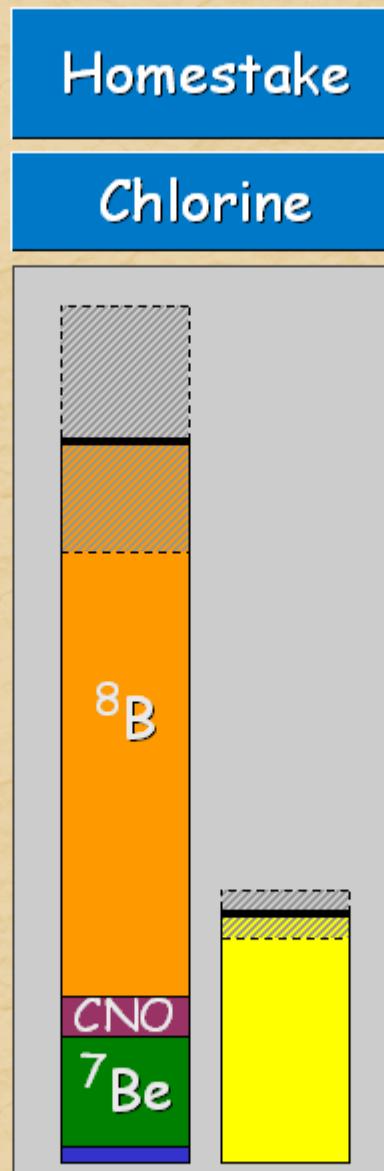
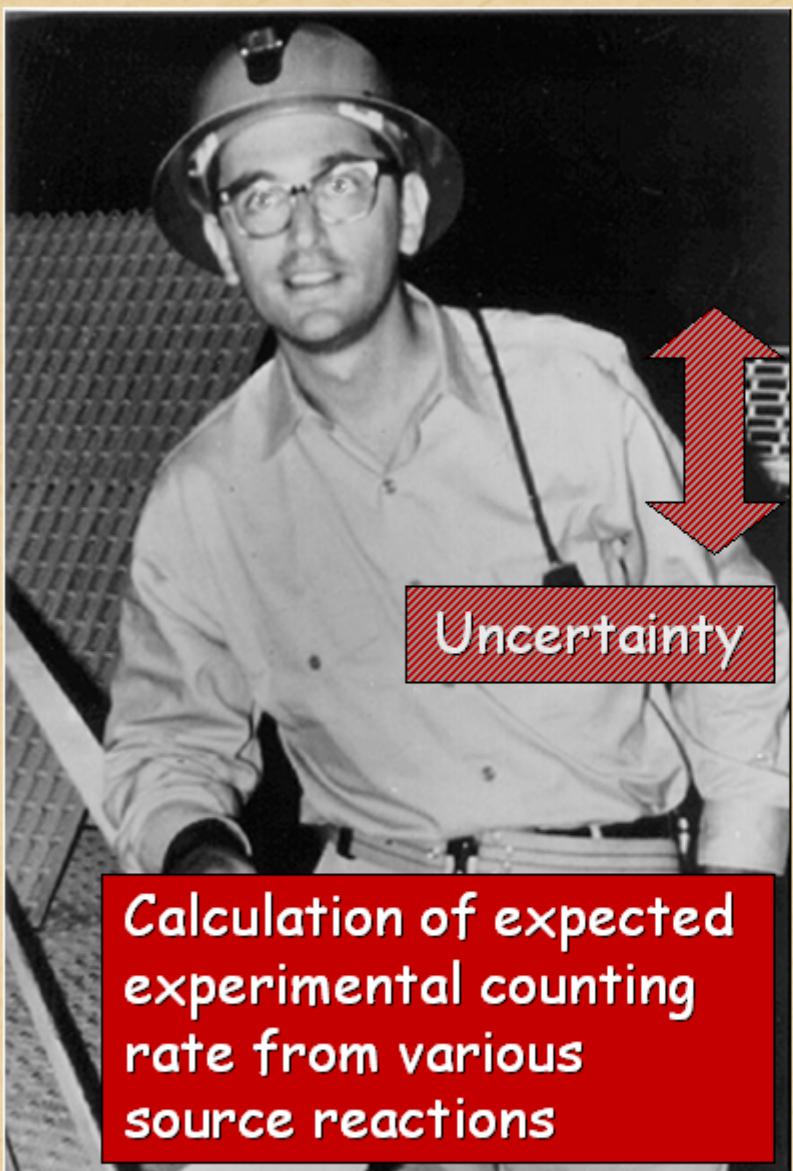


Neutrinos

Georg G. Raffelt

Max-Planck-Institut für Physik, München

Missing Neutrinos from the Sun



John Bahcall

Raymond Davis Jr.

Neutrino Flavor Oscillations

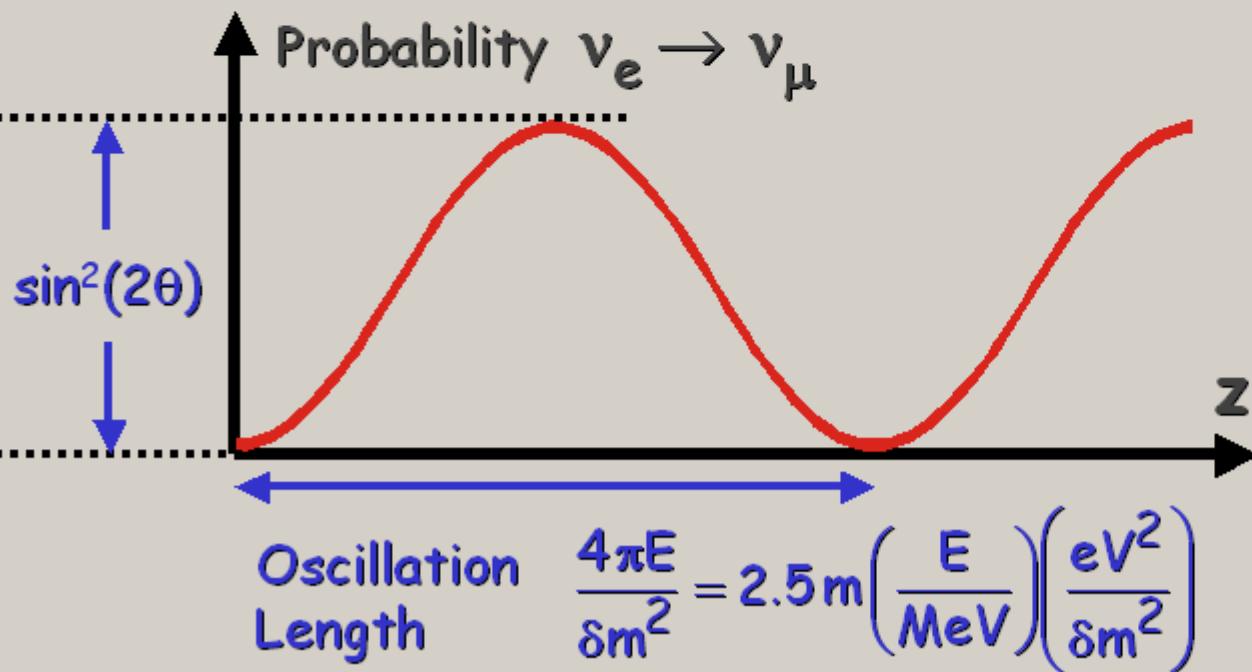
Two-flavor mixing

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

Each mass eigenstate propagates as e^{ipz}

with $p = \sqrt{E^2 - m^2} \approx E - \frac{m^2}{2E}$

Phase difference $\frac{\delta m^2}{2E} z$ implies flavor oscillations



Bruno Pontecorvo
(1913 - 1993)
Invented nu oscillations

Missing Neutrinos from the Sun

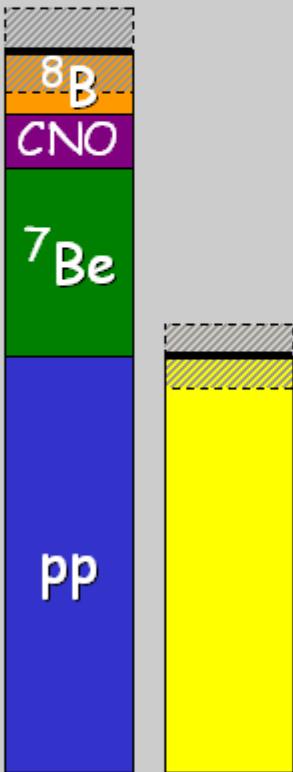
Electron-Neutrino Detectors

All Flavors

Chlorine



Gallium



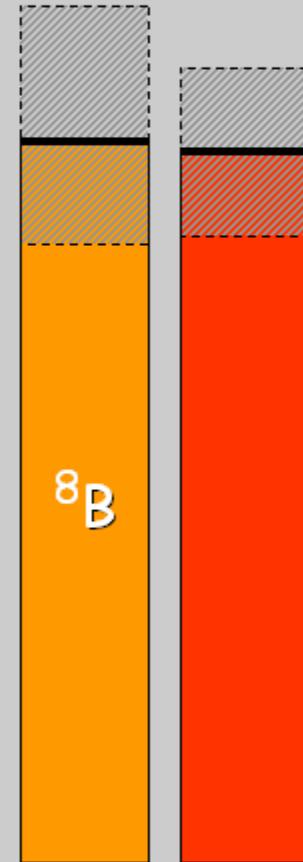
Water
 $\nu + e^- \rightarrow \nu + e^-$



Heavy Water
 $\nu_e + d \rightarrow p + p + e^-$



Heavy Water
 $\nu + d \rightarrow p + n + \nu$



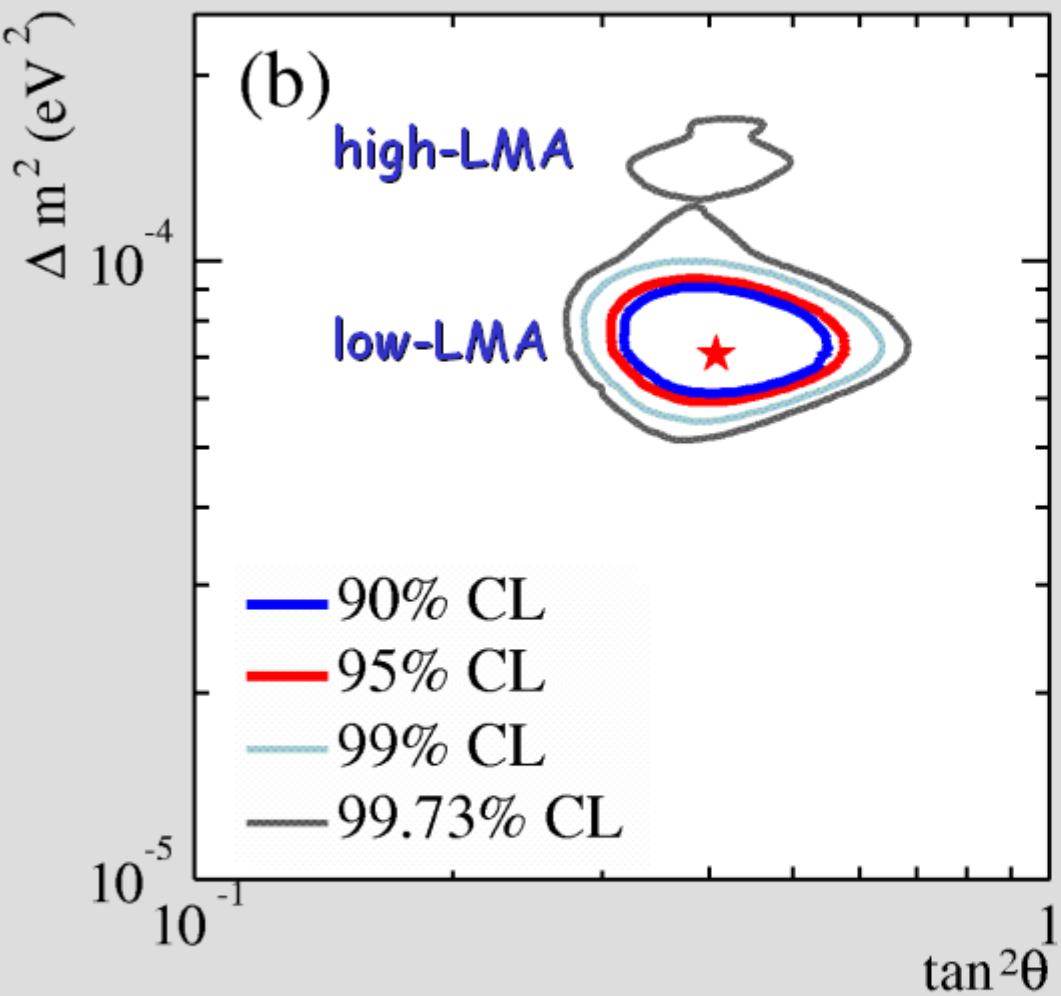
Homestake

Gallex/GNO
SAGE

(Super-)
Kamiokande

SNO

Solar & KamLAND Mixing Parameters



Main features

- Oscillation channel $\nu_e \rightarrow \nu_{\mu\tau}$ (not sterile – full flux at SNO)
- Mass ordering normal ("light side" of mixing angle, medium effect crucial for this information)
- Mixing angle large but not maximal (at 5.4σ after SNO w/salt)
- Good fit to all data

SNO Collaboration, nucl-ex/0309004

Three-Flavor Neutrino Parameters

Atmospheric/K2K

$$37^\circ < \theta_{23} < 55^\circ$$

CHOOZ

$$\theta_{13} < 11^\circ$$

Solar/KamLAND

$$30^\circ < \theta_{12} < 37^\circ$$

2σ ranges

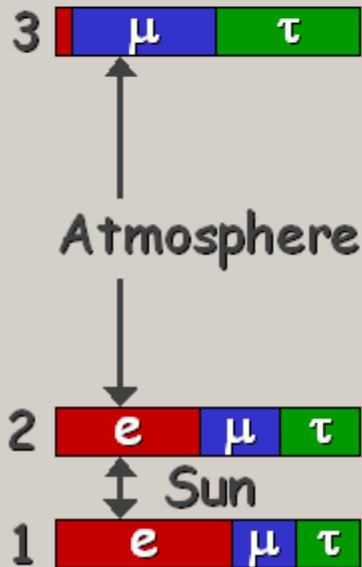
hep-ph/0309130

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & & \\ c_{23} & s_{23} & \\ -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & e^{-i\delta} s_{13} & 1 \\ -e^{i\delta} s_{13} & c_{13} & \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

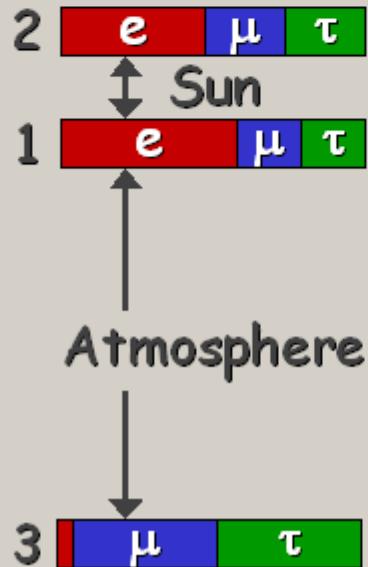
$c_{12} = \cos \theta_{12}$ etc., δ CP-violating phase

Solar
60 – 84
Atmospheric
1800 – 3300
 $\Delta m^2 / \text{meV}^2$

Normal



Inverted



Tasks and Open Questions

- Precision for θ_{12} and θ_{23}
- How large is θ_{13} ?
- CP-violating phase?
- Mass ordering?
(normal vs inverted)
- Absolute masses?
(hierarchical vs degenerate)
- Dirac or Majorana?

Upcoming Long-Baseline Experiments

FermiLab-Soudan (MINOS)



CERN - Gran Sasso

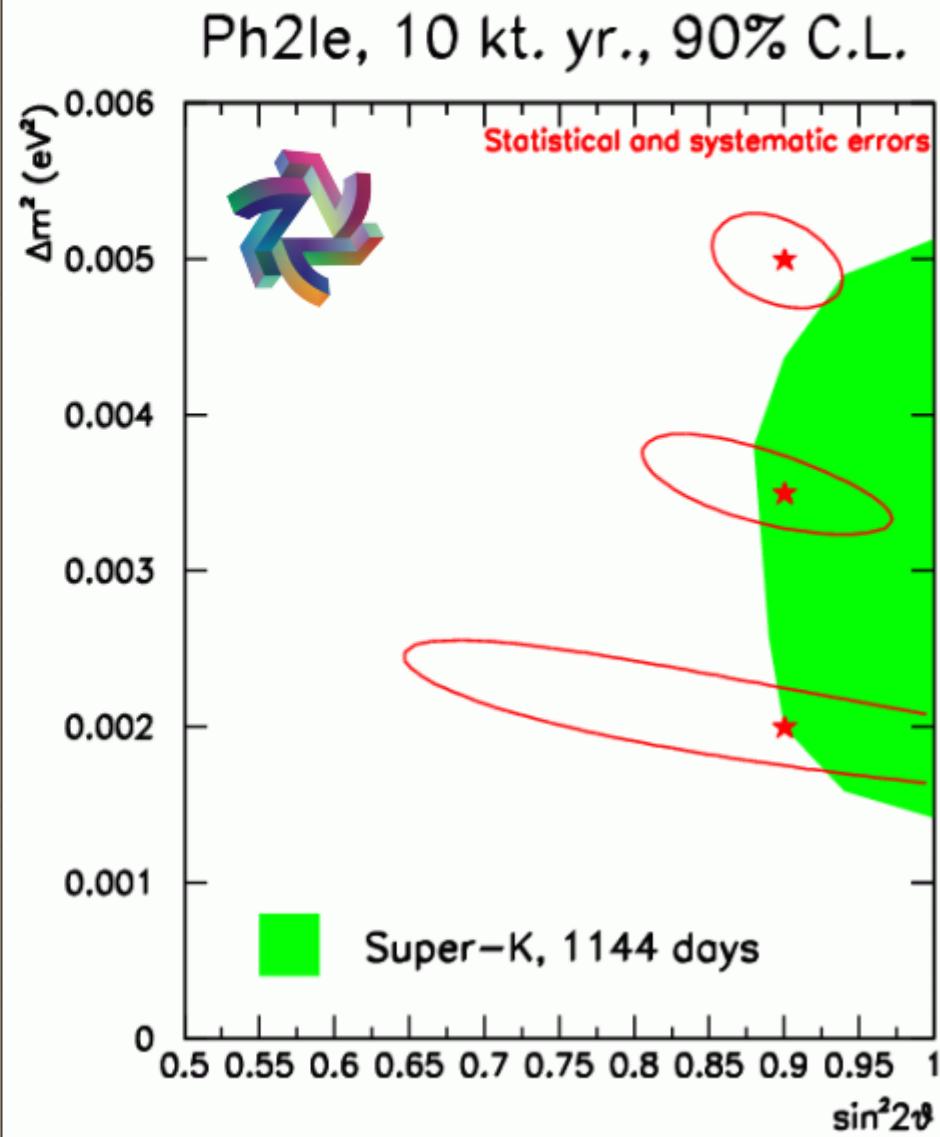


Upcoming Long-Baseline Experiments

FermiLab-Soudan (MINOS)



Sensitivity to Oscillations



JHF-Kamioka Neutrino Experiment

(hep-ex/0106019)

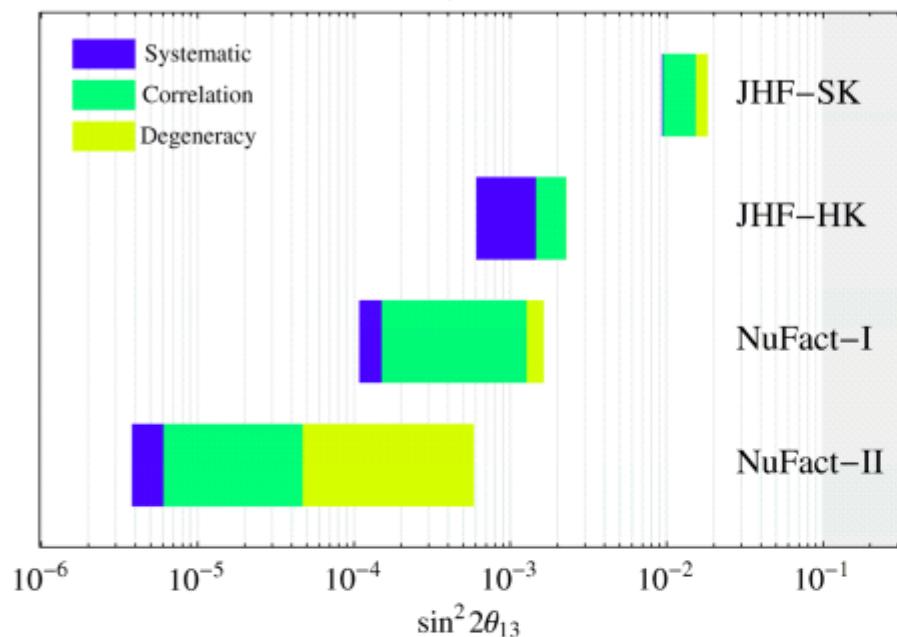


JHF 0.75MW + Super-Kamiokande

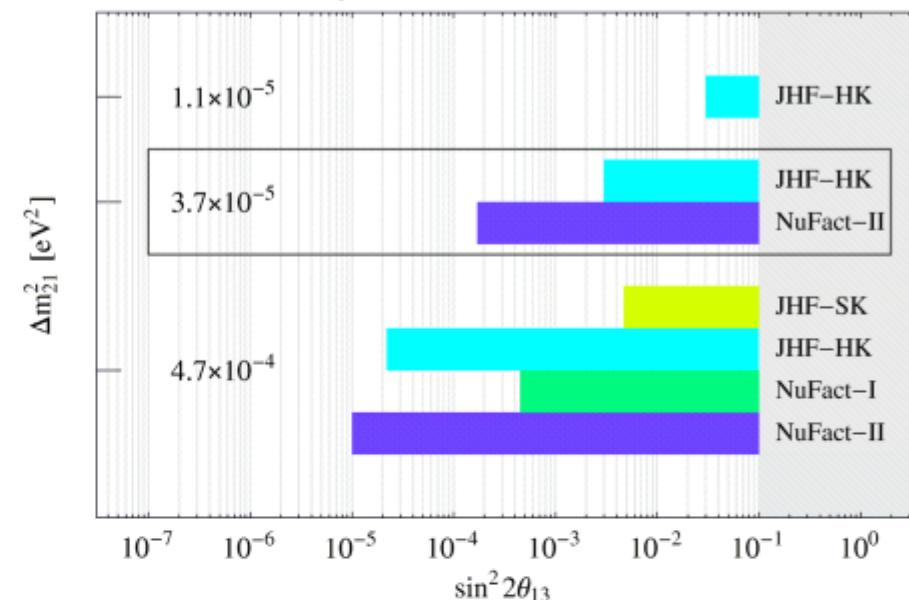
Future Super-JHF 4MW + Hyper-K ~ JHF+SK × 200

Sensitivity to Θ_{13} and CP violation

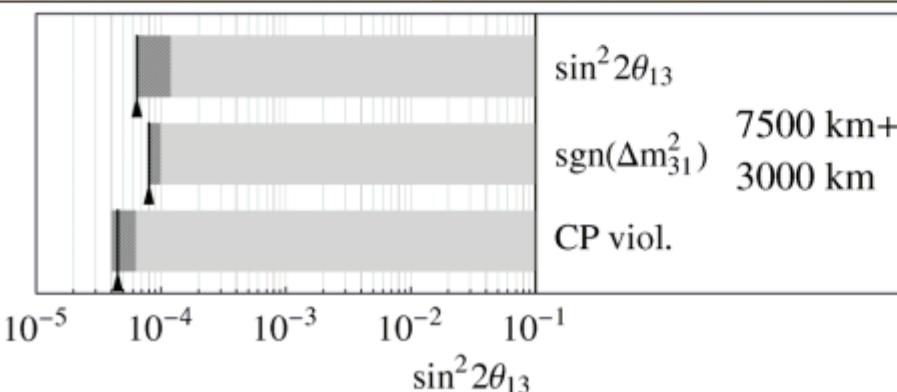
Sensitivity to $\sin^2 2\theta_{13}$



Sensitivity to CP-Violation at $\delta_{CP} = +\pi/2$



Huber, Lindner & Winter: Superbeams vs neutrino factories
[hep-ph/0204352](https://arxiv.org/abs/hep-ph/0204352)



Huber & Winter:
 Neutrino factories and the
 "Magic baseline" (hep-ph/0301257)

Clean up degeneracies with two
 baselines

Neutrino Oscillations with a Long Baseline

The three-flavor oscillation probability at a long-baseline (LBL) experiment can be expanded in the small mixing angle $\sin 2\Theta_{13} < 0.3$

and the small hierarchy parameter $\alpha = \frac{\Delta m_{21}^2}{\Delta m_{31}^2} \approx 0.03$

Other parameters: $\xi = \cos \Theta_{13} \sin 2\Theta_{12} \sin 2\Theta_{23}$, $A = \pm \frac{2\sqrt{2}G_F n_e E}{\Delta m_{31}^2}$, $\Delta = \frac{\Delta m_{31}^2 L}{4E}$

Up to α^2 and $\sin^2(2\Theta_{13})$ the transition probability is

$$P(\nu_e \rightarrow \nu_\mu) = \sin^2 2\Theta_{13} \sin^2 \Theta_{23} \frac{\sin^2 [(1-A)\Delta]}{(1-A)^2} \quad (0)$$

$$+ \alpha \xi \sin 2\Theta_{13} (\cos \delta \cos \Delta \pm \sin \delta \sin \Delta) \frac{\sin(A\Delta)}{A} \frac{\sin[(1-A)\Delta]}{(1-A)} \quad (1)$$

$$+ \alpha^2 \cos^2 \Theta_{23} \sin^2 2\Theta_{12} \frac{\sin^2(A\Delta)}{A^2} \quad (2)$$

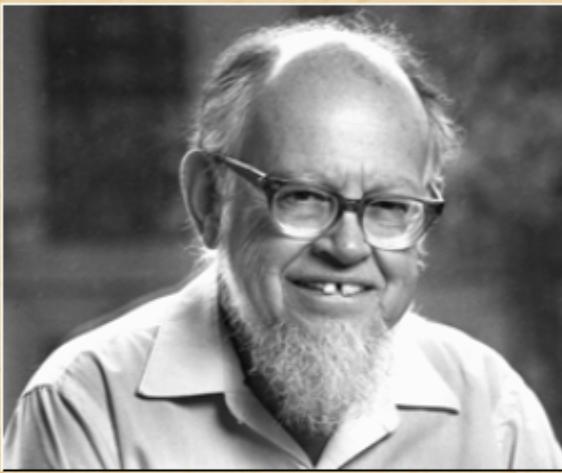
Lower sign for
 $P(\nu_\mu \rightarrow \nu_e)$

(1,2) disappear for "magic baseline" ~ 7500 km where $A\Delta \sim 0$,
assuming a neutrino factory with muon energy ~ 50 GeV

Fiducial Long-Baseline Configurations

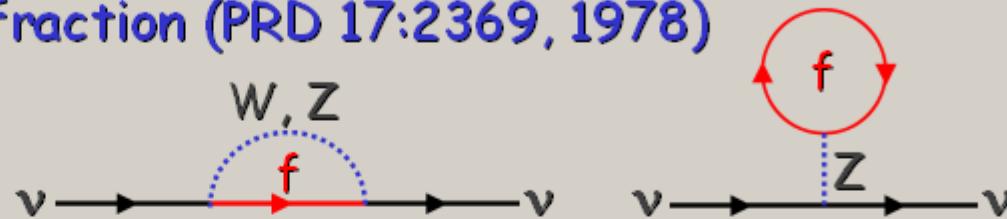
Setup	Baseline	Beam	Detector	Running
JHF-SK	295 km	0.75 MW	Water Cherenkov 23 kt fiducial	v 5 yr
JHF-HK		4 MW	Water Cherenkov 1000 kt fiducial	v 2 yr v 6 yr
NuFact I	3000 km	0.75 MW, $E_\mu = 50 \text{ GeV}$ 10^{20} useful μ decays per year	Magnetized iron calorimeter 10 kt fiducial	v 2.5 yr v 2.5 yr
NuFact II		4 MW, $E_\mu = 50 \text{ GeV}$ 5.3×10^{20} useful μ decays per year	Magnetized iron calorimeter 50 kt fiducial	v 4 yr v 4 yr

Neutrino Oscillations in Matter



Lincoln Wolfenstein

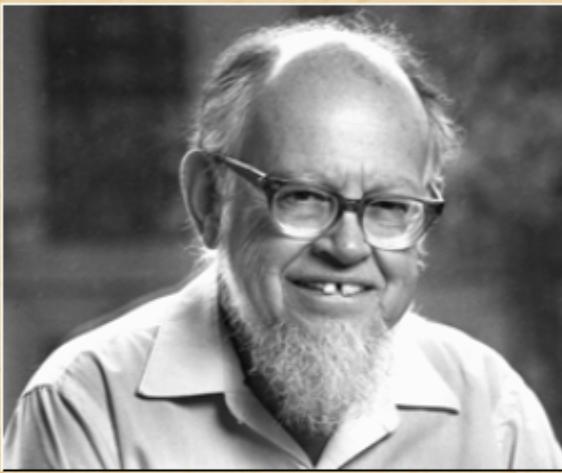
Neutrinos in a medium suffer flavor-dependent refraction (PRD 17:2369, 1978)



$$i \frac{\partial}{\partial z} \begin{pmatrix} v_e \\ v_\mu \end{pmatrix} = \left[\frac{M^2}{2E} + \sqrt{2} G_F \begin{pmatrix} n_e - \frac{1}{2} n_n & 0 \\ 0 & -\frac{1}{2} n_n \end{pmatrix} \right] \begin{pmatrix} v_e \\ v_\mu \end{pmatrix}$$

- "Level crossing" possible in a medium with a gradient (MSW effect)
For solar nus large flavor conversion anyway due to large mixing
Still important for 13-oscillations in supernova envelope
- Breaks degeneracy between Θ and $\pi/2 - \Theta$ (dark vs light side)
12 mass ordering for solar nus established
13 mass ordering (normal vs inverted) at future LBL or SN
- Discriminates against sterile nus in atmospheric oscillations
- CP asymmetry in LBL, to be distinguished from intrinsic CP violation
- Prevents flavor conversion in a SN core and within shock wave
- Strongly affects sterile nu production in SN or early universe

Neutrino Oscillations in Matter

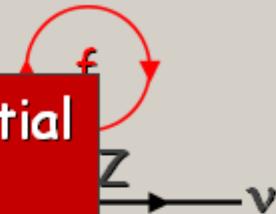


Lincoln Wolfenstein

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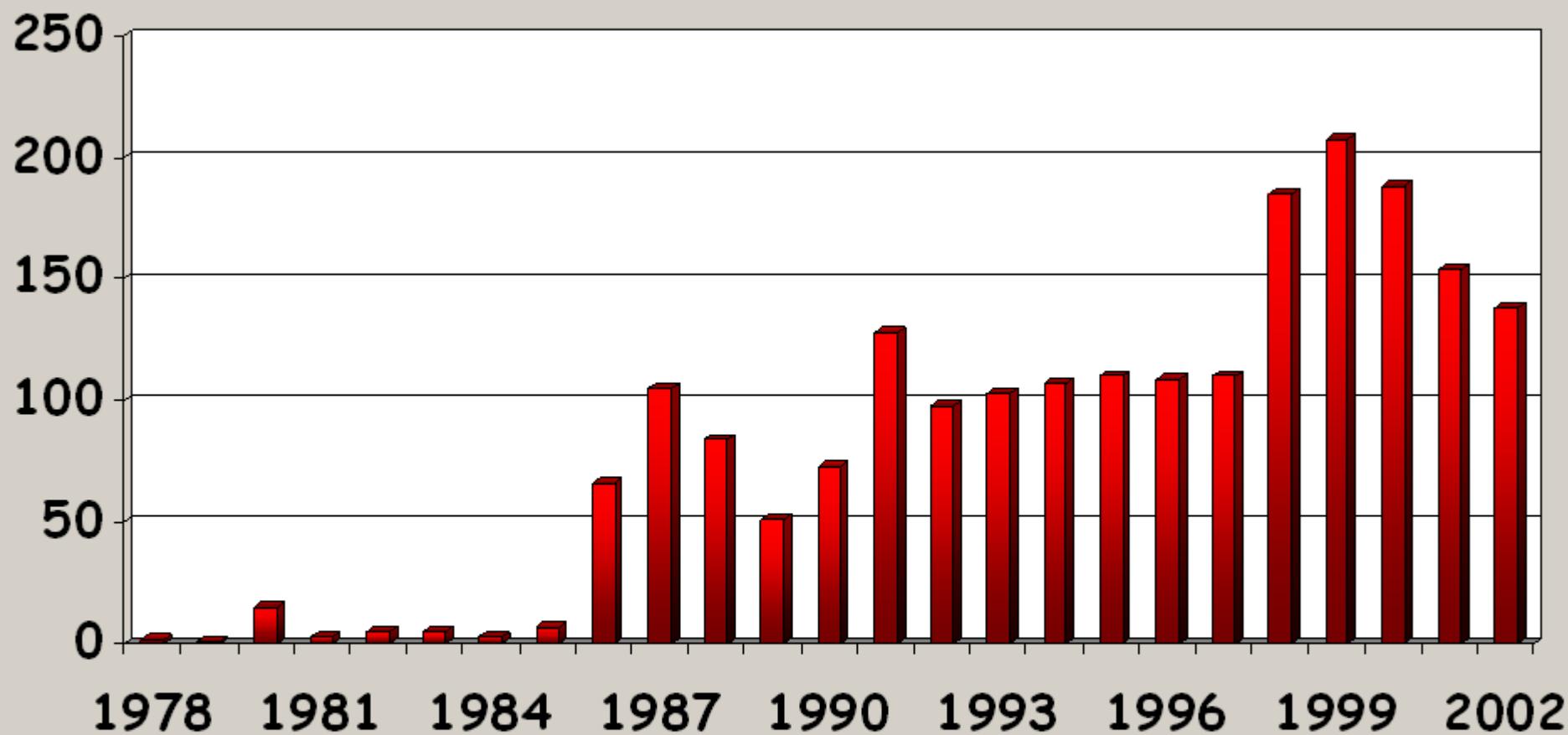
In Earth or Sun weak potential of order 10^{-13} eV

$$i \frac{\partial}{\partial z} \begin{pmatrix} v_e \\ v_\mu \end{pmatrix} = \left[\frac{M^2}{2E} + \sqrt{2} G_F \begin{pmatrix} n_e - \frac{1}{2} n_n & 0 \\ 0 & -\frac{1}{2} n_n \end{pmatrix} \right] \begin{pmatrix} v_e \\ v_\mu \end{pmatrix}$$



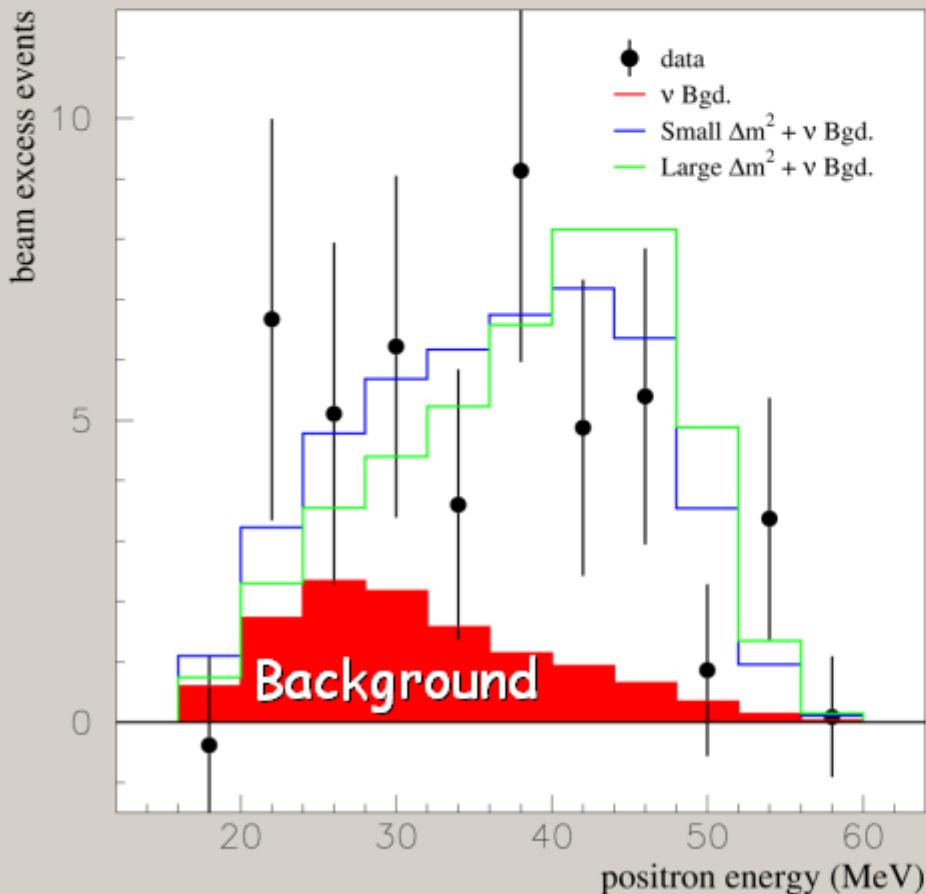
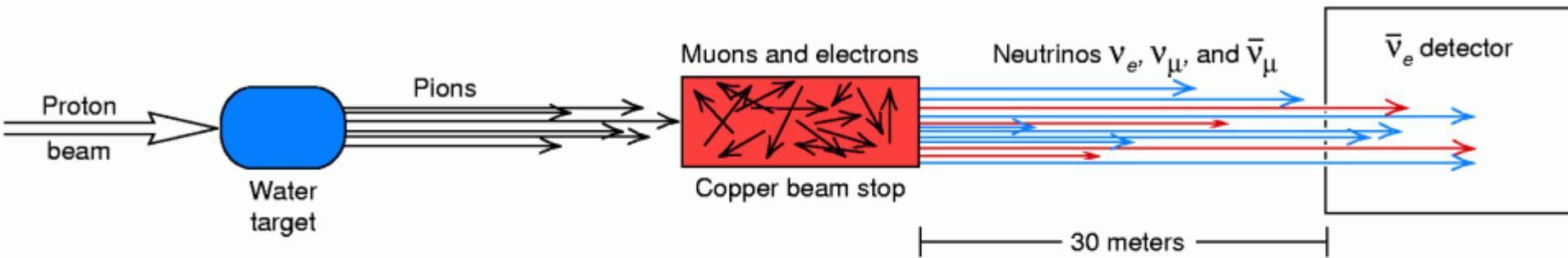
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Citations of Wolfenstein's Paper on Matter Effects



Annual citations of L. Wolfenstein, PRD 17:2369, 1978
in the SPIRES data base (total ~ 2100 citations)

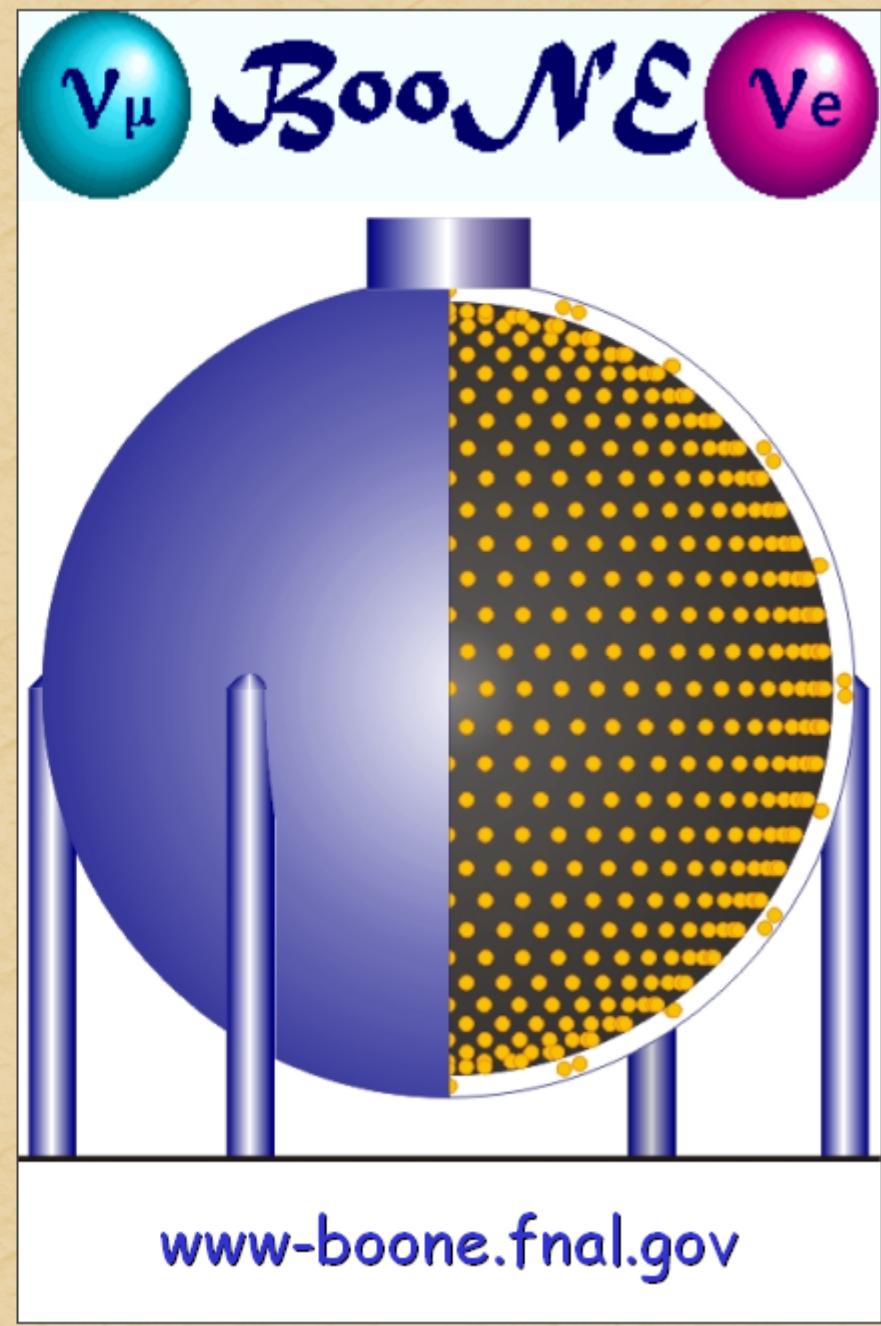
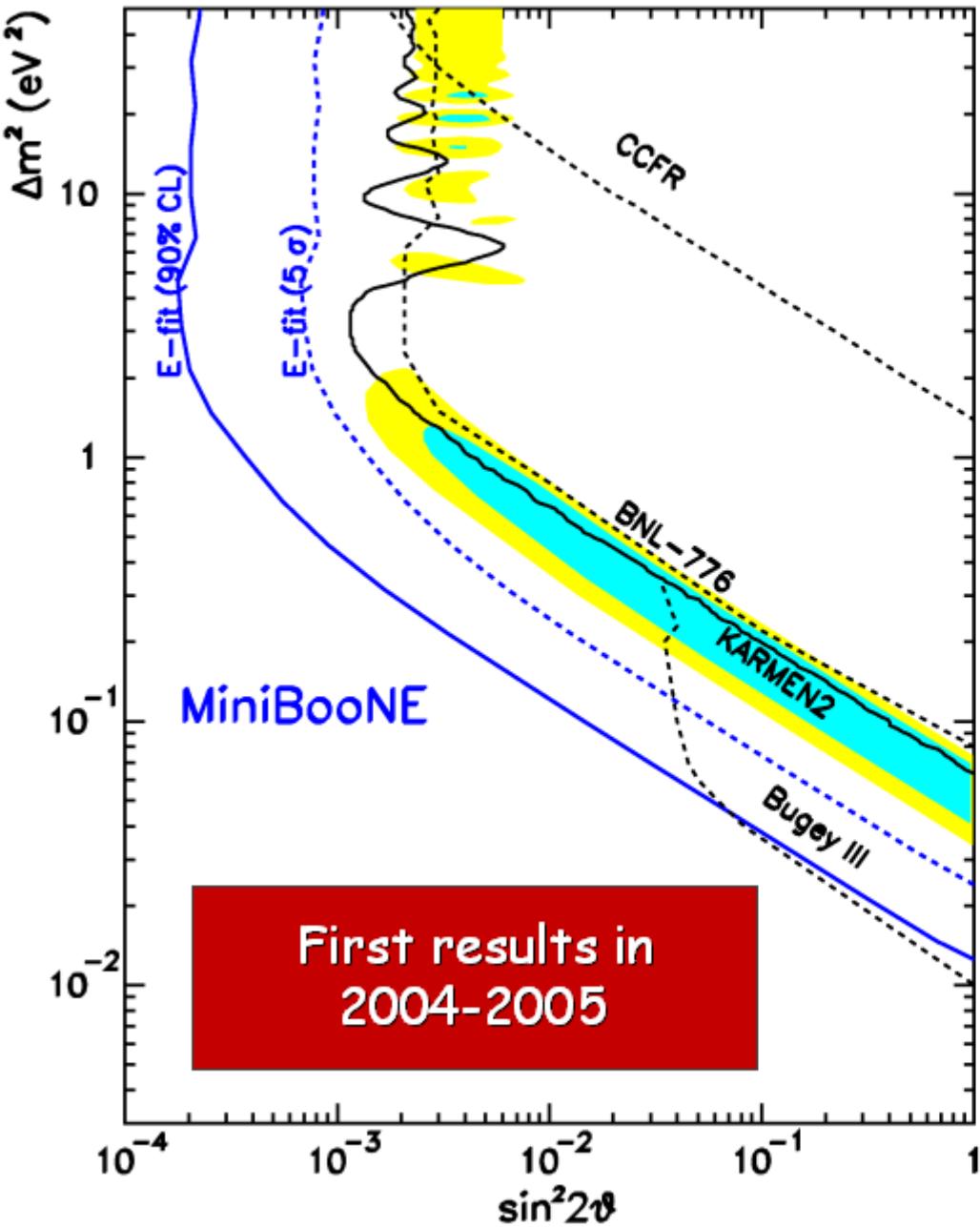
Excess Events at the LSND Experiment



LSND homepage
<http://www.neutrino.lanl.gov/LSND/>

- Oscillation interpretation clashes with solar/KL and atm/K2K results
- Oscillation with one sterile neutrino (3+1) no longer works
- Two sterile neutrinos (3+2) possible, but cosmologically difficult
- CPT violation (nus and anti-nus have different mass spectra) ?

Testing LSND at MiniBooNE



Sterile Neutrinos

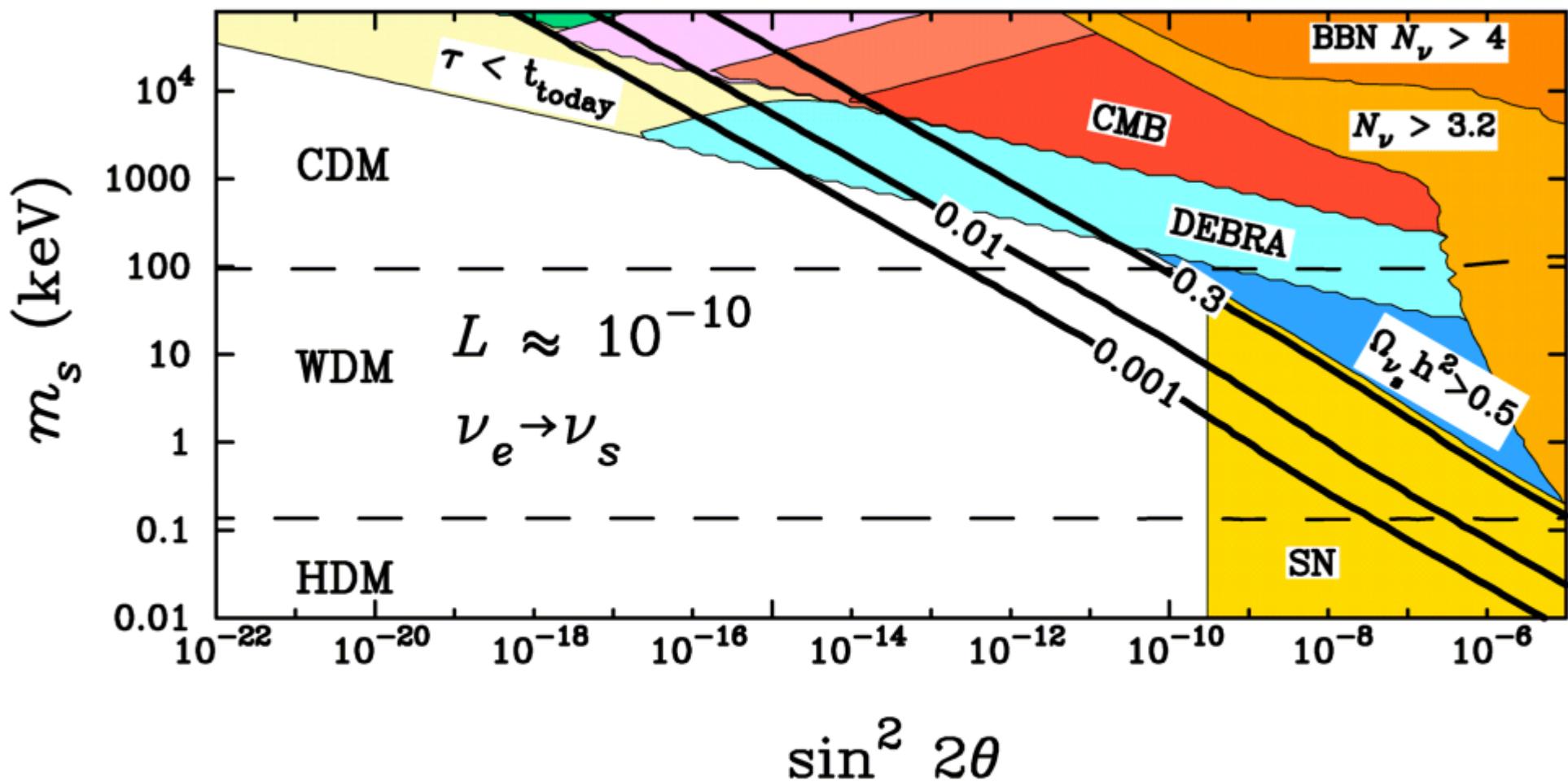
Sterile (right-handed) neutrinos may exist that are not a Dirac partner to an ordinary neutrino

- Unknown mass m_s
- Unknown mixing angles with ordinary neutrinos Θ_{es} , $\Theta_{\mu s}$, and $\Theta_{\tau s}$

Consequences and applications

- May (partially) account for some experimental oscillation results
- Hot, warm, or cold dark matter contribution
- May affect big-bang nucleosynthesis
- Emission from supernova cores
- Affects r-process nucleosynthesis in the SN hot bubble
- Radiative decays → potentially detectable

Sterile Neutrinos as Dark Matter



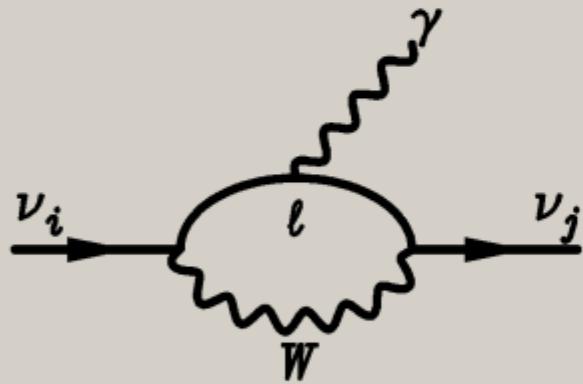
Abazajian, Fuller & Patel, Sterile neutrino hot, warm, and cold dark matter
astro-ph/0101524

Standard Dipole Moments for Massive Neutrinos

Diagonal case
(Magnetic moments
of Dirac neutrinos)

$$\mu_{ii} = \frac{3e\sqrt{2}G_F}{(4\pi)^2} m_i = 3.20 \times 10^{-19} \mu_B \frac{m_i}{eV} \quad \mu_B = \frac{e}{2m_e}$$

Off-diagonal case
(Transition moments)



$$\mu_{ij} = \frac{3e\sqrt{2}G_F}{4(4\pi)^2} (m_i + m_j) \left(\frac{m_\tau}{m_W} \right)^2 \sum_{\ell=e,\mu,\tau} U_{\ell j} U_{\ell i}^* \left(\frac{m_\ell}{m_\tau} \right)^2$$

$$= 3.96 \times 10^{-23} \mu_B \frac{m_i + m_j}{eV} \sum_{\ell=e,\mu,\tau} U_{\ell j} U_{\ell i}^* \left(\frac{m_\ell}{m_\tau} \right)^2$$

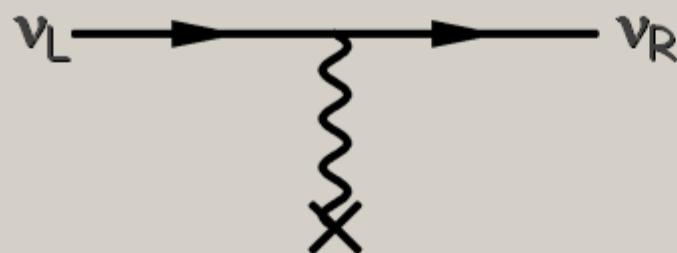
$$\varepsilon_{ij} = \dots (m_i - m_j) \dots$$

Largest mass eigenstate $0.05 \text{ eV} < m < 0.7 \text{ eV}$
For Dirac neutrino expect

$$1.6 \times 10^{-20} \mu_B < \mu_\nu < 2.2 \times 10^{-19} \mu_B$$

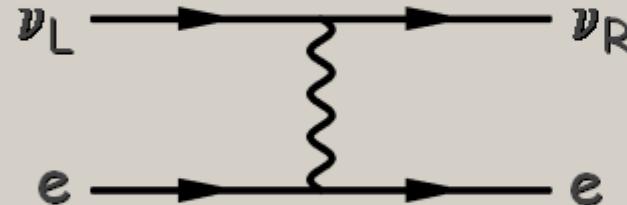
Consequences of Neutrino Dipole Moments

Spin precession in external E or B fields



$$i \frac{\partial}{\partial t} \begin{pmatrix} \nu_L \\ \nu_R \end{pmatrix} = \begin{pmatrix} 0 & \mu_\nu B_T \\ \mu_\nu B_T & 0 \end{pmatrix} \begin{pmatrix} \nu_L \\ \nu_R \end{pmatrix}$$

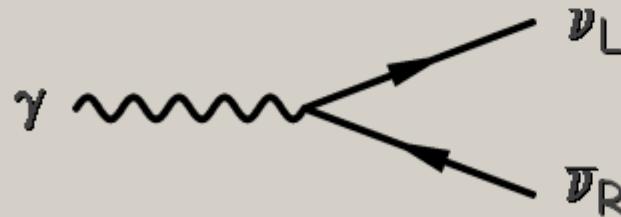
Scattering



$$\frac{d\sigma}{dT} = \frac{G_F^2 m_e}{2\pi} \left[(C_V + C_A)^2 + (C_V - C_A)^2 \left(1 - \frac{T}{E_\nu}\right)^2 + (C_V^2 - C_A^2) \frac{m_e T}{E_\nu^2} \right] + \alpha \mu_\nu^2 \left[\frac{1}{T} - \frac{1}{E_\nu} \right]$$

T electron recoil energy

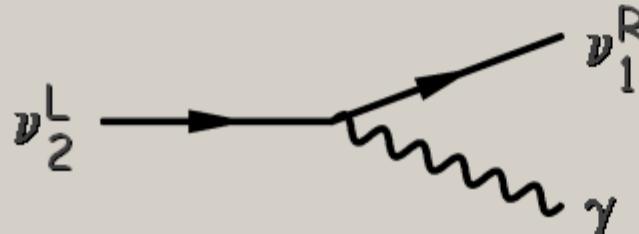
Plasmon decay in stars



$$\Gamma = \frac{\mu_\nu^2}{24\pi} \omega_{pl}^3$$

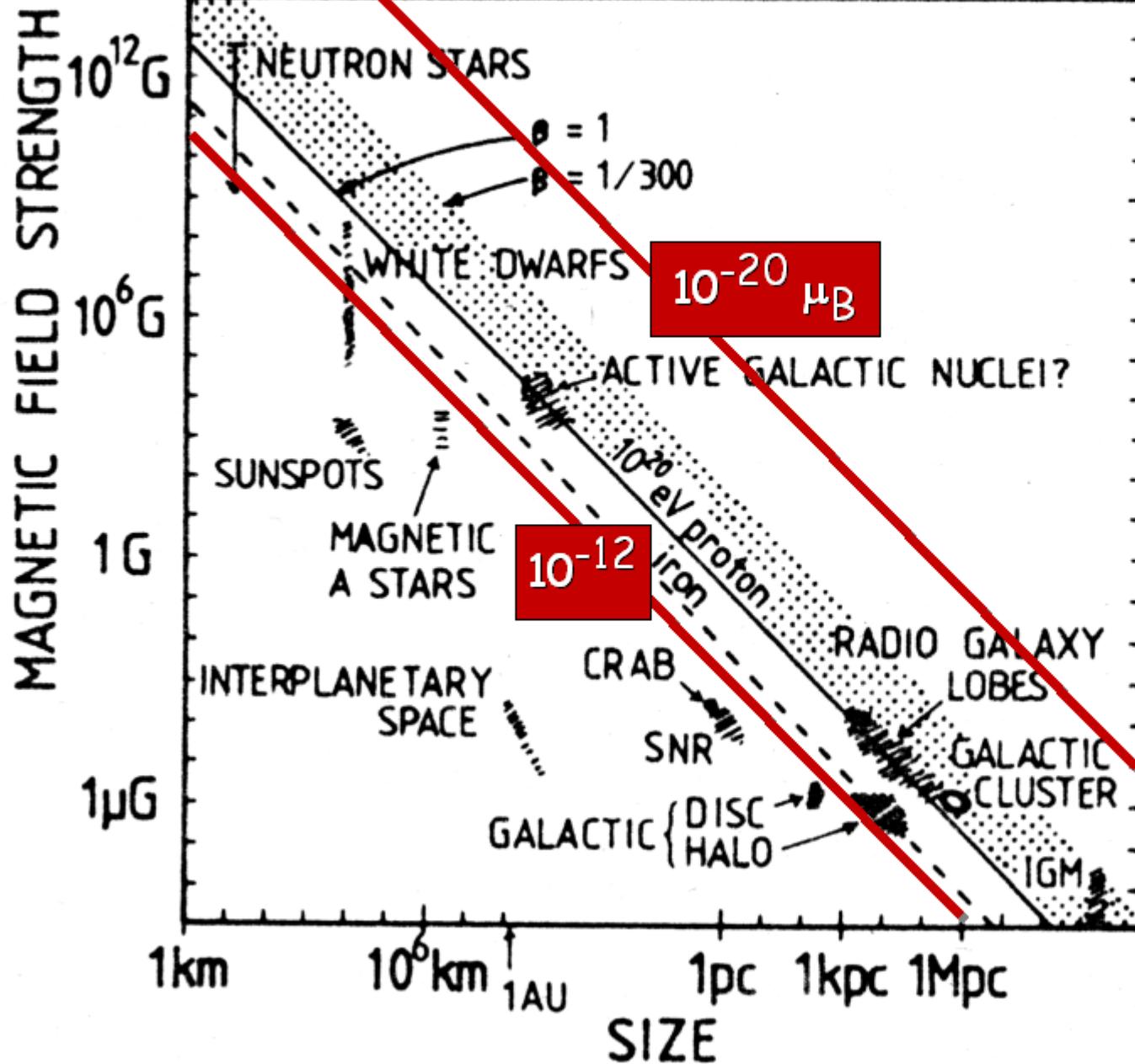
Best limit from globular clusters
 $\mu_\nu < 2 \times 10^{-12} \mu_B$

Decay or Cherenkov effect



$$\Gamma = \frac{\mu_\nu^2}{8\pi} \left(\frac{m_2^2 - m_1^2}{m_2} \right)^3$$

Astrophysical Magnetic Fields

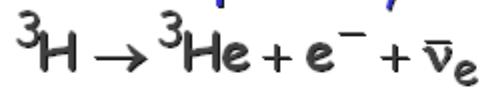


Field strength and length scale where neutrinos with specified dipole moment would suffer complete depolarization

"Hillas Plot"
[ARA 22, 425
(1984)]

Tritium Endpoint Spectrum

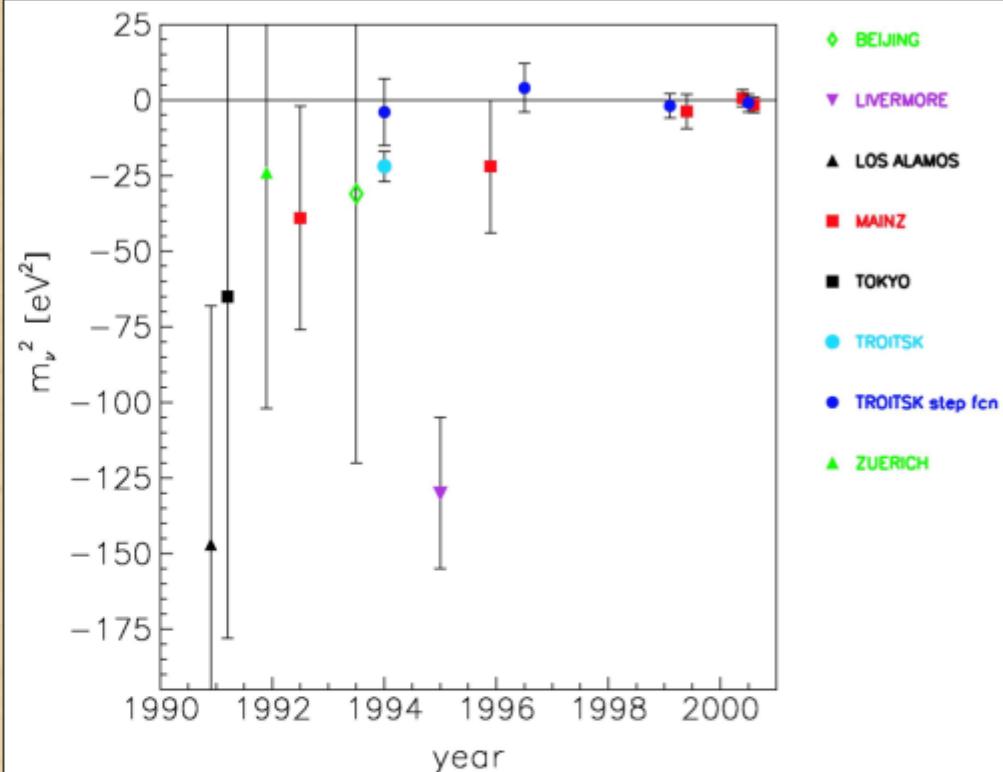
Tritium β -decay



Electron spectrum



Endpoint
energy
18.6 keV



Currently best limits from Mainz
and Troitsk experiments

$$m < 2.2 \text{ eV (95% CL)}$$

- Scaled-up spectrometer (KATRIN) should reach 0.2 eV
- Currently under construction
- Measurements beginning 2007

<http://ik1au1.fzk.de/~katrin>

Cosmological Limit on Neutrino Masses

Cosmic neutrino "sea" $\sim 112 \text{ cm}^{-3}$ neutrinos + anti-neutrinos per flavor

$$\Omega_\nu h^2 = \sum \frac{m_\nu}{94 \text{ eV}} < 0.4$$

$$m_\nu < 40 \text{ eV}$$

For all
stable flavors

REST MASS OF MUONIC NEUTRINO AND COSMOLOGY

S. S. Gershtein and Ya. B. Zel'dovich

Submitted 4 June 1966

ZhETF Pis'ma 4, No. 5, 174-177, 1 September 1966

A classic paper:
Gershtein & Zeldovich
JETP Lett. 4 (1966) 120

Low-accuracy experimental estimates of the rest mass of the neutrino [1] yield $m(\nu_e) < 200 \text{ eV}/c^2$ for the electronic neutrino and $m(\nu_\mu) < 2.5 \times 10^6 \text{ eV}/c^2$ for the muonic neutrino.

Cosmological considerations connected with the hot model of the Universe [2] make it possible to strengthen greatly the second inequality. Just as in the paper by Ya. B. Zel'dovich and Ya. A. Smorodinskii [3], let us consider the gravitational effect of the neutrinos on the dynamics of the expanding Universe. The age of the known astronomical objects is not smaller than 5×10^9 years, and Hubble's constant H is not smaller than $75 \text{ km/sec-Mparsec} = (13 \times 10^9 \text{ years})^{-1}$. It follows therefore that the density of all types of matter in the Universe is at the present time¹⁾

$$\rho < 2 \times 10^{-28} \text{ g/cm}^3.$$

What is wrong with neutrino dark matter?

Galactic Phase Space ("Tremaine-Gunn-Limit")

Maximum mass density of a Fermi gas

$$\rho_{\max} = m_\nu n_{\max} = m_\nu p_{\max}^3 / 3\pi^2 = m_\nu (m_\nu v_{\text{escape}})^3 / 3\pi^2$$

$m_\nu > 20 - 40 \text{ eV}$

Spiral
galaxies

More restrictive from dwarf galaxies
 $m_\nu > 100 - 200 \text{ eV}$

Neutrino Free Streaming (Collisionless Phase Mixing)

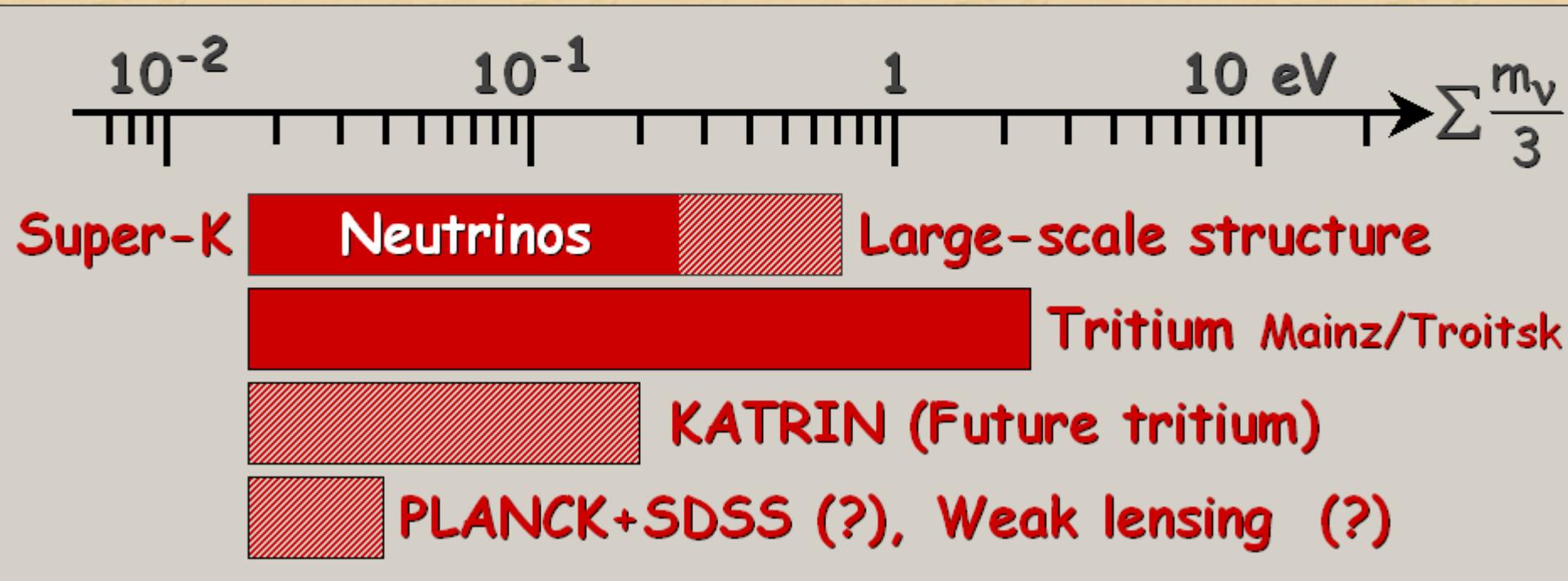
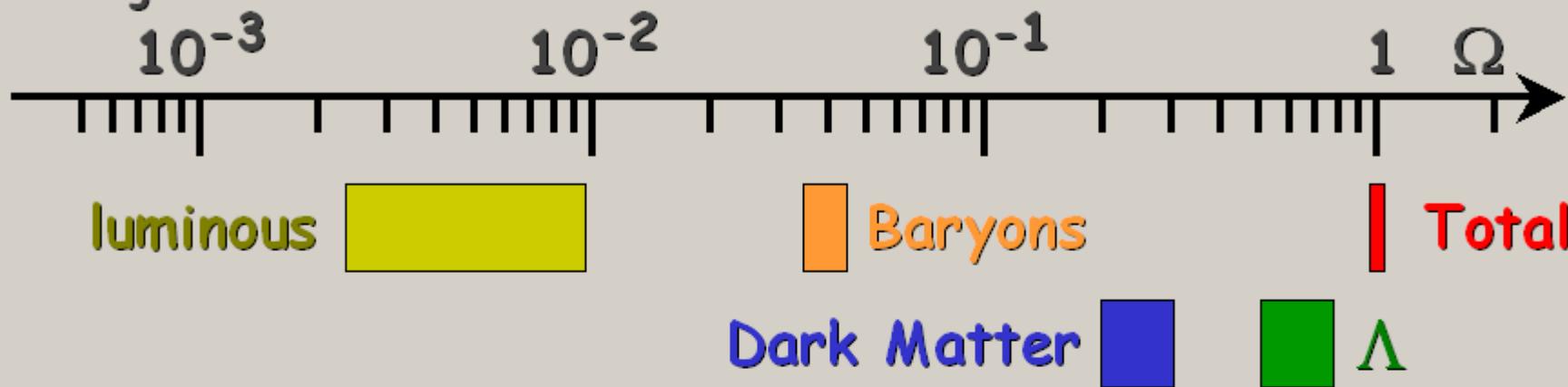
- At $T < 1 \text{ MeV}$ neutrino scattering in early universe ineffective
- Stream freely until nonrelativistic
- Wash out density contrasts on small scales



- Nus are "Hot Dark Matter"
- Ruled out by structure formation

Mass-Energy-Inventory of the Universe

Assuming $h = 0.75$



Thermal Leptogenesis by Majorana Neutrino Decays

In see-saw models for neutrino masses, out-of-equilibrium decay of right-handed heavy Majorana neutrinos provides source for CP- and L-violation

Cosmological evolution:

- $B = L = 0$ early on
- Thermal freeze-out of heavy Majorana neutrinos
- Out-of-equilibrium CP-violating decay creates net L
- Shift L excess into B by sphaleron effects

Sufficient deviation from equilibrium distribution of heavy Majorana neutrinos at freeze-out



Limits on Yukawa couplings



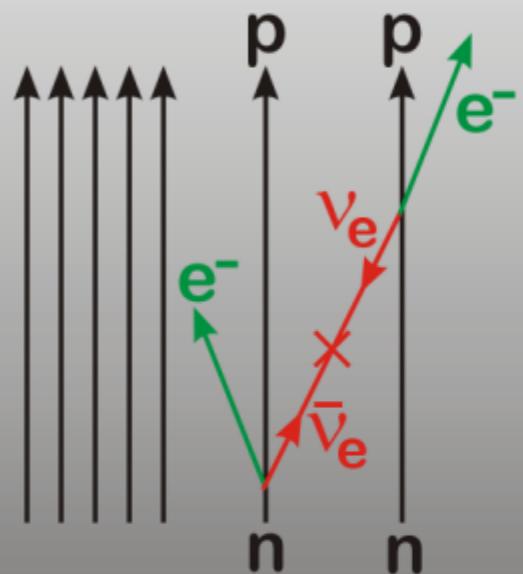
Limits on masses of ordinary neutrinos

Suggests Majorana neutrino masses below ~ 0.1 eV

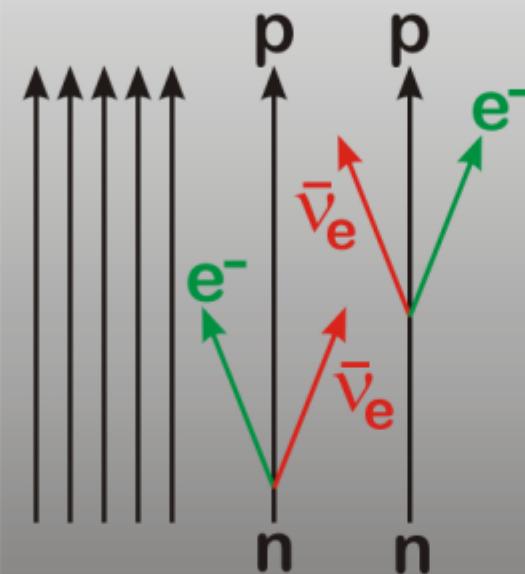
Buchmüller, Di Bari & Plümacher, hep-ph/0209301, hep-ph/0302092

Neutrinoless $\beta\beta$ Decay

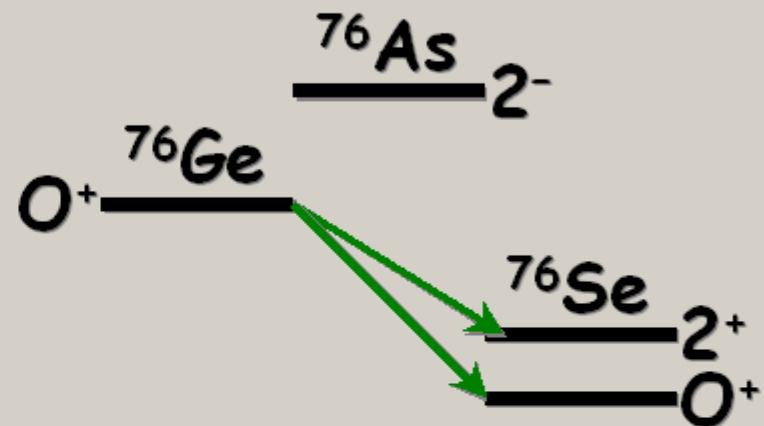
0v mode, enabled by Majorana mass



Standard 2v mode



Some nuclei decay only by the $\beta\beta$ mode, e.g.



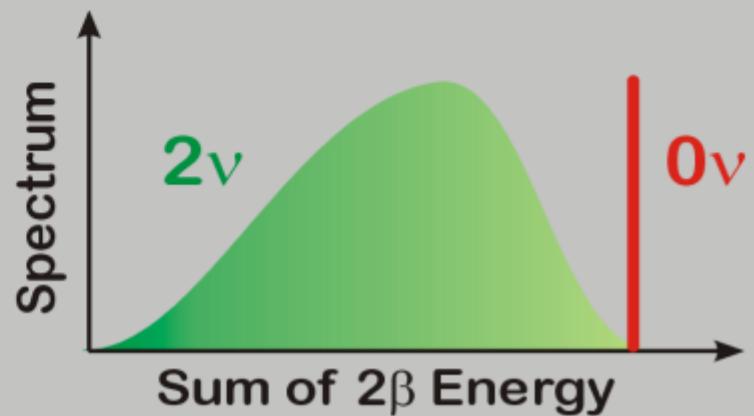
Half life $\sim 10^{21}$ yr

Measured quantity

$$|m_{ee}| = \left| \sum_{i=1}^N \lambda_i |U_{ei}|^2 m_i \right|$$

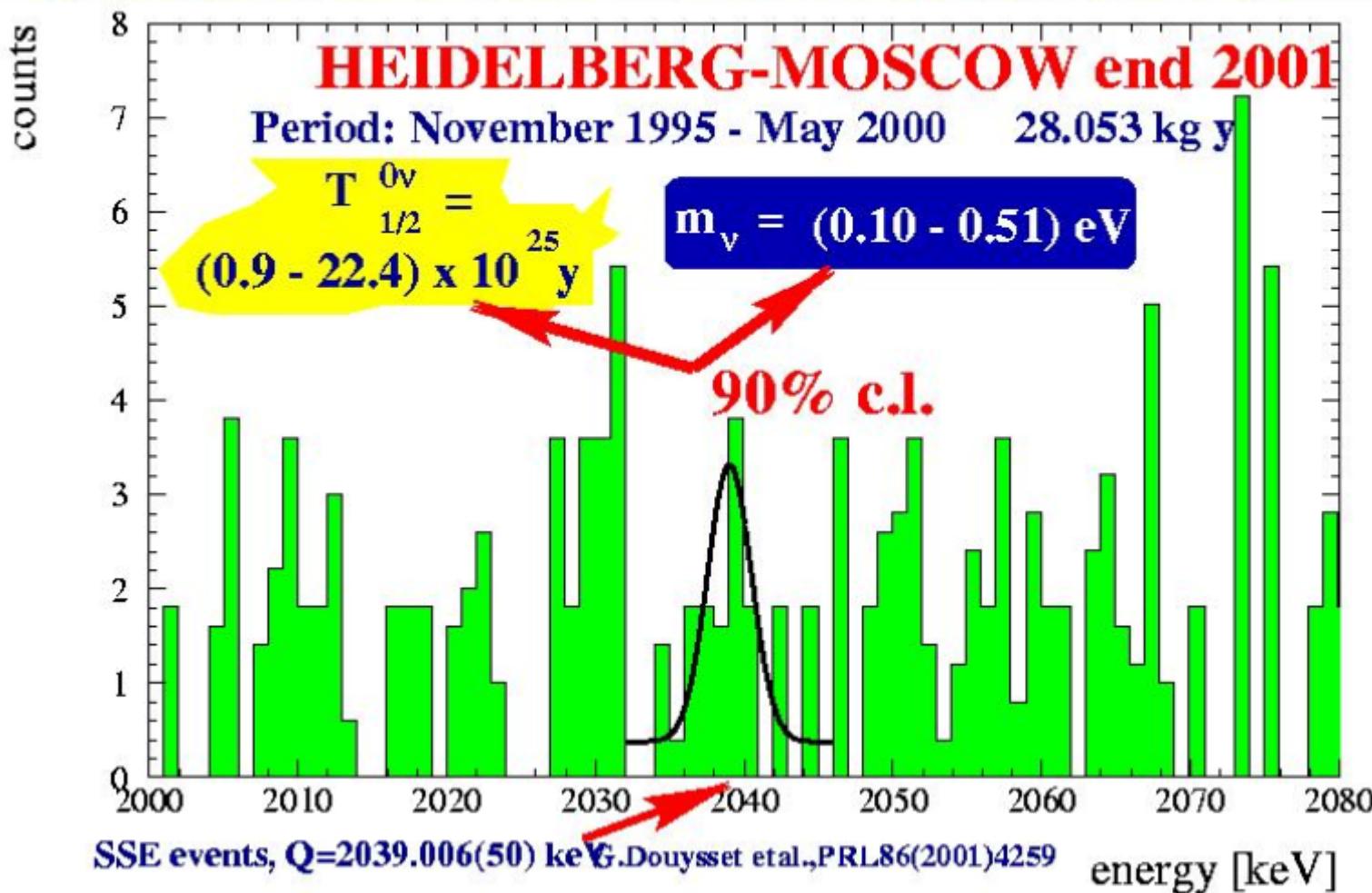
Best limit from ^{76}Ge

$$|m_{ee}| < 0.35 \text{ eV}$$



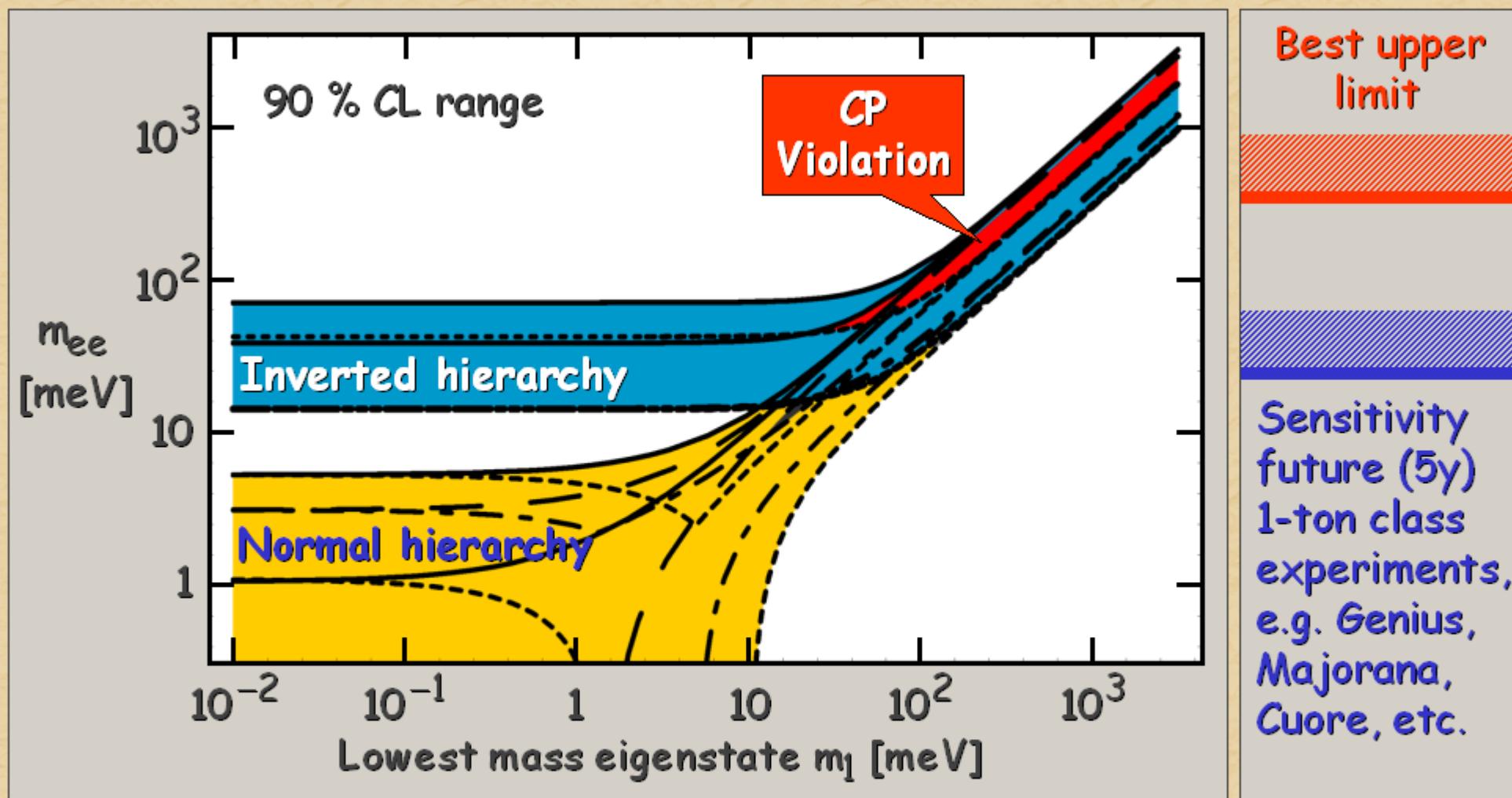
Claimed Evidence for Germanium $\beta\beta$ Decay

Sum spectrum of the ^{76}Ge detectors Nr. 2,3,5



H.V. Klapdor-Kleingrothaus et al. Mod.Phys.Lett. A16 (2001) 2409-2420

Effective Majorana Mass in Plausible Scenarios



Pascoli & Petcov, hep-ph/0205022

See also Feruglio, Strumia & Vissani, hep-ph/0201291

Klapdor-Kleingrothaus, Päs & Smirnov, hep-ph/0103076, and others

Sanduleak -69 202

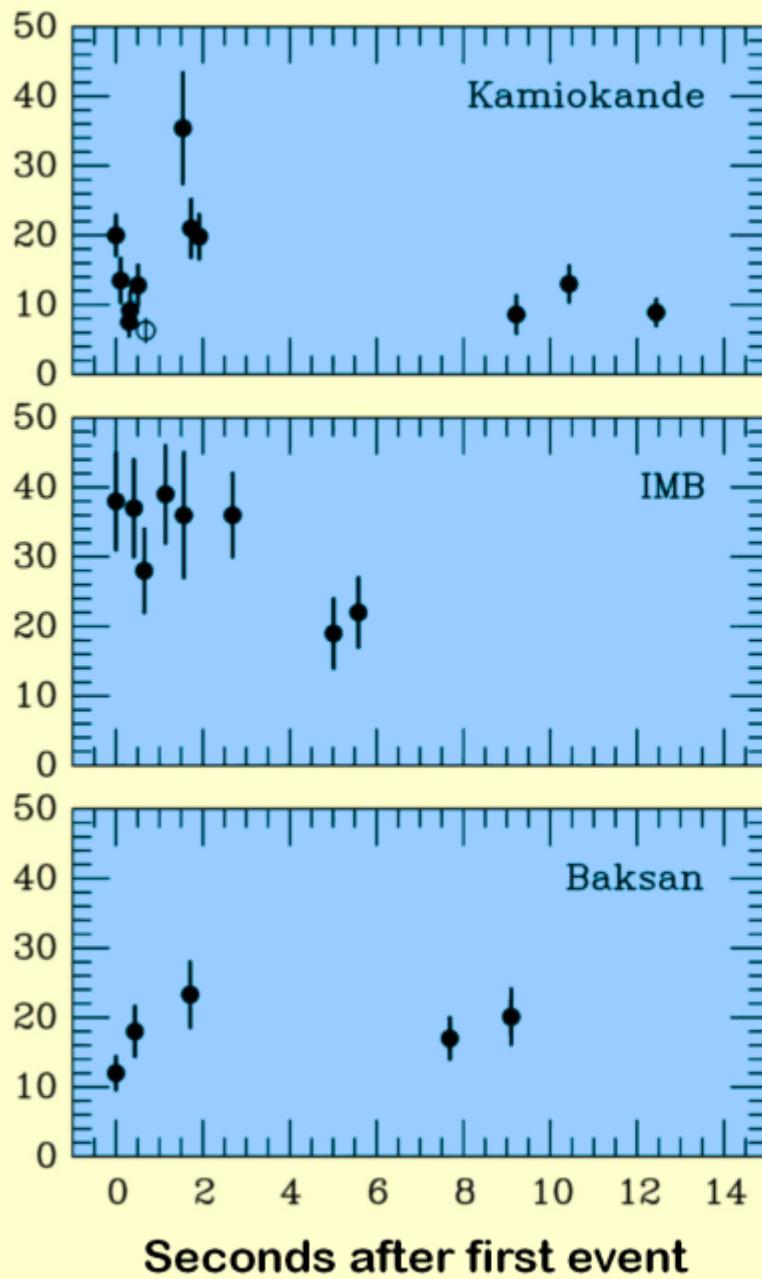


Supernova 1987A
23 February 1987



Neutrino Signal of Supernova 1987A

Positron energy [MeV]



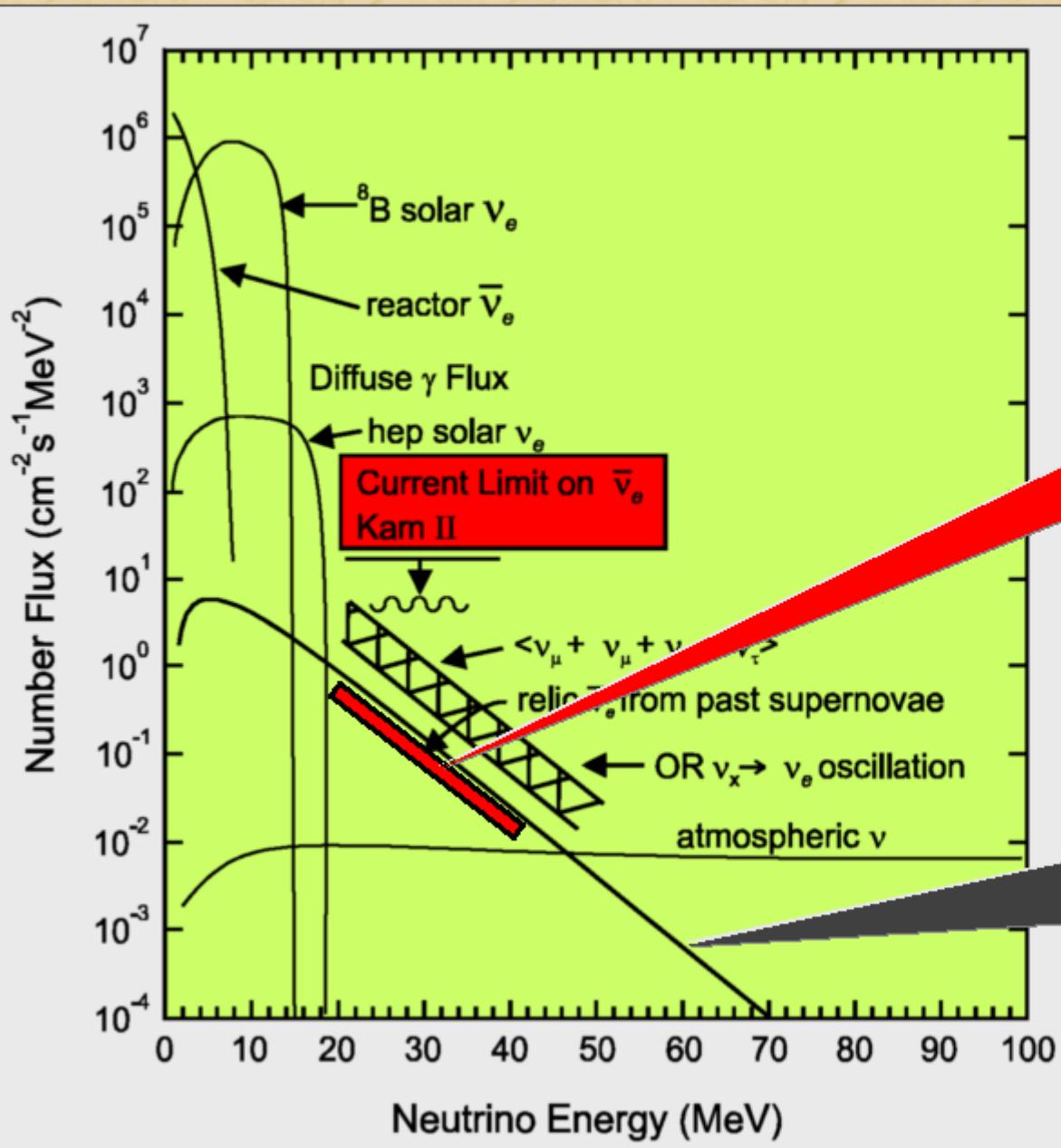
Kamiokande (Japan)
Water Cherenkov detector
Clock uncertainty ± 1 min

Irvine-Michigan-Brookhaven (US)
Water Cherenkov detector
Clock uncertainty ± 50 ms

Baksan Scintillator Telescope
(Soviet Union)
Clock uncertainty +2/-54 s

Within clock uncertainties,
signals are contemporaneous

Experimental Limits on Relic SN Neutrinos



Super-K upper limit
 $29 \text{ cm}^{-2} \text{s}^{-1}$ for
Kaplinghat et al. spectrum
[hep-ex/0209028]

Upper-limit flux of
Kaplinghat et al.,
astro-ph/9912391
Integrated $54 \text{ cm}^{-2} \text{s}^{-1}$

Cline, astro-ph/0103138

Improved Sensitivity with Neutron Tagging

M.Vagins, Talk at NOON 2003, <http://www-sk.icrr.u-tokyo.ac.jp/noon2003/>

Super-Kamiokande limited by

- Solar neutrinos for $E_\nu < 18\text{-}19 \text{ MeV}$
- Sub-Cherenkov muons from atm nus
 $\mu \rightarrow e + \nu_e + \bar{\nu}_\mu$

Solution:

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

Water: Neutron capture on protons

2.2 MeV gammas, invisible in SK

Add gadolinium to SK:

- Efficient neutron capture
- 8 MeV gamma cascade, easily visible
- 0.1 % (100 tons of $GdCl_3$) achieves > 90% tagging efficiency

SN relic nus: A few events per year in SK with no background at all

A Modest Proposal

Pouring a bunch of stuff into Super-K is a big step, and not to be done lightly, no matter how promising things may look initially.

Here's what comes next:

- 1) Spend the next year or so exploring the chemistry, stability, and optical properties of $GdCl_3$ in detail.
- 2) Understand any changes needed in the SK water system and Monte Carlo the modified detector's response using what's learned above as input.
- 3) Build a small test tank (one supermodule) with exactly the same materials as in SK. Put in PMT's, cables, water, and $GdCl_3$ and let it sit for two years. Check for $GdCl_3$ -induced damage.
- 4) If everything looks good, in the last month(s) of SK-II put in 9 tons of $GdCl_3$ to make sure we really understand our backgrounds. Look for reactor antineutrinos!

Large Detectors for SN Neutrinos

SNO (800)

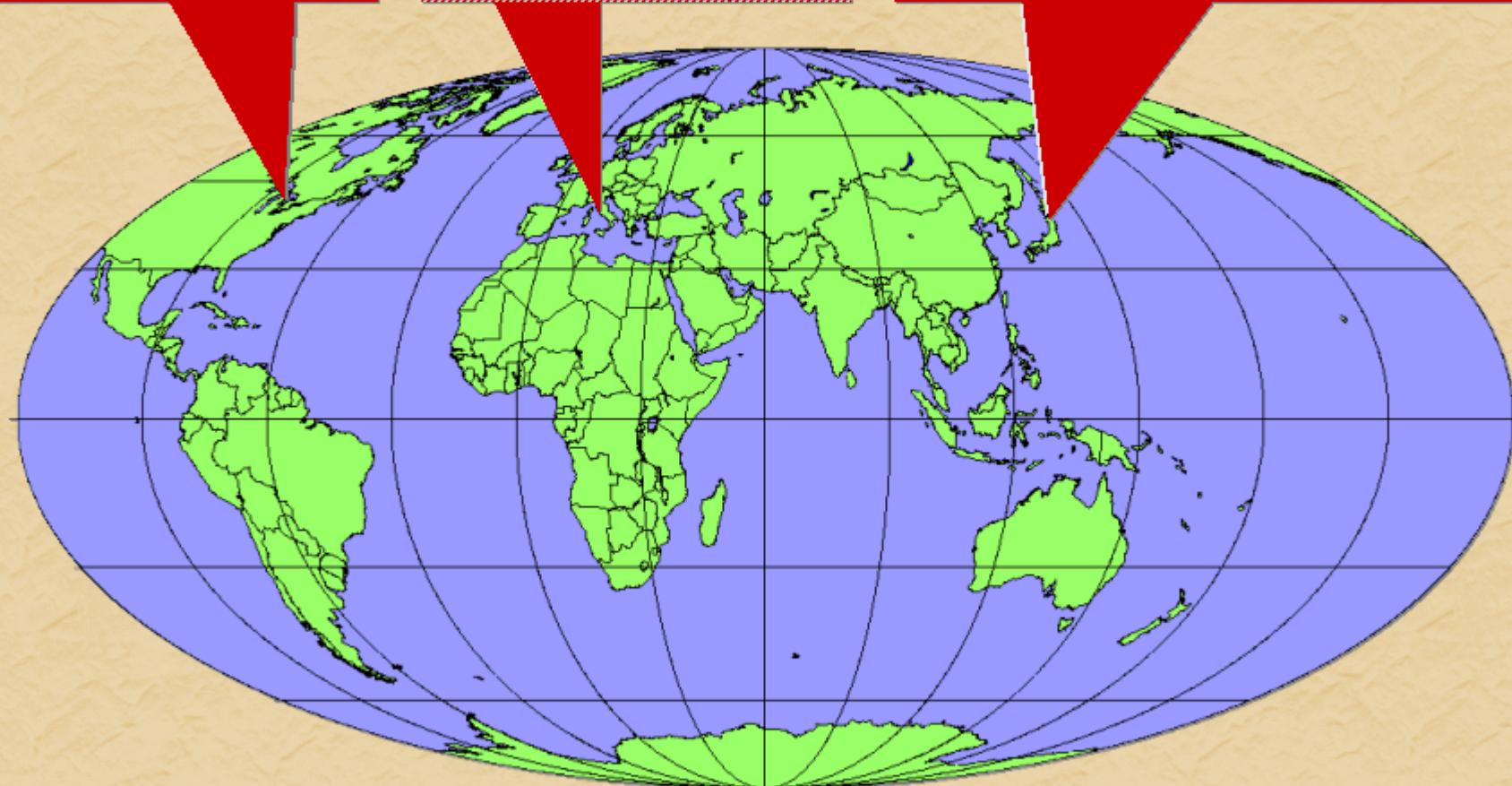
MiniBooNE (190)

LVD (400)

Borexino (80)

Super-Kamiokande (8500)

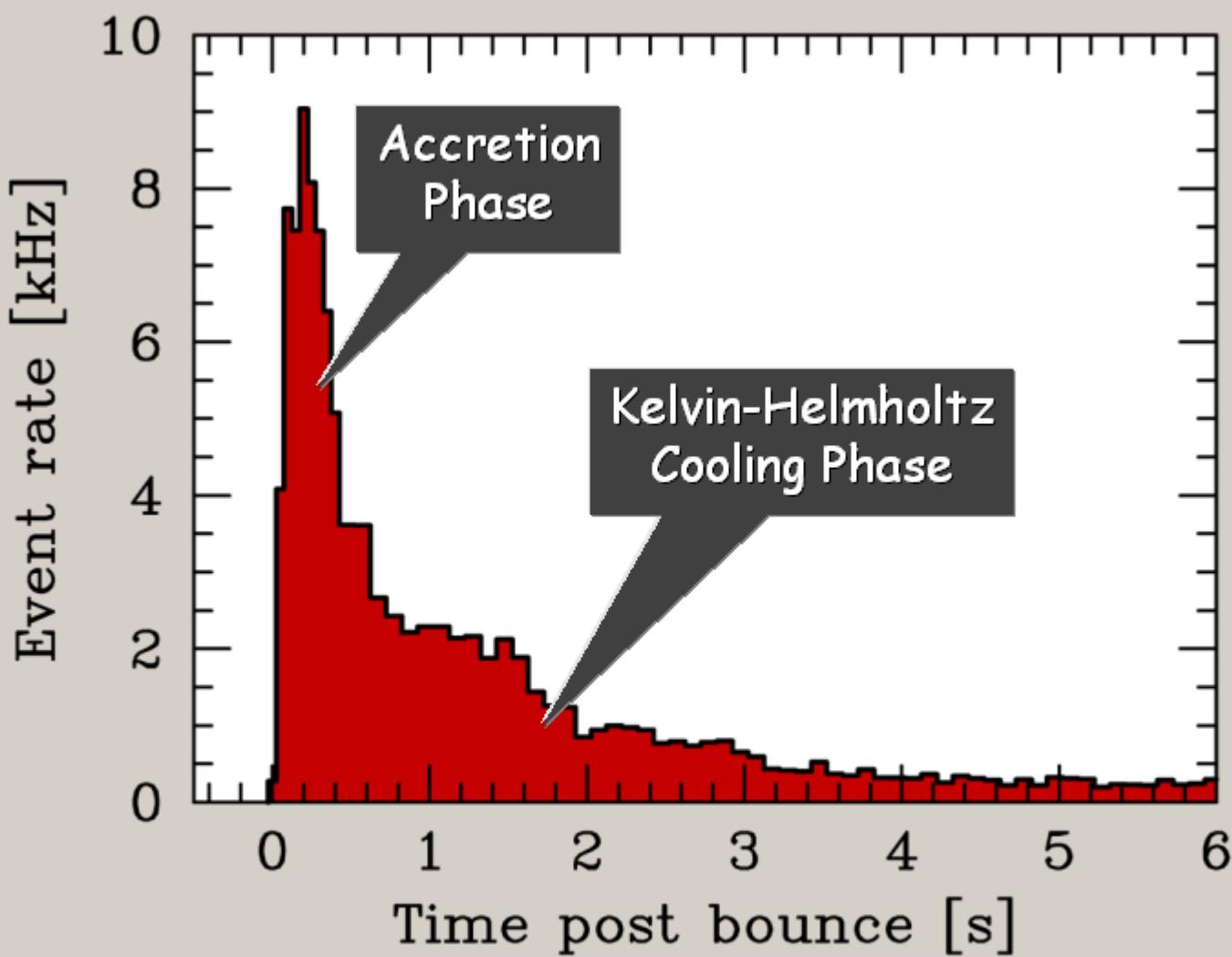
Kamland (330)



Amanda
IceCube

In brackets events
for a "fiducial SN"
at distance 10 kpc

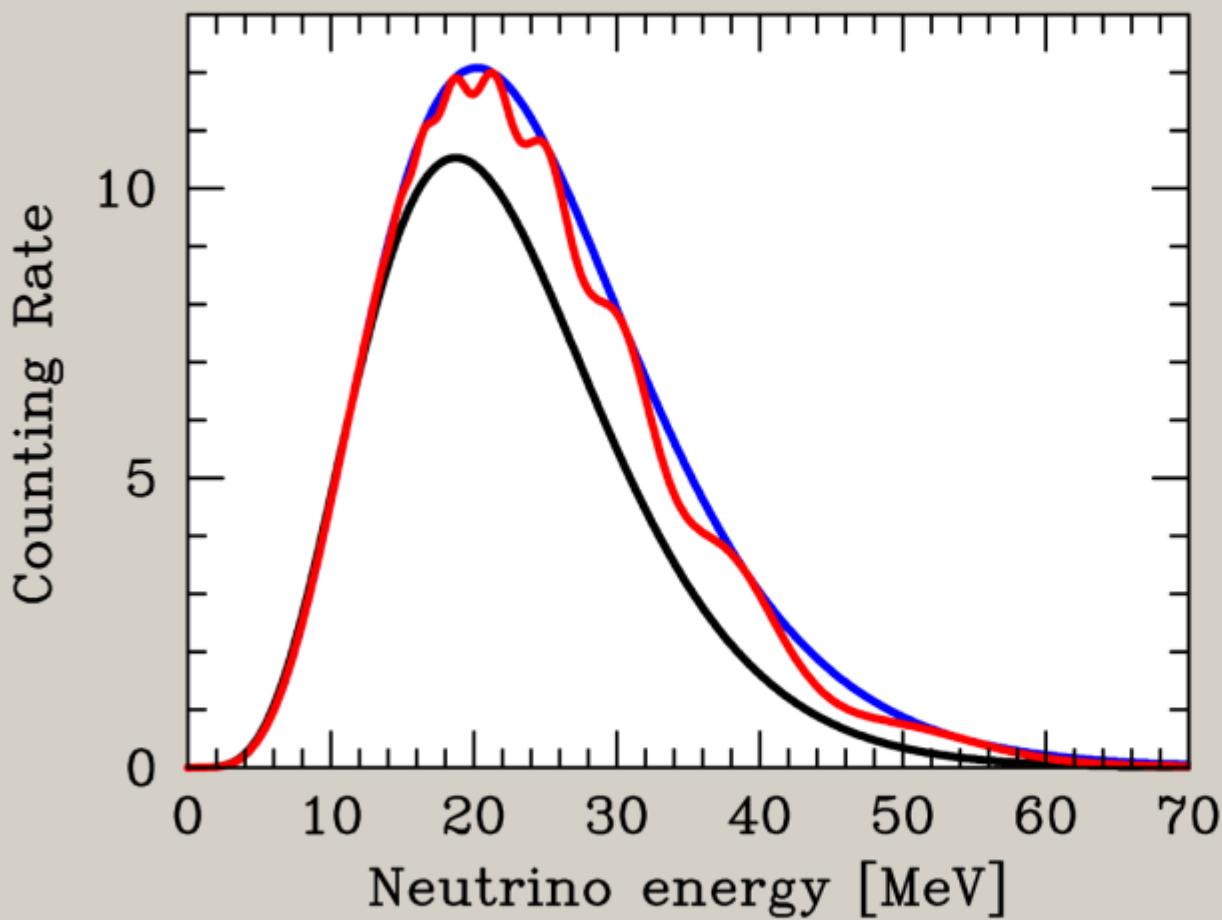
Simulated Supernova Signal at Super-Kamiokande



Simulation for Super-Kamiokande SN signal at 10 kpc,
based on a numerical Livermore model
[Totani, Sato, Dalhed & Wilson, ApJ 496 (1998) 216]

Oscillation of Supernova Anti-Neutrinos

Measured $\bar{\nu}_e$ spectrum at a detector like Super-Kamiokande



Assumed flux parameters:

Flux ratio $\bar{\nu}_e : \bar{\nu}_X = 0.8 : 1$

$\langle E(\bar{\nu}_e) \rangle = 15 \text{ MeV}$

$\langle E(\bar{\nu}_X) \rangle = 18 \text{ MeV}$

Mixing parameters:

$\Delta m_{\text{sun}}^2 = 60 \text{ meV}^2$

$\sin^2(2\theta) = 0.9$

No oscillations

Oscillations in SN envelope

Earth effects included
(ignore detector resolution)

Observing Earth effects in $\bar{\nu}_e$ channel establishes normal mass hierarchy if $\sin^2(\theta_{13}) > 10^{-3}$ established by other methods (e.g. reactor experiment)

The Future: A Megatonne Detector?

Megatonne detector motivated by

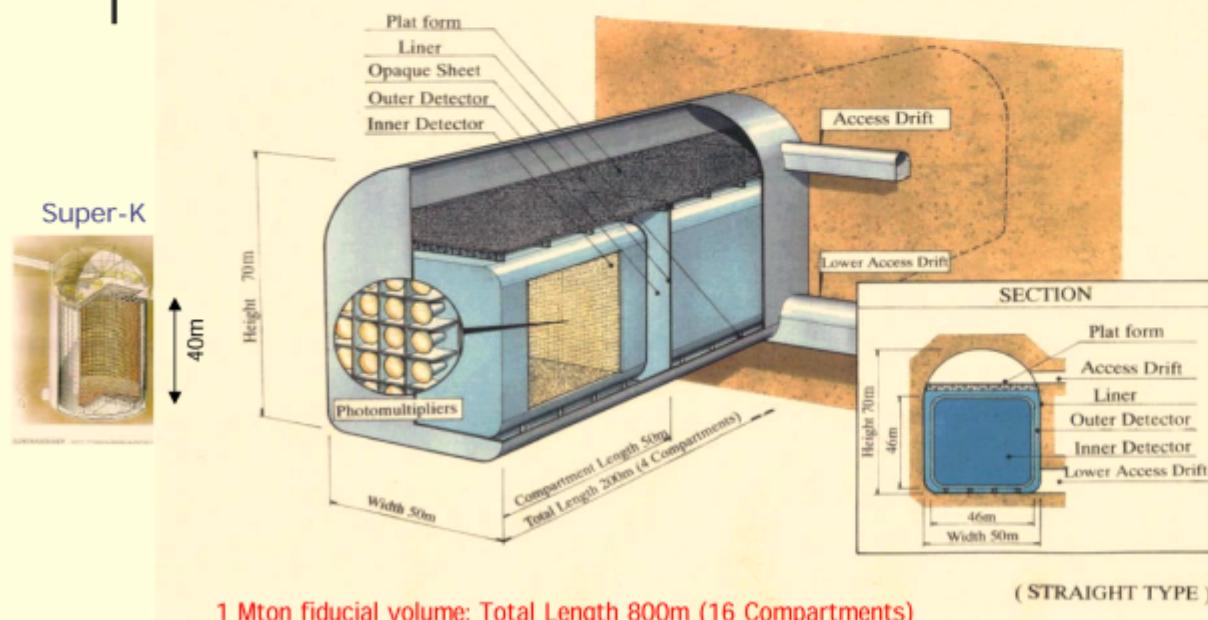
- Long baseline neutrino oscillations
- Proton decay
- Atmospheric neutrinos
- Solar neutrinos
- Supernova neutrinos
($\sim 10^5$ events for SN at 10 kpc)

1. Overview of the experiment

(expect to start in 2007)



Possible Design of Hyper-Kamiokande

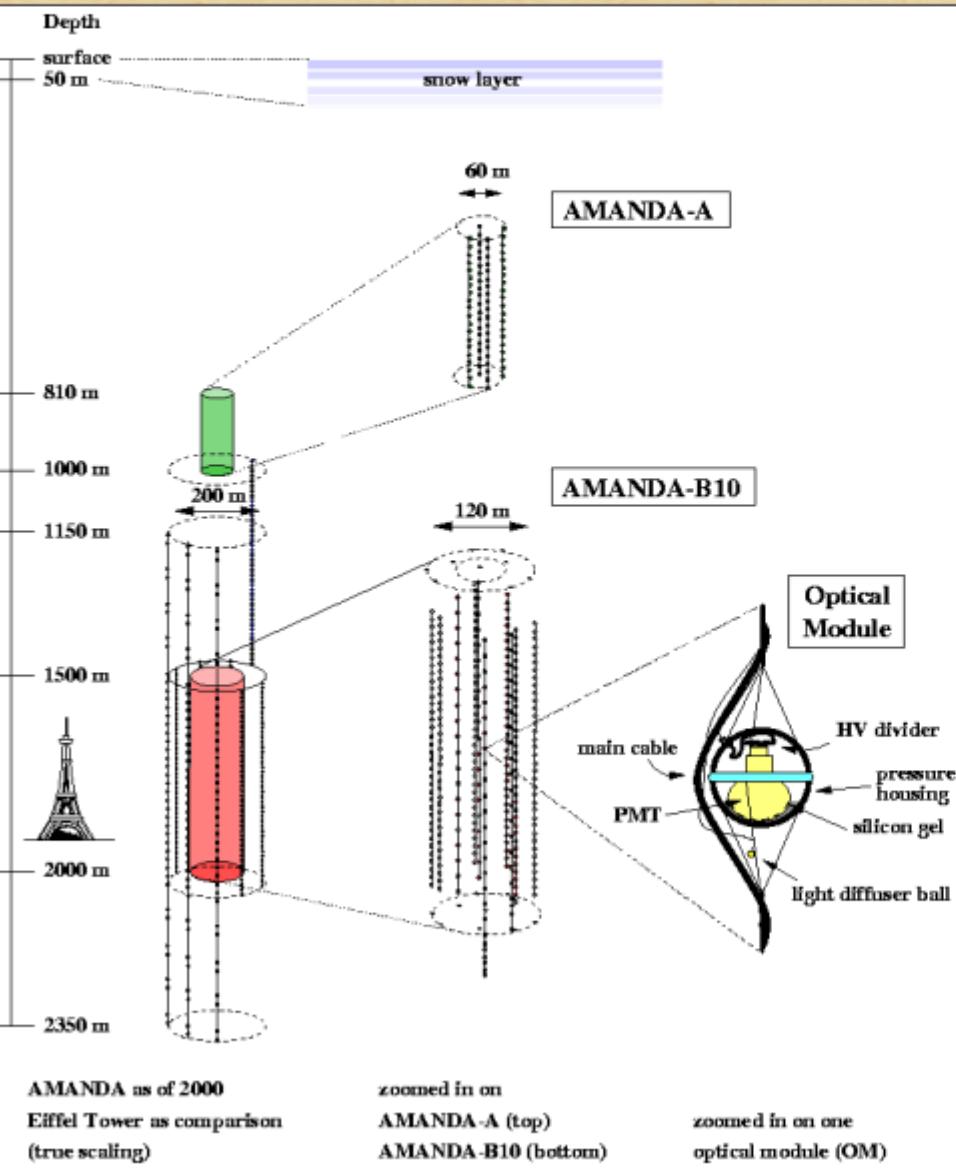


Similar discussions in

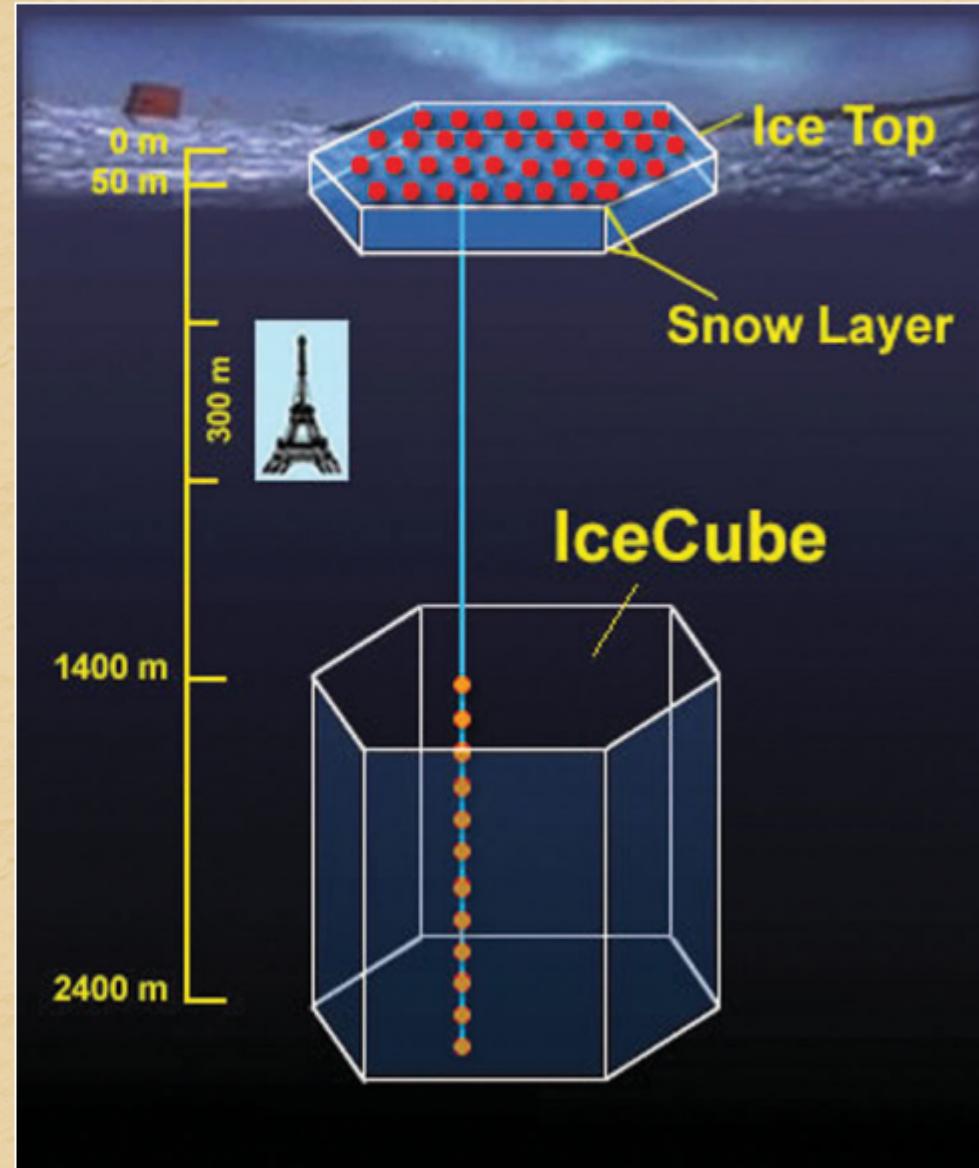
- USA (UNO project)
- Europe (Frejus Tunnel)

Southpole Ice-Cherenkov Neutrino Detectors

AMANDA II (0.1 km^3 , 800 PMTs)



Future IceCube (1 km^3 , 4800 PMTs)

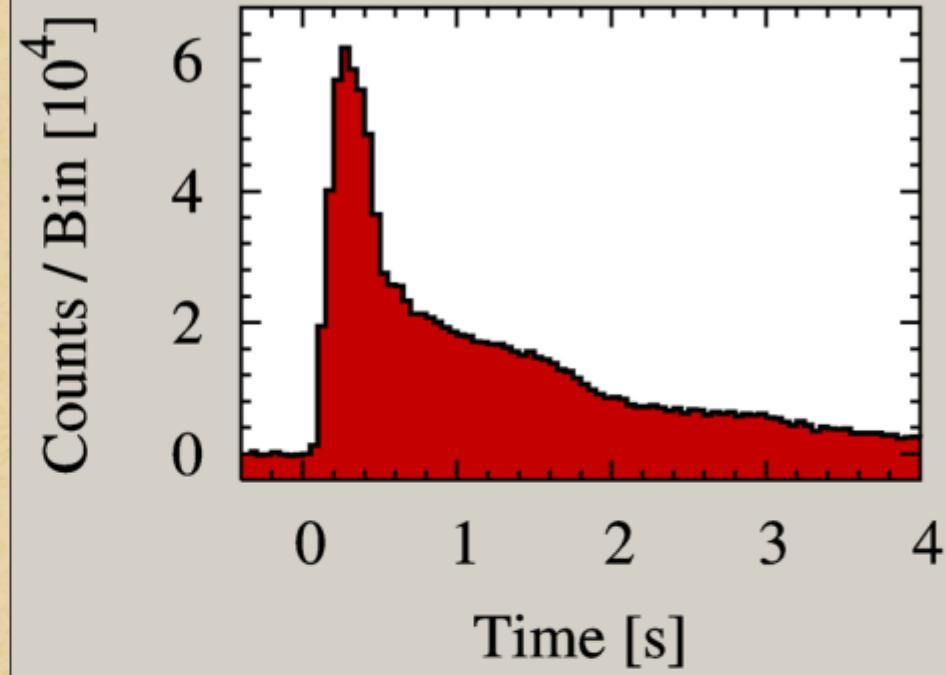
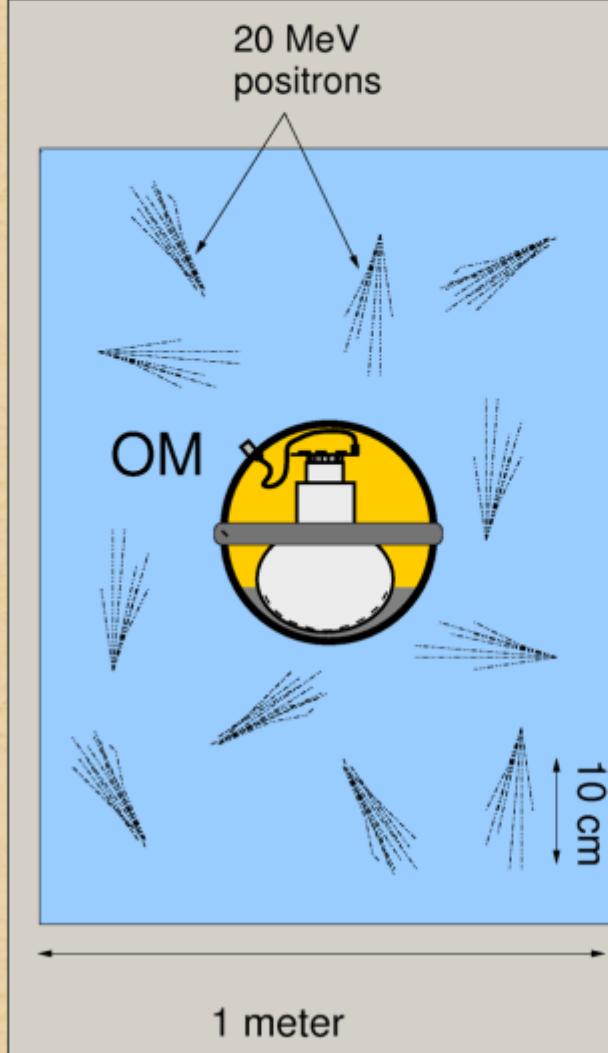


IceCube as a Supernova Neutrino Detector

Each optical module (OM) picks up Cherenkov light from its neighborhood. SN appears as "correlated noise".

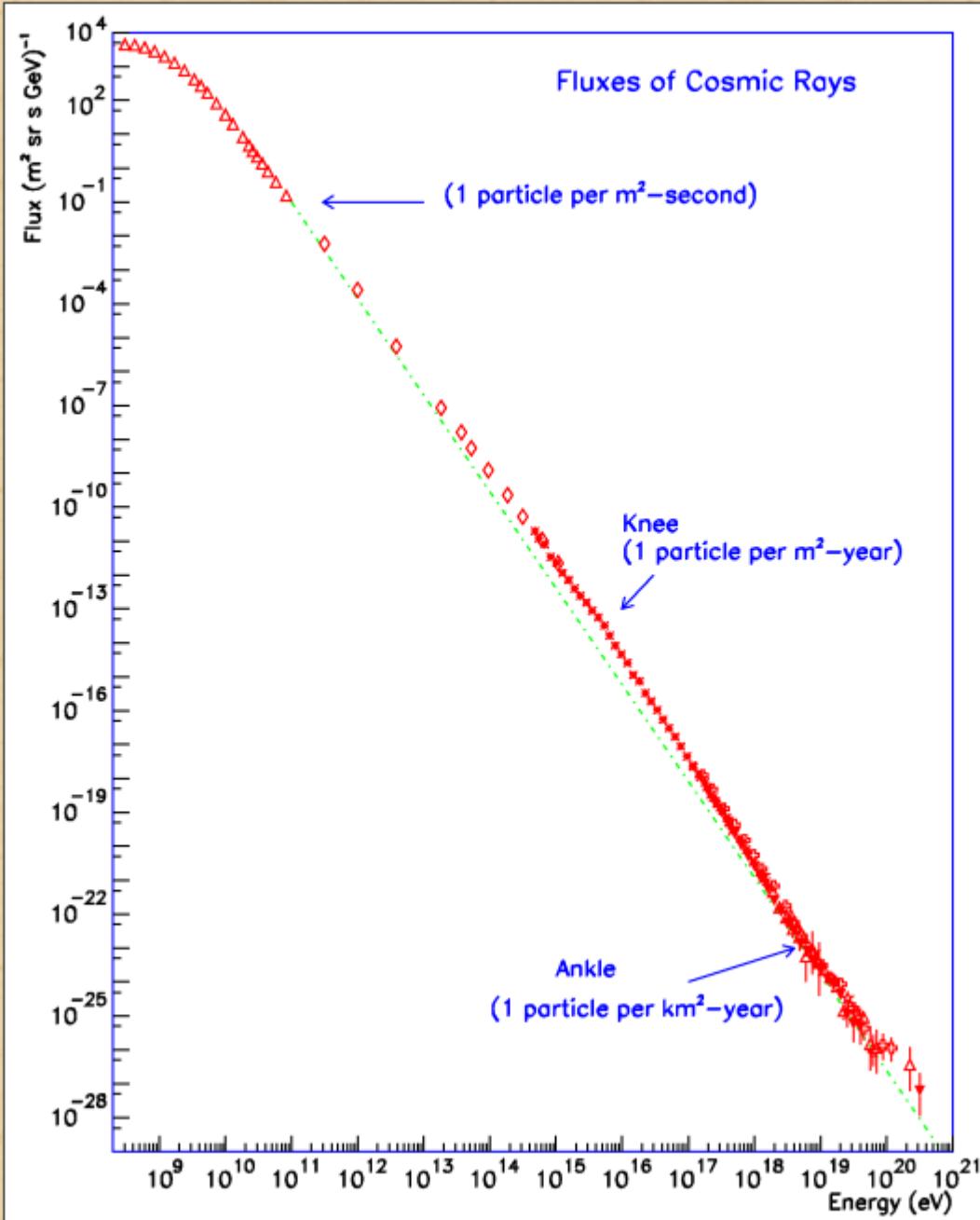
~ 300 Cherenkov photons per OM from SN at 10 kpc

Noise per OM < 500 Hz

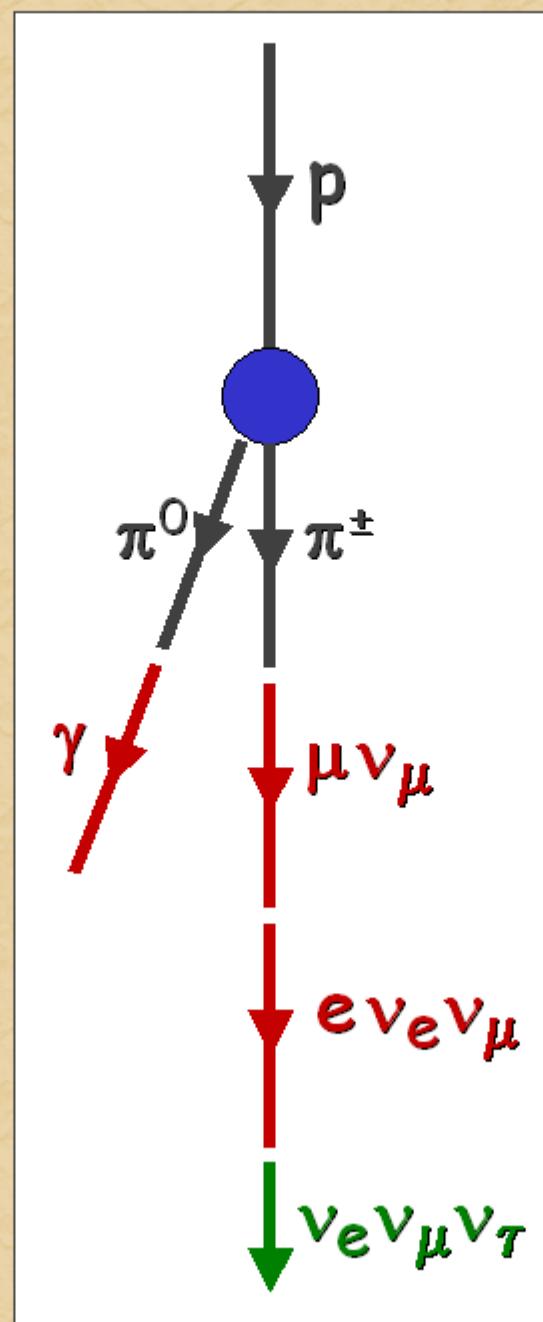
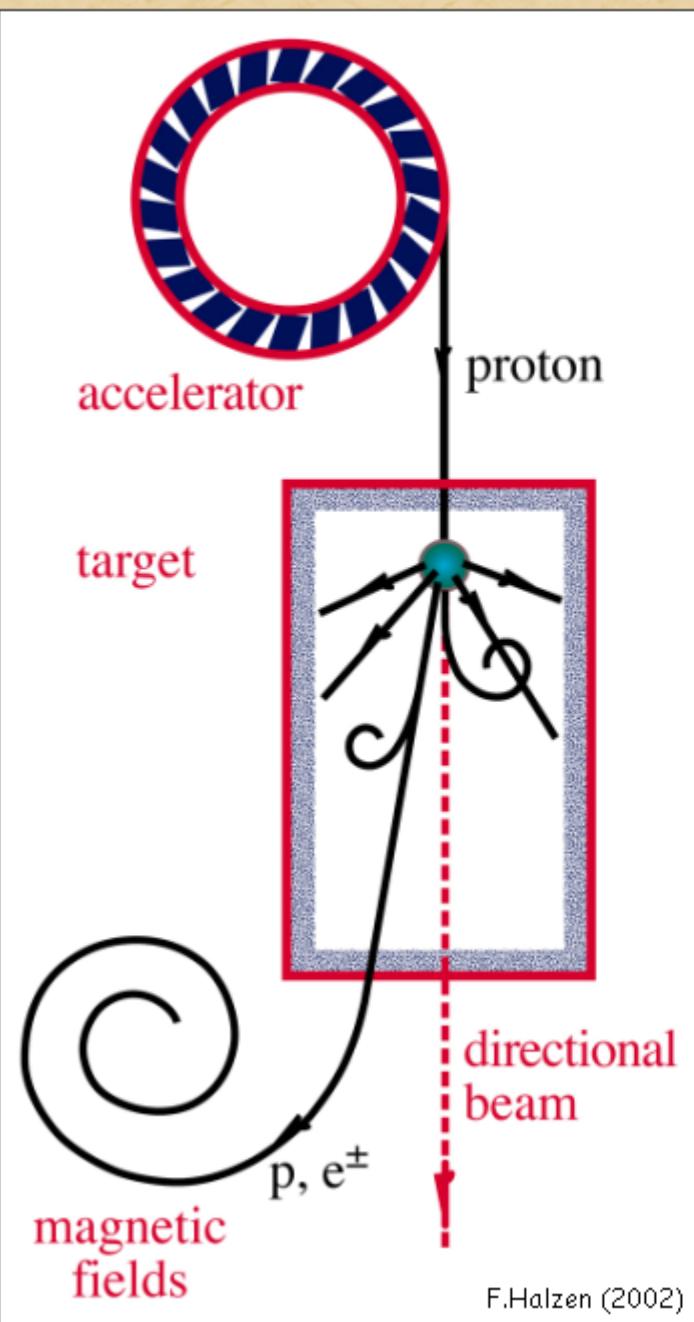


IceCube SN signal at 10 kpc, based on a numerical Livermore model
[Dighe, Keil & Raffelt, hep-ph/0303210]

Global Cosmic Ray Spectrum



Neutrino Beams: Heaven and Earth

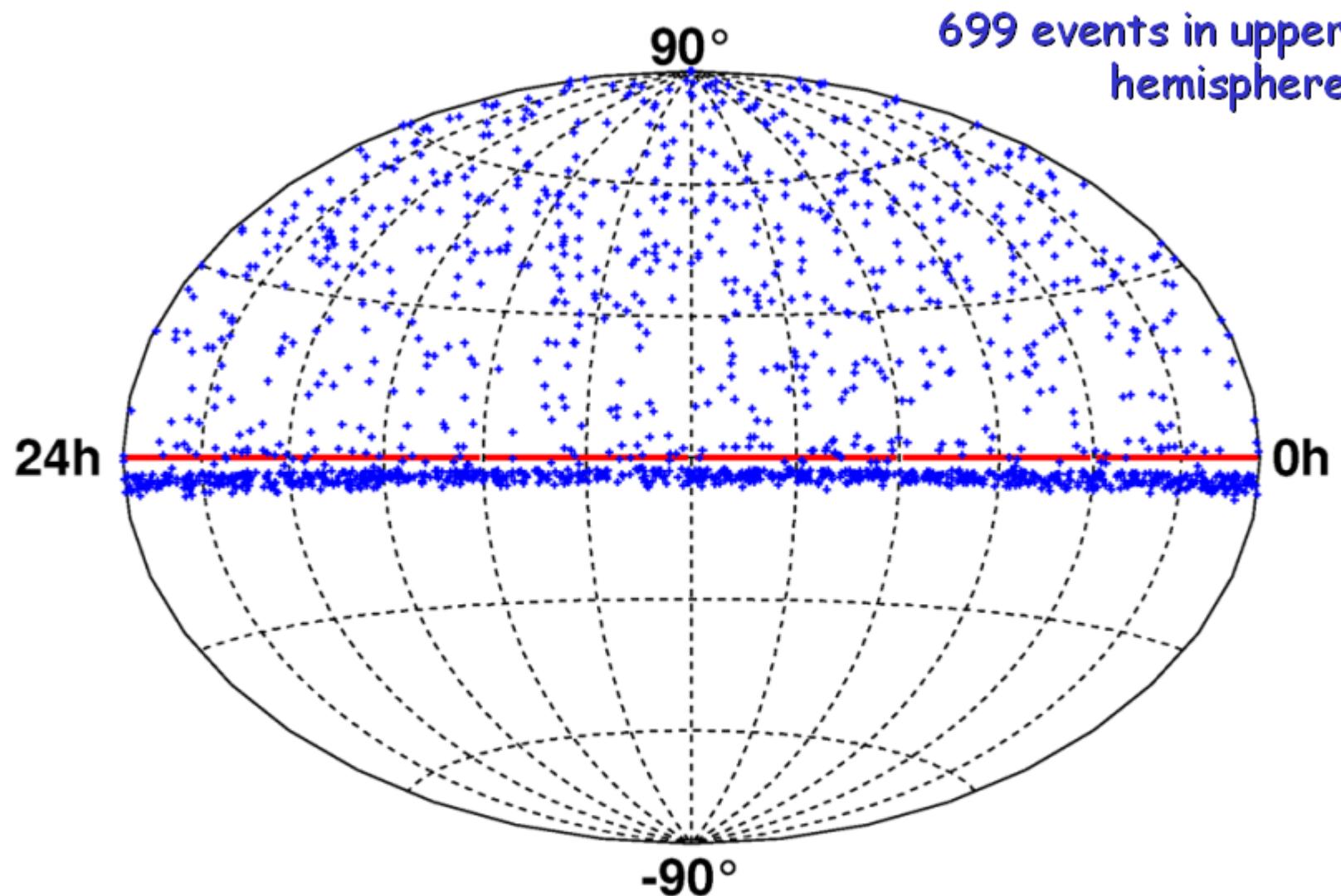


Target:
Protons or Photons

Approx. equal fluxes of
photons & neutrinos

Equal neutrino fluxes
in all flavors due to
oscillations

Neutrino Sky in AMANDA II (2000 Data)



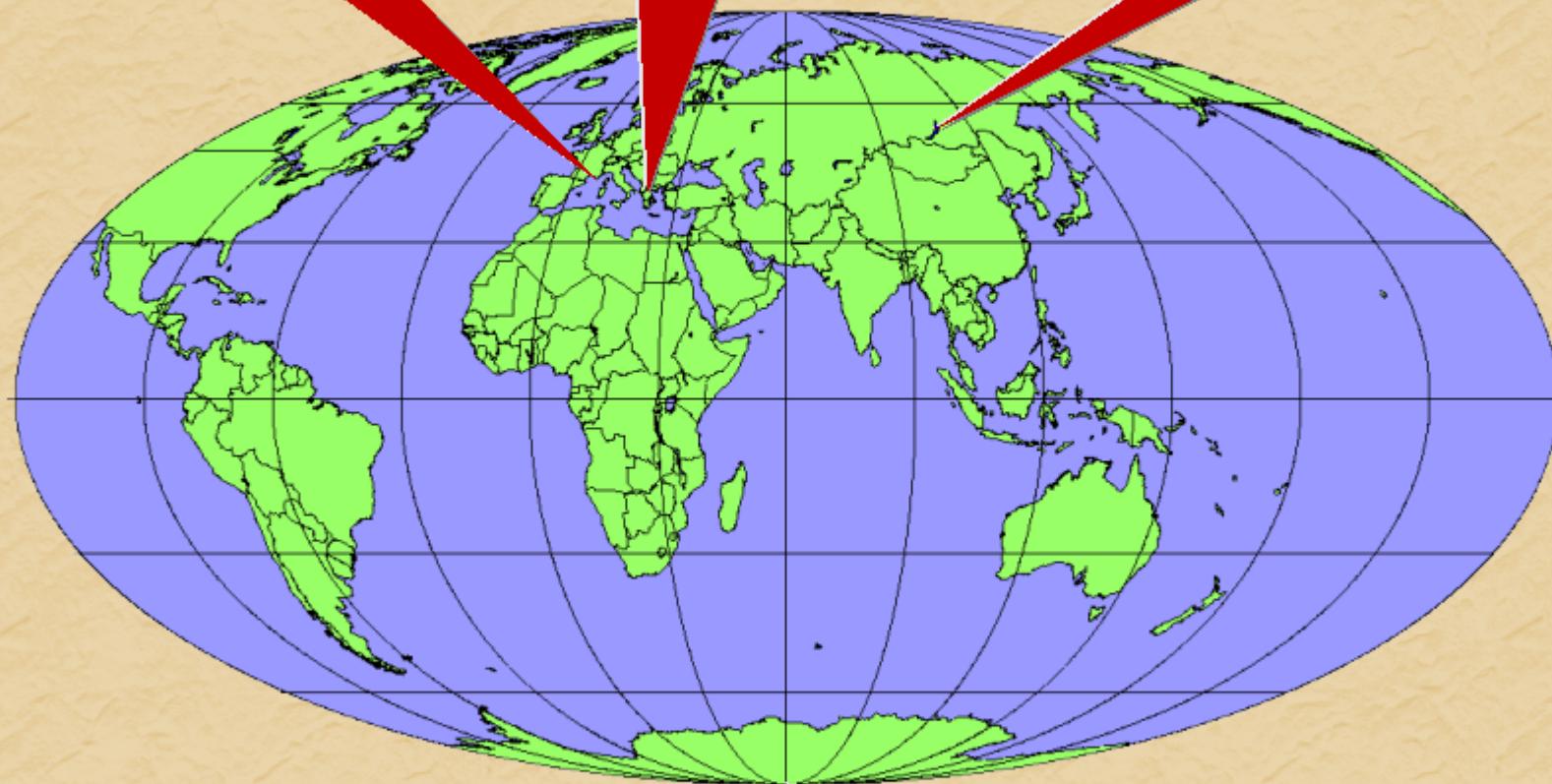
AMANDA Collaboration, astro-ph/0309585

High-Energy Neutrino Telescopes

Antares
Project

Nestor
Project

Baikal
200 PMTs



Amanda II, 800 PMTs
IceCube Project

Where do we stand? Where are we going?

Neutrino oscillations established

Mixing parameters at 2σ

	<u>Sun/KL</u>	<u>Atm/K2K</u>
$\Delta m^2 / \text{meV}^2$	60 – 84	1800 – 3300
$\tan^2 \theta$	0.33 – 0.57	0.57 – 2.0

If MiniBooNE confirms LSND,
more exotic new physics required
(Sterile nus? CPT violation? ...)

Precision for mixing parameters from long-baseline experiments

- K2K: Preliminary atm confirmation
 - Kamland: LMA confirmation 12/2002
 - Minos: Precision for atm parameters
 - CERN-Gran Sasso: ν_τ appearance
 - Future superbeams, nu factory etc.
- Measurement of Θ_{13} , mass ordering & leptonic CP violation (holy grail)

Absolute mass & Dirac vs Majorana

- Precision cosmology
 $\Sigma m_\nu < 0.7\text{--}2.1 \text{ eV}$, will improve
- Tritium endpoint
 $m_\nu < 2.2 \text{ eV}$, KATRIN goal 0.2 eV
- Future $0\nu 2\beta$ decay: Majorana mass
(difficult for normal hierarchy)
- Leptogenesis of baryon asymmetry
Majorana $m_\nu < 0.1 \text{ eV}$ suggested

Sky in the light of neutrinos

- High-E neutrino telescopes (Baikal, Amanda/IceCube, Antares, Nestor ...)
 - Cosmic-ray accelerators
 - Dark matter annihilation
 - Novel high-E phenomena
- Low-E observatories
- Future galactic supernova
 - Diffuse flux from cosmic supernovae