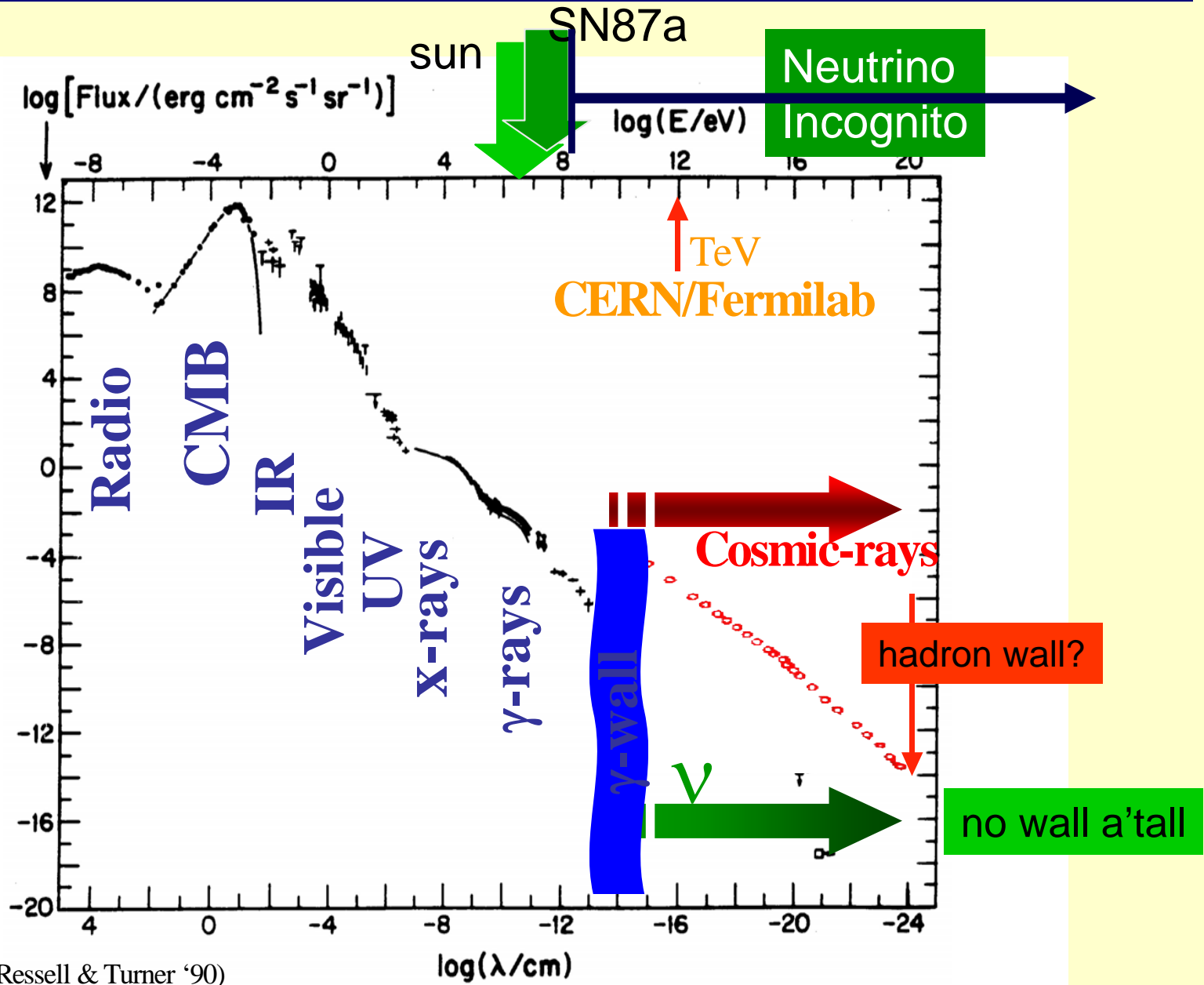


Gleaning Fundamental Physics from Neutrino Astrophysics

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Cosmic Photon- Proton-Spectra



Neutrinos versus Cosmic-Rays and Photons

ν s come from central engines

- near R_s of massive BHs
 - even from dense “hidden” sources
- cf. ν s vs. γ s from the sun

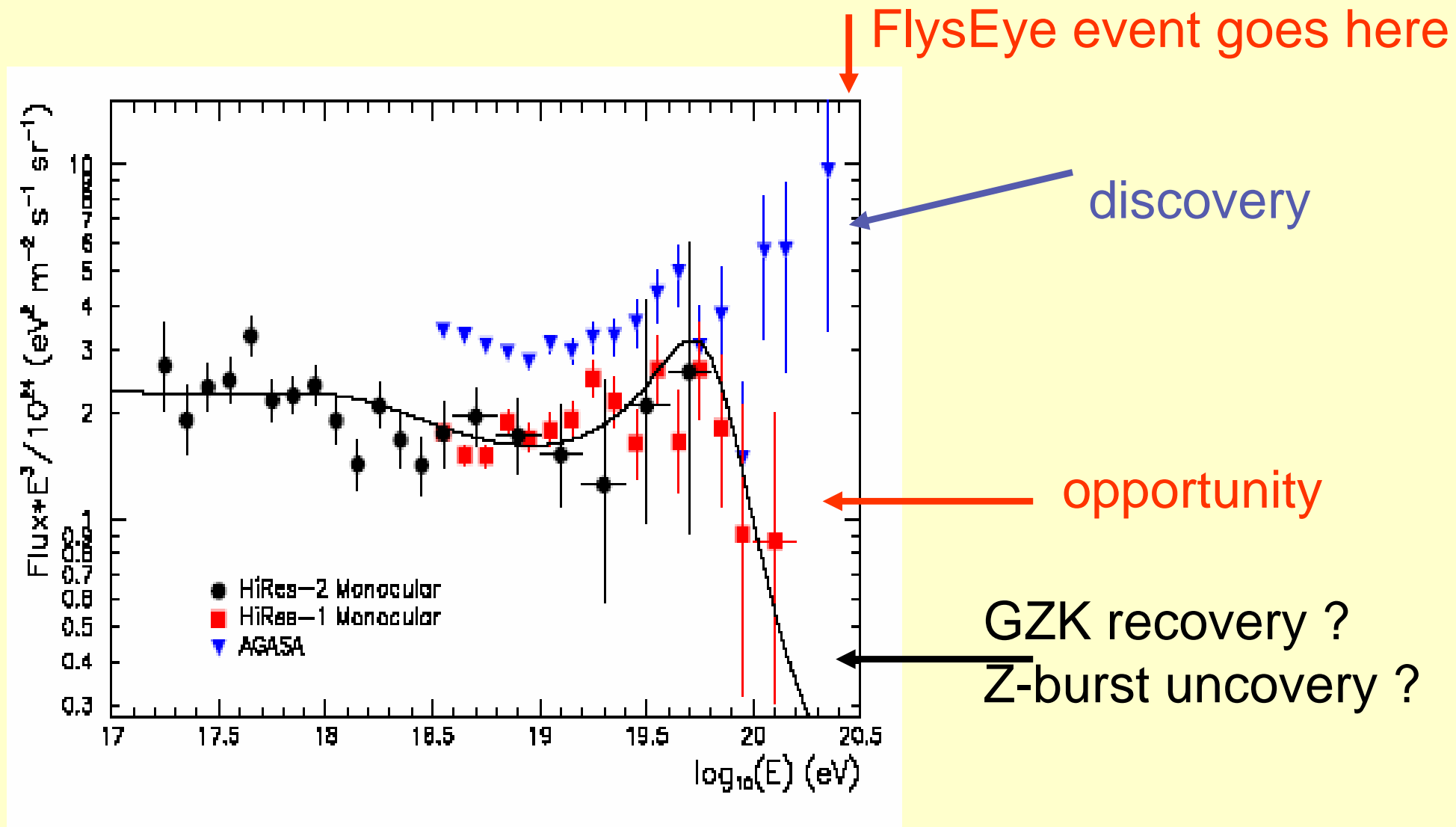
ν s not affected by cosmic radiation
(except for annihilation resonance)

ν s not bent by magnetic fields

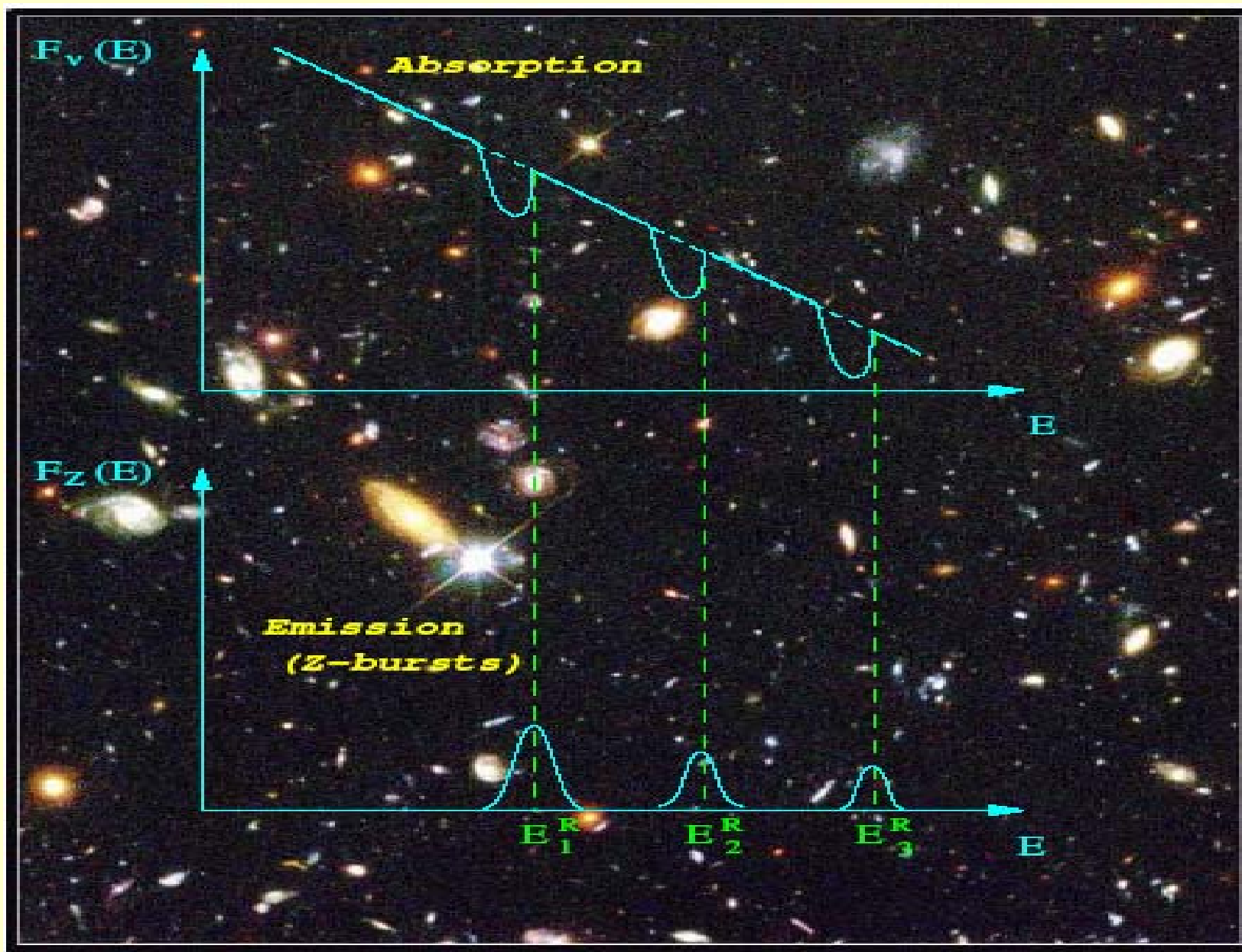
- enables neutrino astronomy

Also, besides Energy and Direction, ν 's carry flavor

HiRes vs. AGASA UHE spectrum



Neutrino mass-spectroscopy: absorption (Z-dips) and emission (Z-bursts)

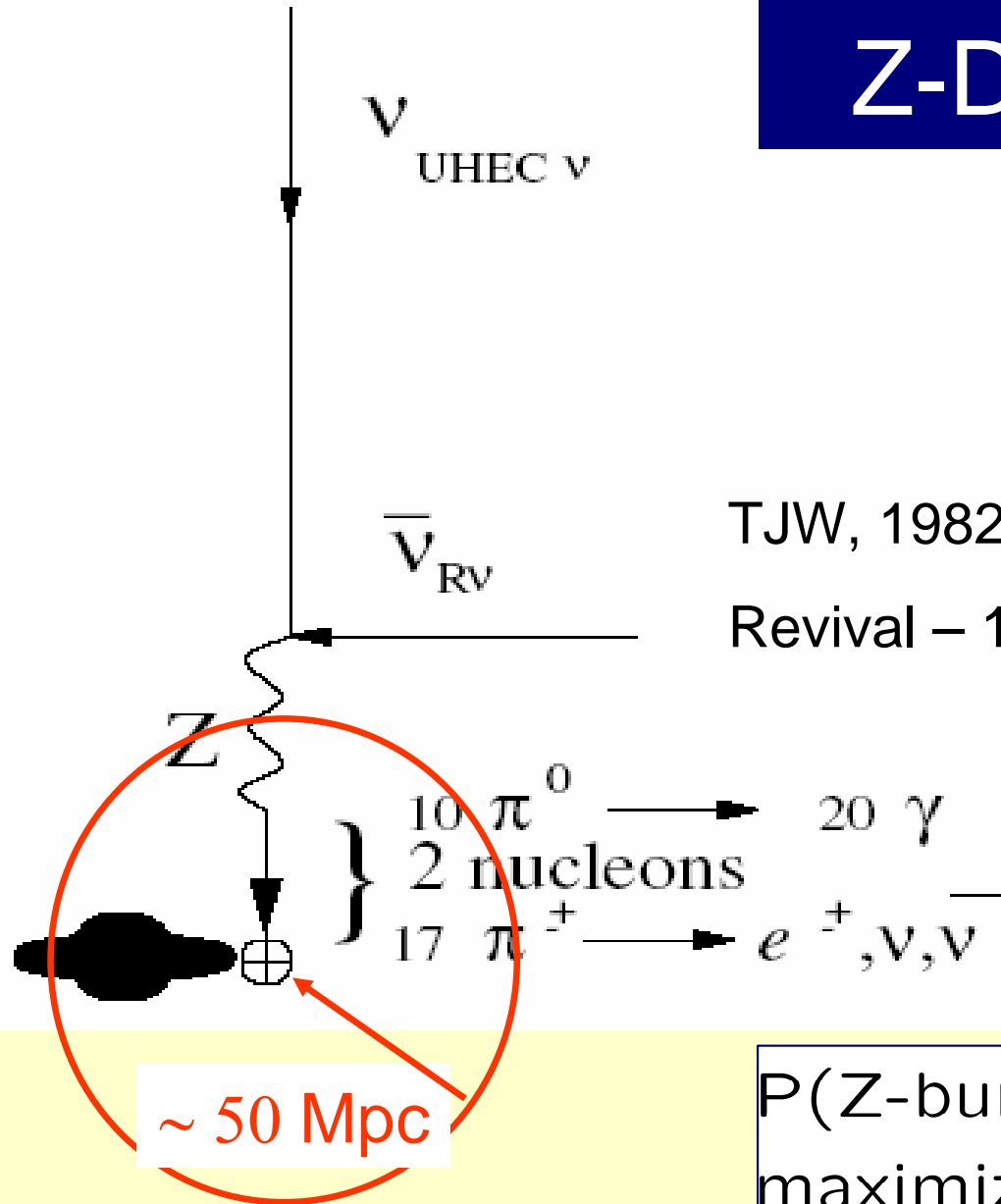


Z-Dips/Bursts

$$E_{\nu_j}^R = \frac{M_Z^2}{2m_j} = 4 \left(\frac{\text{eV}}{m_j} \right) \text{ZeV}$$

TJW, 1982;

Revival – 1997 (Fargion, Mele, Salis; TJW)



$$P(\text{Z-burst}) = E^{-D_H/\lambda} \frac{D_{\text{GZK}}}{\lambda}$$

maximized at $\lambda = D_H$,
neglecting expansion.
Matches to D_H at $1 + z \sim (40)^{1/3}$
i.e. $z \sim 2.5$

Some neutrino Flavor physics

Besides energy and direction, cosmic quanta carry intrinsic information.

For cosmic-rays, it is A and Z;

For photons, it is spin polarization;

For neutrinos, it is flavor:

electron-neutrino

(which showers)

muon neutrino

(whose CC tracks)

tau neutrino

(which double-bangs \sim PeV, showers below,
and tracks above,
and produces “Earth-Skimming” events)

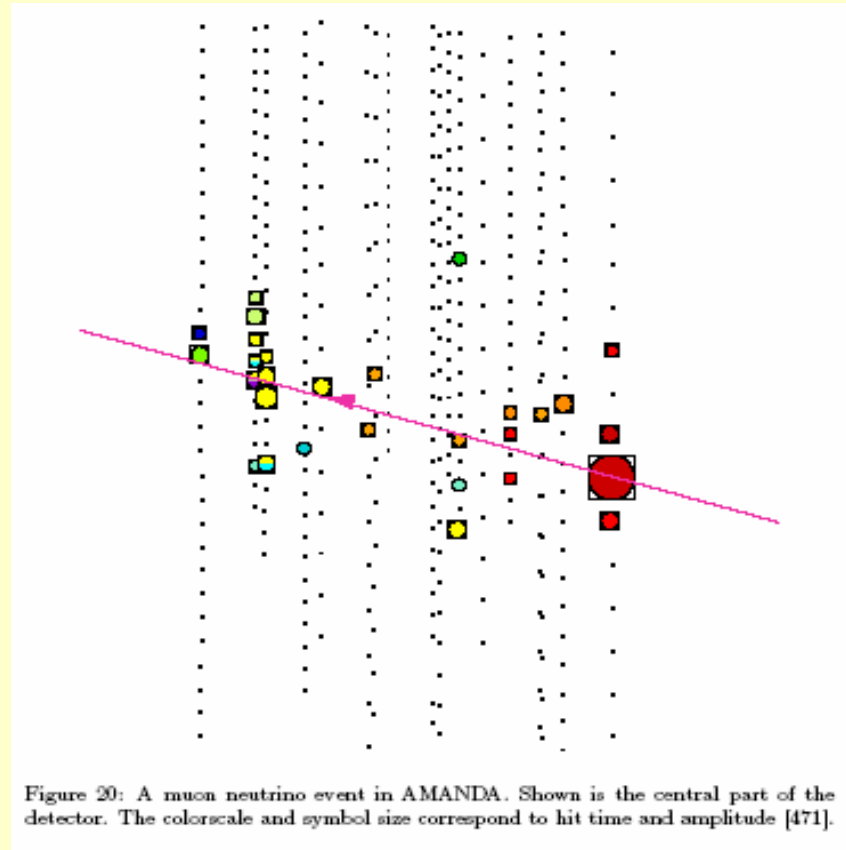
electron-antineutrino

(6.4 PeV ν_{ebar} on $e^- \rightarrow W^-$ resonance)

Moreover, the flavors are mixed in a known way,
which means the flavors oscillate in a calculable L/E-dependent way,
enabling:

Neutrino Interferometry over Cosmic baselines !!
(oscillations are beats)

AMANDA/IceCube ν_μ event



and coming in the Mediterranean: **Nestor, Antares, Nemo**

Decohering the PMNS neutrino-mixing matrix

$$\begin{aligned}
 U = & \text{R}(\theta_{32}) \text{R}(\theta_{13}^*) \text{R}(\theta_{21}) \times \text{MajoranaPhases} = \\
 & \begin{array}{ccc} & \nu_1 & \nu_2 & \nu_3 \\
 \nu_e & c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\
 \nu_\mu & -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\
 \nu_\tau & s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{array} \\
 & \times \text{diag}(e^{i\alpha_1/2}, e^{i\alpha_2/2}, 1) .
 \end{aligned}$$

$$\text{Decoherence} \rightarrow |U_{\alpha j}|^2 = \frac{1}{6} \begin{pmatrix} 4 & 2 & 0 \\ 1 & 2 & 3 \\ 1 & 2 & 3 \end{pmatrix}$$

The cosmic ν flavor-mixing theorem

If θ_{32} is maximal (it is),
And if $\text{Re}(U_{e3})$ is minimal (it is),
Then ν_μ and ν_τ equilibrate.

Further, if initial ν_e flux is $1/3$
(as from pion-muon decay chain),
Then all three flavors equilibrate.



$$\nu_e : \nu_\mu : \nu_\tau = 1 : 1 : 1 \quad \text{at Earth}$$

First noted by Learned and Pakvasa
many moons ago

Democracy Broken:

1. Galactic β -beam
2. Source dynamics
3. ν decay
4. Vacuum resonance
(MaVaNs, LIV vector, Brane-Bulk)
5. Pseudo-Dirac ν oscillations

Caveat: Democracy may be restored by
Spacetime Foam/Quantum Gravity/Virtual Black Holes

Galactic Neutrino β -beam



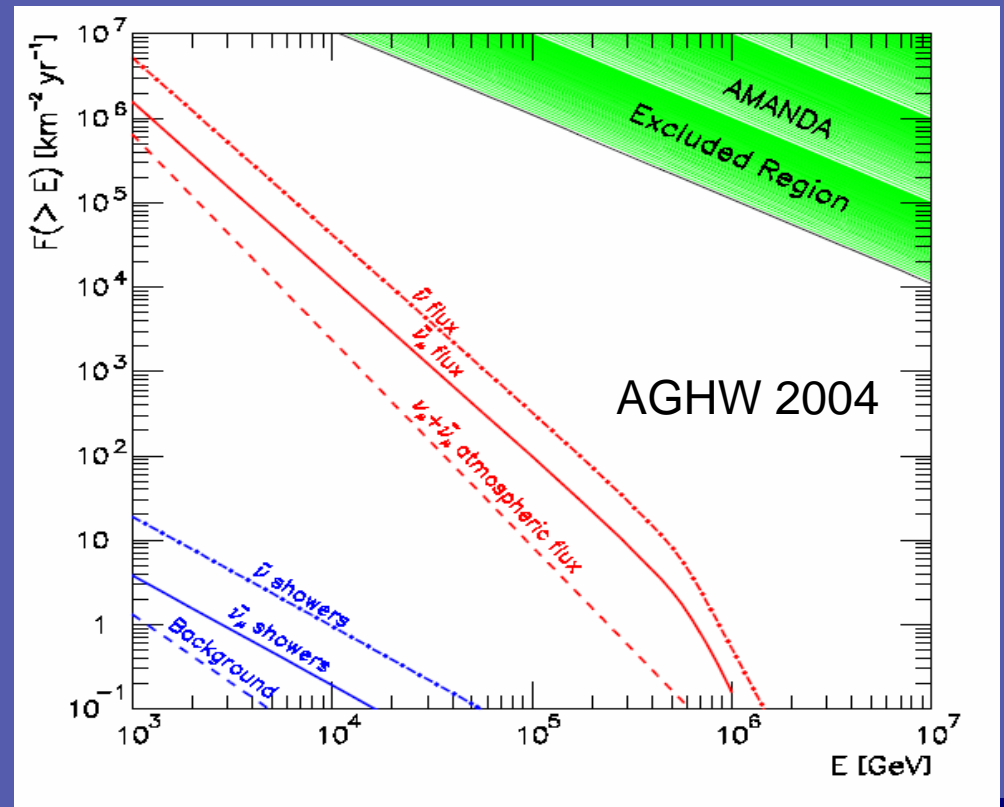
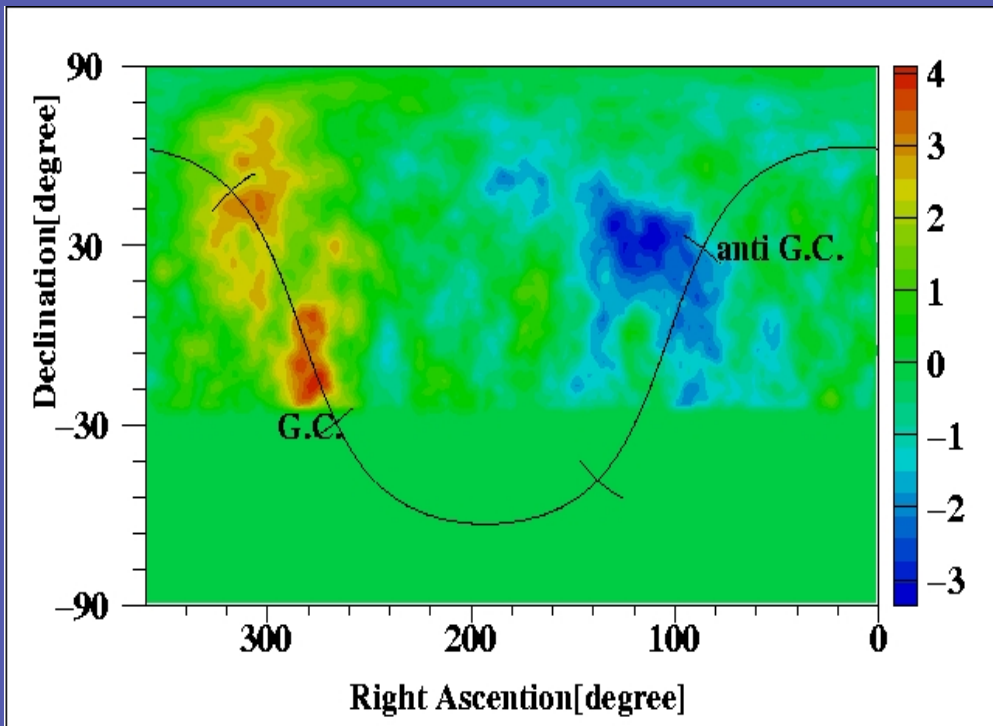
Neutron mfp:

$$c\tau_n = 10 \text{ kpc } (E_n / \text{EeV})$$

and

$$E_\nu / E_n \sim Q / m_n \sim 0.8 \times 10^{-3}$$

$$\rightarrow E_\nu \sim \text{PeV, for } E_n \sim \text{EeV}$$



Decohering the PMNS/tribimaximal neutrino-mixing matrix

$$\text{Decoherence} \rightarrow |U_{\alpha j}|^2 = \frac{1}{6} \begin{matrix} & \nu_1 & \nu_2 & \nu_3 \\ \begin{pmatrix} 4 & 2 & 0 \\ 1 & 2 & 3 \\ 1 & 2 & 3 \end{pmatrix} \end{matrix}$$

$$2/3 \nu_1 + 1/3 \nu_2 \rightarrow \nu_e : \nu_\mu : \nu_\tau = 5:1:1$$

Galactic β -beam also offers excellent opportunity to improve limits (by up to 10^{17}) or discover democracy-restoration due to QG Foam

“no-hair” on virtual
Black Holes
→ 1:1:1 flavor equilibrium

Anchordoqui, Gonzalez-Garcia, Goldberg, Halzen, Hooper, Sarkar, TJW (2005)

ν diagnostic of astro-engines: $pp \rightarrow \pi$ vs. $p\gamma \rightarrow \pi$

The process $\bar{\nu}_e + e^- \rightarrow W^-$ is resonant at 6.4 PeV;

pp make nearly equal $\pi^+\pi^-$, with $P_\pi/P_{CR} \sim 0.6$

$$\rightarrow \nu_\mu : \bar{\nu}_\mu : \nu_e : \bar{\nu}_e = 2:2:1:1$$

\rightarrow flavor democracy, $\bar{\nu}_e = 1/6$ total

$p\gamma$ via Δ^+ make π^+ (per two π^0), with $P_\pi/P_{CR} \sim 0.25$

$$\rightarrow \nu_\mu : \bar{\nu}_\mu : \nu_e = 1:1:1 \text{ (no } \bar{\nu}_e)$$

$\rightarrow \bar{\nu}_e = 1/15$ total

IceCube will have flavor ID, and $\Delta E/E$ of 25%,
and so can measure On-Res/Off-Res ratio and resolve this

-- Anchordoqui, Goldberg, Halzen, TJW (2003)

$$\tau_{\mu} \sim 100 \tau_{\pi} \quad \longrightarrow$$

Predicted change in cosmic flavor ratio with energy probes astro-environment:

From complete π -decay chain, $\pi \rightarrow \mu + \nu_{\mu}$
 $\rightarrow e + 2 \nu_{\mu} + \nu_e$

\rightarrow 1:1:1 at Earth,

To partial π -decay chain (\sim pure ν_{μ} beam),

\rightarrow 4:7:7 at Earth

Kashti, Waxman 2006; Meszaros ...

ν -decay (via majoron emission)

$$P(\text{survive}) = e^{-t/\tau} = e^{-(L/E) (m/\tau_0)}$$

Flavor content of ν_1

$$\Theta_{13} = 0$$



2/3, 1/6, 1/6

$$\sin \Theta_{13} = 0.2$$

$$\delta = 0$$

($\delta = \pi$ flips $\mu \leftrightarrow \tau$)



different

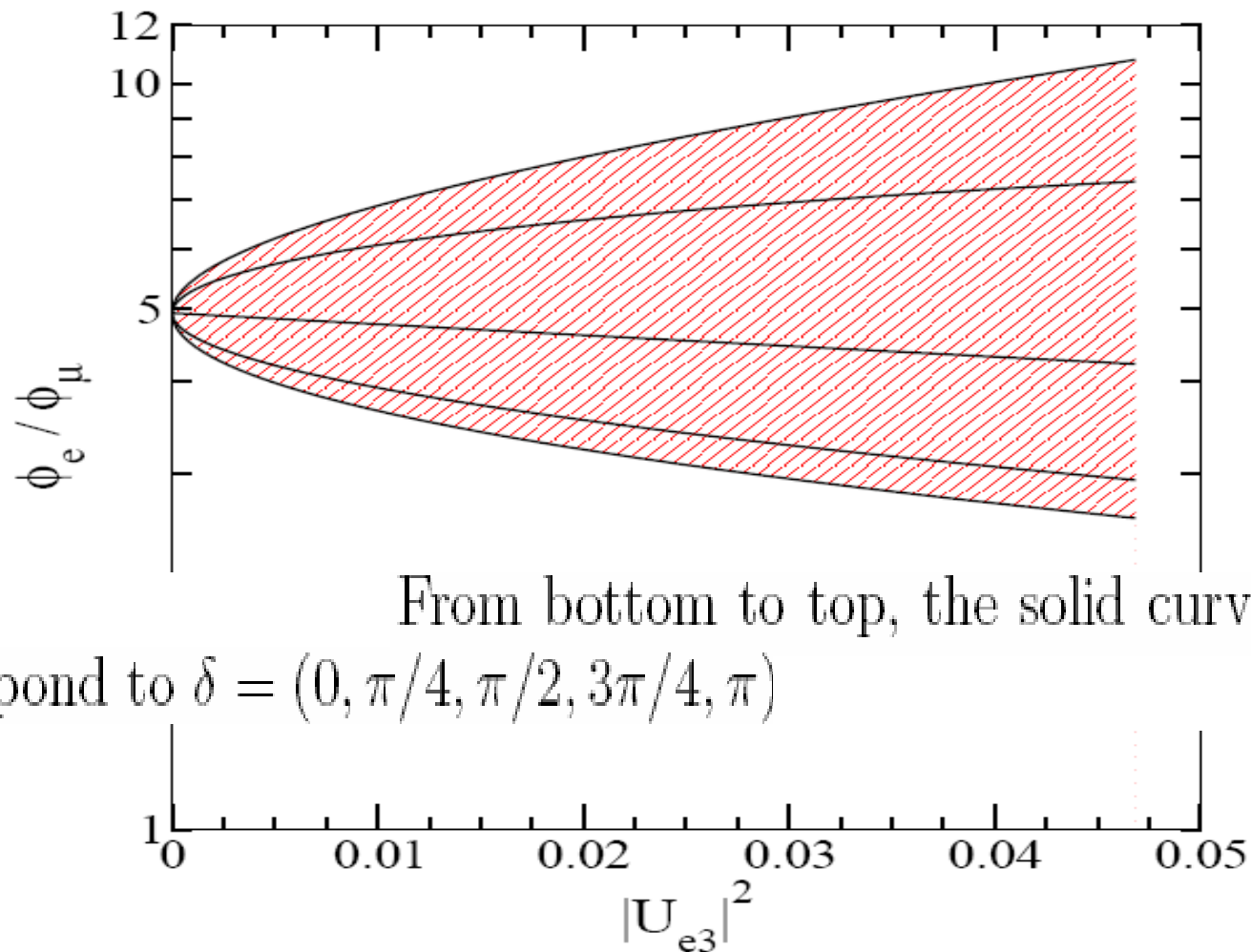
$$\text{i.e. } \frac{\mu}{e + \tau} = \begin{cases} 14\% & (\Theta_{13} = 0) \\ 27\% & (\sin \Theta_{13} = 0.2) \end{cases}$$

Beacom, Bell, Hooper, Pakvasa, TJW, 2003

θ_{13} and δ dependence

Sensitivity to θ_{13} and δ in the Decaying Astrophysical Neutrino Scenario

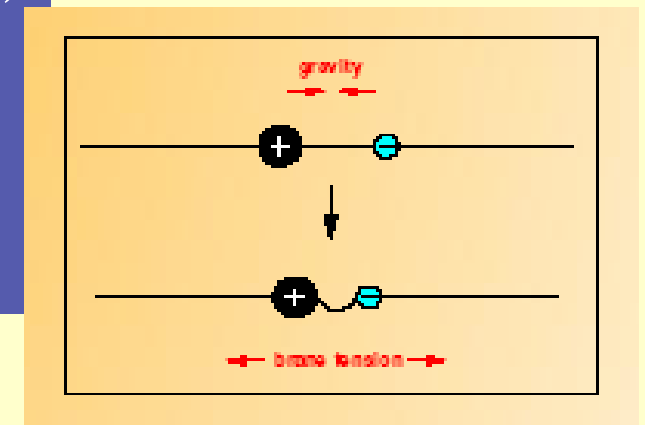
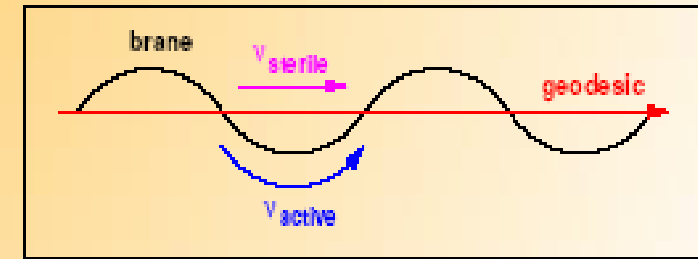
Beacom, Bell, Hooper, Pakvasa, TJW; also Kachelriess & Serpico



In QG/StringTheory, brane is dynamical, fluctuating

due to

Quantum Mechanics
or Thermal Mechanics
or In-Brane stresses (e.g. EM vs. gravity)
or Out of Brane experiences
(e.g. trans-brane gravity)



LSND and Brane-Bulk resonance

Define $|\nu_a\rangle_U = |\nu_4\rangle - \langle \nu_s | \nu_4 \rangle | \nu_s \rangle$

Paes, Pakvasa, TJW 2005

Evolution equation in flavor space:

$$i \frac{d}{dt} \begin{pmatrix} \nu_a(t) \\ \nu_s(t) \end{pmatrix} = H_F \begin{pmatrix} \nu_a(t) \\ \nu_s(t) \end{pmatrix}$$

$$\begin{aligned} \epsilon &= \delta t/t \\ &= \delta x/x \end{aligned}$$

Hamiltonian in the presence of bulk shortcuts:

$$H_F = + \frac{\delta m^2}{4E} \begin{pmatrix} \cos 2\theta & -\sin 2\theta \\ -\sin 2\theta & -\cos 2\theta \end{pmatrix} + E \frac{\epsilon}{2} \begin{pmatrix} -1 & 0 \\ 0 & 1 \end{pmatrix}$$

\Rightarrow A Resonance exists at $E_{\text{res}} = \sqrt{\frac{\delta m^2 \cos 2\theta}{2\epsilon}}$ Energy and nu/nu \bar{a} r independent

\rightarrow choose $E_{\text{res}} = 60 - 500 \text{ MeV} \leftrightarrow \epsilon \simeq 10^{-18} - 10^{-16}$

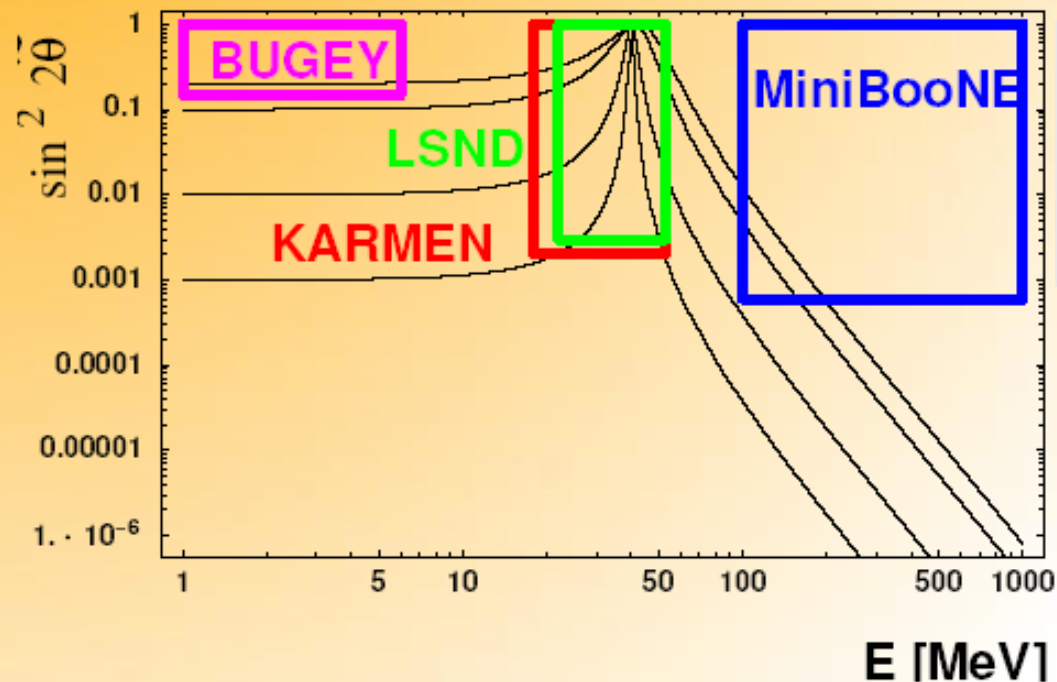
“Typical” Oscillation with Resonance

$$P_{as} = \sin^2 2\tilde{\theta} \sin^2(\delta H D/2)$$

$$\sin^2 2\tilde{\theta} = \left[\frac{\sin^2 2\theta}{\sin^2 2\theta + (\cos 2\theta - A)^2} \right]$$

$$\delta H = \frac{\delta m^2}{2E} \sqrt{(\cos 2\theta - A)^2 + \sin^2 2\theta}$$

$$A = (E_{\text{res}}/E)^2$$



Oscillations at $E \gg E_{\text{res}}$ are suppressed!

Summary

“We are beginning a cosmic voyage into neutrino astrophysics; with this new tool will come inevitable discovery.”

-- somebody really really wise

In particular, the neutrino flavor Q-number may reveal

- neutrino physics (lifetime, pseudoDiracs, steriles)
- extreme astrophysics (source dynamics/environment)
- quantum gravity (decoherence via ST fluctuations)