PHAS1102: Physics of the Universe
Stellar Astrophysics
5. Energy generation (2) (ZG Ch.16)

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Bus tour to MSSL on Wed. Nov. 11!

Please sign up by sending e-mail to d.kawata@ucl.ac.uk
by 26th Oct (Mon) with subject "MSSL tour".
You will receive a confirmation and updates.

Tentative plan:

9:30:
a bus from Bloomsbury
from ~11:00:
talks and tours at MSSL
lunch will be provided.
afternoon reception
(with drinks and etc.)
~17:00: leave MSSL
~19:00: back to Bloomsbury

see also the course web-site,
http://www.mssl.ucl.ac.uk/~dka/phas1102/

Assignment 1
deadline: 28th October

Please download
assignment 1 (1 page, 8 questions)
from
http://www.mssl.ucl.ac.uk/~dka/phas1102/

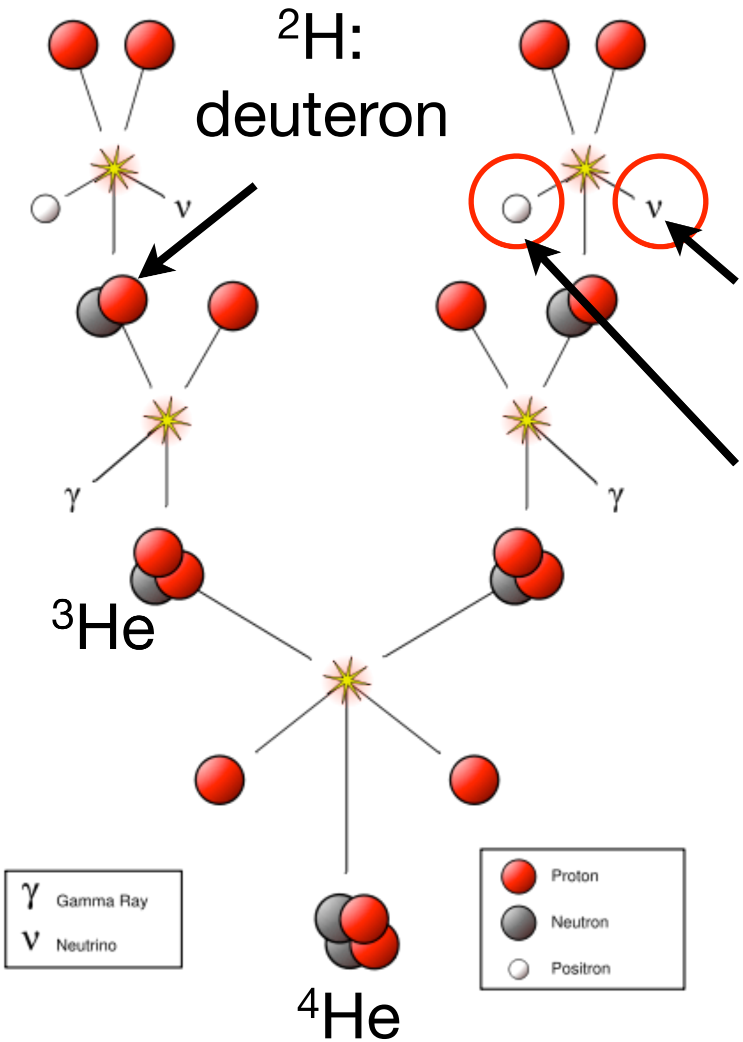
Your answer sheet will be collected
after the lecture on 28th October.

Fusion processes for H $\Rightarrow$ He

- Simultaneous collision of 4 protons very unlikely
- Two thermonuclear processes lead to conversion H$\Rightarrow$He

  1) Proton-proton chain (PP chain)
     Dominates at $T<2\times10^7$ K
  2) Carbon cycle (CNO cycle)
     Dominates at higher temperatures
     (contributes 2 % of solar energy)

Proton-proton chain (PP1), major reactions



$$^1\mathrm{H} + {}^1\mathrm{H} \longrightarrow {}^2\mathrm{H} + e^+ + \nu$$

deuteron
(deuterium core)

neutrinos, ν

very small mass, no charge

positron, e^+

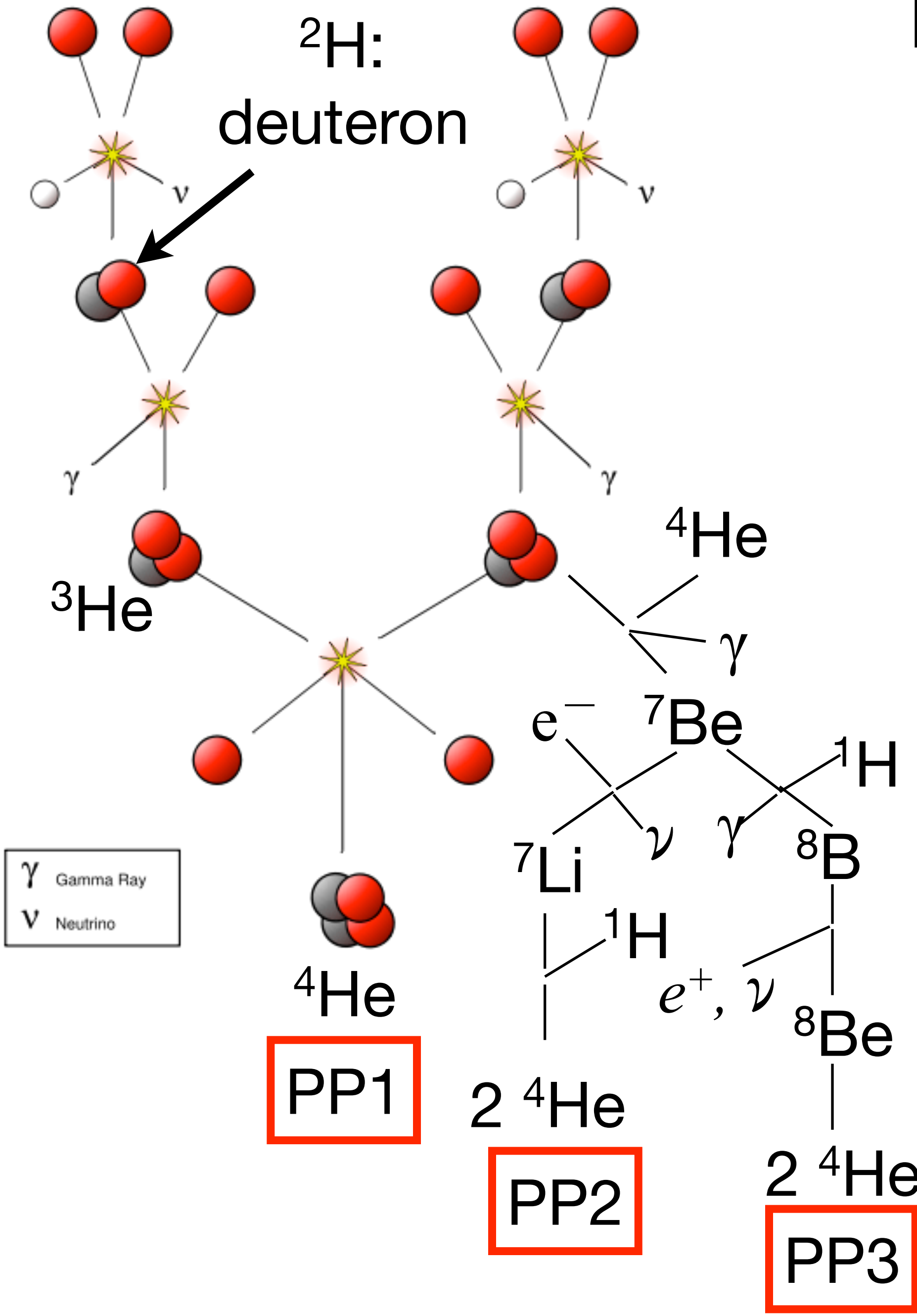
an electrons, but positive charge +e

$$^2\mathrm{H} +^1 \mathrm{H} \longrightarrow^3 \mathrm{He} + \gamma$$

photon, γ, γ-ray

$$^3\mathrm{He} +^3 \mathrm{He} \longrightarrow^4 \mathrm{He} +^1 \mathrm{H} +^1 \mathrm{H}$$

generated energy
→ kinetic energy



PP chain, major reactions

PP1
~85 % frequency
in the Sun

$$^3\mathrm{He} + {}^4\mathrm{He} \rightarrow {}^7\mathrm{Be} + \gamma$$

PP2 (~15 %)

$$^7\mathrm{Be} + e^- \rightarrow {}^7\mathrm{Li} + \nu$$

$$^7\mathrm{Li} + {}^1\mathrm{H} \rightarrow 2\,{}^4\mathrm{He}$$

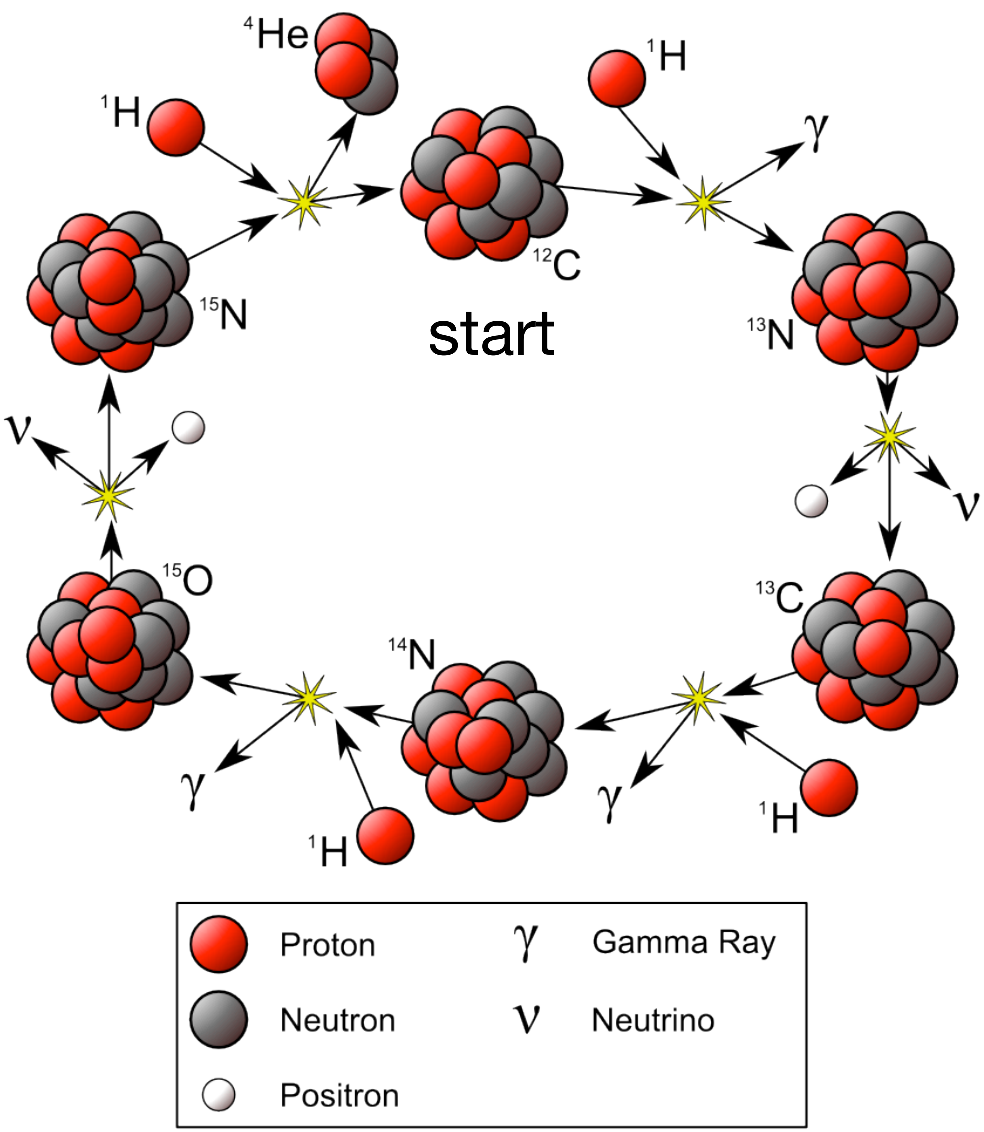
PP3 (~0.02 %)

$$^7\mathrm{Be} + {}^1\mathrm{H} \rightarrow {}^8\mathrm{B} + \gamma$$

$$^8\mathrm{B} \rightarrow {}^8\mathrm{Be} + e^+ + \nu$$

$$^8\mathrm{Be} \rightarrow 2\,{}^4\mathrm{He}$$

CNO cycle, major processes



$$^{12}\mathrm{C} + {}^{1}\mathrm{H} \rightarrow {}^{13}\mathrm{N} + \gamma$$

unstable

$$^{13}\mathrm{N} \rightarrow {}^{13}\mathrm{C} + e^{+} + \nu$$

$$^{13}\mathrm{C} + {}^{1}\mathrm{H} \rightarrow {}^{14}\mathrm{N} + \gamma$$

$$^{14}\mathrm{N} + {}^{1}\mathrm{H} \rightarrow {}^{15}\mathrm{O} + \gamma$$

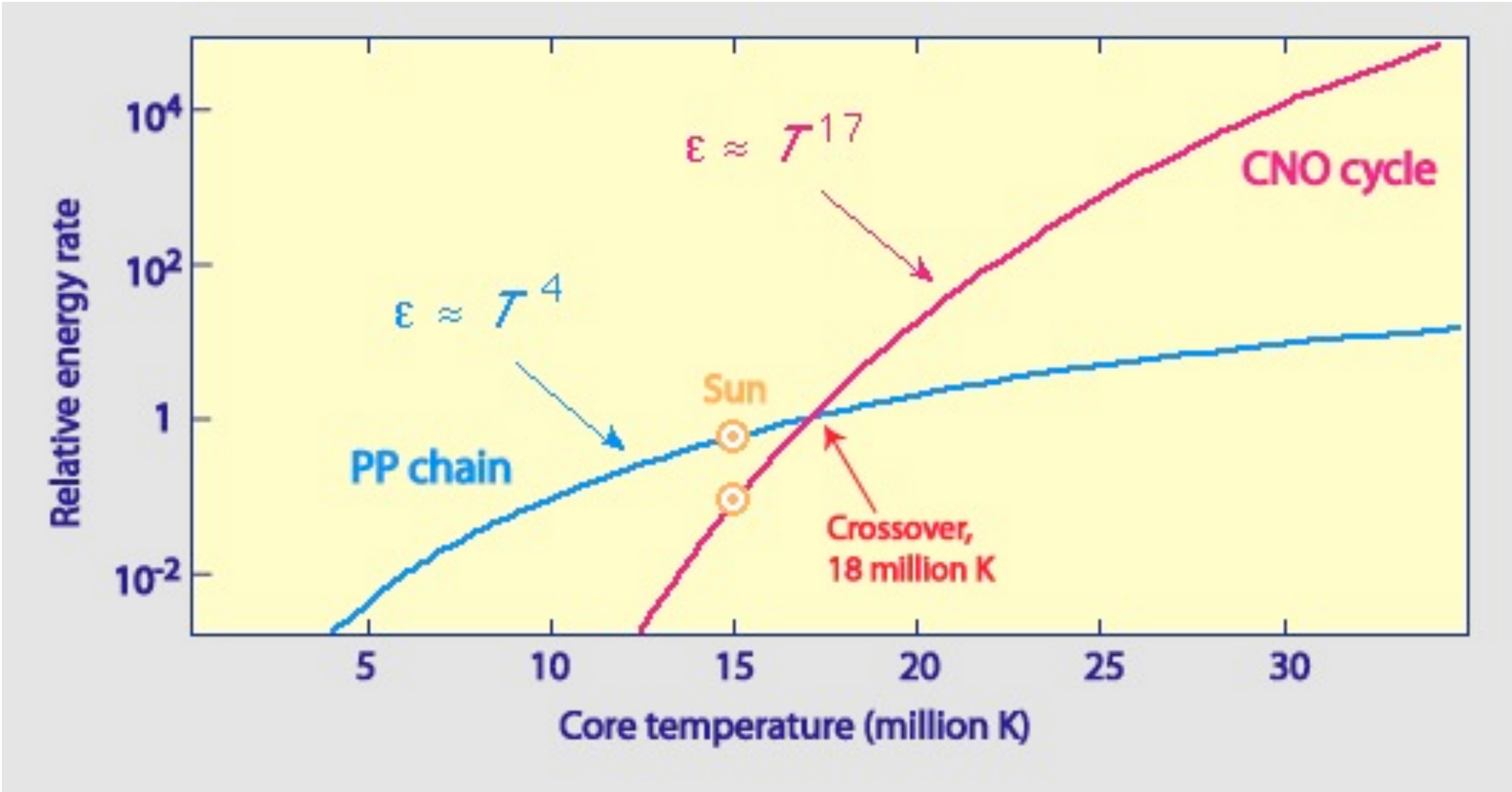
unstable

$$^{15}\mathrm{O} \rightarrow {}^{15}\mathrm{N} + e^{+} + \nu$$

$$^{15}\mathrm{N} + {}^{1}\mathrm{H} \rightarrow {}^{12}\mathrm{C} + {}^{4}\mathrm{He}$$

^{12}C works as a catalyst.

PP chain vs. CNO cycle



As carbon has six protons, the repulsion is greater for the first step of the CNO cycle.
⇒ require higher kinetic energy.

CNO cycle dominates at high temperatures
⇒ more important in more massive stars.

Further fusion processes

At $T>10^8$ K, transmuting helium to heavier elements.

Triple-α process (He nucleus is called "α particle") or He burning

$$^{4}\mathrm{He} + {}^{4}\mathrm{He} \Longleftrightarrow {}^{8}\mathrm{Be} + \gamma$$ (^{8}Be is unstable)

$$^{8}\mathrm{Be} + {}^{4}\mathrm{He} \rightarrow {}^{12}\mathrm{C} + \gamma$$

After all He has burnt, C, Ne, O, Mg, Si burning takes place. Each stage requires higher T, up to ~3×10^9 K, and higher densities, thus only in more massive stars.

Process stops when stellar core is made up of ^{56}Fe (one of the most stable element)

$\Rightarrow$ hydrostatic equilibrium no longer holds

$\Rightarrow$ star collapses

$\Rightarrow$ Supernova explosion!

Average binding energy per nucleon
(Z: Atomic number, A: mass number)

binding energy per nucleon = (mass defect) x c^2/A

m_H = mass of ^{1}H = 1.007825 amu

m_n = mass of neutron = 1.008665 amu

amu: atomic mass unit, 1.66×10^{-27} kg

If atomic mass is M(Z,A),

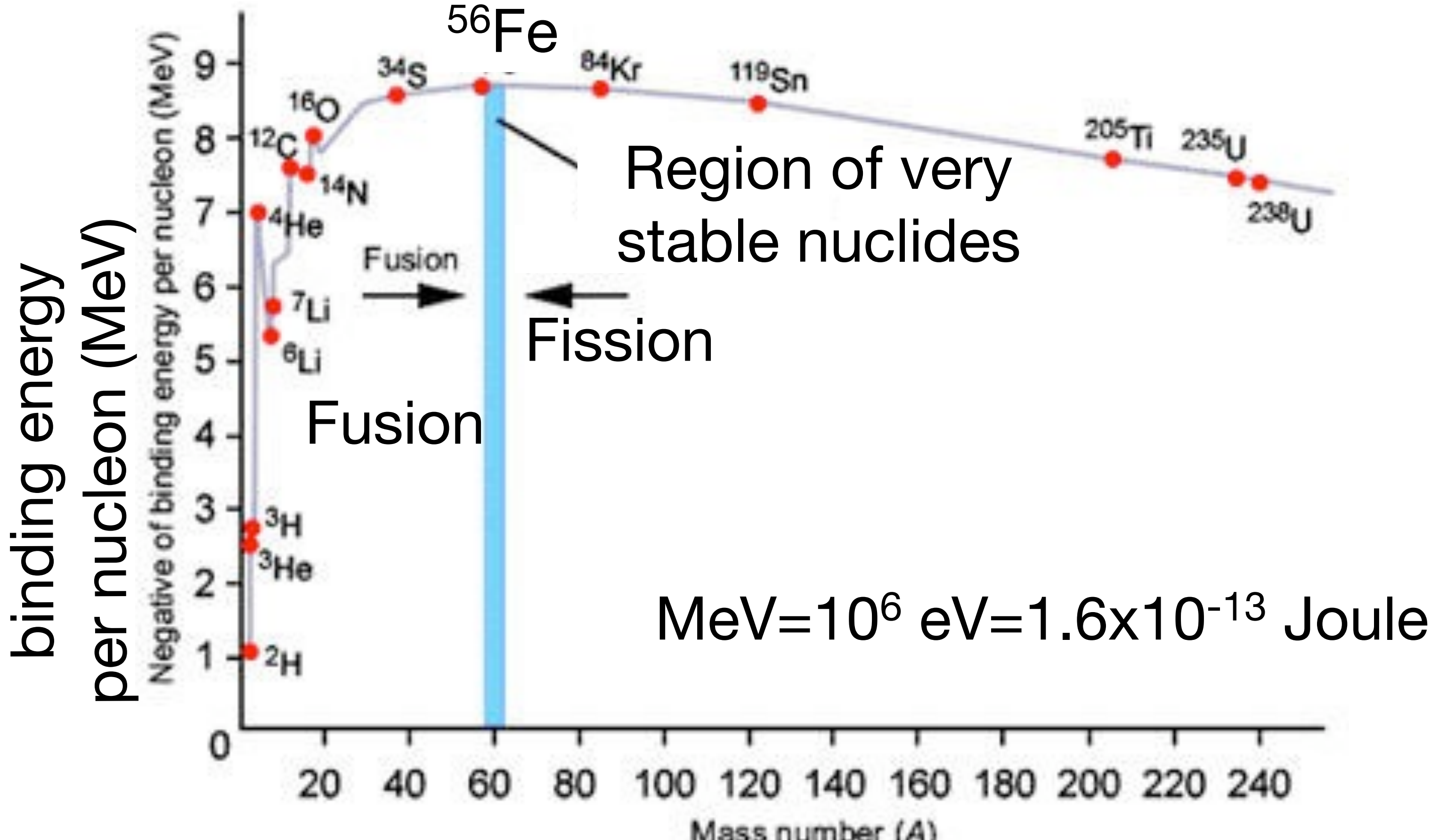
mass defect = $(Z\, m_H + (A - Z)\, m_n) - M(Z,A)$

binding energy = $[(Z\, m_H + (A - Z)\, m_n) - M(Z,A)] \times c^2$

Average binding energy per nucleon

$= [(Z\, m_H + (A - Z)\, m_n) - M(Z,A)] \times c^2 / A$

Average binding energy per nucleon



Curve peaks around ^{56}Fe.

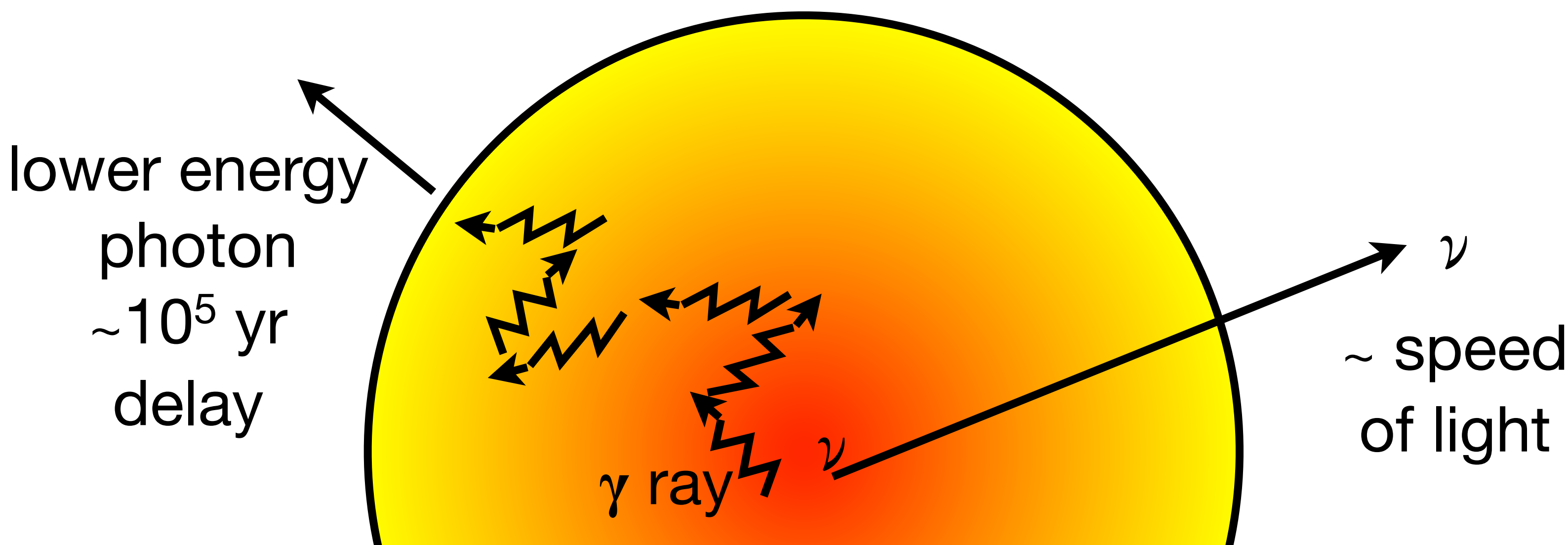
Above peak, nuclear fusion requires input of energy, while nuclear fission releases energy.

Solar neutrino

Generally we do not receive any radiation from the interiors of stars because all photons are absorbed and re-emitted very frequently during their diffusion to the stellar surface.

Since neutrinos do not interact significantly with matter, neutrino can freely escape from the solar interior.

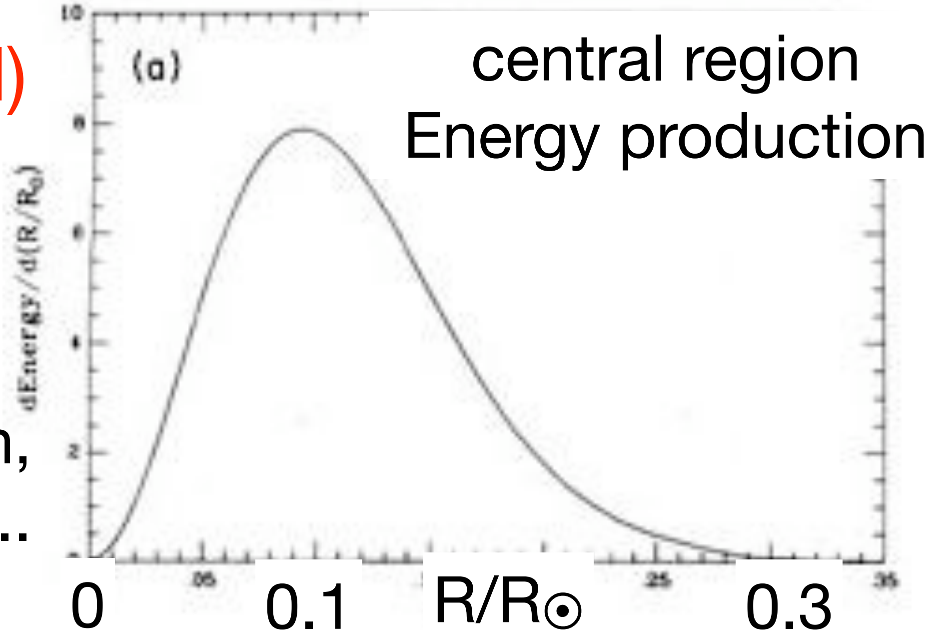
Thus if we can observe these neutrinos, they provide a direct check on nuclear energy generation theory in the Sun.

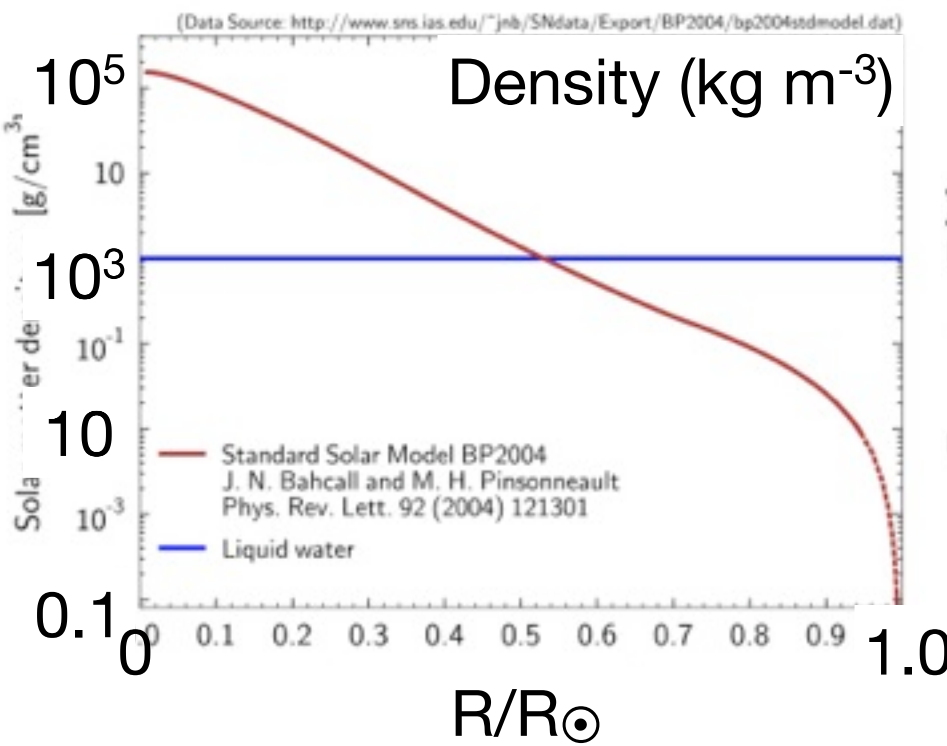


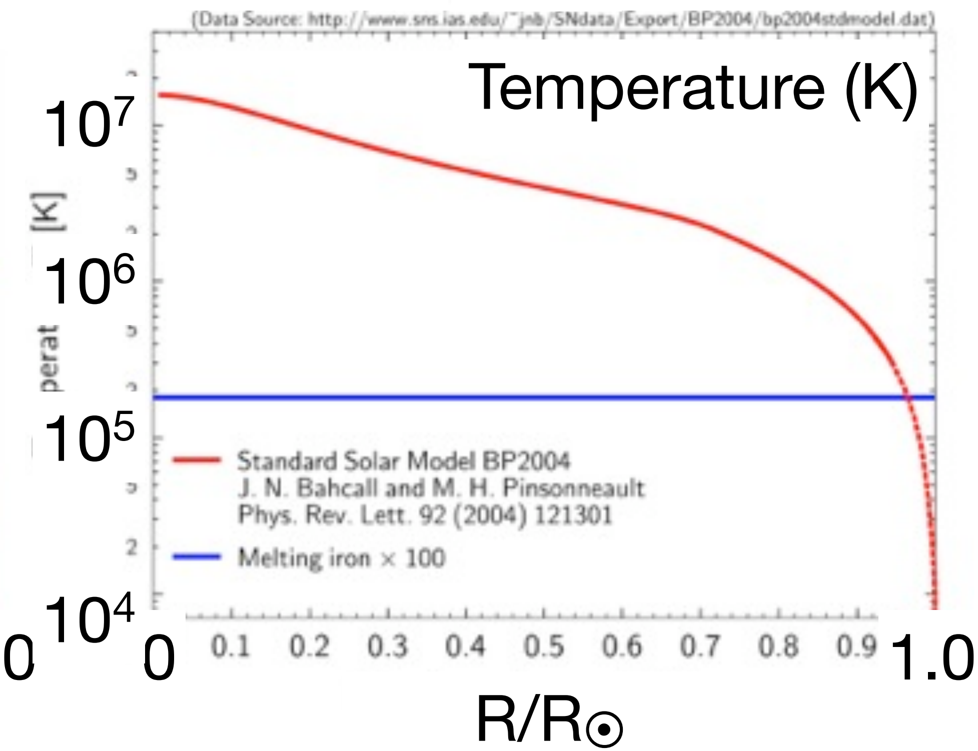
Standard Solar Model (SSM)

Theoretical models that best fit various observations.

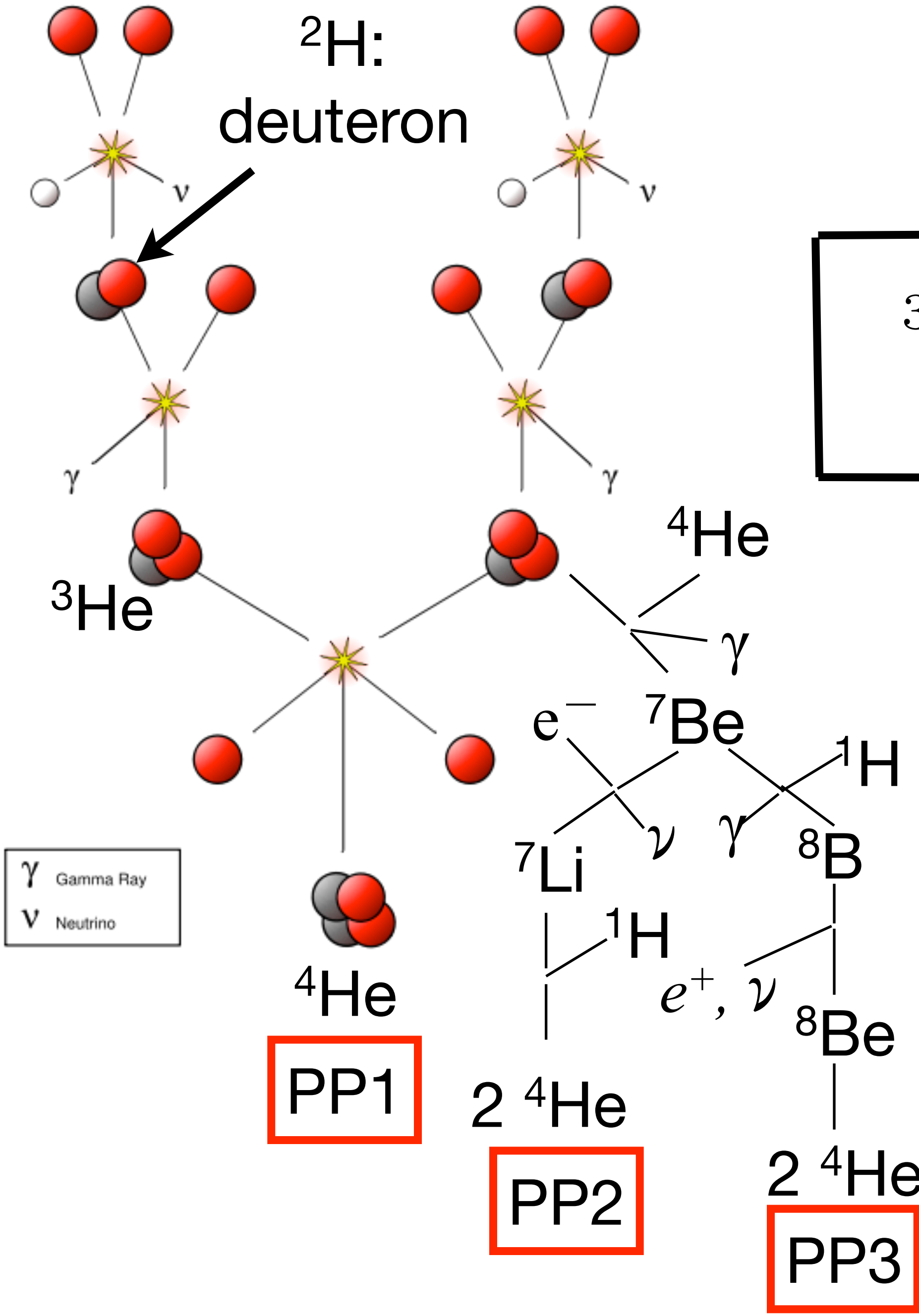
← hydrostatic equilibrium, thermonuclear energy generation, chemical composition, H, He, C... and etc.







PP chain, major reactions



PP1

pp

$$^{1}\mathrm{H} + {}^{1}\mathrm{H} \rightarrow {}^{2}\mathrm{H} + e^{+} + \nu$$

$$^{2}\mathrm{H} + {}^{1}\mathrm{H} \rightarrow {}^{3}\mathrm{He} + \gamma$$

$$^{3}\mathrm{He} + {}^{3}\mathrm{He} \rightarrow {}^{4}\mathrm{He} + {}^{1}\mathrm{H} + {}^{1}\mathrm{H}$$

$$^{3}\mathrm{He} + {}^{4}\mathrm{He} \rightarrow {}^{7}\mathrm{Be} + \gamma$$

PP2

Be

$$^{7}\mathrm{Be} + e^{-} \rightarrow {}^{7}\mathrm{Li} + \nu$$

$$^{7}\mathrm{Li} + {}^{1}\mathrm{H} \rightarrow 2\,{}^{4}\mathrm{He}$$

PP3

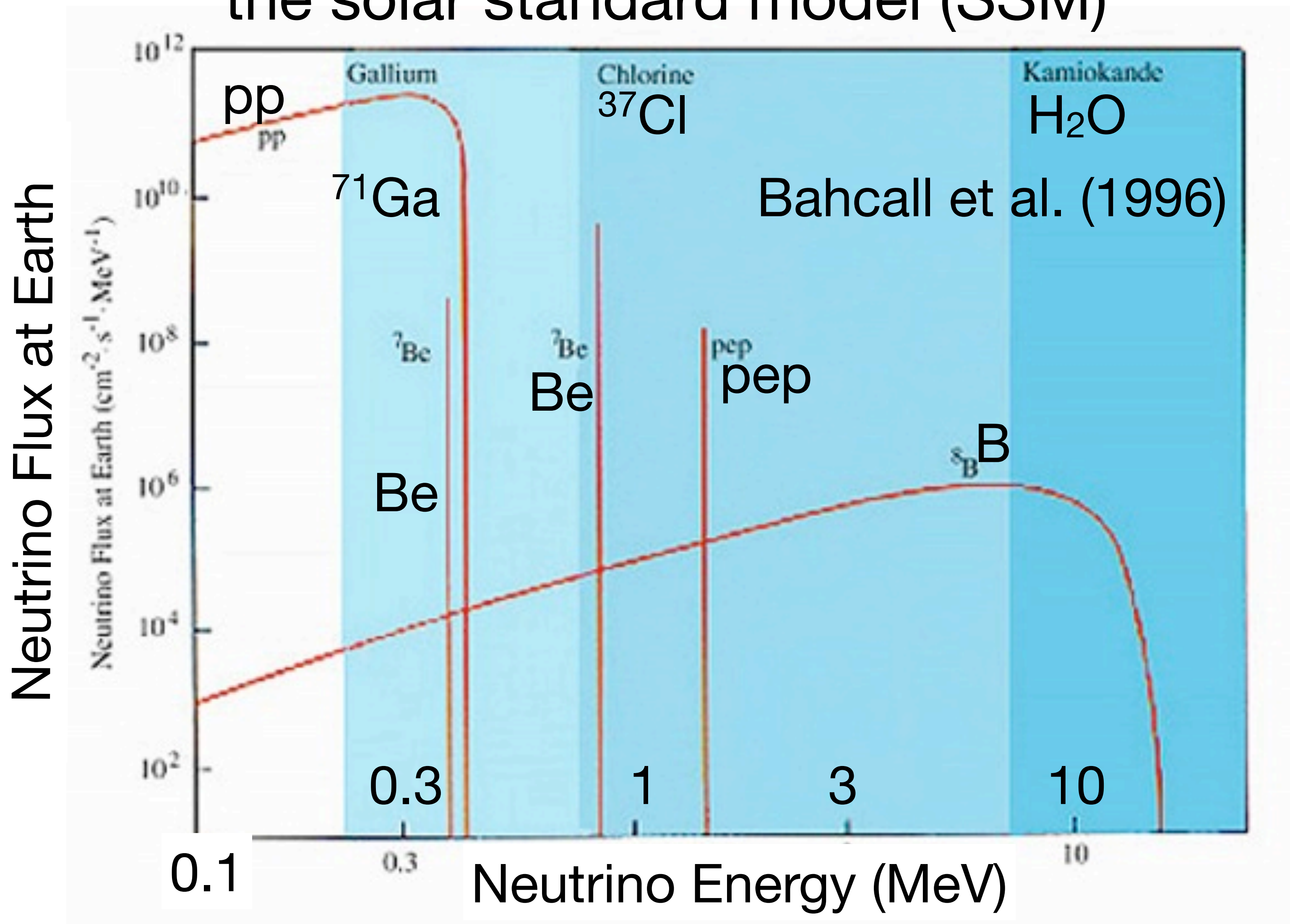
$$^{7}\mathrm{Be} + {}^{1}\mathrm{H} \rightarrow {}^{8}\mathrm{B} + \gamma$$

B

$$^{8}\mathrm{B} \rightarrow {}^{8}\mathrm{Be} + e^{+} + \nu$$

$$^{8}\mathrm{Be} \rightarrow 2\,{}^{4}\mathrm{He}$$

Solar neutrino flux predicted by the solar standard model (SSM)



pep: 0.23 % of 1st process of PP chain

$$^1\mathrm{H} + e^- + {}^1\mathrm{H} \rightarrow {}^2\mathrm{H} + \nu$$

Solar Neutrino detection

Mid-1960s - Raymond Davis (Novel laureate in 2002), Homestake gold mine (South Dakota, USA) experiment, using a tank of 100,000 gallons of tetrachloroethylene C_2Cl_4 one mile underground.

solar neutrinos transmute

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

number of ^{37}Ar (radioactive) atoms → solar neutrino flux

Only 1/3 of expected high-energy (PP3) neutrinos detected

⇒ 'Solar Neutrino Problem' !

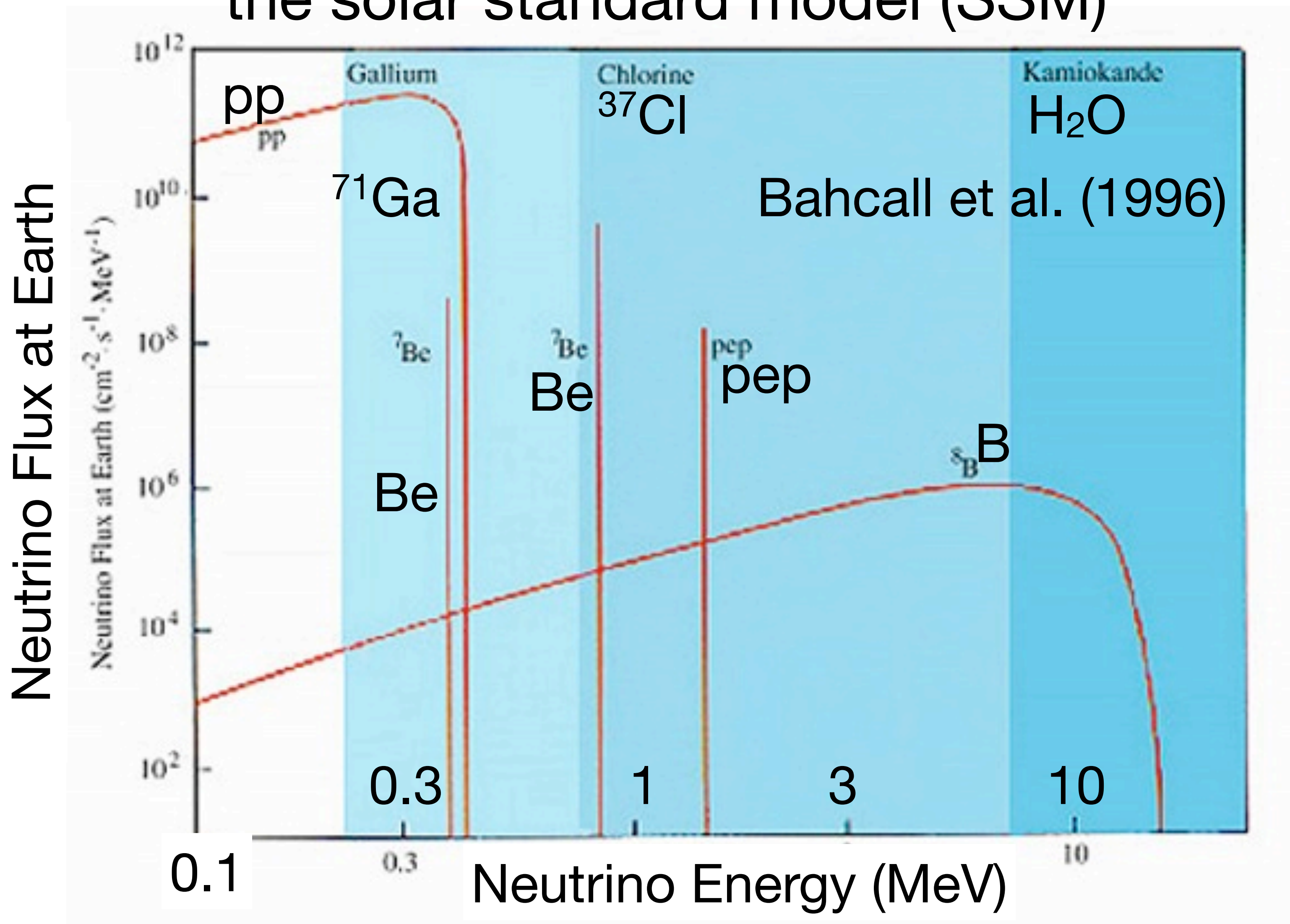
Solar Neutrino Problem

Number of detected neutrinos are much smaller than the predictions of the solar standard model.

1986, Kamiokande experiment (water detectors) - only 1/2 of expected high-energy PP3 B neutrinos

Early 1990s, GALLEX (GALLium EXperiment), and SAGE (RuSsian American Gallium Experiment) detected just over 1/2 of low-energy neutrinos from PP1 (confirm PP is the main energy production mechanism in the Sun.

Solar neutrino flux predicted by the solar standard model (SSM)



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Solar Neutrino Problem

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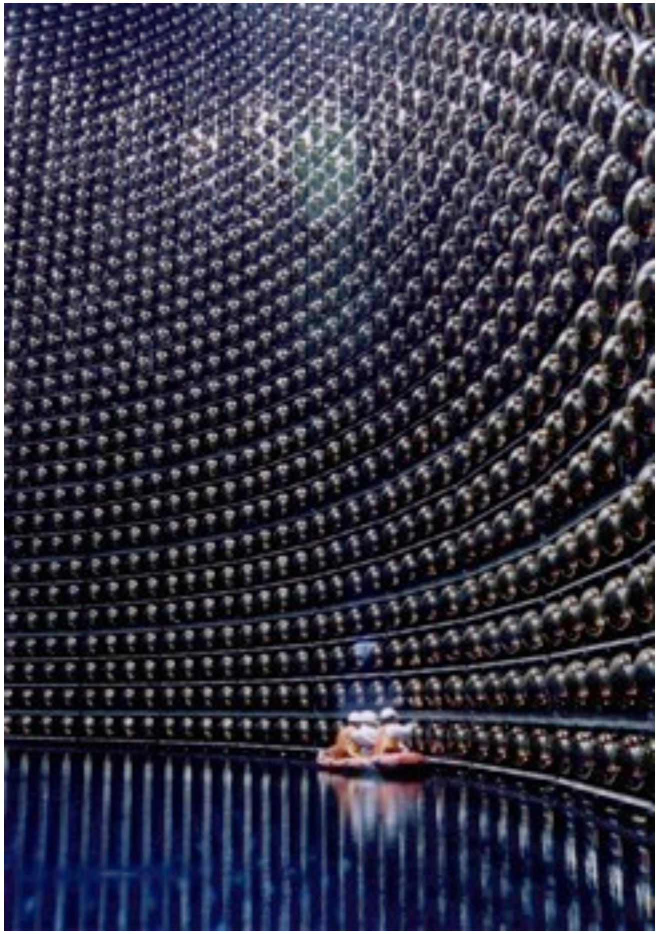
Late 1990s, Super-Kamiokande confirmed high-energy PP3 neutrino deficit by 50%.



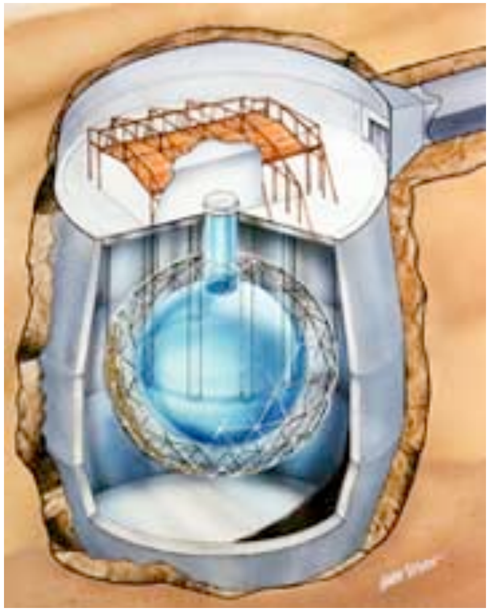
Key to solve the solar neutrino problem.
What is neutrino?
One of the fundamental particles.

	first generation	second generation	third generation	charge
quarks	u (up)	c (charm)	t (top)	+2/3
	d (down)	s (strange)	b (bottom)	−1/3
leptons	ν_e (electron neutrino)	ν_μ (muon neutrino)	ν_τ (tau neutrino)	0
	e (electron)	μ (muon)	τ (tau)	-1

There are “three flavour” of neutrino.

Nuclear fusion in the Sun produces only electron neutrinos, ν_e.

Solution of the Solar Neutrino Problem



18 June 2001, SNO (Sudbury Neutrino Observatory) heavy water (D_2O) experiment announced Solar neutrino problem solution!

Total number of ν_e, ν_μ and ν_τ

= Solar standard model.

~ 2/3, and ν_e produced in the Sun transform into ν_μ and ν_τ

on their way to Earth. ⇐ 'neutrino oscillations'

The Mikheyev-Smirnov-Wolfenstein (MSW) effect: neutrino oscillations enhanced by passage through the Sun.

For neutrino oscillations to occur, neutrinos must have non-zero mass.

⇒ particle physics

The mass of neutrinos

Different flavour neutrinos have different masses with ν_{e} being the lightest.

Mass difference:

$$\Delta m_{21}^2 \simeq 8 \times 10^{-5}\ \mathrm{eV}^2$$

$$\Delta m_{32}^2 \simeq 3 \times 10^{-3}\ \mathrm{eV}^2$$

1eV=1.602×10^{-19} Joule

$E=mc^2$

1eV = 1.78×10^{-36} kg

From observational cosmology:
heaviest neutrino < 0.67 eV

The mass of neutrino is still only upper limit.

Ongoing efforts to measure the absolute mass of neutrinos, including NEMO3, SuperNEMO (UCL P&A participation)
→ sensitivity 0.05 eV.