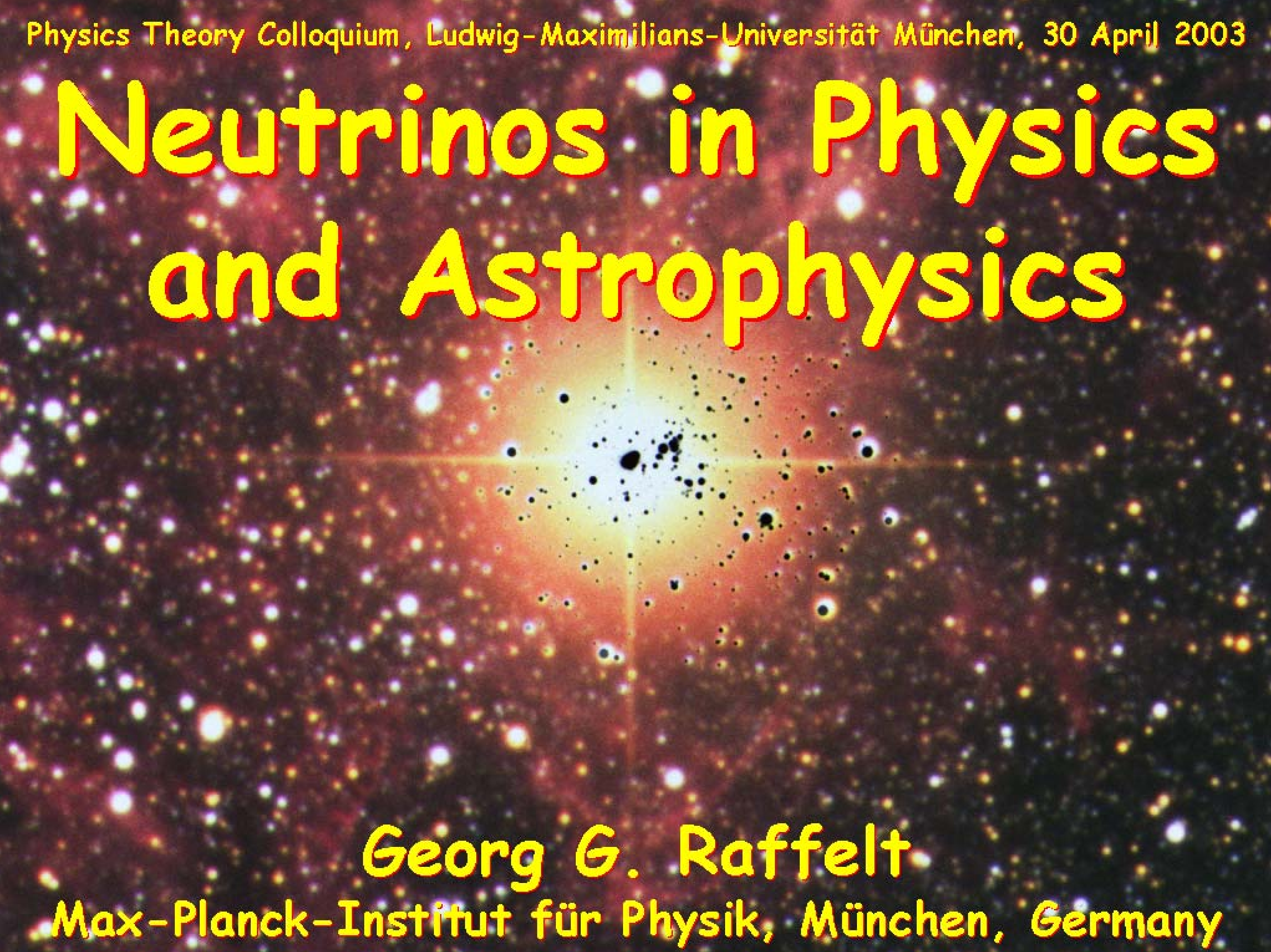
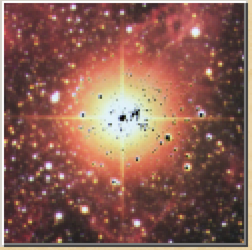
Physics Theory Colloquium, Ludwig-Maximilians-Universität München, 30 April 2003

Neutrinos in Physics and Astrophysics

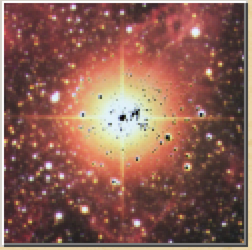


Georg G. Raffelt

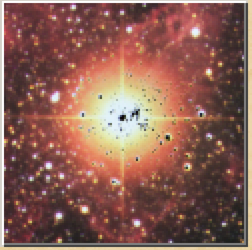
Max-Planck-Institut für Physik, München, Germany



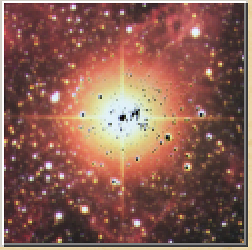
Flavor oscillations and all that



Quest for the absolute mass scale

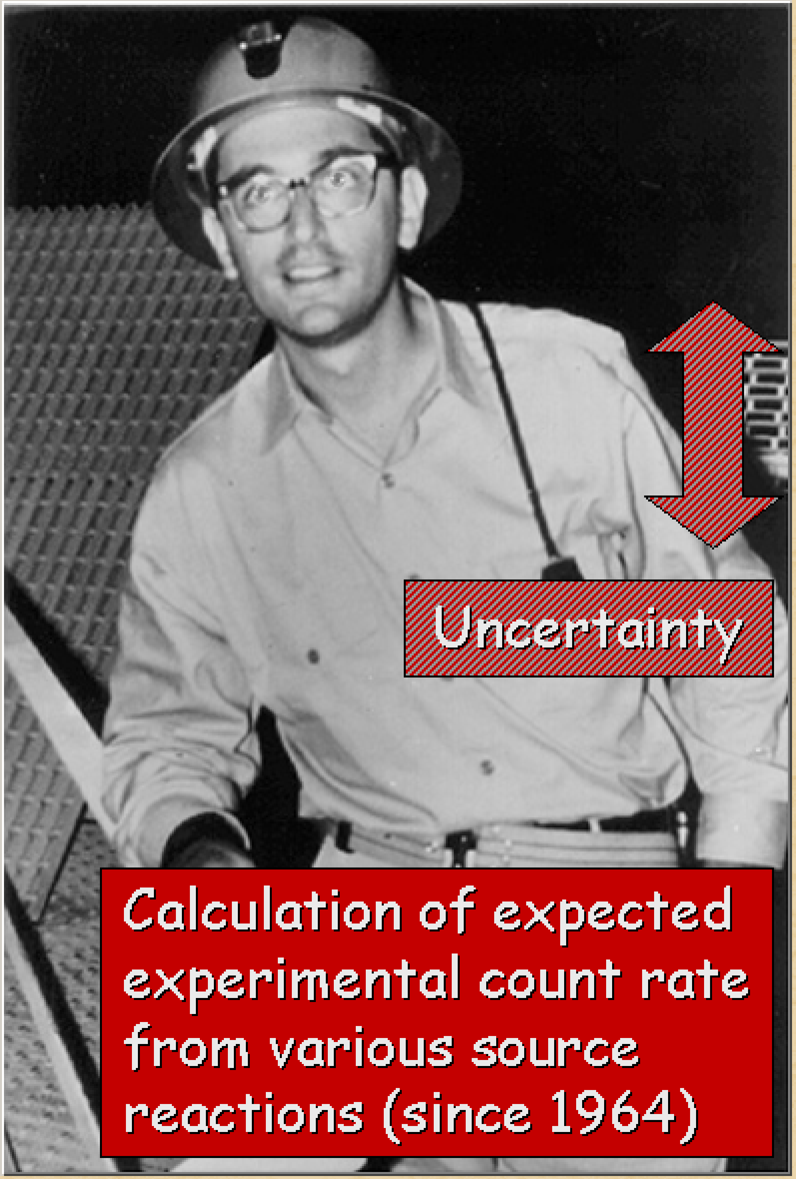


Neutrino mass and the
baryon asymmetry of the universe



Neutrinos as astrophysical messengers

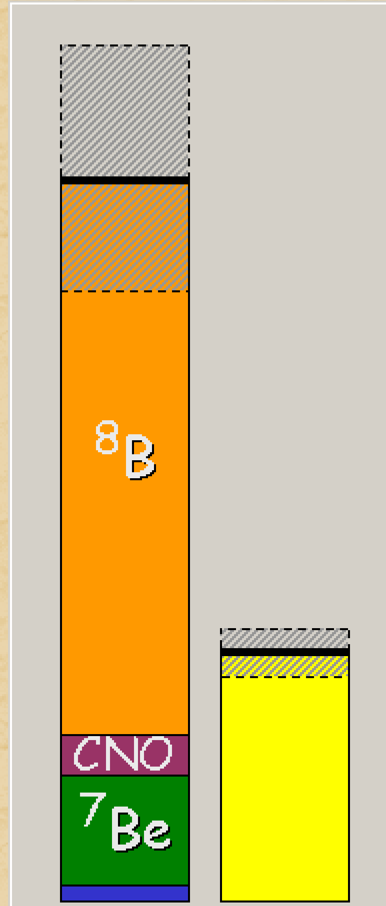
Missing Neutrinos from the Sun



John Bahcall

Homestake

Chlorine



Raymond Davis Jr.

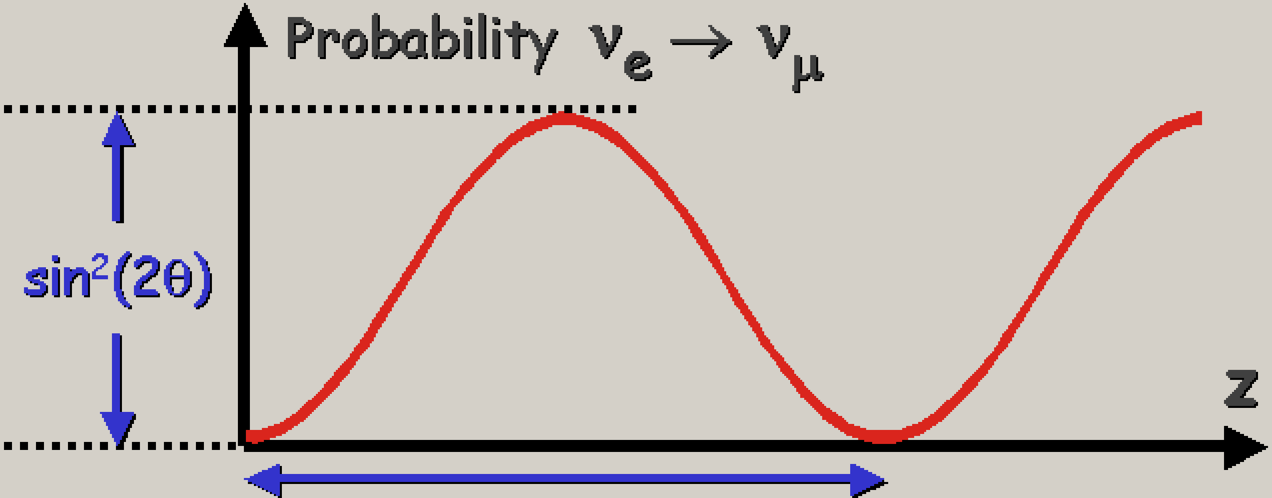
Neutrino Flavor Oscillations

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

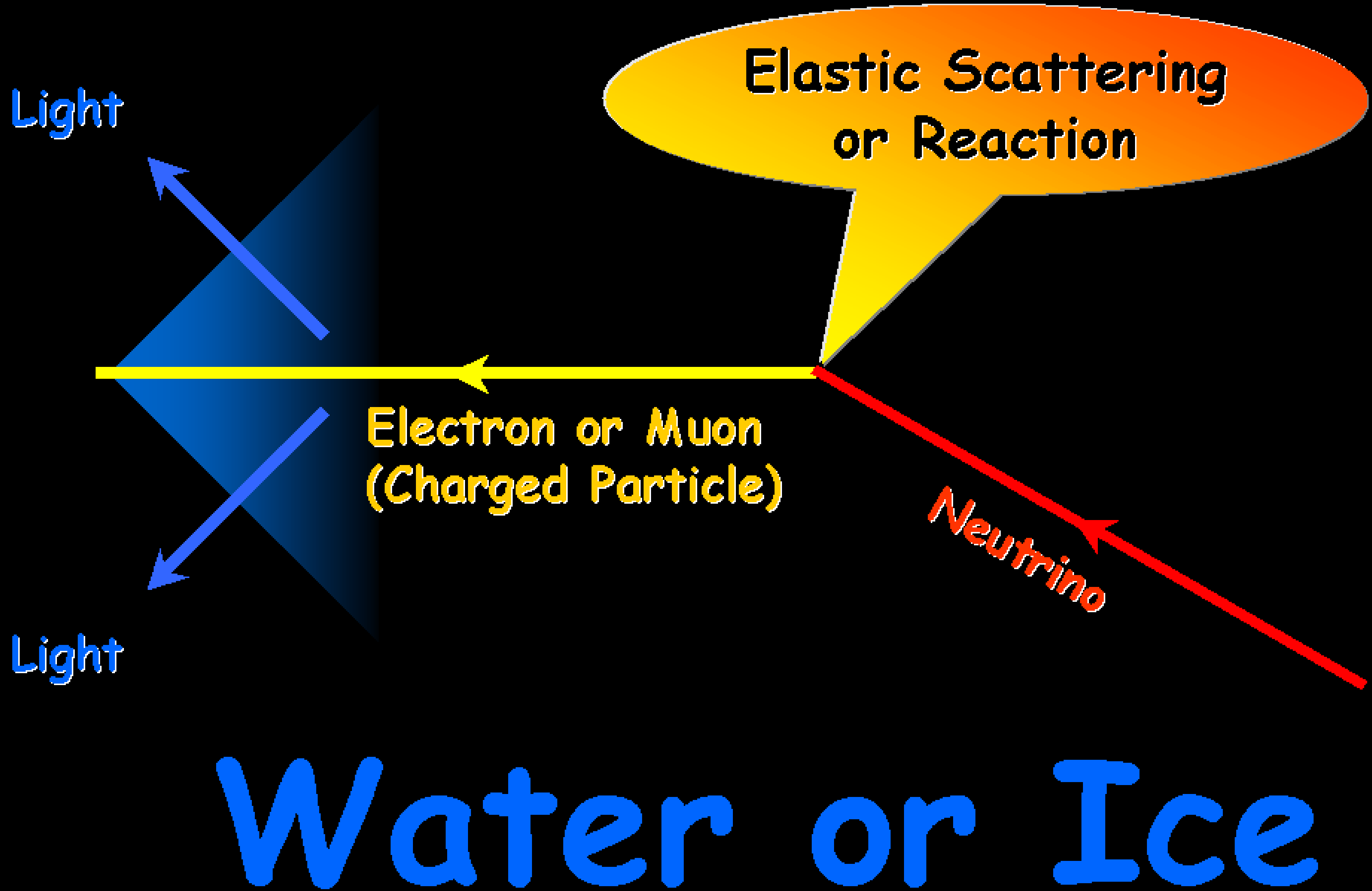
Phase difference $\frac{\Delta m^2}{2E} z$ implies flavor oscillations



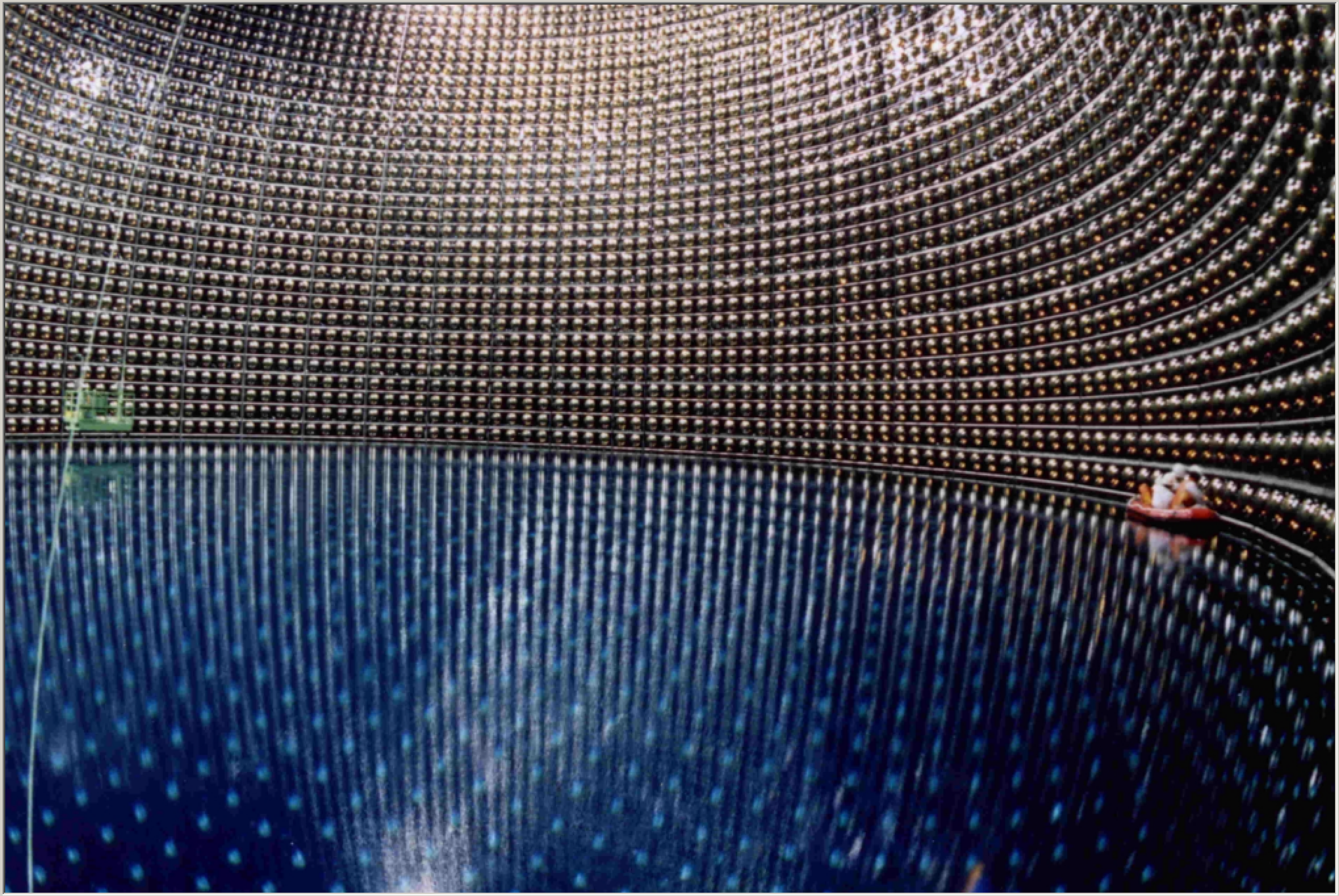
Oscillation Length $\frac{4\pi E}{\Delta m^2} = 2.5\,\mathrm{m} \left(\frac{E}{\mathrm{MeV}}\right)\left(\frac{\mathrm{eV}^2}{\Delta m^2}\right)$

Bruno Pontecorvo
(1913 - 1993)
Invented nu oscillations

Cherenkov Effect



Super-Kamiokande: Sun in the Light of Neutrinos



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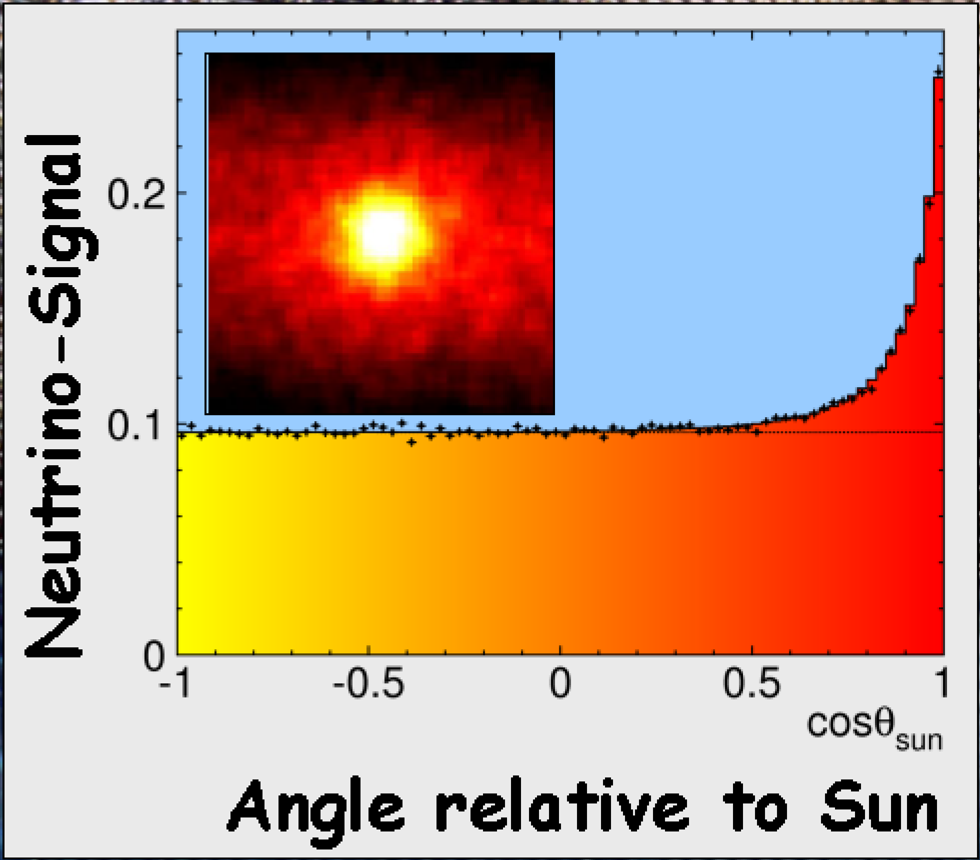

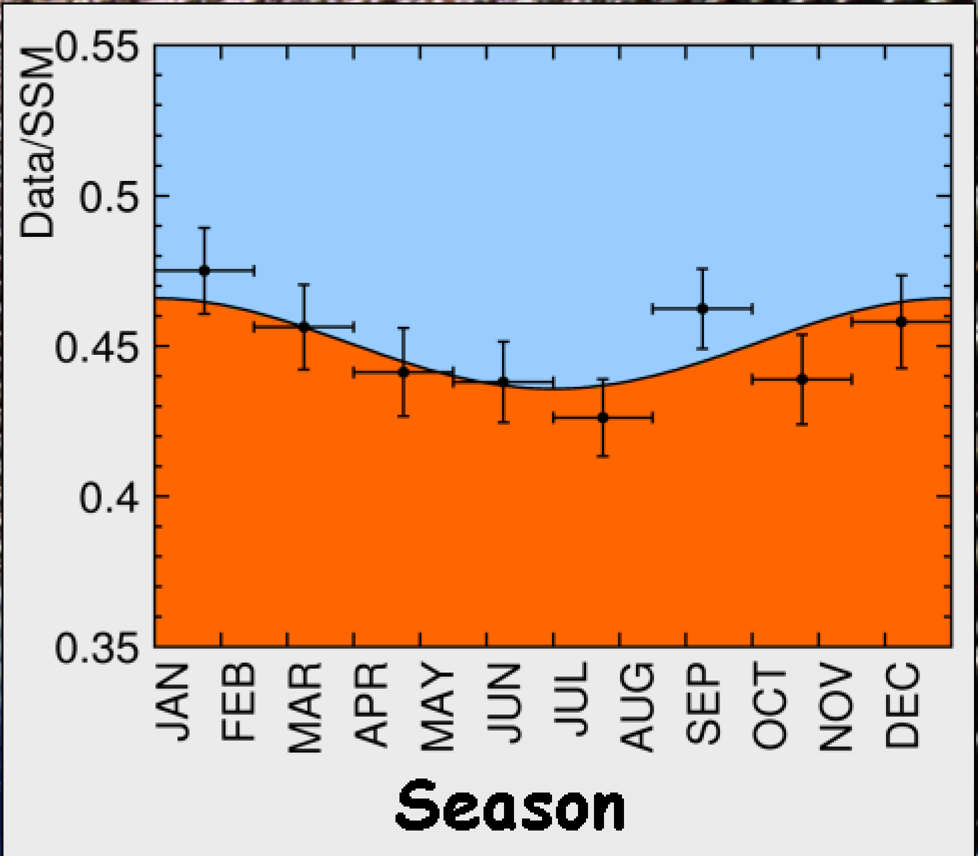

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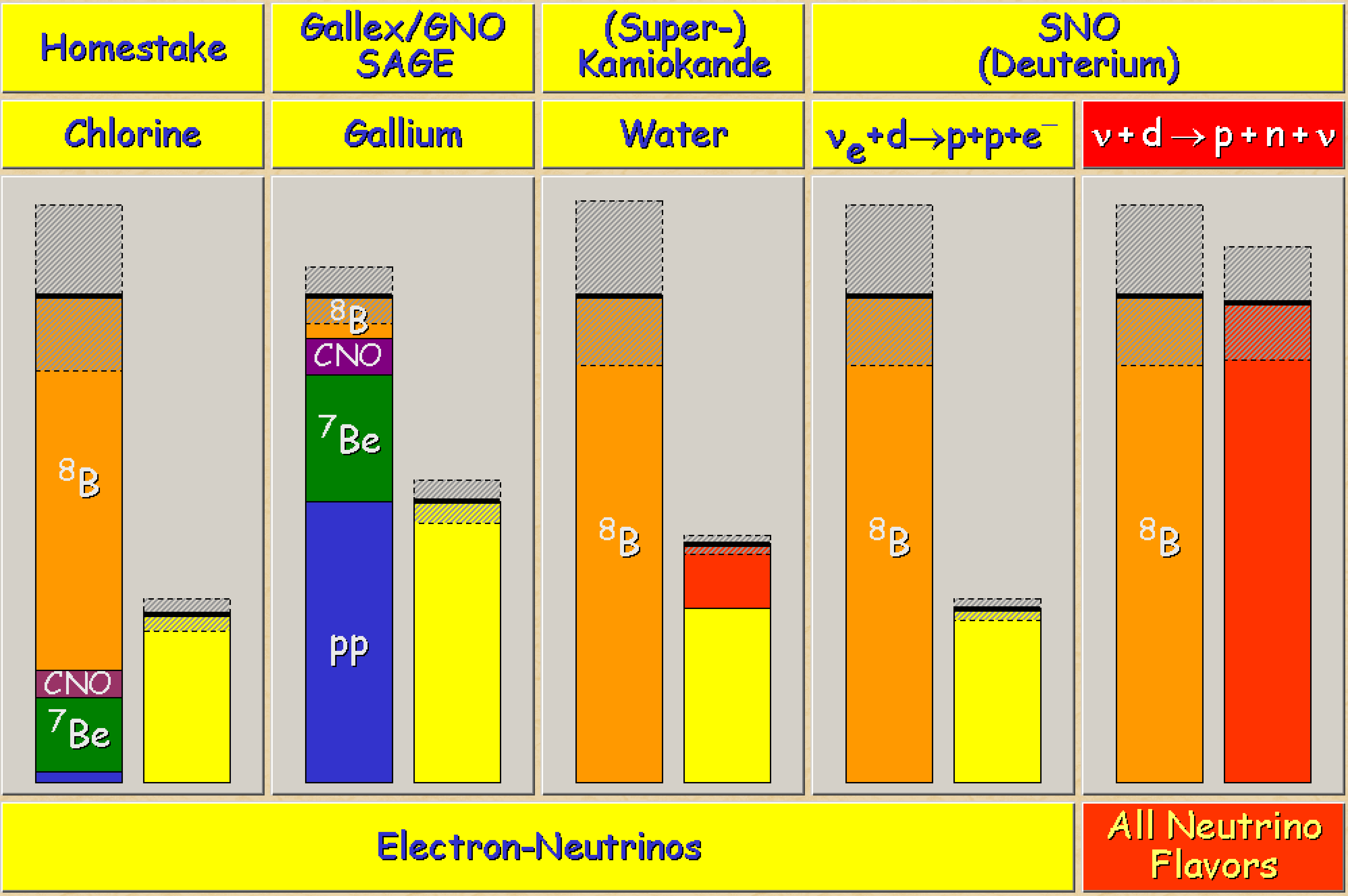

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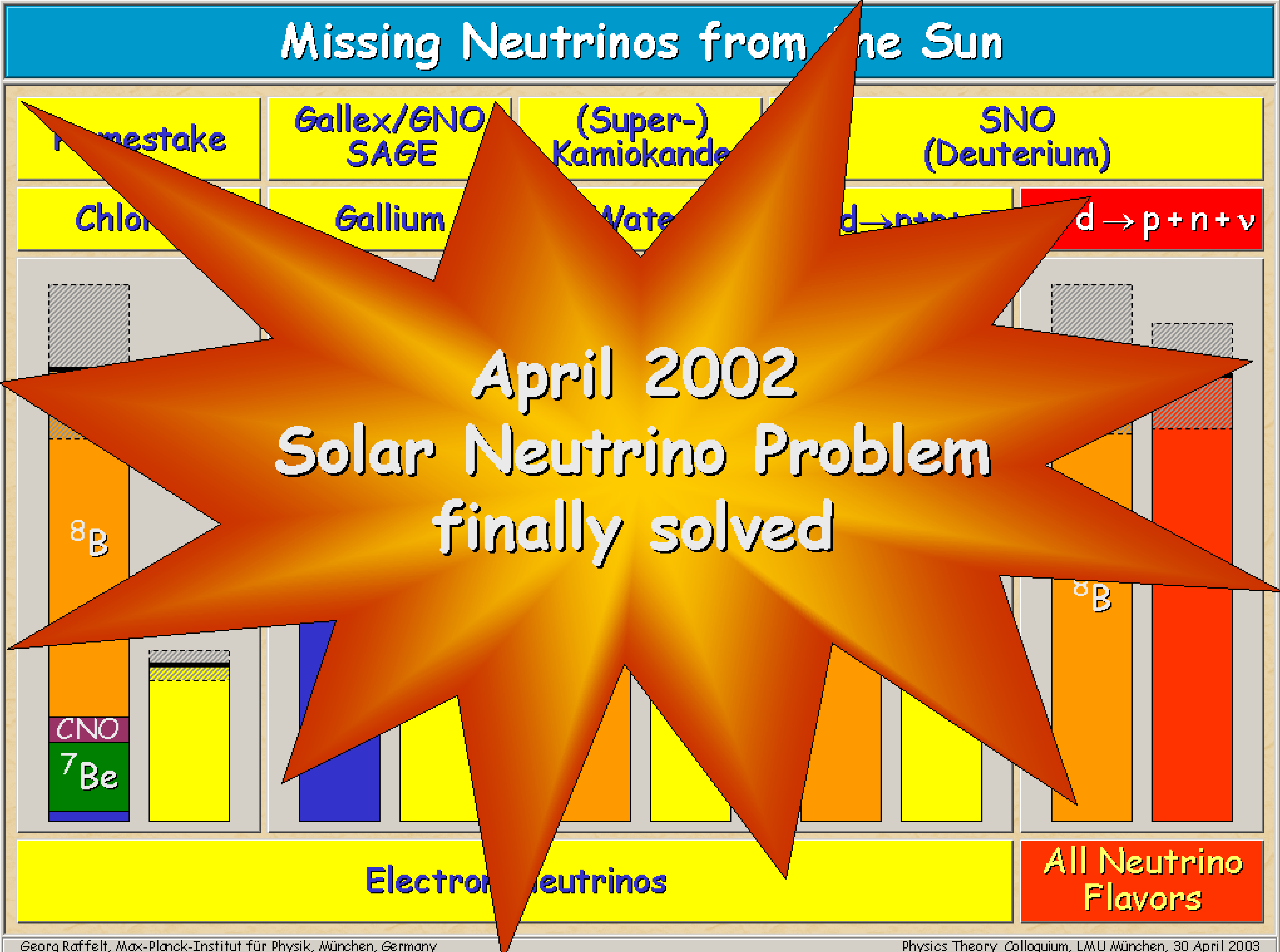
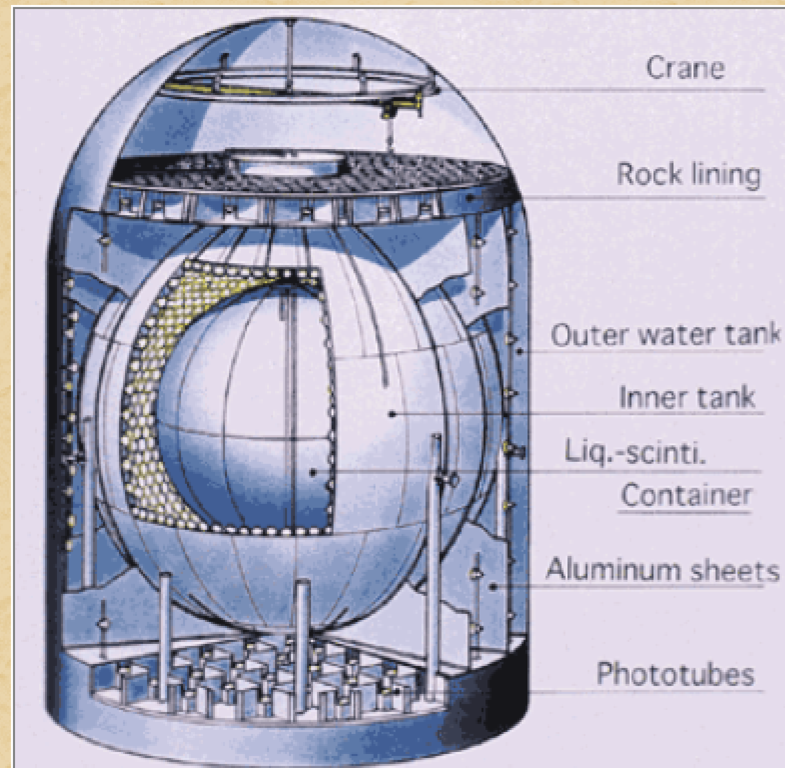


KamLAND Long-Baseline Reactor-Neutrino Experiment

Japanese nuclear reactors
60 GW (20% world capacity)

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



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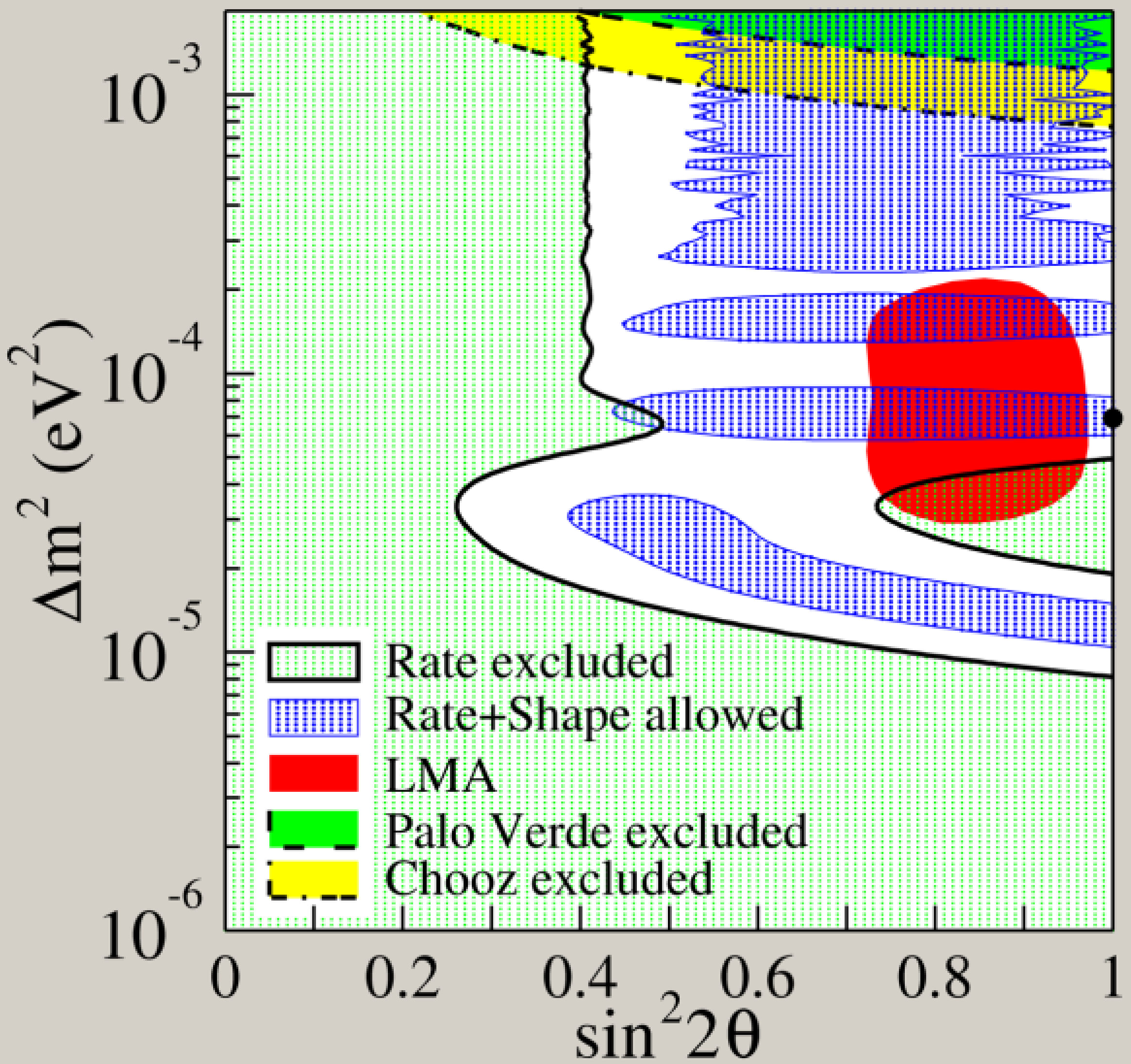

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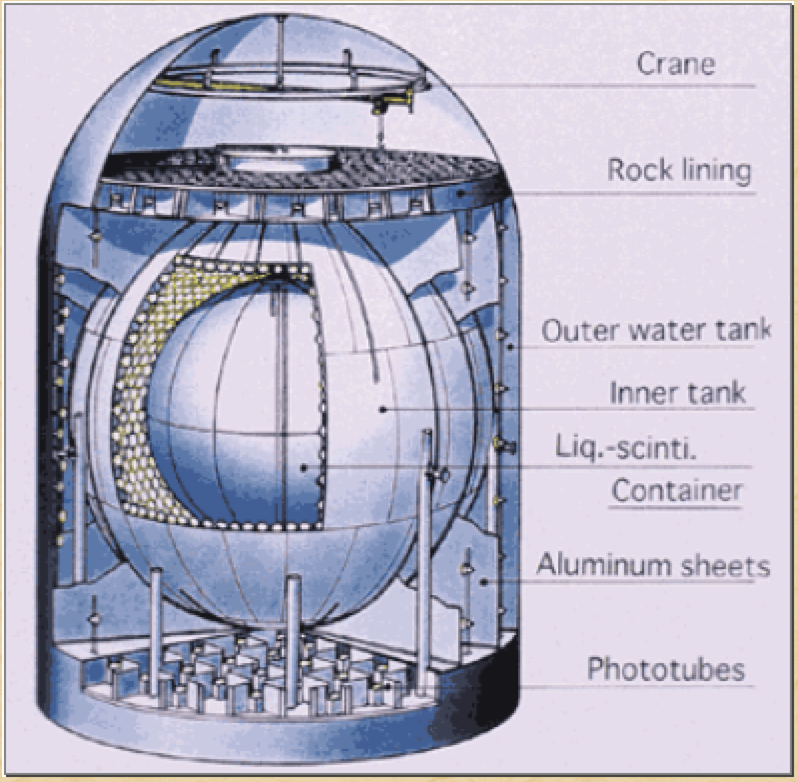


First KamLAND results December 2002
[PRL 90 (2003) 021802, hep-ex/0212021]

Status of Evidence for Neutrino Oscillations

System	Atmospheric	Solar	LSND
Channel	$\nu_\mu \to \nu_\tau$	$\nu_e \to \nu_{\mu\tau}$	$\bar\nu_\mu \to \bar\nu_e$
$\delta m^2 / eV^2$	$(1.5-4)\times 10^{-3}$	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	→ ν…		…$\mu \to \bar{\nu}_e$
$\delta m^2 / eV^2$			…2-2 or 6.5
Statu…			…onfirmed
Test			…004 ?
I…	Eviden…		…neutrino …T violation …) ?
Simplest interpre- tation	Thre… eig… wit… m_1 <… $m_2 \ll m_3$ ~ … (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
$32° < \theta_{23} < 60°$	$\theta_{13} < 14°$	$27° < \theta_{12} < 41°$	

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

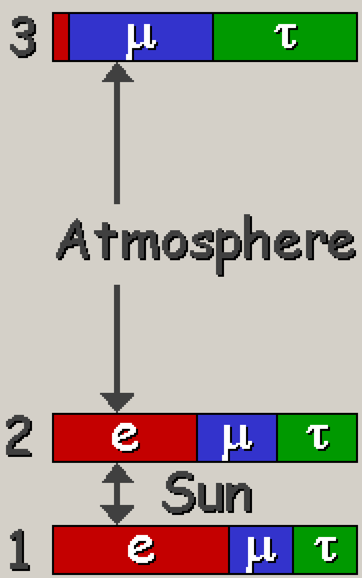
$c_{12} = \cos\theta_{12}$ etc., δ CP-violating phase

Solar
24 - 240

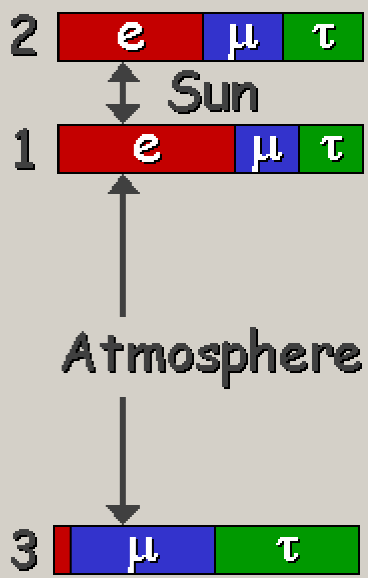
Atmospheric
1400 - 6000

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

Normal



Inverted



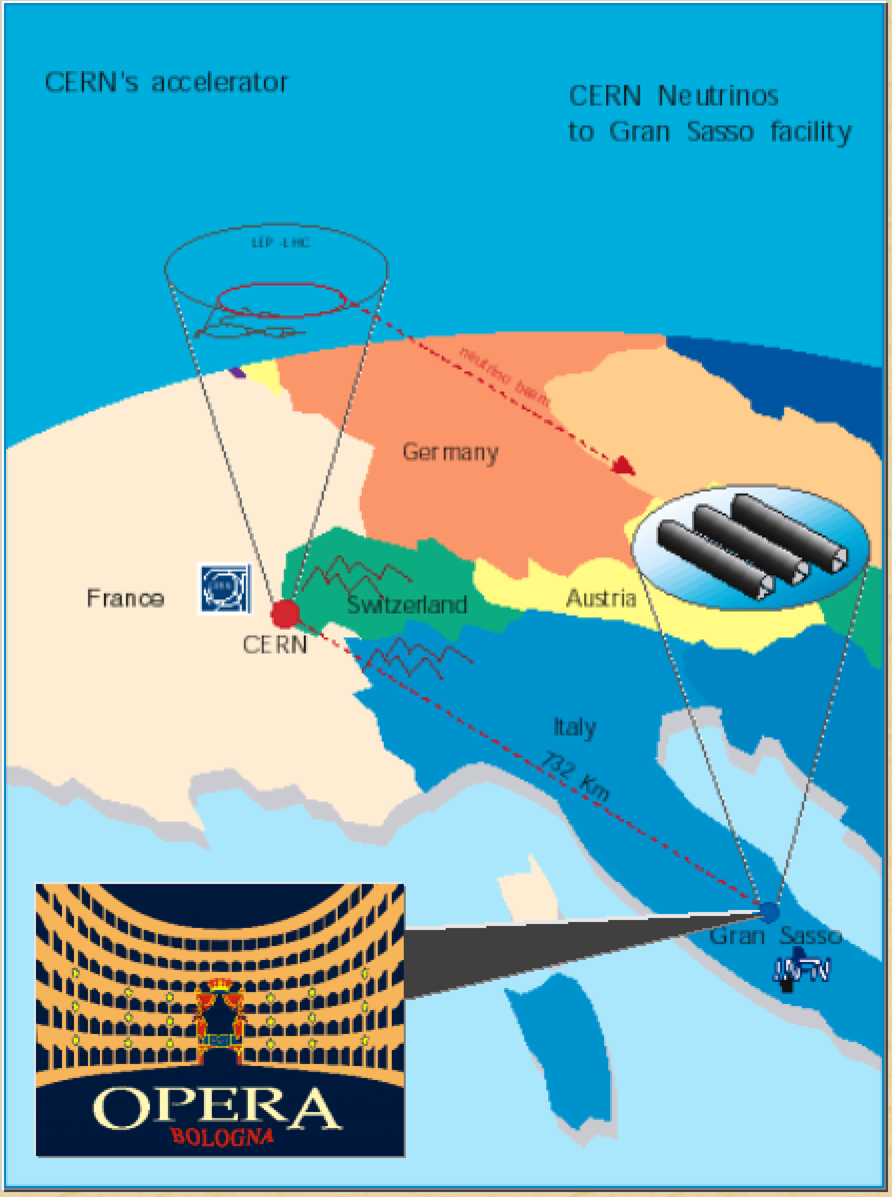
Tasks and Open Questions

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

Upcoming Long-Baseline Experiments (2005)

FermiLab-Soudan (MINOS)

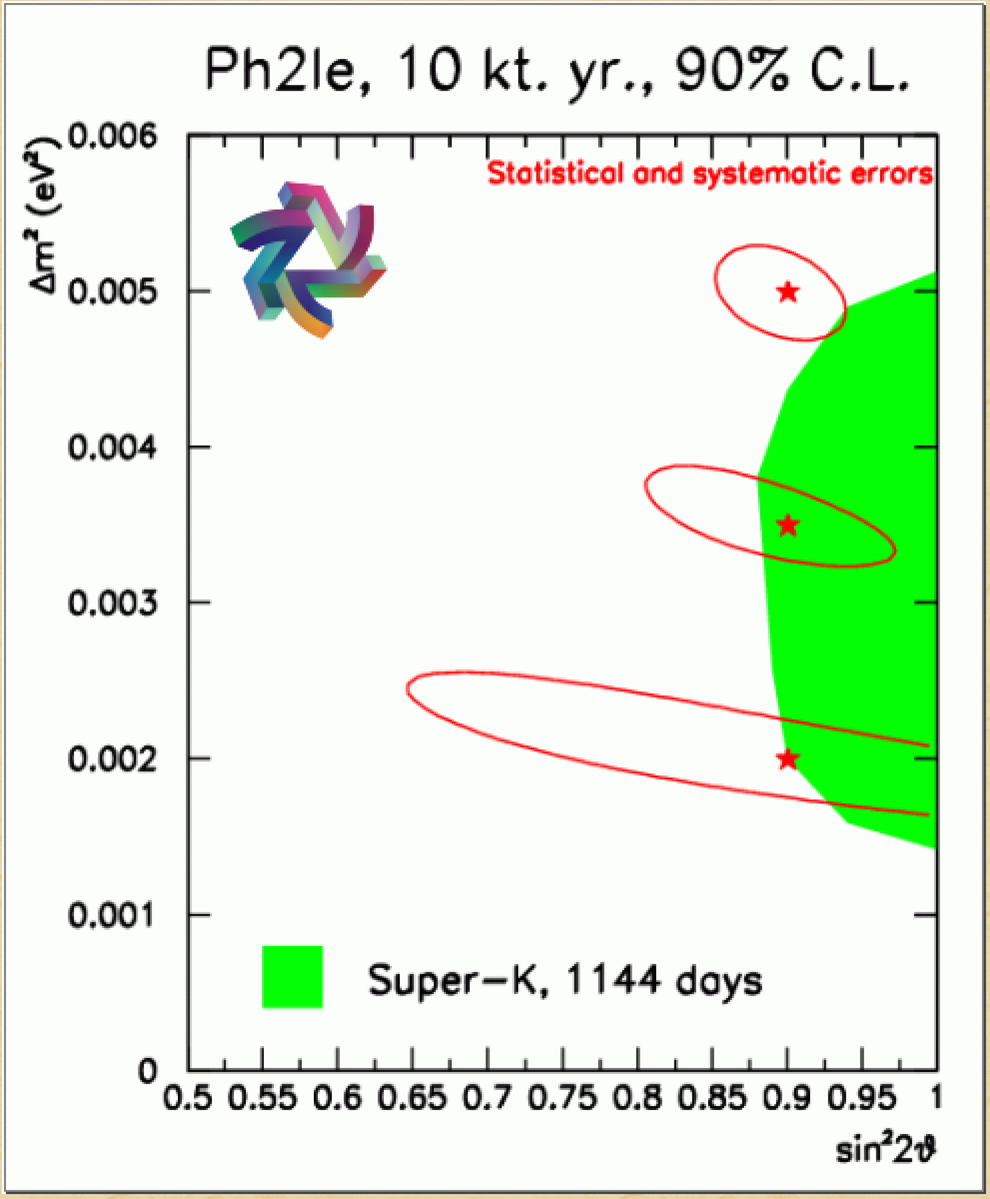
CERN - Gran Sasso



Upcoming Long-Baseline Experiments (2005)

FermiLab-Soudan (MINOS)

MINOS Oscillation Sensitivity



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

~1GeV ν beam

JAERI (Tokai)

Super-K: 22.5 kt

Hyper-K: 1000 kt

0.75MW 50 GeV PS

4MW 50 GeV PS

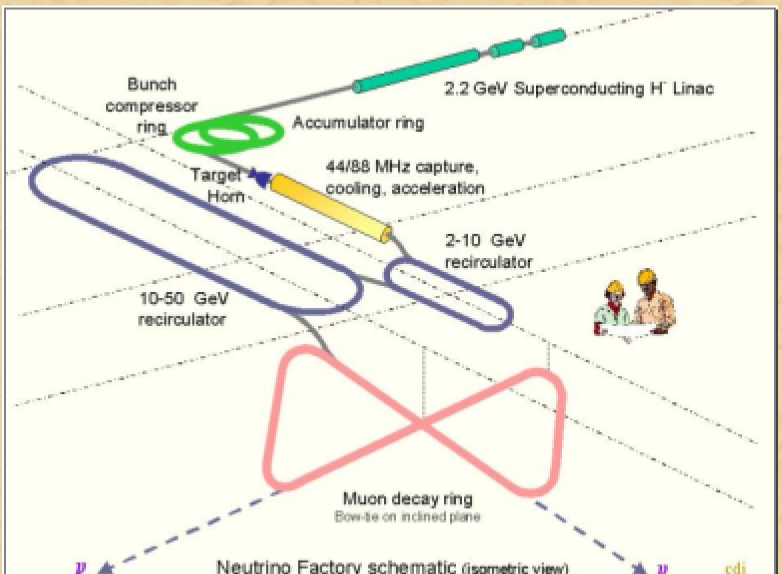
(conventional ν beam)

JHF 0.75MW + Super-Kamiokande

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

Long-Baseline Experiments

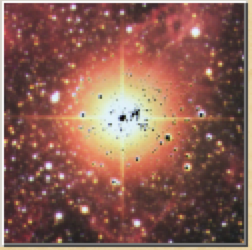
Nuclear reactors	Nuclear decay	Kamland (2002) Borexino (>2003?)	Solar LMA
Conventional beam	Proton beam dump $\rightarrow \pi \rightarrow \mu\nu_\mu \rightarrow e\nu_\mu\nu_\mu\nu_e$	K2K (1999) NuMI (2005) CNGS (2005) JHF (2007)	Test and precision for atm $\sin^2 2\theta_{13} \sim 0.01$
Super beam	Primary 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	$\sin^2 2\theta_{13} \sim 0.0001$ CP violation Mass ordering
Neutrino factory	(see schematic below)	R&D	



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

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

Neutrinos in Physics and Astrophysics



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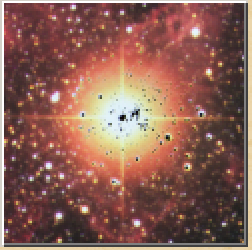

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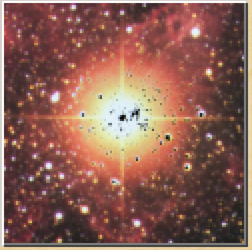

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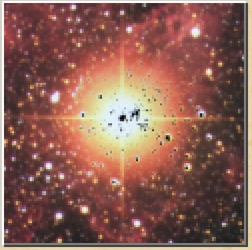
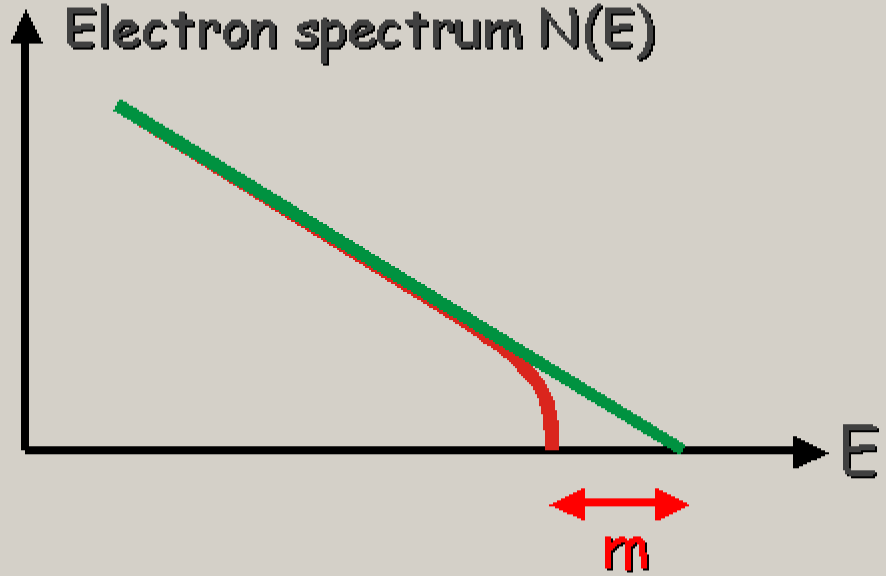


Neutrinos as astrophysical messengers

Tritium Endpoint Spectrum



Tritium Beta Decay

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

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

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

Weakly Interacting Particles as Dark Matter

THE ASTROPHYSICAL JOURNAL, **180**: 7–10, 1973 February 15

GRAVITY OF NEUTRINOS OF NONZERO MASS IN ASTROPHYSICS

R. COWSIK* AND J. MCCLELLAND
Department of Physics, University of California, Berkeley
Received 1972 July 24

ABSTRACT

If neutrinos have a rest mass of a few eV/c^2, then they would dominate the gravitational dynamics of the large clusters of galaxies and of the Universe. A simple model to understand the virial mass discrepancy in the Coma cluster on this basis is outlined.

Subject headings: cosmology — galaxies, clusters of — neutrinos

The possibility of a finite rest mass for the neutrinos has fascinated astrophysicists (Kuchowicz 1969). A recent discussion of such a possibility has been in the context of the solar-neutrino experiments (Bahcall, Cabibbo, and Yahil 1972). Here we wish to point out some interesting consequences of the gravitational interactions of such neutrinos. These considerations become particularly relevant in the framework of big-bang cosmologies which we assume to be valid in our discussion here.

In the early phase of such a Universe when the temperature was ~1 MeV, several processes of neutrino production (Ruderman 1969) would have led to copious production of neutrinos and antineutrinos (Steigman 1972; Cowsik and McClelland 1972). Conditions of thermal equilibrium allow an easy estimate of their number densities (Landau and Lifshitz 1969):

$$n_{\nu i} = \frac{1}{\pi^2 \hbar^3} \int_0^\infty \frac{p^2 dp}{\exp[E/kT(z_{eq})] + 1} \,. \qquad (1)$$

Here $n_{\nu i}$ = number density of neutrinos of the ith kind (notice that in writing this expression we have assumed that both the helicity states are allowed for the neutrinos because of finite rest mass); $E = c(p^2 + m^2c^2)^{1/2}$; k = Boltzmann's constant; $T(z_{eq}) = T_r(z_{eq}) = T_\nu(z_{eq}) = T_e(z_{eq}) \cdots =$ the common temperature of radiation, neutrinos, electrons, etc., at the latest epoch characterized by redshift z_{eq} when they may be assumed to have been in thermal equilibrium; $kT(z_{eq}) \simeq 1$ MeV.

Since the masses of the neutrinos are expected to be small, $kT(z_{eq}) \gg m_{\nu i}c^2$, in the extreme-relativistic limit equation (1) reduces to

$$n_{\nu i}(z_{eq}) \simeq 0.183[T(z_{eq})/\hbar c]^3 \,. \qquad (2)$$

As the Universe expands, only the neutrinos (in contrast to all other known particles) survive annihilation because of extremely low cross-sections (deGraff and Tolhock 1966), and their number density decreases with increasing volume of the Universe, simply as $\sim V(z_{eq})/V(z) = [(1 + z)/(1 + z_{eq})]^3$. Noting that $(1 + z_{eq})/(1 + z) = T_r(z_{eq})/T_r(z)$, the number density at the present epoch ($z = 0$) is given by

$$n_{\nu i}(0) = n_{\nu i}(z_{eq})/(1 + z_{eq})^3 \simeq 0.183[T_r(0)/\hbar c]^3 \simeq 300 \text{ cm}^{-3} \,, \qquad (3)$$

* On leave from the Tata Institute of Fundamental Research, Bombay, India.

7

Almost 30 years ago, beginnings of the idea of weakly interacting particles (neutrinos) as dark matter

Massive neutrinos are no longer a good candidate (hot dark matter)

However, the idea of weakly interacting massive particles as dark matter is now standard

What is wrong with neutrino dark matter?

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

Maximum mass density of a Fermi gas

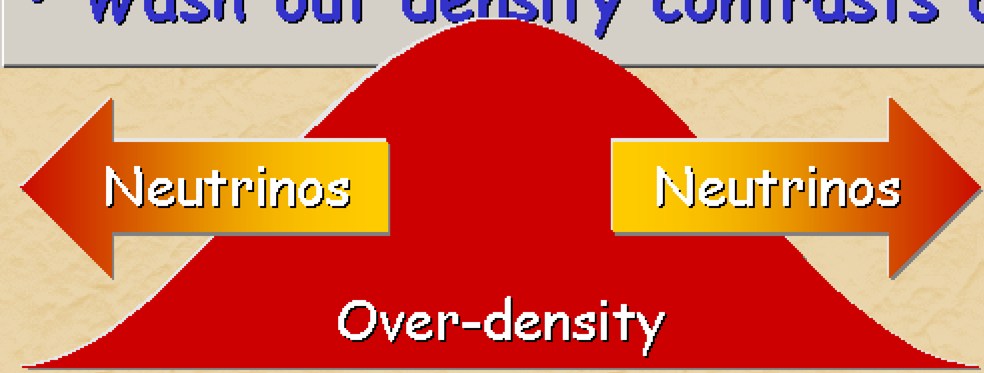
$$\rho_{max} = m_\nu n_{max} = m_\nu p_{max}^3/3\pi^2 = m_\nu (m_\nu v_{escape})^3/3\pi^2$$

$m_\nu > 20 - 40$ eV — Spiral galaxies

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

Neutrino Free Streaming (Collisionless Phase Mixing)

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

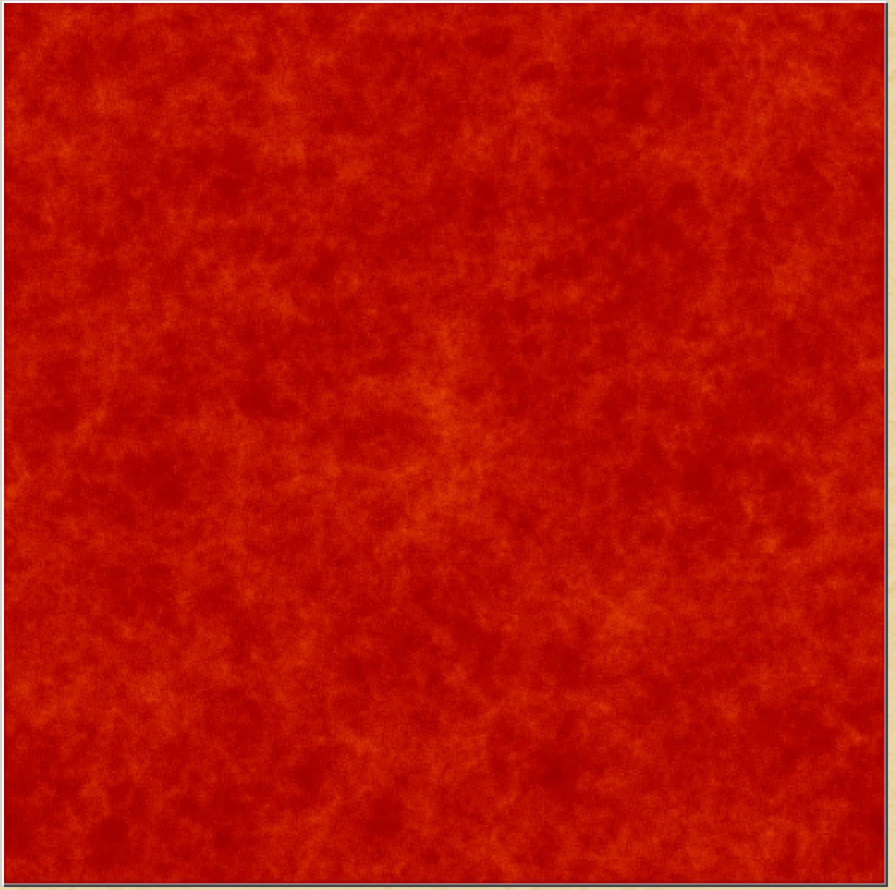


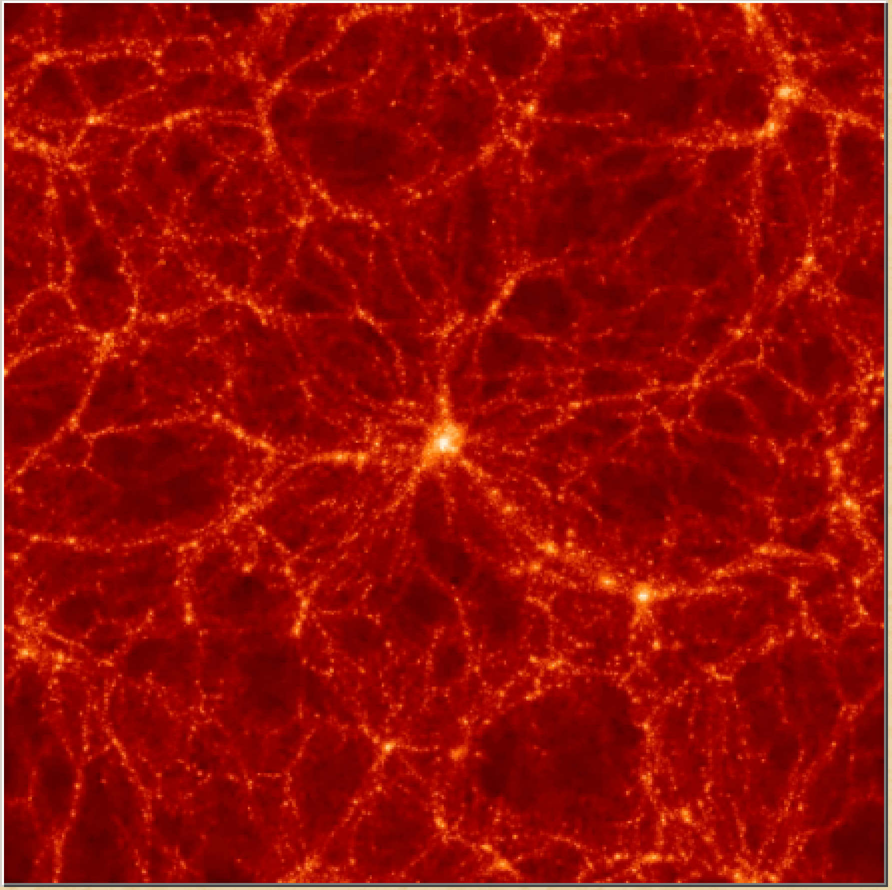
- Nus are "Hot Dark Matter"
- Ruled out by structure formation

Formation of Structure

Numerical Simulation Max-Planck-Institut für Astrophysik, Garching

Smooth → Structured





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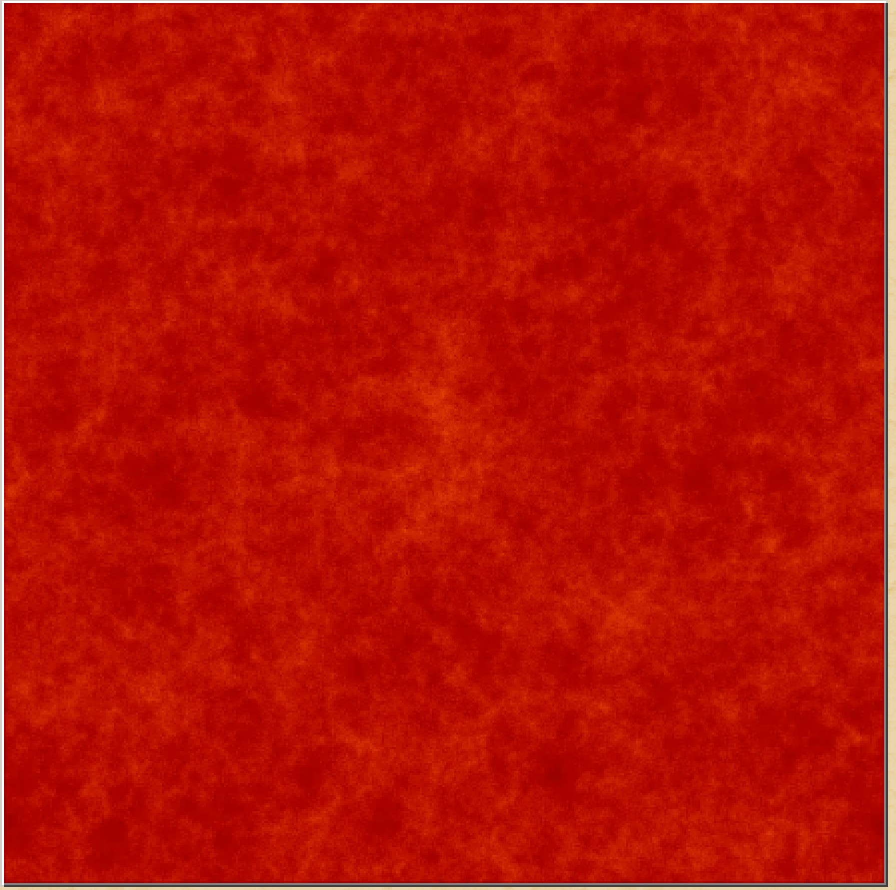
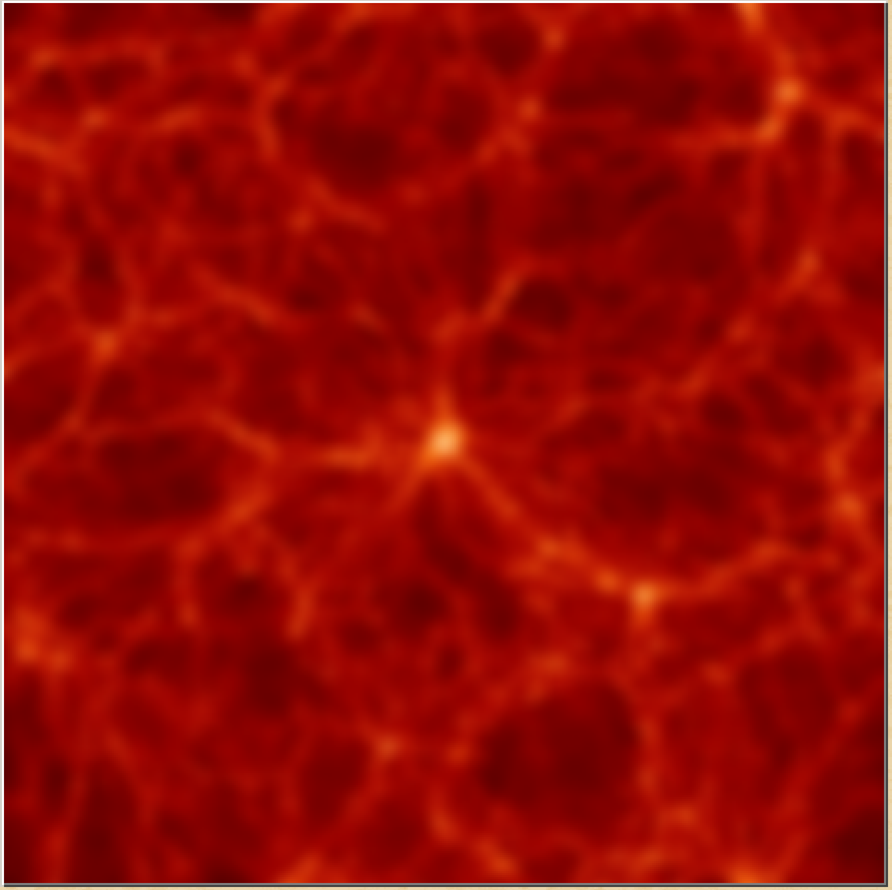
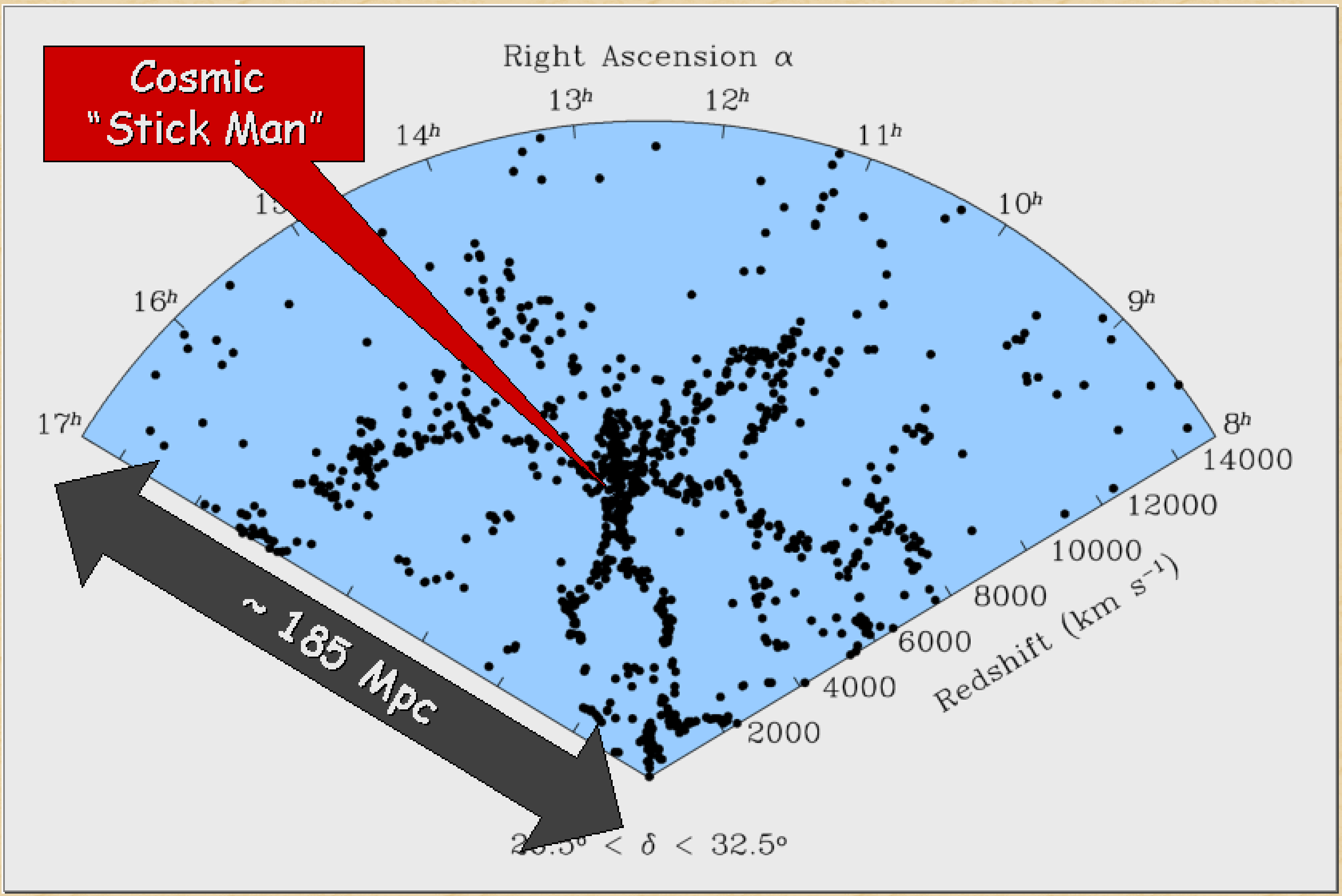




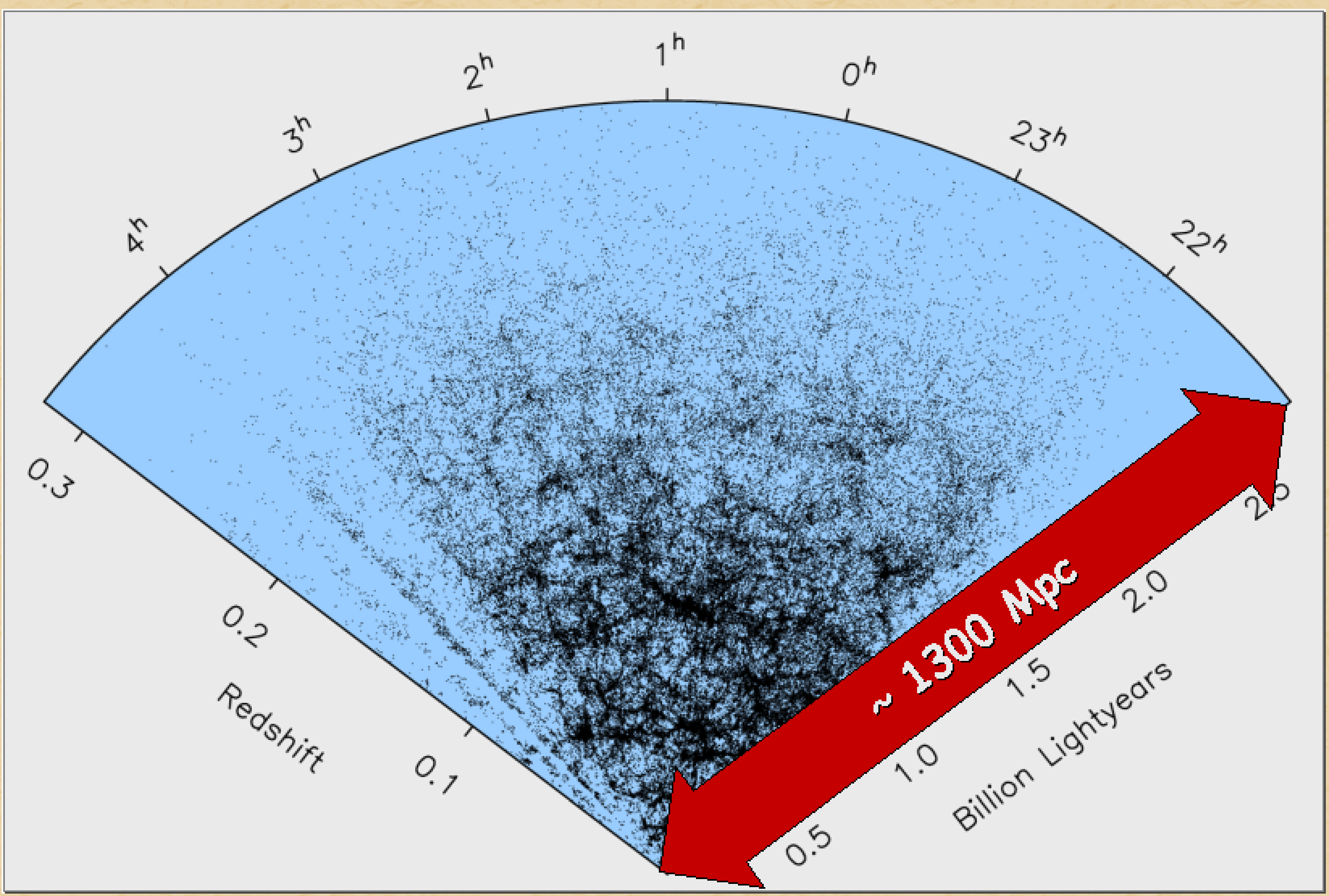
A fraction of hot dark matter suppresses small-scale structure

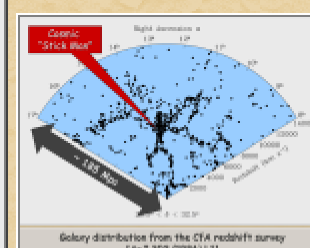
Galaxy Redshift Surveys



Galaxy distribution from the CfA redshift survey
[ApJ 302 (1986) L1]

Galaxy Redshift Surveys



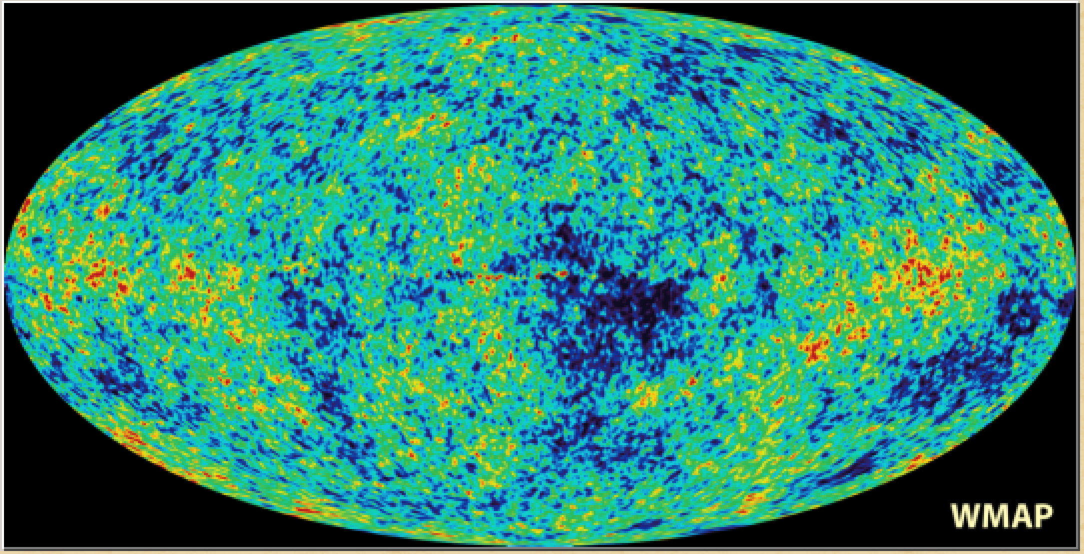


2dF Galaxy Redshift Survey (May 2002), Northern Slice
http://www.mso.anu.edu.au/2dFGRS/

Power Spectrum of CMBR Temperature Fluctuations

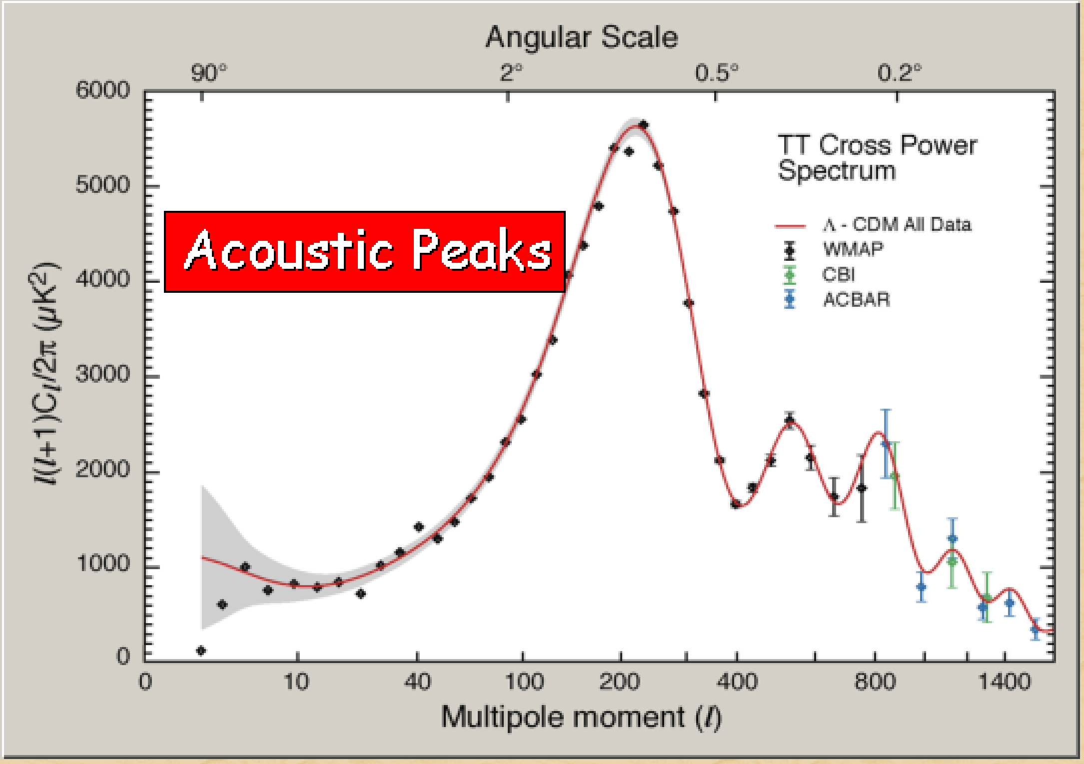
Sky map of CMBR temperature fluctuations

$$\Delta(\theta,\varphi) = \frac{T(\theta,\varphi) - \langle T \rangle}{\langle T \rangle}$$



Multipole expansion

$$\Delta(\theta,\varphi) = \sum_{\ell=0}^{\infty} \sum_{m=-\ell}^{\ell} a_{\ell m} Y_{\ell m}(\theta,\varphi)$$



Angular power spectrum

$$C_\ell = \left\langle a_{\ell m}^{*} a_{\ell m} \right\rangle = \frac{1}{2\ell+1} \sum_{m=-\ell}^{\ell} a_{\ell m}^{*} a_{\ell m}$$

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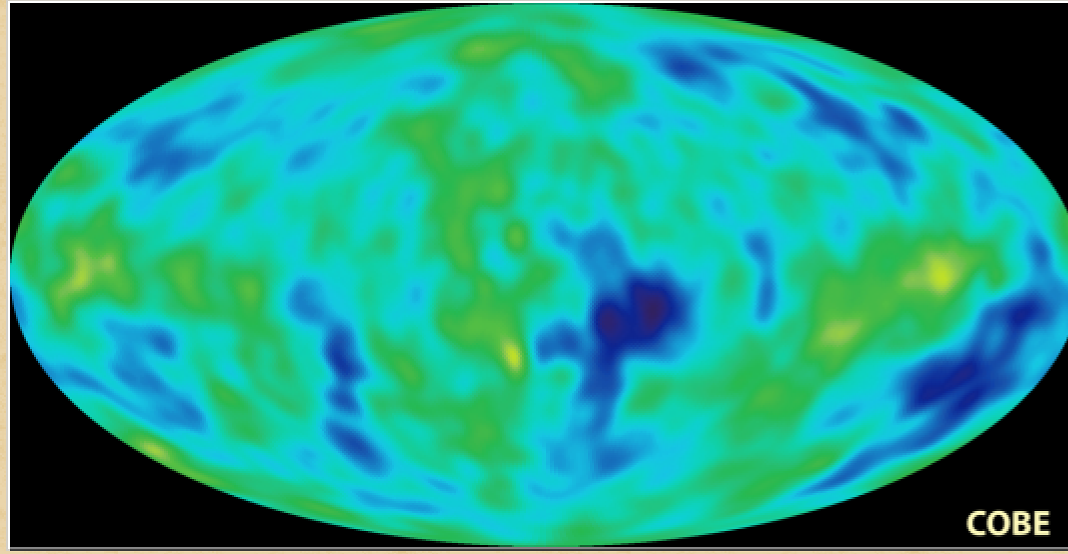

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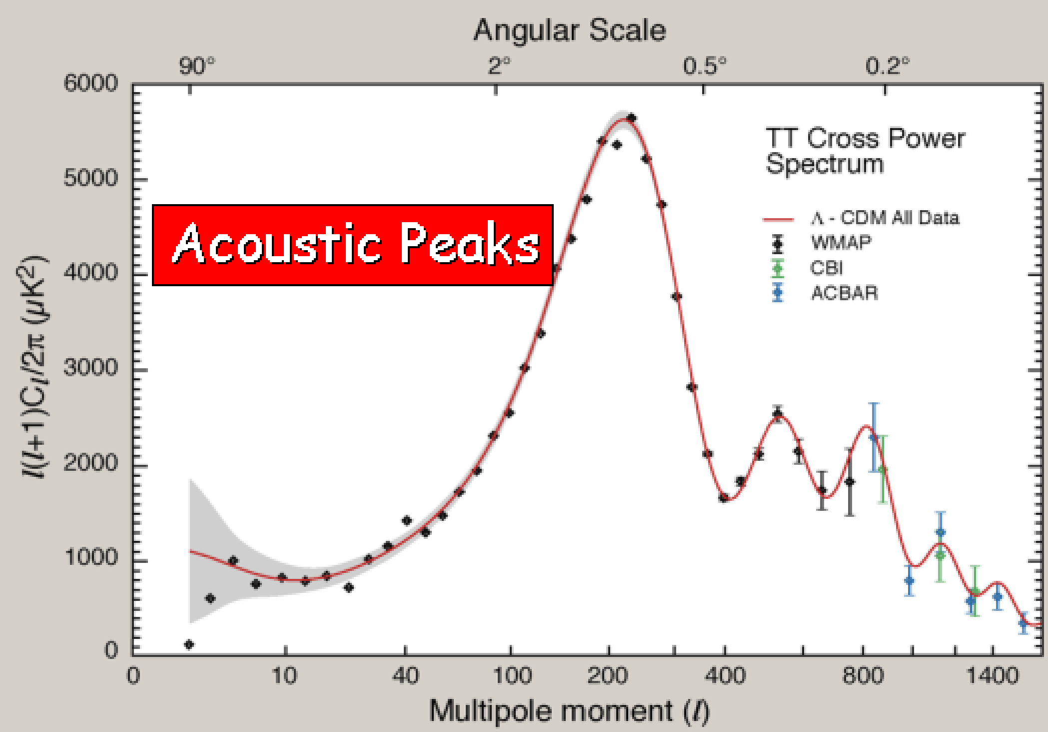


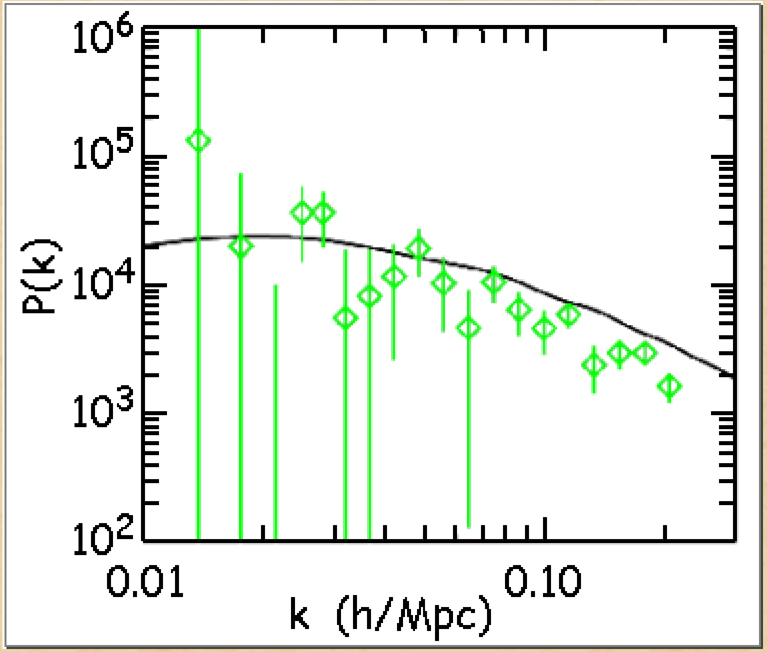
Angular power spectrum

$$C_\ell = \langle a_{\ell m}^* a_{\ell m} \rangle = \frac{1}{2\ell+1} \sum_{m=-\ell}^{\ell} a_{\ell m}^* a_{\ell m}$$

Cosmic Structure Modified by Hot Dark Matter

Galaxy Distribution (2dF, PSCz)

Scales 1–200 Mpc



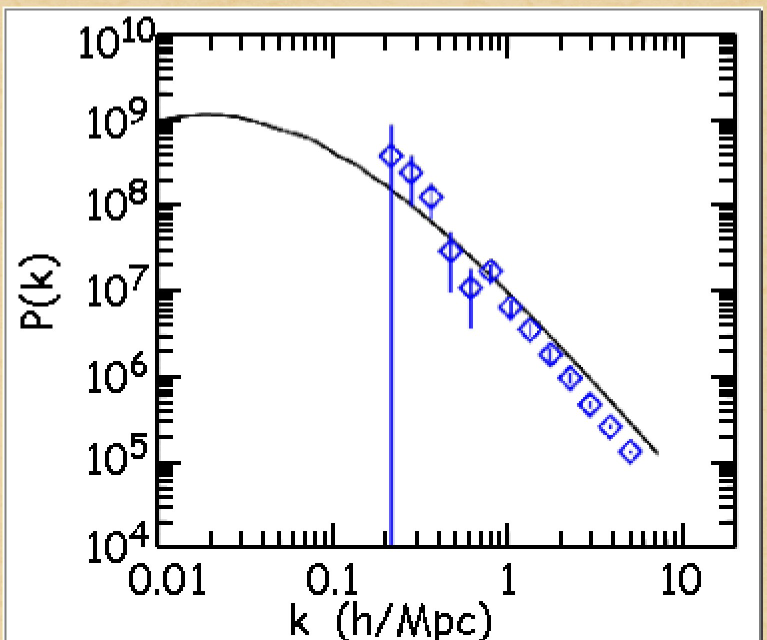
$\Omega_0 = 1$
$\Omega_\Lambda = 0.66$
$\Omega_B = 0.04$
$H_0 = 72$
$n_s = 0.94$

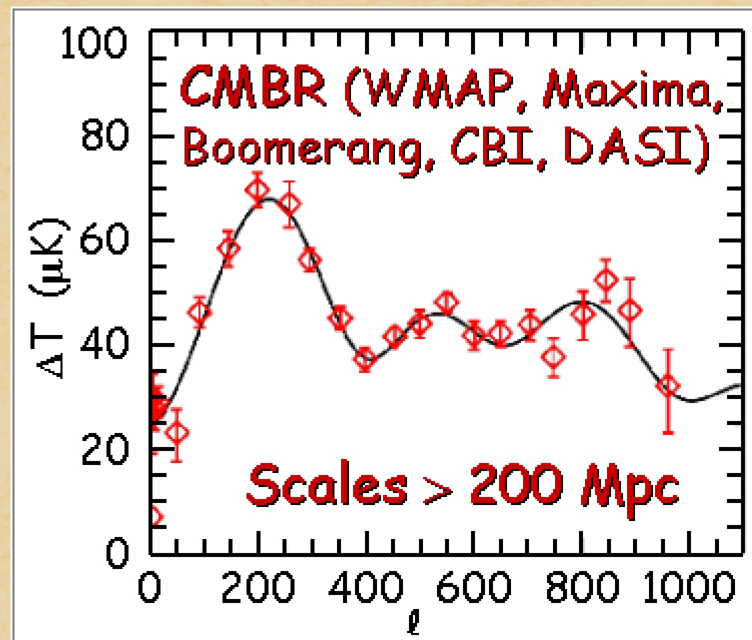
$\Omega_\nu = 0.00$

Adapted from S.Hannestad

Lyman-α forest at large redshift ⟨z⟩ = 2.72

Scales 0.1–10 Mpc

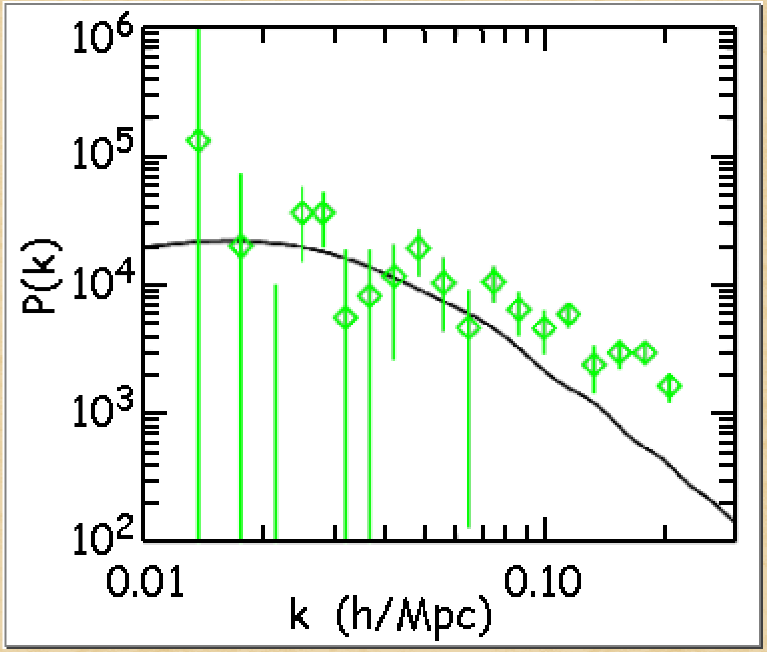




Cosmic Structure Modified by Hot Dark Matter

Galaxy Distribution (2dF, PSCz)

Scales 1–200 Mpc



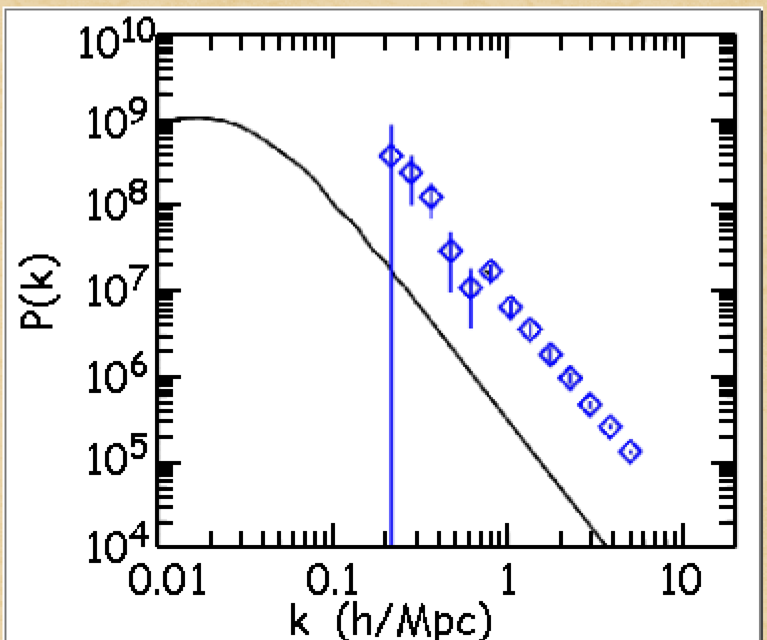
$\Omega_0 = 1$
$\Omega_\Lambda = 0.66$
$\Omega_B = 0.04$
$H_0 = 72$
$n_s = 0.94$

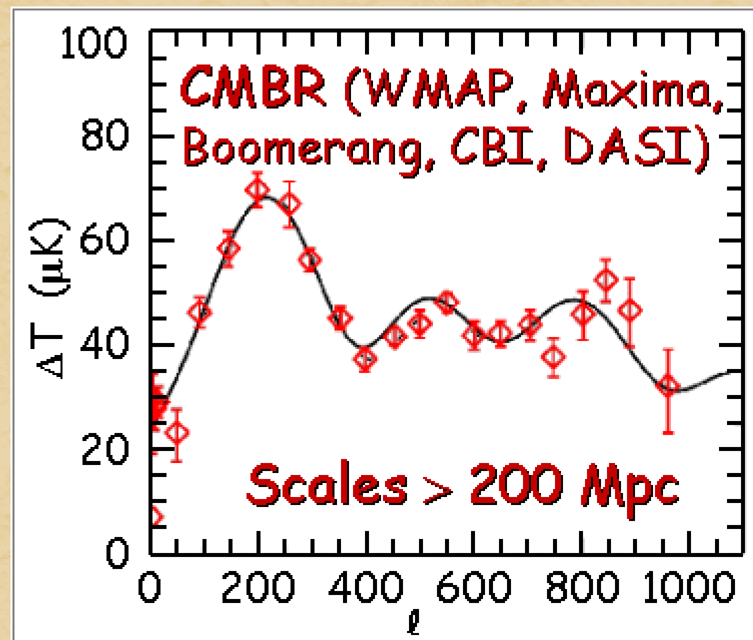
$\Omega_\nu = 0.10$

Adapted from S.Hannestad

Lyman-α forest at large redshift ⟨z⟩ = 2.72

Scales 0.1–10 Mpc





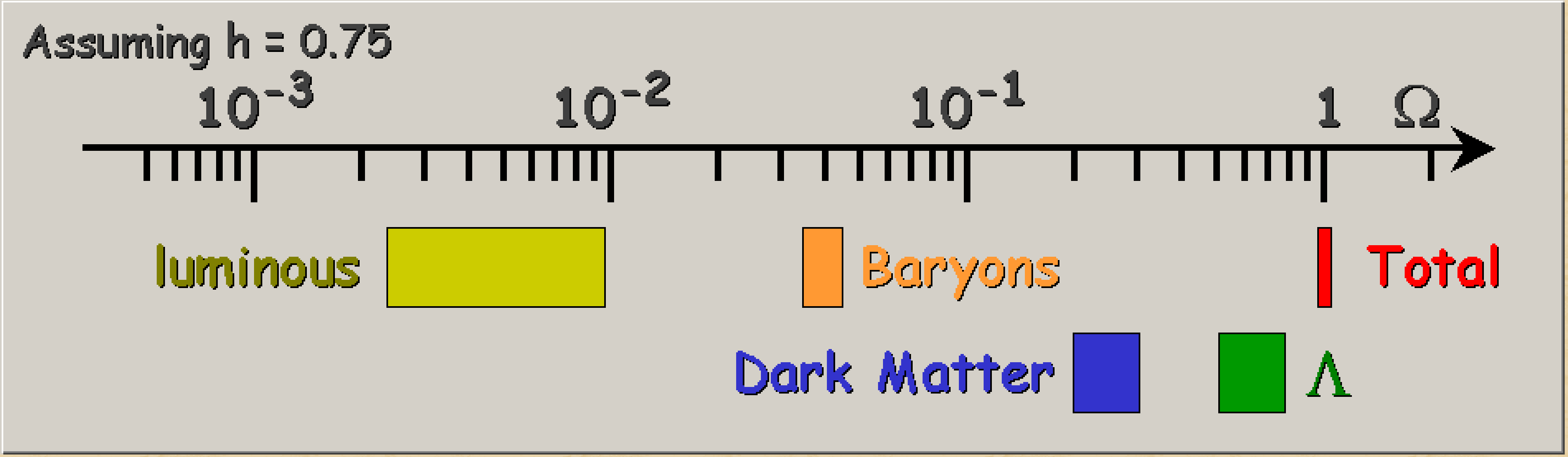
Neutrino Mass Limits from Large-Scale Structure

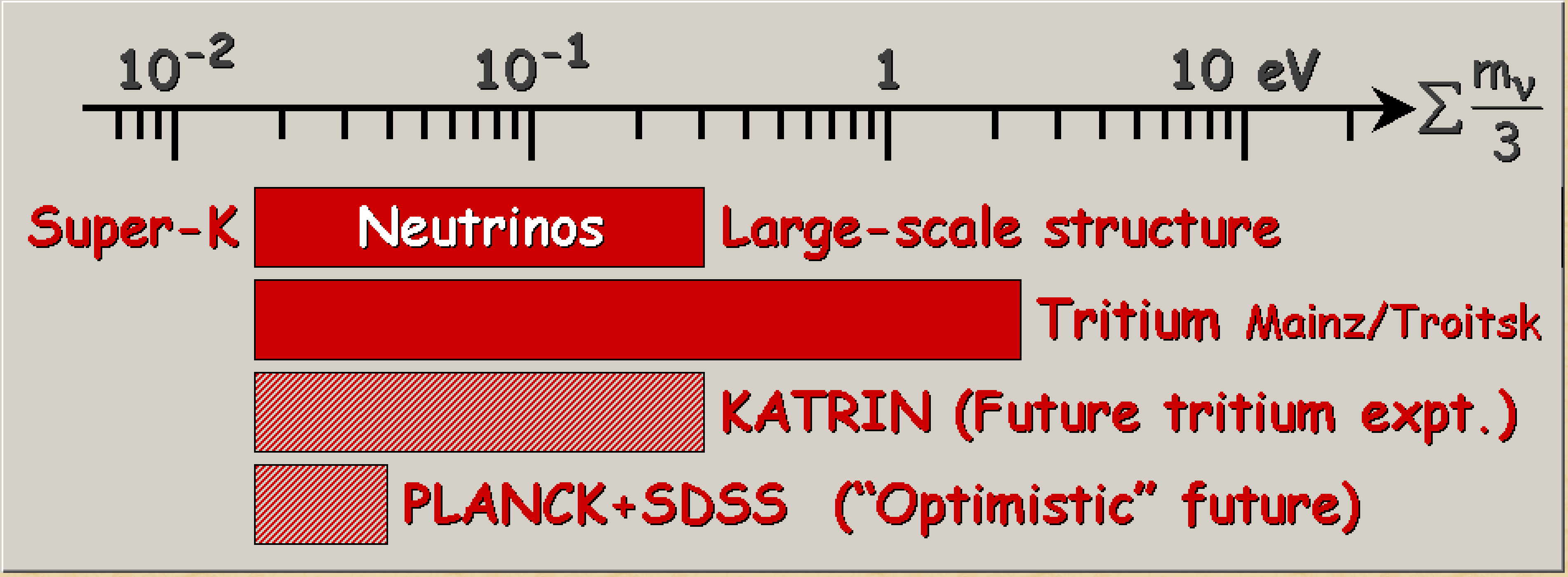
Statistical 95% C.L. limits depend on used data and on priors for other parameters. For detailed analyses see

- Hannestad, astro-ph/0303076
- Elgaroy & Lahav, astro-ph/0303089

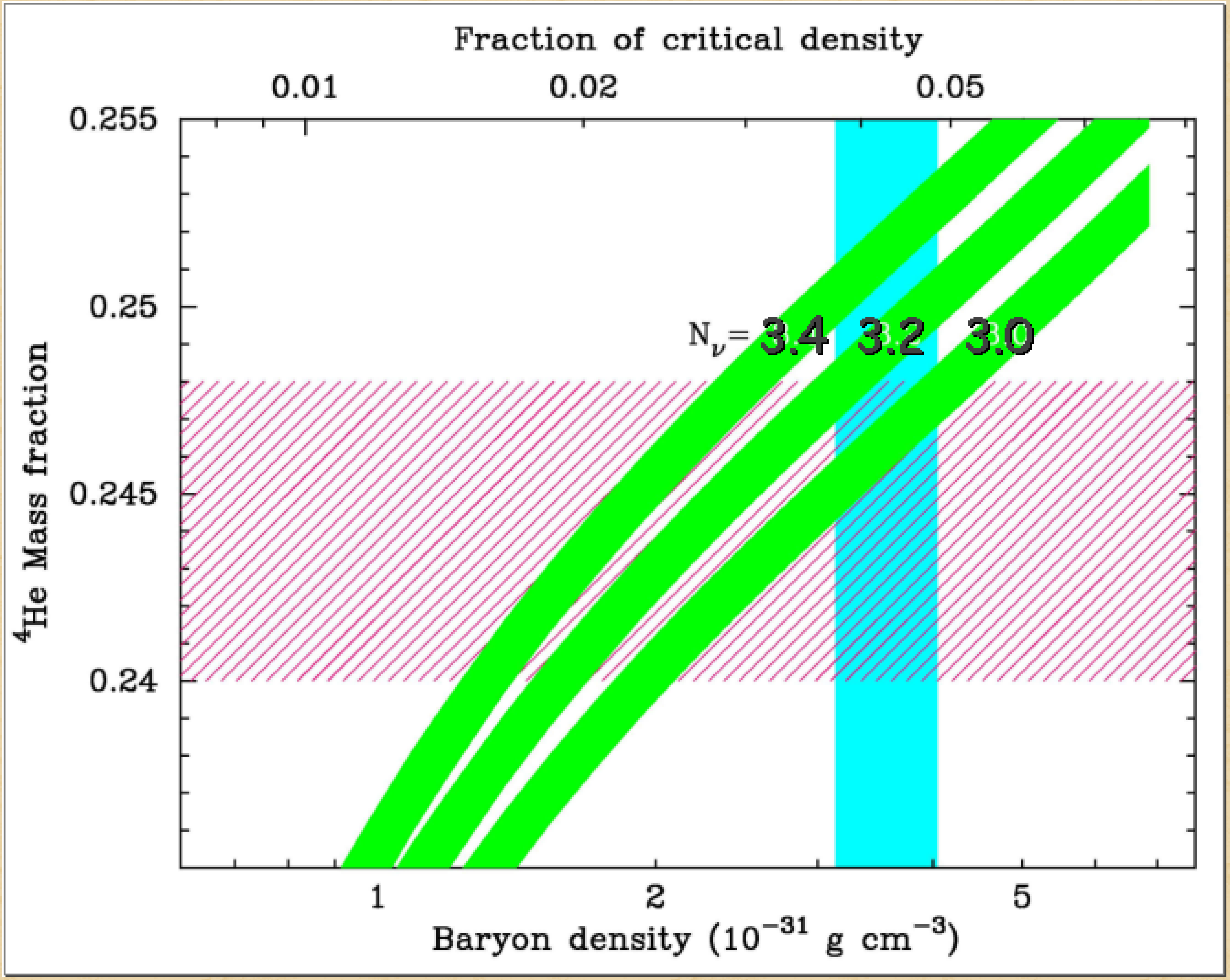
$\Sigma m_\nu < 2.1$ eV	2dF (Galaxy-galaxy correlation) + WMAP (Cosmic microwaves)
$\Sigma m_\nu < 1.2$ eV	+ Small-scale CMBR (breaks degeneracy with bias)
$\Sigma m_\nu < 1.0$ eV	+ Priors (1σ) $h = 0.72 \pm 0.08$ $\Omega_M = 0.28 \pm 0.14$
$\Sigma m_\nu < 0.7$ eV	+ Lyman-α forest data

Mass-Energy-Inventory of the Universe





BBN Limits on Neutrino Flavors



- At BBN one flavor contributes about 16% to cosmic mass-energy density
- Extra flavors modify expansion parameter accordingly

Conservative limit
$|\Delta N_{eff}| < 1$

Burles, Nollett & Turner, astro-ph/9903300

BBN and Neutrino Chemical Potentials

Expansion Rate Effect (all flavors)

Energy density in one neutrino flavor with degeneracy parameter $\xi = \eta/T$

$$\rho_{\nu\bar\nu} = \frac{7\pi^2}{120} T_\nu^4 \left[1 + \underbrace{\frac{30}{7}\left(\frac{\xi}{\pi}\right)^2 + \frac{15}{7}\left(\frac{\xi}{\pi}\right)^4}_{\Delta N_{eff}} \right]$$

Beta equilibrium effect for electron flavor

$n + \nu_e \leftrightarrow p + e^-$

Helium abundance essentially fixed by n/p ratio at beta freeze-out

$$\frac{n}{p} = e^{-(m_n - m_p)/T - \xi_{\nu_e}}$$

Effect on helium equivalent to $\Delta N_{eff} \sim -18\, \xi_{\nu e}$

$|\Delta N_{eff}| < 1$ → $|\xi_{\nu e}| < 0.06$

- ν_e beta effect can compensate expansion-rate effect of $\nu_{\mu,\tau}$
- No significant BBN limit on neutrino number density

Chemical Potentials and Flavor Oscillations

Flavor mixing (neutrino oscillations)

Flavor lepton numbers not conserved

Only one common nu chemical potential

Stringent ξ_{ν_e} limit applies to all flavors

$|\xi_{\nu_{e,\mu,\tau}}| < 0.07$

Extra neutrino density

$\Delta N_{eff} < 0.0064$

Cosmic neutrino density close to standard value

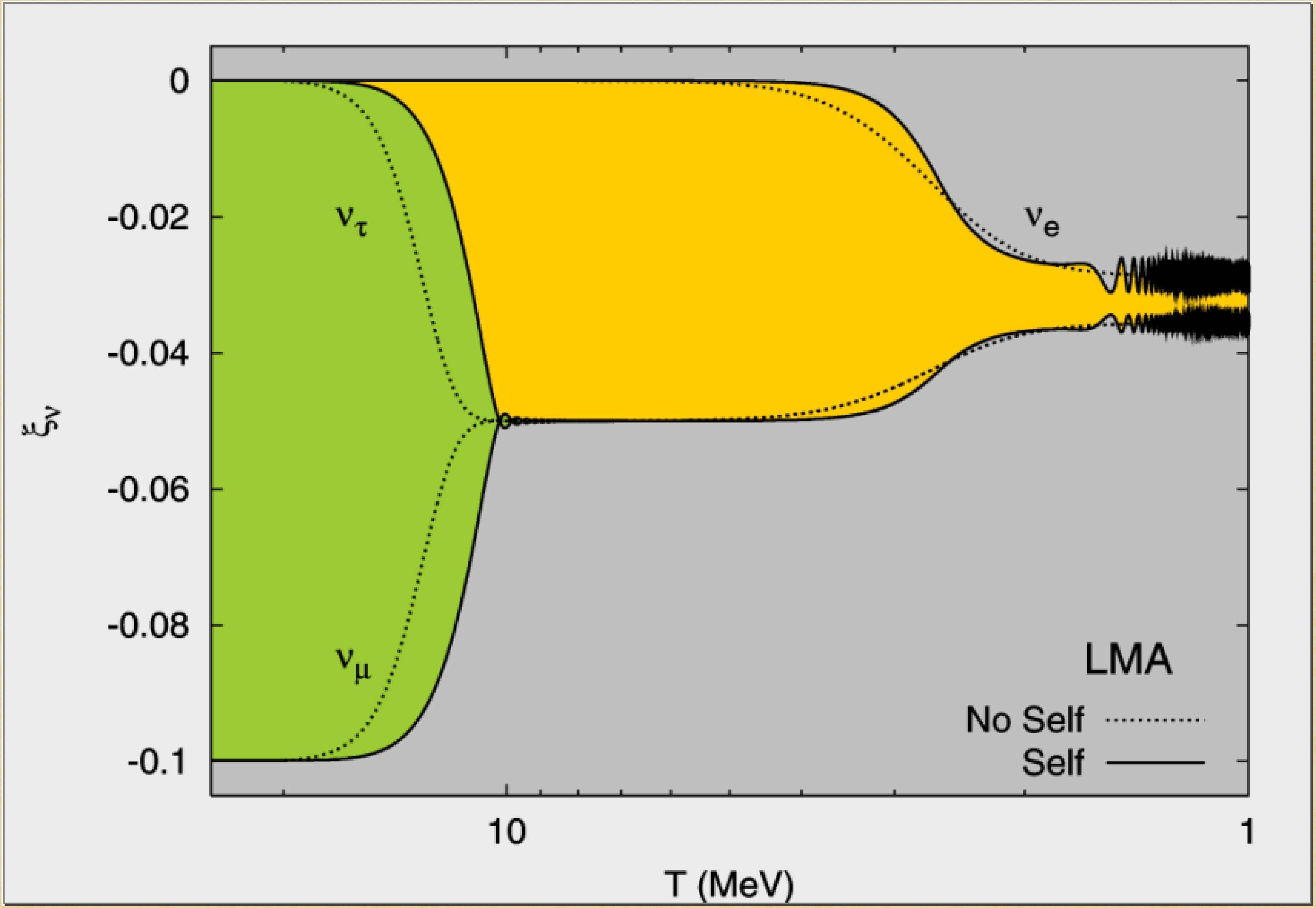
Flavor equilibrium before n/p freeze out?

yes	Solar LMA solution
maybe	LOW (depends on Θ_{13})
no	SMA or VAC

- Our knowledge of the cosmic nu density depends on the solution of the solar neutrino problem
- KamLAND most relevant experiment

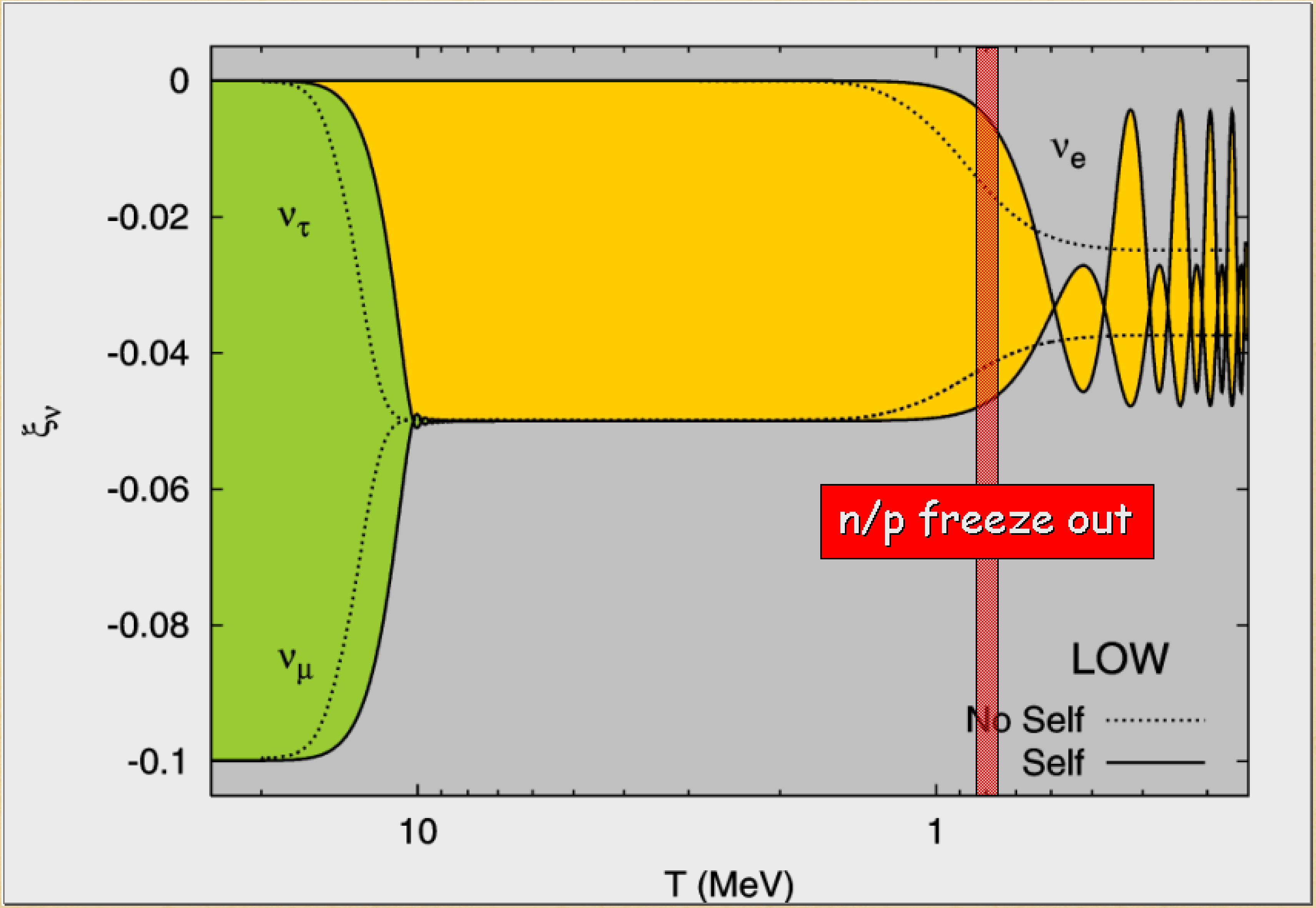
- Lunardini & Smirnov, hep-ph/0012056
- Dolgov, Hansen, Pastor, Petcov, Raffelt & Semikoz, hep-ph/0201287
- Abazajian, Beacom & Bell, astro-ph/0203442
- Wong, hep-ph/0203180

Flavor Equilibration: LMA Solution



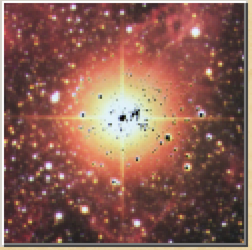
Dolgov, Hansen, Pastor, Petcov, Raffelt & Semikoz, hep-ph/0201287

Flavor Equilibration: LOW Solution

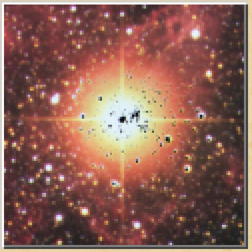


Dolgov, Hansen, Pastor, Petcov, Raffelt & Semikoz, hep-ph/0201287

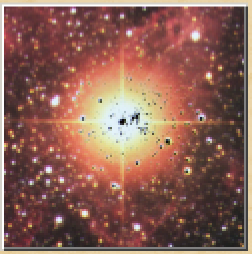
Neutrinos in Physics and Astrophysics



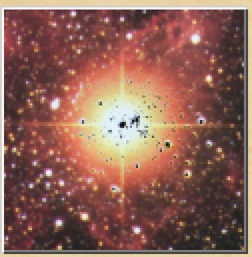
Flavor oscillations and all that



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

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

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

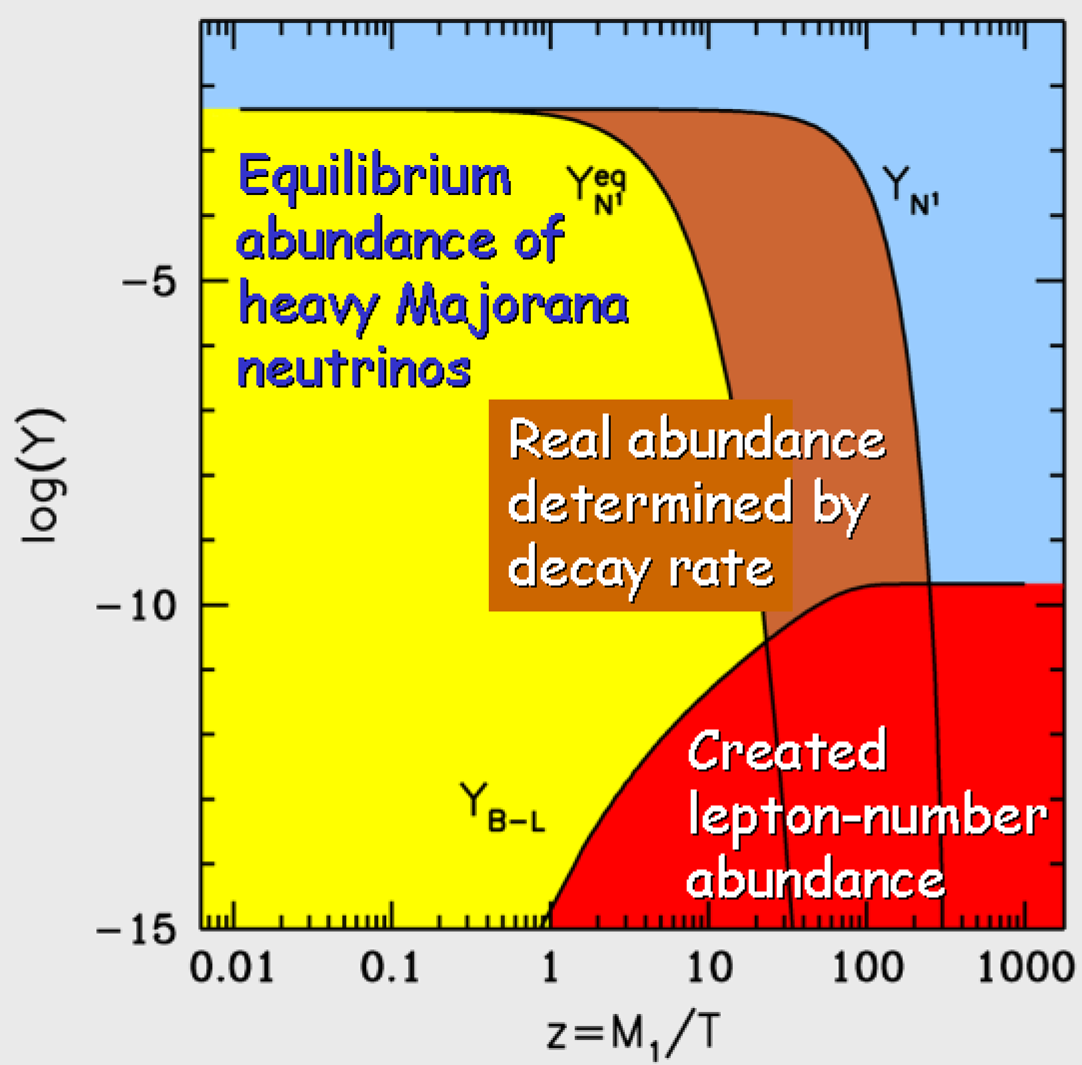
$$\begin{pmatrix} \bar{\nu}_L & \bar{N}_R \end{pmatrix} \begin{pmatrix} 0 & g_\nu \langle\phi\rangle \\ g_\nu \langle\phi\rangle & M \end{pmatrix} \begin{pmatrix} \nu_L \\ N_R \end{pmatrix}$$

Diagonalize

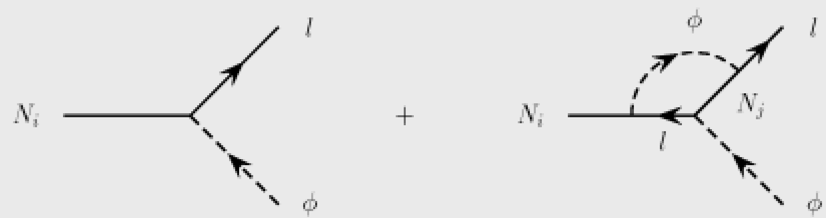
Light Majorana mass

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

Leptogenesis by Out-of-Equilibrium Decay



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



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

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 0.1 eV

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

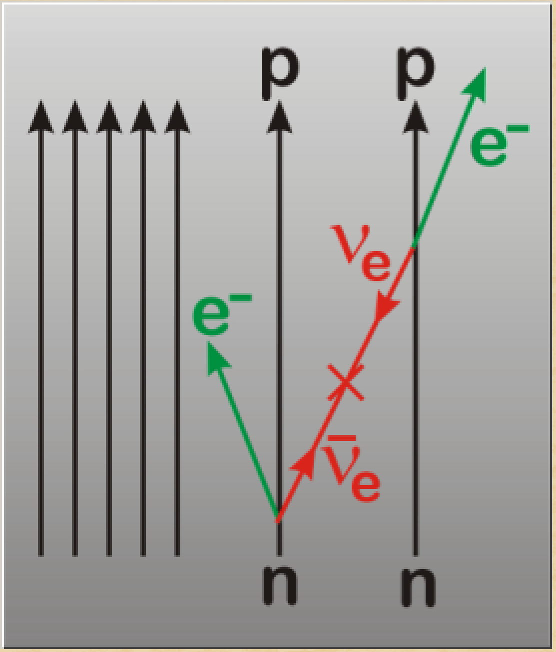
Leptogenesis – A Popular Research Topic

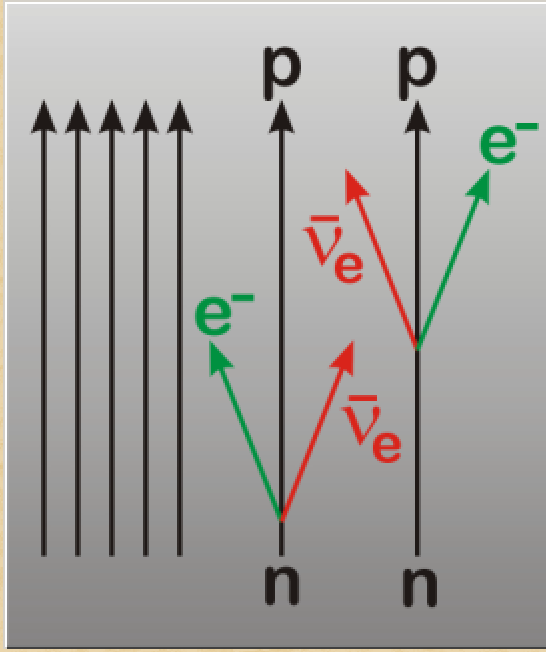
- Fukugita & Yanagida, PLB 174 (1986) 45
- Langacker, Peccei & Yanagida, Mod. Phys. Lett. A 1 (1986) 541
- Campbell, Davidson & Olive, NPB 399 (1993) 111
- Gherghetta & Jungmann, PRD 48 (1993) 1546
- Muryama & Yanagida, PLB 322 (1994) 349
- Worah, PRD 53 (1996) 3902
- Jeannerot, PRL 77 (1996) 3292
-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

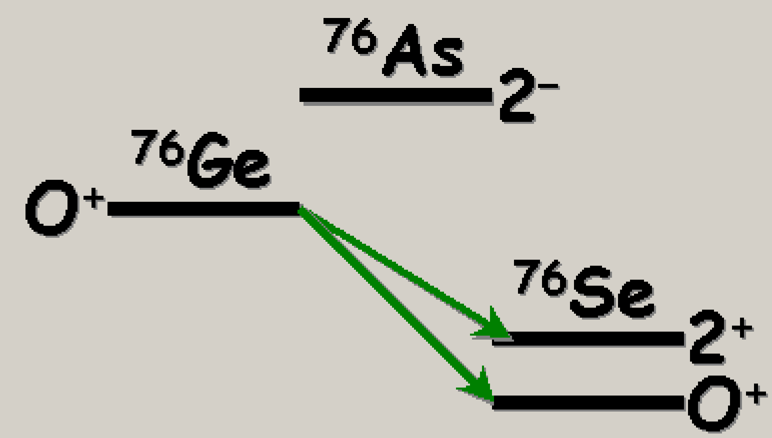
0ν mode, enabled by Majorana mass

Standard 2ν mode





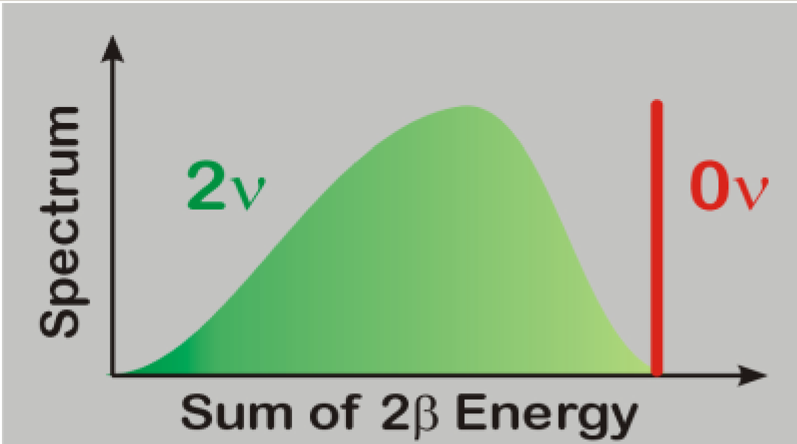
Some nuclei decay only by the ββ mode, e.g.



Half life ~ 10^{21} yr

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

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



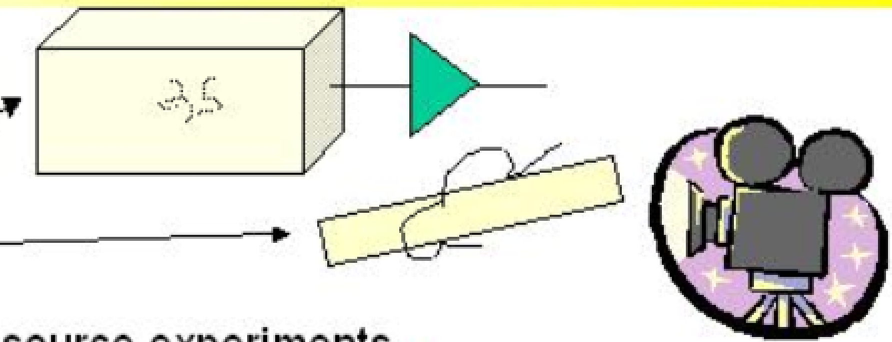
Summary of Current Neutrinoless ββ Decay Limits

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)	$\langle m_\nu \rangle$ (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	$^{130/128}$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

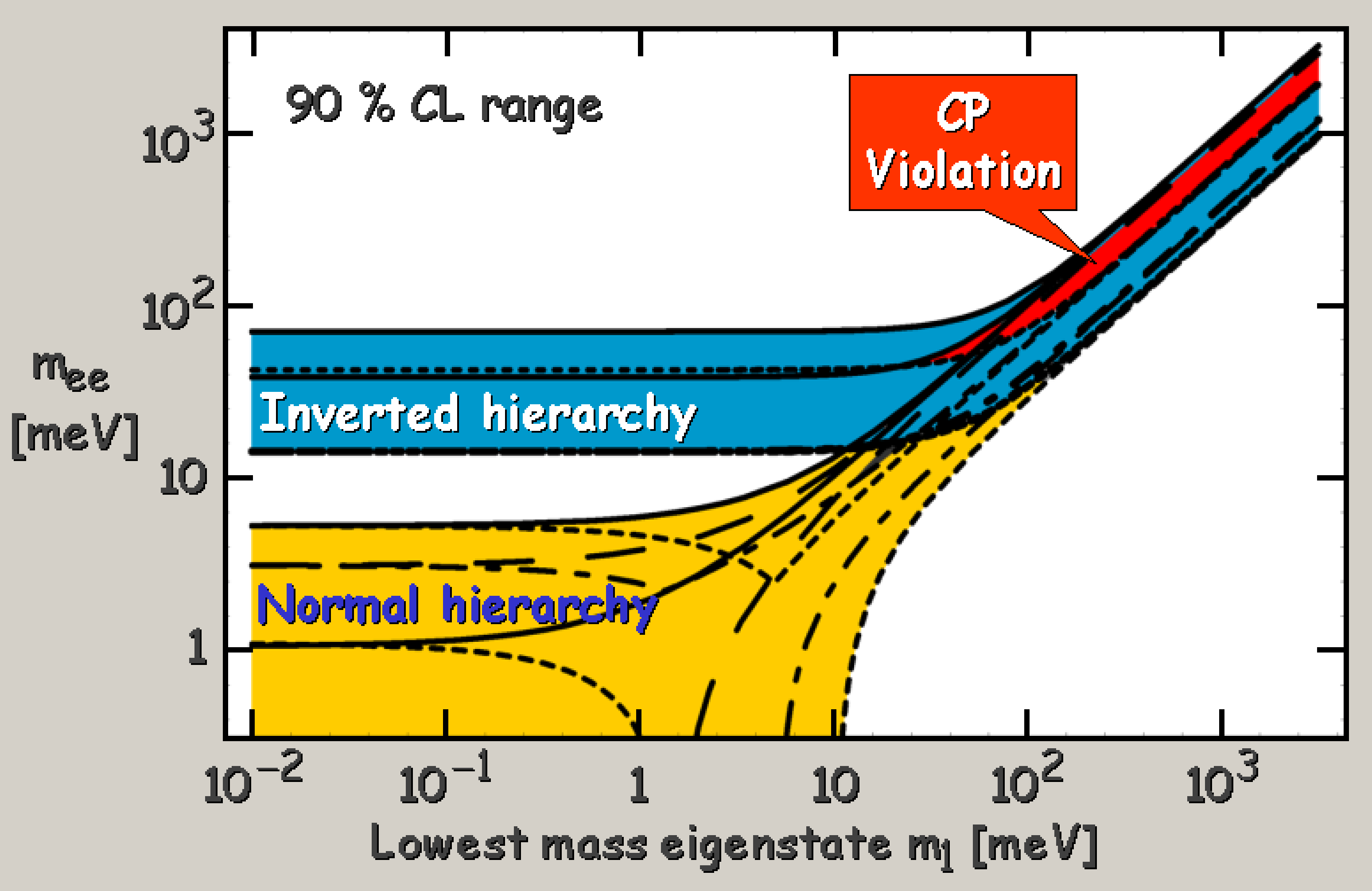
O.Cremonesi at Neutrino 2002

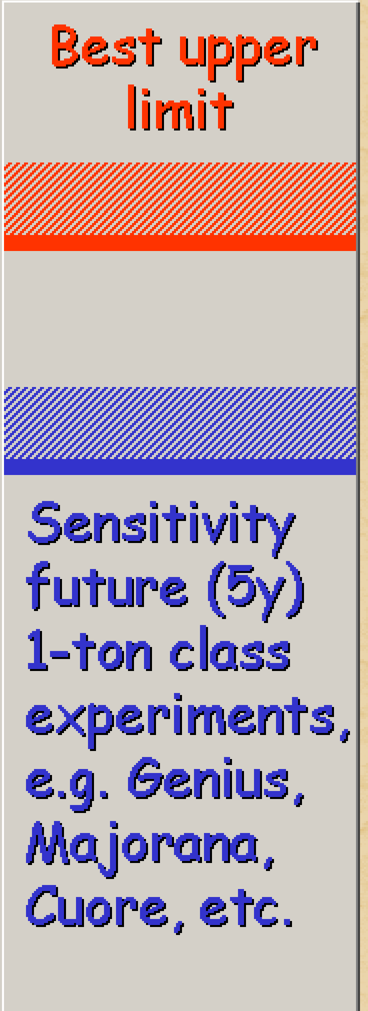
Future projects

Experiment	Author	Isotope	Detector description	$T^{5y}_{1/2}(y)$	$\langle m_\nu \rangle^*$
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 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

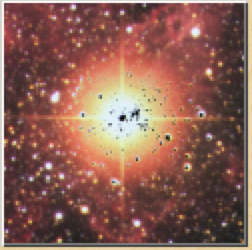
Effective Majorana Mass in Plausible Scenarios



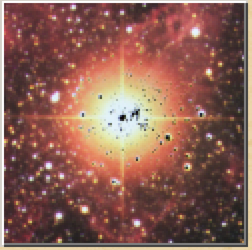


Pascoli & Petcov, hep-ph/0205022
See also Feruglio, Strumia & Vissani, hep-ph/0201291
Klapdor-Kleingrothaus, Päs & Smirnov, hep-ph/0103076, and others

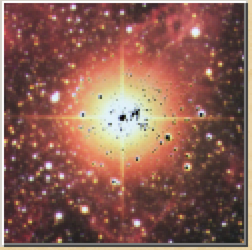
Neutrinos in Physics and Astrophysics



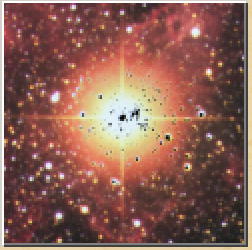
Flavor oscillations and all that



Quest for the absolute mass scale

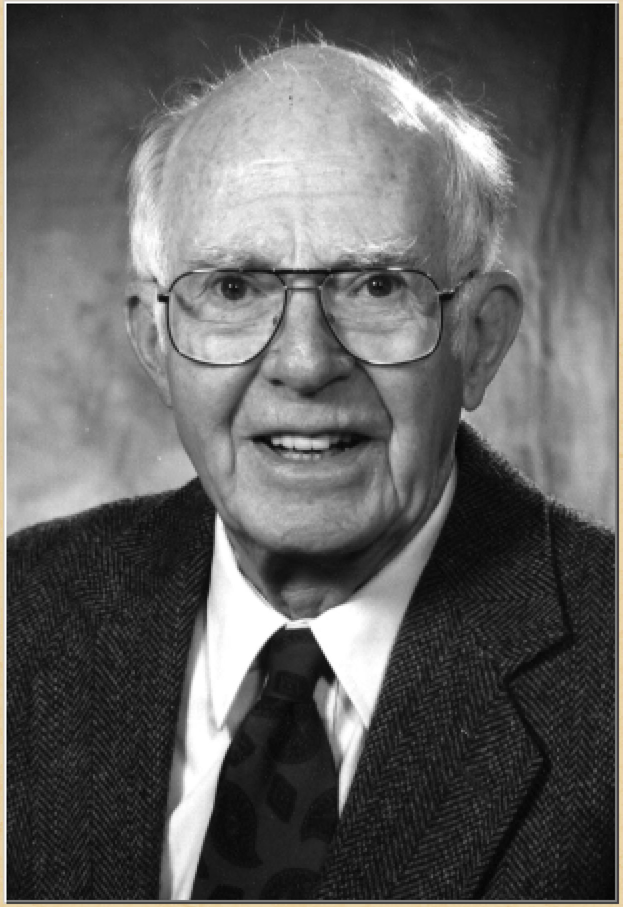


Neutrino mass and the
baryon asymmetry of the universe



Neutrinos as astrophysical messengers

2002 Physics Nobel Prize for Neutrino Astronomy



Ray Davis Jr.
(*1914)

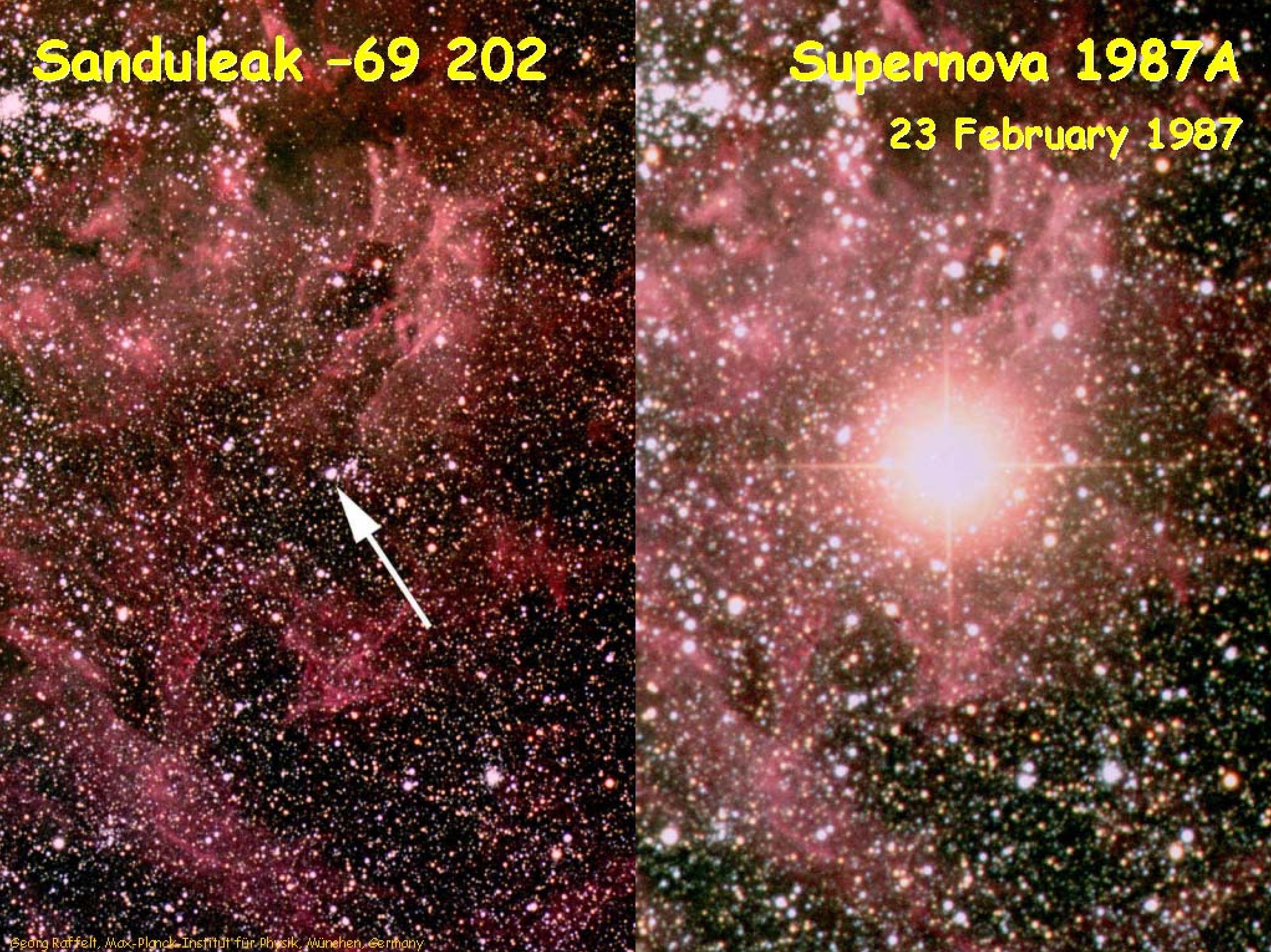
Masatoshi Koshiba
(*1926)

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

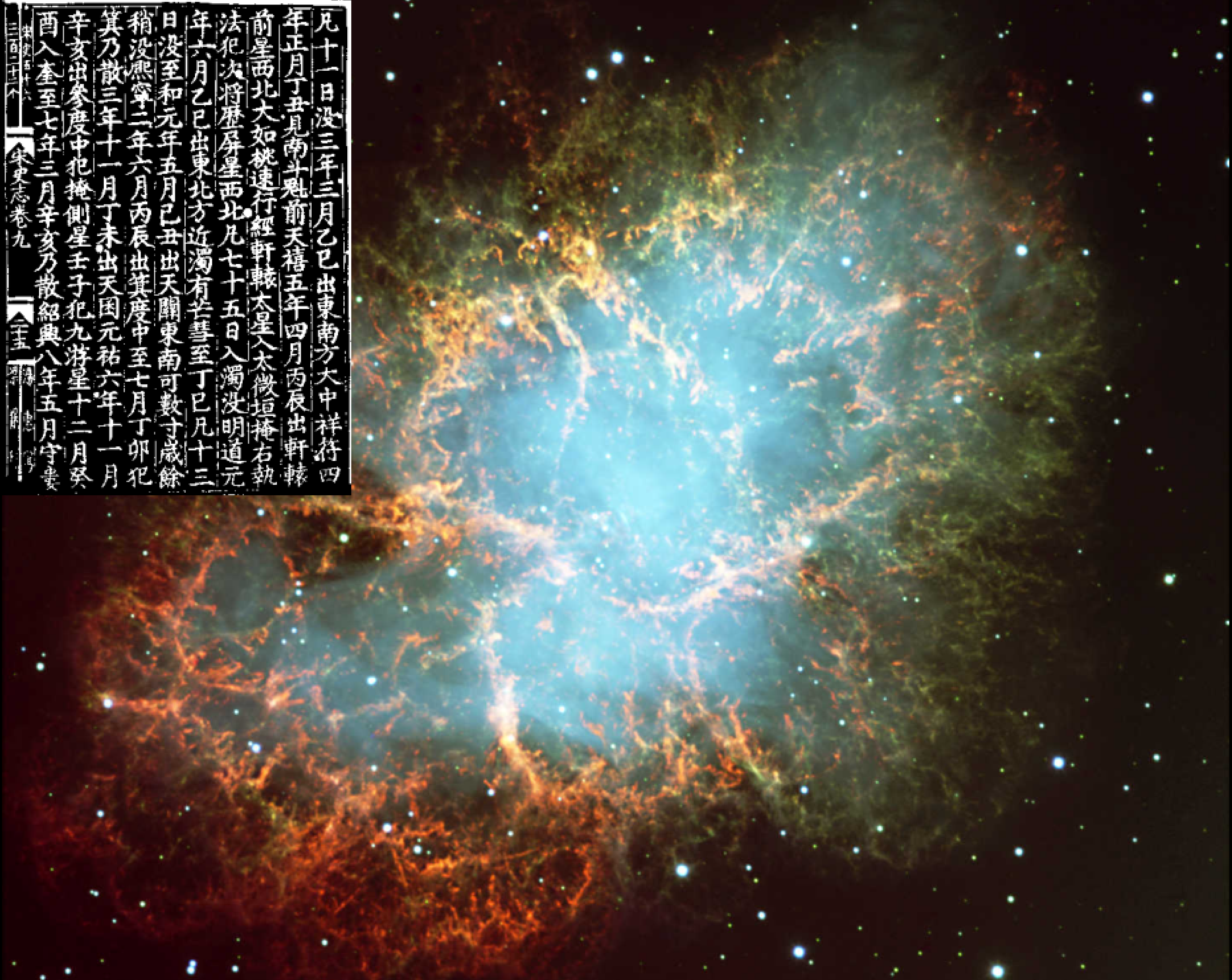

Sanduleak -69 202


Tarantula Nebula


Large Magellanic Cloud
Distance 50 kpc
(160.000 light years)



Sanduleak -69 202
Supernova 1987A
23 February 1987
Georg Raffelt, Max-Planck-Institut für Physik, München, Germany



凡十一日沒三年三月乙巳出東南方大中祥符四年正月丁丑見南斗魁前天禧五年四月丙辰出軒轅前星西北大如桃速行經軒轅太星入太微垣掩右執法犯次將歷屏星西北凡七十五日入濁沒明道元年六月乙巳出東北方近濁有芒彗至丁巳凡十三日沒至和元年五月己丑出天關東南可數寸歲餘稍沒熙寧二年六月丙辰出箕度中至七月丁卯犯箕乃散三年十一月丁未出天囷元祐六年十一月辛亥出參度中犯掩側星壬子犯九游星十二月癸酉入奎至七年三月辛亥乃散紹興八年五月守婁

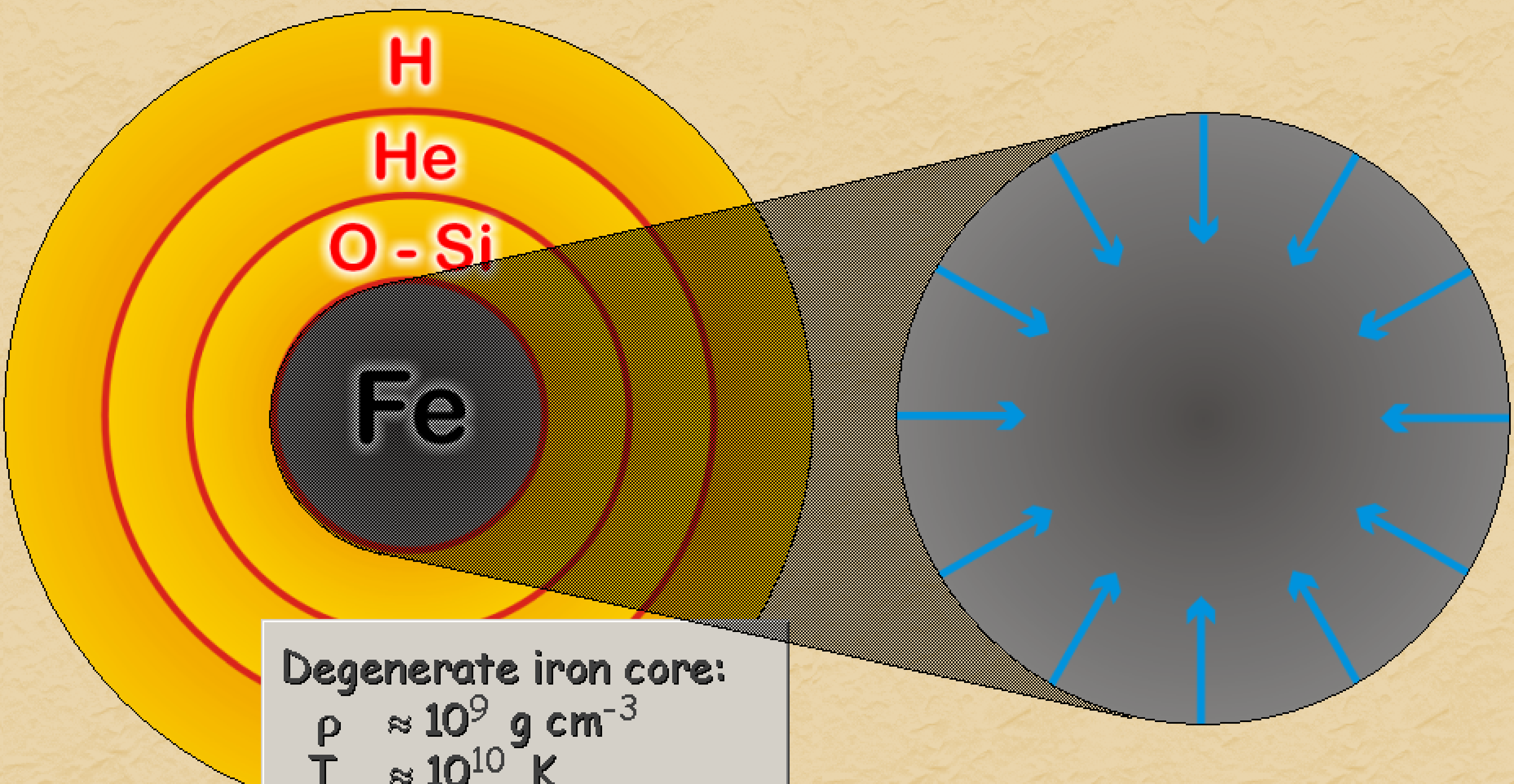
宋史志卷九

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

Stellar Collapse and Supernova Explosion

Onion Structure

Collapse (Implosion)



Degenerate iron core:

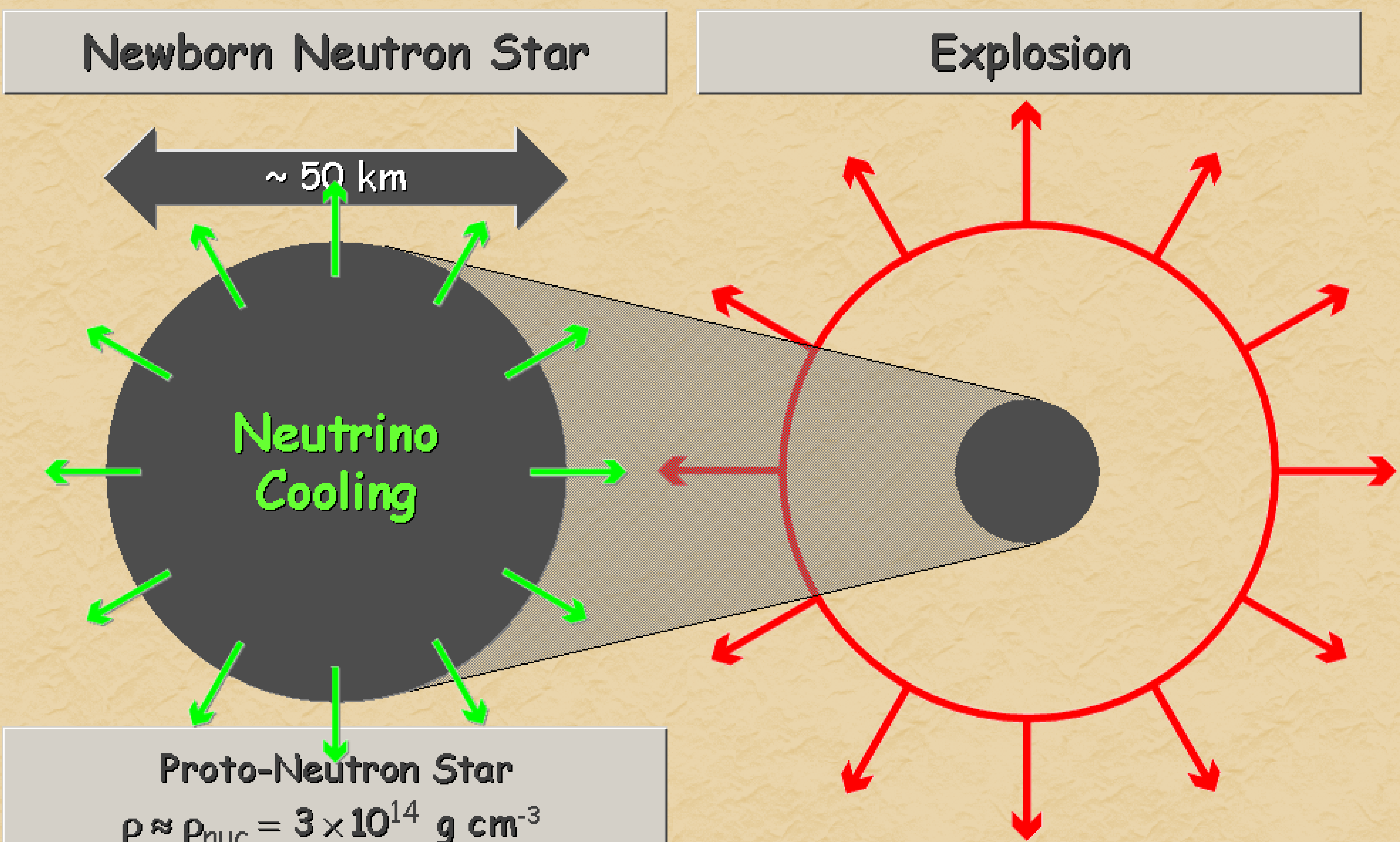
$\rho \approx 10^9$ g cm^{-3}

$T \approx 10^{10}$ K

$M_{Fe} \approx 1.5\ M_{sun}$

$R_{Fe} \approx 8000$ km

Stellar Collapse and Supernova Explosion



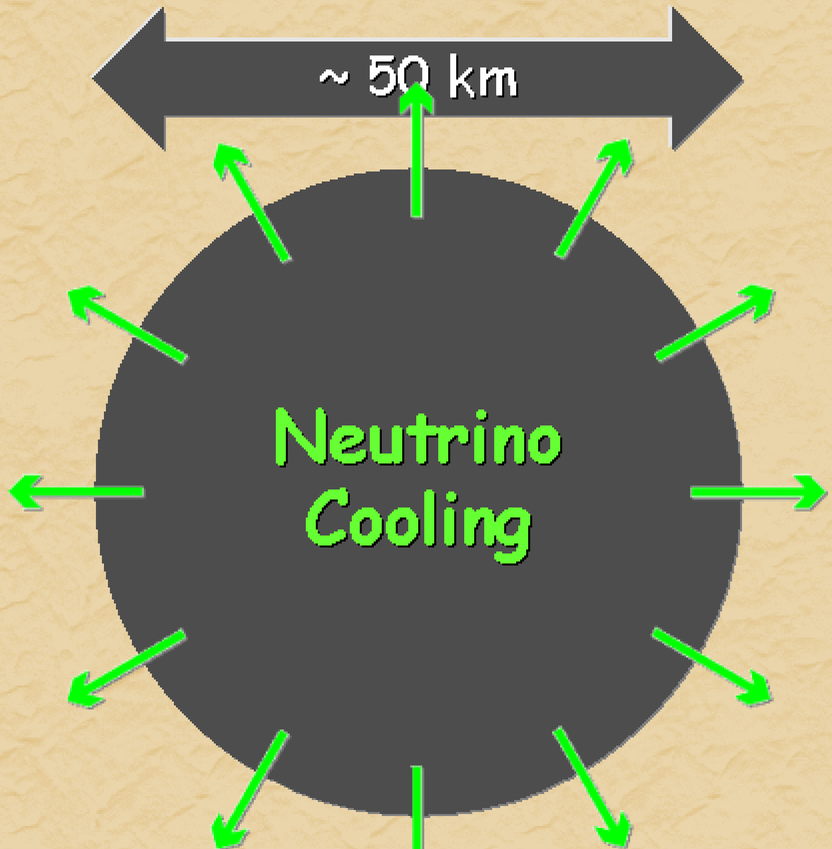
Proto-Neutron Star

$\rho \approx \rho_{nuc} = 3 \times 10^{14}\ \mathrm{g\ cm^{-3}}$

$T \approx 30\ \mathrm{MeV}$

Stellar Collapse and Supernova Explosion

Newborn Neutron Star



Proto-Neutron Star

$\rho \approx \rho_{nuc} = 3 \times 10^{14}\ \mathrm{g\ cm^{-3}}$

$T \approx 30\ \mathrm{MeV}$

Gravitational binding energy

$E_b \approx 3 \times 10^{53}\ \mathrm{erg} \approx 17\%\ M_{SUN}\, c^2$

This shows up as

- 99% Neutrinos
- 1% Kinetic energy of explosion (1% of this into cosmic rays)
- 0.01% Photons, outshine host galaxy

Neutrino luminosity

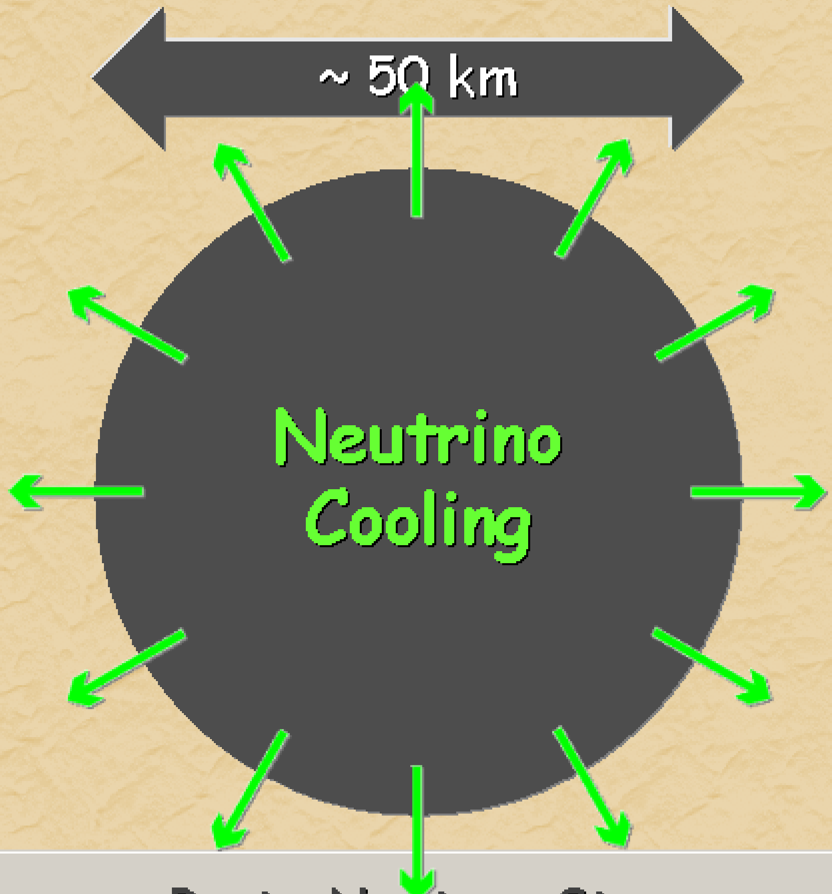
$L_\nu \approx 3 \times 10^{53}\ \mathrm{erg} / 3\ \mathrm{sec}$

$\approx 3 \times 10^{19}\ L_{SUN}$

While it lasts, outshines the entire visible universe

Stellar Collapse and Supernova Explosion

Newborn Neutron Star



Proto-Neutron Star

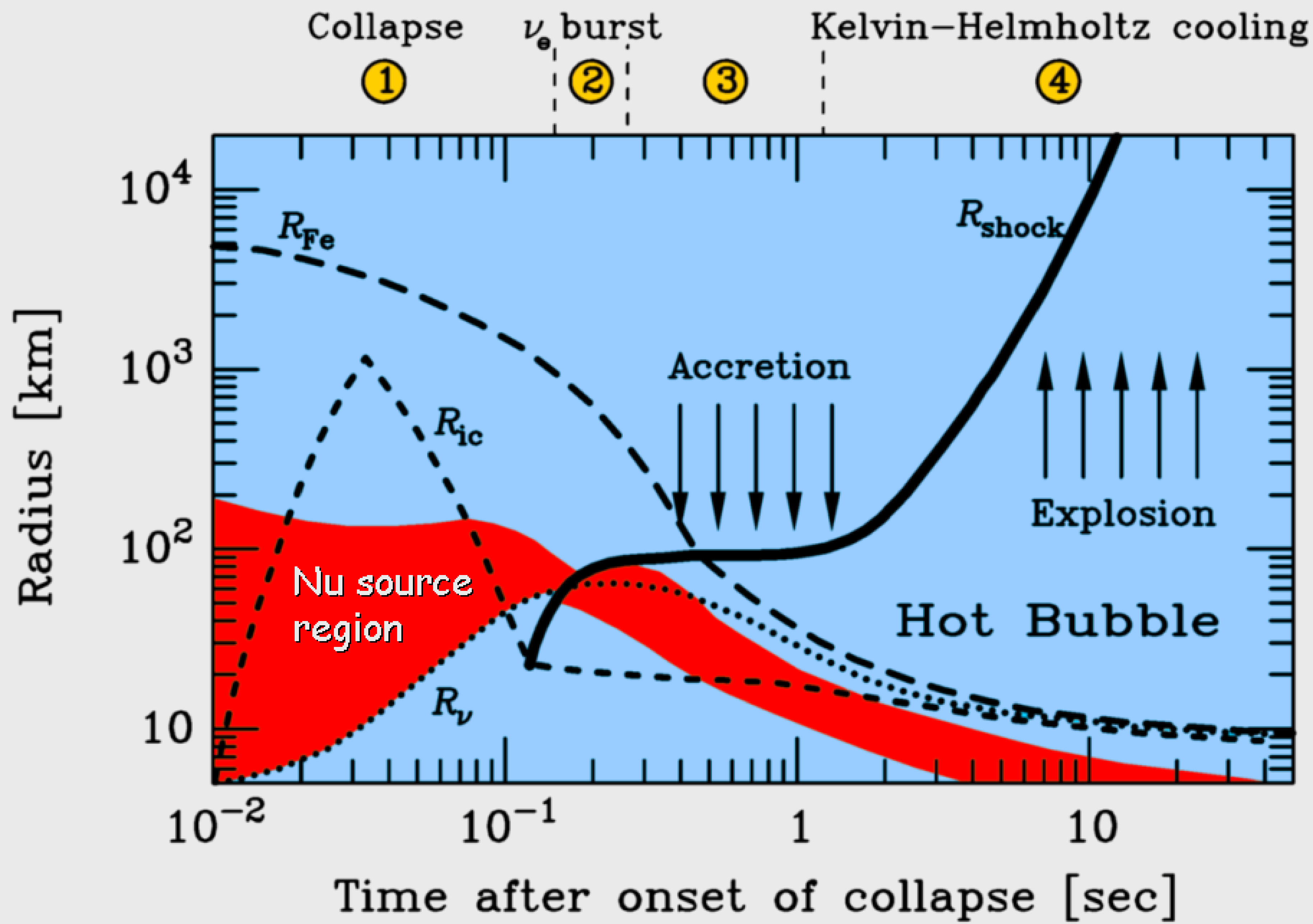
$\rho \approx \rho_{nuc} = 3 \times 10^{14}\ \mathrm{g\ cm^{-3}}$

$T \approx 30\ \mathrm{MeV}$

<u>Neutrino Trapping</u>

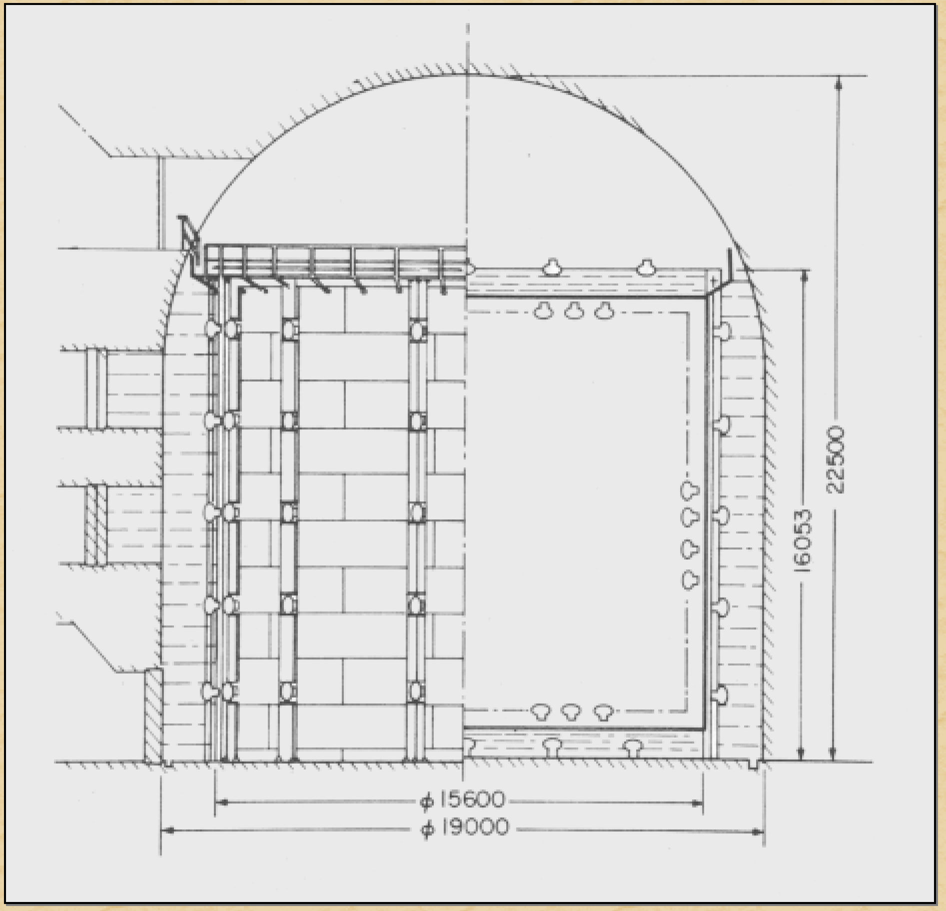
- Neutron star so hot and dense that neutrinos are trapped
- Cooling time scale governed by diffusion time scale
- Neutrinos of all flavors emitted from neutron-star surface
- Essentially a blackbody source for all neutrino flavors
- Oscillation physics:
  Subtle flavor-dependent spectrum and flux differences important

Supernova Collapse and Explosion

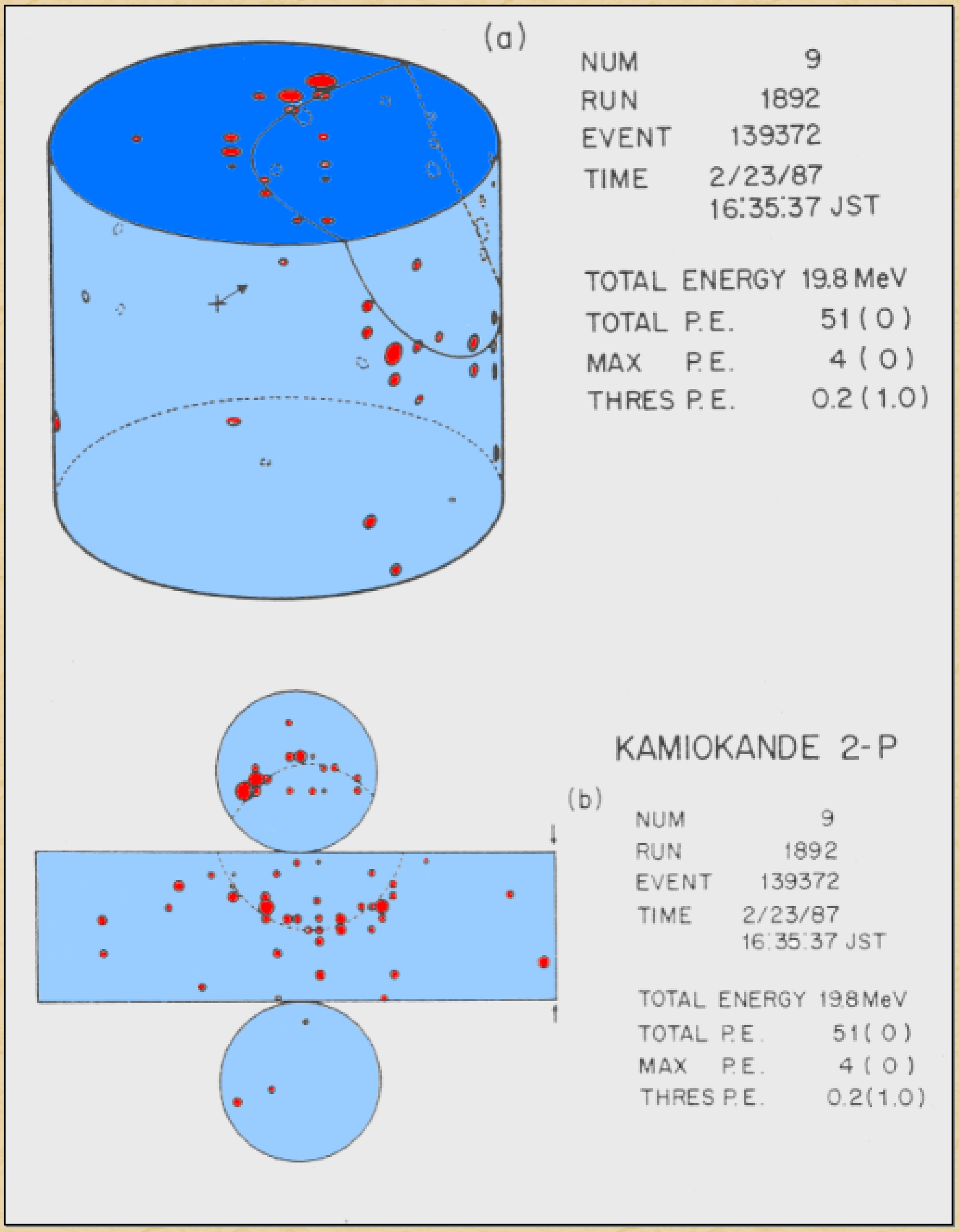


SN 1987A Event No.9 in Kamiokande

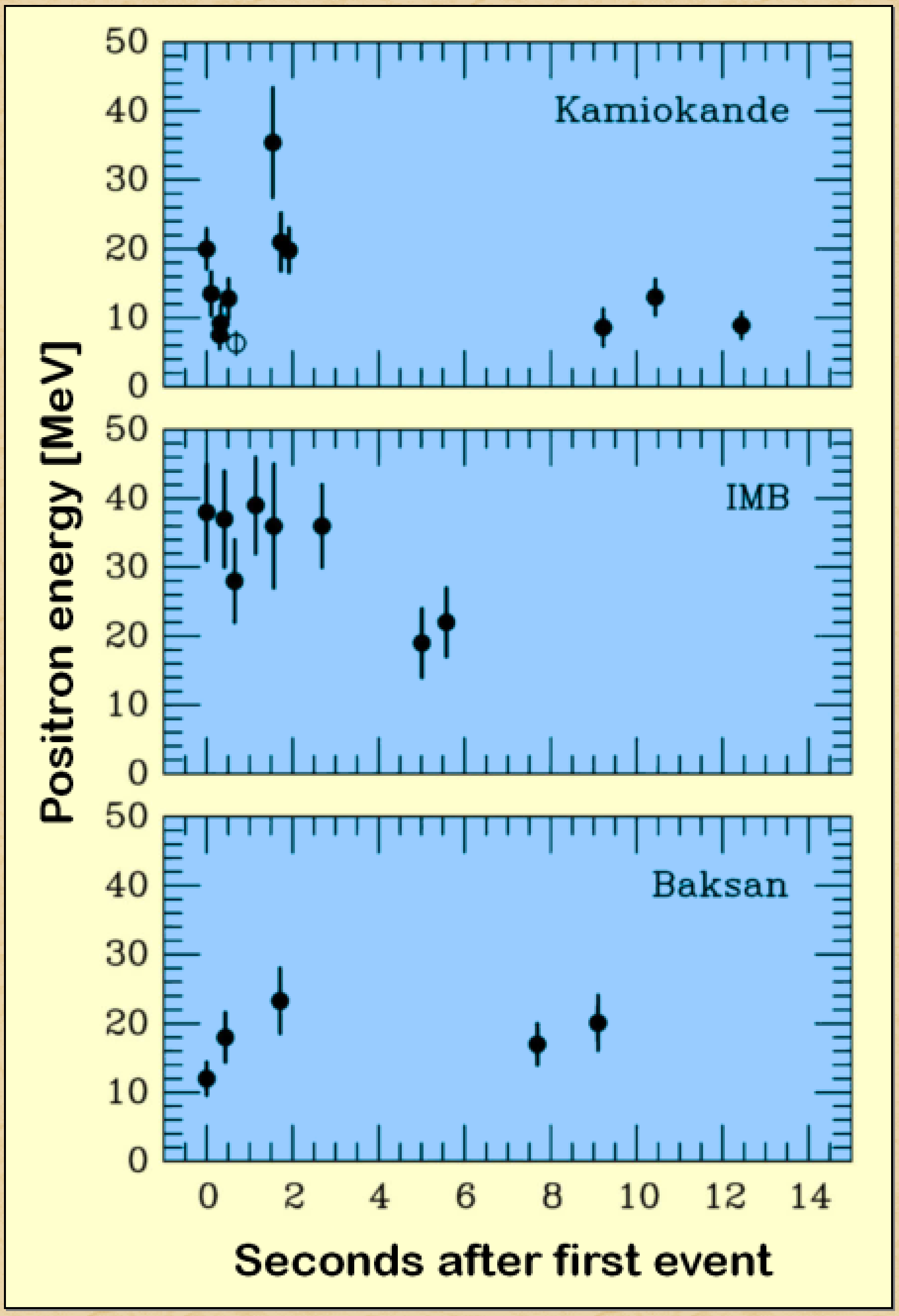
Kamiokande Detector



Hirata et al., PRD 38 (1988) 448



Neutrino Signal of Supernova 1987A



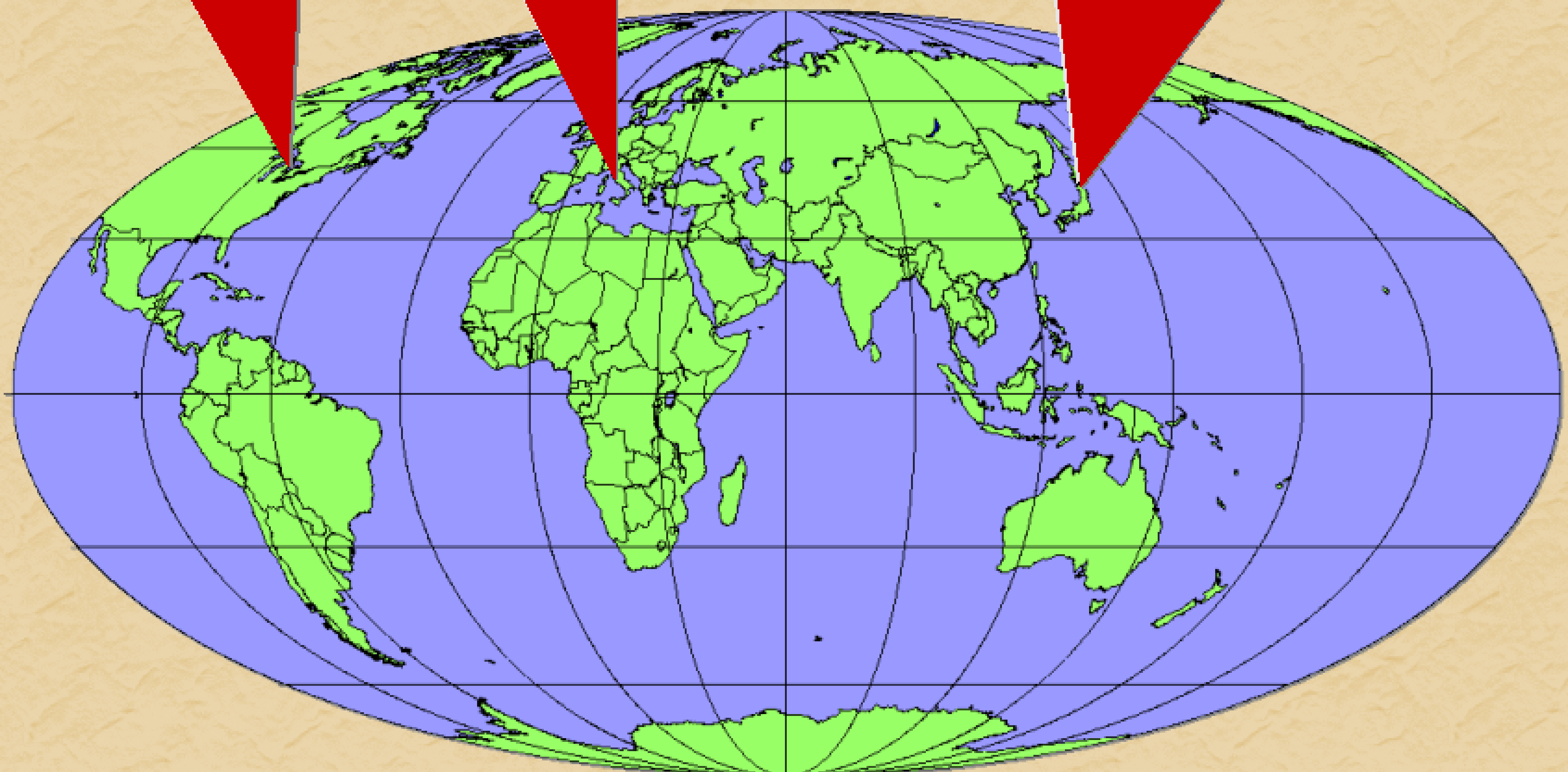
Kamiokande (Japan)
Water Cherenkov detector
Clock uncertainty ±1 min

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

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

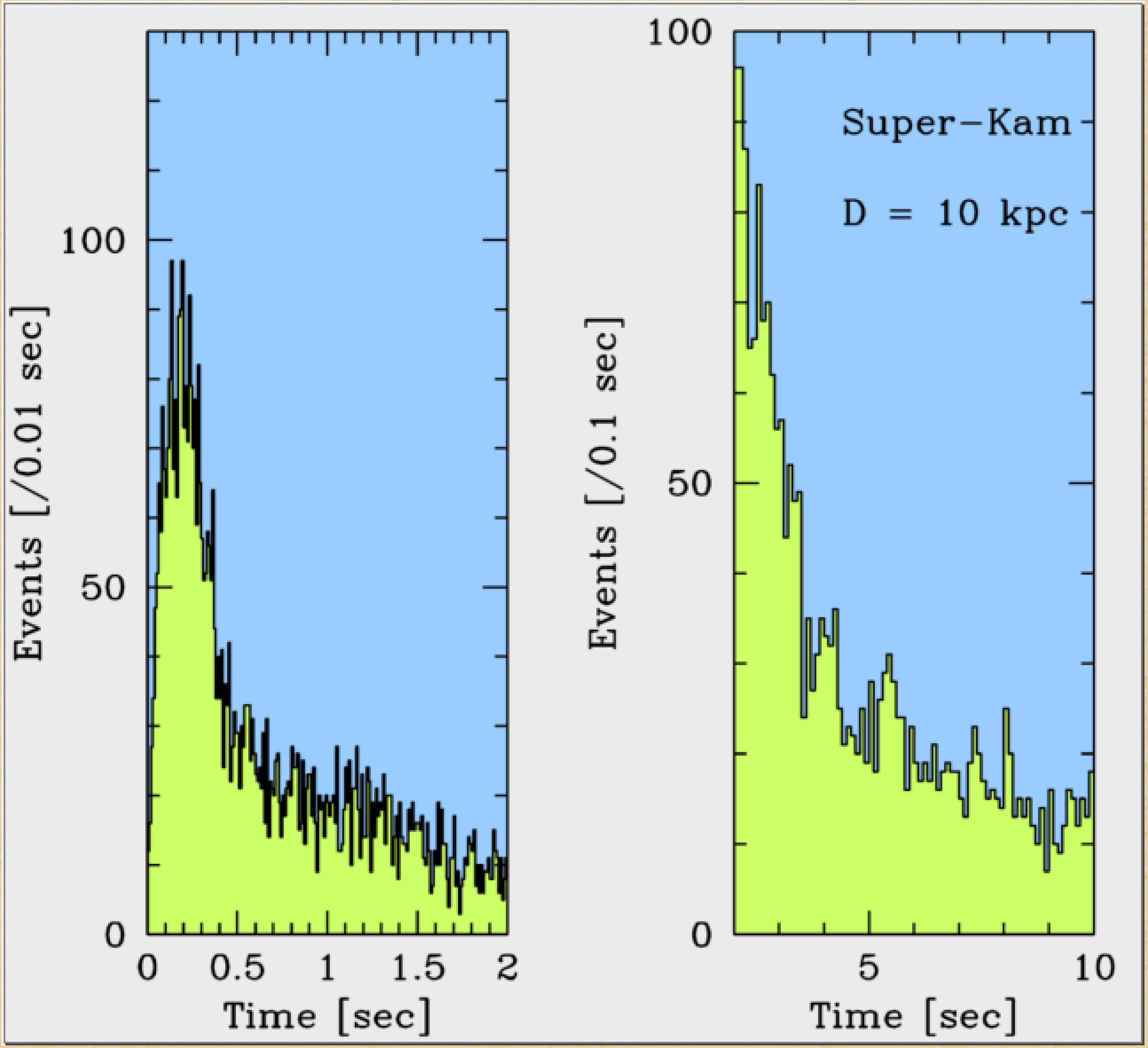
Within clock uncertainties, signals are contemporaneous

Large Detectors for SN Neutrinos



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

Simulated Supernova Signal in Super-Kamiokande

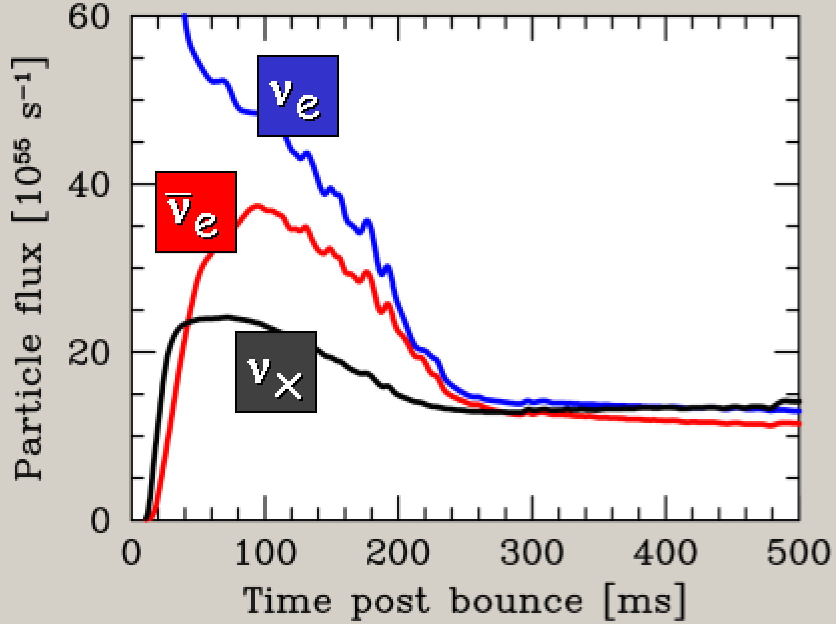


Totani, Sato, Dalhed & Wilson, ApJ 496 (1998) 216

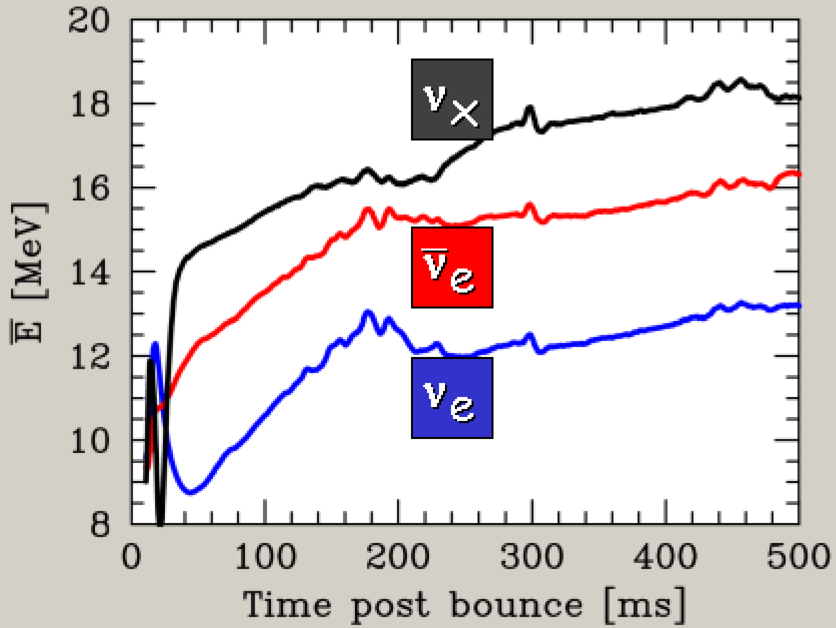
Total of about 8300 events for t < 18 s

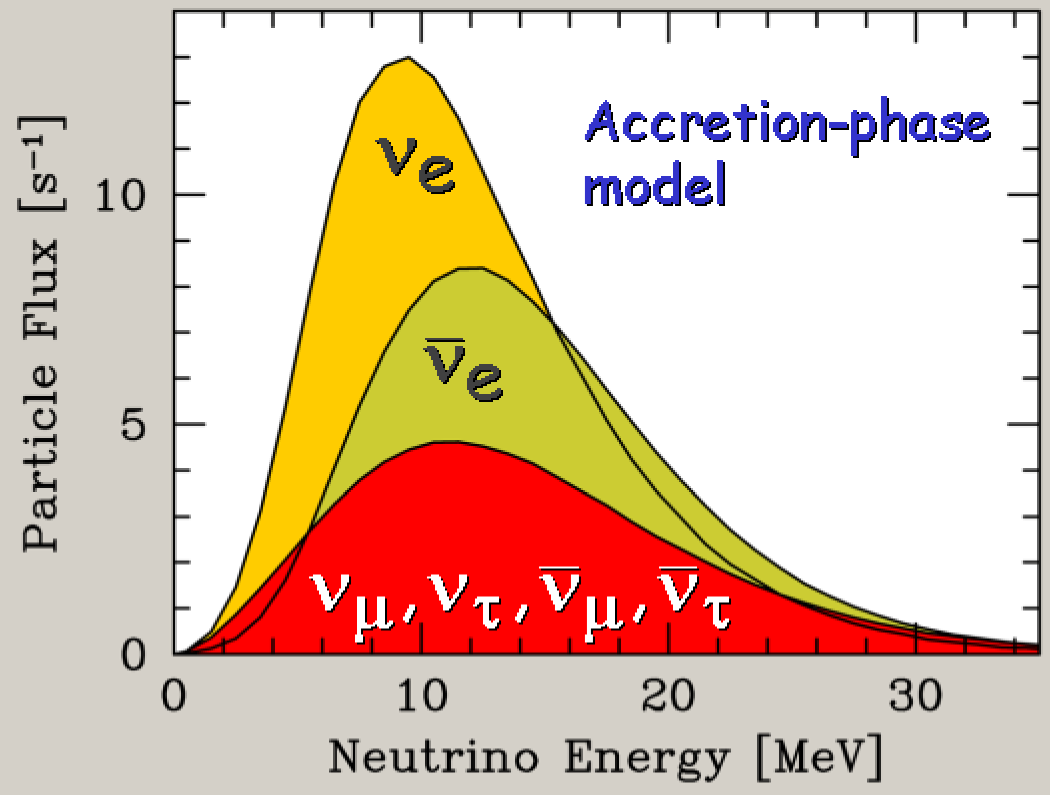
Monte-Carlo simulation for Super-Kamiokande signal of SN at 10 kpc, based on a numerical Livermore model

Flavor-Dependent Fluxes and Spectra



Full-scale simulation with Garching code w/ Boltzmann solver and all microphyiscs [astro-ph/0303226]





Neutrino Spectra Formation

G.Raffelt
astro-ph/0105250

Electron flavor ($\nu_e, \bar{\nu}_e$)

Thermal Equilibrium

$\bar{\nu}_e\, p \leftrightarrow n\, e^+$

$\nu_e\, n \leftrightarrow p\, e^-$

$T_{flux} \sim T_{NS}$

Neutrino sphere (T_{NS})

Other flavors ($\nu_\mu, \nu_\tau, \bar{\nu}_\mu, \bar{\nu}_\tau$)

$\nu N \leftrightarrow N \nu$

$\nu e \leftrightarrow \nu e$

$NN \leftrightarrow NN\nu\bar{\nu}$

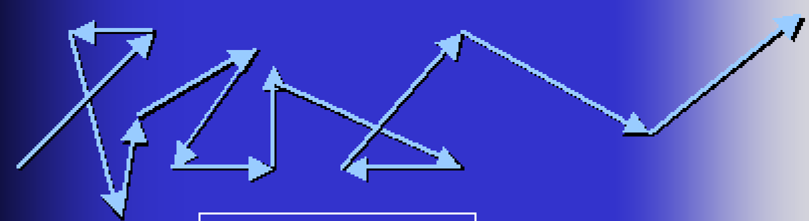
$e^+e^- \leftrightarrow \nu\bar{\nu}$

$\nu_e\bar{\nu}_e \leftrightarrow \nu_\mu\bar{\nu}_\mu$

Thermal Equilibrium

Scattering Atmosphere

$\nu N \leftrightarrow N \nu$



Diffusion

$T_{flux} \sim 0.6\, T_{ES}$

Energy sphere (T_{ES})

Transport sphere

Neutrino Spectra Formation

G.Raffelt
astro-ph/0105250

Electron flavor

Thermal Equilibriu

$T_{flux} \sim T_{NS}$

phere (T_{NS})

Mathias Keil's Ph.D. work:
Study neutrino transport in scattering atmosphere by numerical Monte Carlo method to understand neutrino spectra formation depending on microphysics and background model
(Quantitative understanding of SN as multiflavor nu source)

Other flavors (

$\nu N \leftrightarrow N\nu$

$\nu e \leftrightarrow \nu e$

$NN \leftrightarrow NN\nu\bar{\nu}$

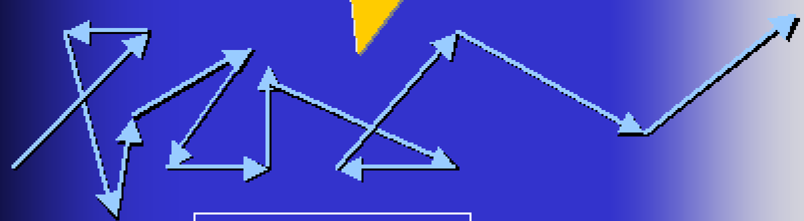
$e^+e^- \leftrightarrow \nu\bar{\nu}$

$\nu_e\bar{\nu}_e \leftrightarrow \nu_\mu\bar{\nu}_\mu$

Thermal Equilibrium

Scattering A here

$\nu N \leftarrow N\nu$



Diffusion

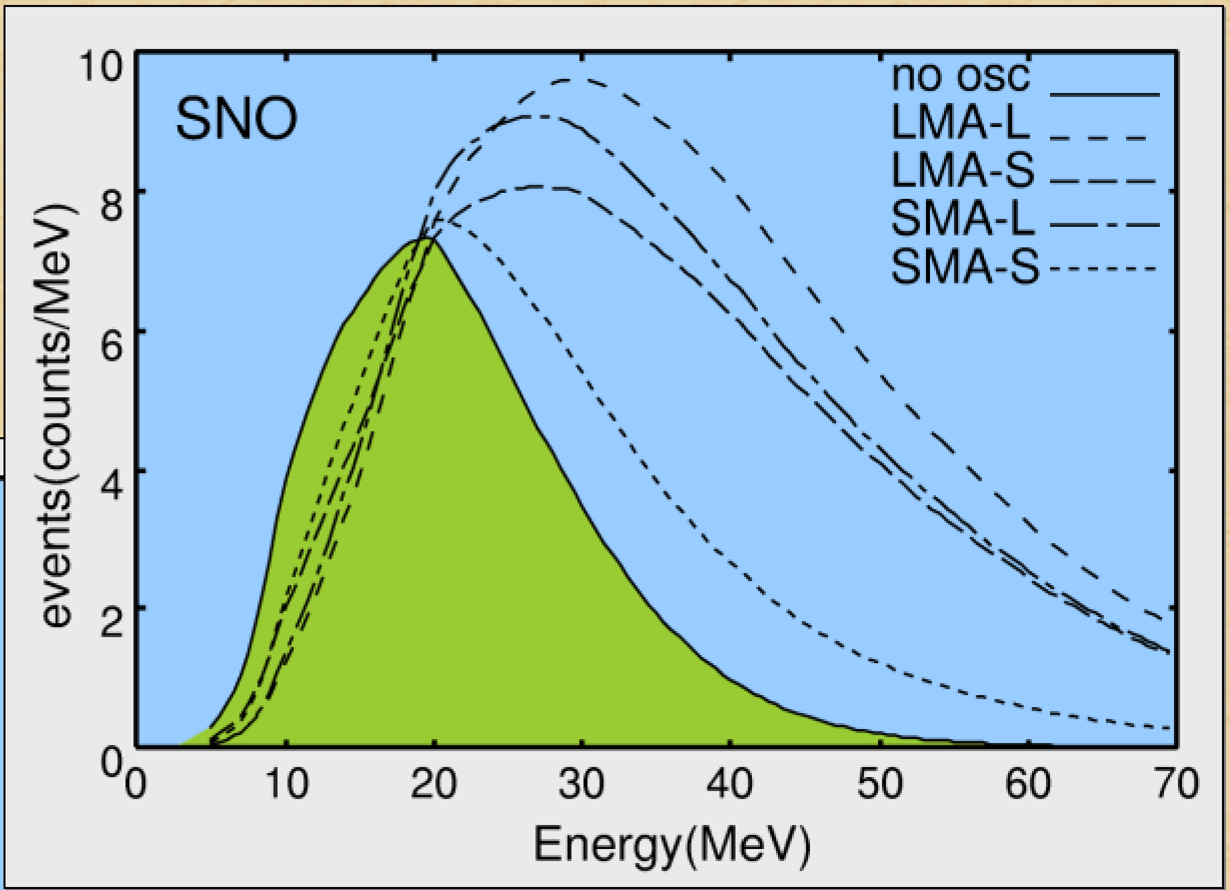
$T_{flux} \sim 0.6 T_{ES}$

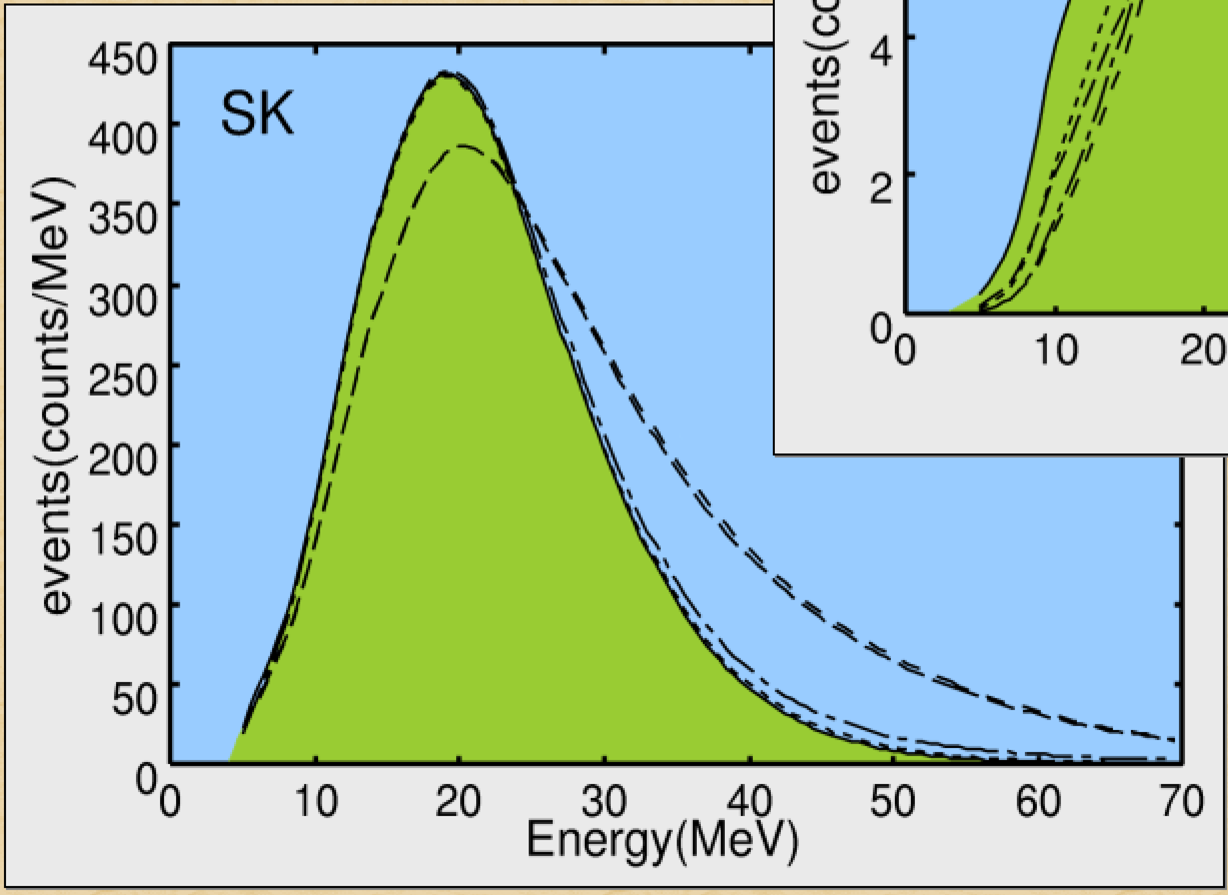
Energy sphere (T_{ES})

Transport sphere

Three-Flavor Oscillation Scenario

Takahashi, Watanabe & Sato, hep-ph/0105204

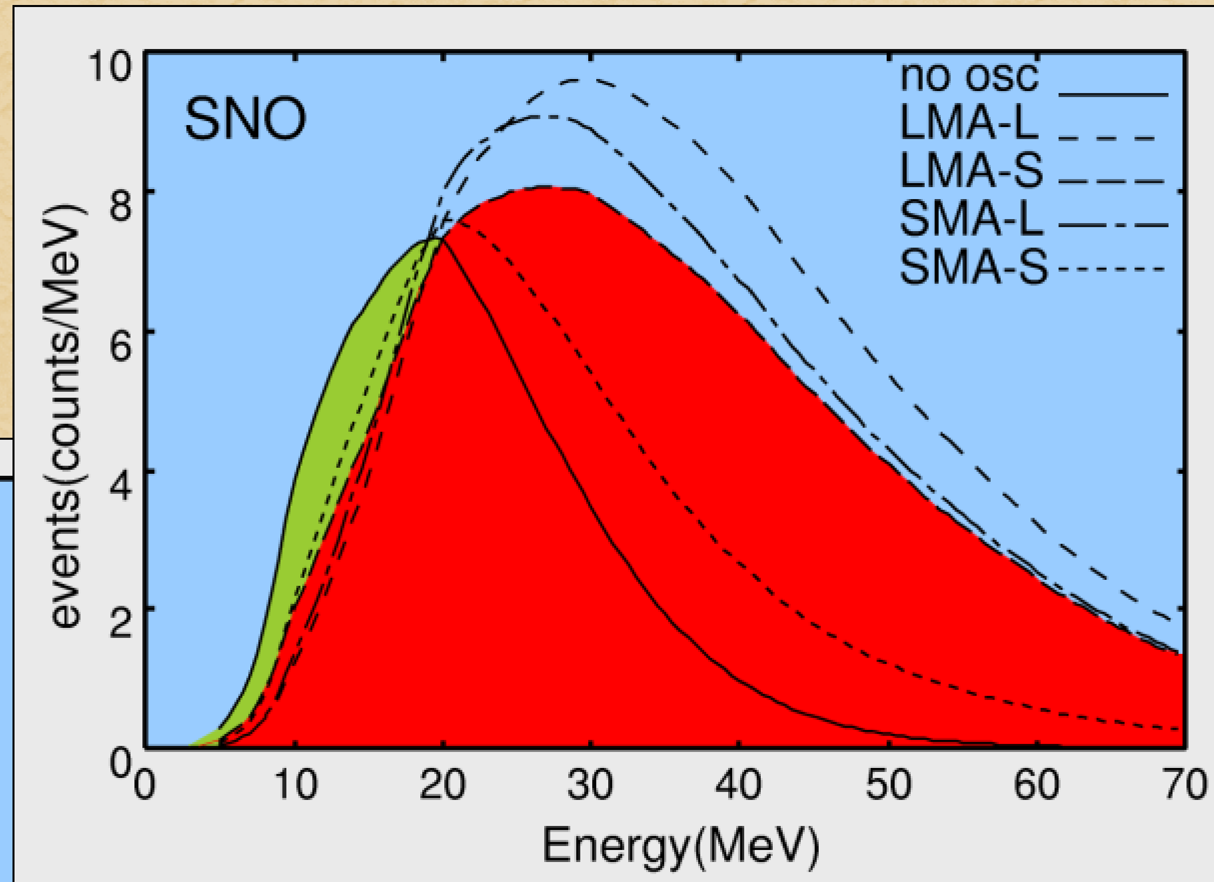


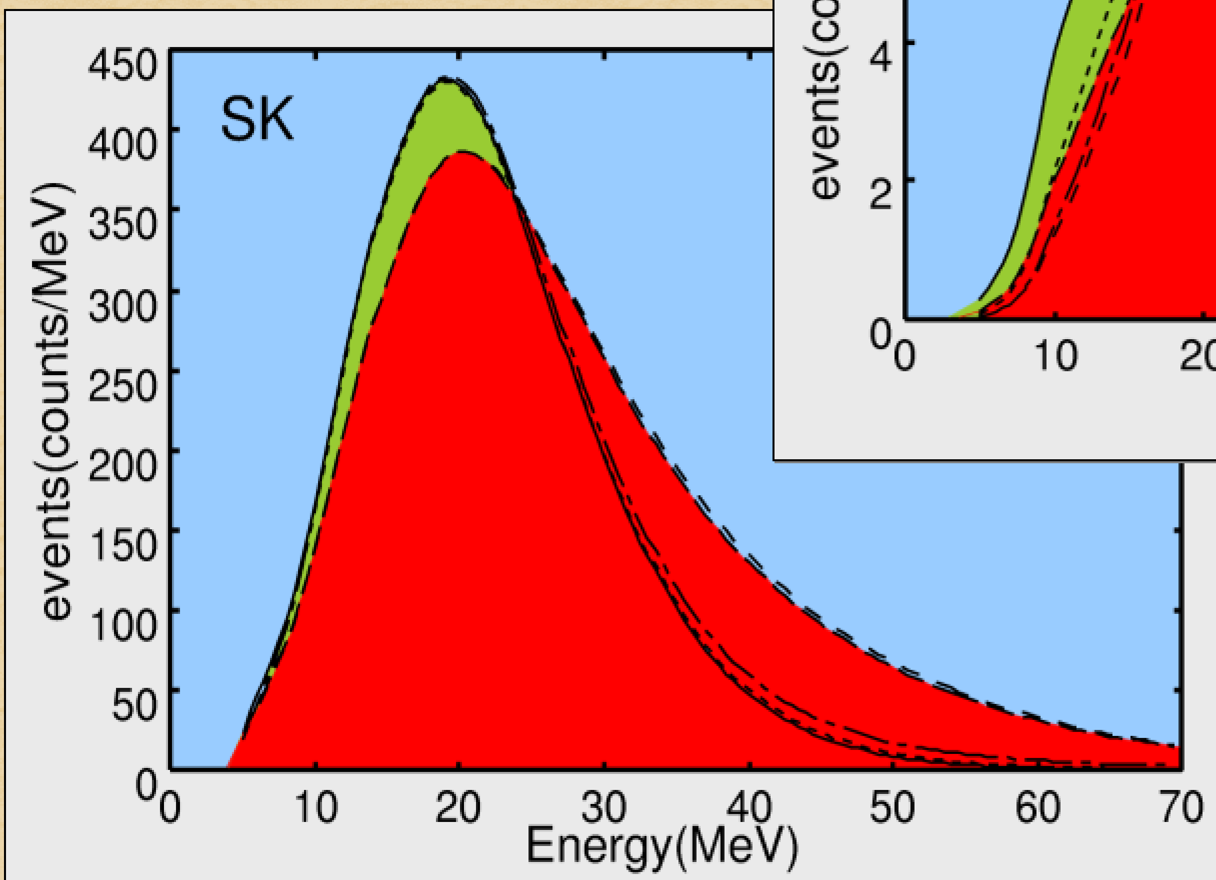


No Oscillations

Three-Flavor Oscillation Scenario

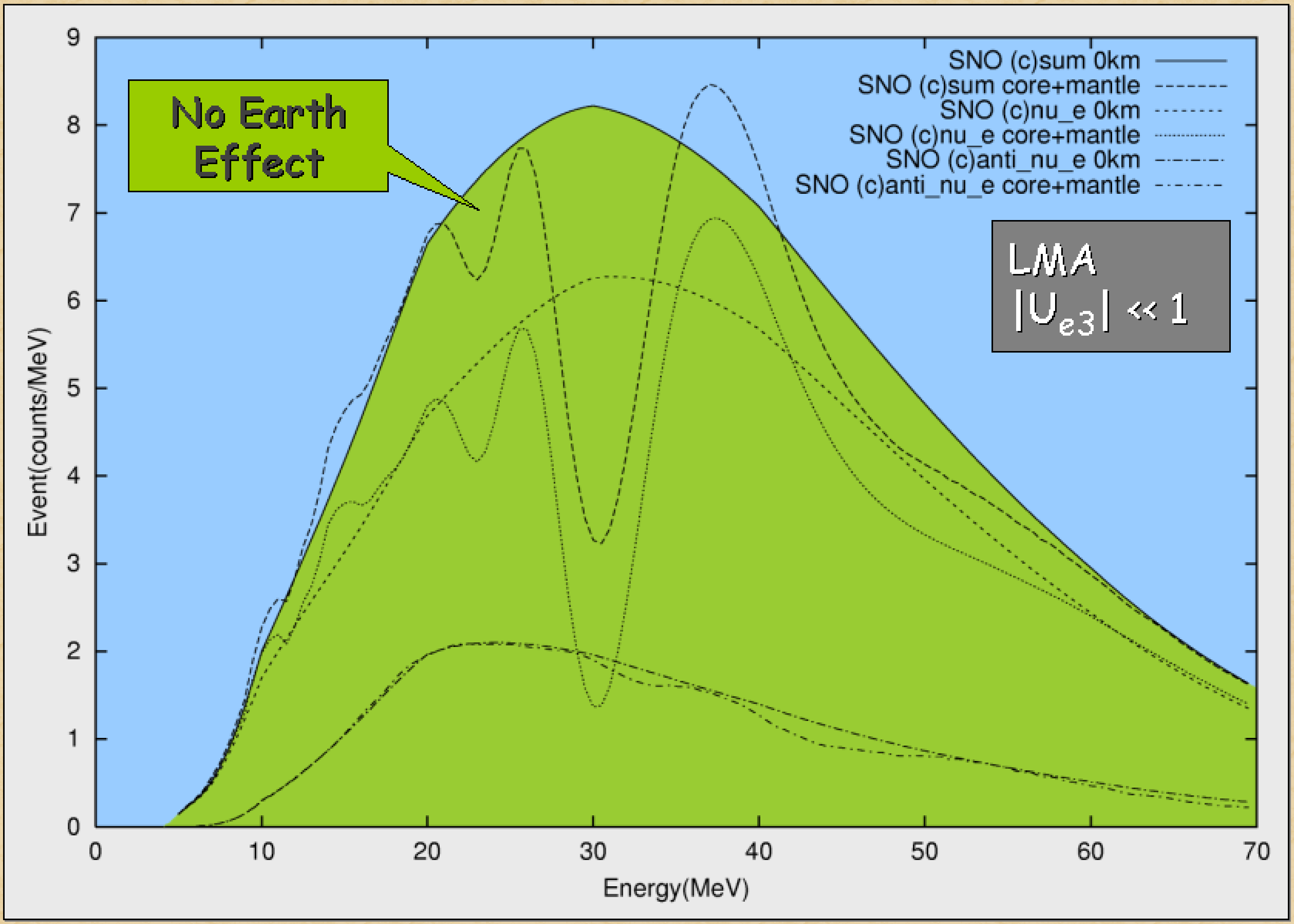
Takahashi, Watanabe & Sato, hep-ph/0105204





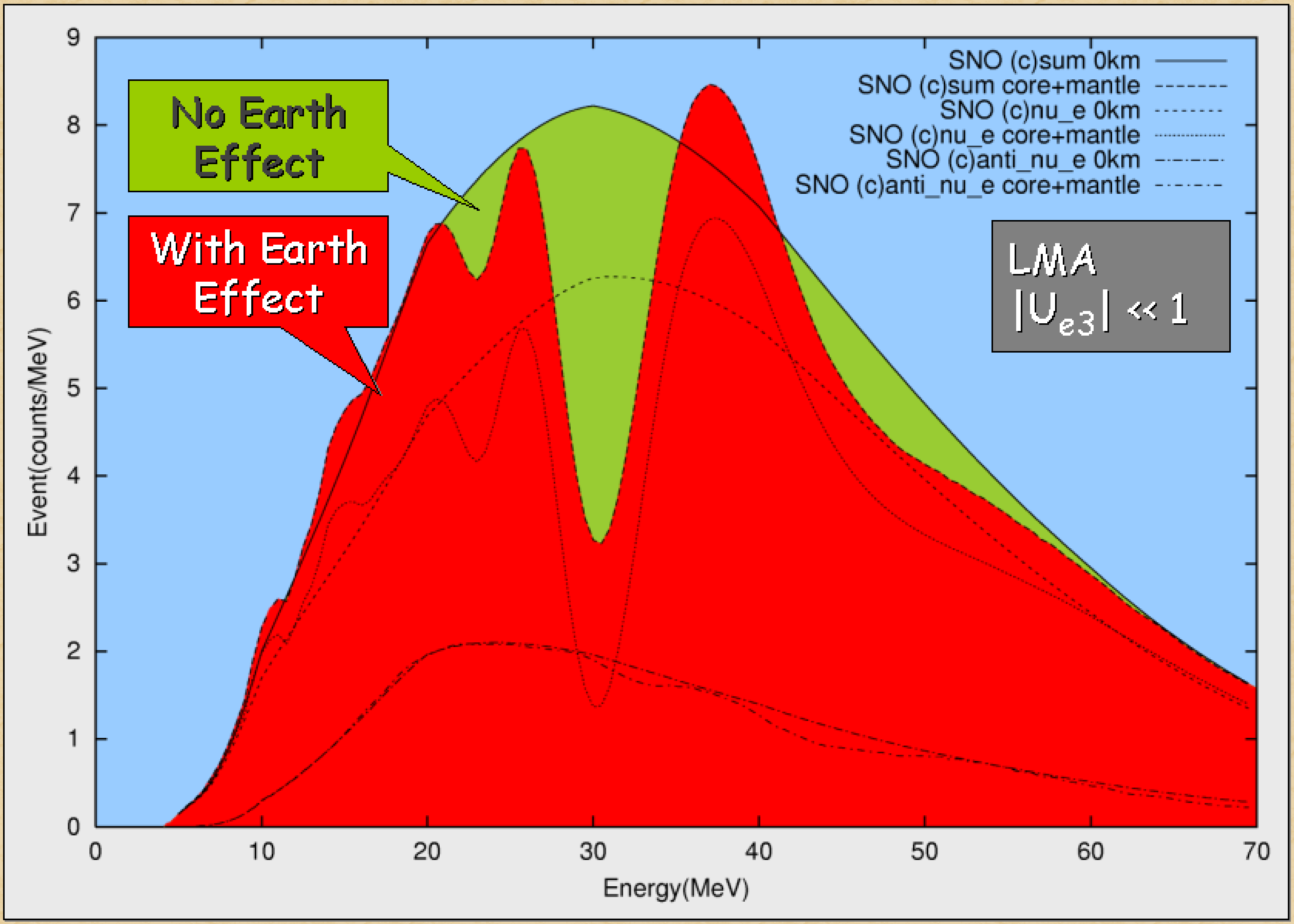
Oscillations with LMA and $|U_{e3}| \ll 1$

Earth Effect at SNO



Takahashi, Watanabe & Sato, hep-ph/0012354

Earth Effect at SNO



Takahashi, Watanabe & Sato, hep-ph/0012354

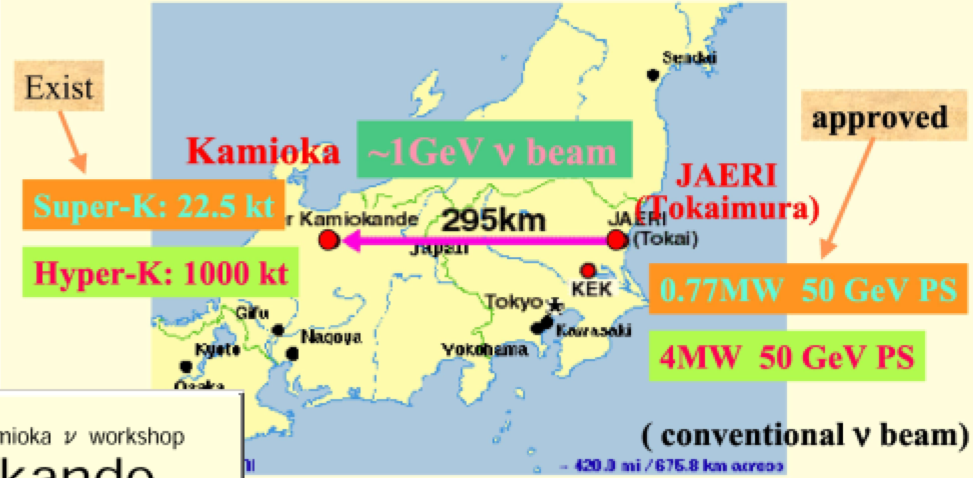
The Future: A Megatonne Detector?

Megatonne detector motivated by

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

1.Overview of the experiment

(expect to start in 2007)

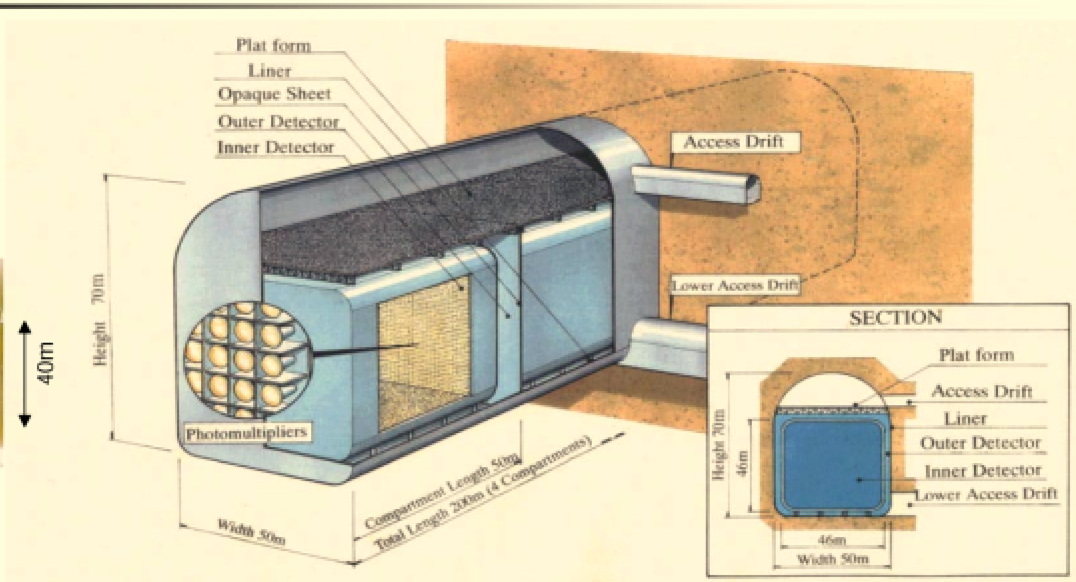


Phase-I (0.77MW + Super-K)

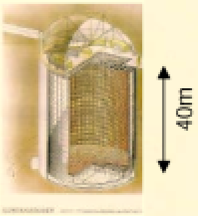
Phase-II (4MW+Hyper-K) ~ Phase-I × 200

May.-2001 JHF-Kamioka ν workshop

Possible Design of Hyper-Kamiokande



Super-K

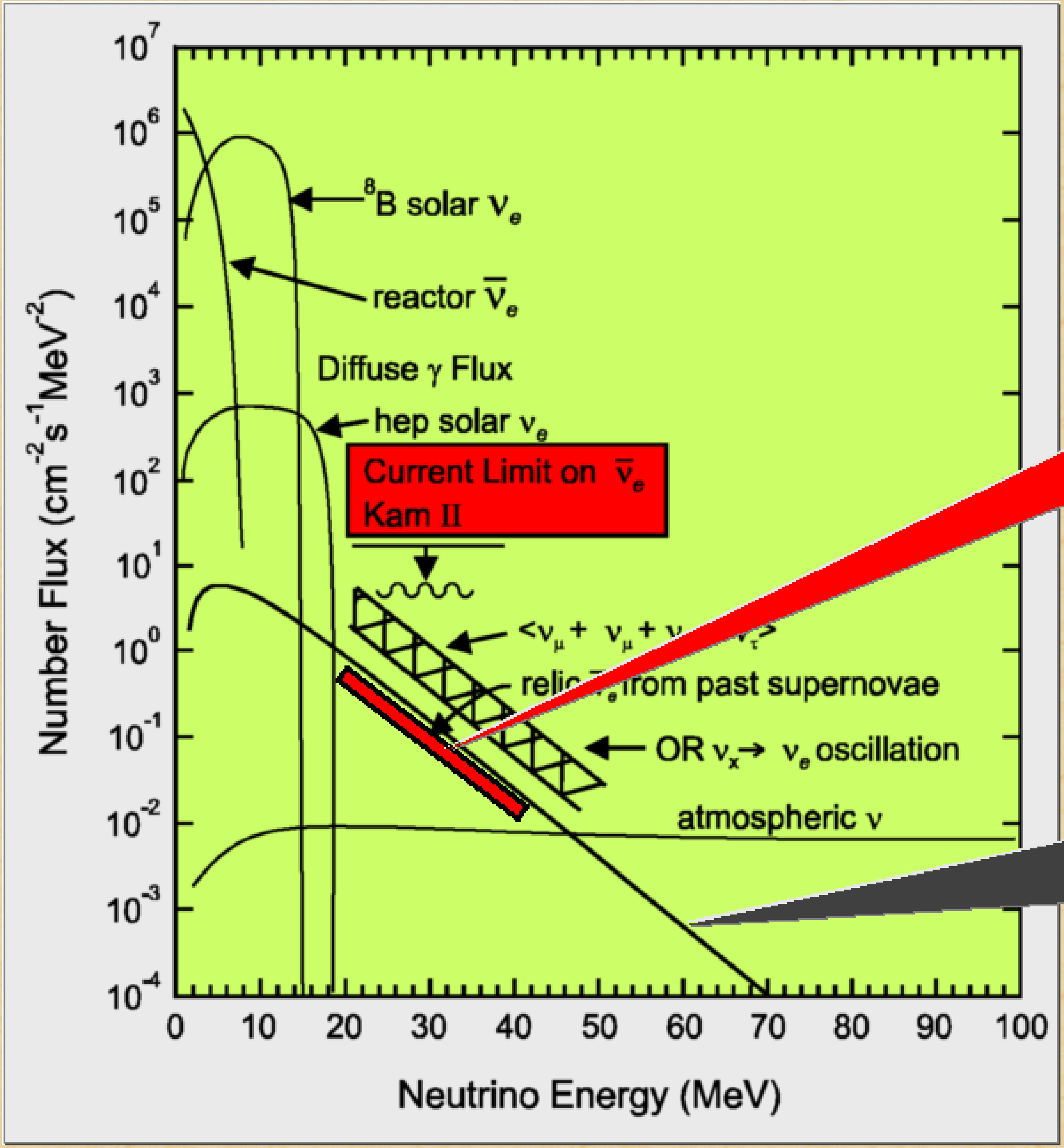


1 Mton fiducial volume: Total Length 800m (16 Compartments)

Similar discussions in

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

Experimental Limits on Relic SN Neutrinos

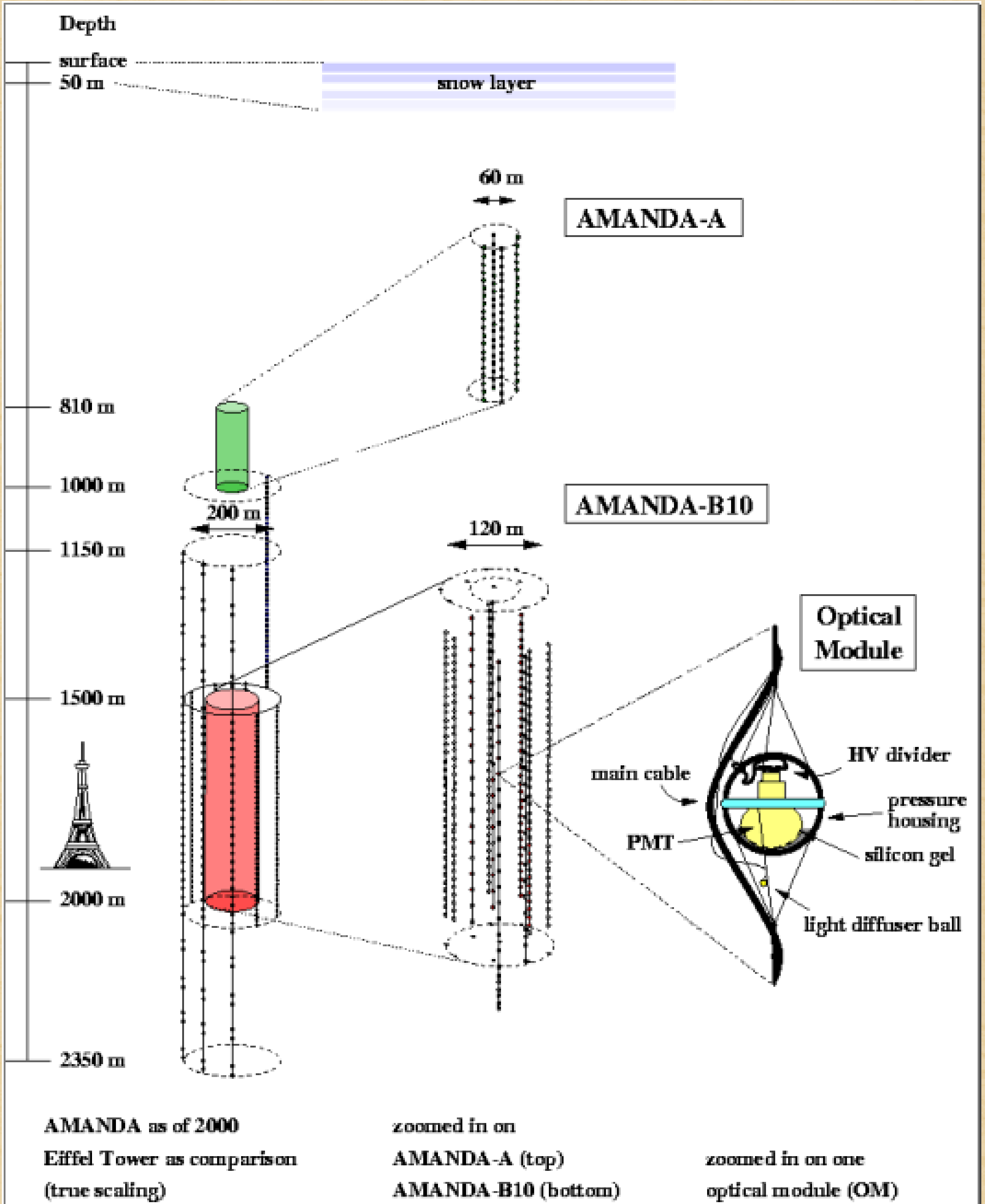


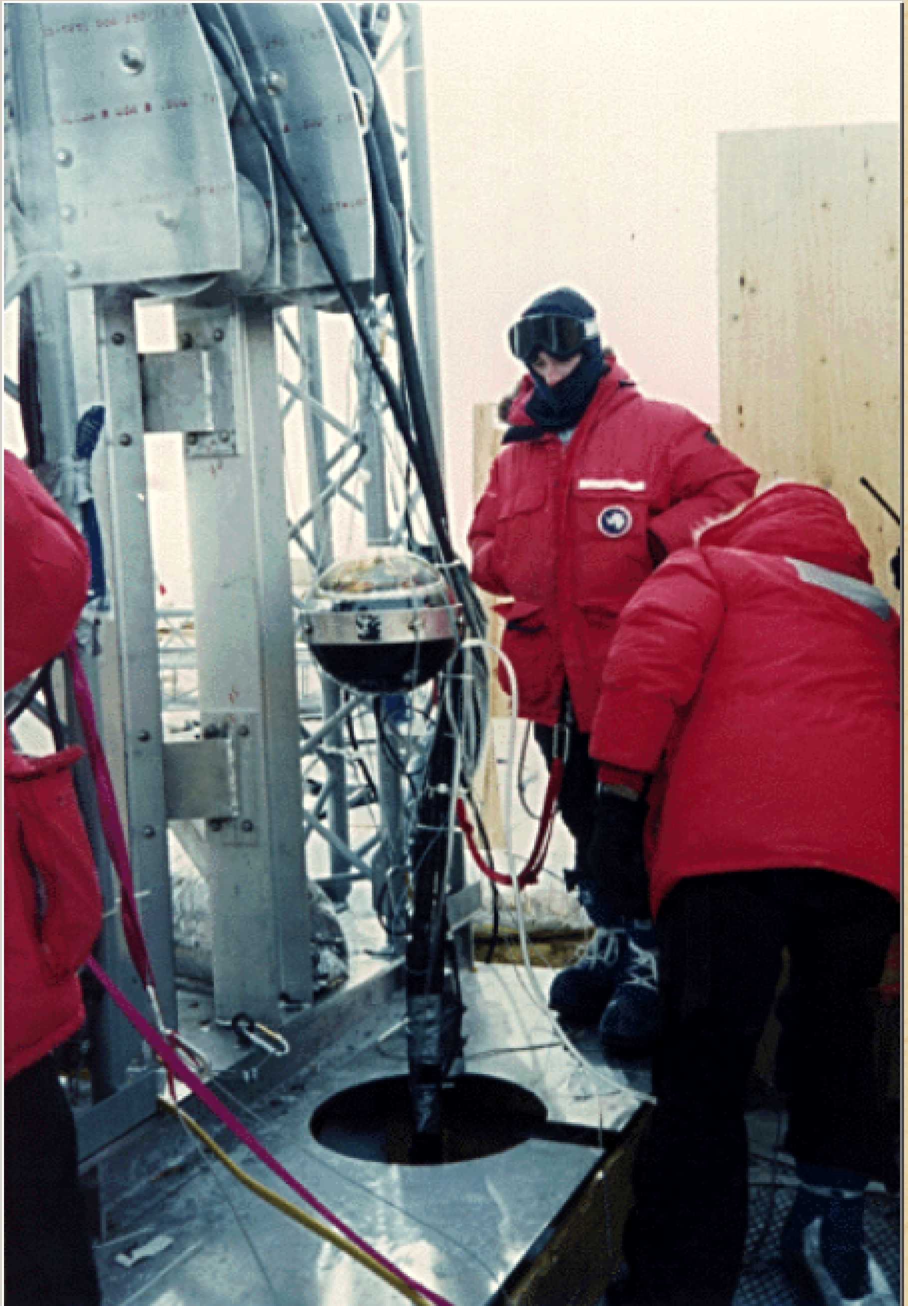
Super-K upper limit
29 cm^{-2} s^{-1} for
Kaplinghat et al. spectrum
[hep-ex/0209028]

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

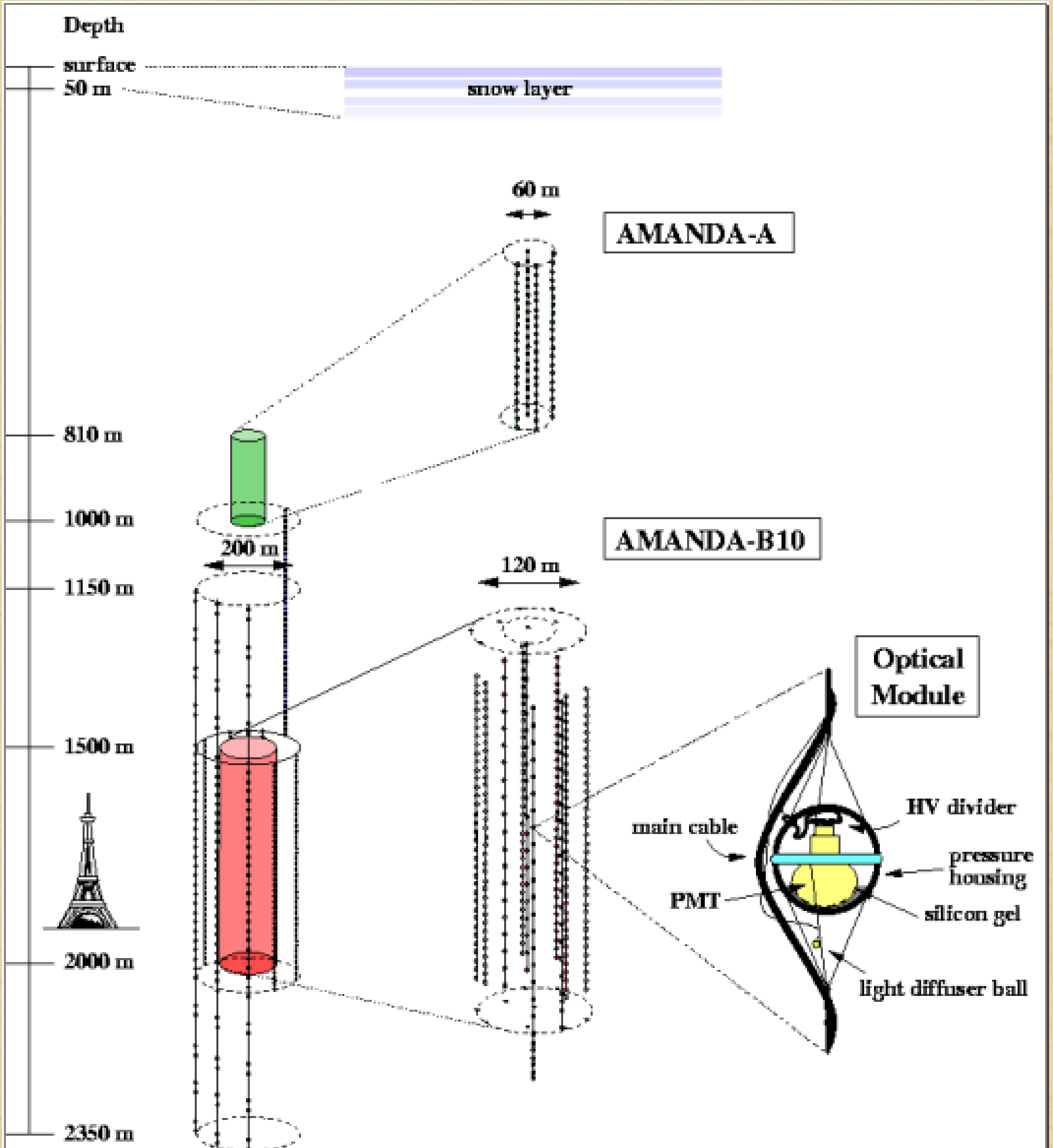
Cline, astro-ph/0103138

AMANDA - South Pole Neutrino Telescope





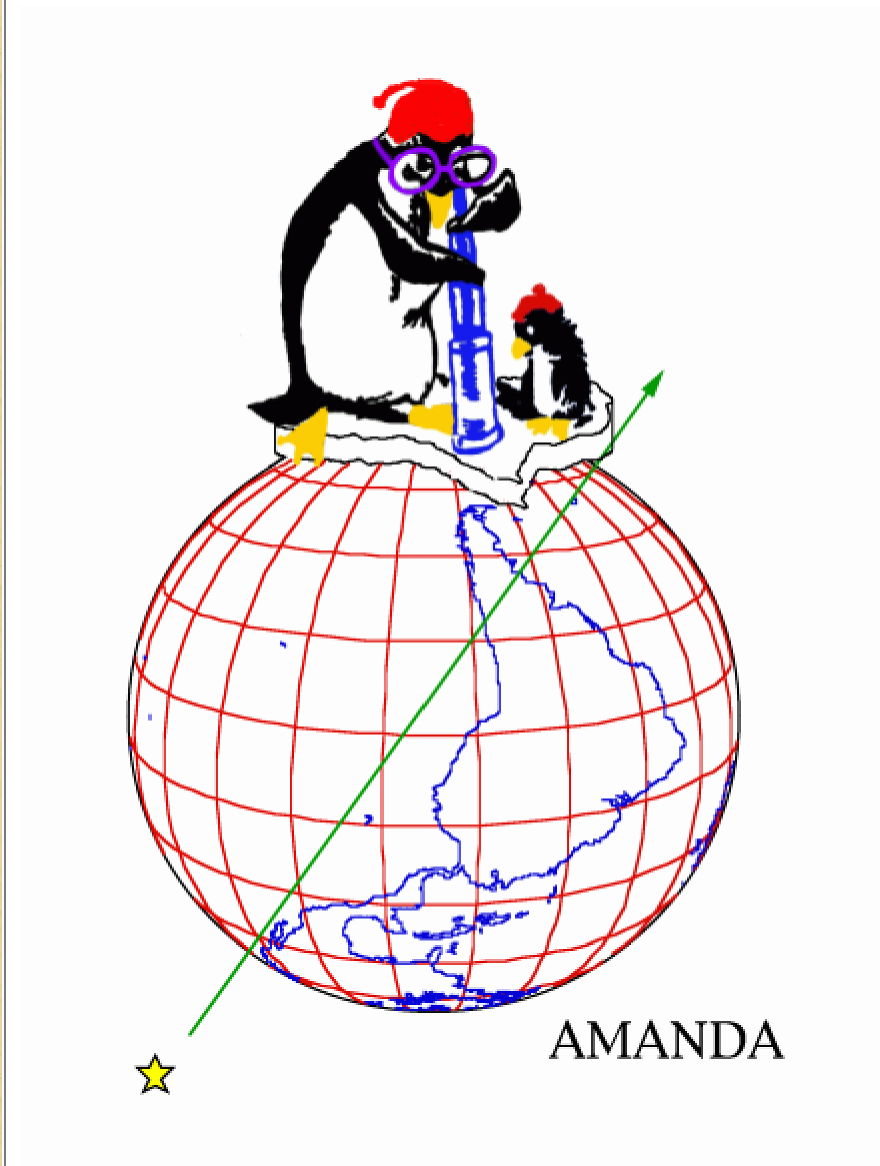
AMANDA - South Pole Neutrino Telescope



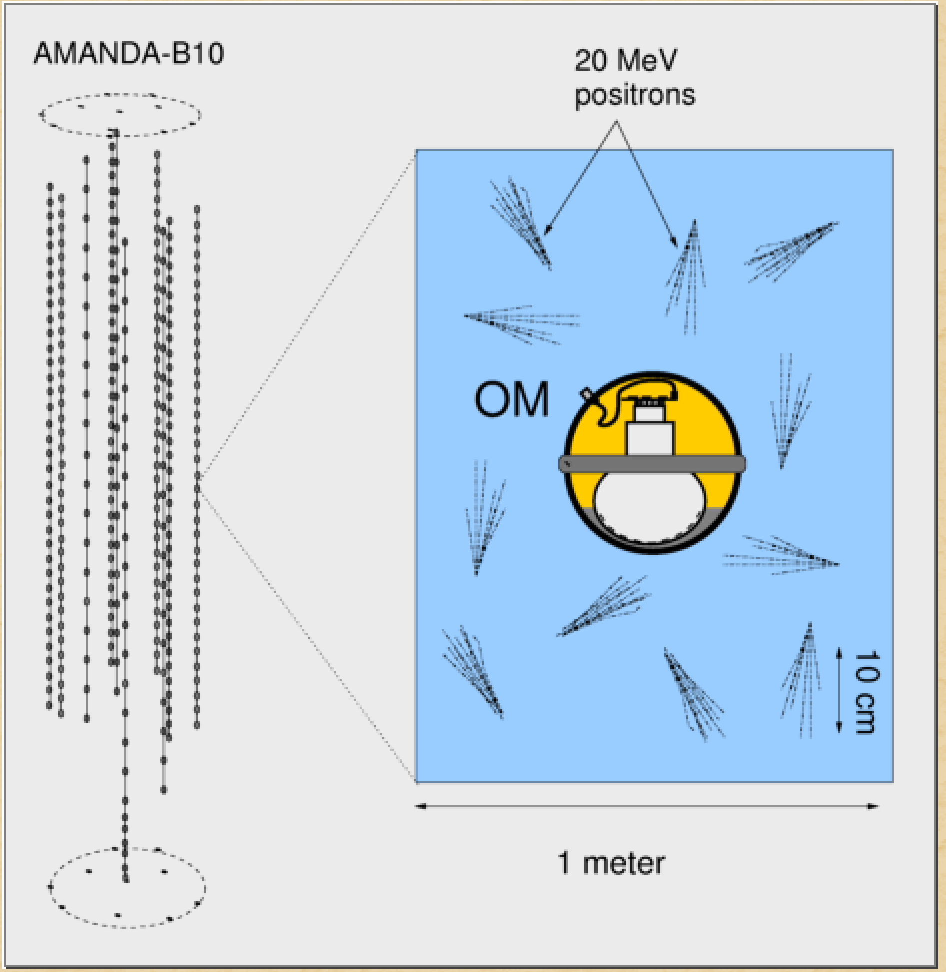
AMANDA as of 2000
Eiffel Tower as comparison
(true scaling)

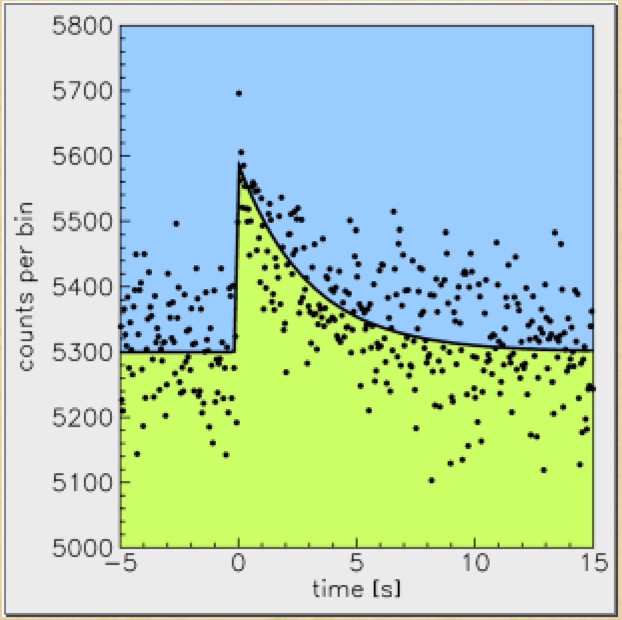
zoomed in on
AMANDA-A (top)
AMANDA-B10 (bottom)

zoomed in on one
optical module (OM)

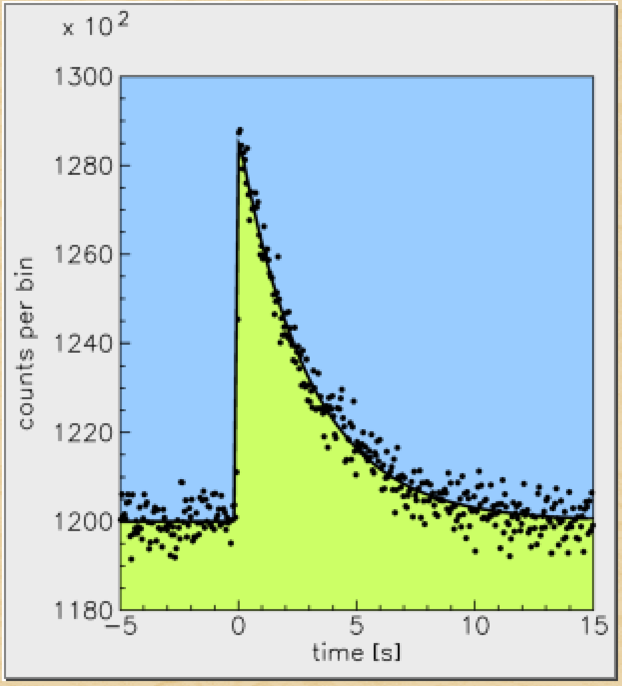


Amanda/IceCube as a Supernova Detector





SN @ 8.5 kpc
Signal in
Amanda

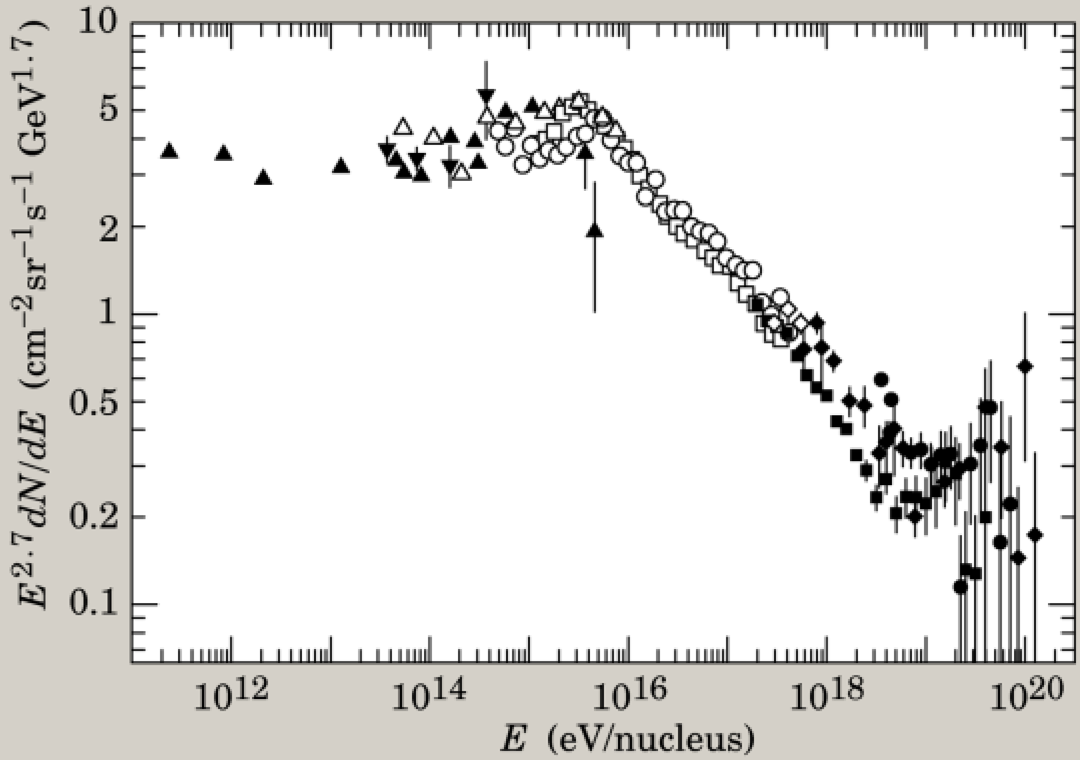


SN @ 8.5 kpc
Signal in
Ice Cube

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

Amanda
Collaboration
(2001)

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

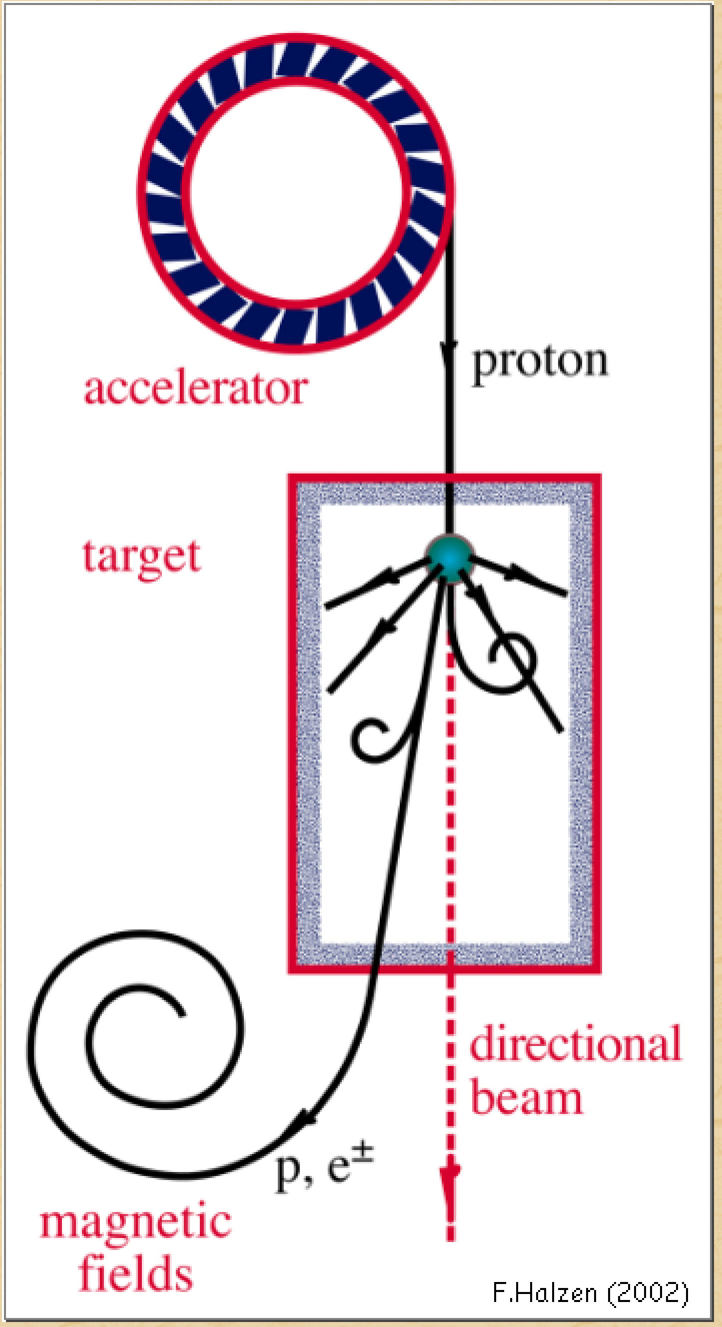
Proton magnetic field deflection

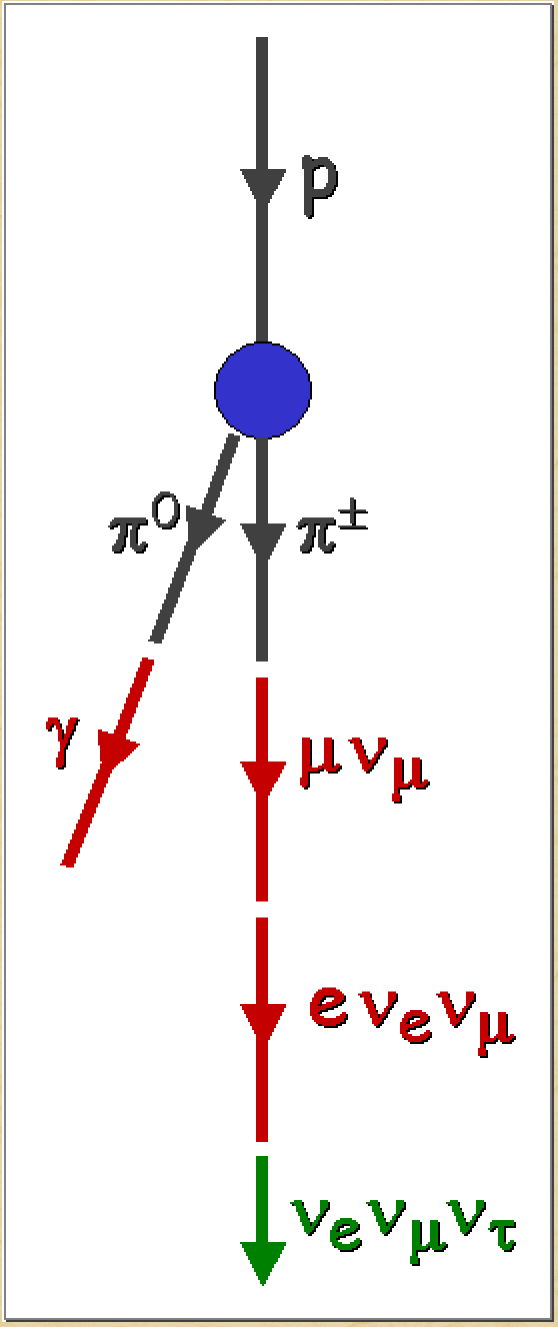
GZK cutoff

Opportunity for neutrino astronomy

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

Neutrino Beams: Heaven and Earth



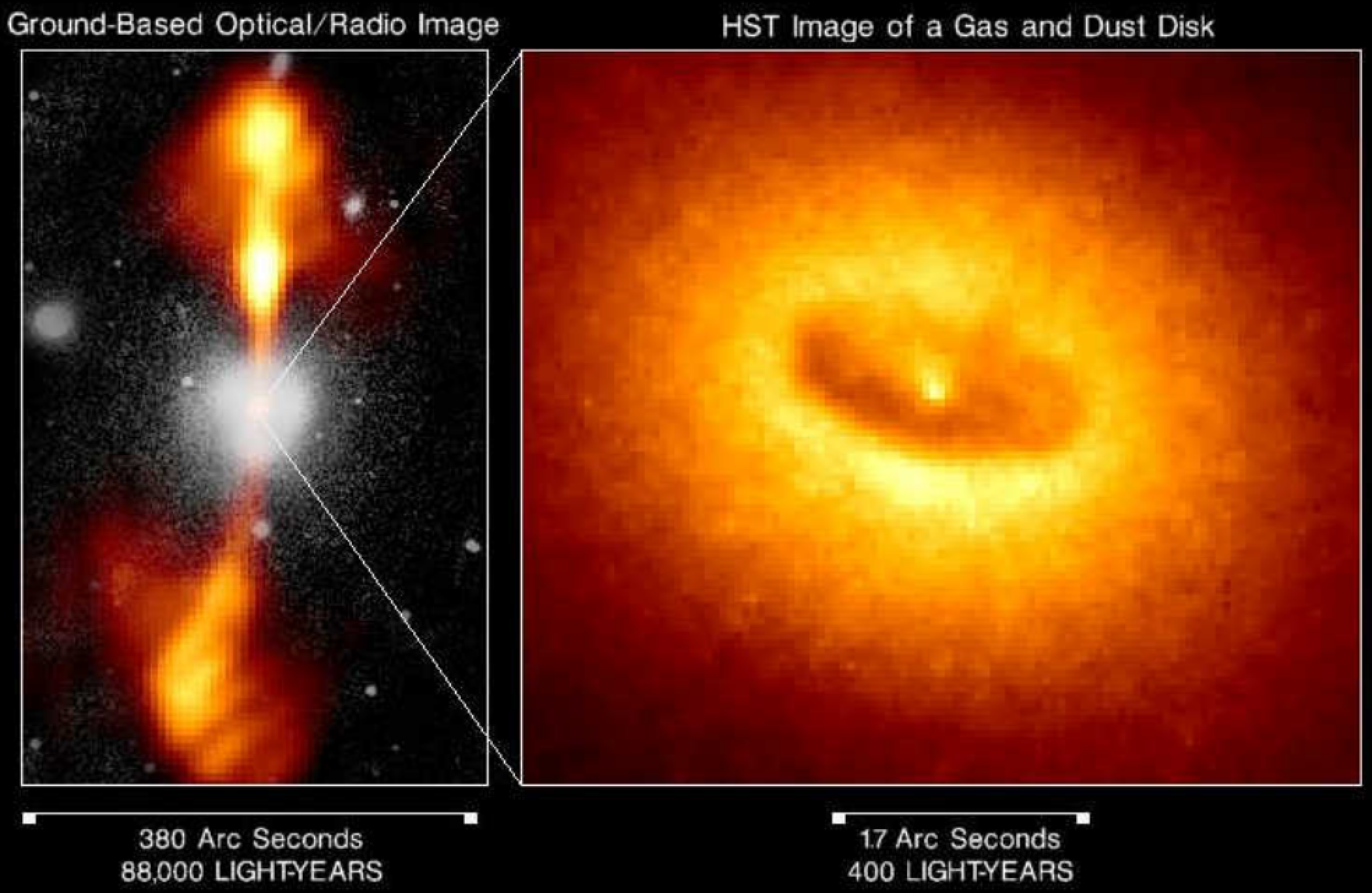


Target:
Protons or Photons

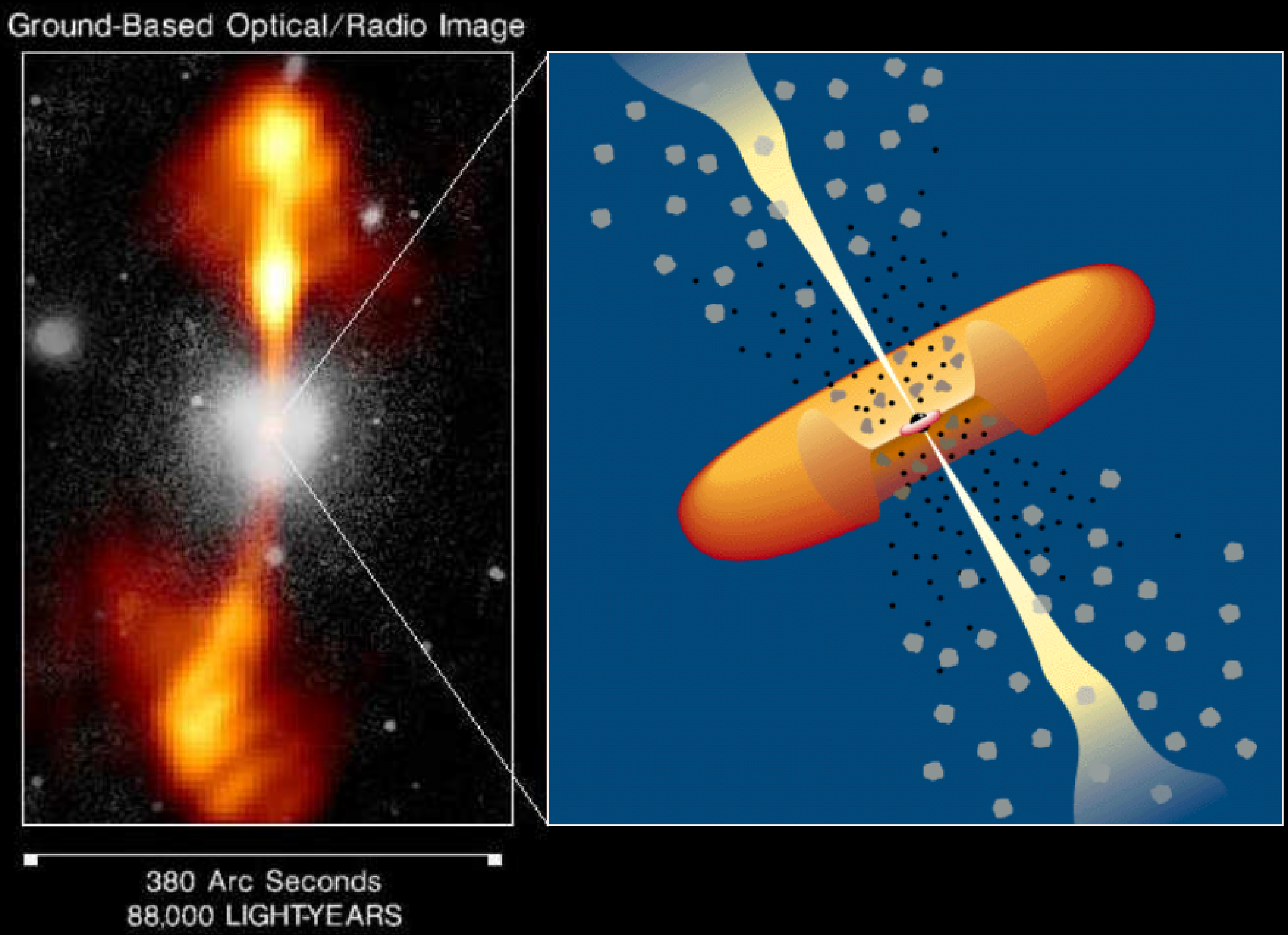
Approx. equal fluxes of photons & neutrinos

Equal neutrino fluxes in all flavors due to oscillations

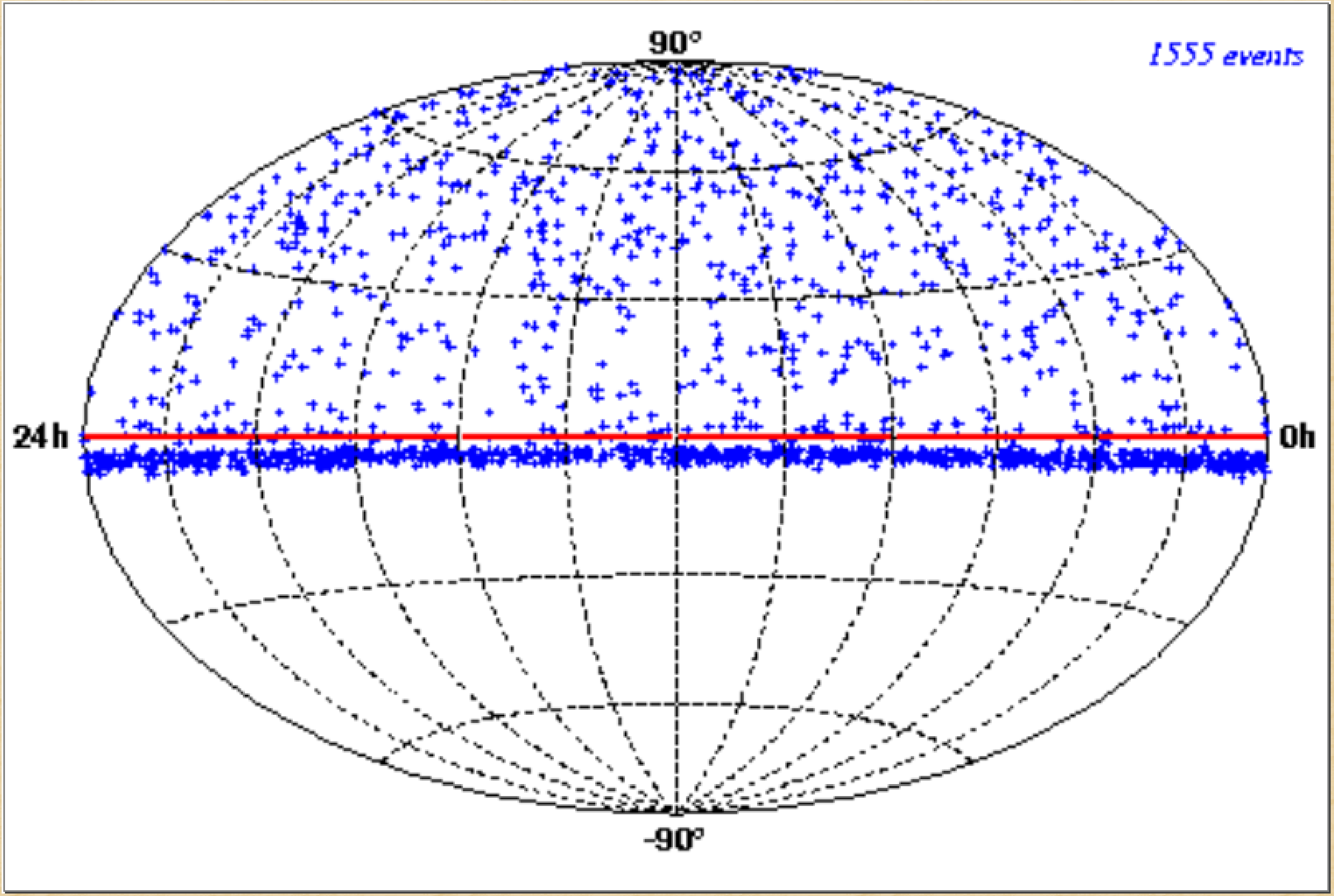
Core of the Galaxy NGC 4261



Core of the Galaxy NGC 4261

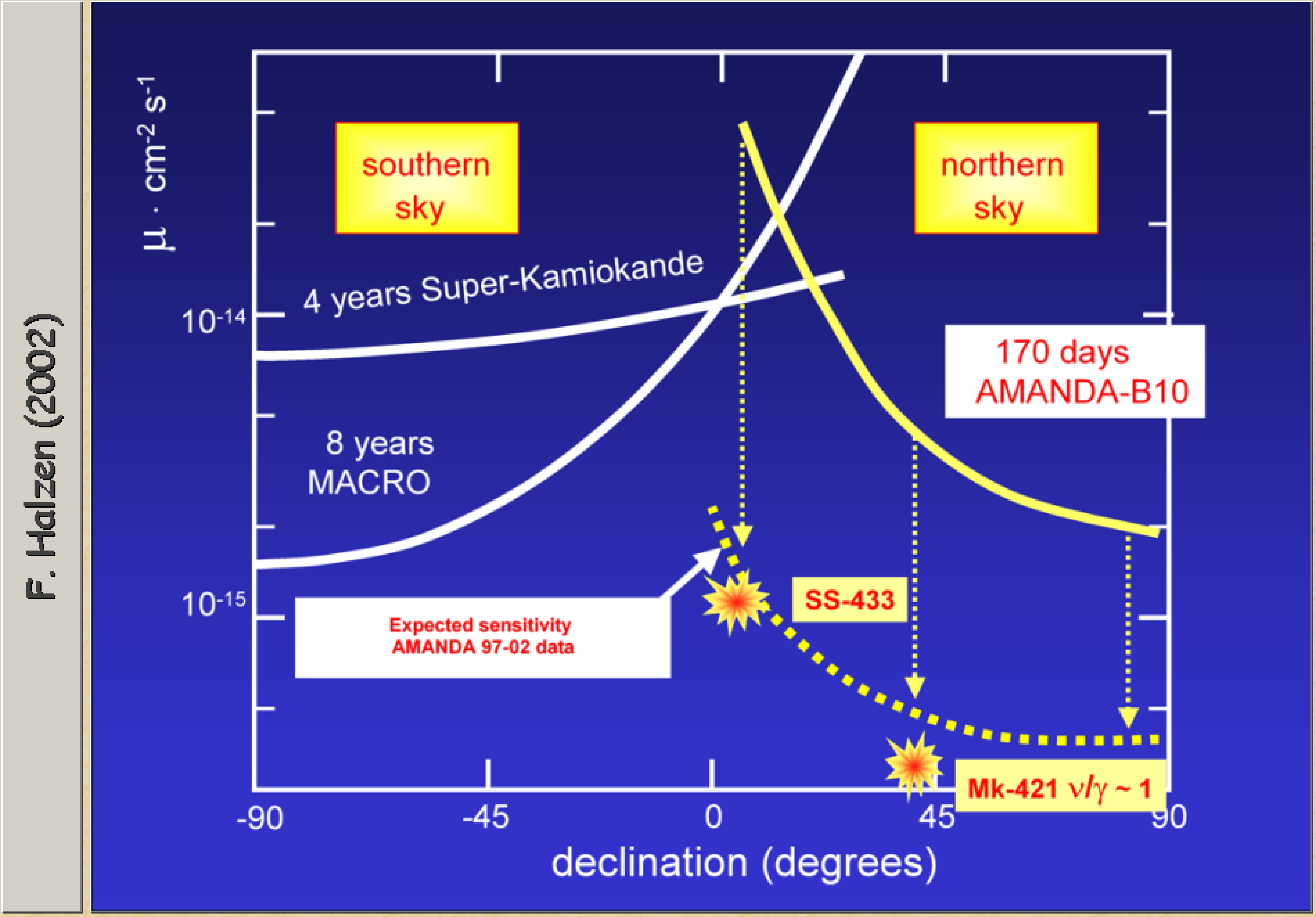


Neutrino Sky at AMANDA (2000)

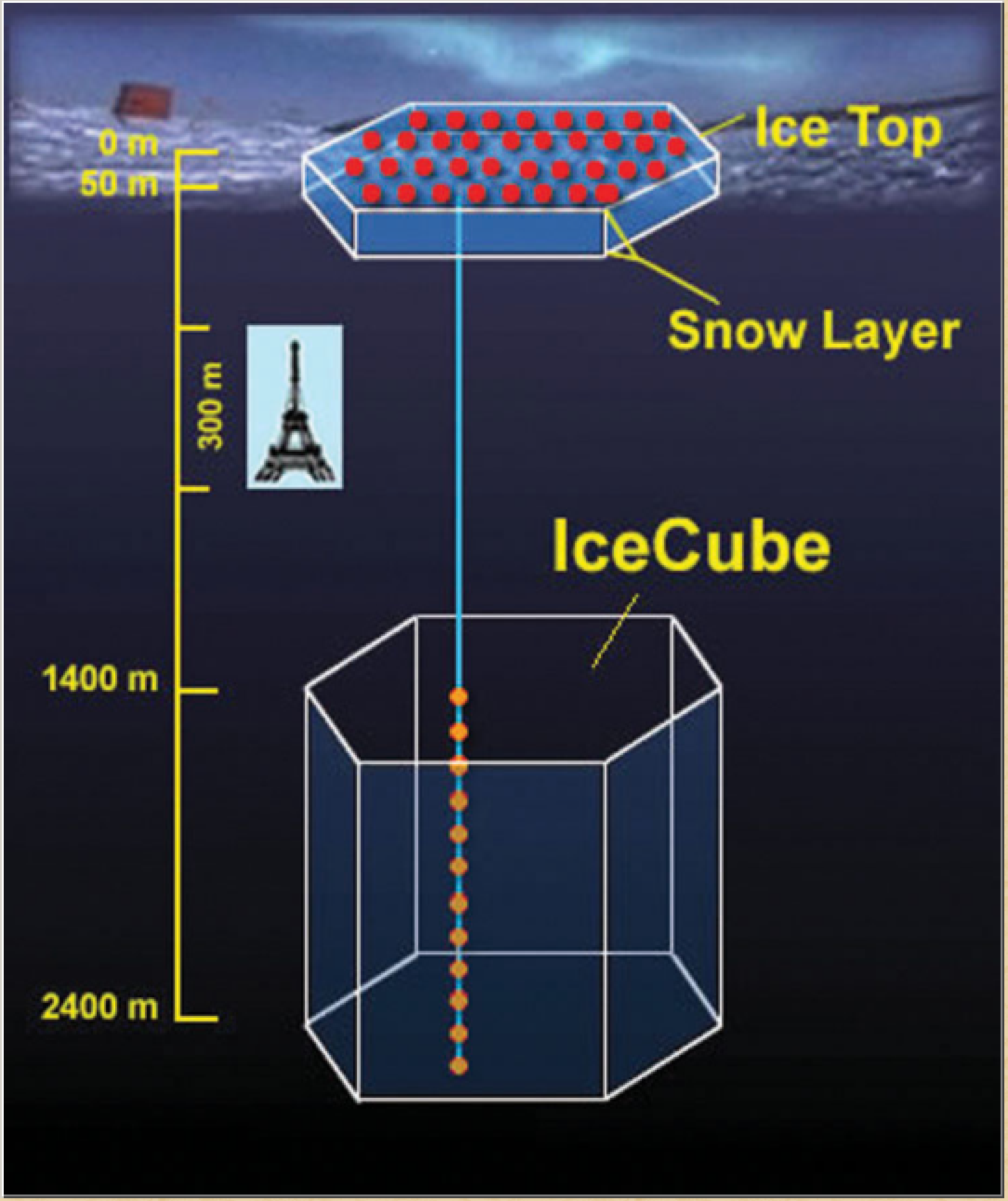


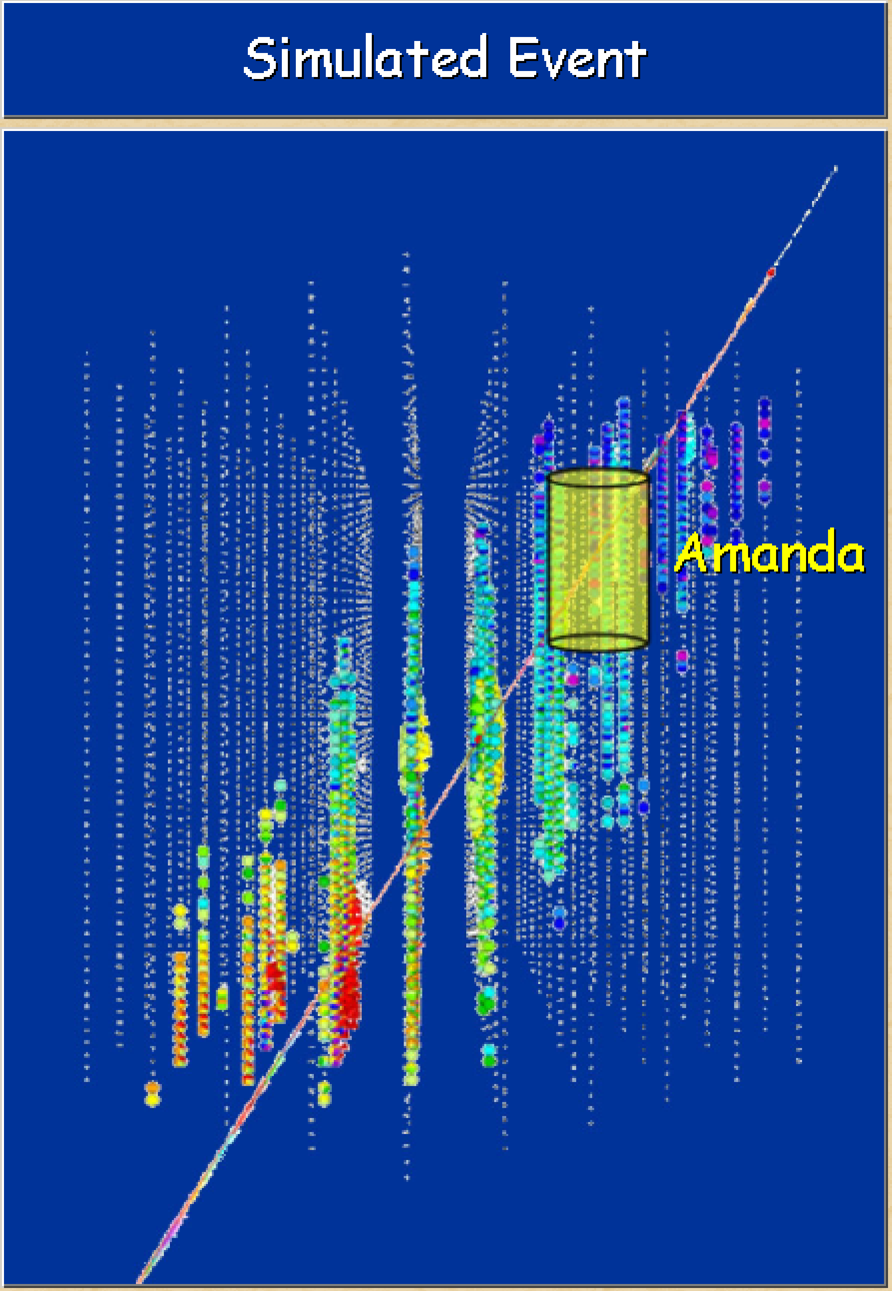
F.Halzen, Workshop "Neutrino Telescopes", Venice, March 03

Amanda Point Search Results

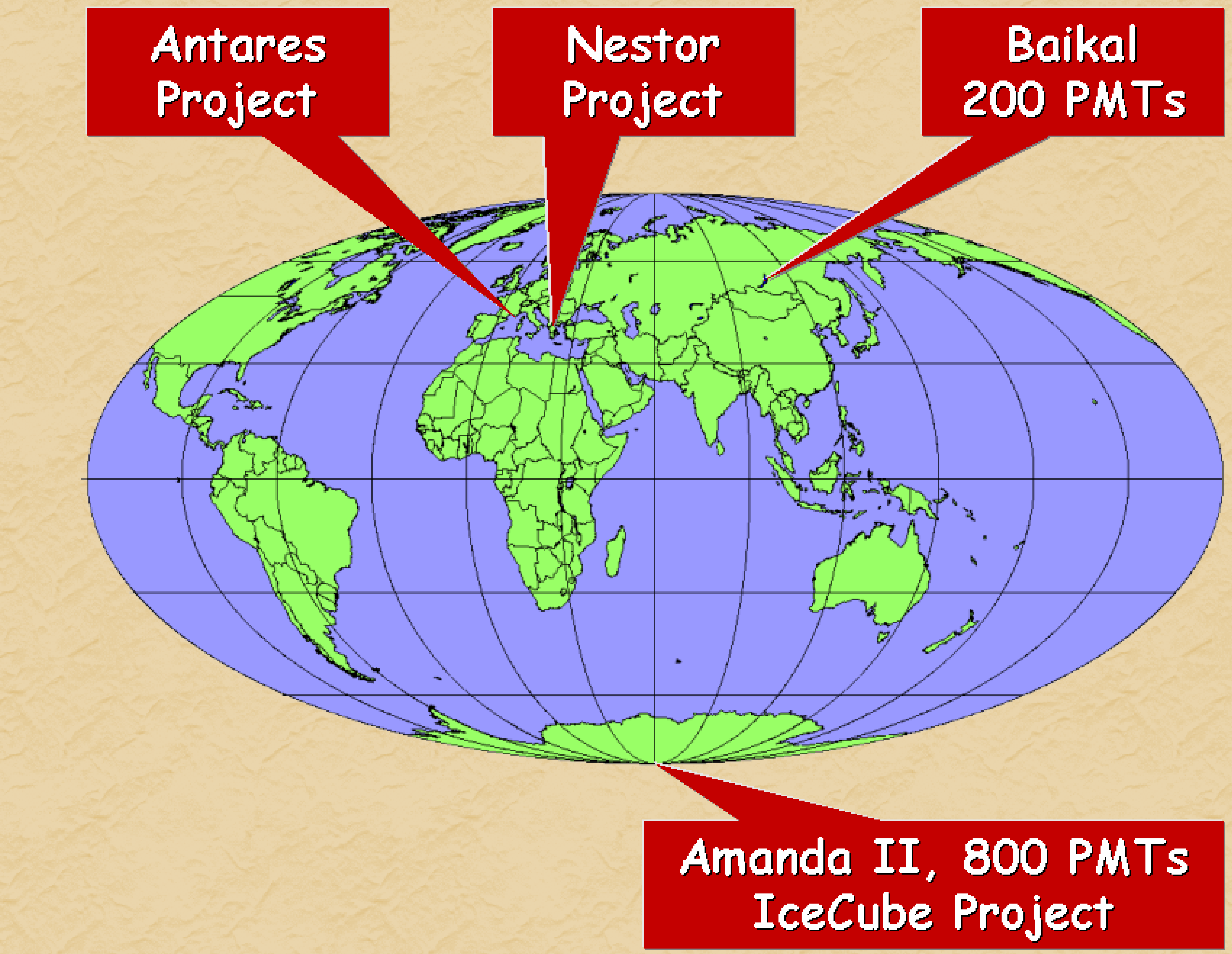


IceCube - Future km^3 South-Pole Detector





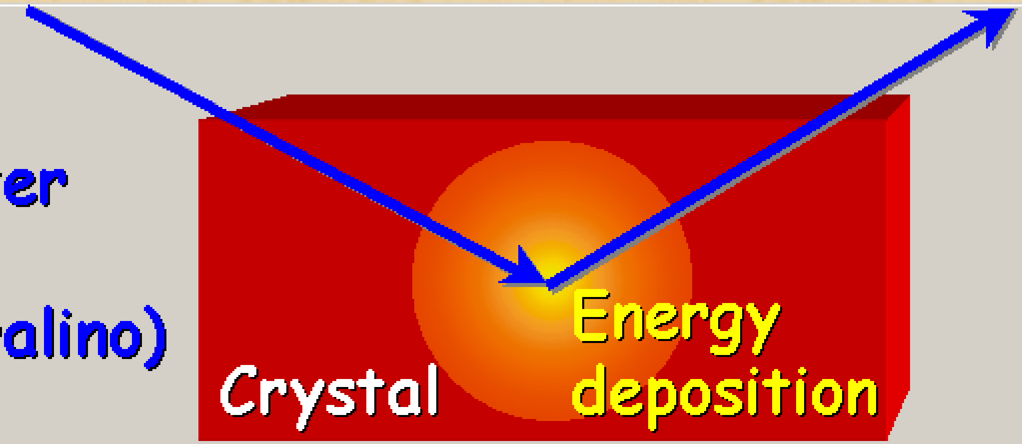
High-Energy Neutrino Telescopes



Search for Neutralino Dark Matter

Direct Method (Laboratory Experiments)

Galactic dark matter particle (e.g. neutralino)

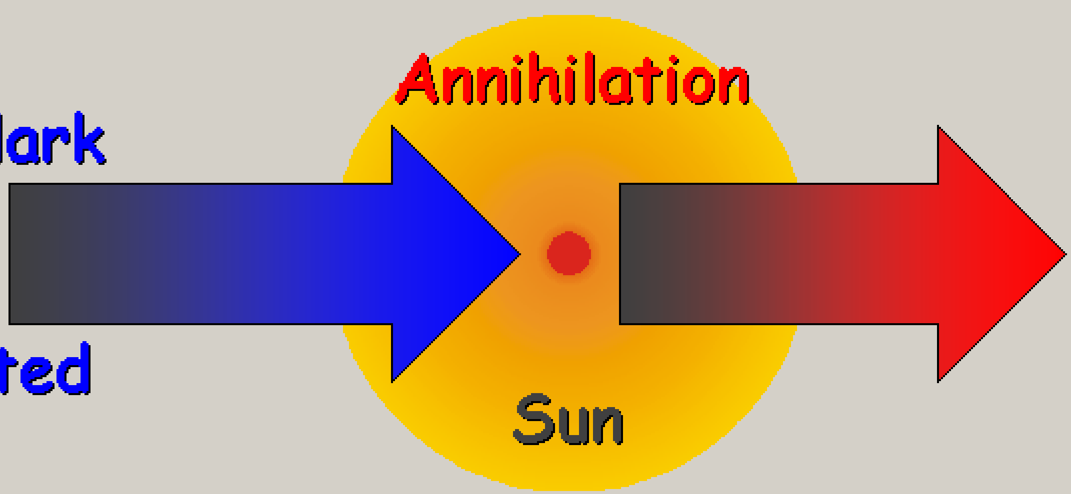


Recoil energy (few keV) is measured by

- Ionisation
- Scintillation
- Cryogenic

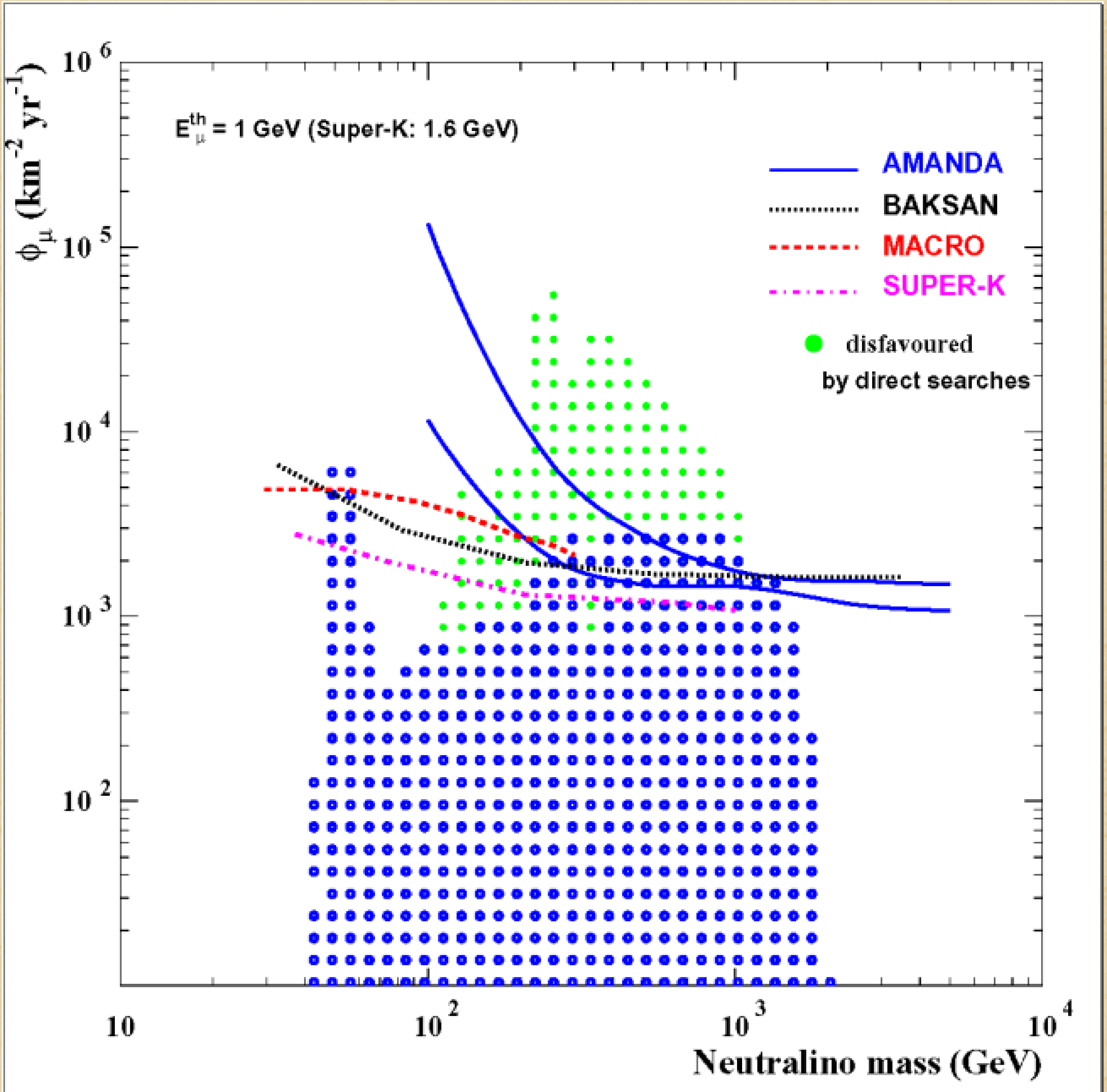
Indirect Method (Neutrino Telescopes)

Galactic dark matter particles are accreted



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

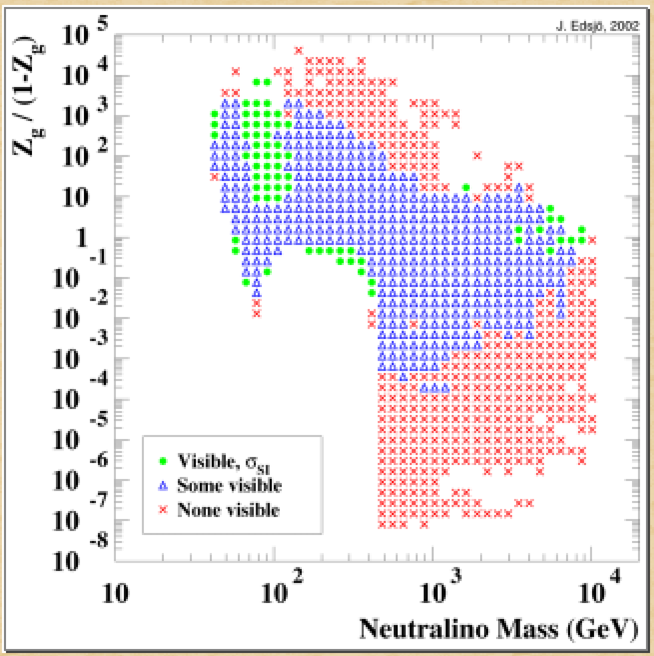
Current Limits from WIMP Searches

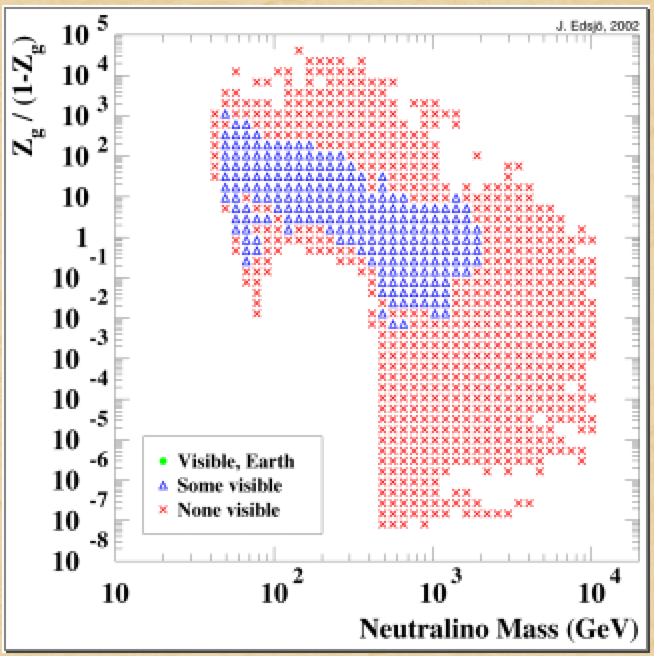


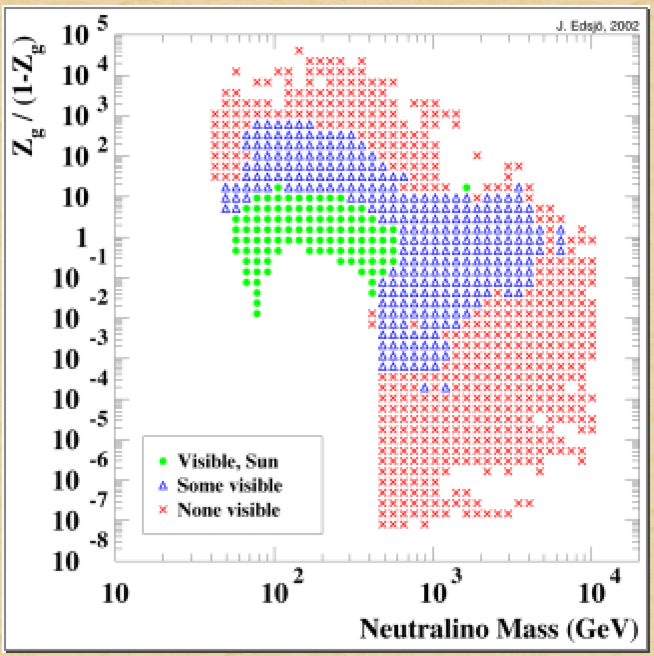
Limits from WIMP Annihilation in the Earth
astro-ph/0202370

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 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
  $\Sigma m_\nu < 1.0$ 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 $m_\nu < 0.1$ eV suggested

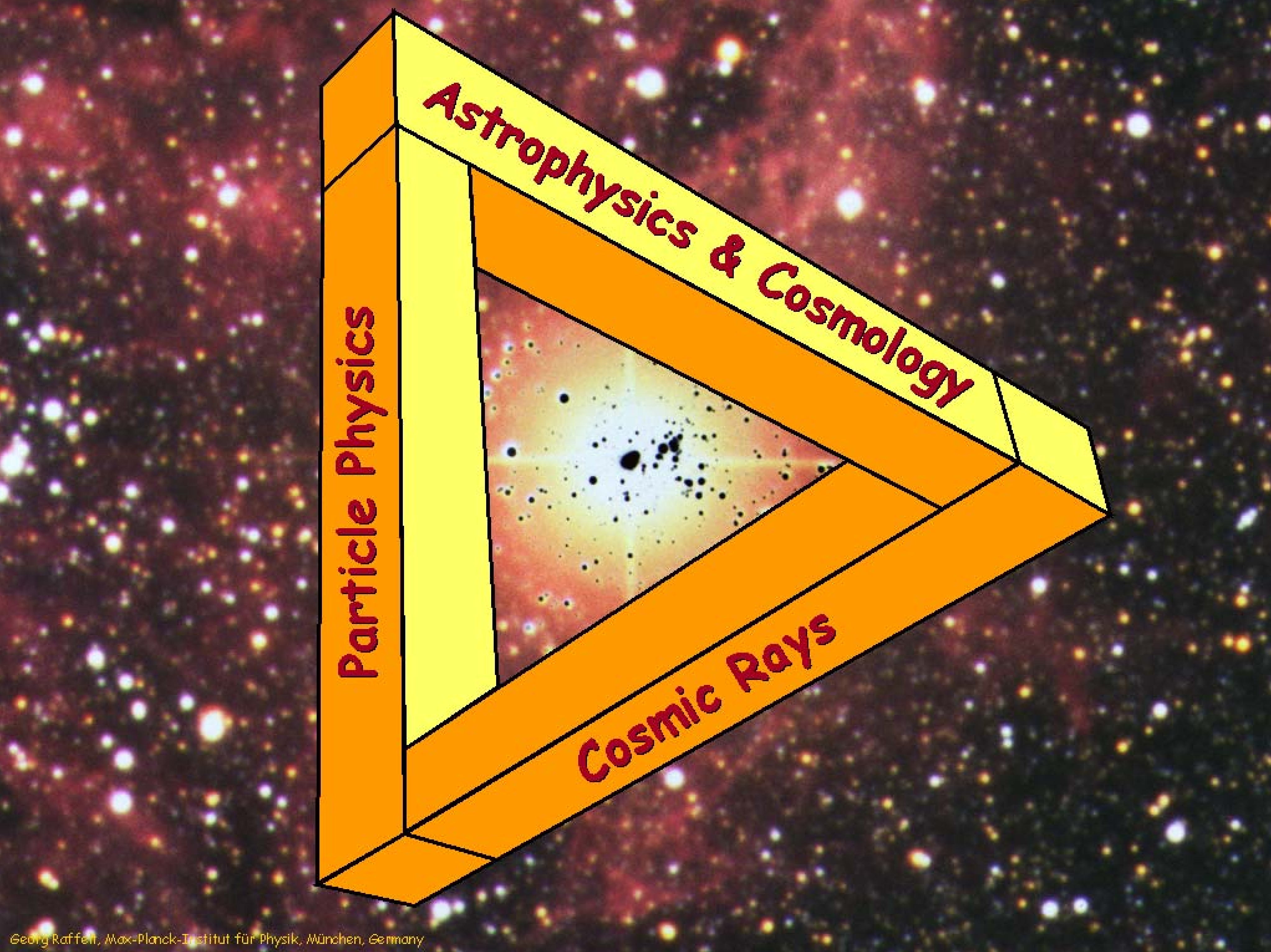
Sky in the light of neutrinos

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


Astrophysics & Cosmology
Particle Physics
Cosmic Rays
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