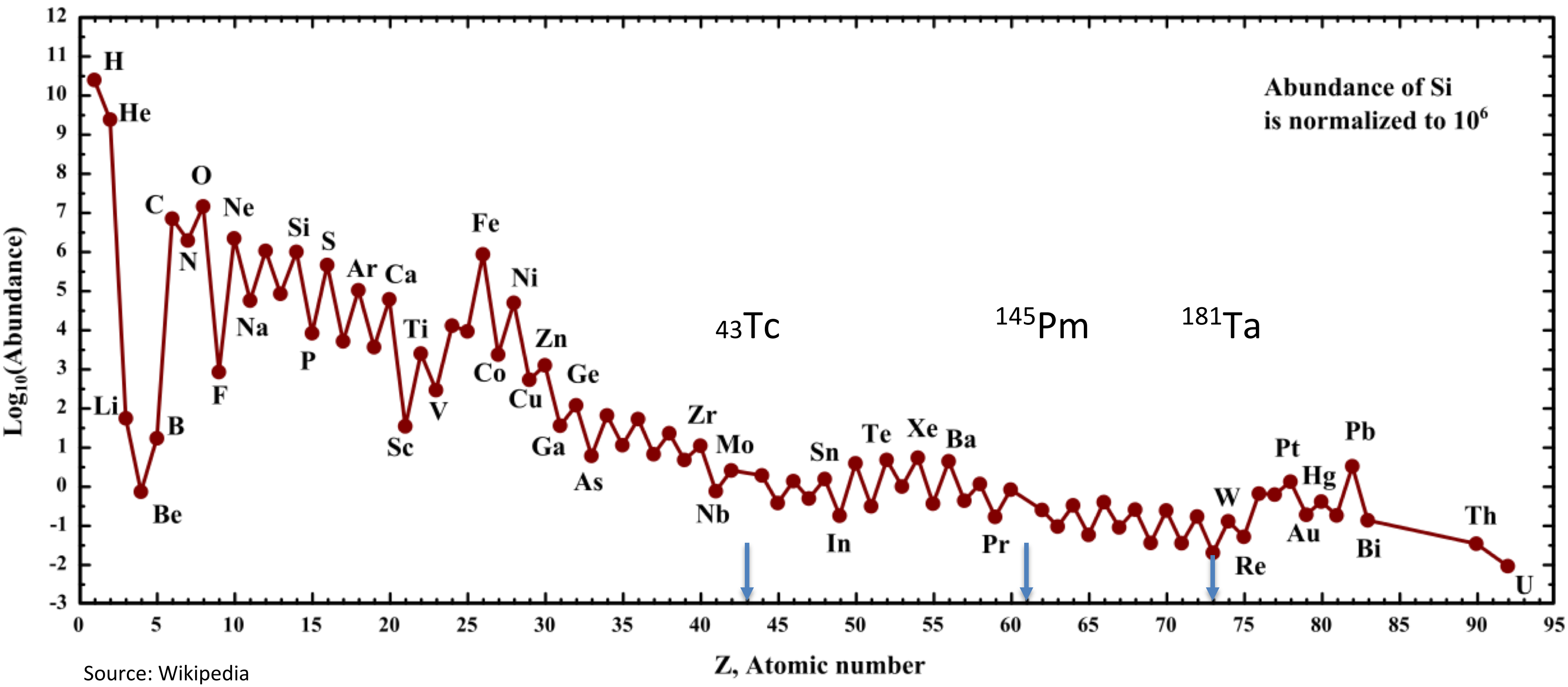
SOLAR ABUNDANCES - KEY FACTS



Source: Wikipedia

^{98}Tc: life time 4.2 My

^{145}Pm: life time 17.7a

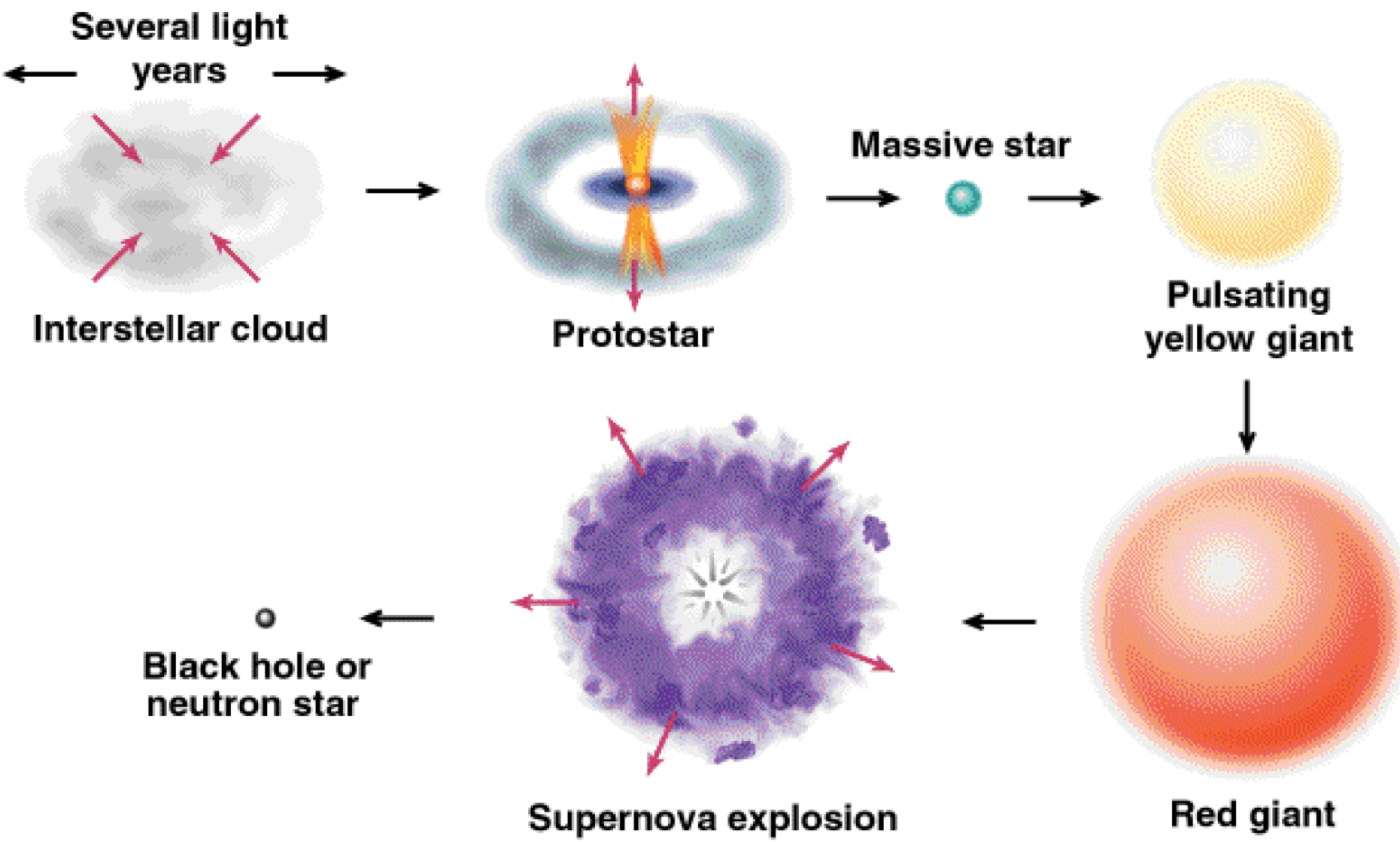
^{181,180}Ta: (meta)stable

ELEMENT FORMATION IN STARS,

FROM H AND HE TO FE

pbm

Life of a High Mass Star



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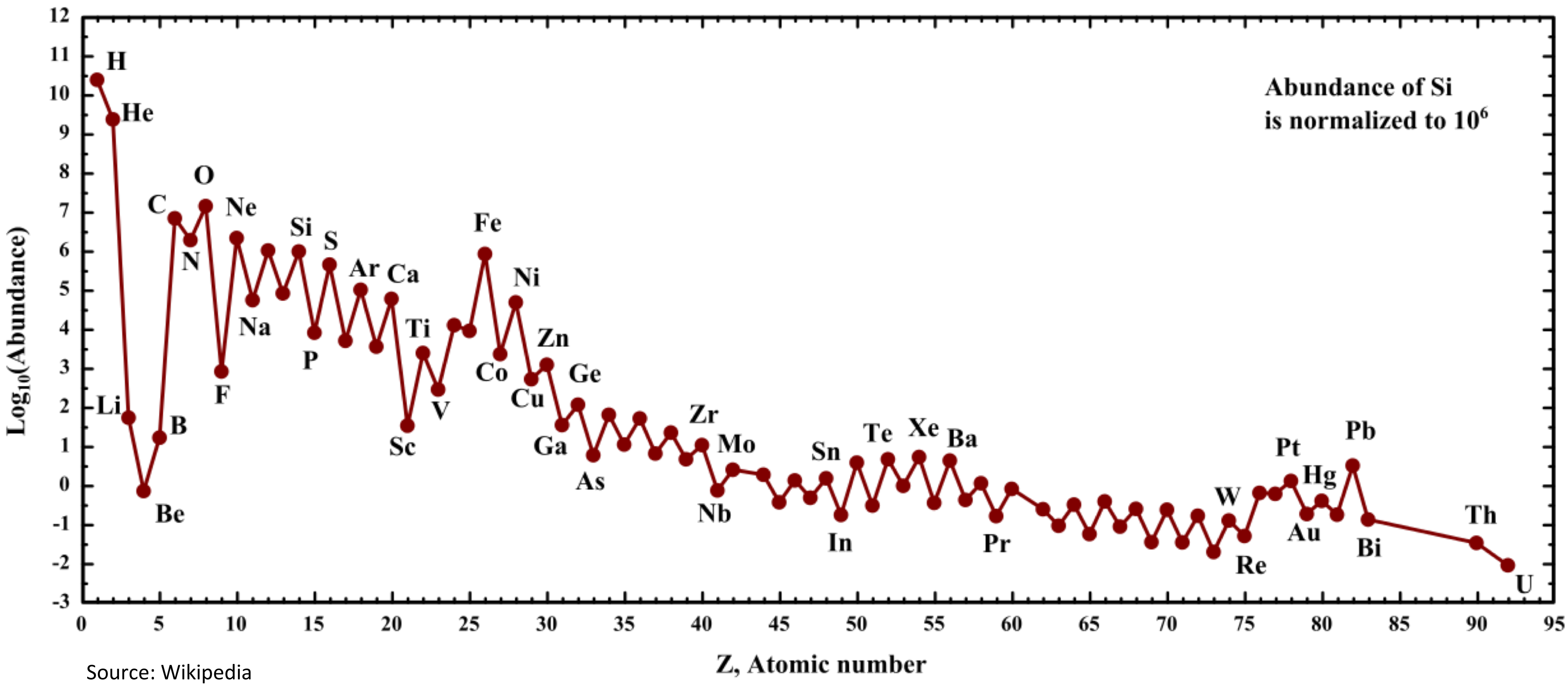


Source: Wikipedia

Decrease in abundance with atomic number:

- Large negative anomaly at Be, B, Li
- Moderate positive anomaly around Fe
- Sawtooth pattern from odd-even effect

ORIGIN OF ELEMENTS - FROM H TO FE

The Big Bang: H, D, $^{3,4}He$, Li

All other nuclei were synthesized in stars

Stellar nucleosynthesis ⇔ 3 key processes:

- Nuclear fusion: pp cycles, CNO bi-cycle, He burning, C burning, O burning, Si burning ⇒ till ^{40}Ca

- Photodisintegration rearrangement: Intense gamma-ray radiation drives nuclear rearrangement ⇒ ^{56}Fe

HYDROGEN BURNING

Coulomb repulsion vs proton wave function tunneling

- No efficient two-particle reactions in H & He matter:

$^{1}H + {}^{1}H = {}^{2}He$ (unstable) $= {}^{1}H + {}^{1}H$

$^{1}H + {}^{4}He = {}^{5}Li$ (unstable) $= {}^{1}H + {}^{4}He$

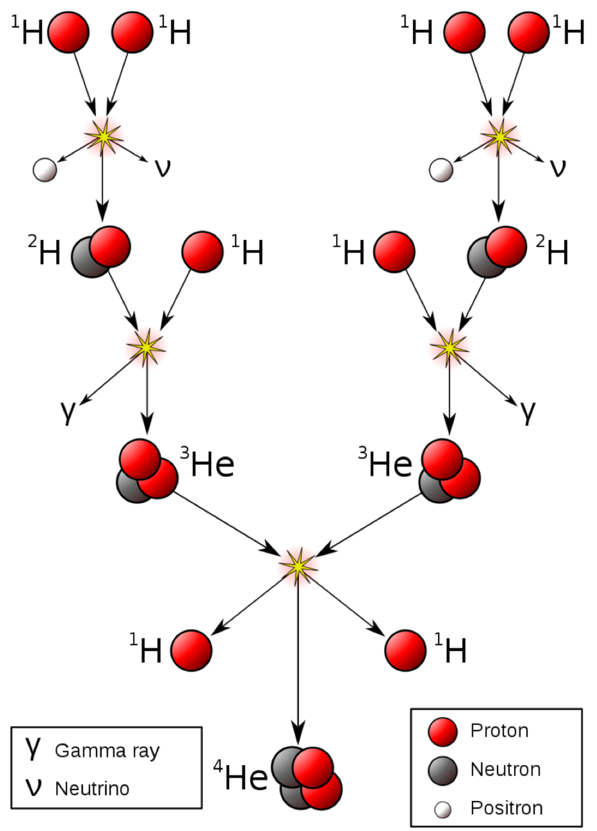
$^{4}He + {}^{4}He = {}^{8}Be$ (unstable) $= {}^{4}He + {}^{4}He$

- Hans Bethe (1939): hydrogen burning via formation of D:

$^{1}H + {}^{1}H = {}^{2}D + \beta^{+} + \nu + 1.442$ MeV

PP-I CYCLE

T > 4 x10^6 K



$$2 \times \begin{cases} (1) & {}^1H + {}^1H \rightarrow {}^2H + e^+ + \nu_e \;+\; 0.42\,\text{MeV} \\ (2) & {}^2H + {}^1H \rightarrow {}^3He + \gamma \;+\; 5.49\,\text{MeV} \end{cases}$$

← +1.02 MeV ee Annihilation

$$(3) \quad {}^3He + {}^3He \rightarrow {}^4He + 2\,{}^1H + 12.85\,\text{MeV}$$

$$4 \cdot {}^1H \rightarrow {}^4He + 2 \cdot (e^+ \nu_e) + 26.7\,\text{MeV}$$

PP-II AND PP-III CYCLE

T > 14 x10^6 K

$$ {}_{2}^{3}He + {}_{2}^{4}He \rightarrow {}_{4}^{7}Be + \gamma $$

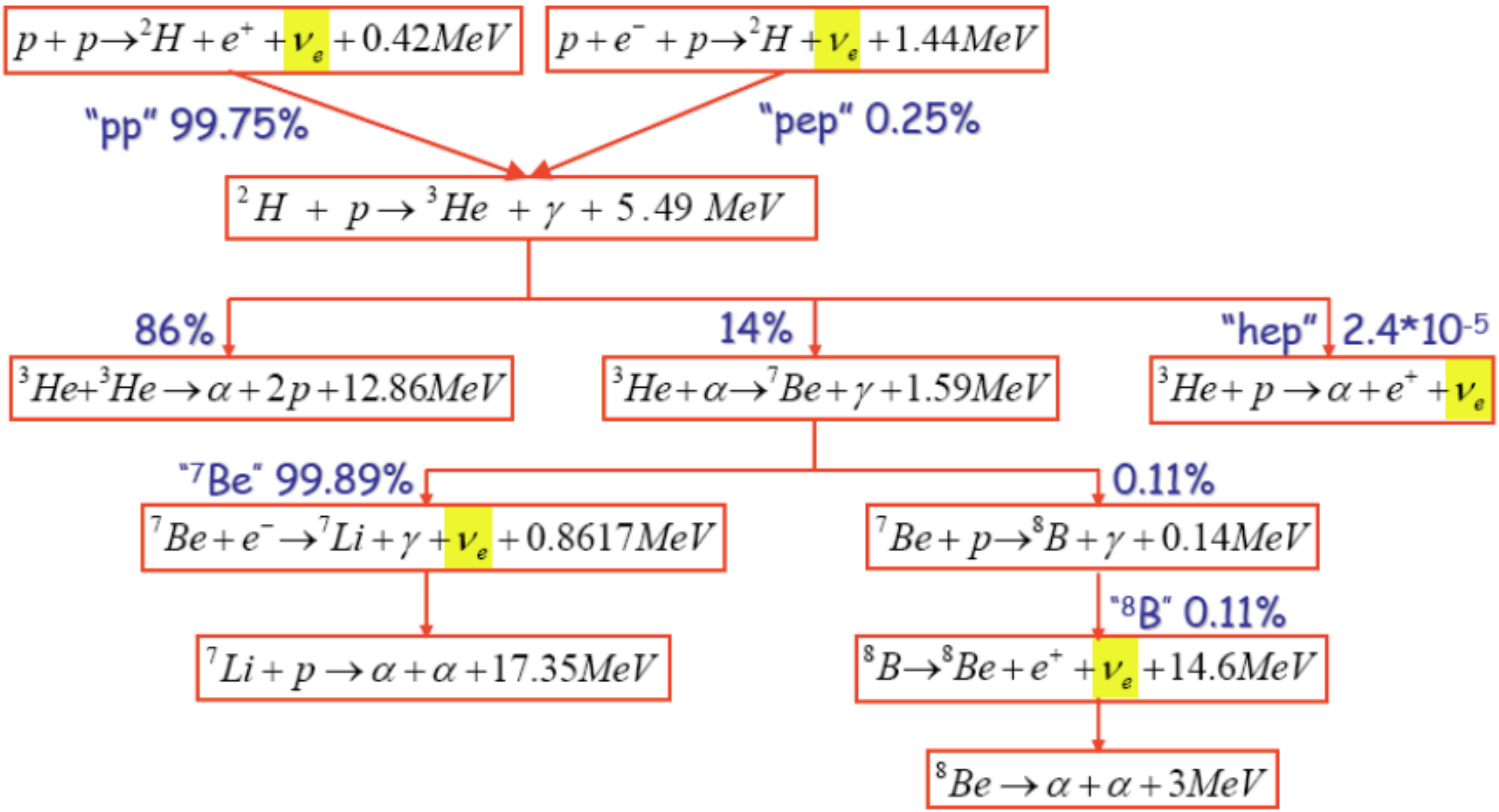
$$ {}_{4}^{7}Be + e^{-} \rightarrow {}_{3}^{7}Li + \underline{\nu} $$

$$ {}_{3}^{7}Li + p \rightarrow 2 \cdot {}_{2}^{4}He $$

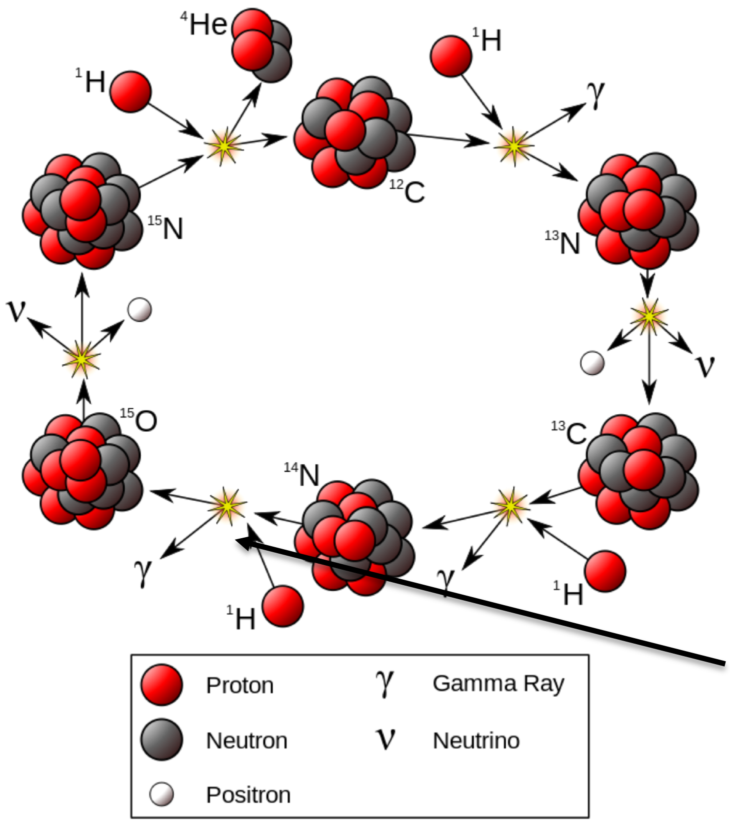
$$ {}_{4}^{7}Be + p \rightarrow {}_{5}^{8}B + \gamma $$

$$ {}_{5}^{8}B + e^{-} \rightarrow 2 \cdot {}_{2}^{4}He + \underline{\nu} $$

FULL PP CYCLE



CNO CYCLE



Bethe–Weizsäcker cycle

- Operates in stars with M > 1.3 M_{sun}
- $T > 15 \times 10^6$ K
- Still, it leads to: $4\ {}^1H \rightarrow {}^4He$ + energy

(catalytic cycle)

limiting (slowest) step

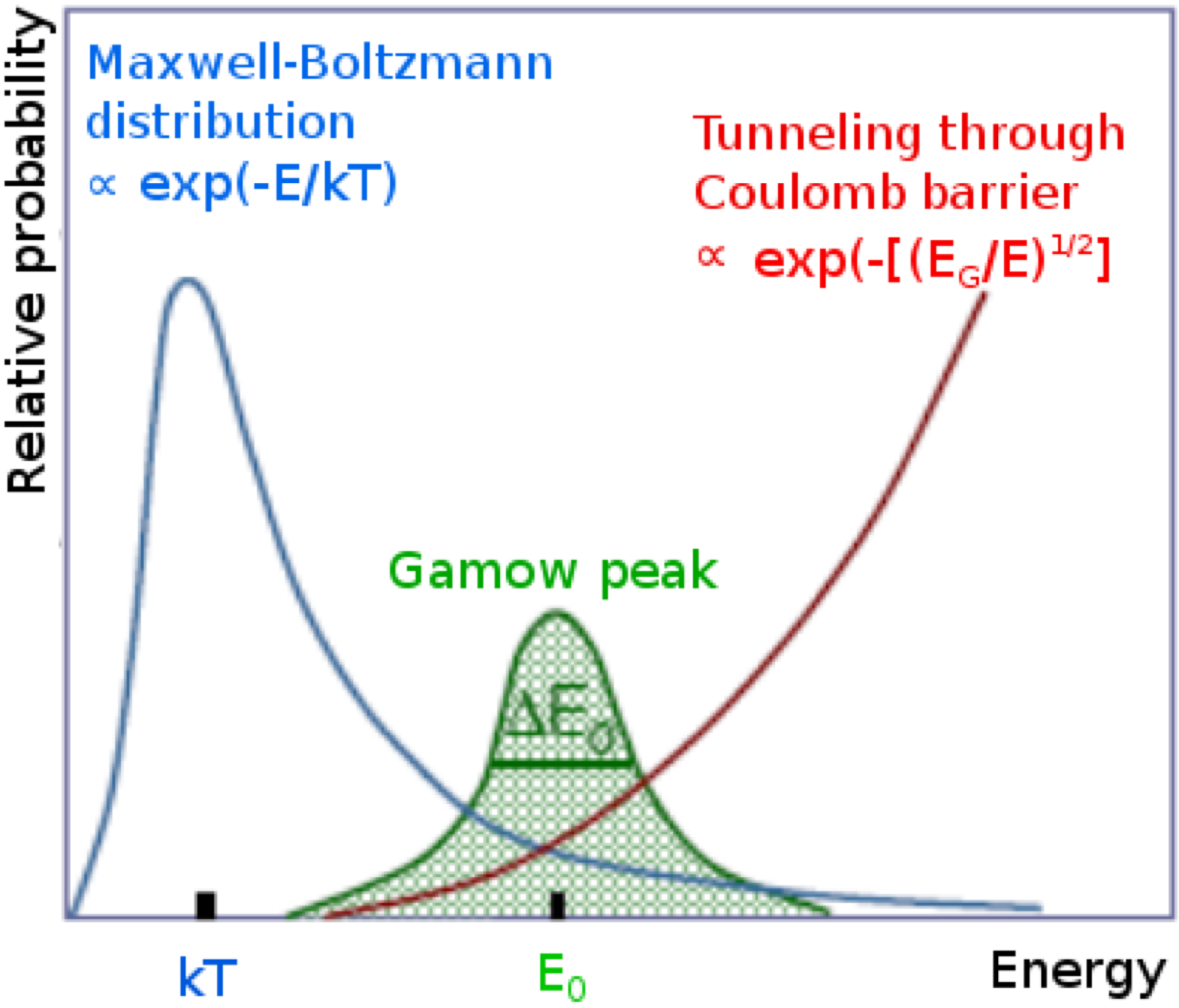
$$^{12}_{6}C \xrightarrow{p} {}^{13}_{7}N \xrightarrow{\beta^+} {}^{13}_{6}C \xrightarrow{p} {}^{14}_{7}N$$

$$\xrightarrow{p} {}^{15}_{8}O \xrightarrow{\beta^+} {}^{15}_{7}N \xrightarrow{p} {}^{12}_{6}C + {}^{4}_{2}He$$

Netto: $4 \cdot p \rightarrow {}^{4}_{2}He + 2 \cdot e^+ + 2 \cdot \nu_e$

Borexino: arxiv.org/abs/2105.09211

GAMOW PEAK



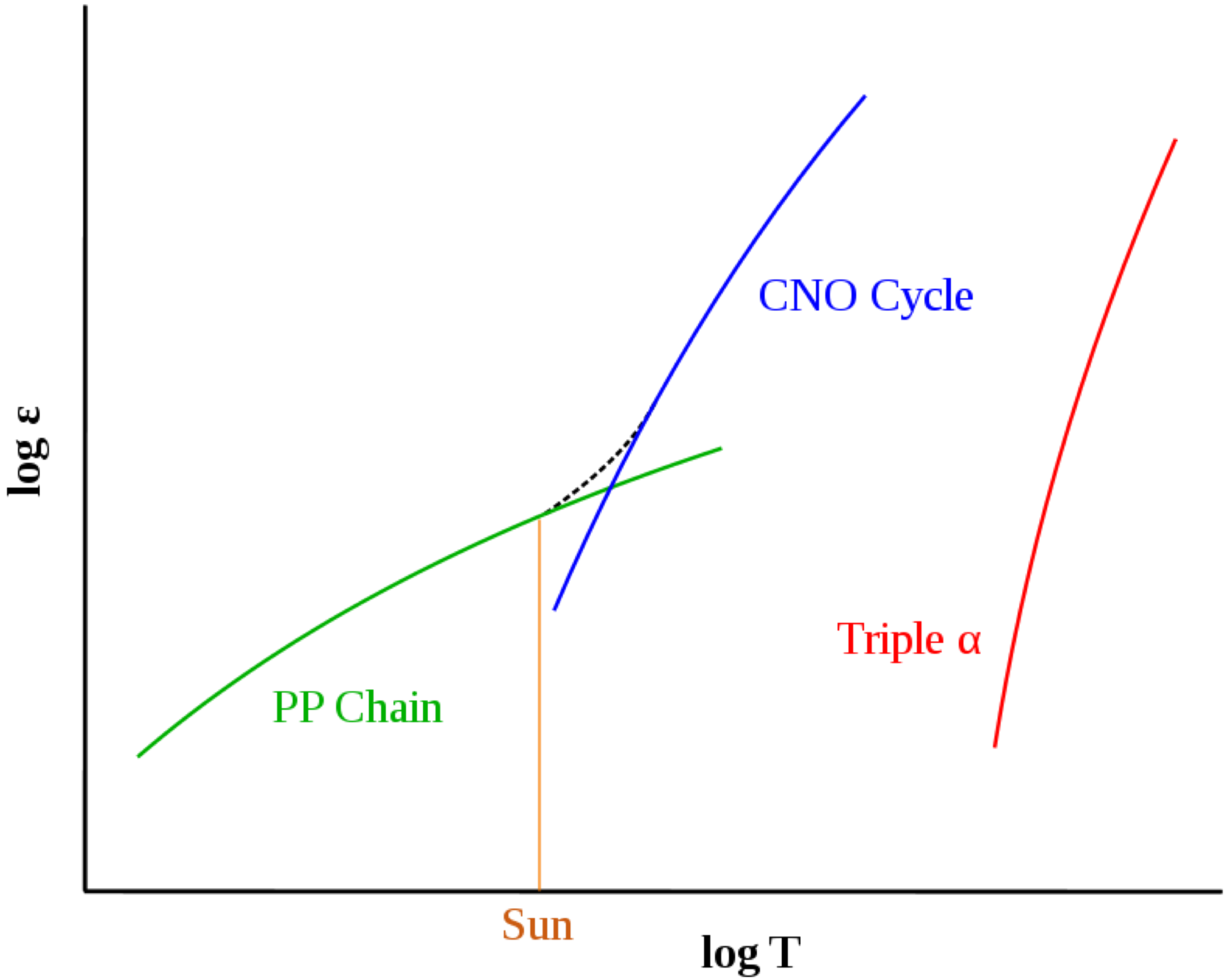
Coulomb barrier pp:

$$V_c \approx \frac{Z_P Z_T}{A_P^{1/3} + A_T^{1/3}} \approx 1 MeV$$

thermal energy, $T = 15 \cdot 10^6 K$

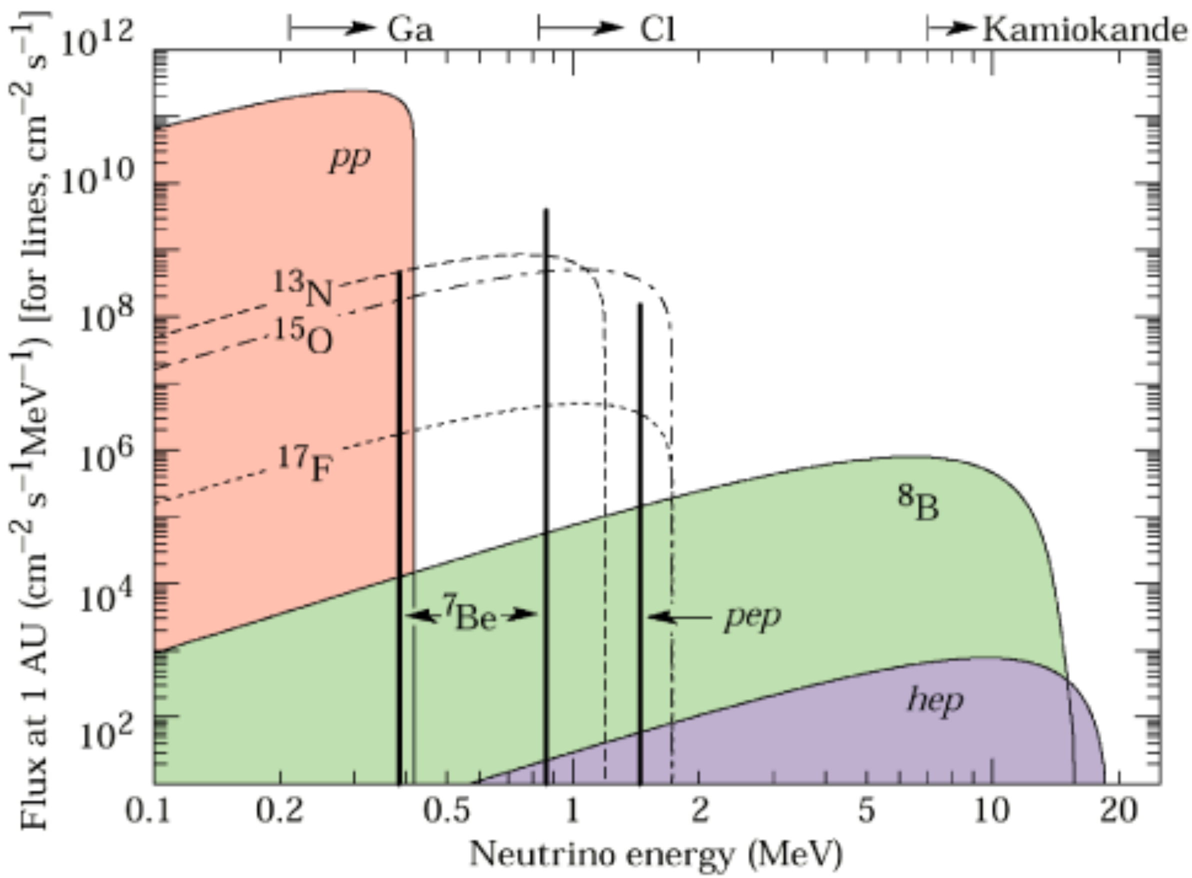
$3/2kT \approx 1.5 keV$

TEMPERATURE DEPENDENCE



SOLAR NEUTRINO SPECTRUM

J. Bahcall, A. Serenelli, S. Basu, ,The Astrophysical Journal621(1) (2005) L85



Cl_2 detector $\nu_e + {}^{37}Cl \rightarrow {}^{37}Ar + e$, ${}^{37}Ar \rightarrow {}^{37}Cl$ (EC) $E_\nu > 0.8$ MeV

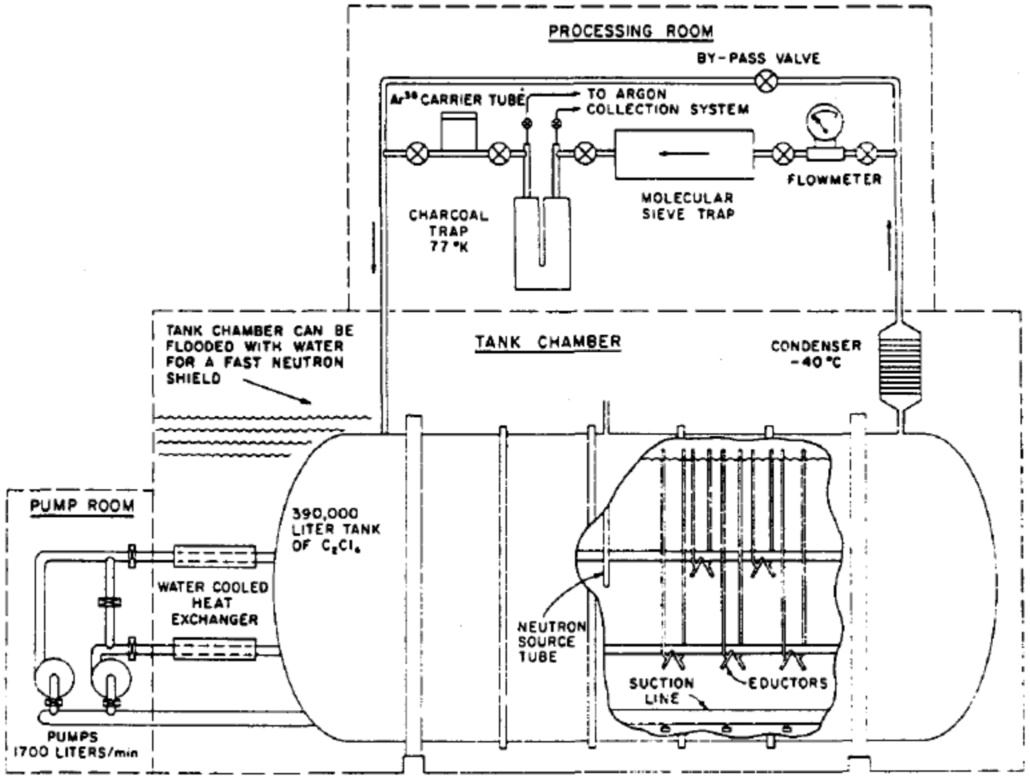
Ga detector $\nu_e + {}^{71}Ga \rightarrow {}^{71}Ge + e$ $E_\nu > 0.2$ MeV

H_2O detector elastic scattering: $\nu_e + e \rightarrow \nu_e + e$ $E_\nu > 5$ MeV

HOMESTAKE EXPERIMENT (1967 - 1994)

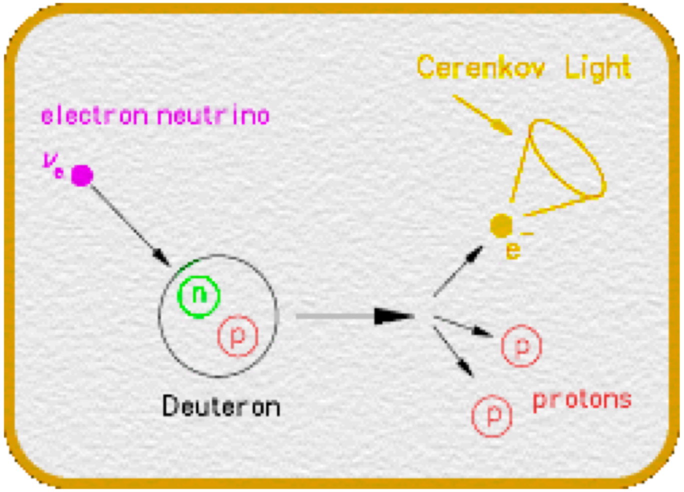
- Raymond Davis (Nobel Price 2002)
- Total Solar Neutrino Flux
- 1478 m below Surface
- 615 Tons C_2Cl_4 (Percloroethylene)
- only 1/3 of predicted yield

- Extracting Ar from Cl

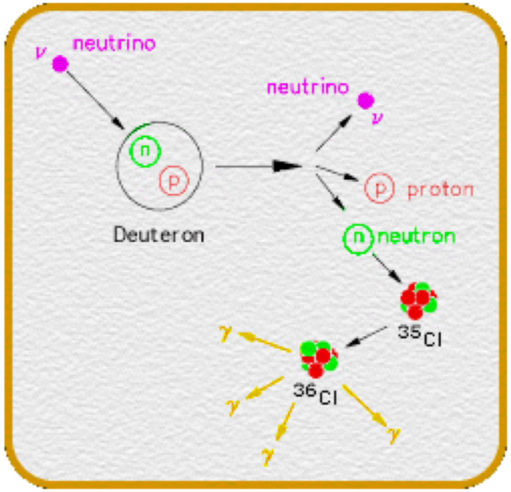


SUDBURY NEUTRINO OBSERVATORY (SNO)

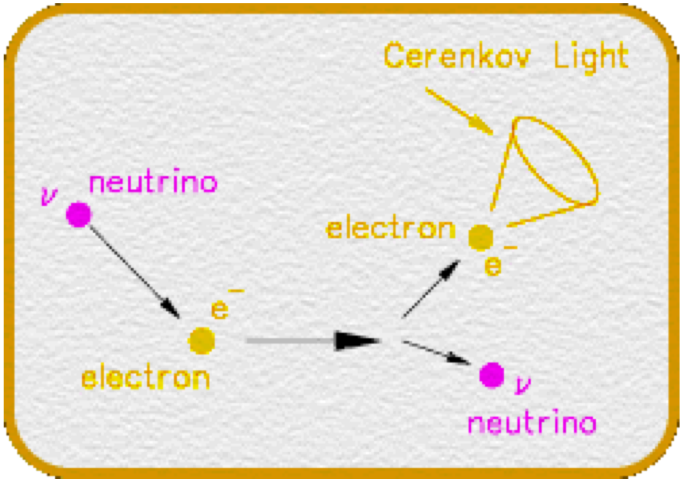
charged current: ν_e



neutral current: $\nu_e + \nu_\mu + \nu_\tau$



elastic scattering: ν_e ($+ \nu_\mu + \nu_\tau$)



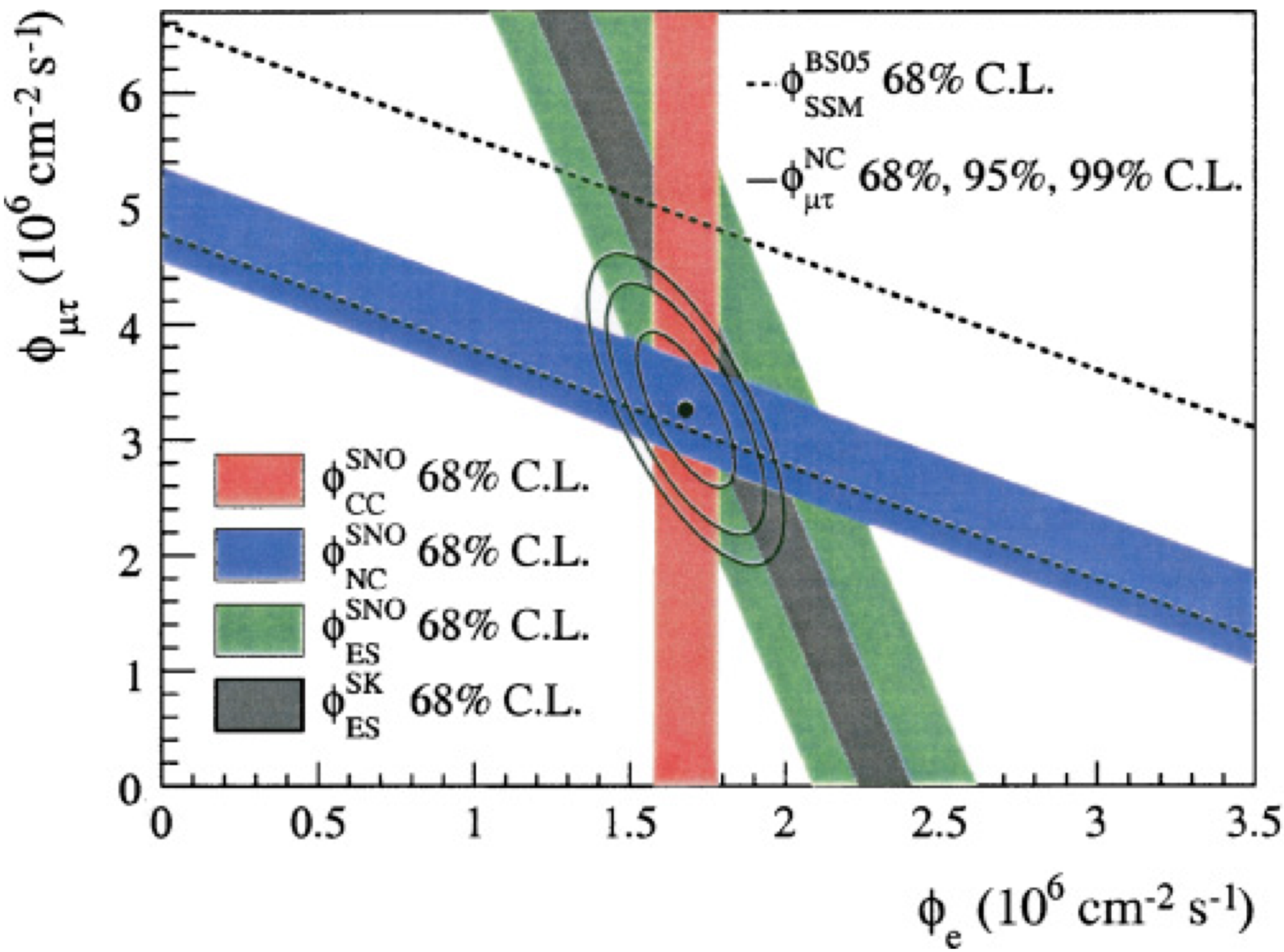
Sensitive to all neutrino flavors

On spot with predictions (2001)

—> neutrinos oscillate !

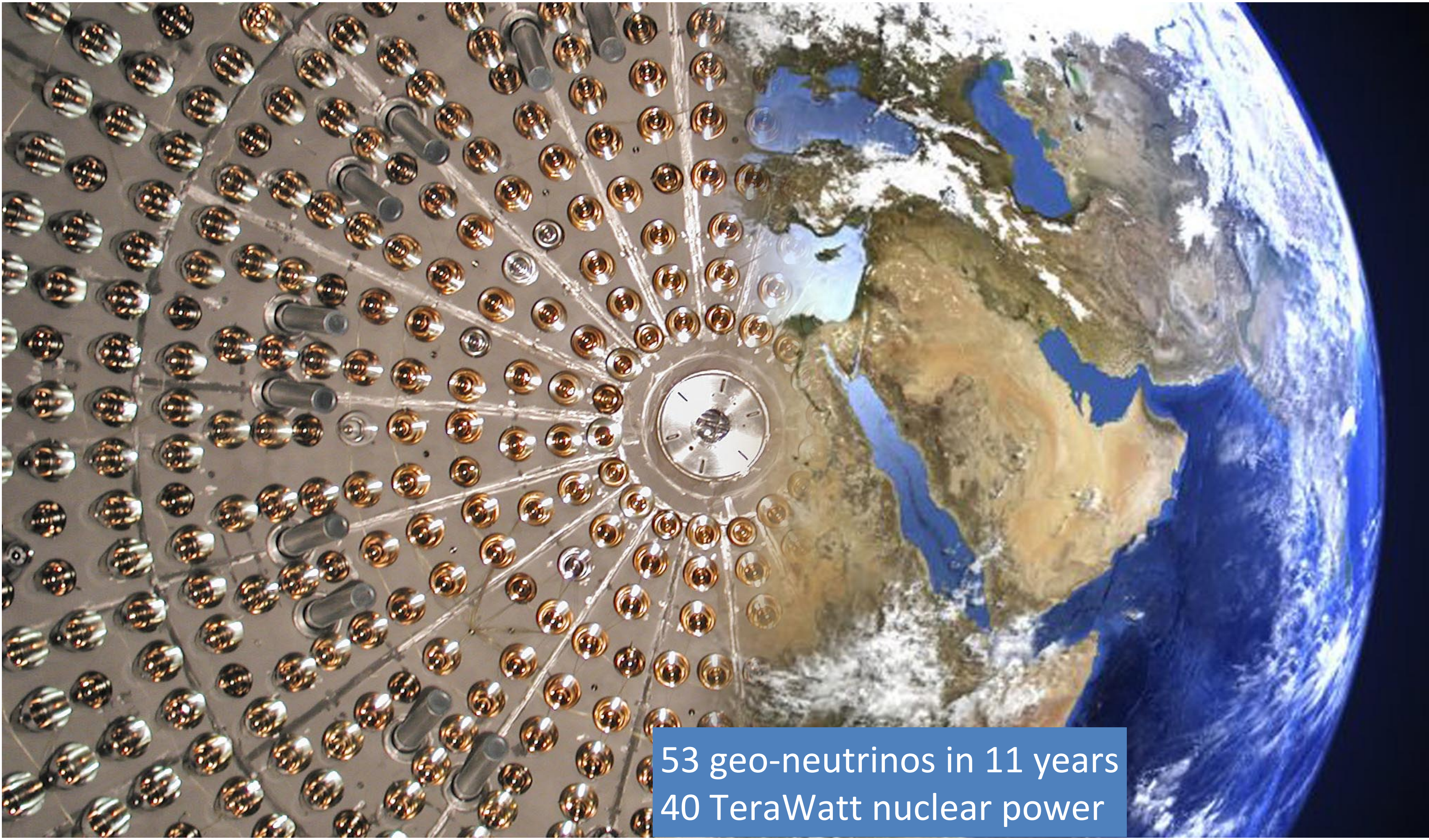
SNO review: arXiv:1602.02469

SOLAR NEUTRINO FROM SNO



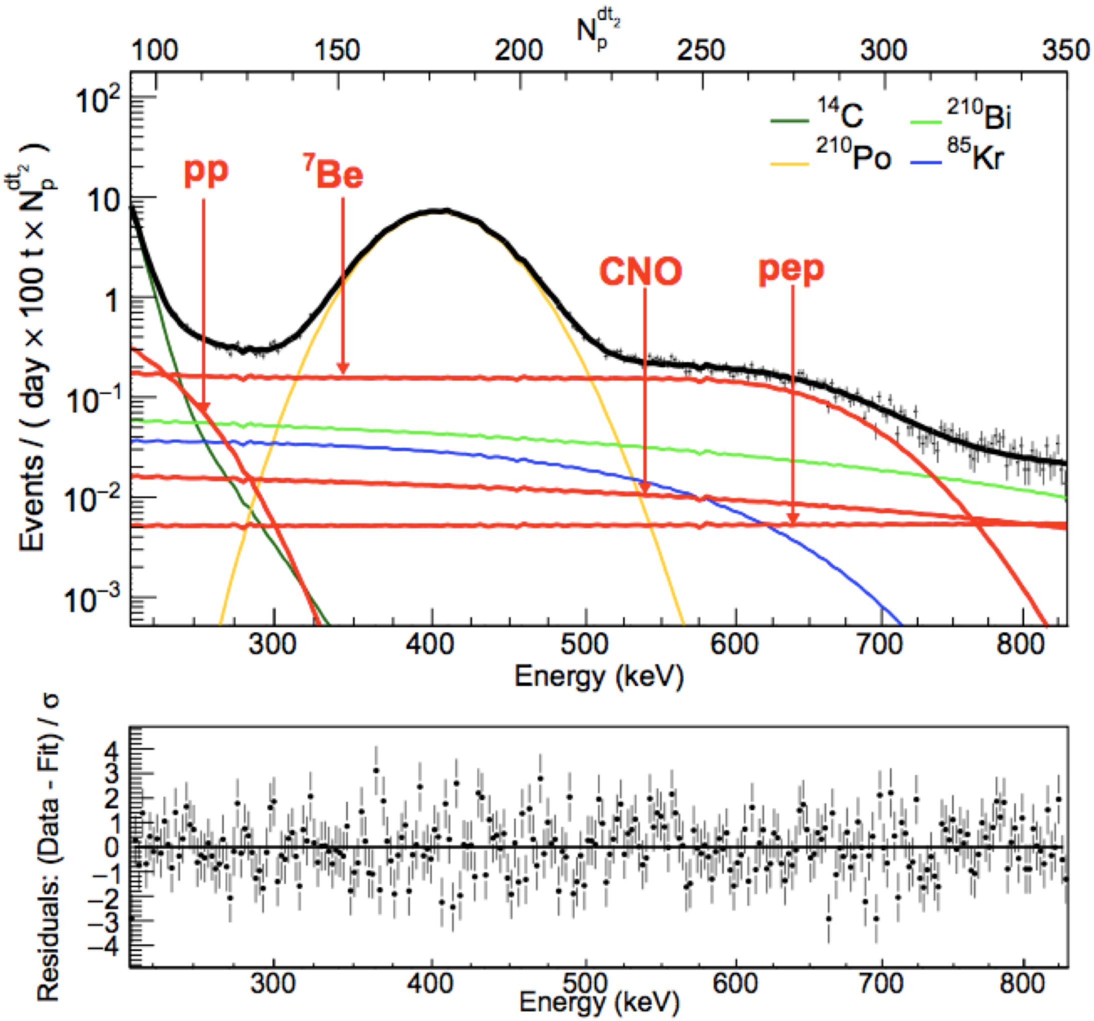
SNO, Phys. Rev. C72(2005) 055502.

GEO-NEUTRINOS - BOREXINO



Source: INFN, Italy; Phys. Rev. D 101, 012009 (2020). Update: https://arxiv.org/pdf/2105.13858.pdf

BOREXINO NEUTRINO SPECTRUM



300t of ultra-pure liquid scintillator

250 keV energy threshold

member of the super-nova early warning system

Borexino, Phys. Rev. D 92, 031101 (2015).

HELIUM BURNING AND MORE

- When H depletes, $^{1}H + ^{1}H$ collisions become too rare to drive PP-I chain fast enough to maintain pressure
- Then core collapses and T rises
- At T ~ 2 x 10^8 K, He burning becomes possible:

$^{4}He + ^{4}He + ^{4}He = ^{12}C + \gamma$ (via formation of ^{8}Be)

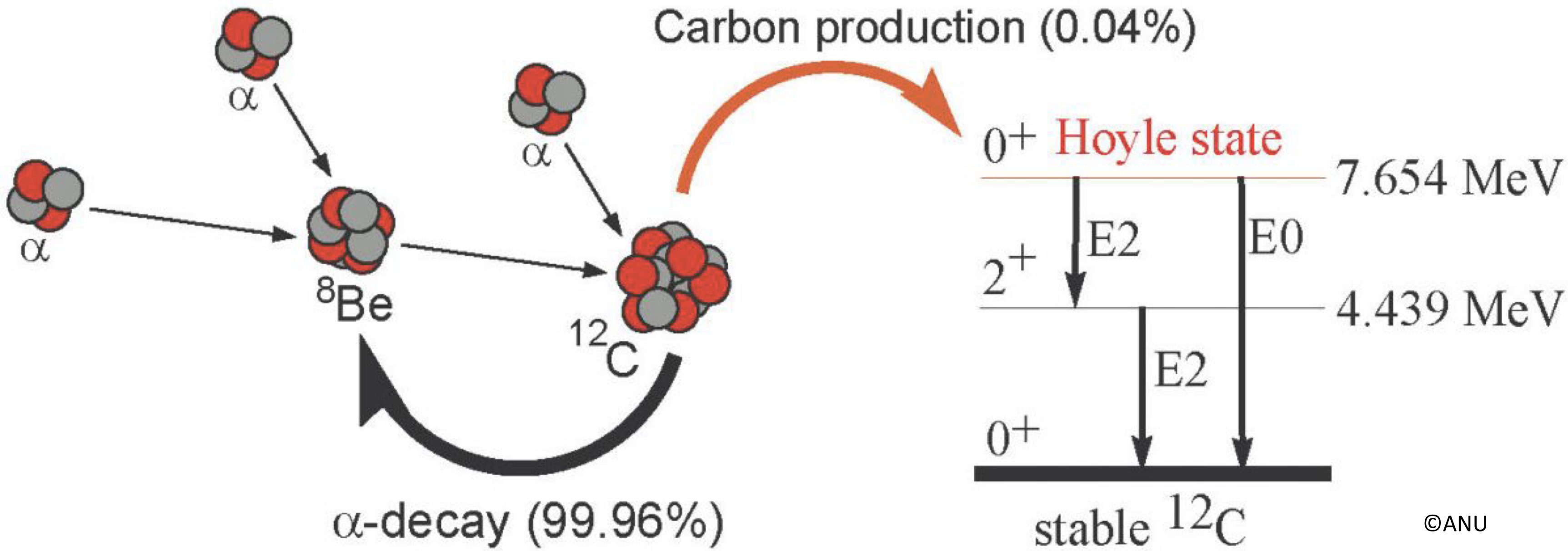
When ^{4}He runs out, another core collapse occurs: C-burning

This continues up through Si-burning

All alpha-particle nuclides are synthesized: ^{4}He, ^{12}C, ^{16}O, ^{20}Ne, ^{24}Mg, ^{28}Si, ^{32}S, ^{36}Ar, ^{40}Ca

Smaller quantities of ^{14}N, ^{15}N, ^{13}C, Na, P

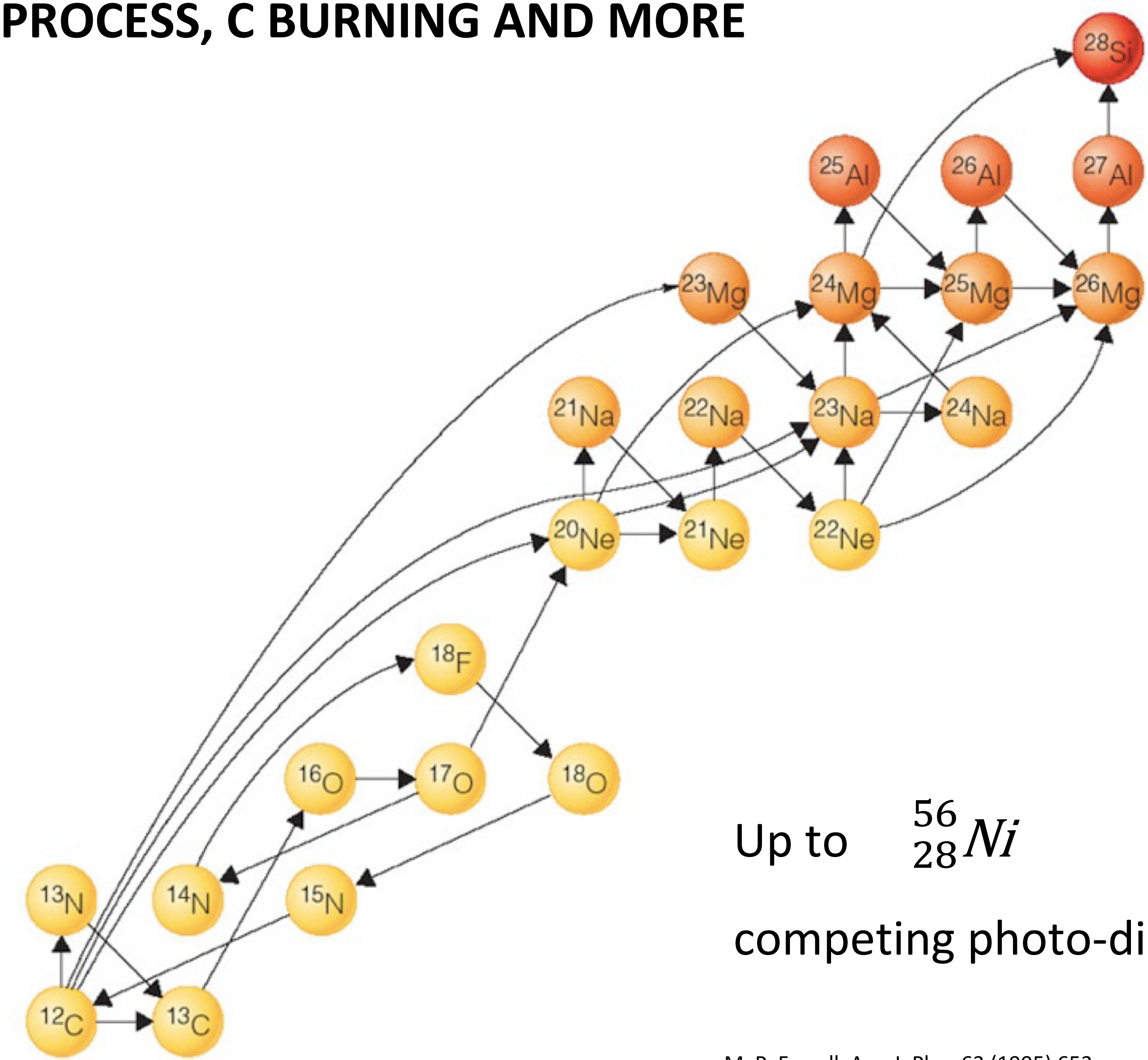
THE HOYLE STATE



the ^{8}Be nucleus is instable, long lifetime (10^{-16} s)! 3 alpha-particles must meet
the Hoyle state is located just above the continuum threshold
the excited carbon nuclei decay in various ways
about 4 of 10000 decays produce stable carbon - no Hoyle state, no human life

predicted: Hoyle, Astrophys. J. Suppl. Ser. 1 (1954) 121
experimentally confirmed: Cook et al., Phys. Rev. 107 (1957) 508
ab initio calculation: Epelbaum, Krebs, Lee, Meissner, Phys. Rev. Lett. 106 (2011) 192501
alpha fine tuned: Meissner, "Anthropic considerations in nuclear physics," Sci. Bull. 60 (2015) 43

ALPHA PROCESS, C BURNING AND MORE



Up to $^{56}_{28}Ni$

competing photo-disintegration

M. P. Fewell, Am. J. Phys 63 (1995) 653.

ALPHA PROCESS

$$^{12}_{6}C + ^{4}_{2}He \rightarrow ^{16}_{8}O + \gamma$$

$$^{16}_{8}O + ^{4}_{2}He \rightarrow ^{20}_{10}Ne + \gamma$$

$$^{52}_{26}Fe + ^{4}_{2}He \rightarrow ^{56}_{28}Ni + \gamma \qquad ^{56}_{28}Ni \rightarrow ^{56}_{27}Co + e^{+} + \overline{\nu}_{e} \rightarrow ^{56}_{26}Fe + e^{+} + \overline{\nu}_{e}$$

$$^{12}_{6}C + ^{12}_{6}C \rightarrow ^{20}_{10}Ne + ^{4}_{2}He$$

$$^{12}_{6}C + ^{12}_{6}C \rightarrow ^{23}_{11}Ne + p$$

$$^{12}_{6}C + ^{12}_{6}C \rightarrow ^{16}_{8}O + 2 \cdot ^{4}_{2}He$$

$$^{12}_{6}C + ^{12}_{6}C \rightarrow ^{23}_{12}Mg + n$$

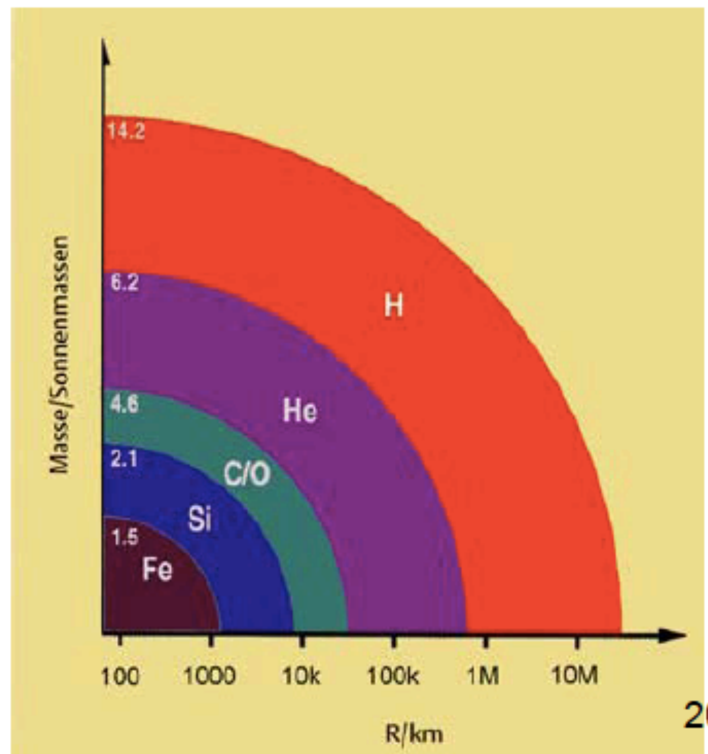
M. P. Fewell, Am. J. Phys 63 (1995) 653.

Nuclear Burning in Star with M = 25 M_{sun}

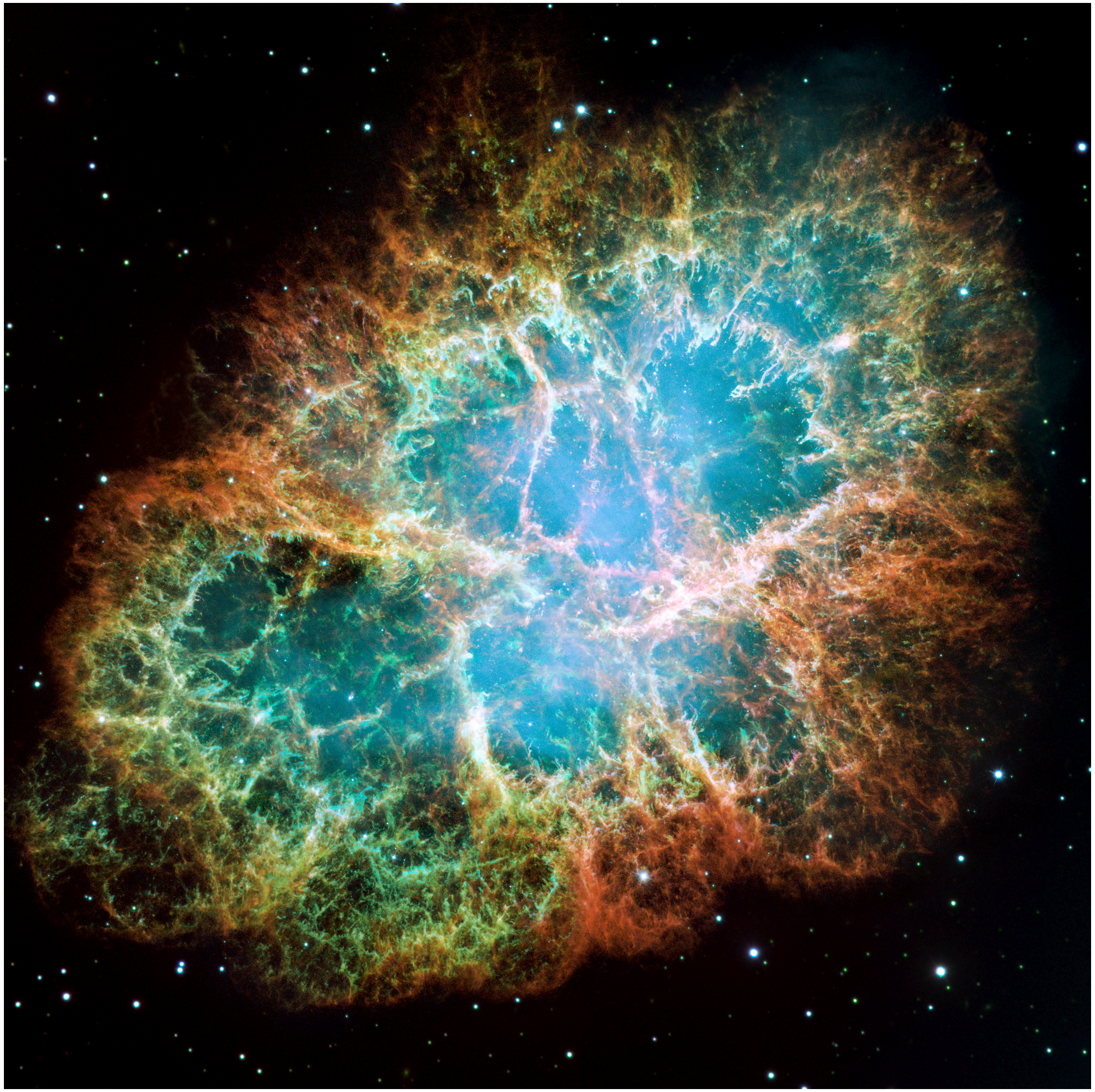
Fusion of	Time to complete	Core temperature (K)	Core density (kg m^{-3})
H	7×10^6 yr	6×10^7	5×10^4
He	5×10^5 yr	2×10^8	7×10^5
C	600 yr	9×10^8	2×10^8
Ne	1 yr	1.7×10^9	4×10^9
O	0.5 yr	2.3×10^9	1×10^{10}
Si	1 day	4.1×10^9	3×10^{10}

onion skin structure
heavy elements settle into layer
shell burning at interfaces

size largely increased, red giant
gravitational pressure wins
—> super-nova



THE END



Source: NASA, Hubble Telescope