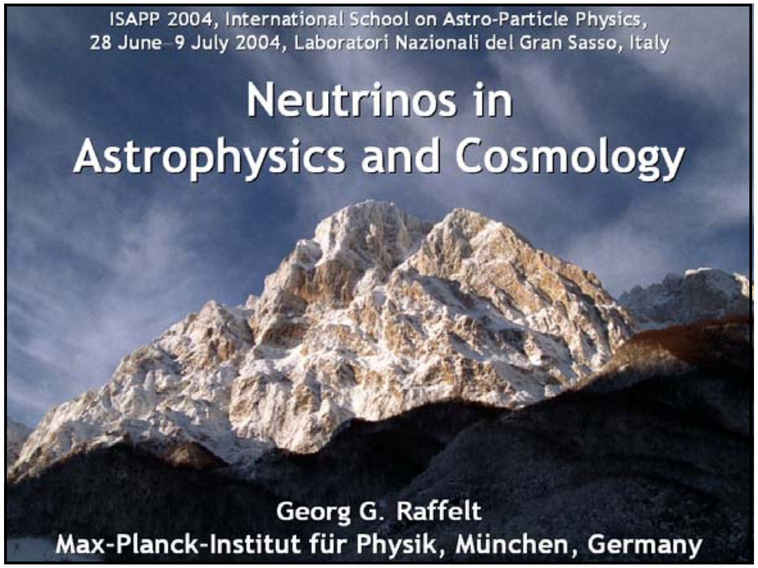
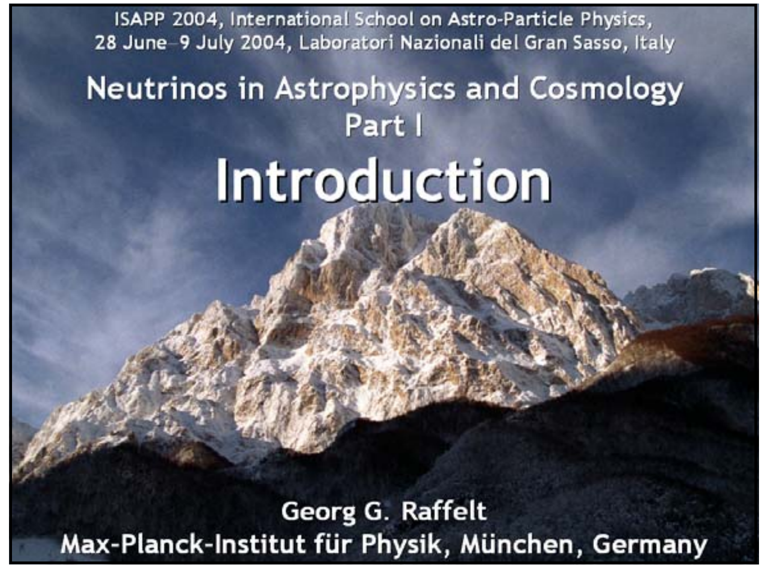
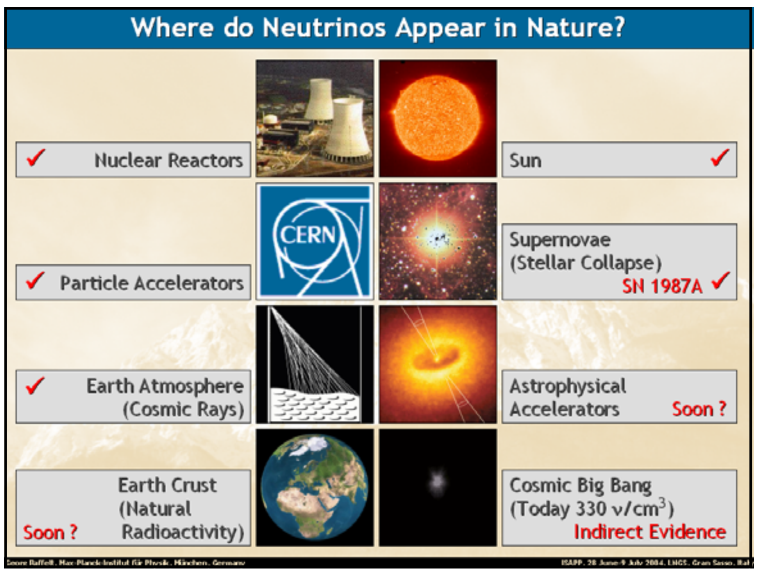
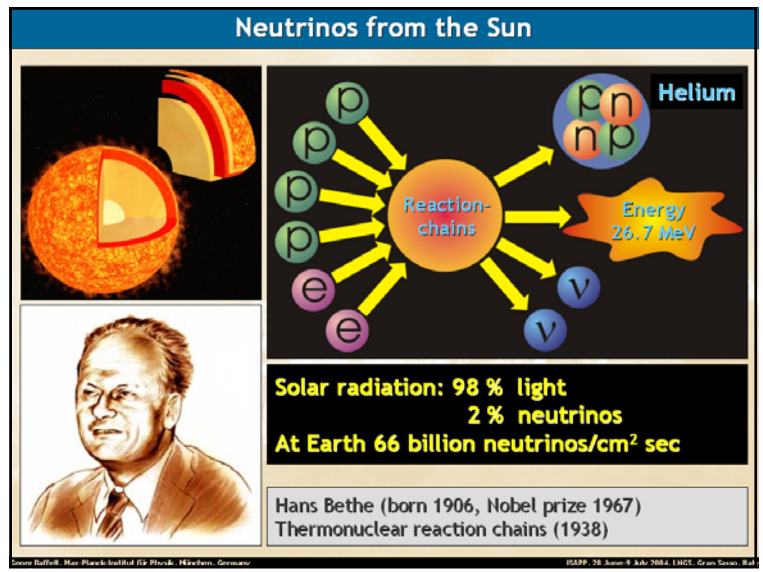

ISAPP 2004, International School on Astro-Particle Physics,
28 June–9 July 2004, Laboratori Nazionali del Gran Sasso, Italy
Neutrinos in
Astrophysics and Cosmology
Georg G. Raffelt
Max-Planck-Institut für Physik, München, Germany


ISAPP 2004, International School on Astro-Particle Physics,
28 June–9 July 2004, Laboratori Nazionali del Gran Sasso, Italy
Neutrinos in Astrophysics and Cosmology
Part I
Introduction
Georg G. Raffelt
Max-Planck-Institut für Physik, München, Germany


Where do Neutrinos Appear in Nature?
✓ Nuclear Reactors
Sun ✓
✓ Particle Accelerators
CERN
Supernovae
(Stellar Collapse)
SN 1987A ✓
✓ Earth Atmosphere
(Cosmic Rays)
Astrophysical
Accelerators Soon ?
Earth Crust
(Natural
Radioactivity)
Soon ?
Cosmic Big Bang
(Today 330 ν/cm³)
Indirect Evidence


Neutrinos from the Sun
p
p
p
p
e
e
Reaction-
chains
p n
n p
Helium
Energy
26.7 MeV
ν
ν
Solar radiation: 98 % light
2 % neutrinos
At Earth 66 billion neutrinos/cm² sec
Hans Bethe (born 1906, Nobel prize 1967)
Thermonuclear reaction chains (1938)

Bethe's Classic Paper on Nuclear Reactions in Stars

The combination of four p[…] and two electrons can occur essentially o[…] two ways. The first mechanism starts with […]ombination of two protons to form a deuter[…] with positron emission, viz.

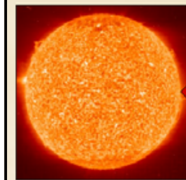
$$H+H=D+e^{+}. \quad (1)$$

The deuteron is then transformed into He^4 by further capture of protons; these captures occur very rapidly compared with process (1). The second mechanism uses carbon and nitrogen as catalysts, according to the chain reaction

$$\begin{array}{ll} C^{12}+H=N^{13}+\gamma, & N^{13}=C^{13}+e^{+} \\ C^{13}+H=N^{14}+\gamma, & \\ N^{14}+H=O^{15}+\gamma, & O^{15}=N^{15}+e^{+} \\ N^{15}+H=C^{12}+He^{4}. & \end{array} \quad (2)$$

No neutrinos from nuclear reactions in 1938 …

Sun Glasses for Neutrinos?

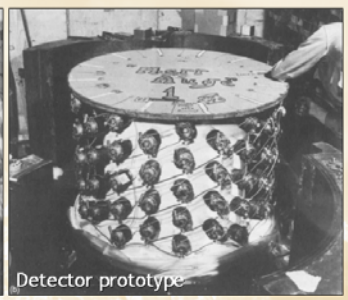


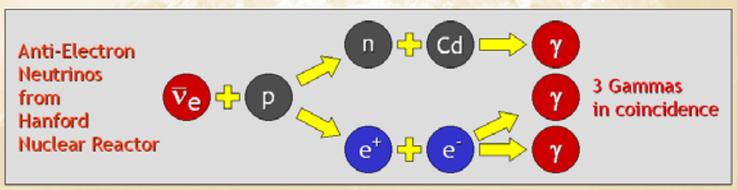
8.3 light minutes

1000 light years of lead needed to shield solar neutrinos

Bethe & Peierls 1934:
"… this evidently means that one will never be able to observe a neutrino."

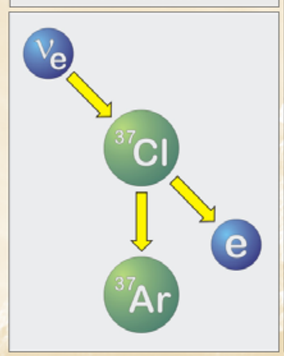
First Detection (1954 - 1956)

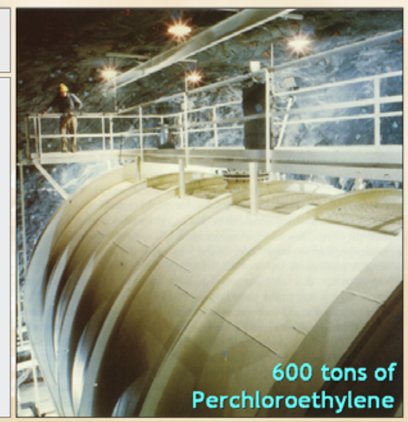




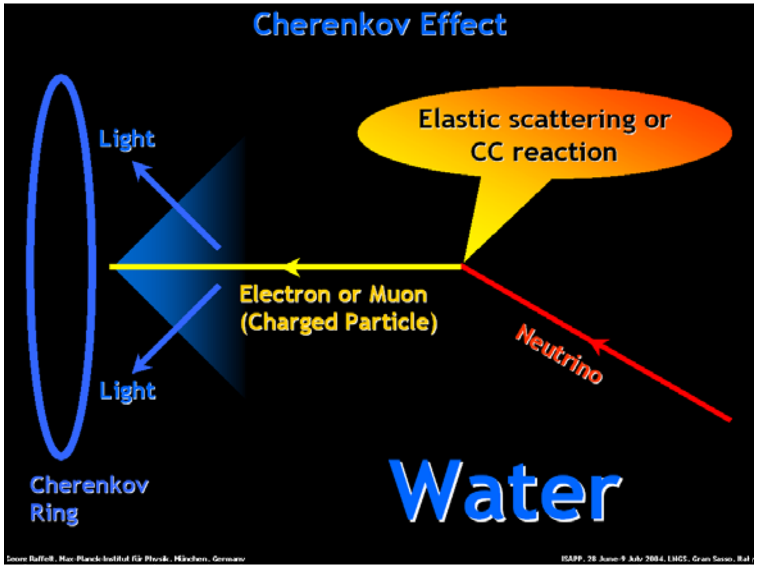
First Measurement of Solar Neutrinos

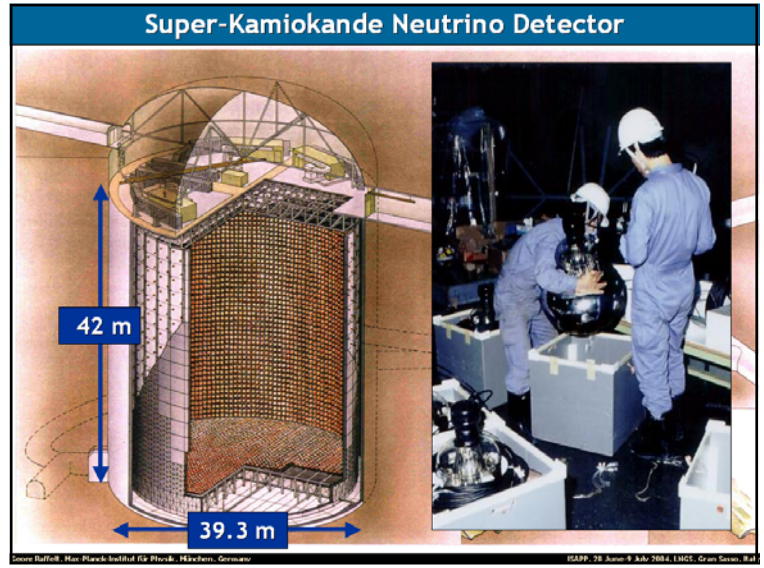
Inverse beta decay of chlorine

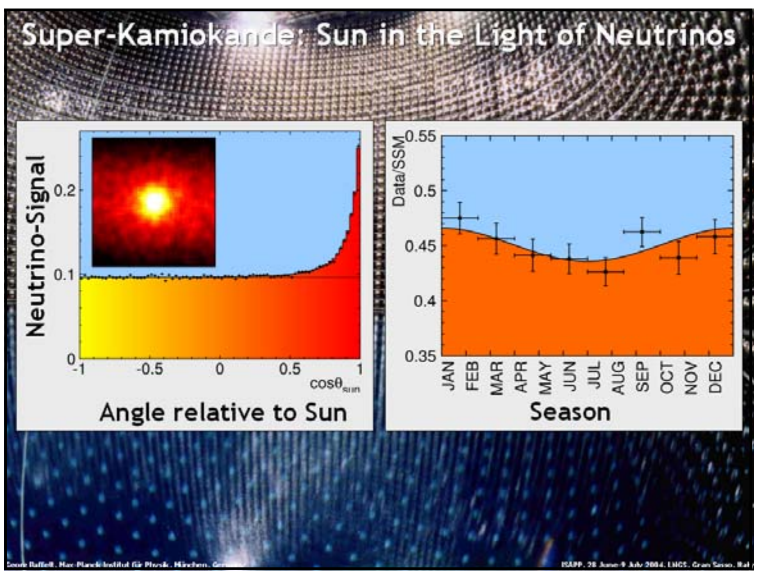


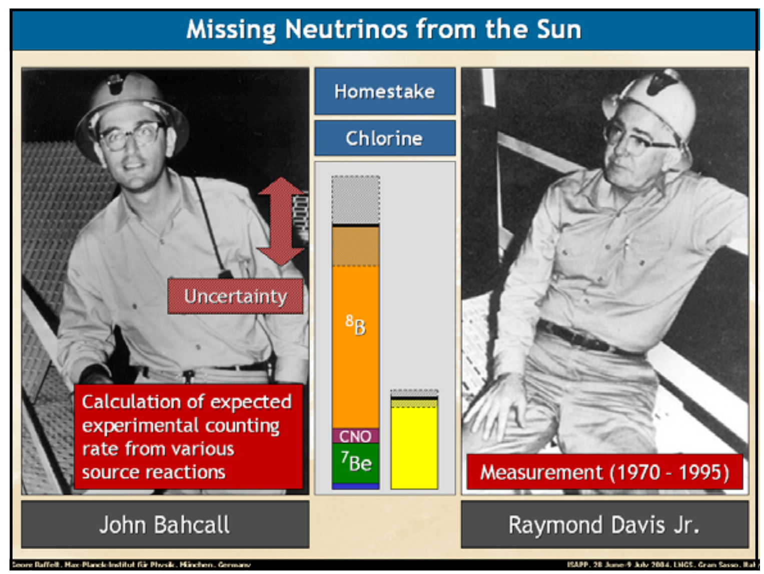


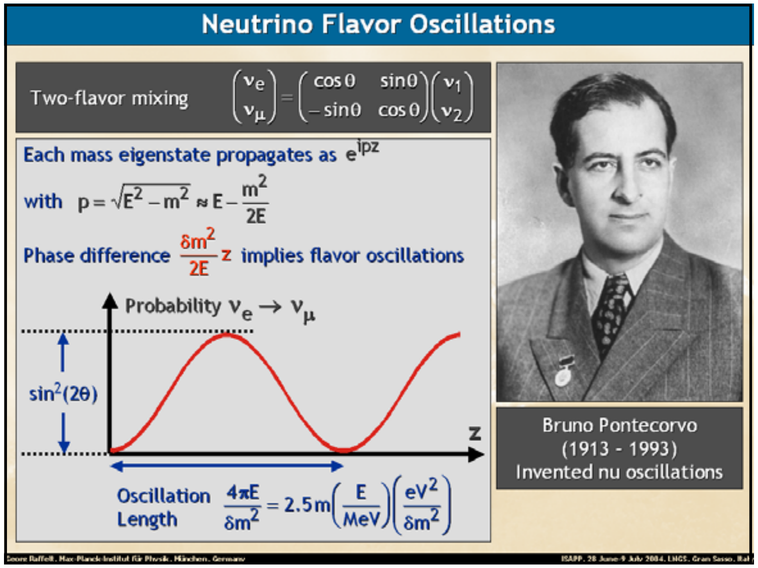
Homestake solar neutrino observatory (1967–2002)

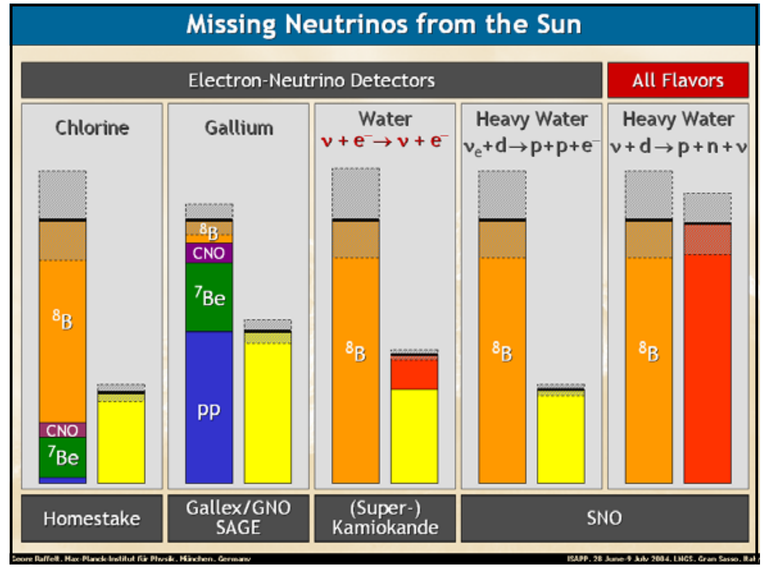

Cherenkov Effect
Light
Elastic scattering or
CC reaction
Electron or Muon
(Charged Particle)
Neutrino
Light
Cherenkov
Ring
Water

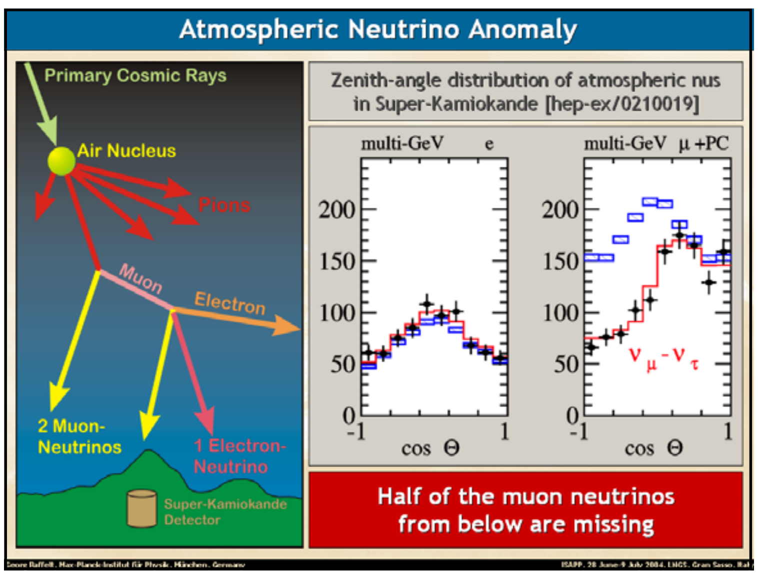

Super-Kamiokande Neutrino Detector
42 m
39.3 m

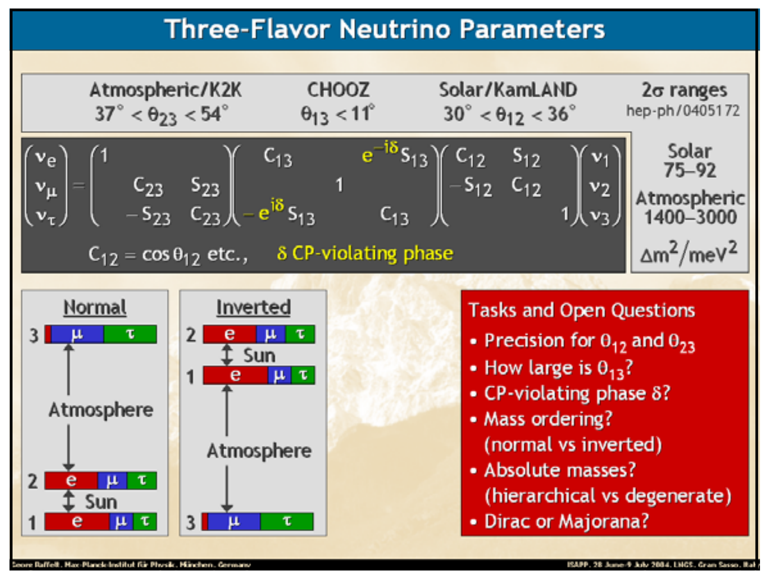

Super-Kamiokande: Sun in the Light of Neutrinos
Neutrino-Signal
0.2
0.1
0
-1
-0.5
0
0.5
1
Angle relative to Sun
Data/SSM
0.55
0.5
0.45
0.4
0.35
JAN FEB MAR APR MAY JUN JUL AUG SEP OCT NOV DEC
Season


Missing Neutrinos from the Sun
Homestake
Chlorine
Uncertainty
8B
CNO
7Be
Calculation of expected experimental counting rate from various source reactions
Measurement (1970 - 1995)
John Bahcall
Raymond Davis Jr.


Neutrino Flavor Oscillations
Two-flavor mixing
$\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix} = \begin{pmatrix}\cos\theta & \sin\theta\\ -\sin\theta & \cos\theta\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\end{pmatrix}$
Each mass eigenstate propagates as e^{ipz}
with $p = \sqrt{E^2 - m^2} \approx E - \frac{m^2}{2E}$
Phase difference $\frac{\delta m^2}{2E} z$ implies flavor oscillations
Probability $\nu_e \to \nu_\mu$
$\sin^2(2\theta)$
z
Oscillation Length $\frac{4\pi E}{\delta m^2} = 2.5\,\mathrm{m}\left(\frac{E}{\mathrm{MeV}}\right)\left(\frac{\mathrm{eV}^2}{\delta m^2}\right)$
Bruno Pontecorvo
(1913 - 1993)
Invented nu oscillations


Missing Neutrinos from the Sun
Electron-Neutrino Detectors
All Flavors
Chlorine
Gallium
Water
$\nu + e^- \to \nu + e^-$
Heavy Water
$\nu_e + d \to p + p + e^-$
Heavy Water
$\nu + d \to p + n + \nu$
^{8}B
CNO
^{7}Be
pp
Homestake
Gallex/GNO
SAGE
(Super-)
Kamiokande
SNO


Atmospheric Neutrino Anomaly
Primary Cosmic Rays
Air Nucleus
Pions
Muon
Electron
2 Muon-
Neutrinos
1 Electron-
Neutrino
Super-Kamiokande
Detector
Zenith-angle distribution of atmospheric nus
in Super-Kamiokande [hep-ex/0210019]
multi-GeV e
multi-GeV μ +PC
200
150
100
50
0
-1
1
cos Θ
$\nu_\mu - \nu_\tau$
Half of the muon neutrinos
from below are missing


Three-Flavor Neutrino Parameters
Atmospheric/K2K
$37^\circ < \theta_{23} < 54^\circ$
CHOOZ
$\theta_{13} < 11^\circ$
Solar/KamLAND
$30^\circ < \theta_{12} < 36^\circ$
2σ ranges
hep-ph/0405172
$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}1 & & \\ & c_{23} & s_{23}\\ & -s_{23} & c_{23}\end{pmatrix}\begin{pmatrix}c_{13} & & e^{-i\delta}s_{13}\\ & 1 & \\ -e^{i\delta}s_{13} & & c_{13}\end{pmatrix}\begin{pmatrix}c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$
$c_{12} = \cos\theta_{12}$ etc., δ CP-violating phase
Solar
75–92
Atmospheric
1400–3000
$\Delta m^2/\mathrm{meV}^2$
Normal
Inverted
e μ τ
Sun
Atmosphere
Tasks and Open Questions
• Precision for θ_{12} and θ_{23}
• How large is θ_{13}?
• CP-violating phase δ?
• Mass ordering?
(normal vs inverted)
• Absolute masses?
(hierarchical vs degenerate)
• Dirac or Majorana?

Neutrinos from Thermal Plasma Processes

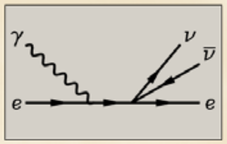
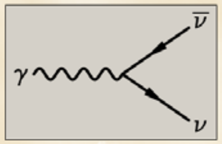
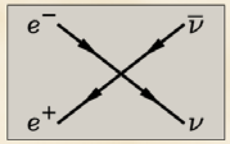


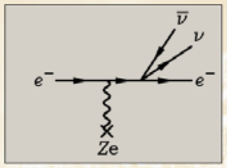
Photo (Compton)



Plasmon decay

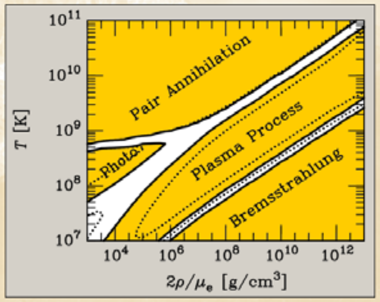


Pair annihilation



Bremsstrahlung

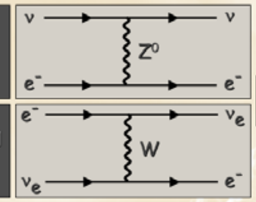
These processes first discussed in 1961-63 after V–A theory



Effective Neutrino Neutral-Current Couplings

Neutral current

Charged current



$E \ll M_{W,Z}$

Effective four fermion coupling

$$H_{int} = \frac{G_F}{\sqrt{2}} \Psi_f \gamma_\mu (C_V - C_A \gamma_5) \Psi_f \; \Psi_\nu \gamma^\mu (1-\gamma_5) \Psi_\nu$$

Neutrino	Fermion	C_V	C_A
ν_e	Electron	$+\frac{1}{2} + 2\sin^2\Theta_W \approx 1$	$+\frac{1}{2}$
ν_μ, ν_τ		$-\frac{1}{2} + 2\sin^2\Theta_W \approx 0$	$-\frac{1}{2}$
ν_e, ν_μ, ν_τ	Proton	$+\frac{1}{2} - 2\sin^2\Theta_W \approx 0$	$+\frac{1.26}{2}$
	Neutron	$-\frac{1}{2}$	$-\frac{1.26}{2}$

$G_F = 1.166 \times 10^{-5}\,\text{GeV}^{-2}$

$\sin^2\Theta_W = 0.231$

Solar Neutrinos from Compton Process

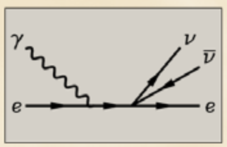


Photo (Compton)

Cross section (non-relativistic limit)

$$\sigma = \frac{32}{105} \frac{\alpha G_F^2 m_e^2}{(4\pi)^2} (C_V^2 + 5C_A^2) \left(\frac{E_\gamma}{m_e}\right)^4$$

$$\sum_{\text{flavors}} \sigma = 1.34 \times 10^{-55}\,\text{cm}^2 \left(\frac{E_\gamma}{10\,\text{keV}}\right)^4$$

Volume energy loss rate

$$Q_{\nu\bar{\nu}} = n_e \int \frac{2d^3\bar{p}_\gamma}{(2\pi)^3} \frac{E_\gamma \sum \sigma}{e^{E_\gamma/T} - 1}$$

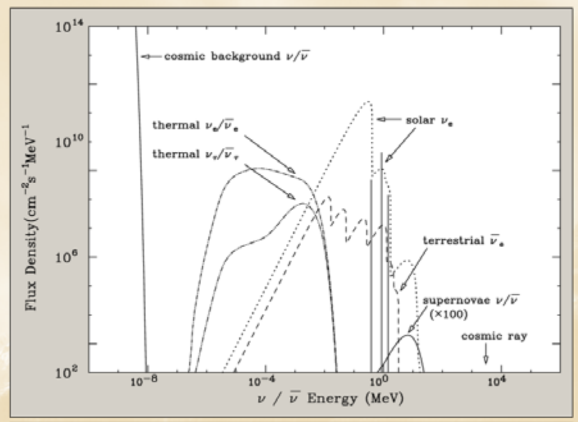
Energy loss rate per unit mass

$$\varepsilon_{\nu\bar{\nu}} = \frac{Q_{\nu\bar{\nu}}}{\rho} = 2.5 \times 10^{-8} \frac{\text{erg}}{\text{g s}} Y_e \left(\frac{T}{\text{keV}}\right)^8$$

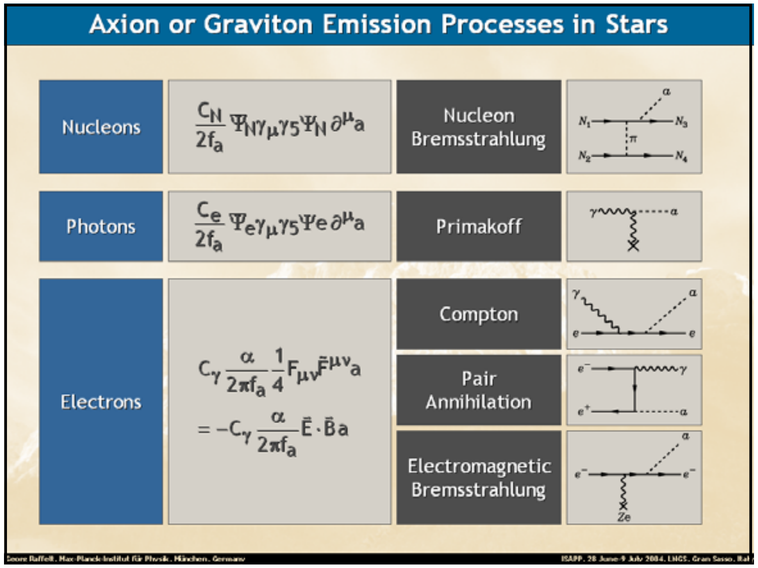
To be compared with nuclear energy generation rate in the Sun

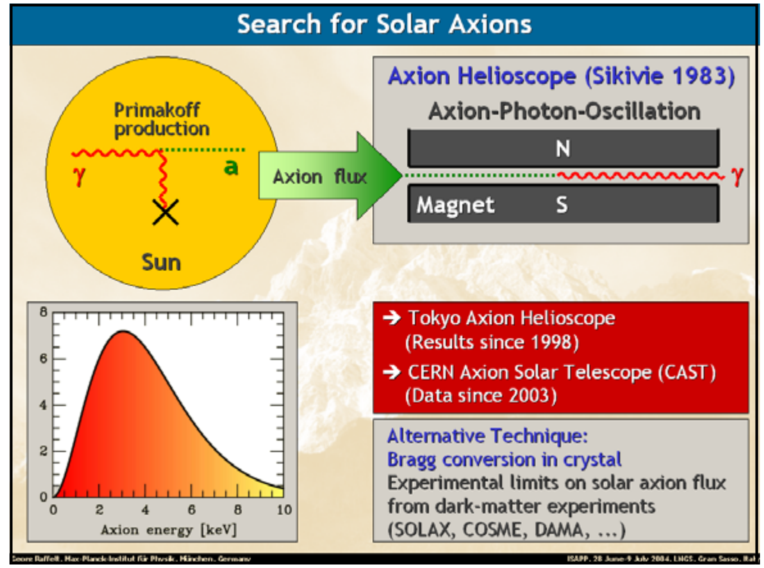
$$\langle \varepsilon_{nuc} \rangle = \frac{L_{sun}}{M_{sun}} = \frac{4 \times 10^{33}\,\text{erg/s}}{2 \times 10^{33}\,\text{g}} = 2 \frac{\text{erg}}{\text{g s}} = 2 \times 10^{-7} \frac{\text{Watts}}{\text{g}} = \frac{200\,\text{Watts}}{\text{kilo-ton}}$$

Thermal vs. Nuclear Neutrinos from Sun

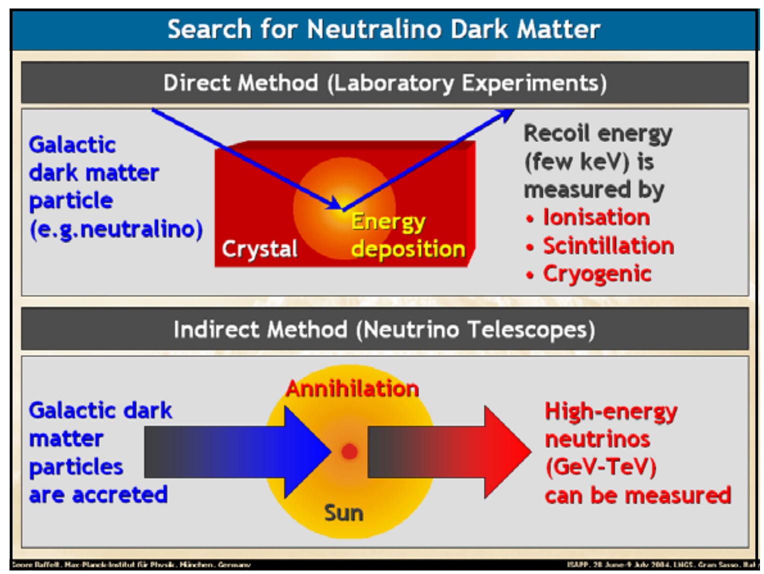


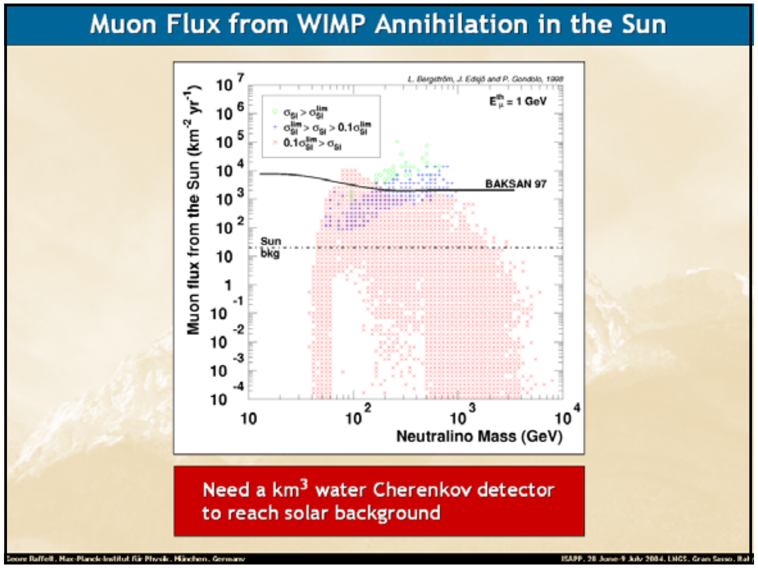
Haxton & Lin, The very low energy solar flux of electron and heavy-flavor neutrinos and anti-neutrinos, nucl-th/0006055

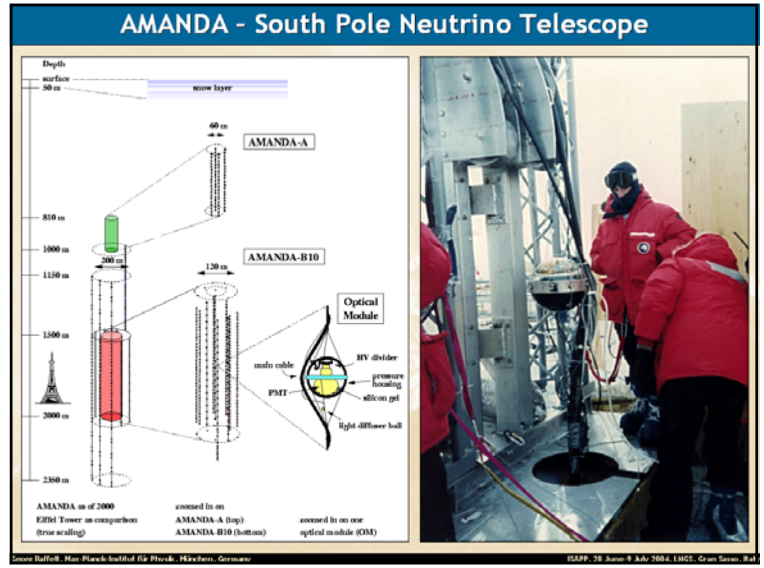

Axion or Graviton Emission Processes in Stars
Nucleons
$\frac{C_N}{2f_a}\bar{\Psi}_N\gamma_\mu\gamma_5\Psi_N\partial^\mu a$
Nucleon Bremsstrahlung
Photons
$\frac{C_e}{2f_a}\bar{\Psi}_e\gamma_\mu\gamma_5\Psi_e\partial^\mu a$
Primakoff
Electrons
$C_\gamma\frac{\alpha}{2\pi f_a}\frac{1}{4}F_{\mu\nu}\tilde{F}^{\mu\nu}a = -C_\gamma\frac{\alpha}{2\pi f_a}\vec{E}\cdot\vec{B}a$
Compton
Pair Annihilation
Electromagnetic Bremsstrahlung

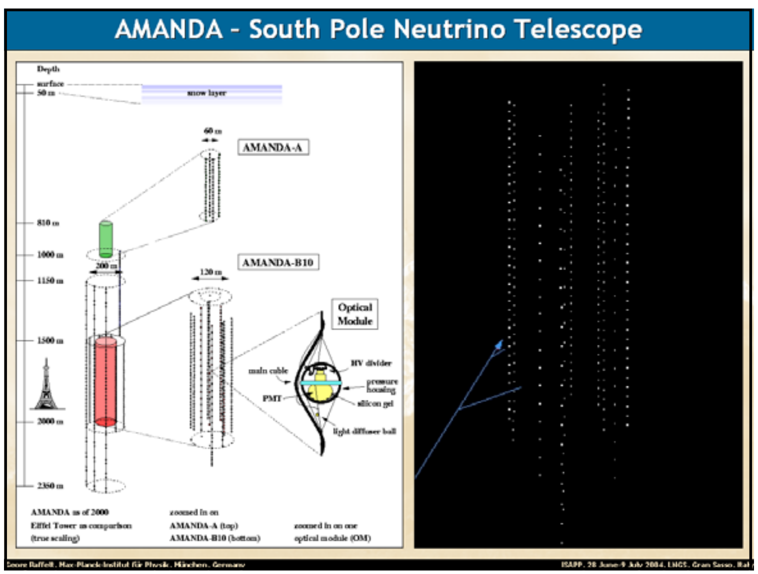

Search for Solar Axions
Primakoff production
γ
a
Sun
Axion flux
Axion Helioscope (Sikivie 1983)
Axion-Photon-Oscillation
N
Magnet S
γ
Axion energy [keV]
→ Tokyo Axion Helioscope (Results since 1998)
→ CERN Axion Solar Telescope (CAST) (Data since 2003)
Alternative Technique:
Bragg conversion in crystal
Experimental limits on solar axion flux from dark-matter experiments (SOLAX, COSME, DAMA, ...)

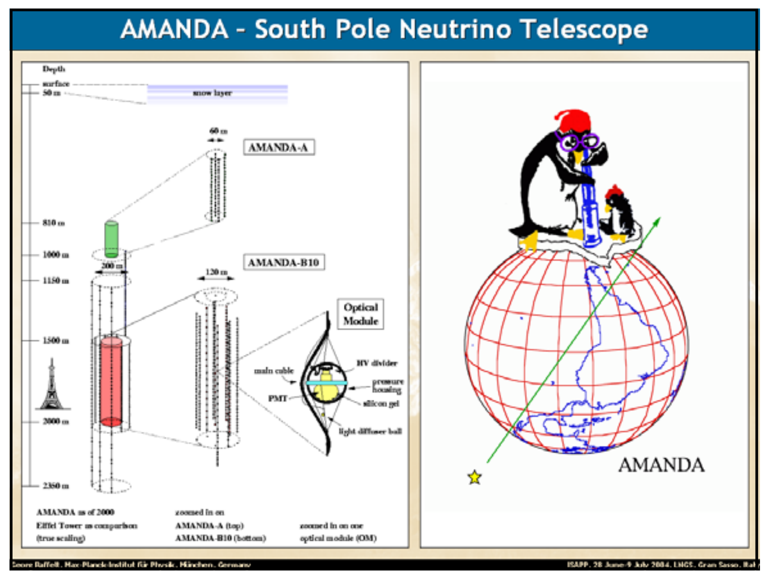

Recent Picture of CAST

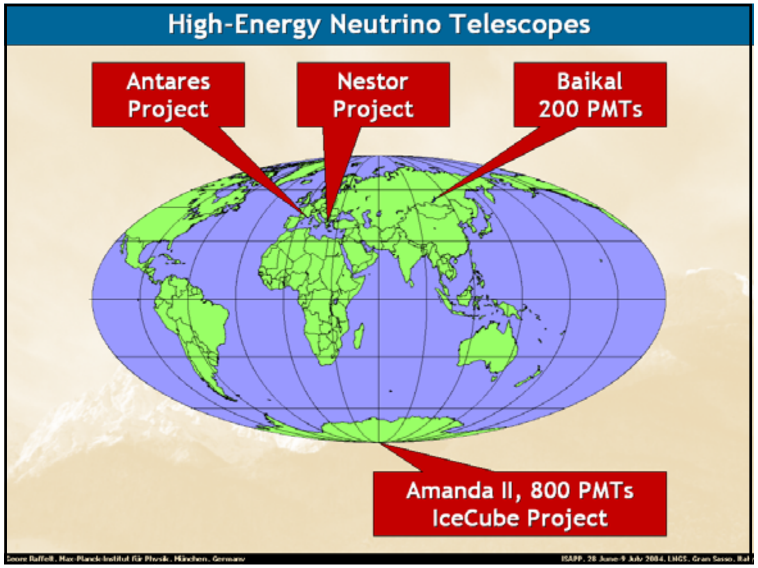

Search for Neutralino Dark Matter
Direct Method (Laboratory Experiments)
Galactic dark matter particle (e.g.neutralino)
Crystal
Energy deposition
Recoil energy (few keV) is measured by
• Ionisation
• Scintillation
• Cryogenic
Indirect Method (Neutrino Telescopes)
Galactic dark matter particles are accreted
Annihilation
Sun
High-energy neutrinos (GeV-TeV) can be measured

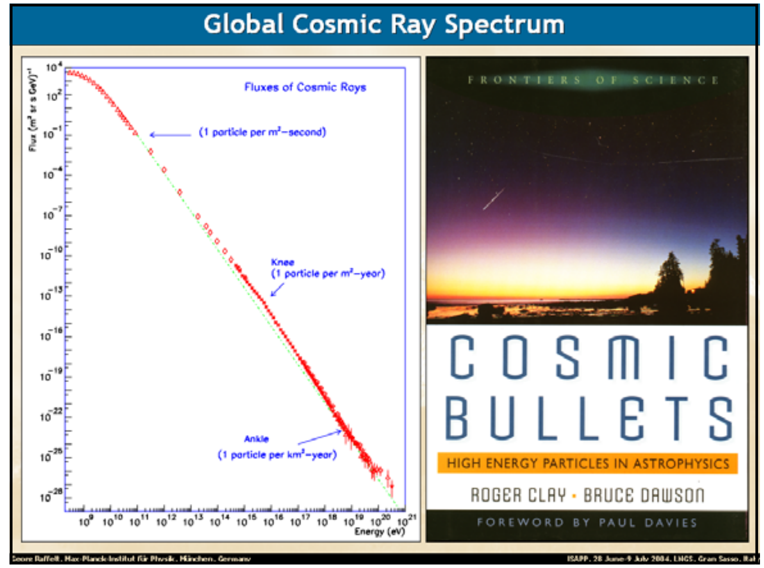

Muon Flux from WIMP Annihilation in the Sun
L. Bergström, J. Edsjö and P. Gondolo, 1998
$E_\mu^{th} = 1$ GeV
$\sigma_{SI} > \sigma_{SI}^{lim}$
$\sigma_{SI}^{lim} > \sigma_{SI} > 0.1\sigma_{SI}^{lim}$
$0.1\sigma_{SI}^{lim} > \sigma_{SI}$
BAKSAN 97
Sun bkg
Muon flux from the Sun (km^{-2} yr^{-1})
Neutralino Mass (GeV)
Need a km^3 water Cherenkov detector to reach solar background

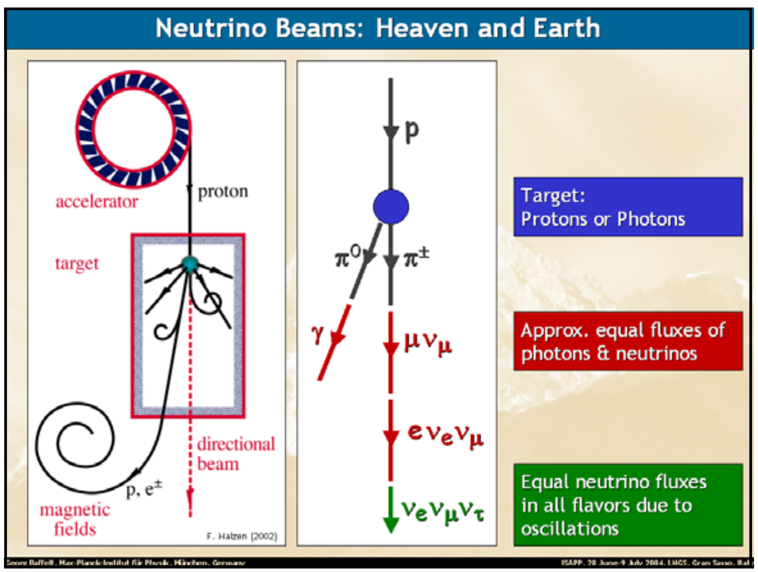

AMANDA - South Pole Neutrino Telescope
Depth
surface
50 m
snow layer
AMANDA-A
AMANDA-B10
Optical Module
810 m
1000 m
1150 m
1500 m
2000 m
2350 m
main cable
HV divider
pressure housing
PMT
silicon gel
light diffuser ball
AMANDA as of 2000
Eiffel Tower as comparison (true scaling)
zoomed in on AMANDA-A (top) AMANDA-B10 (bottom)
zoomed in on one optical module (OM)

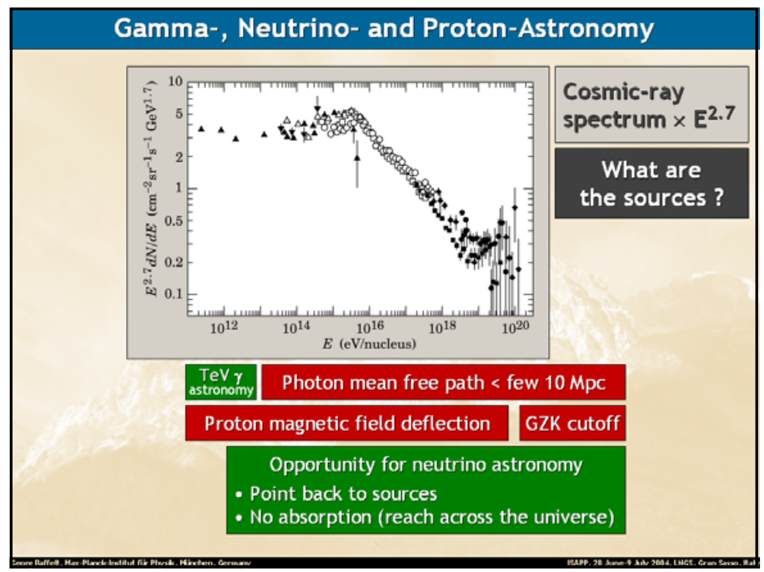

AMANDA - South Pole Neutrino Telescope
Depth
surface
50 m
snow layer
AMANDA-A
AMANDA-B10
Optical Module
810 m
1000 m
1150 m
1500 m
2000 m
2350 m
main cable
HV divider
pressure housing
PMT
silicon gel
light diffuser ball
AMANDA as of 2000
Eiffel Tower as comparison (true scaling)
zoomed in on AMANDA-A (top) AMANDA-B10 (bottom)
zoomed in on one optical module (OM)


AMANDA - South Pole Neutrino Telescope
Depth
surface
50 m
snow layer
AMANDA-A
AMANDA-B10
Optical Module
810 m
1000 m
1150 m
1500 m
2000 m
2350 m
main cable
HV divider
pressure housing
PMT
silicon gel
light diffuser ball
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


High-Energy Neutrino Telescopes
Antares Project
Nestor Project
Baikal 200 PMTs
Amanda II, 800 PMTs IceCube Project
Georg Raffelt, Max-Planck-Institut für Physik, München, Germany
ISAPP, 28 June–9 July 2004, LNGS, Gran Sasso, Italy


Global Cosmic Ray Spectrum
Fluxes of Cosmic Rays
(1 particle per m²–second)
Knee
(1 particle per m²–year)
Ankle
(1 particle per km²–year)
Energy (eV)
FRONTIERS OF SCIENCE
COSMIC BULLETS
HIGH ENERGY PARTICLES IN ASTROPHYSICS
ROGER CLAY · BRUCE DAWSON
FOREWORD BY PAUL DAVIES


Neutrino Beams: Heaven and Earth
accelerator
proton
target
directional beam
magnetic fields
p, e±
F. Halzen (2002)
p
π⁰
π±
γ
μ ν_μ
e ν_e ν_μ
ν_e ν_μ ν_τ
Target: Protons or Photons
Approx. equal fluxes of photons & neutrinos
Equal neutrino fluxes in all flavors due to oscillations


Gamma-, Neutrino- and Proton-Astronomy
E^2.7 dN/dE (cm⁻² sr⁻¹ s⁻¹ GeV^1.7)
E (eV/nucleus)
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)

High-Energy Neutrinos from the Sun

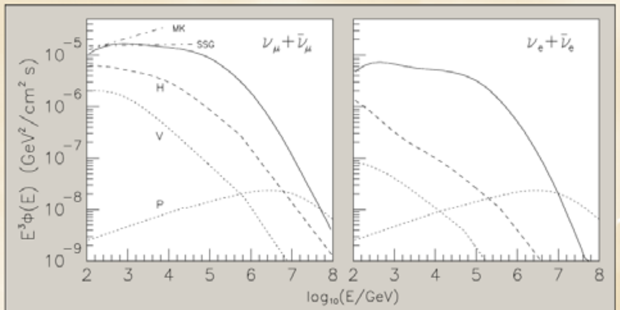


Figure 4: *Cosmic ray induced E^3-weighted neutrino fluxes at the Earth integrated over the solid angle of the Sun. The fluxes from the Sun obtained in this study (solid lines) are compared with the earlier calculation SSG [22] and the one MK derived from [2], as well as those from the Earth's atmosphere as calculated for the vertical flux (curve V) [1], the horizontal flux (curve H) [21], and the prompt charm-induced flux (curve P) [1].*

Ingelman & Thunman, High Energy Neutrino Production by Cosmic Ray Interactions in the Sun [hep-ph/9604288]

Solar Neutrinos

Thermal plasma reactions
E ~ 1 eV - 30 keV
No apparent way to measure

Nuclear burning reactions
E ~ 0.1 - 15 MeV
Routine detailed measurements

Cosmic-ray interactions in the Sun
E ~ 10 - 10^9 GeV
Future high-E neutrino telescopes (?)

Dark matter annihilation in the Sun
E ~ GeV - TeV (?)
Future high-E neutrino telescopes (?)

Cosmological Limit on Neutrino Masses

Cosmic neutrino "sea" ~ 115 cm^{-3} neutrinos + anti-neutrinos per flavor

$$\Omega_\nu h^2 = \sum \frac{m_\nu}{92.5\,\text{eV}} < 0.4$$

$m_\nu \lesssim 40$ 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/c² for the electronic neutrino and $m(\nu_\mu) < 2.5 \times 10^6$ eV/c² for the muonic neutrino. Cosmological considerations connected with the hot model of the Universe [2] make it possible to strengthen greatly the second inequality. Just as in the paper by Ya. B. Zel'dovich and Ya. A. Smorodinskii [3], let us consider the gravitational effect of the neutrinos on the dynamics of the expanding Universe. The age of the known astronomical objects is not smaller than 5×10^9 years, and Hubble's constant H is not smaller than 75 km/sec-Mparsec = $(13 \times 10^9$ years$)^{-1}$. It follows therefore that the density of all types of matter in the Universe is at the present time [1])

$\rho < 2 \times 10^{-28}$ g/cm³.

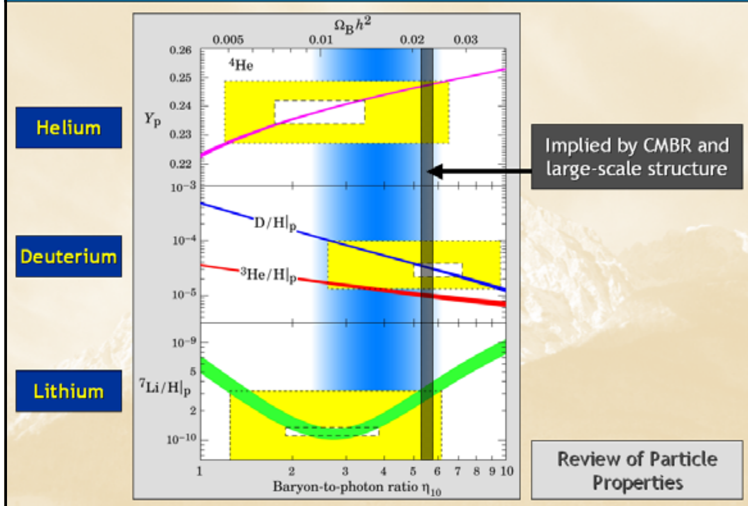
Neutrino Mass Limits from Large-Scale Structure

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 ± 0.08, Ω_M = 0.28 ± 0.14

Georg Raffelt, Max-Planck-Institut für Physik, München, Germany — ISAPP, 28 June-9 July 2004, LNGS, Gran Sasso, Italy

BBN Concordance



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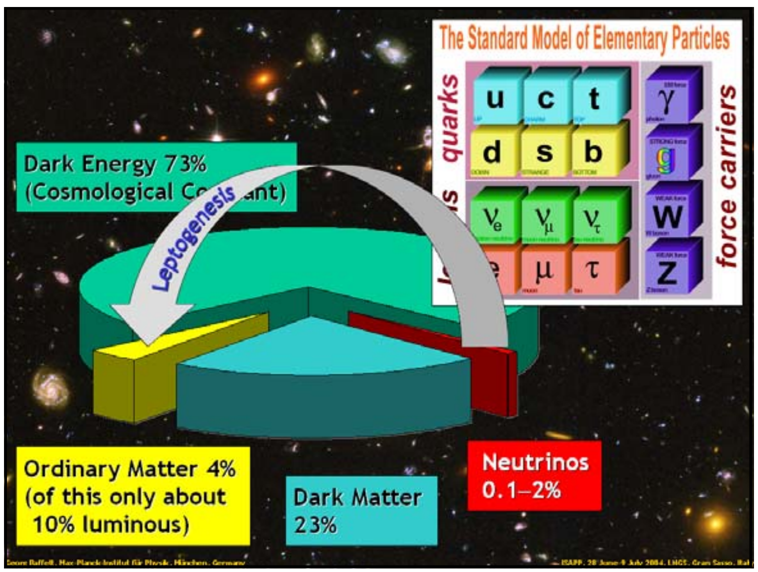

Neutrinos in Astrophysics and Cosmology

Neutrinos responsible for ordinary astrophysical and cosmological phenomena	• Dominant radiation component in the early universe • Crucial role in big-bang nucleosynthesis • Dark-matter component (but subdominant) • May be responsible for baryonic matter in the universe (leptogenesis) • Important (sometimes dominant) cooling agent of stars • May trigger supernova explosions • May be crucial for r-process nucleosynthesis
Heavenly laboratories for new particle physics phenomena	• Cosmological limit (future detection?) of nu mass scale • Flavor oscillations of solar and atmospheric neutrinos • Neutrino oscillations from a future galactic supernova • Limits on "exotic" neutrino properties (dipole moments, right-handed interactions, decays, flavor-violating neutral currents, sterile nus, ...)
Neutrinos as astrophysical messengers	• Look into the solar interior ("measure" temperature) • Watch stellar collapse directly • Neutrinos from all cosmological supernovae • Astrophysical accelerators for cosmic rays • Annihilation signature for neutralino dark matter

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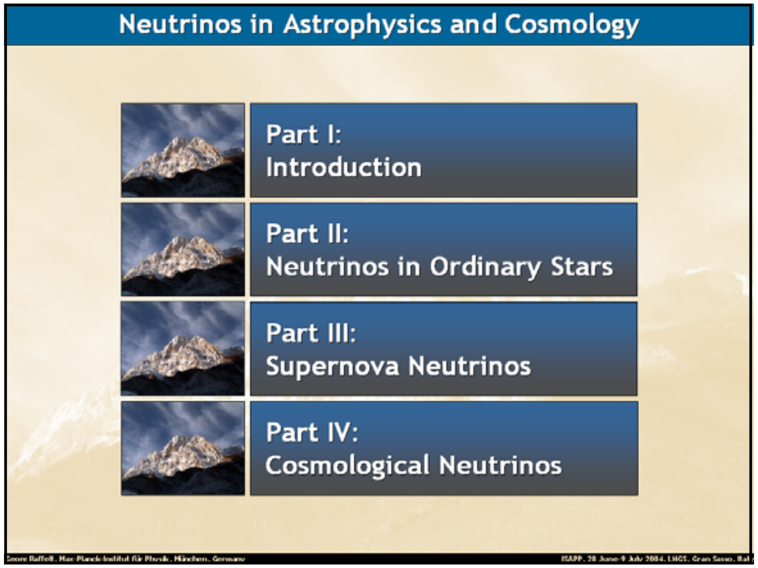
Neutrinos in Astrophysics and Cosmology
Part I:
Introduction
Part II:
Neutrinos in Ordinary Stars
Part III:
Supernova Neutrinos
Part IV:
Cosmological Neutrinos
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