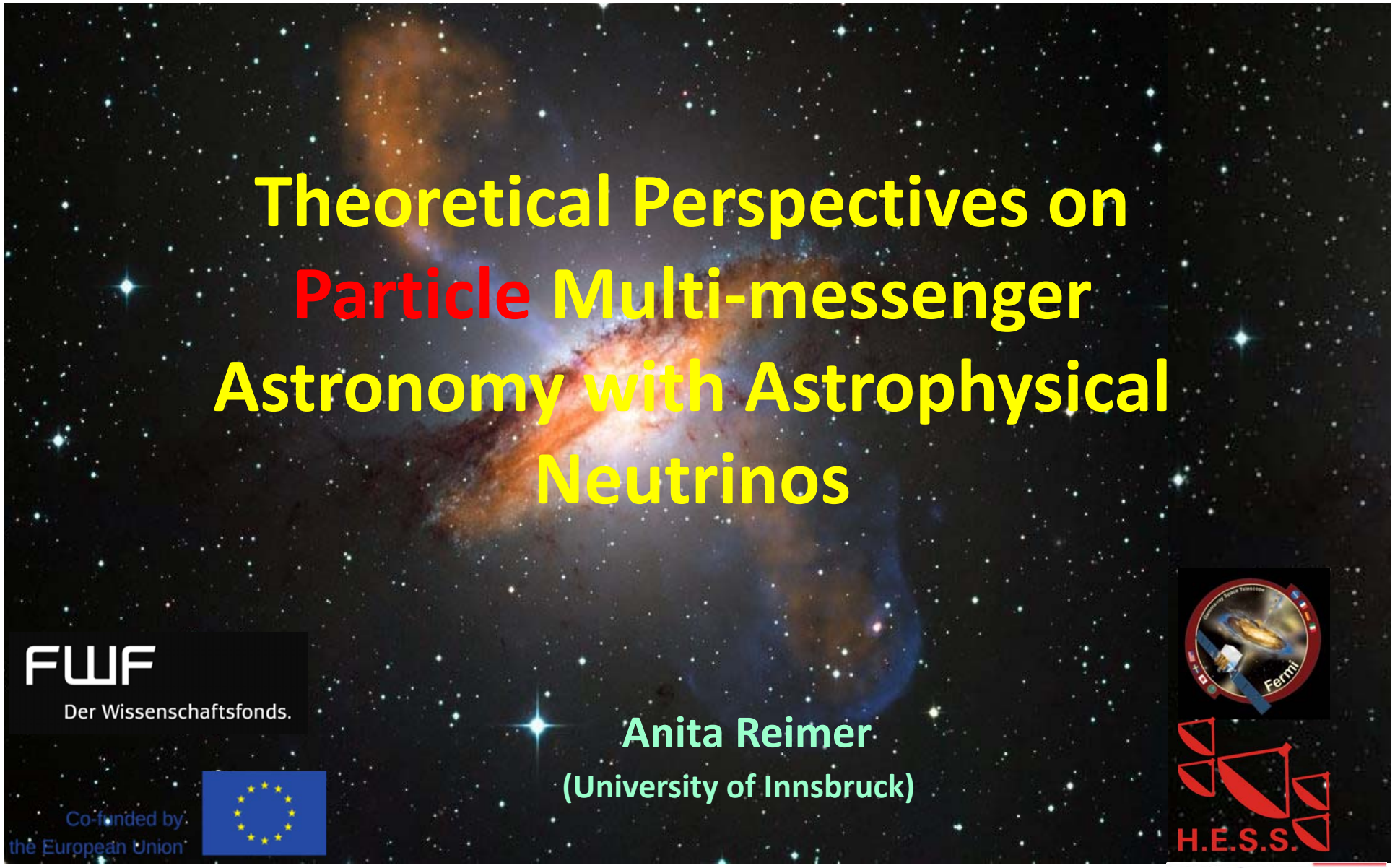

Theoretical Perspectives on Particle Multi-messenger Astronomy with Astrophysical Neutrinos

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FWF Der Wissenschaftsfonds.

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universität innsbruck

9th Fermi Symposium

April 14, 2021

Outline

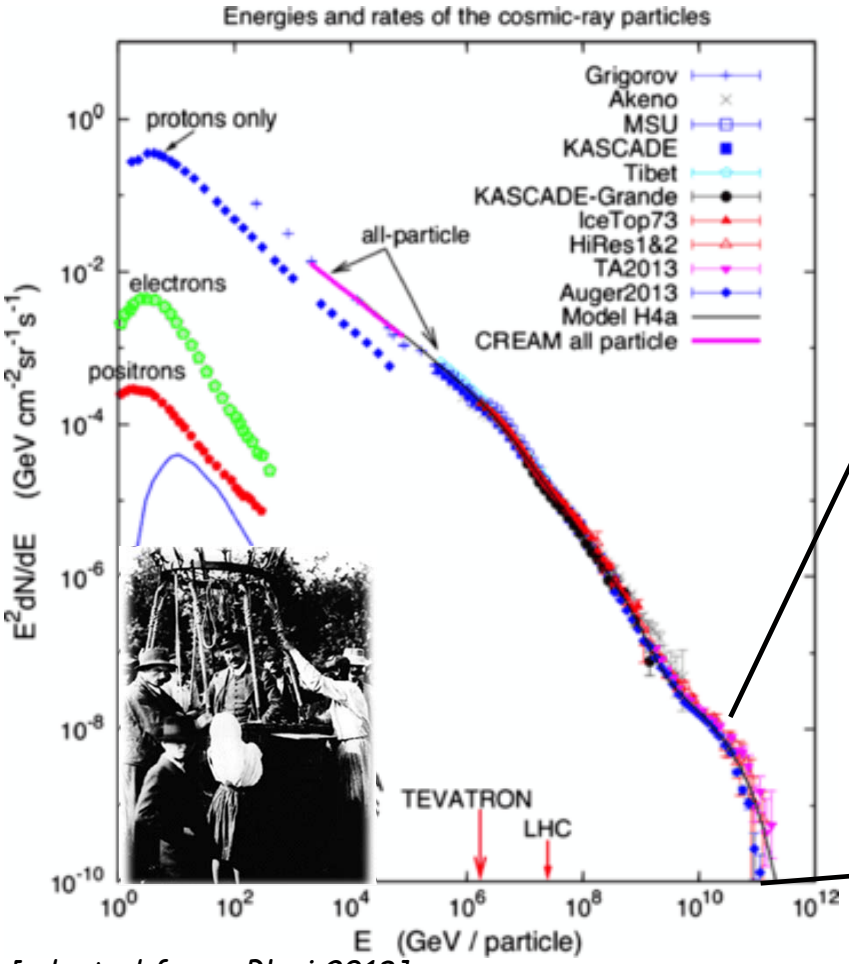
I Open questions in particle multi-messenger astrophysics

II On the particle multi-messenger connection

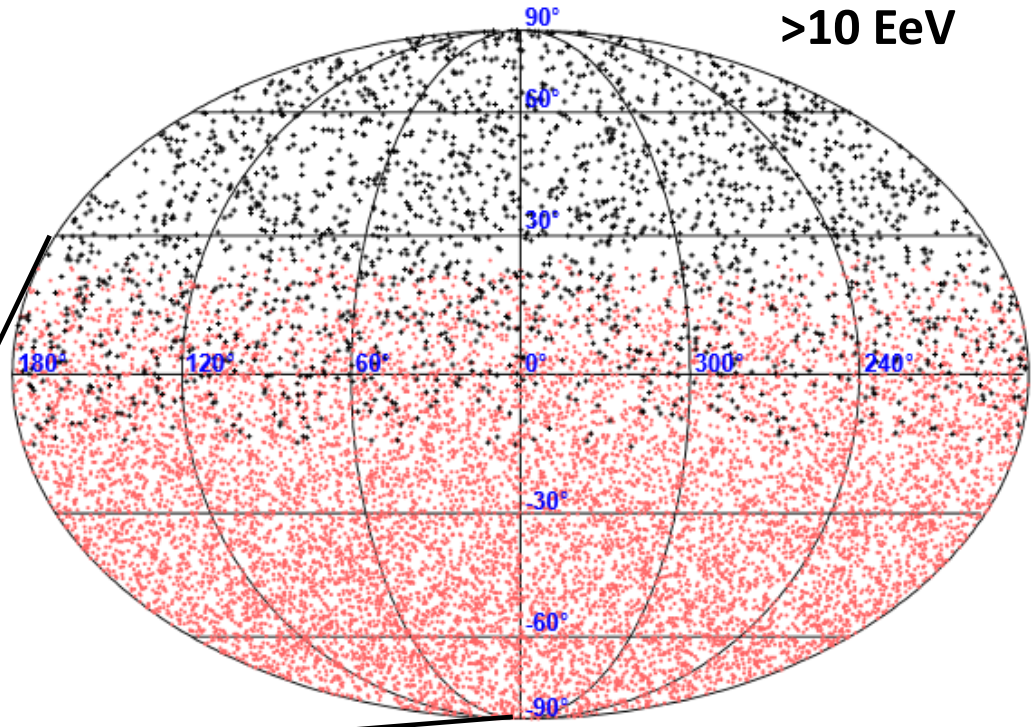
III Exploring the environments of neutrino production

IV Concluding remarks & future perspectives

Cosmic Rays as Messengers of the High-Energy Universe



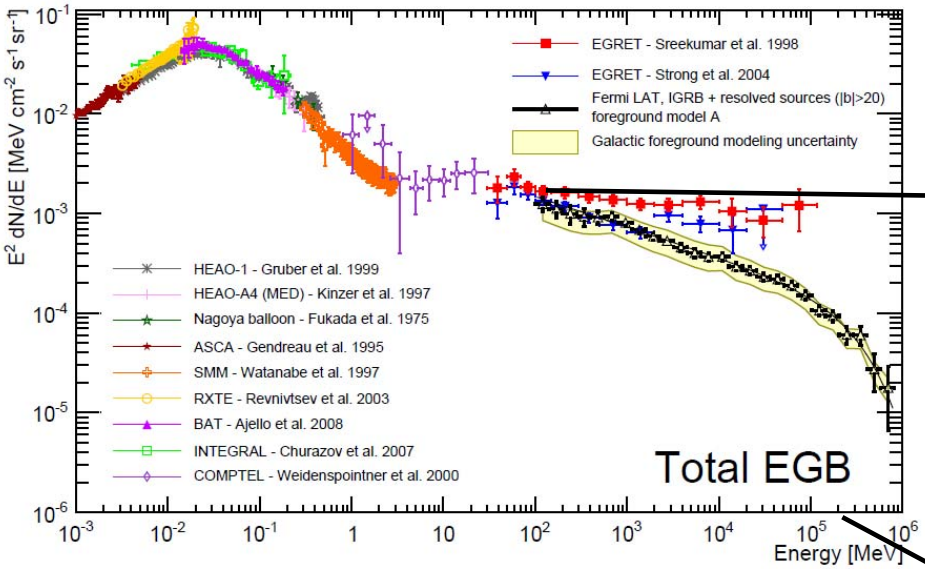
[adapted from: Blasi 2013]



[from: Auger & TA Collab. 2014]

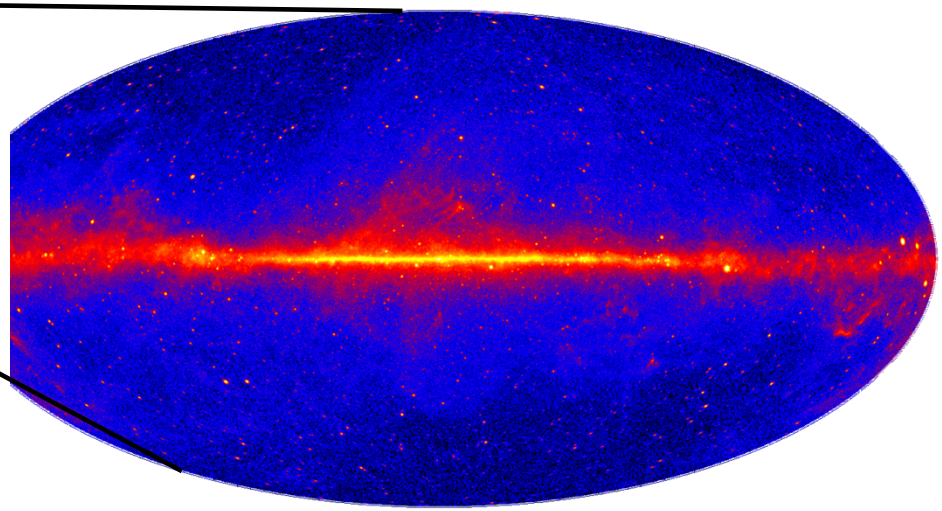
- **Where** do the cosmic rays originate?
- **What** are their sources?
- **How** do these cosmic particle accelerators work? (Mechanisms, environments, ...)

Gamma Rays as Messengers of the High-Energy Universe



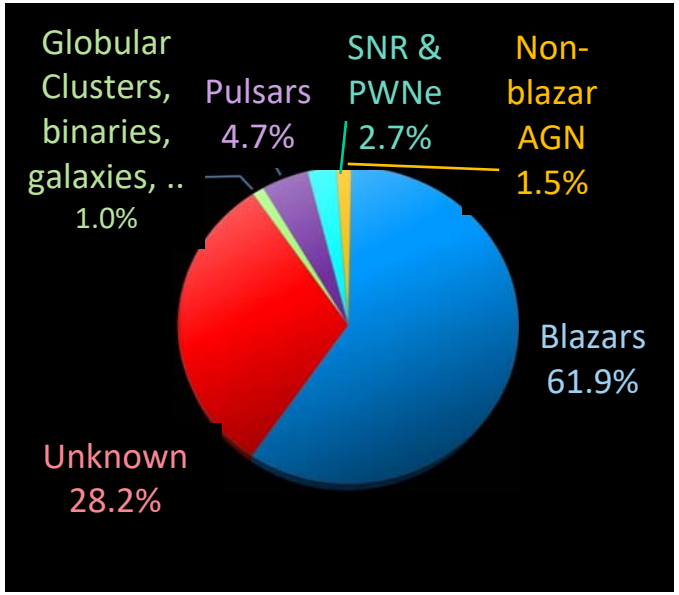
[From: LAT Collab. 2014]

>1 GeV



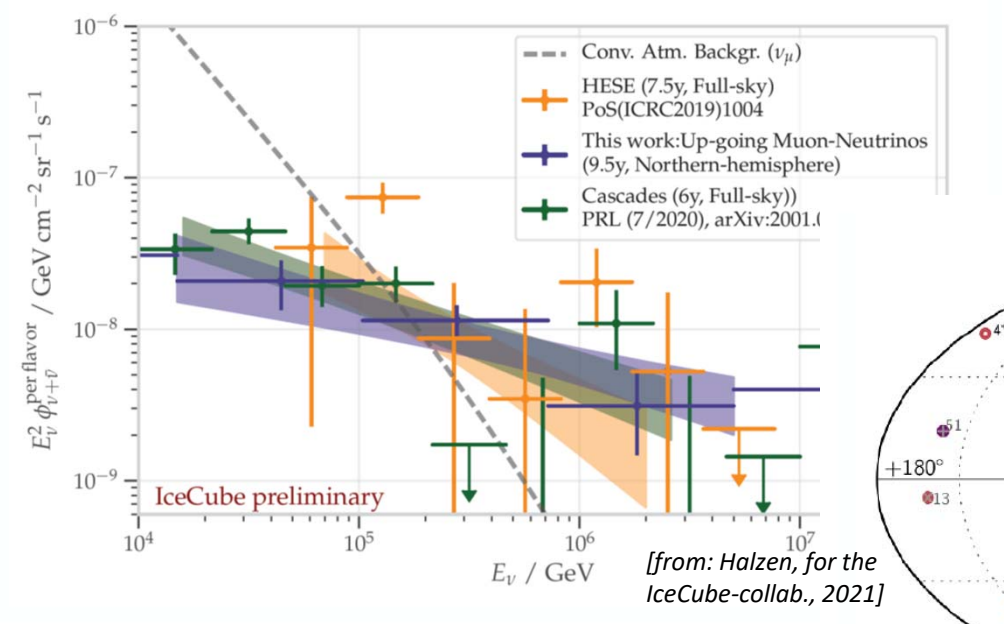
The 4FGL-DR2 All-Sky Map

[from: LAT Collab. 2020]

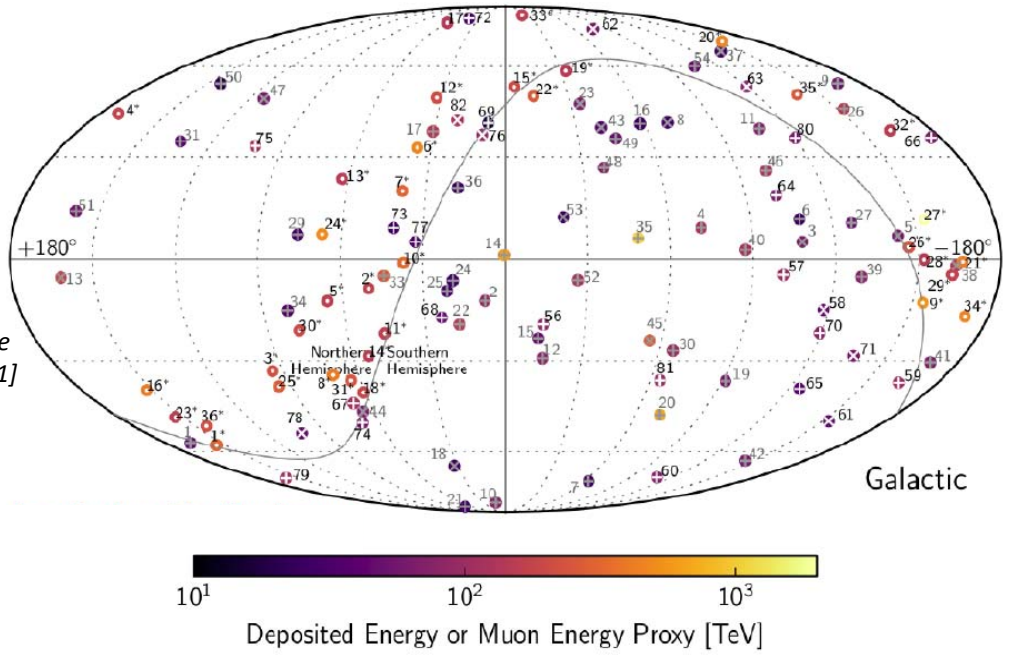


- **How** do these cosmic particle accelerators work? (Mechanisms, environments, ...)
- **What** are the unassociated sources?
- **Where** do they originate?

Neutrinos as Messengers of the High-Energy Universe



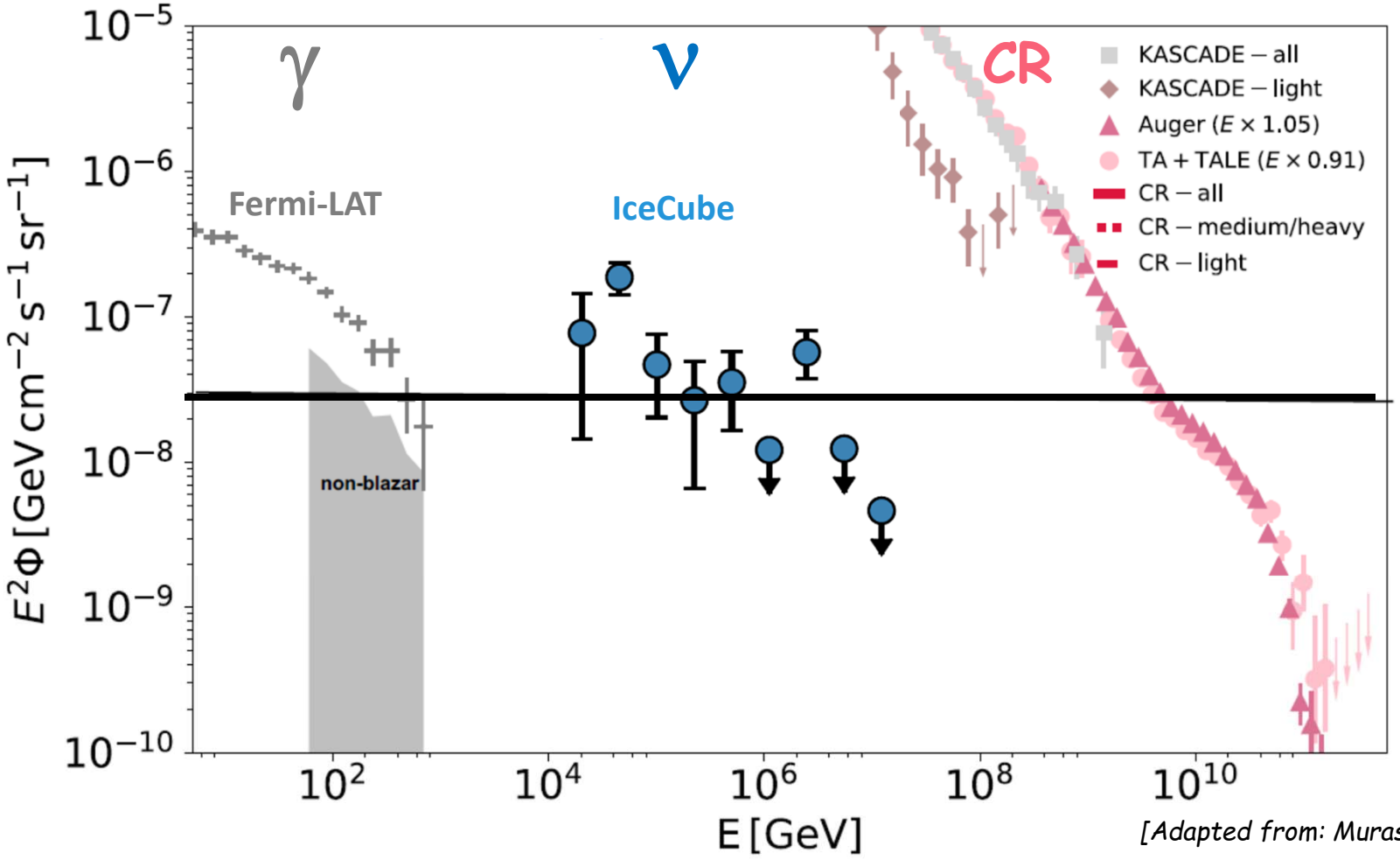
[from: Halzen, for the IceCube-collab., 2021]



Diffuse ν -flux per flavor
~ 10^{-8} GeV cm^{-2}s^{-1}sr^{-1} @ E_ν>200TeV

- **Where** do the astrophysical neutrinos originate?
- **What** are their sources?
- **How** do these cosmic particle accelerators work? (Mechanisms, environments, ...)

Multi-messenger allsky spectrum

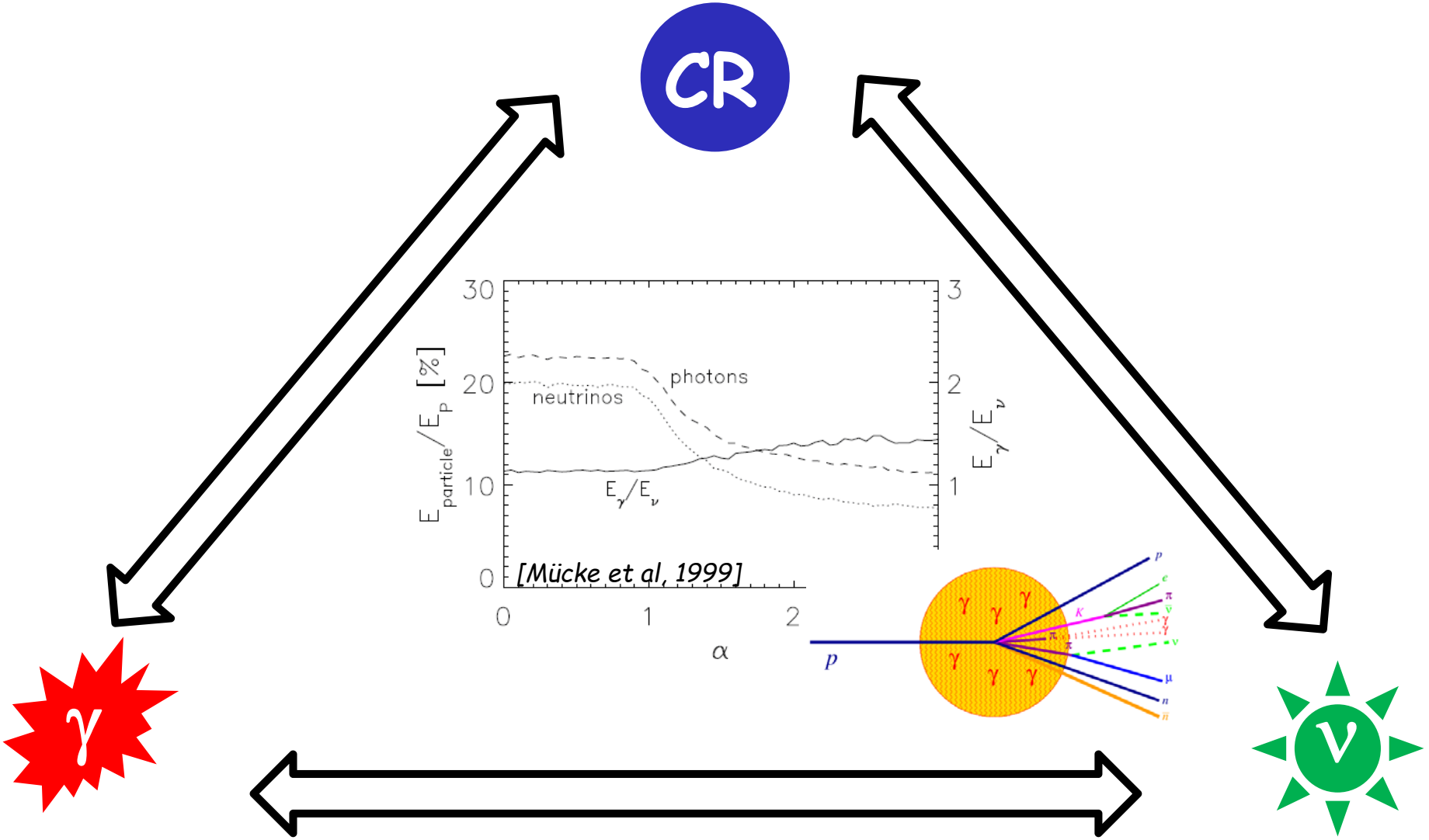


[Adapted from: Murase 2019]

-> Comparable power density in gamma rays, neutrinos & UHECRs
~ $10^{43...44}$erg Mpc^{-3}yrs^{-1}

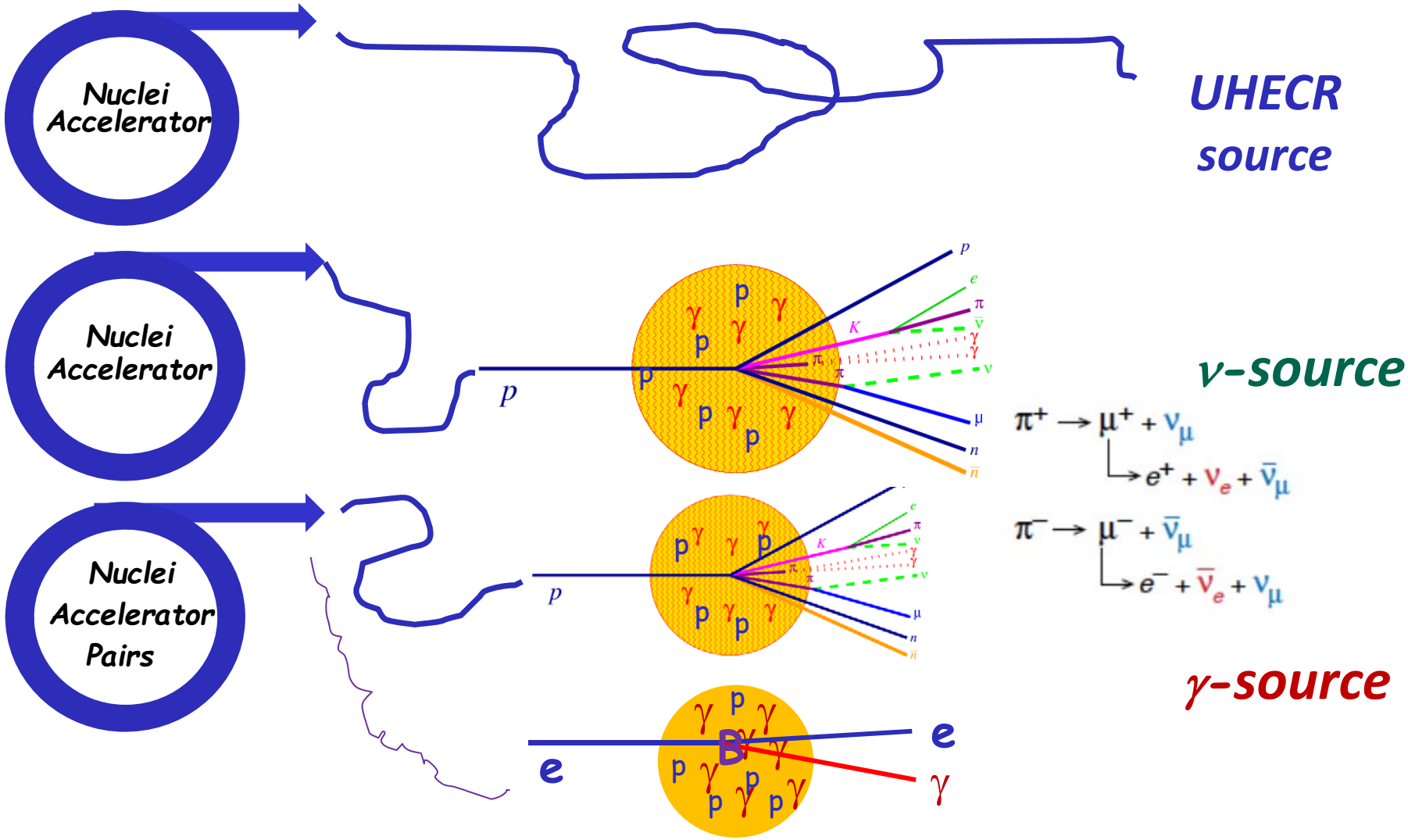
Same source origin of gamma rays, neutrinos, UHECRs then?

Linking cosmic rays - gamma rays - neutrinos



.... is an incomplete picture!

On Multi-messenger sources



Neutrino & gamma-ray production needs targets!

Do UHECR-, γ- & ν-sources look observationally alike?

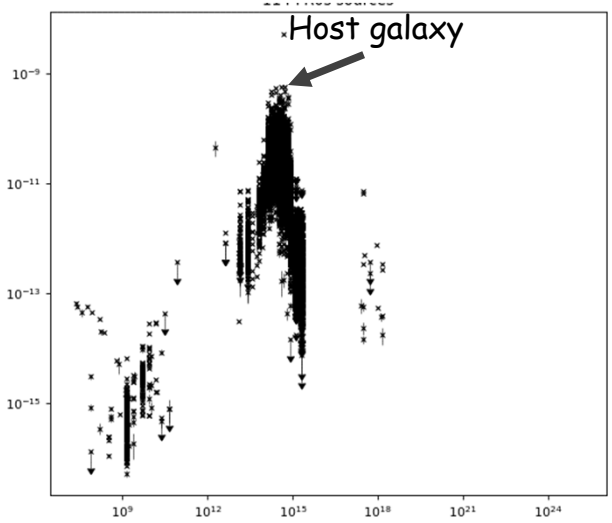
Example of a possible UHECR-source candidate population

Suitable environment for

***survival of nuclei* &**

particle acceleration to

sufficient high energies**?**

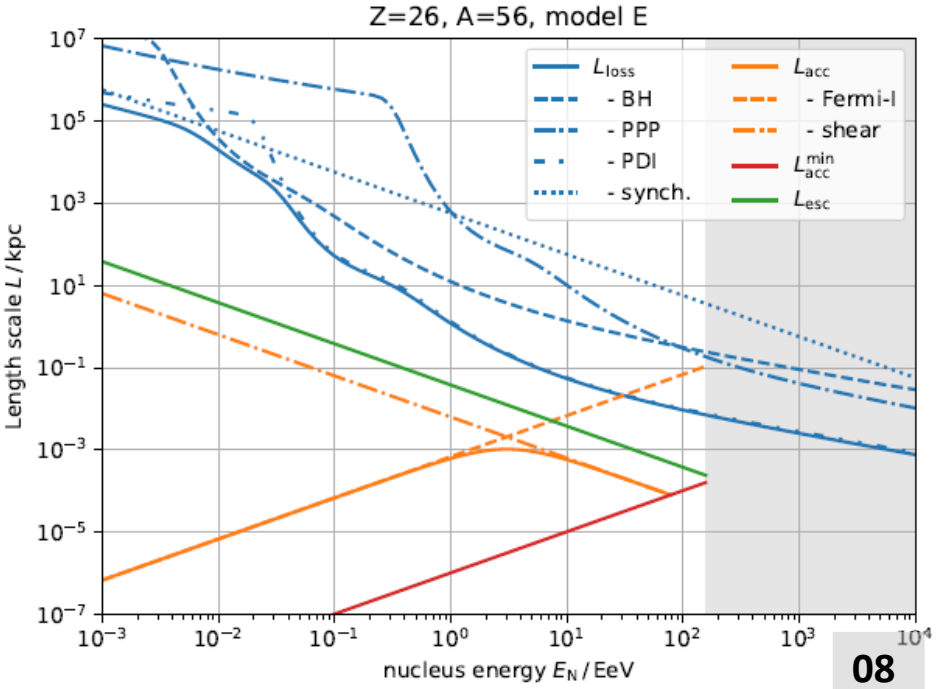


FR0 radio galaxies:

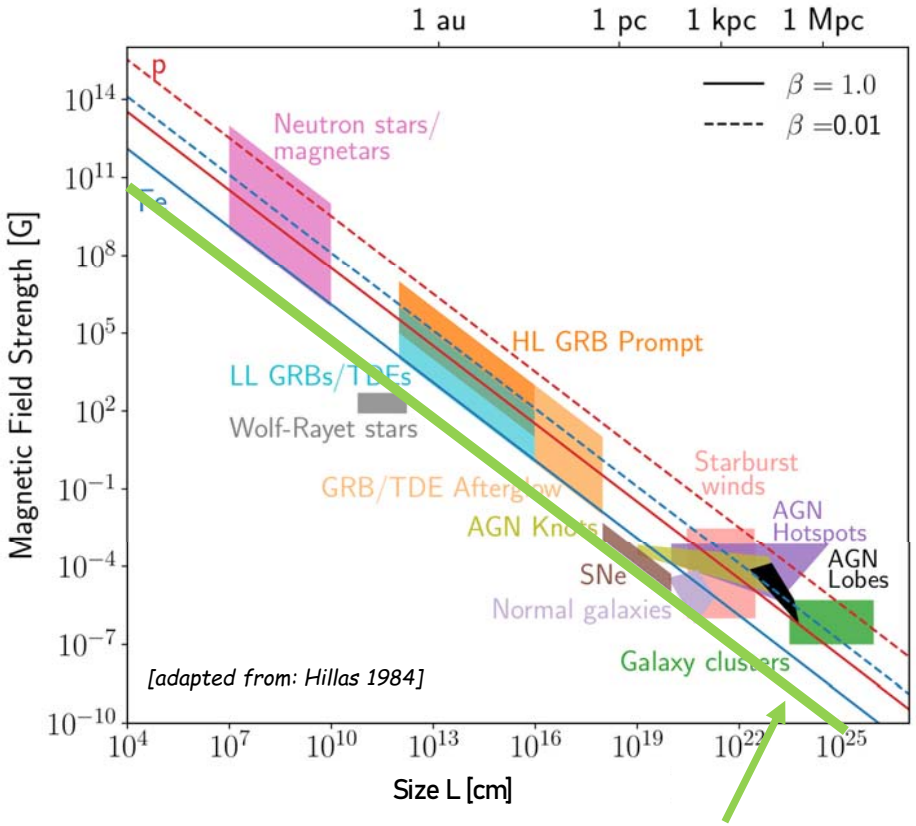
- **pc ... kpc jet lengths**
- **$L_{jet} \approx 10^{42...43}$ erg/s**
- **n_{FR0} ~** a few **10^{-4} Mpc^{-3}**

Turb.	Accel.	Log(E'/eV)			
		p	He	N	Fe
Bohm	Fermi-I	17.4	17.8	18.3	18.8
Bohm	Hybrid	18.8	19.1	19.6	20.2
Kolm.	Fermi-I	14.1	14.4	14.9	15.5
Kolm.	Hybrid	18.8	19.1	19.6	20.2

[Merten, Boughelilba, AR, et al 2021]



Population requirements on HE ν-sources

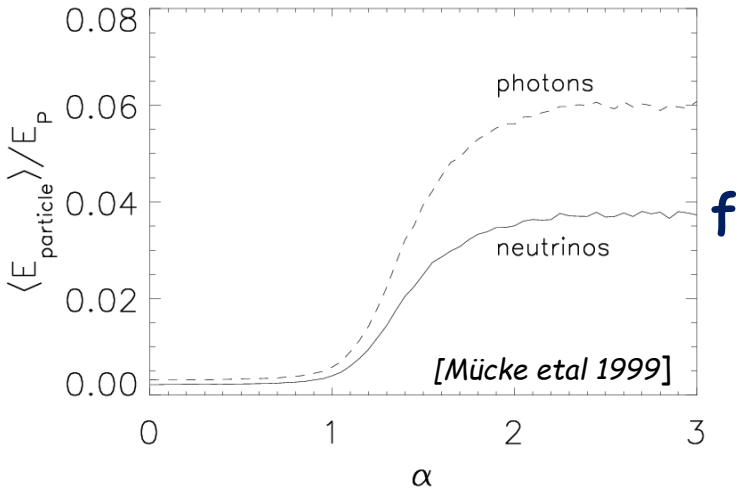


- ***"Hillas"-Criterium:*** $E_{cr,max} \sim 10^{17}\, Z\, \beta\, (B/mG)\, (L/0.1pc)$ eV
- ***Source CR power requirement:*** $P_{source} > 10^{40.5} \Gamma_2^2\, \beta^{-1}\, (E_{\nu,10PeV} / f_{0.05})^2$ erg/s *[Waxman 2004]*
- ***Population power density requirement:*** $U_{\nu,popul} \sim 10^{43....44}$ erg Mpc^{-3} yr^{-1} for $E_\nu \sim 10^{14....16}$ eV

➡ ***Required population density:*** $n_{popul} < 10^{-4 \ldots -5}\, \Gamma_2^{-2} \beta\, (E_{\nu,10PeV}/f_{0.05})^{-2}$ Mpc^{-3}

Requirements on HE ν-source environments

- ***Photomeson production:***



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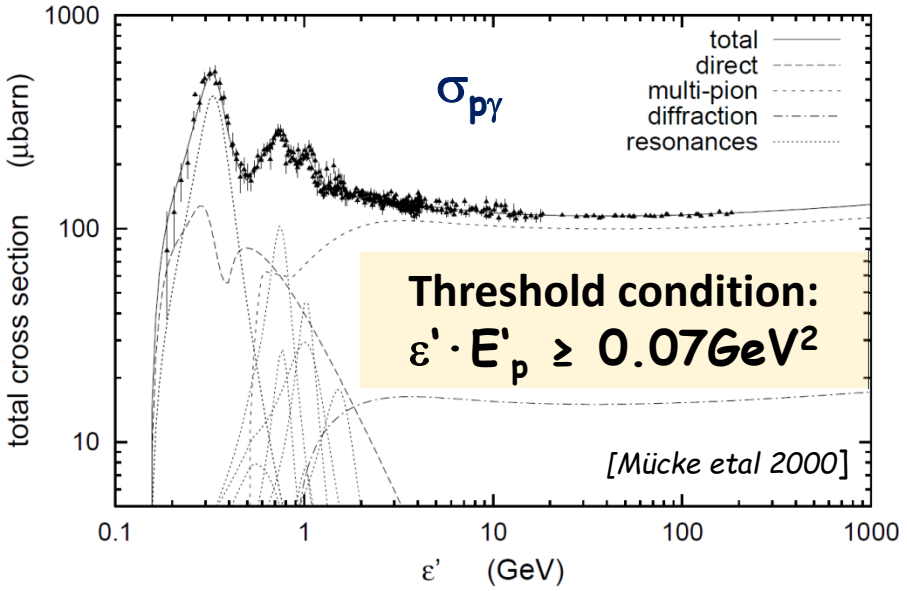


Required nucleon energy:

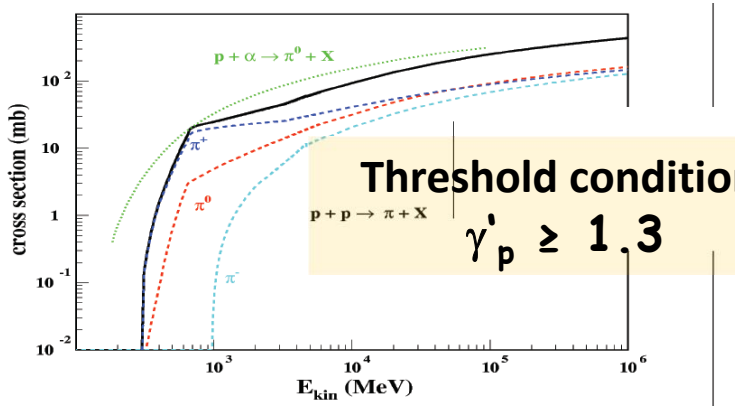
$E'_p \leq 0.2\ (E_{\nu,0.1\,PeV} / D_{10}\, f_{0.05})$ **PeV**

-> Suitable target photons of energy

$\varepsilon' \geq 350\ (E_{\nu,0.1\,PeV} / D_{10} f_{0.05})^{-1}$ **eV**

Soft X-rays!

- ***Hadro-nuclear interaction:***

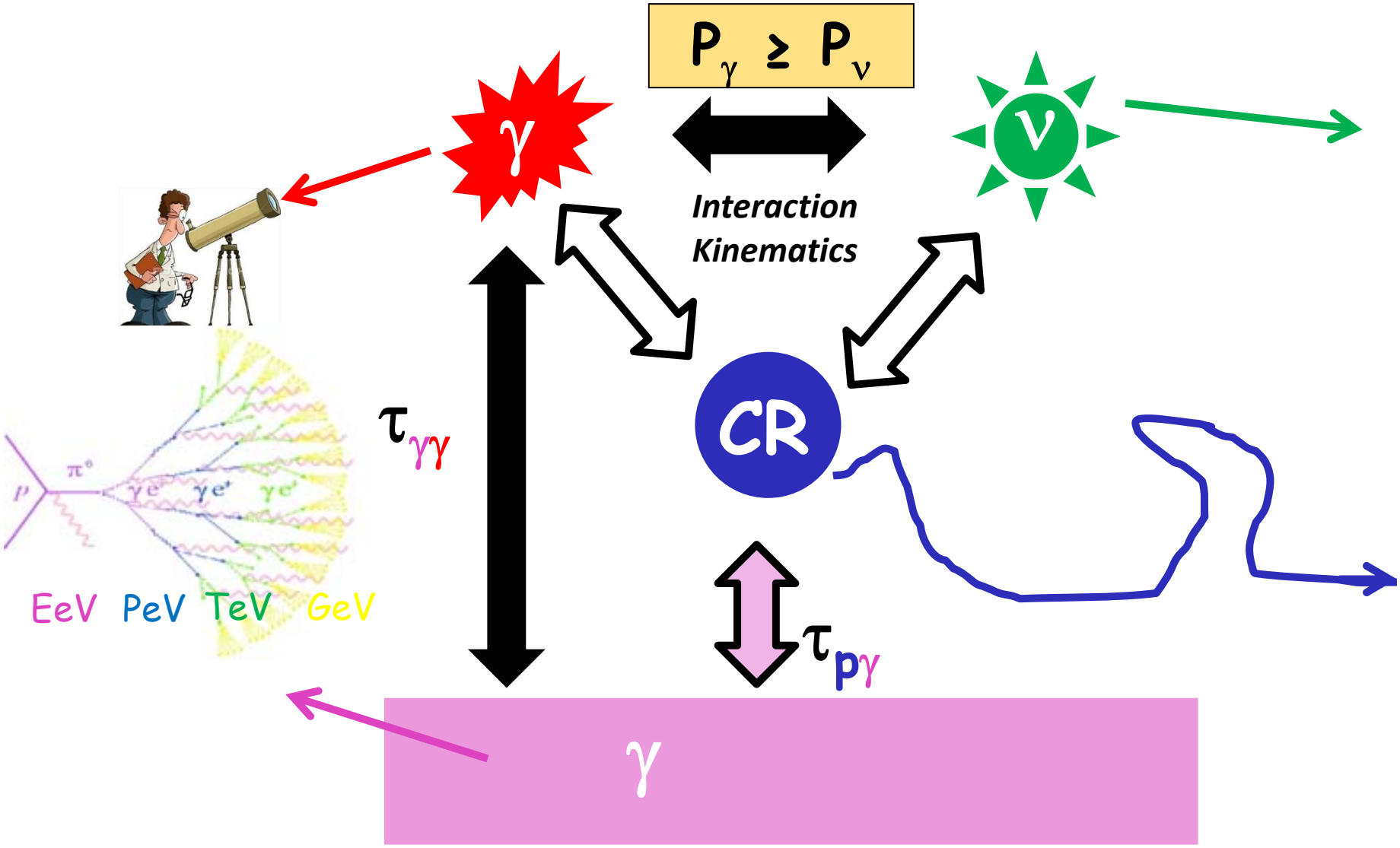


Threshold condition:

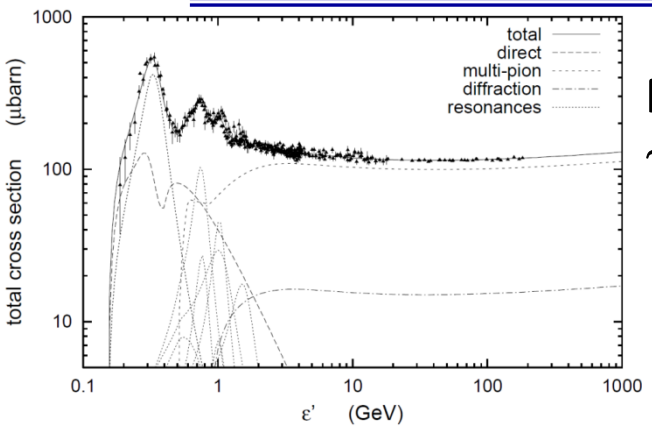
$\gamma'_p \geq 1.3$

Dense targets

Multi-messengers: *The complete picture*



Energy of escaping photons

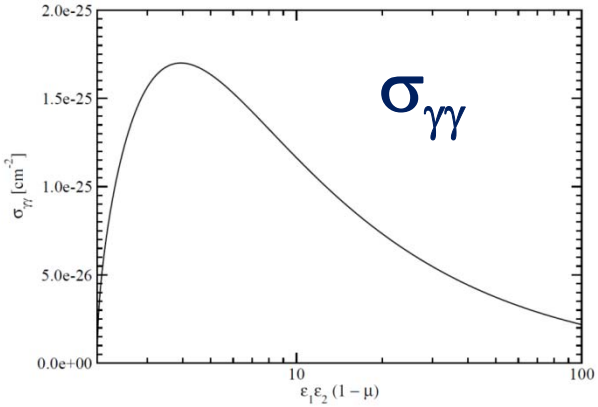


Meson-production

$\sim \tau_{p\gamma} = R\ \sigma_{p\gamma}\ n_{ph,t}$

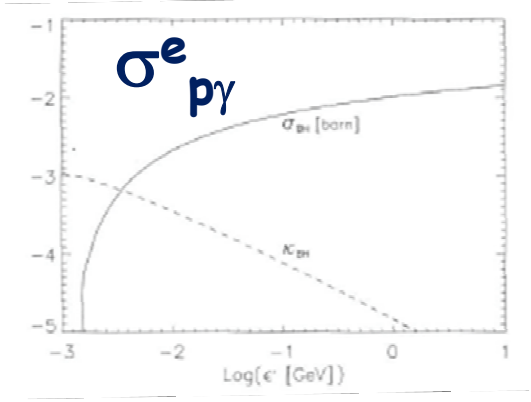
$$E_{\gamma,obs} \ll \frac{4me^2}{(s_{D1232} - mp^2)f}\ E_{\nu,obs}$$

$$\approx 3 \cdot 10^{-5}\ f_{0.05}^{-1} E_{\nu,obs}$$



Absorption probability of γs

$\sim \tau_{\gamma\gamma} = R\ \sigma_{\gamma\gamma}\ n_{ph,t}$



Bethe-Heitler pair production

$\sim \tau_{p\gamma} = R\ \sigma^e_{p\gamma}\ n_{ph,t}$

$$E_{\gamma,obs} \ll \frac{4mpme}{(m_e + mp)}\ \gamma_p D \approx$$

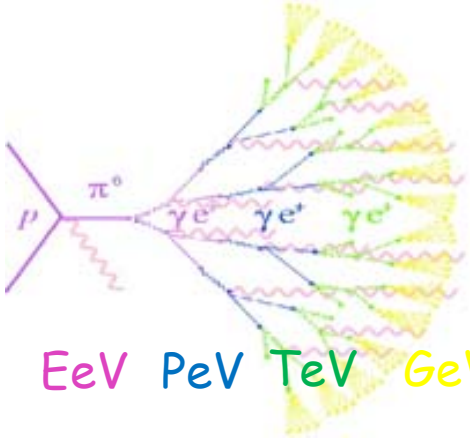
- $5\ \gamma_{p,m} D_{10} MeV$ — *broadband target*
- $250\ \varepsilon'_{10keV} D_{10} MeV$ — *peaked photon target*

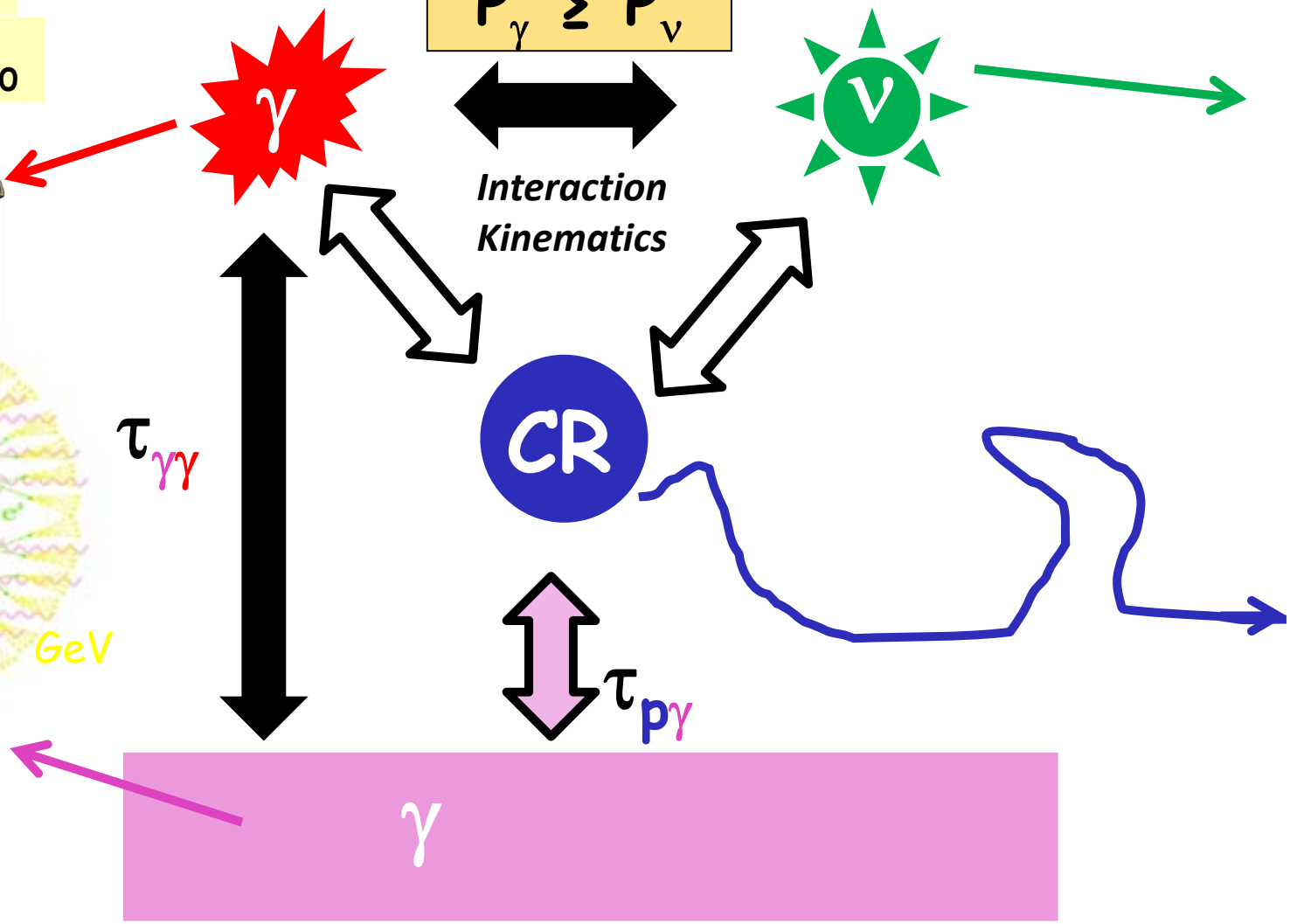
Multi-messengers: *The complete picture*

$E_\gamma \ll 10^{-5} E_\nu$

$E_{\gamma,MeV} \ll 5\ \gamma_p D_{10}$

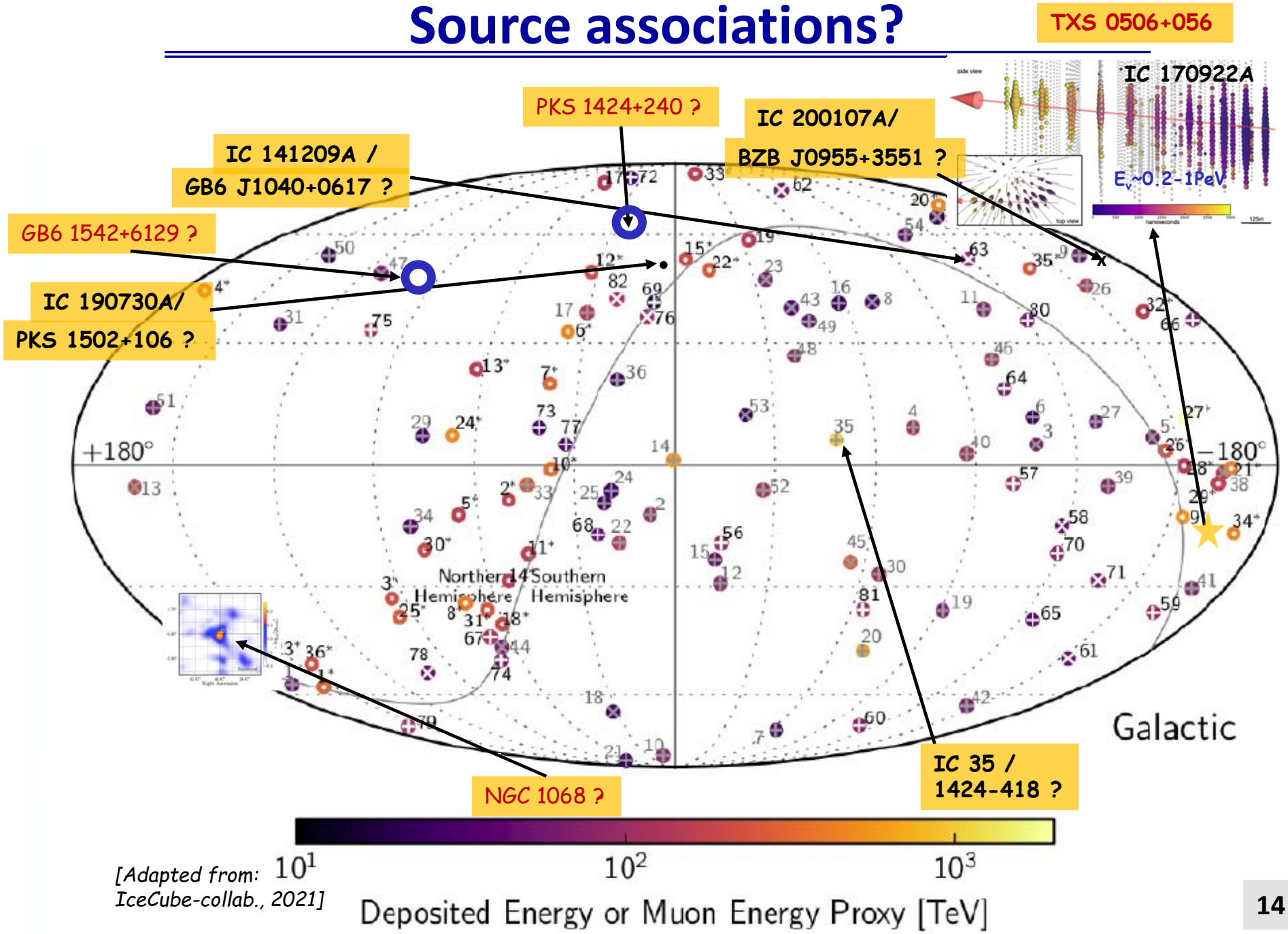
[AR etal 2019]





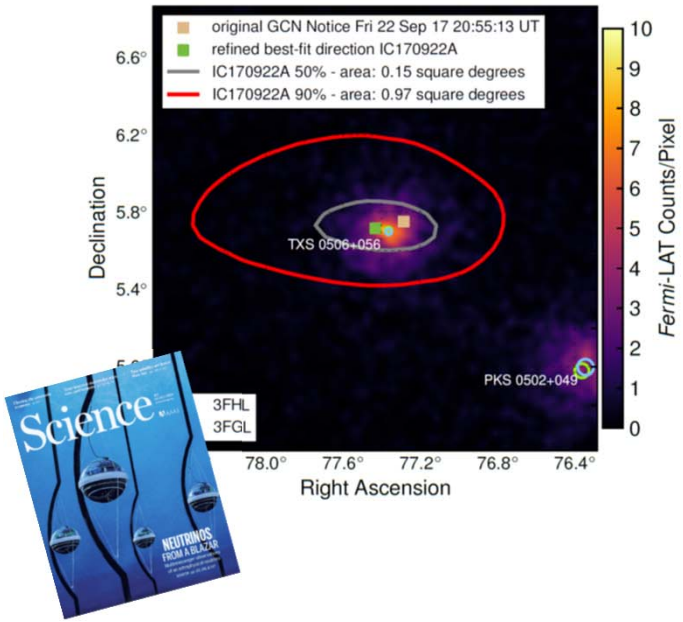
➢ **Gamma-ray opaque sources as "hidden" ν-sources**

Source associations?



[Adapted from: IceCube-collab., 2021]

TXS 0506+056 as archetypal ν-blazar?

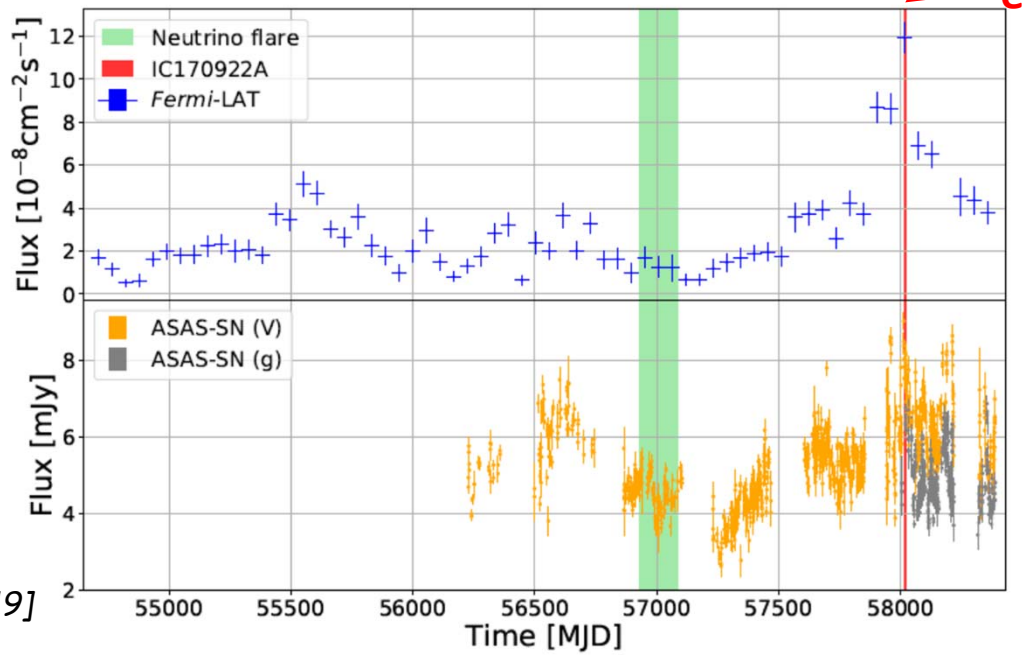


[IceCube-, Fermi-LAT, HESS-, MAGIC-, …,-coll. et al., 2018a]

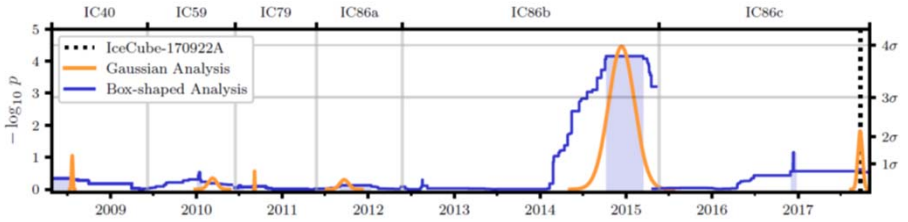
Positional coincidence of IC-EHE-170922A with blazar TXS 0506+056 during a γ-ray high state

Neutrino flare!

IC 170922A event



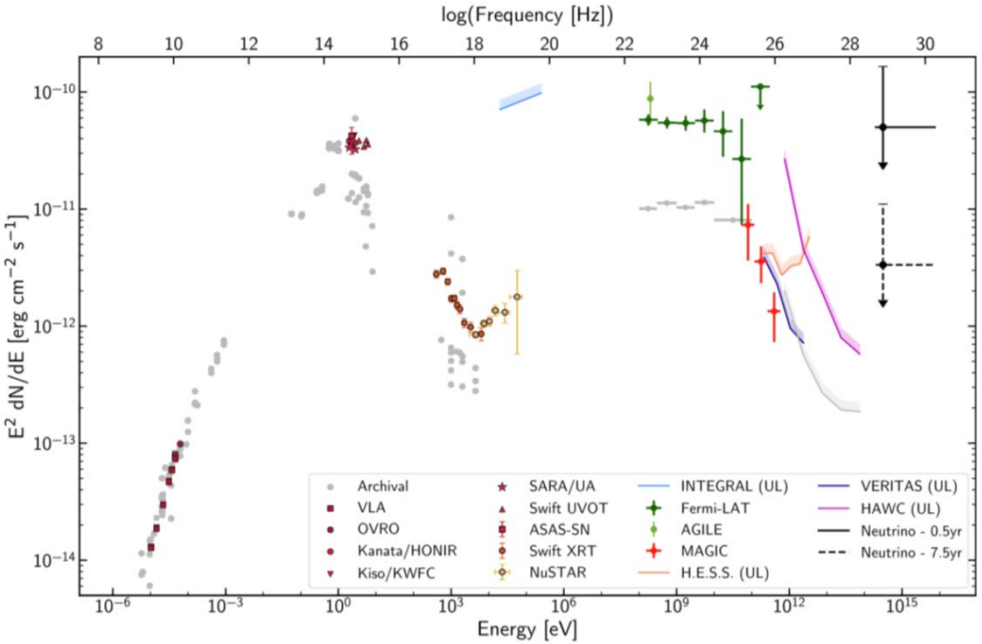
[AR etal 2019]



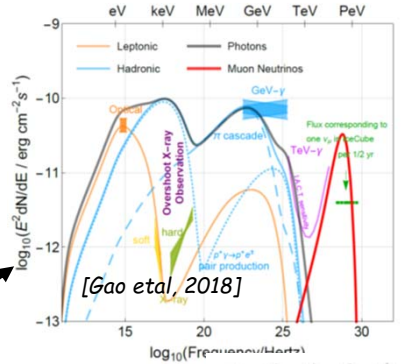
[IceCube-coll. 2018b]

ν

Hybrid SED modeling of TXS 0506+056 in γ-high state

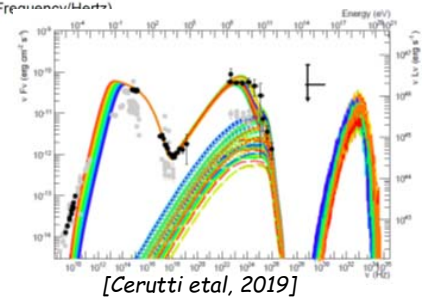


[IceCube, Fermi-LAT, HESS, MAGIC, VERITAS, …..-Collab., Science, 2018]



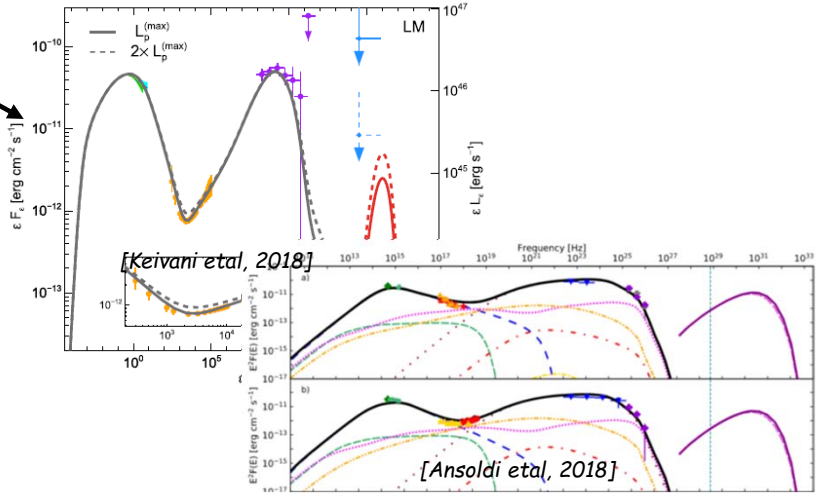
[Gao etal, 2018]

Model overshoots X-ray flux



[Cerutti etal, 2019]

Model doesn't predict correct ν-energy



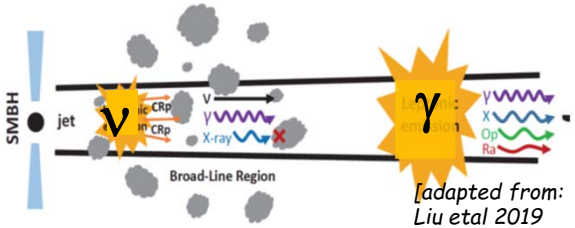
[Keivani etal, 2018]

[Ansoldi etal, 2018]

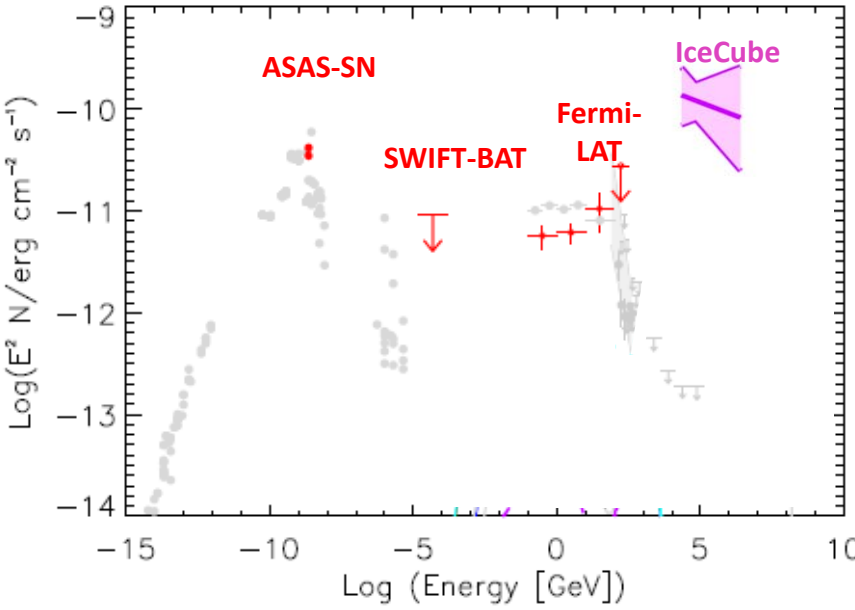
➢ **Leptonic origin of γ-rays required to explain the hybrid SED**

Models require leptonic origin of γ-rays
[see also Petropoulou etal 2020, ...]

Hybrid SED modeling of TXS 0506+056 in ν-flare state

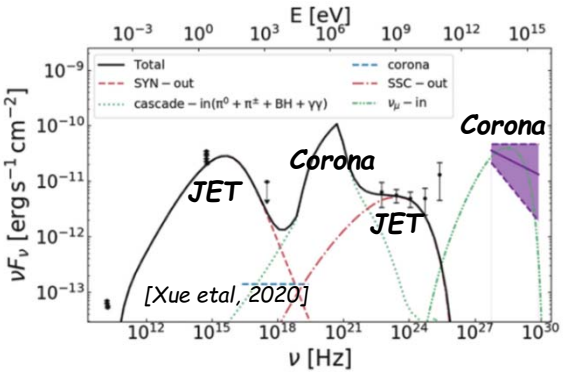


[adapted from: Liu etal 2019

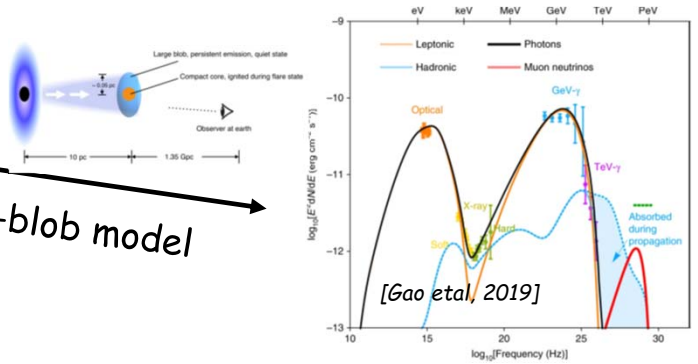


[AR, etal 2019]

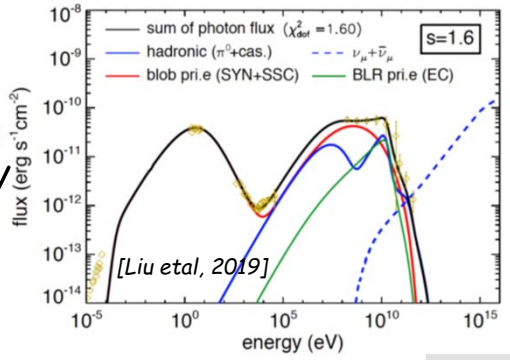
Corona-jet model



Core-in-blob model



External hadronuclear model

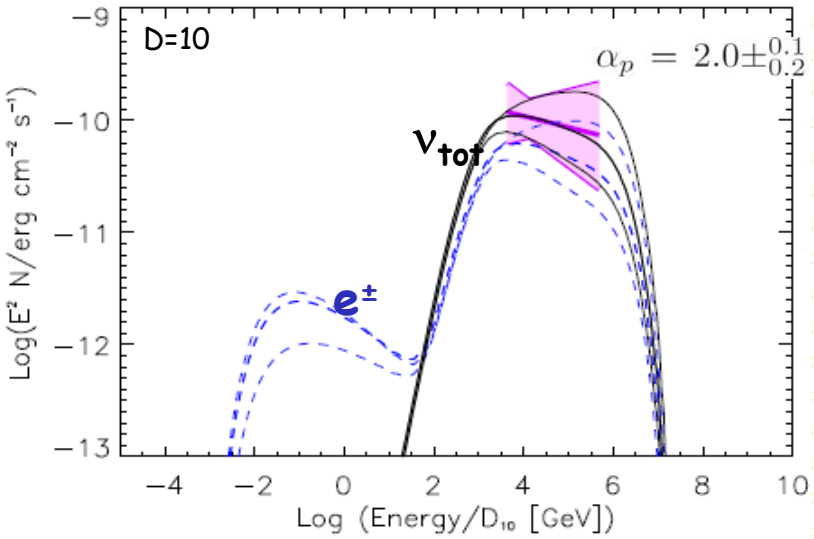


➢ **Photon emission not co-spatially produced with ν-emission**

Constraining the ν-production region

- Cascade constraints -

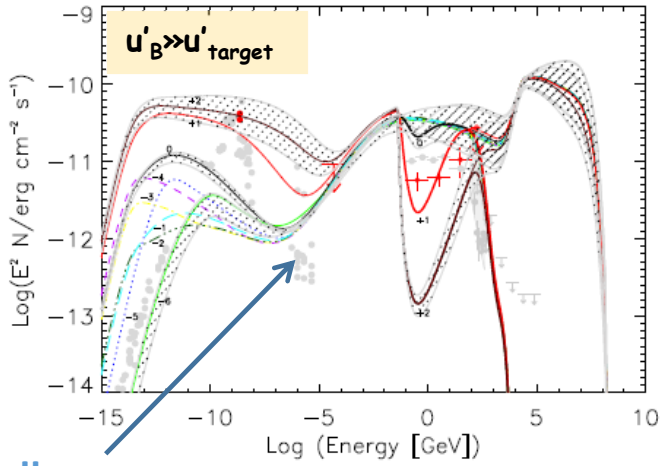
[AR, Böttcher, Buson, 2019]



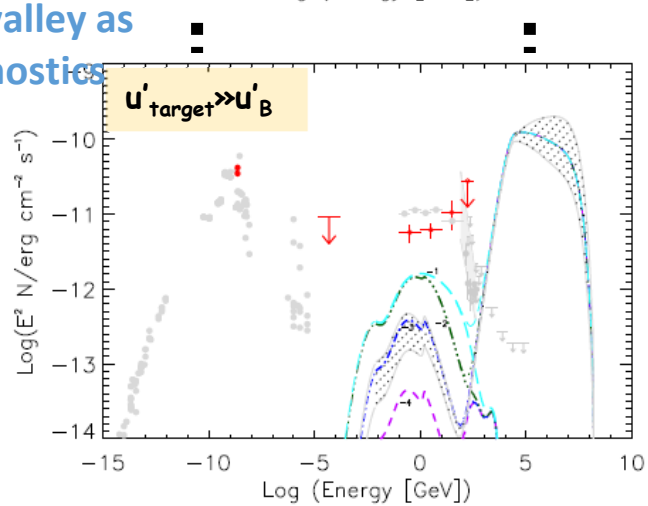
Minimum requirement strategy

$\tau_{p\gamma} \propto \tau_{\gamma\gamma}$

Minimum cascade flux in various environments



X-ray valley as diagnostics

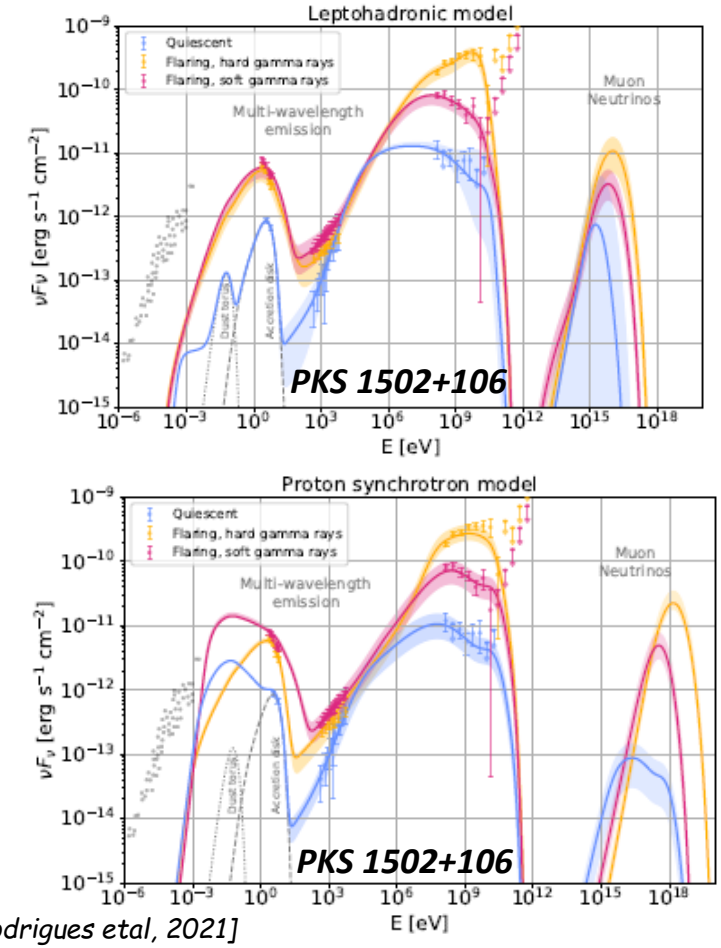


- **External target photon field @UV/X**
- **radiative, not Poynting-flux dominated region**
- **No ν -- γ-ray activity correlation expected**
- **Inefficient ν-producer during ν-flare, or multi-zone emission models required**

[see also Paliya etal '21 for similar conclusions on EHBL BZB J0955+3551]

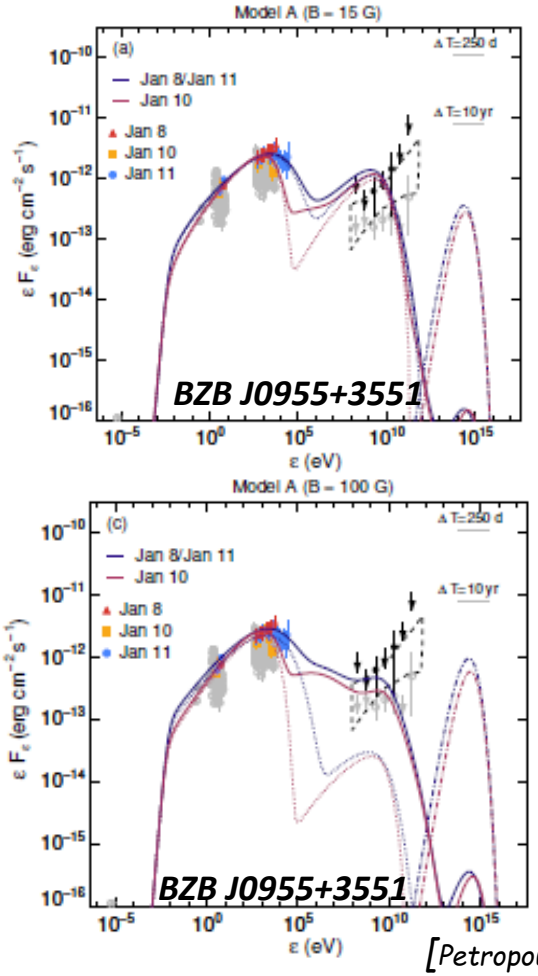
Neutrino-production in various blazar types

FSRQ



[Rodrigues etal, 2021]

EHSP

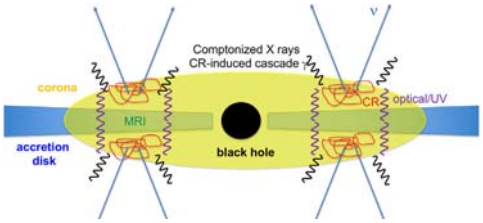


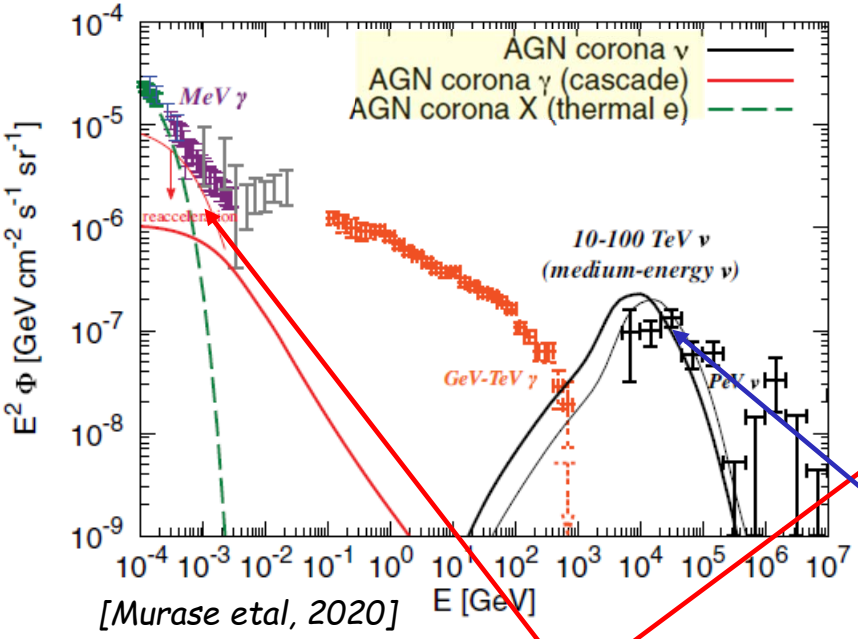
[Petropoulou etal, 2020]

Often require:

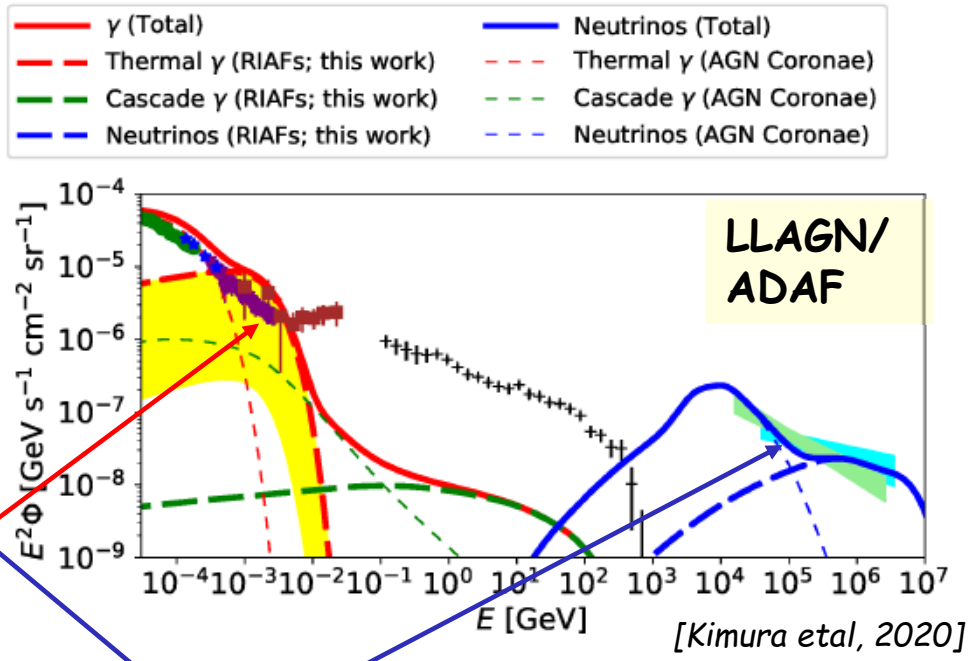
- **Large jet power ($L_{jet} >> L_{edd}$)**
- **Neutrino production in particle dominated environment ($u_p \gg u_B$)**
- **Narrow and/or unsual hard proton injection spectra**

Neutrino production in AGN cores





[Murase etal, 2020]



[Kimura etal, 2020]

Predicted contribution to MeV-photon background

Modeling the IceCube ν-flux

Tens of TeV-to-PeV neutrino flux connected to MeV-background?

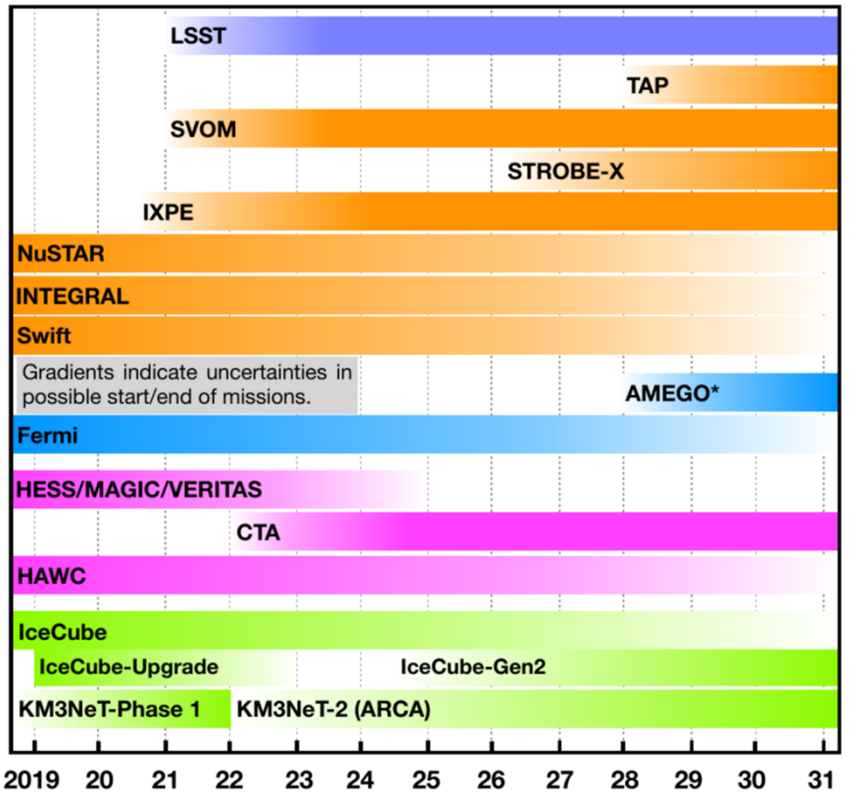
Concluding remarks & multi-messenger future perspectives

- **Multi-messenger** observations provide crucial **information to constrain physical properties of cosmic accelerators**

- If **jets of AGN are sites of numerous TeV-to-PeV νs,** our **understanding of these sources is** very **limited.**

- **Efficiently photo-produced νs** originate from **regions with high γ-ray opacity**

  -> photo-produced νs may **not be traced by bright GeV-TeV emitters**



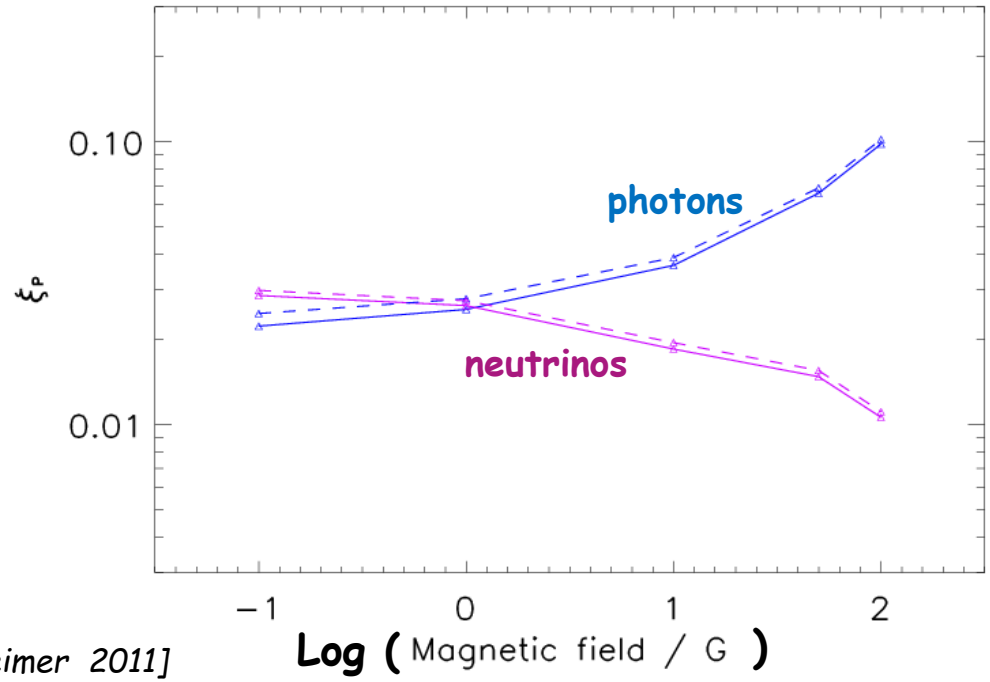
[from: Buson et al 2019, arXiv:1903.0447]

- Exploring **photon MeV (& below)** energy range, with **polarization capabilities,** supports **probing the environments of ν-production**

- Improving **sensitivity, spatial & energy resolution, & sky coverage of neutrino detectors** needed to help finding the dominant ν-source population

- Back-up Slides -

On the magnetization of the ν-production environment



[Reimer 2011]

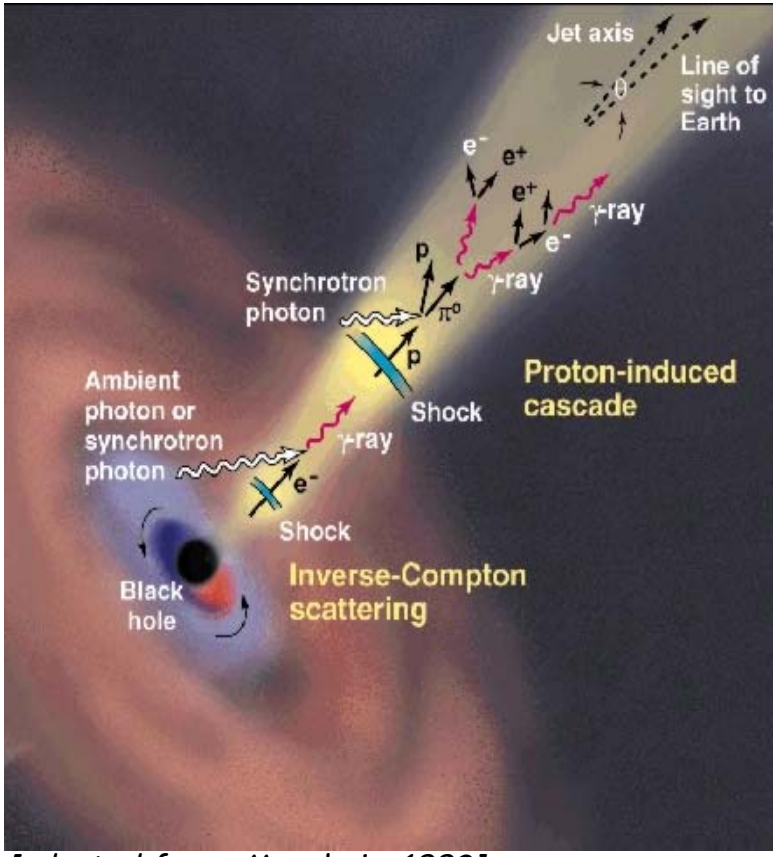
⇒ u_B / u_{target} small for efficient neutrino production

Parameters: $N_{P,inj} \sim E^{-2}$, $R = 10^{16}$cm, $u_\gamma = 10^{11}$eV/cm^3, $E_{p,max} = 10^{11}$GeV, vary B

Proton radiation efficiency: $$\zeta_p = \frac{\int \zeta_p'(\gamma_p')\gamma_p'\gamma_p'^{-2}d\gamma_p'}{\int \gamma_p'\gamma_p'^{-2}d\gamma_p'}$$

with $$\zeta_p'(\gamma_p') = \frac{r'_{\mathrm{syn,p}}(\gamma_p') + r'_{\mathrm{p\gamma\to EM,p}}(\gamma_p')}{r'_{\mathrm{syn,p}}(\gamma_p') + r'_{\mathrm{p\gamma\to any,p}}(\gamma_p') + r'_{\mathrm{adaib}}}$$

Emission Models for AGN Jets



[adapted from: Mannheim 1993]

- **"Leptonic" models:**

Jet material: rel e^+e^- + cold e,p
HE emission e^+e^--initiated

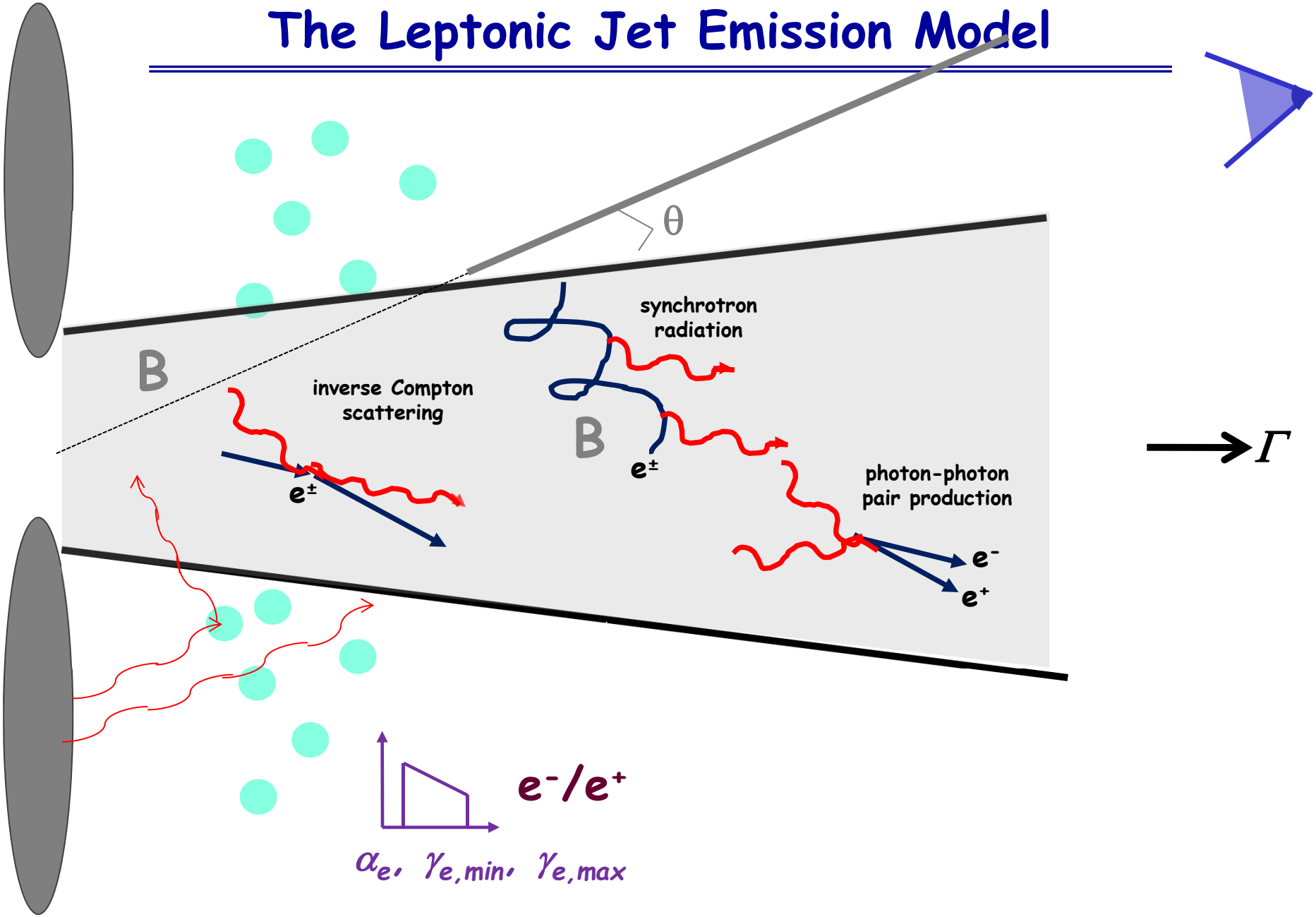
- **"Hadronic" models:**

Jet material: rel e^+e^-p + cold e,p
HE emission dominantly p-initiated

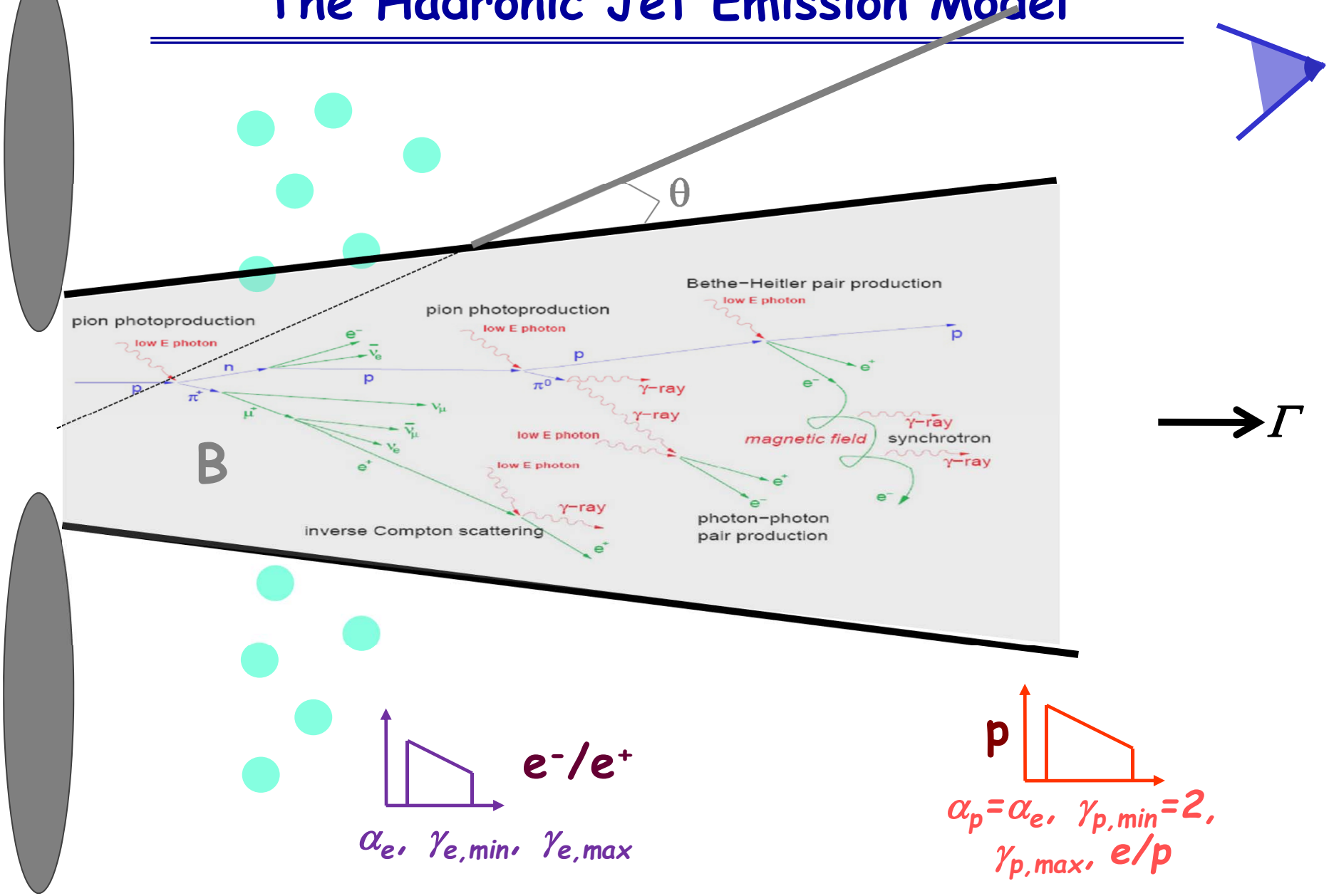
- **"Lepto-hadronic" models:**

Jet material: rel e^+e^-p + cold e,p
HE emission dominantly e^+e^--initiated

The Leptonic Jet Emission Model



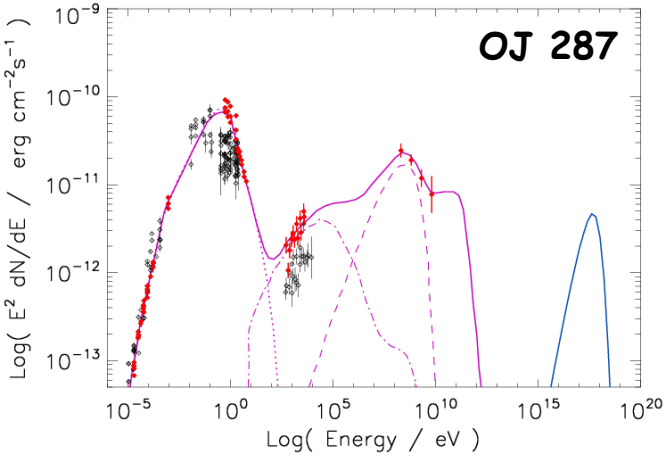
The Hadronic Jet Emission Model

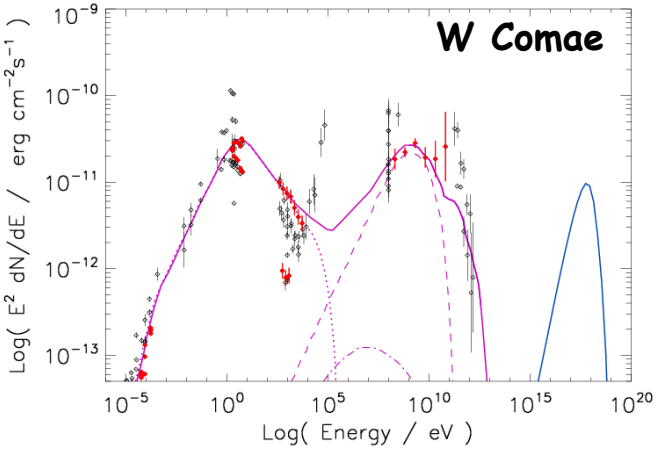


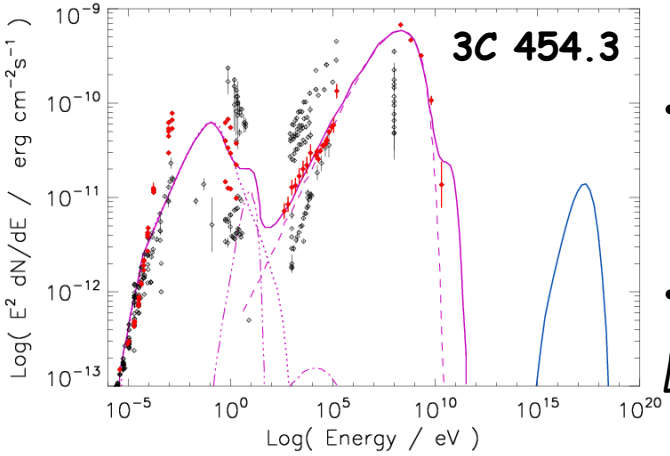
Modeling γ-bright Blazars: Hybrid SEDs

- **Target photon fields =**

  jet synchrotron photons; e.g., PIC [Mannheim etal 1991, 1993, …], SPB [Mücke etal 2001, 2003, …], ….)







[AR 2015]

- **Hadronic models with dominantly jet target photon fields can fit average blazar SEDs;**
- **require large jet powers ~$10^{47…49}$erg/s**

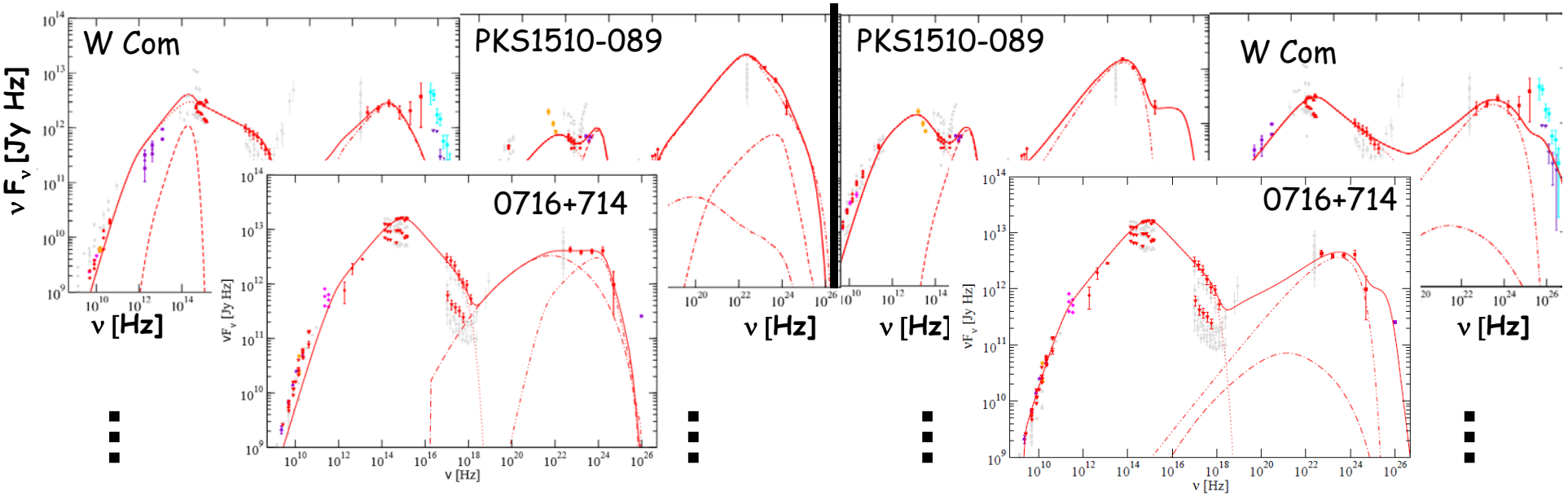
[e.g., Böttcher, AR, etal 2013, AR 2015, ….]

Multifrequency Modelling of *LAT*-detected Blazars

Leptonic Models

*[Böttcher, **AR** et al 2013]*

Hadronic Models



One-zone leptonic models:

- acceptable fits to ~9/12 of all cases
- need external target photons *in all cases*

One-zone hadronic models:

- acceptable fits to ~8/12 of all cases
- proton syn. @GeVs + cascade emission @ higher energies
- require very large jet powers ~$10^{47\text{-}49}$erg/s
- $E_{p,max}$ ~ $10^{17\ldots18}$eV