Ultra-High Energy Neutrinos and Fundamental Tests

- A short introduction to primary cosmic rays
- Diffuse and point source fluxes of gamma-rays and neutrinos
- Neutrino flux sensitivities, detection techniques, and neutrino cross sections
- Testing neutrino properties with astrophysical neutrinos

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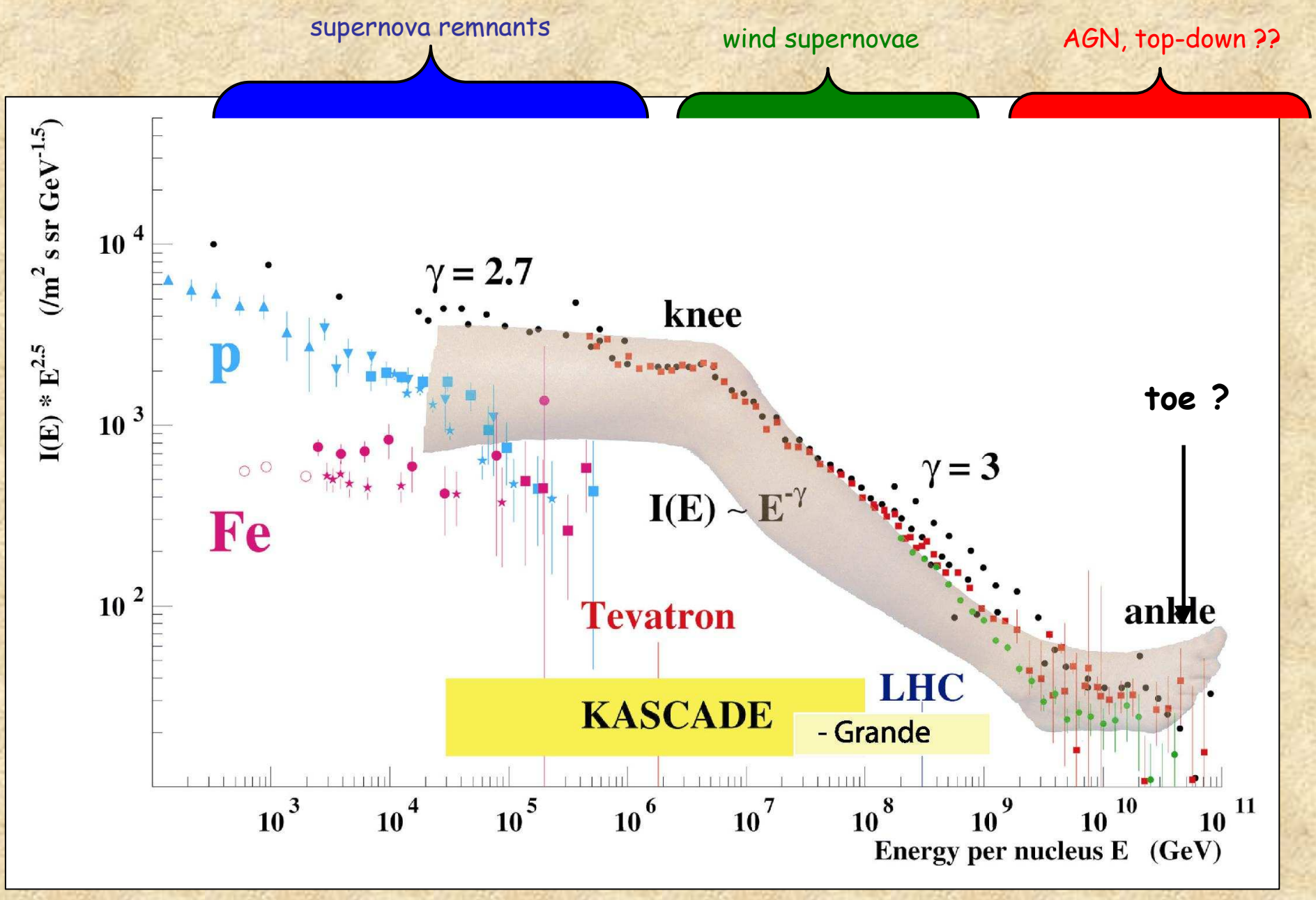
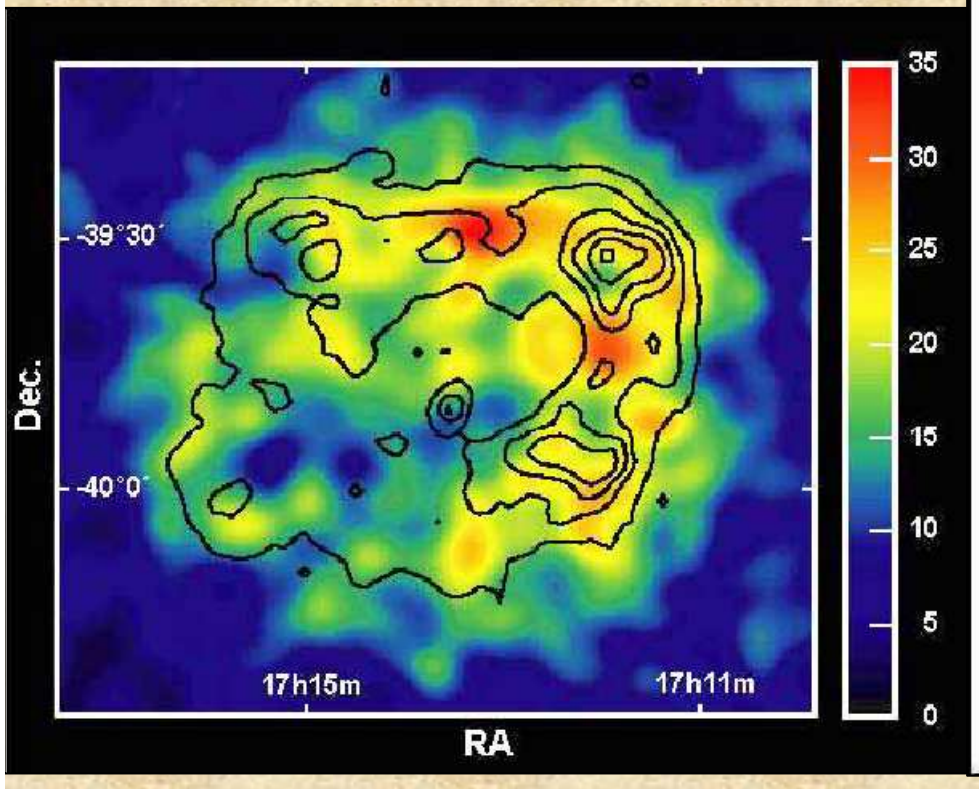
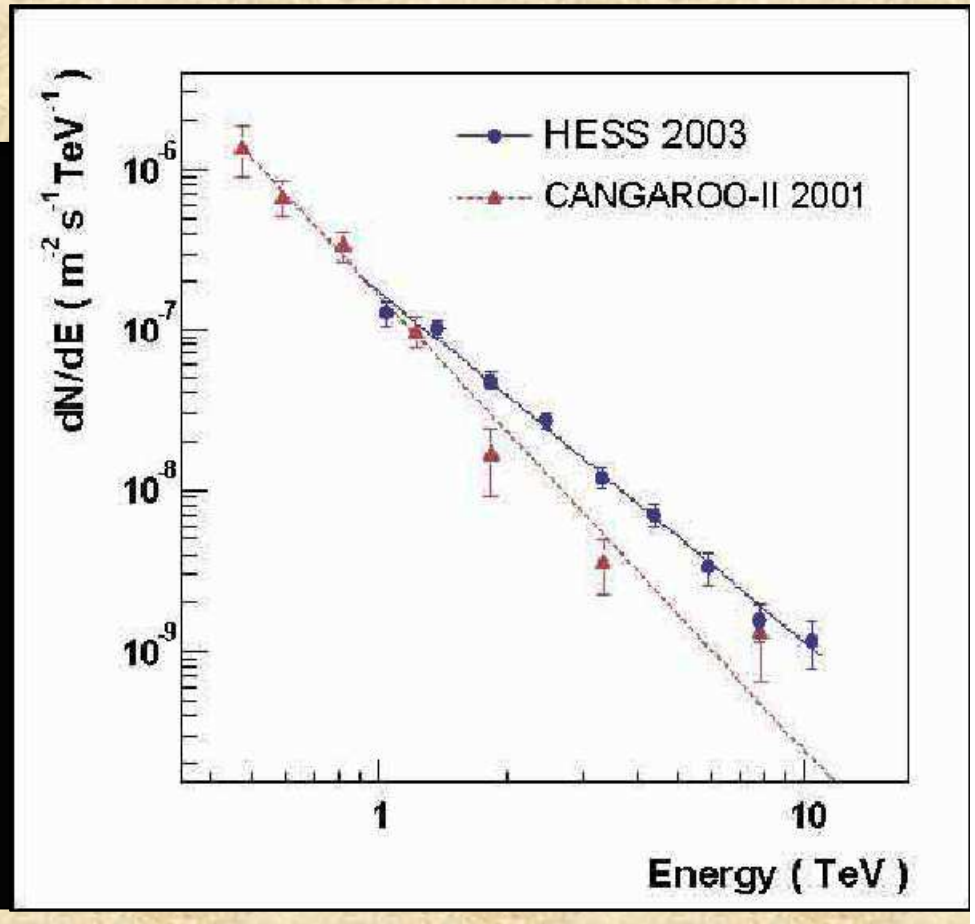
http://www2.iap.fr/users/sigl/homepage.html

The structure of the spectrum and scenarios of its origin



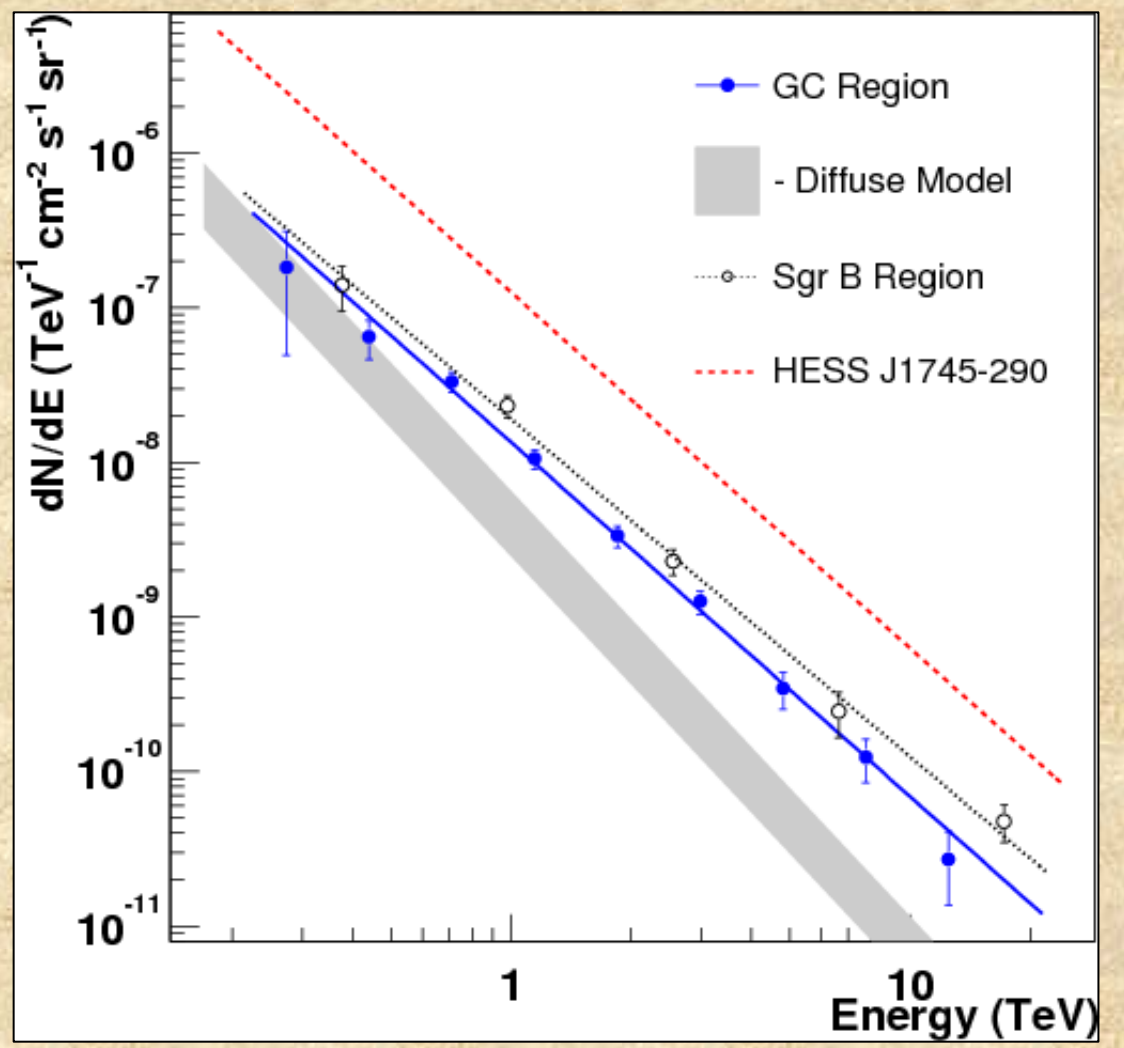
Supernova Remnants and Galactic Cosmic and γ-Rays





Aharonian et al., Nature 432 (2004) 75

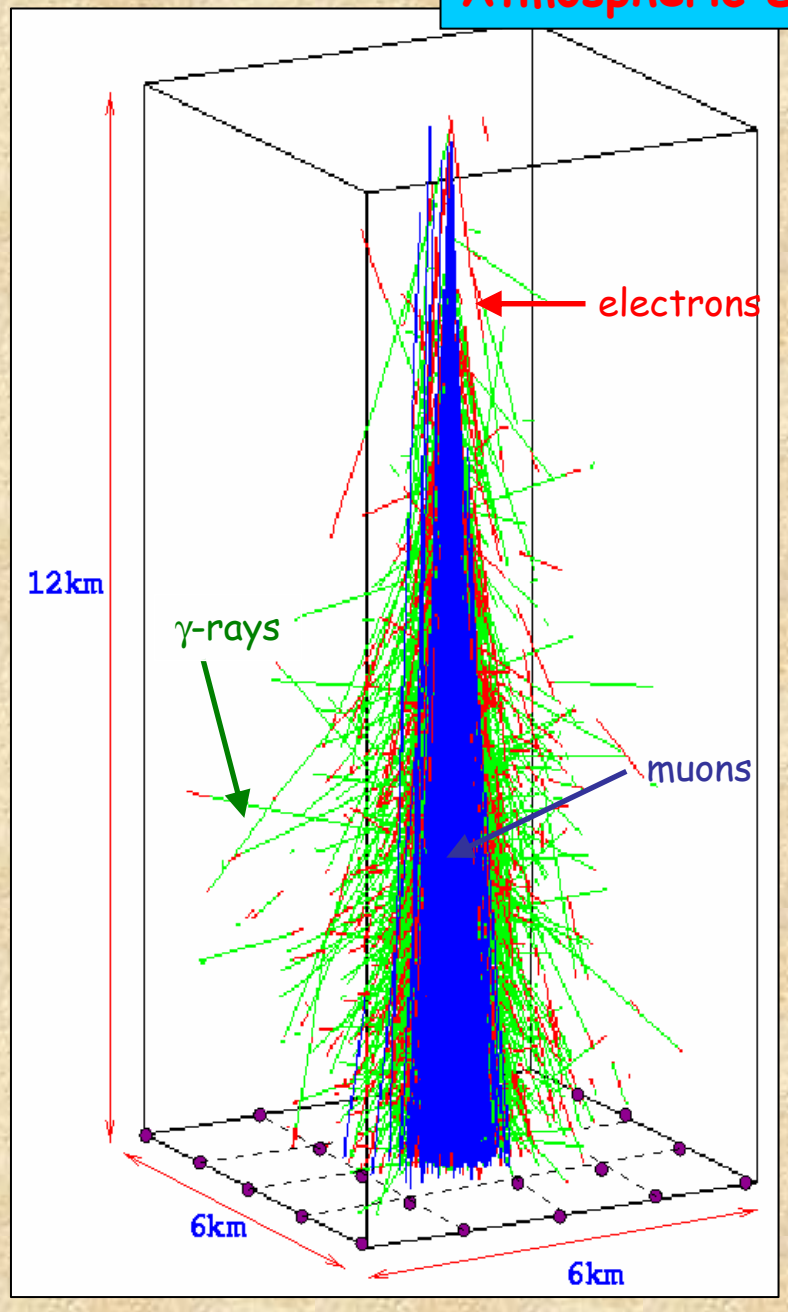
Supernova remnants have been seen by HESS in γ-rays: The remnant RXJ1713-3946 has a spectrum ~$E^{-2.2}$: => Charged particles have been accelerated to > 100 TeV.
Also seen in 1-3 keV X-rays (contour lines from ASCA)



Given the observed spectrum $E^{-2.3}$, this can be interpreted as photons from π^0 decay produced in pp interactions where the TeV protons have the same spectrum and could have been produced in a SN event.

Note that this is consistent with the source spectrum both expected from shock acceleration theory and from the cosmic ray spectrum observed in the solar neighborhood, $E^{-2.7}$, corrected for diffusion in the galactic magnetic field, $j(E) \sim Q(E)\tau_{conf}(E) \sim Q(E)/D(E)$.

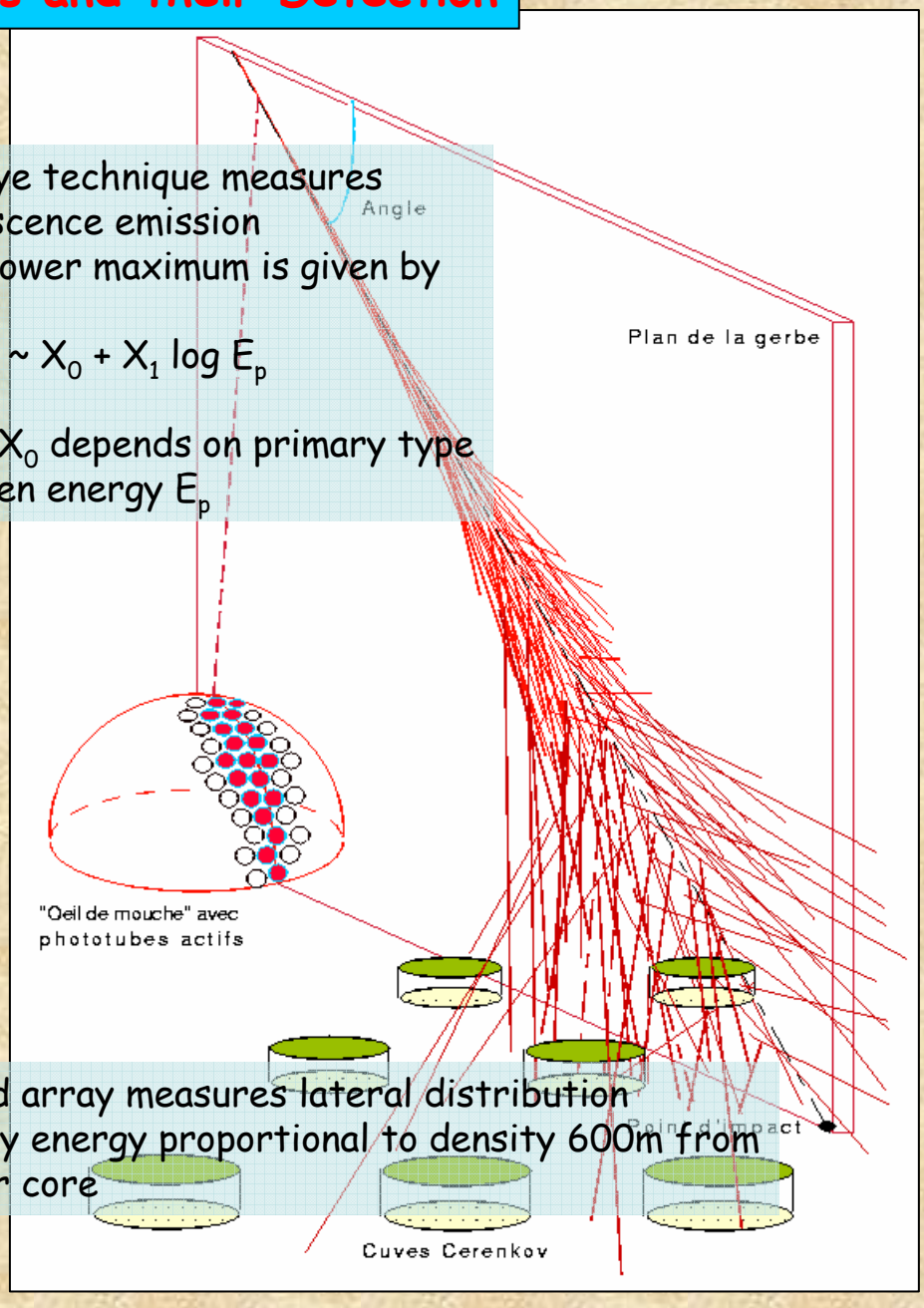
Atmospheric Showers and their Detection



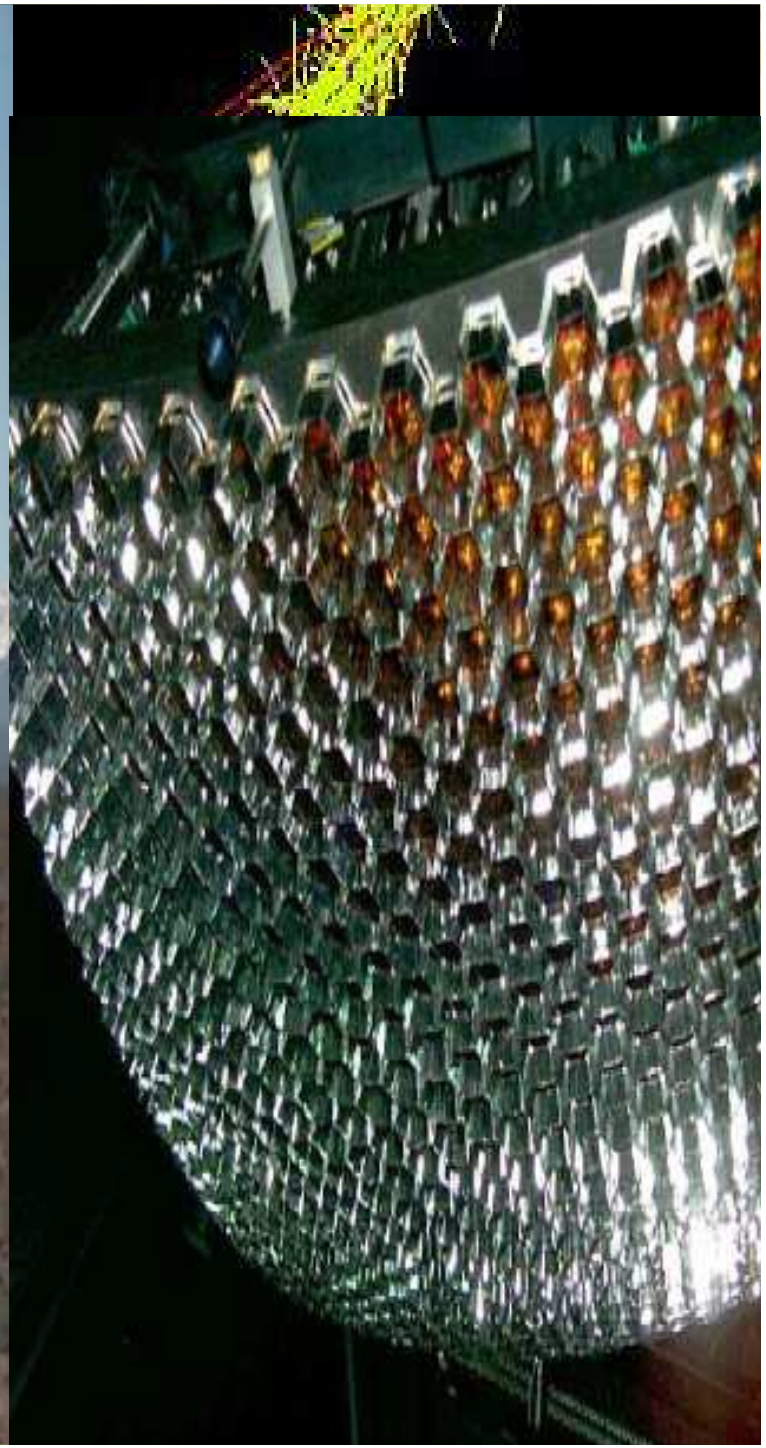
Fly's Eye technique measures fluorescence emission
The shower maximum is given by

$$X_{max} \sim X_0 + X_1 \log E_p$$

where X_0 depends on primary type for given energy E_p

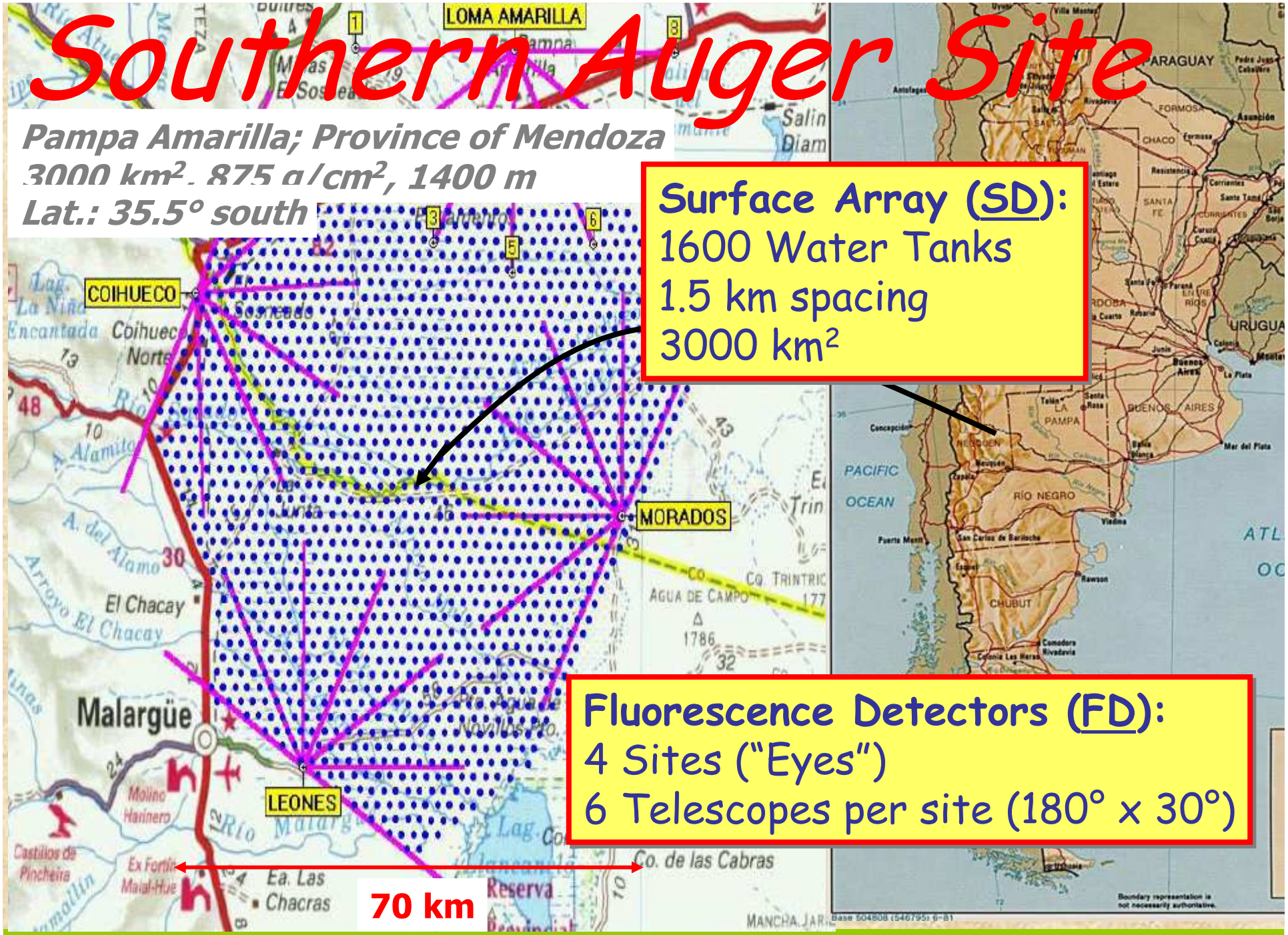


Ground array measures lateral distribution
Primary energy proportional to density 600m from shower core



Southern Auger Site

Pampa Amarilla; Province of Mendoza
3000 km², 875 g/cm², 1400 m
Lat.: 35.5° south

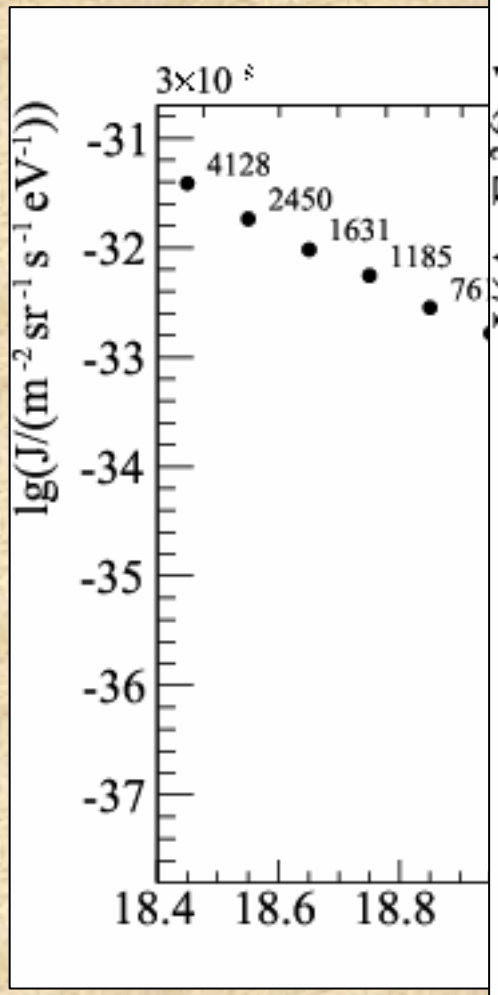


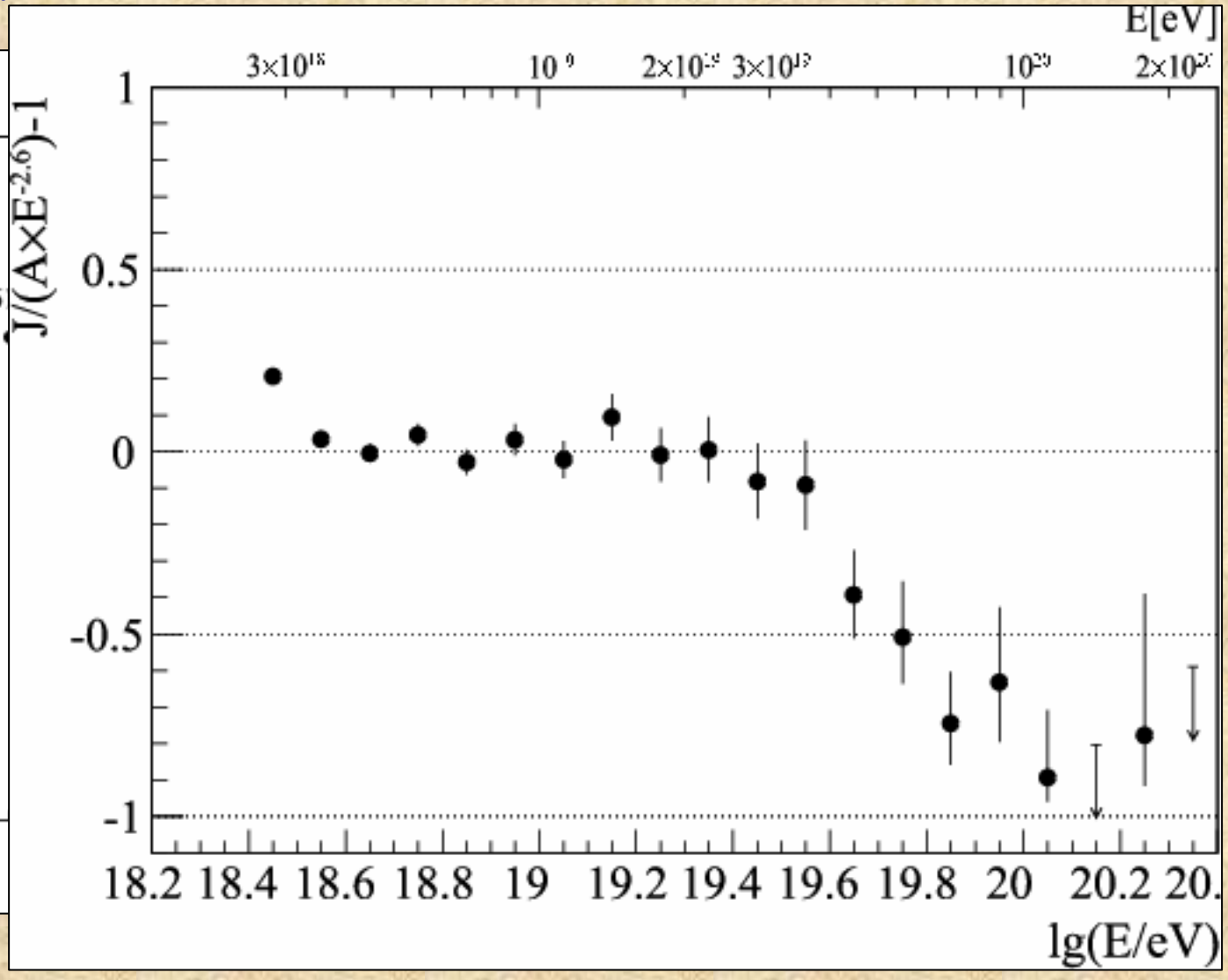
Surface Array (SD):
1600 Water Tanks
1.5 km spacing
3000 km²

Fluorescence Detectors (FD):
4 Sites ("Eyes")
6 Telescopes per site (180° x 30°)

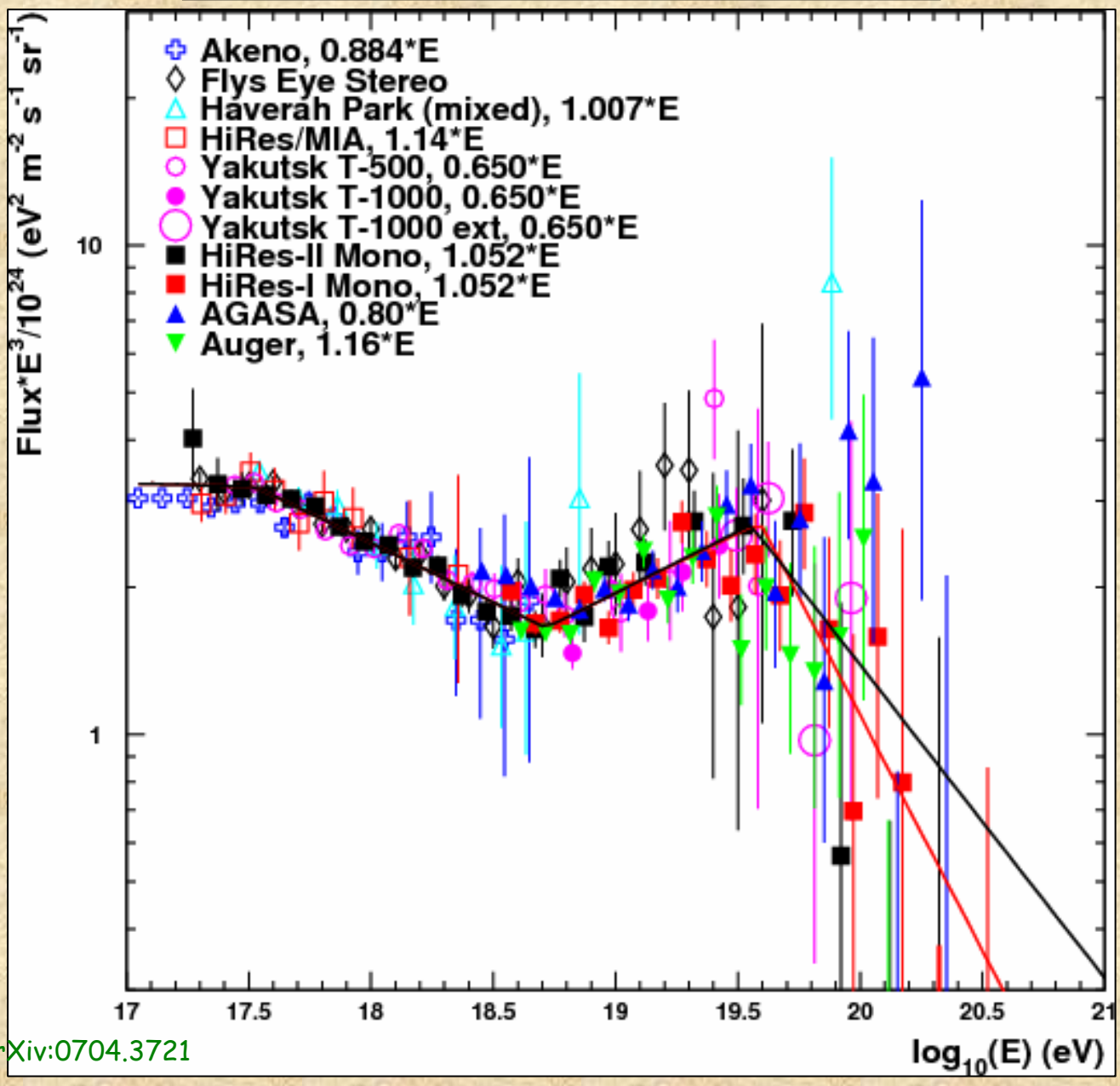
First Auger Spectrum !!

3 times AGASA exposure





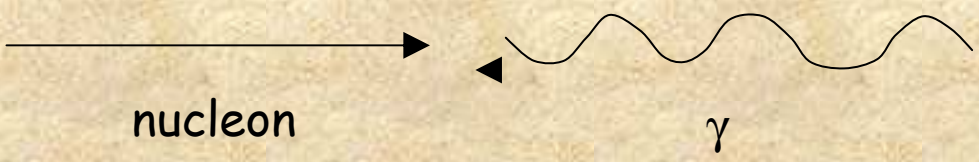
Comparison of Experimental Spectra



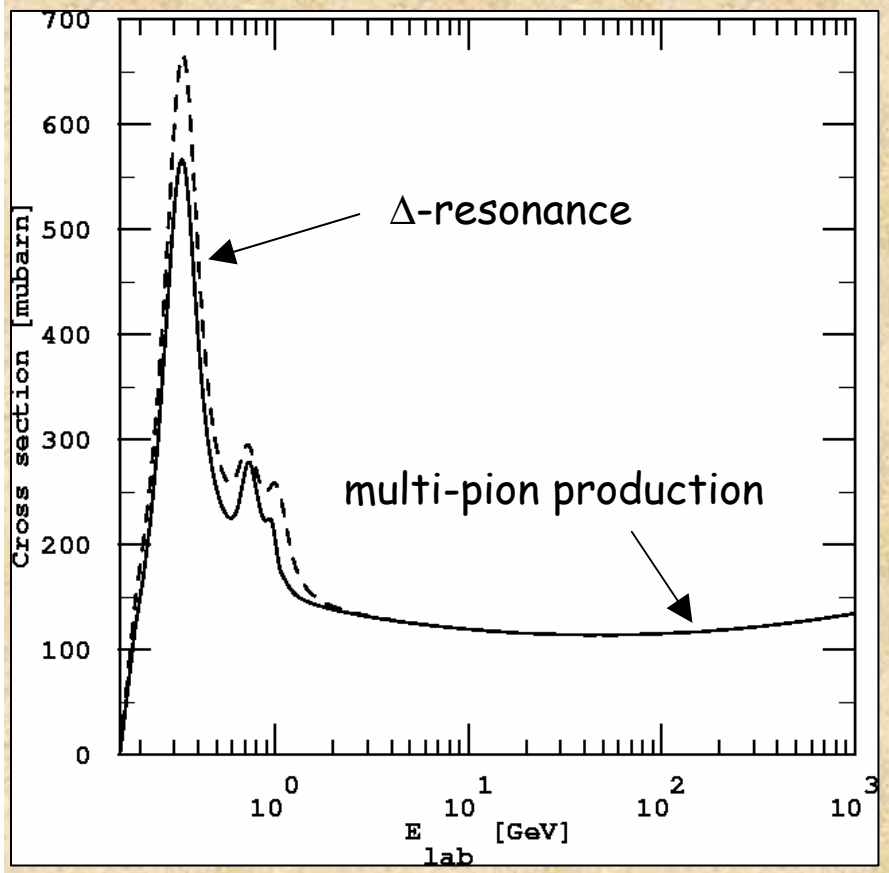
Bergmann, Belz, arXiv:0704.3721

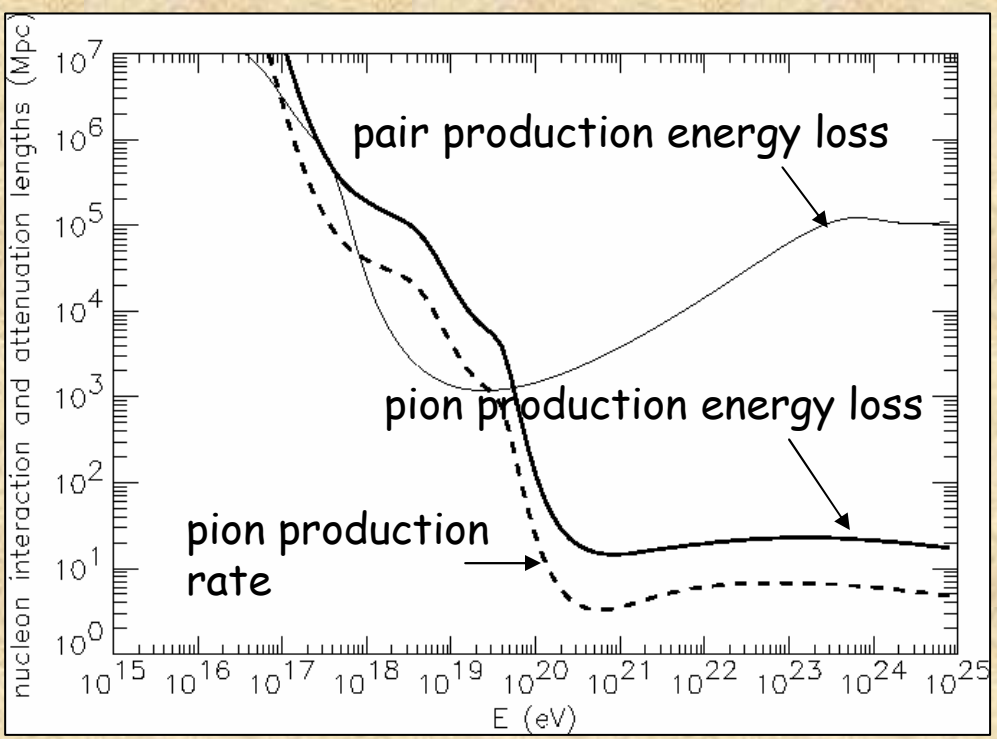
The Greisen-Zatsepin-Kuzmin (GZK) effect

Nucleons can produce pions on the cosmic microwave background



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

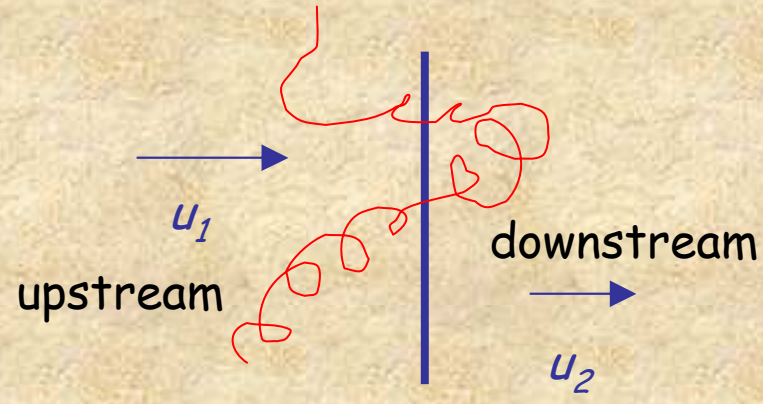




⇒sources must be in cosmological backyard
Only Lorentz symmetry breaking at $\Gamma > 10^{11}$ could avoid this conclusion.

1st Order Fermi Shock Acceleration

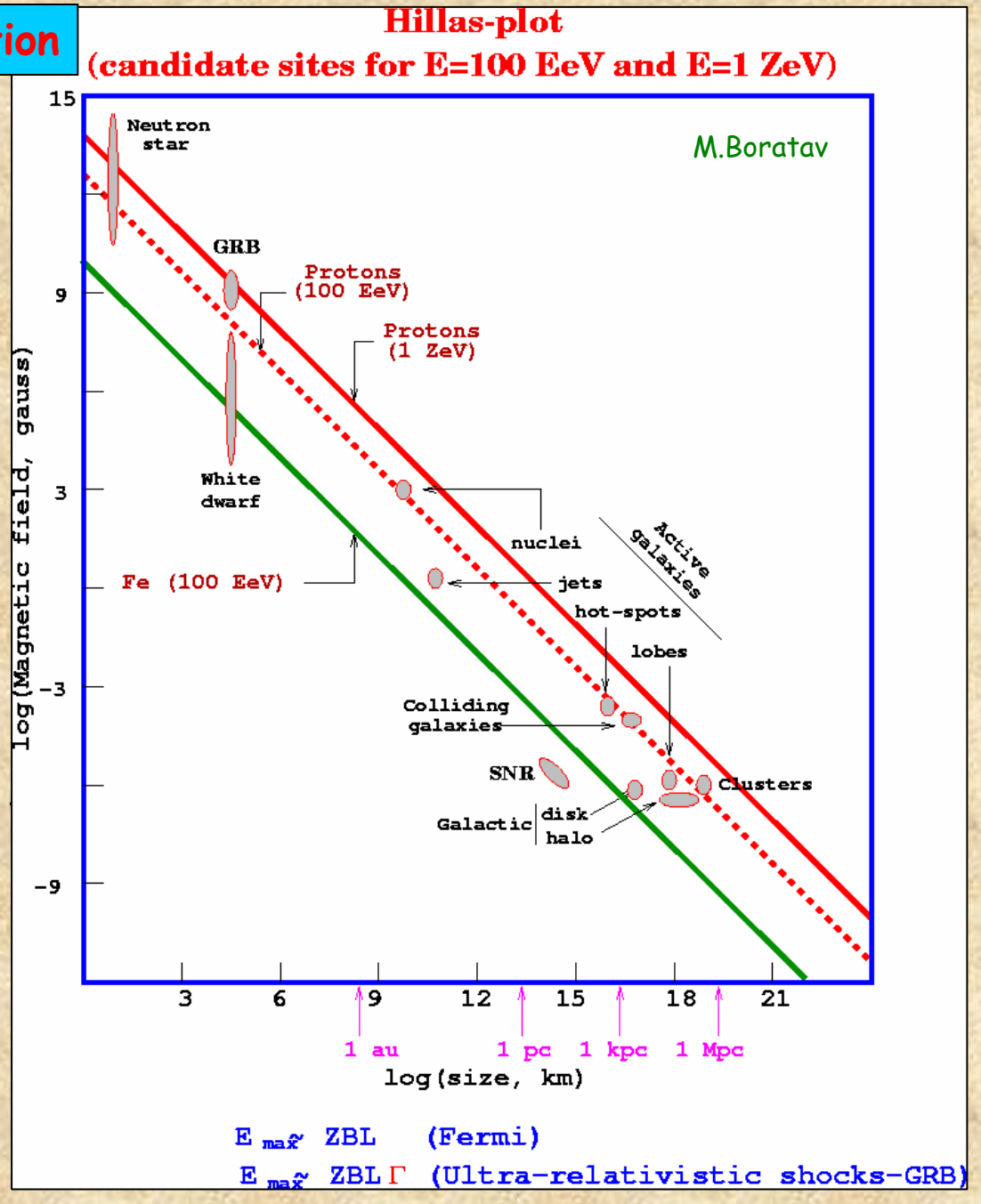
The most widely accepted scenario of cosmic ray acceleration



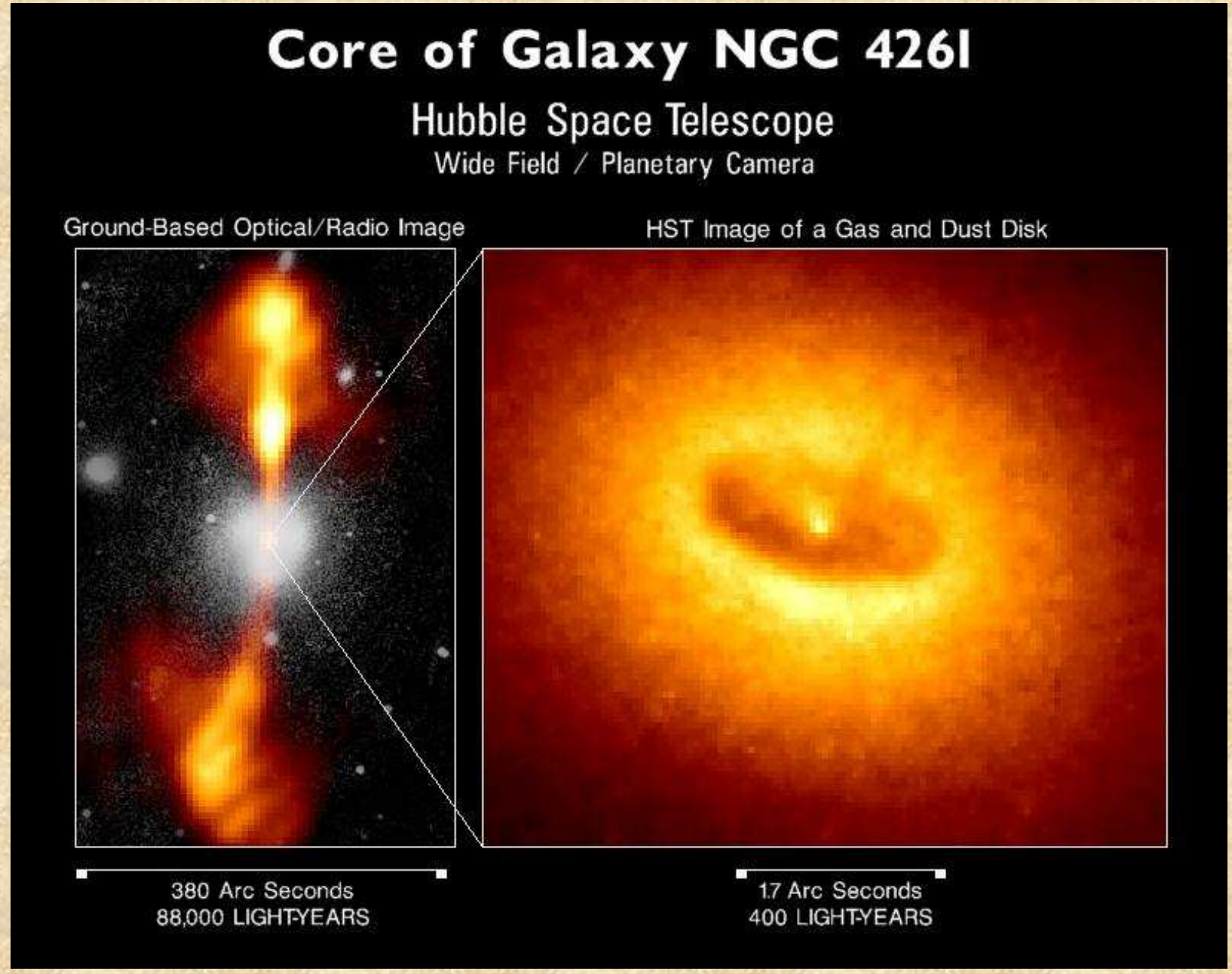
Fractional energy gain per shock crossing $\sim u_1 - u_2$ on time scale $\sim r_L / u_2$

This leads to a spectrum E^{-q} with $q > 2$ typically.

When the gyroradius r_L becomes comparable to the shock size L, the spectrum cuts off.



A possible acceleration site associated with shocks in hot spots of active galaxies



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

accelerated protons interact:

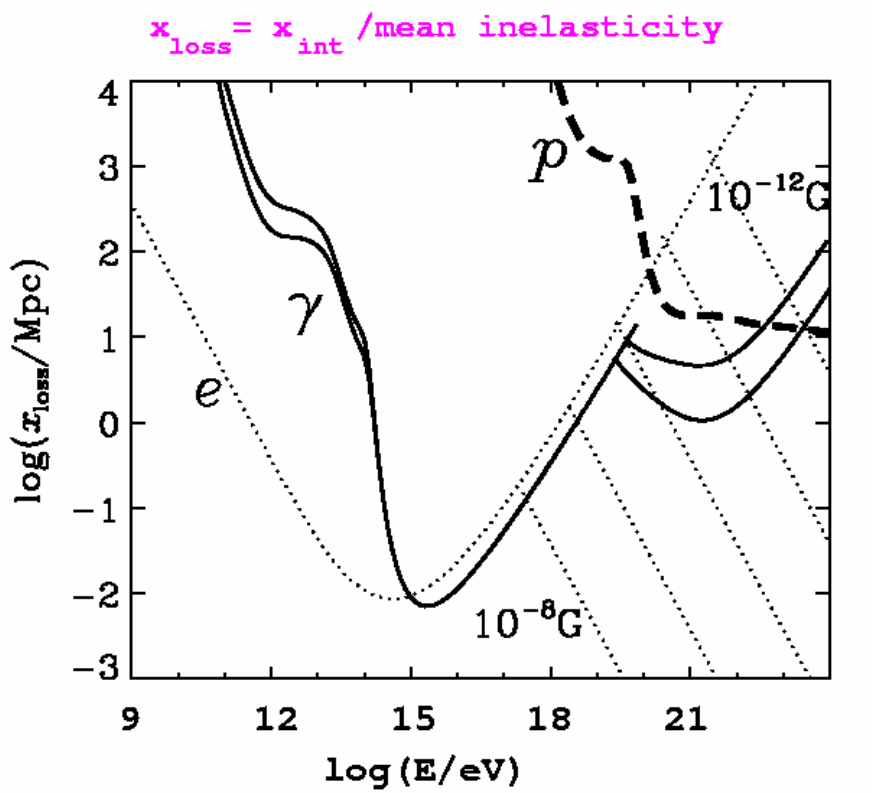
$$p + \begin{matrix} N \\ \gamma \end{matrix} \rightarrow X + \left.\begin{matrix} \pi^{\pm} \rightarrow \text{neutrinos} \\ \pi^{o} \rightarrow \gamma - \text{rays} \end{matrix}\right\}$$

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.



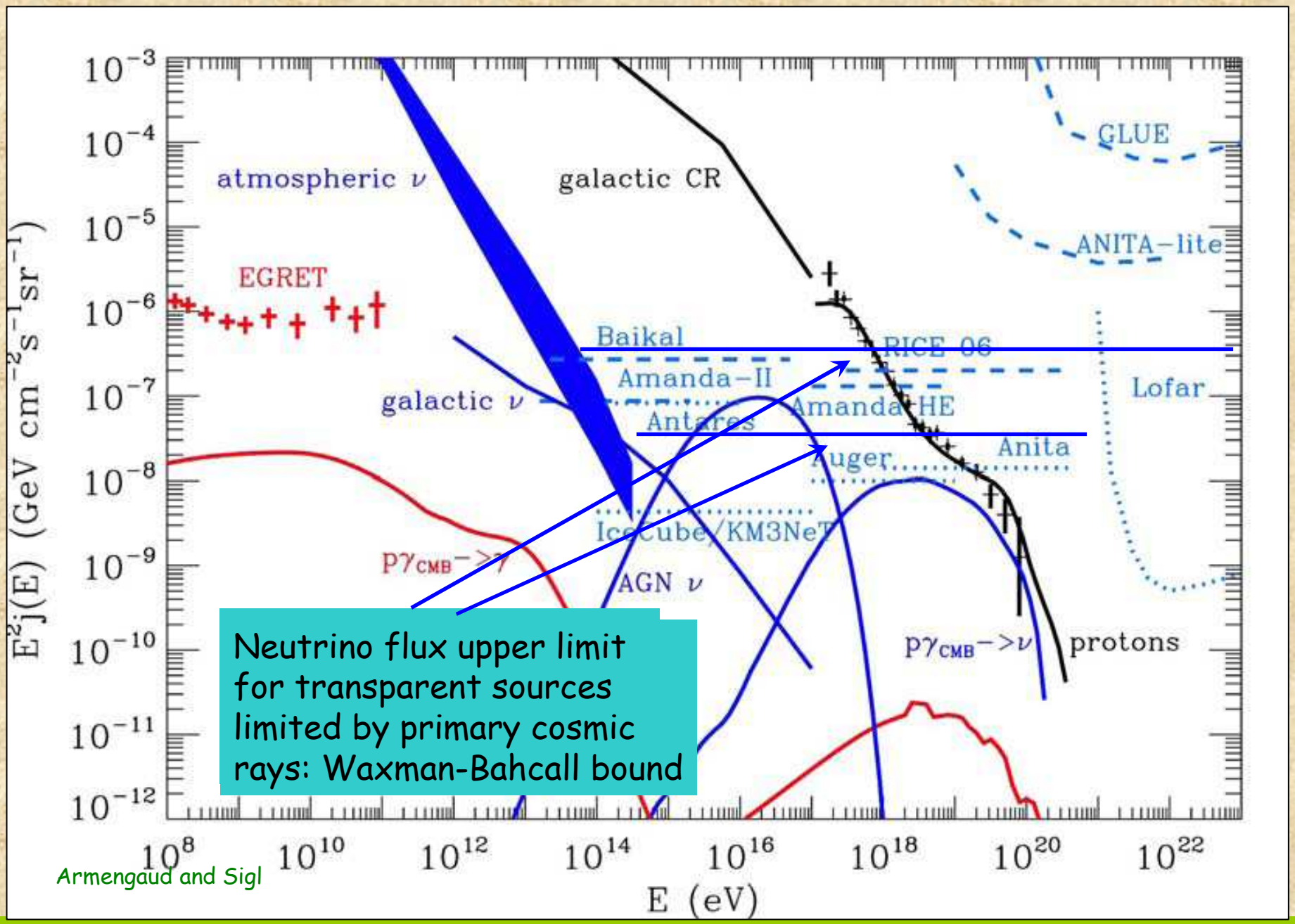
Included processes:

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

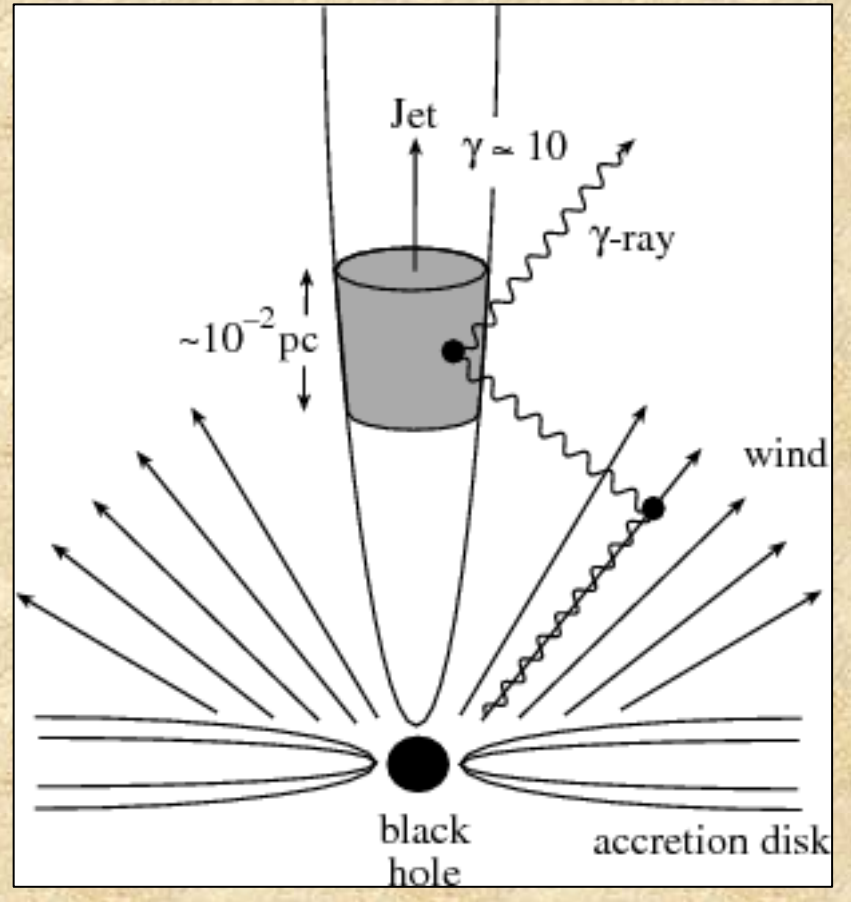
Theoretical Limits, Sensitivities, and "Realistic" Fluxes: A Summary



Neutrino flux upper limit for transparent sources limited by primary cosmic rays: Waxman-Bahcall bound

Armengaud and Sigl

Rough estimate of neutrino flux from hadronic AGN jets: The "proton blazar"



Following
Halzen and Zas, Astrophys.J. 488 (1997) 669

- Size of accelerator $R \sim \Gamma T$, where jet boost factor $\Gamma \sim 10$ and duration of observed bursts $T \sim 1\,\mathrm{day}$.
- Magnetic field strength in jet $B^2 \sim \rho_{\mathrm{electron}} \sim 1\,\mathrm{erg\,cm^{-3}}$ (equipartition).

• "Hillas condition" on maximal proton energy $E_{\rm max} \sim eBR$ and from $p\gamma \to N\pi$ kinematics $E_{{\rm max},\nu} \sim 0.1 E_{\rm max} \sim 10^{18}$ eV.

• Neutrino luminosity related to $\gamma-$ray luminosity by $L_\nu \simeq \frac{3}{13} L_\gamma$ from $p\gamma \to N\pi$ kinematics.

• Assume proton spectrum $dN_p/dE_p \propto E_p^{-2-\varepsilon}$ and $\gamma-$ray spectrum $dN_\gamma/d\varepsilon_\gamma \propto \varepsilon_\gamma^{-2-\alpha}$. If jet is optically thin against $p\gamma$ then

$$\frac{dN_\nu}{dE_\nu} \propto \frac{dN_p}{dE_p}(10E_\nu) \int_{\varepsilon_\gamma^{\rm thr}}^{\infty} d\varepsilon_\gamma \frac{dN_\gamma}{d\varepsilon_\gamma} \propto E_\nu^{-2-\varepsilon} \left(\varepsilon_\gamma^{\rm thr}\right)^{-1-\alpha} \propto E_\nu^{-1-\varepsilon+\alpha},$$

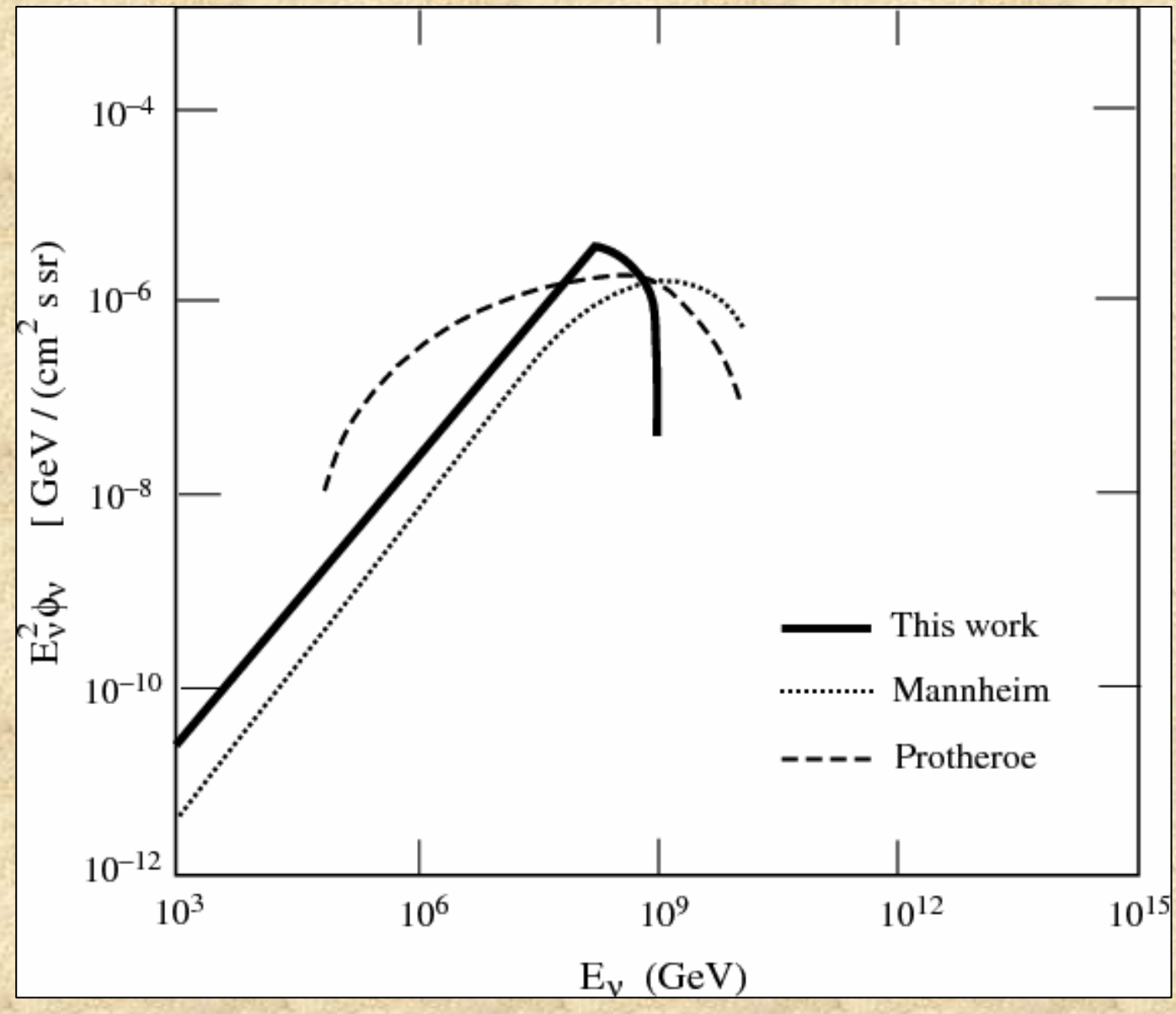
since the pion production threshold $\varepsilon_\gamma^{\rm thr} \propto E_p^{-1} \propto E_\nu^{-1}$.

• Combine with normalization:

$$\frac{dN_\nu}{dE_\nu} \simeq \frac{3}{13} \frac{L_\gamma}{E_{{\rm max},\nu}} \frac{1-\varepsilon+\alpha}{E_\nu} \left(\frac{E_\nu}{E_{{\rm max},\nu}}\right)^{-\varepsilon+\alpha}.$$

• Fold with luminosity function of AGNs in GeV $\gamma-$rays.

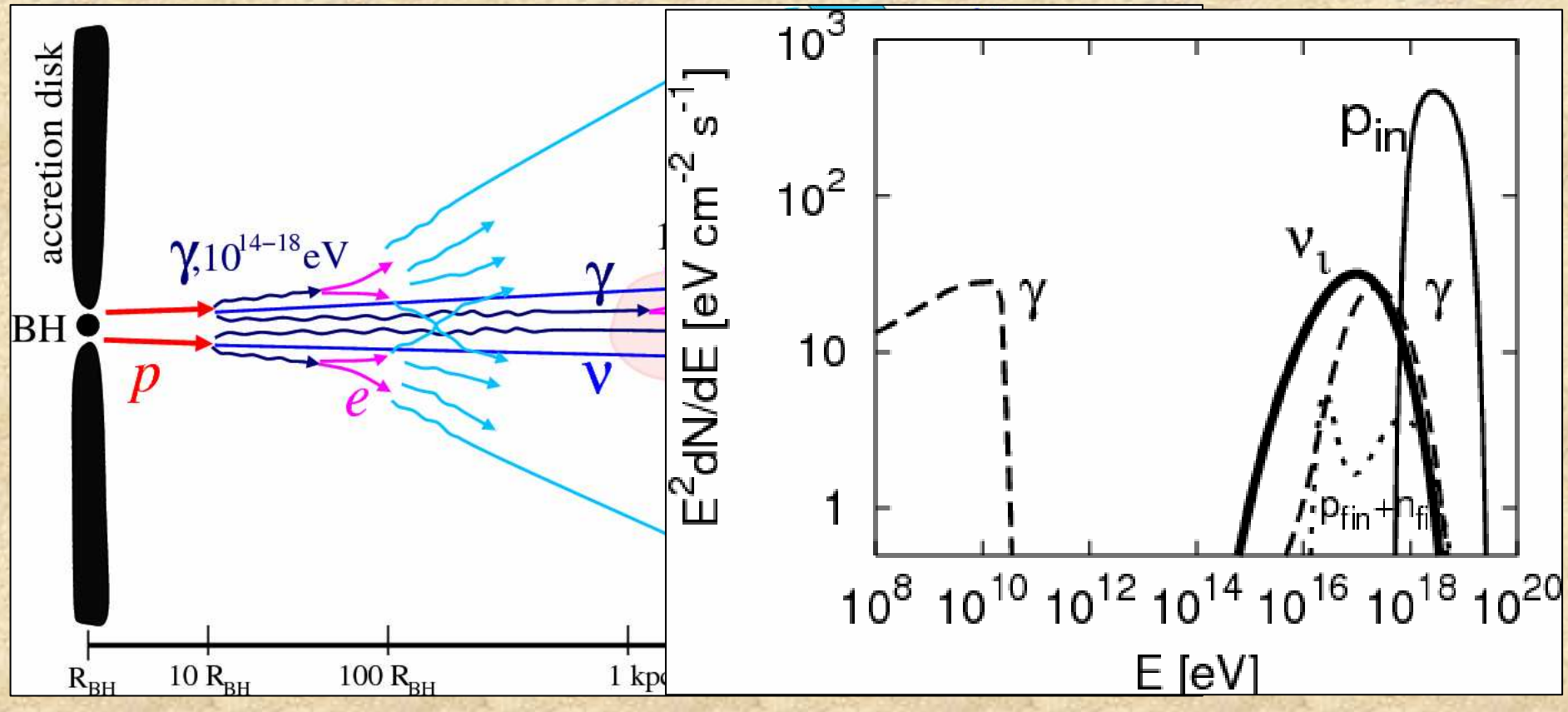
Diffuse Neutrino fluxes from AGN jets



Halzen and Zas, Astrophys.J. 488 (1997) 669

Note, however, that blazars promising as neutrino sources should be loud in GeV γ-rays, but NOT in γ-rays above TeV.

This is because such γ-rays pair produce on "blue bump" photons of ~10 eV energy with a cross section $\sim\sigma_{Th} \sim 1$ b about a factor 10^4 larger than the pγ cross section that produces the neutrinos => If loud in > TeV γ-rays, optical depth for neutrino production would be very small.



Neronov and Semikoz, Phys.Rev.D66 (2002) 123003

Neutrino Fluxes from Compact Sources

For example, γ-ray bursts, neutron stars.

In such sources, pions and/or muons could loose energy before decaying:

$$
\begin{aligned}
t_{\pi,\mu}(E) &= \tau_{\pi,\mu}\,\frac{E}{m_{\pi,\mu}} \\
t_{\rm had}(E) &\simeq \frac{1}{n_p\sigma_h(E)} \propto E^0 \\
t_{\rm rad}(E) &\simeq \frac{1}{U_\gamma\sigma_{\rm rad}(E)\eta(E)} \propto m^4_{\pi,\mu}E^{-1}\,,
\end{aligned}
$$

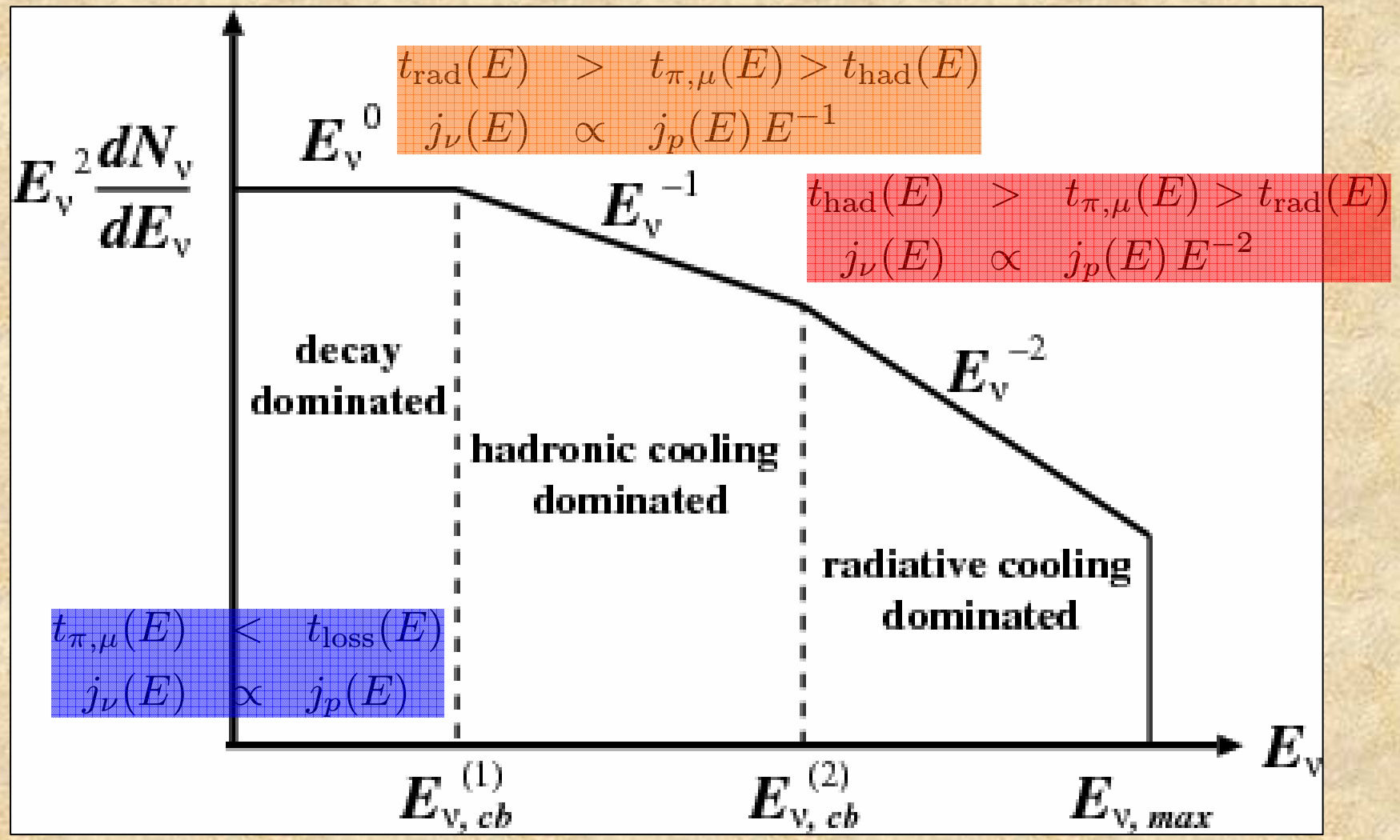
where $\sigma_{\rm rad} \propto E^{-1}$ and the inelasticity $\eta(E) \propto E^2$ in the non-relativistic regime. Then, for the loss rate $t_{\rm loss}(E)^{-1} = t_{\rm had}(E)^{-1} + t_{\rm rad}^{-1}$,one has

$$j_\nu(E) \propto \min[1, t_{\rm loss}(E)/t_{\pi,\mu}(E)]j_p(E) \qquad (1)$$

Because $t_{\rm loss}(E)/t_{\pi,\mu}(E)$ is the probability to decay within the energy loss time.

At low E hadronic losses dominate, whereas at high E radiative losses dominate.

Ando and Beacom, Phys.Rev.Lett. 95 (2005) 061103



Note that $t_\mu \sim 100 t_\pi$, therefore, the critical energies are higher for pion decay. But pion decay into electrons is helicity suppressed, therefore, at high energies source fluxes should be muon neutrino dominated.

Testing Neutrino Properties with Astrophysical Neutrinos

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

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

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

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

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

This implies the following transition probabilities

$$P(\nu_\alpha \to \nu_\beta) = \left| \sum_i U_{\alpha i} U^*_{\beta i} \exp(-iE_i t) \right|^2 \ , P(\bar{\nu}_\alpha \to \bar{\nu}_\beta) = P(\nu_\beta \to \nu_\alpha) \, .$$

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

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

Observed Flavor Ratios can be sensitive to Source Physics

Note that $t_\mu \sim 100 t_\pi$, therefore, there are energies at which pions decay before loosing energy, but muons loose energy before decaying.

But pion decay into electrons is helicity suppressed, therefore, at high energies source fluxes should be muon neutrino dominated.

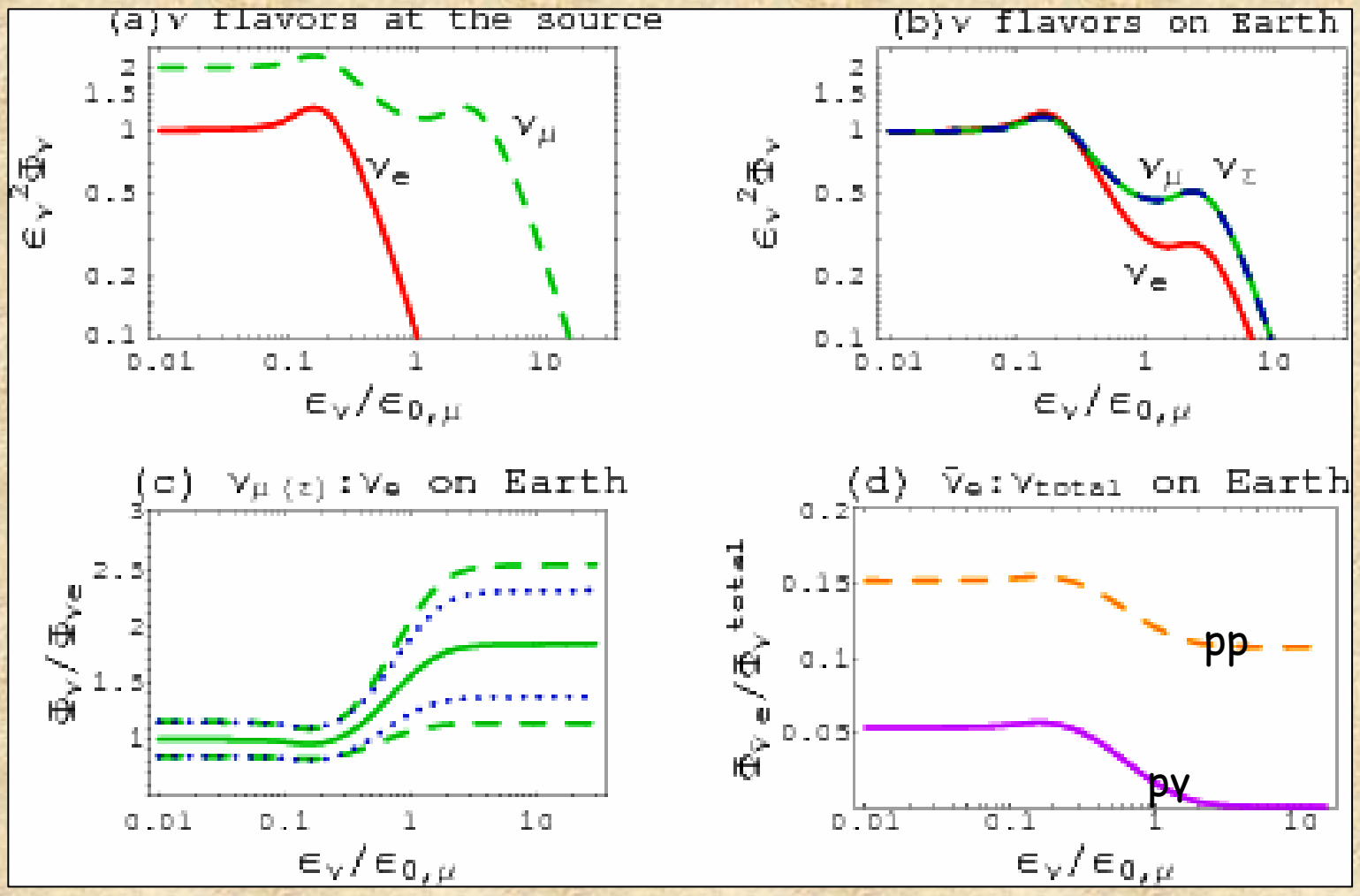
For flavors α injected with relative weights w_α at the source, for distances large compared to oscillation lengths the flux of flavor β at the observer is

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

Therefore, when both pions and muons decay before loosing energy, then $w_e : w_\mu : w_\tau \simeq \frac{1}{3} : \frac{2}{3} : 0$ and thus $\phi_e : \phi_\mu : \phi_\tau \simeq \frac{1}{3} : \frac{1}{3} : \frac{1}{3}$. However, if pions but not muons decay before loosing energy then $w_e : w_\mu : w_\tau \simeq 0 : 1 : 0$ and thus $\phi_e : \phi_\mu : \phi_\tau \simeq \frac{1}{5} : \frac{2}{5} : \frac{2}{5}$.

Finally, pp interactions produce both pion charges and thus give a higher fraction of $\bar{\nu}_e$ than $p\gamma$ interactions.

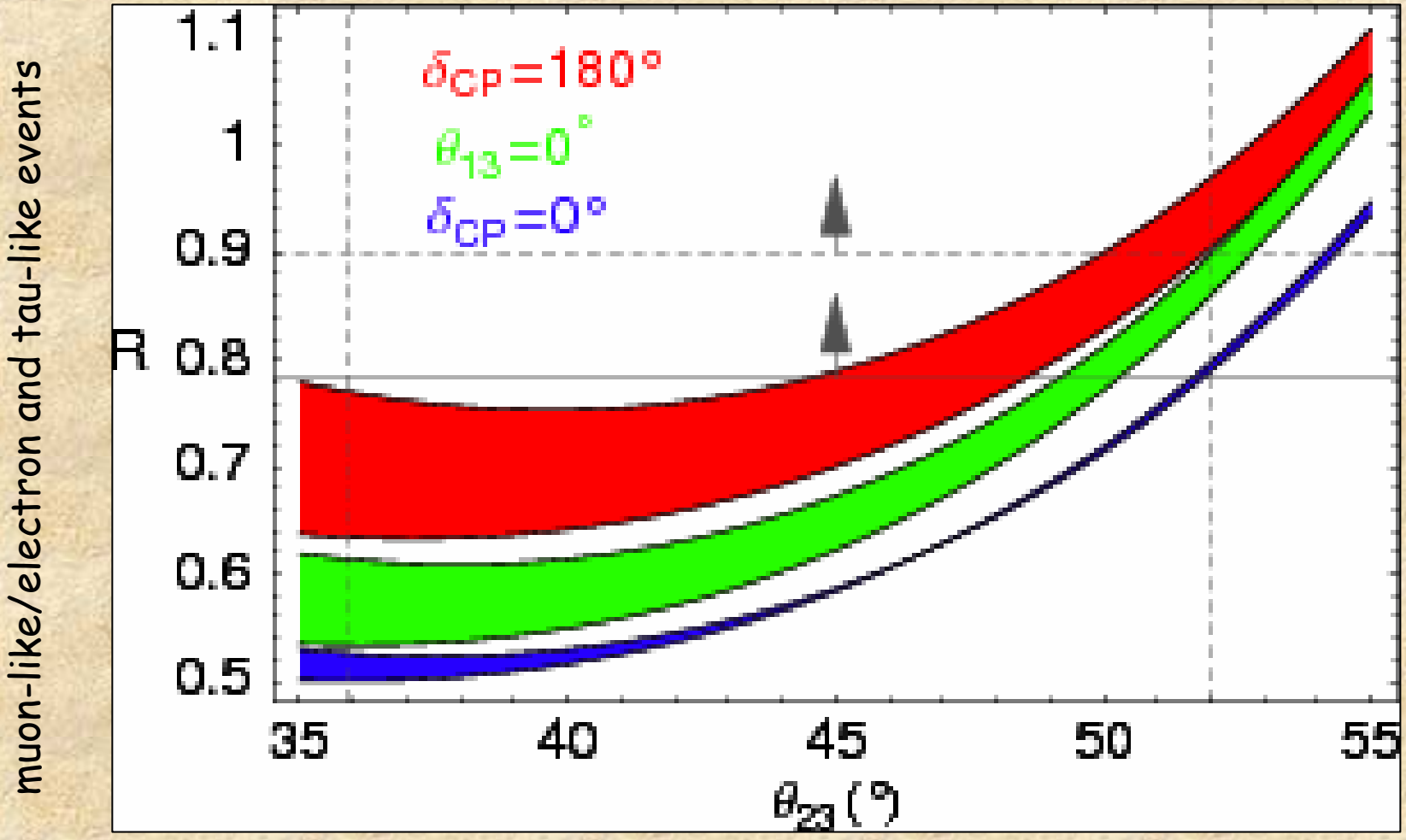
Observed Flavor Ratios can be sensitive to source physics



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

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

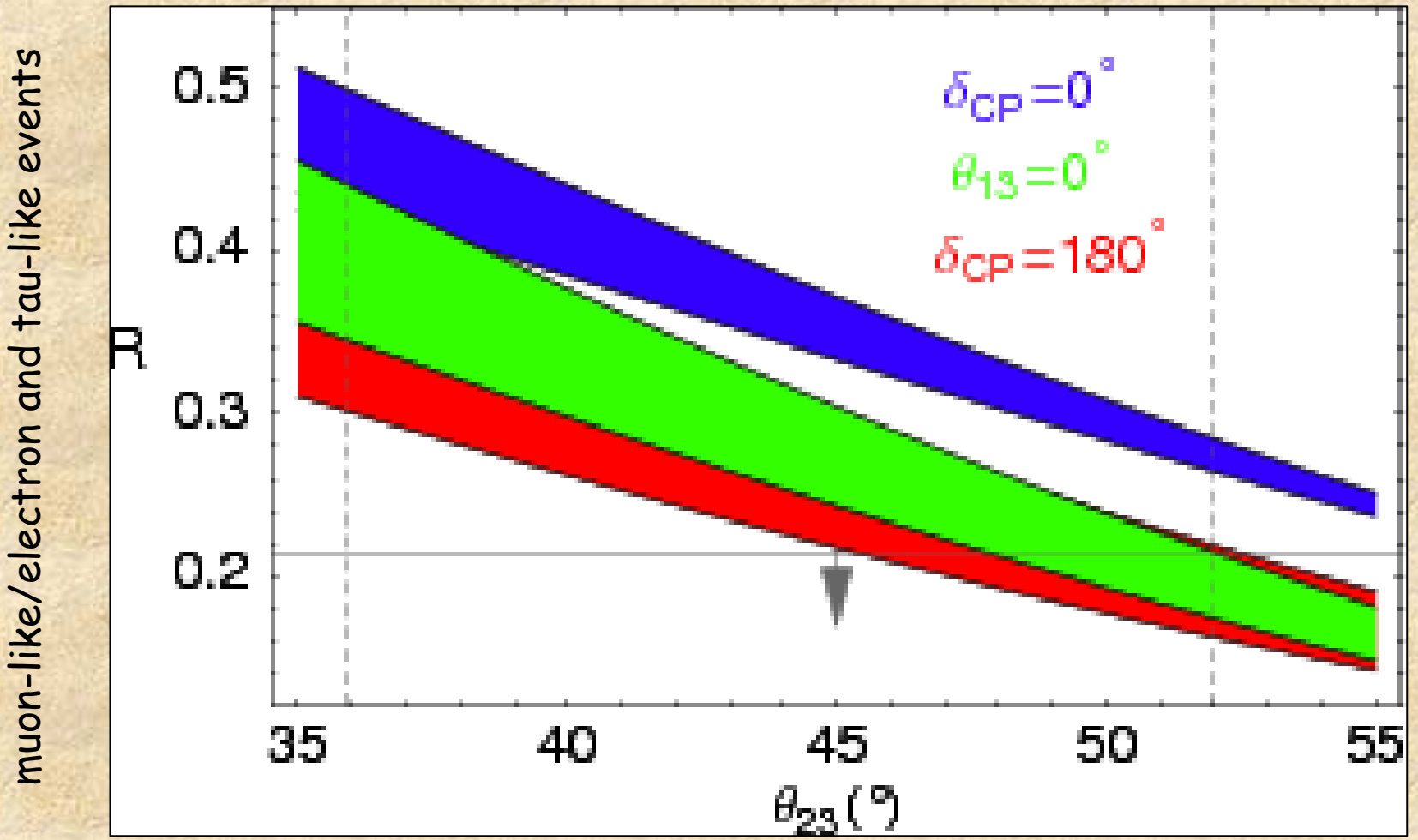
Observed Flavor Ratios can be sensitive to oscillation parameters



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

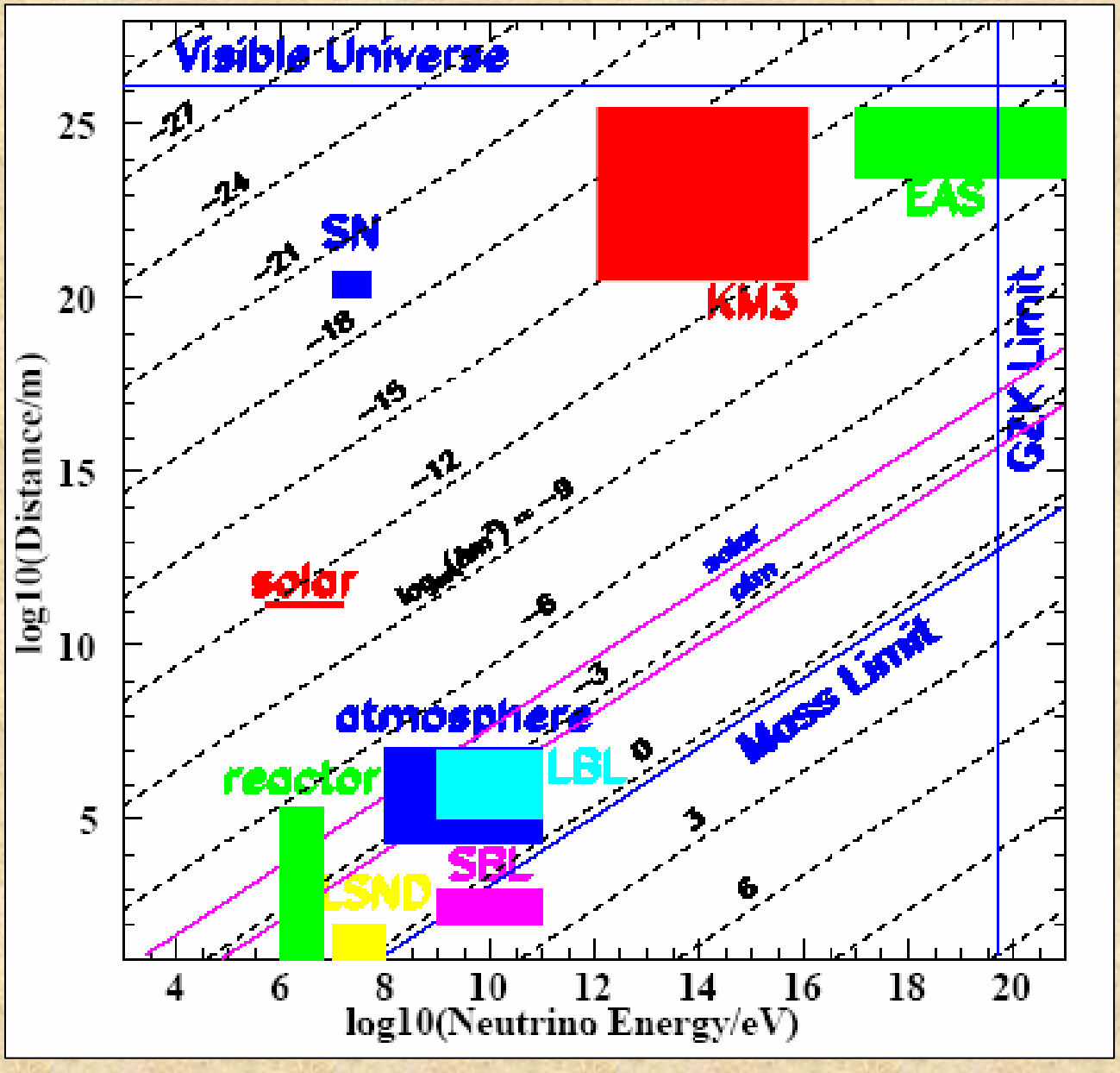
Observed Flavor Ratios can be sensitive to oscillation parameters



For electron anti-neutrinos from neutron decay

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

Sensitivity of astrophysical neutrinos to oscillations: The Learned Plot



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

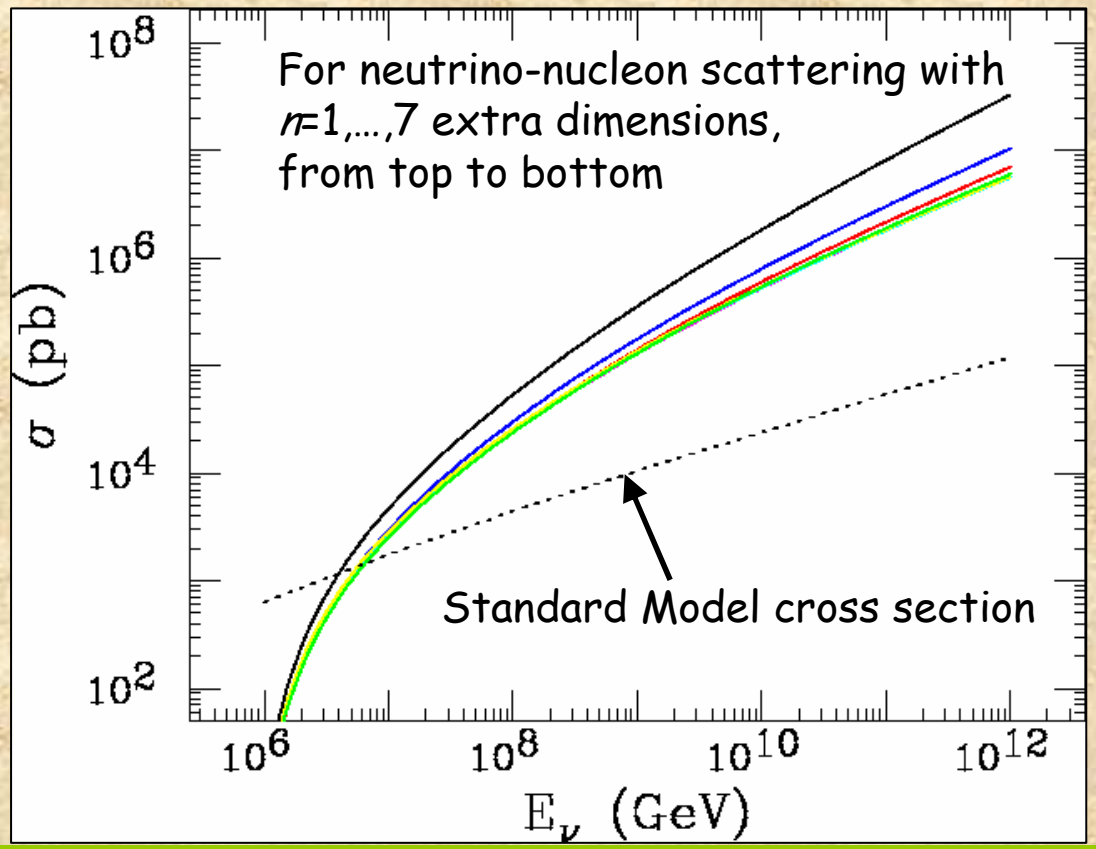
Probes of Neutrino Interactions beyond the Standard Model

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

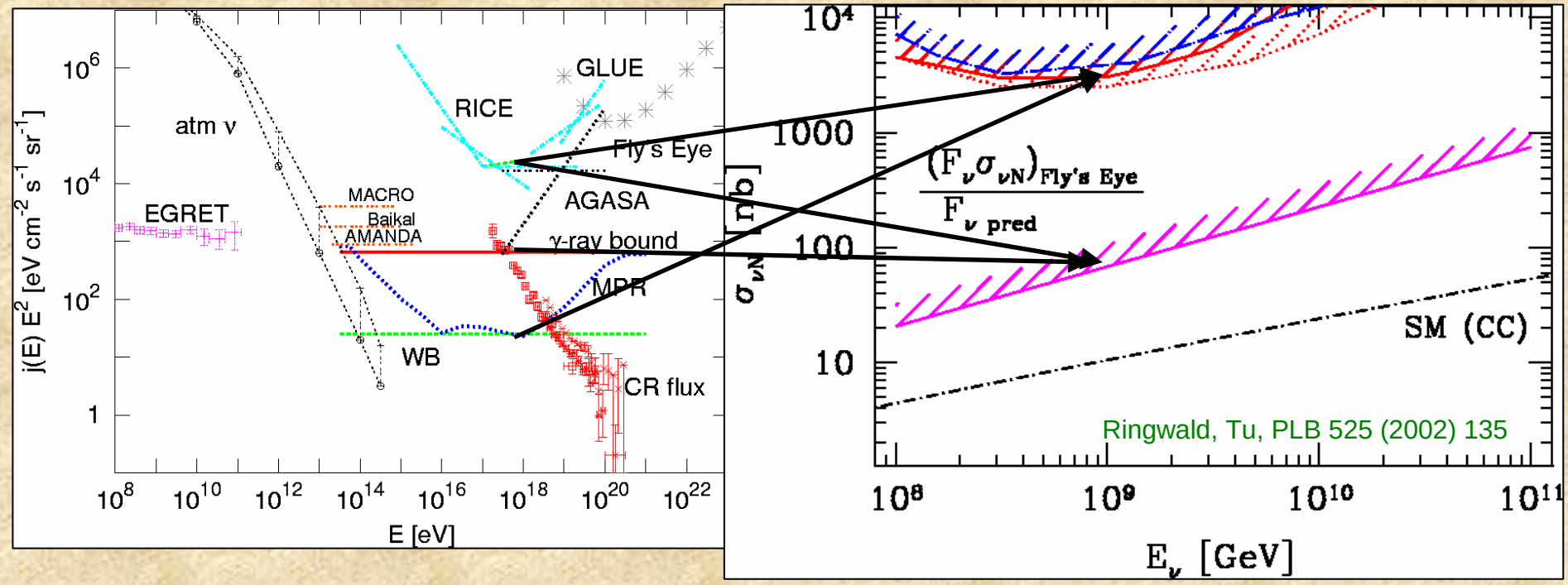
Example: microscopic black hole production in scenarios with a TeV string scale:

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:



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

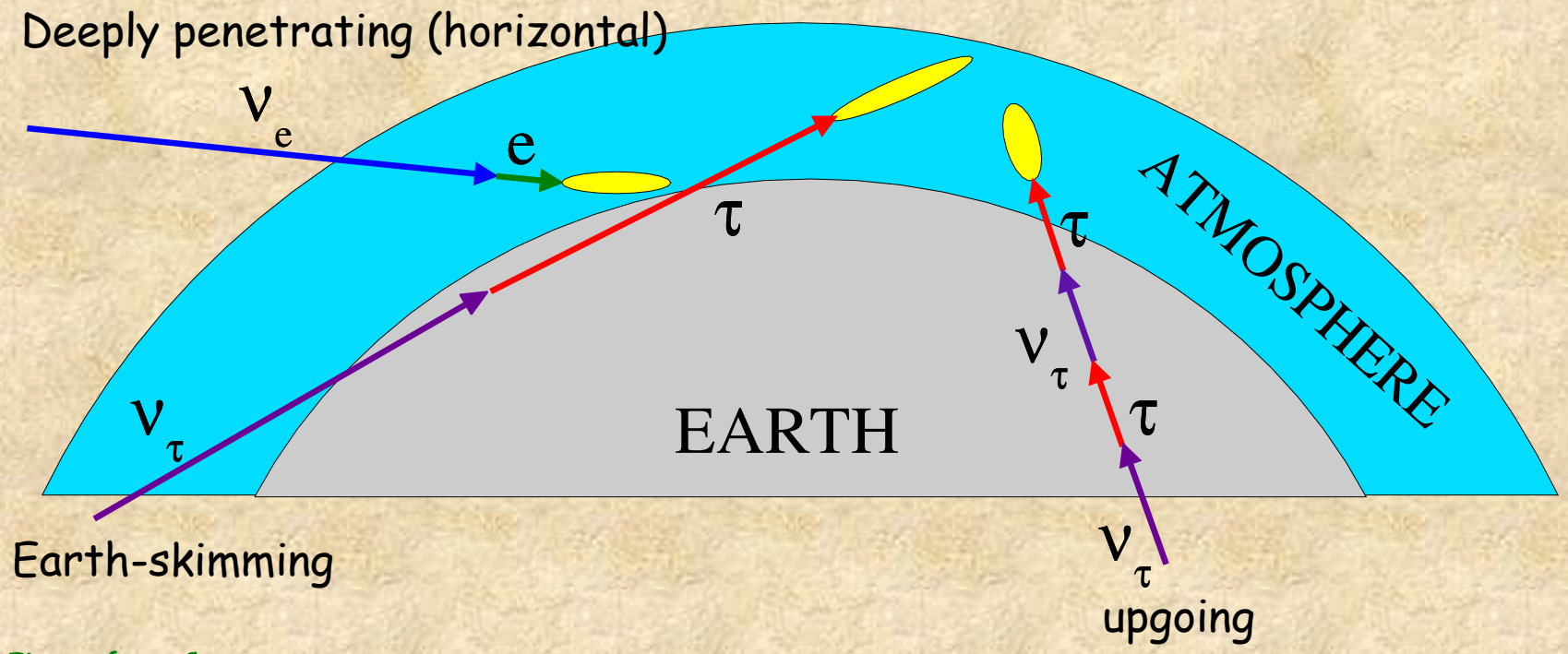
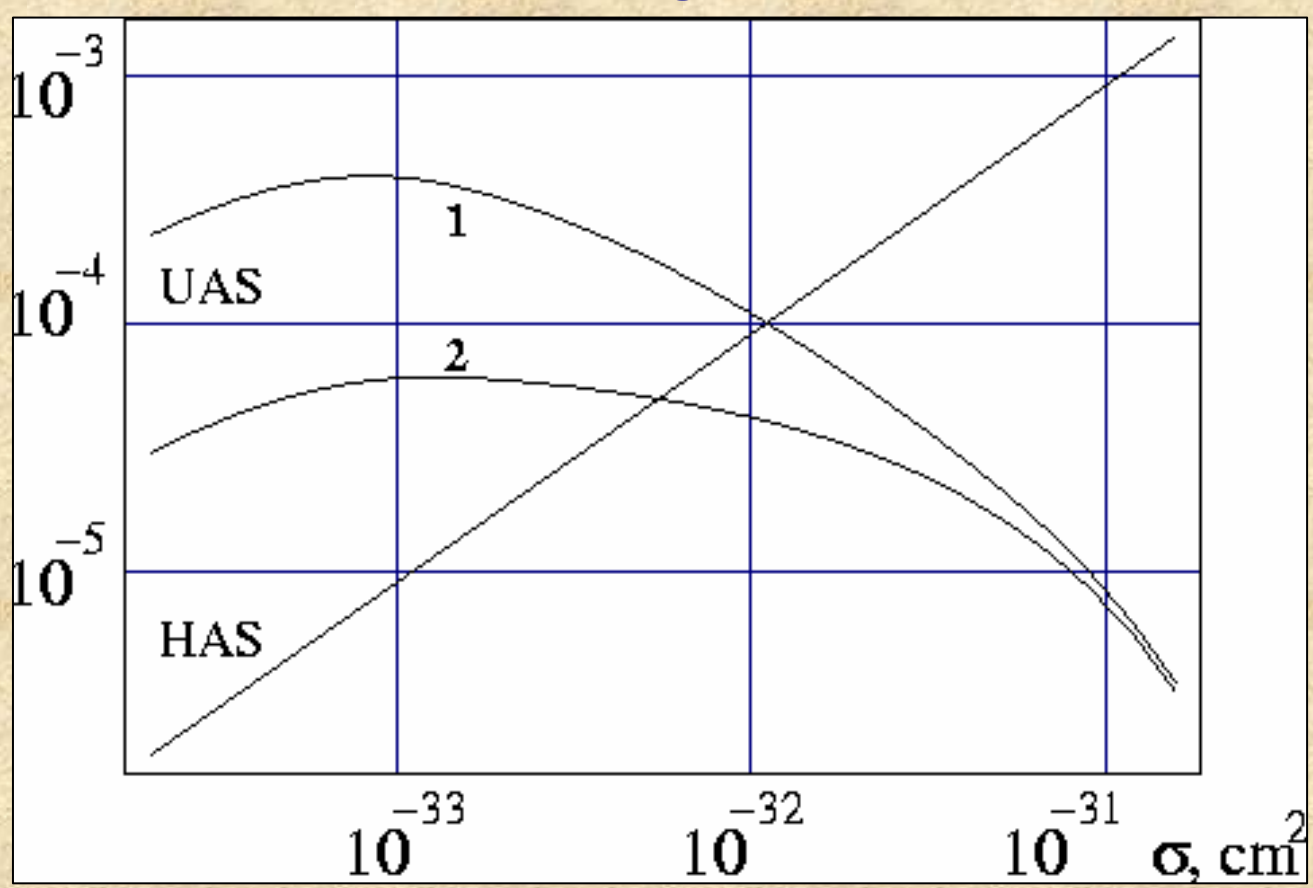


Figure from Cusumano

Earth-skimming τ-neutrinos

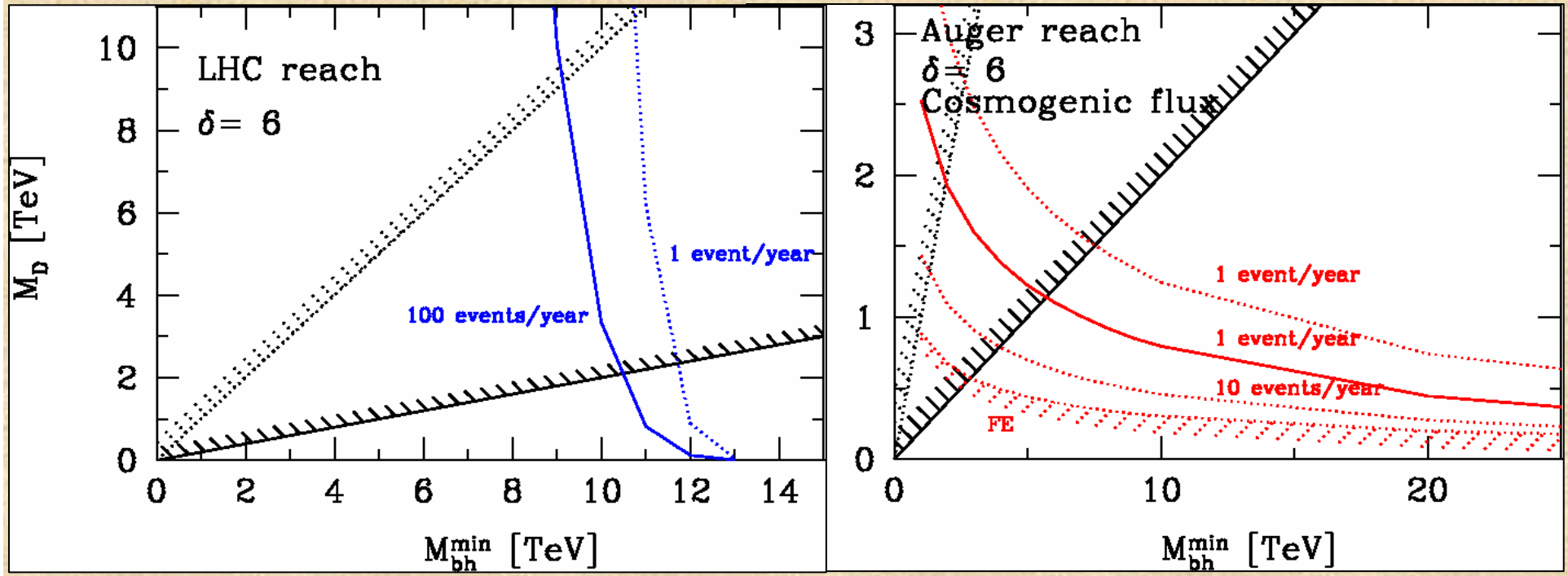


Air-shower probability per τ-neutrino at 10^{20} eV for 10^{18} eV (1) and 10^{19} eV (2) threshold energy for space-based detection.

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

Sensitivities of LHC and the Pierre Auger project to microscopic black hole production in neutrino-nucleon scattering

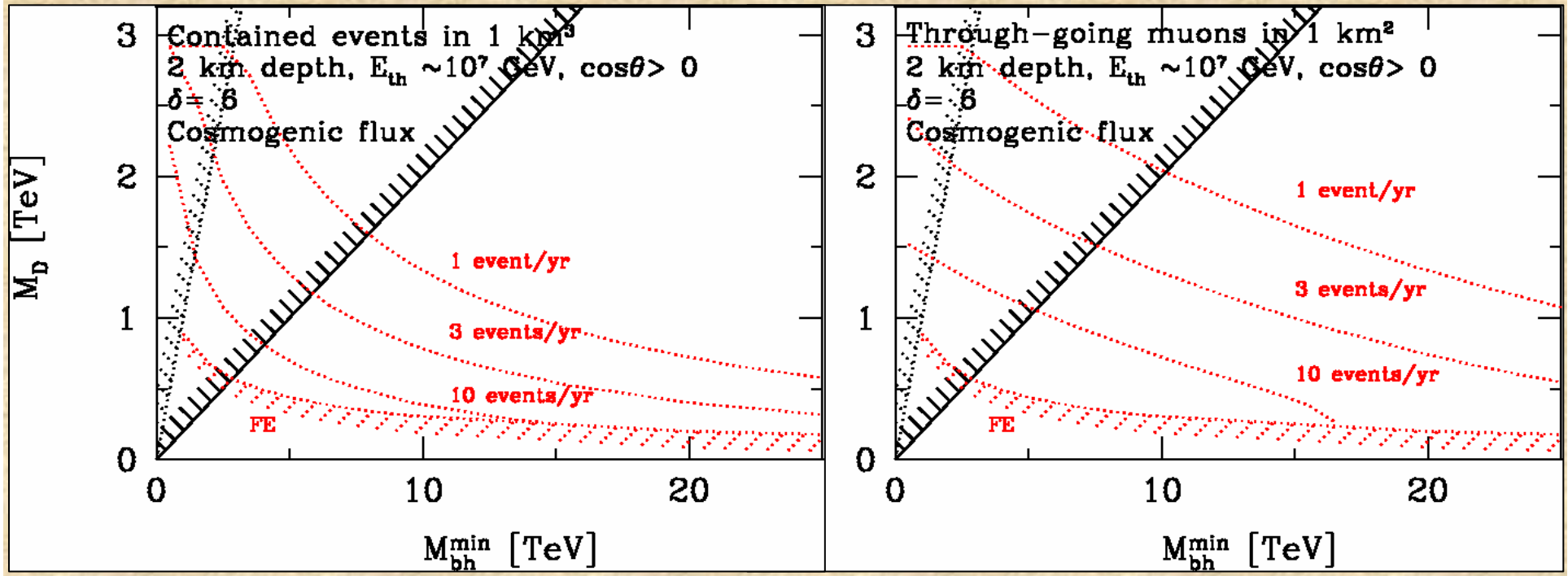


M_D = fundamental gravity scale; M_{bh}^{min} = minimal black hole mass

LHC much more sensitive than Auger, but Auger could "scoop" LHC

Ringwald, Tu, PLB 525 (2002) 135

Sensitivities of future neutrino telescopes to microscopic black hole production in neutrino-nucleon scattering



Contained events: Rate ~ Volume

Through-going events: Rate ~ Area

Ringwald, Kowalski, Tu, PLB 529 (2002) 1

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},

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

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

For the i-th neutrino mass eigenstate this gives

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

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

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

for n=1, 2, 3, 4, respectively, and $\Delta m^2 = 10^{-3}$ eV^2, 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(-aL):

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 $a \sim 10^{-37}$ GeV (somewhat dependent on energy dependence of a)

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

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. All three of these fields should be considered together.

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 ~10^{16} eV and "cosmogenic" neutrinos around 10^{19} eV from photopion production. Flux uncertainties stem from uncertainties in cosmic ray source distribution and evolution.

3.) The flavor composition of the neutrino flux from discrete sources depends on the relative sizes of synchrotron cooling and decay time scales of pions and muons.

4.) The flavor composition of the neutrino flux from discrete sources can also depend on mixing angles and the CP phase.

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.) The coming 3-5 years promise an about 100-fold increase of ultra-high energy cosmic ray data due to experiments that are either under construction or in the proposal stage. This will constrain primary cosmic ray flux models.

7.) Many new interesting ideas on a modest cost scale for ultra-high energy neutrino detection are currently under discussion, see experimental talks.