Neutrino Astrophysics

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Outline

* ν Flux and general remarks
* New physics, two examples
  * Cross-section at 10^20 eV
  * Resonant Absorption/Emission
* finis

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Neutrino-rays versus Cosmic-Rays and Photons

νs come from central engines

- near R_s of massive BHs
- even from dense "hidden" sources
  cf. νs vs. γs from the sun

νs not affected by cosmic radiation

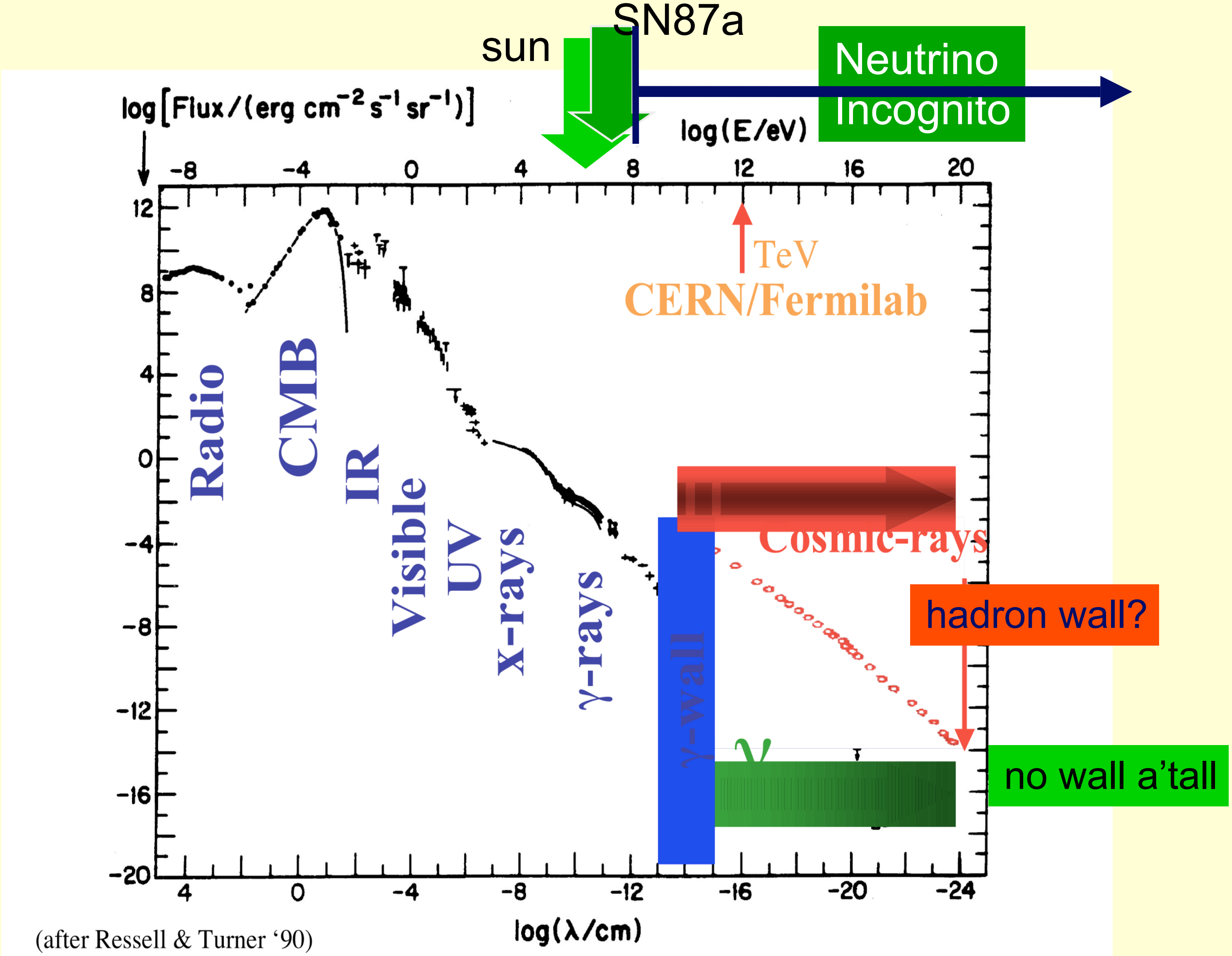
(except for annihilation resonance(s))

νs not bent by magnetic fields

- enables neutrino astronomy

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

Cosmic Photon- Proton-Spectra



(after Ressell & Turner '90)

General Remarks on Neutrinos

Existence of Xgal neutrinos inferred from CR spectrum, up to 10^{20} eV,
and similarly, Galactic up to 10^{18} eV,

Need gigaton (km^3) mass (volume) for TeV to PeV detection [e.g. IceCube Xpt]
but a teraton of mass at 10^{19} eV
➔ SPACE-BASED [e.g. EUSO Xpt]

Neutrino eyes see farther ($z>1$),
and deeper (into compact objects) than gamma-photons,
and straighter than HECRs,
with no absorption at (almost) any energy

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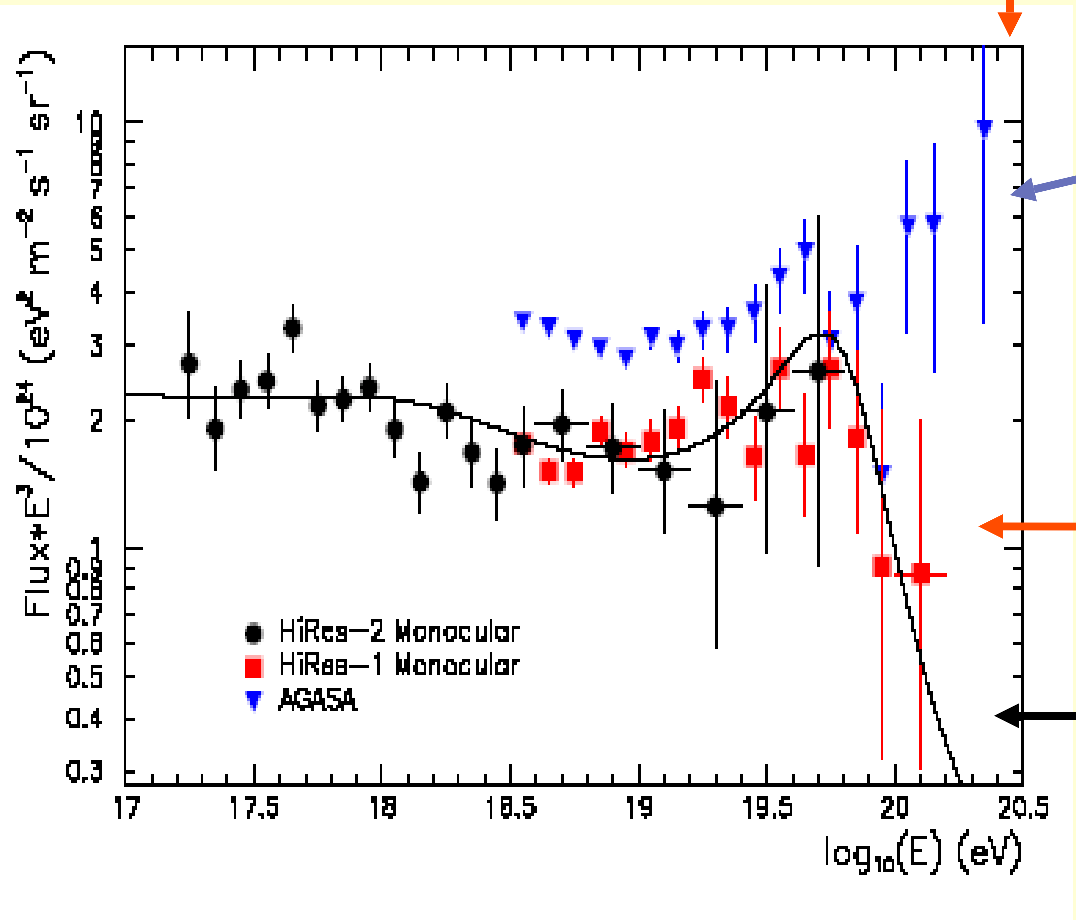
HiRes vs. AGASA UHE spectrum

FlysEye event goes here



discovery

opportunity

GZK recovery ?

Z-burst uncovery ?

Auger reach 70 x better,

"EUSO" reach 10^3 x better !

Extreme Energy (EE) Neutrinos

Sources:

Bottom-Up "Zevatrons" - givens

Cosmogenics $\sim 10^{19}$ eV

- AGNs
- GRBs
- Hidden vs. Transparent (the thick/thin debate)

Top-Down "EE-trons" - pure speculation

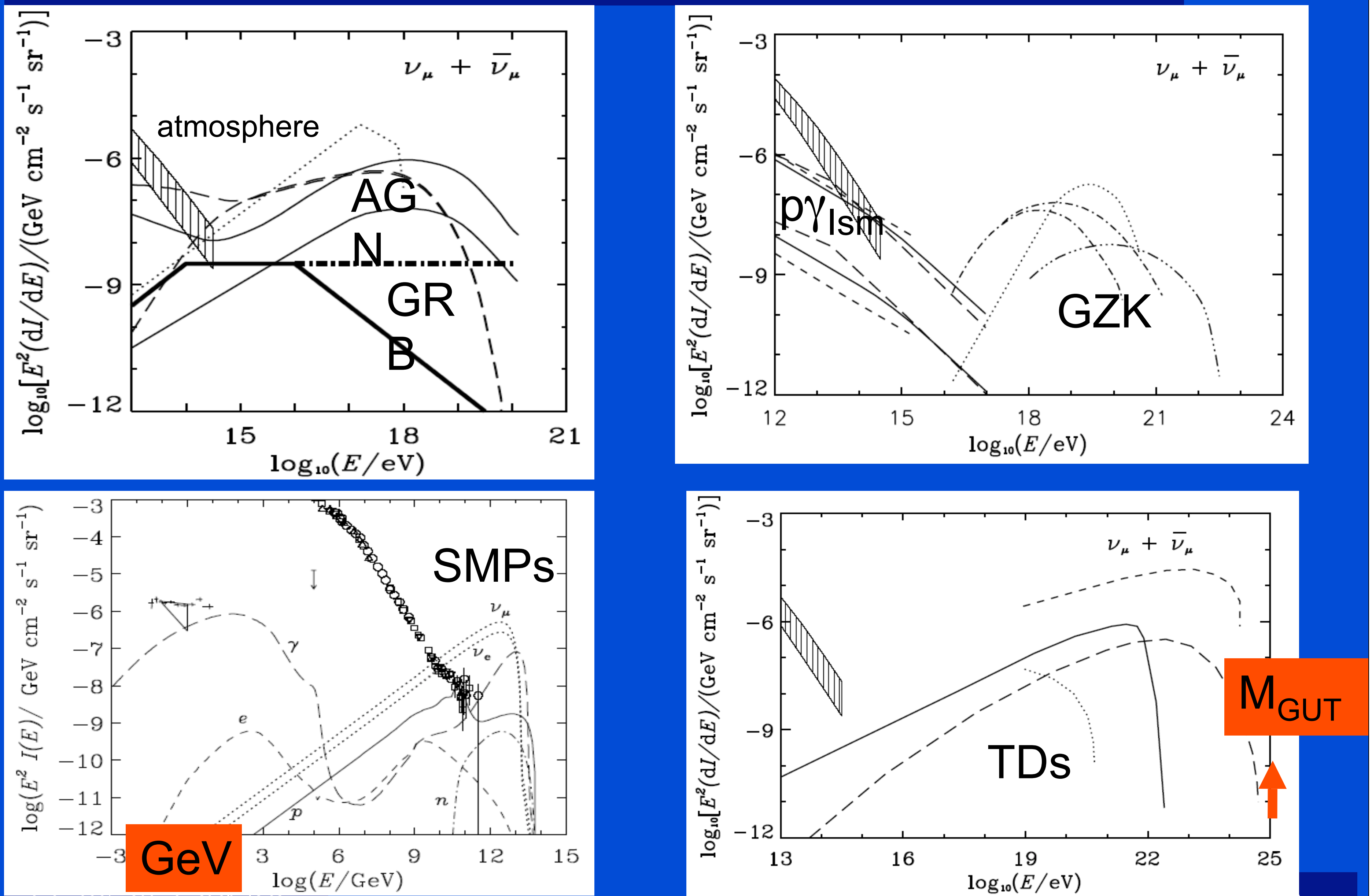
- Topological Defects
- Wimpzillas, M ~H(post-inflation) $\sim 10^{22}$ eV
- $M_{see\text{-}saw}$ $\sim 10^{23}$ eV
- M_{GUT} $\sim 10^{25}$ eV
- And even M_{Planck} $\sim 10^{28}$ eV

Other: - impure thoughts

Mirror-Matter mixing

Multiverse Leakage (Brane-bridges)

Model ν fluxes (Protheroe review 1996)



ν HAS event rate is small at Extreme Energy

$$\text{Rate}(\nu) = 2\pi\, A_{\text{FOV}}\, P(\text{see}\,\nu)\; F_\nu\; (\text{duty cycle})$$

$\text{P}(\text{see}\;\nu) \sim \sigma_{\nu N}\,\rho(0)\,h$

and for EUSO,

$2\pi\, A_{\text{FOV}} \sim 10^6\,\text{km}^2\,\text{ster}$

i.e. 2 teratons!!

and,

duty cycle $\sim$ 15%.

$$\Rightarrow \frac{1}{\text{yr}}\,\sigma_{\text{GQRS}}\,\frac{F_\nu}{\text{km}^{-2}\,\text{ster}^{-1}\,\text{yr}^{-1}} \quad \text{at } 10^{20}\text{ eV}$$

e.g. F_{CR} implies 10^{-2} events/yr at 10^{20} eV;
and 10 events/yr at 10^{19} eV;
and 10^{+4} events/yr at 10^{18} eV.

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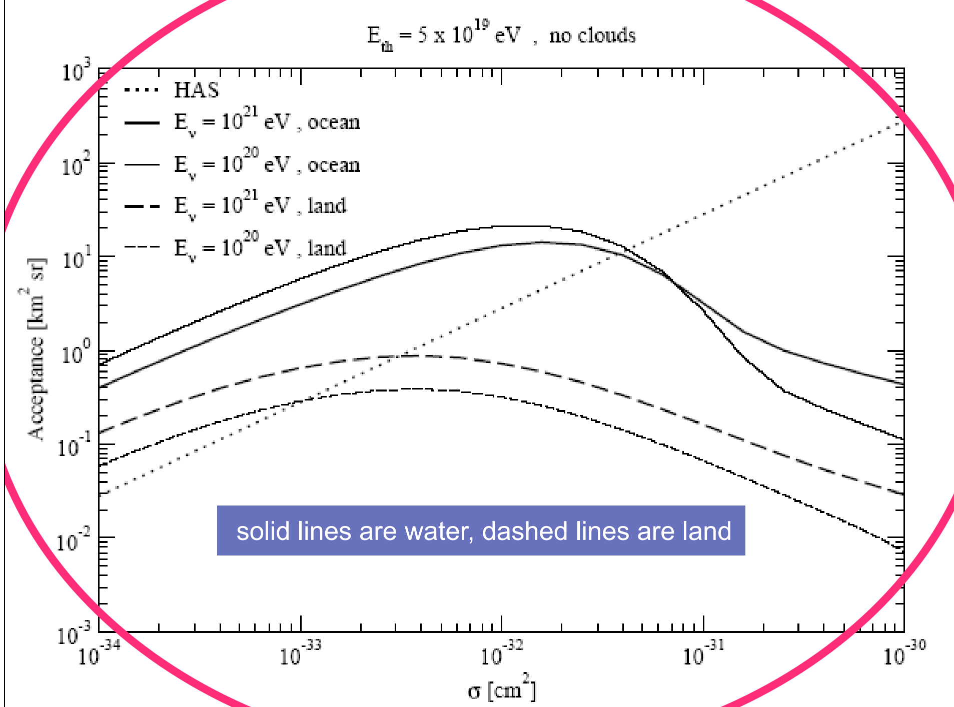
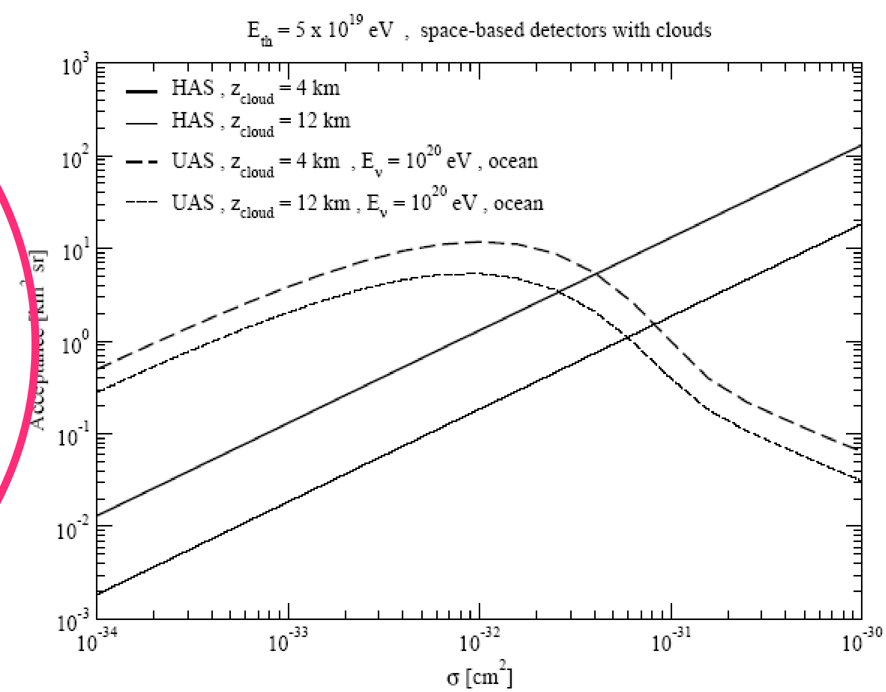
$\sigma_{\nu N}$ with Space-Based HAS/UAS

No clouds

with cirrus (12km) or high cumulus (4km) clouds



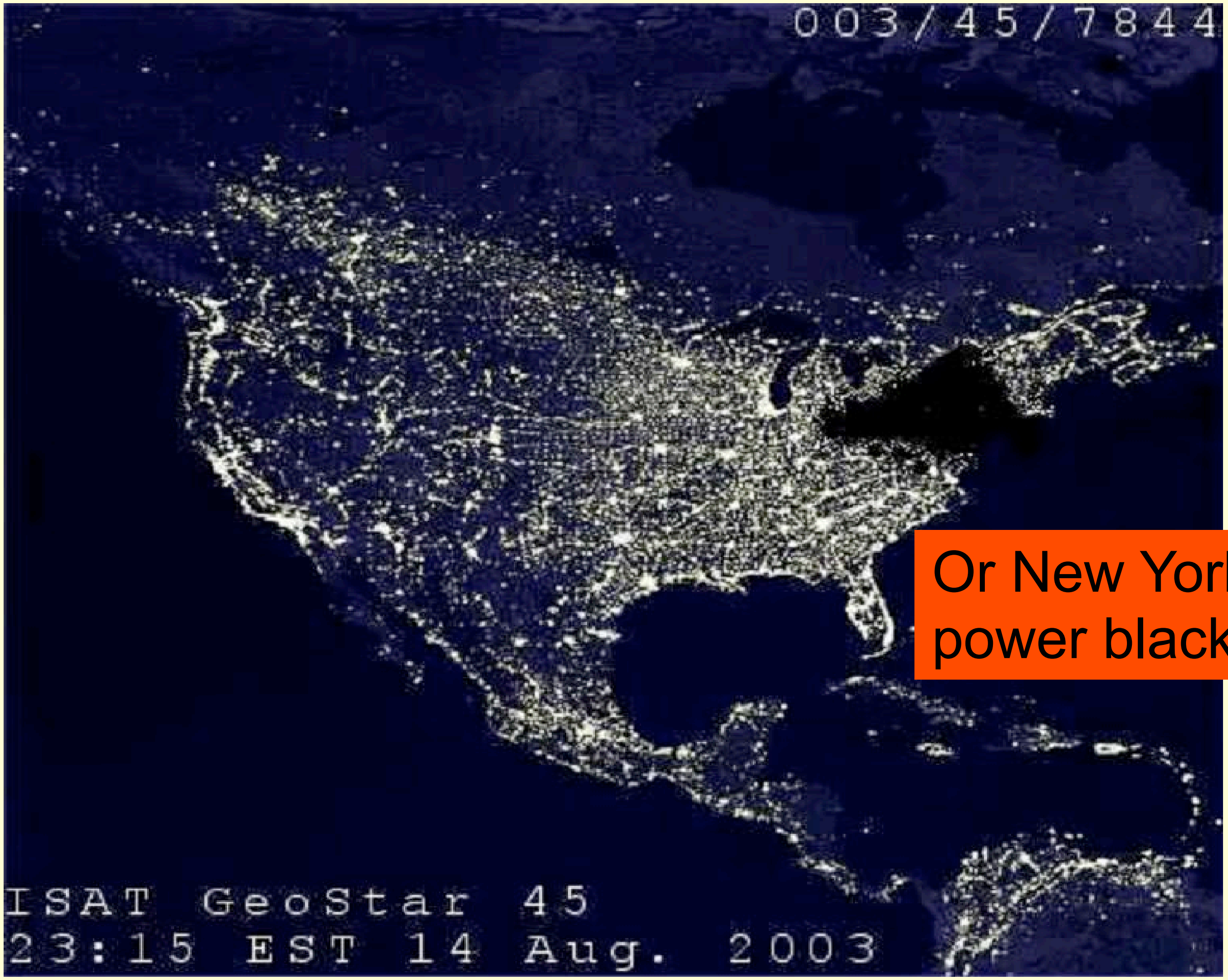


Volume favors space-based over land-based by one or more orders of magnitude; for UAS, water also favors space-based by one or more orders of magnitude

Sergio Palomares-Ruiz, TJW; A. Kusenko,TJW

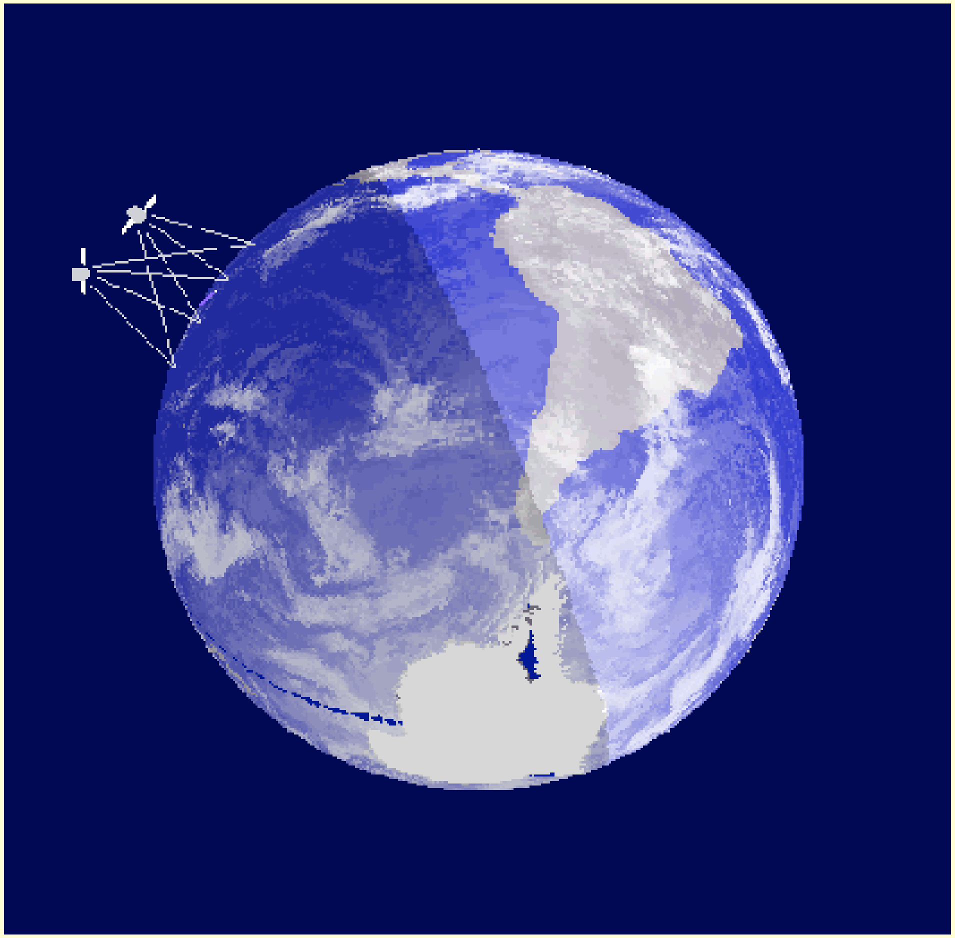
Extreme Universe Space Observatory

"clear moonless nights"



Or New York State power blackout

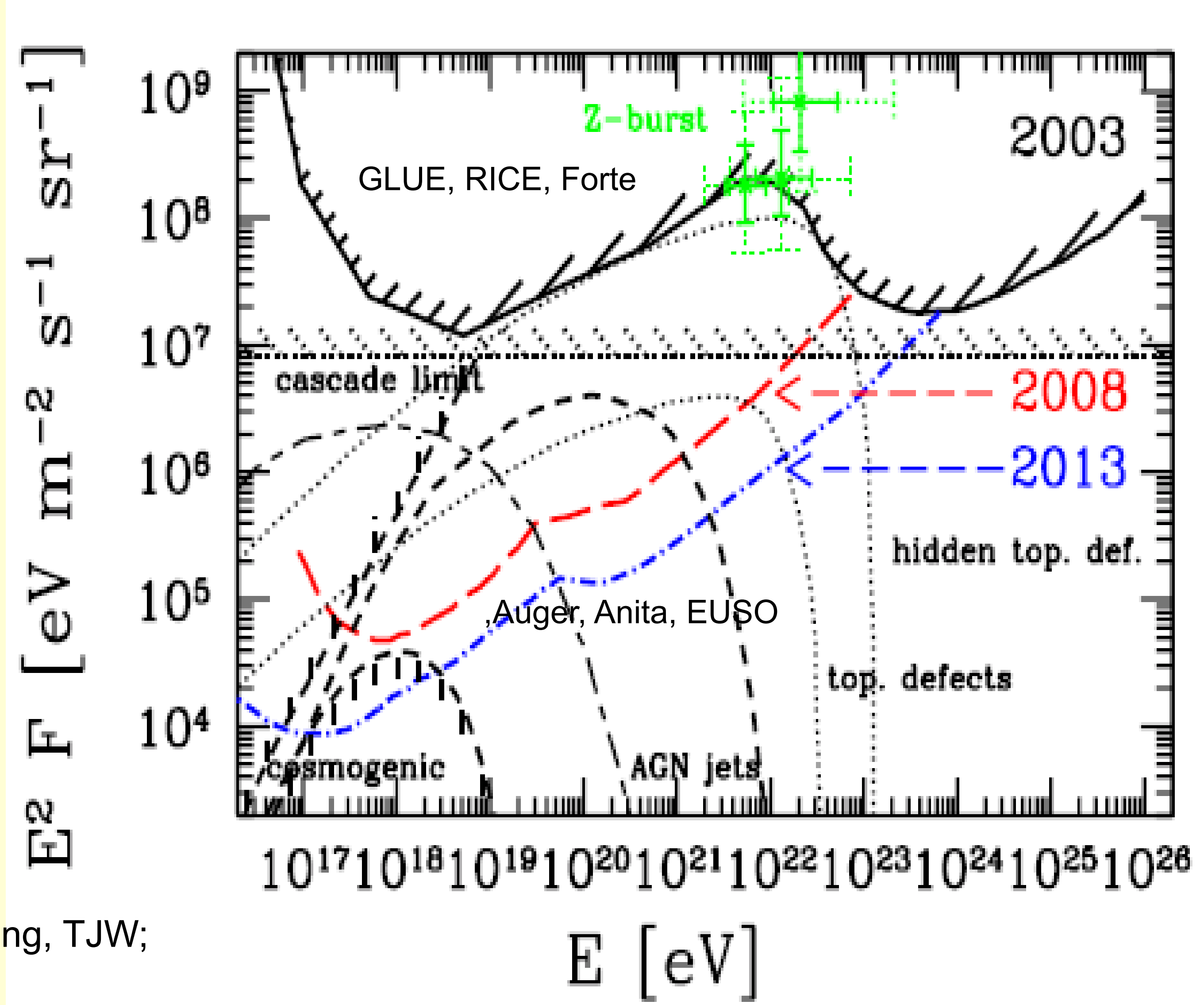
Orbiting Wide-angle Lens (OWL)



3000 CR events/year above 10^{20}eV

and UHE Neutrinos!

Model Neutrino Fluxes and Future Limits



From Eberle, AR, Song, TJW;
Semikoz and Sigl

ν-N cross-section at 10^{20} eV

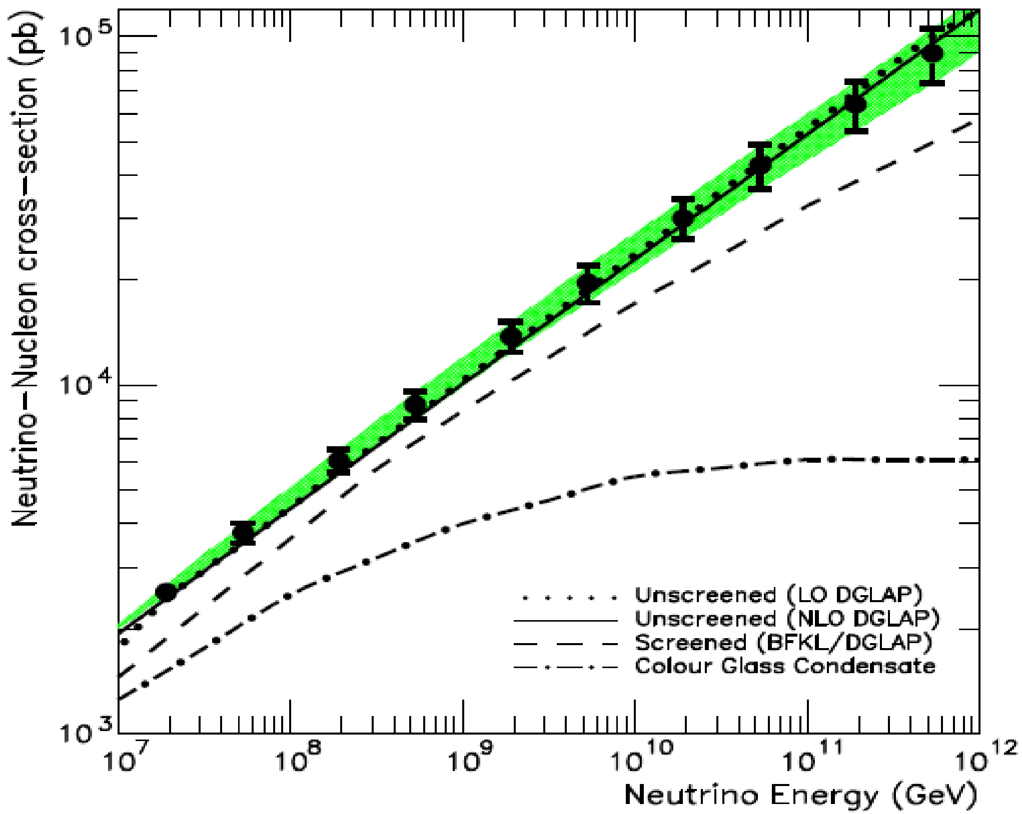
CM energy at HERA is 0.3 TeV;
while at $E_\nu \sim 10^{20}$ eV, Nature gives us $E_{cm} \sim$ PeV!

And so neutrinos probe new thresholds,
e.g. SUSY, X-Dimensions, TeV-scale Gravity,
EW Instantons (NonPert. EW), …

Also provides new QCD information,
probing nucleon structure at unprecedented small-x values.

Reminder: LHC E_{cm} =14 TeV, and ILC E_{cm} =0.5 TeV

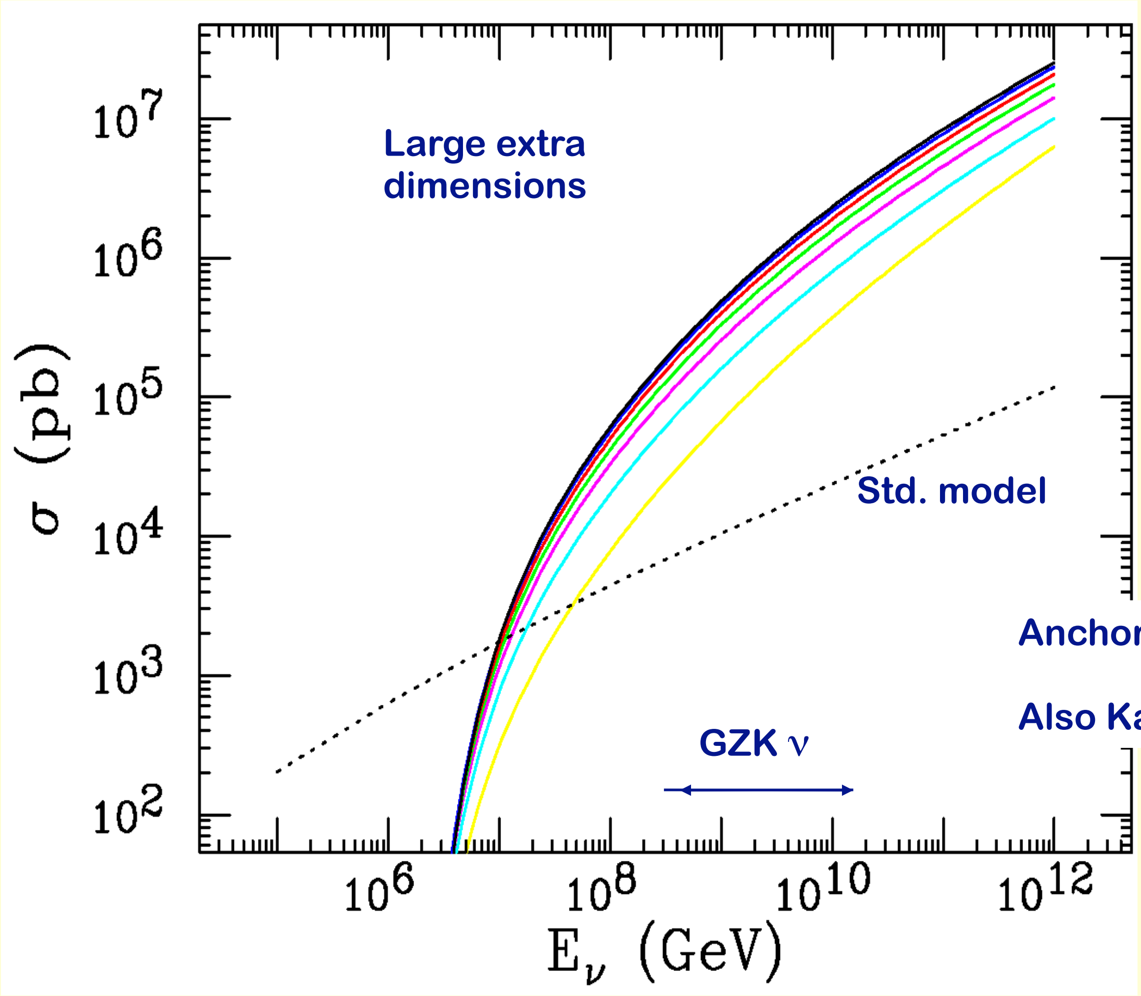
$\sigma_{\nu N}$ (QCD) at 10^{20} eV



Luis A. Anchordoqui,[1,2] Amanda M. Cooper-Sarkar,[3] Dan Hooper,[4] and Subir Sarkar[5]

FIG. 1: Predicted cross-sections for neutrino-nucleon scattering at high energies. The line with its 1σ error band is the fit (Eq.4) to our calculated $\sigma_{\rm uns}^{\rm NLO}(E_\nu)$ (points with error bars). For comparison we show $\sigma_{\rm uns}^{\rm LO}(E_\nu)$ (dotted line) [4], $\sigma_{\rm scr}^{\rm KK}(E_\nu)$ (dashed line) [20], and $\sigma_{\rm scr}^{\rm HJ}(E_\nu)$ (dot-dashed line) [23].

$\sigma_{\nu N}$ can be big



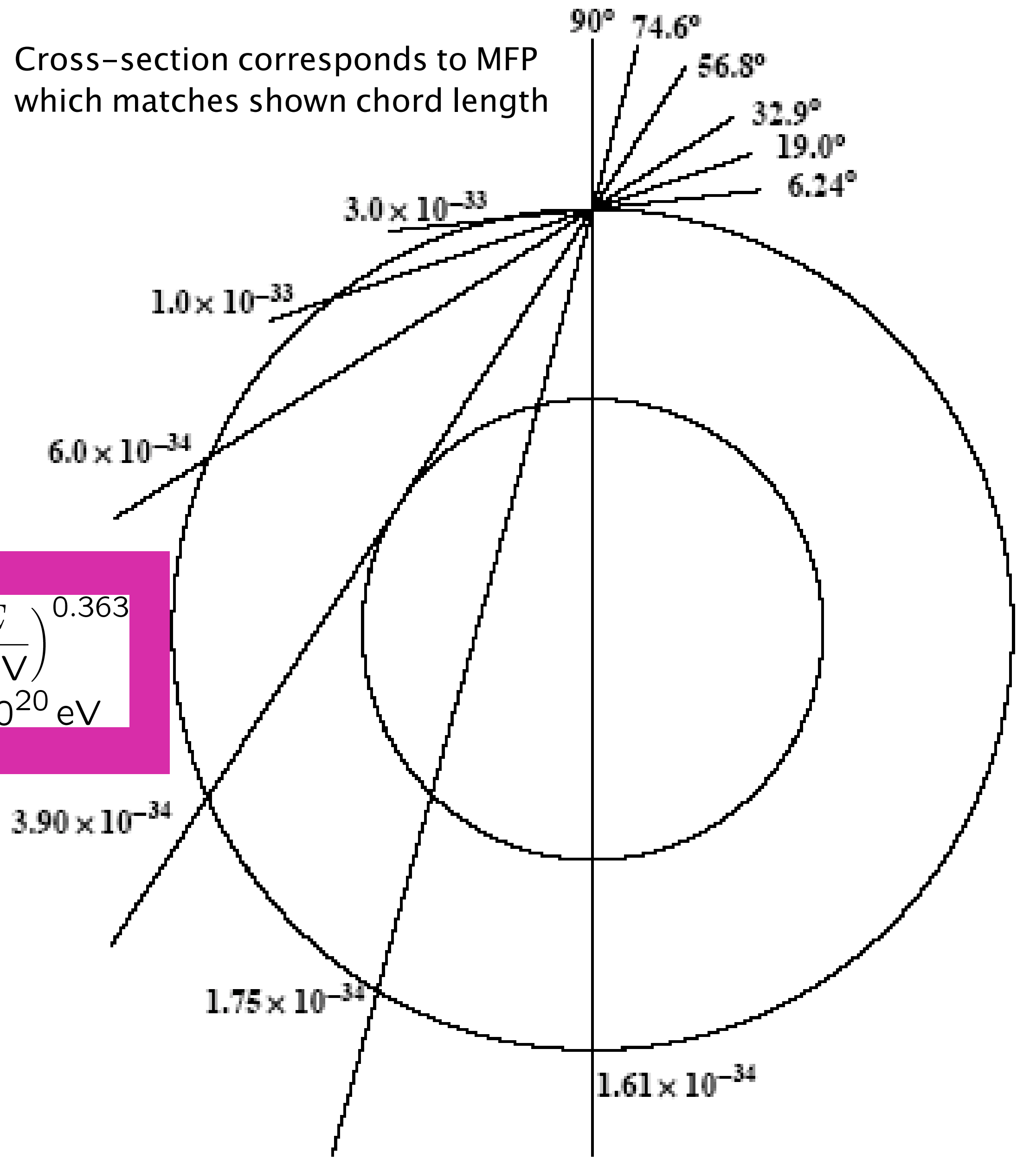
Anchordoqui et al. Astro-ph/0307228

Also Kansans; Ahn,Cavaglia, Olinto; etc

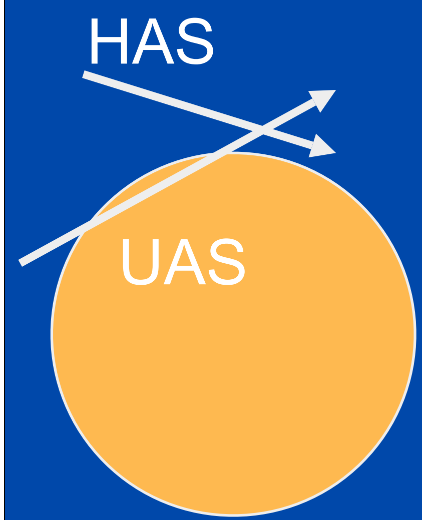
Earth Absorption versus Neutrino Cross-Section

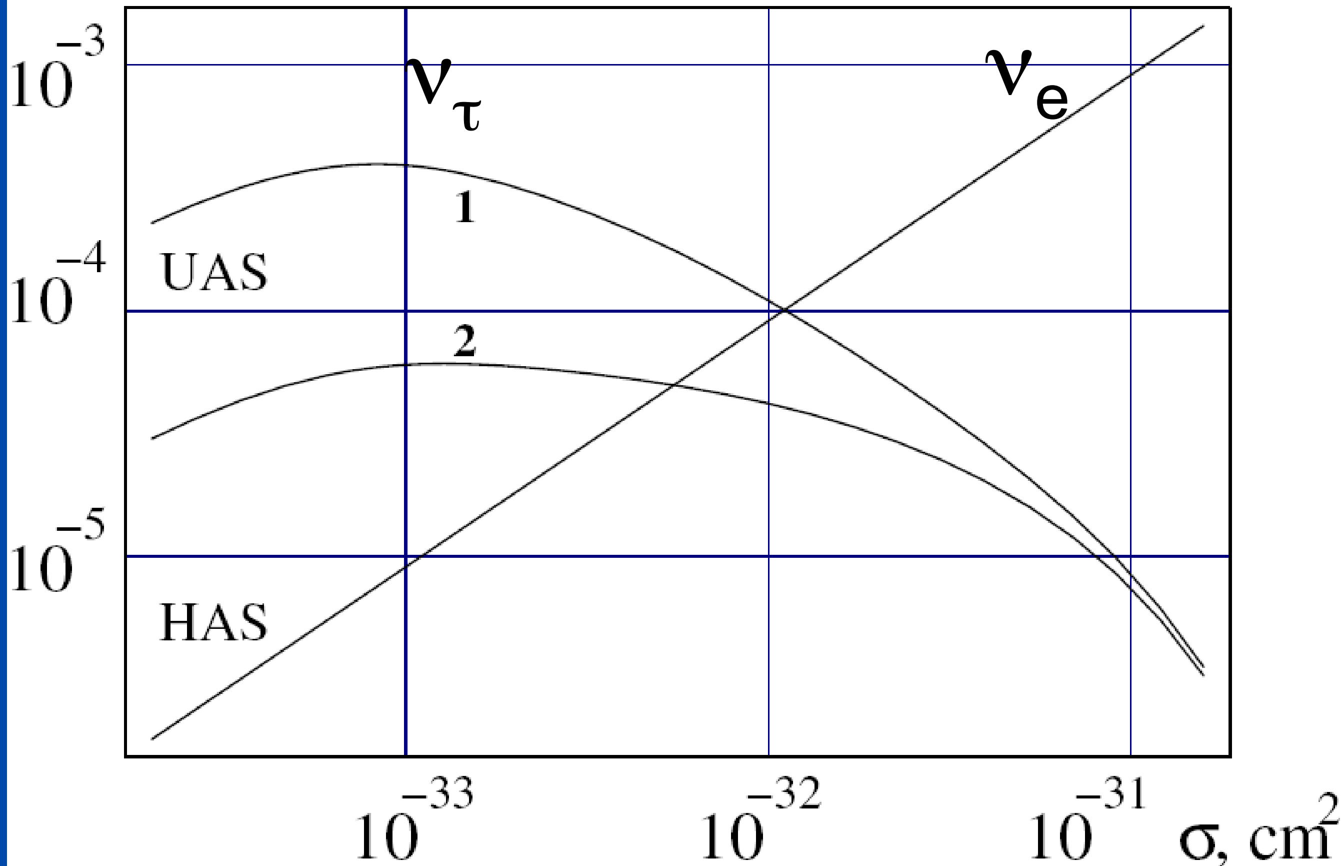
$$\sigma_{\rm GQRS} = 0.5 \times 10^{-33}\,{\rm cm}^2 \left(\frac{E}{\rm PeV}\right)^{0.363}$$
$$= 0.5 \times 10^{-31}\,{\rm cm}^2 \text{ at } 10^{20}\,{\rm eV}$$

Cross-section corresponds to MFP which matches shown chord length



Upward and Horizontal Air-shower Rates Versus Neutrino Cross-section





Kusenko, TJW, PRL2002

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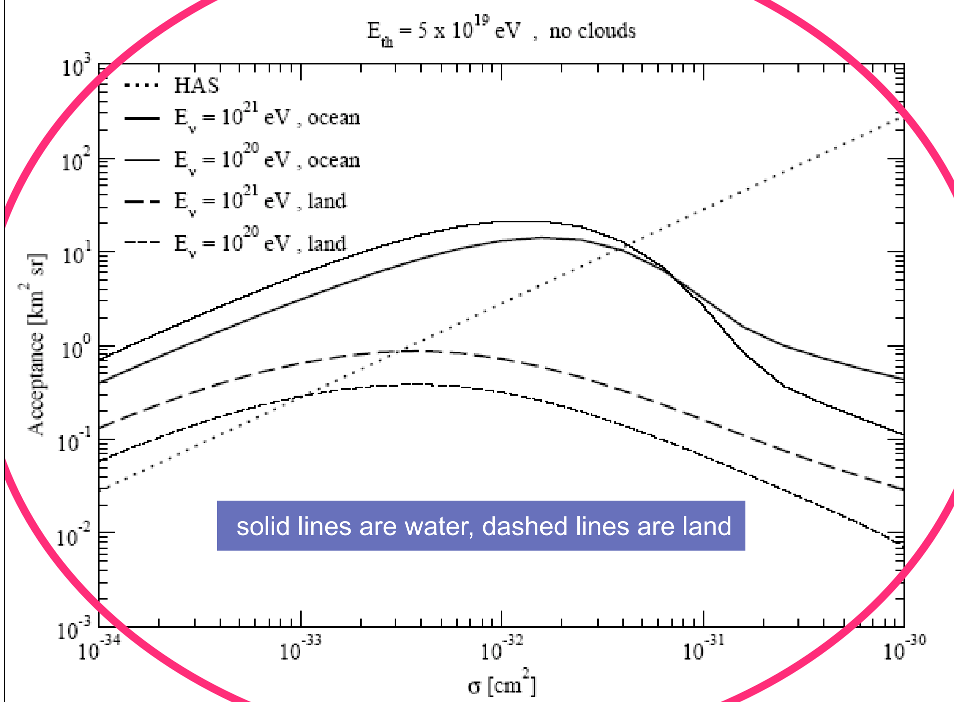

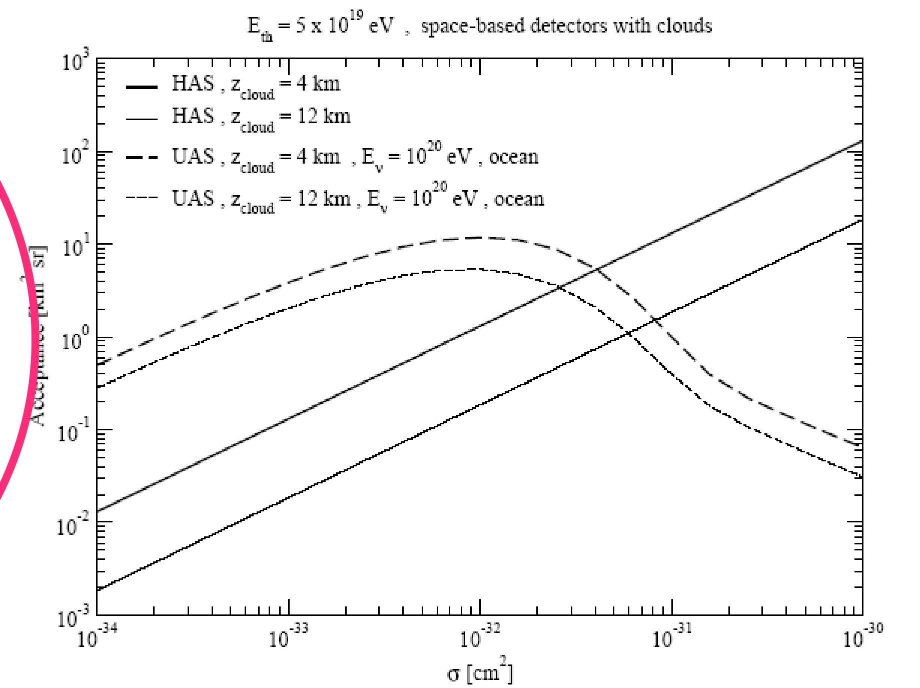

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Sergio Palomares-Ruiz, TJW; A. Kusenko,TJW

Can't Lose Thm for Space-based

Whatever the weak cross-section,
get robust event rate from HAS or UAS!

and

Get measurement of neutrino cross-section

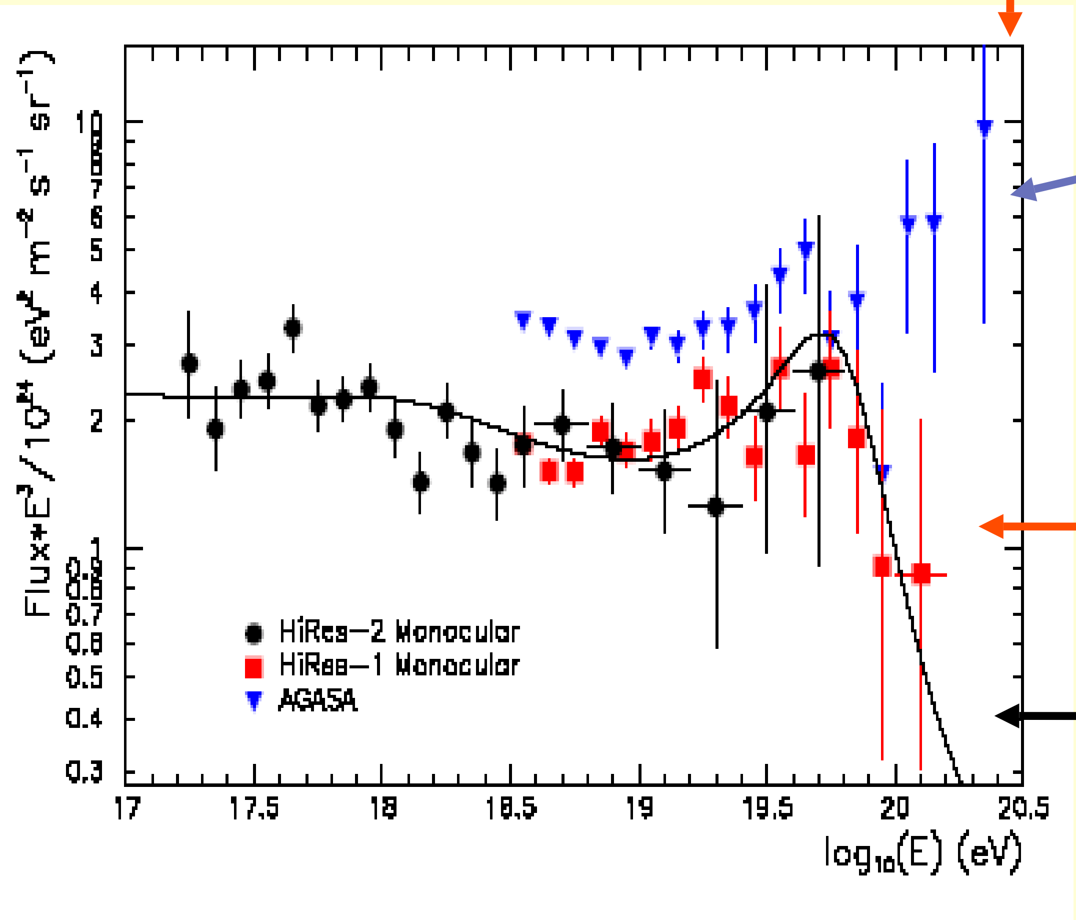
(peak angle also gives $\sigma_{\nu N}$)

A. Kusenko, TJW (PRL2002)

Resonant Bursts/Dips

HiRes vs. AGASA UHE spectrum

FlysEye event goes here



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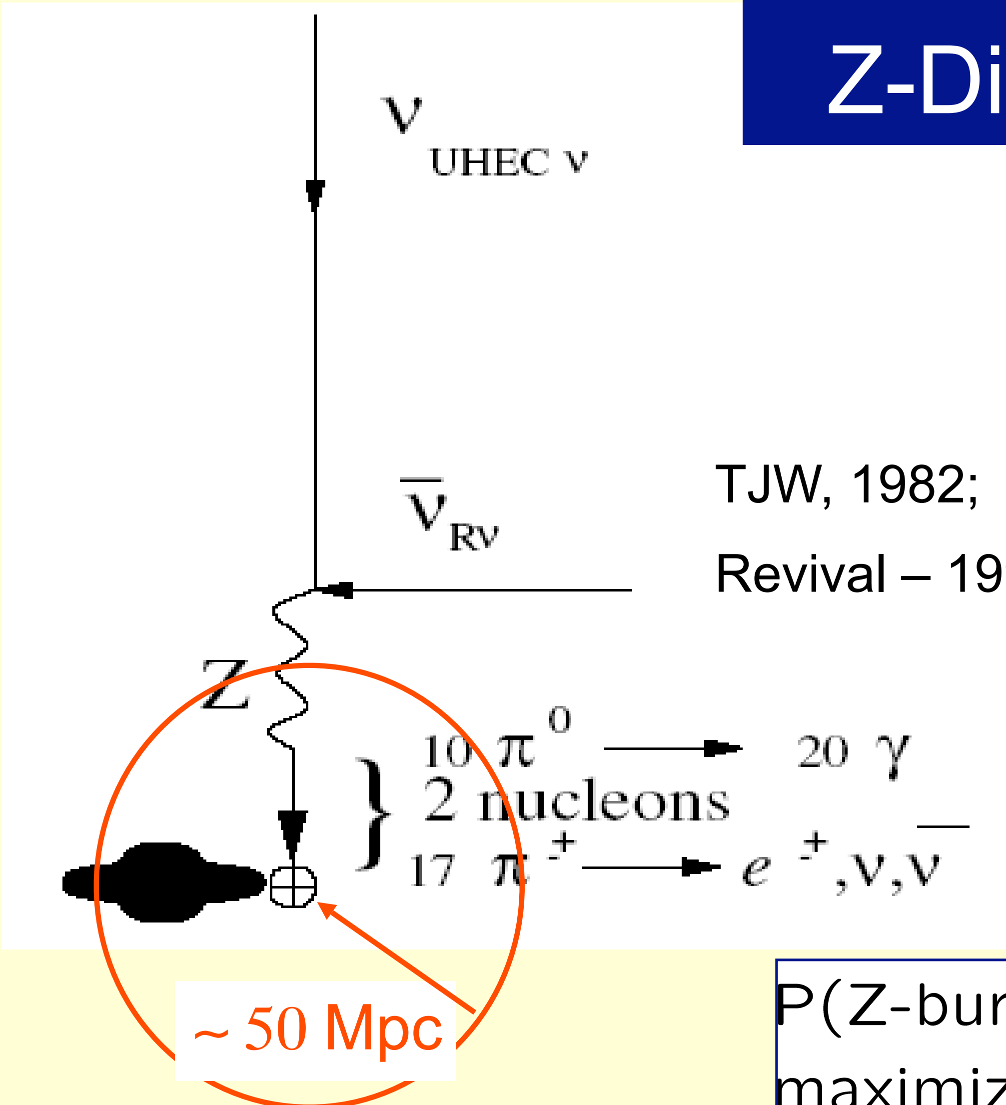
Z-Dips/Bursts



$$E^R_{\nu_j} = \frac{M_Z^2}{2m_j} = 4\,(\frac{\text{eV}}{m_j})\,\text{ZeV}$$

TJW, 1982;

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

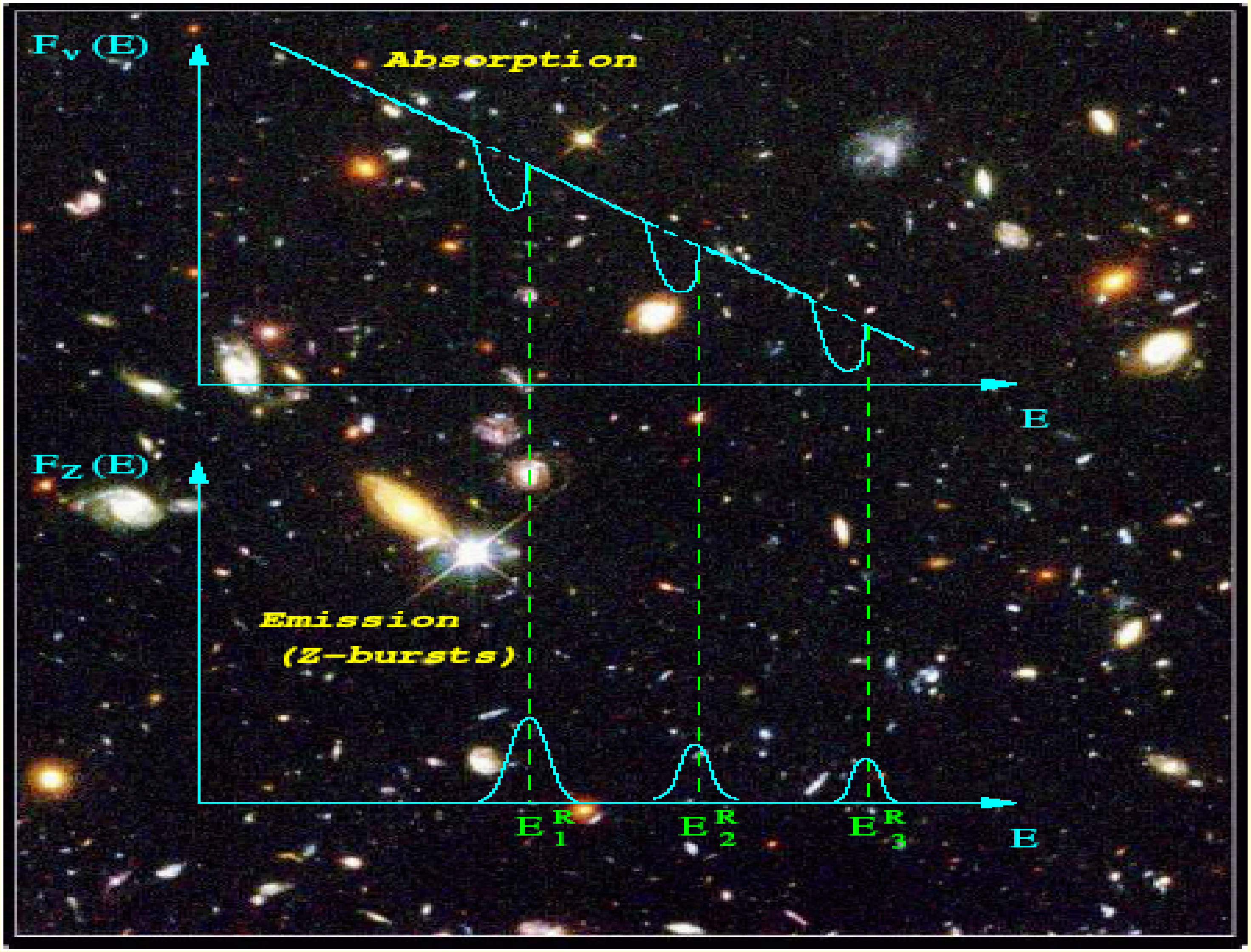
P(Z-burst) $= E^{-D_H/\lambda}\,\frac{D_{\text{GZK}}}{\lambda}$
maximized at $\lambda = D_H$,
neglecting expansion.
Matches to D_H at $1 + z \sim (40)^{1/3}$
i.e. $z \sim 2.5$

Escher's Angels and Devils"

Looking back, $n_\nu \sim (1+z)^3$,

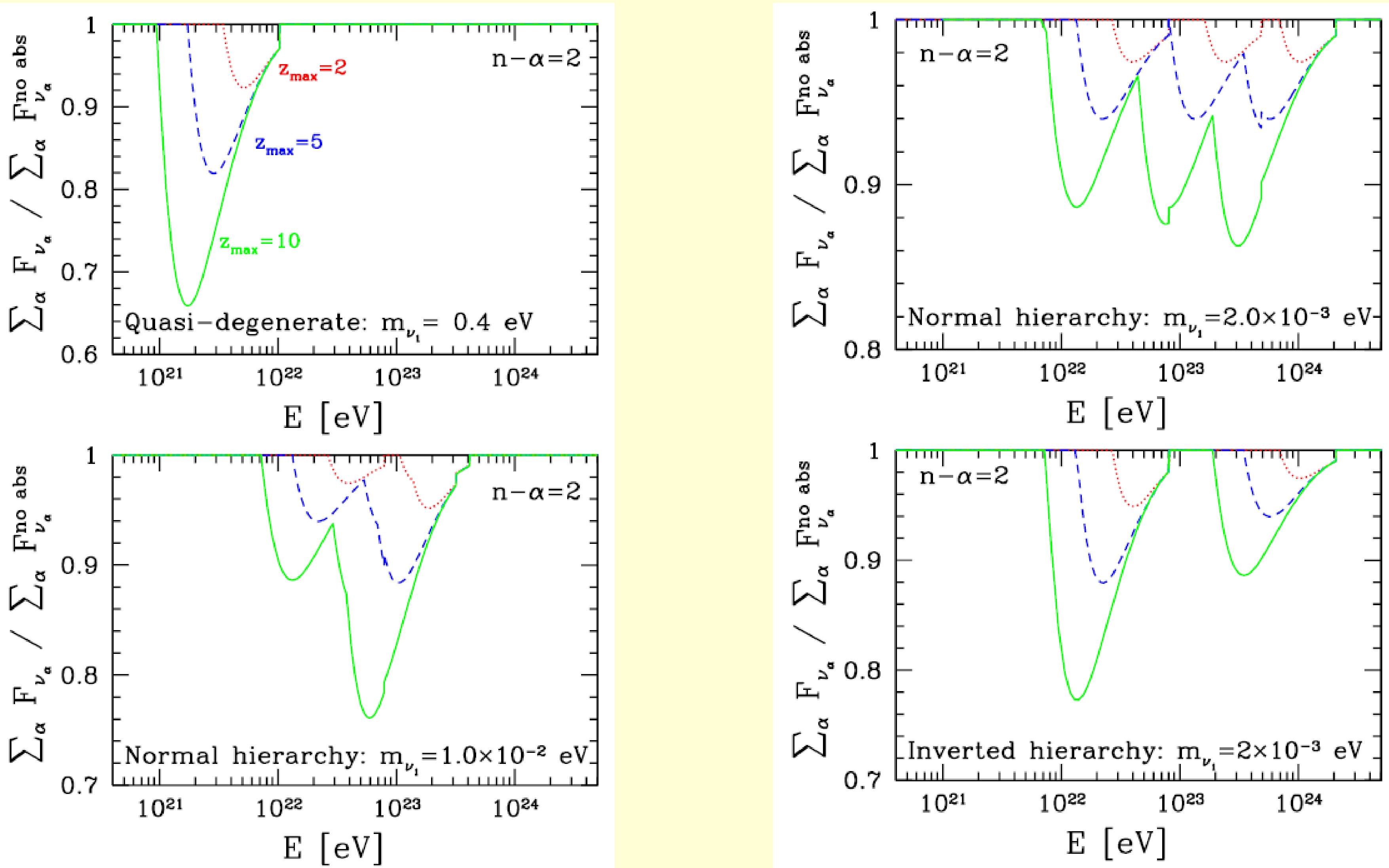
And so the absorption is greatly
Enhanced for ν's from high-z sources

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



ν-mass spectroscopy

z_{max}=2, 5, 20 (top to bottom), n-α=2
(bottom-up acceleration)
Eberle, Ringwald, Song, TJW, 2004



z-Integrated resonances (zIRs)

$$E_{\rm R} = \frac{M_{\rm R}^2 - m_{\rm T}^2 - m_{\rm B}^2}{2\,m_{\rm T}} = \omega\, E_0\,.$$

The probability for a cosmic neutrino to *not* interact is $e^{-\tau}$, where τ is the mean number of interactions (some-

$$\tau = \int \frac{c\,dt}{\lambda_\nu} = \int d\omega\, \frac{dt}{d\omega}\, n(\omega)\, \sigma(\omega)\,, \qquad (12)$$

where λ_ν is the mean-free path of the cosmic neutrino. The definition of ω leads to $dt/d\omega = -1/(\omega\, H(\omega))$. The Friedmann equation relates the Hubble parameter $H(\omega)$ to its present value and the energy partitioned Ω's of the Universe, via:

$$H(\omega) = H_0\,\sqrt{\Omega_\Lambda + \Omega_M\omega^3 + \Omega_R\omega^4 + \Omega_k\omega^2}\,. \qquad (13)$$

to get:

$$\tau(E_0) = 16\,\pi^2 \left(\frac{S_R}{S_i}\right) \left(\frac{\Gamma_i}{M_{\rm R}}\right) \left(\frac{1}{1 - m_{\rm T}^2/M_{\rm R}^2}\right)^2 \left(\frac{n_0}{H_0\, M_{\rm R}^2}\right) \left[\frac{\omega^3}{\sqrt{\Omega_\Lambda + \Omega_M\,\omega^3}}\right]_{\omega = \frac{M_{\rm R}^2 - m_{\rm T}^2}{2\,m_{\rm T}\,E_0}}\,, \quad \omega \le \omega_e \ll \omega_{\rm eq},$$

zIR reach:

$$\left(\frac{\Gamma_i}{M_R}\right)\left(\frac{1}{1-m_T^2/M_R^2}\right)\left(\frac{n_0}{H_0\,M_R^2}\right) \gtrsim 10^{-3}\,\ln(1-f)^{-1} \xrightarrow{f=10\%} 10^{-4}\,. \quad (15)$$

$$\left(\frac{m_T}{M_R}\right) \lesssim 10^6\,\frac{g^2\,\Omega_T}{\Omega_{DM}}\left(\frac{\text{MeV}}{M_R}\right)^3$$

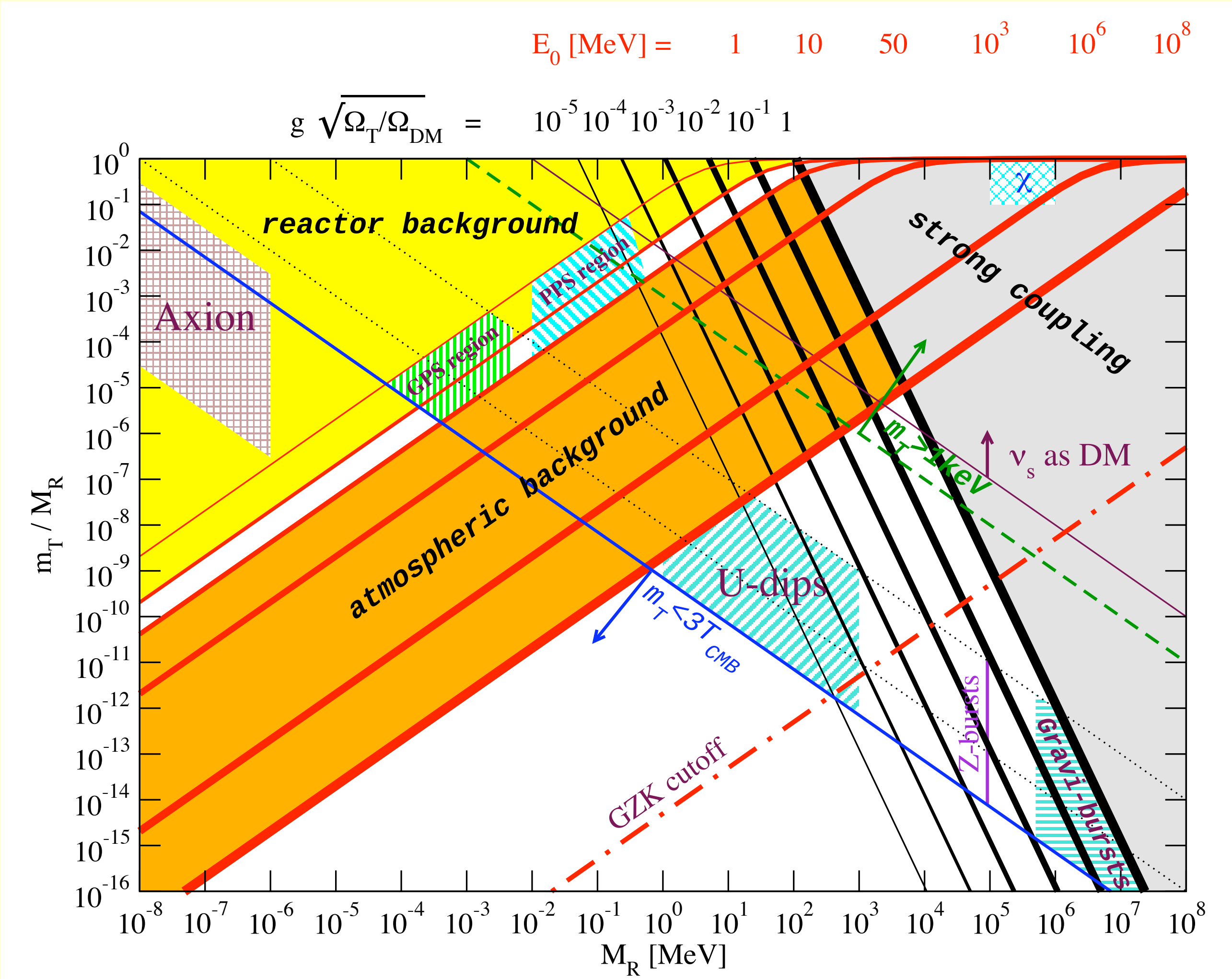
$$\left(\frac{M_R}{\text{MeV}}\right) \lesssim 2\left(\frac{g}{10^{-5}}\right) \qquad \text{[neutrino target]}$$

* Low-reheat scalars

* U boson (Fayet)

* KeV sterile neutrino (Shaposhnikov, Kusenko)

The zIR plane



and Resonant Bursts:

$$R_j = N_j \int dE_\nu \, \frac{\lambda_j(E_j)}{\lambda_\nu(E_\nu)} \, \frac{dF_\nu(E_\nu)}{dE_\nu} \, ,$$

$$\frac{R_j}{\left[E_\nu \, \frac{dF_\nu}{dE_\nu}\right]_{E_{\rm R}}} = \left(\frac{N_j \, \lambda_j}{F(\omega) \, H_0^{-1}} \right) \tau \, . \qquad (33)$$

We note below that $N_j \, \lambda_j$ is about 100 Mpc for both cosmic rays and gamma-rays, and that $f(\omega)$ is typically of order ten. With $H_0^{-1} = 4.09 \, h_{W3}^{-1}$ Gpc being the Hubble size of the Universe, we are left to conclude that measuring an emission spectrum is competitive with measuring an absorption dip if an experiment is sensitive to the rate

$$R_j^{\rm X} \sim \frac{\tau}{500} \left[E_\nu \frac{dF(E_\nu)}{dE_\nu} \right]_{E_{\rm R}} \, . \qquad (34)$$

For example, an absorption depth of, say, 5% may not be measurable, but the burst flux should be measurable by an experiment sensitive to a flux $\sim 10^{-4}$ times what Nature provides for the neutrino flux at resonance.

Z-burst spectrum

mean multiplicity of 30 secondaries in Z decay [24], one has

$$\langle E_p \rangle \sim \frac{E_R}{30} \sim 1.3 \left(\frac{\text{eV}}{m_j}\right) \times 10^{20}\text{eV} .$$

"Explains" AGASA data !!

The photon energy is further reduced by an additional factor of 2 to account for their origin in two-body π^0 decay:

$$\langle E_\gamma \rangle \sim \frac{E_R}{60} \sim 0.7 \left(\frac{\text{eV}}{m_j}\right) \times 10^{20}\text{eV} . \tag{4}$$

Even allowing for energy fluctuations about mean values, it is clear that in the Z-burst model the relevant neutrino mass cannot exceed ~ 1 eV. On the other hand, the neutrino mass cannot be too light of the predicted primary energies will exceed the observed event energies.[2] In this way, one obtains a rough lower limit on the neutrino mass of ~ 0.1 eV for the Z-burst model, when allowance is made for an order of magnitude energy-loss for those secondaries traversing 50 to 100 Mpc.

Summary

Neutrinos from the Cosmos:

Next decade will be critical, and,
the deities/gods willing,
most fruitful !

"Now is an exceptional time for neutrino astrophysics."
-- somebody said this