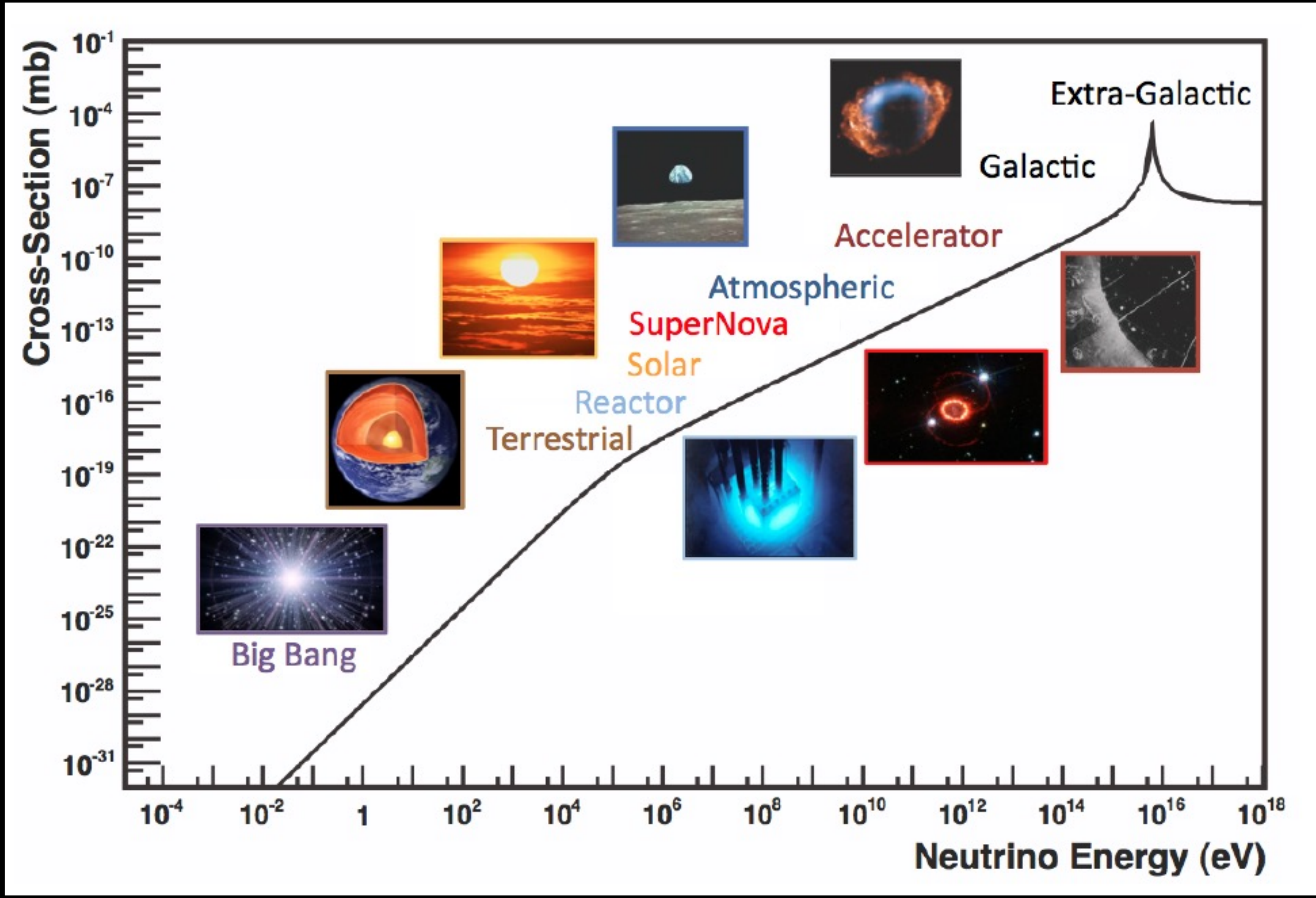
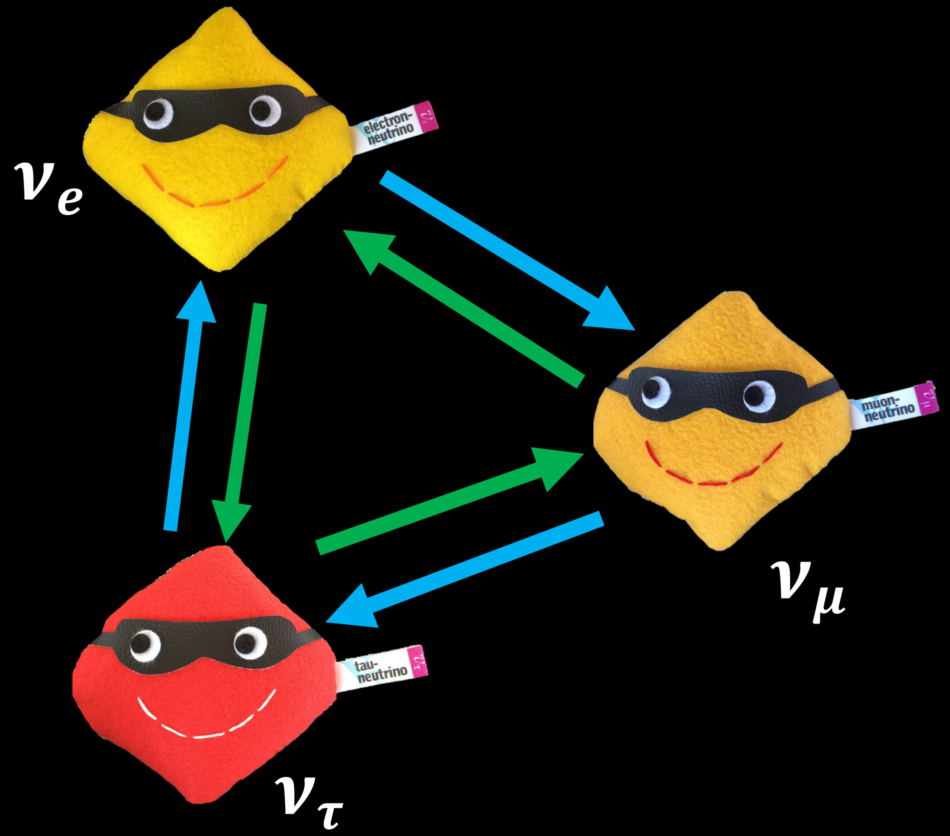
Neutrinos in 15 Minutes

Where do neutrinos come from?



What do we know about neutrinos?

- Have no charge
  - Do not participate in electromagnetism
- Interact very weakly
- Come in three flavours
- They oscillate between the flavours
- Are very light



How do we know about neutrino oscillations?

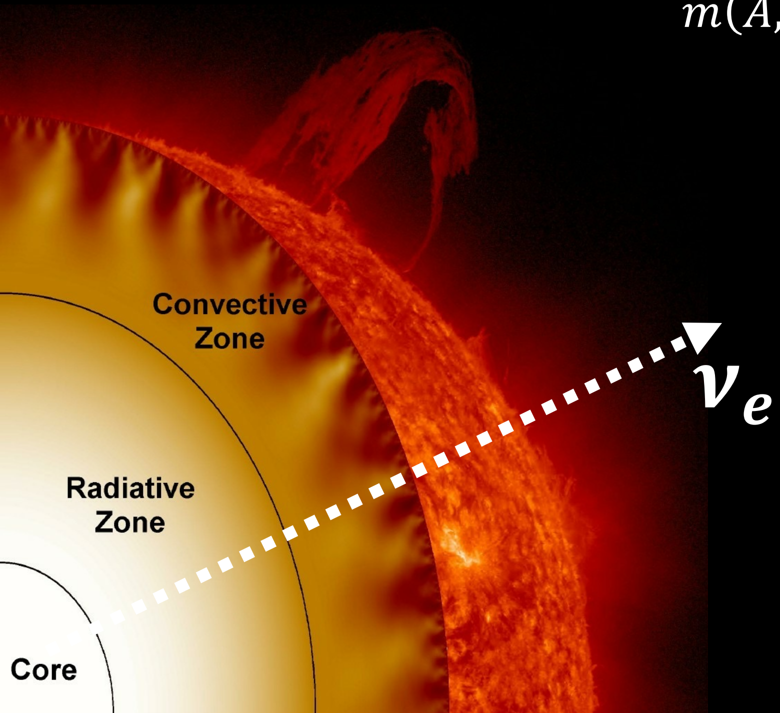
Neutrinos from the Sun

- Electron neutrinos with energy of the order of 1 MeV are produced in the thermonuclear fusion reactions in the solar core.
  - Hans Bethe (1930's): first solar model based on nuclear reactions
  - John Bahcall (1960's): increasingly detailed solar model calculations of the solar neutrino fluxes

- Thermonuclear reactions release energy because the total mass of a nucleus is less than the total mass of the constituent nucleons:

$$m(A,Z) = Zm_p + (A-Z)m_n - B(A,Z)$$

A – atomic mass
Z – atomic number (number of protons)
m_p – proton mass
m_n – neutron mass
$B(A,Z)$ – nuclear binding energy



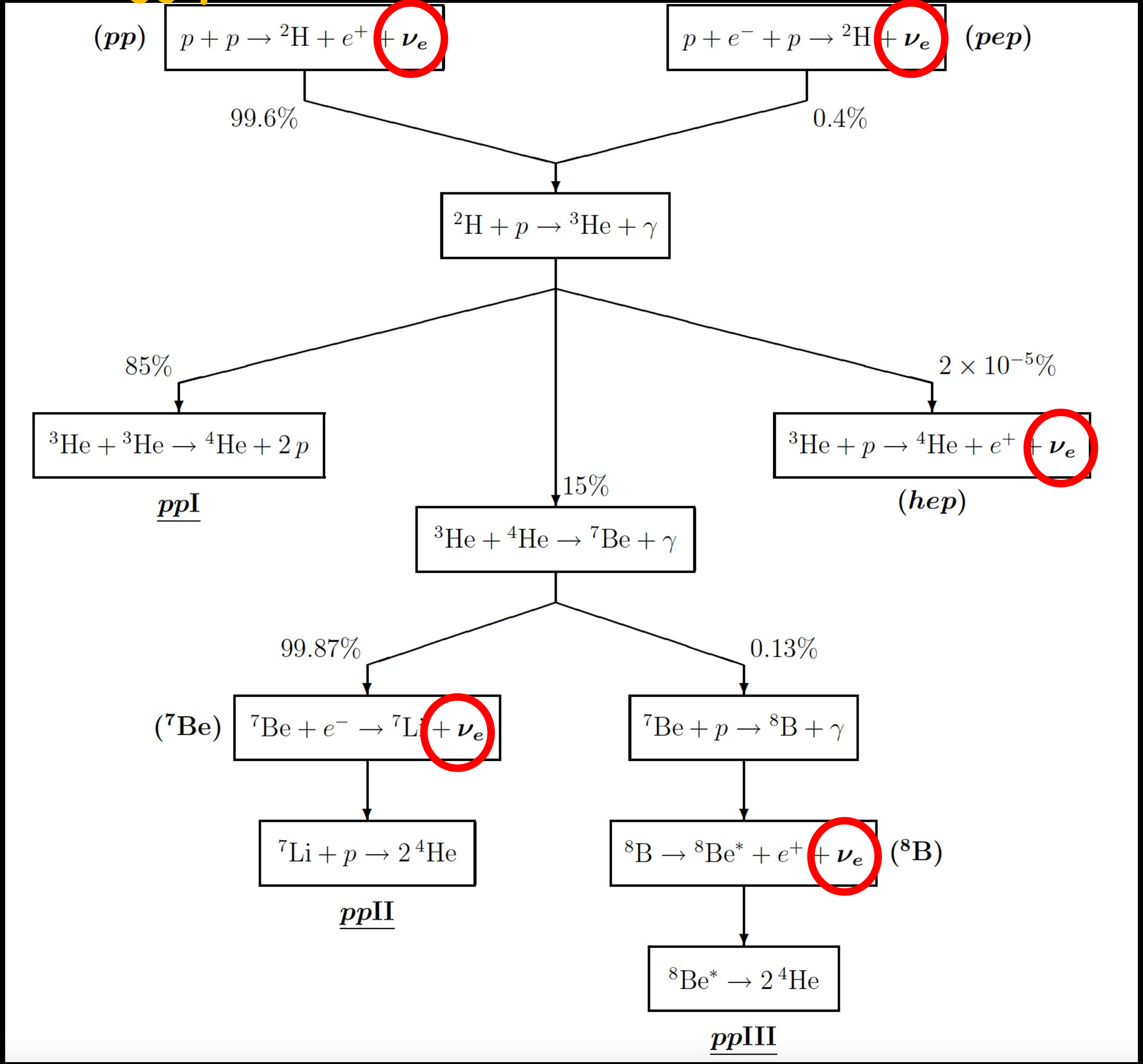
Only neutrinos, with their extremely small interaction cross-sections, can enable us to see into the interior of a star, and thus verify directly the hypothesis of nuclear energy generation in stars.
John N. Bahcall

- Since neutrino interactions with matter is extremely weak, practically all the neutrinos produced in the core of the Sun pass undisturbed through the solar interior and flow in space.

The Sun is powered by two groups of thermonuclear reactions:

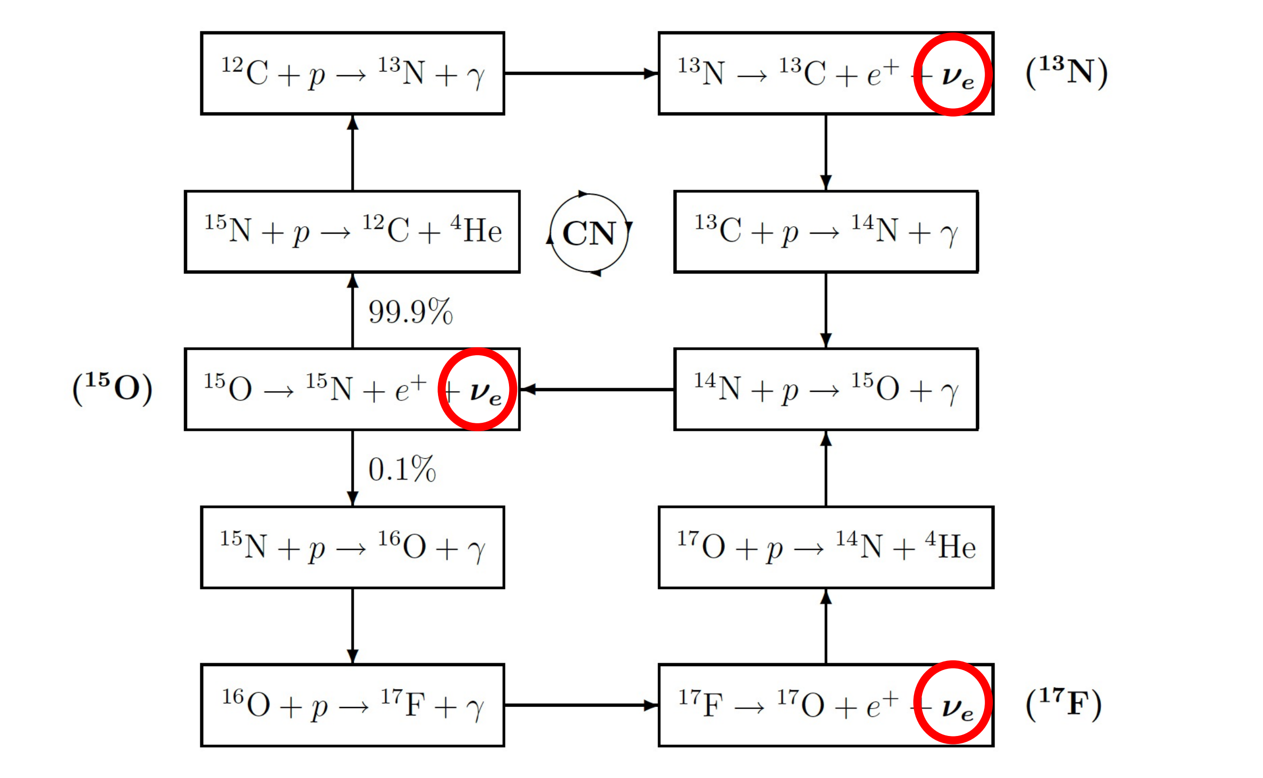
Dominates the energy production

pp chain



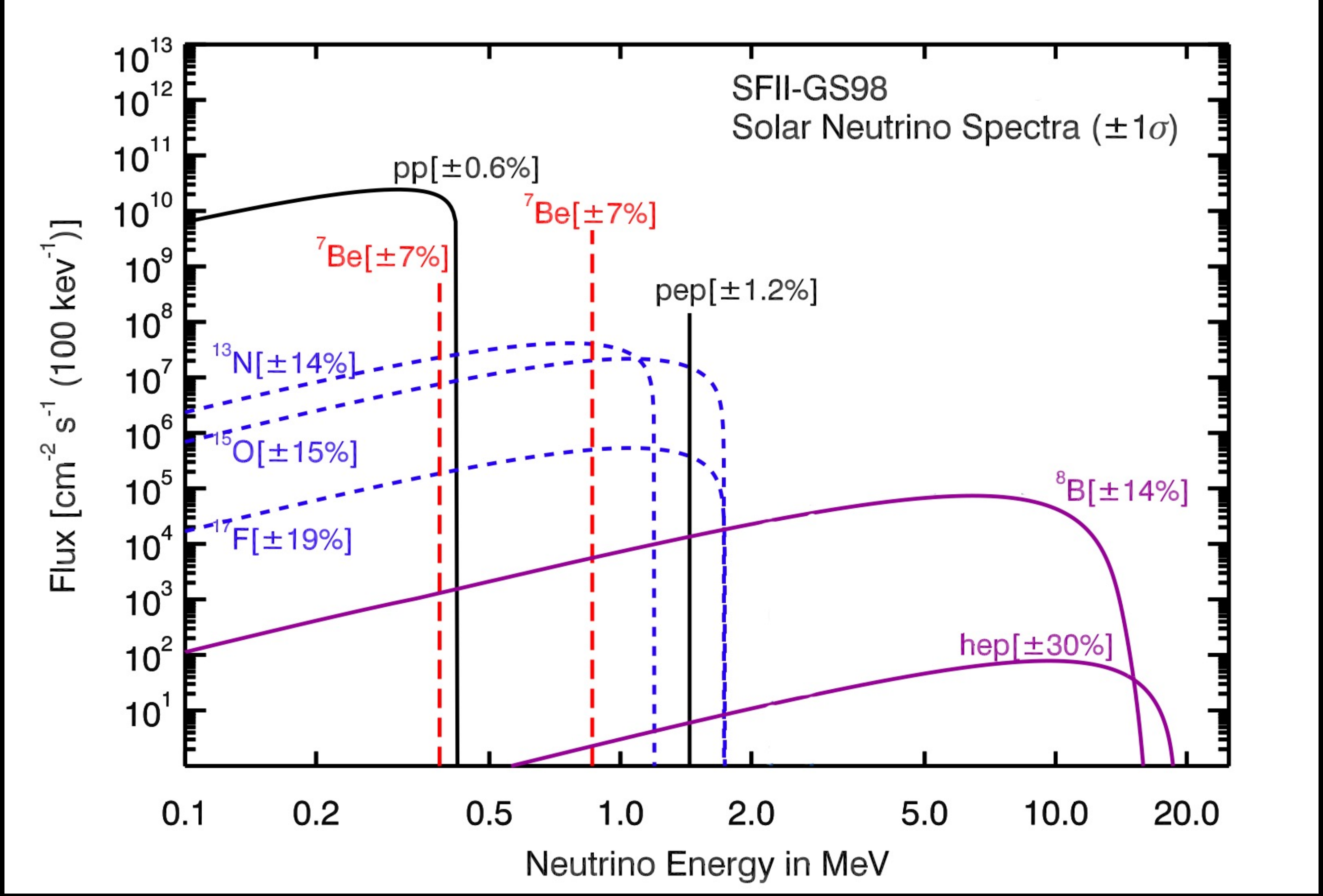
CNO cycle

More important in stars bigger than the Sun



The result of both processes is:

$$4p + 2e^- \to {}^4\mathrm{He} + 2\nu_e + 26.7\ \mathrm{MeV}$$



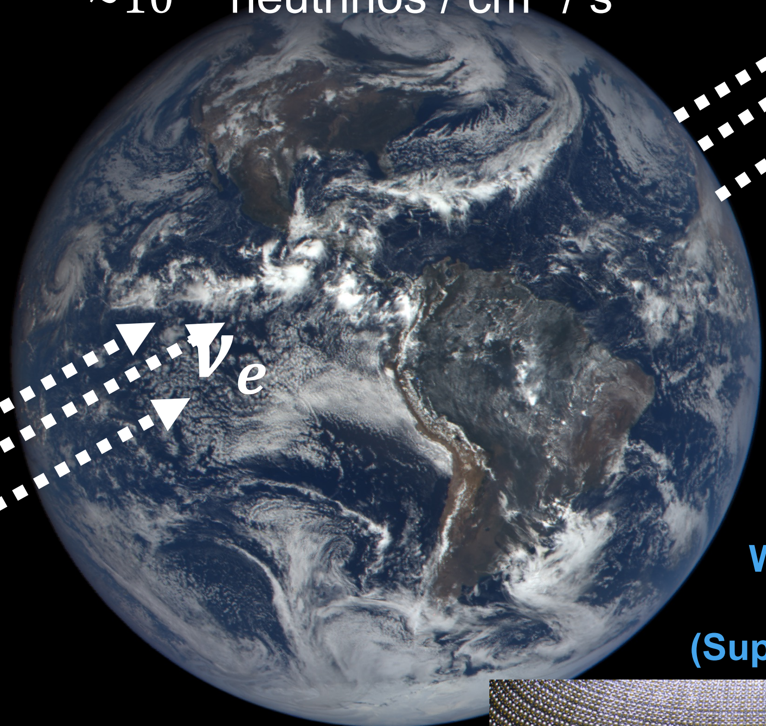
The detailed calculation of the solar neutrino fluxes has been done based on the Standard Solar Model (SSM). The SSM describes the structure and evolution of the Sun based on a variety of inputs such as the mass, luminosity, radius, surface temperature, age, and surface elemental abundances. In addition, the knowledge of the absolute nuclear reaction cross sections for the relevant fusion reactions and the radiative opacities are necessary.

From the 1970s to the 2000s, multiple experiments were measuring neutrinos from the Sun.

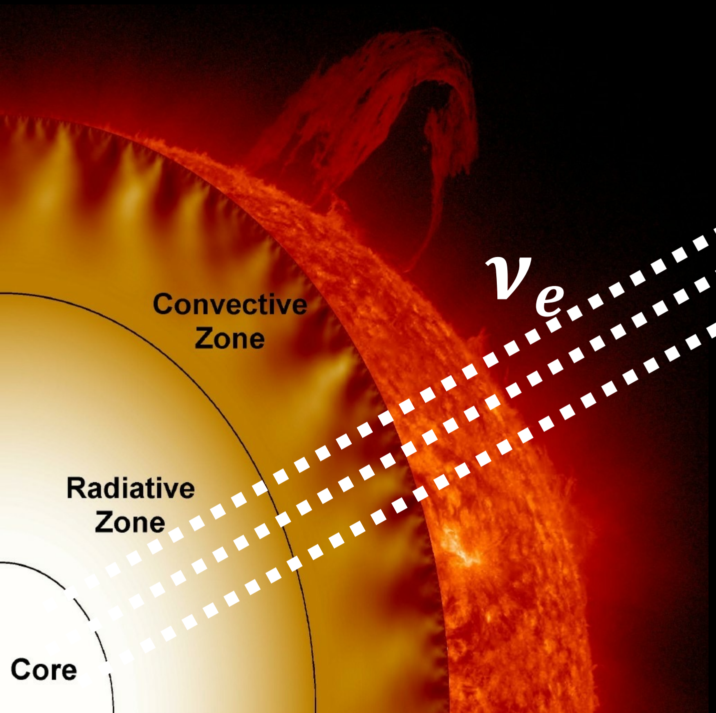
$\sim 10^{10}$ neutrinos / cm^2 / s

A lot of neutrinos, but very small interaction cross-section of $\sim 10^{-44}\ cm^{-2}$

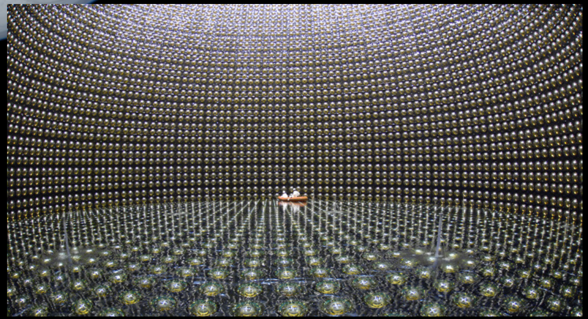
The detectors were placed underground in order to be shielded by rock from cosmic rays.
Muon flux at sea level = 1 / cm^2 / minute



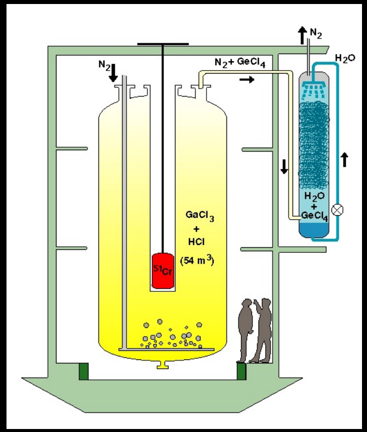
ν_e ν_e ν_e ν_e ν_e ν_e ν_e ν_e



Water Cherenkov Experiments (Super-Kamiokande)



Homestake Experiment (Chlorine)

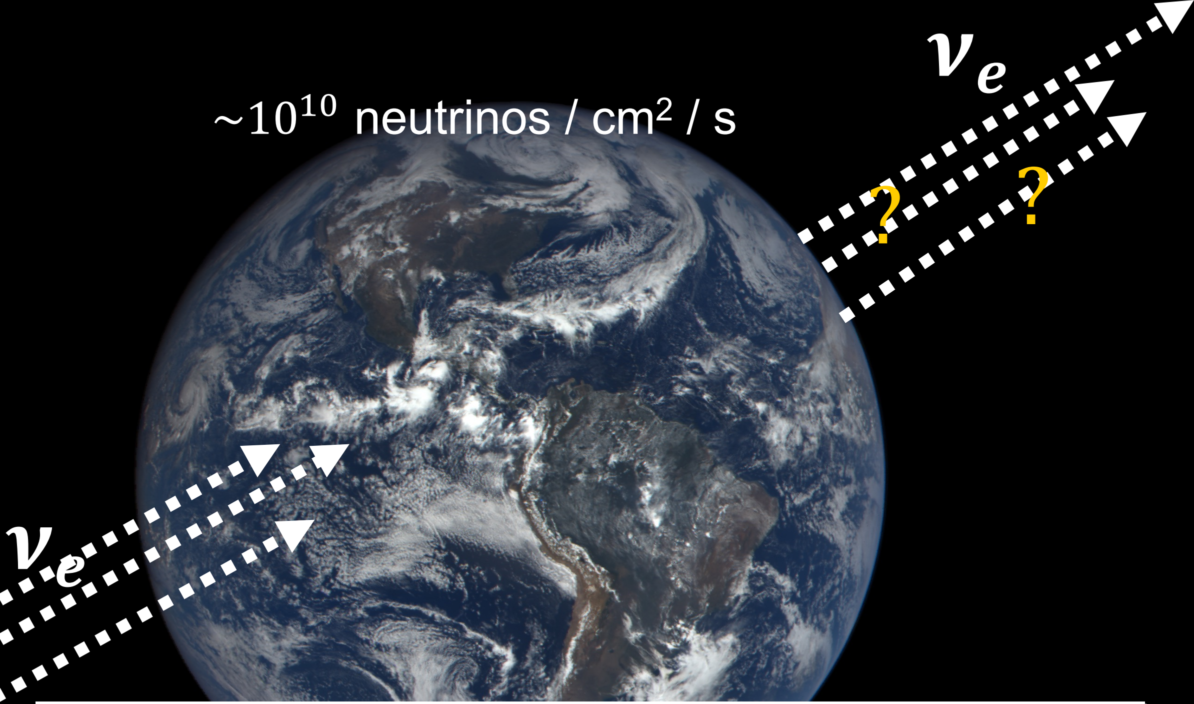


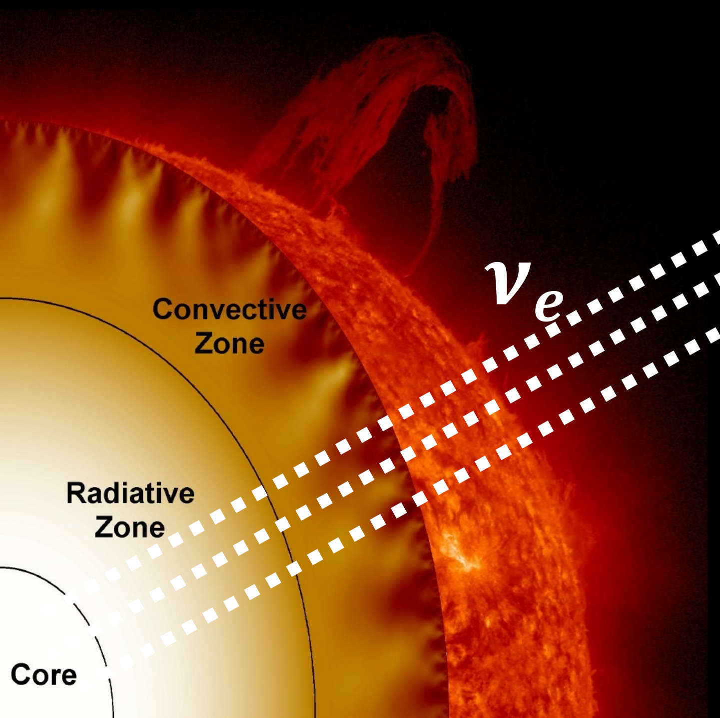
Gallium Experiments (SAGE, GALLEX, GNO)

From the 1970s to the 2000s, multiple experiments were measuring neutrinos from the Sun.

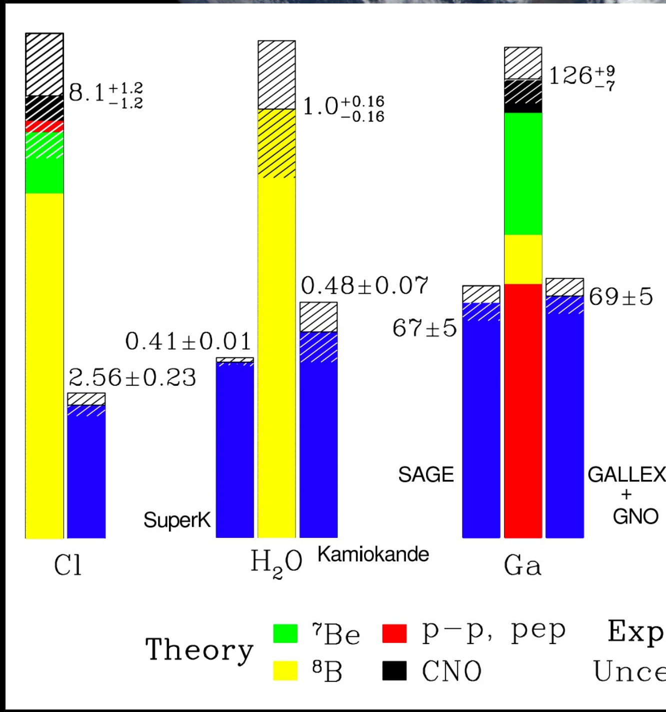
A lot of neutrinos, but very small interaction cross-section of $\sim 10^{-44}\ cm^{-2}$

The detectors were placed underground in order to be shielded by rock from cosmic rays.
Muon flux at sea level = 1 / cm² / minute





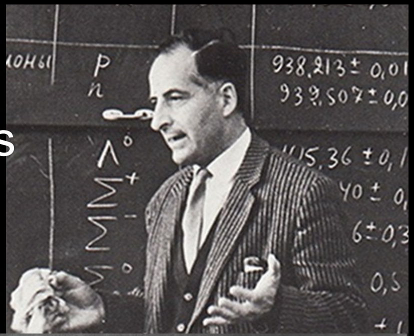
Are we not measuring all the neutrinos from the Sun? What happens to them on the way to Earth?



Observe 1/3 -- 1/2 of the expected number of solar neutrinos!

Neutrinos Oscillate

B. Pontecorvo
$\nu - \bar{\nu}$ oscillations

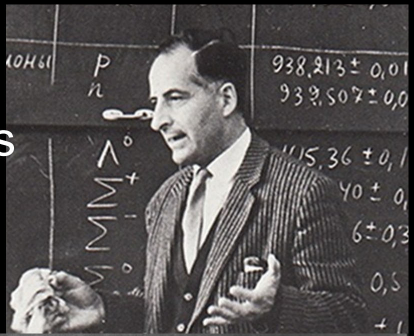


Three flavours of Neutrinos

ν_e ν_μ ν_τ

Neutrinos Oscillate

B. Pontecorvo
$\nu - \bar{\nu}$ oscillations



Three flavours of Neutrinos

$$\nu_e \qquad \nu_\mu \qquad \nu_\tau$$

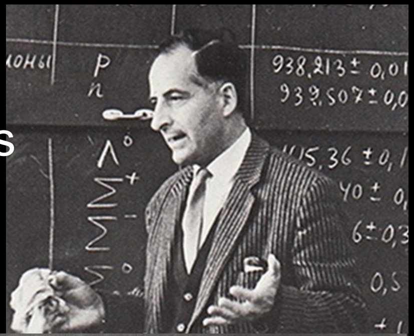
Are a linear combination of three neutrino mass states

$$\nu_1 \qquad \nu_2 \qquad \nu_3$$

$$\nu_e = a\nu_1 + b\nu_2 + c\nu_3$$
$$\nu_\mu = d\nu_1 + e\nu_2 + f\nu_3$$
$$\nu_\tau = g\nu_1 + h\nu_2 + i\nu_3$$

Neutrinos Oscillate

B. Pontecorvo
$\nu - \bar{\nu}$ oscillations



Courtesy of Sakata Memorial Archival Library

S. Sakata 1911-1970 Z. Maki 1929-2005 M. Nakagawa 1932-2001

Three flavours of Neutrinos

$$\nu_e \qquad \nu_\mu \qquad \nu_\tau$$

Are a linear combination of three neutrino mass states

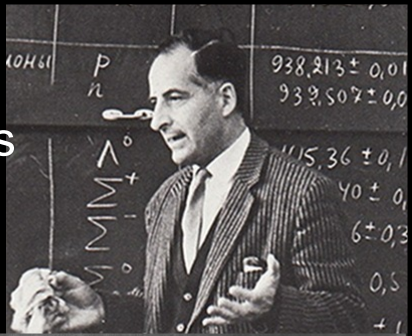
$$\nu_1 \qquad \nu_2 \qquad \nu_3$$

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} a & b & c \\ d & e & f \\ g & h & i \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

The PMNS Matrix

Neutrinos Oscillate

B. Pontecorvo
$\nu - \bar{\nu}$ oscillations



Three flavours of Neutrinos

$$\nu_e \qquad \nu_\mu \qquad \nu_\tau$$

Are a linear combination of three neutrino mass states

$$\nu_1 \qquad \nu_2 \qquad \nu_3$$

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

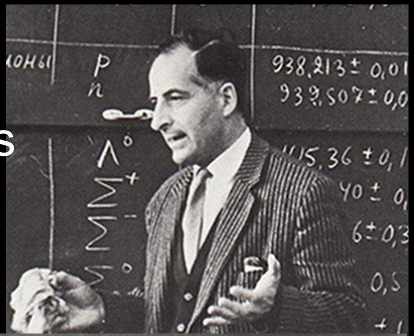
c – cosine
S – sine

The PMNS Matrix

(that looks more like this)

Neutrinos Oscillate

B. Pontecorvo
$\nu - \bar{\nu}$ oscillations



Courtesy of Sakata Memorial Archival Library

S. Sakata 1911-1970 | Z. Maki 1929-2005 | M. Nakagawa 1932-2001

When neutrinos travel, they change from one flavour to the other.

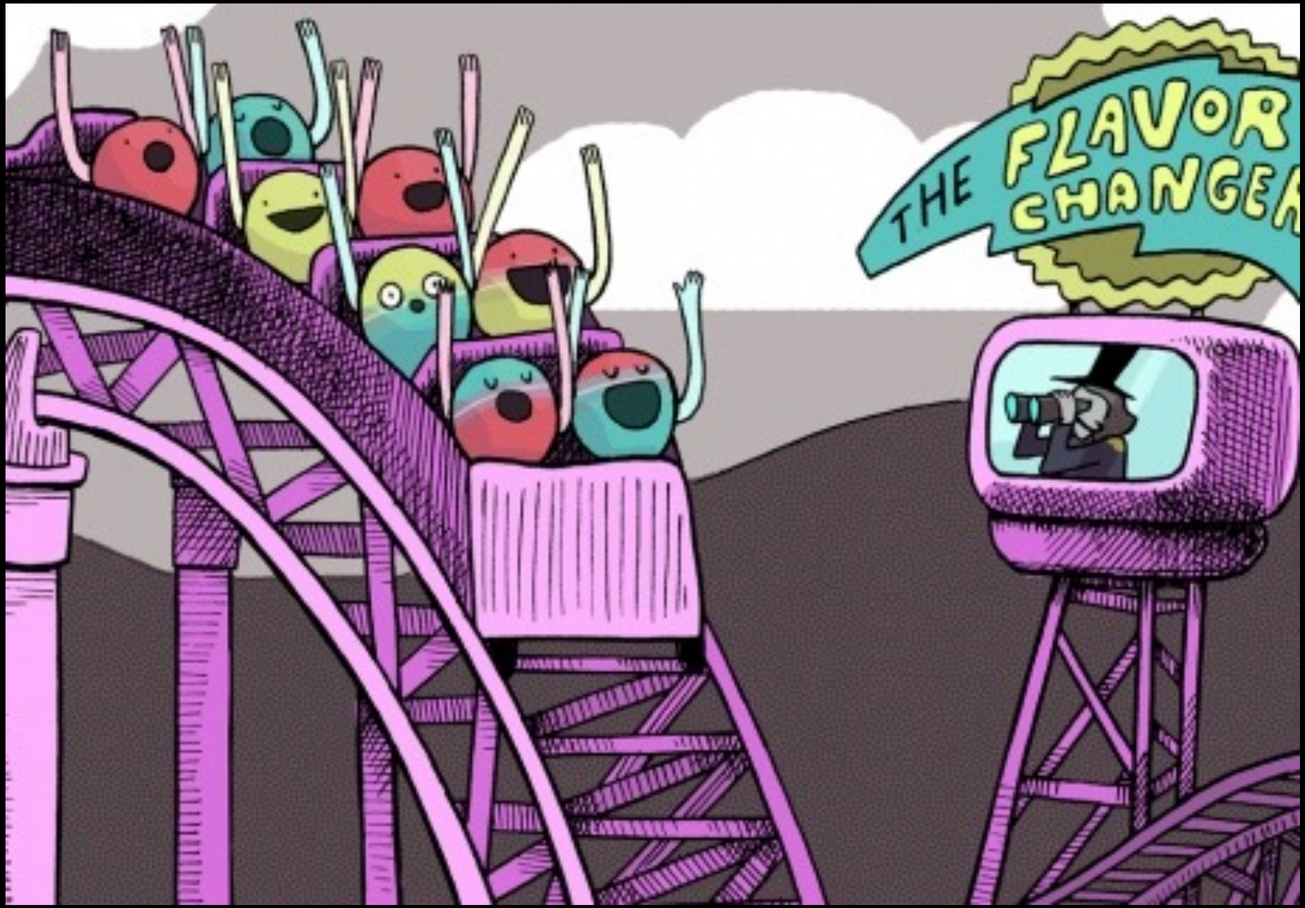
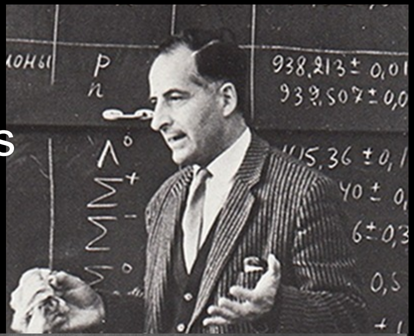


Image from Symmetry Magazine

Neutrinos Oscillate

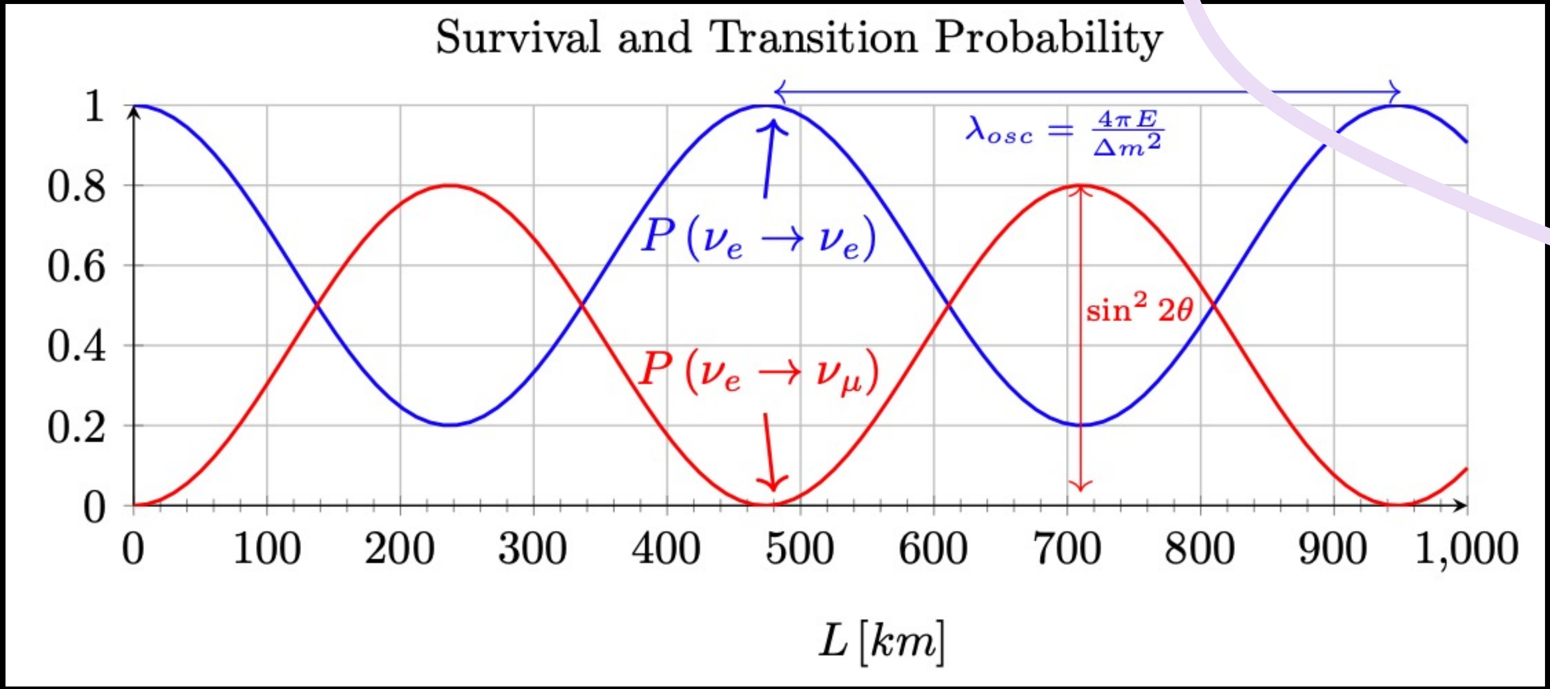
B. Pontecorvo
$\nu - \bar{\nu}$ oscillations



When neutrinos travel, they change from one flavour to the other.

Two neutrino case:

$$P_{oscillation}(\boldsymbol{\nu_e} \to \boldsymbol{\nu_\mu}) = sin^2 2\theta_{12} sin^2\left(1.27\Delta m_{21}^2[\mathrm{eV}^2]\frac{L[\mathrm{m}]}{E[\mathrm{MeV}]}\right)$$

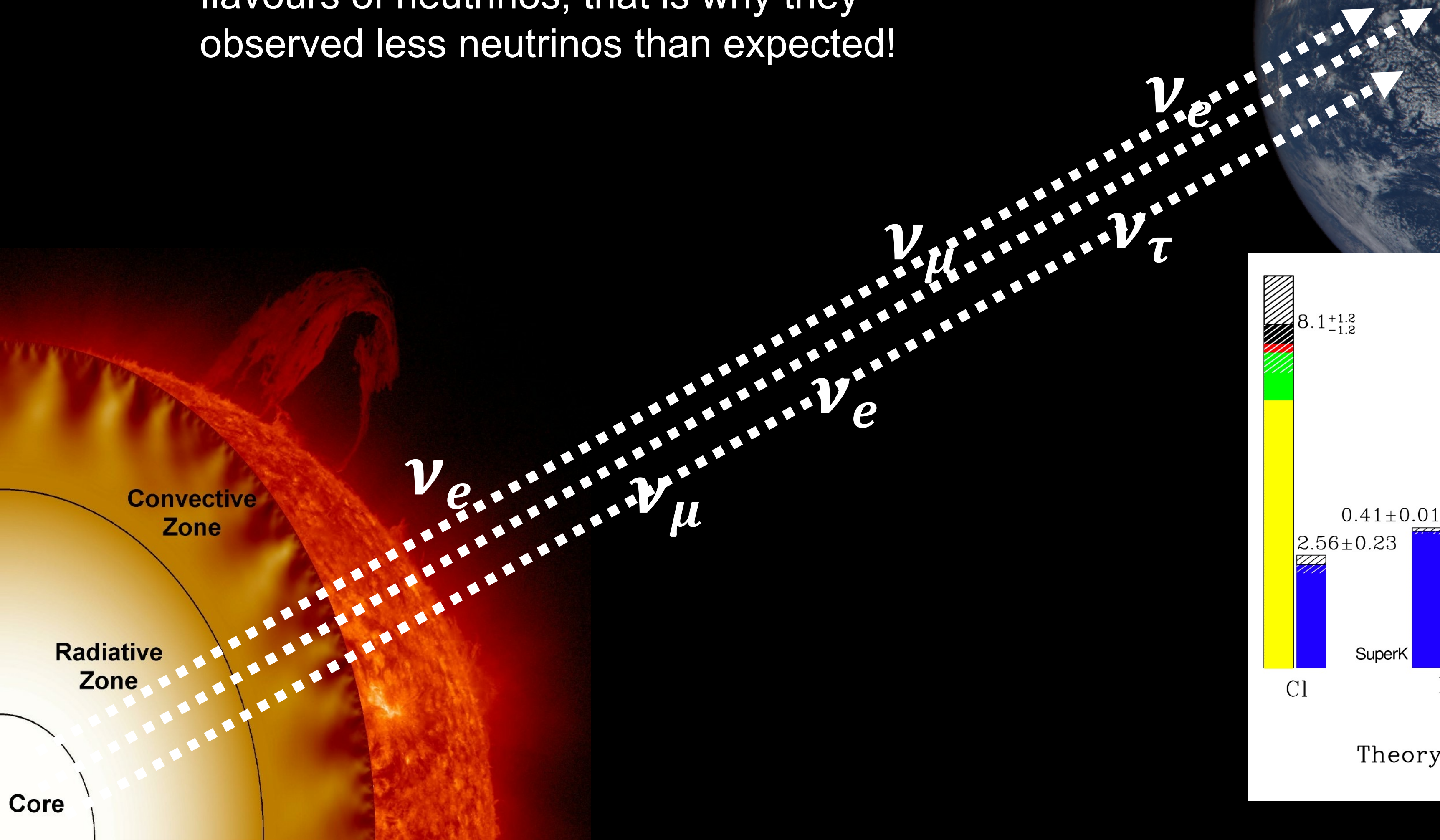


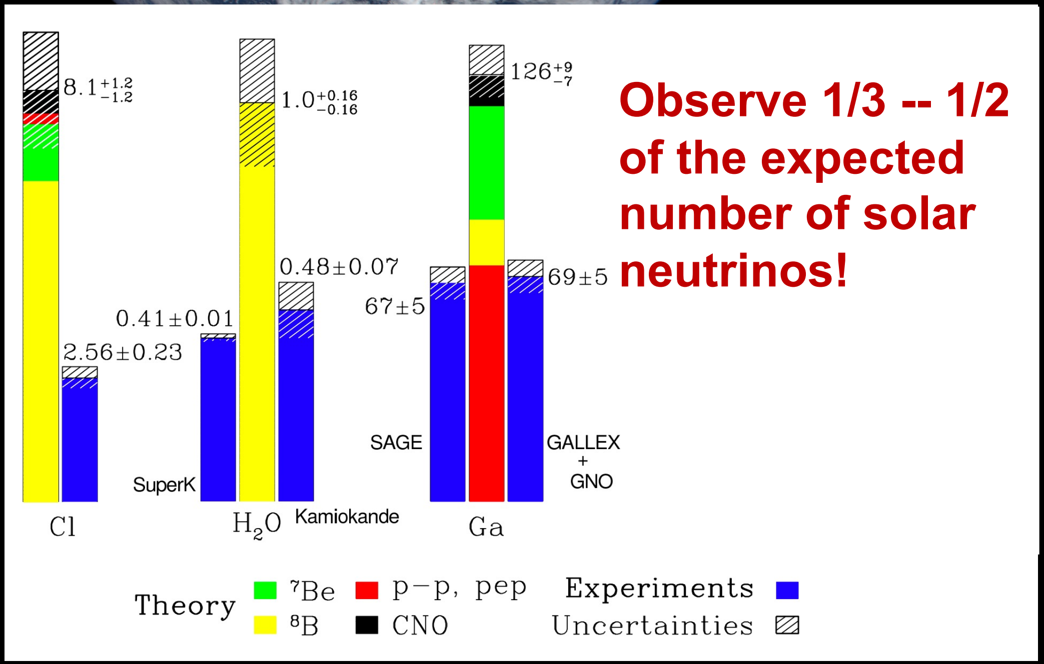
$m_2^2 - m_1^2$

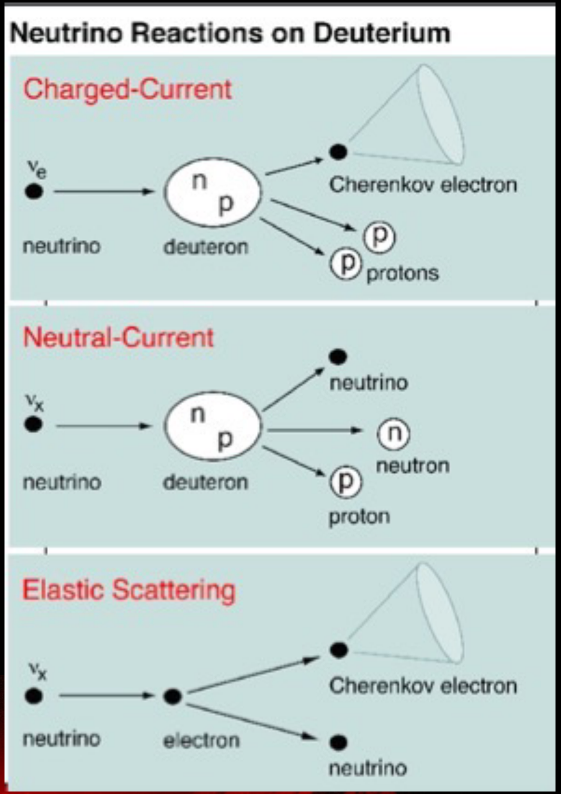
Neutrinos have mass…

Neutrinos Oscillate

The experiments were not sensitive to all flavours of neutrinos, that is why they observed less neutrinos than expected!



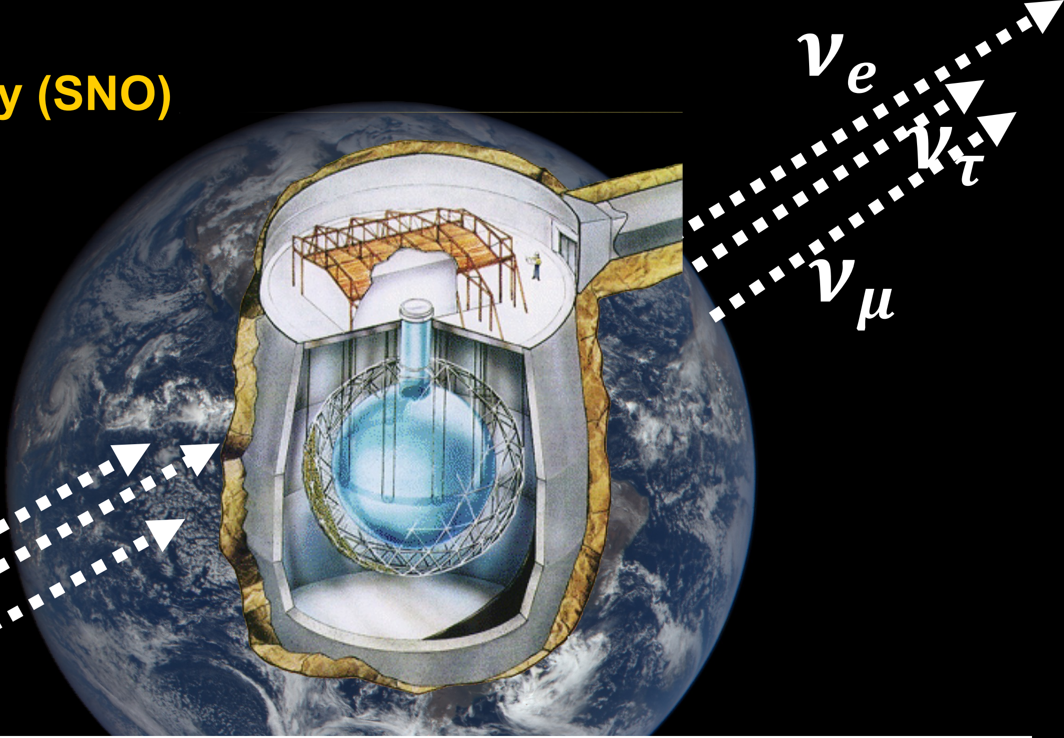


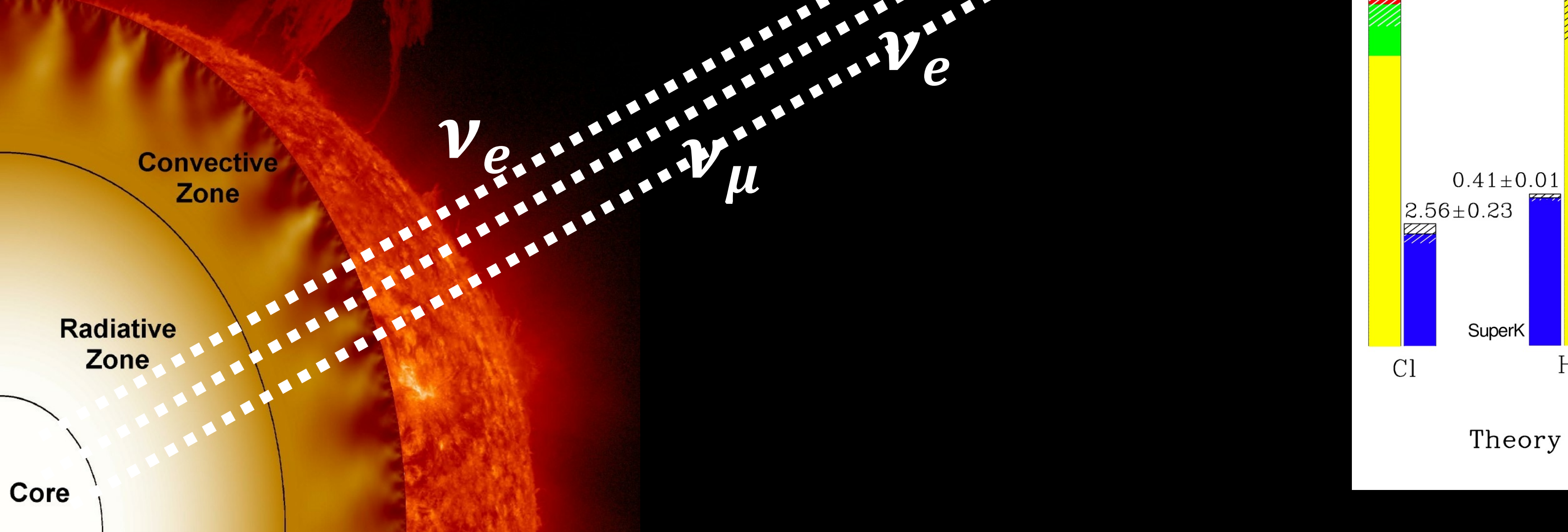


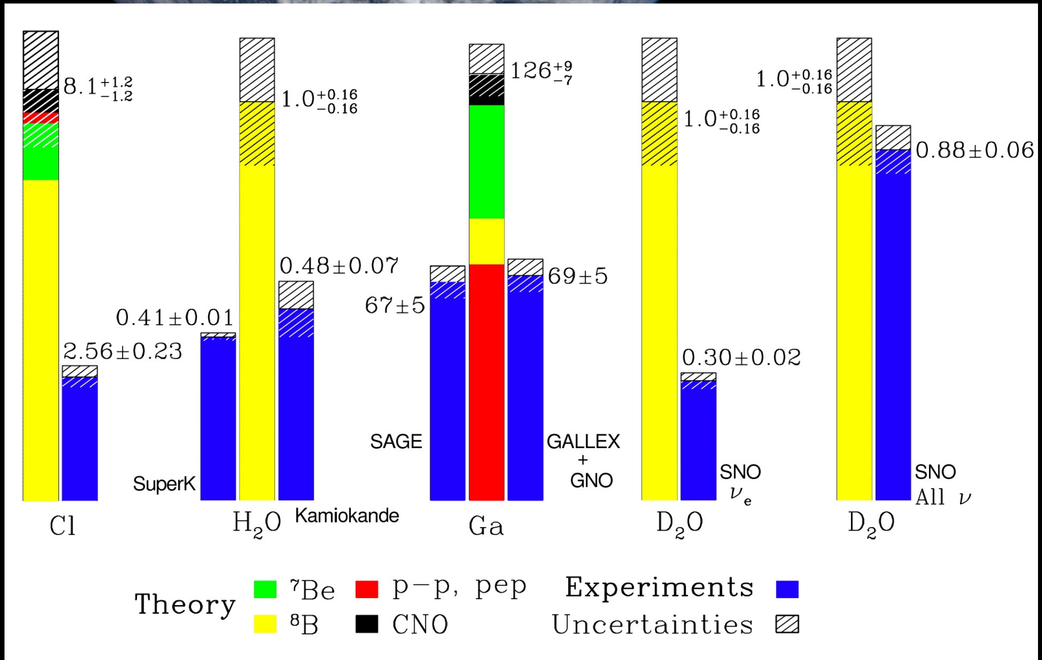
The Sudbury Neutrino Observatory (SNO)

Heavy water (deuterium) Cherenkov detector.

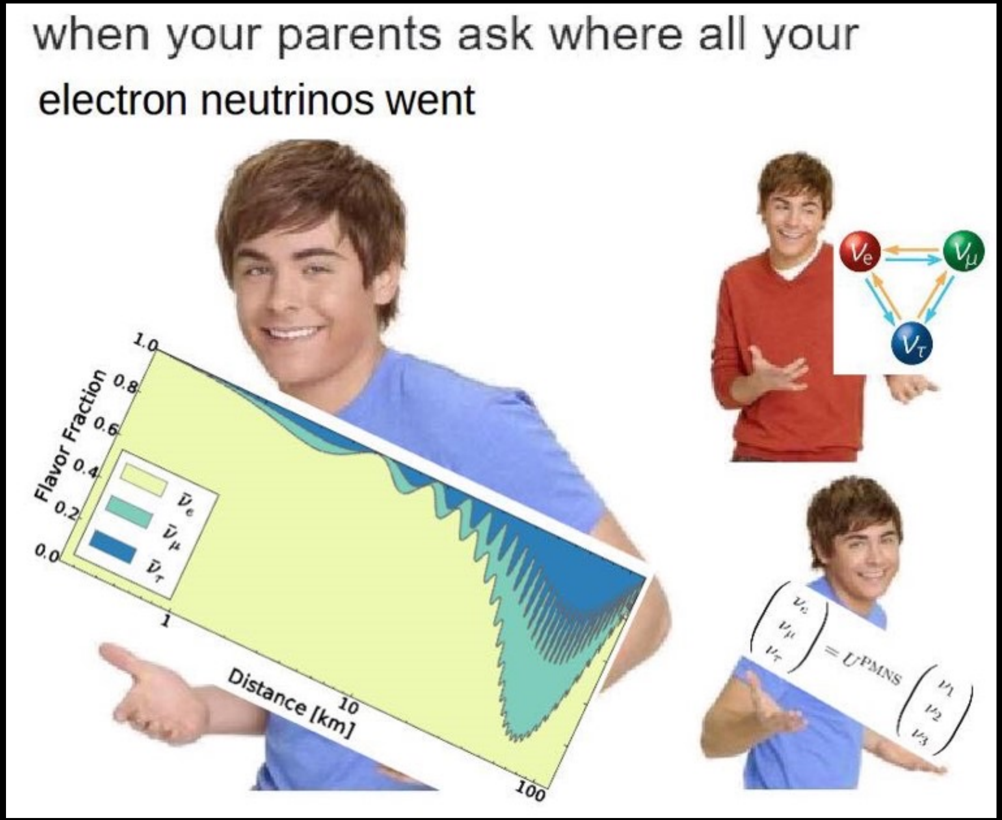
Sensitive to all flavours of neutrinos.







Neutrino Oscillations Discovered!



"...the research group in Canada led by Arthur B. McDonald could demonstrate that the neutrinos from the Sun were not disappearing on their way to Earth. Instead they were captured with a different identity when arriving to the Sudbury Neutrino Observatory."

"...Takaaki Kajita presented the discovery that neutrinos from the atmosphere switch between two identities on their way to the Super-Kamiokande detector in Japan."

Atmospheric Neutrinos

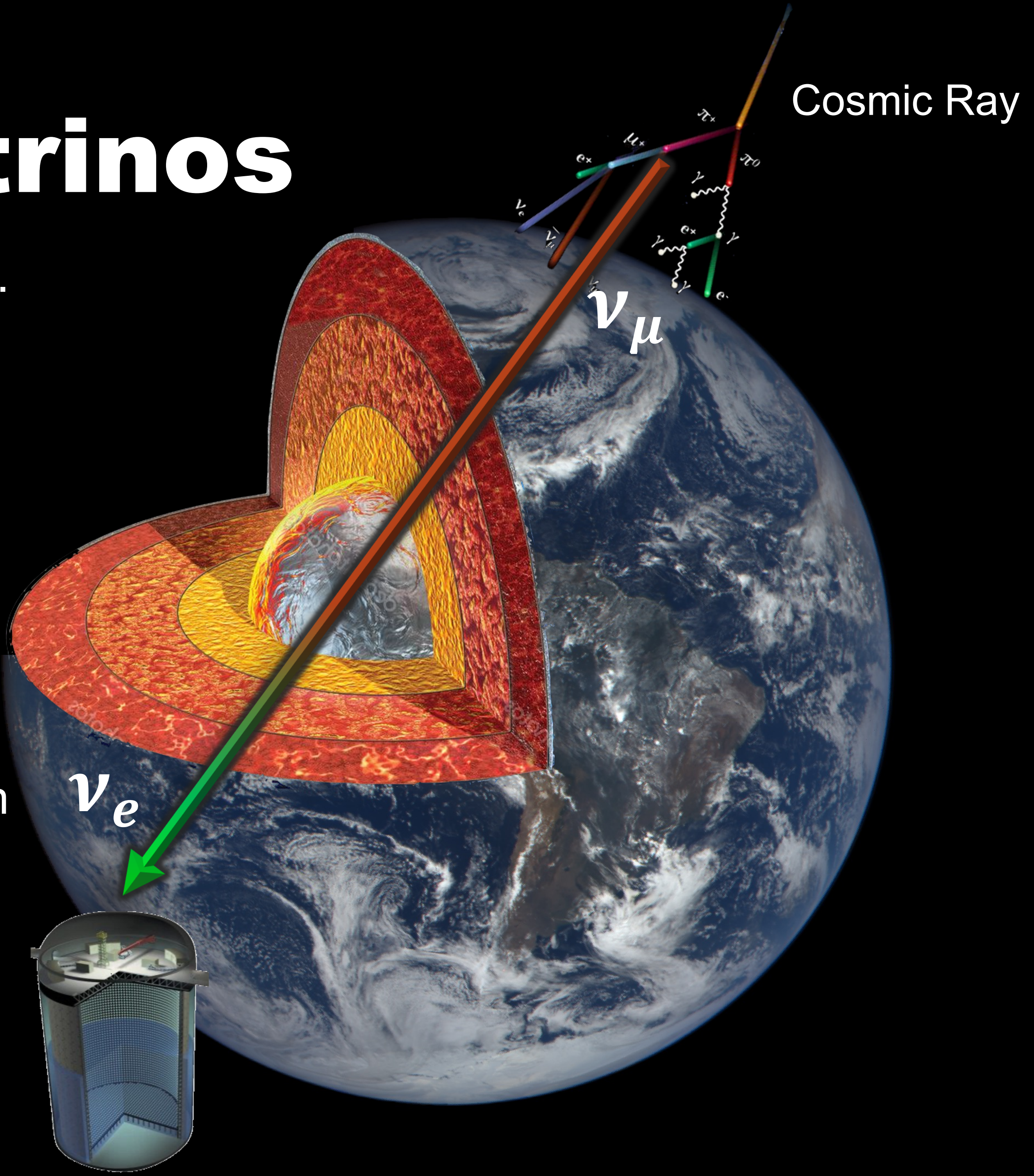
- Produced ~15 kilometers above Earth’s surface.

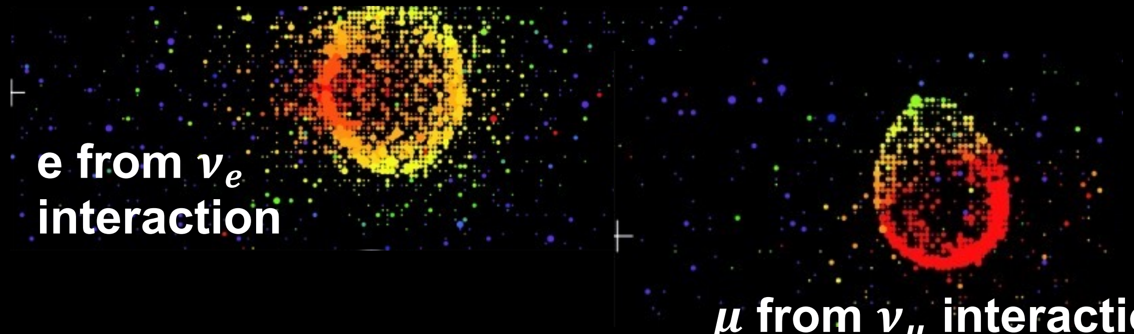
$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e$$

$$\frac{\nu_\mu + \bar{\nu}_\mu}{\nu_e + \bar{\nu}_e} \sim 2$$

- A different ratio shows that neutrinos oscillated.

- That is what Super-Kamiokande observed when comparing the number of ν_e and ν_μ interactions.





μ from ν_μ interaction

But this proves that neutrinos have mass…

$$P_{oscillation}(\boldsymbol{\nu_e} \rightarrow \boldsymbol{\nu_\mu}) = sin^2 2\theta_{12} sin^2\left(1.27\Delta m_{21}^2[\mathrm{eV}^2]\frac{L[\mathrm{m}]}{E[\mathrm{MeV}]}\right)$$

- What is the value of the mass?

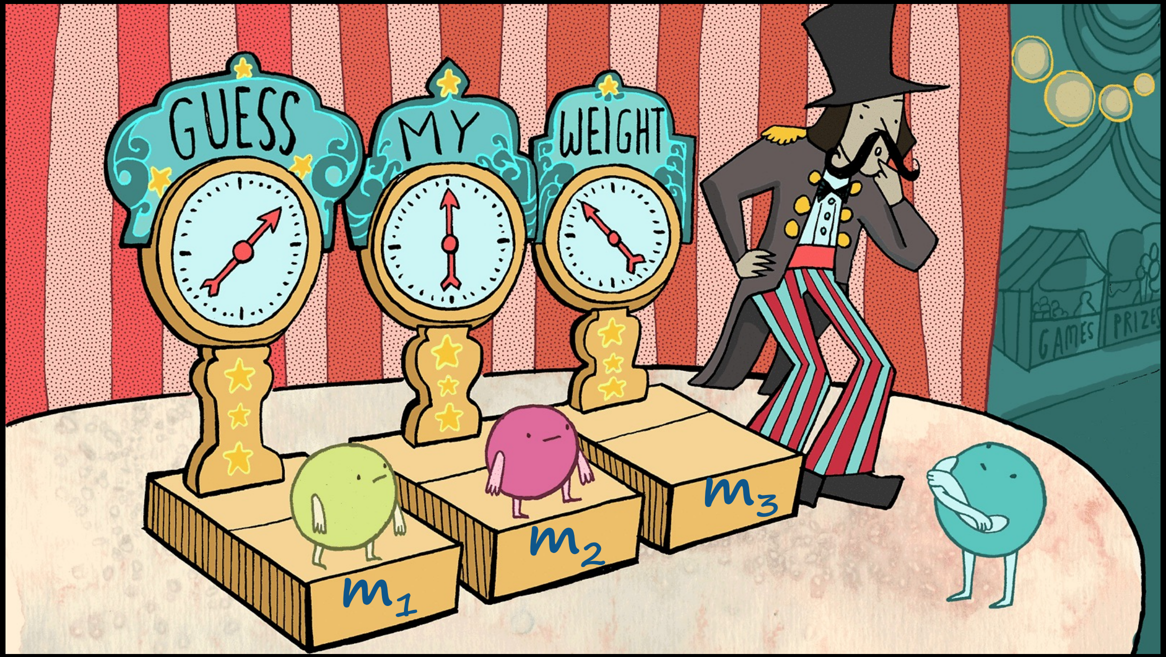
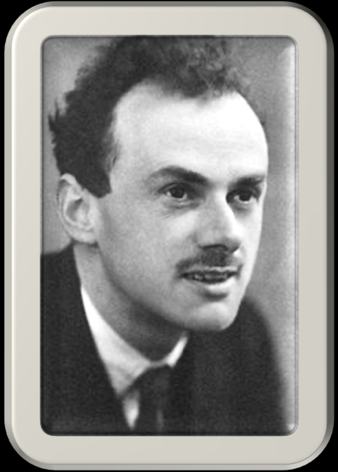


Image from Symmetry Magazine

But this proves that neutrinos have mass…

$$P_{oscillation}(\boldsymbol{\nu_e} \rightarrow \boldsymbol{\nu_\mu}) = sin^2 2\theta_{12} sin^2\left(1.27\Delta m^2_{21}[\mathrm{eV}^2]\,\frac{L[\mathrm{m}]}{E[\mathrm{MeV}]}\right)$$

- What is the value of the mass?
- Where do the masses come from?

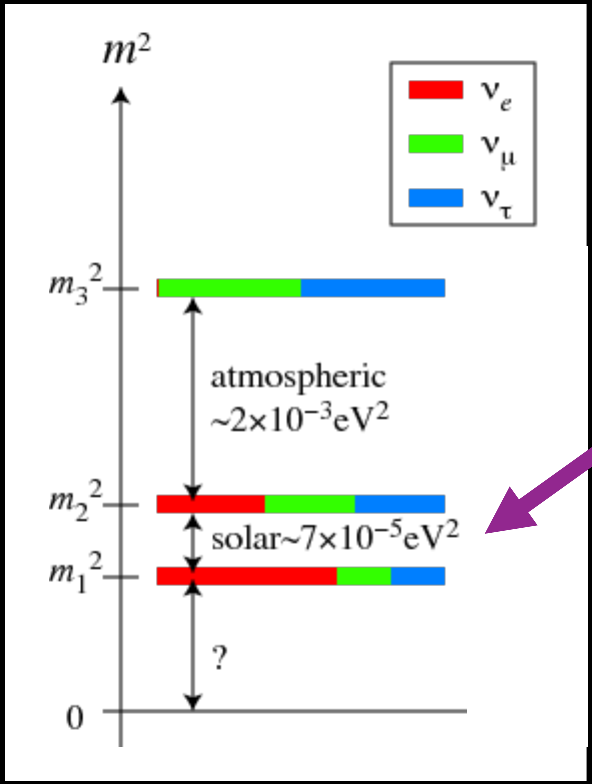


Dirac Neutrinos
Lepton number conservation
Neutrino ≠ anti-neutrino

Majorana Neutrinos
Lepton number violation
Neutrino = anti-neutrino

But this proves that neutrinos have mass...

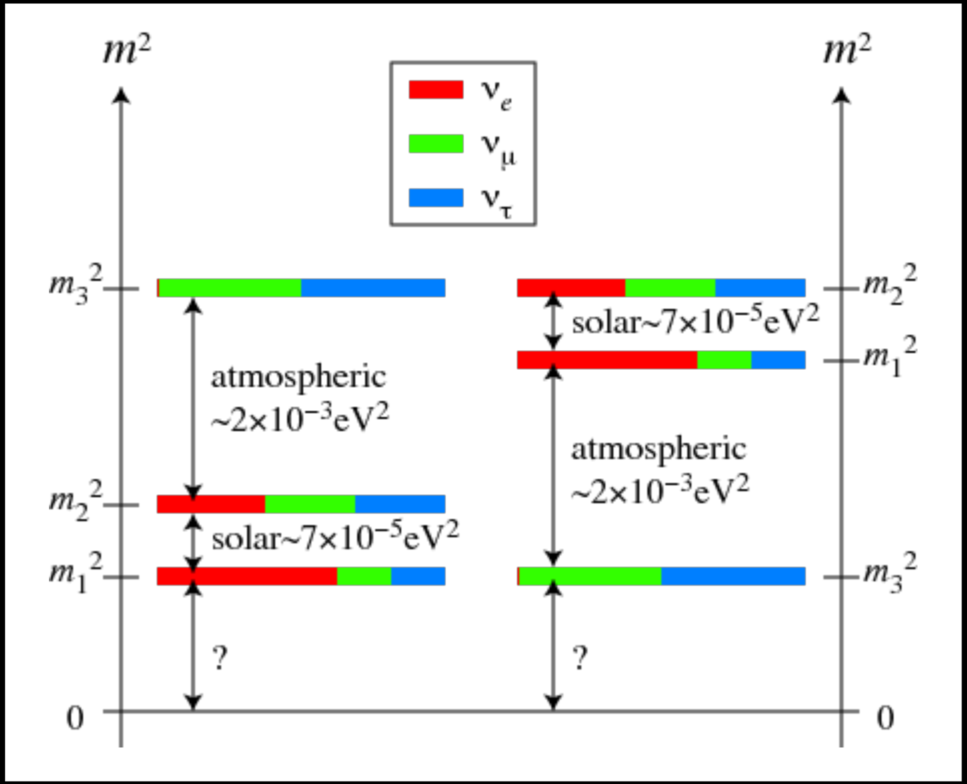
- How are the masses ordered?



Solar experiments have fixed the order between m_1 and m_2

But this proves that neutrinos have mass...

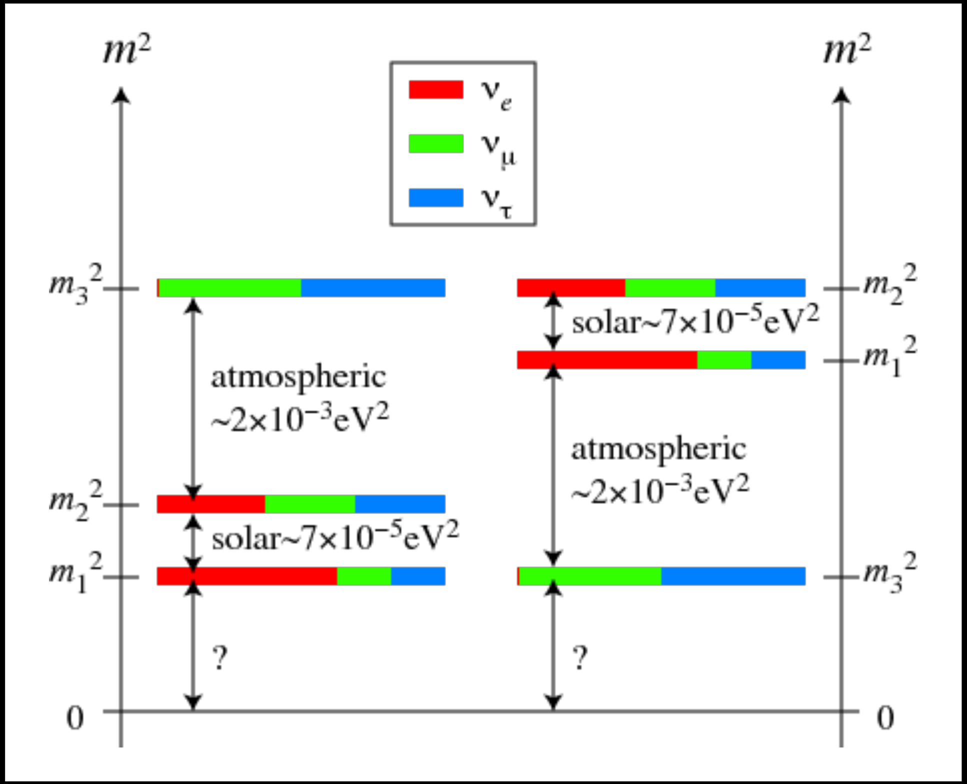
- How are the masses ordered?



But this proves that neutrinos have mass...

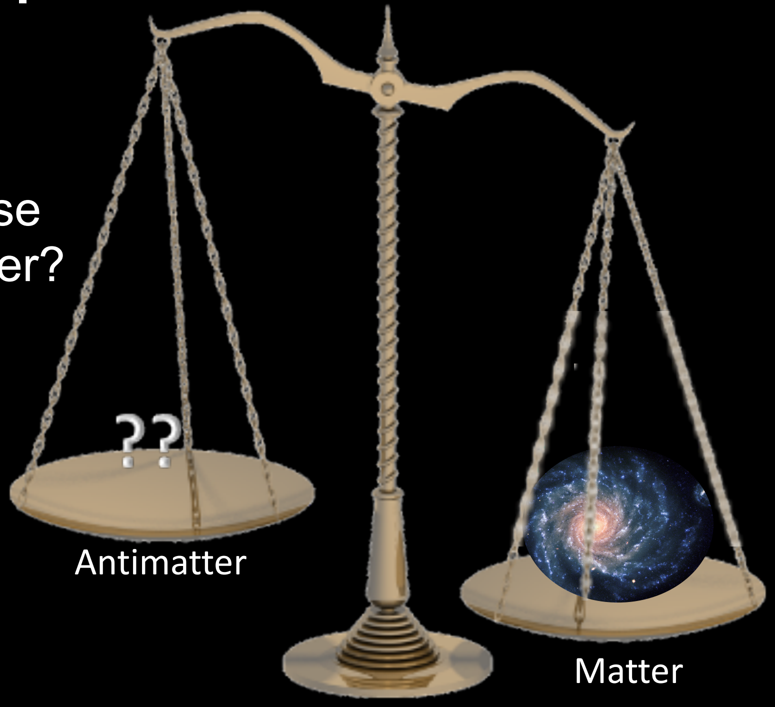
study of differences between neutrino and antineutrino oscillations

- How are the masses ordered?



- Is there CP violation in the lepton sector?

Why is the Universe only made of matter?



Summary

Neutrinos have been revolutionizing the particle physics world since their discovery!

There are many fundamental questions that we still have to answer.

Maybe one day you can help solve some of these mysteries.

Let’s start that journey by learning how to detect reactor neutrinos!

Backup

First detection of Solar Neutrinos

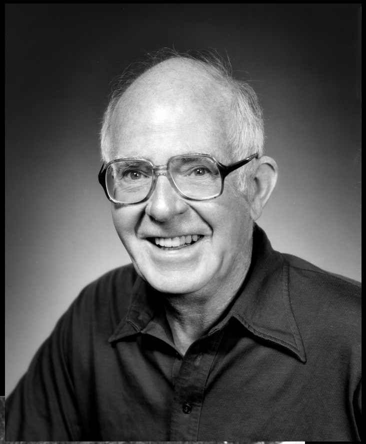
Homestake Experiment

- Proposed in the 70s by Ray Davis
- Radiochemical experiment looking for the Pontecorvo-Alvarez inverse beta-decay Cl-Ar reaction:

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

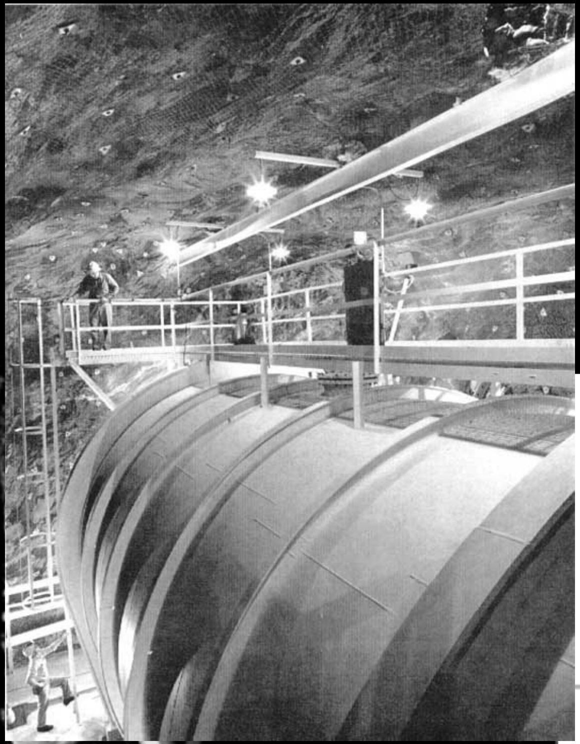
Neutrino energy threshold $E_\nu = 0.814$ MeV
Sensitive to ^{8}B and ^{7}Be solar neutrinos

- Expose large quantities of Chlorine
- Chemically extract the Argon
- Count the radioactive decays of ^{37}Ar

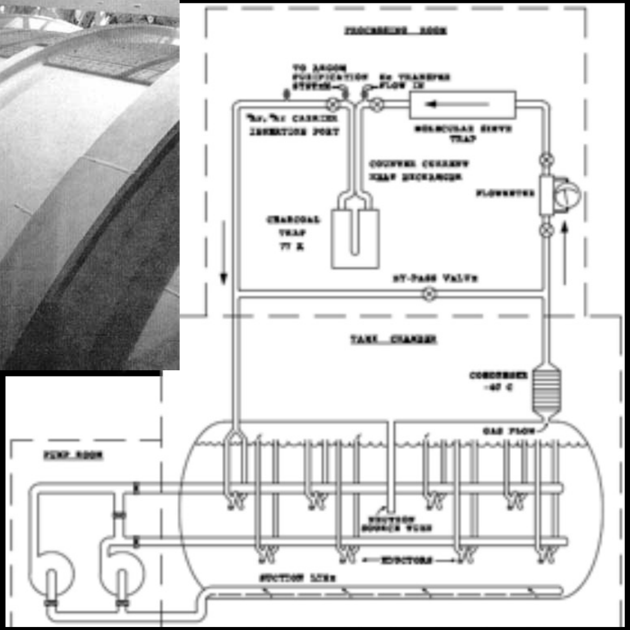


First detection of Solar Neutrinos

Homestake Experiment



- Homestake mine (USA), 1478 m deep
- Used 600 tons of CCl4 (cleaning liquid)
- Flush the Argon out of the tanks using helium, every two to three months (efficiency of 95%)



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9-1307-66

Solar Neutrinos Are Counted At Brookhaven

Dr. Ray Davis of Chemistry is shown placing a low level counter in a cut-down navy gun barrel which acts as a shield from stray cosmic radiation. This equipment is used in the Brookhaven Solar

The extracted Argon is measured in a counter

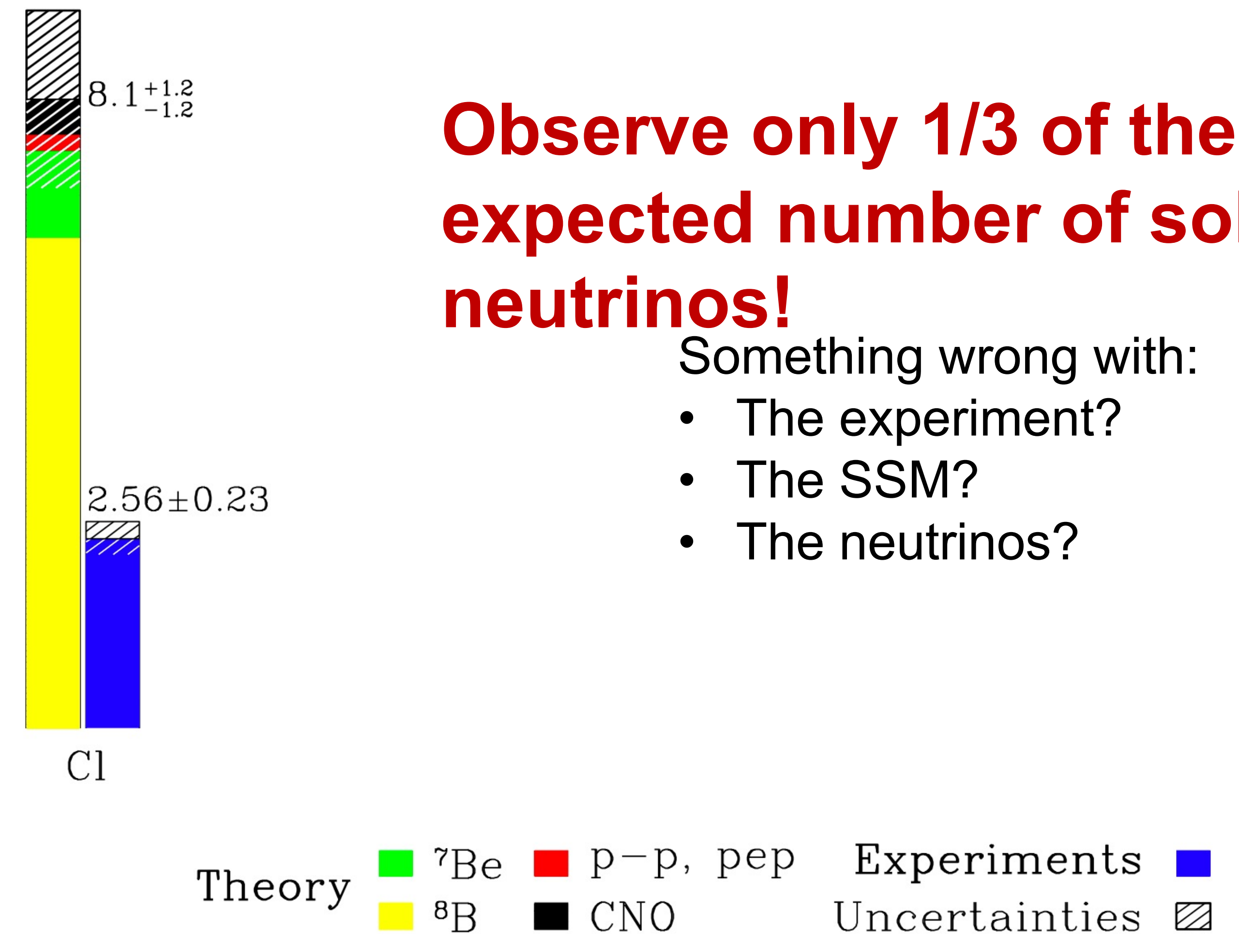
$$^{37}Ar + e^- \rightarrow \nu_e + {}^{37}Cl$$

$$(T_{1/2} = 35d)$$

Acquired data for 24 years!

First detection of Solar Neutrinos

Homestake Experiment Results



Observe only 1/3 of the expected number of solar neutrinos!

Something wrong with:

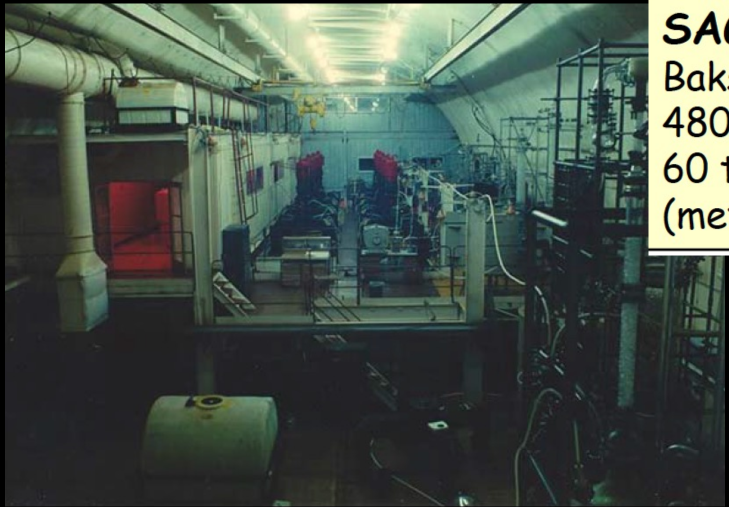
- The experiment?
- The SSM?
- The neutrinos?

Gallium Experiments

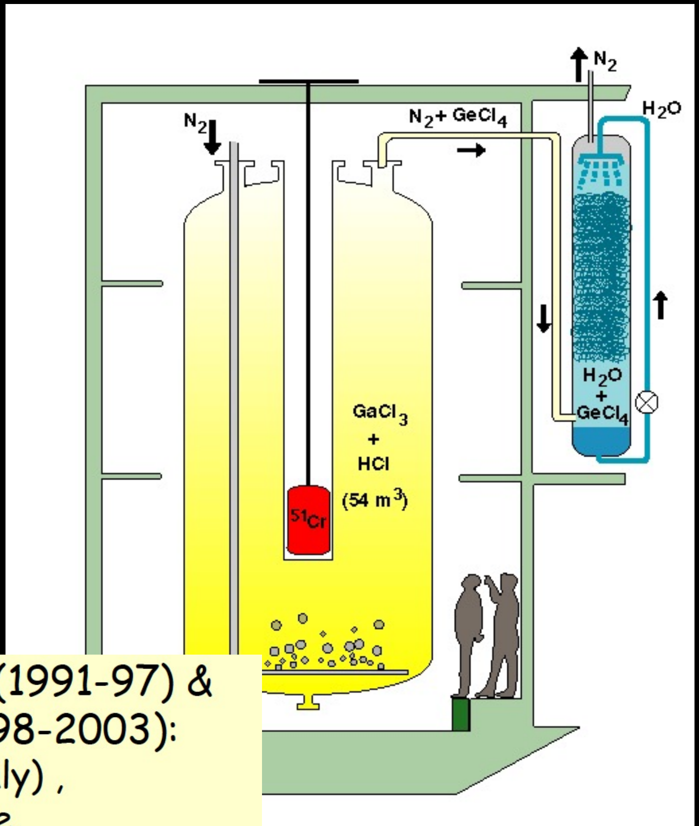
- Similar to Homestake, but using the Gallium reaction

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

Neutrino energy threshold $E_\nu = 0.233$ MeV
Sensitive to ^{8}B, ^{7}Be and high energy pp solar neutrinos



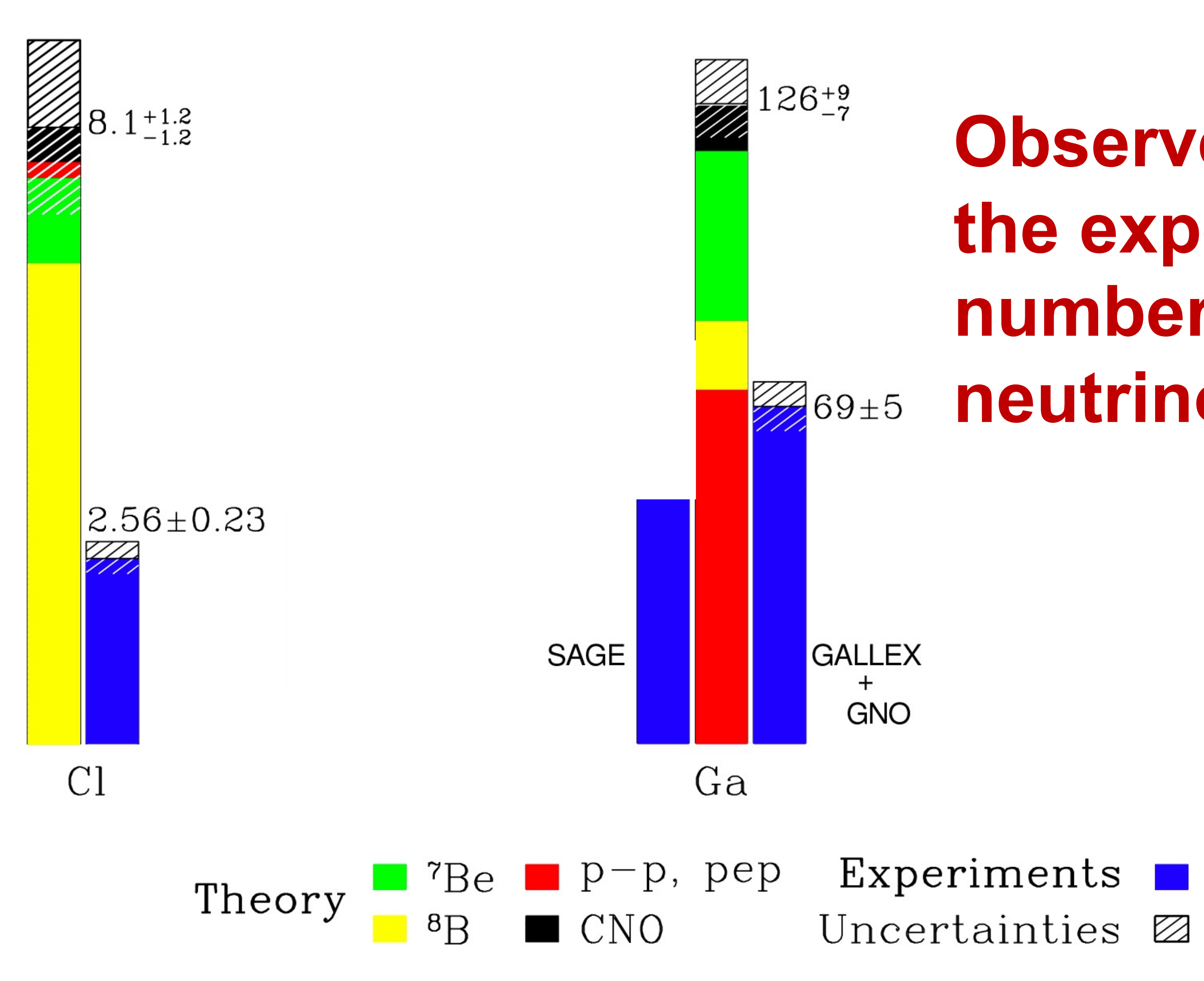
SAGE (1991-93):
Baksan (Russia)
4800 m.w.e.
60 tons of gallium
(metal Ga target)



GALLEX (1991-97) &
GNO (1998-2003):
LNGS (Italy) ,
3200 m.w.e.
30 tons of gallium
(water solution of $GaCl_3$)

SAGE uses metallic gallium (which becomes a liquid at just above room temperature), while GALLEX uses gallium in a liquid-chloride form. The different forms of the gallium are susceptible to very different types of backgrounds, and thus the two experiments provide a check for each other.

Gallium Experiments



Observe 1/2 of the expected number of solar neutrinos!

Water Cherenkov Detectors

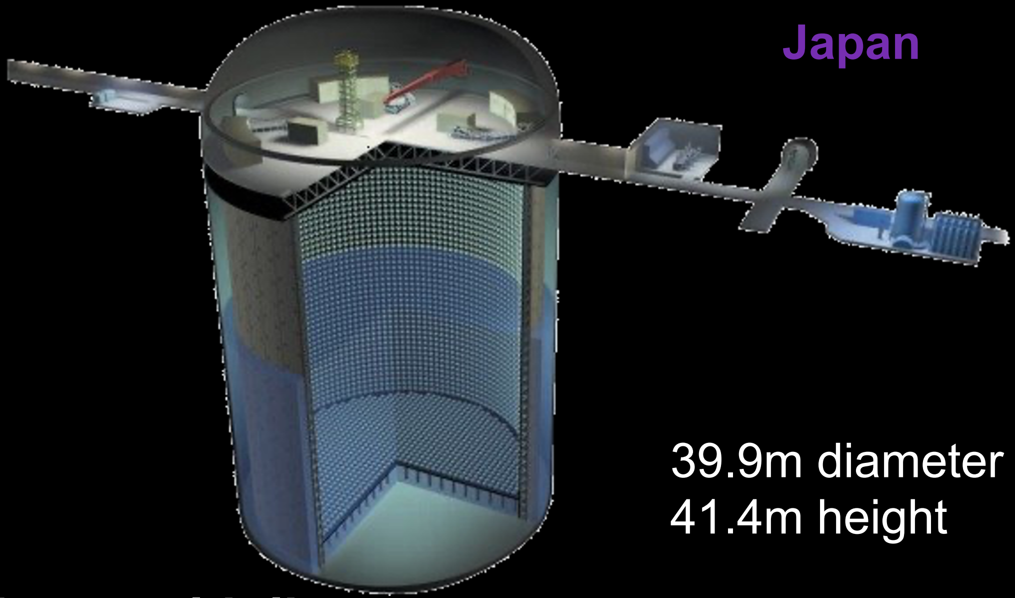
- 1987 Kamiokande
- 1997 Super-Kamiokande
  - Several phases

- Detects neutrino-electron scatterings

$$\nu_l + e^- \rightarrow \nu_l + e^-$$

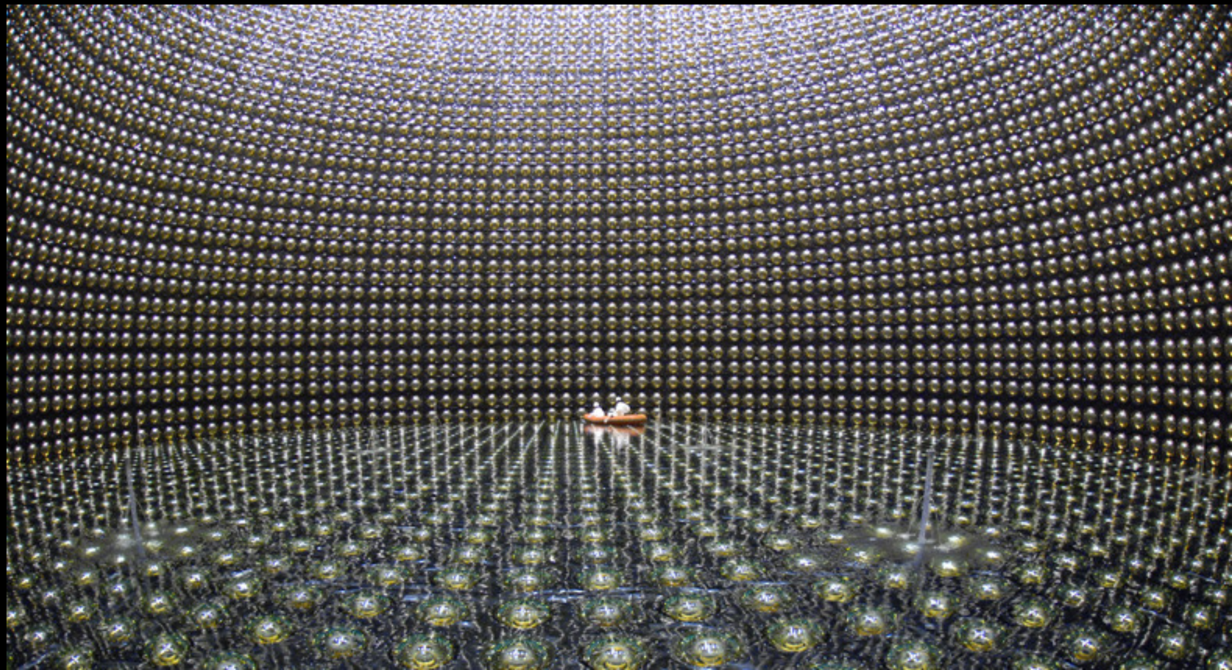
- Sensitive to all neutrino flavours, but mainly ν_e

Japan



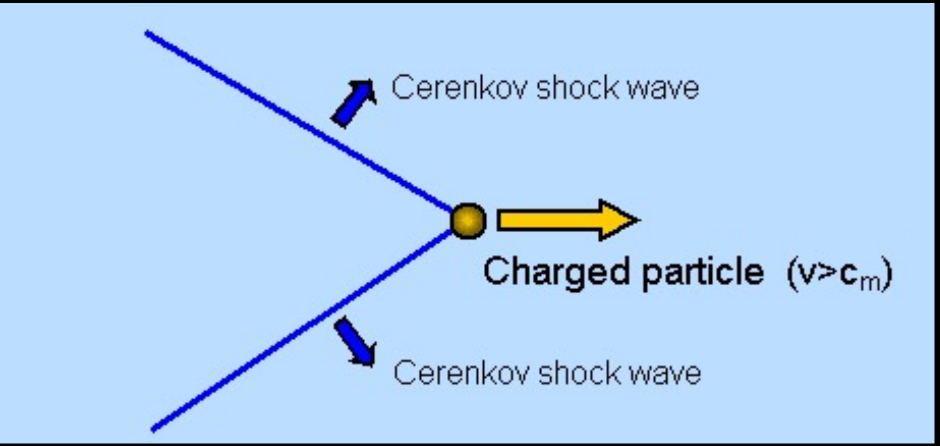
39.9m diameter
41.4m height

11000 photomultipliers
50000 tons of water



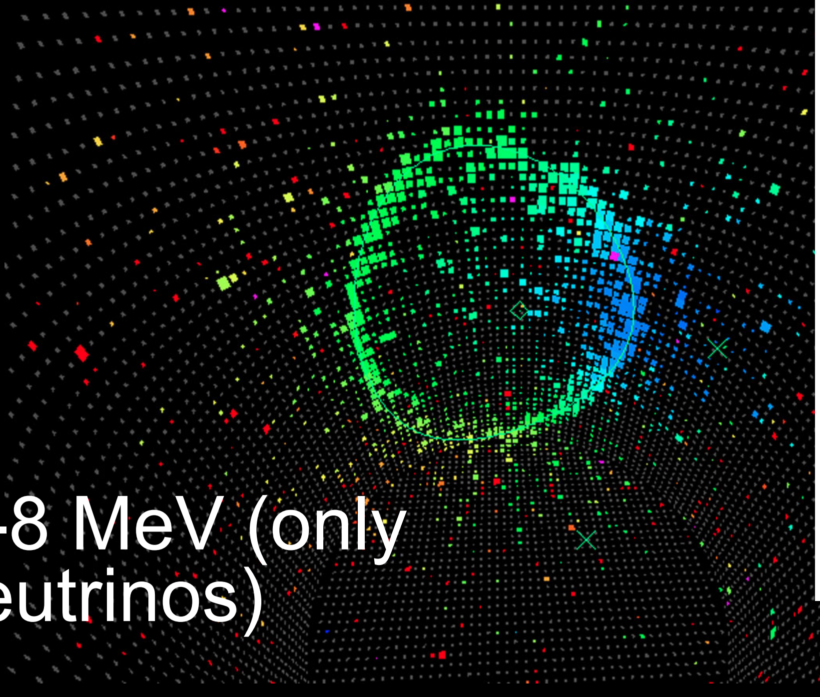
Water Cherenkov Detectors

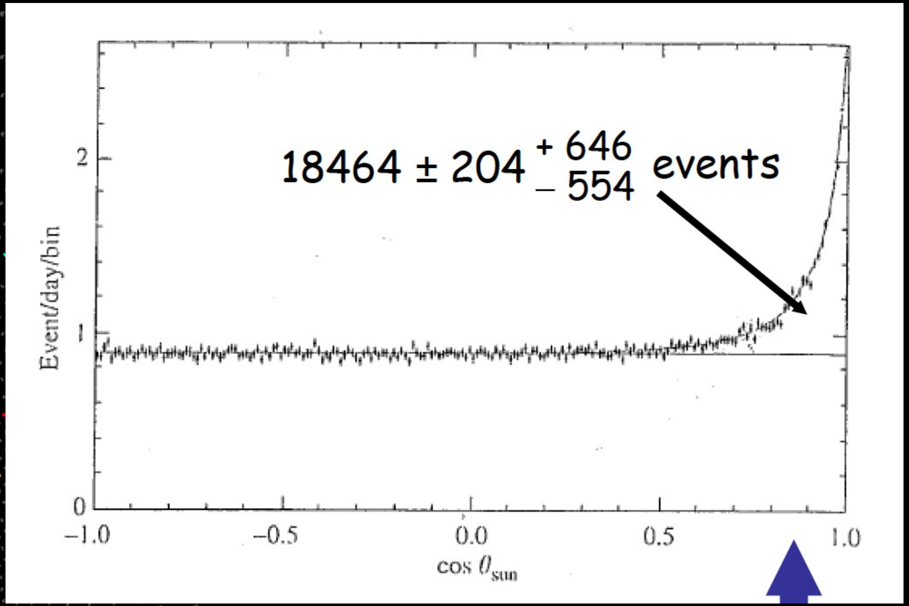
- The scattered electrons produce Cherenkov radiation



Cherenkov radiation is electromagnetic radiation emitted when a charged particle passes through a dielectric medium at a speed greater than the phase velocity of light in that medium

- Allow to know:
  - Directionality
  - Arrival Time
  - Energy

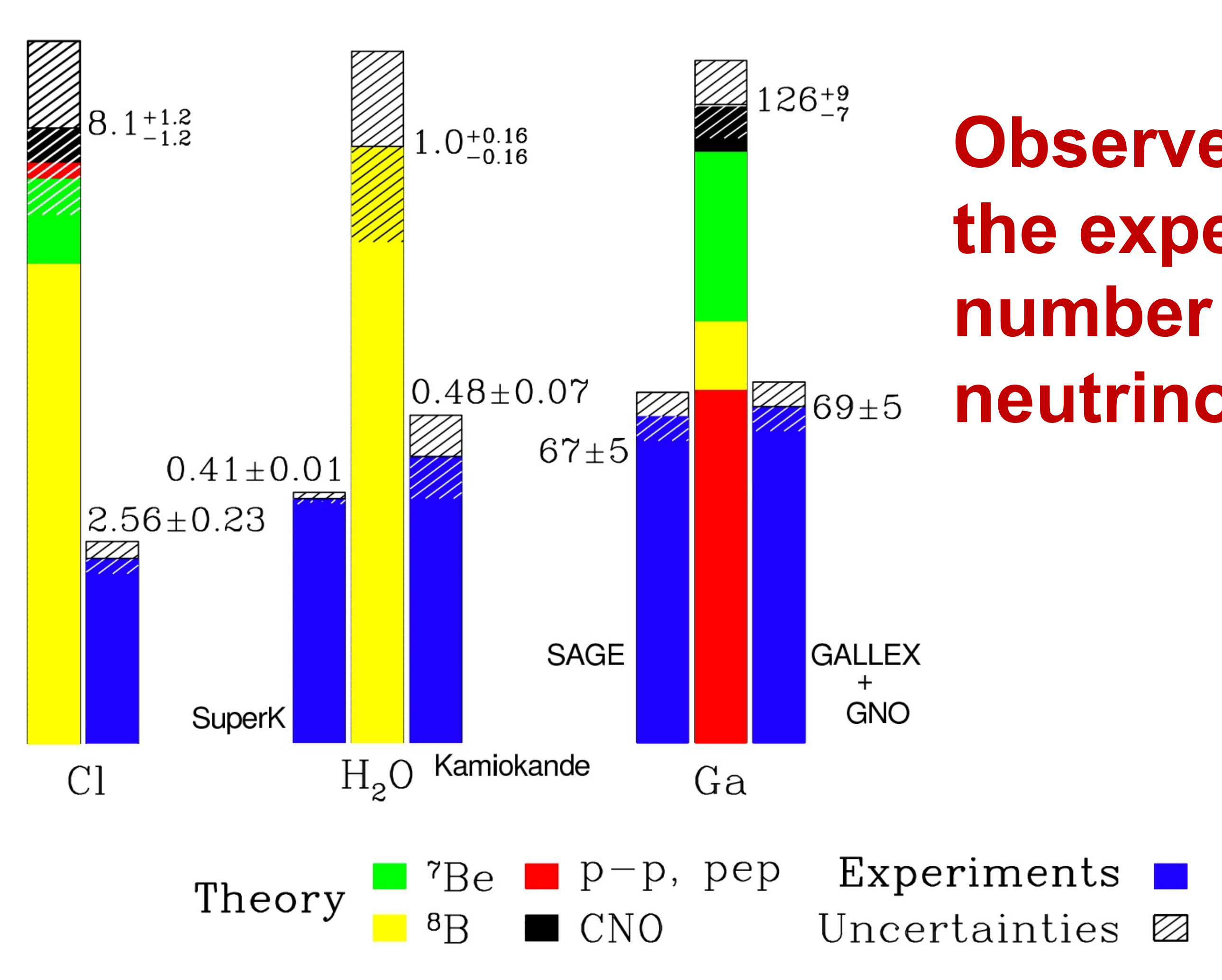




- High threshold 5-8 MeV (only sensitive to ^8B neutrinos)

They could see the events along the direction of the Sun – they are solar ν

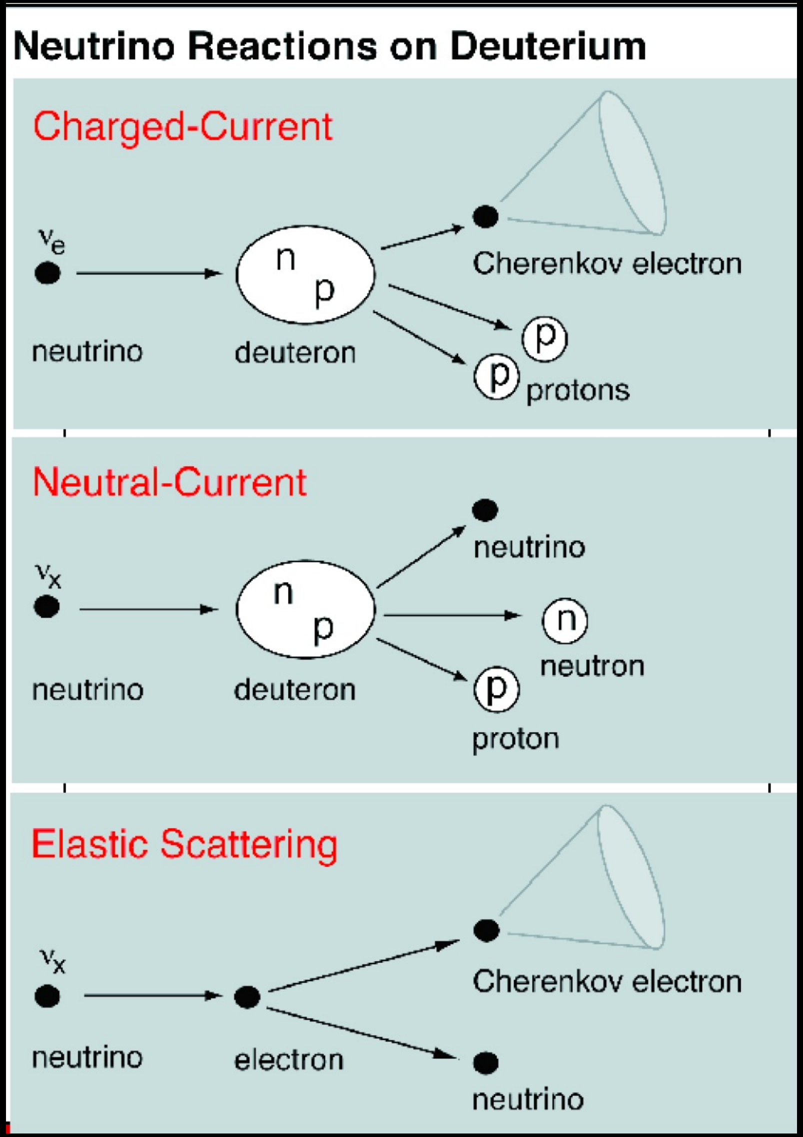
Water Cherenkov Detectors



Observe 1/2 of the expected number of solar neutrinos!

Neutrino Reactions in SNO

- $\nu_e + d \rightarrow p + p + e^-$
  - Signal: Cherenkov light from electron
  - Only sensitive to ν_e
  - Measured ν_e flux
- $\nu_l + d \rightarrow \nu_l + p + n$
  - Signal: neutron capture (6.25 MeV γ) and Cherenkov light from electrons scattered by the γ
  - Measured total neutrino flux
- $\nu_l + e^- \rightarrow \nu_l + e^-$
  - Signal: Cherenkov light from electron
  - Mainly sensitive to ν_e , some ν_μ and ν_τ



Search for Double Beta Decay

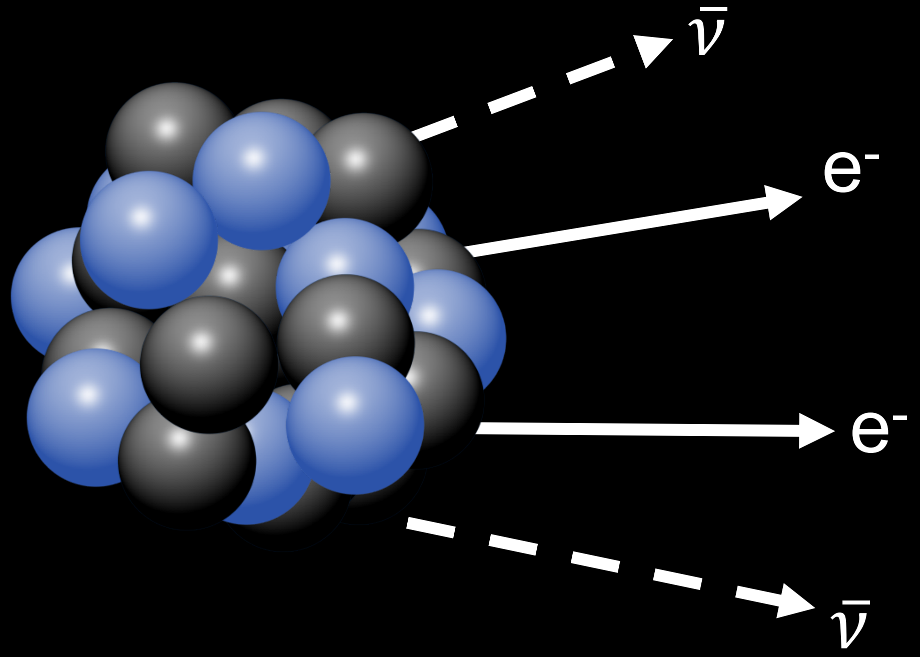
SNO+

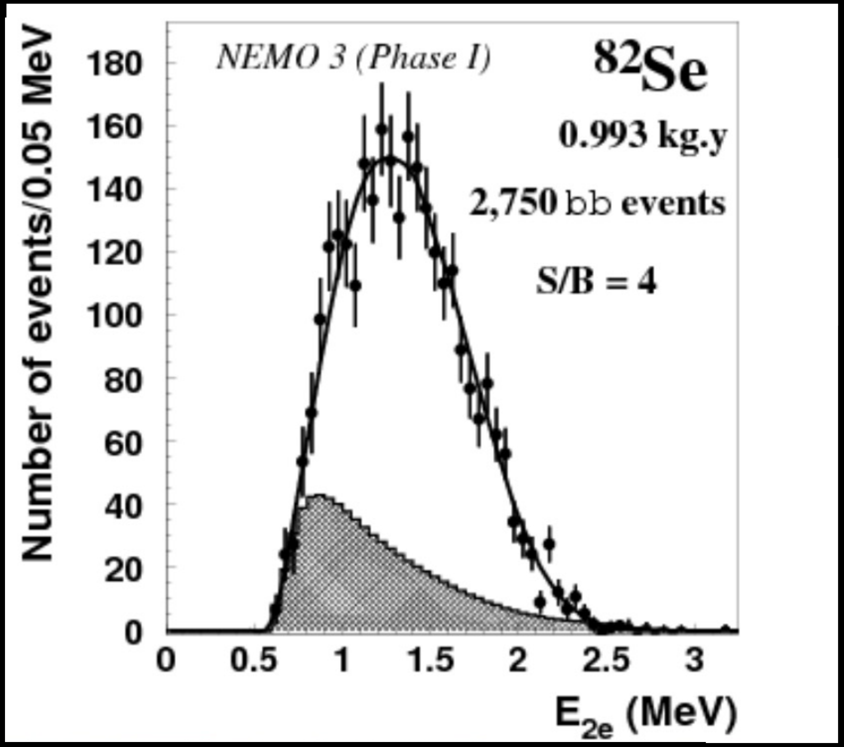
nEXO

Majorana/Legend

2ν Double Beta Decay

A rare nuclear decay through which some nuclei reach stability.

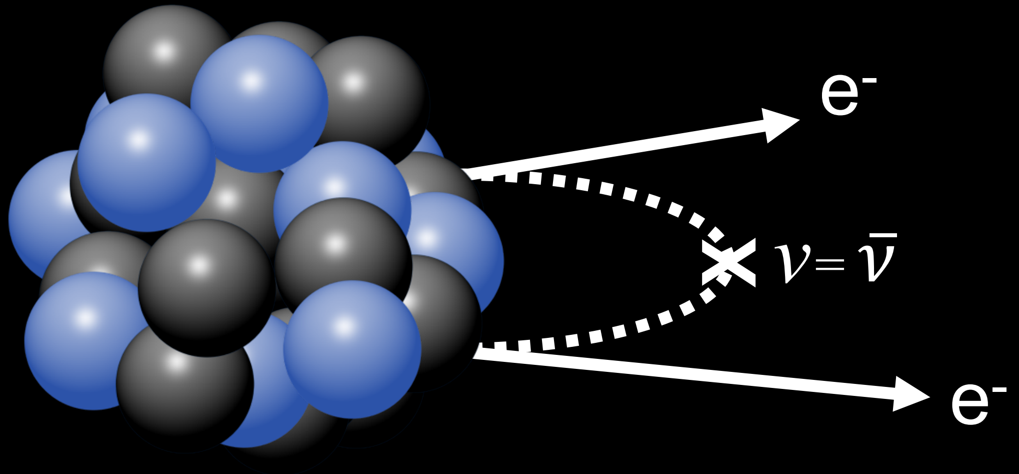


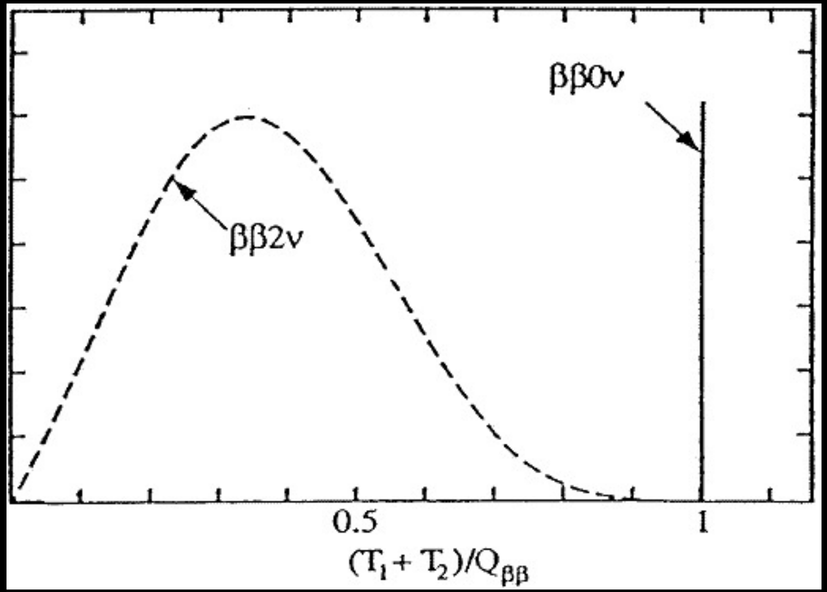


Detected Kinetic Energy of the Two Electrons/Q

- Possible when normal beta decay is not energetically allowed.
- Can happen for 35 natural isotopes. Observed in 11: ^{48}Ca, ^{76}Ge, ^{130}Te, ^{136}Xe...
- Long half-lives between 10^{19} and 10^{24} years.

0ν Double Beta Decay





- Possible if neutrinos are Majorana particles (their own anti-particles).
- Violates lepton number conservation.
- Rate depends on the effective electron neutrino Majorana mass.

$$\left[T_{0\nu}^{1/2}\right]^{-1} = G_{0\nu}|\mathcal{M}_{0\nu}|^2\left|\frac{m_{\beta\beta}}{m_e}\right|^2$$

$$m_{\beta\beta} = \left|\sum_{i=1,2,3} e^{i\xi_i}|U_{ei}^2|m_i\right|$$