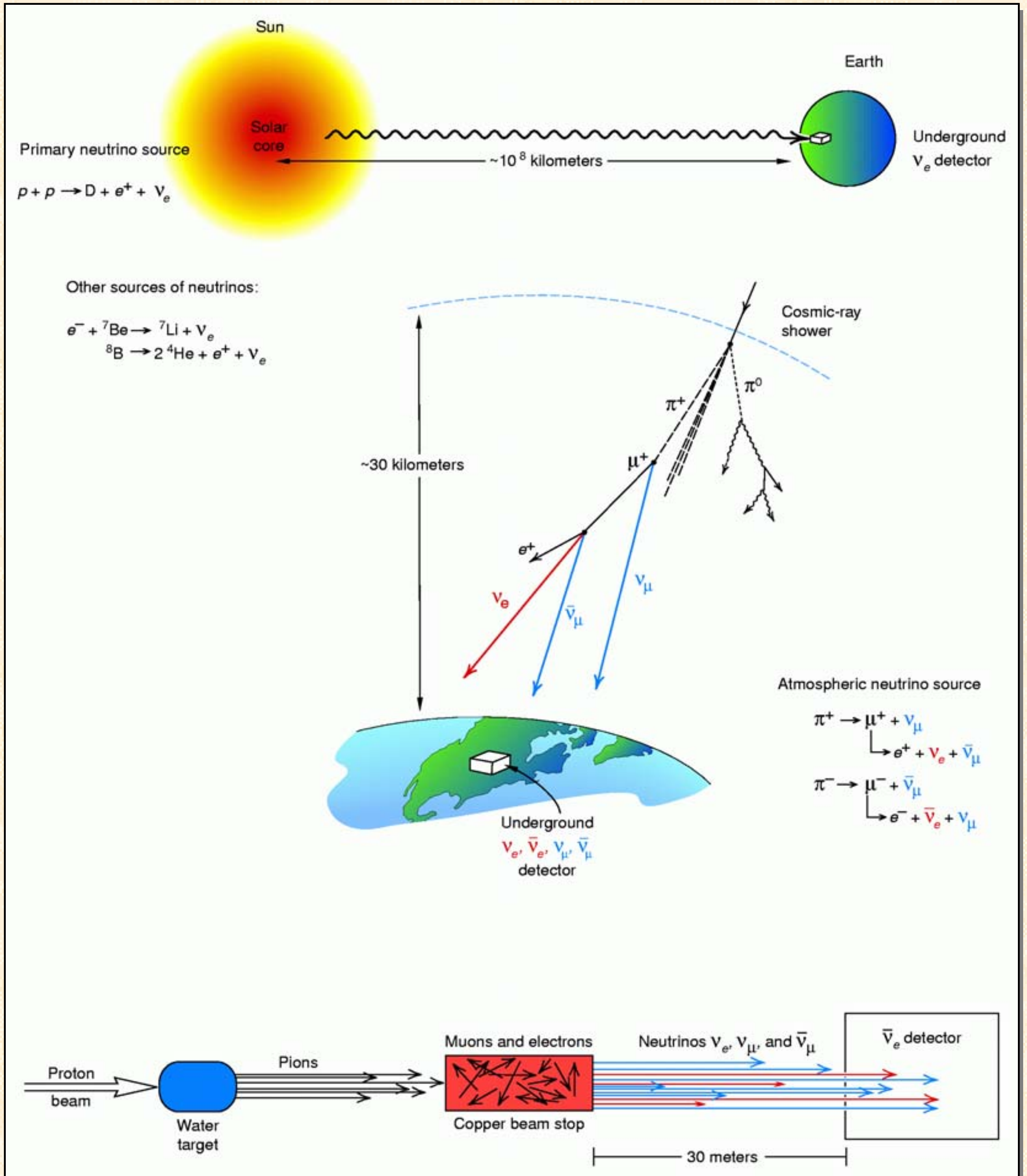
Neutrino Masses in Astrophysics and Cosmology

Georg Raffelt (Max-Planck-Institut für Physik, München)

Evidence for Neutrino Oscillations



Solar Neutrinos

Atmospheric Neutrinos

LSND Experiment

Georg Raffelt, Max-Planck-Institut für Physik (München)

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
$\sin^2 2\theta$	0.9-1	0.2-0.6	0.001-0.03
Status	Established	Established	Unconfirmed
	Mutually inconsistent with 3 mass eigenstates		
Test	Long Baseline	KamLAND 2002 ?	MiniBooNE 2003/4?
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)		Wrong

What is the absolute neutrino mass scale m_ν?

Georg Raffelt, Max-Planck-Institut für Physik (München)

Neutrino Masses in Astrophysics and Cosmology

Time-Of-Flight Sensitivity with Supernova Neutrinos

Neutrino Dark Matter and Cosmic Structure Formation

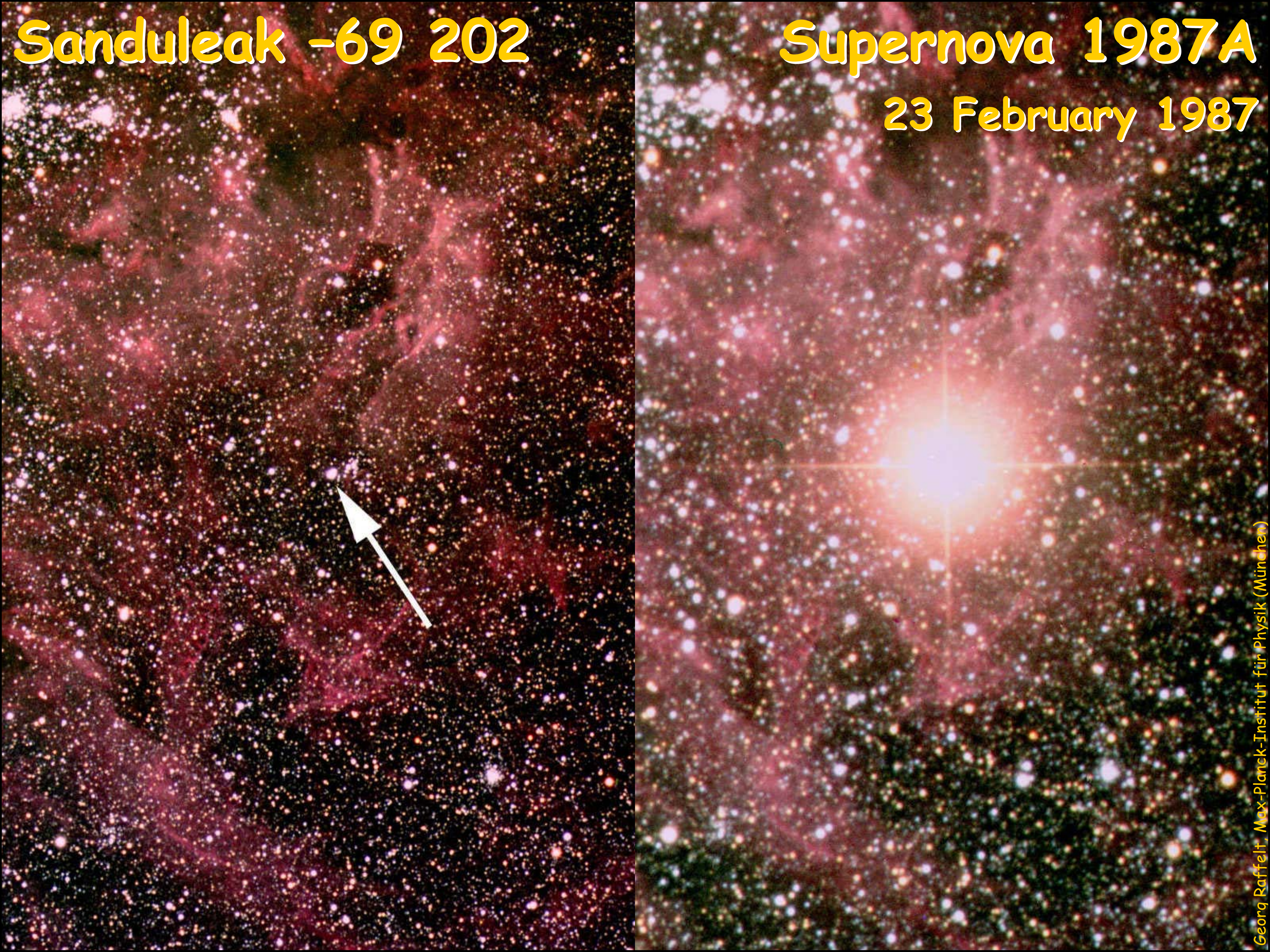
Neutrino Chemical Potentials, Big-Bang Nucleosynthesis, and Flavor Oscillations

Highest-Energy Cosmic Rays and the Cosmic Neutrino Sea

Massive Neutrinos and the Cosmic Baryon Asymmetry

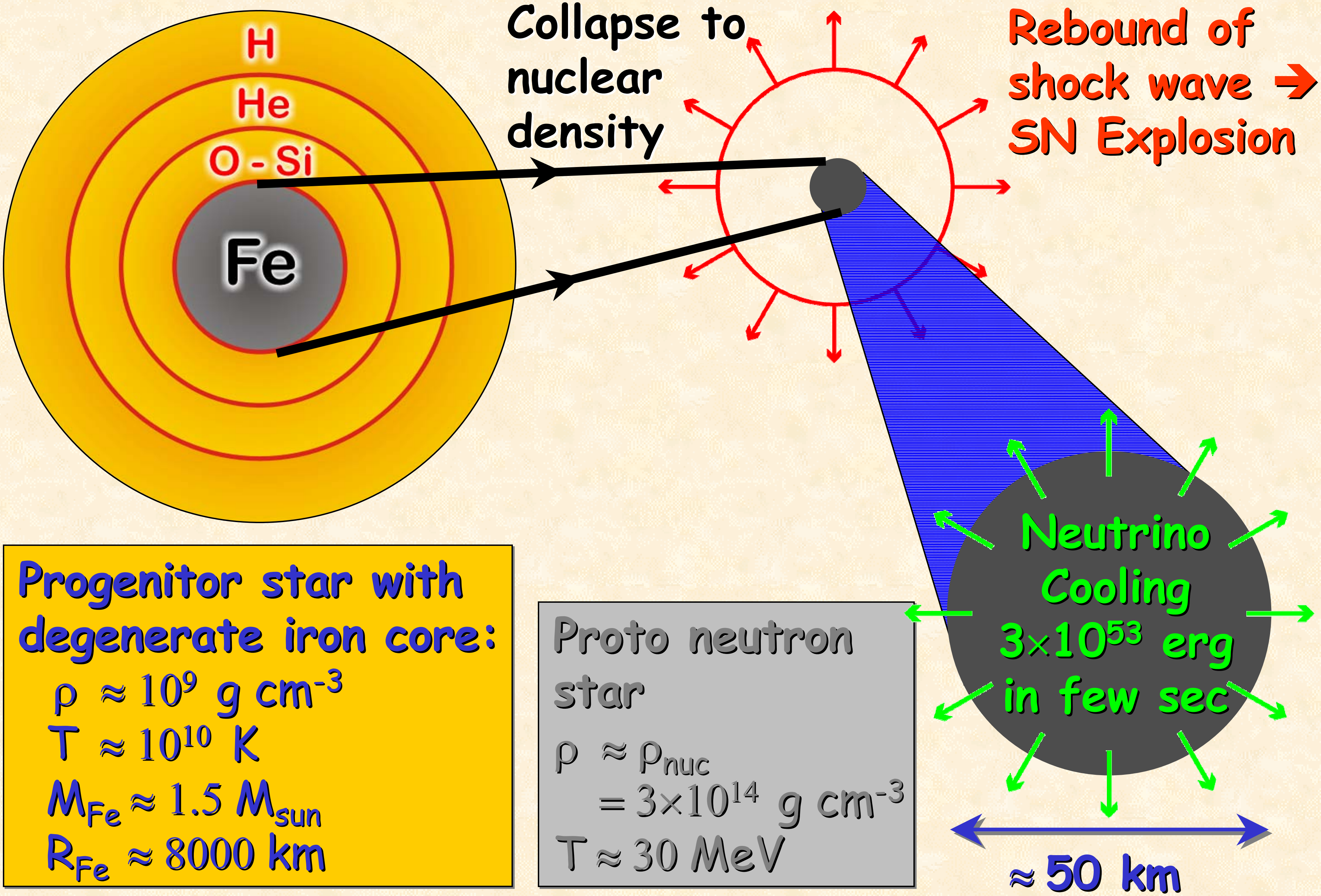
Time-Of-Flight Sensitivity with Supernova Neutrinos

Georg Raffelt, Max-Planck-Institut für Physik (München)



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

Stellar Collapse and Supernova Explosion



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Core Collapse Supernova Energetics

Liberated gravitational binding energy of neutron star:

$E_b \approx 3 \times 10^{53}$ 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

$L_\nu \approx 3\times10^{53}$ erg / 3 sec $\approx 3\times10^{19} L_{SUN}$

While it lasts, outshines the photon luminosity of the entire visible universe!

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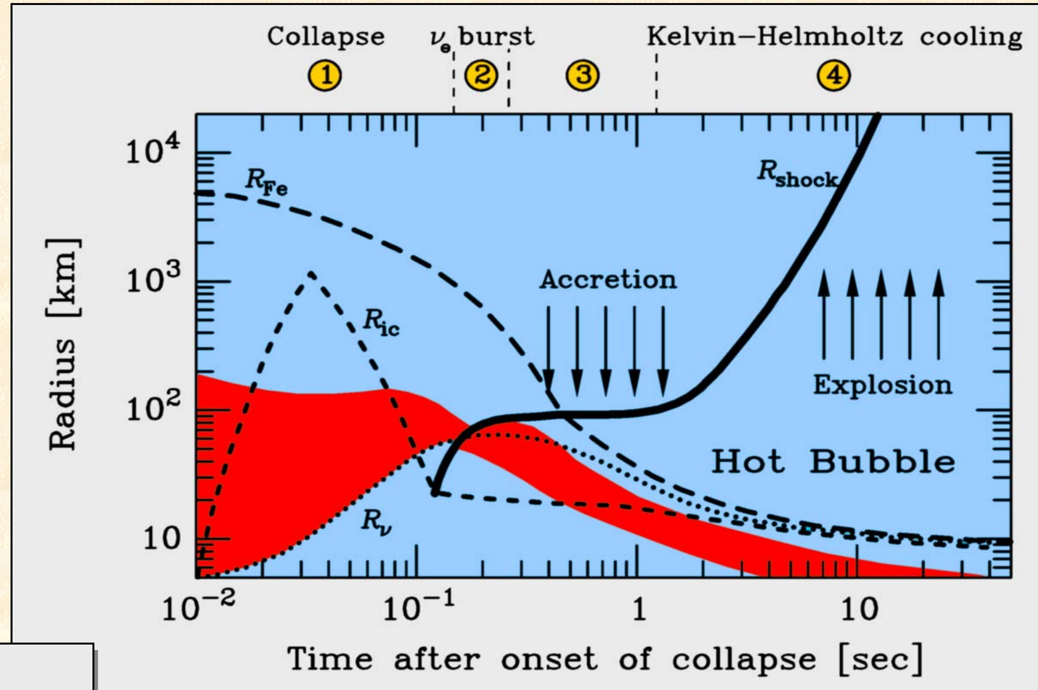
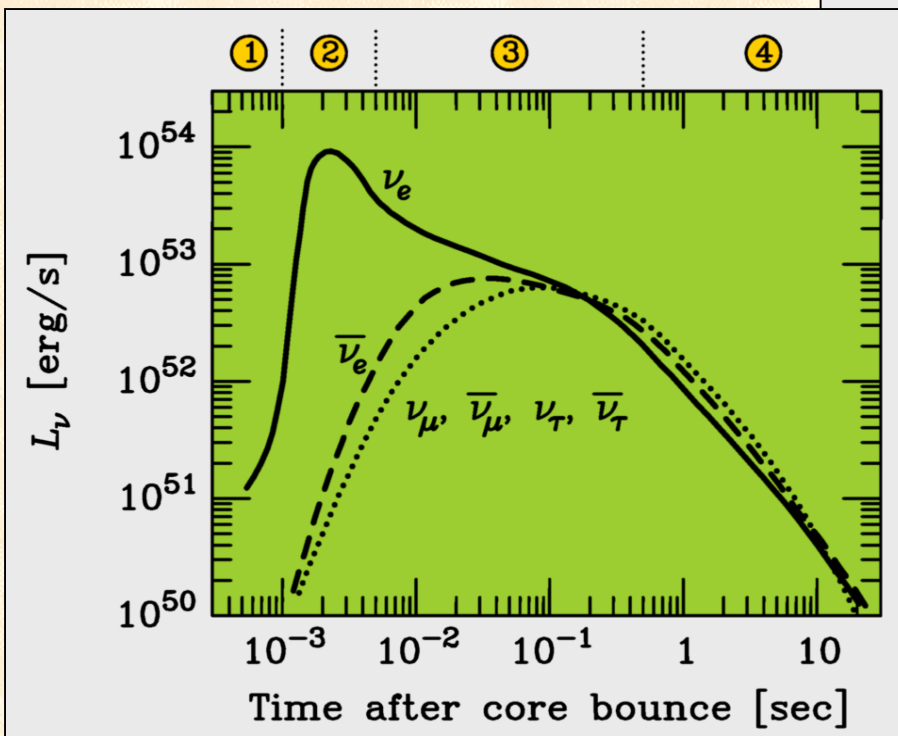
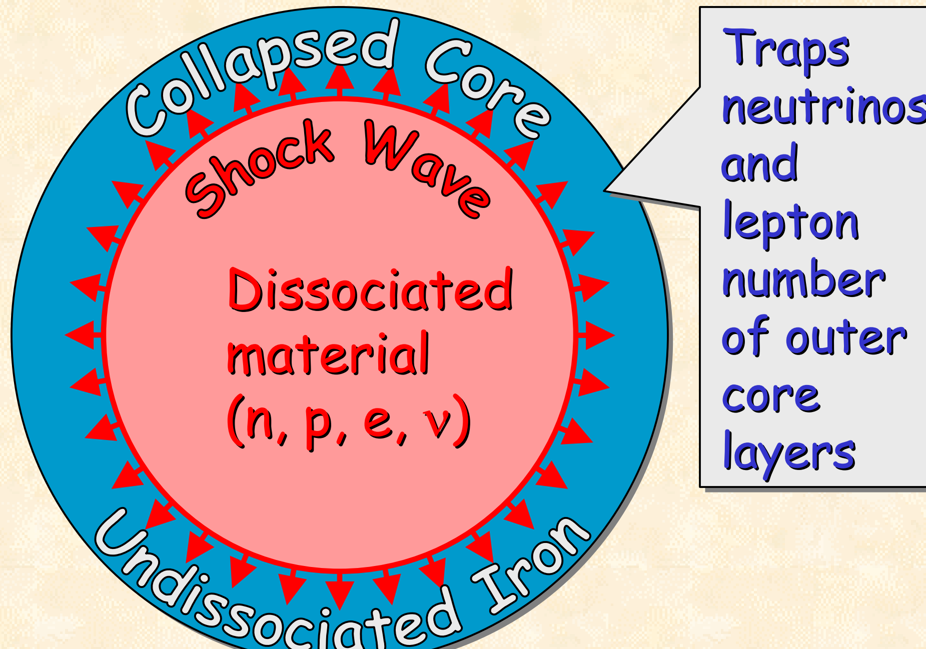
Supernova Neutrino Signal

1. Collapse (infall phase)
2. Shock break out
3. Matter accretion
4. Kelvin-Helmholtz cooling







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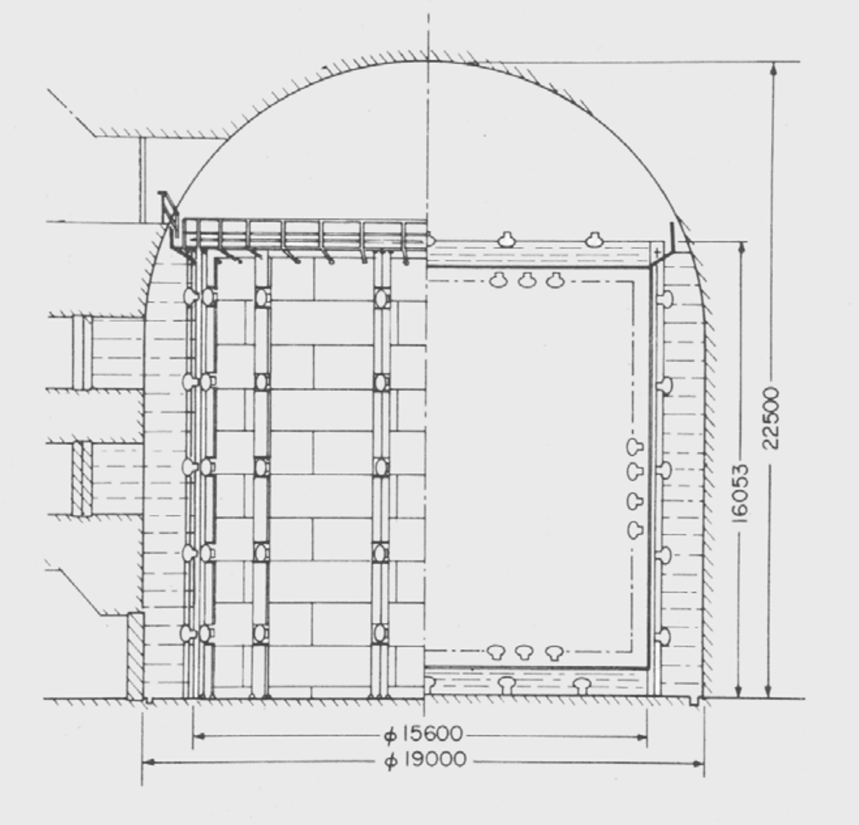
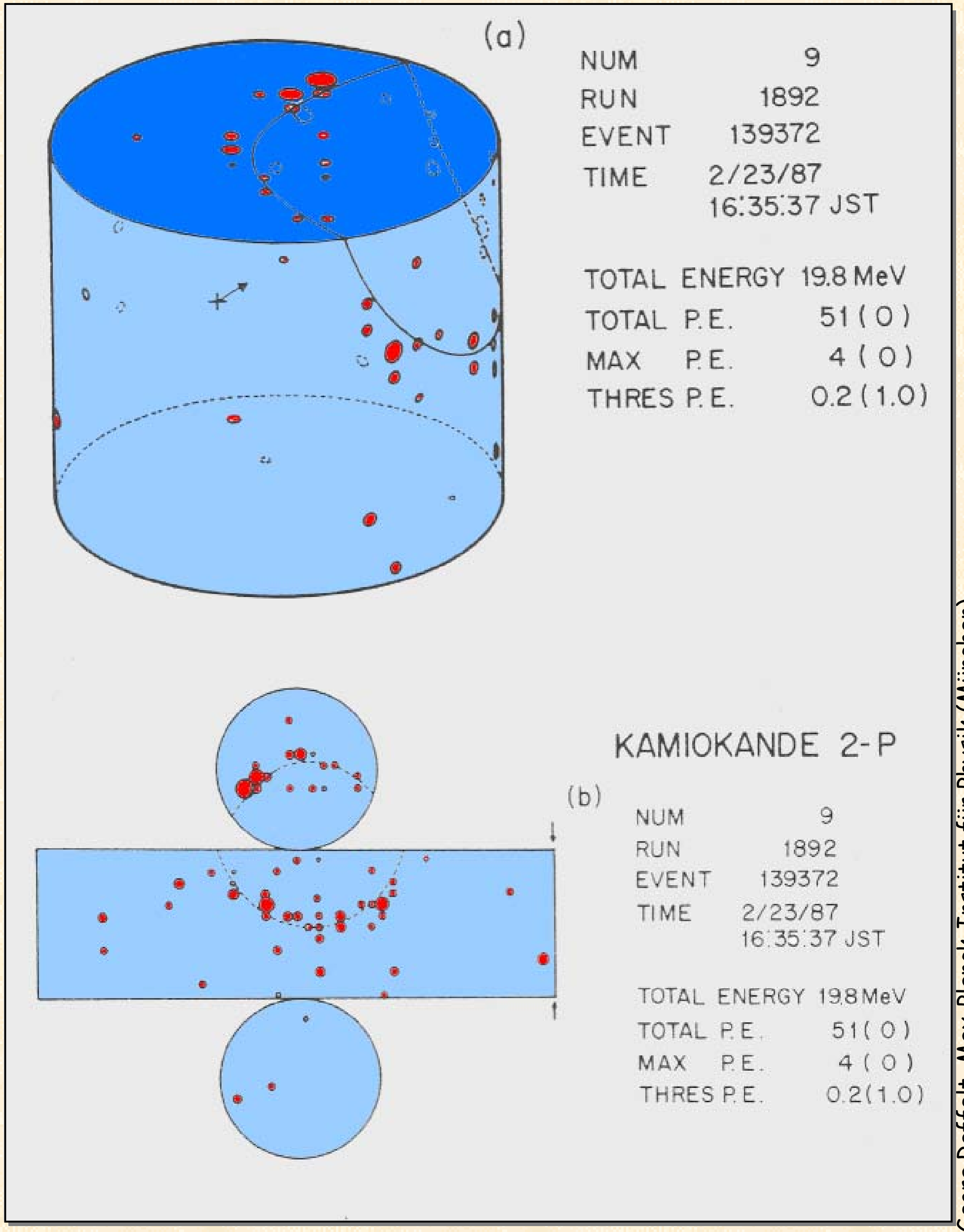
SN 1987A Event No.9 in Kamiokande

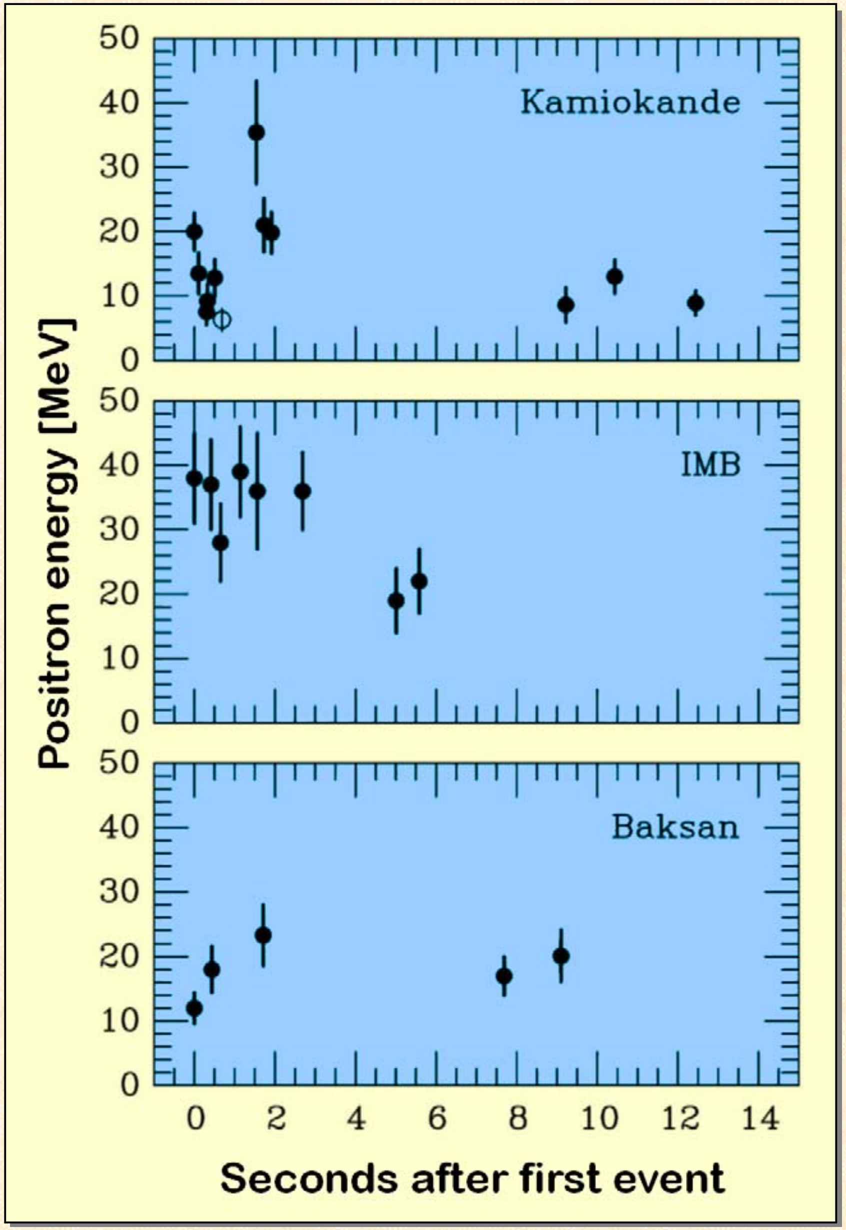
Kamiokande Detector





Hirata et al., PRD 38 (1988) 448

Neutrino Signal of Supernova 1987A



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

Irvine-Michigan-Brookhaven (USA)
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)

Neutrino Limits by Intrinsic Signal Dispersion

Time-of-flight delay of massive neutrinos

$$\Delta t = 2.57\,\mathrm{s}\left(\frac{D}{50\,\mathrm{kpc}}\right)\left(\frac{10\,\mathrm{MeV}}{E_\nu}\right)^2\left(\frac{m_\nu}{10\,\mathrm{eV}}\right)^2$$

SN 1987A	$E \approx 20$ MeV, $\Delta t \approx 10$ s, $D \approx 50$ kpc	$m_{\nu_e} < 20$ eV
	Detailed maximum-likelihood analysis similar result In 1987 competitive with tritium end-point limits	
Future Galactic SN (Super-K)	$D \approx 50$ kpc, Rise-time 0.01 s	
	Sensitivity approximately	$m_{\nu_e} \sim 3$ eV

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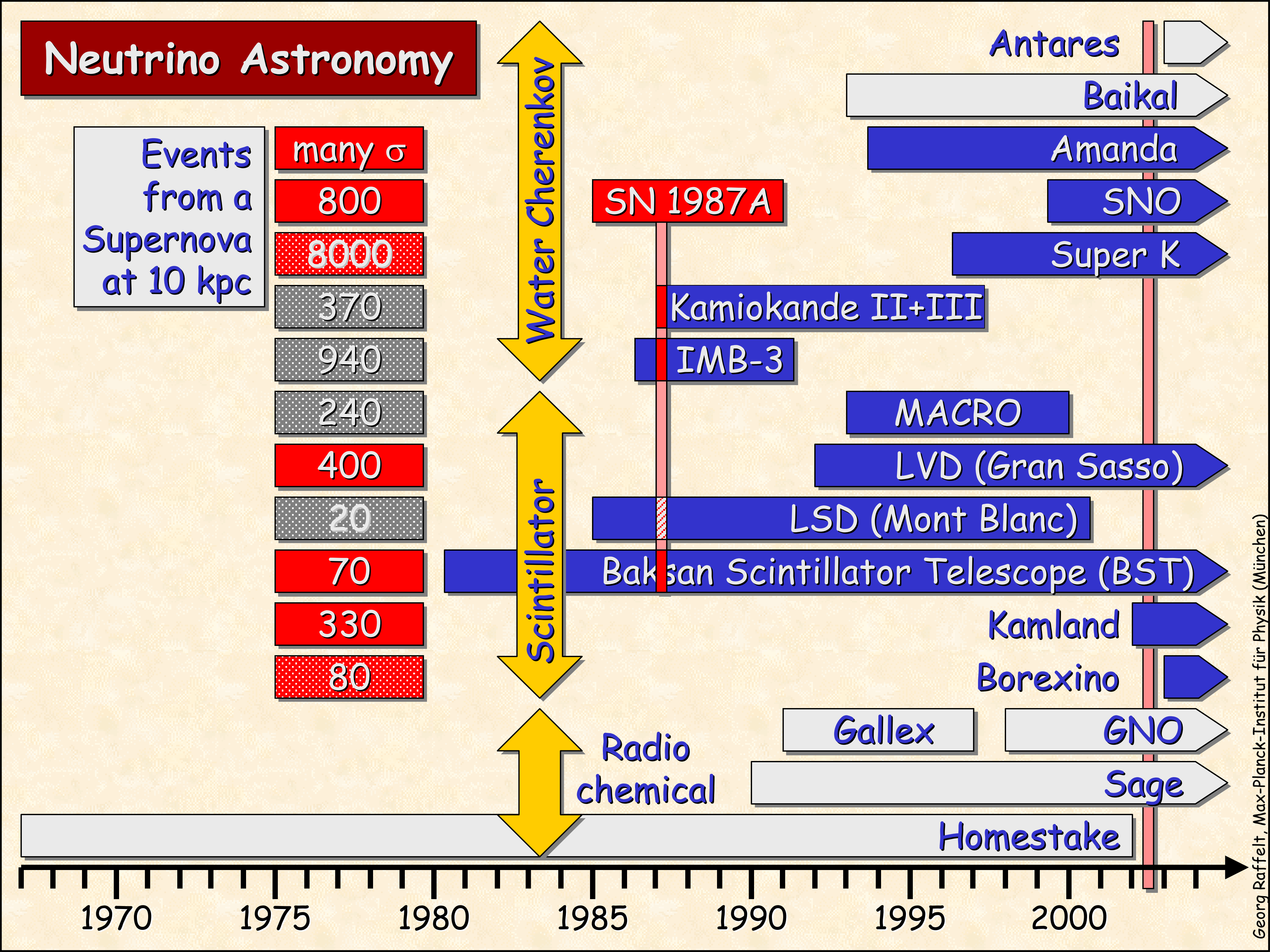
Neutrino Astronomy
Events from a Supernova at 10 kpc
many σ
800
8000
370
940
240
400
20
70
330
80
Water Cherenkov
Scintillator
Radio chemical
Antares
Baikal
Amanda
SNO
SN 1987A
Super K
Kamiokande II+III
IMB-3
MACRO
LVD (Gran Sasso)
LSD (Mont Blanc)
Baksan Scintillator Telescope (BST)
Kamland
Borexino
Gallex
GNO
Sage
Homestake
1970
1975
1980
1985
1990
1995
2000
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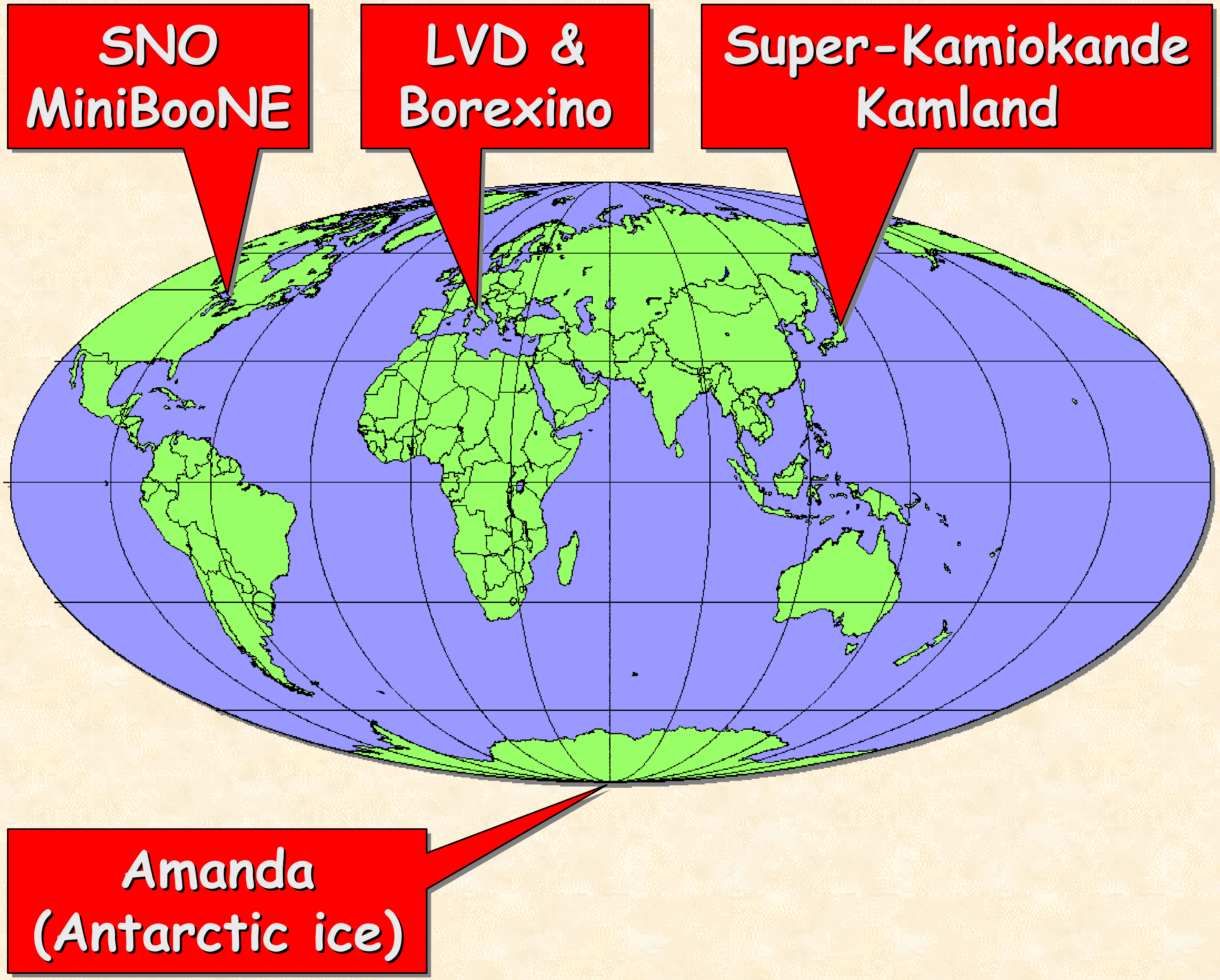
Large Detectors for SN Neutrinos



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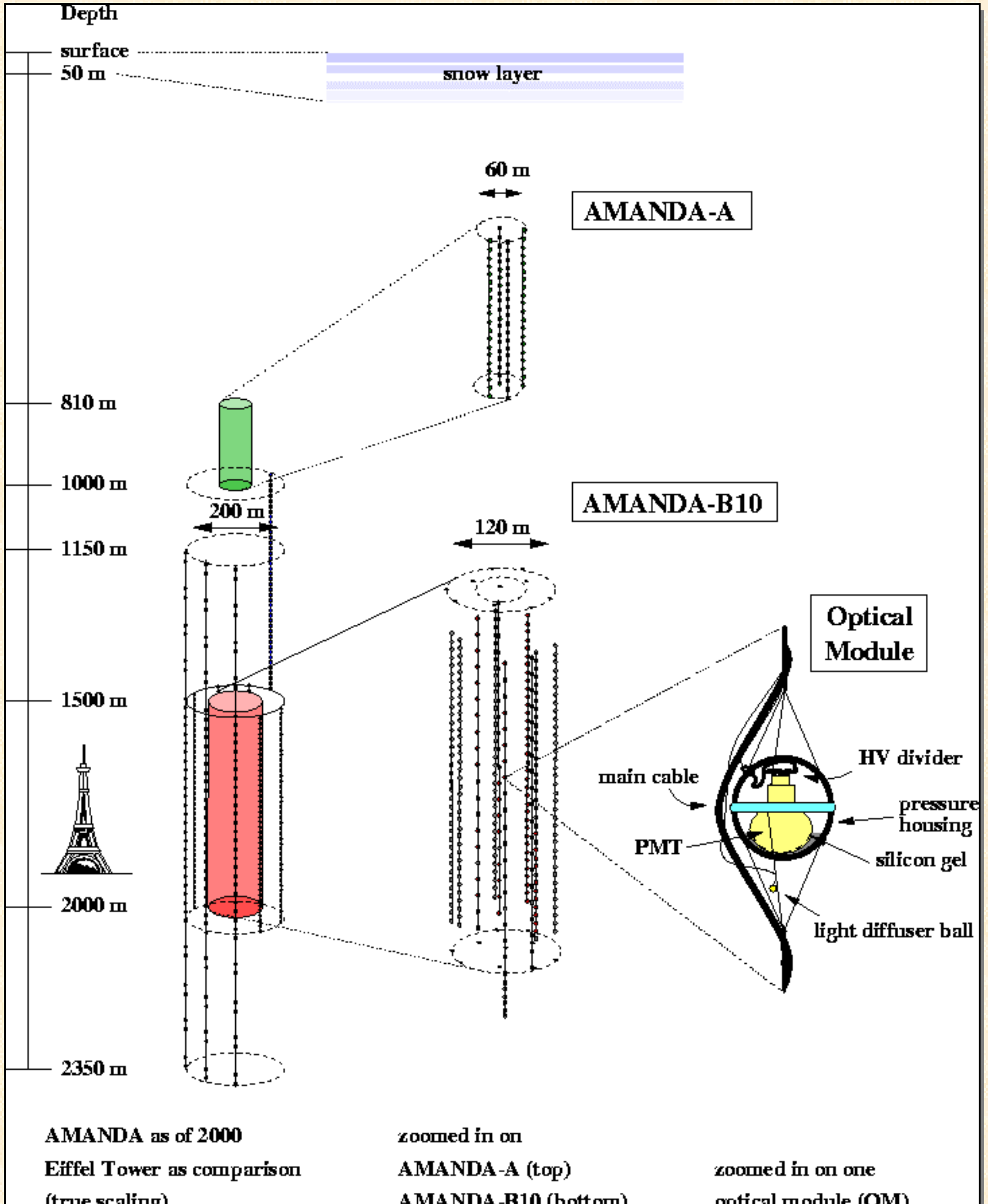
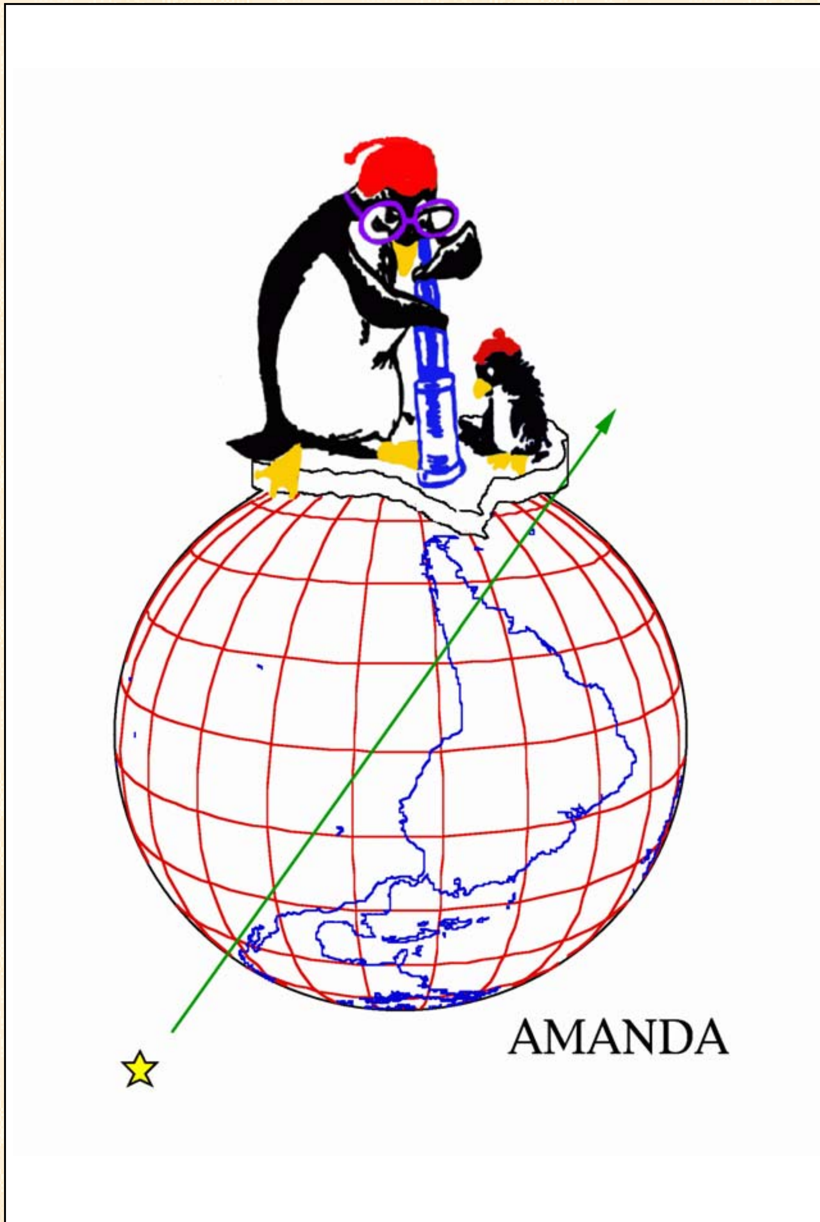
AMANDA – Neutrino Telescope at the Southpole





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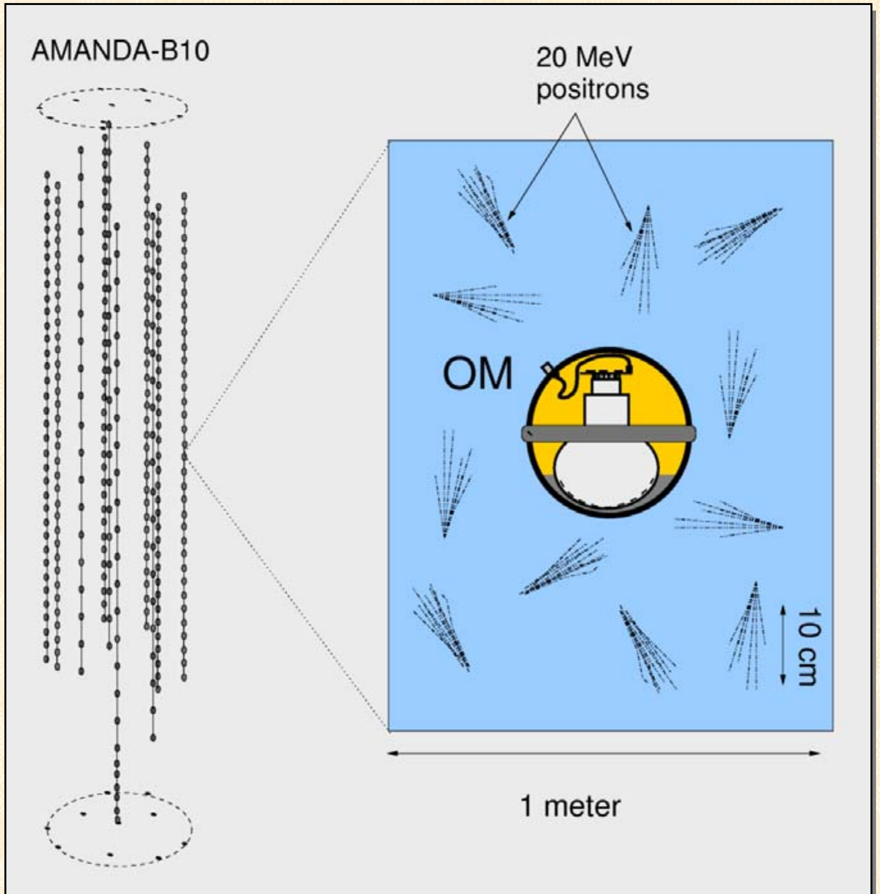
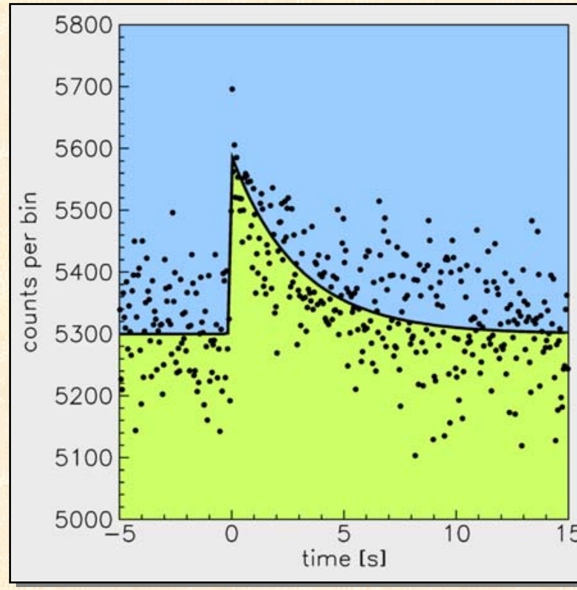
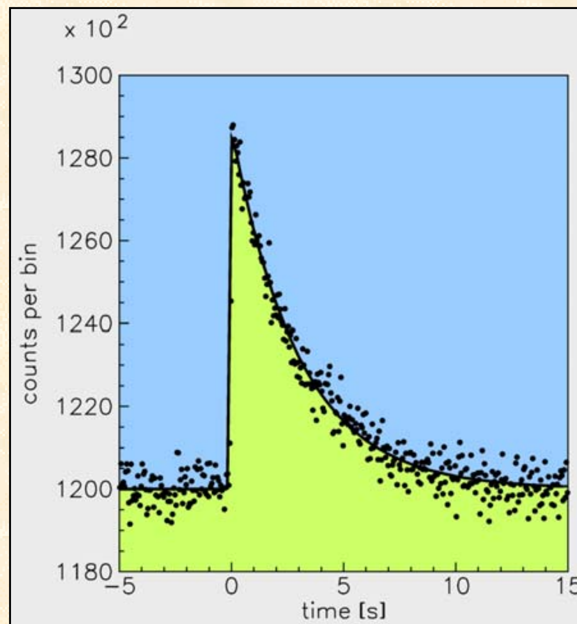
Amanda as a Supernova Detector





SN @ 8.5 kpc
Signal in
Amanda

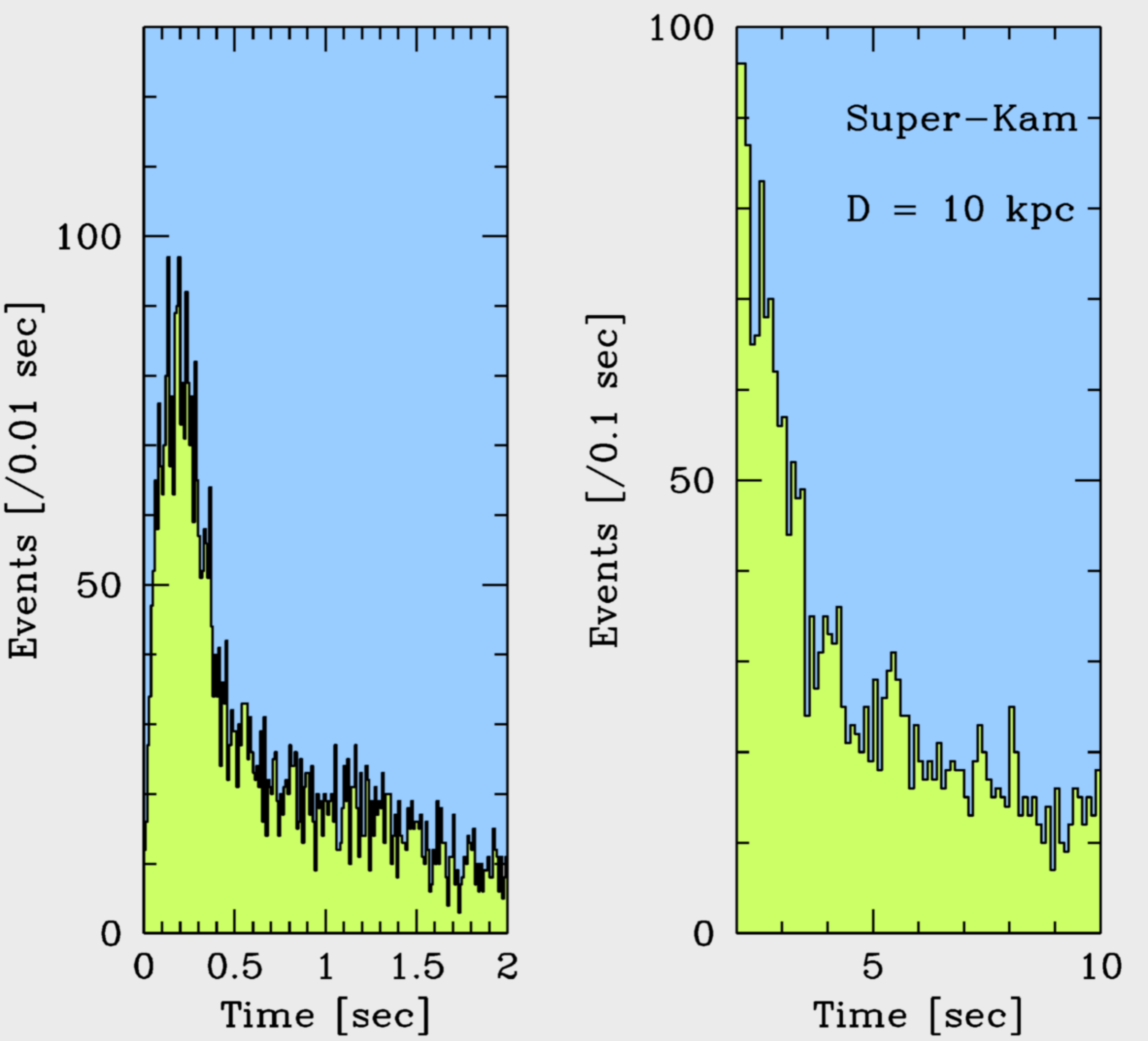


SN @ 8.5 kpc
Signal in
Ice Cube

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

Amanda Coll.
(2001)

Galactic Supernova Signal in Super-Kamiokande



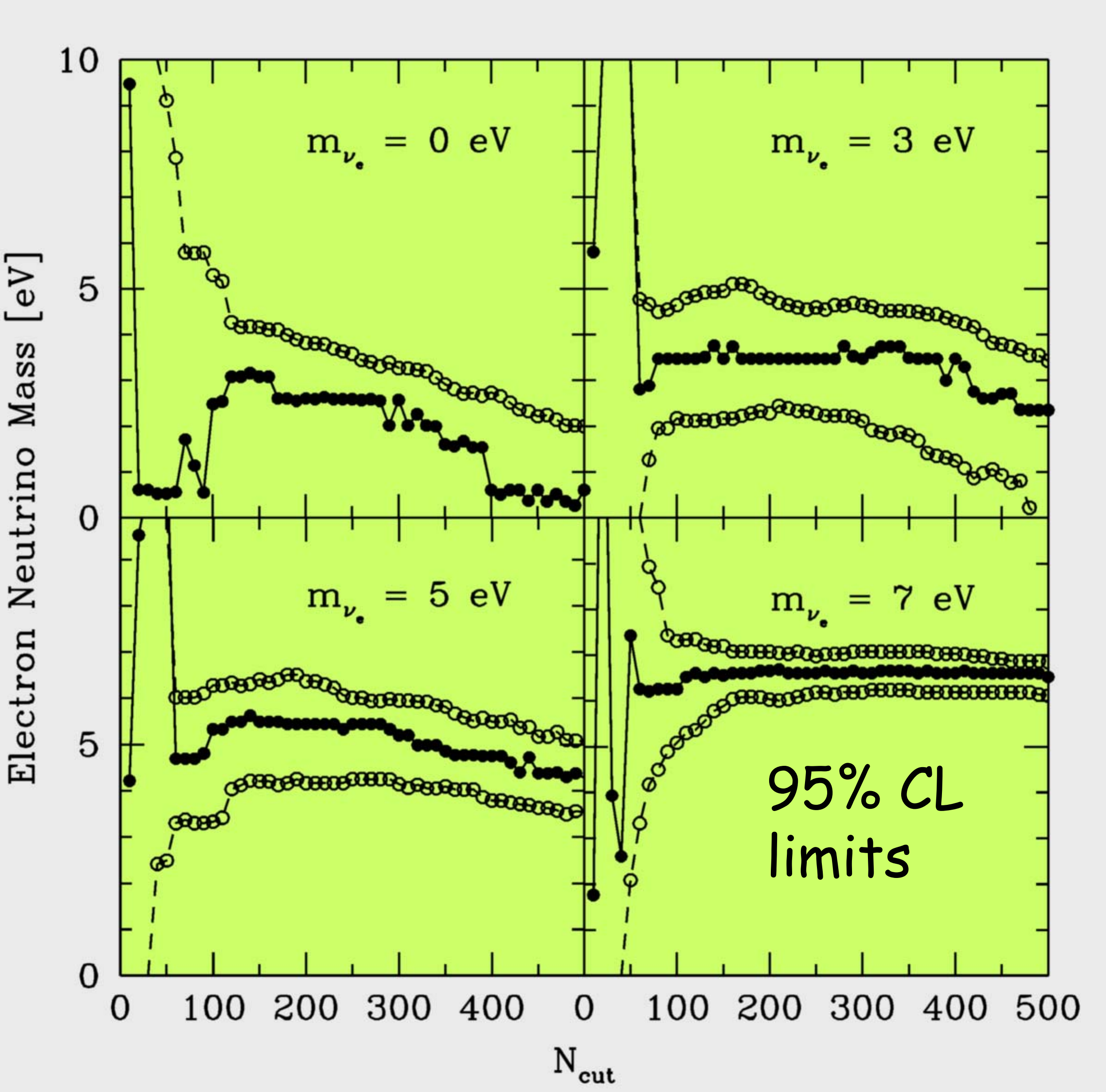
Monte-Carlo simulation for Super-K signal of SN at 10 kpc, based on a numerical model with Livermore code

Total of about 8300 events for t < 18 s

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

Georg Raffelt, Max-Planck-Institut für Physik (München)

Neutrino Mass from a Future Galactic SN

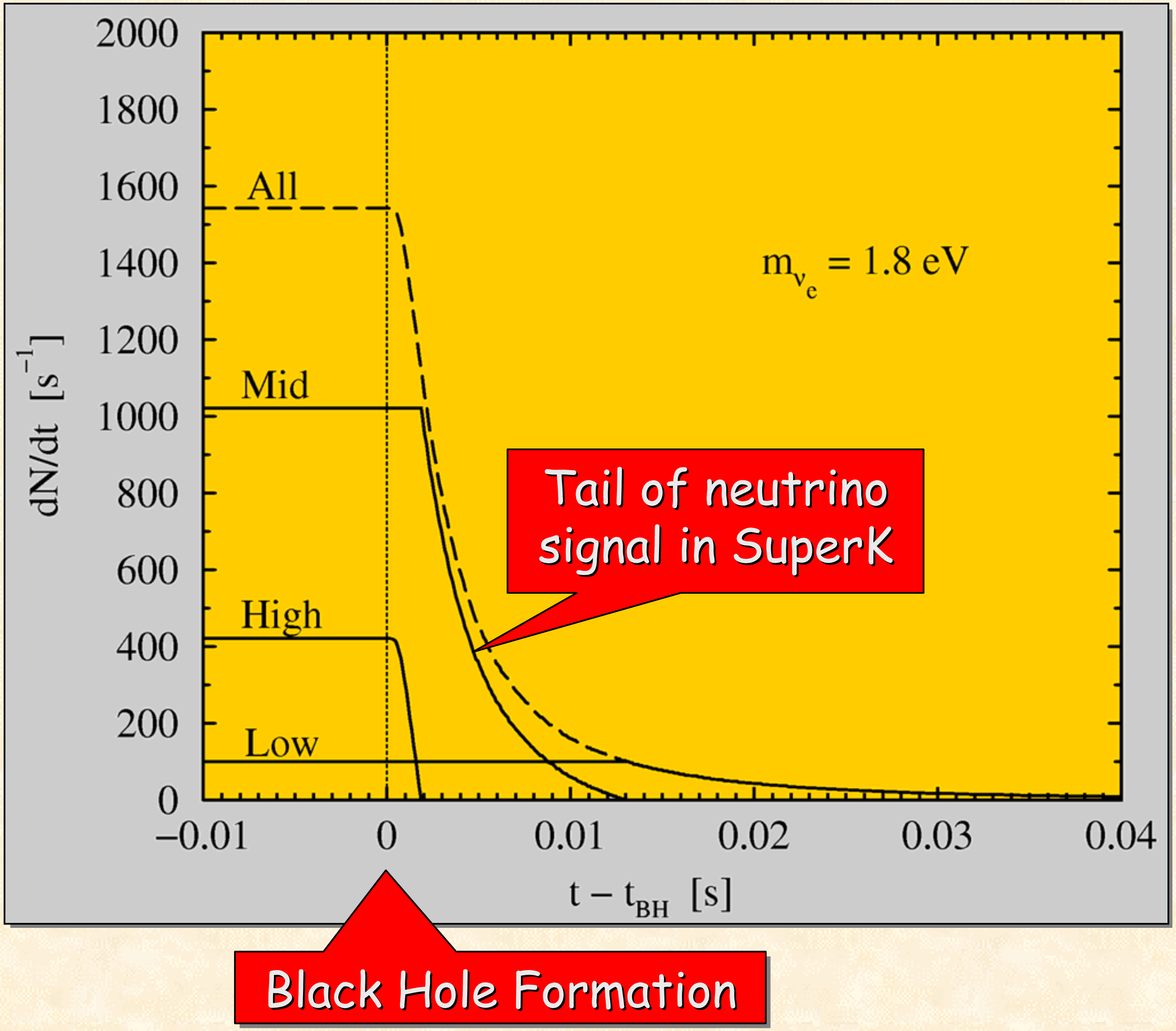


Use correlation between energy & time of arrival as a statistical measure of first N_{cut} events in Monte Carlo simulation of SN signal in SuperK

For SN at 10 kpc sensitive to approx. 3 eV

T.Totani, PRL 80 (1998) 2040

SN Neutrino Mass from Early Black Hole Formation



Beacom, Boyd & Mezzacappa, hep-ph/0006015

Super-Kamiokande sensitivity
$m_\nu \sim 1.8$ eV

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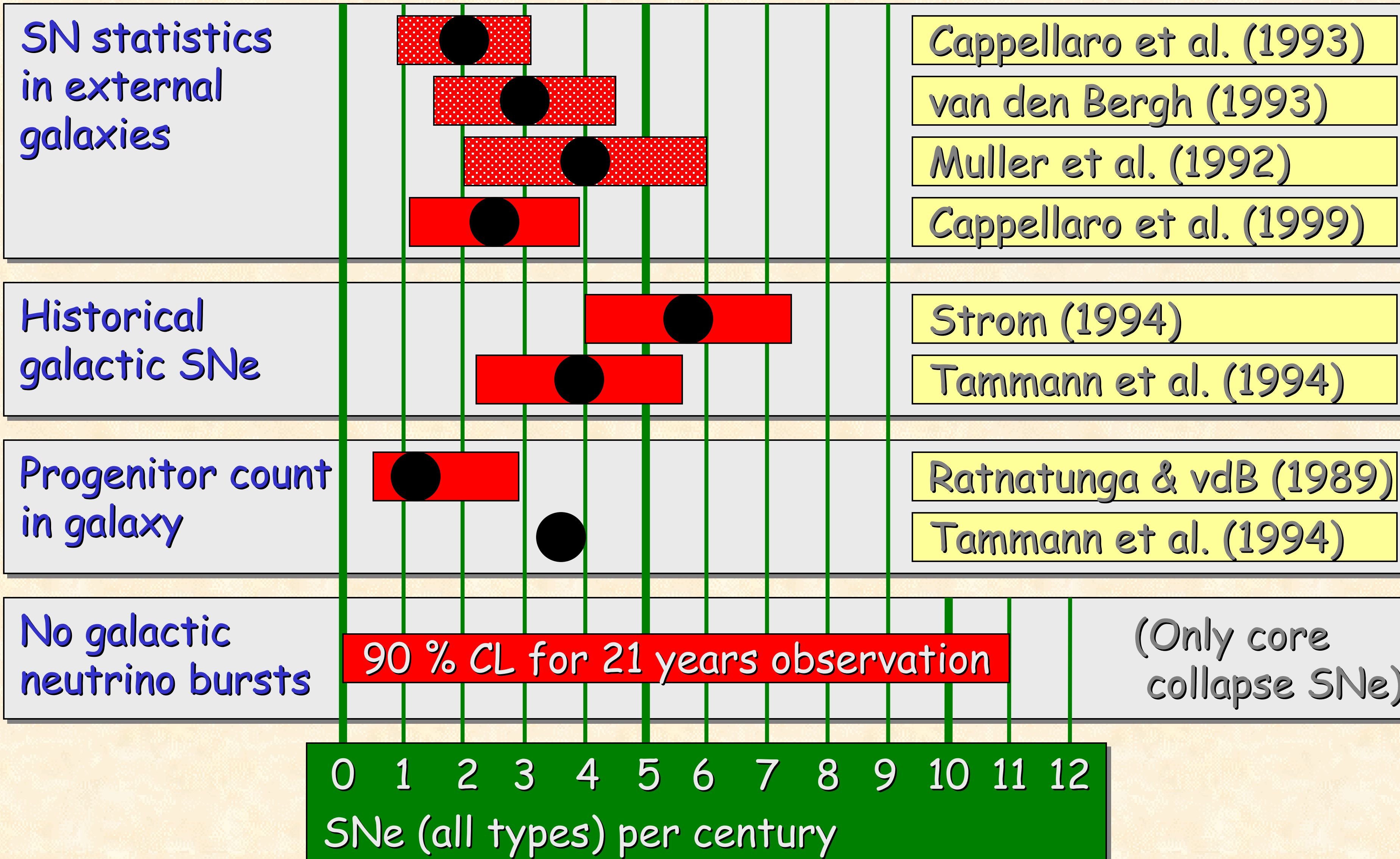
Estimates of the Galactic SN Rate

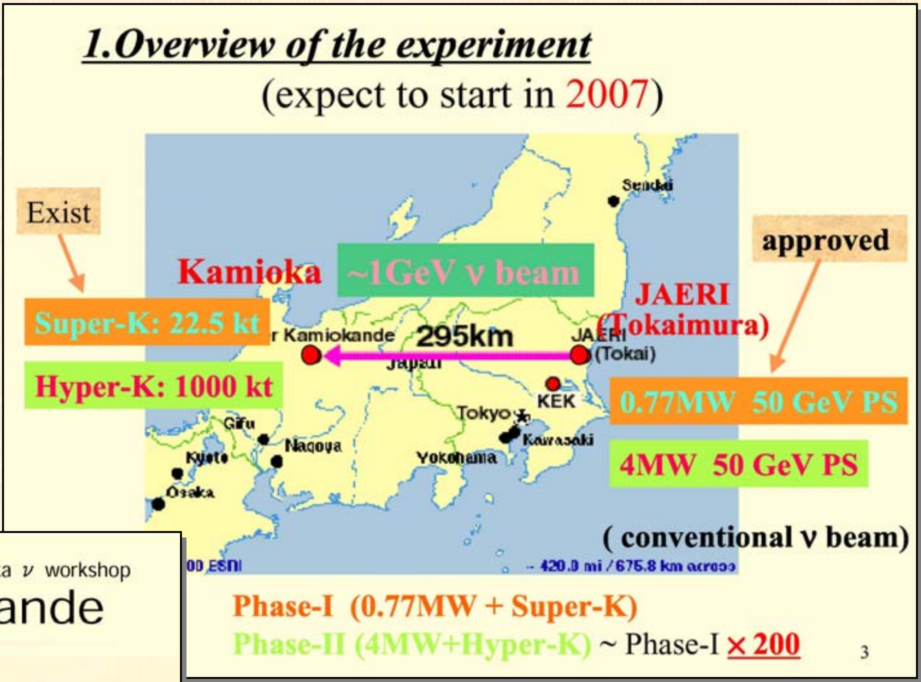


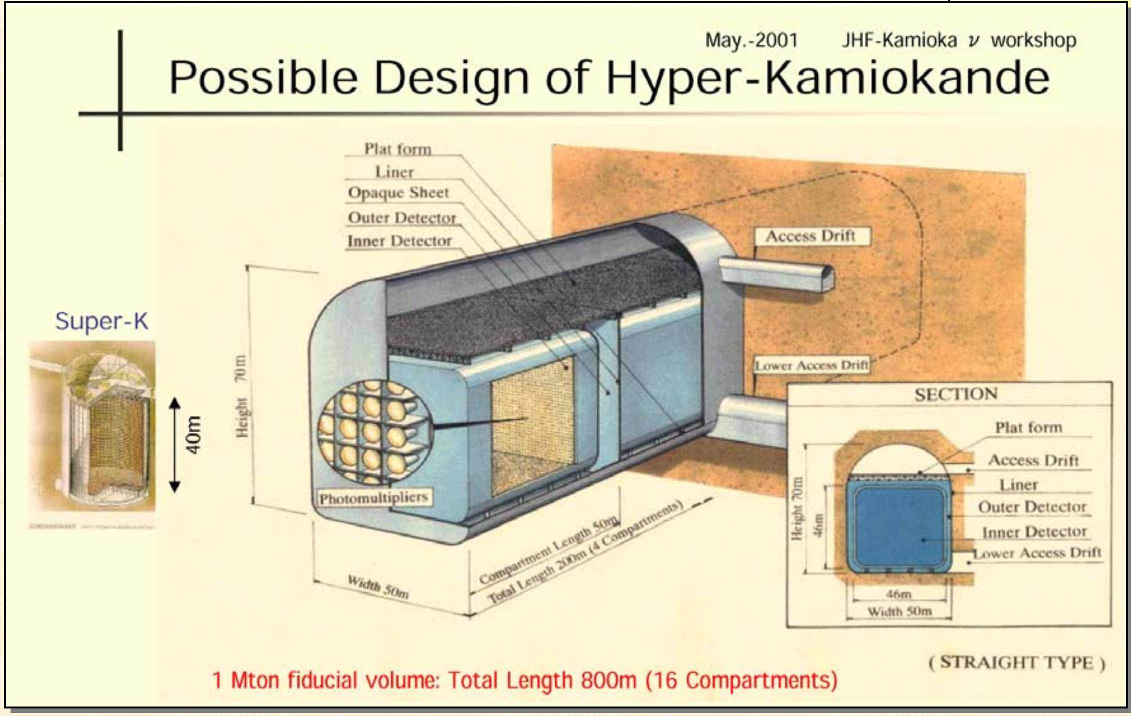
The Future: A Megatonne Detector?

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)

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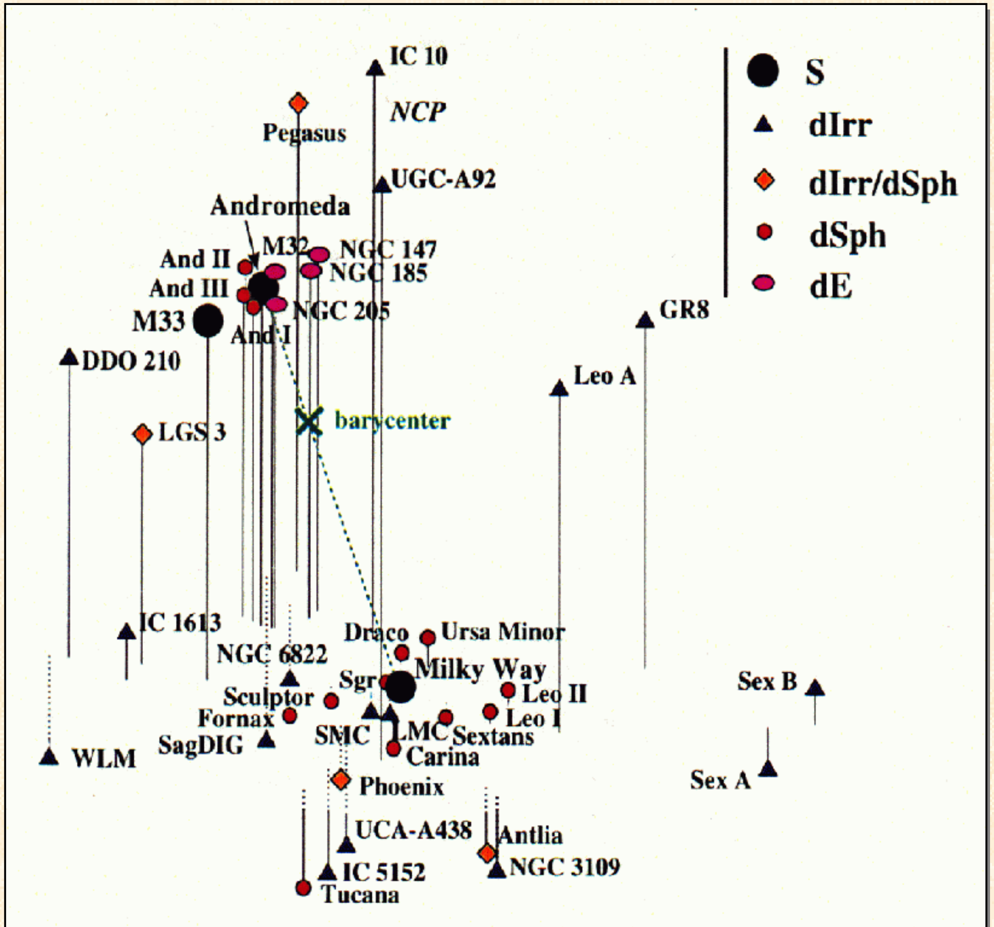
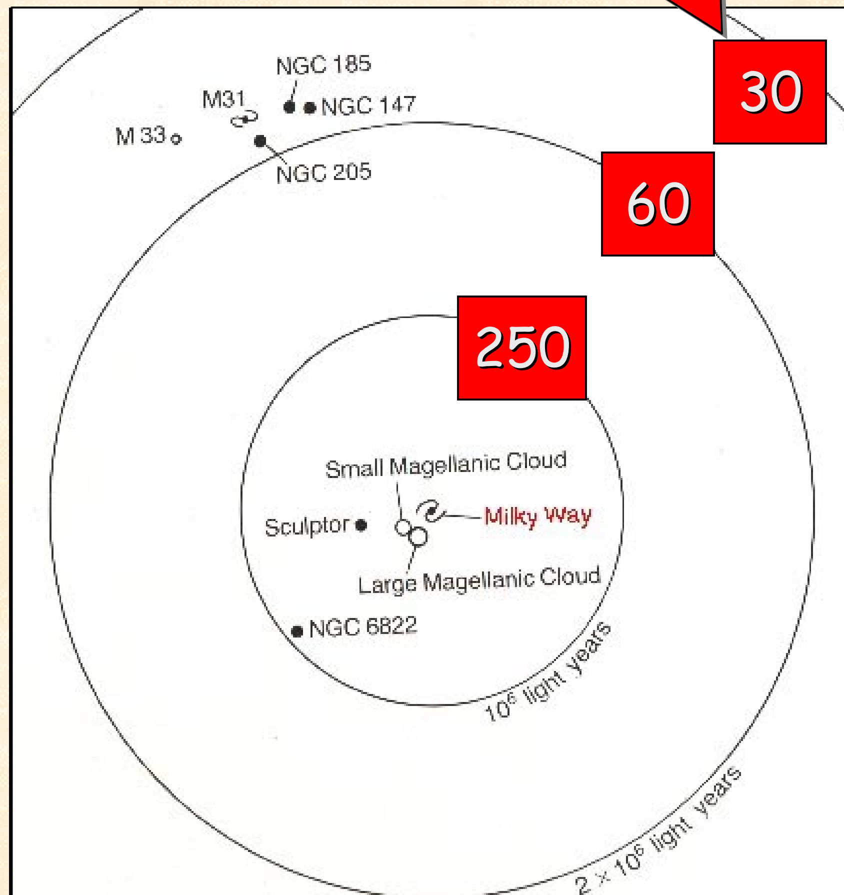
Local Group of Galaxies



Events in a detector with
30 x SuperK fiducial volume
(8000 events in SK at 10 kpc)



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Brightest Members of Local Group

	Type	Lum	D kpc	Neutrino events	SN (all types) per century
Milky Way	S(B)bc	1	8.5	330,000	1-6
LMC	Ir	0.11	50	9,600	0.1 / 0.23 / 0.49
SMC	Ir	0.030	60	6,600	0.065 / 0.12
NGC 6822	Ir	0.011	500	96	0.04
IC 10 (UGC 192)	Ir	0.015	660	55	0.082-0.11
NGC 205	Sph	0.016	760	42	
M32 (NGC 221)	E2	0.017	760	42	
Andromeda (M31)	Sb	1.3	760	42	0.9 / 1.21 / 1.25
Triangulum (M33)	Sc	0.16	790	38	0.28 / 0.35 / 0.68

- Luminosity: Visual in units of the Milky Way
- Neutrino events in 30 x SK fiducial vol. (8000 events in SK for SN at 10 kpc)
- Refs. for SN rates in Pavlidou & Fields, Ap. J. 558 (2001) 63.

Georg Raffelt, Max-Planck-Institut für Physik (München)

Neutrino Limits by Intrinsic Signal Dispersion

Time-of-flight delay of massive neutrinos

$$\Delta t = 2.57\,\mathrm{s}\left(\frac{D}{50\,\mathrm{kpc}}\right)\left(\frac{10\,\mathrm{MeV}}{E_\nu}\right)^2\left(\frac{m_\nu}{10\,\mathrm{eV}}\right)^2$$

SN 1987A

- $E \approx 20$ MeV, $\Delta t \approx 10$ s, $D \approx 50$ kpc — $m_{\nu_e} < 20$ eV
- Detailed maximum-likelihood analysis similar result
- In 1987 competitive with tritium end-point limits

Future Galactic SN (Super-K)

- $D \approx 50$ kpc, Rise-time 0.01 s
- Sensitivity approximately — $m_{\nu_e} \sim 3$ eV

Future SN in Andromeda (Megatonne)

- $D \approx 750$ kpc, $\Delta t \approx 10$ s
- Sensitivity approximately — $m_{\nu_e} \sim 1$-2 eV

Neutrino Mass and SNe – Good or Bad News?

Tritium Limits < 2-3 eV
Future < 0.3 eV
Cosmological LSS similar limits
Oscillations: All mass differences < 0.1 eV

All active flavors likely to have sub-eV masses or less

Supernova time-of-flight dispersion

$$\Delta t = 0.46\,\mathrm{ms}\left(\frac{D}{10\,\mathrm{kpc}}\right)\left(\frac{10\,\mathrm{MeV}}{E_\nu}\right)^2\left(\frac{m_\nu}{0.3\,\mathrm{eV}}\right)^2$$

Measure pristine neutrino light curve, unspoilt by dispersion effects

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Neutrino Dark Matter and Cosmic Structure Formation

Georg Raffelt, Max-Planck-Institut für Physik (München)

Cosmological Limit on Neutrino Masses

Cosmic neutrino "sea":
Approximately **112 cm^{-3}** neutrinos + antineutrinos per flavor

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

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

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

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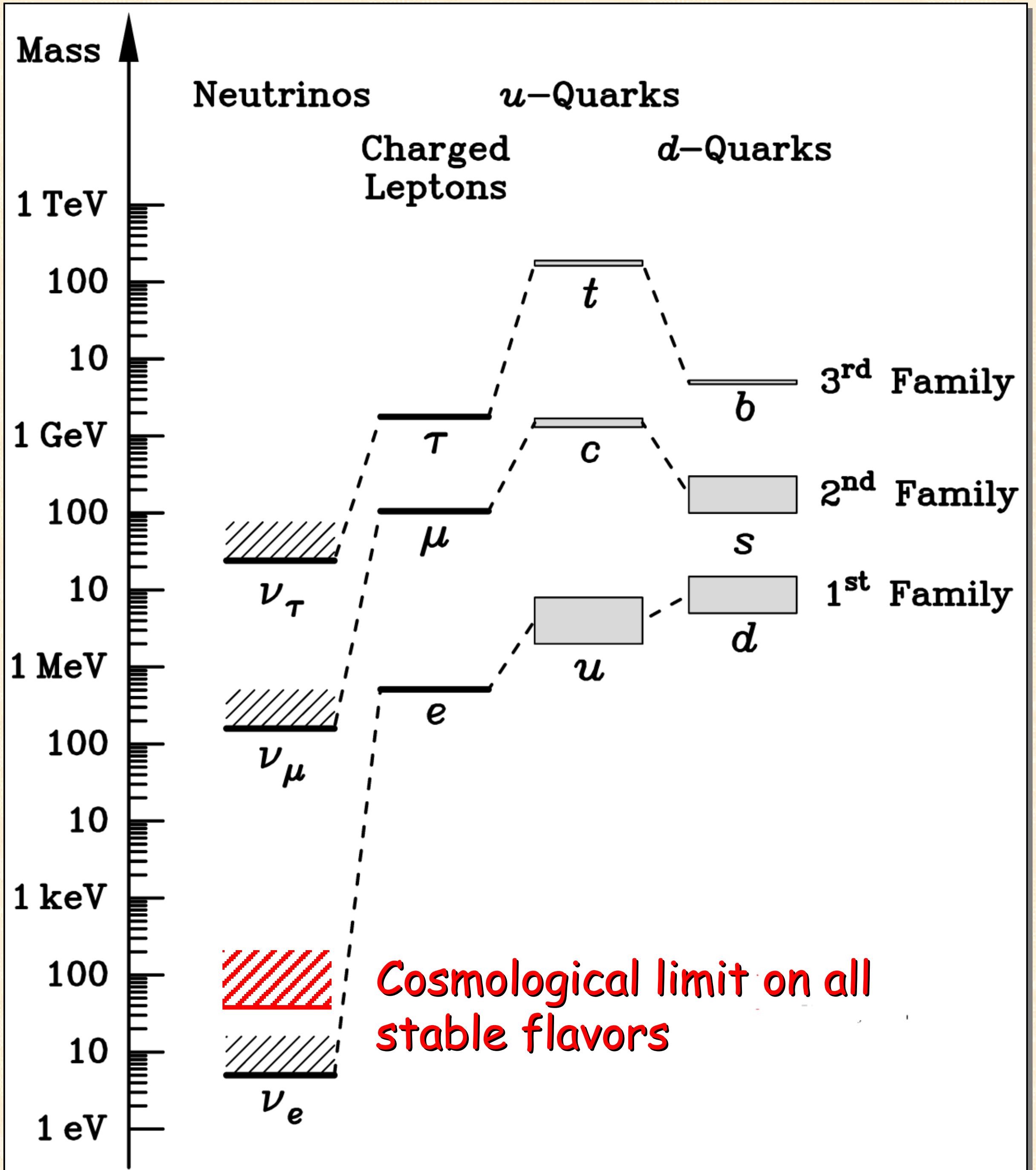
Fermion Mass Spectrum



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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; $T(z_{eq}) = T_\gamma(z_{eq}) = T_\nu(z_{eq}) = T_e(z_{eq}) \cdots =$ 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

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

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 $(1 + z_{eq})/(1 + z) = T_\gamma(z_{eq})/T_\gamma(z)$, the number density at the present epoch ($z = 0$) is given by

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

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

Weakly Interacting Particles as Dark Matter

Almost 30 years ago:

Beginnings of the idea of weakly interacting particles (neutrinos) as dark matter.

Massive neutrinos are no longer thought to be a good dark matter candidate.

However, the idea of weakly interacting massive particles constituting the cosmic dark matter is now standard.

Georg Raffelt, Max-Planck-Institut für Physik (München)

What is wrong with neutrino dark matter?

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

Maximum mass density of a Fermi gas:

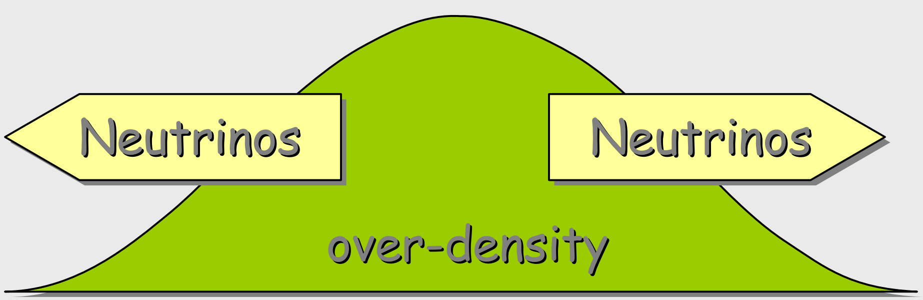
$$\rho_{max} = m_\nu \, n_{max} = m_\nu \, p_{max}{}^3/3\pi^2 = m_\nu \, (m_\nu v_{escape})^3/3\pi^2$$

$m_\nu > (20 - 40)$ eV

Spiral galaxies, more restrictive from dwarf galaxies: $m_\nu > 100\text{-}200$ eV

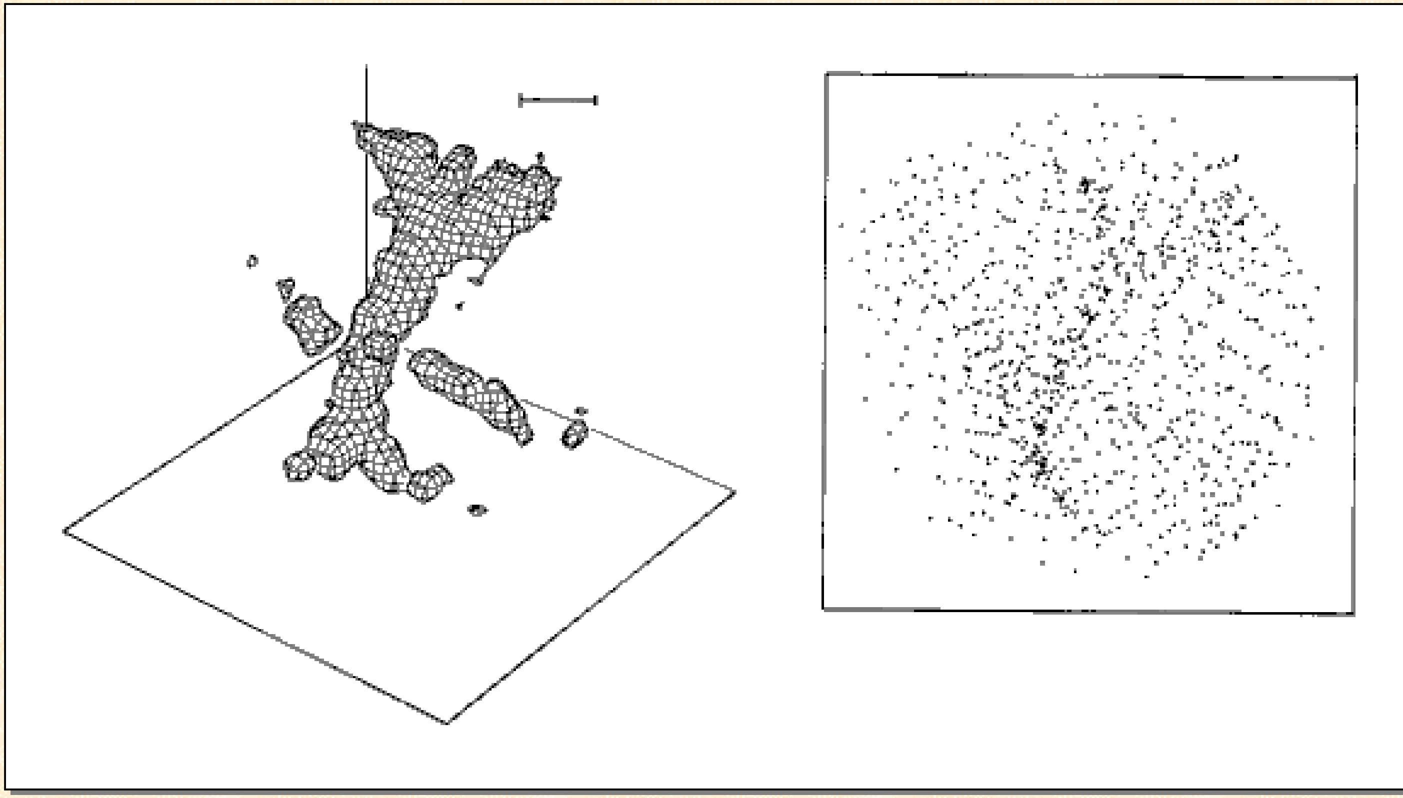
➔ Neutrino Free Streaming (Collisionless Phase Mixing)

At $T < 1$ MeV neutrino scattering ineffective, stream freely until nonrelativistic, wash out density contrasts on small scales.



Neutrinos are "Hot Dark Matter", excluded by structure formation

Hot dark matter ruled out in 1983



1000 particle simulation by Frenk, White & Davis, ApJ 271 (1983) 417

The coherence length of the neutrino distribution … is too large to be consistent with the observed clustering scale of galaxies …
The conventional neutrino-dominated picture appears to be ruled out.
[White, Frenk & Davis, ApJ 274 (1983) L1]

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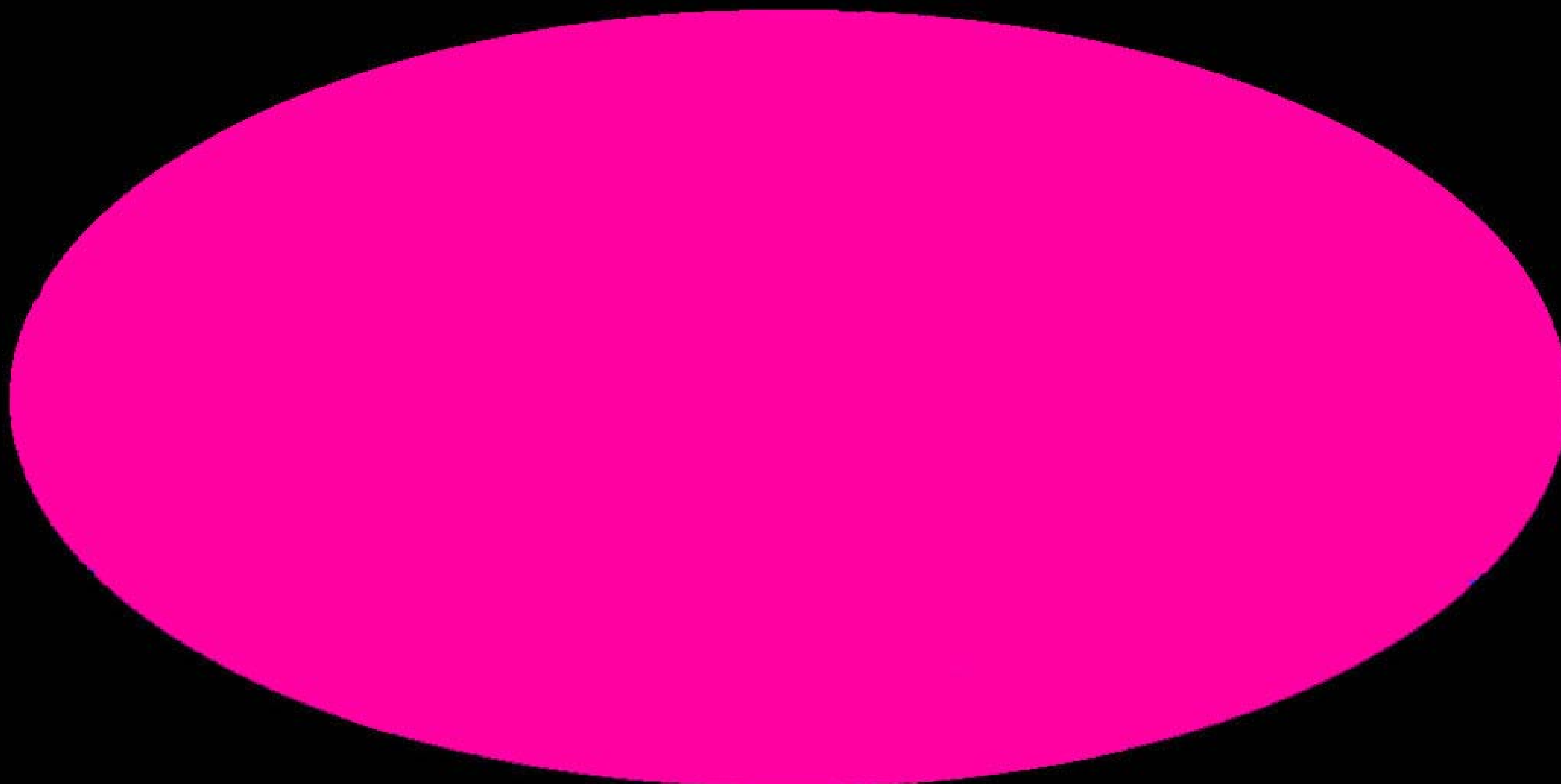
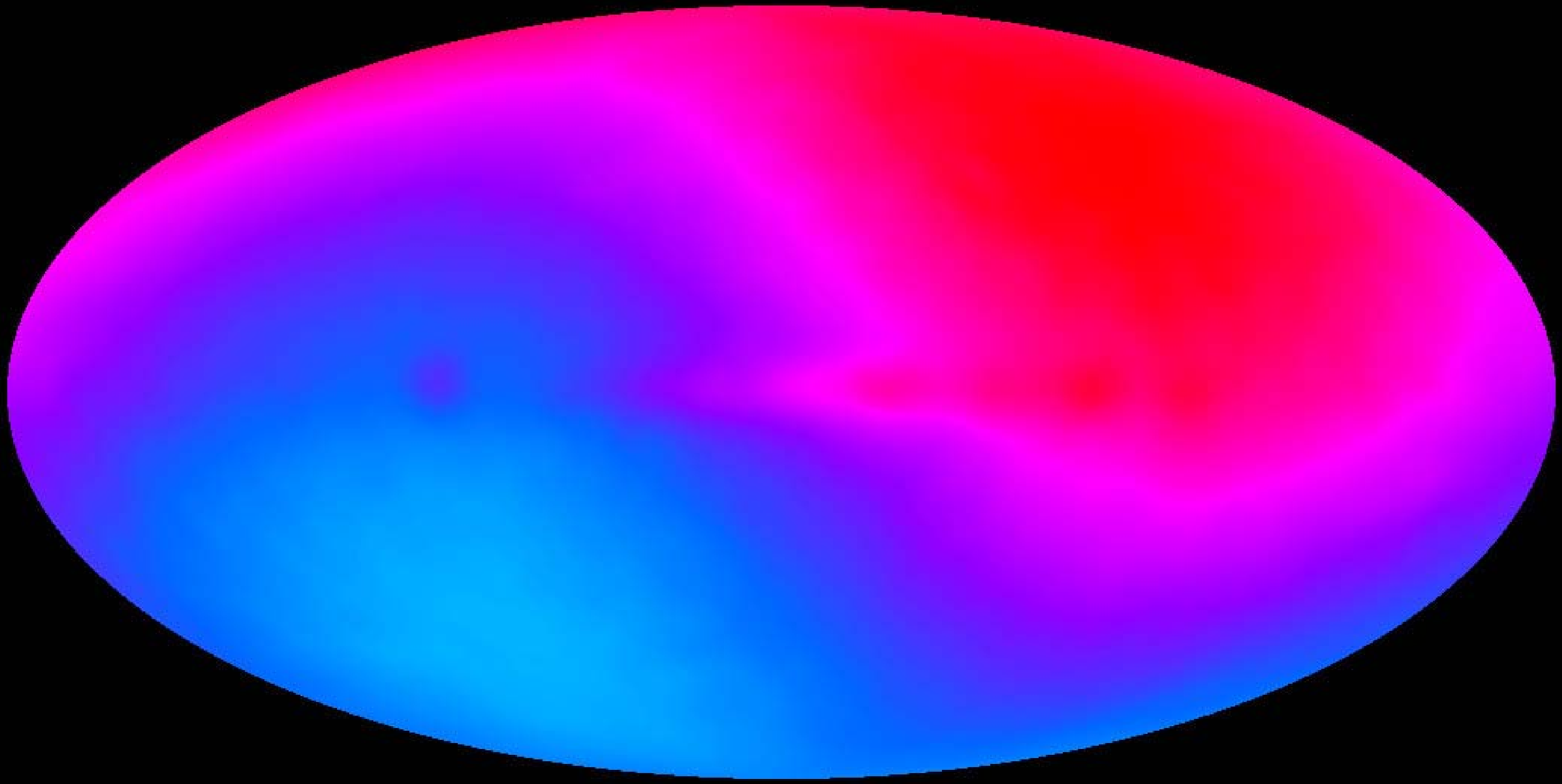
COBE Sky Map of the CMBR Temperature



T = 2.728 K (uniform on the sky)

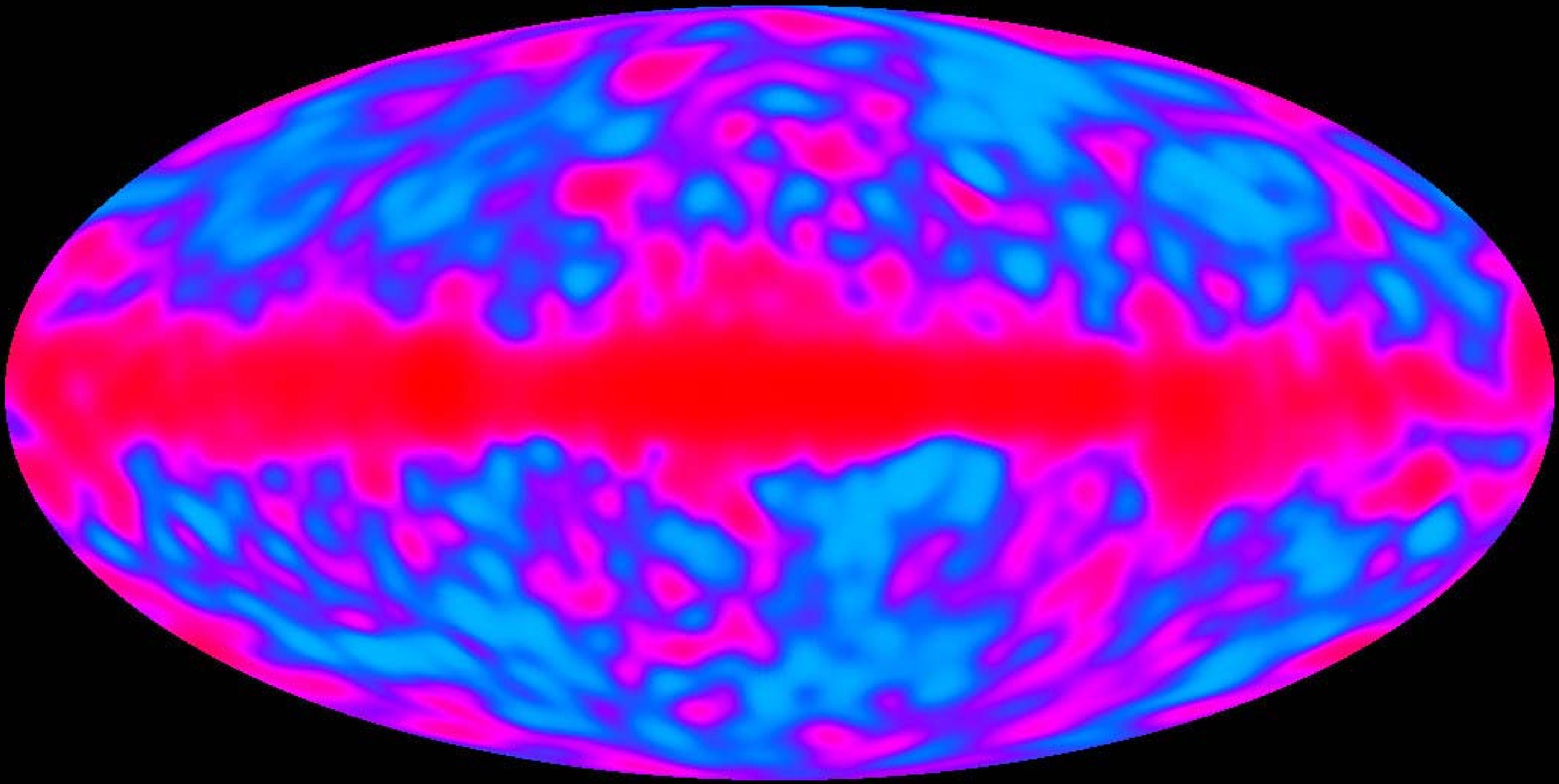
COBE Sky Map of the CMBR Temperature



Dynamical range ΔT = 3.353 mK

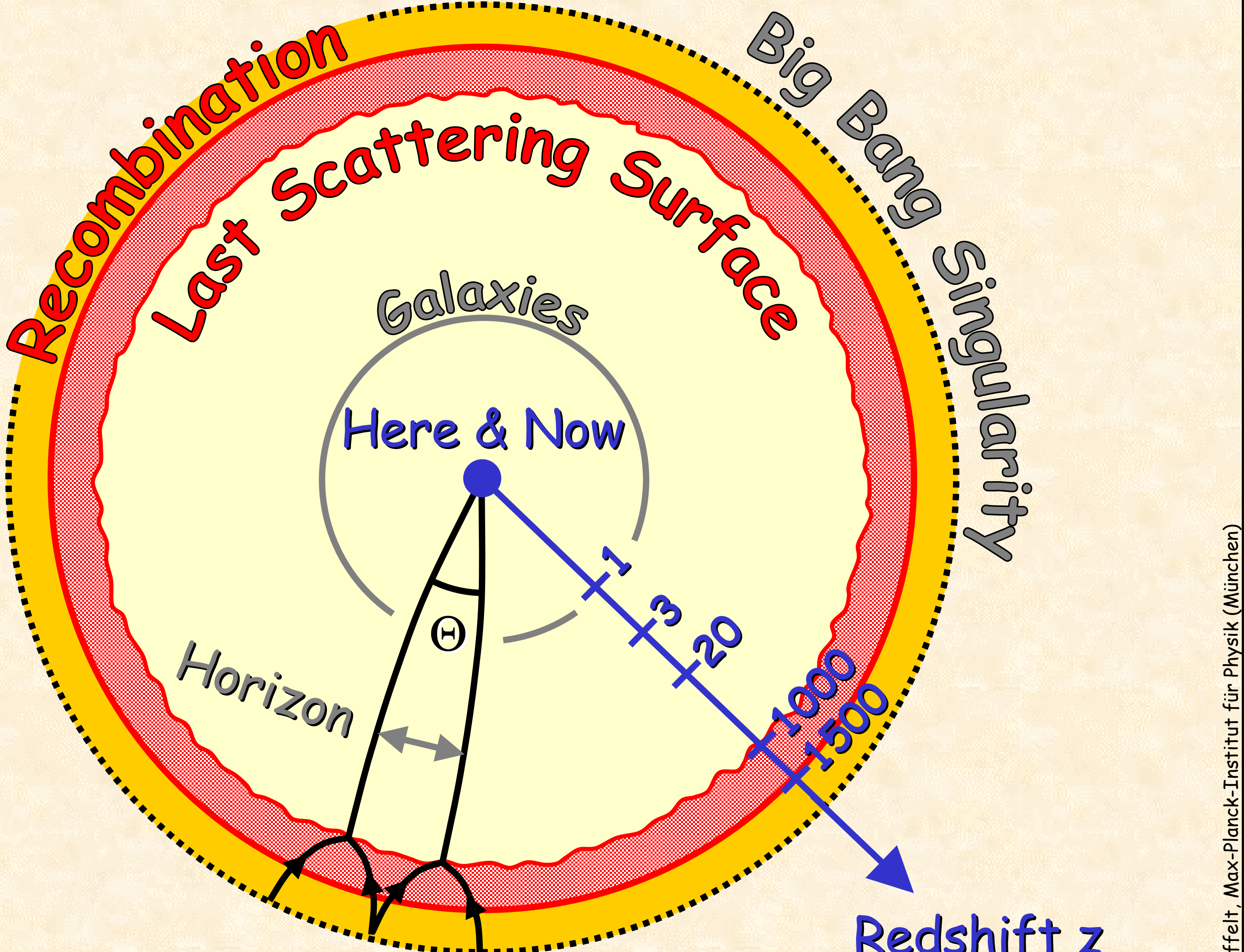
Dipole temperature distribution from Doppler effect due to our motion relative to the cosmic frame

COBE Sky Map of the CMBR Temperature

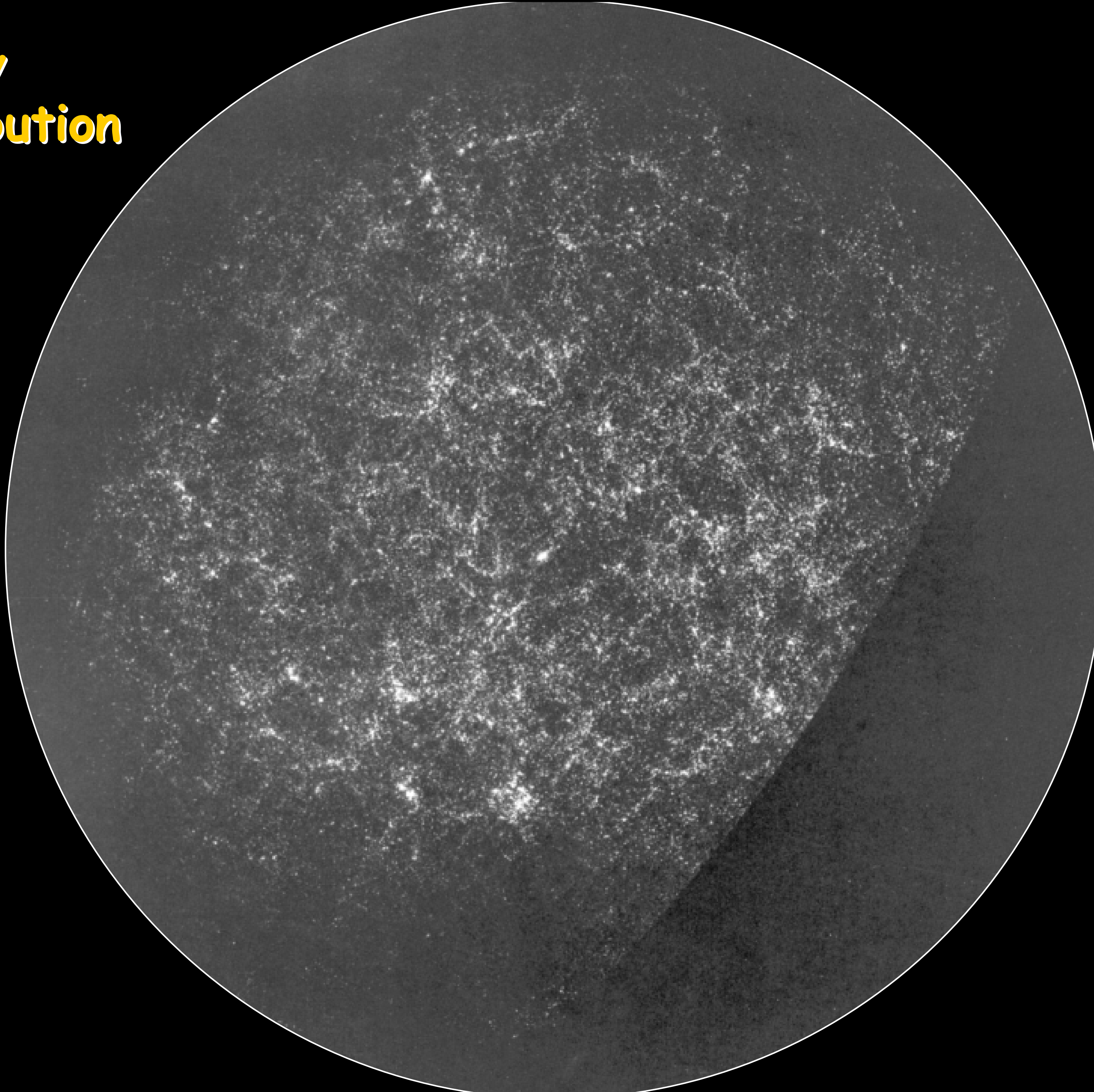


Dynamical range ΔT = 18 μK

Primordial temperature fluctuations!


Recombination
Last Scattering Surface
Big Bang Singularity
Galaxies
Here & Now
Θ
Horizon
1
3
20
1000
1500
Redshift z
Georg Raffelt, Max-Planck-Institut für Physik (München)

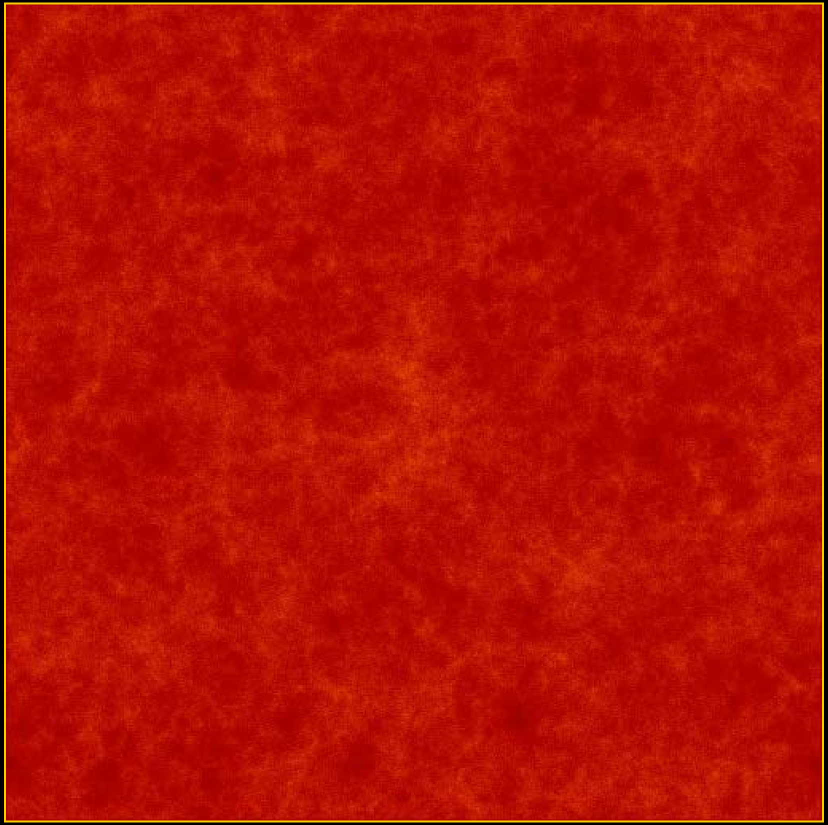
Galaxy distribution in the sky

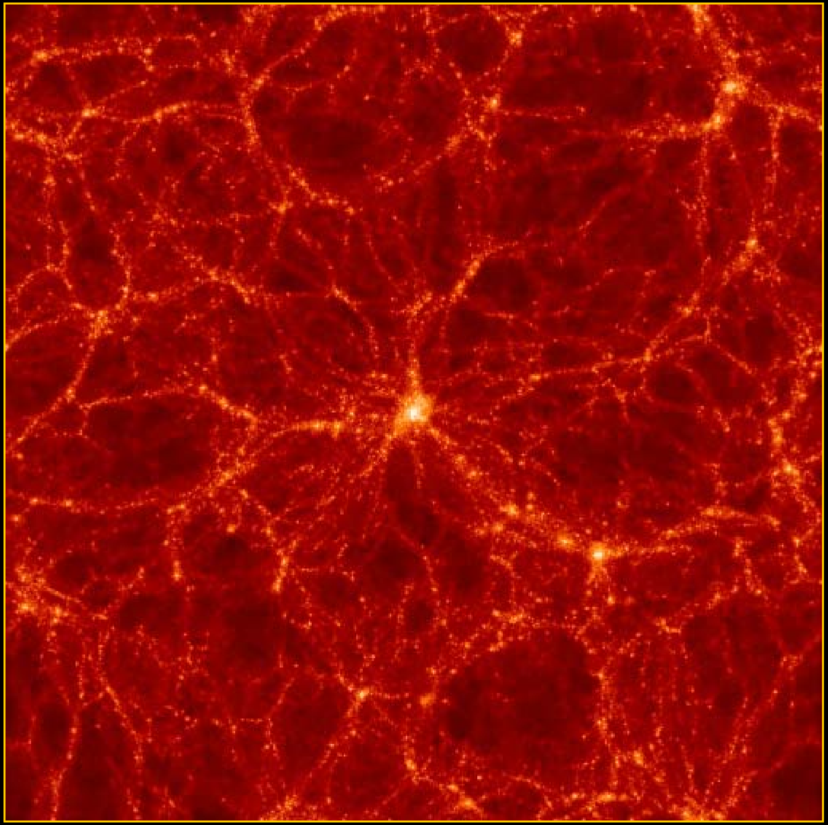


Formation of Structure

[Numerical Simulation Max-Planck-Institut für Astrophysik, Garching]

Smooth ➔ **Structured**





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Power Spectrum of Density Fluctuations

Power Spectrum

Field of Density Fluctuations:

$$\delta(\mathbf{x}) = \frac{\delta\rho(\mathbf{x})}{\bar{\rho}}$$

Fourier Transform:

$$\delta(\mathbf{k}) = \int d^3\mathbf{x}\, e^{-i\mathbf{k}\cdot\cdot x}\,\delta(\mathbf{x})$$

Power Spectrum:

$$\langle\delta(\mathbf{k})\delta(\mathbf{k}')\rangle = (2\pi)^3\,\hat{\delta}(\mathbf{k}-\mathbf{k}')\,P(\mathbf{k})$$

with $\hat{\delta}$ the delta function

Two-Point Correlation Function:

$$\xi(\mathbf{x}) = \langle\delta(\mathbf{x}_2)\delta(\mathbf{x}_1)\rangle = \int \frac{d^3\mathbf{k}}{(2\pi)^3}\, e^{i\mathbf{k}\cdot\mathbf{x}}\, P(\mathbf{k})$$

where $\mathbf{x} = \mathbf{x}_2 - \mathbf{x}_1$.

Gaussian random field fully characterized by power spectrum

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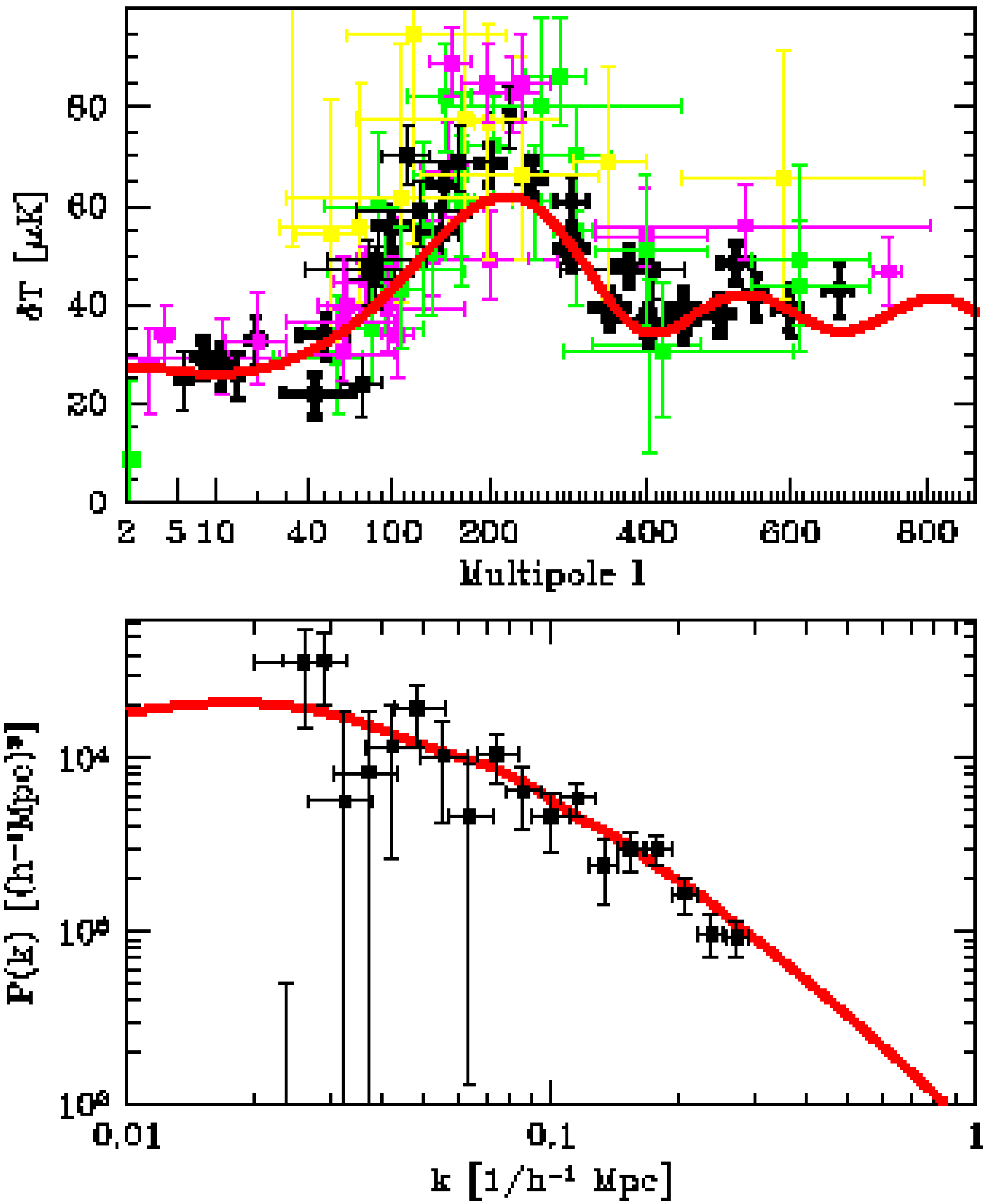
Fitting the Cosmological Model - Neutrinos



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 fraction of DM**
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

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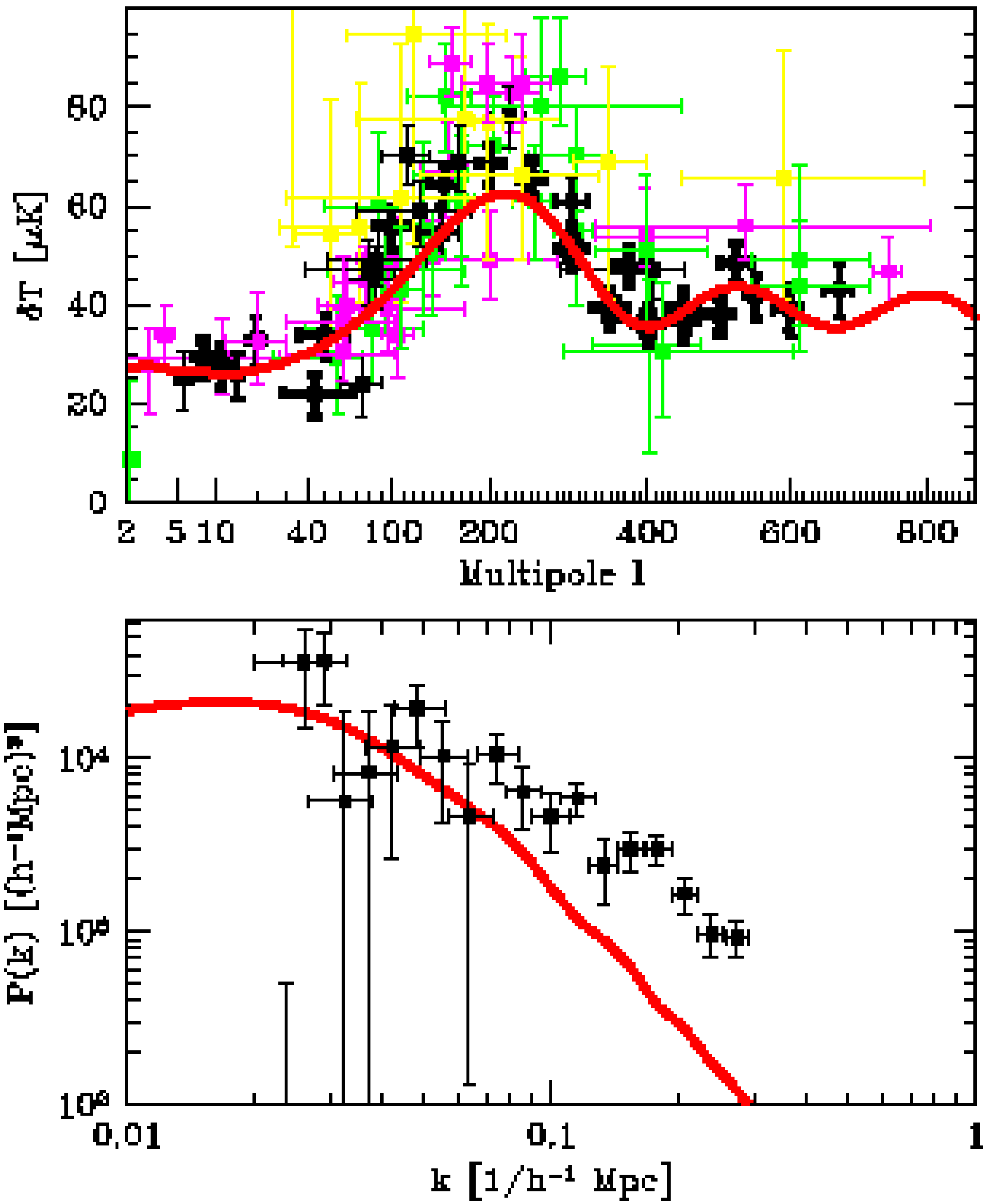
Fitting the Cosmological Model - Neutrinos



$\tau=0.000$	Ionization parameter
$\Omega_k=0.000$	Curvature
$\Omega_\Lambda=0.61$	Cosmological constant
$\omega_d=0.13$	Dark Matter ($\Omega_M h^2$)
$\omega_b=0.020$	Baryons ($\Omega_B h^2$)
$f_\nu=0.36$	**Neutrino fraction of DM**
$n_s=0.90$	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
$h=0.82$	Hubble constant
$\chi^2=0.000$	

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

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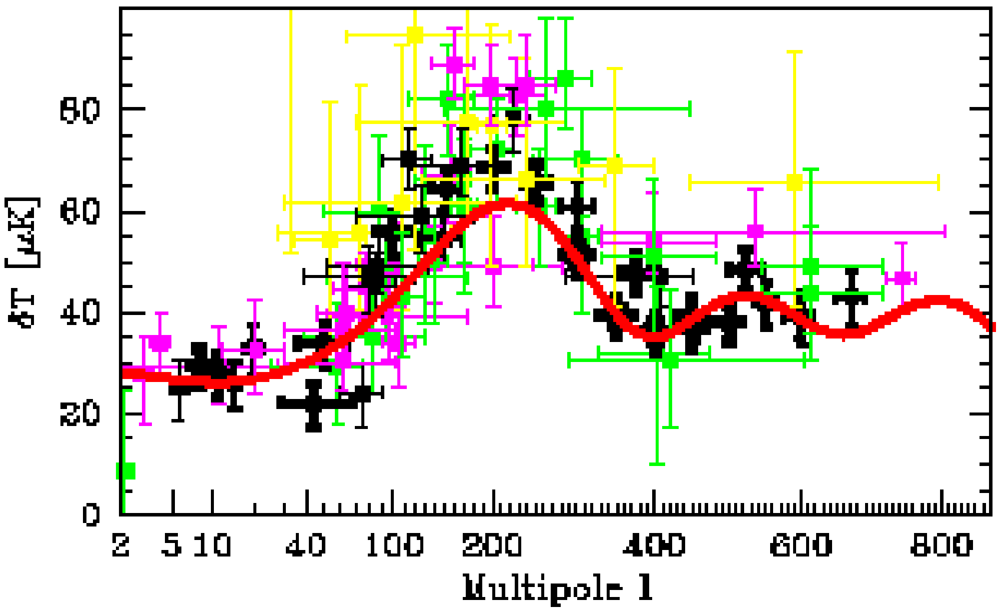
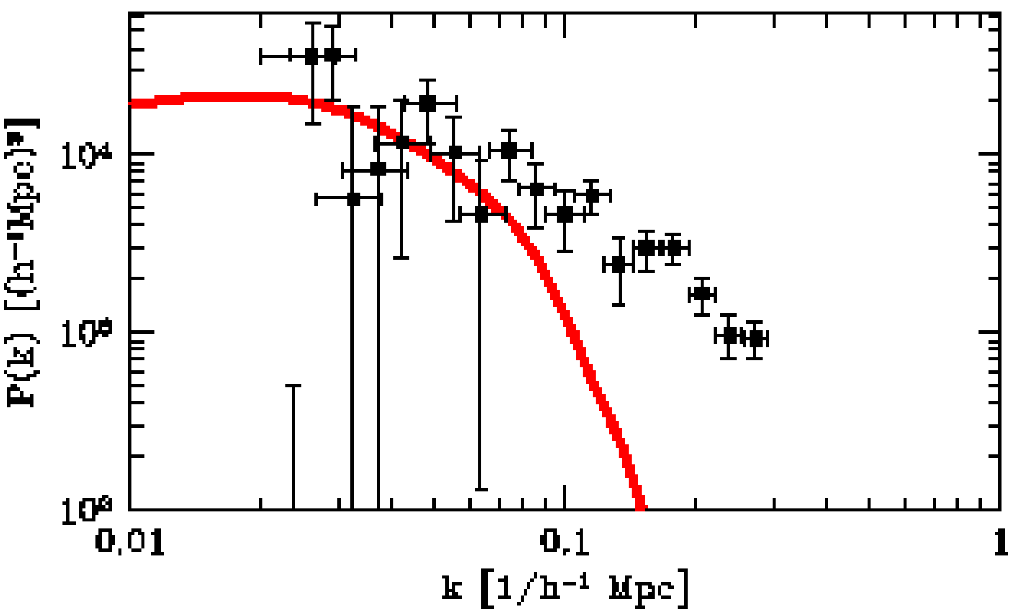
Fitting the Cosmological Model - Neutrinos





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=0.99	Neutrino fraction of DM
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=0.82	Hubble constant
χ^2=0.000	

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

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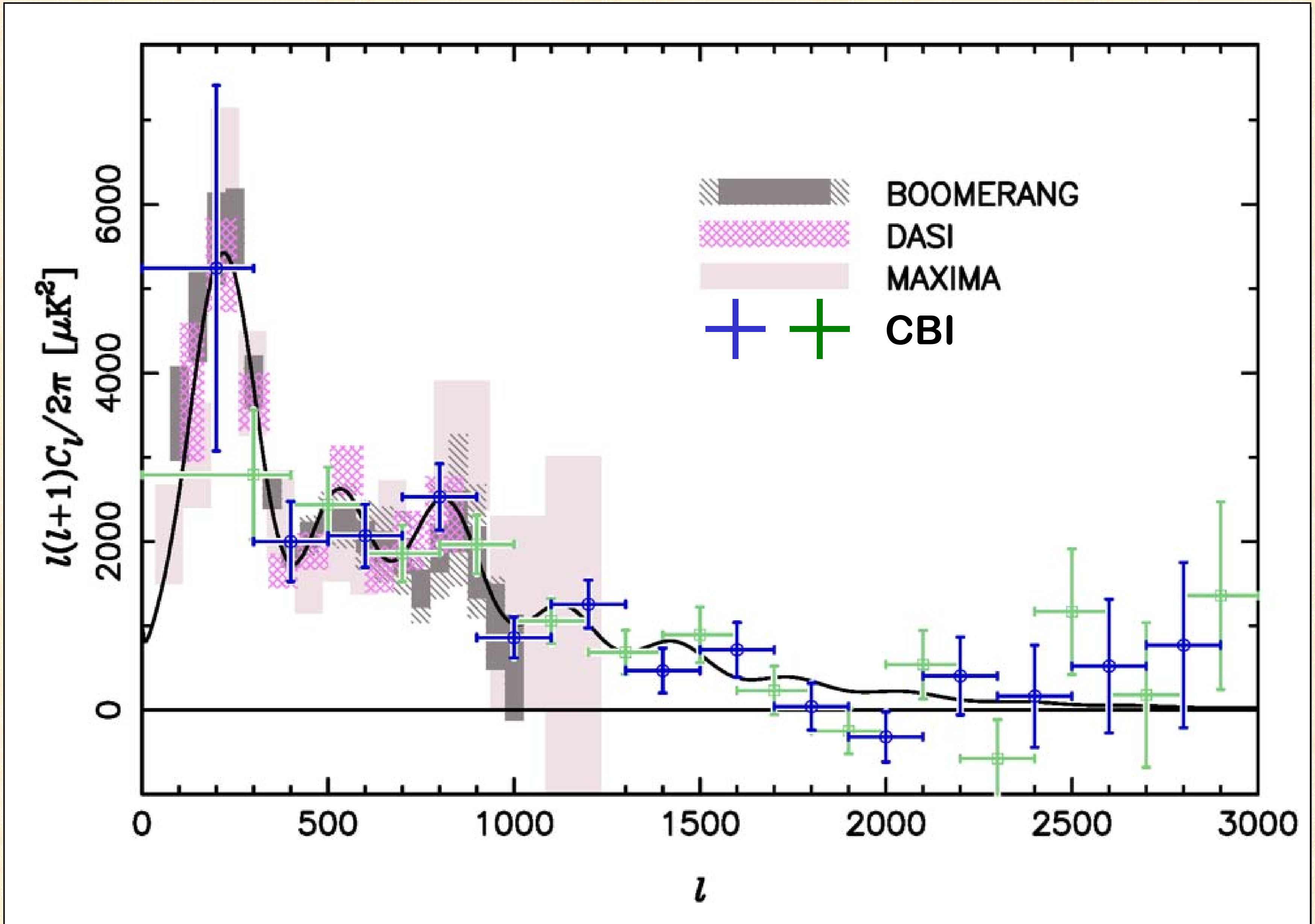
Multiple Peaks in CMBR Angular Power Spectrum



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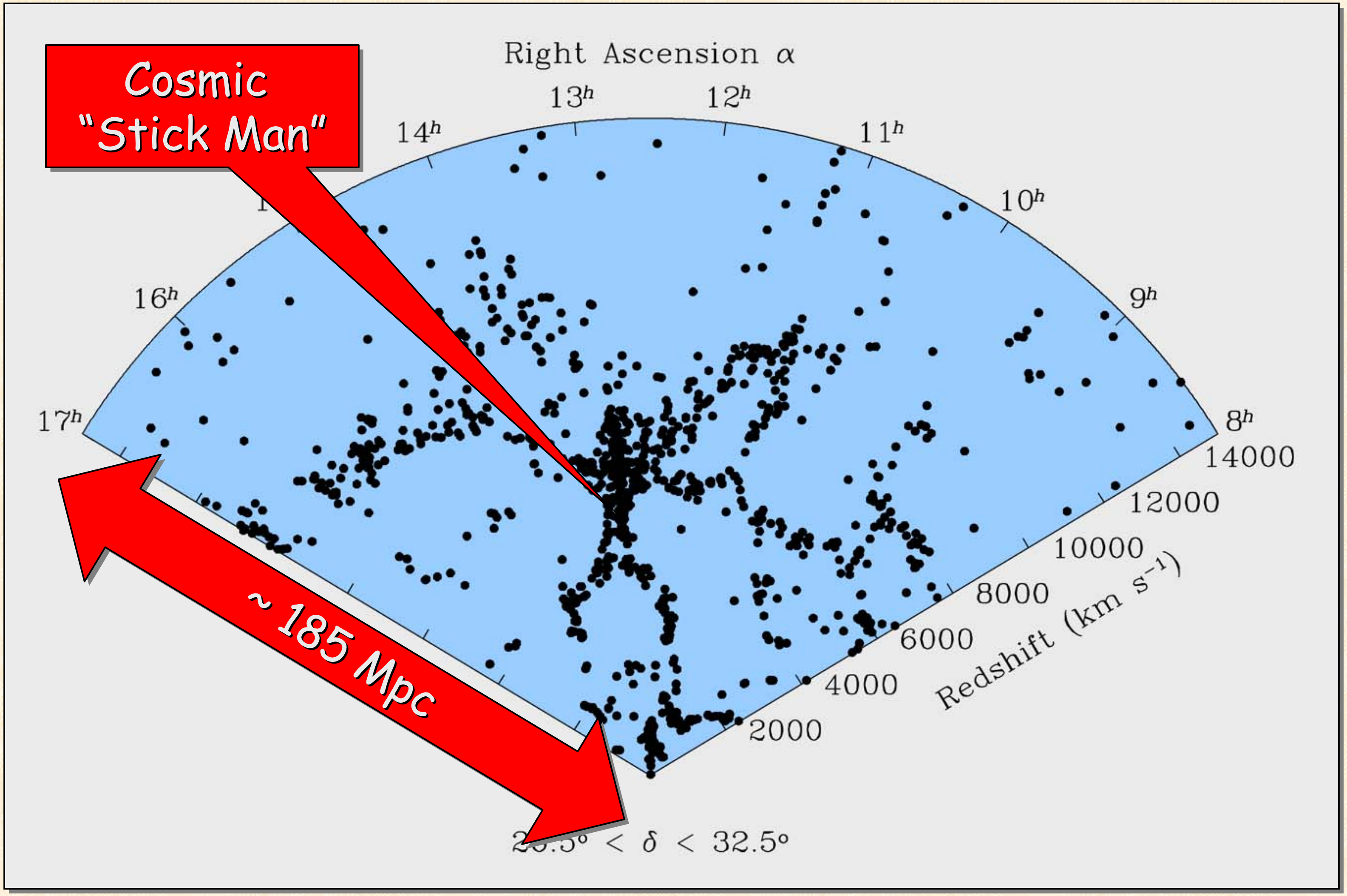
A Slice of the Universe



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

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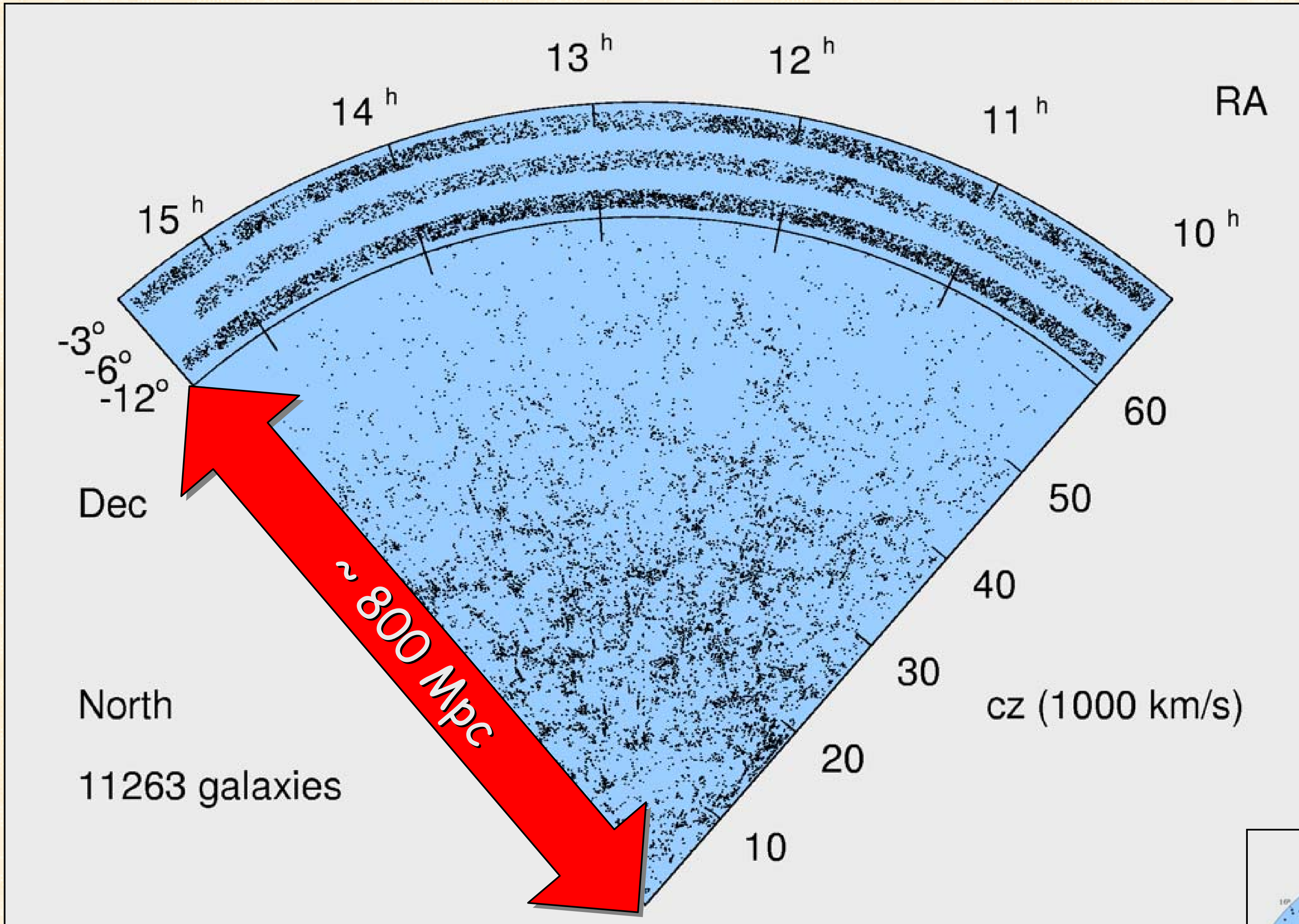
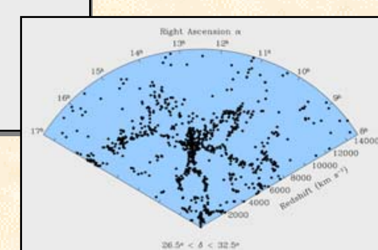
Las Campanas Redshift Survey





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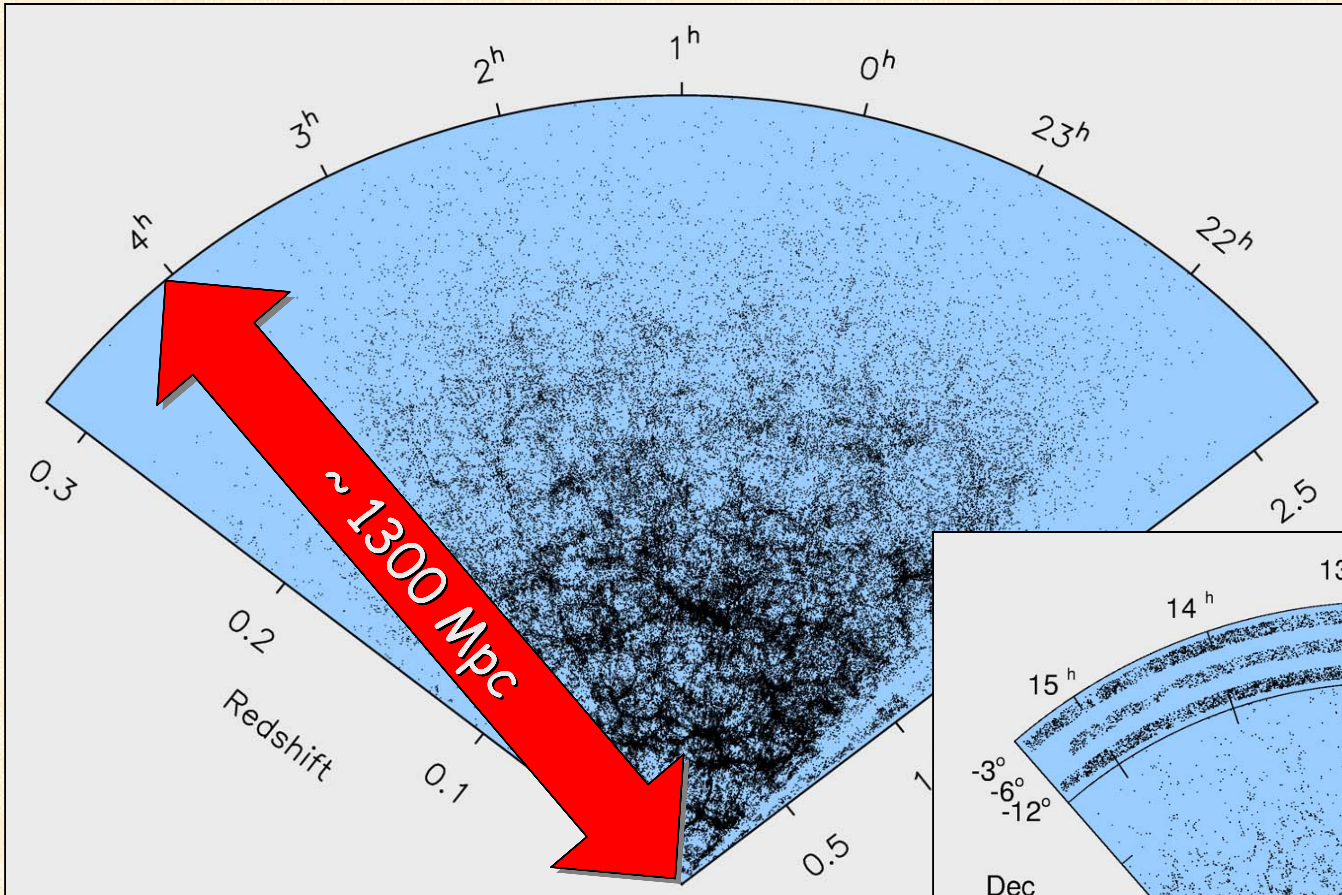
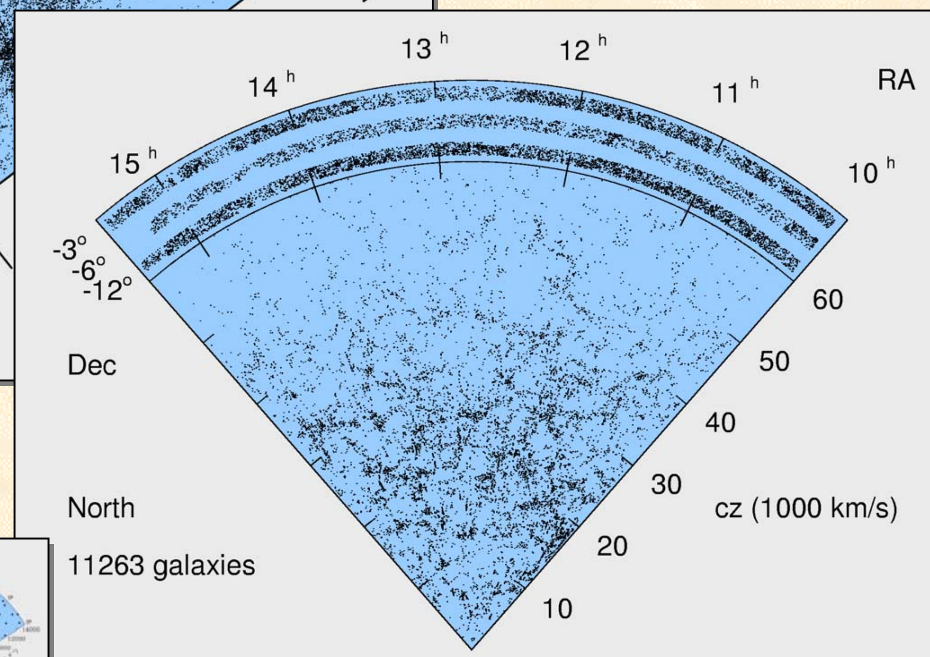
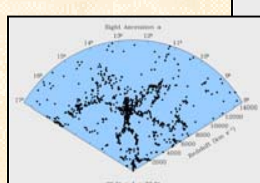
2dF Galaxy Redshift Survey (15 May 2002)







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2dF Galaxy Redshift Survey

Animations from 2dFGRS Homepage http://www.mso.anu.edu.au/2dFGRS/

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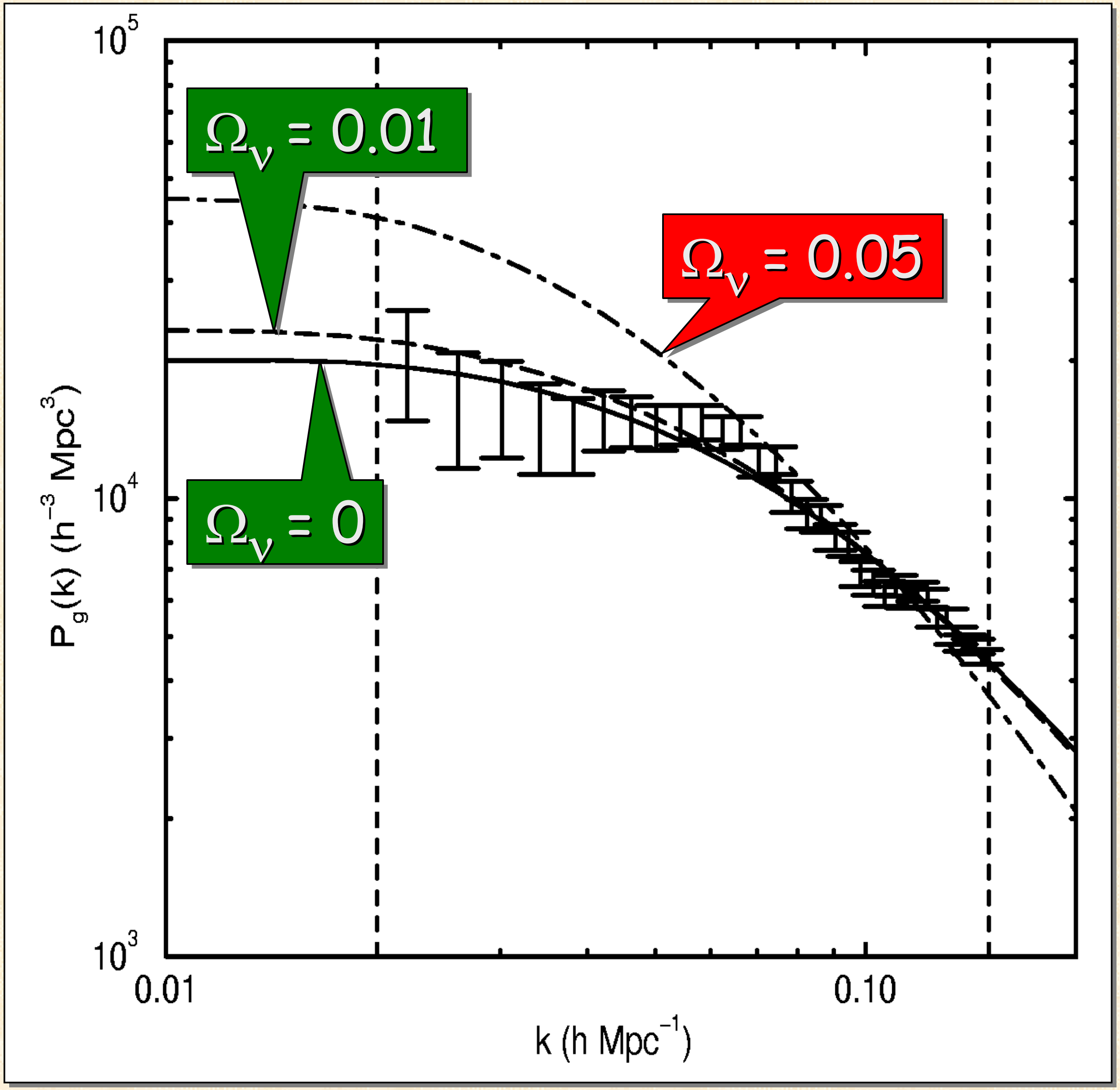
Neutrino Mass Limit from 2dF Galaxy Survey



Elgaroy et al., astro-ph/0204152

$\Sigma m_\nu < 2.2$ eV at 95% CL

For a similar limit based on the 2dF data see Hannestad, astro-ph/0205223

Neutrino Mass Limits from Cosmic Structure

- Global fits to CMBR and LSS data,
- 3 flavors of equal-mass neutrinos

$m_\nu < 2.8$ eV at 95% CL	Novosyadlyj, Durrer & Apunevych, astro-ph/0011055
$m_\nu < 1.4$ eV at 95% CL	Wang, Tegmark & Zaldarriaga, astro-ph/0105091
$m_\nu < 0.8$ eV at 95% CL	Elgaroy et al., astro-ph/0204152 Hannestad, astro-ph/0205223

For similar older limits see
- Croft, Hu & Davé, PRL 83 (1999) 1092
- Fukugita, Liu & Sugiyama, PRL 84 (2000) 1082
- Gawiser, astro-ph/0005475

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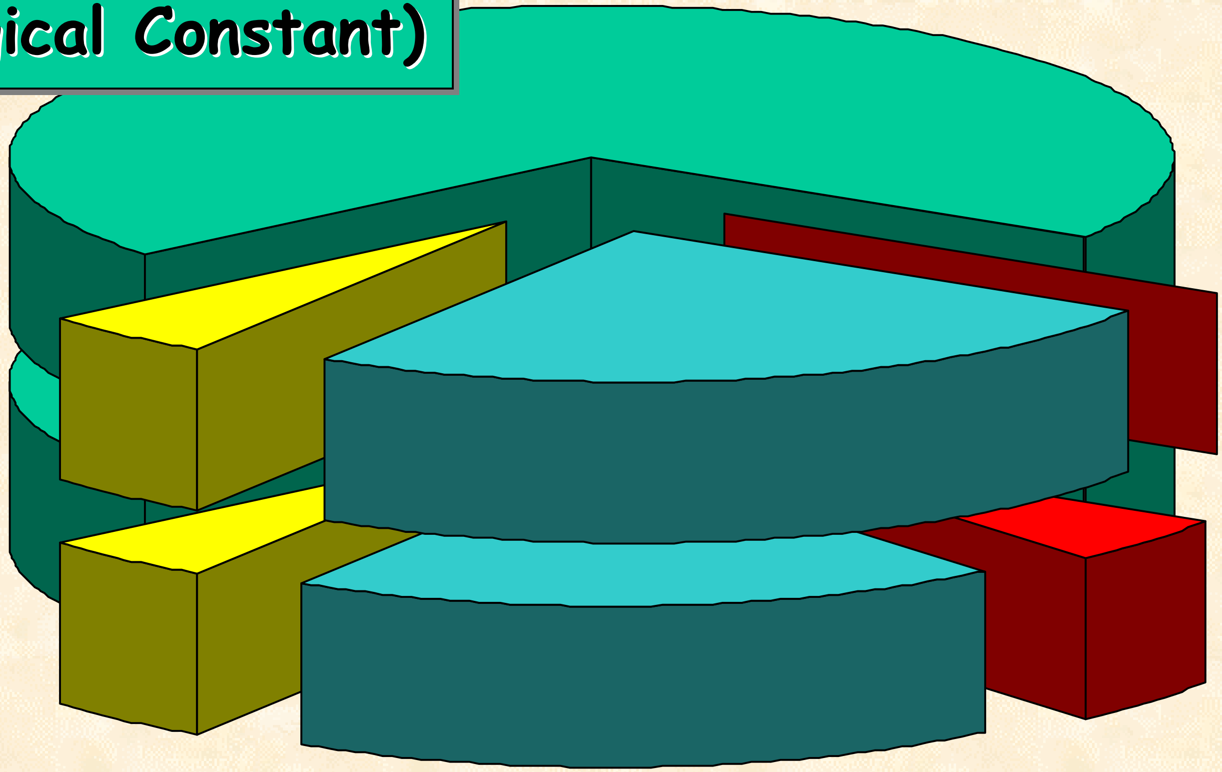
Matter Inventory of the Universe

Dark Energy
(Cosmological Constant)



Baryonic Matter
(of this about
10% luminous)

Dark
Matter

Neutrinos
min. 0.1%
max. 6%

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Neutrino Mass Limits and Future Sensitivity

Tritium endpoint	Mainz/Troitsk	2.5 eV
	KATRIN	0.3 eV
Supernova Neutrinos Time-of-flight	SN 1987A	20 eV
	Super-Kamiokande	3 eV
	with black hole	2 eV
	with gravity waves	1 eV
Cosmic structure	2DF Redshift Survey	$m_\nu < 0.8$ eV
	Sloan Digital Sky Survey	$m_\nu < 0.3$ eV

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Neutrino Chemical Potentials, Big-Bang Nucleosynthesis, and Flavor Oscillations

Georg Raffelt, Max-Planck-Institut für Physik (München)

How Many Relic Neutrinos?

Standard thermal population in one flavor: $n_{\nu\bar{\nu}} = \frac{3}{11} n_\gamma \approx 112\,\text{cm}^{-3}$

Additional active neutrinos beyond standard population of ν_e, ν_μ, ν_τ

Additional families	Excluded by Z^0 width: $N_\nu = 3$
Chemical potentials for ν_e, ν_μ, ν_τ	o.k.

Sterile (right-handed) states, populated by $\nu_L \to \nu_R$

Dirac mass	Too small in eV range
Electromagnetic dipole moments	Excluded by energy loss of globular cluster stars
Right-handed currents	Excluded by energy loss of SN 87A
Oscillations/collisions	o.k., hot/warm DM possible

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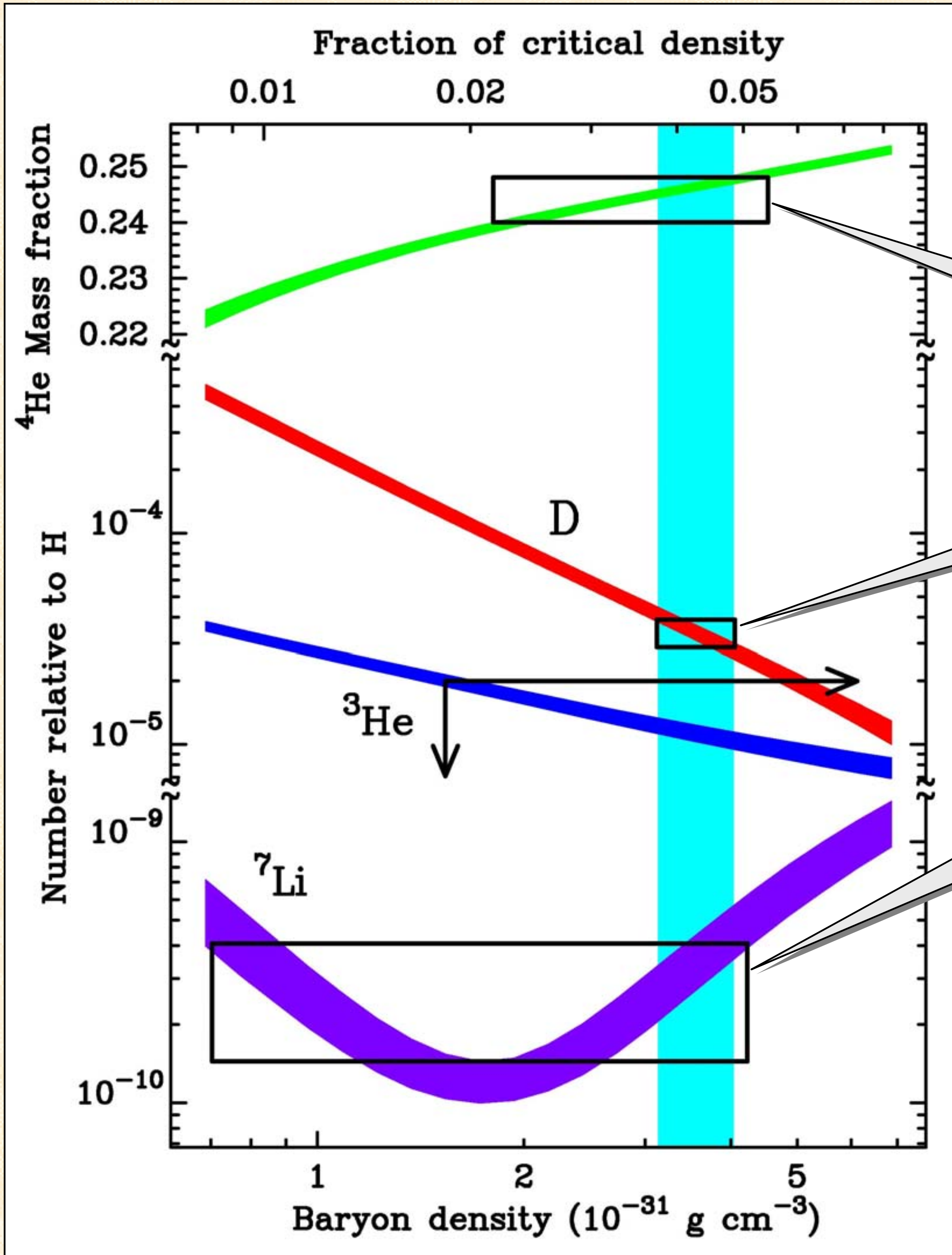
BBN Concordance

[astro-ph/9903300]



Helium 4

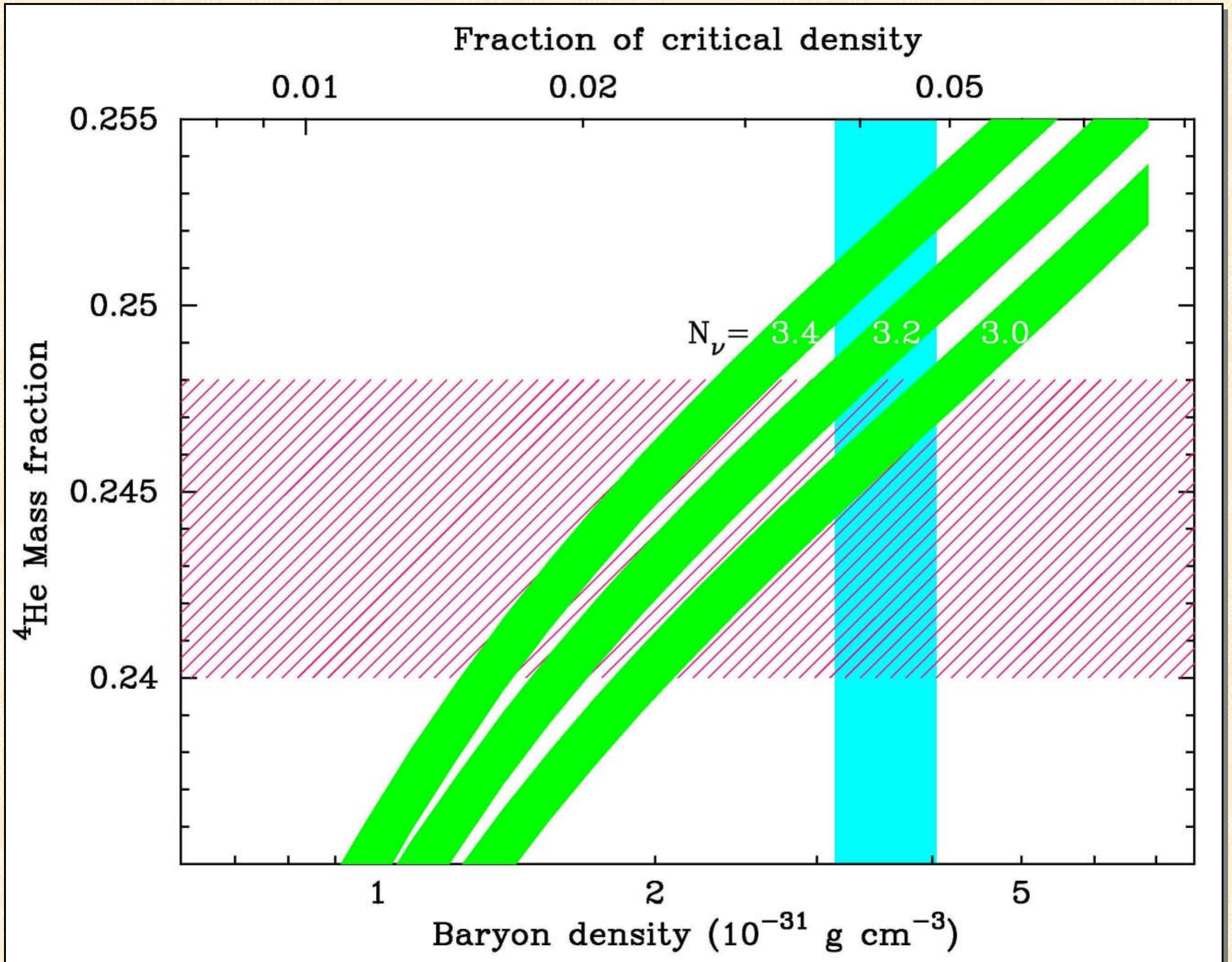
Deuterium

Lithium

Cosmic baryon density implied by deuterium abundance:

$\Omega_B h^2 = 0.019 \pm 0.0024$

BBN Limits on Neutrino Flavors



[astro-ph/9903300]

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

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

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BBN and Neutrino Chemical Potentials

Expansion-rate effect:

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

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

Numerically effect on helium analogous to $\Delta N_{eff} \sim -18\, \xi_{\nu e}$.

$|\Delta N_{eff}| < 1$ ➔ $|\xi_{\nu e}| < 0.057$

Beta effect of ν_e can compensate expansion-rate effect of ν_μ or ν_τ
No significant BBN limit on neutrino number density

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Chemical Potentials and Flavor Oscillations

Flavor mixing (neutrino oscillations)

Flavor lepton numbers not conserved

Only one common chemical potential ξ

Stringent $\xi_{\nu e}$ limit applies to all flavors

For all flavors $|\xi_{\nu e,\mu,\tau}| < 0.07$

Extra neutrino density $\Delta N_{eff} < 0.0064$

Cosmic neutrino density very close to standard value. Neutrino-mass experiments indeed measure or constrain cosmic neutrino density

Chain of arguments only valid if relaxation to flavor equilibrium obtains before n/p freeze-out, i.e. before T ~ 1 MeV

Flavor Equilibrium Before N/P Freeze-Out ?

yes	• Atmospheric neutrinos: Maximally mixed $\nu_\mu \to \nu_\tau$ oscillations • Solar neutrinos by LMA solution
maybe	Solar LOW solution (Quasi-equilibrium depends on unknown third mixing angle 13)
no	Solar SMA solution

Our knowledge of the cosmic neutrino density depends on the solution of the solar neutrino problem: KamLAND most relevant current 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

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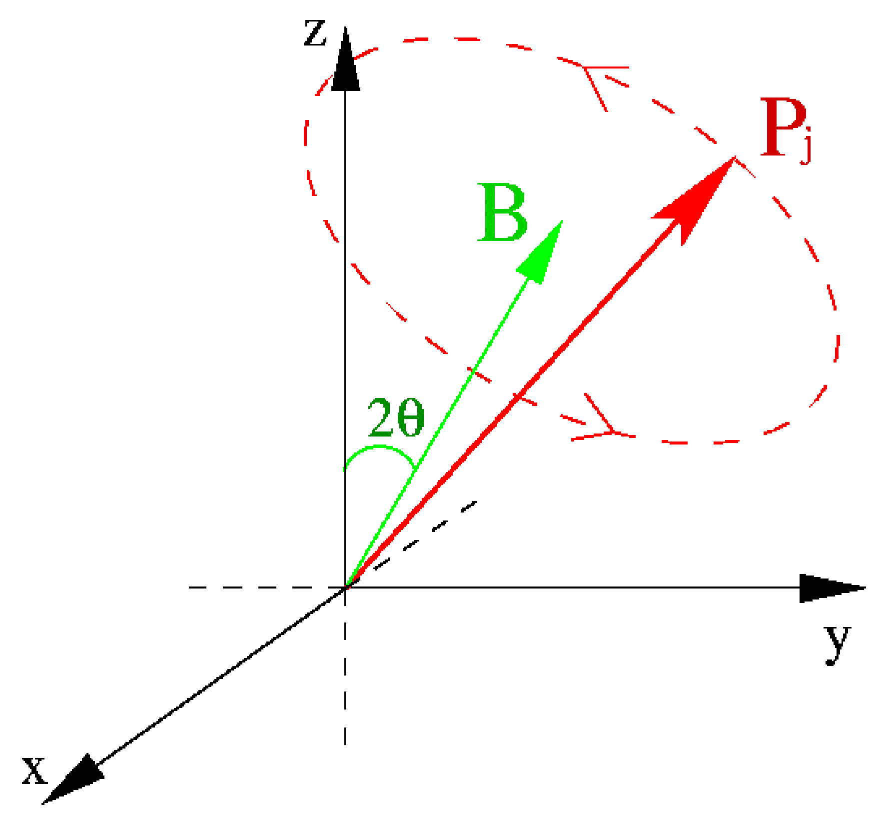
Two-Flavor Neutrino Oscillations

Evolution of neutrino ensemble described in terms of density matrices:

$$f_p \to \rho_p = \begin{pmatrix} f_p^e & f_p^{\mu e} \\ f_p^{e\mu} & f_p^{\mu} \end{pmatrix} = \frac{1}{2}\left(f_p + \vec{\sigma}\cdot\vec{P}_p\right)$$



Flavor oscillations in vacuum:

$$\partial_t \vec{P}_p = \frac{\delta m^2}{2p}\vec{B}\times\vec{P}_p$$

with

$$\vec{B} = \begin{pmatrix} \sin 2\theta \\ 0 \\ \cos 2\theta \end{pmatrix}$$

and

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}\begin{pmatrix} \nu_1 \\ \nu 2 \end{pmatrix}$$

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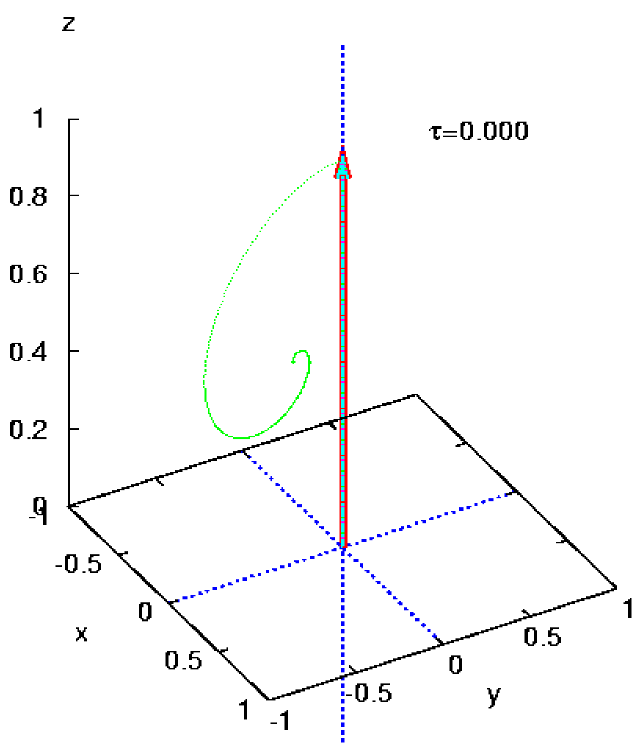
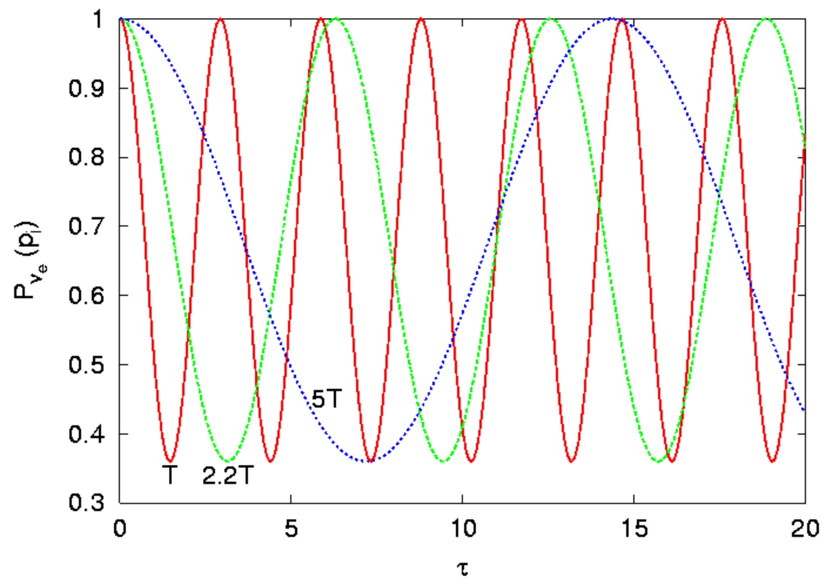
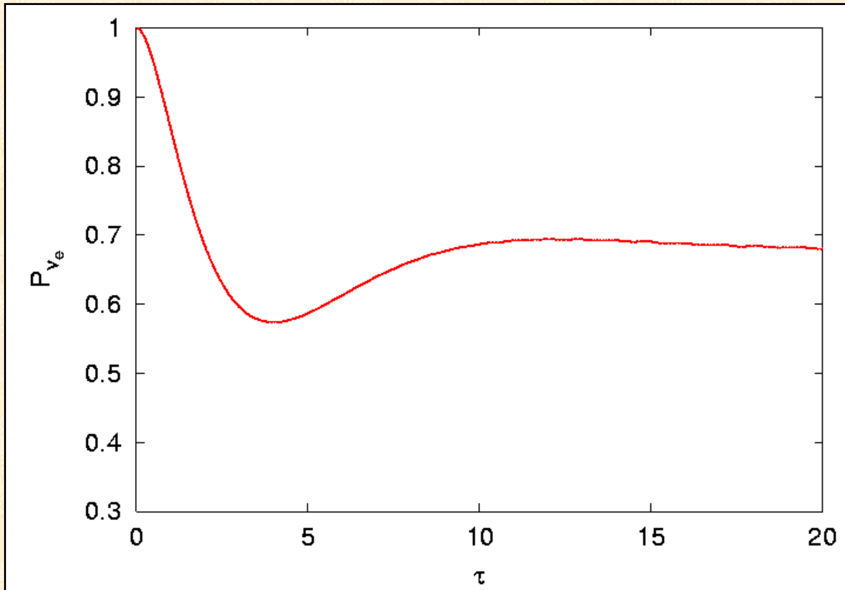
Vacuum Oscillations with Distribution of Energies







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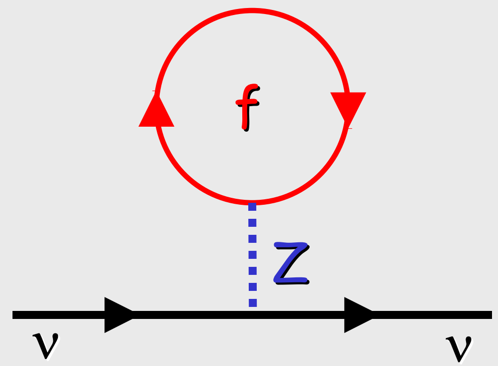
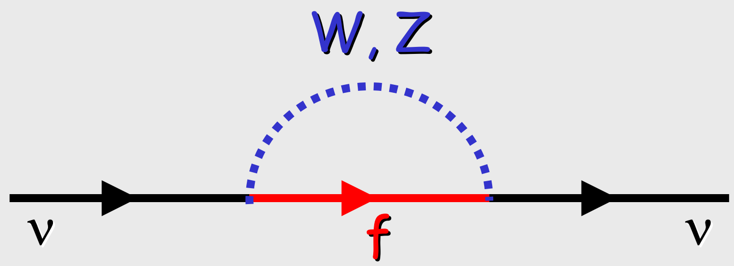
Two-Flavor Oscillations in Media

Neutrinos propagating in a medium suffer refraction (Wolfenstein 1978)





Effect is usually different for different flavors

Equation of motion in early universe (ignoring neutrino background)

$$\partial_t \vec{P}_p = \left(\frac{\delta m^2}{2p} \vec{B} - \frac{8\sqrt{2} G_F p}{3 m_W^2} \rho_e \vec{z} \right) \times \vec{P}_p$$

with ρ_e the e^+e^- energy density

Oscillations begin when background medium is sufficiently diluted to avoid large medium effect compared to vacuum mixing

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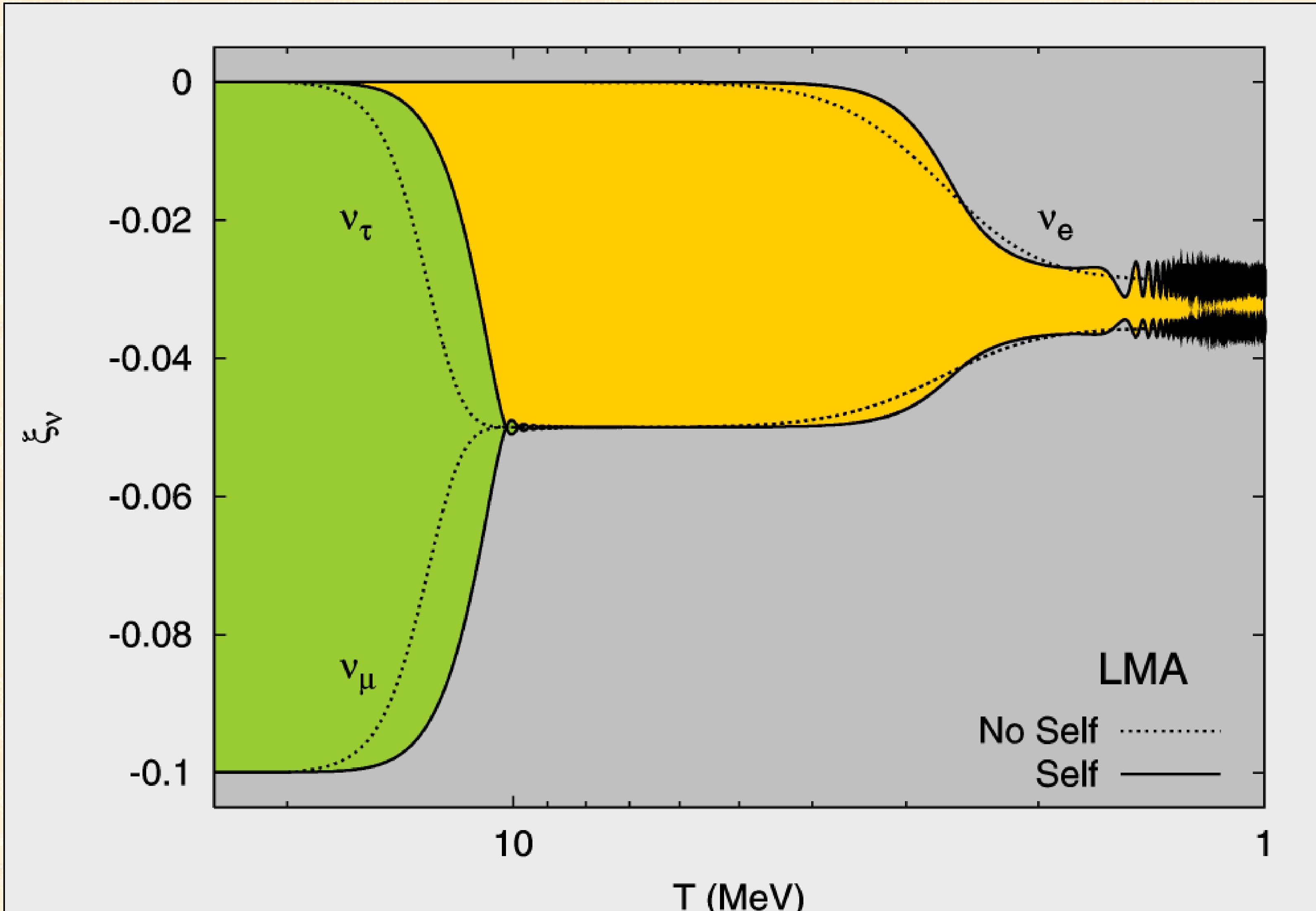
Flavor Equilibration: LMA Solution



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

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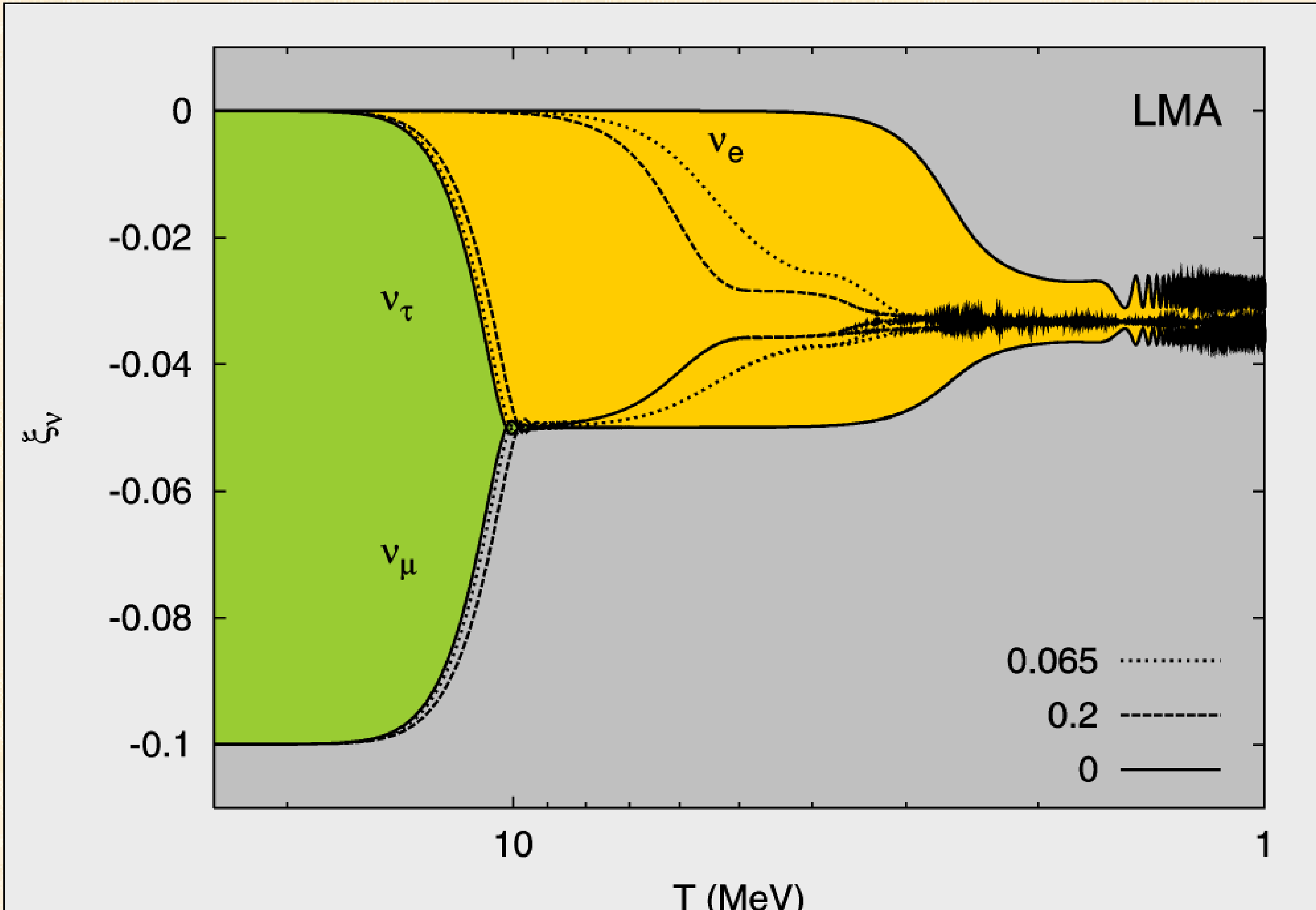
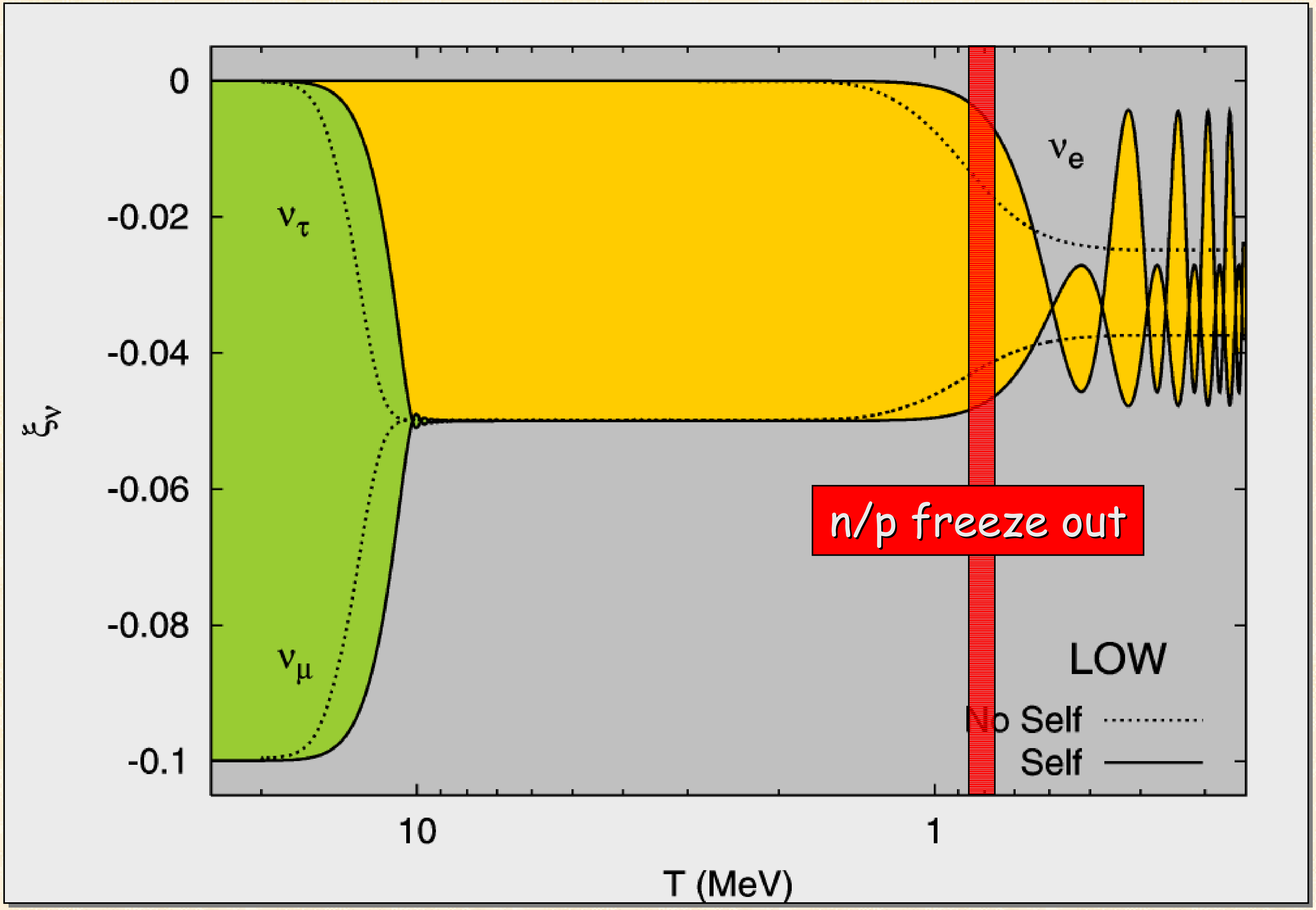
Flavor Equilibration: LMA With Non-Zero Θ_{13}



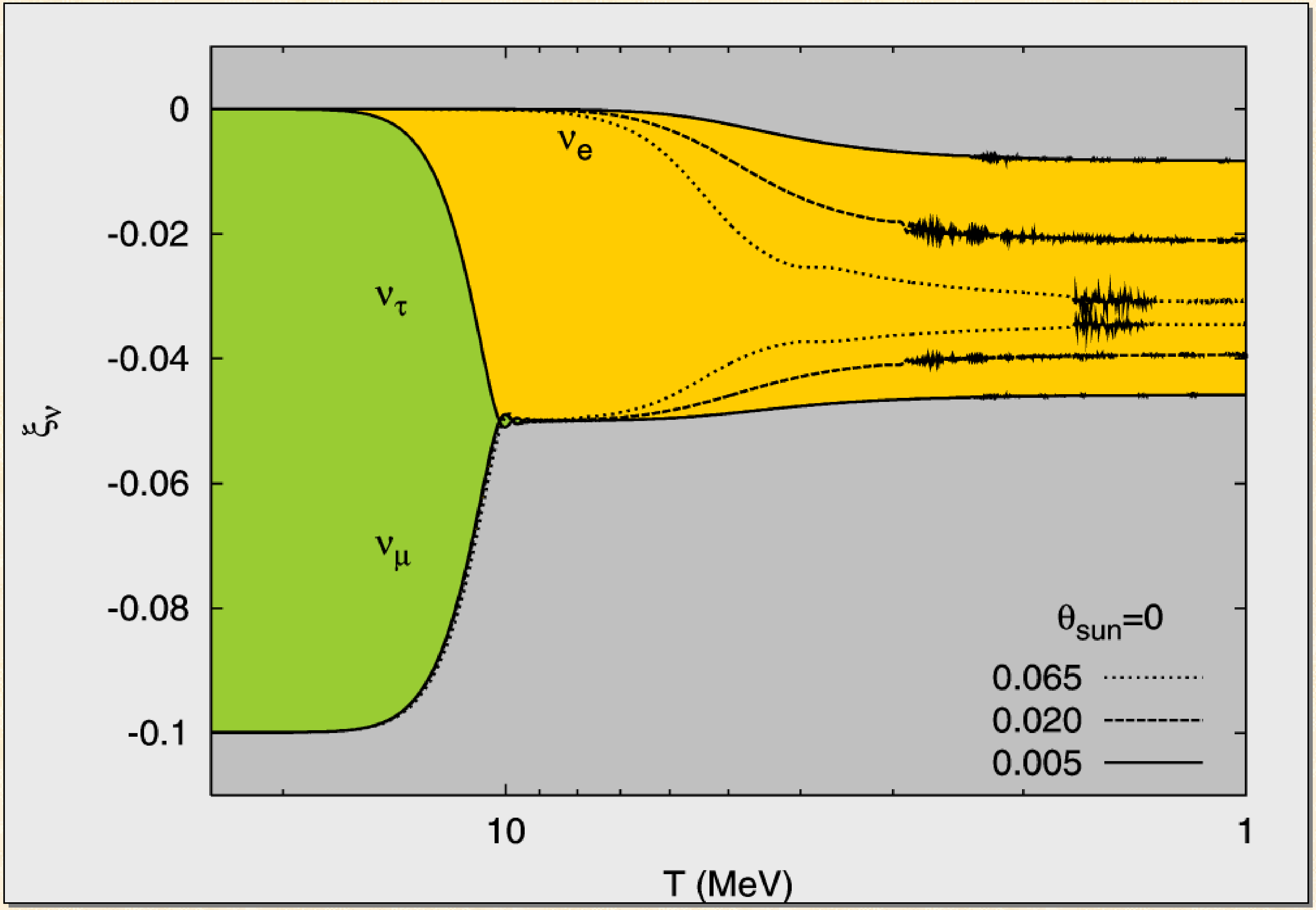
Dolgov, Hansen, Pastor, Petcov, Raffelt & Semikoz, hep-ph/0201287

Flavor Equilibration: LOW Solution



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

Flavor Equilibration: SMA With Non-Zero Θ_{13}



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

Synchronized Oscillations by Self-Interactions

Equation of motion in early universe with neutrino background

$$\partial_t \mathbf{P}_p = +\left(\frac{\delta m^2}{2p}\mathbf{B} - \frac{8\sqrt{2}G_F p}{3m_W^2}\rho_e \mathbf{z}\right)\times \mathbf{P}_p + \sqrt{2}G_F\left(\mathbf{P}-\bar{\mathbf{P}}\right)\times \mathbf{P}_p \qquad \text{neutrinos}$$

$$\partial_t \bar{\mathbf{P}}_p = -\left(\frac{\delta m^2}{2p}\mathbf{B} - \frac{8\sqrt{2}G_F p}{3m_W^2}\rho_e \mathbf{z}\right)\times \bar{\mathbf{P}}_p + \sqrt{2}G_F\left(\mathbf{P}-\bar{\mathbf{P}}\right)\times \bar{\mathbf{P}}_p \qquad \text{anti-neutrinos}$$

with the integrated neutrino polarization vectors

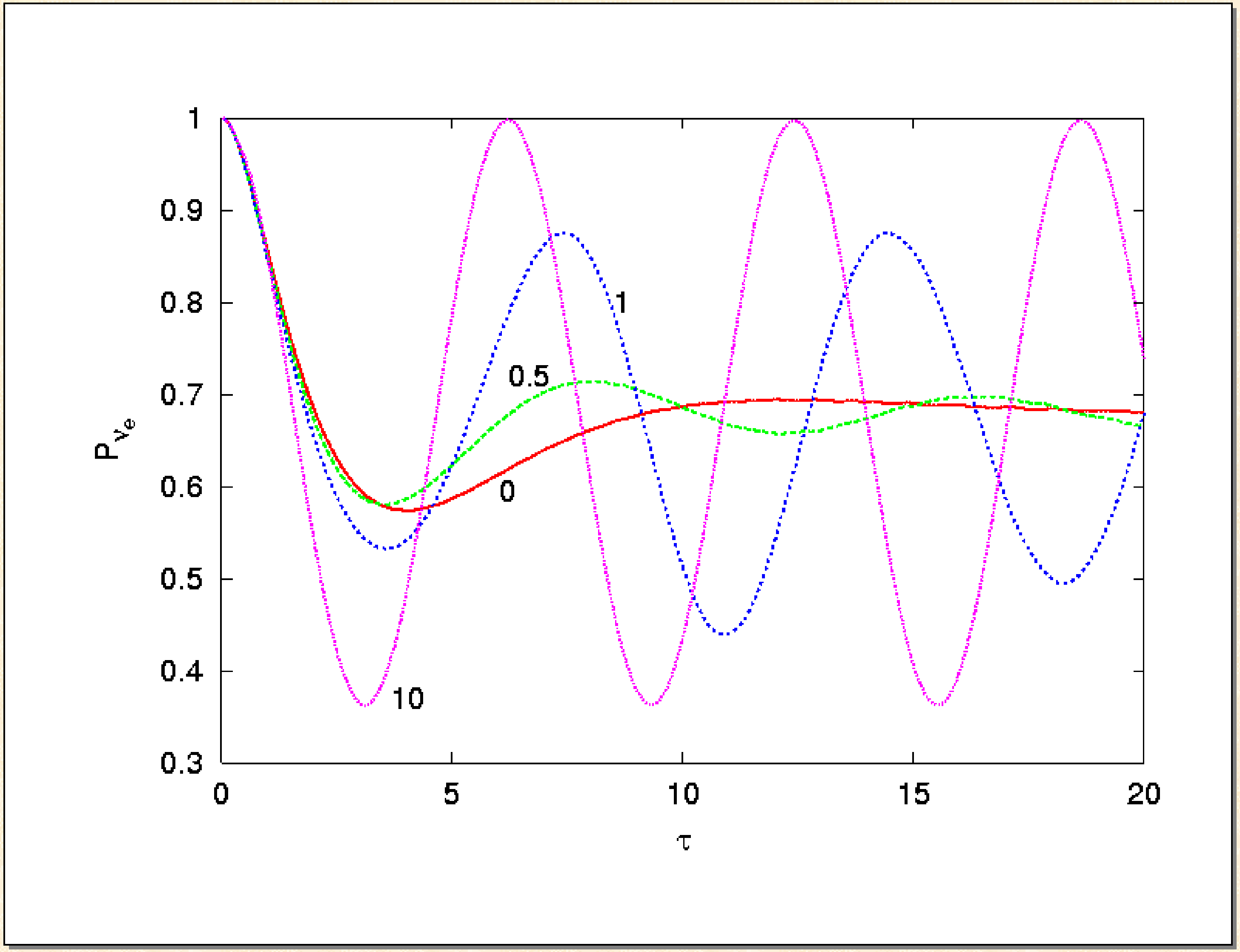
$$\mathbf{P} = \int \frac{d^3p}{(2\pi)^3}\mathbf{P}_p \quad \text{and} \quad \bar{\mathbf{P}} = \int \frac{d^3p}{(2\pi)^3}\bar{\mathbf{P}}_p$$

"Magnetic field" caused by neutrinos themselves much larger than vacuum or medium terms.
Couples "magnetic moments" to one large dipole which precesses with a single frequency.

Pastor, Raffelt & Semikoz, PRD 65 (2002) 053011

Georg Raffelt, Max-Planck-Institut für Physik (München)

Synchronized Oscillations by Self-Interactions



Pastor, Raffelt & Semikoz, PRD 65 (2002) 053011

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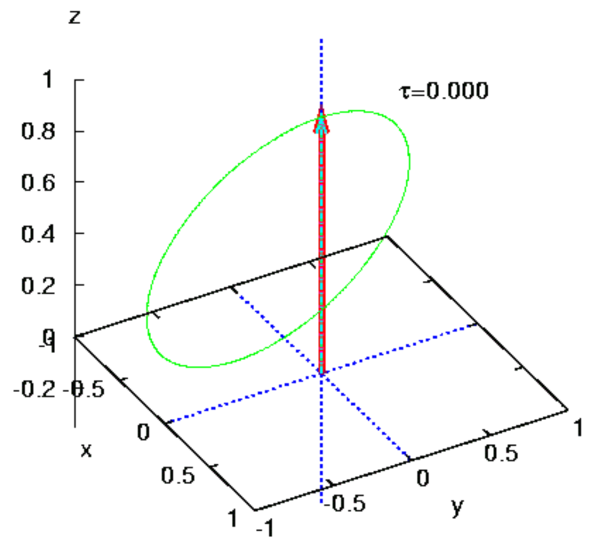
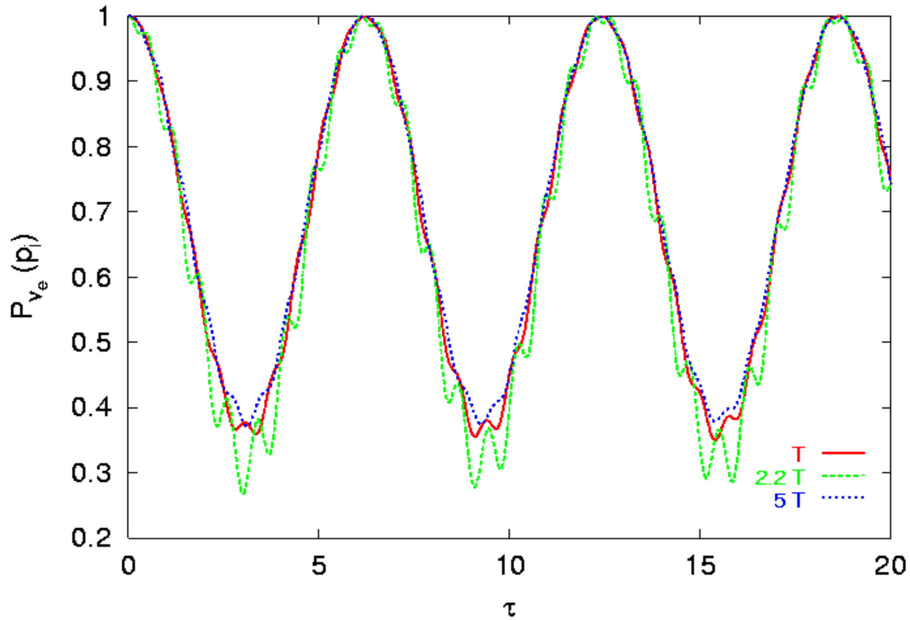
Synchronized Oscillations by Self-Interactions





Pastor, Raffelt & Semikoz, PRD 65 (2002) 053011

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Zero-Frequency Synchronized Oscillations

Synchronized oscillation frequency, assuming all polarization vectors initially parallel or antiparallel to z-axis

$$\omega_{synch} = \frac{\int \frac{d^3p}{(2\pi)^3} \frac{\delta m^2}{2p} \left(P_p + \overline{P}_p\right)}{\left| \int \frac{d^3p}{(2\pi)^3} \left(P_p - \overline{P}_p\right) \right|}$$

Only neutrinos (no anti-neutrinos):

$$\omega_{synch} = \frac{\delta m^2}{2} \left\langle \frac{1}{p} \right\rangle$$

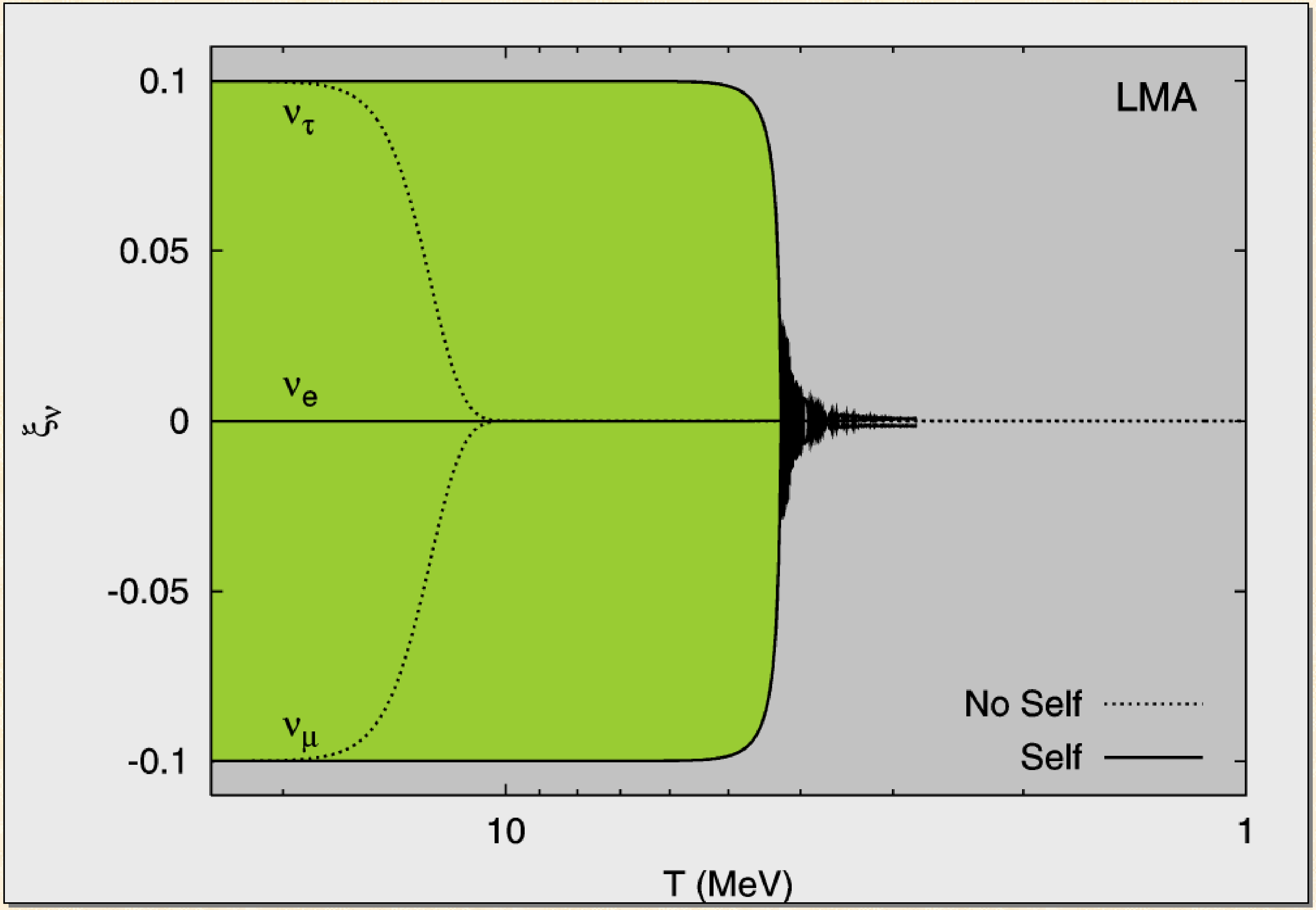
Equal distribution of neutrinos of one flavor and anti-neutrinos of the other:

$$\omega_{synch} = 0$$

Oscillations completely suppressed

Pastor, Raffelt & Semikoz, PRD 65 (2002) 053011

Flavor Equilibration: LMA and $\xi(\nu_\mu) = -\xi(\nu_\tau)$



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

Zero-Frequency Synchronized Oscillations

In a three-flavor system with dominant self-term, oscillations are suppressed (or infinitesimally slow) when

$$|\xi(\nu_e)| = |\xi(\nu_\mu)| = |\xi(\nu_\tau)|$$

Therefore, "equilibrium" in a strict sense not assured, but in that case number densities anyway equal between all flavors.

This situation requires a nonvanishing total lepton number.
If total lepton number is zero, oscillation suppression by self-term not possible.

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

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Summary

If KamLAND confirms LMA solar oscillation solution,
BBN implies
that the total number density of relic neutrinos agrees
with the standard value to better than 1%

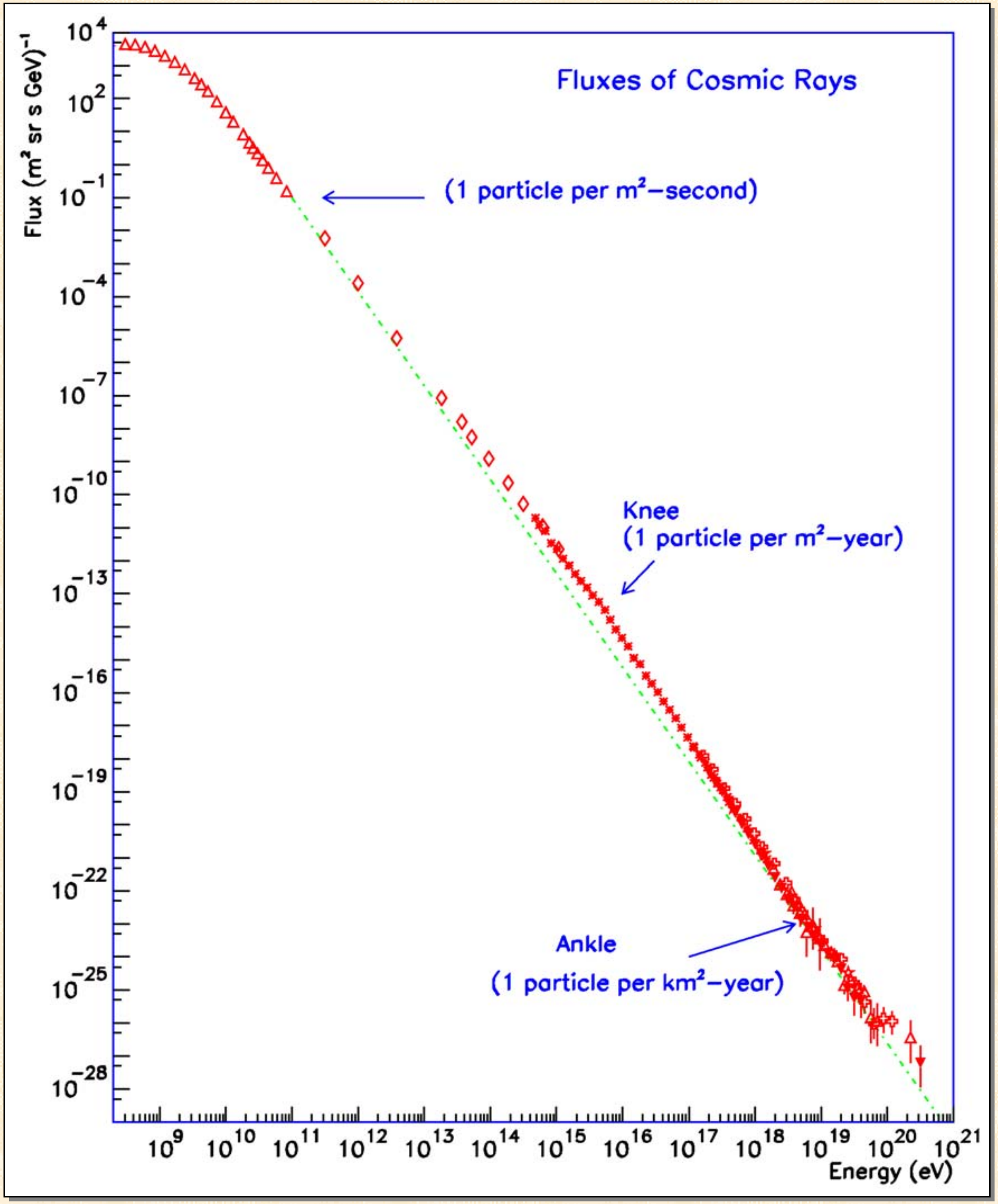
Strict relation between cosmological limits on
hot dark matter component
and neutrino mass

Georg Raffelt, Max-Planck-Institut für Physik (München)

Highest-Energy Cosmic Rays and the Cosmic Neutrino Sea

Georg Raffelt, Max-Planck-Institut für Physik (München)

Global Cosmic Ray Spectrum



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END TO THE COSMIC-RAY SPECTRUM?

Kenneth Greisen

Cornell University, Ithaca, New York
(Received 1 April 1966)

Greisen-Zatsepin-Kuzmin (GZK) Cutoff

$$p + \gamma \rightarrow \Delta^{+} \rightarrow p + \pi^{0}$$

PRL 16 (1966) 748

UPPER LIMIT OF THE SPECTRUM OF COSMIC RAYS

G. T. Zatsepin and V. A. Kuz'min
P. N. Lebedev Physics Institute, USSR Academy of Sciences
Submitted 26 May 1966
ZhETF Pis'ma 4, No. 3, 114-117, 1 August 1966

JETP Lett. 4 (1966) 78

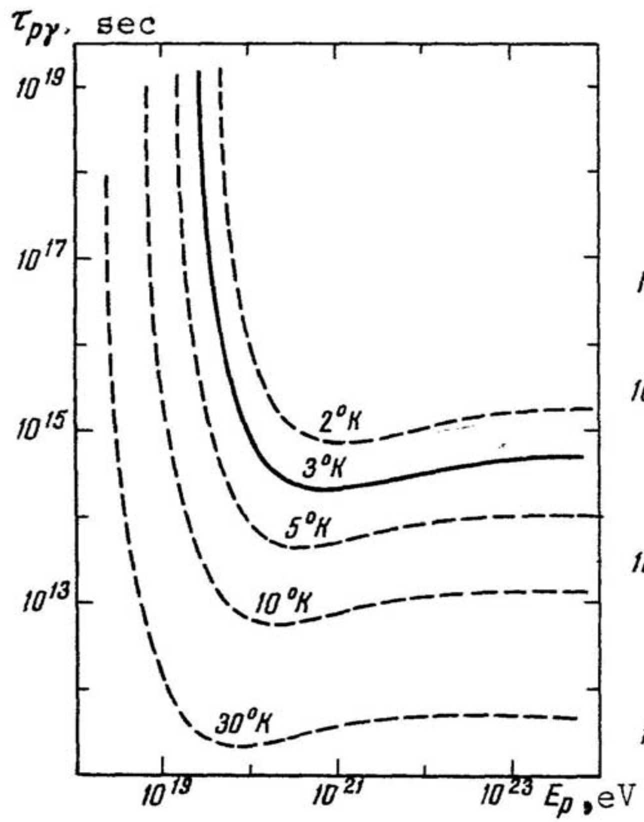

Fig. 1

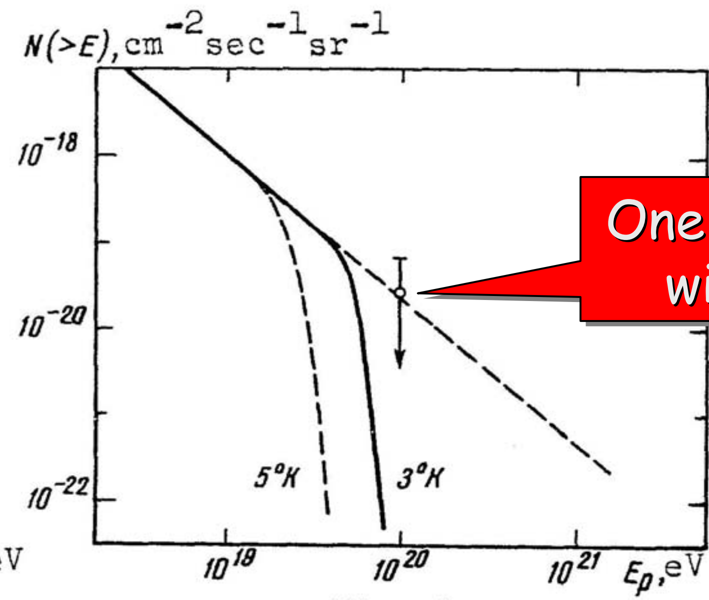

Fig. 2

One event (1962) with 10^{20} eV

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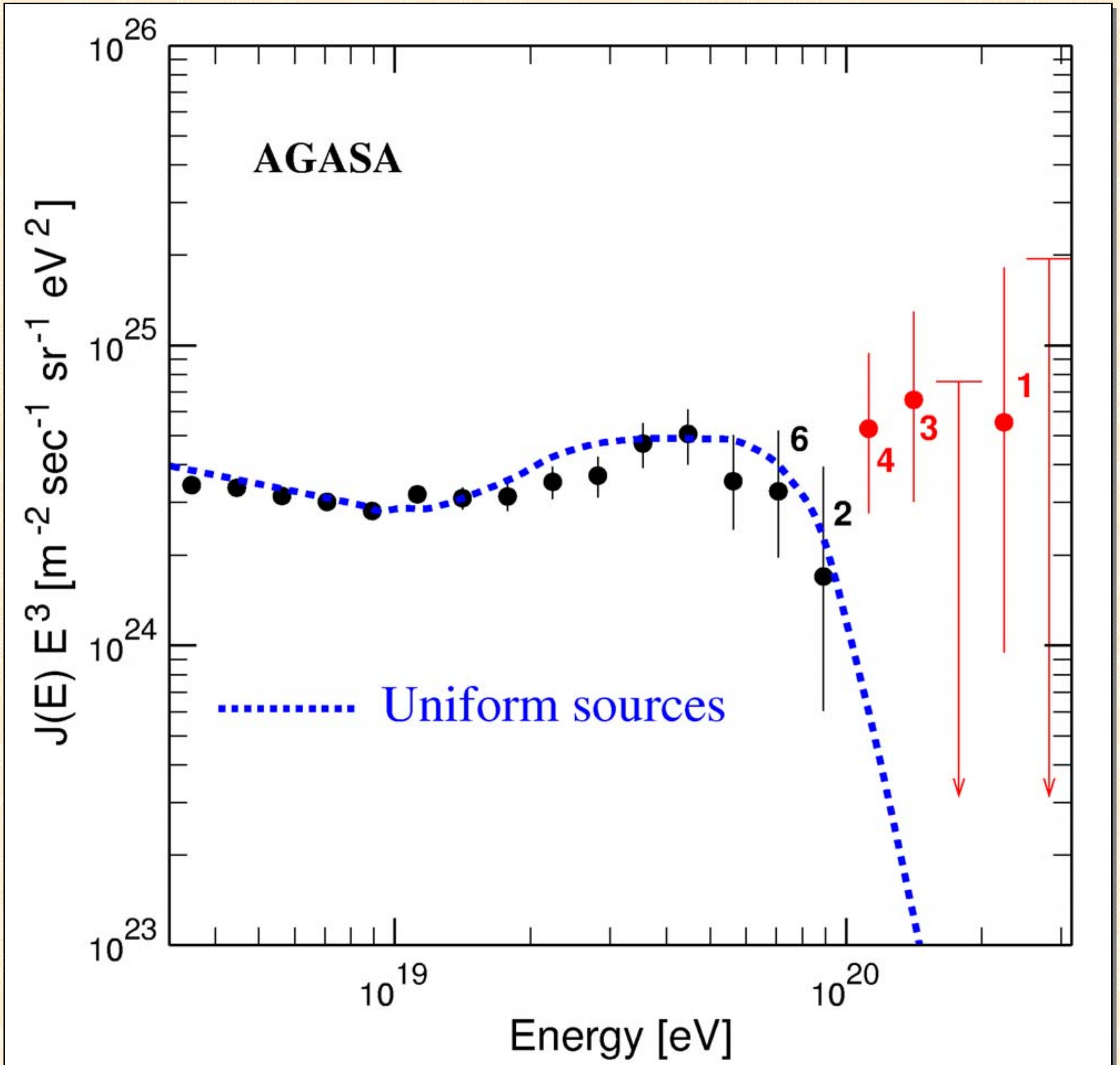
Spectrum of Highest-Energy AGASA Events

astro-ph/0008102



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Z-Bursts and Highest-Energy Cosmic Rays

Neutrinos
$E_\nu \sim 10^{21} - 10^{22}$ eV
from unknown sources

Resonant
Z-Boson
Production

Cosmic relic
neutrinos
$m_\nu \sim 1$ eV

Neutrino energy
on resonance

$$E_\nu = \frac{M_Z^2}{2m_\nu} = \frac{4.2\times10^{21}\,\mathrm{eV}}{m_{\mathrm{eV}}}$$

Decay
(Z-Burst)

2 Nucleons
$10\ \pi^0 \to 20\ \gamma$
$17\ \pi^\pm \to e^\pm\,\nu\,\underline{\nu}$

Measured cosmic rays

For example:
- Weiler
  hep-ph/9710431;
- Fargion et al.
  hep-ph/0112014
- Fodor, Katz, Ringwald
  hep-ph/0203198;

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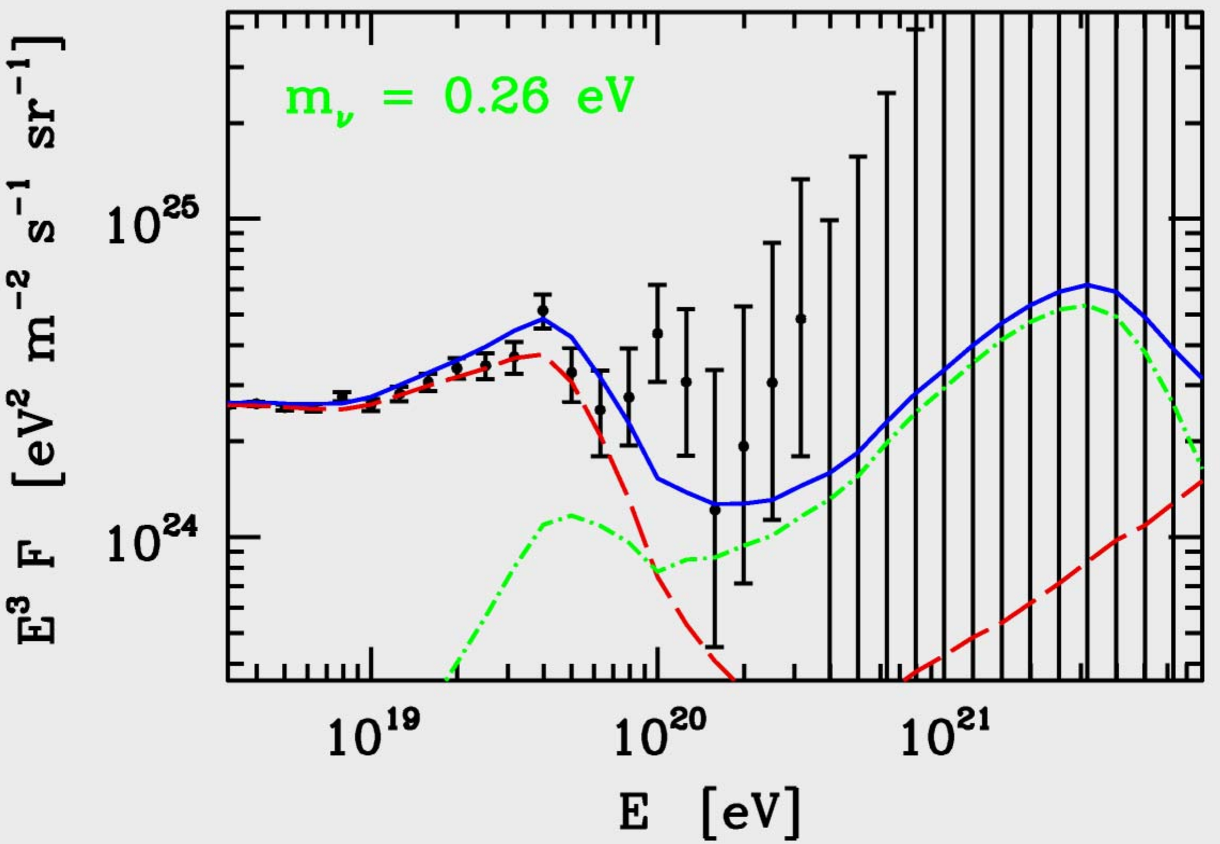
Fitting the Cosmic Ray Spectrum with Z-Bursts

Cosmic ray spectrum near cutoff can be fit for a wide range of allowed neutrino masses



Fodor, Katz & Ringwald, hep-ph/0203198

Main problems:

- Huge source flux of EHE neutrinos required
- No plausible sources known
- Accompanying photons must be perfectly obscured

Kalashev et al. hep-ph/0112351

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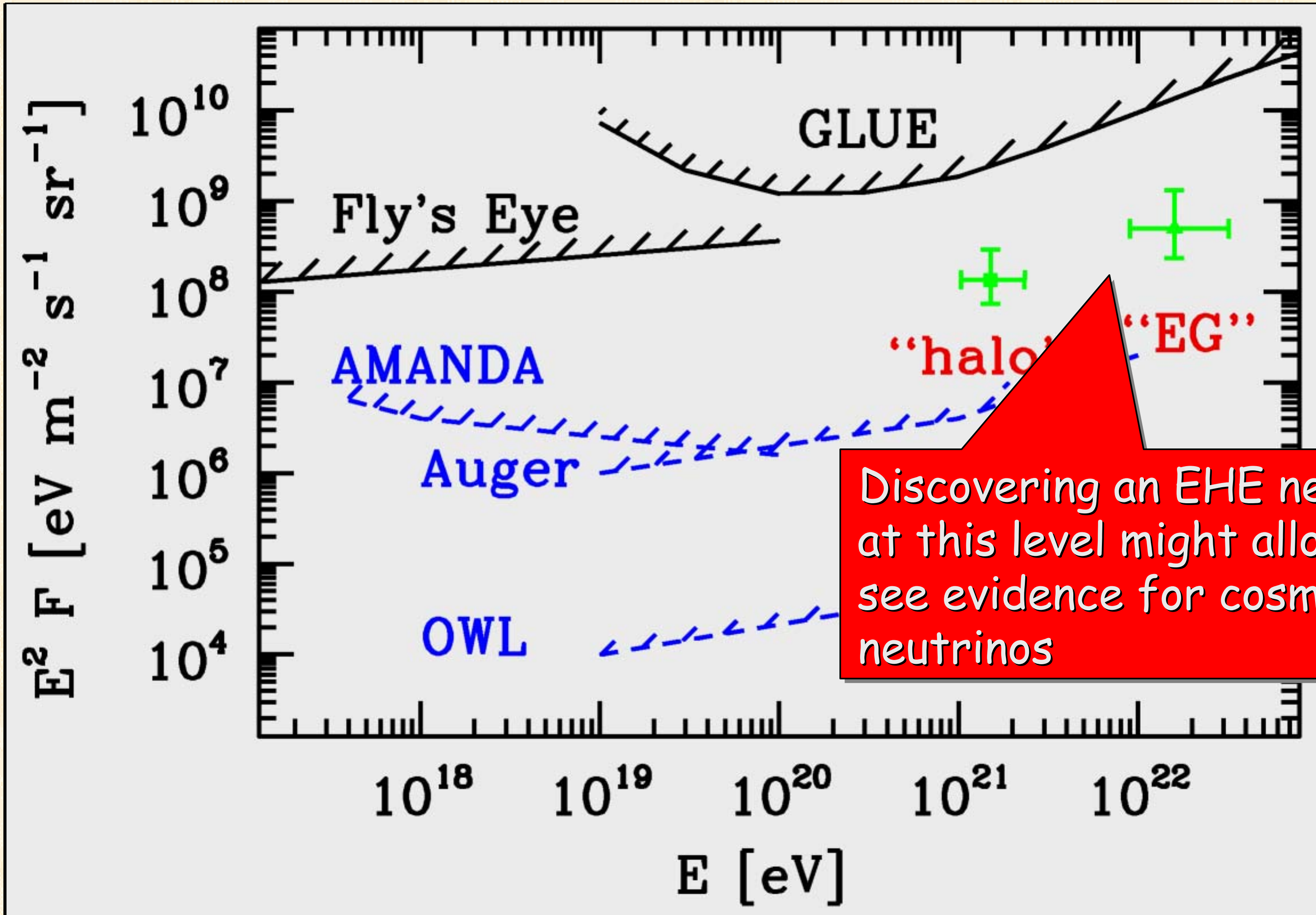
Discovery Potential for Required Neutrino Fluxes



Discovering an EHE neutrino flux at this level might allow one to see evidence for cosmic relic neutrinos

Fodor, Katz & Ringwald, hep-ph/0203198

Massive Neutrinos and the Cosmic Baryon Asymmetry

Georg Raffelt, Max-Planck-Institut für Physik (München)

Baryogenesis in the Early Universe

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 B and L by electroweak instanton effects
- Conserves B – L

In cosmological evolution

- Pre-existing B+L erased at EW phase transition
- Creation of BAU at phase transition not possible, except for special parameters in SUSY models

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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

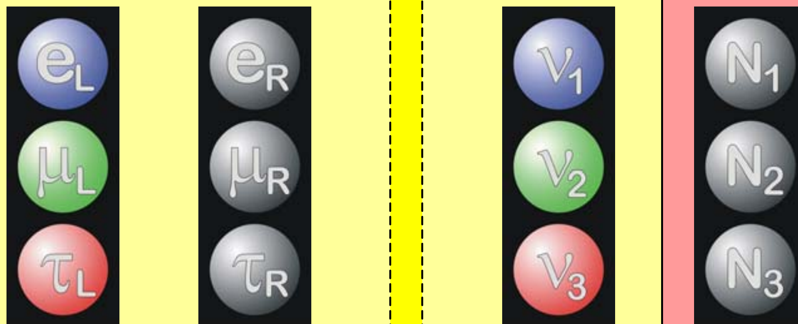
Received 8 March 1986

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

Charged Leptons	Neutrinos

Dirac masses from coupling to standard Higgs field ϕ



Heavy Majorana masses M_j

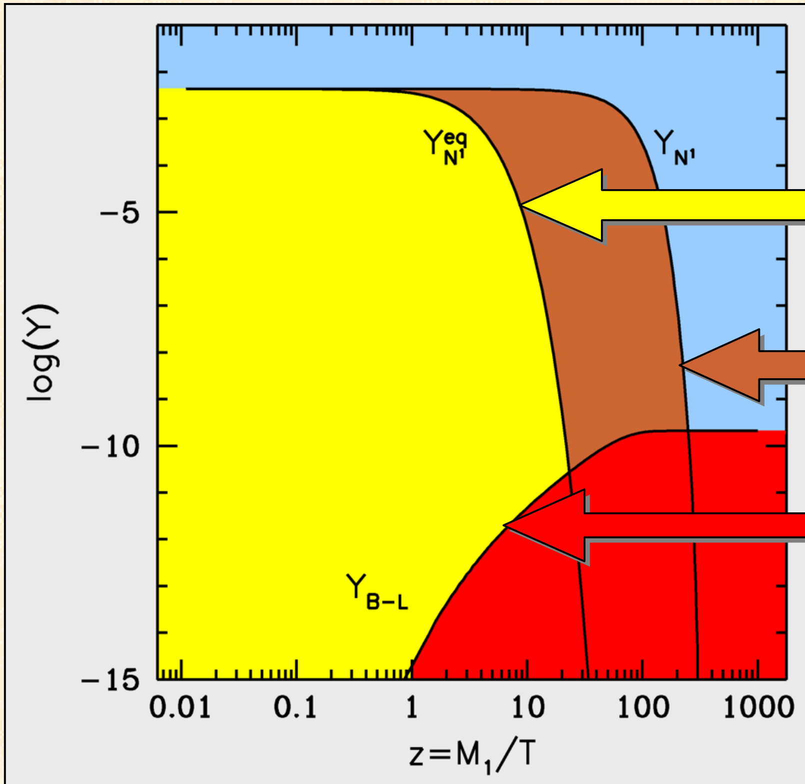
Lagrangian for particle masses

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

Light Majorana mass

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

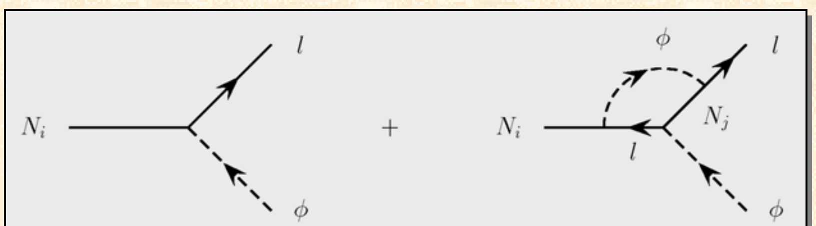
Leptogenesis by Out-of-Equilibrium Decay



Equilibrium abundance of heavy Majorana neutrinos

Real non-equilibrium abundance determined by decay rate

Lepton-number abundance created by CP-violating decays



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

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

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Connection to Neutrino Mass

$\Gamma_{\rm Decay} = g_\nu^2 \frac{M}{8\pi}$	Decay rate of heavy Majorana neutrino
$H \approx \sqrt{g_{\rm eff}}\, \frac{T^2}{m_{\rm Pl}}$	Cosmic expansion rate
$\Gamma_{\rm Decay} < H\|_{T=M}$	Requirement for strong deviation from equilibrium ...
$g_\nu^2 \frac{M}{8\pi} < \sqrt{g_{\rm eff}}\, \frac{M^2}{m_{\rm Pl}}$	
$\frac{g_\nu^2}{M} < \frac{8\pi\sqrt{g_{\rm eff}}}{m_{\rm Pl}}$	
$m_\nu = \frac{g_\nu^2 \langle\phi\rangle^2}{M} < \frac{8\pi\sqrt{g_{\rm eff}}}{m_{\rm Pl}} \langle\phi\rangle^2 \sim 10^{-3}\,{\rm eV}$	... translates into a limit on the observable neutrino mass

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Leptogenesis by Majorana Neutrino Decays

In see-saw models of neutrino masses, right-handed heavy Majorana neutrinos provide source for L-violation

Cosmological evolution:

- B = L = 0 early on
- Thermal freeze-out of heavy Majorana neutrinos
- Out-of-equilibrium decay creates net L
- Shift L excess into B at EW phase transition

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

Consistent with hierarchical masses below 0.1 eV

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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 ...

Conclusions

Future galactic SN signal is
- Sensitive to ~ 1-3 eV mass
- But not sub-eV range

Large-scale galaxy redshift surveys:
- Best limit of $m_\nu < 0.8$ eV,
- Future sensitivity ~ 0.3 eV

If solar LMA solution applies, cosmic neutrino number density precisely determined by BBN

If highest-E cosmic-ray neutrinos are found, Z-bursts provide handle on m_ν

Majorana neutrino masses in the favored range may indicate a leptogenesis scenario for generating cosmic baryon asymmetry

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