# PHAS 1102
# Physics of the Universe

## 4 - Stellar energy generation

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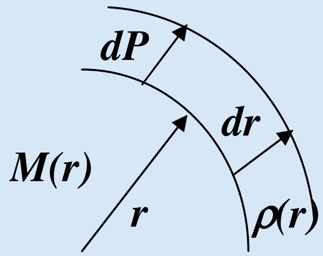
# Stellar energy generation (ZG Ch. P5; FK Ch. 18)

Stars are balls of very hot gas. They are generally very stable. Assuming that only the inward gravitational force and the outward (thermal) pressure are at work in the gas, a star is in hydrostatic equilibrium:

Gravitational acceleration

$$\boxed{\frac{dP}{dr} = \frac{-G\,M(r)\,\rho(r)}{r^2}} \quad [\mathrm{N\ m^{-3}}]$$




where $P$: outward pressure (force per unit area)

$r$: radius from the centre of the star

$G$: gravitational constant

$M(r)$: mass within radius $r$

$\rho(r)$: density at radius $r$

For the Sun: $\langle P \rangle \approx 10^{14}$ Pa = $10^{14}$ N m$^{-2}$ (average core pressure)
From $\boldsymbol{P = nkT}$ ➔ Sun's internal (core) temperature $\langle T \rangle \approx 10^7$ K

# ***Stellar stability and star formation***

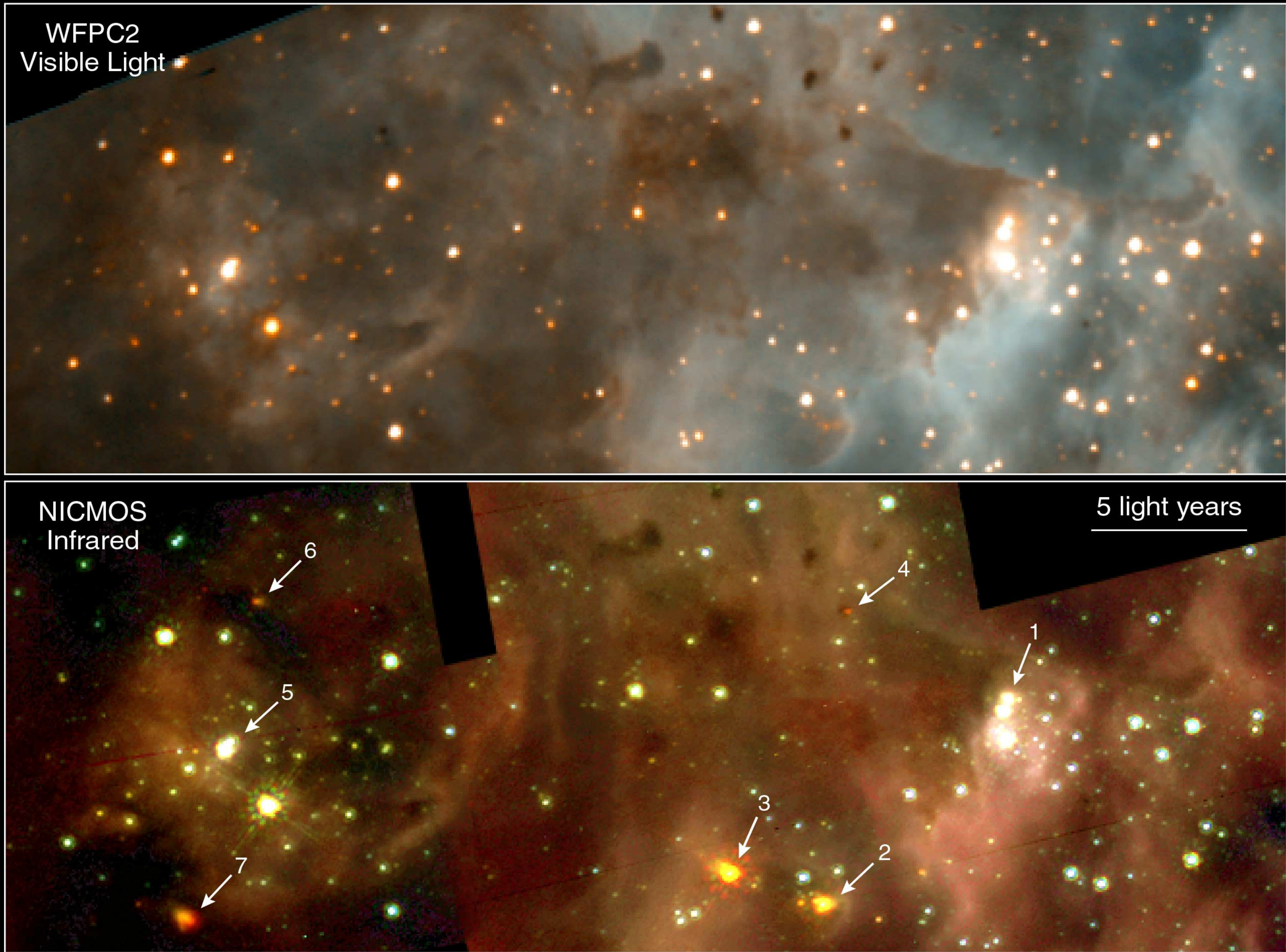
$P = nkT$ is the 'perfect gas equation' ($n$: number density,
$k$: Boltzmann constant)

Cooling of core ➔ outward pressure decreases ➔ star contracts ➔ gas heats up ➔ outward pressure increases … and reverse happens if core heats up …

Self-governing process, so stars are <u>stable</u> unless something dramatic upsets this balance drastically …

Stars likely to form from the gravitational collapse of large clouds of gas which may fragment into protostars when density is high enough.

Temperature of collapsing protostar increases. At some stage, temperature and density high enough to ignite
nuclear fusion reactions.

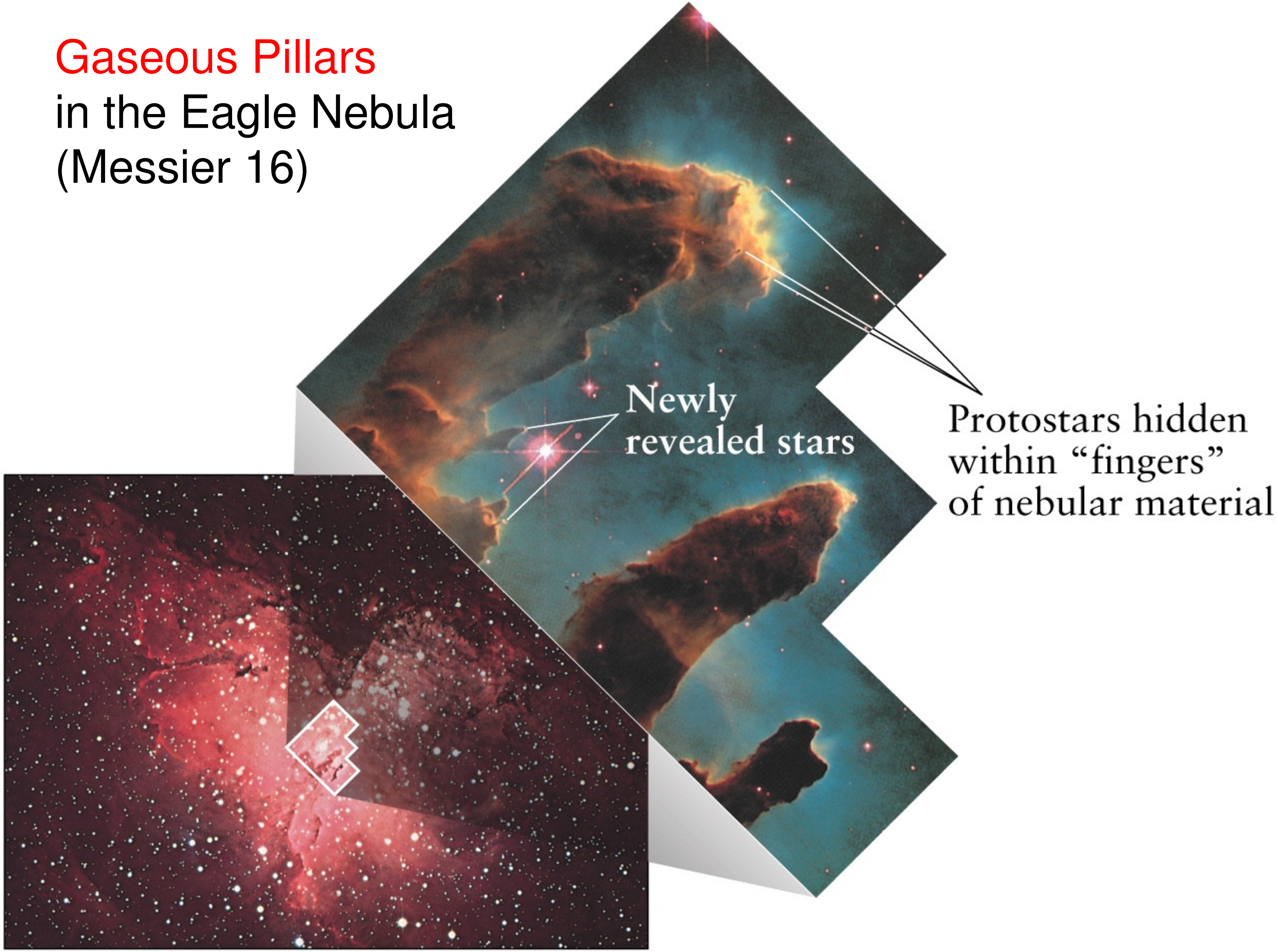


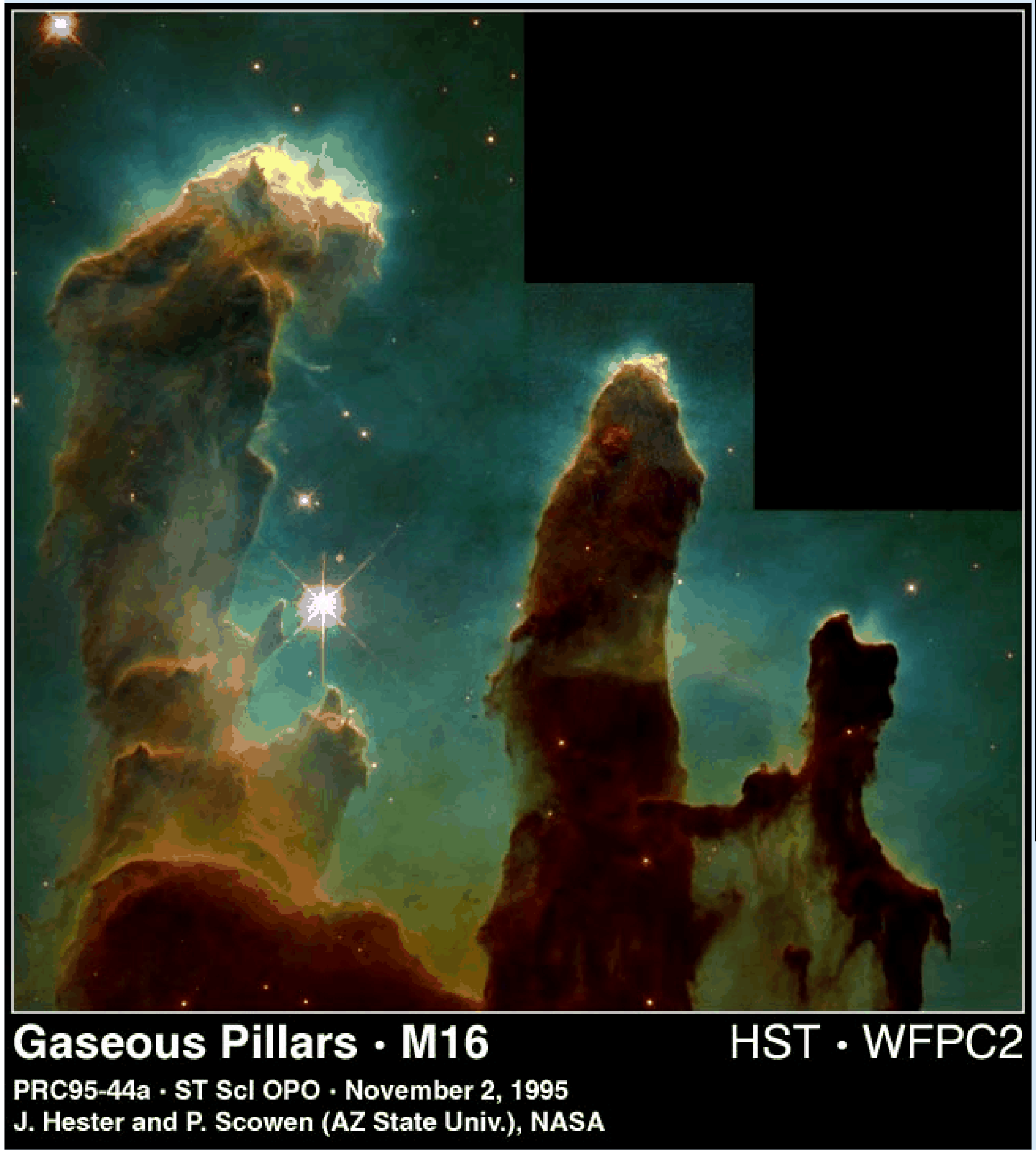

# 30 Doradus Details

Hubble Space Telescope • WFPC2 • NICMOS

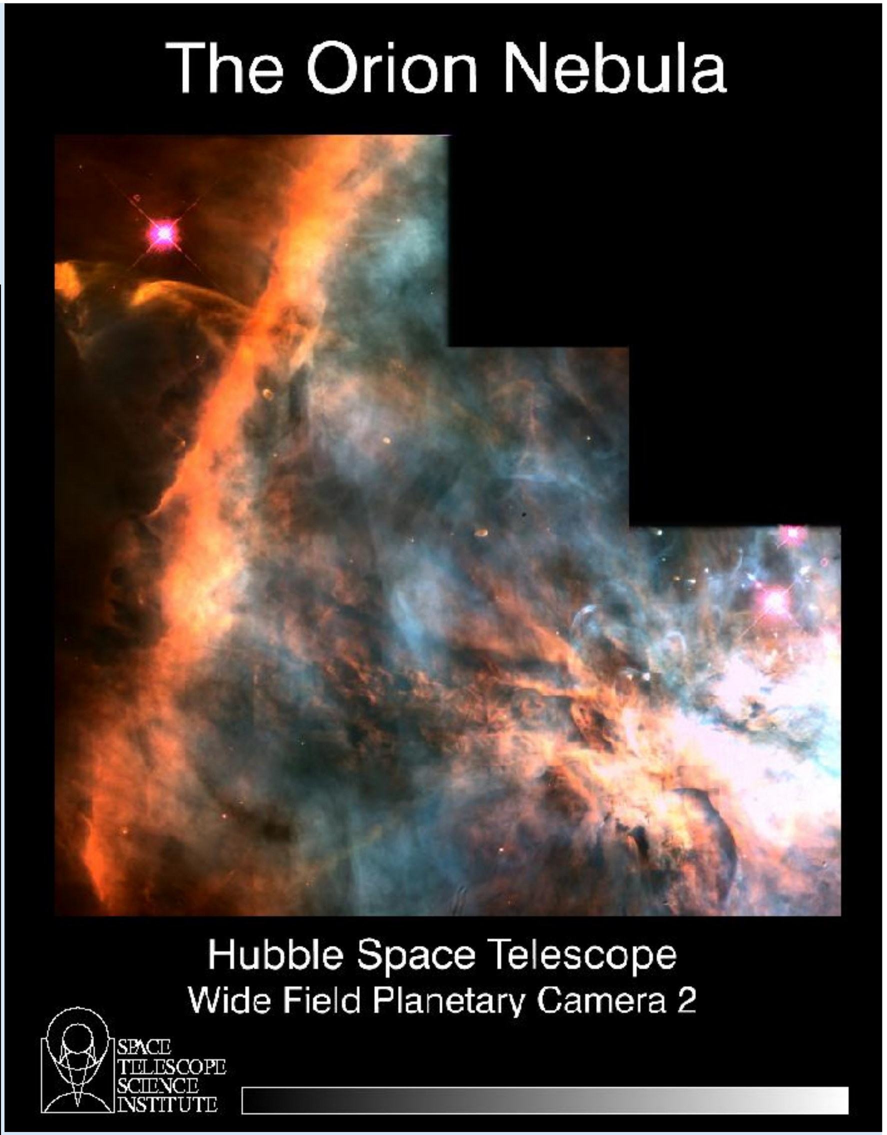
PRC99-33b • STScI OPO • N. Walborn (STScI), R. Barbá (La Plata Observatory) and NASA

# Gaseous Pillars
in the Eagle Nebula
(Messier 16)





Gaseous Pillars · M16
HST · WFPC2
PRC95-44a · ST ScI OPO · November 2, 1995
J. Hester and P. Scowen (AZ State Univ.), NASA

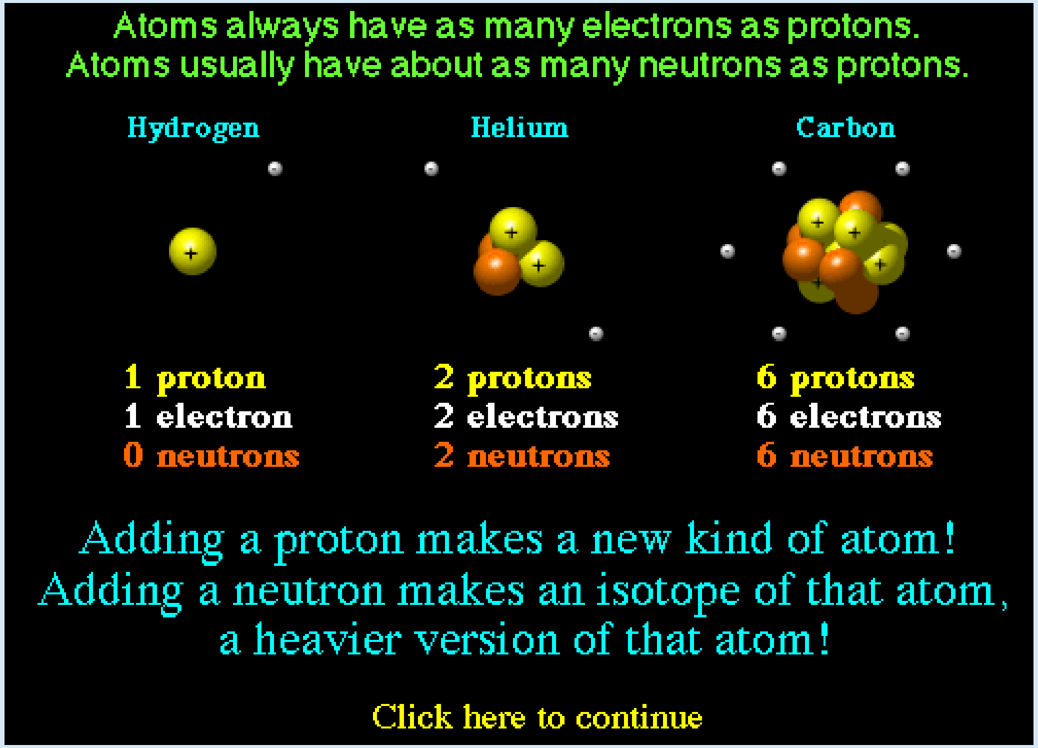
The Orion Nebula
Hubble Space Telescope
Wide Field Planetary Camera 2
SPACE TELESCOPE SCIENCE INSTITUTE

# ***Nuclear fusion reactions***

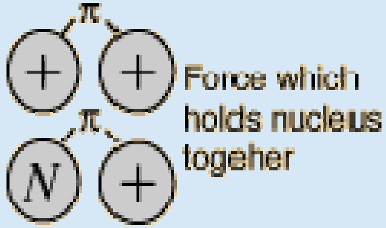
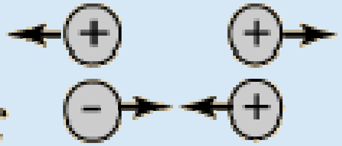
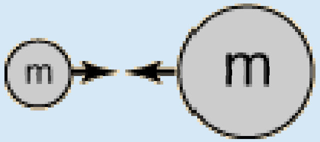
Fusion is the process by which small nuclei of atoms are joined into larger ones, and in this much energy is generated.

Hydrogen and Helium are the most abundant elements in the Universe, so fusion is important and these are the most common fuels.

Electromagnetic forces would keep two protons away from each other. However quantum mechanics allows them to 'tunnel' through the repulsion barrier and allows nuclear forces to 'turn on' when they are close enough (~$10^{-15}$ m).



# The four fundamental forces of Nature

| Force | | Strength | Range (m) | Carrier | Particles acted on |
|---|---|---|---|---|---|
| *Strong nuclear* |   | 1 | $10^{-15}$ (diameter of a medium sized nucleus) | gluons, | quarks (make up $p$ and $n$) |
| *Electro-magnetic* |  | $\frac{1}{137}$ | Infinite | photon<br>mass = 0<br>spin = 1 | any particle with charge |
| *Weak nuclear* |   | $10^{-6}$ | $10^{-18}$ (0.1% of the diameter of a proton) | Intermediate vector bosons<br>$W^+$, $W^-$, $Z_0$,<br>mass > 80 GeV<br>spin =1 | quarks and leptons ($e$, $\mu$, $\tau$, $\nu$) |
| *Gravity* |   | $6 \times 10^{-39}$ | Infinite | graviton ?<br>mass = 0<br>spin = 2 | any particle with mass |

# ***Proton and neutron masses***

Proton mass = 1.6725 x $10^{-27}$ kg charge = +e
Neutron mass = 1.6748 x $10^{-27}$ kg charge = 0
(e = 1.6 x $10^{-19}$ Coulomb)

Protons and neutrons are made up of quarks. There are 6 types of quarks (*up*, *down*, *charm*, *strange*, *top*, *bottom*); the only stable ones are *up* and *down*, and they differ by electric charge and mass: *up* has charge +2/3 e, *down* -1/3 e
*up* has smaller mass than *down*
(but precise values not known yet)

Proton = 2 *up* + 1 *down* → charge = +e

Neutron = 1 *up* + 2 *down* →charge = 0

... and protons have smaller mass than neutrons

## ***Mass deficit and binding energy*** ***(ZG Ch. 16)***

The simplest fusion reaction, becoming significant at T ~ $10^7$ K, involves 2 protons (H nuclei) and 2 neutrons combining in the next stable nucleus, $^4$He (α particle).

Atomic mass of proton: 1.0078 amu
Atomic mass of 4 protons: 4.0312 amu
Atomic mass of $^4$He nucleus: 4.0026 amu ➔ mass deficit of 0.0286 amu

amu: atomic mass unit (1/12 of the mass of a $^{12}$C atom, = 1.66 x $10^{-27}$ kg)

Mass deficit = nuclear binding energy that holds nucleus together

Mass deficit converted into energy according to Einstein's equation:

$$E = mc^2 = 0.0286 \times (1.66 \times 10^{-27}) \times (9 \times 10^{16})$$
$$= 4.3 \times 10^{-12} \text{ Joule}$$

## Total nuclear energy in the Sun (ZG Ch. 16)

Assume 10% of H in the Sun (temperature and density are high enough only in the core) converts into $^4$He.

Fraction of mass liberated into energy: $\frac{0.0286}{4.0312} = 0.0071$
(i. e. efficiency ~ 0.7%)

So

$$\boxed{\begin{aligned} E_{\text{total}} &= mc^2 = 0.0071 \times 0.1 \times M_{\text{Sun}} \times c^2 \\ &= 0.0071 \times 0.1 \times (2 \times 10^{30}) \times (9 \times 10^{16}) \text{ Joule} \\ &= 1.3 \times 10^{44} \text{ Joule} \end{aligned}}$$

Then the Sun can continue to radiate for

$$\boxed{\frac{E_{\text{total}}}{L_{\text{Sun}}} = \frac{1.3 \times 10^{44}}{4 \times 10^{26}} \text{ s} = 3 \times 10^{17} \text{ s} = 10^{10} \text{ yr}}$$

Solar system age: 5 x $10^9$ years ➔ Sun is ~ halfway through its H-burning phase

# ***Fusion processes for H → He***

Simultaneous collision of 4 protons very unlikely!

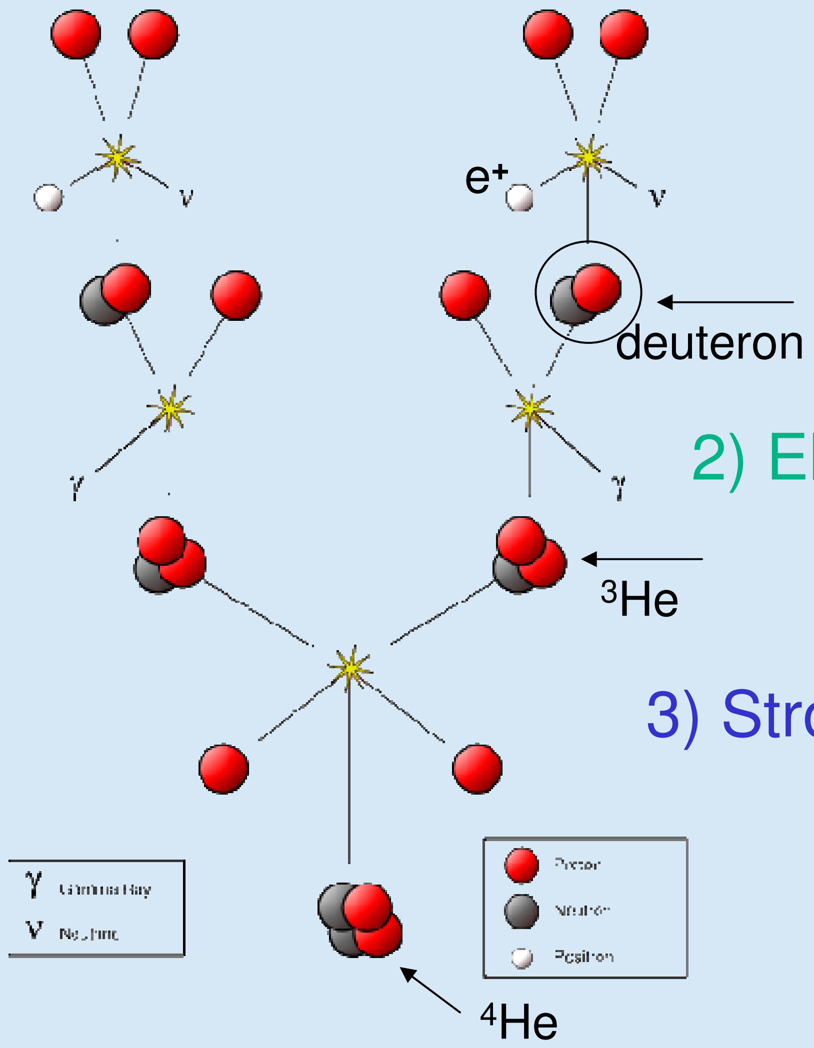
Two thermonuclear processes lead to conversion H → He:

1) Proton-proton chain (PP)
   Dominates at $T < 2 \times 10^7$ K
2) Carbon cycle (CNO)
   Dominates at higher temperatures
   (contributes 2% of solar energy)

Particles involved: Protons, neutrons, electrons,
positrons, $e^+$ (= electrons, but charge = $+e$)
neutrinos, $\nu$ (very small mass, no charge, only energy and spin)

# Proton-proton chain (PP1)

Mass difference before and after turned into energy: $E = mc^2$




1) Weak nuclear force ($5 \times 10^9$ yr)

➔ 0.42 + 1.02 = 1.44 MeV

2) Electromagnetic force (1 s)

➔ 5.49 MeV

3) Strong nuclear force ($3 \times 10^5$ yr)

➔ 12.86 MeV

Total energy produced from mass conversion: 26.7 MeV.

Dominates in stars the size of the Sun, or less. Slow step 1 ensures Sun does not exhaust its fuel too quickly!

# ***Proton-proton chains (PP1, PP2, PP3)***

Proton-proton chain PP1 takes place 86% of the times.

Other PP reactions occur less frequently, thus contribute less to the Sun's luminosity.

Following first two steps of PP1,

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

PP2 (14%) - $^{7}Be + e^{-} \rightarrow {}^{7}Li + \nu$ $E_{\nu}$ = 0.86 MeV, 90%

$^{7}Li + {}^{1}H \rightarrow {}^{4}He + {}^{4}He$ = 0.38 MeV, 10%

PP3 (0.1%) - $^{7}Be + {}^{1}H \rightarrow {}^{8}B + \gamma$

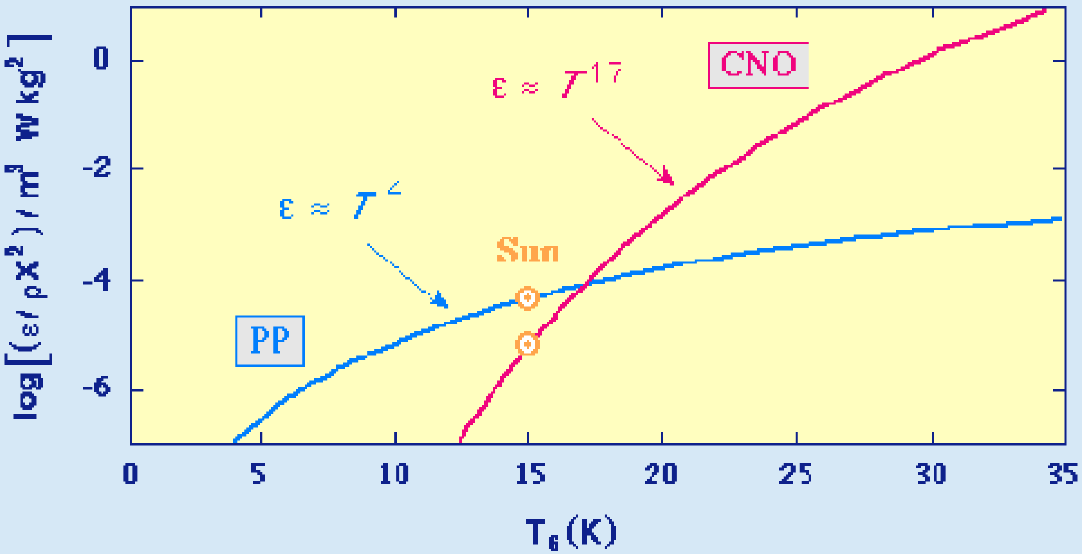
$^{8}B \rightarrow {}^{8}Be + e^{+} + \nu$ $E_{\nu}$ up to ~15 MeV

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

# ***Proton-proton chains vs CNO cycle***

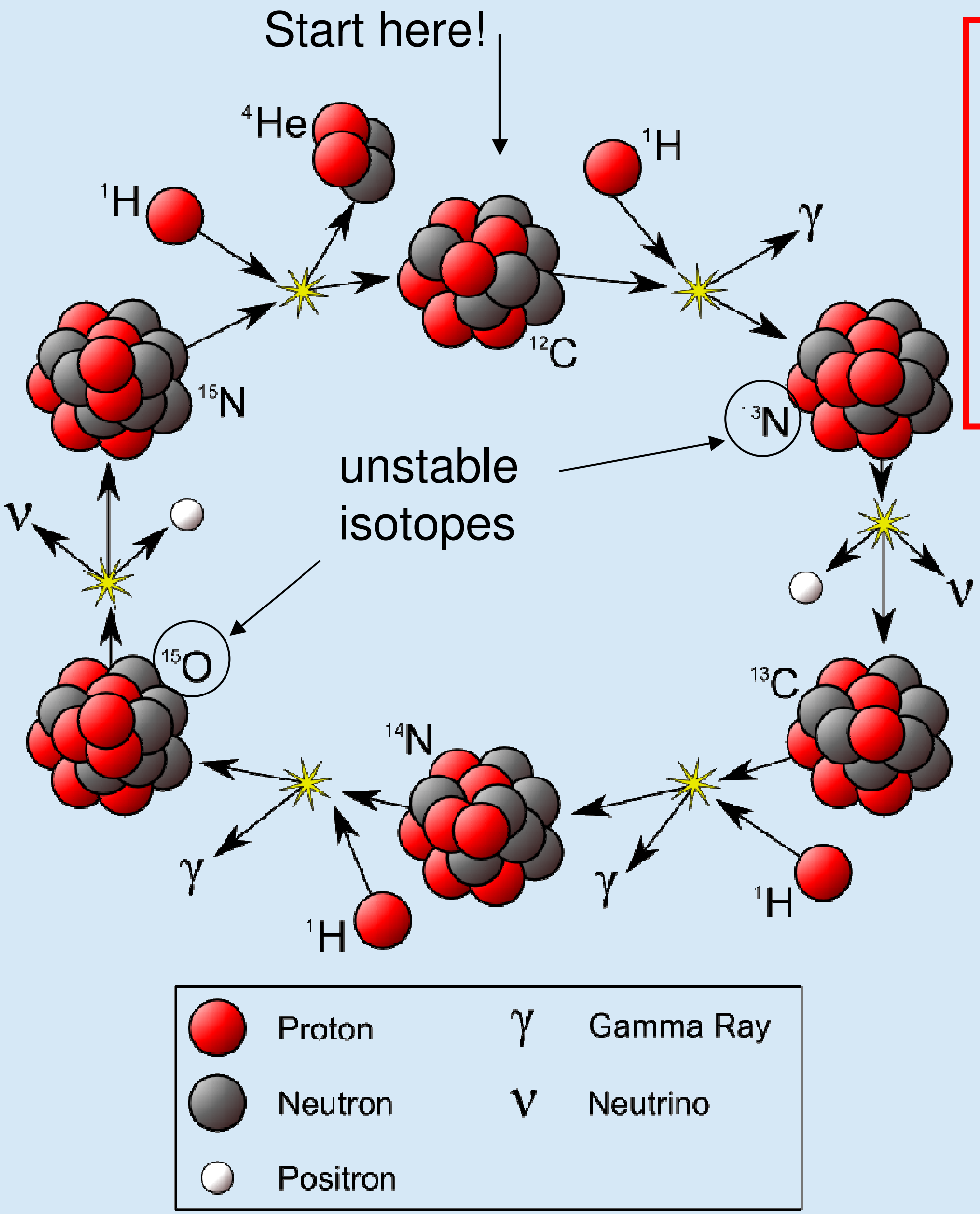
PP chains and CNO cycle compete with each other in the production of fusion energy.

CNO cycle requires C, N and O to be present. Also energy production rates have different temperature dependence:




CNO cycle dominates at high temperatures → more important in more massive stars, which have higher interior temperatures.

# ***The CNO cycle***




Net result is to fuse four protons into an α-particle (Helium nucleus, $^4$He).
C, N and O nuclei serve as catalysts.

CNO cycle, proposed in 1938 by Hans Bethe, is dominant source of energy in massive stars. Also needs C to be present!

Total energy production from mass conversion is ~ 25 MeV.

# Further fusion processes

At $T$ > $10^8$ K, other reactions start transforming He into heavier elements:

Triple-α or He burning

$$^4\text{He} + {}^4\text{He} \rightarrow {}^8\text{Be} + \gamma \qquad (^8\text{Be unstable})$$

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

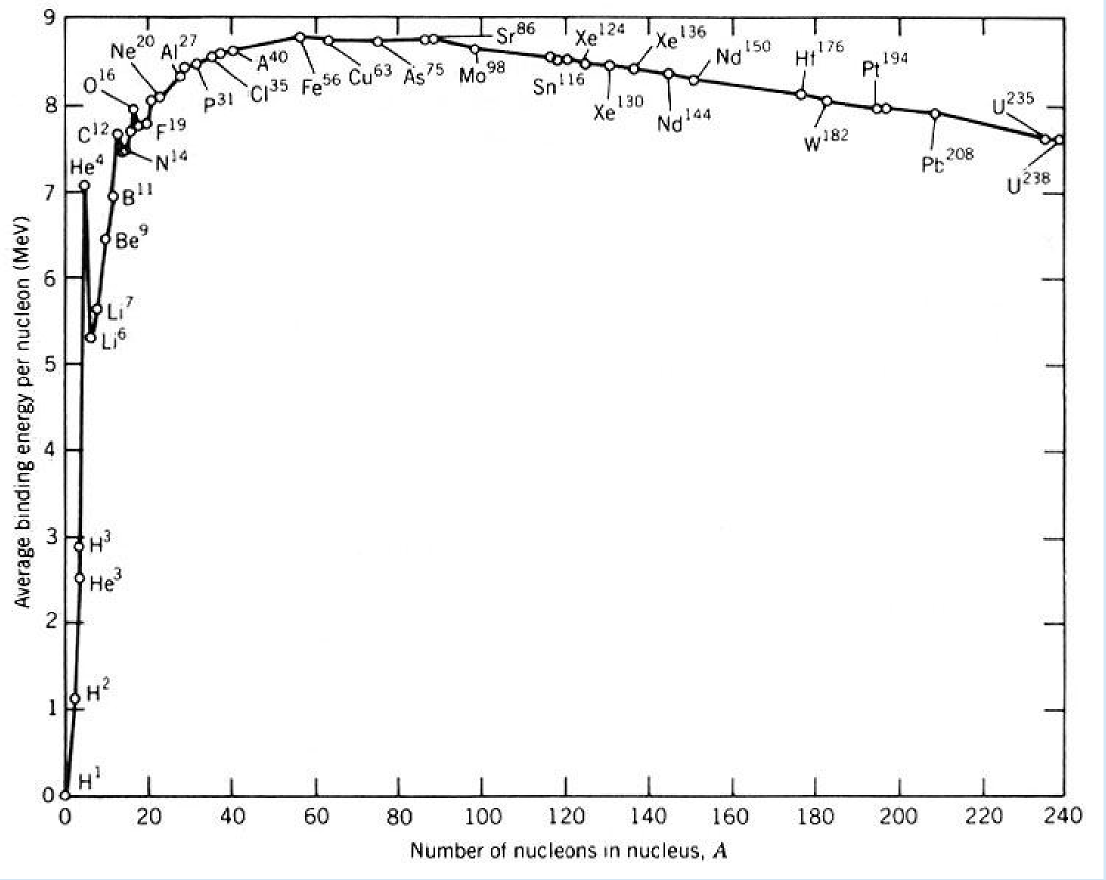
After all He has been burnt, C, Ne, O, Mg, Si burning take place: each stage requires higher $T$, up to ~3 x $10^9$ K, and higher densities, thus more massive stars.

Process stops when stellar core is made up of $^{56}$Fe (further fusion would absorb energy!)

➔ Hydrostatic equilibrium no longer holds ➔ star collapses

➔ Supernova

# ***Average binding energy per nucleon***




Curve peaks around $A$ = 60 ($^{62}$Ni is the tightest bound nucleus, but $^{56}$Fe is 10x more abundant)

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

# ***Thermonuclear energy generation in stars***

Only energy released as $\gamma$-rays will interact with electrons and protons and heat the interior of a star, such as the Sun. This heating supports the star and prevents it from collapsing under its own weight.

Neutrinos do not interact significantly with matter and do not help support the Sun against gravitational collapse. In a few seconds they escape.

The neutrinos in the PP1, PP2 and PP3 chains carry away 2.0%, 4.0% and 28.3% of the energy respectively.

Thus it will be possible to <u>detect the neutrinos on Earth</u> and <u>verify</u> the theory of the thermonuclear reactions occurring in the Sun (Solar Standard Model = SSM).

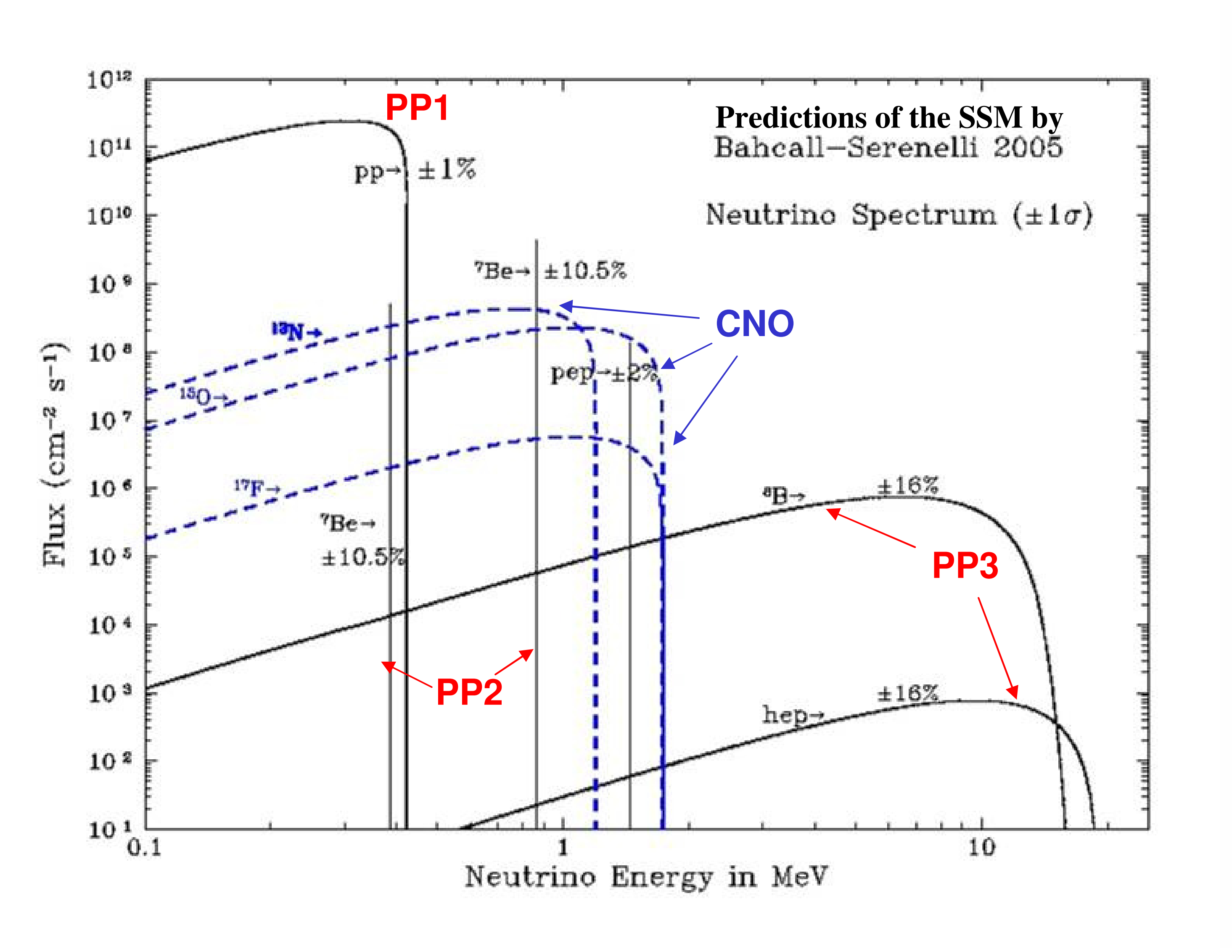
# ***Three neutrino 'flavours'***

Three types of neutrinos are known:

Nuclear fusion in the Sun produces only neutrinos that are associated with electrons ('electron neutrinos', $\nu_e$) .

Laboratory accelerators or exploding stars produce 'muon neutrinos' ($\nu_\mu$) and 'tau neutrinos' ($\nu_\tau$), which are associated with the muon and tau particles (leptons heavier than the electron).

# *The solar electron neutrino $\nu_e$ energy spectrum*



## ***Solar Neutrino Problem (1)***

From H burning in the Sun's core, ~ 2 x $10^{38}$ neutrinos $s^{-1}$ expected to be produced ➔ ~ 7 x $10^{14}$ neutrinos $m^{-2}$ $s^{-1}$ at Earth

Since the 1960s neutrino detectors have been built on the Earth to measure the flux of solar neutrinos and verify the SSM:

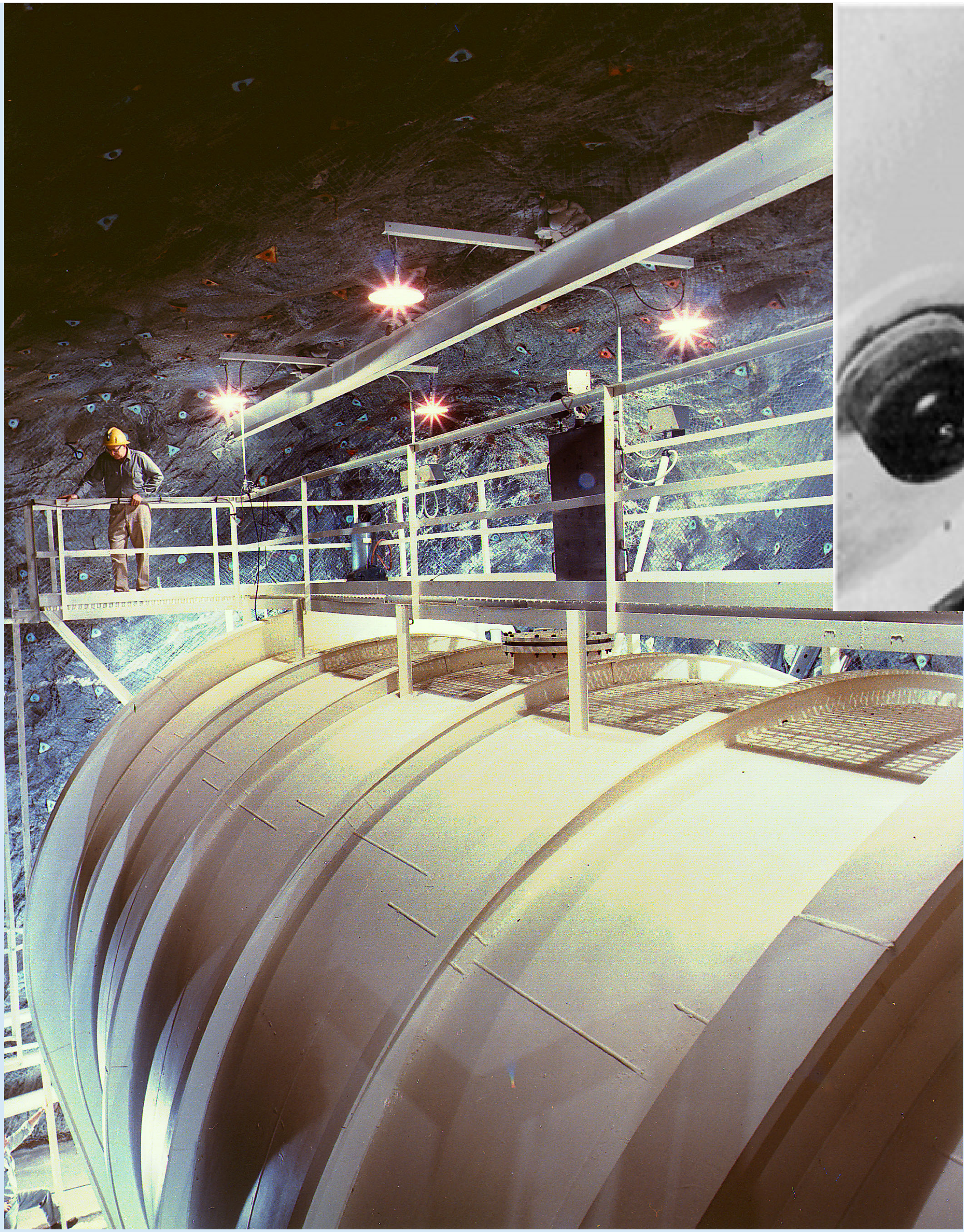
Mid -1960s - Raymond Davis, Homestake gold mine (South Dakota, USA) experiment, using a tank of 100,000 gallons of tetrachloroethylene $C_2Cl_4$ one mile underground:

solar neutrinos transmute $^{37}Cl \rightarrow {}^{37}Ar$ (radioactive)

number of $^{37}Ar$ atoms ➔ solar neutrino flux

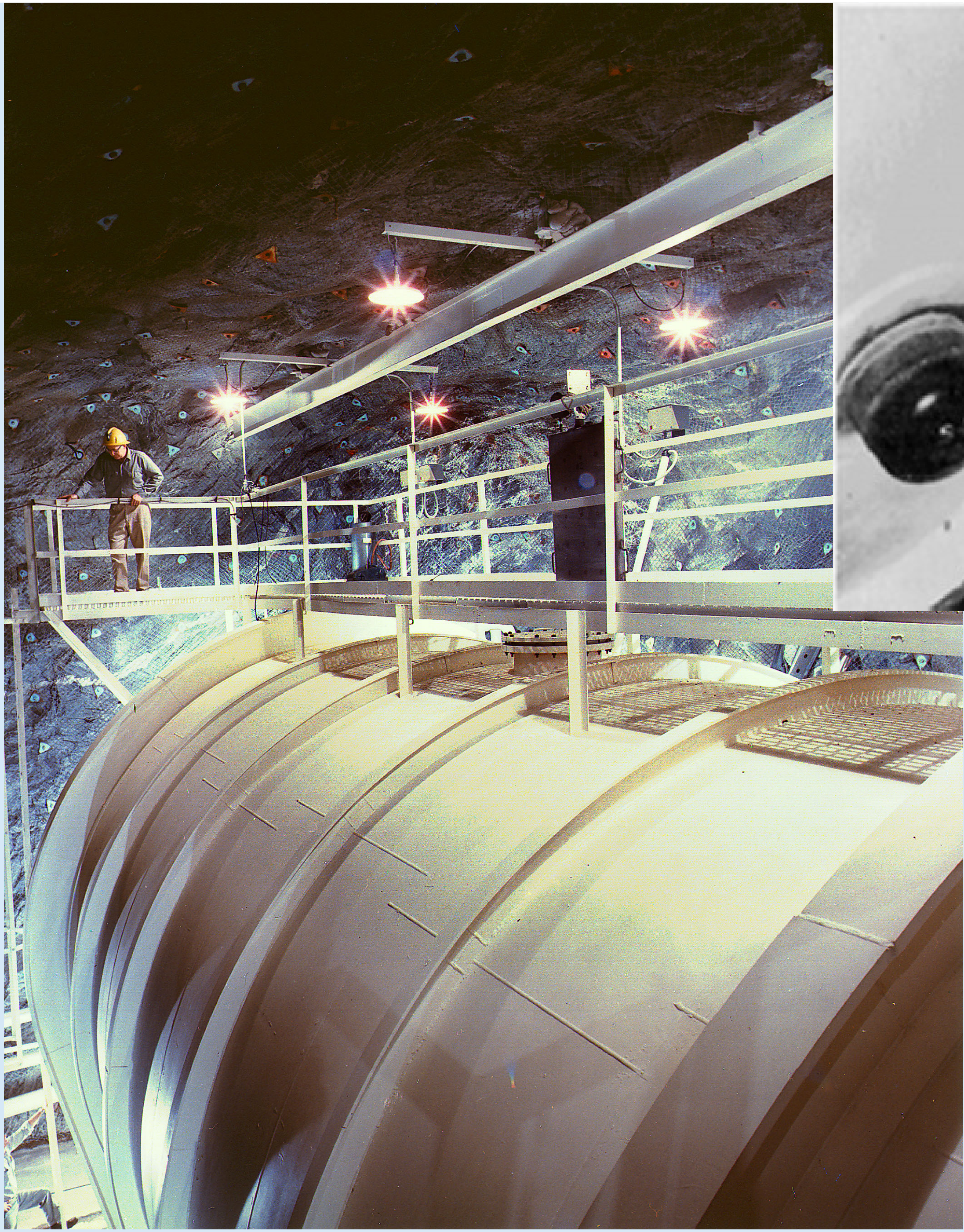
Only 1/3 of expected high-energy (PP3) neutrinos detected

➔ 'Solar Neutrino Problem' (SNP) !



Davis and Bahcall, 1967

So, what’s SNU?



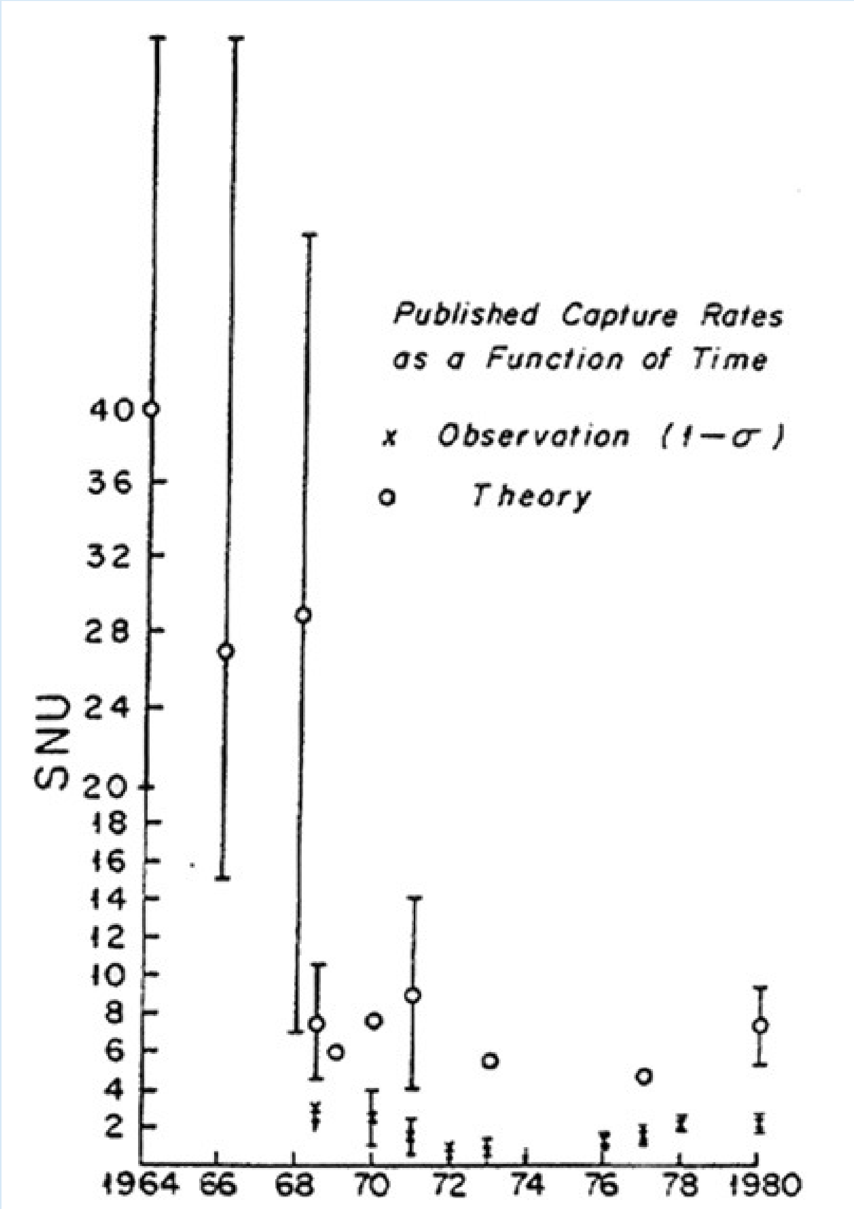
Davis and Bahcall, 1967

So, what’s SNU?

Solar Neutrino Unit =
Number of captures
per second per $10^{36}$
target atoms

# ***Solar Neutrino Problem (2)***

At the same time that experiments were improving in sensitivity, theoretical modelling of the energy generation in the Sun was evolving, and more and more accurate calculations (particularly by John Bahcall) were carried out to predict the number of expected neutrinos (very dependent on Sun's core temperature):

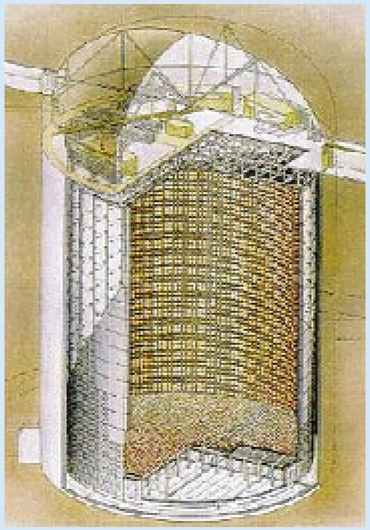


# ***Solar Neutrino Problem (3)***

1989, Kamiokande experiment (water detectors) - only 1/2 of expected high-energy PP3 neutrinos

Early 1990s, GALLEX (GALLium EXperiment), and SAGE (RuSsian American Gallium Experiment) detected just over 1/2 of low-energy neutrinos from PP1 (important because dominant, and calculations more accurate – confirmed PP is the main energy production mechanism in the Sun)

Late 1990s, Super-Kamiokande → (with some sensitivity to flavours other than electron neutrinos) confirmed high-energy PP3 neutrino deficit by ~50%



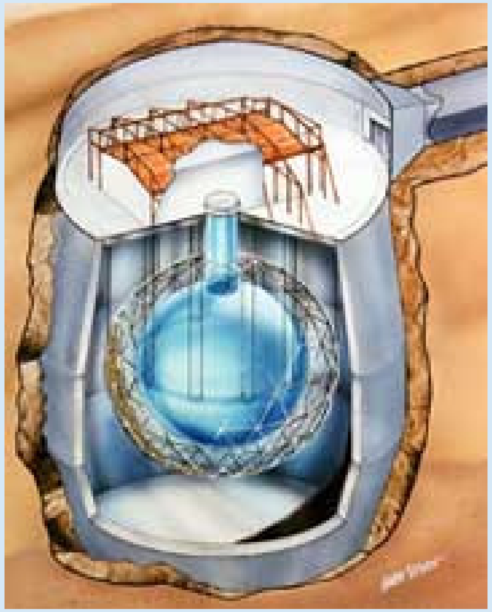
# ***Solar Neutrino Problem (4)***

Relative sensitivity of Cl and water experiments to neutrino number and energy suggested something was happening to neutrinos on their way from Sun to Earth.

Meanwhile, SSM being tested, and becoming more reliable
➔ Need new neutrino physics? (as suggested by Pontecorvo and Gribov back in 1969) but very hard to challenge established Standard Model of Particle Physics!

1999, SNO (Sudbury Neutrino Observatory)

heavy water ($D_2O$) experiment came on-line with similar sensitivity to all three types of neutrinos ➔ detection of $\nu_\mu$ and $\nu_\tau$ as well as $\nu_e$



# ***Solution of the Solar Neutrino Problem***

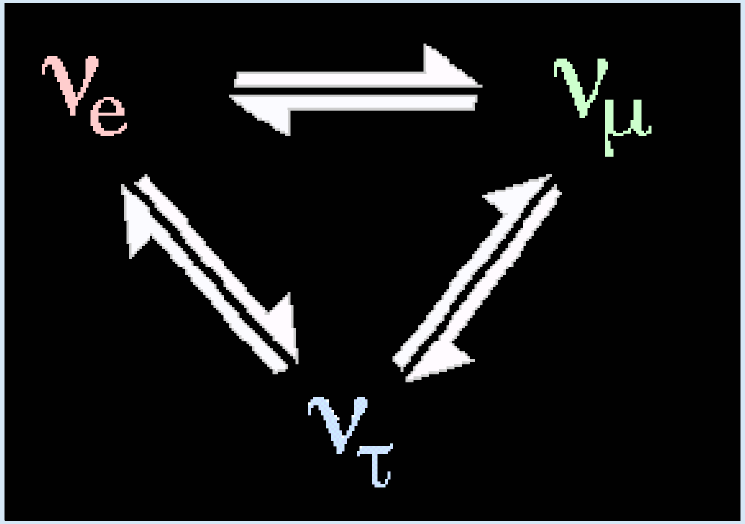
18 June 2001, SNO collaboration announced SNP solution:

~2/3 $\nu_e$ produced in the Sun transform into $\nu_\mu$ and $\nu_\tau$ on their way to Earth

Total number of $\nu_e$, $\nu_\mu$, $\nu_\tau$ is = SSM predictions

Explained by the Mikheyev-Smirnov-Wolfenstein (MSW) effect of 'neutrino oscillations' (enhanced by passage through the Sun)

For neutrino oscillations to occur, neutrinos must have masses (and the Standard Model of Particle Physics has to be revised!)



## ***The mass of neutrinos***

Different flavour neutrinos have different masses, with $\nu_e$ being the lightest

From experiments, $\nu_e$ mass < 2.2 eV
From cosmology, sum of masses < 1 eV

Among current experiments, MINOS and NEMO3 (with UCL, P&A Dep.t participation) → few 0.1 eV mass sensitivity limit

Future experiments planned may reach mass sensitivity limit ~0.01 eV (SUPERNEMO)

2002, Nobel Prize in Physics to Raymond Davis and Masatoshi Koshiba for the detection of cosmic neutrinos