The Multi-Messenger View of AGN

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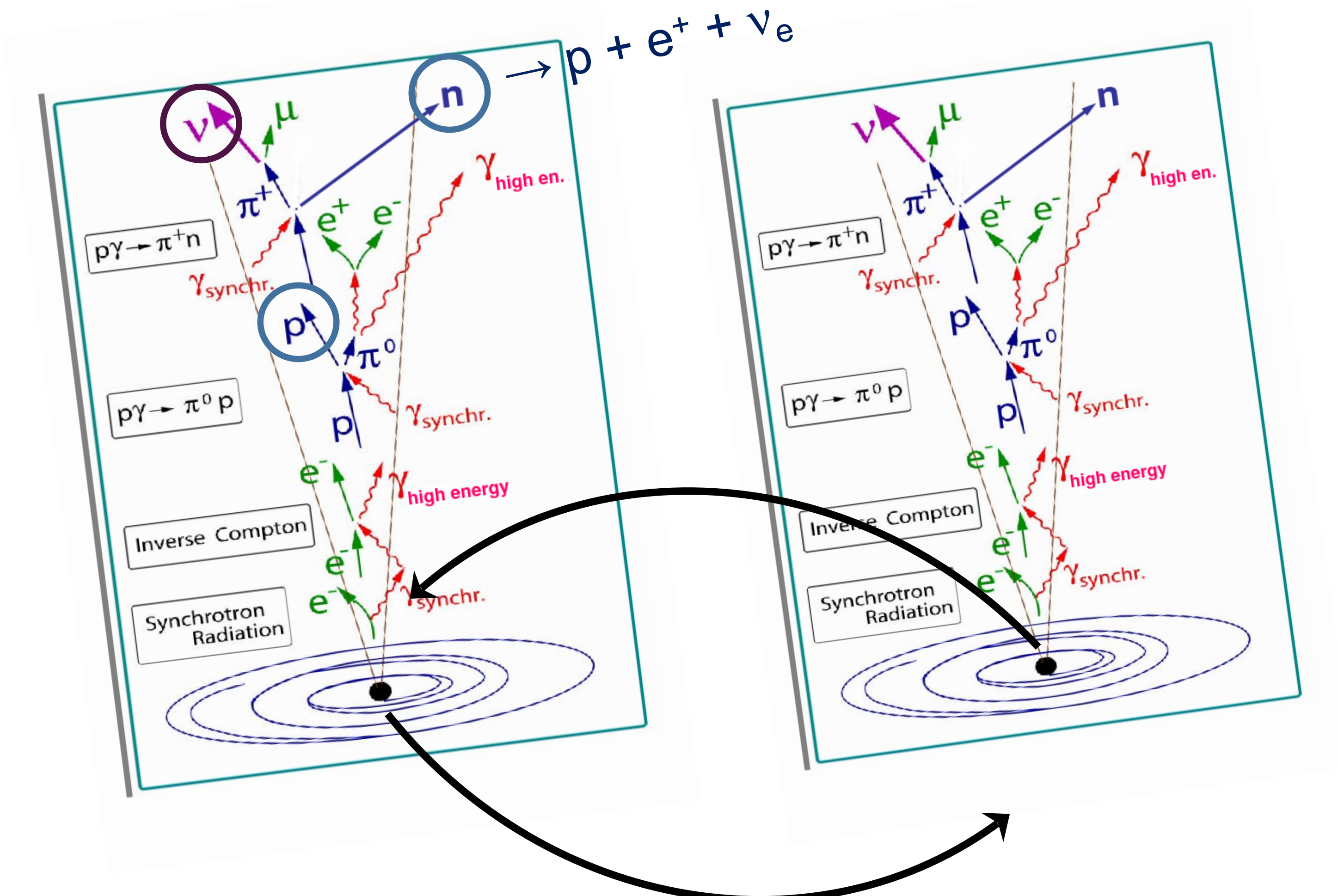
Multi-Messenger Signals from AGN (hadronic / lepto-hadronic models)

Cosmic Rays (p)

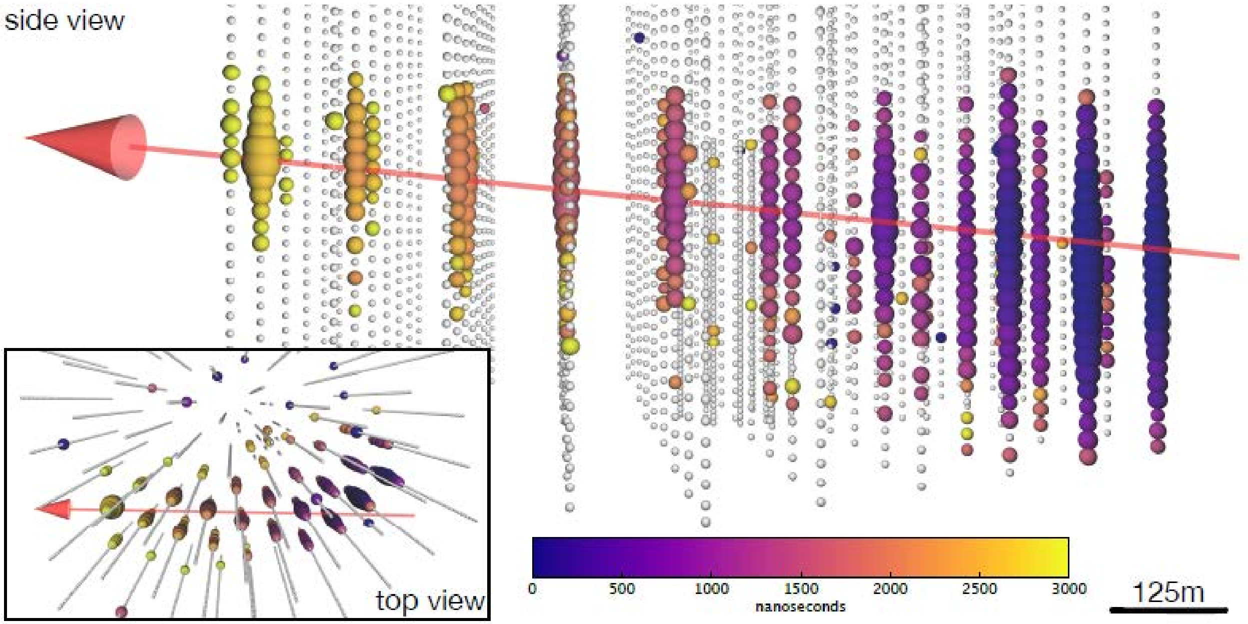
Neutrinos



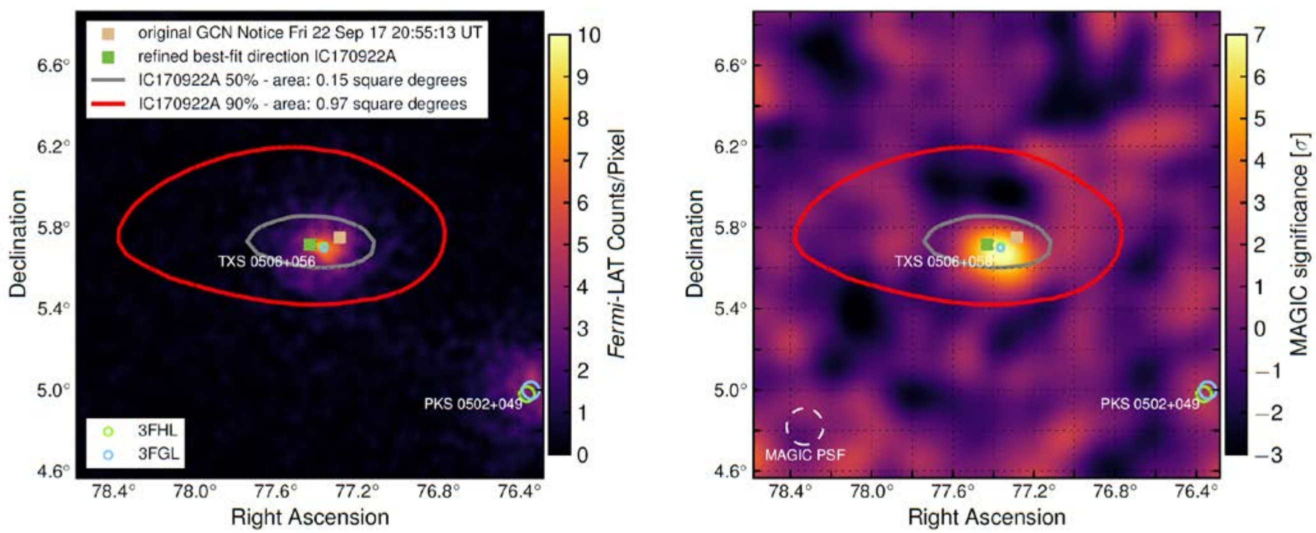
Gravitational Waves

Illustrations: Katz et al. (2012)

Neutrino Production in Blazars



IceCube-170922A



TXS 0506+056

(IceCube et al. 2018)

Basics of Neutrino Production

- $p + \gamma \rightarrow p + \pi^0$

  or $n + \pi^+$

$$\pi^0 \rightarrow 2\gamma$$

$$\pi^+ \rightarrow \mu^+ + \nu_\mu \qquad \tau = 2.55\times10^{-8}\ \mathrm{s}$$

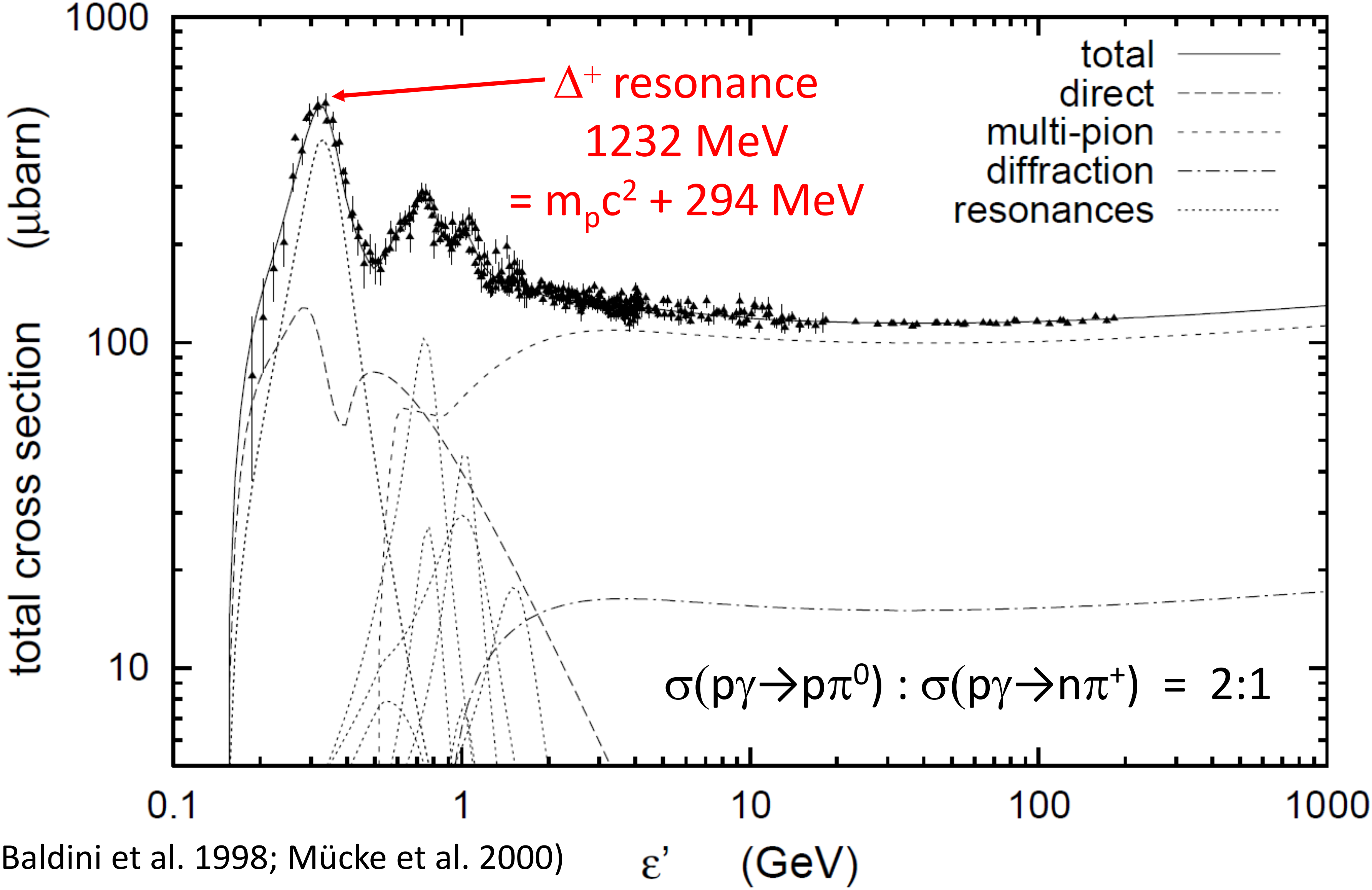
$$\pi^- \rightarrow \mu^- + \nu_\mu$$

$$\mu^+ \rightarrow e^+ + \nu_\mu + \nu_e \qquad \tau = 2.2\times10^{-6}\ \mathrm{s}$$

$$\mu^- \rightarrow e^- + \nu_\mu + \nu_e$$

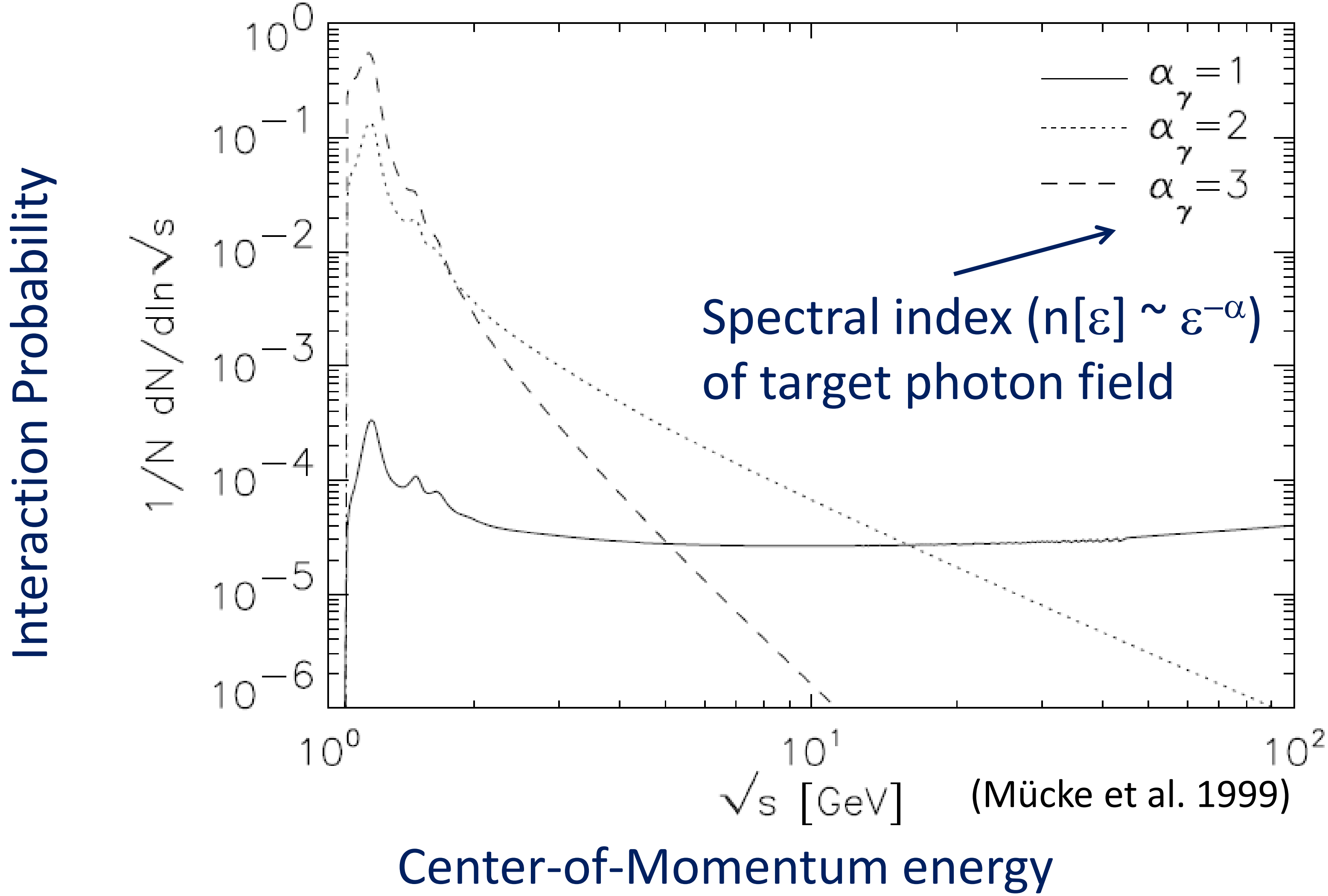
$p\gamma$ likely strongly dominant over pp
in AGN jet environments.

Photo-Pion Production



(Baldini et al. 1998; Mücke et al. 2000)

Photo-Pion Production



For realistic target photon fields,
most interactions occur near Δ^+ resonance.

Photo-pion production - Energetics

At Δ^+ resonance:

$$s = E'_p\, E'_t\, (1 - \beta_p'\, \mu) \sim E'_p\, E'_t \sim E_{\Delta^+}{}^2 = (1232\ \mathrm{MeV})^2$$

and $$E'_\nu \sim 0.05\, E'_p$$

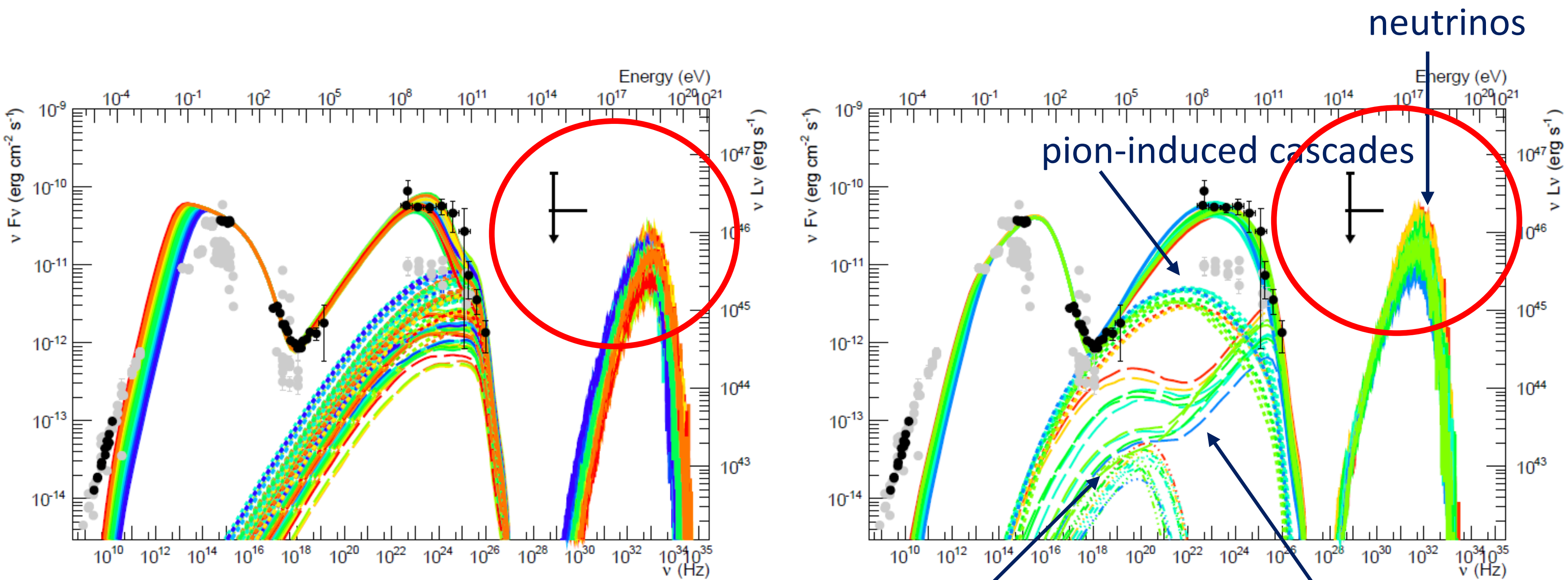
$\Rightarrow$ To produce IceCube neutrinos (~ 100 TeV $\rightarrow$ $E_\nu = 10^{14}\, E_{14}$ eV):

(i.e., $E'_\nu = 10\, E_{14}\, \delta_1^{-1}$ TeV)

Need protons with $E'_p \sim 200\, E_{14}\, \delta_1^{-1}$ TeV => PeV CRs

and target photons with $E'_t \sim 1.6\, E_{14}^{-1}\, \delta_1$ keV => X-rays

Photo-Pion Models for TXS 0506+056



(a) Proton synchrotron modeling of TXS 0506+056

(b) Lepto-hadronic modeling of TXS 0506+056

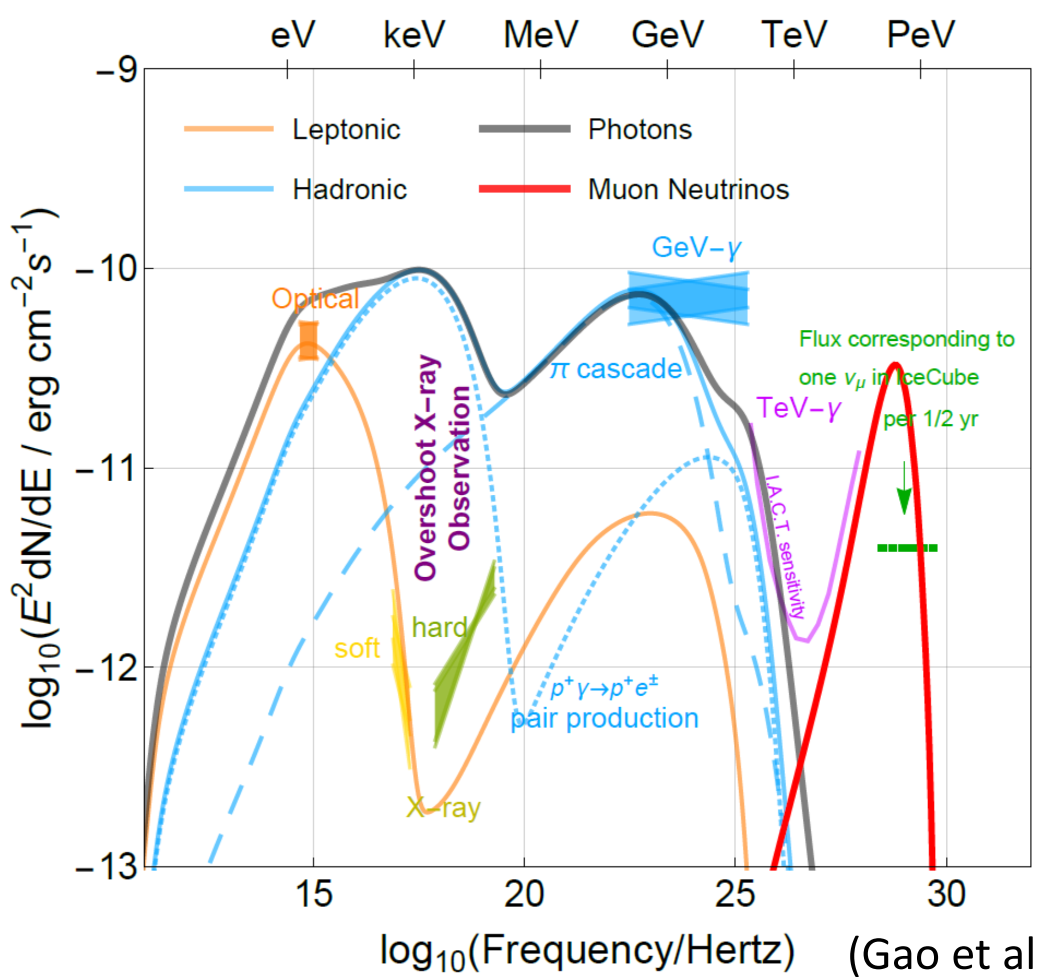
(Cerruti et al. 2019: MNRAS, 483, L12)

Proton-synchrotron

Bethe-Heitler-induced cascades

Models producing neutrinos and gamma-rays through the same proton population, predict too high neutrino energies!

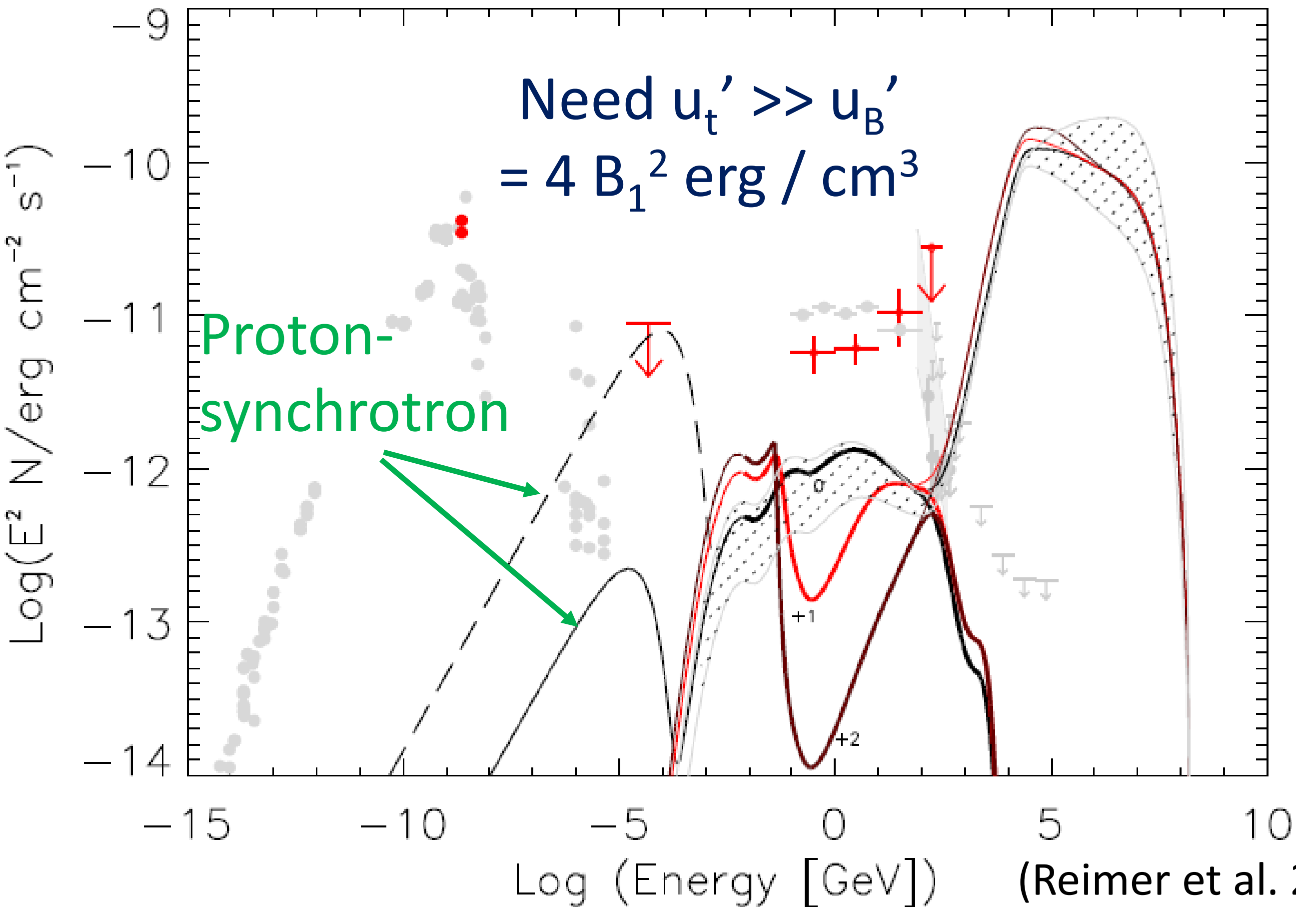
Photo-Pion Models for TXS 0506+056



(Gao et al. 2018, Nature Astron., 3, 88)

Models with p-γ induced γ-ray emission over-produce X-rays due to cascades!

Photo-Pion Models for TXS 0506+056



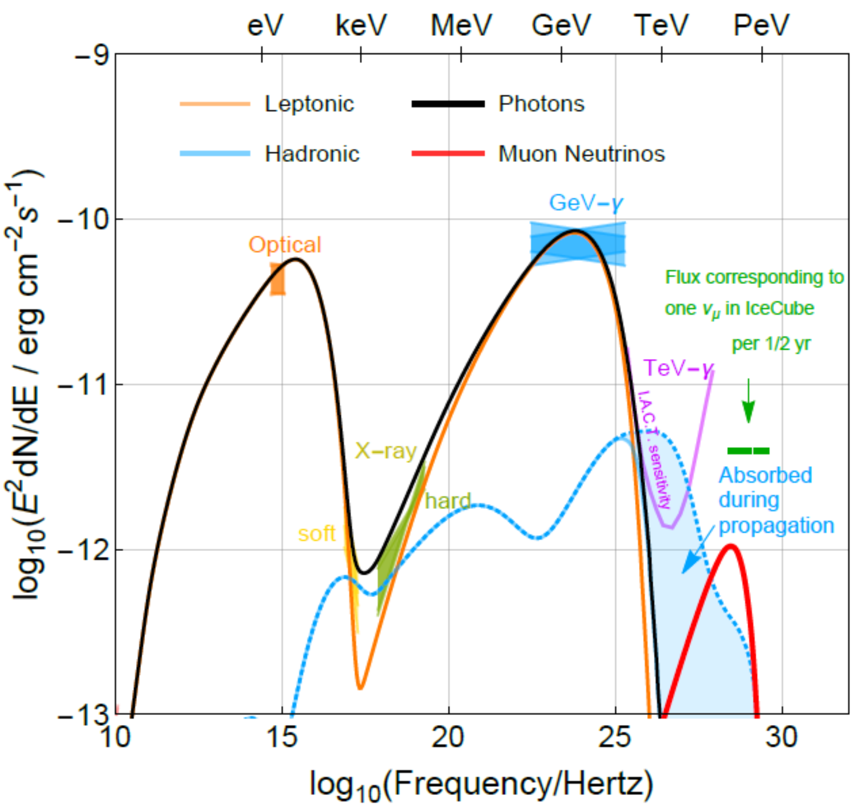
(Reimer et al. 2019: ApJ, 881, 46)

From cascading constraints:

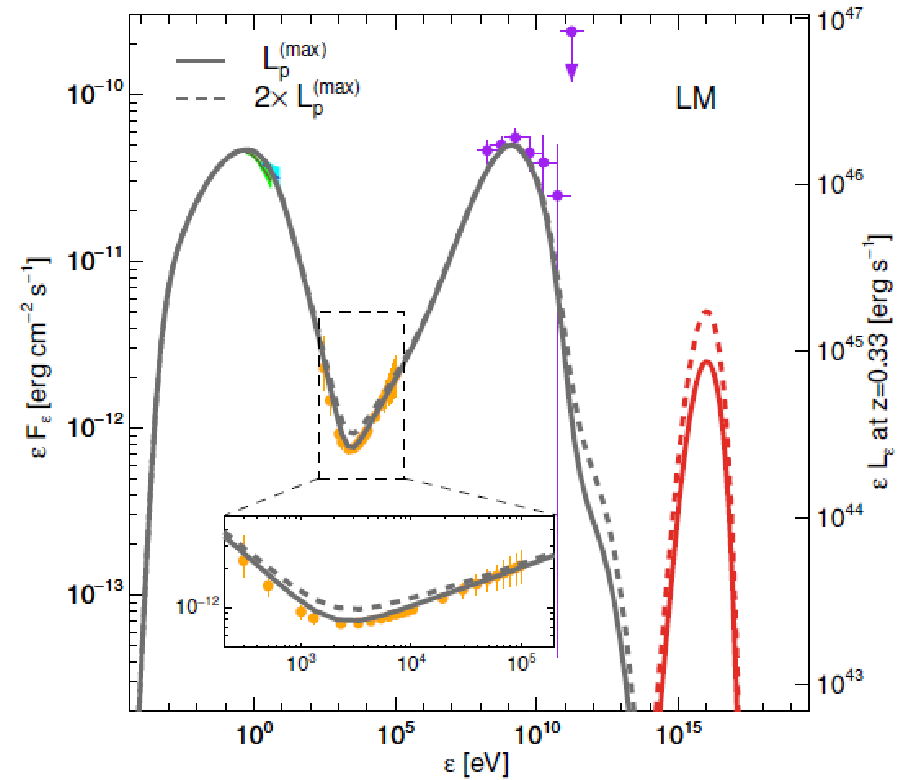
pγ neutrino production in TXS 0506+056 possible with strong external UV/X-ray radiation field, but under-predicts Fermi γ-rays.

=> No neutrino – γ-ray correlation expected!

Photo-Pion Models for TXS 0506+056



(Gao et al. 2018, Nature Astron., 3, 88)

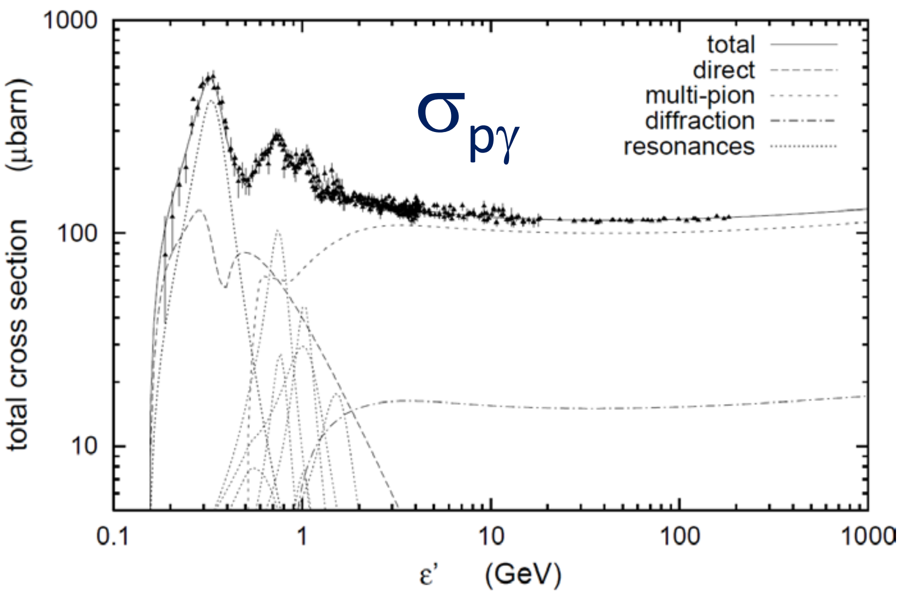


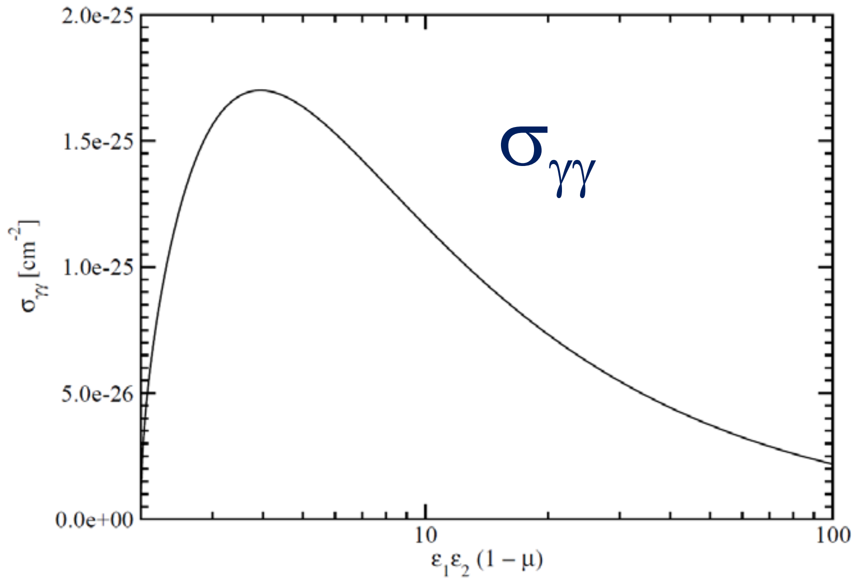
(Keivani et al. 2018, ApJ, 864, 84)

Models producing neutrinos and gamma-rays require leptonically dominated gamma-ray production!

The pγ Efficiency Problem

- Efficiency for protons to undergo pγ interaction ~ $\tau_{p\gamma} = \ell_{esc}\, \sigma_{p\gamma}\, n_{ph}$
- Likelihood of γ-ray photons to be absorbed ~ $\tau_{\gamma\gamma} = R\, \sigma_{\gamma\gamma}\, n_{ph}$





$$\frac{\tau_{p\gamma}}{\tau_{\gamma\gamma}} = \frac{\sigma_{p\gamma}\,\ell_{esc}}{\sigma_{\gamma\gamma}\,R} \approx \frac{1}{300}\,\frac{\ell_{esc}}{R}$$

ℓ_{esc} = average length travelled by protons until escape

at $$E_\gamma \sim \frac{m_e{}^2 c^4}{E_t} \sim 3.3 \times 10^{-5} E_\nu$$ ← ~ GeV – TeV γ-rays

The pγ Efficiency Problem

$$\frac{\tau_{p\gamma}}{\tau_{\gamma\gamma}} = \frac{\sigma_{p\gamma}\,\ell_{esc}}{\sigma_{\gamma\gamma}\,R} \approx \frac{1}{300}\frac{\ell_{esc}}{R}$$

ℓ_{esc} = average length travelled by protons until escape

ℓ_{esc} from random walk:

mean free path $\lambda = \eta(\gamma)\, r_g(\gamma)$

Number of scatterings to escape, N_s: $R = \sqrt{N_s}\,\lambda$

$$\ell_{esc} = N_s\,\lambda = \frac{R^2}{\lambda} \approx 3.3 \times 10^{21}\, \eta(\gamma)^{-1}\, R_{16}^{2}\, B_2\, E_{15}^{-1}\ \mathrm{cm}$$

$$\Rightarrow \quad \frac{\tau_{p\gamma}}{\tau_{\gamma\gamma}} = \frac{\sigma_{p\gamma}\,\ell_{esc}}{\sigma_{\gamma\gamma}\,R} \approx 1.1 \times 10^{3}\, \eta(\gamma)^{-1}\, R_{16}\, B_2\, E_{15}^{-1}$$

$\Rightarrow$ Proton pγ efficiency can be >> $\tau_{\gamma\gamma}$, but misleading, as $t_{cool,p\gamma}$ and $t_{esc,p}$ >> R/c

The pγ Efficiency Problem

Relevant constraint for proton bulk kinetic luminosity:

$$L'_{\nu} \approx \frac{1}{2}\, m_p c^2 \int d\gamma_p\, N_p(\gamma_p) |\dot{\gamma}_{p,\,p\gamma}| = L'_{\nu}\,(\mathrm{obs})$$

$$\dot{\gamma}_{p,\,p\gamma} \approx -c < \sigma_{p\gamma} f > \frac{u'_{ph}}{m_e\, c^2}\, \gamma_p$$

$$\Rightarrow \quad L_p\, u'_{ph} \approx 1.4\times 10^{52}\, \delta_1^{-4}\, \Gamma_1^{\,2}\, R_{16}^{\,-1} \left(\frac{erg}{s}\right) \left(\frac{erg}{cm^3}\right)$$

(Reimer et al. 2019: ApJ, 881, 46)

Cosmic-Ray Acceleration in Blazars

- No conclusive correlation between AGN and UHECR arrival directions observed.

- To produce > 100 TeV neutrinos $\rightarrow$ Need PeV protons

- Simplest constraint: Confinement (Hillas Criterion):

$$E_n < Z\,e\,B\,R = 3 \times 10^{18}\,B_2\,R_{16}\ \mathrm{eV}$$

(Z = 1 for protons)

for hadronic blazar models with $B = 100\,B_2$ G

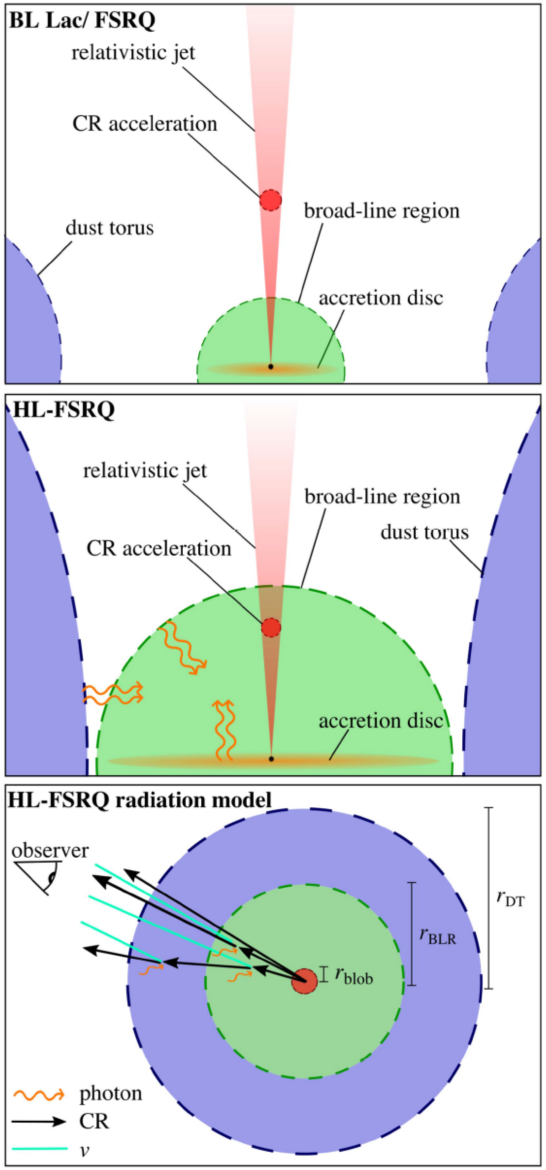
$R = 10^{16}\,R_{16}$ cm

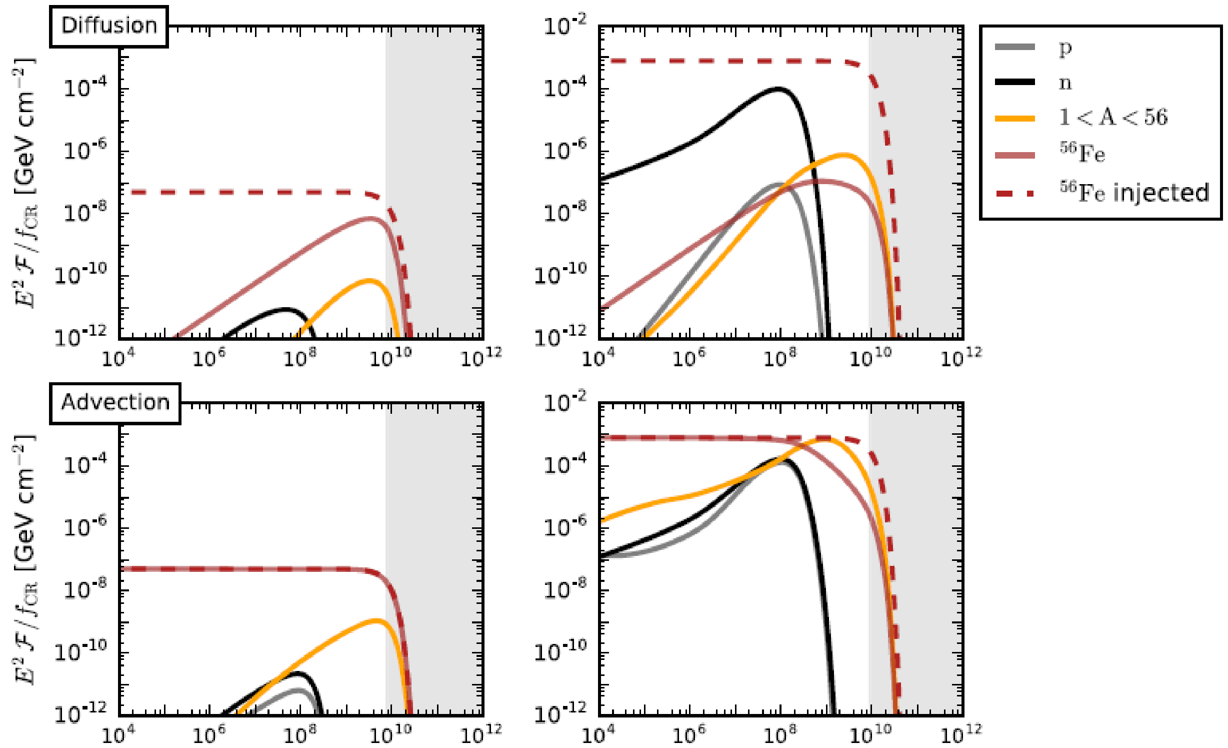
$\Rightarrow$ Protons for IceCube neutrino production: 

$\Rightarrow$ UHECRs ($E > 10^{19}$ eV): Plausible for heavy elements ($Z \gg 1$)

(e.g., Rodrigues et al., 2018: ApJ, 854, 54)

Cosmic-Ray Acceleration in Blazars



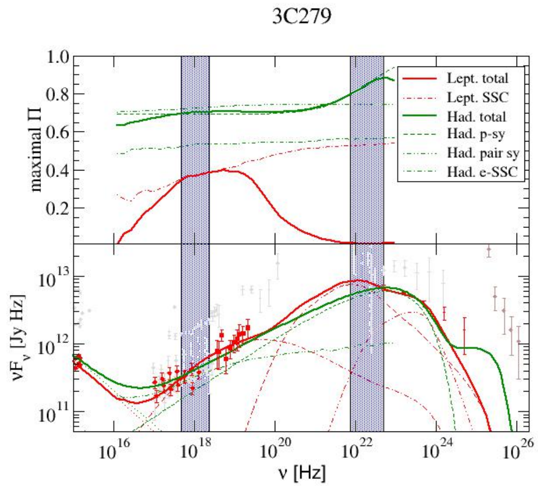


Acceleration of Fe and subsequent spallation may produce UHECR spectra and composition similar to the observed ones.

(Rodrigues et al., 2018: ApJ, 854, 54)

Observable signatures of proton / CR acceleration in blazars

- X-ray / γ-ray polarization

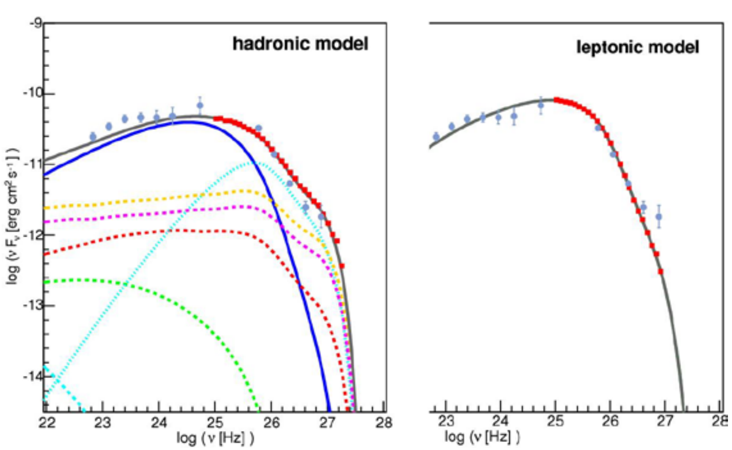


→ IXPE / AMEGO

Requires simultaneous optical polarimetry for comparison.

(Zhang & Böttcher 2013: ApJ, 744, 18)

- Spectral signatures of pγ induced cascades



→ CTA

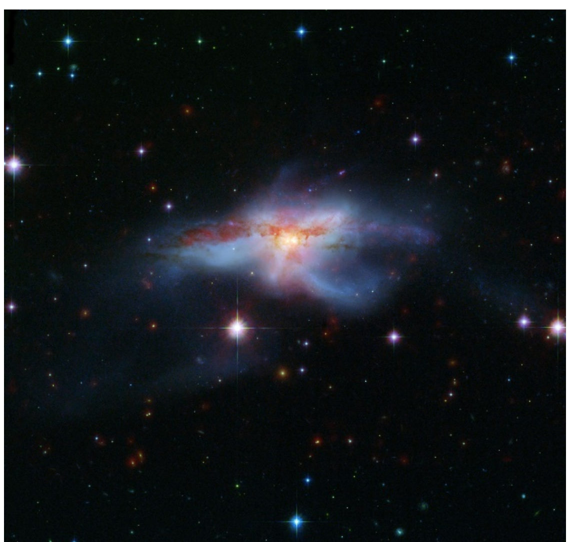
Requires simultaneous MWL (OIR-UV-X-ray) coverage.

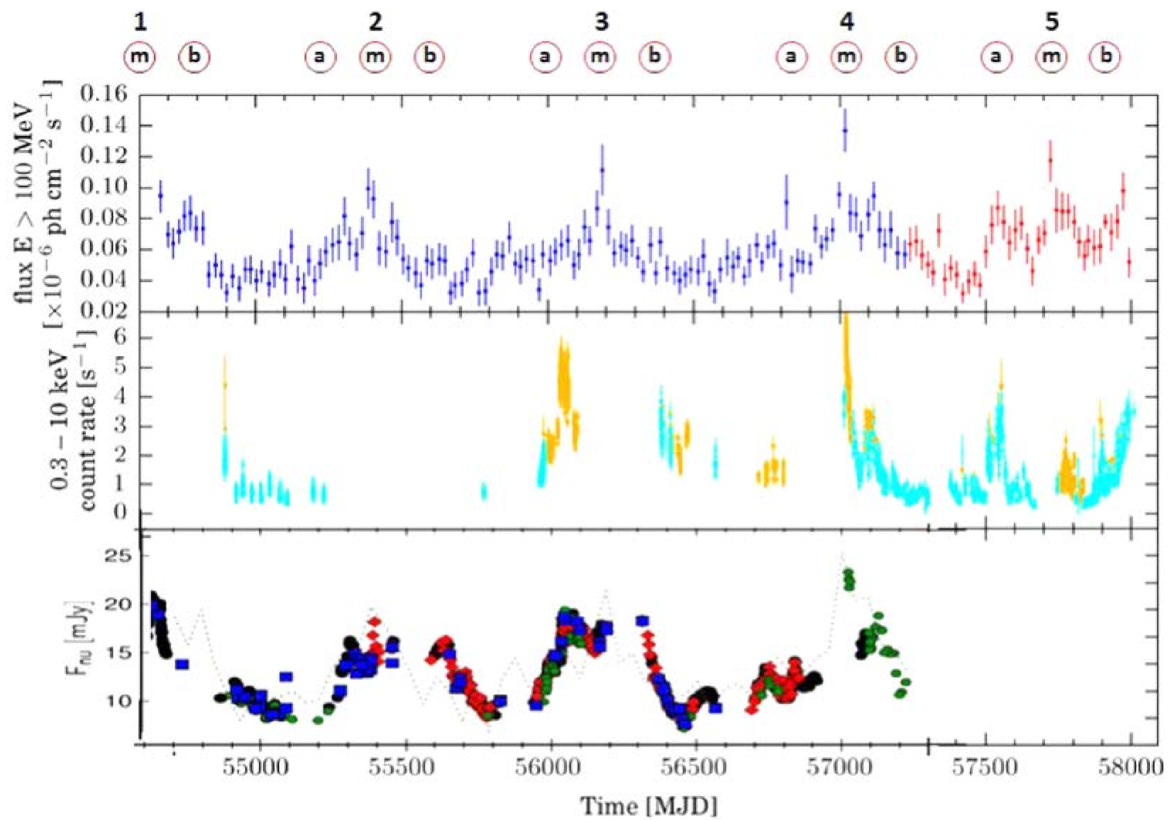
(Zech et al. 2017: A&A, 602, A25)

Binary Super-Massive Black Holes – Gravitational Waves

Evidence for periodicity in some AGN, e.g., OJ 287, PG 1553+113

Possible signature of binary super-Massive black holes

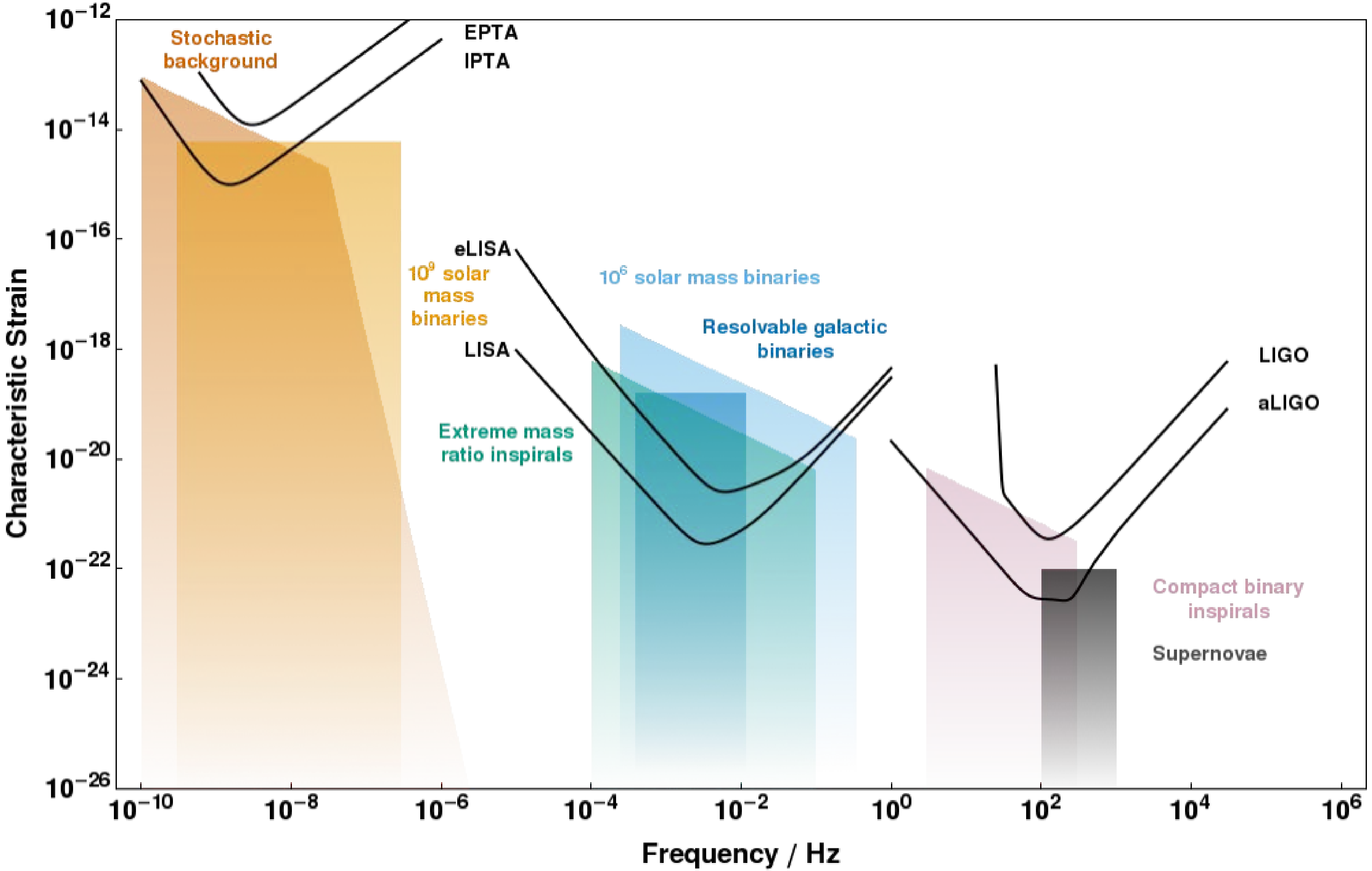




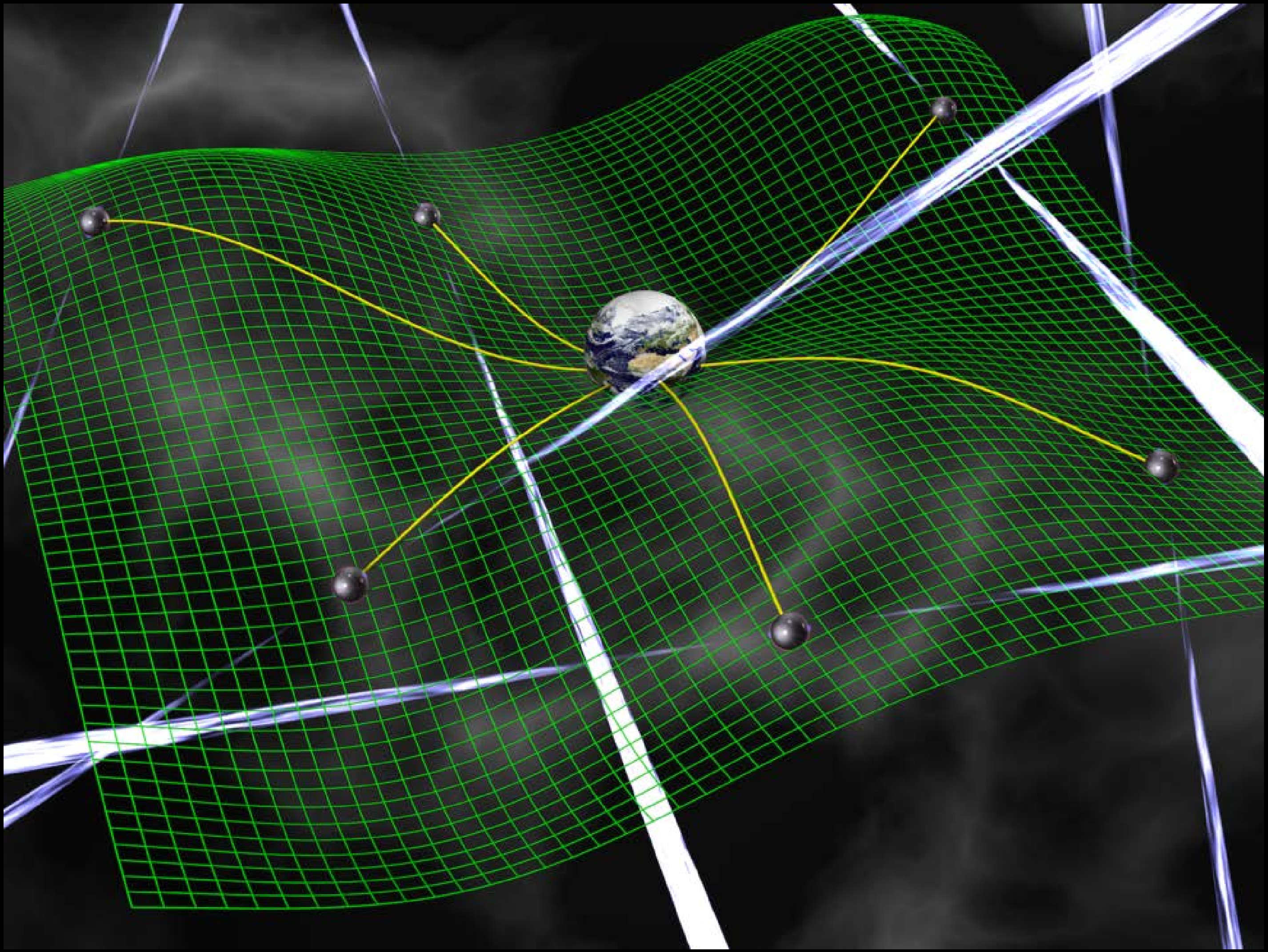
(Tavani et al., 2018, ApJ, 851, 11)

Gravitational Waves from supermassive black hole binaries

GW frequencies: $f \sim 30\ P_y^{-1}$ nHz



Pulsar Timing Arrays

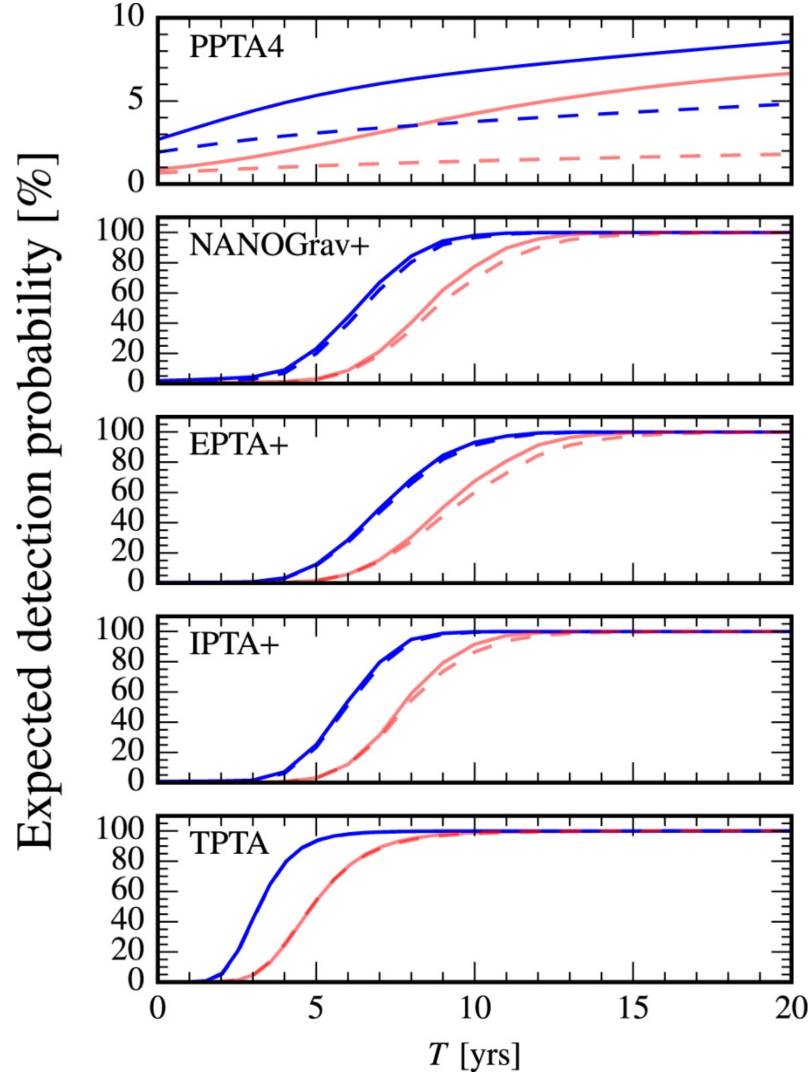


Search for relative distortions of pulsar timing signals in various directions

Gravitational Waves from supermassive black hole binaries

Prospects for detection with Pulsar Timing Arrays (PTAs):

Large Pulsar Timing Ararys (incl. Parkes PTA) may detect SMBH binary GW background within the next ~ 5 – 10 years.



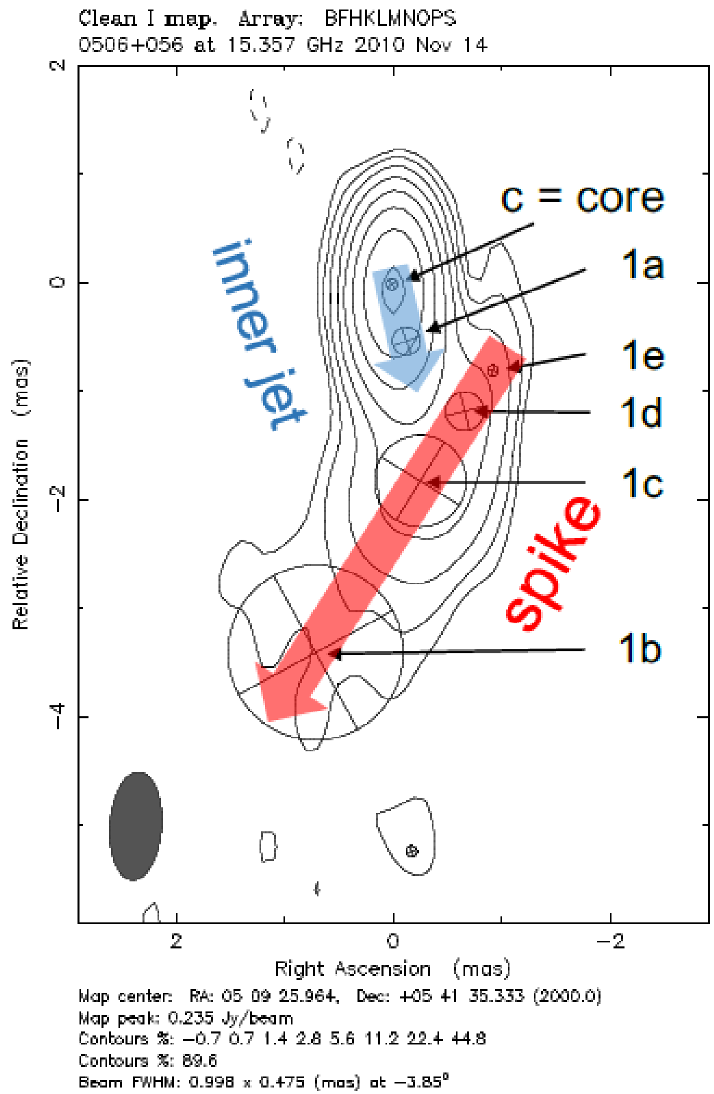
(Taylor et al. 2016, ApJ, 819, L6)

Supermassive black hole binaries

No detection of individual binaries, but estimates of total number of binary SMBHs.

→ disk/jet precession
→ feasibility of precessing-jet models for blazar variability

SMBH binaries: Possible site of jet-jet interaction → VHE neutrino production (?)



(Britzen et al., 2019: A&A, 630, 103)

Summary

- Production of IceCube neutrinos in AGN / blazars plausible, but no correlation between γ-ray and neutrino activity necessarily expected.
- Blazar jets are plausible accelerators of PeV – EeV CRs; UHECR acceleration plausible for primary acceleration of heavier nuclei (Fe).
- Binary Supermassive black holes (Periodicity / precessing / interacting jets) produce nHz gravitational-wave background, which may be detectable by PTAs within the next decade.

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Thank you!

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