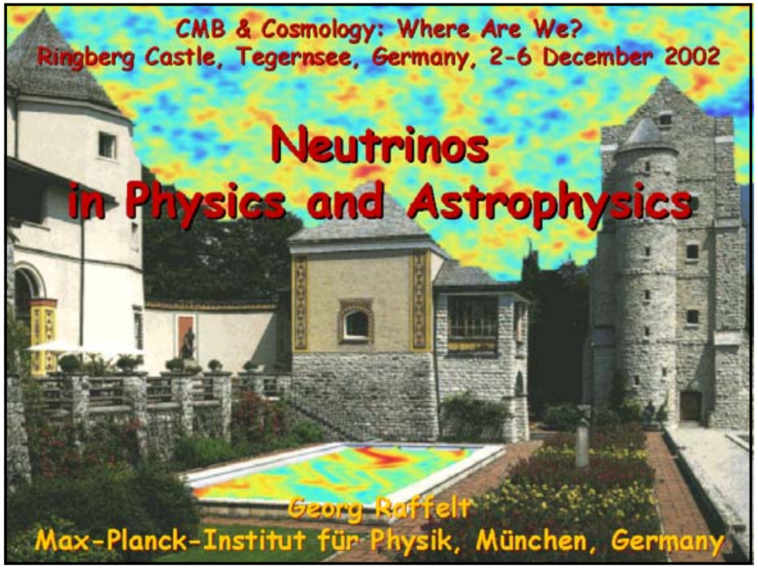
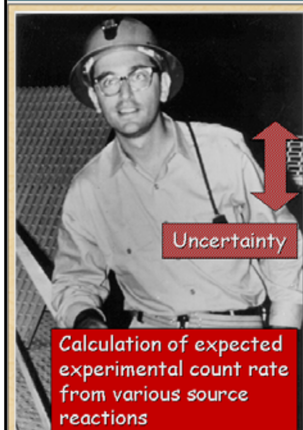


Neutrinos in Physics and Astrophysics

- Flavor oscillations and all that
- Quest for the absolute mass scale
- Neutrino mass and the baryon asymmetry of the universe
- Neutrinos as astrophysical messengers

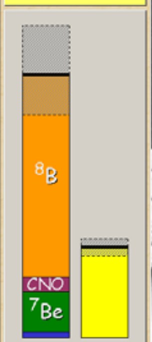
Missing Neutrinos from the Sun



John Bahcall

Homestake

Chlorine



Raymond Davis Jr.

Georg Raffelt, Max-Planck-Institut für Physik, München, Germany
CMB & Cosmology: Where Are We?, Ringberg Castle, Tegernsee, Germany, 2-6 December 2002

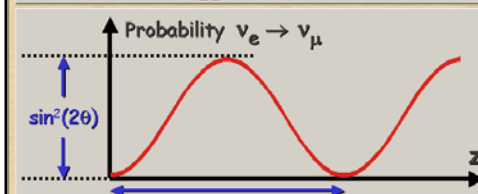
Neutrino Flavor Oscillations

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

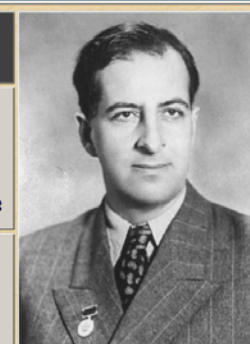
Each mass eigenstate propagates as e^{ipz}

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

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

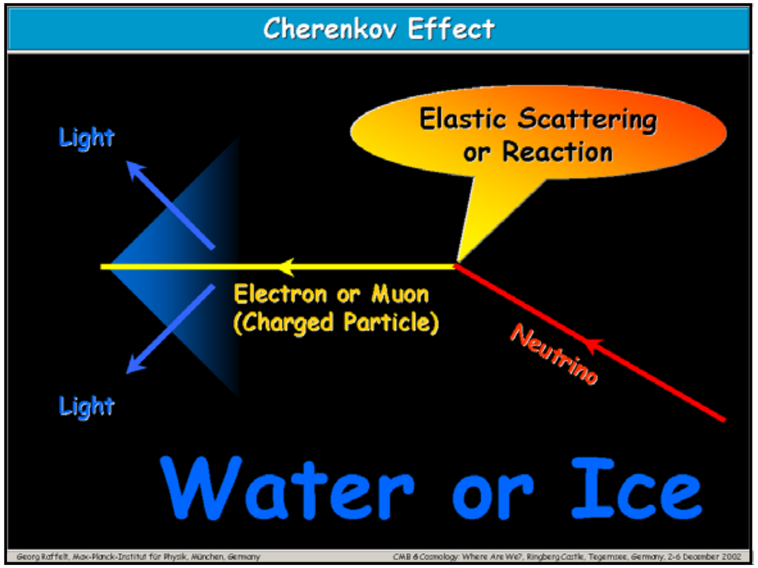


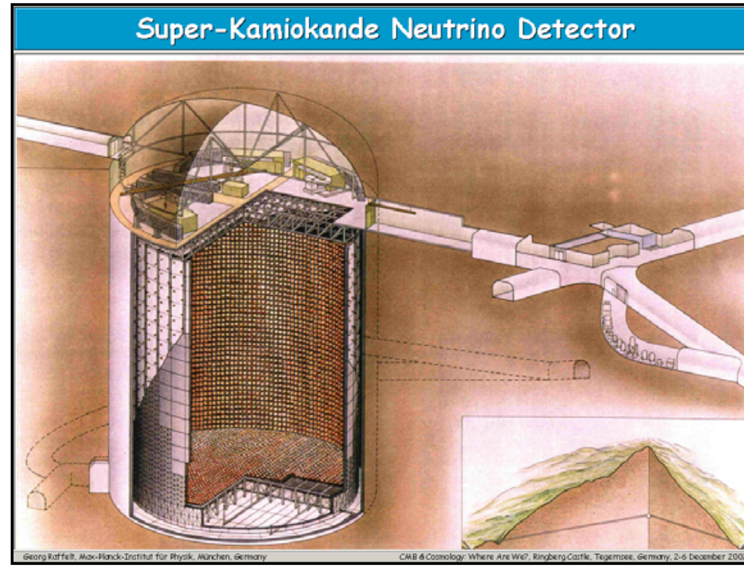
Oscillation Length $\frac{4\pi E}{\Delta m^2} = 2.5\,\mathrm{m} \left(\frac{E}{\mathrm{MeV}}\right)\left(\frac{\mathrm{eV}^2}{\Delta m^2}\right)$

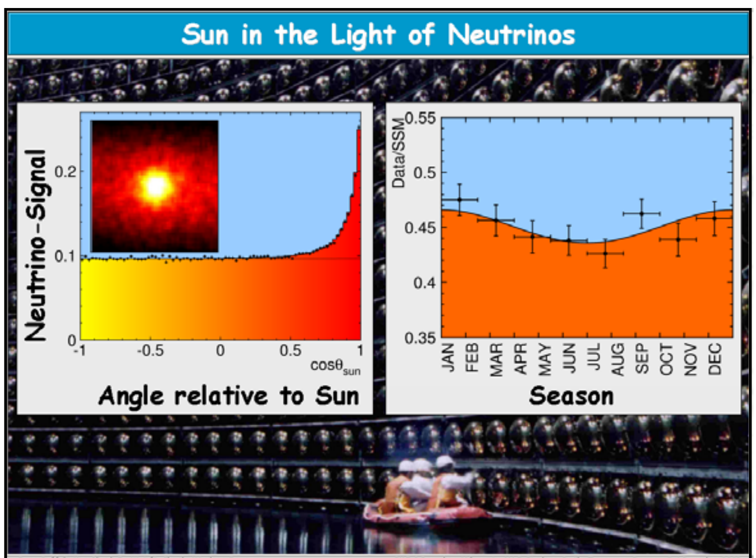


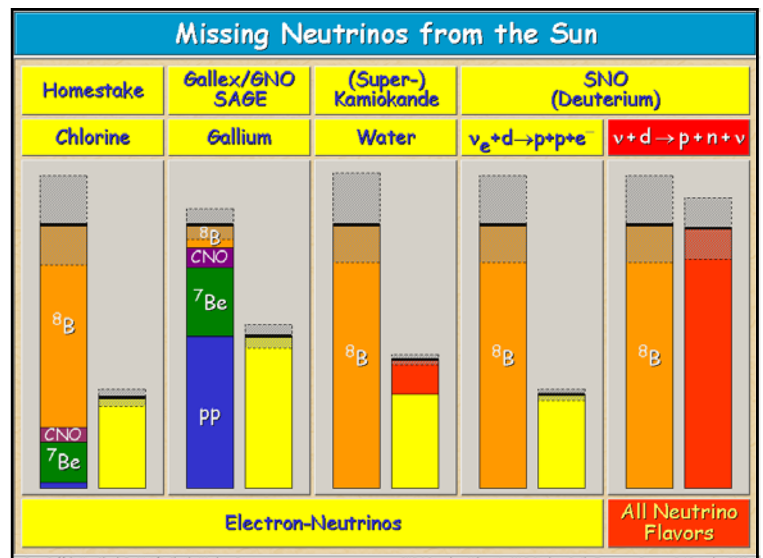
Bruno Pontecorvo (1913 - 1993) Invented nu oscillations

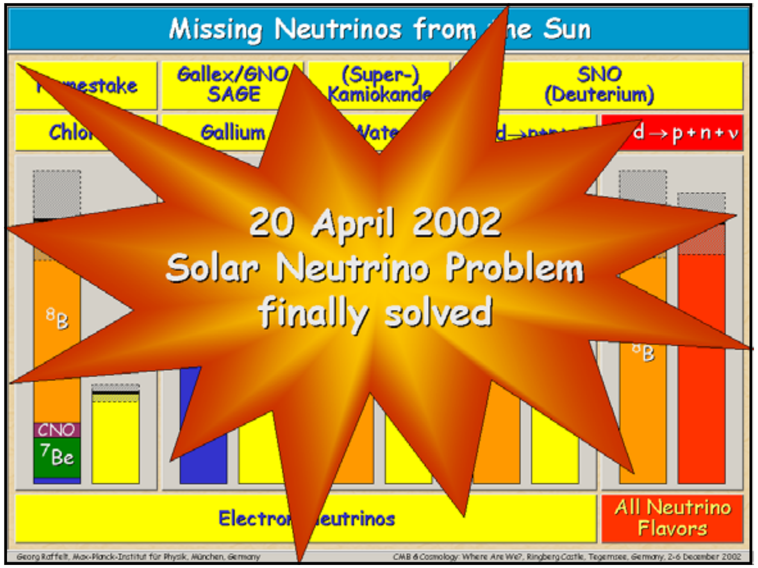
Georg Raffelt, Max-Planck-Institut für Physik, München, Germany
CMB & Cosmology: Where Are We?, Ringberg Castle, Tegernsee, Germany, 2-6 December 2002

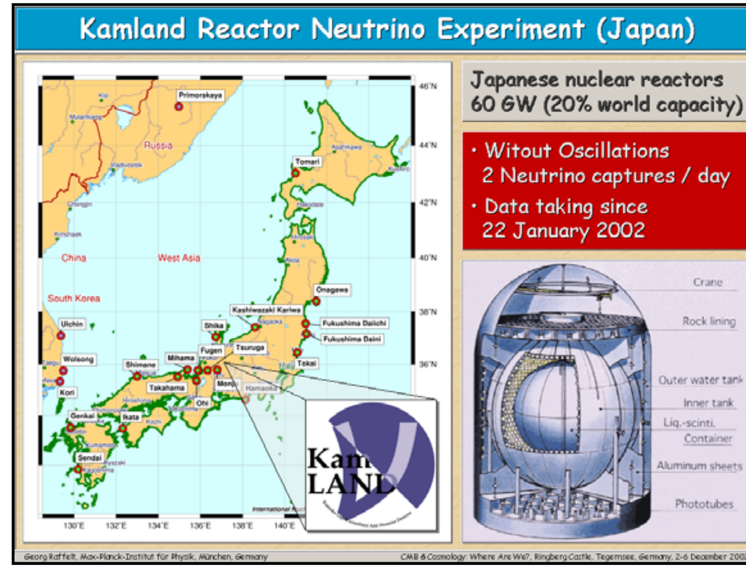

Cherenkov Effect
Elastic Scattering or Reaction
Light
Light
Electron or Muon (Charged Particle)
Neutrino
Water or Ice
Georg Raffelt, Max-Planck-Institut für Physik, München, Germany
CMB & Cosmology: Where Are We?, Ringberg Castle, Tegernsee, Germany, 2-6 December 2002

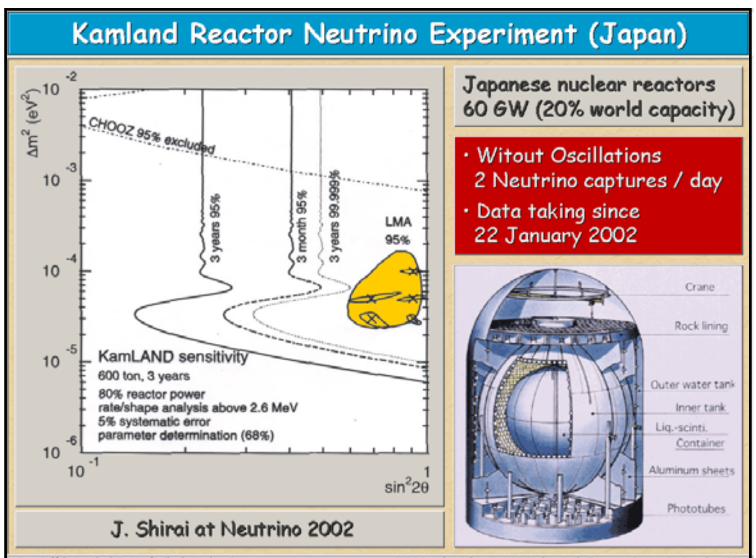

Super-Kamiokande Neutrino Detector
Georg Raffelt, Max-Planck-Institut für Physik, München, Germany
CMB & Cosmology: Where Are We?, Ringberg Castle, Tegernsee, Germany, 2-6 December 2002

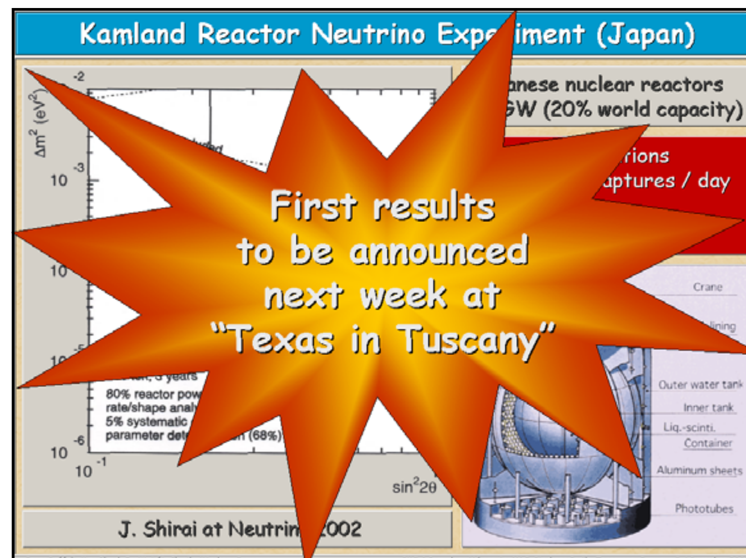

Sun in the Light of Neutrinos
Neutrino-Signal
0.2
0.1
0
-1
-0.5
0
0.5
1
cosθsun
Angle relative to Sun
Data/SSM
0.55
0.5
0.45
0.4
0.35
JAN FEB MAR APR MAY JUN JUL AUG SEP OCT NOV DEC
Season
Georg Raffelt, Max-Planck-Institut für Physik, München, Germany
CMB & Cosmology: Where Are We?, Ringberg Castle, Tegernsee, Germany, 2-6 December 2002


Missing Neutrinos from the Sun
Homestake
Gallex/GNO SAGE
(Super-) Kamiokande
SNO (Deuterium)
Chlorine
Gallium
Water
νe+d→p+p+e−
ν+d→p+n+ν
8B
CNO
7Be
8B
CNO
7Be
pp
8B
8B
8B
Electron-Neutrinos
All Neutrino Flavors
Georg Raffelt, Max-Planck-Institut für Physik, München, Germany
CMB & Cosmology: Where Are We?, Ringberg Castle, Tegernsee, Germany, 2-6 December 2002

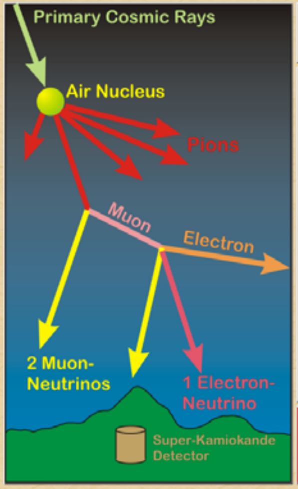

Missing Neutrinos from the Sun
Gallex/GNO
SAGE
(Super-)
Kamiokande
SNO
(Deuterium)
Chlor
Gallium
Wate
d → p + n + ν
8B
CNO
7Be
8B
Electron
eutrinos
All Neutrino
Flavors
20 April 2002
Solar Neutrino Problem
finally solved
Georg Raffelt, Max-Planck-Institut für Physik, München, Germany
CMB & Cosmology: Where Are We?, Ringberg Castle, Tegernsee, Germany, 2-6 December 2002


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
Russia
China
South Korea
Kam
LAND
Crane
Rock lining
Outer water tank
Inner tank
Liq.-scinti.
Container
Aluminum sheets
Phototubes
Georg Raffelt, Max-Planck-Institut für Physik, München, Germany
CMB & Cosmology: Where Are We?, Ringberg Castle, Tegernsee, Germany, 2-6 December 2002

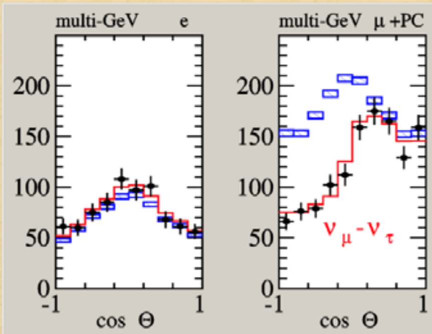

Kamland Reactor Neutrino Experiment (Japan)
Δm² (eV²)
CHOOZ 95% excluded
3 years 95%
3 month 95%
3 years 99.999%
LMA
95%
KamLAND sensitivity
600 ton, 3 years
80% reactor power
rate/shape analysis above 2.6 MeV
5% systematic error
parameter determination (68%)
sin²2θ
J. Shirai at Neutrino 2002
Japanese nuclear reactors
60 GW (20% world capacity)
• Witout Oscillations
2 Neutrino captures / day
• Data taking since
22 January 2002
Crane
Rock lining
Outer water tank
Inner tank
Liq.-scinti.
Container
Aluminum sheets
Phototubes
Georg Raffelt, Max-Planck-Institut für Physik, München, Germany
CMB & Cosmology: Where Are We?, Ringberg Castle, Tegernsee, Germany, 2-6 December 2002


Kamland Reactor Neutrino Experiment (Japan)
First results
to be announced
next week at
"Texas in Tuscany"
J. Shirai at Neutrin 2002
Crane
Outer water tank
Inner tank
Liq.-scinti.
Container
Aluminum sheets
Phototubes
Georg Raffelt, Max-Planck-Institut für Physik, München, Germany
CMB & Cosmology: Where Are We?, Ringberg Castle, Tegernsee, Germany, 2-6 December 2002

Atmospheric Neutrino Anomaly

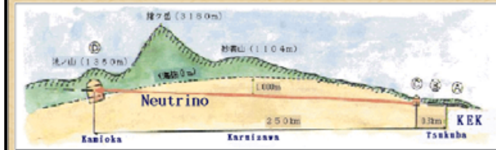


Zenith-angle distribution of atmospheric nus in Super-Kamiokande [hep-ex/0210019]

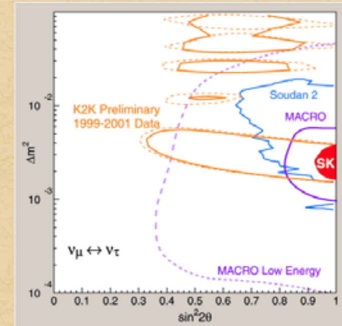


Half of the muon neutrinos from below are missing

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

Georg Raffelt, Max-Planck-Institut für Physik, München, Germany
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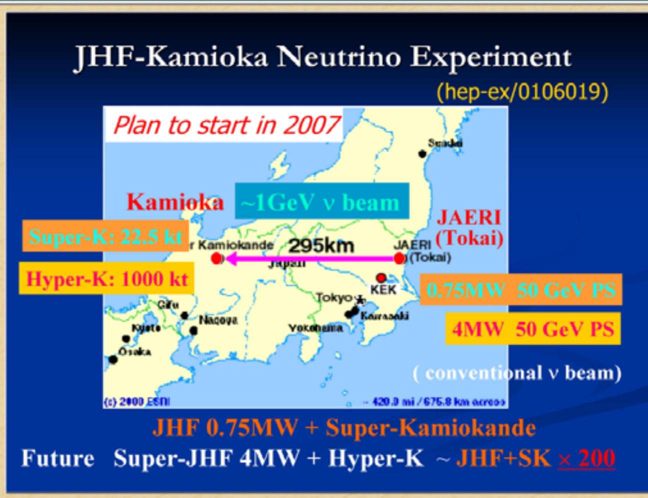
Japanese Hadron Facility (JHF) to Kamioka (2007)

Y. Itow (ICRR,Univ. Tokyo), ICHEPO2 Amsterdam



Georg Raffelt, Max-Planck-Institut für Physik, München, Germany
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Upcoming Long-Baseline Experiments (2005)

FermiLab-Soudan (MINOS)

CERN – Gran Sasso

Georg Raffelt, Max-Planck-Institut für Physik, München, Germany
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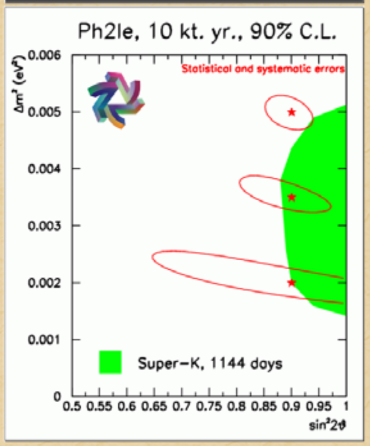
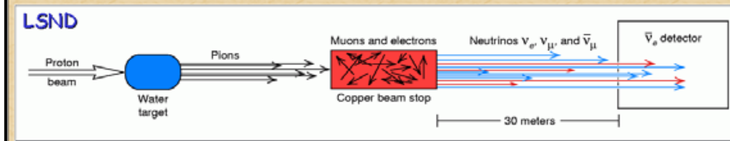
Upcoming Long-Baseline Experiments (2005)

FermiLab-Soudan (MINOS)

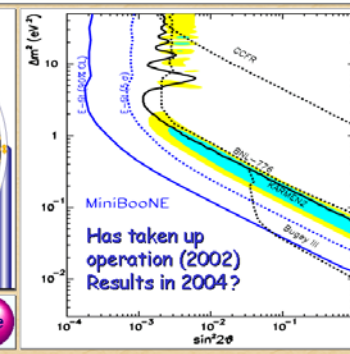
MINOS Oscillation Sensitivity



Testing LSND at MiniBooNE



www-boone.fnal.gov



Status of Evidence for Neutrino Oscillations

System	Atmospheric	Solar	LSND
Channel	$\nu_\mu \to \nu_\tau$	$\nu_e \to \nu_{\mu\tau}$	$\bar\nu_\mu \to \bar\nu_e$
$\delta m^2/\mathrm{eV}^2$	$(1.5-4)\times10^{-3}$	LMA $(0.2-2)\times10^{-4}$	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 interpre-tation	Three mass eigenstates with $m_1 \ll m_2 \ll m_3 \sim 50$ meV (hierarchical) $m_1 \sim m_2 \sim m_3 \gg 50$ 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?**

Three-Flavor Neutrino Parameters (Ignoring LSND)

Atmospheric	Chooz Limit	Solar	3σ ranges
$32^\circ < \theta_{23} < 60^\circ$	$\theta_{13} < 14^\circ$	$27^\circ < \theta_{12} < 41^\circ$	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

$\Delta m^2/\mathrm{meV}^2$

Normal

3 — μ τ

Atmosphere

2 — e μ τ

Sun

1 — e μ τ

Inverted

2 — e μ τ

Sun

1 — e μ τ

Atmosphere

3 — μ τ

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

$\nu_e \to \nu_\mu$ ⟷ CP ⟷ $\bar\nu_e \to \bar\nu_\mu$

T ↕ CPT ✕ ↕ T

$\nu_\mu \to \nu_e$ ⟷ CP ⟷ $\bar\nu_\mu \to \bar\nu_e$

CP Particle ↔ 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" $\bar\nu_\mu \to \bar\nu_e$ and $\nu_\mu \to \nu_e$

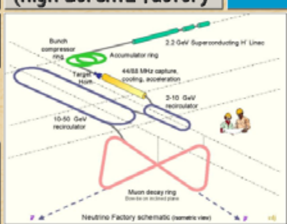
$$\left.\begin{array}{l}P(\nu_\mu \to \nu_e)\\ P(\bar\nu_\mu \to \bar\nu_e)\end{array}\right\} = \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\Delta_{atm}$$

$$+\sin 2\theta_{12}\sin 2\theta_{23}\sin 2\theta_{13}\cos\theta_{13}\Delta_{sun}\sin\Delta_{atm}\left(\cos\delta\cos\Delta_{atm} \pm \sin\delta\sin\Delta_{atm}\right)$$

where $\Delta_{atm} = \dfrac{\Delta m^2_{atm}L}{4E}$ and $\Delta_{sun} = \dfrac{\Delta m^2_{sun}L}{4E}$

Long-Baseline Experiments

Nuclear reactors	Nuclear decay	Kamland (2002) Borexino (>2003?)	Solar LMA
Conventional beam	Proton beam dump $\to \pi \to \mu\nu_\mu \to e\nu_\mu\nu_\mu\nu_e$	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	$\sin^2 2\theta_{13} \sim 0.0001$ CP violation Mass ordering
Neutrino factory		R&D	



Muon storage ring $\mu \to e\nu_\mu\bar\nu_e$

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

Neutrinos in Physics and Astrophysics

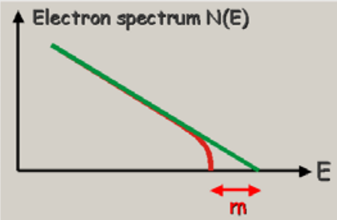
Flavor oscillations and all that

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

$^3H \rightarrow {}^3He + e^- + \bar{\nu}_e$

Endpoint energy 18.6 keV

Mainz Experiment, PLB 460 (1999) 219
m < 2.8 eV (95% CL)

Troitsk Experiment, ibid. 227
m < 2.5 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" ~ 112 cm^{-3} neutrinos + anti-neutrinos per flavor

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

m_ν < 40 eV — For all stable flavors

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

REST MASS OF MUONIC NEUTRINO AND COSMOLOGY

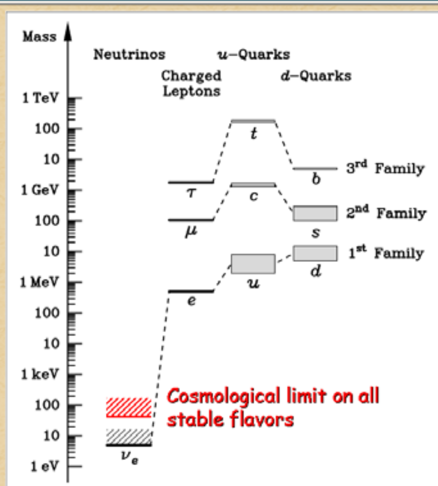
S. S. Gershtein and Ya. B. Zel'dovich
Submitted 4 June 1966
ZhETF Pis'ma 4, No. 5, 174-177, 1 September 1966

Low-accuracy experimental estimates of the rest mass of the neutrino [1] yield $m(\nu_e) < 200$ eV/c^2 for the electronic neutrino and $m(\nu_\mu) < 2.5 \times 10^6$ 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-Mparsec = $(13 \times 10^9$ years$)^{-1}$. It follows therefore that the density of all types of matter in the Universe is at the present time [1])

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

Georg Raffelt, Max-Planck-Institut für Physik, München, Germany
CMB & Cosmology: Where Are We?, Ringberg Castle, Tegernsee, Germany, 2-6 December 2002

Fermion Mass Spectrum



Georg Raffelt, Max-Planck-Institut für Physik, München, Germany
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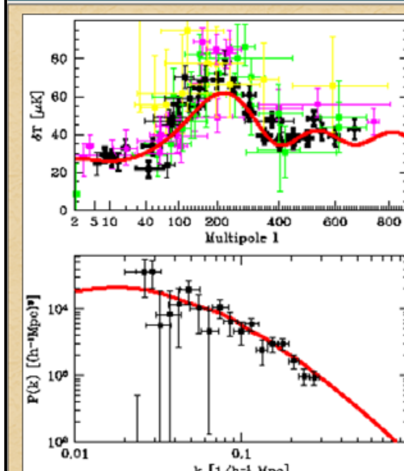
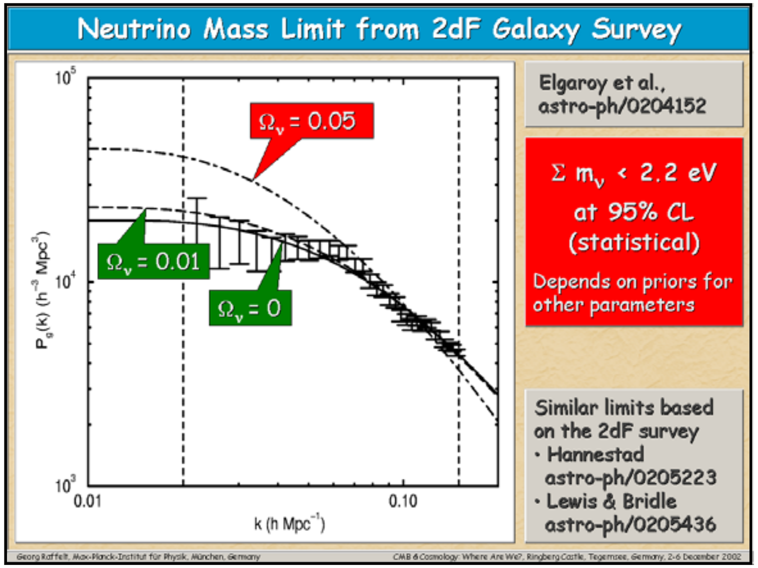
Fitting the Cosmological Model - Neutrinos

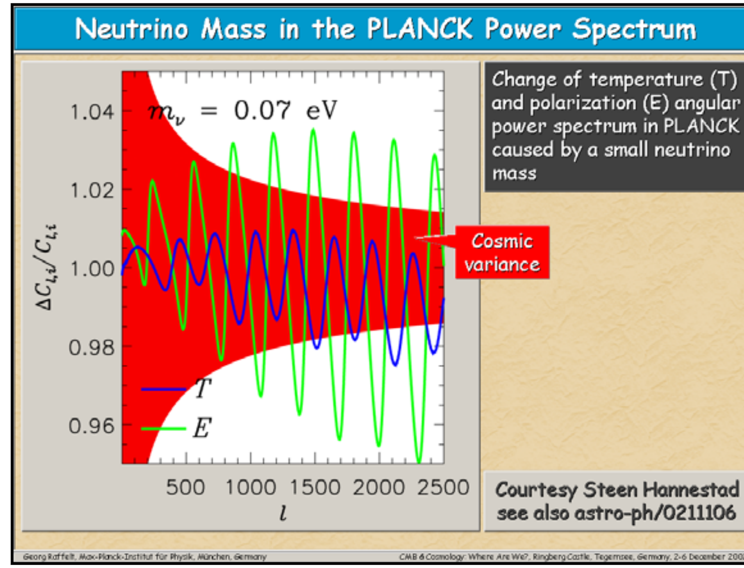


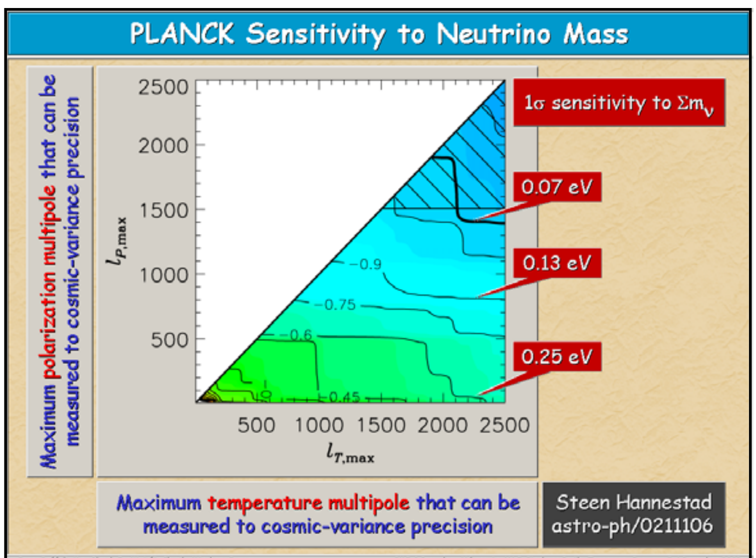
τ=0.000	Ionization parameter
Ω_k=0.000	Curvature
Ω_Λ=0.61	Cosmological constant
ω_d=0.13	Dark Matter ($\Omega_M h^2$)
ω_b=0.020	Baryons ($\Omega_B h^2$)
f_ν=0.000	Neutrino DM fraction
n_s=0.90	Scalar power-law index
n_t=−1.000	Tensor power-law index
A_s=0.44	Scalar Amplitude
A_t=0.000	Tensor Amplitude
b=1.2	Biasing parameter
h=0.62	Hubble constant
χ^2=0.000	

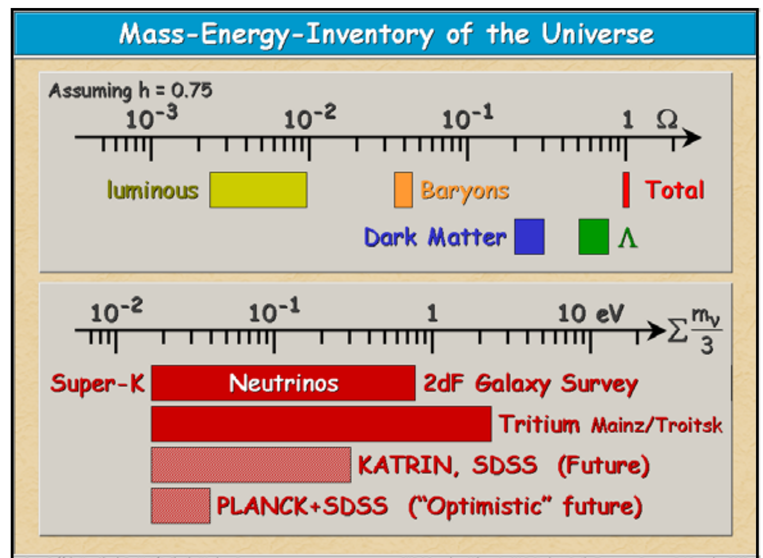
Max Tegmark,
www.hep.upenn.edu/~max/concordance.html

Georg Raffelt, Max-Planck-Institut für Physik, München, Germany
CMB & Cosmology: Where Are We?, Ringberg Castle, Tegernsee, Germany, 2-6 December 2002


Neutrino Mass Limit from 2dF Galaxy Survey
$\Omega_\nu = 0.05$
$\Omega_\nu = 0.01$
$\Omega_\nu = 0$
$P_g(k)$ (h^{-3} Mpc^3)
k (h Mpc^{-1})
0.01
0.10
Elgarøy et al., astro-ph/0204152
$\Sigma m_\nu < 2.2$ 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
Georg Raffelt, Max-Planck-Institut für Physik, München, Germany
CMB & Cosmology: Where Are We?, Ringberg Castle, Tegernsee, Germany, 2-6 December 2002


Neutrino Mass in the PLANCK Power Spectrum
m_ν = 0.07 eV
$\Delta C_{l,i}/C_{l,i}$
l
T
E
Cosmic variance
Change of temperature (T) and polarization (E) angular power spectrum in PLANCK caused by a small neutrino mass
Courtesy Steen Hannestad see also astro-ph/0211106
Georg Raffelt, Max-Planck-Institut für Physik, München, Germany
CMB & Cosmology: Where Are We?, Ringberg Castle, Tegernsee, Germany, 2-6 December 2002


PLANCK Sensitivity to Neutrino Mass
Maximum polarization multipole that can be measured to cosmic-variance precision
$l_{P,\max}$
$l_{T,\max}$
1σ 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
Georg Raffelt, Max-Planck-Institut für Physik, München, Germany
CMB & Cosmology: Where Are We?, Ringberg Castle, Tegernsee, Germany, 2-6 December 2002


Mass-Energy-Inventory of the Universe
Assuming h = 0.75
10^{-3} 10^{-2} 10^{-1} 1 Ω
luminous
Baryons
Total
Dark Matter
Λ
10^{-2} 10^{-1} 1 10 eV $\Sigma \frac{m_\nu}{3}$
Super-K
Neutrinos
2dF Galaxy Survey
Tritium Mainz/Troitsk
KATRIN, SDSS (Future)
PLANCK+SDSS ("Optimistic" future)
Georg Raffelt, Max-Planck-Institut für Physik, München, Germany
CMB & Cosmology: Where Are We?, Ringberg Castle, Tegernsee, Germany, 2-6 December 2002

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

Baryogenesis in the Early Universe

Andrei Sakharov
1921 - 1989

Sakharov conditions for creating the Baryon Asymmetry of the Universe (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

Leptogenesis by Majorana Neutrino Decays

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

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

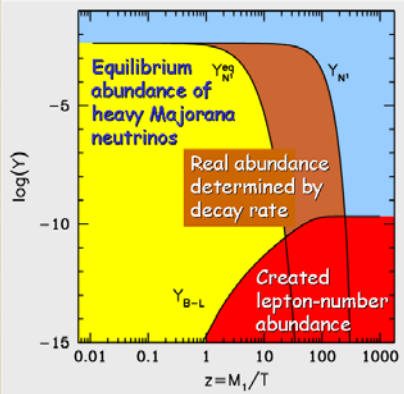
Lagrangian for particle masses

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

Light Majorana mass

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

Leptogenesis by Out-of-Equilibrium Decay



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

$$\Gamma_{\rm Decay} = g_\nu^2 \frac{M}{8\pi}$$

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

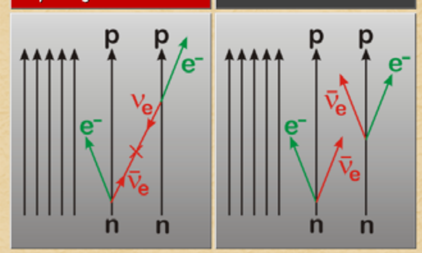
Buchmüller, Di Bari & Plümacher, PLB 547 (2002) 128 [hep-ph/0209301]

Leptogenesis – A Popular Research Topic

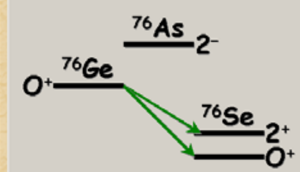
- Fukugita & Yanagida PLB 174 (1986) 45
- Langacker, Peccei & Yanagida Mod. Phys. Lett. A 1 (1986) 541
- Campbell, Davidson & Olive NPB 399 (1993) 111
- Gherghetta & Jungmann PRD 48 (1993) 1546
- Muryama & Yanagida PLB 322 (1994) 349
- Worah PRD 53 (1996) 3902
- Jeannerot PRL 77 (1996) 3292
- Dine, Randall & 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, Frére & 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
- Frére, 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
- Joshipura, 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 ββ Decay

0ν mode, enabled by Majorana mass	Standard 2ν mode



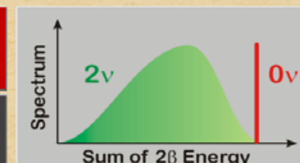
Some nuclei decay only by the ββ mode, e.g.



Half life ~ 10^{21} yr

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

Best limit from ^{76}Ge $\quad |m_{ee}| < 0.35\,\mathrm{eV}$



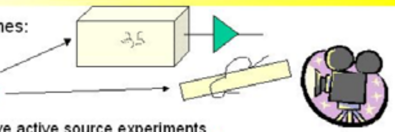
Summary of Current Neutrinoless ββ Decay Limits

O.Cremonesi at Neutrino 2002

$0\nu2\beta$ 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)	$<m_\nu>$ (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	$^{130/128}$Te*	$(3.52 \pm 0.11) \times 10^{-4}$	< 1.1 – 1.5
Bernatowicz et al. 1993	^{128}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 ββ Decay Projects

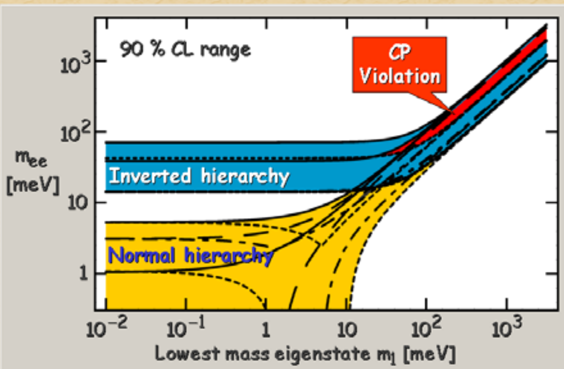
O.Cremonesi at Neutrino 2002

Future projects

Experiment	Author	Isotope	Detector description	$T^{5y}_{1/2}$(y)	$<m_\nu>$*
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 Gd_2SiO_5: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



Best upper limit

Sensitivity future (5y) 1-ton class experiments, e.g. Genius, Majorana, Cuore, etc.

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
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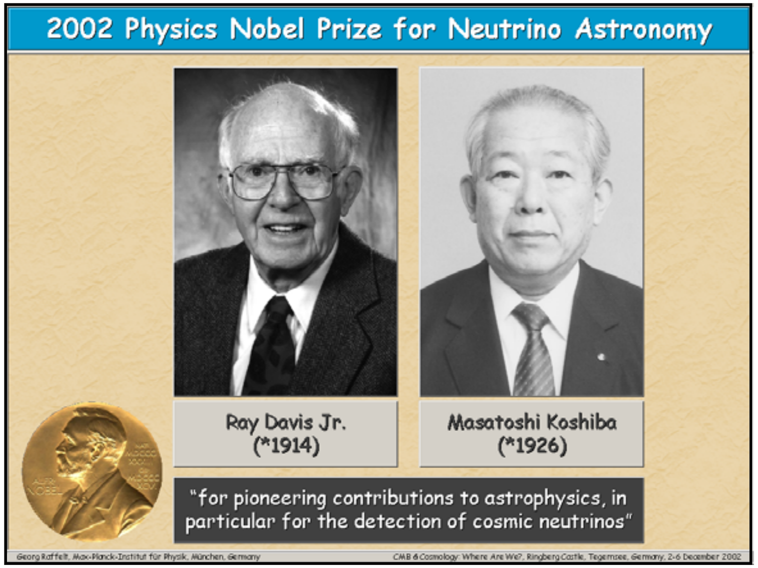
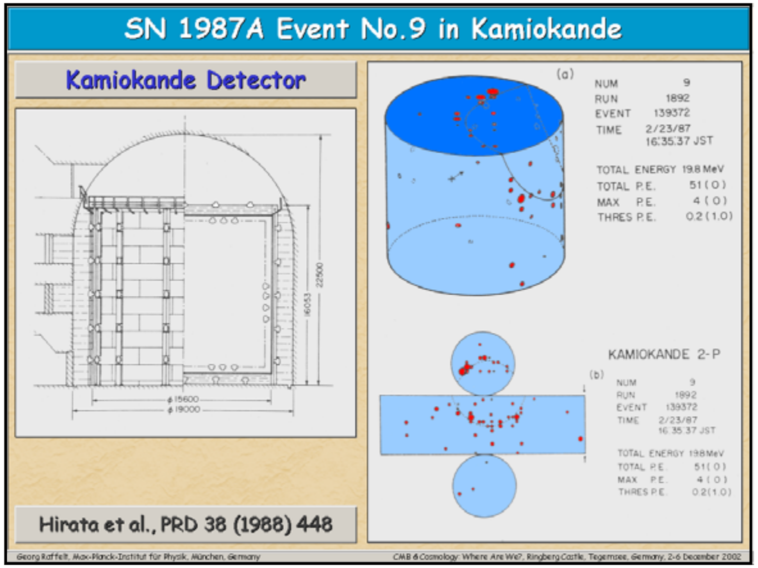
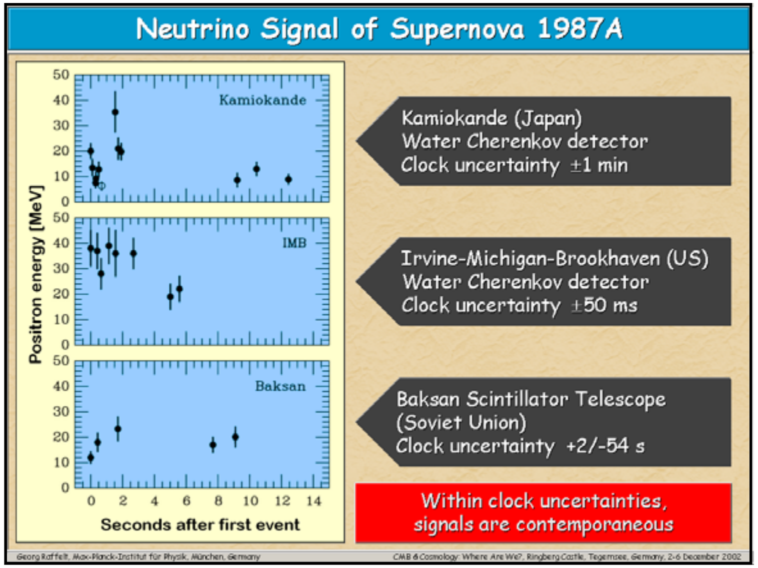
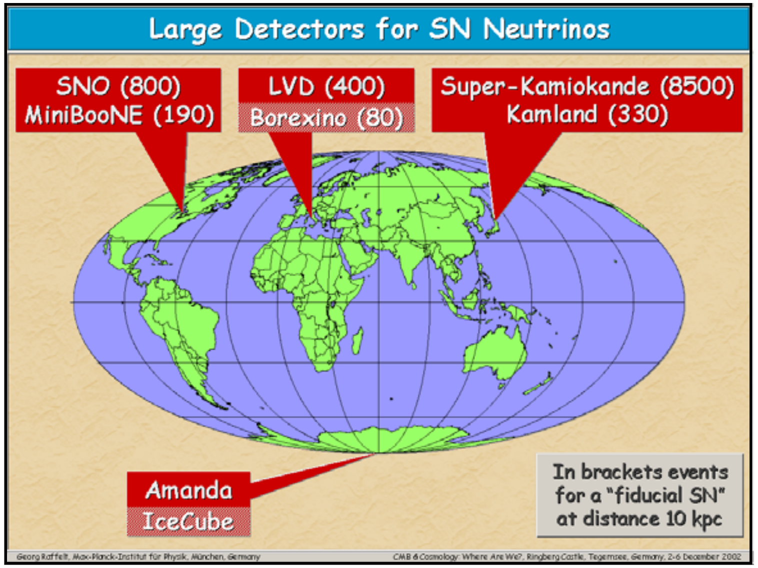
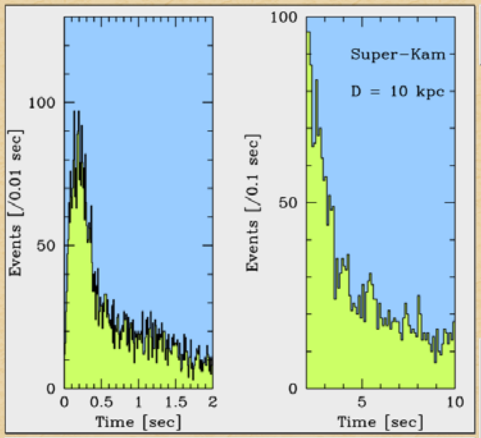

2002 Physics Nobel Prize for Neutrino Astronomy
Ray Davis Jr.
(*1914)
Masatoshi Koshiba
(*1926)
"for pioneering contributions to astrophysics, in particular for the detection of cosmic neutrinos"
Georg Raffelt, Max-Planck-Institut für Physik, München, Germany
CMB & Cosmology: Where Are We?, Ringberg Castle, Tegernsee, Germany, 2-6 December 2002


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
KAMIOKANDE 2-P
Georg Raffelt, Max-Planck-Institut für Physik, München, Germany
CMB & Cosmology: Where Are We?, Ringberg Castle, Tegernsee, Germany, 2-6 December 2002


Neutrino Signal of Supernova 1987A
Kamiokande
IMB
Baksan
Positron energy [MeV]
Seconds after first event
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
Georg Raffelt, Max-Planck-Institut für Physik, München, Germany
CMB & Cosmology: Where Are We?, Ringberg Castle, Tegernsee, Germany, 2-6 December 2002


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
Georg Raffelt, Max-Planck-Institut für Physik, München, Germany
CMB & Cosmology: Where Are We?, Ringberg Castle, Tegernsee, Germany, 2-6 December 2002

Simulated Supernova Signal in Super-Kamiokande

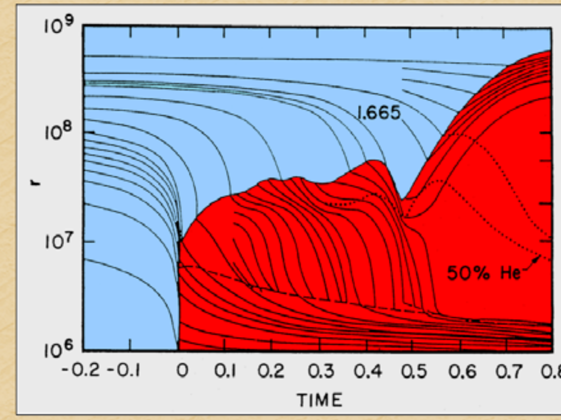


Totani, Sato, Dalhed & Wilson, ApJ 496 (1998) 216

Total of about 8300 events for t < 18 s

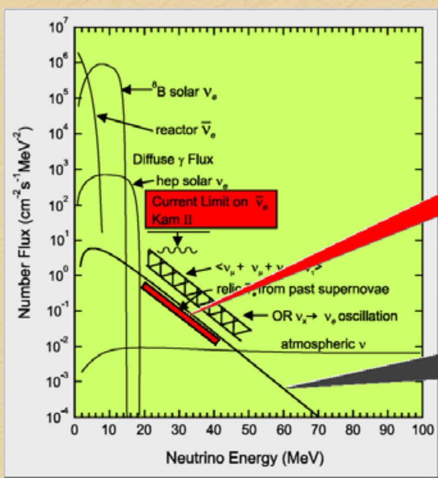
Monte-Carlo simulation for Super-Kamiokande signal of SN at 10 kpc, based on a numerical Livermore model

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



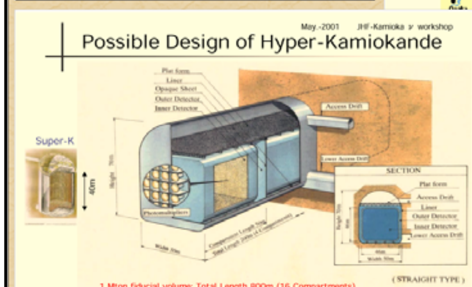
Super-K upper limit 29 cm^{-2} s^{-1} for Kaplinghat et al. spectrum [hep-ex/0209028]

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

Cline, astro-ph/0103138

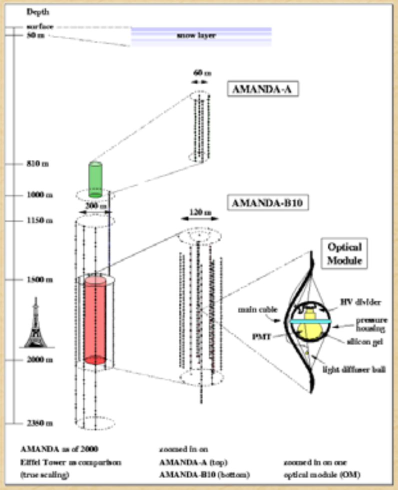
The Future: A Megatonne Detector?

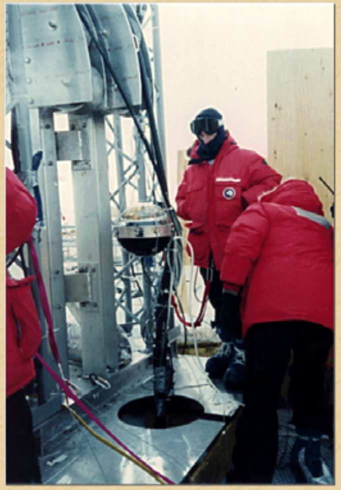
Megatonne detector motivated by
- Long baseline neutrino oscillations
- Proton decay
- Atmospheric neutrinos
- Solar neutrinos
- Supernova neutrinos
  (~10^5 events for SN at 10 kpc)



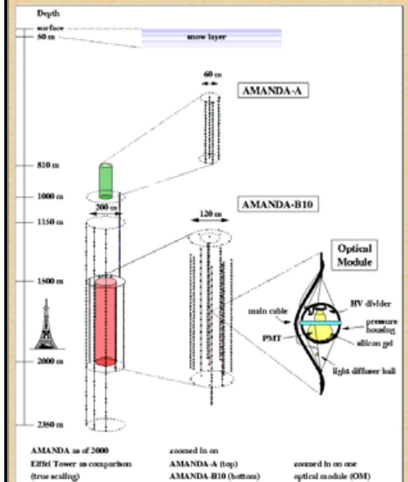
Similar discussions in
- USA (UNO project)
- Europe (Frejus Tunnel)

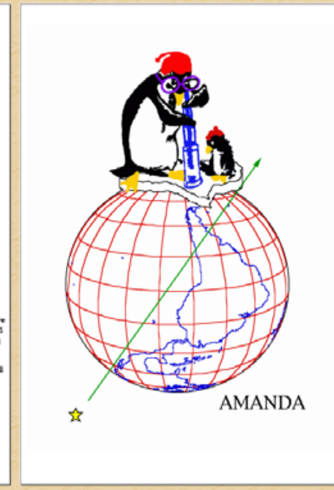
AMANDA - South Pole Neutrino Telescope





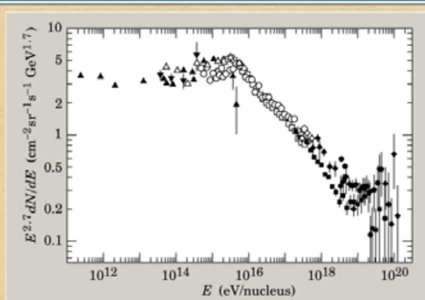
AMANDA - South Pole Neutrino Telescope





Georg Raffelt, Max-Planck-Institut für Physik, München, Germany
CMB & Cosmology: Where Are We?, Ringberg Castle, Tegernsee, Germany, 2-6 December 2002

Gamma-, Neutrino- and Proton-Astronomy



Cosmic-ray spectrum × $E^{2.7}$

What are the sources ?

TeV γ astronomy

Photon mean free path < few 10 Mpc

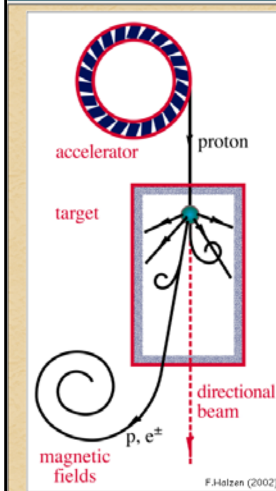
Proton magnetic field deflection

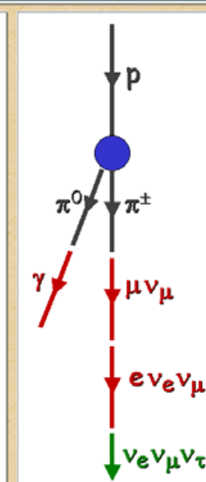
GZK cutoff

Opportunity for neutrino astronomy

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

Neutrino Beams: Heaven and Earth



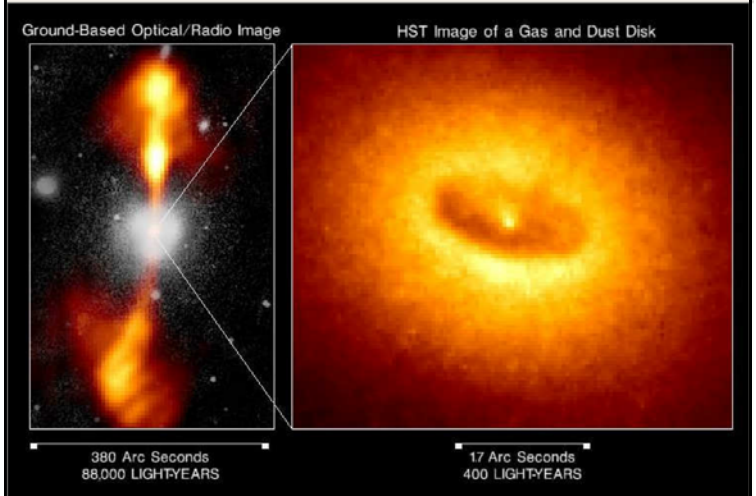


Target: Protons or Photons

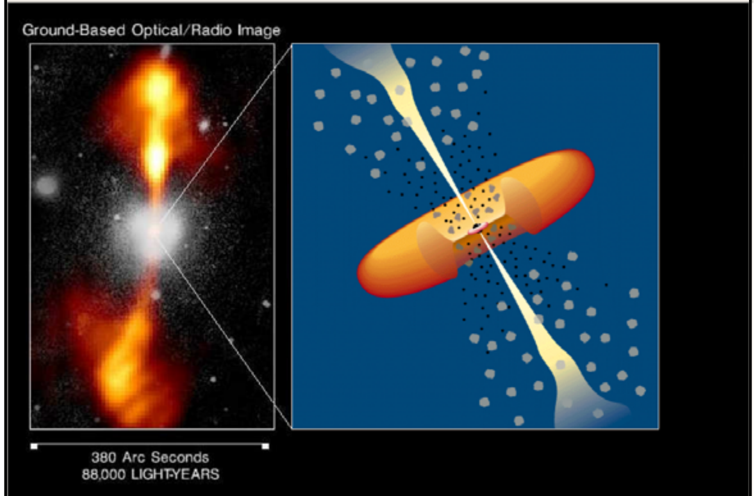
Approx. equal fluxes of photons & neutrinos

Equal neutrino fluxes in all flavors due to oscillations

Core of the Galaxy NGC 4261

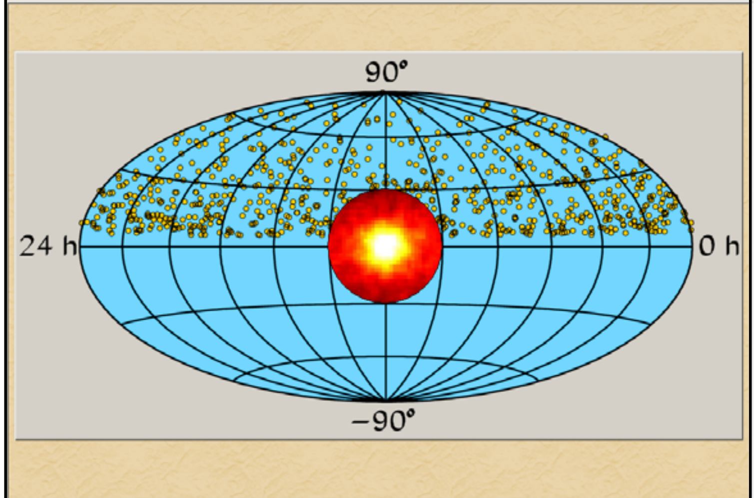


Core of the Galaxy NGC 4261



Georg Raffelt, Max-Planck-Institut für Physik, München, Germany
CMB & Cosmology: Where Are We?, Ringberg Castle, Tegernsee, Germany, 2-6 December 2002

Neutrino Sky in Amanda and Super-Kamiokande



Georg Raffelt, Max-Planck-Institut für Physik, München, Germany
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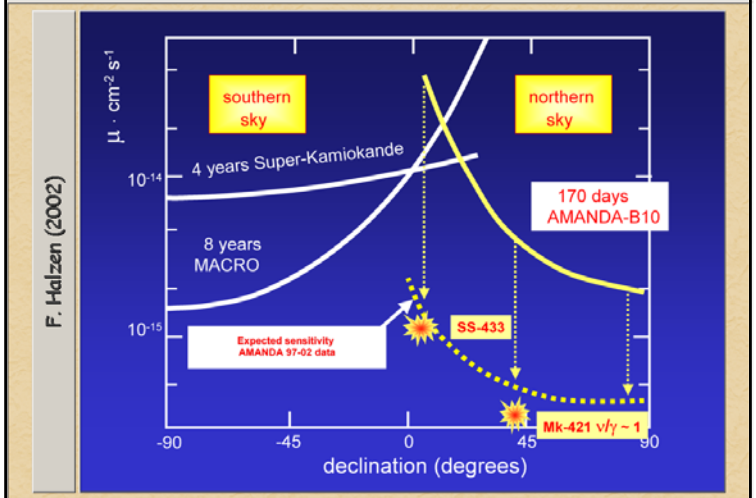
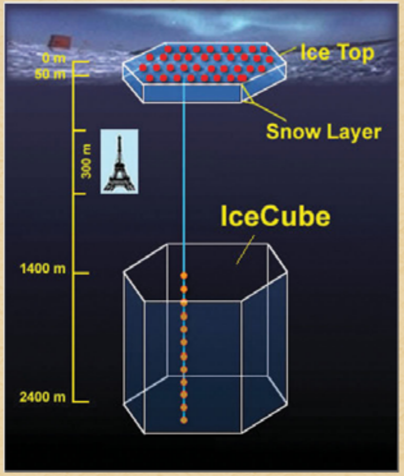
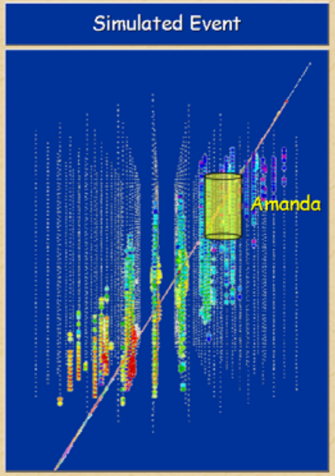
Amanda Point Search Results



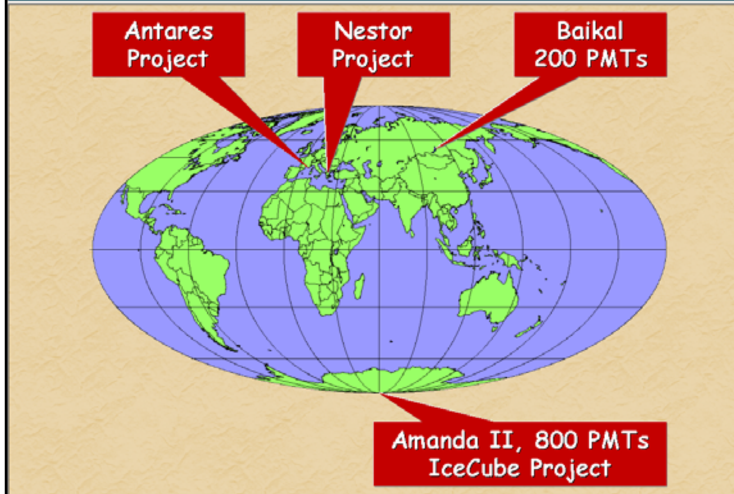
Georg Raffelt, Max-Planck-Institut für Physik, München, Germany
CMB & Cosmology: Where Are We?, Ringberg Castle, Tegernsee, Germany, 2-6 December 2002

IceCube - Future km^3 South-Pole Detector

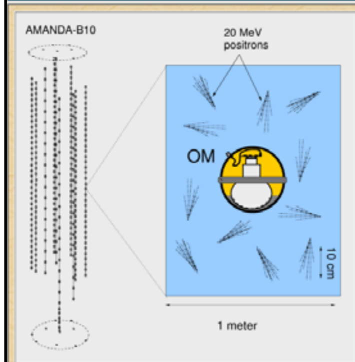




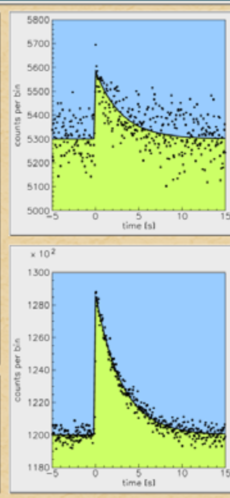
High-Energy Neutrino Telescopes



Amanda/IceCube as a Supernova Detector



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

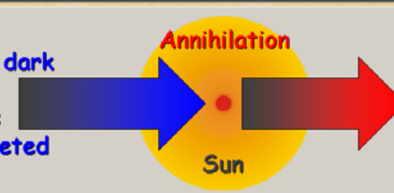
Direct Method (Laboratory Experiments)

Galactic dark matter particle (e.g. neutralino)

Recoil energy (few keV) is measured by
- Ionisation
- Scintillation
- Cryogenic

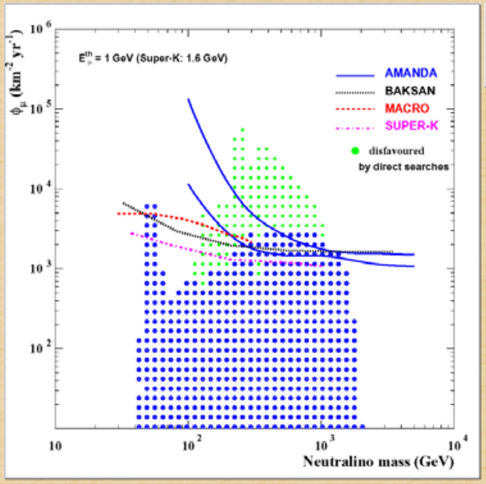
Indirect Method (Neutrino Telescopes)

Galactic dark matter particles are accreted



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

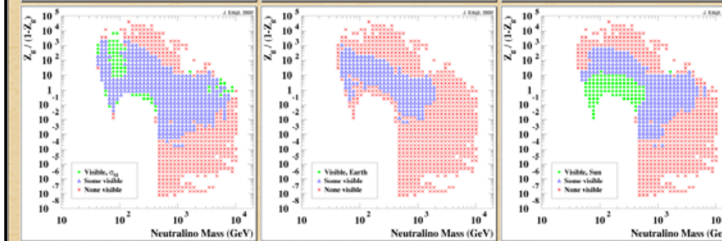
Current Limits from WIMP Searches



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

Future WIMP Sensitivities

Direct Detection	Indirect, km^3 Detector	
Genius/CRESST	Earth	Sun



Where do we stand? Where are we going?

Neutrino oscillations established

Mixing parameters at 3σ

	Sun	Atmosphere
$\Delta m^2 / \mathrm{meV}^2$	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 nus? CPT violation? ...)

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)

Absolute mass & Dirac vs Majorana

- Precision cosmology
  $\Sigma m_\nu < 2.2$ eV, 50 meV reachable?
- Tritium endpoint
  $m_\nu < 2.2$ eV, KATRIN goal 0.3 eV
- Future 0ν2β decay: Majorana mass (difficult for normal hierarchical)
- Leptogenesis of baryon asymmetry
  Majorana $m_\nu < 0.2$ 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 & experiments
- Future galactic supernova
- Diffuse flux from cosmic supernovae