Topics in Nuclear Astrophysics

John Beacom

Theoretical Astrophysics Group, Fermilab

Classical Nuclear Astrophysics

- How do stars shine?
- How old is the Universe?
- How do supernovae work?
- How do neutron stars work?
- How are the elements synthesized?
- What are the cosmic rays?

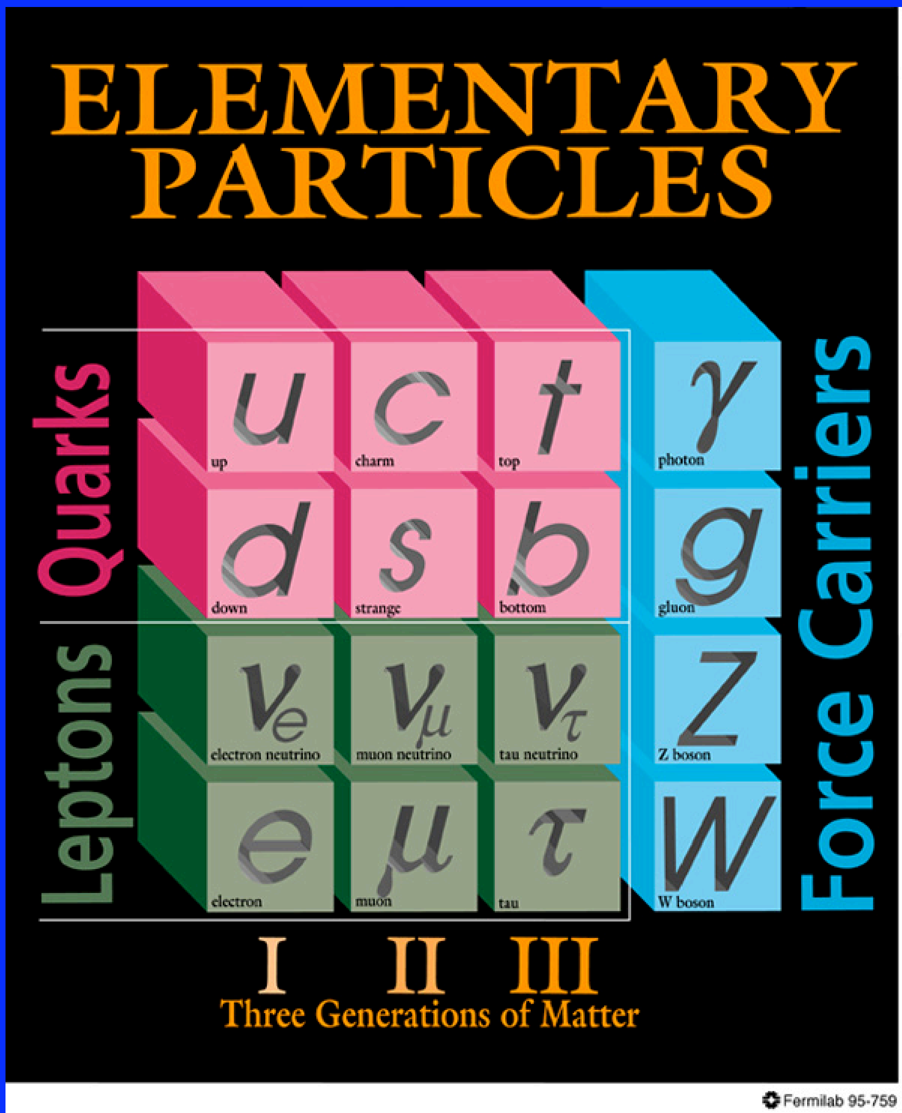
Hans Bethe, b. 1906

The Forces of Darkness

versus

The Forces of Weakness

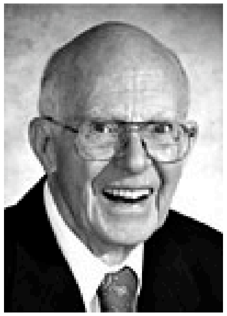
Lucky Neutrinos



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)

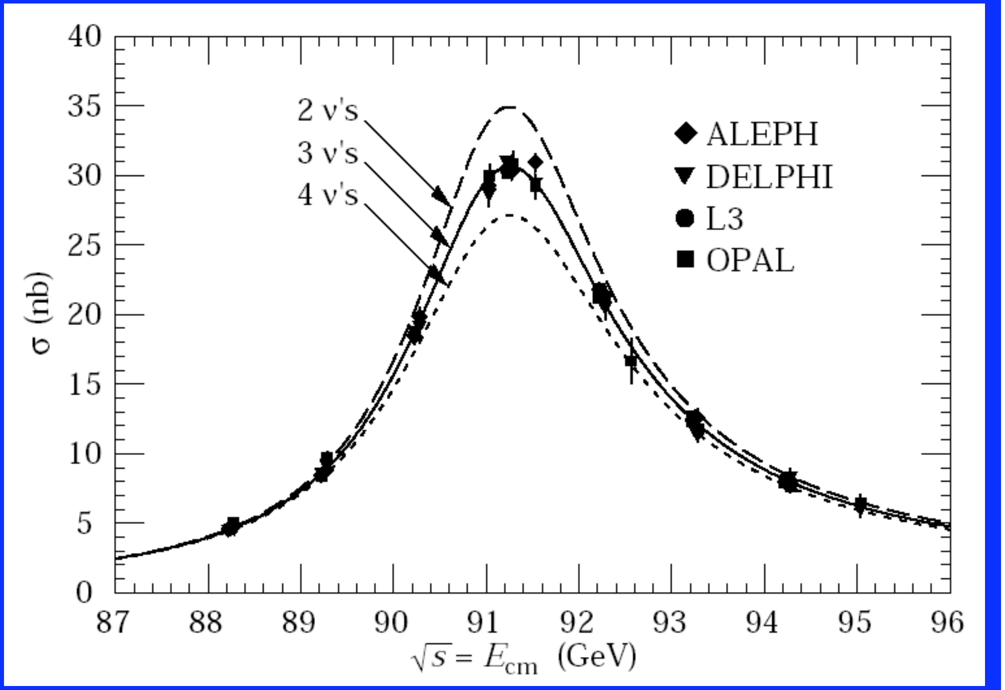
Three Weak Pieces

$\nu_e, \nu_\mu, \nu_\tau,$

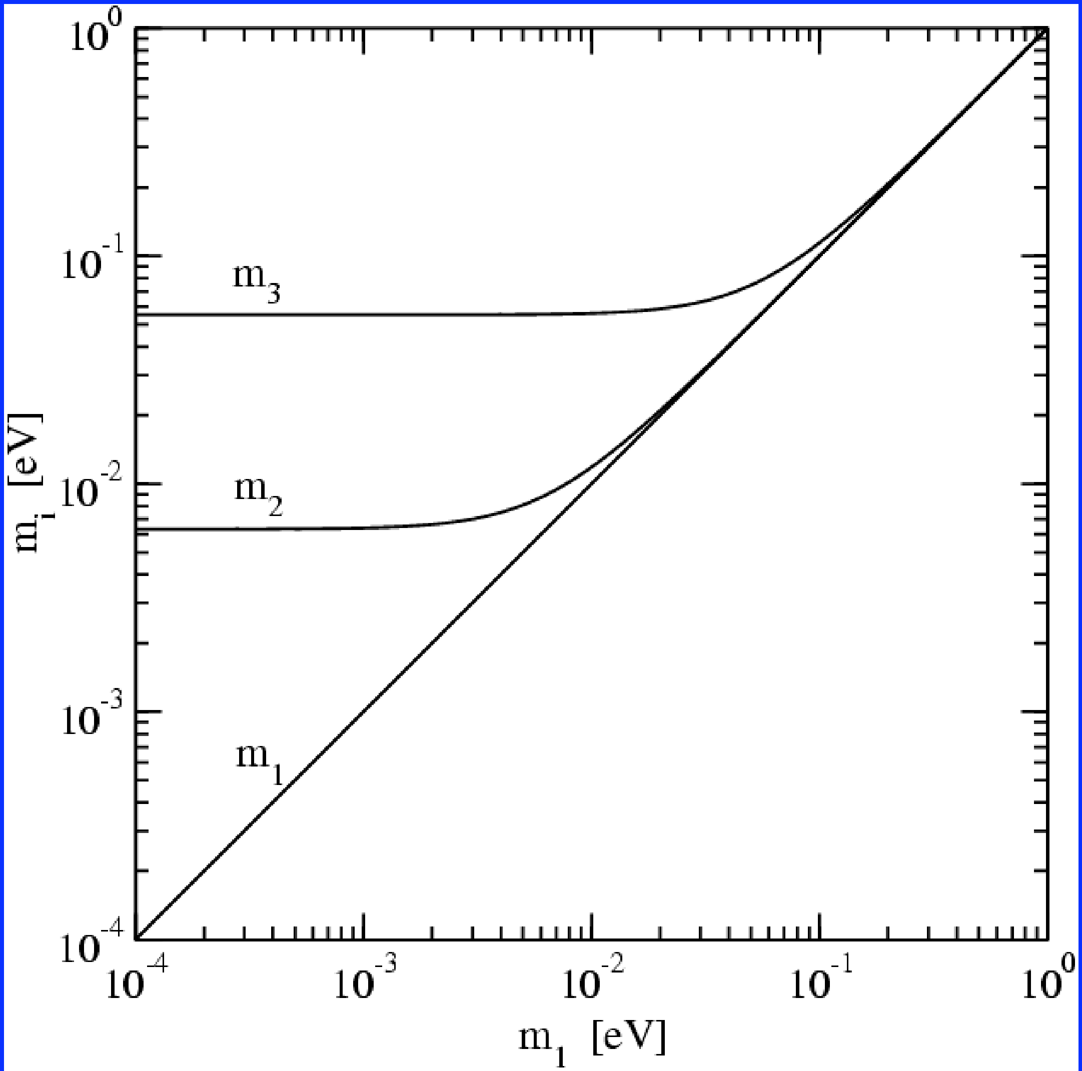
defined by $W^+ \rightarrow e^+\nu_e, \mu^+\nu_\mu, \tau^+\nu_\tau$

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?



Neutrino Masses



Beacom and Bell, PRD 65, 113009 (2002)

Normal Hierarchy

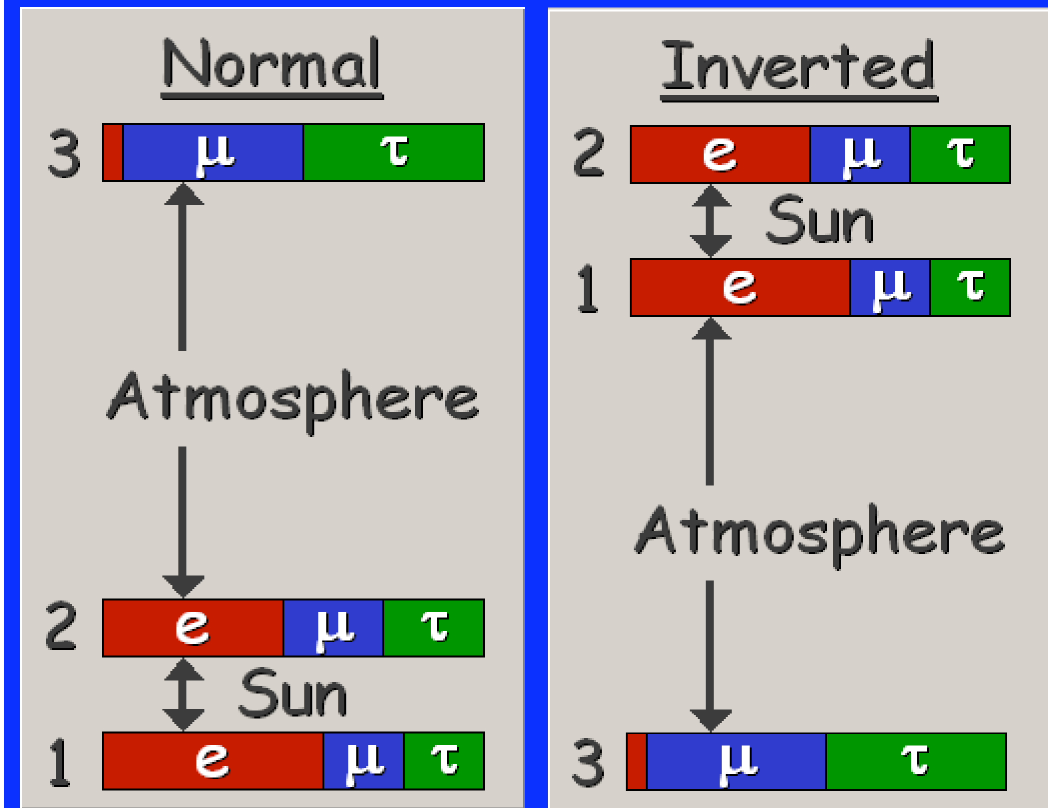
$$m_1 = m_1$$

$$m_2 = \sqrt{m_1^2 + \delta m^2_{solar}}$$

$$m_3 = \sqrt{m_1^2 + \delta m^2_{solar} + \delta m^2_{atm}}$$

$$\frac{m_3}{m_2} \leq \frac{\sqrt{\delta m^2_{atm}}}{\sqrt{\delta m^2_{solar}}} \leq 10$$

Neutrino Mixing



(graphic from Georg Raffelt)

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

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

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

Perspective

"If [there are no new forces] ---- one can conclude that there is no practically possible way of observing the neutrino." Bethe and Peierls, Nature (1934)

- 10 years ago

Solar neutrino problem

Atmospheric neutrino problem

Large neutrino masses

Nonzero magnetic moments, decay, etc.

Key Observational Results

Cosmological

- Big-bang nucleosynthesis consistency
- Neutrino hot dark matter models ruled out

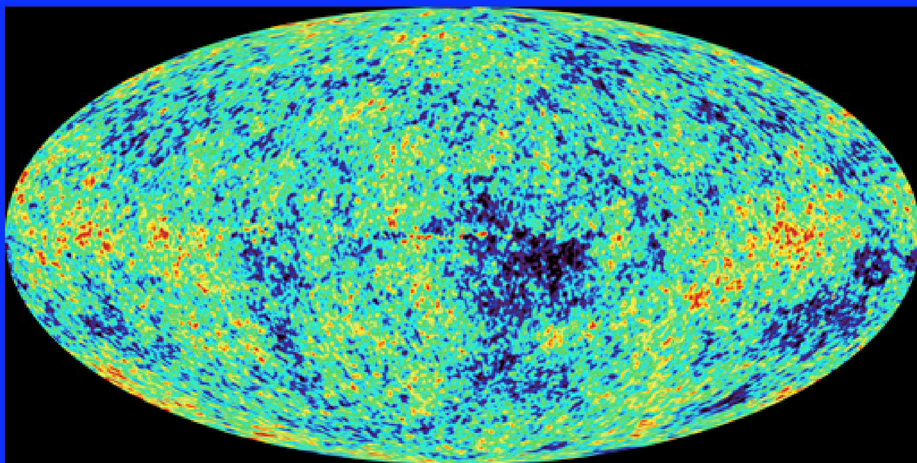
Astrophysical

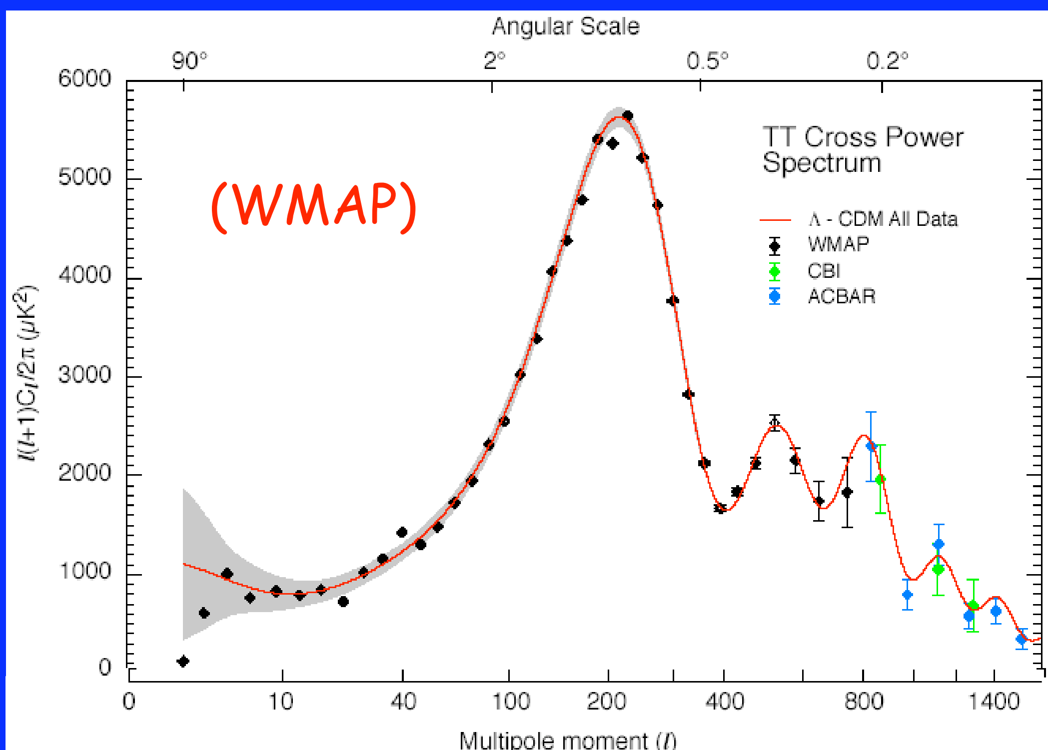
- Neutrinos from SN 1987A observed
- The solution of the solar neutrino problem

Fundamental

- Neutrinos have mass and mixing
- Non-discovery of all manner of exotica

Cosmological Parameters





$\Omega_{total} = 1.02 \pm 0.02$

$\Omega_{matter} h^2 = 0.14 \pm 0.01$

$\Omega_{baryon} h^2 = 0.022 \pm 0.001$

$\Omega_{neutrino} h^2 < 0.01$

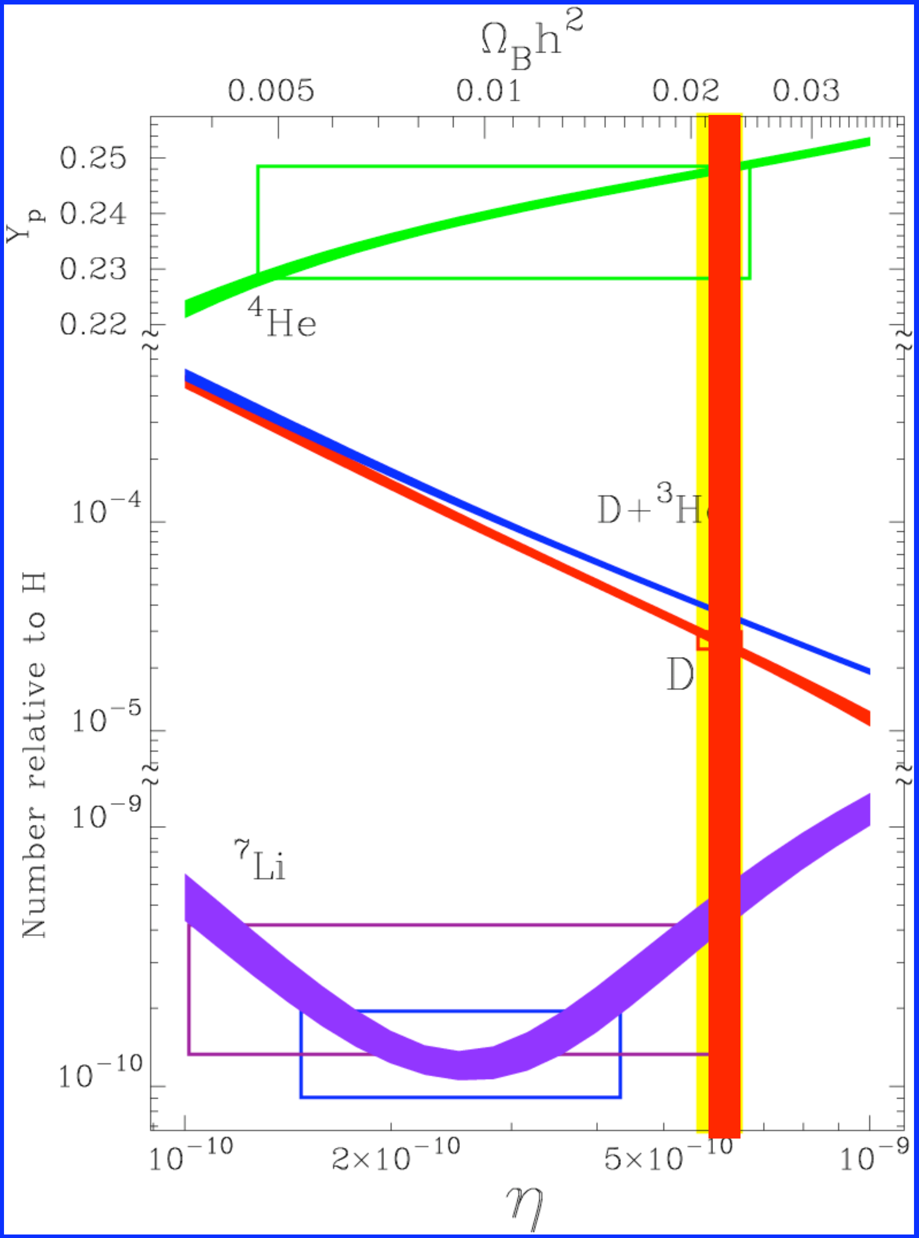
$h = 0.71 \pm 0.04$

etc.

$\Omega_\Lambda = 0.7$

$m_\nu < 0.23$ eV

Neutrino Number Densities



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

$N_\nu < 4$ (99% CL) BBN

Abazajian, Astropart. 19, 303 (2003)

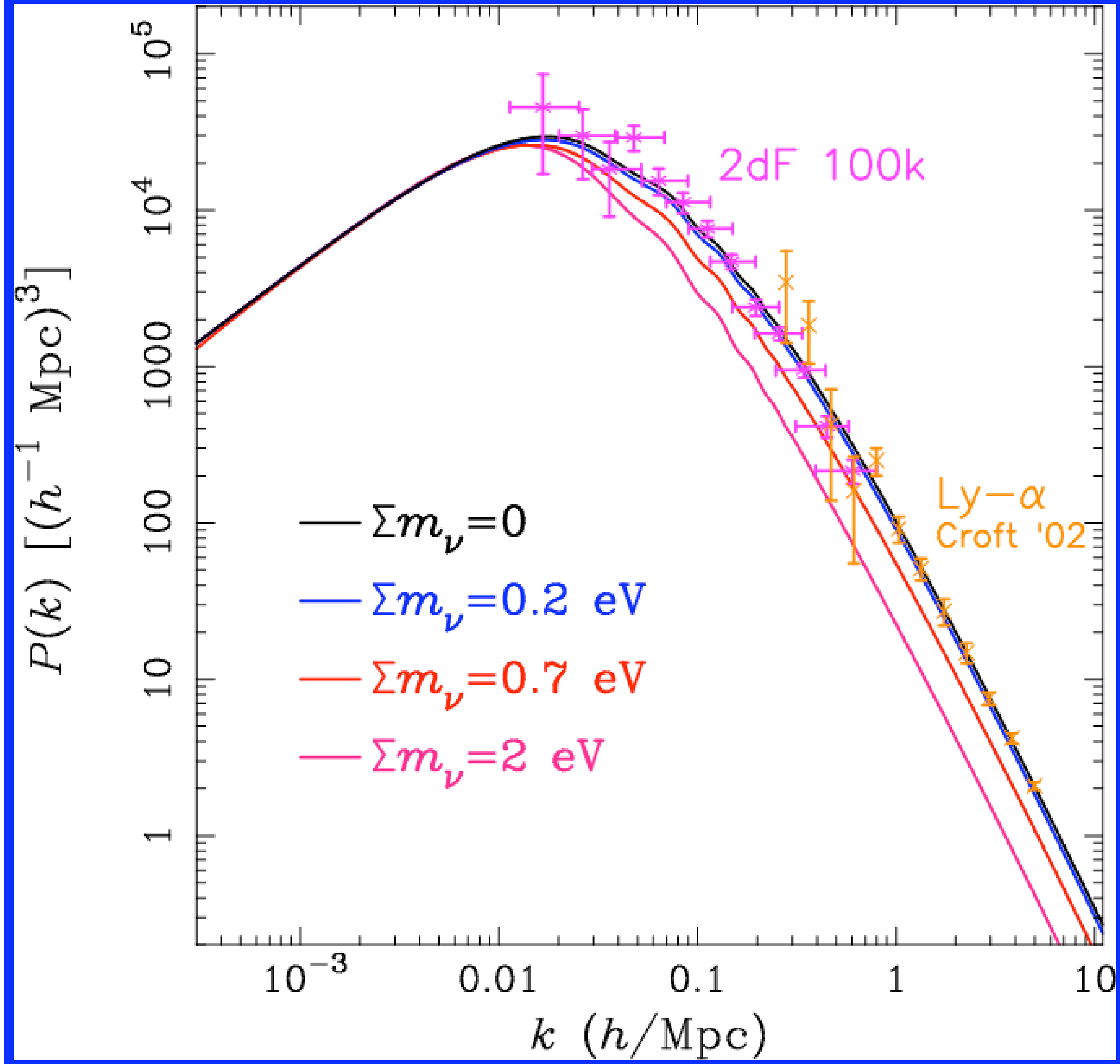
$1.5 \le N_\nu \le 7.2$ WMAP++

Crotty, Lesgourgues, and Pastor, PRD 67, 123005 (2003)

$n_\nu \simeq n_{\bar{\nu}}$

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

Neutrino Dark Matter



(graphic from Kev Abazajian)

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

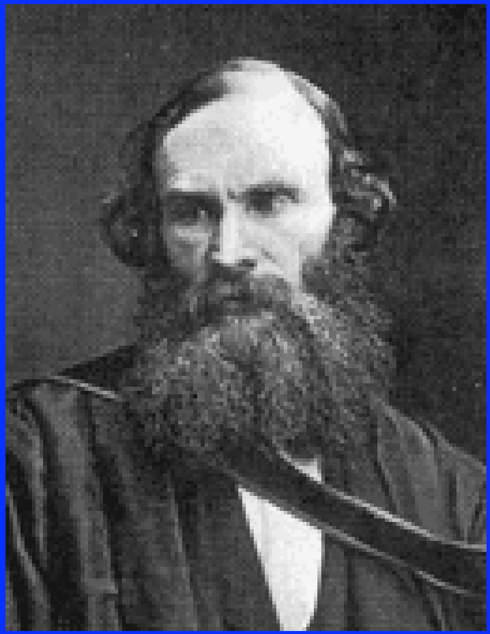
$$\rho_\nu = m_\nu n_\nu$$

Future discovery range:
Abazajian & Dodelson, PRL 91, 041301 (2003)

Kaplinghat, Knox & Song, PRL 91, 241301 (2003)

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

  (Yeah, right)

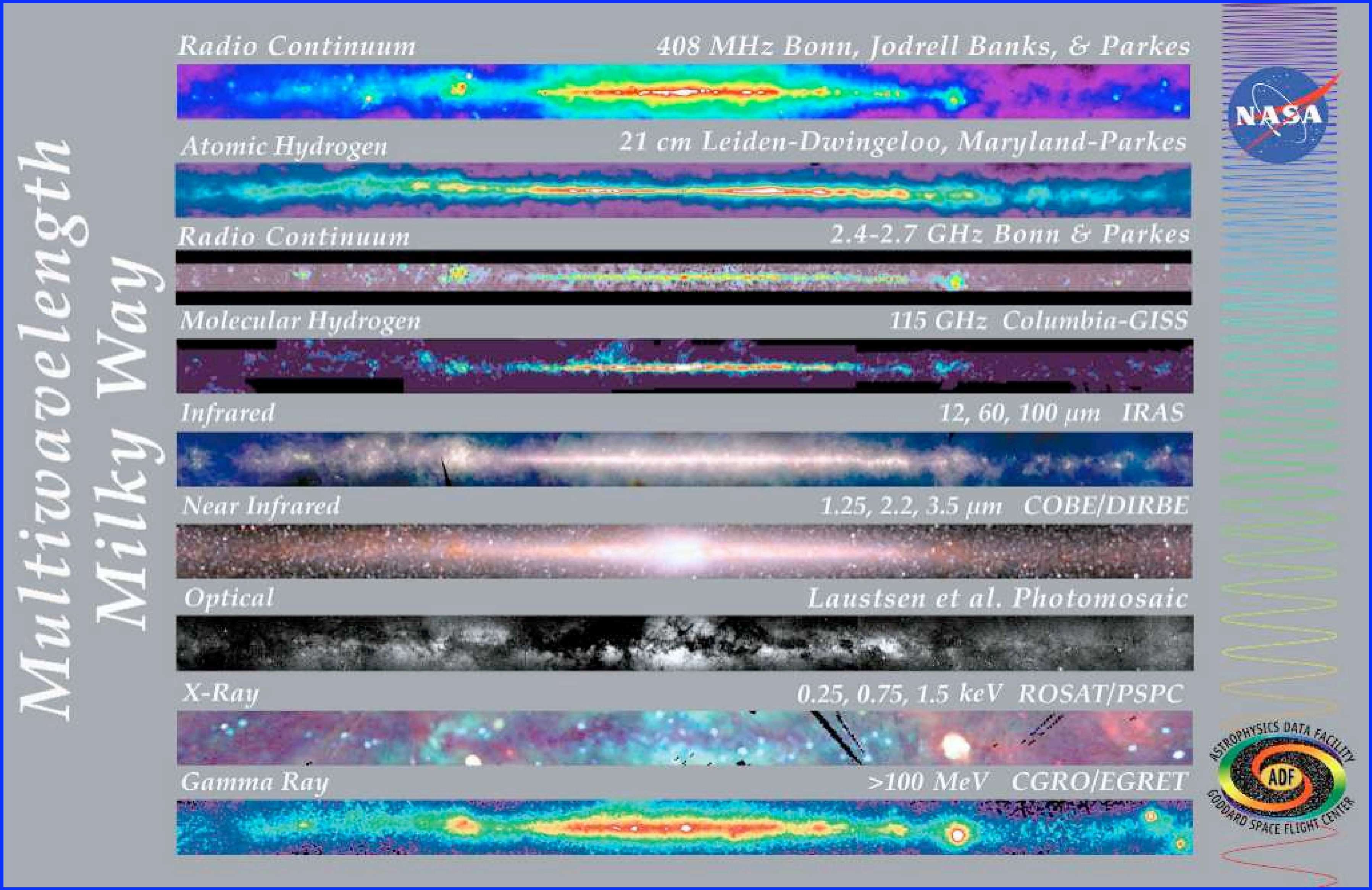
- We now understand cosmology

  (Yeah, right)

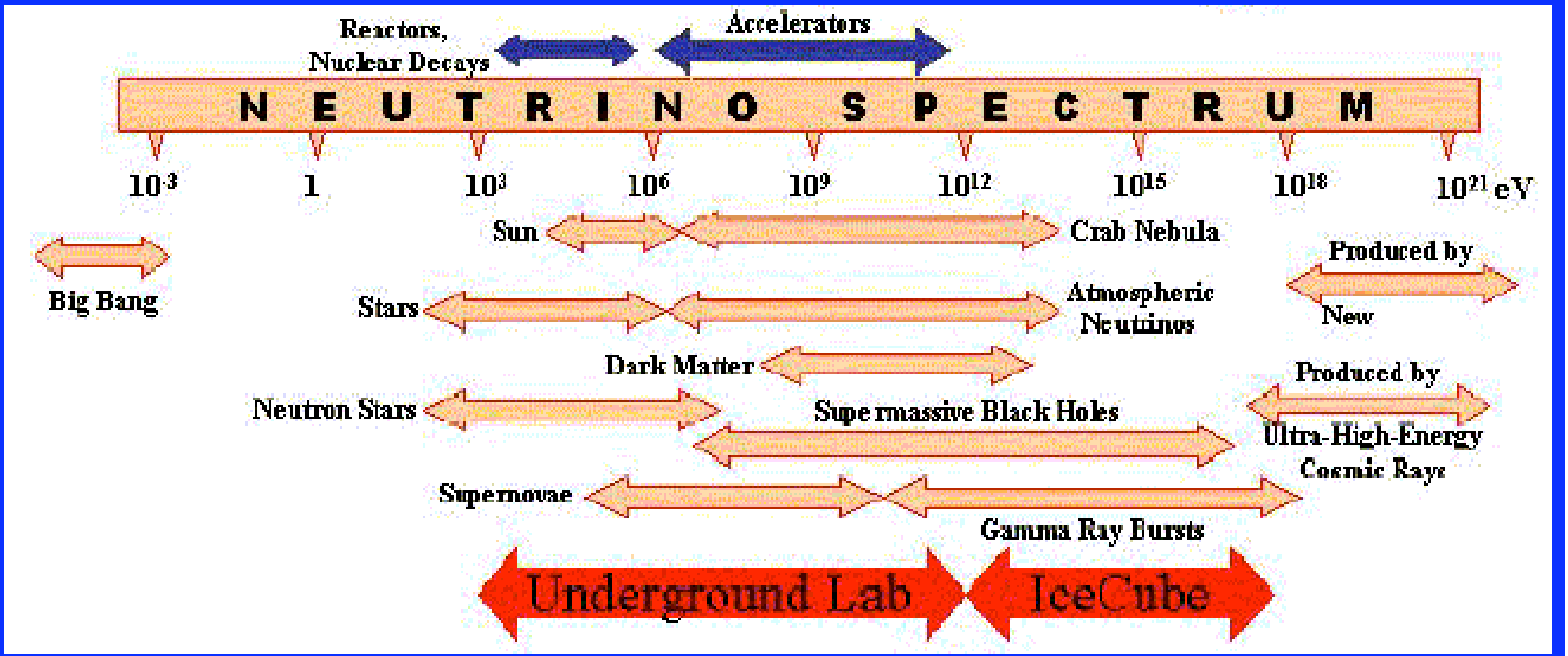
- We now understand astrophysical sources

  (Yeah, right)

Photon Windows



Neutrino Windows

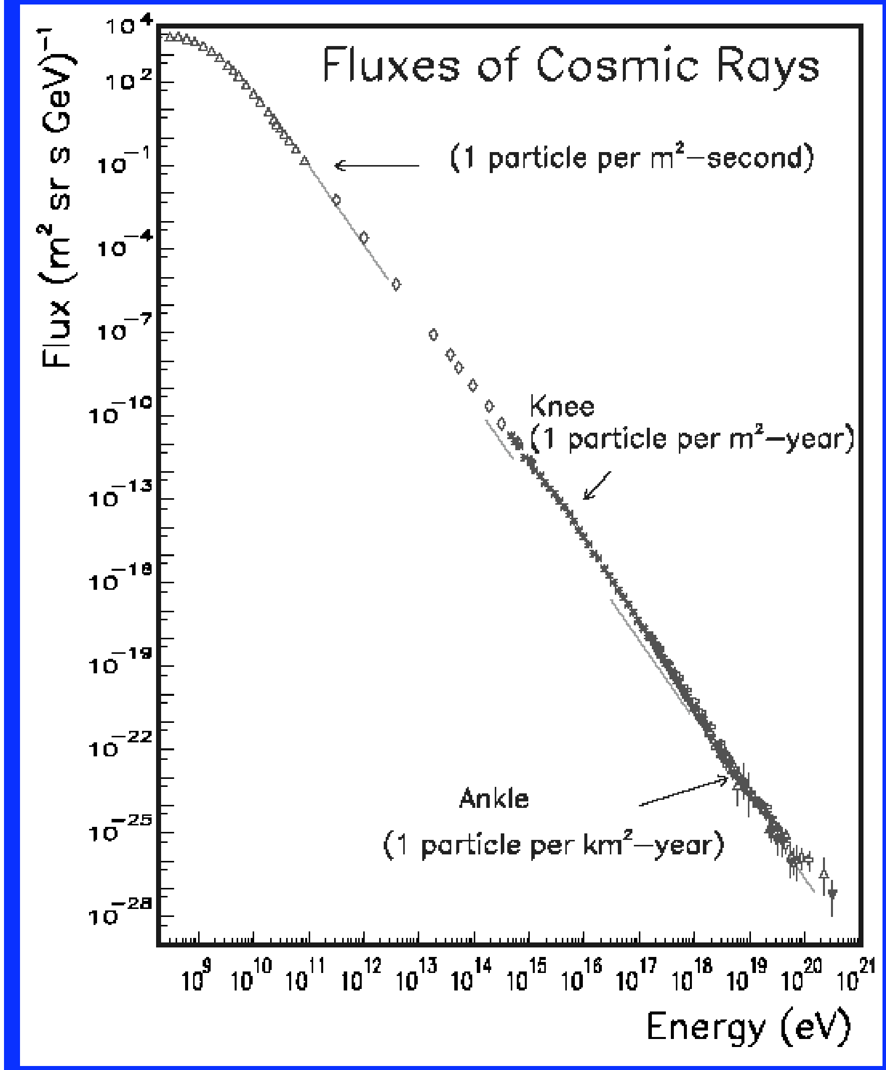


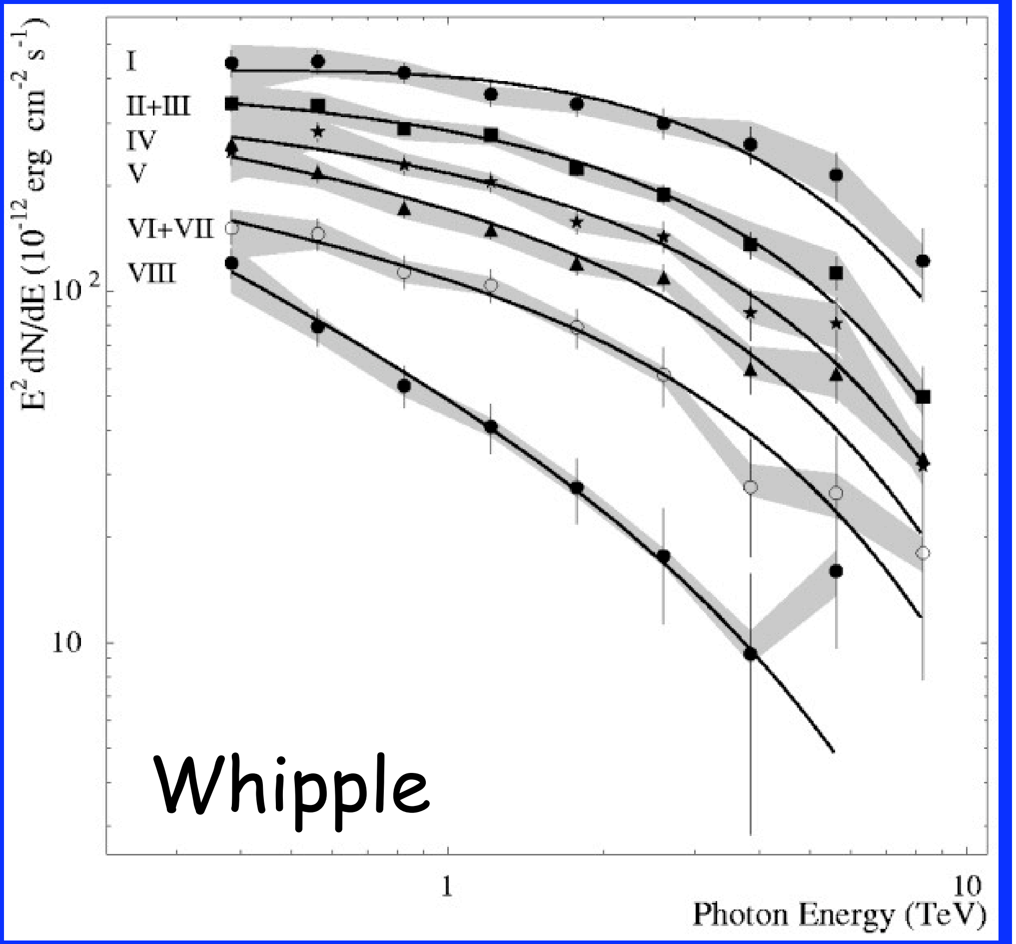
Neutrino Facilities Assessment Committee, NAS (2002)

Astrophysical Neutrinos: Searching High

E ~ TeV

High Energy Messengers



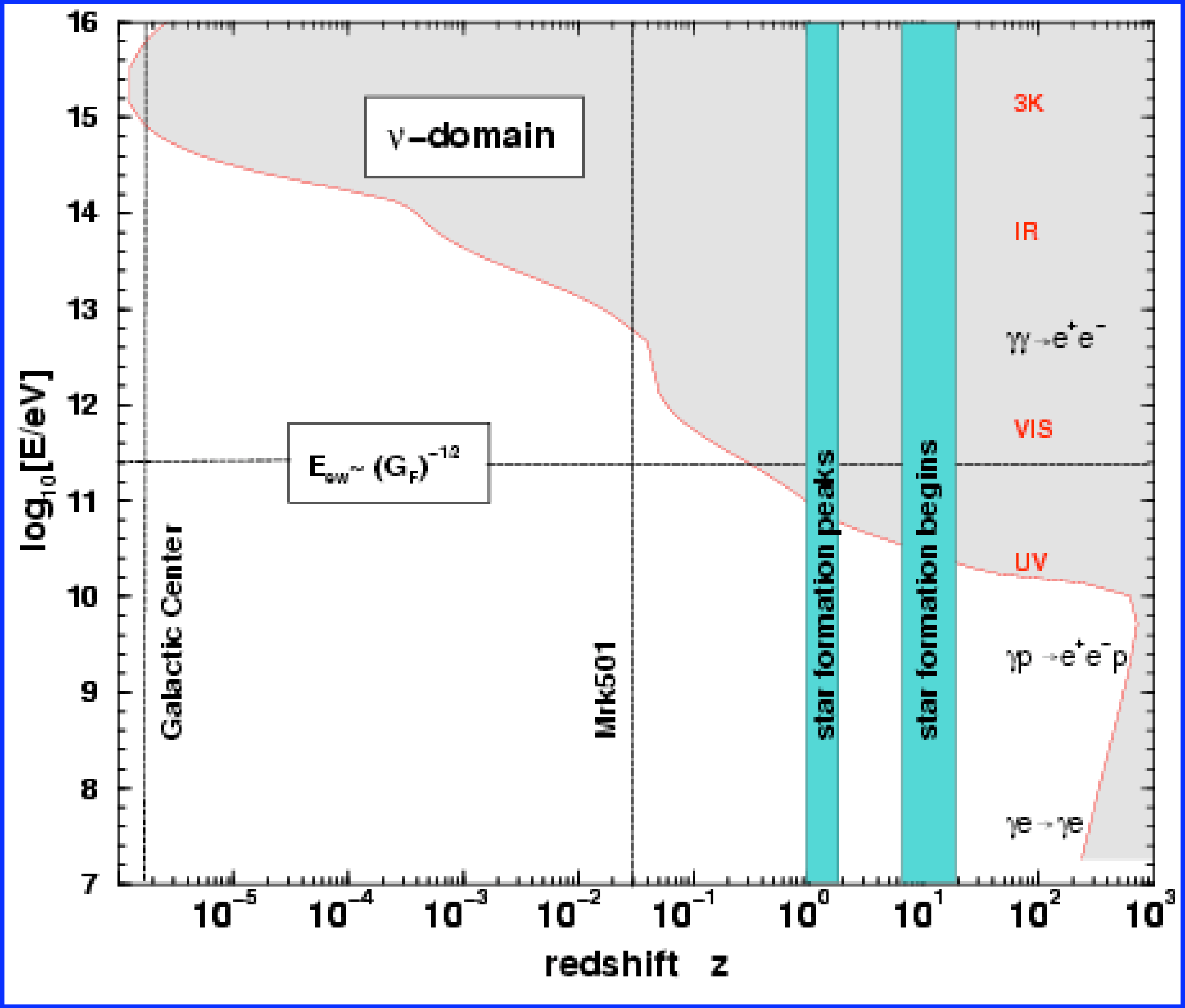


F. Krennrich et al., ApJ 575, L9 (2002)

Protons (diffuse)

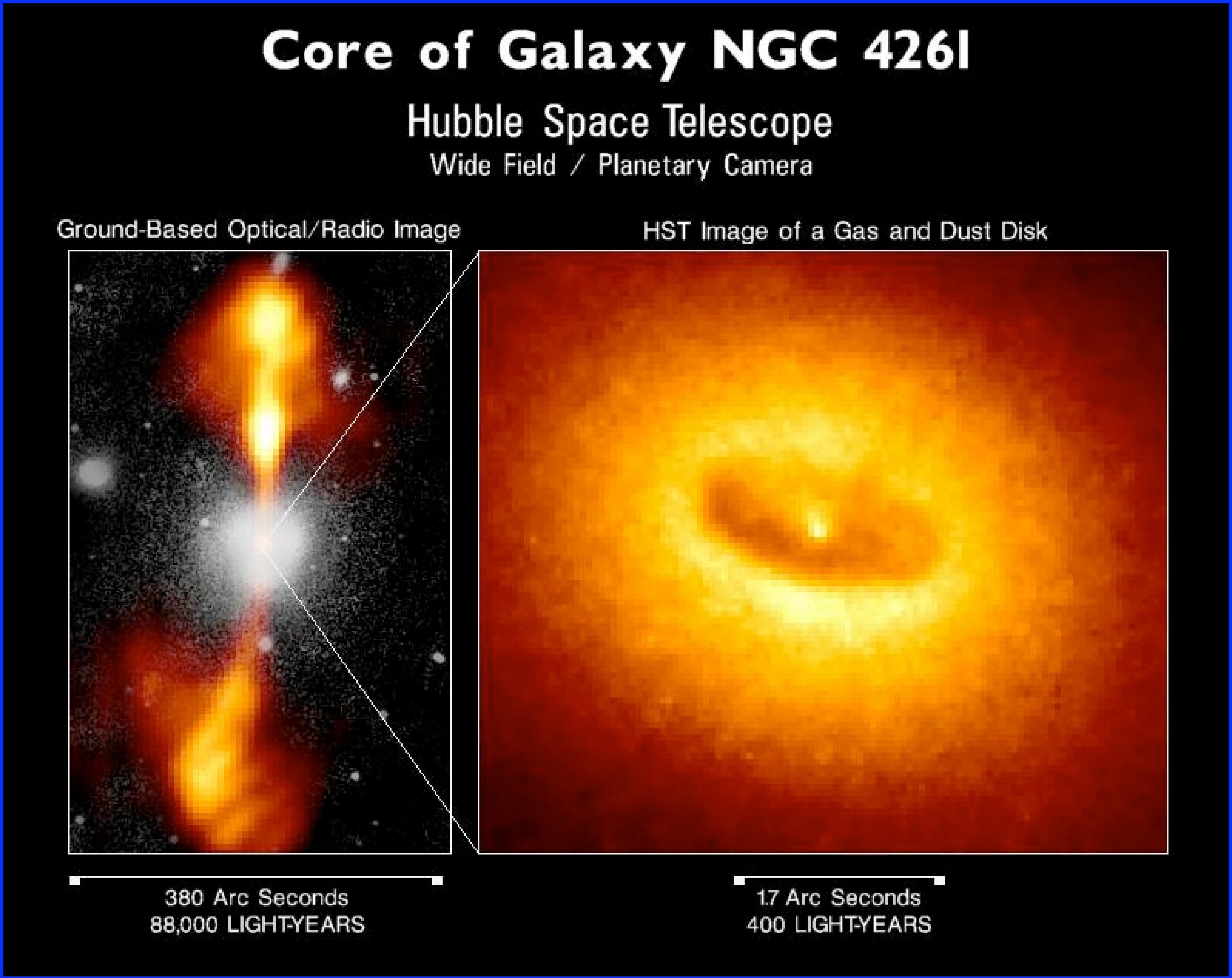
Photons (Markarian 421)

Beyond the Veil



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

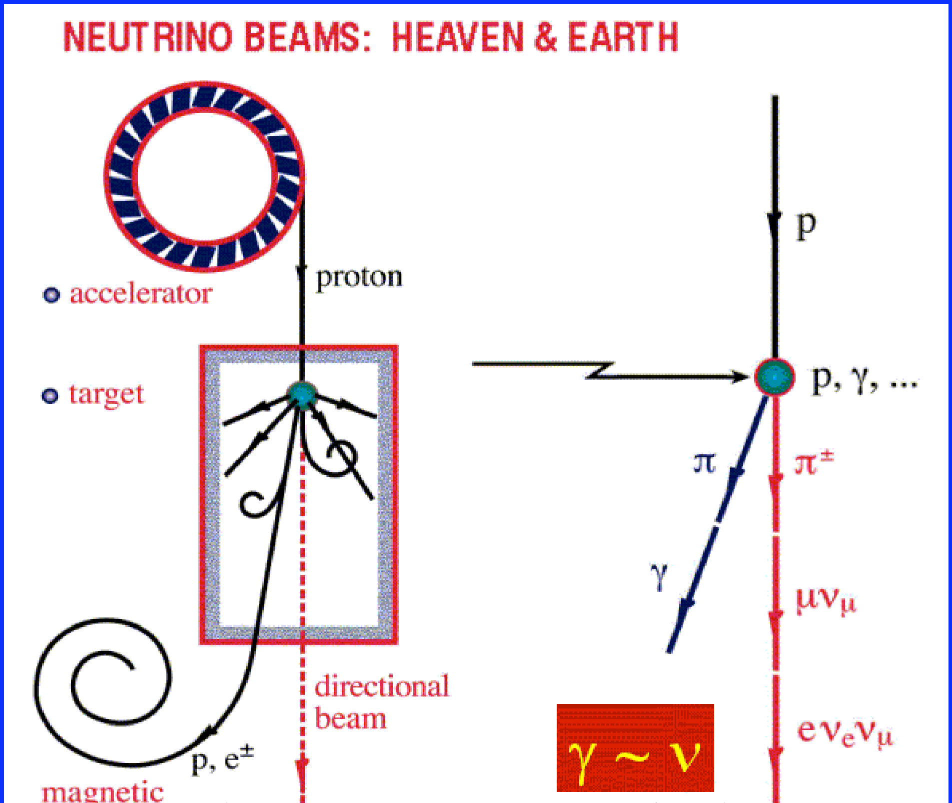
Active Galaxies



UHE Neutrinos

$$\pi^0 \rightarrow \gamma\gamma$$

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



(graphic from Francis Halzen)

initial fluxes are

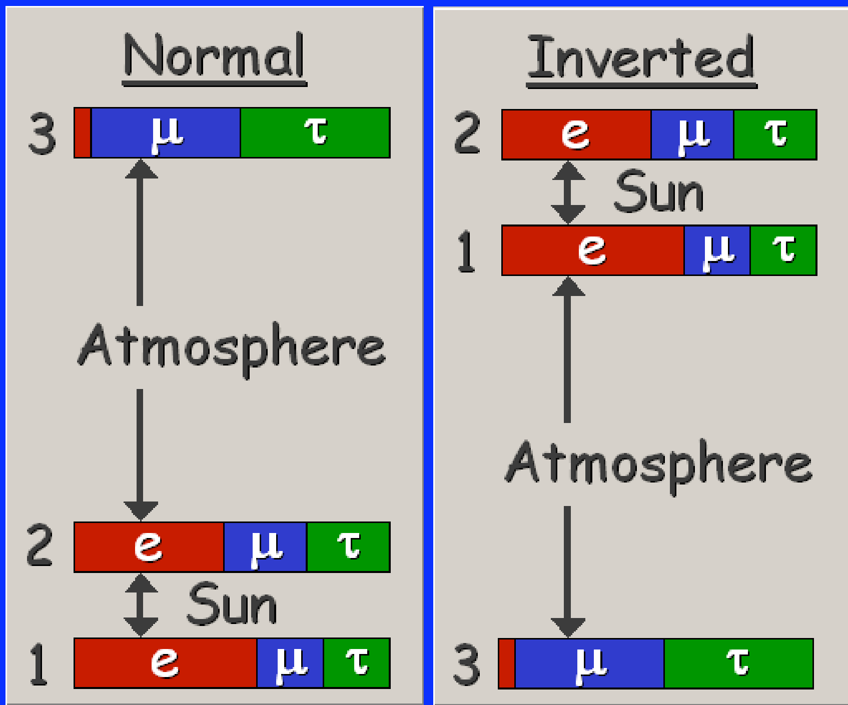
$$\varphi_{\nu_e} : \varphi_{\nu_\mu} : \varphi_{\nu_\tau} = 1:2:0$$

after oscillations

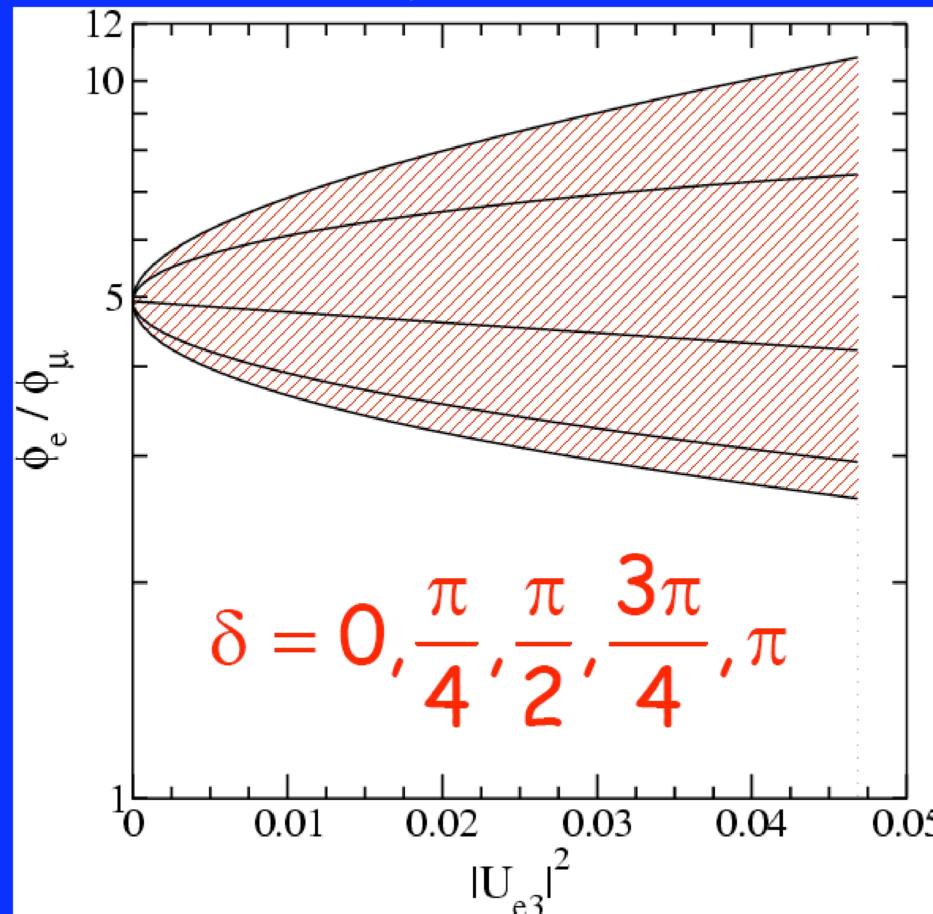
$$\varphi_{\nu_e} : \varphi_{\nu_\mu} : \varphi_{\nu_\tau} = 1:1:1$$

Earth opacity effects above E ~ 100 TeV

Neutrino Decay



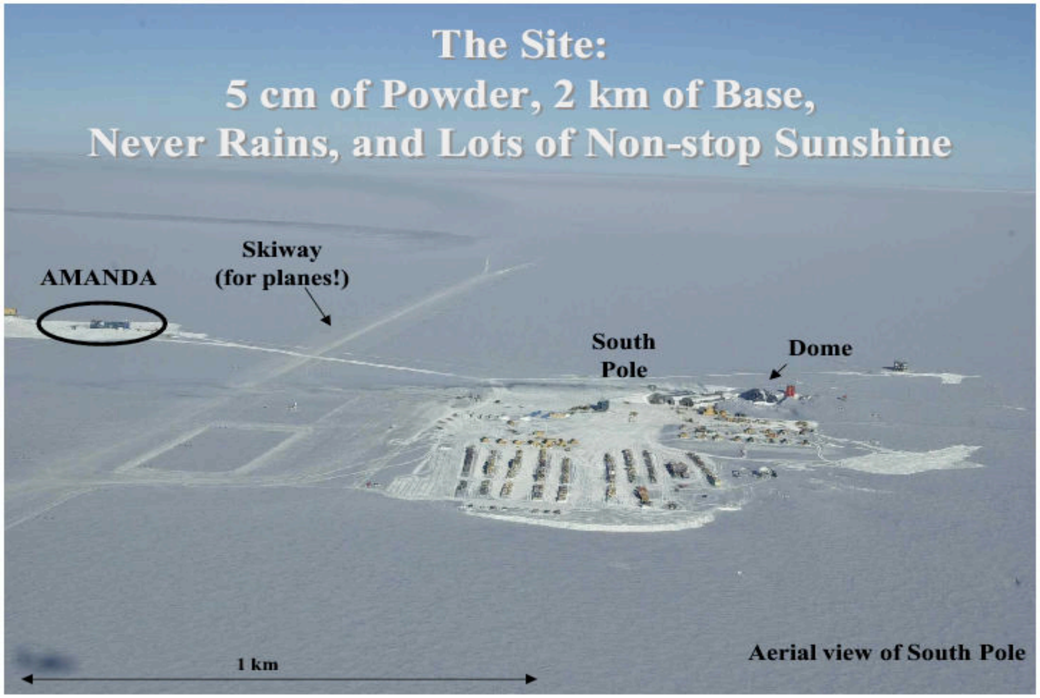
~ 5:1:1 ~ 0:1:1

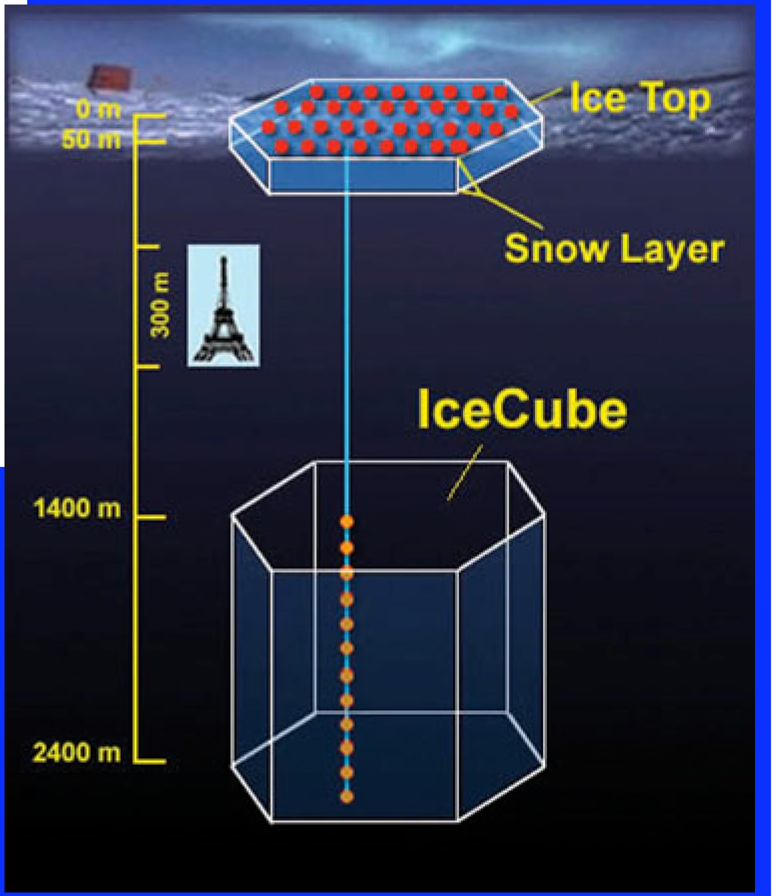


Possible direct measurement of CP phase δ too!

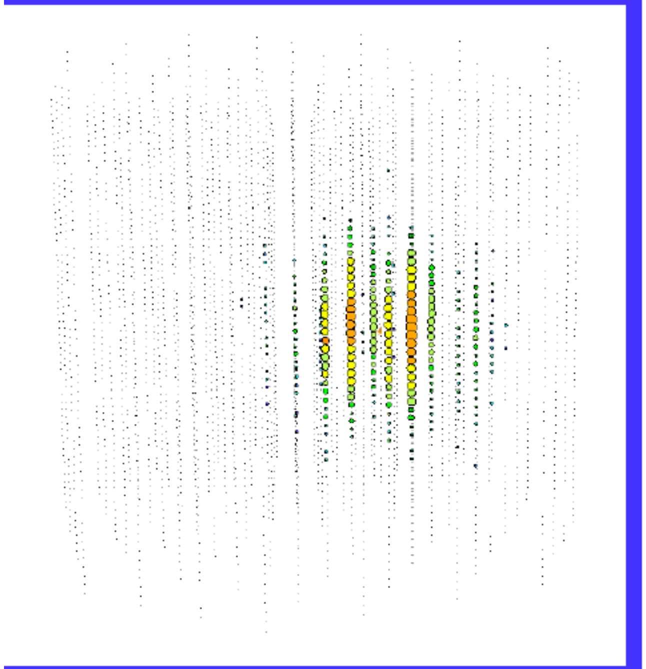
Beacom, Bell, Hooper, Pakvasa, Weiler, PRL 90, 181301 (2003);
Beacom, Bell, Hooper, Pakvasa, Weiler, hep-ph/0309267

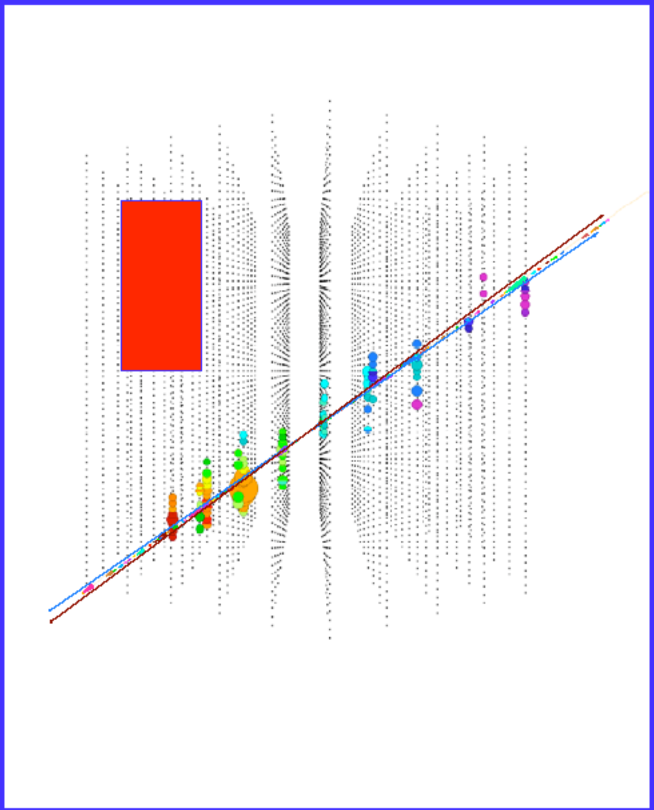
ICECUBE

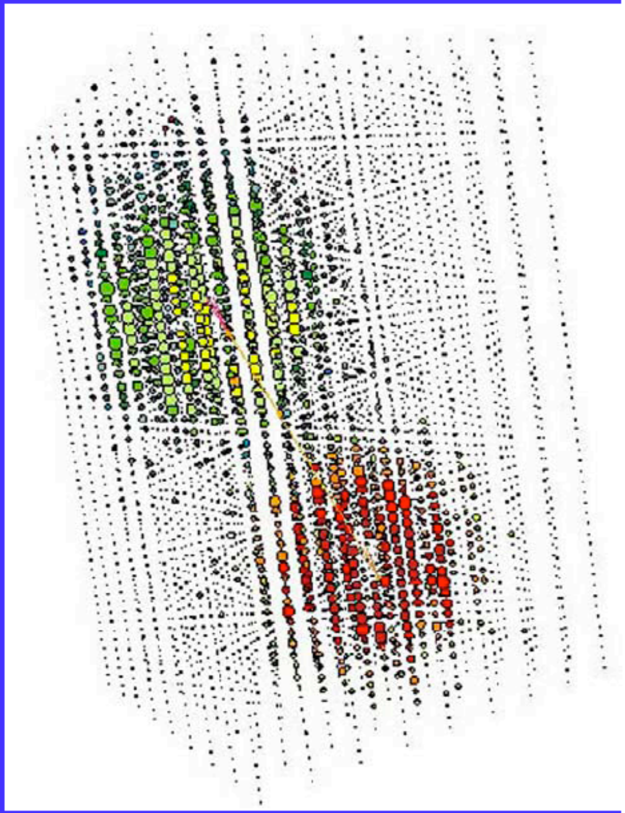

The Site:
5 cm of Powder, 2 km of Base,
Never Rains, and Lots of Non-stop Sunshine
AMANDA
Skiway
(for planes!)
South
Pole
Dome
1 km
Aerial view of South Pole


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

Flavor Identification

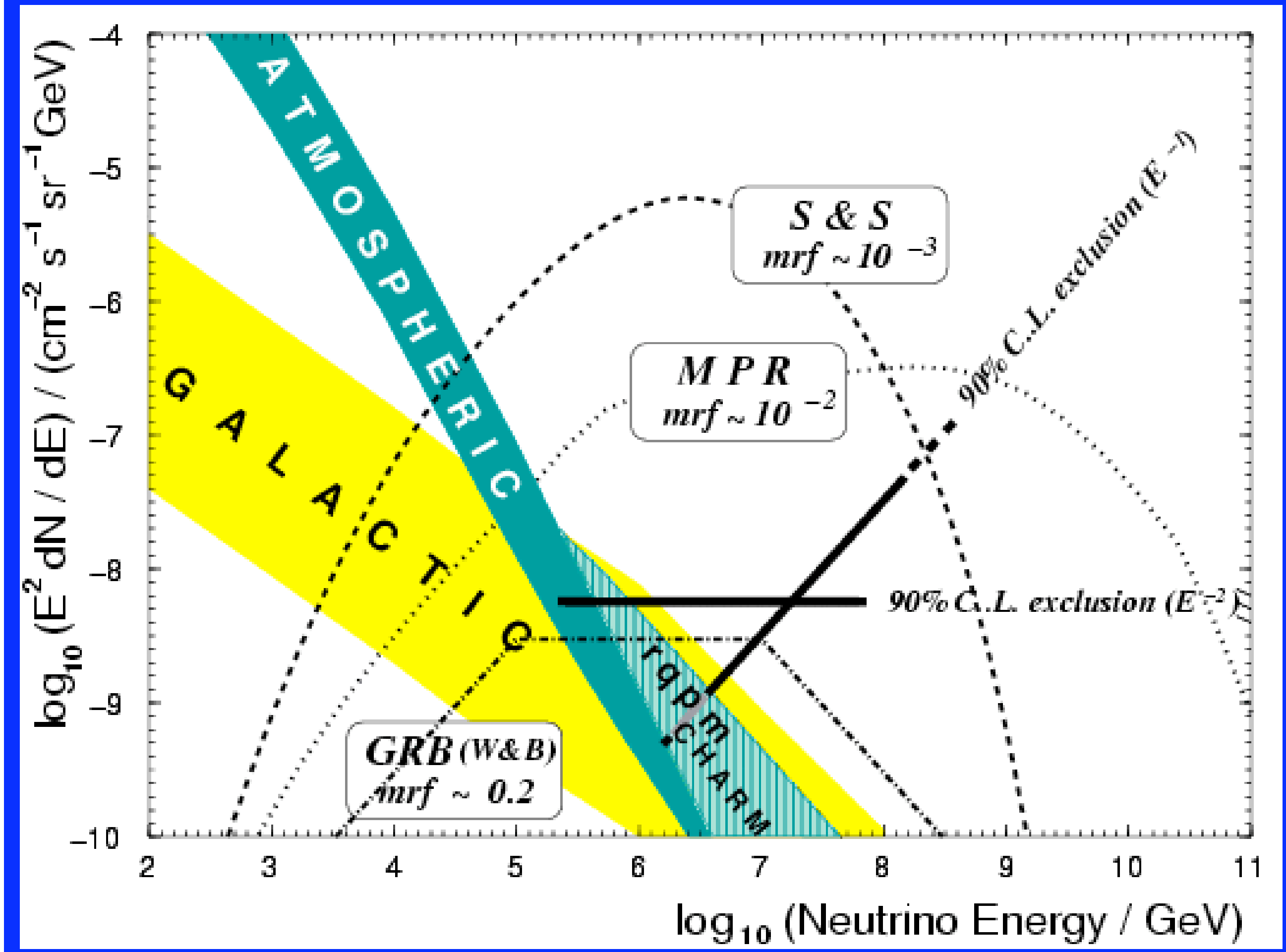






$\sim$100 TeV ν_e $\sim$10 TeV ν_μ $\sim$10 PeV ν_τ

IceCube (Diffuse) Sensitivity

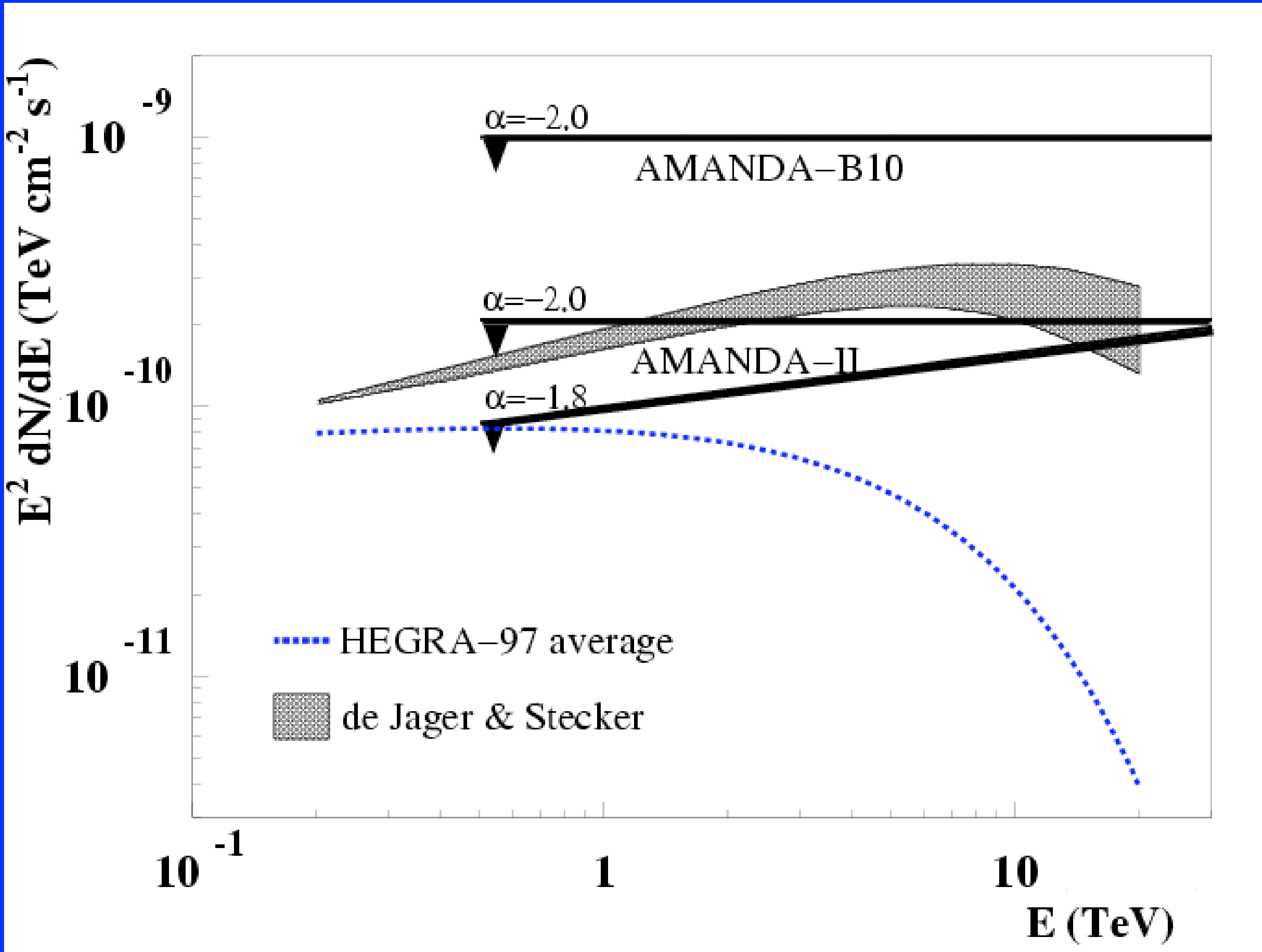


AMANDA-B10

AMANDA-II

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

Neutrino-Gamma Connection



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

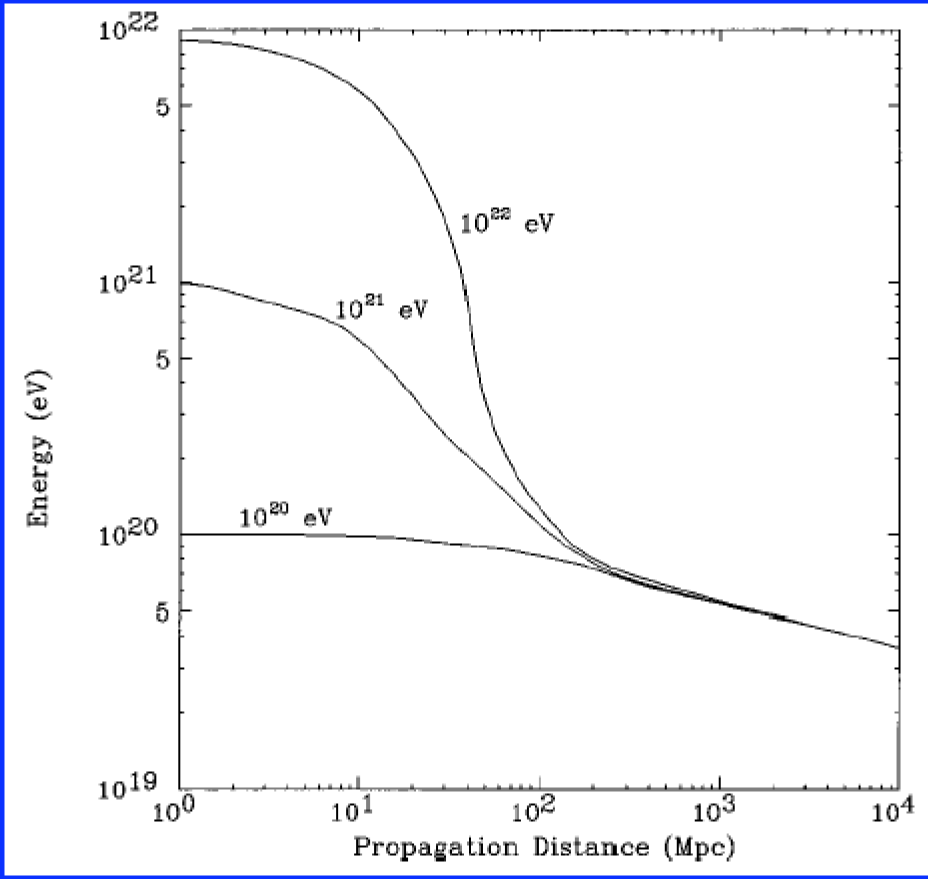
Astrophysical Neutrinos: Searching Very High

E ~ Mega-TeV

GZK Neutrinos

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

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

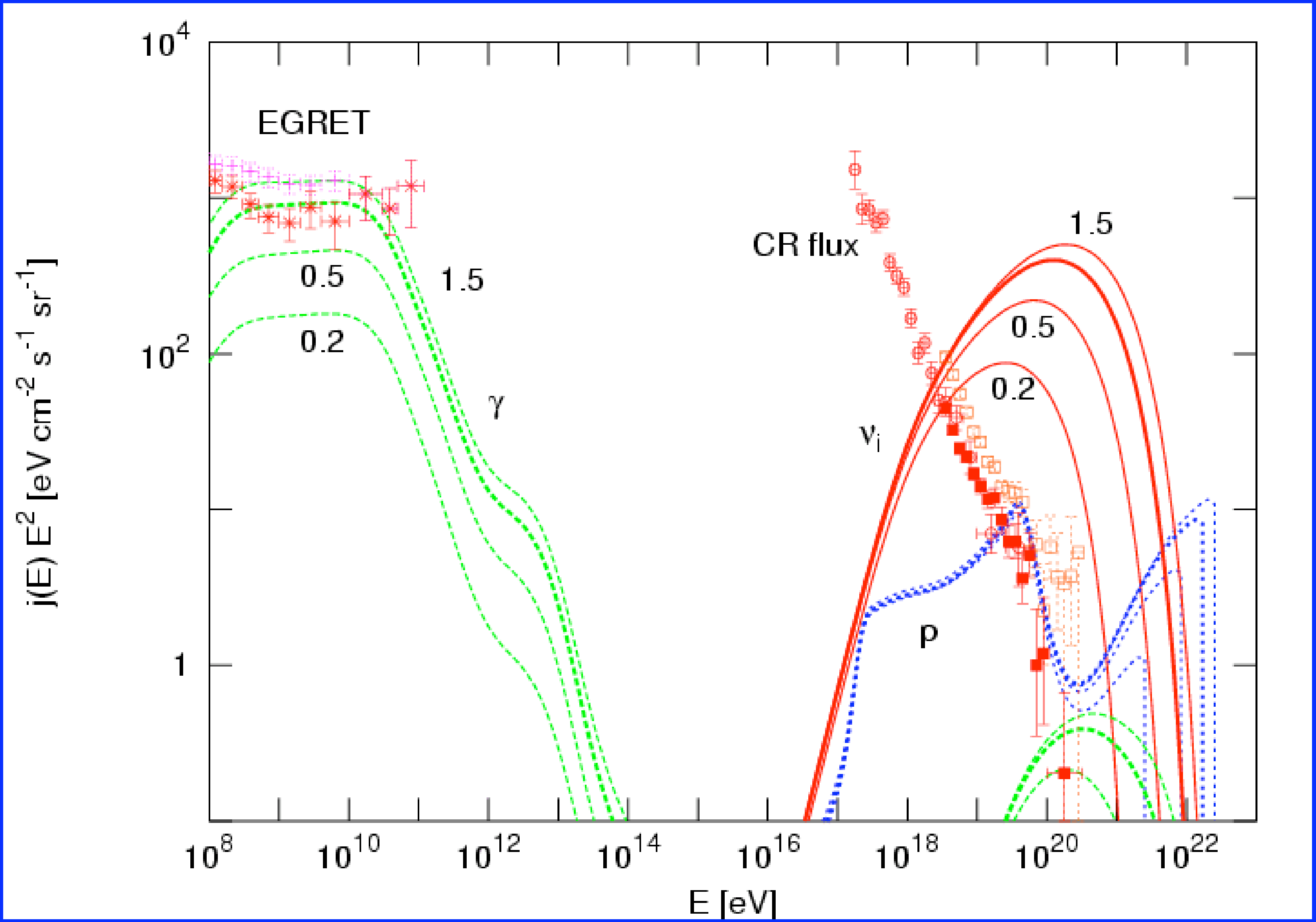


Connected observables:

- Protons
- Photons
- Neutrinos

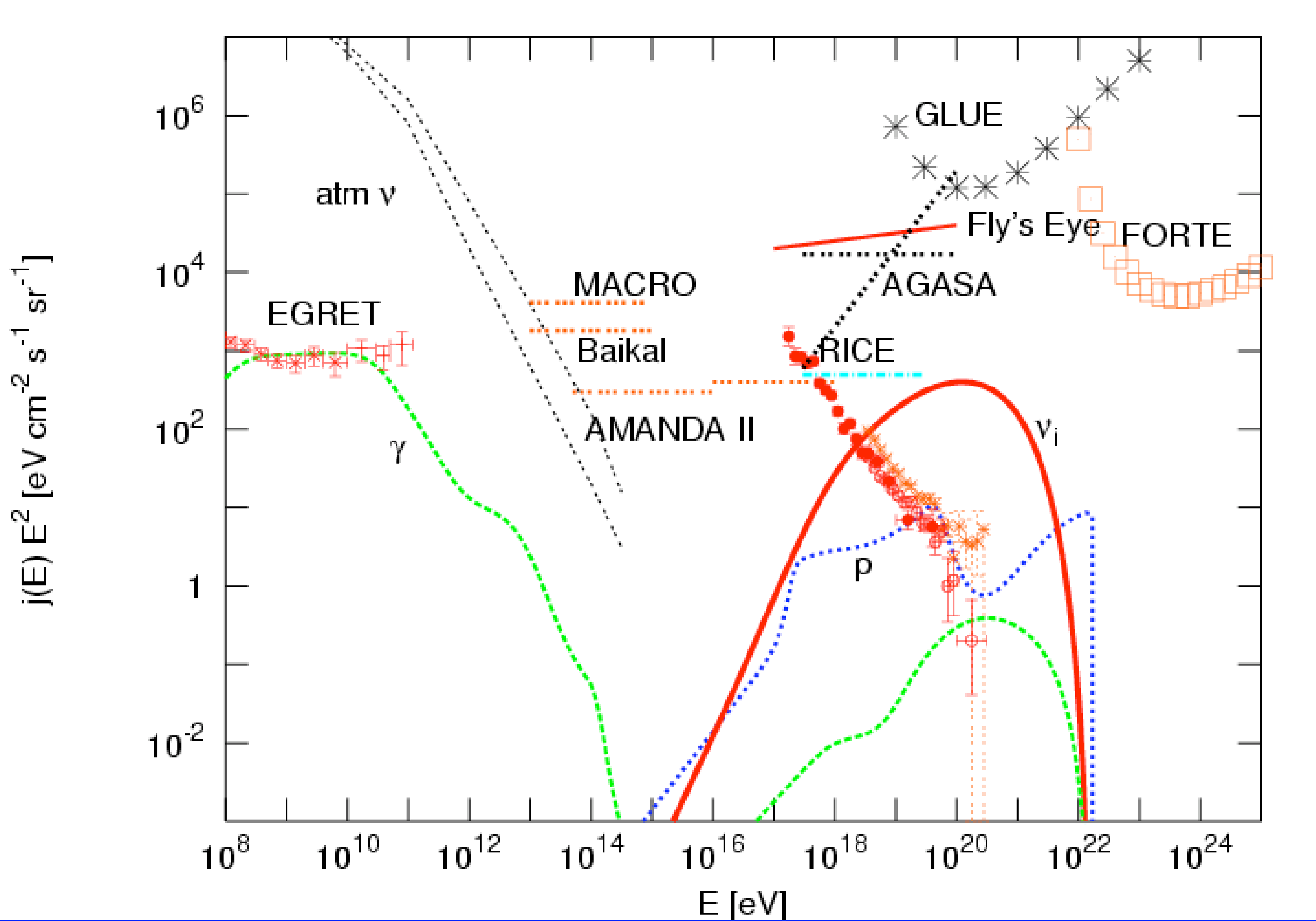
Cronin

Protons, Photons, and Neutrinos



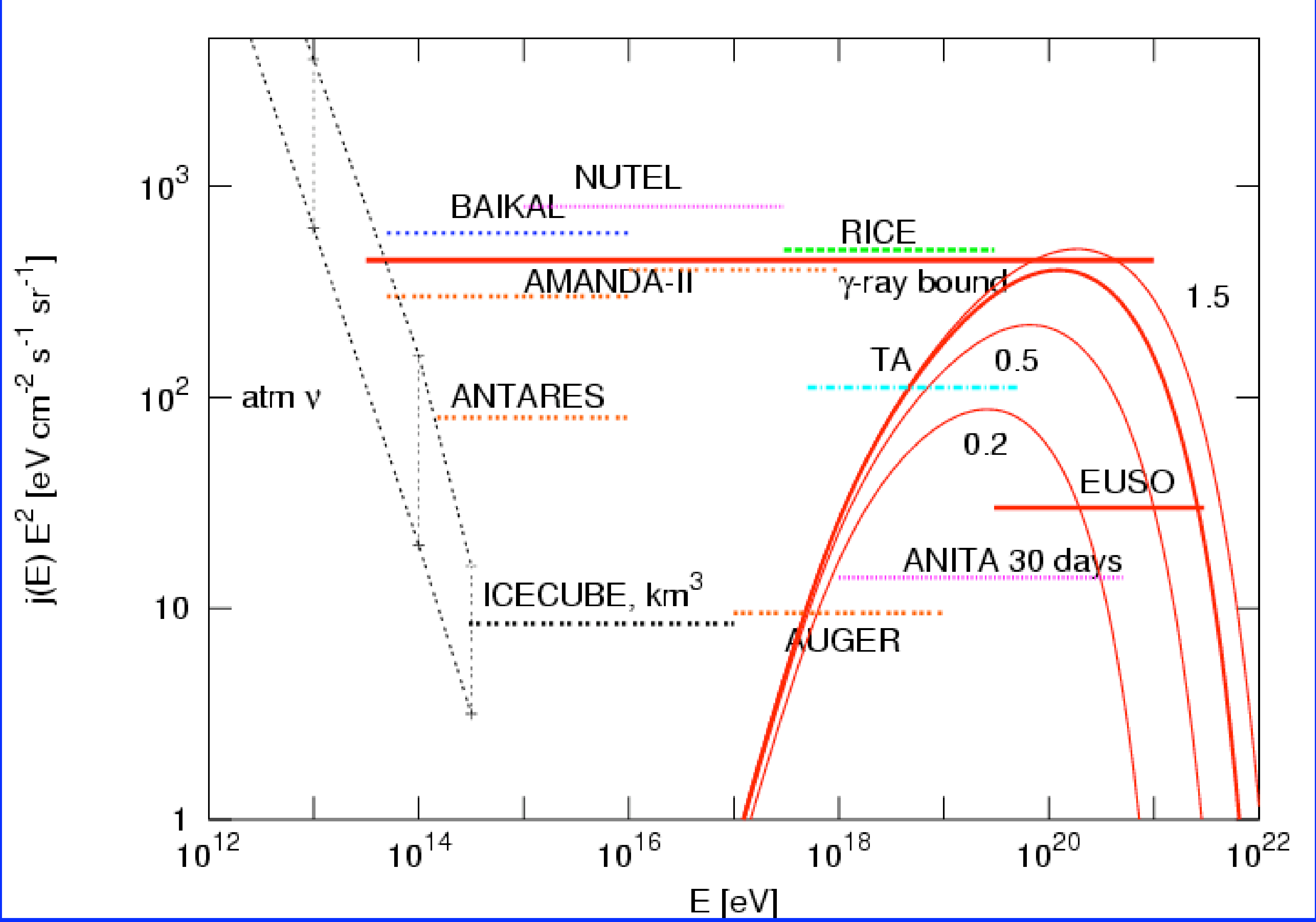
Semikoz, Sigl, hep-ph/0309328

Existing Neutrino Limits



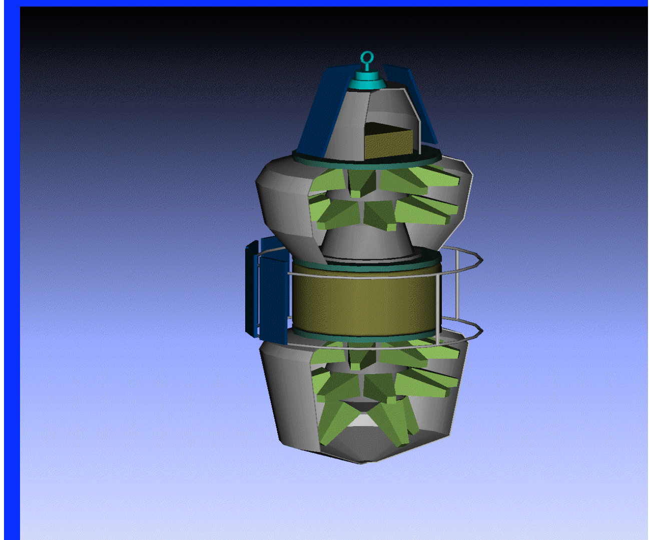
Semikoz, Sigl, hep-ph/0309328

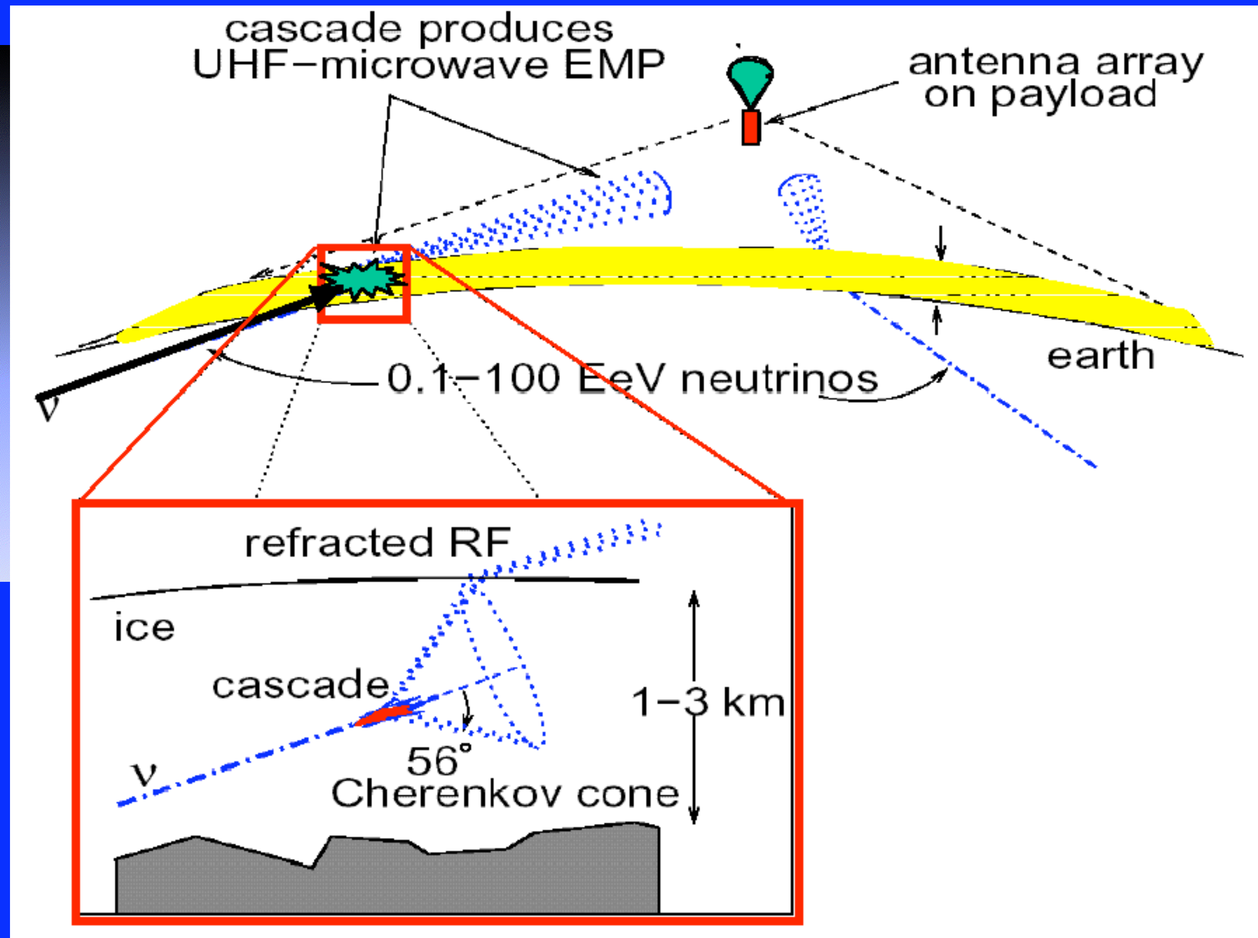
Future Neutrino Sensitivity



Semikoz, Sigl, hep-ph/0309328

ANITA



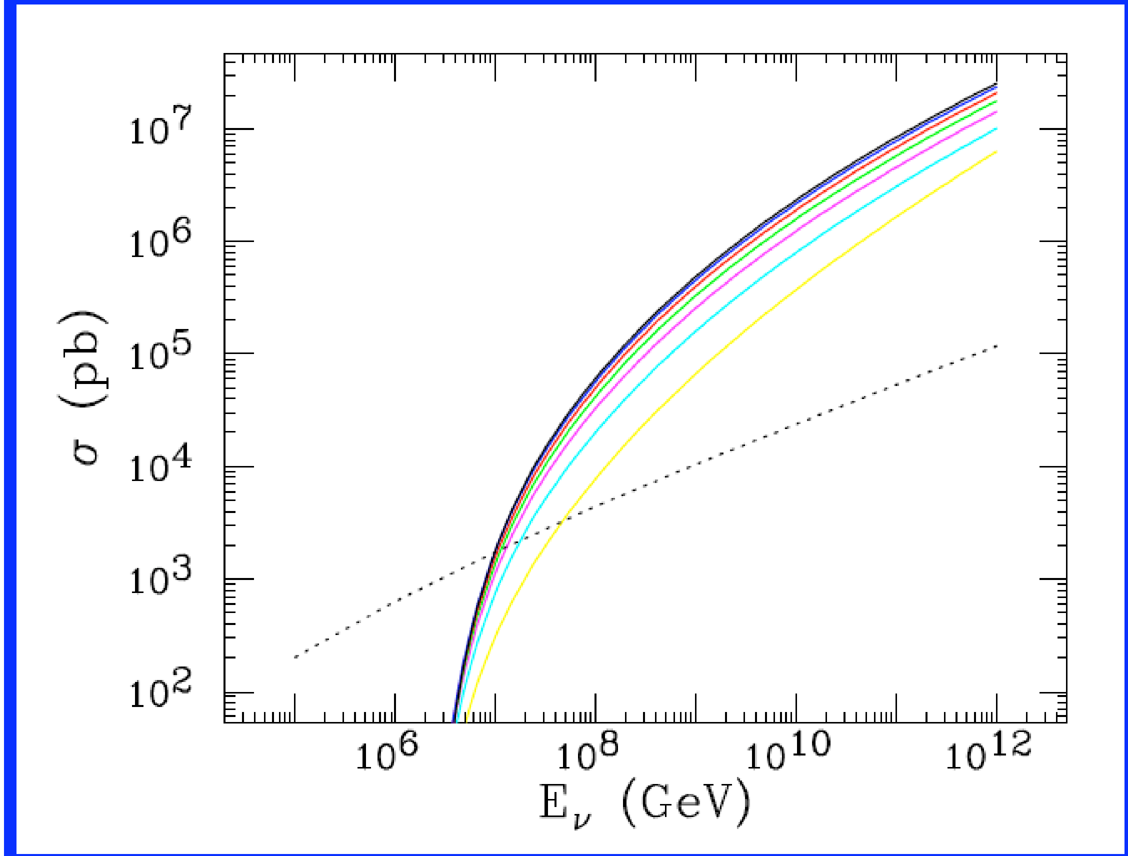


Funded 2003

Flies 2006

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

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)

Astrophysical Neutrinos: Searching Very Low

E ~ Micro-TeV (point sources)

Supernovae

SN1999dk, z = 0.015

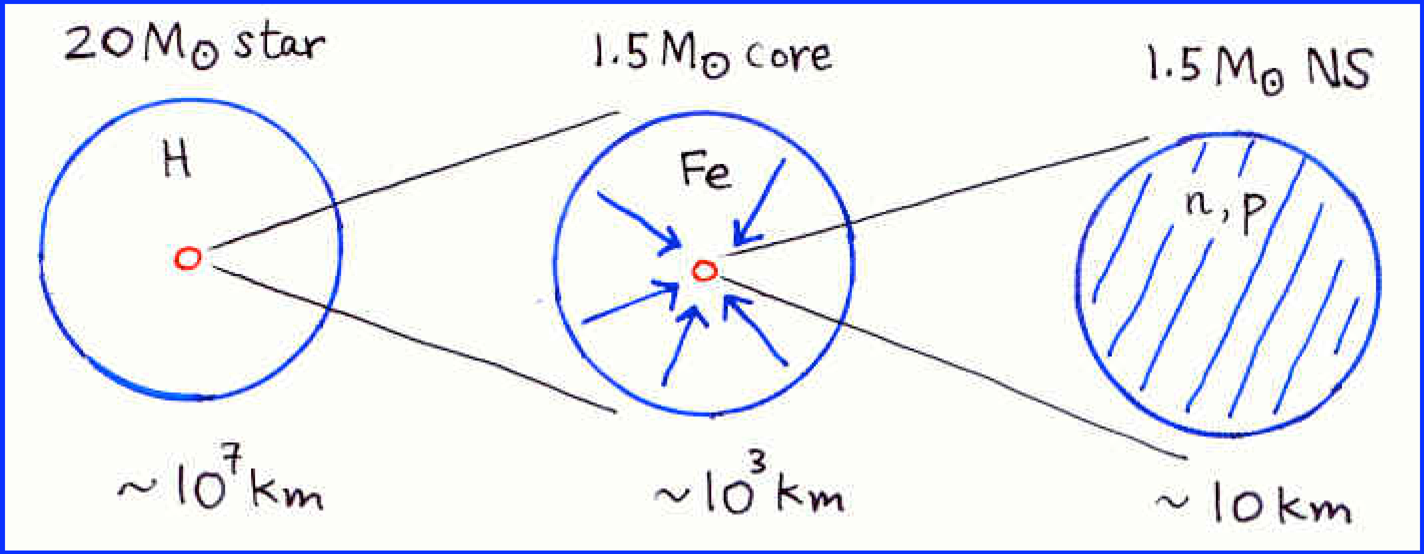
SN Types

SN Rates

SN Detection

Modeling (1d, 2d, 3d)

Supernova Energetics

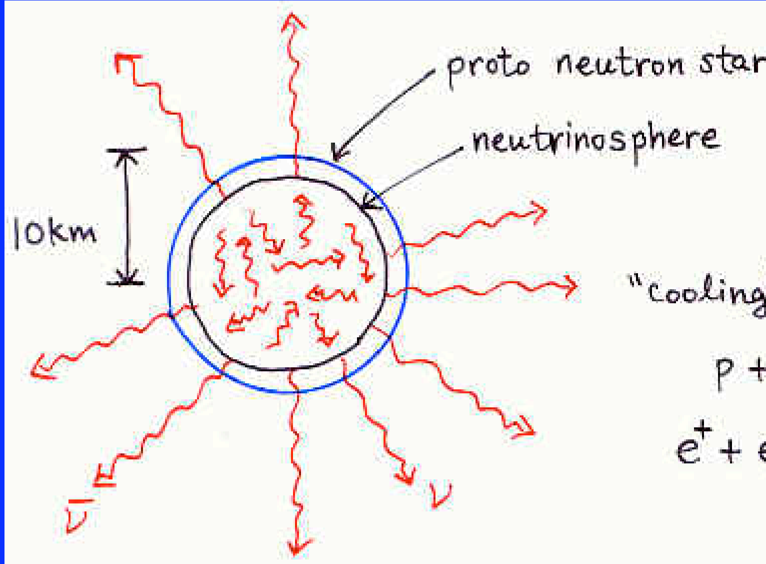


$$\Delta E_B \simeq \frac{3}{5}\frac{G M_{NS}^2}{R_{NS}} - \frac{3}{5}\frac{G M_{NS}^2}{R_{core}} \simeq 3\times 10^{53}\ \text{ergs} \simeq 2\times 10^{59}\ \text{MeV}$$

K.E. of explosion $\simeq 10^{-2}\,\Delta E_B$

E.M. radiation $\simeq 10^{-4}\,\Delta E_B$

Supernova Neutrino Emission



"cooling" by neutrino emission :

$$p + e^- \longrightarrow n + \nu_e$$

$$e^+ + e^- \longrightarrow \nu_e + \bar{\nu}_e,\ \nu_\mu + \bar{\nu}_\mu,\ \nu_\tau + \bar{\nu}_\tau$$

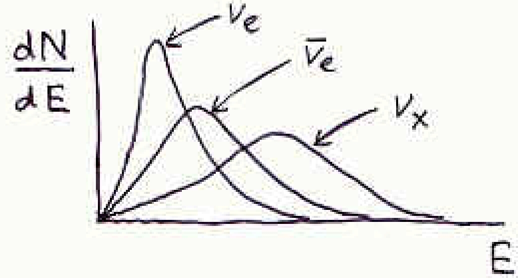
etc.

diffusion until $\lambda = 1/\rho\sigma$ from surface, then escape

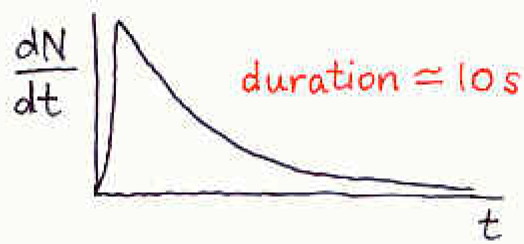
$\langle E_{\nu_e} \rangle \simeq 11$ MeV

$\langle E_{\bar{\nu}_e} \rangle \simeq 16$ MeV

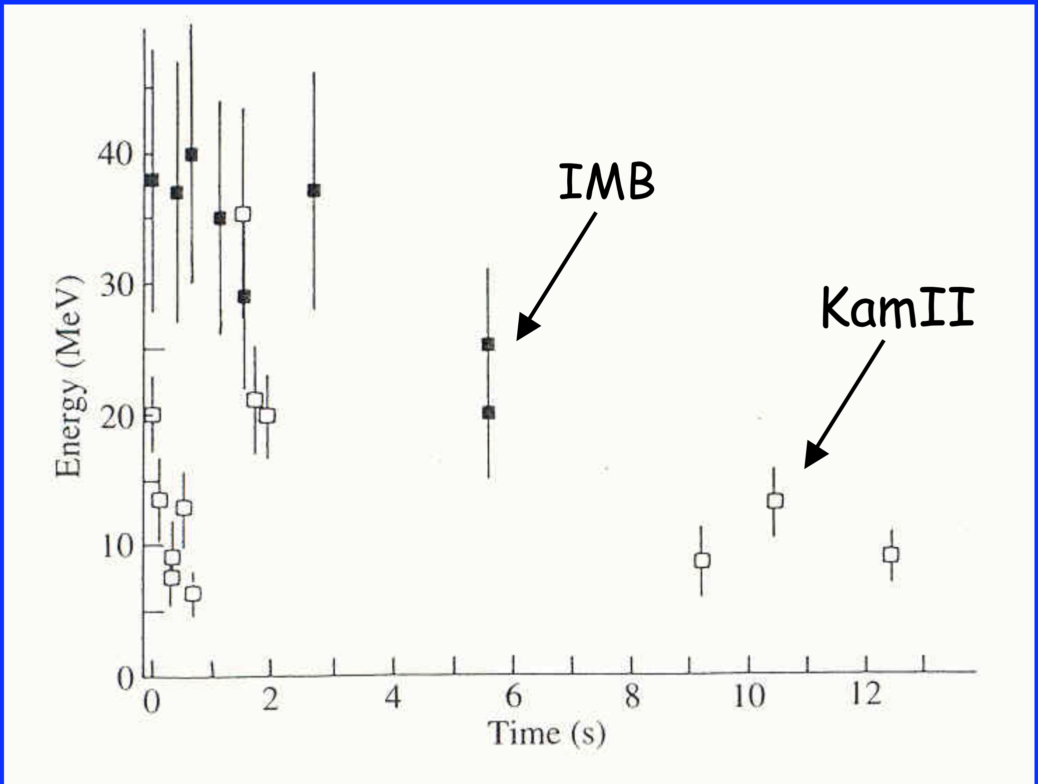
$\langle E_{\nu_x} \rangle \simeq 25$ MeV



$L_{\nu_e}(t) \simeq L_{\bar{\nu}_e}(t) \simeq L_{\nu_x}(t)$



Supernova Neutrino Detection



SN1987A :

$\sim 20\ \ \bar{\nu}_e p \rightarrow e^+ n$ events

SN200?? :

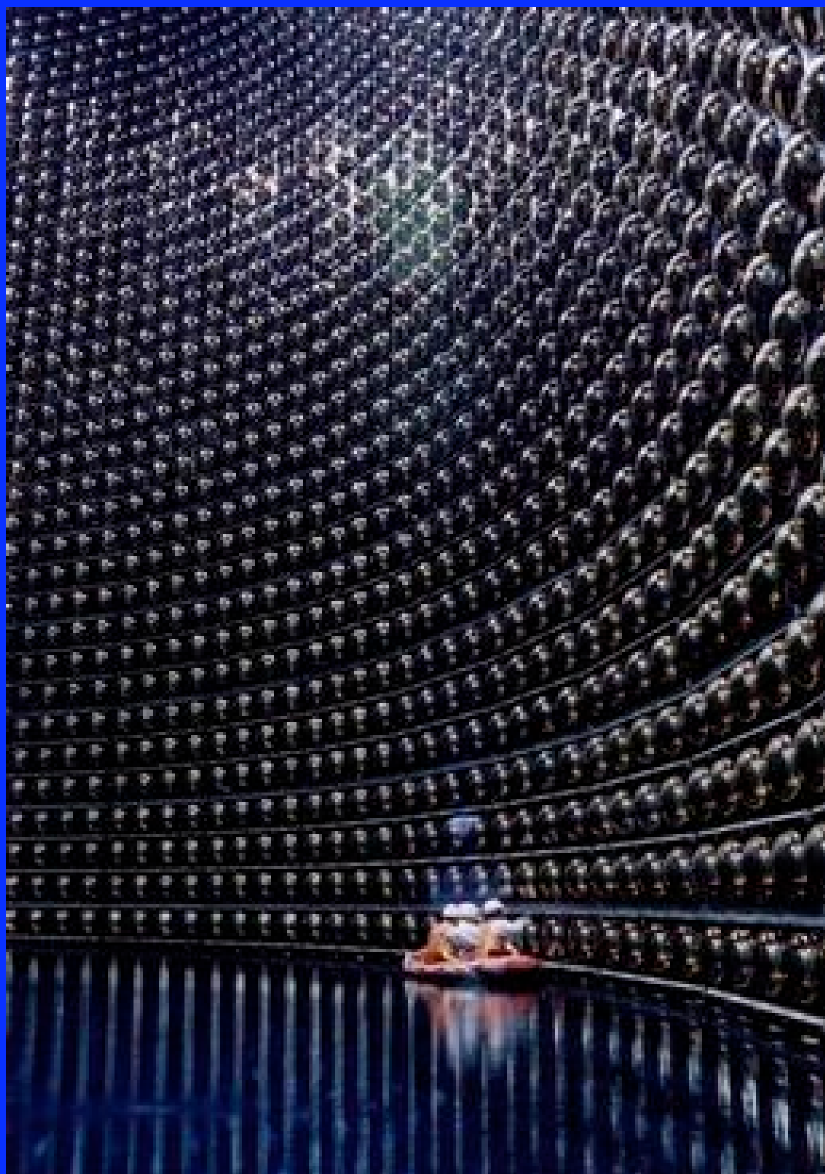
$\sim 10^4$ *CC* events

$\sim 10^3$ NC events

Supernova physics (models, black holes, progenitors…)

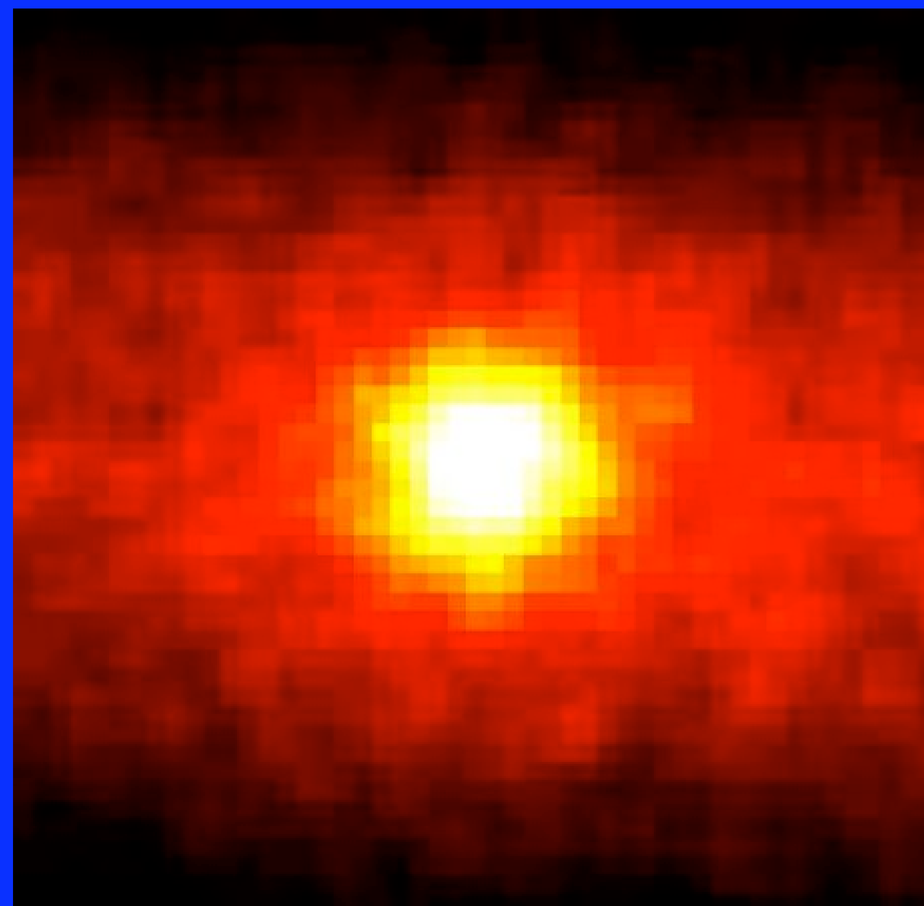
Particle physics (neutrino properties, new particles, …)

Super-Kamiokande

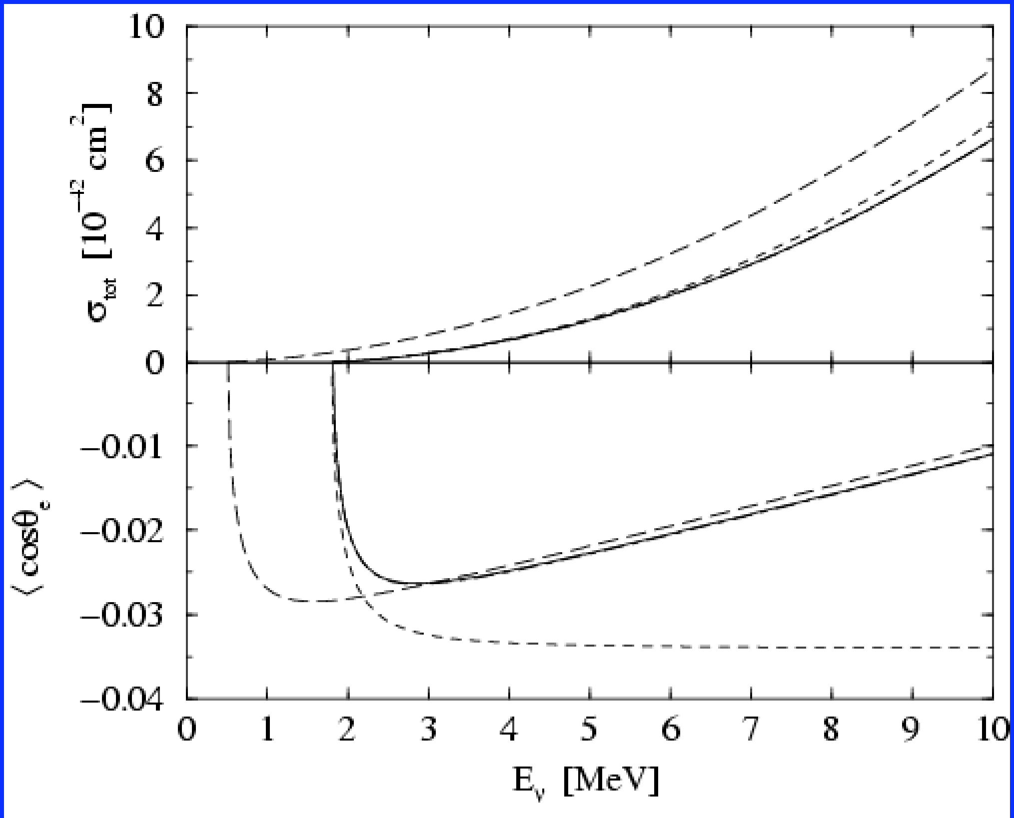


e^-, e^+, γ

convert to Cerenkov light



Inverse Beta Cross Section



$$\sigma^{(0)} = \frac{2\pi^2 / m_e^5}{f^R \tau_n} E_e^{(0)} p_e^{(0)}$$

$$E_e^{(0)} = E_\nu - (M_n - M_p)$$

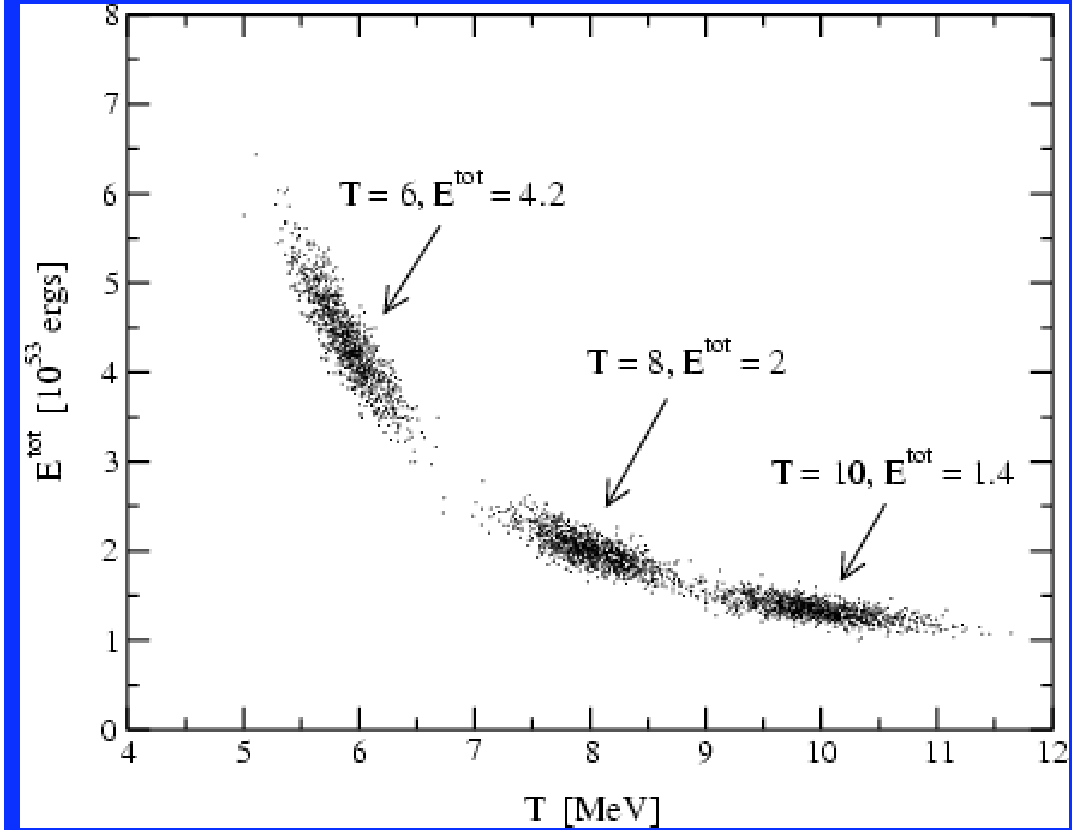
Corrections of order $1/M_p$ are very important

Vogel and Beacom, PRD 60, 053003 (1999)

Supernova NC Bolometry

For CC $\bar{\nu}_e + p \to e^+ + n$: $\quad N_e \sim E^{tot}_{\bar{\nu}_e} T_{\bar{\nu}_e} \quad \langle E_e \rangle \sim T_{\bar{\nu}_e}$

For NC $\nu + d \to \nu + p + n$: $\quad N \sim E^{tot}_{\nu} T_{\nu}$ only



A new idea:

$\nu + p \to \nu + p$

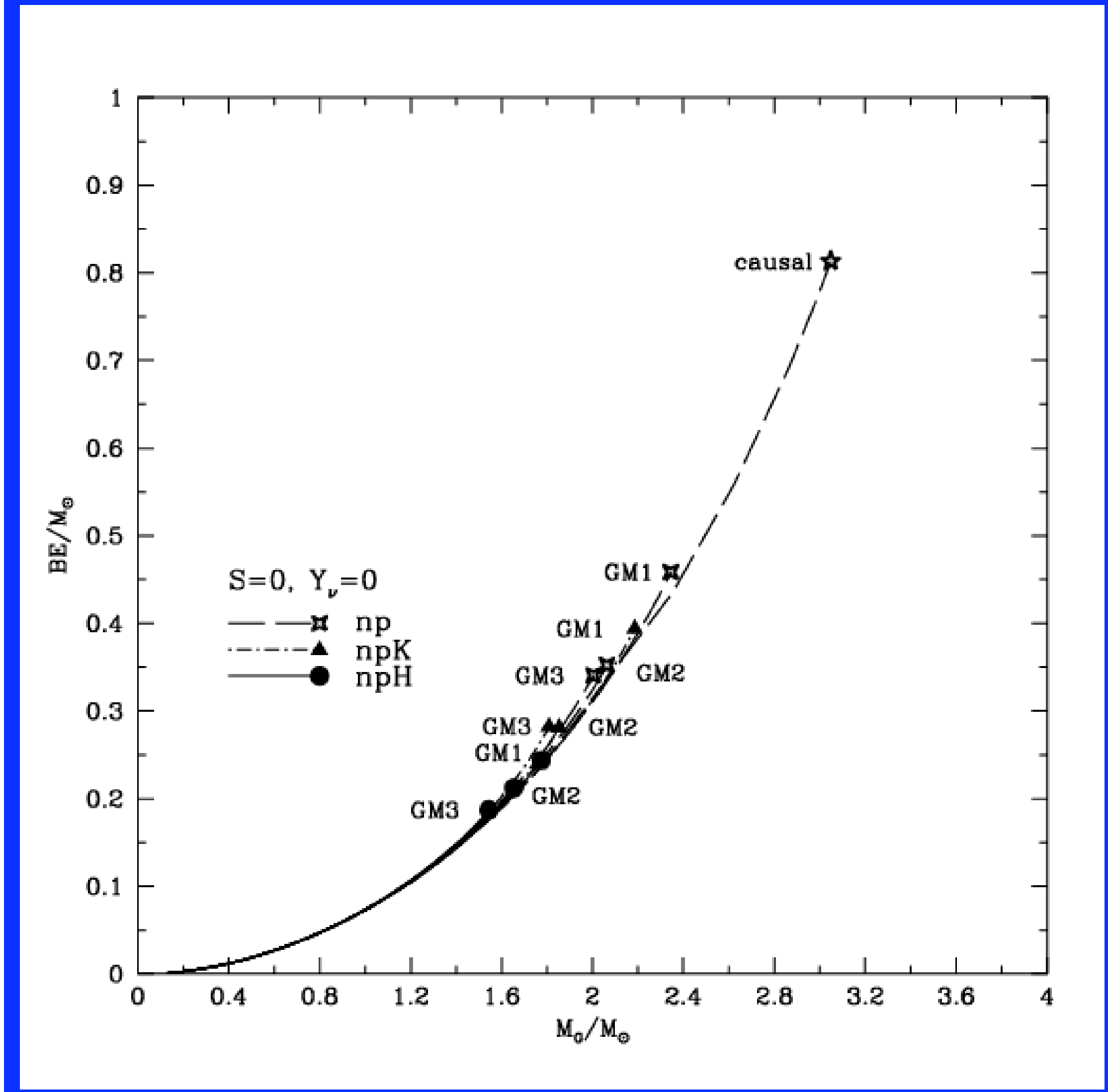
in KamLAND, Borexino

N ~ 300 above threshold

$\delta E^{tot}, \delta T \simeq 5\%$

Beacom, Farr, and Vogel, PRD 66, 033001 (2002)

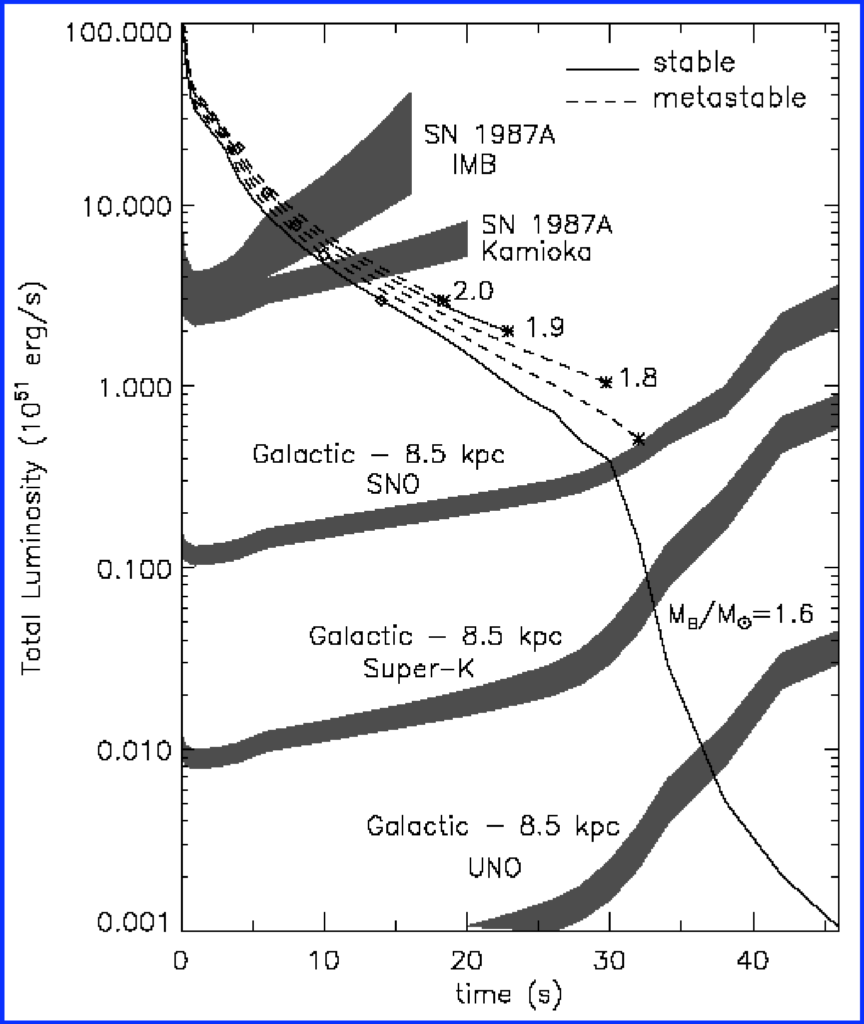
Neutron Star Mass Measurement

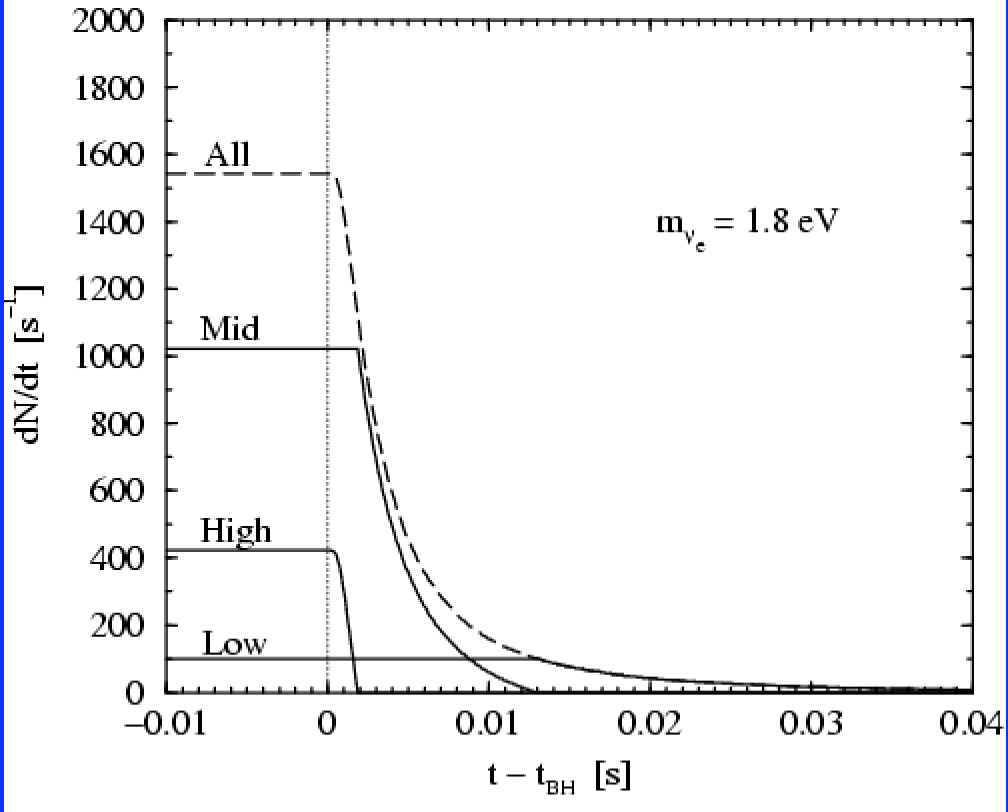


$$\Delta E_B \simeq \frac{3}{5} \frac{G M_{NS}^2}{R_{NS}}$$

Prakash and Lattimer, Phys. Rept. 280, 1 (1997)

Black Hole Formation

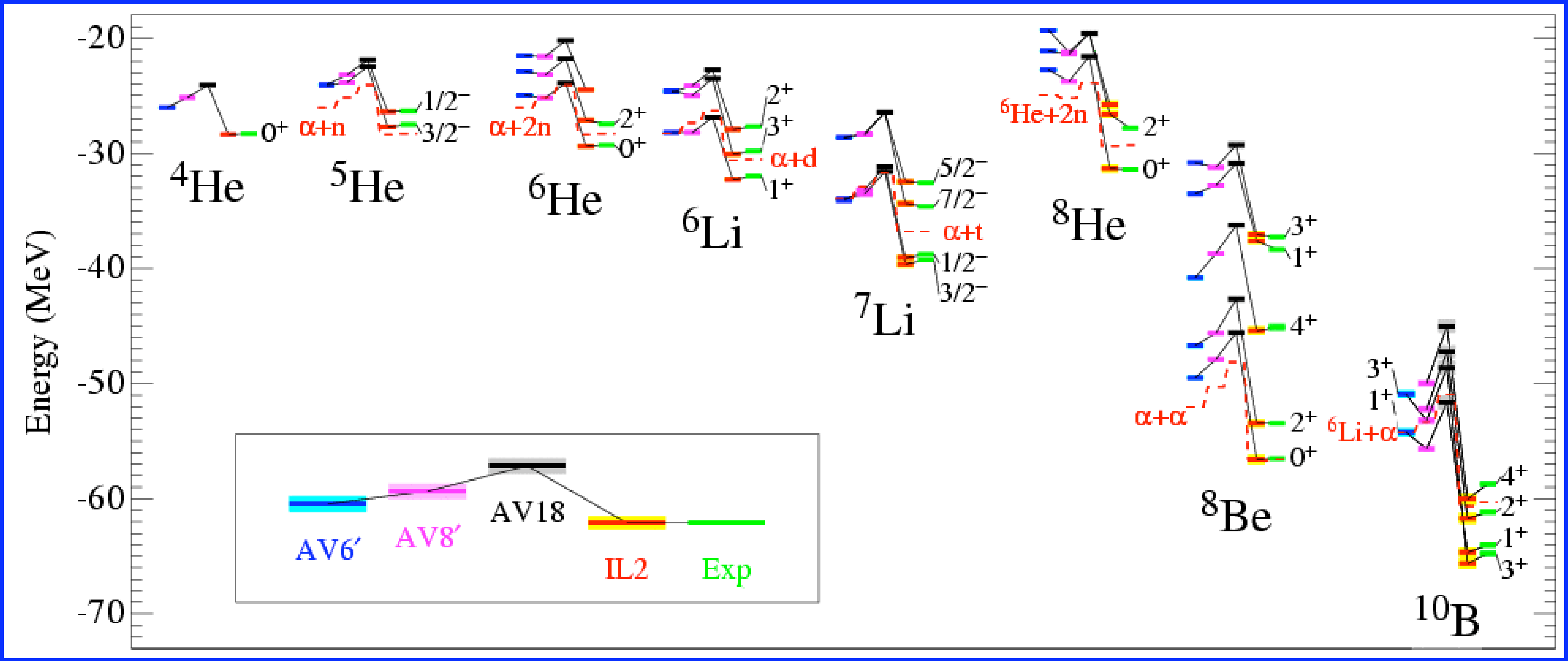




Beacom, Boyd, and Mezzacappa, PRL 85, 3568 (2000)

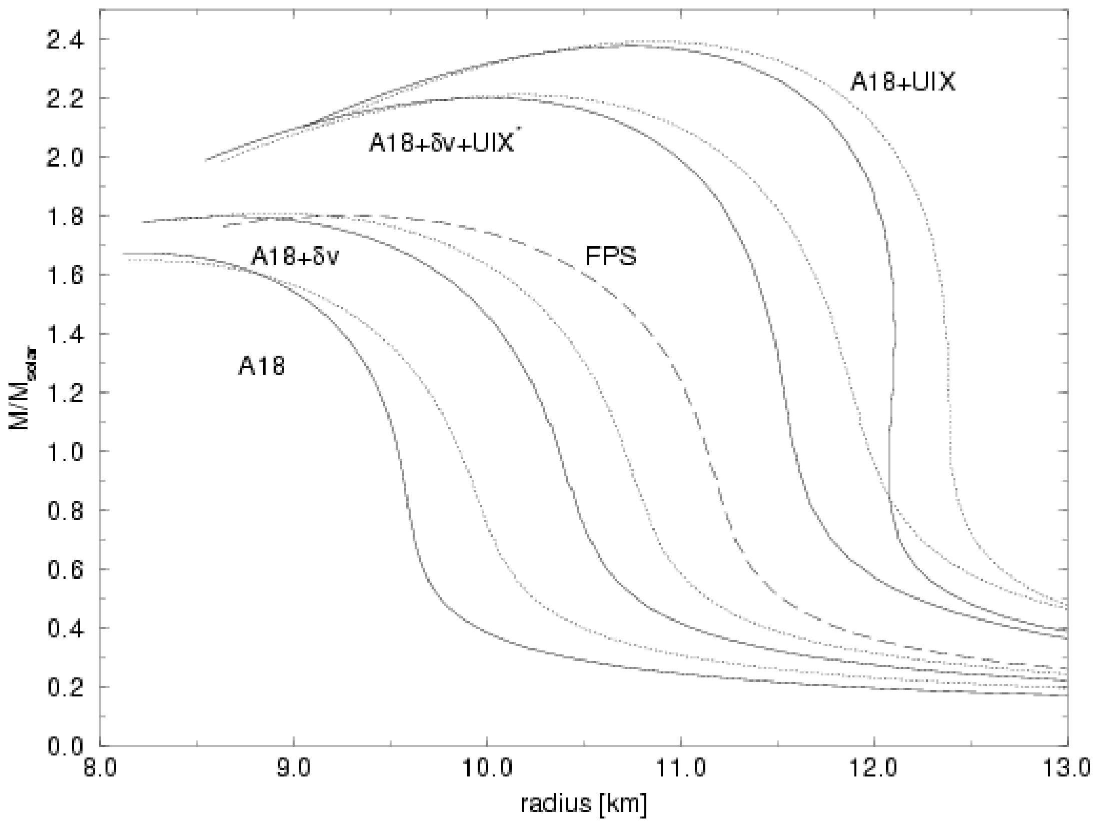
Pons et al., PRL 86, 5223 (2001)

EOS and Nuclear Forces



Wiringa and Pieper, PRL 89, 182501 (2002)

EOS and Neutron Stars



Akmal, Pandharipande, and Ravenhall, PRC 58, 1804 (1998)

Astrophysical Neutrinos:
Searching Very Low

E ~ Micro-TeV
(diffuse background)

Waiting Is Boring

"Everybody complains about the supernova rate, but nobody does anything about it."

Supernova Neutrino Background

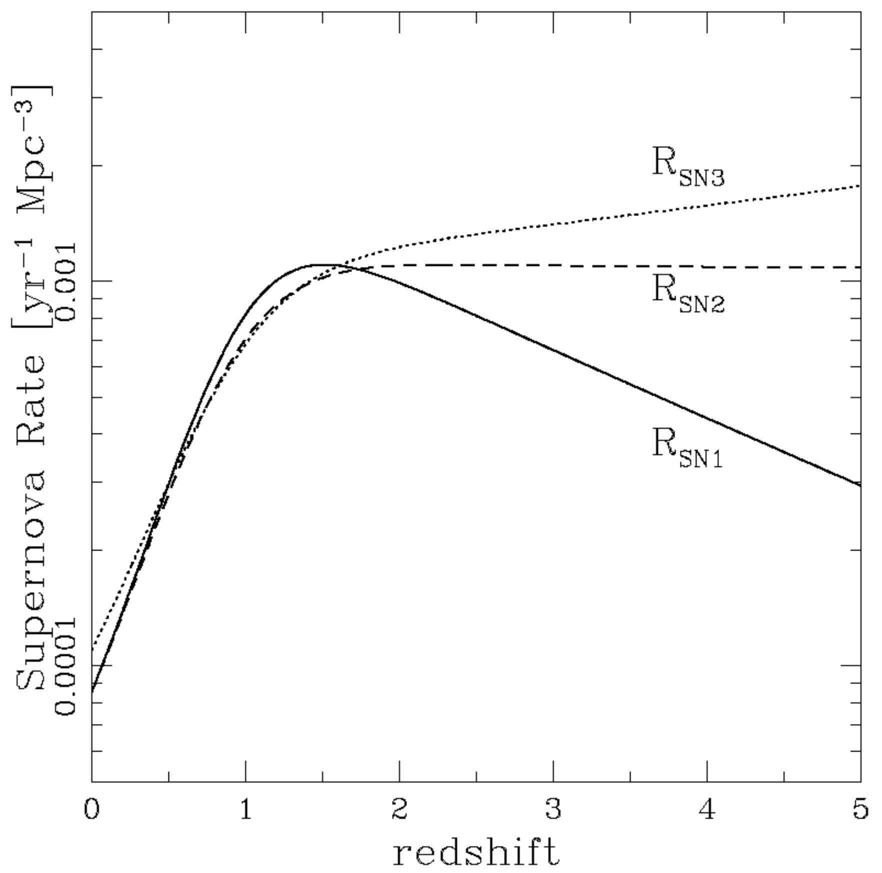


Fig. 2. Supernova rate evolution on the cosmological time scale. These lines are for a Λ-dominated cosmology ($\Omega_m = 0.3, \Omega_\lambda = 0.7$). The Hubble constant is taken to be 70 km s^{-1} Mpc^{-1}.

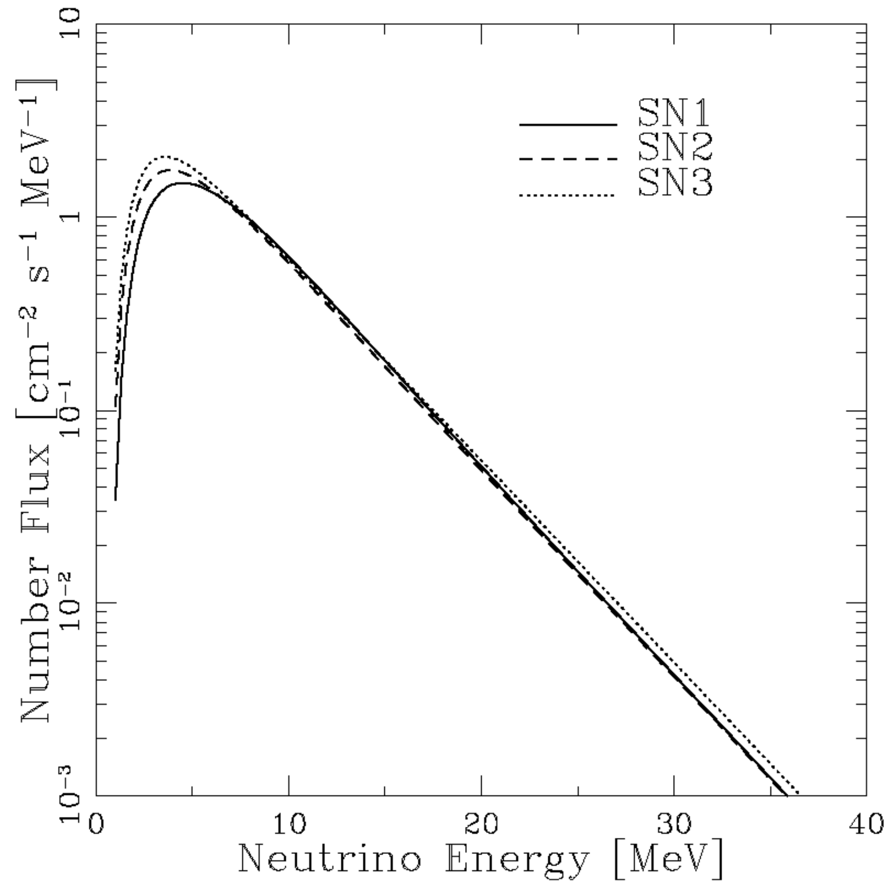
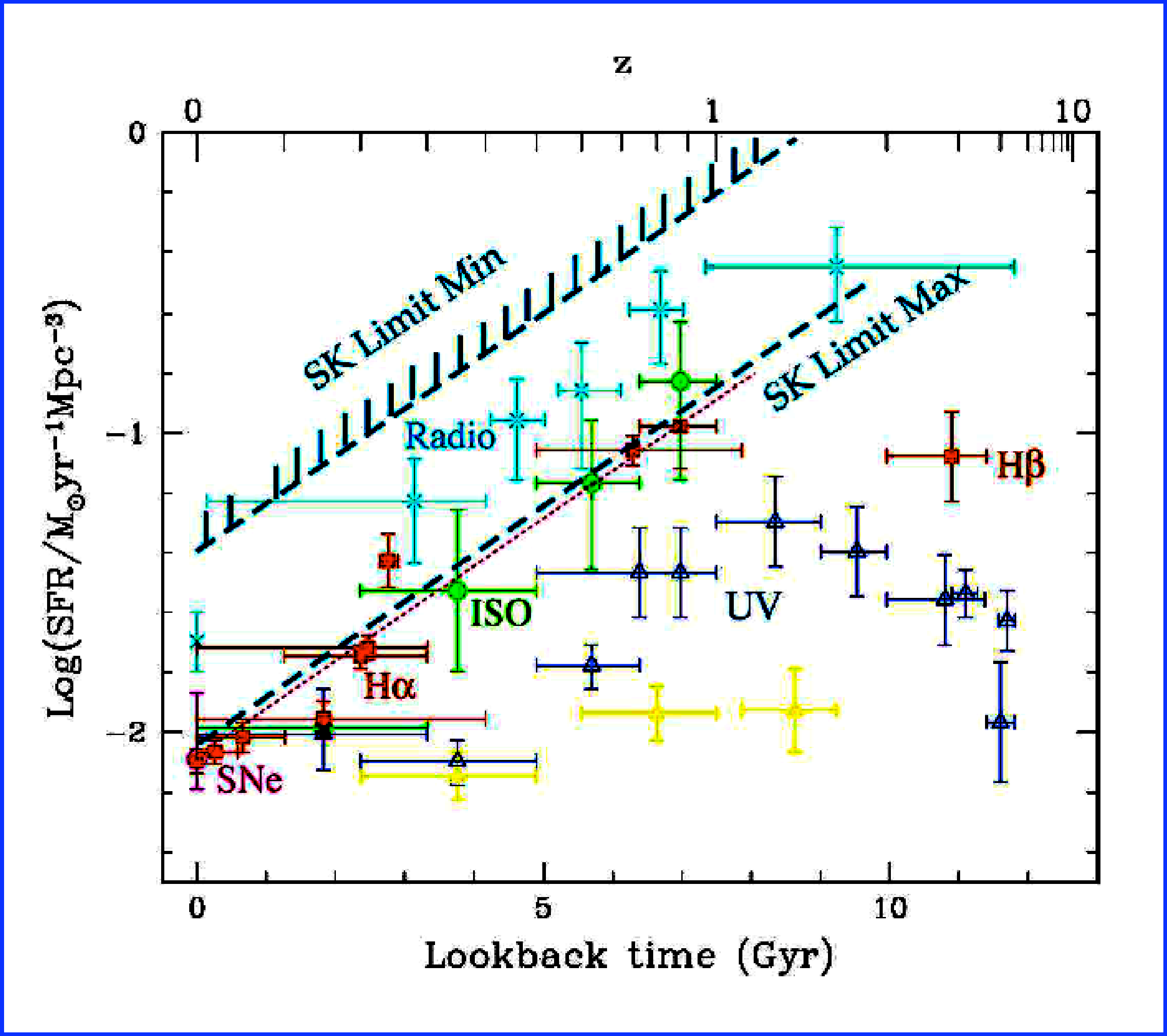


Fig. 3. Number flux of $\bar{\nu}_e$'s for the three supernova rate models, assuming "no oscillation" case.

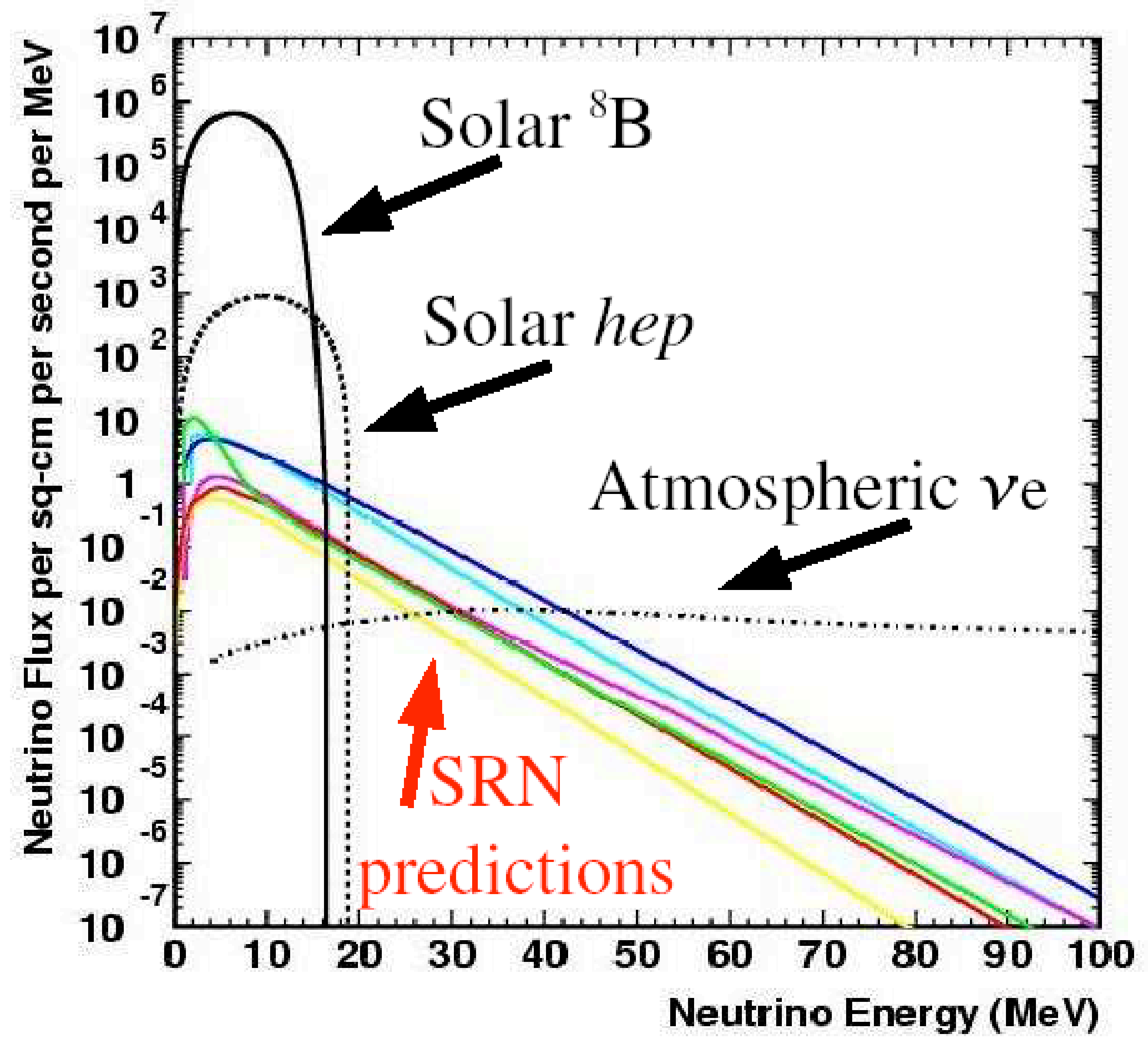
Ando, Sato, and Totani, Astropart. Phys. 18, 307 (2003)

Star Formation Rate Constraints (?)



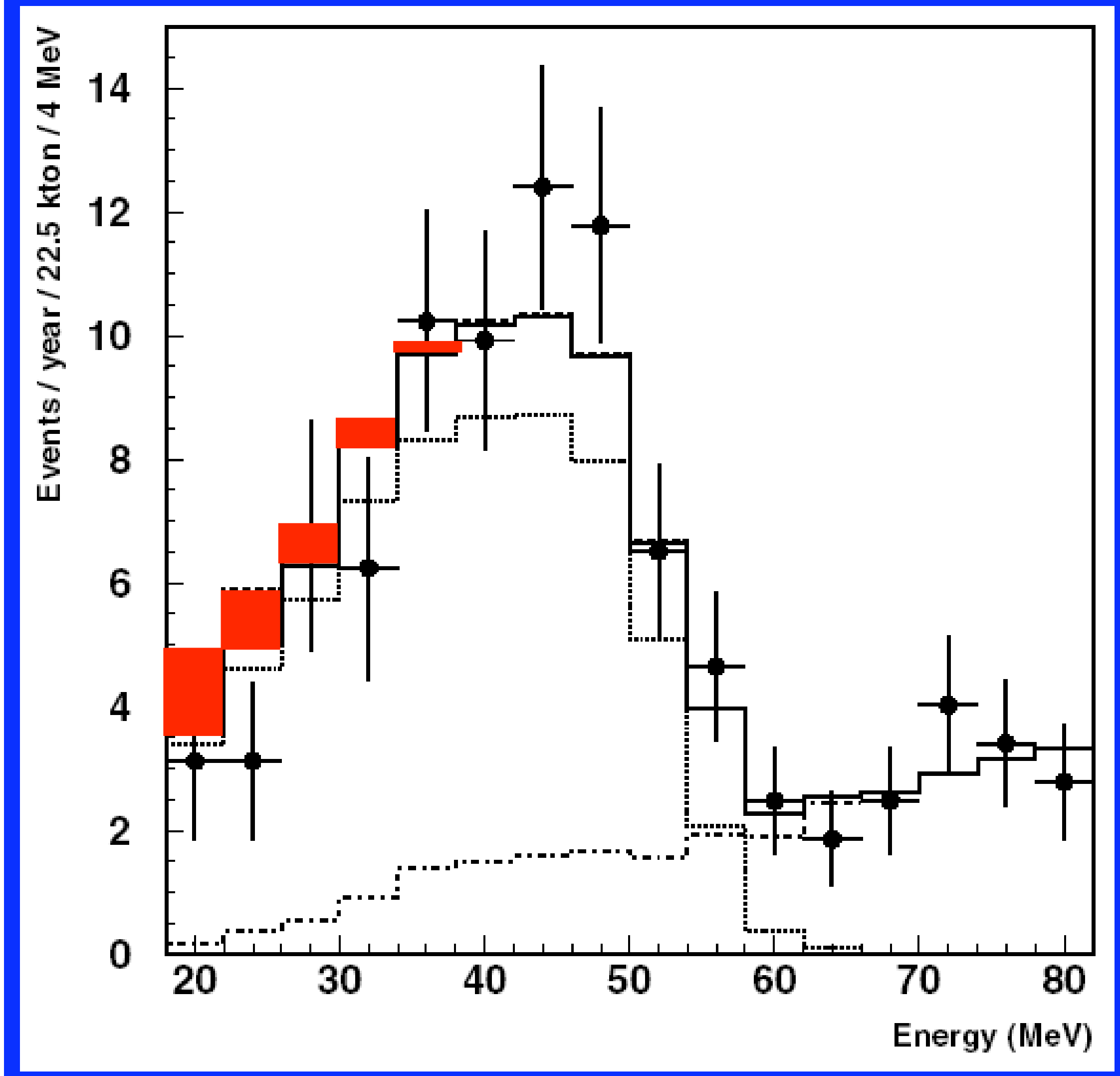
Fukugita and Kawasaki, MNRAS 340, L7 (2003)

Relative Spectra



(M. Malek)

SK Data Limit



- 4.1 years of SK data
- Background limited
- Some improvement is possible

Malek et al. (SK), PRL 90, 061101 (2003)

SNB Flux Limit

- Predictions roughly agree on spectrum shape

- Main question is normalization of

$$\bar{\nu}_e / cm^2 / s, \quad E_\nu > 19.3 \text{ MeV}$$

2.2	Kaplinghat, Steigman, Walker, PRD 62, 043001 (2000)
< 1.2	Malek et al. (SK), PRL 90, 061101 (2003)
0.4	Fukugita and Kawasaki, MNRAS 340, L7 (2003)
0.4	Ando, Sato, and Totani, Astropart. Phys. 18, 307 (2003)

- Last two based on multiwavelength measurements of the star formation rate as a function of redshift

Inverse Beta Decay

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

- Cross section is “large” and “spectral”

$$\sigma \simeq 0.095(E_\nu - 1.3\,\mathrm{MeV})^2\, 10^{-42}\,\mathrm{cm}^2$$

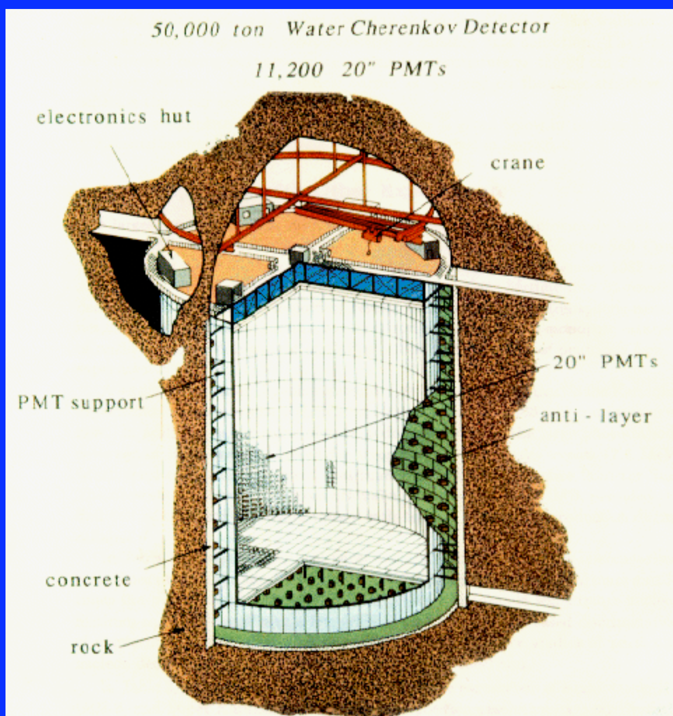
$$E_e \simeq E_\nu - 1.3\,\mathrm{MeV}$$

Corrections in Vogel and Beacom, PRD 60, 053003 (1999)

- We must detect the neutron, but how?

Add Gadolinium to SK?

GADZOOKS!



Gadolinium
Antineutrino
Detector
Zealously
Outperforming
Old
Kamiokande,
Super!

Beacom and Vagins, hep-ph/0309300

Neutron Capture

Capture on H: sigma = 0.3 barns

E_{gamma} = 2.2 MeV

Capture on Gd: sigma = 49100 barns

E_{gamma} = 8 MeV

(Equivalent E_e ~ 5 MeV)

$$\frac{1}{\lambda_{total}} = \frac{1}{\lambda_H} + \frac{1}{\lambda_{Gd}} = n_H \sigma_H + n_{Gd} \sigma_{Gd}$$

At 0.2% $GdCl_3$:

Capture fraction = 90%

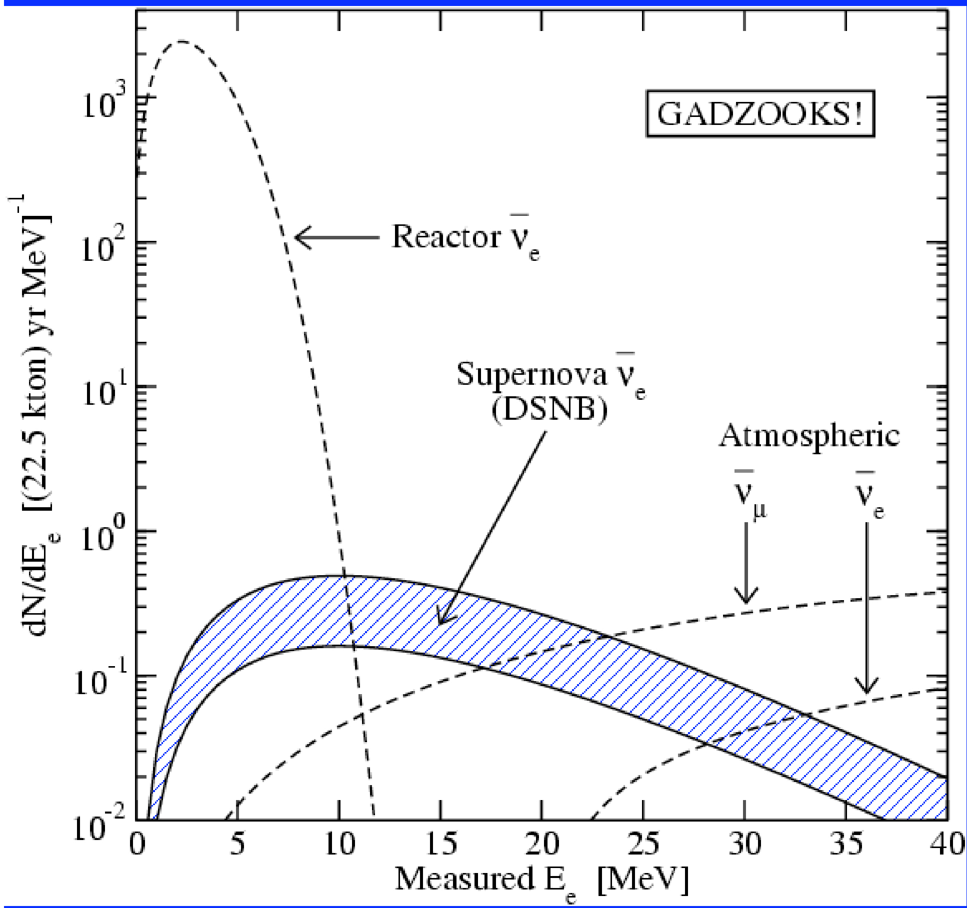
$\lambda = 4\,\mathrm{cm}, \tau = 20\ \mu\mathrm{s}$

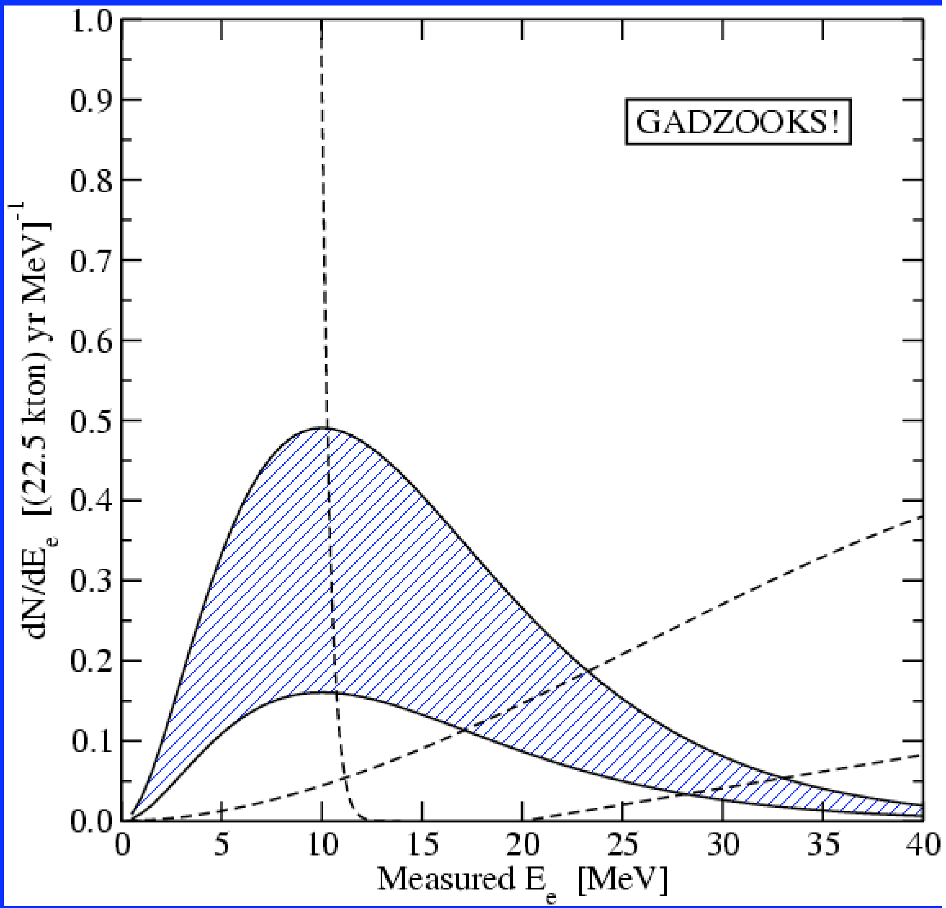
Cost of Gd

Based on 100 tons of $GdCl_3$ in SK (0.2% by mass)

1984:	$4,000/kg	$400,000,000/SK
1993:	$485/kg	$48,500,000/SK
1999:	$115/kg	$11,500,000/SK
2002:	$3/kg	$300,000/SK

Spectrum With GADZOOKS!





Beacom and Vagins, hep-ph/0309300

Supernova Gamma-ray Background

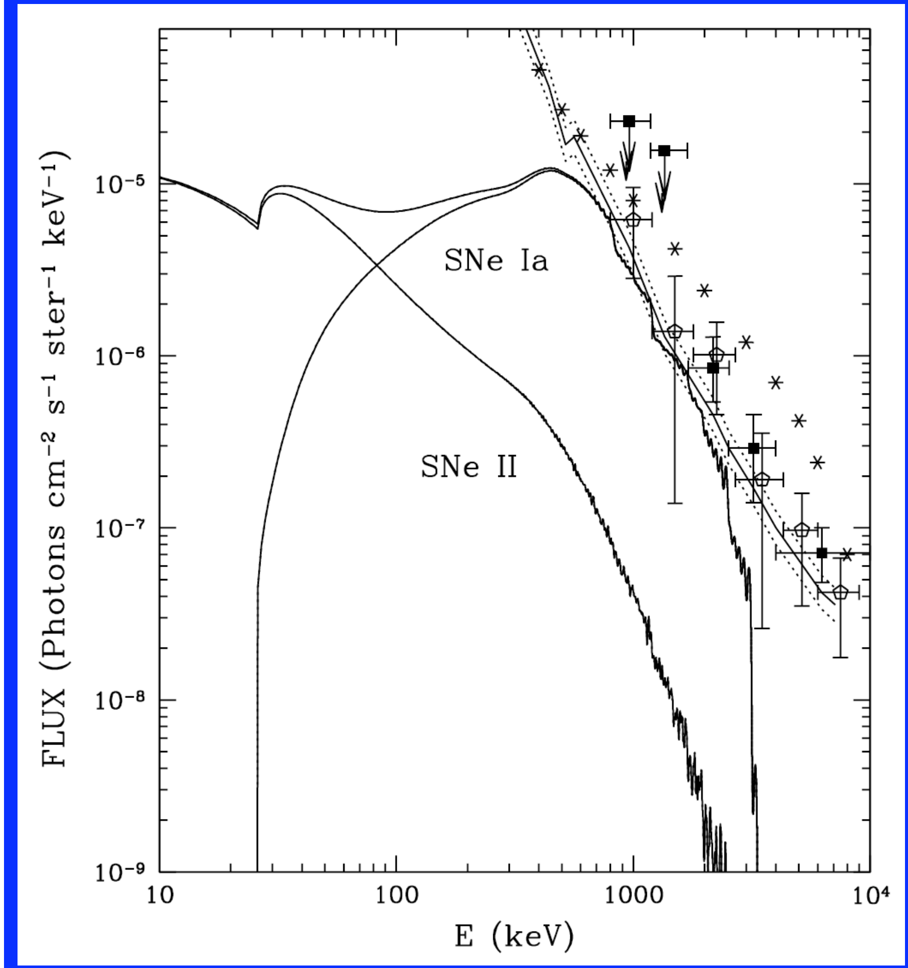


Figure from Ruiz-Lapuente, Casse, Vangioni-Flam, ApJ 549, 483 (2001)

- 1-3 MeV data consistent with expected SNIa origin
- Angular correlations may help extract SNIa contribution
- $F(\gamma, SNIa) / F(\nu, SNII) \sim 10^{-4}$, canceling the SFR(z < 1), *unless* there are new physics sources

Zhang, Beacom, astro-ph/0401351

Physics Reach

- *Detect* the Diffuse Supernova Neutrino Background
  - Astrophysical neutrinos from redshift $z < 1$
  - Unique probe of the *dark* supernova rate
  - Measurement of supernova neutrino spectrum
  - New tests of neutrino properties

- And the Diffuse Supernova Gamma-ray Background
  - Another new test of the star formation rate
  - Consistency check compared to neutrinos

- Together, more stringent tests of new physics

Conclusions

Major Topics

- Leptogenesis
- BBN
- Dark energy
- Dark matter
- WIMP detection
- UHE neutrinos
- SN neutrinos

↔

- Number of flavors
- Sterile neutrinos
- Dirac vs. Majorana
- Mass scale
- Mixing parameters
- Cross sections
- Exotic properties

Neutrinos are a key to

New physics in the Universe

New physics beyond the Standard Model

Selected Key Opportunities

- Discovery of neutrino mass using cosmological data
  - Key hint for model-building
  - Guide and foil for beta / double beta experiments

- Discovery of astrophysical neutrinos
  - Unique probe of extreme environments
  - Unique probe of neutrino properties, energy frontier

- Connections to new astrophysical/cosmological data
  - Detailed astrophysical models
  - Quest for identifying the particle dark matter
  - Fundamental theory towards the GUT scale