ISAPP 2003, International School on Astroparticle Physics
European Doctorate School, 14-19 July 2003, Madonna di Campiglio, Italy

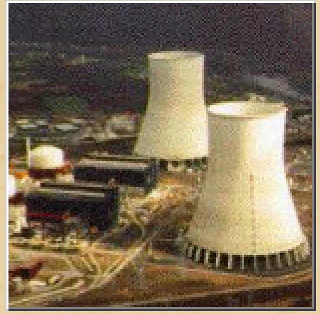
# Astrophysical Neutrinos

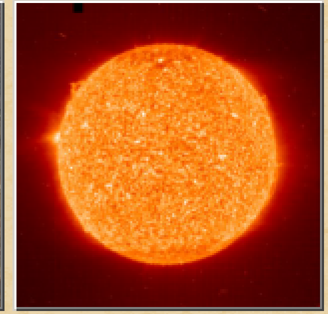

**Georg G. Raffelt**

Max-Planck-Institut für Physik, München, Germany

# Where do Neutrinos Appear in Nature?

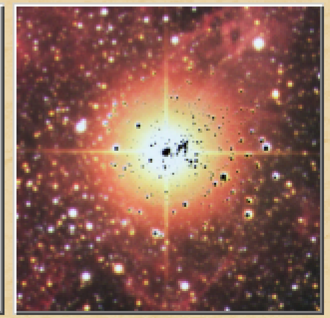
✓ Nuclear Reactors





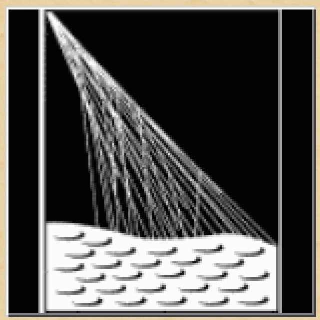
Sun ✓

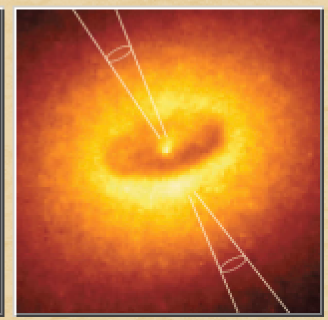
✓ Particle-Accelerators



Supernovae (Stellar Collapse)
SN 1987A ✓

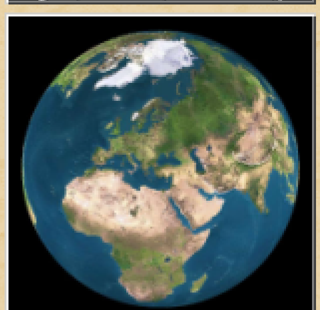
✓ Earth Atmosphere (Cosmic Rays)

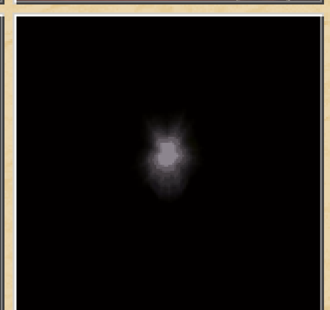




Astrophysical Accelerators Soon ?

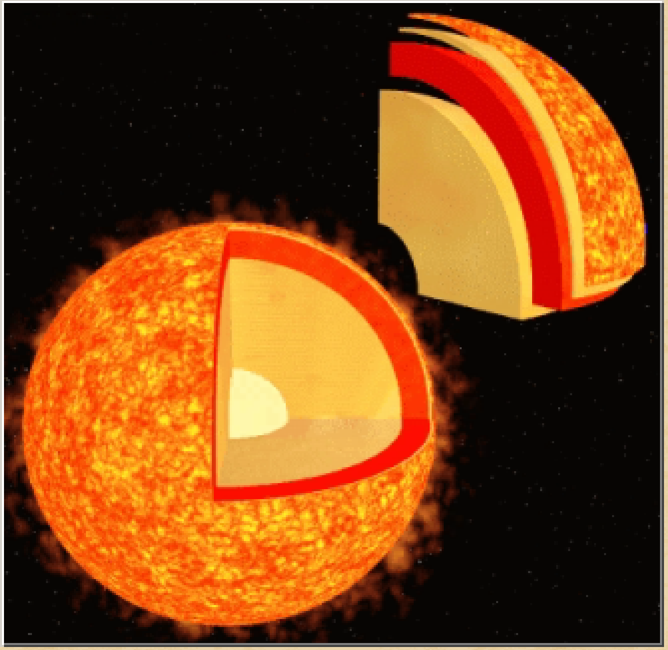
2003 ? Earth Crust (Natural Radioactivity

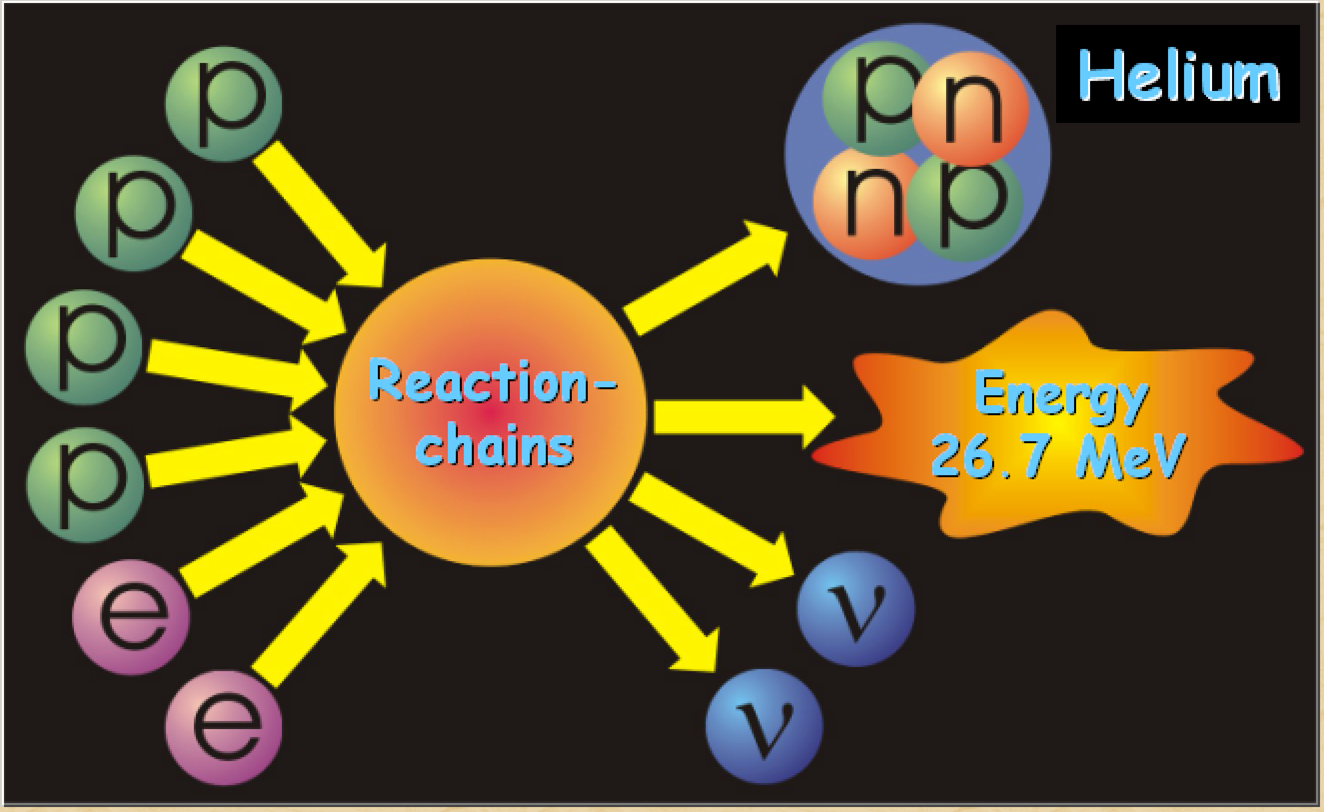




Cosmic Big Bang (Today 330 $\nu/\mathrm{cm}^3$)
Indirect Evidence

# 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 reactions of carbon and nitrogen with protons.* These reactions form a cycle in which the original nucleus is reproduced, *viz.* $C^{12}+H=N^{13}$, $N^{13}=C^{13}+\epsilon^+$, $C^{13}+H=N^{14}$, $N^{14}+H=O^{15}$, $O^{15}=N^{15}+\epsilon^+$, $N^{15}+H=C^{12}+He^4$. Thus carbon and nitrogen merely serve as catalysts for the combination of four protons (and two electrons) into an $\alpha$-particle (§7).

The carbon-nitrogen reactions are unique in their cyclical character (§8). For all nuclei lighter than carbon, reaction with protons will lead to the emission of an $\alpha$-particle so that the original nucleus is permanently destroyed. For all nuclei heavier than fluorine, only radiative capture of the protons occurs, also destroying the original nucleus. Oxygen and fluorine reactions mostly lead back to nitrogen. Besides, these heavier nuclei react much more slowly than C and N and are therefore unimportant for the energy production.

The agreement 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 18.5 million degrees while integration of the Eddington equations gives 19. For the brilliant star Y Cygni the corresponding figures are 30 and 32. This good agreement holds for all bright stars of the main sequence, but, of course, not for giants.

For fainter stars, with lower central temperatures, the reaction $H+H=D+\epsilon^+$ and the reactions following it, are believed to be mainly responsible for the energy production. (§10)

It is shown further (§5–6) that *no elements heavier than He⁴ can be built up in ordinary stars.* This is due to the fact, mentioned above, that all elements up to boron are disintegrated by proton bombardment ($\alpha$-emission!) rather than built up (by radiative capture). The instability of $Be^8$ reduces the formation of heavier elements still further. The production of neutrons in stars is likewise negligible. The heavier elements found in stars must therefore have existed already when the star was formed.

Finally, the suggested mechanism of energy production is used to draw conclusions about astrophysical problems, such as the mass-luminosity relation (§10), the stability against temperature changes (§11), and stellar evolution (§12).

### §1. INTRODUCTION

THE progress of nuclear physics in the last few years makes it possible to decide rather definitely which processes can and which cannot occur in the interior of stars. Such decisions will be attempted in the present paper, the discussion being restricted 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 must assume that the heavier elements 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 into an $\alpha$-particle. This simplifies the discussion of stellar evolution inasmuch as the amount of heavy matter, and therefore the opacity, does not change with time.

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.*

$$H+H=D+\epsilon^+. \quad (1)$$

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

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

The catalyst $C^{12}$ is reproduced in all cases except about one in 10,000, therefore the abundance of carbon and nitrogen remains practically unchanged (in comparison with the change of the number of protons). The two reactions (1) and

* Awarded an A. Cressy Morrison Prize in 1938, by the New York Academy of Sciences.



**No neutrinos from nuclear reactions in 1938 …**

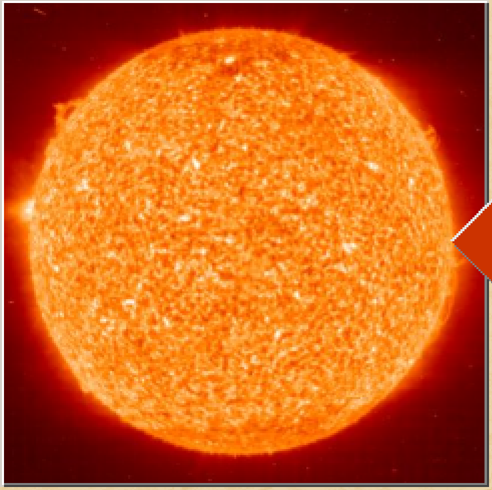
The combination of four pr… nd two electrons can occur essentially on… wo ways. The first mechanism starts with t… ombination of two protons to form a deutero… ith positron emission, *viz.*

$$H+H=D+\epsilon^+. \quad (1)$$

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

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

# Sun Glasses for Neutrinos?

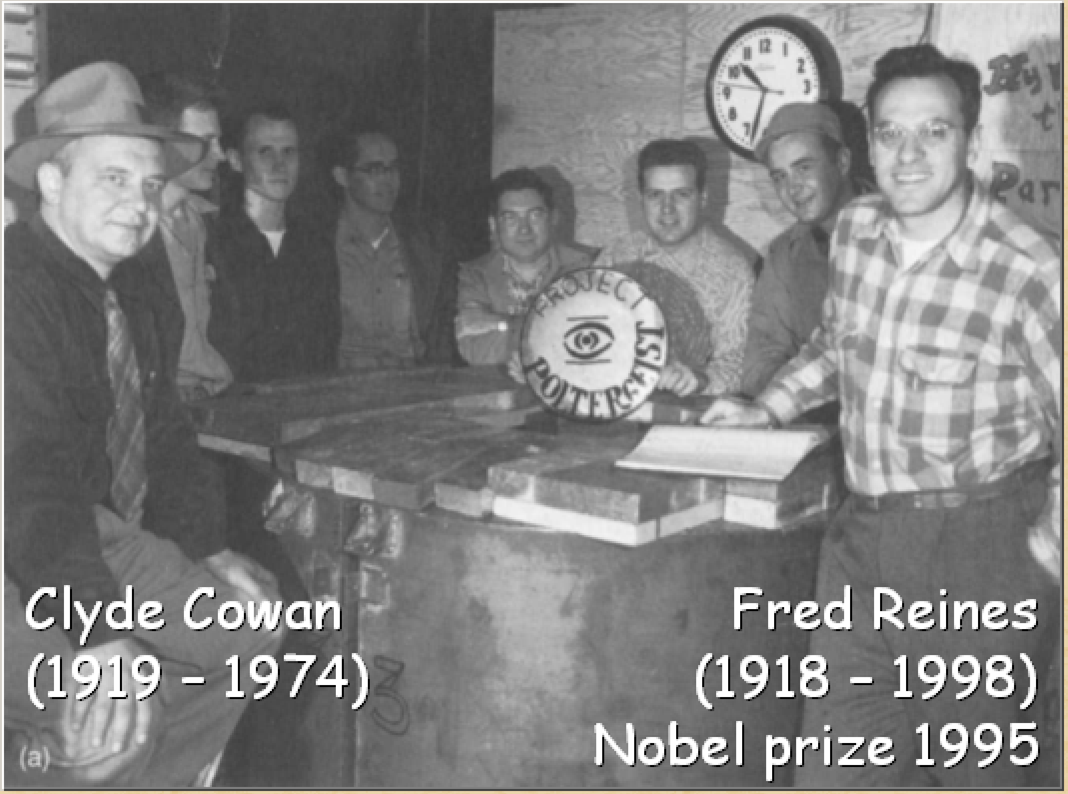


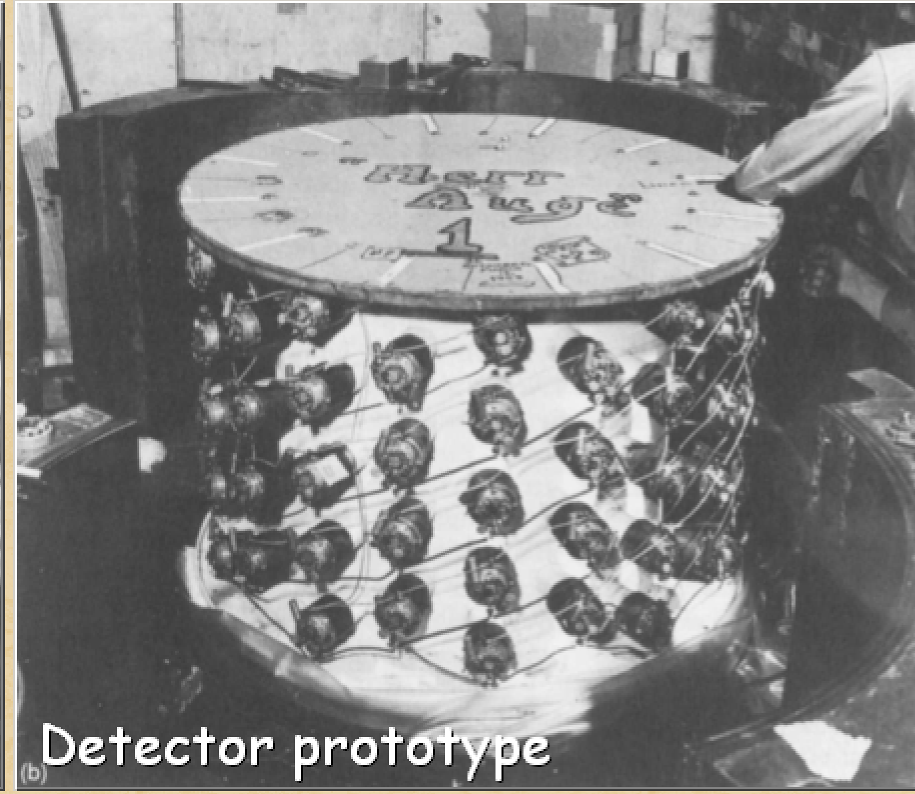
8.3 light minutes

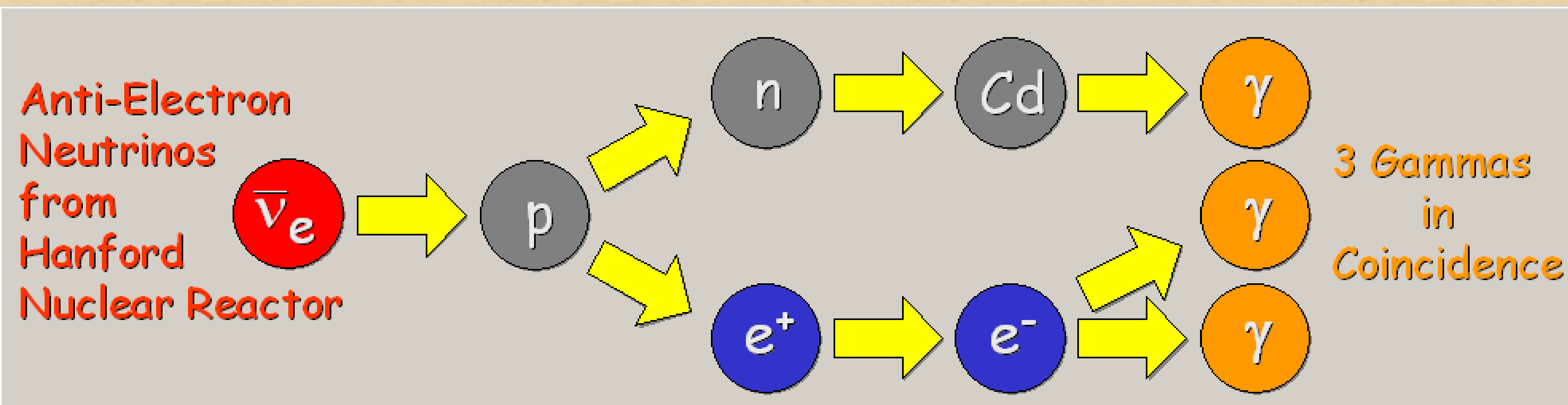
**1000 light years of lead needed to shield solar neutrinos**

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

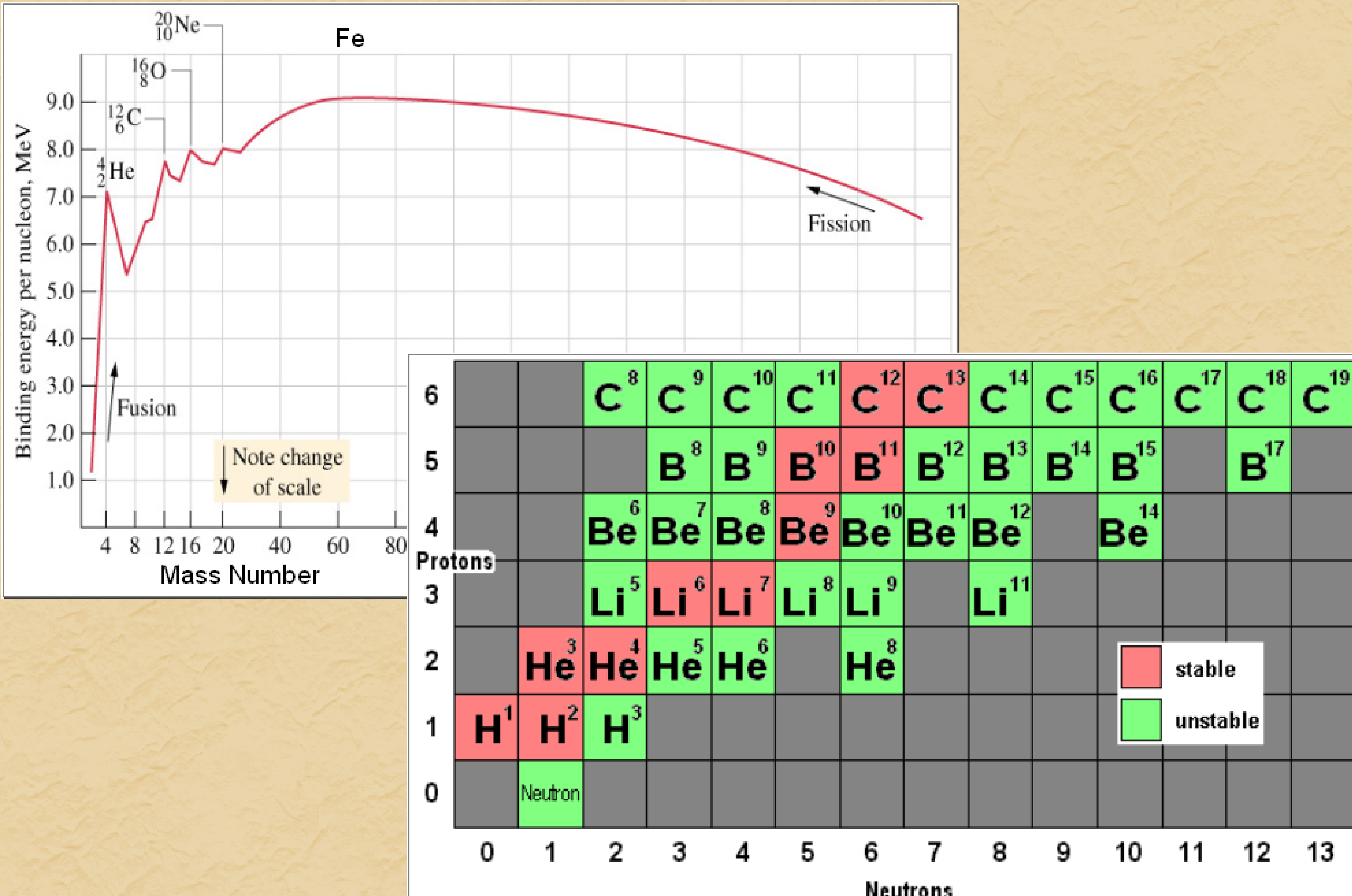
# First Detection (1954 - 1956)



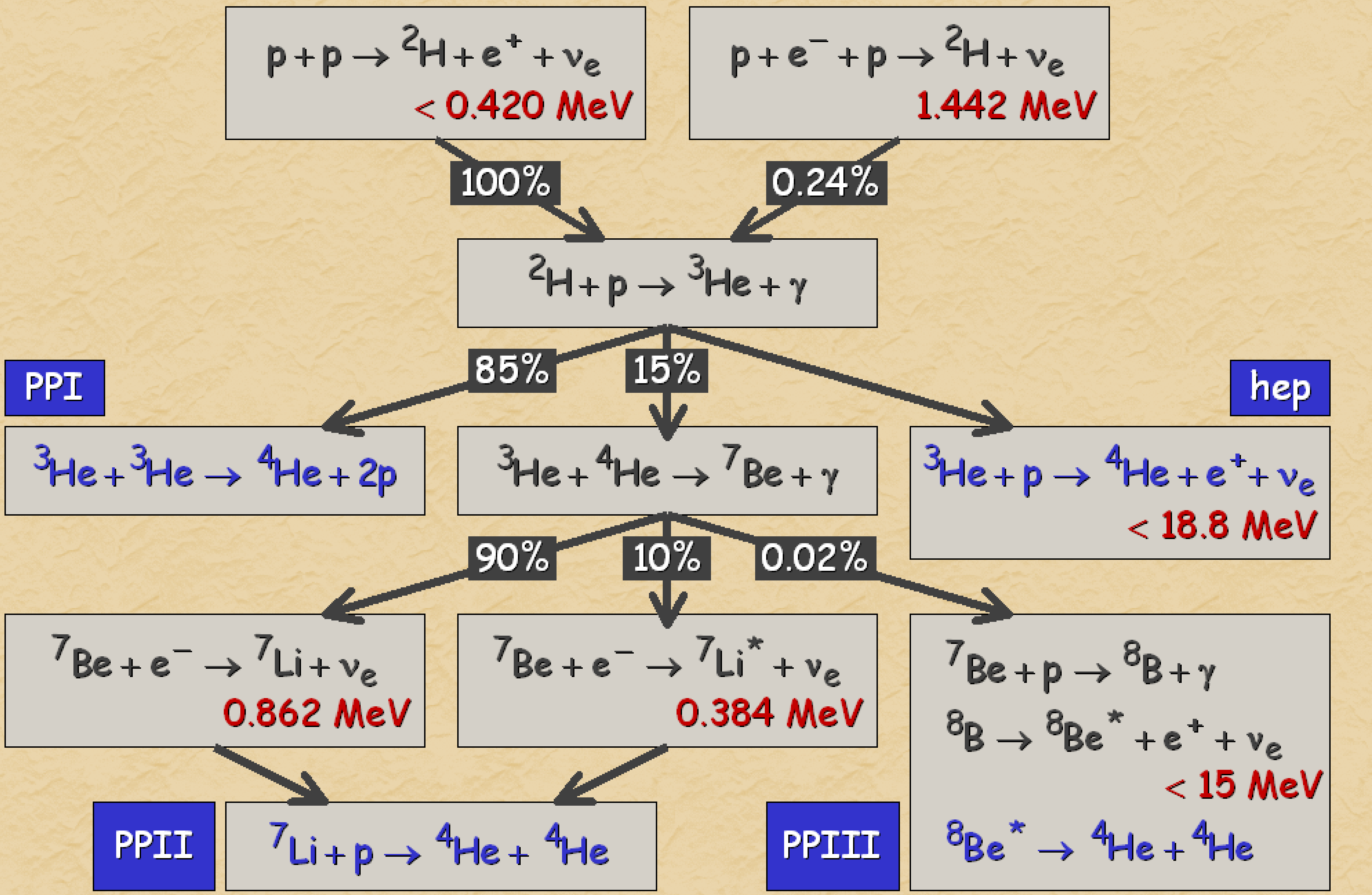



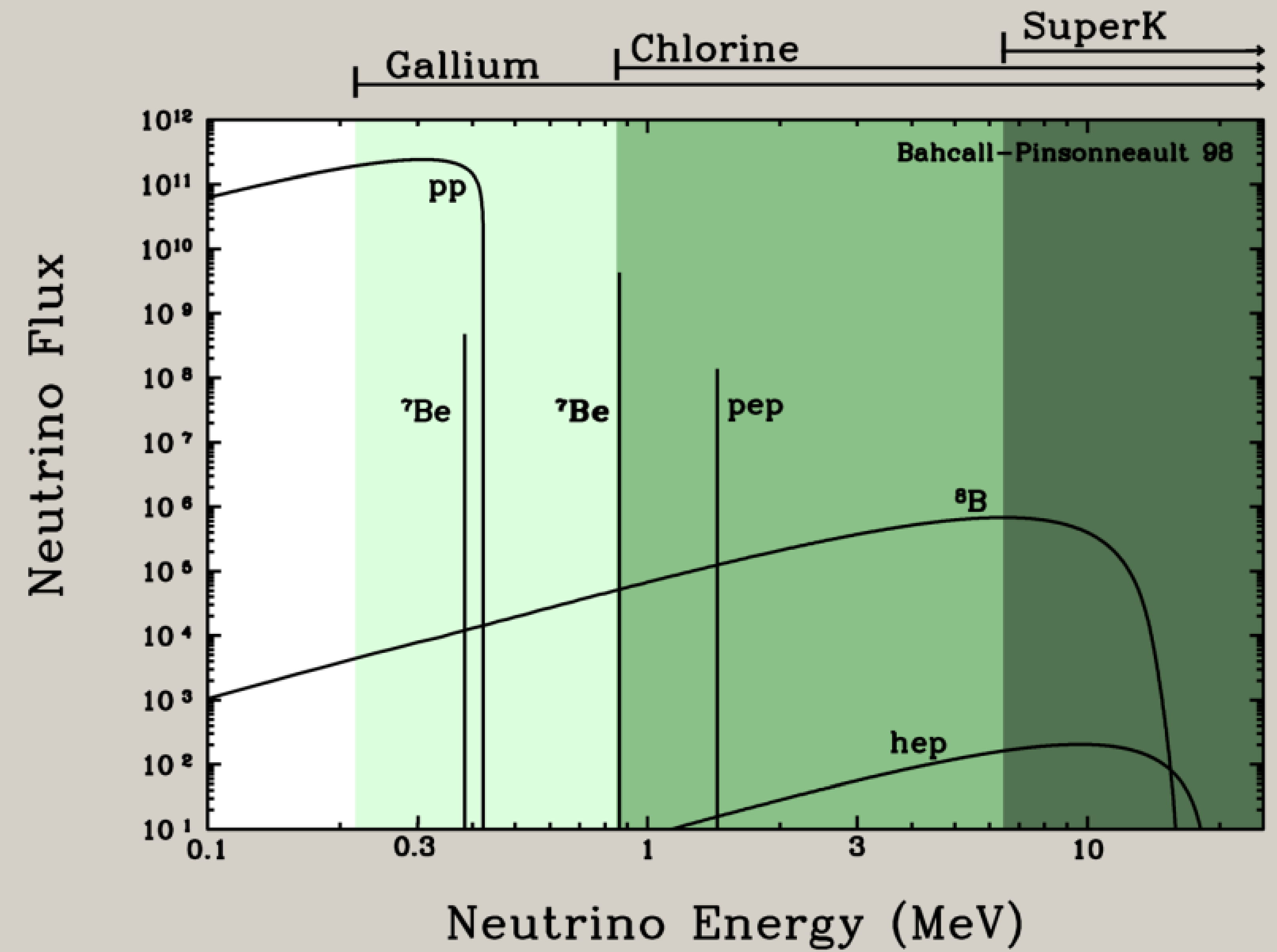
# Nuclear Binding Energy



# Hydrogen burning: Proton-Proton Chains

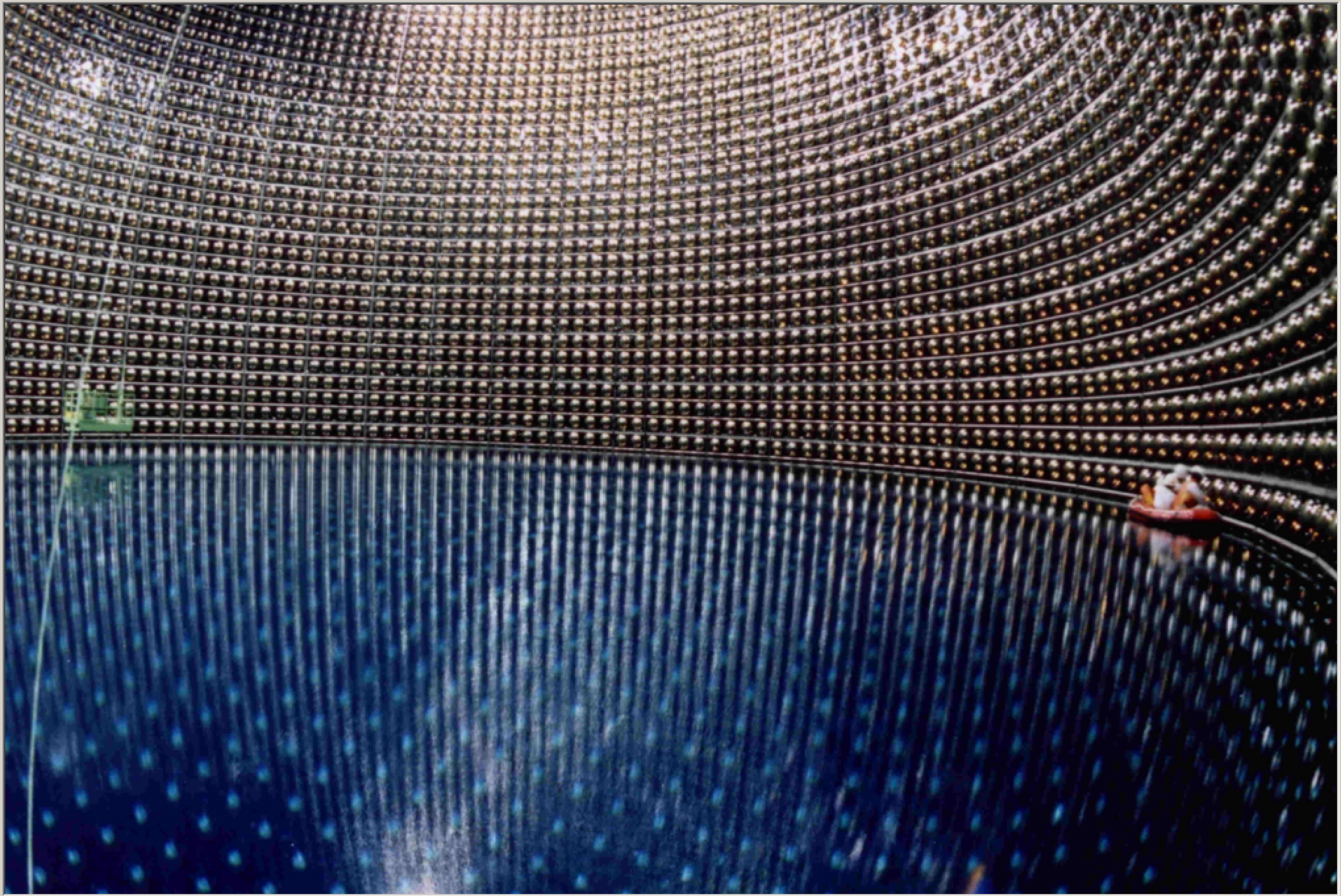


# Solar Neutrino Spectrum

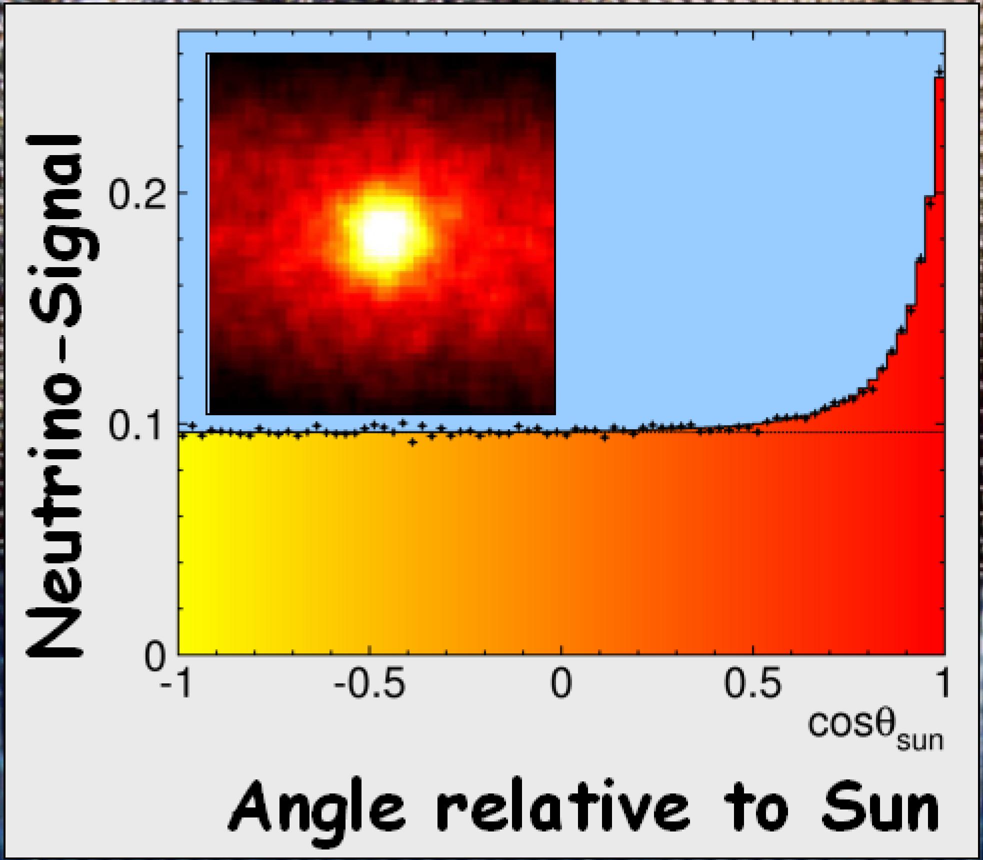


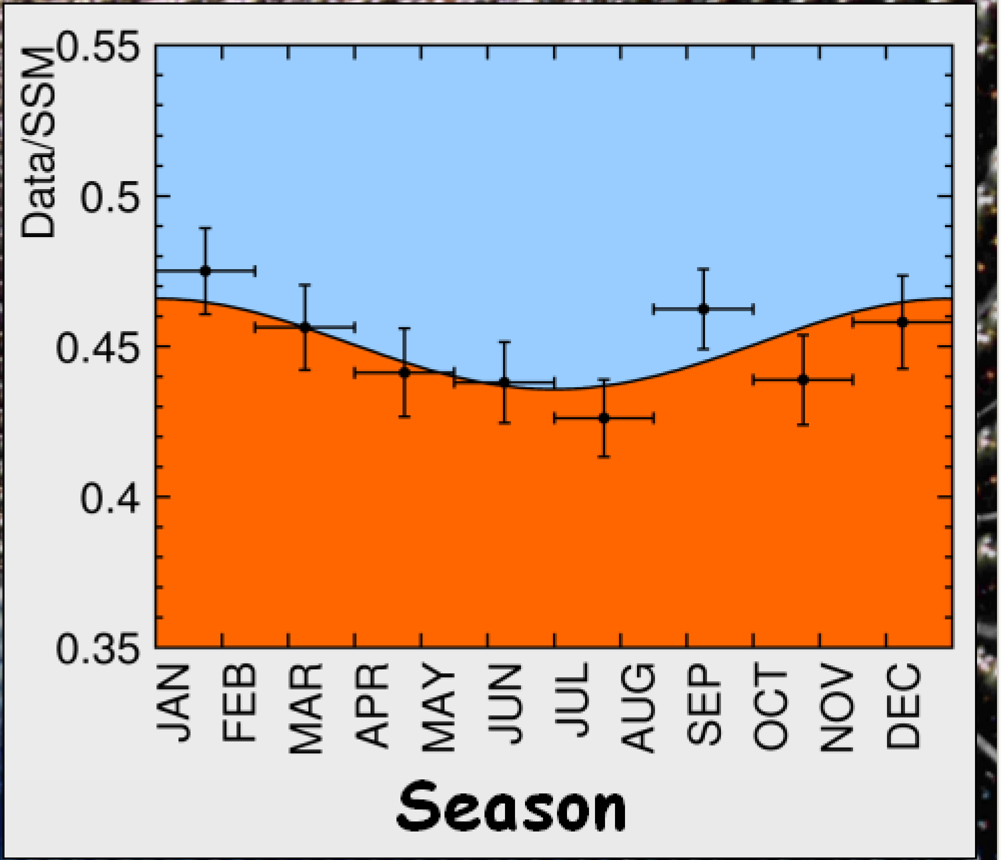

Solar neutrino energy spectrum

# Super-Kamiokande: Sun in the Light of Neutrinos



# Super-Kamiokande: Sun in the Light of Neutrinos



# Neutrinos from Thermal Plasma Processes

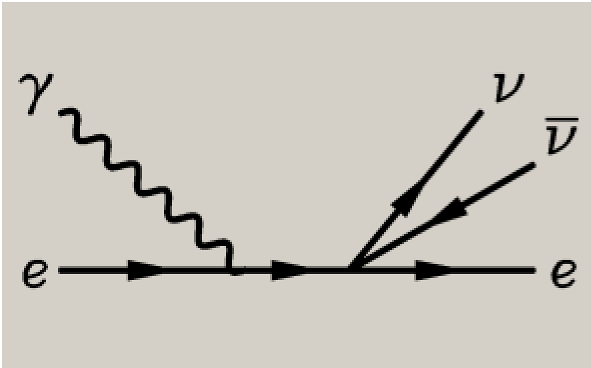
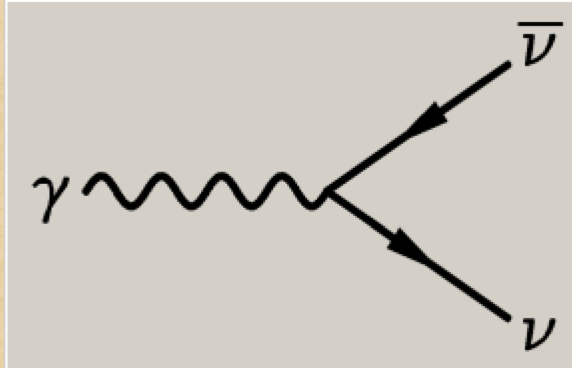
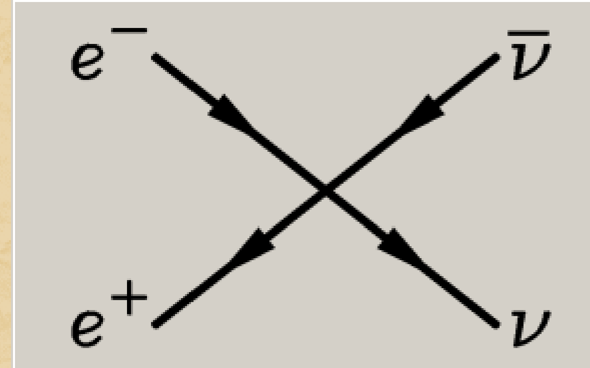


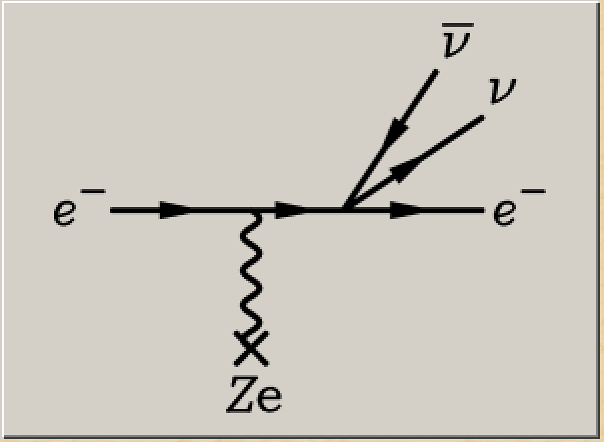

Photo (Compton)




Plasmon decay

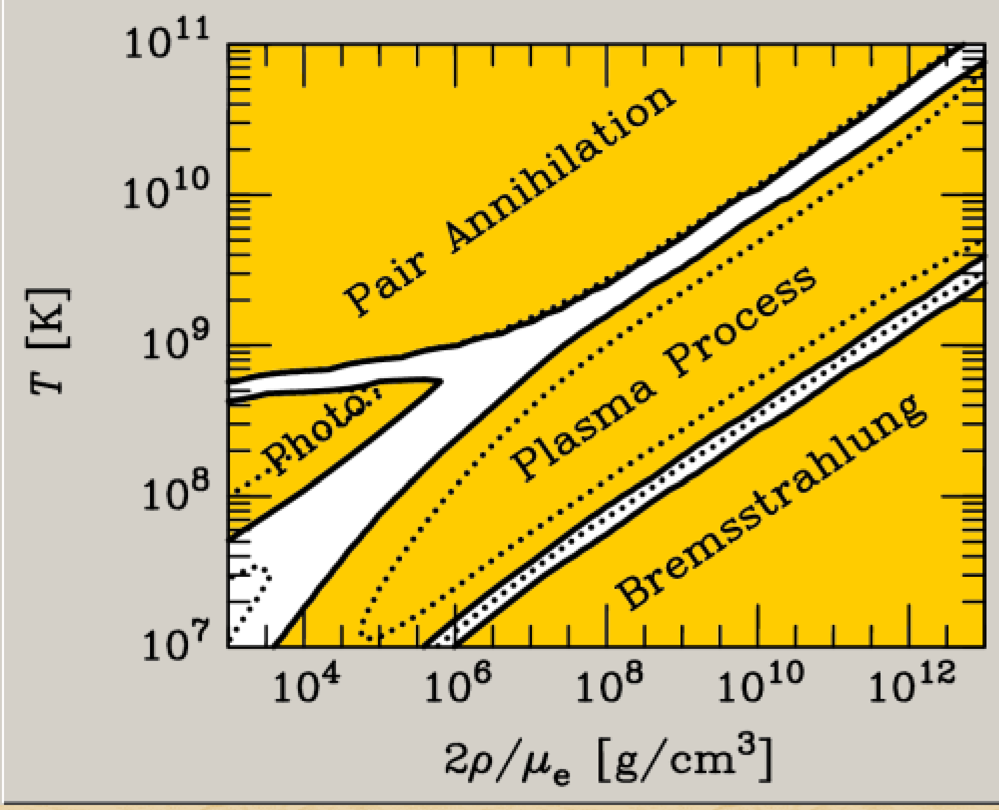



Pair annihilation



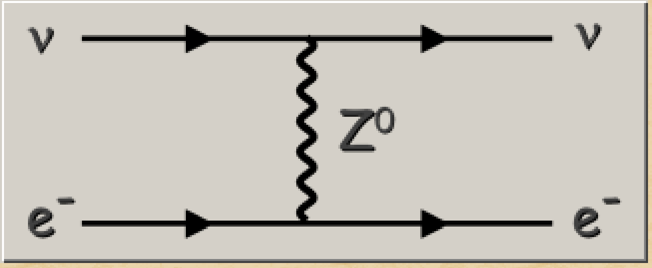

Bremsstrahlung

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

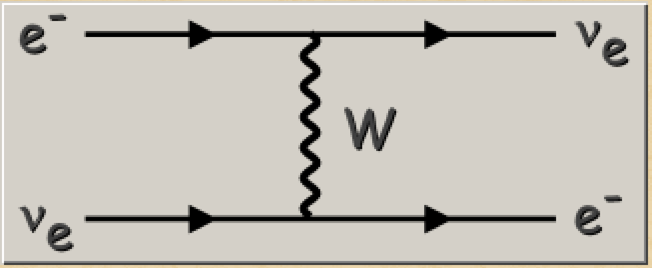


# Effective Neutrino Neutral-Current Couplings

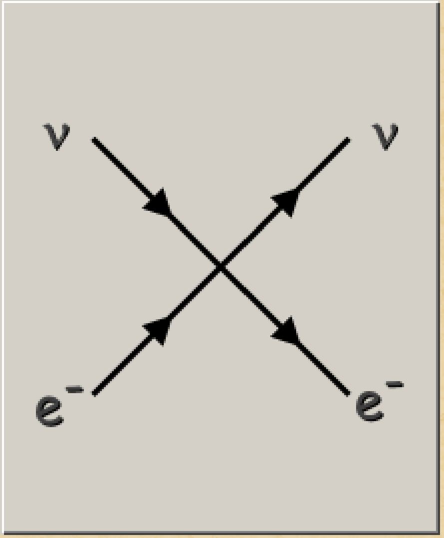
**Neutral current**




**Charged current**




$E \ll M_{W,Z}$




**Effective four fermion coupling**

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

| Neutrino | Fermion | $C_V$ | $C_A$ |
|---|---|---|---|
| $\nu_e$ | Electron | $+\frac{1}{2} + 2\sin^2\Theta_W \approx 1$ | $+\frac{1}{2}$ |
| $\nu_\mu, \nu_\tau$ | Electron | $-\frac{1}{2} + 2\sin^2\Theta_W \approx 0$ | $-\frac{1}{2}$ |
| $\nu_e, \nu_\mu, \nu_\tau$ | Proton | $+\frac{1}{2} - 2\sin^2\Theta_W \approx 0$ | $+\frac{1.26}{2}$ |
| $\nu_e, \nu_\mu, \nu_\tau$ | 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

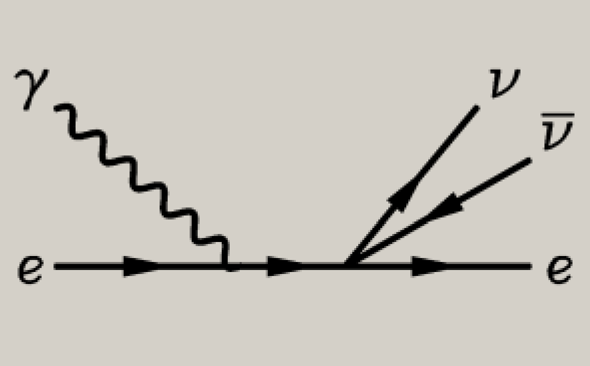



Photo (Compton)

**Cross section in non-relativistic limit**

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

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

**Volume energy loss rate**

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

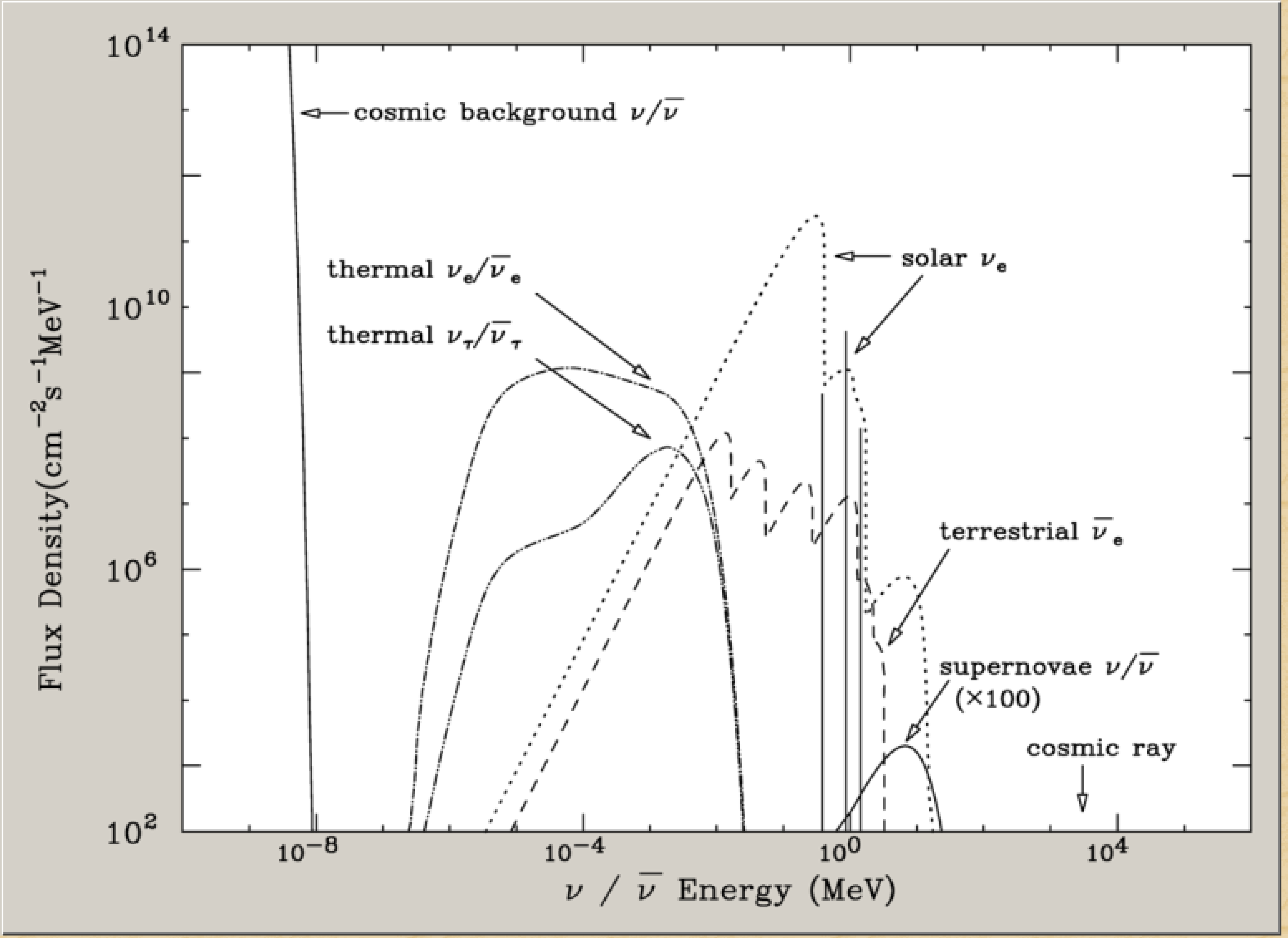
**Energy loss rate per unit mass**

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

**To be compared with nuclear energy generation in the Sun**

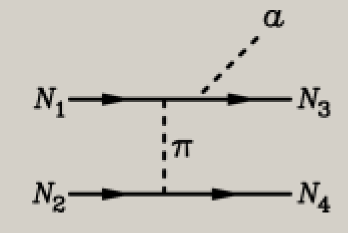
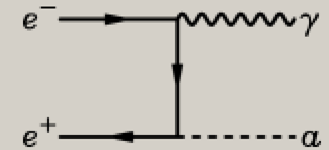
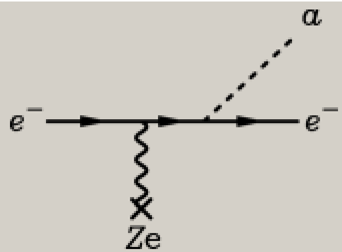
$$\langle \varepsilon_{\text{nuc}} \rangle = \frac{L_\odot}{M_\odot} = \frac{4\times 10^{33}\,\text{erg/s}}{2\times 10^{33}\,\text{g}} = 2\,\frac{\text{erg}}{\text{g s}} = 2\times 10^{-7}\,\frac{\text{Watts}}{\text{g}} = \frac{200\ \text{Watts}}{\text{kilo-ton}}$$

# Thermal vs. Nuclear Neutrinos from Sun

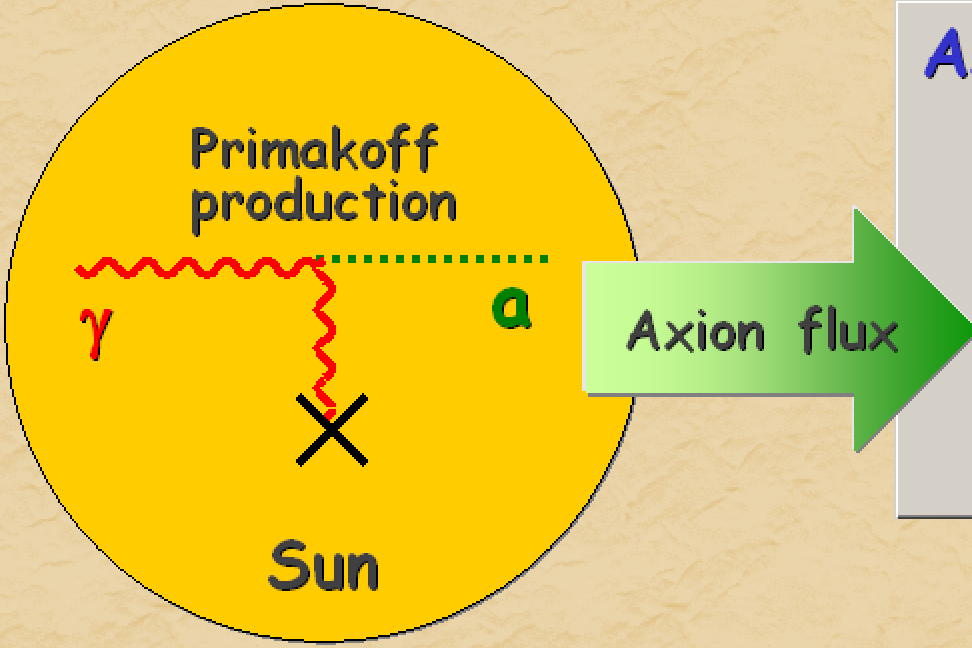



Haxton & Lin, The very low energy solar flux of electron and heavy-flavor neutrinos and anti-neutrinos, nucl-th/0006055

# Axion or Graviton Emission Processes in Stars

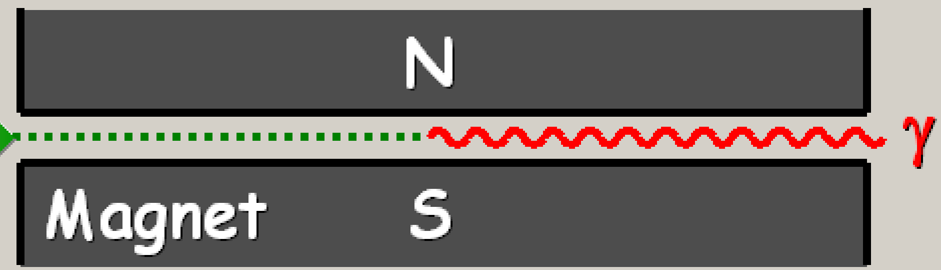
| | | | |
|---|---|---|---|
| Nucleons | $\frac{C_N}{2f_a}\overline{\Psi}_N\gamma_\mu\gamma_5\Psi_N\,\partial^\mu a$ | Nucleon Bremsstrahlung |  |
| Photons | $\frac{C_e}{2f_a}\overline{\Psi}_e\gamma_\mu\gamma_5\Psi_e\,\partial^\mu a$ | Primakoff |  |
| Electrons | $C_\gamma\frac{\alpha}{2\pi f_a}\frac{1}{4}F_{\mu\nu}\tilde{F}^{\mu\nu}a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

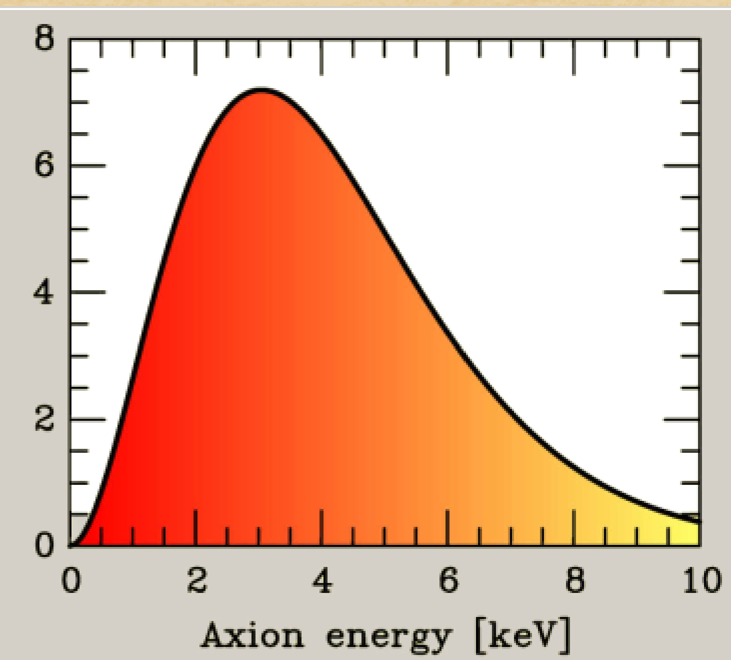
# Search for Solar Axions




## Axion Helioscope (Sikivie 1983)

Axion-Photon-Oscillation

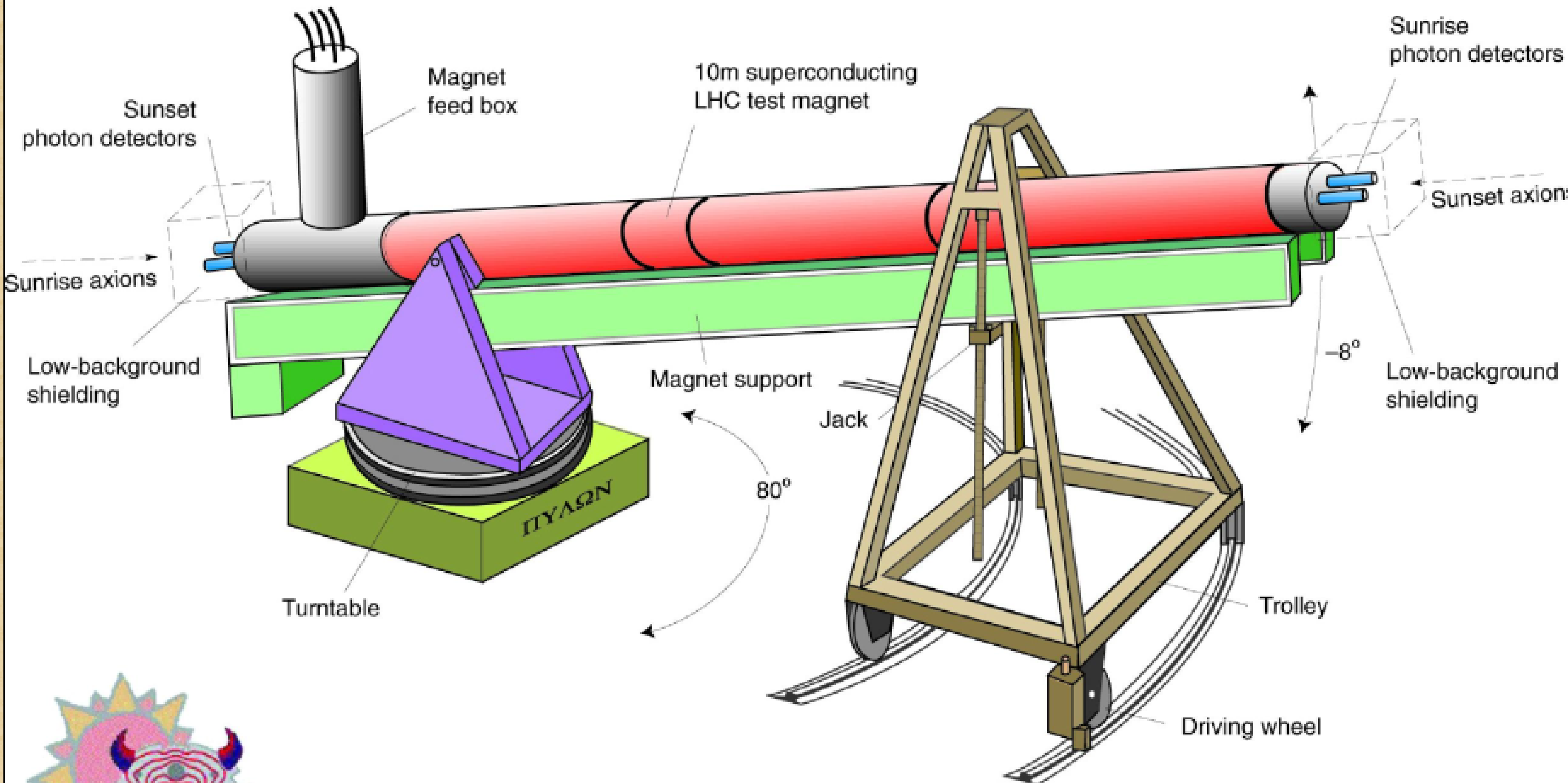


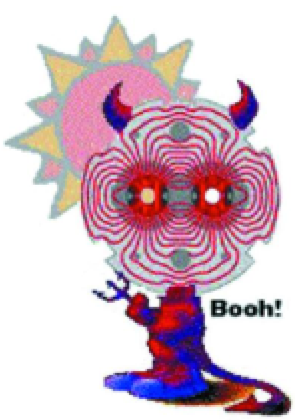




- → Tokyo Axion Helioscope (Results since 1998)
- → CERN Axion Solar Telescope (CAST) (just started)

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

# Horizontally Moving Platform



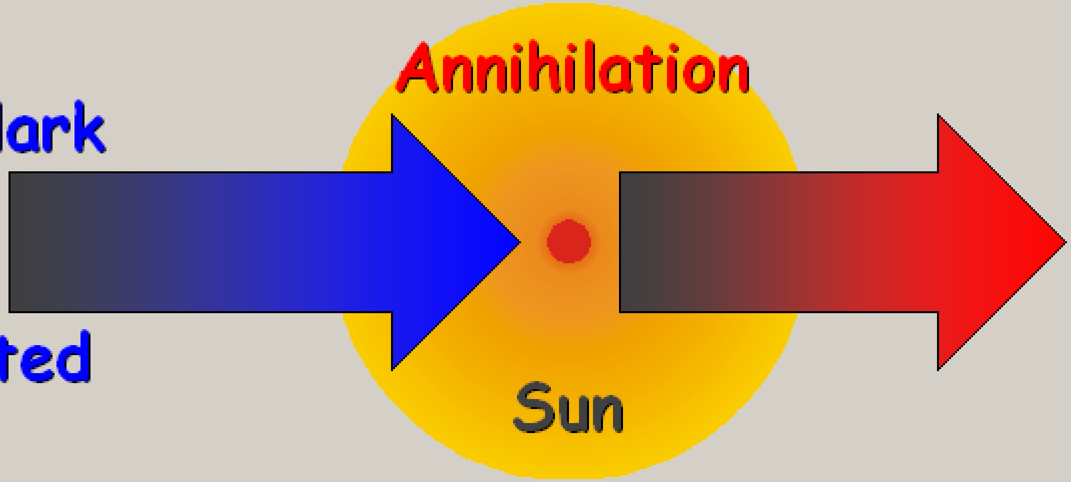

**Cern Axion Solar Telescope**

# Recent Picture of CAST

# Search for Neutralino Dark Matter

## Indirect Method (Neutrino Telescopes)

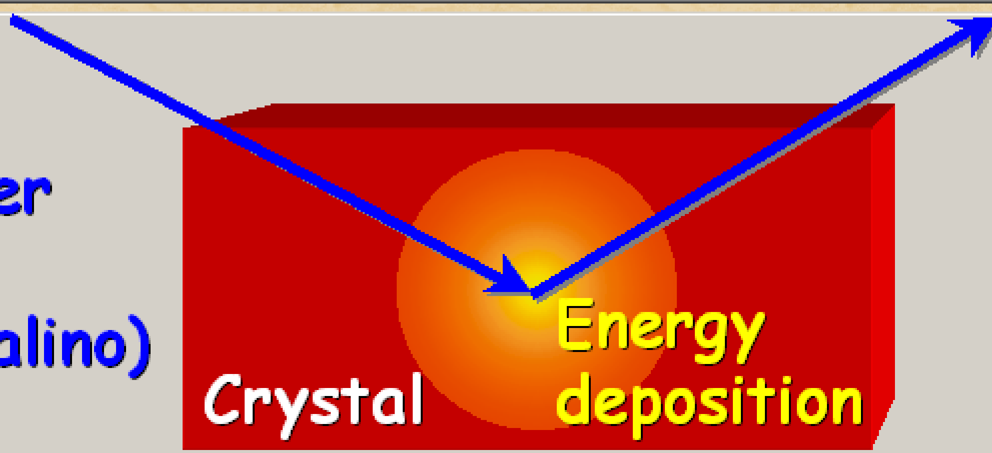
Galactic dark matter particles are accreted




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

## Direct Method (Laboratory Experiments)

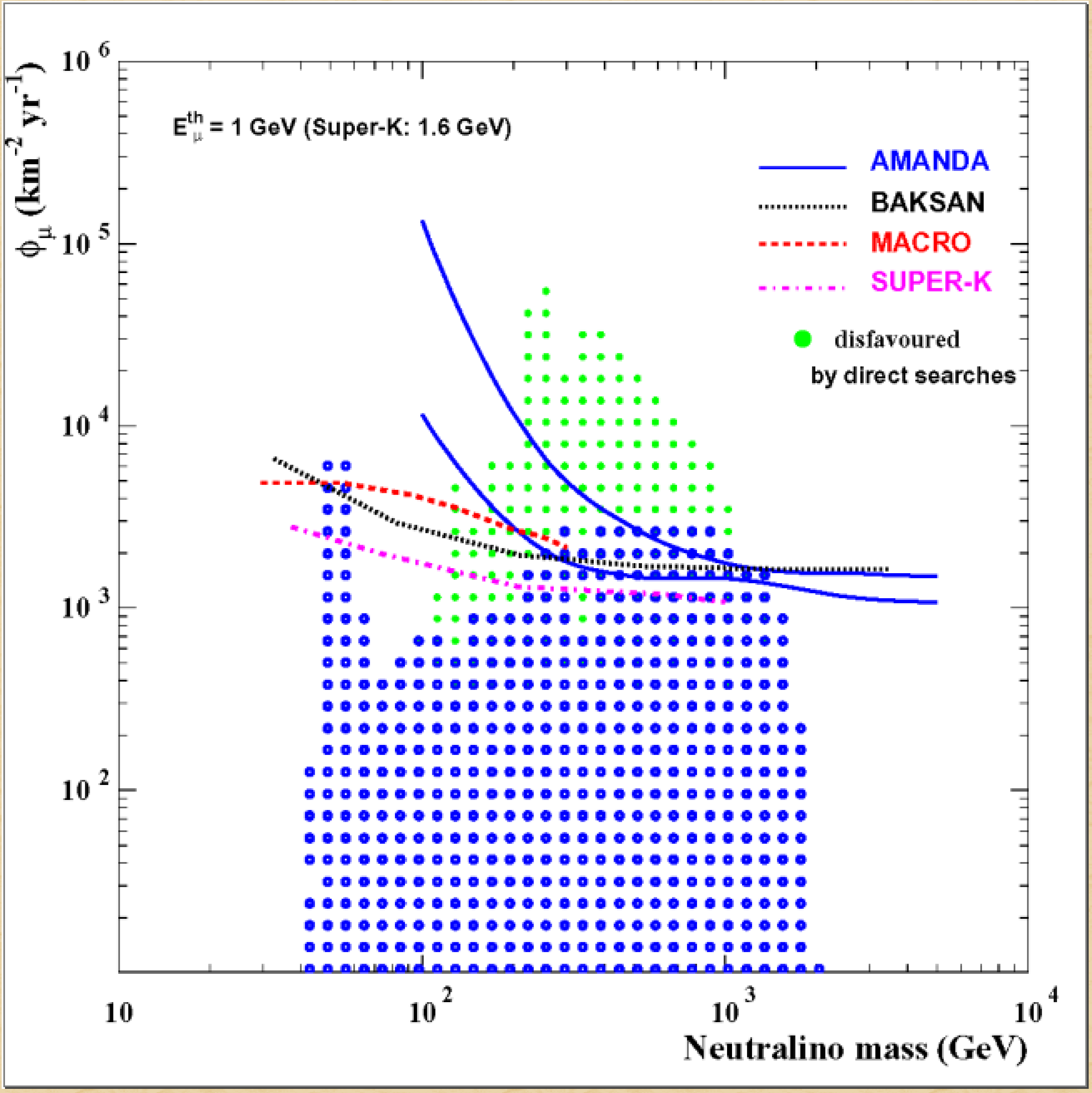
Galactic dark matter particle (e.g.neutralino)




Recoil energy (few keV) is measured by

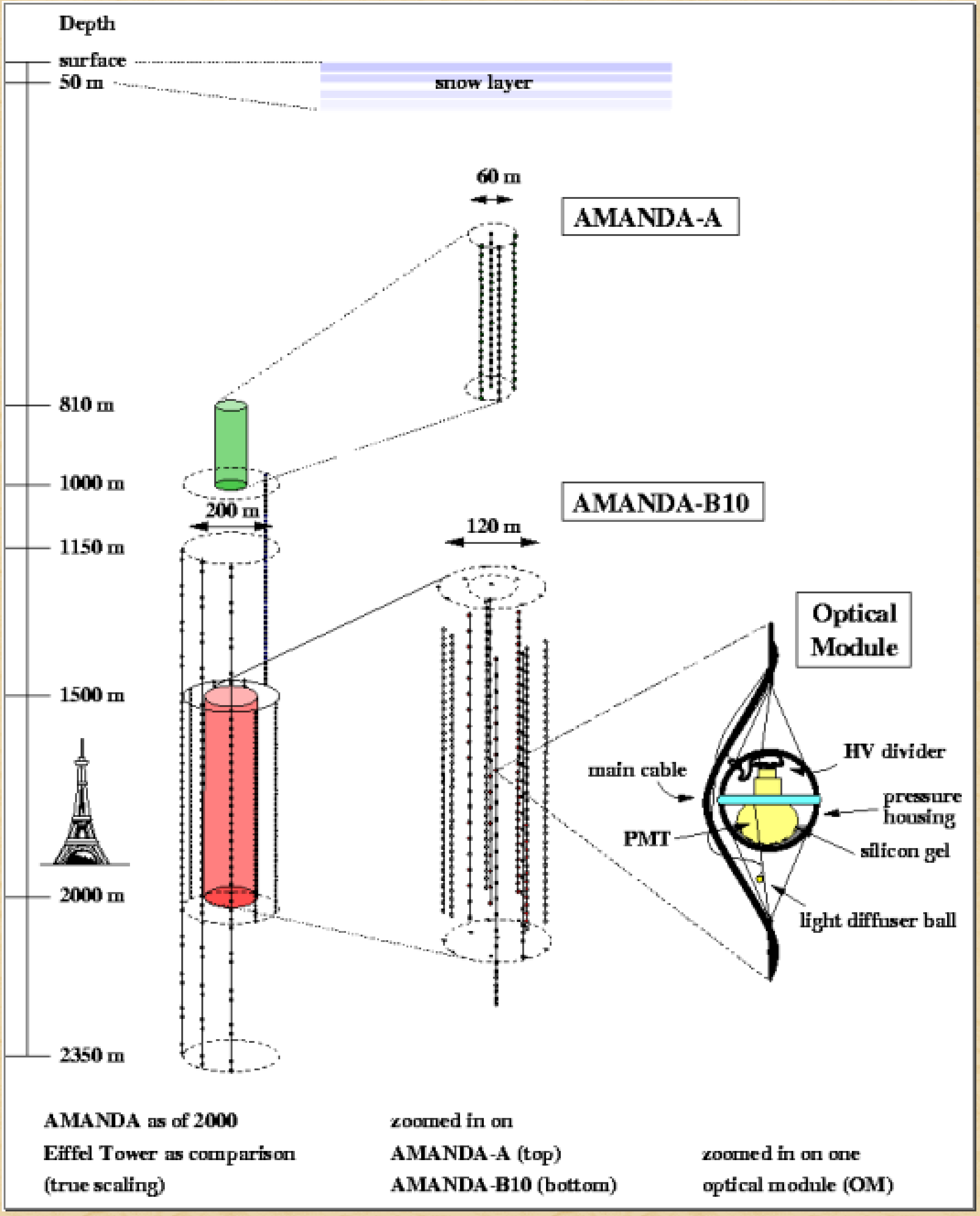
- Ionisation
- Scintillation
- Cryogenic

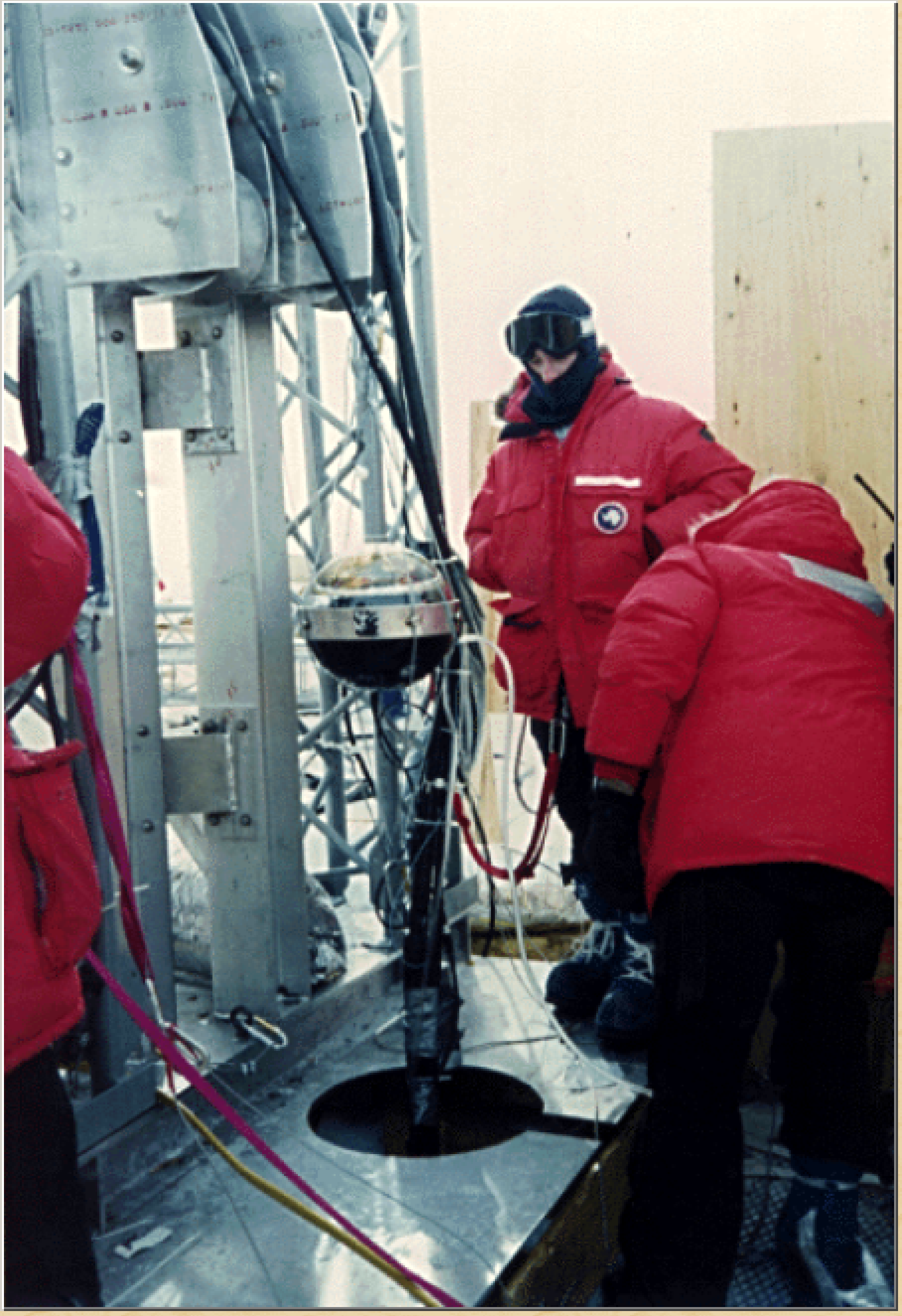
# Current Limits from WIMP Searches



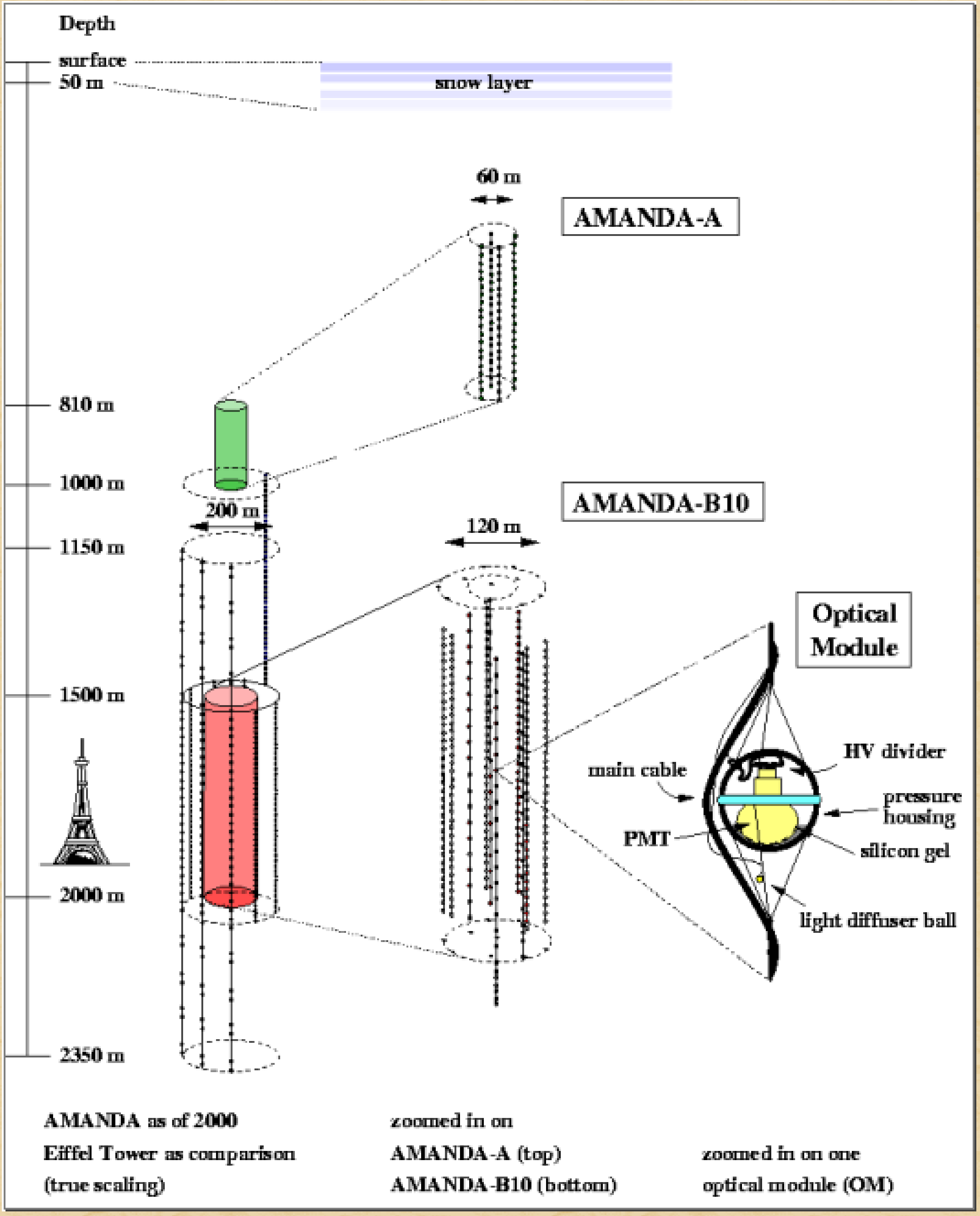

Limits from WIMP Annihilation in the Earth astro-ph/0202370

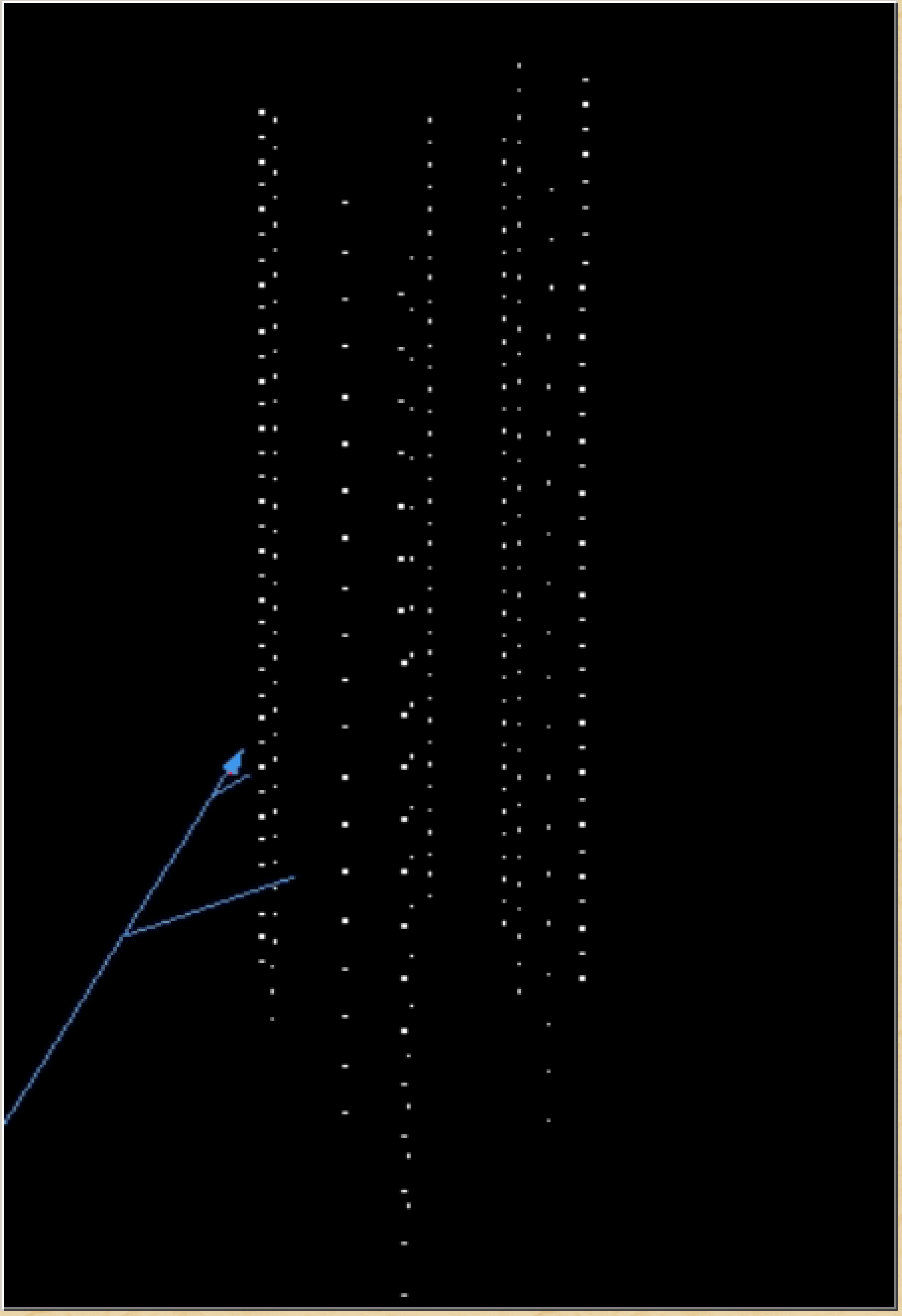
# AMANDA - South Pole Neutrino Telescope



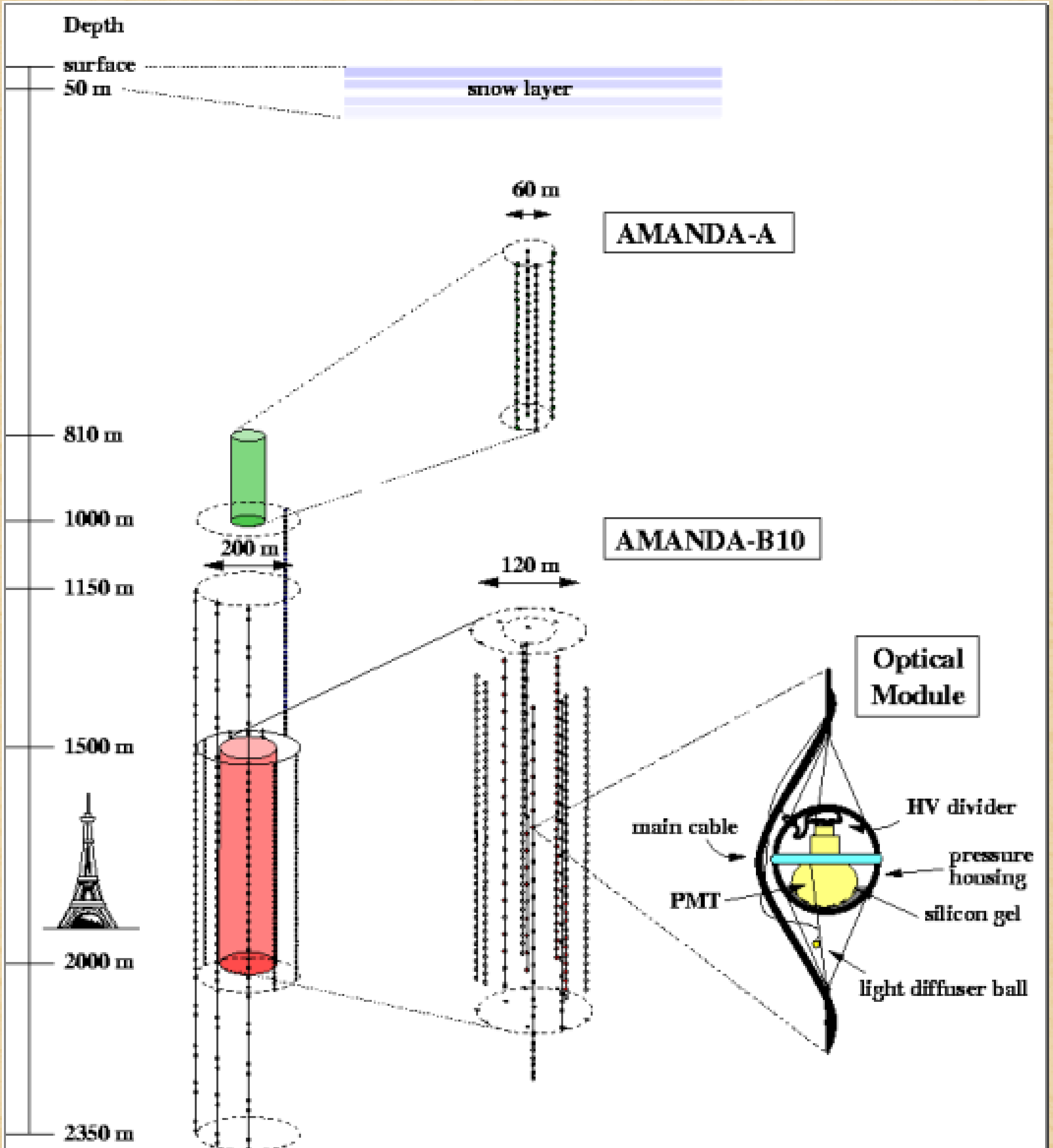



# AMANDA - South Pole Neutrino Telescope



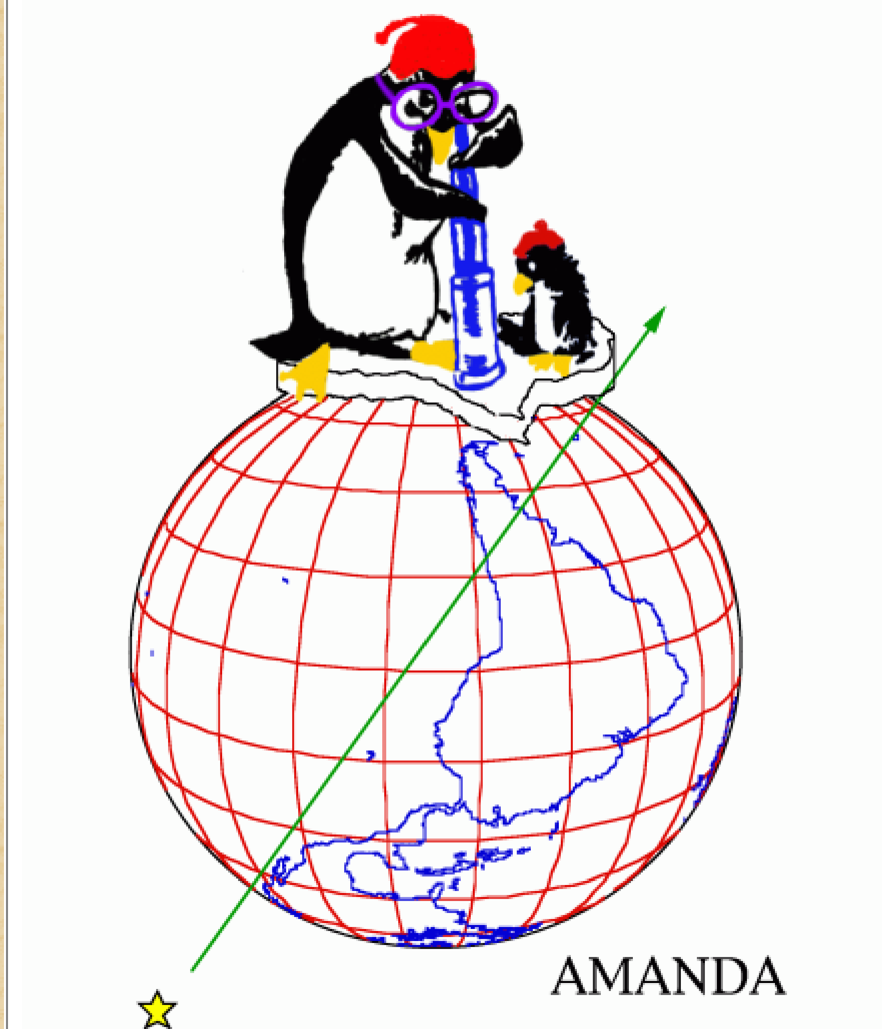
# AMANDA - South Pole Neutrino Telescope



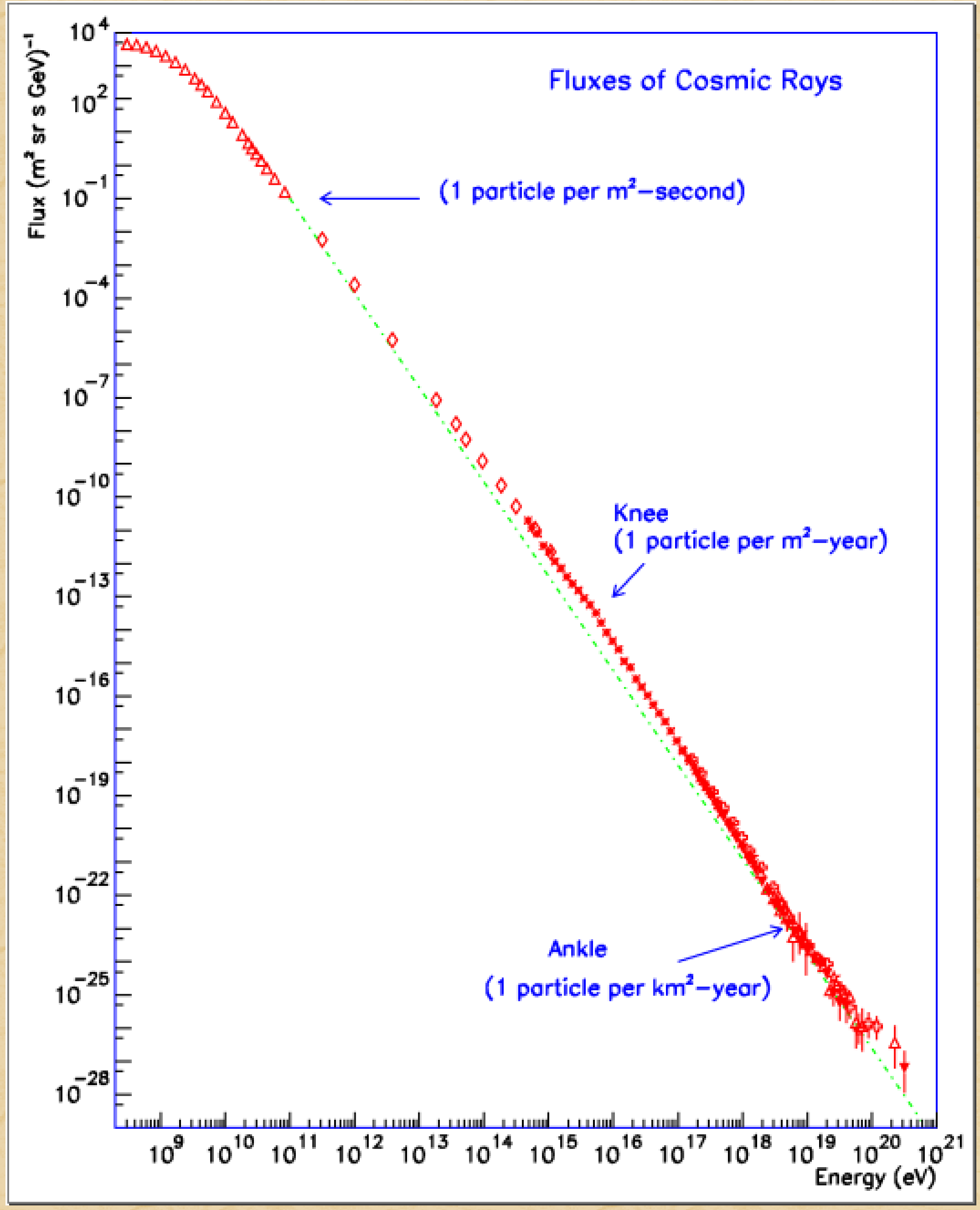

AMANDA as of 2000
Eiffel Tower as comparison
(true scaling)

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

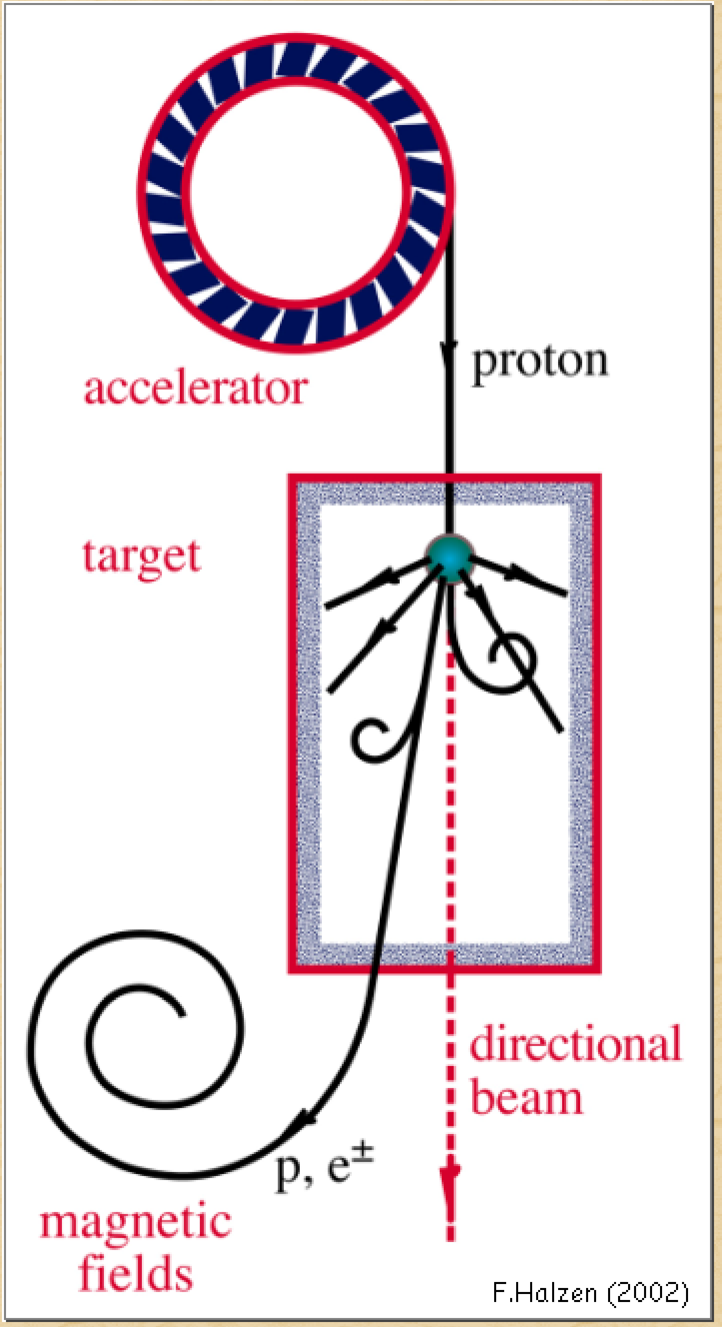
zoomed in on one
optical module (OM)

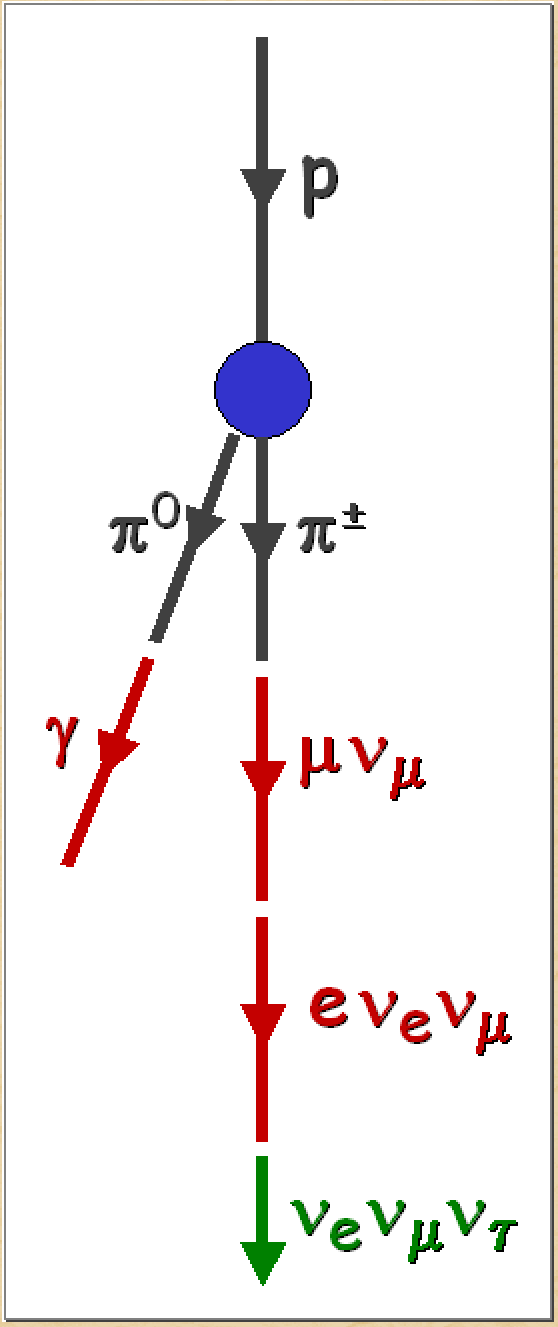


# Global Cosmic Ray Spectrum



# Neutrino Beams: Heaven and Earth



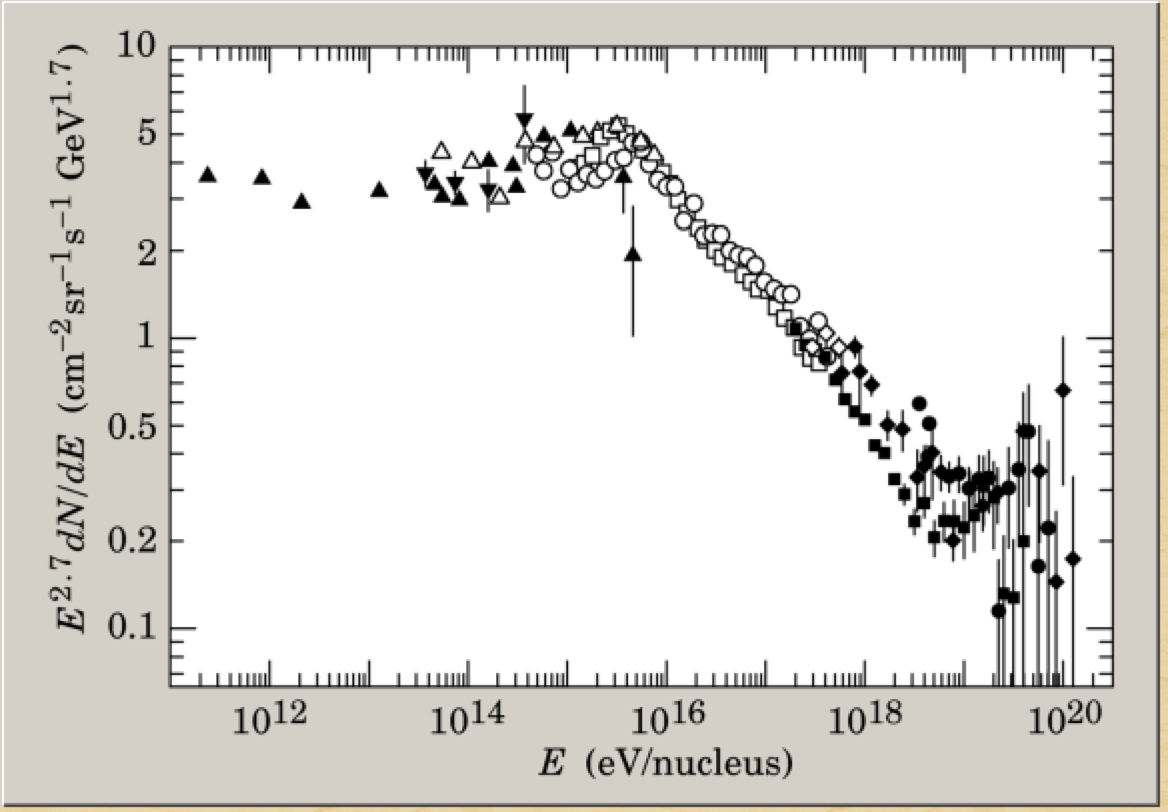




**Target:**
**Protons or Photons**

**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

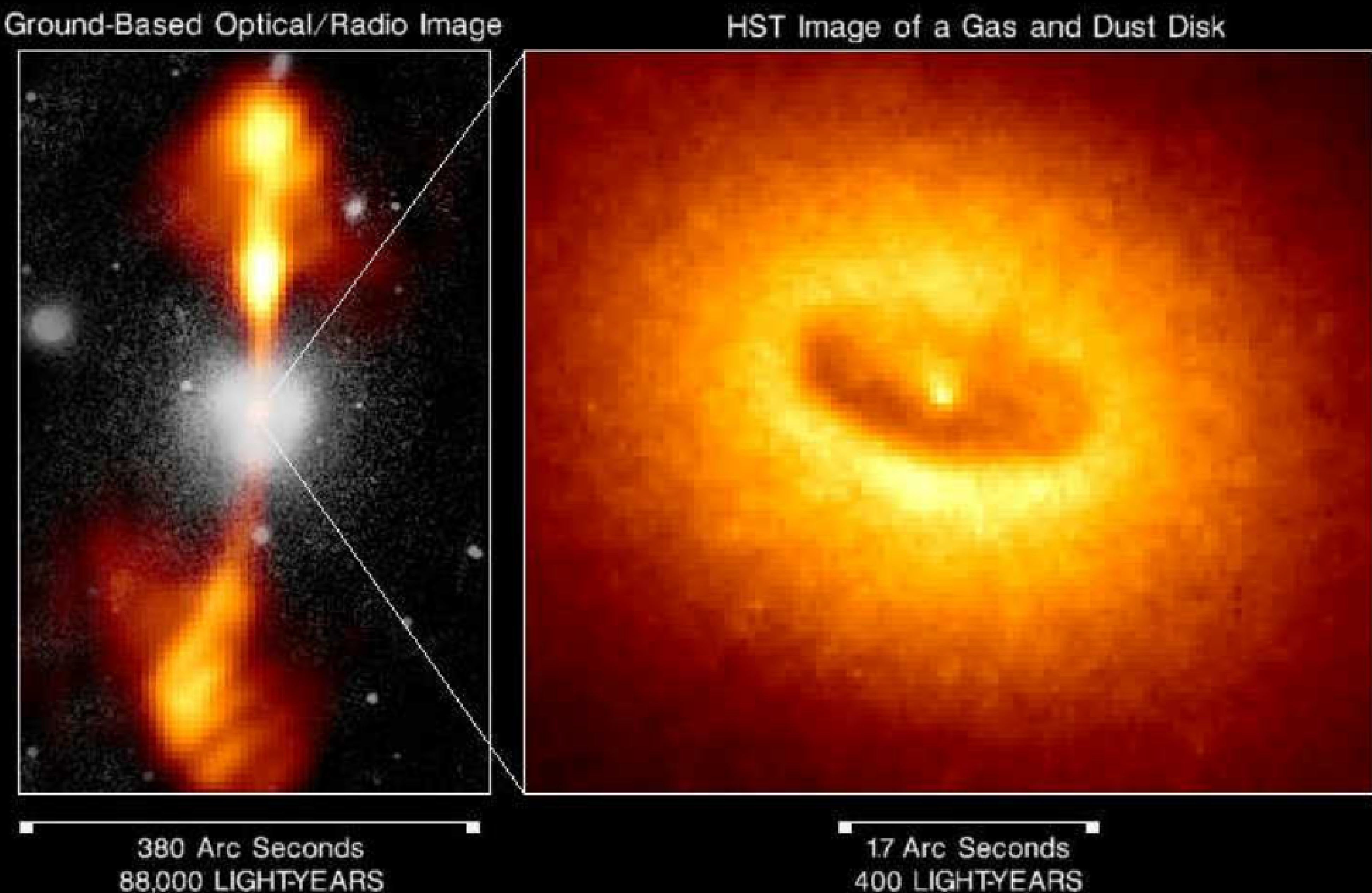
Proton magnetic field deflection

GZK cutoff

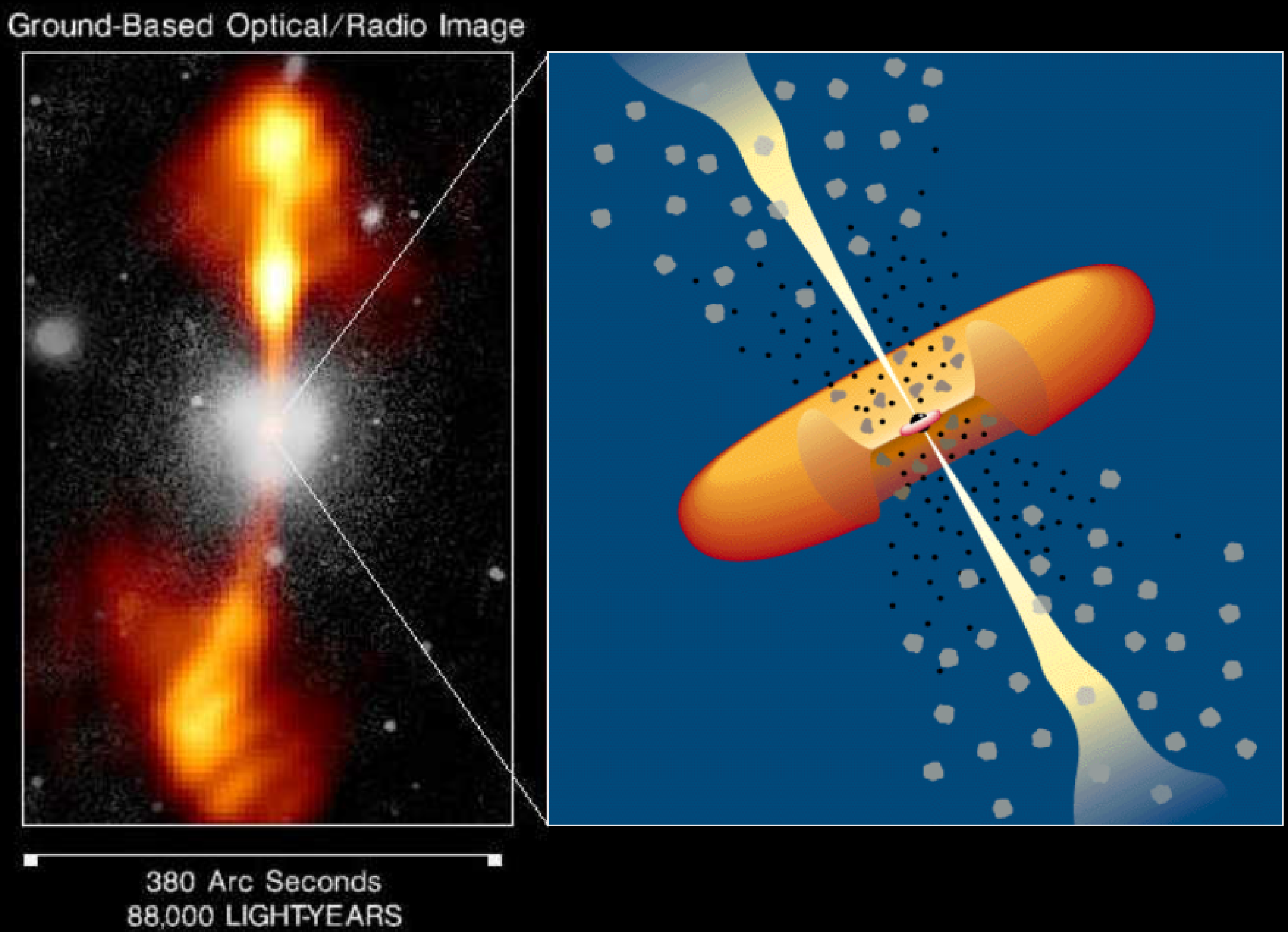
**Opportunity for neutrino astronomy**

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

# Core of the Galaxy NGC 4261



# Core of the Galaxy NGC 4261



# High-Energy Neutrinos from the Sun

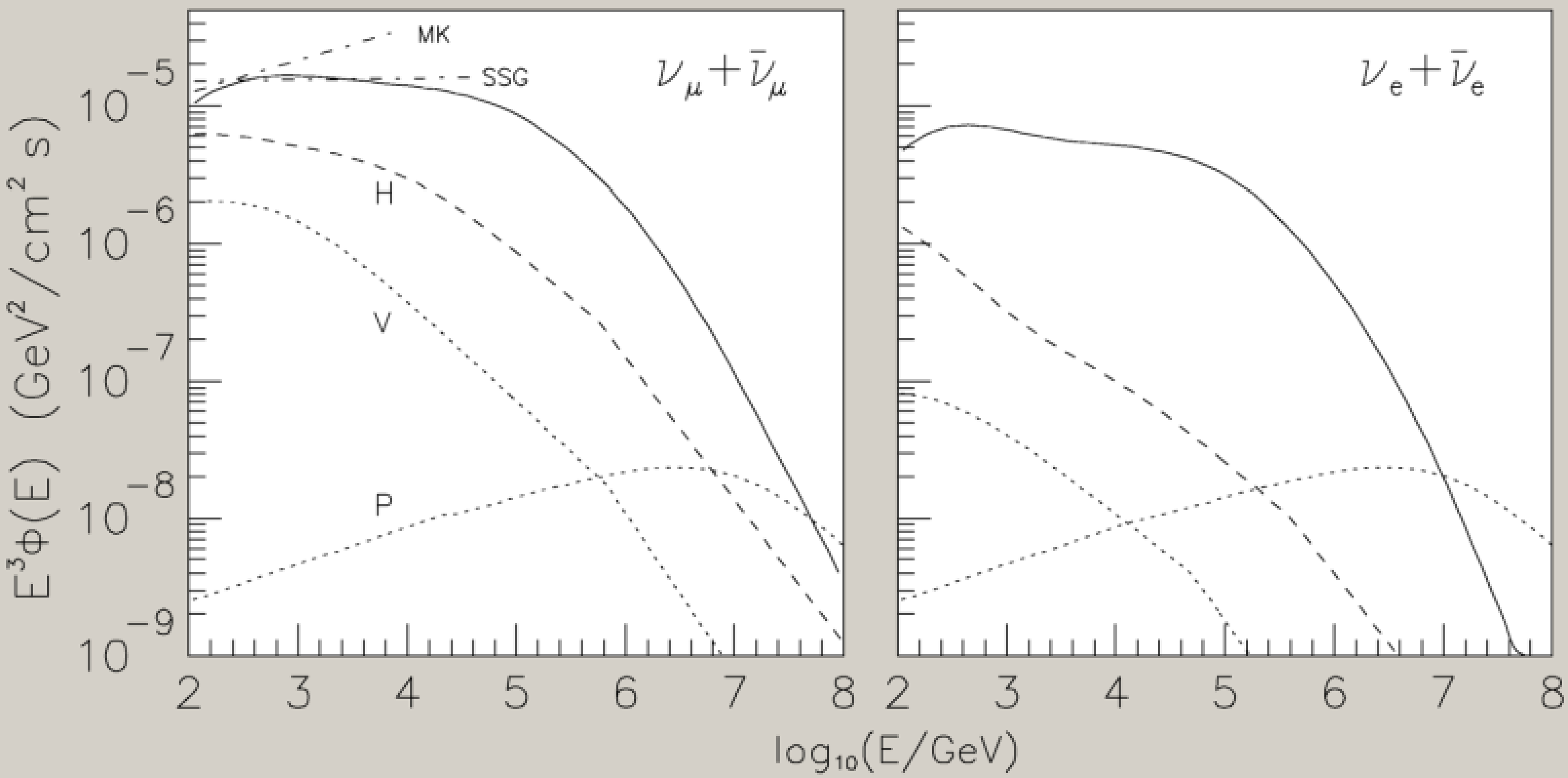
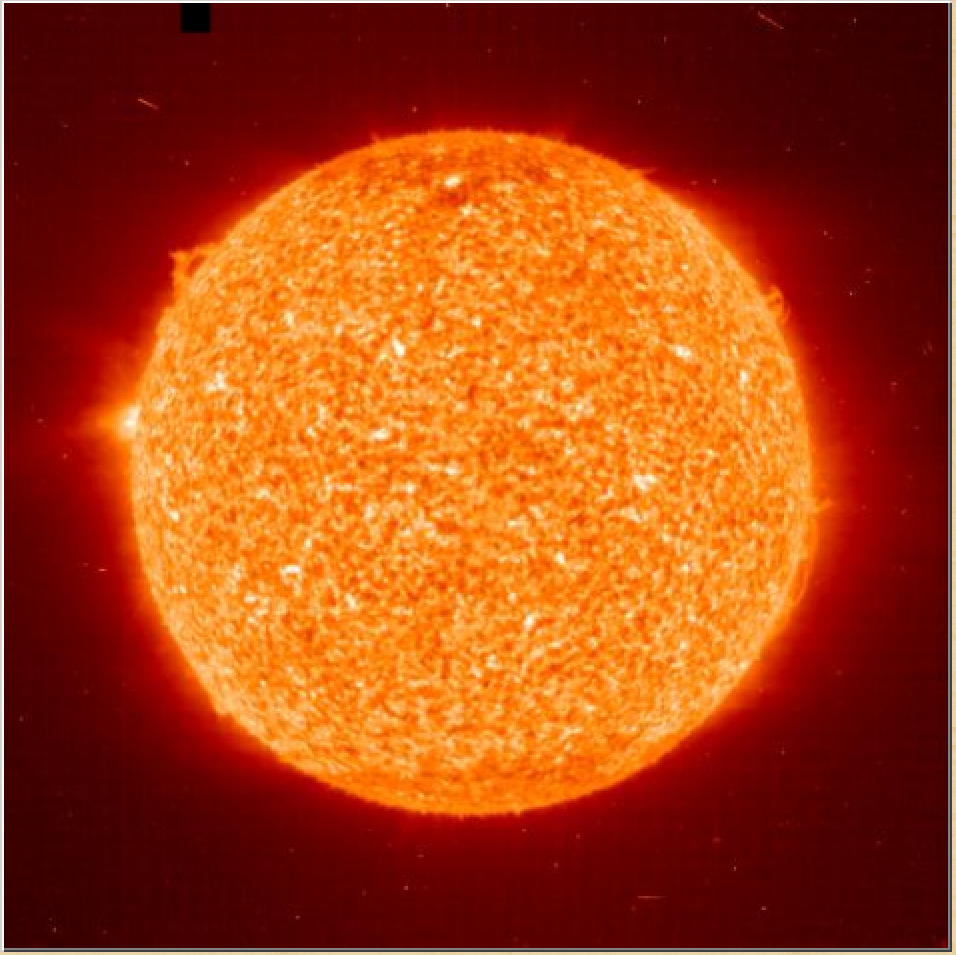



Figure 4: *Cosmic ray induced $E^3$-weighted neutrino fluxes at the Earth integrated over the solid angle of the Sun. The fluxes from the Sun obtained in this study (solid lines) are compared with the earlier calculation SSG [22] and the one MK derived from [2], as well as those from the Earth's atmosphere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



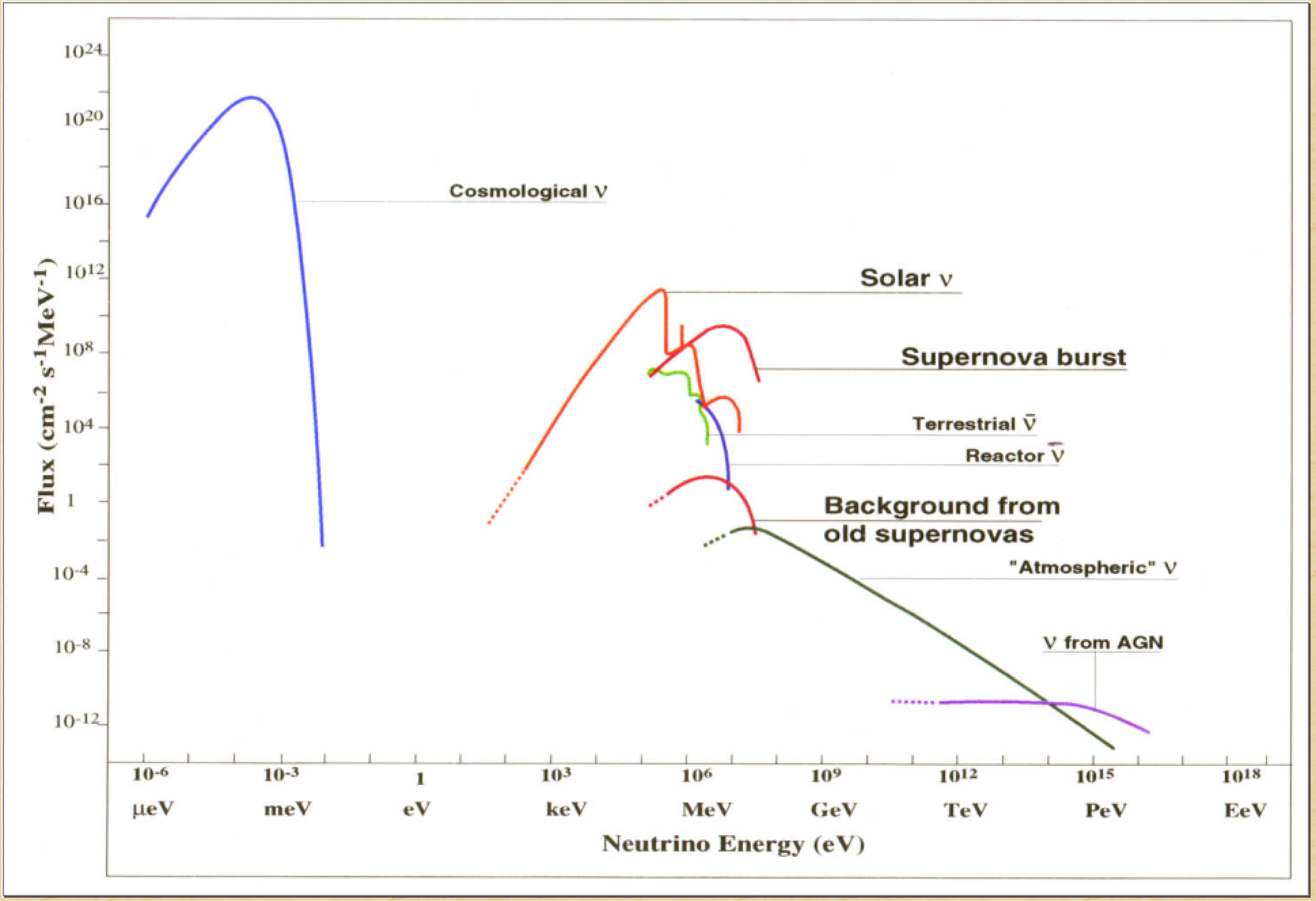
**Thermal plasma reactions**
E ~ 1 eV - 30 keV
No apparent way to measure

**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<br>• Crucial role in big-bang nucleosynthesis<br>• Dark-matter component (but subdominant)<br>• May be responsible for baryonic matter in the universe (leptogenesis)<br>• Important/dominant cooling agent of stars<br>• May trigger supernova explosions<br>• May be crucial for r-process nucleosynthesis |
| Heavenly laboratories for particle physics | • Cosmological limit on neutrino mass scale<br>• Flavor oscillations of solar neutrinos<br>• Neutrino oscillations of future galactic supernova<br>• 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)<br>• Watch stellar collapse directly<br>• Neutrinos from all cosmological supernovae<br>• Astrophysical accelerators for cosmic rays |