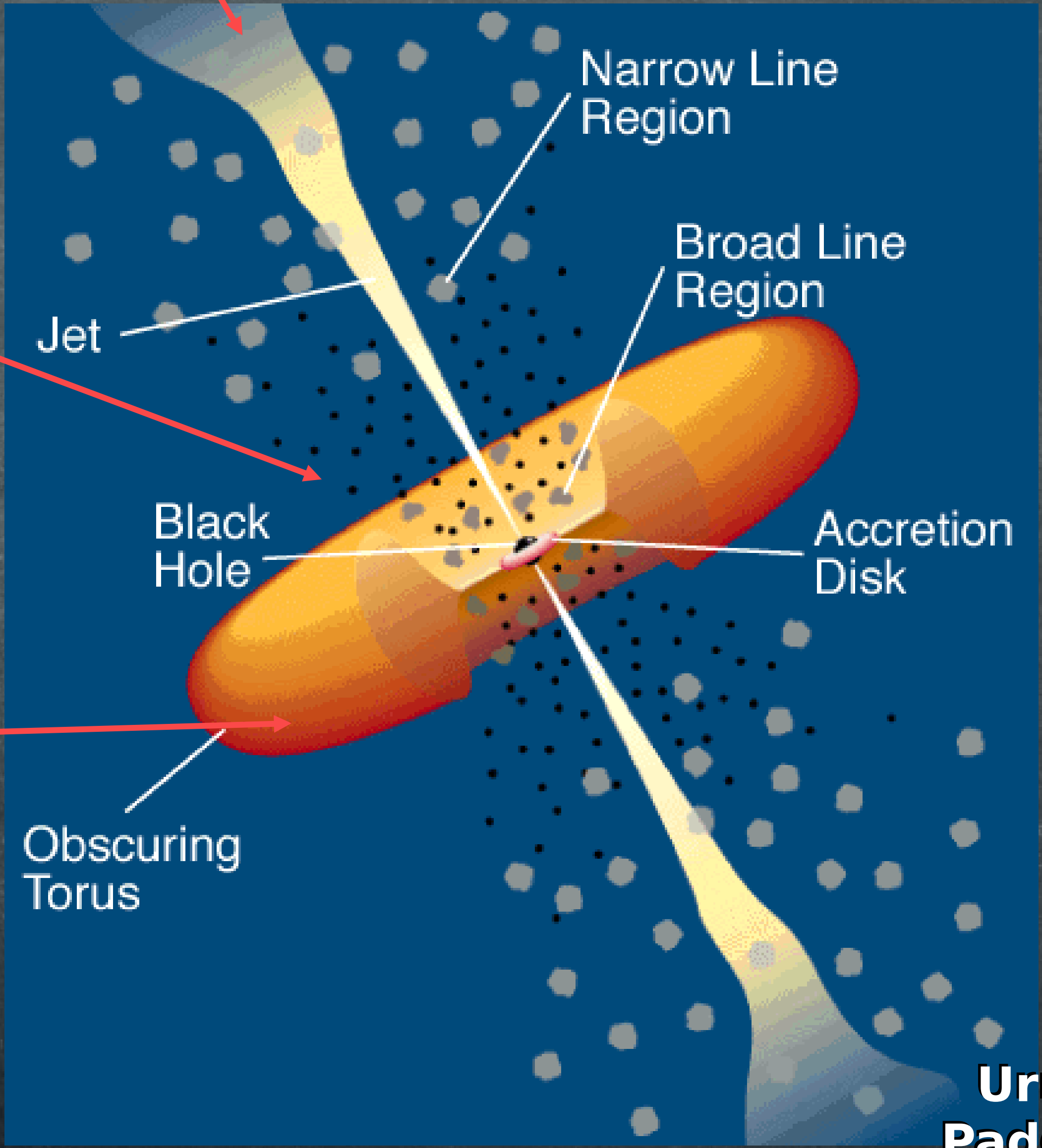


AGN UNIFICATION

- blazar

- Sy 1
- BLRG
- QSO

- Sy 2
- NLRG

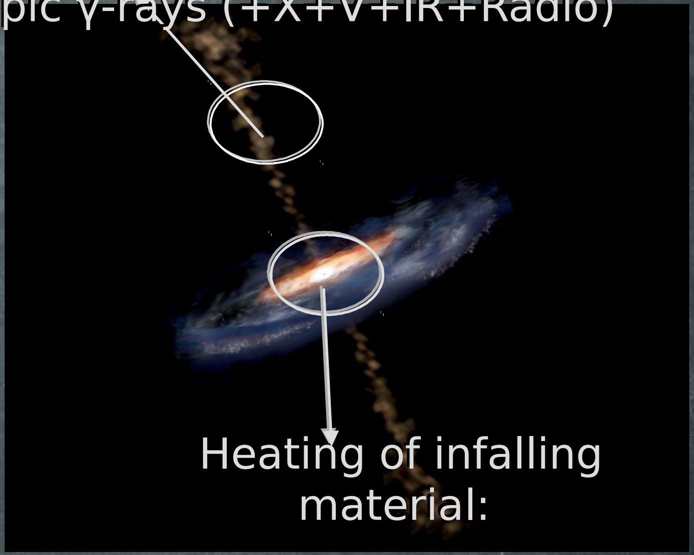


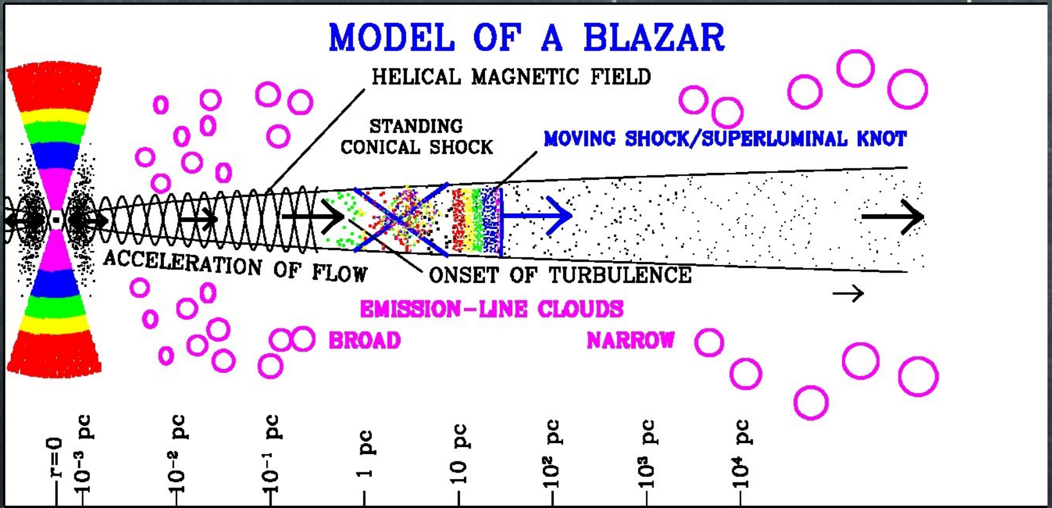
Urry & Padovani

HIGH ENERGY EMISSION FROM AGN

- **Radio Quiet AGN:**
  X-rays: Mostly thermal emission from accretion disk-corona

- **Radio Loud AGN:**
  γ-rays: Non-thermal emission from ultrarelativistic electrons and/or protons
  → particle acceleration

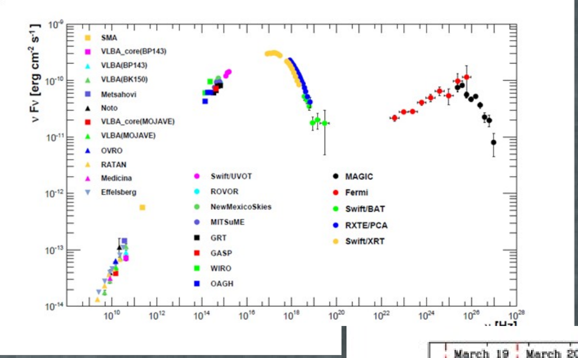


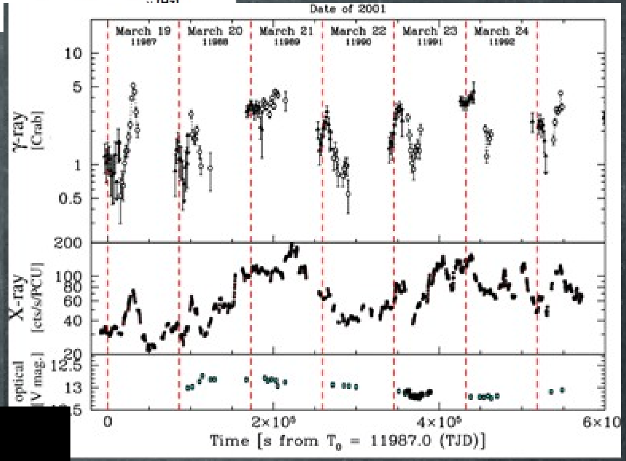


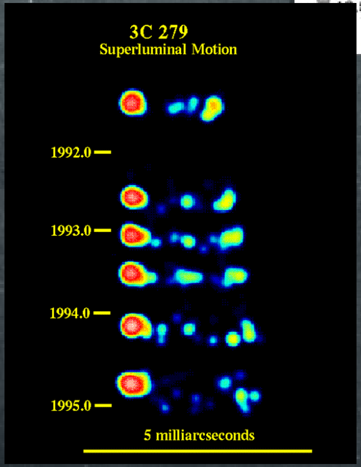
A. Marscher

BLAZARS: OBSERVATIONAL FACTS

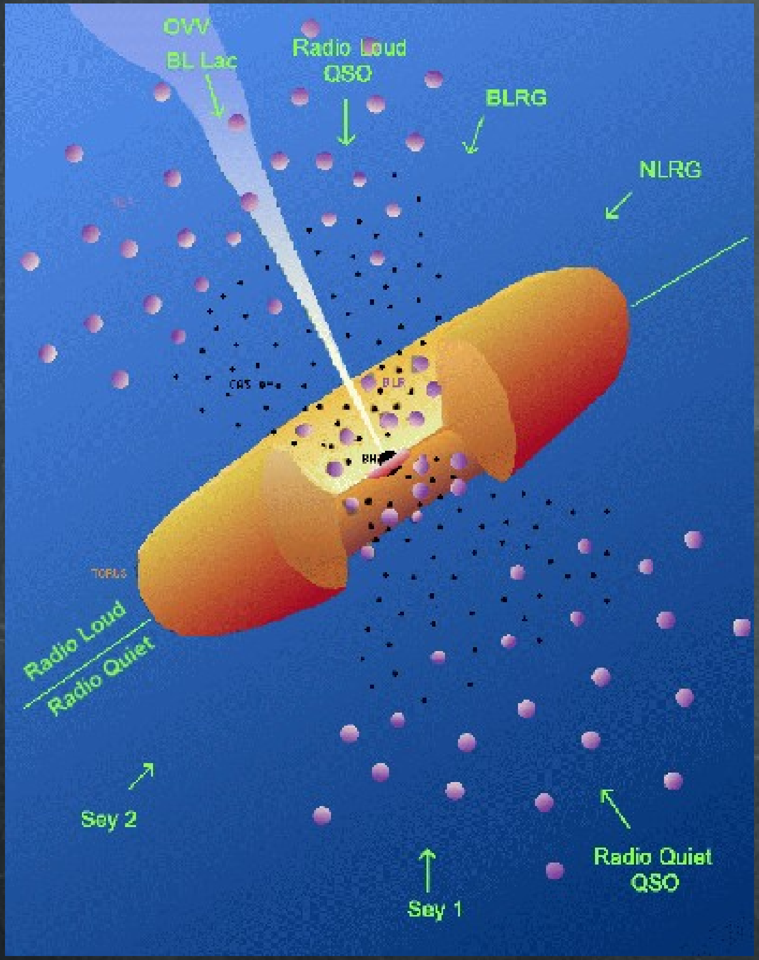
- MW Spectrum → Non-thermal radiation mechanisms
- Gamma-ray emission → High energy particles → Acceleration
- Fast + correlated variability → emission from a localized region
- Superluminal motion → emission from inside the jet → relativistic beaming







OPEN ISSUES



– Distance of the active region

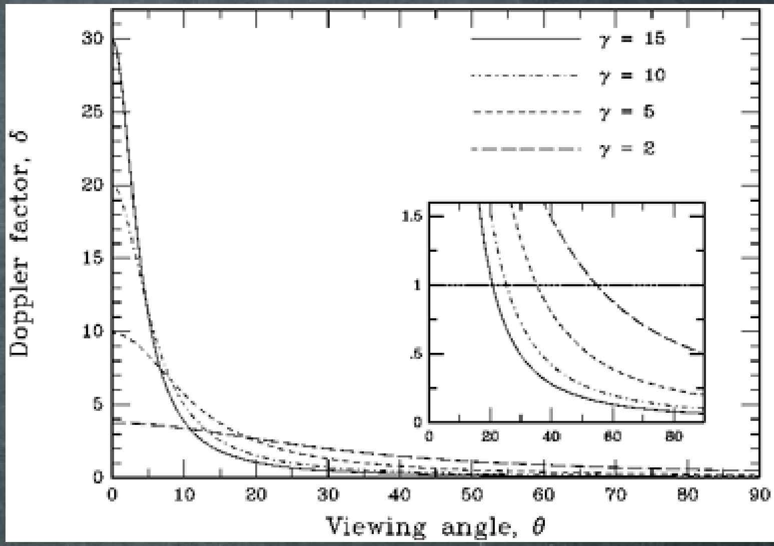
– Geometry of the active region

– Species of radiating particles

– Acceleration of the radiating particles

RELATIVISTIC BEAMING AND JET ORIENTATION

Relativistic effects are important



Doppler boosting:

$F = \delta^4 F'$ (F observed flux)

$\delta = [\Gamma\,(1-\beta\cos\theta)]^{-1}$ Doppler factor

$\beta = v/c$

$\Gamma = (1-\beta^2)^{-1/2}$ Lorentz factor of the flow

For Γ>>1 and θ<<1

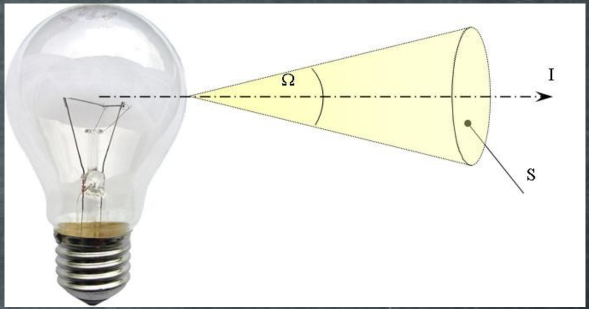
(superluminal motion)

→ δ>>1

RADIATIVE TRANSFER

Observed flux $$F_\nu = I_\nu \, . \, d\Omega$$

Specific intensity

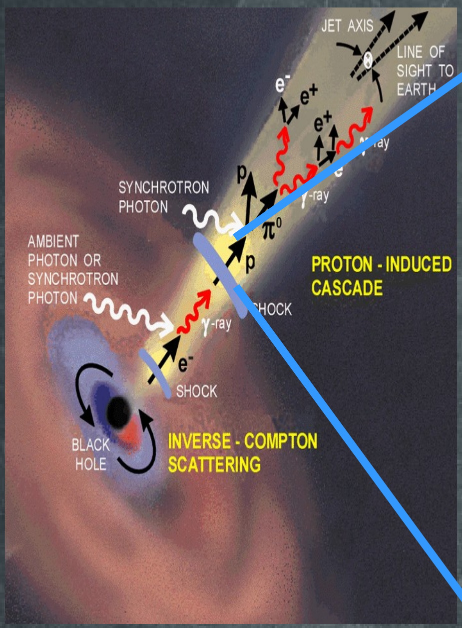


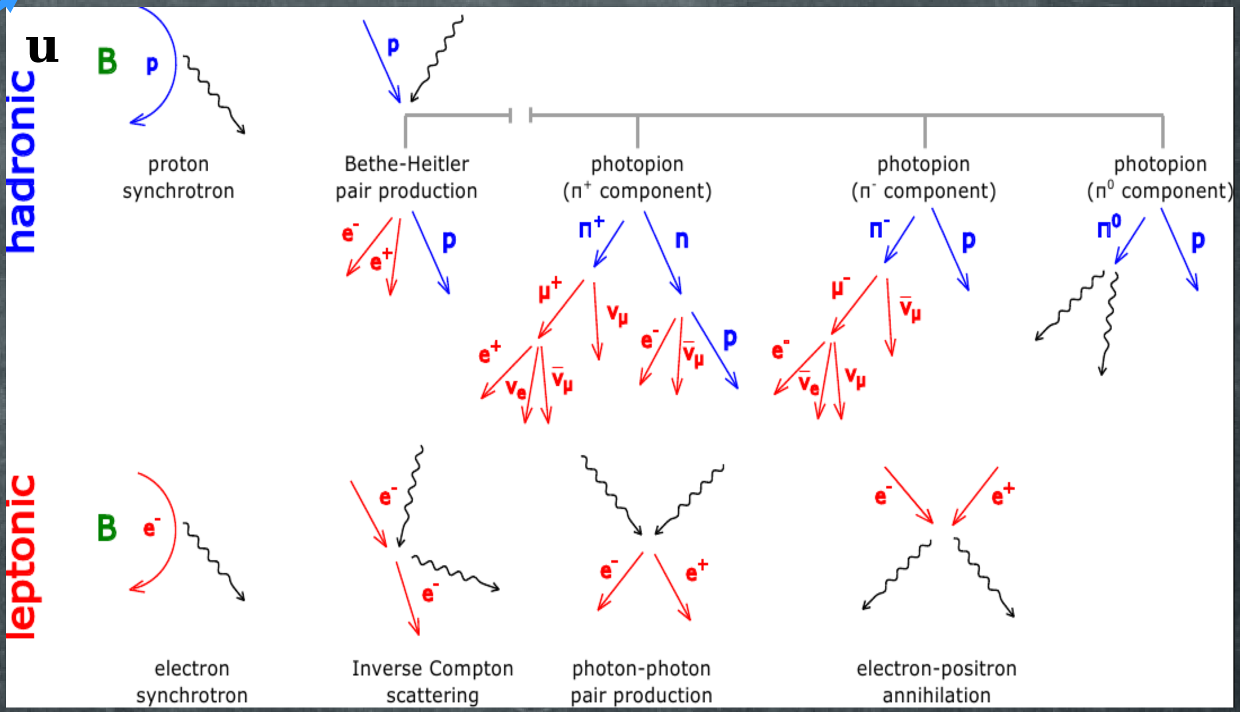
RTE $$\frac{dI_\nu}{ds} = j_\nu - a_\nu \, . \, I_\nu$$

emission absorption

For Blazar jets: Specify j, α and geometry of emitting region →
Solve RTE in the comoving frame → Specific Intensity →
Doppler boosting → Flux

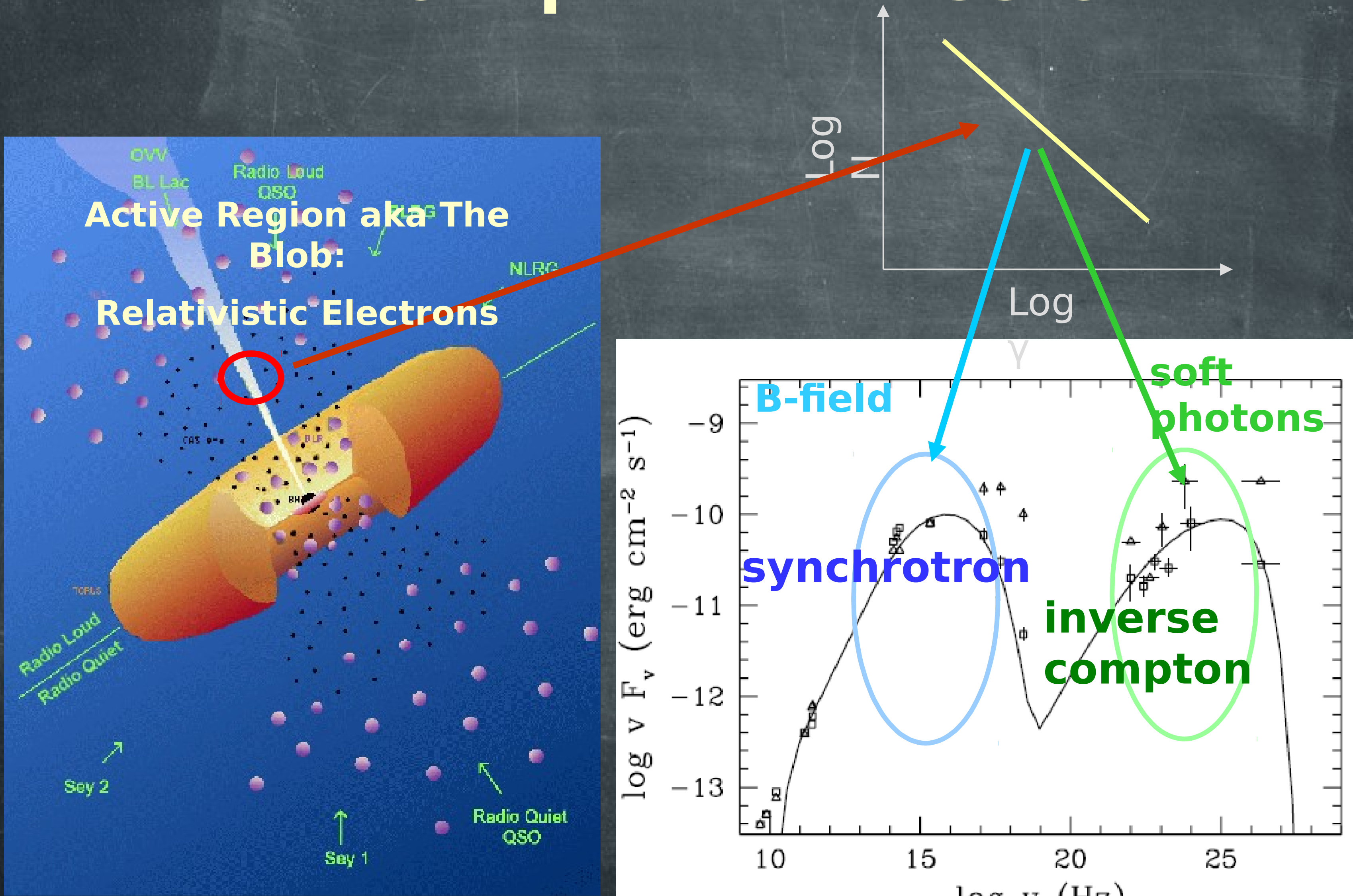
PHYSICAL PROCESSES FOR SPECTRAL FORMATION



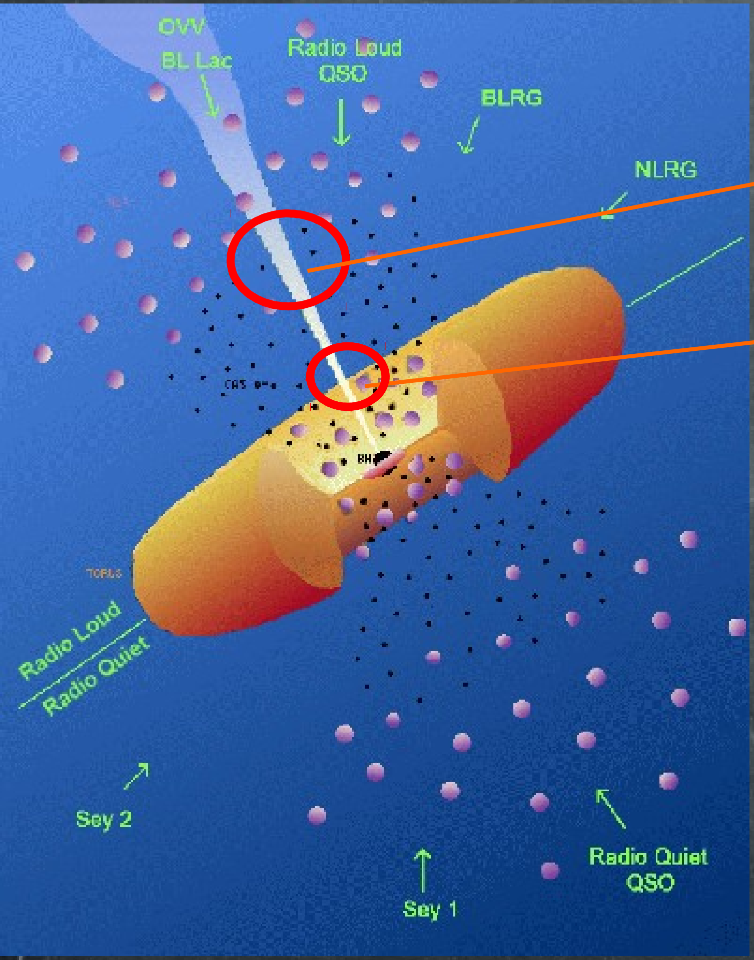


Other processes less relevant but can be added extra spice
- Relativistic Bremsstrahlung
- Double Compton scattering
- Triplet Pair Production
- Proton-proton interactions

THE ONE-ZONE LEPTONIC MODEL FOR γ-RAY EMISSION



SOURCES OF PHOTON TARGETS FOR INVERSE COMPTON



External to the radiation zone

BLR photons
(D~pc)

Accretion disc photons
(D~100s Rg)

Internal to the radiation zone

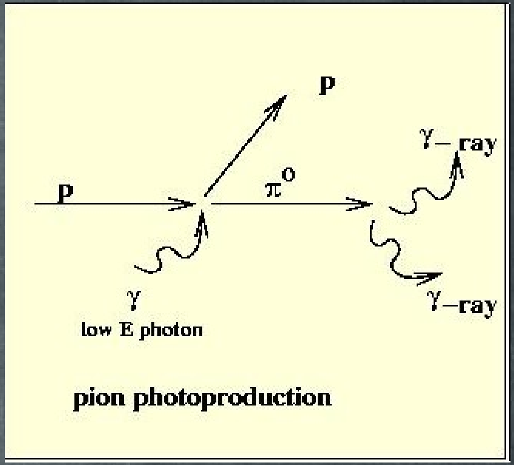
Synchrotron Self-Compton

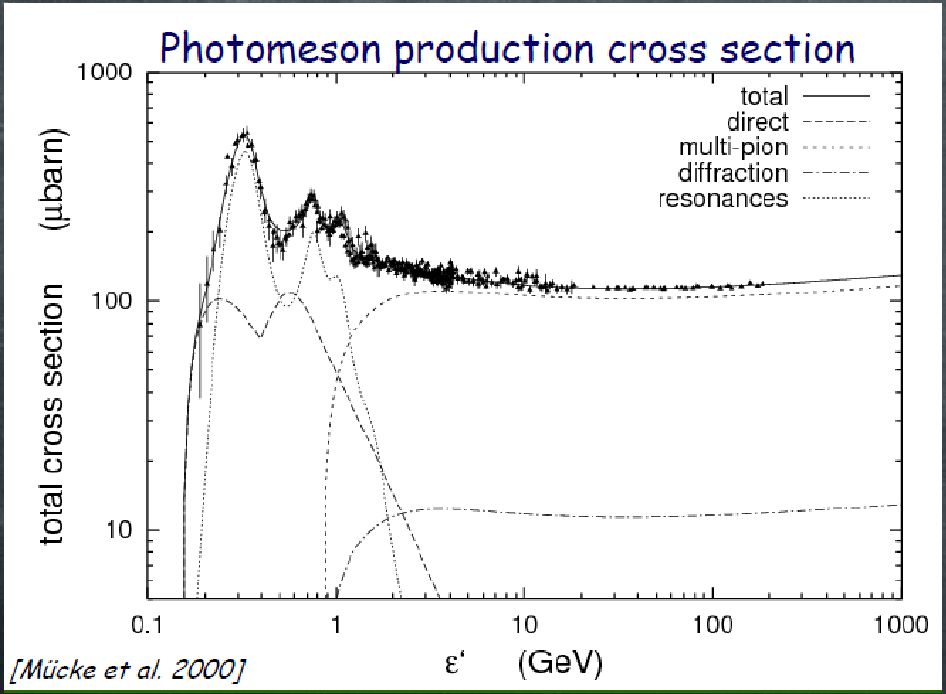
Importance of each photon source depends on its energy density

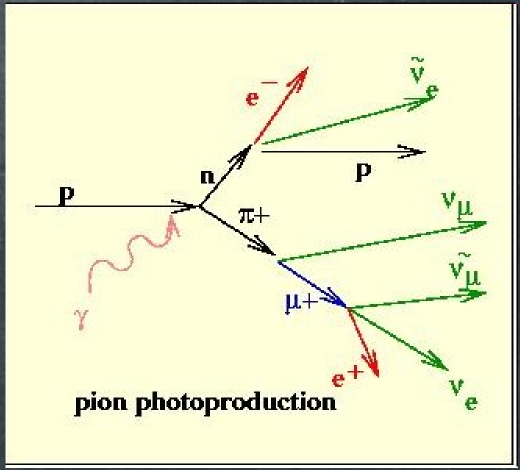
INTERACTIONS OF PROTONS WITH PHOTON FIELDS – PHOTOPION

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

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



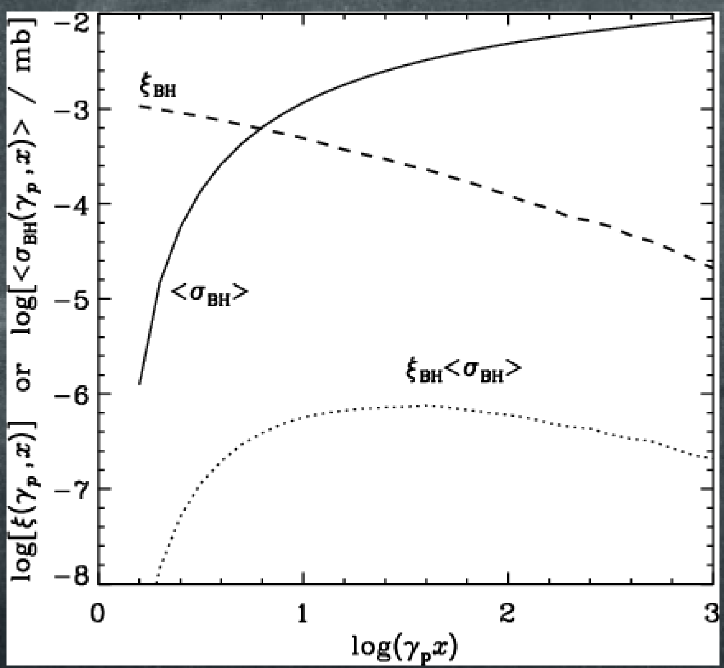


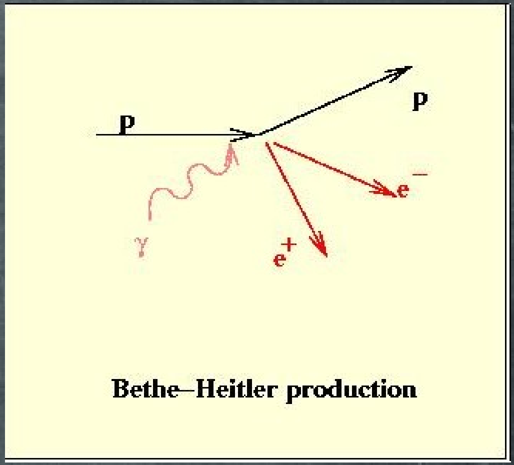


INTERACTIONS OF PROTONS WITH PHOTON FIELDS – PHOTOPAIR

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

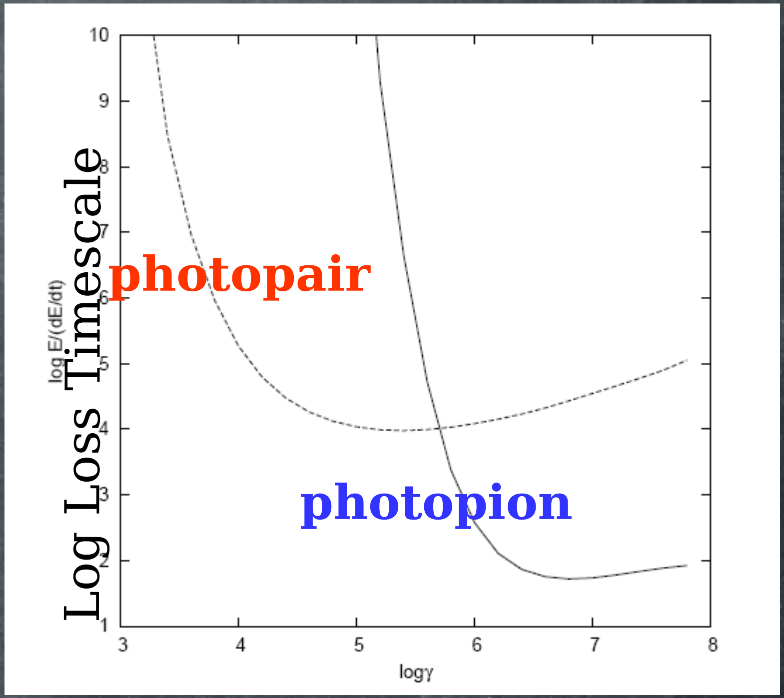
$$s^{1/2}_{\mathrm{threshold}} = m_p + 2m_e$$





PHOTOPAIR vs PHOTOPION

Both processes involve high energy protons and soft photons → direct competition for proton energy losses



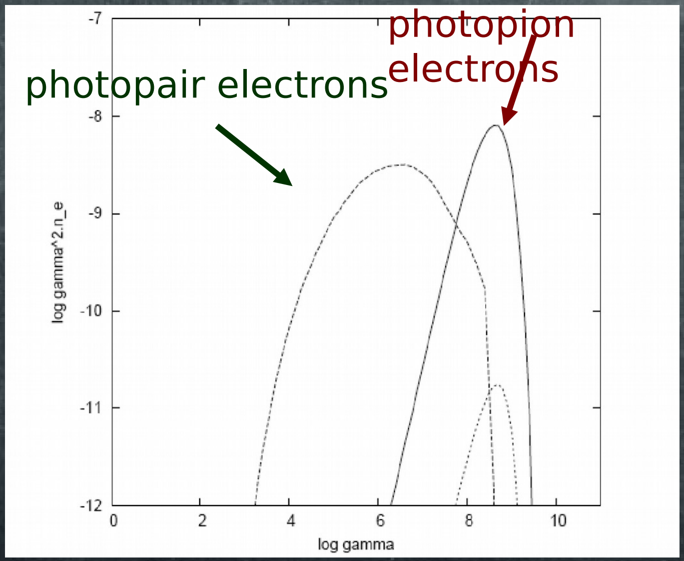
	photopair	photopion
Threshold (PRF) (MeV)	~1	~140
Cross section (mb)	~10	~0.1
Inelasticity	~0.001	~0.1

INJECTION OF SECONDARY ELECTRONS AND PHOTONS

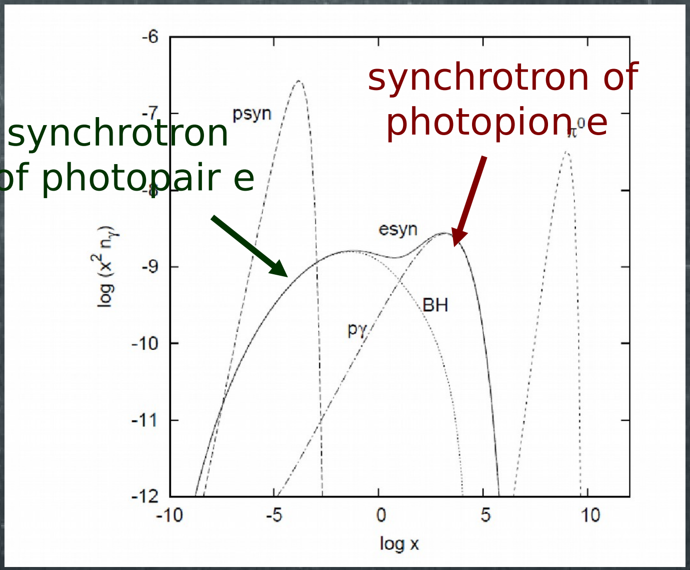
Photo-pair secondary production spectra:
Protheroe & Johnson (1996)

Photopion: SOPHIA event generator
(Muecke et al 2000)

electrons

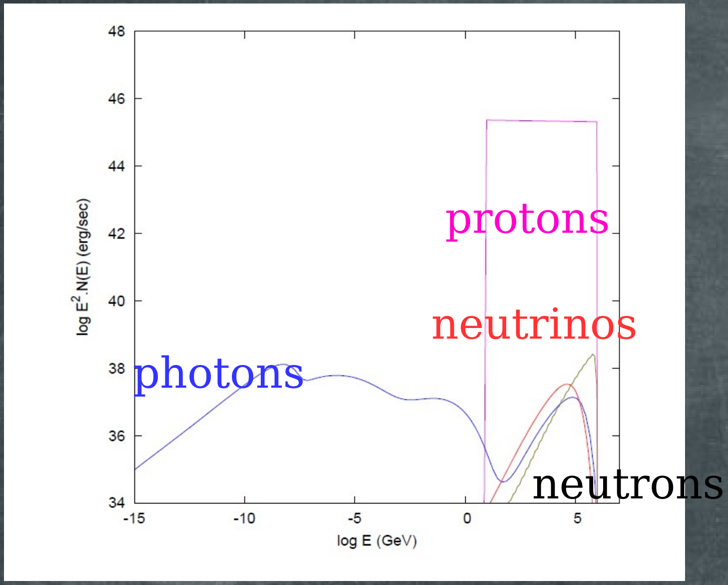


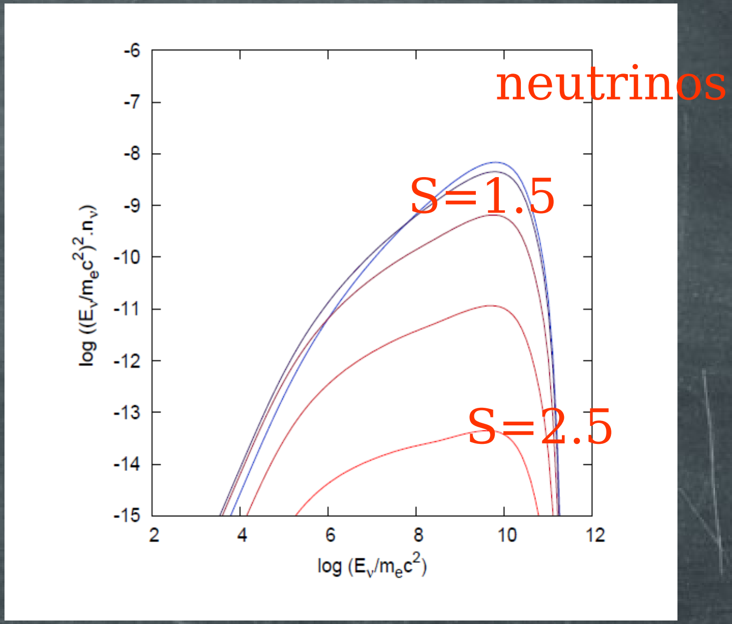
photons



S. Dimitrakoudis et al. 2012

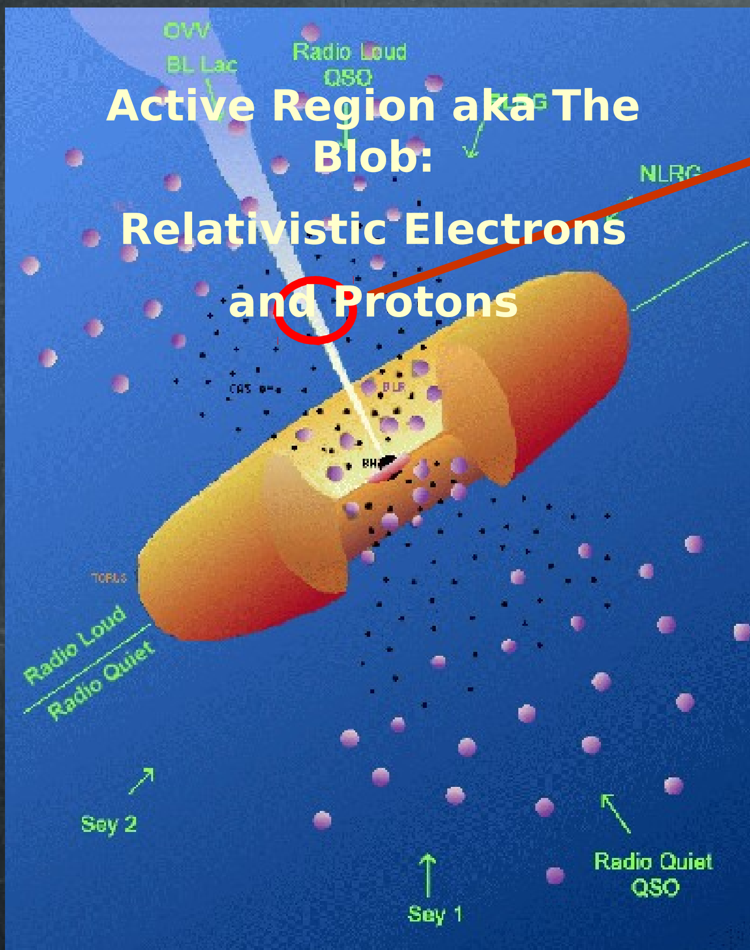
PRODUCTION SPECTRA OF SECONDARIES





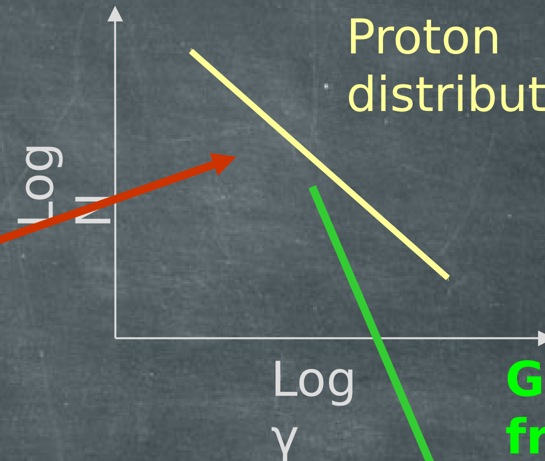
Dimitrakoudis et al 2012

THE (LEPTO)HADRONIC MODEL

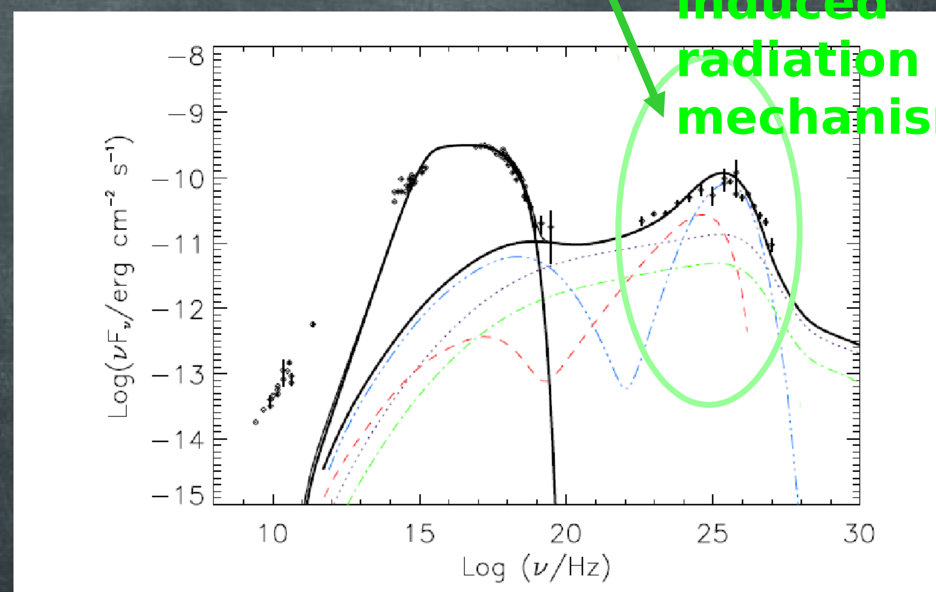


Active Region aka The Blob:

Relativistic Electrons and Protons

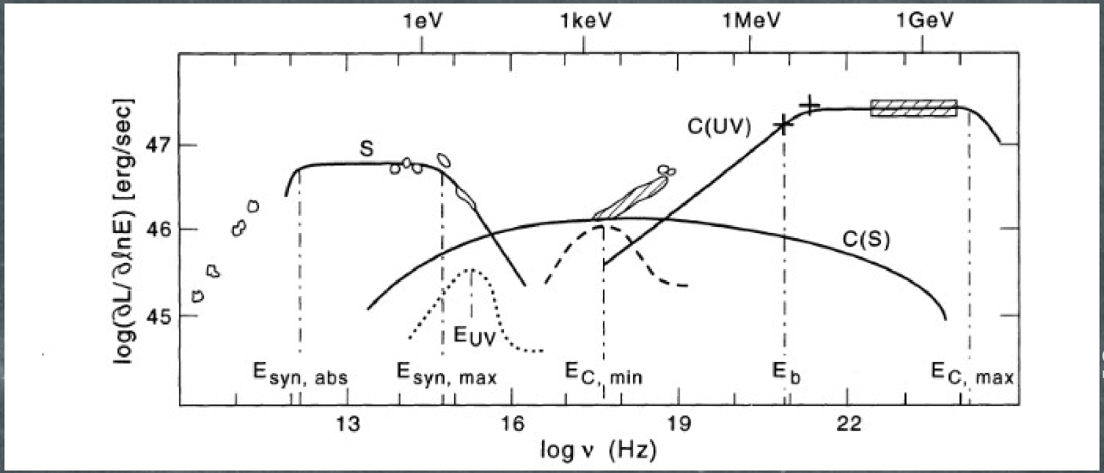


Proton distribution

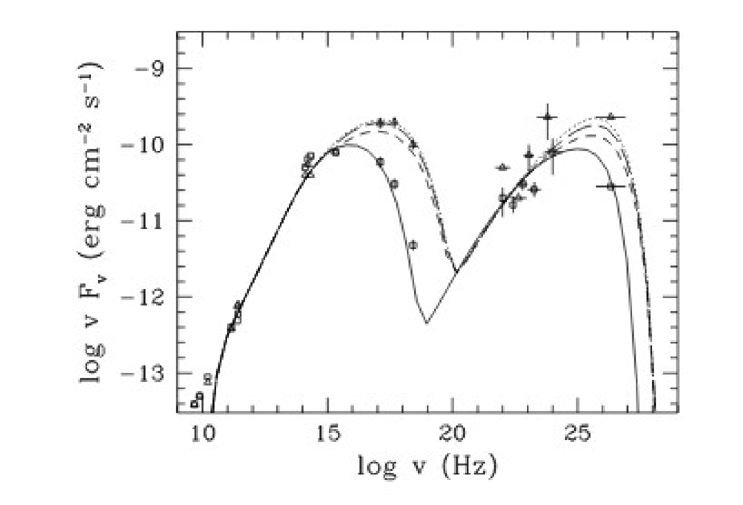


Gamma-rays from proton induced radiation mechanisms

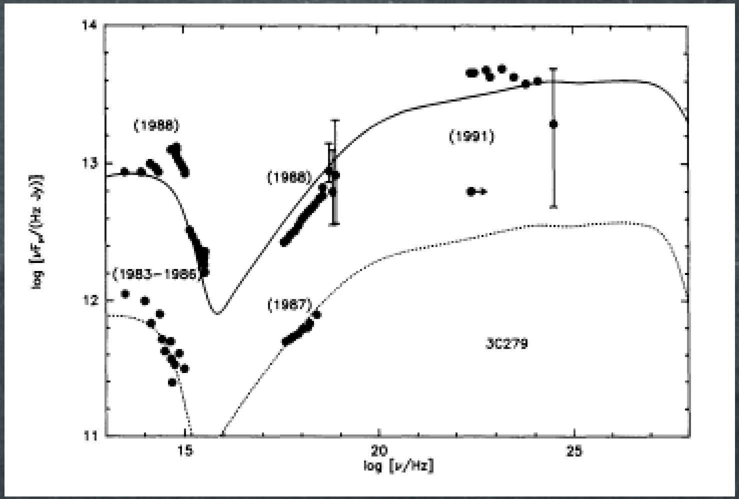
FOSSILS UNEARTHED



Sikora et al 1994



AM & Kirk 1997



Mannheim 1993

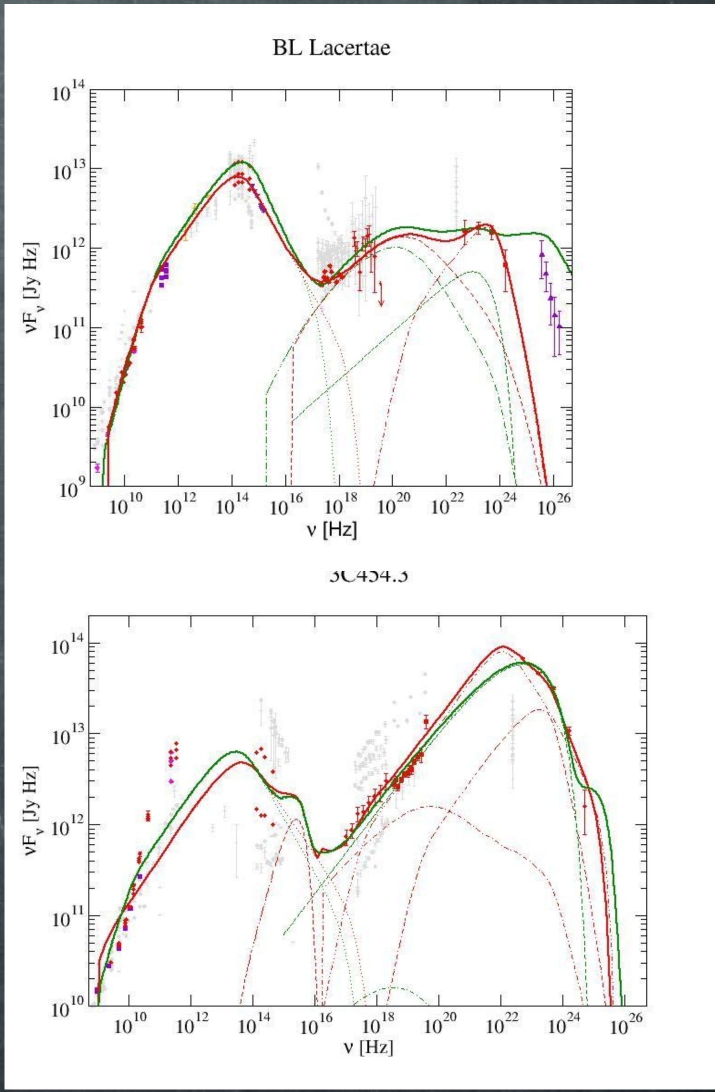
PRESENT-DAY STATUS

– Both classes produce equally good fits

– Leptonic models mostly in particle - B-field Equipartition

– Hadronic models require
1. High power (L~ 10^48 erg/s)
   – hadronic processes are inefficient
2. High E_max
   For TeV emission
   – Photo-hadronic ~ PeV (threshold V-phot)
   – Proton synchrotron ~ EeV
3. High B (>10 G) – gyroradii < source size
   (+ supress the SSC component)

– How to discriminate?
   – Variability?



Boettcher et al 2013

CONTESTED ASTROPHYSICS

Dublin, 12-14 April, 2016

When Experts Disagree
WEXD

Organised by DIAS, the workshop will examine areas of current disagreement in high-energy astrophysics and will be attended by scientists as well as some philosophers of science and experimental philosophers. It forms part of an interdisciplinary project between philosophy and science on expert disagreement funded by the Irish Research Council. There will be no written proceedings and we hope to emulate something of the open discussion of the Aspen workshops with frank discussions of disputed areas, if desired under the Chatham House rule (you can say what was said, but not who said it).

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 in power-law distributions)

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

SPECTRAL FORMATION: THREE DIFFERENT APPROACHES

Use a ‘tailor-made’ particle distribution function + textbook emissivities

- Very good fits

- Some ad-hoc assumptions (e.g. multiple breaks in power-law distribution)Use a ‘tailor-made’ particle distribution function + textbook emissivities

2. Create particle distribution functions from injection rates → kinetic equations (→ RTE analogy)

   - Self-consistency (energy conserved)

   - Temporal studies (flaring)

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

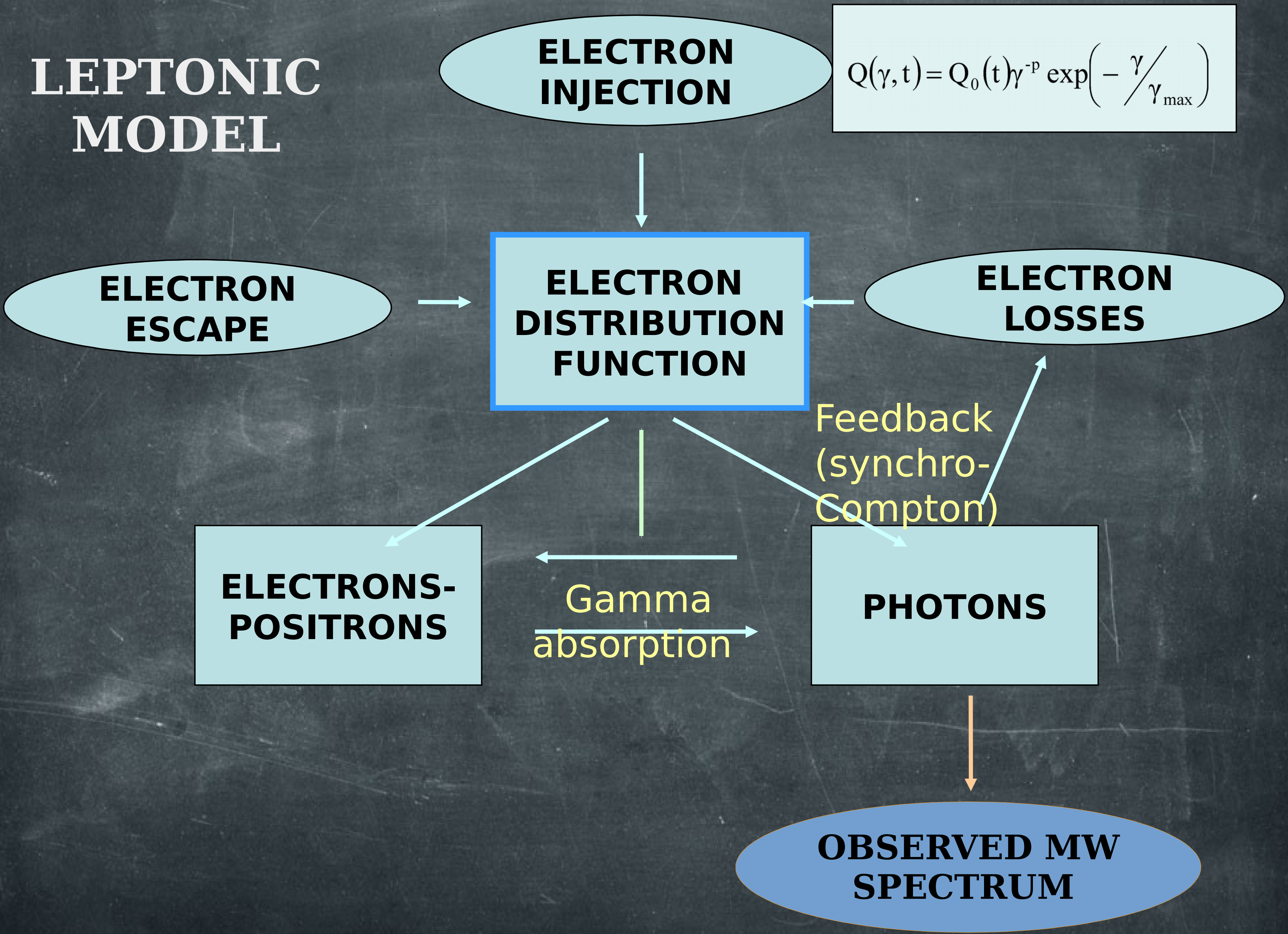
3. Use acceleration scheme → injection rates

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

   - Simplified acceleration schemes

complexity

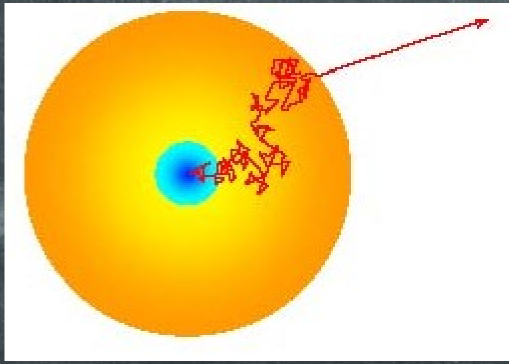
LEPTONIC MODEL



RADIATIVE TRANSFER: AN ANALOGY

STELLAR ASTROPHYSICS

- Stellar core emits hard photons ε_γ (nuclear lines)
- Energy is degraded as photons diffuse on stellar envelope
- Surface emits $\varepsilon_\nu \sim \kappa T << \varepsilon_\gamma$

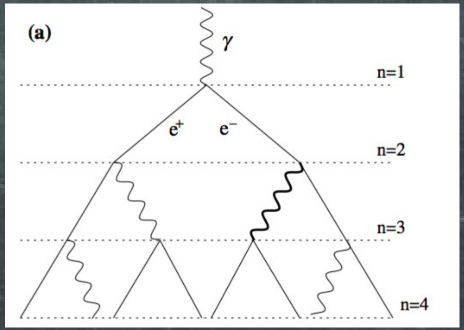


HIGH ENERGY ASTROPHYSICS

- Blob emits gamma-rays
- If absorbed → creation of secondary ee pairs
- Pairs emit more gamma rays

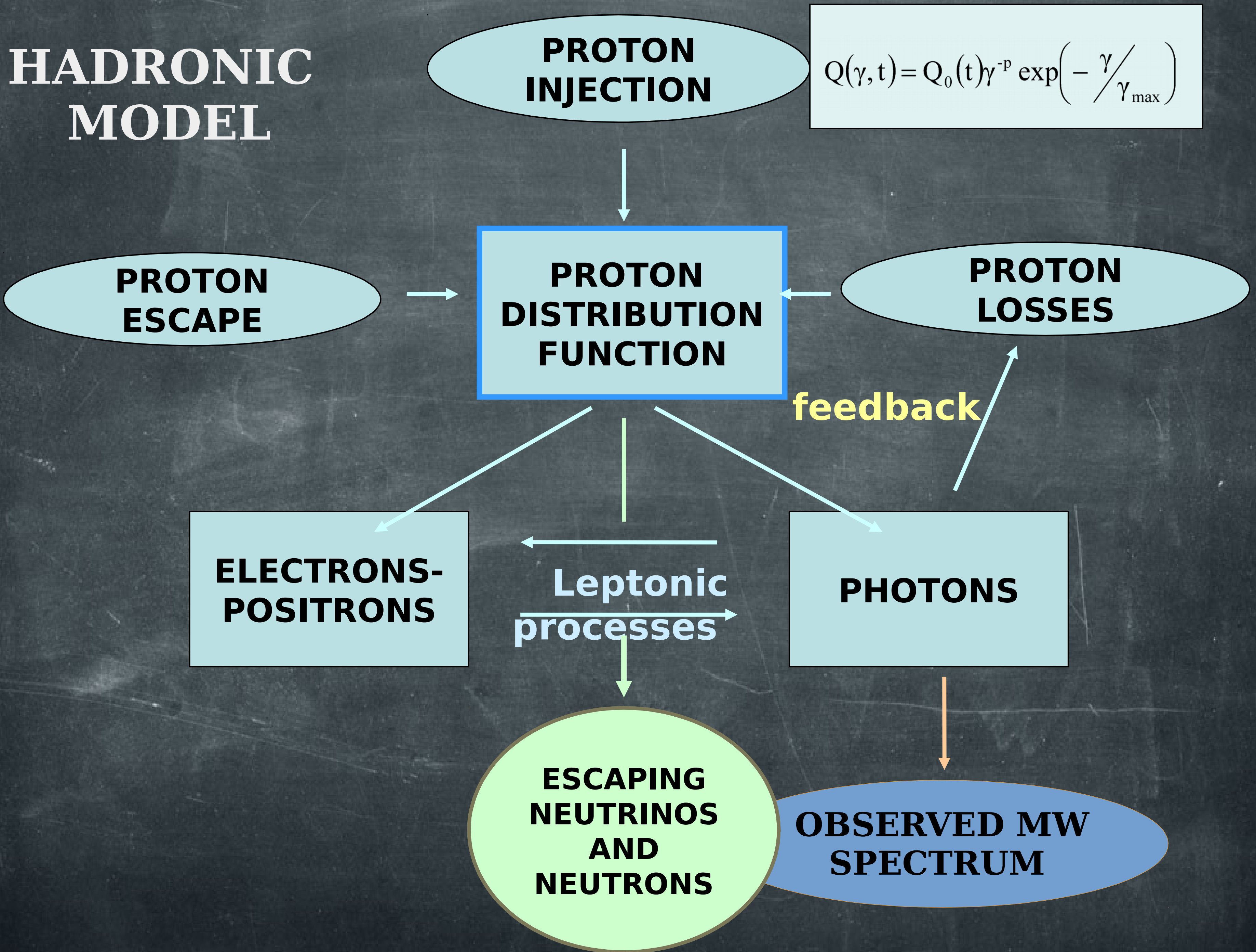
→ photon energy is degraded (initial energy is shared by many)

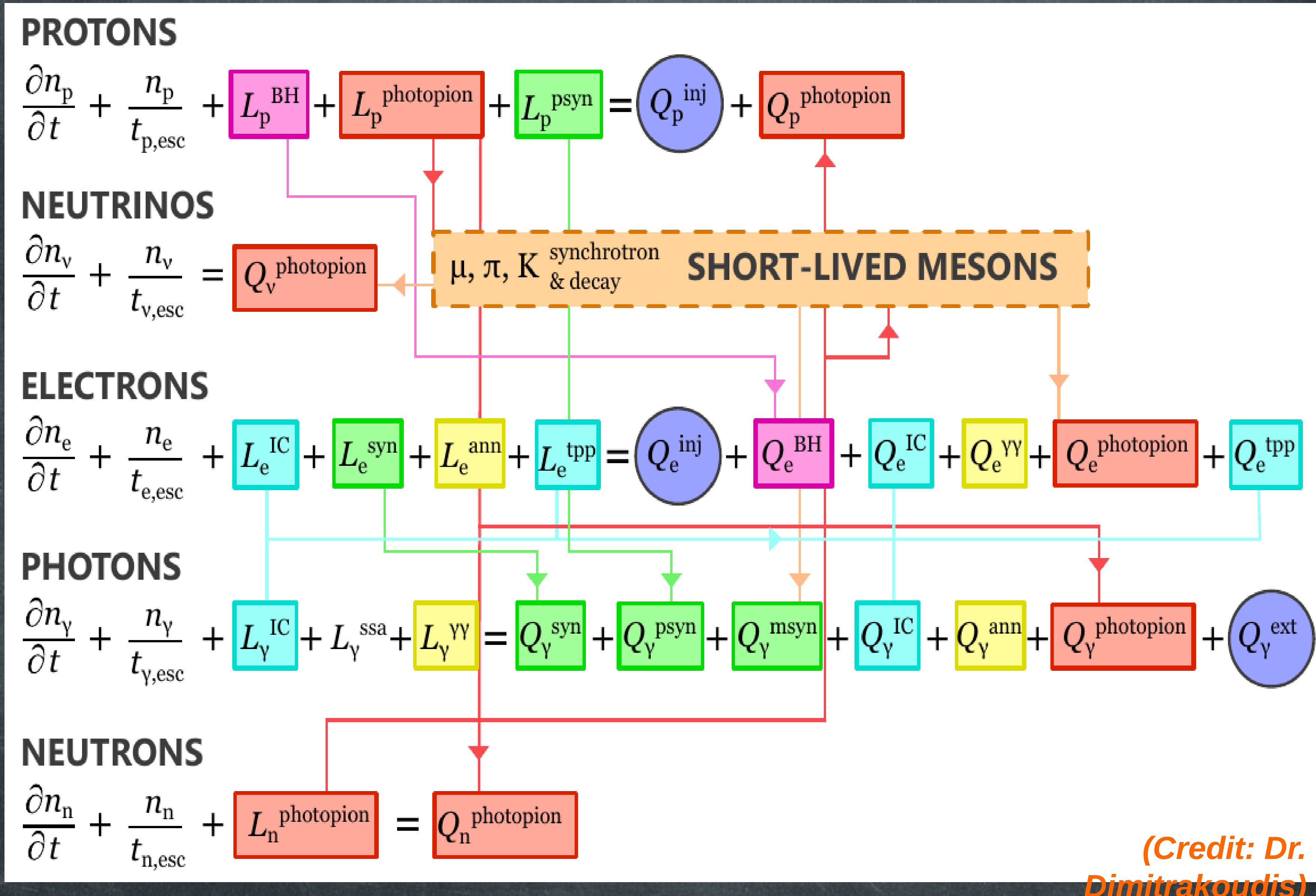
→ electromagnetic cascade



Luminosity is conserved **but** photon energy is downgraded

HADRONIC MODEL





AM & Kirk 1995

Dimitrakoudis et al. 2012

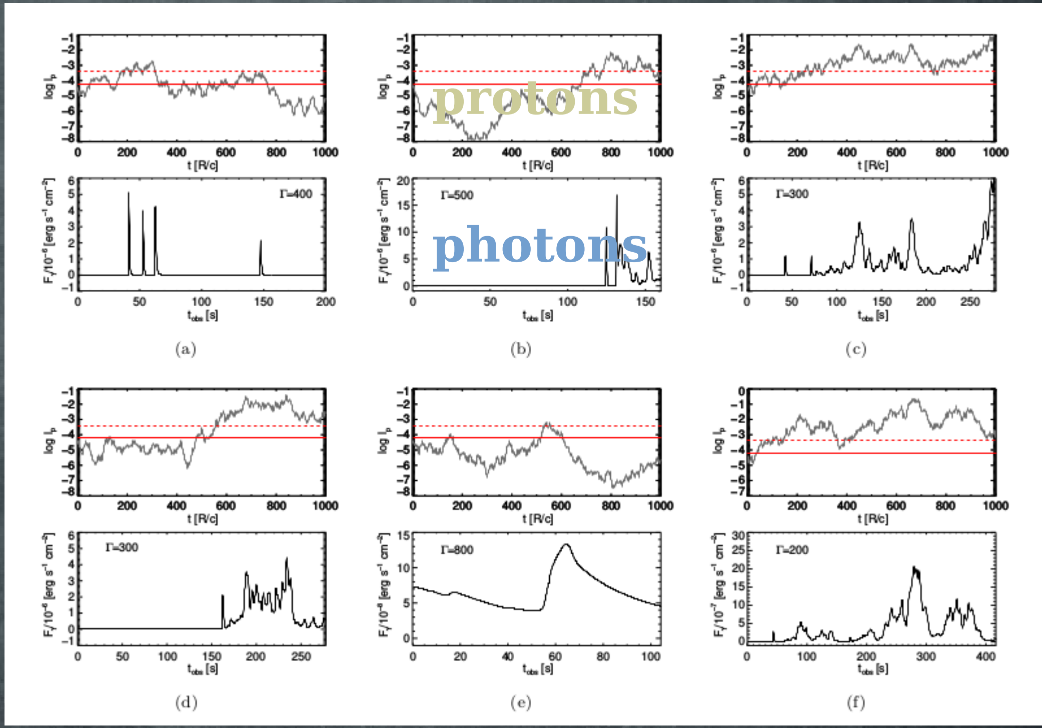
PROTON SUPERCRITICALITIES

Hadronic systems are inherently non-linear (Kirk & AM 1992)

Lotke-Volterra type of equations

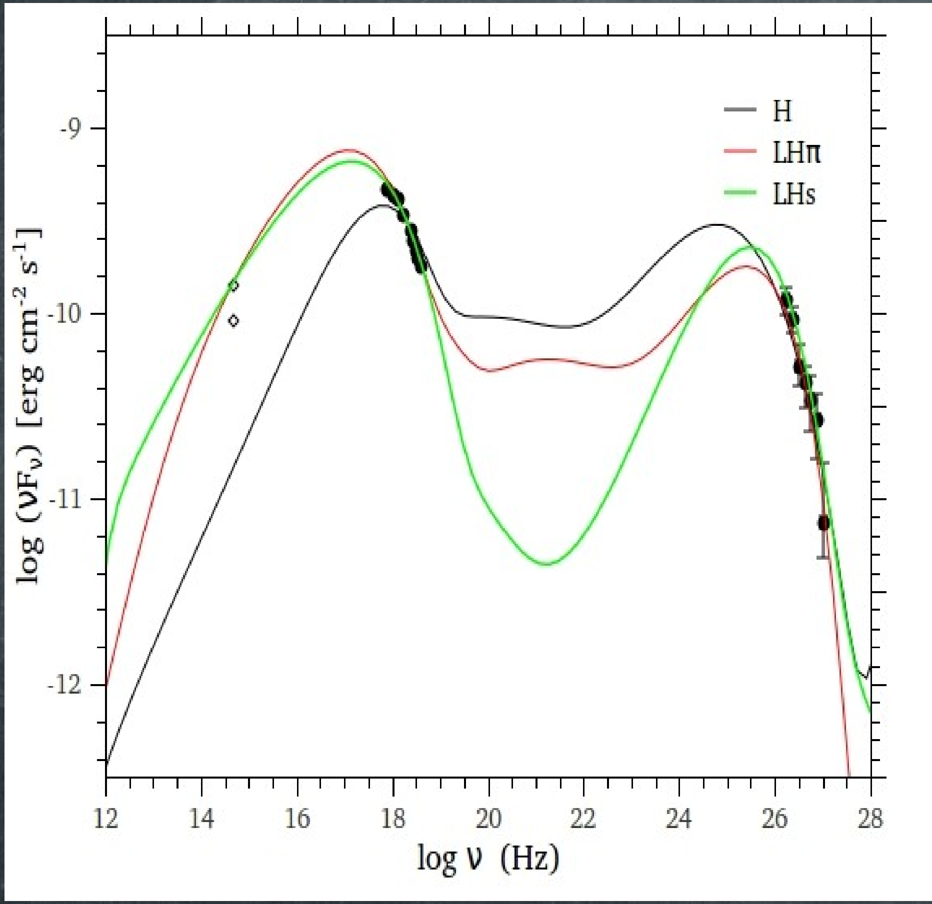
For low proton densities (subcritical): steady-state

For high proton densities (supercritical):
photon outbursts / complicated time behaviour



Petropoulou & AM 2018

SED OF Mrk 421: LEPTO-HADRONIC MODELING



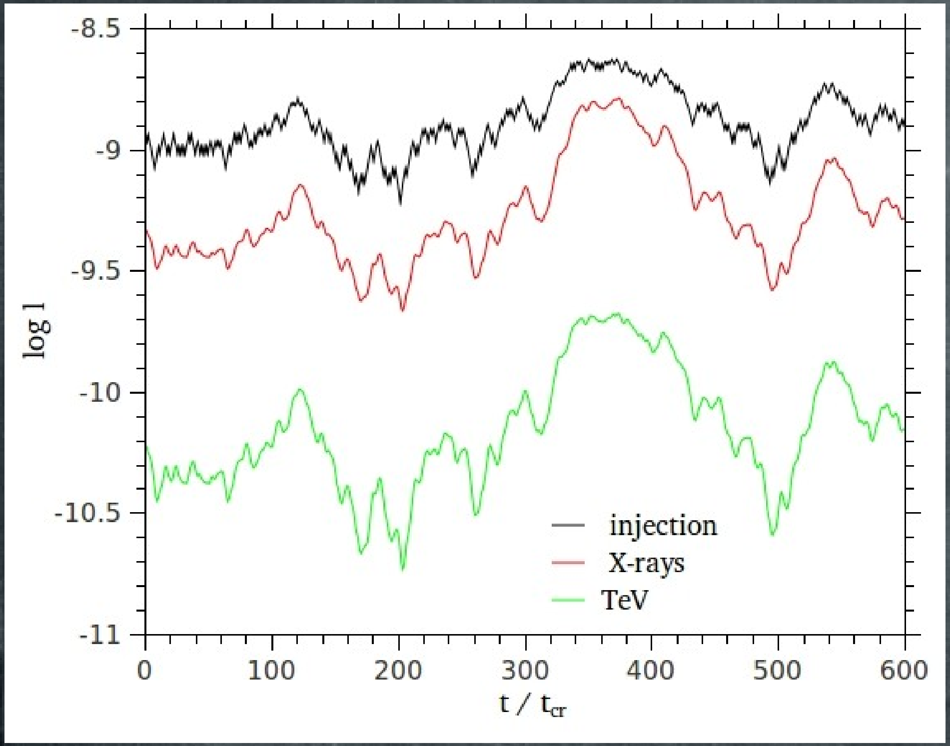
	V-X-rays	γ-rays
LH-π model	e-syn	photopion
LH-s model	e-syn	p-syn

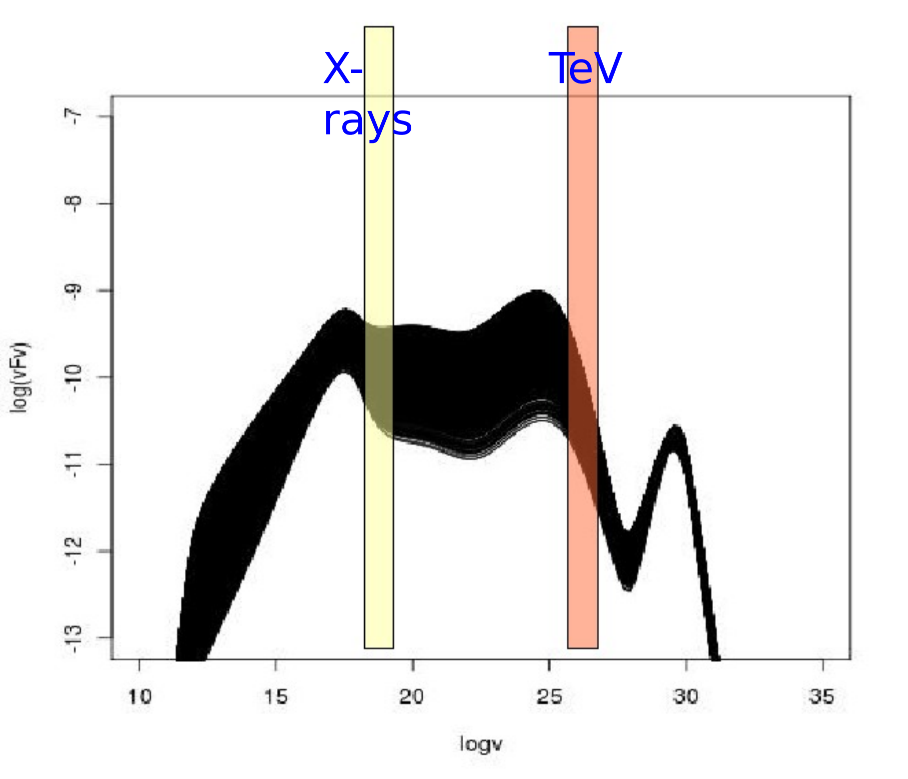
	LH-π	LH-s
Dominant energy density	Protons	B-field
Maximum proton energy	~PeV	~EeV

AM, M. Petropoulou, S. Dimitrakoudis 2013

VARYING THE INJECTION LUMINOSITY

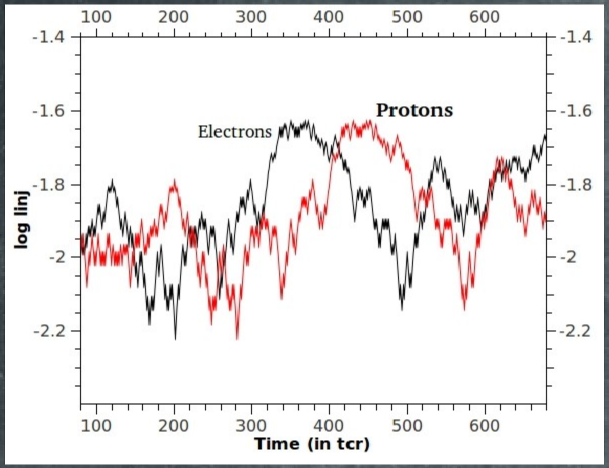
Assume small amplitude random-walk variations in proton and electron injection

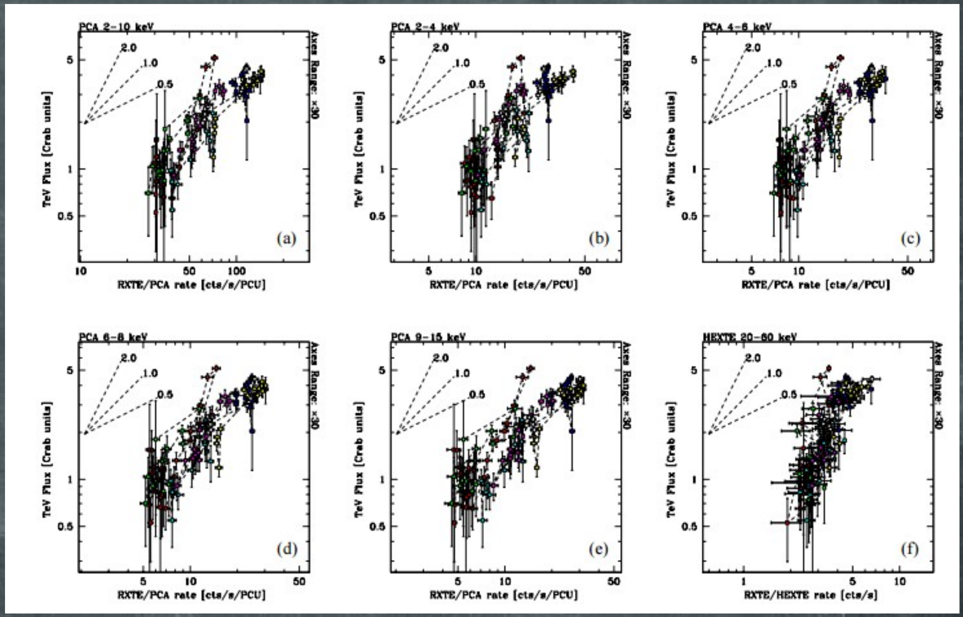




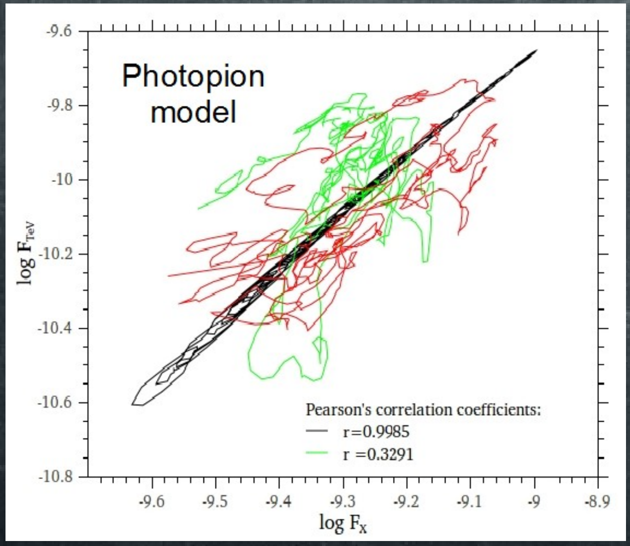
Injection and spectra when p and e totally correlated

X-RAY – GAMMA-RAY CORRELATIONS





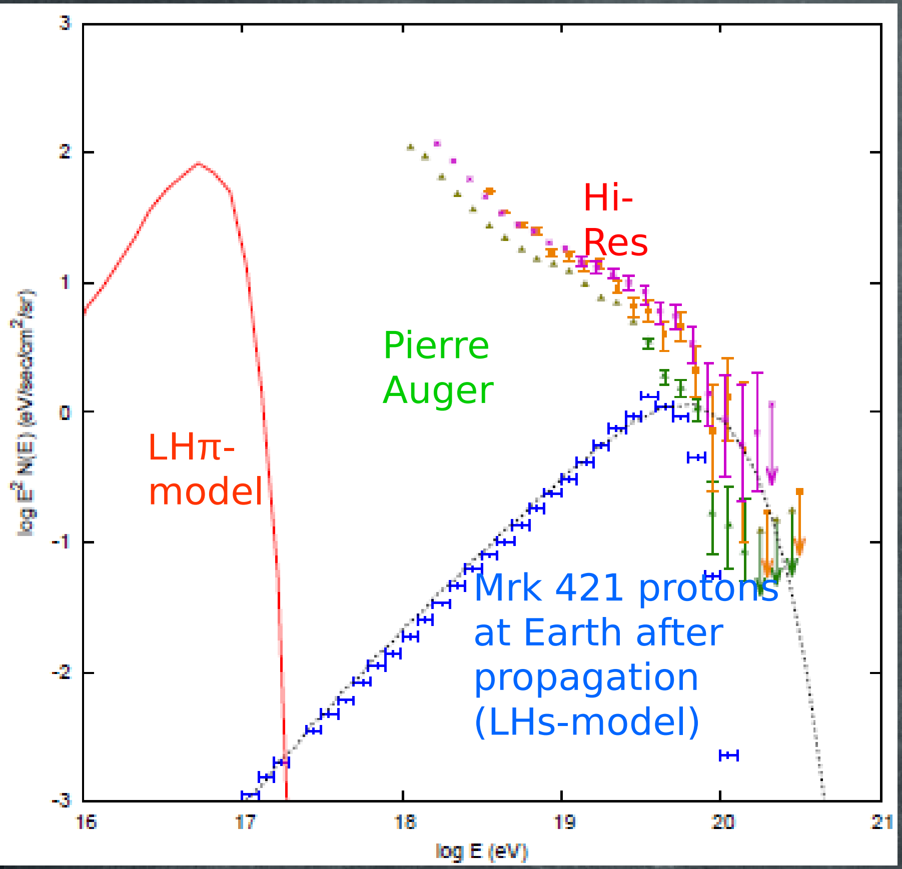
Fossati 2008



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 → observations

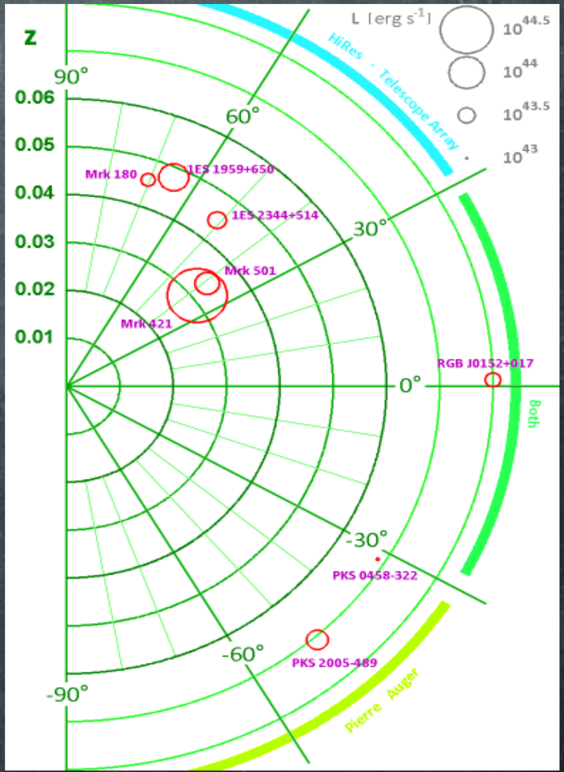
MODEL SIGNATURES: COSMIC RAYS

CR protons from escaping the source n → p (Kirk & AM 1989)



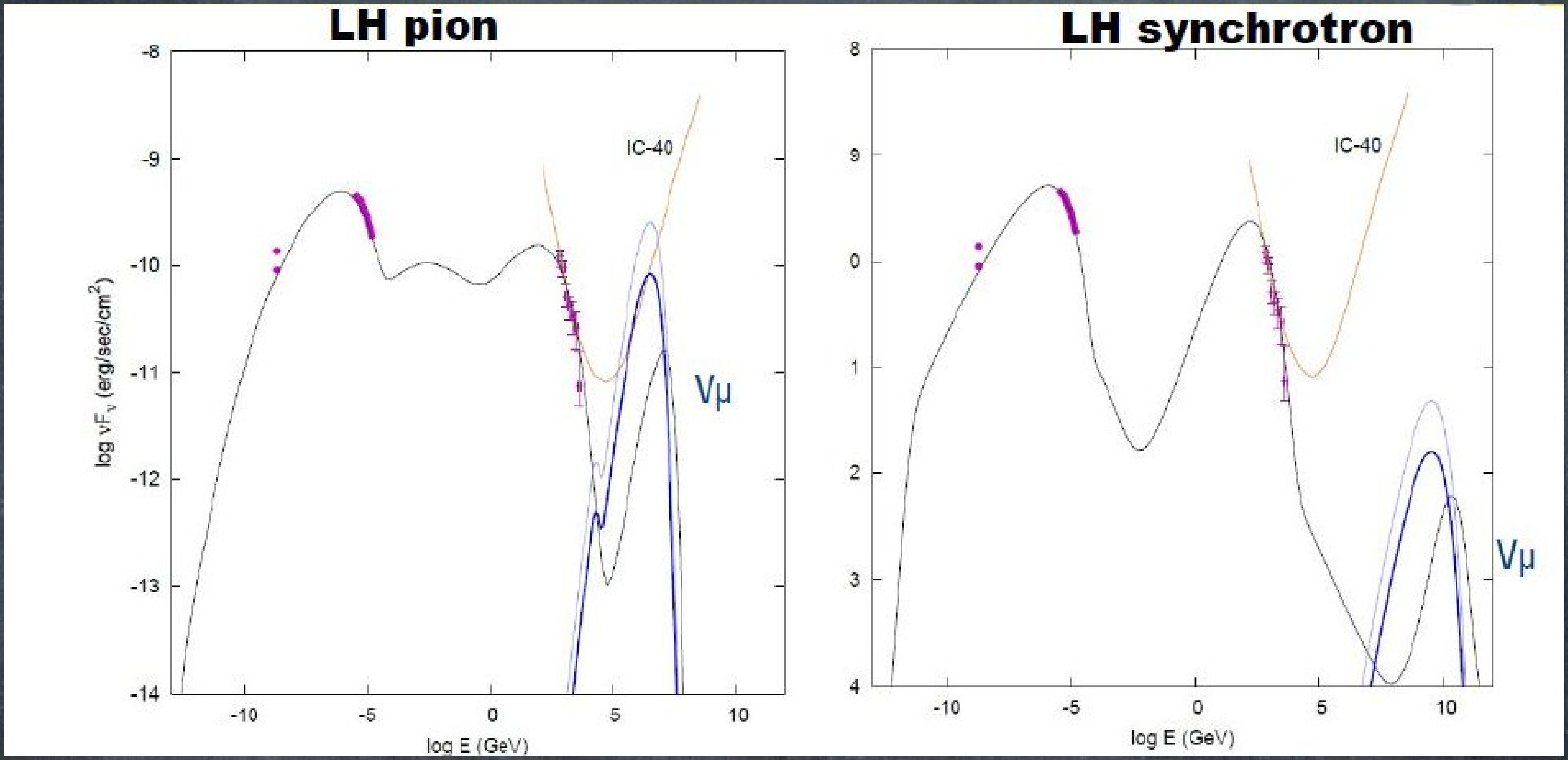
Small UHECR contribution from nearby BL Lac objects if similar to Mrk 421

- ➢ Lower luminosities
- ➢ Larger distances



LHs model: Mrk 421 CR peak at ~30 EeV

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

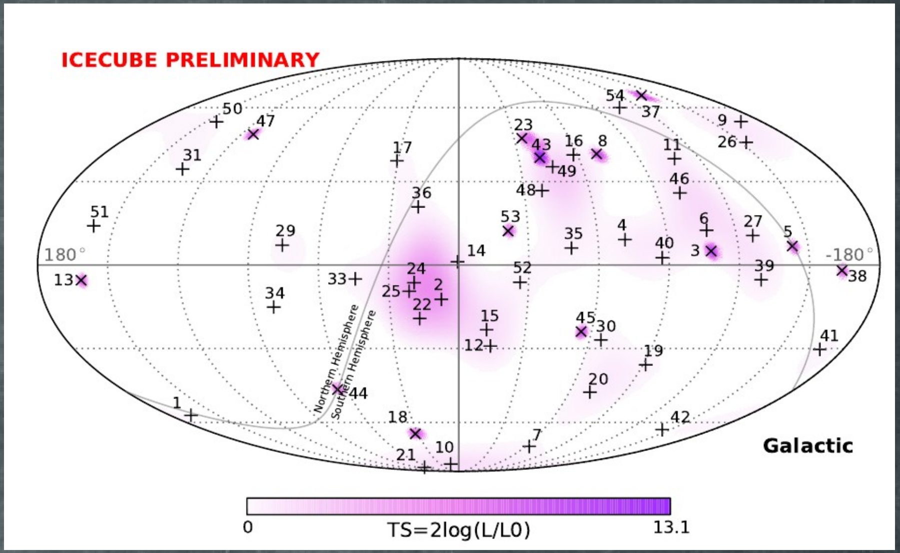
BL Lac – IceCube EVENTS ASSOCIATION?

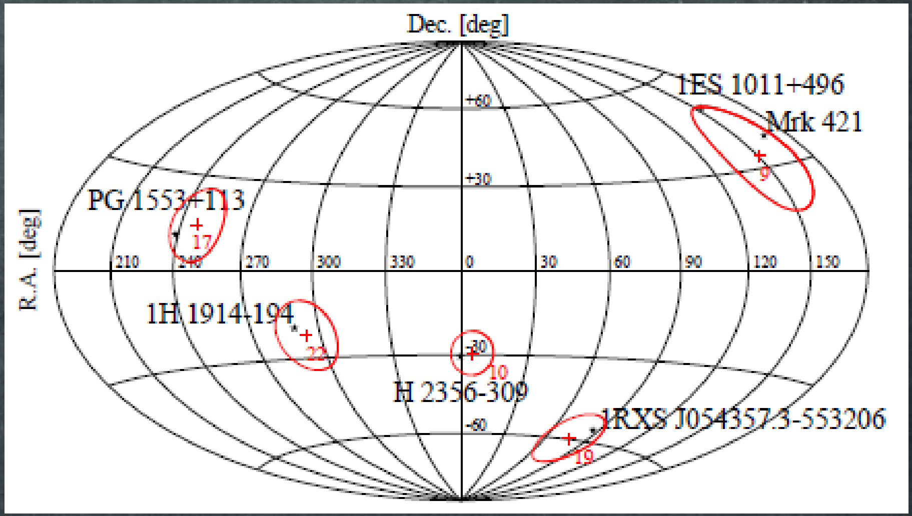
The facts

- 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

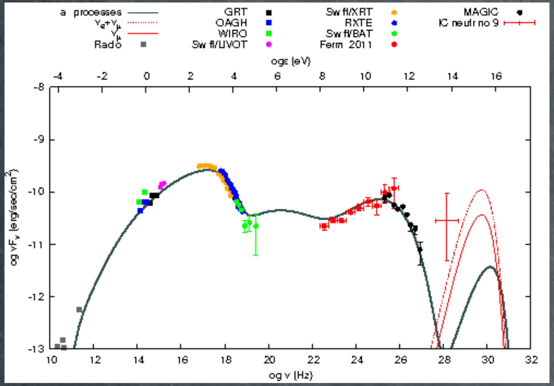
The challenges

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? *(SED fit → source parameters → neutrino flux)*

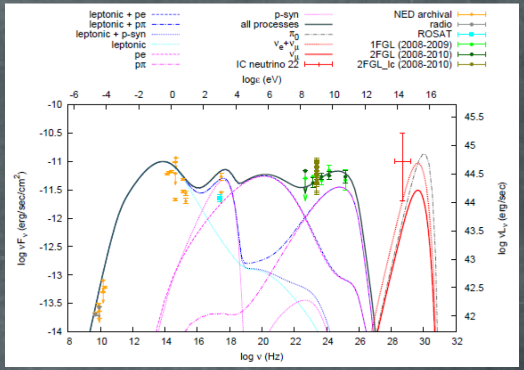




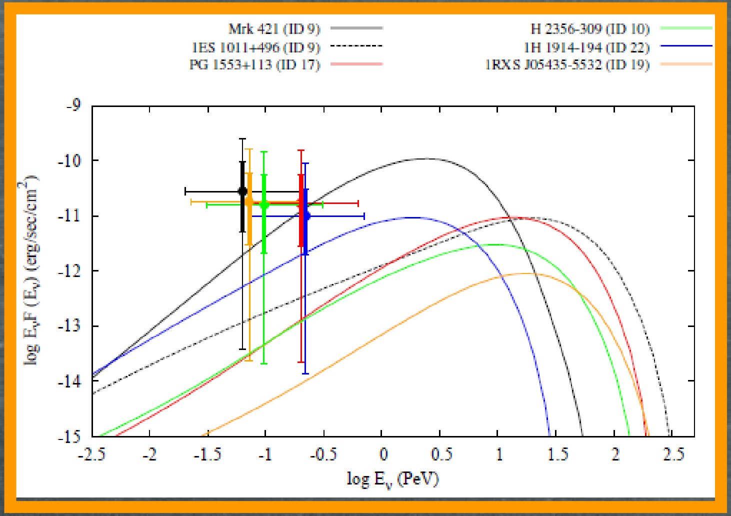
Padovani & Resconi 2014

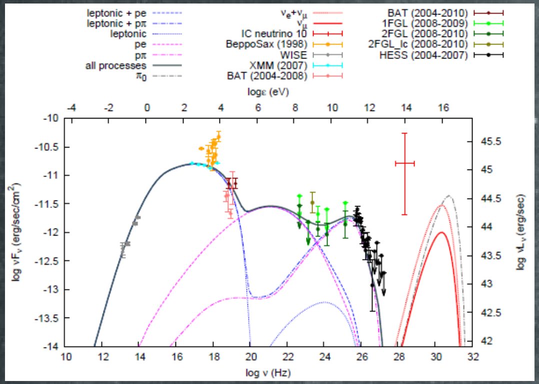


Mrk 421



H 1914-194





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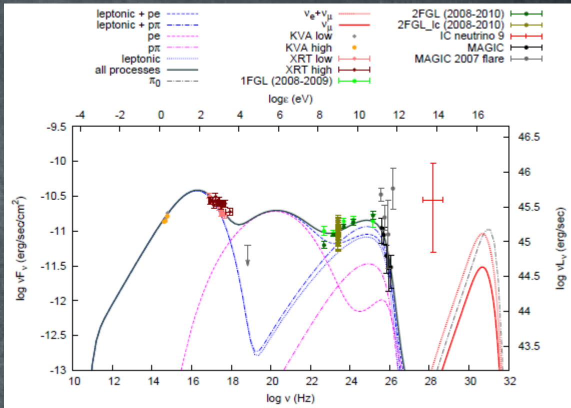

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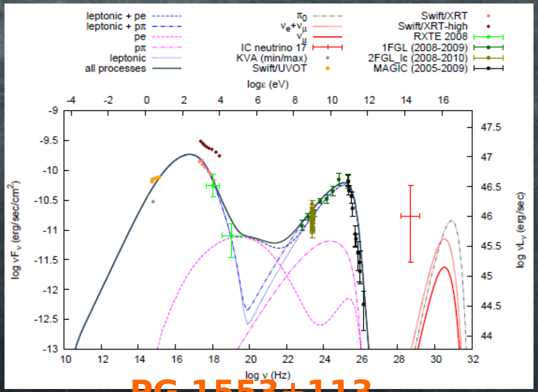
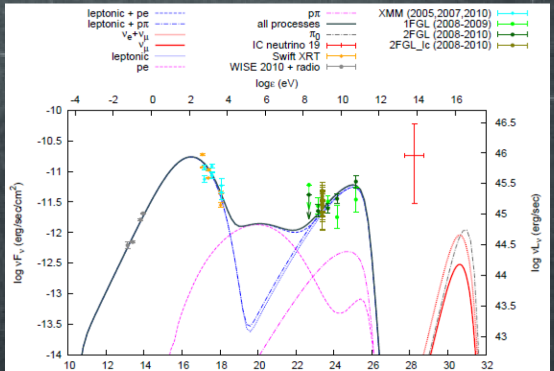


PG 1553+113



1 RXS J054357.3-553206

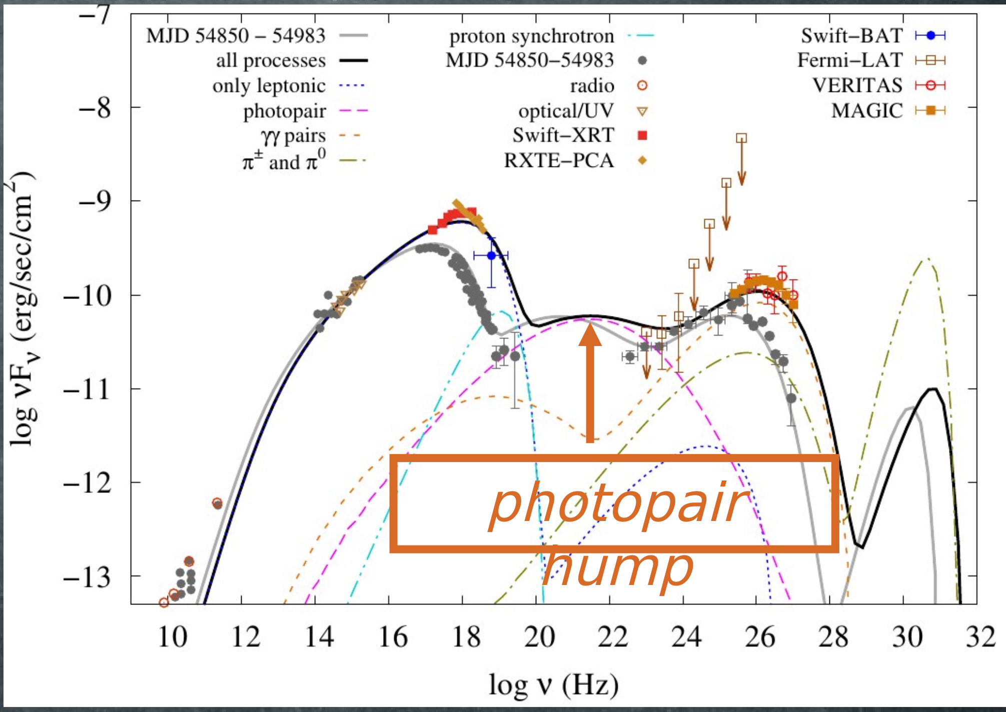
Petropoulou et al 201

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

OVERALL ENERGETICS

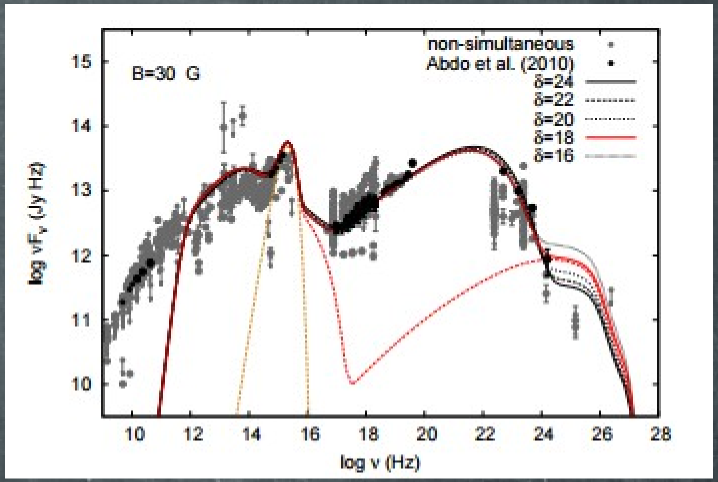
- Simple one-zone synchrotron hadronic fits can be degenerate → different sets of parameters give same fits.
- Minimize the power (similar to equipartition arguments in radio sources with gamma-rays replacing radio and protons replacing electrons) (*Petropoulou & AM 2012*)

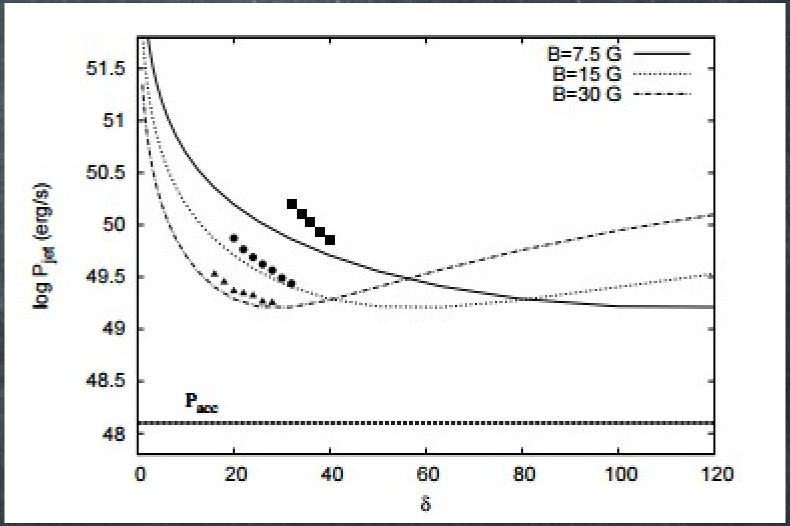
$$P_{jet} \approx \pi R^2 \Gamma^2 c (u_p + u_B)$$

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

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

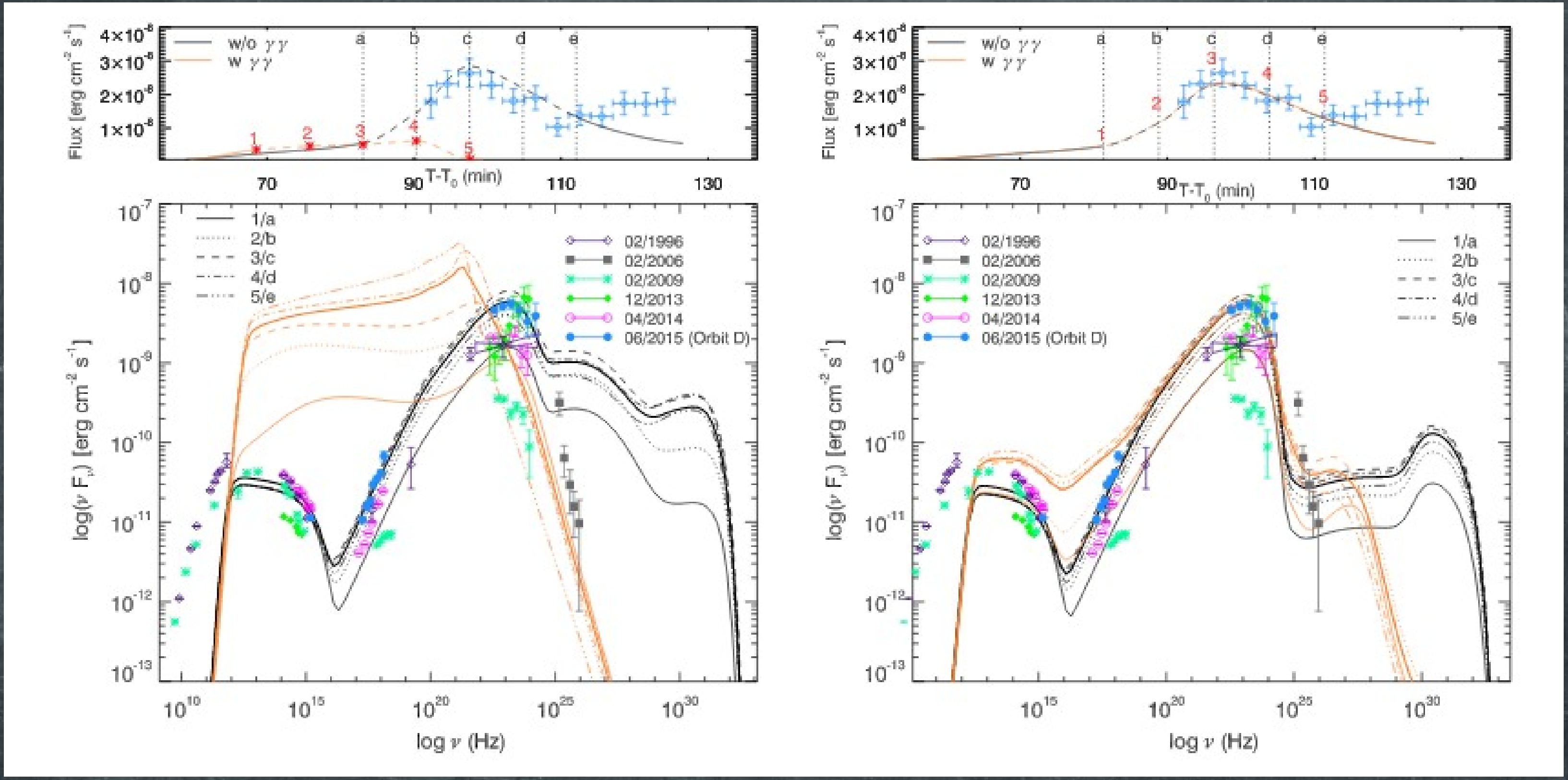
3C273





Petropoulou & Dimitrakoudis 2015

HADRONIC MODELS NOT ALWAYS SUCCESSFUL



Petropoulou et al 2017

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 in power-law distributions)

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

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

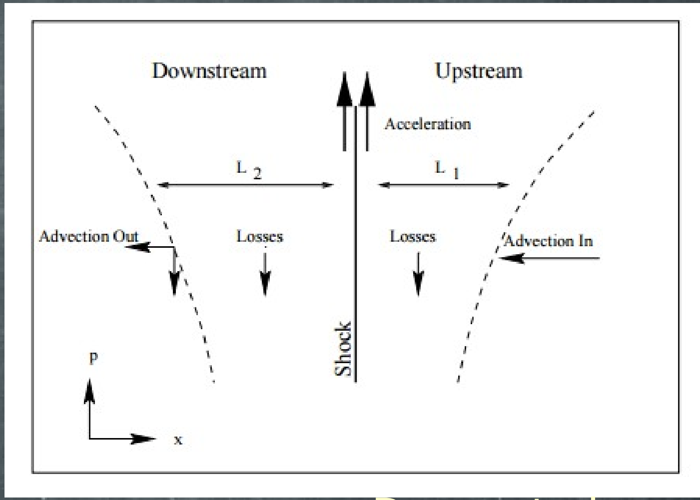
energy loss

particle injection
at low momenta

escape

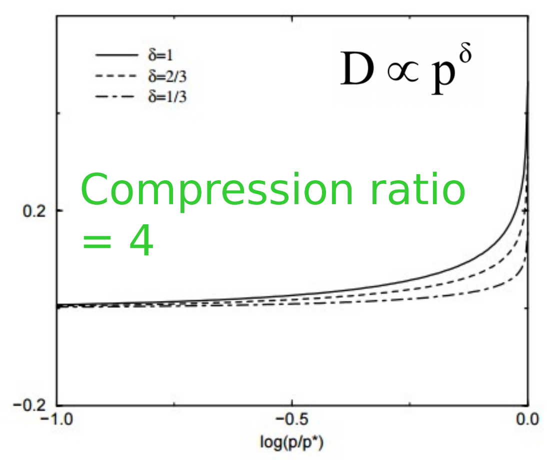
$$r_{acc} = \frac{u.(u_1 - u_2)}{3L}$$

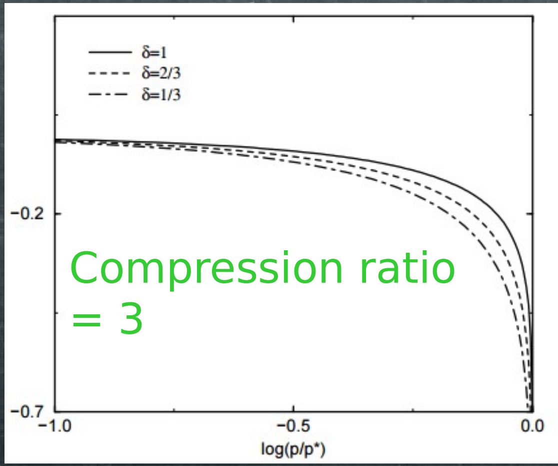
$$r_{esc} = \frac{u.u_2}{L}$$



Drury et al.

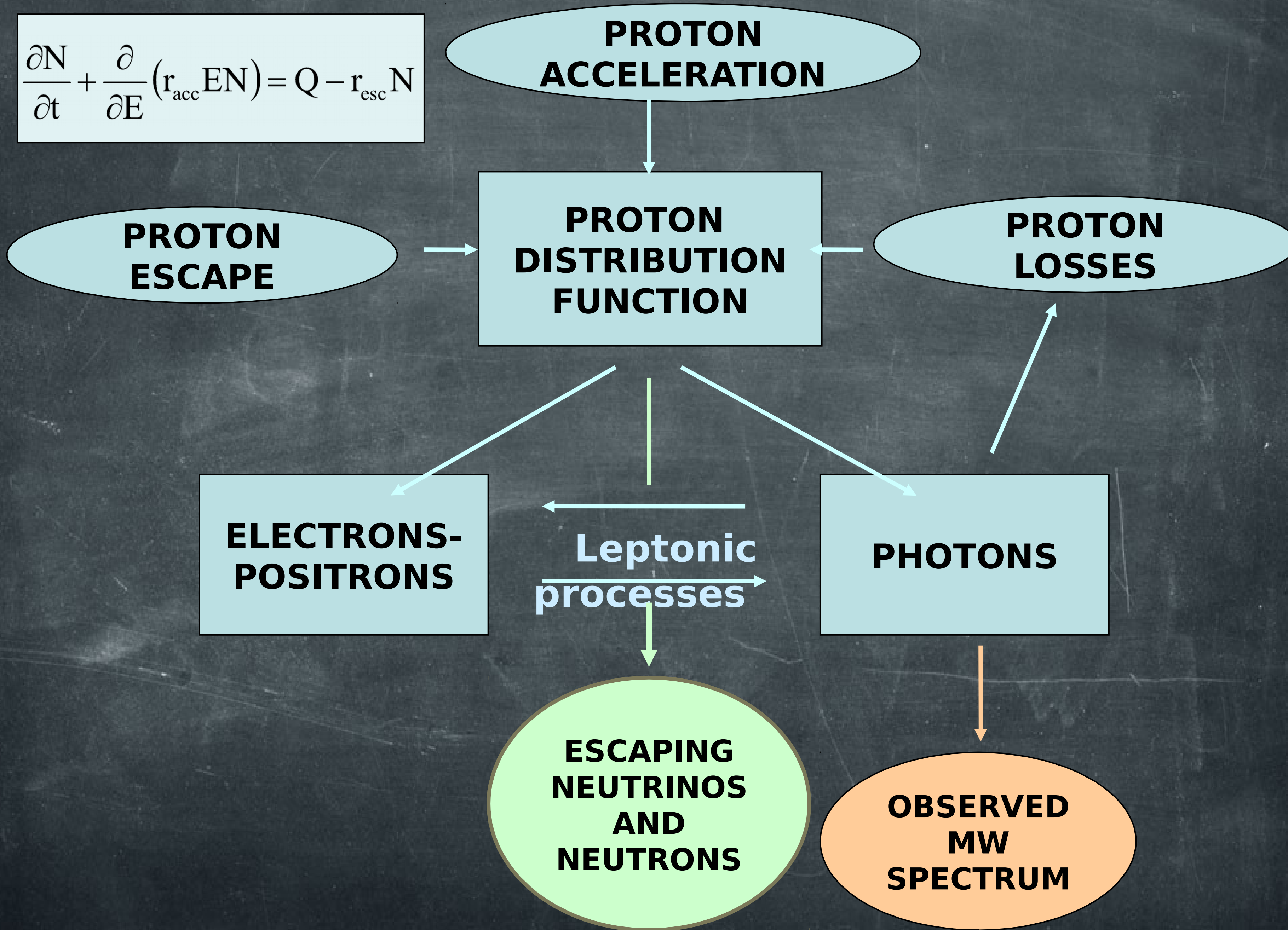
1999





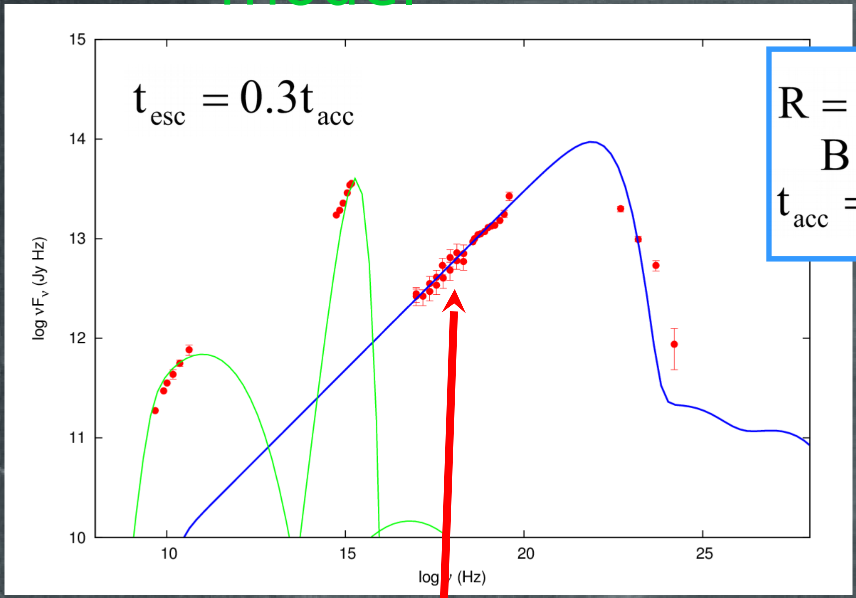
Particle distribution up to a max energy where Tacc=Tloss. Shape of cutoff not *a-priori* assumed (obtained shape non-trivial, *e.g.* pile-ups)

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

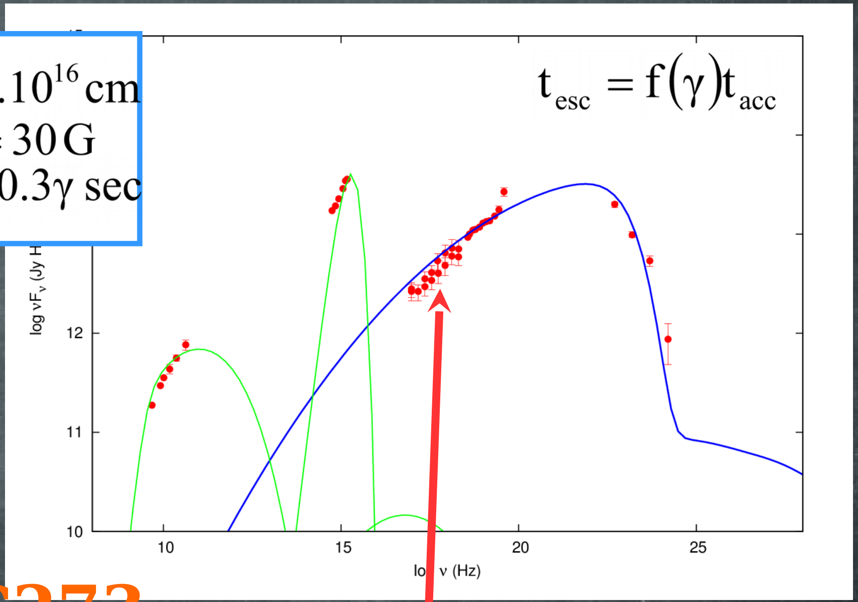


Standard box model

Modified box model



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



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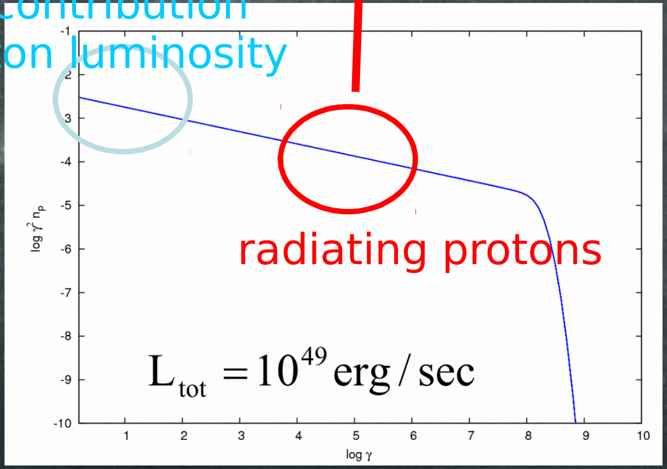
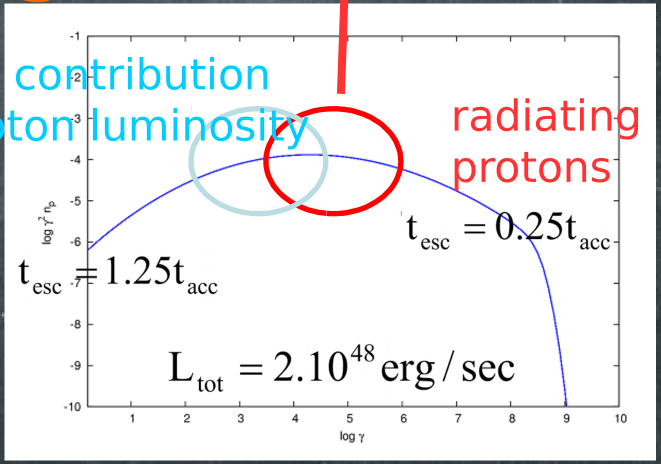
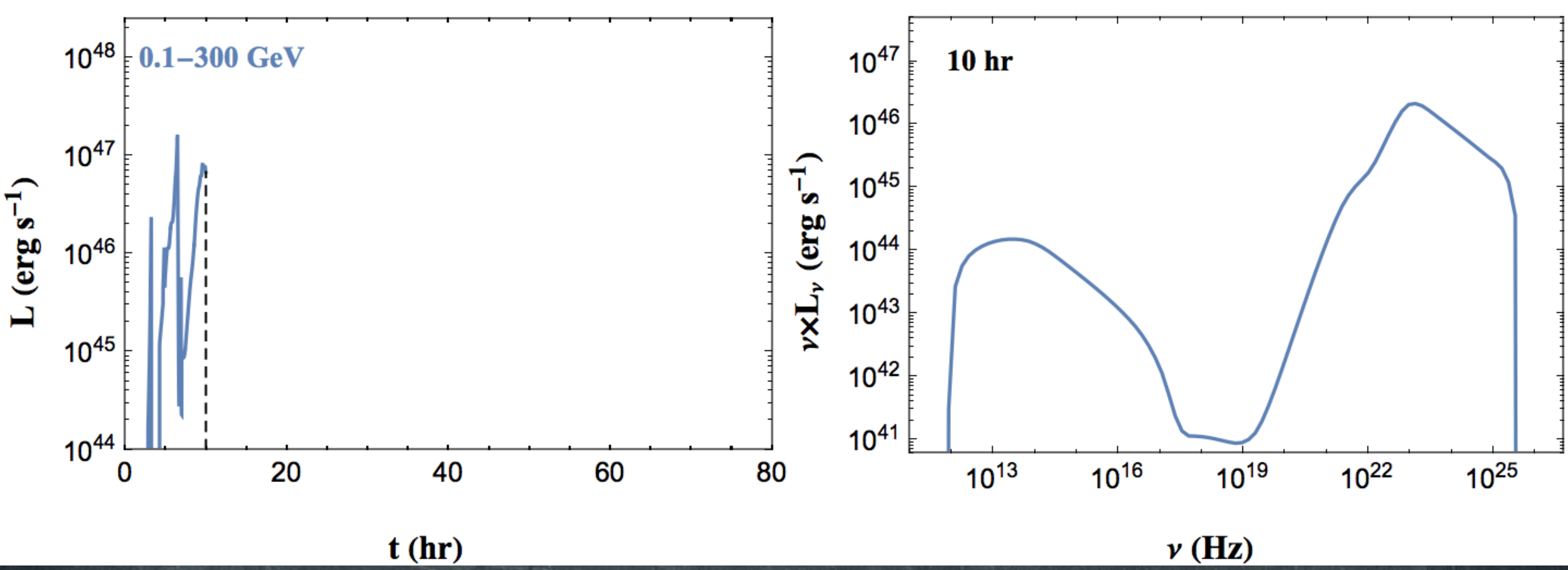




VARIABILITY FROM MAGNETIC RECONNECTION



Preview from Maria's talk next week

CONCLUSIONS

- 25 years after the Blazar gamma-ray discovery, leptonic and hadronic models continue being successful in
  – producing very good fits to MW spectra
  – explaining the observed X-ray – gamma-ray correlations
- Hadronic models are more ‘expensive’ (energy budget) but more interesting (non-linearities).
- Both models are mature enough to apply particle acceleration theories
- Only neutrinos can definitely tell them apart, e.g. some extraordinary neutrino event coupled to a photon flare.
- If not, see you in another 25 years! (With the same arguments).

BACK UP SLIDES

INJECTION OF SECONDARY ELECTRONS - RESULTING PHOTON SPECTRA

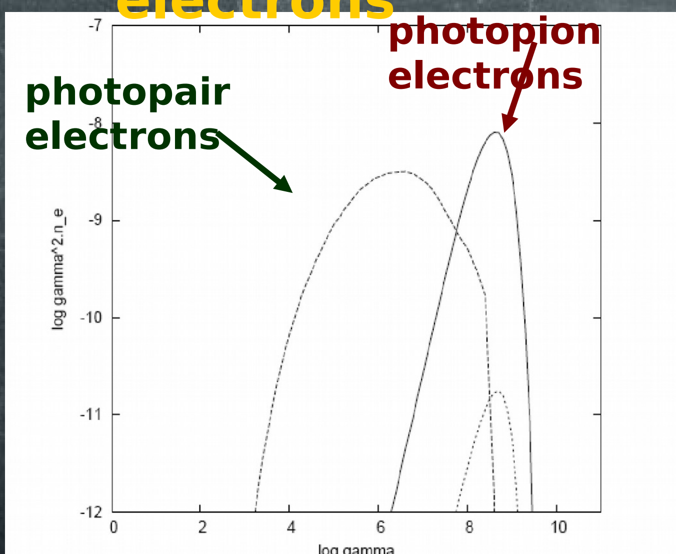
- Energy lost from protons = Energy injected in secondaries

  = Energy radiated in photons
- Photopair injection spectrum different from photopion

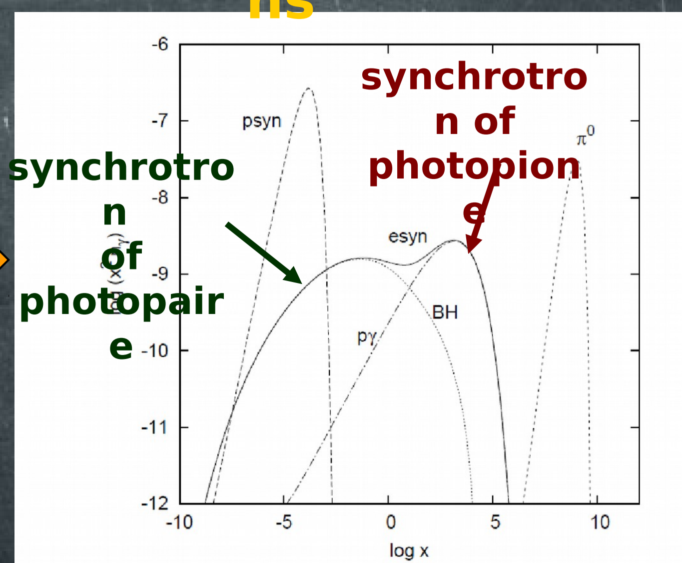
  → the two processes have inherently different radiative signatures

A SIMPLE CASE

injected electrons



photons



S. Dimitrakoudis et al.

SPECTRAL FORMATION

Three observational facts

- MW Spectrum → Particle acceleration to high energies + non-thermal radiation mechanisms
- Fast + correlated variability → emission from a localized region
- Superluminal motion → emission from inside the jet → relativistic beaming

Radiation transfer problem: theoretical questions

(1) Geometry of emitting region

(2) Photon emission + absorption mechanisms

(3) Particle energization/acceleration

(4) Species of radiating particles

(5) Location of ‘active’ region