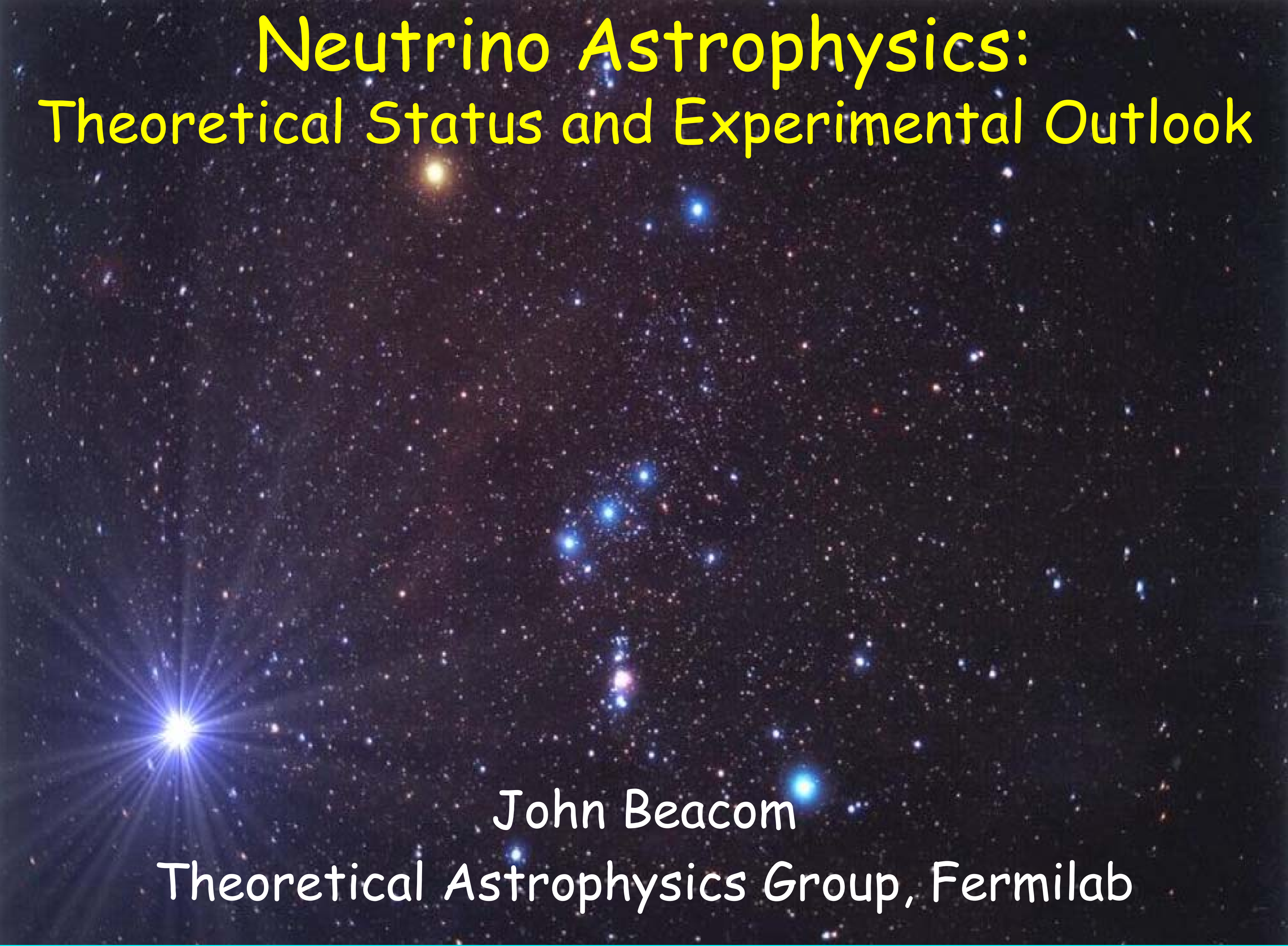
Neutrino Astrophysics:
Theoretical Status and Experimental Outlook



John Beacom
Theoretical Astrophysics Group, Fermilab

Introductory Remarks

Past Frontiers

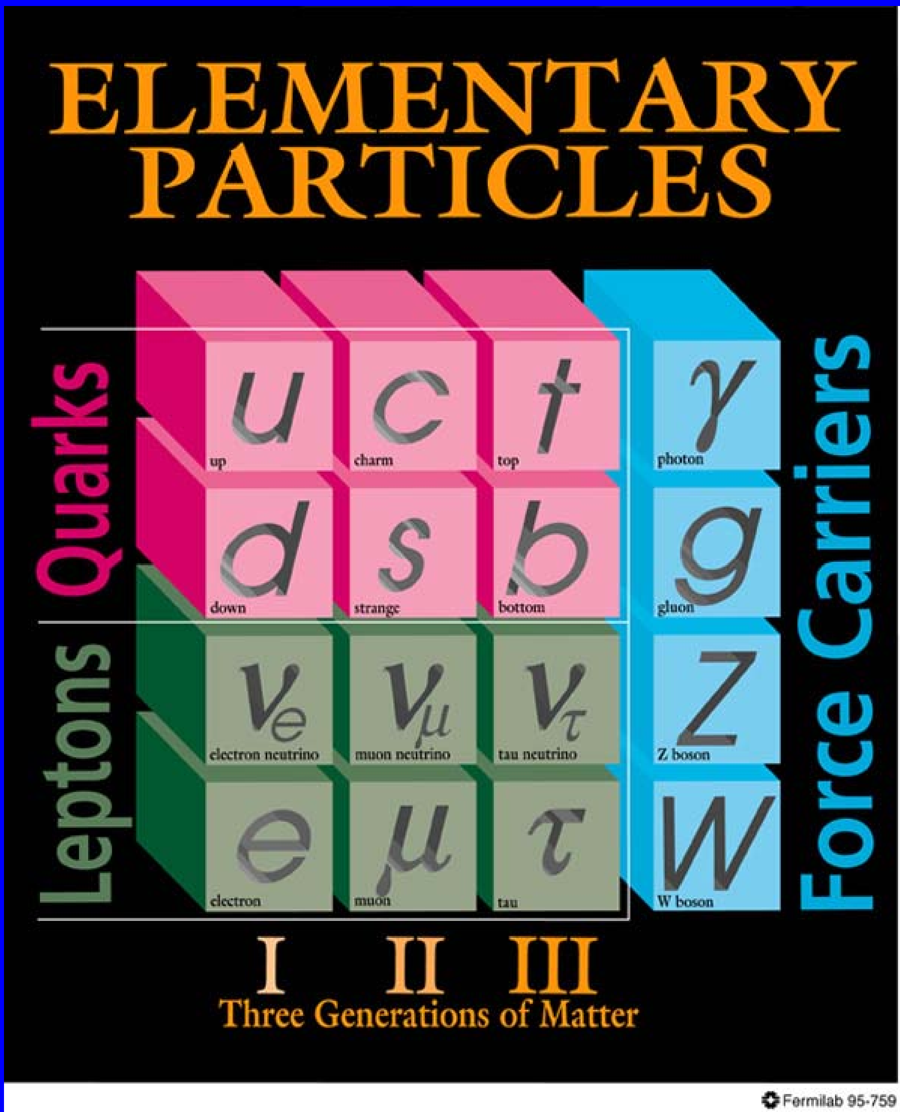
- Bethe and Peierls, Nature (1934)

"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.

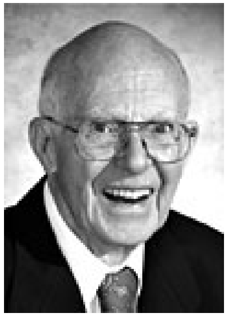
Lucky Neutrinos



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

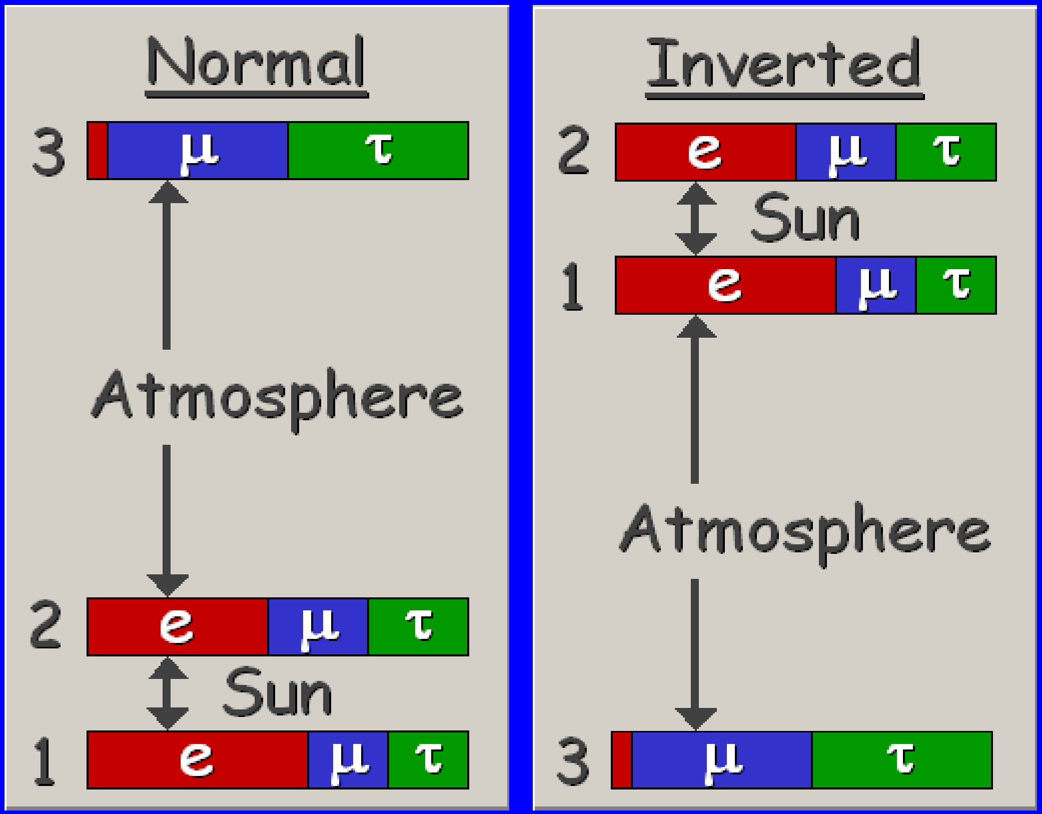
Riccardo Giacconi
1/2 of the prize
USA
Associated Universities Inc.
Washington, DC, USA
b. 1931
(in Genoa, Italy)

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 high-energy astrophysics
  (Yeah, right)

Neutrino Mixing



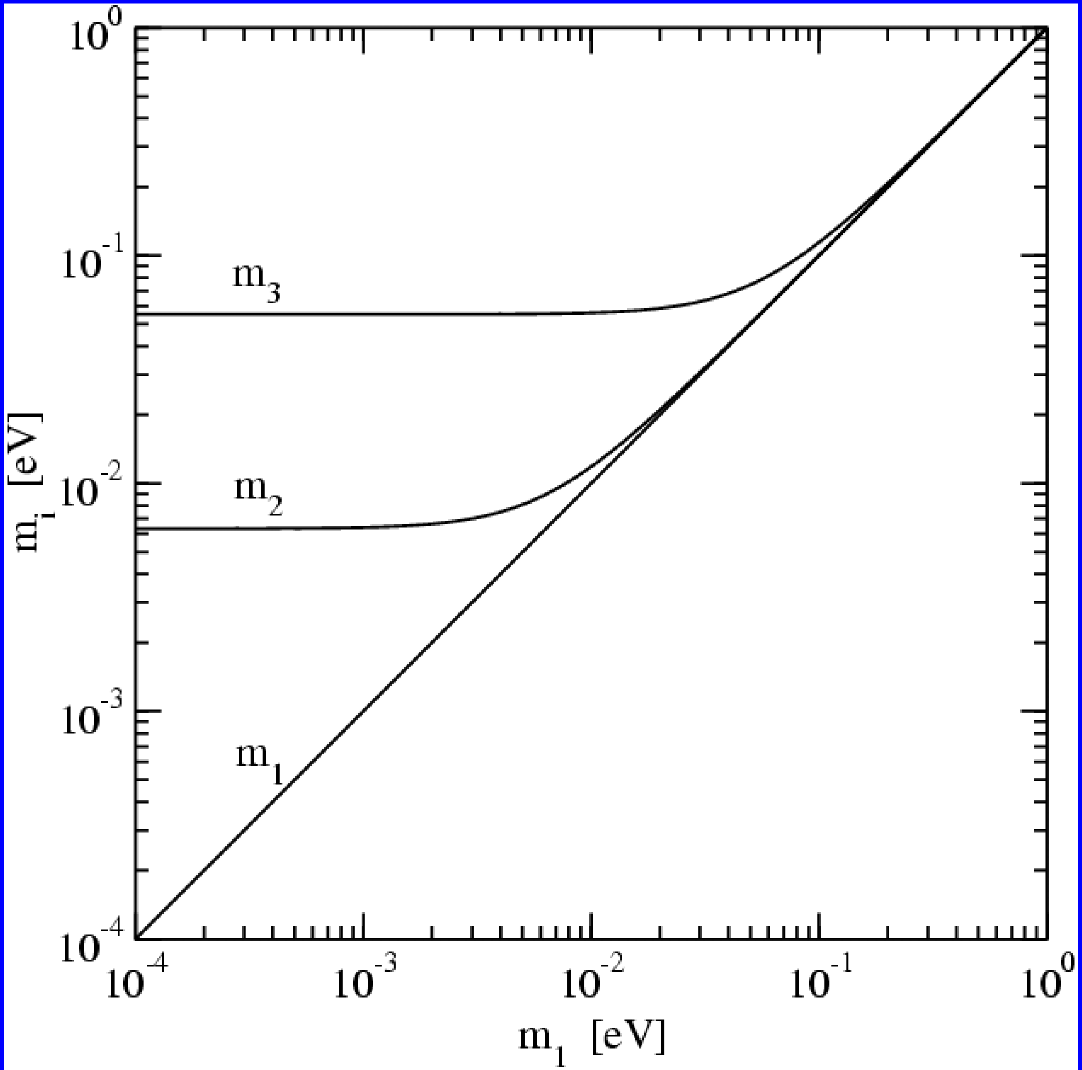
(graphic from Georg Raffelt)

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

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

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

Neutrino Masses



Beacom and Bell, PRD 65, 113009 (2002)

Normal Hierarchy

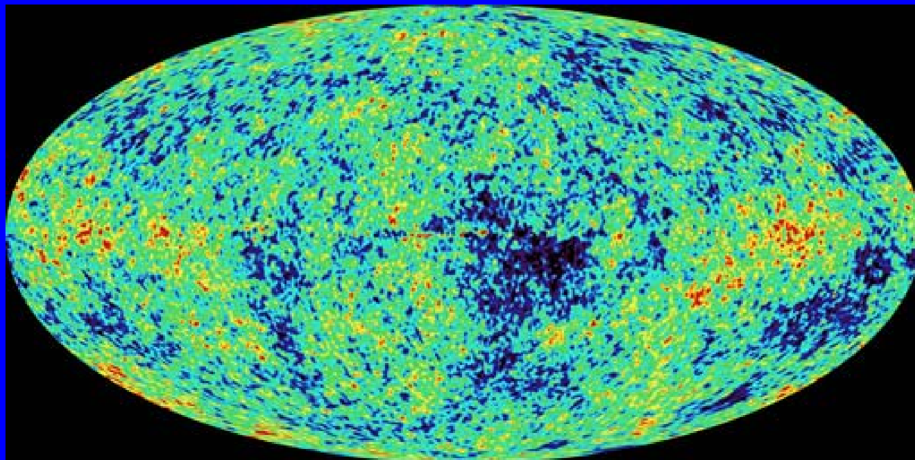
$$m_1 = m_1$$

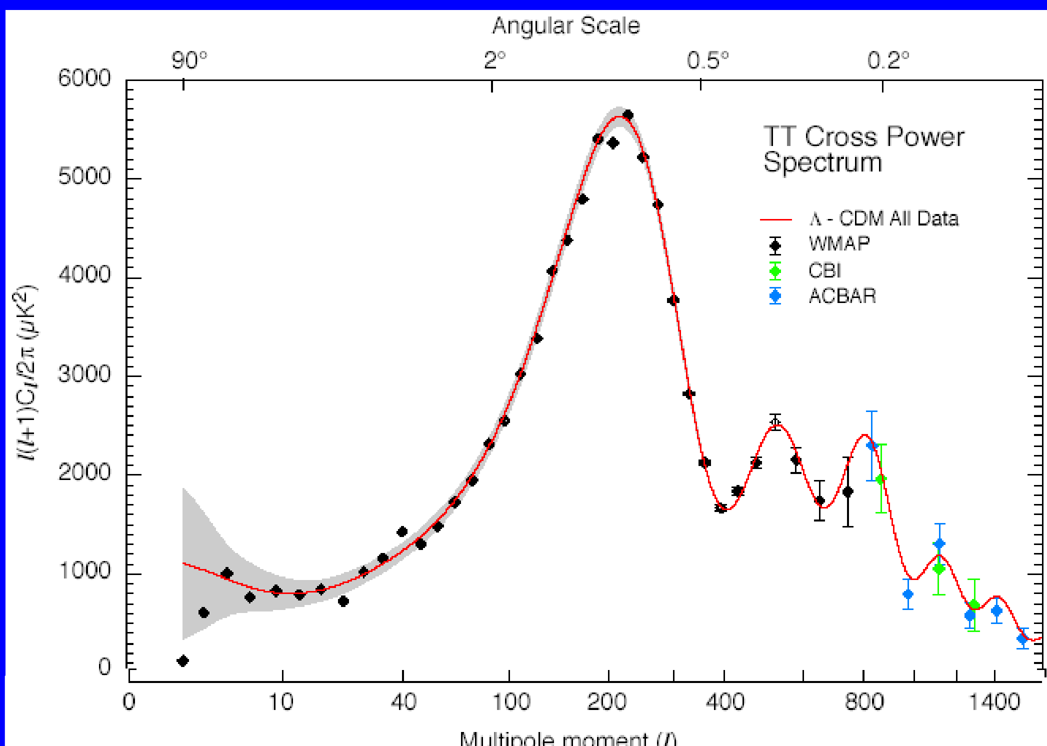
$$m_2 = \sqrt{m_1^2 + \delta m^2_{solar}}$$

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

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

Cosmological Parameters





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

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

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

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

$h = 0.71 \pm 0.04$

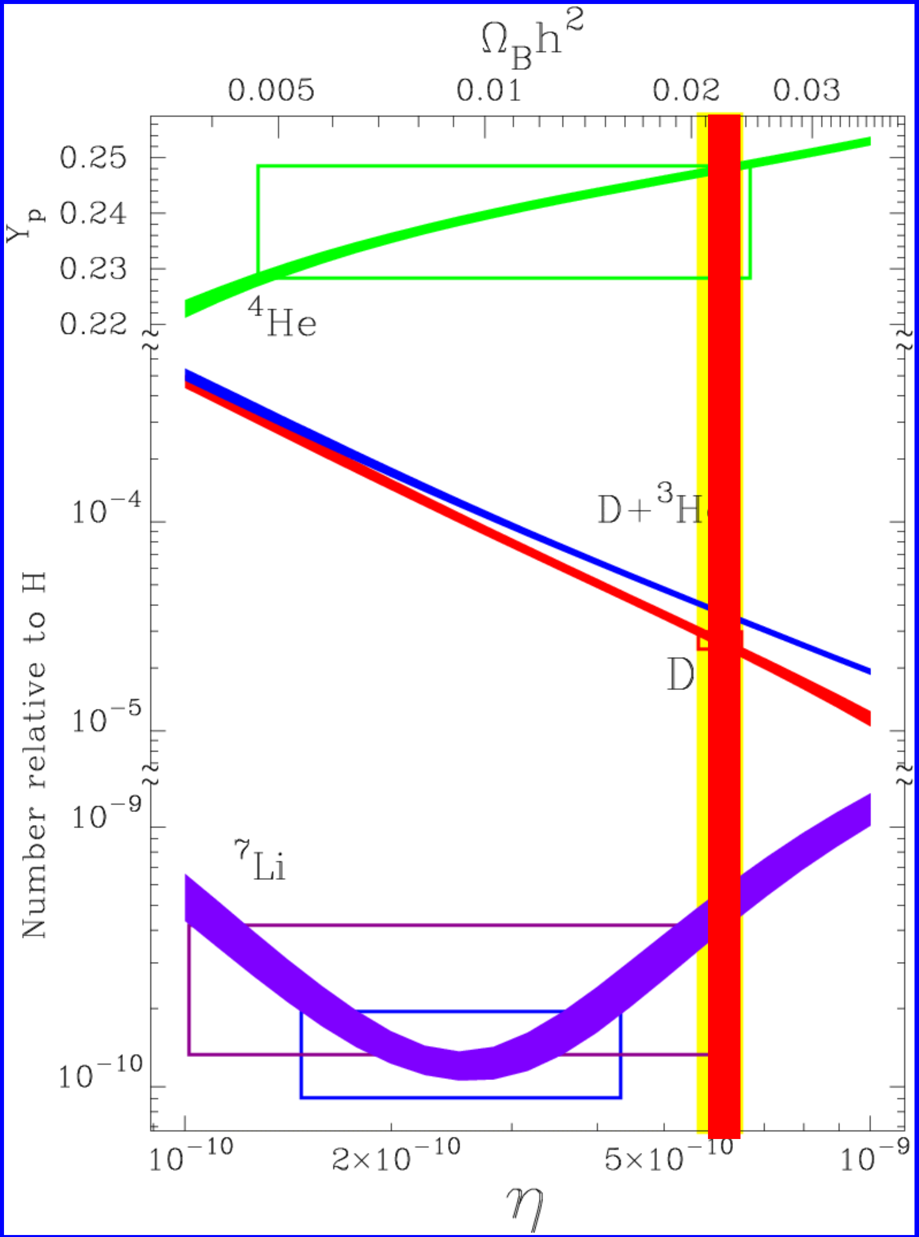
etc.

$\Omega_{\Lambda} = 0.7$

$m_{\nu} < 0.23 \text{ eV}$

(WMAP)

Neutrino Number Densities



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

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

Abazajian, Astropart. 19, 303 (2003)

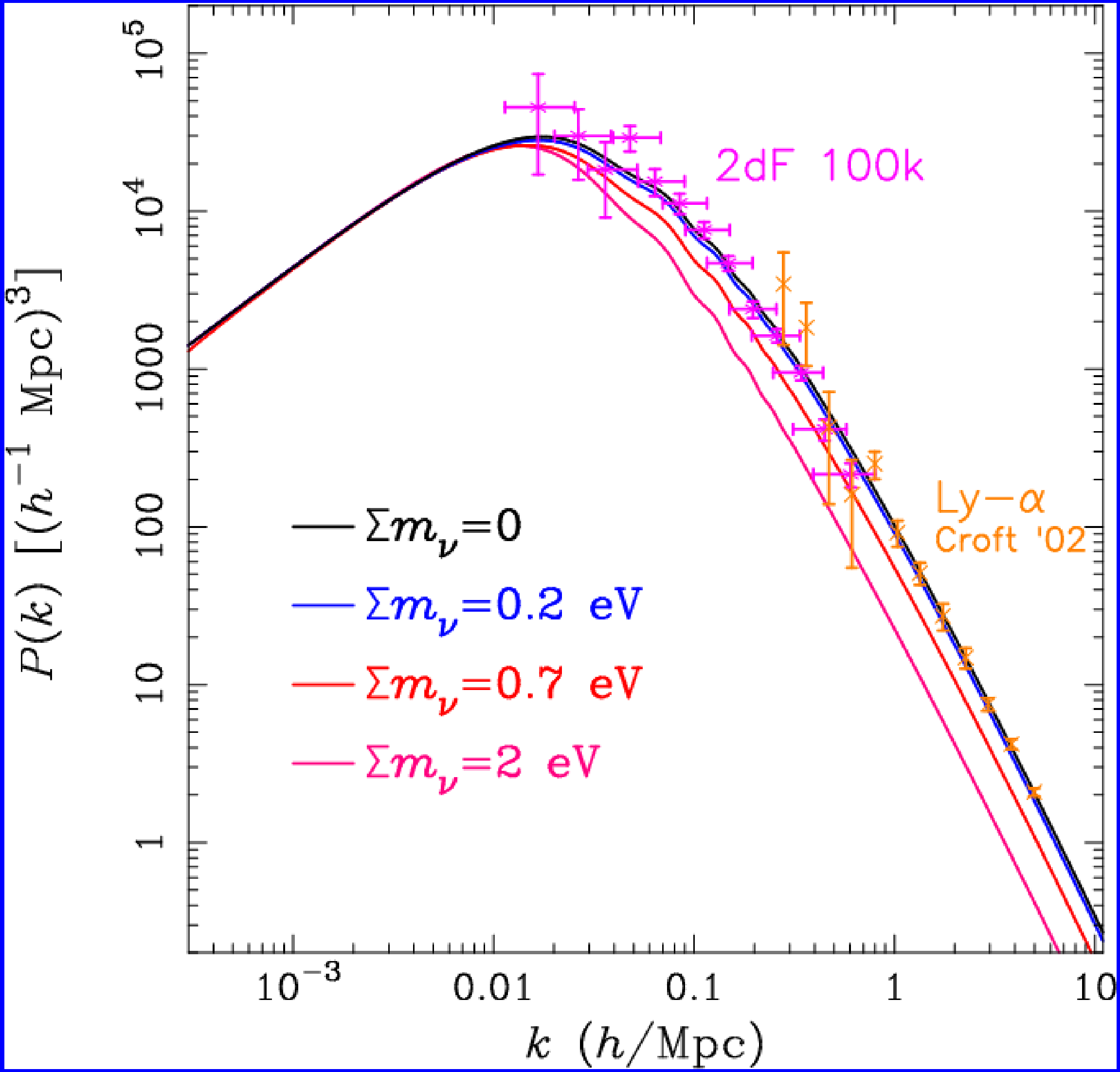
$1.5 \le N_\nu \le 7.2$ WMAP++

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



$\rho_{matter} = \rho_{CDM}$

$+ \rho_{baryons}$

$+ \rho_{neutrinos}$

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

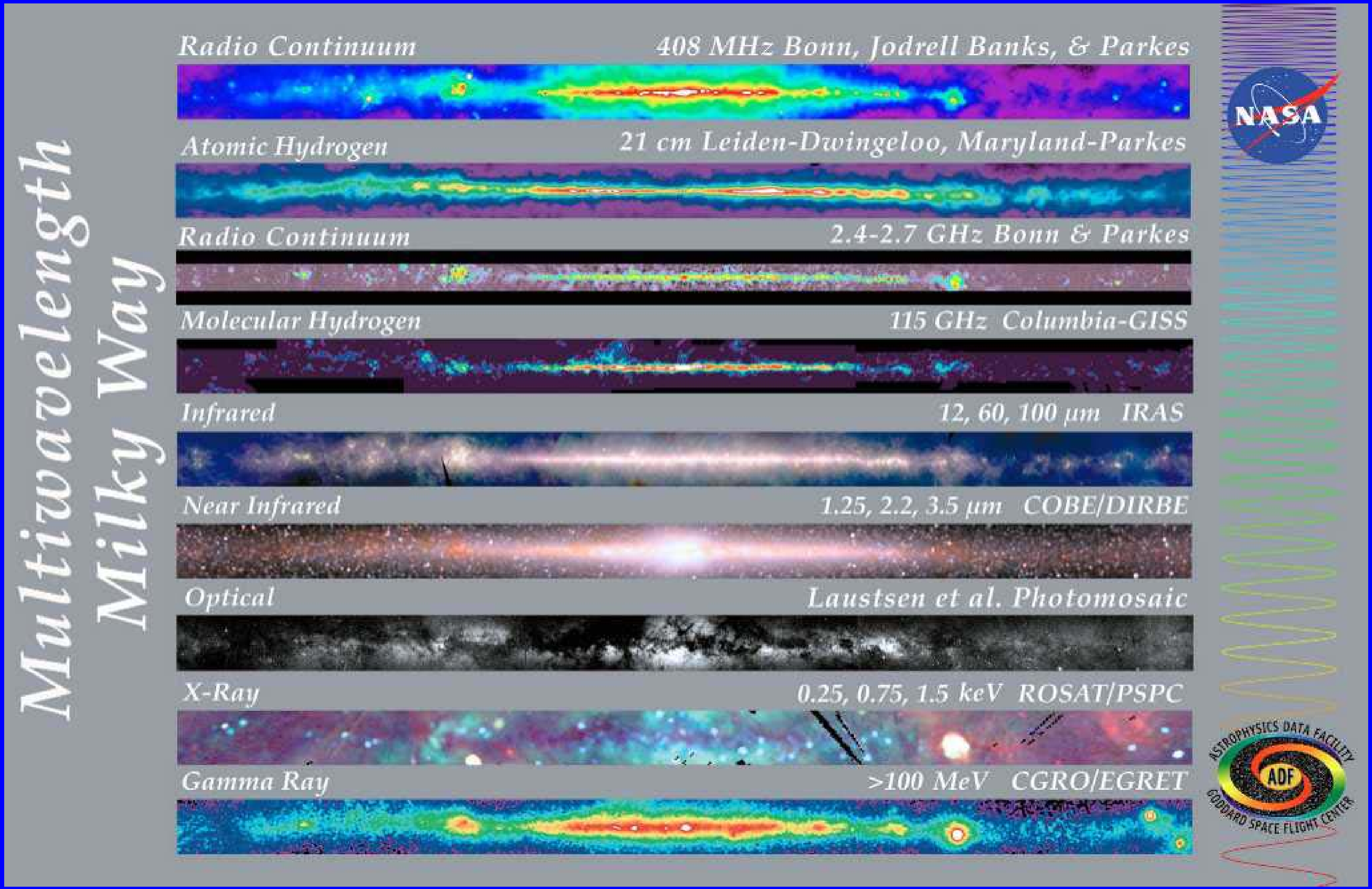
Future discovery range:
Abazajian & Dodelson, PRL 91, 041301 (2003)

Kaplinghat, Knox & Song, astro-ph/0303344

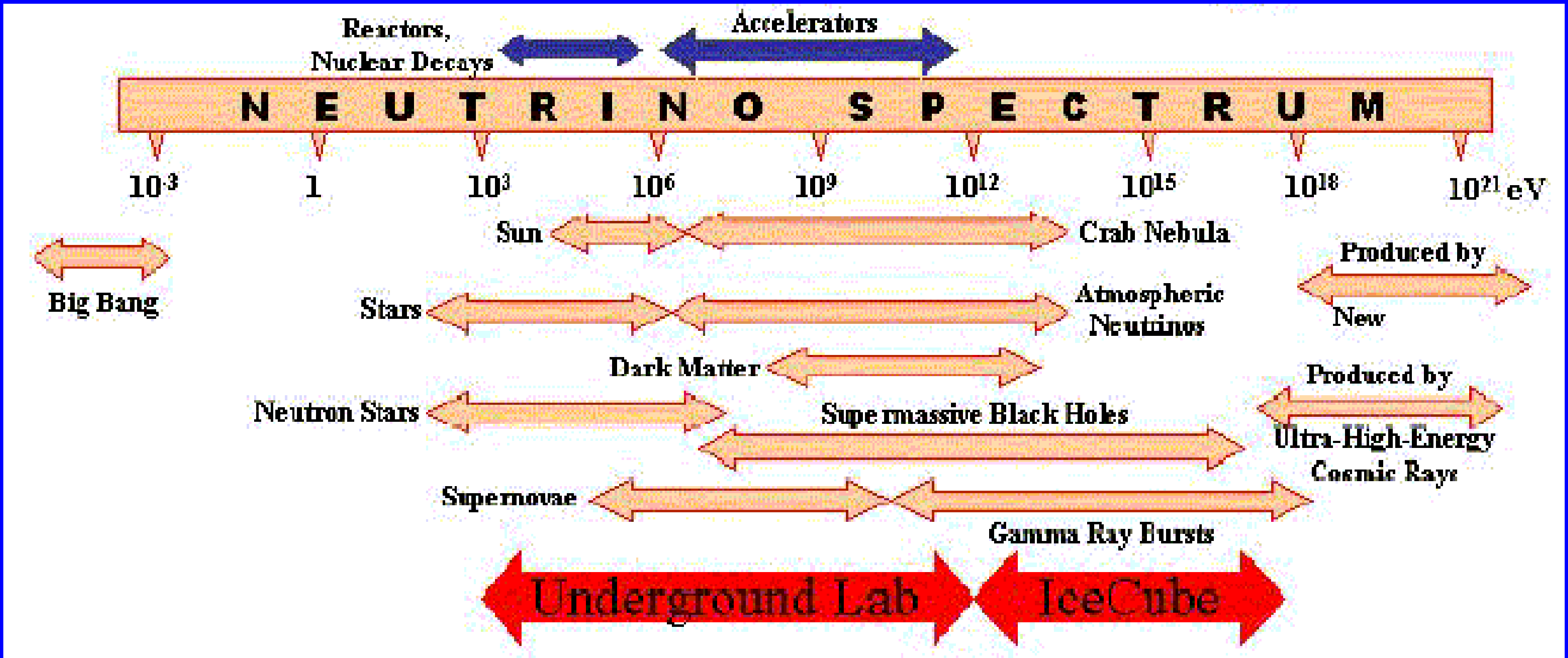
(graphic from Kev Abazajian)

See Abazajian parallel talk

Photon Windows



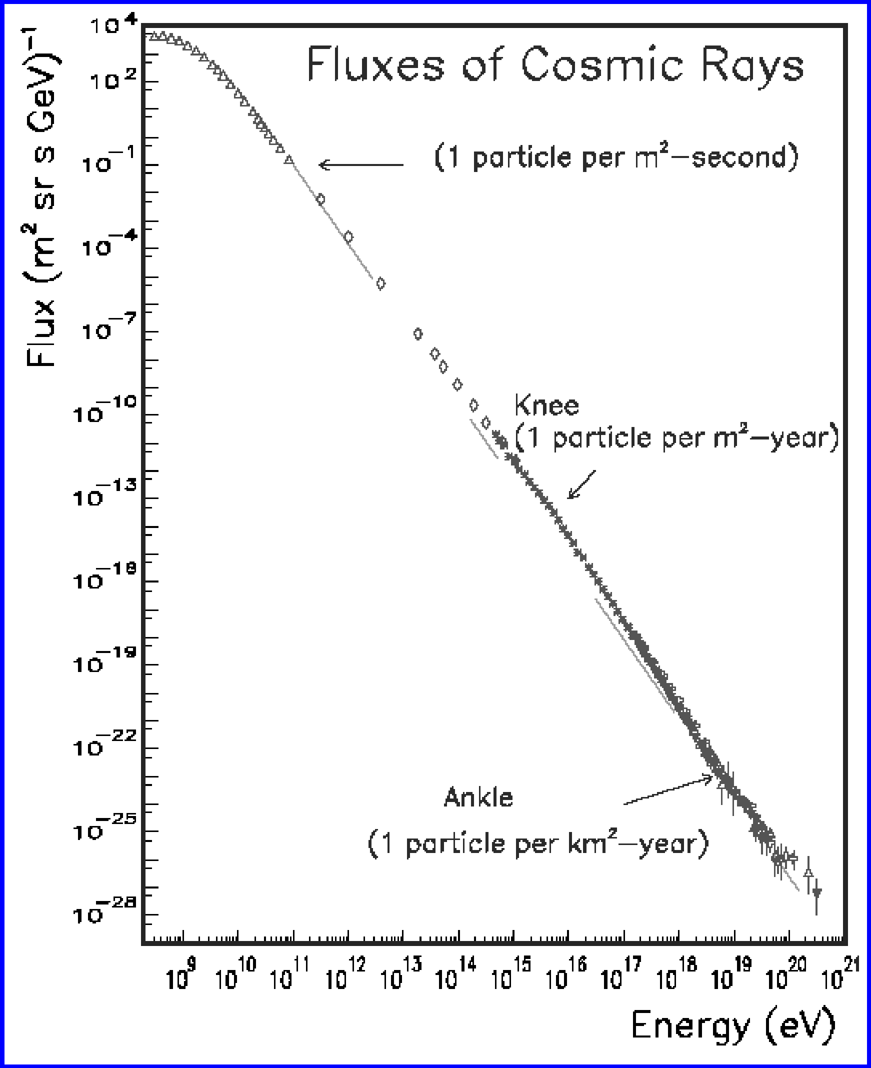
Neutrino Windows

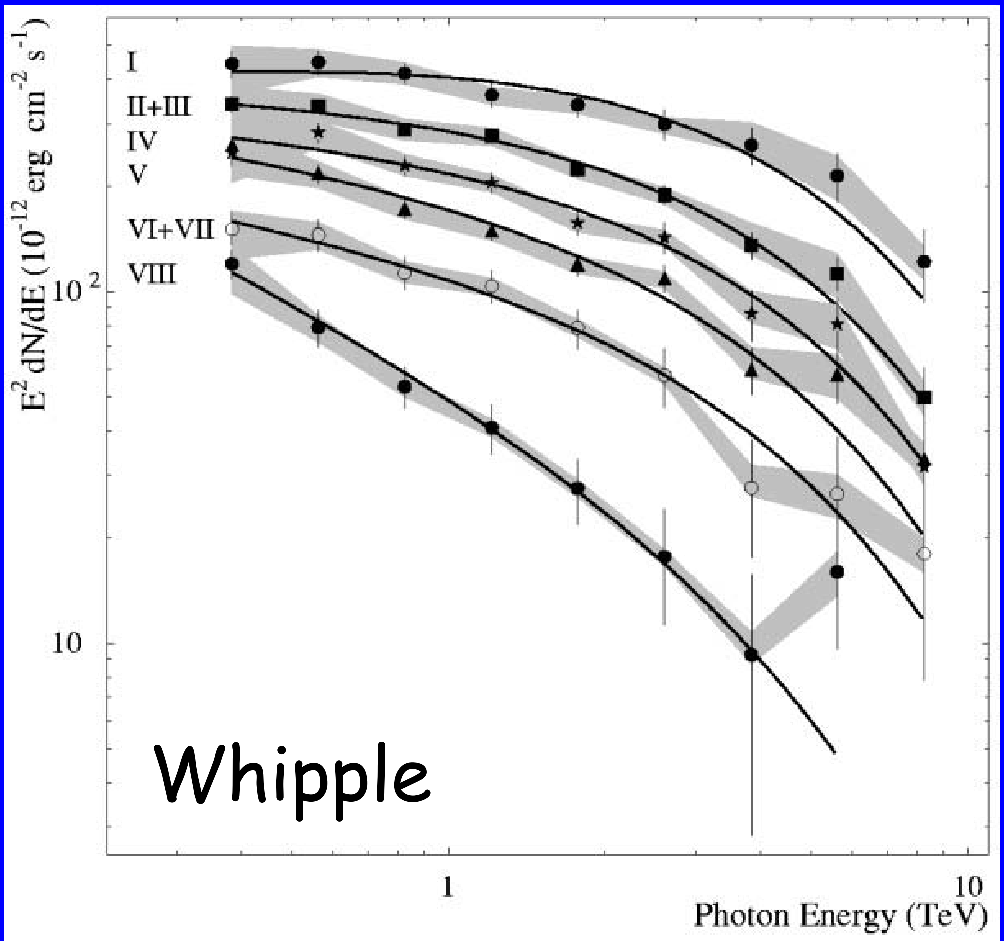


Neutrino Facilities Assessment Committee, NAS (2002)

Astrophysical Neutrinos: Searching High

High Energy Messengers



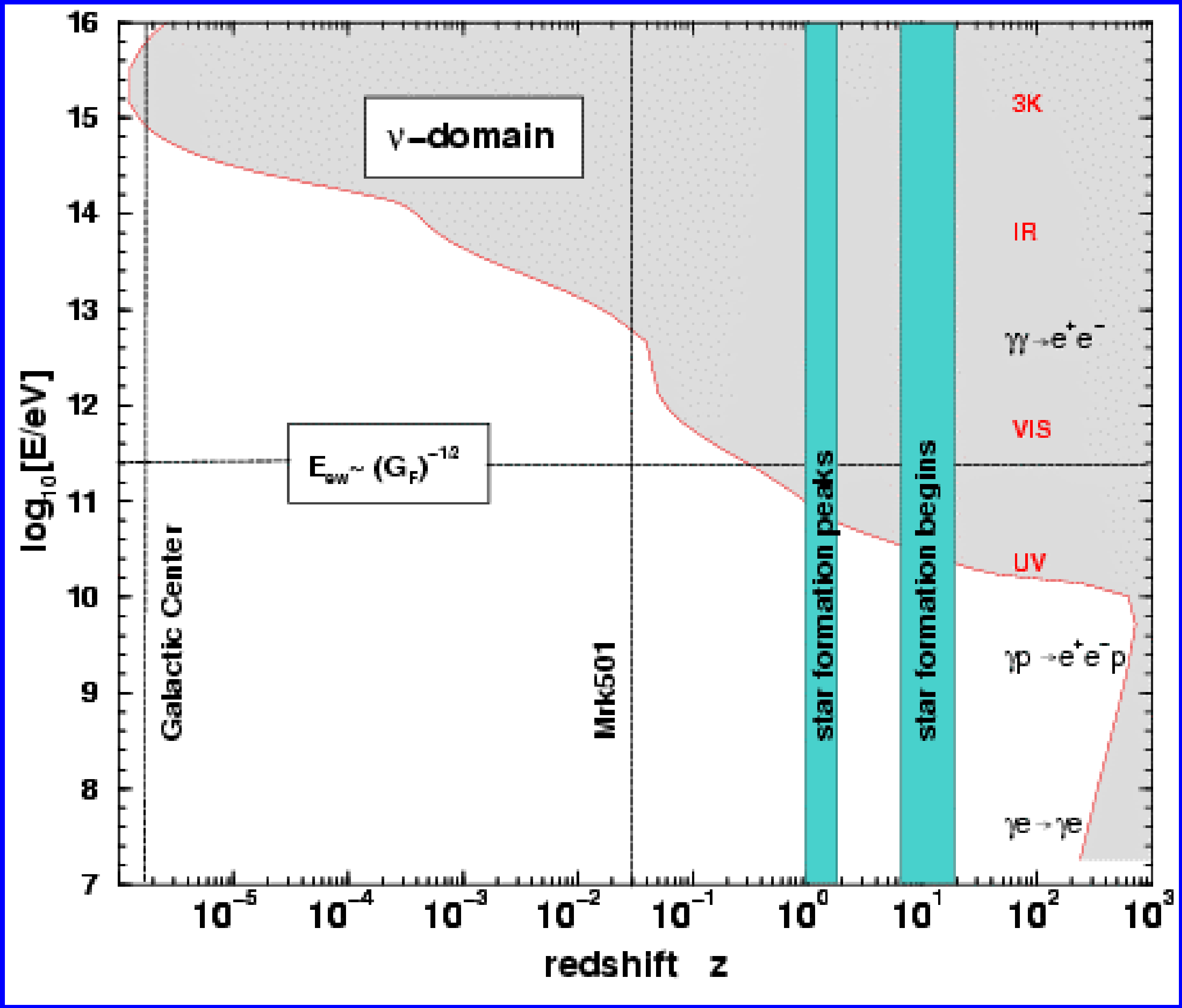


F. Krennrich et al., ApJ 575, L9 (2002)

Protons (diffuse)

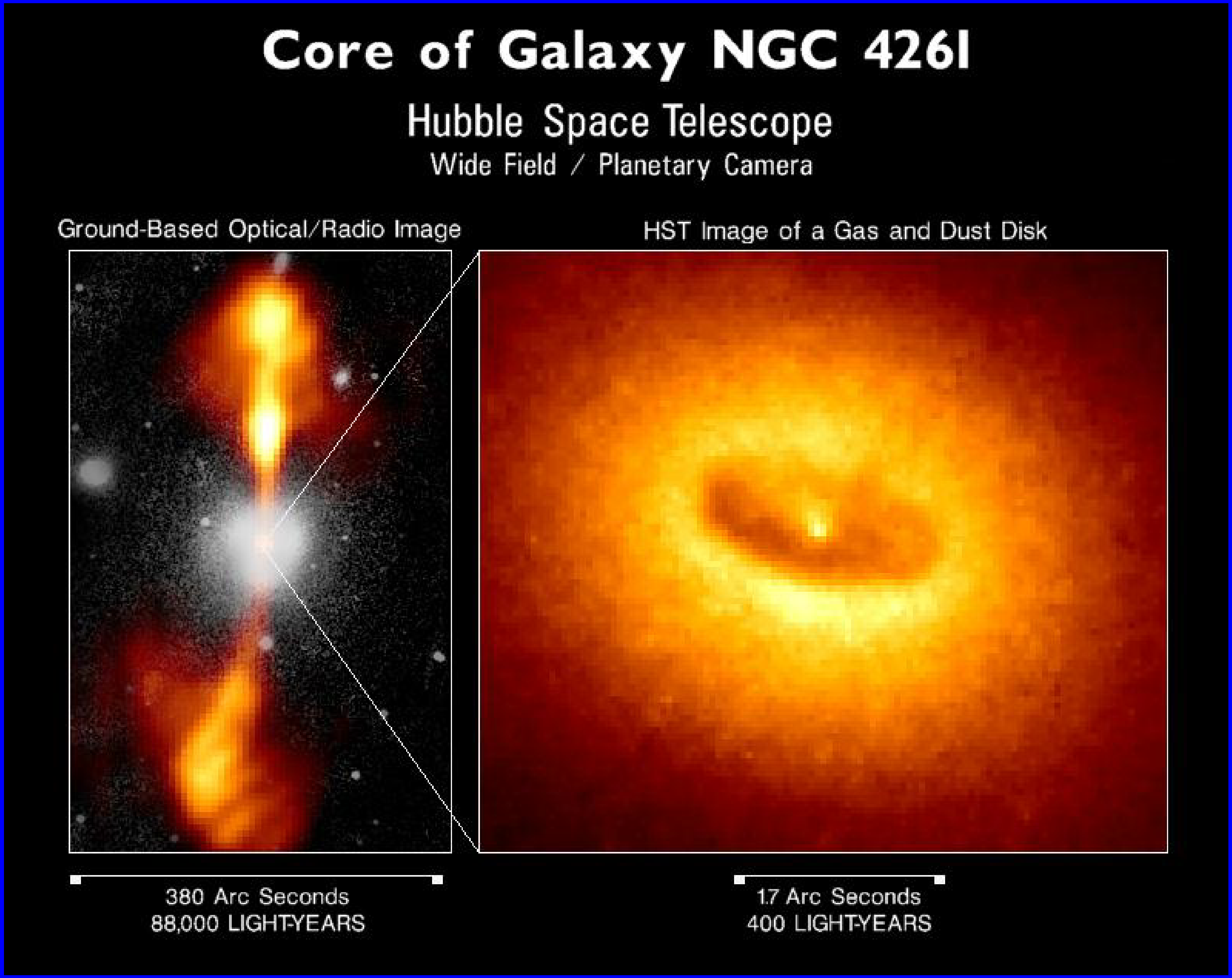
Photons (Markarian 421)

Beyond the Veil

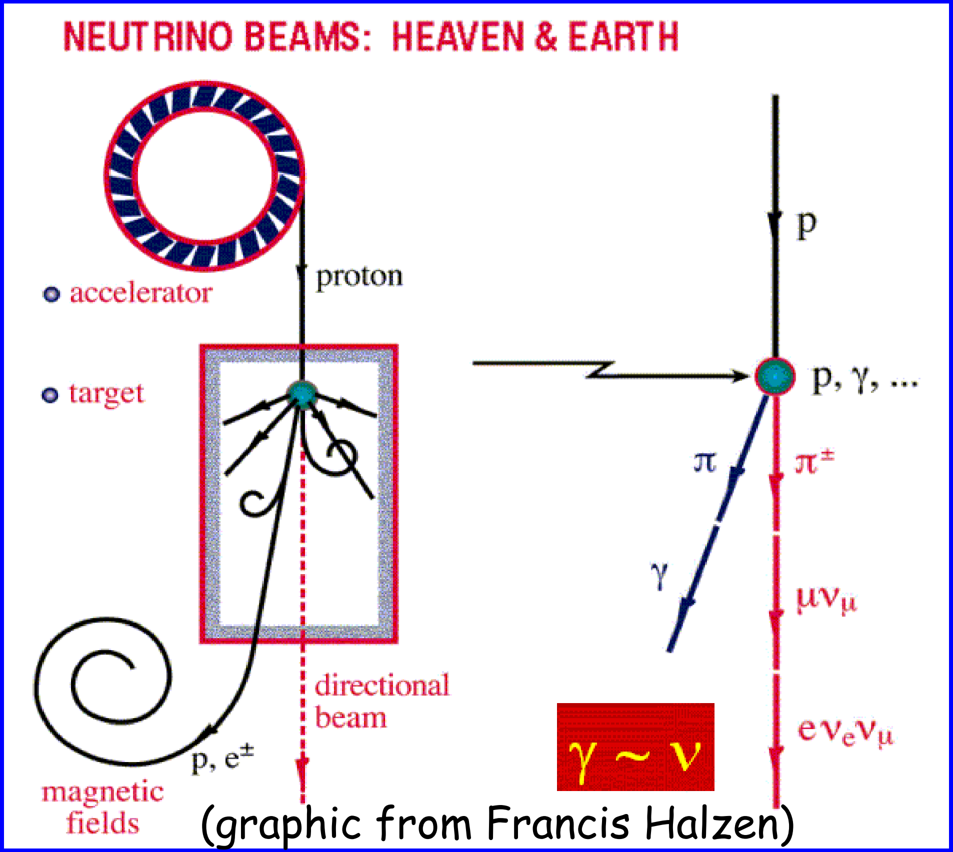


Learned and Mannheim, Ann.Rev.Nucl.Part.Sci 50, 679 (2000)

Active Galaxies



UHE Neutrinos



initial fluxes are

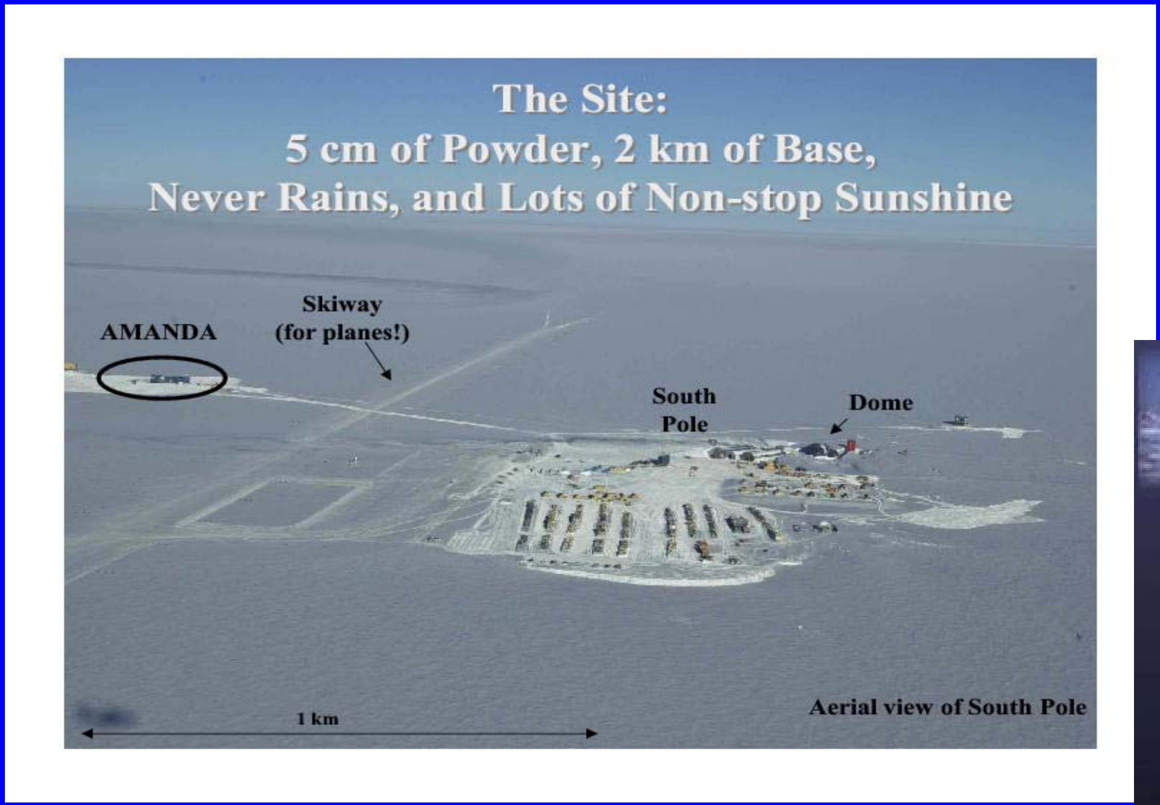
$$\varphi_{\nu_e} : \varphi_{\nu_\mu} : \varphi_{\nu_\tau} = 1:2:0$$

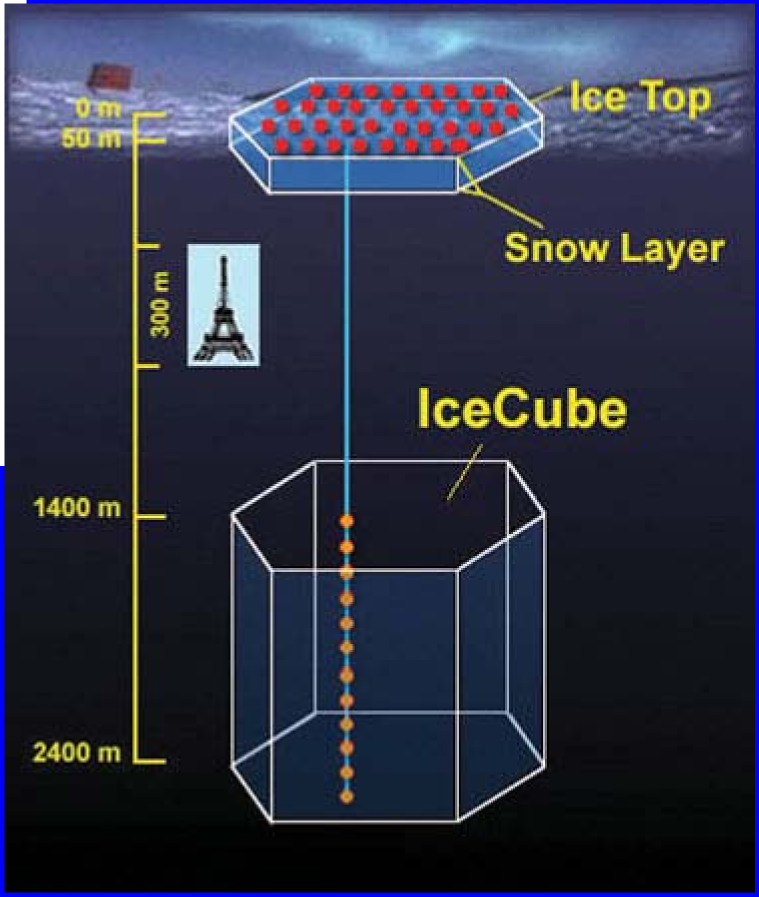
after oscillations

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

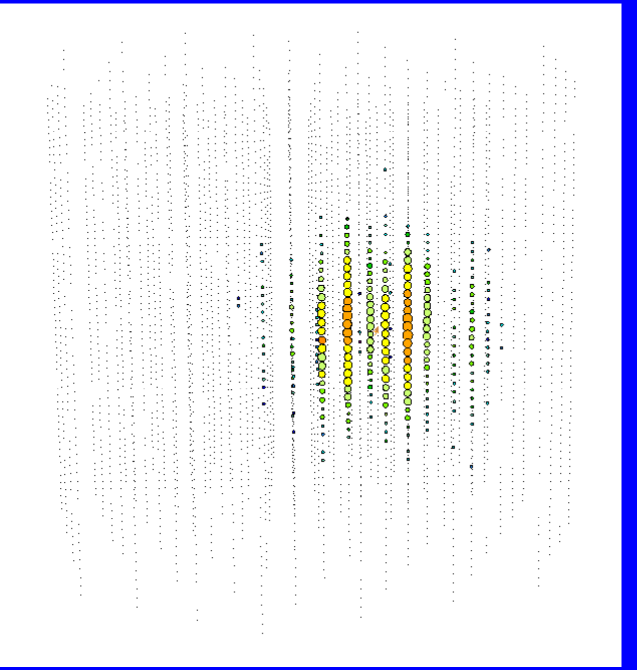
Earth opacity effects above E ~ 100 TeV

ICECUBE

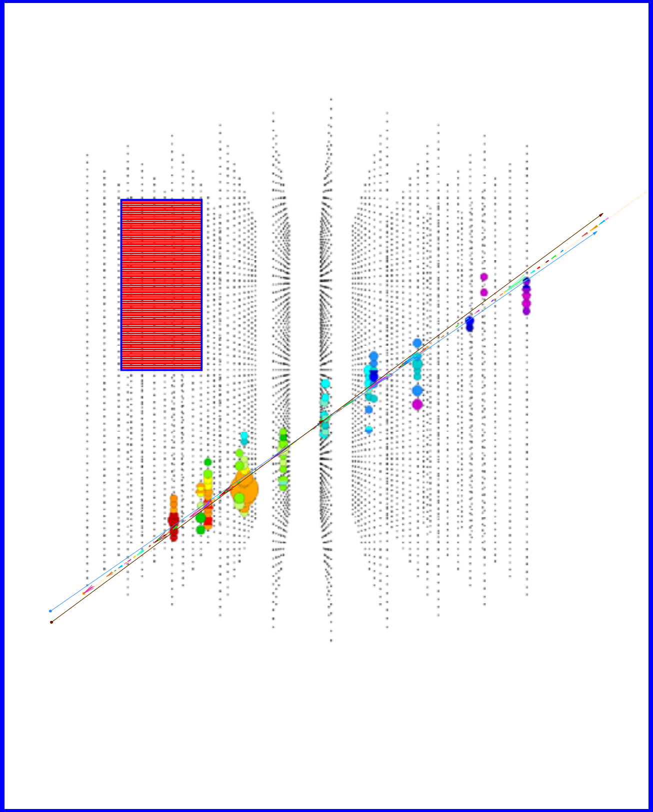

The Site:
5 cm of Powder, 2 km of Base,
Never Rains, and Lots of Non-stop Sunshine
AMANDA
Skiway
(for planes!)
South
Pole
Dome
1 km
Aerial view of South Pole


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

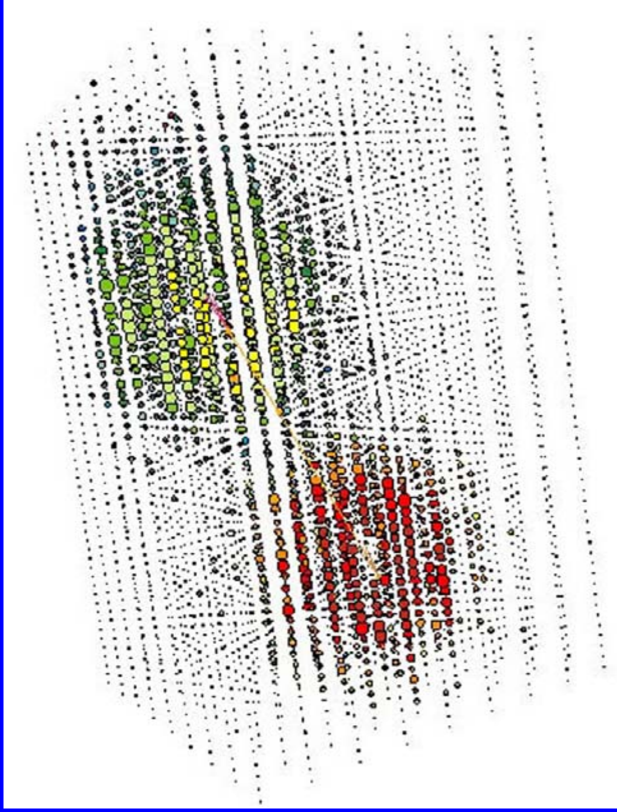
Flavor Identification



~ 100 TeV ν_e

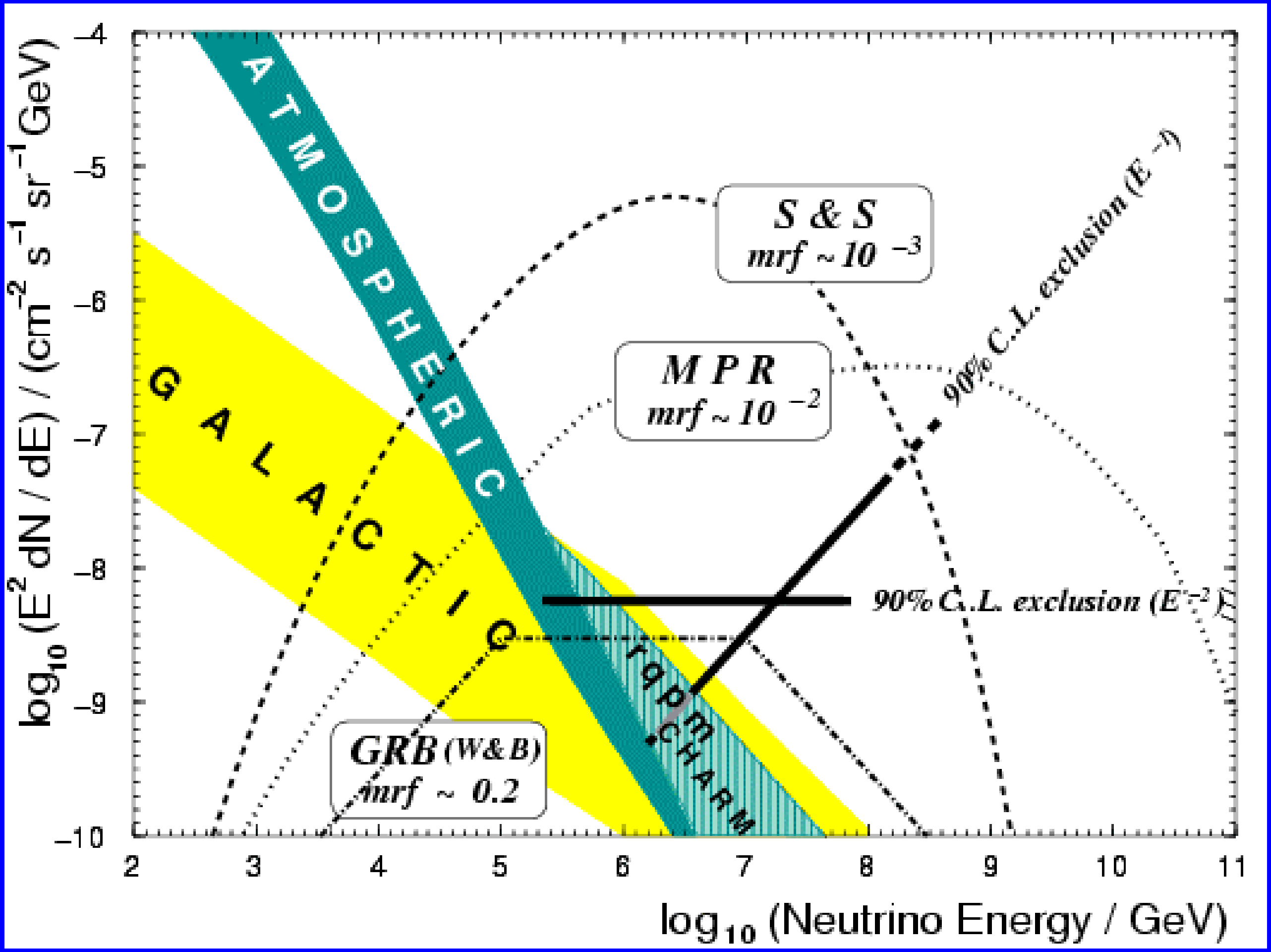


~ 10 TeV ν_μ



~ 10 PeV ν_τ

IceCube Sensitivity

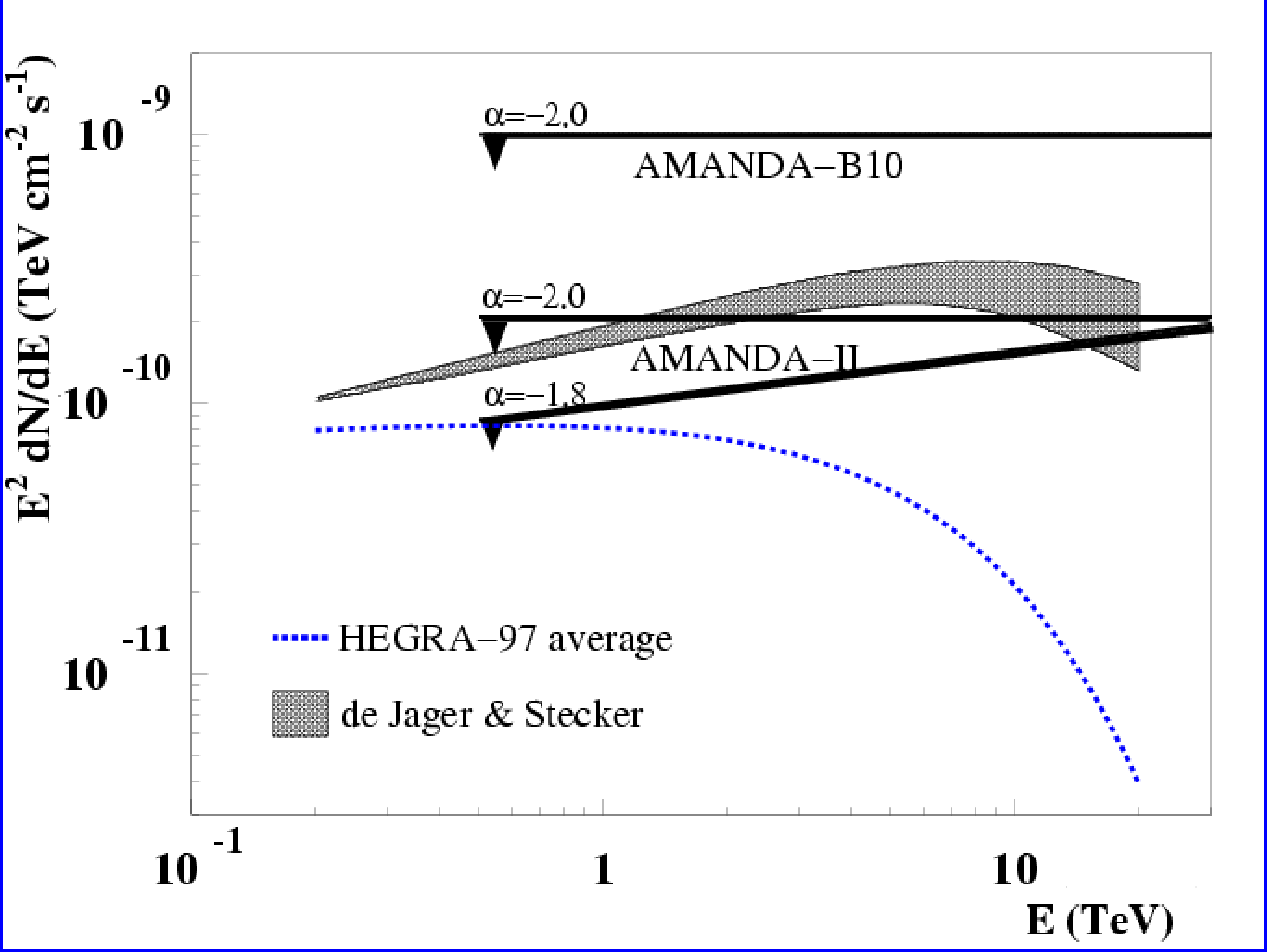


AMANDA-B10

AMANDA-II

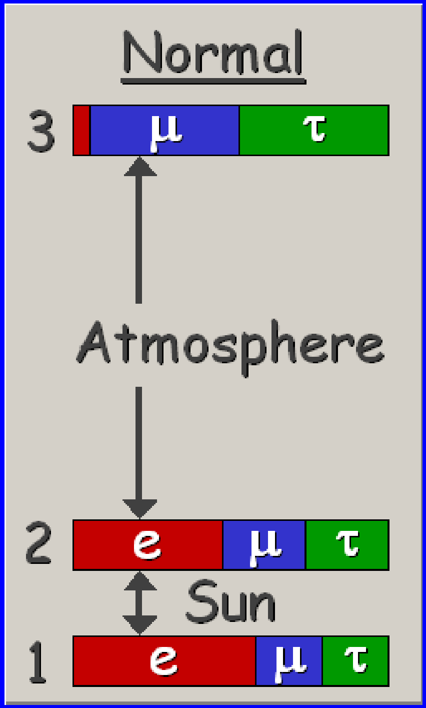
J. Ahrens et al. (IceCube), astro-ph/0305196

Neutrino-Gamma Connection

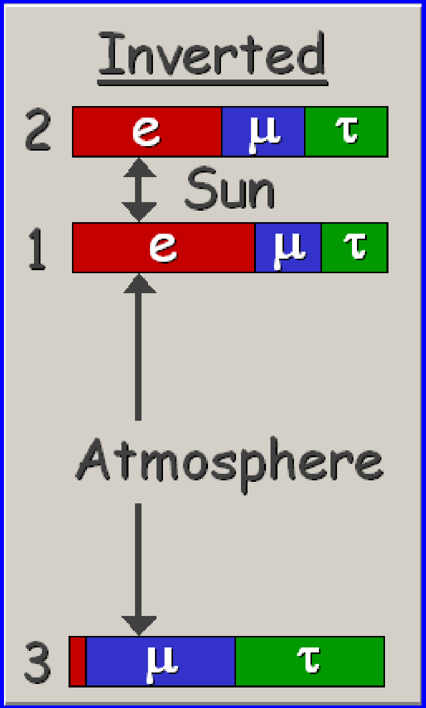


J. Ahrens et al. (AMANDA-II), astro-ph/0309585

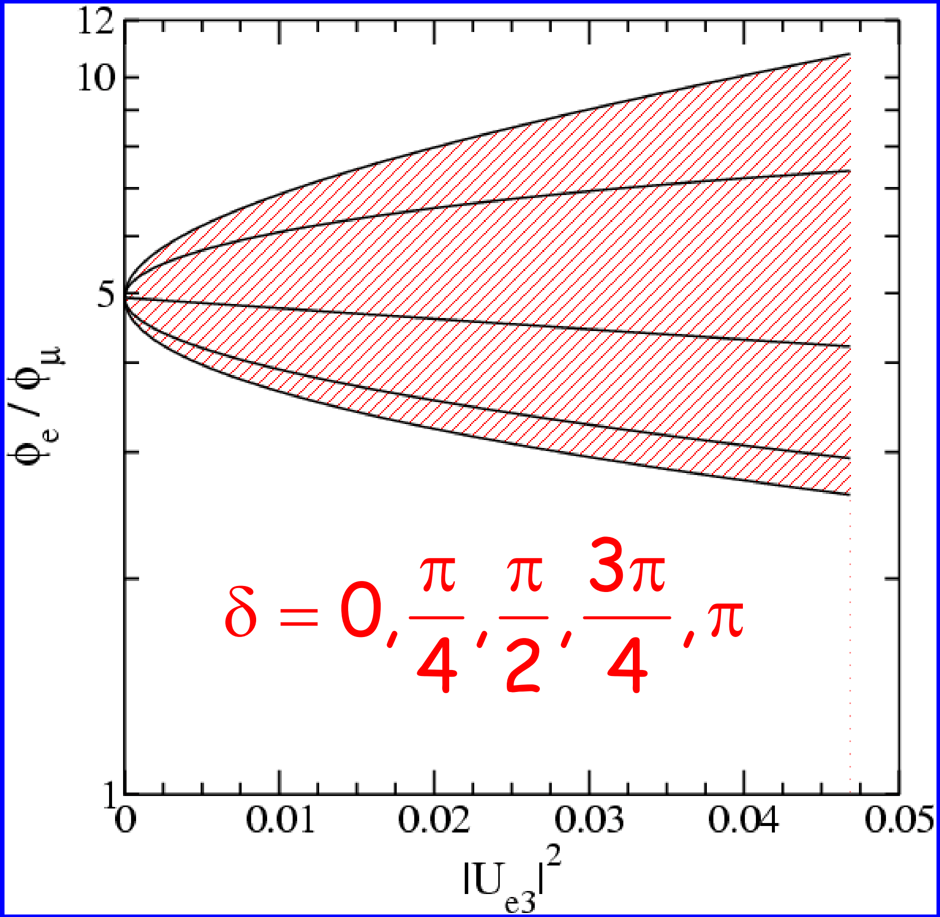
Neutrino Decay



~ 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

Nonstandard Flavor Ratios

Flavor ratios can also deviate from 1:1:1 due to:

- Tiny-δm^2 mixing to steriles

  Crocker, Melia, Volkas, ApJS 130, 339 (2000); 141, 147 (2002);
  Berezinsky, Narayan, Vissani, NPB 658, 254 (2003);
  Keranen, Maalampi, Myyrylainen, Riittinen, hep-ph/0307041;
  Beacom, Bell, Hooper, Learned, Pakvasa, Weiler, hep-ph/0307151

- CPT violation

  Barenboim, Quigg, PRD 67, 073024 (2003)

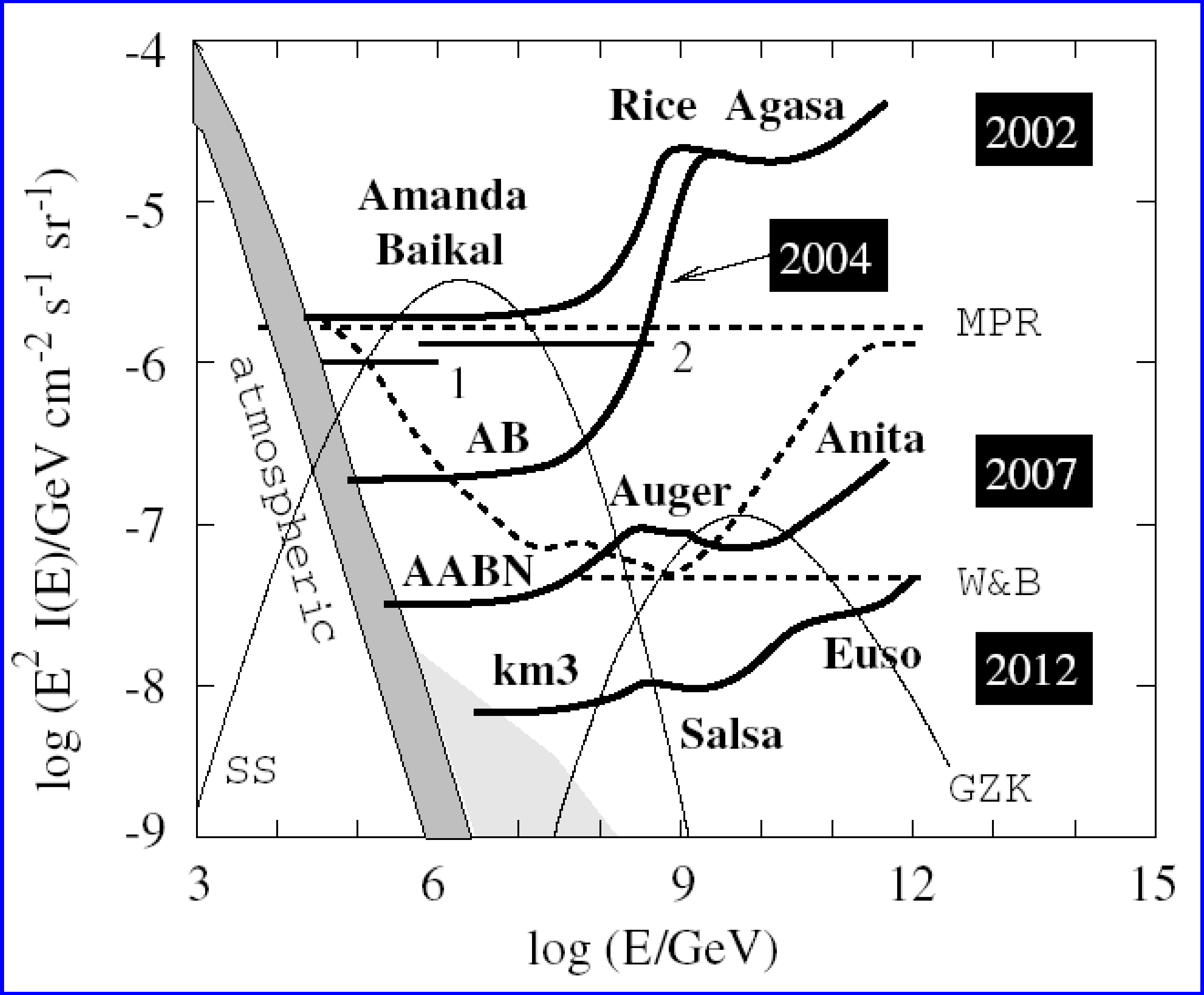
- For these and astrophysical reasons, it is very important to test the flavor ratios directly!

  Barenboim, Quigg, PRD 67, 073024 (2003);
  Beacom, Bell, Hooper, Pakvasa, Weiler, hep-ph/0307025;
  Jones, Mocioiu, Reno, Sarcevic, hep-ph/0308042

See Bell parallel talk

Astrophysical Neutrinos: Searching Very High

UHE Neutrino Prospects



Importance of neutrino mixing

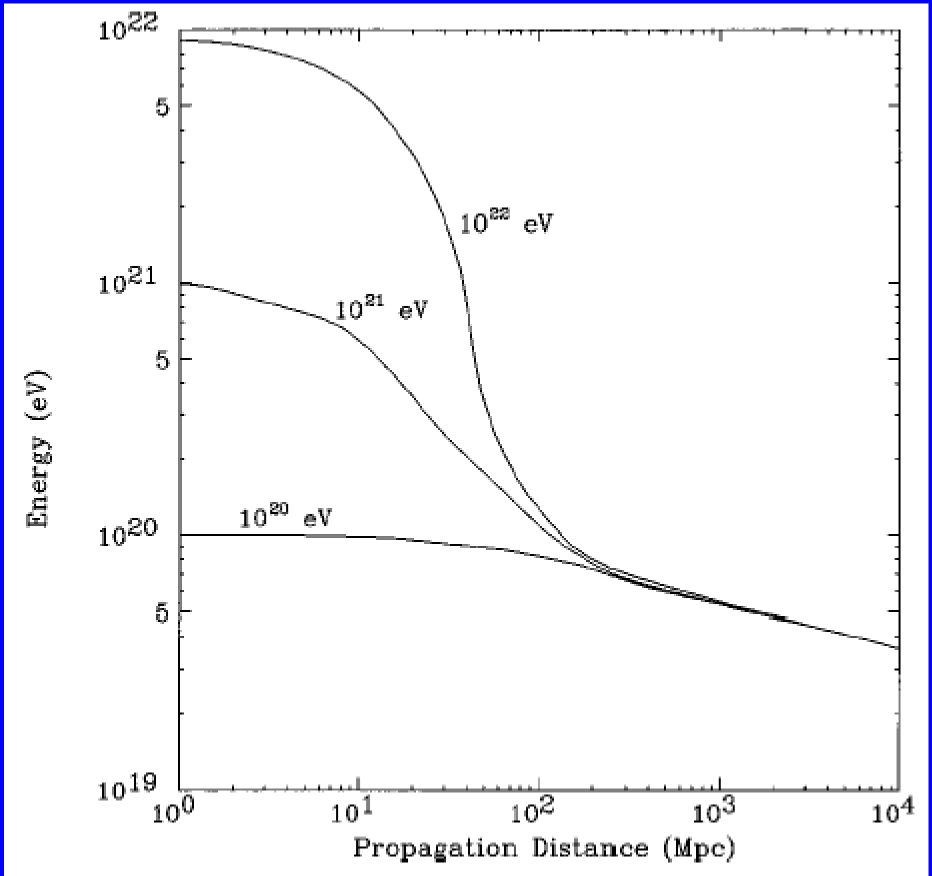
Spiering, J. Phys. *G29*, 843 (2003)

See Besson parallel talk

GZK Neutrinos

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

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

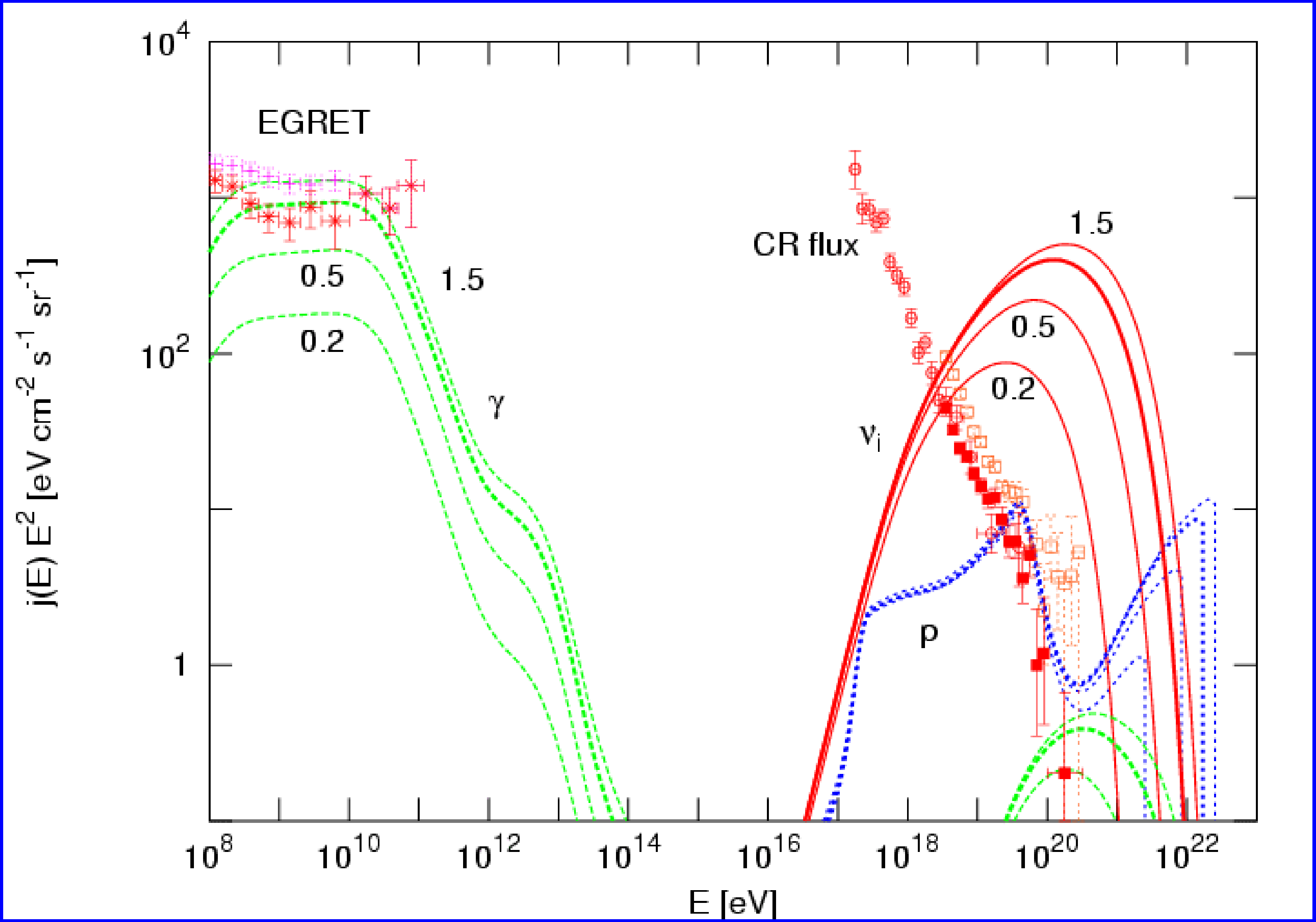


Connected observables:

- Protons
- Photons
- Neutrinos

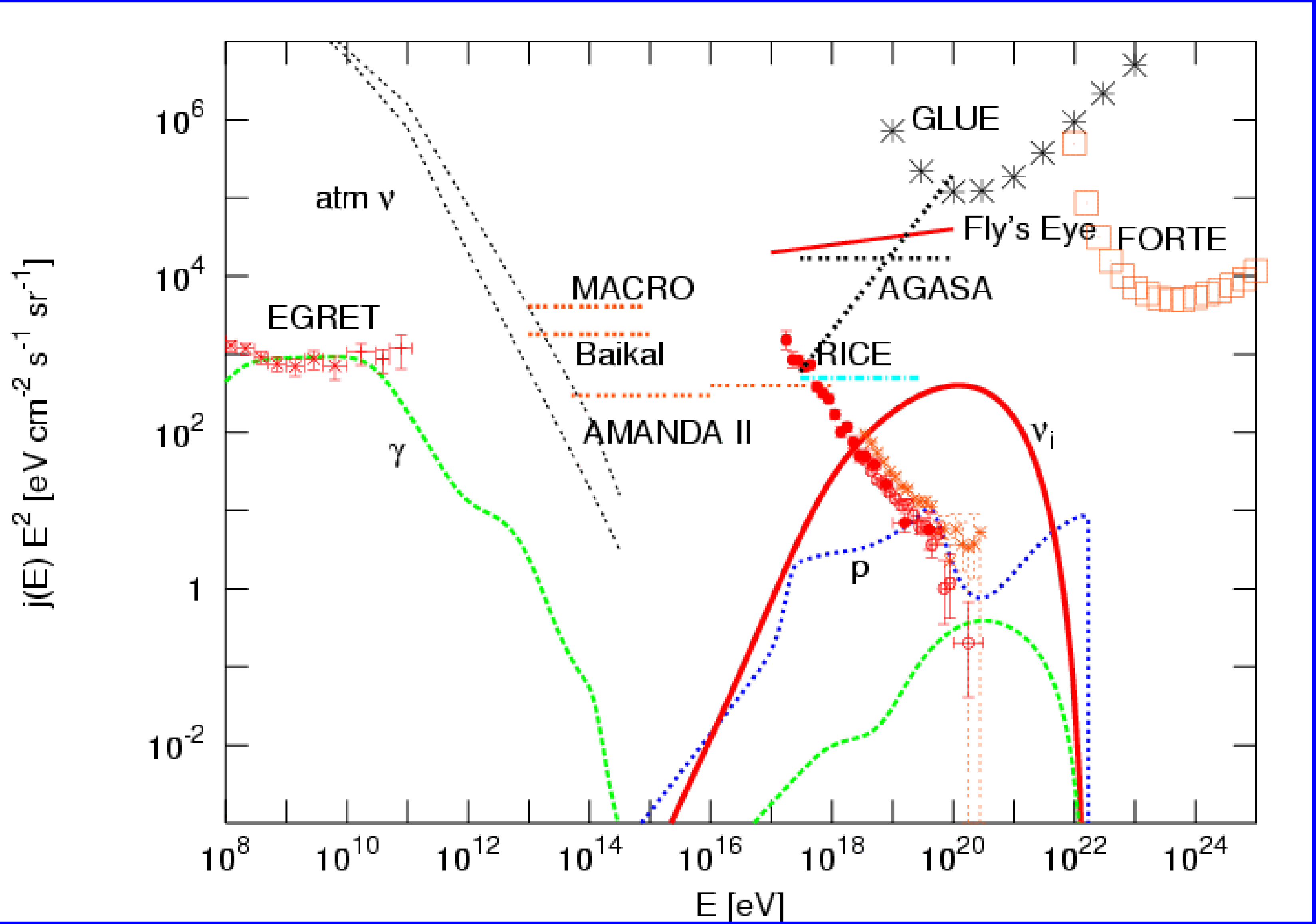
Cronin

Protons, Photons, and Neutrinos



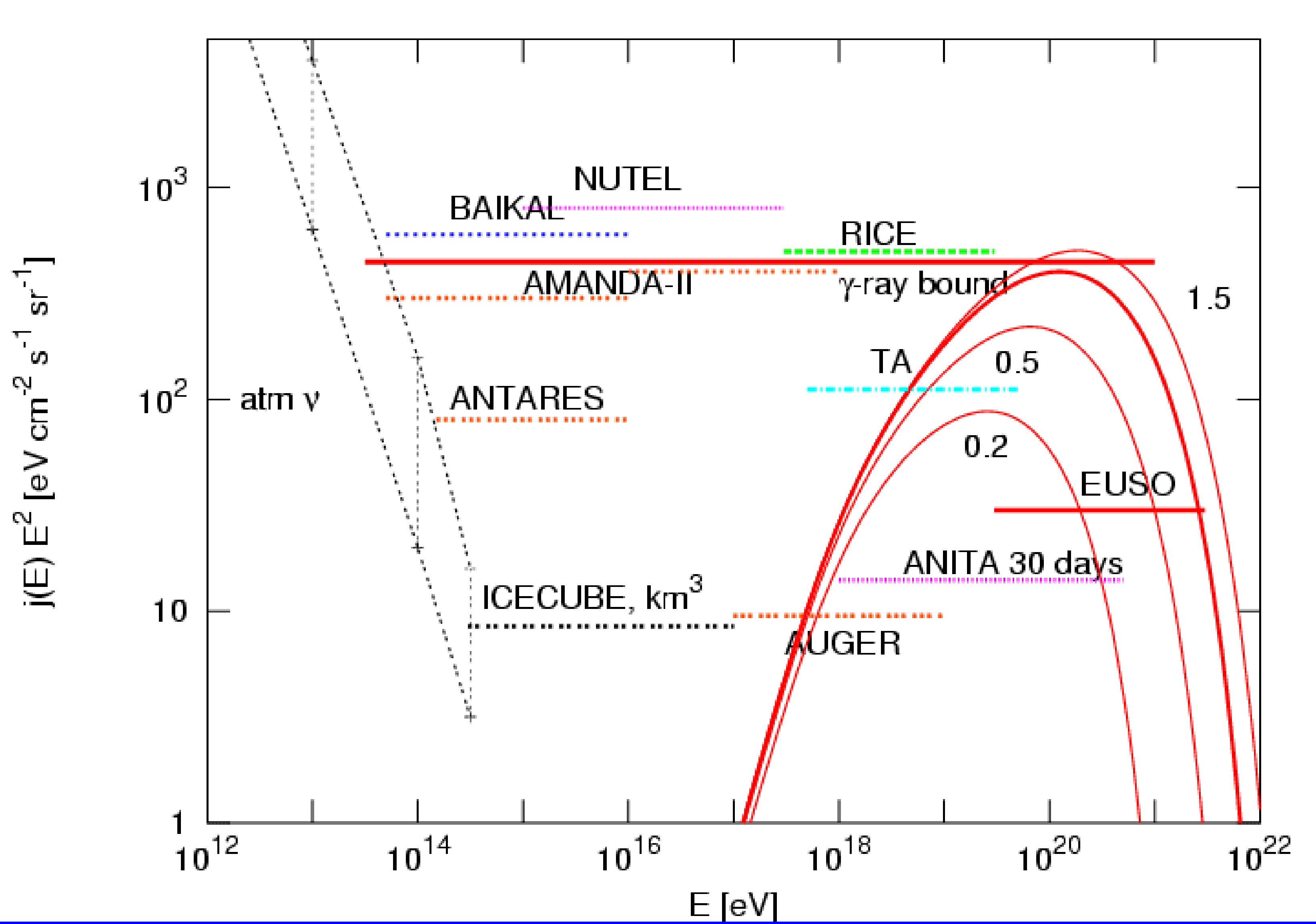
Semikoz, Sigl, hep-ph/0309328

Existing Neutrino Limits



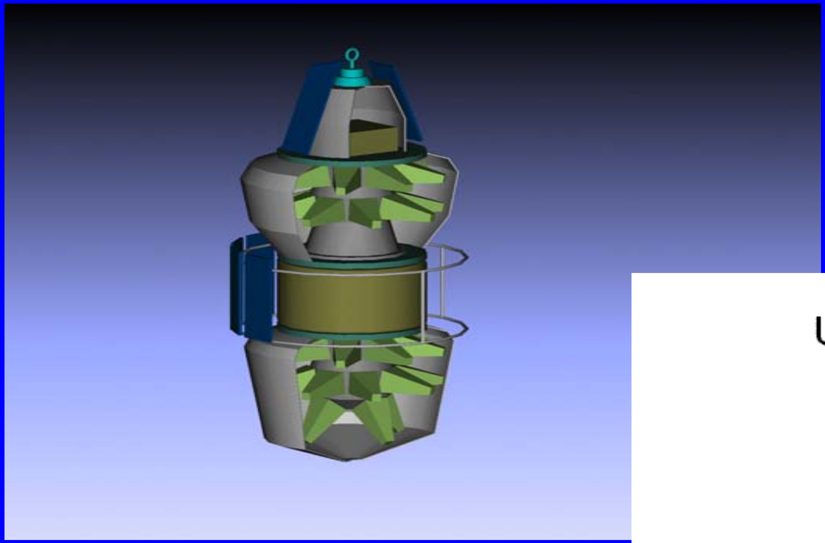
Semikoz, Sigl, hep-ph/0309328

Future Neutrino Sensitivity



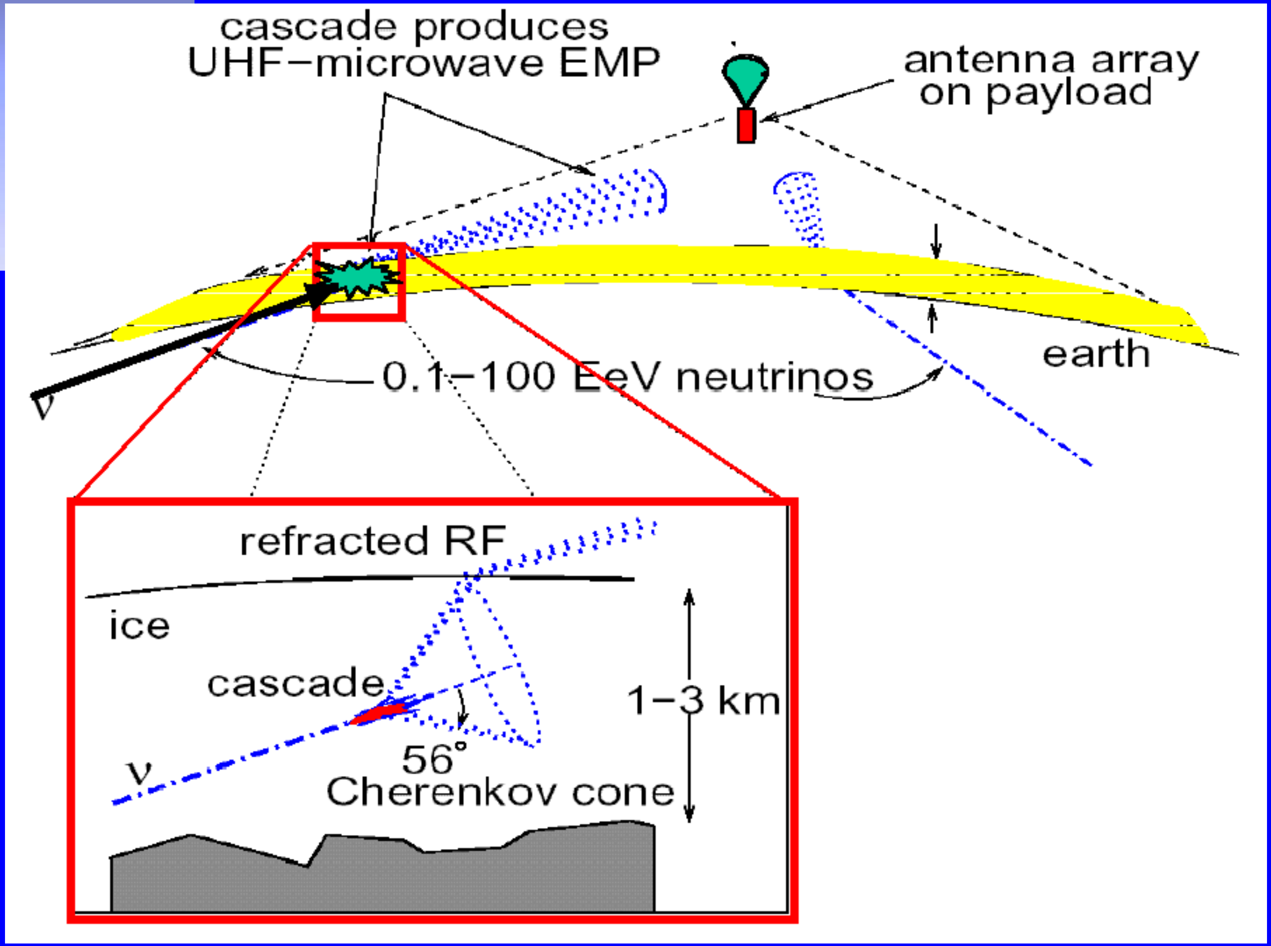
Semikoz, Sigl, hep-ph/0309328

ANITA



Funded 2003

Flies 2006



Other Physics

- Neutrino-nucleon cross section at high energies
  Domokos, Kovesi-Domokos, Burgett, Wrinkle, JHEP 0107, 017 (2001);
  Tyler, Olinto, Sigl, PRD 63, 055001 (2001);
  Jain, Kar, McKay, Panda, Ralston, PRD 66, 065018 (2002);
  Anchordoqui, Feng, Goldberg, Shapere, PRD 66, 103002 (2002);
  Friess, Han, Hooper, PLB 547, 31 (2002)

- Z-bursts, supermassive dark matter, top-down
  Gorbunov, Tinyakov, Troitsky, Astropart. Phys. 18, 463 (2003);
  Jones, Mocioiu, Reno, Sarcevic, hep-ph/0308042;
  Fodor, Katz, Ringwald, Tu, hep-ph/0309171

- New astrophysical sources

- New tests of neutrino properties

Astrophysical Neutrinos: Searching Very Low

Supernovae

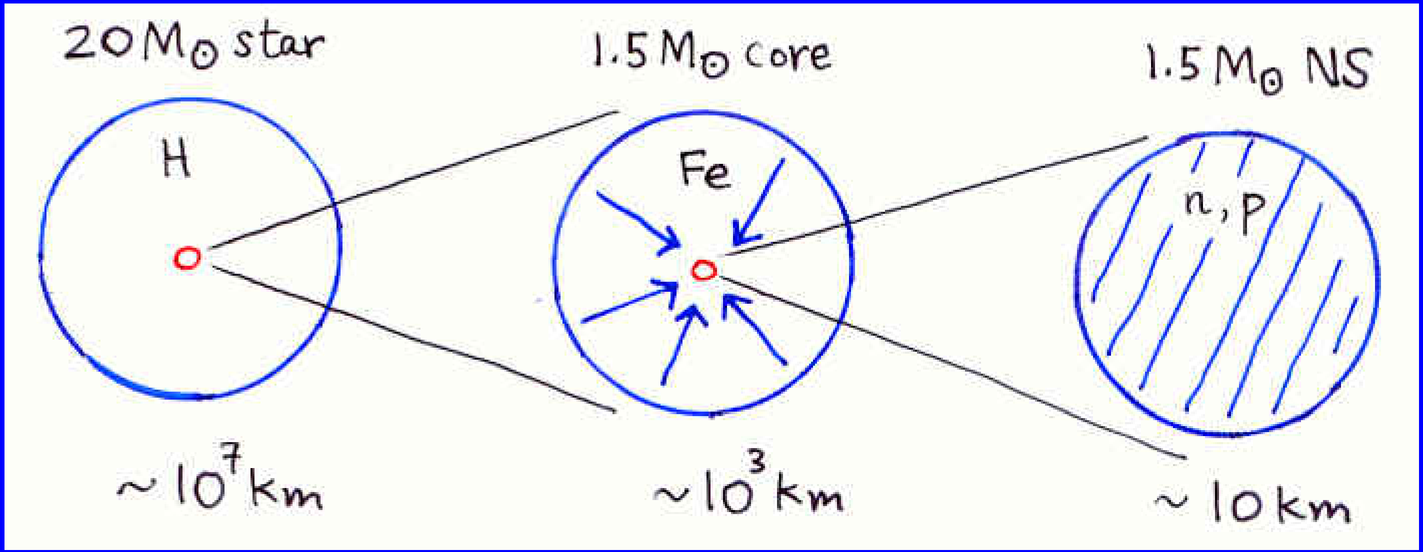
SN1999dk, z = 0.015

SN Rates

SN Detection

Modeling (1d, 2d, 3d)

Supernova Energetics

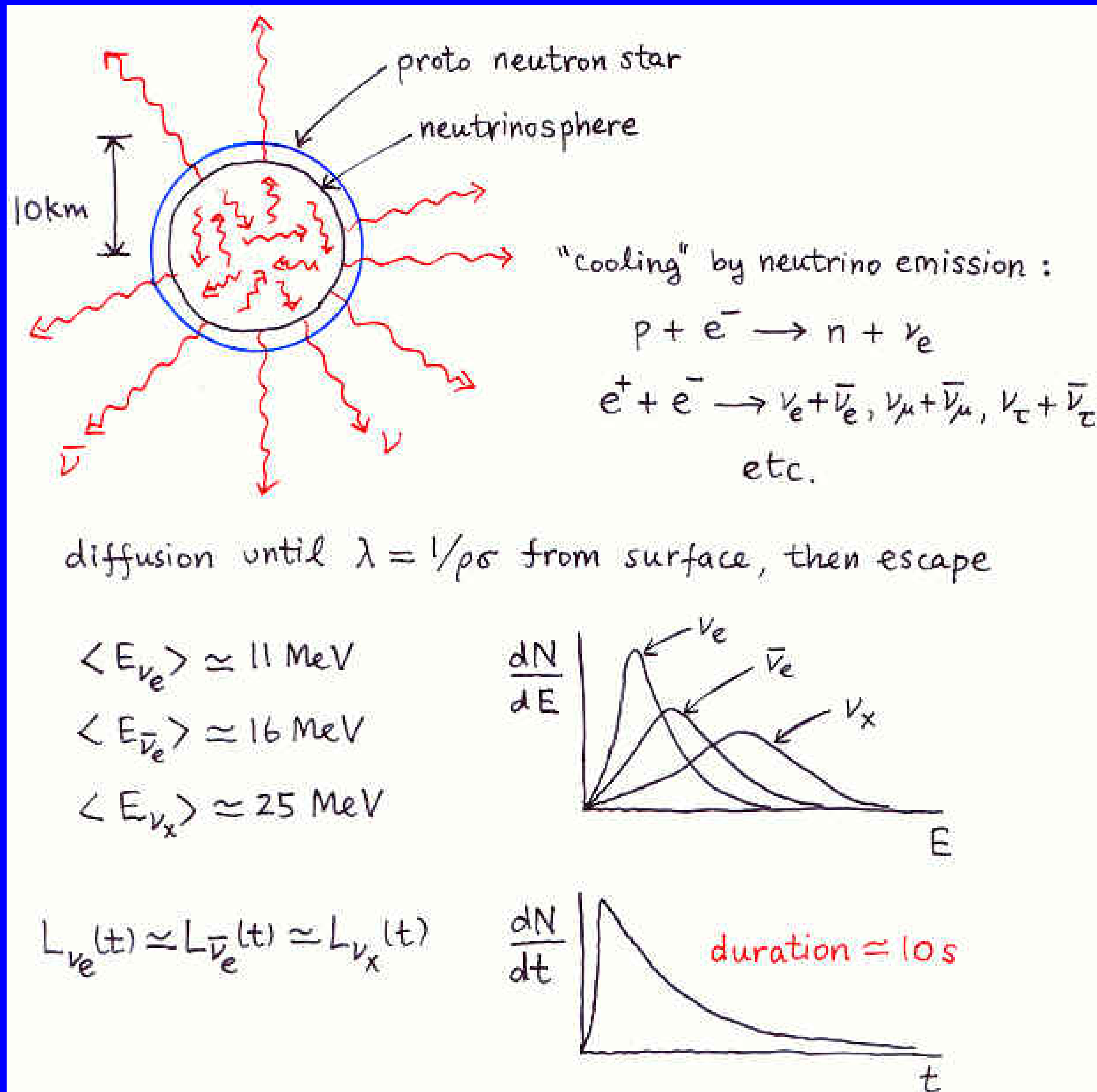


$$\Delta E_B \simeq \frac{3}{5}\frac{G M_{NS}^2}{R_{NS}} - \frac{3}{5}\frac{G M_{NS}^2}{R_{core}} \simeq 3 \times 10^{53} \text{ ergs} \simeq 2 \times 10^{59} \text{ MeV}$$

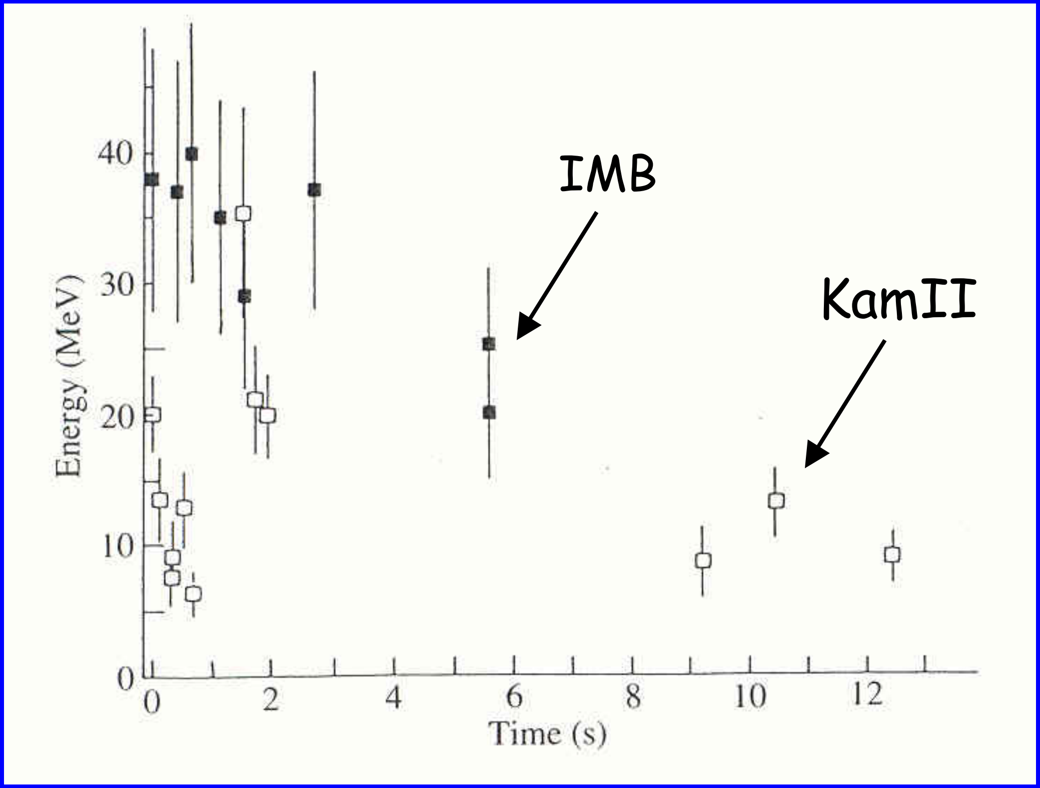
K.E. of explosion $\simeq 10^{-2}\,\Delta E_B$

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

Supernova Neutrino Emission



Supernova Neutrino Detection



SN1987A :

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

SN200?? :

~ 10^4 CC events

~ 10^3 NC events

Supernova physics (models, black holes, progenitors…)

Particle physics (neutrino properties, new particles, …)

Waiting Is Boring

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

Supernova Neutrino Background

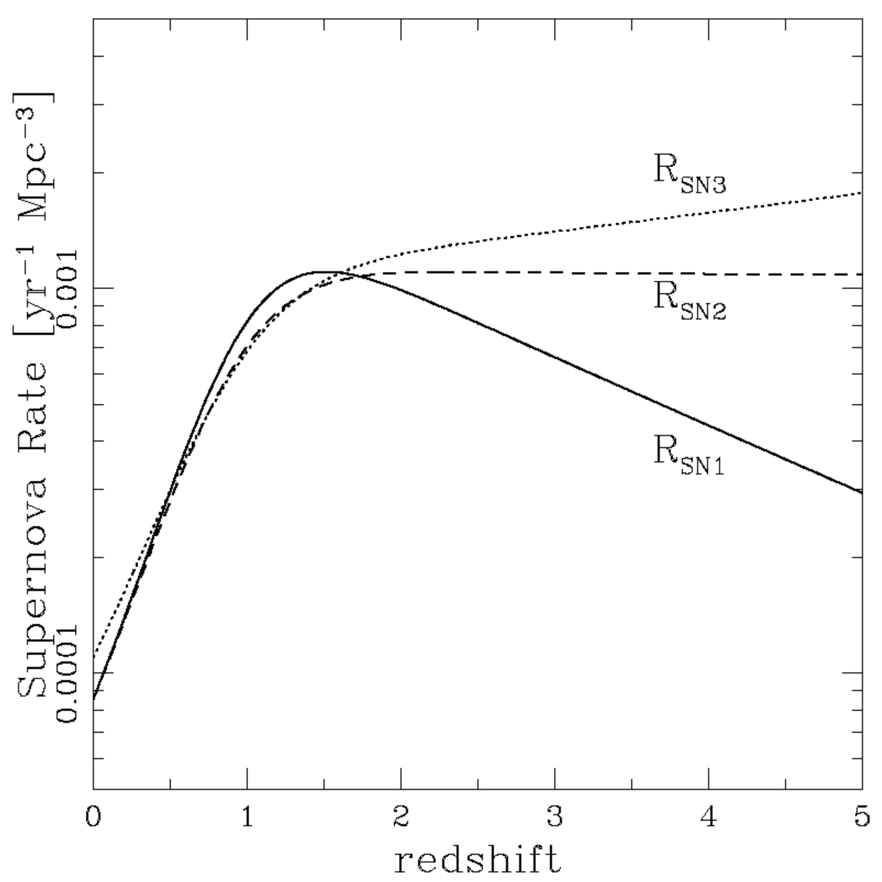


Fig. 2. Supernova rate evolution on the cosmological time scale. These lines are for a Λ-dominated cosmology ($\Omega_m = 0.3, \Omega_\lambda = 0.7$). The Hubble constant is taken to be 70 km s^{-1} Mpc^{-1}.

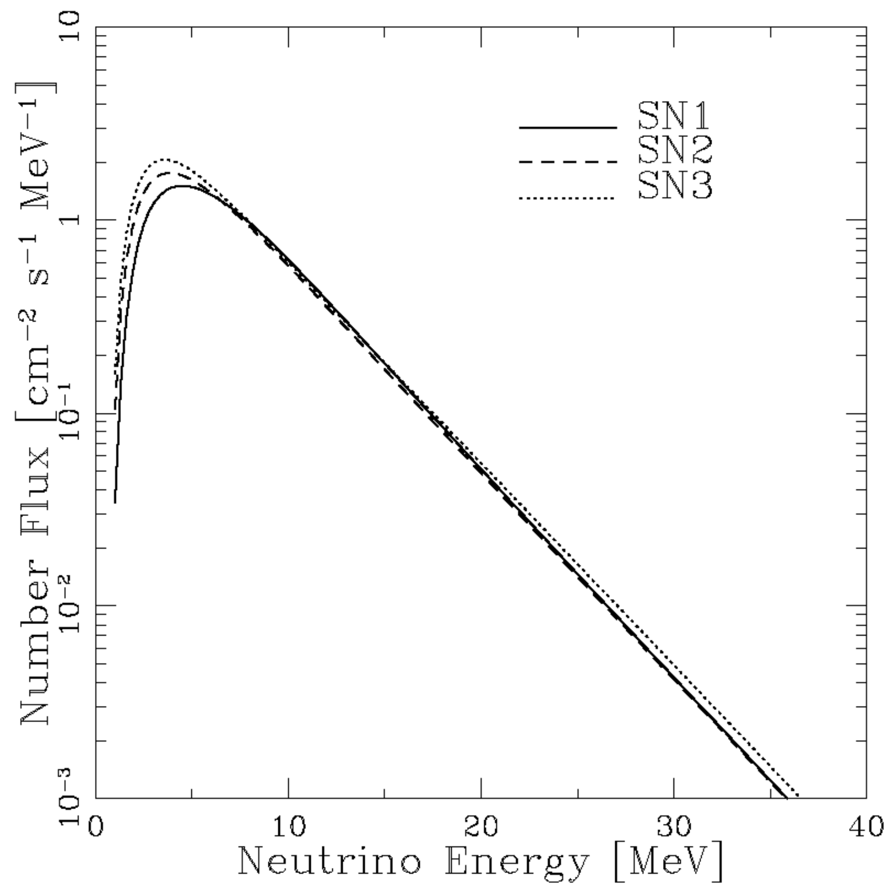
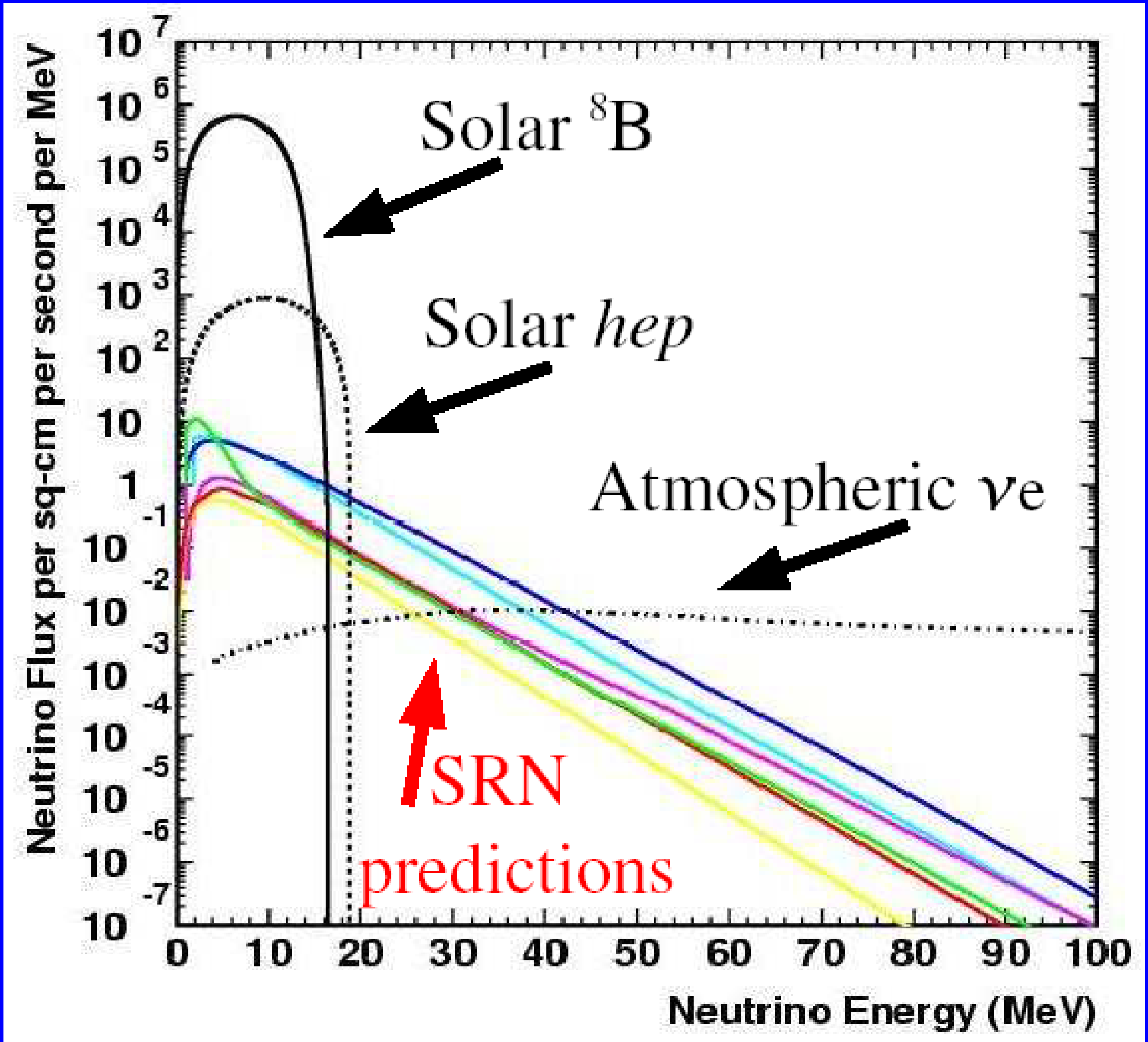


Fig. 3. Number flux of $\bar{\nu}_e$'s for the three supernova rate models, assuming "no oscillation" case.

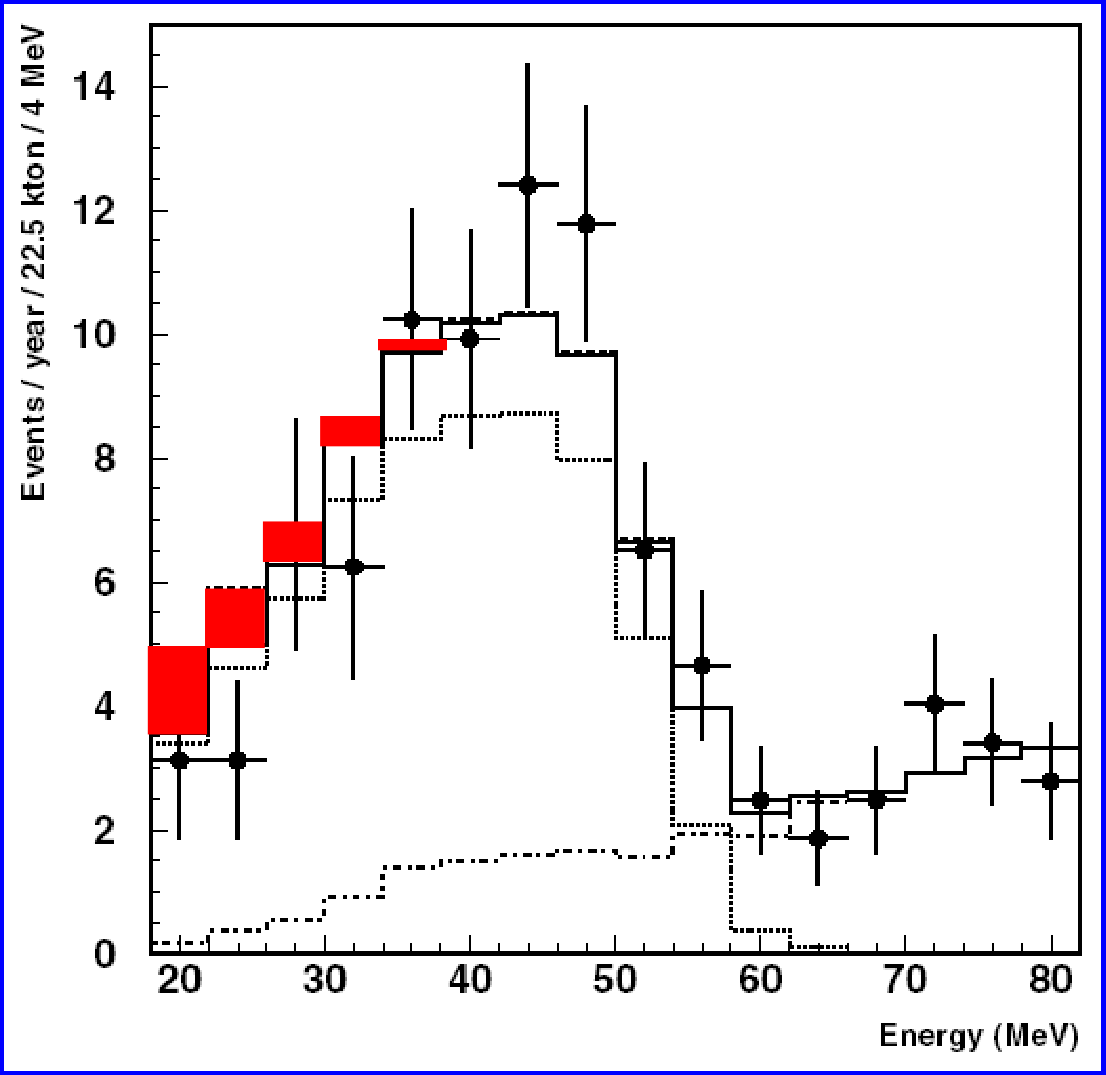
Ando, Sato, and Totani, Astropart. Phys. 18, 307 (2003)

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"

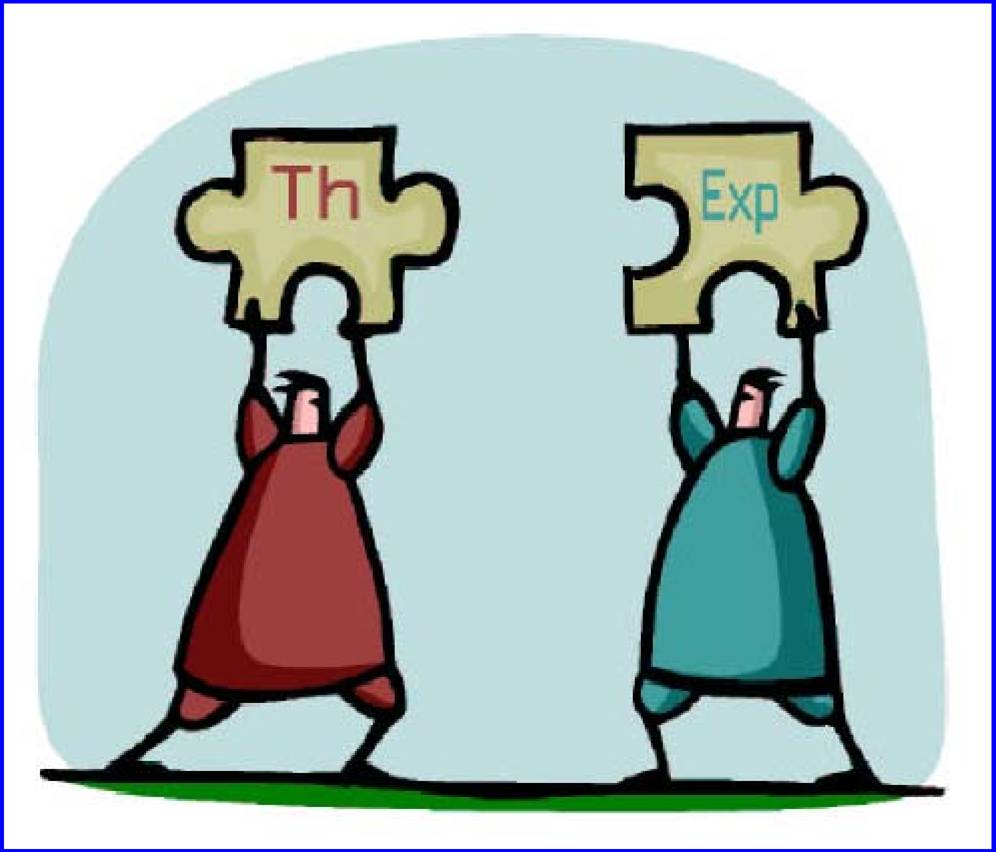
$$\sigma \simeq 0.095(E_\nu - 1.3\,MeV)^2\, 10^{-42} cm^2$$

$$E_e \simeq E_\nu - 1.3\,MeV$$

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

- We must detect the neutron, but how?

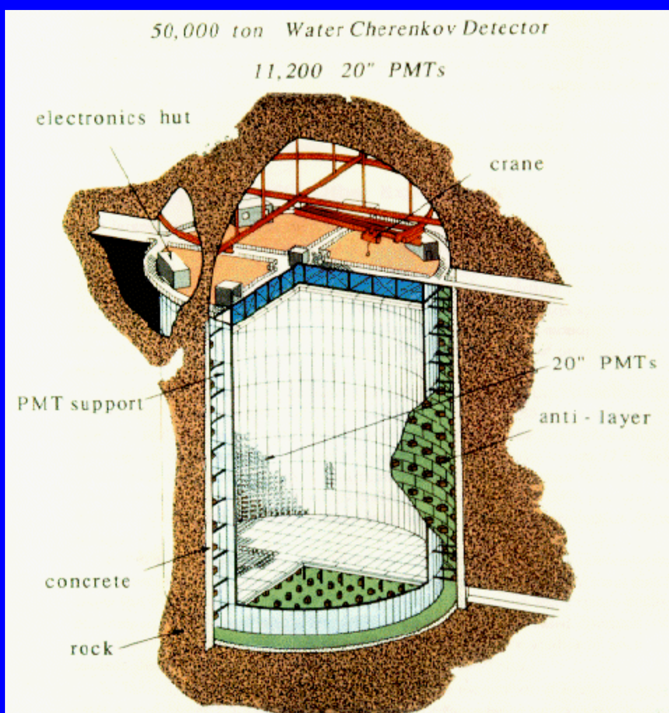
A Proposed Solution



John Beacom and Mark Vagins, hep-ph/0309300

Add Gadolinium to SK?

GADZOOKS!



Gadolinium
Antineutrino
Detector
Zealously
Outperforming
Old
Kamiokande,
Super!

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

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:	$4/kg	$400,000/SK

Important $GdCl_3$ Properties

- *Soluble* in water (unlike mineral oil)
- Initial chemical and radiological purity excellent
- Initial water transparency tests excellent
- 100 tons? No problem
- Gadolinium used in MRI contrasting agents
- You could drink 12 liters of GADZOOKS! water every day

Gadolinium Supplements

Try "gadolinium health buy" in Google

1.25 ng/liter Gadolinium

"Supports healthy cellular functions"

"Not carcinogenic"

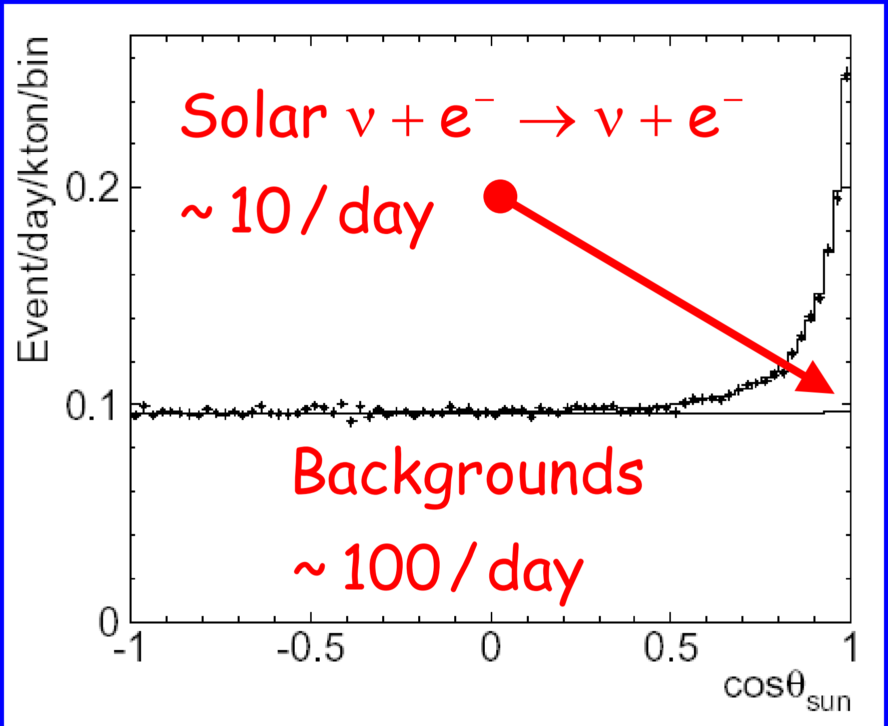
Note: sea water is 0.7 ng/liter Gadolinium

But it doesn't come in raspberry flavor

Neutron Backgrounds in SK

Don't want captures on Gd to dilute the solar signal

How many neutrons are in SK anyway?



•Spallation ~ 10^5/day but can be easily cut

•Reactor ~ 20/day (more likely a signal!)

•^{152}Gd decay 10^{10} alpha/day, P(alpha,n) on ^{17}O is 10^{-10}

•U/Th contamination in $GdCl_3$ must be controlled

Correlated Backgrounds

- Singles event rate above 5 MeV is ~ 1/ton/year
  so accidental background rate is vanishing

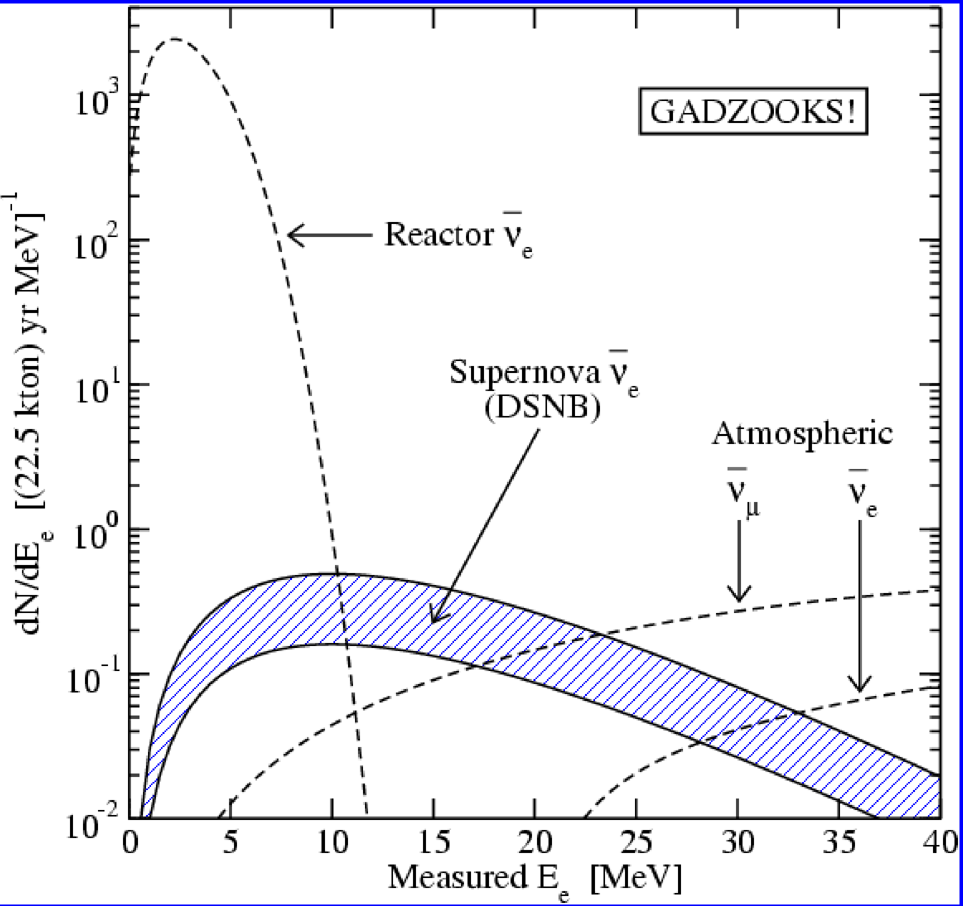
- $^{8}He/^{9}Li/^{11}Li$ produced by spallation
  Beta decay followed by neutron emission
  Rare, controlled by timing and energy cuts

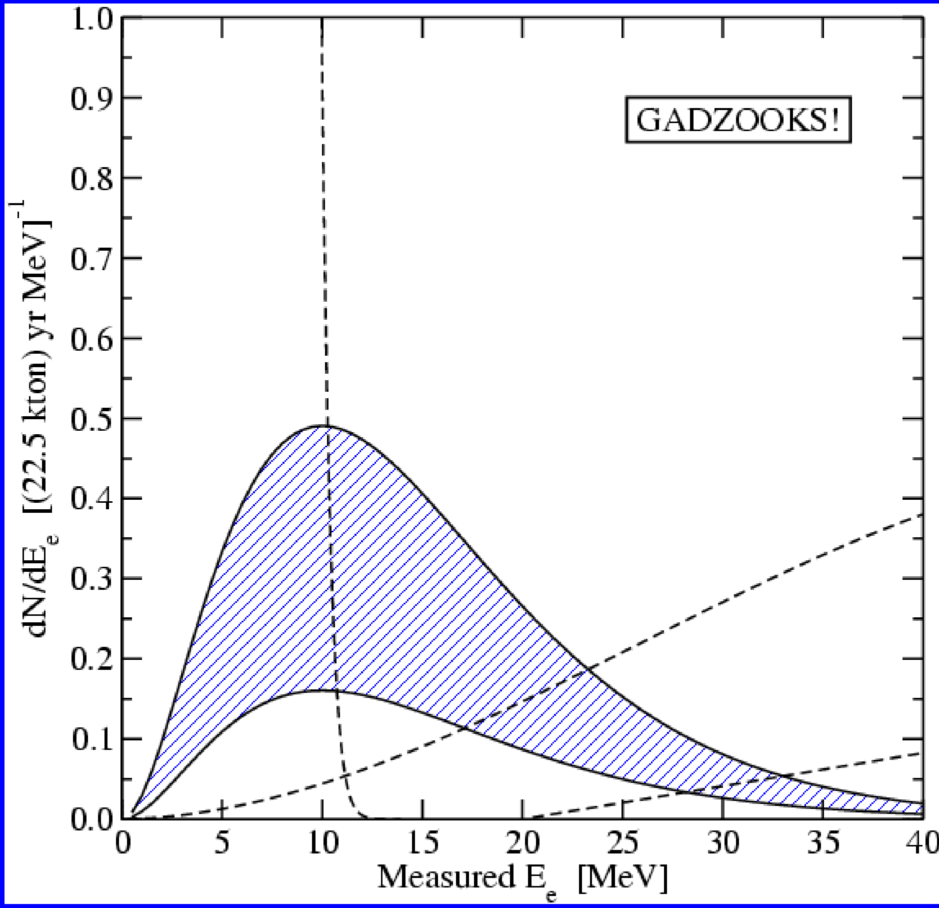
- Reactor $\bar{\nu}_e + p \rightarrow e^+ + n$

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

- Atmospheric $\bar{\nu}_\mu + p_{bound} \rightarrow \mu^+_{invisible} + n_{free} + invisible$

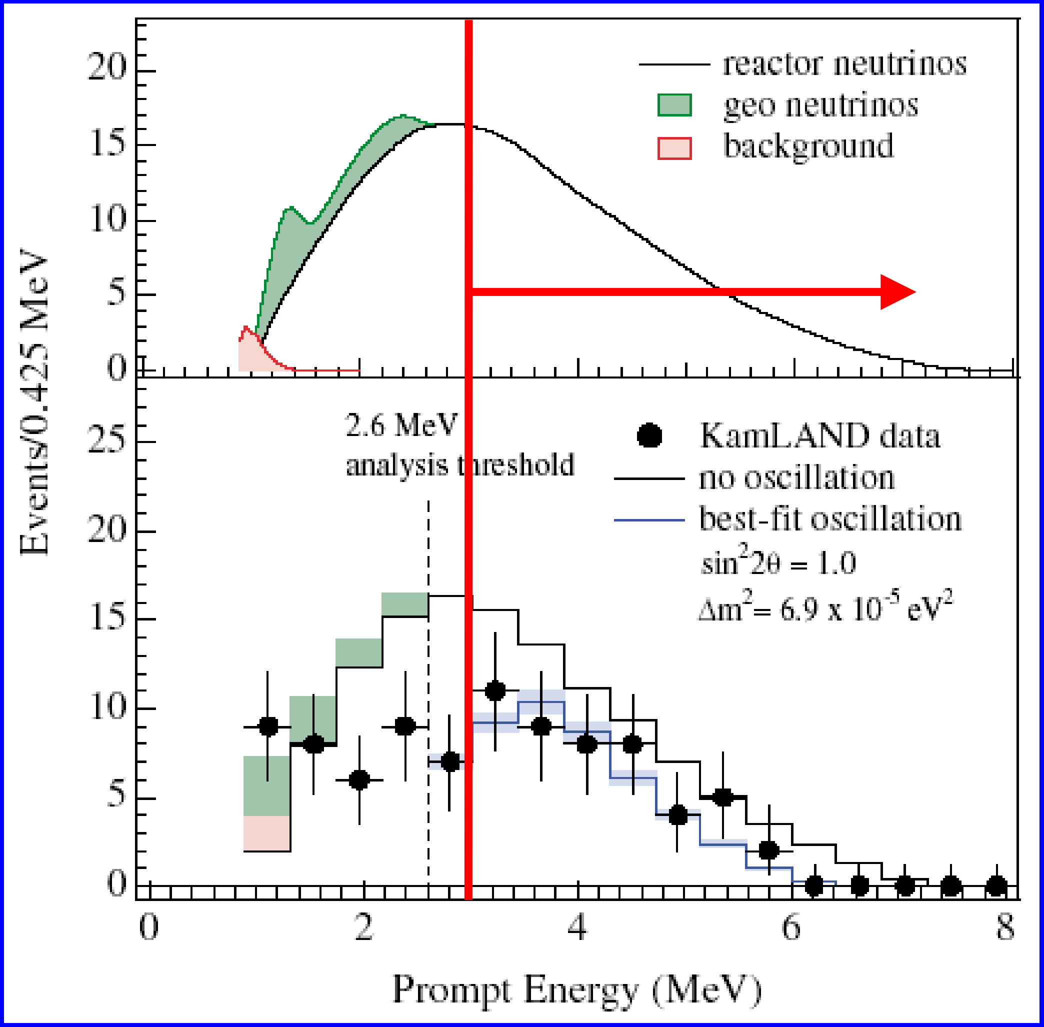
Spectrum With GADZOOKS!





Beacom and Vagins, hep-ph/0309300

Reactor Antineutrinos



KamLAND first data
0.16 kton yr

Just 3 days in
SK GADZOOKS!

"High" energies only,
less resolution

Eguchi et al. (KamLAND), PRL 90, 021802 (2003)

Galactic Supernova Detection

$\simeq 8000 \quad \bar{\nu}_e + p \rightarrow e^+ + n$

$\simeq 700 \quad \nu + {}^{16}O \rightarrow \nu + \gamma + X \quad (E = 5 - 10\ \text{MeV})$

$\simeq 300 \quad \nu + e^- \rightarrow \nu + e^- \quad (e^-\ \text{is forward})$

$\sim 100 \quad \nu_e + {}^{16}O \rightarrow e^- + X \quad (\text{buried})$

$\bar{\nu}_e + {}^{16}O \rightarrow e^+ + X$

With GADZOOKS!, we can separate reactions

Real chance to see CC reactions on ${}^{16}O$
Haxton, PRD 36, 2283 (1987)
Oscillations can increase those yields by ~ 10

Atm. Neutrinos and Proton Decay

- Atmospheric neutrino charged-current interactions

$$\bar{\nu}_\ell + p_{bound}(^{16}O) \rightarrow \ell^+ + n_{free} + X$$

$$\nu_\ell + n_{bound}(^{16}O) \rightarrow \ell^- + p_{free} + X$$

Flux ratio predictions
Matter effects in oscillations
CPT violation (Barenboim, Lykken, et al.) tests

- Nucleon decay

γ, γp, γn from ^{15}O and ^{15}N

following $N \rightarrow K\nu$

Conclusions

- GADZOOKS!
  Propose to add 0.2% $GdCl_3$ to Super-Kamiokande
  (Beacom and Vagins, paper in preparation)

- Potentially quick and inexpensive

- *Detect* the Supernova Neutrino Background (SNB)
  - Astrophysical neutrinos from redshift z ~ 0.5
  - Unique probe of the *dark* supernova rate
  - Measurement of supernova neutrino spectrum
  - New tests of neutrino properties

- New results on reactor, solar, atmospheric, and nucleon decay

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 ~ $(1\ \text{meV})^4 \sim m^4$?

- 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!

Conclusions

Not the beginning of the end in neutrino physics, but just the end of the beginning.

Neutrino astrophysics, lots of data just ahead,
On three frontiers:
1-10^4 TeV: AGN, GRB, etc in IceCube, others
10^6 TeV: GZK, Z-burst, SDM, etc
10^-6 TeV: supernova in GADZOOKS!

Neutrino telescopes approaching comparable sensitivity to photon observations.

Also key for testing dark matter models.

Lutefisk

Codfish soaked in lye (HNaO, see Material Safety Data Sheet)