Diffuse Ultrahigh Energy Neutrino Fluxes and Physics beyond the Standard Model

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work done with **Atri Bhattacharya, Sandhya Choubey and Atsushi Watanabe**

Introduction . . .

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- **Inspite of the fact that almost all of our information has been garnered from experiments below a ~ 10 GeV, it has become clear that neutrino physics provides a unique window into physics beyond the SM. .**

- Although the neutrino is the most abundant particle in the universe after the photon, the only extra-terrestial neutrinos observed are those from the sun and the few events fron SN1987A.

Introduction: The Neutrino Sky . . .

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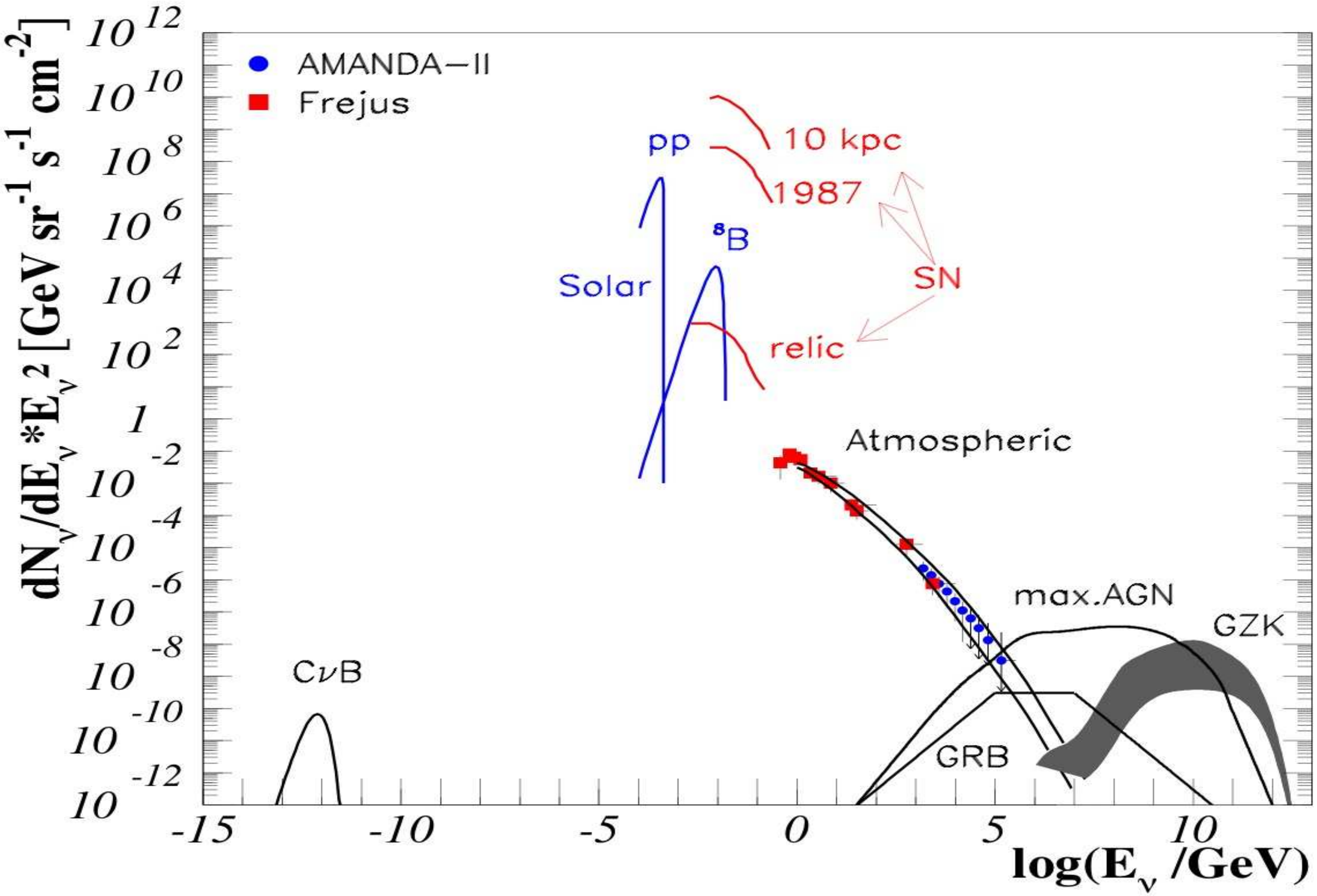

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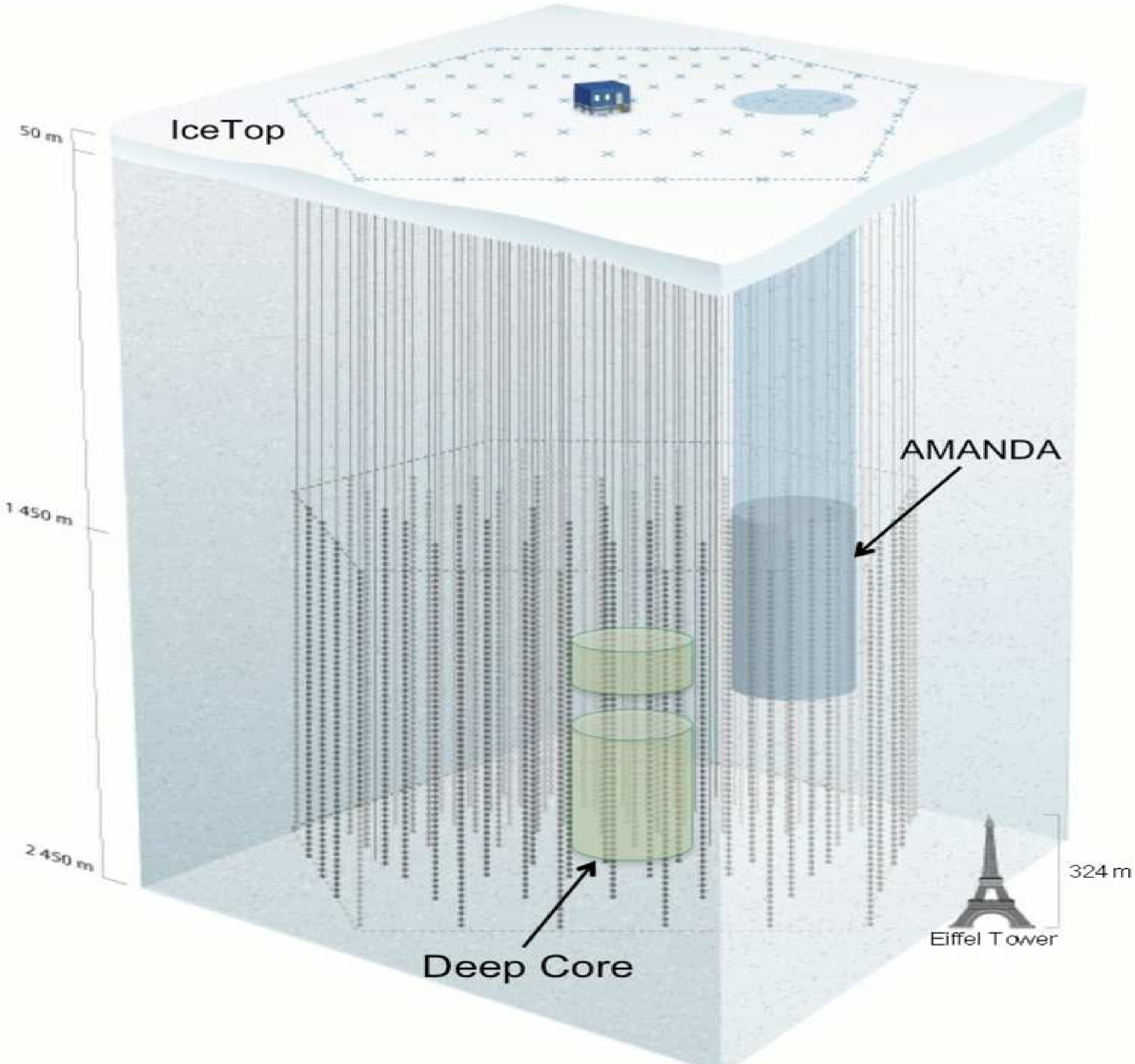
Current and Future Detectors . . . *ICECUBE*



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- **ANTARES, NEMO Cerenkov detectors in the Mediterrenean, eventually to be part of KM3NET. AMADEUS, an accoustic detector taking data since Dec 07, is also part of ANTARES setup.**

Current and Future Detectors

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- **ANITA, a balloon payload experiment over the Antarctic,monitoring an effective volume of 10^6 Km^3 (!) of Ice for Radio emission by EM showers created by neutrino events with energies in excess of 10^9 GeV (Askaryan effect). Bound on total ν flux at these energies set.**

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- Flavour identification of muons possible via the long charged track and (hadronic) shower characteristic of ν_μ CC interactions. .

- Counting of the combined total of ν_e CC and NC interactions of all flavours via identification of electromagnetic and hadronic showers unaccompanied by long charged lepton track.

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- **ν_τ CC interactions produce a rapidly decaying τ in most cases, along with a (hadronic) shower. Above a PeV, τ events detectable as "double bang", "lollipops" or "earth-skimming" (AUGER). ν_τ remains alive in the earth, unlike ν_μ, ν_e which get attenuated above a PeV. .**

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- The 3 categories of detected events are thus:
  - Long muon tracks, counting ν_μ CC events
  - Showers, counting ν_e CC + NC, ν_τ (CC at lower E) + NC and ν_μ NC.
  - Double bang and lollipops, counting ν_τ above a few PeV

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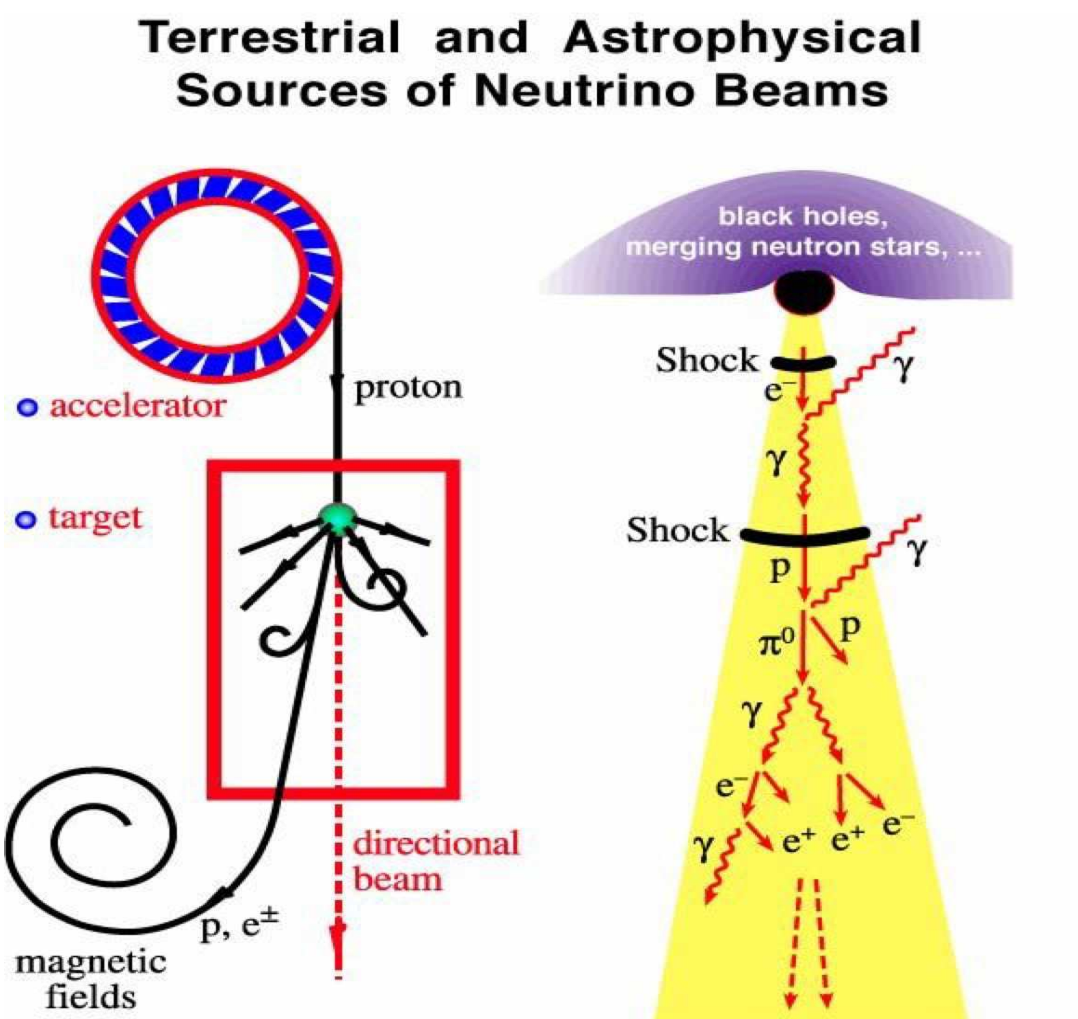
- Conservatively, assume that within a given decade of energy, the number of ν_μ events and the number of ν_e events can be measured to within 20%.
- The number of shower events in the energy bin then becomes a measure of the distortion from the spectral shape set by the muon events

The Generic UHE Accelerator . . .



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- **Charged particle ($e, p,$ions) acceleration acheived by confining them in its B field. Electrons quickly lose their energy via synchrotron radiation, and the photons created act as targets for the protons.**
- $p + \gamma \rightarrow \Delta^+ \rightarrow \pi^0 + p$ **and** $p + \gamma \rightarrow \Delta^+ \rightarrow \pi^+ + n$ **interactions. Pions decay to μ and ν, protons tend to stay confined, neutrons and neutrinos leave the accelerator, with the former later decaying to give protons.**

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- **The branching ratios, all of $\sim O(1)$ are known from particle physics, giving comparable and co-related fluxes for CR, γ rays and ν .Observations of TeV γ rays and CR thus can put bounds on the UHE ν fluxes**
  (Waxman and Bahcall; Mannheim, Protheroe and Rachen)

Calculating the Diffuse UHE fluxes . . .

- Spectral shape at source depends on the astrophysics model for that particular class of sources. A very important class of sources are Active Galactic Nuclei (AGN). Typically, AGNs lead to UHE neutrino fluxes which are much above those from other types of sources.

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- **Once the source flux of neutrons (protons), photons and neutrinos is known, two important steps are necessary to arrive at a prediction for the diffuse neutrino flux at Earth.**

Calculating the Diffuse UHE fluxes . . .

- **Accounting for Energy losses for the particles as they propagate through the universe. Besides redshift, extra-galactic CR suffer from losses due to photo-hadronic interactions with the photon background, and due to the Bethe-Heitler process.**

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- **The flux is integrated over the source distribution and normalized using the observations of the Extra Galactic Gamma Ray background and the measured flux of UHE Cosmic Rays.**
  (Mannheim,Protheroe and Stanev,Protheroe and Johnson, Waxman and Bahcall; Mannheim, Protheroe and Rachen)

Bounding the Diffuse UHE fluxes . . .

- **This normalization leads to upper bounds on the UHE neutrino fluxes.** **(Waxman and Bahcall; Mannheim, Protheroe and Rachen)**

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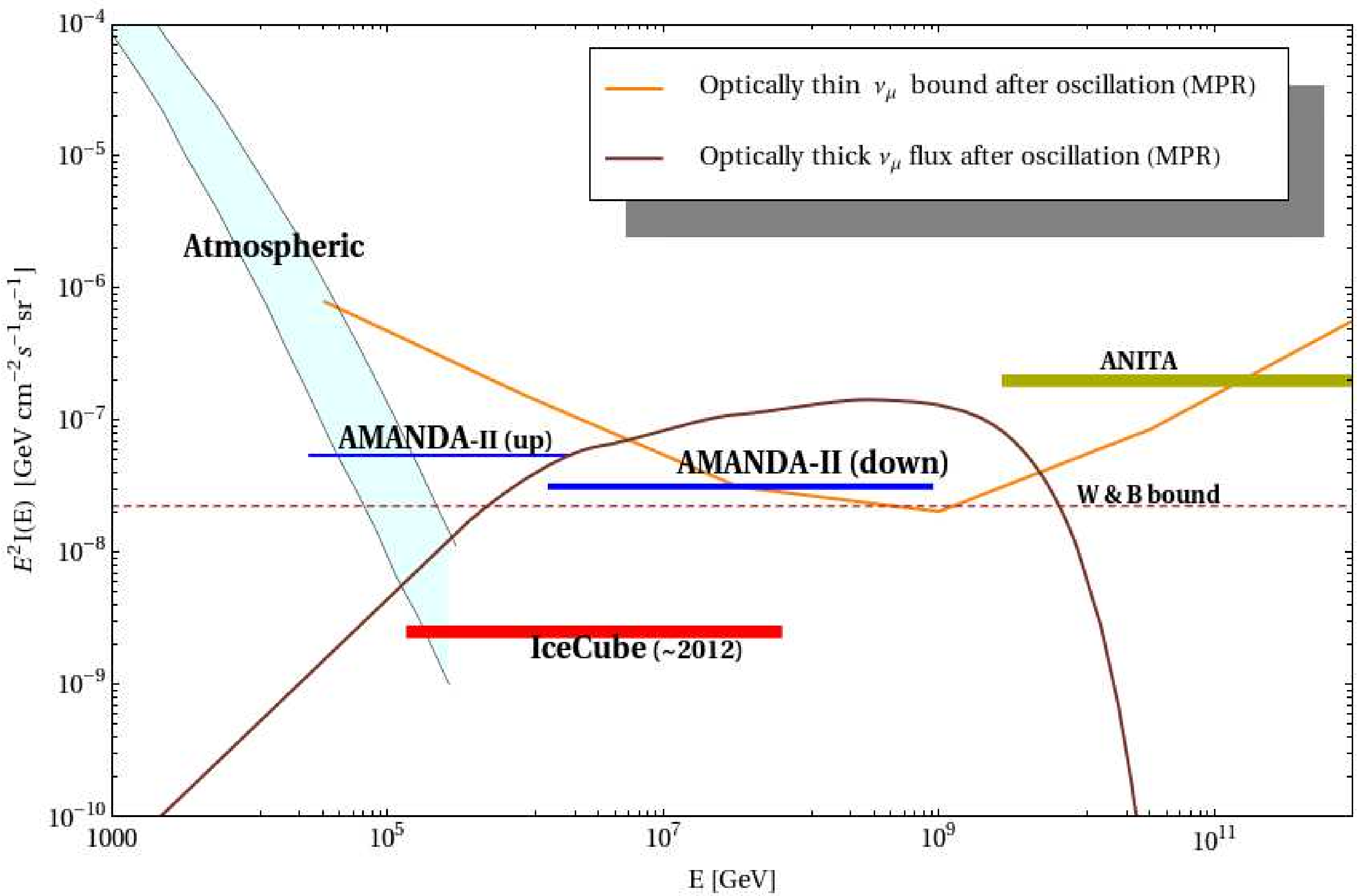
- **This normalization leads to upper bounds on the UHE neutrino fluxes.** (Waxman and Bahcall; Mannheim, Protheroe and Rachen)
- **Since the bounds are obtained using maximal values of the flux possible at a given energy, flux distortions (enhancements, supressions) are reflected by them. We use them as a means of studying the effects of physics beyond the SM.**

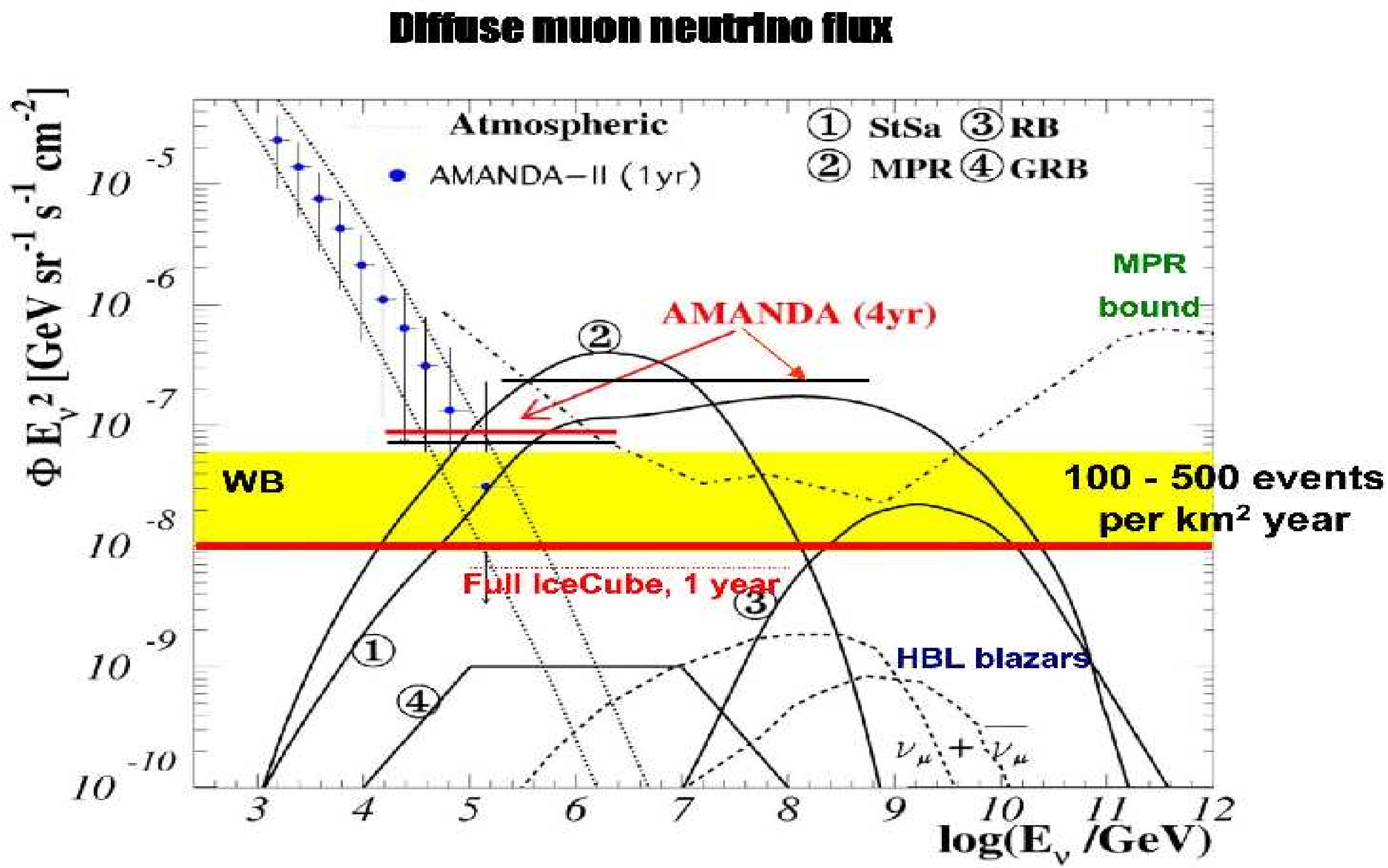
Diffuse Fluxes . . . Bounds

All reference plots



- **Bounds on Diffuse optically thin (neutron transparent) source fluxes (Waxman and Bahcall, Mannheim, Protheroe and Rachen)**
- **Maximal Diffuse flux from Optically thick (neutron opaque) sources (Mannheim, Protheroe and Rachen)**
- **Note that all bounds are flavour-independant, since oscillations democratize flavours in a standard source**

Diffuse Fluxes . . .



Inferring the Spectral Shape of Diffuse UHE fluxes . . .

- **Neutrinos from pion decay have the flavour content $\nu_e : \nu_\mu : \nu_\tau = 1 : 2 : 0$. With $L_{osc} = \frac{4\pi E_\nu}{\Delta m^2} \sim 2.5 \times 10^{-24} \frac{E}{1eV}$ Mpc, oscillations over cosmological length scales average out and give a flavour content at Earth $\nu_e : \nu_\mu : \nu_\tau = 1 : 1 : 1$ It has been shown that these ratios can be altered by physics beyond the Standard Model** **(Beacom, Bell, Hooper, Pakvasa and Weiler)**

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- **We note that oscillations make the flavour spectra identical in shape due to averaging. Muon events provide the most reliable mode of measuring this common spectral shape, expected to follow an E^{-2} behaviour.**

Calculating the Diffuse UHE fluxes . . .

- **Knowing that shower events comprise ν_e CC and all NC events, one can infer, given the spectral shape from muon events and the $1:1:1$ ratio induced by oscillations (for the standard source ratio $1:2:0$) the expected number of shower events in an appropriate energy bin.**

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- **Distortions in the expected spectrum of shower versus muon events would be indicative of non-standard physics, some possibilities of which we examine here.**

BSM Physics . . .ν Decay

- **Two body neutrino decay**
  $\nu_i \to \nu_j + X, \nu_i \to \bar{\nu}_j + X$
  where X is a light or massless are only weakly constrained, with the limit being $\tau/m \geq 10^{-4}$ sec/eV.

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- **Depending on the hierarchy, for decays which are complete, ratios will change from $\nu_e : \nu_\mu : \nu_\tau = 1:1:1$ to $6:1:1$ (NH) or $0:1:1$ (IH)**

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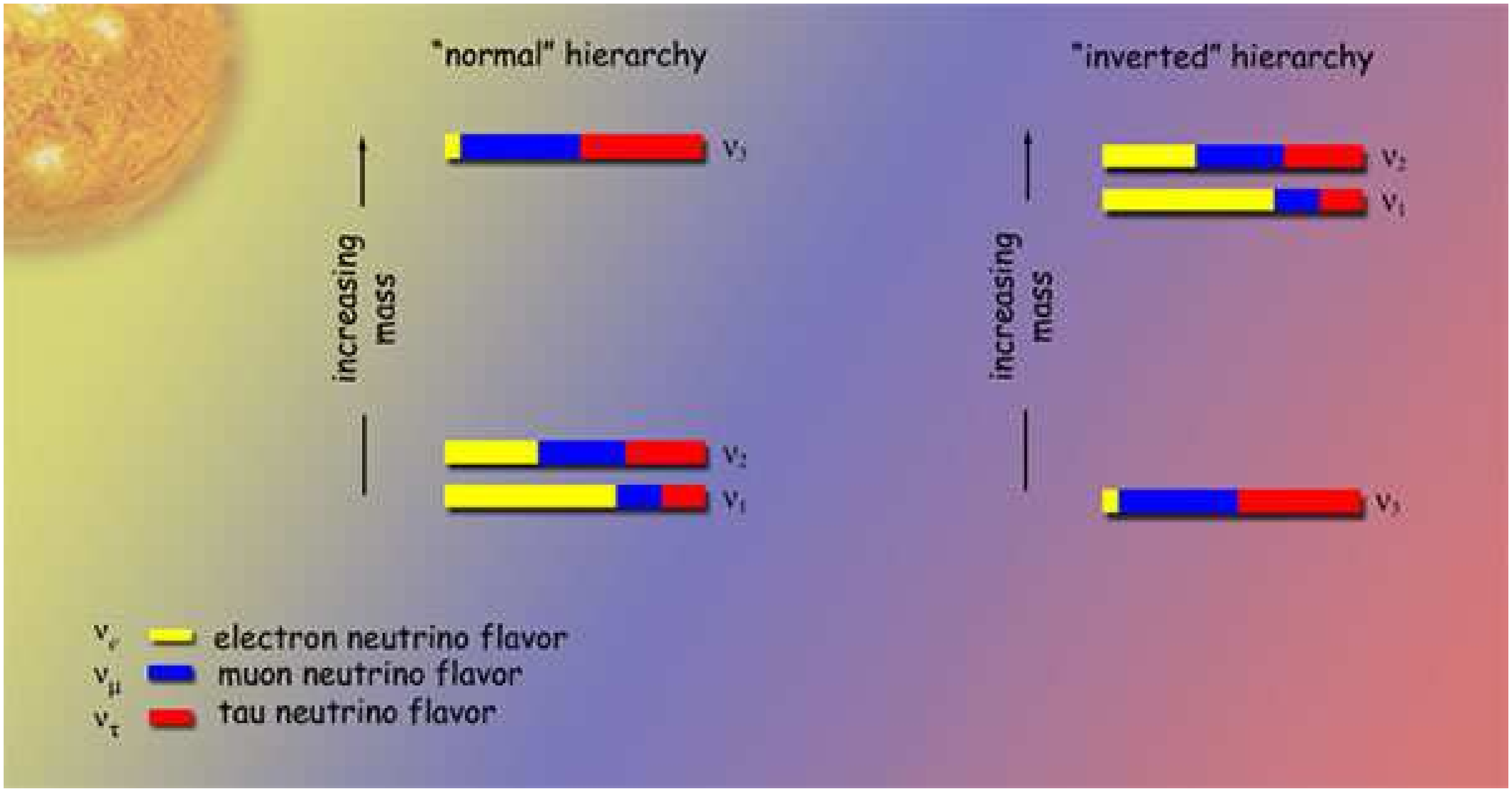
- **Ratios will exhibit energy dependance if decays are incomplete**
  (Barenboim and Quigg)

The Connection between Hierarchy and Decay . . .



- **Decay in the Normal hierarchy leads to large number of shower events, comprable (but less) muon flux**
- **Decay in the Inverted hierarchy case leads to highly suppressed shower fluxes.**

Decay . . . Partial and Complete

- **The flux at Earth for a given flavour α is**

$$\phi_{\nu_\alpha}(E) = \sum_{i\beta} \phi^{\text{source}}_{\nu_\beta}(E)|U_{\beta i}|^2|U_{\alpha i}|^2 e^{-L/\tau_i(E)} \quad (1)$$

$$\xrightarrow{L\gg\tau_i} \sum_{i(stable),\beta} \phi^{\text{source}}_{\nu_\beta}(E)|U_{\beta i}|^2|U_{\alpha i}|^2, \quad (2)$$

- **Besides partial decay, other new physics,in combination or by itself, like CP violation, Lorentz Violation and the presence of Pseudo-Dirac neutrino states would affect the final magnitude and spectral shape of the flux of flavour ν_α.**

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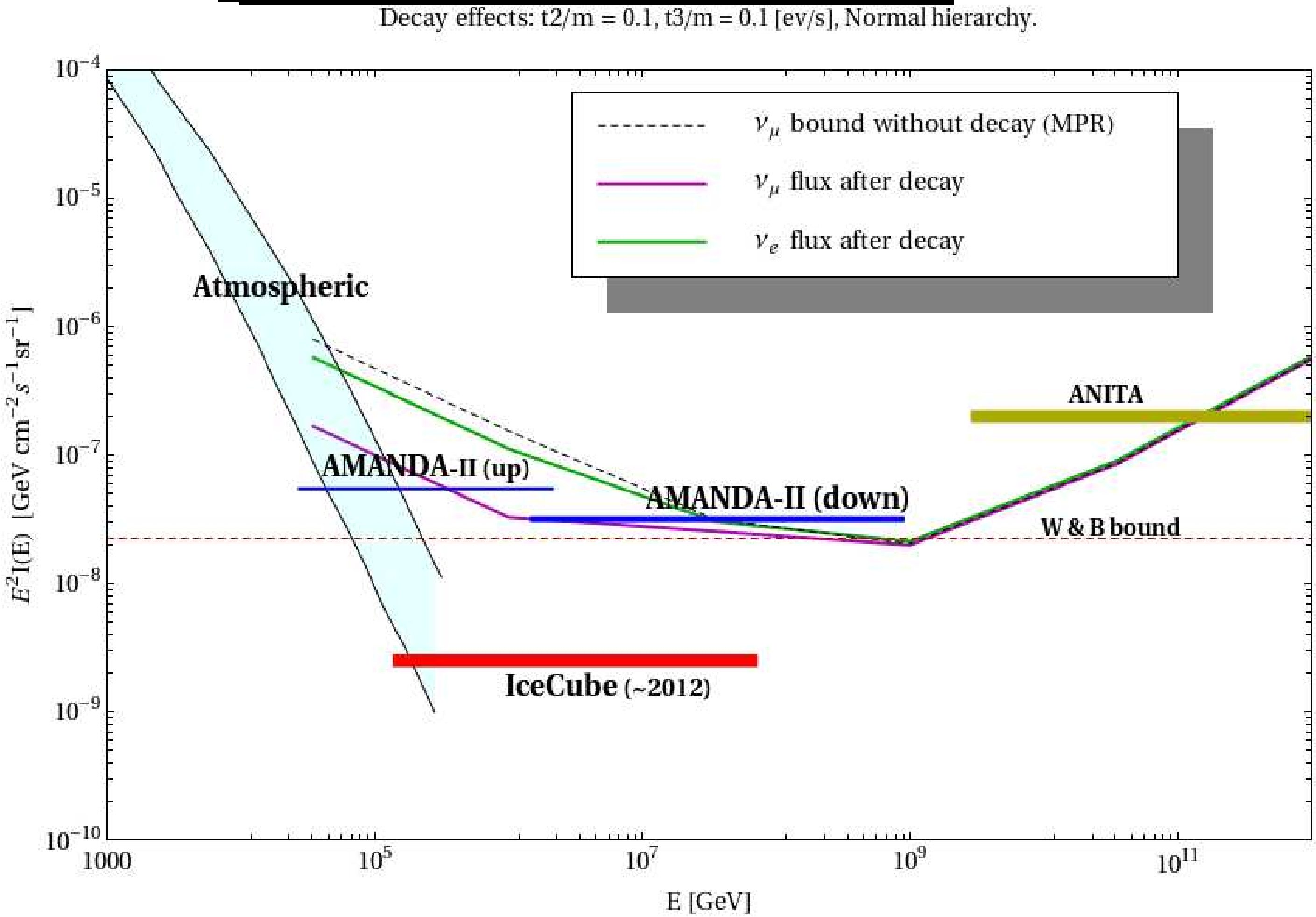
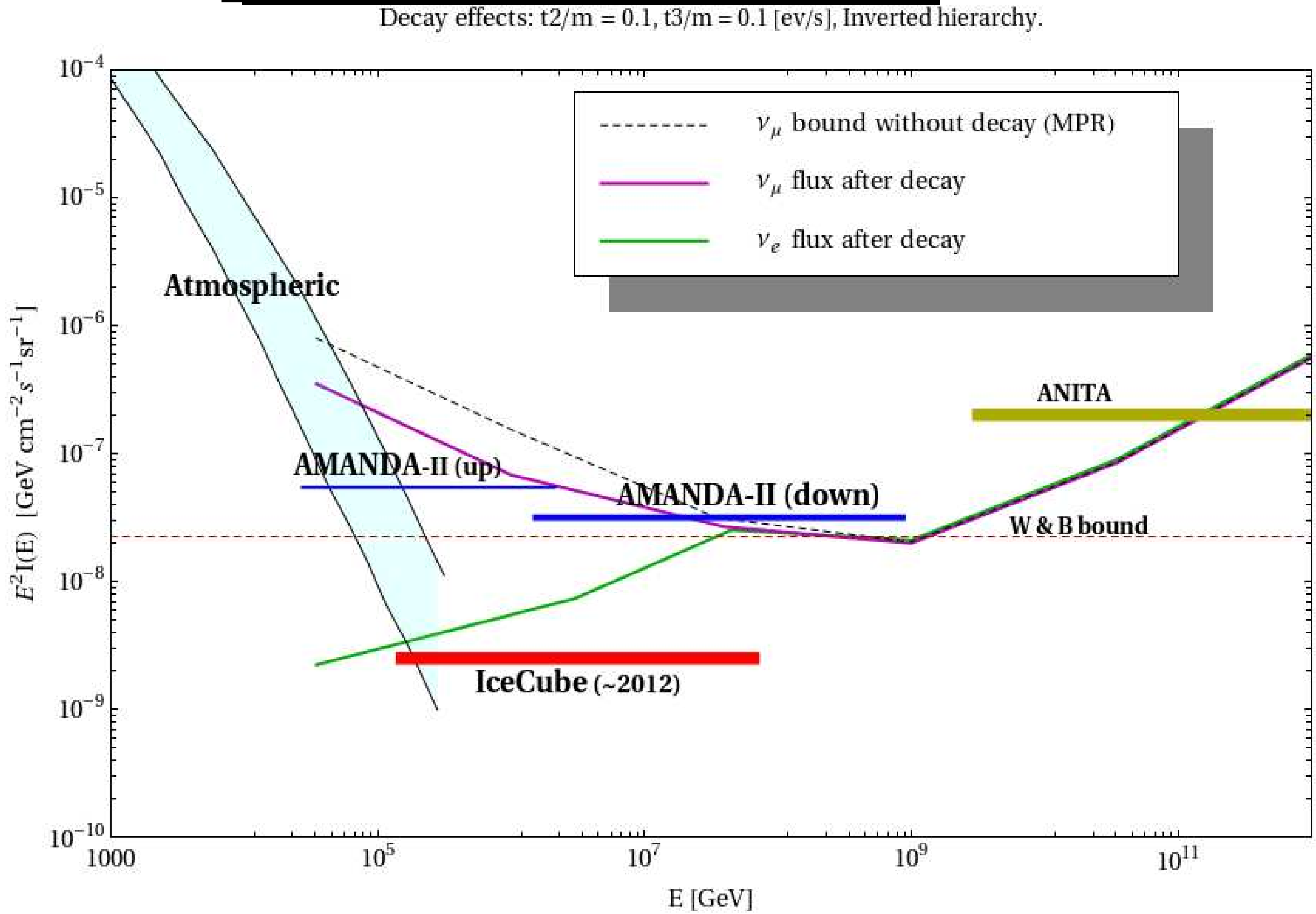


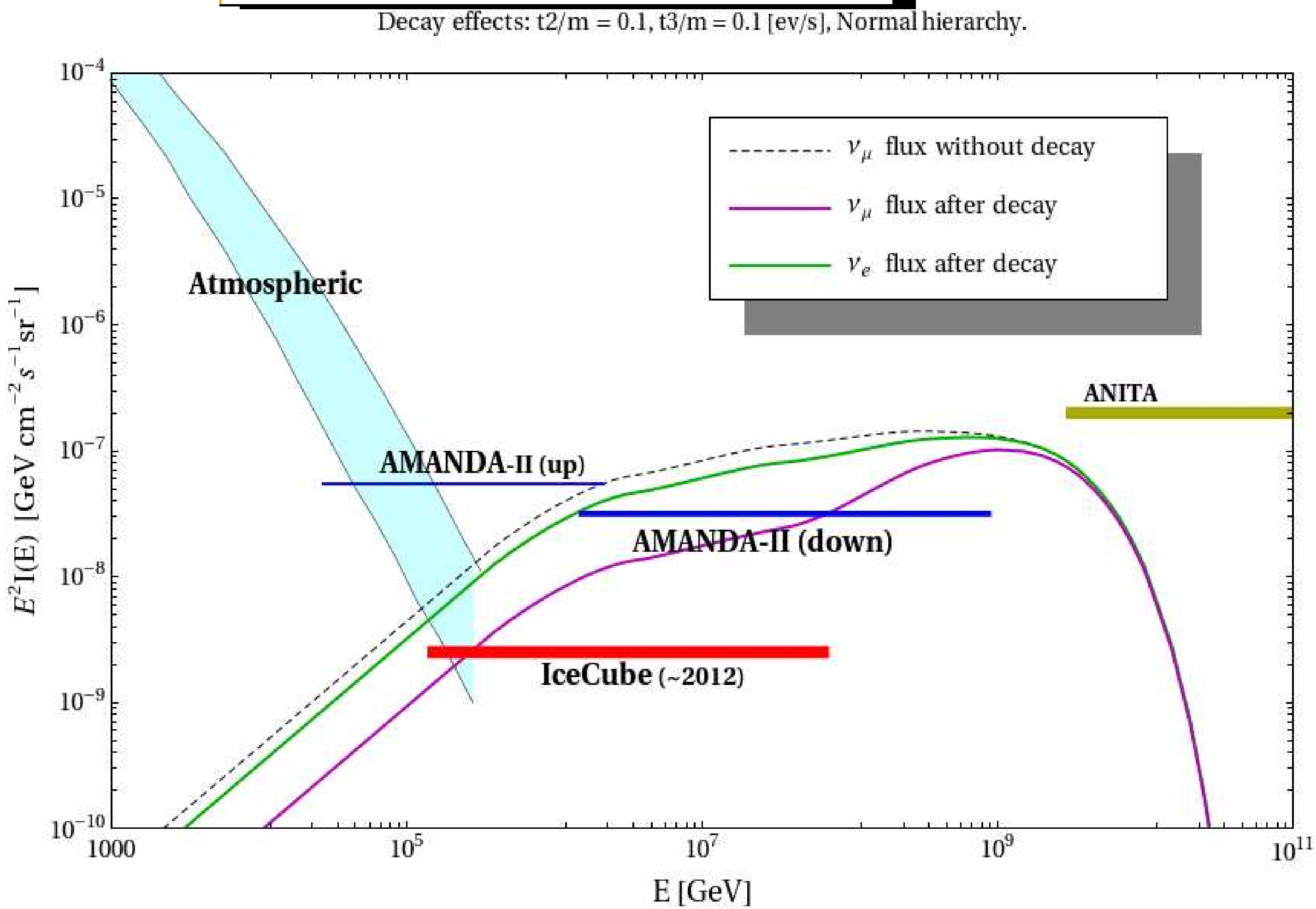
- $\tau/m = 0.1 sec/eV$, **Normal Hierarchy, Optically Thin Sources**
- **Shower Events significantly rise above Muon events below 10^7 GeV and become equal thereafter.**

Diffuse Fluxes . . .Decay...



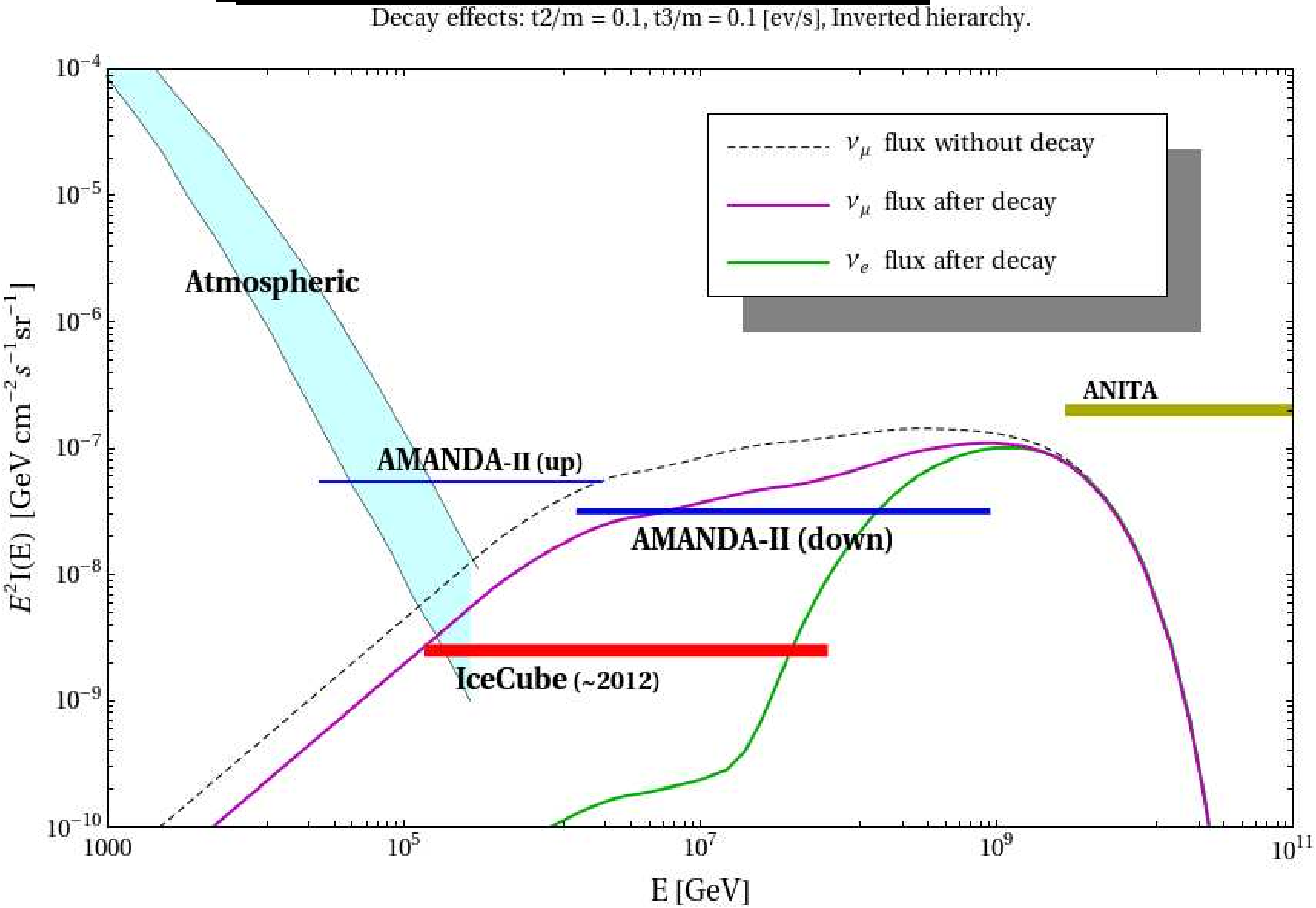
- $\tau/m = 0.1 sec/eV$, **Inverted Hierarchy, Optically Thin Sources**
- **Shower Events significantly below Muon events for energy $< 10^7$ GeV and become equal thereafter.**
- **Decay offers high level of sensitivity to the hierarchy, and the possibility of ball-park estimations of lifetimes.**

Diffuse Fluxes . . .Decay..



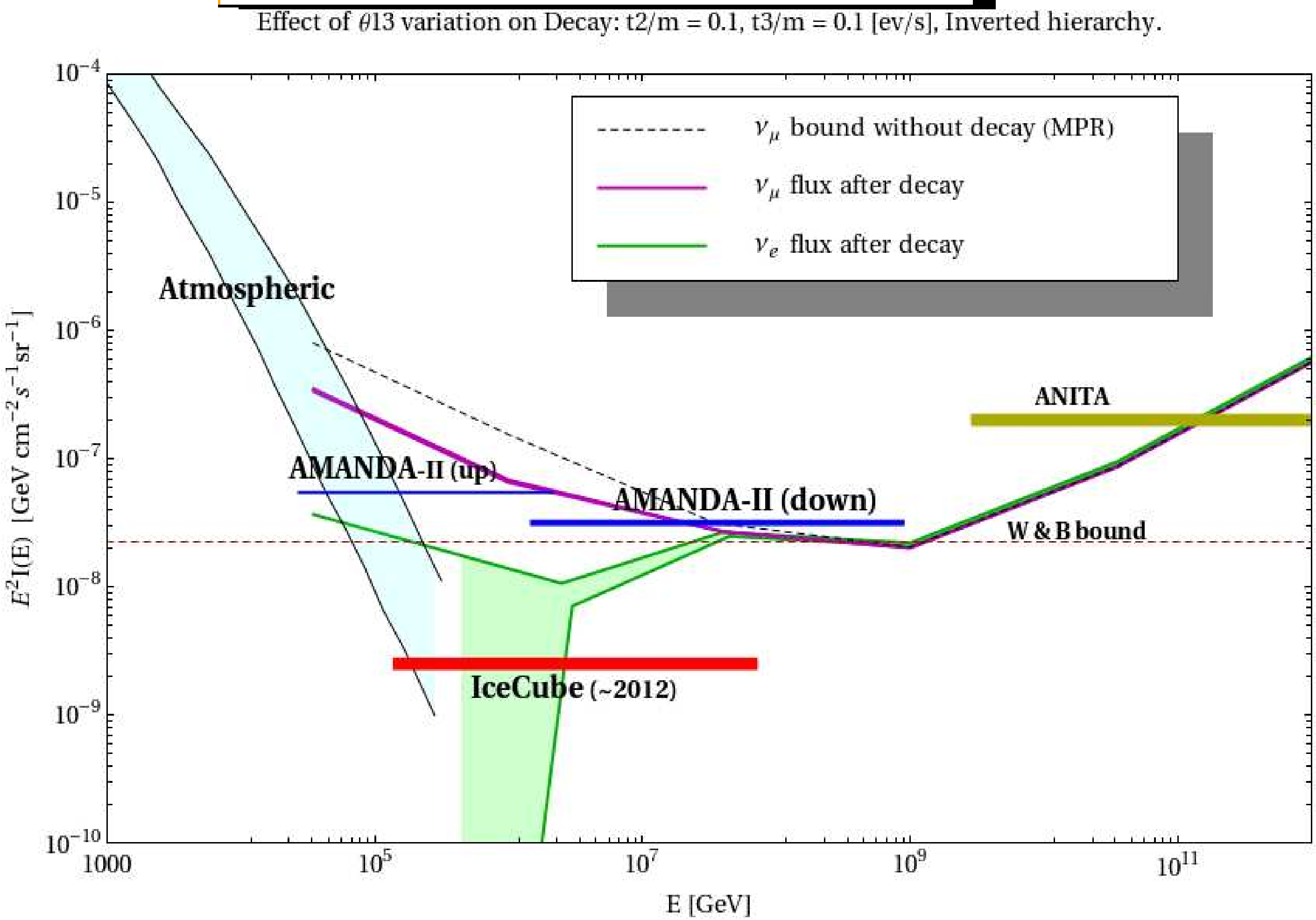
- $\tau/m = 0.1$ **sec/eV, Normal Hierarchy, Optically Thick Sources**
- **Shower Events above Muon events for 10^8 GeV and become equal thereafter. Spectral shapes similar.**
- **Sensitivity in the range $10^3 \geq \tau/m \geq 10^{-3}$ sec/eV**

Diffuse Fluxes . . . Decay...



- $\tau/m = 0.1$ **sec/eV, Inverted Hierarchy, Optically Thick Sources**
- **Shower Events undetectably below Muon events for energy** $< 10^7$ **GeV and rising between** $10^7 - 10^8$ **GeV, become equal thereafter. Spectral shapes distinguishably altered**
- **Sensitivity in the range** $10^3 \geq \tau/m \geq 10^{-3}$ **sec/eV**

Decay . . .Sensitivity to θ_{13}...



- $\tau/m = 0.1 sec/eV$, **Inverted Hierarchy, Optically Thin Sources**
- **Shower Events significantly below Muon events for energy $< 10^7$ GeV and become equal thereafter.**
- **Shower events above Icecube threshold for non-zero θ_{13} and undetectably low as it approaches zero.**

Decay . . . Sensitivity to the CP phase

- **A non-zero CP phase δ for decaying neutrinos imposes a $cos\delta$ dependance on the fluxes.** **(Beacom, Bell, Hooper, Pakvasa, Weiler)**

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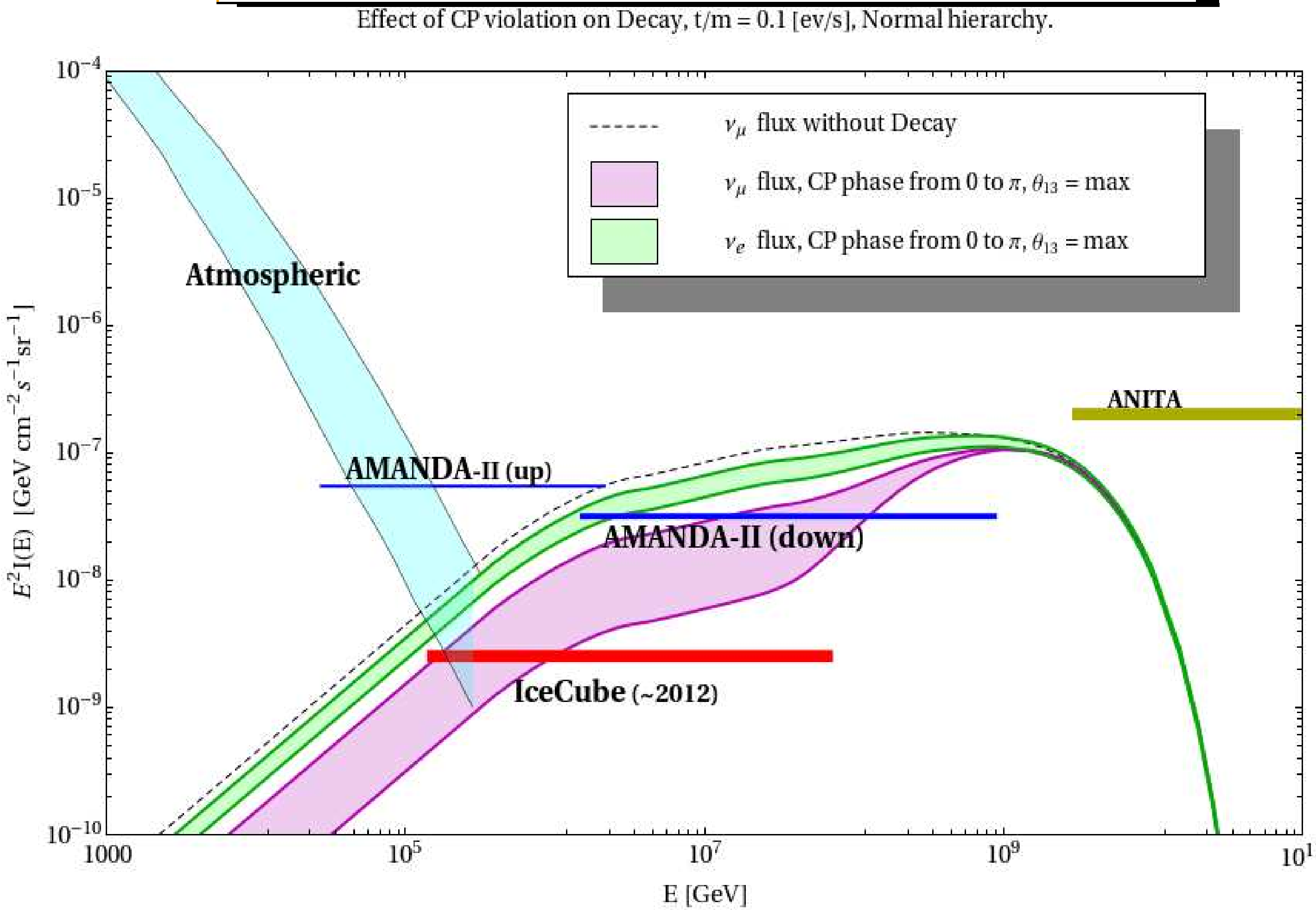
- Large correlated variations in the ν_τ and ν_μ fluxes for normal hierarchy, reflected in the relative number of long track muon events versus showers.

Decay . . . Sensitivity to the CP phase

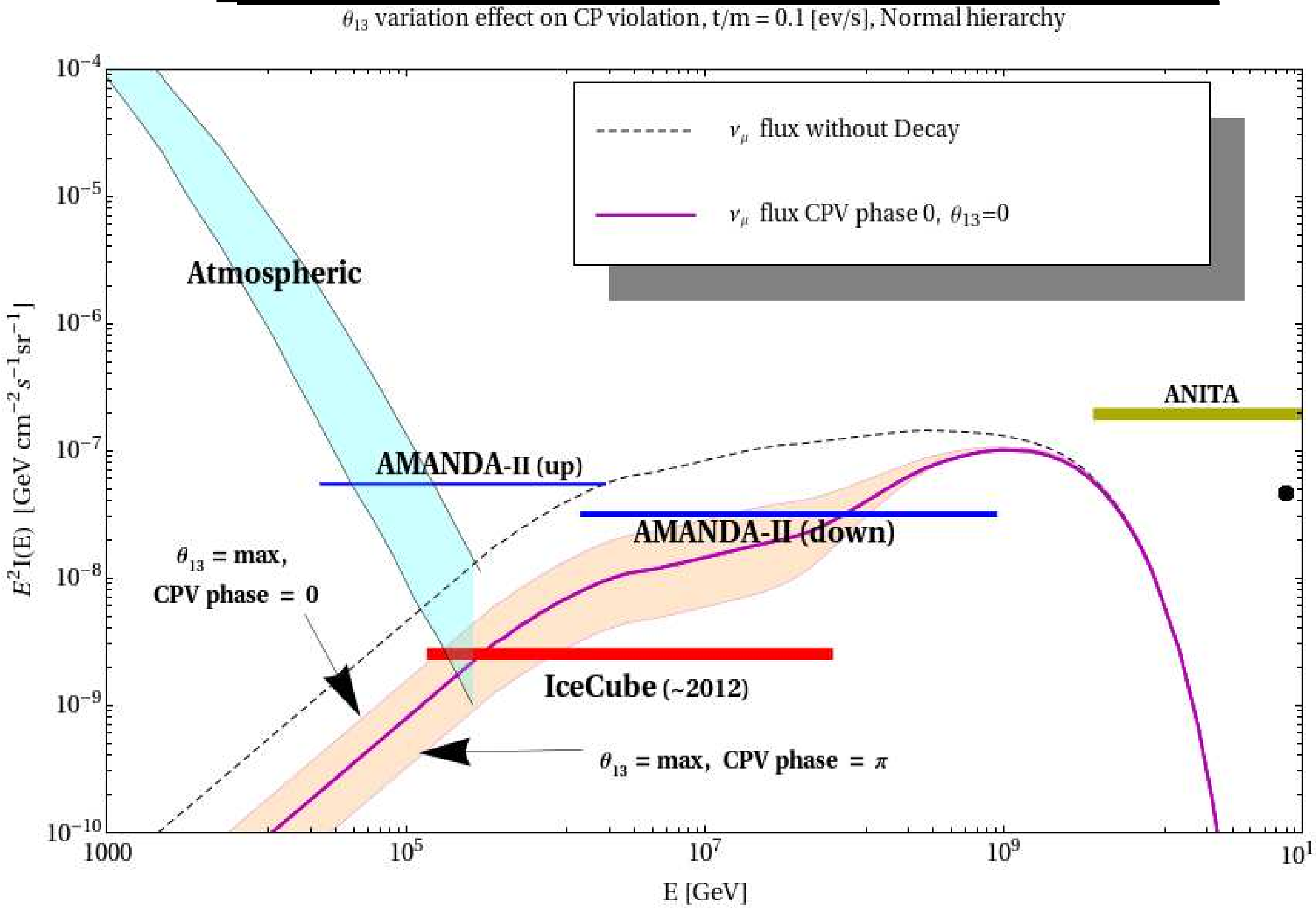
- **A non-zero CP phase δ for decaying neutrinos imposes a $cos\delta$ dependance on the fluxes.** **(Beacom, Bell, Hooper, Pakvasa, Weiler)**
- **Large correlated variations in the ν_τ and ν_μ fluxes for normal hierarchy, reflected in the relative number of long track muon events versus showers.**
- **Heightened sensitivity to variations in θ_{13}. Detection of τ events assumes importance here.**
  (Beacom, Bell, Hooper, Pakvasa, Weiler)

Sensitivity to the CP Phase . . . Decay..



- $\tau/m = 0.1$ **sec/eV, Normal Hierarchy, Optically Thick Sources**
- **Shower Events versus long track events very sensitive to this variation which causes a large change in number of muon events**

Sensitivity to the CP Phase . . . Decay..



- $\tau/m = 0.1$ **sec/eV, Normal Hierarchy, Optically Thick Sources CP phase effect enhanced if variation over range of** θ_{13}

Sensitivity to Pseudo-Dirac Neutrino States

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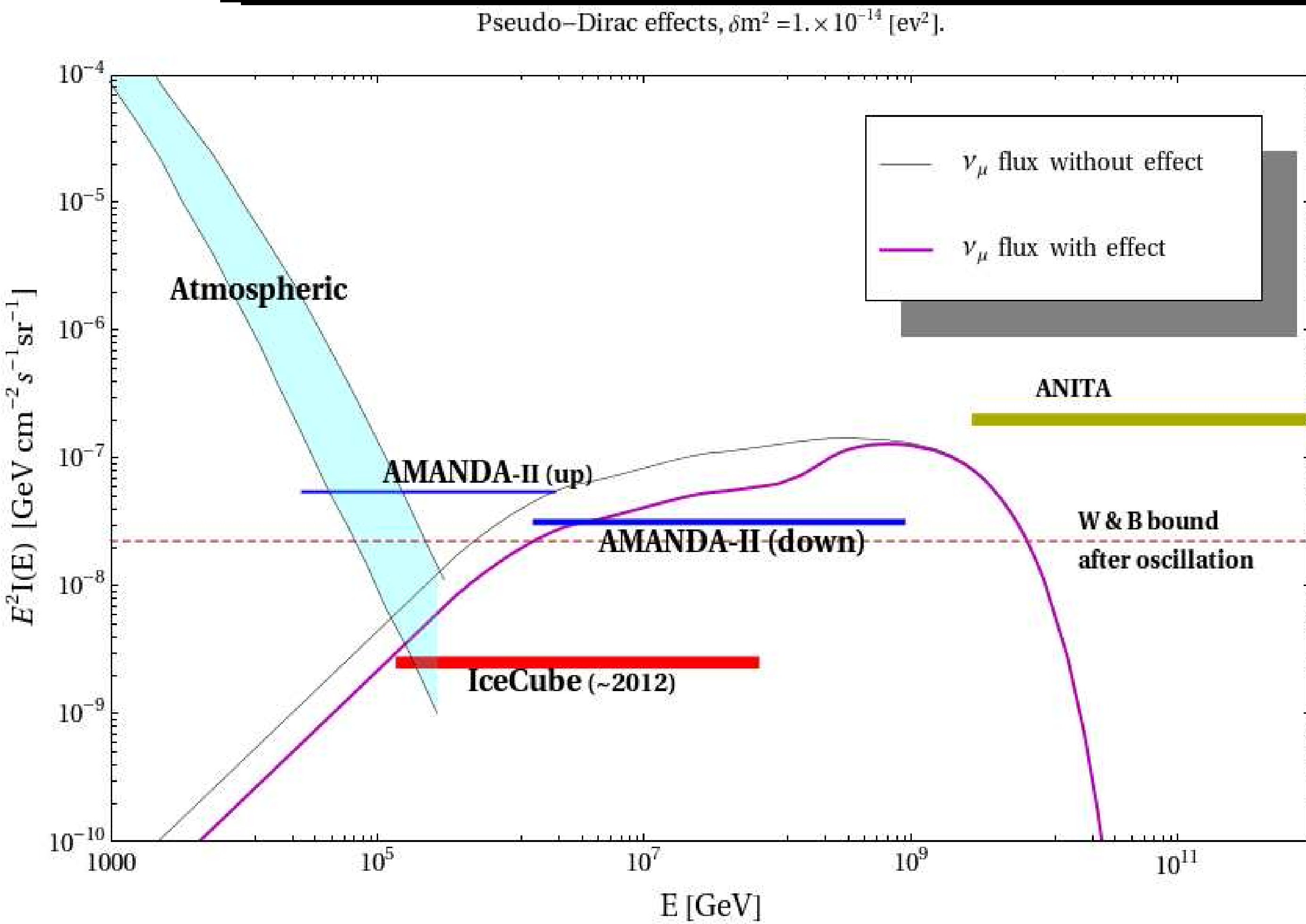
- **The presence of very small Majorana mass terms (compared to the Dirac mass scale) leads to almost degenerate Majorana states , each of mass** m_D
- **UHE neutrinos provide perhaps the only possibility of probing mass differences much smaller than solar and atmospheric** Δm^2
  (Keranen, Maalampi and Myyrylainen; Beacom, Bell, Hooper, Pakvasa, Weiler)

Sensitivity to Pseudo-Dirac neutrino States . . ...



- $\Delta m^2 = 10^{-14}$**eV^2, Optically Thick Sources**
- **Flux distortions small, with factor of 2 fall where oscillations present.**
- **Sensitivity in the range** $\Delta m^2 = 10^{-12} - 10^{-17}$**eV^2**

Effects of Lorentz Violation . . .

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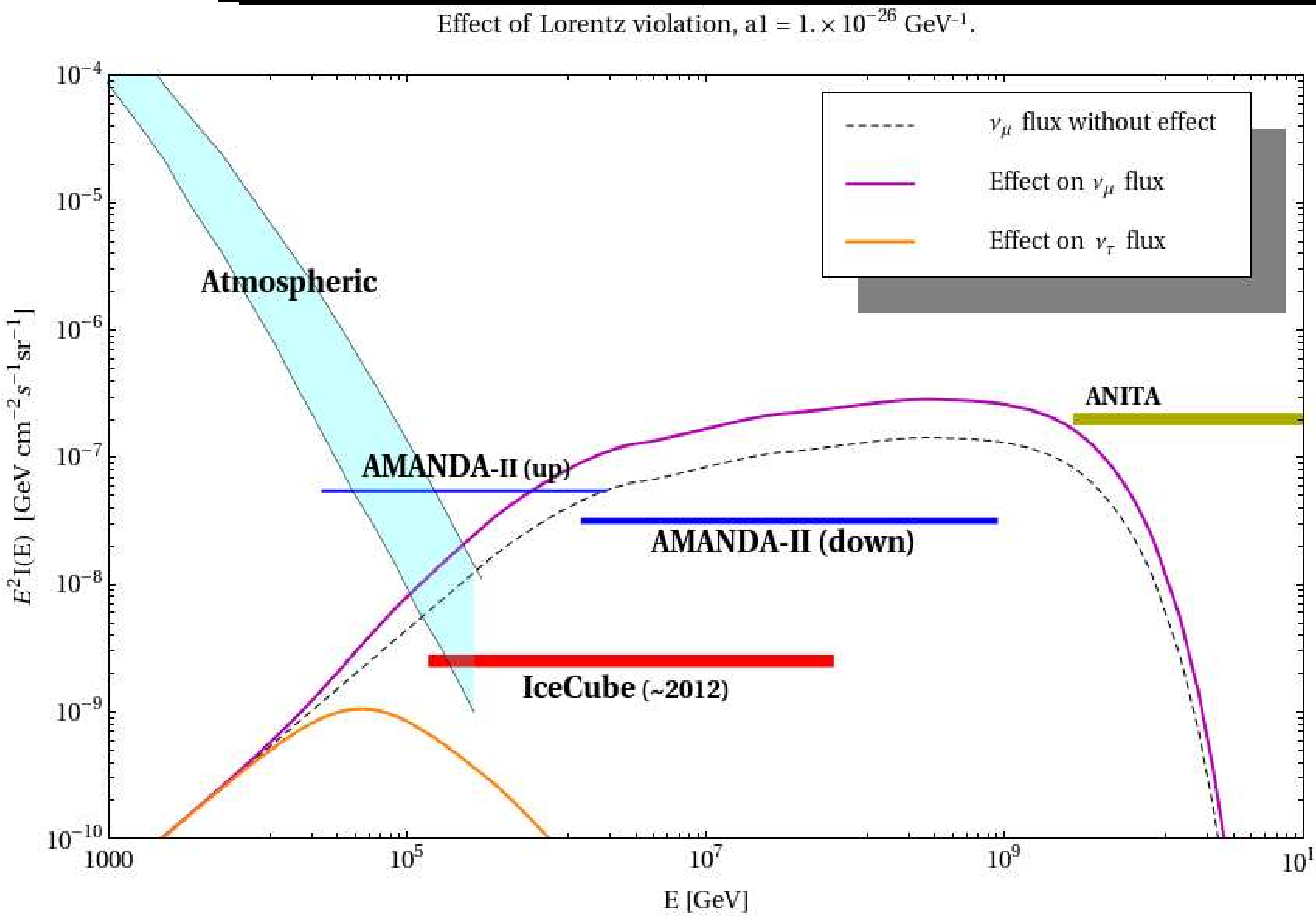
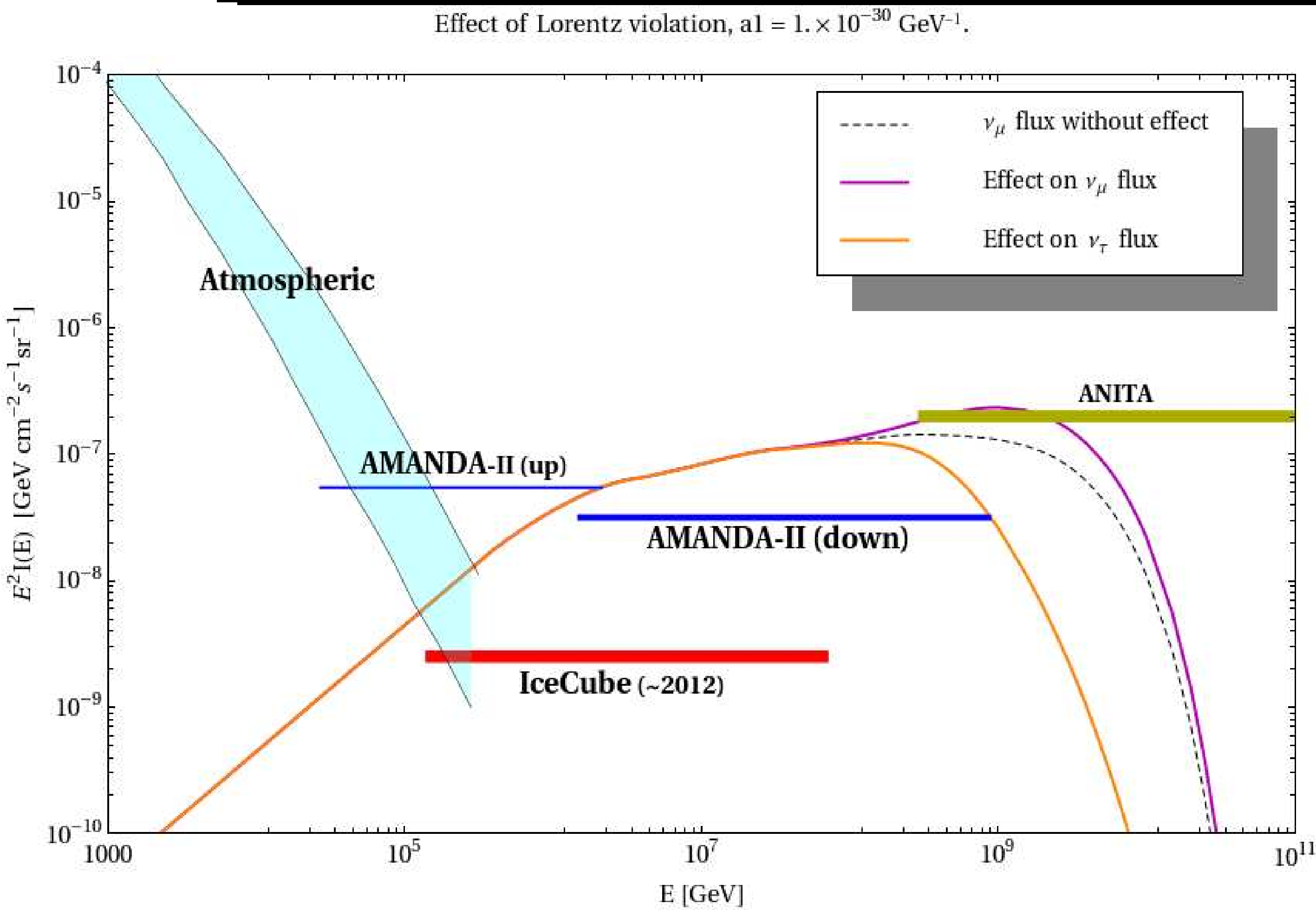
- As a simple example, we consider Lorentz violations arising from differences in propagation for different flavours, parametrised by an off diagonal parameter in a 2 flavour effective Hamiltonian. (Kostelecky and Mewes; Hooper, Morgan and Winstanley)
- Fluxes and bounds strongly sensitive to LV.

Lorentz Violation induced Flux changes . . ...



- τ **events completely suppressed, Optically Thick Sources**
- **AUGER, ICECUBE would record deficit of double-bang, lolipop and earth-skimming events**

Lorentz Violation induced Flux changes . . ...



- **Sensitivity range covers 4-5 orders of magnitude**
- **In general, muon events enhanced, whereas shower and tau events supressed.**

Conclusions

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- **Diffuse fluxes of all flavours are massaged into a common spectral shape by oscillations, and MPR and WB bounds tell us their max vaues using EGRB and CR data**
- **BSM physics changes this picture, e.g. if neutrinos decay with lifetimes in the range $\tau/m = 10^{-3} - 10^{3}$ sec/eV, with/without a non-zero CP phase, or pseudo Dirac neutrinos with very small mass differences are present, or we have Lorentz violation or some combination of these effects.**

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Conclusions . . .

- **Large spectral distortions in the diffuse flux are possible. One way of representing that is to look at the alterations in the MPR and WB bounds. .**
- **Overlapping effects possible. Careful comparisons of all 3 flavours necessary. (τ detection important)**
- **Future detectors using different techniques may play an important role towards distinguishing between various scenarios.**