Hadronic Models of Blazars: Principles & Current Status

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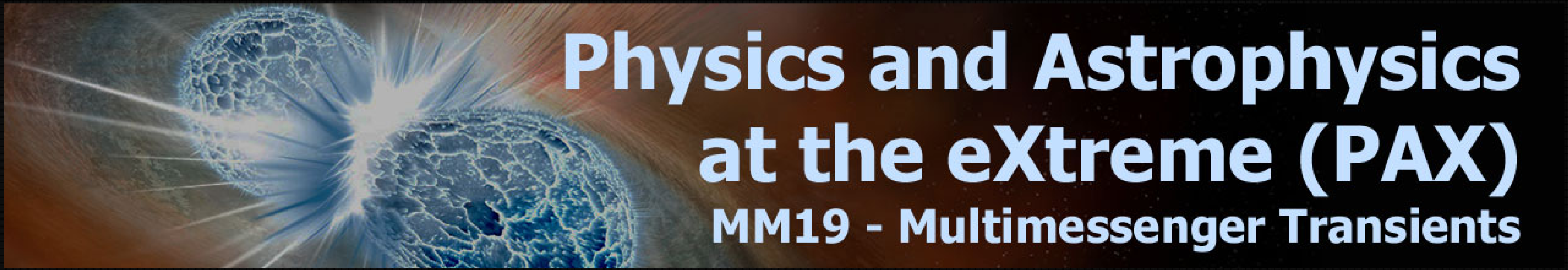
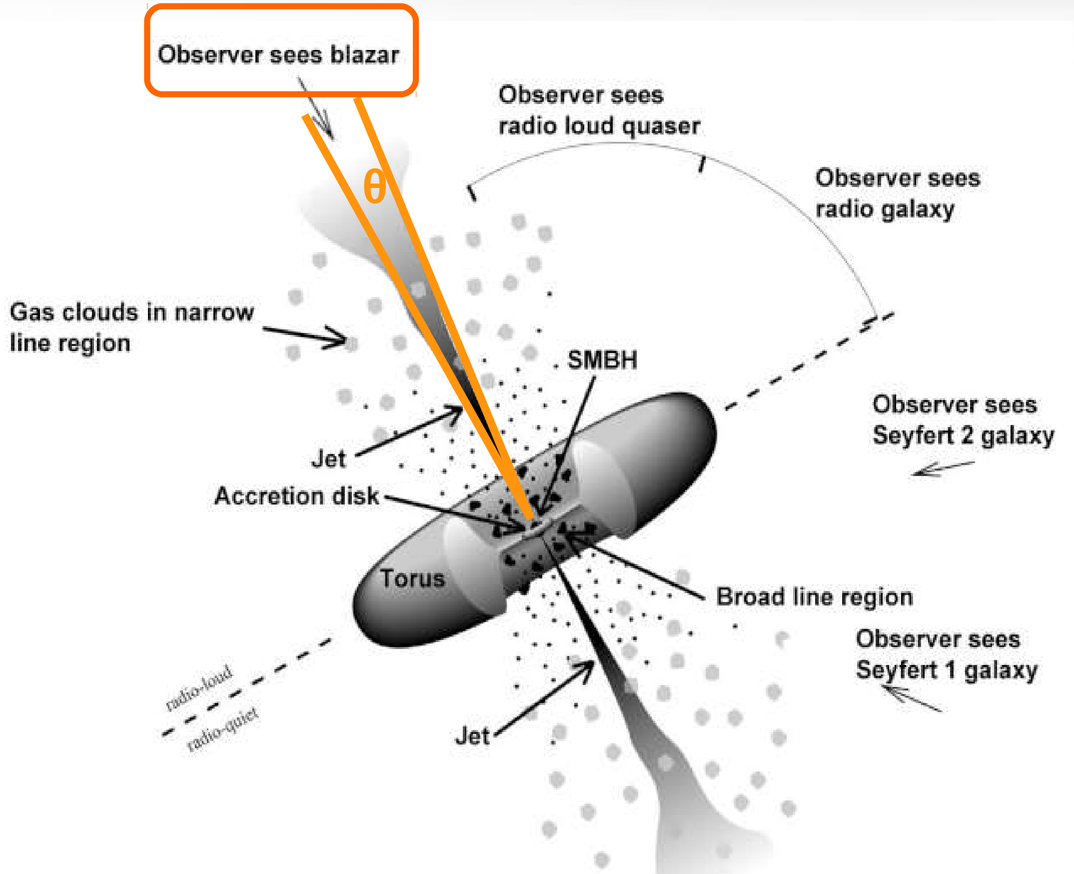
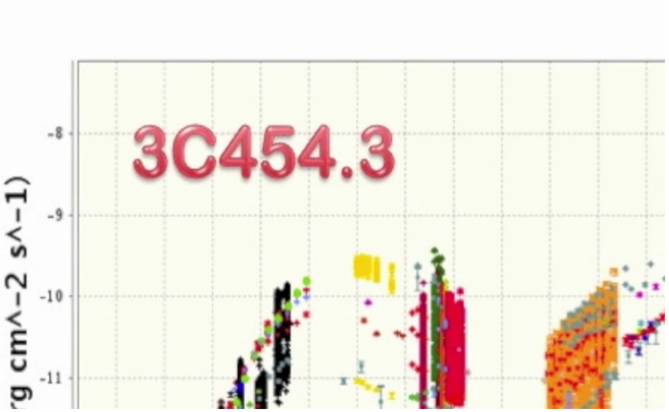


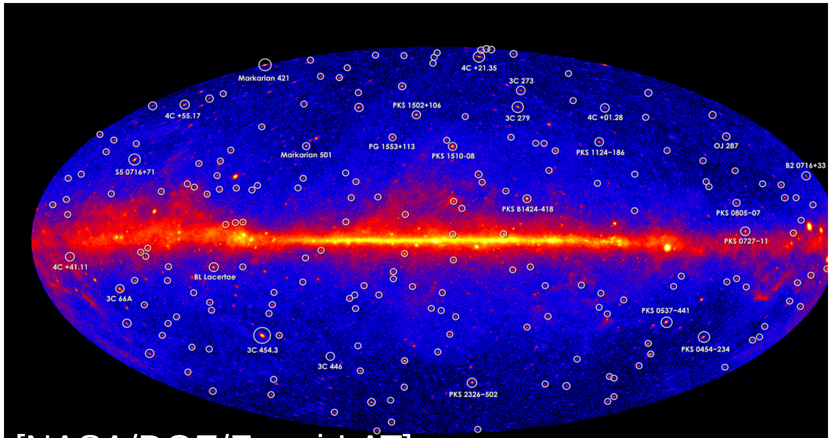
Blazars
AGN with jets viewed face-on



[Urry & Padovani 1995]



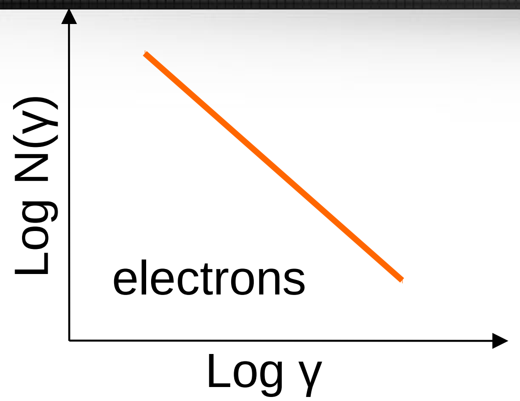
Giommi 2015, JHEA (https://tools.asdc.asi.it/SED/)

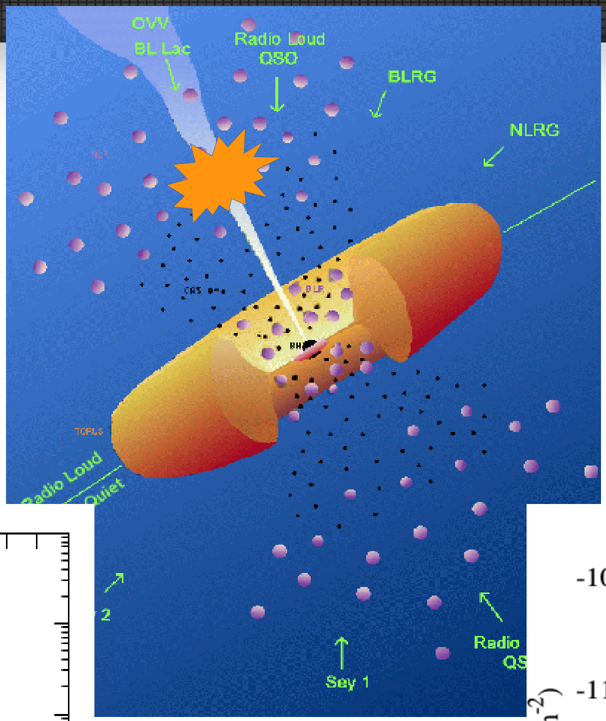


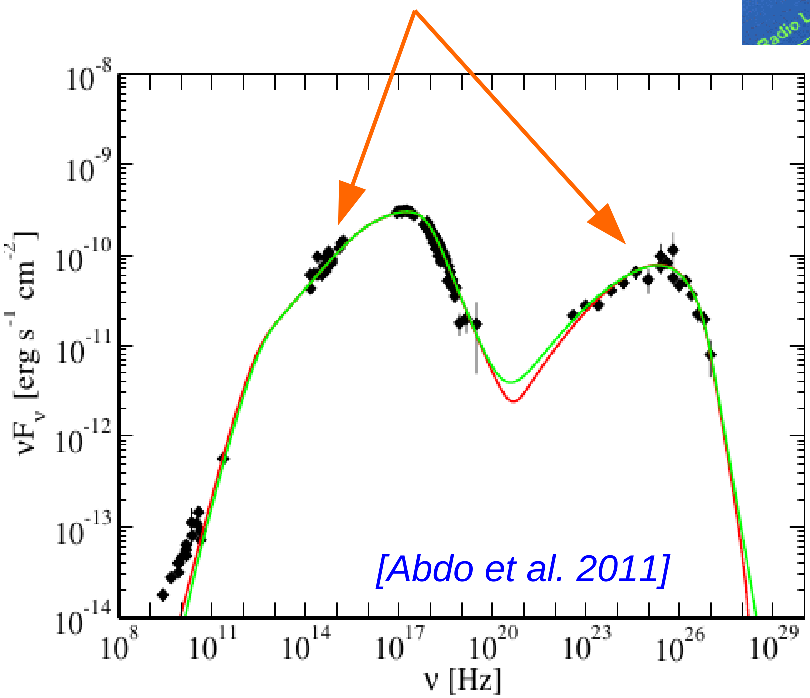
[NASA/DOE/Fermi-LAT]

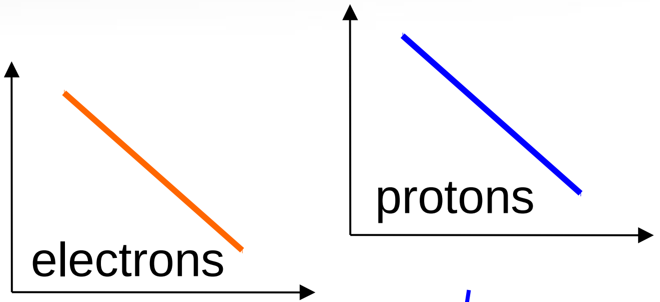
Origin of γ-ray emission

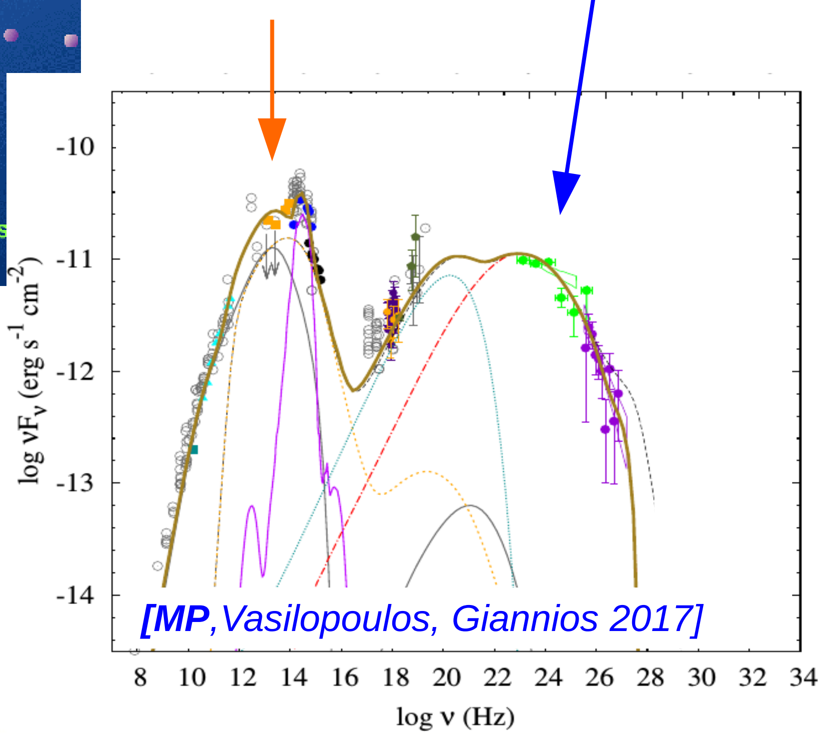
leptonic or hadronic?



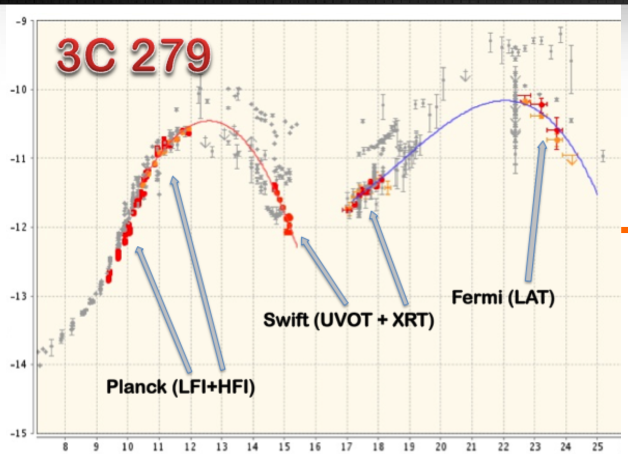








Radiative transfer
the principles

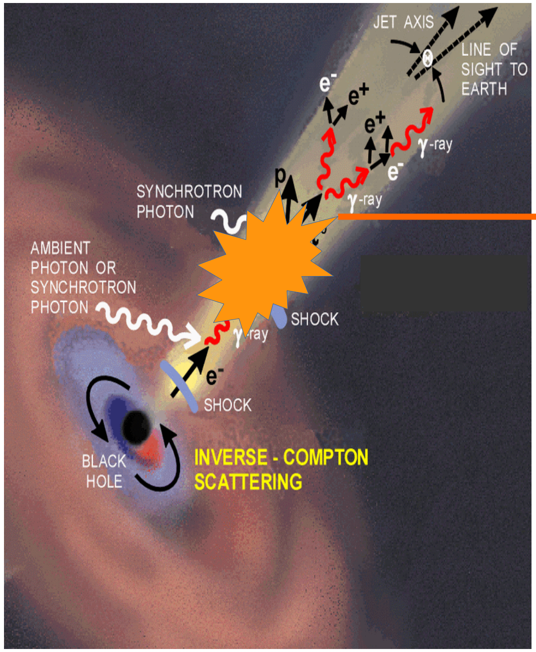


$$F_\nu = I_\nu \Delta\Omega$$

Observed flux

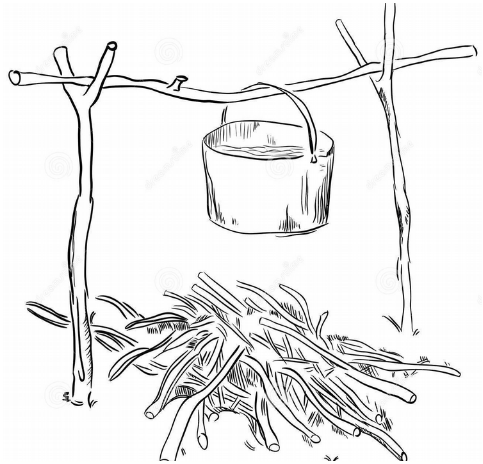
$$\frac{dI_\nu}{ds} = j_\nu - a_\nu I_\nu$$

Radiative transfer equation (RTE)

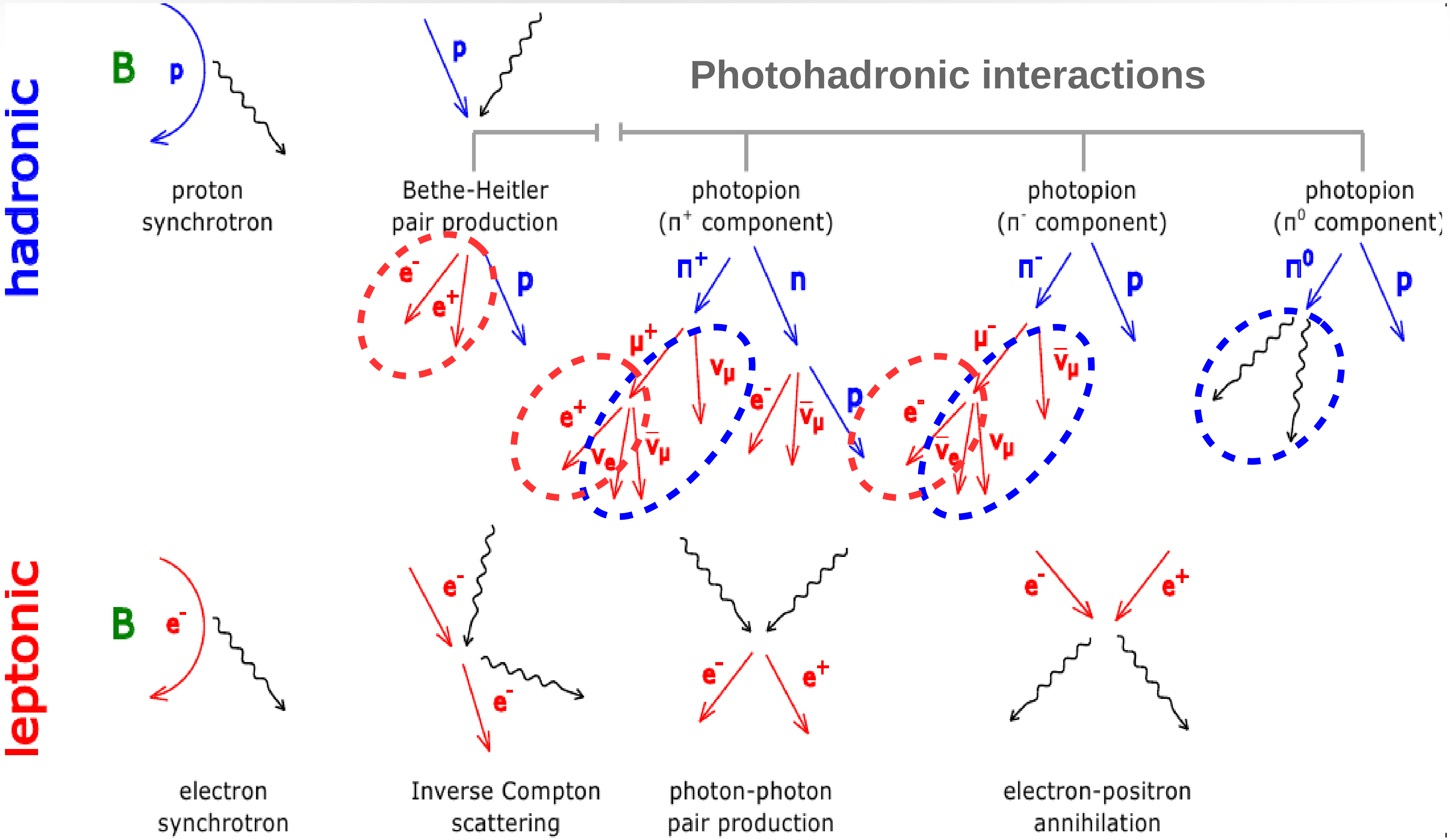


<u>Recipe for relativistic jets:</u>

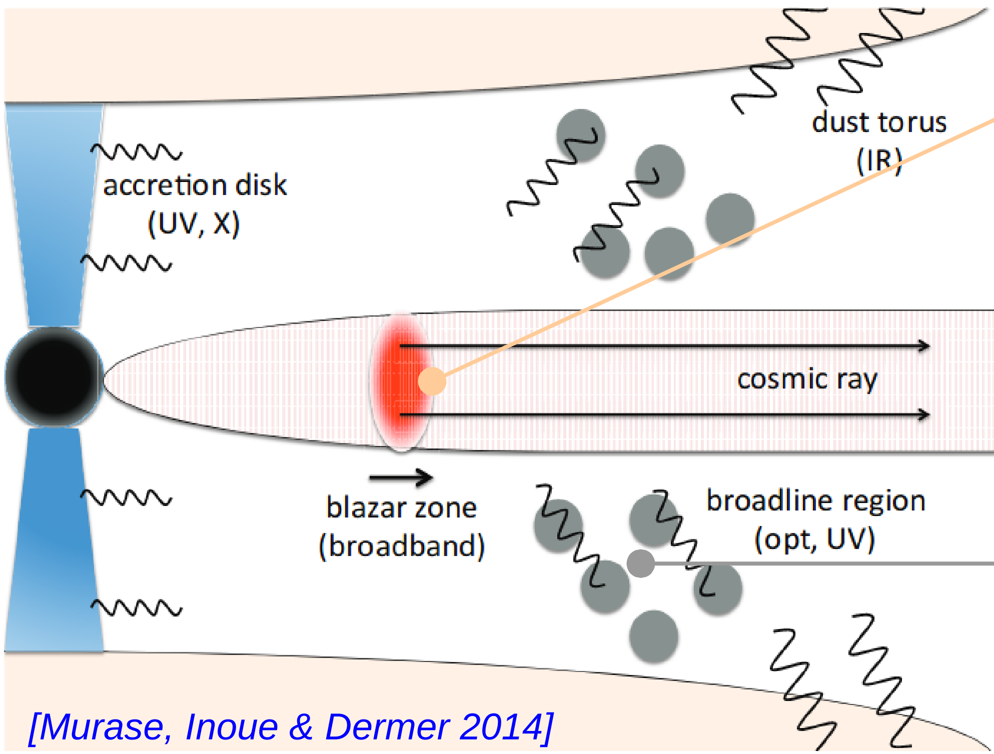
- Specify j_ν, a_ν
- Specify geometry
- Solve RTE in comoving frame
- Apply Doppler boost



Non-thermal radiative processes
in a nutshell



Radiation fields in blazars
are abundant



[Murase, Inoue & Dermer 2014]

Non-thermal radiation (jet)

$$E_\nu \approx 0.05\, E_p \gtrsim 90\, PeV\, \Gamma_1^2 \left(\varepsilon_s / 10\, eV\right)^{-1}$$

$$f_{p\gamma} \propto \frac{L_{ph}}{\varepsilon_{ph} R\, \delta^3} \propto \frac{L_{ph}}{\varepsilon_{ph} t_\nu\, \delta^4}$$

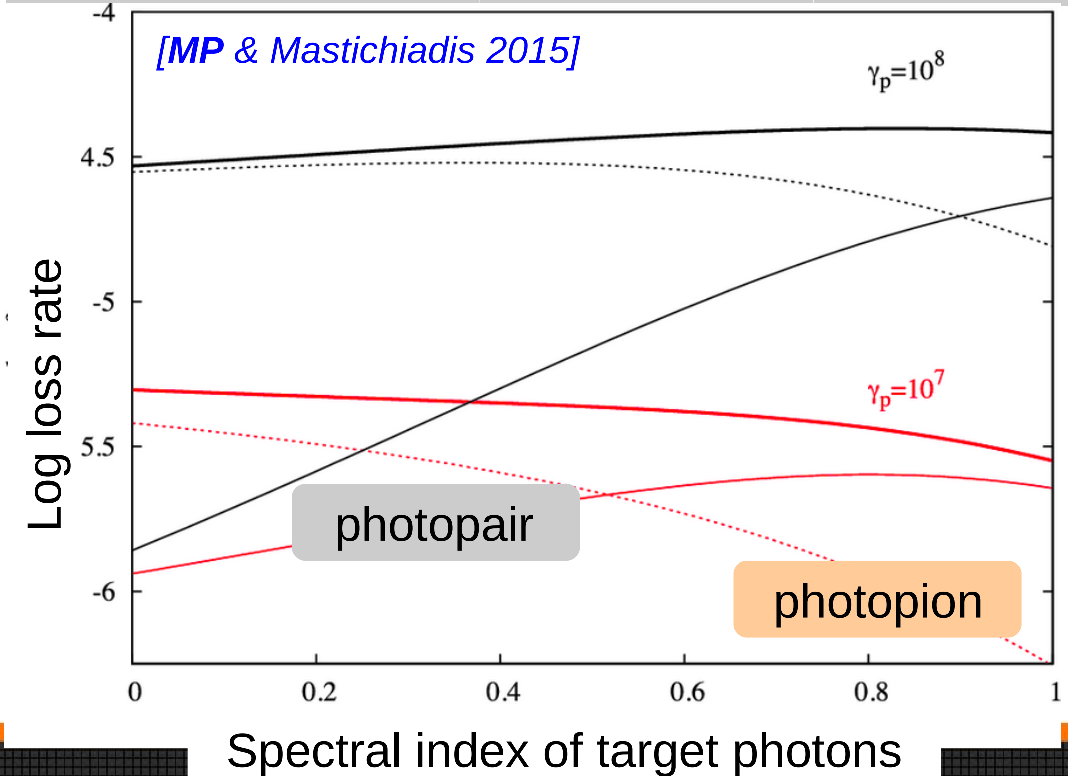
Thermal radiation (BLR)

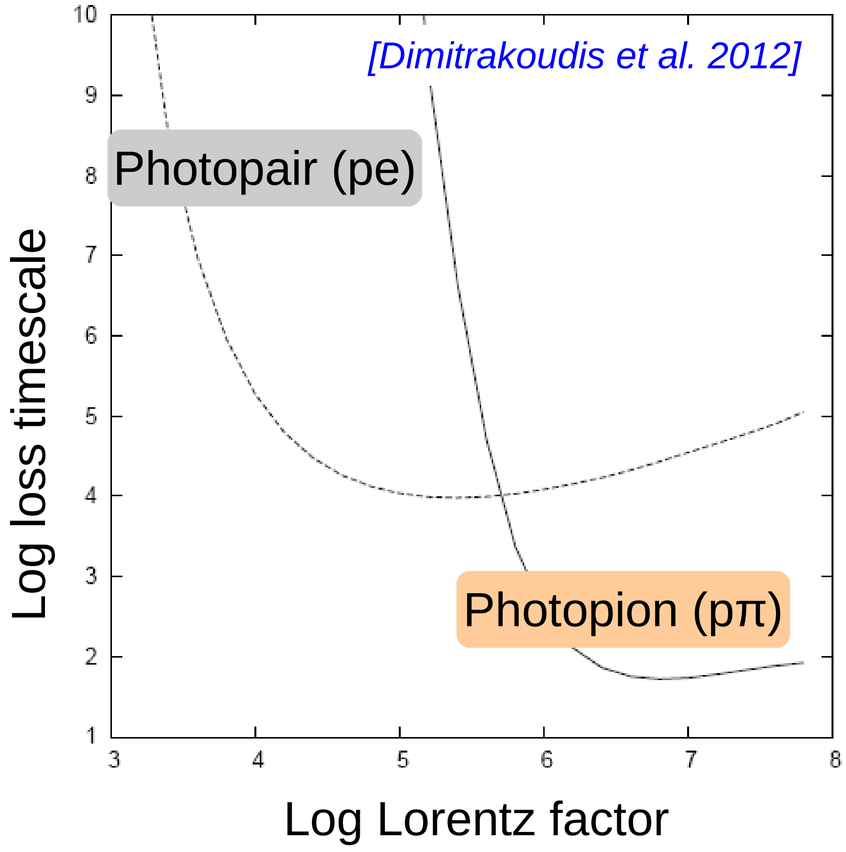
$$E_\nu \approx 0.05\, E_p \gtrsim 0.9\, PeV \left(\varepsilon_{BLR} / 10\, eV\right)^{-1}$$

$$f_{p\gamma} \propto \frac{L_{BLR}}{\varepsilon_{BLR} R_{BLR}}$$

Photopair vs Photopion
a quick comparison

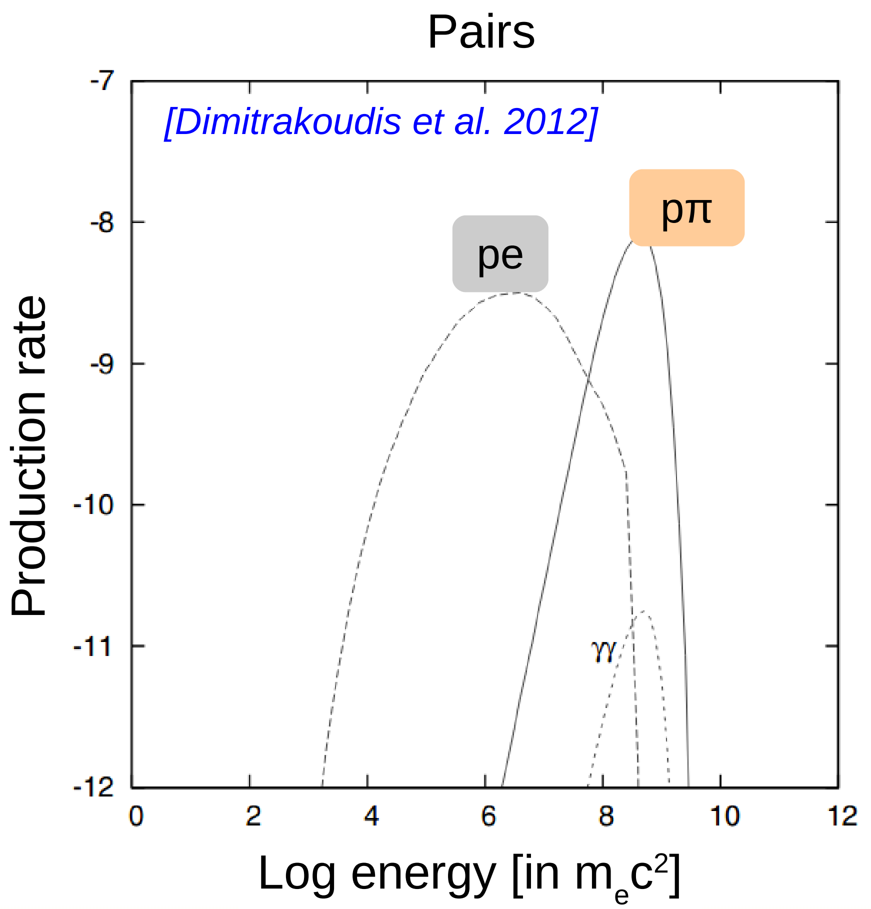
	Photopair	Photopion
Threshold (PRF) [MeV]	~ 1	~ 140
Cross section [mb]	~ 10	~ 0.1
Inelasticity	~ 0.001	~ 0.1

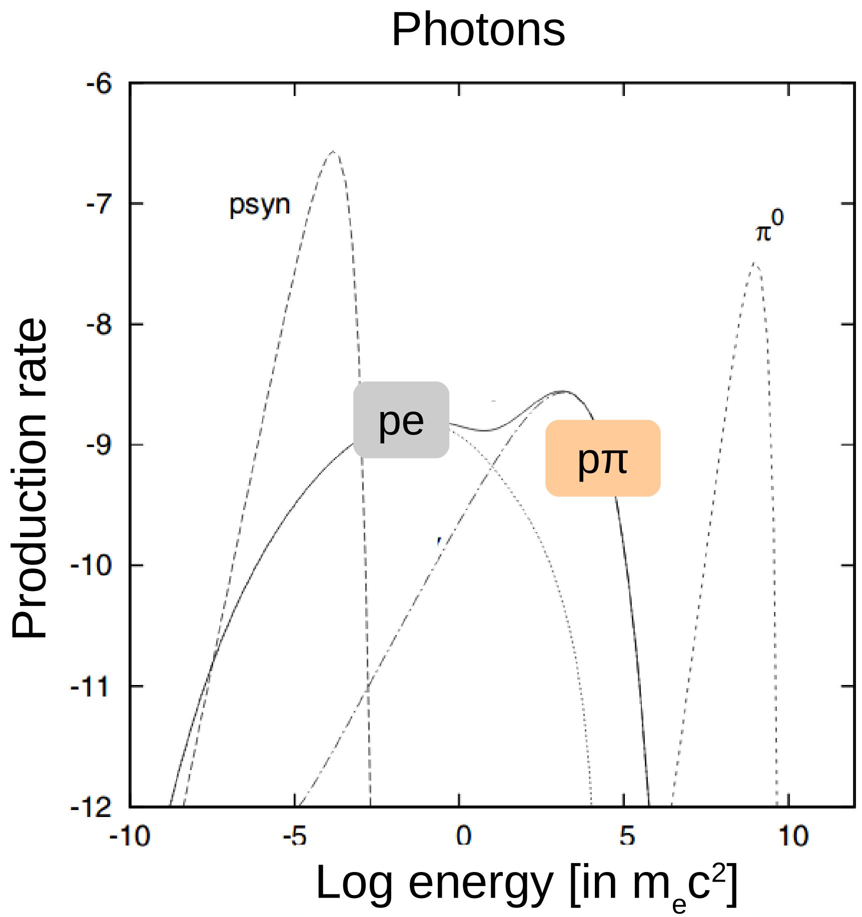




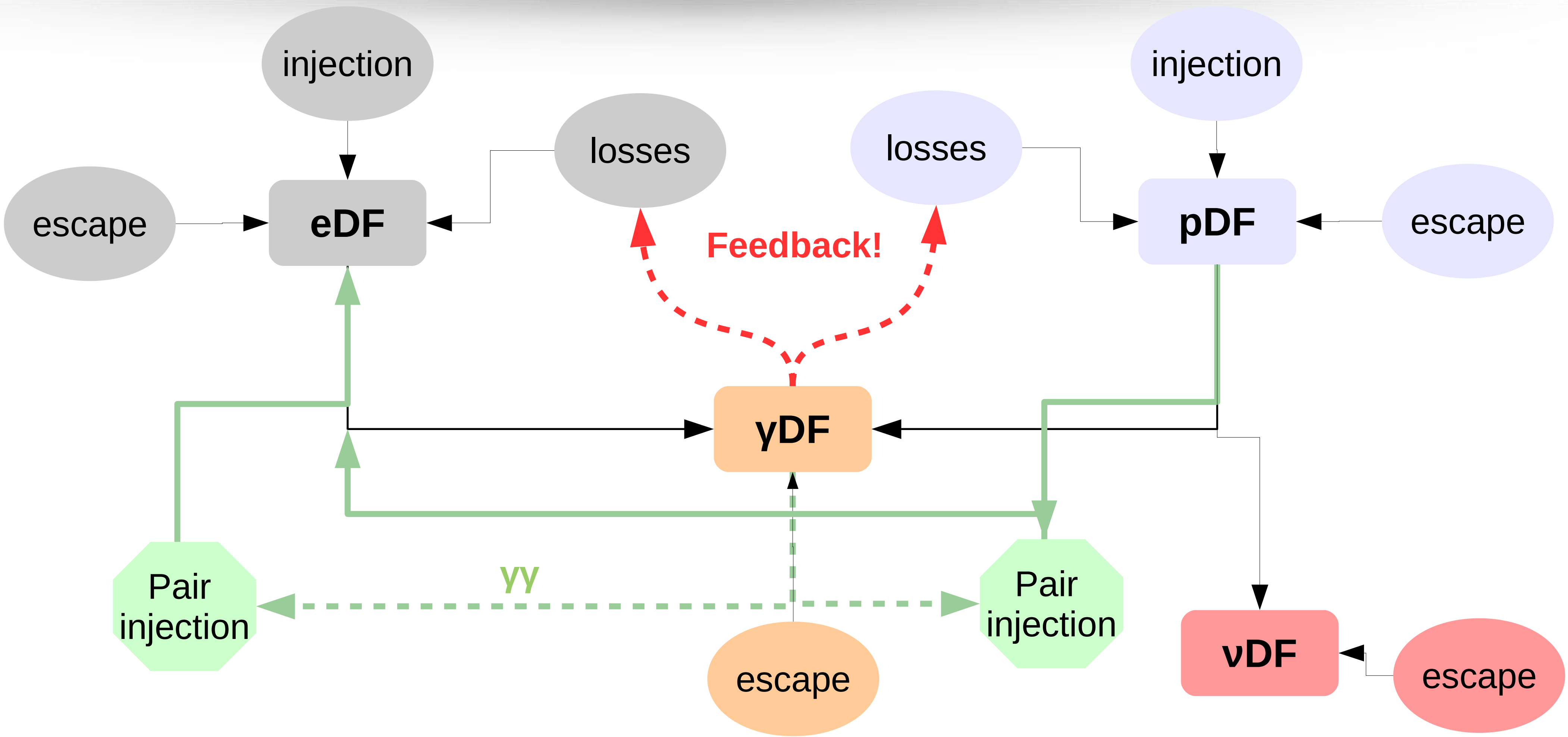
Production of secondaries
electron-positron pairs & photons

- Photopion: Monte Carlo generator [SOPHIA; Muecke et al 2000] or analytical parametrizations by Kelner & Aharonian (2008)
- Photopair: Monte Carlo results by Protheroe & Johnson (1996) or analytical parametrizations by Kelner & Aharonian (2008)





Computation of spectra
a non-linear problem*



*[Mastichiadis & Kirk 1995; Dimitrakoudis et al. 2012; Mastichiadis & Kirk 2005; **MP,** Dimitrikoudis et al. 2015; Diltz, Boettcher, Fossati 2015; **MP**, Coenders et al. 2016; Gao, Winter & Pohl 2017 *for other schemes, see Boettcher et al. 2013, Cerruti et al. 2015]*

Current status
general considerations

How to discriminate?

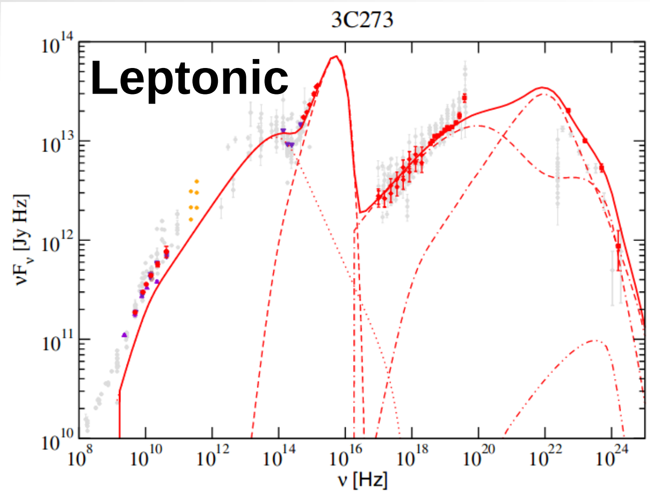
- Leptonic & hadronic models can produce equally good fits to the photon spectra

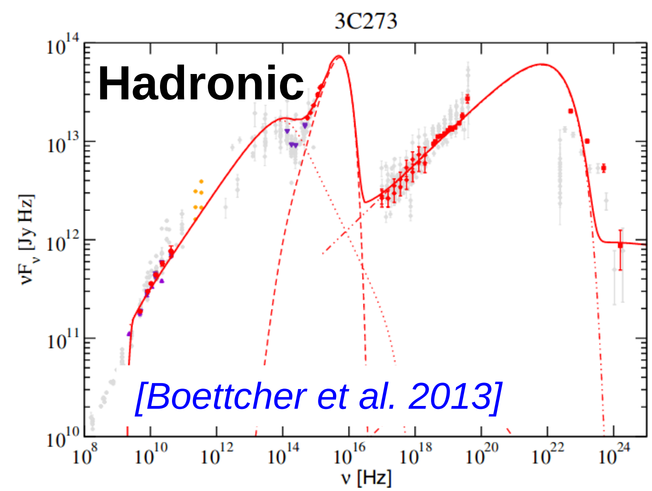
- Typical requirements of **p-syn hadronic** models:

a) Work for both FSRQs and BL Lacs
b) High jet power **L_j~ 10^{47} – 10^{48} erg/s** for FSRQs, but can be **lower for BL Lacs**
c) High proton energies, e.g. **E_{pmax} ~ 10 EeV** (for BL Lacs)
d) Strong magnetic fields, e.g. **B ~1-100 G**
e) **~ EeV** neutrinos

- Typical requirements of **photo-pion hadronic** models:

a) Work for BL Lacs, but unlikely for FSRQs
b) High jet power **L_j~ 10^{47} – 10^{48} erg/s**
c) Moderate proton energies e.g. **E_{pmax} ~ 10 PeV**
d) Moderate magnetic fields, e.g. **B ~ 0.1-1 G**
e) **~ PeV** neutrinos





*[e.g. Boettcher et al. 2013; **MP** 2014; Dimitrakoudis, **MP**, Mastichiadis 2014; **MP,** Dimitrikoudis et al. 2015; Cerruti et al. 2015; Diltz, Boettcher & Fossati 2015; **MP** & Dermer 2016; Gao, Winter & Pohl 2017; **MP**, Nalewajko et al. 2017; Cerruti et al. 2017]*

Current status
the case of TXS 056+056

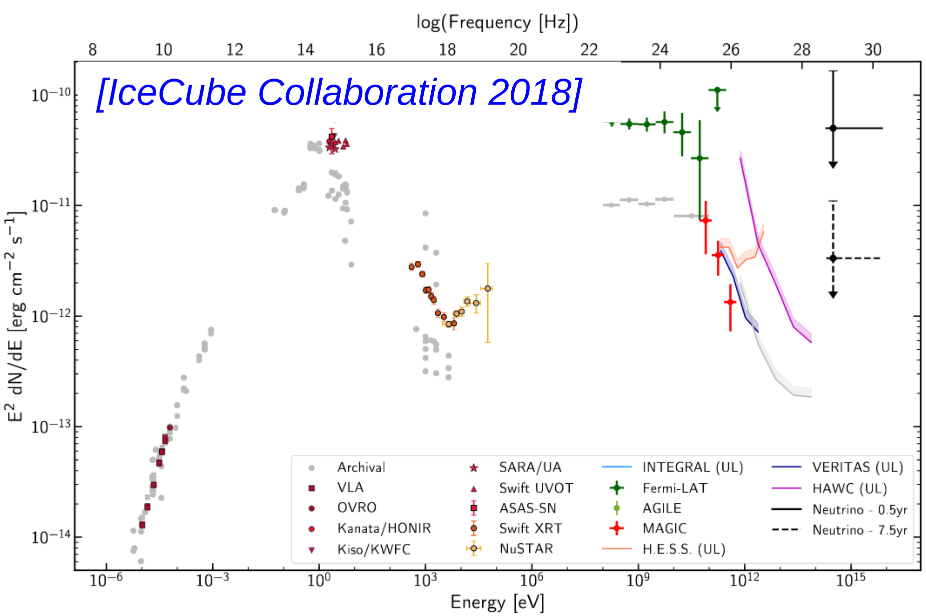
See Cerruti's talk!

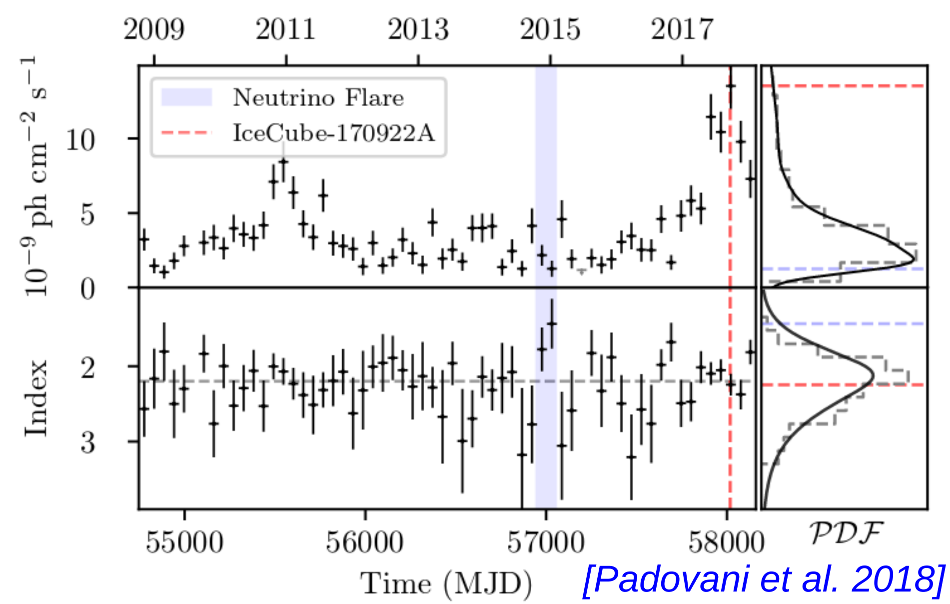
The 2017 multi-messenger flare

- Major GeV γ-ray flare and enhanced fluxes in optical, soft/hard X rays, TeV γ rays.
- $\mathbf{L_\nu \sim L_\gamma}$ (1 event with E_ν ~290 TeV)
- Modeling papers: *Ansoldi et al. 2018; Keivani, Murase, **MP**, Fox et al. 2018; Murase, Oikonomou & **MP** 2018; Sahakyan 2018; Wang et al. 2018; Gao et al. 2019; Cerruti et al. 2019*

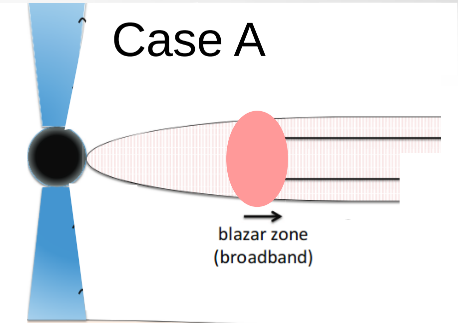
The neutrino 2014-15 "flare"

- Neither GeV γ-ray nor optical flare
- $\mathbf{L_\nu \sim 10\ L_\gamma}$ (13 +- 5 events with E_ν ~32 TeV – 3.6 PeV)
- Modeling papers: *Reimer, Boettcher & Buson 2018; Rodrigues et al. 2018; Murase, Oikonomou & **MP** 2018; **MP**, Murase, Fox et al. (in prep); Zhang, Murase, **MP** (in prep)*

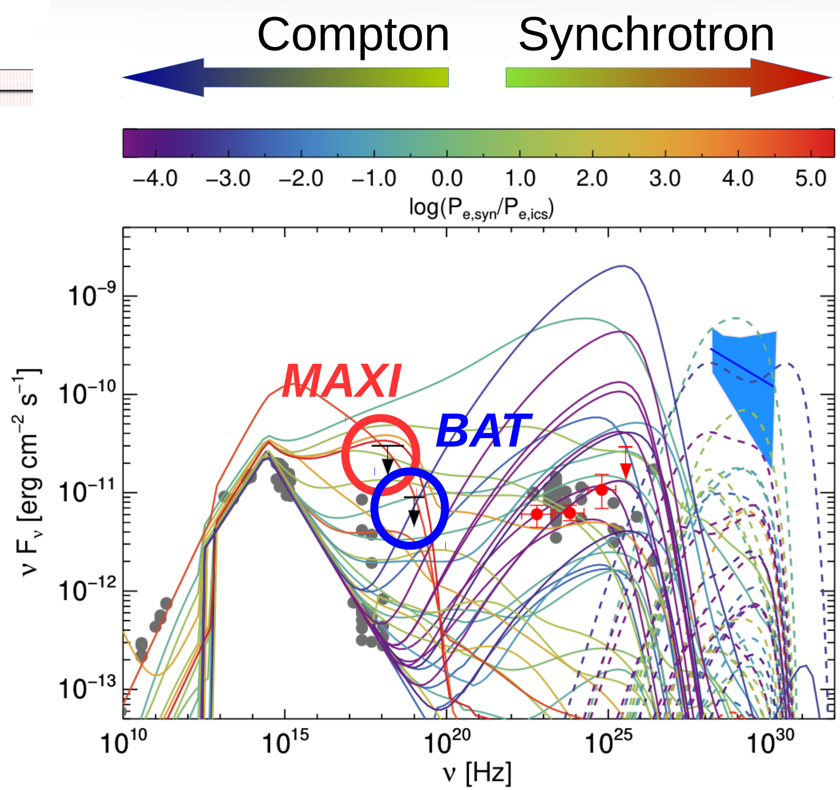




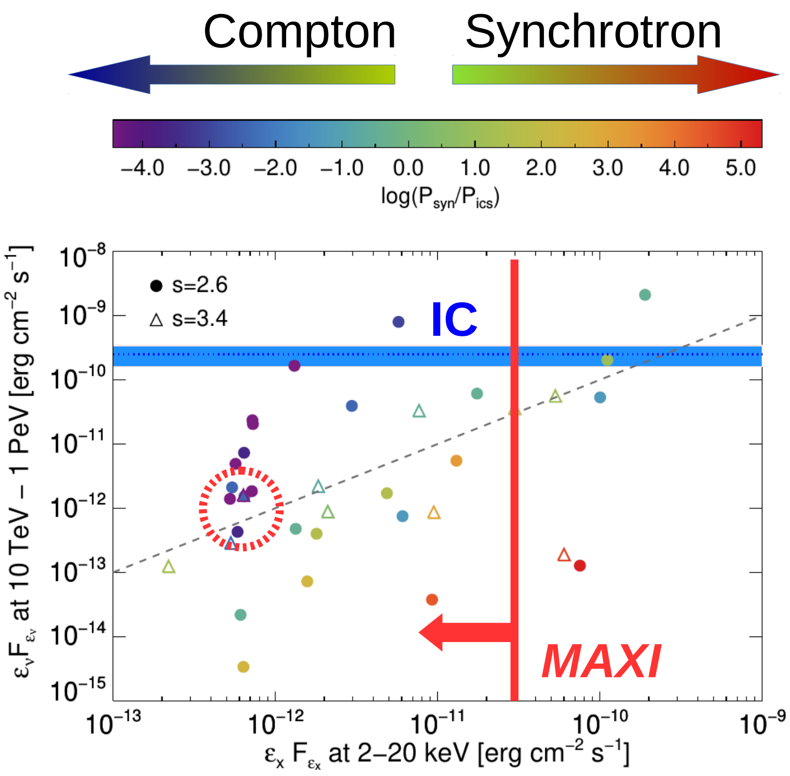
The 2014-15 neutrino flare
a challenge for models



- Wide parameter search (> 40 parameter sets)
- Linear & non-linear cascades
- Synchrotron & Compton supported cascades



- MAXI UL @ 2-20 keV: 3×10^{-11} erg/cm^2/s
- BAT UL @ 20-85 keV: 9×10^{-12} erg/cm2/s



No model compatible with E/M constraints and $L_\nu > L_\gamma$

*[**MP**, Murase, Fox et al., in prep.]*

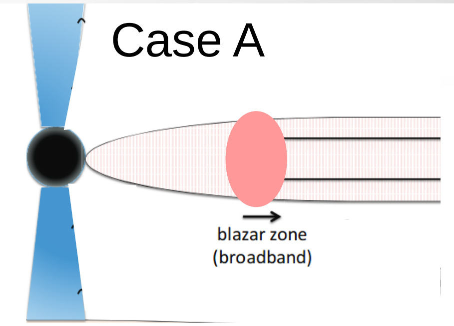
The 2014-15 neutrino flare

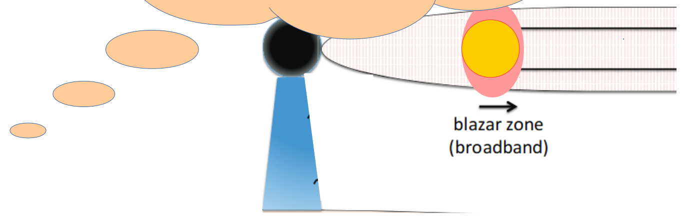
a challenge for models

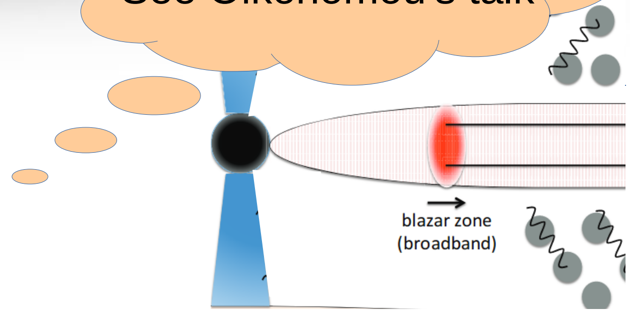
What happens to escaping particles from the core?

TXS has a BLR! See Oikonomou's talk

Case A



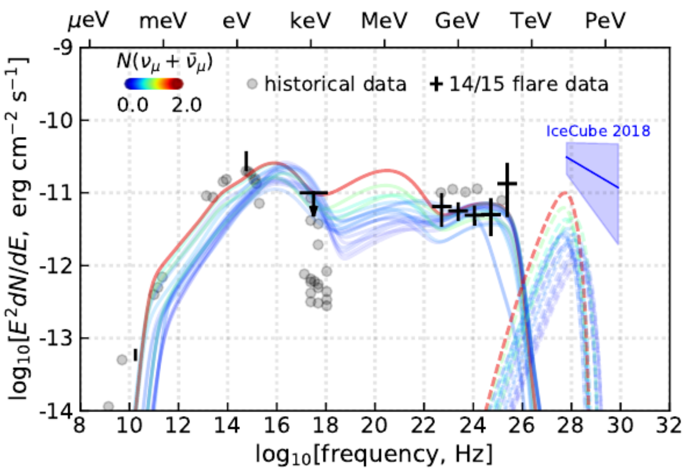


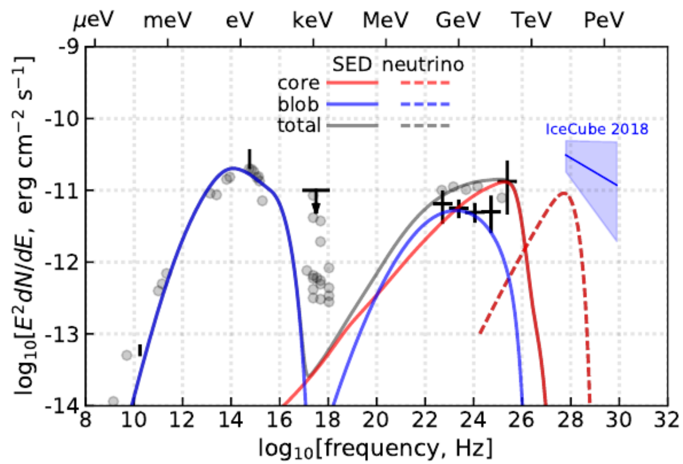


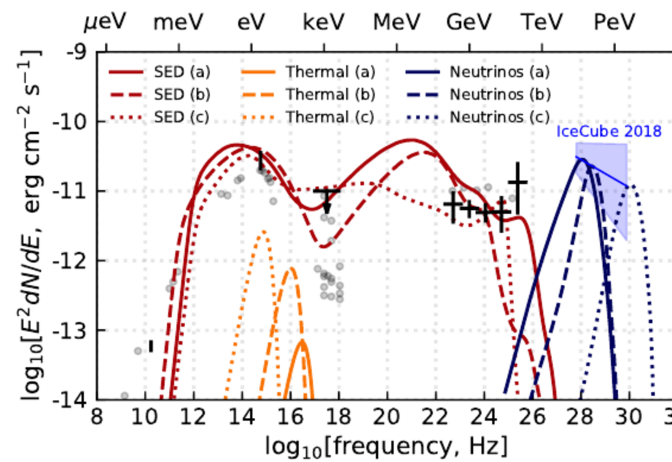
- Parameter space search
- < 1.8 events
- MeV band unconstrained!

- < 1.9 events
- Fine-tuning of model

- < 4.8 events
- Attenuation > 10 GeV
- X-ray flux close to UL

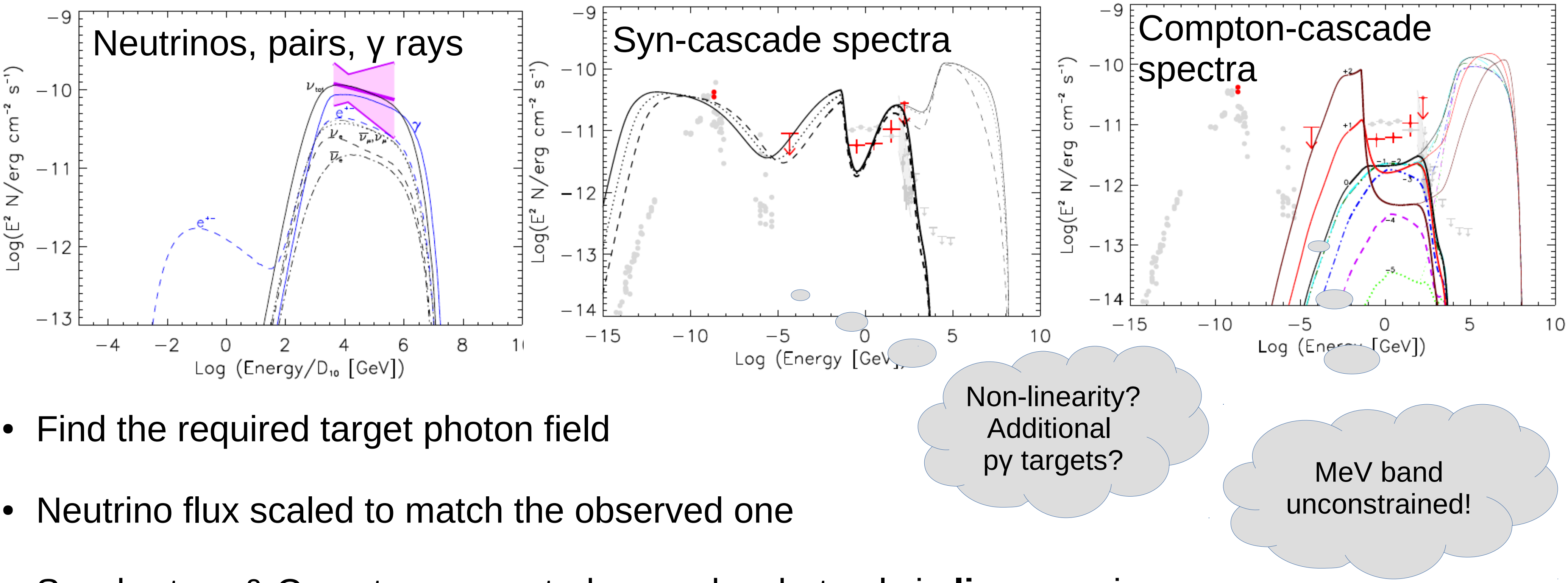






[Rodrigues et al. 2018]

The 2014-15 neutrino flare
minimal requirements



- Find the required target photon field
- Neutrino flux scaled to match the observed one
- Synchrotron & Compton supported cascades, but only in **linear** regime
- Stationary X-ray photon field as target for photo-pion with Compton cascade.
- *No correlation between TeV/PeV neutrinos with GeV γ rays*

[Reimer, Boettcher & Buson 2018]

The 2014-15 neutrino flare
the neutron beam model

Step 1: Photo-disintegration of nuclei

$$f_{A\gamma} \sim L_{\gamma,46} r_{16}^{-1} \delta_{1.3}^{-3} \varepsilon_{\gamma,1eV}^{-1} \left(\frac{\varepsilon'_{\gamma} \varepsilon_{p}'}{\varepsilon'_{th,A\gamma}}\right)^{\beta-1}$$

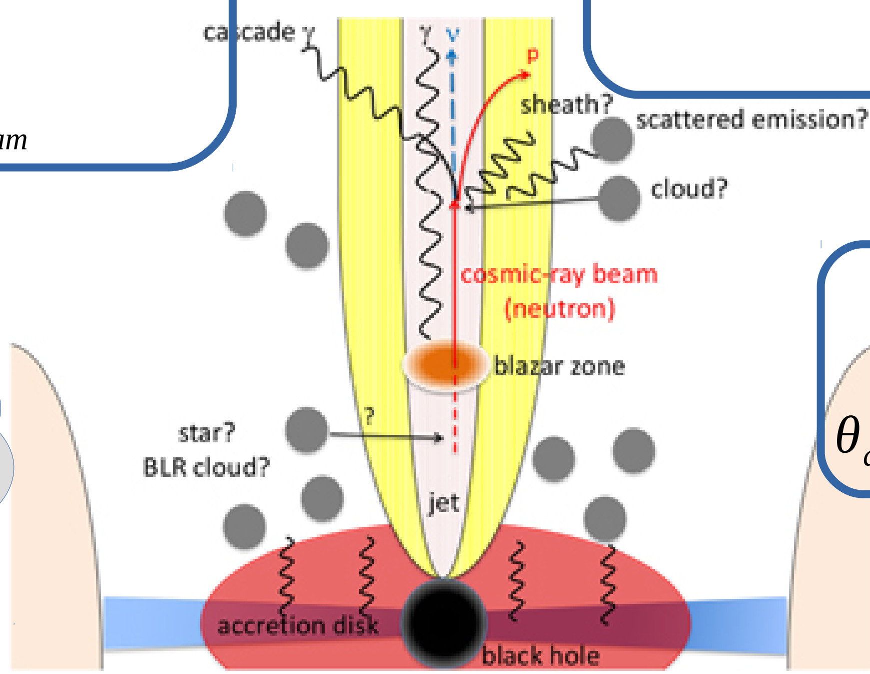
$$L_n \approx 0.5 f_{A\gamma} L_p$$

$$L_p \sim 2 f_{fl} \varepsilon_p L_j / \theta_{beam}^2$$

Step 2: Photopion interactions of neutrons

$$f_{n\gamma} \sim 3\times 10^{-3} L_{ext,45.5} R_{ext,19.5}^{-1} \varepsilon_{ext,10eV}^{-1} \left(\frac{\varepsilon_{ext} \varepsilon_{n}}{\varepsilon_{th,n\gamma}}\right)^{\beta-1}$$

$$L_\nu \approx (8/3) f_{n\gamma} L_n$$



Step 3: Isotropization of pairs

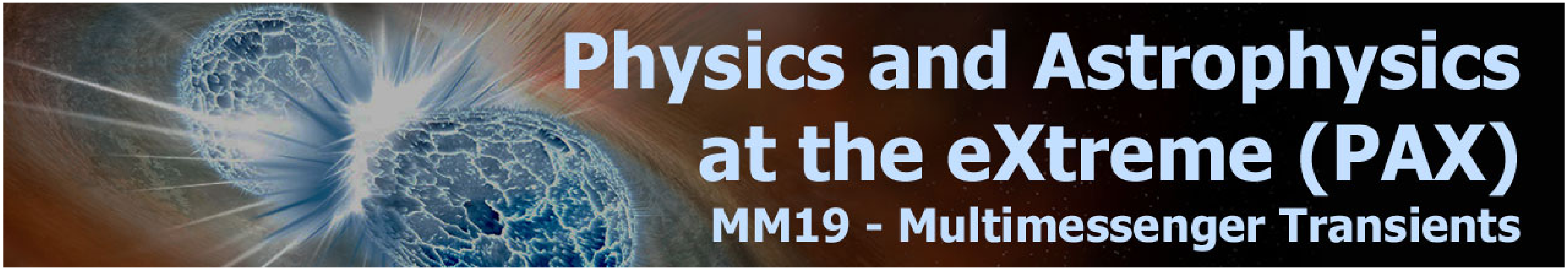
$$\theta_{defl} \approx 0.8\, ct_{syn} / r_g \approx 3.5 \gamma_{e,9}^{-2} B_{ext,-2.5}^{-1}$$

Photopair production
of nuclei?
Common framework
for 2 flares?

*[e.g. Dermer et al. 2012, 2014; for TXS 0506+056: Murase, Oikonomou, **MP** 2018; Zhang, Murase, **MP** (prep)]*

Open questions

- Is there a consistent physical picture for the multi-messenger emission of TXS 0506+056 in 2014-15 and 2017?
- What makes the 2014-15 period favorable for neutrino production? How can we distinguish it from other periods of less efficient neutrino production using EM observations?
- Is TXS 0506+056 different than other blazars of the same type?
- What do the requirements for the proton population tell us about the acceleration mechanisms?
- What is the best observing strategy for searching for neutrino point sources, if GeV γ rays flares are not correlated with periods of high TeV/PeV neutrino flux?



Back-up slides

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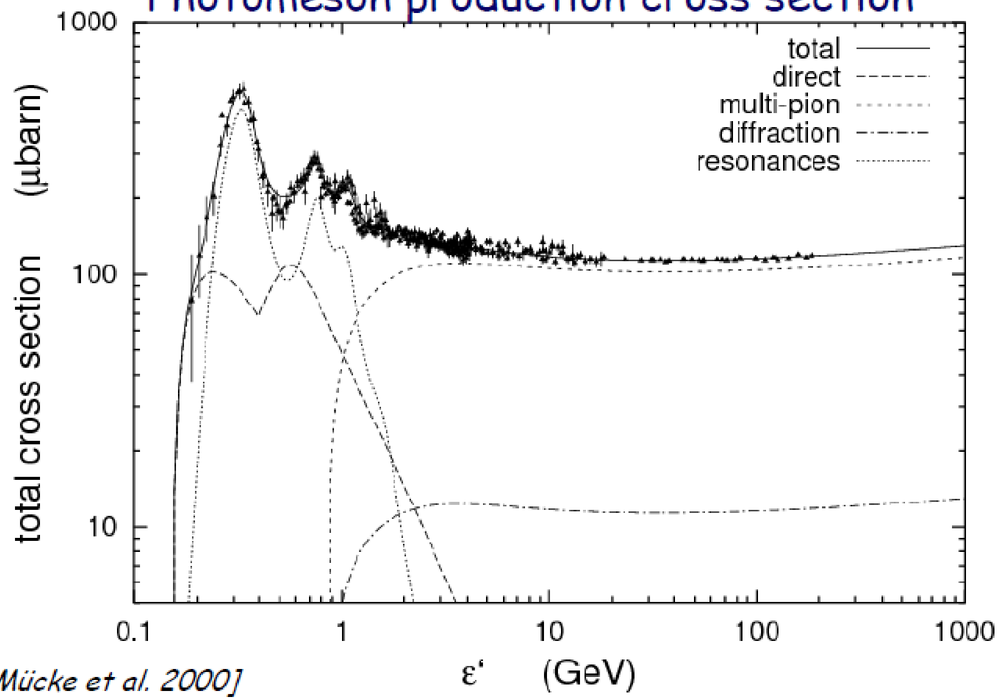
Photopion interactions

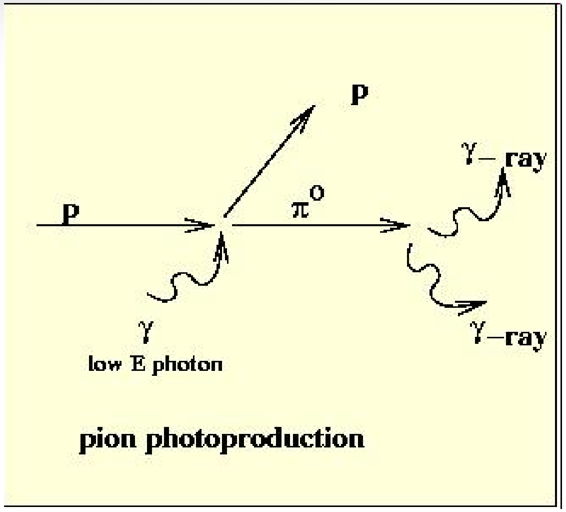
$$N + \gamma_{target} \longrightarrow N + \pi s + \ldots$$

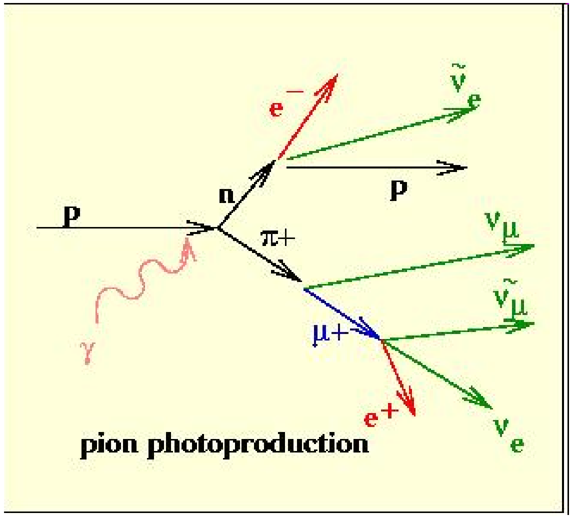
$$s^{1/2}_{threshold} = m_p + m_{\pi 0}$$

Photomeson production cross section



[Mücke et al. 2000]





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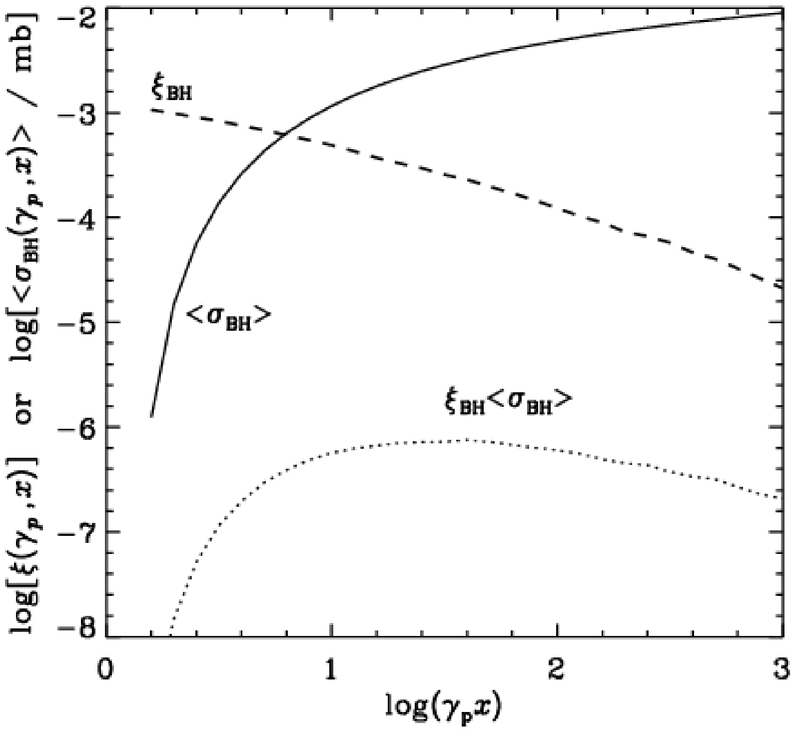
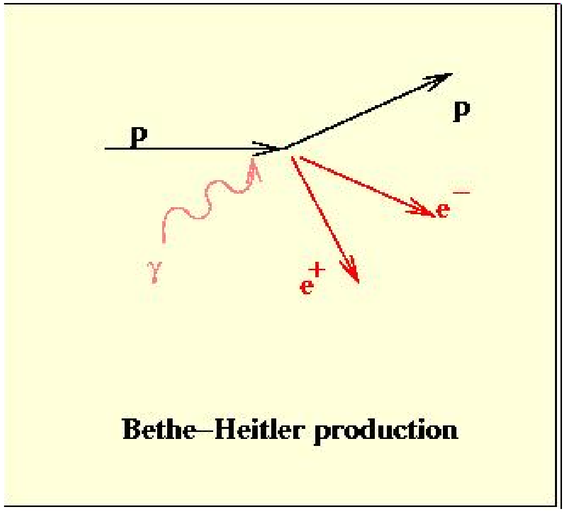
Photopair interactions

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

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





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