The Abdus Salam
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World Year of
PHYSICS
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SUMMER SCHOOL ON PARTICLE PHYSICS

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Neutrino Physics - Part 4

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Lecture 4: High Energy Neutrinos

John Beacom, The Ohio State University

Elevator Pitch

We need complementary searches for new physics

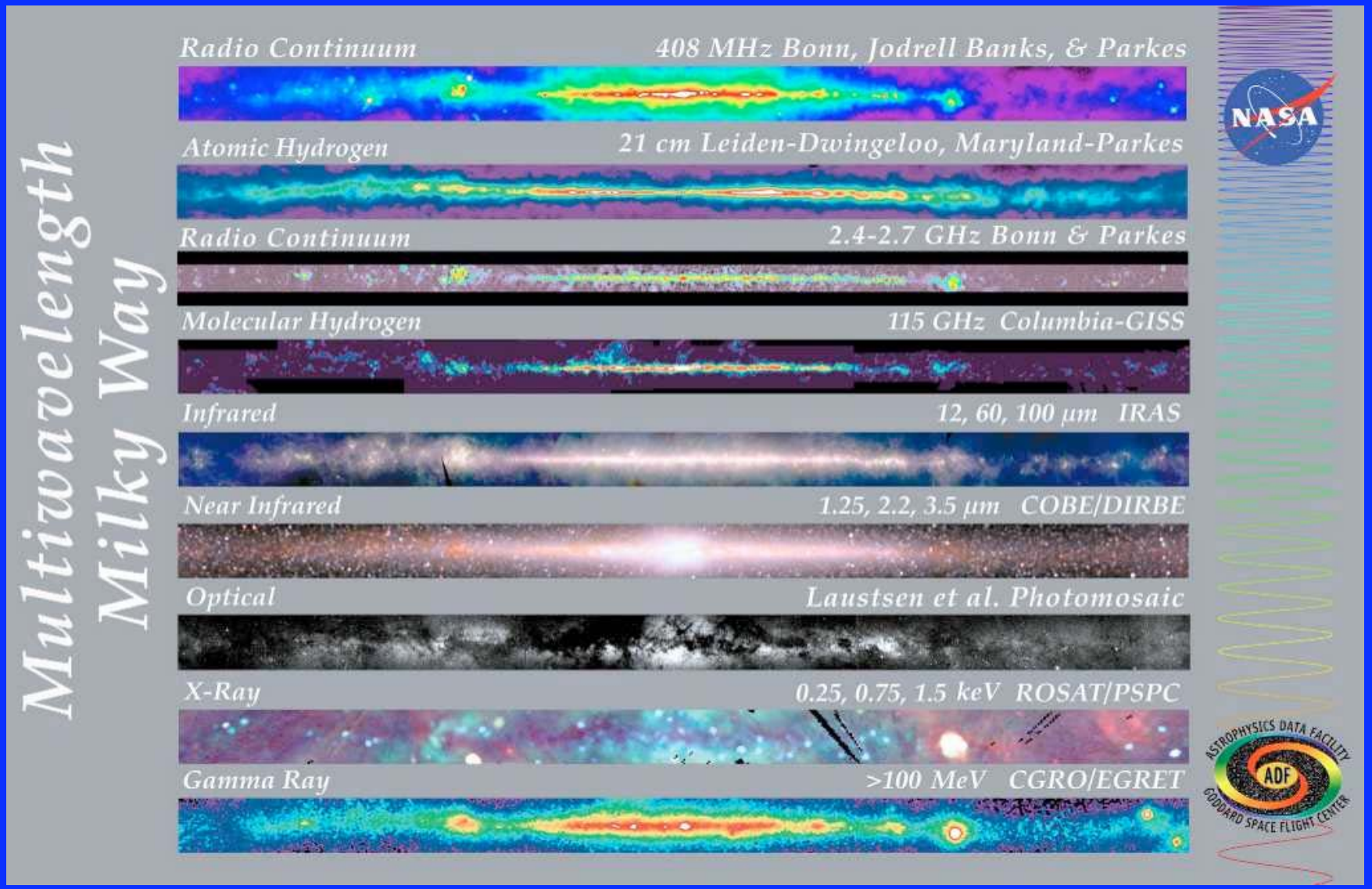
High energy neutrinos will be an important probe of astrophysical sources, the origin of the cosmic rays, and the energy frontier, complementing other techniques...especially once they are detected!

proton + target --> Delta --> pion --> neutrino, gamma

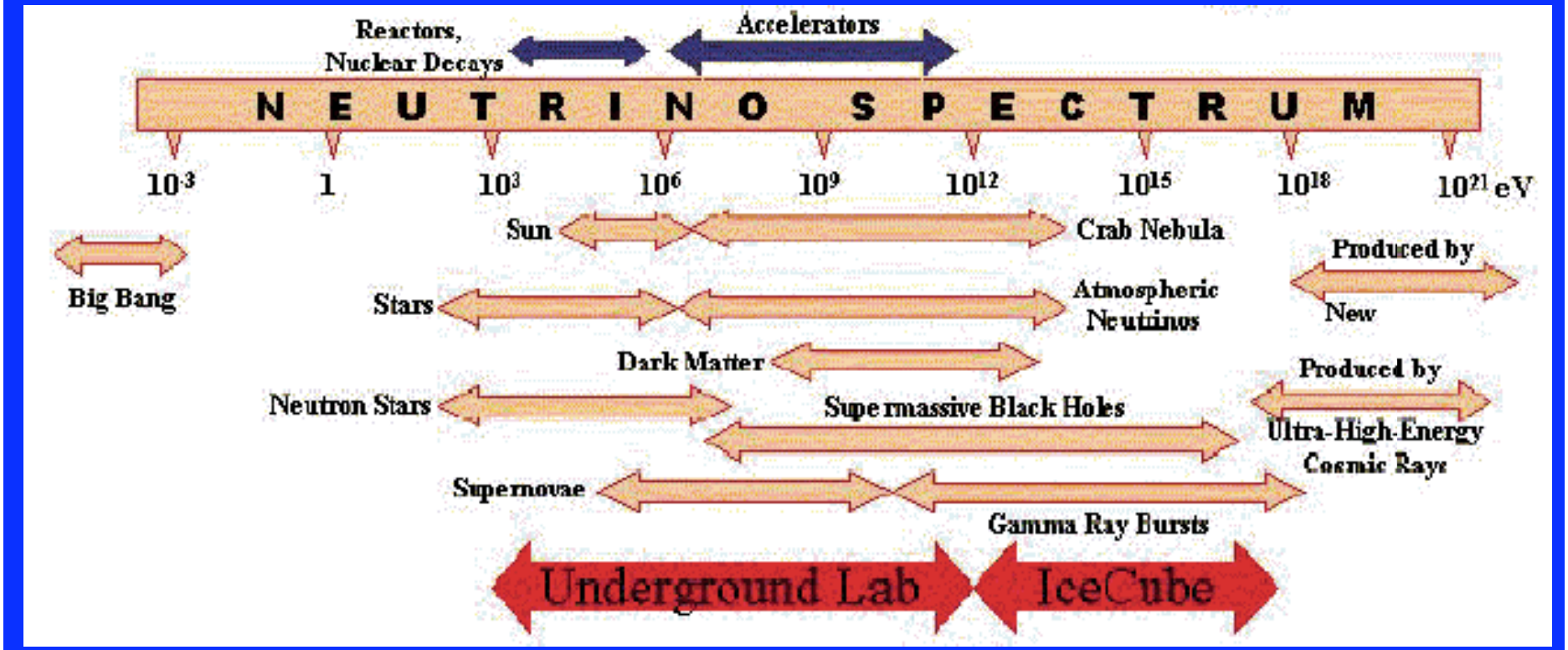
AGN: pion production on source protons, photons

GZK: pion production on CMB photons

Photon Windows

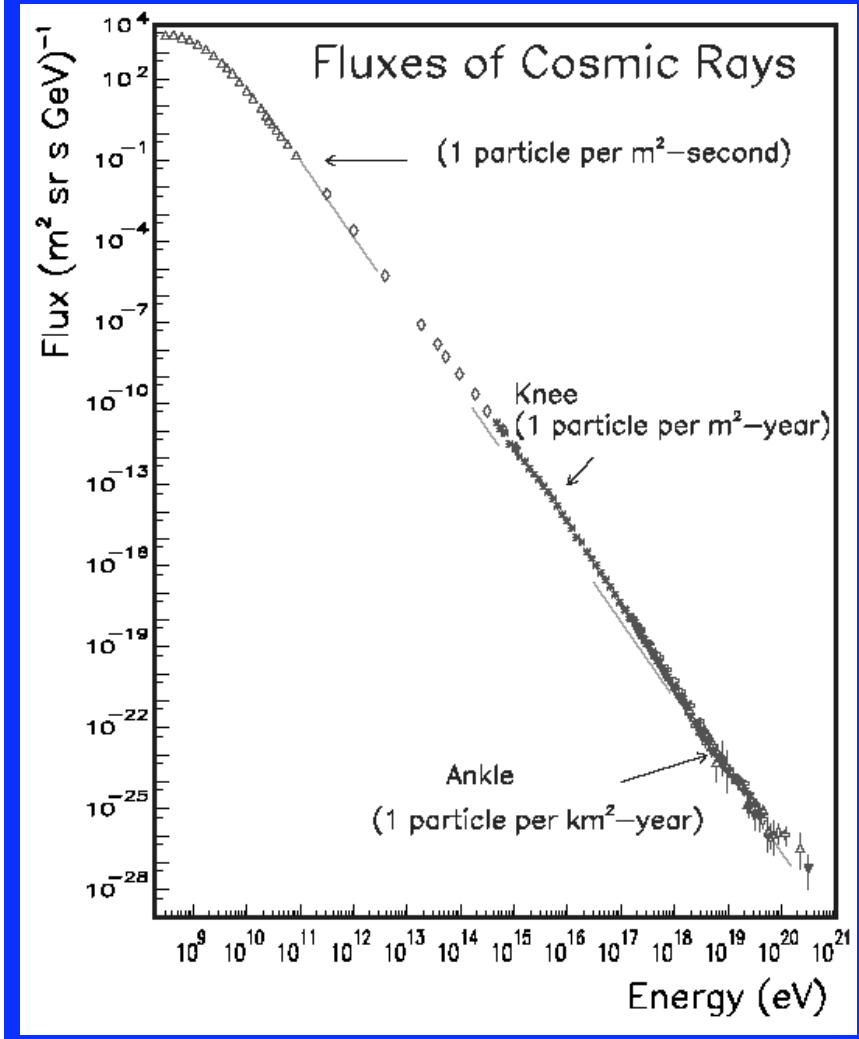


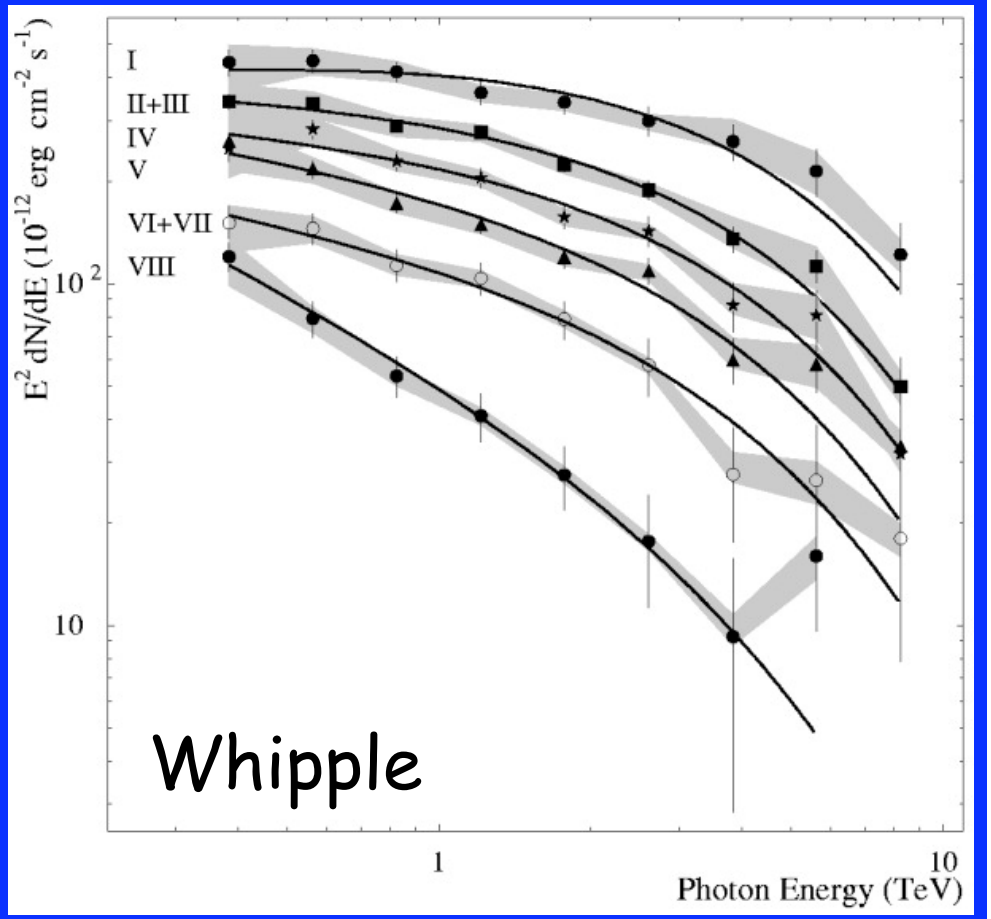
Neutrino Windows



Neutrino Facilities Assessment Committee, NAS (2002)

High Energy Messengers



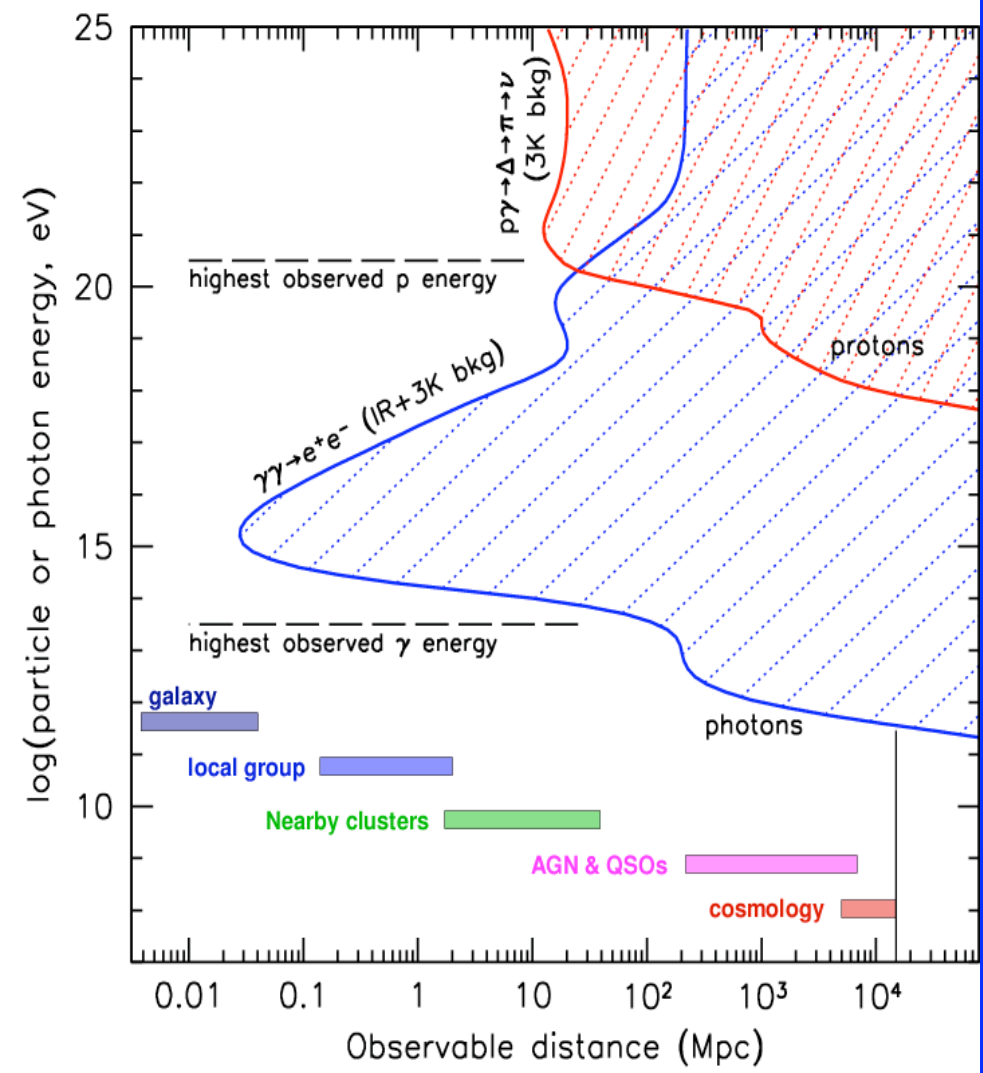


F. Krennrich et al., ApJ 575, L9 (2002)

Protons (diffuse)

Photons (Markarian 421)

Beyond the Veil



(Peter Gorham)

At high energies, the universe is opaque...

...except to neutrinos

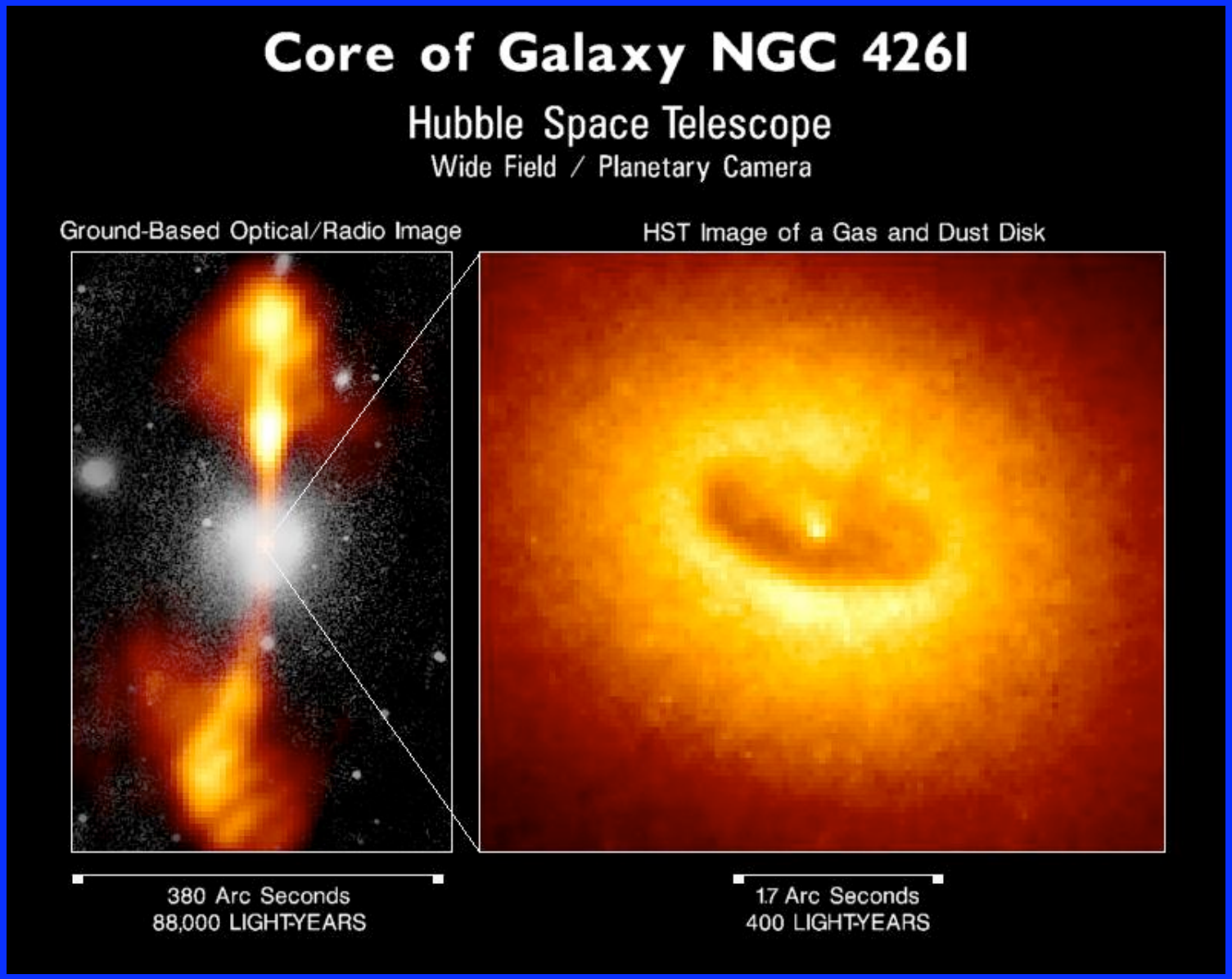
Three Neutrino Frontiers

E ~ MeV (micro-TeV)	E ~ TeV ~ erg (natural scale)	E ~ EeV (mega-TeV)
Visible Universe: Supernovae	*Nonthermal Universe*: AGN, GRB	*Extreme Universe*: UHE cosmic rays
Super-Kamiokande	IceCube, etc.	ANITA, etc.
Nucleosynthesis, dark matter	Black holes, dark matter	Energy frontier, dark matter

The Neutrino Universe Awaits Us

Neutrinos at ~ 1 TeV

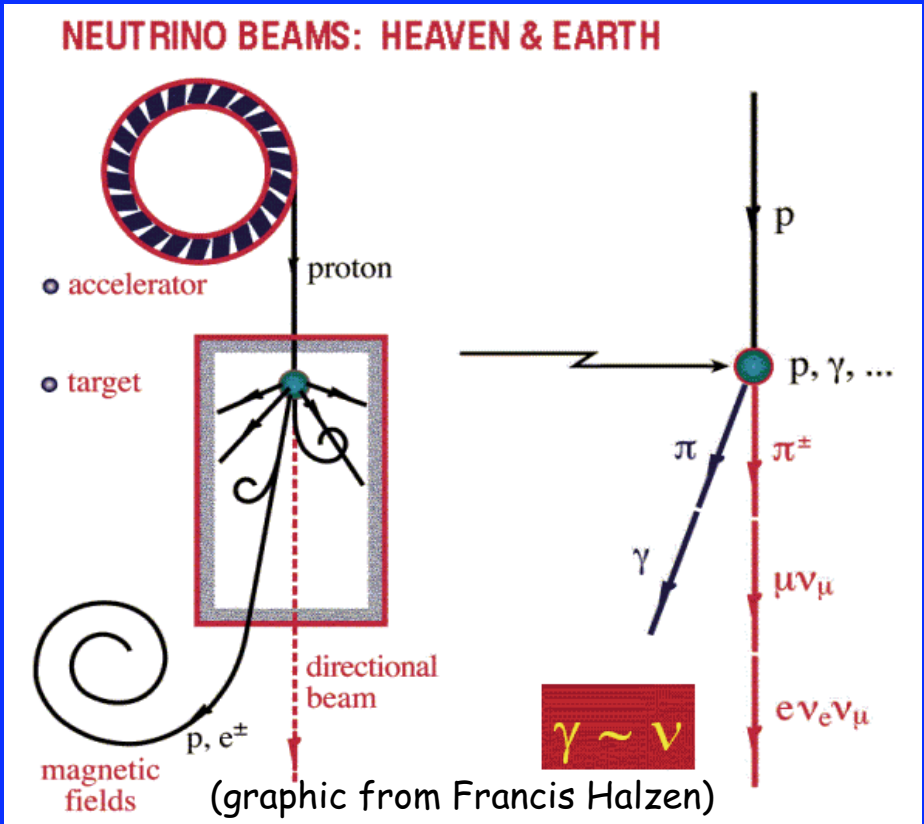
Active Galaxies



AGN/GRB Neutrinos

$$\pi^0 \to \gamma\gamma$$

$$\pi^+ \to \mu^+ \nu_\mu \,,\; \mu^+ \to e^+ \nu_e \bar{\nu}_\mu$$



(graphic from Francis Halzen)

initial fluxes are

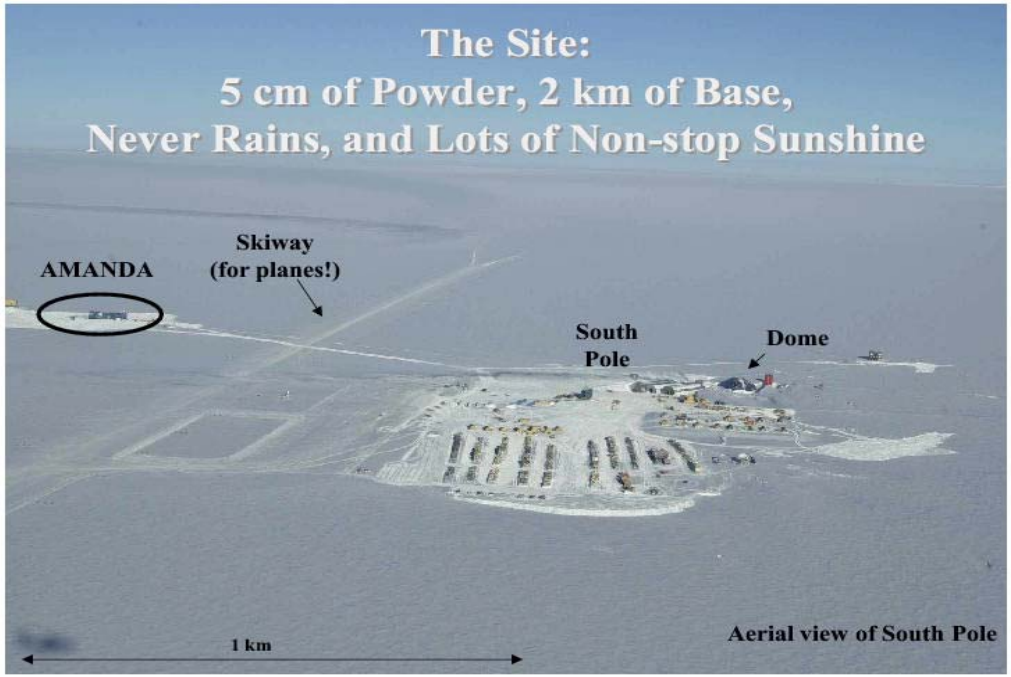
$$\varphi_{\nu_e} : \varphi_{\nu_\mu} : \varphi_{\nu_\tau} = 1 : 2 : 0$$

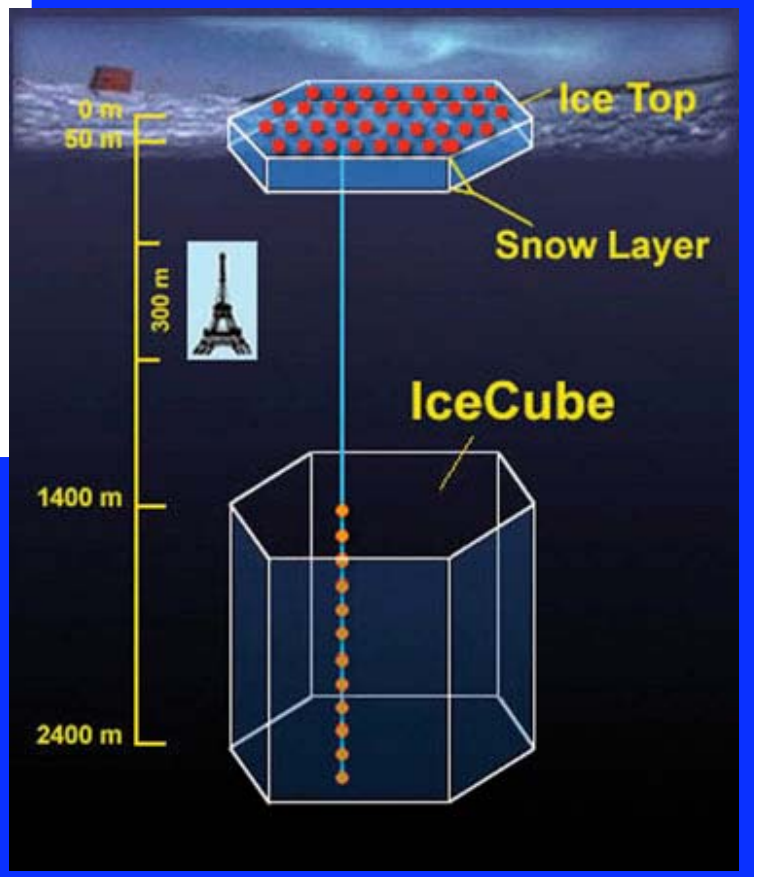
after oscillations

$$\varphi_{\nu_e} : \varphi_{\nu_\mu} : \varphi_{\nu_\tau} = 1 : 1 : 1$$

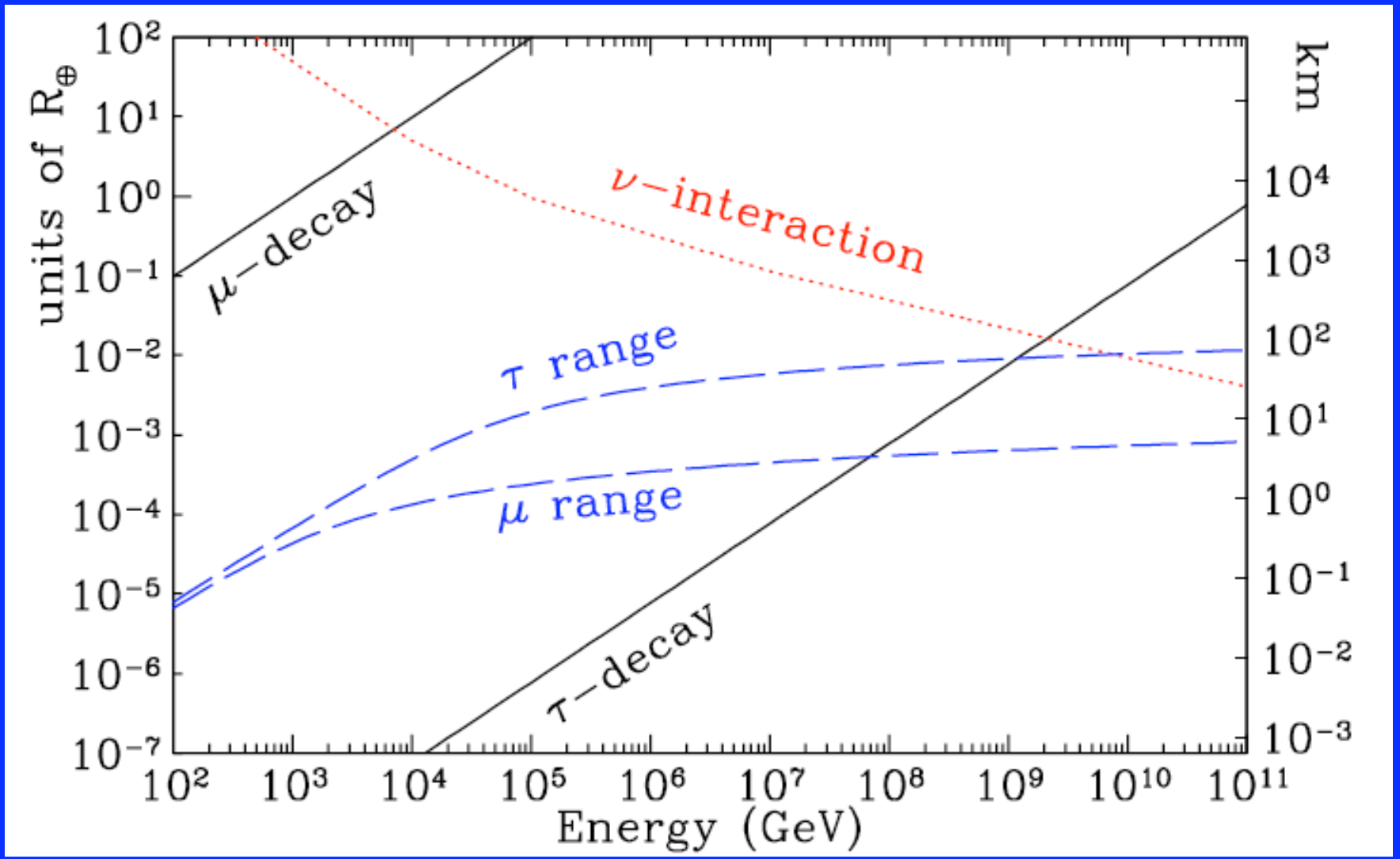
Earth opacity effects above E ~ 100 TeV

ICECUBE


The Site:
5 cm of Powder, 2 km of Base,
Never Rains, and Lots of Non-stop Sunshine
AMANDA
Skiway
(for planes!)
South
Pole
Dome
1 km
Aerial view of South Pole


0 m
50 m
Ice Top
Snow Layer
300 m
IceCube
1400 m
2400 m

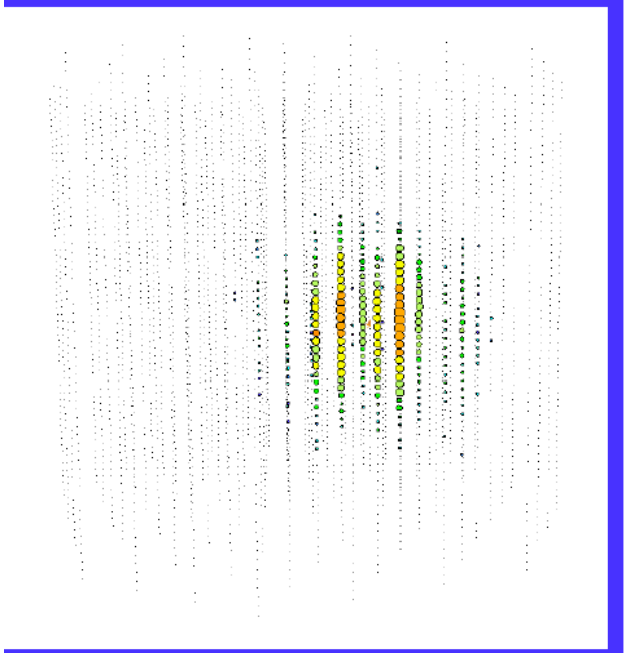
Length Scales in Earth

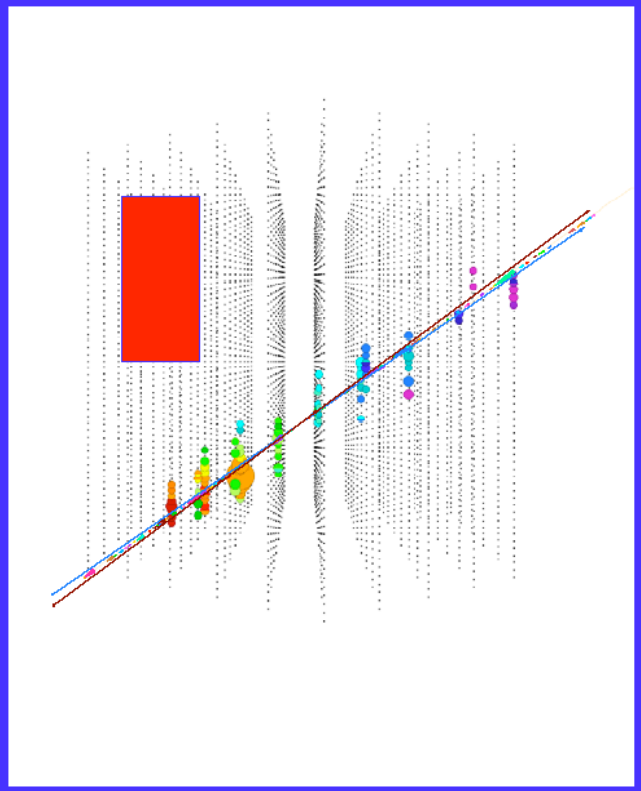


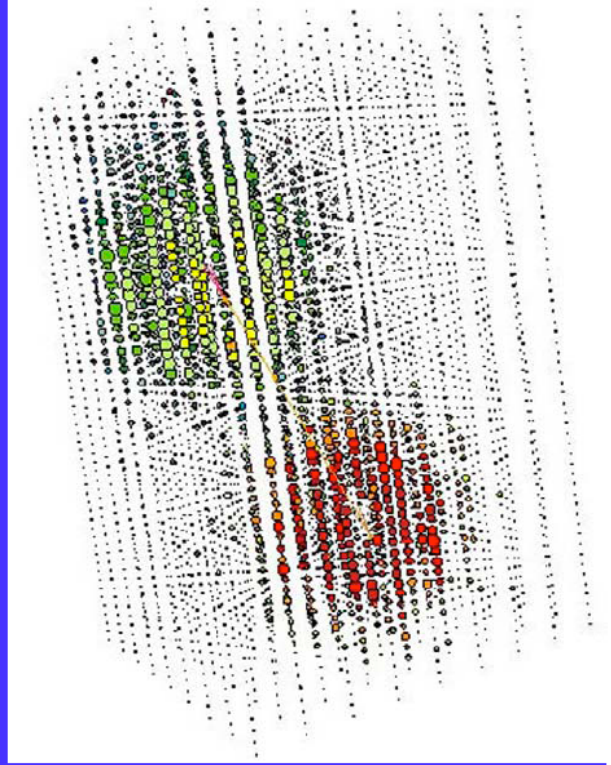
ρ = 8 g/cc used

Beacom, Crotty, and Kolb, PRD 66, 021302 (2002)

Flavor Identification

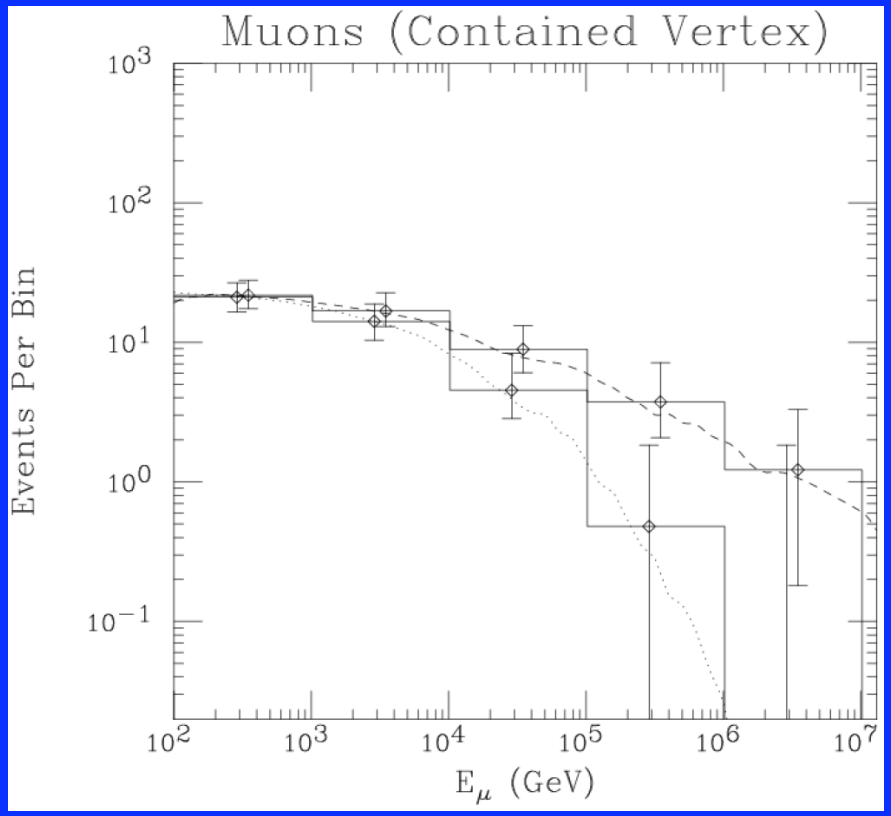


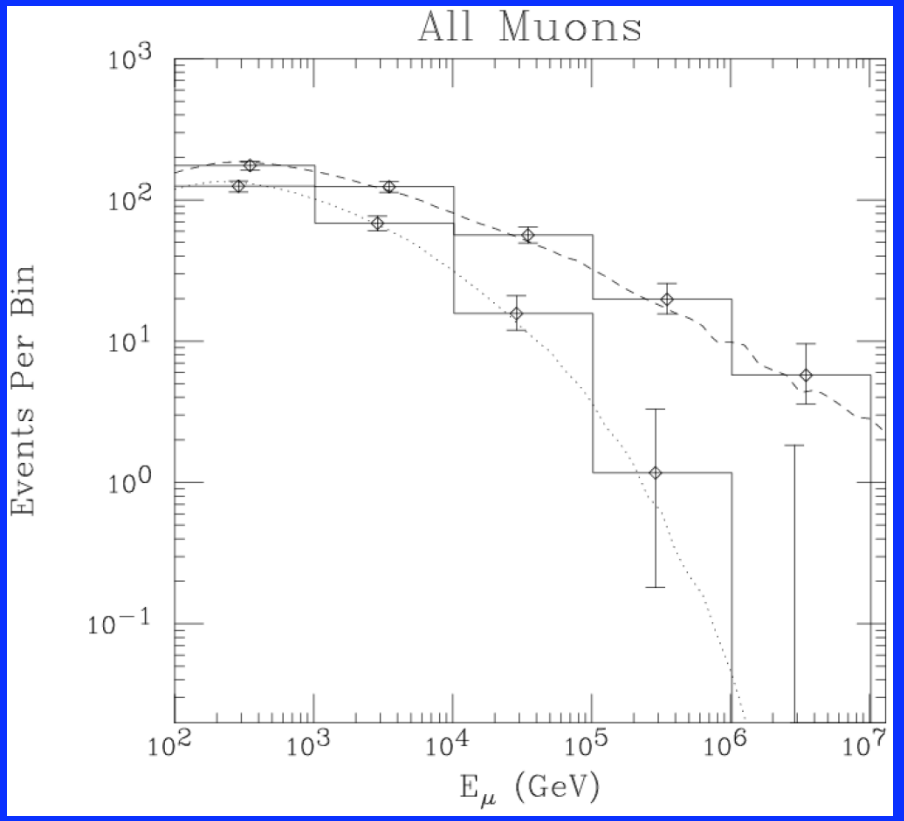




~ 100 TeV ν_e ~ 10 TeV ν_μ ~ 10 PeV ν_τ

Neutrino Detection

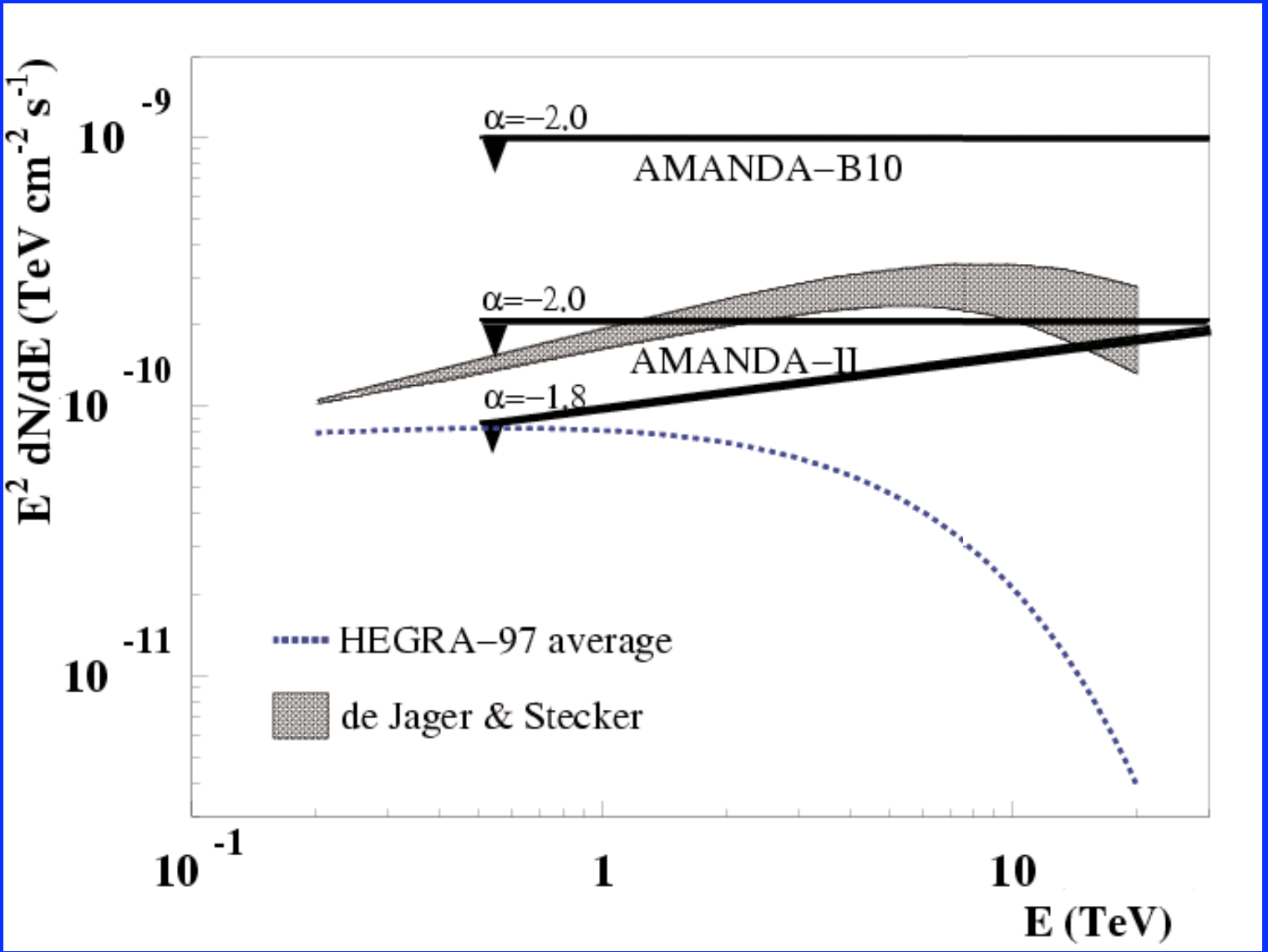




Beacom, Bell, Hooper, Pakvasa, Weiler, PRD 68, 093005 (2003) [Erratum]

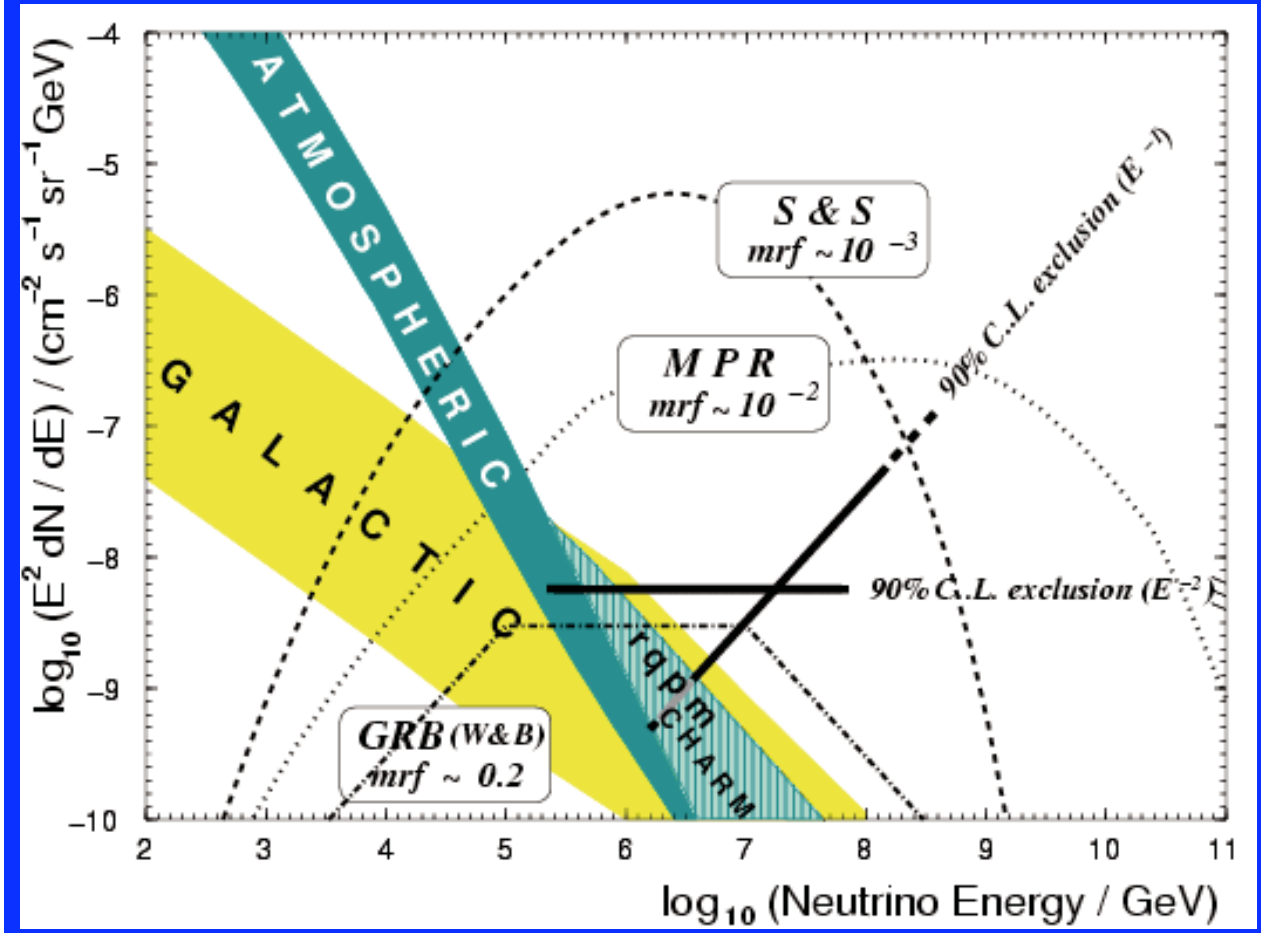
Can analytically estimate from $dN/dE \sim 1/E^2$ flux

Neutrino-Gamma Connection



J. Ahrens et al. (AMANDA-II), astro-ph/0309585

IceCube (Diffuse) Sensitivity

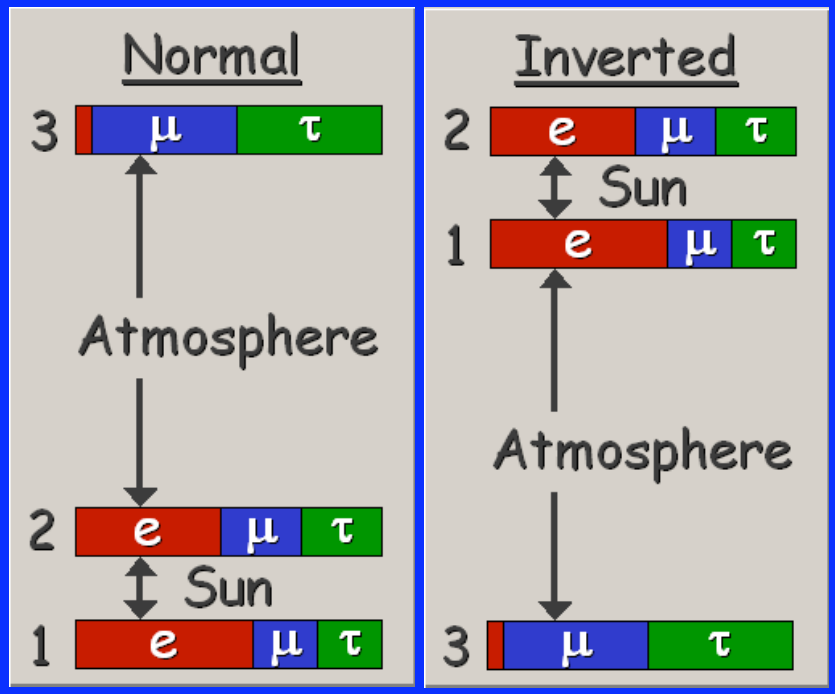


AMANDA-B10

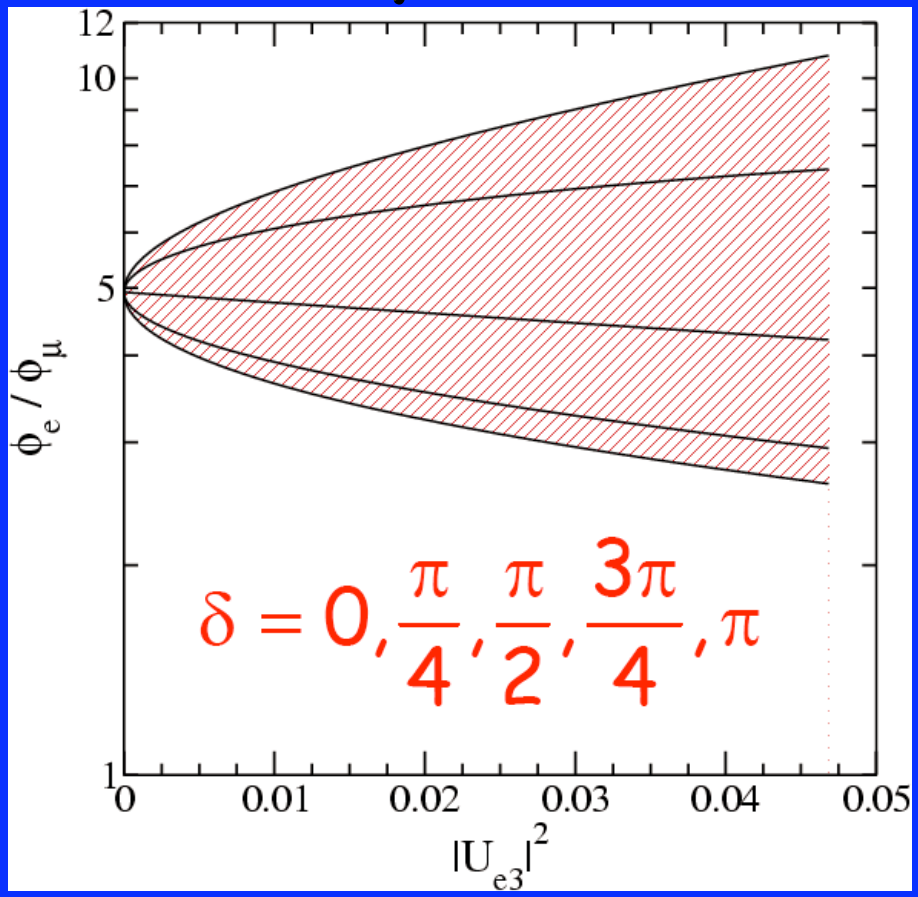
AMANDA-II

J. Ahrens et al. (IceCube), astro-ph/0305196

Neutrino Decay



~ 5:1:1 ~ 0:1:1



Possible direct measurement of CP phase δ too!

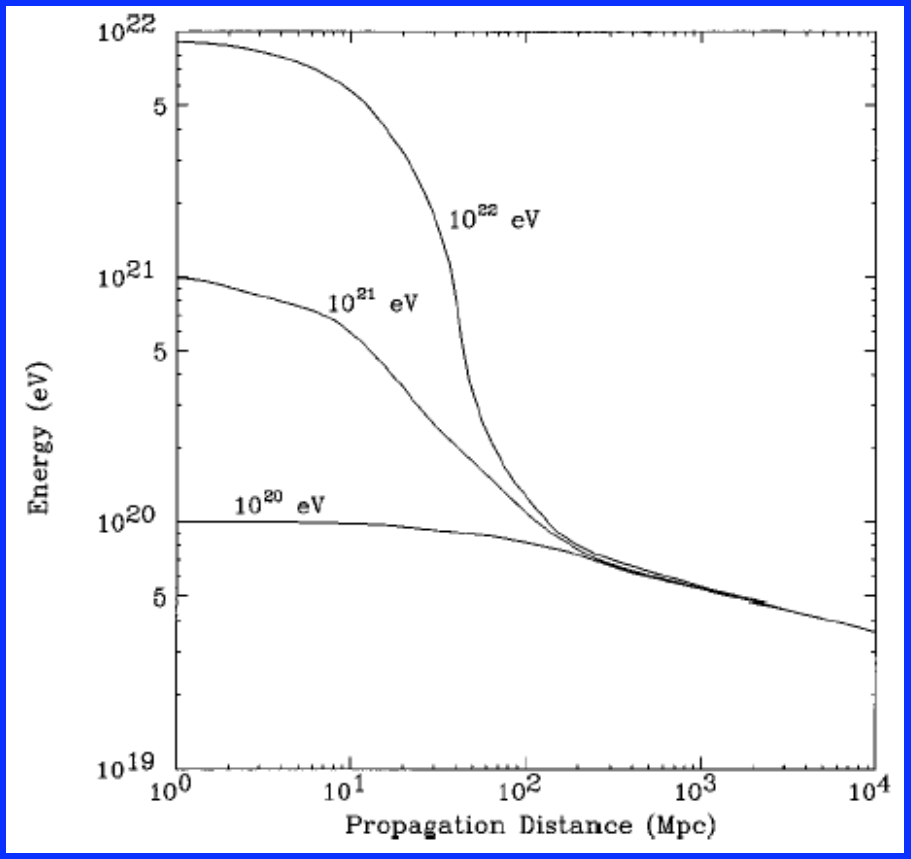
Beacom, Bell, Hooper, Pakvasa, Weiler, PRL 90, 181301 (2003);
Beacom, Bell, Hooper, Pakvasa, Weiler, PRD 69, 017303 (2004)

Neutrinos at ~ 1 Mega-TeV

GZK Neutrinos

$$p_{CR} + \gamma_{CMB} \rightarrow \Delta \rightarrow p + \pi^0 \qquad \pi^0 \rightarrow \gamma\gamma$$

$$\rightarrow n + \pi^+ \qquad \pi^+ \rightarrow \mu^+ \nu_\mu$$

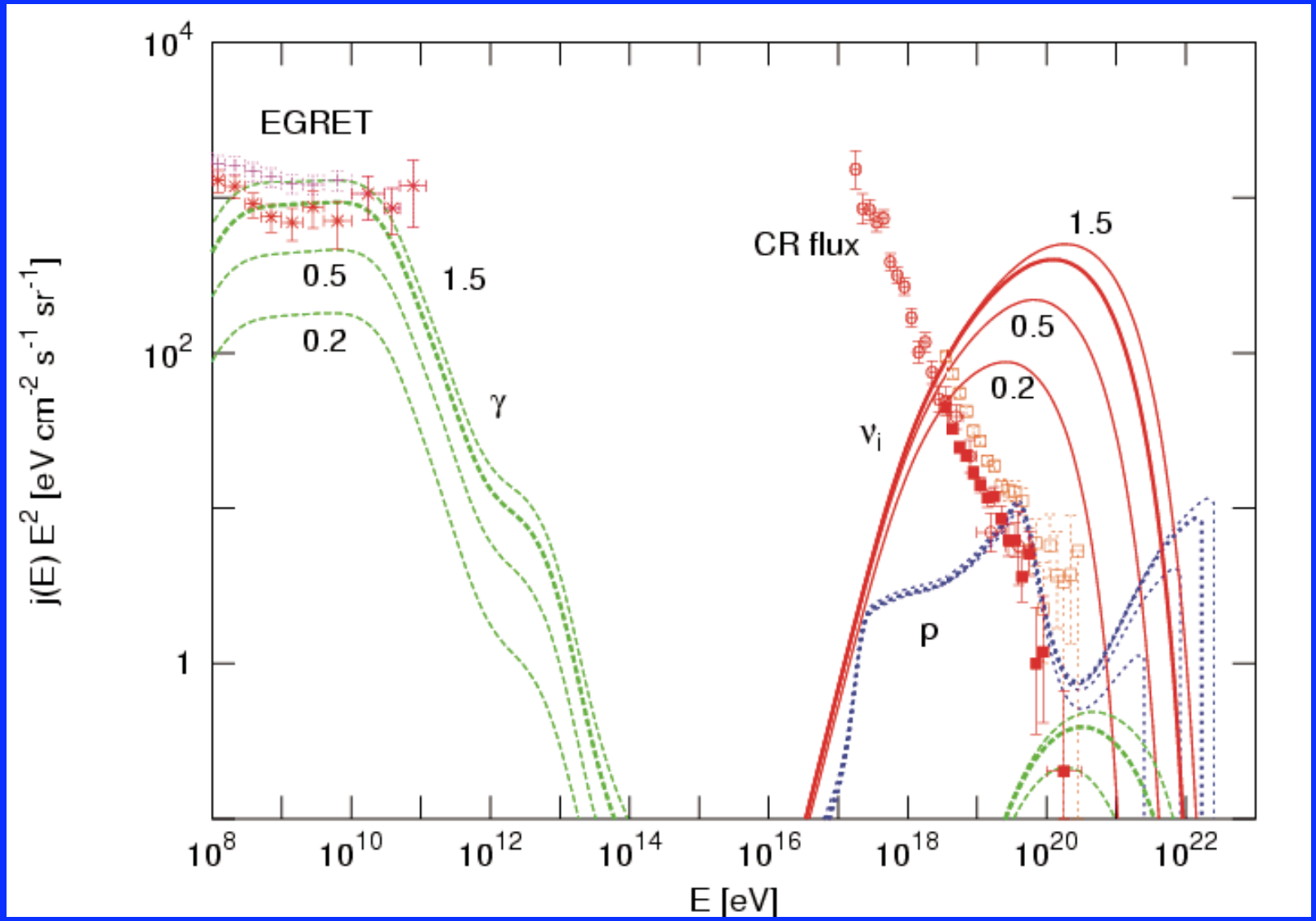


Connected observables:

- Protons
- Photons
- Neutrinos

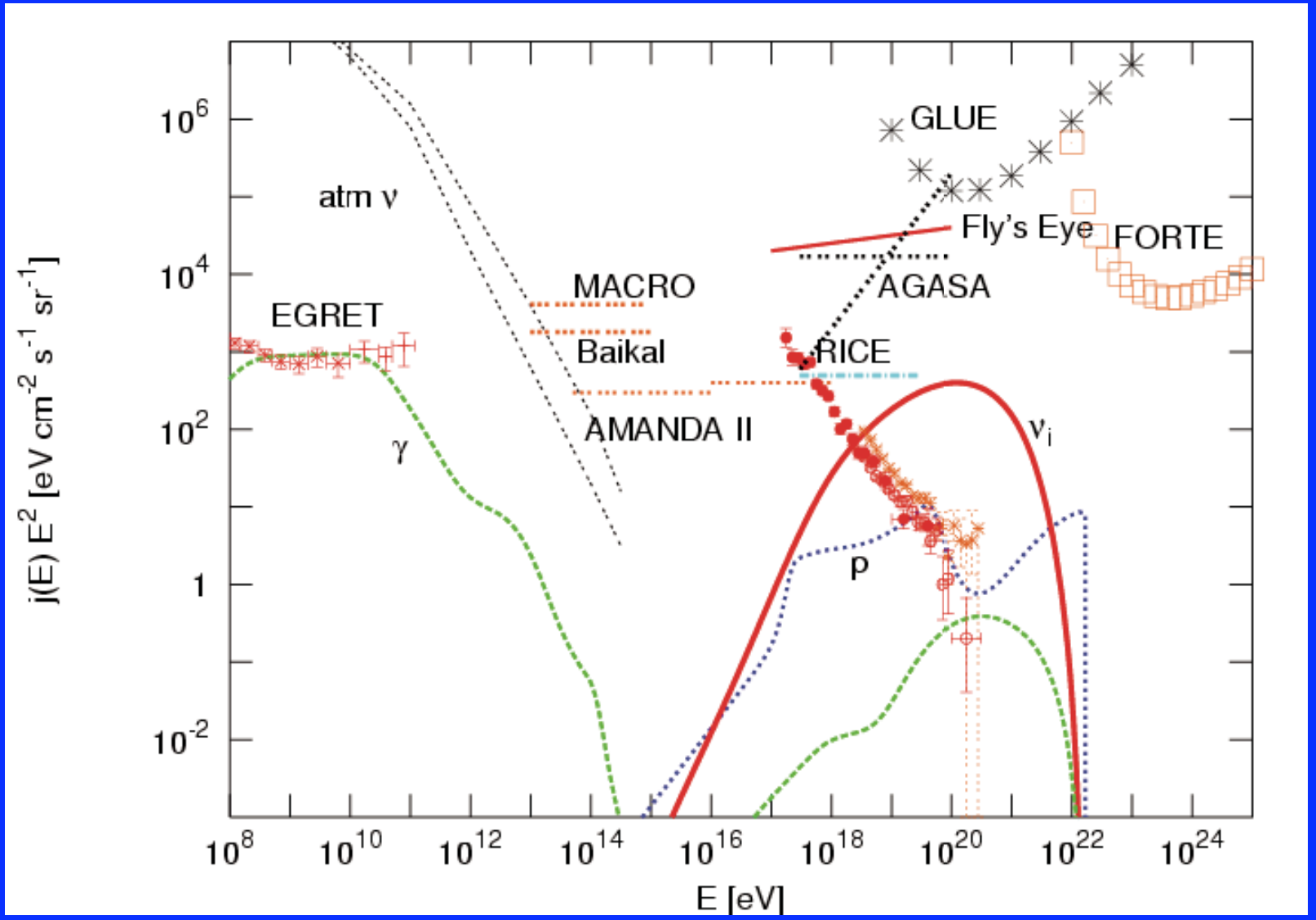
Cronin

Protons, Photons, and Neutrinos



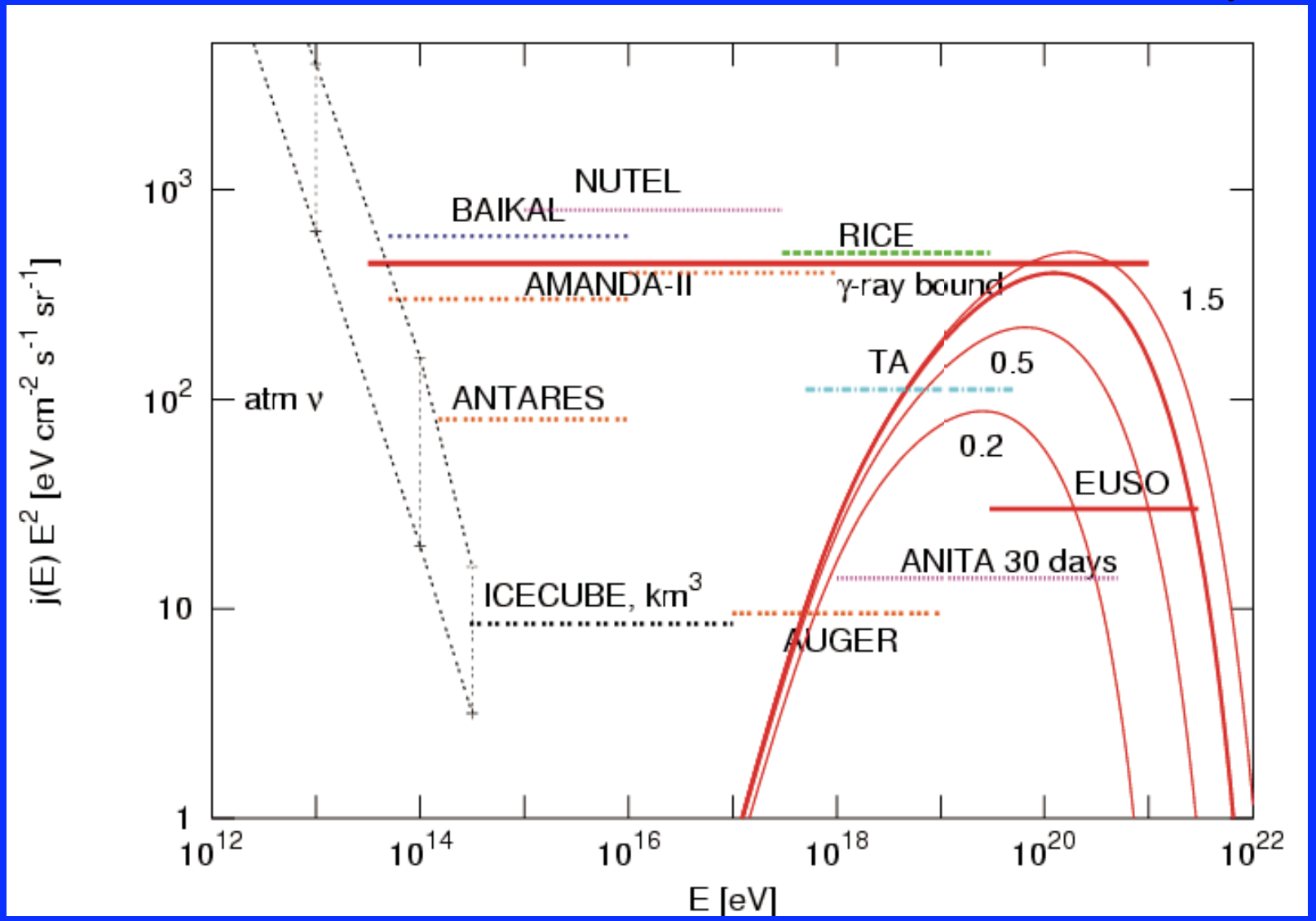
Semikoz, Sigl, hep-ph/0309328

Existing Neutrino Limits



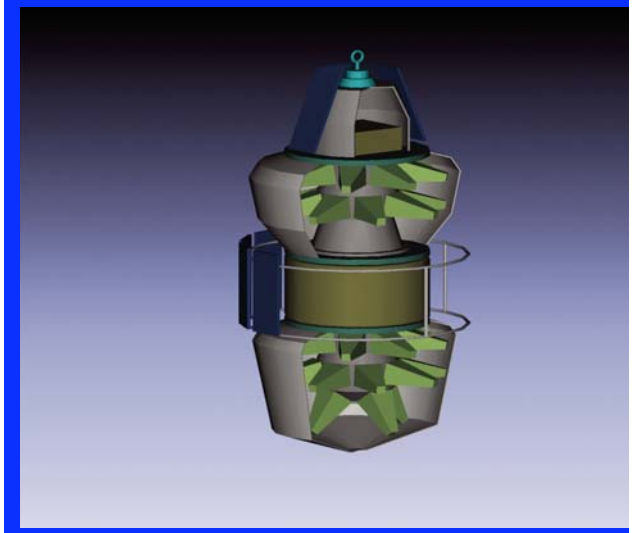
Semikoz, Sigl, hep-ph/0309328

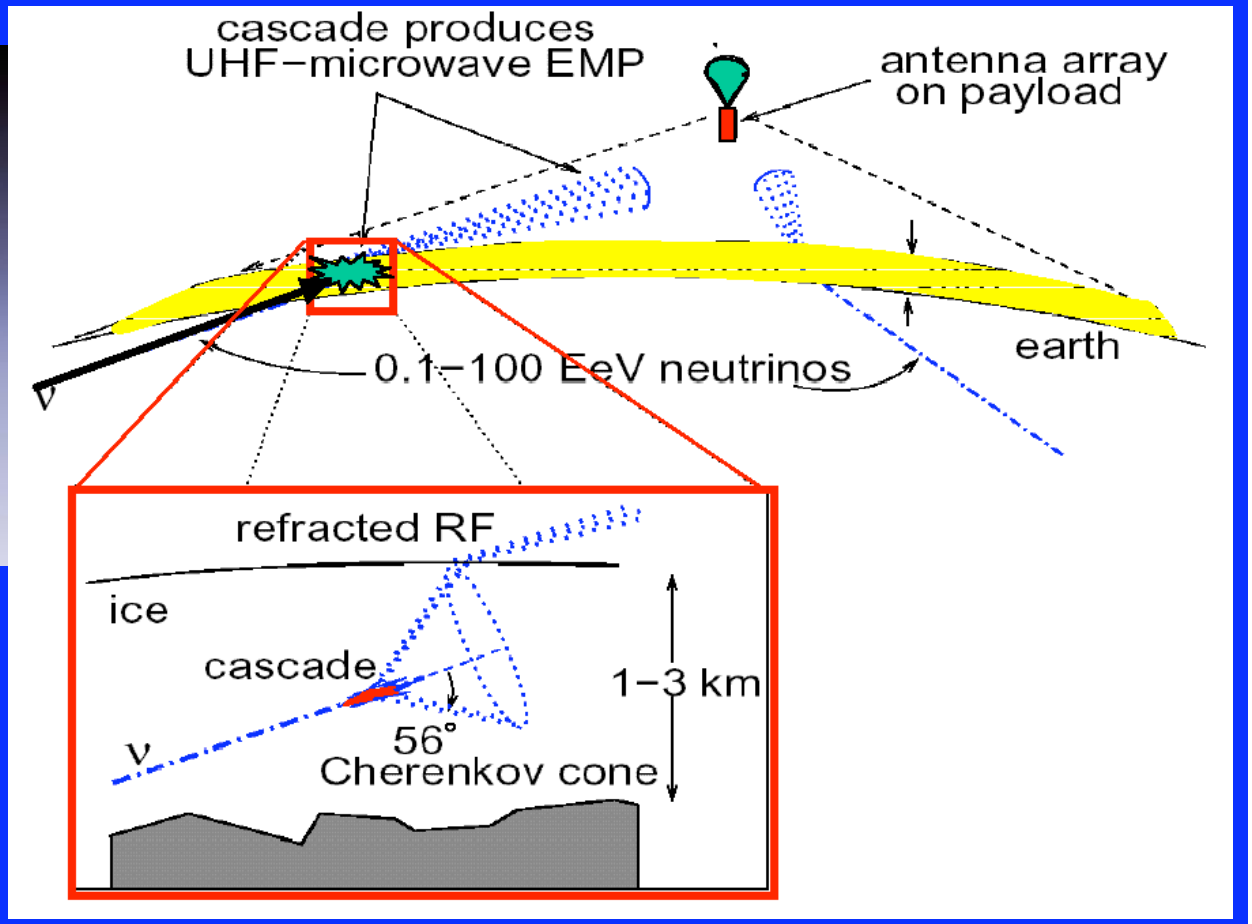
Future Neutrino Sensitivity



Semikoz, Sigl, hep-ph/0309328

ANITA





Funded 2003
Flies 2006

Predictions:

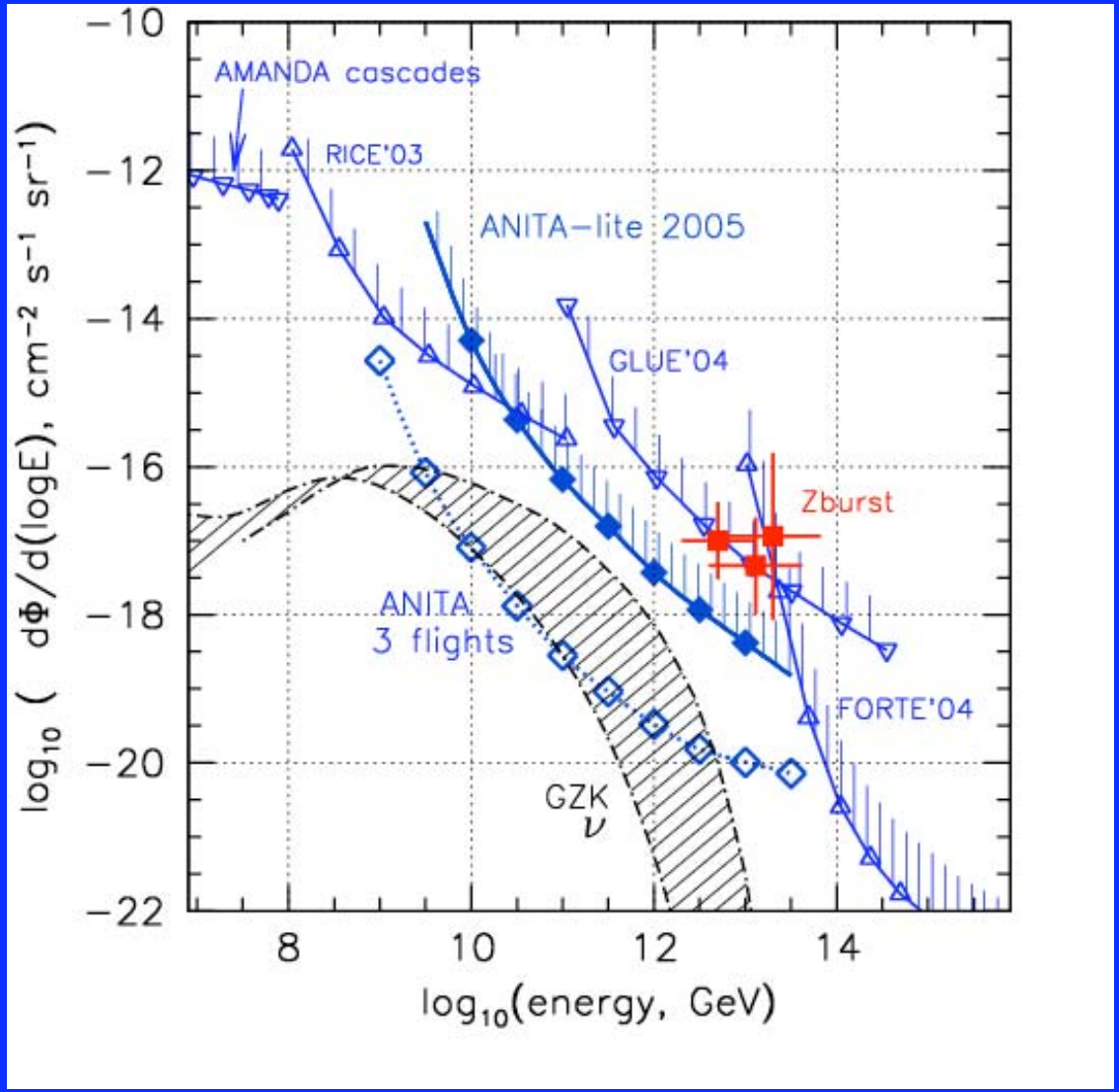
Bertou et al., Astropart. 17, 183 (2002);
Kusenko, Weiler, PRL 88, 161101 (2002);
Feng, Fisher, Wilczek, Yu, PRL 88, 161102 (2002)

2005 ANITA-lite Run

(Peter Gorham)

No evidence for
non-Newtonian gravity

2005 ANITA-lite Results

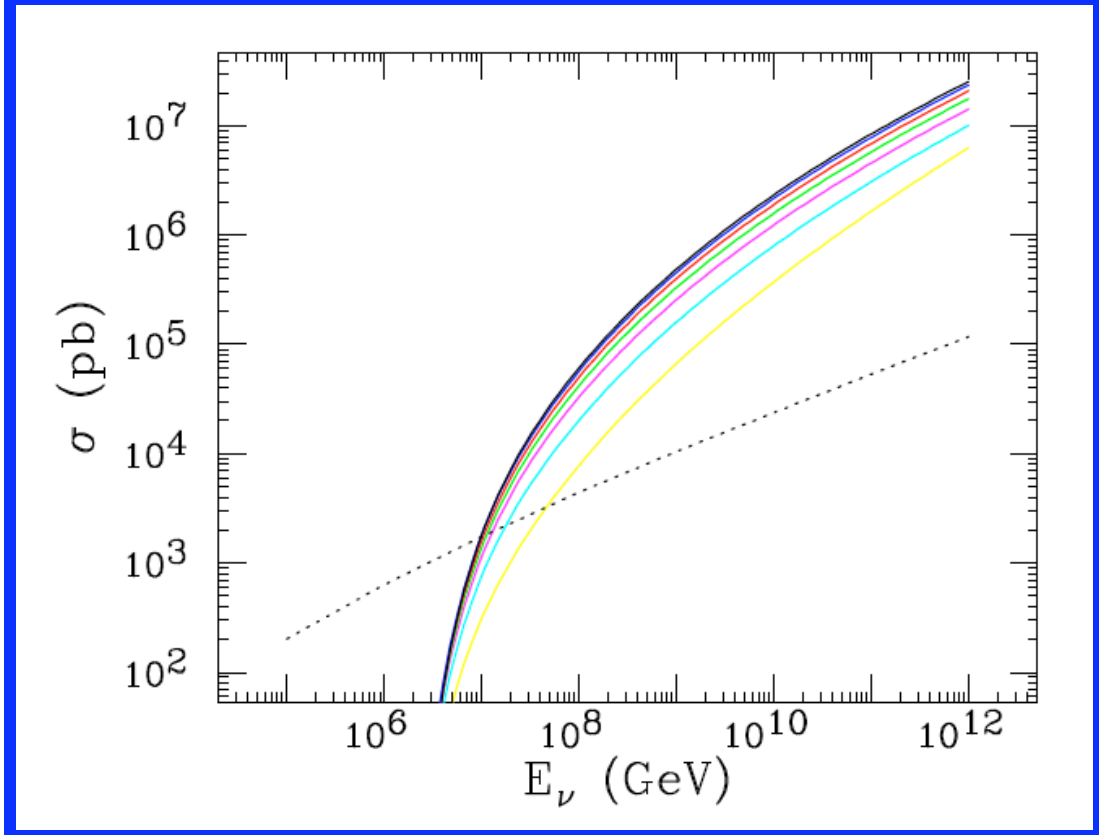


No Signal Seen...

...and no Background either!

(ANITA Collaboration)

Growth of σ(ν + N)



Lower bound on flux gives upper bound on cross section, already probing $E > 1$ TeV

Anchordoqui, Feng, Goldberg, Shapere, PRD 68, 104025 (2003)

Domokos, Kovesi-Domokos, Burgett, Wrinkle, JHEP 0107, 017 (2001);
Tyler, Olinto, Sigl, PRD 63, 055001 (2001);
Dutta, Reno, Sarcevic, PRD 66, 033002 (2002);
Jain, Kar, McKay, Panda, Ralston, PRD 66, 065018 (2002);
Friess, Han, Hooper, PLB 547, 31 (2002)

Conclusions

- No high energy astrophysical neutrinos detected
- However, the near-term prospects are very good:
- ~ 1 TeV range: Baikal, AMANDA, ANTARES, NEMO, NESTOR, IceCube
- ~ 10^6 TeV range: RICE, IceCube, ANITA, Auger
- Real potential for new physics!

Further Reading

- "High-Energy Neutrino Astronomy: The Cosmic Ray Connection," Halzen and Hooper, Rept. Prog. Phys. 65, 1025 (2002)

- "High-Energy Neutrino Astrophysics," Learned and Mannheim, Ann. Rev. Nucl. Part. Sci. 50, 679 (2000)

- "High Energy Neutrino Astronomy: The Experimental Road," Spiering, J. Phys. G29, 843 (2003)

- "APS Neutrino Study: Report of the Neutrino Astrophysics and Cosmology Working Group,'' Barwick et al., astro-ph/0412544