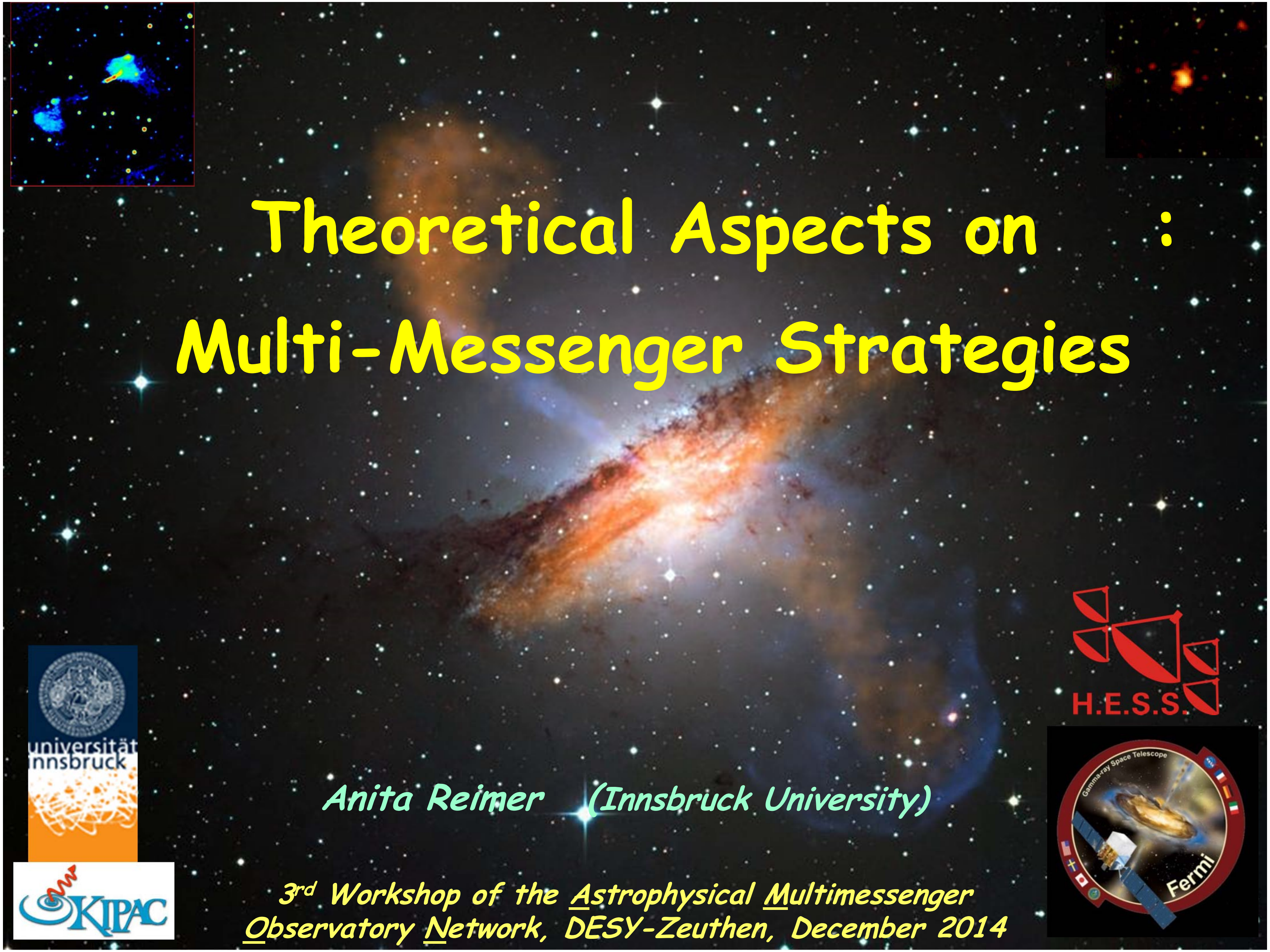
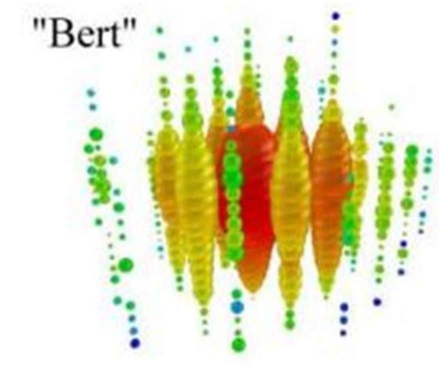


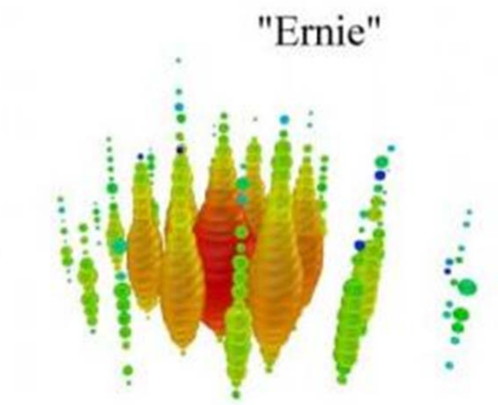
Theoretical Aspects on :
Multi-Messenger Strategies

Anita Reimer (Innsbruck University)

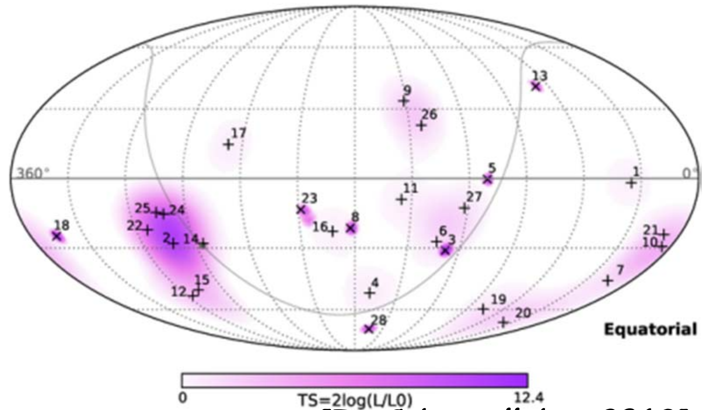
3rd Workshop of the Astrophysical Multimessenger Observatory Network, DESY-Zeuthen, December 2014

Neutrino events counterparts?





[IceCube collab., 2013]

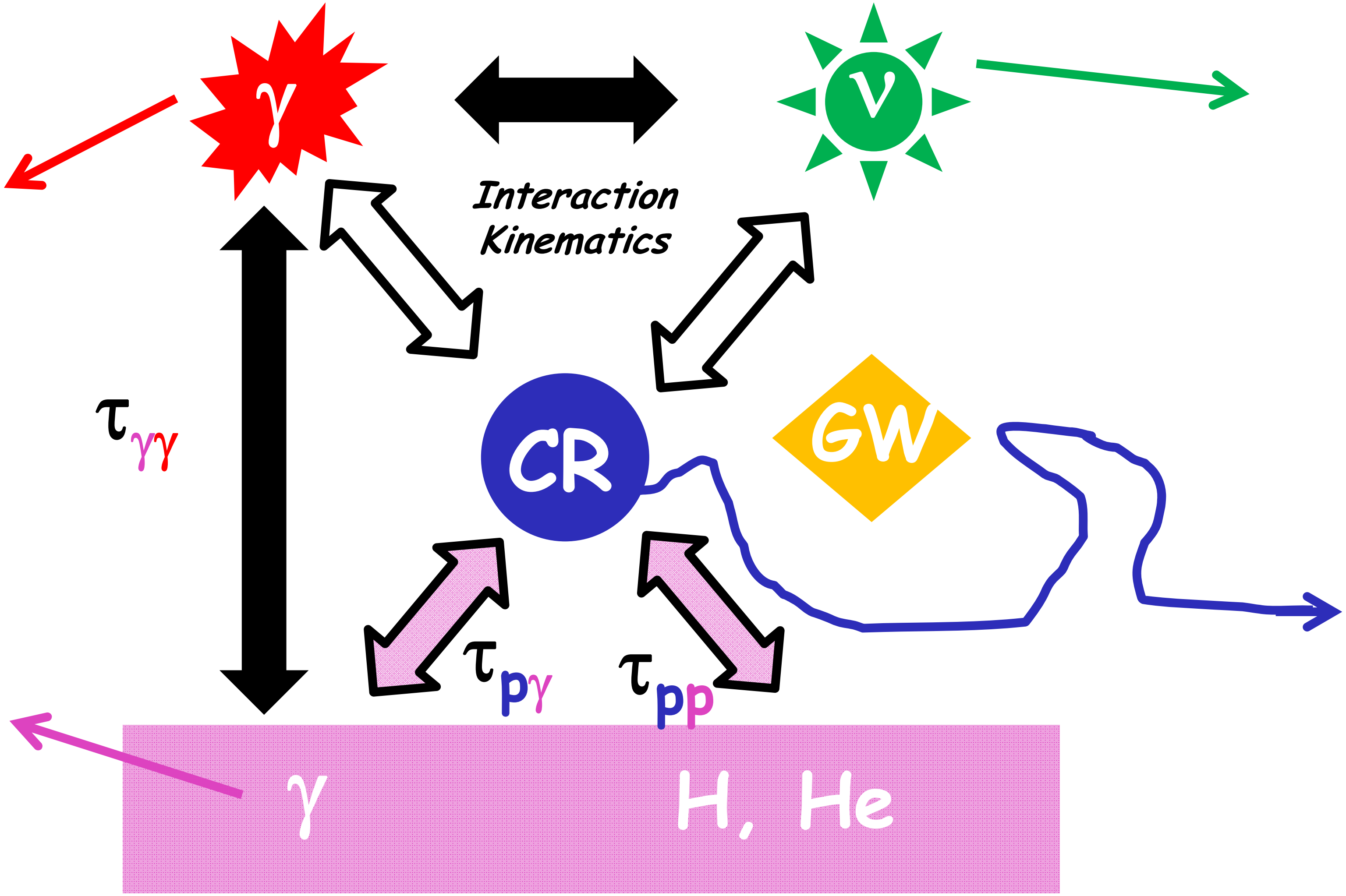


[IceCube collab., 2013]

- ***IceCube detects extraterrestrial (~5.7σ) neutrinos:***
  3-yrs data: 28 shower-like, 9 track-like, fully contained events [IceCube coll. 2014]
- ***reconstructed energies ~tens of TeV – ~3 PeV***
- ***compatible with isotropic source distribution & ~$E^{-2.5}$ spectrum with cutoff above PeV energies***
- ***all-sky integrated flux ~10^{-8}GeV $cm^{-2}s^{-1}sr^{-1}$ (60-3000TeV) per flavor for E^{-2} spect***
- ***compatible with neutrino flavor ratio $\nu_e:\nu_\mu:\nu_\tau$ = 1:1:1***

=> Evidence for hadronic (pp, pγ) interactions in cosmic sources

Hadronic Interactions in Astrophysics



Multi-messenger approach for identifying cosmic ray sources

Outline

I Hadronic Interactions in Astrophysics

1. Properties & interaction kinematics
2. Secondary particle spectra (ν,γ)

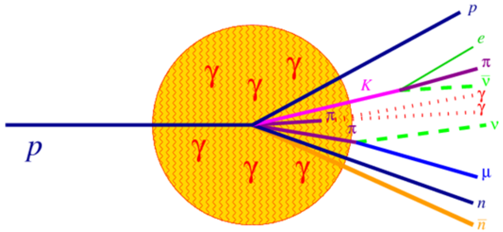
II Applications to Active Galactic Nuclei

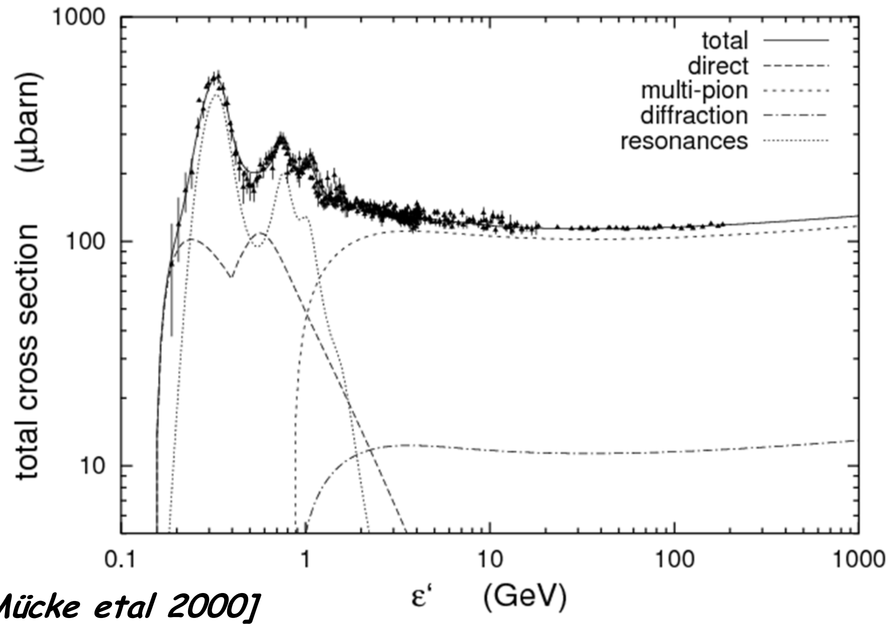
1. Photon-neutrino scaling?
2. Impact of $\gamma\gamma$-opacity
3. Modeling broadband SEDs of Fermi-blazars

III Conclusions

Hadronic Interactions: Interaction Kinematics

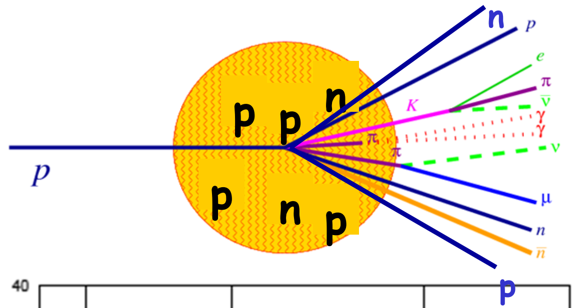
- **Photomeson Production**

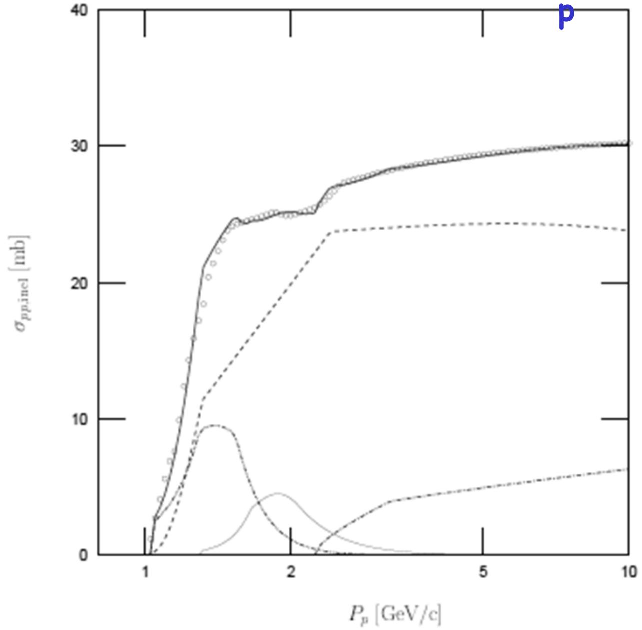




[Mücke etal 2000]

- **Nucleon-Nucleon Interaction**





[Kamae etal 2006]

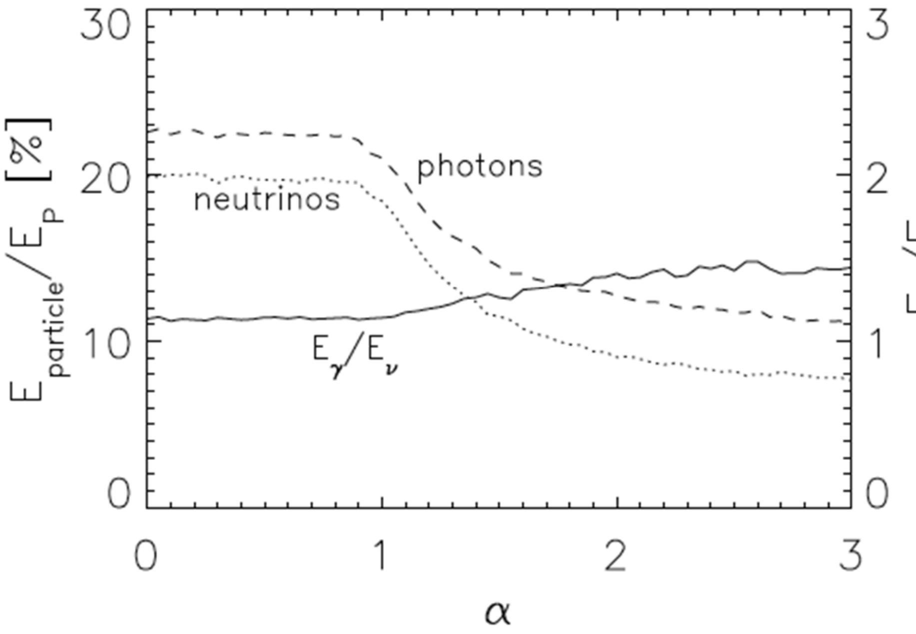
Threshold: $s^{1/2}_{threshold} = m_p + m_{\pi 0}$ $\qquad s^{1/2}_{threshold} = 2m_p + m_{\pi 0}$

$\varepsilon' \cdot E'_p \geq 0.07\,GeV^2$ $\qquad$ -> $E_p > 1.23\,GeV$

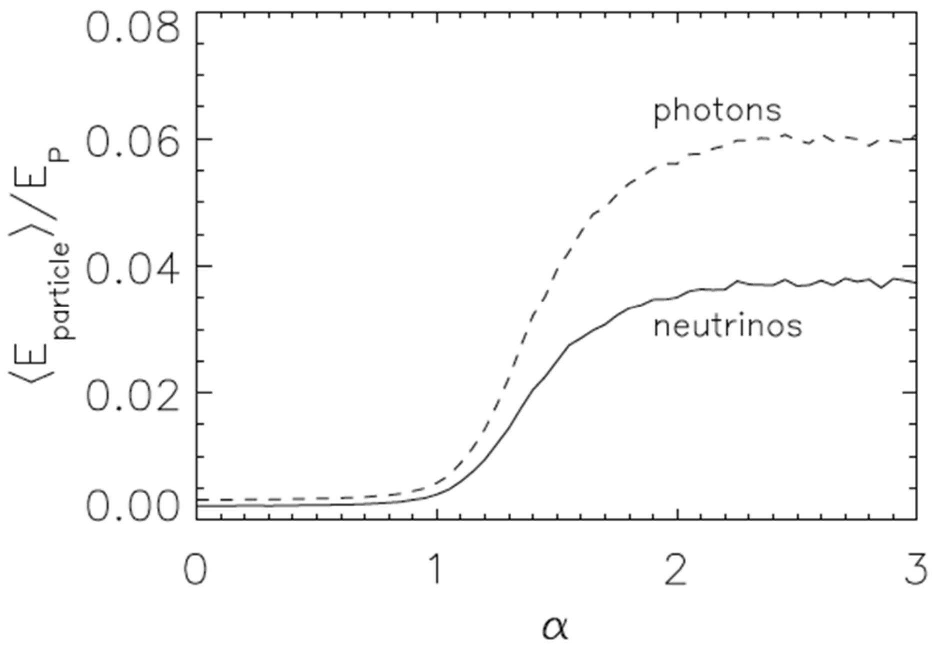
Hadronic Interactions: Interaction Kinematics

• Photomeson Production	• Nucleon-Nucleon Interaction
• Inelasticity: $K_p \sim 0.2 - 0.6$	$K_p \sim 0.5$
• Neutrino energy: $\langle E_\nu \rangle \approx \frac{1}{4} E_\pi$, $\gamma_p \approx \gamma_\pi$	$\langle E_\nu \rangle \approx \frac{1}{4} E_\pi$
$\langle E_\nu \rangle / E_p \approx 0.04$ in resonance region	$\langle E_\nu \rangle / E_p \approx 0.05$
$\langle E_\nu \rangle / E_p < 0.01$ at high E	
• Photon energy: $\langle E_\gamma \rangle \approx \frac{1}{2} E_{\pi 0}$, $\gamma_p \approx \gamma_\pi$	$\langle E_\gamma \rangle \approx \frac{1}{2} E_{\pi 0}$
$\langle E_\gamma \rangle / E_p \approx 0.06$ in resonance region	$\langle E_\gamma \rangle / E_p \approx 0.1$
$\langle E_\gamma \rangle / E_p < 0.01$ at high E	
$\Sigma E_\nu \sim \Sigma E_\gamma$	$\Sigma E_\nu \sim \Sigma E_\gamma$

Photomeson production: Interaction Kinematics



[Mücke et al. 1999, 2000]



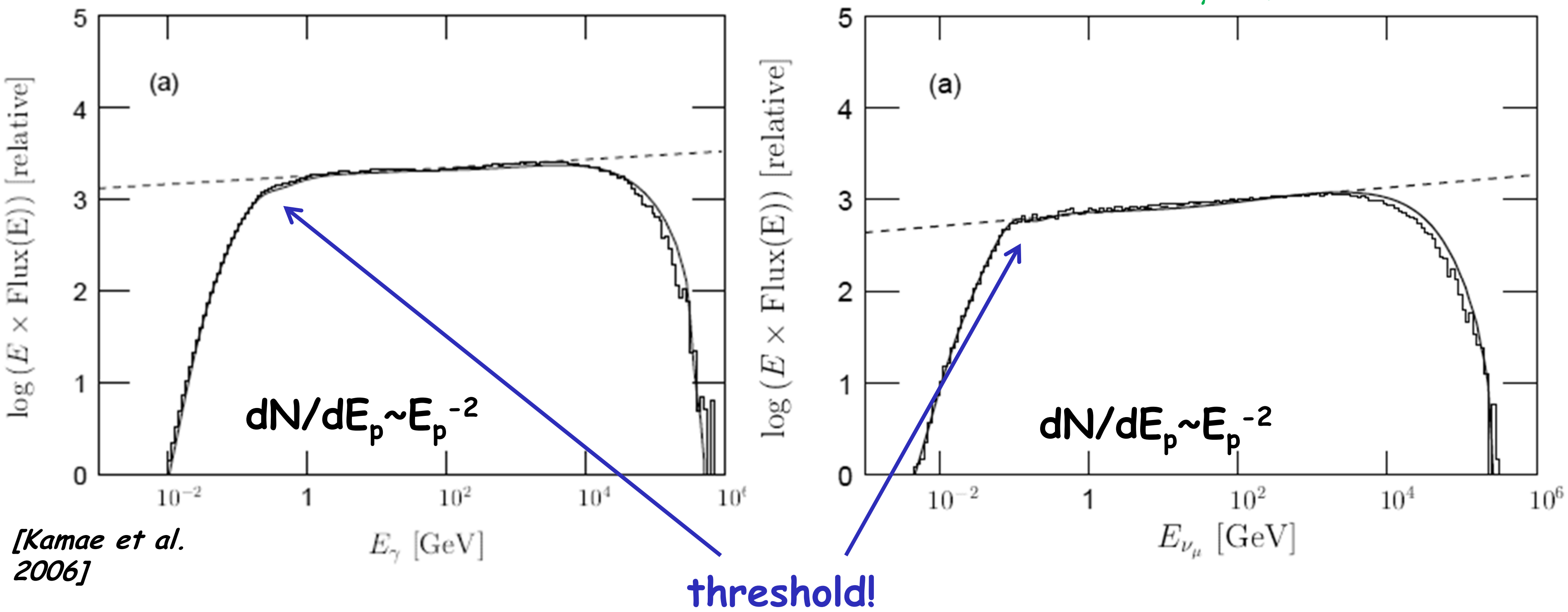
- **average energy of produced photon/neutrino sensitive to steepness of photon target**

- **$\Sigma E_\gamma/\Sigma E_\nu \approx 1$-$1.5$**
- **~20% & ~25% dissipation in ν & γ**

} **in photomeson production**

Nucleon-Nucleon Interactions: Secondary particle spectra

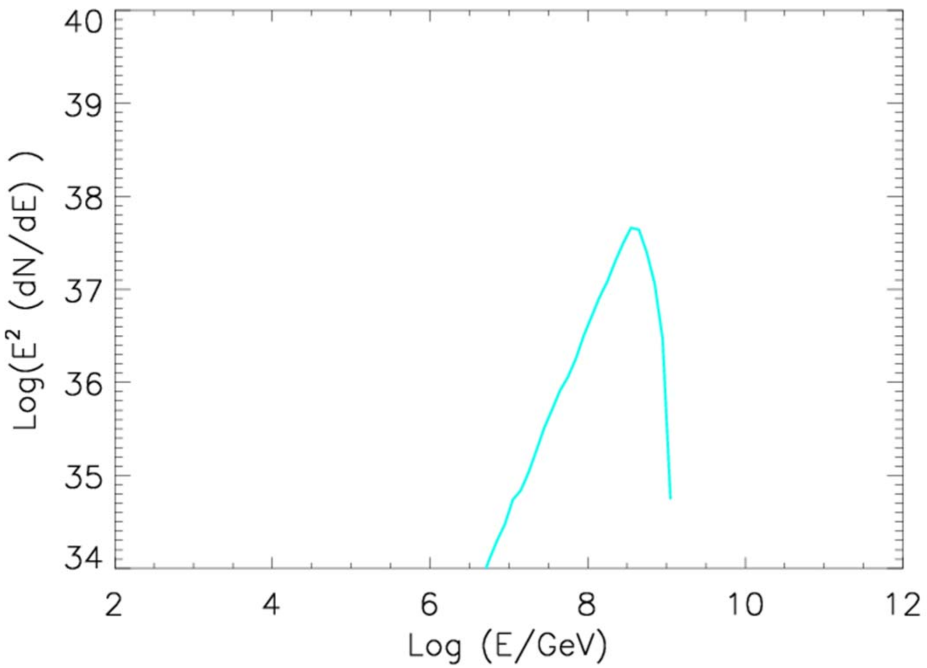
Gamma-ray spectrum *Neutrino (ν_μ) spectrum*



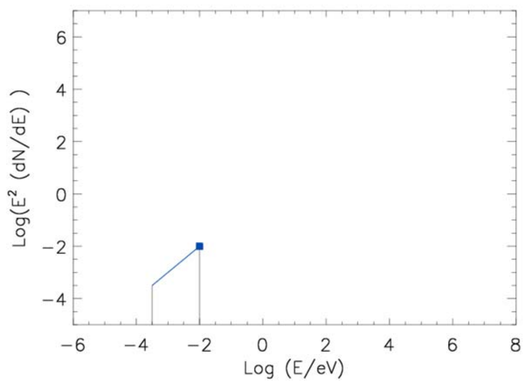
[Kamae et al. 2006]

-> above threshold secondary particle spectrum (γ, ν) follows ambient CR spectrum

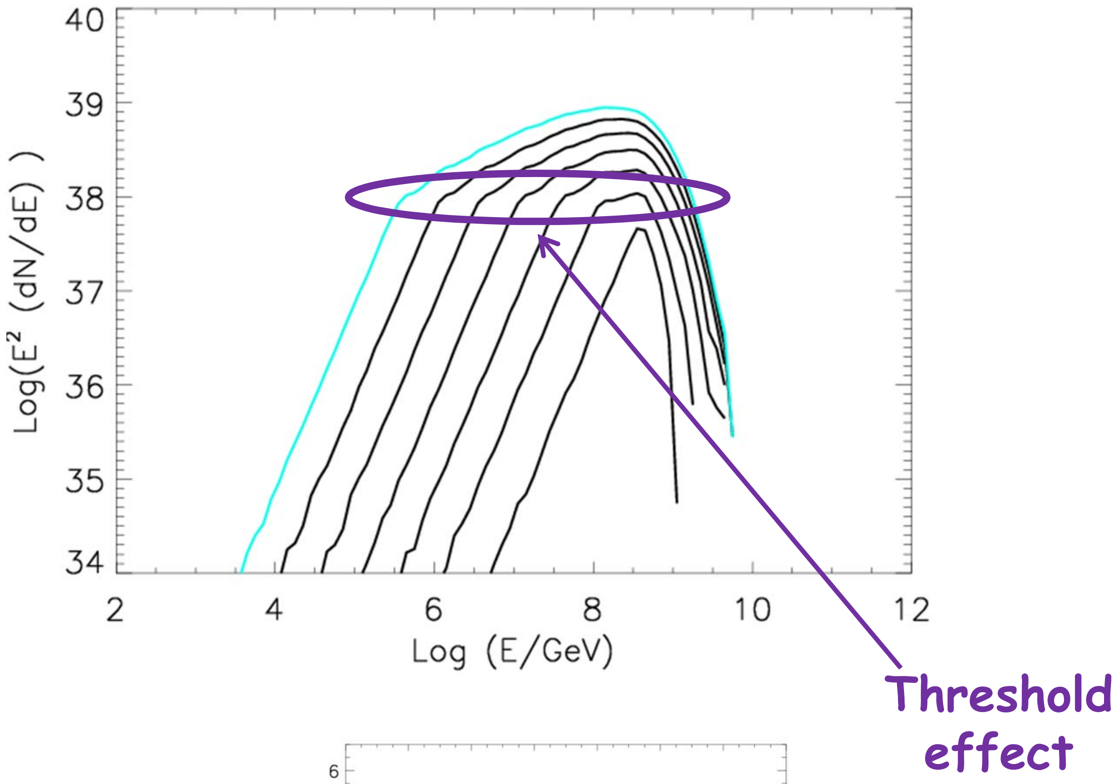
Neutrino (ν_μ) spectra from pγ-interactions



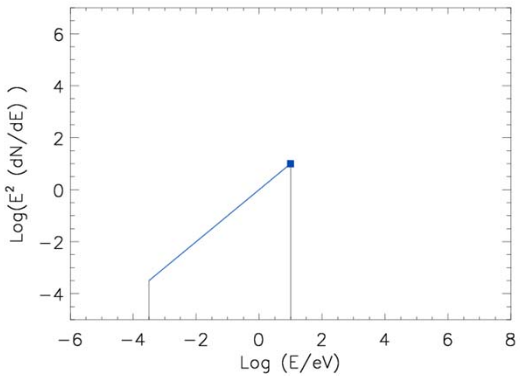
target



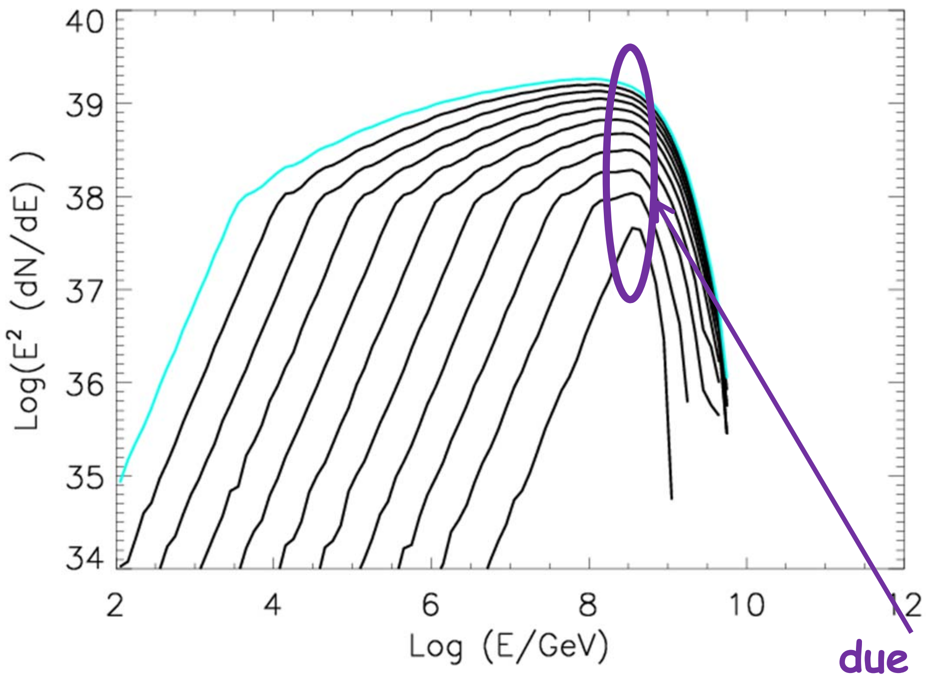
Neutrino (ν_μ) spectra from pγ-interactions



target

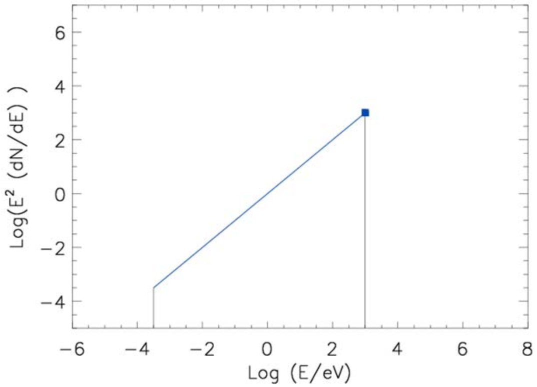


Neutrino (ν_μ) spectra from pγ-interactions

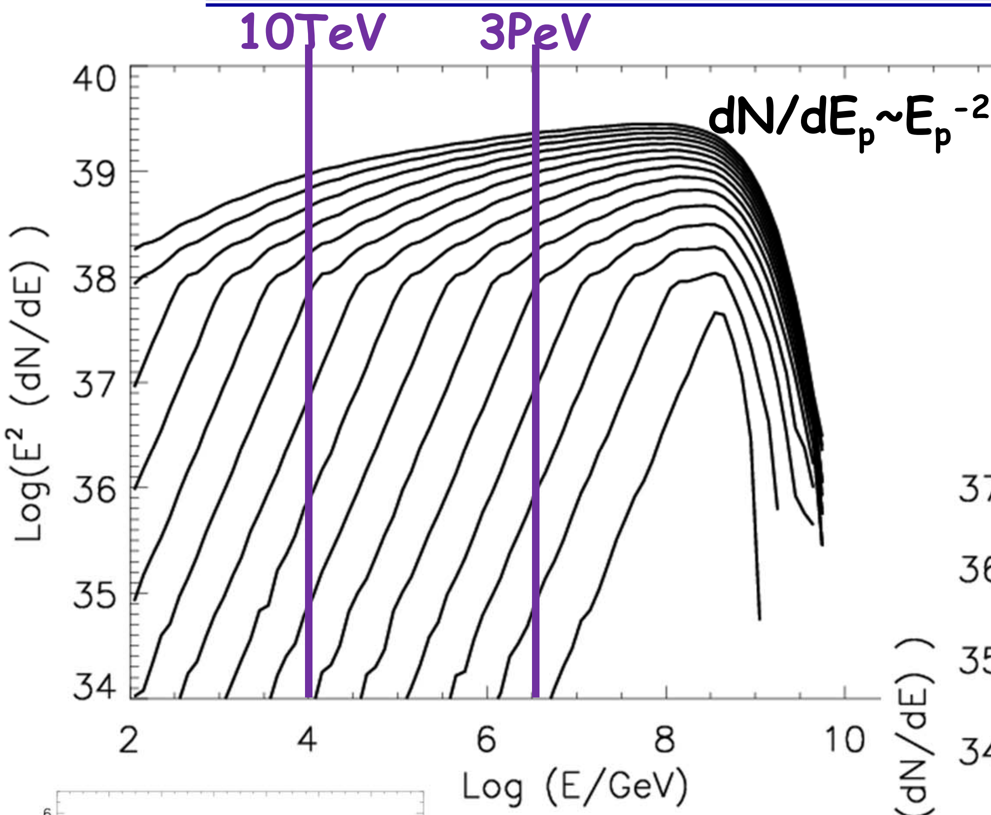


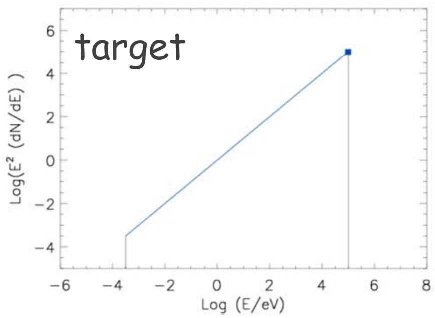
due to cutoff of ambient CR-spectrum

target

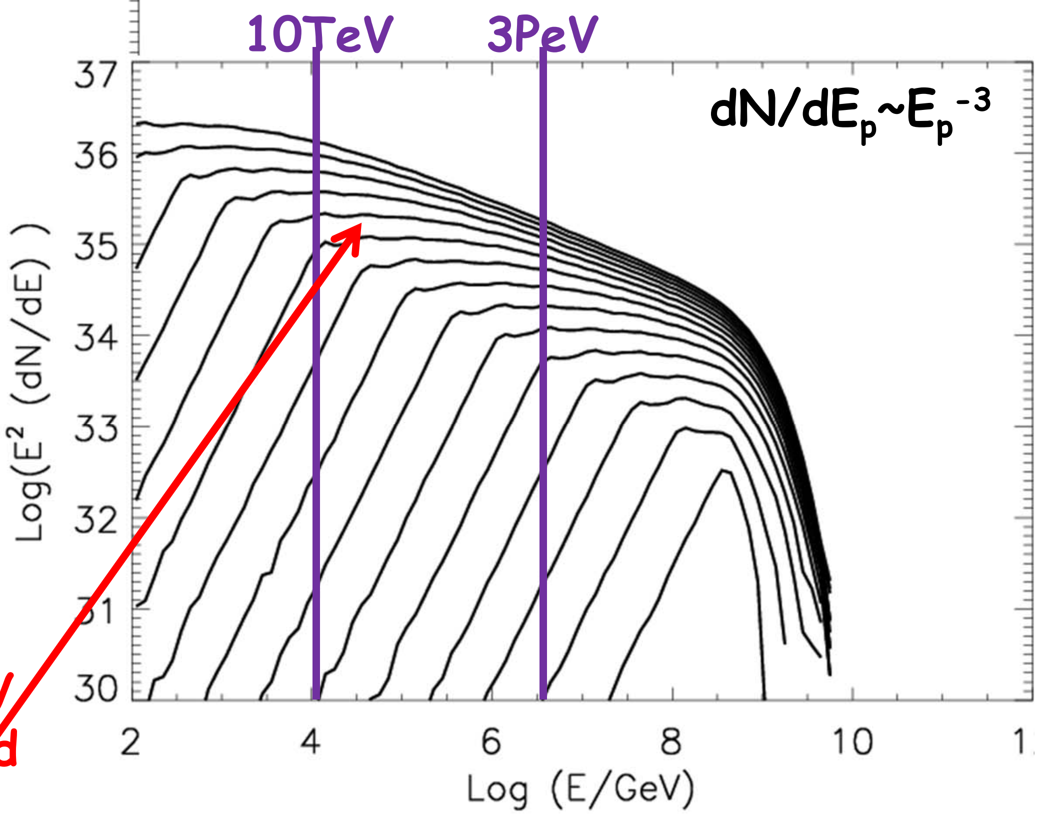


Neutrino (ν_μ) spectra from pγ-interactions





ν-spectral shape above threshold roughly follows ambient CR spectrum



soft ν-spectrum >10TeV requires prominent >0.3keV target photon field

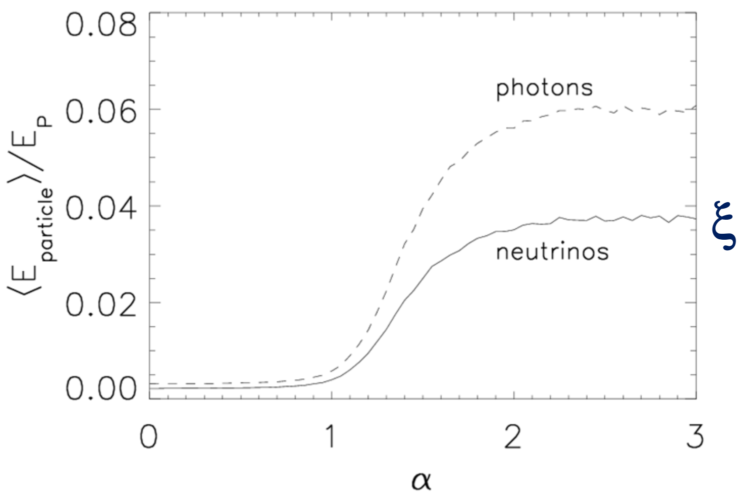
Applications

Are jetted AGN the counterpart sources of the detected IceCube neutrino events?

Requirements on jetted neutrino sources

- **Targets for hadronic interactions:**
  photons -> radiative jets
  material -> heavy jets

- **Hadron energy in photohadronic interactions:**



Required nucleon energy:

$$E'_p \leq 20\ (E_{\nu,10PeV} / D_{10}\xi_{0.05})\ \mathrm{PeV}$$

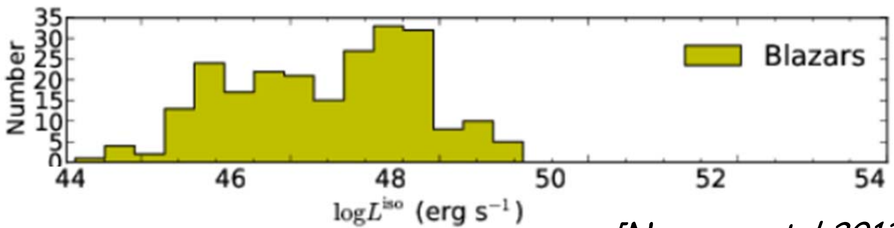
Threshold condition: $\varepsilon' \cdot E'_p \geq 0.07\mathrm{GeV}^2$

Suitable target photons of energy
$\varepsilon' \geq 3\ (E_{\nu,10PeV} / D_{10}\xi_{0.05})^{-1}\ \mathrm{eV}$

Hillas criterium *[Hillas 1984]*:

$$E'_p \leq \Gamma \cdot e \cdot Z \cdot B' \cdot R'$$

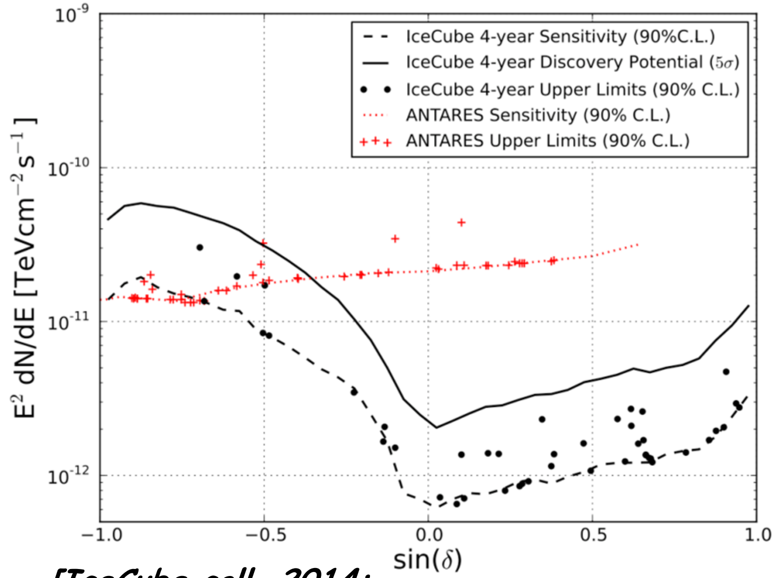
- **Source energetics:**
  $P_{jet} > 10^{43}\ \Gamma_{30}^{2} \beta^{-1} (E_{\nu,10PeV} / \xi_{0.05})^2$ erg/s
  [Waxman 2004]



[Nemmen etal 2013]

Requirements on jetted neutrino sources

- comply with observations!

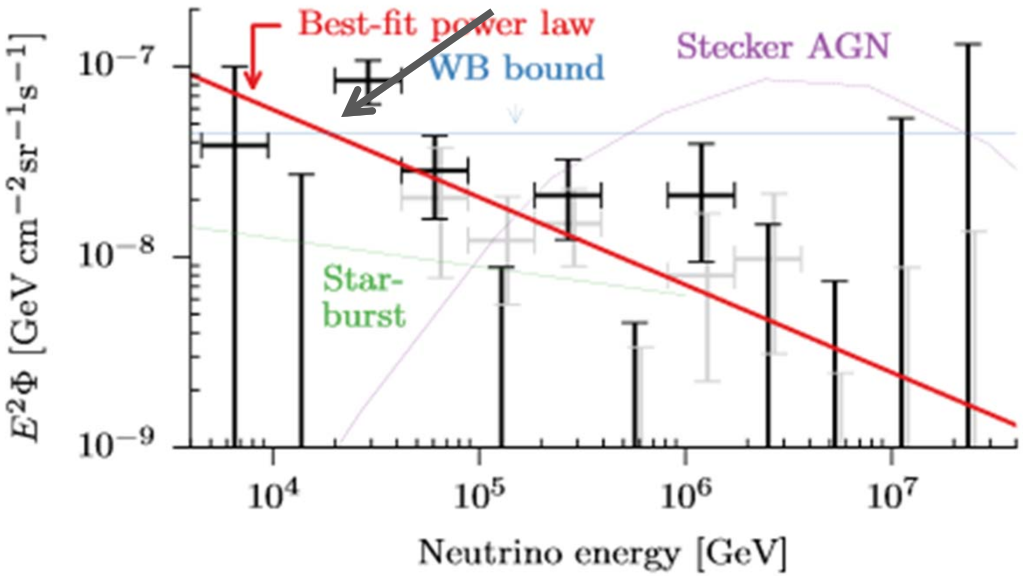


[IceCube coll. 2014: arXiv:1406.6757]

Point source ν-limits

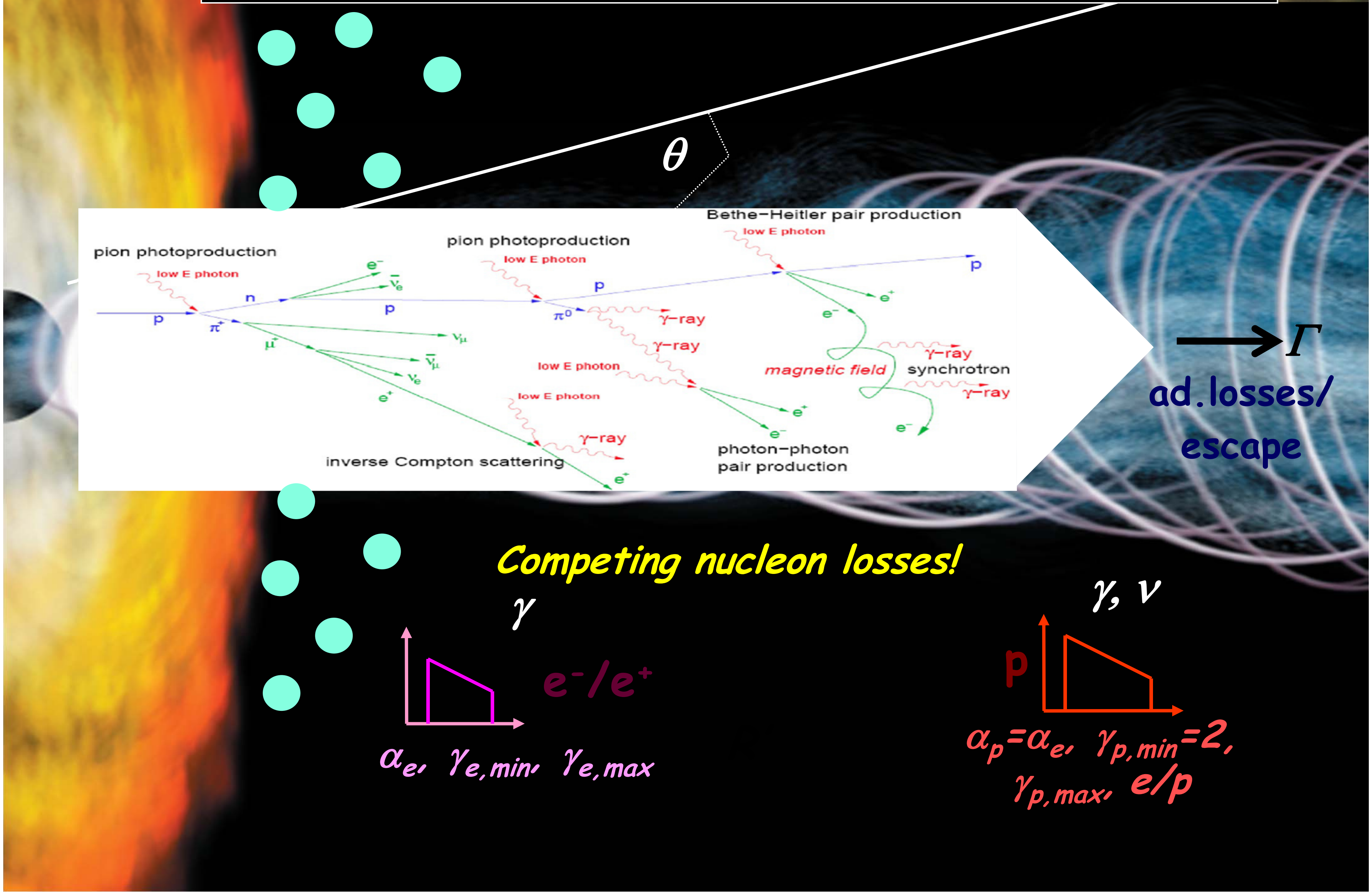
All-sky flux

dN/dE~$E^{-2.5}$

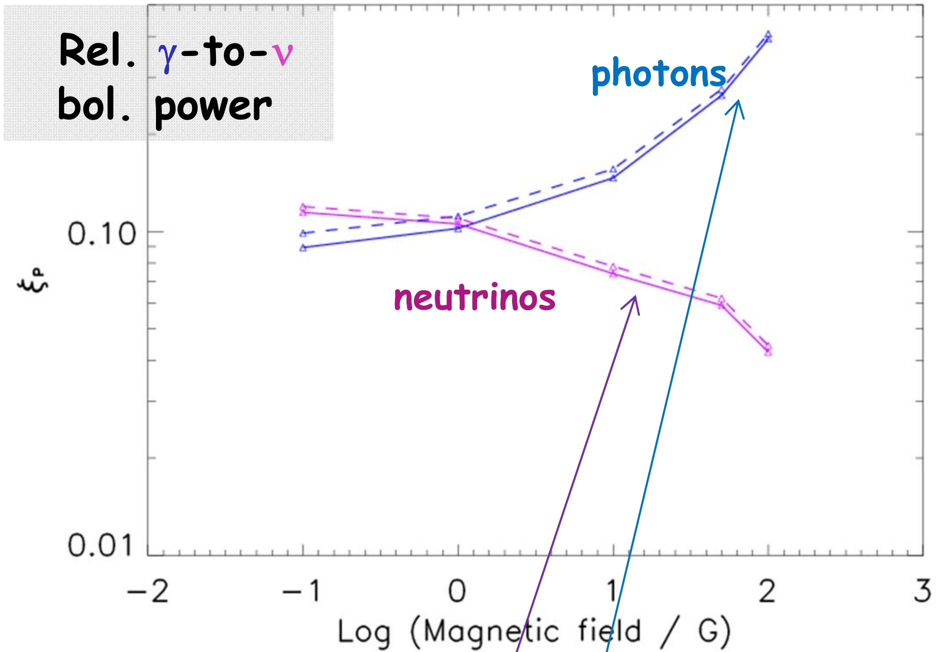


[Aartsen etal 2014]

Non-thermal Emission Processes in AGN Jets: Leptons & Hadrons

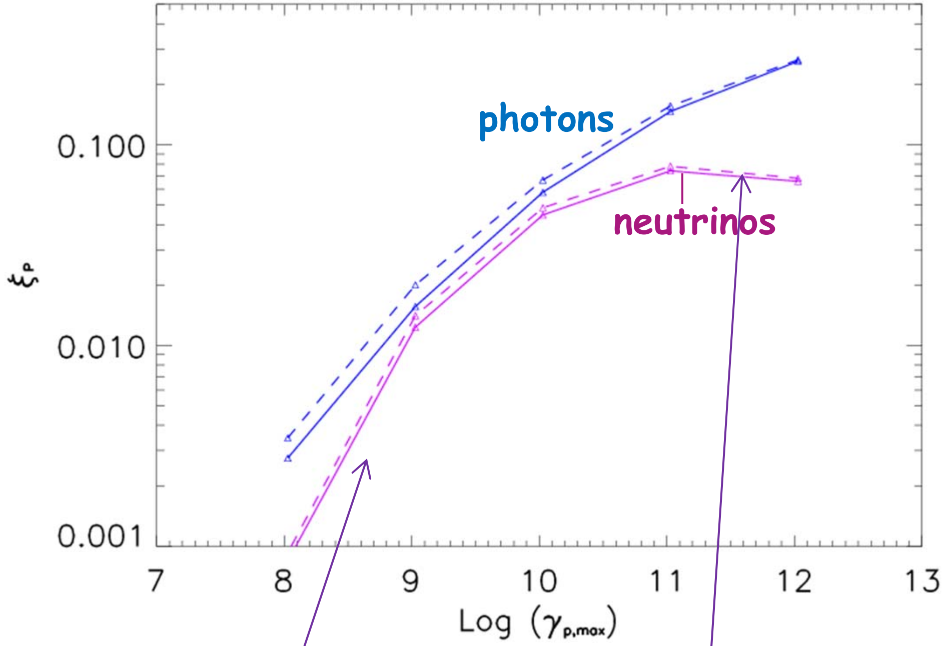


Photon-neutrino scaling?



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

syn. losses!



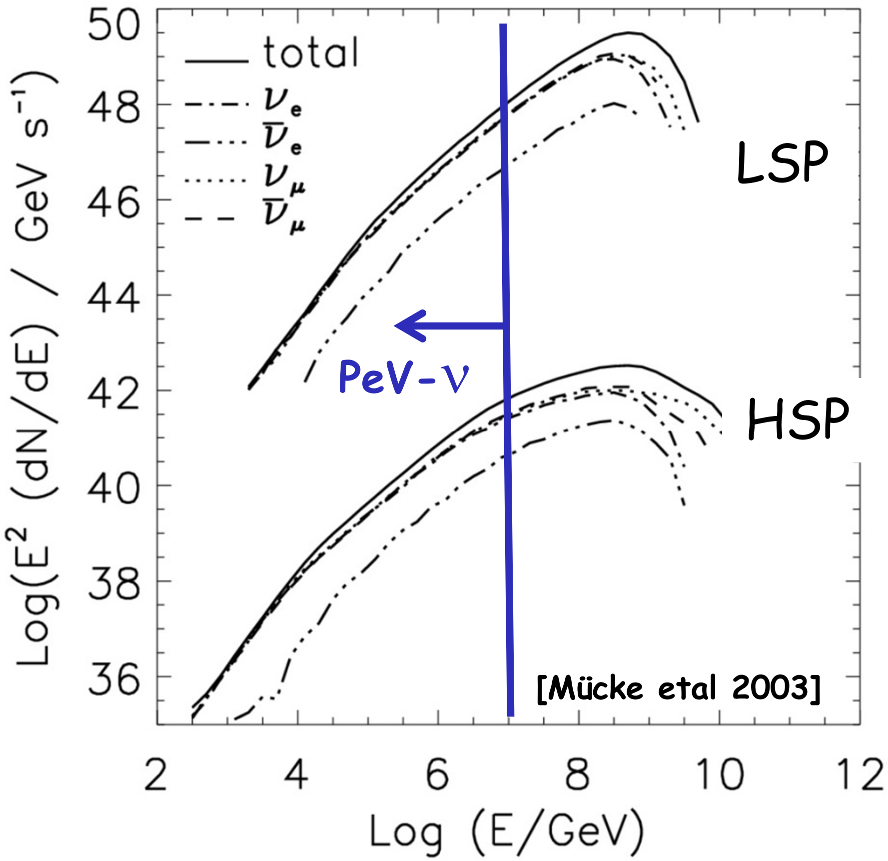
Parameters: $N_{p,inj} \sim E^{-2}$, B=10G, $u_\gamma=10^{11}$eV/cm^3, $R=10^{16}$cm, vary $E_{p,max}$

π prod. threshold! **π/μ syn. losses!**

⇒ ν-flux estimates from observed γ-ray fluxes must take into account competing loss channels (e.g., synchrotron channel)

⇒ optimal ν-production in <u>limited</u> $\gamma_{p,max}$-range

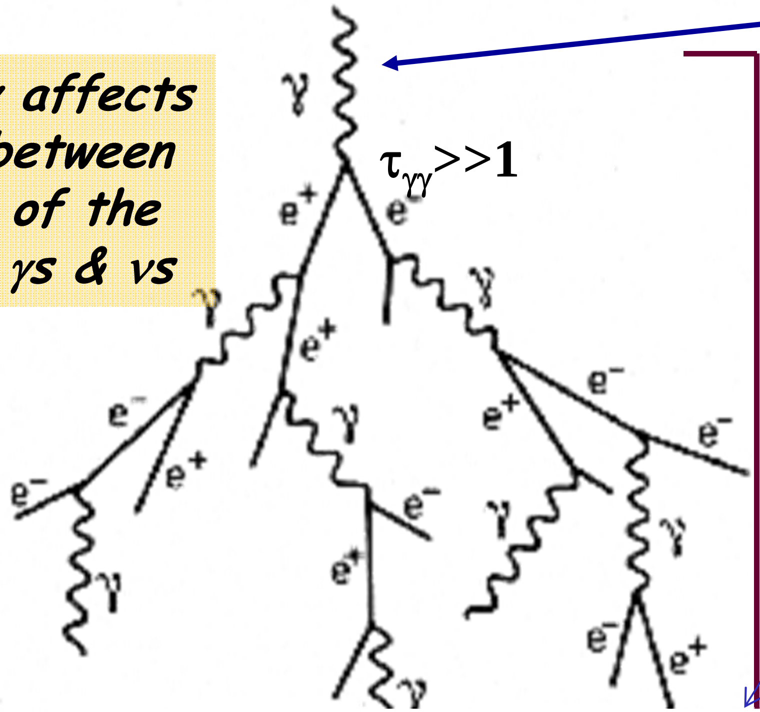
LSPs versus HSPs as neutrino source candidates



=> Among blazars LSP-type AGN produce potentially higher neutrino luminosities than HSP-type AGN

Cascade development

Energy injection



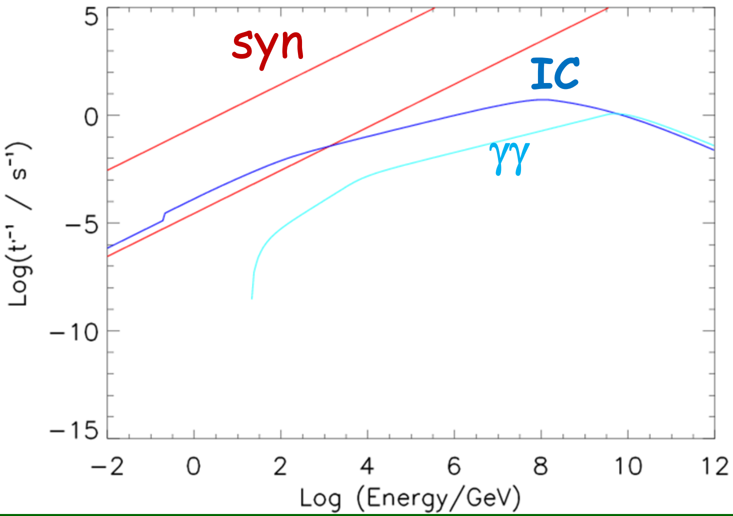
Degrading of photon/ particle energy:

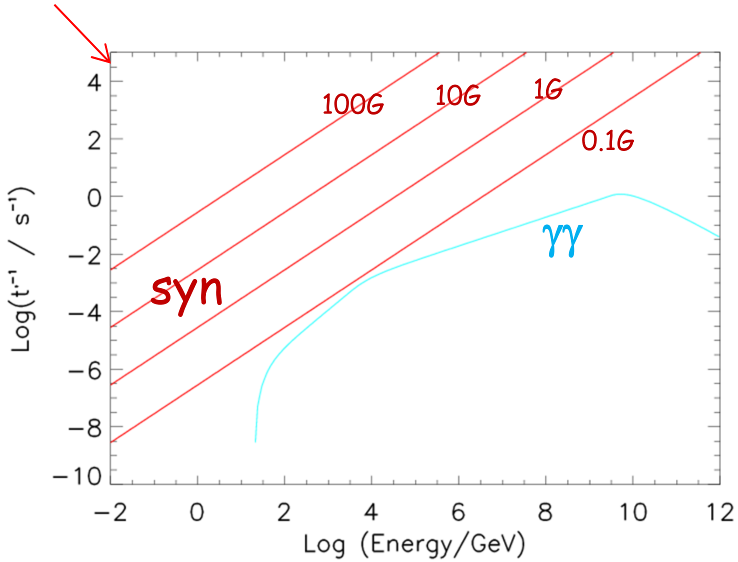
(1) Conversion of γ-photons into $e^{\pm}$ by γγ-pair production

(2) Radiation from $e^{\pm}$-pairs by
- Compton scattering or/and
- Synchrotron radiation

γγ-opacity affects relation between energies of the emerging γs & νs

γγ-opacity grossly determines cascade time scale

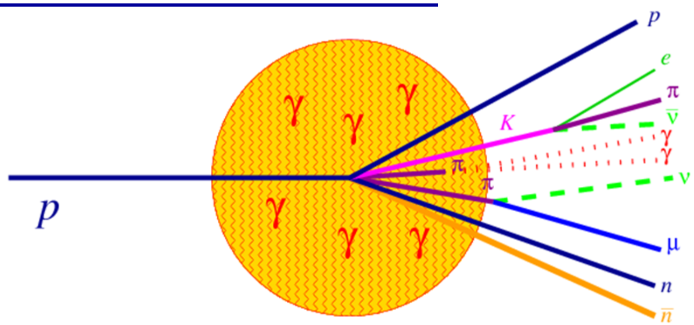




Target photon fields

- **Internal photon fields**

  (jet synchrotron radiation; z.B. PIC, SPB
  [Mücke et al 2003, …])



- **External photon fields:**

  e.g., - accretion disk radiation field **-> redshifted in jet frame!**

  [e.g. Protheroe 1996; Bednarek & Protheroe 1999, ….]

  - BLR lines & at BLR scattered accretion disk radiation

  [e.g. Atoyan & Dermer 2003, Dermer etal 2014, Murase etal 2014, ….]

  - IR/dust torus

  [e.g. Murase etal 2014]

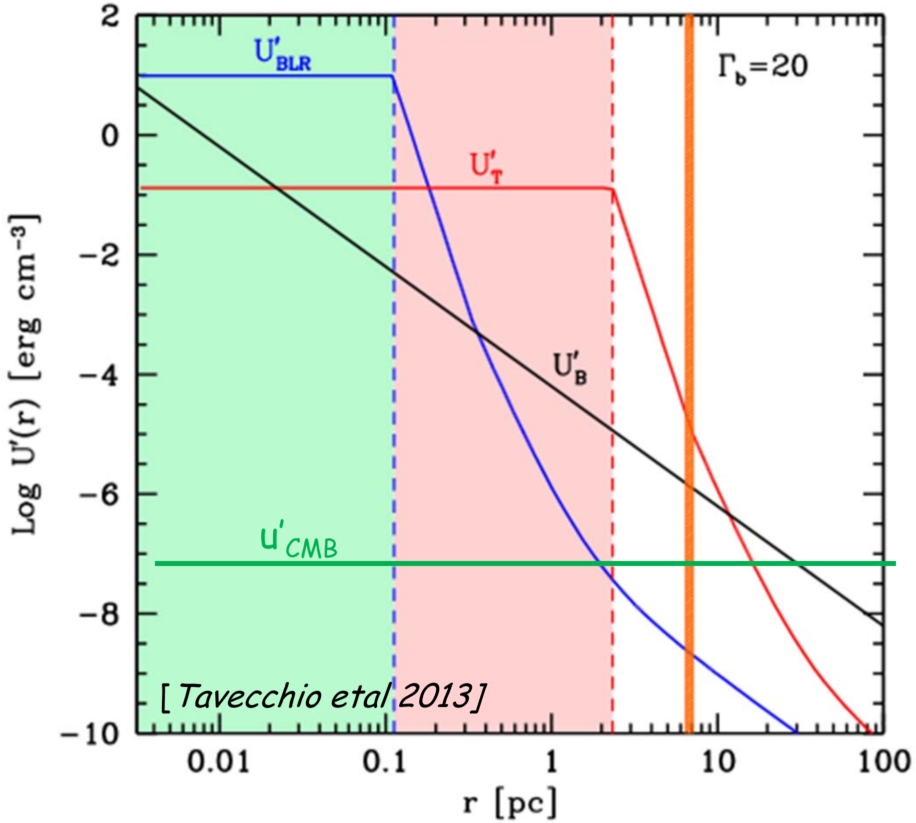
  - Spine/sheeth within structured jet model

  [e.g. Tavecchio etal 2014]

External radiation blueshifted in jet frame relaxes required γ_p for π-production

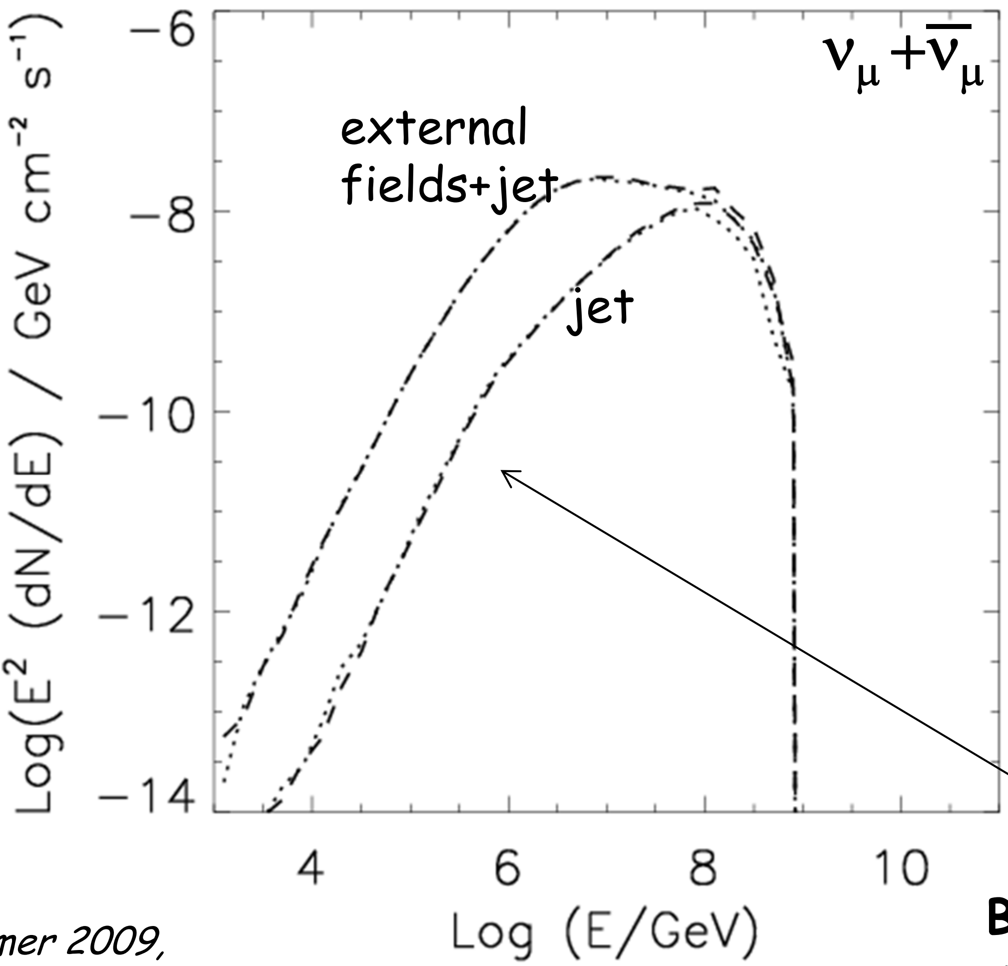
Location of the γ-ray emitting region

-> implications for dominating target photon field for particle-photon interactions



=> Nature (& frequency) of dominating external target photon field depends on distance from the central engine

Neutrino fluxes: External versus jet target photons



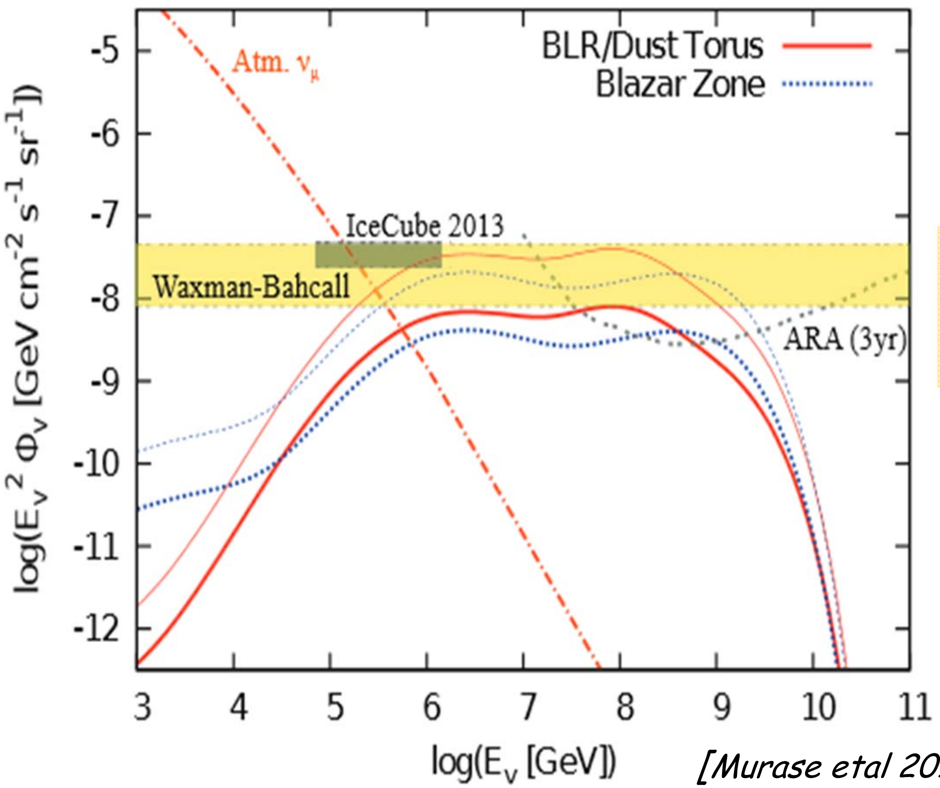
[Reimer 2009, Abbasi etal 2009]

π-production in BLR radiation field adds predominantly > PeV neutrinos

Blazars with highly magnetized emission regions – if sources of the HECRs – are *weak, hard-spectrum* TeV-PeV ν-emitter!

Predicted diffuse neutrino fluxes .....

…. from π-production in external blazar radiation fields

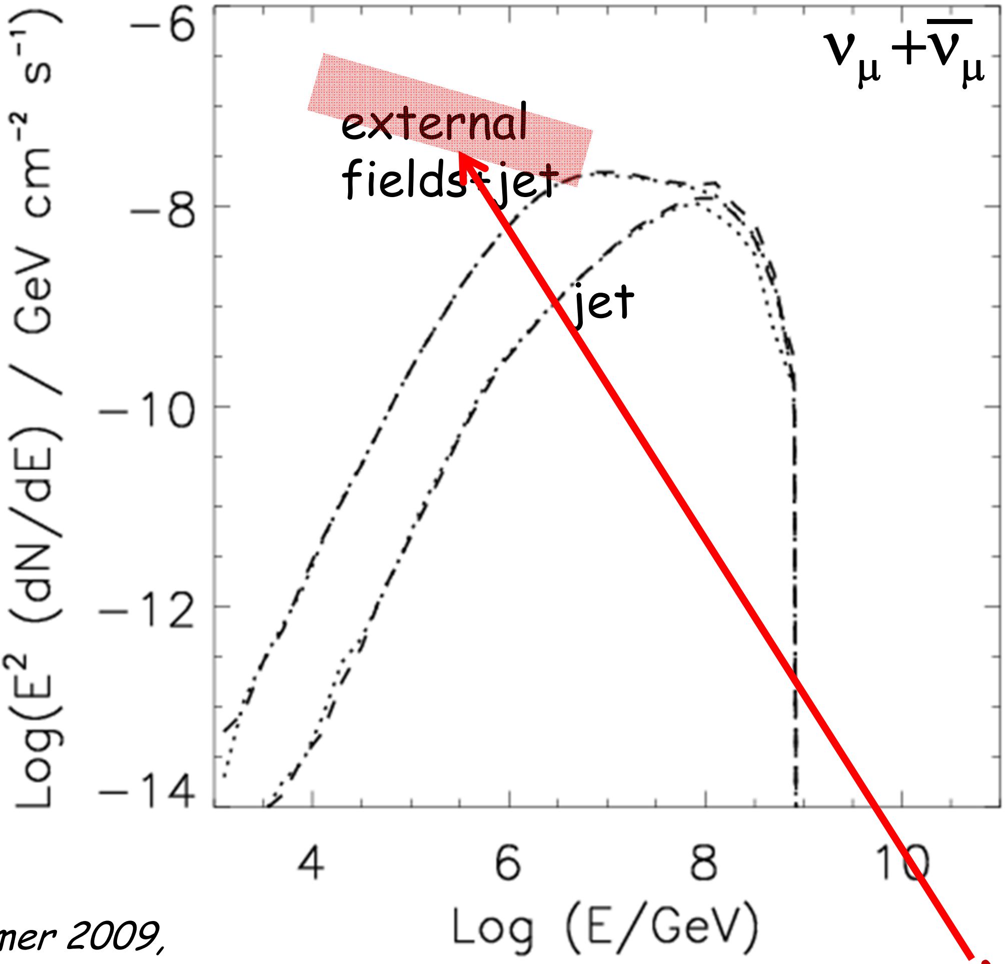


[Murase etal 2014]

➡ predict hard ν-spectra below PeV energies

…. possibly in tension with observed soft all-sky ν-spectrum!

Neutrino fluxes: External versus jet target photons



[Reimer 2009, Abbasi etal 2009]

π-production in BLR radiation field adds predominantly > PeV neutrinos

Need prominent (jet-frame) x-ray target photon field!

On co-spatial GeV-photon & 10TeV ν-emission

If γ-ray & ν-emission *co-spatial*:

- Significant >GeV emission requires:

  $\tau_{\gamma\gamma} = n_{T,\gamma\gamma}\,\sigma_{\gamma\gamma} R \ll 1$ with $n_{T,\gamma\gamma} = n_x$

  [Threshold condition: $E_T \cdot E_\gamma > (m_e c^2)^2$]

- Significant >tens of TeV ν-production from pγ-interactions requires:

  $\tau_{p\gamma} = n_{T,p\gamma}\,\sigma_{p\gamma} R \gg 1$ with $n_{T,p\gamma} = n_x$

→ Together: $1 \gg \tau_{\gamma\gamma} / \tau_{p\gamma} \approx \sigma_{\gamma\gamma} / \sigma_{p\gamma} \gg 1$

requirement

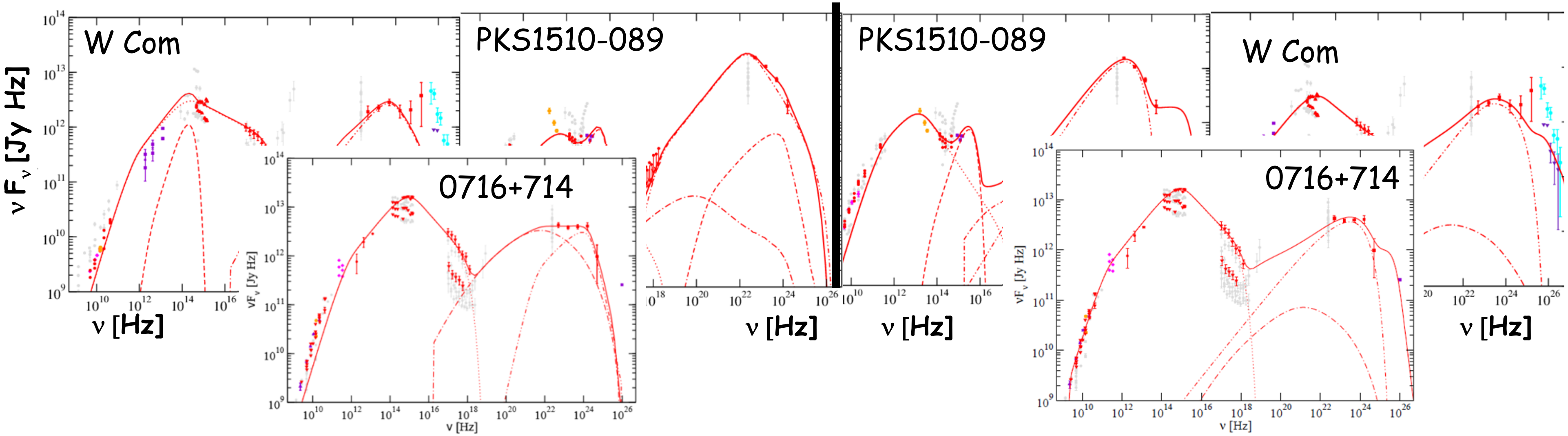
if same target photon field for $\gamma\gamma$- & pγ-interactions

>Tens GeV-photon emission suppressed in regions where significant ~10TeV soft-spectrum ν-flux is photohadronically produced.

Multifrequency Modelling of *LAT*-detected Blazars

[Böttcher, Reimer et al 2013]

Leptonic Models | **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 $\sim 10^{47-49}$erg/s
- $E_{p,max} \sim 10^{17...18}$eV

Conclusions

- Photon-neutrino flux scaling? -

- $L_\gamma \sim L_\nu$ flux scaling from interaction kinematics reflects only upper limit of expected ν-flux.
- Flux ratios F_ν/F_γ from multi-messenger modeling indicate significantly lower values (due to competing loss processes).

- On the counterpart sources of the IceCube TeV-PeV events -

- Soft >tens of TeV ν-spectra unlikely produced photohadronically by luminous photon emitters peaking >tens of GeV if γ-ray & ν-emission co-spatial.

γγ-opacity effects!