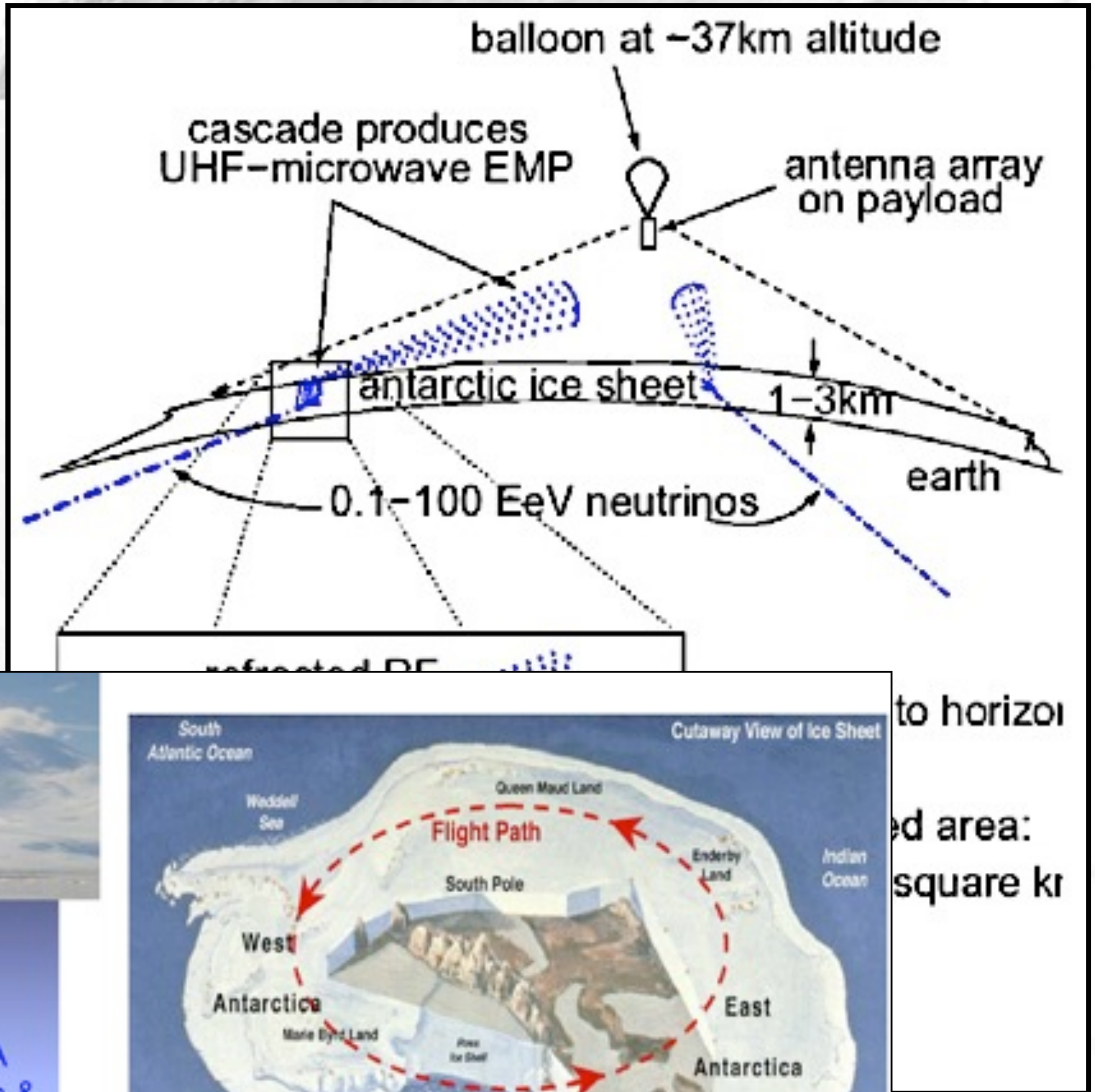
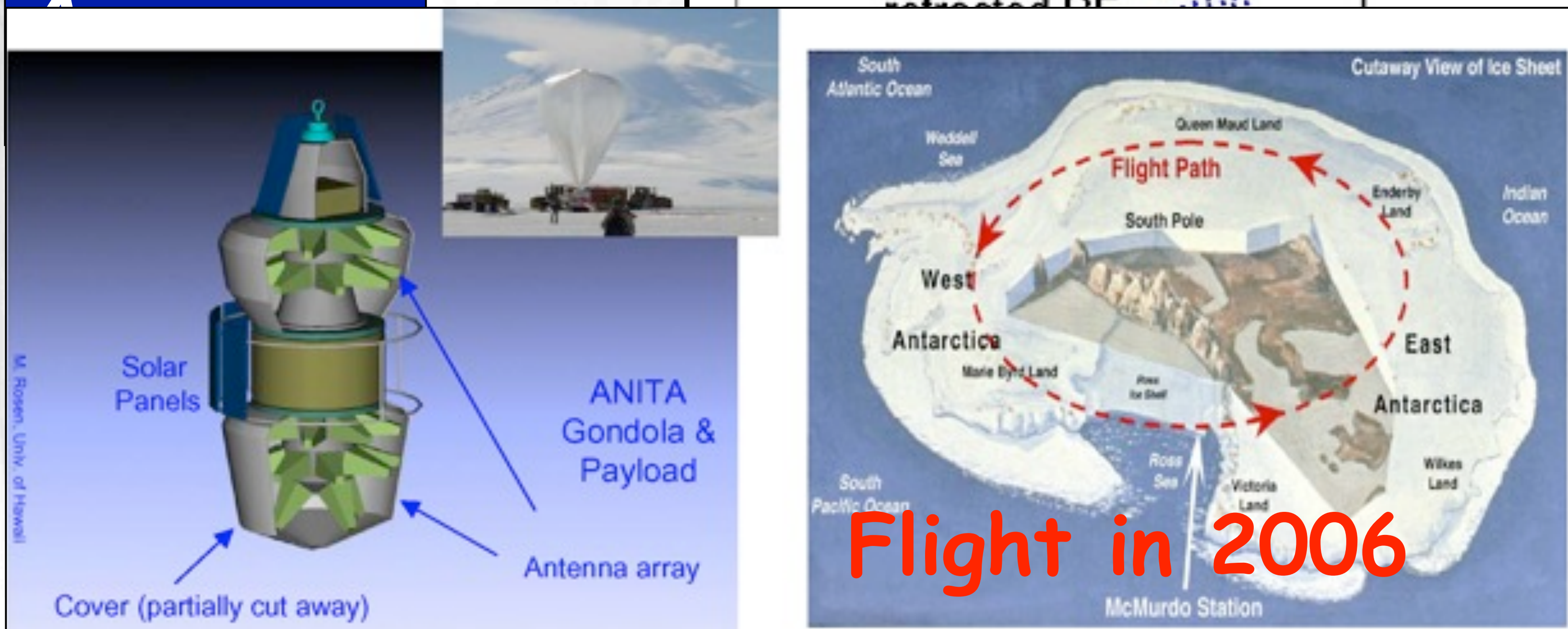
ANITA

Antarctic

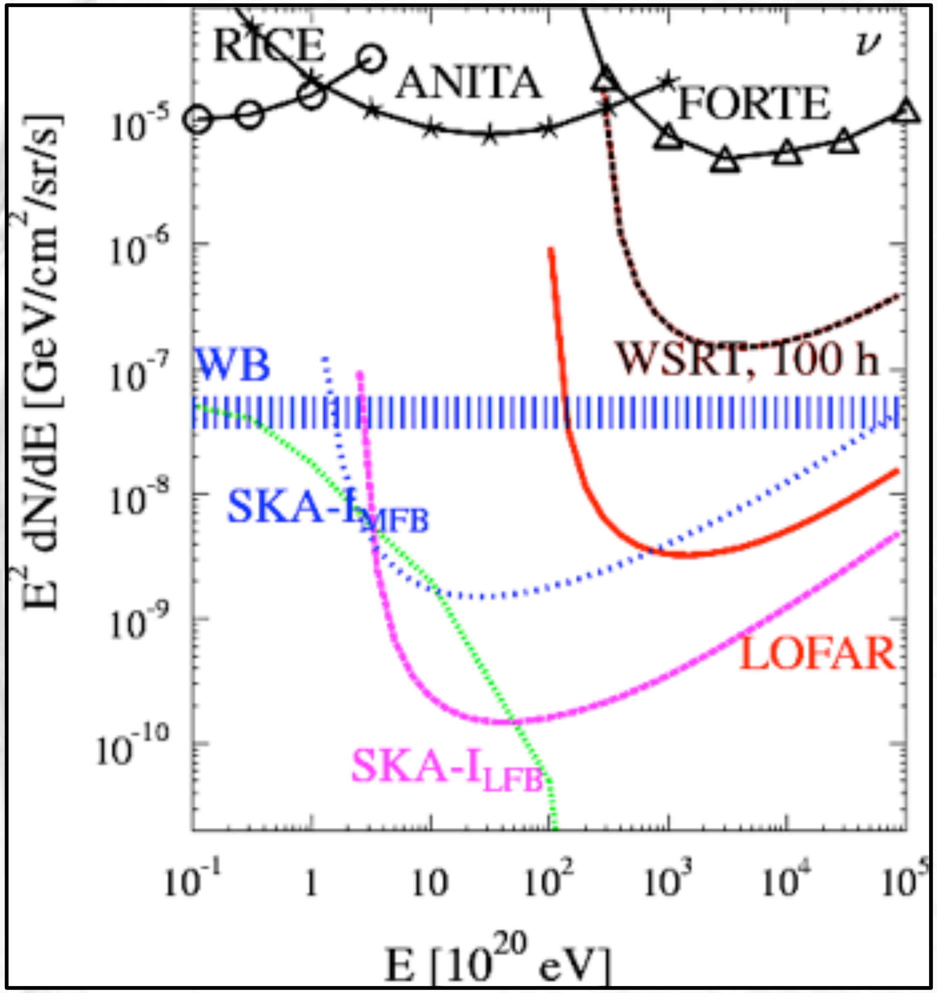
Impulsive

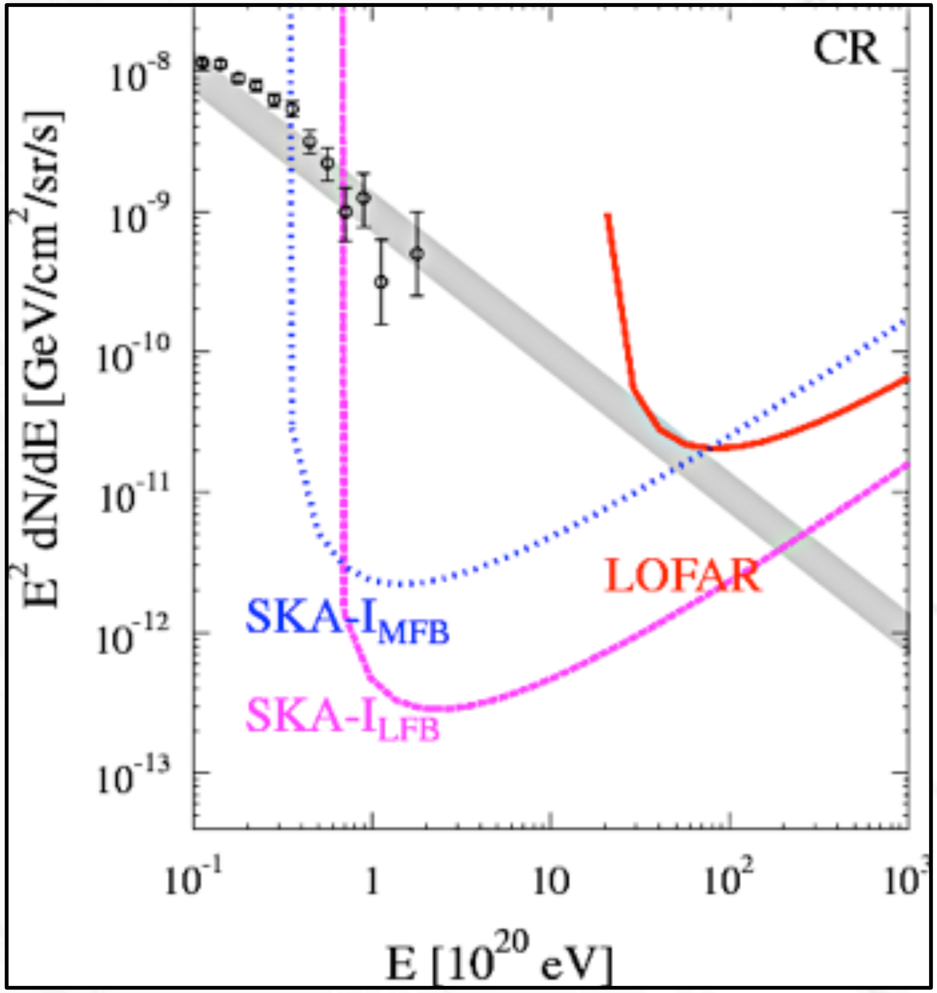
Transient





Sensitivity of radio technique to UHE cosmic rays and neutrinos

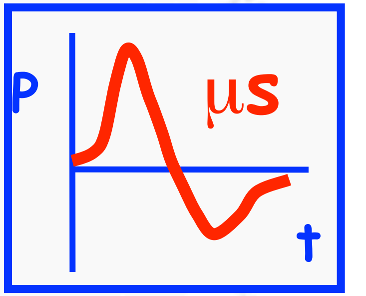


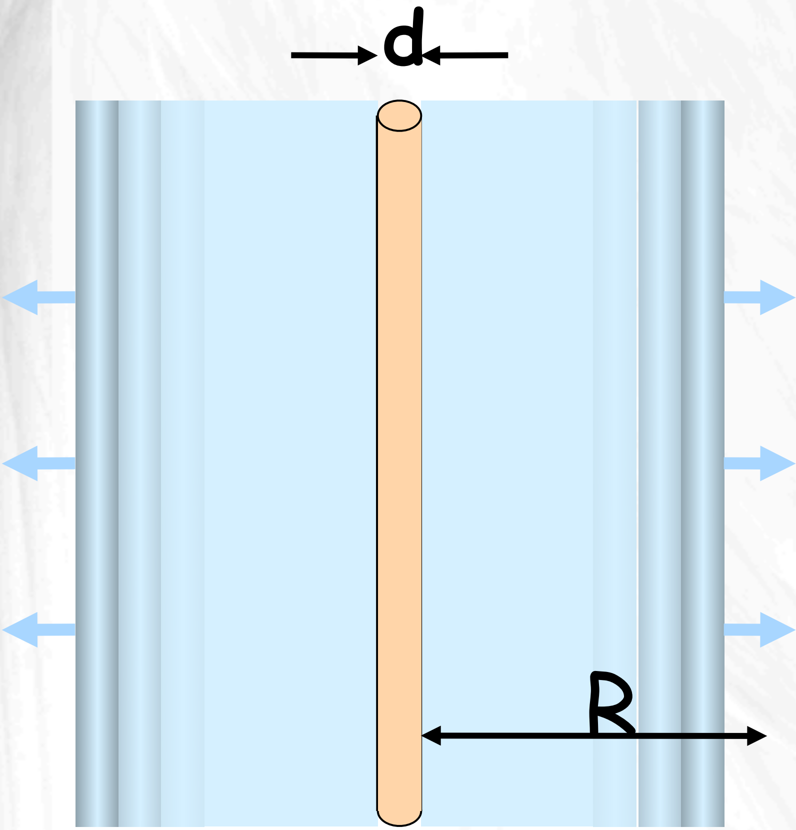


O. Scholten et al., arXiv:0810.3624

Acoustic detection of Neutrinos

Particle cascade → ionization
→ heat
→ pressure wave





Maximum of emission at ~ 20 kHz

Attenuation length of sea water at 15-30 kHz: **a few km**
(light: a few tens of meters)

→ given a large initial signal, huge detection volumes can be achieved.

Threshold > 10^{16} eV

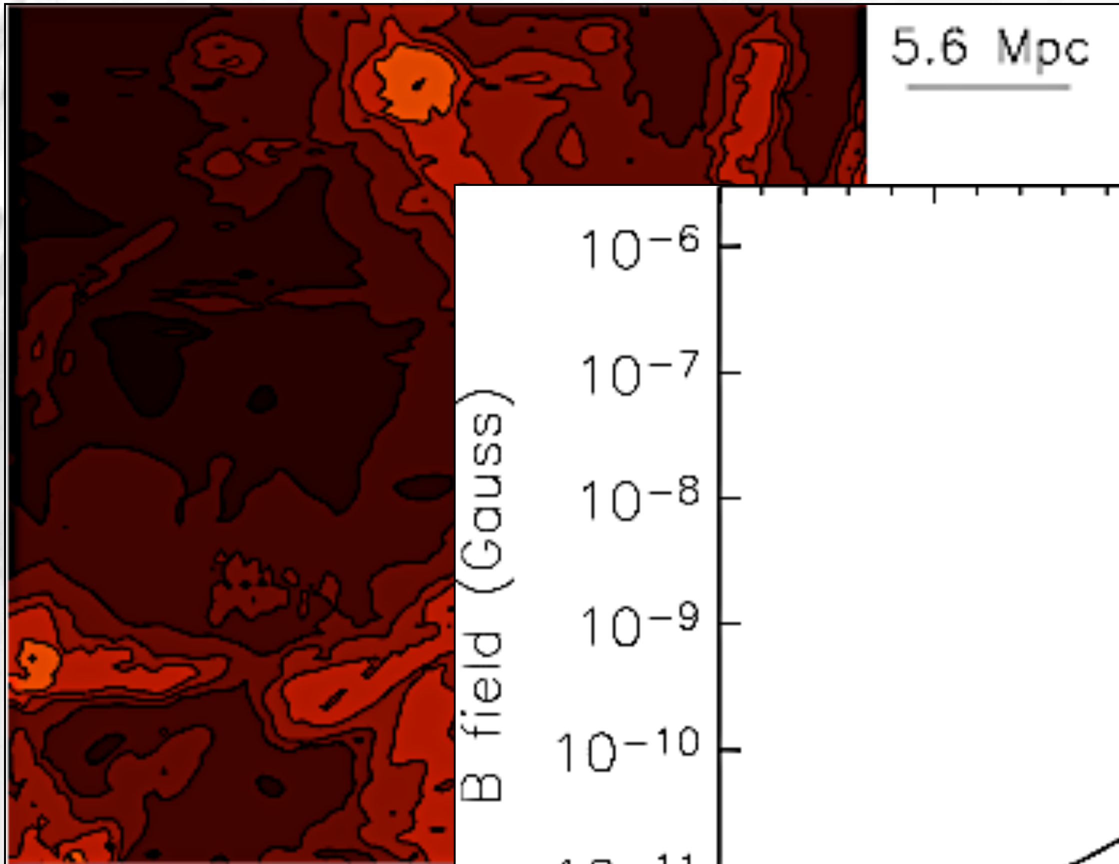
Cosmic Rays, Gamma-Rays, Neutrinos, and Magnetized Sources

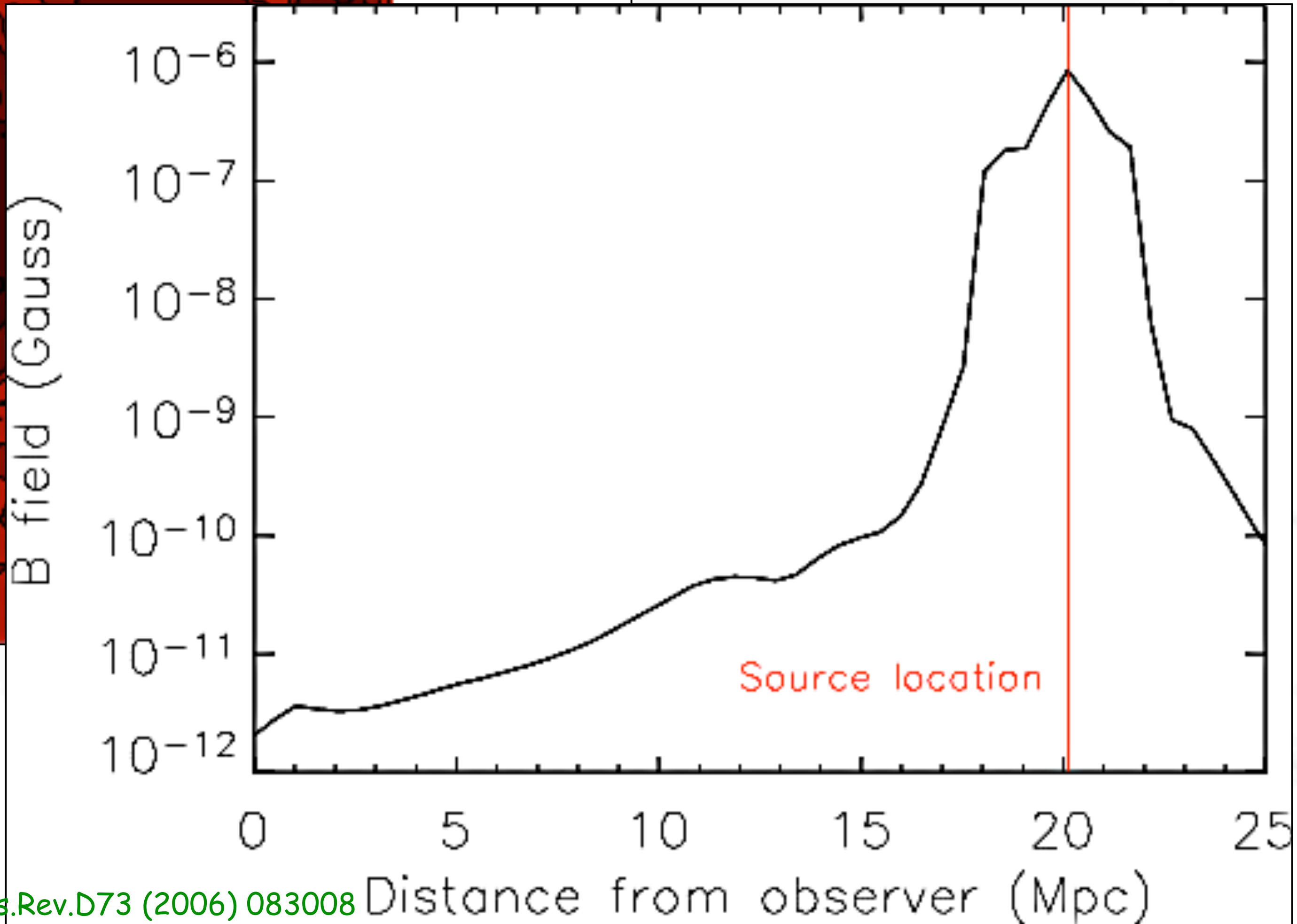
Various connections:
Magnetic fields influence propagation path lengths. This influences:

photo-spallation and thus observable composition, interpretation of ankle

production of secondary gamma-rays and neutrinos, thus detectability of their fluxes and identification of source mechanisms and locations.

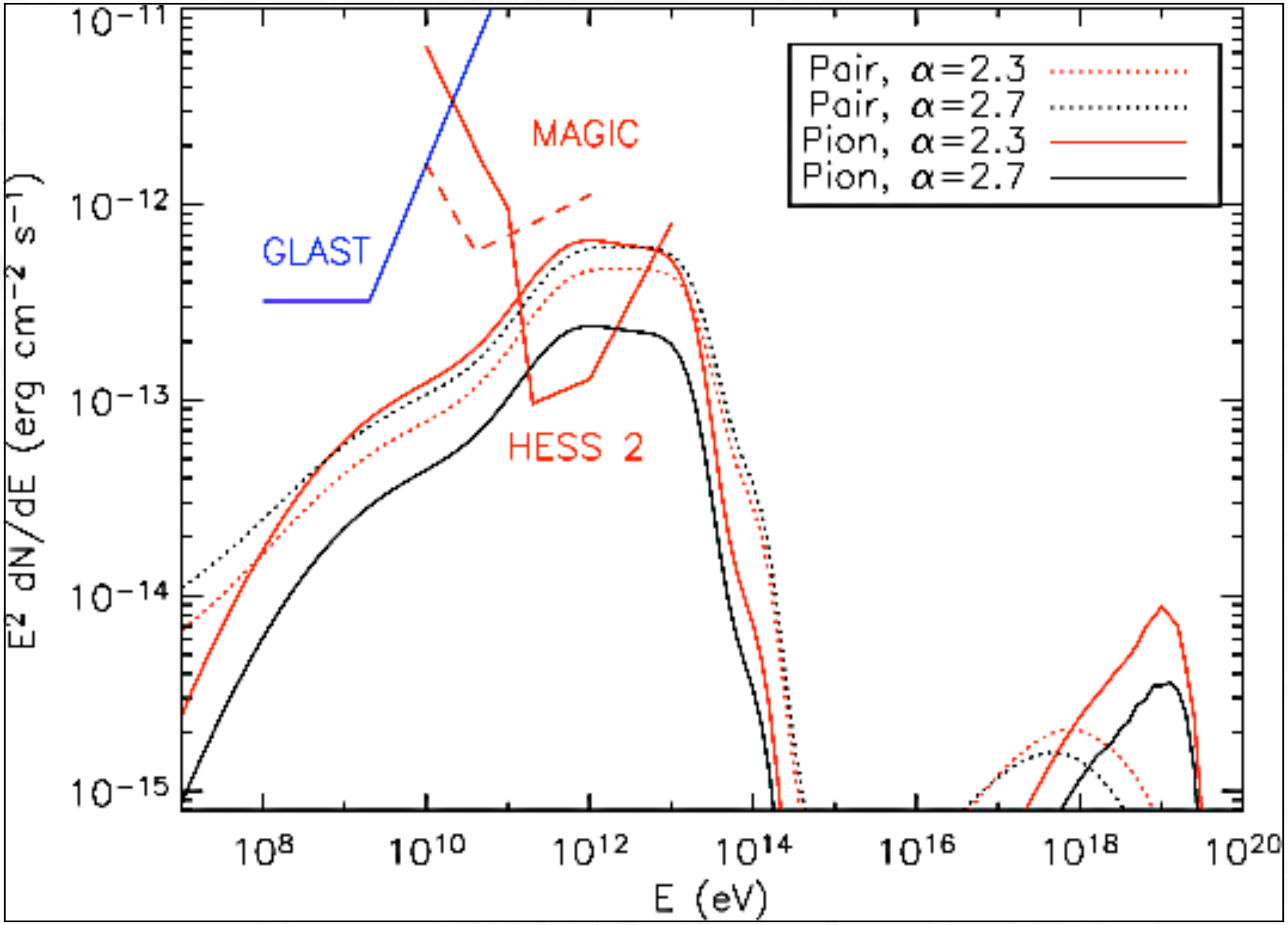
Example:
Discrete Source in a magnetized galaxy cluster injecting protons up to 10^{21} eV





Armengaud, Sigl, Miniati, Phys.Rev.D73 (2006) 083008

Pair production by protons can dominate the GeV-TeV photon flux if injection spectrum is steep. Example for a cluster at 100 Mpc.



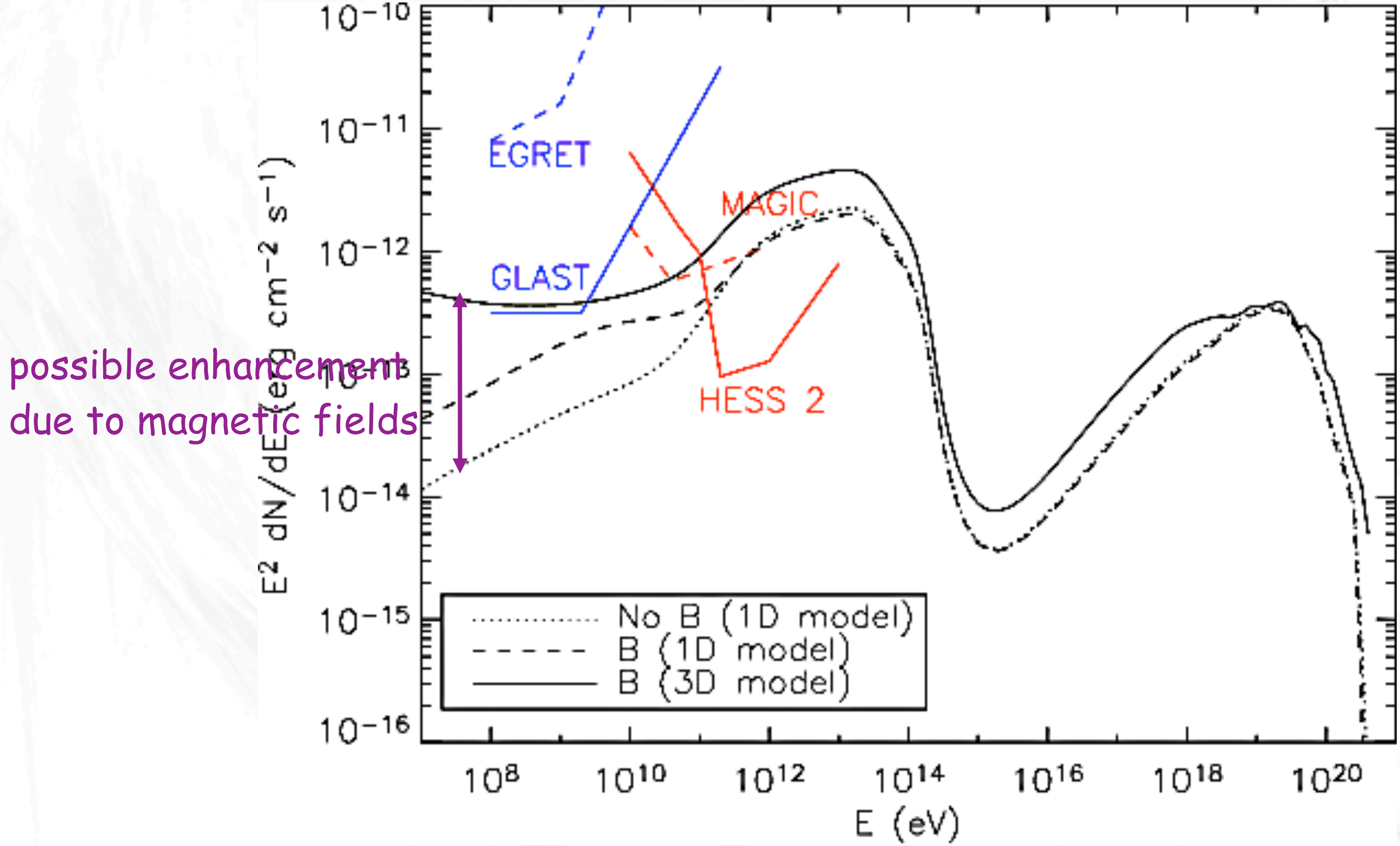
In a magnetic field B, pairs emit synchrotron photons of typical energy

$$E_{\rm syn} \simeq 6.8 \times 10^{11} \left(\frac{E_e}{10^{19}\,{\rm eV}}\right)^2 \left(\frac{B}{0.1\,\mu{\rm G}}\right) {\rm eV}$$

For pion production $E_e \sim 5 \times 10^{18}$ eV. Thus, in a 0.1 Gauss field, synchrotron radiation ends up below ~ 0.1TeV.

Pair production occurs for proton energies 10^{18} eV ≤ E ≤ 4×10^{19} eV which in ~ 0.1G fields thus ends up in synchrotron photons below ~ 1GeV. If the proton spectrum is steeper then ~ E^{-2}, the sub-GeV photon flux is dominated by synchrotron photons from pair production.

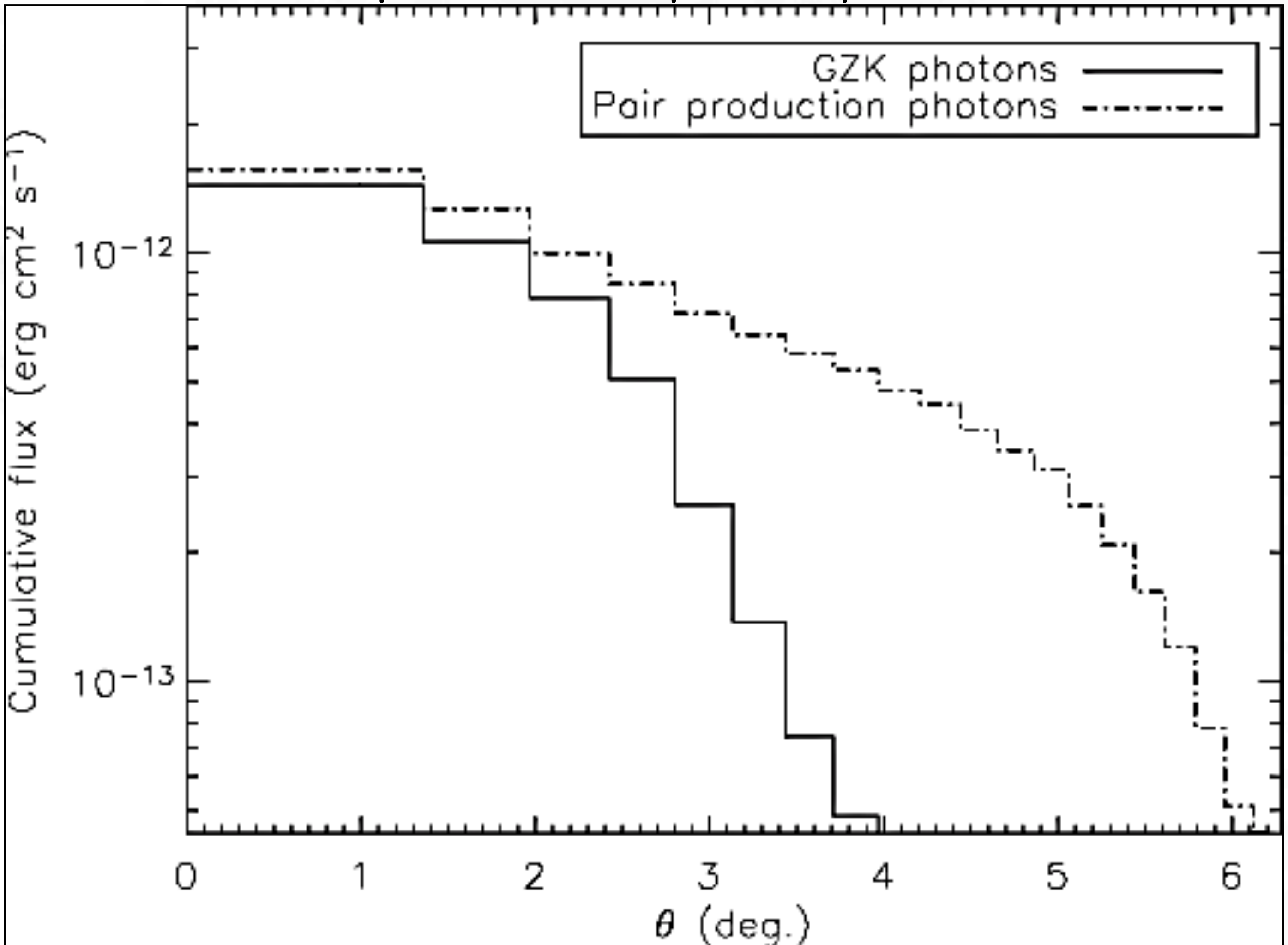
Source at 20 Mpc, $E^{-2.7}$ proton injection spectrum with 4×10^{42} erg/s above 10^{19} eV



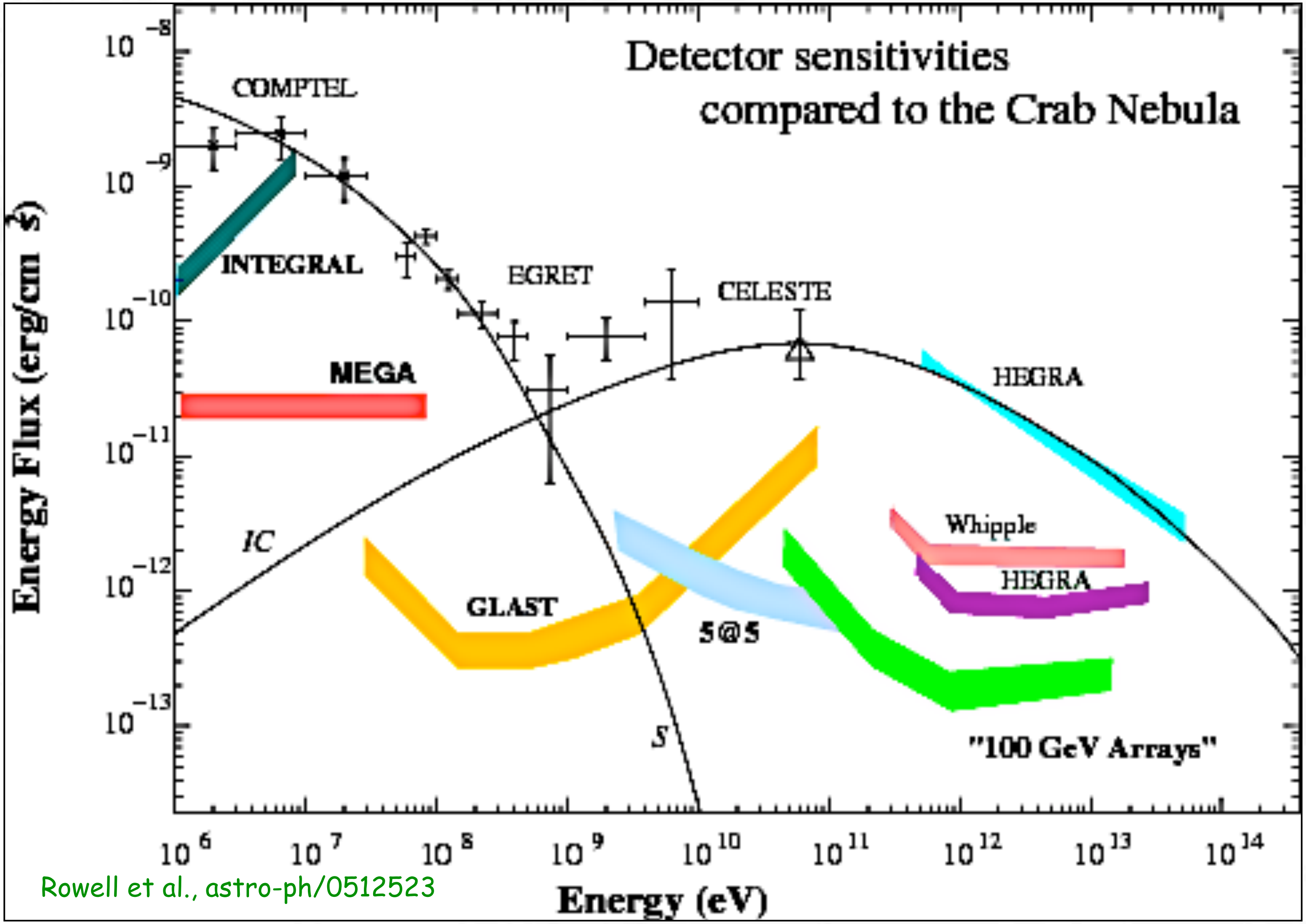
Note that the 3d structure of the field matters and leads to further enhancement of GeV γ-ray fluxes.

The source magnetic fields can give rise to a **GeV-TeV γ-ray halo** that would be easily resolvable by instruments such as HESS

In case of previous example, γ-rays above 1 TeV:

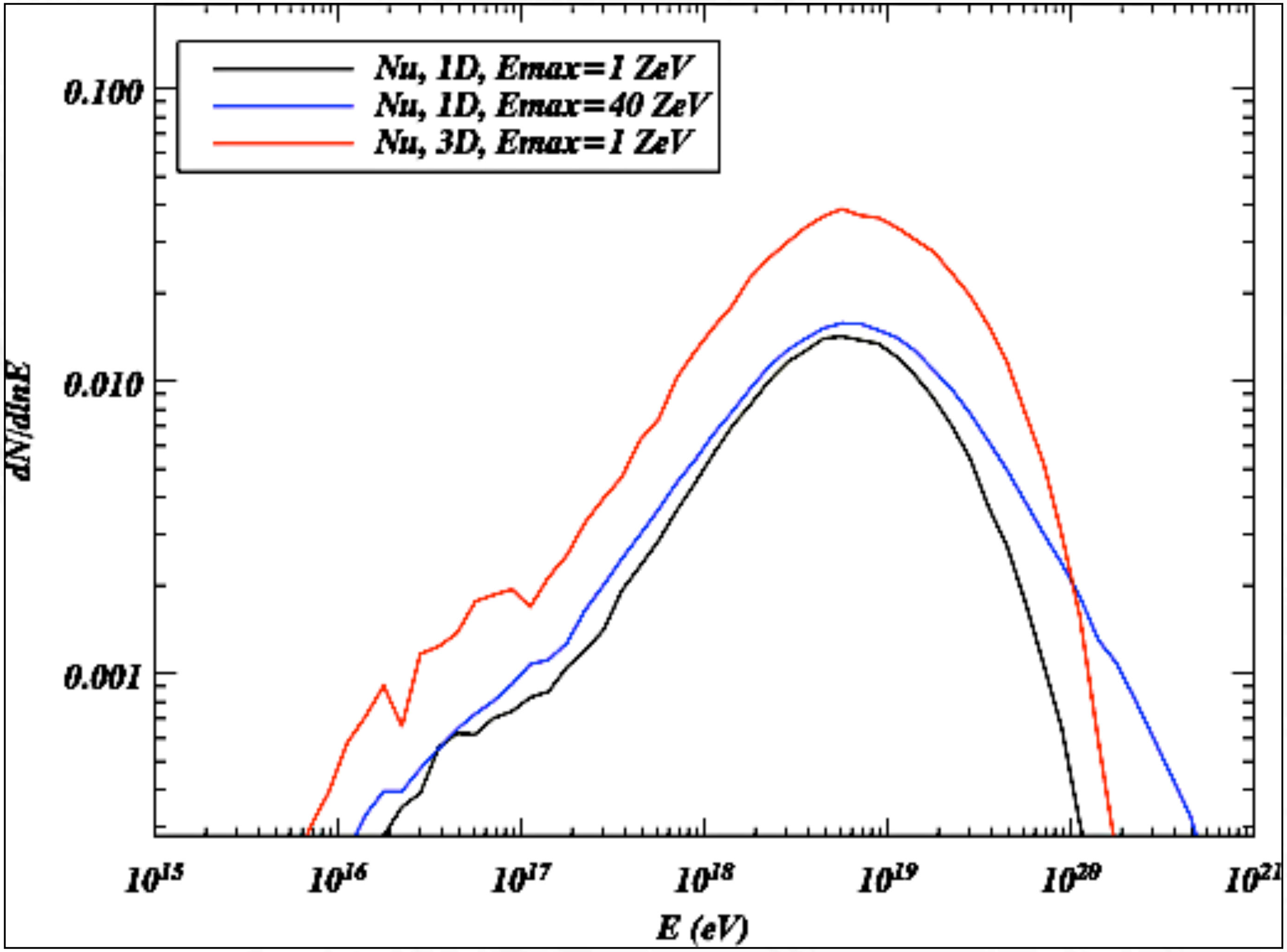


This is quite relevant for γ-ray astronomy in the GeV-TeV band

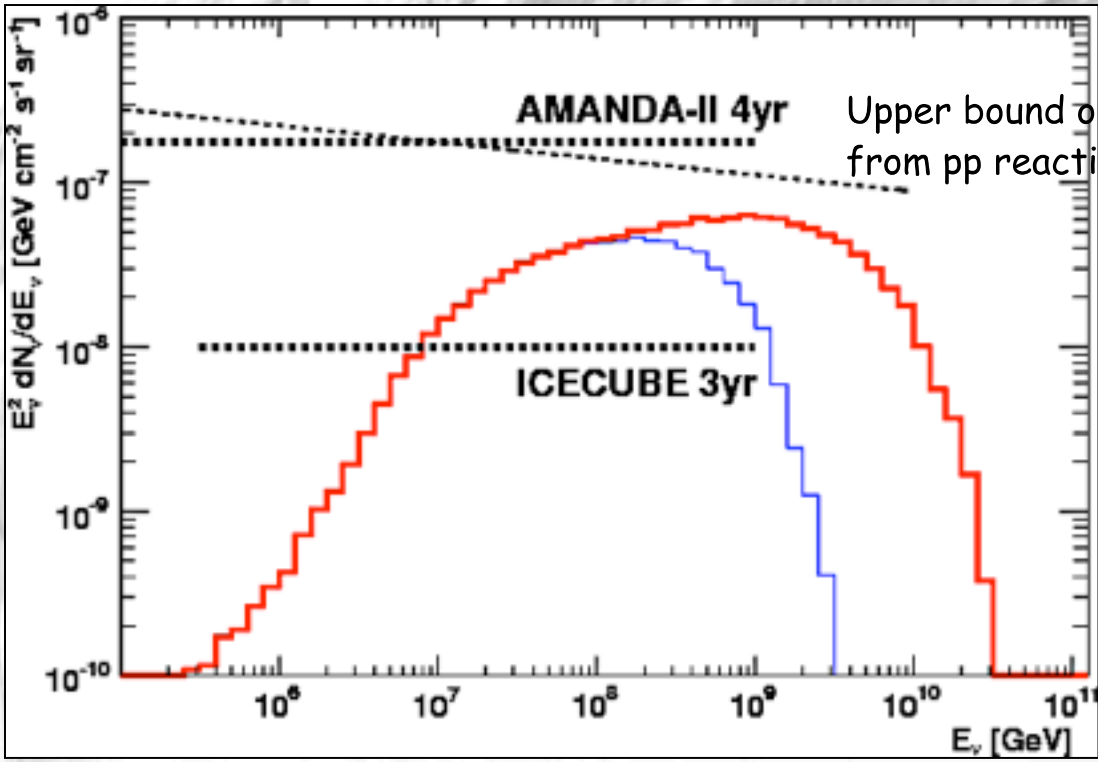


Rowell et al., astro-ph/0512523

The GZK neutrino flux can also be enhanced by magnetic fields

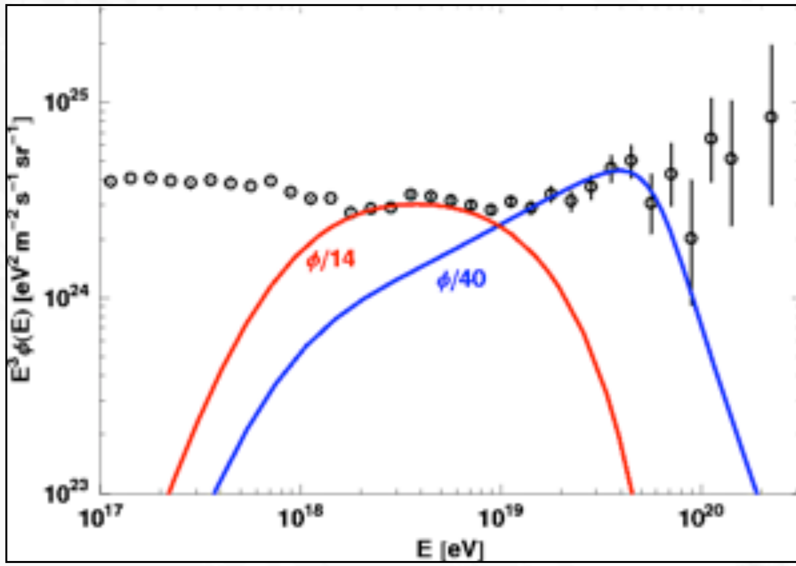


Maximal diffuse neutrino flux from magnetized galaxy clusters



Upper bound of ν-flux from pp reactions

De Marco et al., Phys.Rev.D73 (2006) 043004



Shortcomings:

- overproduces UHECR flux by factors 10-40 if not blocked by magnetic horizon effects
- neglects neutrinos produced by photo-reactions outside the clusters

Neutrino Fluxes from Compact Sources

For example, γ-ray bursts, neutron stars.

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

$$t_{\pi,\mu}(E) = \tau_{\pi,\mu}\frac{E}{m_{\pi,\mu}} \propto E^1$$

$$t_{\rm had}(E) \simeq \frac{1}{n_p\sigma_h(E)} \propto E^0$$

$$t_{\rm rad}(E) \simeq \frac{1}{u_\gamma\sigma_{\rm rad}\eta(E)} \propto m^4_{\pi,\mu}E^{-1}$$

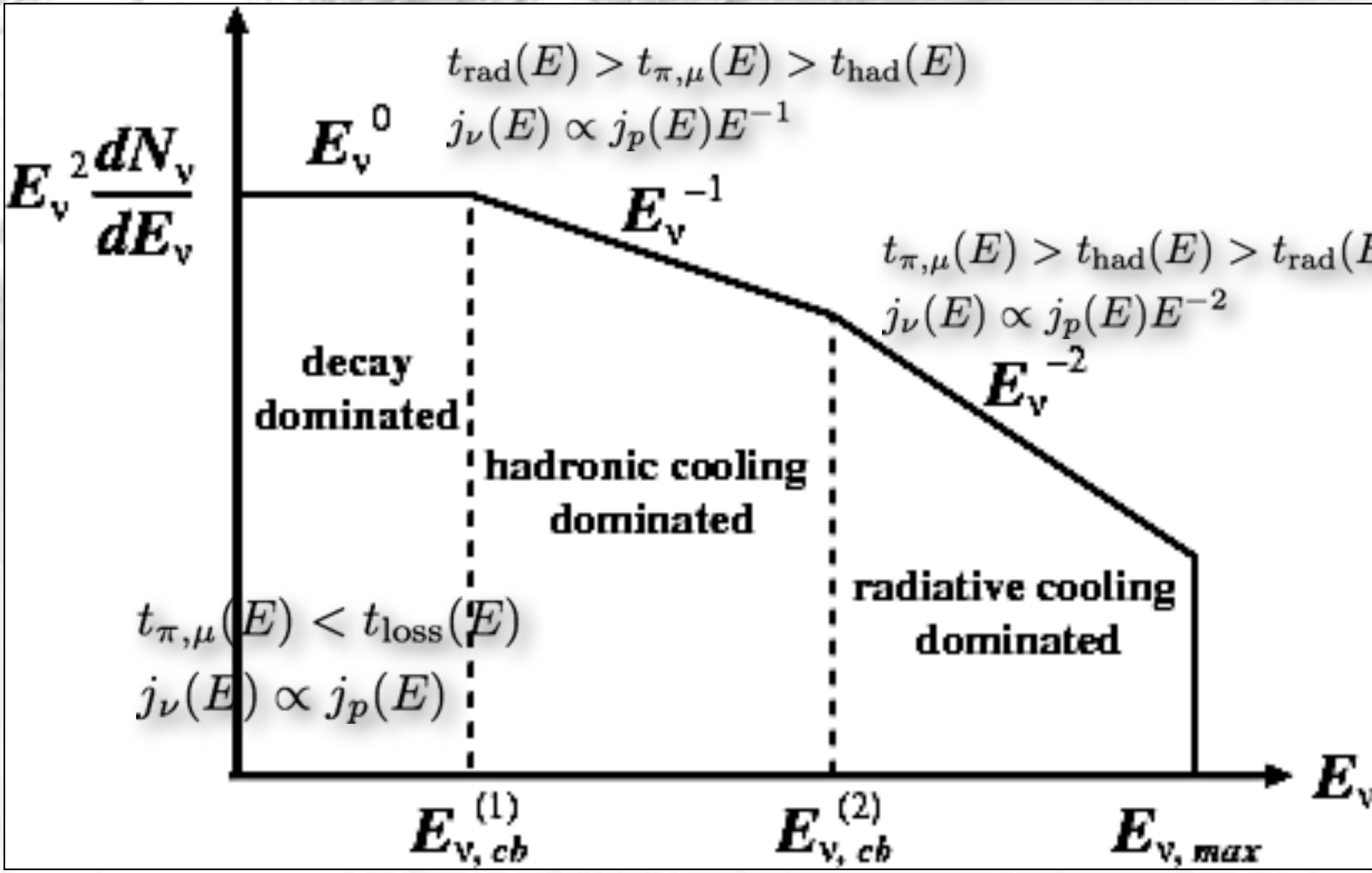
where $\sigma_{rad} \propto E^{-1}$ and the inelasticity $\eta(E) \propto E^2$ in the non-relativistic regime.

Then, for the loss rate $t_{loss}(E)^{-1} = t_{had}(E)^{-1} + t_{rad}(E)^{-1}$,

one has $j_\nu(E) \propto \min[1, t_{loss}(E)/t_{\pi,\mu}(E)]j_p(E)$ because $t_{loss}(E)/t_{\pi,\mu}(E)$ 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 $t_\mu \sim 100 t_\pi$ such that 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, 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

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

For flavors $|\nu_\alpha\rangle$ injected with relative weights w_α at the source, the flux of flavor $|\nu_\beta\rangle$ at the observer is then (averaged over the oscillations)

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

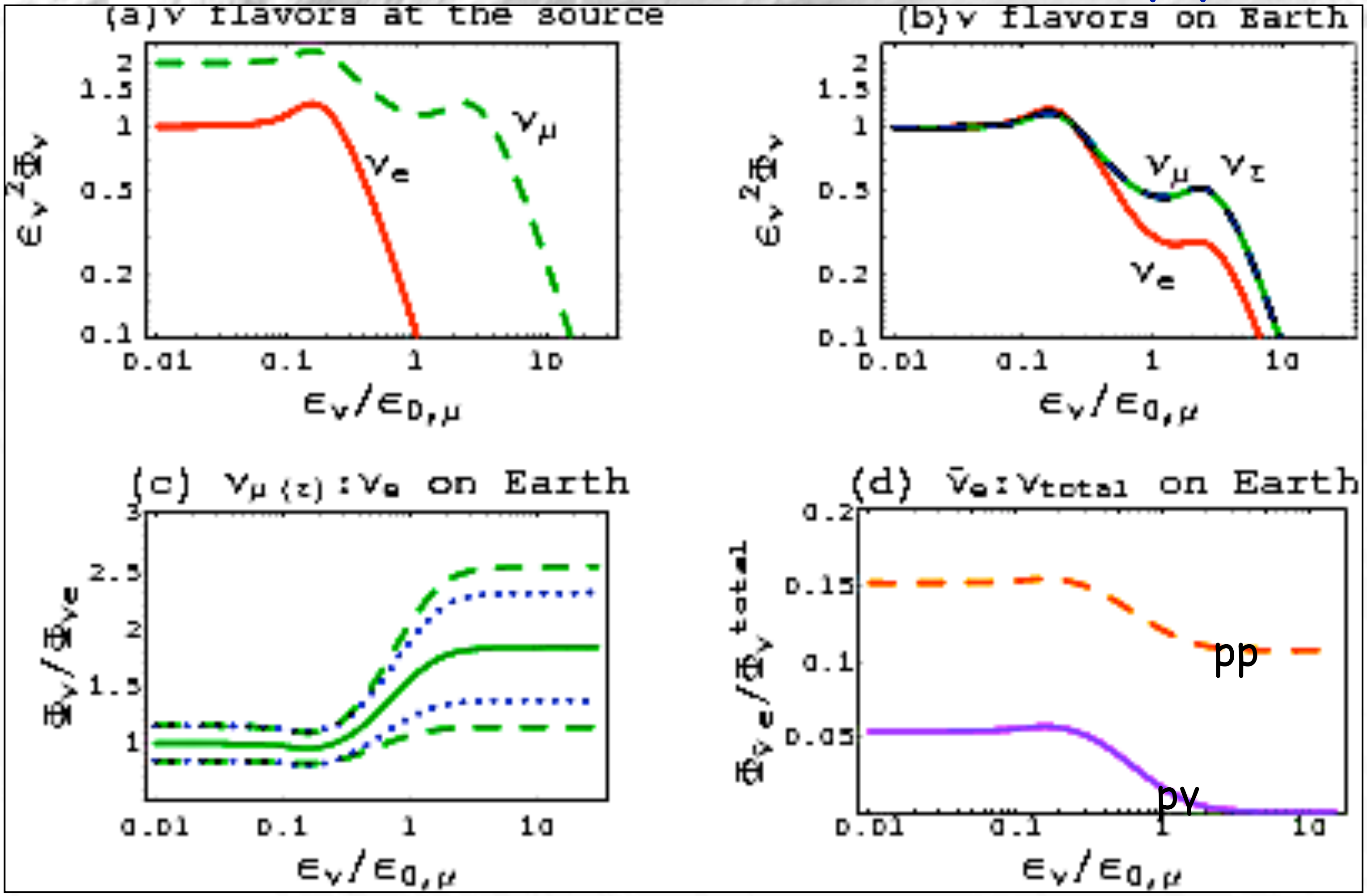
Examples for detectable flavor effects

Sensitivity to source physics: 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 $\phi_e : \phi_\mu : \phi_\tau \simeq \frac{1}{3} : \frac{1}{3} : \frac{1}{3}$. 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 $\phi_e : \phi_\mu : \phi_\tau \simeq \frac{1}{3} : \frac{1}{3} : \frac{1}{3}$.

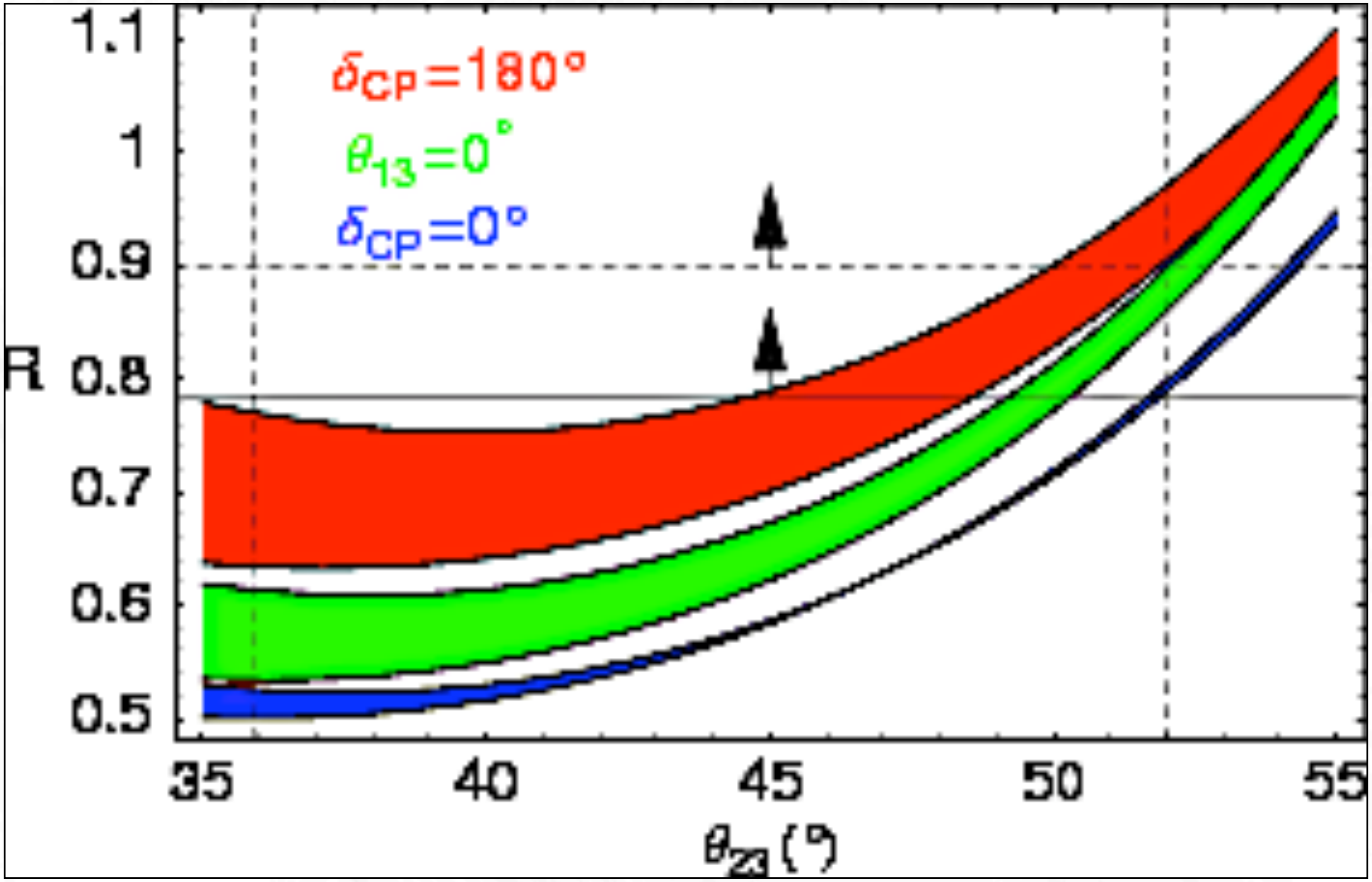
Observed Flavor Ratios can be sensitive to source physics



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.

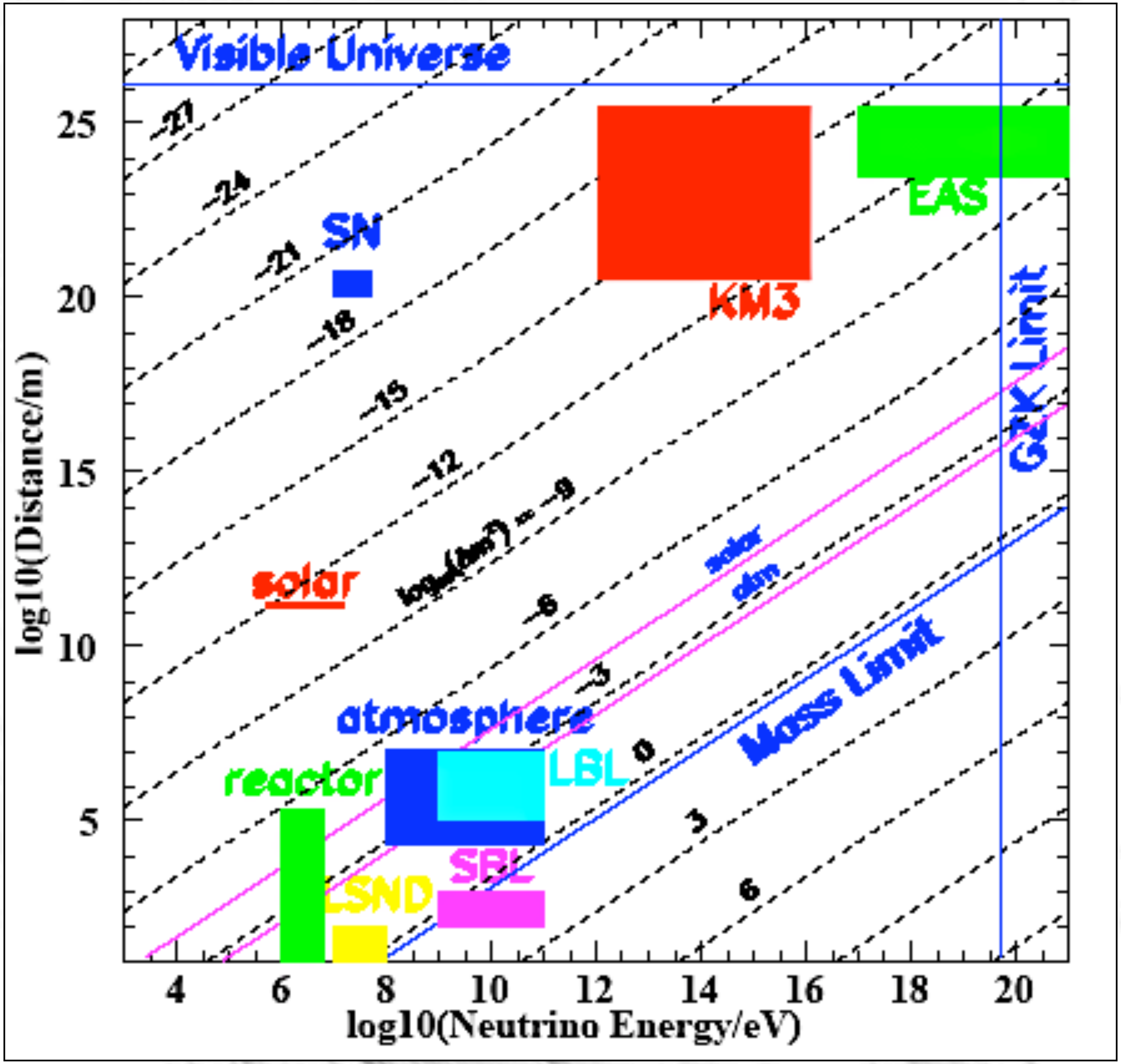
Observed Flavor Ratios can be sensitive to oscillation parameters



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

Sensitivity of astrophysical neutrinos to oscillations: The Learned Plot



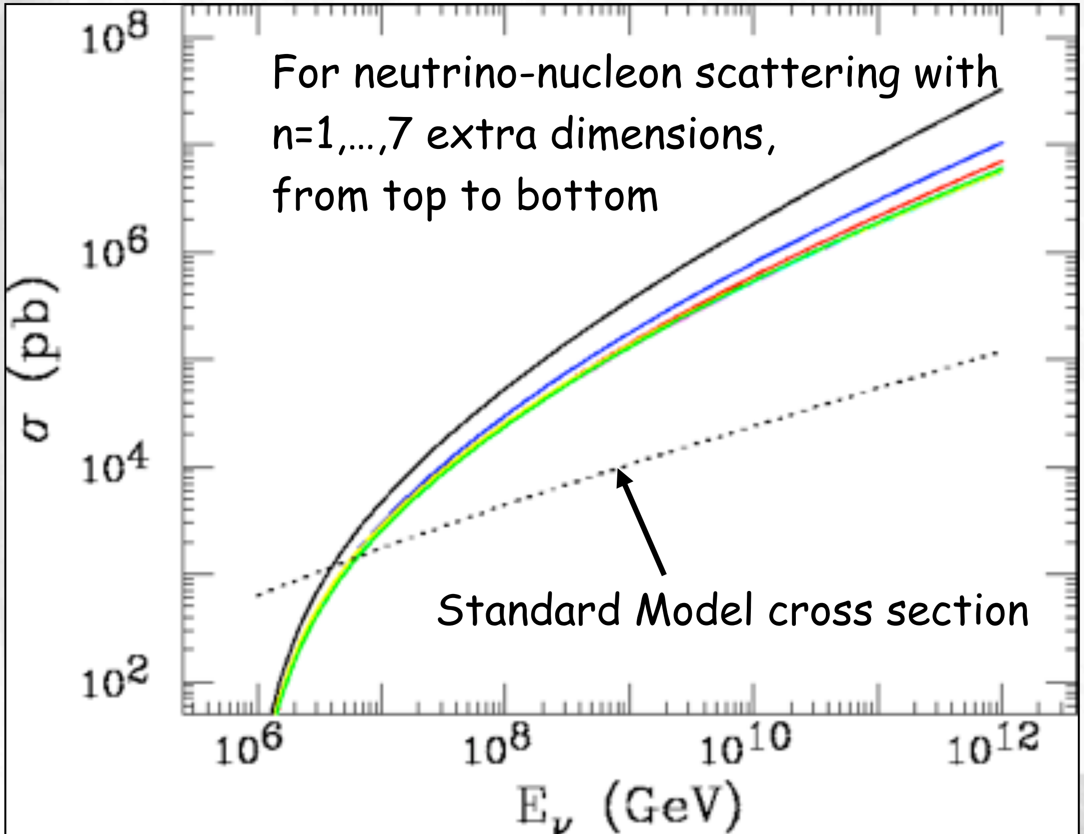
Oscillation phase is
(L Δm^2 / 4 E_n)
Numbers indicate Δm^2/eV^2.

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

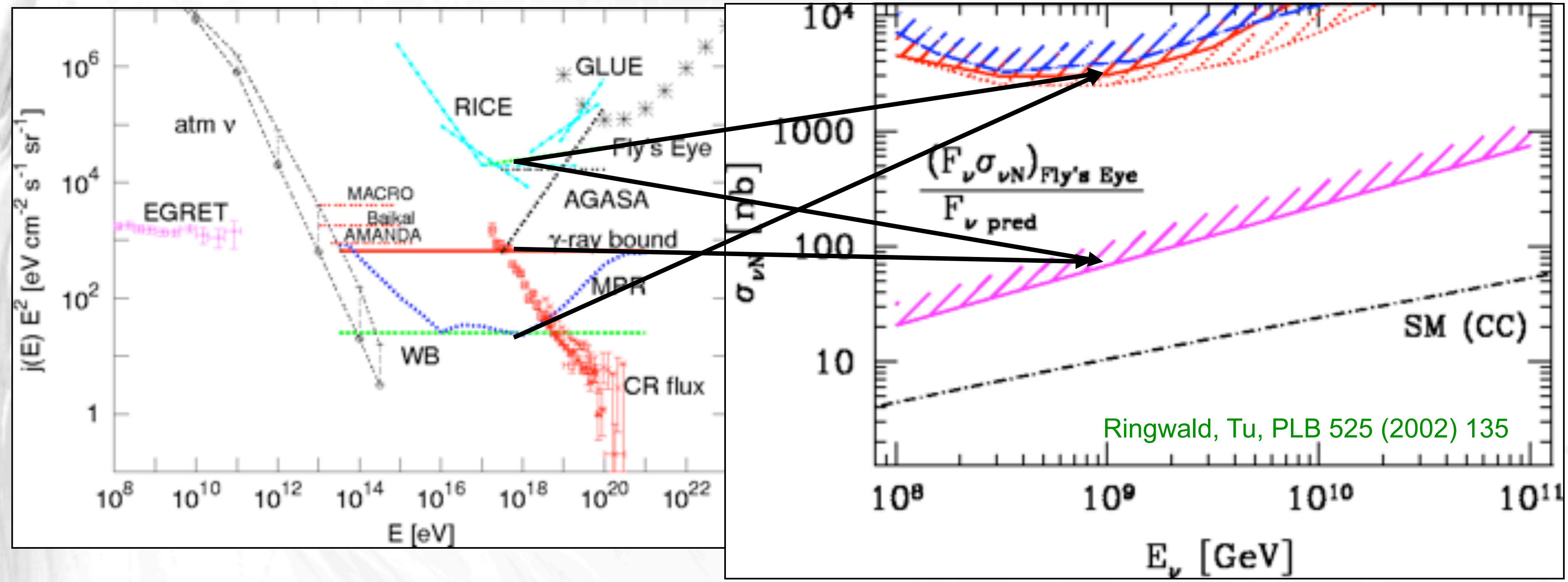
Example: microscopic black hole production in scenarios with a TeV string scale:



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

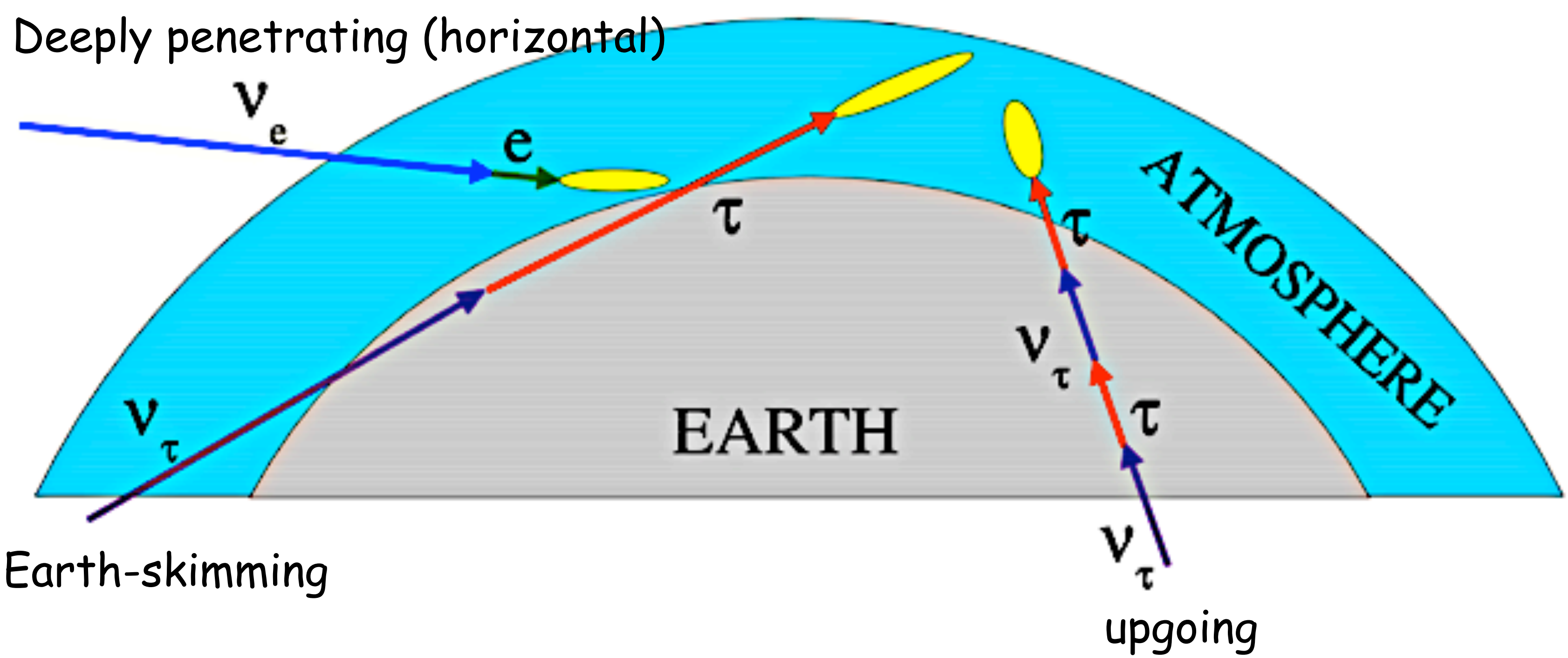
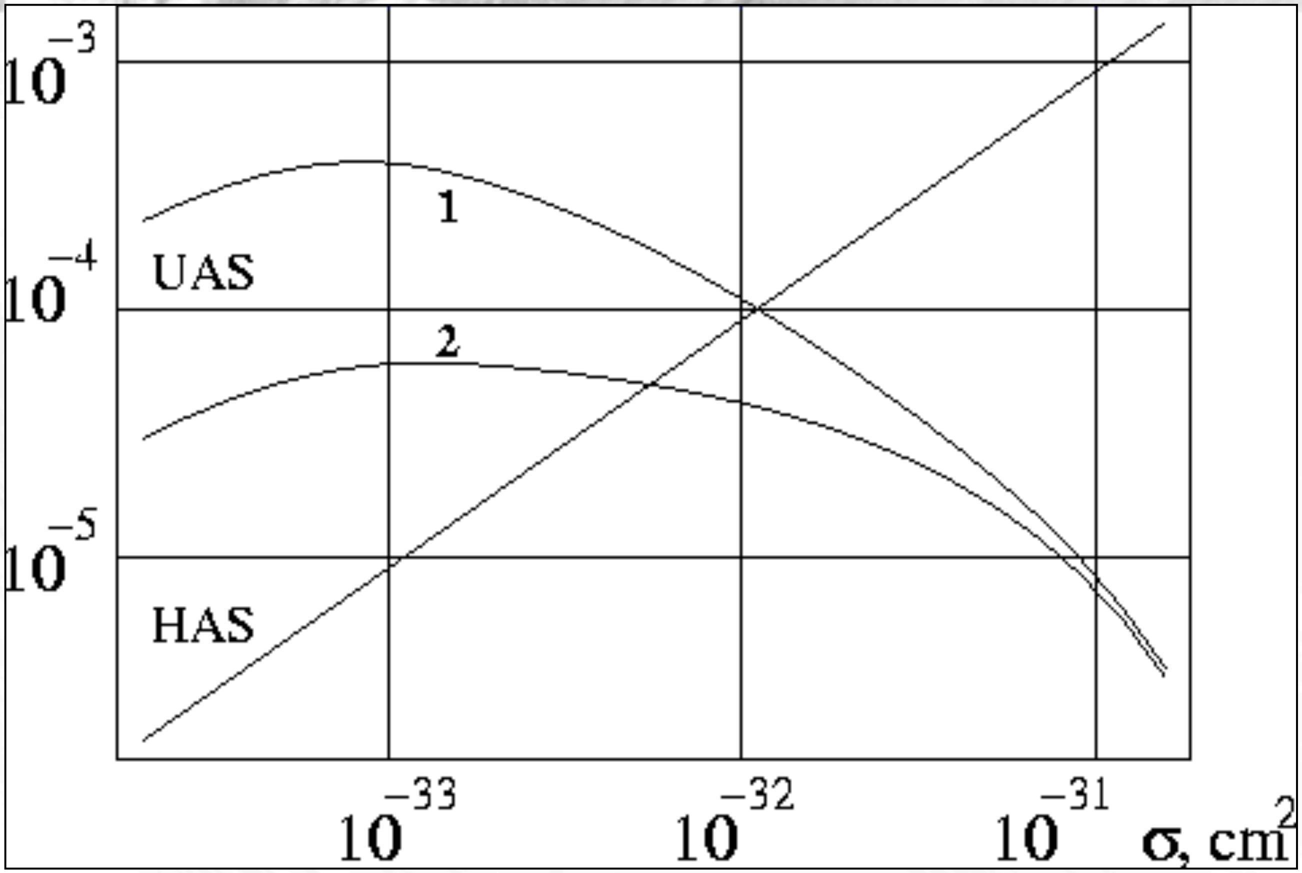


Figure from Cusumano

Earth-skimming τ-neutrinos

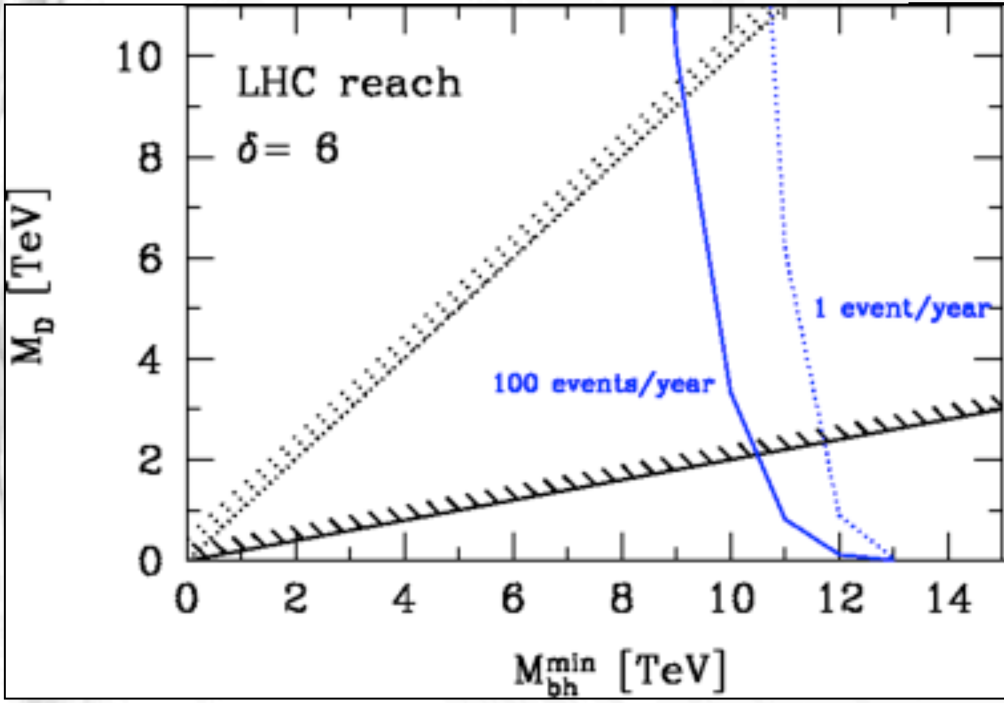


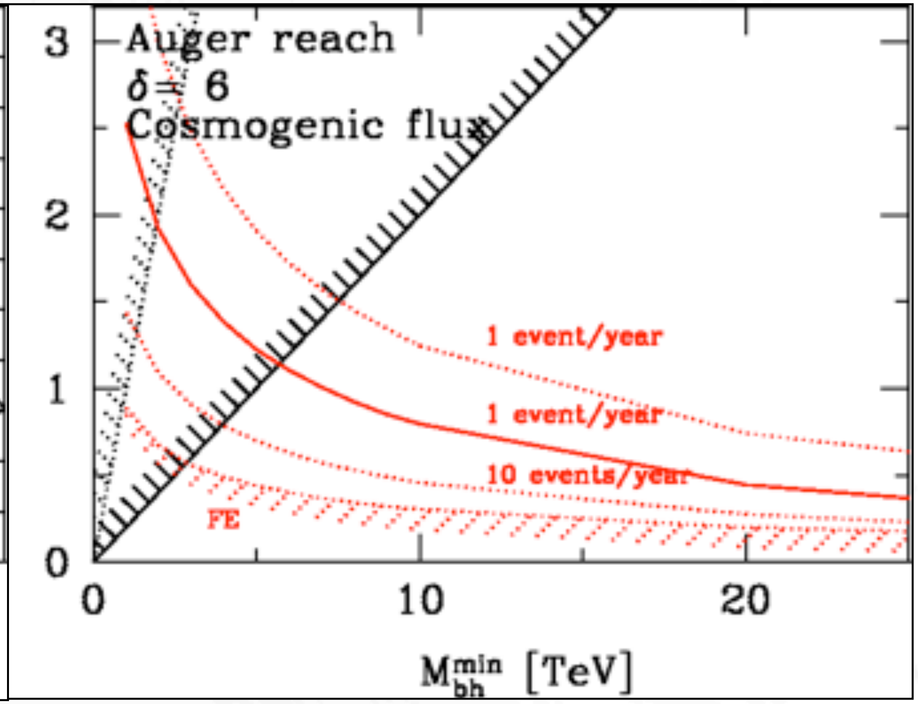
Air-shower probability per τ-neutrino at 10^{20} eV for 10^{18} eV (1) and 10^{19} eV (2) threshold energy for space-based detection.

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



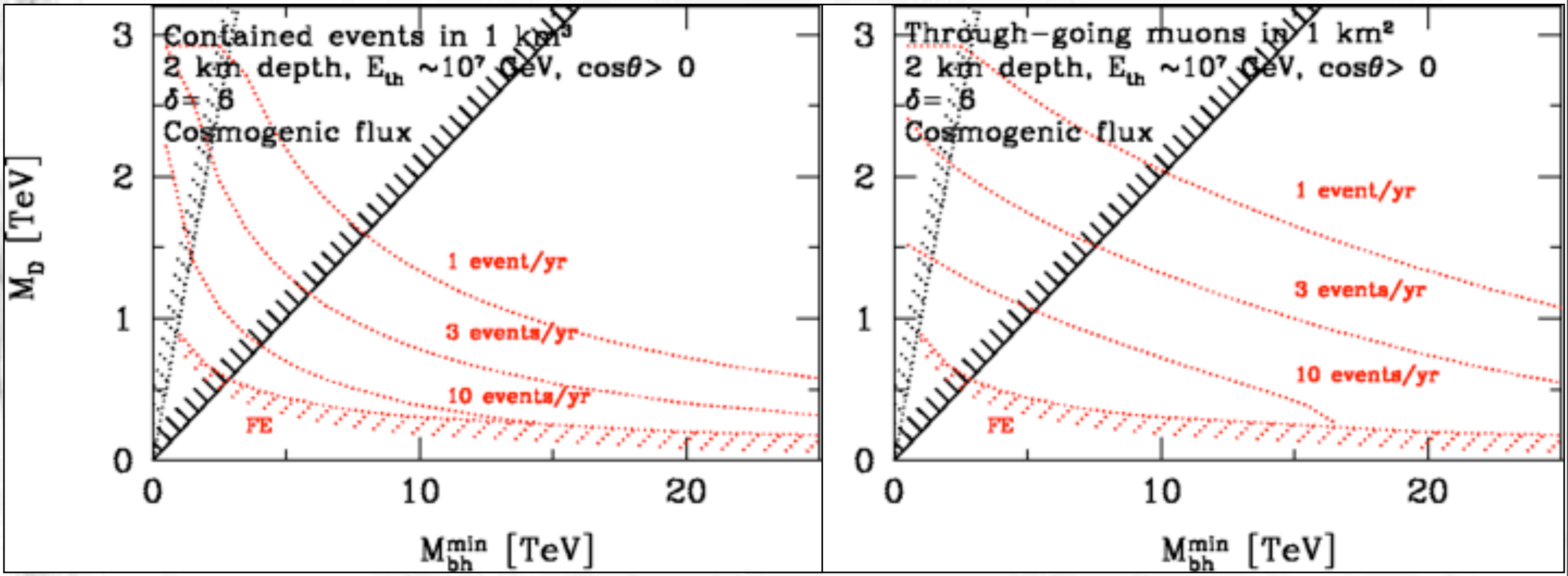


M_D = fundamental gravity scale; M_{bh}^{min} = minimal black hole mass

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},

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

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

For the i-th neutrino mass eigenstate this gives

$$p_i \simeq E + \frac{m_i^2}{2E} + \frac{1}{2} \sum_{n=1}^{\infty} \xi_n^{(i)} \frac{E^{n+1}}{M_{\rm Pl}}$$

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

$$E \simeq M_{\rm Pl} \left(\frac{\Delta m^2}{M_{\rm Pl}^2 \xi_n} \right)^{\frac{1}{n+2}} \simeq 0.2\,,\, 2\times 10^4\,,\, 1.8\times 10^7\,,\, 1.7\times 10^9\,\mathrm{GeV}$$

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 $\exp(-\alpha L)$:
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

Lorentz symmetry violations in the Nucleon Sector

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

$$E^2 - p^2 \simeq m^2 - \xi \frac{p^3}{M_{\rm Pl}} - \zeta \frac{p^4}{M_{\rm Pl}^2} + \cdots$$

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

Introducing the standard threshold momentum for pion production, N+γ->Nπ,

$$p_0 = \frac{2m_N m_\pi + m_\pi^2}{4\epsilon}$$

the threshold momentum p_{th} in the modified theory is given by

$$-\frac{p_0^3}{(m_\pi^2 + 2m_\pi m_N)M_{\rm Pl}} \frac{m_\pi m_N}{(m_\pi + m_N)^2} \left[2\xi \left(\frac{p_{\rm th}}{p_0}\right)^3 + 3\zeta \frac{p_0}{M_{\rm Pl}} \left(\frac{p_{\rm th}}{p_0}\right)^4 + \cdots \right] + \frac{p_{\rm th}}{p_0} = 1$$

Attention: this assumes standard energy-momentum conservation which is not necessarily the case.

Coleman, Glashow, PRD 59 (1999) 116008; Alosio et al., PRD 62 (2000) 053010

For $\xi \sim \zeta \sim 1$ this equation has no solution => No GZK threshold!

For $\zeta \sim 0$, $\xi \sim -1$ the threshold is at ~1 PeV!
For $\xi \sim 0$, $\zeta \sim -1$ the threshold is at ~1 EeV!

Confirmation of a normal GZK threshold would imply the following limits:

$|\xi| < 10^{-13}$ for the first-order effects.
$|\zeta| < 10^{-6}$ for the second-order effects.

Energy-independent (renormalizable) corrections to the maximal speed $V_{max} = \lim_{E \to \infty} \partial E/\partial p = 1 - d$ can be constrained by substituting $d \to (\xi/2)(E/M_{Pl}) + (\zeta/2)(E/M_{Pl})^2$.

The modified dispersion relation also leads to energy dependent group velocity $V = \partial E/\partial p$ and thus to an energy-dependent time delay over a distance d:

$$\Delta t = -\xi \, d \frac{E}{M_{\rm Pl}} \simeq -\xi \left(\frac{d}{100\,{\rm Mpc}} \right) \left(\frac{E}{\rm TeV} \right) {\rm sec}$$

for $\zeta = 0$. GRB observations in TeV γ-rays can therefore probe quantum gravity. The current limit is $M_{Pl}/\xi > 8\times10^{15}$ GeV (Ellis et al.).