Testing Neutrino Properties with Astrophysics and Cosmology

- High Energy Neutrinos: The connection to high energy cosmic and gamma-rays
- Testing Oscillation Parameters and Source Physics
- Testing Physics beyond the Standard Model: Cross Sections at PeV scales, Lorentz symmetry violation
- Neutrinos in Cosmology

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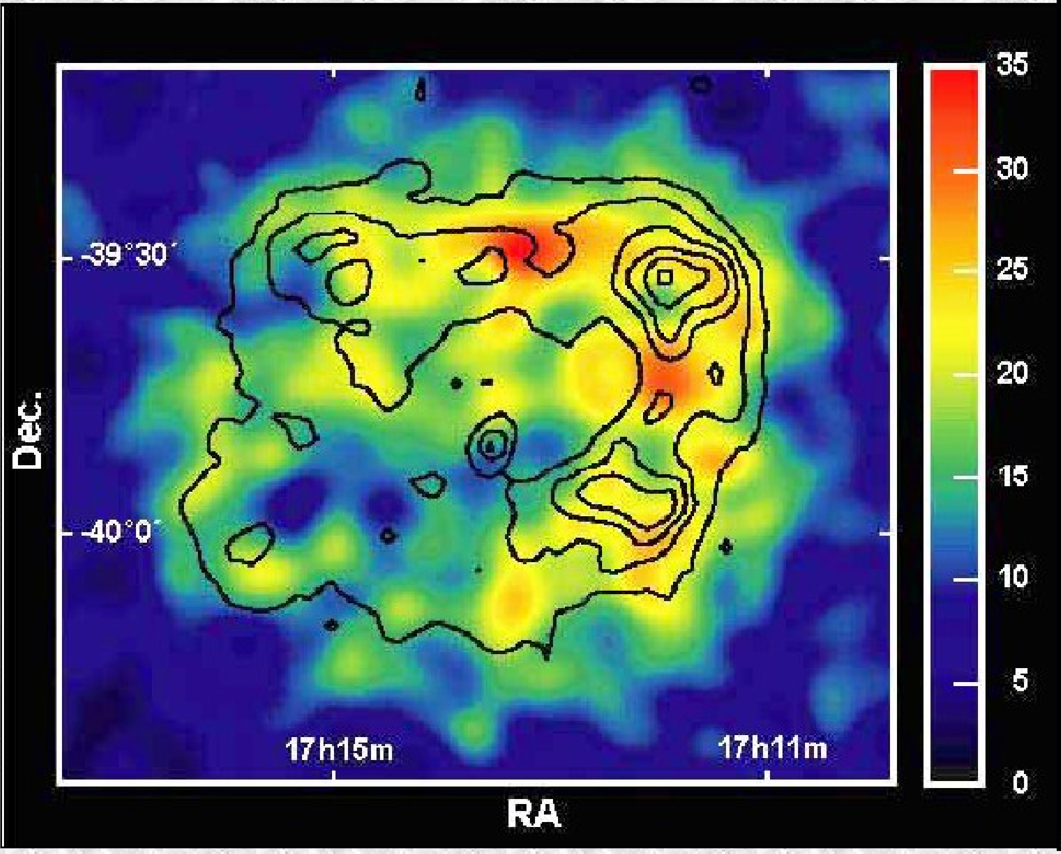
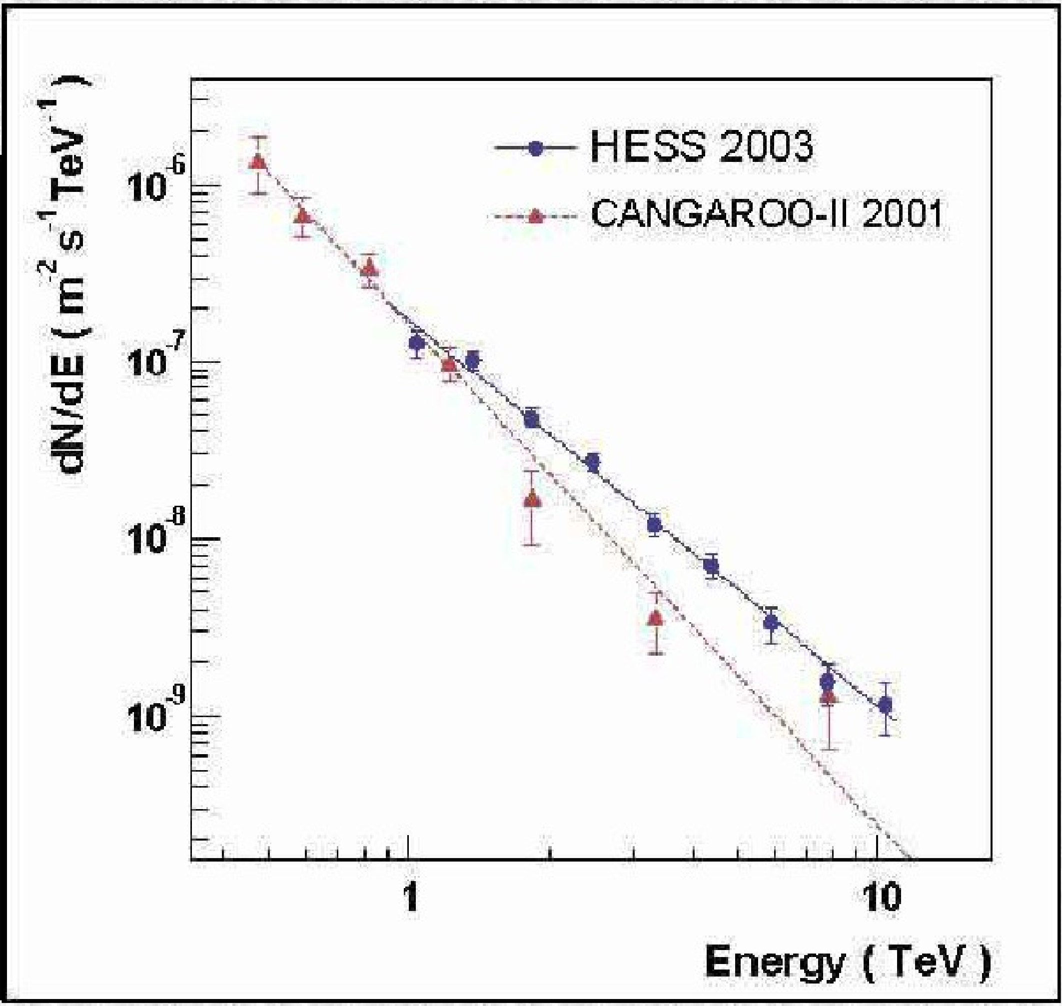
http://www2.iap.fr/users/sigl/homepage.html

Supernova Remnants and Galactic Cosmic and γ-Rays

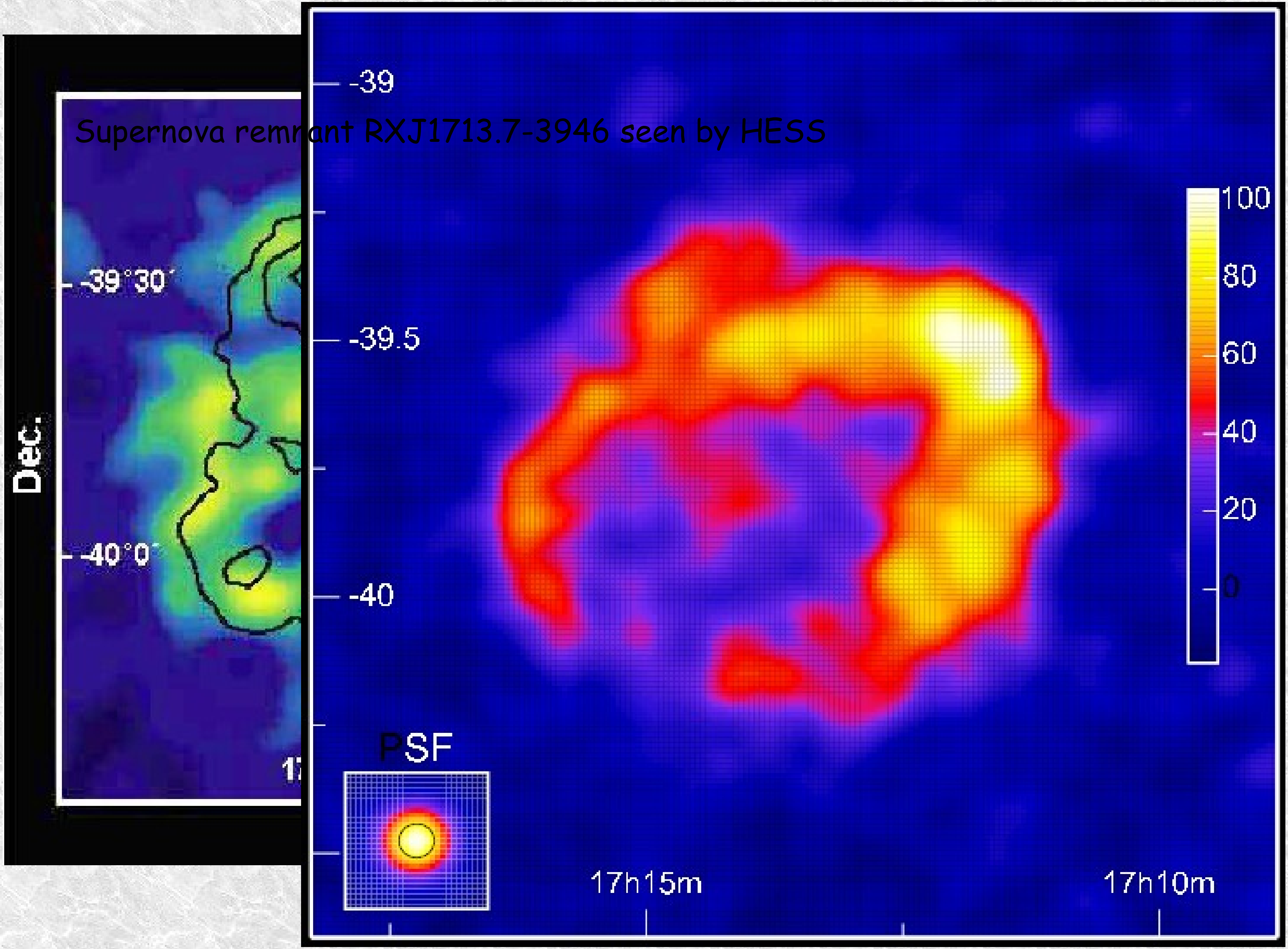




Aharonian et al., Nature 432 (2004) 75

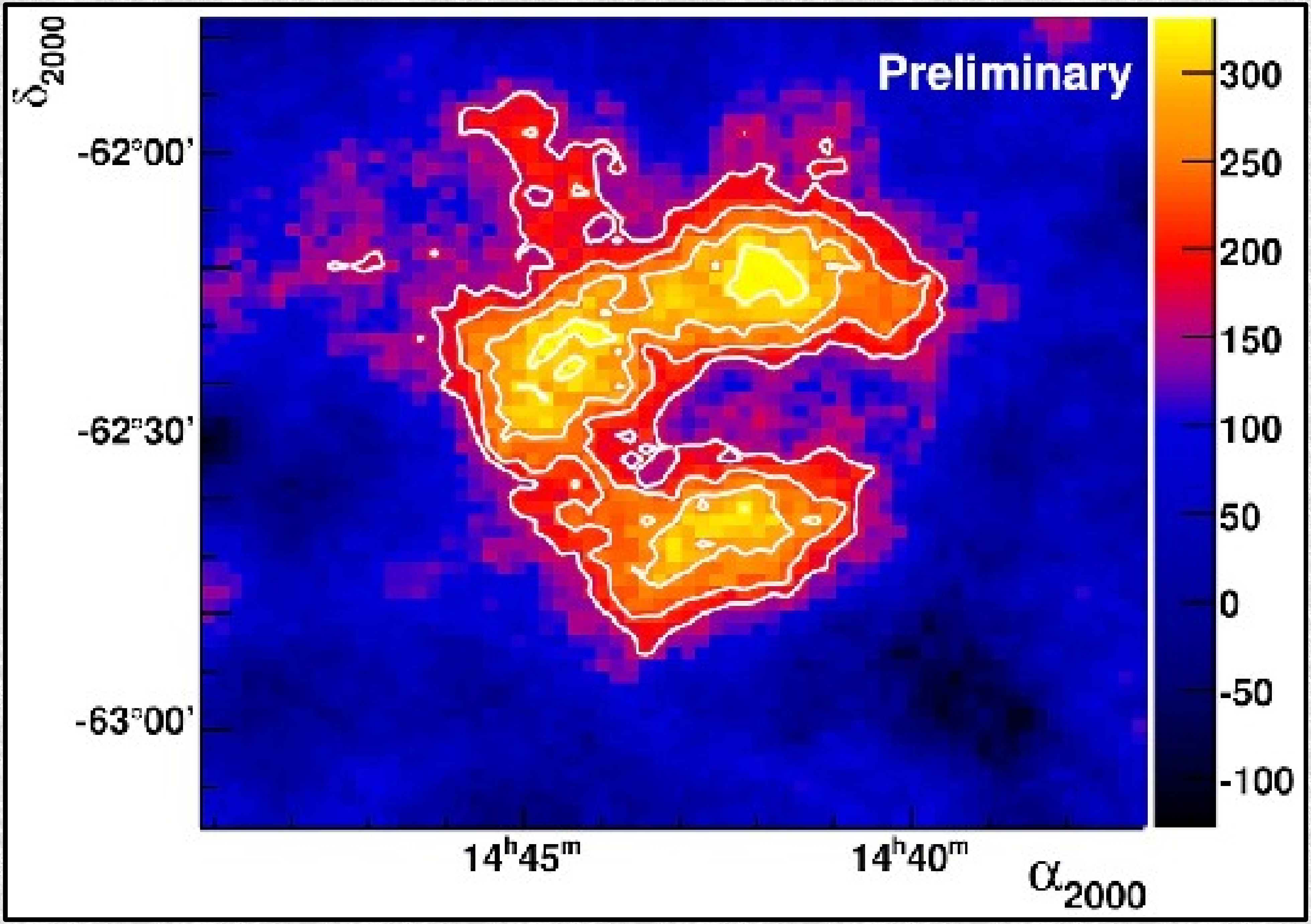
Supernova remnants have been seen by HESS in γ-rays: The remnant RXJ1713-3946 has a spectrum ~$E^{-2.2}$: => Charged particles have been accelerated to > 100 TeV. Also seen in 1-3 keV X-rays (contour lines from ASCA)

Identifying galactic sources from their secondary gamma-ray signatures

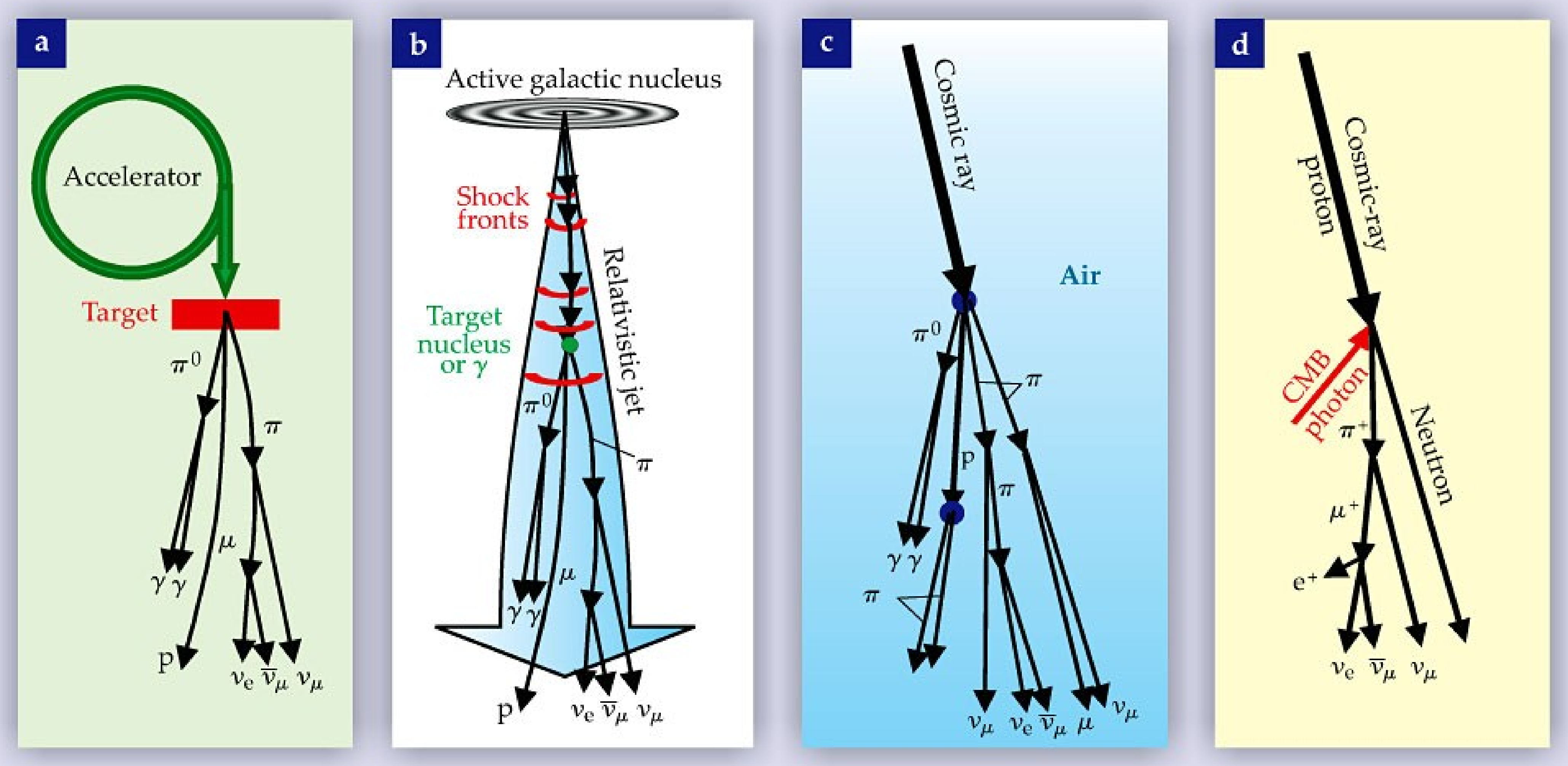


Supernova remnant RXJ1713.7-3946 seen by HESS

Shell-type supernova remnant RCW 86 seen by HESS



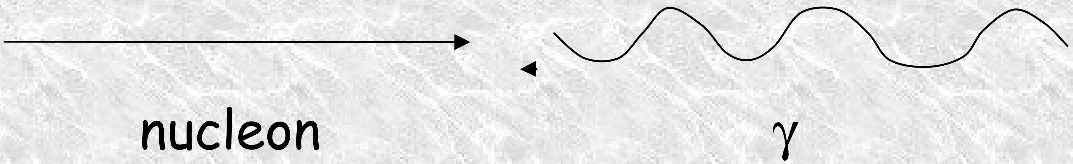
Summary of neutrino production modes



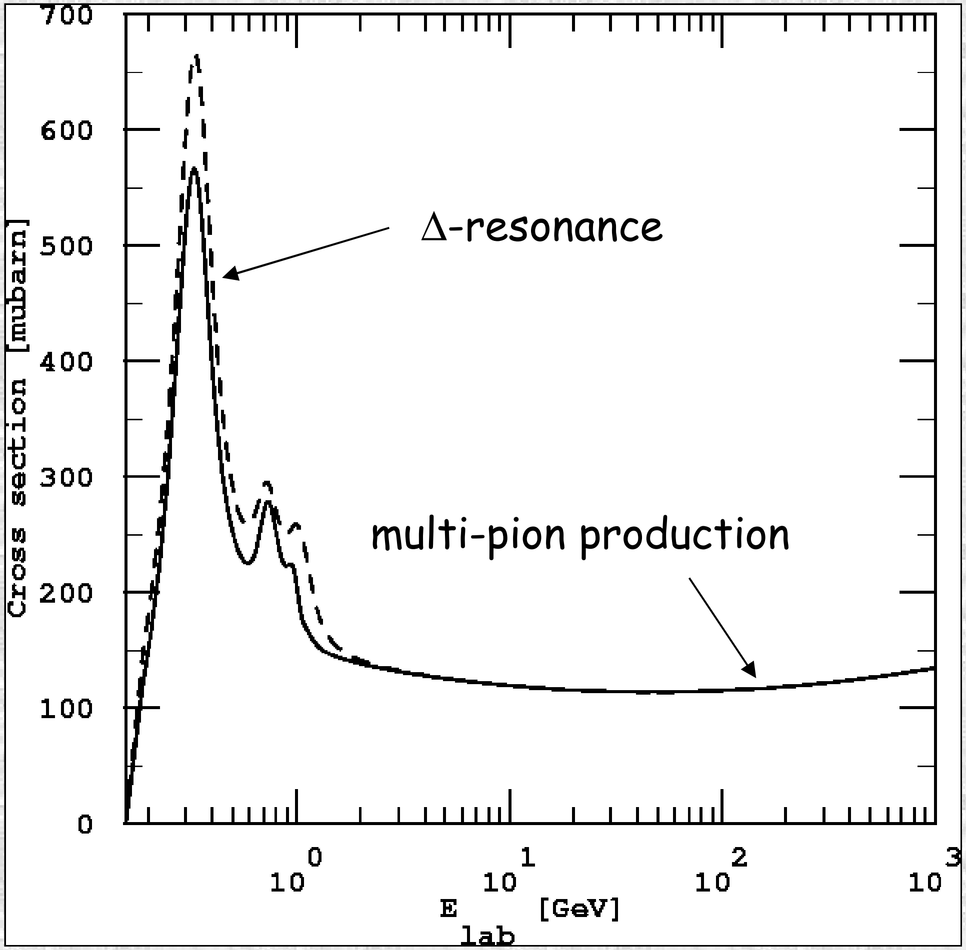
From Physics Today

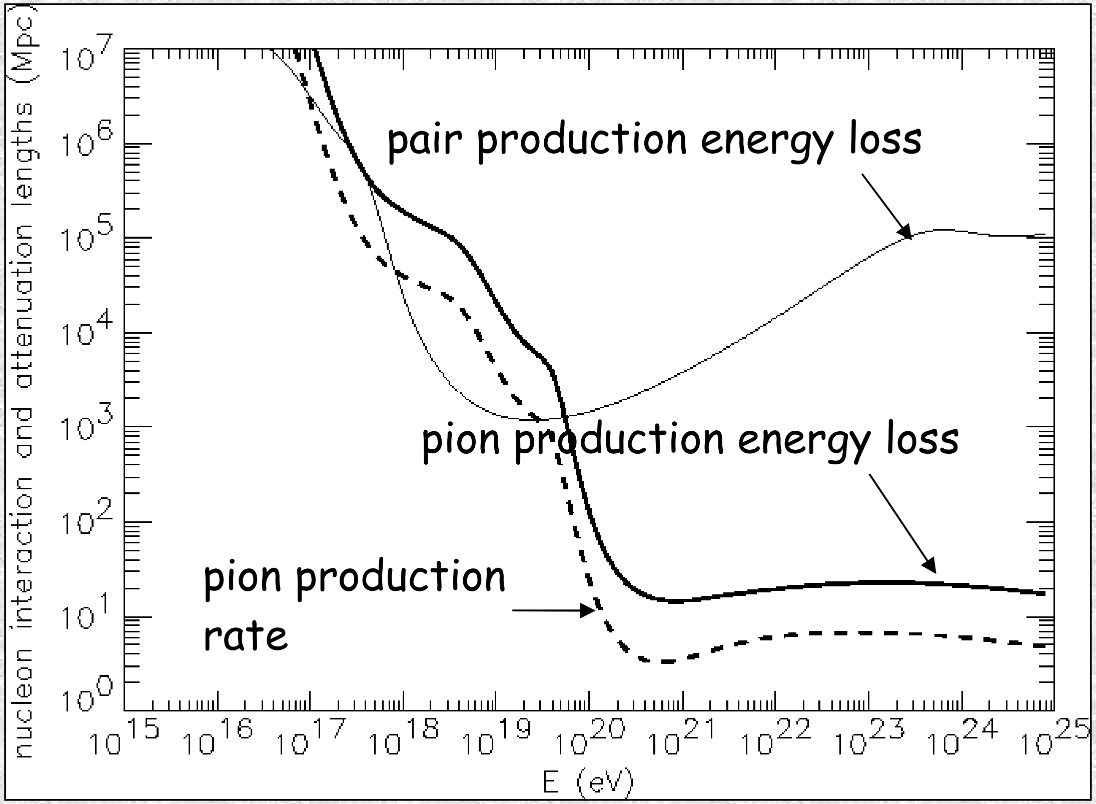
The Greisen-Zatsepin-Kuzmin (GZK) effect

Nucleons can produce pions on the cosmic microwave background



$$E_{th} = \frac{2m_N m_\pi + m_\pi^2}{4\varepsilon} \approx 4\cdot 10^{19}\,\mathrm{eV}$$

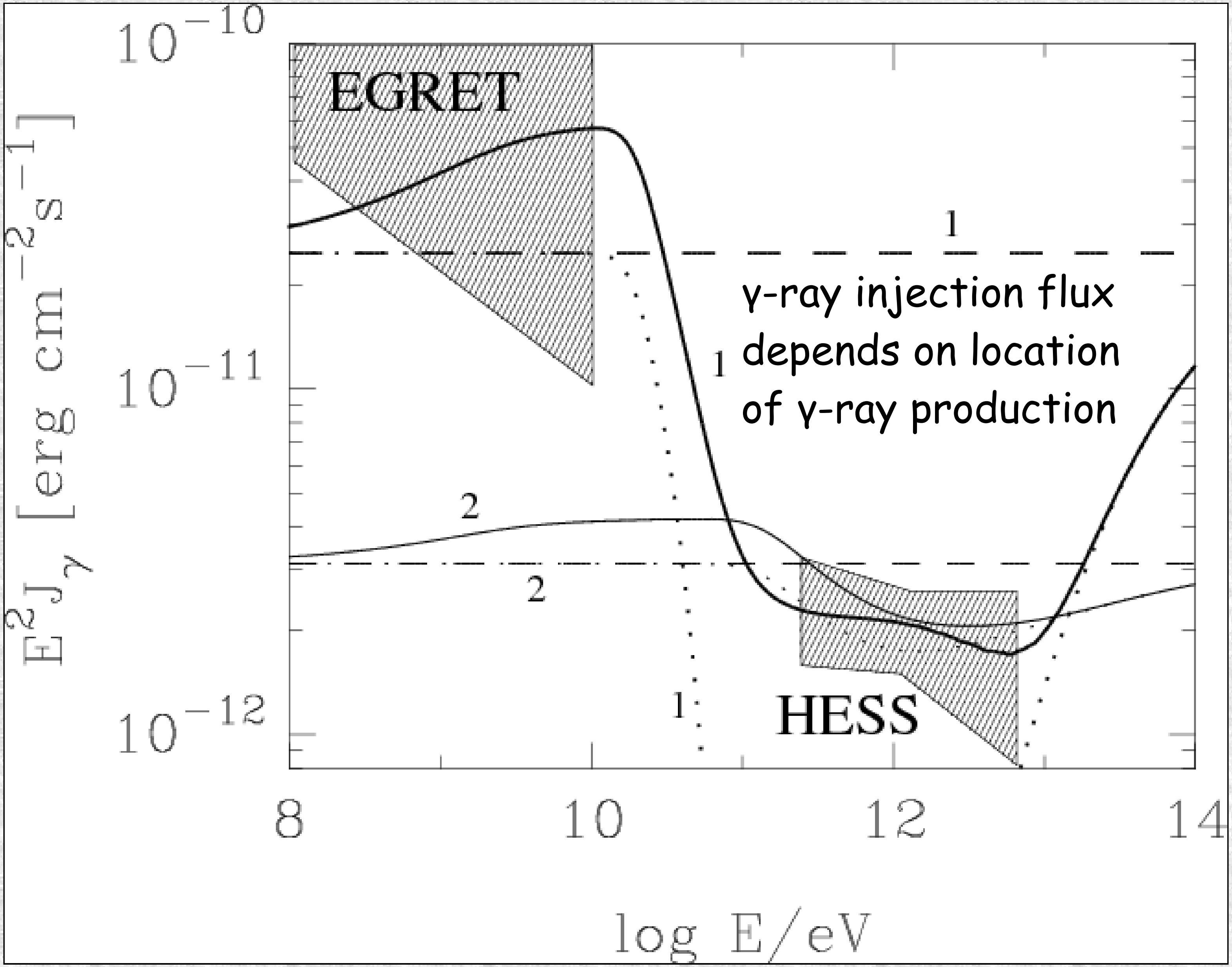




⇒sources must be in cosmological backyard
Only Lorentz symmetry breaking at $\Gamma>10^{11}$ could avoid this conclusion.

HESS sources: X-ray binary LS 5039

Secondary γ-rays and neutrinos mostly produced by pp interactions in this model

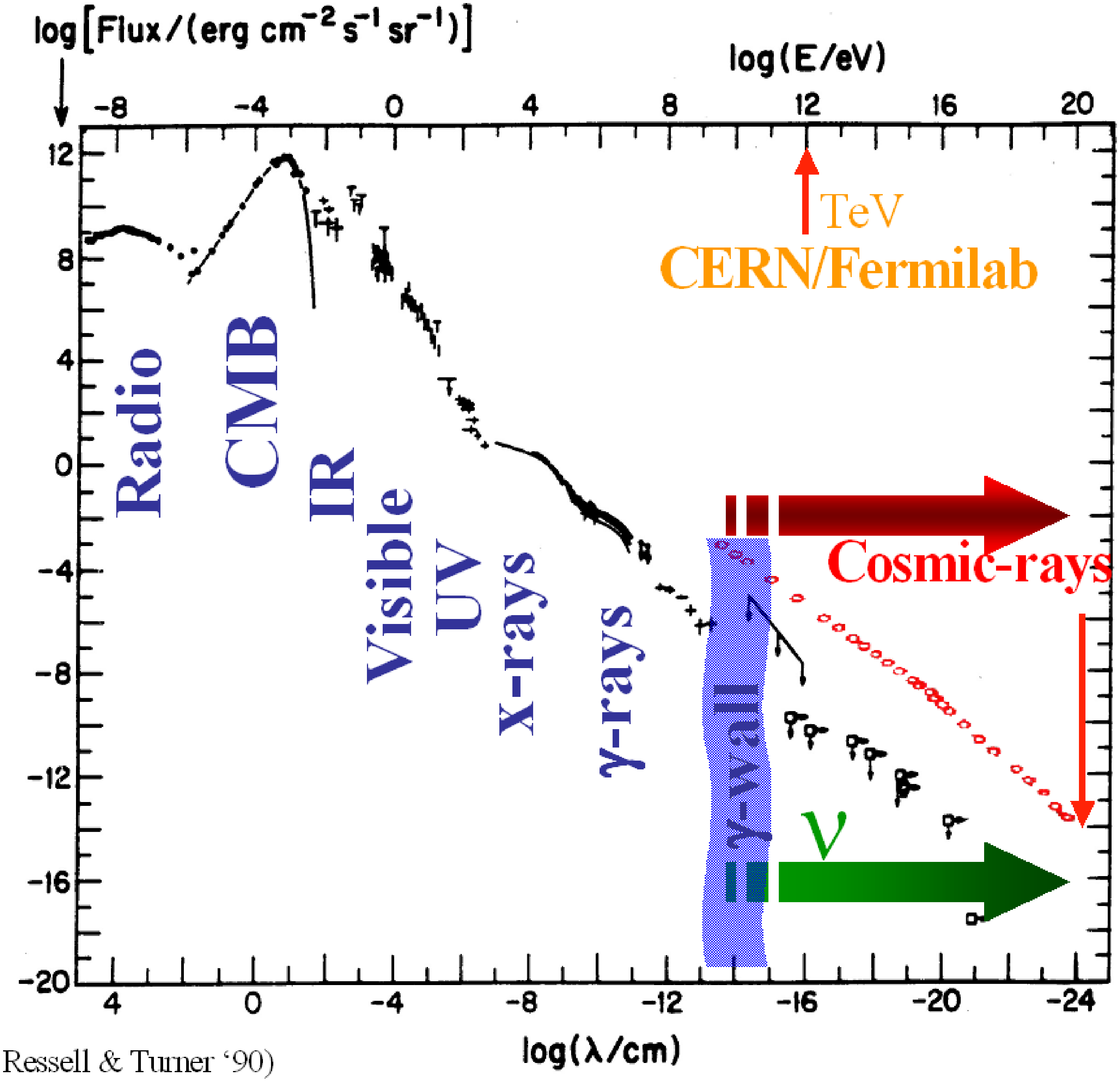


γ-ray injection flux depends on location of γ-ray production

F.Aharonian et al., astro-ph/0508658

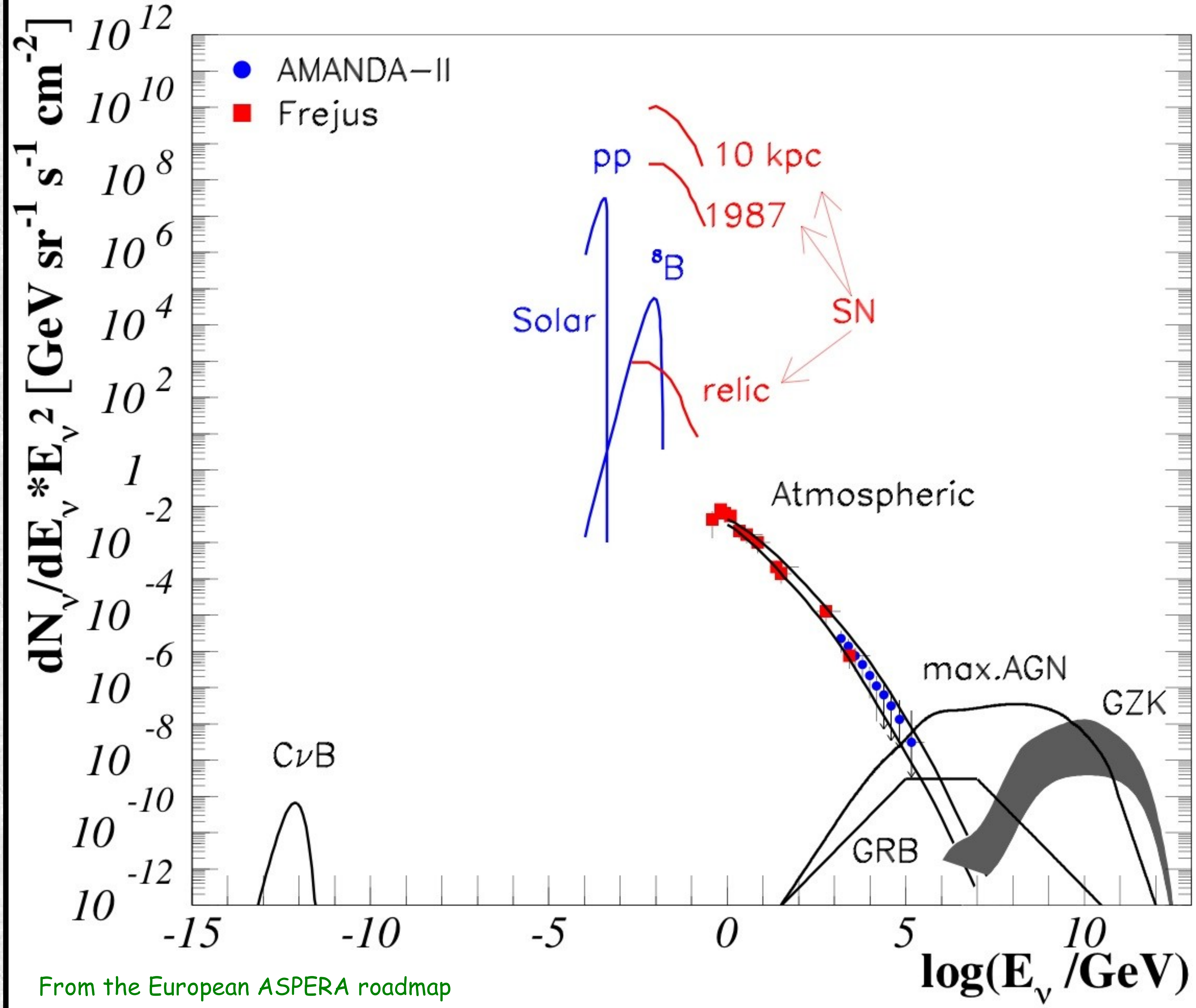
Expected neutrino fluxes above TeV ~10^{-9}-10^{-7} GeV cm^{-2}s^{-1}

The universal photon spectrum



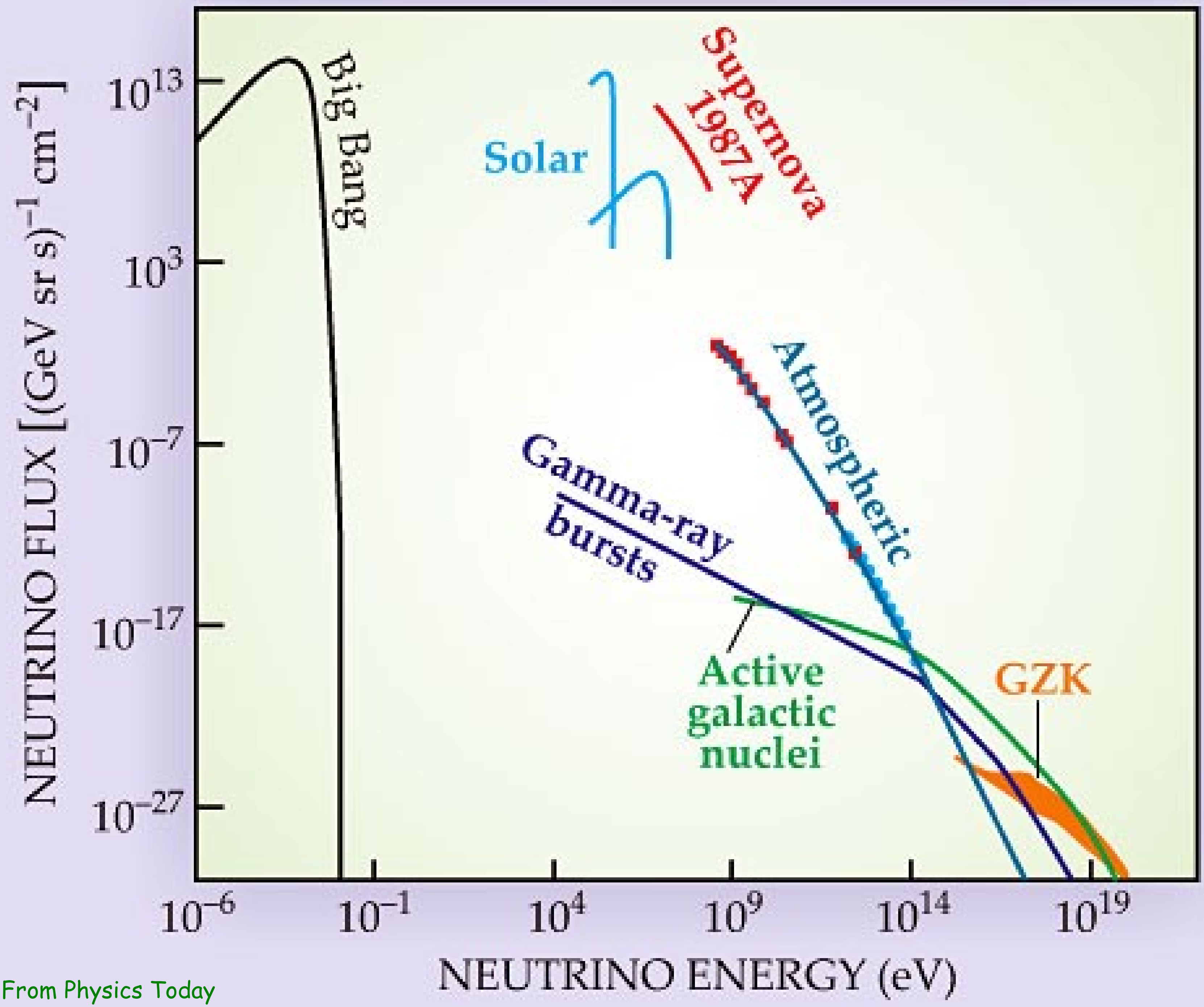
(after Ressell & Turner ‘90)

The „grand unified" neutrino energy flux spectrum



From the European ASPERA roadmap

The „grand unified" differential neutrino number spectrum



From Physics Today

Ultra-High Energy Cosmic Rays and the Connection to γ-ray and Neutrino Astrophysics

accelerated protons interact:

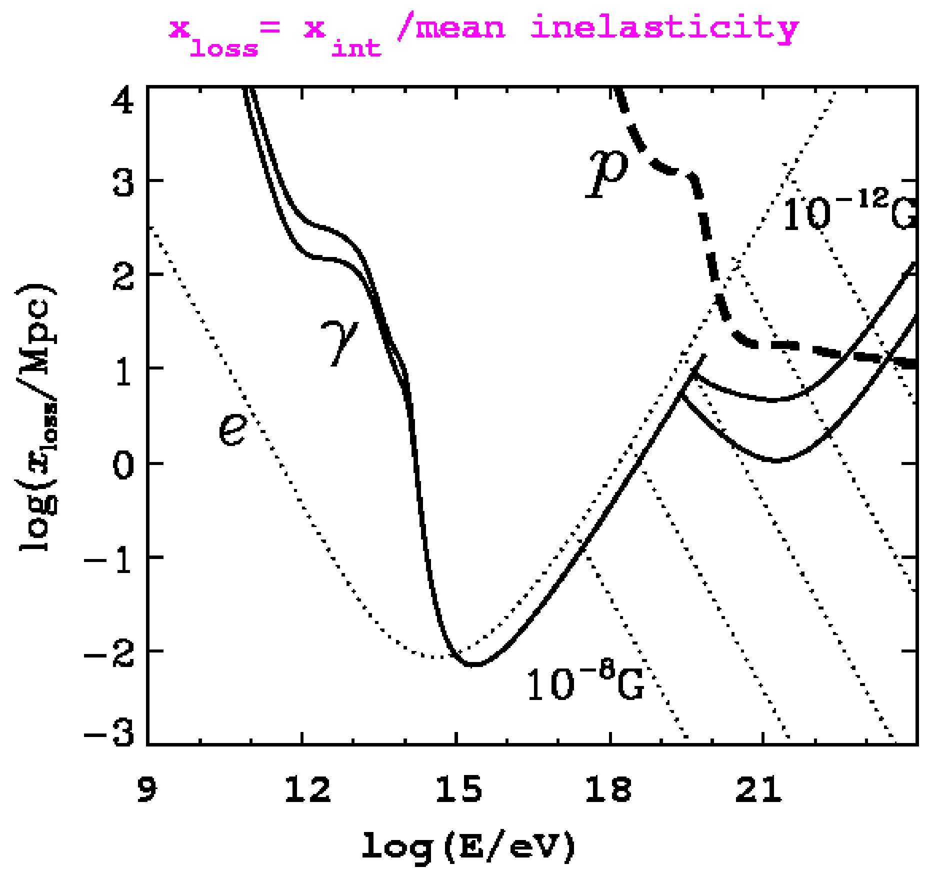
$$p + \begin{matrix} N \\ \gamma \end{matrix} \to X + \left. \begin{matrix} \pi^{\pm} \to \text{neutrinos} \\ \pi^{o} \to \gamma\text{ - rays} \end{matrix} \right\}$$

during propagation ("cosmogenic")
or in sources (AGN, GRB, ...)

=> energy fluences in γ-rays and neutrinos are comparable due to isospin symmetry.

Neutrino spectrum is unmodified,
γ-rays pile up below pair production threshold on CMB at a few 10^{14} eV.

Universe acts as a calorimeter for total injected electromagnetic energy above the pair threshold.
=> neutrino flux constraints.



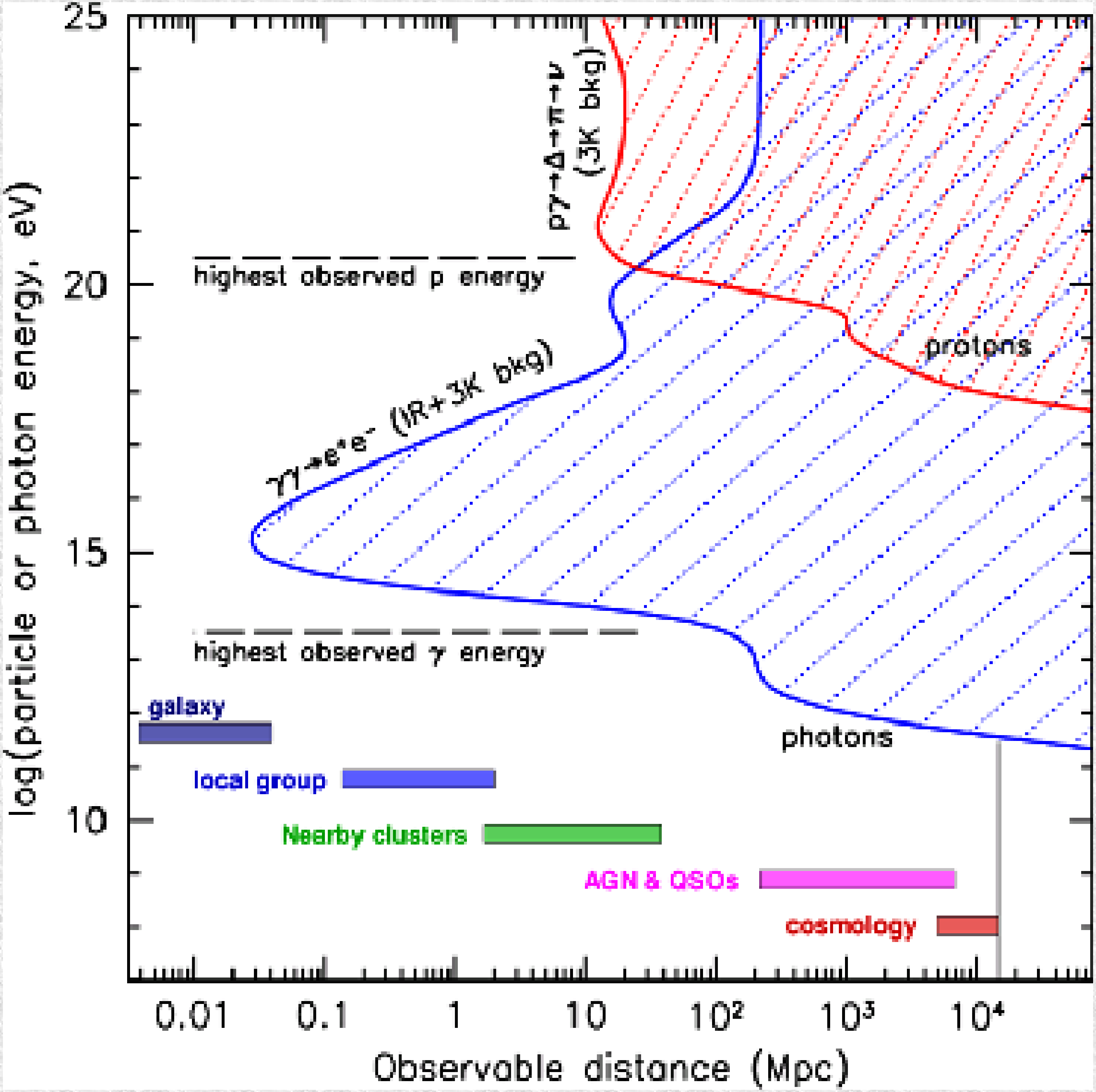
Included processes:

Electrons: inverse Compton; synchrotron rad (for fields from pG to 10 nG)

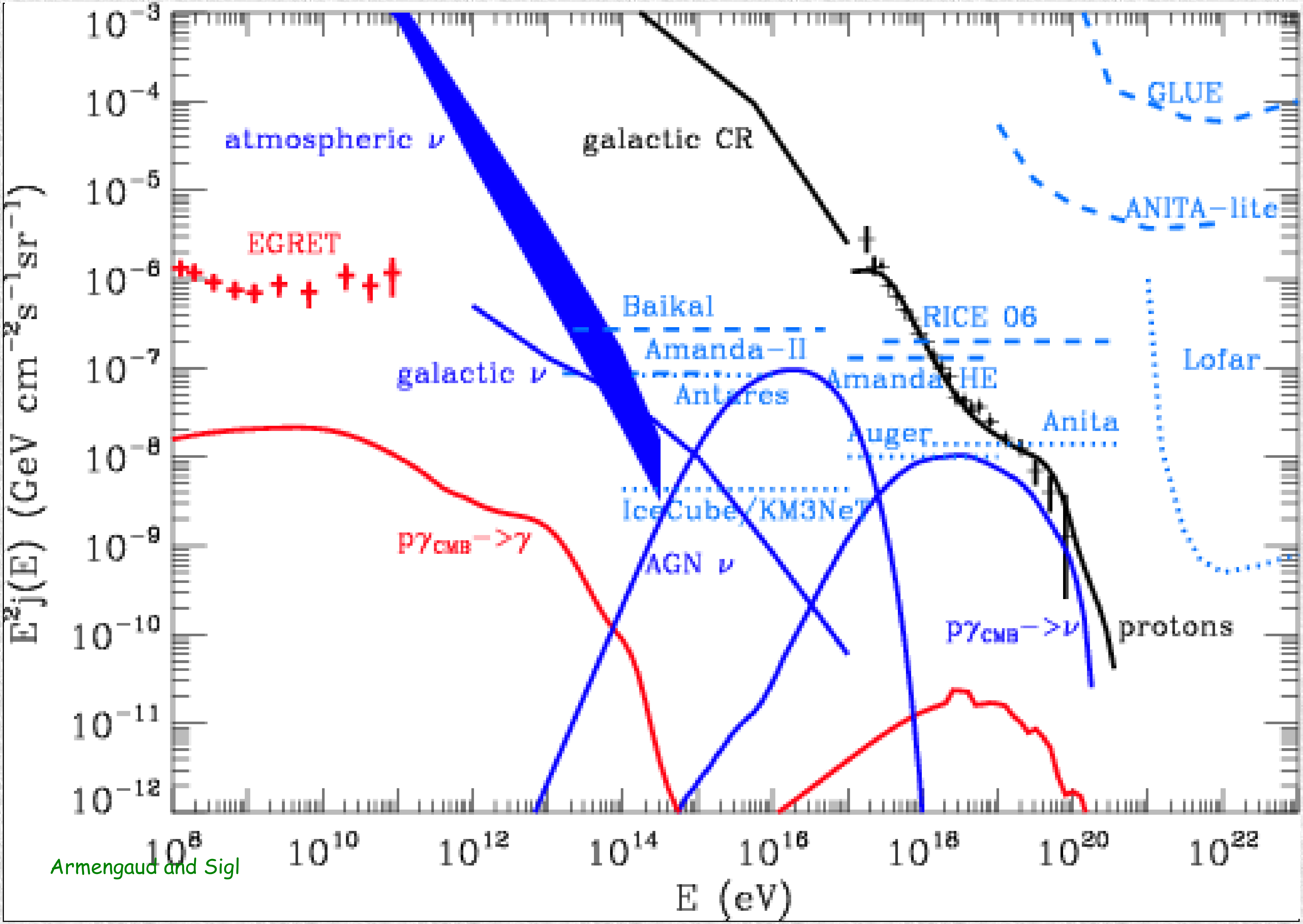
Gammas: pair-production through IR, CMB, and radio backgrounds

Protons: Bethe-Heitler pair production, pion photoproduction

Interaction Horizons

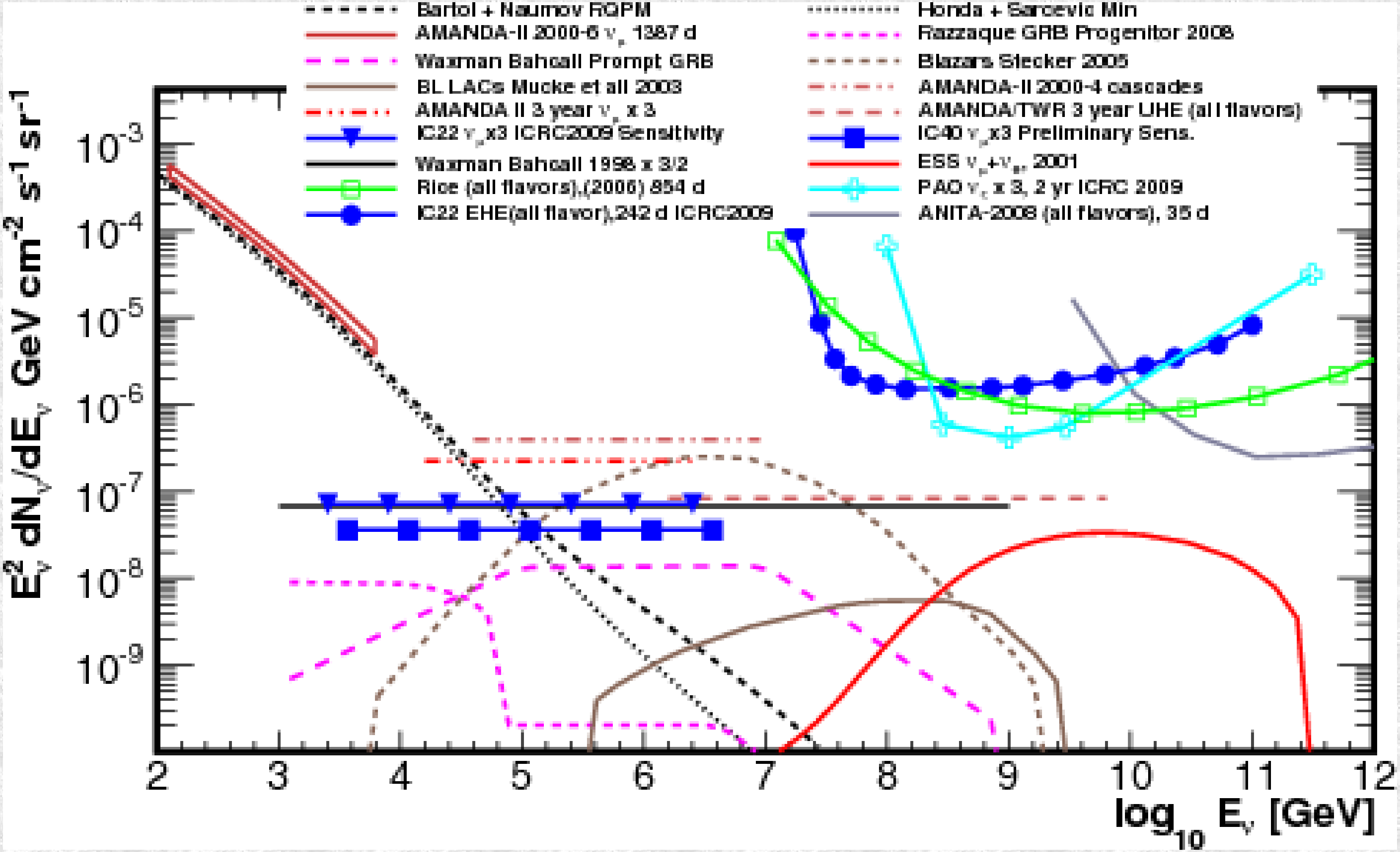


Theoretical Limits, Sensitivities, and "Realistic" Fluxes: A Summary



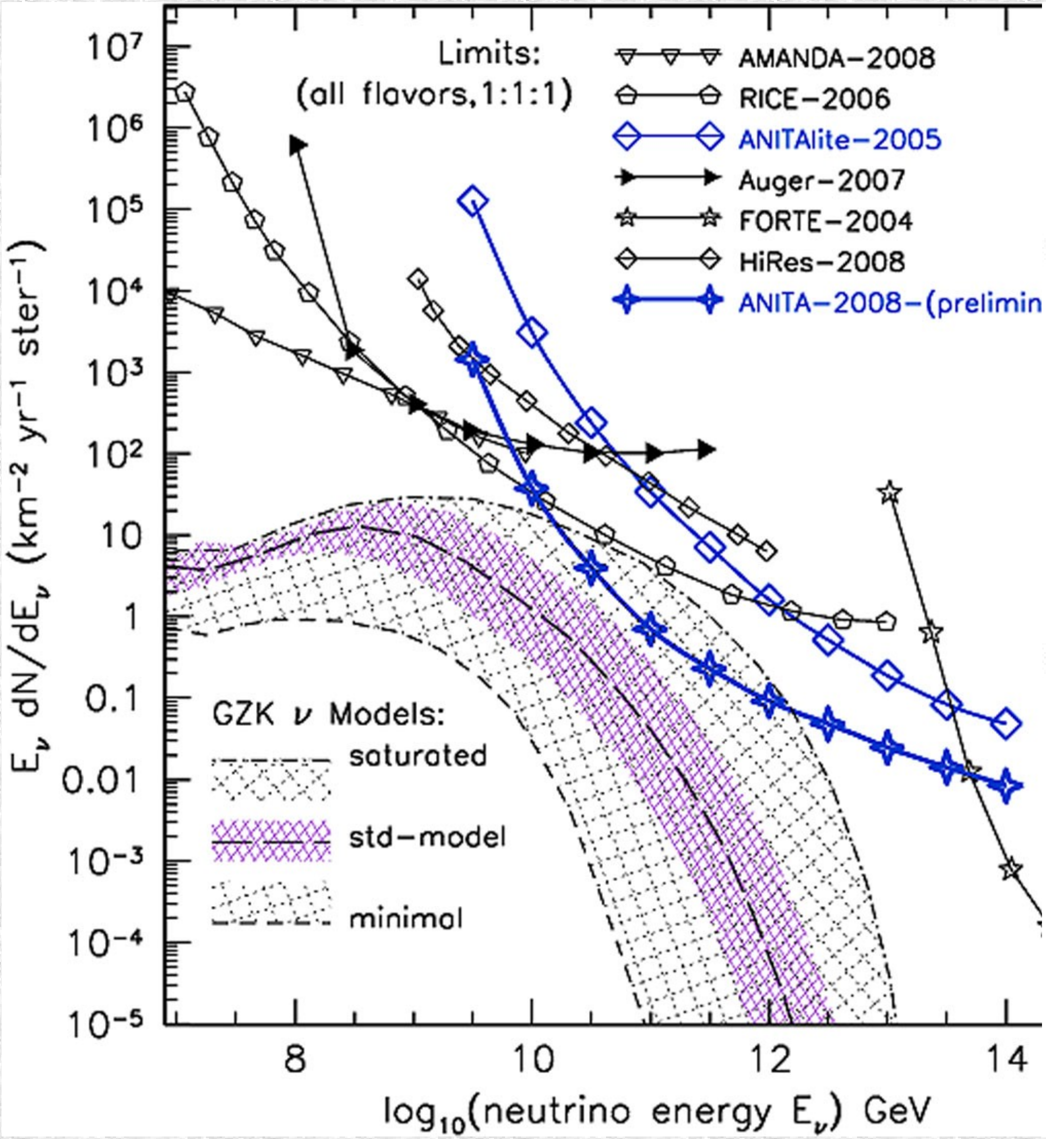
Armengaud and Sigl

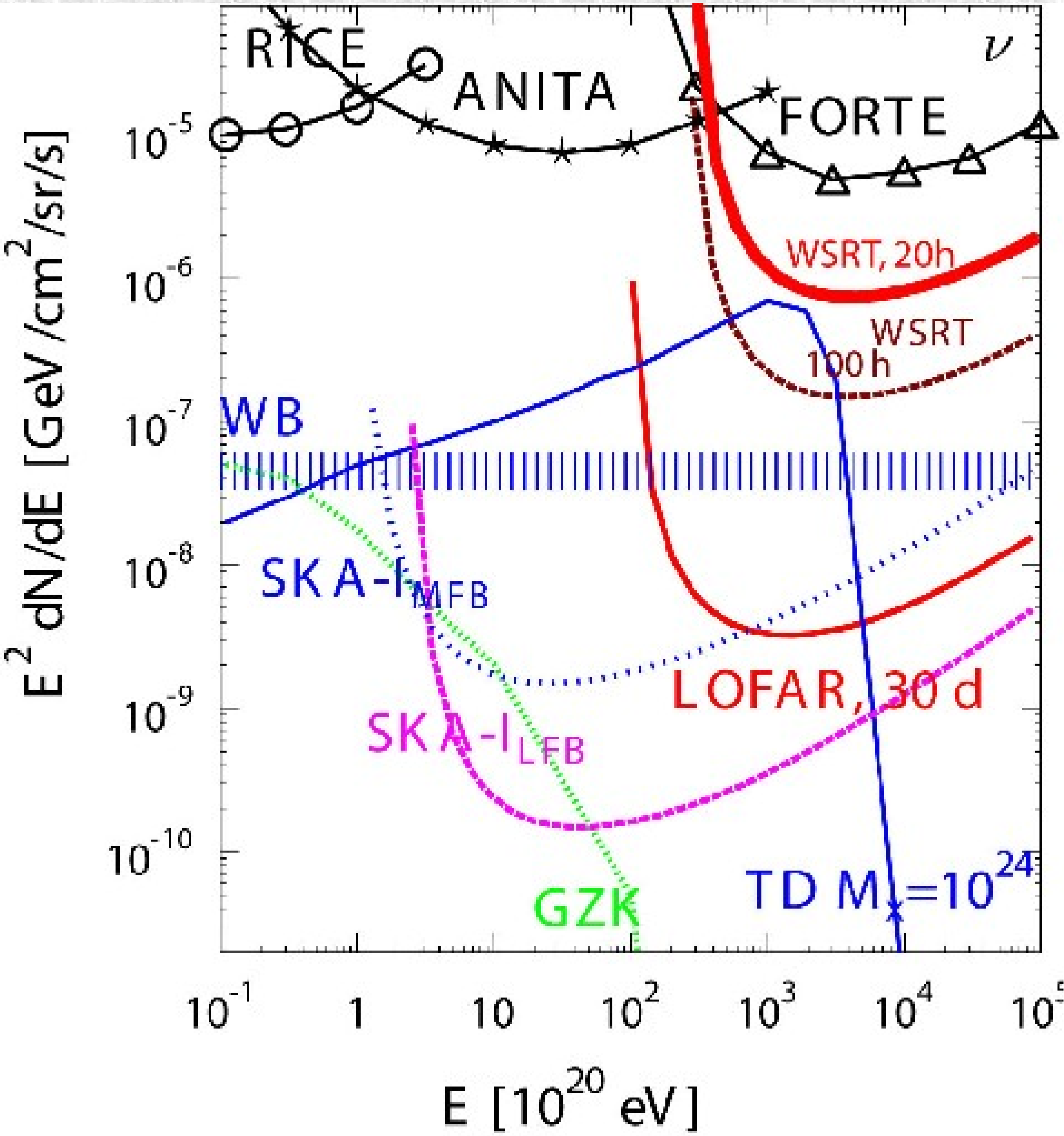
Current upper limits on diffuse neutrino fluxes



T. de Young for ICECUBE., arXiv:0910.3644

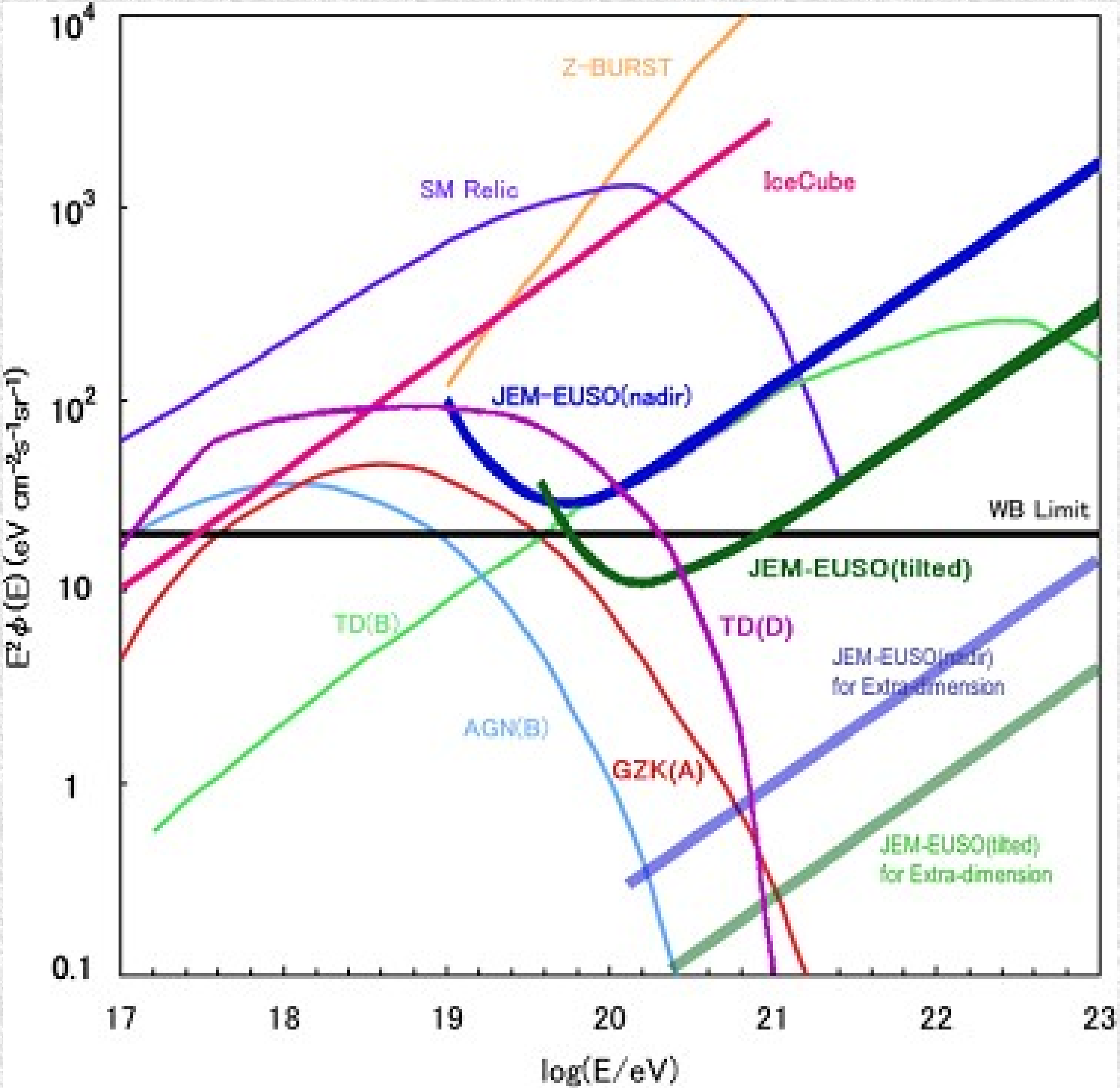
Limits and future Sensitivities to UHE neutrino fluxes



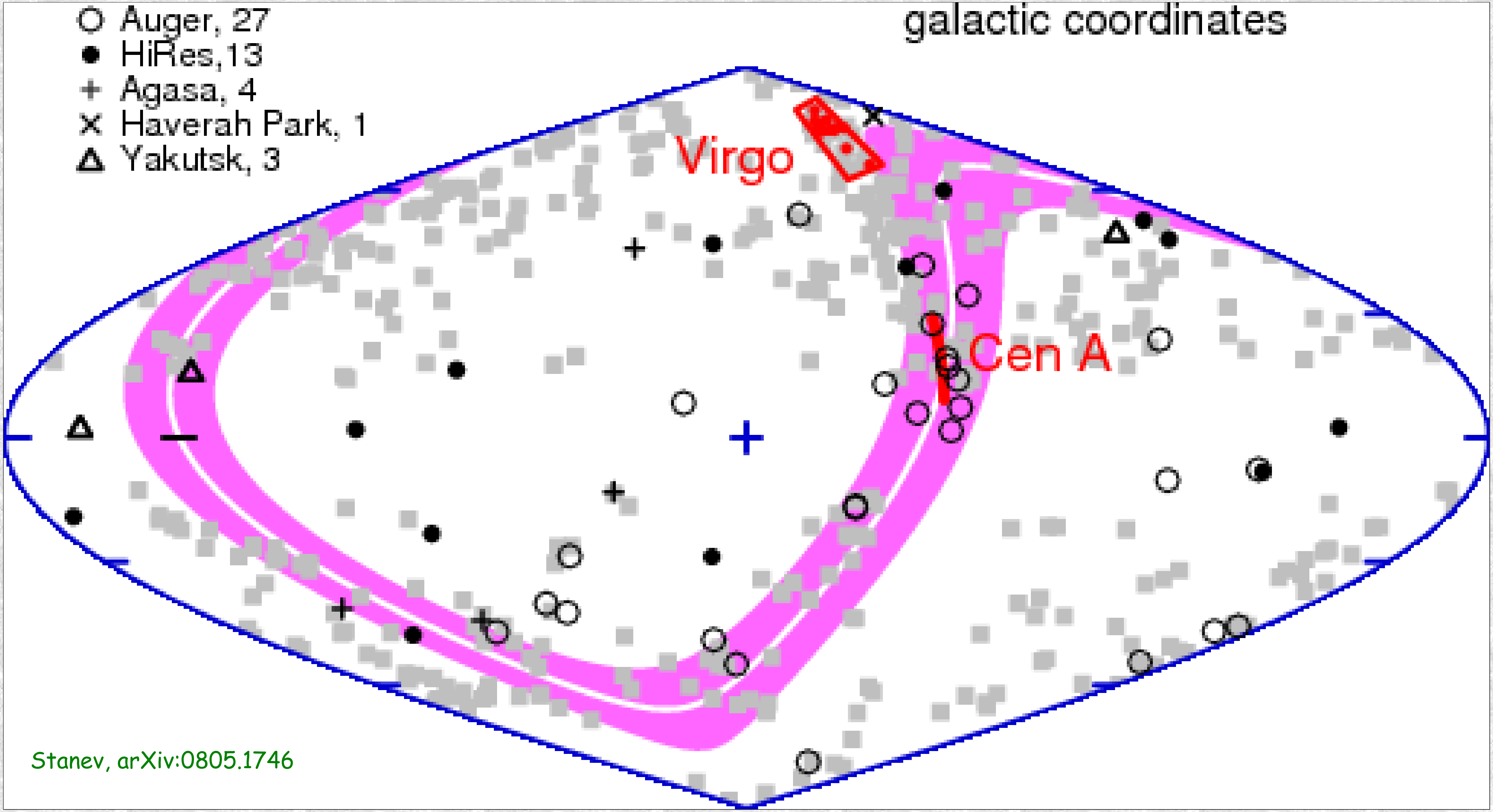


A. Haungs, arXiv:0811.2361

JEM-EUSO Sensitivities to UHE neutrino fluxes

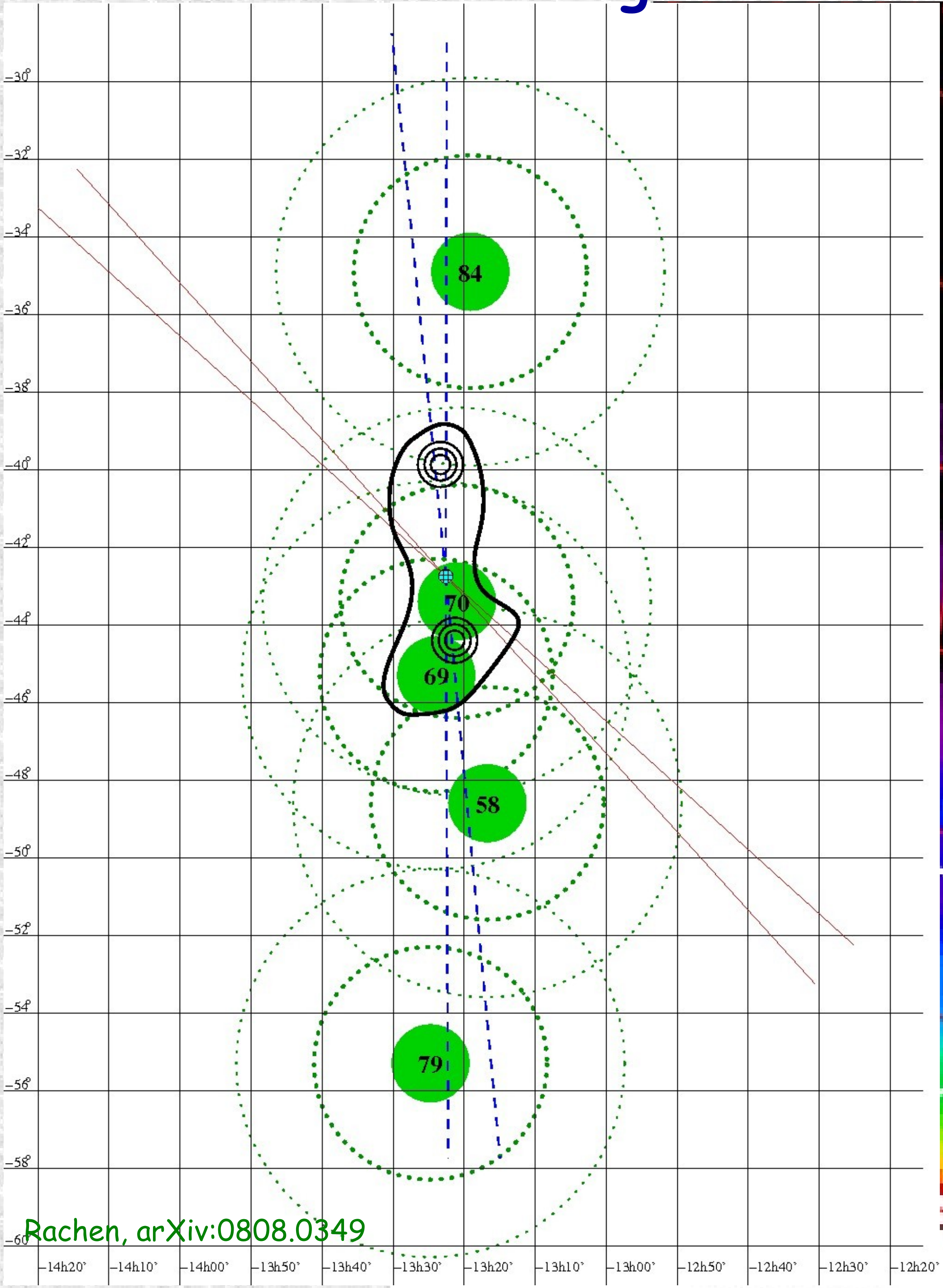


Centaurus A as a possible local UHECR source

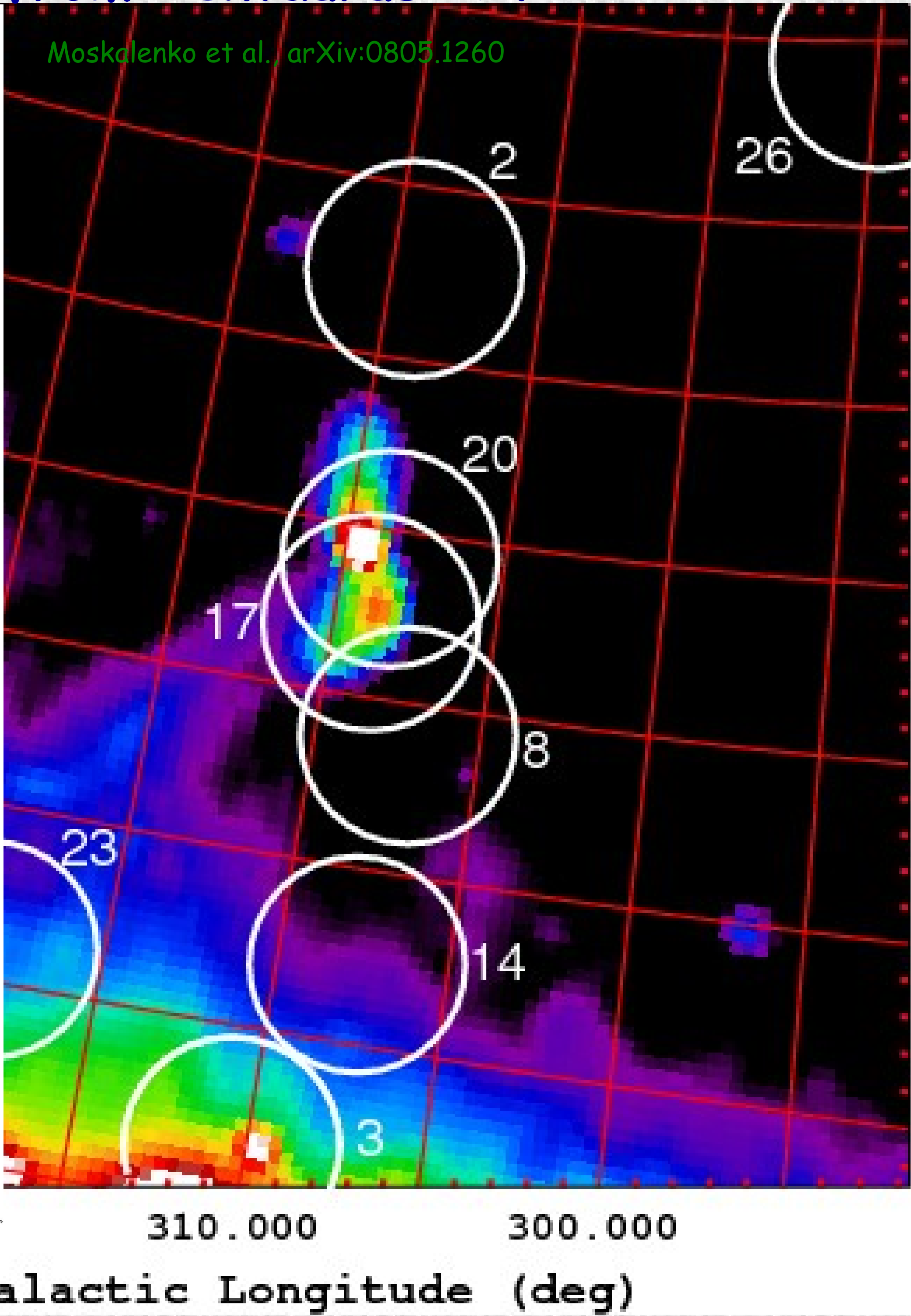


Stanev, arXiv:0805.1746

Pierre Auger events from Centaurus A ?

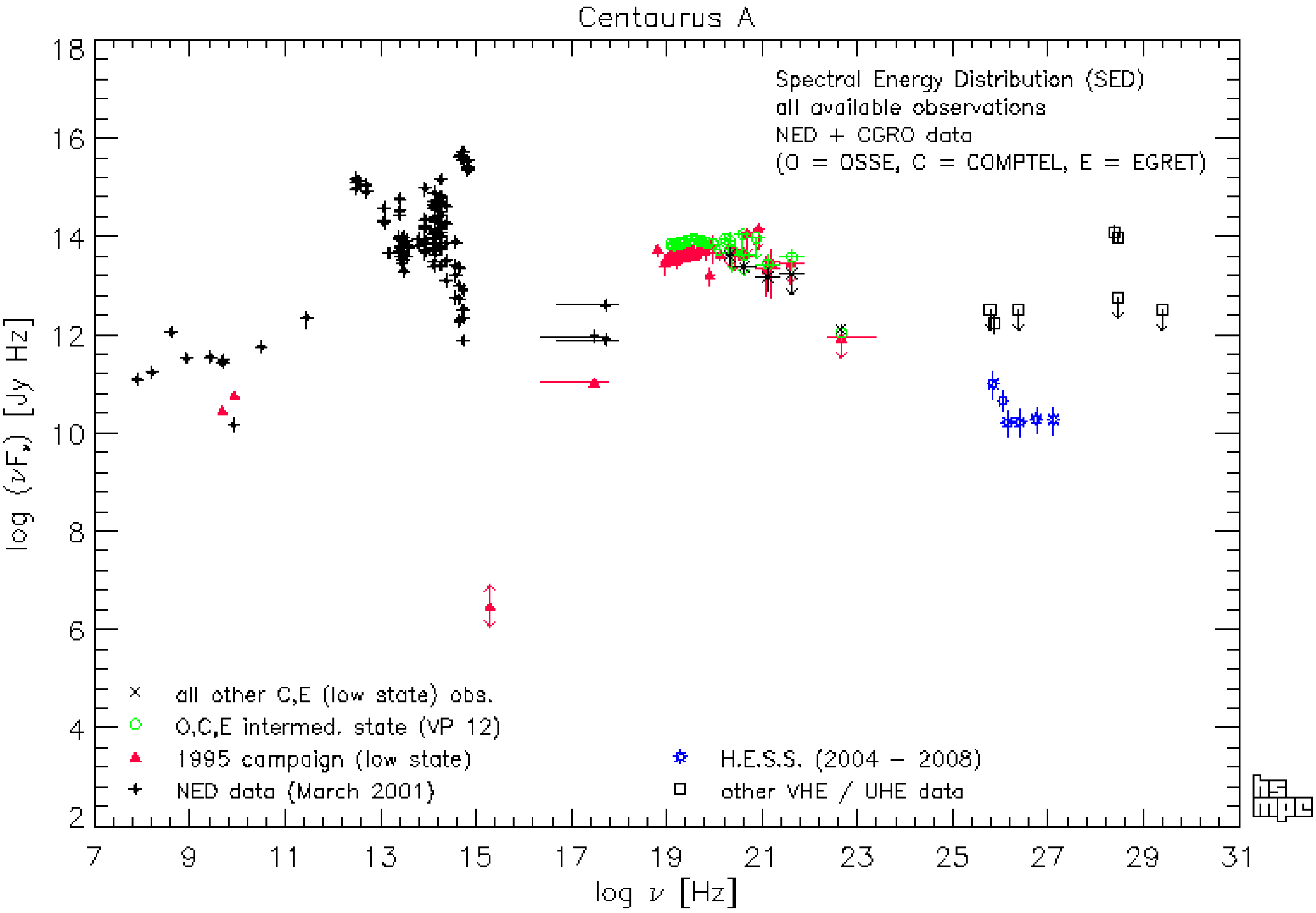


Rachen, arXiv:0808.0349

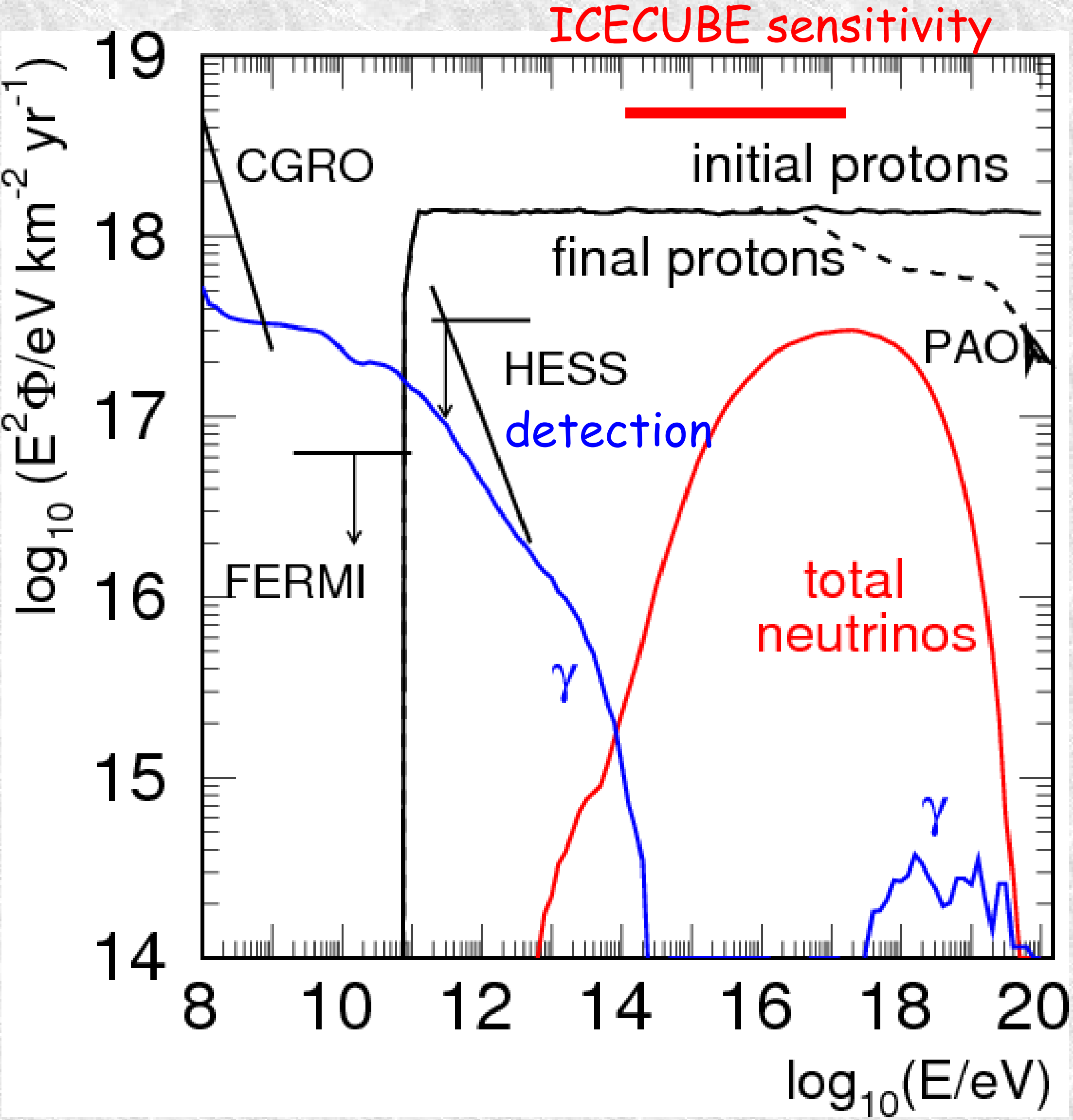


Moskalenko et al., arXiv:0805.1260

Centaurus A was recently seen by H.E.S.S.



Centaurus A as Multimessenger Source



E^{-2} acceleration of protons around the core E^{-2} acceleration of protons in the jet

Kachelriess, Ostapchenko, Tomas, arXiv:0805.2608

Testing Neutrino Properties with Astrophysical Neutrinos

- Oscillation parameters, source physics, neutrino decay and decoherence
- Collective effects in supernova neutrino oscillations
- Neutrino-nucleon cross sections
- Quantum Gravity effects

For n neutrino flavors, eigenstates $\left|\nu_i\right\rangle$ of mass m_i and interaction eigenstates $\left|\nu_\alpha\right\rangle$ are related by a unitary $n\times n$ matrix U:

$$\left|\nu_\alpha\right\rangle = \sum_i U_{\alpha i}\left|\nu_i\right\rangle$$

If at $t=0$ a flavor eigenstate $\left|\nu_\alpha\right\rangle = \sum_i U_{\alpha i}\left|\nu_i\right\rangle$ is produced in an interaction, in vacuum the time development will thus be

$$\left|\nu(t)\right\rangle = \sum_i U_{\alpha i}\, e^{-iE_i t}\left|\nu_i\right\rangle = \sum_{i,\beta} U_{\alpha i}\, U^*_{\beta i}\, e^{-iE_i t}\left|\nu_\beta\right\rangle .$$

This implies the following transition probabilities

$$P(\nu_\alpha \rightarrow \nu_\beta) = \left|\sum_i U_{\alpha i}\, U^*_{\beta i}\, e^{-iE_i t}\right|^2$$

For flavors α injected with relative weights w_α at the source,the flux of flavor β at the observer is then (averaged over the oscillations)

$$\phi_\beta(E) \;\propto\; \sum_\alpha w_\alpha P(\nu_\alpha \rightarrow \nu_\beta) \;\simeq\; \sum_{\alpha,i} w_\alpha \left|U_{\alpha i}\right|^2 \left|U_{\beta i}\right|^2 .$$

Examples for standard mixing parameters:

Sensitivity to source physics: When both pions and muons decay before loosing energy, then $w_e : w_\nu : w_\tau \simeq \frac{1}{3} : \frac{2}{3} : 0$ and thus $\phi_e : \phi_\mu : \phi_\tau \simeq \frac{1}{3} : \frac{1}{3} : \frac{1}{3}$

If pions but not muons decay before loosing energy then $w_e : w_\mu : w_\tau \simeq 0 : 1 : 0$ and thus $\phi_e : \phi_\mu : \phi_\tau \simeq \frac{1}{5} : \frac{2}{5} : \frac{2}{5}$

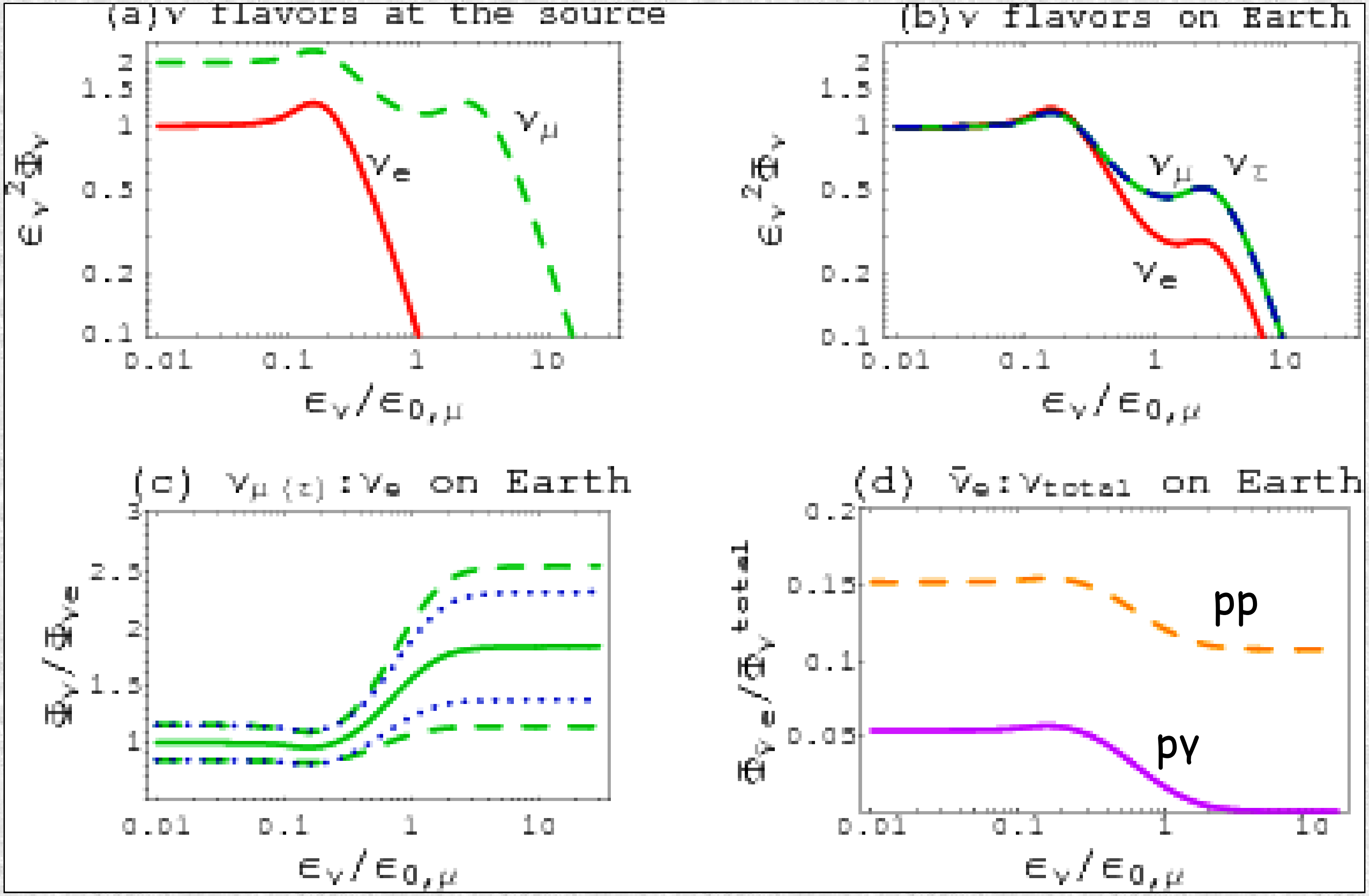
For unstable mass eigenstates introduce a factor $\exp\left[-(m_i/\tau_i)(t/E)\right]$.

In normal hierarchy if ν_2 and ν_3 decay completely, then $\phi_e : \phi_\mu : \phi_\tau \simeq \frac{3}{4} : \frac{1}{8} : \frac{1}{8}$

In inverted hierarchy if ν_1 and ν_2 decay completely, then $\phi_e : \phi_\mu : \phi_\tau \simeq 0 : \frac{1}{2} : \frac{1}{2}$

For quantum decoherence on scales smaller than t one always has $\phi_e : \phi_\mu : \phi_\tau \simeq \frac{1}{3} : \frac{1}{3} : \frac{1}{3}$

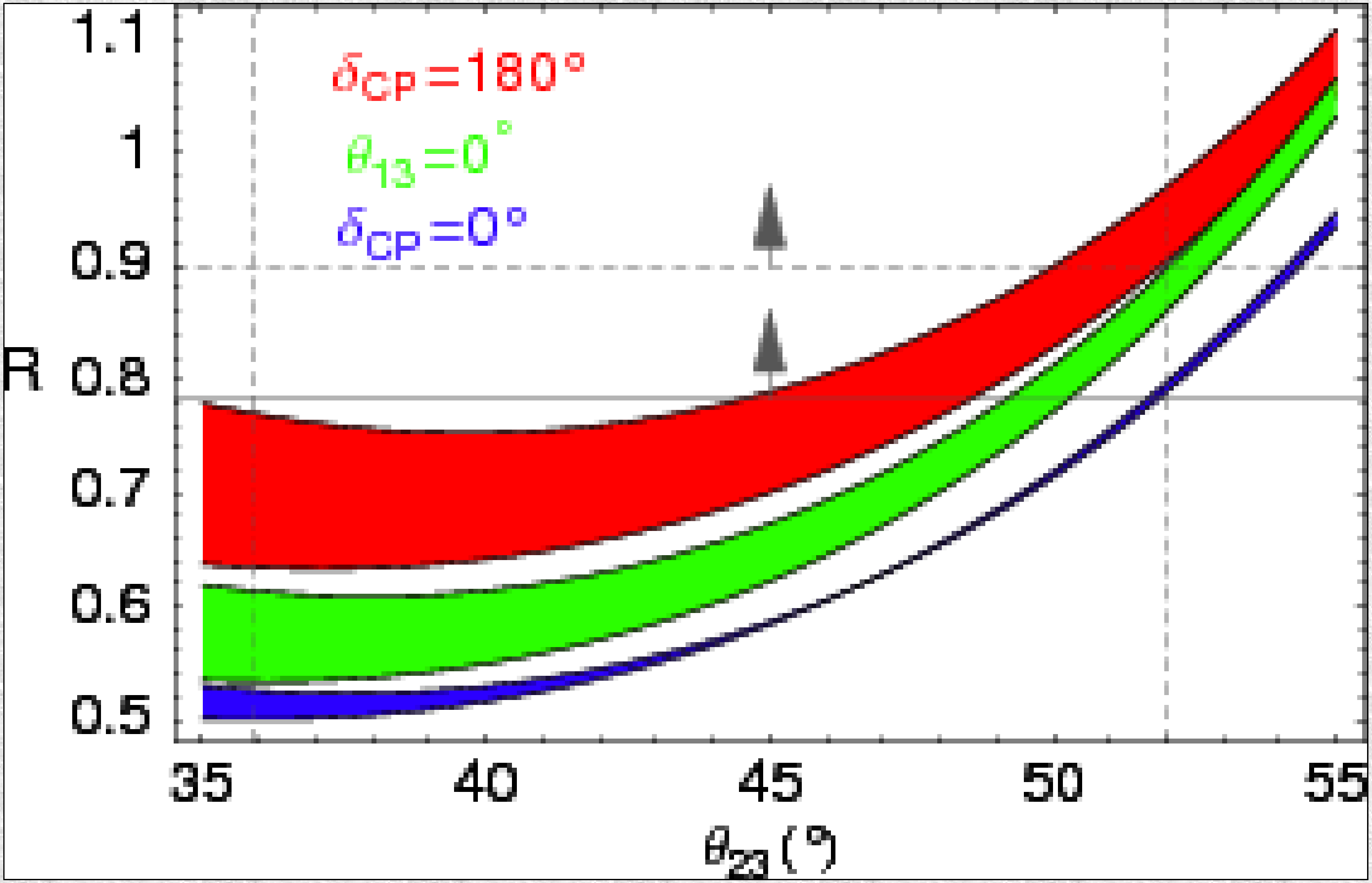
Observed Flavor Ratios can be sensitive to source physics



Kashti and Waxman, Phys.Rev.Lett. 95 (2005) 181101

Injection of pions of energy ϵ_π with spectrum $\propto \epsilon_\pi^{-2}$ with energy losses $\dot{\epsilon}_\pi \propto \epsilon_\pi^2$.
$\epsilon_{0,\mu}$ is the energy at which decay equals synchrotron loss.

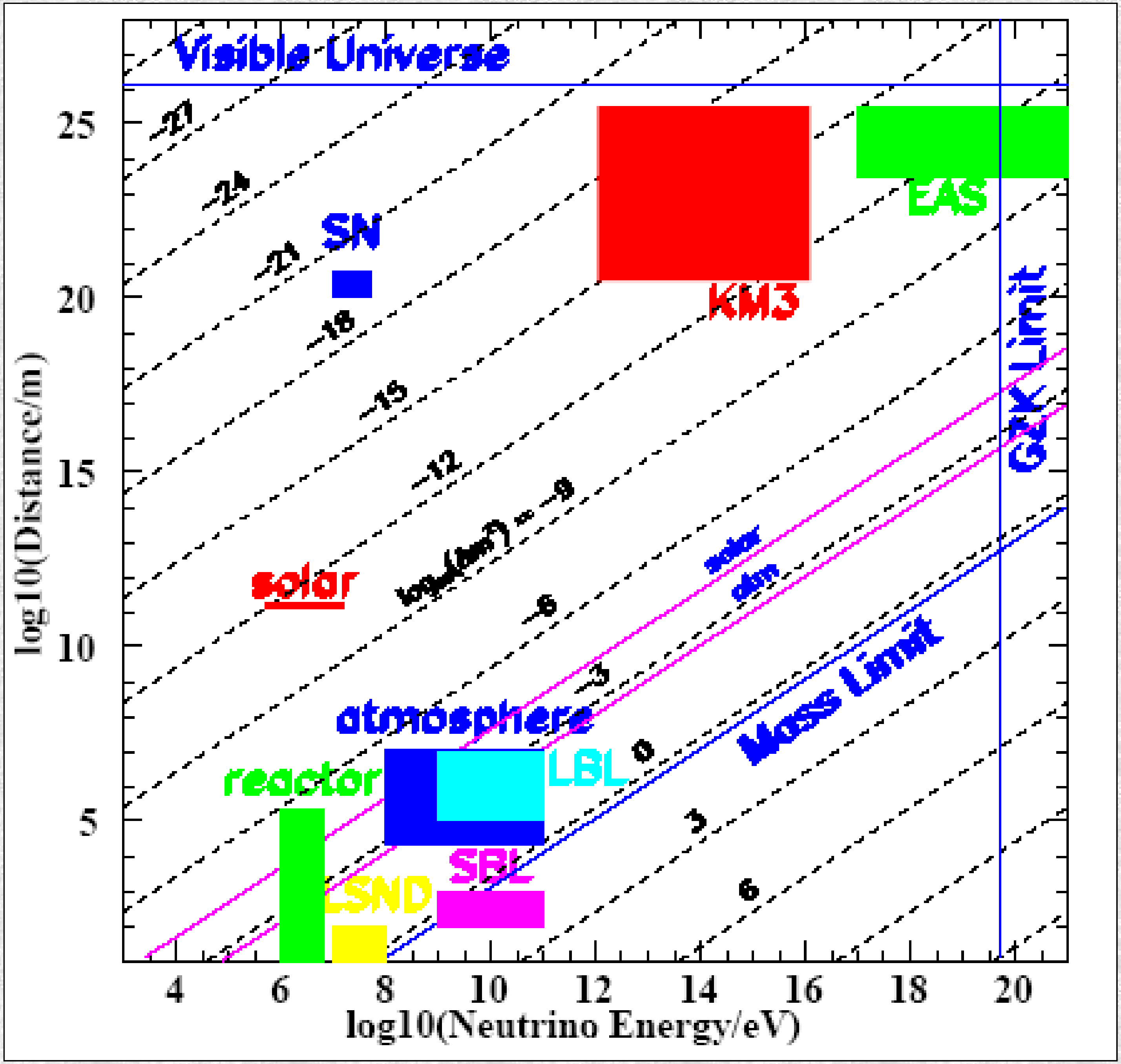
Observed Muon to Non-Muon Ratios can be sensitive to oscillation parameters



For a source optically thick to muons but not to pions: Pions decay right away, but muons loose energy by synchro before decaying

Serpico, Phys.Rev.D 73 (2006) 047301

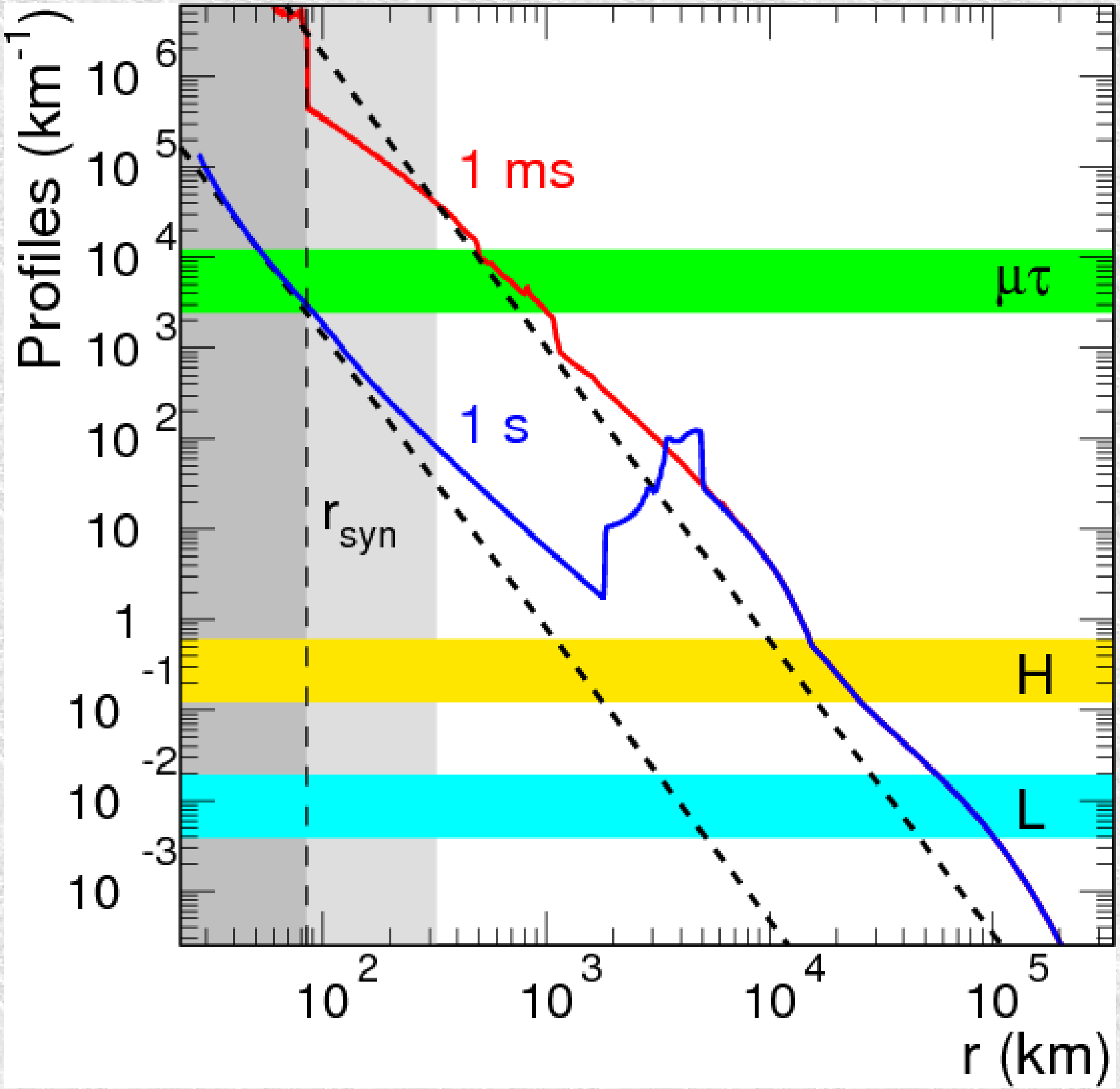
Sensitivity of astrophysical neutrinos to oscillations: The Learned Plot



Oscillation phase is
($L \Delta m^2 / 4 E_n$)
Numbers indicate
$\Delta m^2/eV^2$.

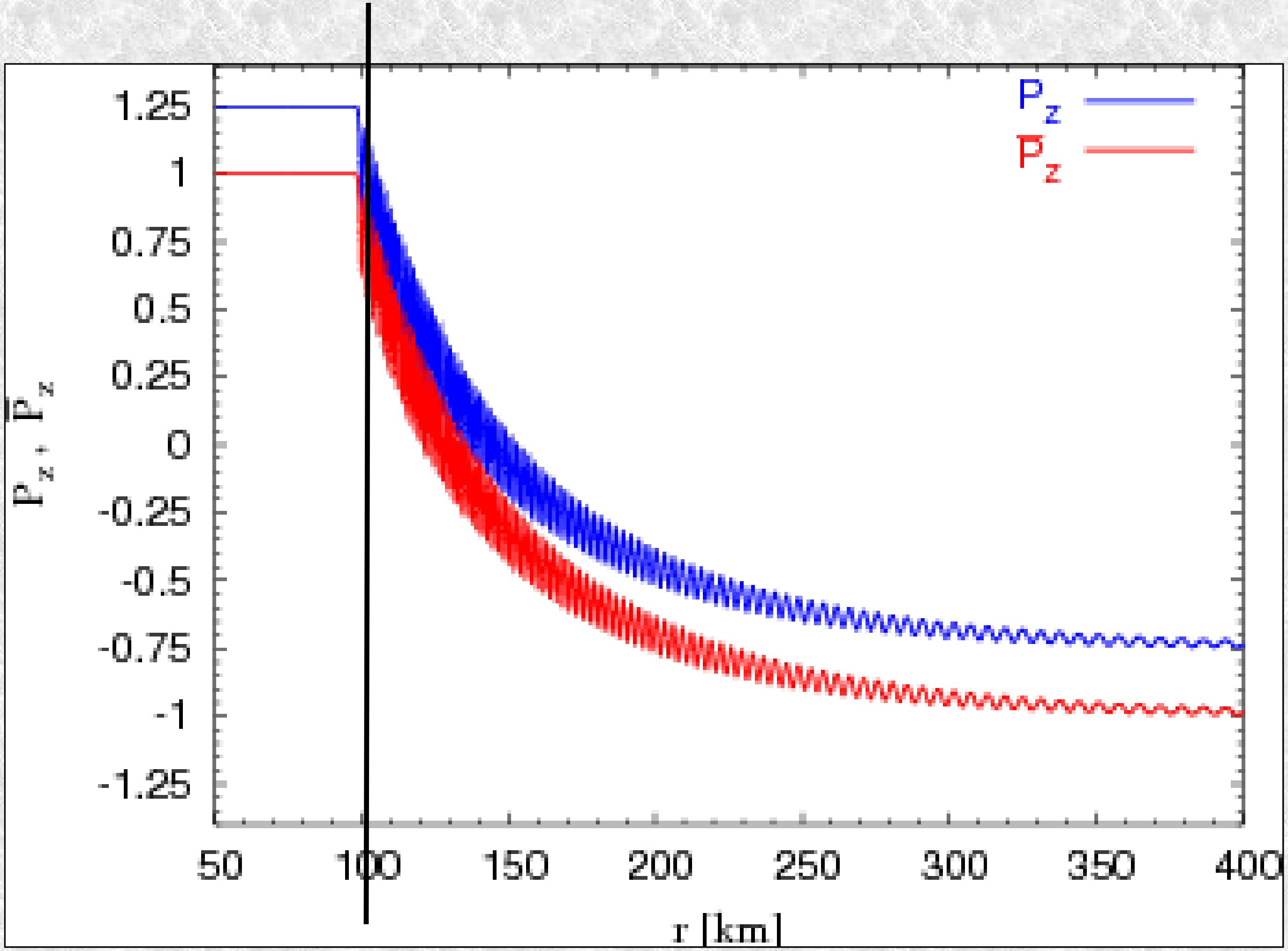
Collective Neutrino Oscillations in Supernovae

In a supernova neutrino self-interactions contribute to the refractive index
Which leads to interesting collective effects:



Most relevant are the (unknown) atmospheric hierarchy Δm_{atm}^2 and Θ_{13}

Schematic example for the inverted hierarchy



$$P_z = \frac{F(\nu_e) - F(\nu_x)}{F_0(\bar{\nu}_e) - F_0(\bar{\nu}_x)}$$

$$\bar{P}_z = \frac{F(\bar{\nu}_e) - F(\bar{\nu}_x)}{F_0(\bar{\nu}_e) - F_0(\bar{\nu}_x)}.$$

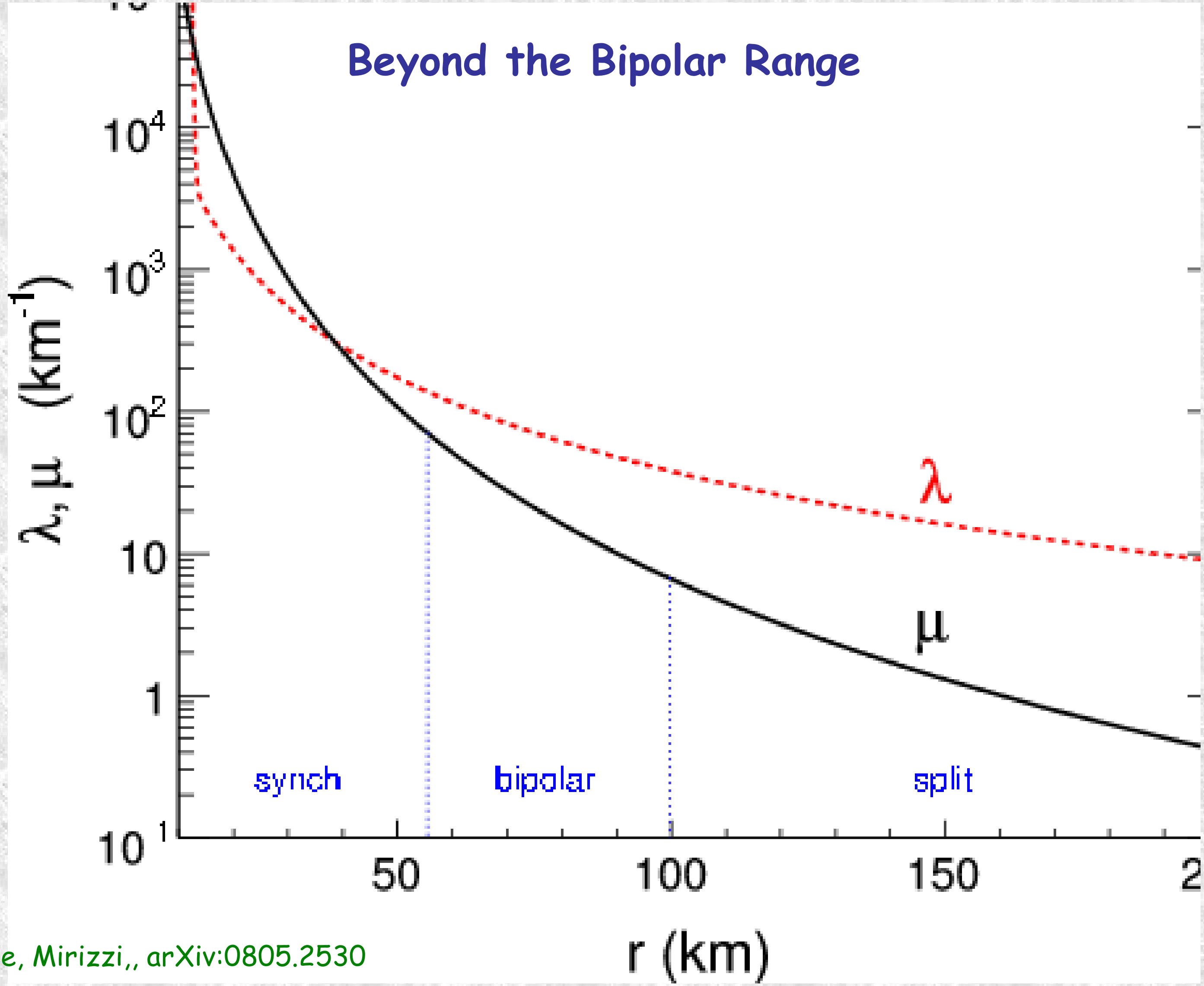
synchronized bipolar

for the inital flux hierarchy $F_0(\nu_e) > F_0(\bar{\nu}_e) > F_0(\nu_x) = F_0(\bar{\nu}_x)$

corresponding to initial energy hierarchy $\langle \epsilon_0(\nu_e)\rangle > \langle \epsilon_0(\bar{\nu}_e)\rangle > \langle \epsilon_0(\nu_x)\rangle = \langle \epsilon_0(\bar{\nu}_x)\rangle$

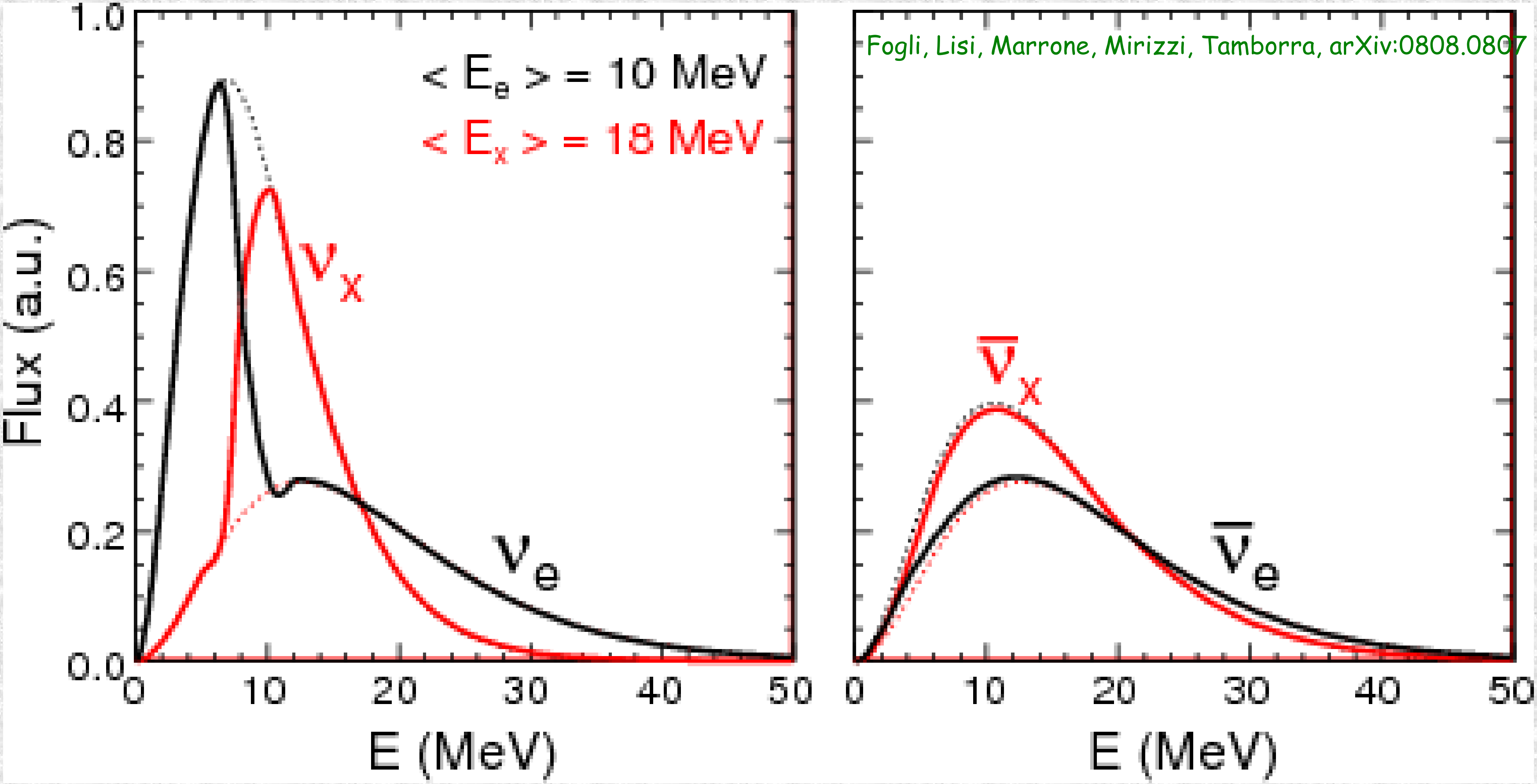
Note: In inverted hierarchy, bipolar oscillations occur for arbitrarily small Θ_{13}.

This can be used as experimental test by observing a supernova with mega-ton detectors that are mostly sensitive to electron-antineutrinos



Fogli, Lisi, Marrone, Mirizzi,, arXiv:0805.2530

Energy Modes and Spectral Splits



Fogli, Lisi, Marrone, Mirizzi, Tamborra, arXiv:0808.0807

The spectral split is governed by lepton number conservation for both flavors separately:

Anti-neutrinos swap completely; to compensate, neutrinos can only swap partially because

$$\left|F(\nu_x)-F(\nu_e)\right|>\left|F(\bar{\nu}_x)-F(\bar{\nu}_e)\right|$$

$$\bar{\nu}_e + p \rightarrow n + e^+$$

Following Dasgupta, Dighe, Mirizzi,, arXiv:0802.1481
relate fluxes $F(\bar{\nu}_e)$ at detector to fluxes $F_0(\bar{\nu}_e)$ at neutrino-sphere:
No swapping of $\bar{\nu}_e$ and $\bar{\nu}_\tau{}'$ if either normal hierarchy or inverted hierarchy with $\sin^2\theta_{13} \geq 10^{-3}$ (such that bipolar transition followed by adiabatic MSW):

$$F(\bar{\nu}_e) \approx \cos^2\theta_{12} F_0(\bar{\nu}_e) + \sin^2\theta_{12} F_0(\bar{\nu}_\mu{}')$$

Swapping of $\bar{\nu}_e$ and $\bar{\nu}_\tau{}'$ if inverted hierarchy with $\sin^2\theta_{13} \leq 10^{-5}$ (such that bipolar transition followed by non-adiabatic MSW) with $F_0(\bar{\nu}_\tau{}') = F_0(\bar{\nu}_\mu{}')$:

$$F(\bar{\nu}_e) \approx \cos^2\theta_{12} F_0(\bar{\nu}_\tau{}') + \sin^2\theta_{12} F_0(\bar{\nu}_\mu{}') = F_0(\bar{\nu}_\tau{}')$$

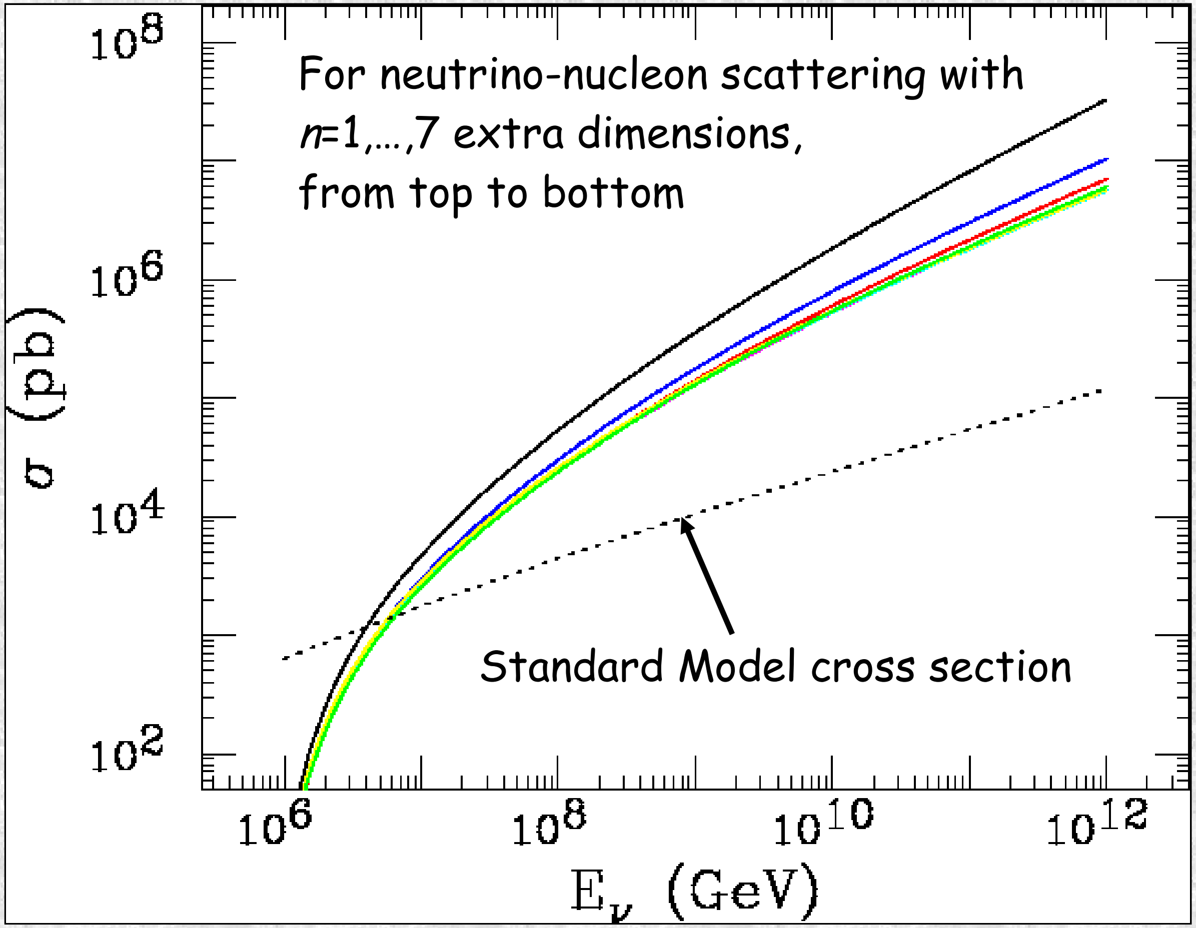
For Earth matter effects $\cos^2\theta_{12} \rightarrow P(\bar{\nu}_\mu{}' \rightarrow \bar{\nu}_e)$

Probes of Neutrino Interactions beyond the Standard Model

Note: For primary energies around 10^{20} eV:

- Center of mass energies for collisions with relic backgrounds
  ~100 MeV – 100 GeV —> physics well understood
- Center of mass energies for collisions with nucleons in the atmosphere
  ~100 TeV – 1 PeV —> probes physics beyond reach of accelerators

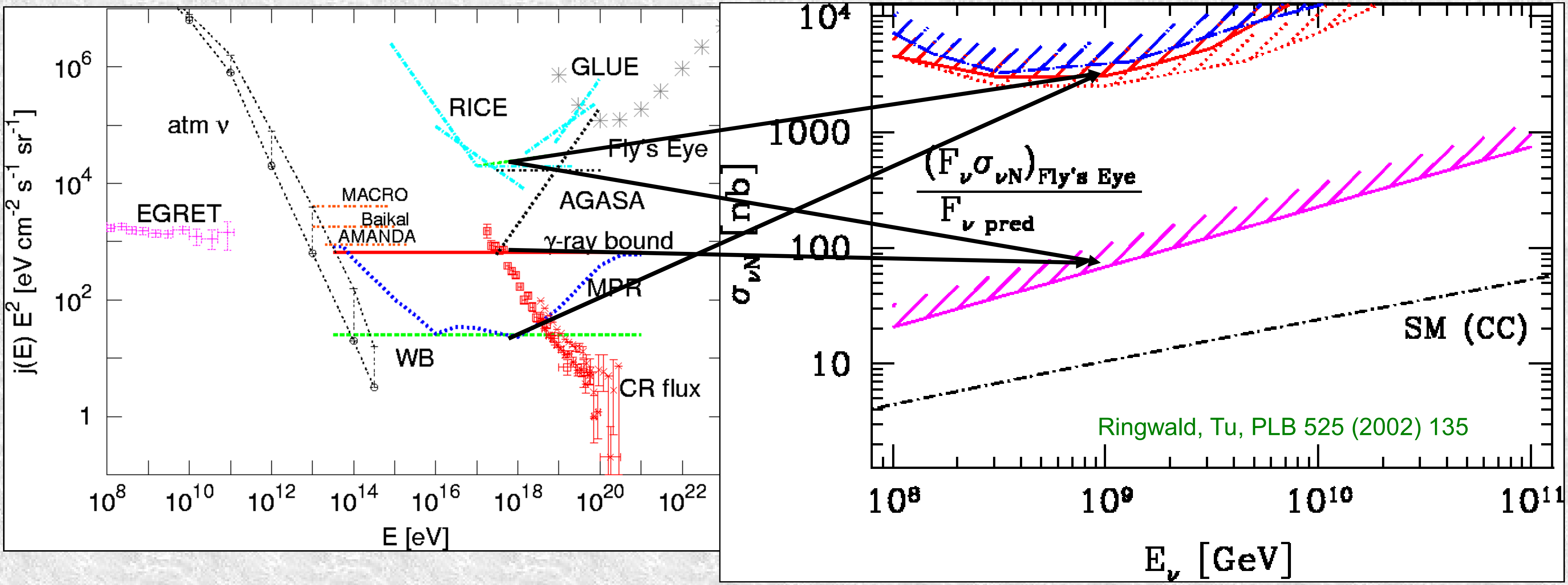
Example: microscopic black hole production in scenarios with a TeV string scale:



Feng, Shapere, PRL 88 (2002) 021303

This increase is not sufficient to explain the highest energy cosmic rays, but can be probed with deeply penetrating showers.

However, the neutrino flux from pion-production of extra-galactic trans-GZK cosmic rays allows to put limits on the neutrino-nucleon cross section:



Ringwald, Tu, PLB 525 (2002) 135

Comparison of this Nγ- (“cosmogenic”) flux with the non-observation of horizontal air showers results in the present upper limit about 10^3 above the Standard Model cross section.

Future experiments will either close the window down to the Standard Model cross section, discover higher cross sections, or find sources beyond the cosmogenic flux. How to disentangle new sources and new cross sections?

Solution: Compare rates of different types of neutrino-induced showers

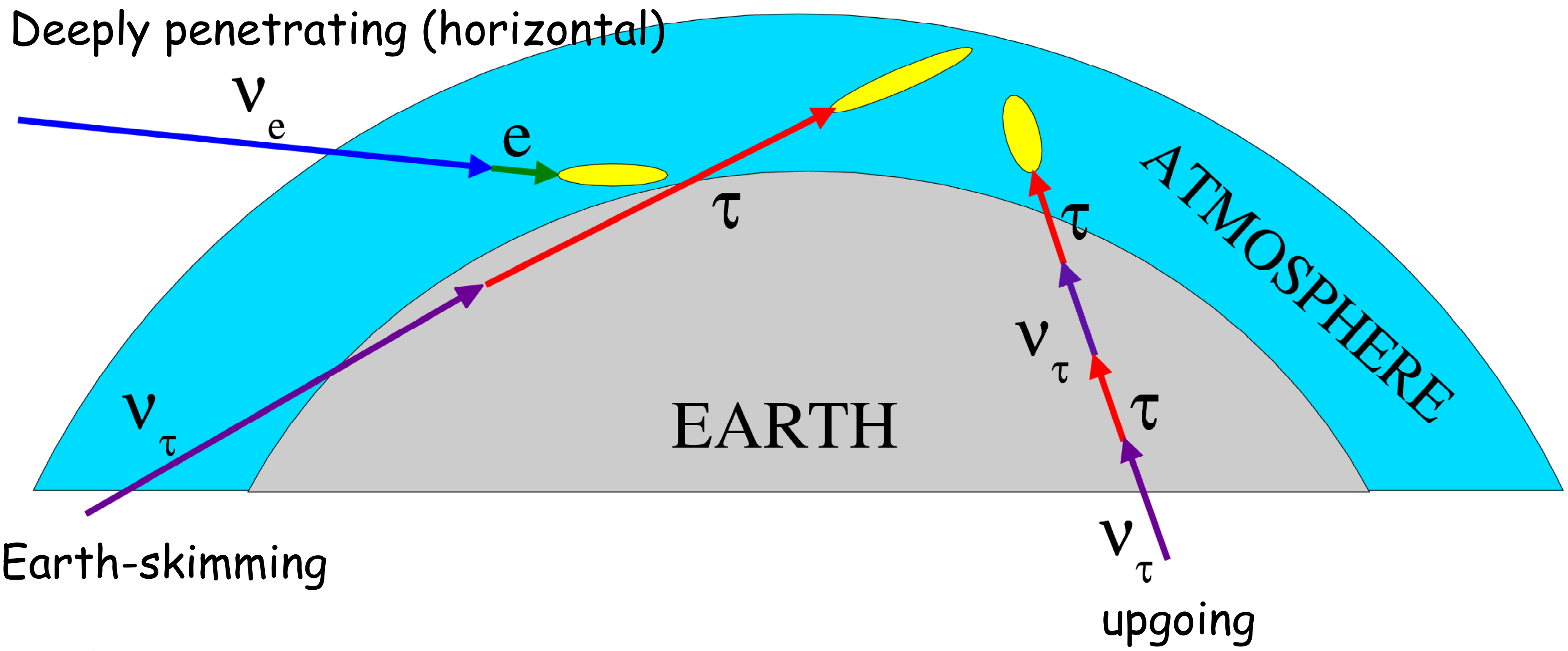
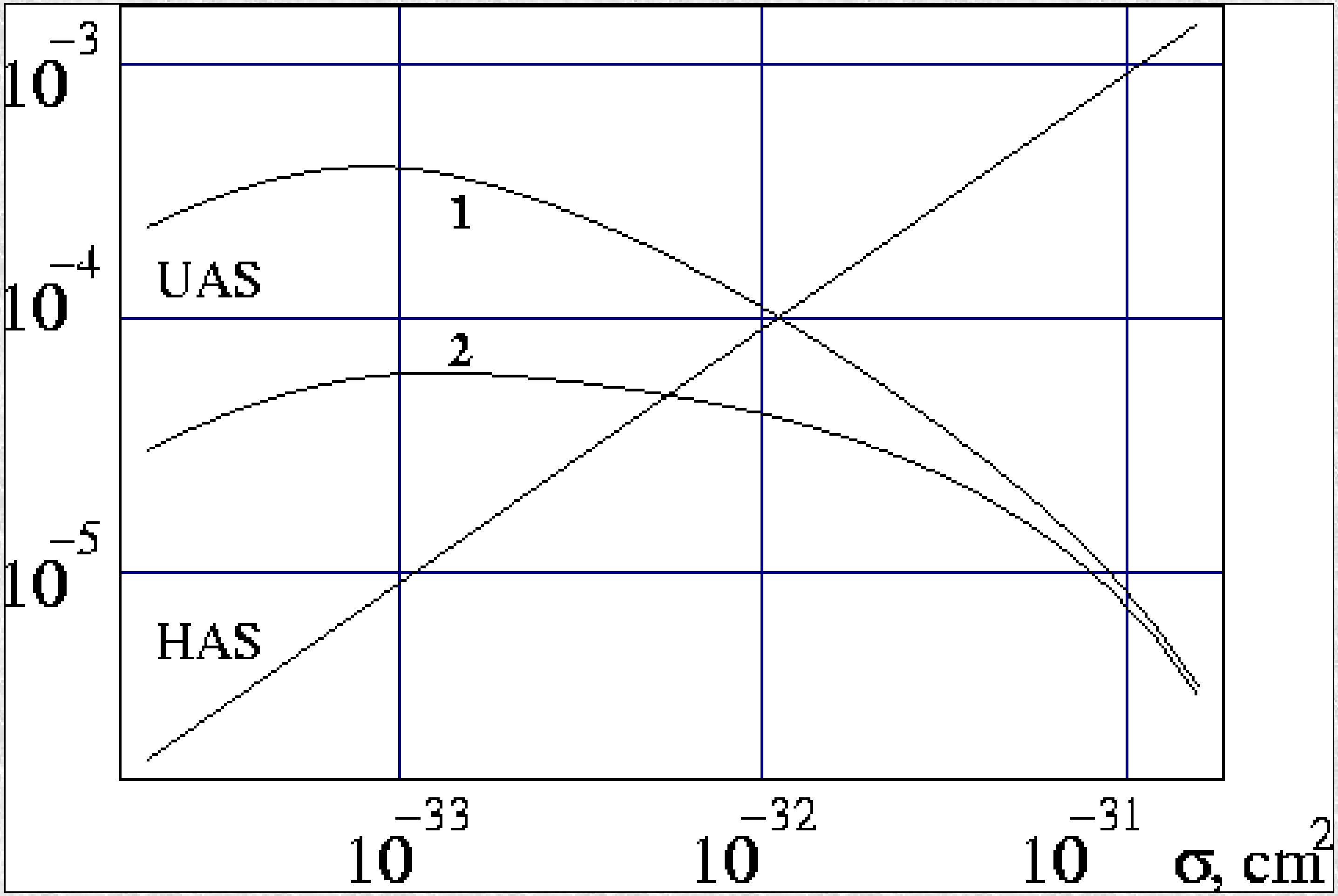


Figure from Cusumano

Earth-skimming τ-neutrinos



Air-shower probability per τ-neutrino at 10^{20} eV for 10^{18} eV (1) and 10^{19} eV (2) threshold energy for space-based detection.

Comparison of earth-skimming and horizontal shower rates allows to measure the neutrino-nucleon cross section in the 100 TeV range.

Kusenko, Weiler, PRL 88 (2002) 121104

Probes of Quantum Gravity Effects with Neutrinos

Dispersion relation between energy E, momentum p, and mass m may be modified by non-renormalizable effects at the Planck scale M_{Pl},

$$p^2 + m^2 = E^2\left[1 - \sum_{n=1}^{\infty} \eta_n \left(\frac{E}{m_{\mathrm{Pl}}}\right)^n\right]$$

where most models, e.g. critical string theory, predict η=0 for lowest order.

For the i-th neutrino mass eigenstate this gives

$$p_i \approx E + \frac{m_i^2}{2E} + \frac{1}{2}\sum_{n=1}^{\infty} \eta_n^{(i)} \frac{E^{n+1}}{m_{\mathrm{Pl}}}$$

The « standard » oscillation term becomes comparable to the new terms at energies

$$E \approx m_{\mathrm{Pl}}\left(\frac{\Delta m^2}{m_{\mathrm{Pl}}^2 \eta_n}\right)^{\frac{1}{n+2}} \approx 0.2\,,\, 2\mathrm{x}10^4\,,\, 1.8\mathrm{x}10^7\,,\, 1.7\mathrm{x}10^9\ \mathrm{GeV}$$

for n=1, 2, 3, 4, respectively, and $\Delta m^2 = 10^{-3}$ eV², for which ordinary Oscillation length is ~2.5(*E*/MeV) km.

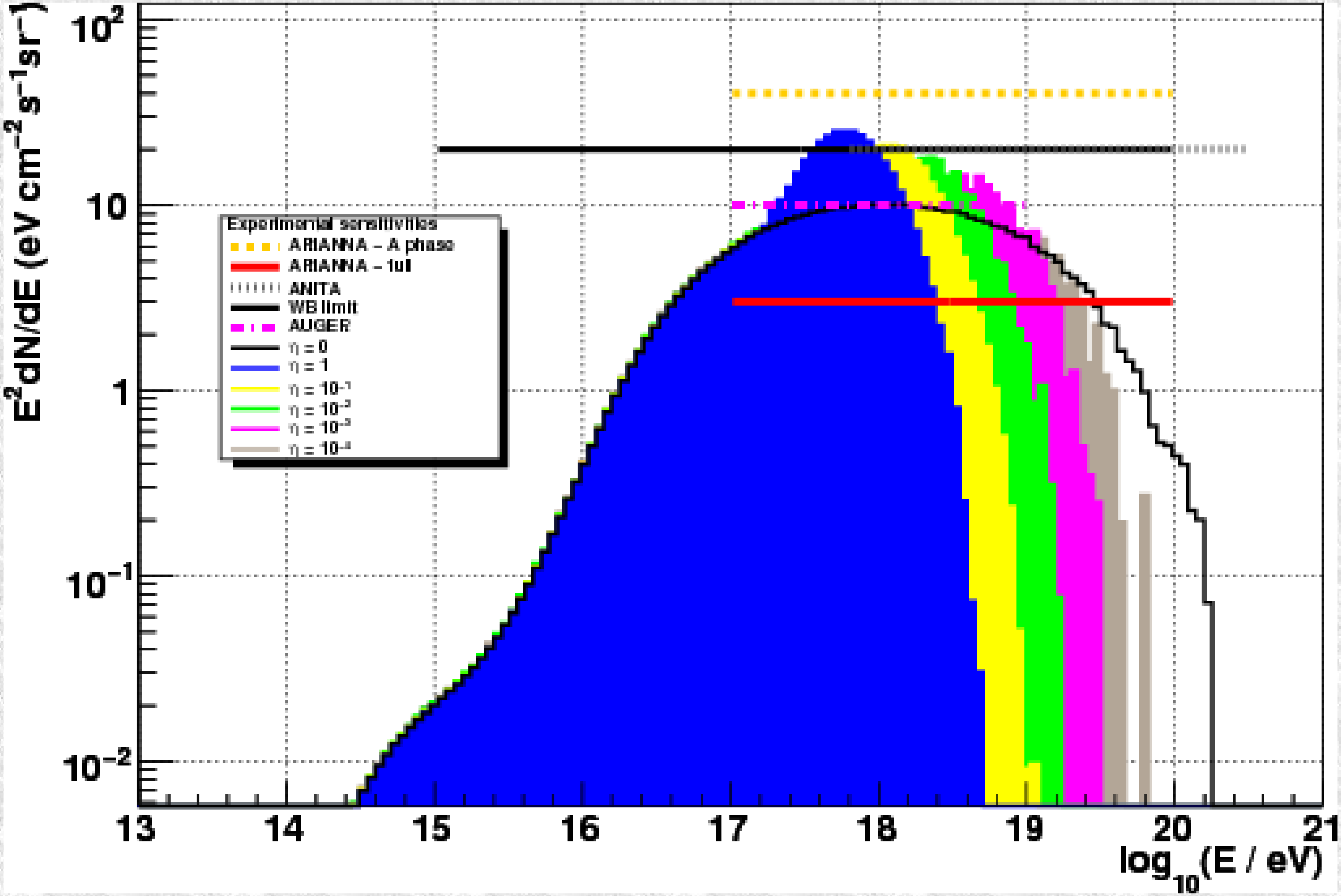
See, e.g., Christian, Phys.Rev.D71 (2005) 024012

Other possible effects: Decoherence of oscillation amplitude with $\exp(-\alpha L)$:
Assume galactic neutron sources, L~10 kpc, giving exclusively electron-anti-neutrinos before oscillation. After oscillation the flavor ratio becomes 1:0:0 -> 0.56:0.24:0.20 without decoherence, but 0.33:0.33:0.33 with decoherence.

At E~1 TeV one has a sensitivity of $\alpha \sim 10^{-37}$ GeV (somewhat dependent on energy dependence of α)

Hooper, Morgan, Winstanley, Phys.Lett.B609 (2005): 206

Modification of GZK neutrino flux by Lorentz Invariance Variation



Mattingly et al., arXiv:0911.0521

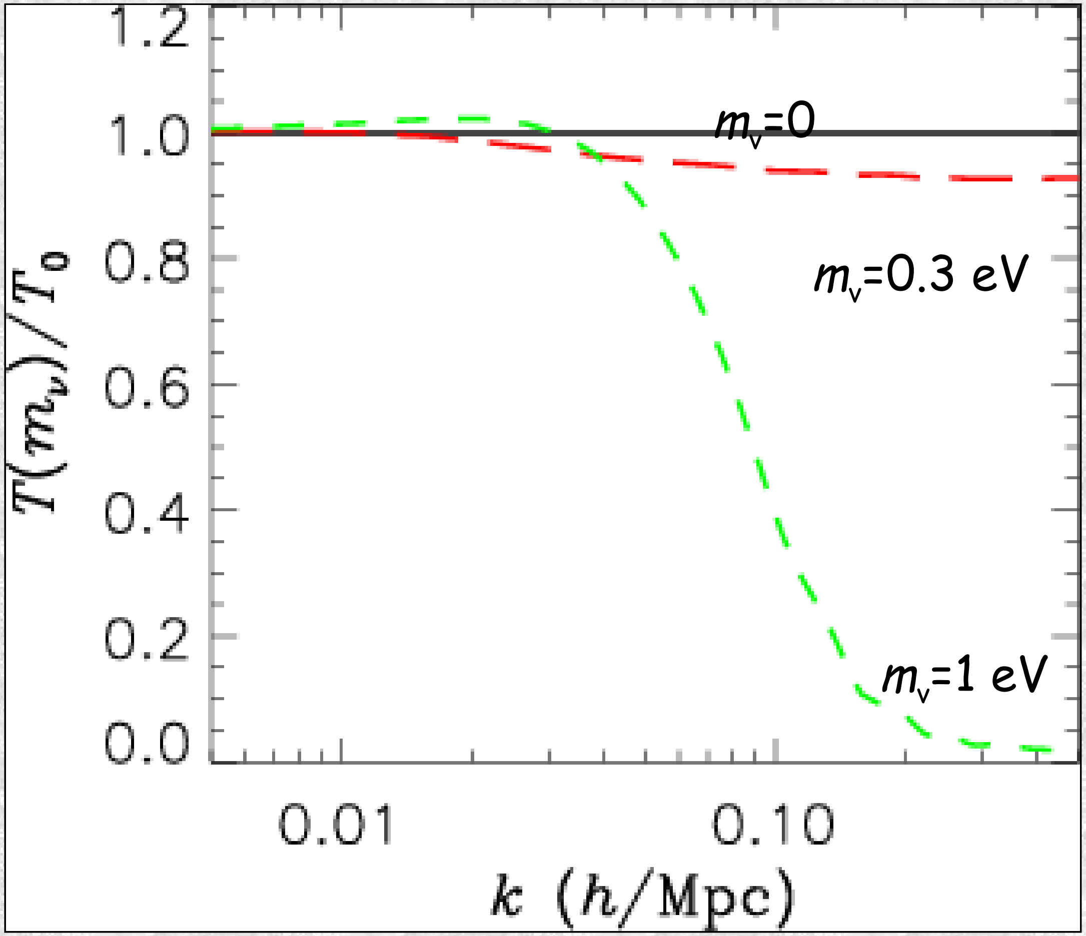
Example: If a neutrino with energy E_{obs} is observed, the constraint

$$\eta_2 \leq \left(\frac{E_{\mathrm{obs}}}{6 \times 10^{18}\,\mathrm{eV}} \right)^{-13/4}$$

results, otherwise neutrino would decay on short length scale

Testing Neutrino Properties with Cosmology

- Cosmological Structure Formation and Neutrino Mass



The transfer function determines power spectrum at small (Mpc) scales

Hannestad, astro-ph/0602058

The fact that freely streaming neutrinos suppress the large scale galaxy power $\Delta P_m/P_m = -8\Omega_\nu/\Omega_m$ allows to put a (somewhat model dependent) limit on the sum of neutrino masses

Future weak lensing surveys (cosmic shear) are expected to bring sensitivity down to the 0.05 eV level.

Some Recent Cosmological Limits on Neutrino Masses

	Σm_ν/eV (limit 95%CL)	Data / Priors
Hannestad 2003 [astro-ph/0303076]	1.01	WMAP-1, CMB, 2dF, HST
Spergel et al. (WMAP) 2003 [astro-ph/0302209]	0.69	WMAP-1, 2dF, HST, σ_8
Crotty et al. 2004 [hep-ph/0402049]	1.0 0.6	WMAP-1, CMB, 2dF, SDSS & HST, SN
Hannestad 2004 [hep-ph/0409108]	0.65	WMAP-1, SDSS, SN Ia gold sample, Ly-α data from Keck sample
Seljak et al. 2004 [astro-ph/0407372]	0.42	WMAP-1, SDSS, Bias, Ly-α data from SDSS sample
Hannestad et al. 2006 [hep-ph/0409108]	0.30	WMAP-1, CMB-small, SDSS, 2dF, SN Ia, BAO (SDSS), Ly-α (SDSS)
Spergel et al. 2006 [hep-ph/0409108]	0.68	WMAP-3, SDSS, 2dF, SN Ia, σ_8
Seljak et al. 2006 [astro-ph/0604335]	0.14	WMAP-3, CMB-small, SDSS, 2dF, SN Ia, BAO (SDSS), Ly-α (SDSS)

after G. Raffelt

Conclusions1

1.) Pion-production establishes a very important link between the physics of high energy cosmic rays on the one hand, and γ-ray and neutrino astrophysics on the other hand.

2.) There are many potential high energy neutrino sources including speculative ones. But the only guaranteed ones are due to pion production of primary cosmic rays known to exist: Galactic neutrinos from hadronic interactions up to $\sim 10^{16}$ eV and "cosmogenic" neutrinos around 10^{19} eV from photopion production. Good experimental prospects to detect them in near future

3.) Flavor composition of ultra-high energy neutrinos can test the source physics as well as possibly physics beyond the Standard Model

4.) Collective supernova neutrino oscillations probe the neutrino mass hierarchy

Conclusions2

5.) At energies above ~10^{18} eV, the center-of mass energies are above a TeV and thus beyond the reach of accelerator experiments. Especially in the neutrino sector, where Standard Model cross sections are small, this probes potentially new physics beyond the electroweak scale, including possible quantum gravity effects.

6.) Cosmological relic neutrinos are a very sensitive probe for the neutrino mass