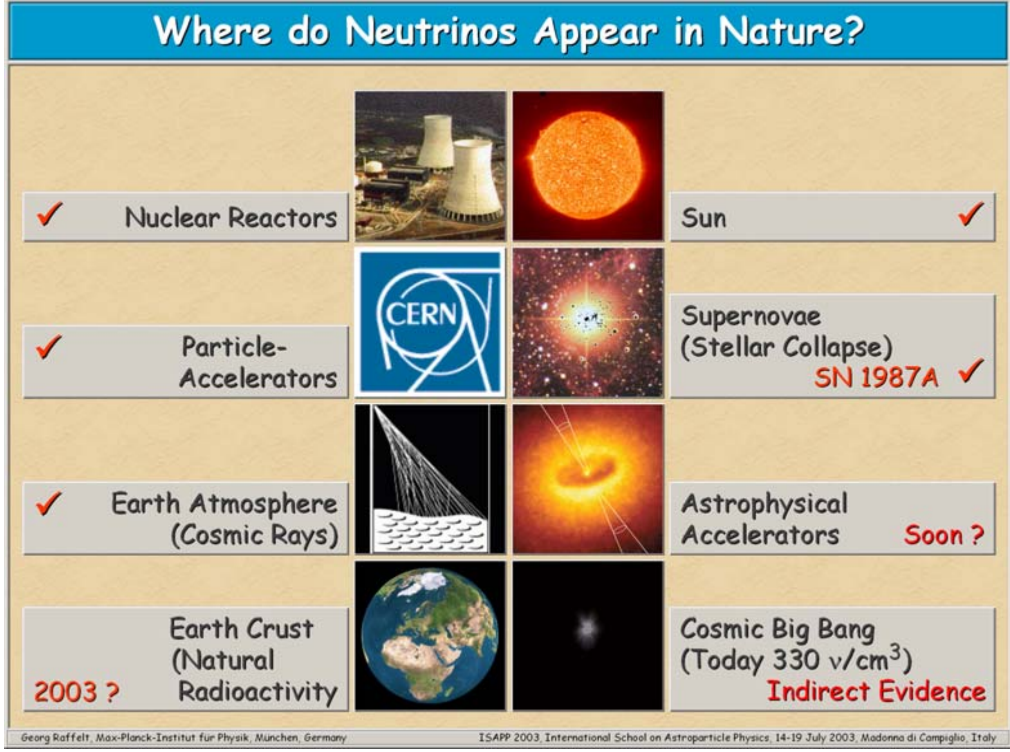

ISAPP 2003, International School on Astroparticle Physics
European Doctorate School, 14-19 July 2003, Madonna di Campiglio, Italy
Astrophysical Neutrinos
Georg G. Raffelt
Max-Planck-Institut für Physik, München, Germany


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 2003 ?
Cosmic Big Bang (Today 330 ν/cm³) Indirect Evidence
Georg Raffelt, Max-Planck-Institut für Physik, München, Germany
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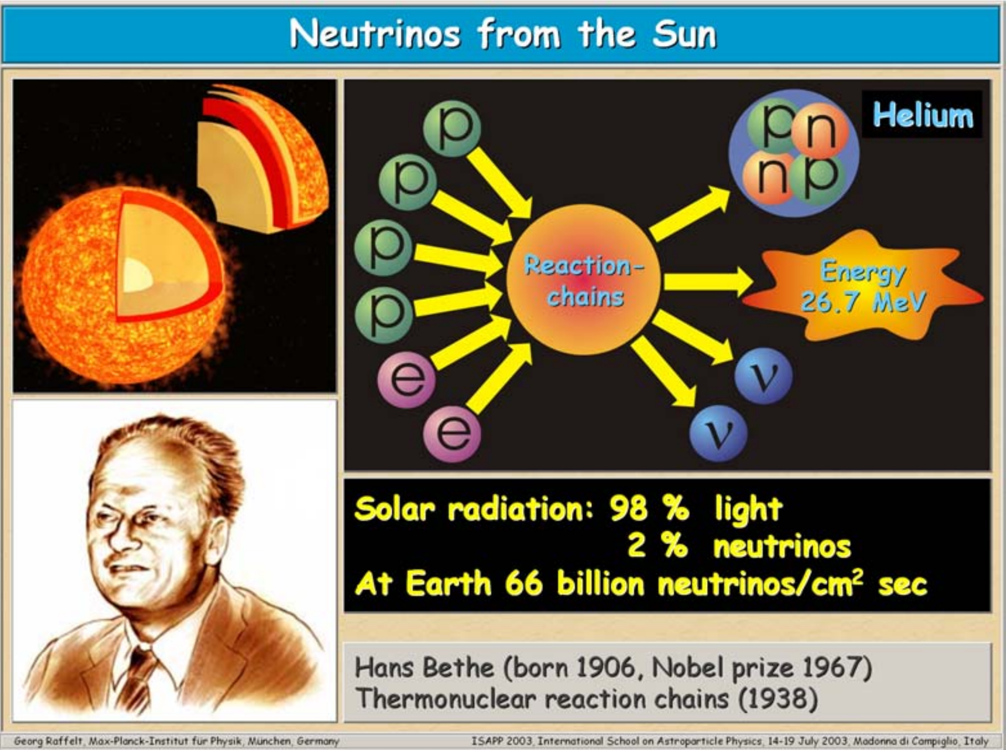
Neutrinos from the Sun
p
p
p
p
e
e
Helium
p n
n p
Reaction-chains
Energy 26.7 MeV
ν
ν
Solar radiation: 98 % light
2 % neutrinos
At Earth 66 billion neutrinos/cm² sec
Hans Bethe (born 1906, Nobel prize 1967)
Thermonuclear reaction chains (1938)
Georg Raffelt, Max-Planck-Institut für Physik, München, Germany
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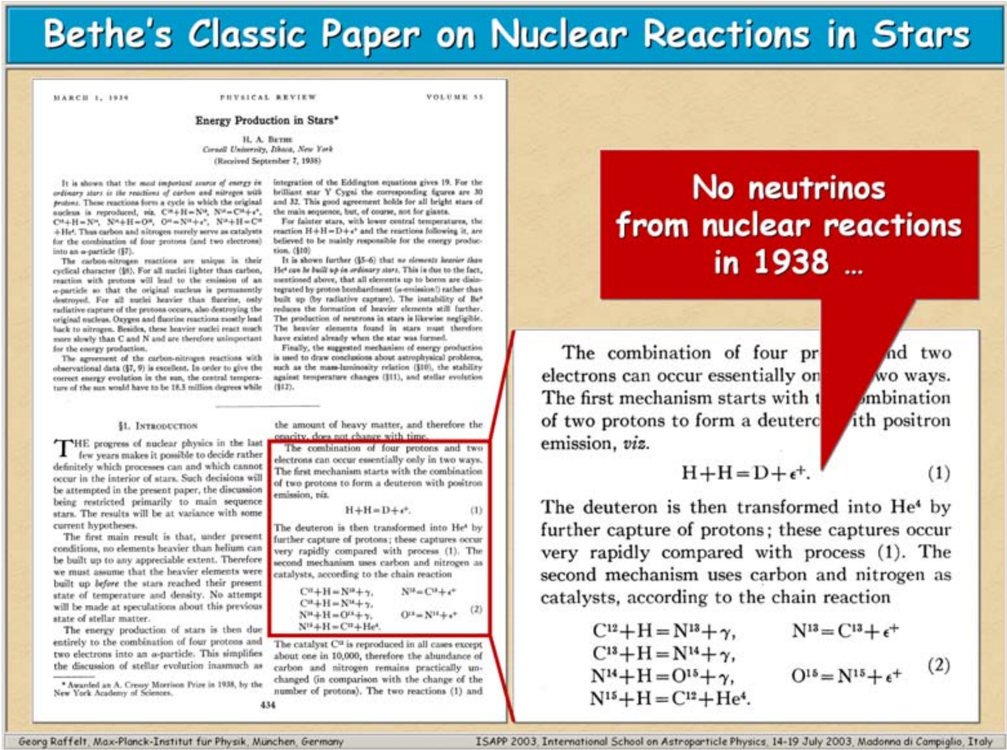
Bethe's Classic Paper on Nuclear Reactions in Stars
MARCH 1, 1939 PHYSICAL REVIEW VOLUME 55
Energy Production in Stars*
H. A. Bethe
Cornell University, Ithaca, New York
(Received September 7, 1938)
No neutrinos from nuclear reactions in 1938 ...
The combination of four pr nd two electrons can occur essentially on wo ways. The first mechanism starts with t ombination of two protons to form a deuterc ith positron emission, viz.
H+H=D+ε⁺. (1)
The deuteron is then transformed into He⁴ 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
C¹²+H=N¹³+γ, N¹³=C¹³+ε⁺
C¹³+H=N¹⁴+γ,
N¹⁴+H=O¹⁵+γ, O¹⁵=N¹⁵+ε⁺ (2)
N¹⁵+H=C¹²+He⁴.
Georg Raffelt, Max-Planck-Institut für Physik, München, Germany
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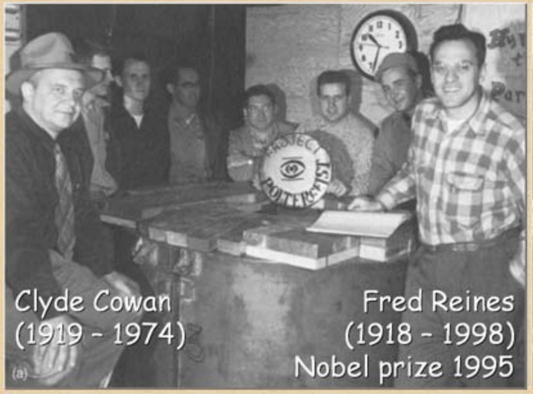
Sun Glasses for Neutrinos?

8.3 light minutes

1000 light years of lead needed to shield solar neutrinos

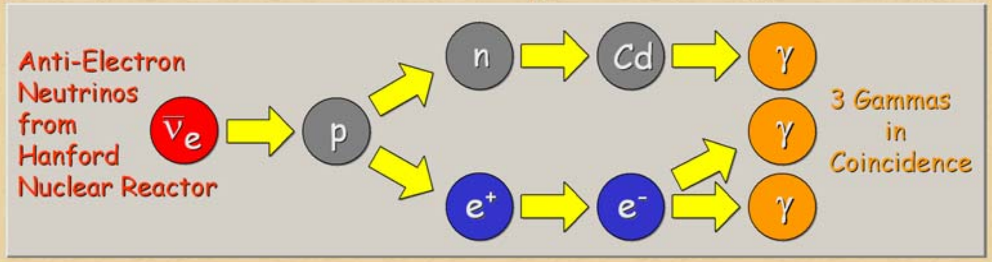
__Bethe & Peierls 1934:__
"… this evidently means that one will never be able to observe a neutrino."

First Detection (1954 - 1956)

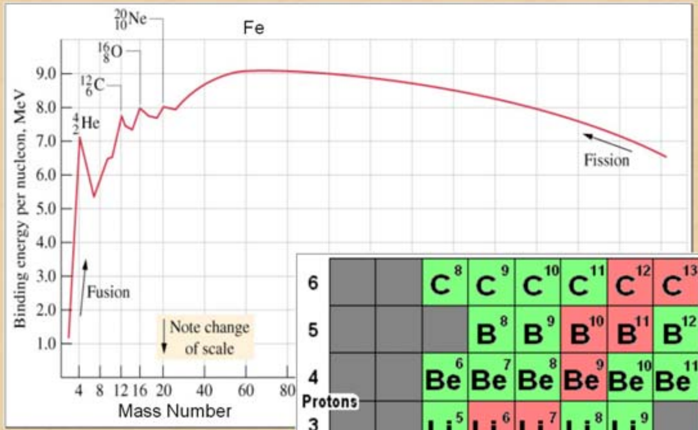


Clyde Cowan (1919 - 1974)
Fred Reines (1918 - 1998) Nobel prize 1995

Detector prototype



Nuclear Binding Energy



Protons														
6			C8	C9	C10	C11	C12	C13	C14	C15	C16	C17	C18	C19
5				B8	B9	B10	B11	B12	B13	B14	B15		B17	
4			Be6	Be7	Be8	Be9	Be10	Be11	Be12		Be14			
3			Li5	Li6	Li7	Li8	Li9		Li11					
2		He3	He4	He5	He6		He8							
1	H1	H2	H3											
0		Neutron												
Neutrons	0	1	2	3	4	5	6	7	8	9	10	11	12	13

stable / unstable

Hydrogen burning: Proton-Proton Chains

$p+p \to {}^2H + e^+ + \nu_e$ < 0.420 MeV — 100%

$p + e^- + p \to {}^2H + \nu_e$ 1.442 MeV — 0.24%

$^2H + p \to {}^3He + \gamma$

85% — **PPI**: $^3He + {}^3He \to {}^4He + 2p$

15%: $^3He + {}^4He \to {}^7Be + \gamma$

hep: $^3He + p \to {}^4He + e^+ + \nu_e$ < 18.8 MeV

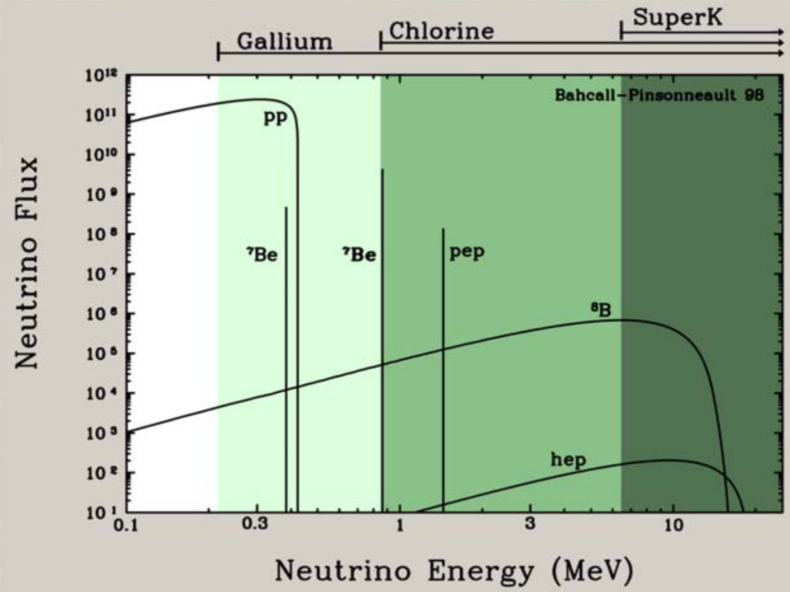
90%: $^7Be + e^- \to {}^7Li + \nu_e$ 0.862 MeV

10%: $^7Be + e^- \to {}^7Li^* + \nu_e$ 0.384 MeV

PPII: $^7Li + p \to {}^4He + {}^4He$

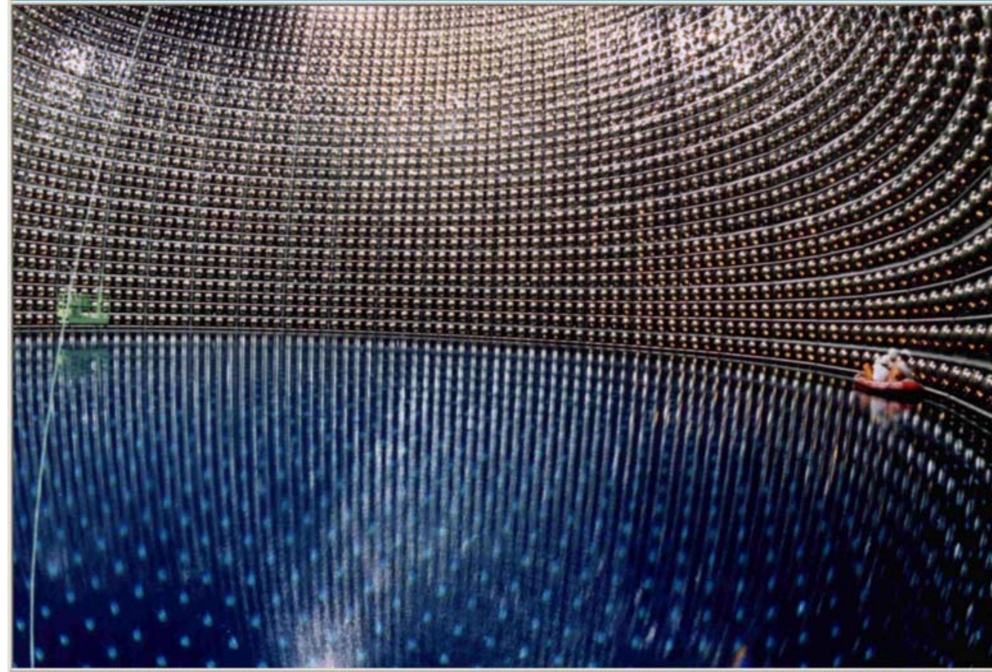
0.02% — **PPIII**:
$^7Be + p \to {}^8B + \gamma$
$^8B \to {}^8Be^* + e^+ + \nu_e$ < 15 MeV
$^8Be^* \to {}^4He + {}^4He$

Solar Neutrino Spectrum

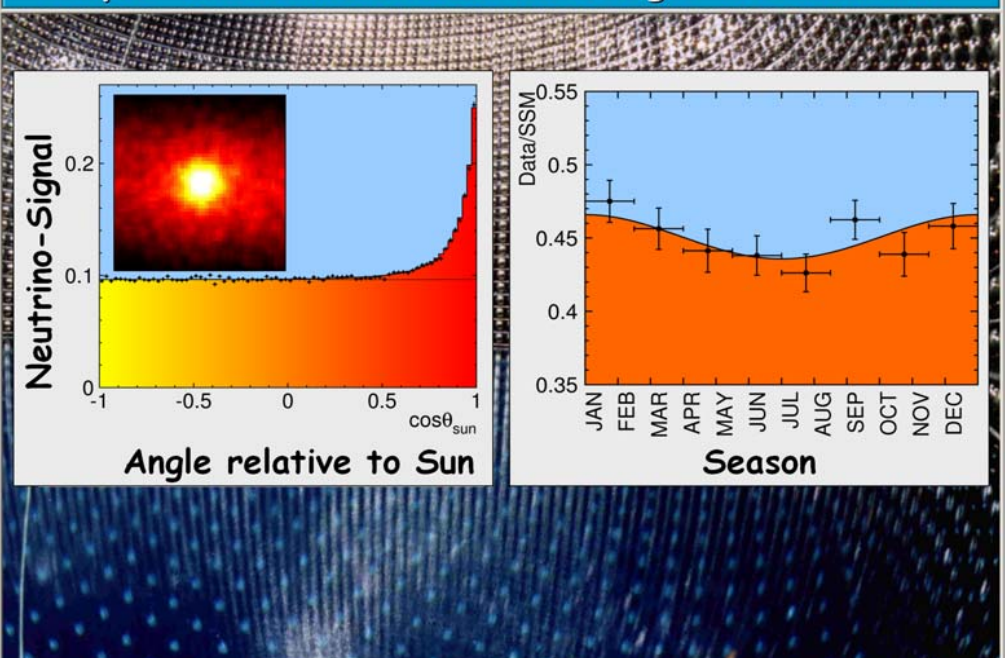


Solar neutrino energy spectrum

Super-Kamiokande: Sun in the Light of Neutrinos



Super-Kamiokande: Sun in the Light of Neutrinos



Neutrinos from Thermal Plasma Processes

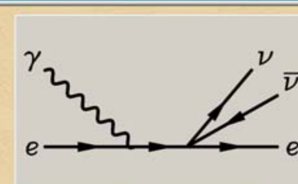
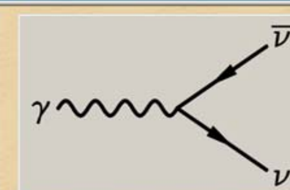
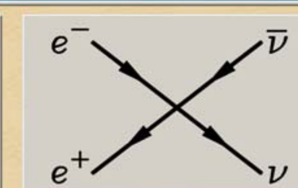


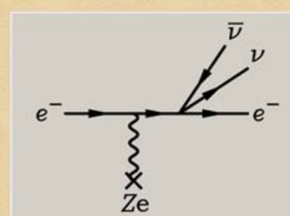
Photo (Compton)



Plasmon decay

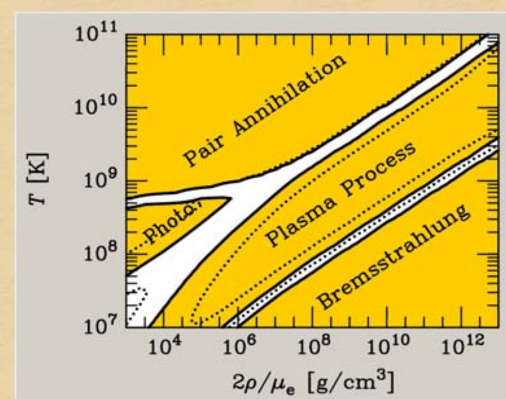


Pair annihilation



Bremsstrahlung

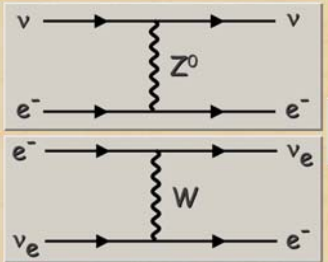
These processes first discussed 1961-63 after V-A theory



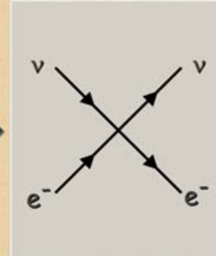
Effective Neutrino Neutral-Current Couplings

Neutral current

Charged current



$E \ll M_{W,Z}$



Effective four fermion coupling

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

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

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

$\sin^2\Theta_W = 0.231$

Solar Neutrinos from Compton Process

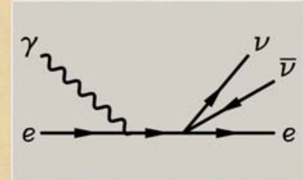


Photo (Compton)

Cross section in non-relativistic limit

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

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

Volume energy loss rate

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

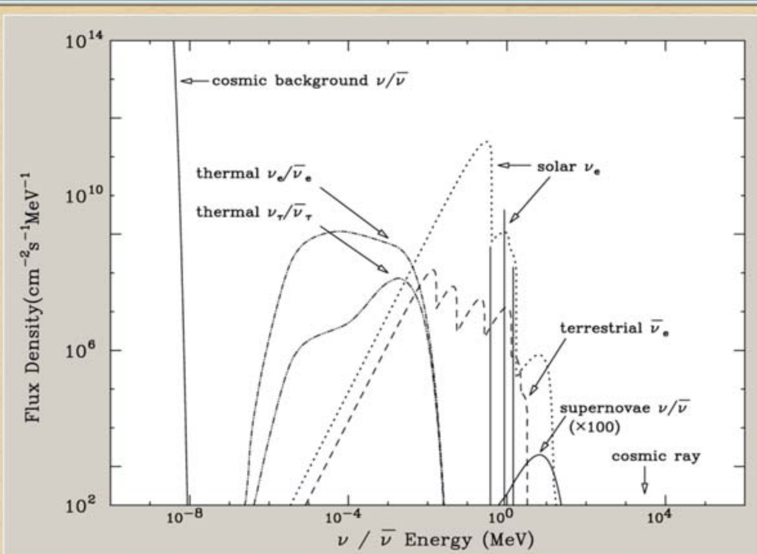
Energy loss rate per unit mass

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

To be compared with nuclear energy generation in the Sun

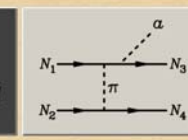
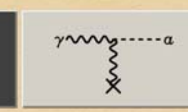
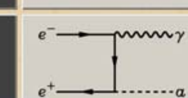
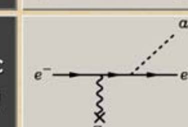
$$\langle \varepsilon_{nuc} \rangle = \frac{L_\odot}{M_\odot} = \frac{4 \times 10^{33}\,\mathrm{erg/s}}{2 \times 10^{33}\,\mathrm{g}} = 2\,\frac{\mathrm{erg}}{\mathrm{g\,s}} = 2 \times 10^{-7}\,\frac{\mathrm{Watts}}{\mathrm{g}} = \frac{200\,\mathrm{Watts}}{\mathrm{kilo-ton}}$$

Thermal vs. Nuclear Neutrinos from Sun

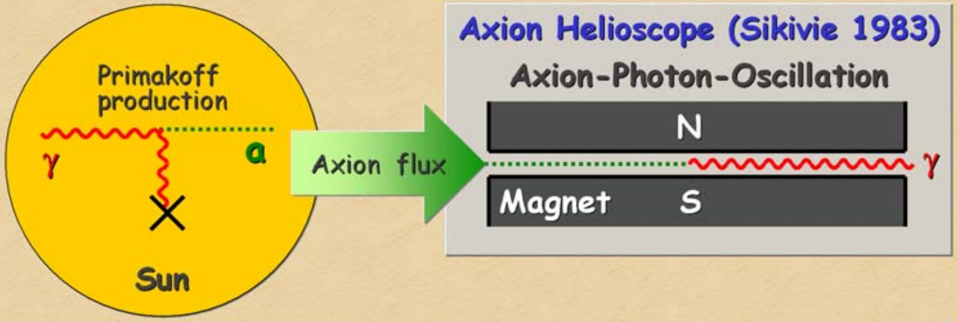


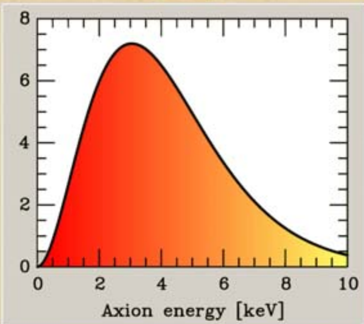
Haxton & Lin, The very low energy solar flux of electron and heavy-flavor neutrinos and anti-neutrinos, nucl-th/0006055

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

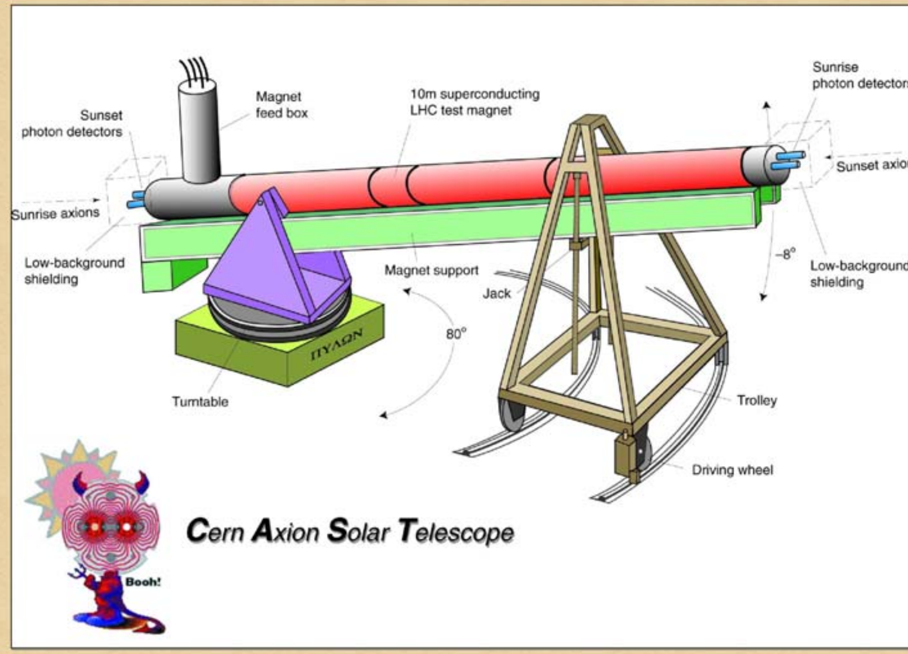




- ➔ Tokyo Axion Helioscope (Results since 1998)
- ➔ CERN Axion Solar Telescope (CAST) (just started)

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

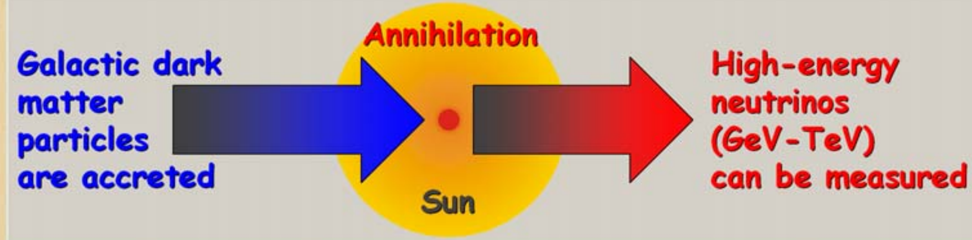
Horizontally Moving Platform



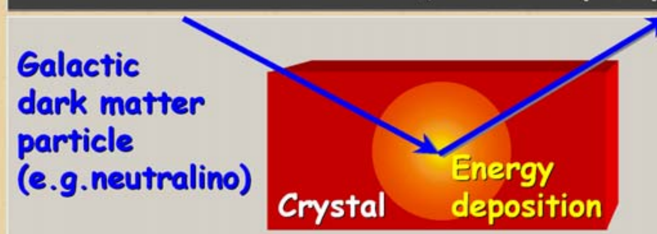
Recent Picture of CAST

Search for Neutralino Dark Matter

Indirect Method (Neutrino Telescopes)

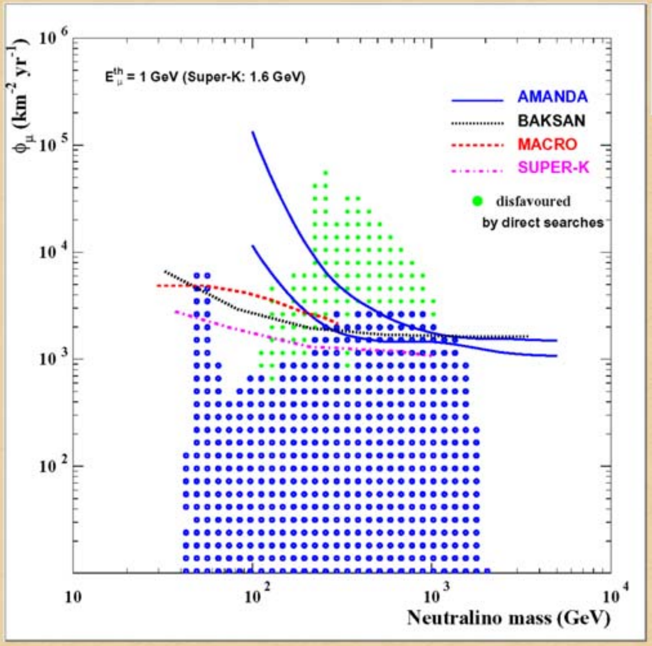


Direct Method (Laboratory Experiments)



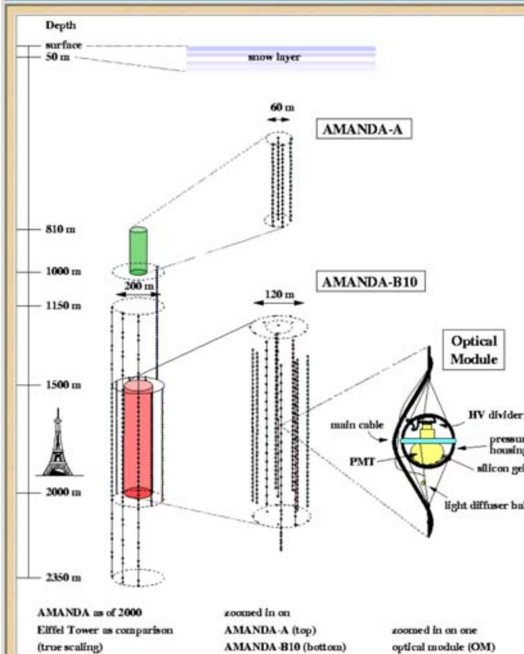
Recoil energy (few keV) is measured by
- Ionisation
- Scintillation
- Cryogenic

Current Limits from WIMP Searches

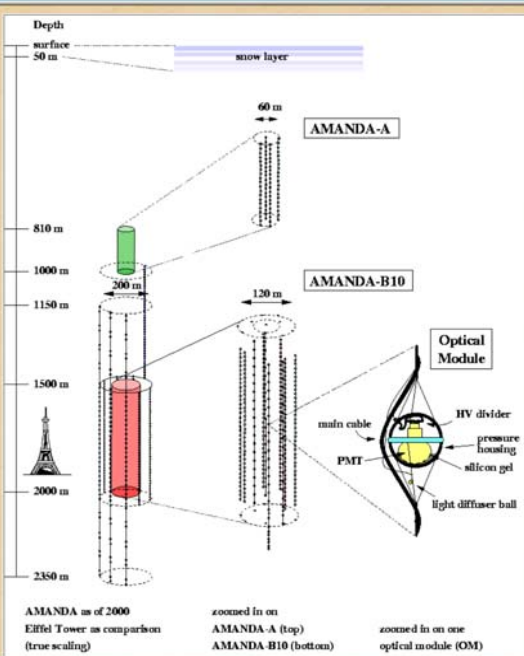


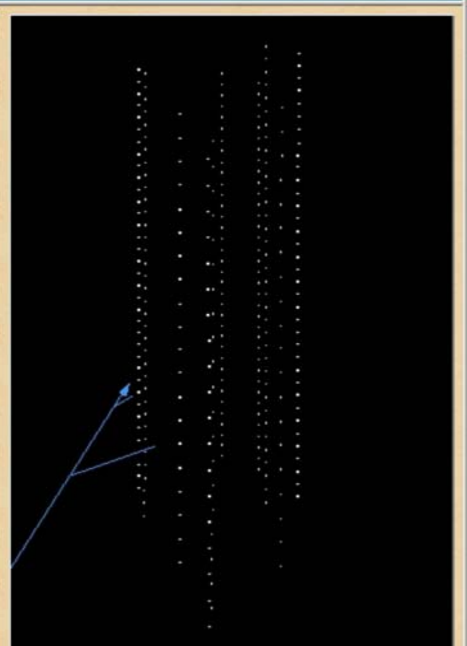
Limits from WIMP Annihilation in the Earth
astro-ph/0202370

AMANDA – South Pole Neutrino Telescope

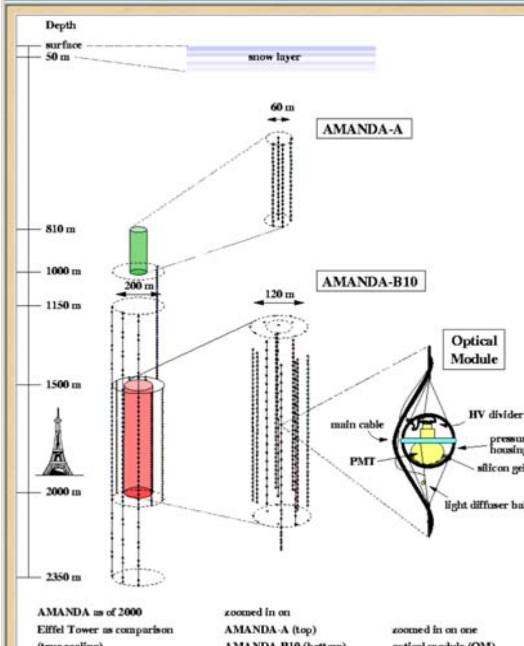


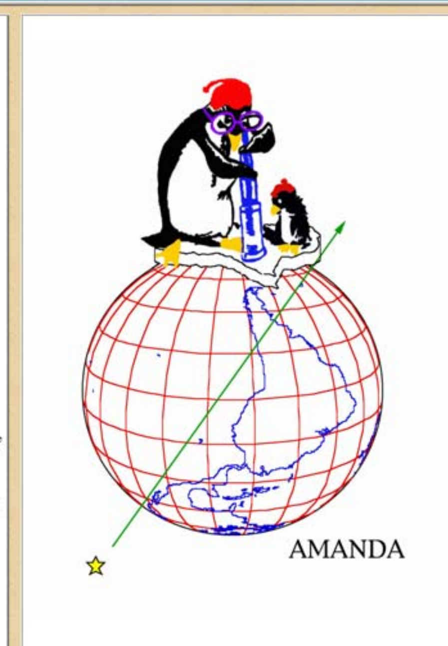
AMANDA – South Pole Neutrino Telescope



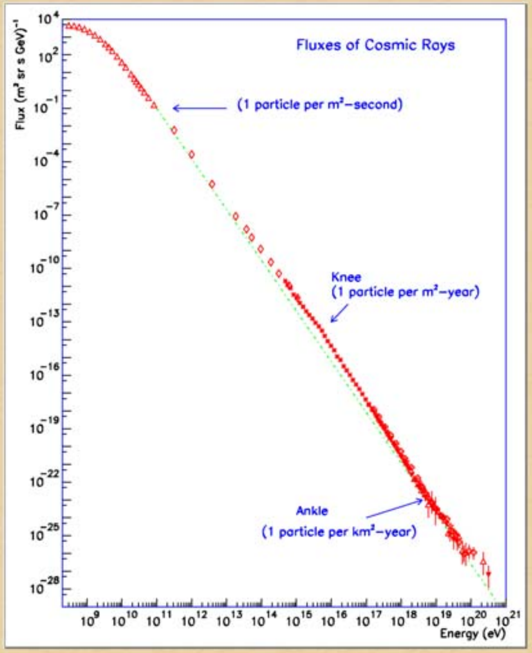


AMANDA – South Pole Neutrino Telescope

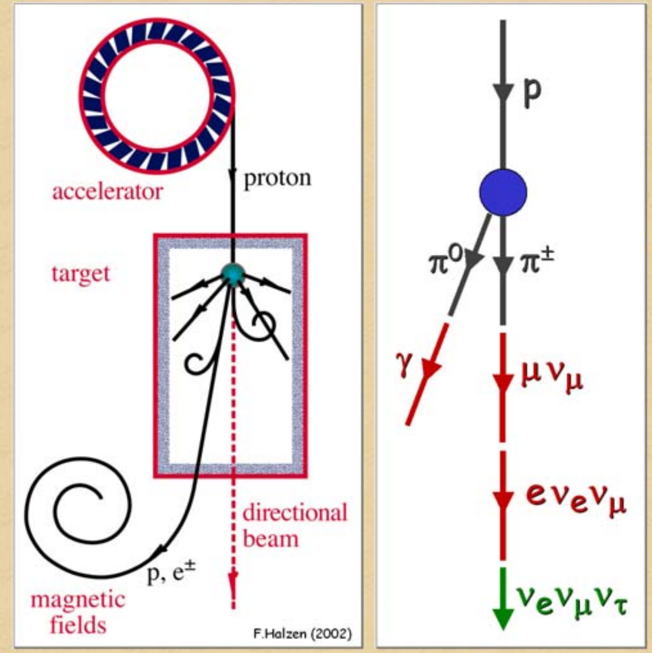




Global Cosmic Ray Spectrum



Neutrino Beams: Heaven and Earth

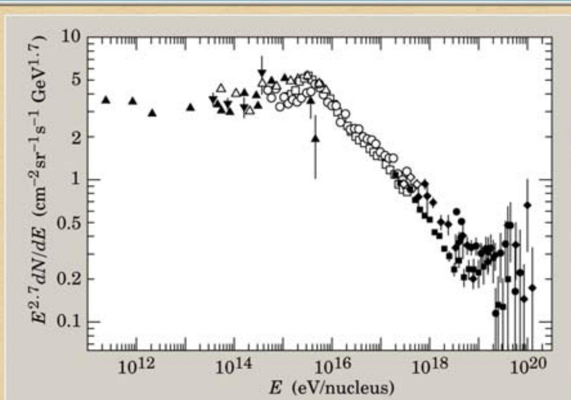


Target:
Protons or Photons

Approx. equal fluxes of photons & neutrinos

Equal neutrino fluxes in all flavors due to oscillations

Gamma-, Neutrino- and Proton-Astronomy



Cosmic-ray spectrum × $E^{2.7}$

What are the sources ?

TeV γ astronomy

Photon mean free path < few 10 Mpc

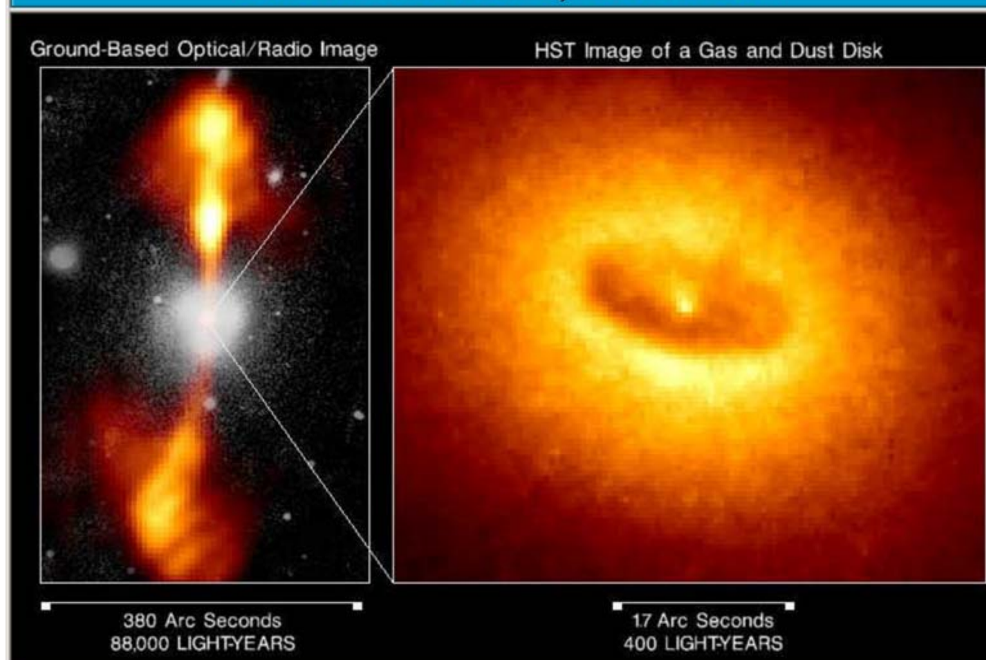
Proton magnetic field deflection

GZK cutoff

Opportunity for neutrino astronomy

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

Core of the Galaxy NGC 4261



High-Energy Neutrinos from the Sun

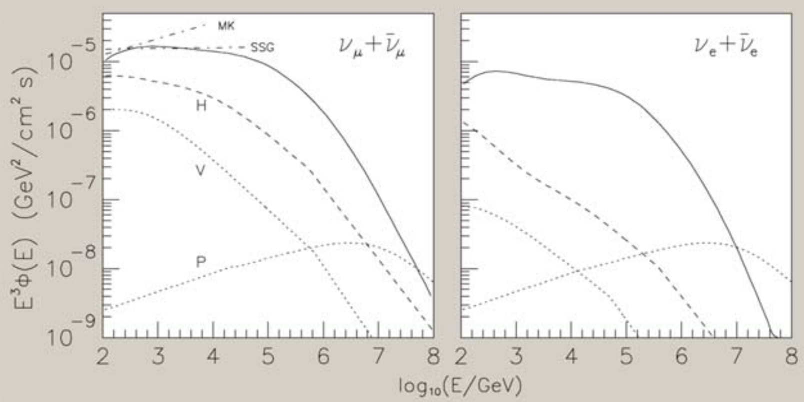
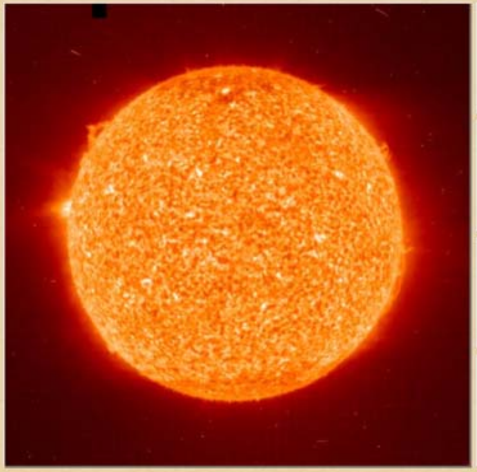


Figure 4: *Cosmic ray induced E^3-weighted neutrino fluxes at the Earth integrated over the solid angle of the Sun. The fluxes from the Sun obtained in this study (solid lines) are compared with the earlier calculation SSG [22] and the one MK derived from [2], as well as those from the Earth's atmosphere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

Solar Neutrinos



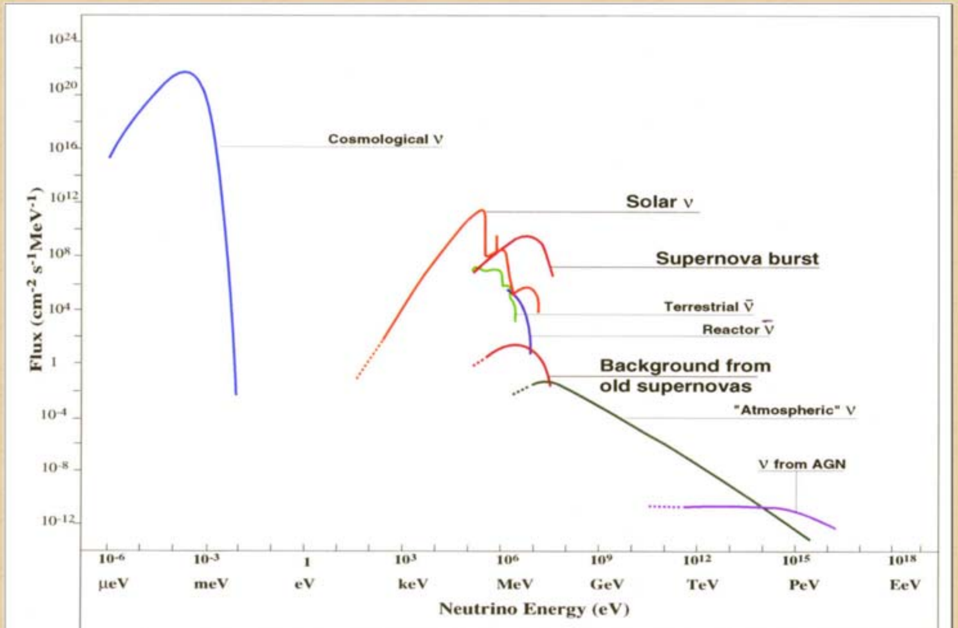
Thermal plasma reactions
E ~ 1 eV - 30 keV
No apparent way to measure

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 (?)

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