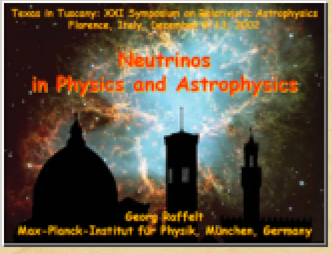
Texas in Tuscany: XXI Symposium on Relativistic Astrophysics
Florence, Italy, December 9-13, 2002

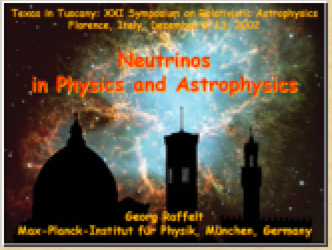
Neutrinos in Physics and Astrophysics

Georg Raffelt
Max-Planck-Institut für Physik, München, Germany

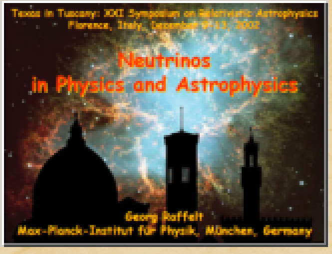
Neutrinos in Physics and Astrophysics



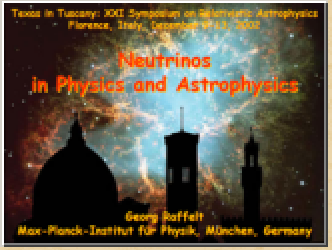
Flavor oscillations and all that



Quest for the absolute mass scale



Neutrino mass and the
baryon asymmetry of the universe

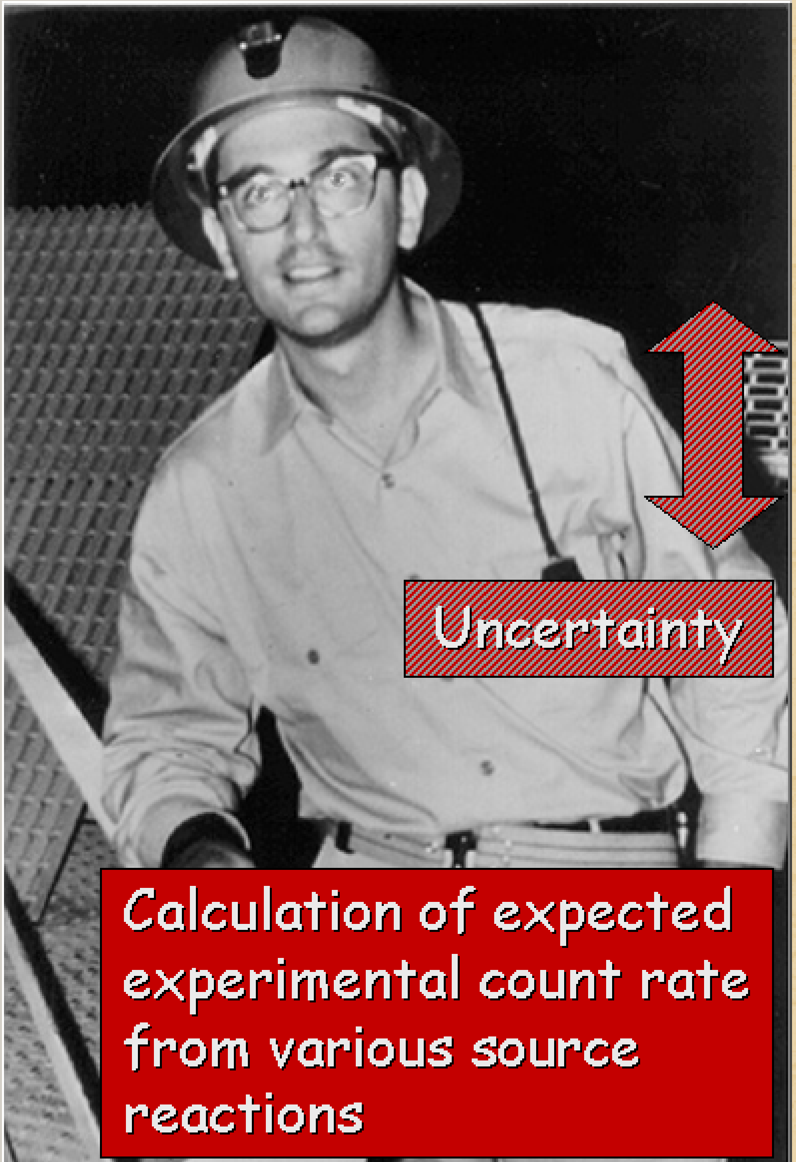


Neutrinos as astrophysical messengers

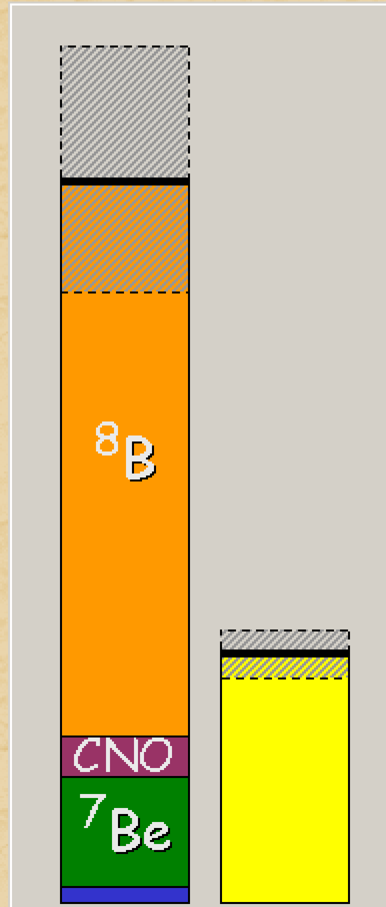
Missing Neutrinos from the Sun

Homestake

Chlorine



John Bahcall



Raymond Davis Jr.

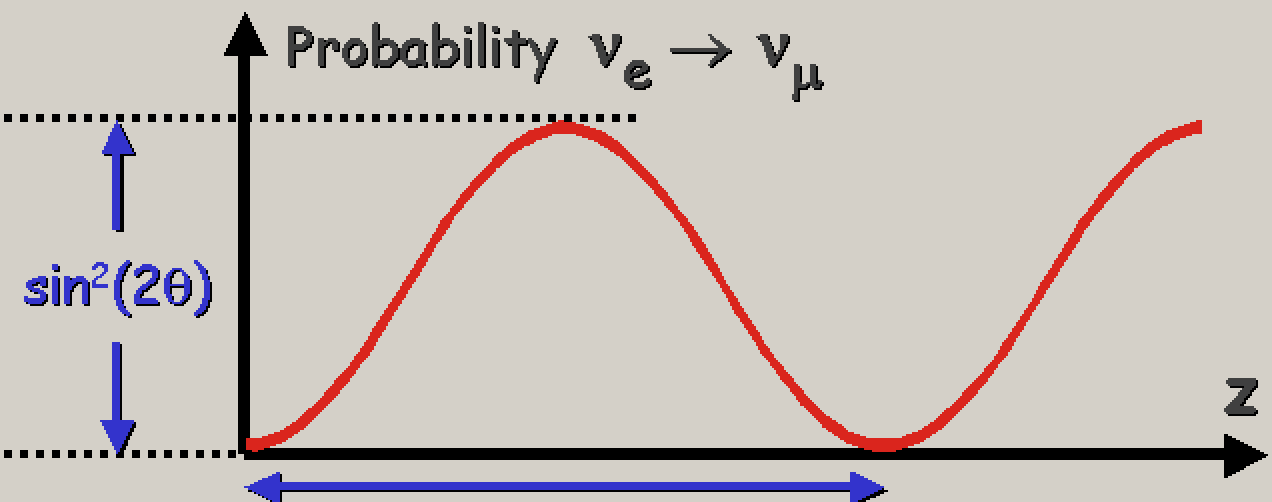
Neutrino Flavor Oscillations

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

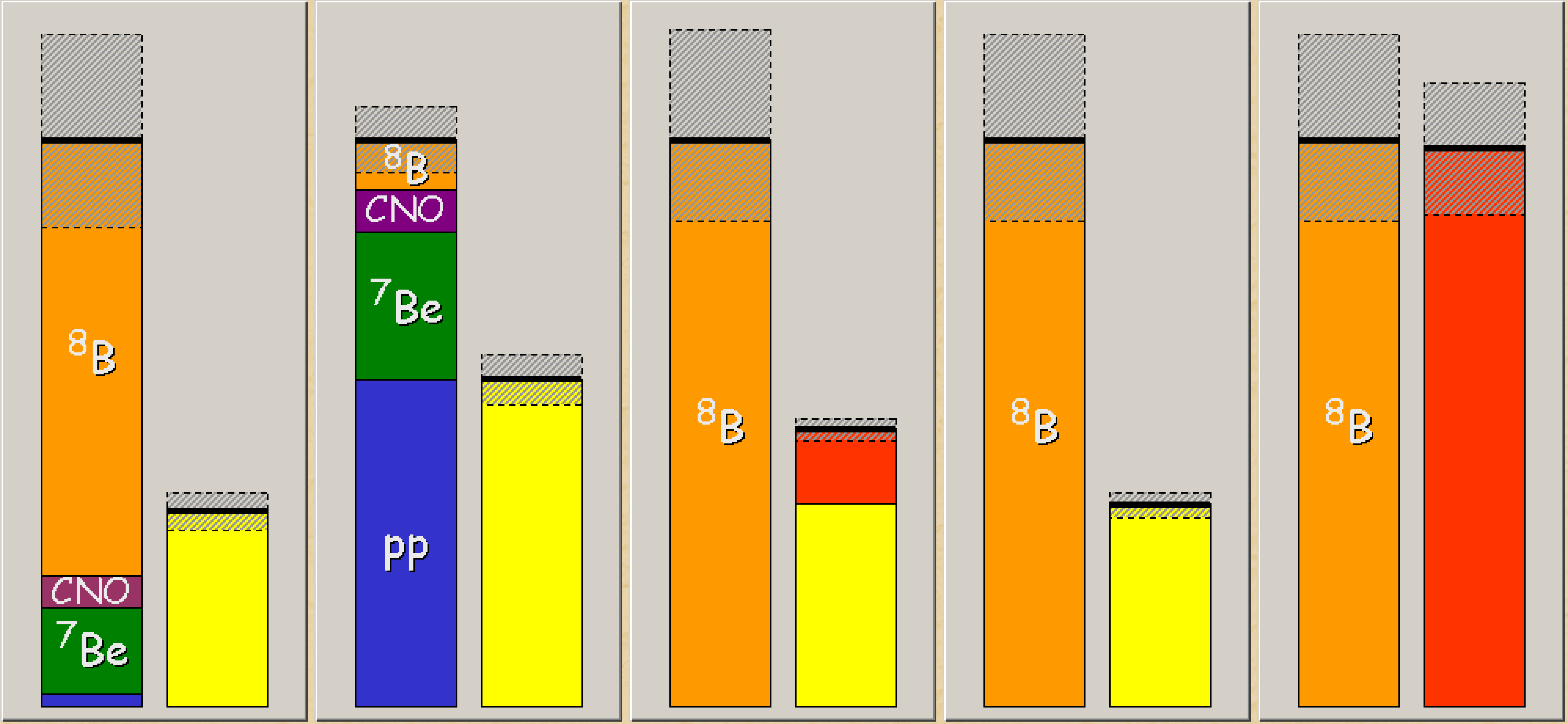


Oscillation Length $\frac{4\pi E}{\Delta m^2} = 2.5\,\mathrm{m} \left(\frac{E}{\mathrm{MeV}}\right) \left(\frac{\mathrm{eV}^2}{\Delta m^2}\right)$

Bruno Pontecorvo
(1913 - 1993)
Invented nu oscillations

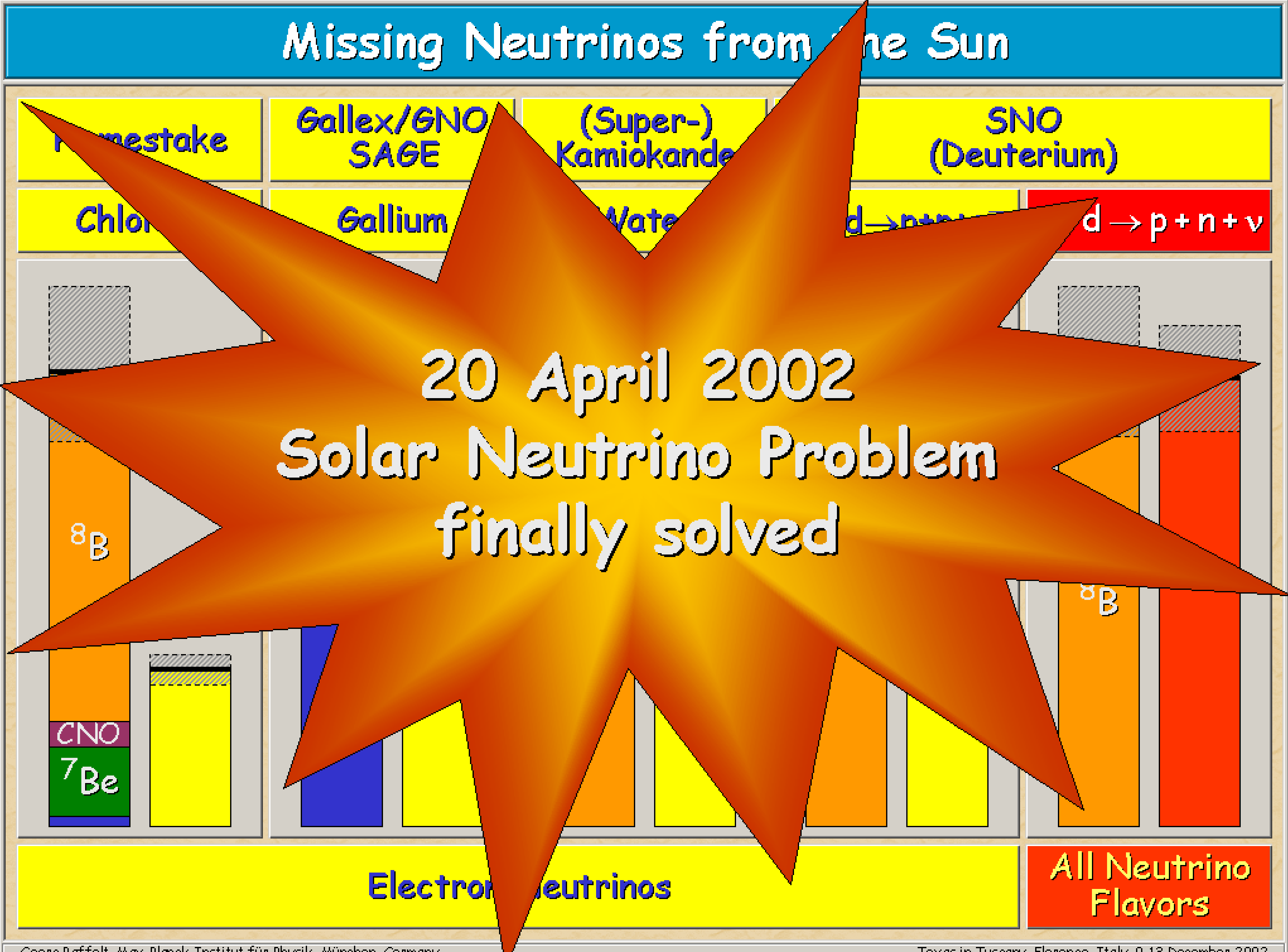
Missing Neutrinos from the Sun

Homestake	Gallex/GNO SAGE	(Super-) Kamiokande	SNO (Deuterium)	
Chlorine	Gallium	Water	$\nu_e + d \to p + p + e^-$	$\nu + d \to p + n + \nu$



Electron-Neutrinos	All Neutrino Flavors

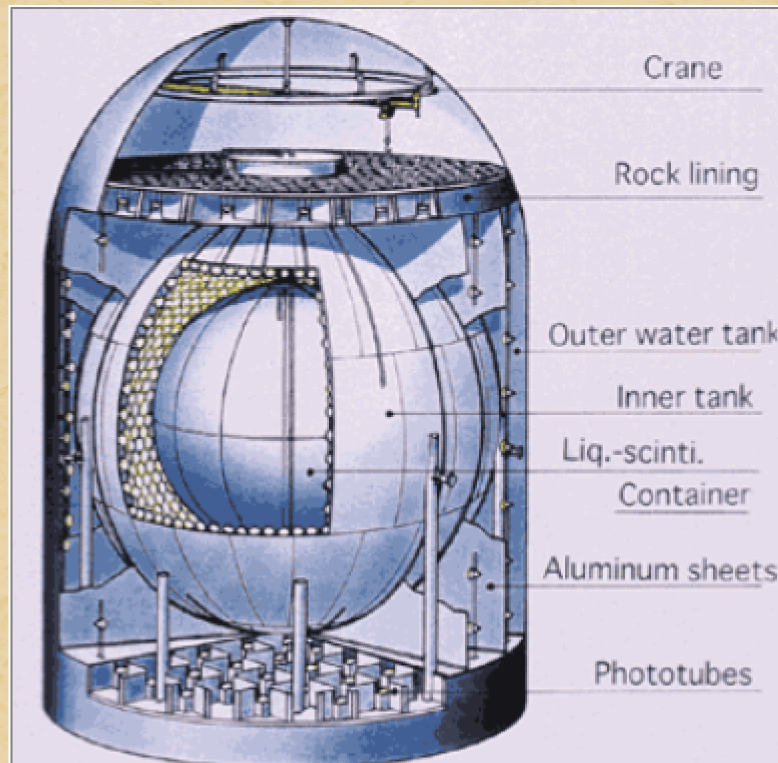
Missing Neutrinos from the Sun



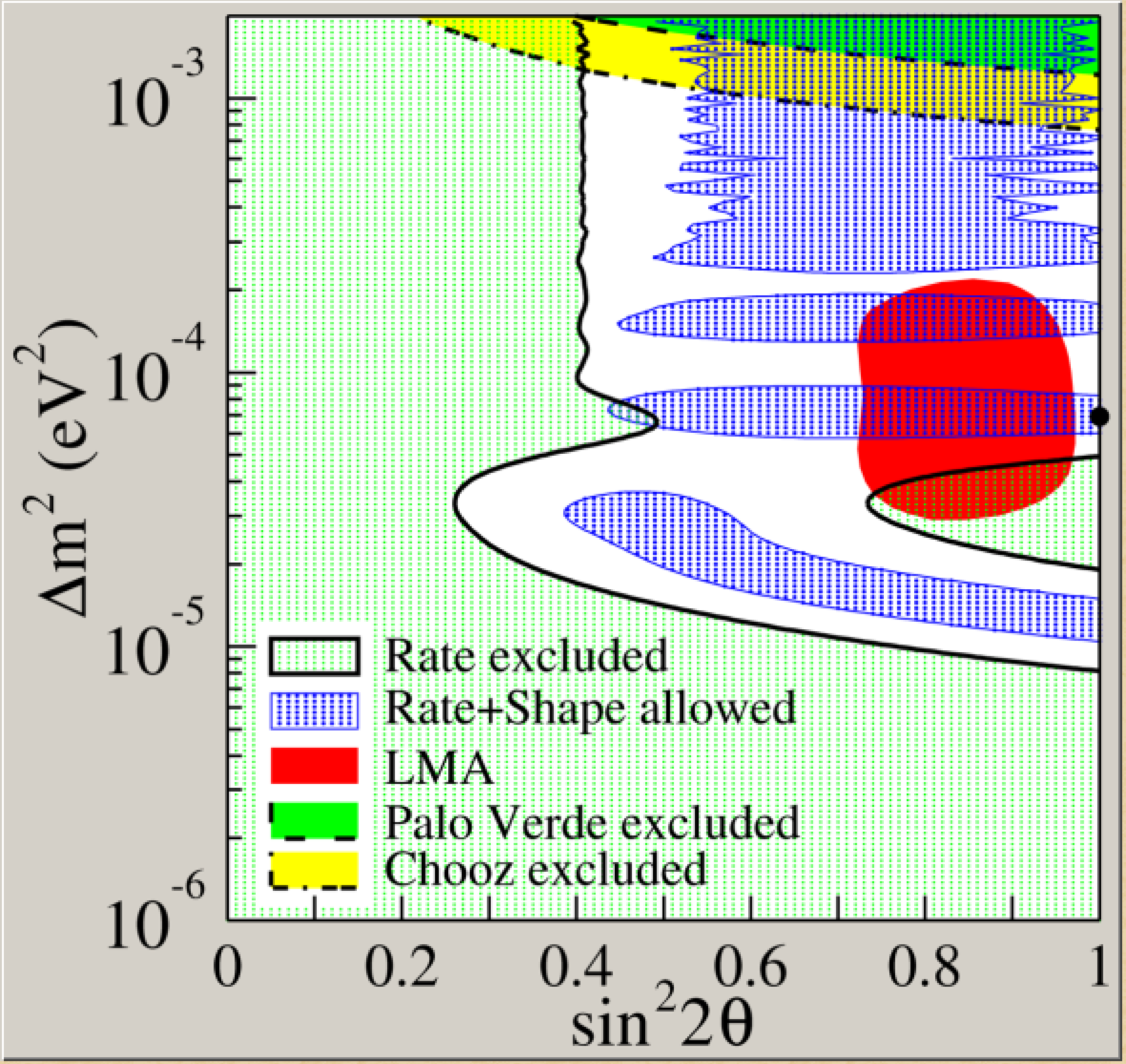
Kamland Reactor Neutrino Experiment (Japan)

Japanese nuclear reactors 60 GW (20% world capacity)

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

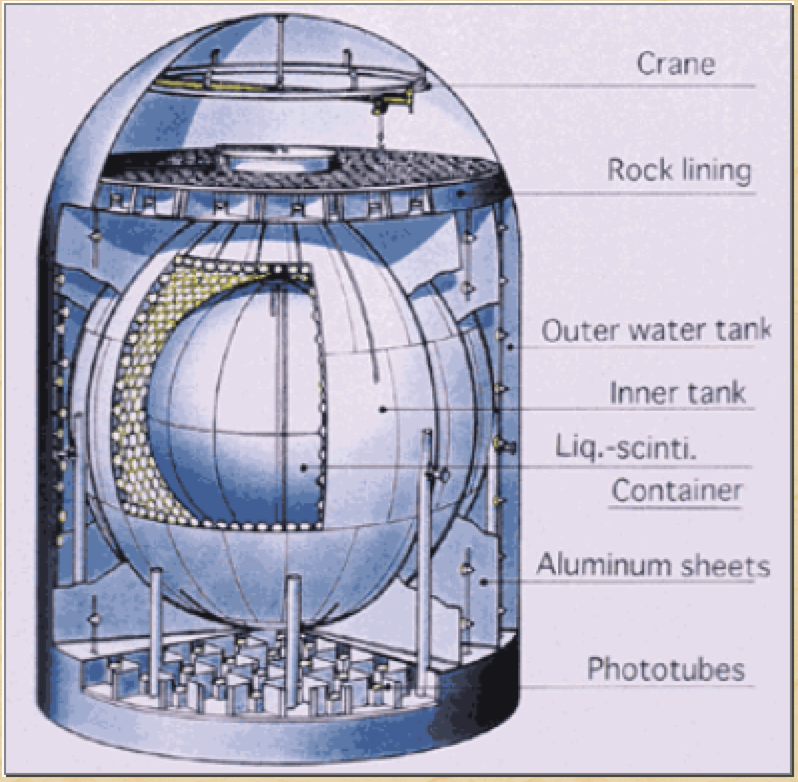


Kamland Reactor Neutrino Experiment (Japan)



Japanese nuclear reactors
60 GW (20% world capacity)

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



First Kamland results earlier at this conference and hep-ex/0212021

Status of Evidence for Neutrino Oscillations

System	Atmospheric	Solar	LSND
Channel	$\nu_\mu \to \nu_\tau$	$\nu_e \to \nu_{\mu\tau}$	$\bar{\nu}_\mu \to \bar{\nu}_e$
$\delta m^2 / \mathrm{eV}^2$	$(1.5-4)\times 10^{-3}$	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	KamLAND 12/2002	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 Neutri... Oscillations

Syst...	Atmospheri...	S...	LSND
Channel	$\to \nu$...		...$\mu \to \bar{\nu}_e$
$\delta m^2 / eV^2$			...2-2 or 6.5
Status			...onfirmed
Test			...004 ?
I...	Evider...		...neutrino ...T violation ...) ?
Simplest interpre- tation	Thre... eig... wit... m_1 <... $m_2 \ll m_3 \sim$ ... (hier...) $m_1 \sim m_2 \sim m_3 \gg$ ... V (degene...)		...rimental or ...tistical ...luke

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 hep-ph/0211054
$32^\circ < \theta_{23} < 60^\circ$	$\theta_{13} < 14^\circ$	$27^\circ < \theta_{12} < 41^\circ$	

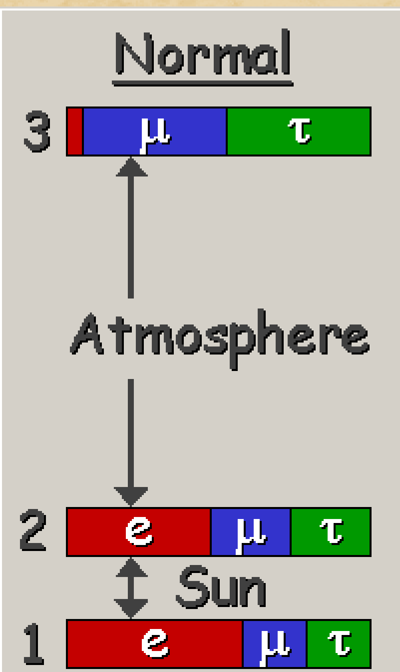
$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}1 & & \\ & c_{23} & s_{23}\\ & -s_{23} & c_{23}\end{pmatrix}\begin{pmatrix}c_{13} & & e^{-i\delta}s_{13}\\ & 1 & \\ -e^{i\delta}s_{13} & & c_{13}\end{pmatrix}\begin{pmatrix}c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1\end{pmatrix}\begin{pmatrix}\nu_1\\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

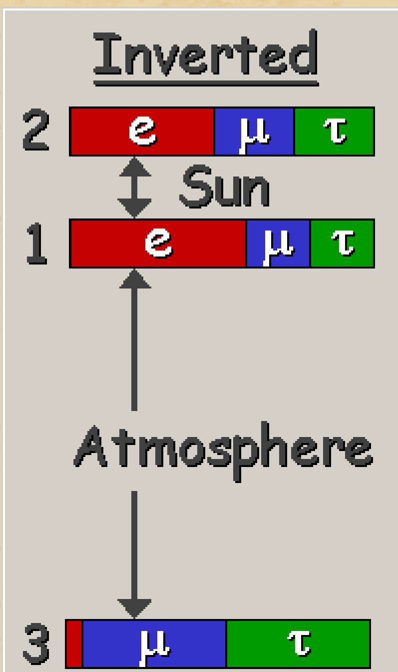
$c_{12} = \cos\theta_{12}$ etc., δ CP-violating phase

Solar 24 - 240

Atmospheric 1400 - 6000

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

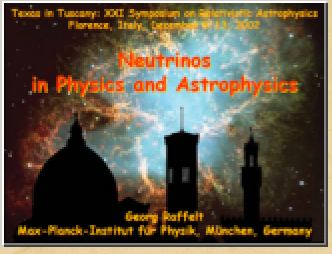




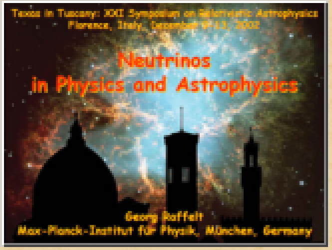
Tasks and Open Questions

- 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?

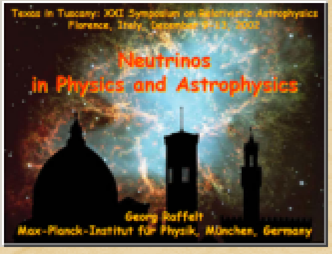
Neutrinos in Physics and Astrophysics



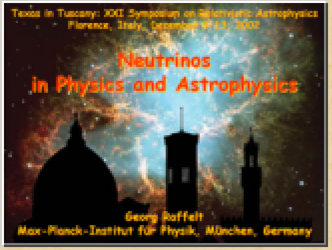
Flavor oscillations and all that



Quest for the absolute mass scale

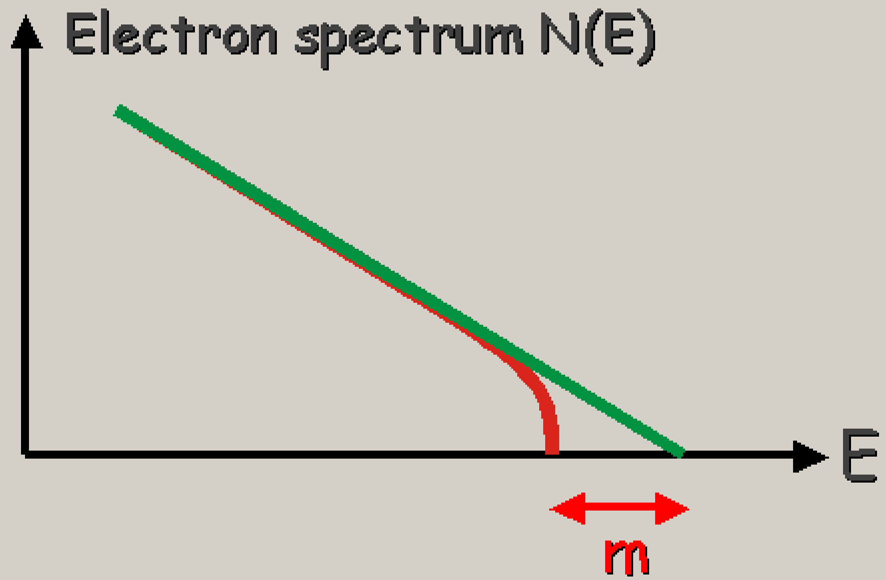


Neutrino mass and the
baryon asymmetry of the universe



Neutrinos as astrophysical messengers

Tritium Endpoint Spectrum



Tritium Beta Decay

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

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)

These 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

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

$m_\nu < 40$ 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

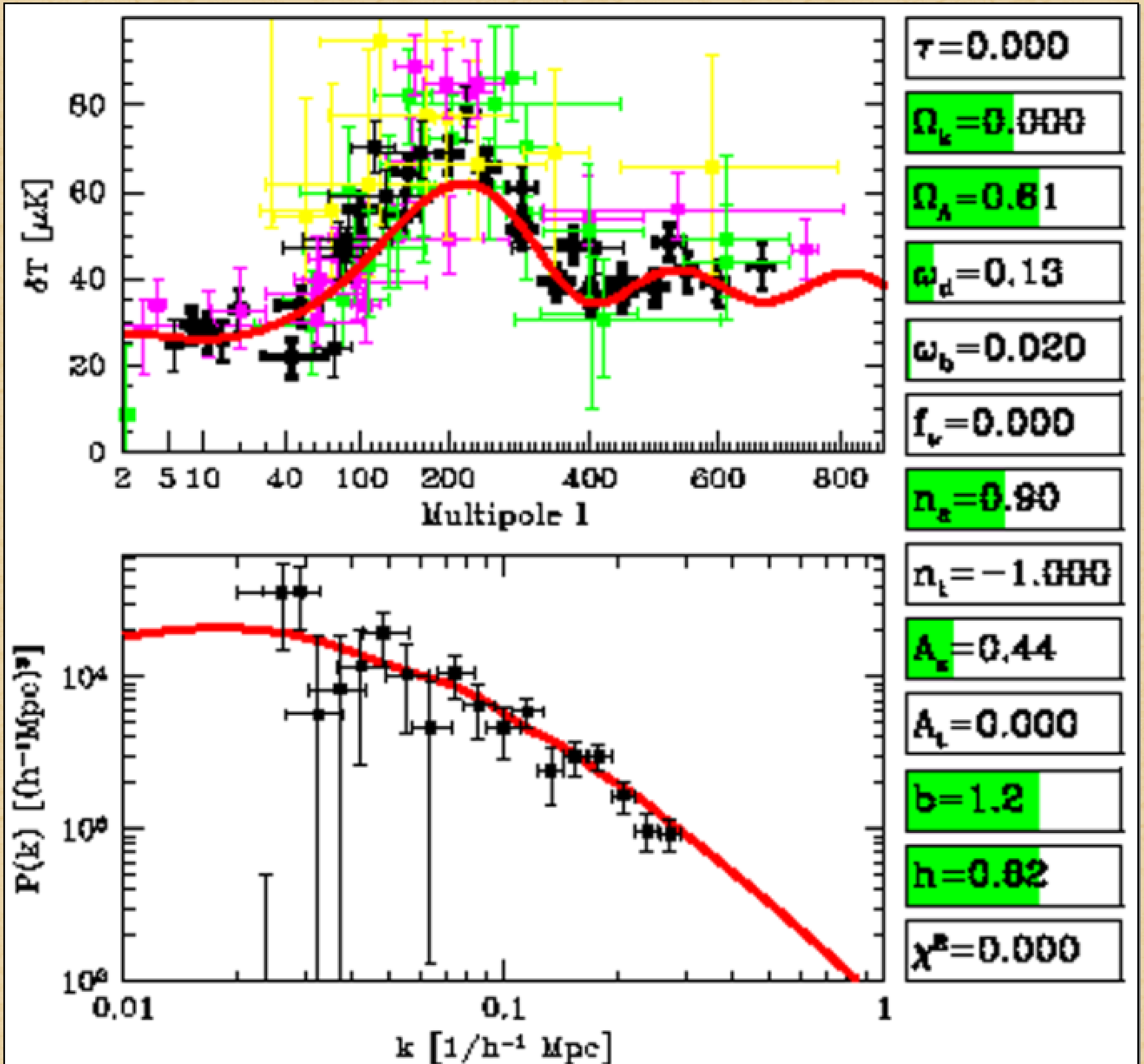
Low-accuracy experimental estimates of the rest mass of the neutrino [1] yield $m(\nu_e) < 200$ eV/c^2 for the electronic neutrino and $m(\nu_\mu) < 2.5 \times 10^6$ eV/c^2 for the muonic neutrino.

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 $= (13 \times 10^9 \text{ years})^{-1}$. It follows therefore that the density of all types of matter in the Universe is at the present time [1)]

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

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

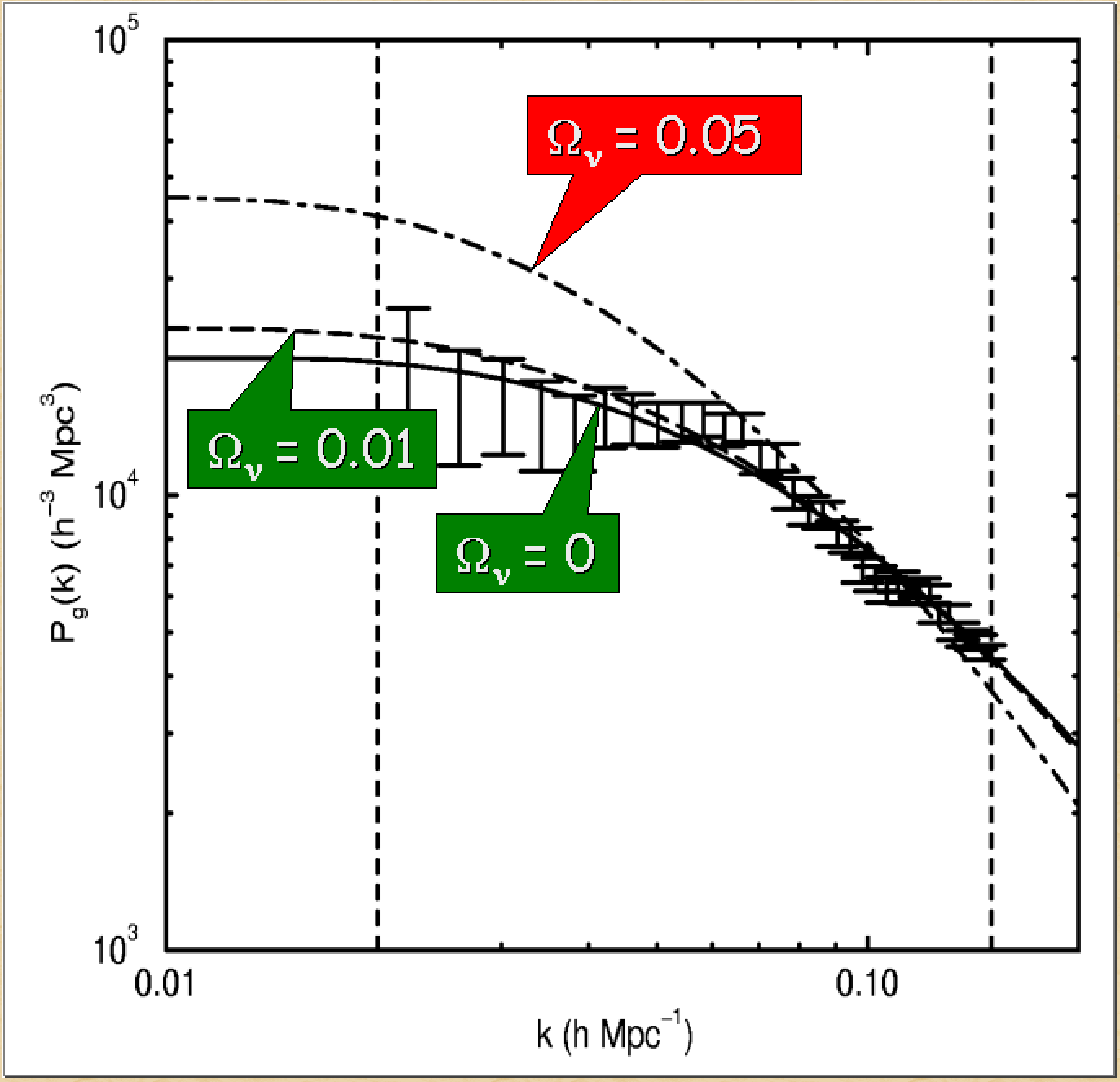
Fitting the Cosmological Model - Neutrinos



- 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 Redshift Survey



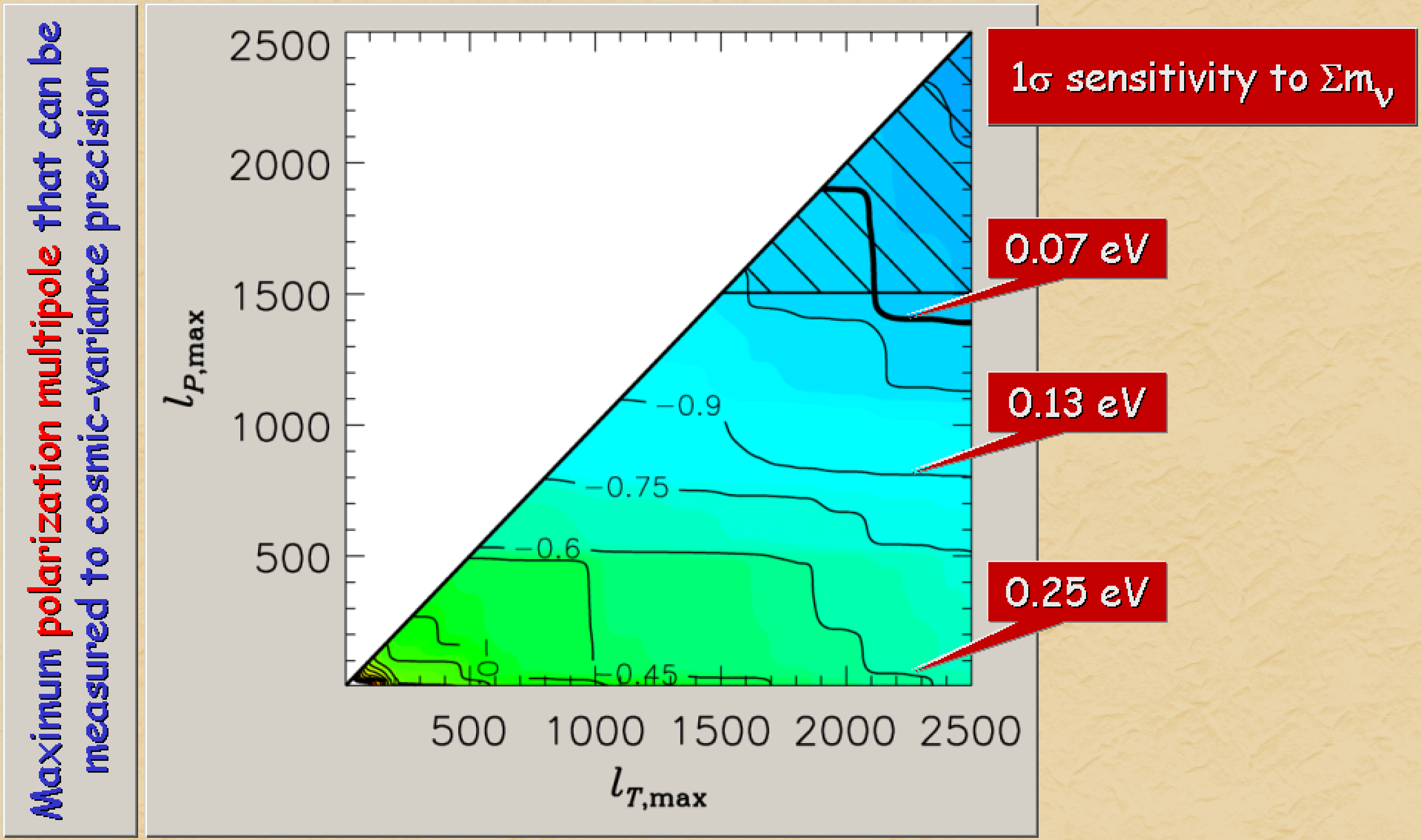
Elgaroy et al., astro-ph/0204152

$\Sigma m_\nu < 2.2$ 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

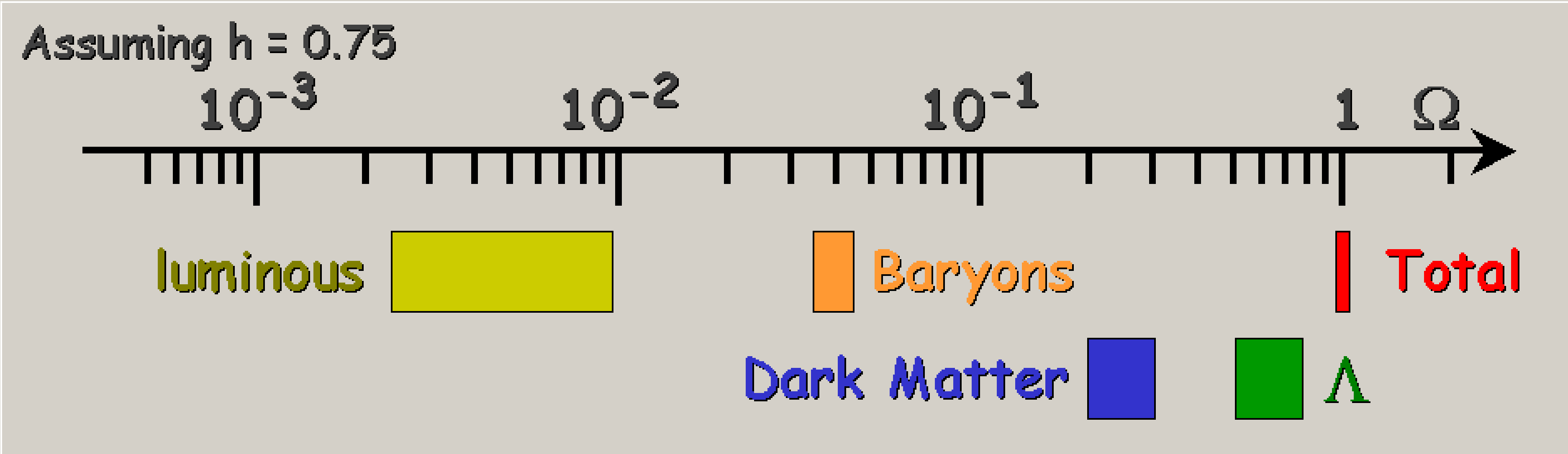
PLANCK Sensitivity to Neutrino Mass

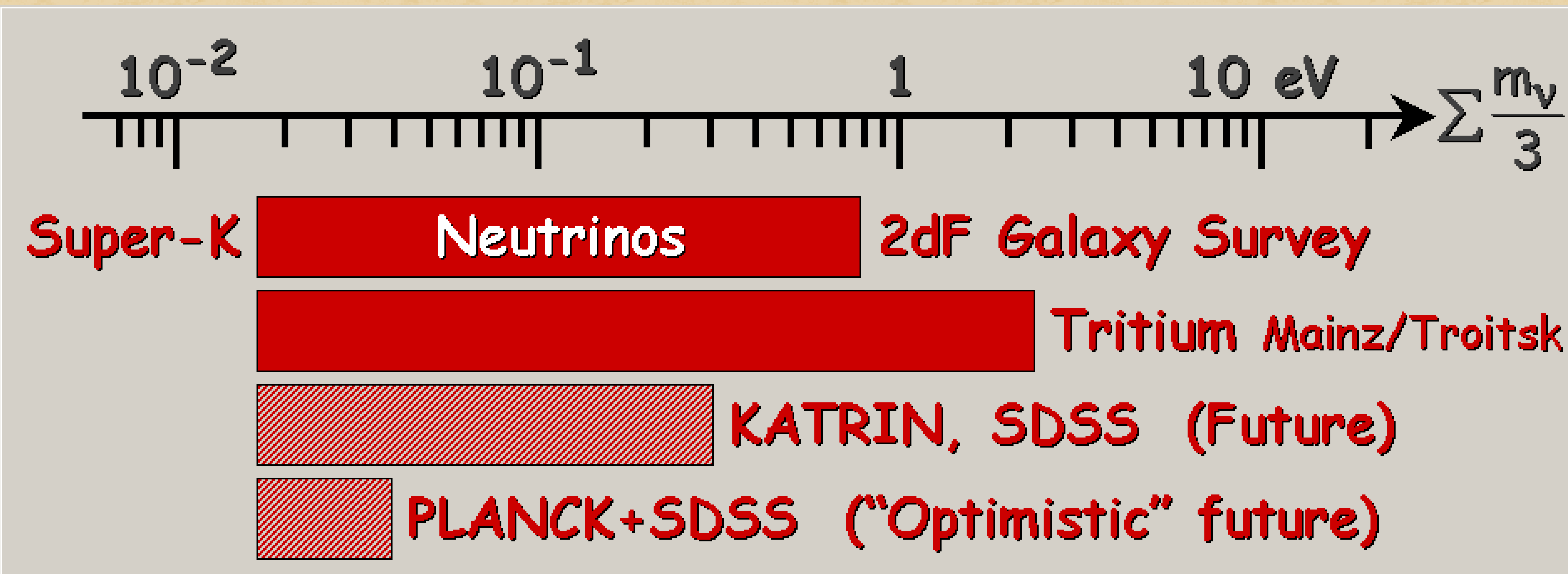


Maximum temperature multipole that can be measured to cosmic-variance precision

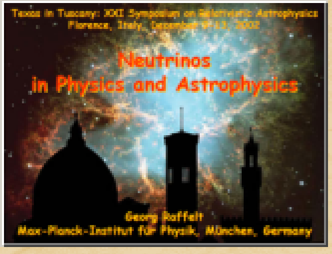
Steen Hannestad
astro-ph/0211106

Mass-Energy-Inventory of the Universe

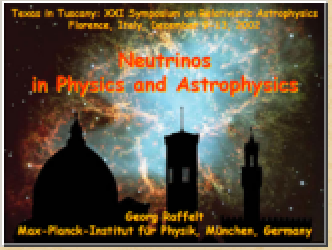




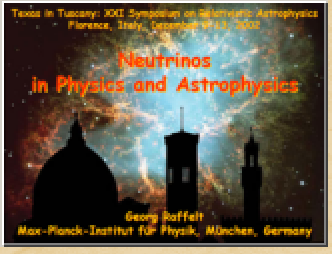
Neutrinos in Physics and Astrophysics



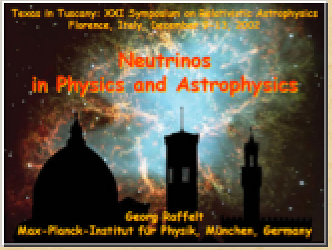
Flavor oscillations and all that



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

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

e_L	e_R
μ_L	μ_R
τ_L	τ_R

Neutrinos

ν_1	N_1
ν_2	N_2
ν_3	N_3

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

Lagrangian for particle masses

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

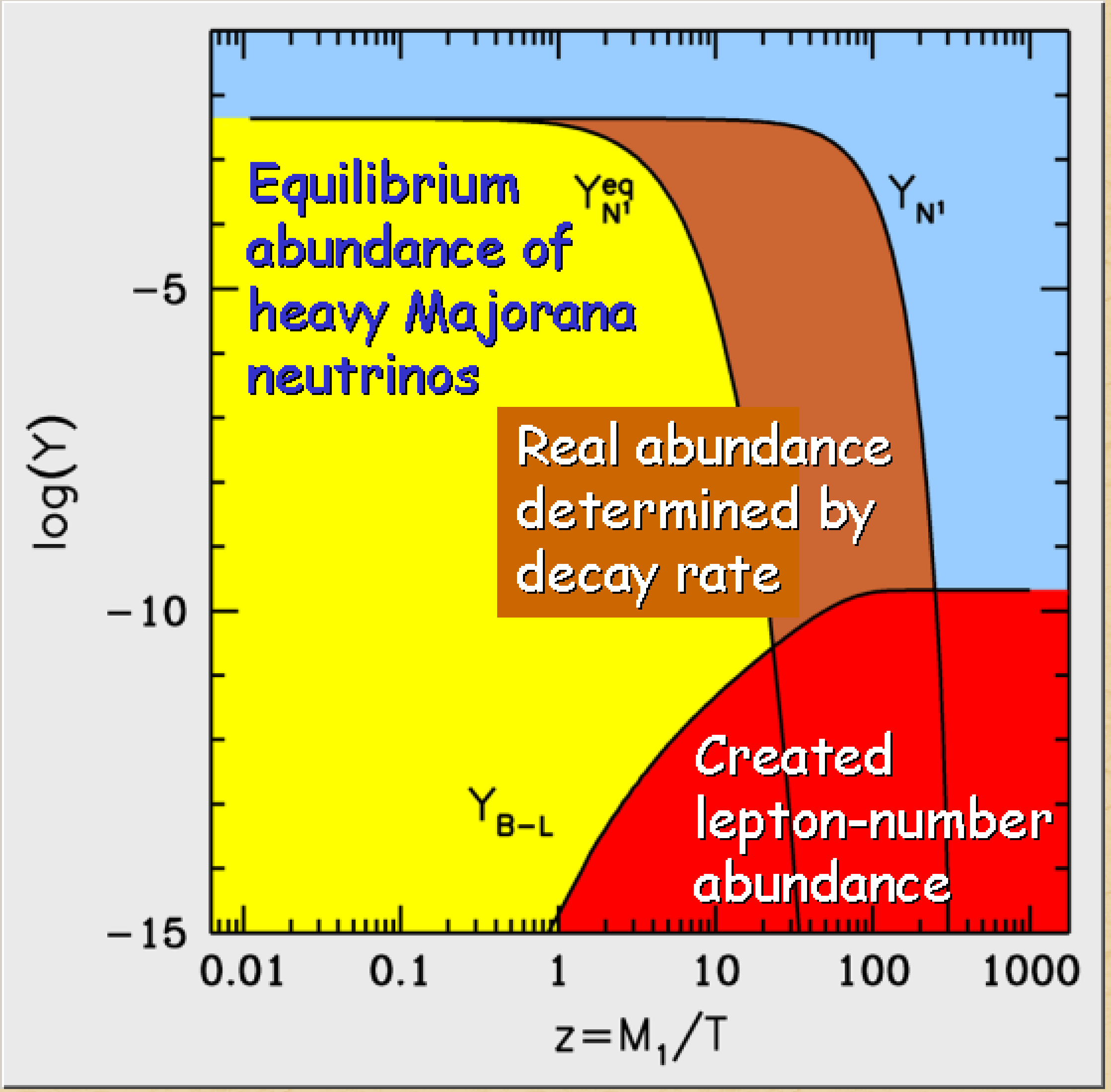
$$\begin{pmatrix} \bar{\nu}_L & \bar{N}_R \end{pmatrix} \begin{pmatrix} 0 & g_\nu \langle\phi\rangle \\ g_\nu \langle\phi\rangle & M \end{pmatrix} \begin{pmatrix} \nu_L \\ N_R \end{pmatrix}$$

Diagonalize $\Rightarrow$

Light Majorana mass

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

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

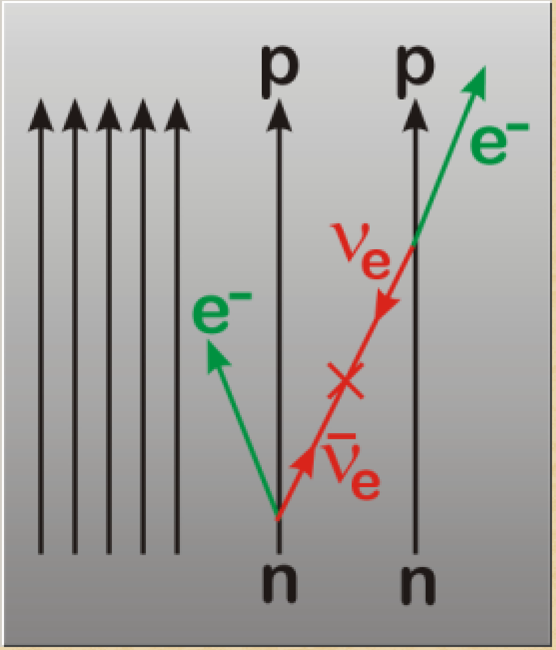
Sufficient deviation from equilibrium distribution of heavy Majorana neutrinos at freeze-out → Limits on Yukawa couplings → Limits on masses of ordinary neutrinos

Requires Majorana neutrino masses below 0.2 eV

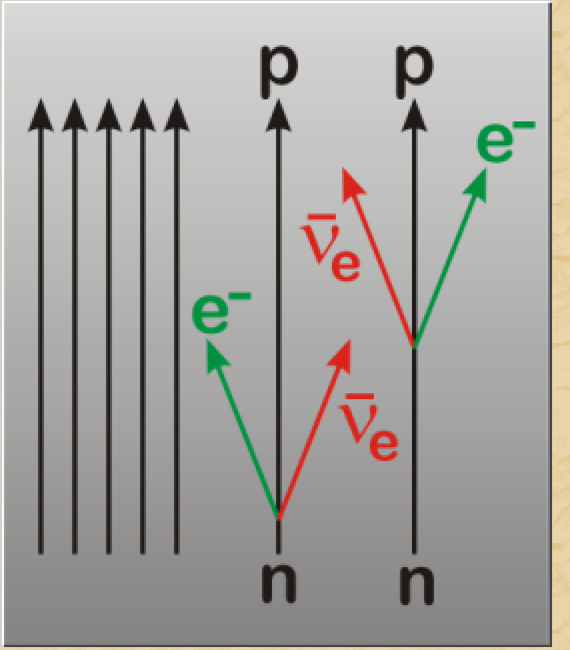
Buchmüller, Di Bari & Plümacher, PLB 547 (2002) 128 [hep-ph/0209301]

Neutrinoless ββ Decay

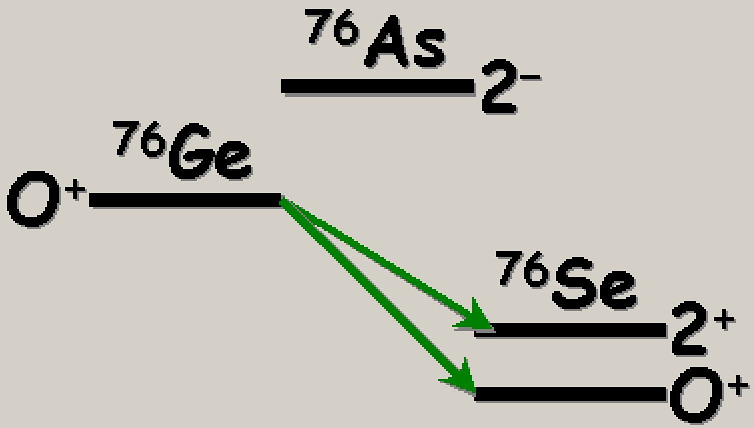
0ν mode, enabled by Majorana mass



Standard 2ν mode



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



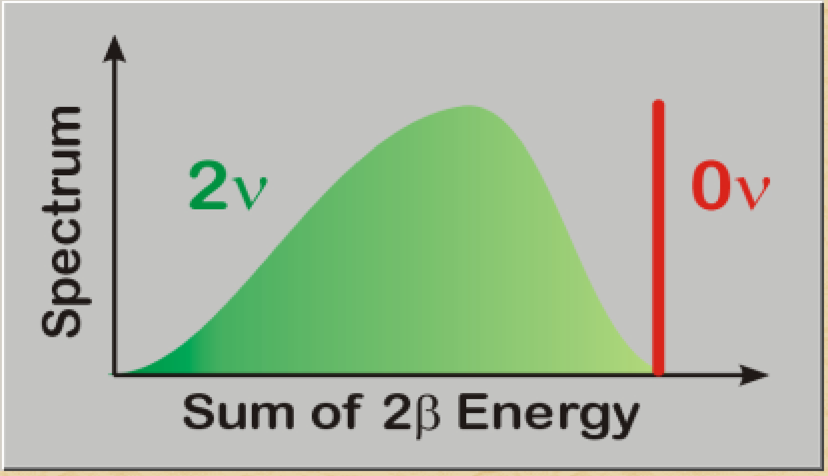
Half life ~ 10^{21} yr

Measured quantity

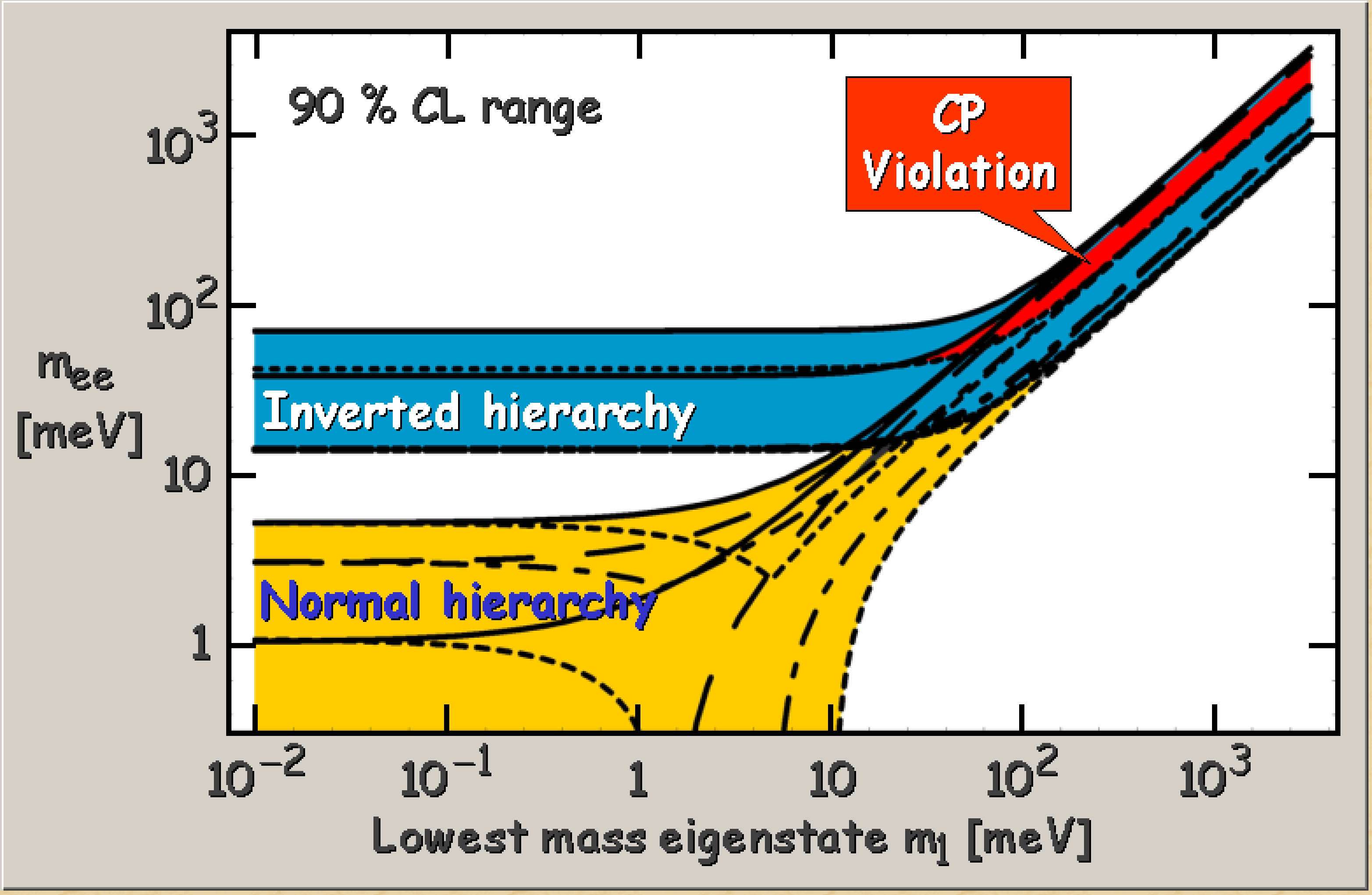
$$|m_{ee}| = \left|\sum_{i=1}^{N} \lambda_i \, |U_{ei}|^2 \, m_i\right|$$

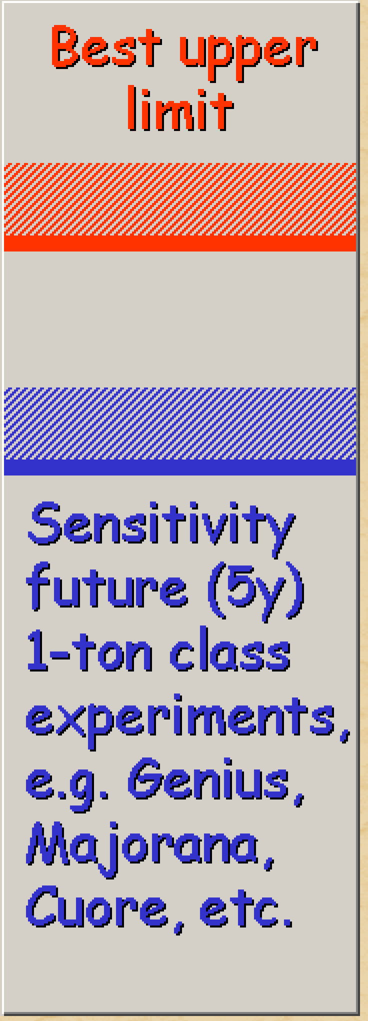
Best limit from ^{76}Ge

$$|m_{ee}| < 0.35\,\mathrm{eV}$$



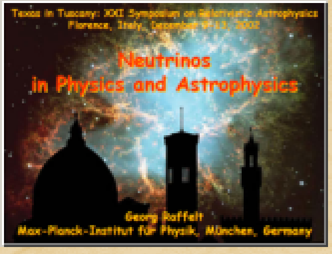
Effective Majorana Mass in Plausible Scenarios



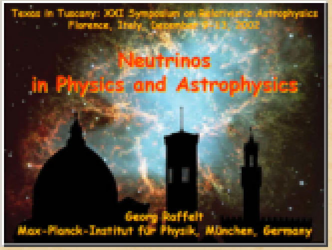


Pascoli & Petcov, hep-ph/0205022
See also Feruglio, Strumia & Vissani, hep-ph/0201291
Klapdor-Kleingrothaus, Päs & Smirnov, hep-ph/0103076, and others

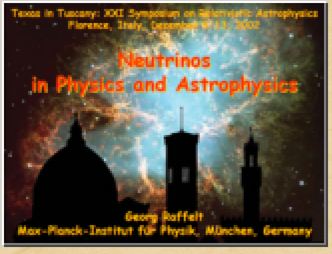
Neutrinos in Physics and Astrophysics



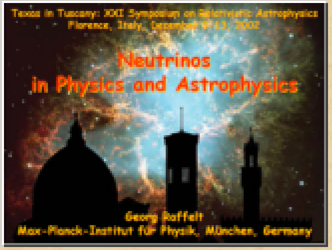
Flavor oscillations and all that



Quest for the absolute mass scale

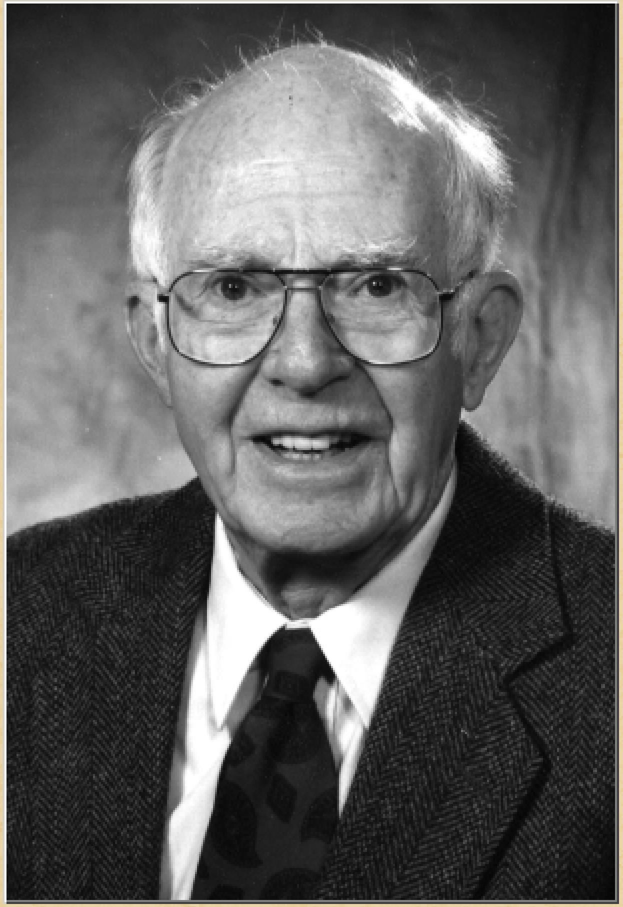


Neutrino mass and the
baryon asymmetry of the universe



Neutrinos as astrophysical messengers

2002 Physics Nobel Prize for Neutrino Astronomy

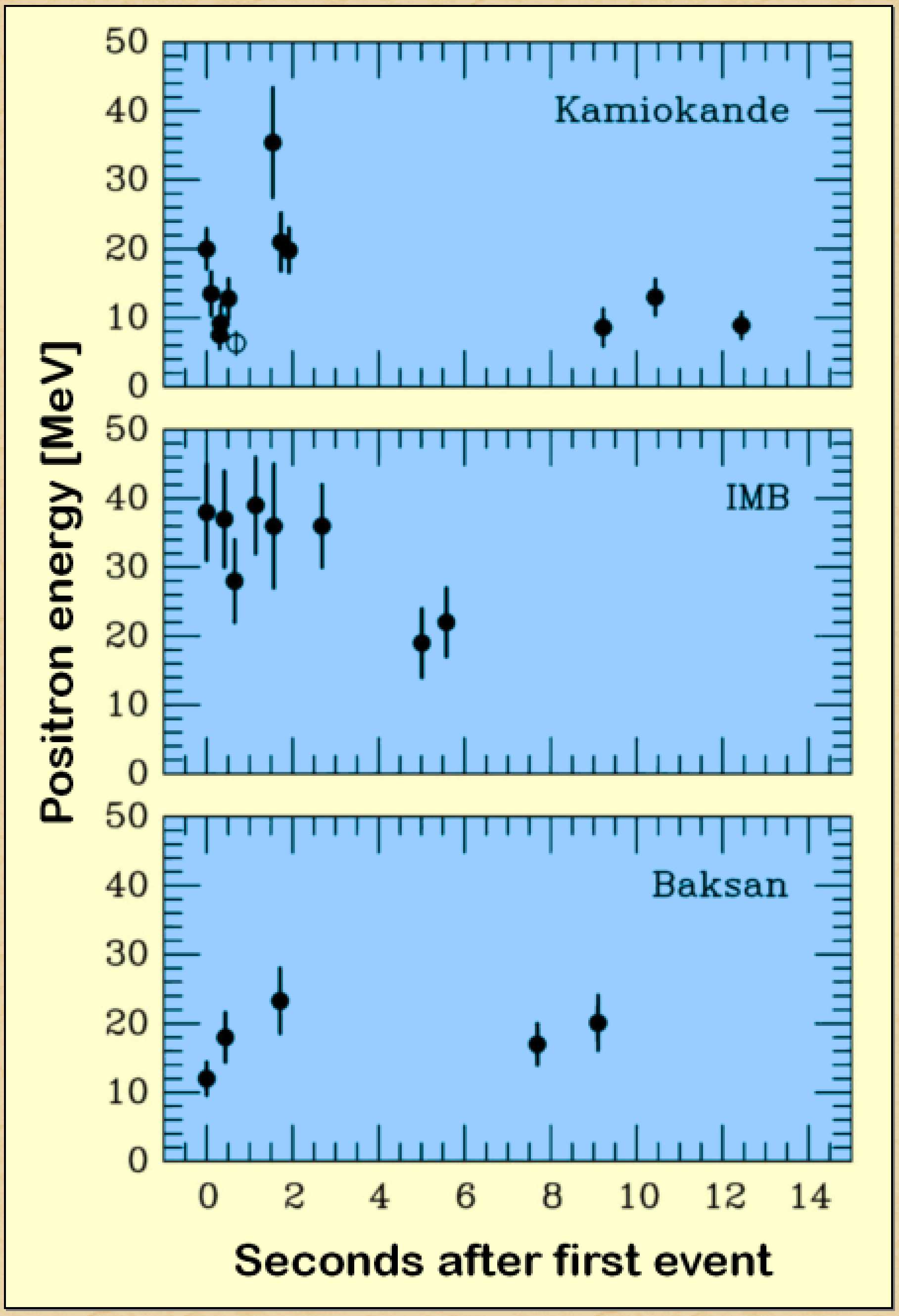


Ray Davis Jr.
(*1914)

Masatoshi Koshiba
(*1926)

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

Neutrino Signal of Supernova 1987A



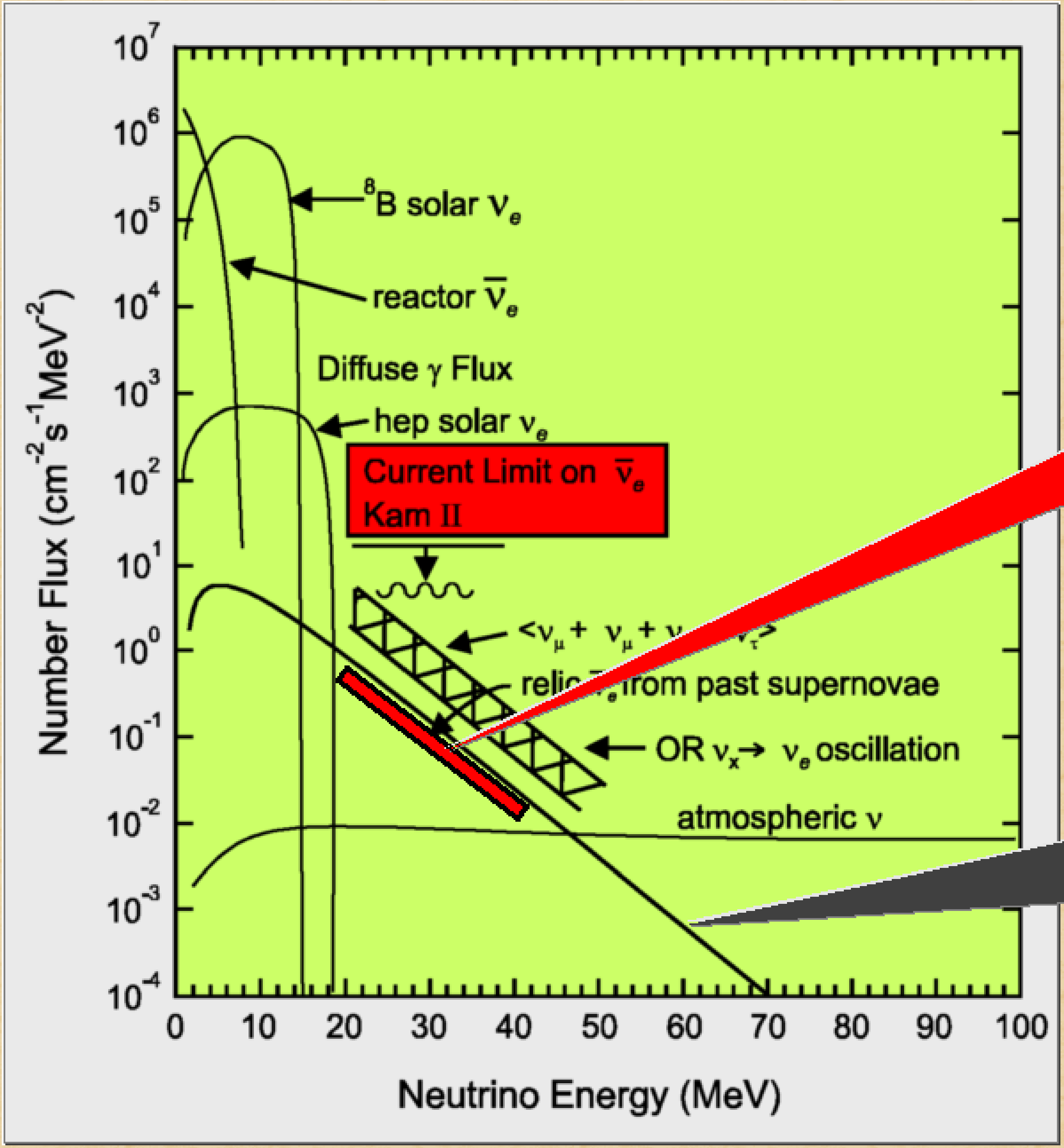
Kamiokande (Japan)
Water Cherenkov detector
Clock uncertainty ±1 min

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

Experimental Limits on Relic SN Neutrinos

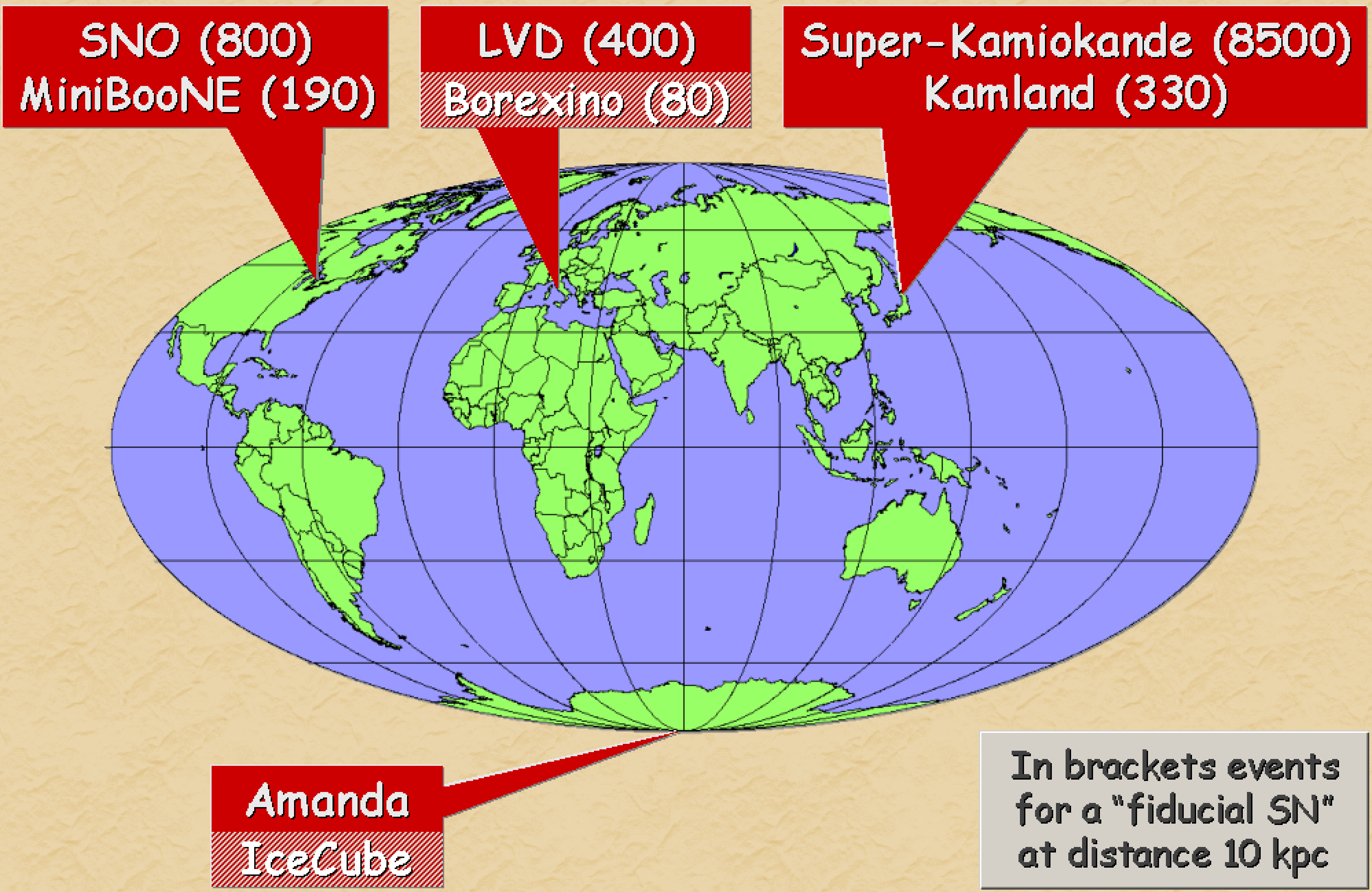


Super-K upper limit
29 cm^{-2} s^{-1} for
Kaplinghat et al. spectrum
[hep-ex/0209028]

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

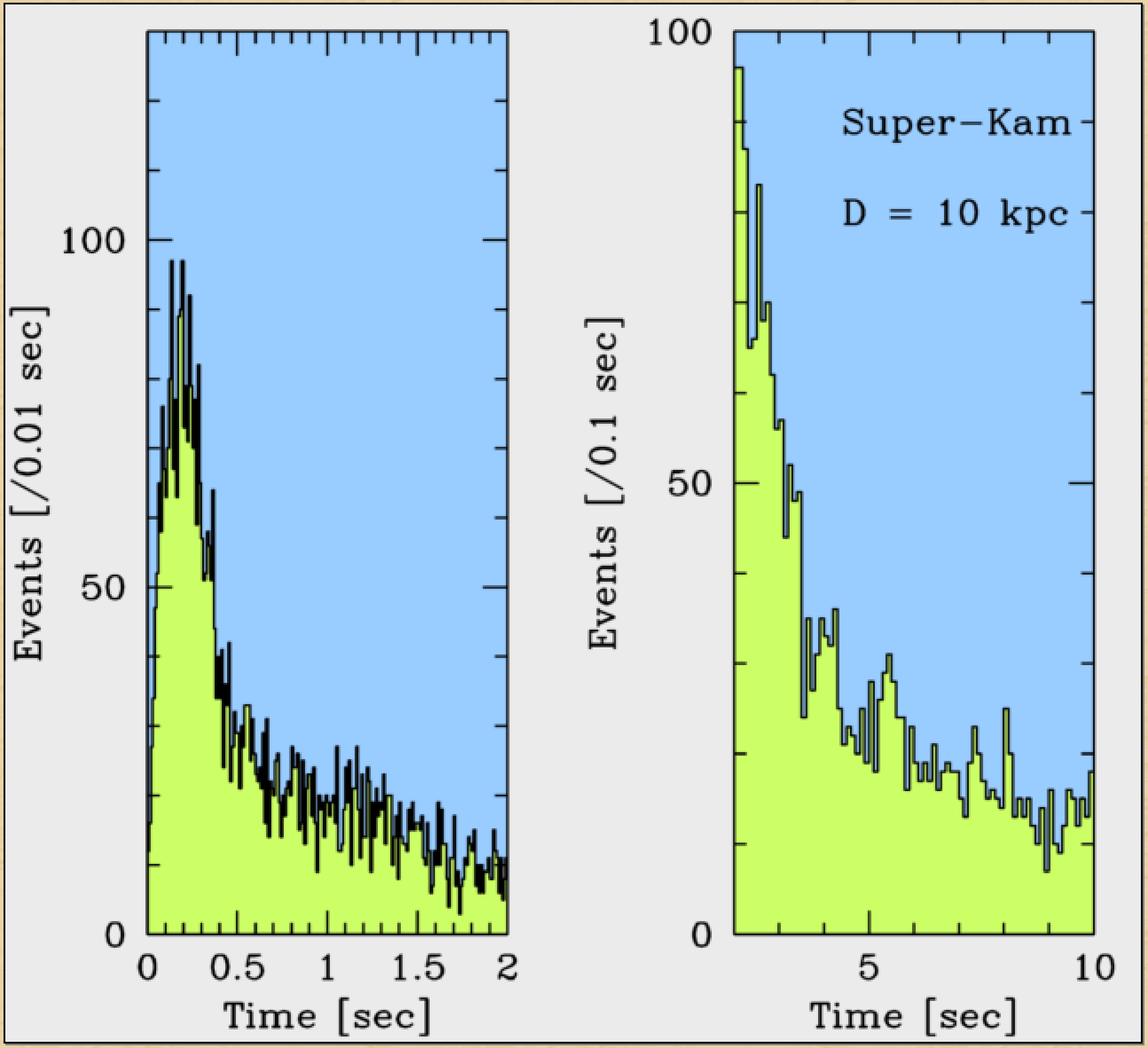
Cline, astro-ph/0103138

Large Detectors for SN Neutrinos



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

Simulated Supernova Signal in Super-Kamiokande



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

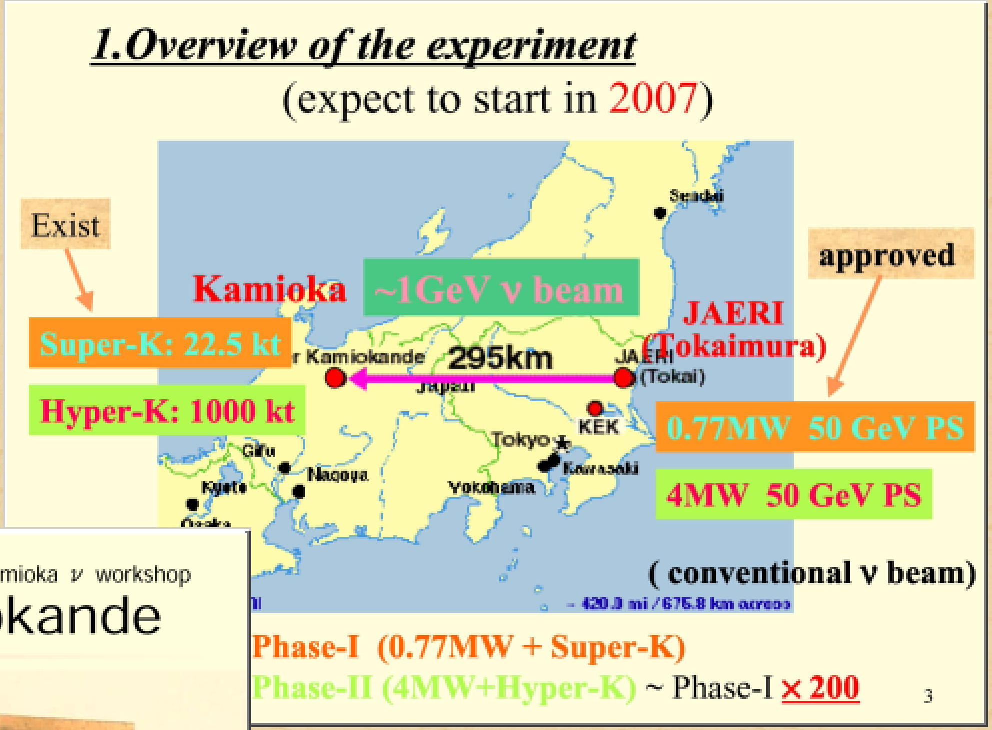
Total of about 8300 events for t < 18 s

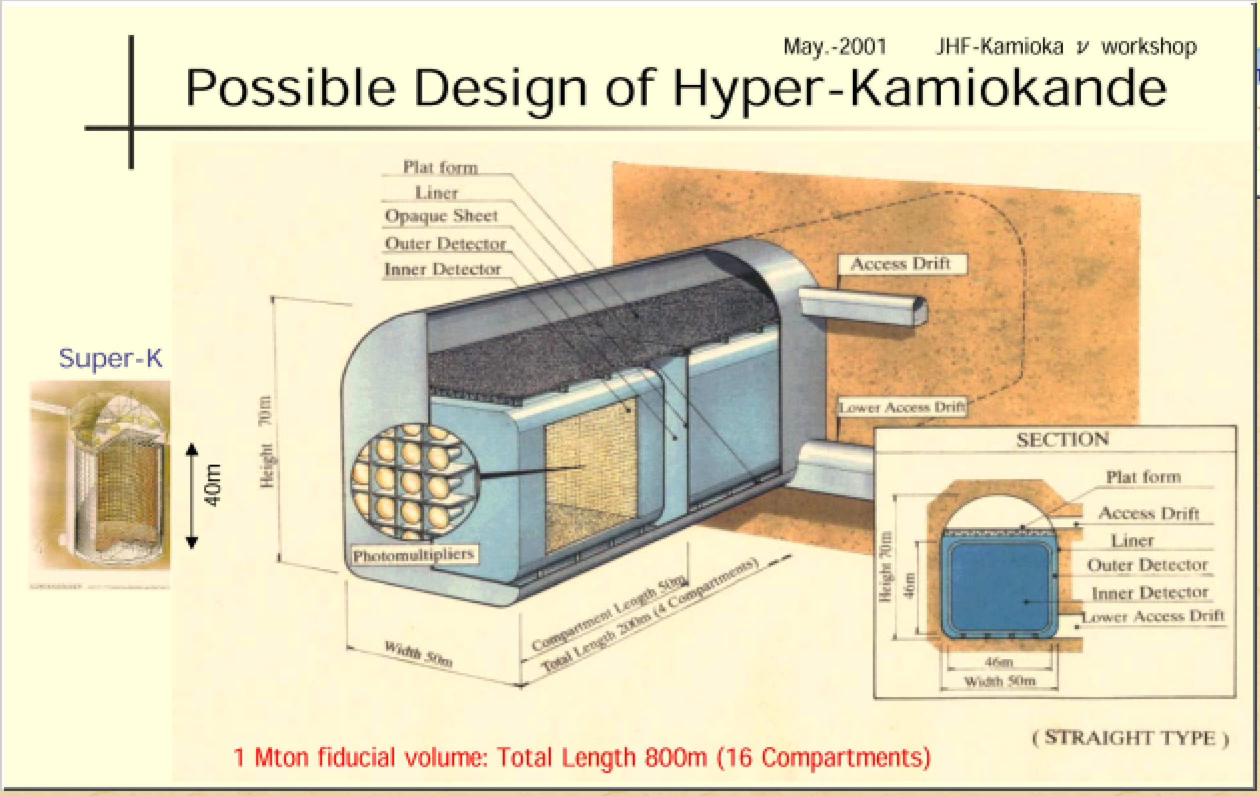
Monte-Carlo simulation for Super-Kamiokande signal of SN at 10 kpc, based on a numerical Livermore model

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)

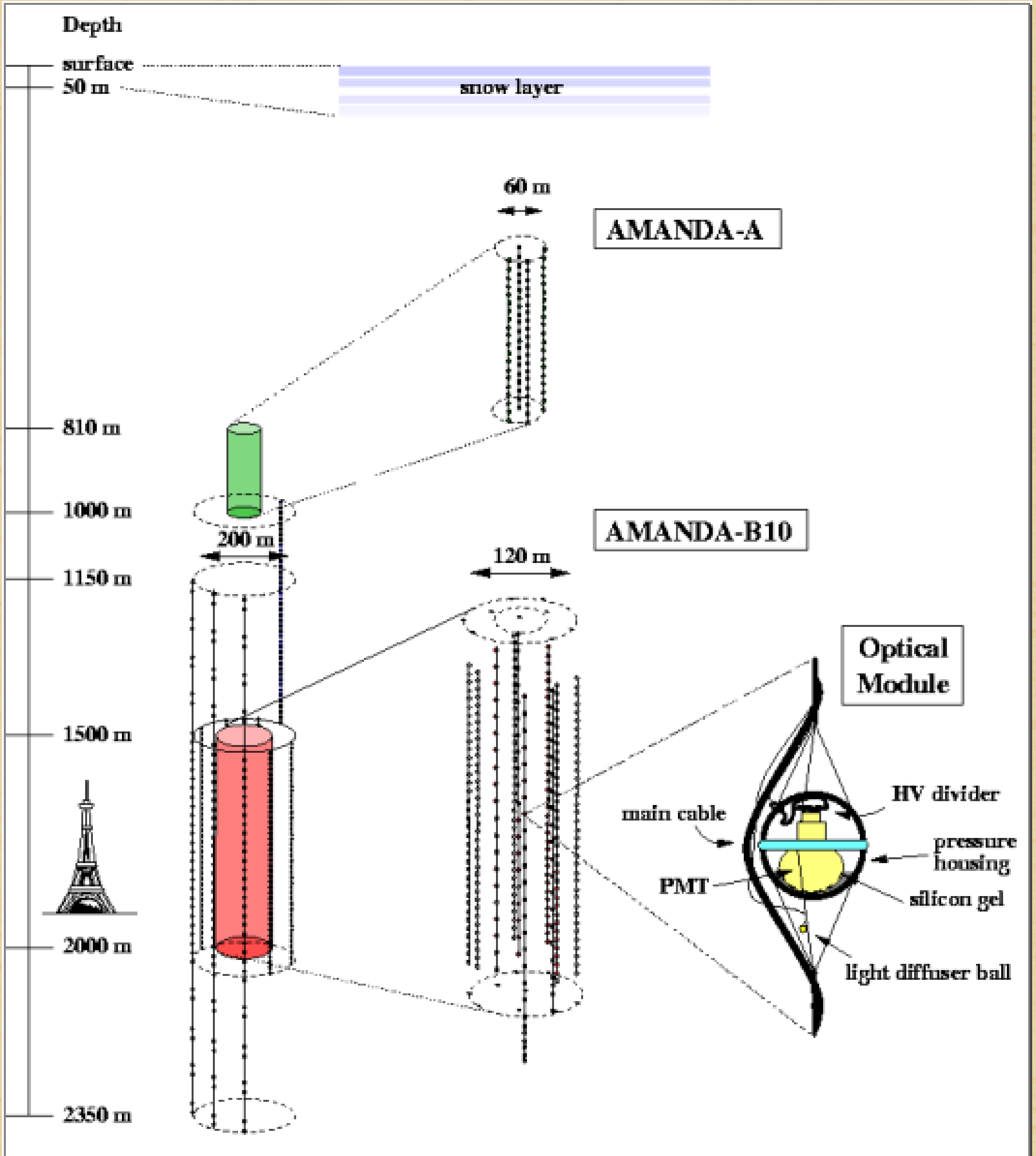




Similar discussions in

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

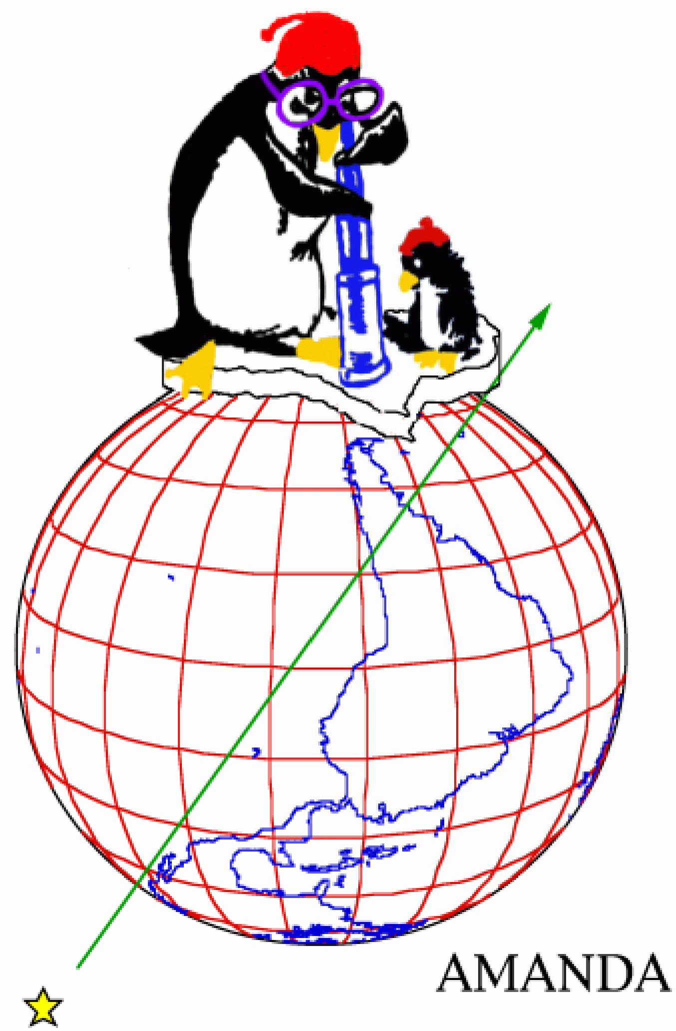
AMANDA - South Pole Neutrino Telescope



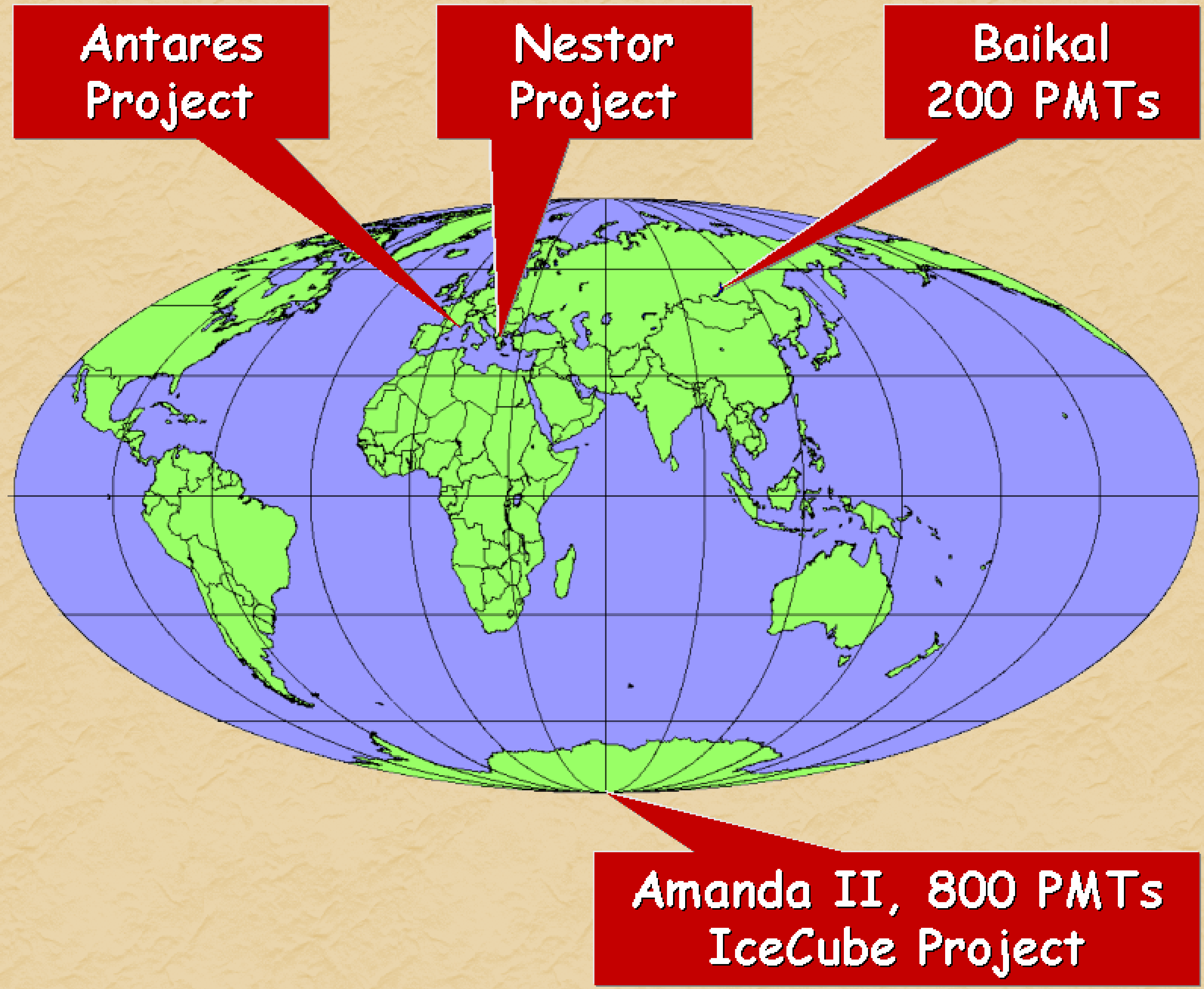
AMANDA as of 2000
Eiffel Tower as comparison
(true scaling)

zoomed in on
AMANDA-A (top)
AMANDA-B10 (bottom)

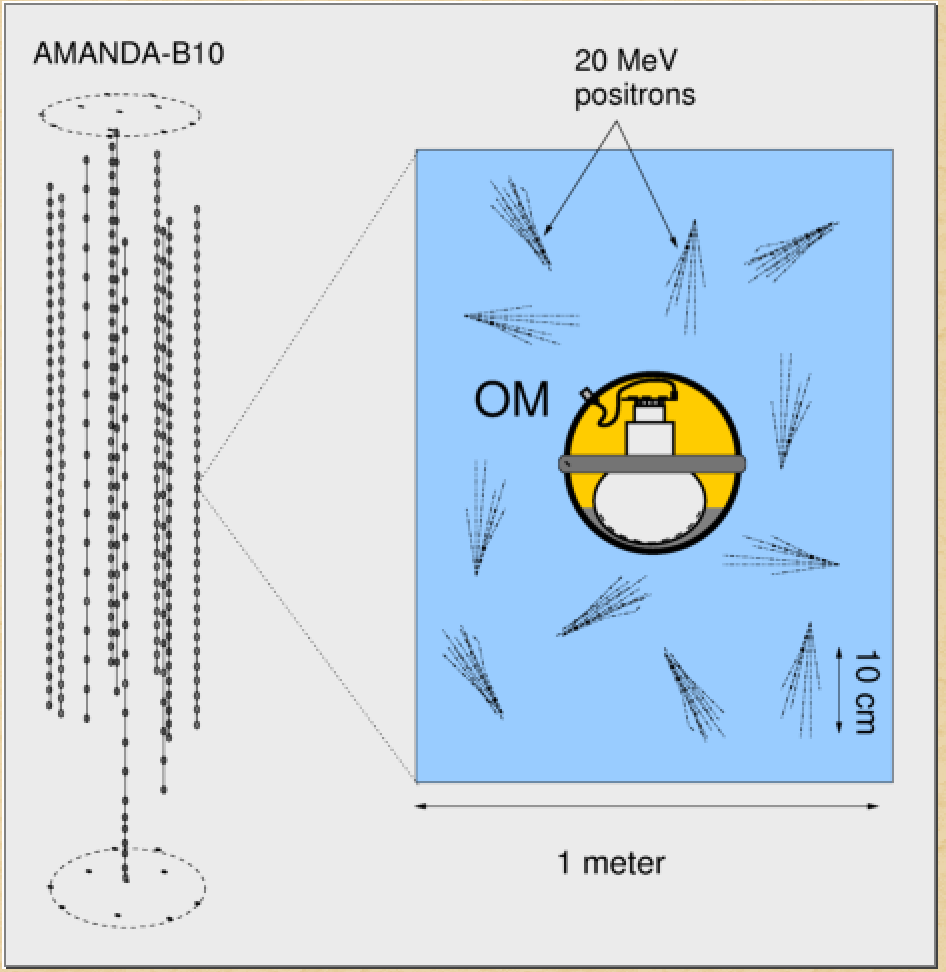
zoomed in on one
optical module (OM)

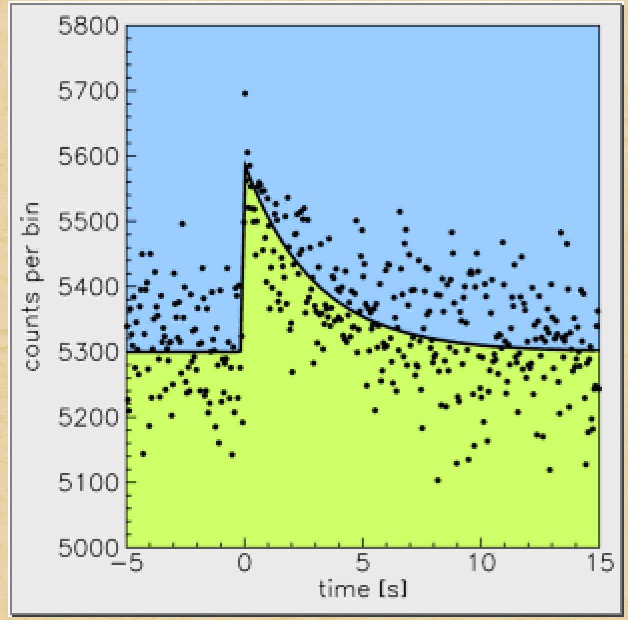


High-Energy Neutrino Telescopes

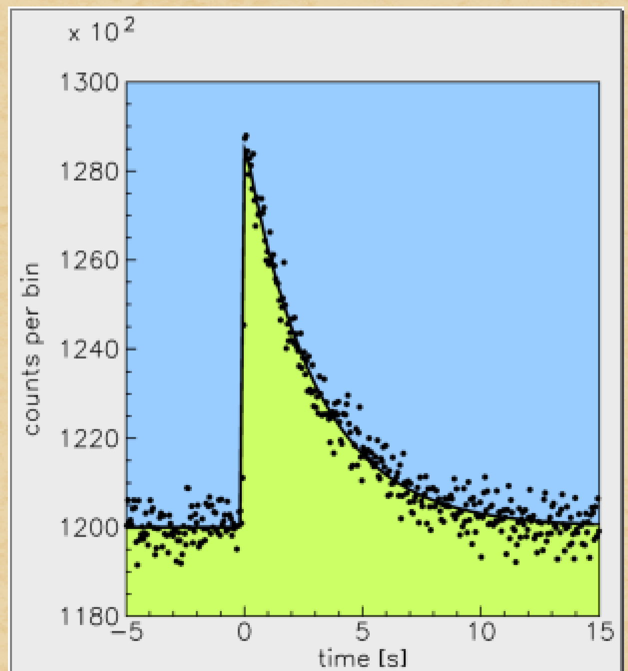


Amanda/IceCube as a Supernova Detector





SN @ 8.5 kpc
Signal in
Amanda



SN @ 8.5 kpc
Signal in
Ice Cube

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

Amanda
Collaboration
(2001)

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 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 $\Sigma m_\nu < 2.2$ eV, 50 meV reachable?
- Tritium endpoint $m_\nu < 2.2$ eV, KATRIN goal 0.3 eV
- Future $0\nu2\beta$ decay: Majorana mass (difficult for normal hierarichal)
- Leptogenesis of baryon asymmetry Majorana $m_\nu < 0.2$ eV suggested

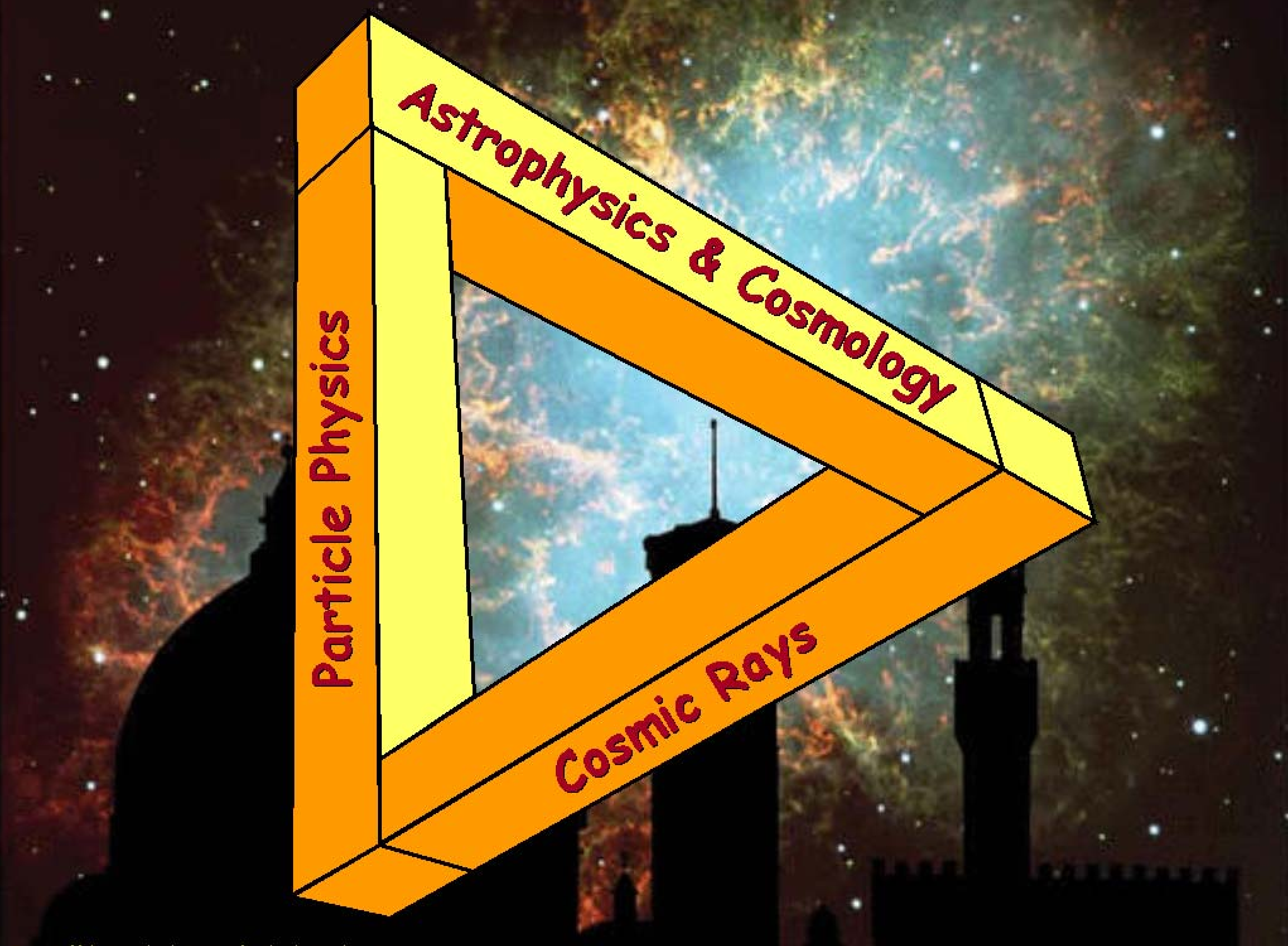
Sky in the light of neutrinos

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



Georg Raffelt, Max-Planck-Institut für Physik, München, Germany