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

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Neutrinos in Astrophysics and Cosmology
Part I
Introduction

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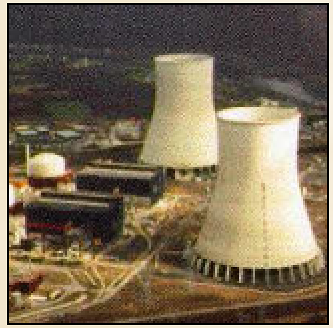
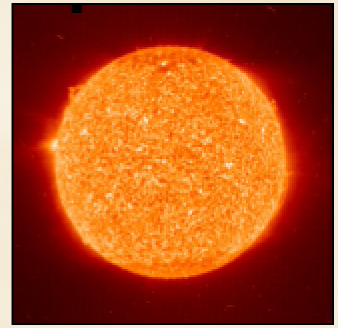
Where do Neutrinos Appear in Nature?

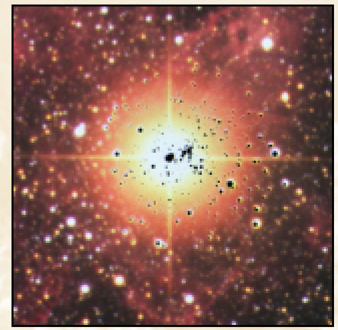
✓ Nuclear Reactors





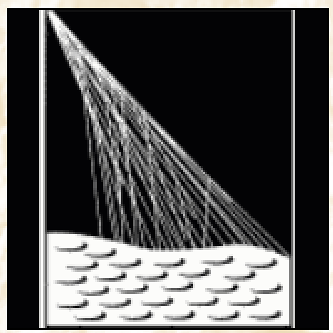
Sun ✓

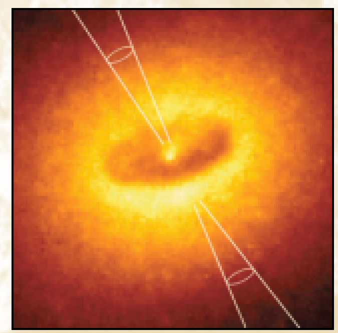
✓ Particle Accelerators



Supernovae
(Stellar Collapse)
SN 1987A ✓

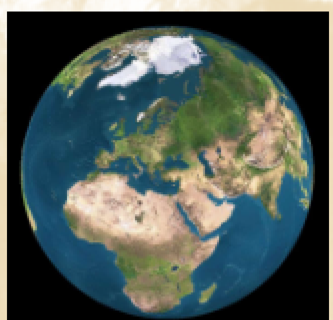
✓ Earth Atmosphere
(Cosmic Rays)





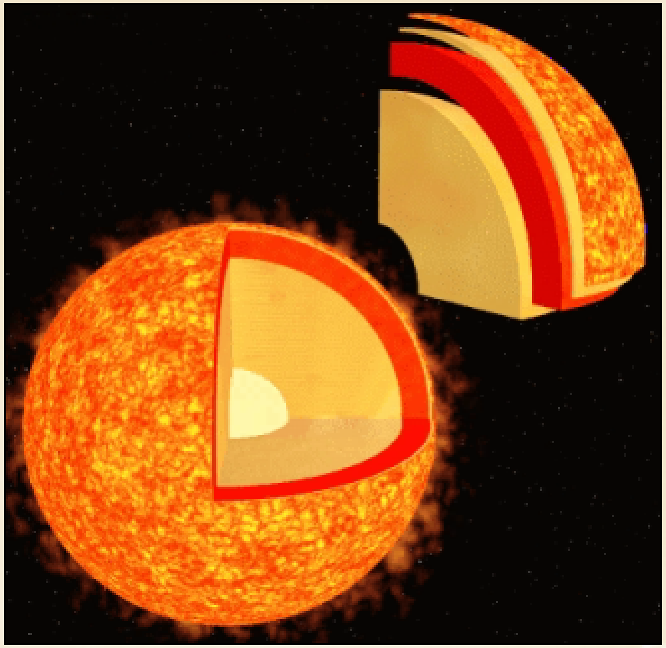
Astrophysical
Accelerators Soon ?

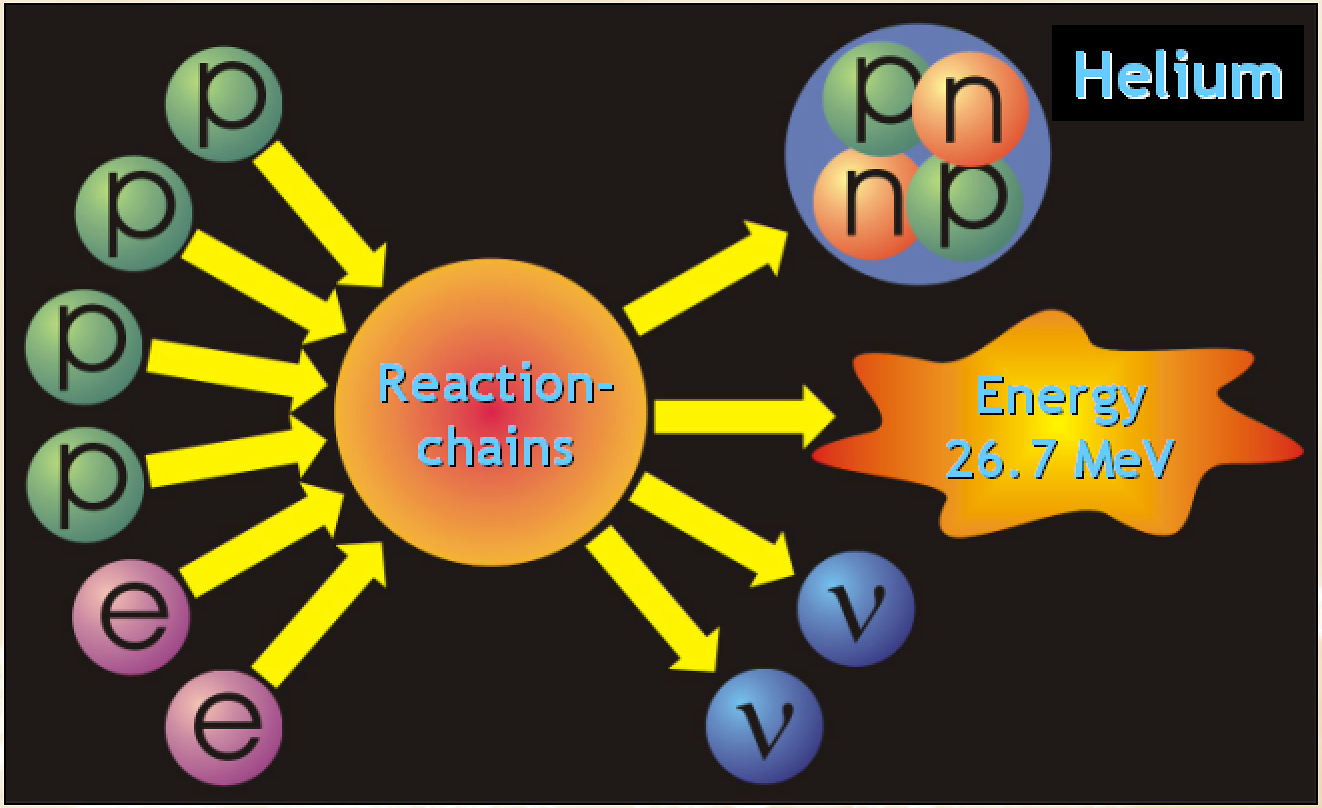
Earth Crust
(Natural
Radioactivity)
Soon ?



Cosmic Big Bang
(Today 330 ν/cm^3)
Indirect Evidence

Neutrinos from the Sun





Solar radiation: 98 % light
2 % neutrinos
At Earth 66 billion neutrinos/cm^2 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 α-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 α-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* He^4 *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 (α-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 α-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

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

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 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.*

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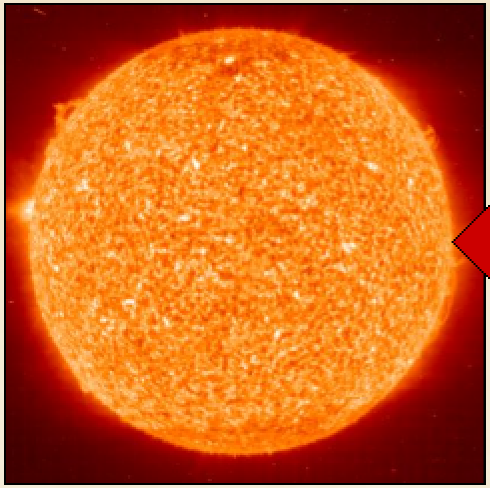
Sun Glasses for Neutrinos?

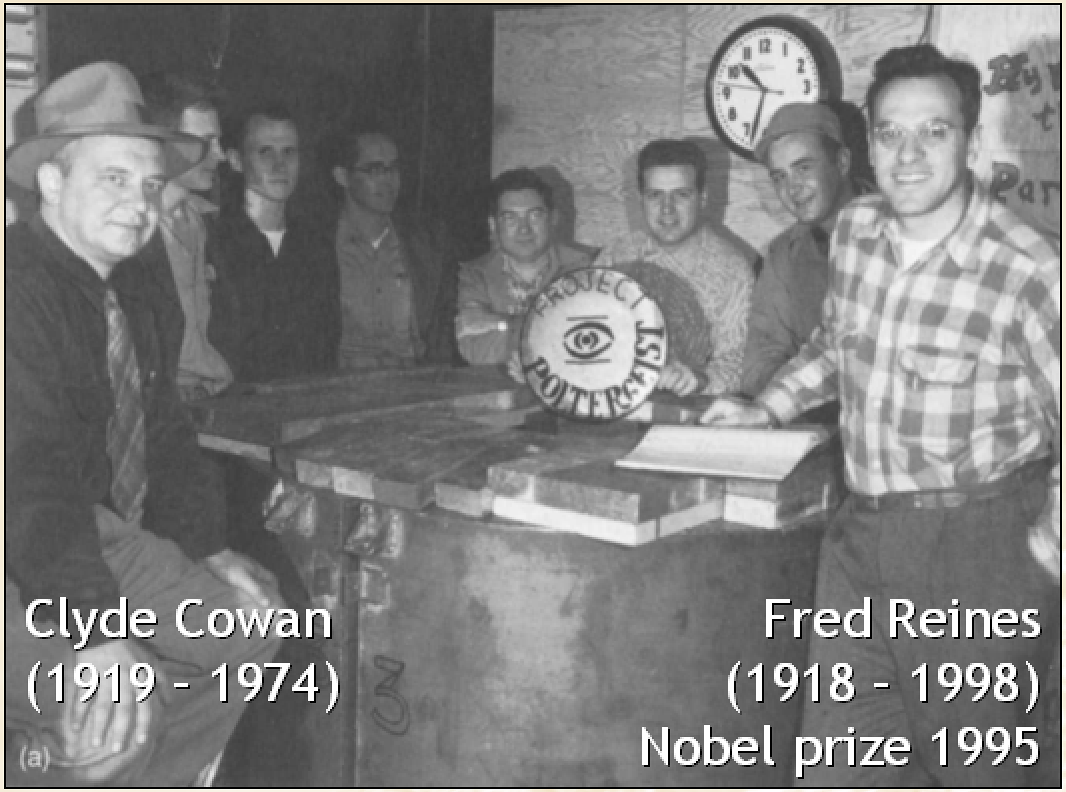


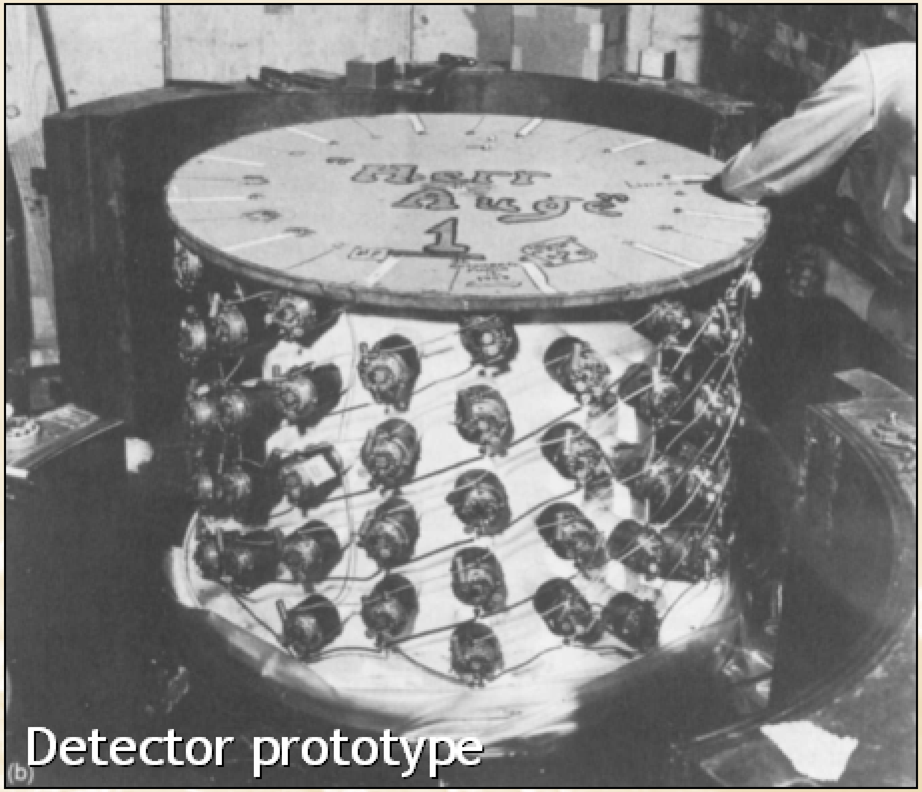
8.3 light minutes

1000 light years of lead needed to shield solar neutrinos

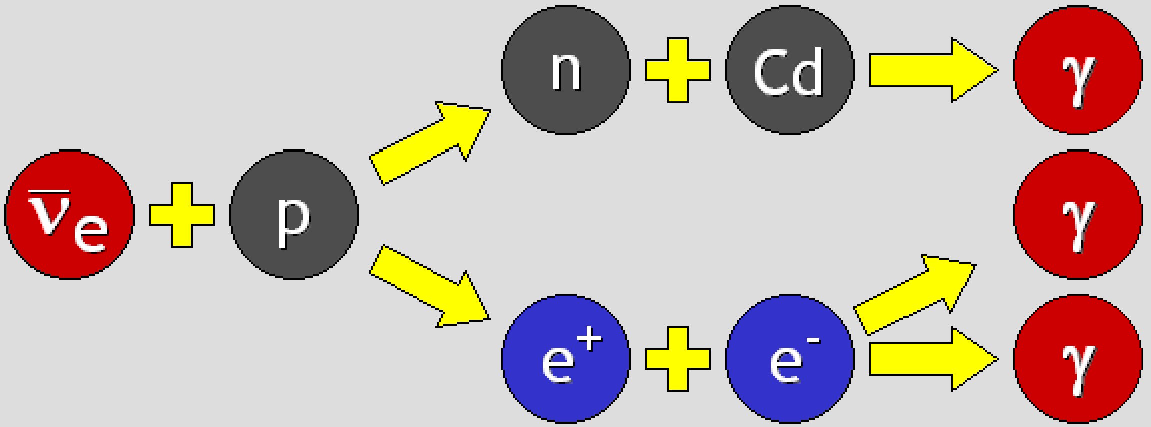
<u>Bethe & Peierls 1934:</u>
"… this evidently means that one will never be able to observe a neutrino."

First Detection (1954 - 1956)





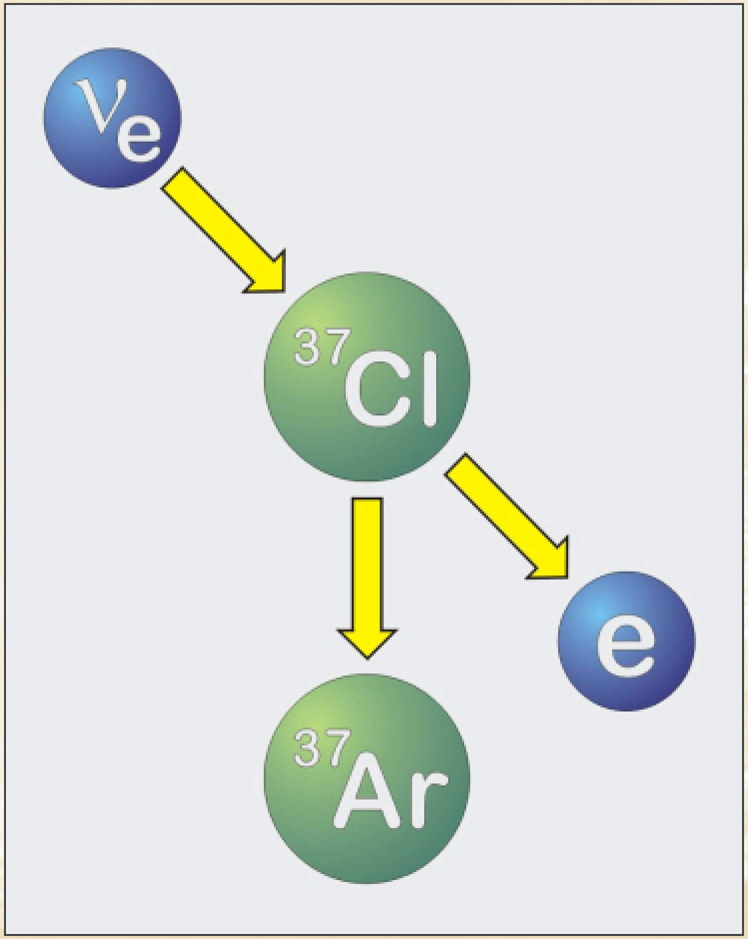
Anti-Electron
Neutrinos
from
Hanford
Nuclear Reactor

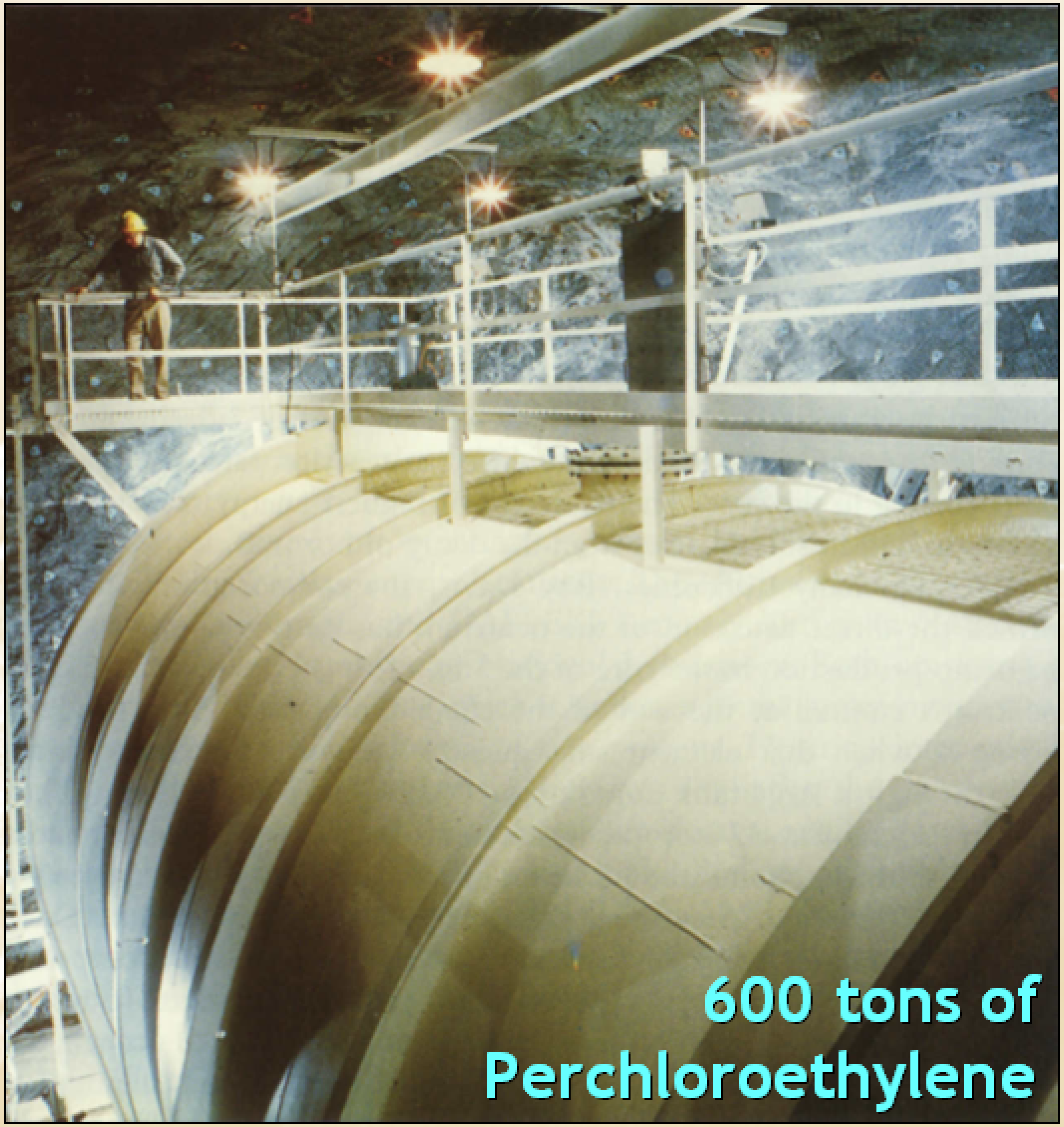


3 Gammas
in coincidence

First Measurement of Solar Neutrinos

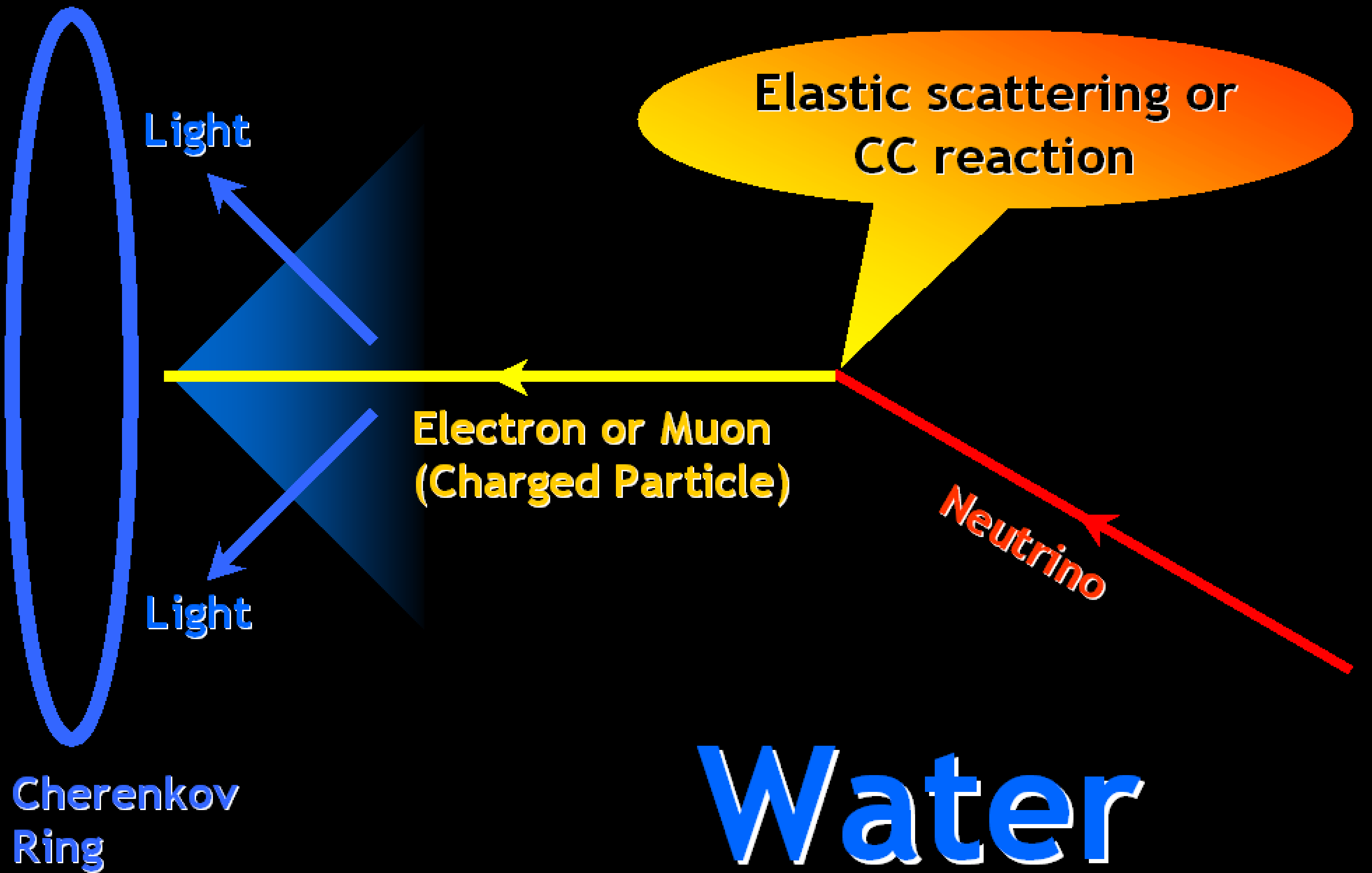
Inverse beta decay of chlorine



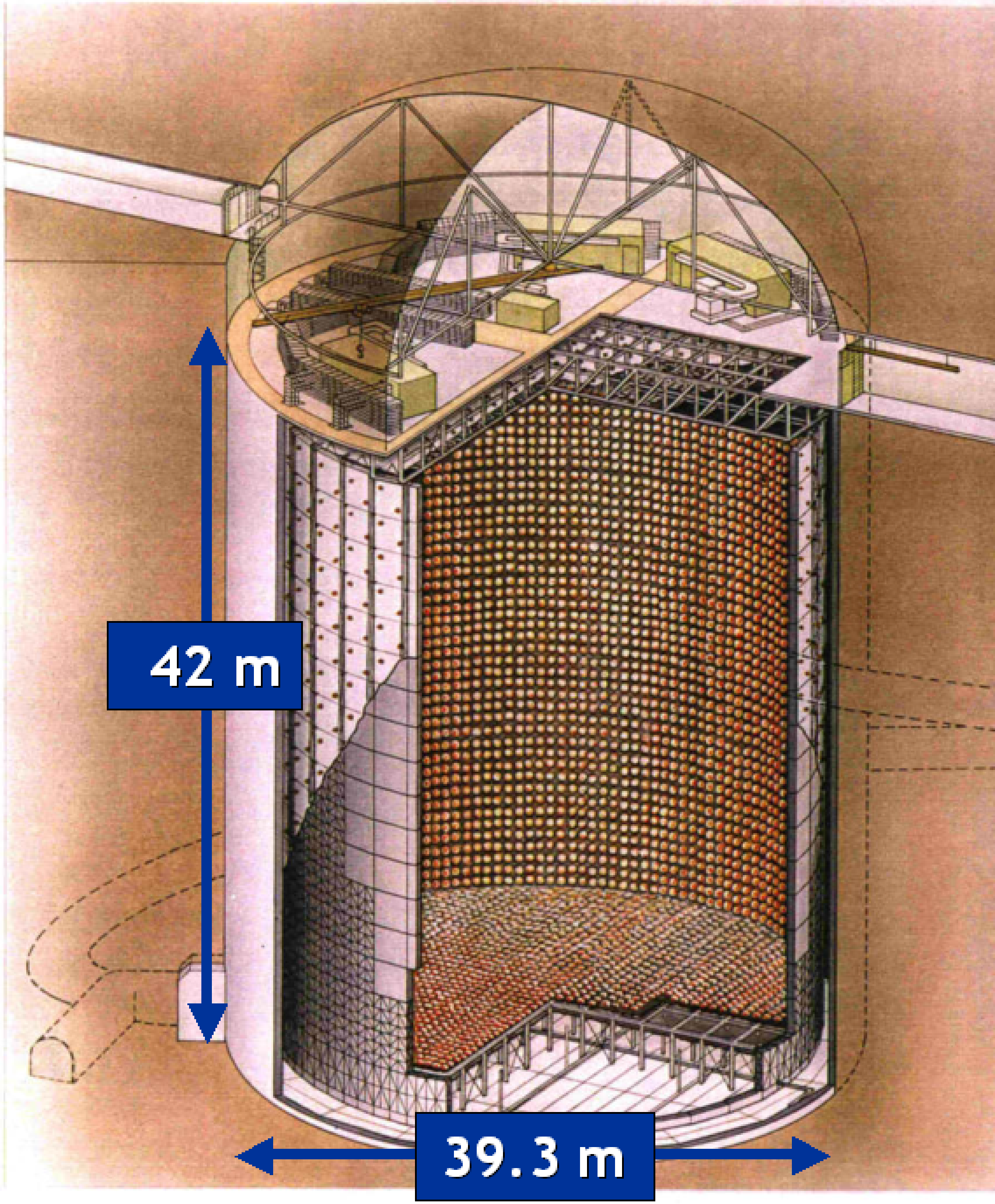


Homestake solar neutrino observatory (1967–2002)

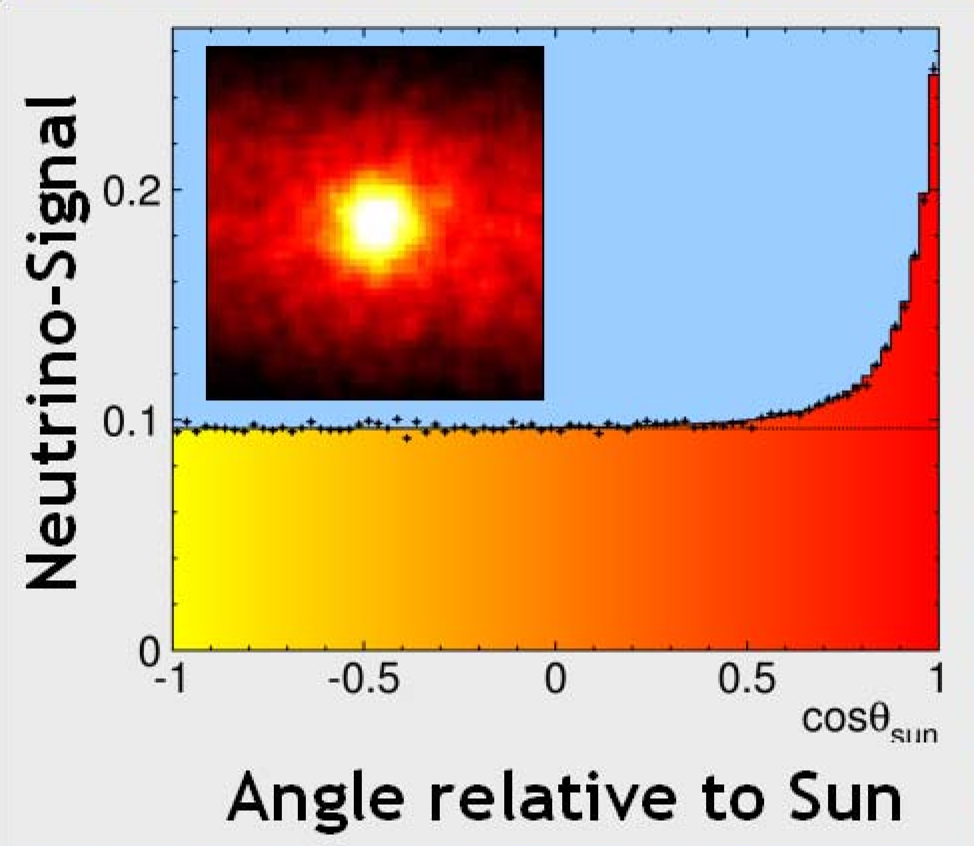
Cherenkov Effect

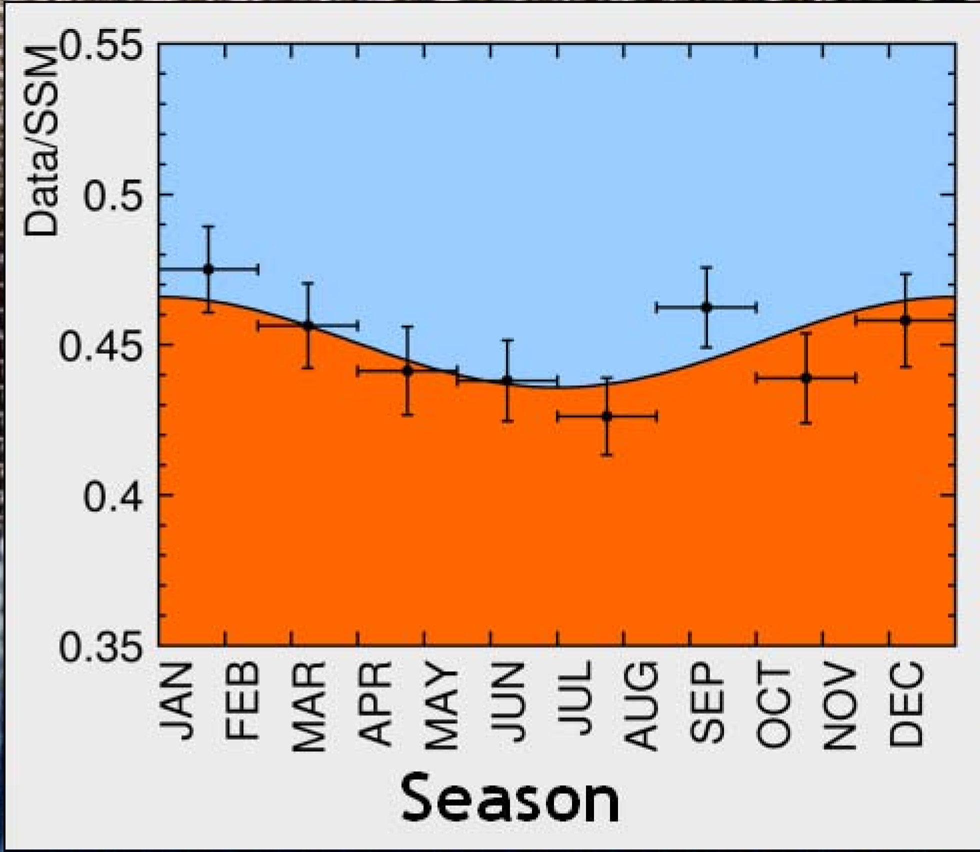


Super-Kamiokande Neutrino Detector

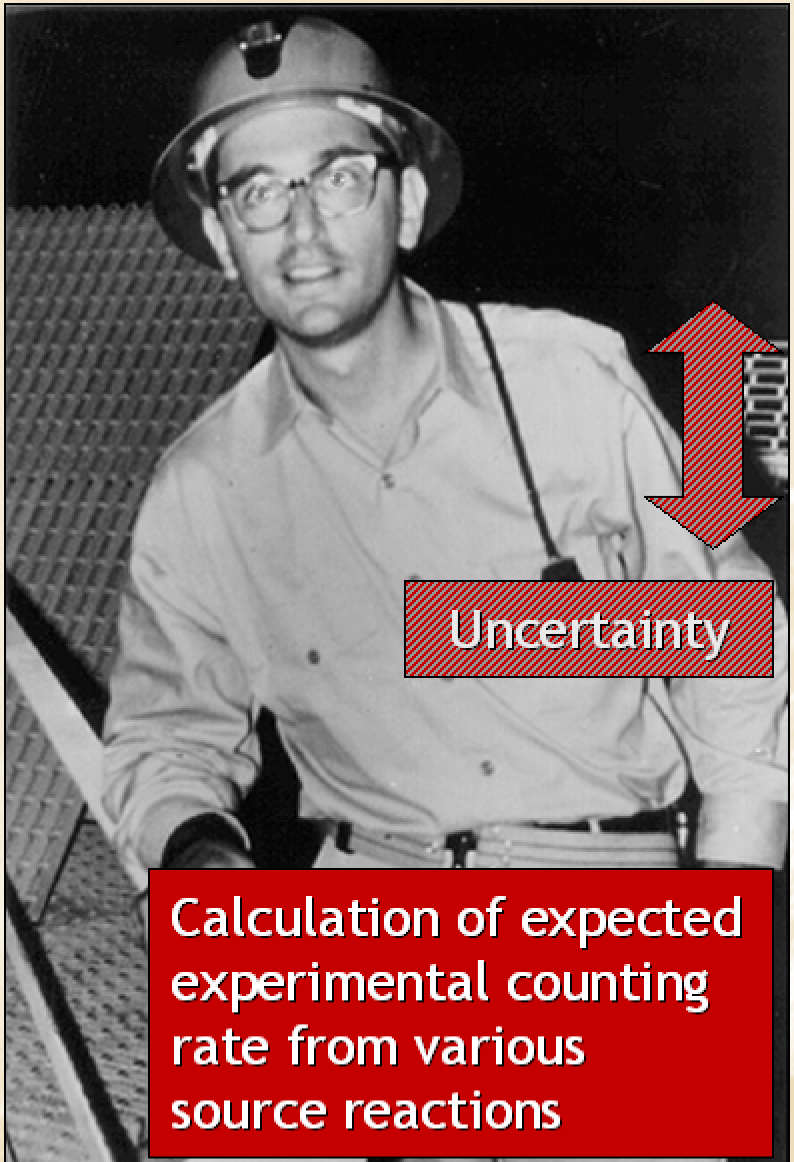


Super-Kamiokande: Sun in the Light of Neutrinos





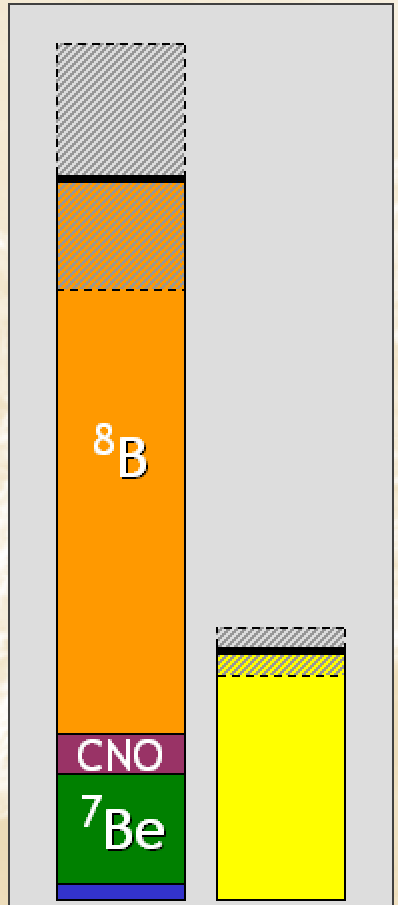
Missing Neutrinos from the Sun



John Bahcall

Homestake

Chlorine



Raymond Davis Jr.

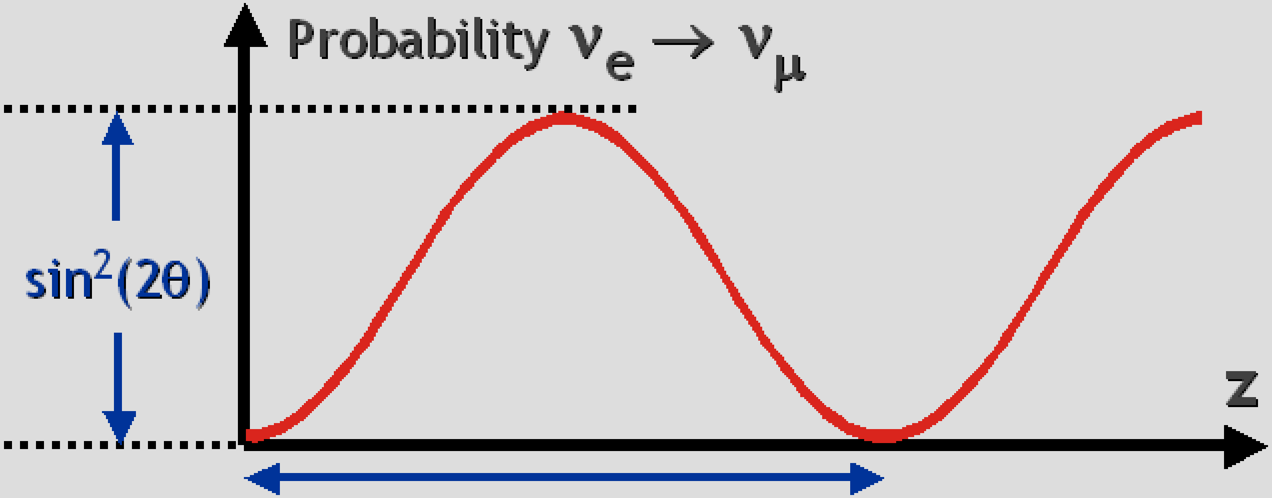
Neutrino Flavor Oscillations

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 $p = \sqrt{E^2 - m^2} \approx E - \frac{m^2}{2E}$

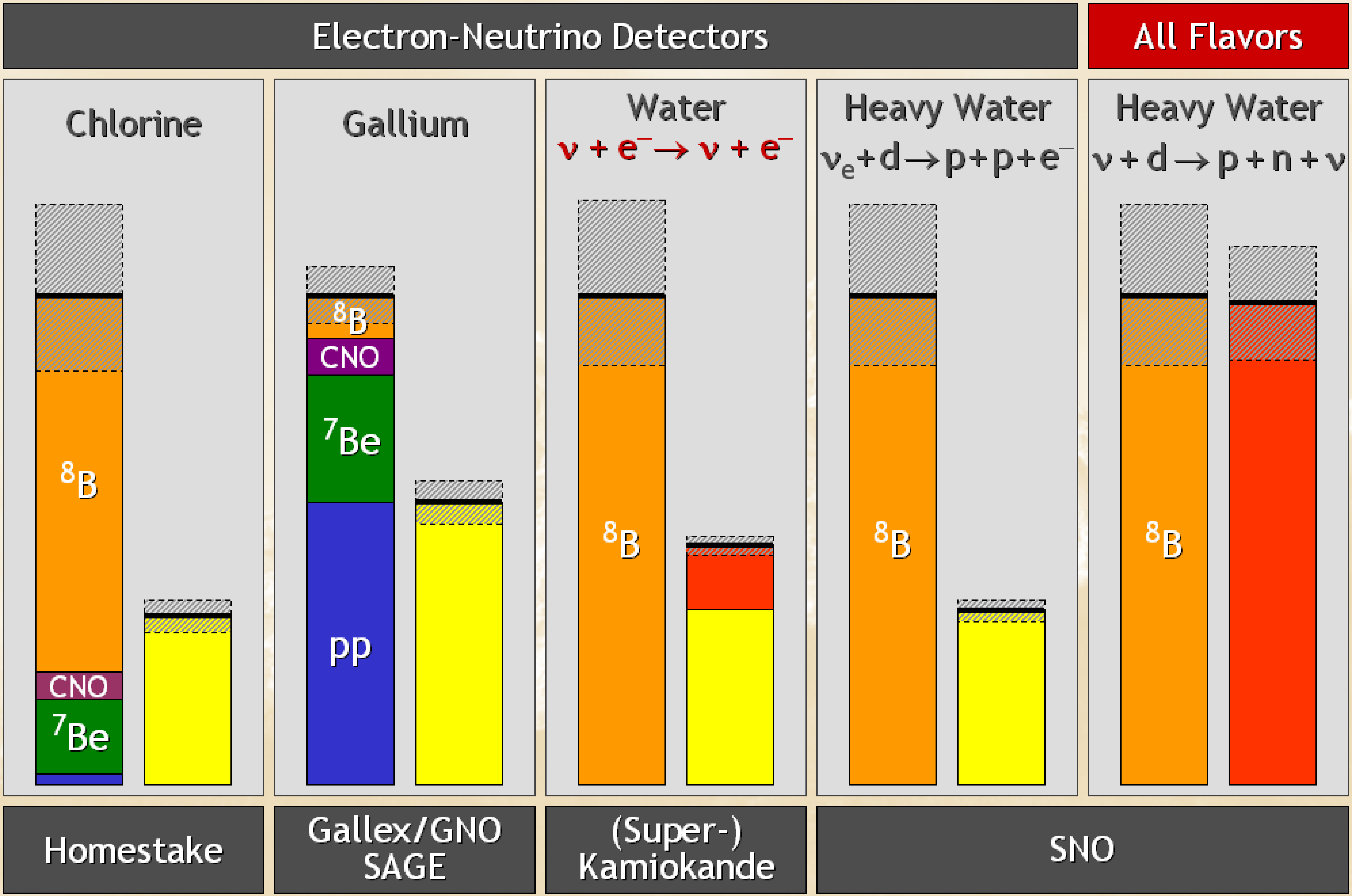
Phase difference $\frac{\delta m^2}{2E} z$ implies flavor oscillations



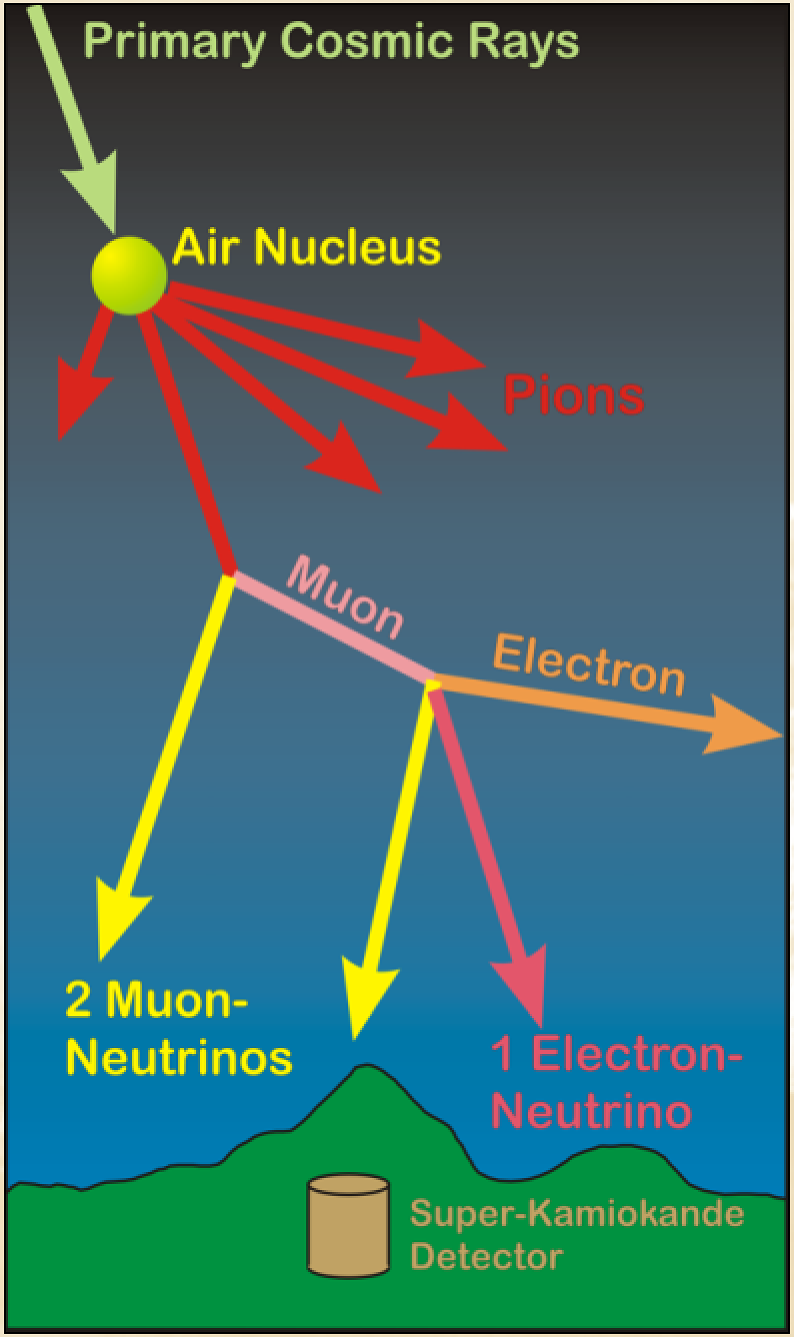
Oscillation Length $\frac{4\pi E}{\delta m^2} = 2.5\,\text{m} \left(\frac{E}{\text{MeV}}\right) \left(\frac{\text{eV}^2}{\delta m^2}\right)$

Bruno Pontecorvo
(1913 - 1993)
Invented nu oscillations

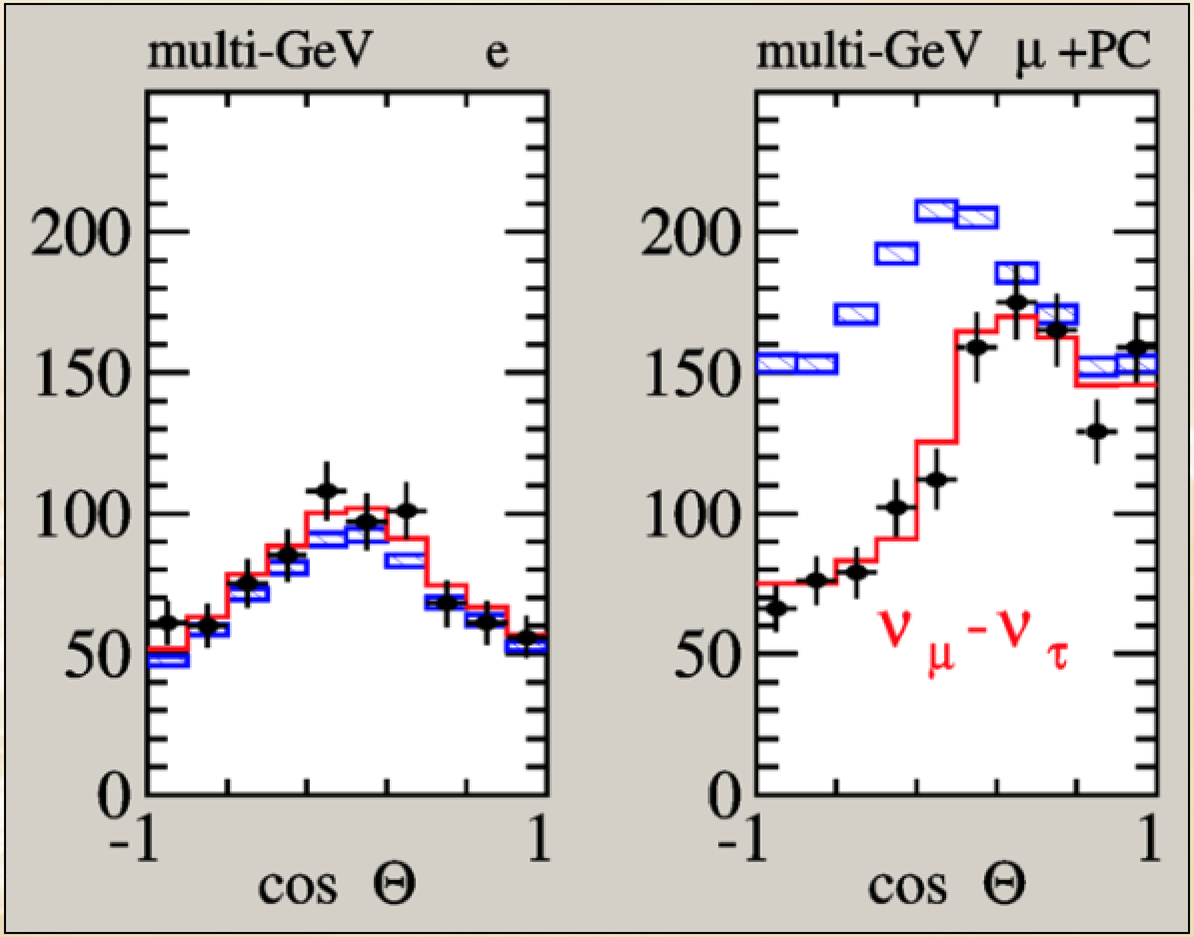
Missing Neutrinos from the Sun



Atmospheric Neutrino Anomaly



Zenith-angle distribution of atmospheric nus in Super-Kamiokande [hep-ex/0210019]



Half of the muon neutrinos from below are missing

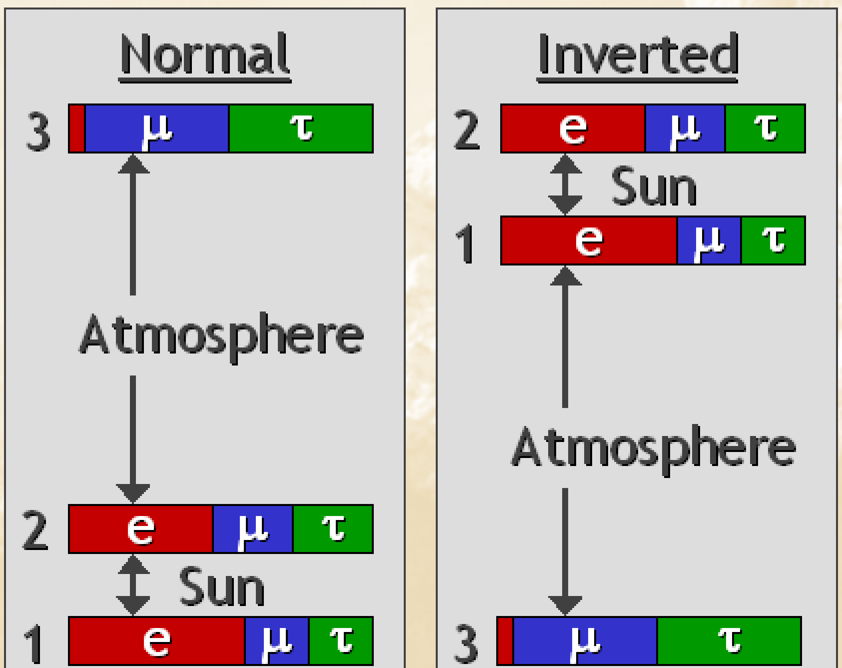
Three-Flavor Neutrino Parameters

Atmospheric/K2K	CHOOZ	Solar/KamLAND	2σ ranges hep-ph/0405172
$37^\circ < \theta_{23} < 54^\circ$	$\theta_{13} < 11^\circ$	$30^\circ < \theta_{12} < 36^\circ$	

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}1 & & \\ & c_{23} & s_{23}\\ & -s_{23} & c_{23}\end{pmatrix}\begin{pmatrix}c_{13} & & e^{-i\delta}s_{13}\\ & 1 & \\ -e^{i\delta}s_{13} & & c_{13}\end{pmatrix}\begin{pmatrix}c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

$c_{12} = \cos\theta_{12}$ etc., δ CP-violating phase

Solar 75–92
Atmospheric 1400–3000
$\Delta m^2/\mathrm{meV}^2$



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

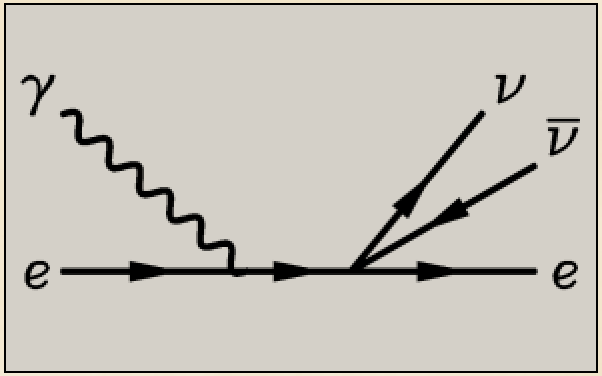
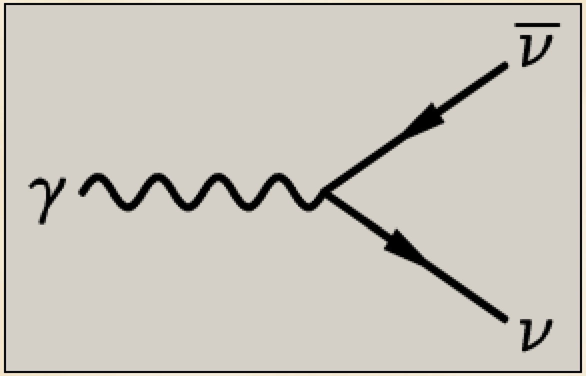
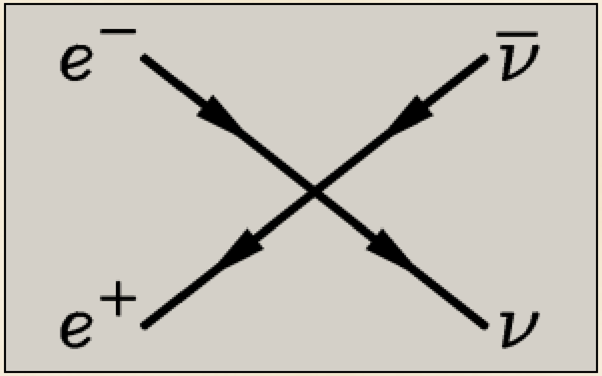


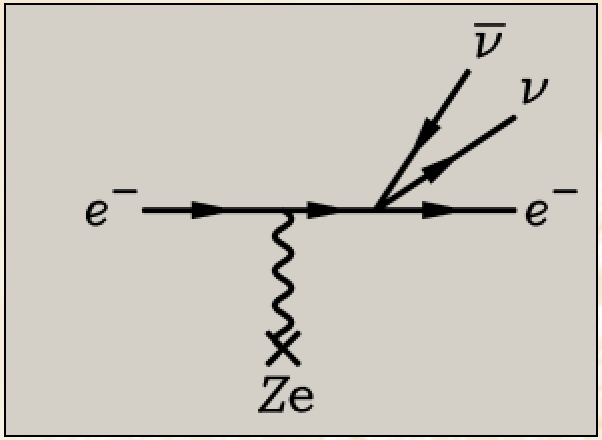
Photo (Compton)



Plasmon decay

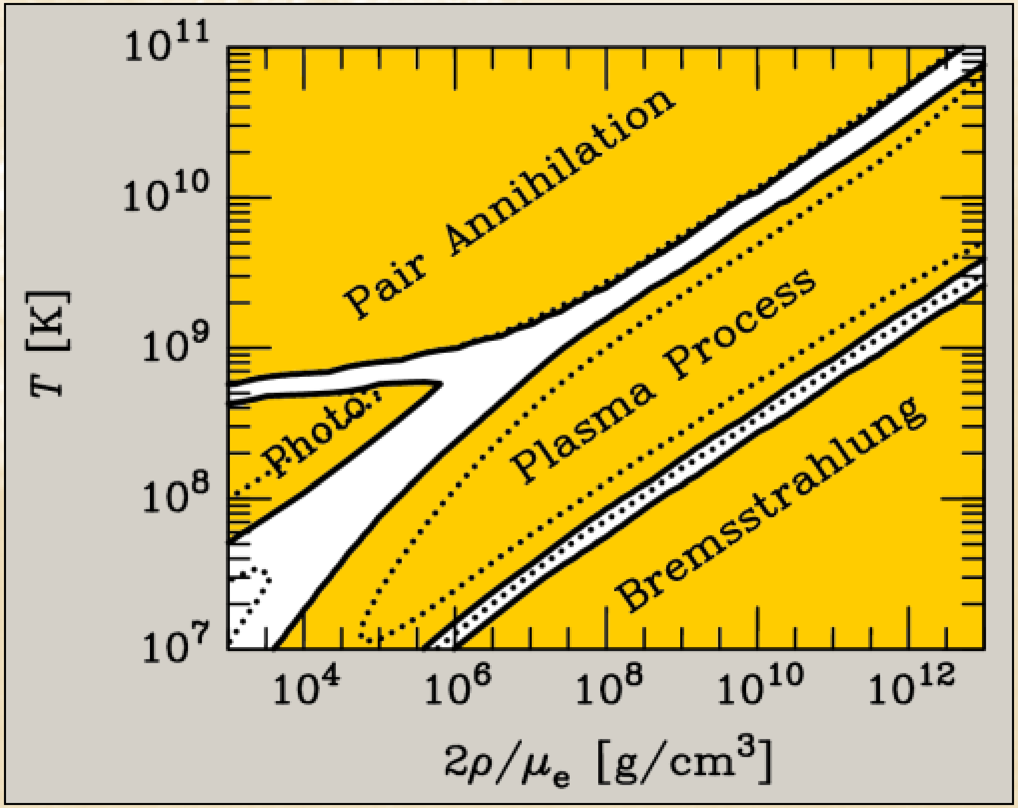


Pair annihilation



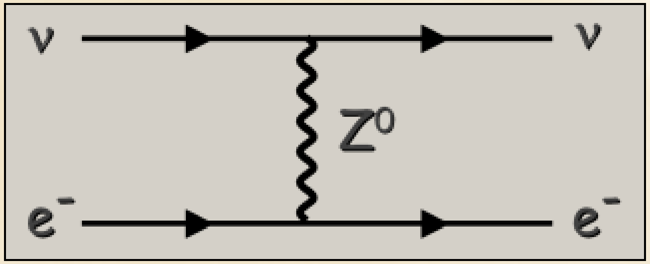
Bremsstrahlung

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

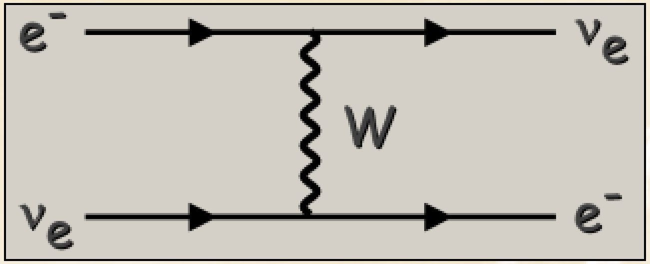


Effective Neutrino Neutral-Current Couplings

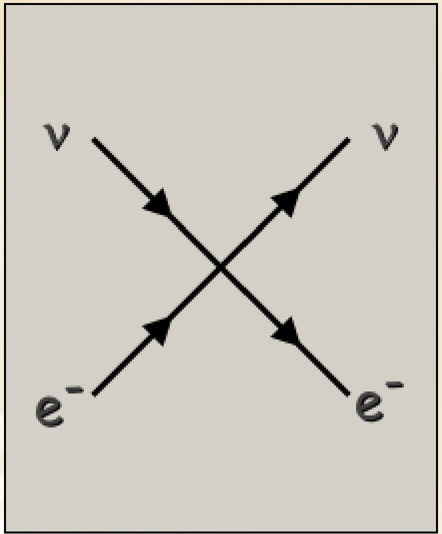
Neutral current



Charged current



$E \ll M_{W,Z}$



Effective four fermion coupling

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

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

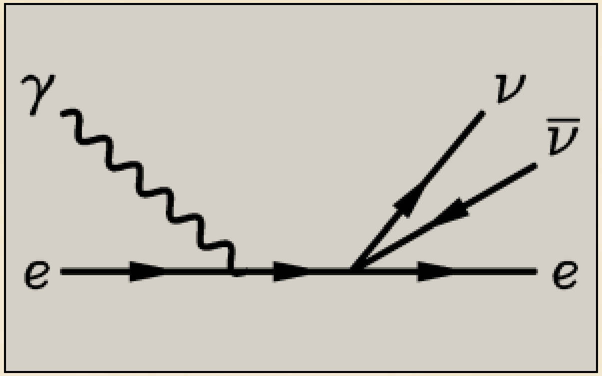


Photo (Compton)

Cross section (non-relativistic limit)

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

$$\sum_{\text{flavors}} \sigma = 1.34\times10^{-55}\,\text{cm}^2\left(\frac{E_\gamma}{10\,\text{keV}}\right)^4$$

Volume energy loss rate

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

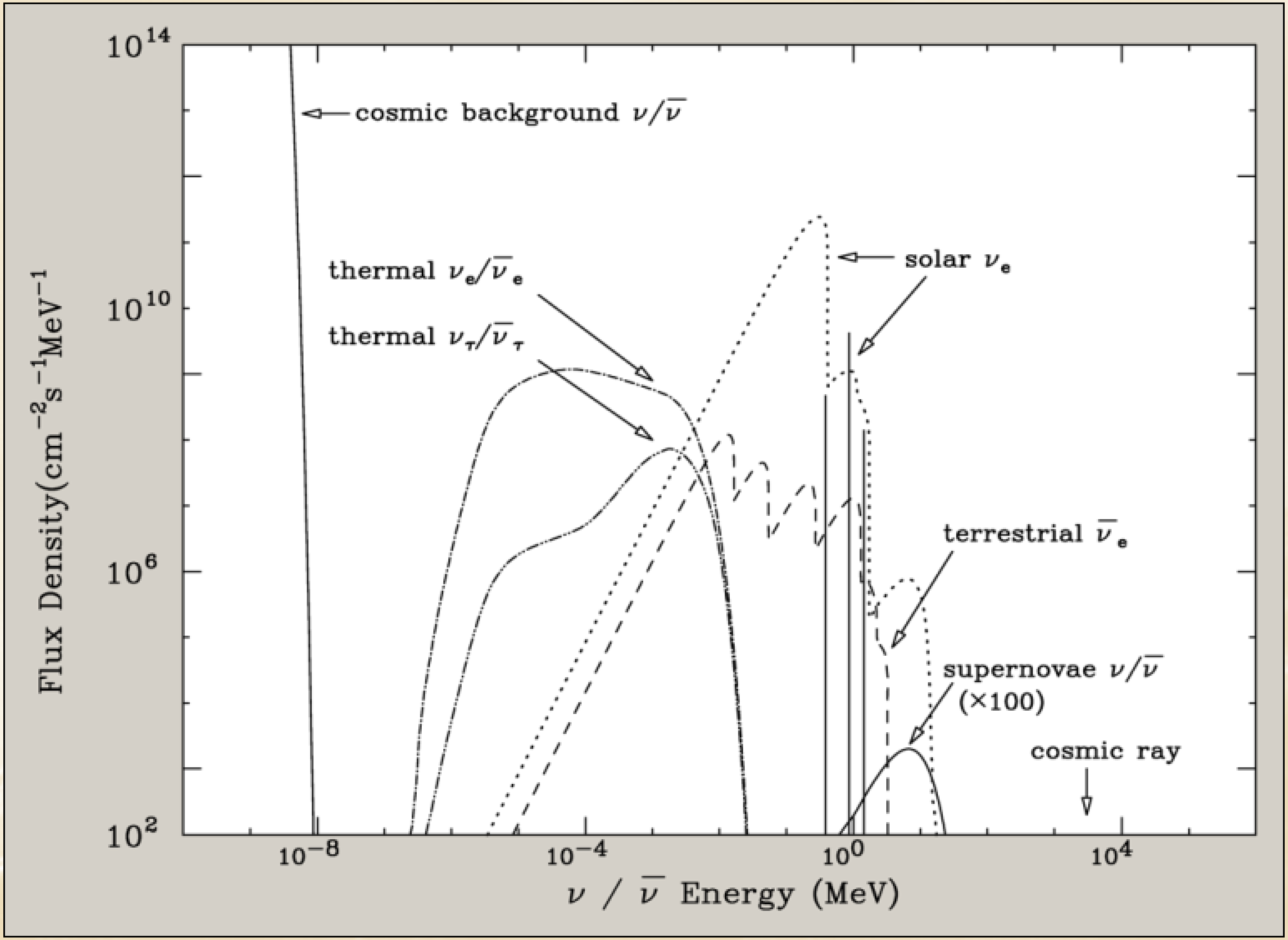
Energy loss rate per unit mass

$$\varepsilon_{\nu\bar\nu} = \frac{Q_{\nu\bar\nu}}{\rho} = 2.5\times10^{-8}\,\frac{\text{erg}}{\text{g s}}\,Y_e\left(\frac{T}{\text{keV}}\right)^8$$

To be compared with nuclear energy generation rate in the Sun

$$\langle\varepsilon_{\text{nuc}}\rangle = \frac{L_{\text{sun}}}{M_{\text{sun}}} = \frac{4\times10^{33}\,\text{erg/s}}{2\times10^{33}\,\text{g}} = 2\,\frac{\text{erg}}{\text{g s}} = 2\times10^{-7}\,\frac{\text{Watts}}{\text{g}} = \frac{200\,\text{Watts}}{\text{kilo-ton}}$$

Thermal vs. Nuclear Neutrinos from Sun



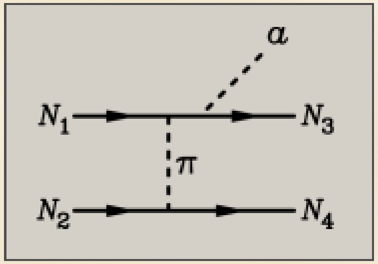
Haxton & Lin, The very low energy solar flux of electron and heavy-flavor neutrinos and anti-neutrinos, nucl-th/0006055

Axion or Graviton Emission Processes in Stars

Nucleons

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

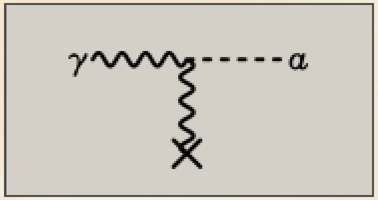
Nucleon Bremsstrahlung



Photons

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

Primakoff

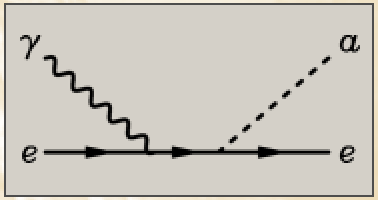


Electrons

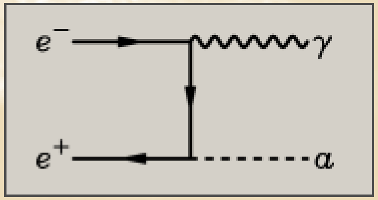
$$C_\gamma\frac{\alpha}{2\pi f_a}\frac{1}{4}F_{\mu\nu}\tilde{F}^{\mu\nu}a$$

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

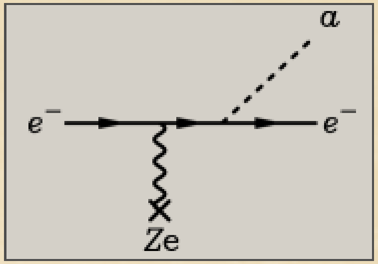
Compton



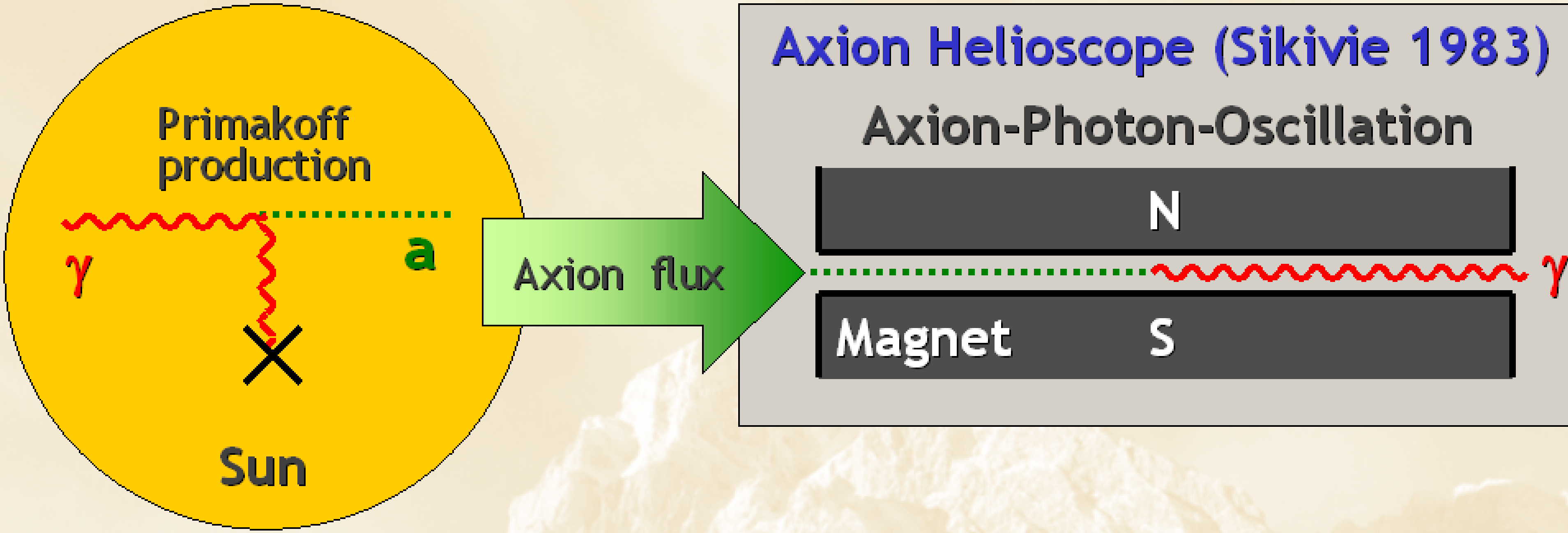
Pair Annihilation

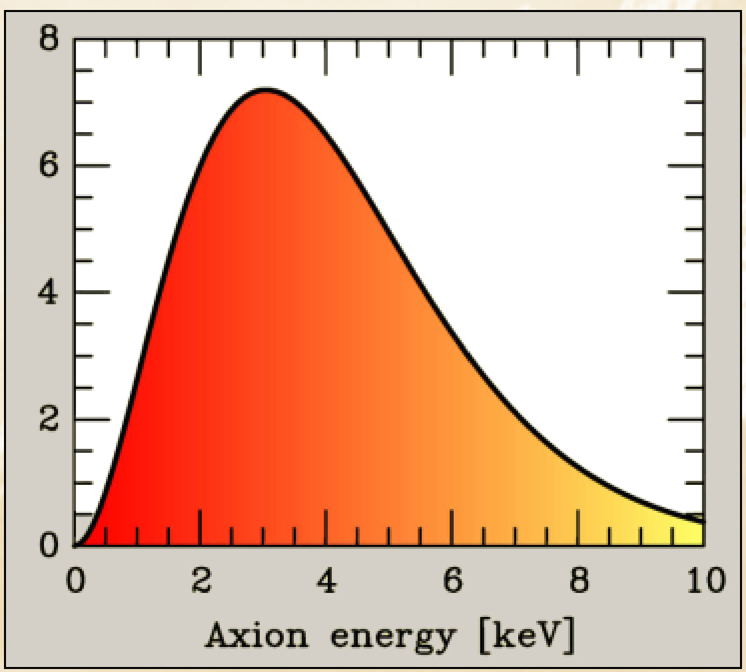


Electromagnetic Bremsstrahlung



Search for Solar Axions





- ➔ Tokyo Axion Helioscope (Results since 1998)
- ➔ CERN Axion Solar Telescope (CAST) (Data since 2003)

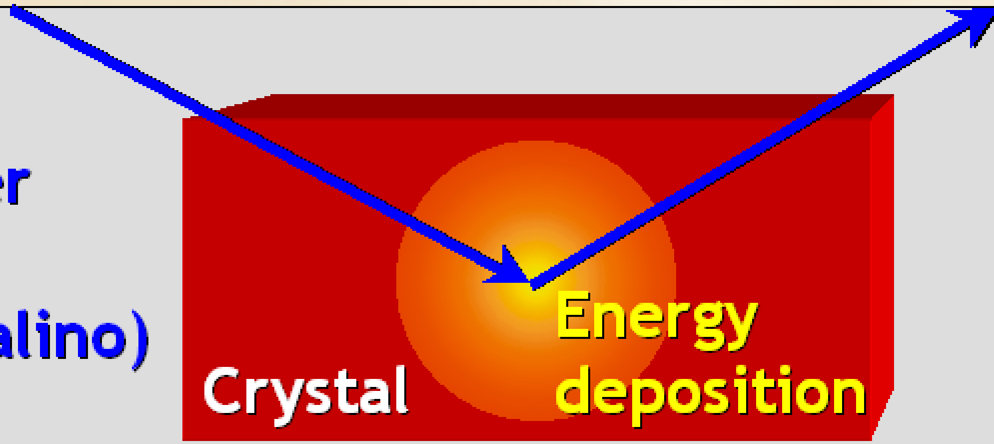
Alternative Technique:
Bragg conversion in crystal
Experimental limits on solar axion flux from dark-matter experiments (SOLAX, COSME, DAMA, ...)

Recent Picture of CAST

Search for Neutralino Dark Matter

Direct Method (Laboratory Experiments)

Galactic dark matter particle (e.g.neutralino)

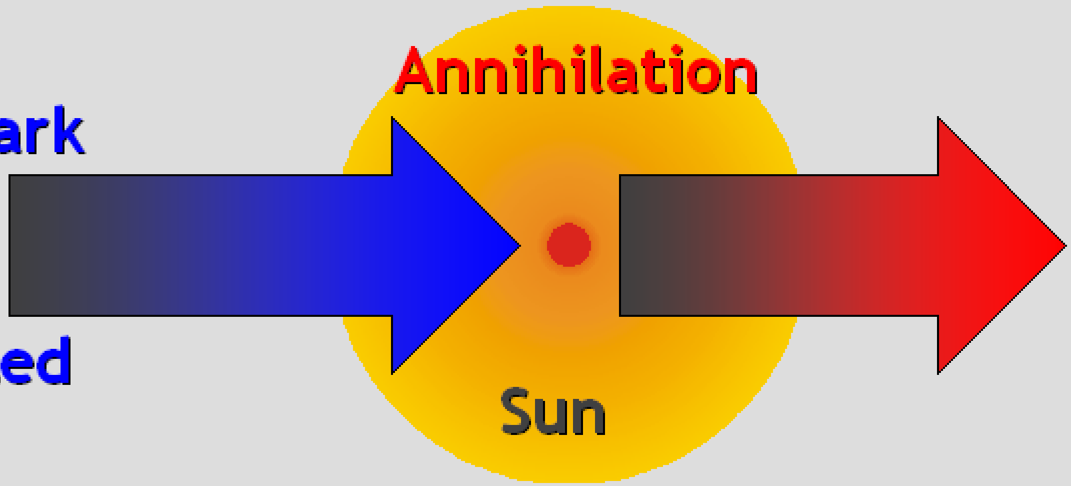


Recoil energy (few keV) is measured by

- Ionisation
- Scintillation
- Cryogenic

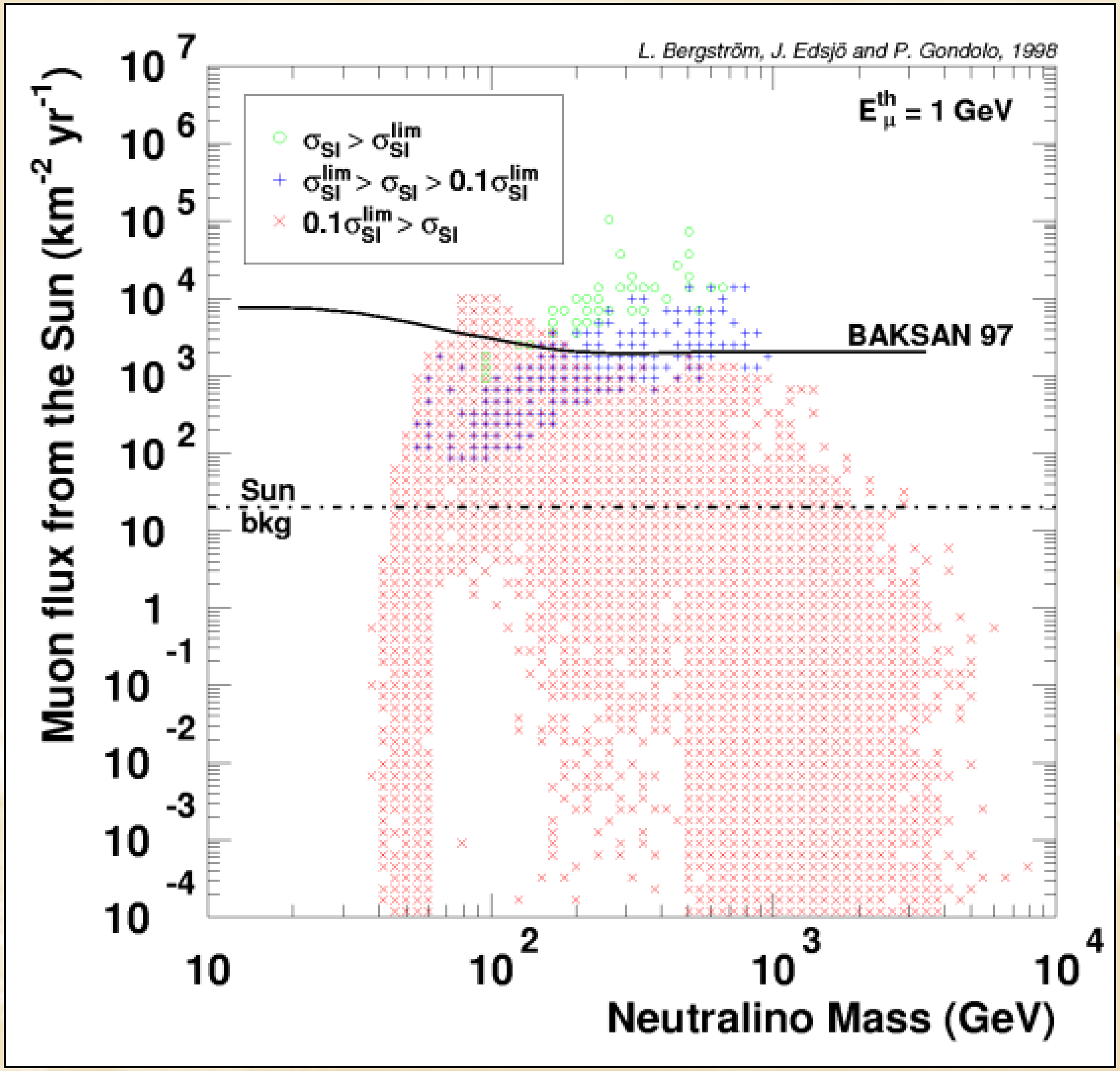
Indirect Method (Neutrino Telescopes)

Galactic dark matter particles are accreted



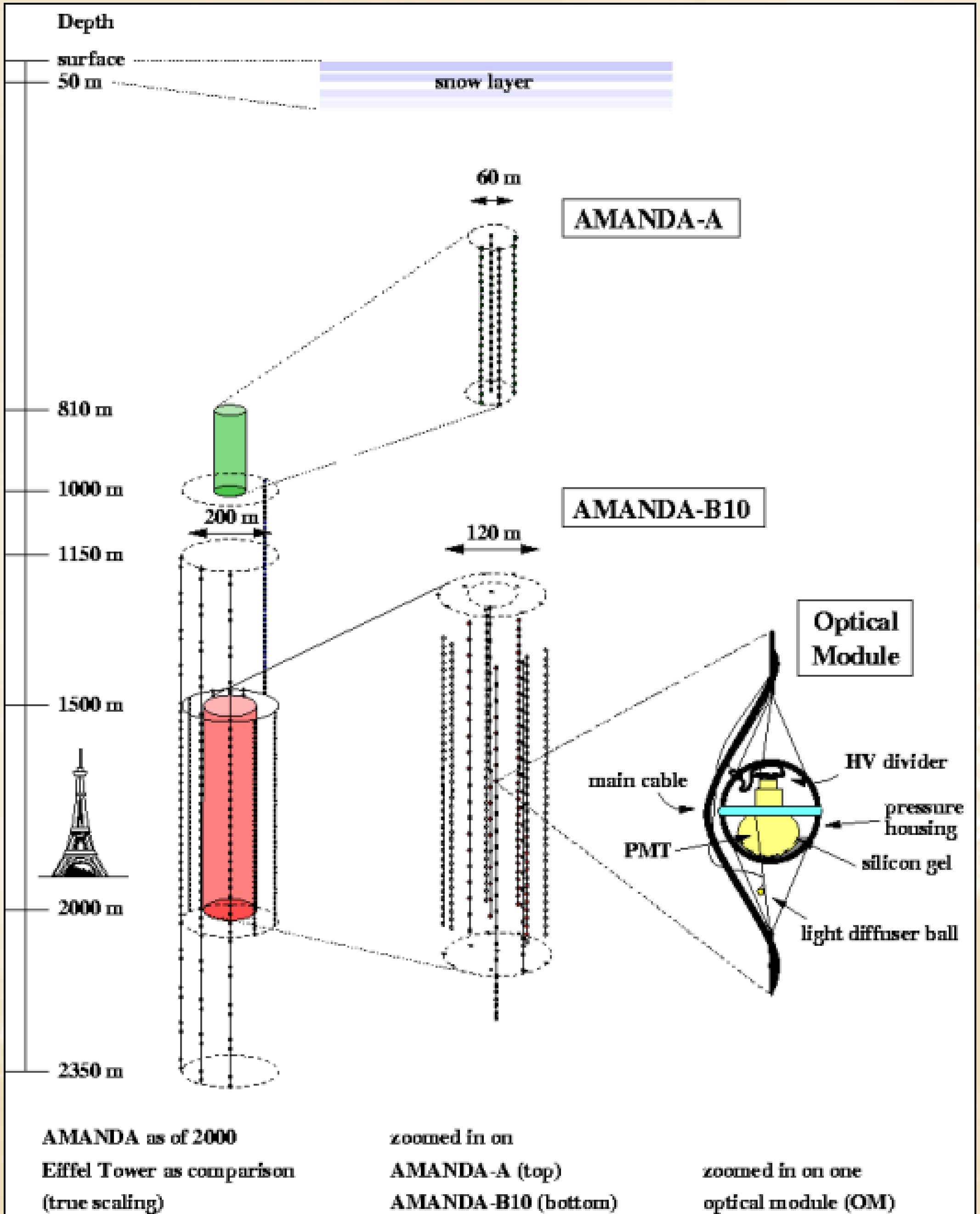
High-energy neutrinos (GeV-TeV) can be measured

Muon Flux from WIMP Annihilation in the Sun

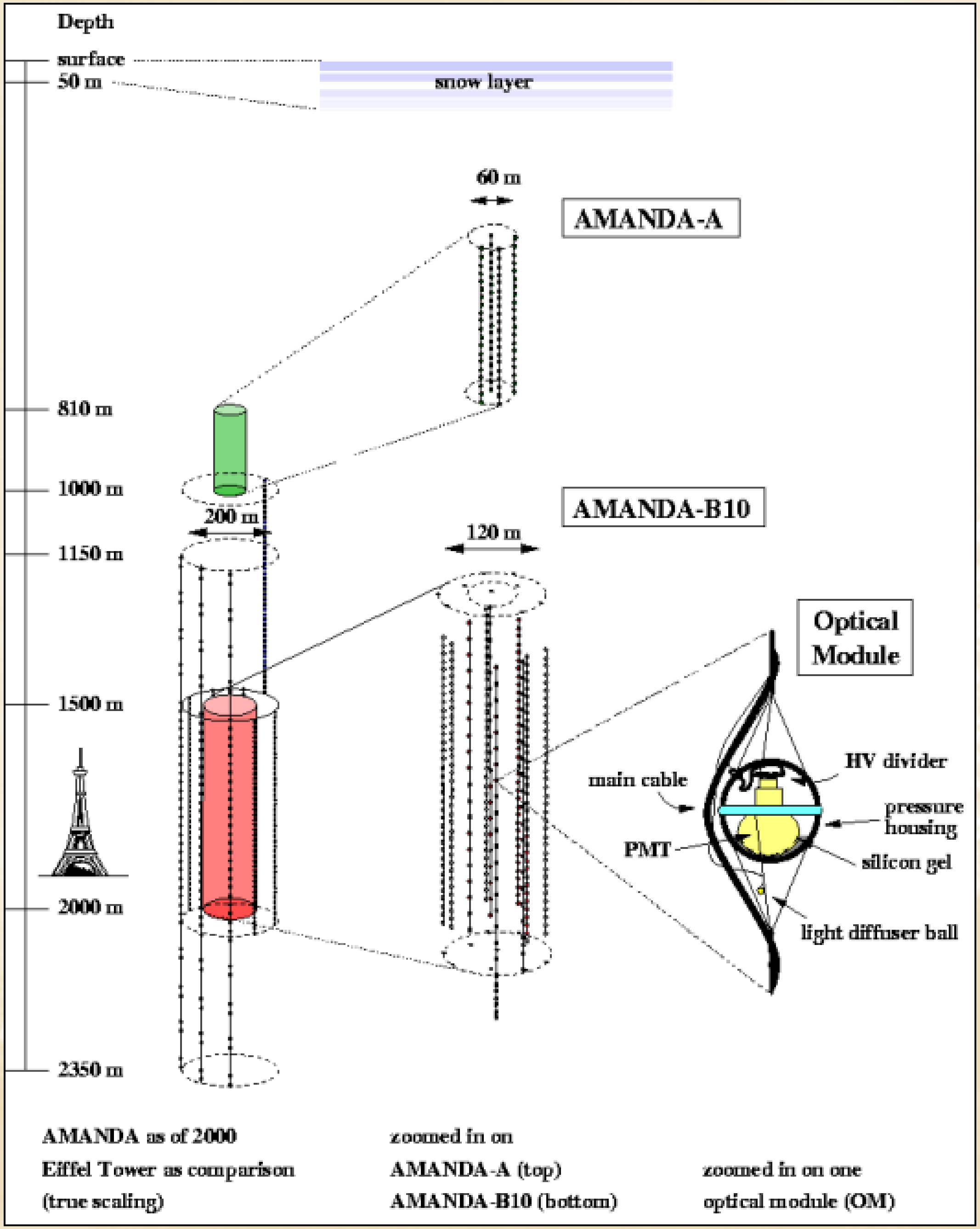


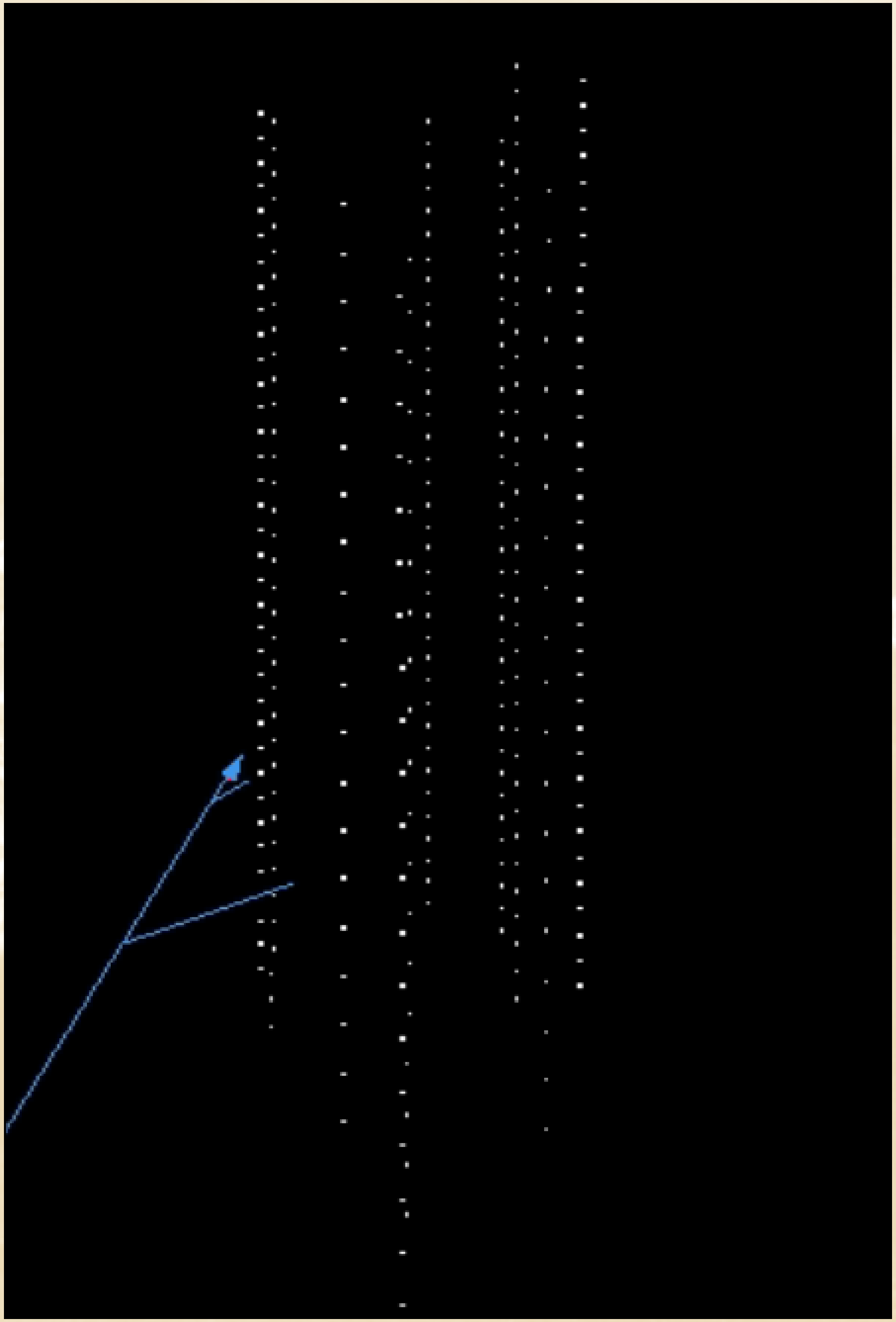
Need a km^3 water Cherenkov detector to reach solar background

AMANDA - South Pole Neutrino Telescope

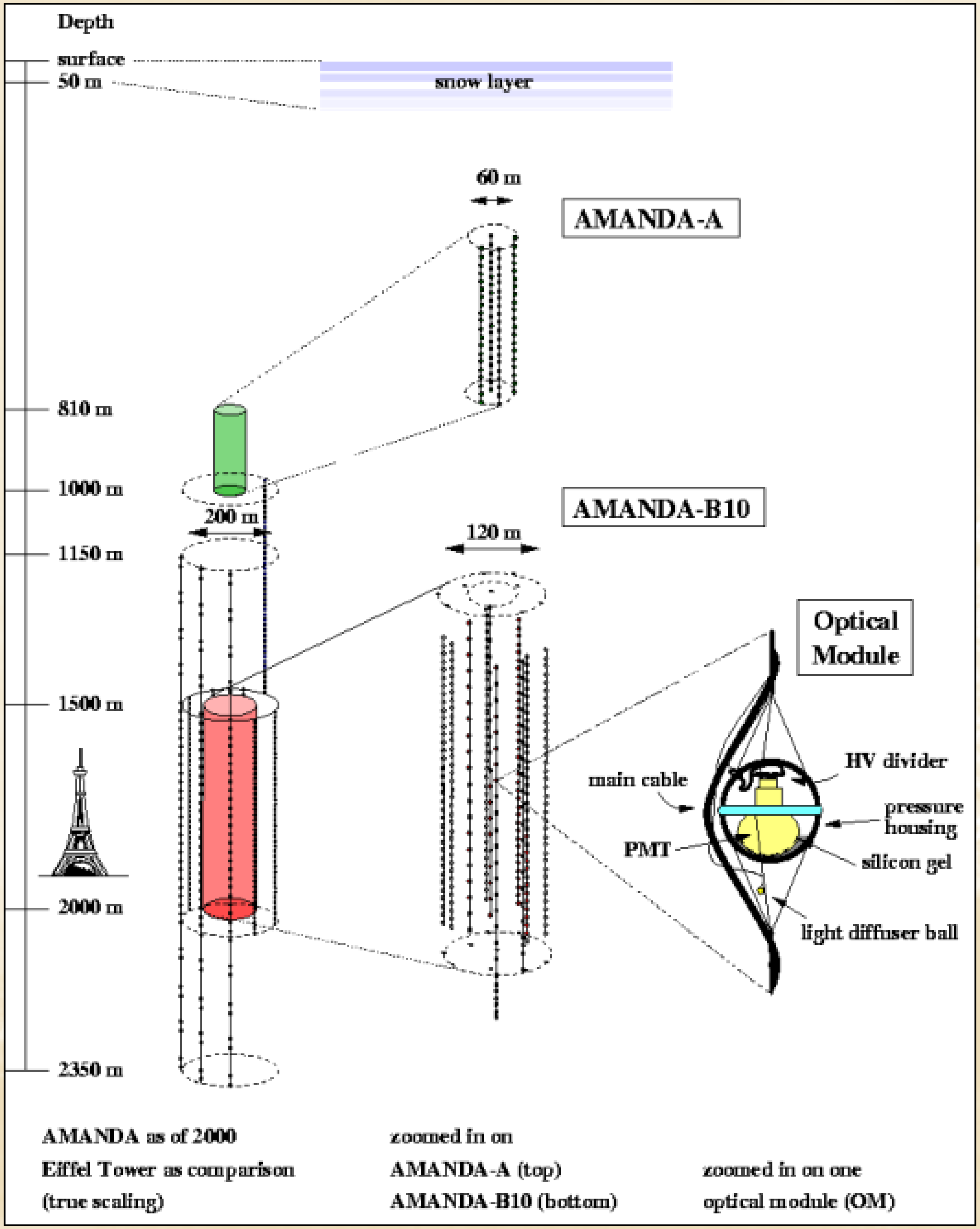


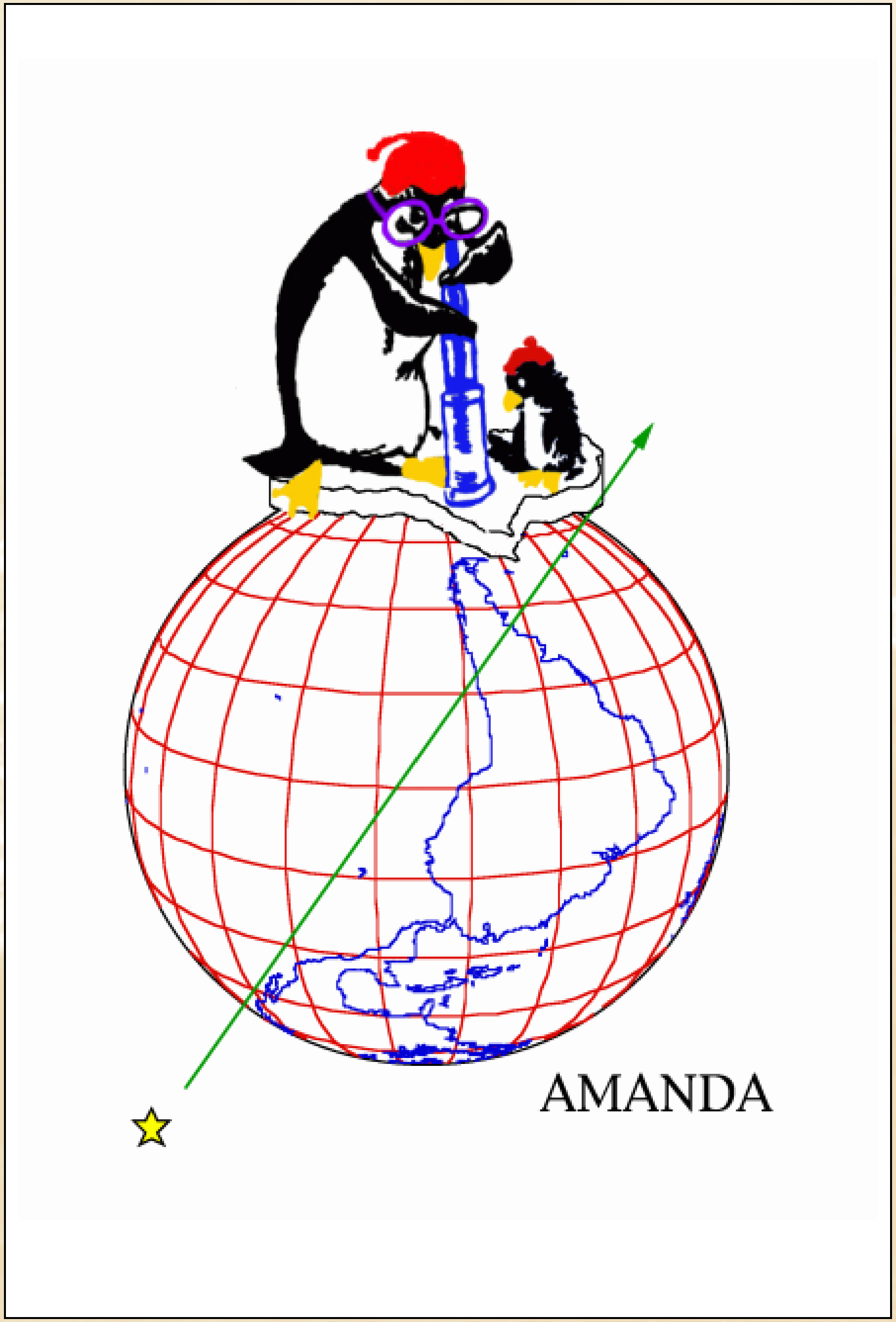
AMANDA – South Pole Neutrino Telescope



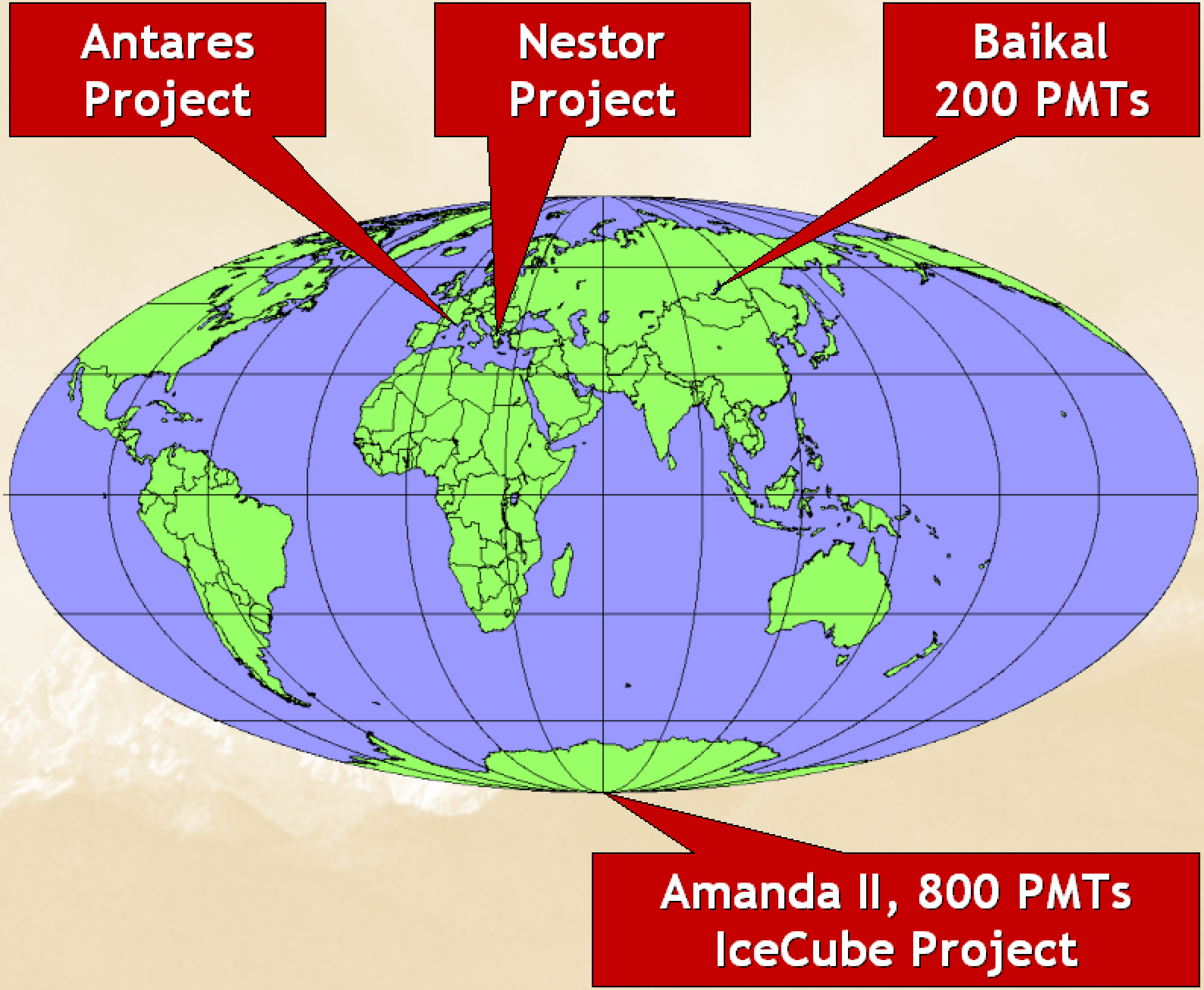


AMANDA – South Pole Neutrino Telescope

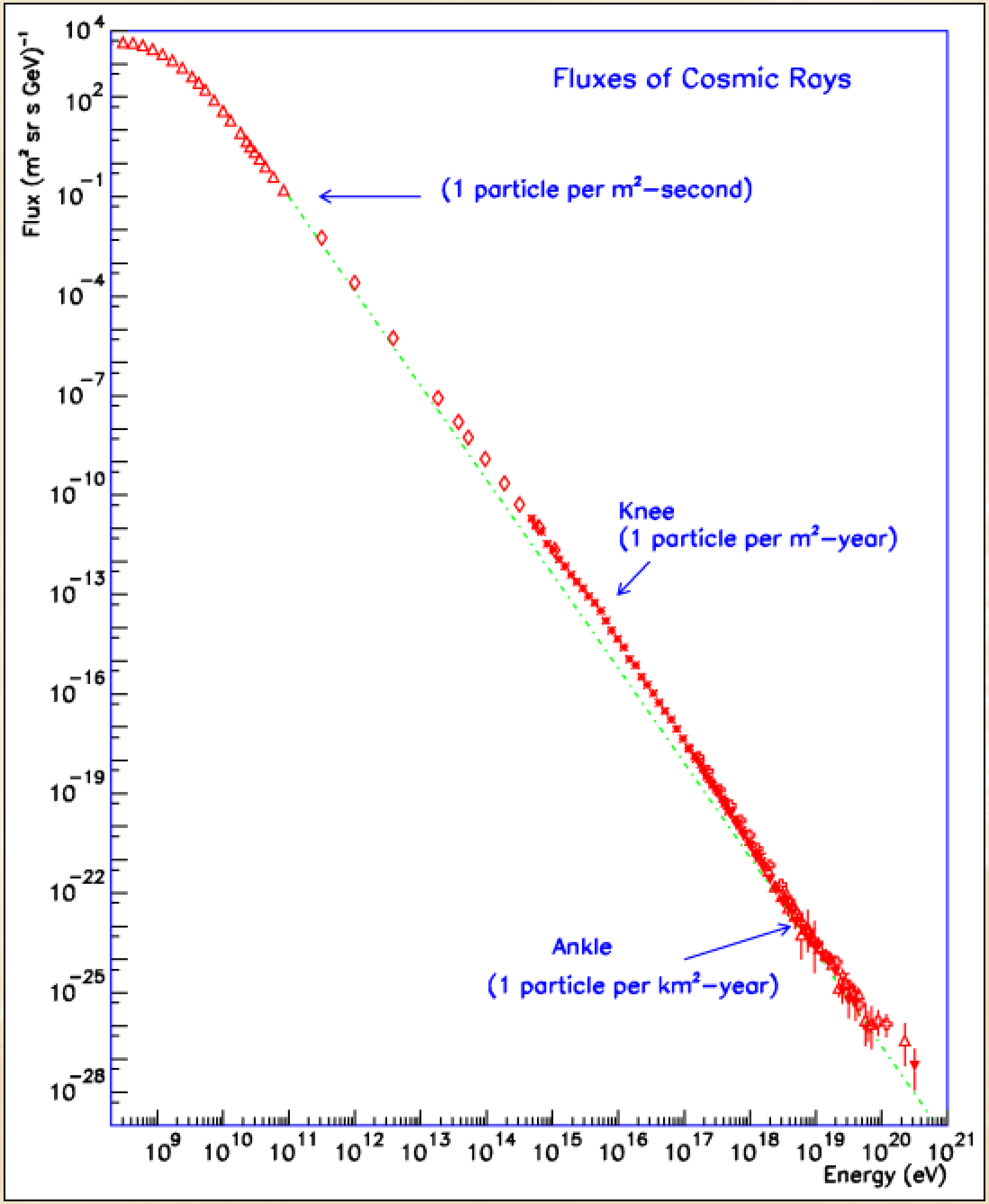


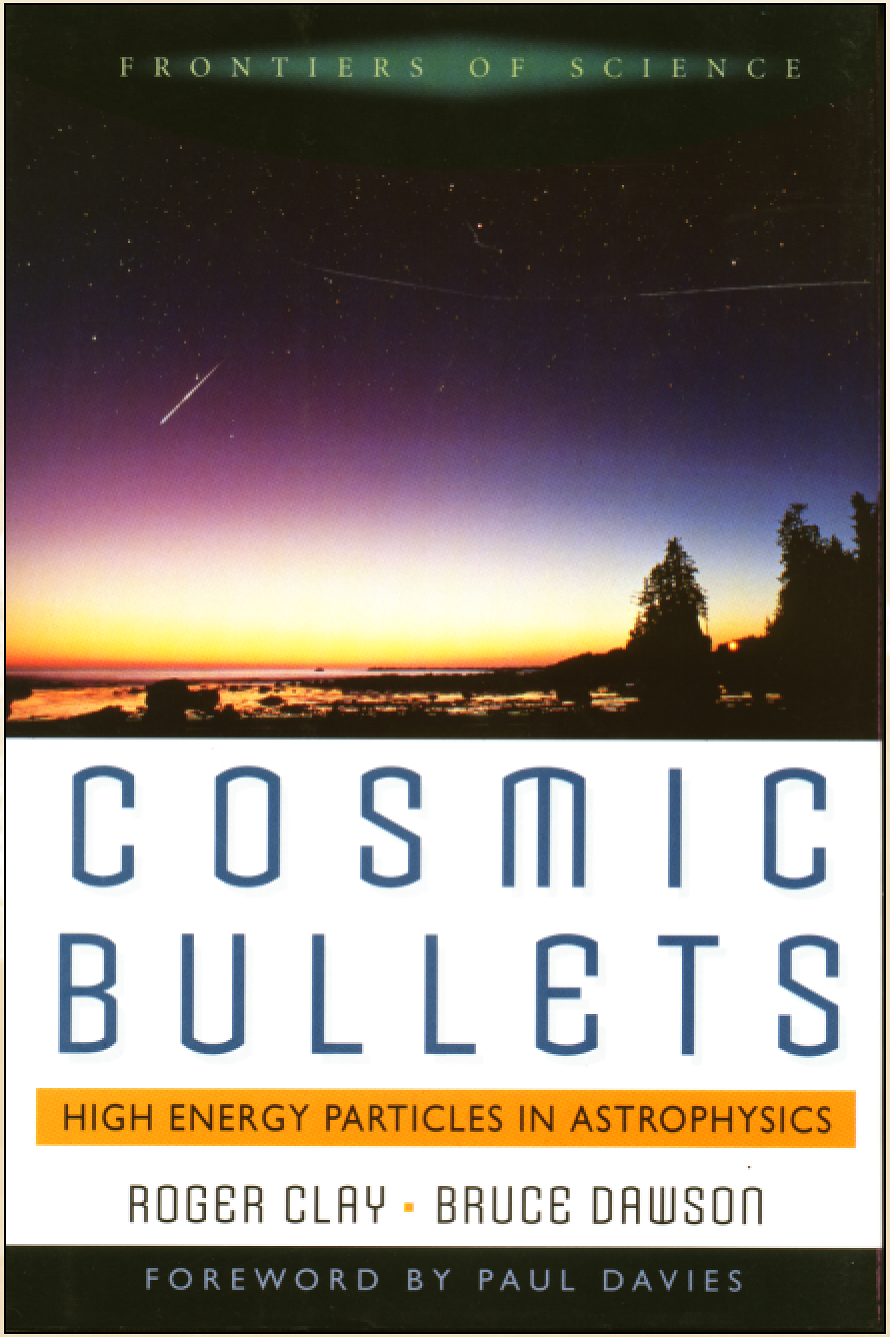


High-Energy Neutrino Telescopes

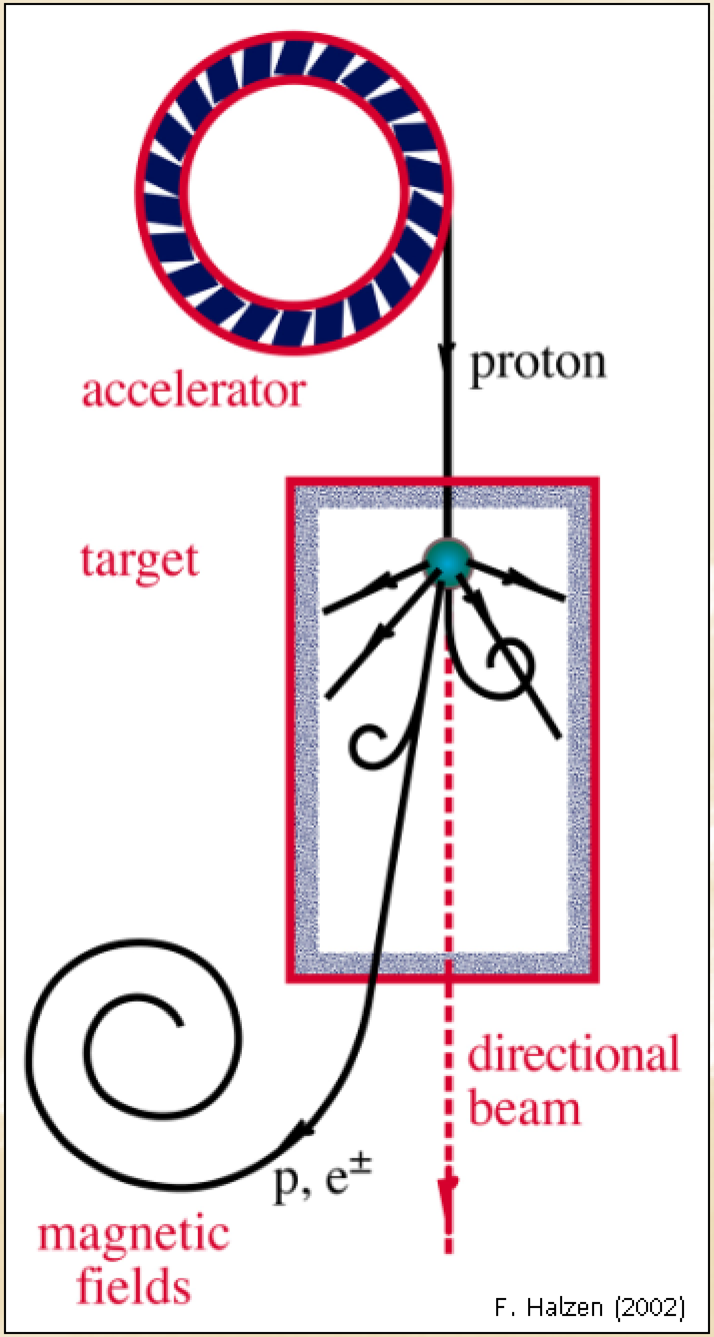


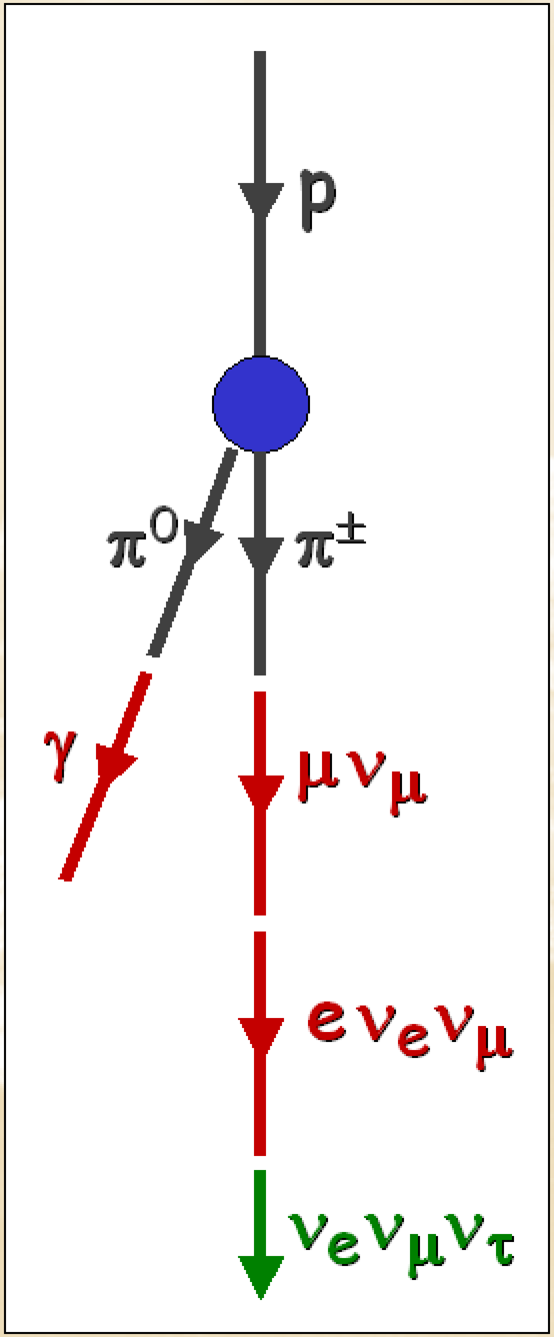
Global Cosmic Ray Spectrum





Neutrino Beams: Heaven and Earth



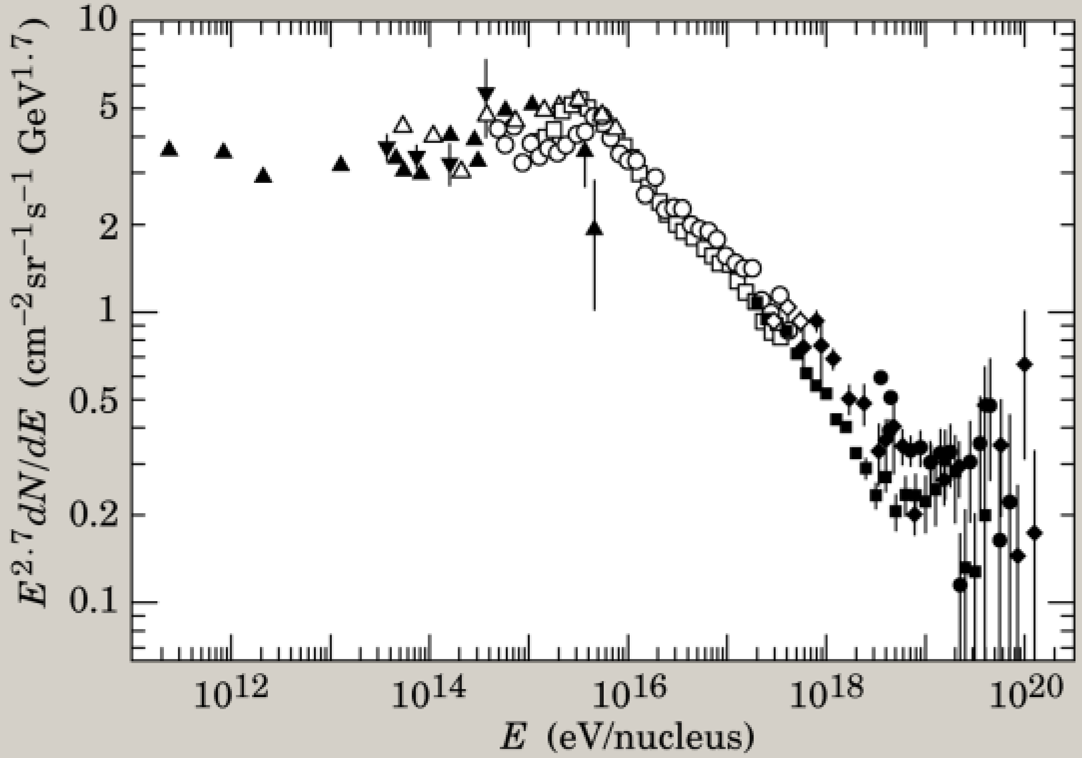


Target:
Protons or Photons

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)

High-Energy Neutrinos from the Sun

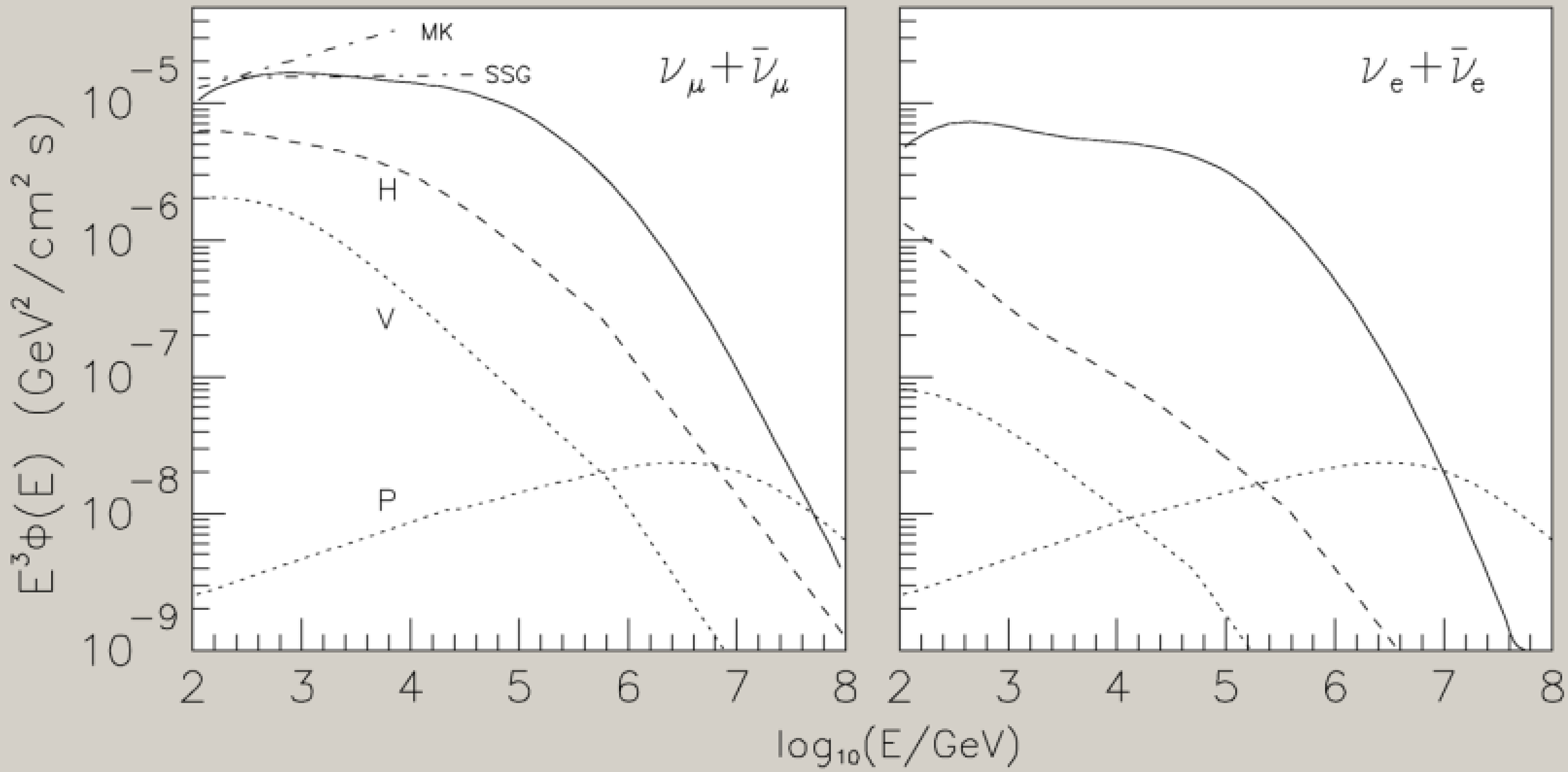
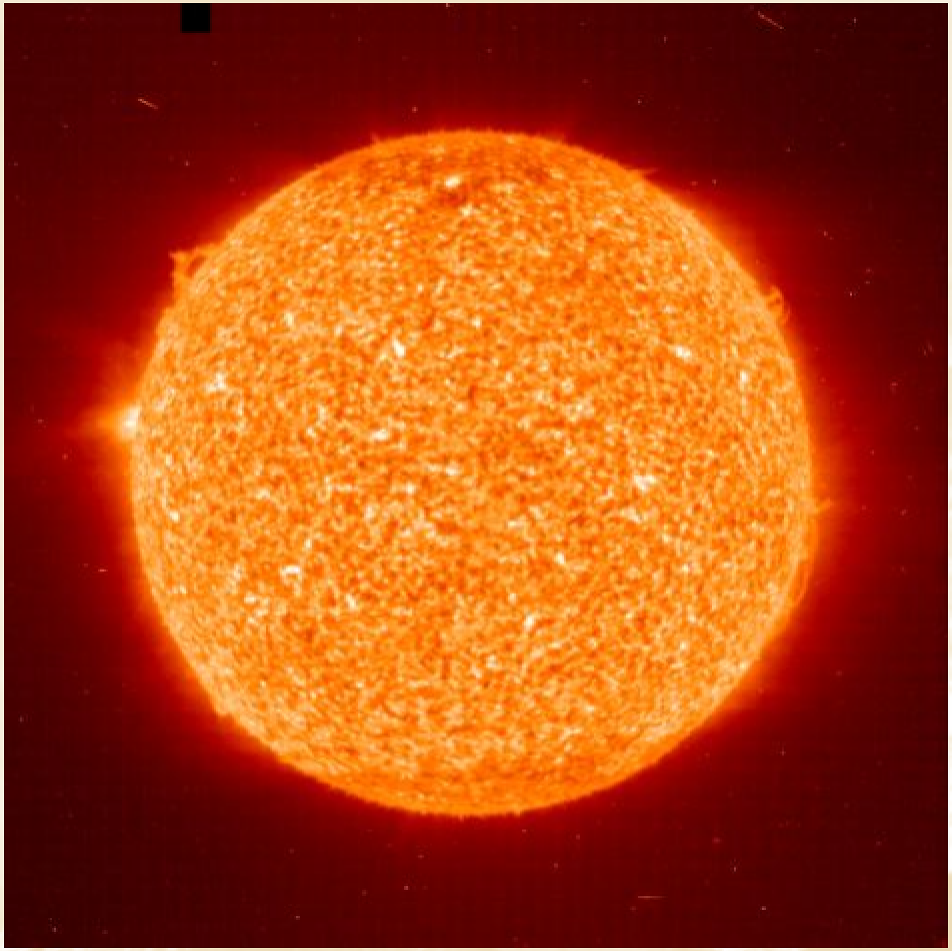


Figure 4: *Cosmic ray induced E^3-weighted neutrino fluxes at the Earth integrated over the solid angle of the Sun. The fluxes from the Sun obtained in this study (solid lines) are compared with the earlier calculation SSG [22] and the one MK derived from [2], as well as those from the Earth's atmosphere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

Portion of the Hubble Ultra Deep Field

Cosmological Limit on Neutrino Masses

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

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

$m_\nu \lesssim 40$ eV For all stable flavors

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 $m(\nu_e) < 200\ \mathrm{eV}/c^2$ for the electronic neutrino and $m(\nu_\mu) < 2.5 \times 10^6\ \mathrm{eV}/c^2$ 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 $= (13 \times 10^9\ \mathrm{years})^{-1}$. It follows therefore that the density of all types of matter in the Universe is at the present time [1)]

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

A classic paper:
Gershtein & Zeldovich
JETP Lett. 4 (1966) 120

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

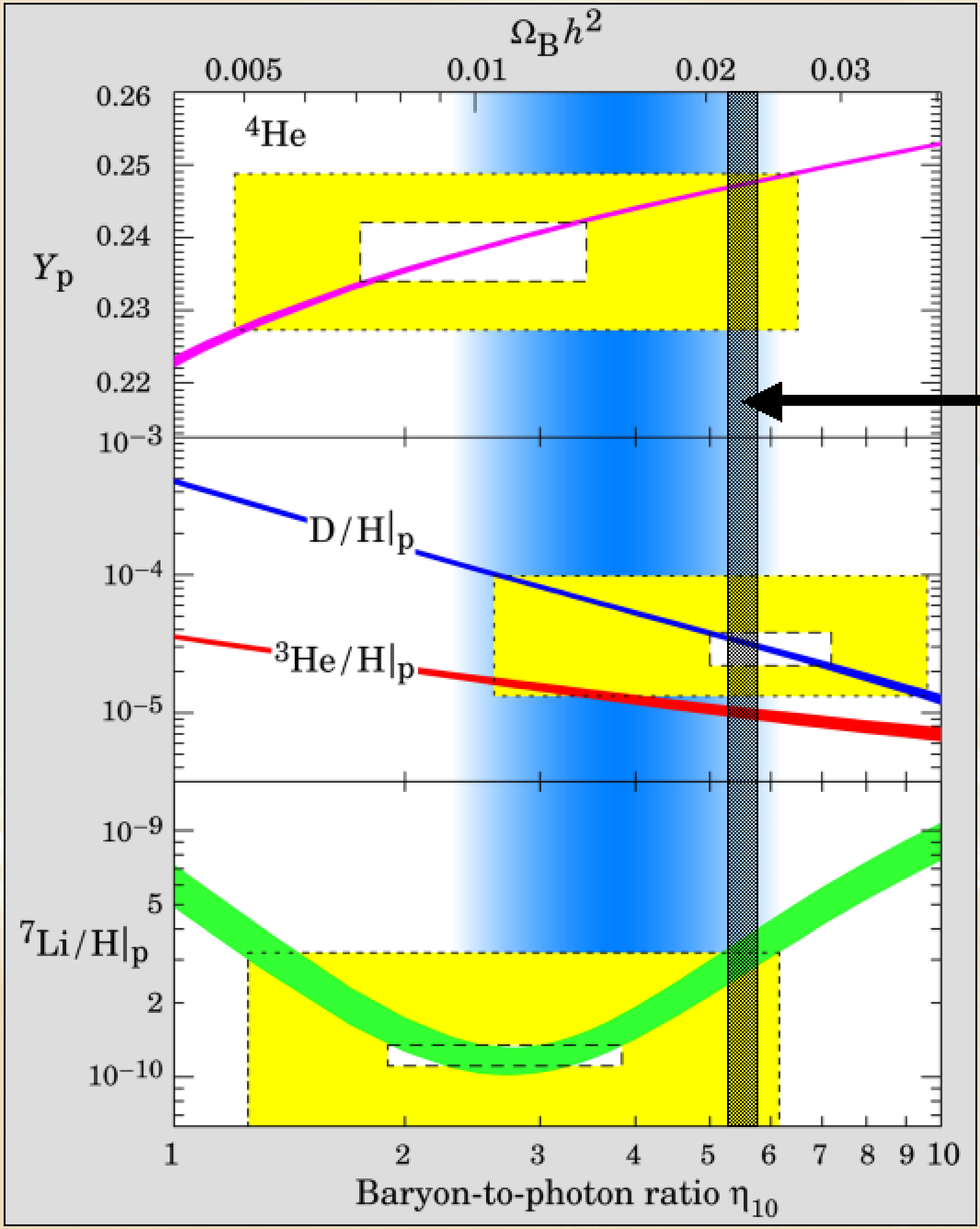
$\Sigma m_\nu < 2.1$ eV	2dF (Galaxy-galaxy correlation) + WMAP (Cosmic microwaves)
$\Sigma m_\nu < 1.2$ eV	+ Small-scale CMBR (breaks degeneracy with bias)
$\Sigma m_\nu < 1.0$ eV	+ Priors (1σ) $h = 0.72 \pm 0.08$, $\Omega_M = 0.28 \pm 0.14$

BBN Concordance

Helium

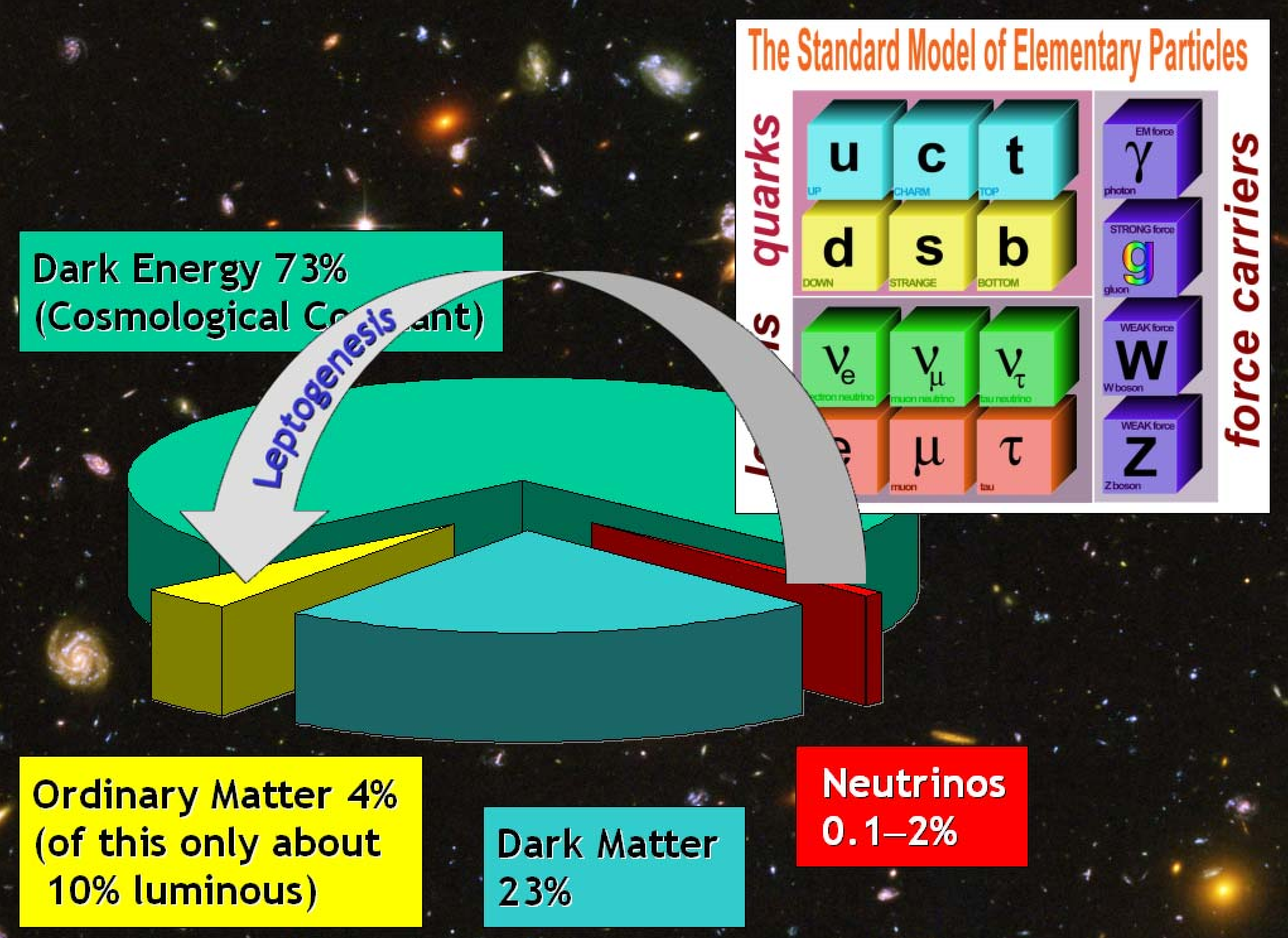
Deuterium

Lithium



Implied by CMBR and large-scale structure

Review of Particle Properties


The Standard Model of Elementary Particles
quarks
u
UP
c
CHARM
t
TOP
d
DOWN
s
STRANGE
b
BOTTOM
ν_e
ν_μ
muon neutrino
ν_τ
tau neutrino
μ
muon
τ
tau
force carriers
EM force
γ
photon
STRONG force
g
gluon
WEAK force
W
W boson
WEAK force
Z
Z boson
Leptogenesis
Dark Energy 73%
Ordinary Matter 4%
(of this only about
10% luminous)
Dark Matter
23%
Neutrinos
0.1–2%

Neutrinos in Astrophysics and Cosmology

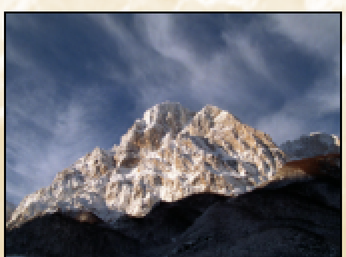
Neutrinos responsible for ordinary astrophysical and cosmological phenomena	• Dominant radiation component in the early universe • Crucial role in big-bang nucleosynthesis • Dark-matter component (but subdominant) • May be responsible for baryonic matter in the universe (leptogenesis) • Important (sometimes 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

Neutrinos in Astrophysics and Cosmology

Part I: Introduction

Part II: Neutrinos in Ordinary Stars

Part III: Supernova Neutrinos



Part IV: Cosmological Neutrinos