

Astrophysical Neutrinos



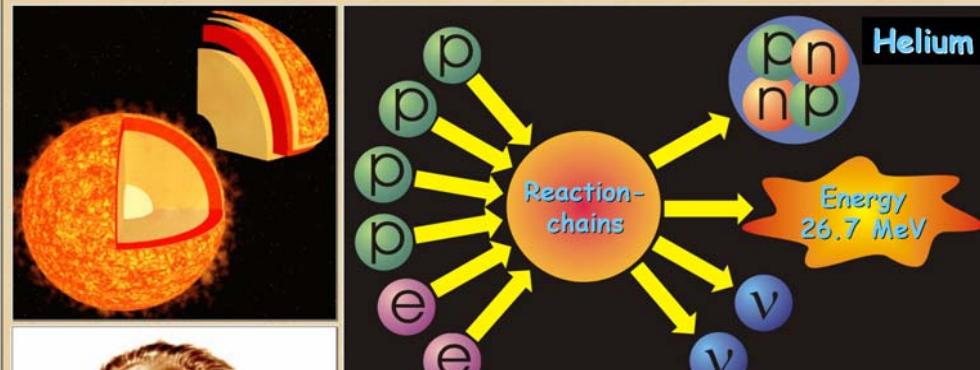
Where do Neutrinos Appear in Nature?

<input checked="" type="checkbox"/> Nuclear Reactors			Sun
<input checked="" type="checkbox"/> Particle-Accelerators			Supernovae (Stellar Collapse) SN 1987A <input checked="" type="checkbox"/>
<input checked="" type="checkbox"/> Earth Atmosphere (Cosmic Rays)			Astrophysical Accelerators Soon ?
<input checked="" type="checkbox"/> Earth Crust (Natural Radioactivity)			Cosmic Big Bang (Today 330 v/cm^3) Indirect Evidence
2003 ?			

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

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Neutrinos from the Sun



**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

MARCH 1, 1939 PHYSICAL REVIEW VOLUME 55

Energy Production in Stars*

H. A. BETHE
Cornell University, Ithaca, New York
(Received September 7, 1938)

It is shown that the most important source of energy in ordinary stars is the reaction of carbon and nitrogen with protons. These reactions form a cycle in which the original nucleus is reproduced, $\text{C}^1 + \text{H} = \text{N}^2$, $\text{N}^2 + \text{H} = \text{C}^1 + e^-$, $\text{C}^1 + \text{H} = \text{D}^2 + e^-$, $\text{D}^2 + \text{H} = \text{He}^3$. In the center of the main sequence, the reaction $\text{H} + \text{H} = \text{D} + e^-$ and the reactions following it, are believed to be mainly responsible for the energy production.

It is shown further (§§6) that no elements heavier than Helium can be built up in ordinary stars. This is due to the fact, mentioned above, that all elements up to boron are directly produced by the proton-proton reaction (§§1-5) and that those built up (by radiative capture), the formation of Be^7 reduces the formation of heavier elements still further. The same applies to the formation of B^11 and Li^7 . The heavier elements found in stars must therefore have existed already when the star was formed.

The theory of the carbon-nitrogen reactions with observational data (§7, 9) is excellent. In order to give the correct energy evolution in the sun, the central temperature of the sun would have to be 18.3 million degrees while

§1. INTRODUCTION

The progress of nuclear physics in the last few years makes it possible to decide rather definitely which processes can and cannot occur in the interior of stars. Such decisions will be attempted in the present paper; the discussion being limited primarily to main sequence stars. The results will be at variance with some current hypotheses.

The first main result is that, under present conditions, no elements heavier than helium can be built up to any appreciable extent. Therefore we are limited to the formation of elements which were built up before the stars reached their present state of temperature and density. No attempt will be made at speculations about this previous state of stellar matter.

The energy production of stars is then due entirely to the combination of four protons and two electrons to form two deuterons with positron emission, $\text{H} + \text{H} = \text{D} + e^+$.

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:

$\text{C}^12 + \text{H} = \text{N}^{13} + \gamma, \quad \text{N}^{13} + \text{C}^12 + \text{e}^+ \rightarrow \text{C}^{13} + \text{N}^{14} + \gamma,$
 $\text{C}^{13} + \text{H} = \text{O}^{14} + \gamma, \quad \text{O}^{14} + \text{C}^{13} + \text{e}^+ \rightarrow \text{N}^{15} + \text{He}^4,$
 $\text{N}^{15} + \text{H} = \text{C}^{12} + \text{He}^4.$

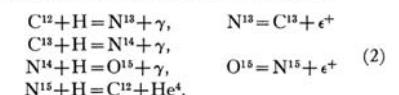
The catalyst C^{12} is reproduced in all cases except one in 10,000, therefore the abundance of C^{12} is not affected. The total energy released is changed (in comparison with the change of the number of protons). The two reactions (1) and

No neutrinos from nuclear reactions in 1938 ...

The combination of four protons and two electrons can occur essentially only in two ways. The first mechanism starts with the combination of two protons to form a deuteron with positron emission, *viz.*



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



Sun Glasses for Neutrinos?



1000 light years of lead
needed to shield solar
neutrinos

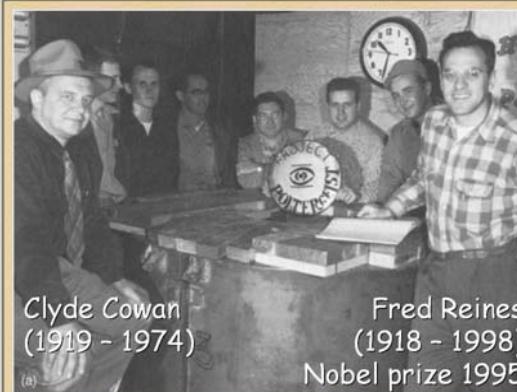


Bethe & Peierls 1934:
"... this evidently means
that one will never be able
to observe a neutrino."

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First Detection (1954 - 1956)

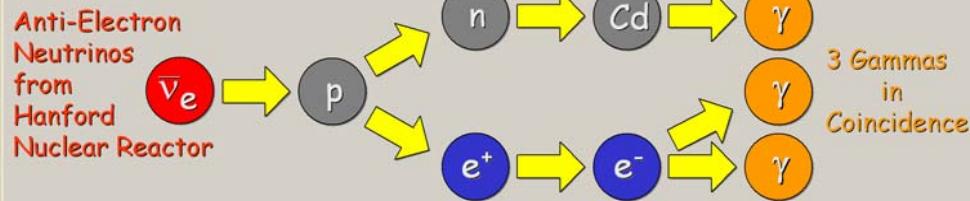


Clyde Cowan
(1919 - 1974)

Fred Reines
(1918 - 1998)
Nobel prize 1995



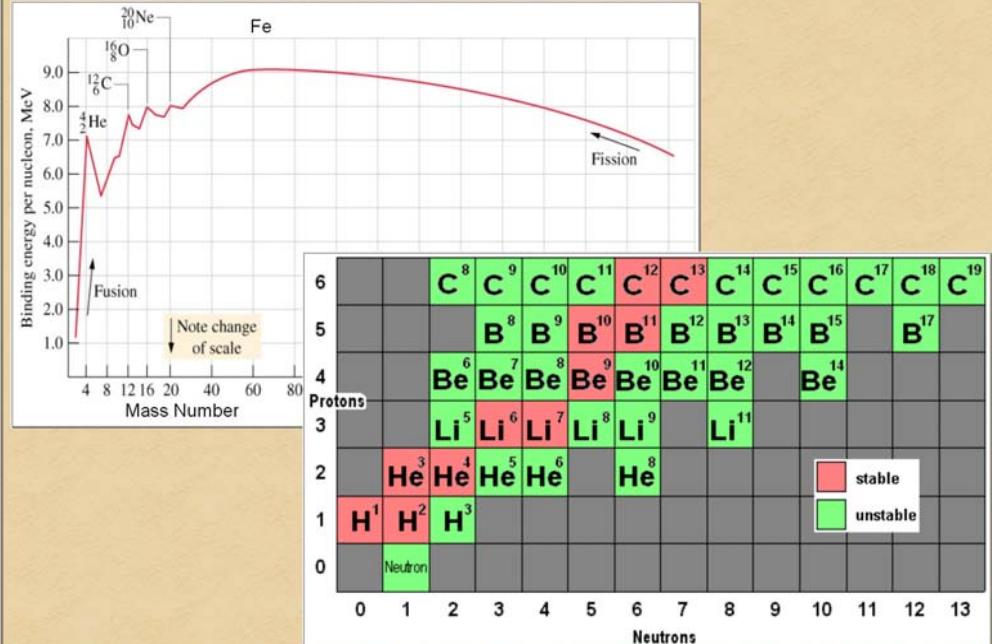
(b) Detector prototype



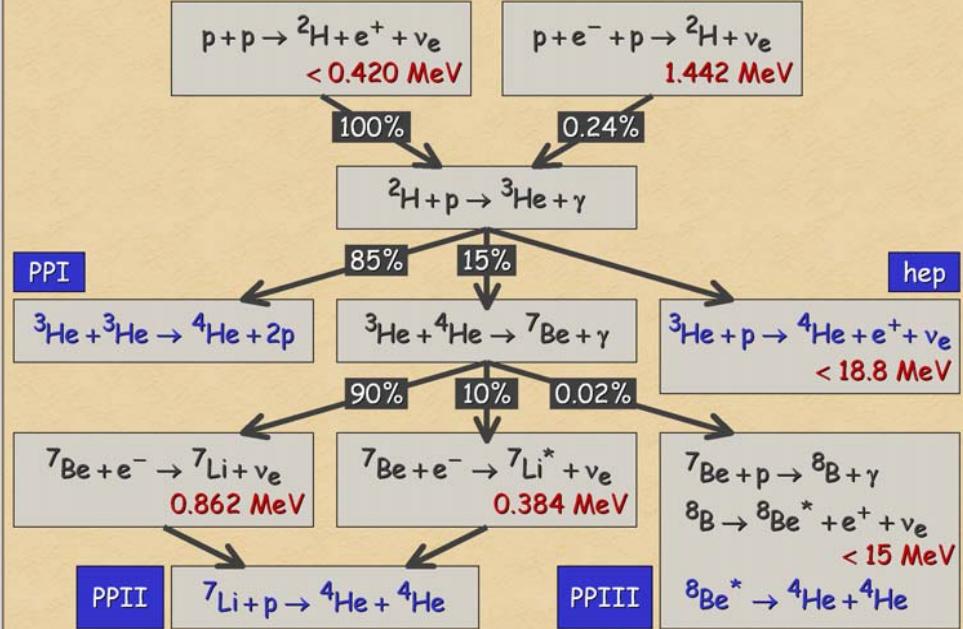
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Nuclear Binding Energy



Hydrogen burning: Proton-Proton Chains



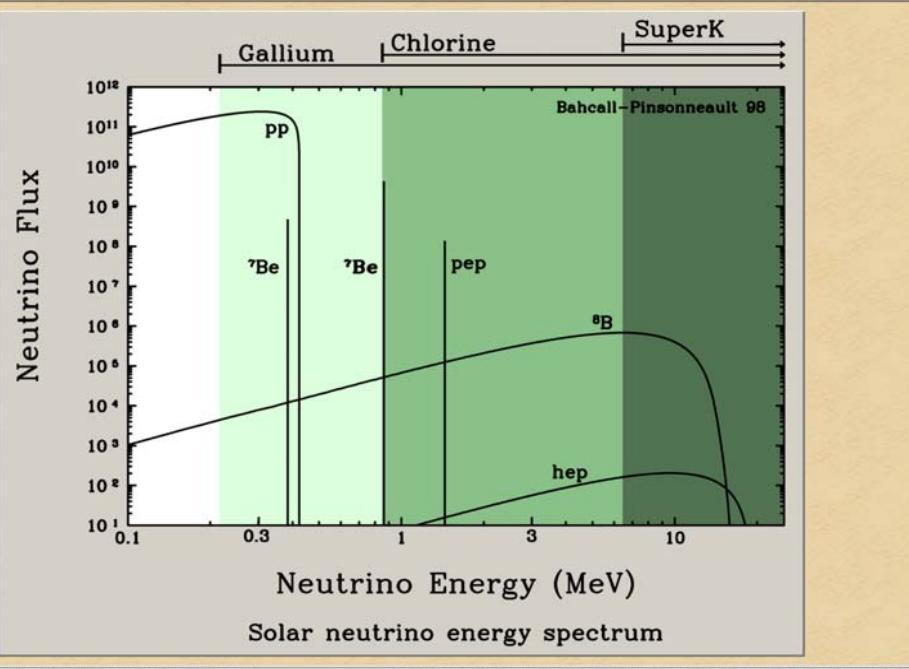
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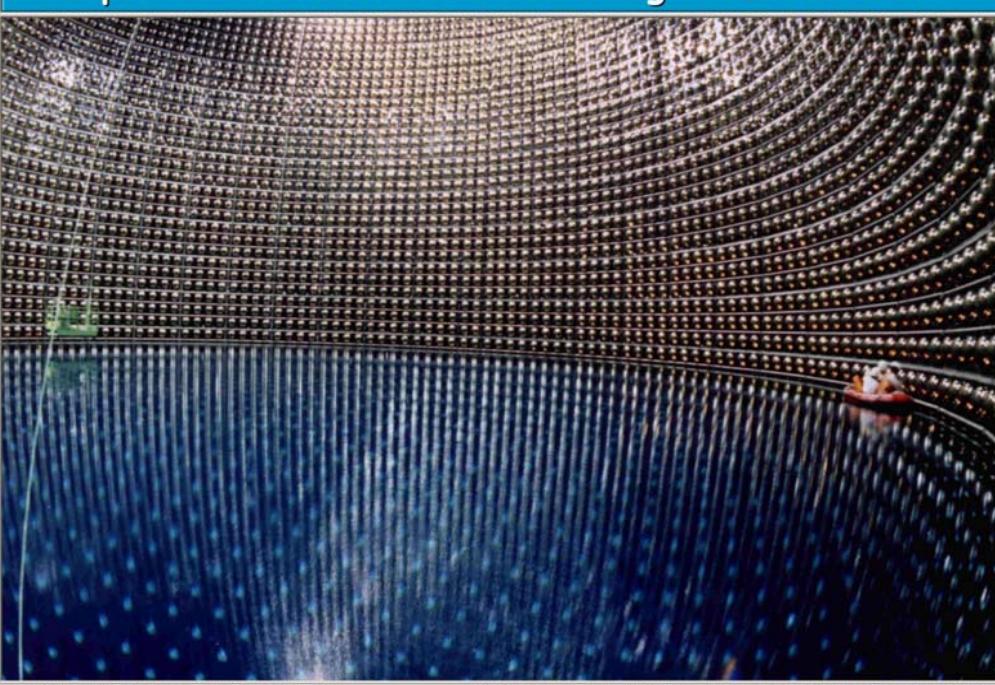
Solar Neutrino Spectrum



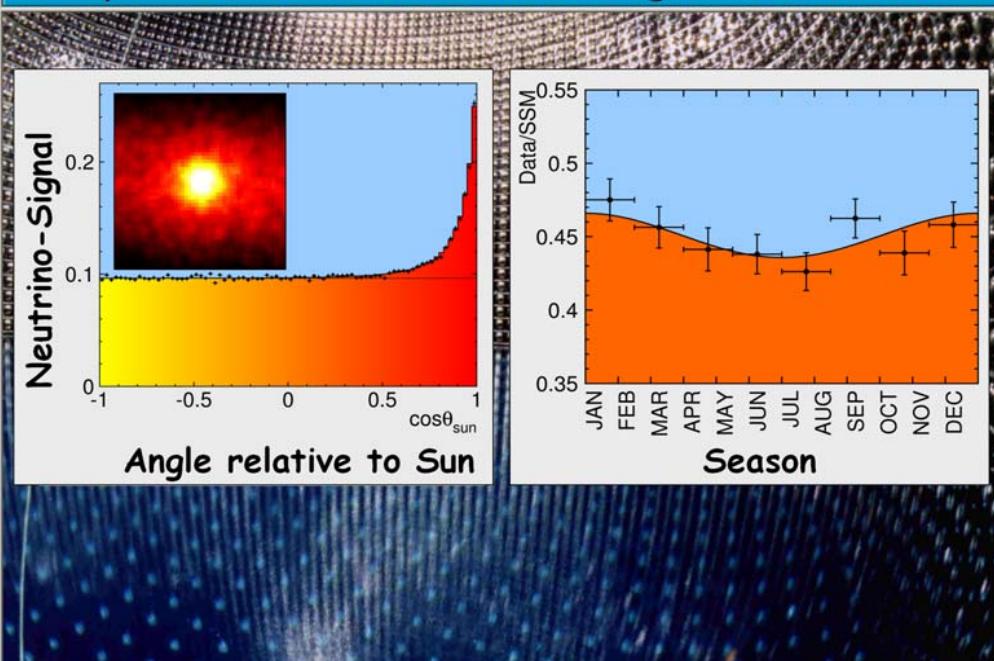
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Super-Kamiokande: Sun in the Light of Neutrinos



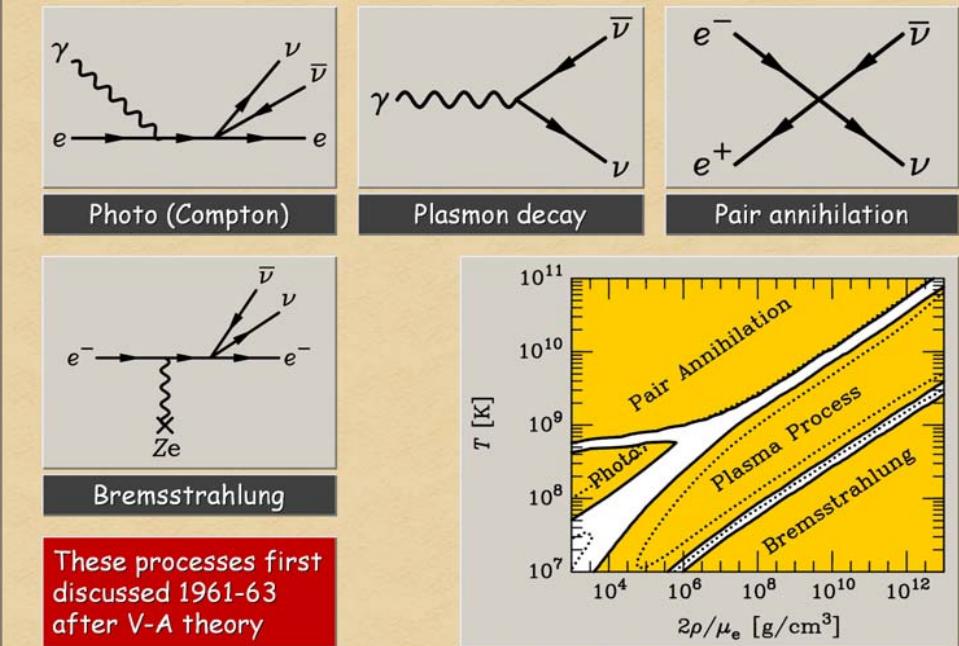
Super-Kamiokande: Sun in the Light of Neutrinos



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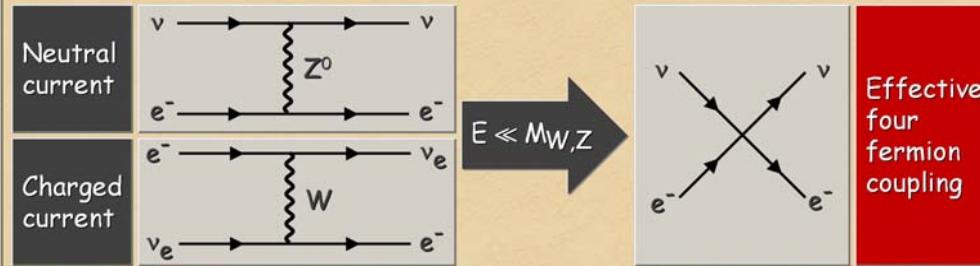
Neutrinos from Thermal Plasma Processes



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Effective Neutrino Neutral-Current Couplings



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

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

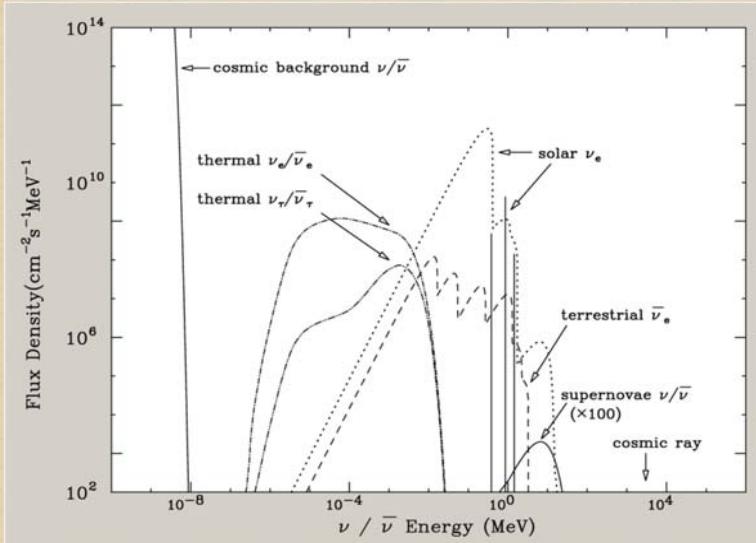
$$G_F = 1.166 \times 10^{-5} \text{ GeV}^{-2}$$

$$\sin^2 \Theta_W = 0.231$$

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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

Solar Neutrinos from Compton Process

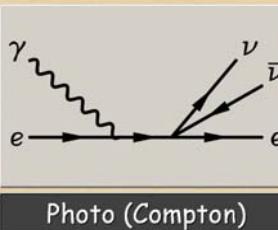


Photo (Compton)

Cross section in non-relativistic limit

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

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

Volume energy loss rate

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

Energy loss rate per unit mass

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

To be compared with nuclear energy generation in the Sun

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

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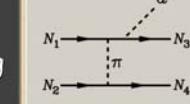
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Axion or Graviton Emission Processes in Stars

Nucleons

$$\frac{C_N}{2f_a} \bar{\Psi}_N \gamma_\mu \gamma_5 \Psi_N \partial^\mu a$$

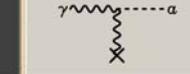
Nucleon Bremsstrahlung



Photons

$$\frac{C_e}{2f_a} \bar{\Psi}_e \gamma_\mu \gamma_5 \Psi_e \partial^\mu a$$

Primakoff



Electrons

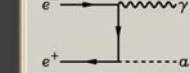
$$C_\gamma \frac{\alpha}{2\pi f_a} \frac{1}{4} F_{\mu\nu} \tilde{F}^{\mu\nu} a$$

$$= -C_\gamma \frac{\alpha}{2\pi f_a} \vec{E} \cdot \vec{B} a$$

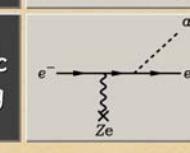
Compton



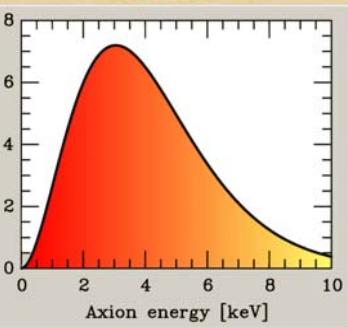
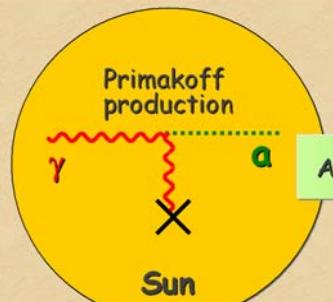
Pair Annihilation



Electromagnetic Bremsstrahlung



Search for Solar Axions



Axion Helioscope (Sikivie 1983)

Axion-Photon-Oscillation



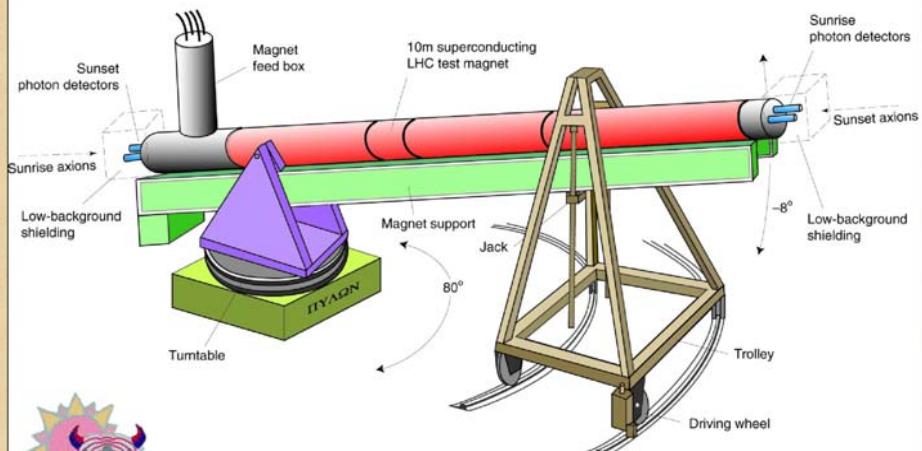
- Tokyo Axion Helioscope (Results since 1998)
- CERN Axion Solar Telescope (CAST) (just started)

Alternative Technique:
Bragg conversion in crystal
Experimental limits on solar axion flux from dark-matter experiments (SOLAX, COSME, DAMA, ...)

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Horizontally Moving Platform



Cern Axion Solar Telescope

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Recent Picture of CAST



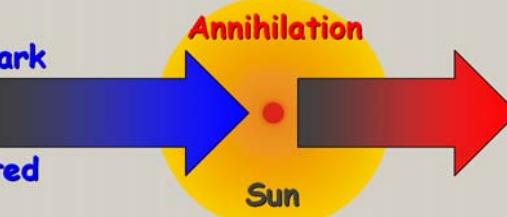
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COSMO 02, Chicago (18-21 September 2002)

Search for Neutralino Dark Matter

Indirect Method (Neutrino Telescopes)

Galactic dark matter particles are accreted



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

Direct Method (Laboratory Experiments)

Galactic dark matter particle (e.g. neutralino)



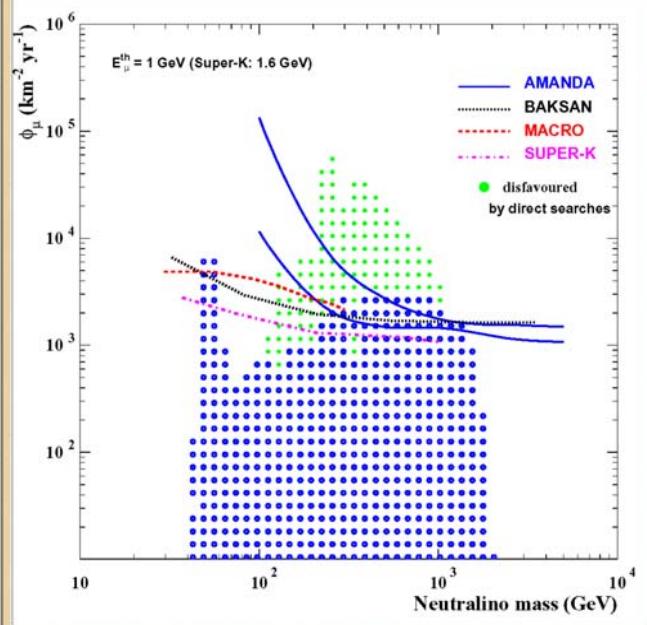
Recoil energy (few keV) is measured by

- Ionisation
- Scintillation
- Cryogenic

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Current Limits from WIMP Searches

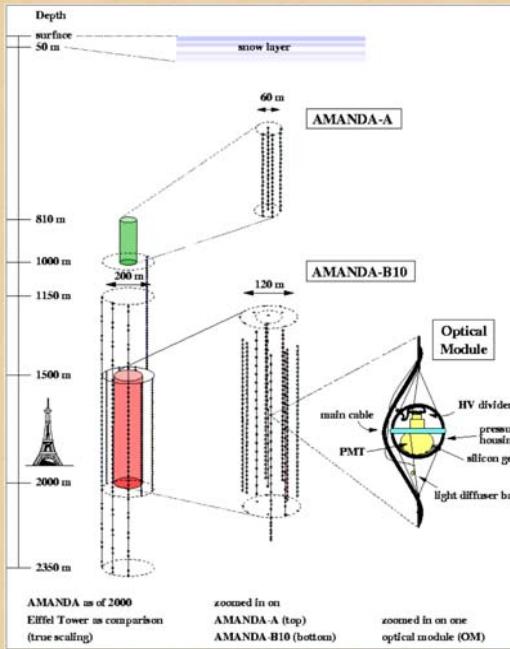


Limits from WIMP Annihilation in the Earth
astro-ph/0202370

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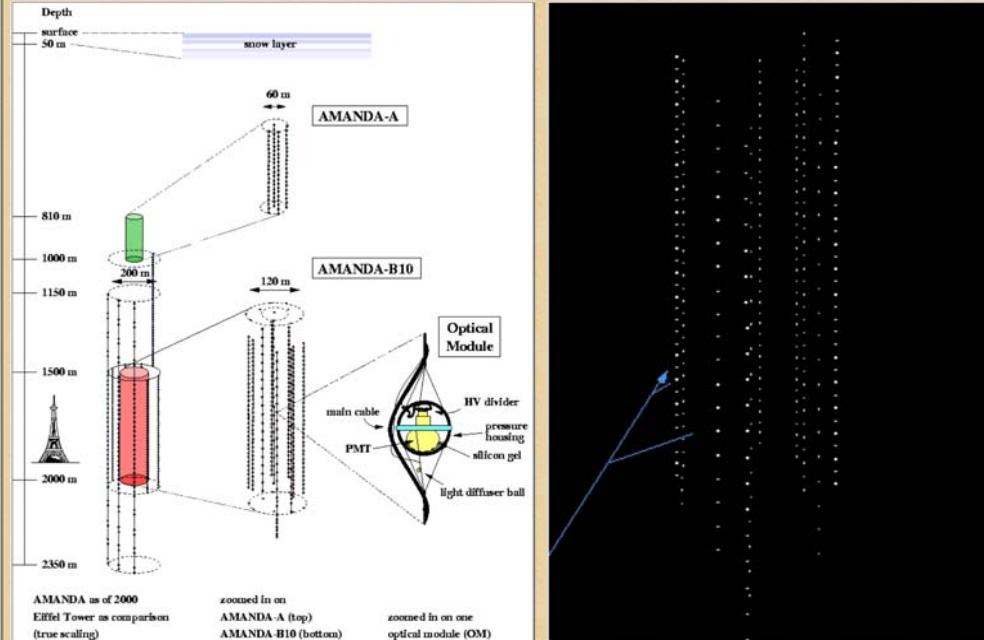
AMANDA - South Pole Neutrino Telescope



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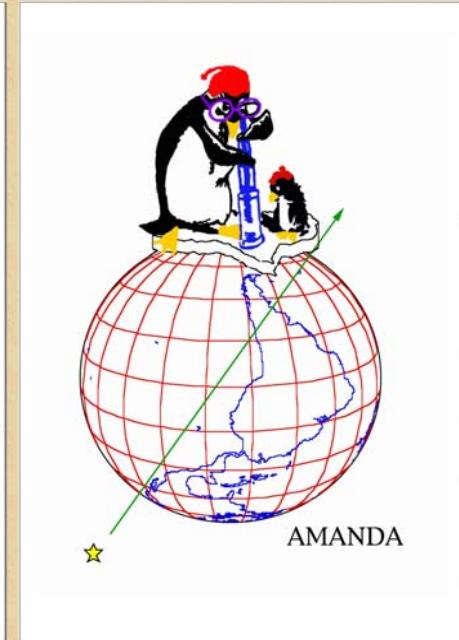
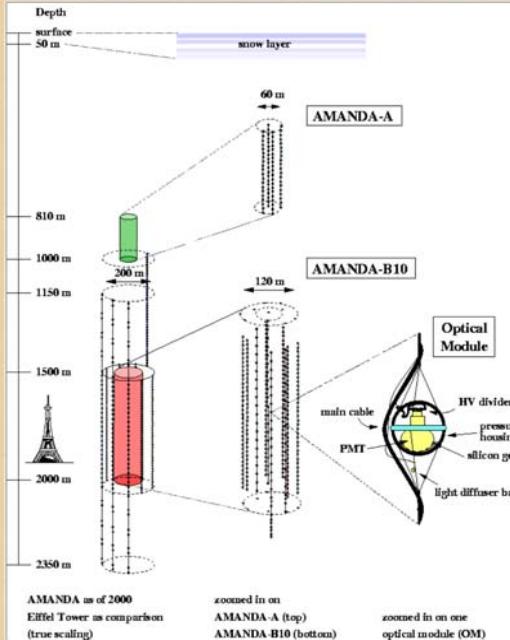
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AMANDA - South Pole Neutrino Telescope



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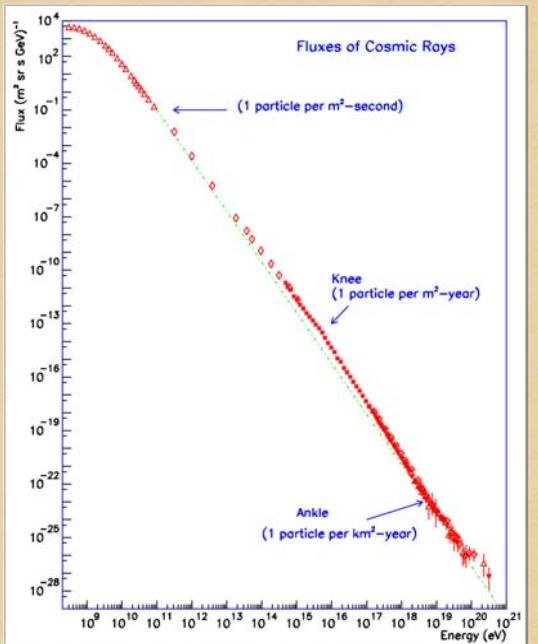
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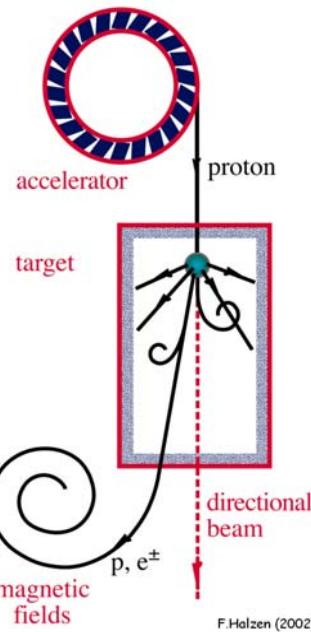
Global Cosmic Ray Spectrum



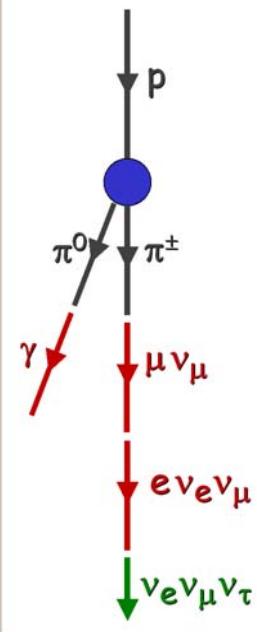
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Neutrino Beams: Heaven and Earth



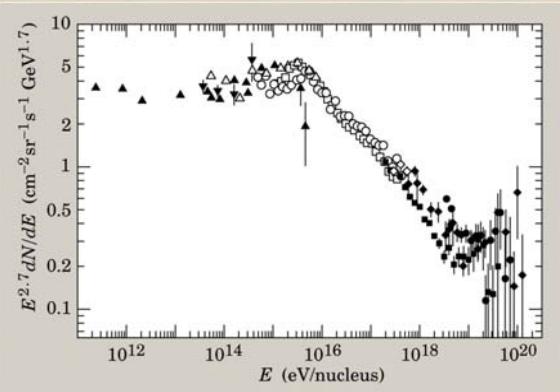
Target:
Protons or Photons



Approx. equal fluxes of
photons & neutrinos

Equal neutrino fluxes
in all flavors due to
oscillations

Gamma-, Neutrino- and Proton-Astronomy



Cosmic-ray
spectrum $\times E^{2.7}$

What are
the sources?

TeV γ astronomy

Photon mean free path < few 10 Mpc

Proton magnetic field deflection

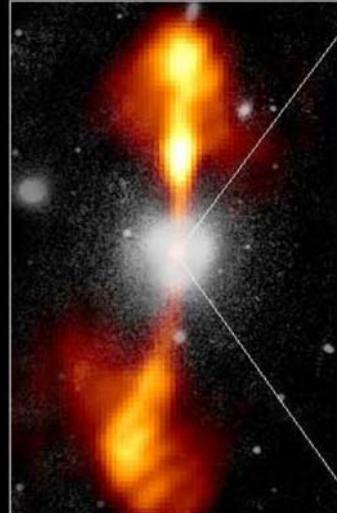
GZK cutoff

Opportunity for neutrino astronomy

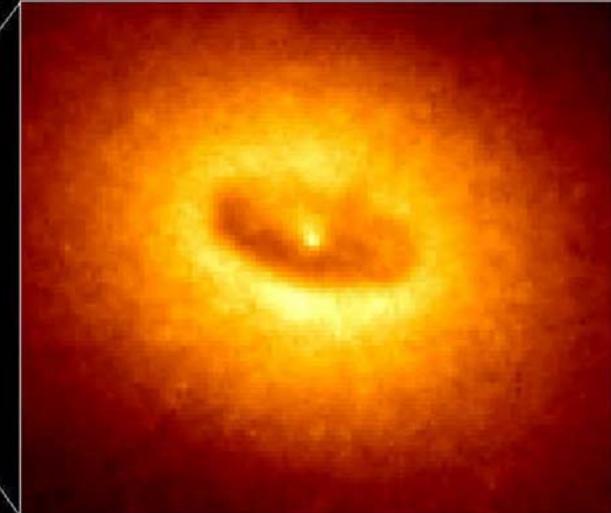
- Point back to sources
- No absorption (reach across the universe)

Core of the Galaxy NGC 4261

Ground-Based Optical/Radio Image



HST Image of a Gas and Dust Disk



High-Energy Neutrinos from the Sun

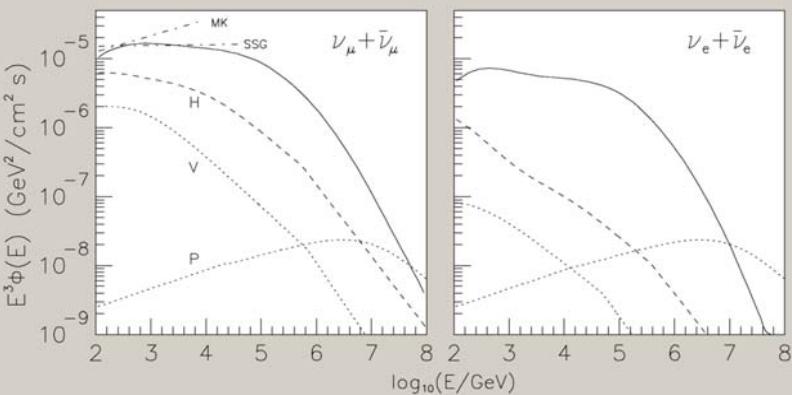


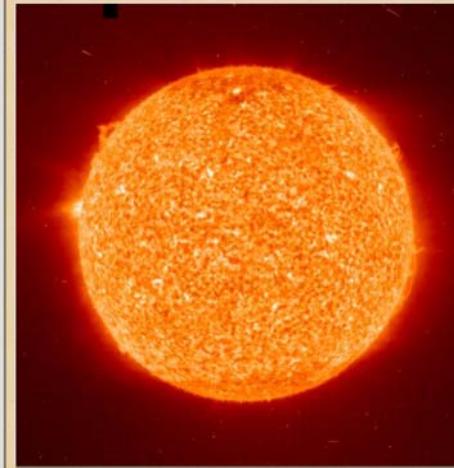
Figure 4: Cosmic ray induced E^3 -weighted neutrino fluxes at the Earth integrated over the solid angle of the Sun. The fluxes from the Sun obtained in this study (solid lines) are compared with the earlier calculation SSG [22] and the one MK derived from [2], as well as those from the Earth's atmosphere 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, Phys. Rev. D 54 (1996) 4385 [hep-ph/9604288]

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Solar Neutrinos



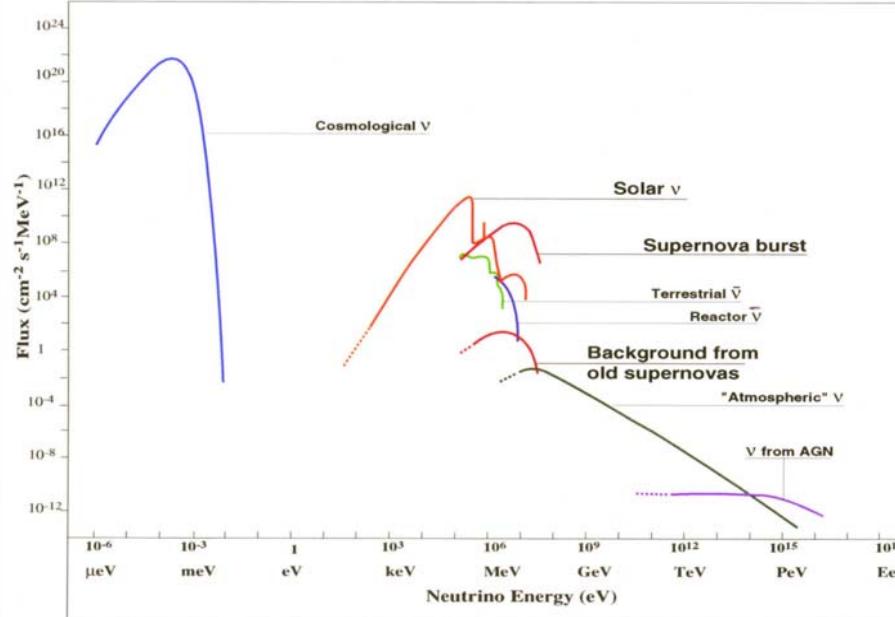
Thermal plasma reactions
 $E \sim 1 \text{ eV} - 30 \text{ keV}$
 No apparent way to measure

Nuclear burning reactions
 $E \sim 0.1 - 15 \text{ MeV}$
 Routine detailed measurements

Cosmic-ray interactions in the Sun
 $E \sim 10 - 10^9 \text{ GeV}$
 Future high-E neutrino telescopes (?)

Dark matter annihilation in the Sun
 $E \sim \text{GeV} - \text{TeV} (?)$
 Future high-E neutrino telescopes (?)

Astrophysical Neutrino Fluxes



Neutrinos in Astrophysics and Cosmology

Neutrinos responsible for astrophysical and cosmological phenomena

- Dominant radiation component in early universe
- Crucial role in big-bang nucleosynthesis
- Dark-matter component (but subdominant)
- May be responsible for baryonic matter in the universe (leptogenesis)
- Important/dominant cooling agent of stars
- May trigger supernova explosions
- May be crucial for r-process nucleosynthesis

Heavenly laboratories for particle physics

- Cosmological limit on neutrino mass scale
- Flavor oscillations of solar neutrinos
- Neutrino oscillations of 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

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