

CMB & Cosmology: Where Are We?
Ringberg Castle, Tegernsee, Germany, 2-6 December 2002

Neutrinos in Physics and Astrophysics

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Max-Planck-Institut für Physik, München, Germany

Neutrinos in Physics and Astrophysics



Flavor oscillations and all that



Quest for the absolute mass scale

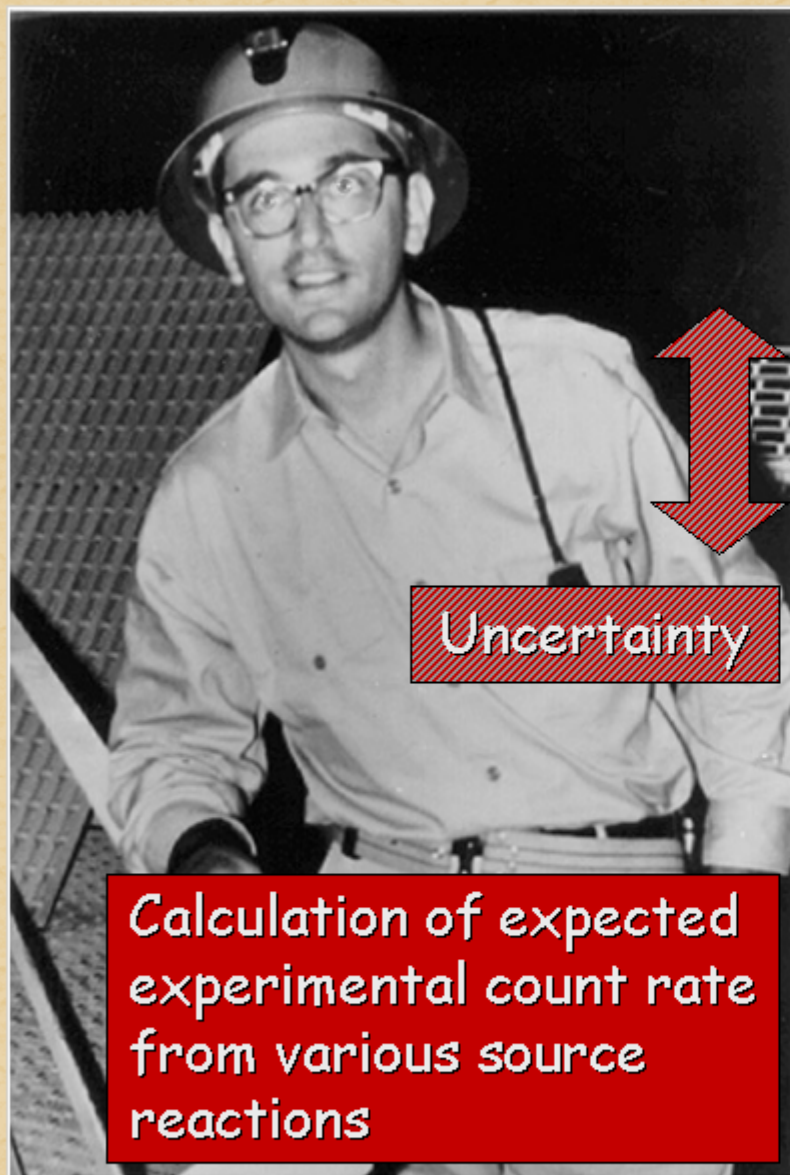


Neutrino mass and the
baryon asymmetry of the universe



Neutrinos as astrophysical messengers

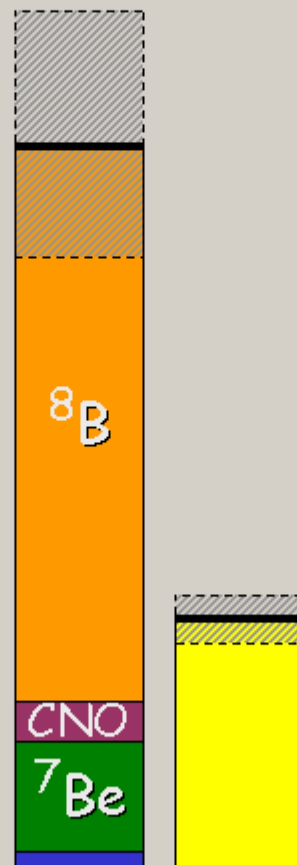
Missing Neutrinos from the Sun



John Bahcall

Homestake

Chlorine



Raymond Davis Jr.

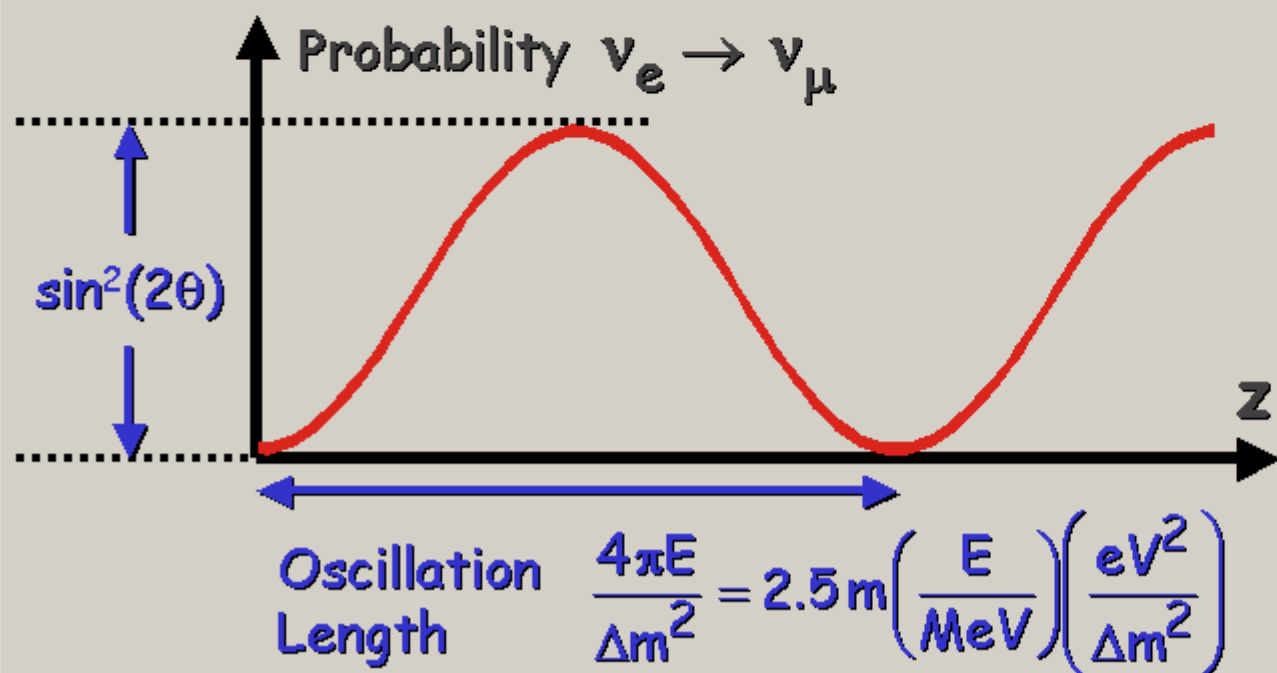
Neutrino Flavor Oscillations

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}

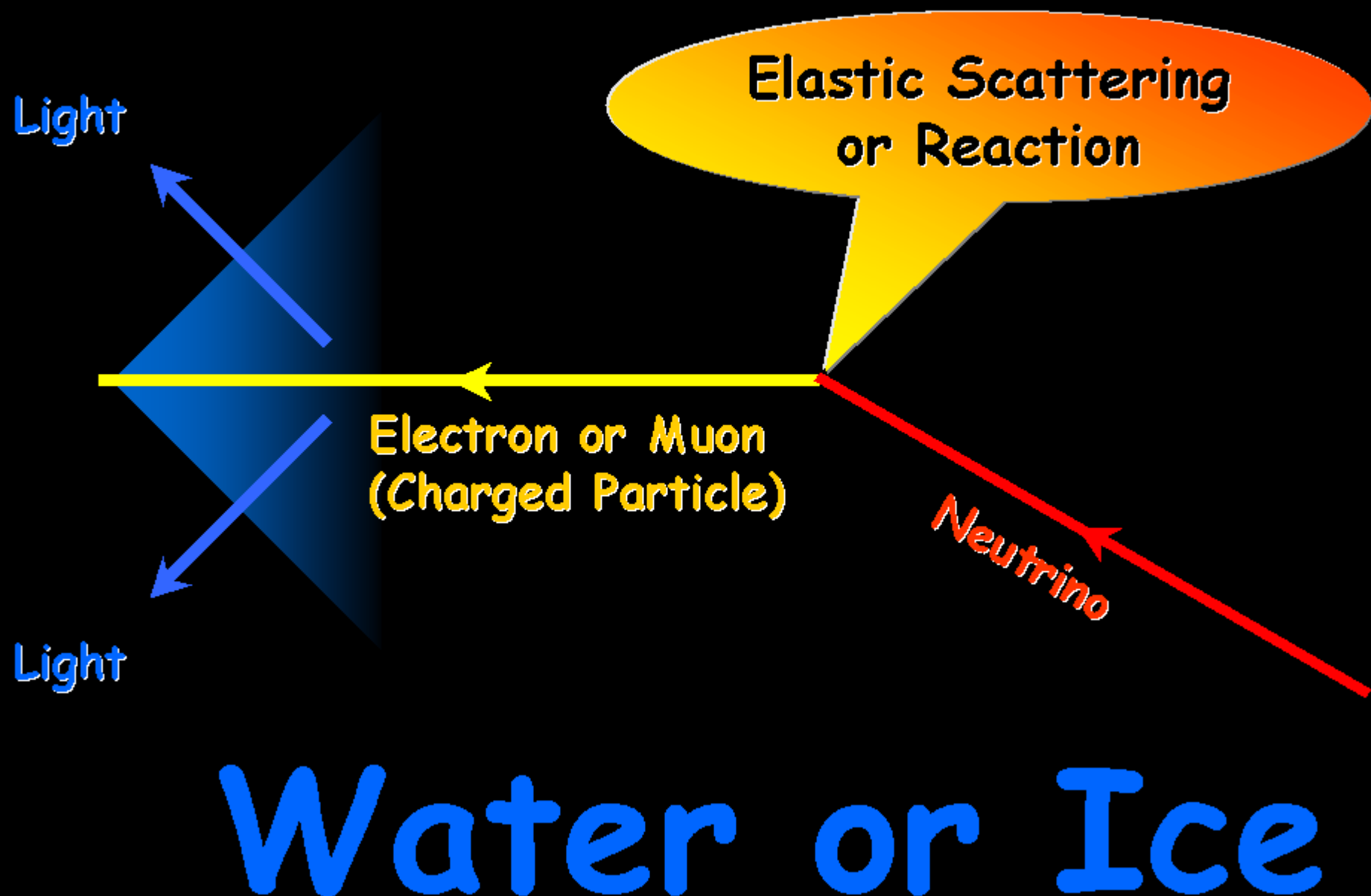
with $p = \sqrt{E^2 - m^2} \approx E - \frac{m^2}{2E}$

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

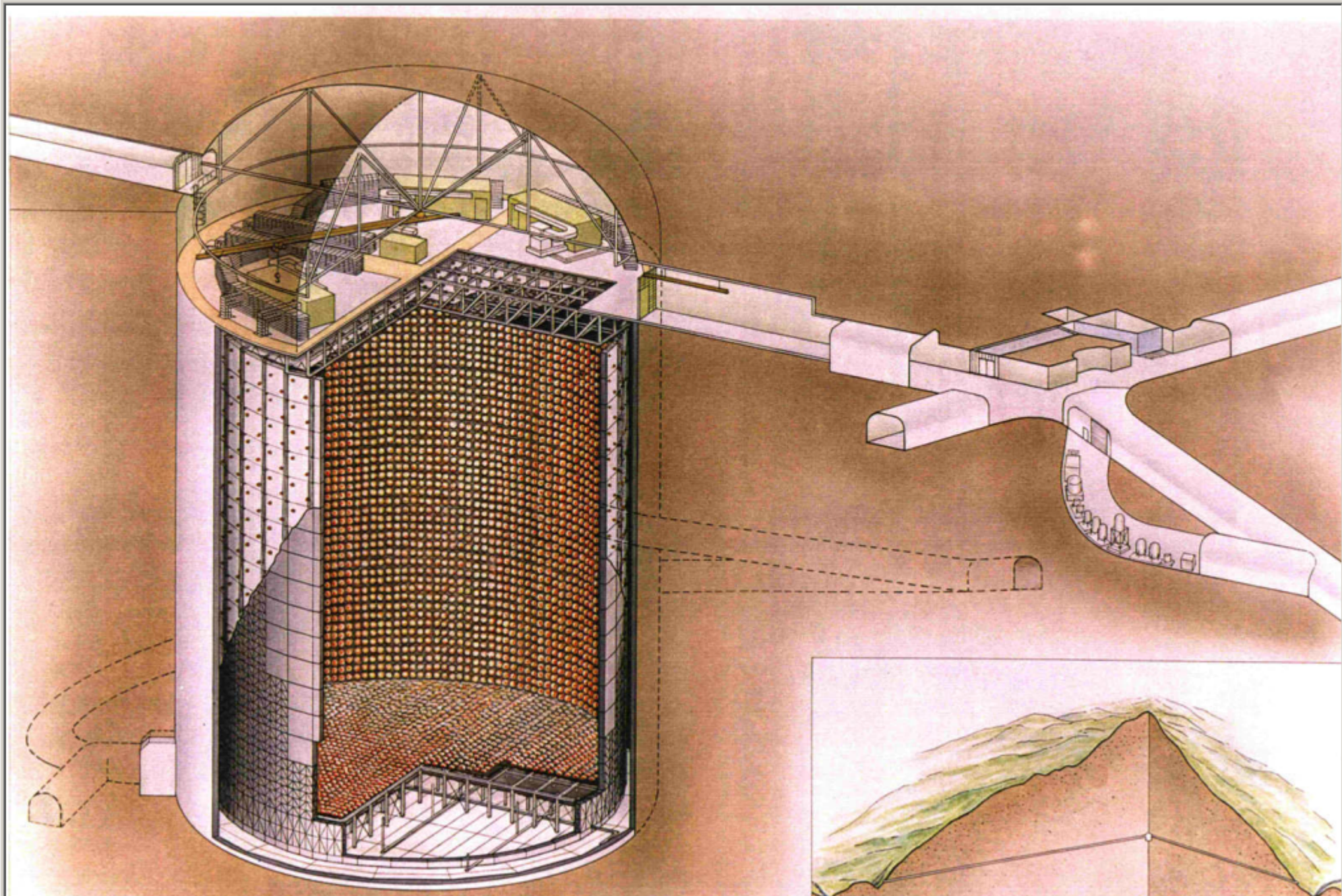


Bruno Pontecorvo
(1913 - 1993)
Invented nu oscillations

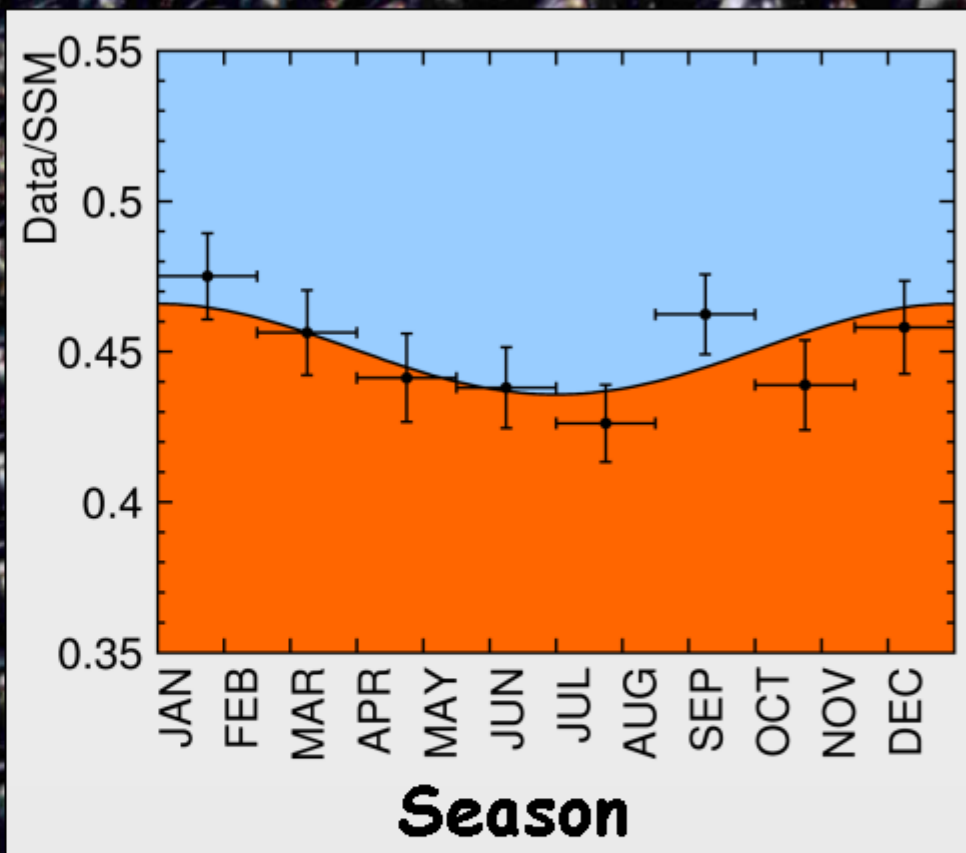
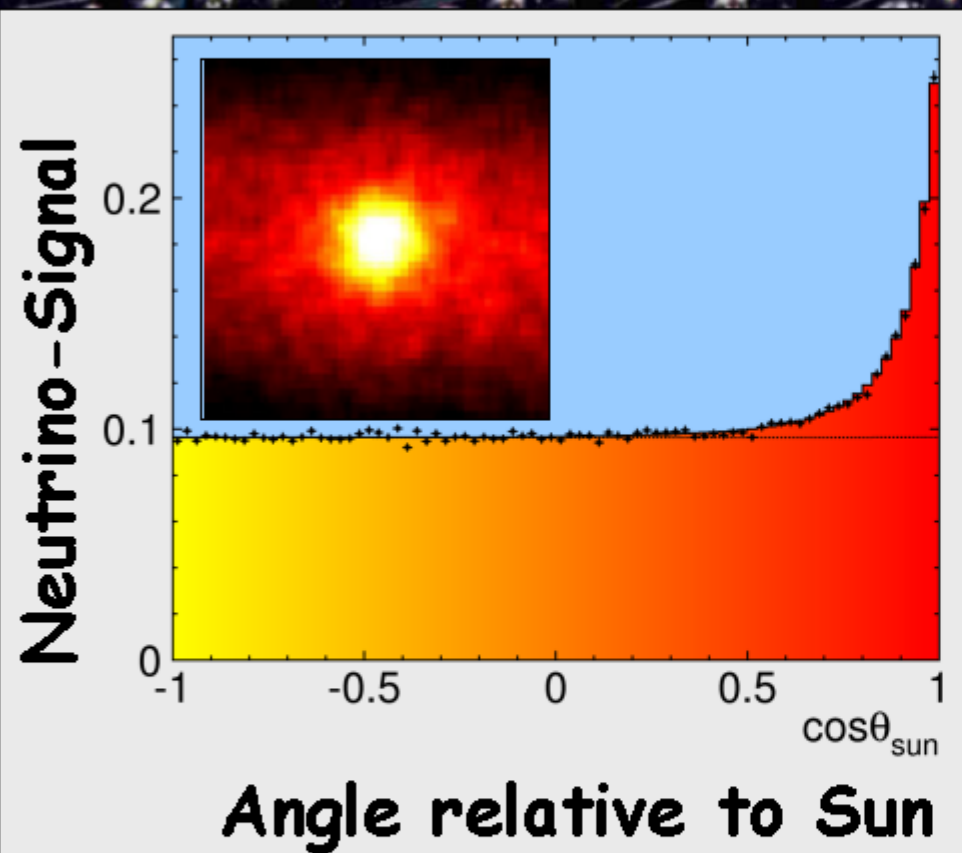
Cherenkov Effect



Super-Kamiokande Neutrino Detector



Sun in the Light of Neutrinos



Missing Neutrinos from the Sun

Homestake

Gallex/GNO
SAGE

(Super-)
Kamiokande

SNO
(Deuterium)

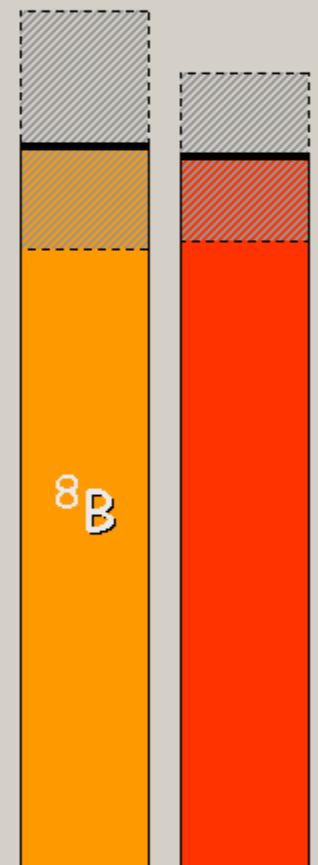
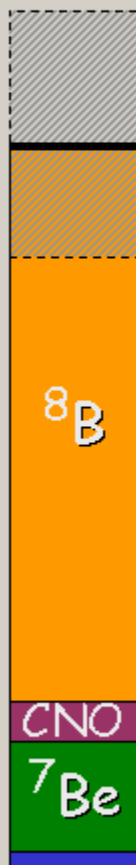
Chlorine

Gallium

Water

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

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



Electron-Neutrinos

All Neutrino
Flavors

Missing Neutrinos from the Sun

20 April 2002
Solar Neutrino Problem
finally solved

Homestake

Gallex/GNO
SAGE

(Super-)
Kamiokande

SNO
(Deuterium)

Chlorine

Gallium

Water

$d \rightarrow p + n + \bar{\nu}_e$

$d \rightarrow p + n + \nu$

^8B

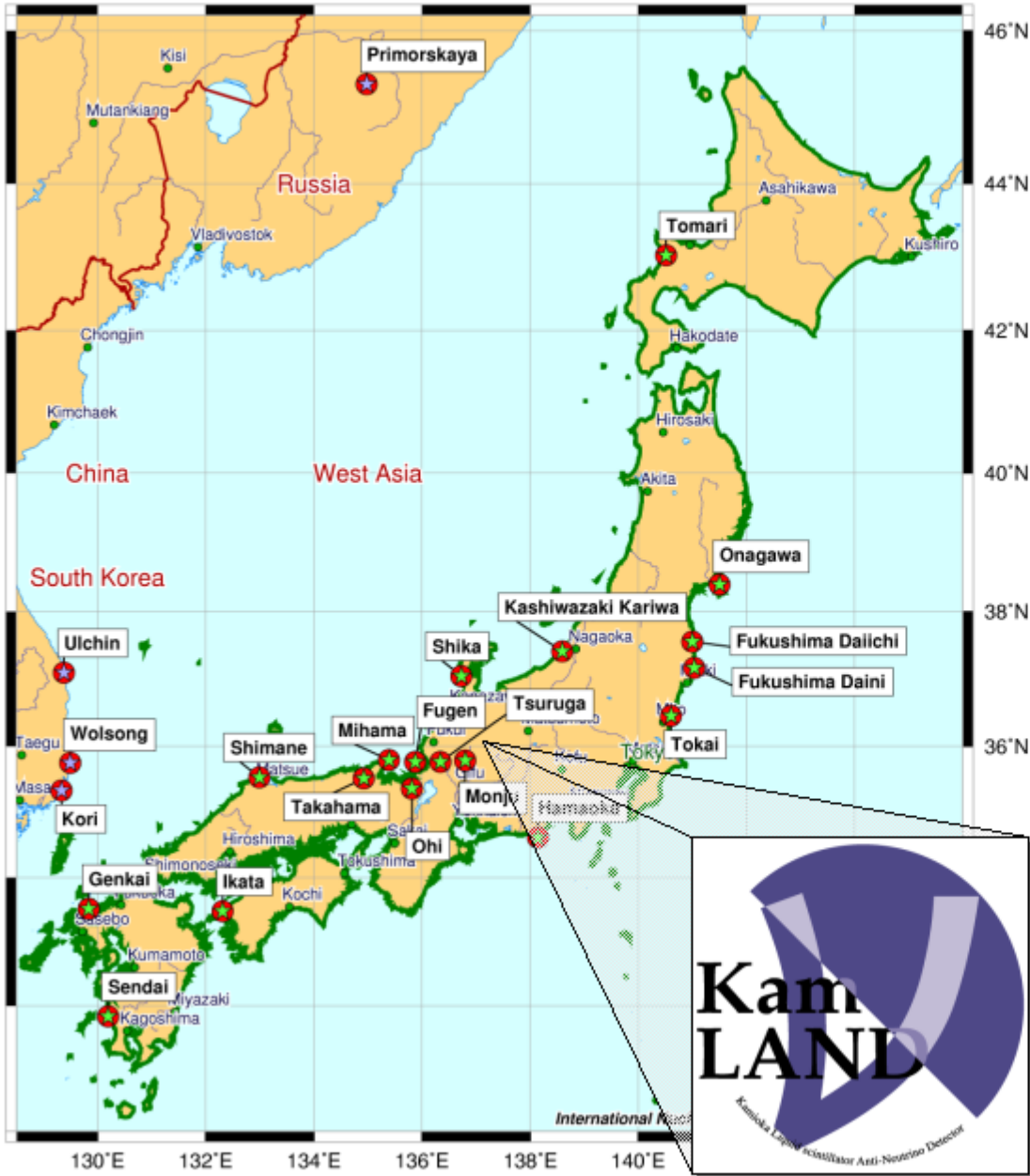
CNO
 ^7Be

^8B

Electron Neutrinos

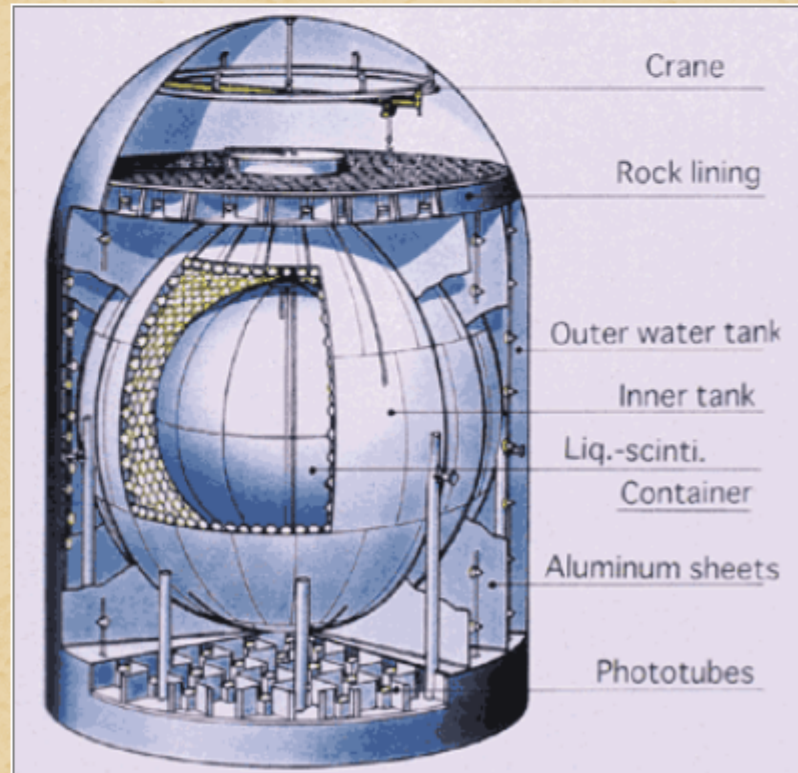
All Neutrino
Flavors

Kamland Reactor Neutrino Experiment (Japan)

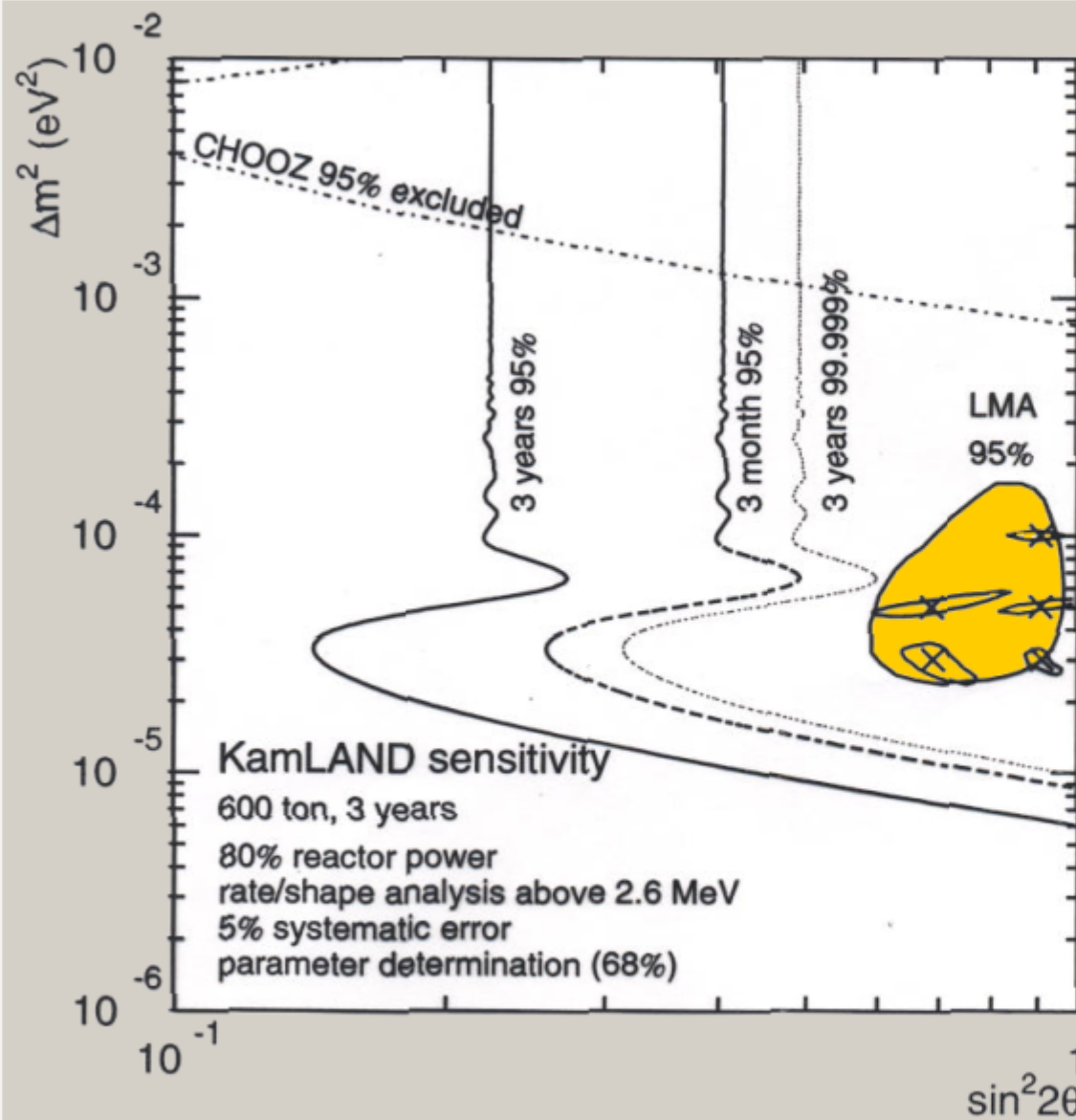


Japanese nuclear reactors
60 GW (20% world capacity)

- Witout Oscillations
2 Neutrino captures / day
- Data taking since
22 January 2002



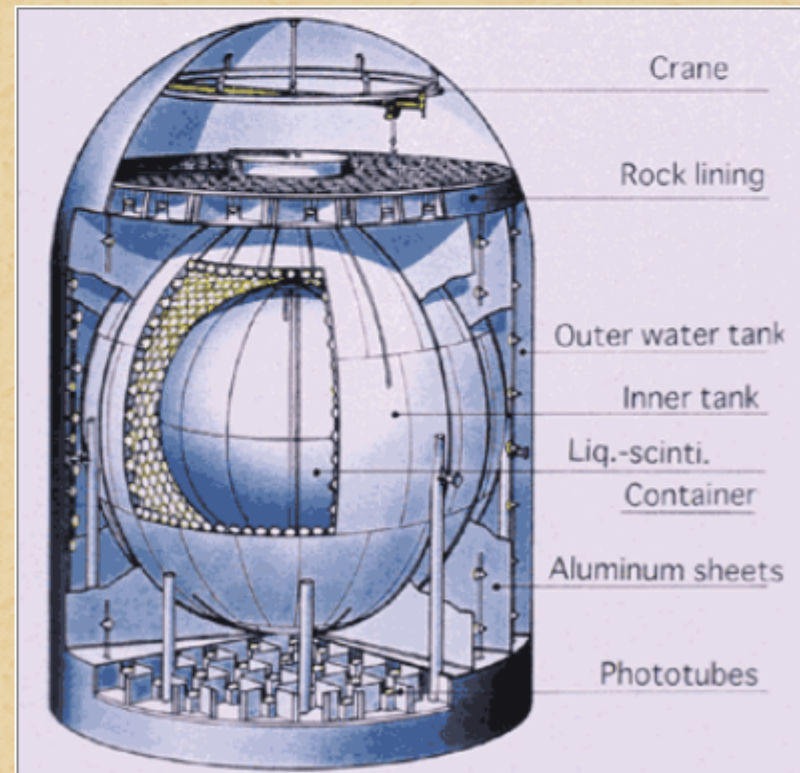
Kamland Reactor Neutrino Experiment (Japan)



J. Shirai at Neutrino 2002

Japanese nuclear reactors
60 GW (20% world capacity)

- Without Oscillations
2 Neutrino captures / day
- Data taking since
22 January 2002



Kamland Reactor Neutrino Experiment (Japan)



Japanese nuclear reactors
6 GW (20% world capacity)

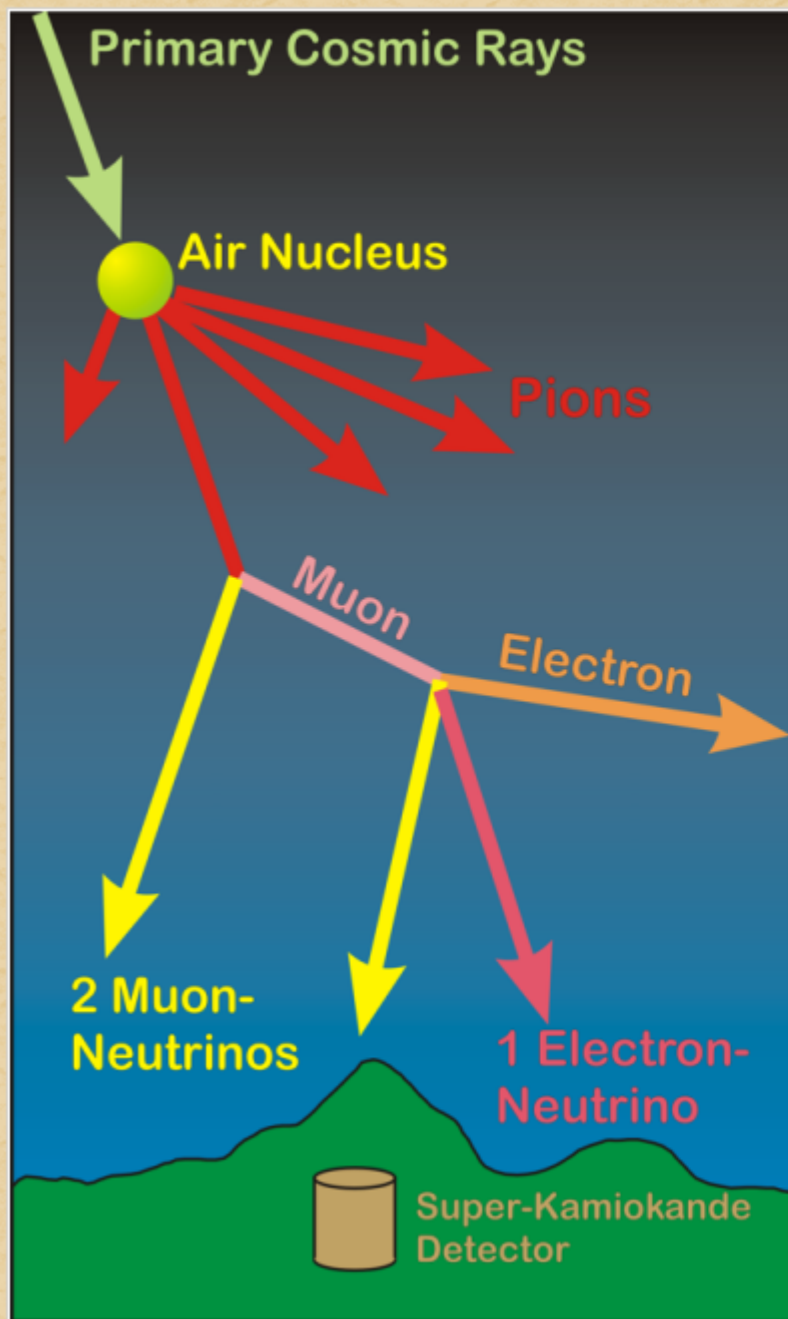
neutrino captures / day

First results
to be announced
next week at
"Texas in Tuscany"

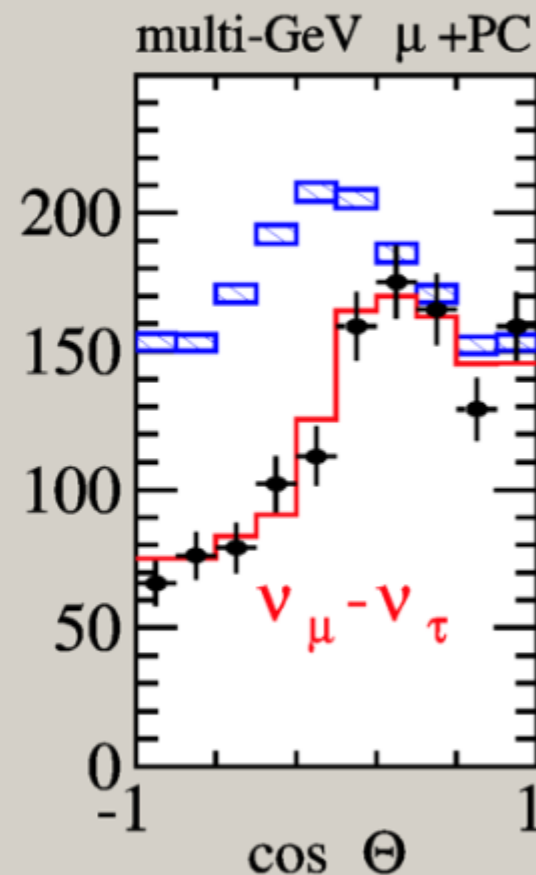
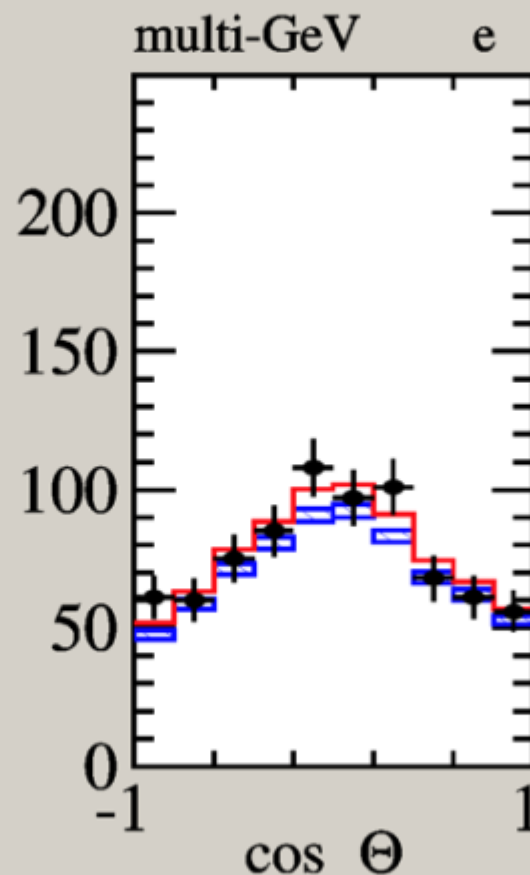
J. Shirai at Neutrino 2002



Atmospheric Neutrino Anomaly

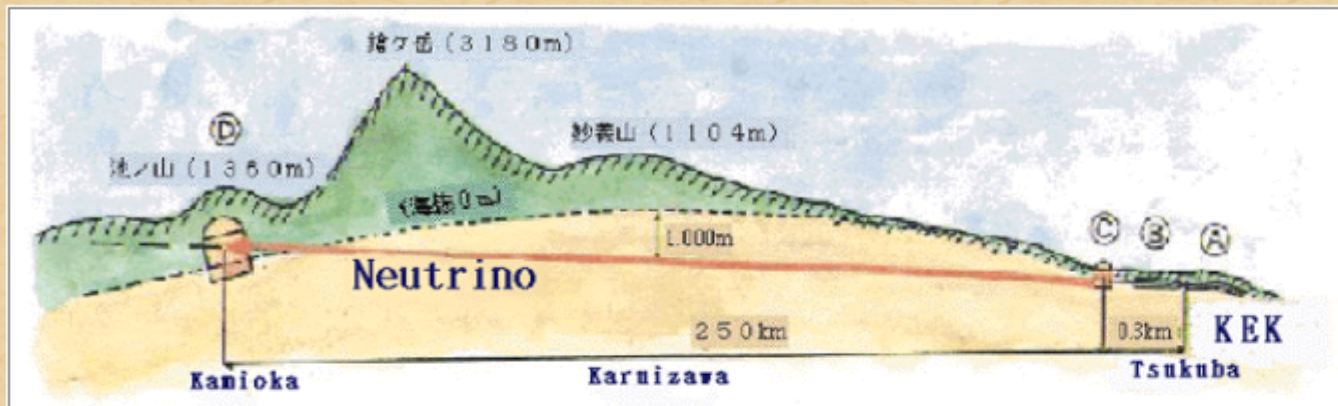


Zenith-angle distribution of atmospheric nus
in Super-Kamiokande [hep-ex/0210019]

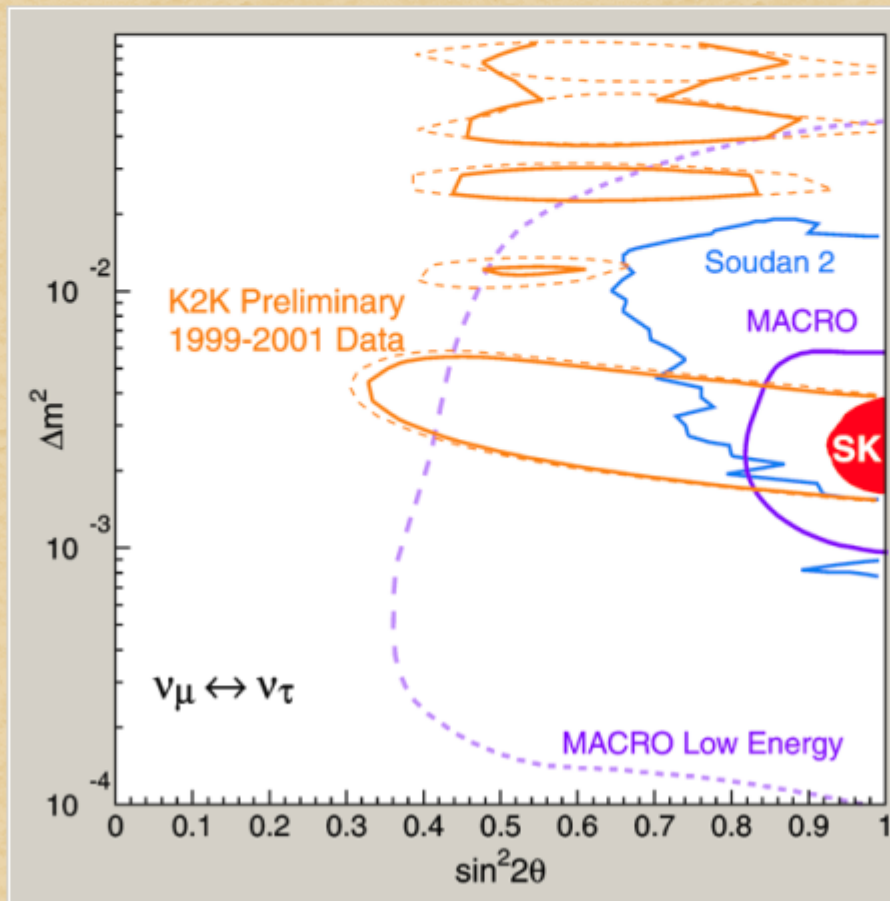


Half of the muon neutrinos
from below are missing

K2K Long-Baseline Experiment (since 1999)



Neutrino beam
from KEK
250 km to
Super-Kamiokande



First data confirm
flavor oscillations
in atmospheric
parameter region
Currently no data
taking
(Super-K accident)

hep-ex/0210019

Japanese Hadron Facility (JHF) to Kamioka (2007)

Y. Itow (ICRR, Univ. Tokyo), ICHEP02 Amsterdam

JHF-Kamioka Neutrino Experiment

(hep-ex/0106019)

Plan to start in 2007

Kamioka

$\sim 1\text{GeV}$ ν beam

Super-K: 22.5 kt

Hyper-K: 1000 kt

295km

**JAERI
(Tokai)**

0.75MW 50 GeV PS

4MW 50 GeV PS

(conventional ν beam)

(c) 2000 ESRI

420.0 mi / 675.8 km across

JHF 0.75MW + Super-Kamiokande

Future Super-JHF 4MW + Hyper-K $\sim$ JHF+SK $\times$ 200

Upcoming Long-Baseline Experiments (2005)

FermiLab-Soudan (MINOS)



CERN - Gran Sasso



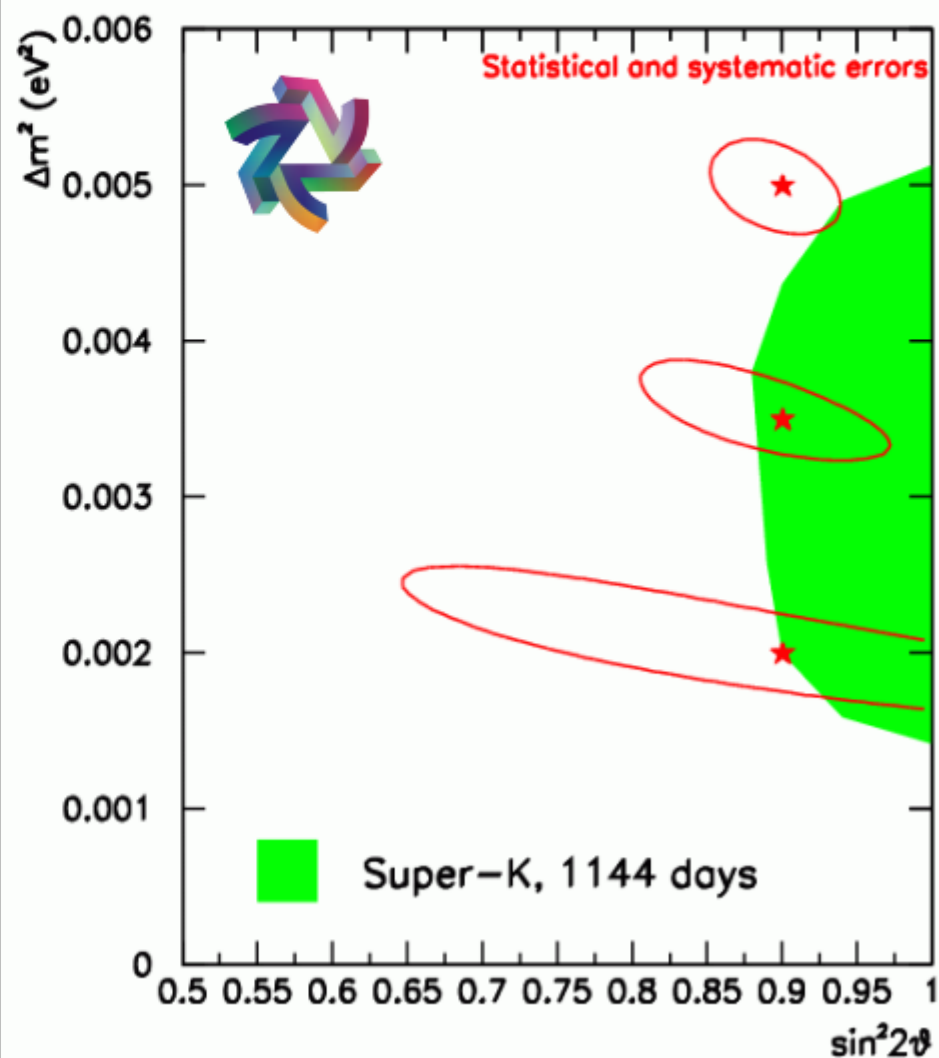
Upcoming Long-Baseline Experiments (2005)

FermiLab-Soudan (MINOS)



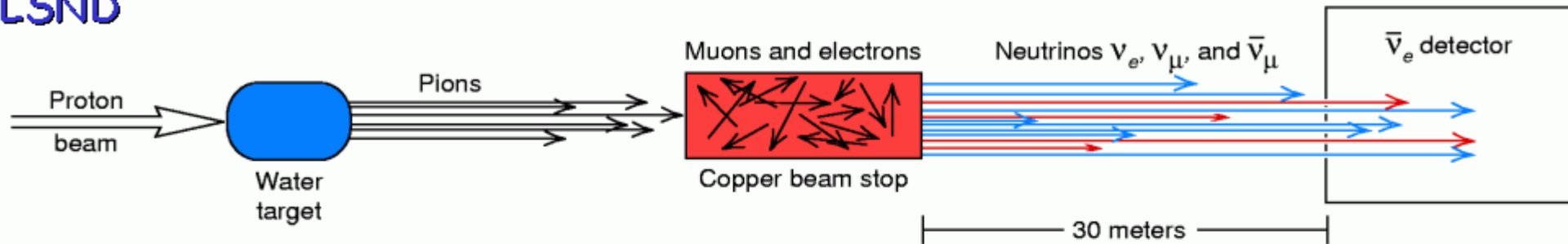
MINOS Oscillation Sensitivity

Ph2le, 10 kt. yr., 90% C.L.

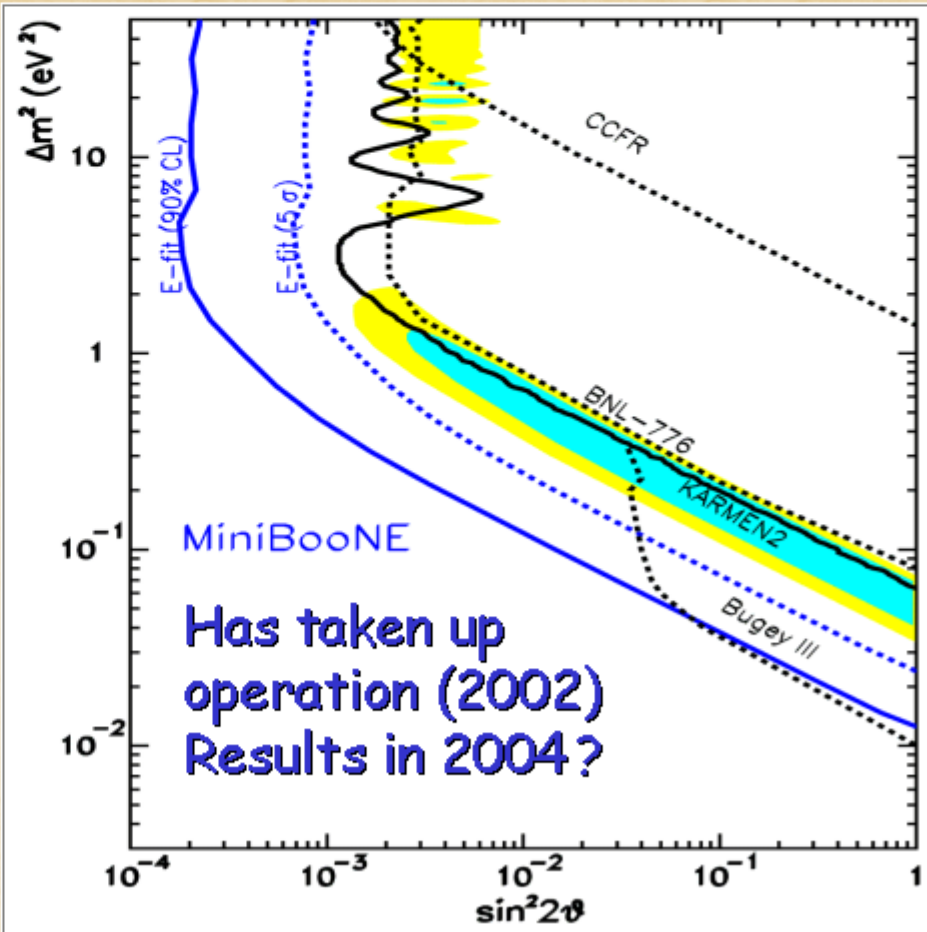
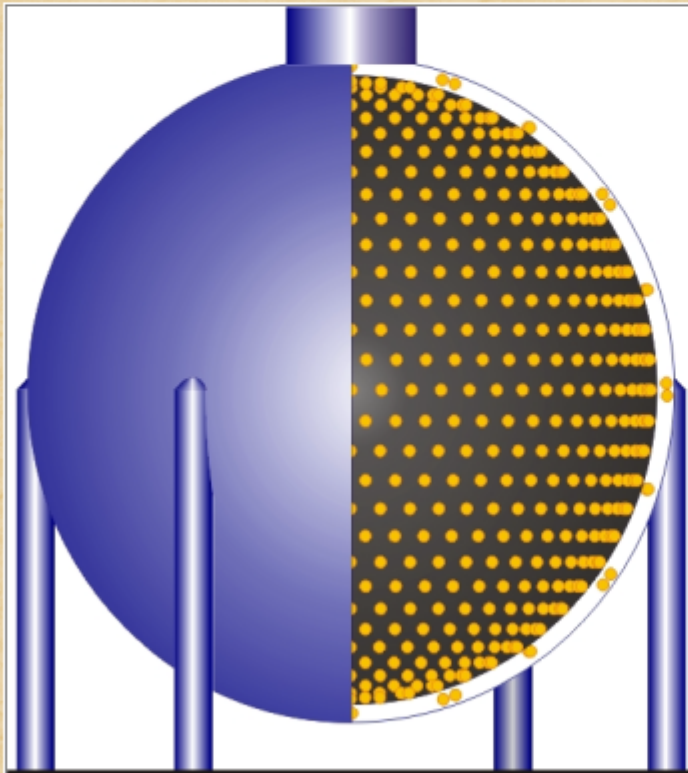


Testing LSND at MiniBooNE

LSND



www-boone.fnal.gov



Status of Evidence for Neutrino Oscillations

System	Atmospheric	Solar	LSND
Channel	$\nu_\mu \rightarrow \nu_\tau$	$\nu_e \rightarrow \nu_{\mu\tau}$	$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
$\delta m^2 / \text{eV}^2$	$(1.5 - 4) \times 10^{-3}$	LMA $(0.2 - 2) \times 10^{-4}$	0.2-2 or 6.5
$\sin^2 2\theta$	0.9-1	0.2-0.6	0.001-0.03
Status	Established	Established	Unconfirmed
Test	Long Baseline (K2K)	KamLAND 2002 ?	MiniBooNE 2004 ?
Implication	Mutually inconsistent, even with a sterile neutrino Evidence for physics beyond flavor oscillations (CPT violation ...)?		
Simplest interpretation	Three mass eigenstates with $m_1 \ll m_2 \ll m_3 \sim 50 \text{ meV}$ (hierarchical) $m_1 \sim m_2 \sim m_3 \gg 50 \text{ meV}$ (degenerate)		Experimental or Statistical Fluke

Status of Evidence for Neutrino Oscillations

**A MiniBooNE
confirmation of LSND would
be another revolution.
Too good to be true?**

System

Atmospheric

LSND

Channel

$\rightarrow \nu_\mu$

$\mu \rightarrow \bar{\nu}_e$

$\delta m^2 / \text{eV}^2$

1.2-2 or 6.5

Status

Confirmed

Test

2004 ?

Interpretation

Evidence

neutrino
(CP violation ...)?

Simplest
interpre-
tation

Three eigenstates with
 $m_1 < m_2 \ll m_3 \sim$
 $m_1 \sim m_2 \sim m_3 \gg$

with
(hierarchical)
(degenerate)

Experimental or
statistical
fluke

Three-Flavor Neutrino Parameters (Ignoring LSND)

Atmospheric
 $32^\circ < \theta_{23} < 60^\circ$

Chooz Limit
 $\theta_{13} < 14^\circ$

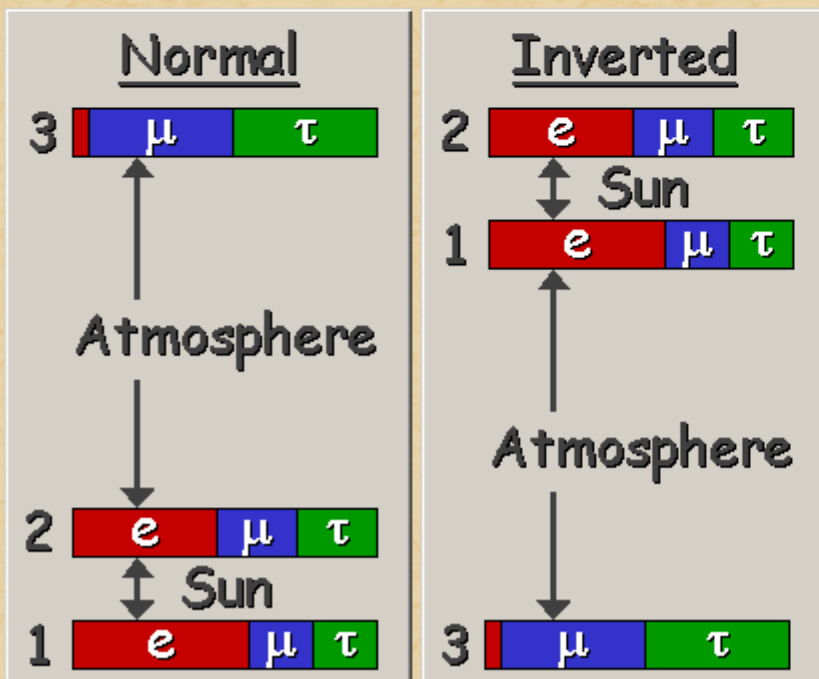
Solar
 $27^\circ < \theta_{12} < 41^\circ$

3σ ranges
 hep-ph/0211054

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

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

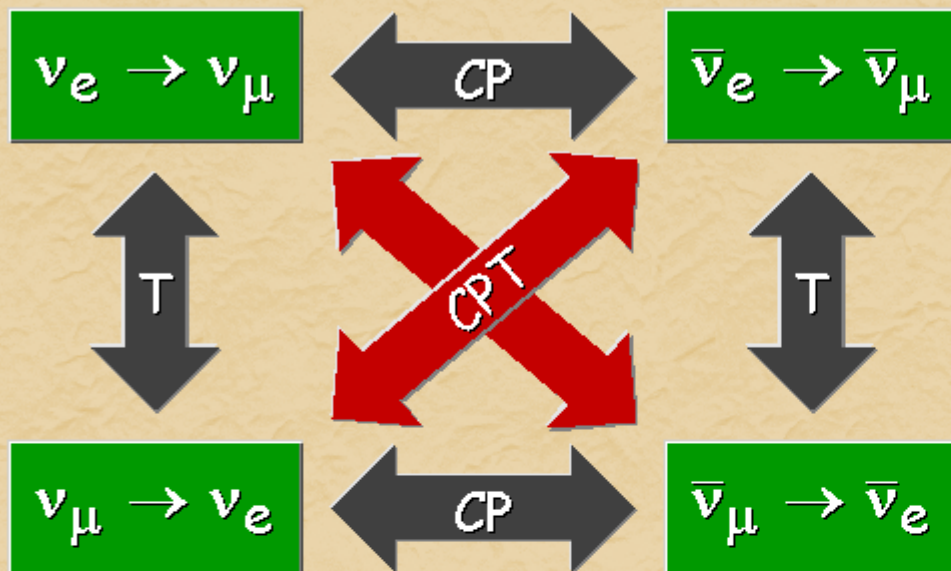
Solar
 24 - 240
 Atmospheric
 1400 - 6000
 $\Delta m^2 / \text{meV}^2$



Tasks and Open Questions

- Precision for θ_{12} and θ_{23} ($\theta_{12} < 45^\circ$ and $\theta_{23} = 45^\circ$?)
- How large is θ_{13} ?
- CP-violating phase?
- Mass ordering? (normal vs inverted)
- Absolute masses? (hierarchical vs degenerate)
- Dirac or Majorana?

Discrete Symmetries in Neutrino Oscillations



CP Particle $\leftrightarrow$ antiparticle
 T Time reversal
 CPT Should be conserved
 in local field theories

Analogous relations for
any pair of neutrino flavors

Probability for the "key process" $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ and $\nu_\mu \rightarrow \nu_e$

$$\left. \begin{aligned} P(\nu_\mu \rightarrow \nu_e) \\ P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) \end{aligned} \right\} = \sin^2 \theta_{23} \sin^2 2\theta_{13} \sin^2 \Delta_{\text{atm}} \\
 + \sin 2\theta_{12} \sin 2\theta_{23} \sin 2\theta_{13} \cos \theta_{13} \Delta_{\text{sun}} \sin \Delta_{\text{atm}} (\cos \delta \cos \Delta_{\text{atm}} \pm \sin \delta \sin \Delta_{\text{atm}})$$

where $\Delta_{\text{atm}} = \frac{\Delta m_{\text{atm}}^2 L}{4E}$ and $\Delta_{\text{sun}} = \frac{\Delta m_{\text{sun}}^2 L}{4E}$

Long-Baseline Experiments

Nuclear
reactors

Nuclear decay

Kamland (2002)
Borexino (>2003?)

Solar LMA

Conventional
beam

Proton beam dump
 $\rightarrow \pi \rightarrow \mu \nu_\mu \rightarrow e \nu_\mu \nu_\mu \nu_e$

K2K (1999)
NuMI (2005)
CNGS (2005)
JHF (2007)

Test and precision
for atm
 $\sin^2 2\theta_{13} \sim 0.01$

Super beam

Primary proton beam
> 1 MW

Super-JHF,
Super-NuMI, ...

$\sin^2 2\theta_{13} \sim 0.001$

Beta beam

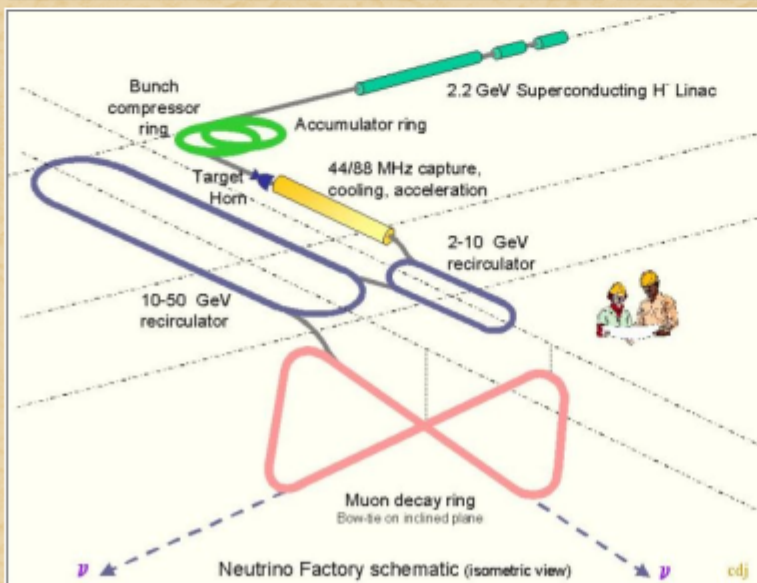
Nuclear decay
(high Lorentz factor)

R&D

$\sin^2 2\theta_{13} \sim 0.0001$

Neutrino
factory

Muon
storage ring
 $\mu \rightarrow e \nu_\mu \bar{\nu}_e$



R&D



CP violation
Mass ordering

Neutrino Factory Working
Group homepage at CERN
<http://nfwg.home.cern.ch/nfwg/nufactwg/nufactwg.html>

Neutrinos in Physics and Astrophysics



Flavor oscillations and all that



Quest for the absolute mass scale

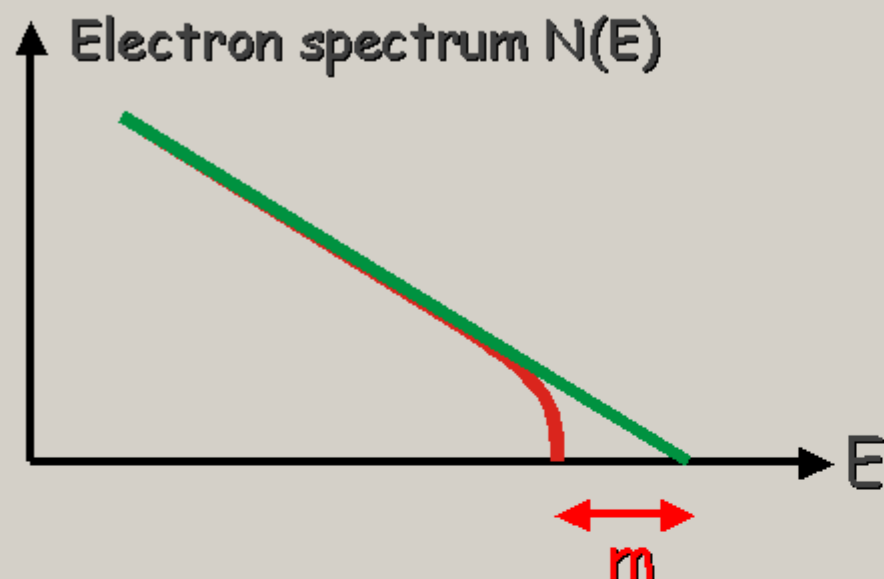


Neutrino mass and the
baryon asymmetry of the universe



Neutrinos as astrophysical messengers

Tritium Endpoint Spectrum



Tritium Beta Decay



Endpoint energy 18.6 keV

Mainz Experiment, PLB 460 (1999) 219

$m < 2.8 \text{ eV}$ (95% CL)

Troitsk Experiment, ibid. 227

$m < 2.5 \text{ eV}$ (95% CL)

Current
experiments
have reached

2.2 eV
(Neutrino 2002)

Scaled-up spectrometer (KATRIN) may reach 0.3 eV
Currently in preparation - Results in > 5 years

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

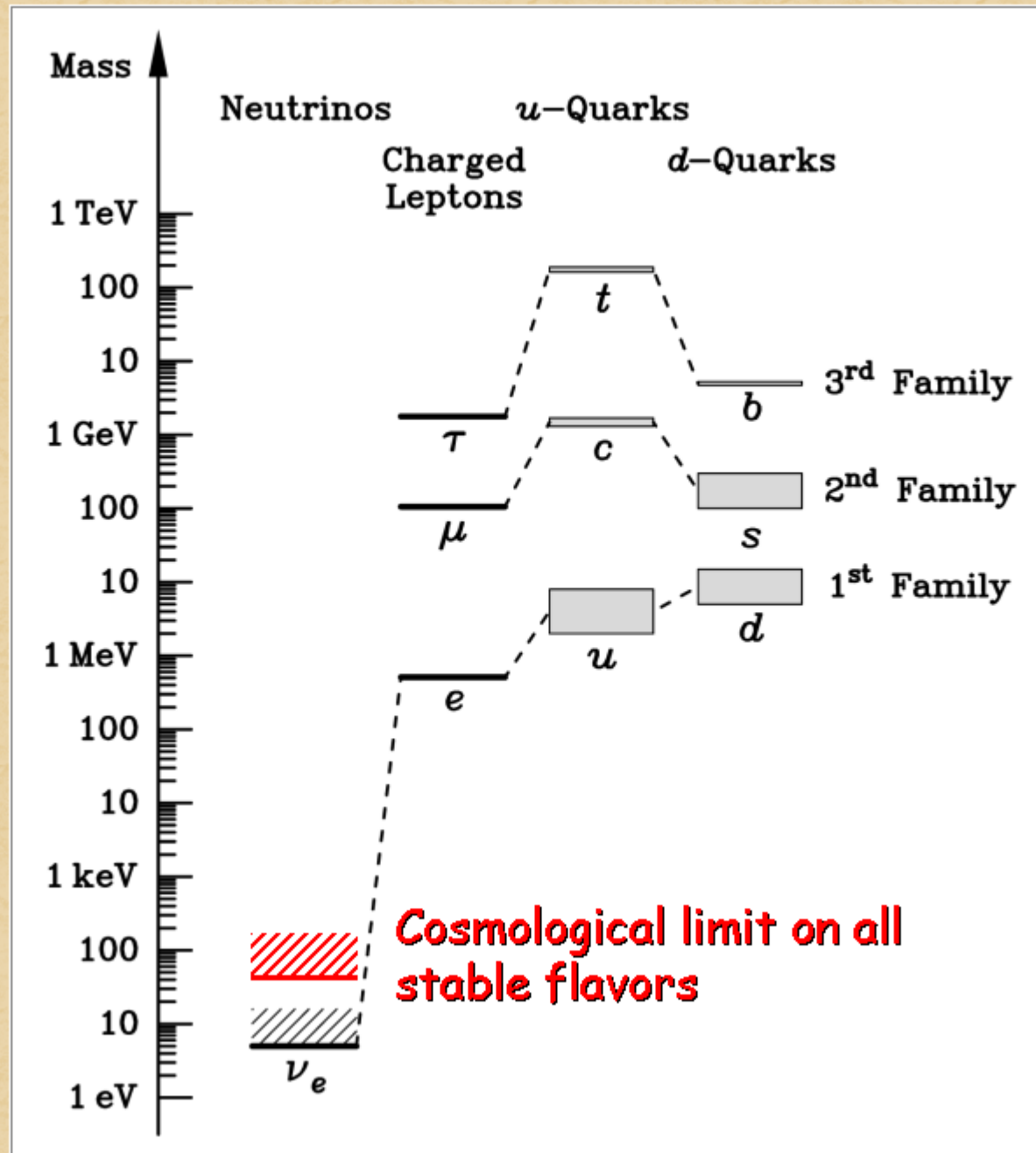
A classic paper:
Gershtein & Zeldovich
JETP Lett. 4 (1966) 120

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.

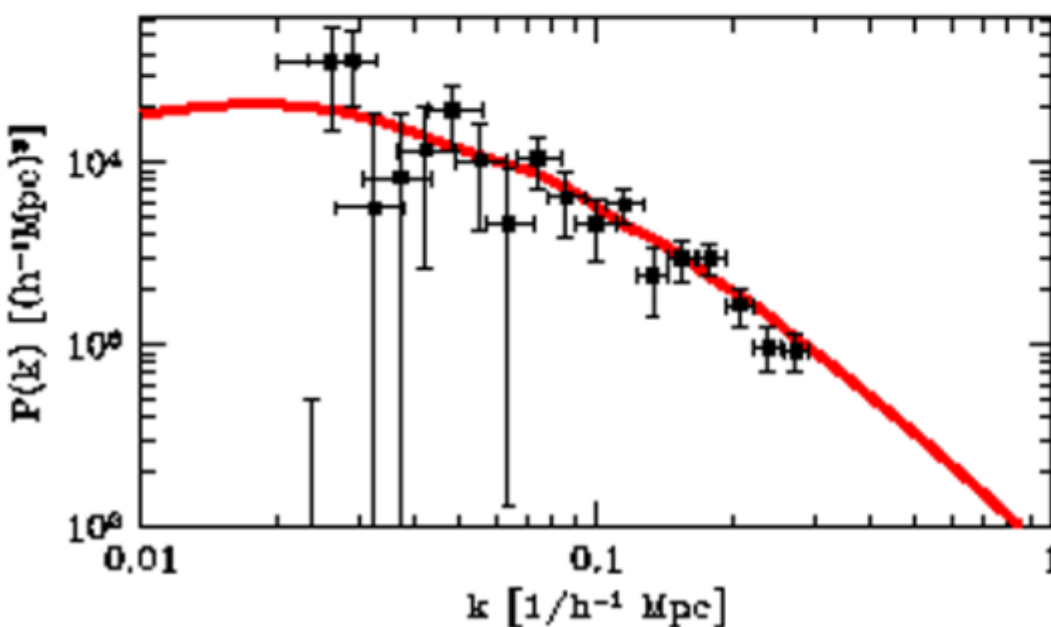
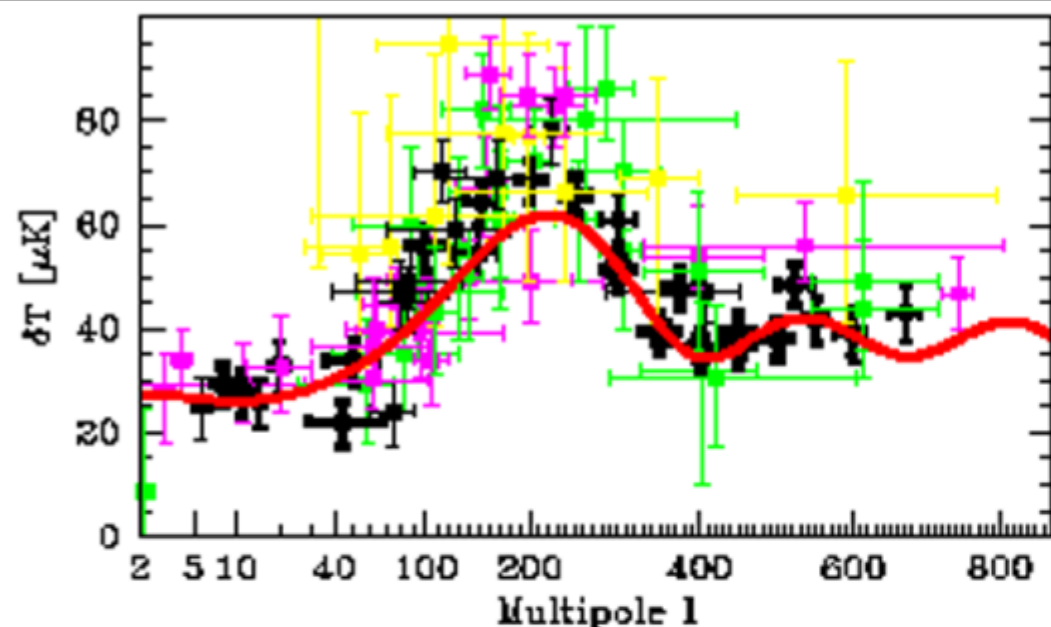
Cosmological considerations connected with the hot model of the Universe [2] make it possible to strengthen greatly the second inequality. Just as in the paper by Ya. B. Zel'dovich and Ya. A. Smorodinskii [3], let us consider the gravitational effect of the neutrinos on the dynamics of the expanding 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 km/sec-Mpc = $(13 \times 10^9 \text{ years})^{-1}$. It follows therefore that the density of all types of matter in the Universe is at the present time ¹⁾

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

Fermion Mass Spectrum



Fitting the Cosmological Model - Neutrinos



$\tau=0.000$

$\Omega_k=0.000$

$\Omega_\Lambda=0.61$

$\omega_d=0.13$

$\omega_b=0.020$

$f_\nu=0.000$

$n_s=0.90$

$n_t=-1.000$

$A_s=0.44$

$A_t=0.000$

$b=1.2$

$h=0.62$

$\chi^2=0.000$

Ionization parameter

Curvature

Cosmological constant

Dark Matter ($\Omega_M h^2$)

Baryons ($\Omega_B h^2$)

Neutrino DM fraction

Scalar power-law index

Tensor power-law index

Scalar Amplitude

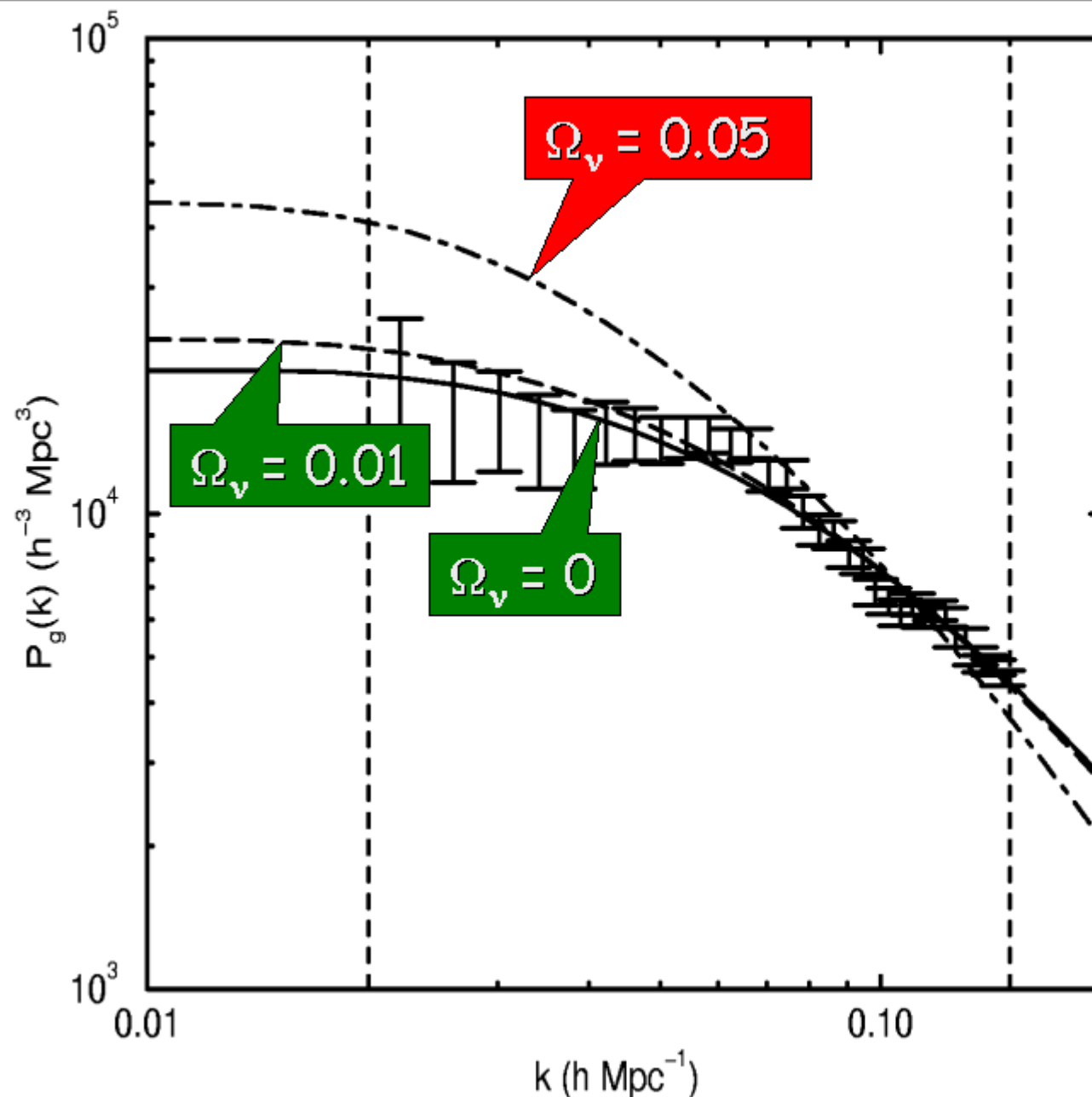
Tensor Amplitude

Biasing parameter

Hubble constant

Max Tegmark,
www.hep.upenn.edu/~max/concordance.html

Neutrino Mass Limit from 2dF Galaxy Survey



Elgaroy et al.,
astro-ph/0204152

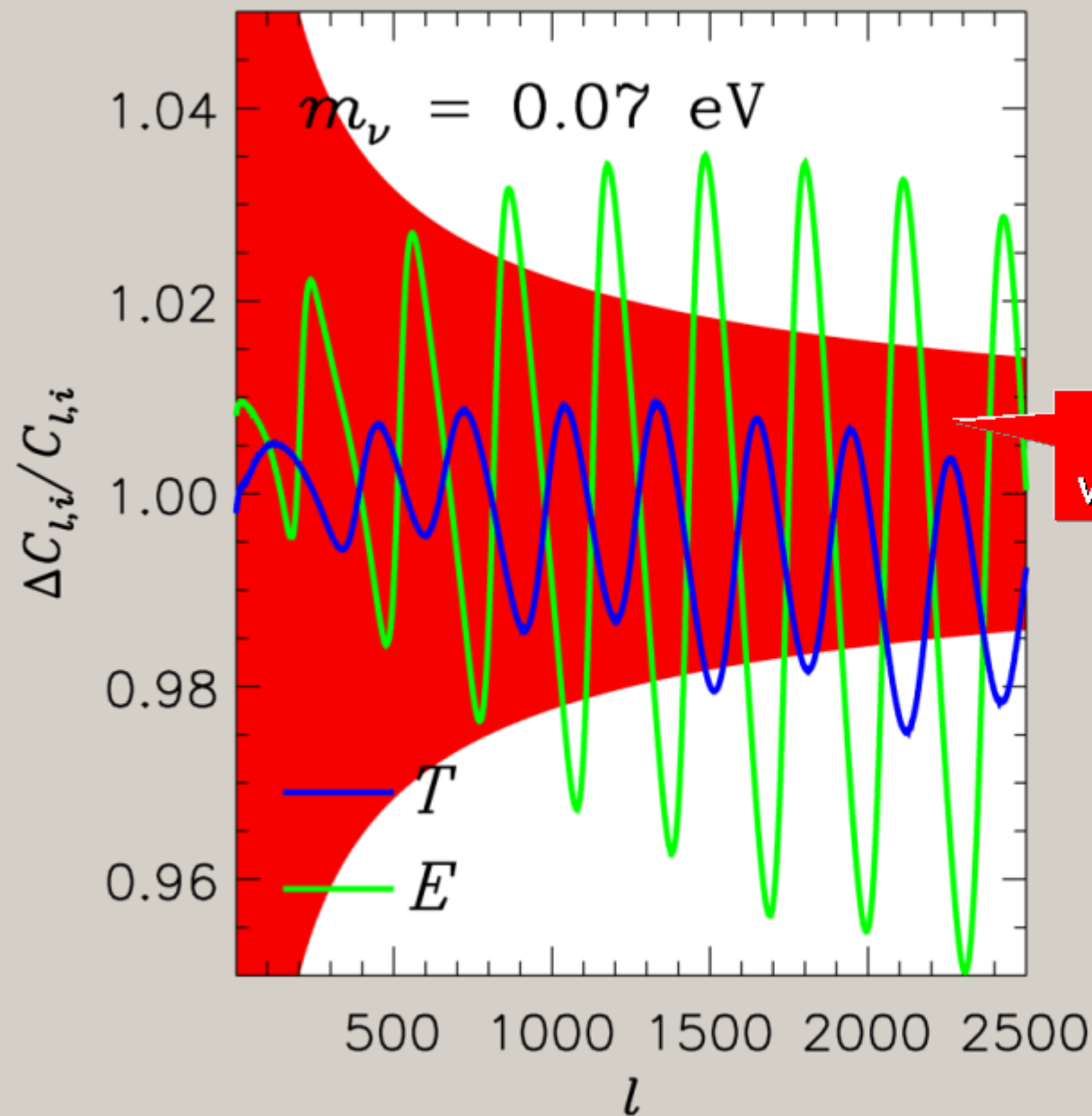
$\Sigma m_\nu < 2.2 \text{ eV}$
at 95% CL
(statistical)

Depends on priors for
other parameters

Similar limits based
on the 2dF survey

- Hannestad
astro-ph/0205223
- Lewis & Bridle
astro-ph/0205436

Neutrino Mass in the PLANCK Power Spectrum



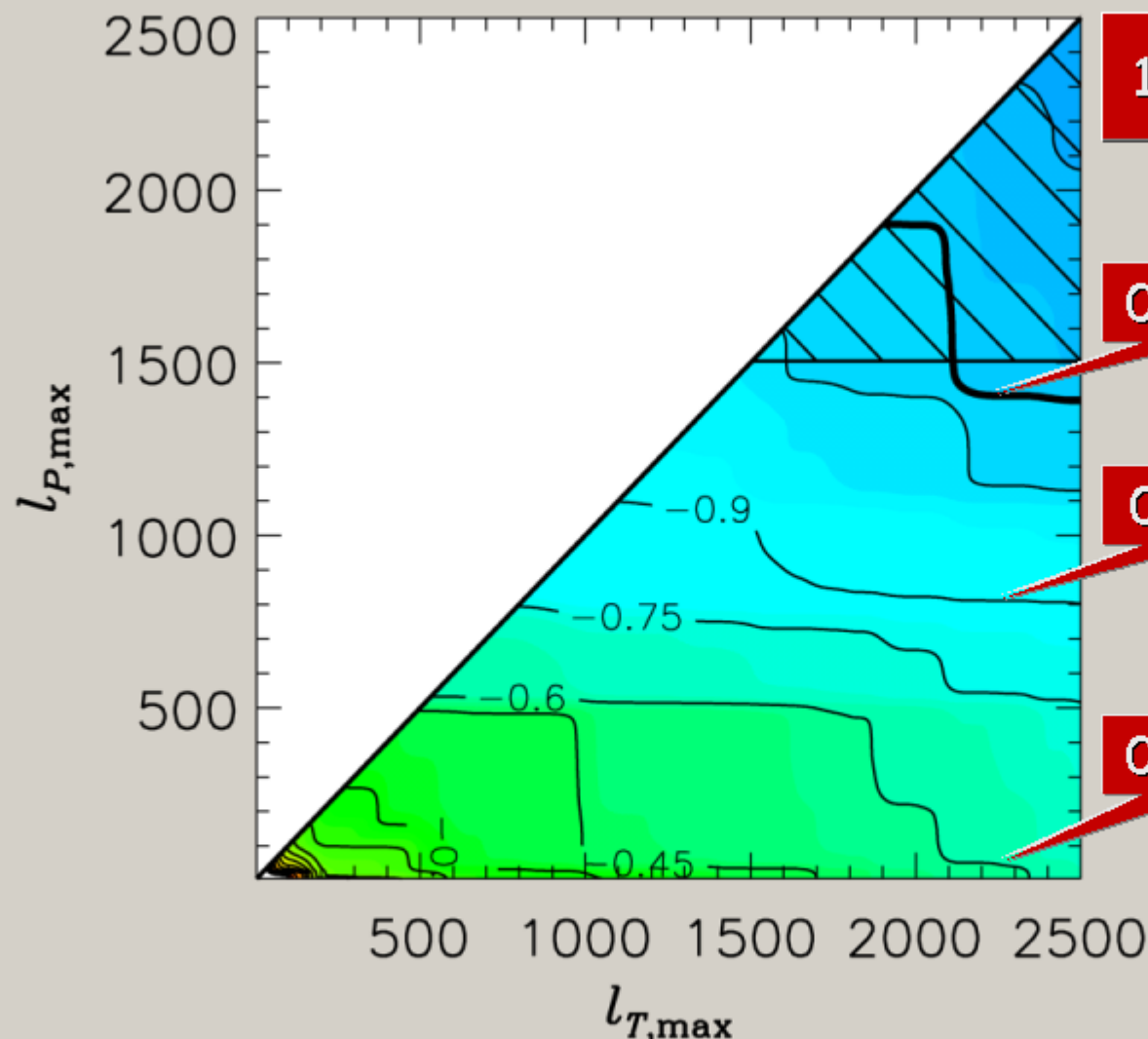
Change of temperature (T) and polarization (E) angular power spectrum in PLANCK caused by a small neutrino mass

Cosmic variance

Courtesy Steen Hannestad
see also [astro-ph/0211106](#)

PLANCK Sensitivity to Neutrino Mass

Maximum polarization multipole that can be measured to cosmic-variance precision



1 σ sensitivity to Σm_ν

0.07 eV

0.13 eV

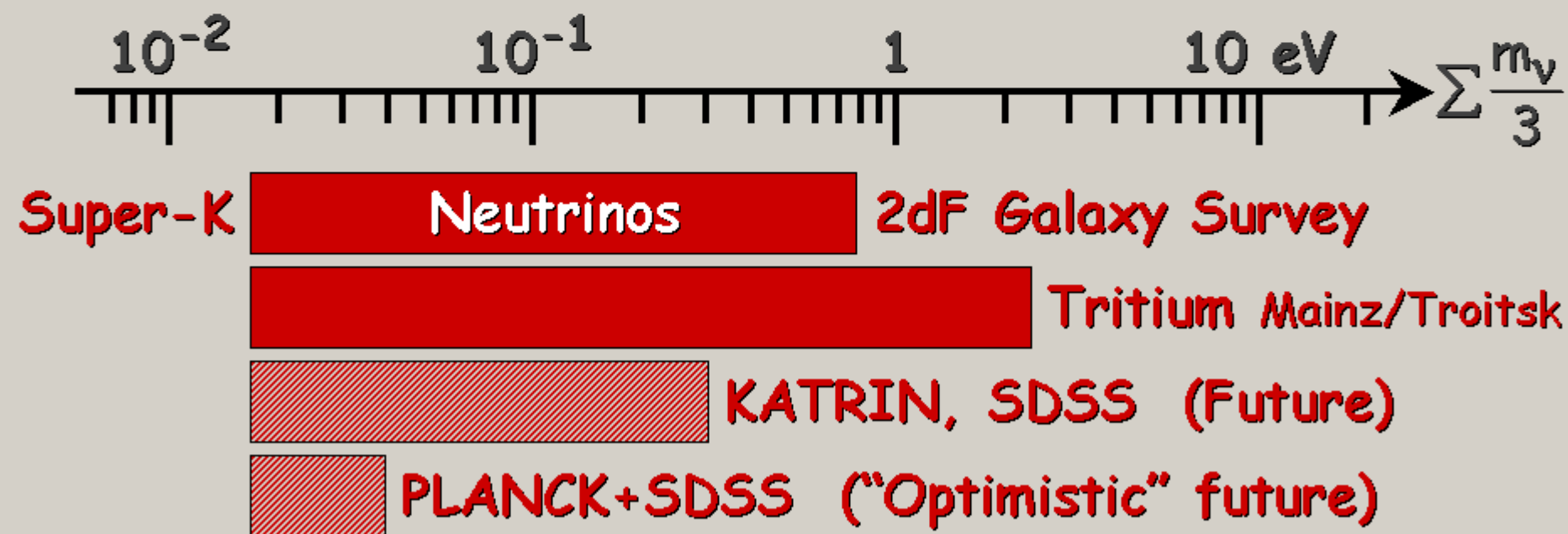
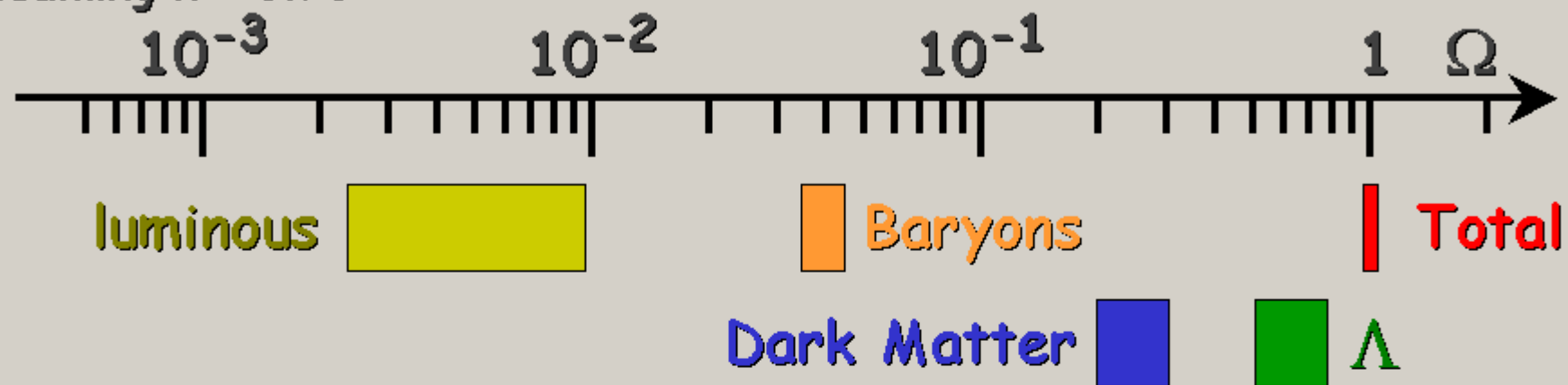
0.25 eV

Maximum temperature multipole that can be measured to cosmic-variance precision

Steen Hannestad
astro-ph/0211106

Mass-Energy-Inventory of the Universe

Assuming $h = 0.75$



Neutrinos in Physics and Astrophysics



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Neutrino mass and the
baryon asymmetry of the universe



Neutrinos as astrophysical messengers

Baryogenesis in the Early Universe



Andrei Sakharov
1921 - 1989

Sakharov conditions for creating the
Baryon **A**symmetry of the **U**niverse (**BAU**)

- **C** and **CP** violation
- Baryon number violation
- Deviation from thermal equilibrium

Particle-physics standard model

- Violates **C** and **CP**
- Violates **B** and **L** by EW instanton effects
(**B - L** conserved)

- However, electroweak baryogenesis not quantitatively possible within particle-physics standard model
- Works in SUSY models for small range of parameters

A.Riotto & M.Trodden: Recent progress in baryogenesis
Ann. Rev. Nucl. Part. Sci. 49 (1999) 35

A classic paper

Volume 174, number 1

PHYSICS LETTERS B

26 June 1986

BARYOGENESIS WITHOUT GRAND UNIFICATION

M. FUKUGITA

Research Institute for Fundamental Physics, Kyoto University, Kyoto 606, Japan

and

T. YANAGIDA

*Institute of Physics, College of General Education, Tohoku University, Sendai 980, Japan
and Deutsches Elektronen-Synchrotron DESY, D-2000 Hamburg, Fed. Rep. Germany*

Received 8 March 1986

A mechanism is pointed out to generate cosmological baryon number excess without resorting to grand unified theories. The lepton number excess originating from Majorana mass terms may transform into the baryon number excess through the unsuppressed baryon number violation of electroweak processes at high temperatures.

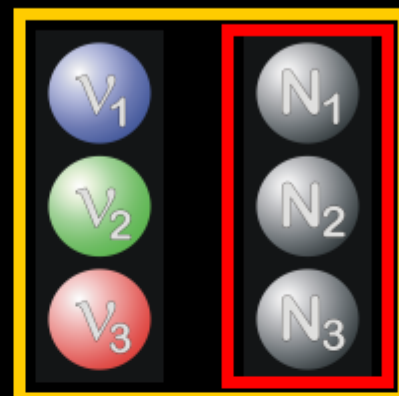
See-Saw Model for Neutrino Masses

Dirac masses
from coupling
to standard
Higgs field ϕ

Charged Leptons



Neutrinos



Heavy
Majorana
masses
 $M_j > 10^{10} \text{ GeV}$

Lagrangian for
particle masses

$$\mathcal{L}_{\text{mass}} = -\bar{\ell}_L \phi g_\ell e_R - \bar{\ell}_L \phi g_\nu N_R - \frac{1}{2} \overline{N_R^c} M N_R + \text{h.c.}$$

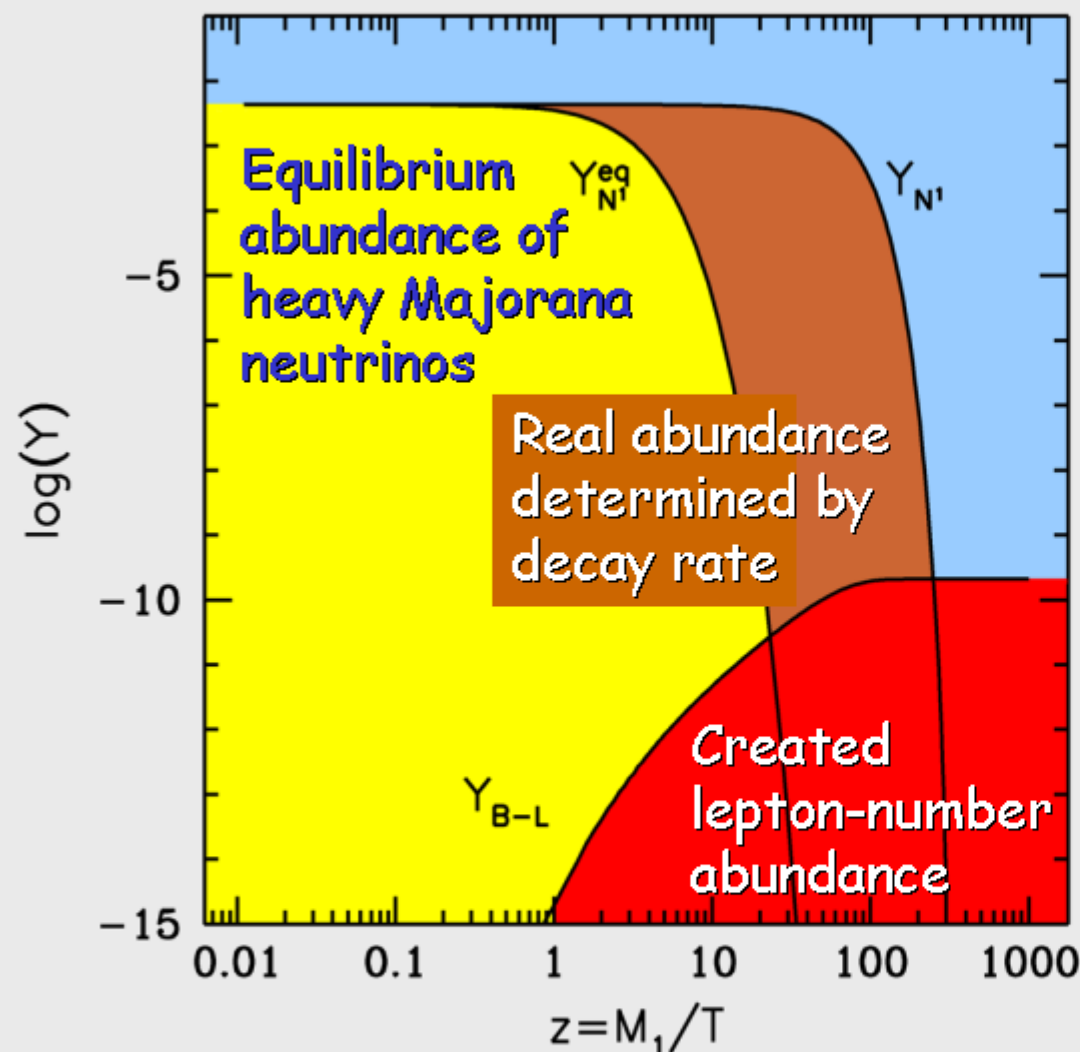
Light Majorana mass

$$(\bar{\nu}_L \quad \bar{N}_R) \begin{pmatrix} 0 & g_\nu \langle \phi \rangle \\ g_\nu \langle \phi \rangle & M \end{pmatrix} \begin{pmatrix} \nu_L \\ N_R \end{pmatrix}$$

Diagonalize

$$(\bar{\nu}_L \quad \bar{N}_R) \begin{pmatrix} \frac{g_\nu^2 \langle \phi \rangle^2}{M} & 0 \\ 0 & M \end{pmatrix} \begin{pmatrix} \nu_L \\ N_R \end{pmatrix}$$

Leptogenesis by Out-of-Equilibrium Decay



CP-violating decays by interference of tree-level with one-loop diagram



$$\Gamma_{\text{Decay}} = g_v^2 \frac{M}{8\pi}$$

W. Buchmüller & M. Plümacher: Neutrino masses and the baryon asymmetry
Int. J. Mod. Phys. A15 (2000) 5047-5086

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

Requires Majorana neutrino masses below 0.2 eV

Buchmüller, Di Bari & Plümacher, PLB 547 (2002) 128 [hep-ph/0209301]

Leptogenesis - A Popular Research Topic

Fukugita & Yanagida
PLB 174 (1986) 45

Langacker, Peccei & Yanagida
Mod. Phys. Lett. A 1 (1986) 541

Campbell, Davidson & Olive
NPB 399 (1993) 111

Gherghetta & Jungmann
PRD 48 (1993) 1546

Muryama & Yanagida
PLB 322 (1994) 349

Worah
PRD 53 (1996) 3902

Jeannerot
PRL 77 (1996) 3292

Dine, Randall & Thomas
NPB 458 (1996) 291

Buchmüller & Plümacher
PLB 389 (1996) 73

Lazarides, Schaefer & Shafi
PRD 56 (1997) 1324

Ma & Sarkar
PRL 80 (1998) 5716

Plümacher
NPB 530 (1998) 207

Flanz & Paschos
PRD 58 (1998) 113009

Lazarides & Shafi
PRD 58 (1998) 071702

Akhmedov, Rubakov & Smirnov
PRL 81 (1998) 1562

Carlier, Frère & Ling
PRD 60 (1999) 096003

Giudice, Peloso, Riotto & Tkachev
JHEP 9908 (1999) 014

Berger & Brahmachari
PRD 60 (1999) 073009

Ellis, Lola & Nanopoulos
PLB 452 (1999) 87

Barbieri, Creminelli, Strumia & Tetradis
NPB 575 (2000) 61

Frère, Ling, Tytgat & v.Elewyck
PRD 60 (1999) 016005

Dick, Lindner, Ratz & Wright
PRL 84 (2000) 4039

Lalakulich, Paschos & Flanz
PRD 62 (2000) 053006

Asaka, Hamaguchi, Kawasaki & Yanagida
PRD 61 (2000) 083512

Berger
PRD 62 (2000) 013007

Hambye, Ma & Sarkar
PRD 62 (2000) 015010

Mangano & Miele
PRD 62 (2000) 063514

Goldberg
PLB 474 (2000) 389

Rangarajan & Mishra
PRD 61 (2000) 043509

Hirsch & King
PRD 64 (2001) 113005

Falcone & Tramontano
PRD 63 (2001) 073007

Bastero-Gil & King
PRD 63 (2001) 123509

Joshiyura, Paschos & Rodejohann
NPB 611 (2001) 227

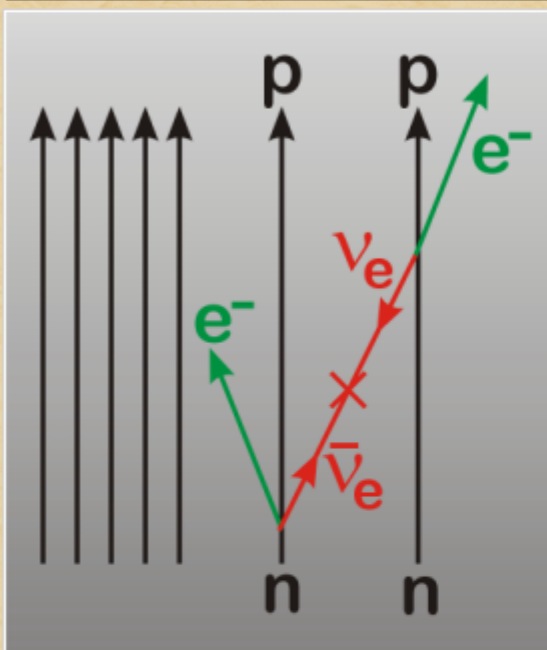
Branco, Morozumi, Nobre & Rebelo
NPB 617 (2001) 475

Hambye, Ma & Sarkar
NPB 602 (2001) 23

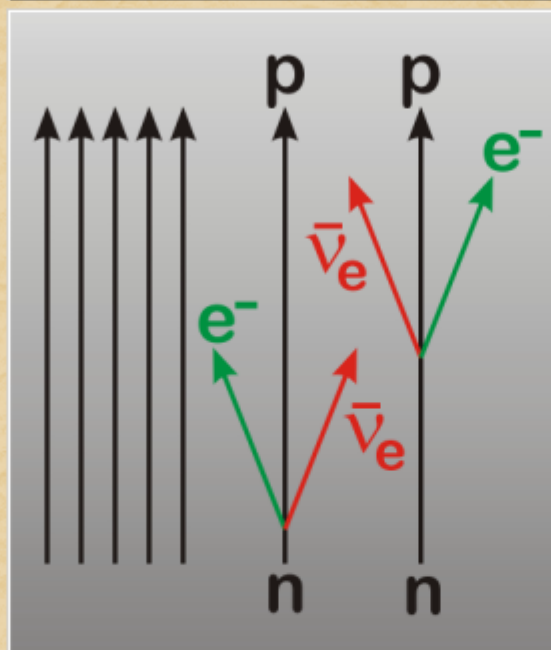
AND MANY MORE ...

Neutrinoless $\beta\beta$ Decay

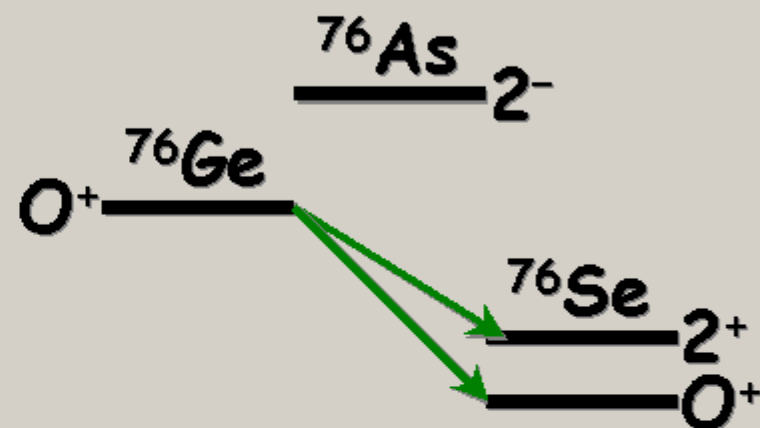
0ν mode, enabled by Majorana mass



Standard 2ν mode



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



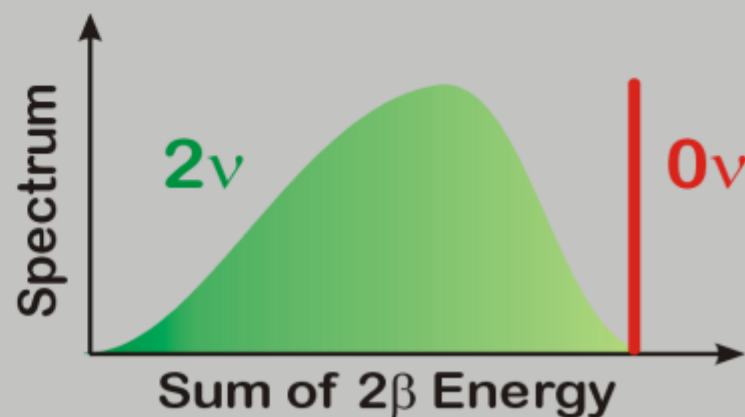
Half life $\sim 10^{21}$ yr

Measured quantity

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

Best limit from ^{76}Ge

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

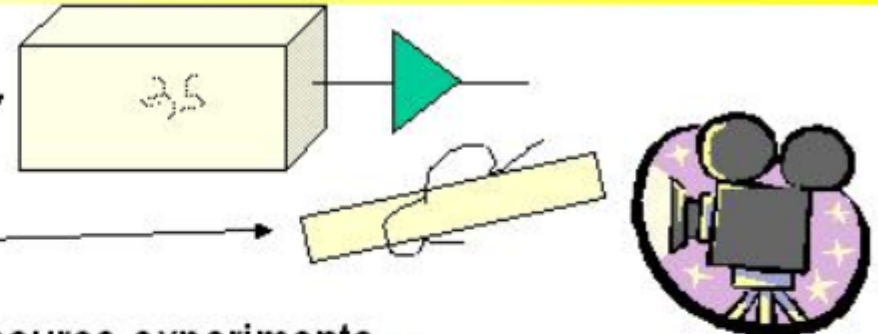


Summary of Current Neutrinoless $\beta\beta$ Decay Limits

$0\nu2\beta$ Experimental Situation

2 main experimental approaches:

- Active Source
- Passive Source



Best $0\nu2\beta$ results involve active source experiments

Experiment	Isotope	$T_{1/2}^{0\nu}$ (y)	$\langle m_\nu \rangle$ (eV)
You Ke et al. 1998	^{48}Ca	$> 9.5 \times 10^{21}$ (76%)	< 8.3
Klapdor-Kleingrothaus 2001	^{76}Ge	$> 1.9 \times 10^{25}$	< 0.35
Aalseth et al 2002		$> 1.57 \times 10^{25}$	$< 0.33 - 1.35$
Elliott et al. 1992	^{82}Se	$> 2.7 \times 10^{22}$ (68%)	< 5
Ejiri et al. 2001	^{100}Mo	$> 5.5 \times 10^{22}$	< 2.1
Danevich et al. 2000	^{116}Cd	$> 7 \times 10^{22}$	< 2.6
Bernatowicz et al. 1993	$^{130/128}\text{Te}^*$	$(3.52 \pm 0.11) \times 10^{-4}$	$< 1.1 - 1.5$
Bernatowicz et al. 1993	$^{128}\text{Te}^*$	$> 7.7 \times 10^{24}$	$< 1.1 - 1.5$
Mi DBD – ν 2002	^{130}Te	$> 2.1 \times 10^{23}$	$< 0.85 - 2.1$
Luescher et al. 1998	^{136}Xe	$> 4.4 \times 10^{23}$	$< 1.8 - 5.2$
Belli et al. 2001	^{136}Xe	$> 7 \times 10^{23}$	$< 1.4 - 4.1$
De Silva et al. 1997	^{150}Nd	$> 1.2 \times 10^{21}$	< 3
Danevich et al. 2001	^{160}Gd	$> 1.3 \times 10^{21}$	< 26

Summary of Future $\beta\beta$ Decay Projects

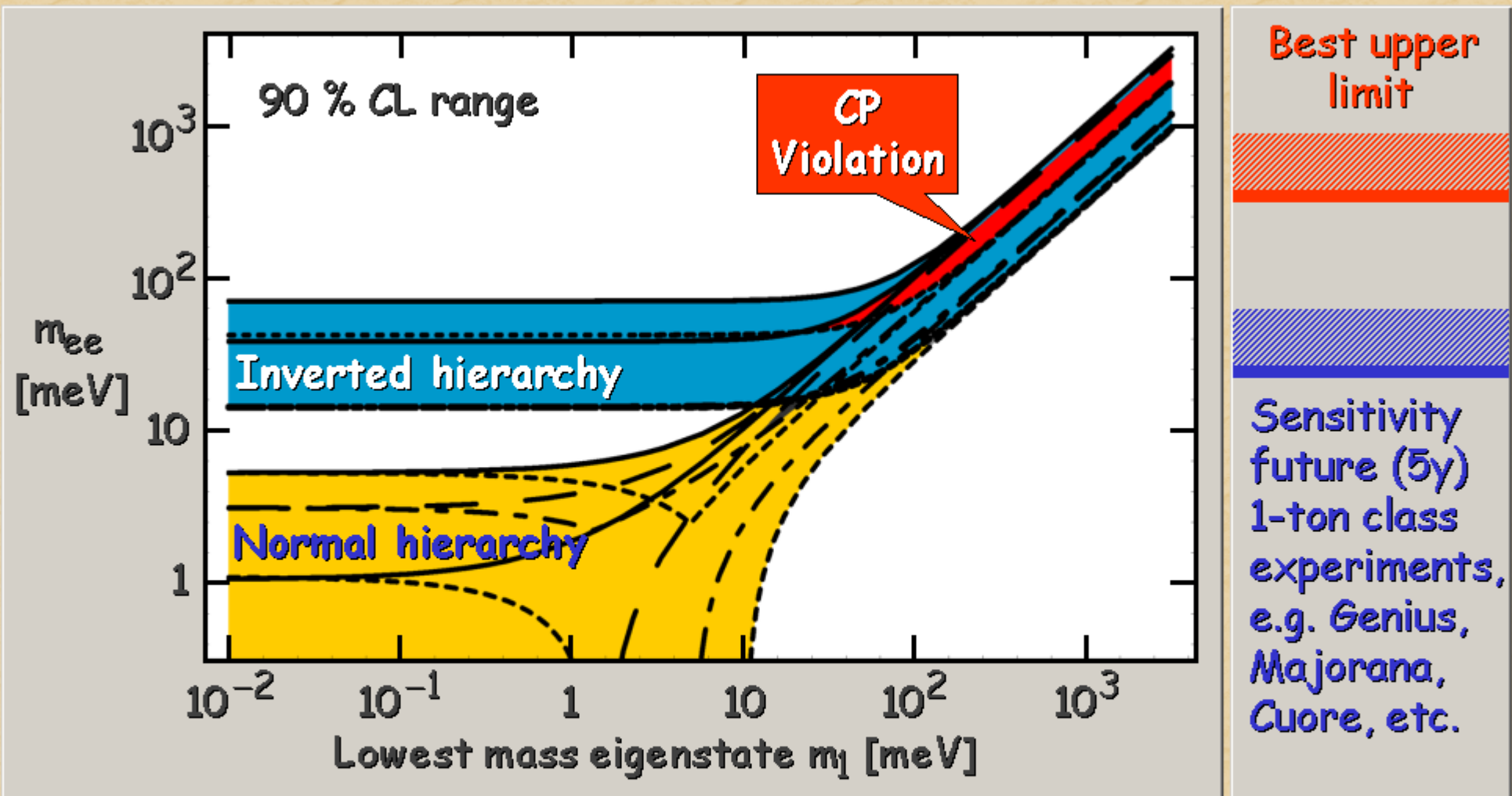
O.Cremonesi at Neutrino 2002

Future projects

Experiment	Author	Isotope	Detector description	$T_{1/2}^{5y}$ (y)	$\langle m_{\nu} \rangle^*$
COBRA	Zuber 2001	^{130}Te	10 kg CdTe semiconductors	1×10^{24}	0.71
CUORICINO	Arnaboldi et al 2001	^{130}Te	40 kg of TeO_2 bolometers	1.5×10^{25}	0.19
NEMO3	Sarazin et al 2000	^{100}Mo	10 kg of bb(0n) isotopes (7 kg Mo) with tracking	4×10^{24}	0.56
CUORE	Arnaboldi et al. 2001	^{130}Te	760 kg of TeO_2 bolometers	7×10^{26}	0.027
EXO	Danevich et al 2000	^{136}Xe	1 t enriched Xe TPC	8×10^{26}	0.052
GEM	Zdesenko et al 2001	^{76}Ge	1 t enriched Ge diodes in liquid nitrogen + water shield	7×10^{27}	0.018
GENIUS	Klapdor-Kleingrothaus et al 2001	^{76}Ge	1 t enriched Ge diodes in liquid nitrogen	1×10^{28}	0.015
MAJORANA	Aalseth et al 2002	^{76}Ge	0.5 t enriched Ge segmented diodes	4×10^{27}	0.025
DCBA	Ishihara et al 2000	^{150}Nd	20 kg enriched Nd layers with tracking	2×10^{25}	0.035
CAMEO	Bellini et al 2001	^{116}Cd	1 t CdWO_4 crystals in liquid scintillator	$> 10^{26}$	0.069
CANDLES	Kishimoto et al	^{48}Ca	several tons of CaF_2 crystal in liquid scintillator	1×10^{26}	
GSO	Danevich 2001	^{160}Gd	2 t $\text{Gd}_2\text{SiO}_5:\text{Ce}$ cristal scintillator in liquid scintillator	2×10^{26}	0.065
MOON	Ejiri et al 2000	^{100}Mo	34 t natural Mo sheets between plastic scintillator	1×10^{27}	0.036
Xe	Caccianiga et al 2001	^{136}Xe	1.56 t of enriched Xe in liquid scintillator	5×10^{26}	0.066
XMASS	Moriyama et al 2001	^{136}Xe	10 t of liquid Xe	3×10^{26}	0.086

* Staudt, Muto, Klapdor-Kleingrothaus Europh. Lett 13 (1990) 31

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

Neutrinos in Physics and Astrophysics



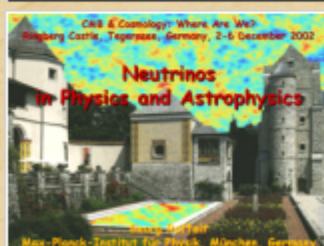
Flavor oscillations and all that



Quest for the absolute mass scale

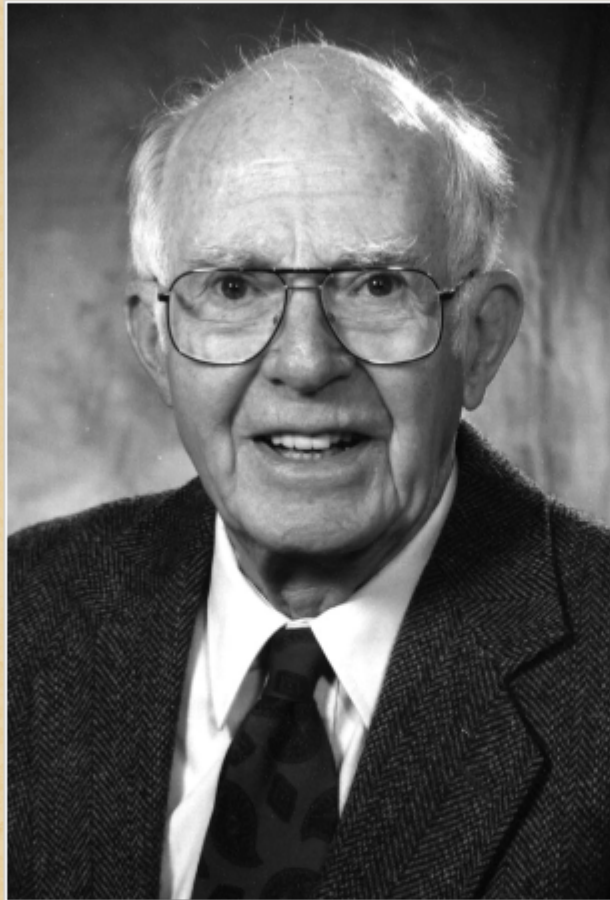


Neutrino mass and the
baryon asymmetry of the universe



Neutrinos as astrophysical messengers

2002 Physics Nobel Prize for Neutrino Astronomy



Ray Davis Jr.
(*1914)



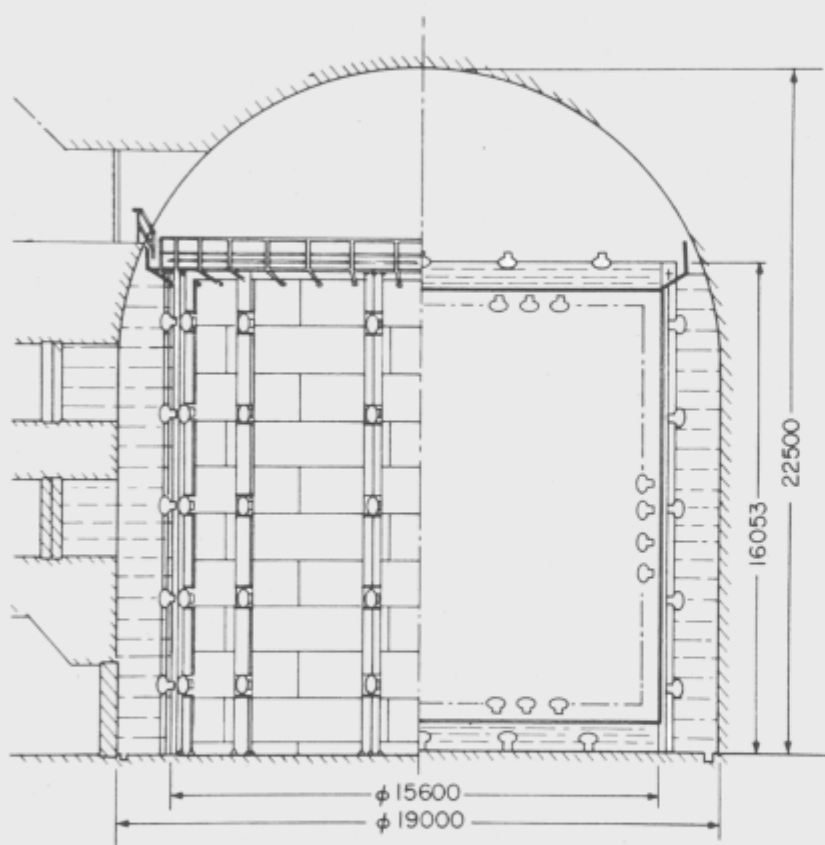
Masatoshi Koshihara
(*1926)



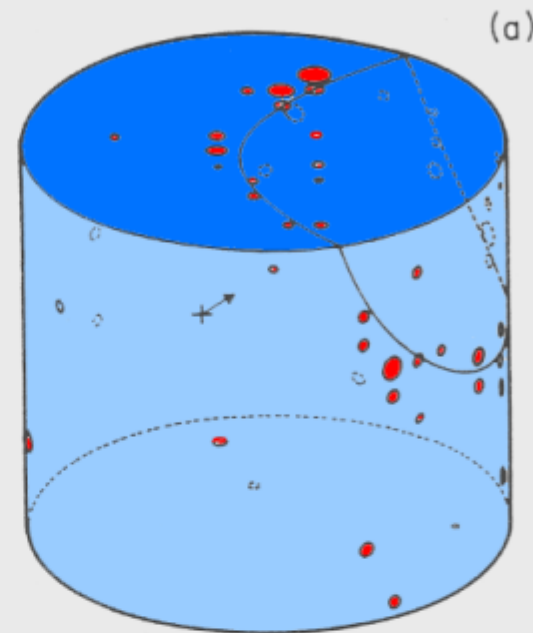
"for pioneering contributions to astrophysics, in particular for the detection of cosmic neutrinos"

SN 1987A Event No.9 in Kamiokande

Kamiokande Detector

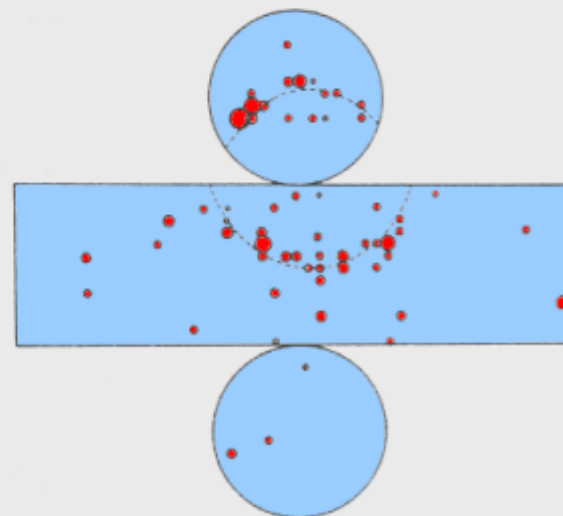


Hirata et al., PRD 38 (1988) 448



NUM 9
RUN 1892
EVENT 139372
TIME 2/23/87
16:35:37 JST

TOTAL ENERGY 19.8 MeV
TOTAL P.E. 51 (0)
MAX P.E. 4 (0)
THRES P.E. 0.2 (1.0)

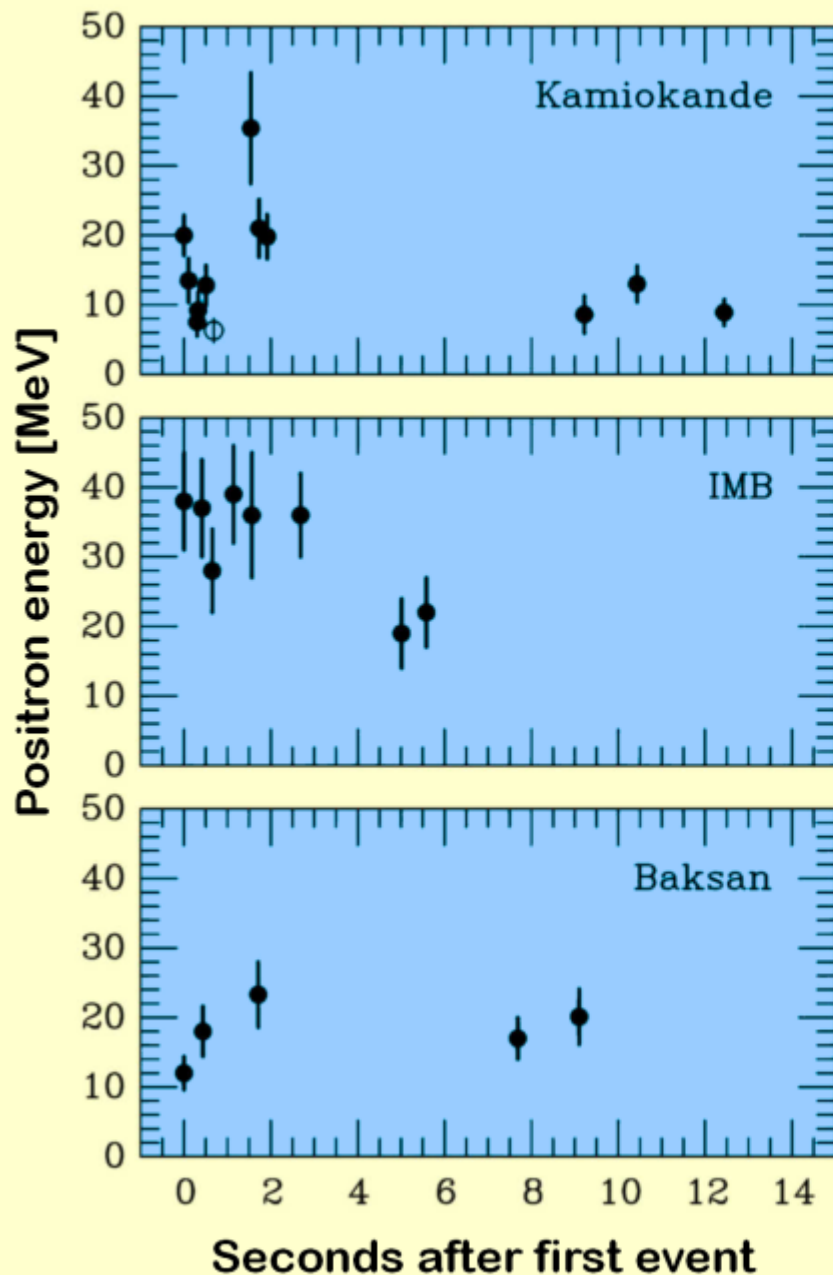


KAMIOKANDE 2-P

NUM 9
RUN 1892
EVENT 139372
TIME 2/23/87
16:35:37 JST

TOTAL ENERGY 19.8 MeV
TOTAL P.E. 51 (0)
MAX P.E. 4 (0)
THRES P.E. 0.2 (1.0)

Neutrino Signal of Supernova 1987A



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

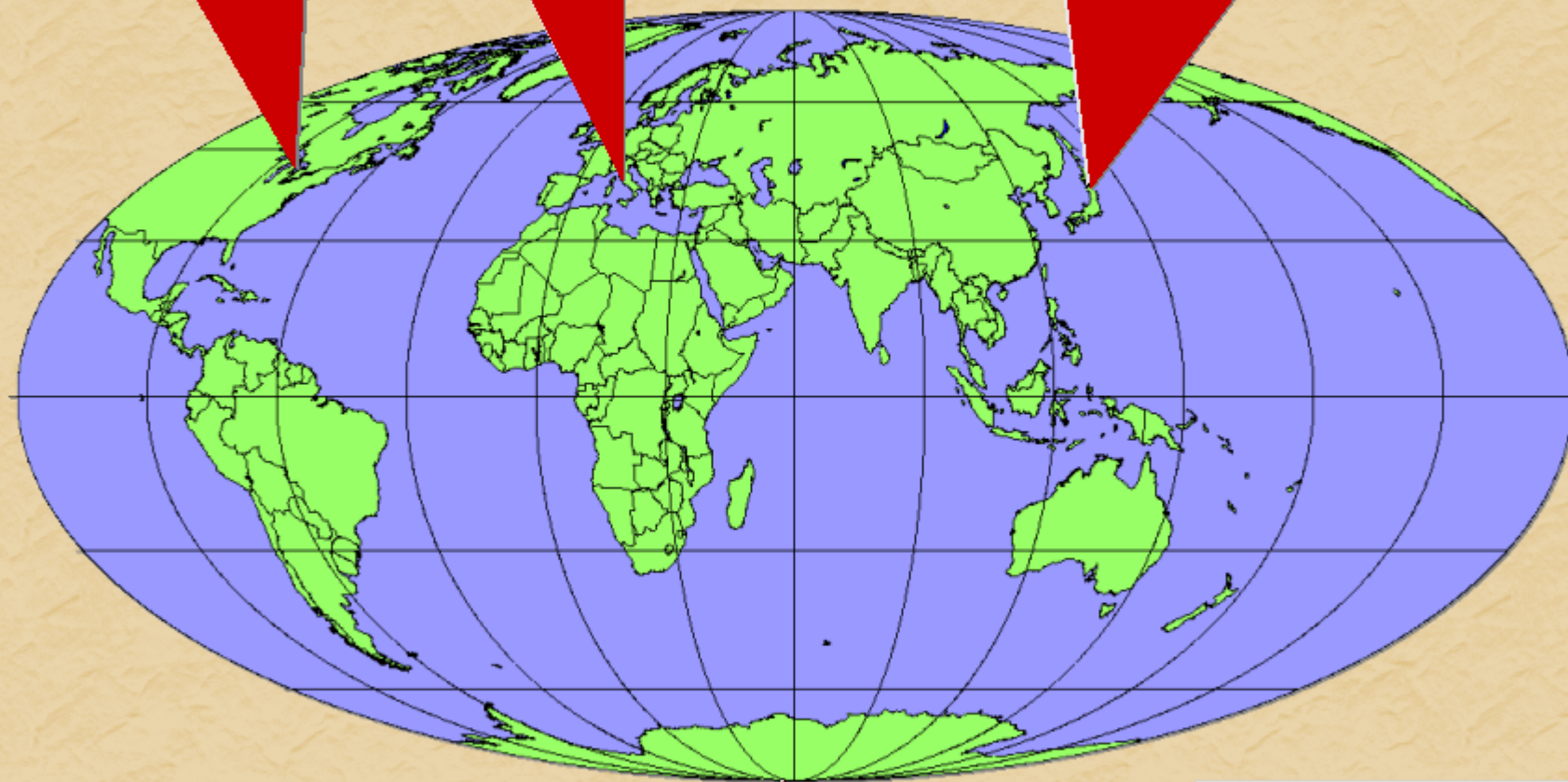
Within clock uncertainties,
signals are contemporaneous

Large Detectors for SN Neutrinos

SNO (800)
MiniBooNE (190)

LVD (400)
Borexino (80)

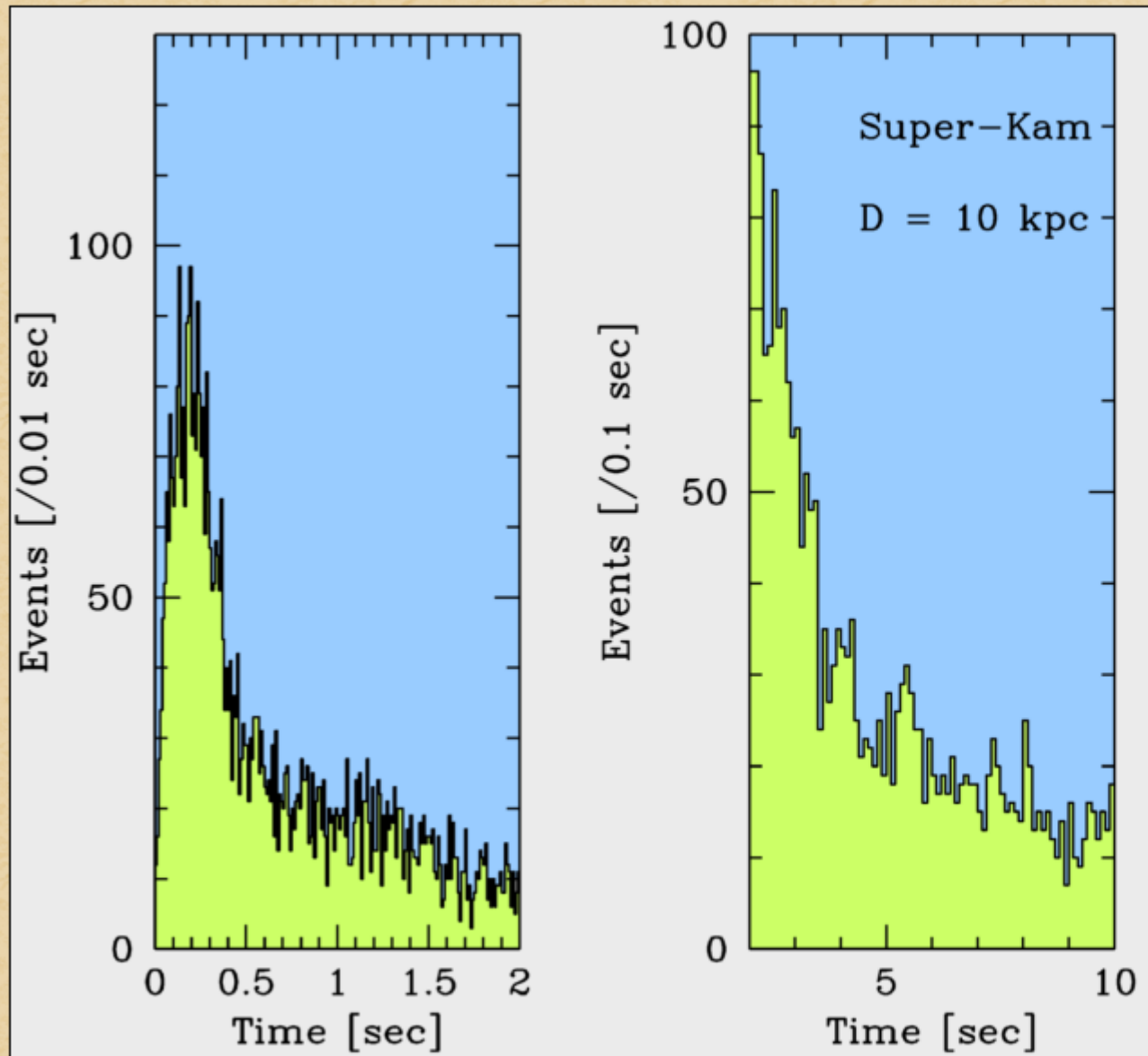
Super-Kamiokande (8500)
Kamland (330)



Amanda
IceCube

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

Simulated Supernova Signal in Super-Kamiokande

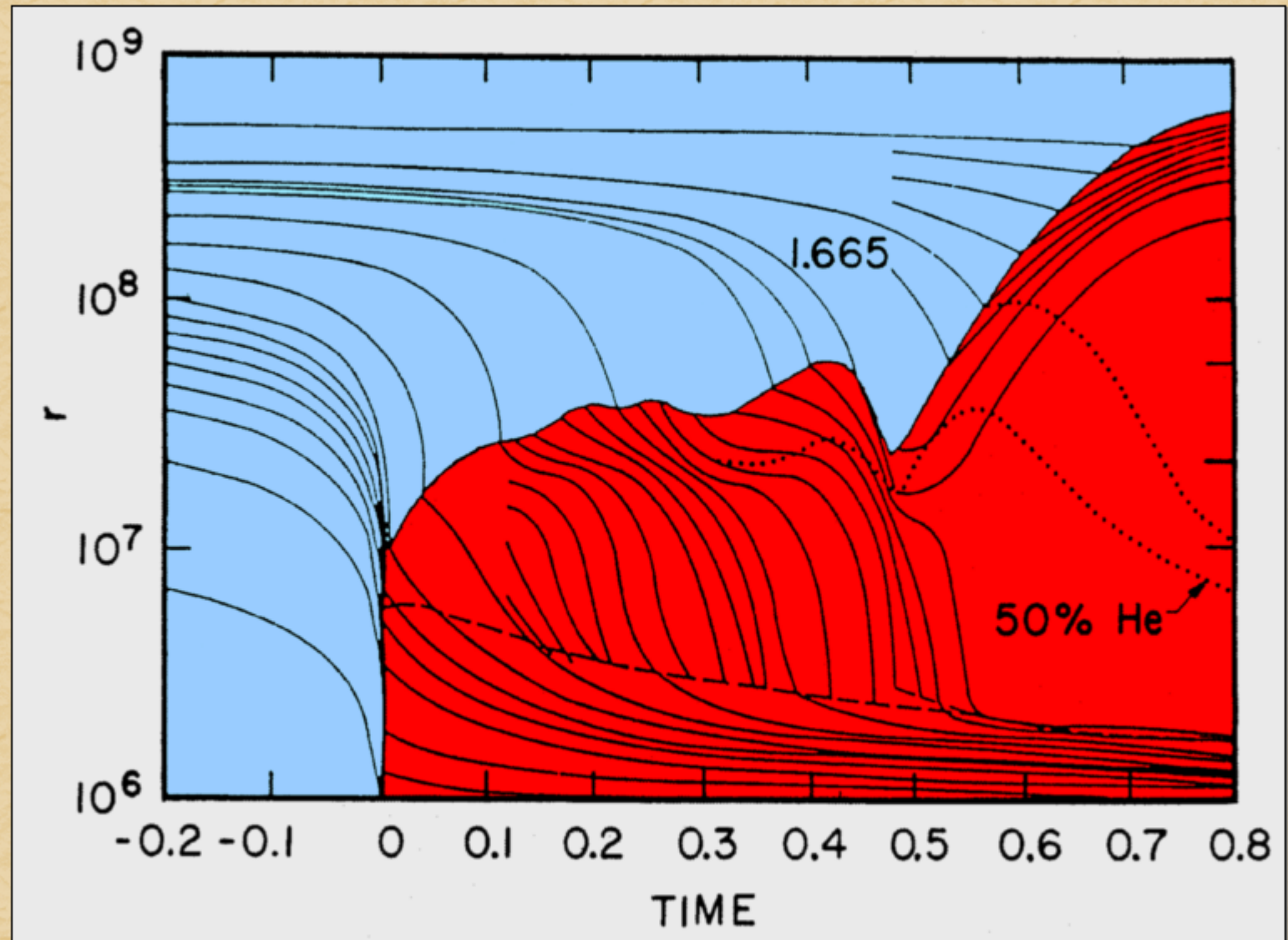


Total of about 8300
events for $t < 18$ s

Monte-Carlo simulation
for Super-Kamiokande
signal of SN at 10 kpc,
based on a numerical
Livermore model

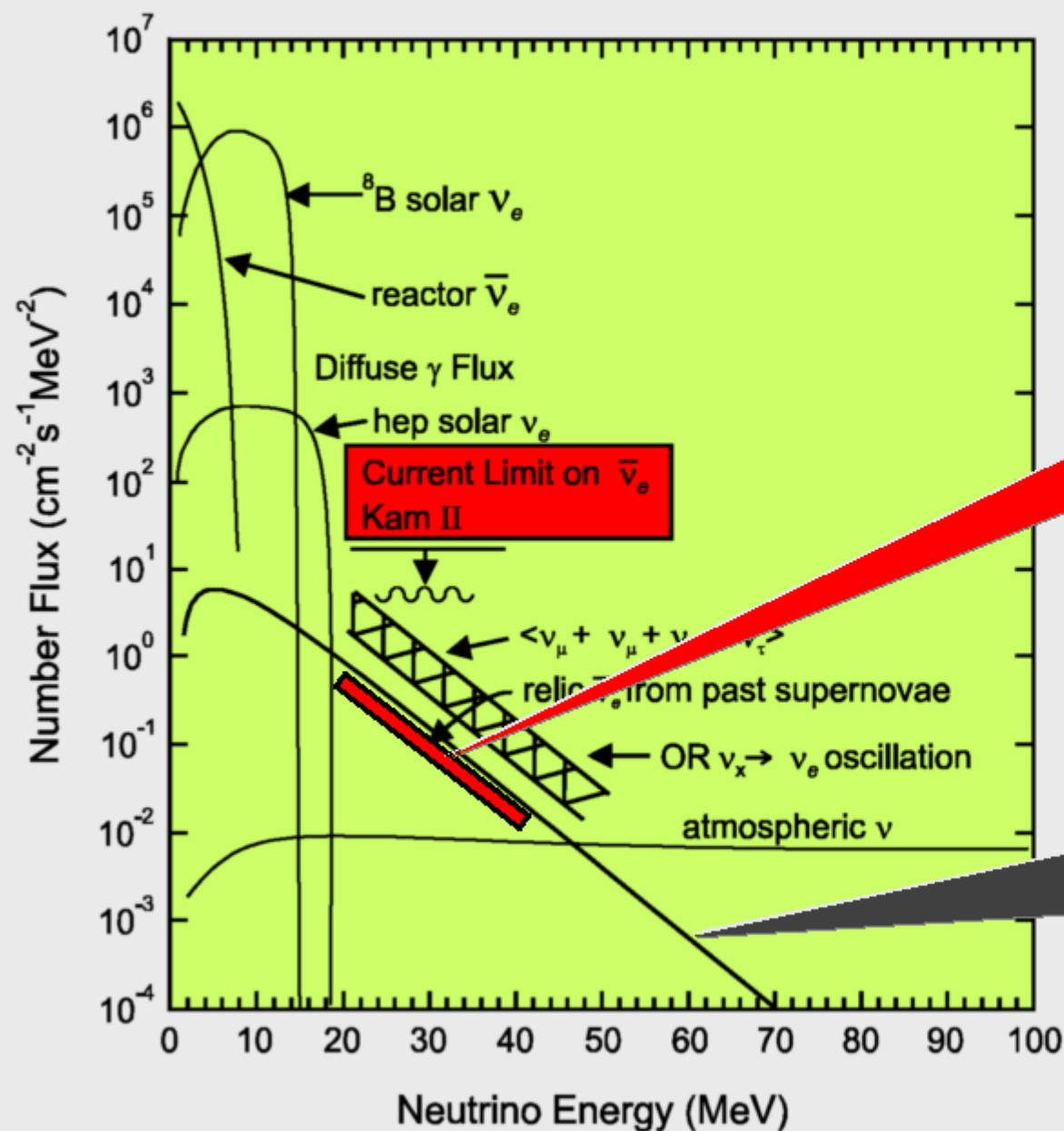
Totani, Sato, Dalhed & Wilson, ApJ 496 (1998) 216

Revival of a Stalled Supernova Shock by Neutrino Heating



Wilson, Proc. Univ. Illinois Meeting on Numerical Astrophysics (1982)
Bethe & Wilson, ApJ 295 (1985) 14

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

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)



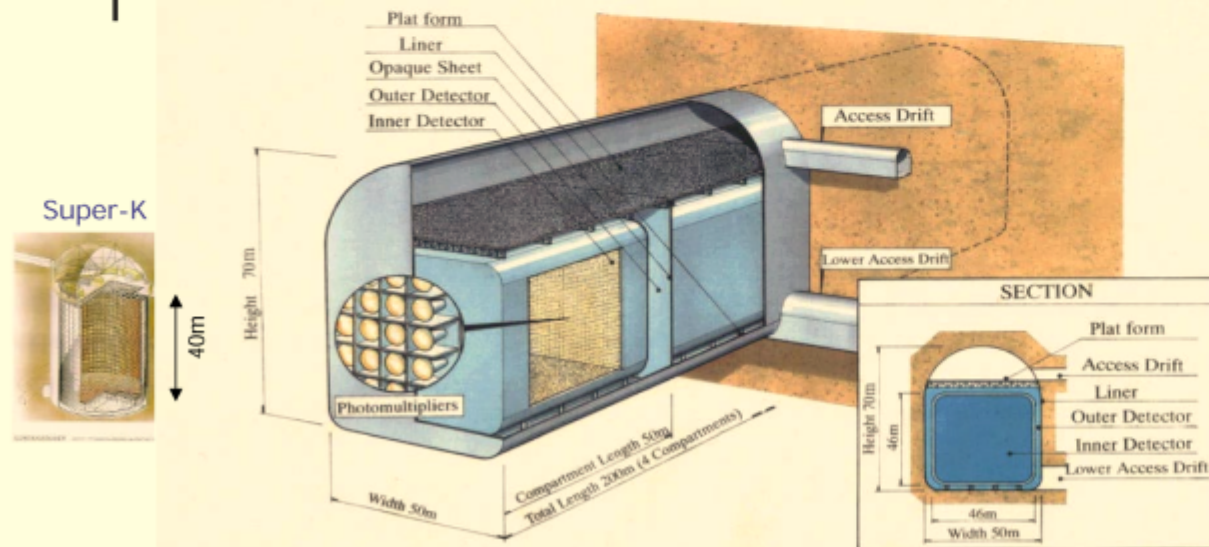
Phase-I (0.77MW + Super-K)

Phase-II (4MW+Hyper-K) $\sim$ Phase-I $\times 200$

3

Possible Design of Hyper-Kamiokande

May.-2001 JHF-Kamiooka ν workshop



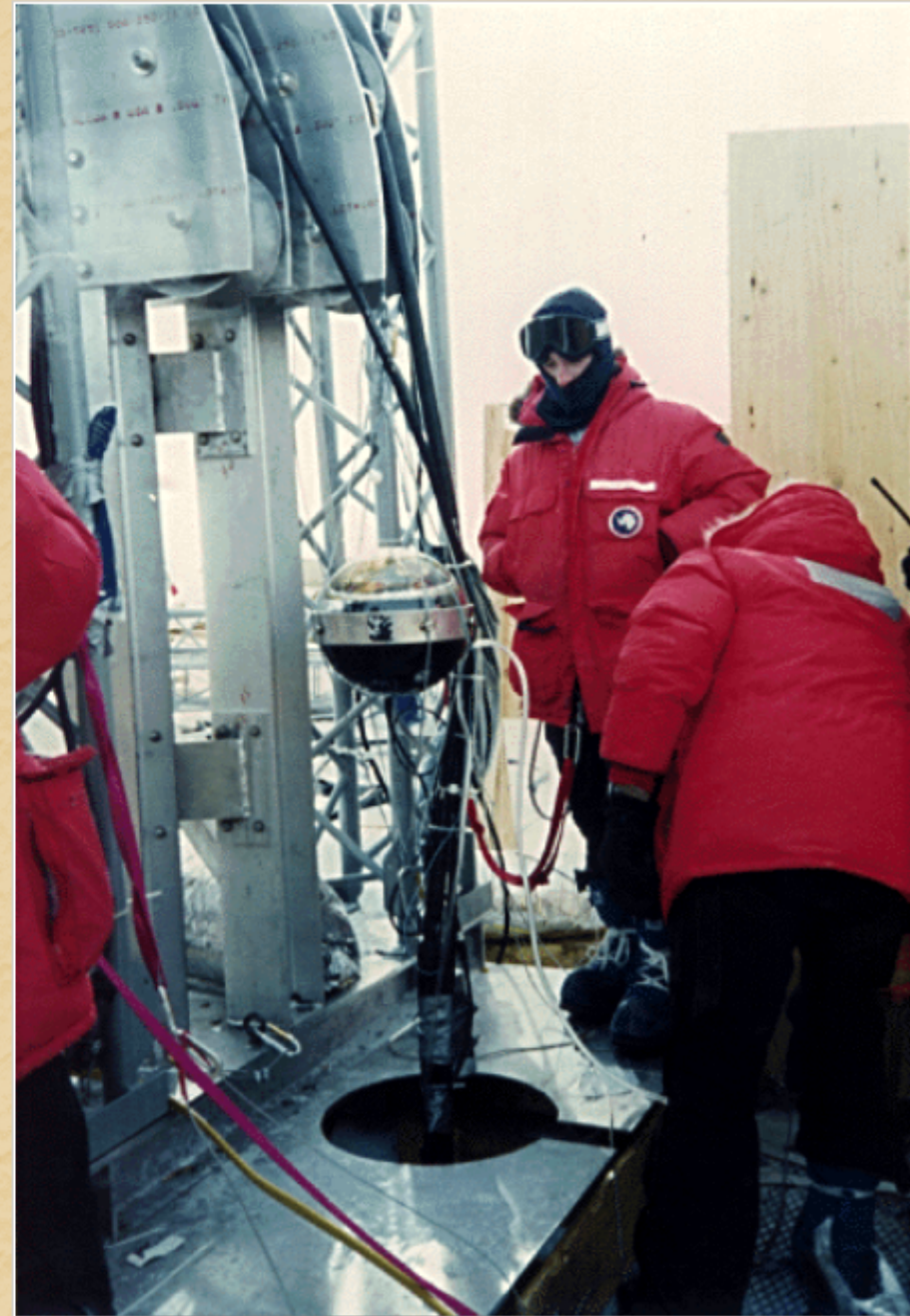
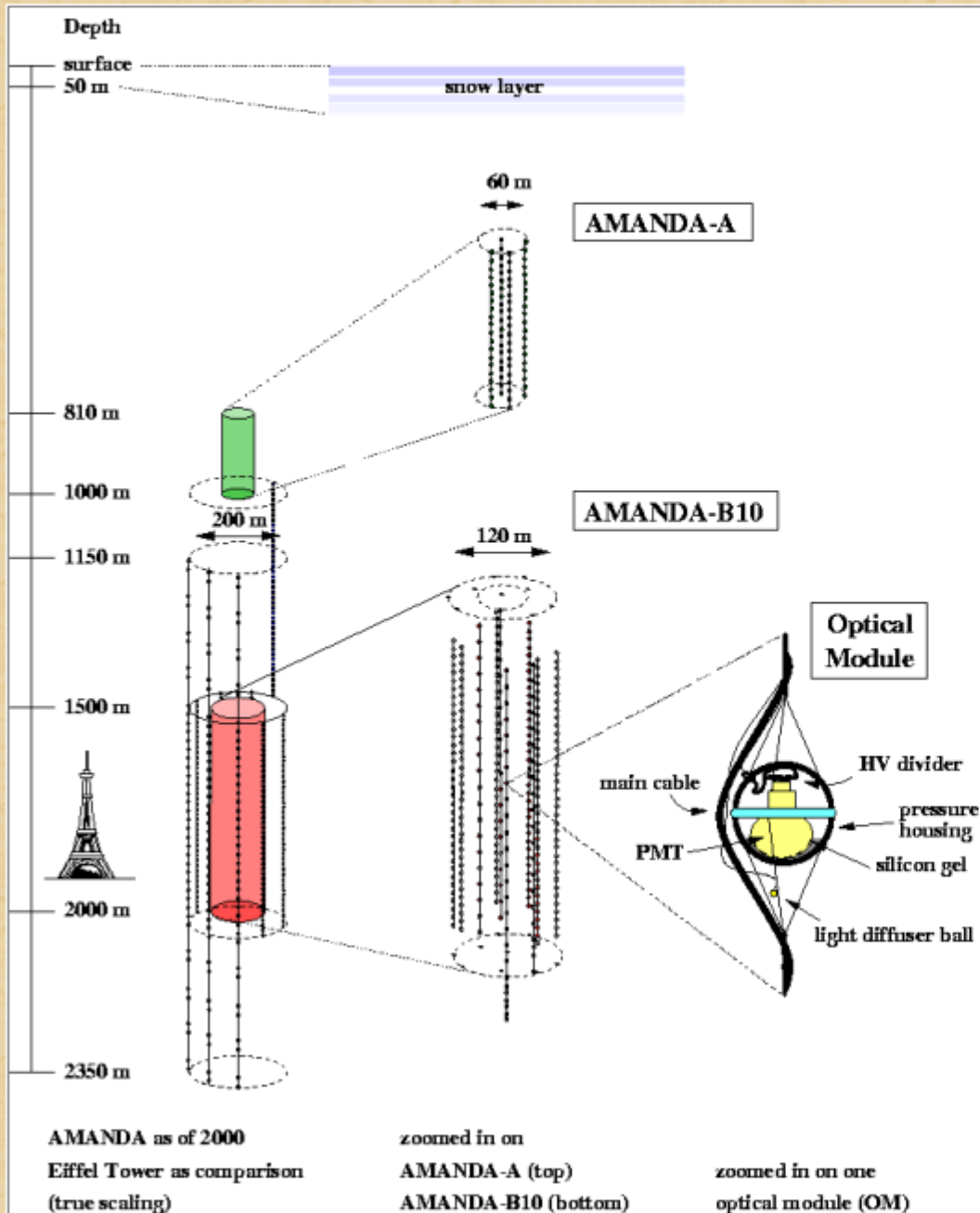
1 Mton fiducial volume: Total Length 800m (16 Compartments)

(STRAIGHT TYPE)

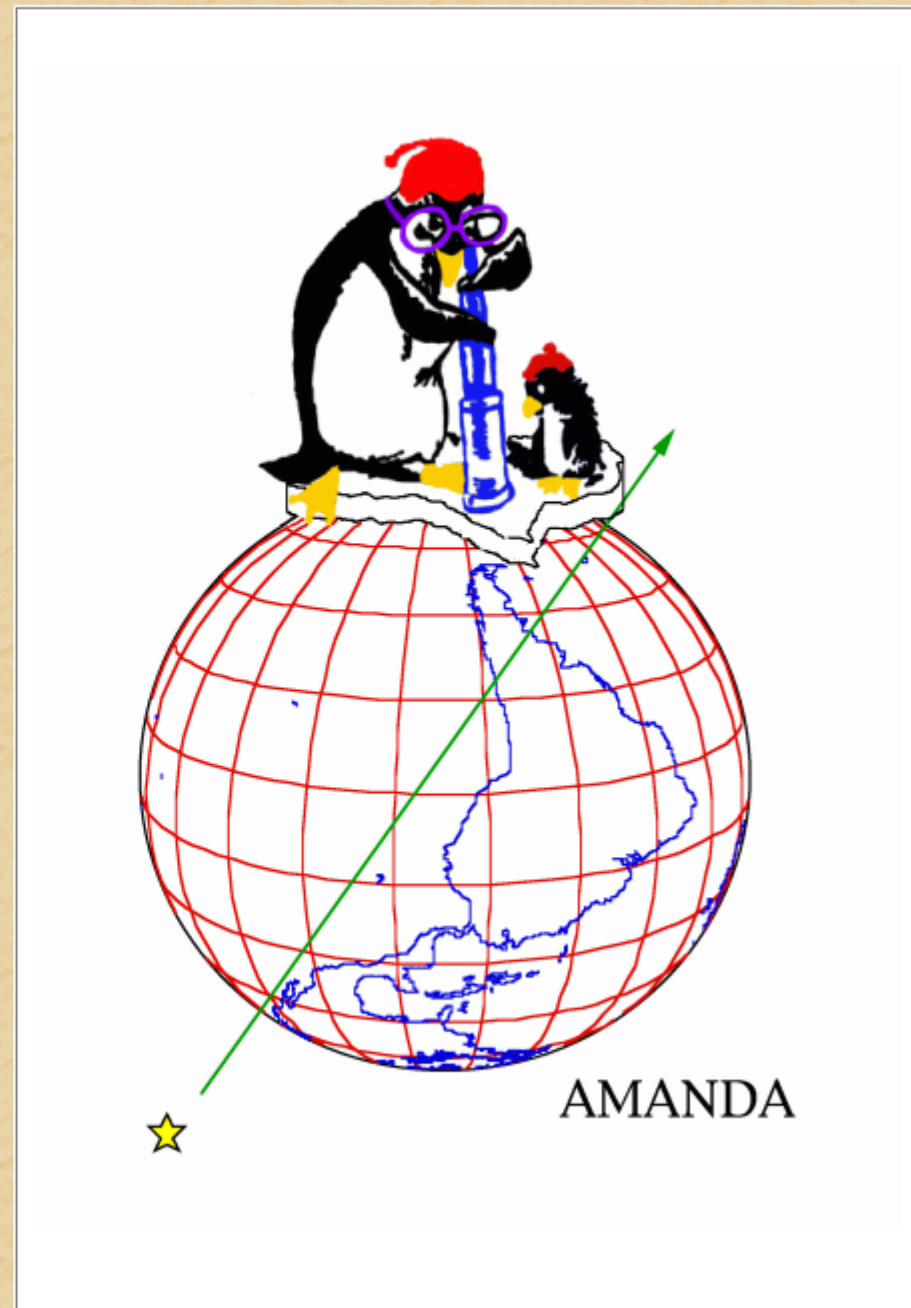
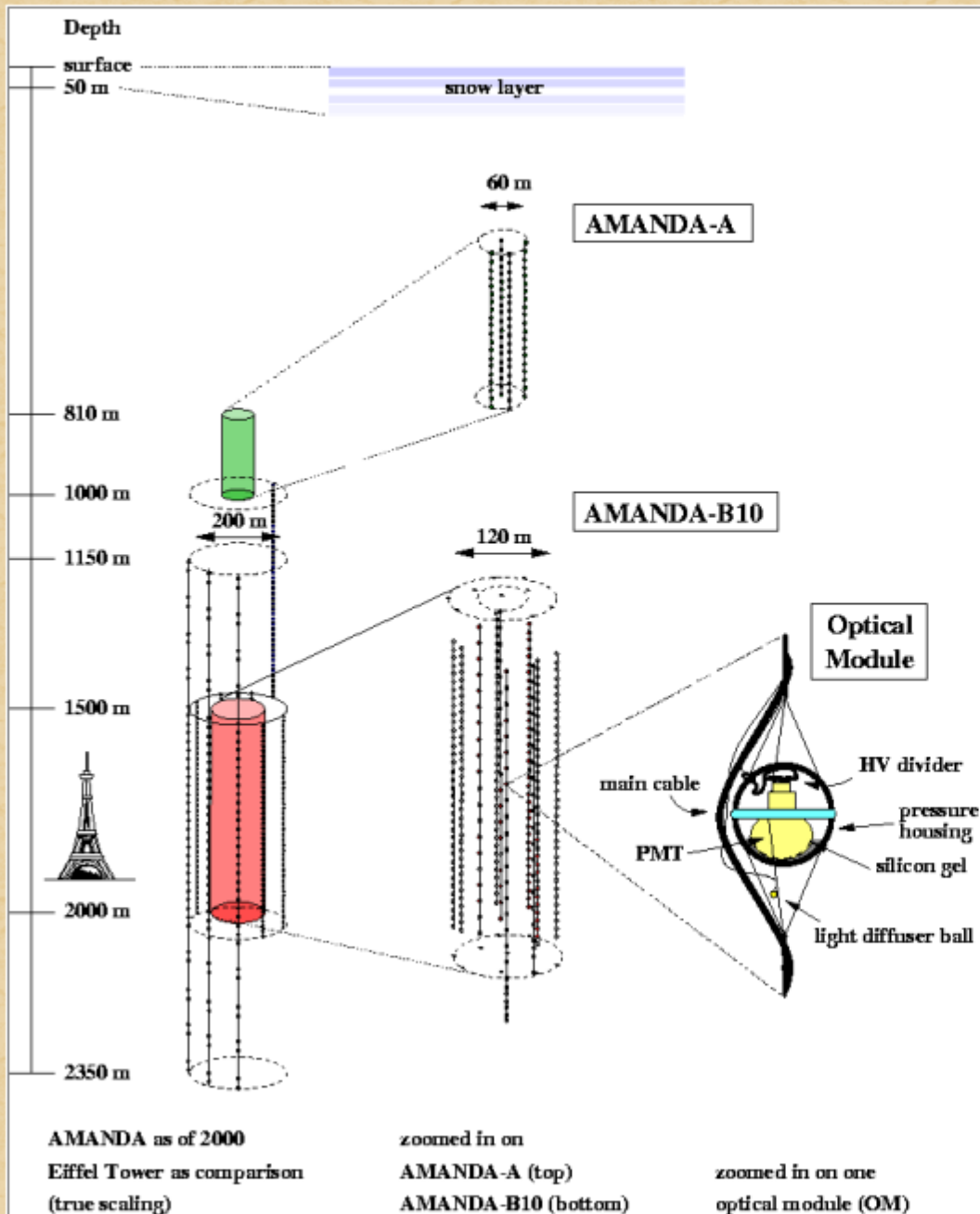
Similar discussions in

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

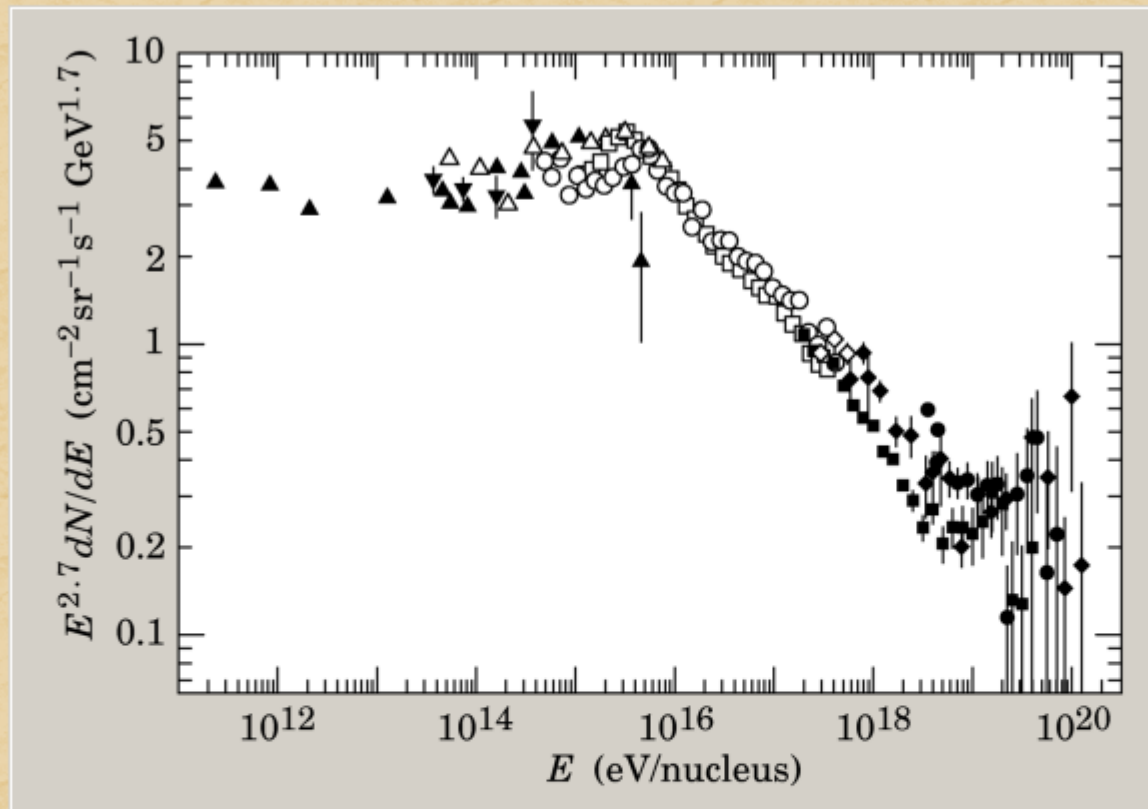
AMANDA - South Pole Neutrino Telescope



AMANDA - South Pole Neutrino Telescope



Gamma-, Neutrino- and Proton-Astronomy



Cosmic-ray
spectrum $\times E^{2.7}$

What are
the sources ?

TeV γ astronomy

Photon mean free path < few 10 Mpc

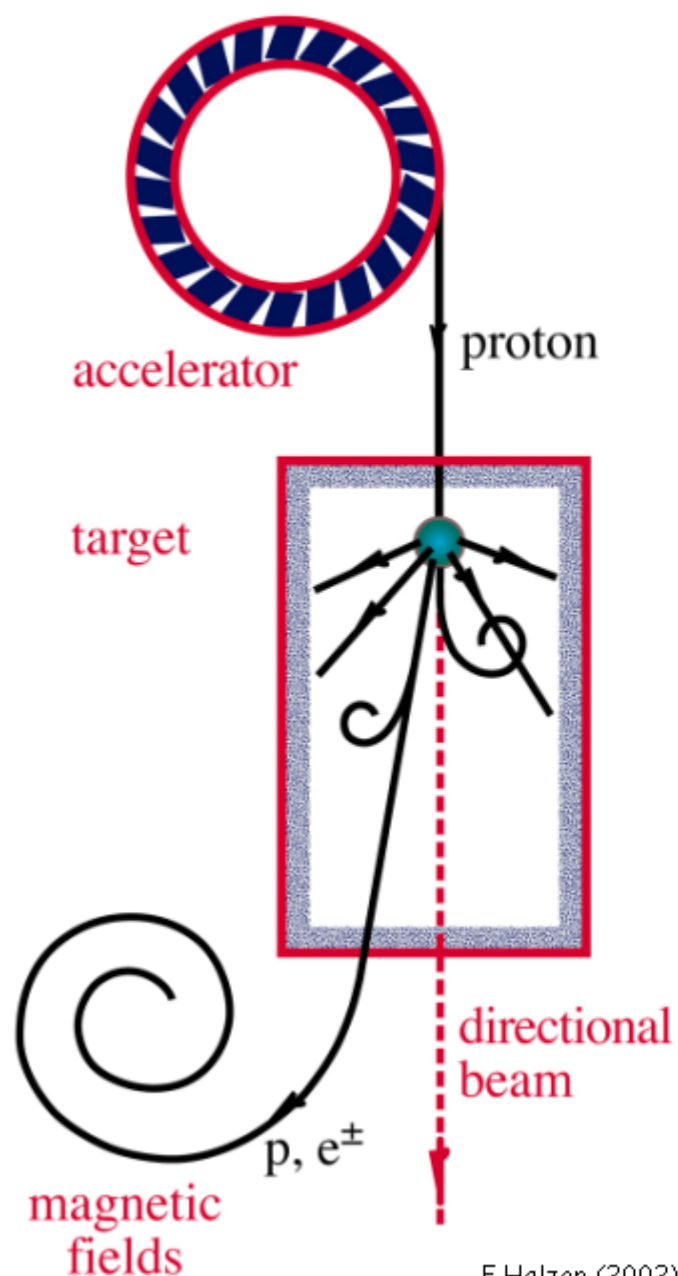
Proton magnetic field deflection

GZK cutoff

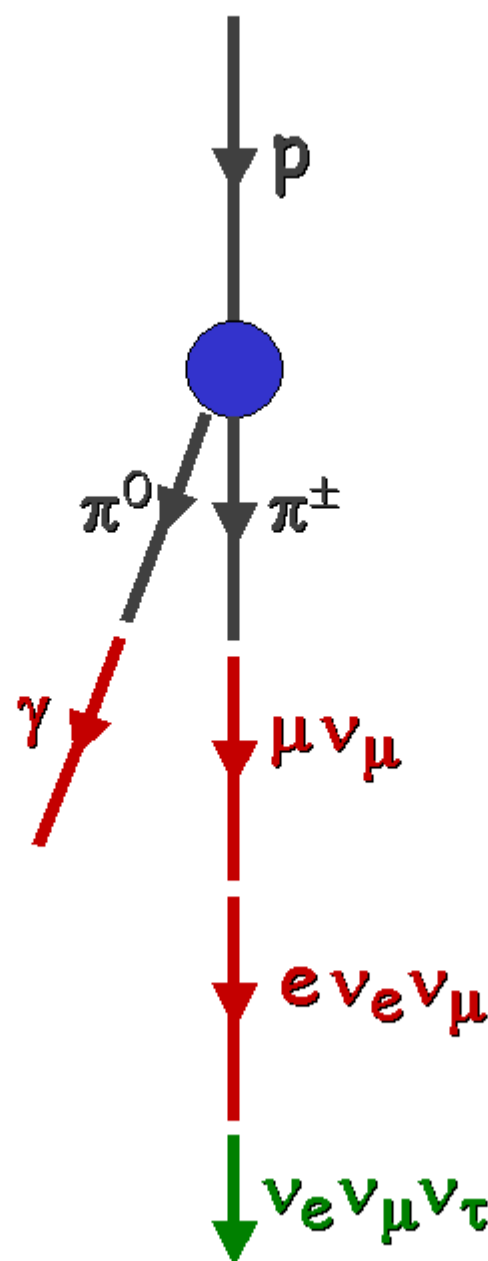
Opportunity for neutrino astronomy

- Point back to sources
- No absorption (reach across the universe)

Neutrino Beams: Heaven and Earth



F. Halzen (2002)



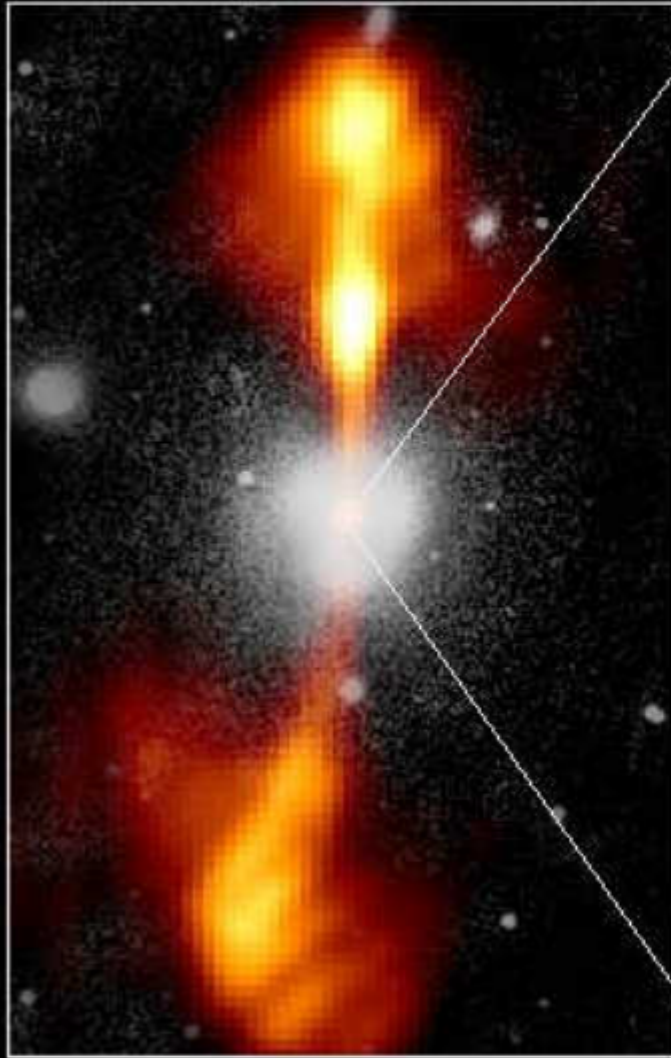
Target:
Protons or Photons

Approx. equal fluxes of
photons & neutrinos

Equal neutrino fluxes
in all flavors due to
oscillations

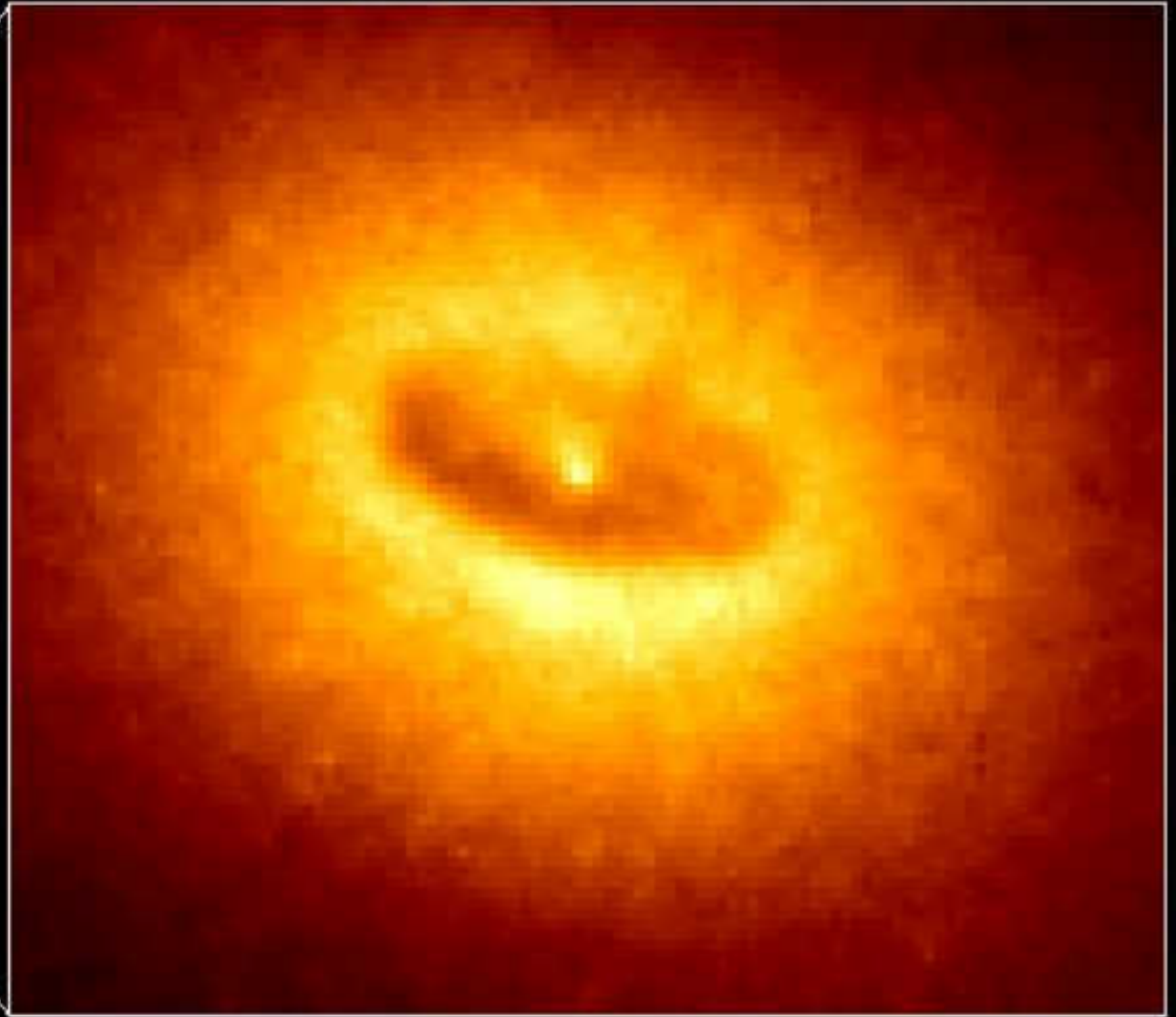
Core of the Galaxy NGC 4261

Ground-Based Optical/Radio Image



380 Arc Seconds
88,000 LIGHT-YEARS

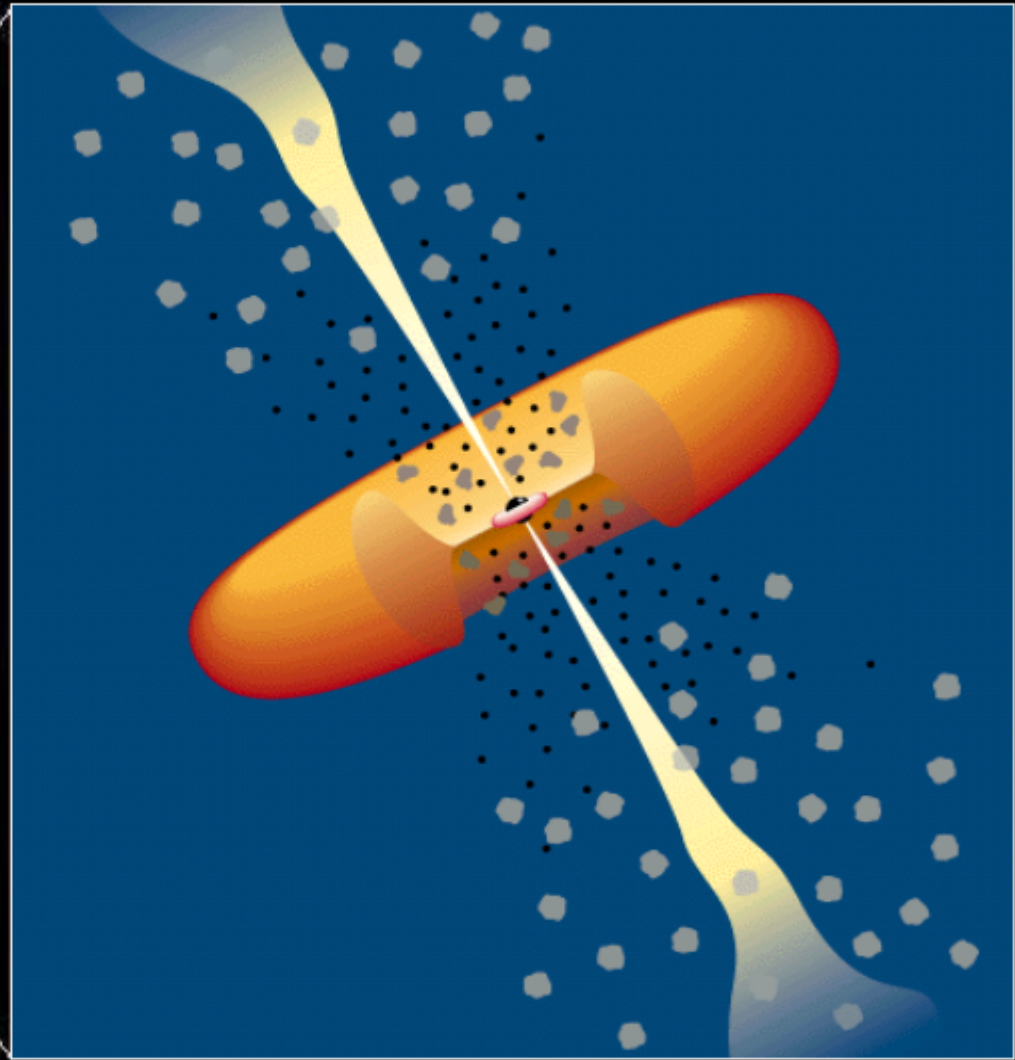
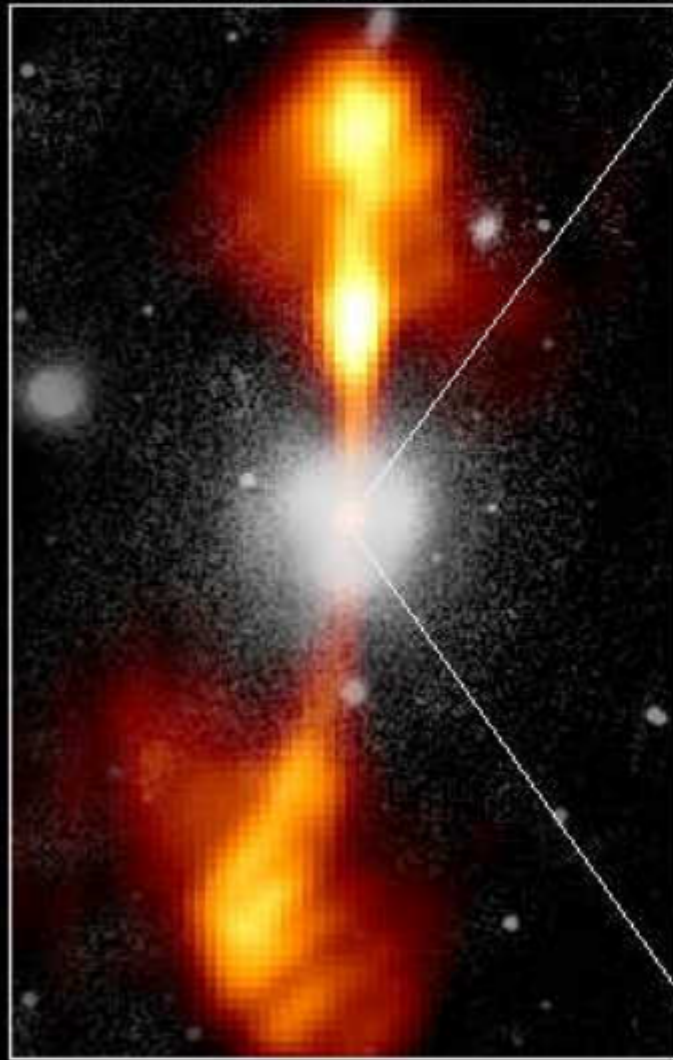
HST Image of a Gas and Dust Disk



1.7 Arc Seconds
400 LIGHT-YEARS

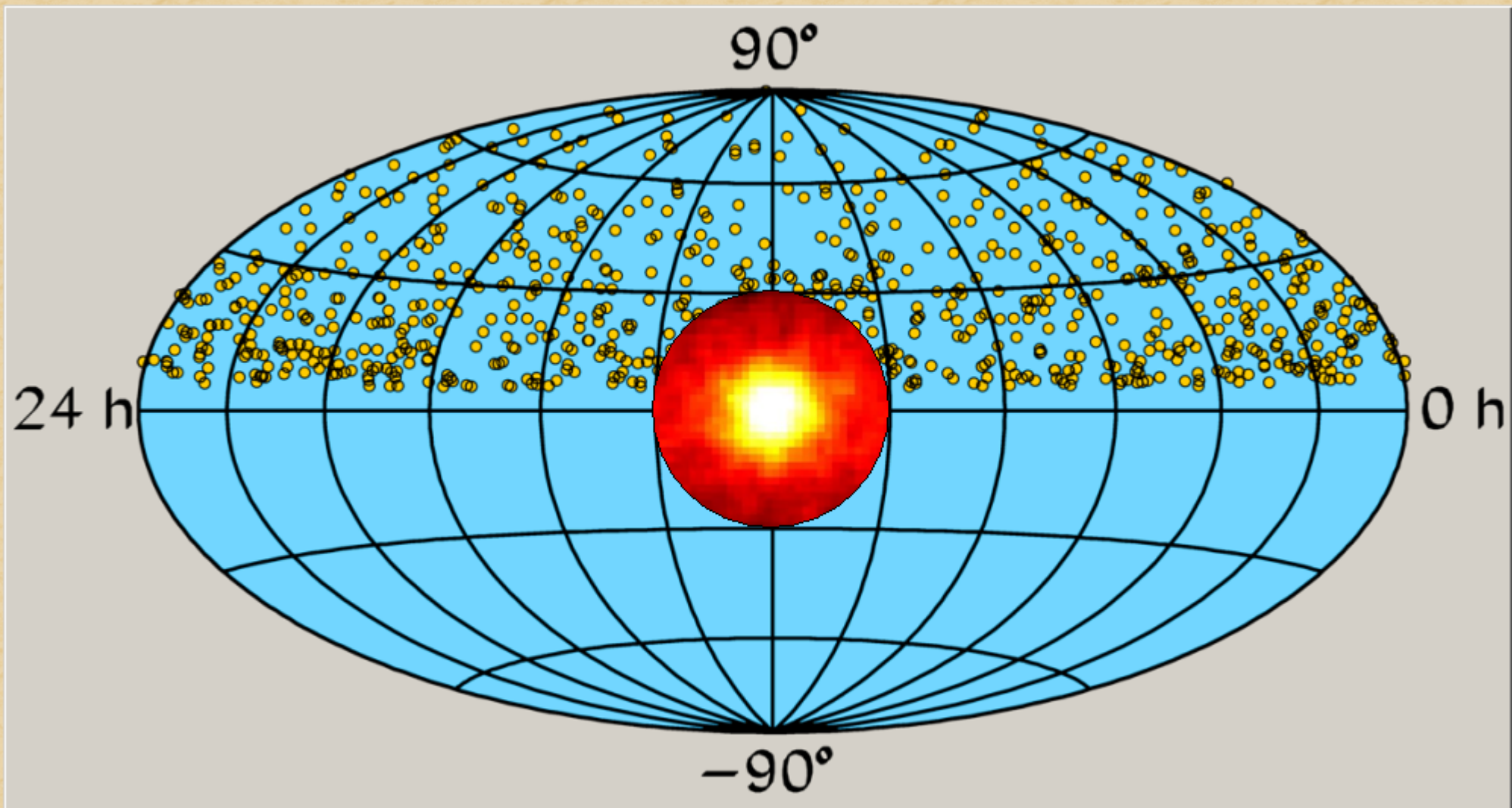
Core of the Galaxy NGC 4261

Ground-Based Optical/Radio Image



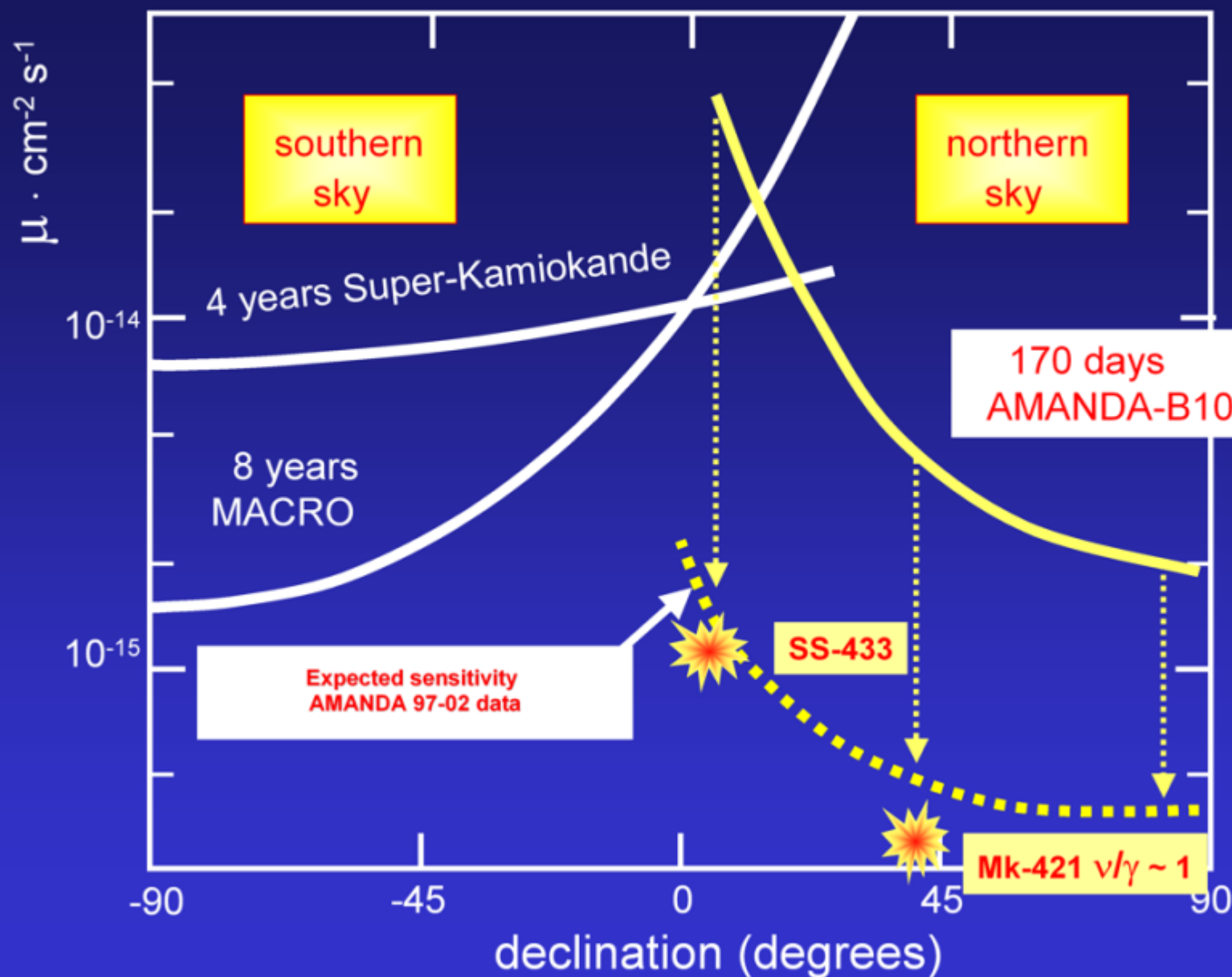
380 Arc Seconds
88,000 LIGHT-YEARS

Neutrino Sky in Amanda and Super-Kamiokande

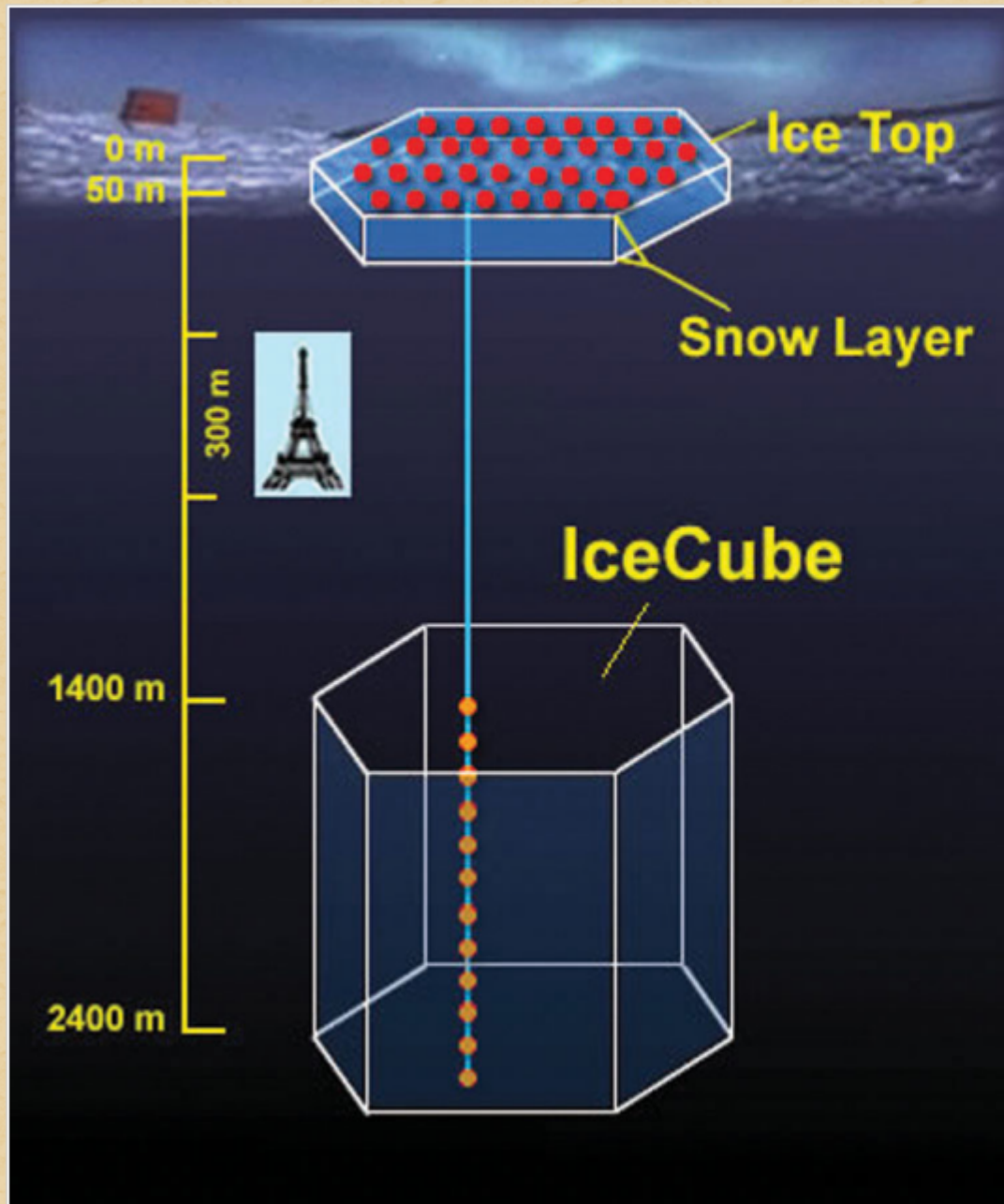


Amanda Point Search Results

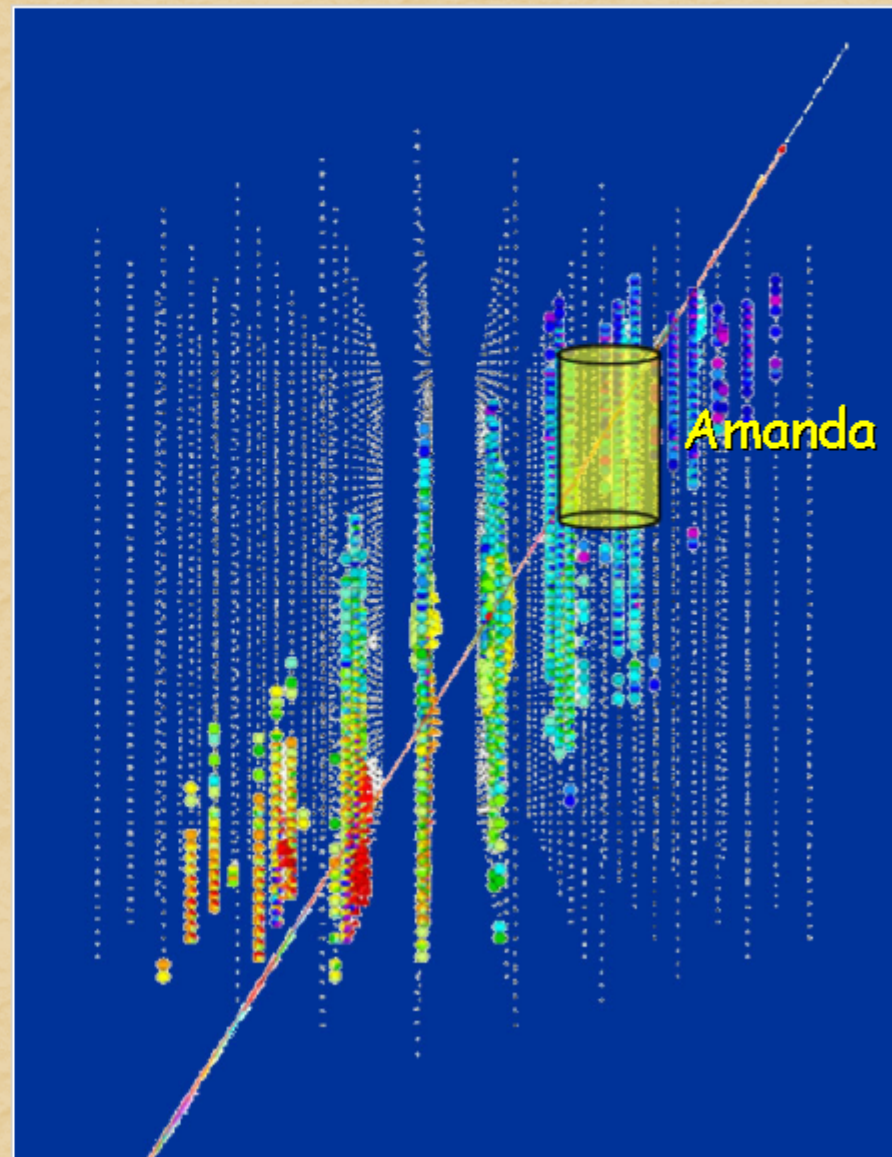
F. Halzen (2002)



IceCube - Future km³ South-Pole Detector



Simulated Event

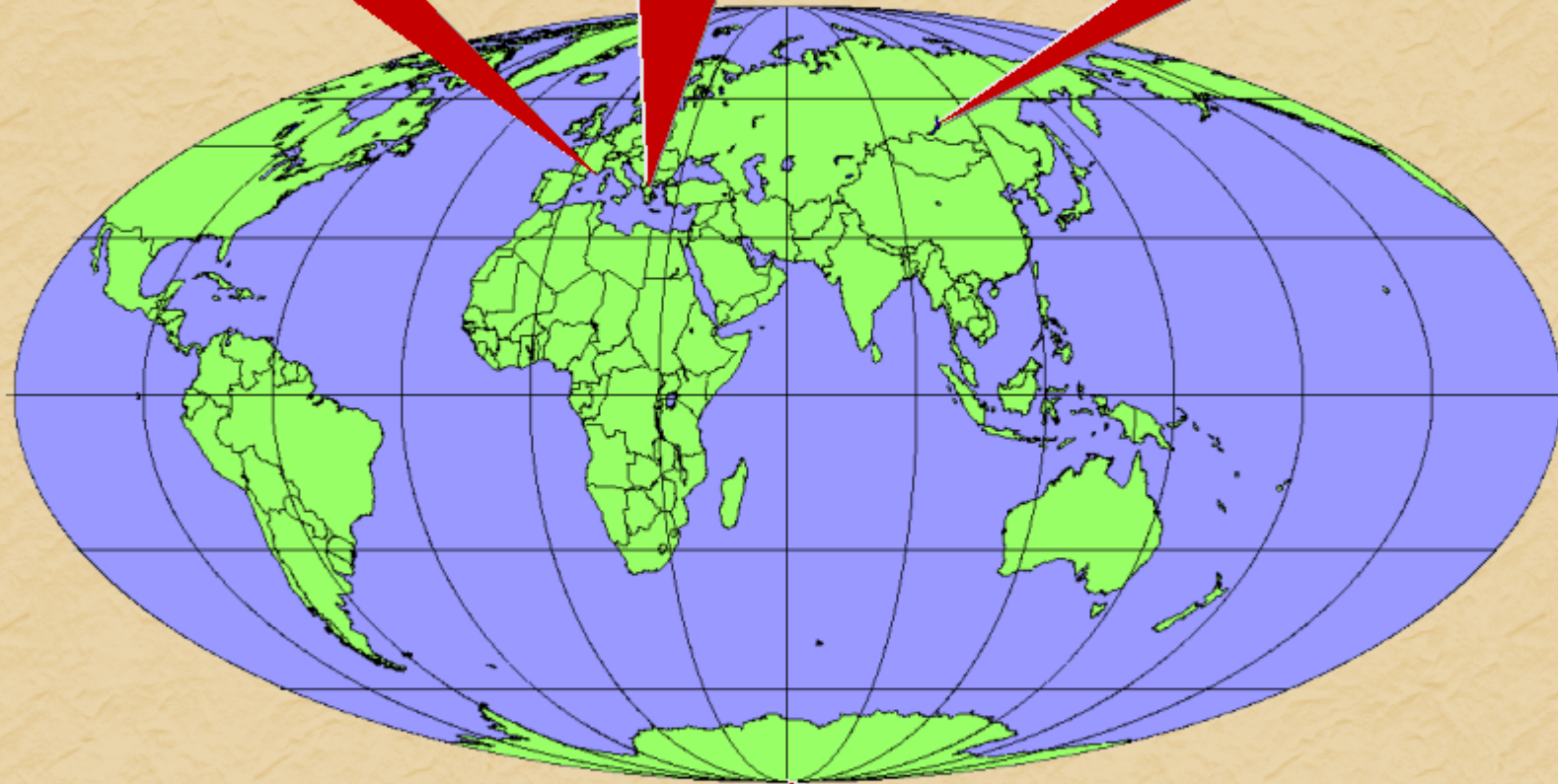


High-Energy Neutrino Telescopes

**Antares
Project**

**Nestor
Project**

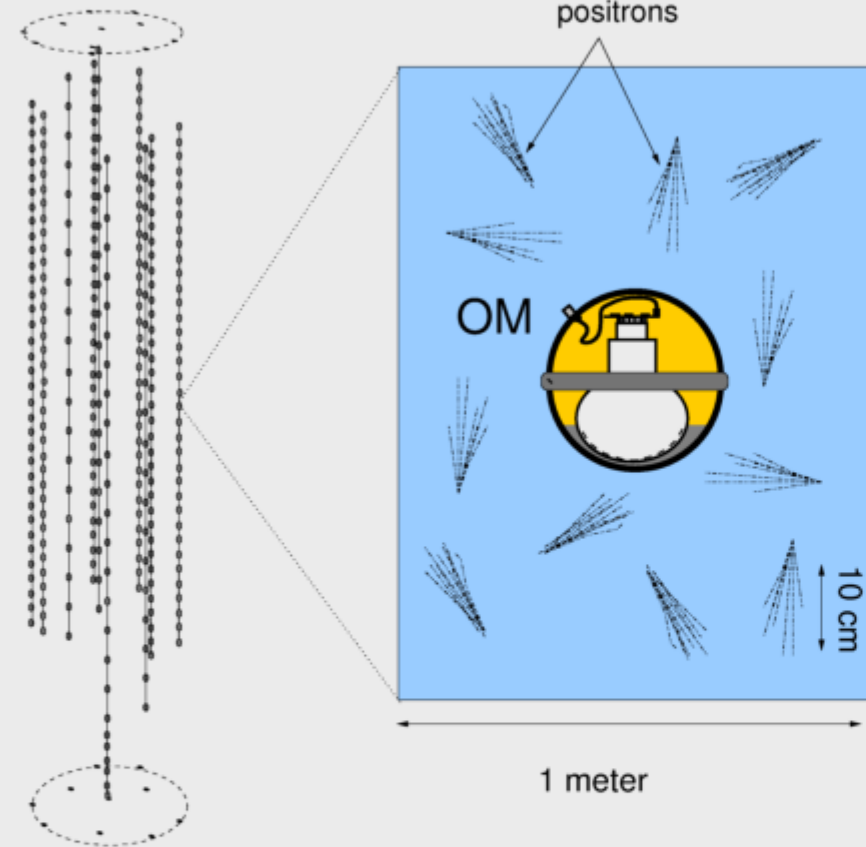
**Baikal
200 PMTs**



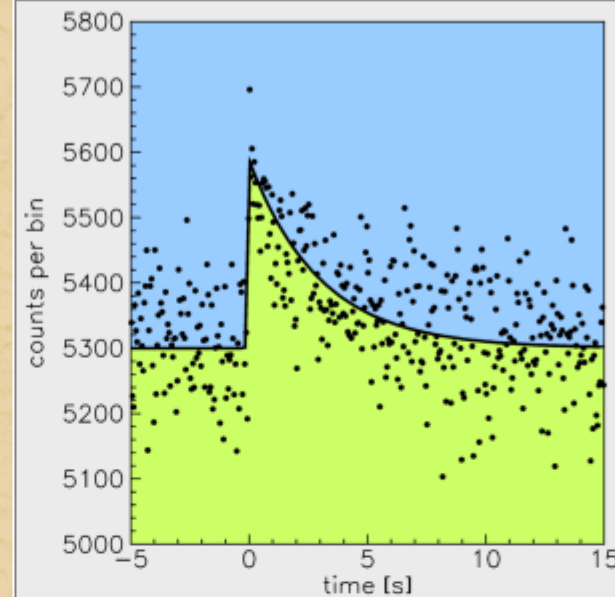
**Amanda II, 800 PMTs
IceCube Project**

Amanda/IceCube as a Supernova Detector

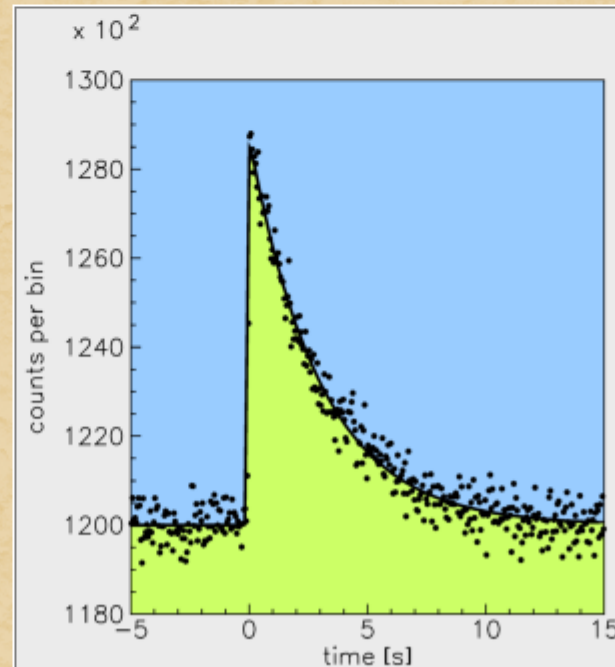
AMANDA-B10



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



**SN @ 8.5 kpc
Signal in
Amanda**



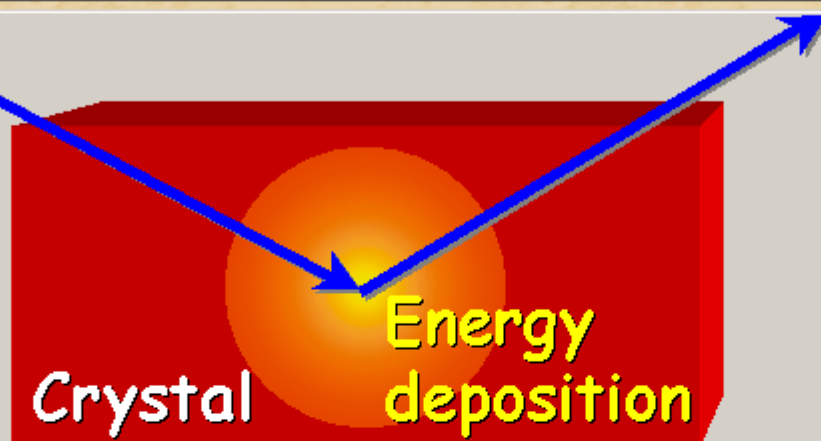
**SN @ 8.5 kpc
Signal in
Ice Cube**

**Amanda
Collaboration
(2001)**

Search for Neutralino Dark Matter

Direct Method (Laboratory Experiments)

Galactic dark matter particle
(e.g. neutralino)

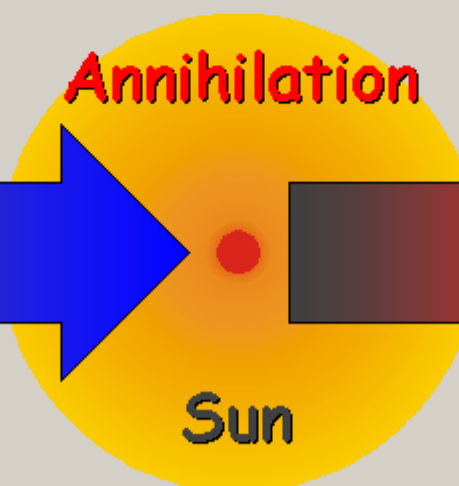


Recoil energy
(few keV) is
measured by

- Ionisation
- Scintillation
- Cryogenic

Indirect Method (Neutrino Telescopes)

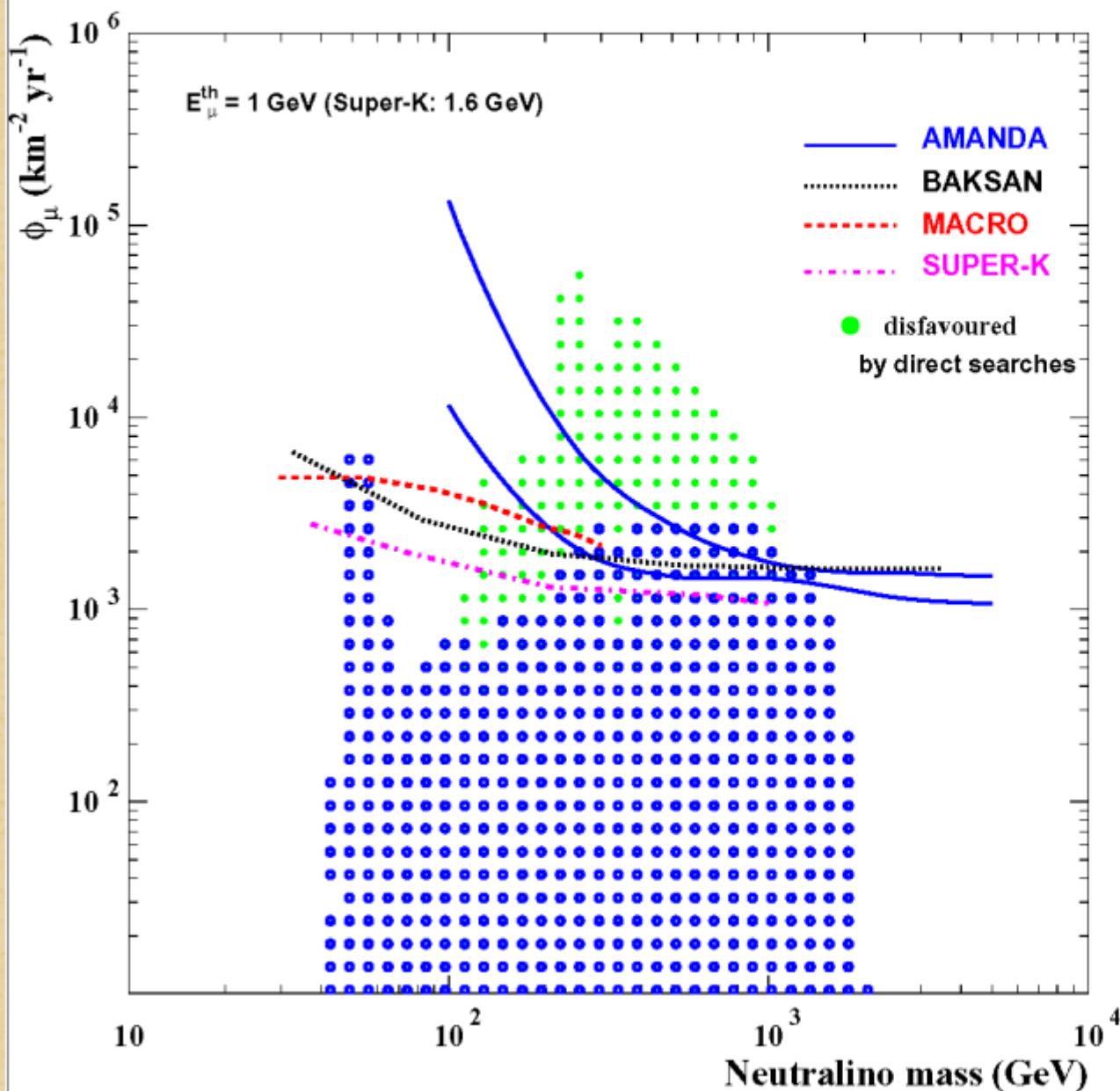
Galactic dark
matter
particles
are accreted



High-energy
neutrinos
(GeV-TeV)
can be measured

Current Limits from WIMP Searches

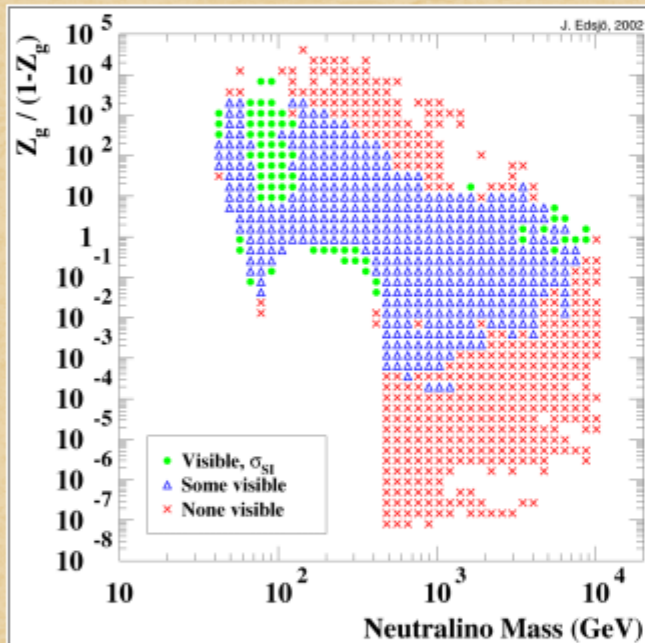
Limits from WIMP
Annihilation in the Earth
astro-ph/0202370



Future WIMP Sensitivities

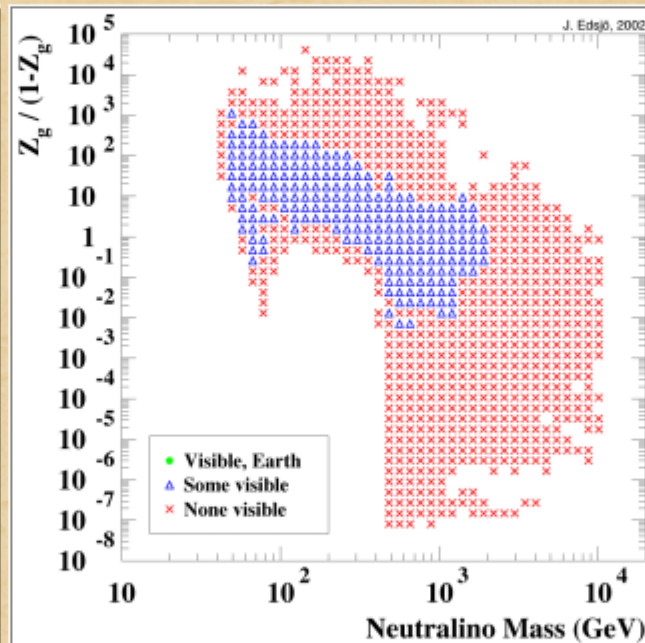
Direct Detection

Genius/CRESST

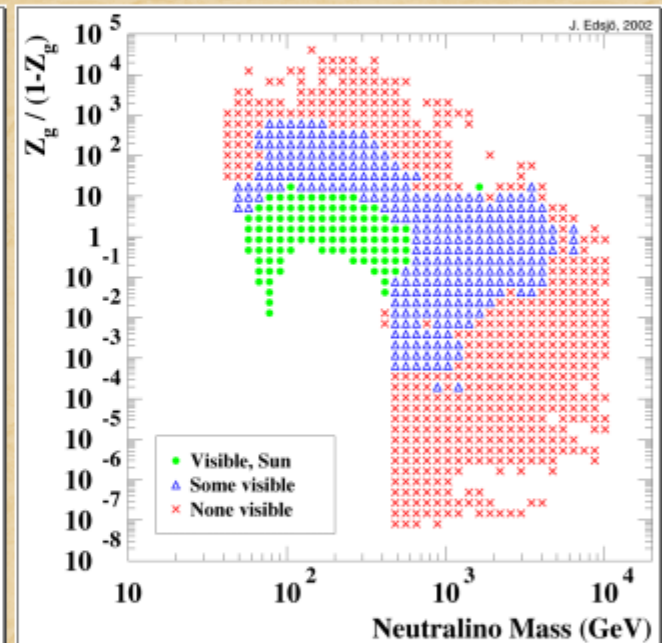


Indirect, km^3 Detector

Earth



Sun



Where do we stand? Where are we going?

Neutrino oscillations established

Mixing parameters at 3σ

	<u>Sun</u>	<u>Atmosphere</u>
$\Delta m^2 / \text{meV}^2$	24 – 240	1400 – 6000
$\tan^2 \theta$	0.27 – 0.77	0.4 – 3.0

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

Absolute mass & Dirac vs Majorana

- Precision cosmology
 $\Sigma m_\nu < 2.2 \text{ eV}$, 50 meV reachable?
- Tritium endpoint
 $m_\nu < 2.2 \text{ eV}$, KATRIN goal 0.3 eV
- Future $0\nu 2\beta$ decay: Majorana mass
(difficult for normal hierarchical)
- Leptogenesis of baryon asymmetry
Majorana $m_\nu < 0.2 \text{ eV}$ suggested

Precision for mixing parameters from long-baseline experiments

- K2K: Preliminary atm confirmation
- Kamland: LMA confirmation soon?
- 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)

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 & experiments
- Future galactic supernova
- Diffuse flux from cosmic supernovae