The origin of hydrogen and helium?

Anders & Grevesse 1989
• Universe is about $14 \cdot 10^9$ years old
  → pp-chain too slow to produce enough helium
• massive stars burn beyond He
• stars must have been born with H and He!

Big bang nucleosynthesis
• The Universe was in an extremely dense and hot state

• rapid expansion

  → cooler

• continues to expand today
Evidence for the Big Bang

1) 2.7 K black body radiation
   = cosmic microwave background
   = “cooled” original electromagnetic radiation from the Big Bang

2) Expanding Universe

3) Abundances of H and He
1) Cosmic microwave background

Arno Penzias & Robert Wilson 1964

- attempted to contact a satellite with a radio receiver
- "background noise" when the wavelength was 7.35 cm
- noise = real signal
- uniformly from all directions and at all times

Figure 19.3  The wavelength spectrum of the cosmic microwave background radiation. The dots are data points and the solid curve is a blackbody spectrum for $T = 2.7$ K.
WMAP
(Wilkinson Microwave Anisotropy Probe)

- project of NASA and Princeton University
- measures cosmic microwave anisotropies
- launched June 2001
- new Planck satellite (ESA) 14.5.2009
2) Expanding Universe

Redshift in the absorption line spectra from distant galaxies (compare Doppler shift!)

- Redshift $\rightarrow$ velocity $v$ of recession of the galaxies relative to Earth
- Distances $d$ already known from independent observations
- Linear relationship: $v = Hd$
Hubble parameter $H$

$$v = H d$$

$H = 67 \text{ (km/s)/Mpc}$

1 Mpc
= 1 megaparsec
= $3.26 \times 10^6$ lightyears

*Figure 19.1* Velocity-distance relationship for groups and clusters of galaxies. The straight line demonstrates the Hubble relationship. From M. Rowan-Robinson, *The Cosmological Distance Ladder* (New York: Freeman, 1985).

*Space is big. Really big. You won't believe how hugely mindboggling big it really is.*
Particle and nuclear interactions in the early Universe

At time $t=0$:
- Enormous temperature and pressure
- Hot “quarksoup”
- No protons nor neutrons
- Expansion $\rightarrow$ cooling and lower pressure

$t \approx 10^{-12} \text{ s}, \ T = 10^{16} \text{ K}$
$\rightarrow$ all known particles can be readily created

$t < 10^{-6} \text{ s}, \ T > 10^{13} \text{ K}$:
- Photons $\leftrightarrow$ $p + \bar{p}, \ n + \bar{n}$
t > 10^{-6} \text{ s} (T < 10^{13} \text{ K}): 

- Photons do not have enough energy to create nucleon-antinucleon pairs $\rightarrow$ annihilation
- Charge-Parity (CP) violation: small imbalance of matter over antimatter, FORTUNATELY!
  - an abundance of leptons and neutrinos
  - Weak interaction can occur:
    \[ p + \bar{\nu}_e \leftrightarrow n + e^+ \]
    \[ n + \nu_e \leftrightarrow p + e^- \]
  - $N_p \approx N_n$
**t = 0.01-1 s**

**t=0.01 s (T=10^{11} K, E=10 MeV):**
- \( m_p < m_n \) \( \rightarrow \) proton more stable \( \rightarrow \) \( N_p > N_n \)

\[
\frac{N_n}{N_p} = \exp\left(-\frac{\Delta E}{kT}\right)
\]

where \( \Delta E = (m_n - m_p)c^2 = 1.29 \text{ MeV} \)

**t~1 s:**
- \( p^+\bar{\nu}_e, n^+\nu_e \) neutrino interactions are no longer important \( \rightarrow \) neutrino decoupling
- e\(^+\)e\(^-\) production ends
- e\(^+\) annihilates \( \rightarrow \) excess of electrons
t = 3-225 s

\( t \approx 3 \text{ s} \) (\( T=10^{10} \text{ K}, \ kT \approx 1 \text{ MeV} \)):
- \( N_n/N_p \approx 1/5 \)
- Temperature still too high for fusion reactions:
  - Number of photons/number of nucleons \( \approx 10^9 \)
  - Photons have a black body spectrum
    \[ n + p \leftrightarrow d + \gamma \]
    \( Q = 2.22 \text{ MeV} \)

\( t = 225 \text{ s} \) (\( T \approx 9 \times 10^8 \text{ K} \)):
- \( N_n/N_p \approx 1/7 \)
- Neutrons decay: \( n \rightarrow p + e^- + \overline{\nu}_e \) (\( t_{1/2} = 10.24 \text{ min} \))
3) Fusion reactions soon after the Big Bang

= primordial nucleosynthesis (225 s < t < 10^6 years)

\( T < 9 \times 10^8 \text{ K} \):

- Cold enough so that \( n \) and \( p \) exist
  \[ n + p \rightarrow d + \gamma \quad Q = 2.22 \text{ MeV} \]

- Note! \( d = ^2\text{H} = \text{deuteron (nucleus)} \)
  \( D = \text{deuterium (atom)} \)
  \( t = ^3\text{H} = \text{triton (nucleus)} \)
  \( T = \text{tritium (atom)} \)
Deuterium formation vs photodissociation

\[ n + p \rightarrow d + \gamma \quad \text{Q} = 2.22 \text{ MeV} \]

If \( E_{\gamma} > 2.22 \text{ MeV} \)

The reverse reaction

\[ d + \gamma \rightarrow n + p \]

is possible and the deuteron is destroyed

BUT: there are \( 10^9 \) times more photons than protons or neutrons!

Require: \( N_{\gamma} (E>2.22 \text{ MeV}) < N_n (N_n < N_p) \)

\[ E_0 = 2.22 \text{ MeV} \]
\[ T=9 \times 10^8 \text{ K} \]
\[ kT= 77.56 \text{ keV} \]
\[ E_0/kT\sim28 \]

**Figure 19.4** The number of blackbody photons at energy \( E \) for a temperature \( T = 9 \times 10^8 \text{ K} \).

**Figure 19.5** The fraction \( f \) of photons of energies above \( E_0 \).
Further reactions

- Enough energy to overcome Coulomb barrier:
  
  \[ d + p \rightarrow ^3\text{He} + \gamma \quad Q = 5.49 \text{ MeV} \]
  \[ d + n \rightarrow t + \gamma \quad Q = 6.26 \text{ MeV} \]
  
  or
  
  \[ d + d \rightarrow t + p \quad \text{(unlikely)} \]
  \[ d + d \rightarrow ^3\text{He} + n \quad \text{(unlikely)} \]

- both t and $^3\text{He}$ are more bound than deuteron

  \[ p + t \rightarrow \alpha + \gamma \quad Q = 19.81 \text{ MeV} \]
  \[ n + ^3\text{He} \rightarrow \alpha + \gamma \quad Q = 20.58 \text{ MeV} \]

- $\alpha$ (= $^4\text{He}$) is the most bound of the products \( \rightarrow \) the main product

- no stable isotopes at \( A=5 \) and \( A=8 \)

- Small production of $^7\text{Li}$ and $^7\text{Be}$ (Coulomb barrier inhibits):

  \[ \alpha + t \rightarrow ^7\text{Li} + \gamma \]
  \[ \alpha + ^3\text{He} \rightarrow ^7\text{Be} + \gamma \]

- Coulomb barrier is too high for heavier nuclei
End of the primordial nucleosynthesis

- Essentially all neutrons end as part of $^4\text{He}$ nuclei
- $N_n/N_p = 1/5$ at $t=3$ s
- Neutron decay from 3 s to 225 s $\rightarrow N_n/N_p = N(^4\text{He})/N(^1\text{H})$
  - Exercise: calculate the primordial $Y(^4\text{He})$

- Formation of nuclei ends after 30 min (at $T \sim 3 \times 10^8$ K)

- Observed abundances: 76 % $p$
  - 24 % $\alpha$
  - small amounts of $d$, $^3\text{He}$ ja $^7\text{Li}$

- $t \sim 10^6$ years ($T\sim 2000$K): electrons+nuclei $\rightarrow$ atoms
How do the stars form?

Gas pressure vs gravitation

Giant Molecular Clouds (H, He) in interstellar space "stellar nurseries"

Sphere of plasma

LH 95 stellar nursery in the Large Magellanic Cloud
Source: HubbleSite.
Life of a star

- Gravitational energy released in the collapse
- Individual atoms: potential energy $\rightarrow$ kinetic energy
  $\rightarrow$ kT increases
  $\rightarrow$ enough energy to overcome Coulomb barriers
  $\rightarrow$ exothermic thermonuclear reactions
  Note! B/A-curve: Q >0 until Fe
- Radiation pressure from the fusion halts the collapse
- Equilibrium stage: star radiates energy until it consumes the fuel
- Z of the fusion products increases
- higher Coulomb barriers, fusion reactions inhibited
- star collapses $\rightarrow$ kT increases etc
How does the Sun generate its energy?
Poets say science takes away from the beauty of the stars - mere globs of gas atoms. I, too, can see the stars on a desert night, and feel them. But do I see less or more?
Richard P. Feynman
Its all nuclear physics!

• 1905 Einstein finds $E=mc^2$
• 1920 Aston measures mass defect of helium (=! 4p’s)
• 1920 Nuclear Astrophysics is born with Sir Arthur Eddington remarks in his presidential address to the British Association for the Advancement of Science:

“Certain physical investigations in the past year make it probable to my mind that some portion of sub-atomic energy is actually set free in the stars … If only five percent of a star’s mass consists initially of hydrogen atoms which are gradually being combined to form more complex elements, the total heat liberated will more than suffice for our demands, and we need look no further for the source of a star’s energy”

“If, indeed, the sub-atomic energy in the stars is being freely used to maintain their great furnaces, it seems to bring a little nearer to fulfillment our dream of controlling this latent power for the well-being of the human race or for its suicide.”
1928 G. Gamov: Tunnel Effect

1938 H. A. Bethe and C. L. Critchfield: “The formation of deuterons by proton combination”

1938/1939 H. A. Bethe
C. F. Weizaecker

CNO Cycle

H. Bethe in Michigan
Energy generated via nuclear reactions

According to this book the Sun produces its energy via nuclear reactions...
Hydrogen burning

The sun shines $3.85 \times 10^{33}$ erg/s = $3.85 \times 10^{26}$ W for at least ~4.5 billion years

<table>
<thead>
<tr>
<th>CGS units</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Centimeter-Gram-Second)</td>
</tr>
<tr>
<td>1 erg = $10^{-7}$ J</td>
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</tbody>
</table>

Mass composition:
- Hydrogen 73.46%
- Helium 24.85%
- Oxygen 0.77%
- Carbon 0.29%
- Iron 0.16%
- Neon 0.12%
- Nitrogen 0.09%
- Silicon 0.07%
- Magnesium 0.05%
- Sulfur 0.04%
As a star forms density and temperature (heat source ?) increase in its center.

Fusion of hydrogen ($^1\text{H}$) is the first long term nuclear energy source that can ignite. Why?

With only hydrogen available (for example in a first generation star right after it’s formation) the ppl chain is the only possible sequence of reactions. (all other reaction sequences require the presence of catalyst nuclei)

3- or 4-body reactions are too unlikely – chain has to proceed by steps of 2-body reactions or decays.
**The ppi chain**

**Step 1:**

- $p + p \rightarrow ^2\text{He}$  
  $p + p \beta^+ \rightarrow d + e^+ + \nu_e$  
  $^2\text{He}$ is unstable  
  $Q = 0.42$ MeV

**Step 2:**

- $d + p \rightarrow ^3\text{He}$  
  $d + d \rightarrow ^4\text{He}$  
  $d$ abundance is too low  
  $Q = 5.5$ MeV

**Step 3:**

- $^3\text{He} + p \rightarrow ^4\text{Li}$  
  $^3\text{He} + d \rightarrow ^4\text{He} + n$  
  $^4\text{Li}$ is unstable  
  $d$ abundance is too low  
  $Q = 12.9$ MeV

$d + d$ not going because $Y_d$ is small as $d + p$ leads to rapid destruction

$^3\text{He} + ^3\text{He}$ goes because $Y_{^3\text{He}}$ gets large as there is no other rapid destruction
Net reaction: $4p \rightarrow \alpha$  \[ Q=26.7 \text{ MeV} \]

ppl chain
Summary of the ppi chain

On chart of nuclides:

Or as a chain of reactions:

Very low probability: $\sigma \approx 10^{-23}$ b

$\beta^+$ weak interaction (slow process) AND p+p must interact with each other

An average lifetime of a proton in the Sun is $10^{10}$ years
For simplicity consider chain of proton captures:

\[ \begin{align*}
1 & \xrightarrow{(p,\gamma)} 2 \\
2 & \xrightarrow{(p,\gamma)} 3 \\
3 & \xrightarrow{(p,\gamma)} 4
\end{align*} \]

Assumptions:

- \( Y_1 \sim \text{const} \) as depletion is very slow because of “bottle neck”
- Capture rates constant (\( Y_p \sim \text{const} \) because of large “reservoir”, conditions constant as well)

Abundance of nucleus 2 evolves according to:

\[
\frac{dY_2}{dt} = Y_1 \lambda_{12} - Y_2 \lambda_{23}
\]

\[
\lambda_{12} = \frac{1}{1 + \delta^{p1}_{\gamma}} Y_p \rho N_A <\sigma v>_{1\rightarrow2}
\]
For our assumptions \( Y_1 \sim \text{const} \) and \( Y_p \sim \text{const} \), \( Y_2 \) will then, after some time reach an equilibrium value regardless of its initial abundance:

\[
\frac{dY_2}{dt} = Y_1 \lambda_{12} - Y_2 \lambda_{23} = 0
\]

and

\[
Y_2 \lambda_{23} = Y_1 \lambda_{12}
\]

(this is equilibrium is called steady flow)

Same for \( Y_3 \) (after some longer time)

\[
\frac{dY_3}{dt} = Y_2 \lambda_{23} - Y_3 \lambda_{34} = 0
\]

and

\[
Y_3 \lambda_{34} = Y_2 \lambda_{23}
\]

with result for \( Y_2 \):

\[
Y_3 \lambda_{34} = Y_1 \lambda_{12}
\]

and so on ...

So in steady flow:

\[
Y_i \lambda_{i,i+1} = \text{const} = Y_1 \lambda_{12} \quad \text{or} \quad Y_i \propto \tau_i
\]

steady flow abundance destruction rate
for $\lambda \sim \text{const}$

$$\frac{dY_2}{dt} = Y_1 \lambda_{12} - Y_2 \lambda_{23}$$

has the solution:

$$Y_2(t) = \bar{Y}_2 - (\bar{Y}_2 - Y_{2\text{initial}}) e^{-t/\tau_2}$$

with $\bar{Y}_2$ equilibrium abundance

$Y_{2\text{initial}}$ initial abundance

so independently of the initial abundance, the equilibrium is approached on an exponential timescale equal to the lifetime of the nucleus.
Back to the ppl chain

“bottle neck”

\[ ^1\text{H} \xrightarrow{(p,e^+)} \text{d} \xrightarrow{(p,\gamma)} ^3\text{He} \xrightarrow{(3\text{He},2p)} ^4\text{He} \]

large reservoir \((Y_p \sim \text{const ok for some time})\)

d steady flow abundance?

\[
\begin{align*}
Y_d \lambda_{d+p} &= \text{const} = Y_p \lambda_{p+p} \\
\frac{Y_d}{Y_p} &= \frac{\lambda_{p+p}}{\lambda_{d+p}} = \frac{1}{2} \frac{Y_p \rho N_A <\sigma v>_{p+p}}{Y_p \rho N_A <\sigma v>_{d+p}} \\
Y_d &= \frac{<\sigma v>_{p+p}}{2 <\sigma v>_{d+p}}
\end{align*}
\]

\[ S = 3.8 \times 10^{-22} \text{ keV barn} \quad \text{and} \quad S = 2.5 \times 10^{-4} \text{ keV barn} \]

therefore, equilibrium d-abundance extremely small (of the order of 4e-18 in the sun)

equilibrium reached within lifetime of d in the sun:

\[ N_A <\sigma v>_{pd} = 1 \times 10^{-2} \text{ cm}^3/\text{s/mole} \quad \tau_d = \frac{1}{(Y_p \rho N_A <\sigma v>_{p+d})} = 2 \text{s} \]
$^3$He equilibrium abundance

Different because two identical particles fuse therefore destruction rate $\lambda_{^3\text{He}+^3\text{He}}$ obviously NOT constant:

$$\lambda_{^3\text{He}+^3\text{He}} = \frac{1}{2} Y_{^3\text{He}} \rho N_A \langle \sigma v \rangle_{^3\text{He}+^3\text{He}}$$

But depends strongly on $Y_{^3\text{He}}$ itself

But equations can be solved again (see Clayton)
$^3$He to d ratio

$^3$He has a much higher equilibrium abundance than d
- therefore $^3$He+$^3$He possible ...
$^3$He abundance depends on the age of the star

$T_6 < 8$: $t_f > 10^9$ a
Hydrogen burning with catalysts

1. ppII chain
2. ppIII chain
3. CNO cycle

1. ppII and ppIII:
   once $^4\text{He}$ has been produced it can serve as catalyst of the ppII and ppIII chains to synthesize more $^4\text{He}$:

   $^3\text{He}$ $\rightarrow^{(4\text{He},\gamma)}$ $^7\text{Be}$ $\rightarrow^{(\text{e}^-,\nu)}$ $^7\text{Li}$ $\rightarrow^{(p,\text{He}^4)}$ $^4\text{He}$

   ppII (sun 14%)

   $^8\text{B}$ $\rightarrow^{(p,\gamma)}$ $^8\text{Be}$ $\rightarrow^{(\beta^+)}$ $^8\text{Be}$ $\rightarrow$ decay $^2\text{He}^4$

   ppIII (sun 0.02%)
Greater abundance of \(^{3}\text{He}\) than \(D\) achieved before equilibrium

\[\tau_{^{3}\text{He}} = 2.2 \times 10^5 \text{ a} \]
\[\tau_{\text{H}(D)} = 1.6 \text{ s} \]

**Figure 6.7.** Plotted are the equilibrium lifetimes of \(^{3}\text{He}\) resulting from different burning processes (Table 6.2). The \(^{3}\text{He}(\alpha, \gamma)^{7}\text{Be}\) reaction leading to the \(\tau_{^{4}\text{He}}(^{3}\text{He})\)–curve is important only in stars which have an appreciable amount of \(^{4}\text{He}\). Shown for comparison is the lifetime of hydrogen against destruction via the \(p + p\) reaction and those of \(D\), \(^{7}\text{Li}\), and \(^{7}\text{Be}\) against destruction via hydrogen-burning interactions. The electron-capture lifetime of \(^{7}\text{Be}\) in stars, \(\tau_{^{7}\text{Be}}\), and the laboratory lifetime of the positron decay for \(^{8}\text{B}\) are also shown. All curves assume conditions of \(\rho = 100 \text{ g cm}^{-3}, X_{\text{H}} = X_{\text{He}} = 0.5\).
Electron capture decay of $^7\text{Be}$

Why electron capture:

$Q_{\text{EC}} = 862$ keV

$Q_{\beta^+} = Q_{\text{EC}} - 1022 = -160$ keV  

only possible decay mode

Earth:  
- Capture of bound K-electron
- $\tau = 77$ days

Sun:  
- Ionized fraction: Capture of continuum electrons depends on density and temperature
  
  $\tau_{7\text{Be}} = 4.72 \times 10^8 \frac{T_6^{1/2}}{\rho(1 + X_H)} s$
  
  - Not completely ionized fraction: capture of bound K-electron (21% correction in sun)
  
  $\tau = 120$ days
Why do additional pp chains matter?

- **p+p dominates timescale**
- **BUT**
- **ppI** produces 1/2 $^4$He per p+p reaction
- **ppI+II+III** produces 1 $^4$He per p+p reaction

**Double burning rate**
CNO cycle

- $^{12}\text{C}$ acts as a catalyst
- Does not require $\beta^+$ and fusion at the same time (as in the ppl chain) $\rightarrow$ faster BUT
- Coulomb barriers $p + C, N, O$ much higher than in $p+p$ $\rightarrow$ the reactions not so easy
- Dominates at higher temperatures
- Net reaction: $4\ p \rightarrow \alpha\ Q=26.7\ \text{MeV}$ (same as in the ppl chain)
The CNO cycle involves the following reactions:

1. $^{12}\text{C} + \gamma \rightarrow ^{13}\text{N}$
2. $^{13}\text{N} + p \rightarrow ^{13}\text{C} + e^+ + \nu$
3. $^{13}\text{C} + \gamma \rightarrow ^{14}\text{N}$
4. $^{14}\text{N} + p \rightarrow ^{15}\text{O} + e^+$
5. $^{15}\text{O} + p \rightarrow ^{15}\text{N} + \gamma$
6. $^{15}\text{N} + p \rightarrow ^{12}\text{C} + ^{4}\text{He} + \gamma$
CNO cycle

CN cycle (99.9%)
O Extension 1 (0.1%)
O Extension 2
O Extension 3

All initial abundances within a cycle serve as catalysts and accumulate at largest $\tau$

Extended cycles introduce outside material into CN cycle (Oxygen, ...)

neutron number

C(6) N(7) O(8) F(9) Ne(10)
• p-p chain is the principal energy source in the sun and stars with \( m < m_{\text{Sun}} \)
• changeover depends also on the abundance of C, N, and O in the star
• The sun is not a first generation star!
Neutrino emission

$<E> = 0.27$ MeV

$p(p, e^- \nu) d$
$d(p, \gamma)^3\text{He}$

$86\%$

$^3\text{He} (\text{He, 2p})^4\text{He}$

$14\%$

$^3\text{He}(\alpha, \gamma)^7\text{Be}$

$E = 0.39, 0.86$ MeV

$Be(e^- \nu)^7\text{Li}$
$^7\text{Li}(p, \alpha)^4\text{He}$

$14\%$

$7\text{Be}(p, \gamma)^8\text{B}$
$^8\text{B}(e^- \nu)^8\text{Be}$

$0.02\%$

$ppI$ loss: $\sim 2\%$

$ppII$ loss: 4%

$ppIII$ loss: 28%

$Total\ loss: 2.3\%$
Two neutrino energies from $^7$Be electron capture?

$^7$Be + e$^-$ → $^7$Li + $\nu_\epsilon$

![Diagram showing electron capture process with energy levels and decay modes.](Image)
Neutrino fluxes

Continuous fluxes in \(\text{cm}^2/\text{s}/\text{MeV}\)
Discrete fluxes in \(\text{cm}^2/\text{s}\)

Neutrino Flux

Neutrino Energy (MeV)

Gallium  Chlorine  SuperK, SNO
Neutrino Astronomy

Photons emitted from the sun are not the photons created by nuclear reactions (heat is transported by absorption and emission of photons plus convection to the surface over timescales of $10^6$ years)

But neutrinos escape!

Every second, $10^9$ solar neutrinos pass through your thumbnail!

But hard to detect (they pass through $1e33$ g solar material largely undisturbed!)
First experimental detection of solar neutrinos

- **1964** John Bahcall and Ray Davis have the idea to detect solar neutrinos using the reaction:

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

- **1967** Homestake experiment starts taking data
  - 100,000 Gallons of cleaning fluid in a tank 4850 feet underground
  - \(^{37}\text{Ar}\) extracted chemically every few months (single atoms !)
    and decay counted in counting station (35 days half-life)
  - event rate: ~1 neutrino capture per day !

- **1968** First results: only 34% of predicted neutrino flux !
  solar neutrino problem is born - for next 20 years no other detector !

**Neutrino production in solar core \(\sim T^{25}\)**

- nuclear energy source of sun directly and unambiguously confirmed
- solar models precise enough so that deficit points to serious problem
Are the neutrinos really coming from the sun?

Water Cerenkov detector:

\[ \nu + e^- \rightarrow \nu + e^- \]

- high energy (compared to rest mass)
- produces Cerenkov radiation when traveling in water (can get direction)

Neutral current (NC):

\[ \nu_x \]

Charged current (CC):

\[ \nu_e \]

Super-Kamiokande Detector
Deficit to solar model

all show deficit to standard solar model

$\nu_e$ only

all flavors, but $\nu_\tau, \nu_\mu$ only 16% of $\nu_e$ cross section because no CC (charged current), only NC (neutral current)
Neutrino image of the sun by Super-Kamiokande

White colour corresponds to the highest number of registered neutrinos and colours from yellow, through red to blue correspond to decreasing intensity of observed neutrinos.

Obtained via registering neutrinos emitted from the solar core and detected in a 50 000-ton water pool located 1 km underground
Exposure time: 503 days
The solution: neutrino oscillations

Neutrinos can change flavor while travelling from sun to earth

The arguments:

1. SNO solar neutrino experiment

uses three reactions in heavy water:

\[
\begin{align*}
\text{CC} & \quad \nu_e + d \rightarrow p + p + e^- \quad \text{(Cerenkov)} \\
\text{ES} & \quad \nu + e^- \rightarrow \nu + e^- \quad \text{(Cerenkov)} \\
\text{NC} & \quad \nu + d \rightarrow p + n + \nu \quad \text{(n-capture by } ^{35}\text{Cl - } \gamma \text{ scatter - Cerenkov)}
\end{align*}
\]

• NC independent of flavor - should always equal solar model prediction if oscillations explain the solar neutrino problem
• Difference between CC and ES (elastic scattering) indicates additional flavors present
Sudbury Neutrino Observatory (SNO)
With SNO results:

Homestake, SAGE, GALLEX, GNO, Kamiokande, Super Kamiokande, SNO CC, SNO NC, SNO EC.
2. **Indication for neutrino oscillations in two other experiments:**

- 1998 Super Kamiokande reports evidence for $\nu_\mu \rightarrow \nu_\tau$ oscillations for neutrinos created by cosmic ray interaction with the atmosphere.
- 2003 KamLAND reports evidence for disappearance of electron antineutrinos from reactors.

3. **There is a (single) solution for oscillation parameters that is consistent with all solar neutrino experiments and the new KamLAND results**

**KamLAND:**

- Reactor produces $\bar{\nu}_e$ from beta decay of radioactive material in core.
- Detection in liquid scintillator tank in Kamiokande mine $\sim$180 km away.
- Check whether neutrinos disappear.
2003 Results

K. Eguchi, PRL 90 (2003) 021802

- Dashed: Best fit: LMA (large mixing angle solution) $\sin^22\Theta=0.833$, $\Delta m^2=5.5\times10^{-5}$ eV$^2$
- Shaded: 95% CL LMA from solar neutrino data