

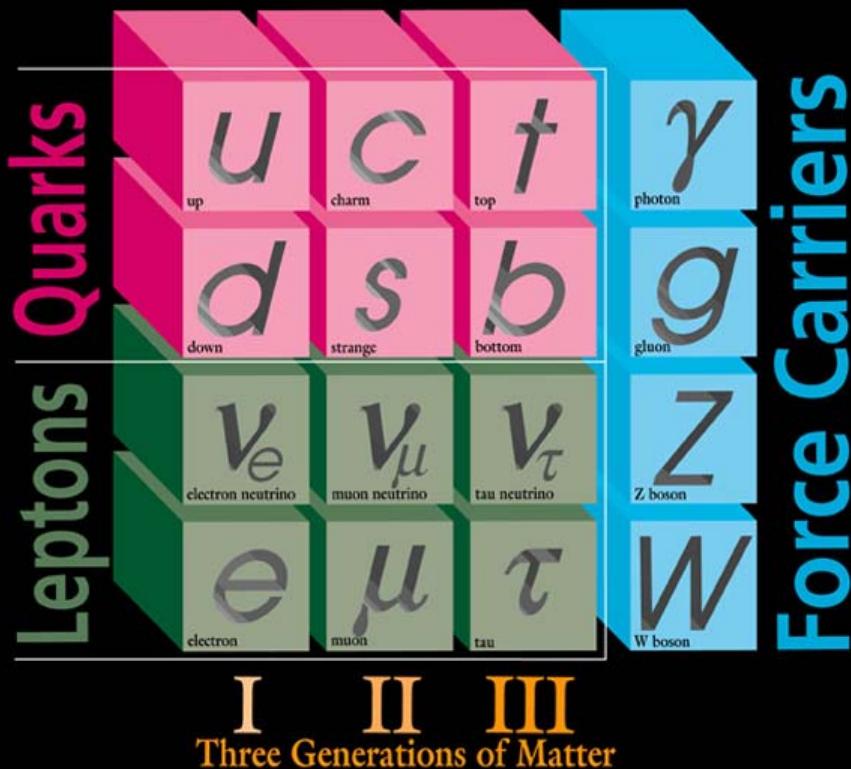
Neutrino Masses and Mixing: Implications

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Theoretical Astrophysics Group, Fermilab

Lucky Neutrinos

ELEMENTARY PARTICLES



Fermilab 95-759



The Nobel Prize in Physics 2002

"for pioneering contributions to astrophysics, in particular for the detection of cosmic neutrinos"

"for pioneering contributions to astrophysics, which have led to the discovery of cosmic X-ray sources"



Raymond Davis Jr.

1/4 of the prize

USA

University of Pennsylvania
Philadelphia, PA,
USA

b. 1914



Masatoshi Koshiba

1/4 of the prize

Japan

University of Tokyo
Tokyo, Japan

b. 1926



Riccardo Giacconi

1/2 of the prize

USA

Associated Universities Inc.
Washington, DC,
USA

b. 1931
(in Genoa, Italy)

Past Frontiers

- Bethe and Peierls, Nature (1934)

"If [there are no new forces] ----
one can conclude that there is no practically
possible way of observing the neutrino."

- 10 years ago

Solar neutrino problem

Atmospheric neutrino problem

Large neutrino masses

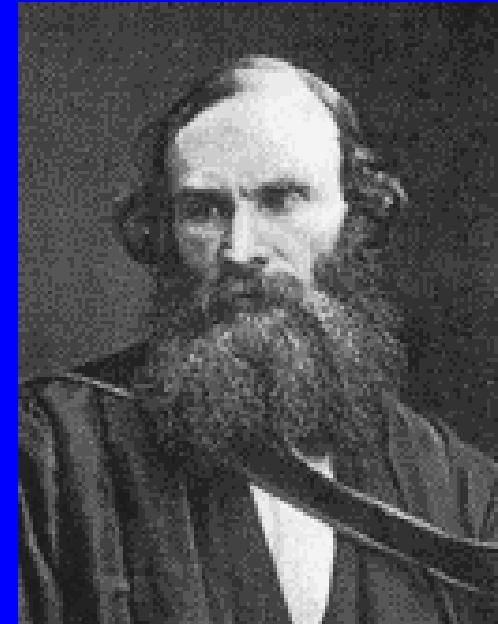
Nonzero magnetic moments, decay, etc.

State of the Field

*“There is nothing new to be discovered in physics now,
All that remains is more and more precise measurement.”*

-- Kelvin, c. 1900

- We now understand neutrinos
(Well, maybe)
- We now understand cosmology
(Well, maybe)
- We now understand high-energy astrophysics
(Well, maybe)



Neutrino Properties

Three Weak Pieces

ν_e, ν_μ, ν_τ

defined by $W^+ \rightarrow e^+ \nu_e, \mu^+ \nu_\mu, \tau^+ \nu_\tau$

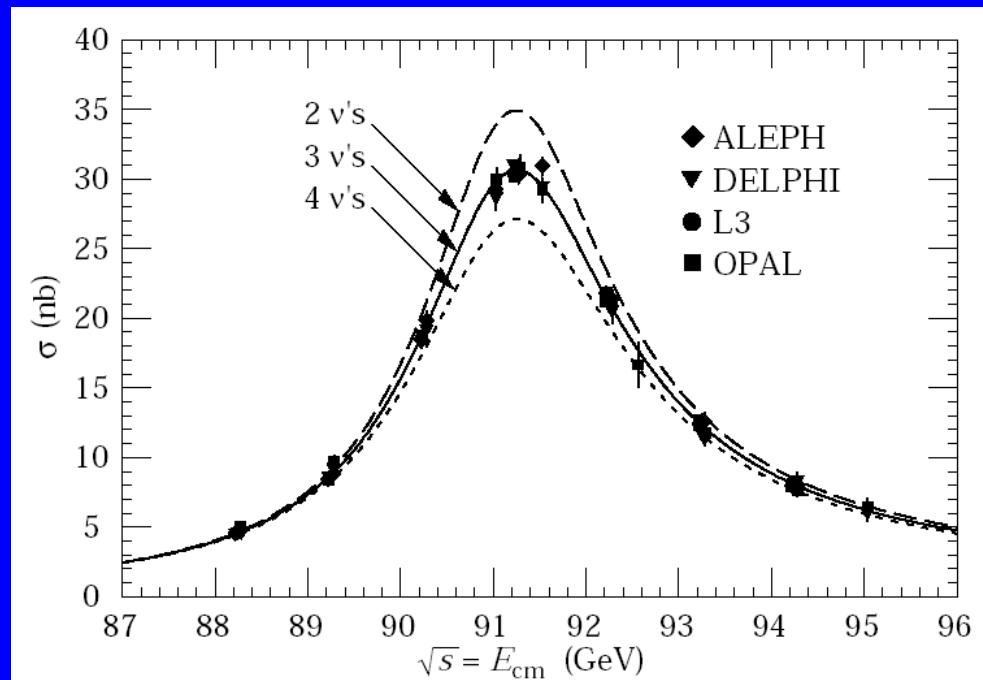
and neutral couplings $Z^0 \rightarrow \nu_e \bar{\nu}_e, \nu_\mu \bar{\nu}_\mu, \nu_\tau \bar{\nu}_\tau$

- Three (2.984 ± 0.008)

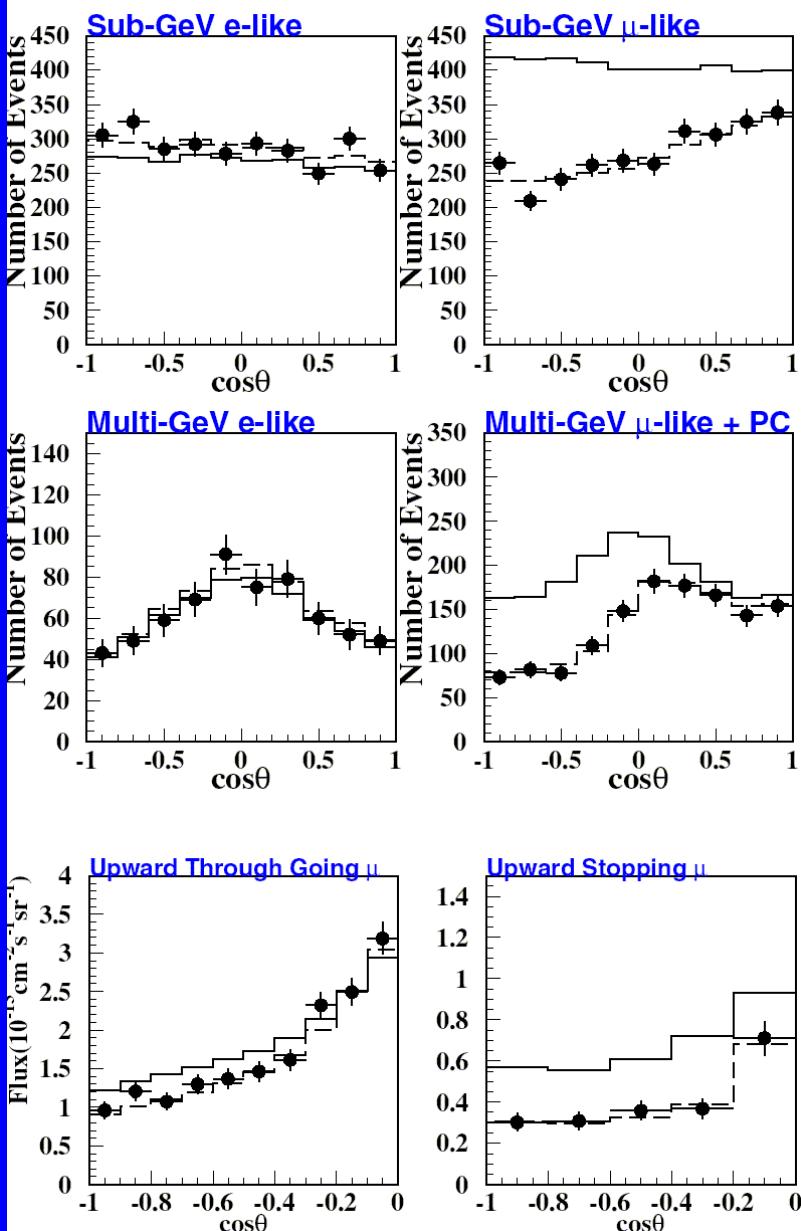
- Weak

- Massless in SM

- Lepton number?



Atmospheric Neutrino Results



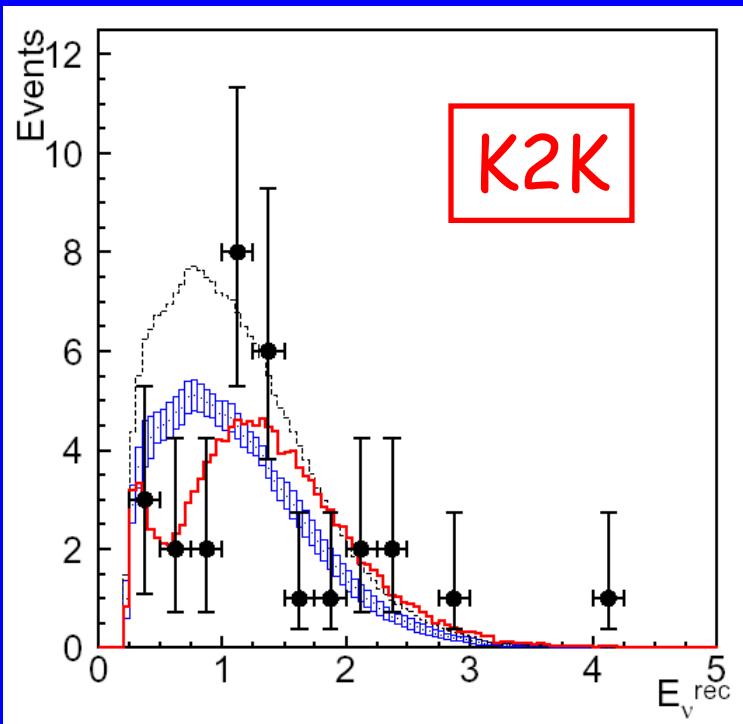
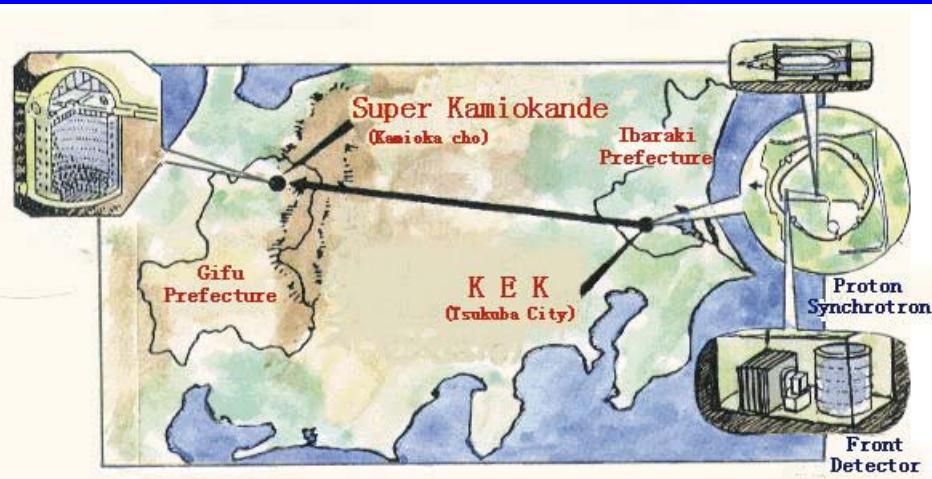
Super – Kamiokande :

$$\sin^2 2\theta \approx 1$$
$$\delta m^2 \approx 2 \times 10^{-3} \text{ eV}^2$$
$$\nu_\mu \rightarrow \nu_\tau \text{ preferred}$$

$\nu_\mu \rightarrow \nu_\tau$ versus $\nu_\mu \rightarrow \nu_s$:
different NC rates
different matter effects

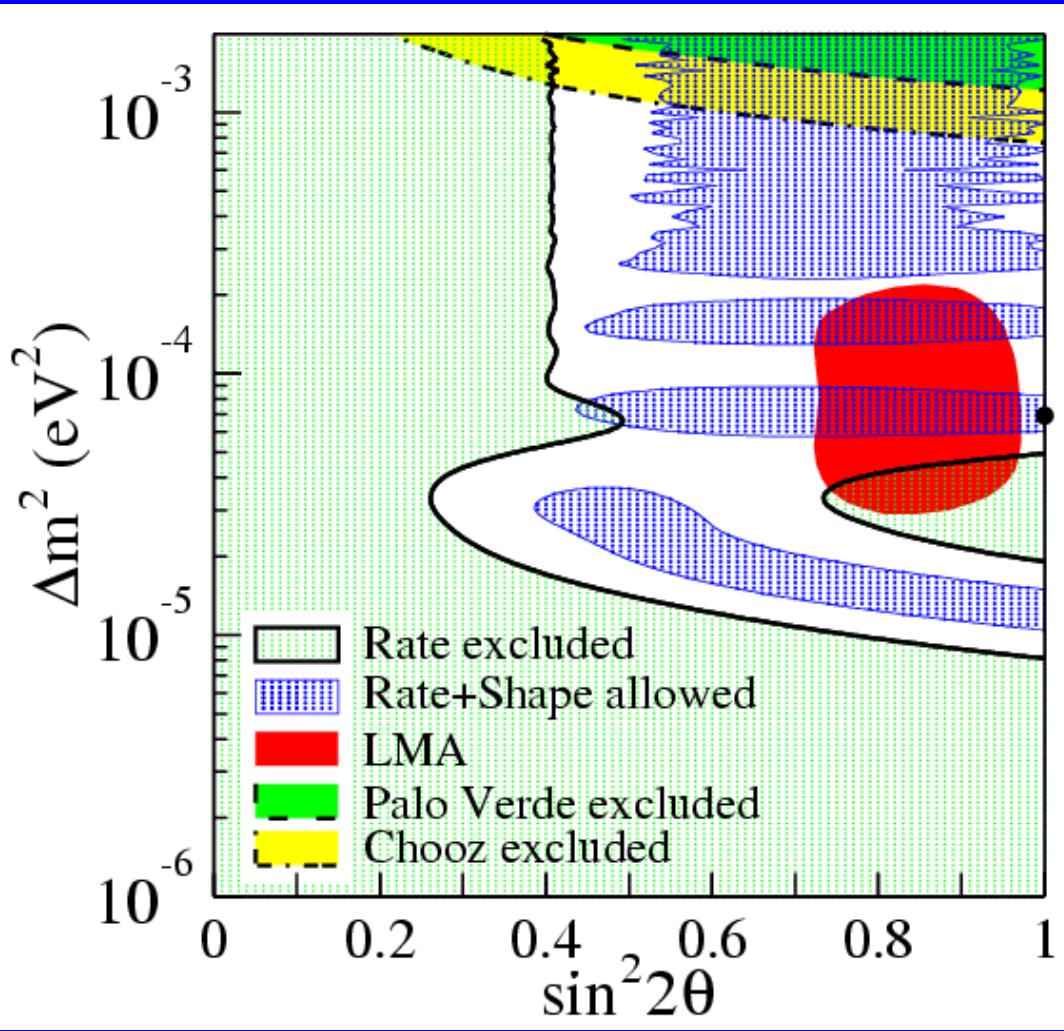
$\nu + p \rightarrow \nu + p$ in SK?
Beacom and Palomares-Ruiz,
PRD 67, 093001 (2003)

Long-Baseline Oscillations



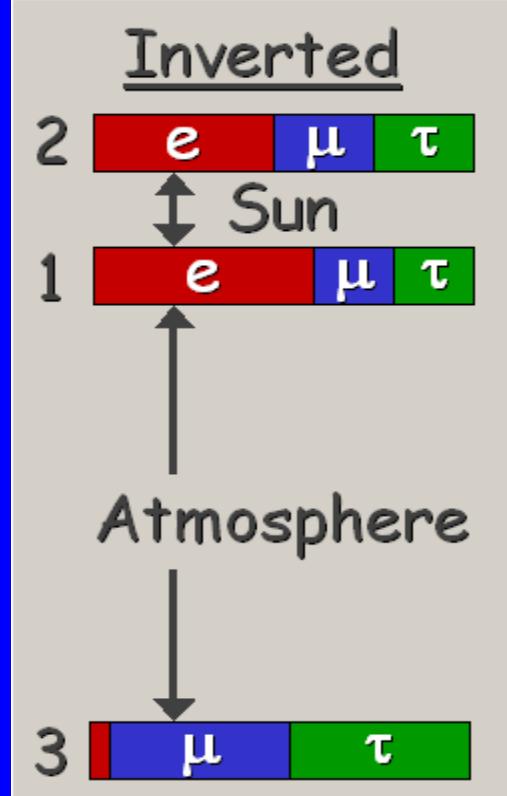
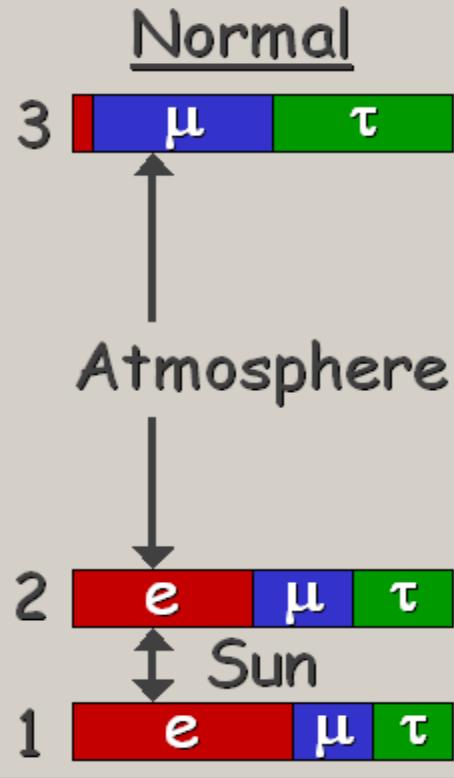
measure $\nu_\mu \rightarrow \nu_\tau$
search for $\nu_\mu \rightarrow \nu_e$

Solar and KamLAND Results



Very different technique
No solar physics
No MSW effects
 $\bar{\nu}_e$, not ν_e
No neutrino decay
No magnetic fields
No matter FCNC

Neutrino Mixing



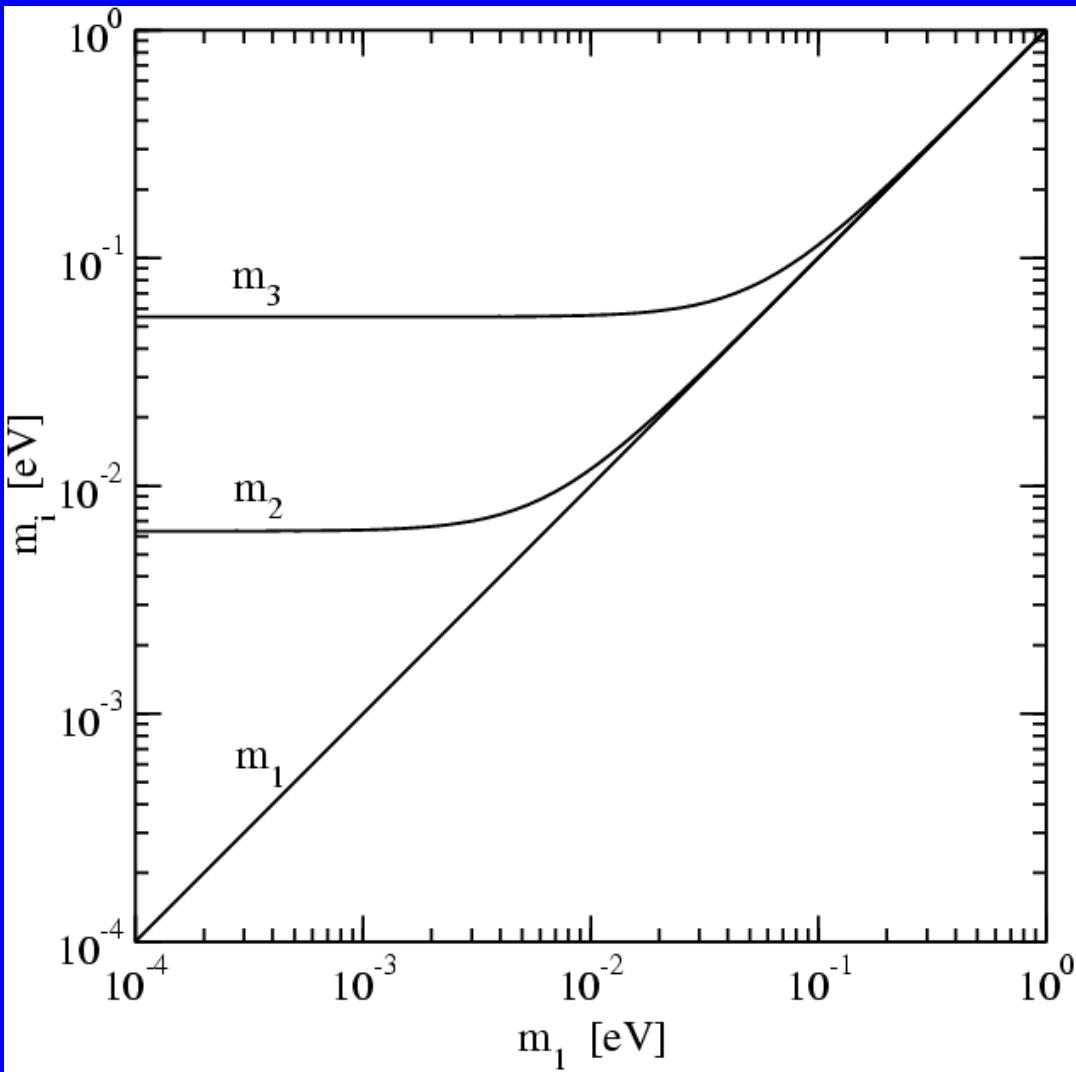
$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = U_{\alpha j} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

$$U \square \begin{bmatrix} c_\square & s_\square & s_{13} e^{-i\delta} \\ -s_\square / \sqrt{2} & c_\square / \sqrt{2} & 1/\sqrt{2} \\ s_\square / \sqrt{2} & -c_\square / \sqrt{2} & 1/\sqrt{2} \end{bmatrix}$$

(graphic from Georg Raffelt)

$$\theta_{\text{atm}} \square 45^\circ, \quad \theta_{\text{solar}} \square 35^\circ, \quad \theta_{13} \leq 10^\circ$$

Neutrino Masses



Normal Hierarchy

$$m_1 = m_1$$

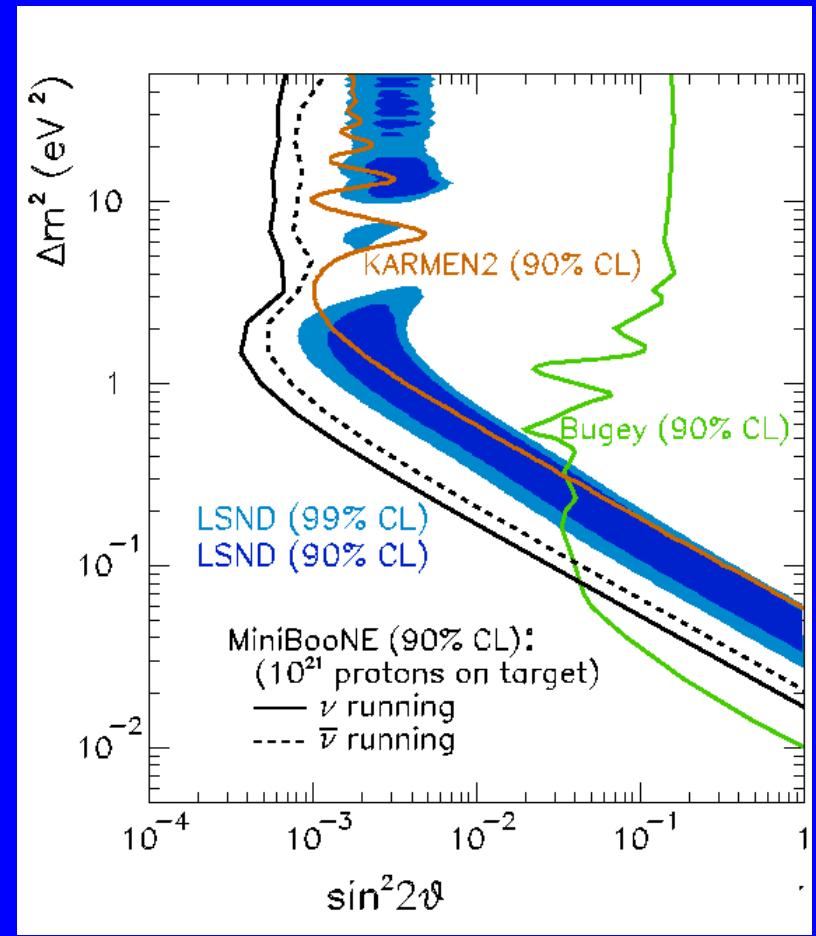
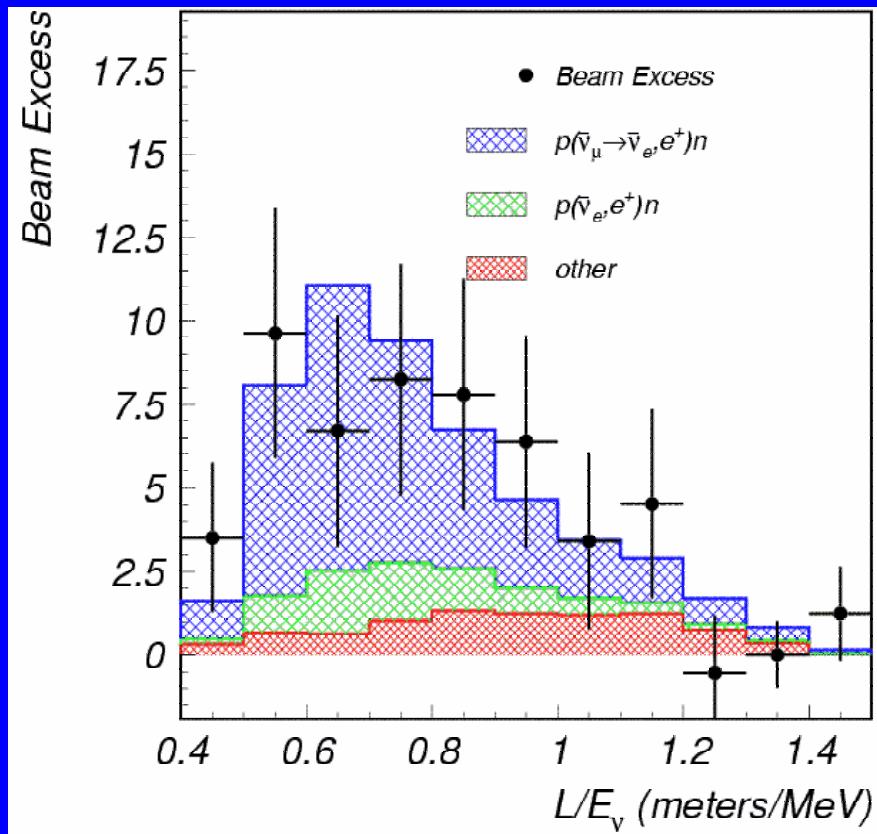
$$m_2 = \sqrt{m_1^2 + \delta m_{\text{solar}}^2}$$

$$m_3 = \sqrt{m_1^2 + \delta m_{\text{solar}}^2 + \delta m_{\text{atm}}^2}$$

$$\frac{m_3}{m_2} \leq \frac{\sqrt{\delta m_{\text{atm}}^2}}{\sqrt{\delta m_{\text{solar}}^2}} \leq 10$$

Beacom and Bell, PRD 65, 113009 (2002)

LSND Signal



LSND:

$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ appearance signal

MiniBooNE:

$\nu_\mu \rightarrow \nu_e$ appearance search

Some Mysteries

- Tiny masses

$$m_{\nu_\ell} \ll \frac{m_\ell^2}{m_{\text{big}}} ?$$

$$1 \text{ meV} \ll \frac{(100 \text{ GeV})^2}{10^{16} \text{ GeV}}$$

- Large mixing angles

Maybe even $\theta_{13} \ll \theta_{\text{Cabibbo}}$?

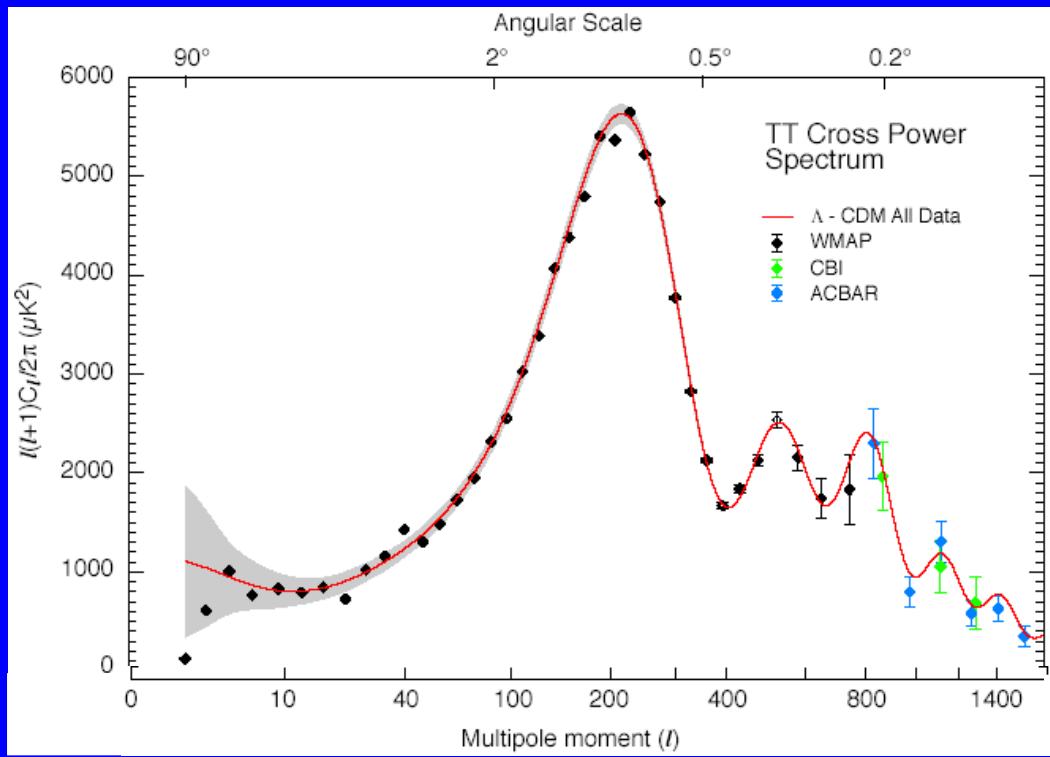
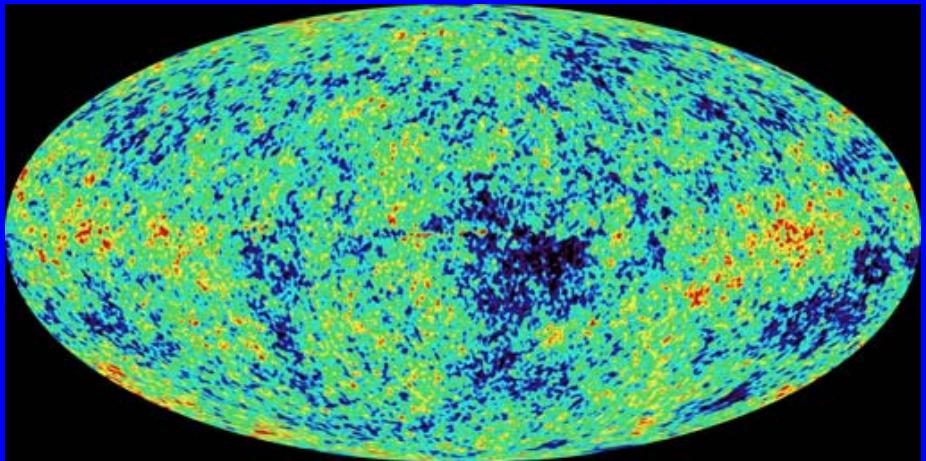
- Possible symmetries

$\theta_{13} = 0$ and $\theta_{\text{atm}} = 45^\circ$ means $\nu_\mu - \nu_\tau$ symmetry

- Dirac or Majorana?

Neutrino Cosmology

Cosmological Parameters

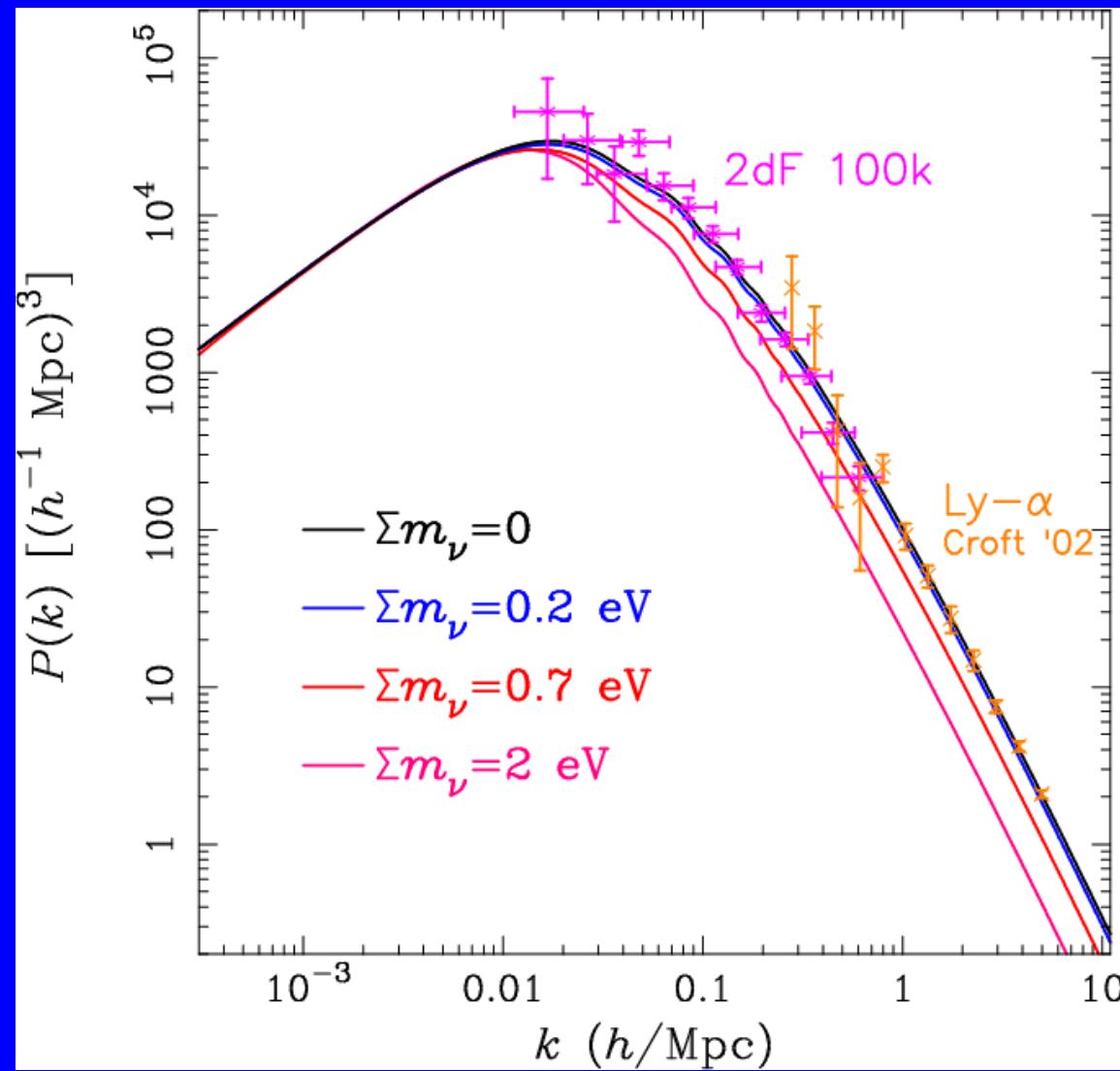


$\Omega_{\text{total}} = 1.02 \pm 0.02$
 $\Omega_{\text{matter}} h^2 = 0.14 \pm 0.01$
 $\Omega_{\text{baryon}} h^2 = 0.022 \pm 0.001$
 $\Omega_{\text{neutrino}} h^2 < 0.01$
 $h = 0.71 \pm 0.04$
etc.

$\Omega_\Lambda = 0.7$
 $m_\nu < 0.23 \text{ eV}$

(WMAP)

Dark Matter

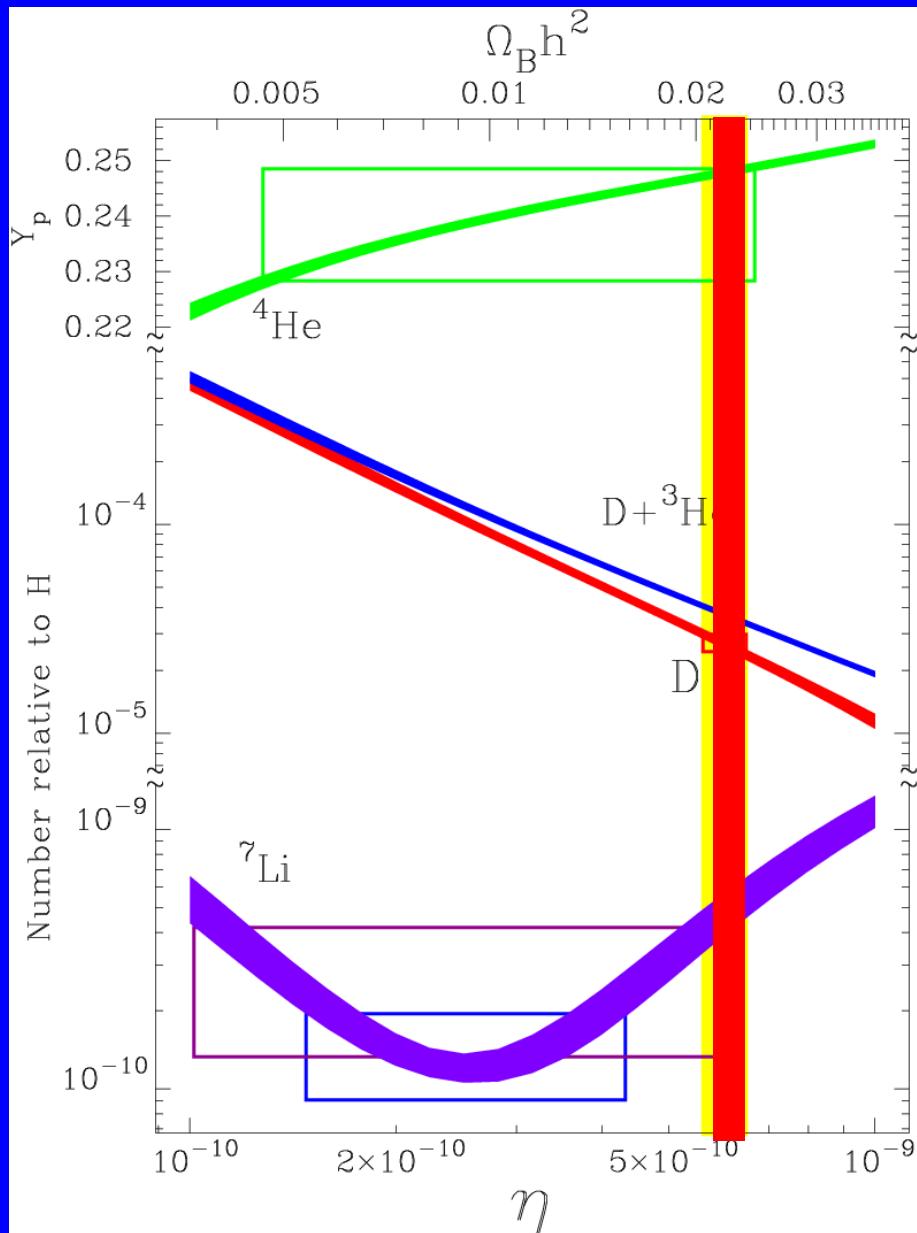


(graphic from Kev Abazajian)

$$\rho_{\text{matter}} = \rho_{\text{CDM}} + \rho_{\text{baryons}} + \rho_{\text{neutrinos}}$$

$$\rho_\nu = m_\nu n_\nu$$

Neutrino Number Densities



$$\rho_\nu = \sum m_\nu n_\nu$$

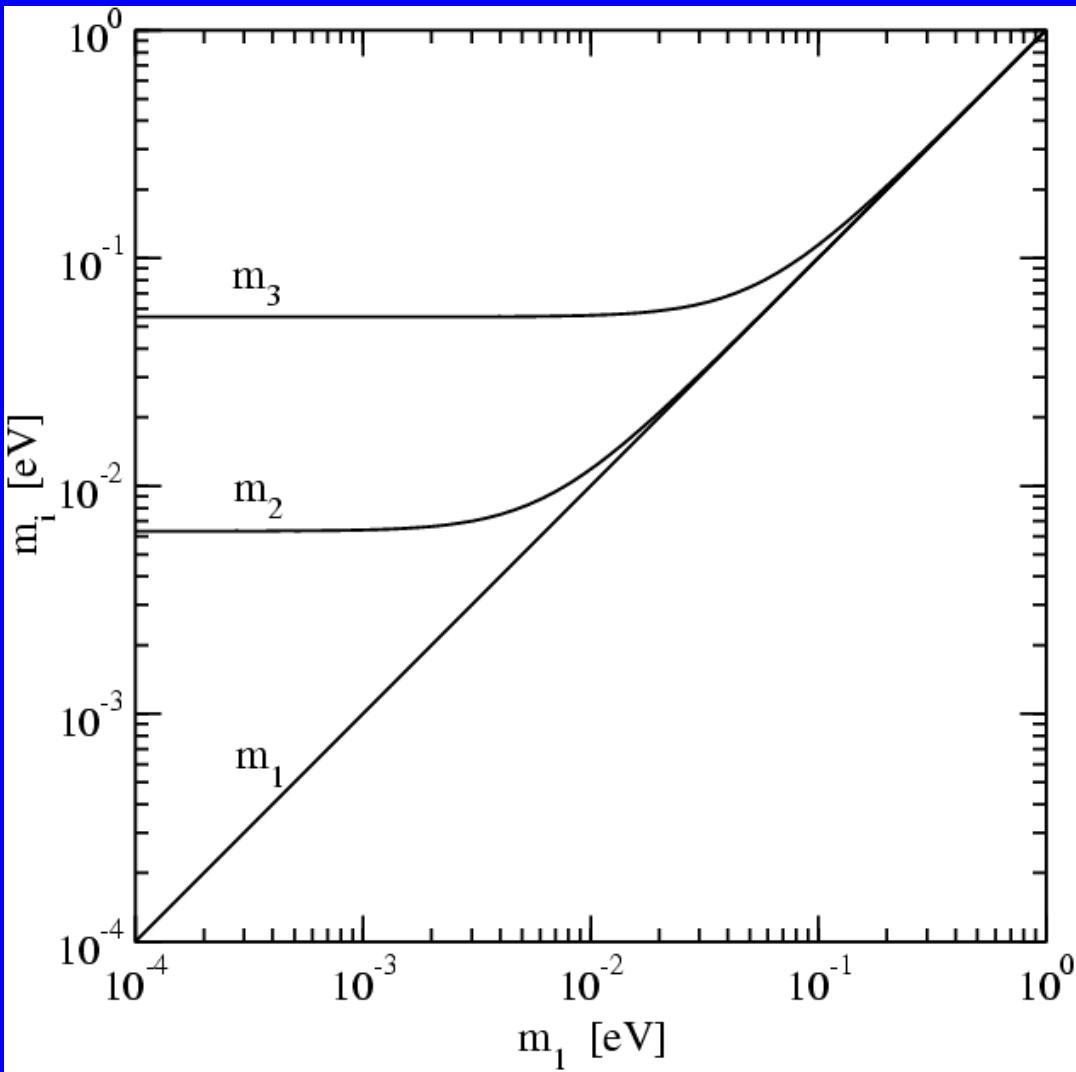
$N_\nu < 4$ (99% CL) BBN
Abazajian, Astropart. 19, 303 (2003)

$1.5 \leq N_\nu \leq 7.2$ WMAP ++
Crotty, Lesgourgues, and Pastor,
PRD 67, 123005 (2003)

$$n_\nu \square n_{\bar{\nu}}$$

Dolgov et al., NPB 632, 363 (2002);
Wong, PRD 66, 025015 (2002);
Abazajian, Beacom, and Bell,
PRD 66, 013008 (2002)

Neutrino Masses



Normal Hierarchy

$$m_1 = m_1$$

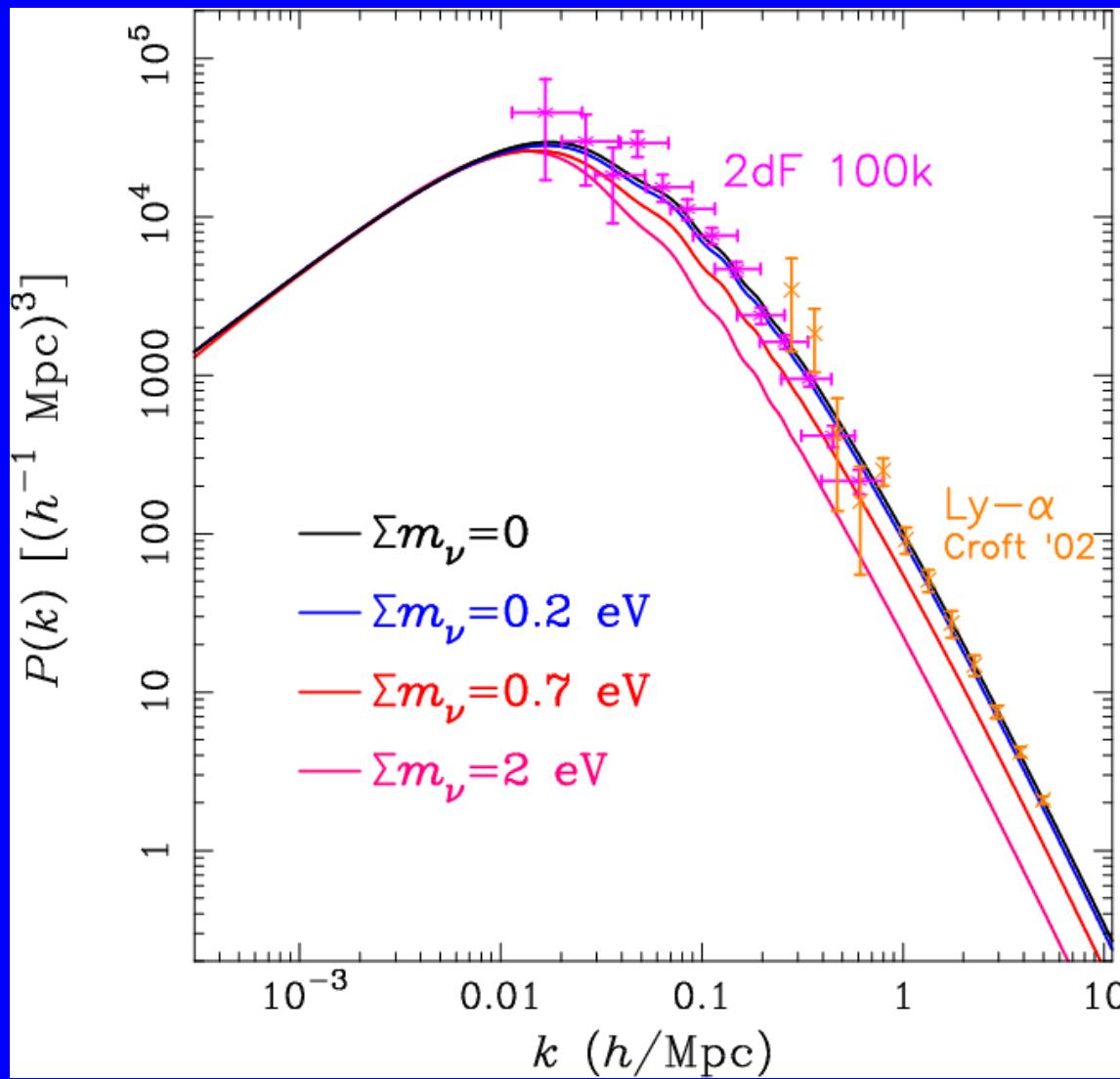
$$m_2 = \sqrt{m_1^2 + \delta m_{\text{solar}}^2}$$

$$m_3 = \sqrt{m_1^2 + \delta m_{\text{solar}}^2 + \delta m_{\text{atm}}^2}$$

$$\frac{m_3}{m_2} \leq \frac{\sqrt{\delta m_{\text{atm}}^2}}{\sqrt{\delta m_{\text{solar}}^2}} \leq 10$$

Beacom and Bell, PRD 65, 113009 (2002)

Neutrino Dark Matter



$$\rho_{\text{matter}} = \rho_{\text{CDM}} + \rho_{\text{baryons}} + \rho_{\text{neutrinos}}$$

$$\rho_\nu = m_\nu n_\nu$$

Enough reach:

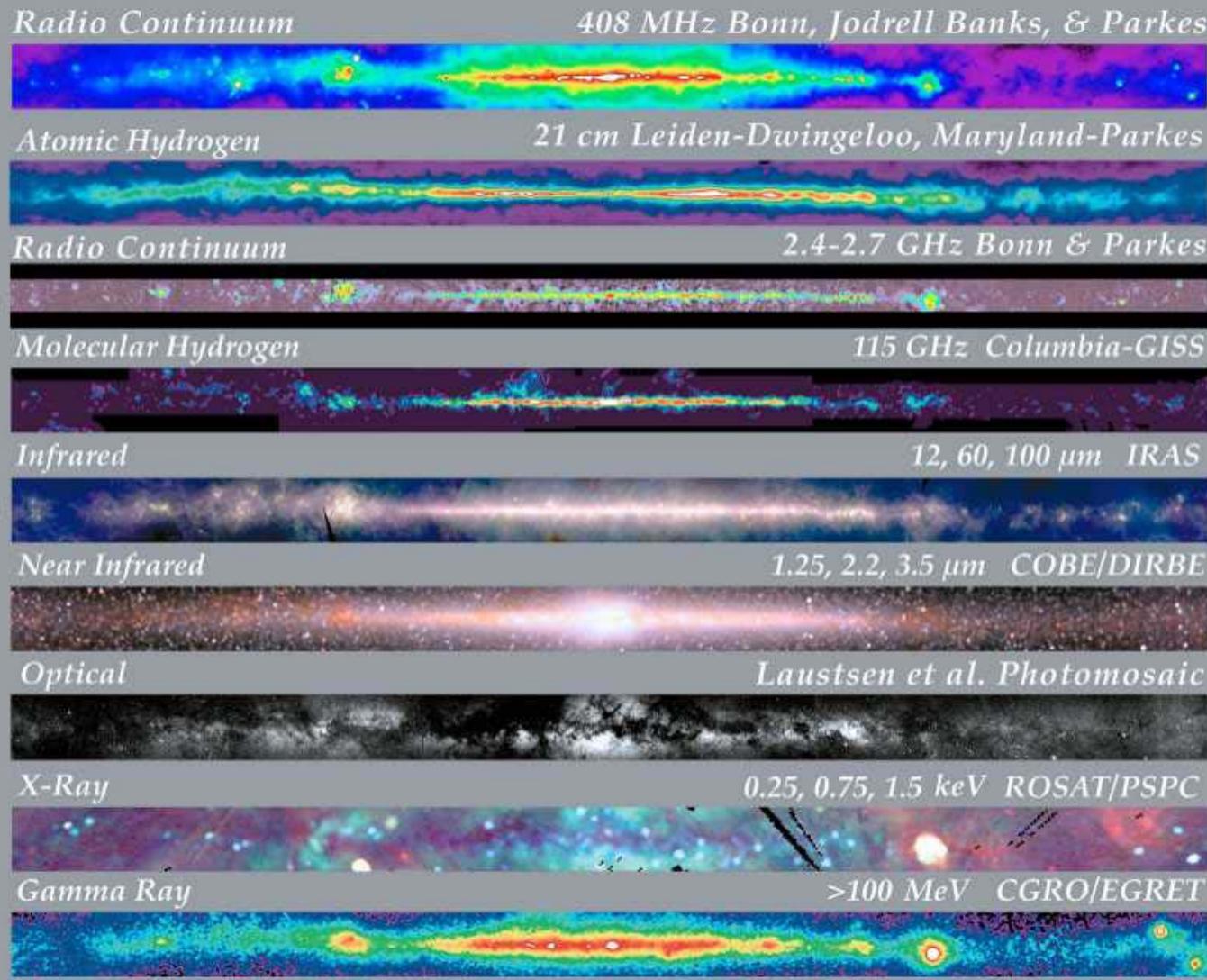
Abazajian & Dodelson,
PRL 91, 041301 (2003)

Kaplinghat, Knox & Song,
astro-ph/0303344

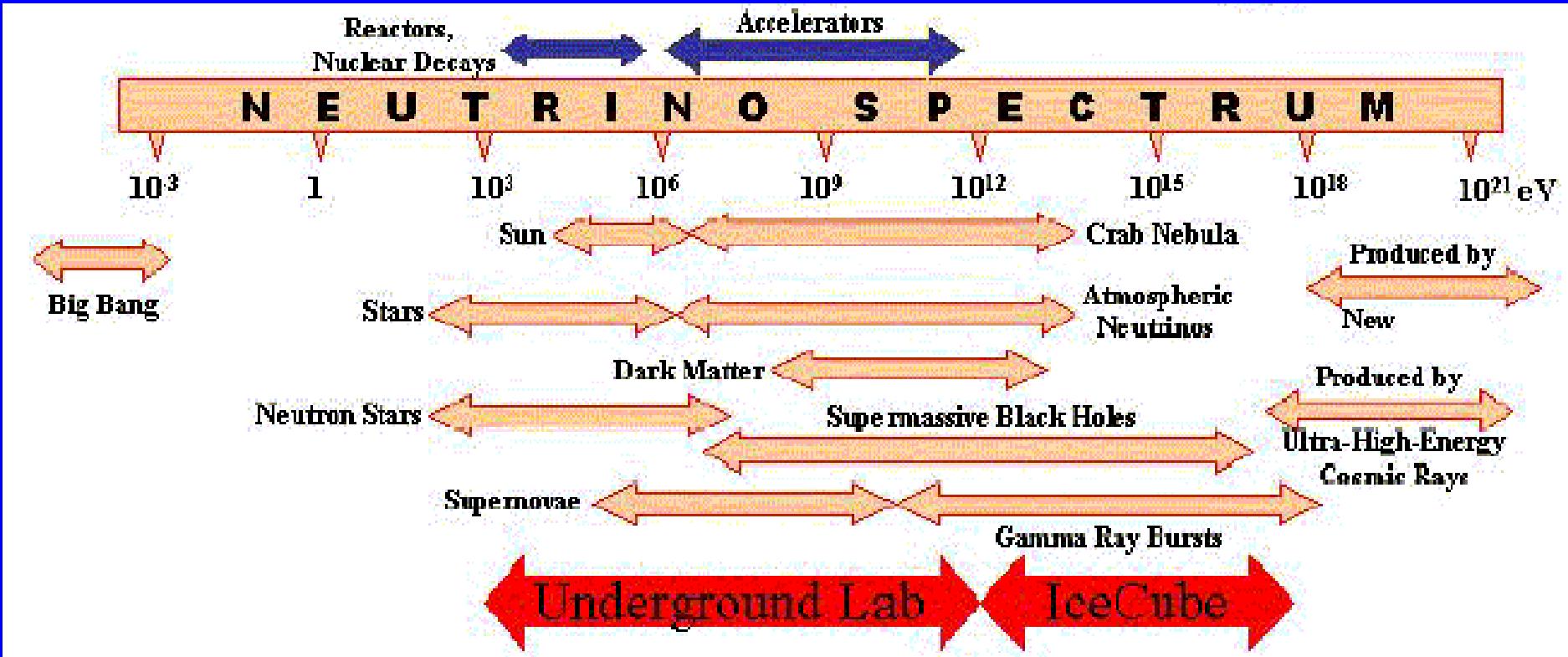
Neutrino Astrophysics

Mult wavelength Milky Way

Photon Windows

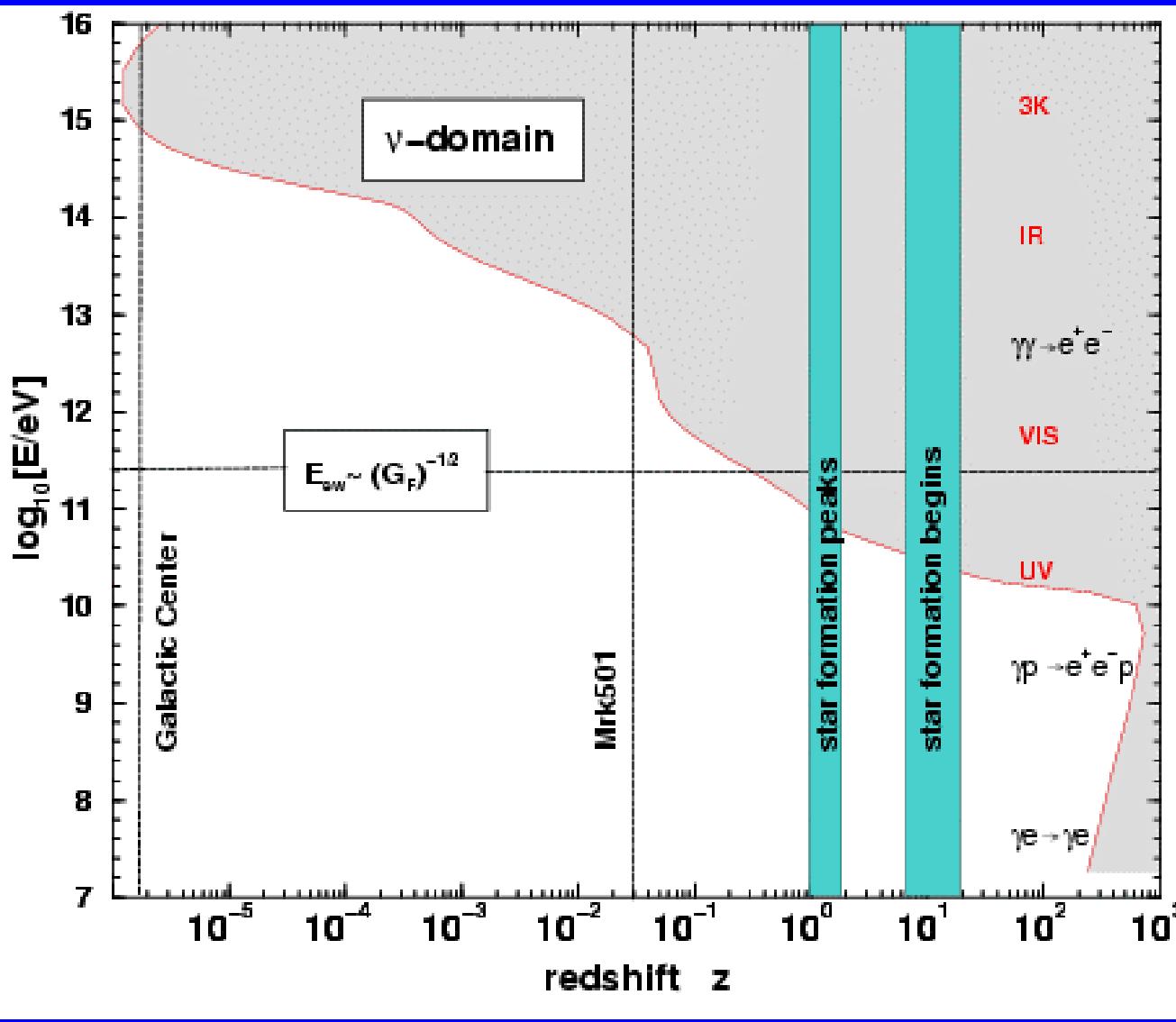


Neutrino Windows



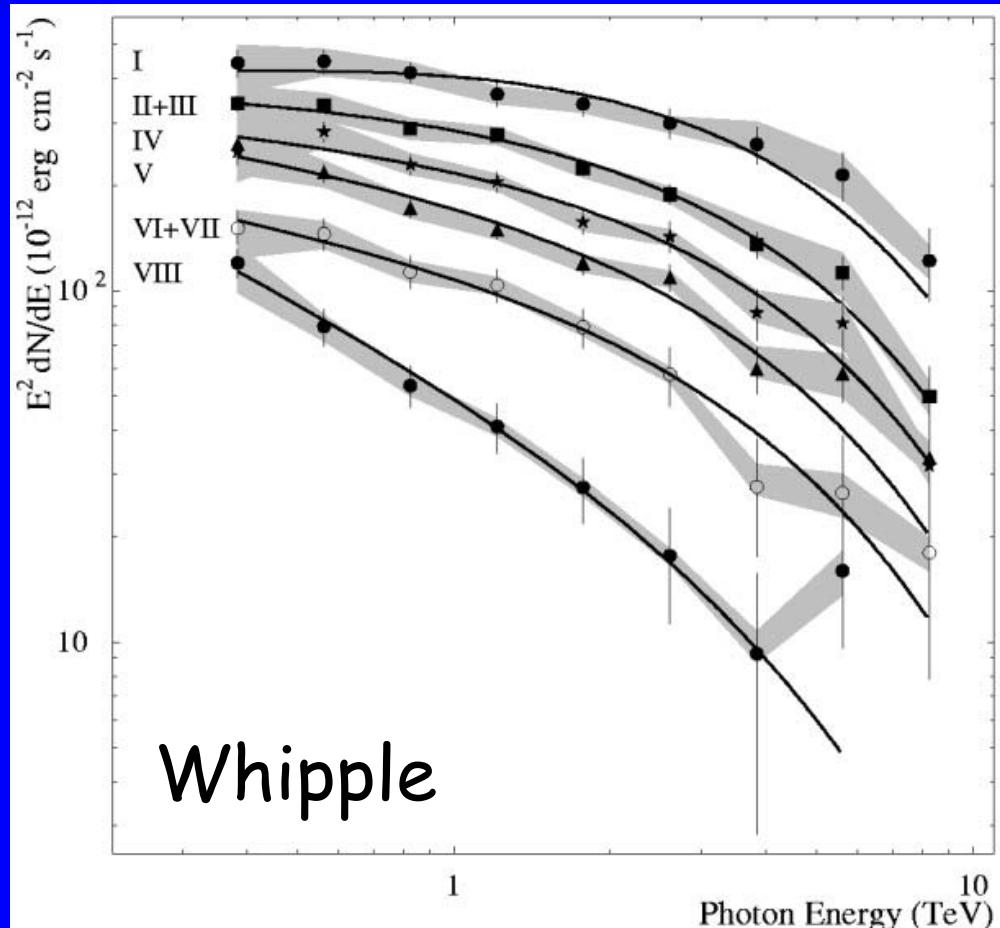
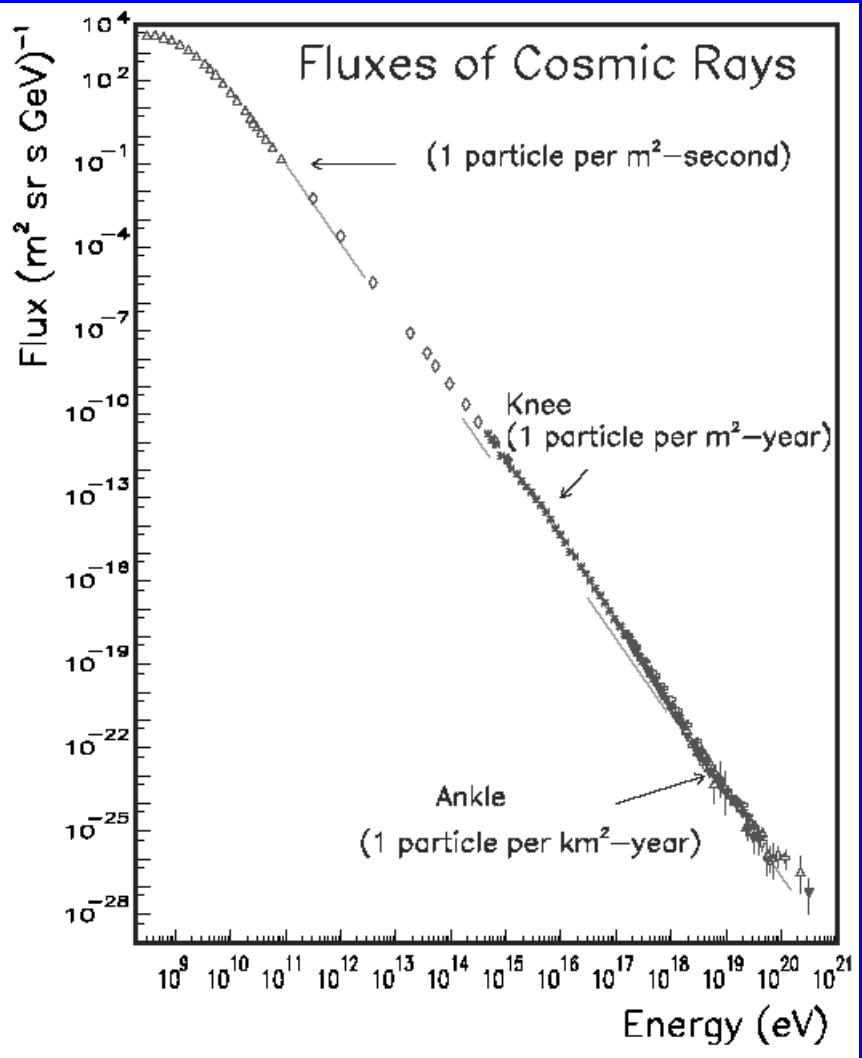
Neutrino Facilities Assessment Committee, NAS (2002)

Beyond the Veil



Learned and Mannheim,
Ann.Rev.Nucl.Part.Sci
50, 679 (2000)

High-Energy Messengers



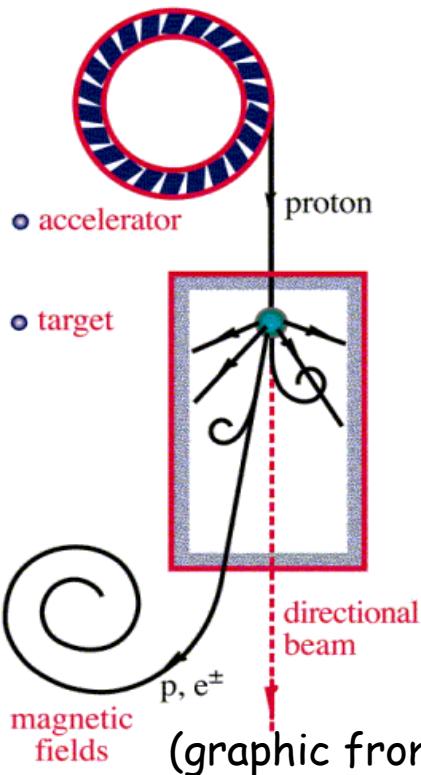
F. Krennrich et al., ApJ 575, L9 (2002)

Protons (diffuse)

Photons (Markarian 421)

UHE Neutrinos

NEUTRINO BEAMS: HEAVEN & EARTH



initial fluxes are

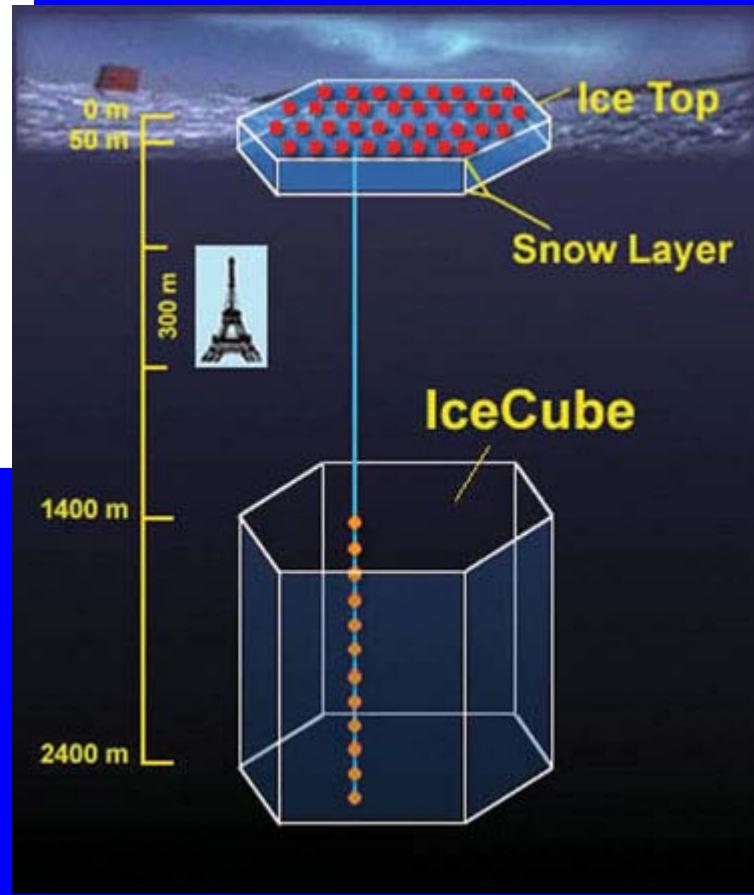
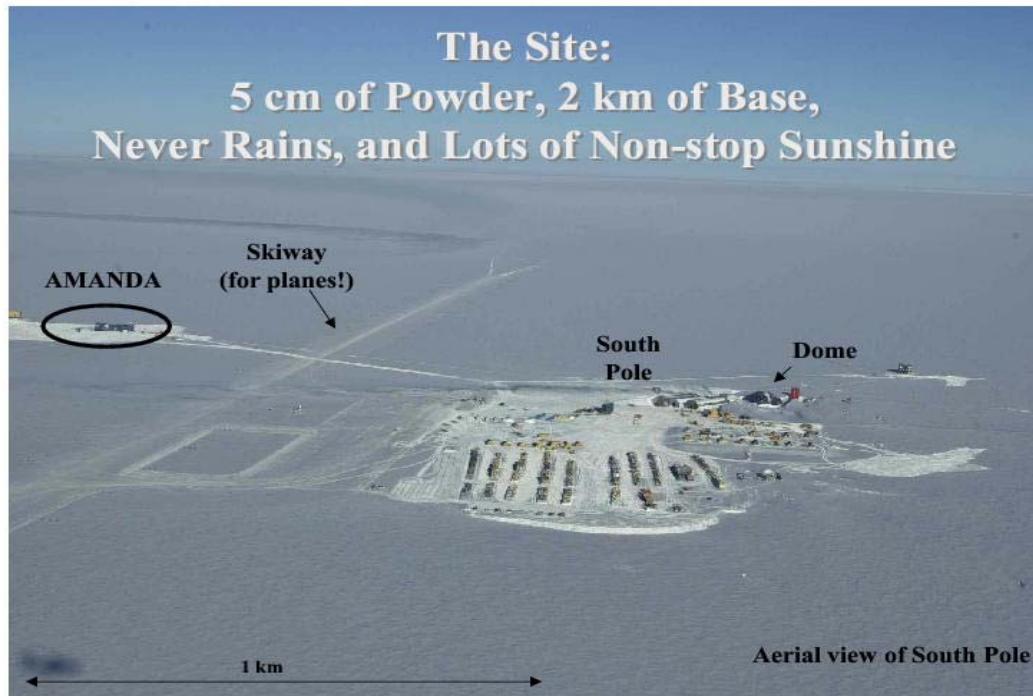
$$\Phi_{\nu_e} : \Phi_{\nu_\mu} : \Phi_{\nu_\tau} = 1 : 2 : 0$$

after oscillations

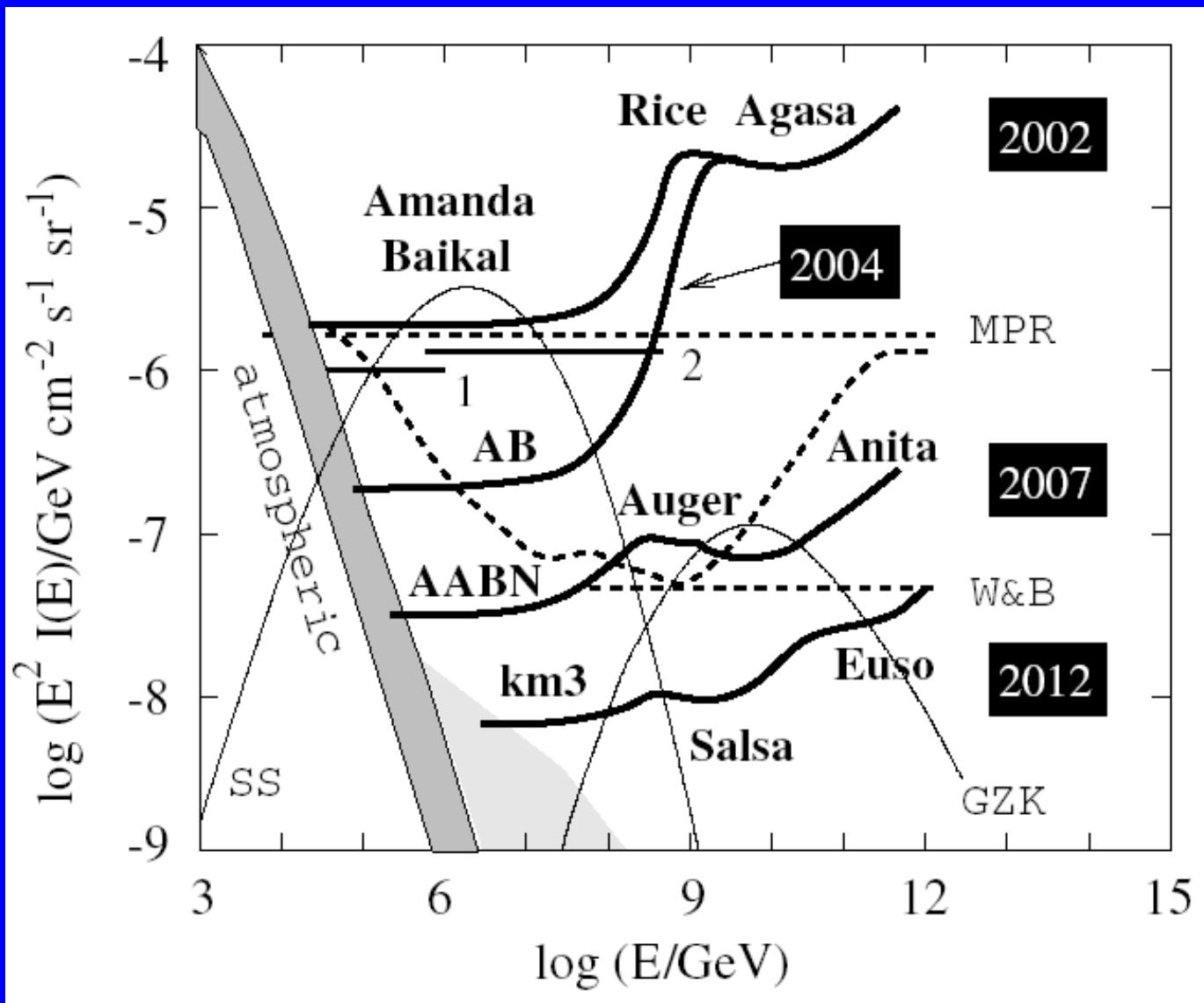
$$\Phi_{\nu_e} : \Phi_{\nu_\mu} : \Phi_{\nu_\tau} = 1 : 1 : 1$$

Earth opacity effects
above $E \sim 100$ TeV

ICECUBE



UHE Neutrino Prospects



Spiering, J. Phys. G29, 843 (2003)

Neutrino Decay

Neutrino decay applies to *mass eigenstates*

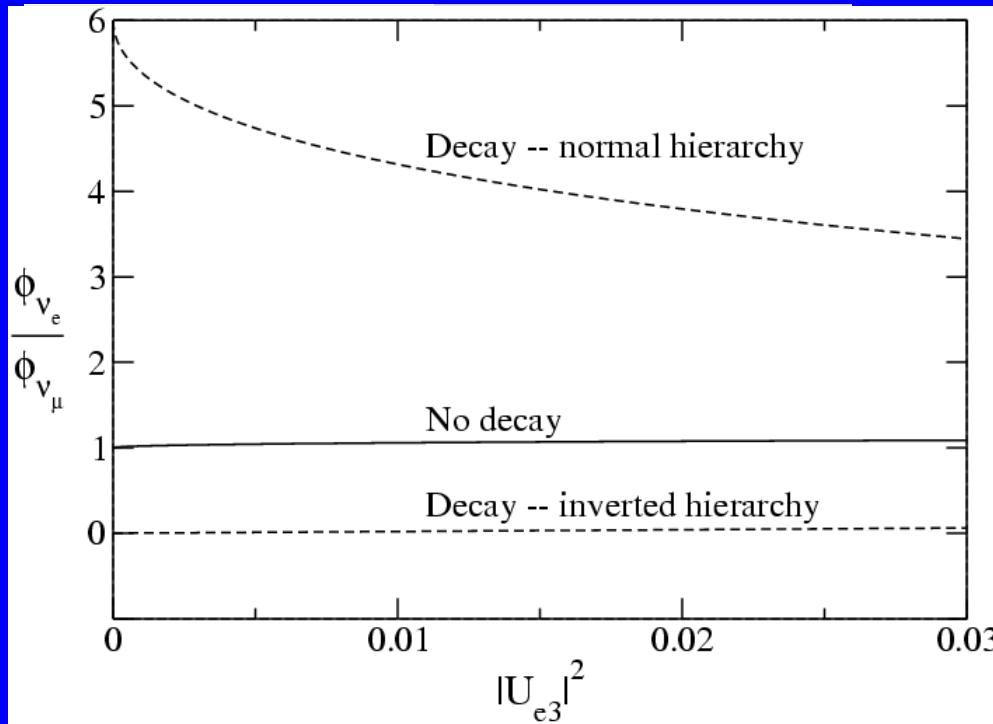
Flux depletion as $\exp(-t/\tau_{\text{lab}}) = \exp\left(-\frac{L}{E} \times \frac{m}{\tau}\right)$

Can decay to either sterile or active daughters
of either full or reduced energy

Neutrino source	L/E	τ/m (s/eV)
Accelerator	30 m / 10 MeV	10^{-14}
Atmosphere	10^4 km / 300 MeV	10^{-10}
Sun	500 s / 5 MeV	10^{-4}
Supernova	10 kpc / 10 MeV	10^5
AGN	100 Mpc / 1 TeV	10^4

Also direct probes of new couplings, e.g., Farzan, PRD 67, 073015 (2002)

UHE Neutrino Decay



$\sim 6:1:1$

$\sim 0:1:1$

$$\text{decay} \square \exp\left(\frac{L}{E} \times \frac{m}{\tau}\right)$$

$$L/E \square 100 \text{ Mpc}/1 \text{ TeV}$$

$$\Rightarrow \tau/m \square 10^4 \text{ s/eV}$$

No bound from SN 1987A

Beacom and Bell, PRD 65, 113009 (2002);

Beacom et al., PRL 90, 181301 (2003);

Barenboim and Quigg, PRD 67, 073024 (2003);

Beacom et al., hep-ph/0307025, hep-ph/0307151

Conclusions

Neutrinos are central to many important questions:

- **Beyond the Standard Model**

- What chooses the neutrino masses and mixing angles?

- Are neutrinos Majorana or Dirac particles?

- Tests for exotic neutrino properties

- **Cosmology**

- Cosmological parameter determination

- Dark matter properties

- Dark energy? Lambda $\sim (1 \text{ meV})^4 \sim m^4$?

- **High-energy astrophysics**

- Conventional sources at highest energies, densities, and distances

- Unconventional sources, e.g., dark matter decay or annihilation

- Origins of the high-energy gamma and proton fluxes

And best of all...there's data aplenty!

Further Reading

- Kayser in the RPP: http://pdg.lbl.gov/2002/neutrino_mixing_s805.pdf
(and also related listings and reviews)
Waltham, arXiv:physics/0303116
- Goodman's page: <http://www.neutrinooscillation.org/>
Giunti's page: <http://www.to.infn.it/~giunti/NU/>
NuCosmo02: <http://www-astro-theory.fnal.gov/Conferences/NuCosmo/>
- Learned and Mannheim, Ann.Rev.Nucl.Part.Sci. 50,679 (2000)
Halzen and Hooper, Rept.Prog.Phys.65,1025 (2002)
- Bahcall, Neutrino Astrophysics
Boehm and Vogel, Physics of Massive Neutrinos
Kayser, The Physics of Massive Neutrinos
Raffelt, Stars as Laboratories for Fundamental Physics
- Kolb and Turner, The Early Universe
Dodelson, Modern Cosmology