Astrophysical Neutrinos

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HELMHOLTZ
ASSOCIATION

DESY

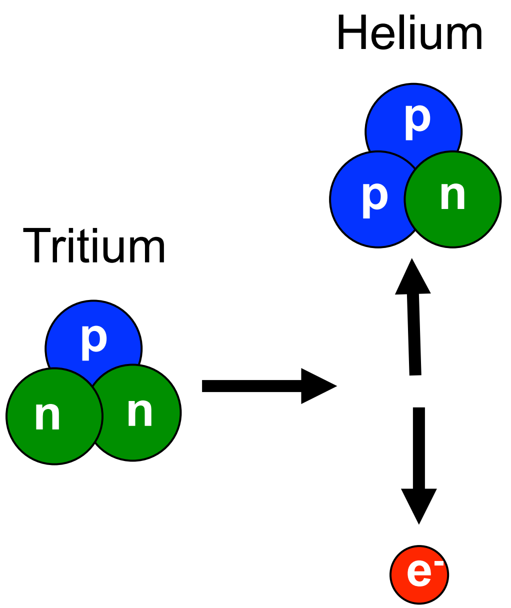
Content

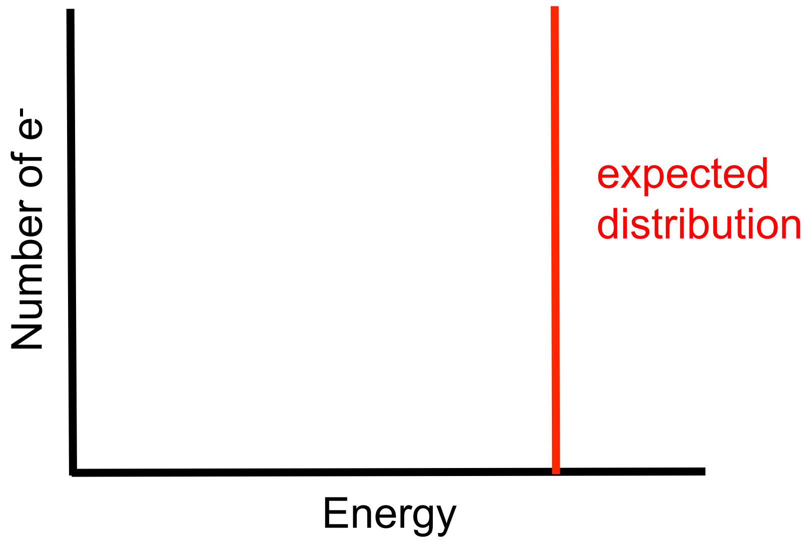
- Prediction of the neutrino
- First detection of neutrinos
- Neutrinos from the sun
- Neutrinos from supernova 1987A

- Neutrino cosmic-ray connection
- High-energy neutrino astronomy
- Multi-messenger astronomy with neutrinos

The Beta-Decay Problem

Two-Body Final State

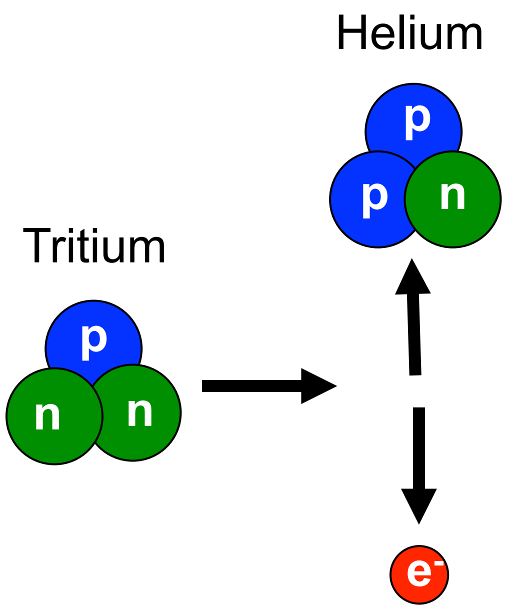


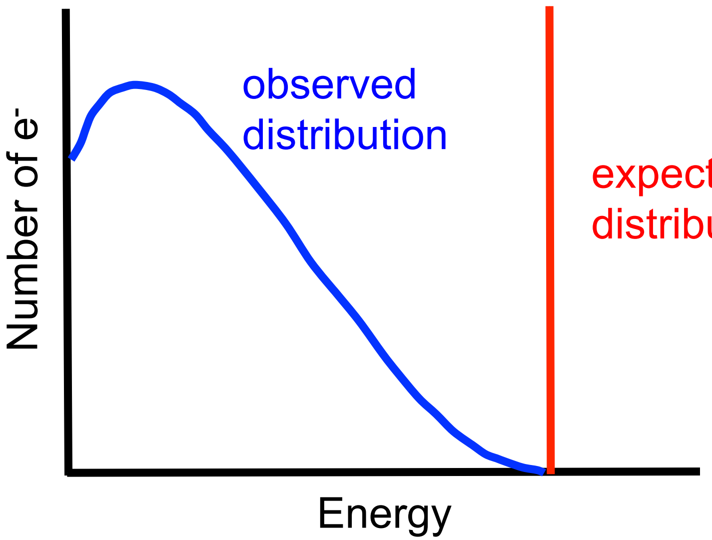


Recoil nucleus and e$^-$ separate with equal and opposite momentum

The Beta-Decay Problem

Two-Body Final State





Recoil nucleus and e^- separate with equal and opposite momentum

Pauli had a desperate remedy

4 December 1930
Gloriastr.
Zürich

Physical Institute of the
Federal Institute of Technology (ETH)
Zürich

Dear radioactive ladies and

As the bearer of these li
graciously, will explain mo
'false' statistics of N-14
continuous β-spectrum, I hav
to save the "exchange theorem"
theorem. Namely [there is] the pos
exist in the nuclei electrically neutral
wish to call neutrons,** which have spin 1/2 and obey the exclusion principle, and additionally differ from light quanta in that they do not travel with the velocity of light:

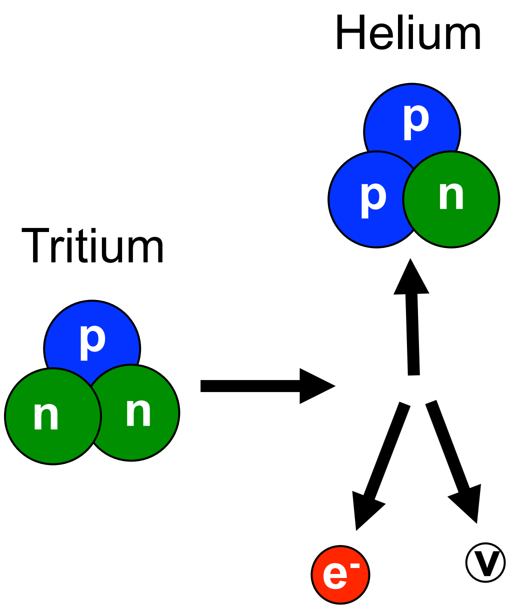
...

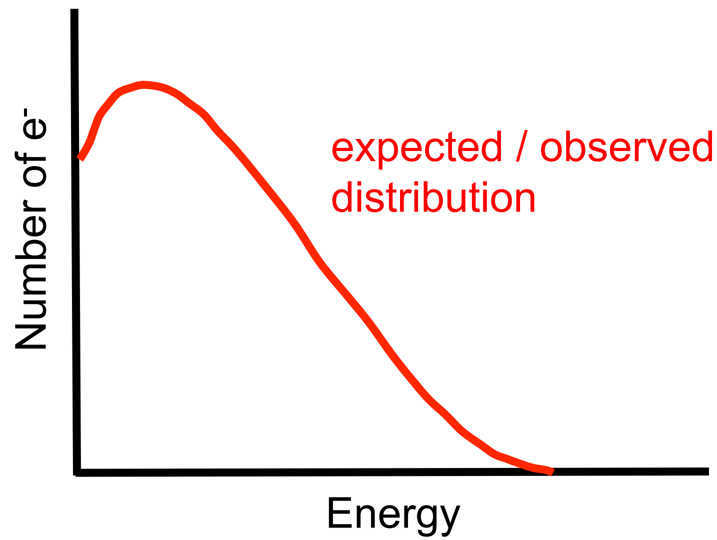
I admit that my remedy may appear to have a small *a priori* probability because neutrons, if they exist, would probably have long ago been seen. However, only those who wager can win, and the seriousness of the situation of the continuous β-spectrum can be made clear by the saying of my honored predecessor in office, Mr. Debye, who told me a short while ago in Brussels, "One does best not to think about that at all, like the new taxes." Thus one should earnestly discuss every way of salvation.—So, dear radioactives, put it to test and set it right.—Unfortunately, I cannot personally appear in Tübingen, since I am indispensable here on account of a ball taking place in Zürich in the night from 6 to 7 of December.—With many greetings to you, also to Mr. Back, your devoted servant,

W. Pauli

The Beta-Decay Problem

Three-Body Final State



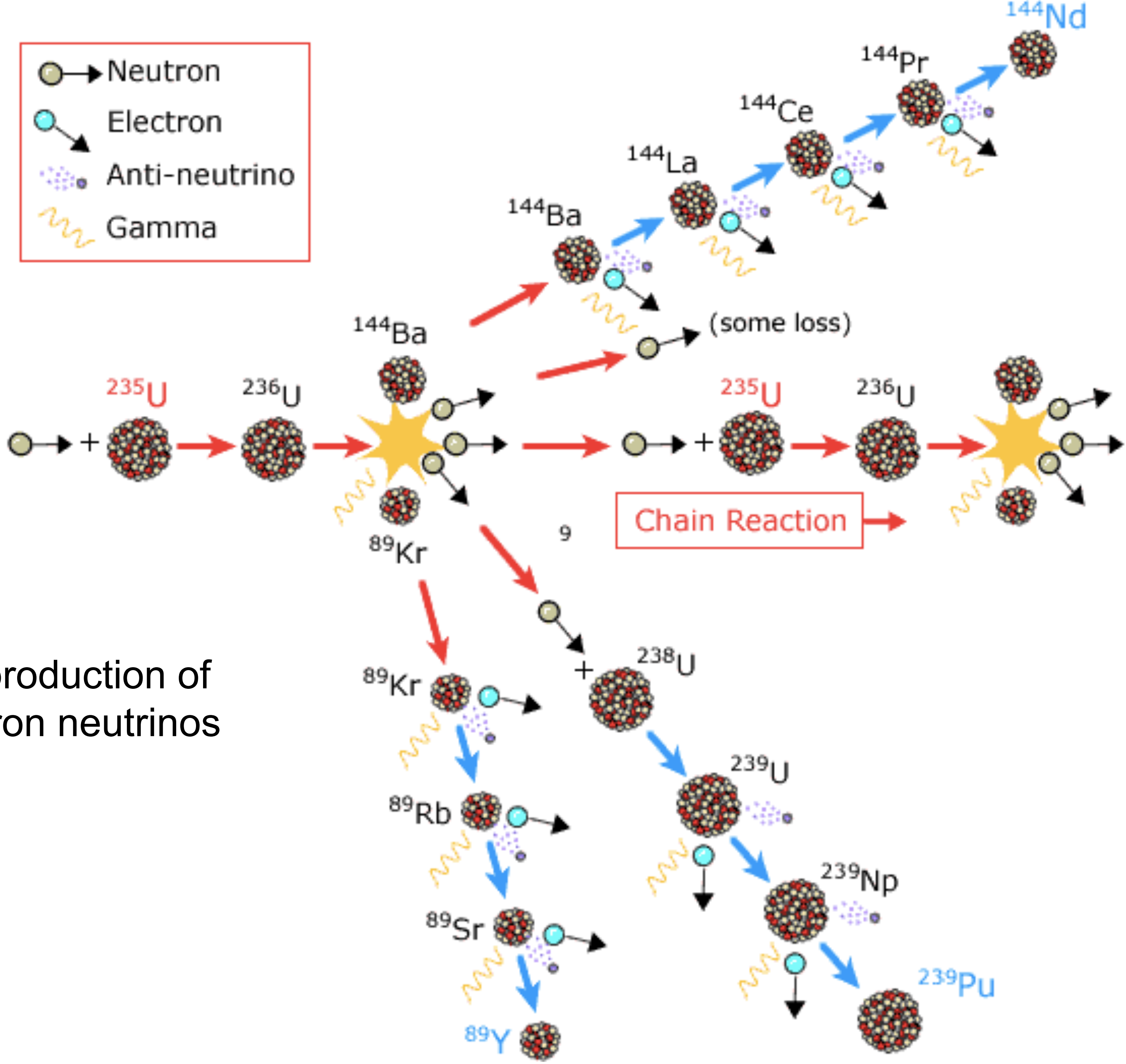


e^- and ν share the available energy and momentum

$$n \rightarrow p + e^- + \bar{\nu}_e$$

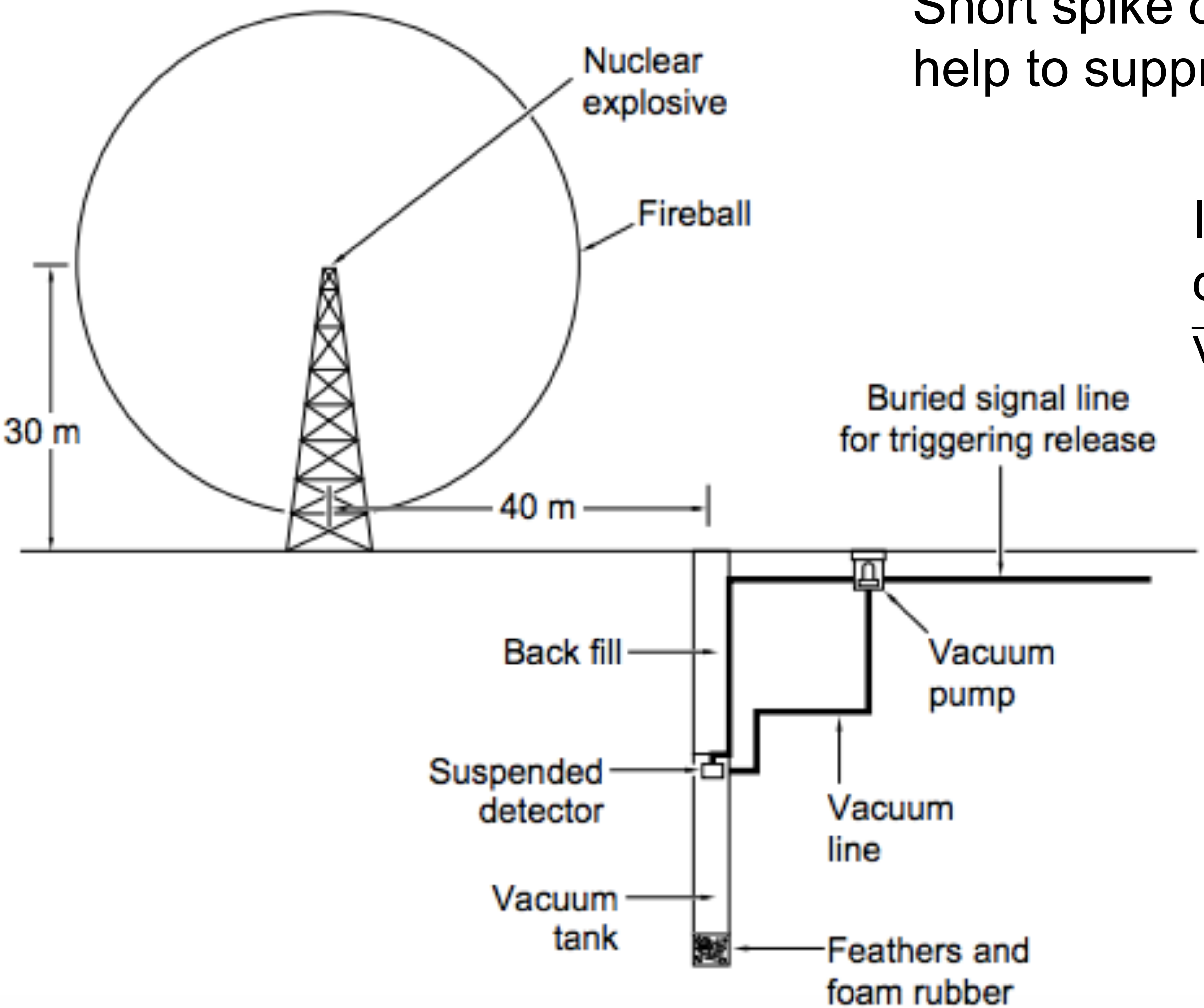
Neutrino Detection

Nuclear Fission



Efficient production of anti electron neutrinos

First idea: Detect neutrinos from a nuclear explosion?



Short spike of neutrino signal would help to suppress background

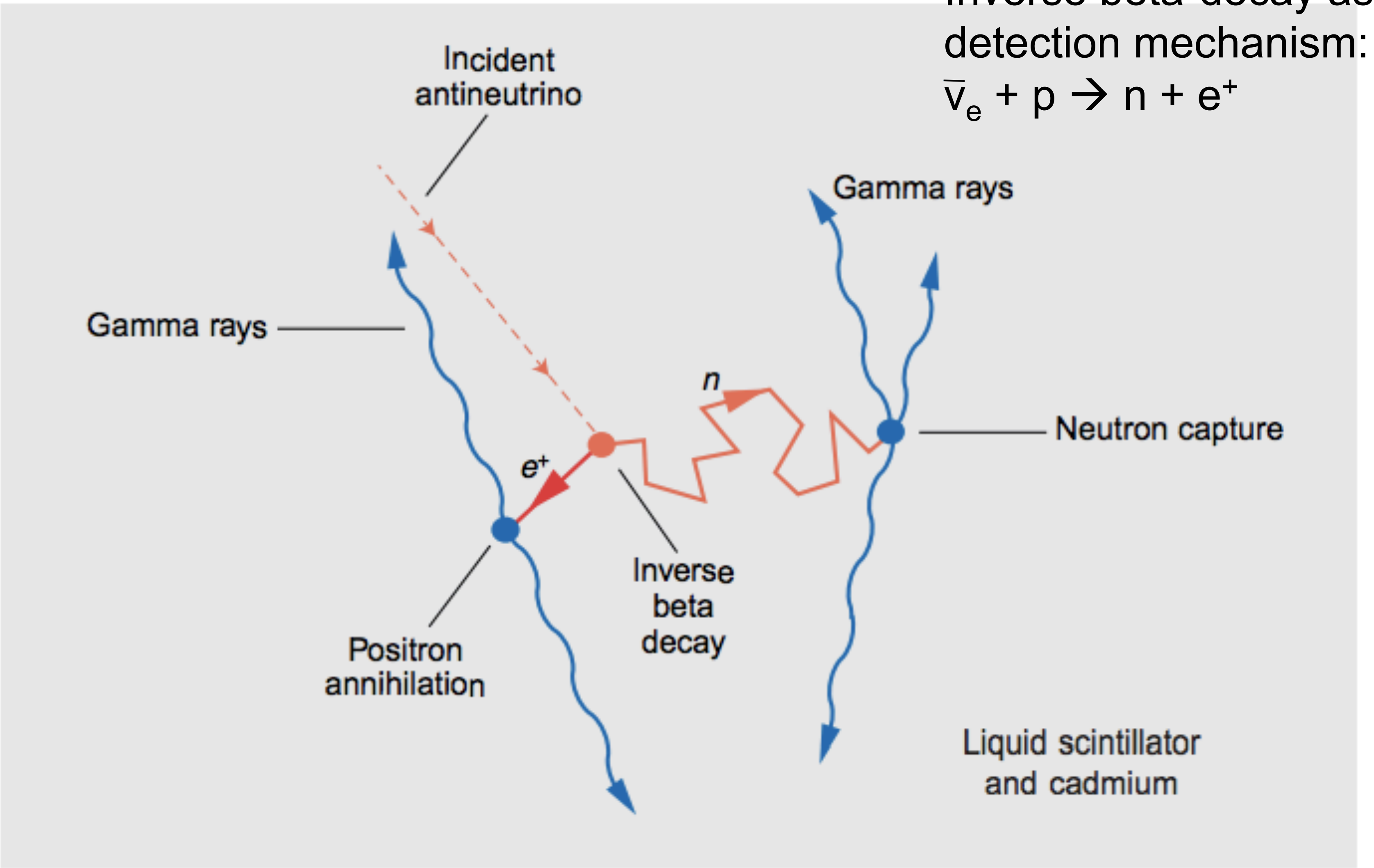
Inverse beta-decay as detection mechanism:
$\bar{\nu}_e + p \rightarrow n + e^+$

Second idea: Detecting neutrinos at a nuclear reactor

Flux 1000 times smaller than from nuclear explosion, but advantage of continuous measurement

2×10^{20} anti electron neutrinos / s per GW of thermal power

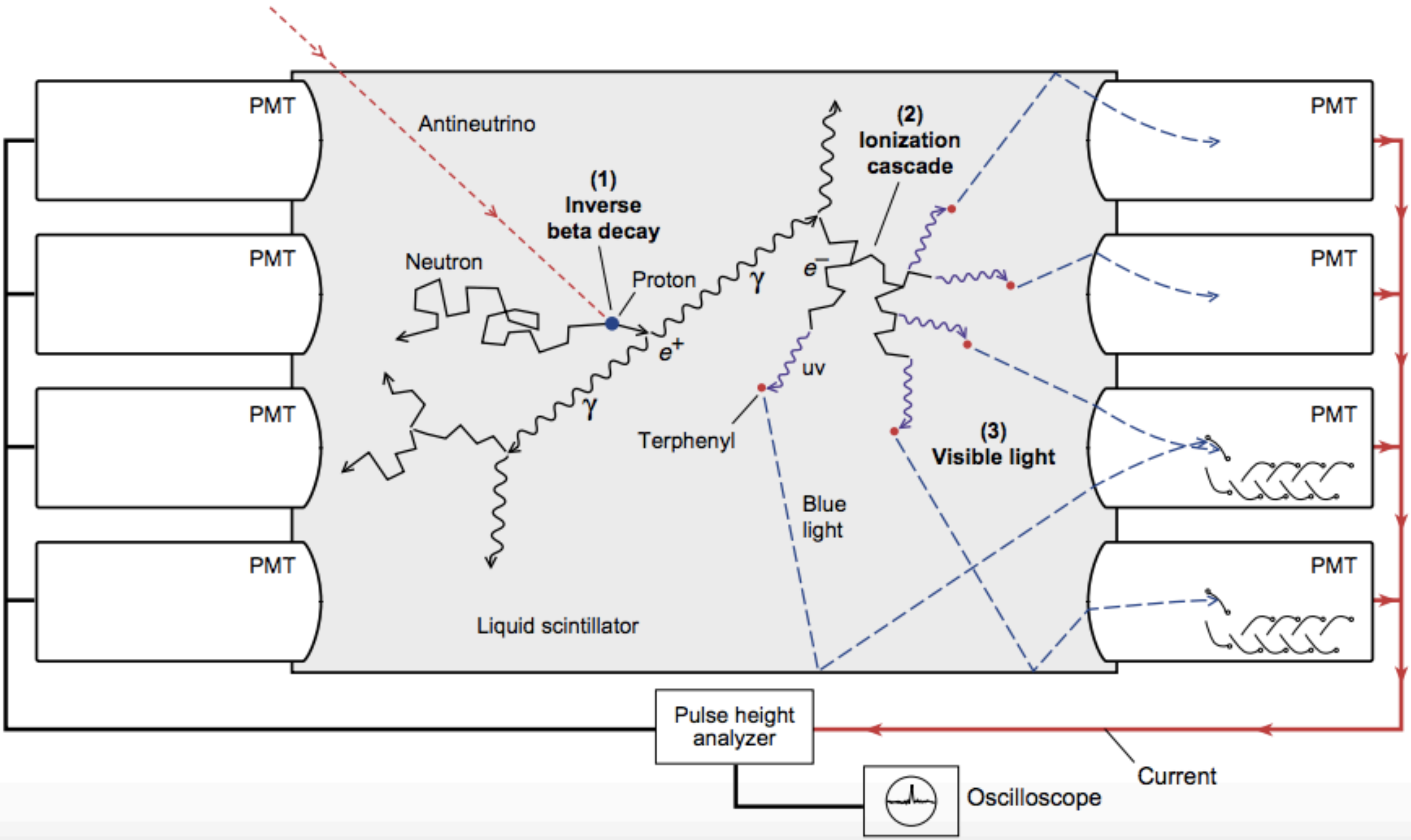
Double Signature of Inverse Beta Decay



Inverse beta-decay as detection mechanism:

$\bar{\nu}_e + p \rightarrow n + e^+$

Liquid Scintillator



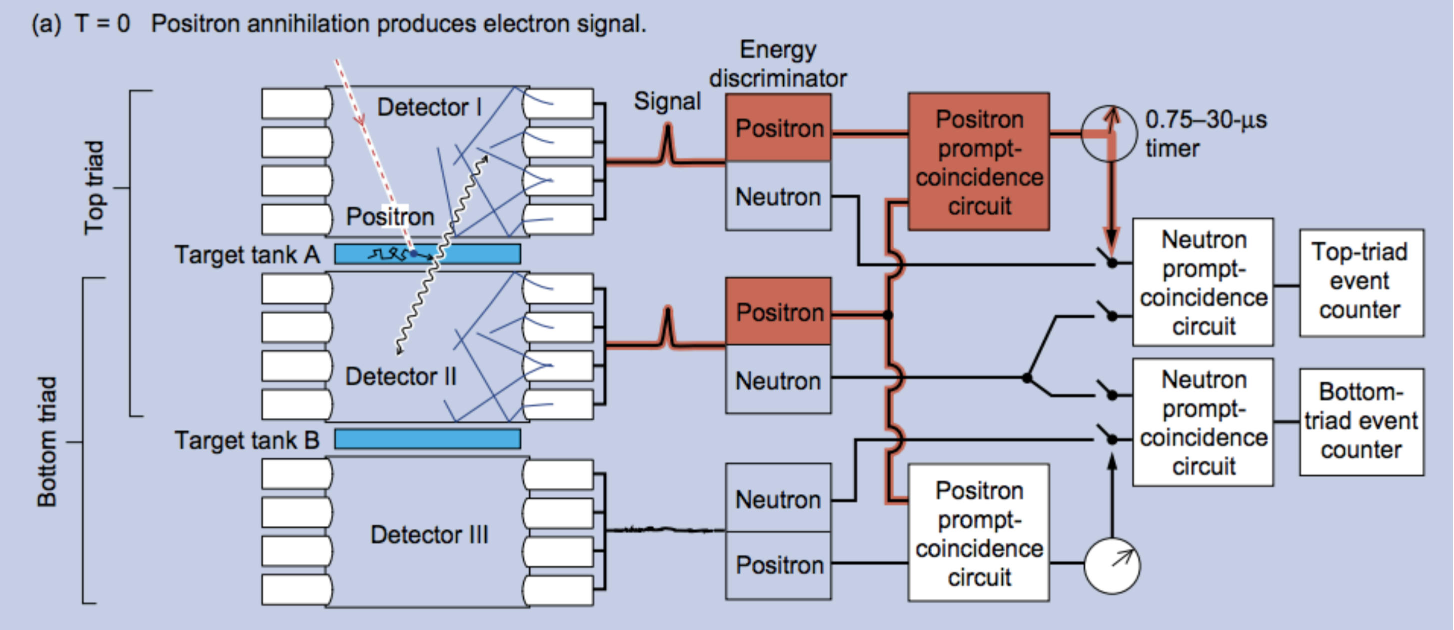
Cowen-Reines Neutrino Experiment

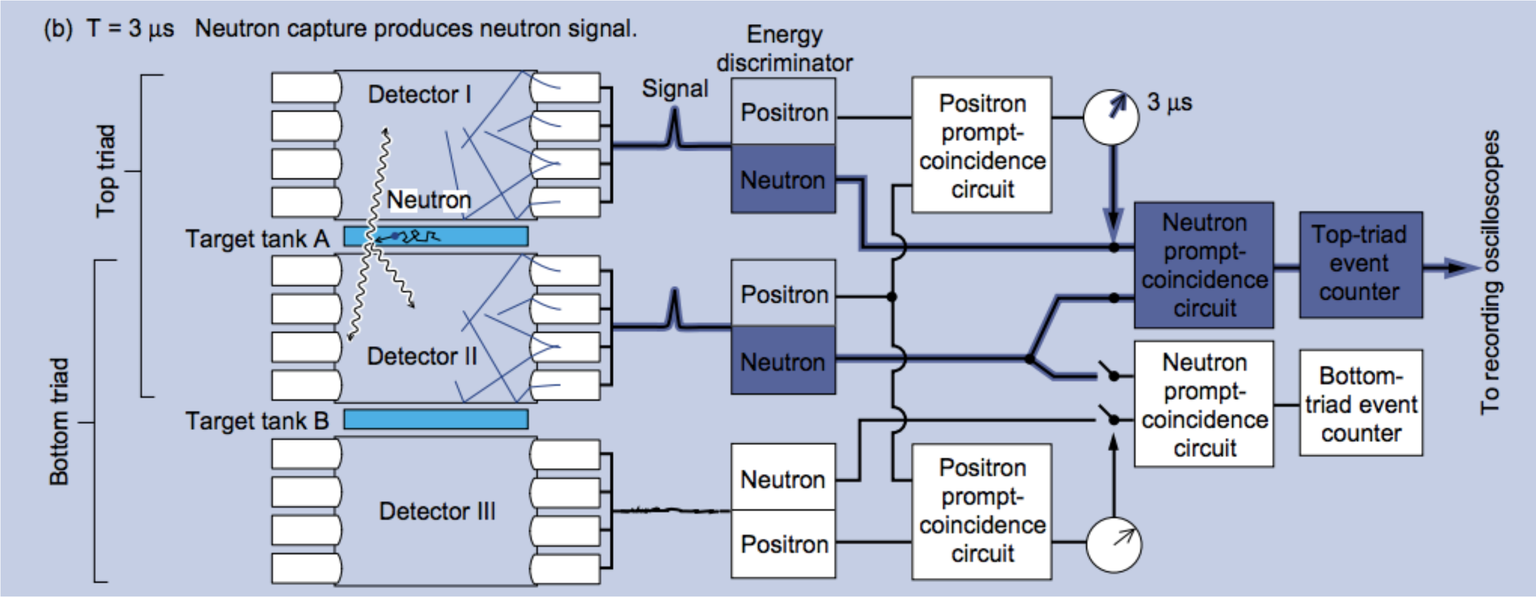
1995

- First try: Hanford Experiment
  - 300 liter scintillator detector
  - Expected signal: 0.1-0.3 counts/min
  - Background: 5 counts/min from cosmic rays (neutrons and gamma-rays from the reactor could be shielded)
  - Small but not statistically significant excess
- Success: Savannah River Experiment
  - 4200 liters of scintillator split into 3 sandwiched tanks
  - Advanced trigger algorithm allowed to suppress background
  - Measured cross section within 5% from theoretical value of $6.3 \times 10^{-44} cm^2$

Science, 1956, DOI: 10.1126/science.124.3212.103

Advanced Trigger in Savannah River Experiment



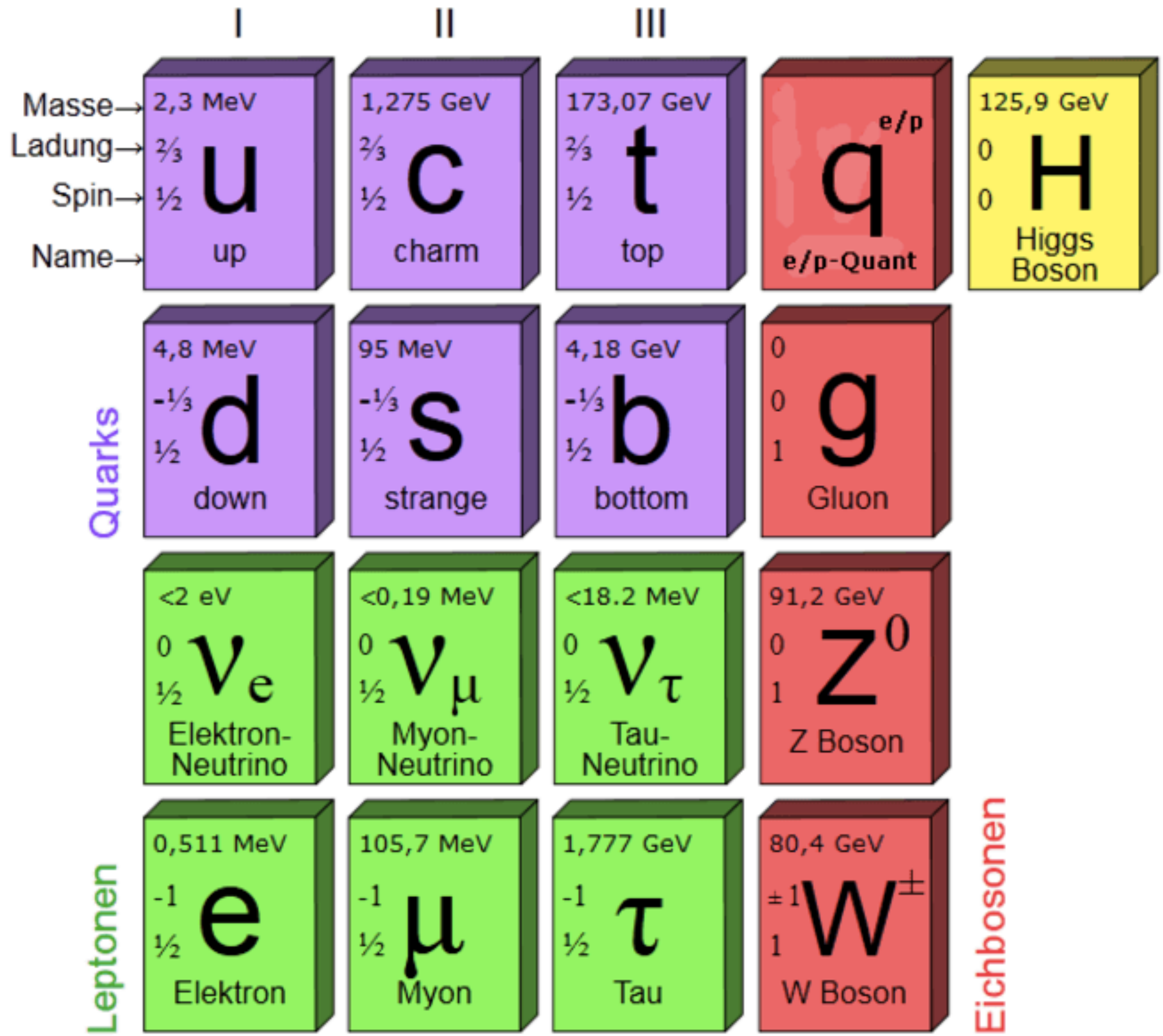


Pauli was notified on June 14th 1956

- Telegram: “We are happy to inform you that we have definitely detected neutrinos from fission fragments by observing inverse beta decay of protons. Observed cross section agrees well with expected six times ten to minus forty-four square centimeters”
- Pauli and some friends consumed a case of champagne in celebration.

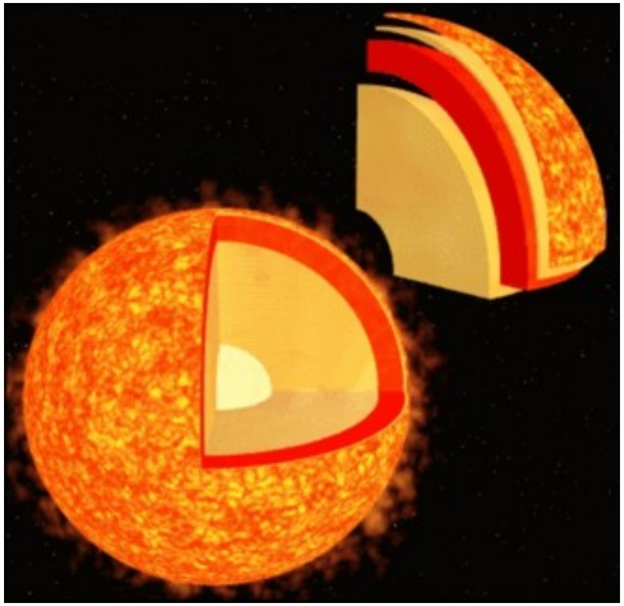
The Neutrino as a particle

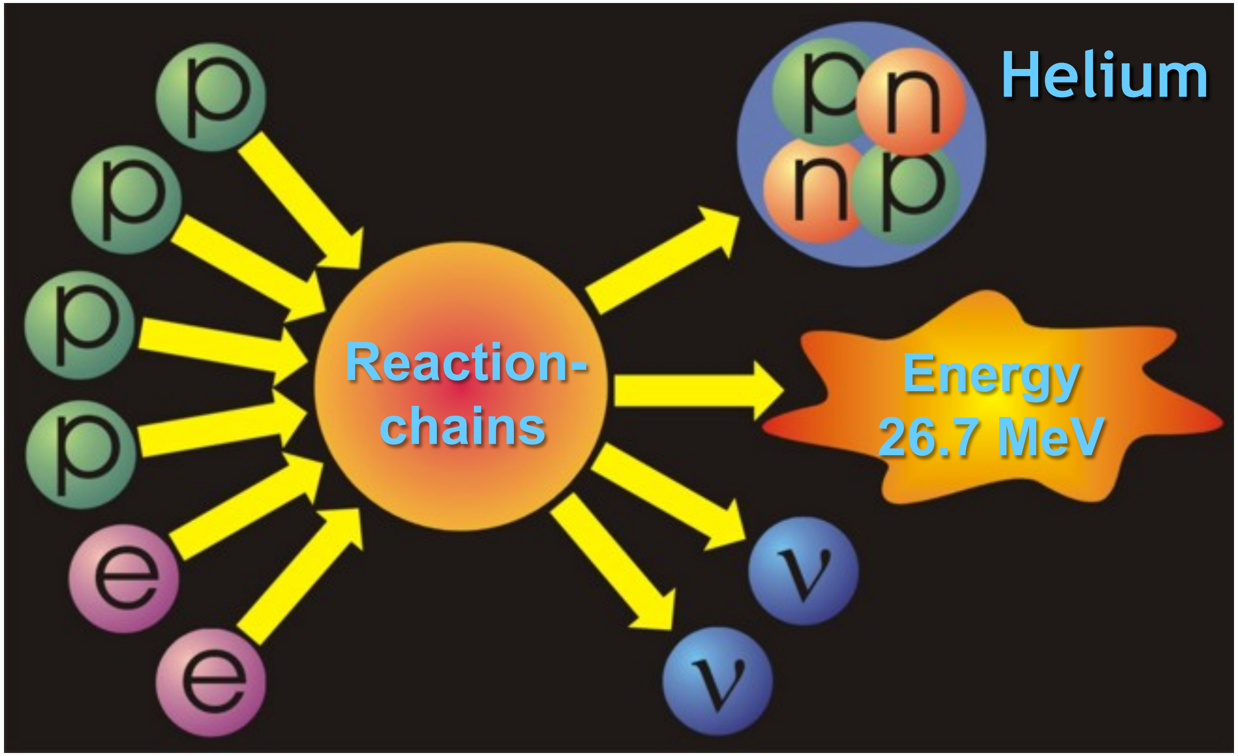
- Part of the standard model
  - Three flavors
- Spin: 1/2



Neutrinos from the Sun

Solar Neutrinos





Solar radiation: 98 % light

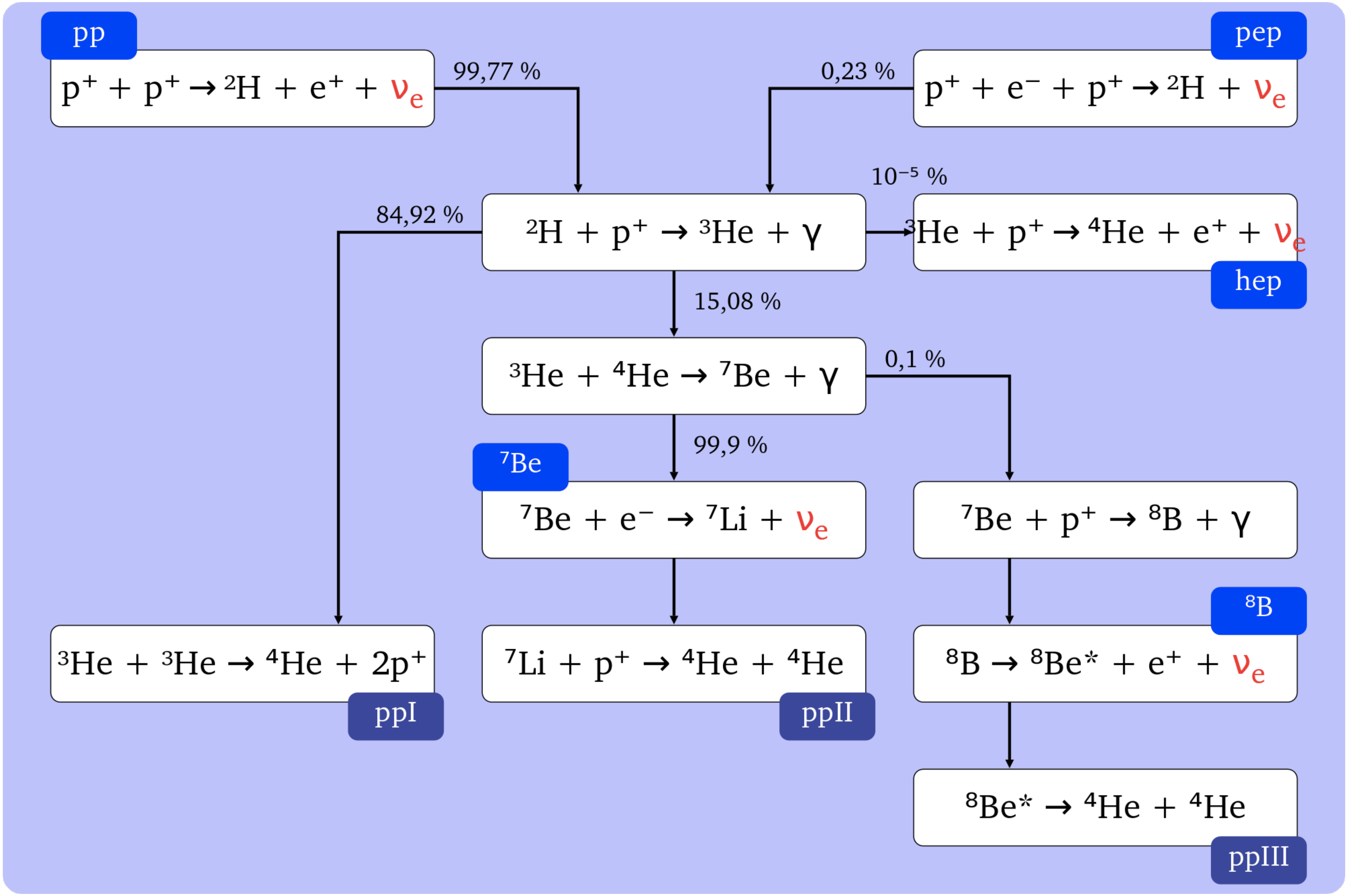
2 % neutrinos

At Earth 66 billion neutrinos $cm^{-2}\ s^{-1}$

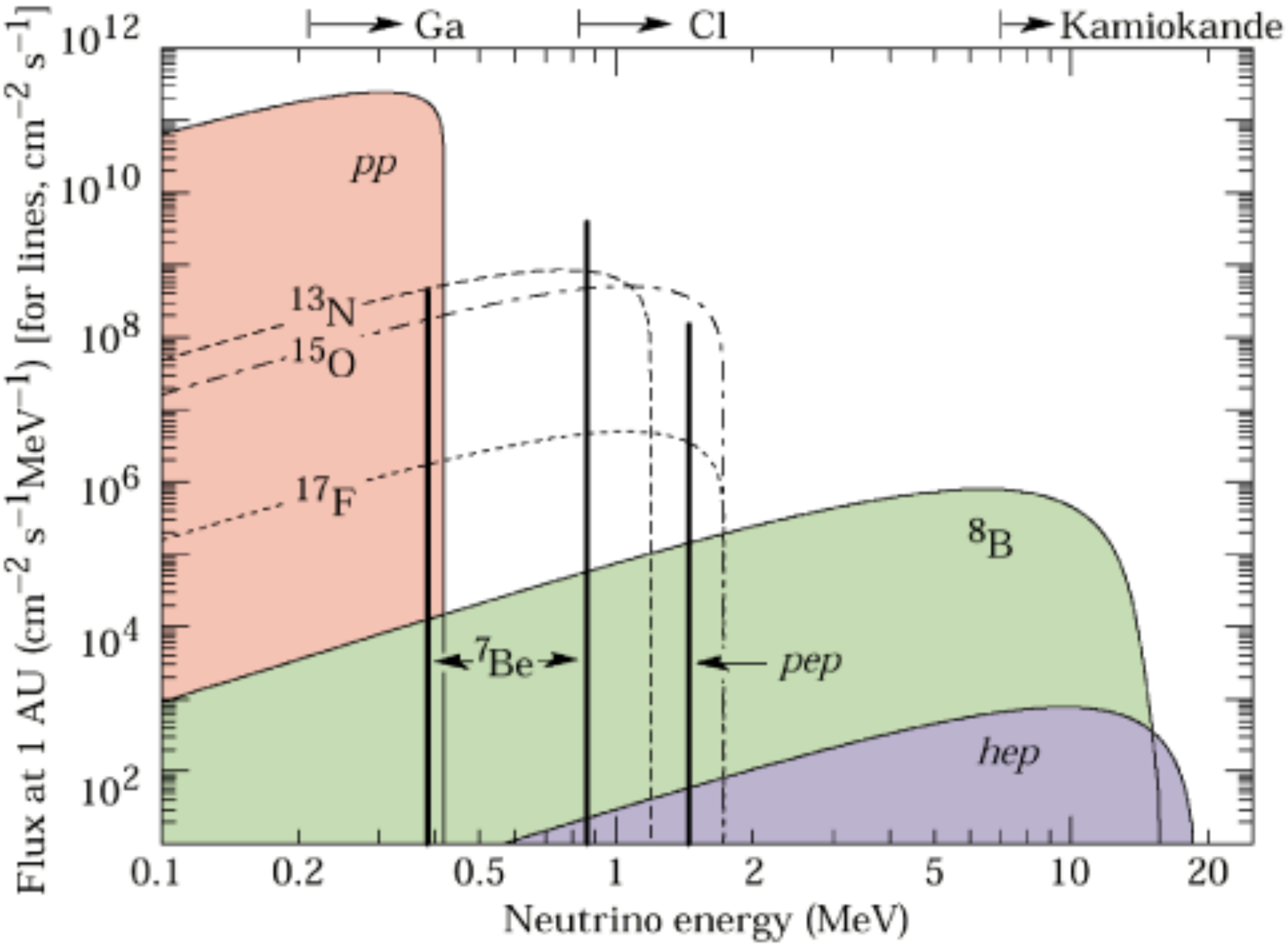
Hans
Bethe

1967

Neutrino Production in the Sun



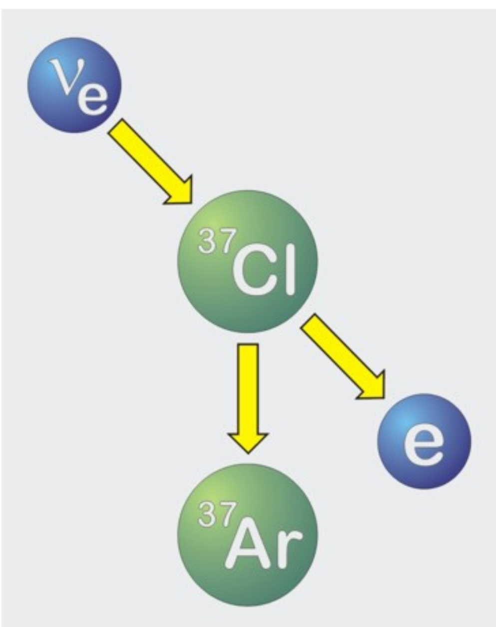
Solar Neutrino Spectrum

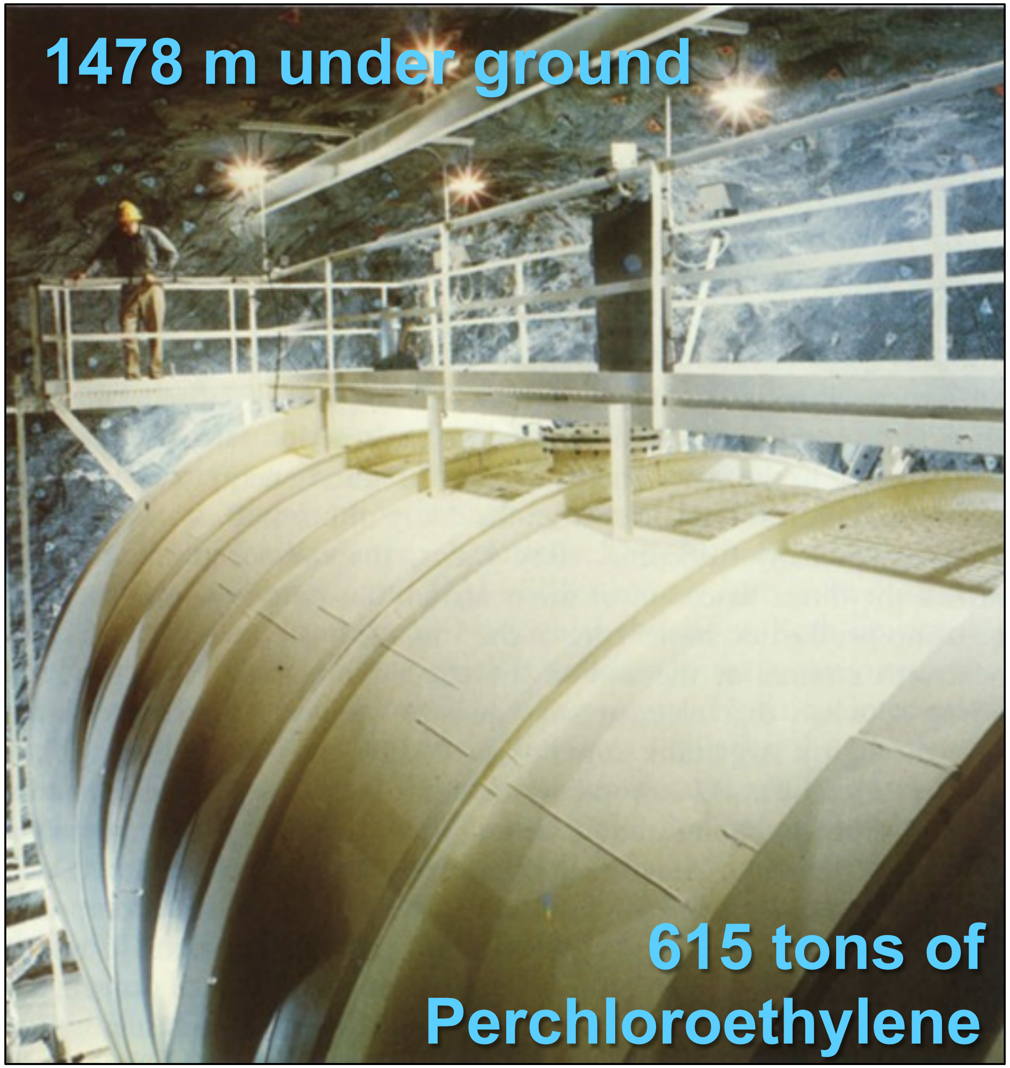


The Homestake Experiment

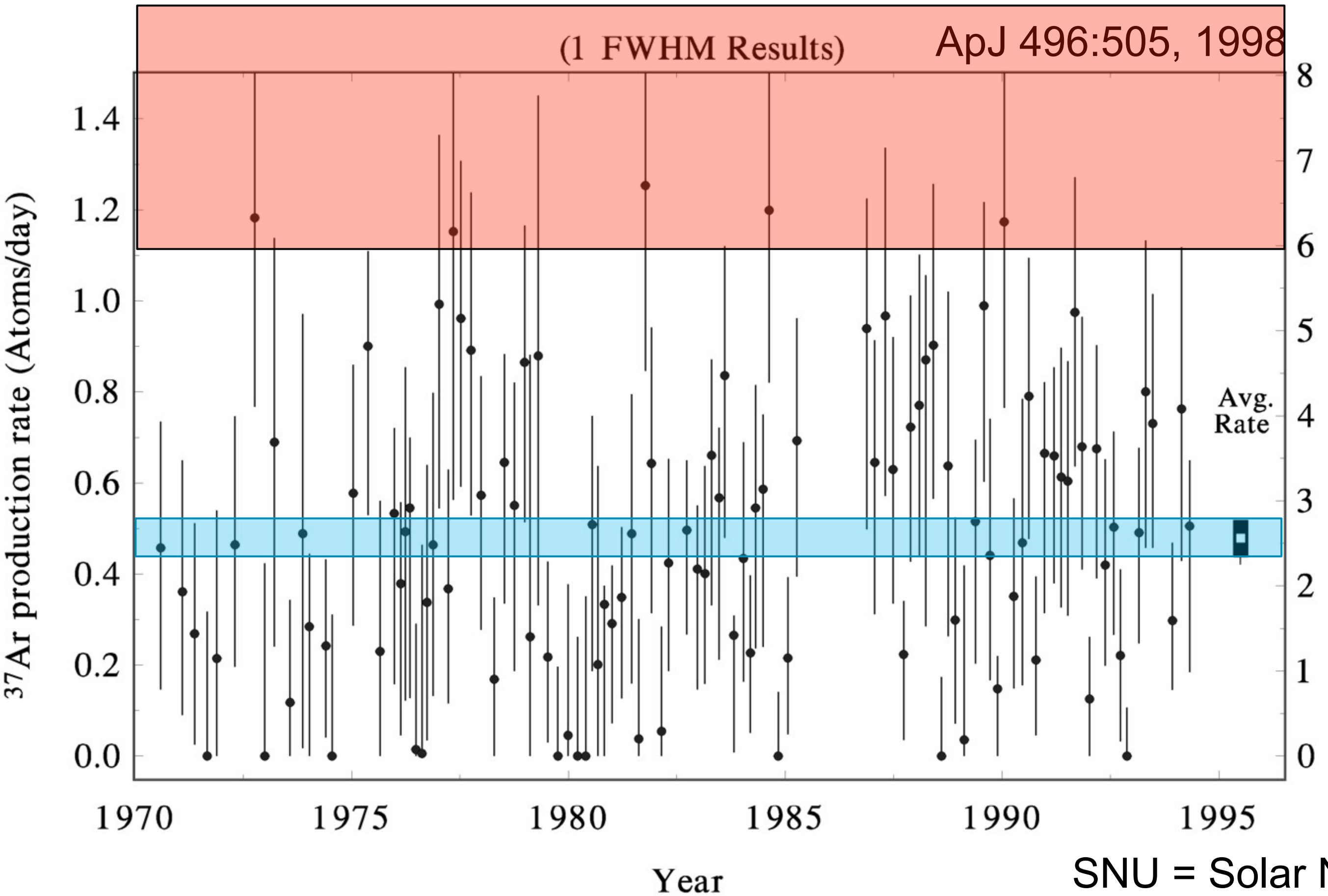
- The first measurement of solar neutrinos
- Energy threshold: 0.8 MeV
- Argon chemically extracted

$$\nu_e + {}^{37}\mathrm{Cl} \longrightarrow {}^{37}\mathrm{Ar} + e^-$$





Homestake: Results



Theoretical Prediction: 6-9 SNU

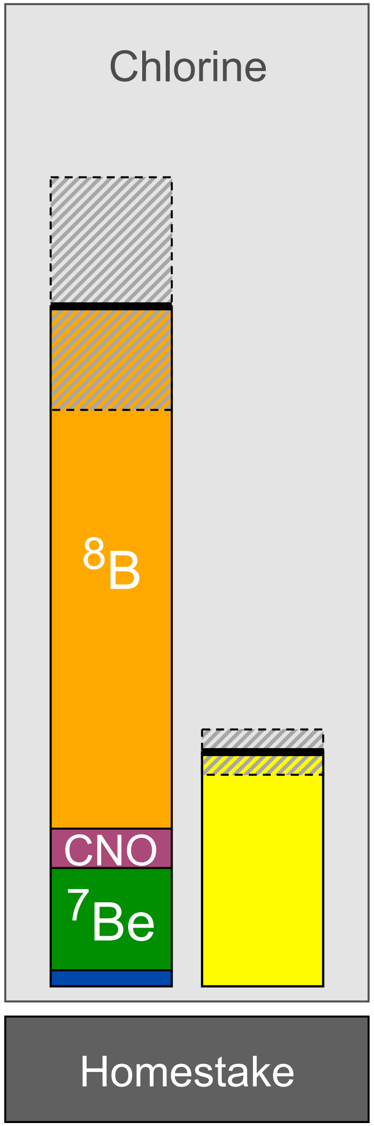
Average Rate
$2.56 \pm 0.16_{stat} \pm 0.16_{sys}$ SNU

SNU = Solar Neutrino Unit = 1 Absorption / sec / 10^{36} Atoms

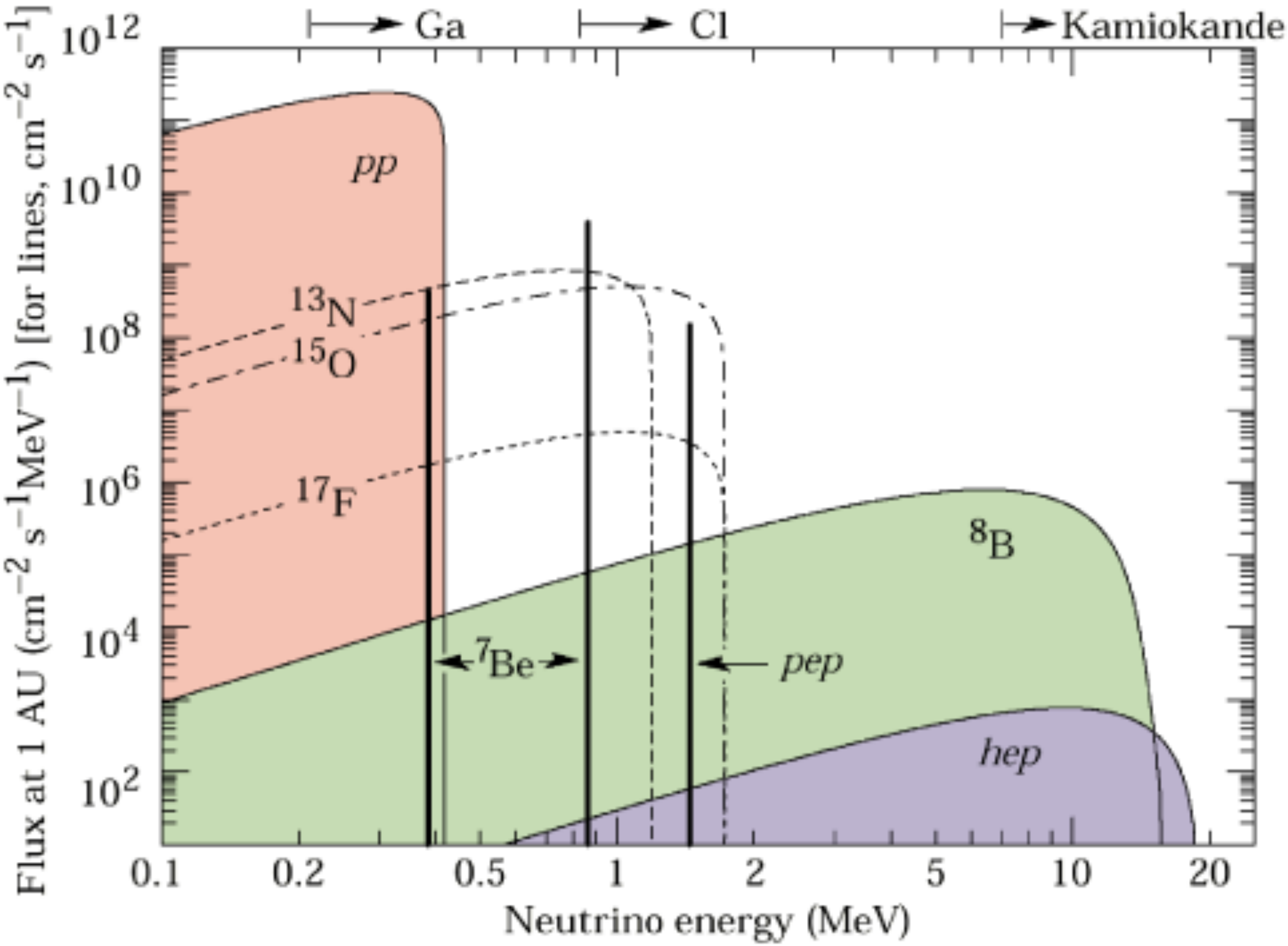
→ Solar neutrino problem

Solution to the solar neutrino problem

Electron-Neutrino Detectors



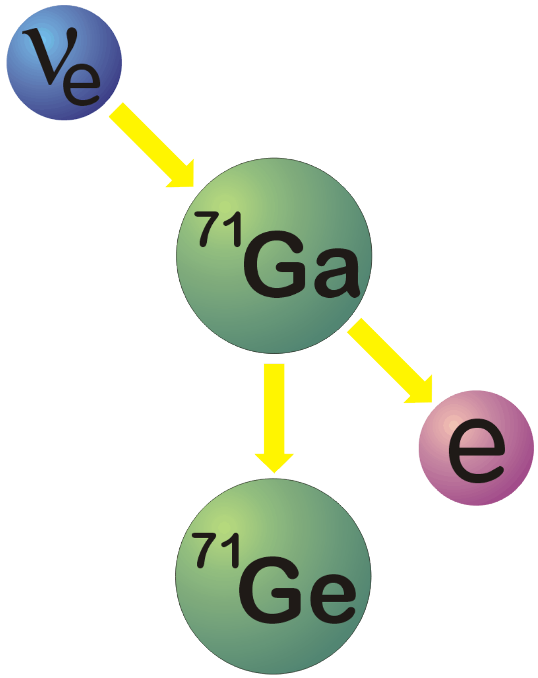
Solar Neutrino Spectrum

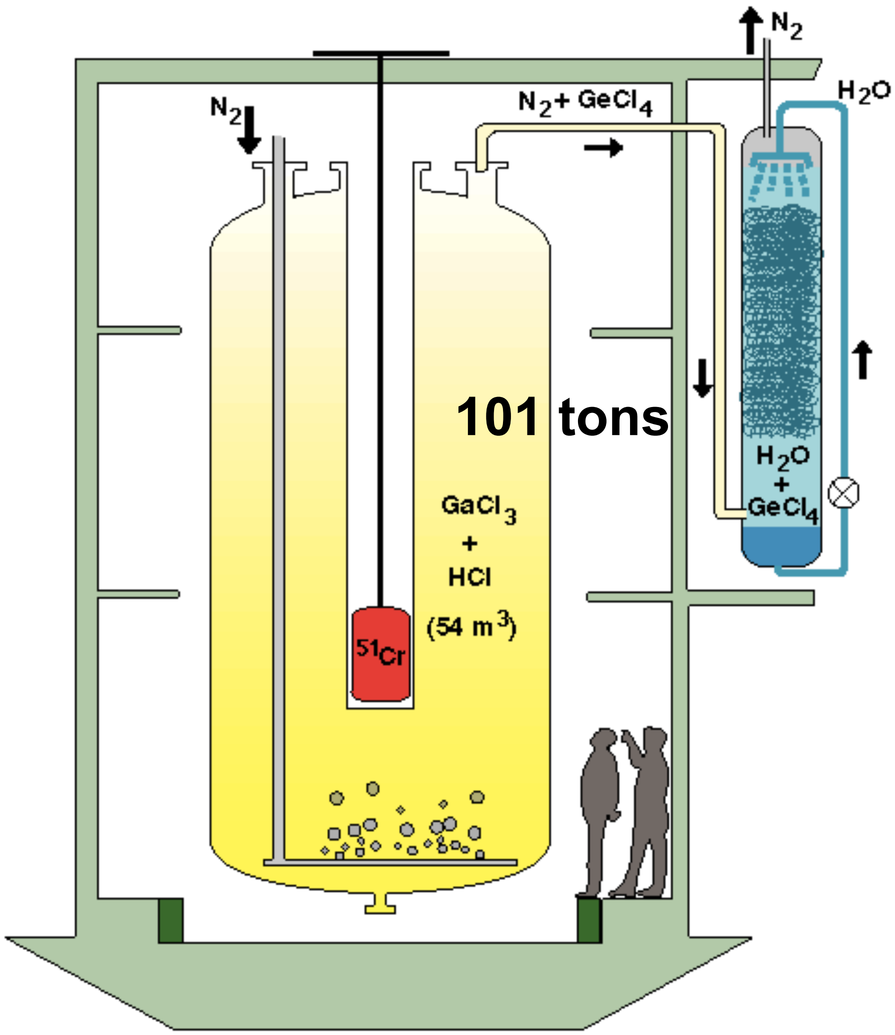


GALLEX / SAGE (1991-2003)

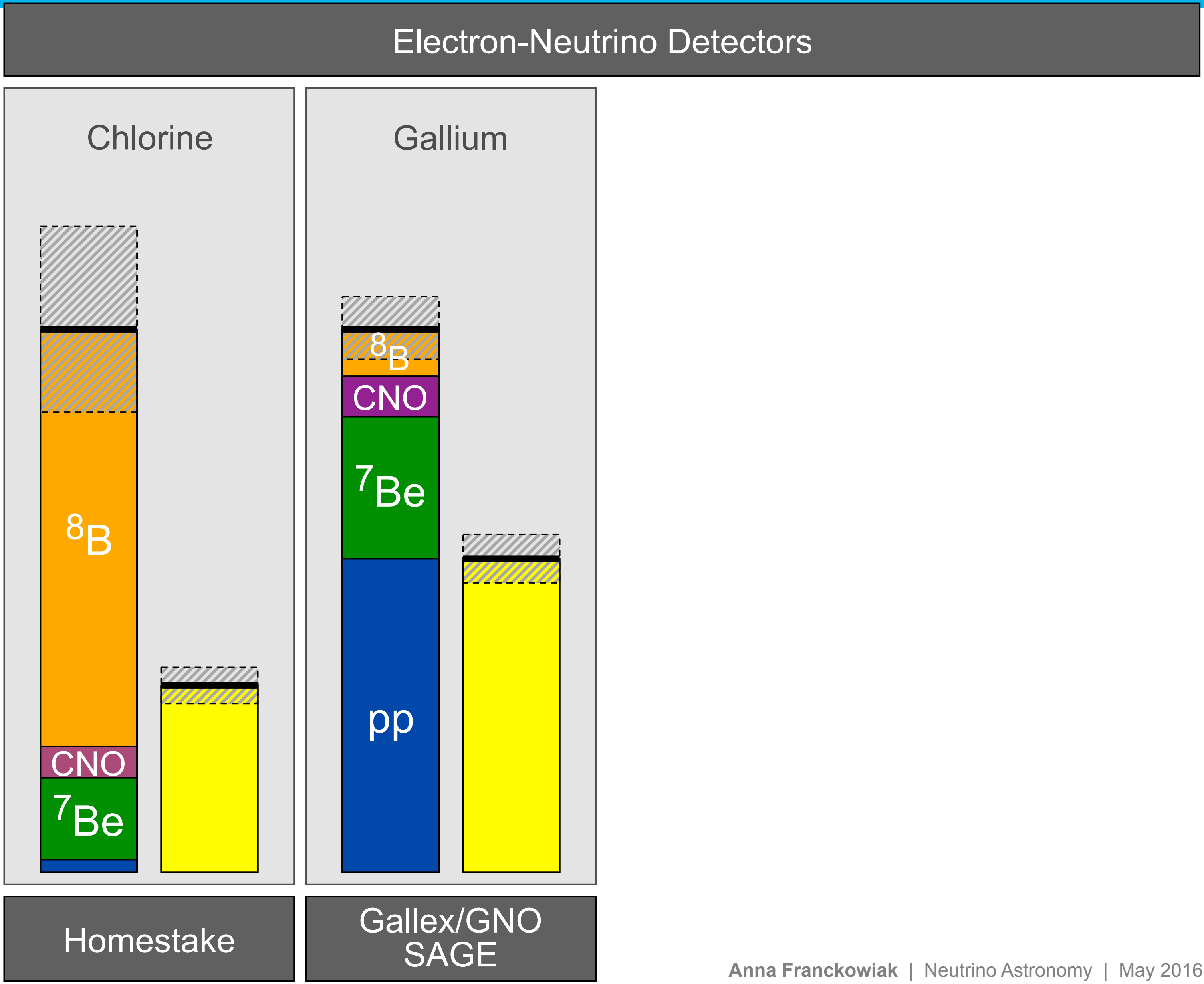
- Chemical extraction of ^{71}Ge from detector, converted to $^{71}GeH_4$ with lifetime of ~11 days
- Energy threshold: 0.23 MeV

$$\nu_e + {}^{71}\mathrm{Ga} \longrightarrow {}^{71}\mathrm{Ge}^+ + e^-$$

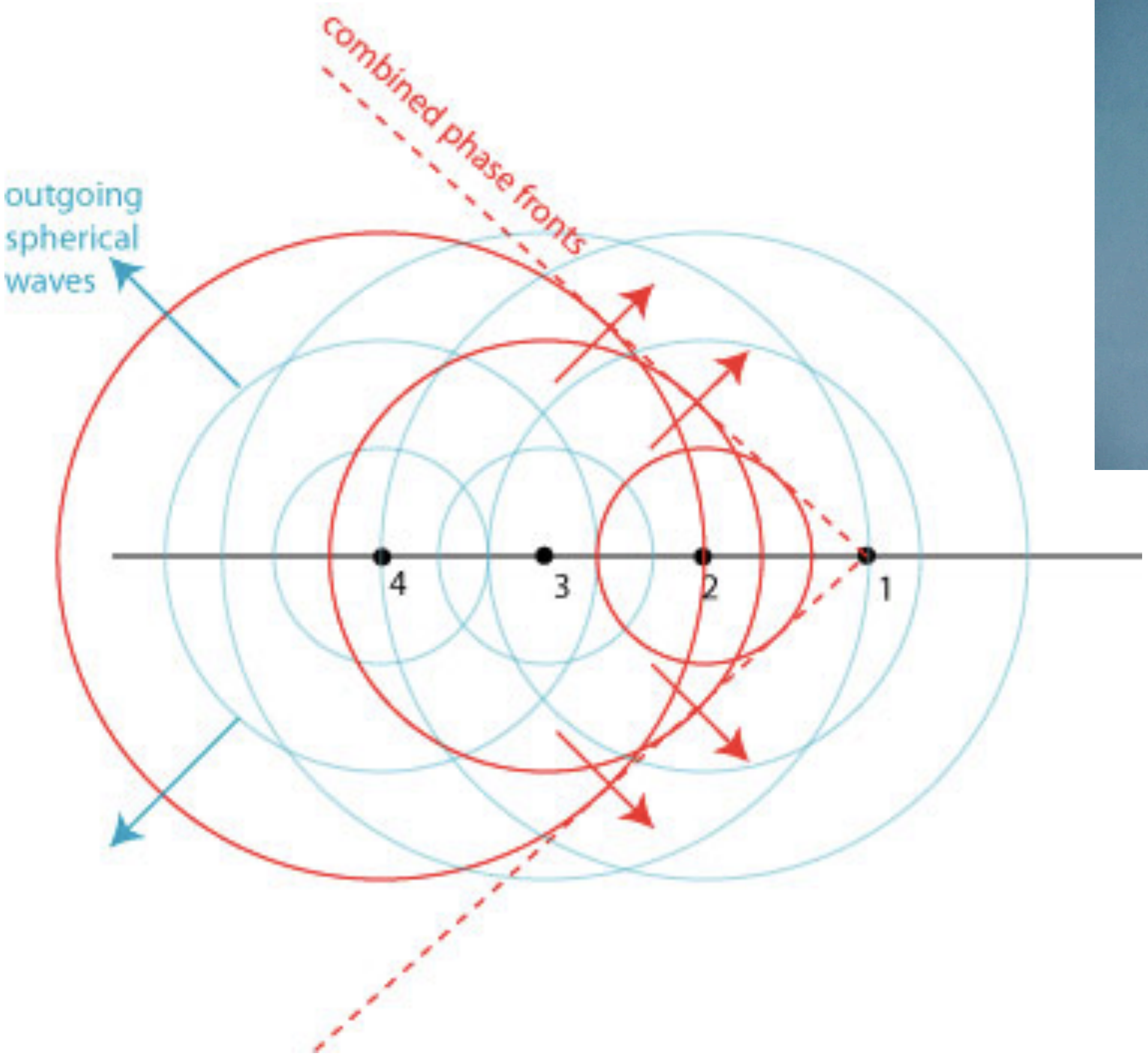




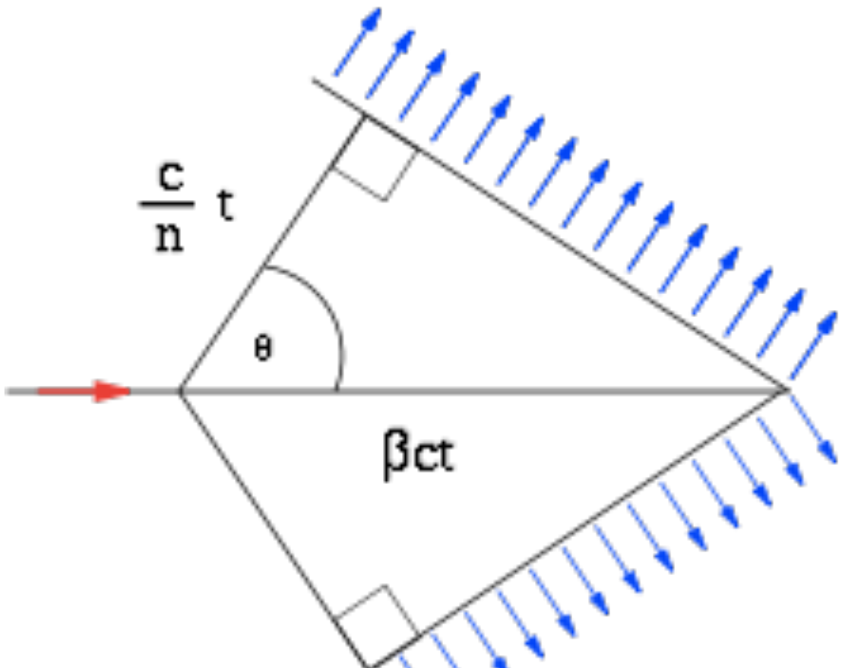
Solution to the solar neutrino problem



Different detection technique: Cherenkov Effect

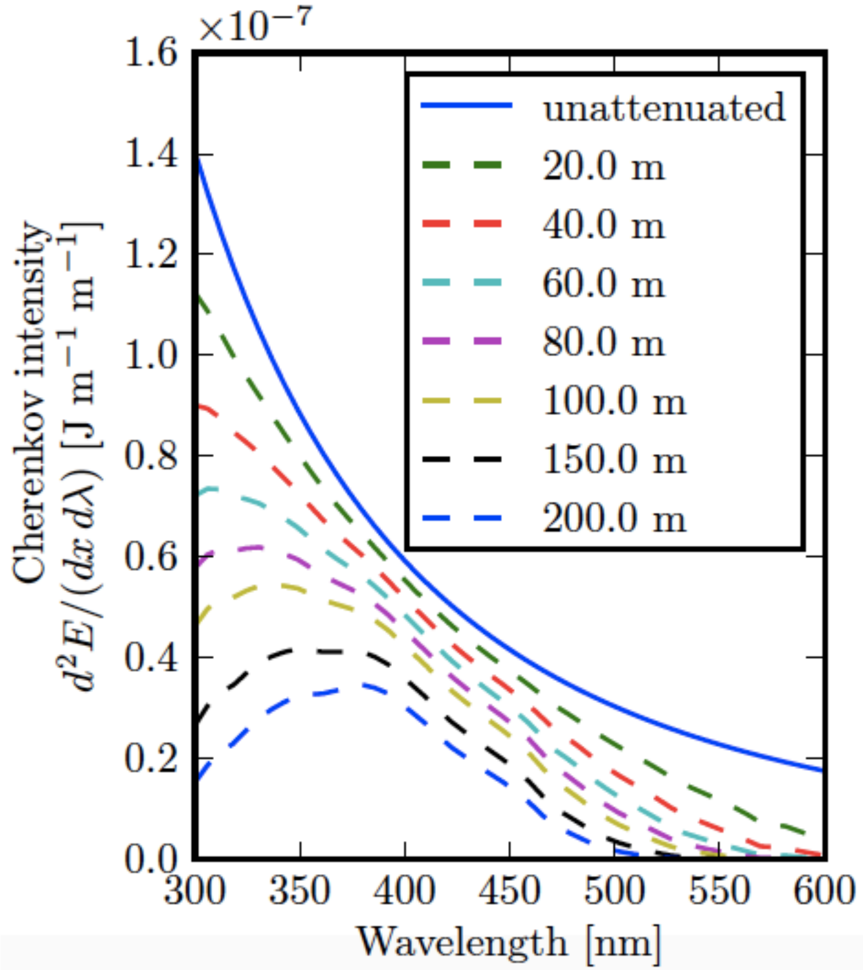


Cherenkov Effect



$$\cos\theta = \frac{1}{n\beta}.$$

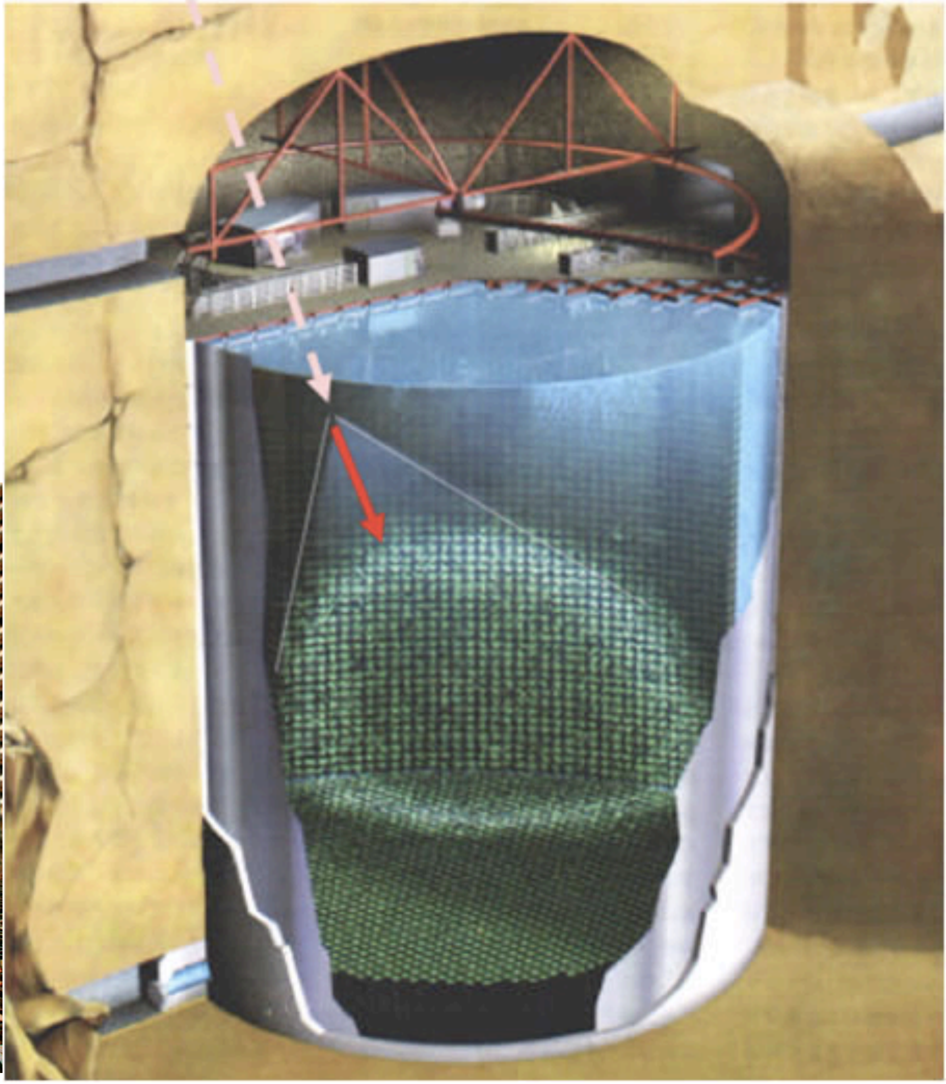
Medium	n	θ
Water	1.33	43
ice	1.31	41
air	1.0003	1.4



Cherekov intensity for e with β=1 in ice

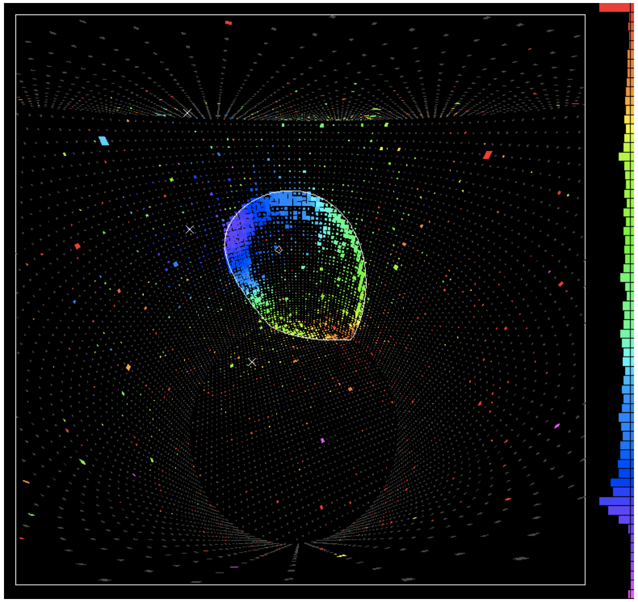
Super Kamiokande

- mine in Japan
- 1km below ground
- 50000 t of water, 13000 PMTs
- 15 solar neutrinos / day

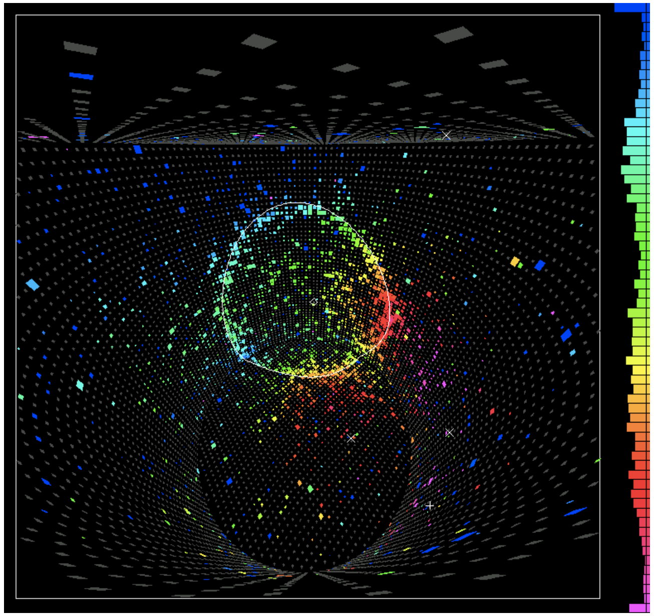


Super Kamiokande – Event Displays

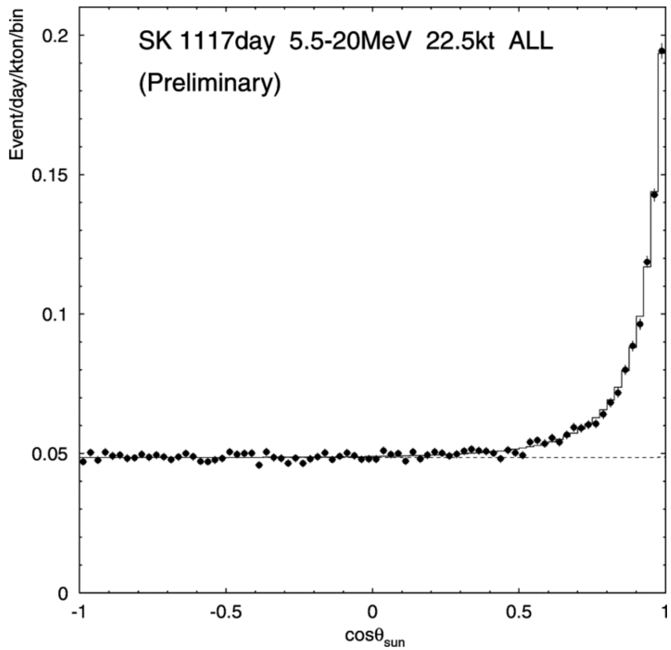
Muon neutrino event (1 GeV)
Cherenkov cone with well defined edges, different colors show different arrival times

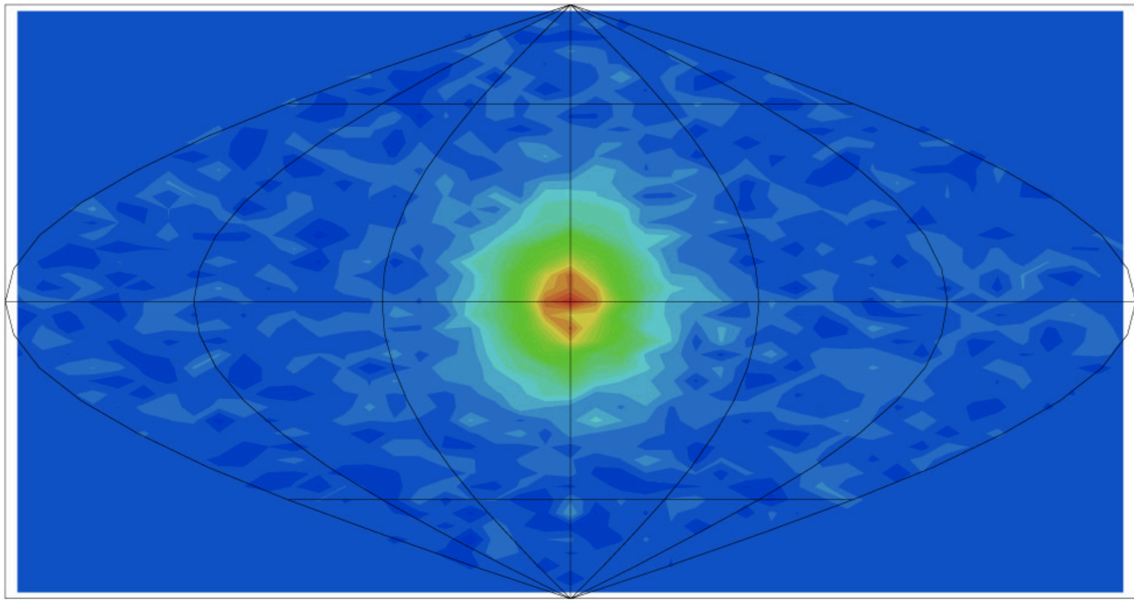


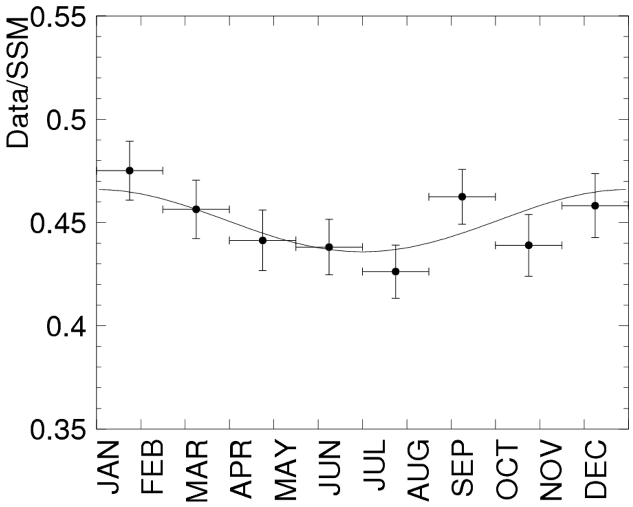
Electron neutrino event (0.6 GeV)
Cherenkov cone more fuzzy due to many e- and e+ produced in particle shower



Super-Kamiokande – “Image” of the Sun

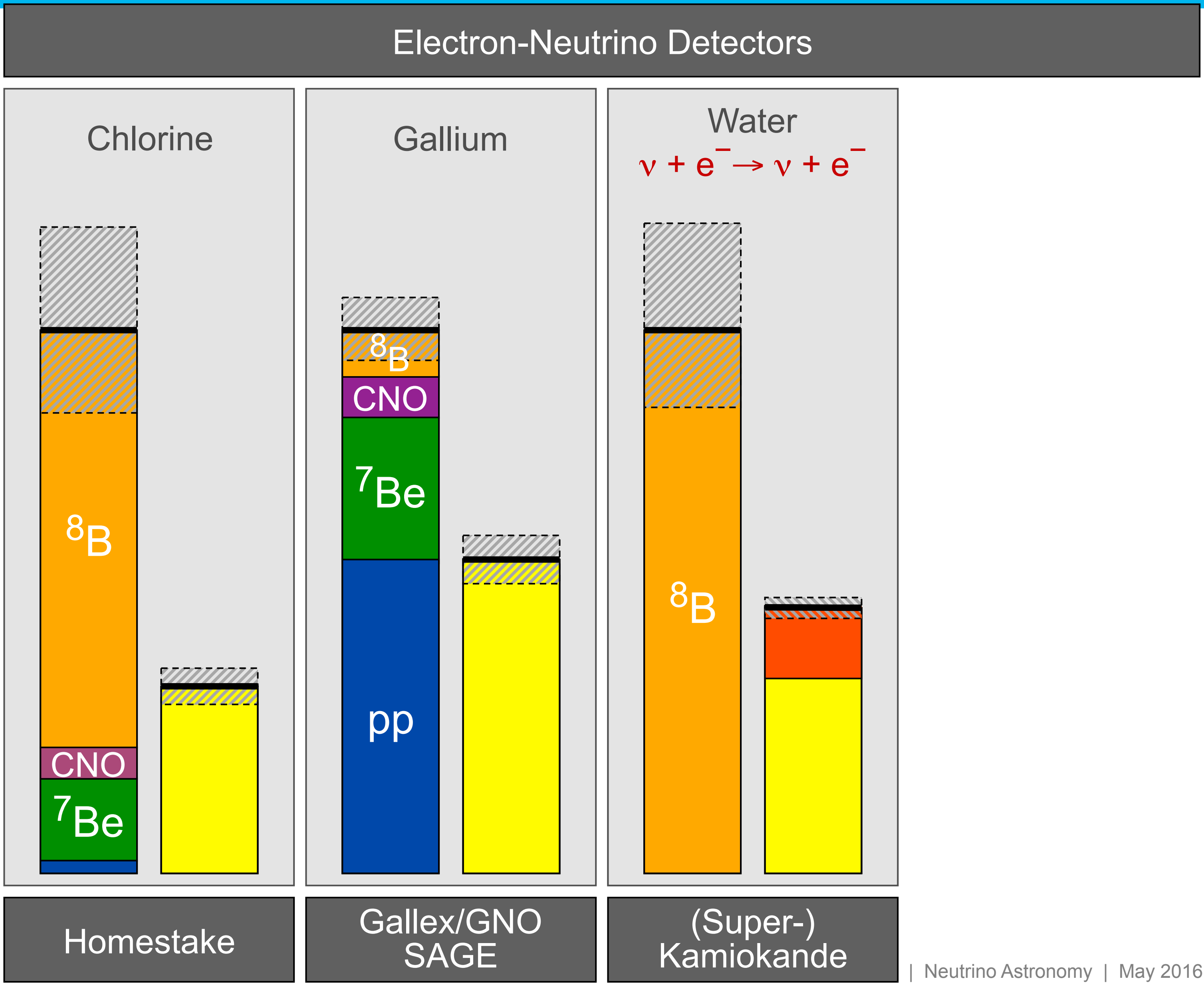






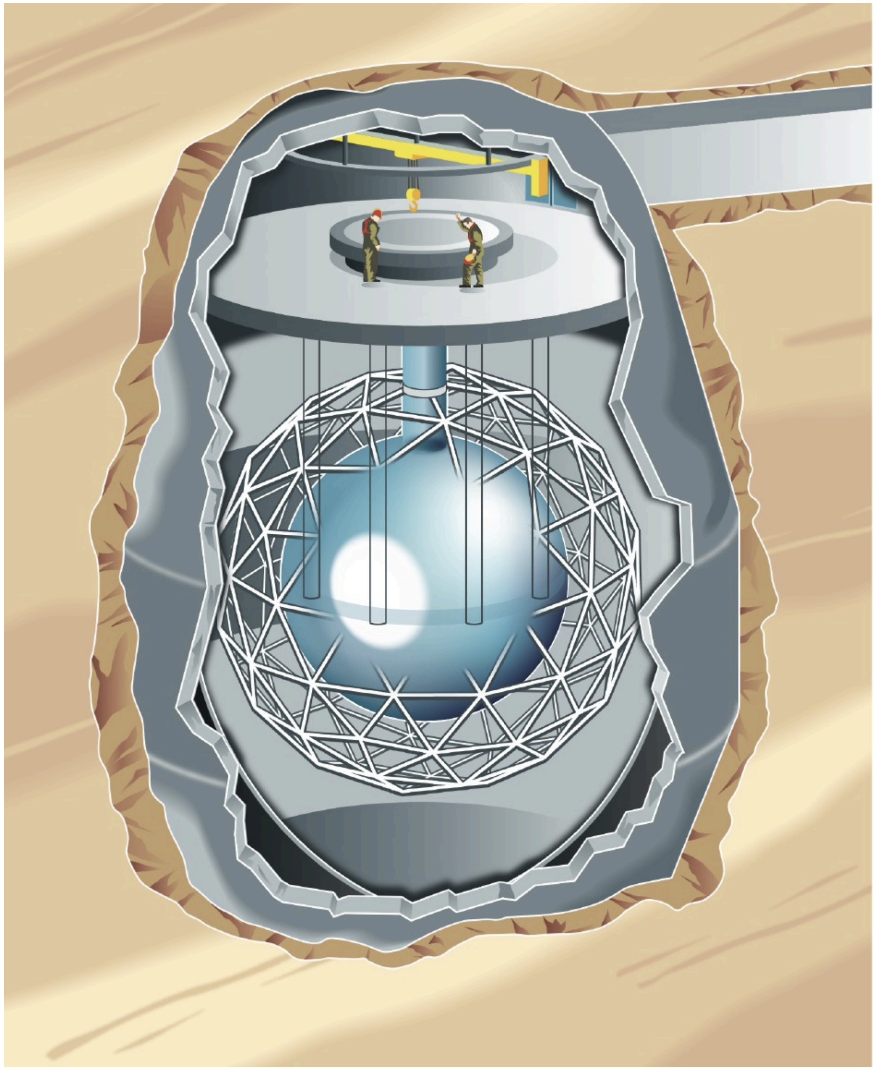
Seasonal variation due to elliptic orbit of Earth around sun

Solution to the solar neutrino problem



Sudbery Neutrino Observatory (SNO)

- Operational 1999 – 2006
- Mine in Canada
- 2.1km underground
- 1000 t of heavy water
- 9600 PMTs



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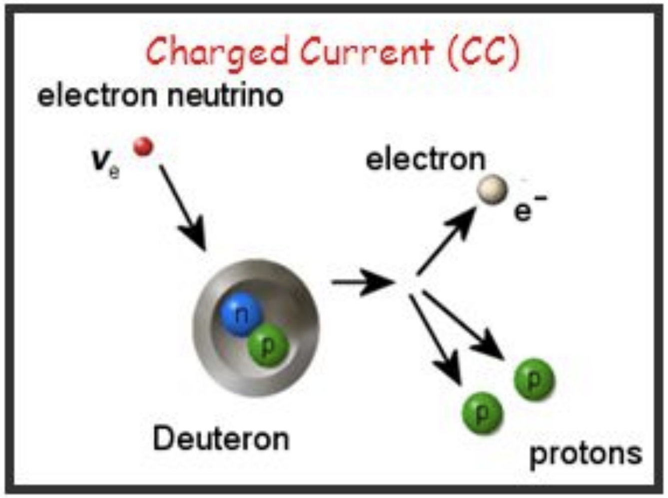
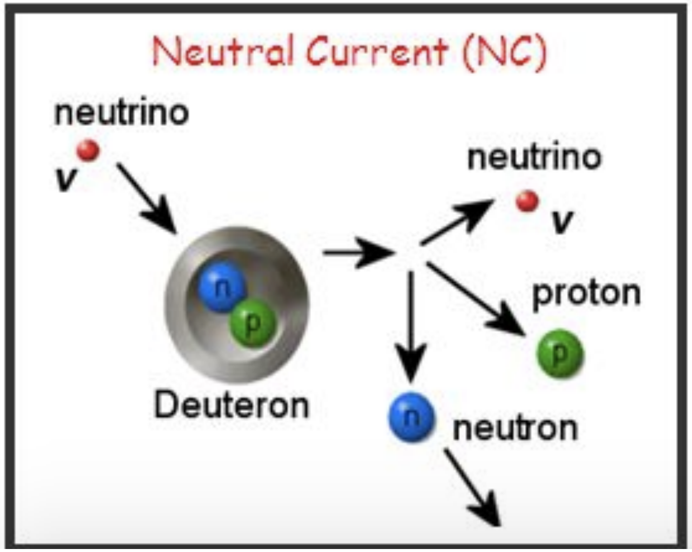
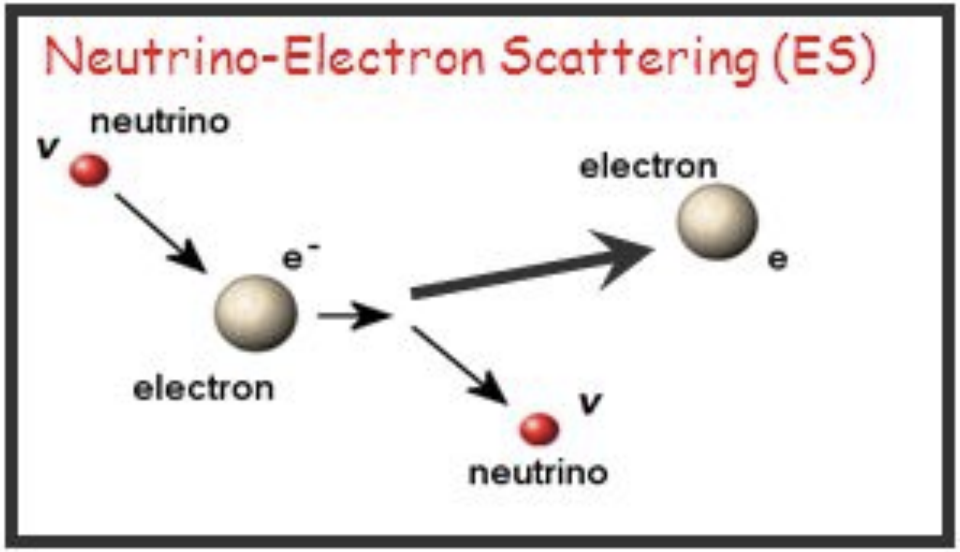


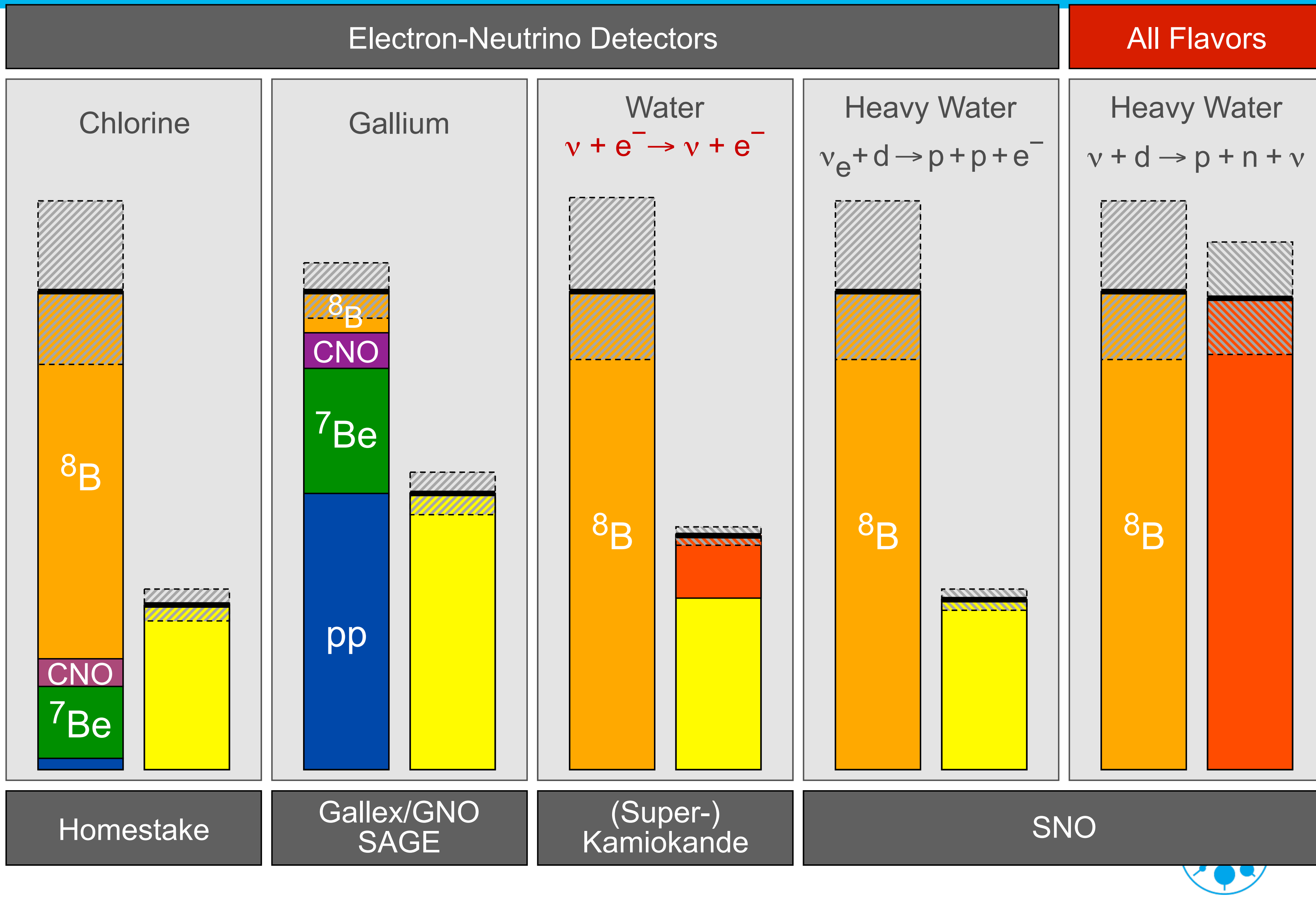
CC Charged Current Reaction	$\upsilon_e + d \rightarrow p + p + e^-$	$E_{threshold} = 1.4 MeV$
NC Neutral Current Reaction	$\upsilon_x + d \rightarrow \upsilon_x + p + n$	$E_{threshold} = 2.2 MeV$
ES Elastic Scattering Reaction	$\upsilon_x + e^- \rightarrow \upsilon_x + e^-$	$E_{threshold} \approx 0$

x denotes that this reaction will take place with any neutrino.

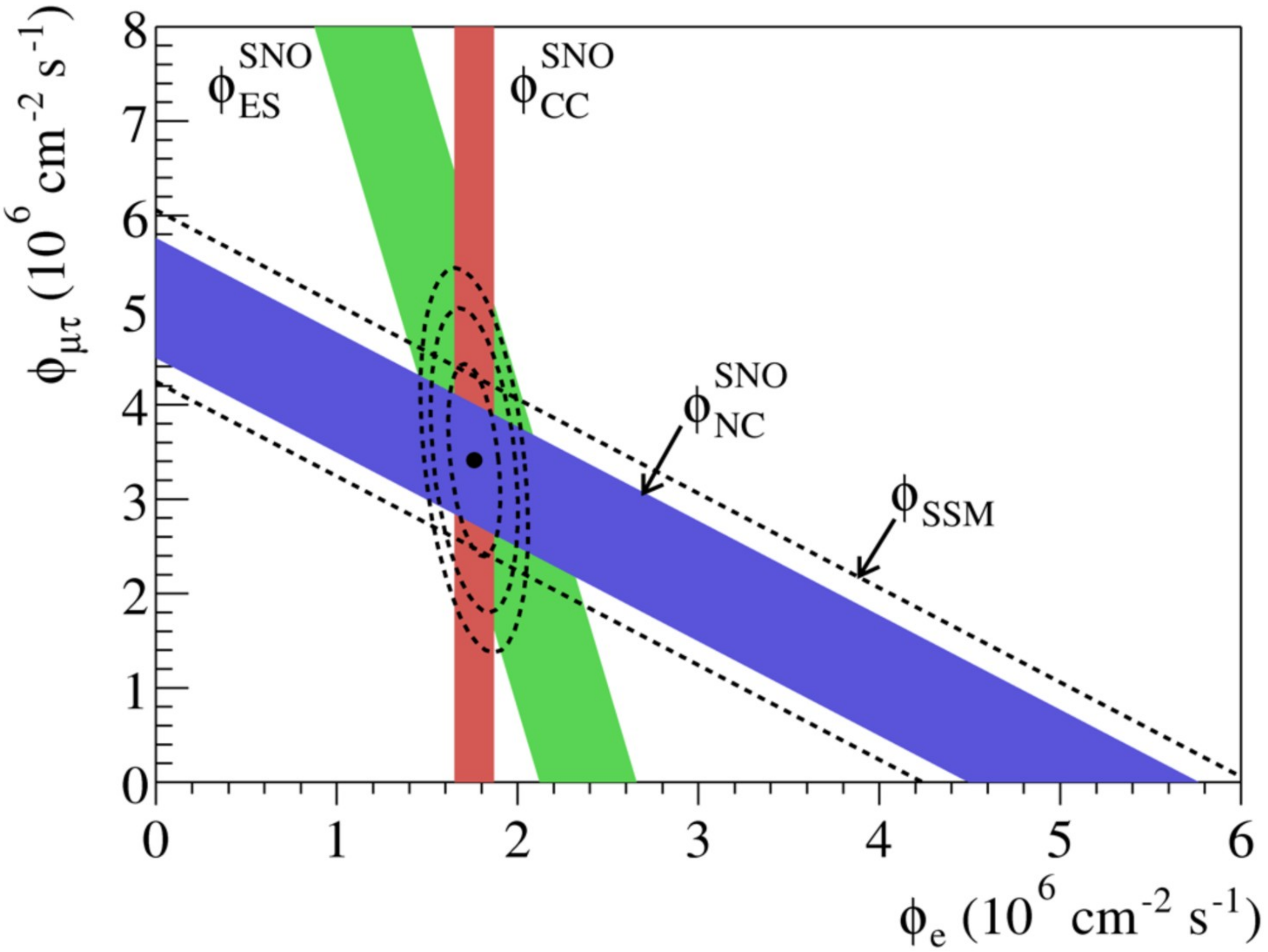




Solution to the solar neutrino problem



Charged and Neutral Current Solar Flux Measurement



Ahmad et al. (SNO Collaboration), PRL 89:011301,2002

Neutrino Oscillations

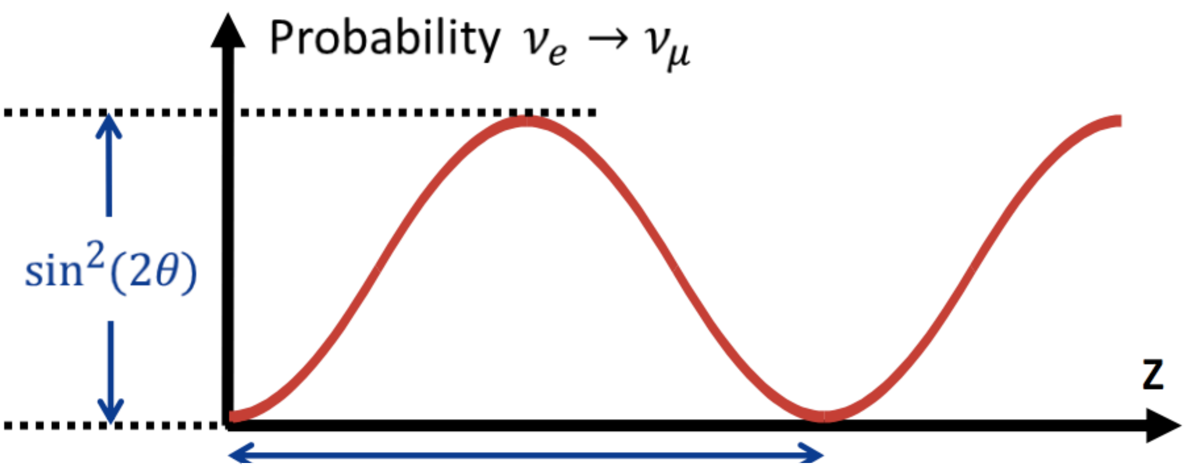
- Mass states ≠ flavor states
- Two flavor mixing: $\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$

flavor states   mass states

Different mass states propagate with different momenta:

$$p_{1,2} = (E^2 - m_{1,2}^2)^{1/2} \approx E - m_{1,2}^2/2E$$

$$P_{\nu_e \to \nu_\mu} = \sin^2(2\theta)\,\sin^2\left(\frac{\Delta m^2}{4E} L\right) \qquad \Delta m^2 = m_2^2 - m_1^2$$



$$L_{\text{osc}} = \frac{4\pi E}{\Delta m^2} = 2.5\ \text{m}\ \frac{E}{\text{MeV}}\ \frac{\text{eV}^2}{\Delta m^2}$$

Neutrino Oscillation with 3 neutrinos

$$U = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix}$$

$$= \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

phase factor: non-zero only if neutrino oscillation violates CP symmetry

where cij = cos θij and sij = sin θij.

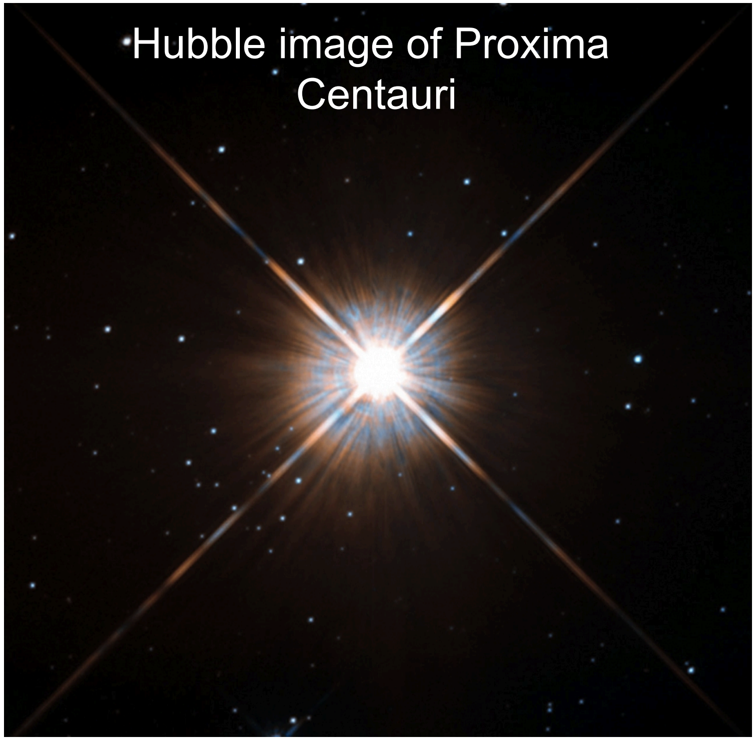
phase factors α_1 and α_2 meaningful only if neutrinos are Majorana particles (neutrino is identical to its antineutrino)

Matter effects

- The electrons in matter change the effective mass of the electron neutrino
- Charged current coherent forward scattering (analogous to the electromagnetic process leading to the refractive index of light in a medium)
- Neutrino oscillation depend on squared mass difference
- Effect depends on neutrino energy
- Important in large densities in the sun and the earth

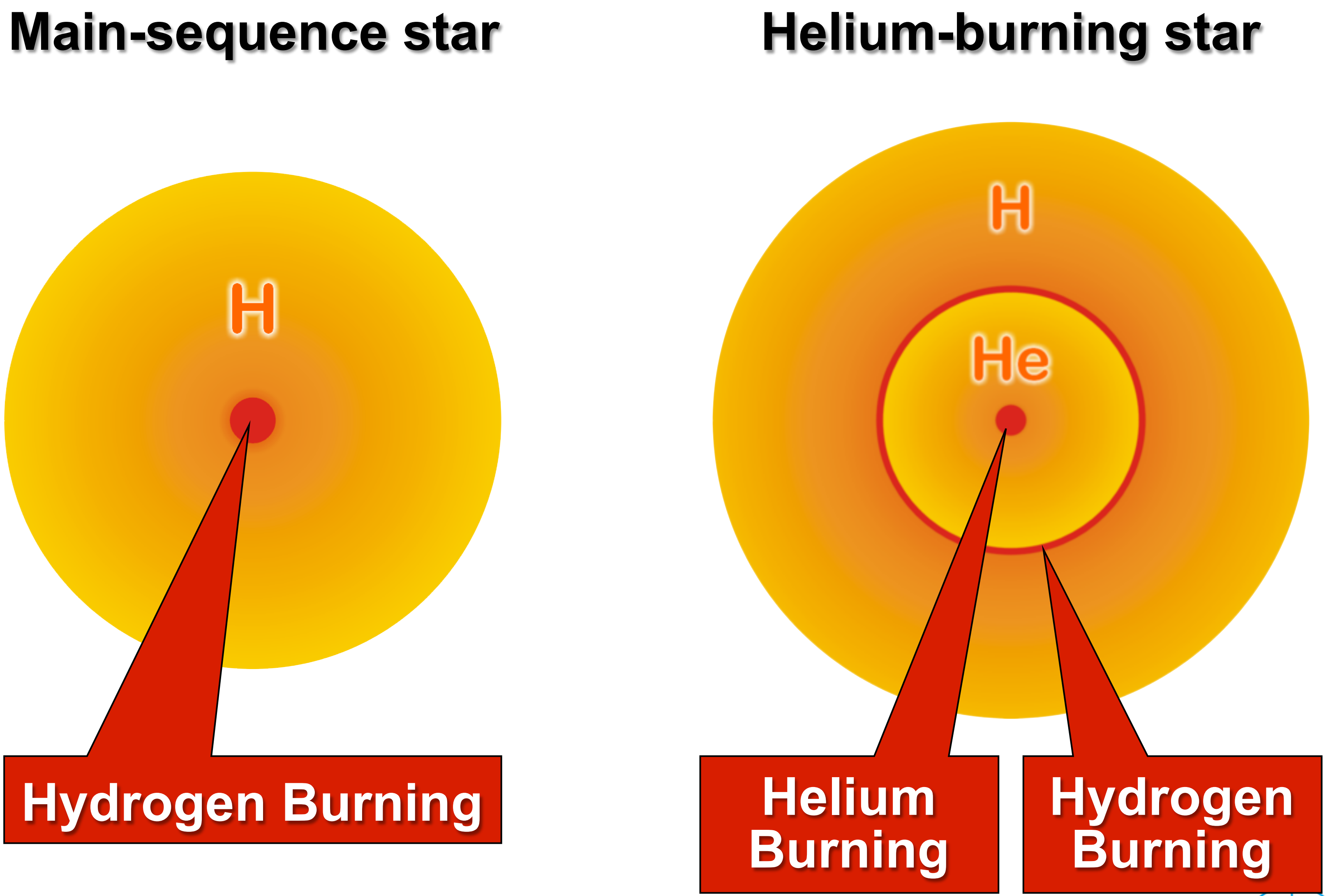
Neutrinos from the Sun – could we see other stars?

- Closest star: Proxima Centauri at 4.24 light years
- 15 neutrinos / day from the sun → 0.1 neutrino / 1 million years from Proxima Centauri



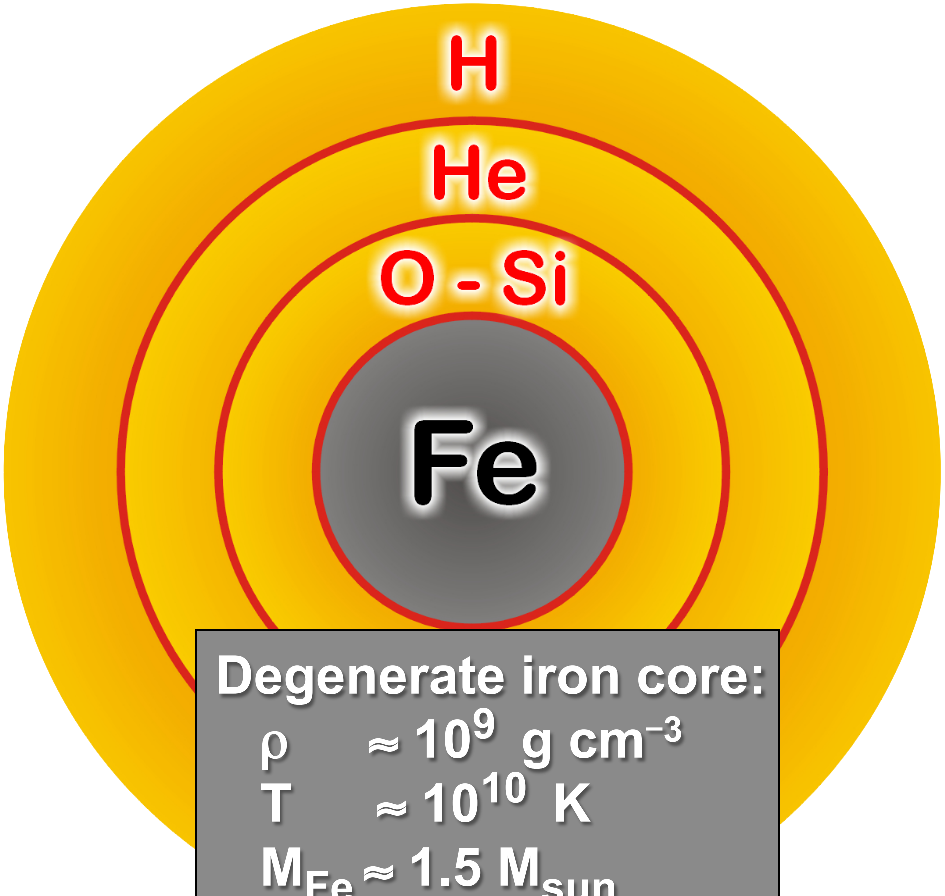
Neutrinos from the Supernovae

Core-Collapse Supernova



Core-Collapse Supernova

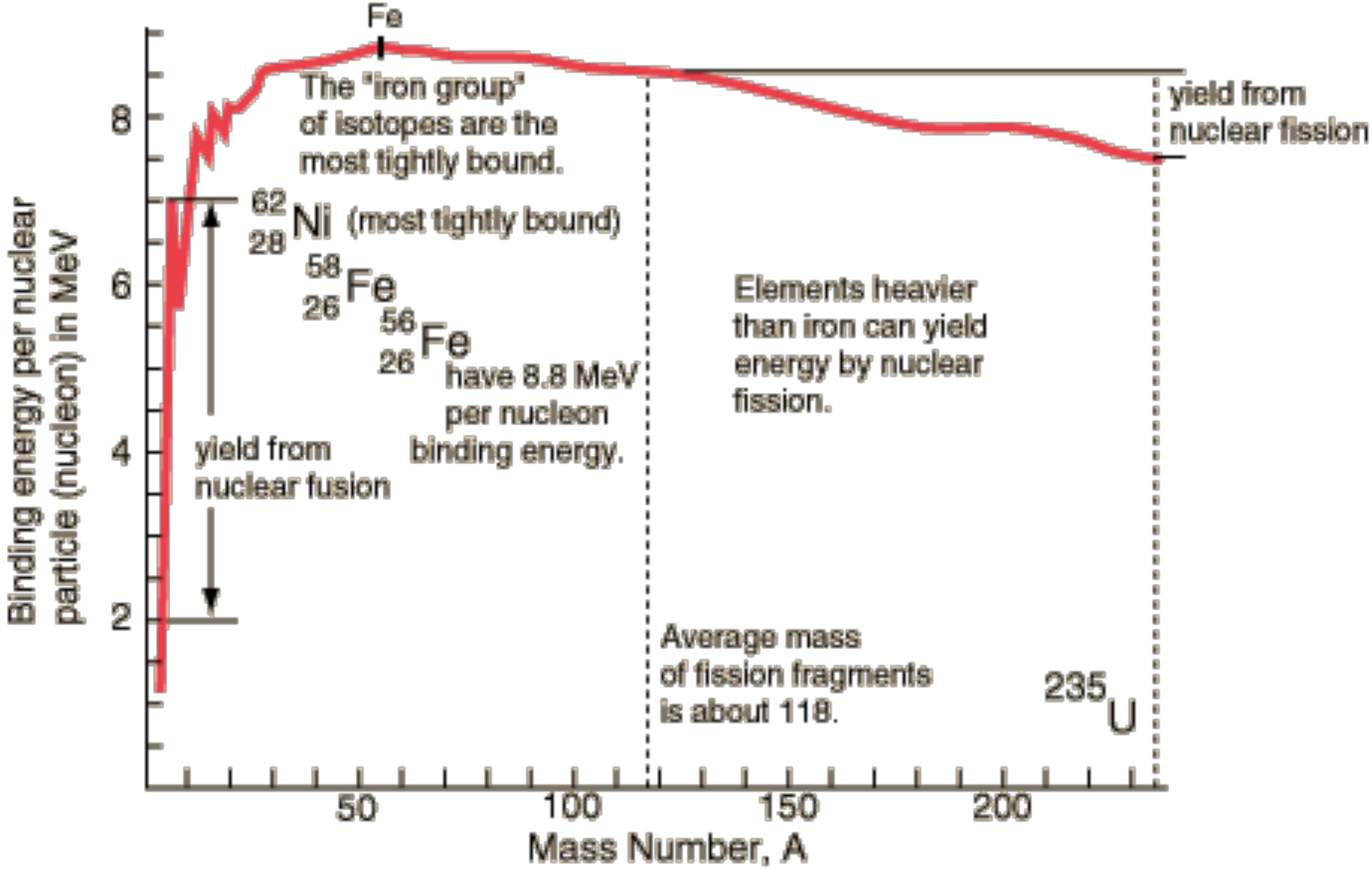
Onion structure



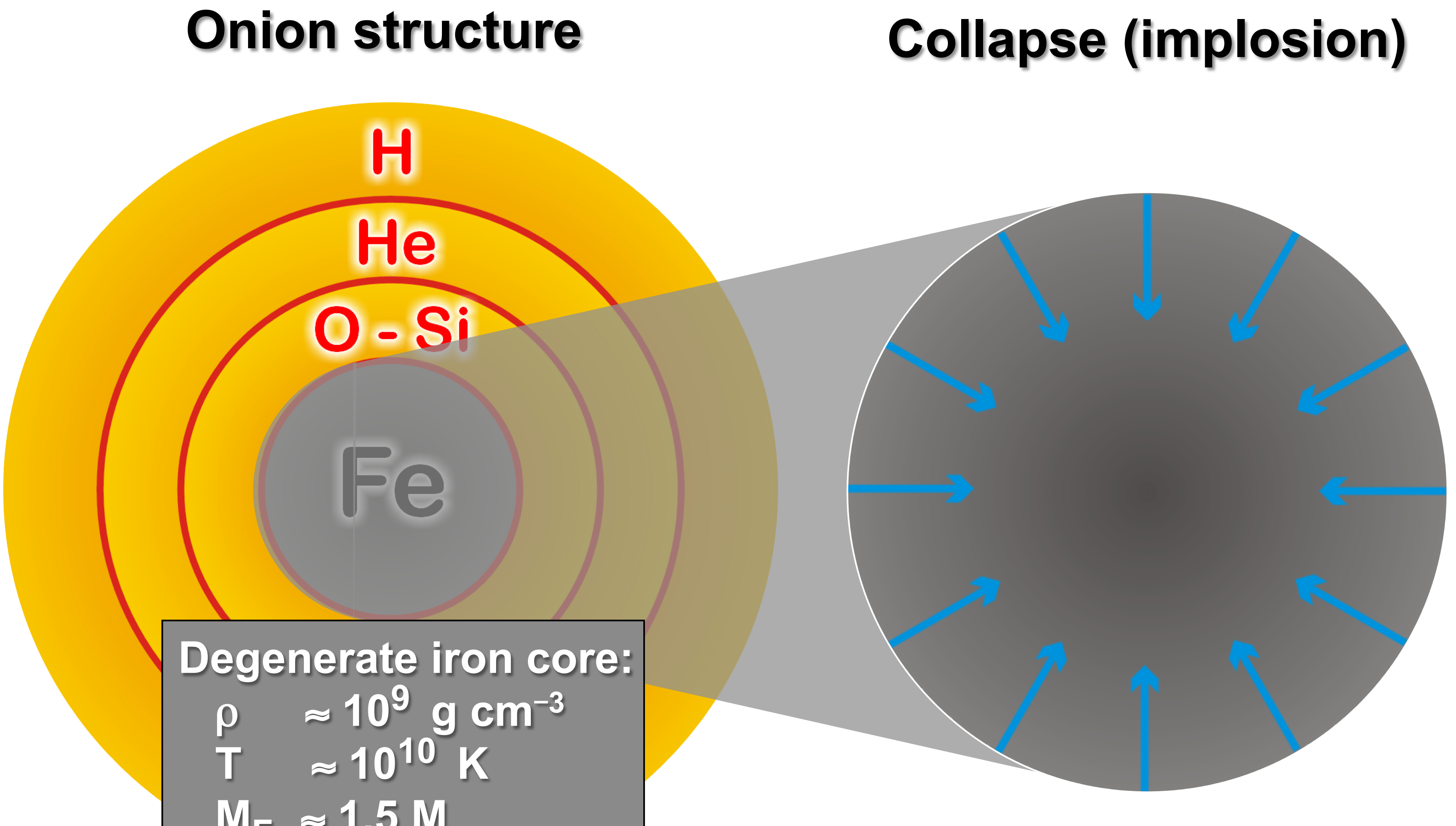
Degenerate iron core:

$\rho \approx 10^9$ g cm^{-3}
$T \approx 10^{10}$ K
$M_{Fe} \approx 1.5\ M_{sun}$
$R_{Fe} \approx 3000$ km

Fusion can only go up to iron



Core-Collapse Supernova



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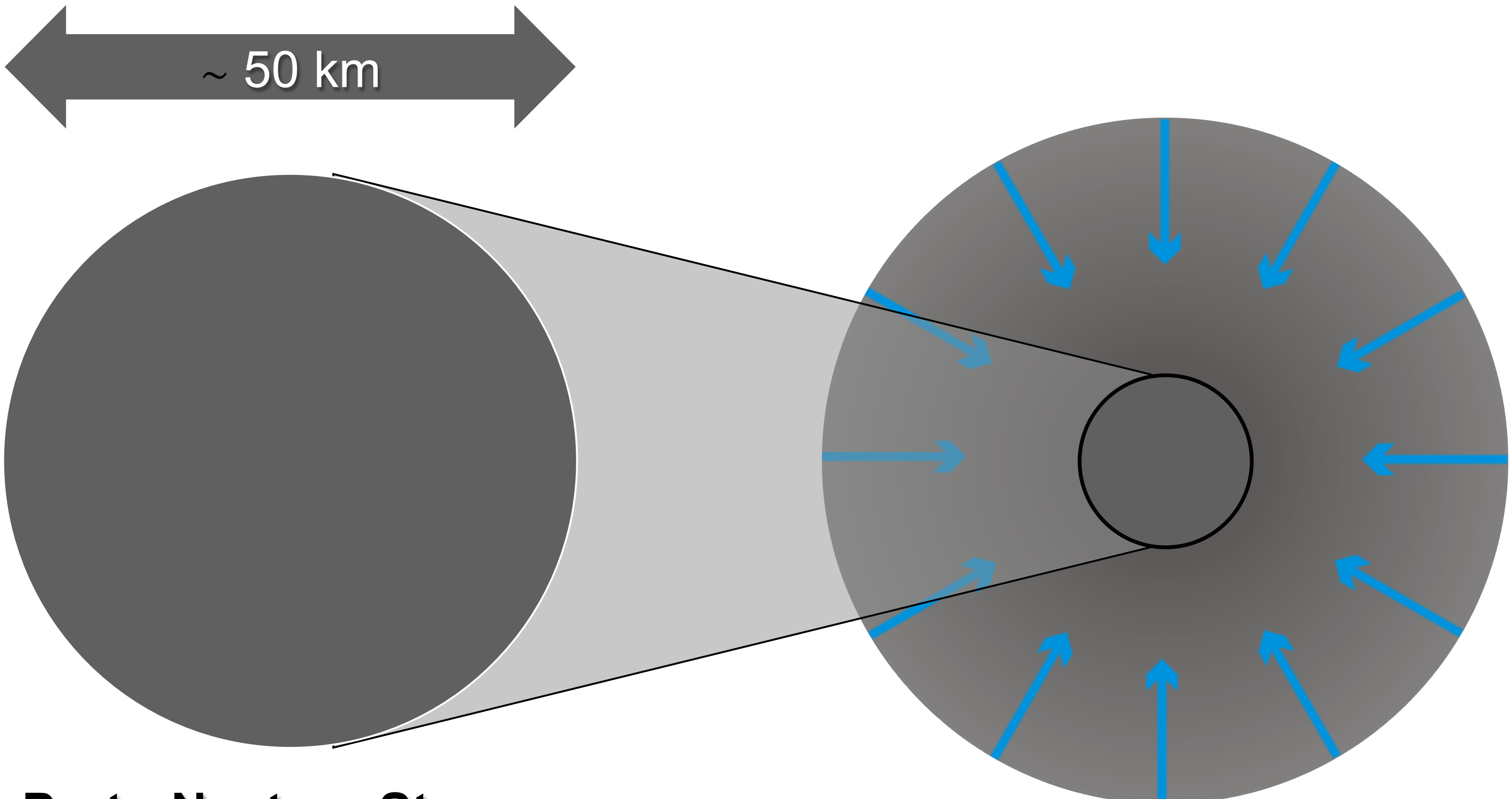
Core-Collapse Supernova

Newborn Neutron Star

Collapse (implosion)

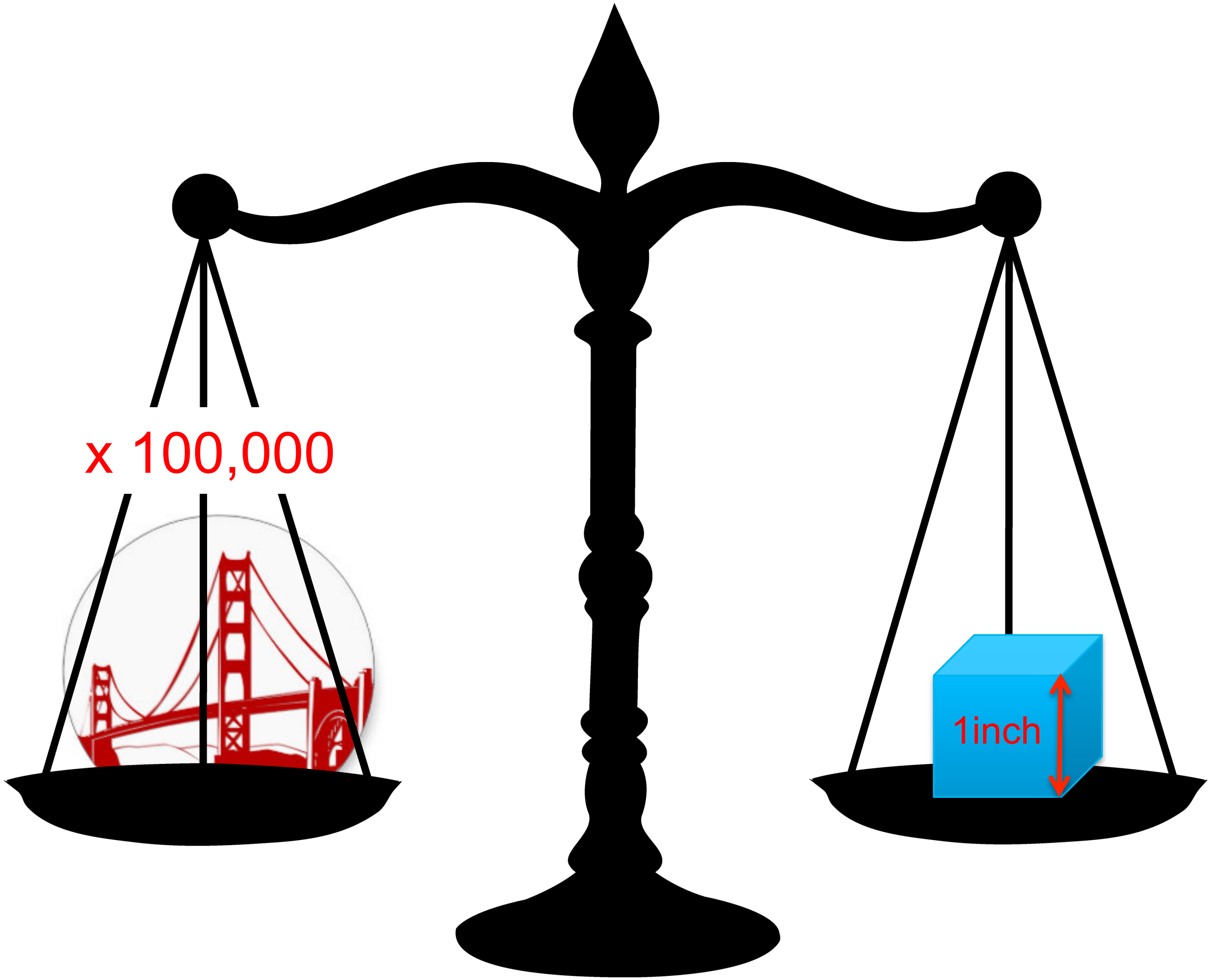


Proto-Neutron Star

$\rho \quad \rho_{nuc} = 3 \times 10^{14}\ \mathrm{g\ cm^{-3}}$

$T \quad 10\ \mathrm{MeV}$

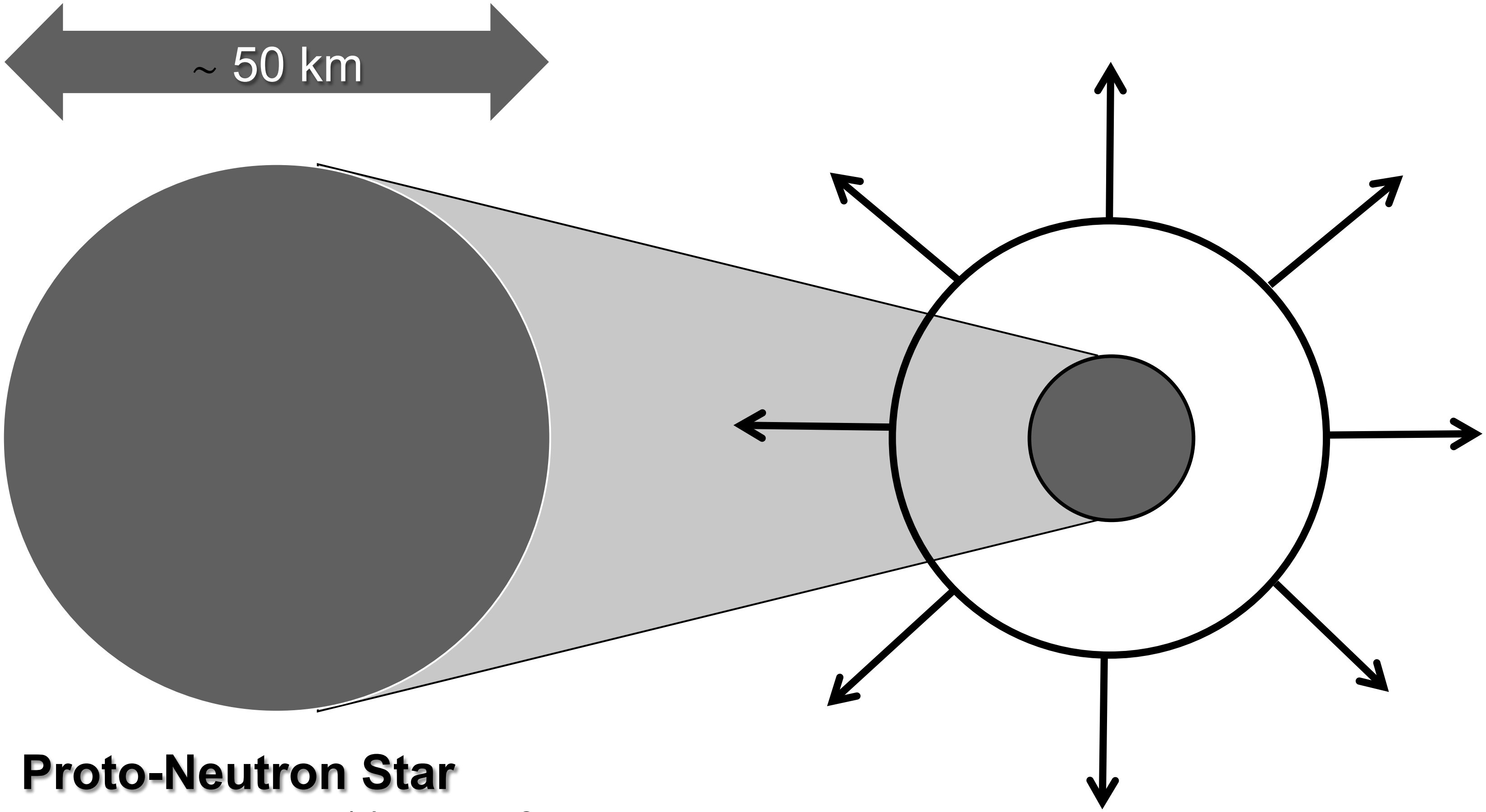
Density of a Neutron star



Core-Collapse Supernova

Newborn Neutron Star

Explosion



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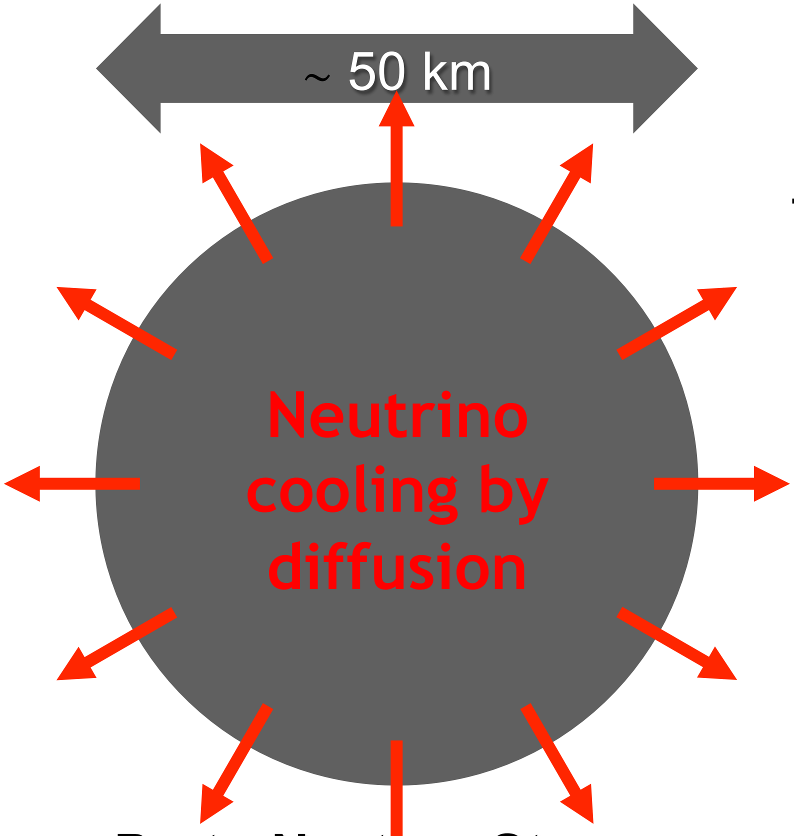


Proto-Neutron Star

ρ $\rho_{nuc} = 3 \times 10^{14}$ g cm^{-3}

T 10 MeV

Gravitational binding energy

$E_b \approx 3 \times 10^{53}$ erg $\approx$ 17% $M_{SUN} c^2$

This shows up as

99% Neutrinos

1% Kinetic energy of explosion

0.01% Photons, outshine host galaxy

Neutrino luminosity

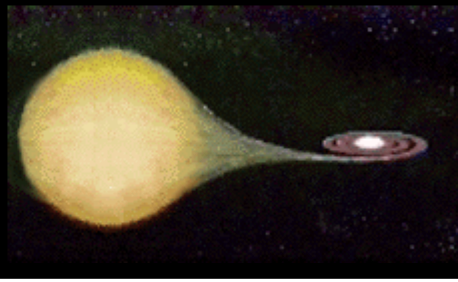
L_ν 3×10^{53} erg / 3 sec

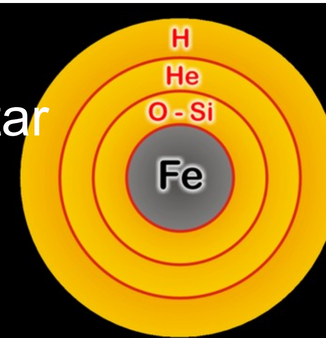
3×10^{19} L_{SUN}

While it lasts, outshines the entire visible universe

Thermonuclear vs. Core-collapse Supernova

Thermonuclear (Spectral type Ia)	Core collapse (Spectral type II, Ib/c)
• Carbon-oxygen white dwarf (remnant of low-mass star) • Accretes matter from companion	• Degenerate iron core of evolved massive star • Accretes matter by nuclear burning at its surface





Chandrasekhar limit is reached — $M_{Ch} \approx 1.5\ M_{sun}$

C O L L A P S E   S E T S   I N

Thermonuclear	Core collapse
Nuclear burning of C and O ignites → Nuclear deflagration (“Fusion bomb” triggered by collapse)	Collapse to nuclear density Bounce & shock Implosion → Explosion
Powered by nuclear binding energy	Powered by gravity
Gain of nuclear binding energy ~ 1 MeV per nucleon	Gain of gravitational binding energy ~ 100 MeV per nucleon 99% into neutrinos

Comparable “visible” energy release of ~ 3×10^{51} erg

Spectral classification of supernovae

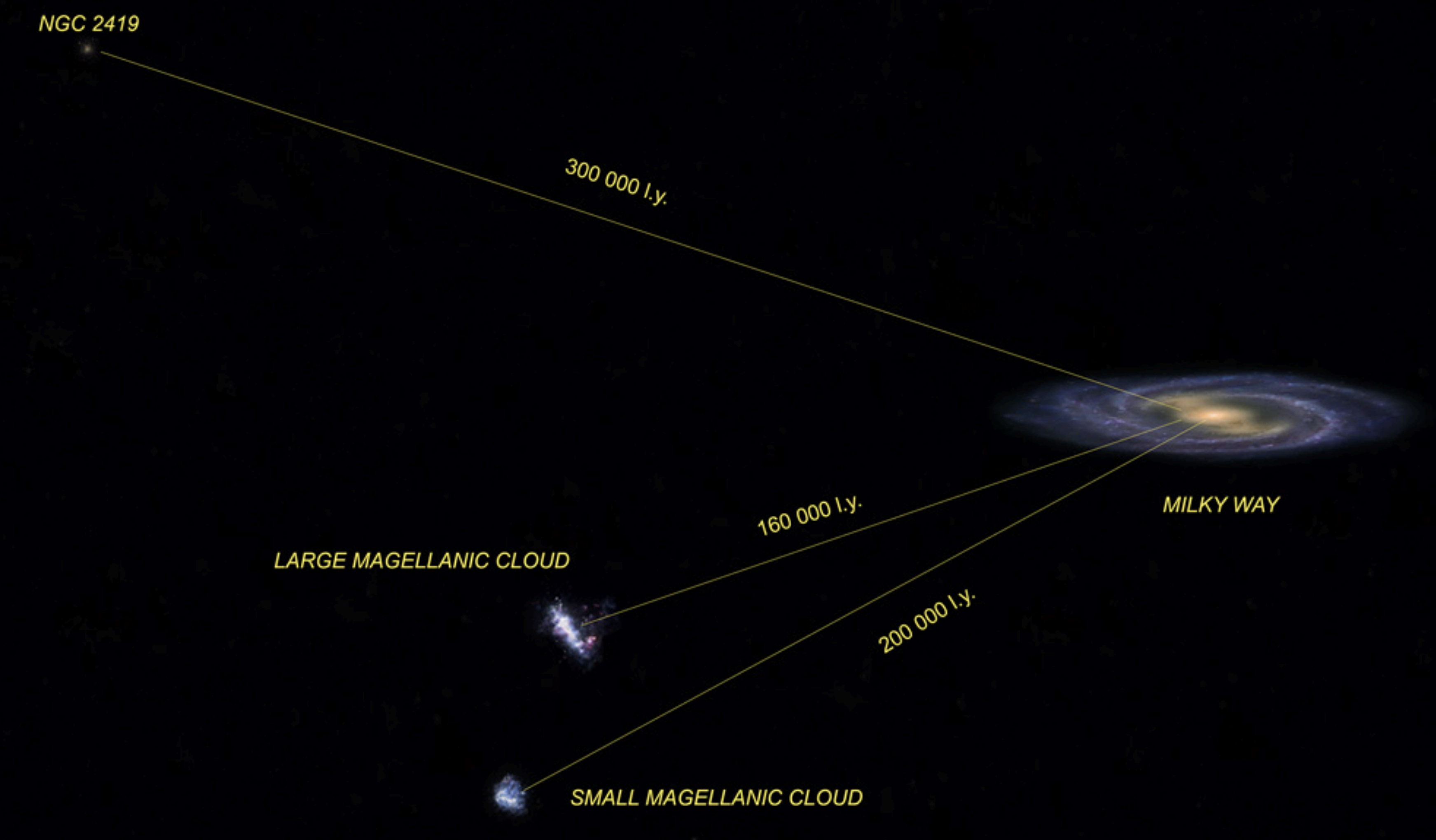
<table>
<tr><th>Spectral Type</th><th>Ia</th><th>Ib</th><th>Ic</th><th>II</th></tr>
<tr><td rowspan="3">Spectrum</td><td colspan="3">No Hydrogen</td><td rowspan="3">Hydrogen</td></tr>
<tr><td rowspan="2">Silicon</td><td colspan="2">No Silicon</td></tr>
<tr><td>Helium</td><td>No Helium</td></tr>
<tr><td>Physical Mechanism</td><td>Nuclear explosion of low-mass star</td><td colspan="3">Core collapse of evolved massive star (may have lost its hydrogen or even helium envelope during red-giant evolution)</td></tr>
<tr><td>Light Curve</td><td>Reproducible</td><td colspan="3">Large variations</td></tr>
<tr><td>Neutrinos</td><td>Insignificant</td><td colspan="3">~ 100 × Visible energy</td></tr>
<tr><td>Compact Remnant</td><td>None</td><td colspan="3">Neutron star (typically appears as pulsar)
Sometimes black hole (few 10% ?)</td></tr>
<tr><td>Rate / h^2 SNu</td><td>0.36 ± 0.11</td><td colspan="2">0.14 ± 0.07</td><td>0.71 ± 0.34</td></tr>
</table>

SN1987A

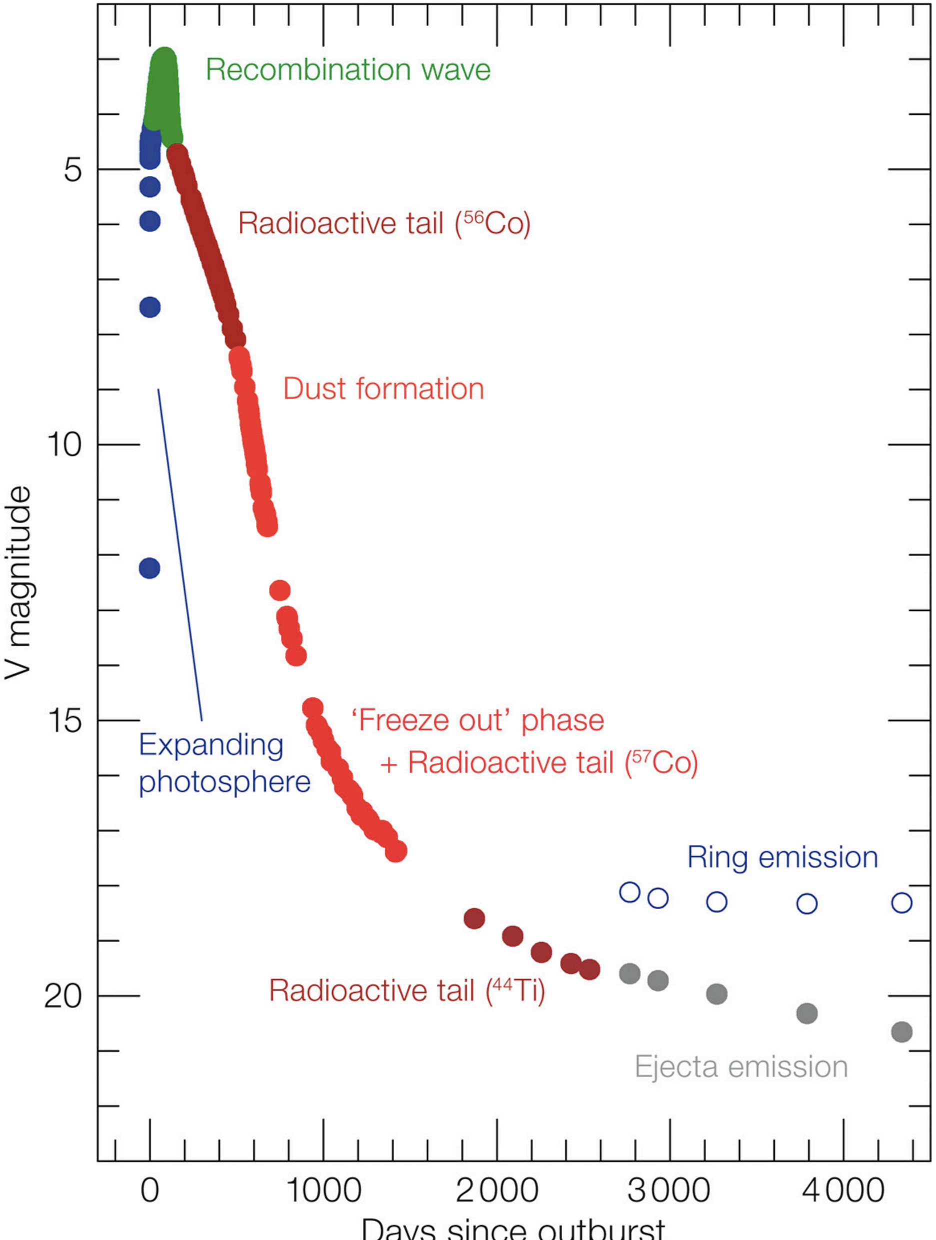
- 24. Februar 1987, Large Margellanic Cloud, type II

Location of Magellanic Clouds

Distance: 50kpc = 160000 Ly (remember Proxima Centauri 4.2 Ly)

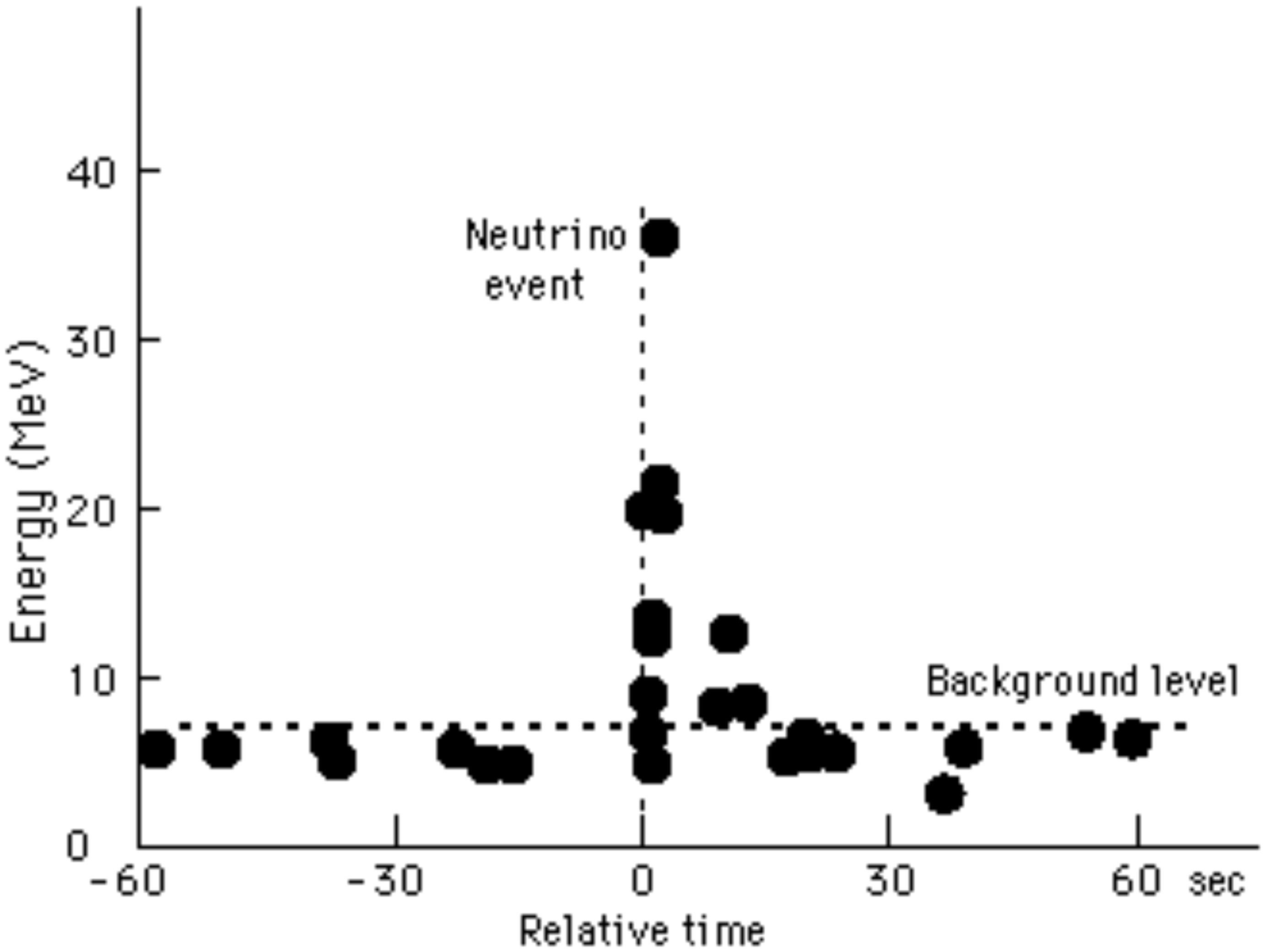


SN1987A light curve

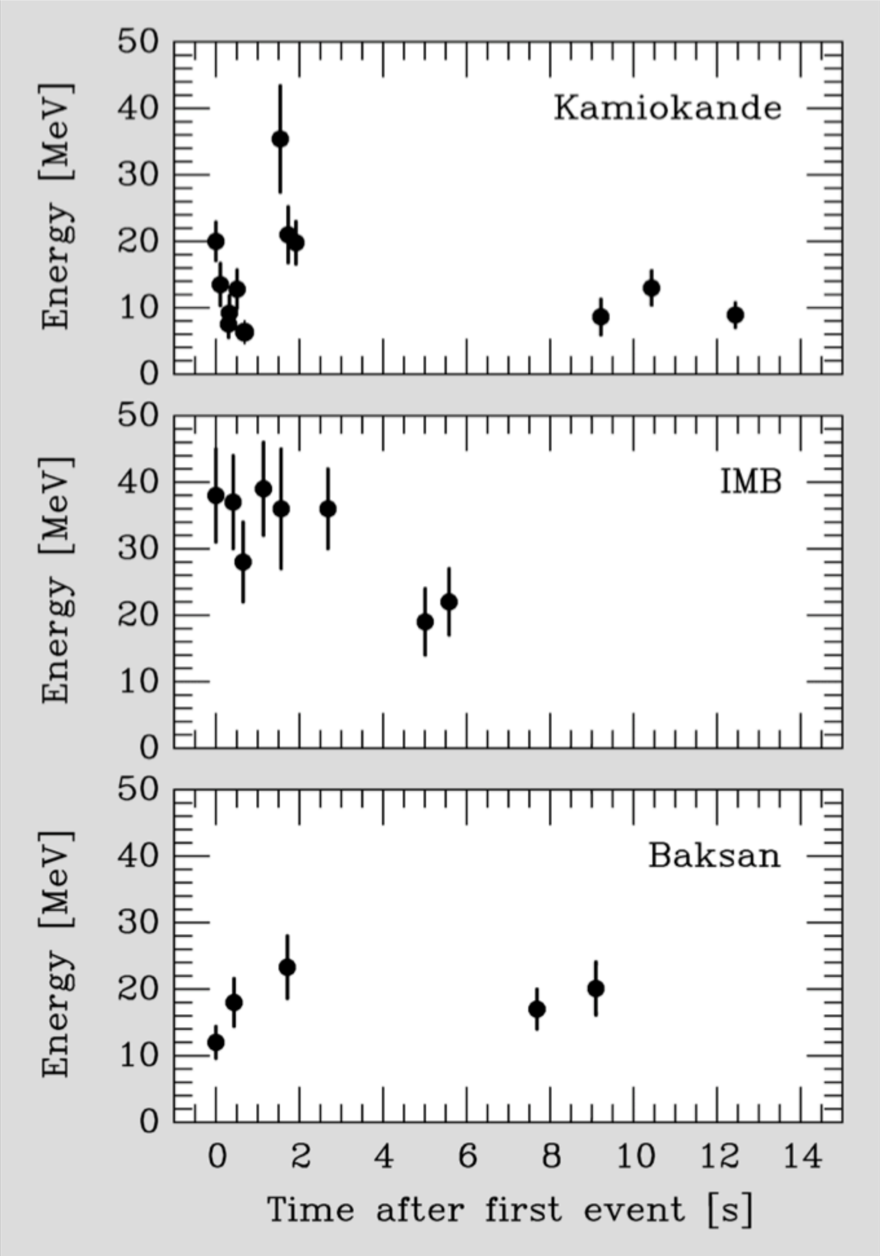


Credit: ESO

SN1987A in Kamiokande

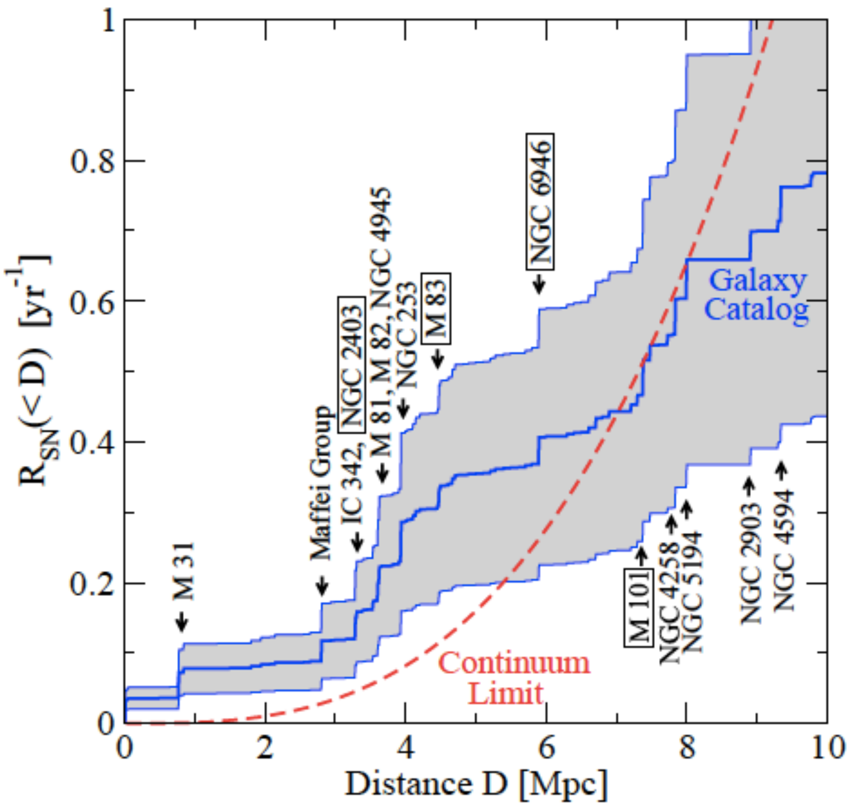


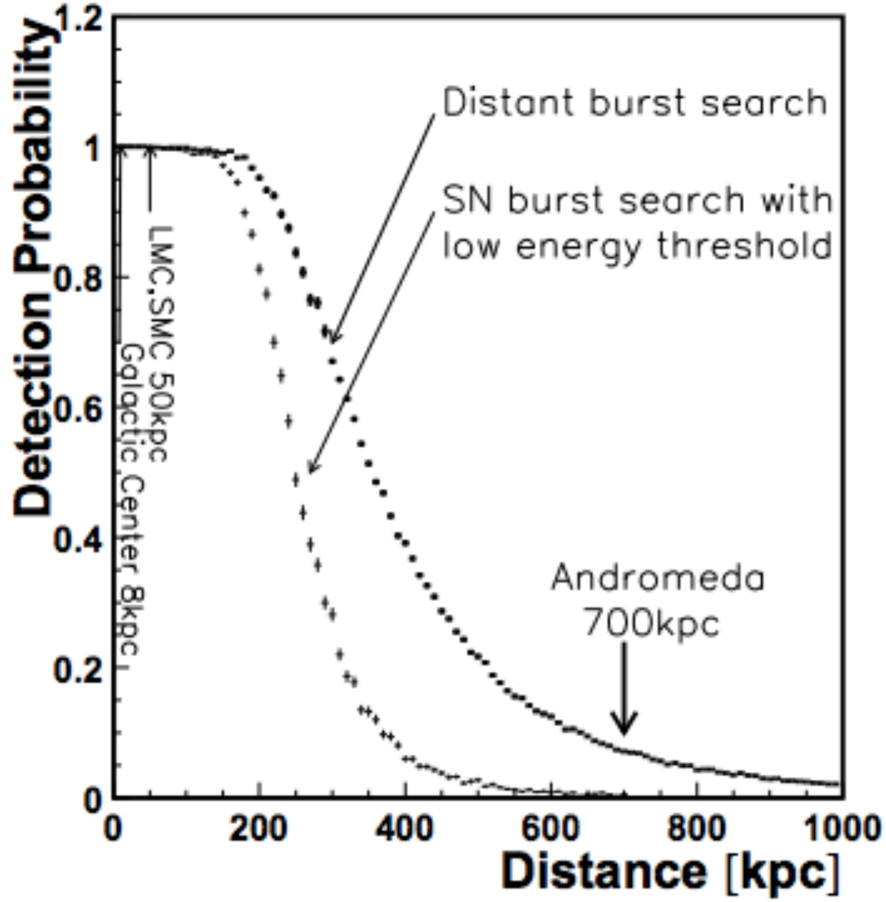
SN1987A – Other neutrino detectors



Detector	#neutrinos
Kamiokande	11
IMB	8
Baksan	5
Total	**24**

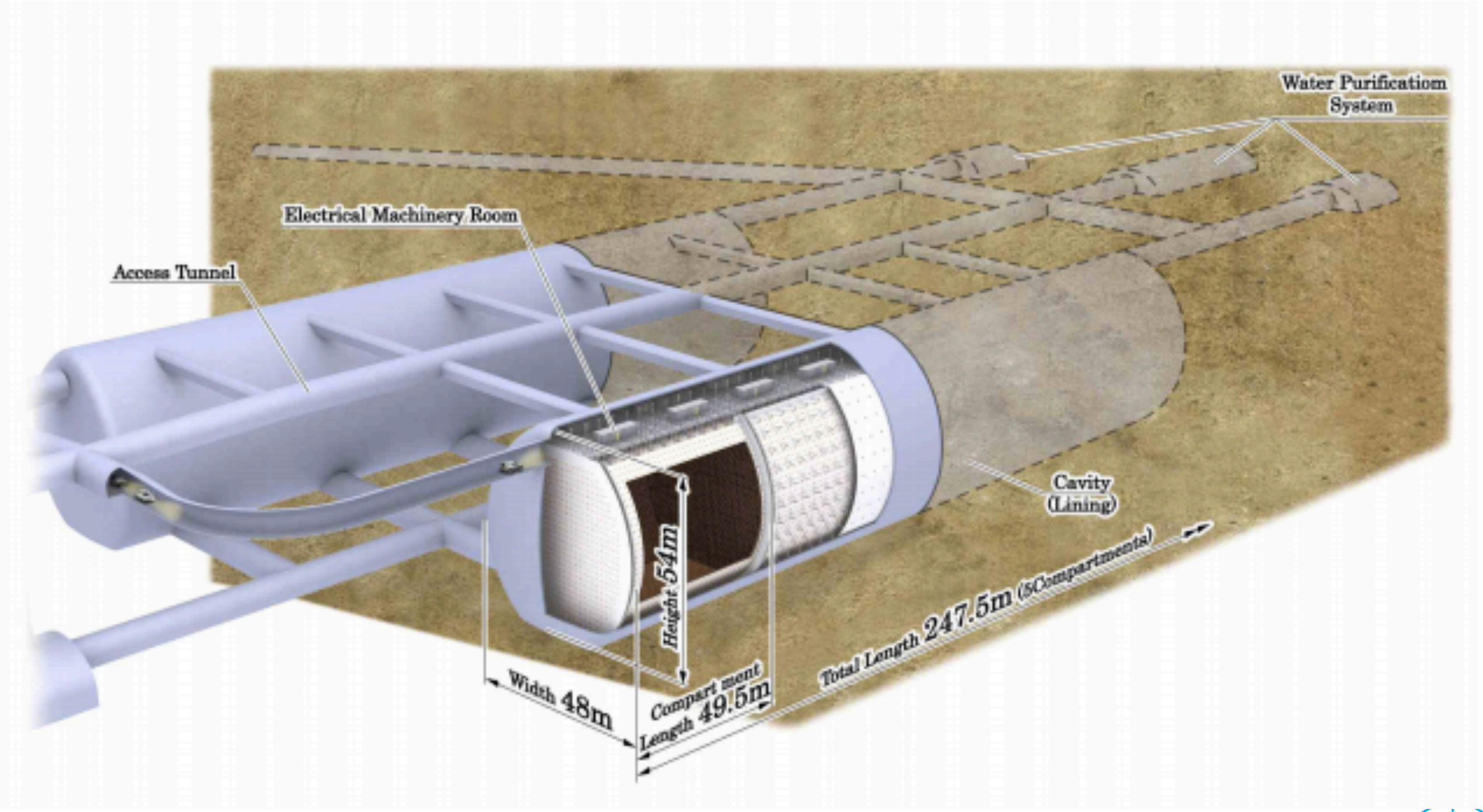
Sensitivity to SN today





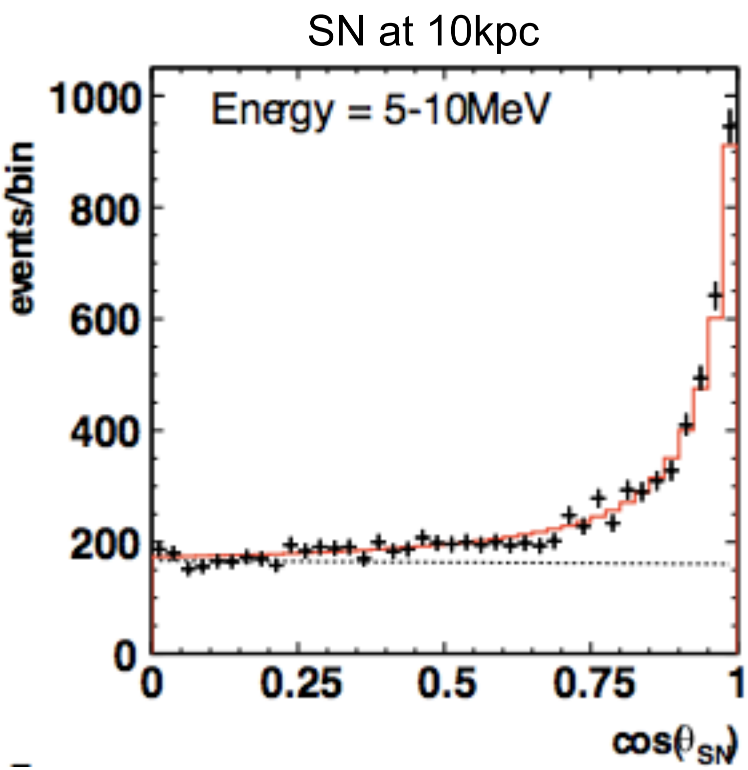
Hyper-K

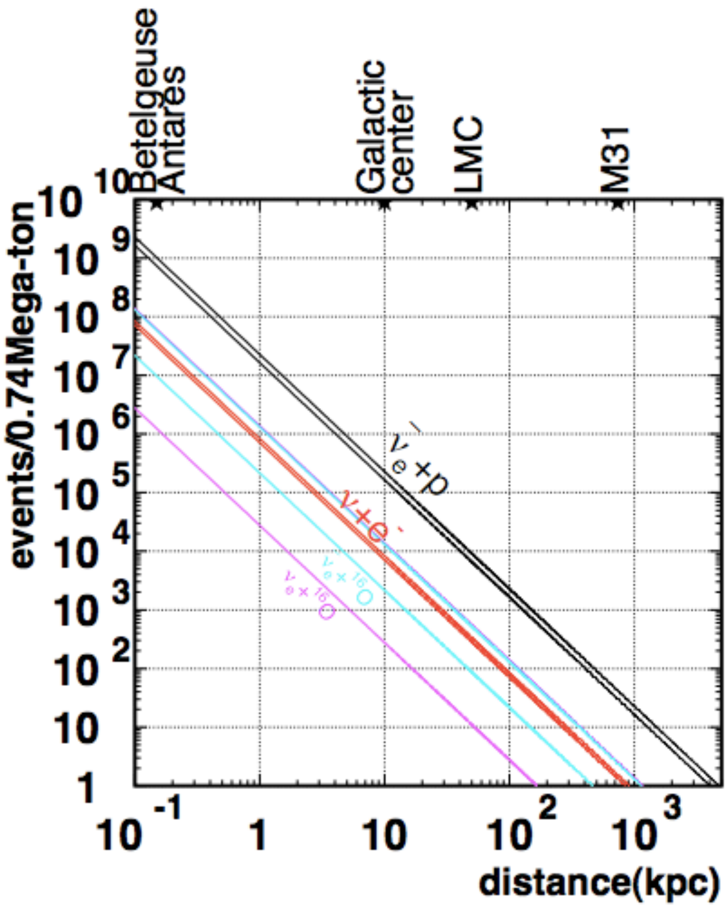
Volume: 0.5Mt, ten times larger than Super-K



Hyper-K

SN in M31 (Andromeda): 30-50 events in Hyper-K
SN in LMC: 7000~10000 events





Summary

- Pauli was right: Neutrinos exist!
- Two extraterrestrial neutrino sources found: Sun and SN1987A
- Next: high-energy neutrino astronomy