Intro to Solar neutrinos, and the Solar neutrino problem

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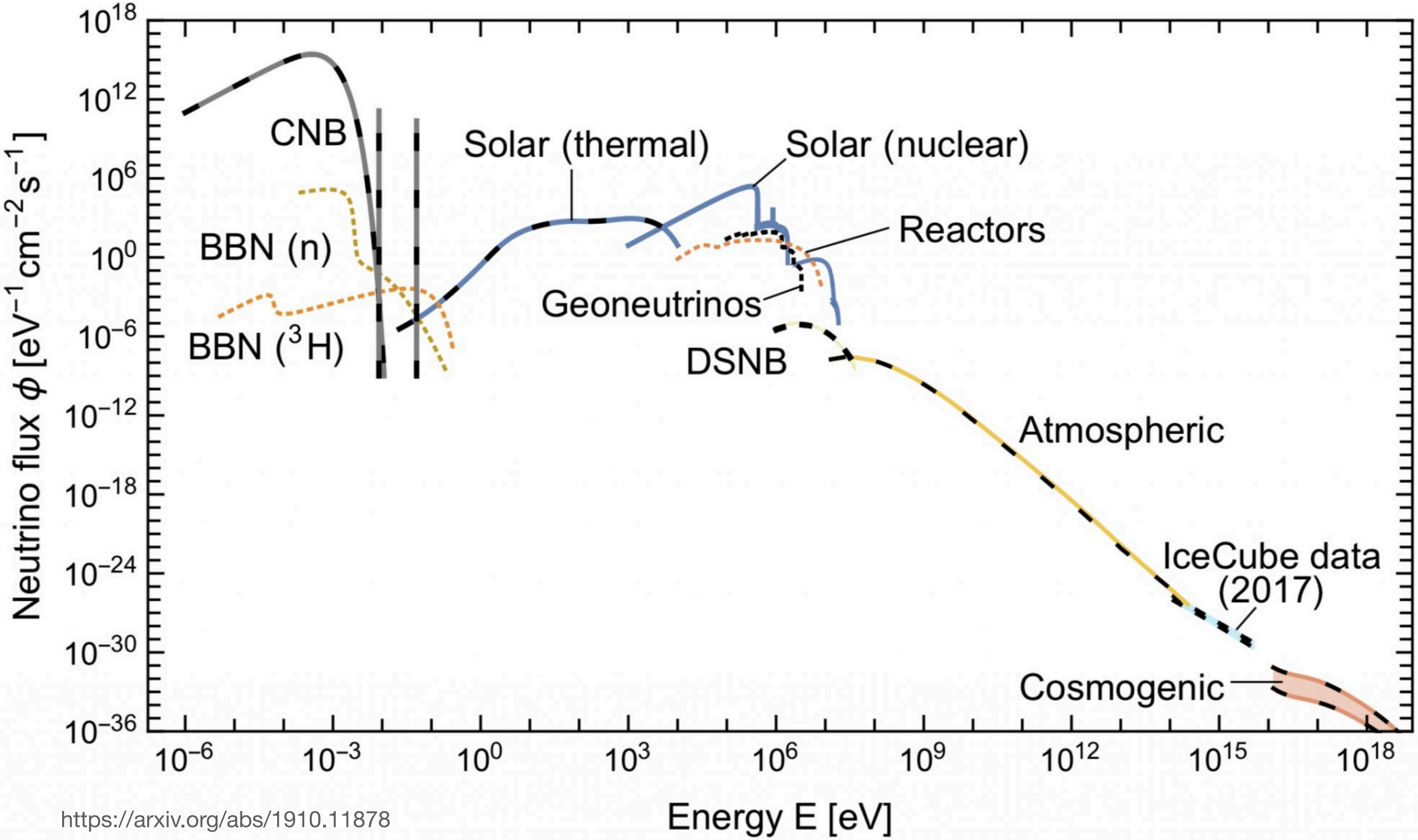
- Course webpage: https://blackboard.cuhk.edu.hk

The Grand Unified Neutrino Spectrum



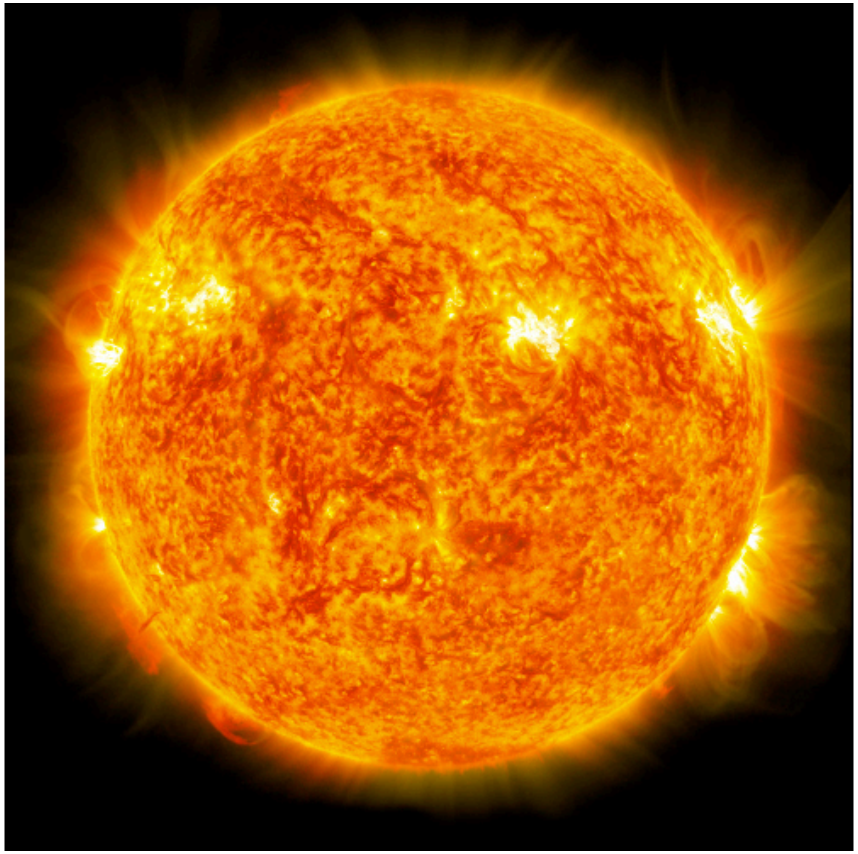
https://arxiv.org/abs/1910.11878

The Standard Solar Model

- What is a star?

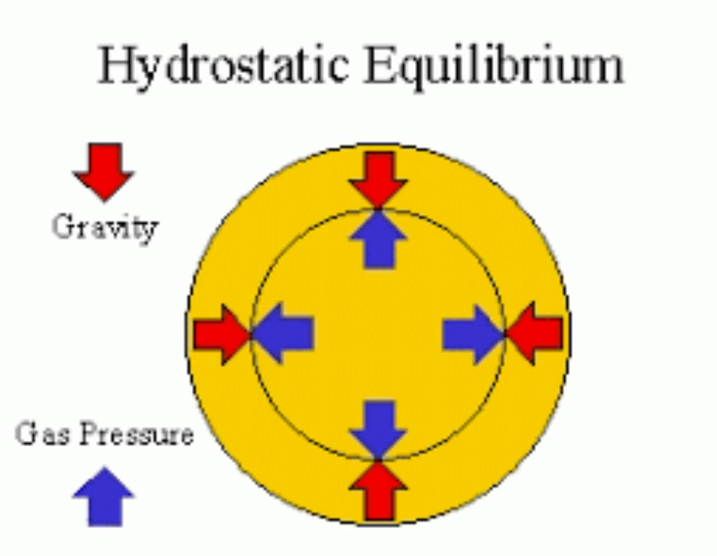
- A stable ball of gas that shines

- Macroscopically, stars with similar parameters should be similar

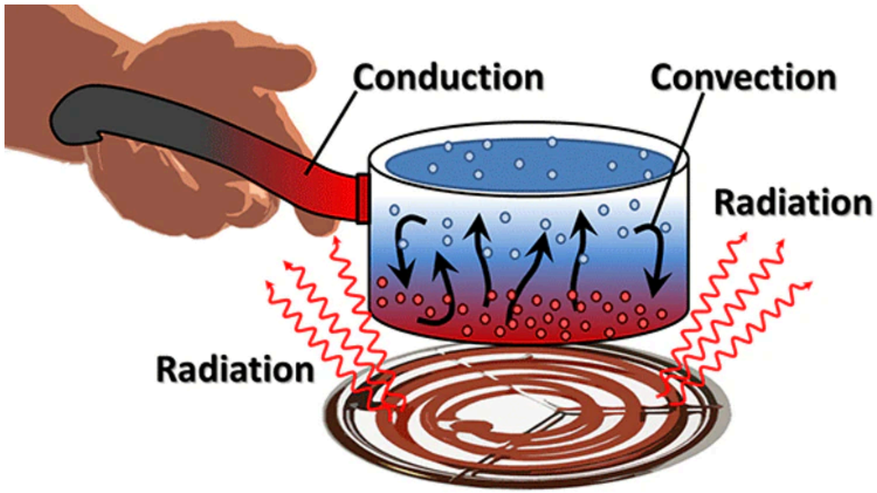


The Standard Solar Model

- Pressure - Gravity equilibrium $\left(\frac{dP}{dr}\right)$
  - Hydrostatic equilibrium

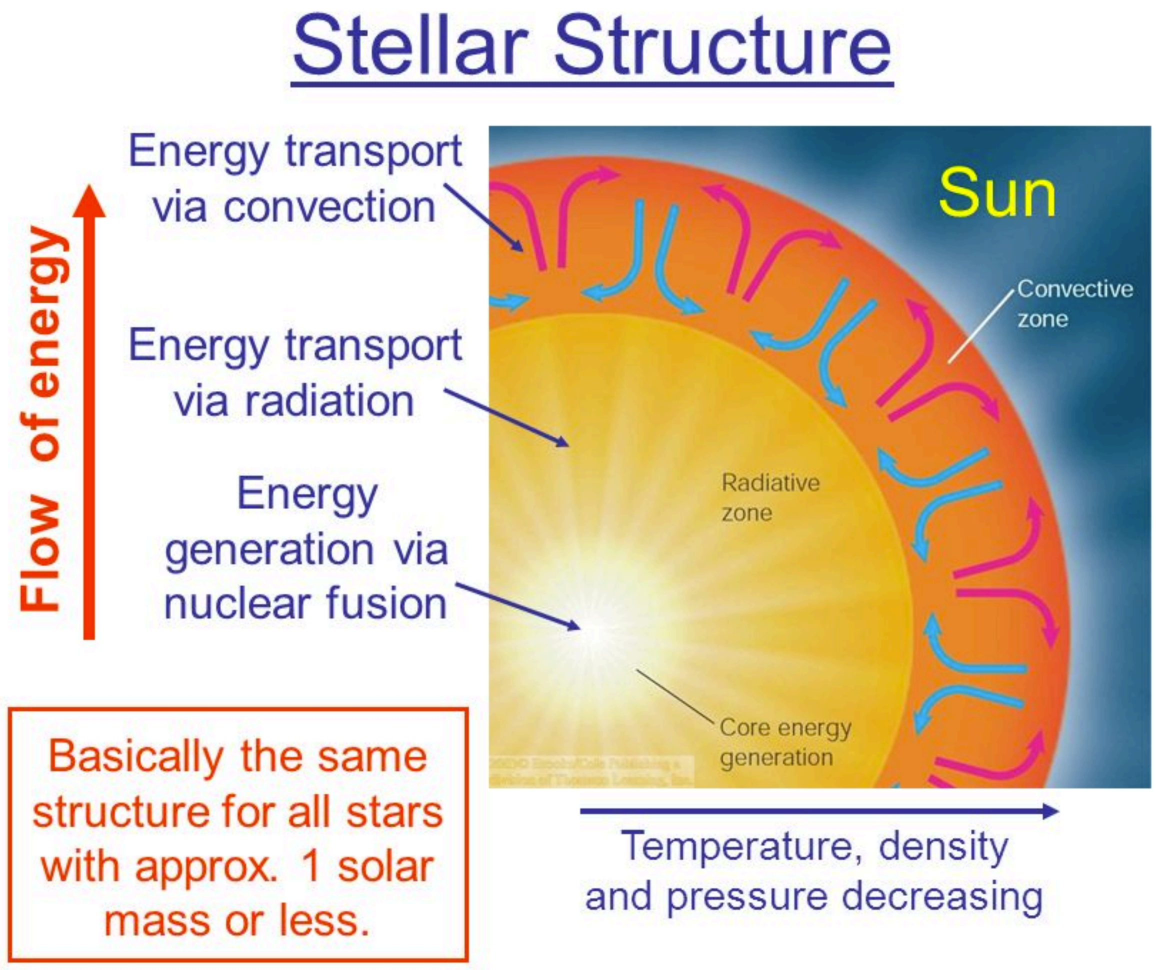


- Energy transport $\left(\frac{dT}{dr}\right)$
  - radiative
  - Conductive



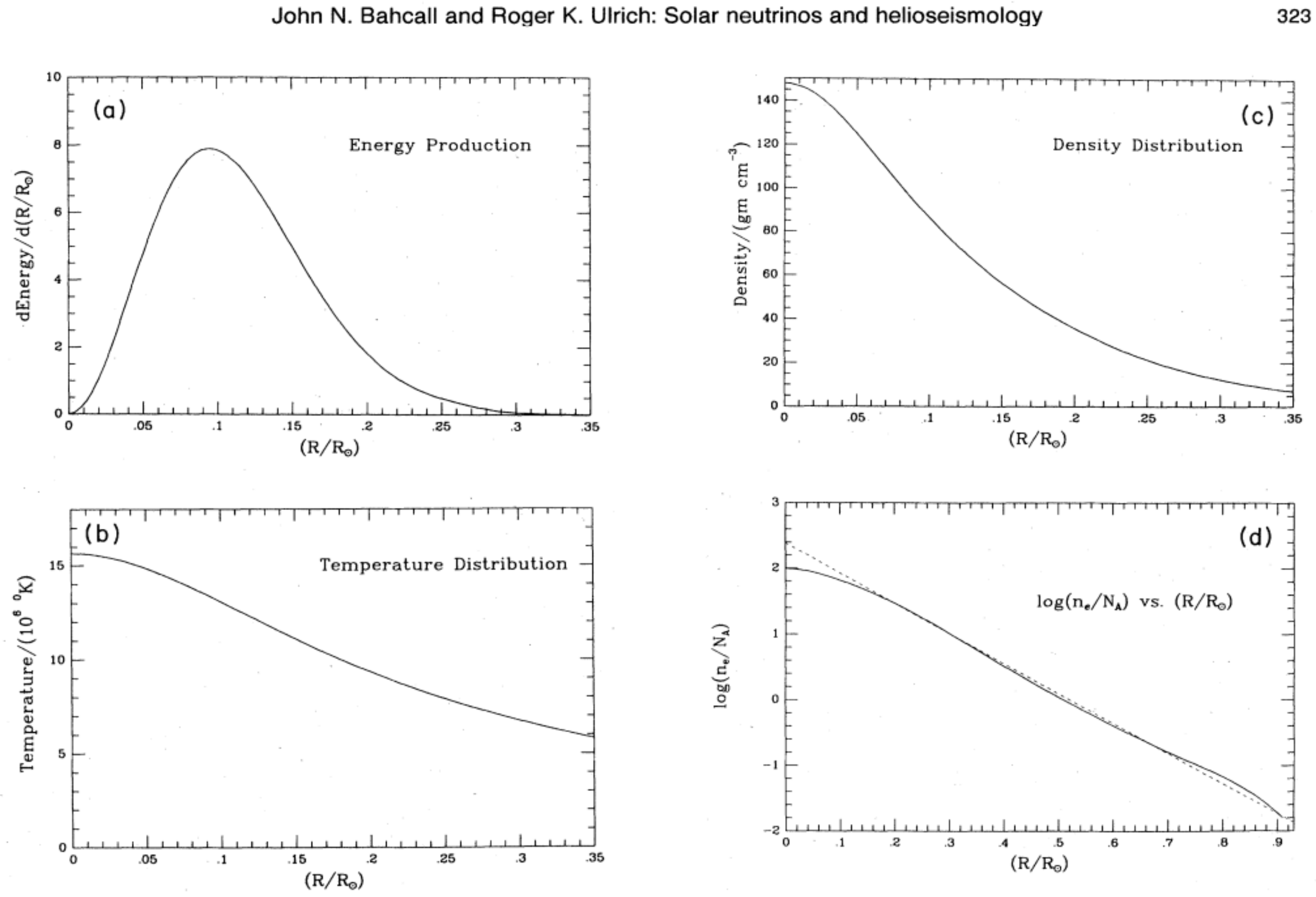
The Standard Solar Model

- Pressure - Gravity equilibrium $\left(\frac{dP}{dr}\right)$
  - Hydrostatic equilibrium
- Energy transport $\left(\frac{dT}{dr}\right)$
  - radiative + Conductive
- Energy generation $\left(\frac{dL}{dr}\right)$



The Standard Solar Model

- Pressure - Gravity equilibrium $\left(\frac{dP}{dr}\right)$
  - Hydrostatic equilibrium
- Energy transport $\left(\frac{dT}{dr}\right)$
  - radiative + Conductive
- Energy generation $\left(\frac{dL}{dr}\right)$
- Plus boundary conditions (the Sun)



Equations of Stellar Structure

At radius *r* in a static, spherically symmetric star and the density ϱ:

$$\frac{dm}{dr} = 4\pi r^2 \rho$$ **Mass conservation**

$$\frac{dP}{dr} = -\frac{Gm}{r^2}\rho$$ **Hydrostatic equilibrium**

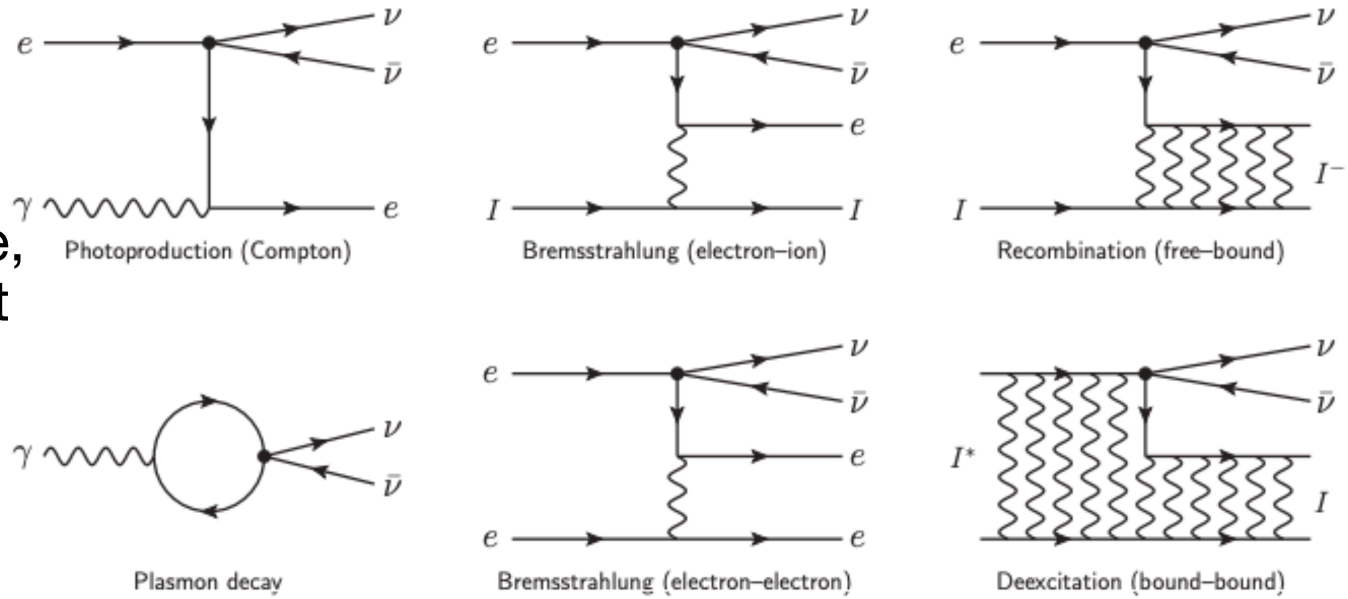
$$\frac{dT}{dr} = -\frac{3}{4ac}\frac{\kappa\rho}{T^3}\frac{L}{4\pi r^2}$$ **Energy transport due to radiation (only)**

$$\frac{dL}{dr} = 4\pi r^2 \rho q$$ **Energy generation**

4 equations with 4 unknowns - enough for a solution once we know P(ϱ ,T), opacity κ, and *q*

Solar thermal neutrinos

- The interior of the Sun is a plasma
- photons and charged particles are tightly coupled.
- With high enough scattering rate, rare process becomes important
- Can be computed with the Temperature profile of the Sun

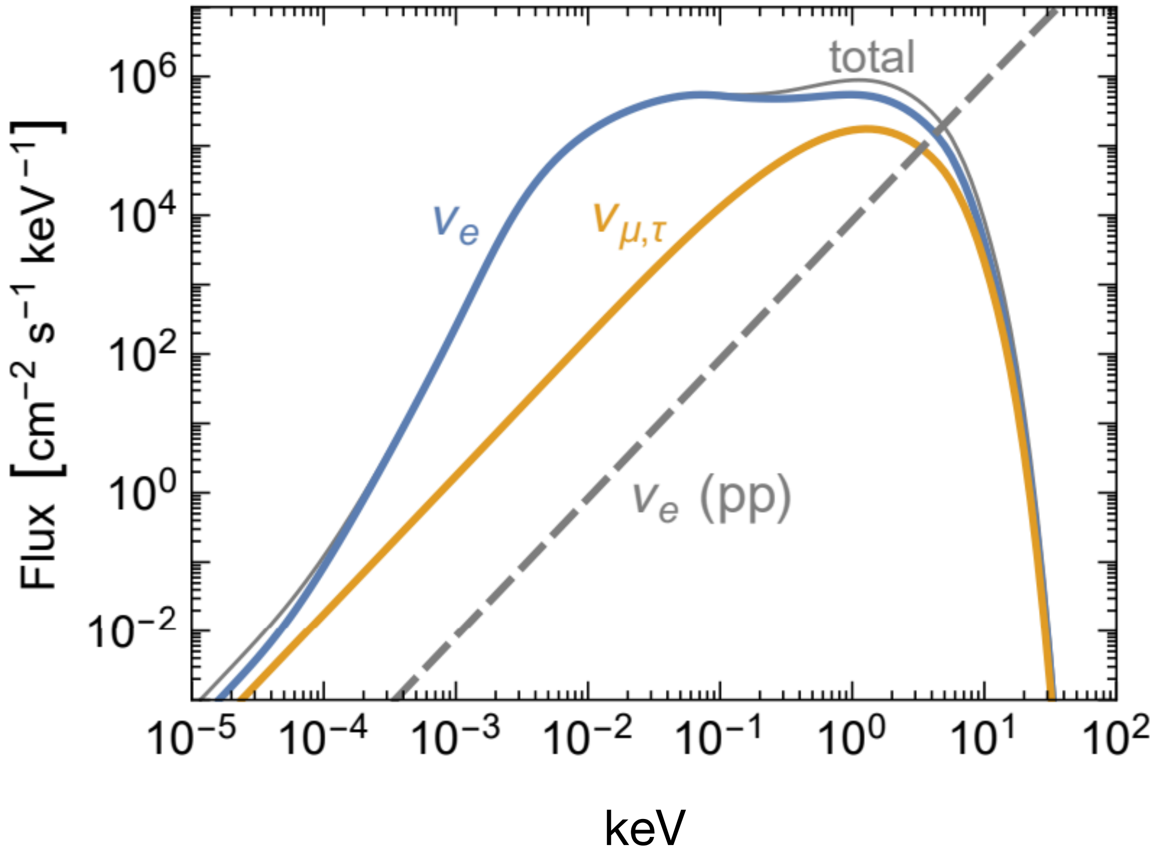


Solar thermal neutrinos

- Has not been detected.

- Difficult (energy is low)
- flux is small

- Can $C\nu B$ experiments like Ptolemy detect this?
  - let me know!



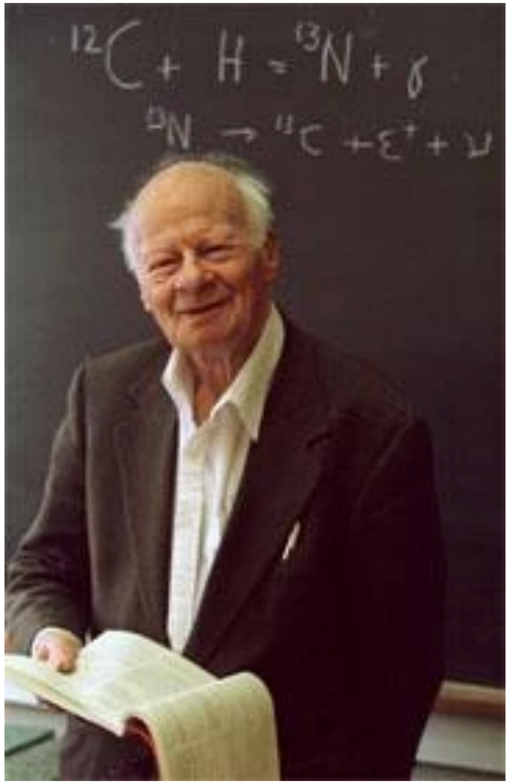
Solar neutrinos (nuclear)

- Energy source of Stars
  - Gravity is not enough
  - Chemical energy is not enough
  - **Nuclear energy!**

Hans Bethe

1967 Nobel

1/1

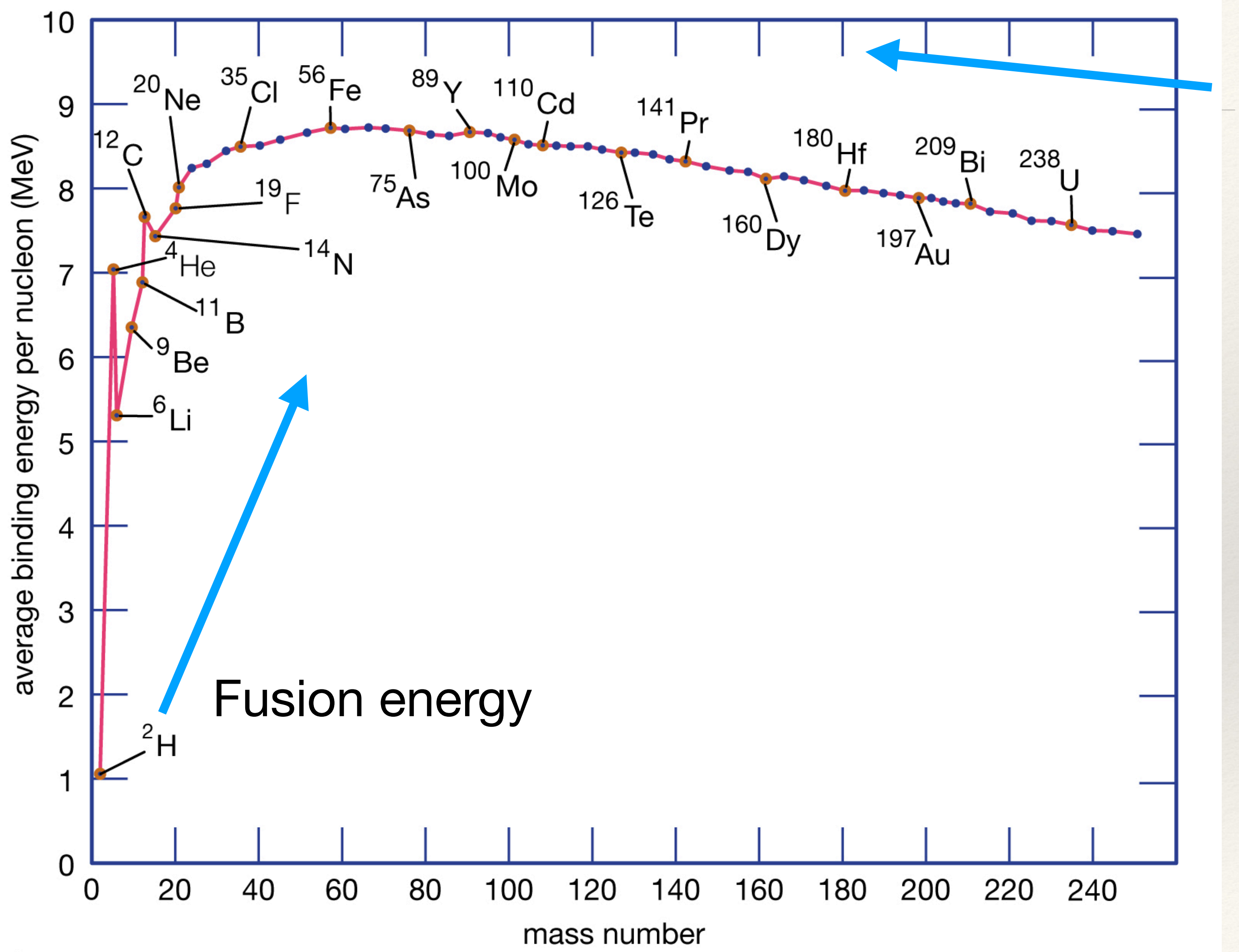


The Nobel Prize in Physics 1967 was awarded to Hans Albrecht Bethe "for his contributions to the theory of nuclear reactions, especially his discoveries concerning the energy production in stars"

Binding energy

- $m(A,Z) = Zm_p + (A - Z)m_n - B$
- Deuterium
  - $B(2,1) = 2.2$ MeV
- Helium-4
  - $B(4,2) = 28.3$ MeV

Fission energy



Fusion

- Energy released in Fusion

- E.g.

- $4p + 2e^- \rightarrow^4 \mathrm{He} + 2\nu_e + Q$

- $Q = 4m_p + 2m_e - m_{\mathrm{He}}$

- $Q = B(4,2) + 2m_e - m_{\mathrm{He}} - 2(m_n - m_p)$

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

Fusion

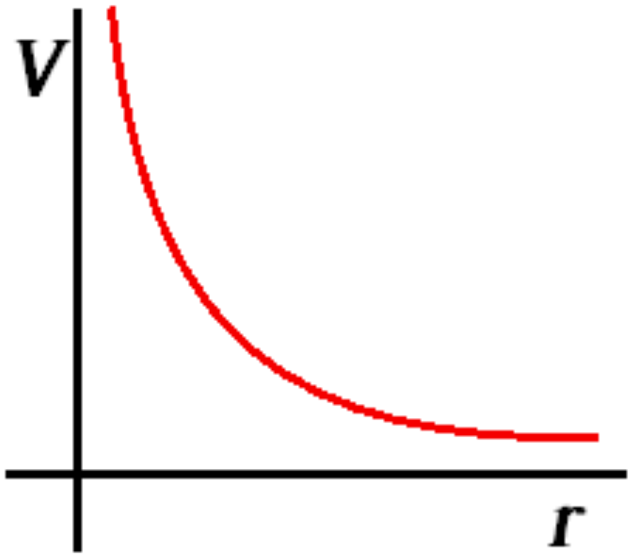
- Rate of fusion reaction $A + B$

- $R_{A+B} = \dfrac{N_A N_B}{1 + \delta_{AB}} \langle \sigma v \rangle$, where δ is the Kronecker delta function

- Need to overcome the Coulomb potential

- $U = \dfrac{Z_1 Z_2 e^2}{r}$

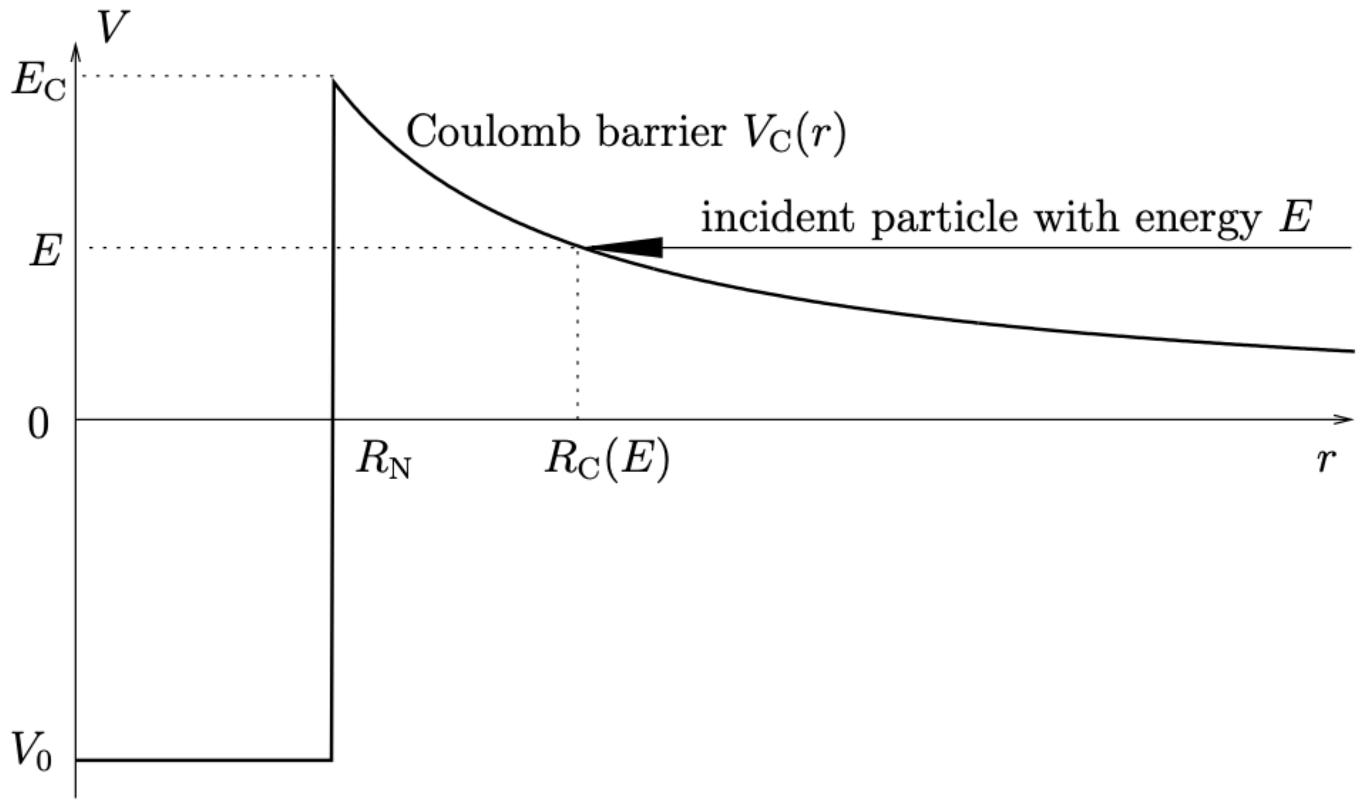
- $U(1\ \mathrm{fm}) \sim 10^6\,\mathrm{eV} \sim 10^{10}\,\mathrm{K}$



- However, from hydrostatic equilibrium, given the mass and radius you can estimate the core temperature of the Sun is about $10^7\,\mathrm{K}$

Overcoming the Coulomb Barrier

- To overcome 1fm



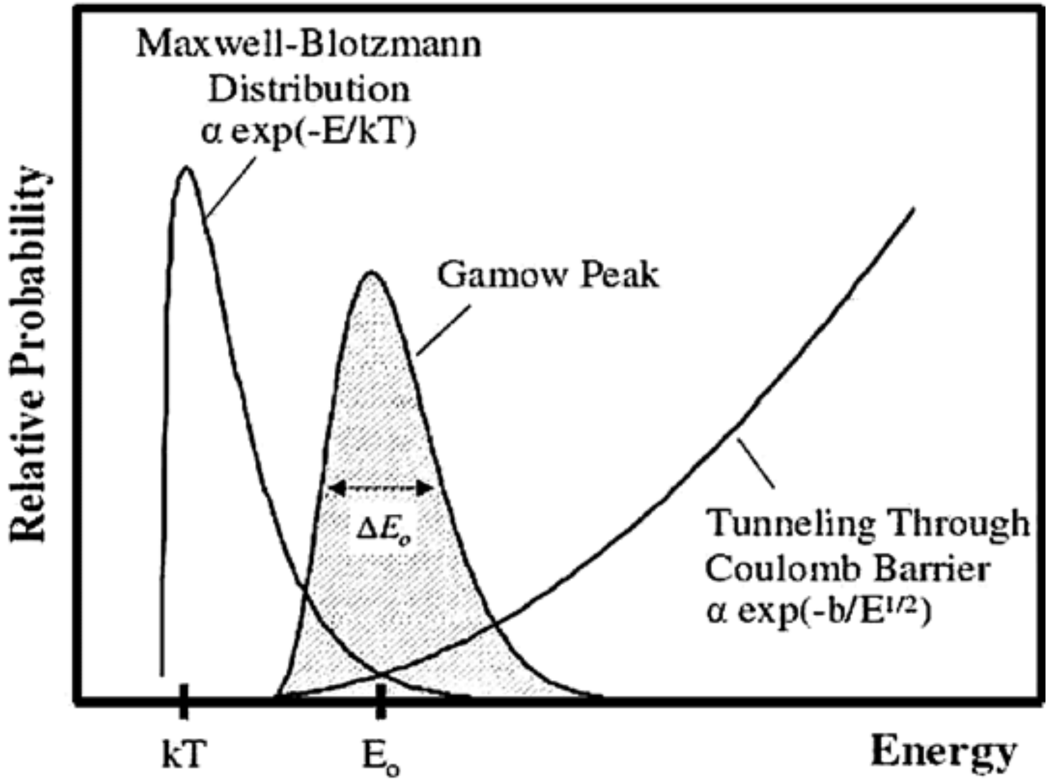
Fusion probability

- Reaction rate $\propto N^2 P_t$

- $N \propto e^{-\frac{E}{T}}$
  - from Maxwell-Boltzmann
- $P_t \propto e^{-\frac{b}{\sqrt{E}}}$
  - Tunneling probability

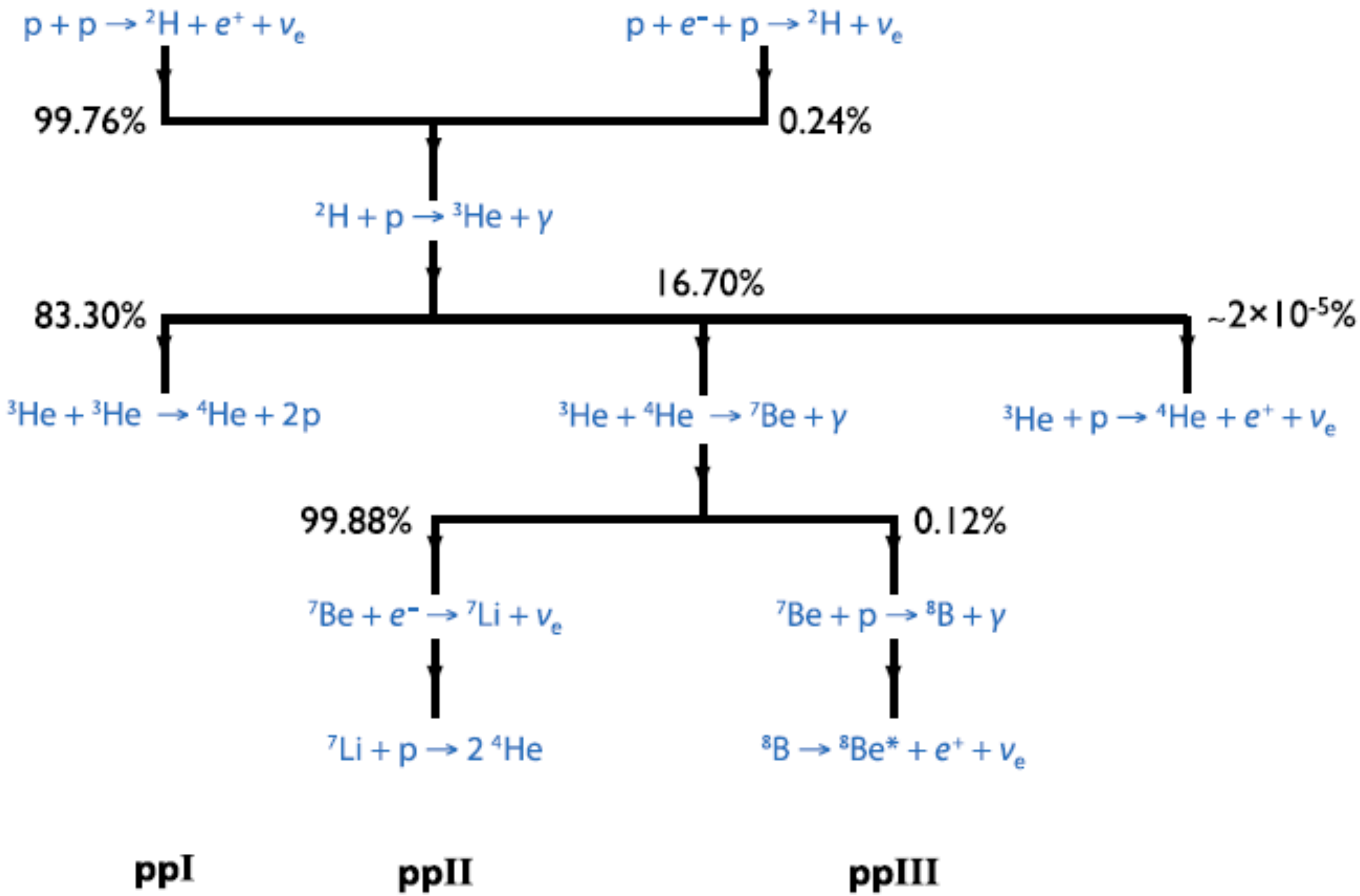
- Due to the exponential, the rates changes rapidly with temperature

- ~ lifetime of the star inversely related to Mass



Nuclear reactions

- PP chain
- Neutrinos
- pp
- pep
- Be
- B



Nuclear reactions

- CNO cycle

$$^{12}_{6}C \rightarrow ^{13}_{7}N \rightarrow ^{13}_{6}C \rightarrow ^{14}_{7}N \rightarrow ^{15}_{8}O \rightarrow ^{15}_{7}N \rightarrow ^{12}_{6}C$$

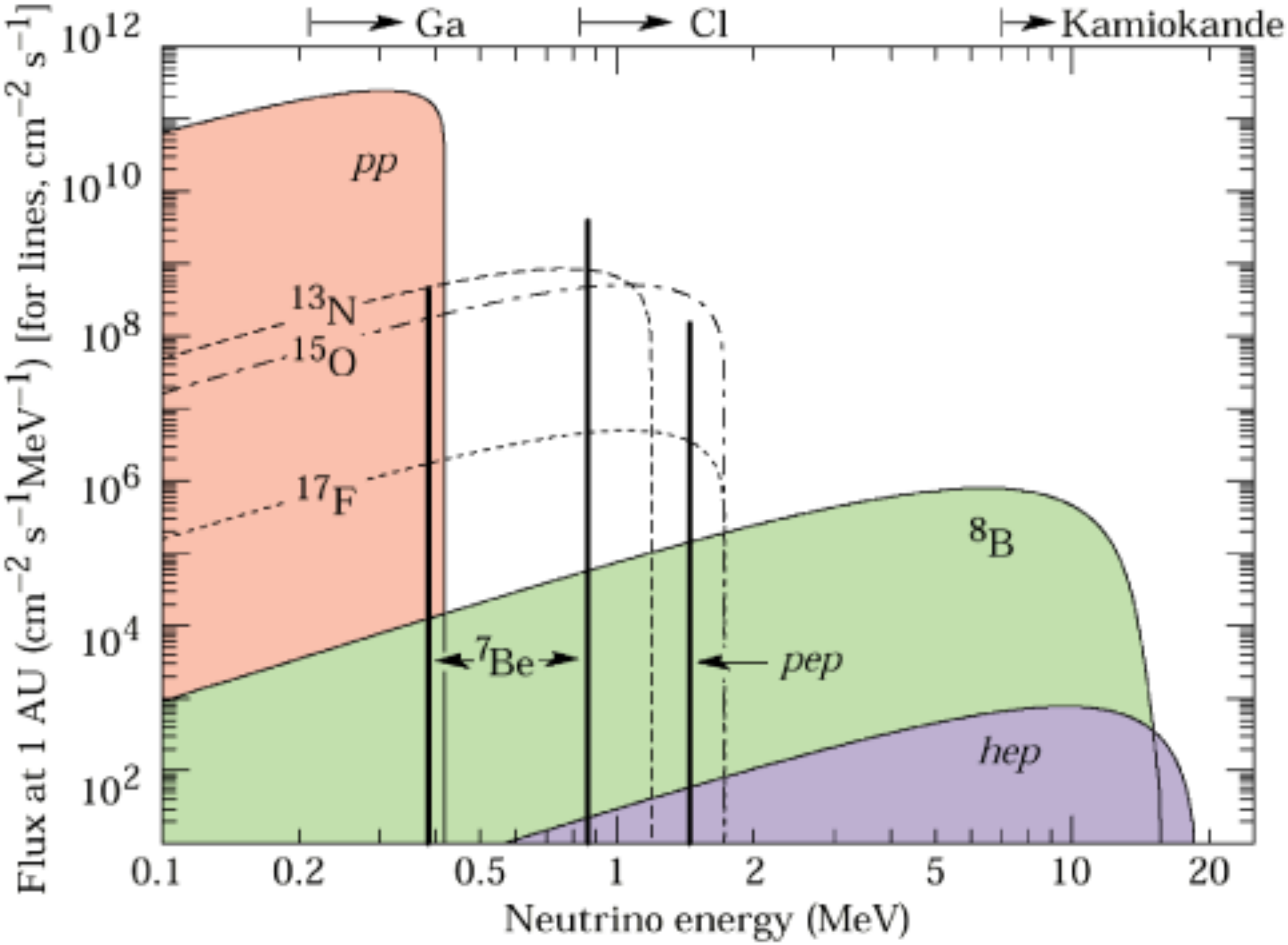
$^{12}_{6}C + ^{1}_{1}H \rightarrow ^{13}_{7}N + \gamma$		$+ 1.95$ MeV
$^{13}_{7}N \rightarrow ^{13}_{6}C + e^{+}$	$+ \nu_e$	$+ 1.20$ MeV (half-life of 9.965 minutes[14])
$^{13}_{6}C + ^{1}_{1}H \rightarrow ^{14}_{7}N + \gamma$		$+ 7.54$ MeV
$^{14}_{7}N + ^{1}_{1}H \rightarrow ^{15}_{8}O + \gamma$		$+ 7.35$ MeV
$^{15}_{8}O \rightarrow ^{15}_{7}N + e^{+}$	$+ \nu_e$	$+ 1.73$ MeV (half-life of 2.034 minutes[14])
$^{15}_{7}N + ^{1}_{1}H \rightarrow ^{12}_{6}C + ^{4}_{2}He$		$+ 4.96$ MeV

- Triple alpha process

$$^{4}_{2}He + ^{4}_{2}He \rightarrow ^{8}_{4}Be$$

$$^{8}_{4}Be + ^{4}_{2}He \rightarrow ^{12}_{6}C + 2\gamma$$

Solar neutrino spectrum

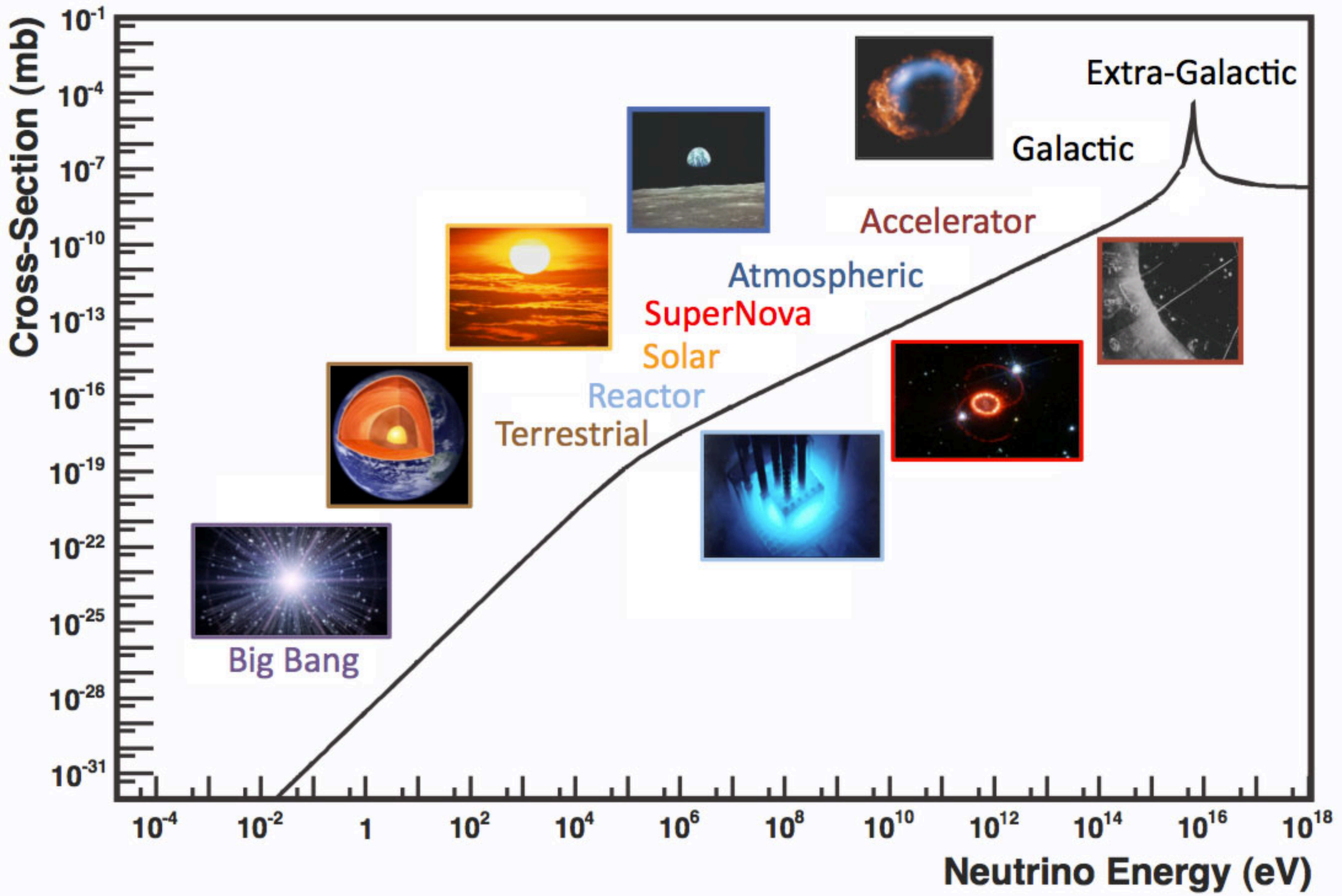


How to detect neutrinos?

- We need to know neutrino interactions

Some general ideas first.

Neutrino cross sections

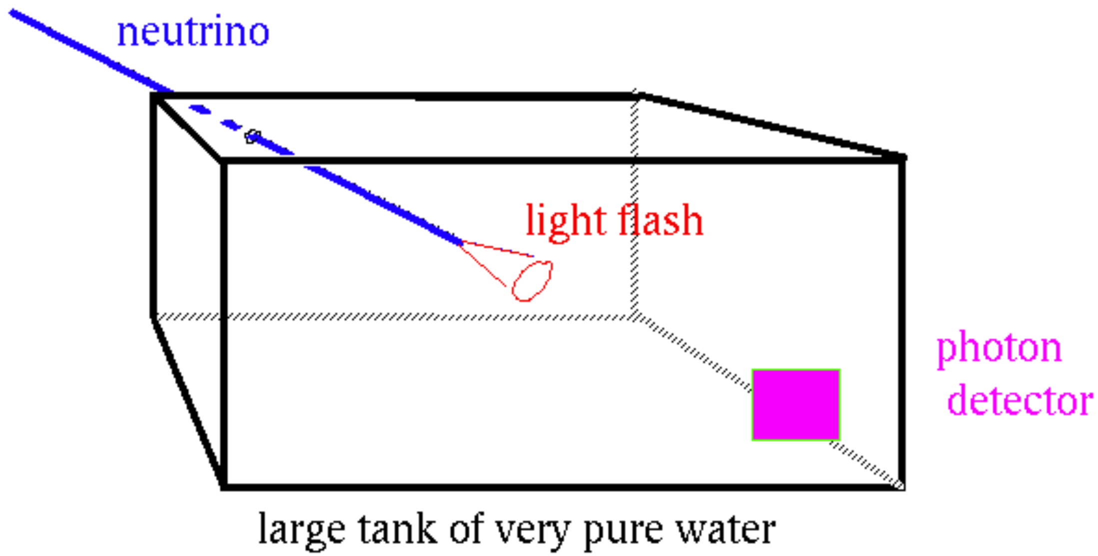


Simple game of numbers

- Number of interactions
- Probability of interaction = target density x cross section x crossing length
  - $P = n_t \sigma L$

What is the hidden assumption in this page?

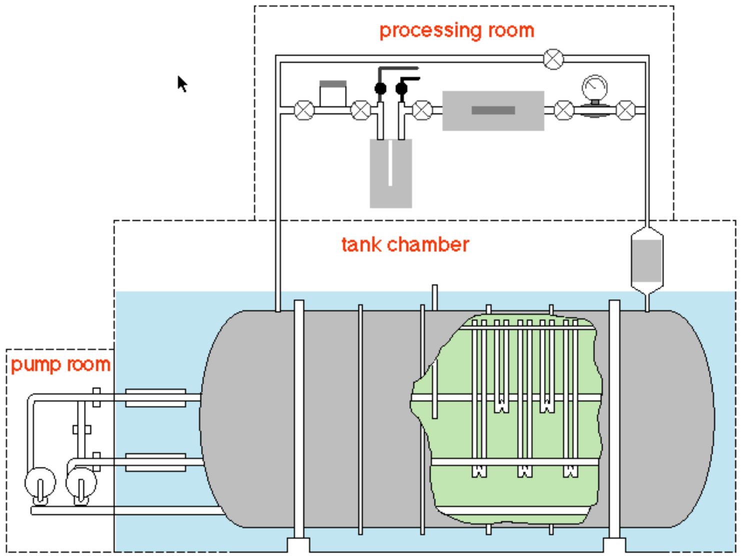
- number of interactions in the detector
- Flux X cross section area x P x running time
  - $N = F \times A \times P \times T$
  - $N = F \times V n_t \times \sigma \times T$



1967 Homestake experiment

- 600 tons of C_2Cl_4 (cleaning fluids)

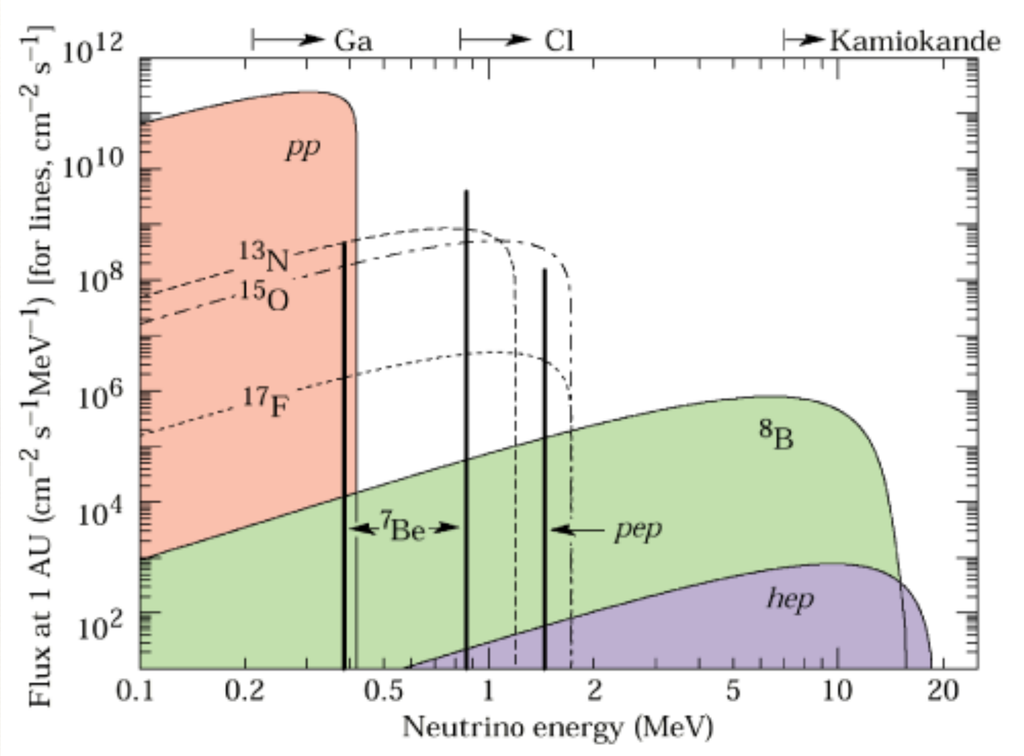
- $\nu + ^{37}_{17}\mathrm{Cl} \rightarrow ^{37}_{18}\mathrm{Ar} + e^-$, argon-37 radioactive in 35 days



Neutrino detection
Simple game of numbers

Given cross section between neutrino and Cl atom $\sigma \sim 10^{-42}$ cm^2

- $N = F \times V n_t \times \sigma \times T$
- Flux at 10 MeV
- $\frac{dF}{dE} dE \simeq 10^6 \times 10$ /cm2/s
- 1month ~ 3×10^6 s
- $\sigma \sim 10^{-42}$ cm2
- You need around 3×10^{29} Cl atoms to see 10 events per month
- mass ~ $3 \times 10^{29} \times 37 \times \frac{1}{6 \times 10^{23}} g$ ~ 20 ton



1967 Homestake experiment

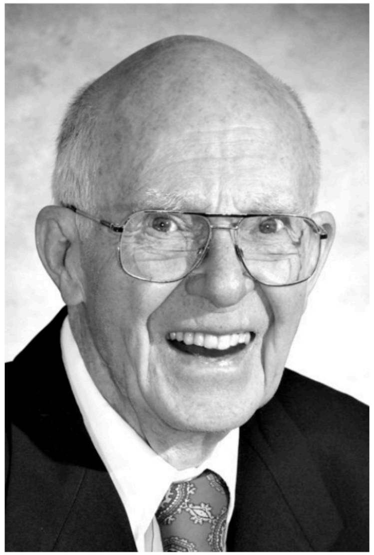


Photo from the Nobel Foundation archive.

Raymond Davis Jr.

Prize share: 1/4

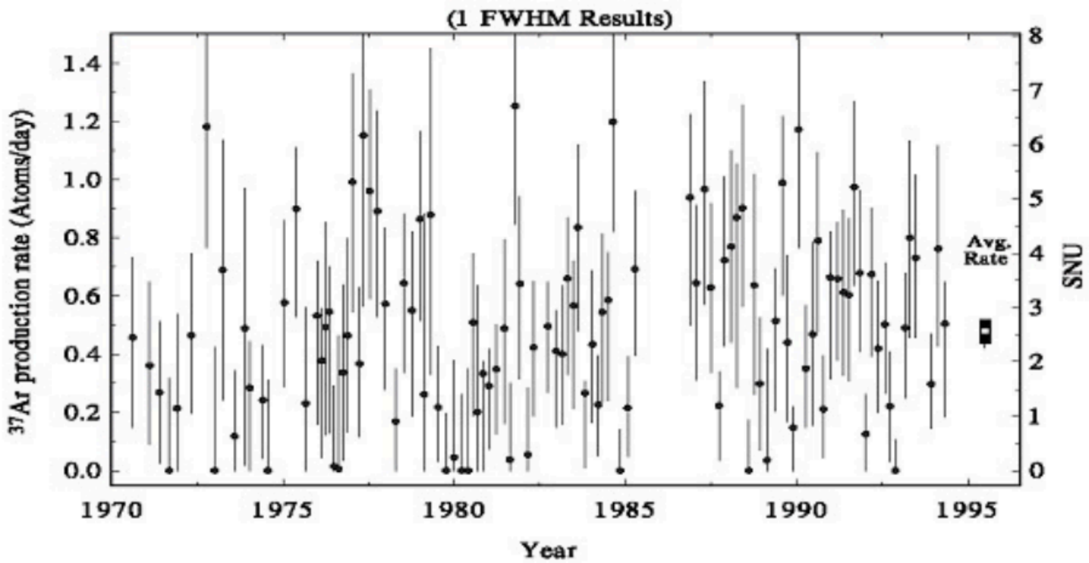


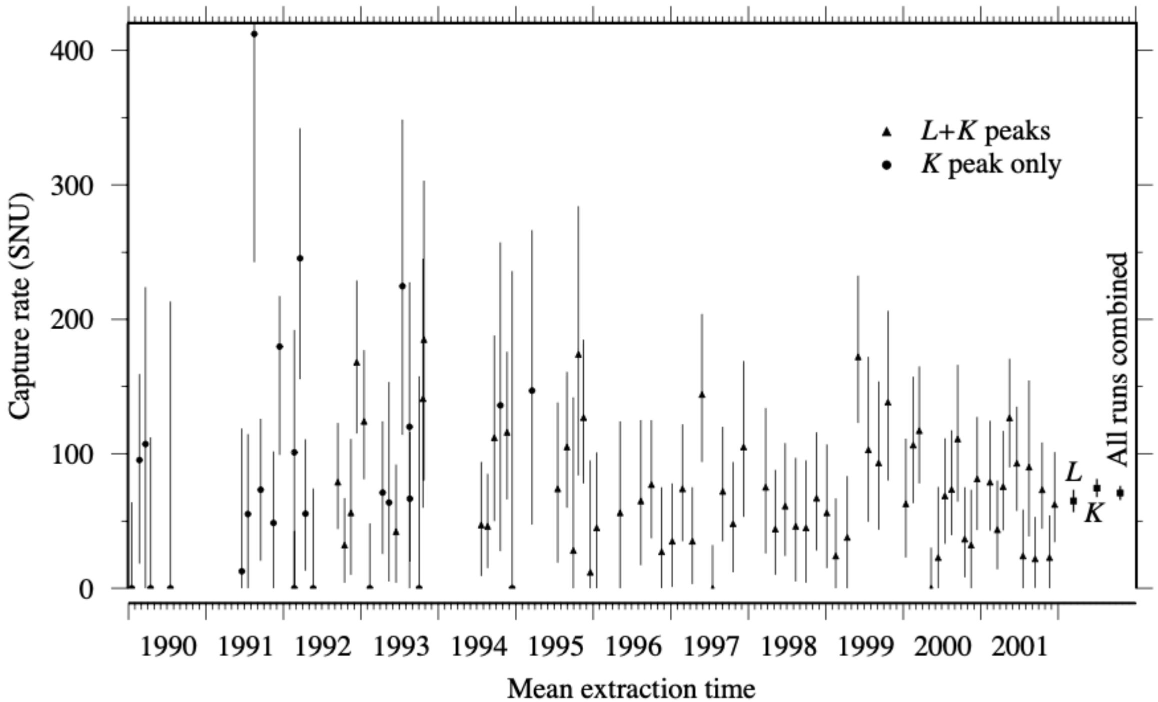
Fig. 2 Final results of Davis experiment (Cleveland et al. 1998). The average rate of about 2.5 SNU is much lower than the calculated rate of about 8.6.

The Nobel Prize in Physics 2002

- 1SNU = 10^{-36} interactions/atom/s

SAGE and GALLEX/GNO

- The Soviet–American Gallium Experiment (SAGE)
- The Gallium experiment (GALLEX/GNO)
- $\nu_e +^{71} Ga \rightarrow^{71} Ge + e^-$

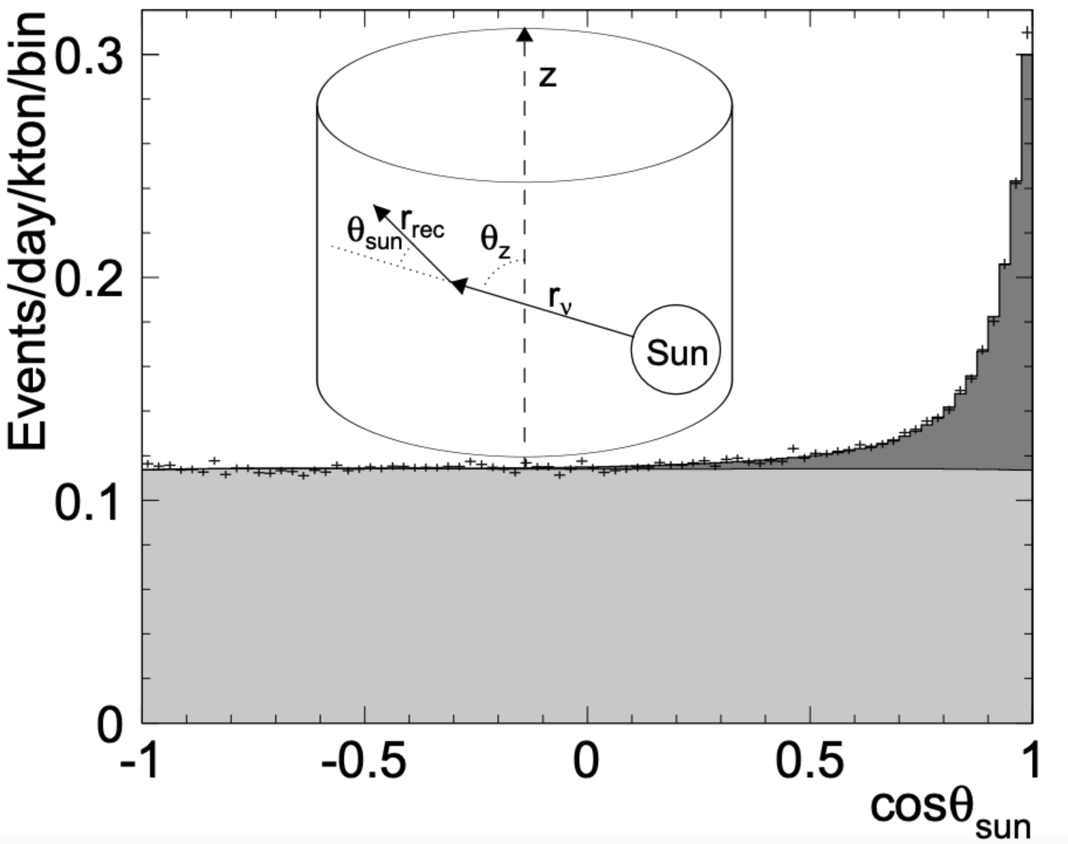


- SAGE

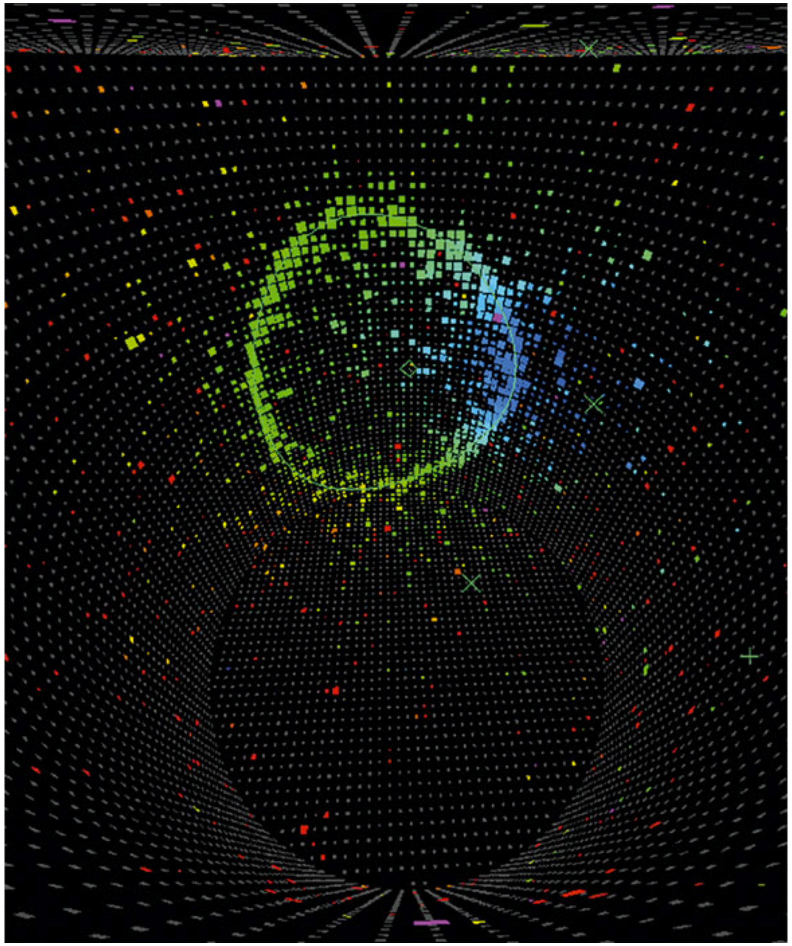
Kamiokande and Super-Kamiokande

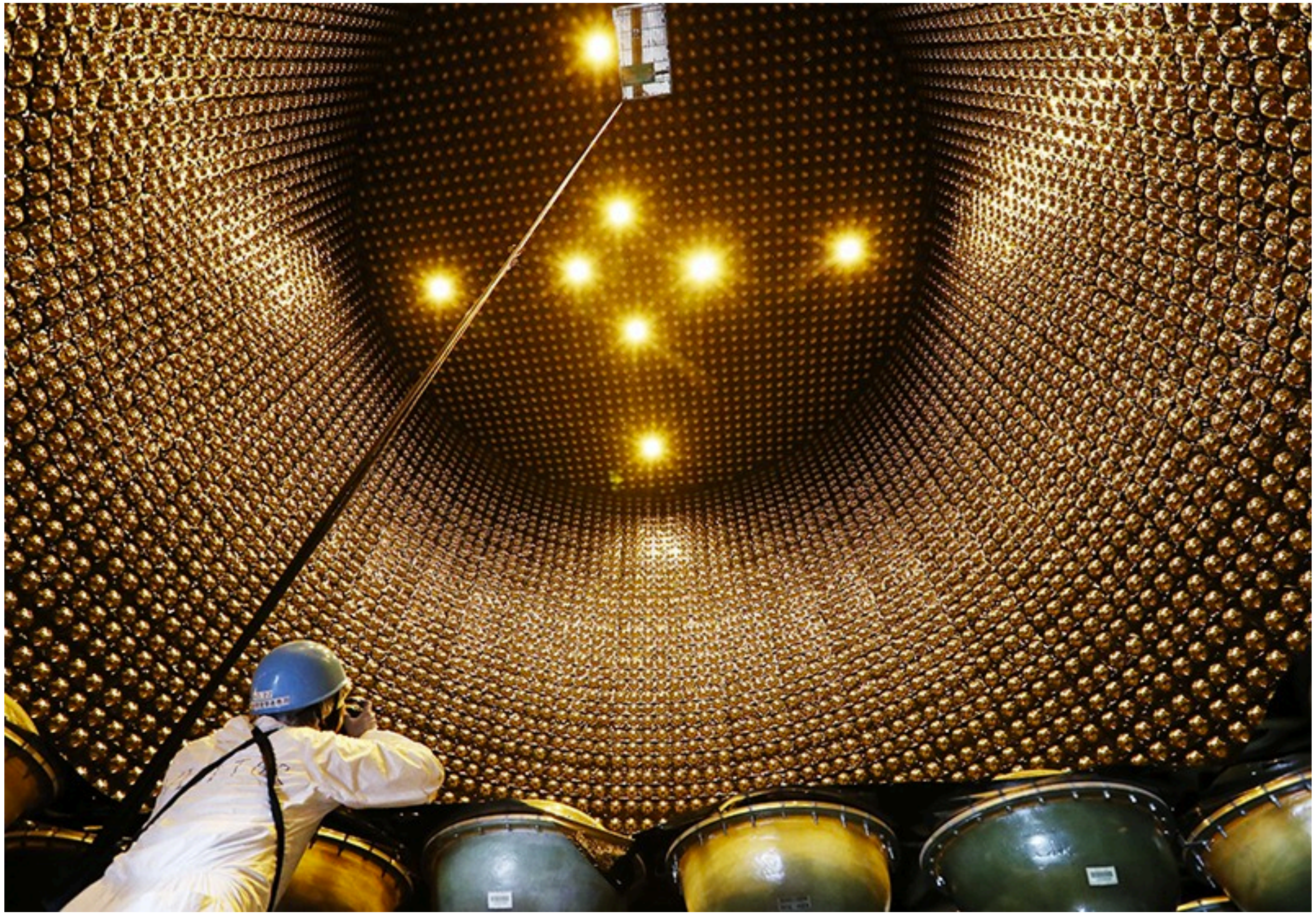
- Water Cherenkov detector
- neutrino electron scattering
- Real time event reconstruction

- Reaction has no threshold.
- But detector has,
  - Cherenkov light $\propto E_e$



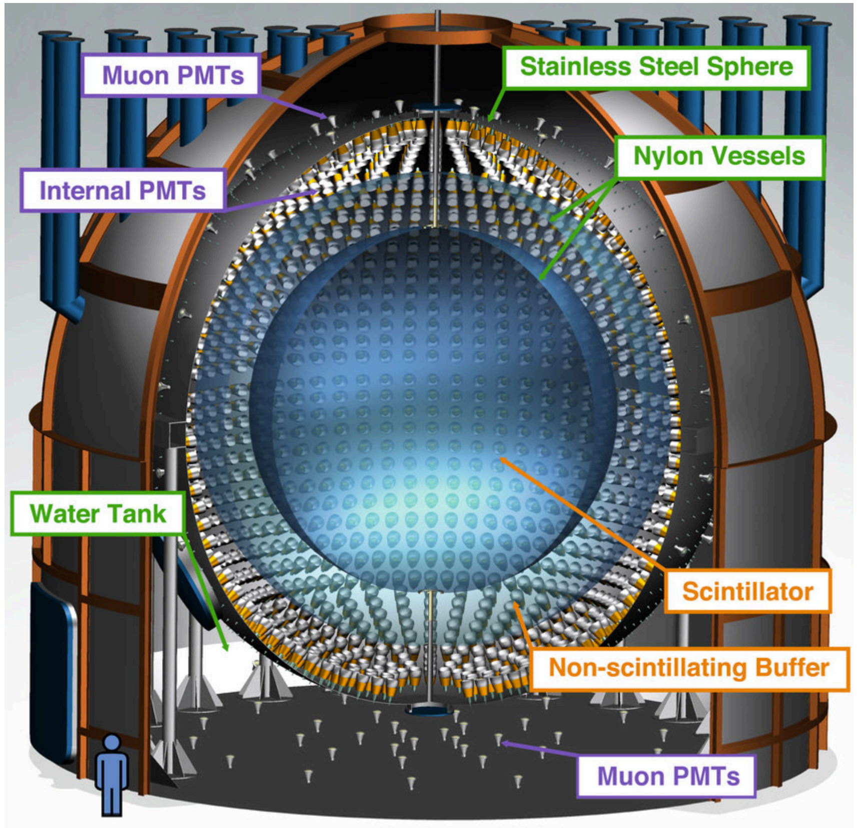
Kamiokande and Super-Kamiokande





Borexino

- First detection of CNO neutrino!
- Nov 2020



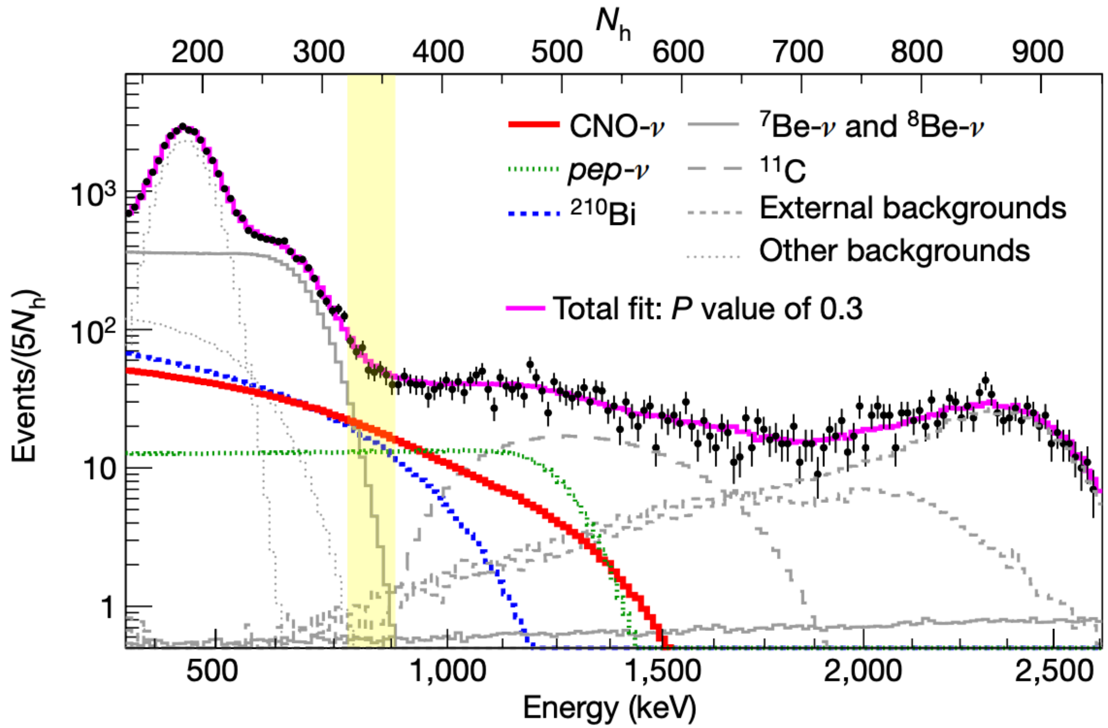


Fig. 2 | Spectral fit of the Borexino data. Distribution of the electron recoil energy scattered by solar neutrinos in the Borexino detector (black points) and corresponding spectral fit (magenta). CNO-neutrinos, ^{210}Bi and *pep*-neutrinos are highlighted in solid red, dashed blue and dotted green, respectively, and all other components are in grey. The energy estimator N_h represents the number of photoelectrons detected by photomultipliers, normalized to 2,000 live channels. The yellow band represents the region with the largest signal-to-background ratio for CNO-neutrinos.

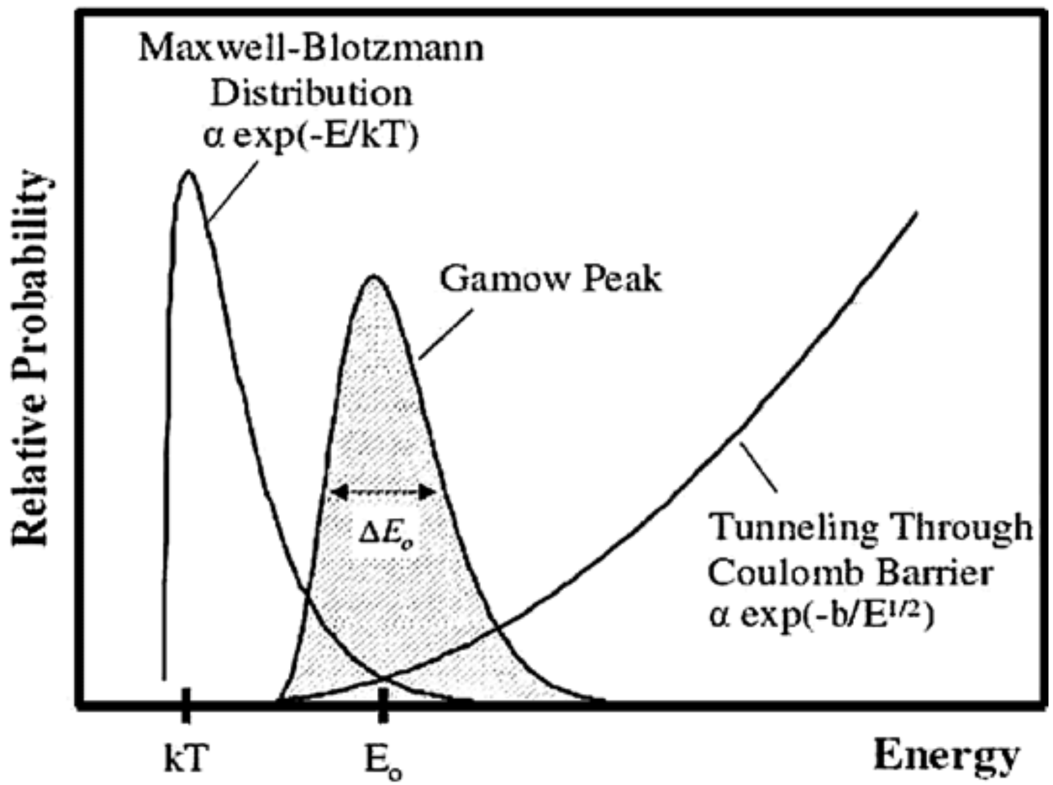
https://www.nature.com/articles/s41586-020-2934-0.pdf

Solar neutrino as precision probe of solar condition

- The flux of solar neutrinos depends sensitively on the core temperature

$$\boxed{\Phi_B \sim T_c^{\ 20}}$$

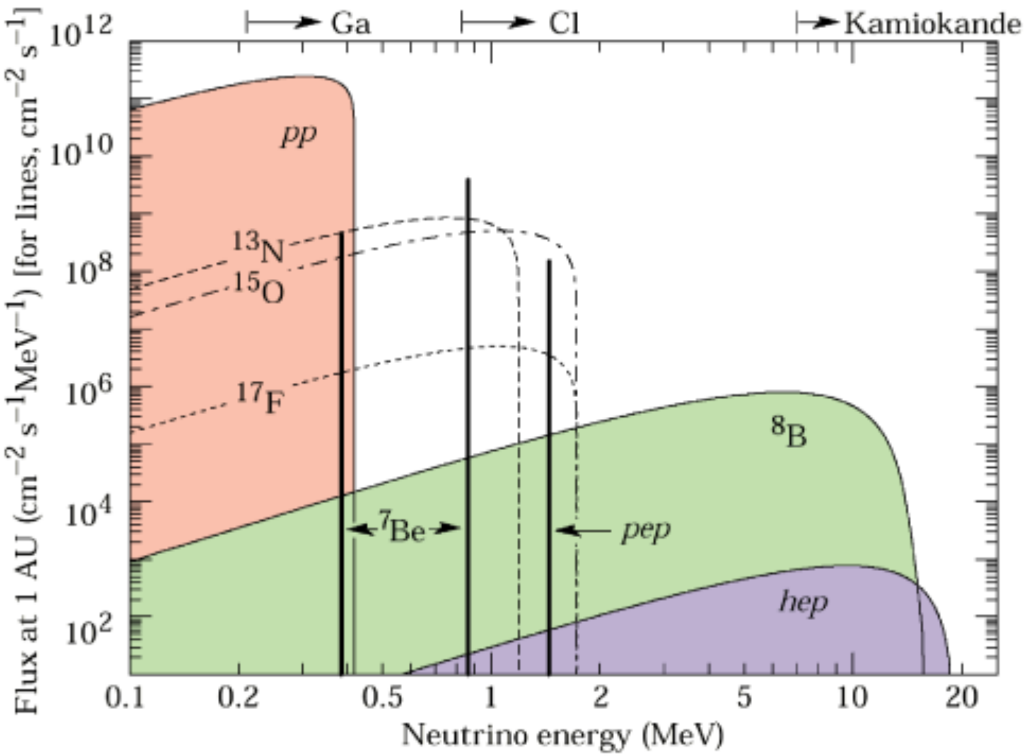
$$\boxed{\Phi_{Be} \sim T_c^{\ 10}}$$

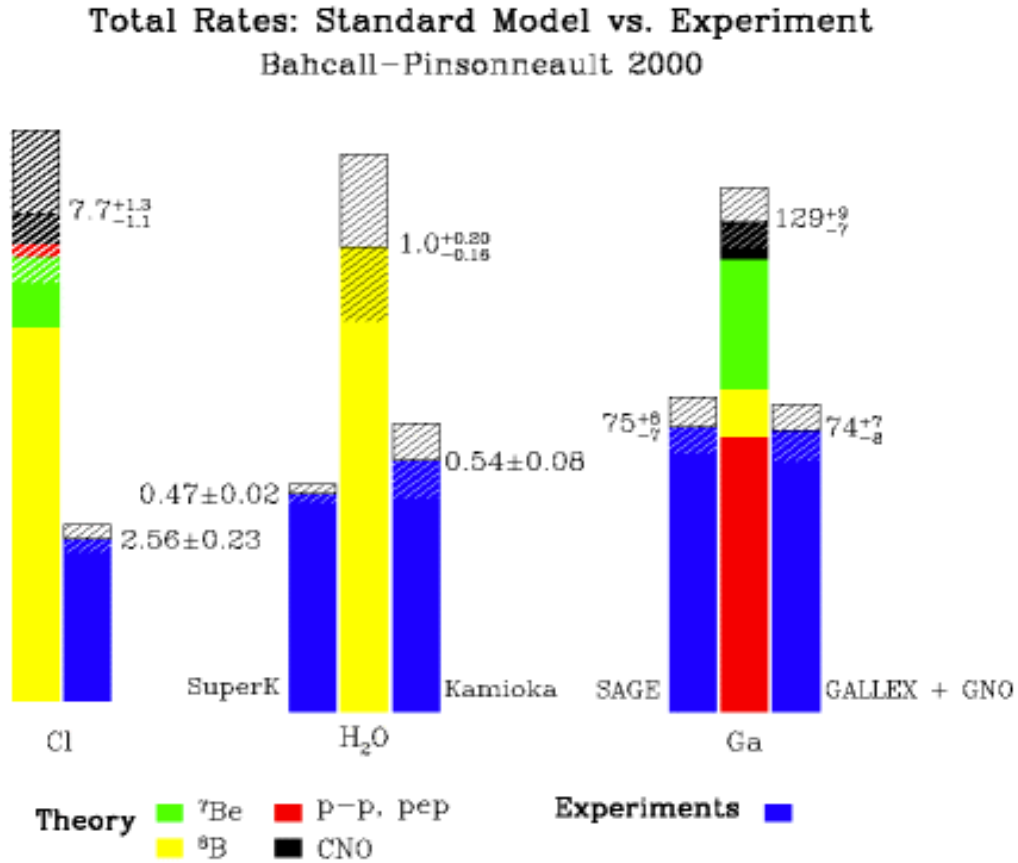


https://www.nature.com/articles/s41586-020-2934-0.pdf

The solar neutrino problem

- Different experiment saw different amount of deficits.





NEUTRINO MOMENTS, MASSES AND CUSTODIAL SU(2) SYMMETRY *

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Lyman Laboratory of Physics, Harvard University, Cambridge, MA 02138, USA

Received 17 April 1990

We identify and exemplify a new mechanism which leads to a nonzero magnetic moment for a neutrino, while suppressing the neutrino's mass. The mechanism requires that the contribution to the neutrino mass of the new particles that are responsible for its magnetic moment is approximately canceled by a contribution from neutral particles, related by a custodial SU(2) symmetry.

1. The problem

Most likely, the solar neutrino problem [1] has nothing whatever to do with particle physics. It is a great triumph that astrophysicists are able to predict the number of B^8 neutrinos coming from the sun as well as they do, to within a factor of 2 or 3 [2]. However, one aspect of the solar neutrino data, the apparent

Career [edit]

In early 1974 Georgi (with Sheldon Glashow) published the first grand unified theory (GUT), the Minimal SU(5) Georgi–Glashow model.[3] Georgi independently (alongside Harald Fritzsch and Peter Minkowski) published a minimal SO(10) GUT model in 1974.[4]

	Unparticle physics Trinification
Awards	Sakurai Prize (1995) Dirac Medal (2000) Pomeranchuk Prize (2006)
	Scientific career
Fields	theoretical physics
Institutions	Harvard University