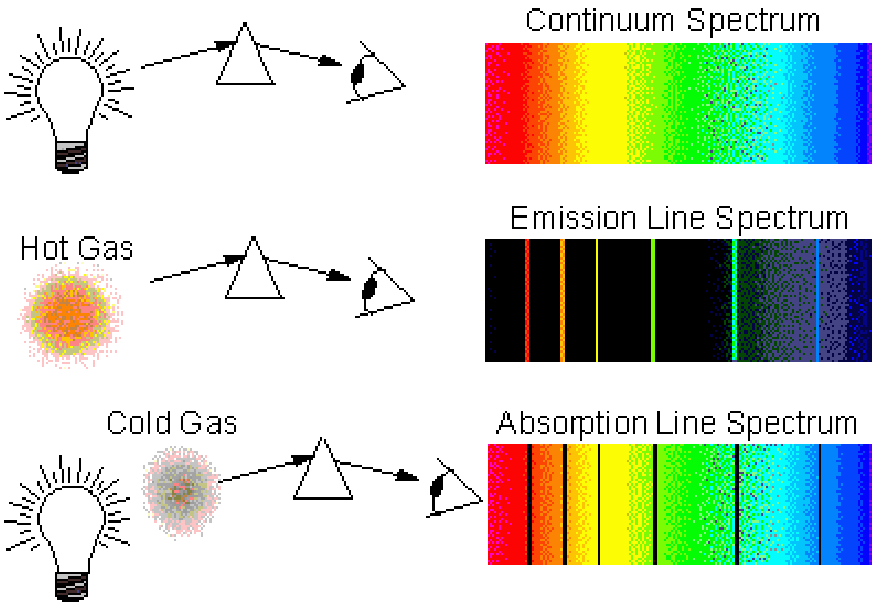
Cosmic Alchemy:

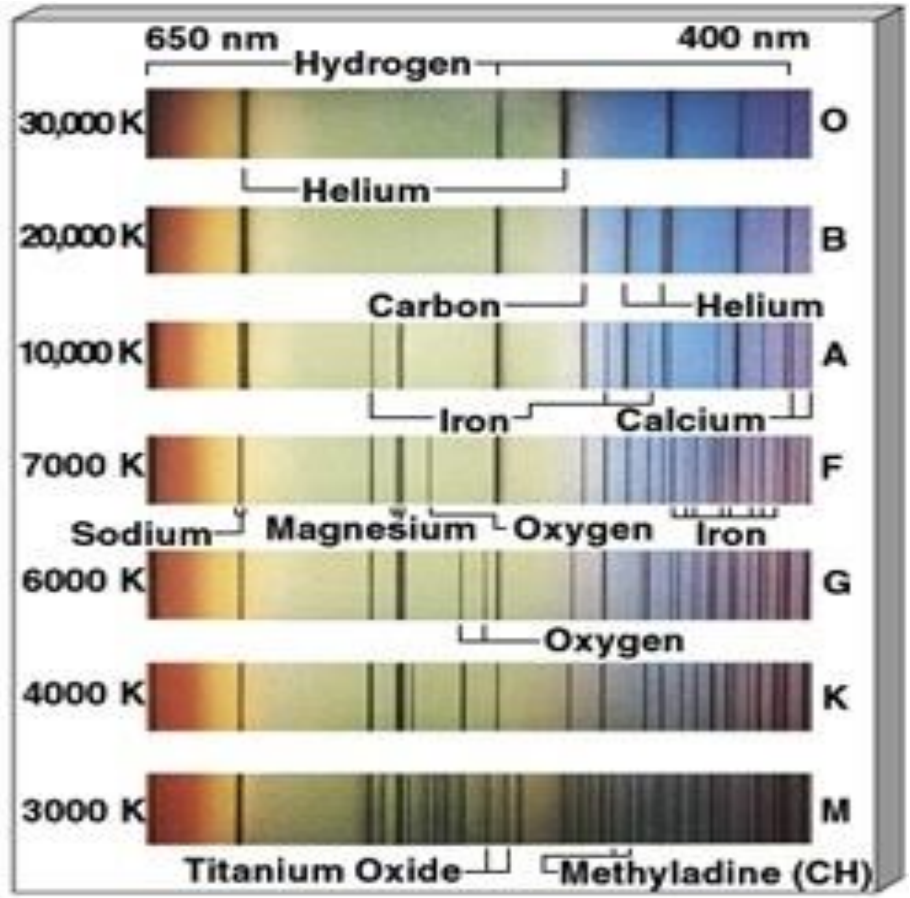
The Origin of the Chemical Elements

Eric Norman
Nuclear Engineering Dept.
Univ. of California at Berkeley

Dark Night Sky

Visible EM Spectrum





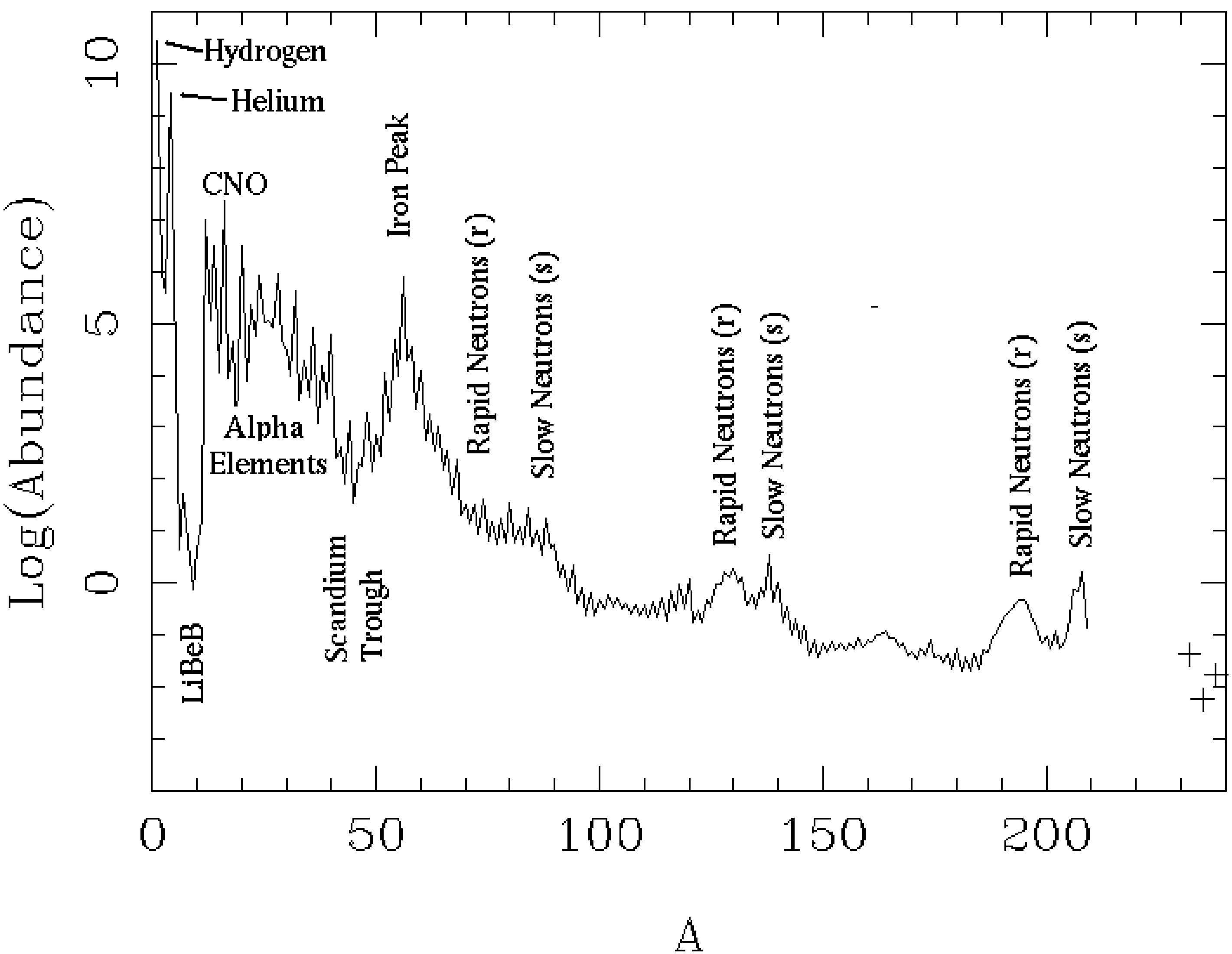
What is the universe made of ?

- Hydrogen = 75%, by mass

- Helium = 23 %

- Everything Else = 2%

Standard Abundance Distribution (SAD) vs. A



Evidence for Big Bang

1. Expansion of the universe

2. Cosmic microwave background

3. Light element abundances

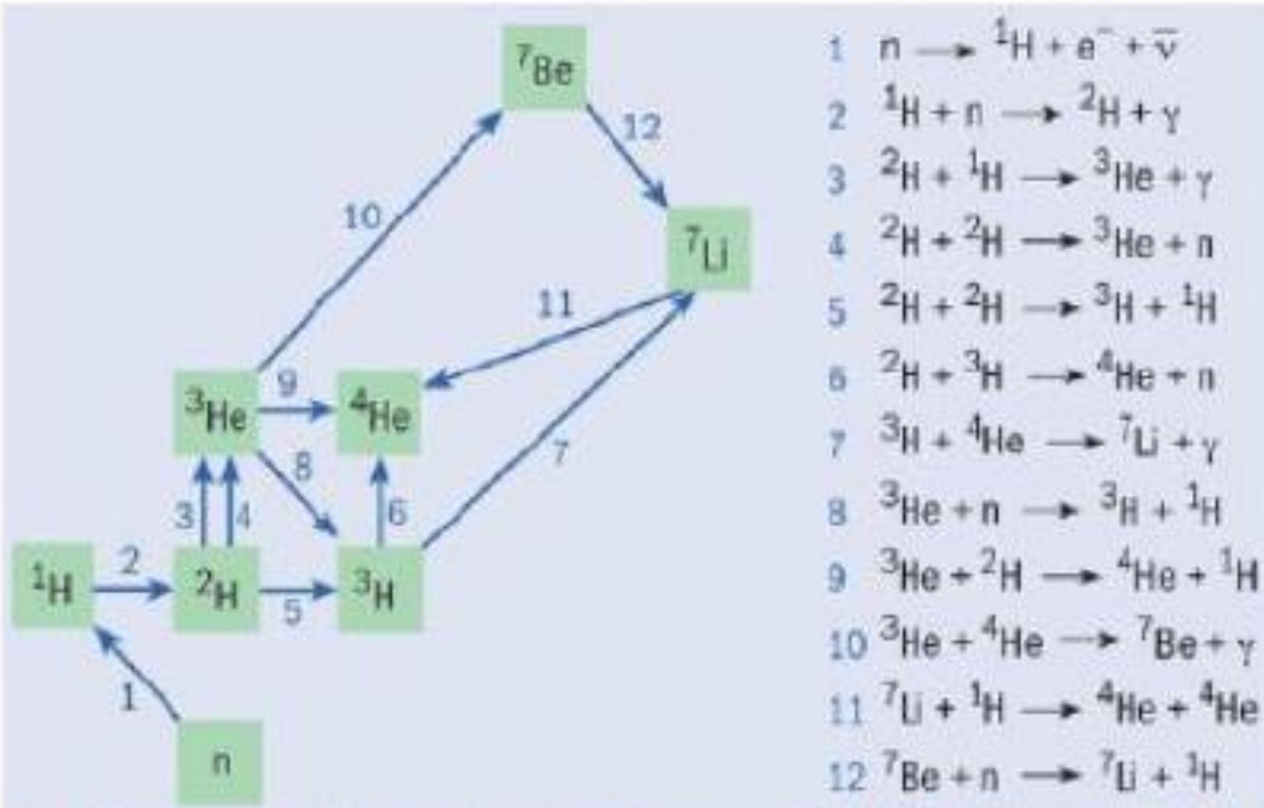


Figure 1: Nuclear reactions - http://physicsworld.com/cws/article/print/30680/1/PWfea4_08-07

Benjamin Topper

Lack of stable A = 5 or A = 8 nuclei prevents heavy element production in Big Bang

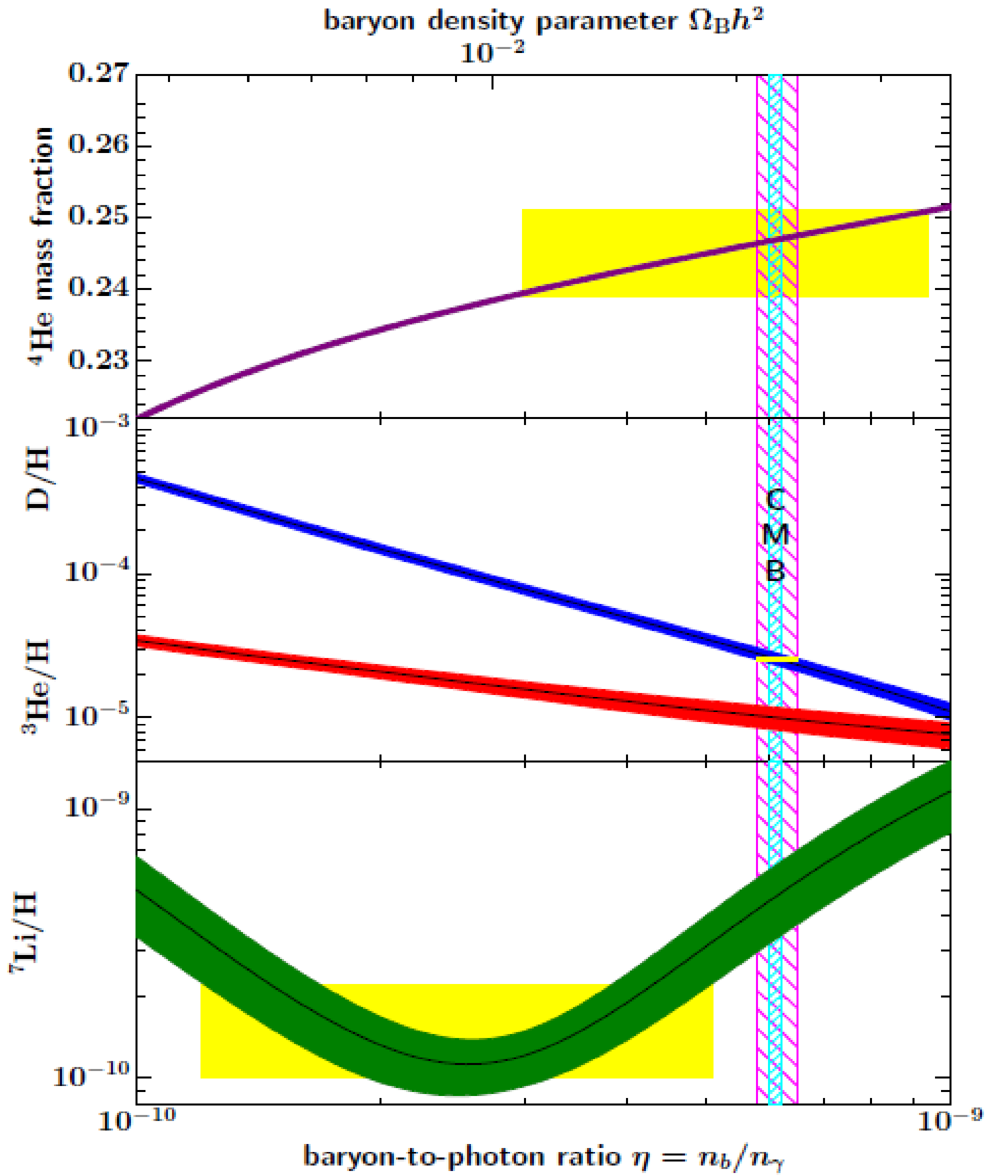
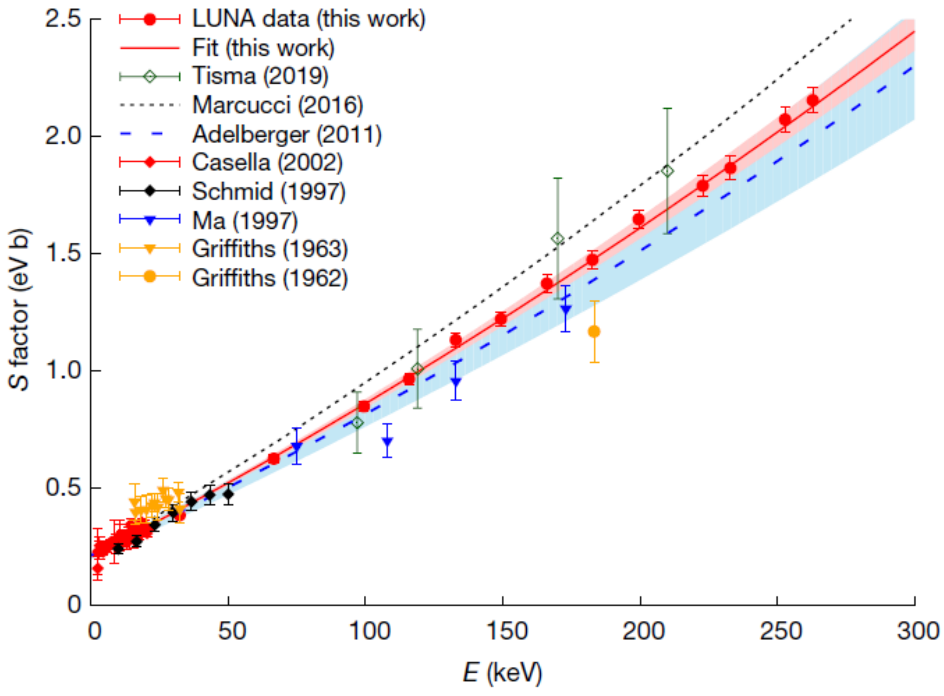


Figure 24.1: The primordial abundances of ^{4}He, D, ^{3}He, and ^{7}Li as predicted by the standard model of Big-Bang nucleosynthesis — the bands show the 95% CL range [47]. Boxes indicate the observed light element abundances. The narrow vertical band indicates the CMB measure of the cosmic baryon density, while the wider band indicates the BBN D+^{4}He concordance range (both at 95% CL).

Particle Data Group 2020

Recent results from LUNA collaboration
Nature **587** (2020) 210



S-factor for the $d(p,\gamma)^3He$ reaction

Table 1 | Mean values and 68% confidence level ranges for $\Omega_b h^2$ (with relative uncertainties δ) and N_{eff}

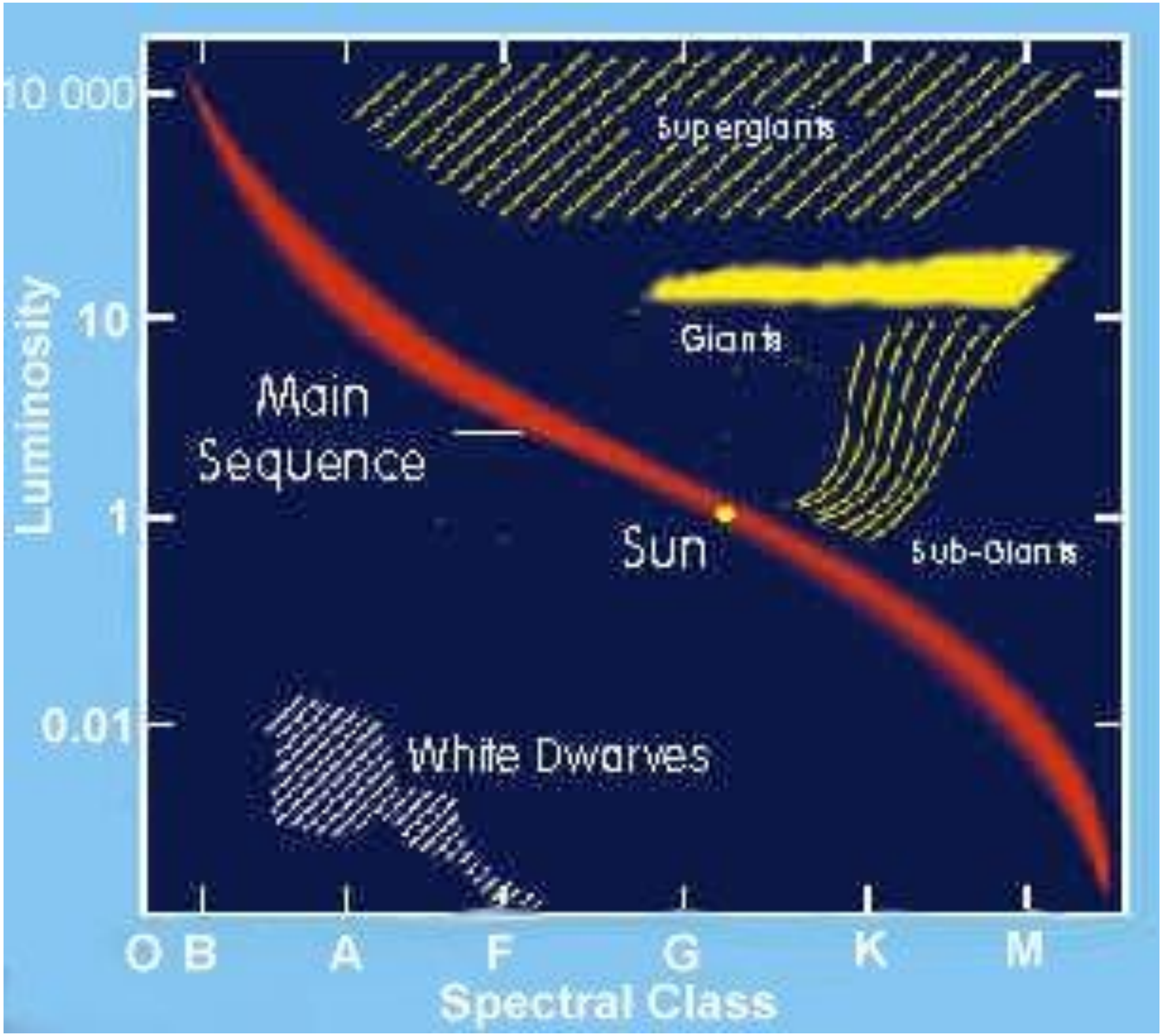
	$\Omega_b h^2$	δ (%)	N_{eff}
D + 3ν (without LUNA data)	0.02271 ± 0.00062	2.73	3.045
D + 3ν (with new LUNA data)	0.02233 ± 0.00036	1.61	3.045
CMB + 3ν	0.02230 ± 0.00021[a]	0.94	3.045
Planck + 3ν	0.02236 ± 0.00015	0.67	3.045
(D + CMB)	0.02224 ± 0.00022	0.99	2.95 ± 0.22
(D + Y_p)	0.0221 ± 0.0006	2.71	$2.86^{+0.28}_{-0.27}$

Implications:

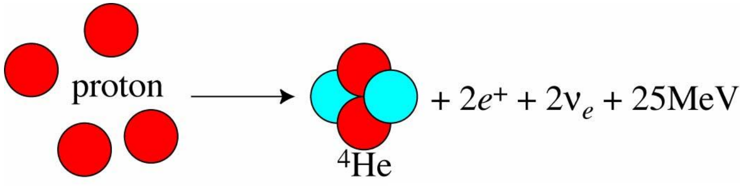
Baryonic matter represents only a few percent of the critical density

There are only 3 active neutrino species

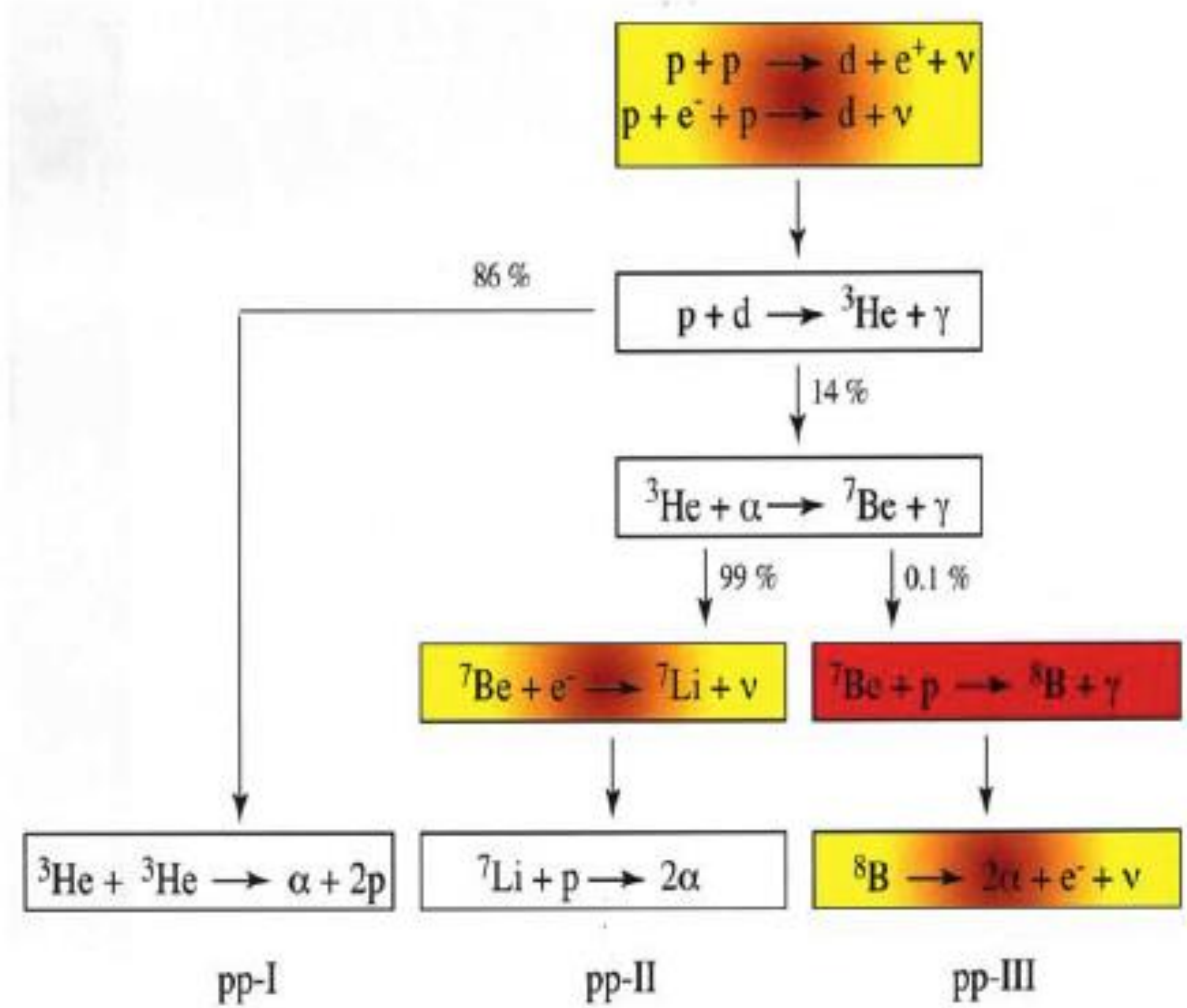
Hertzsprung-Russell Diagram



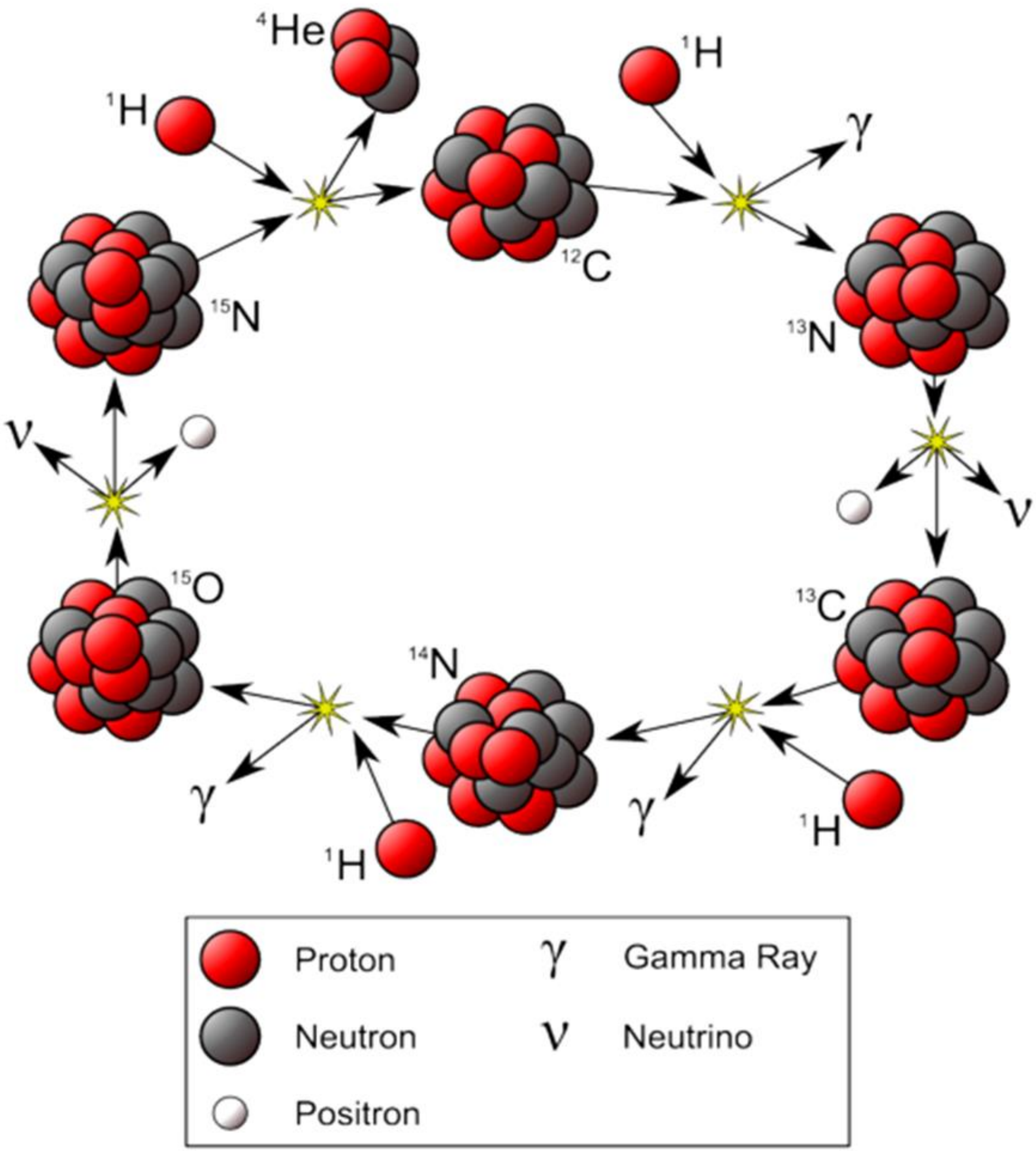
The Sun shines by nuclear fusion reactions!



Hans Bethe
Nobel Prize 1967



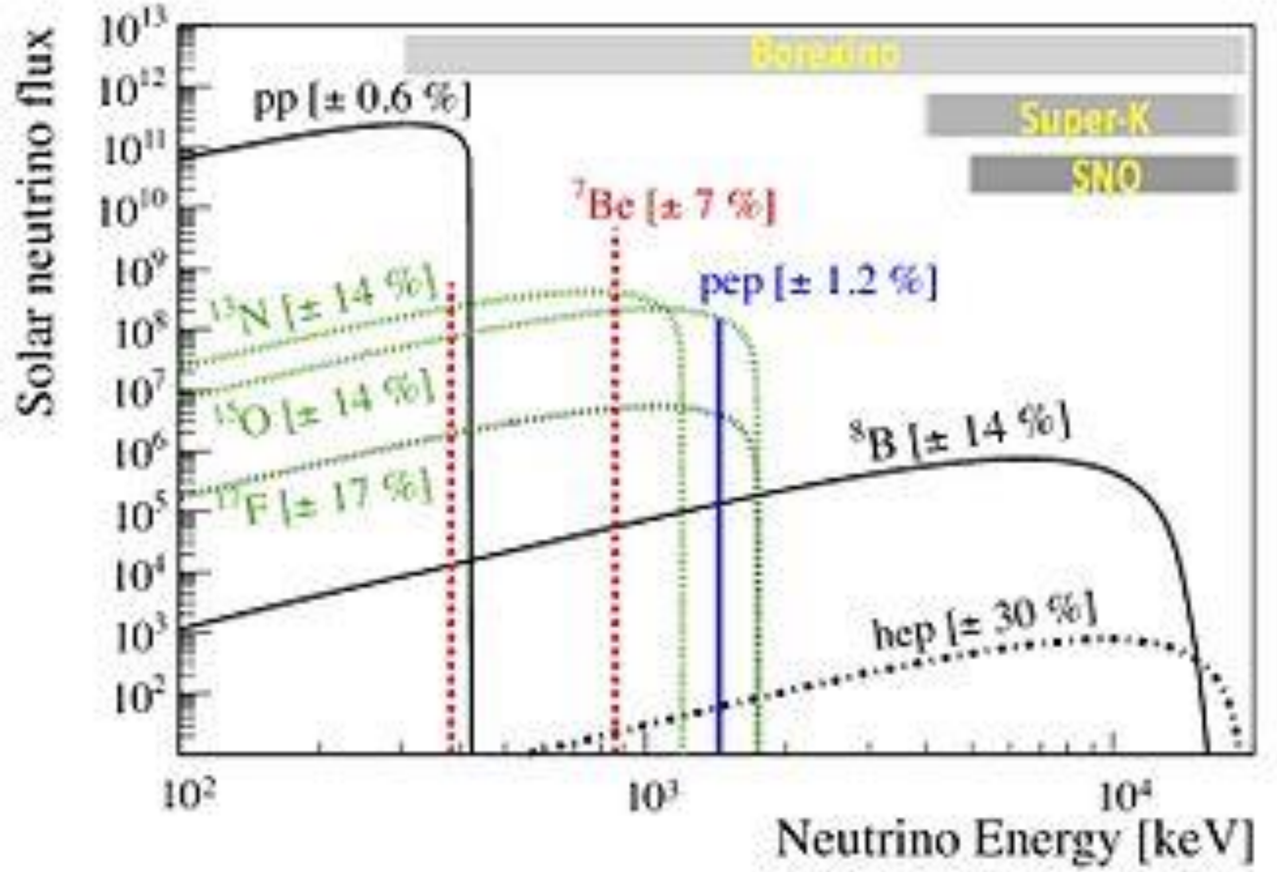
CNO Cycle



Main hydrogen burning mechanism in more massive stars

Predicted fluxes of solar neutrinos at Earth

John Bahcall

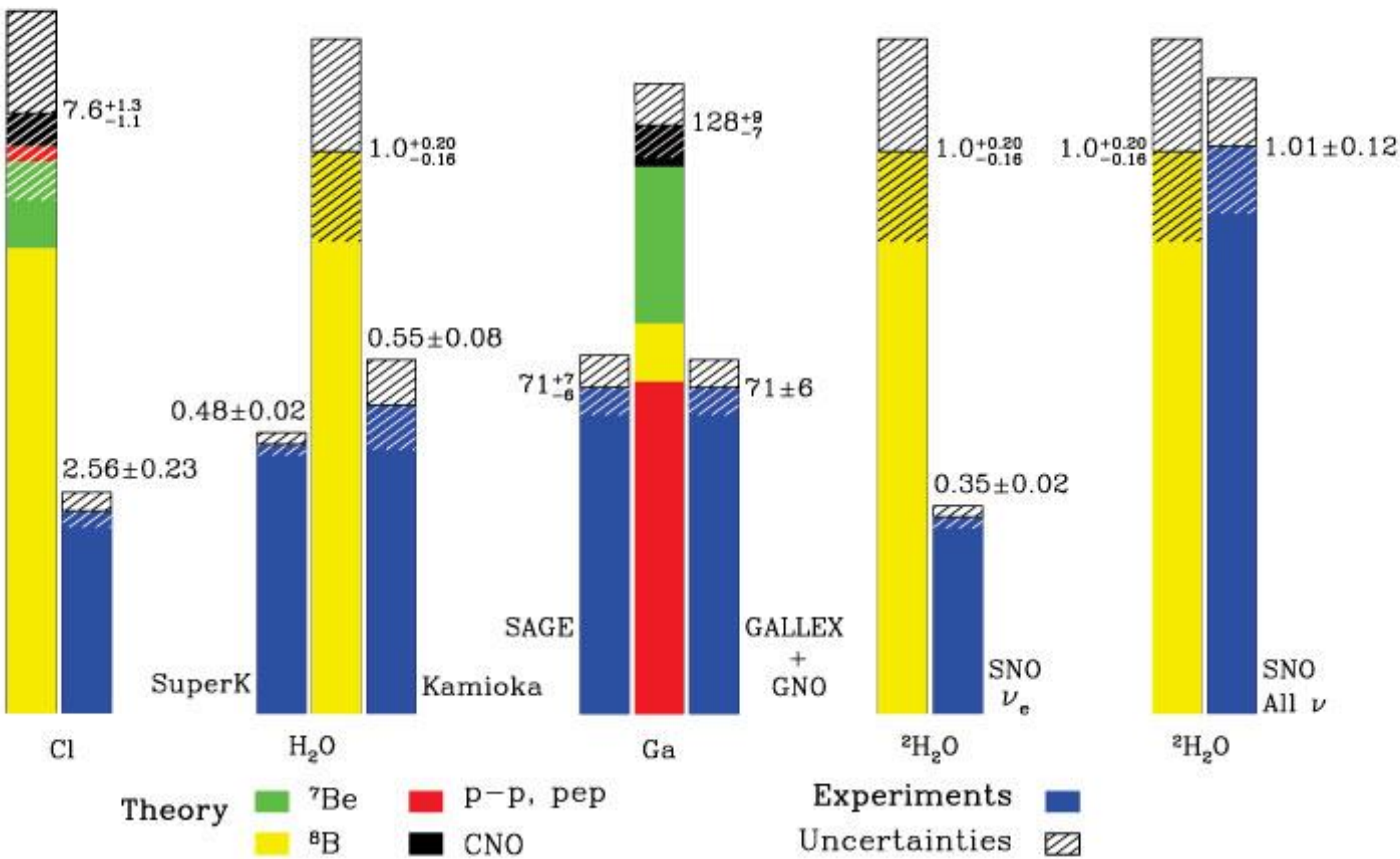


$\Phi_\nu = 2 \times L_{sun}/Q$ and $L_{sun} = 1.2\ kW/m^2$

$Q = 25\ MeV \rightarrow \Phi_\nu = 6 \times 10^{10}/cm^2/sec$

Total Rates: Standard Model vs. Experiment

Bahcall–Pinsonneault 2000



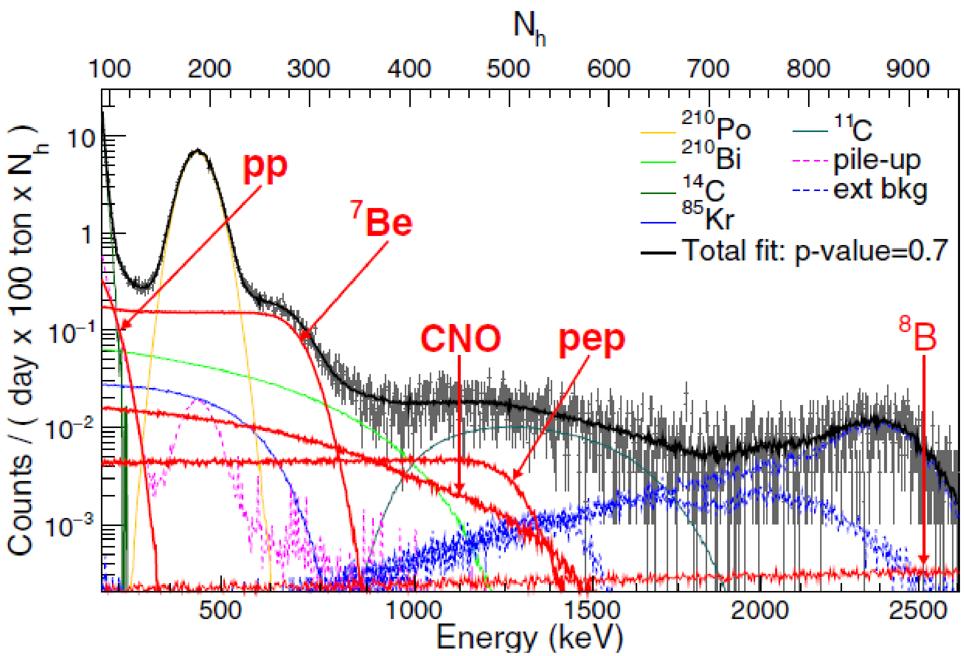
Recent Observations of Solar pp, pep, ^{7}Be, and CNO Neutrinos by Borexino Collaboration

$\Phi_{\nu pp} = (6.1 \pm 0.5^{+0.3}_{-0.5}) \times 10^{10}$ $cm^{-2}\ s^{-1}$

$\Phi_{\nu pep} = (1.27 \pm 0.19^{+0.08}_{-0.12}) \times 10^{8}$ $cm^{-2}\ s^{-1}$

$\Phi_{\nu ^7Be} = (4.99 \pm 0.11^{+0.06}_{-0.08}) \times 10^{9}$ $cm^{-2}\ s^{-1}$

Nature 512 (2014) 383
Phys. Rev. D 100 (2019) 082004



$\Phi_{\nu CNO} = 7.0^{+3.0}_{-2.0} \times 10^{8}\ cm^{-2}\ s^{-1}$

Nature 587 (2020) 577

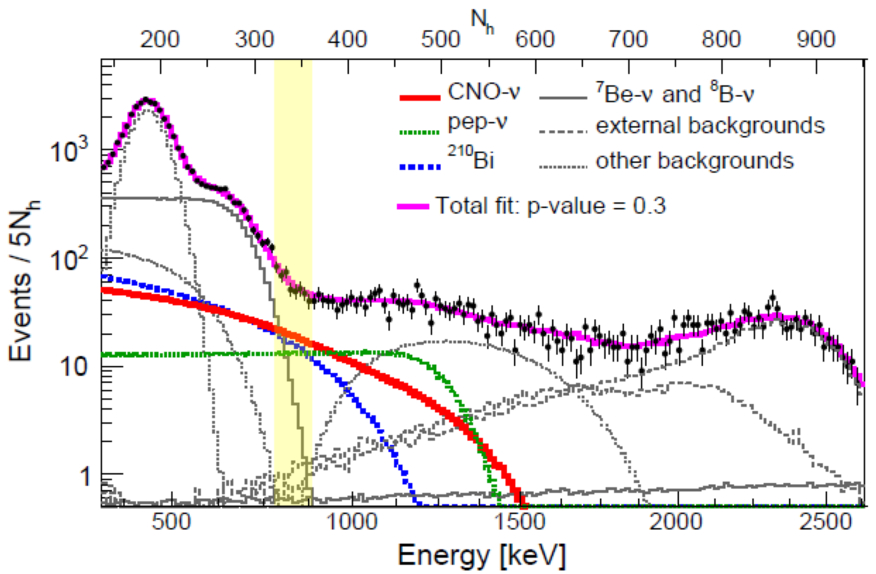
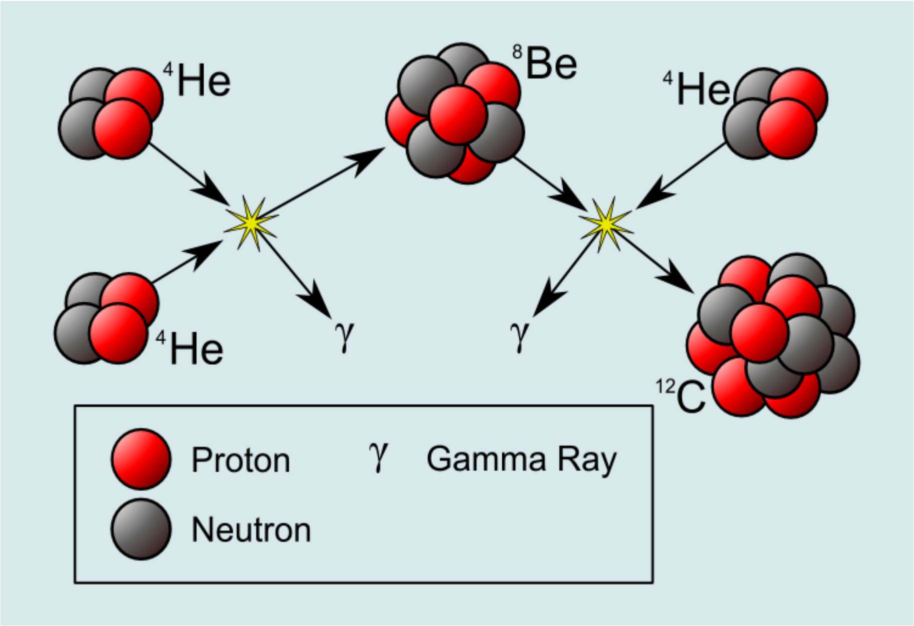
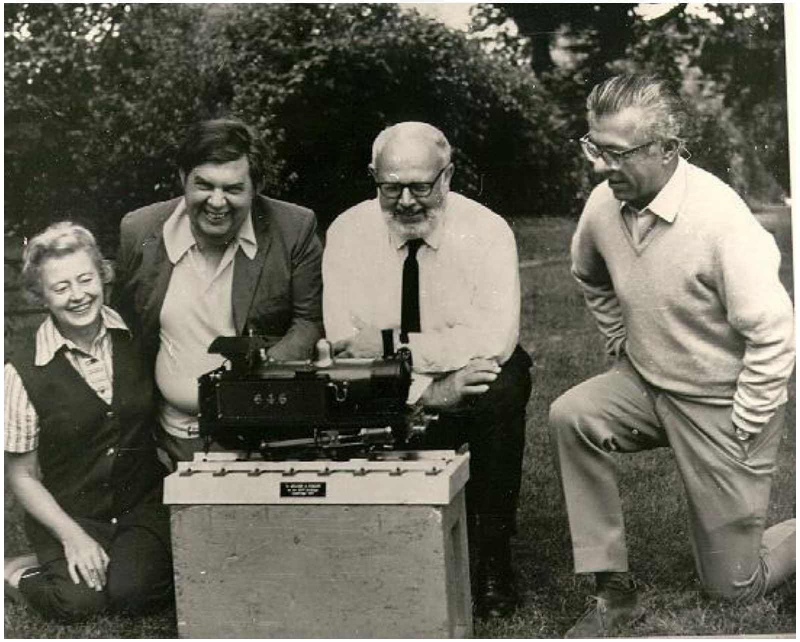


Figure 2: Energy distribution of Borexino events (black points) and spectral fit (magenta). CNO-ν, ^{210}Bi, and *pep*-ν are highlighted in solid red, dashed blue, and dotted green, respectively. All other components are in grey. The yellow band represents the region with the largest signal-to-background ratio for CNO-ν.

Helium Burning in Red-Giant Stars





$t_{1/2}(^8Be) = 10^{-16}$ sec

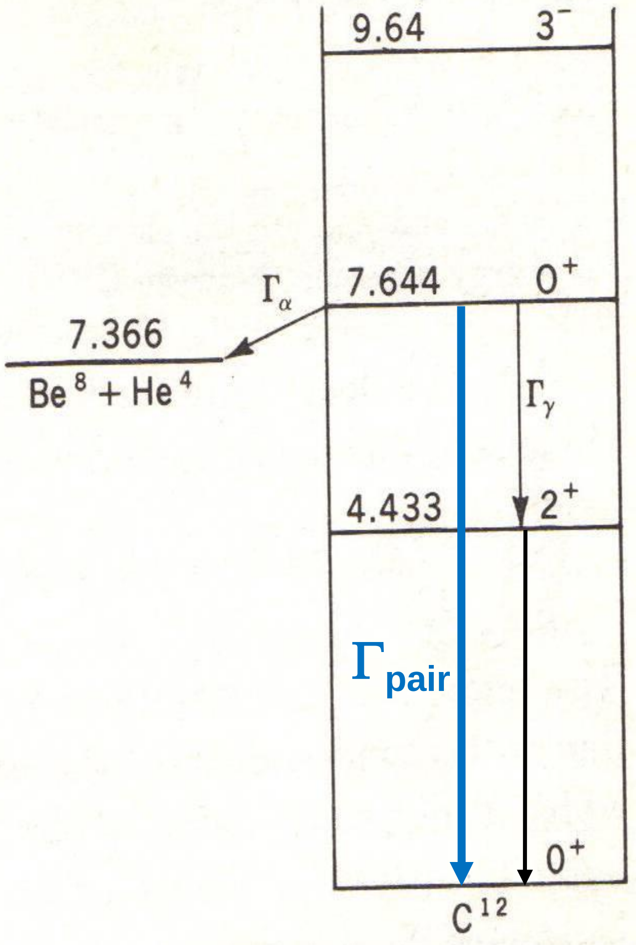
At $T = 1x10^8$K and $\rho = 10^5$ g/cc:
$N(^8Be)/N(^4He) = 1x10^{-9}$

Burbidge, Burbidge, Fowler, Hoyle

B^2FH (1957)

Fig. 5-18 The energy-level diagram of C^{12}. Alpha particles may fuse with the transient Be^8 nuclei to form the 7.644-Mev state of C^{12}. This state usually breaks up by rejecting the alpha particle, but with a smaller probability it also decays electromagnetically to the 4.433-Mev state.

Clayton



See talk by Tibor Kibedi and
Phys. Rev. Lett. 182 (2020) 182701
for recent measurements of Γ_{pair} , Γ_γ

THE $^{12}C(\alpha, \gamma)^{16}O$ REACTION AND STELLAR HELIUM BURNING †

P. DYER and C. A. BARNES
California Institute of Technology, Pasadena, California 91109

Nuclear Physics A
233 (1974) 495

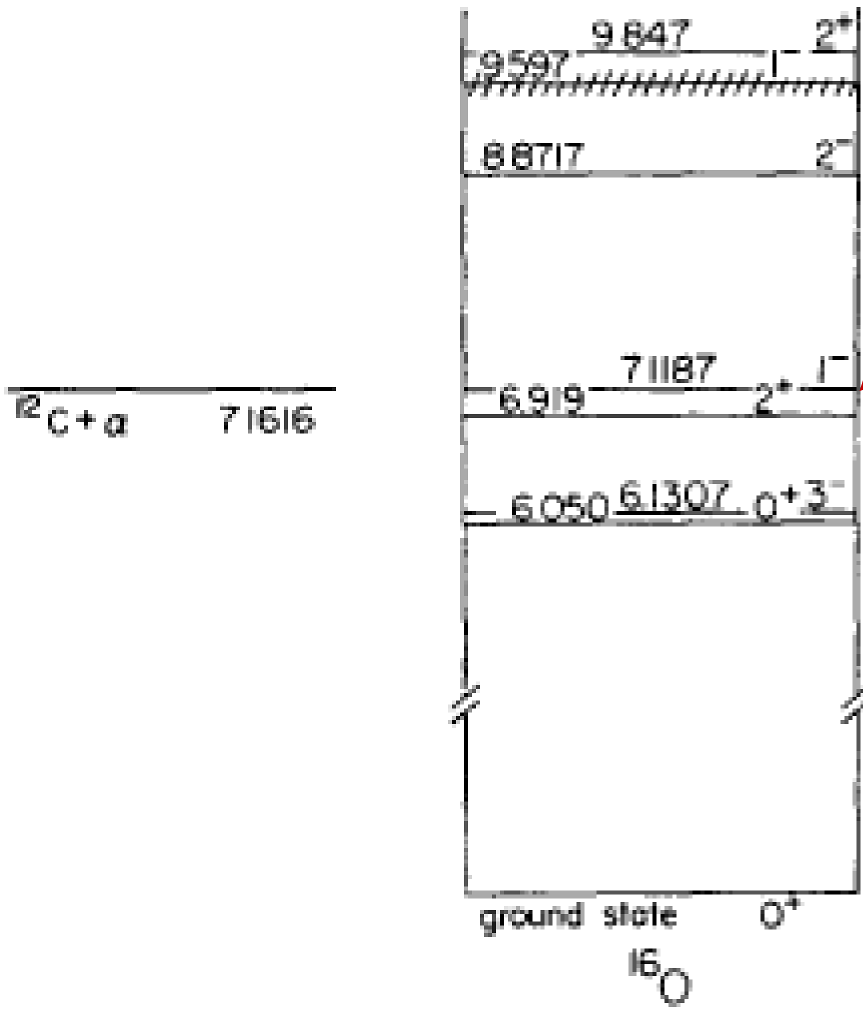


Fig. 1. Lowest states of the ^{16}O nucleus [3]).

Subthreshold 1^- state plays major role in ^{16}O production

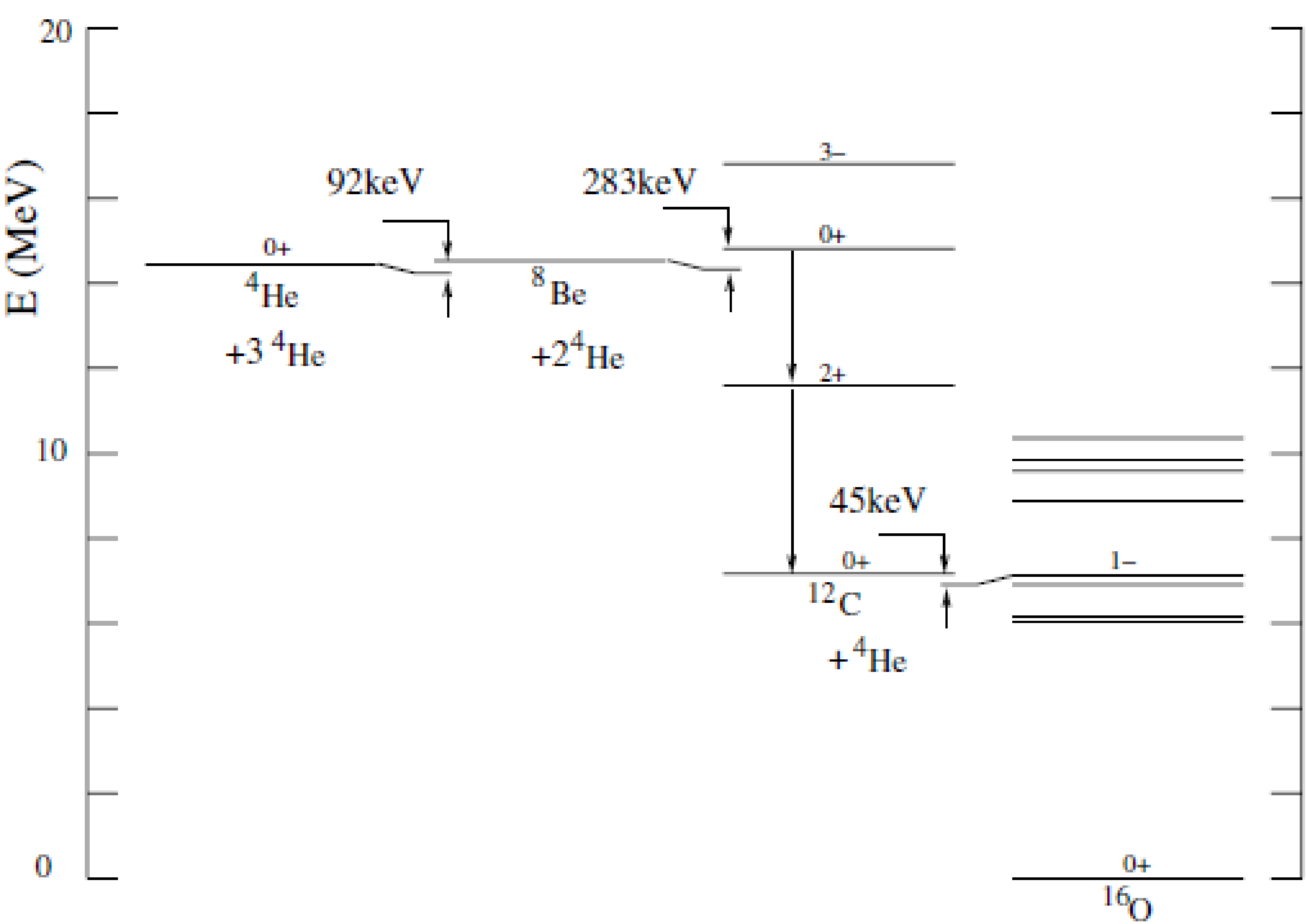
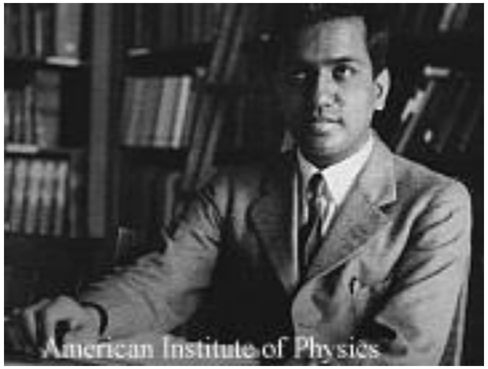


Fig. 8.5. The energy levels of four ^{4}He nuclei.

Basdevant *et al*. argue that this arrangement of nuclear levels is the only one that allows for significant amounts of ^{12}C to be produced in stars.
(Fundamentals in Nuclear Physics, Springer, 2005)

Fate of Stars



Subrahmanyan
Chandrasekhar
Nobel Prize 1983

For stars with masses < 10 M_{Sun}

No further nuclear reactions possible

→ White Dwarf (maximum mass = 1.4 M_{Sun})

Chandrasekhar Mass limit

Supported by electron degeneracy pressure

For more massive stars,

No such quiet fate possible

→ Neutron Star or Black Hole

Advanced stellar burning

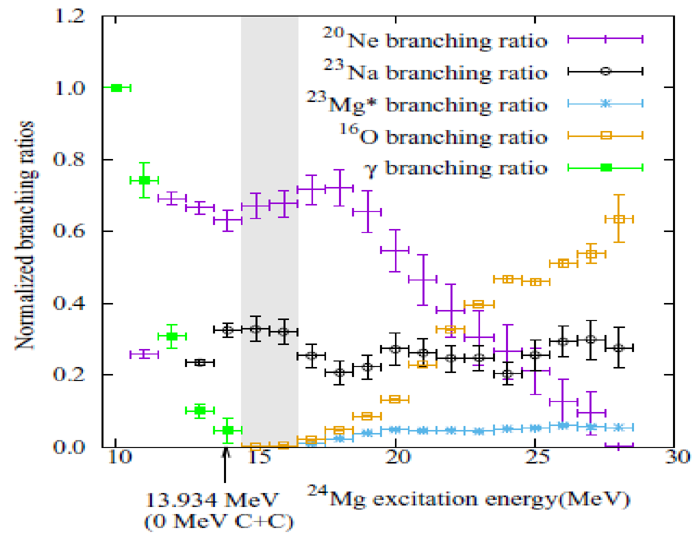
$^{12}C + ^{12}C \rightarrow ^{24}Mg + \gamma, \quad ^{20}Ne + ^{4}He$

$^{16}O + ^{16}O \rightarrow ^{32}S + \gamma, \quad ^{28}Si + ^{4}He$

PHYSICAL REVIEW C 95, 015805 (2017)

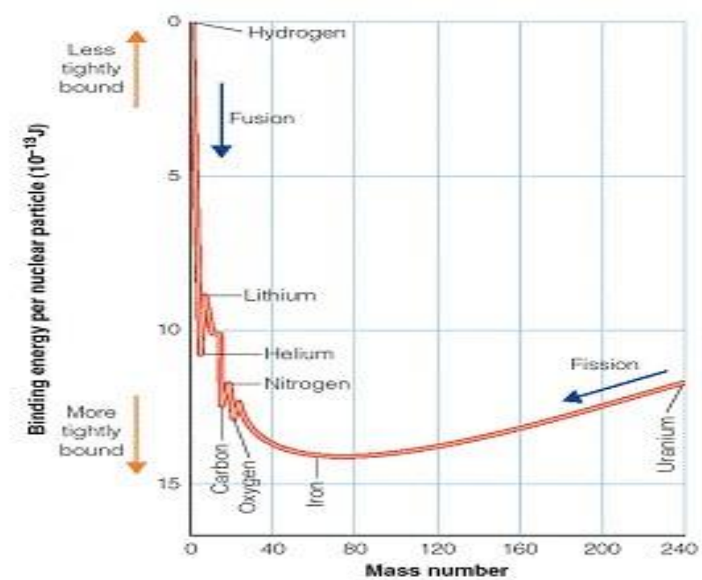
Decay branching ratios of excited ^{24}Mg

J. M. Munson *et al.*



Then through successive captures of ^{4}He,

$^{28}Si \rightarrow ^{56}Ni$

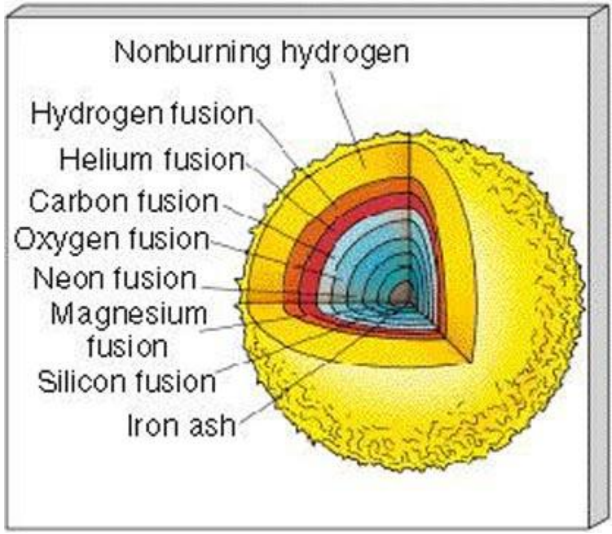


At this point the star is on its deathbed,

No further energy generation possible

Late stage massive star

Burning Stage	Temperature (keV)	Density (g/cm³)	Timescale
Hydrogen	5	5	7×10^6 years
Helium	20	700	5×10^5 years
Carbon	80	2×10^5	600 years
Neon	150	4×10^6	1 year
Oxygen	200	1×10^7	6 months
Silicon	350	3×10^7	1 day
Collapse	600	3×10^9	seconds
Bounce	3000	10^{14}	milliseconds
Explosion	100 - 600	varies	0.1 – 10 seconds

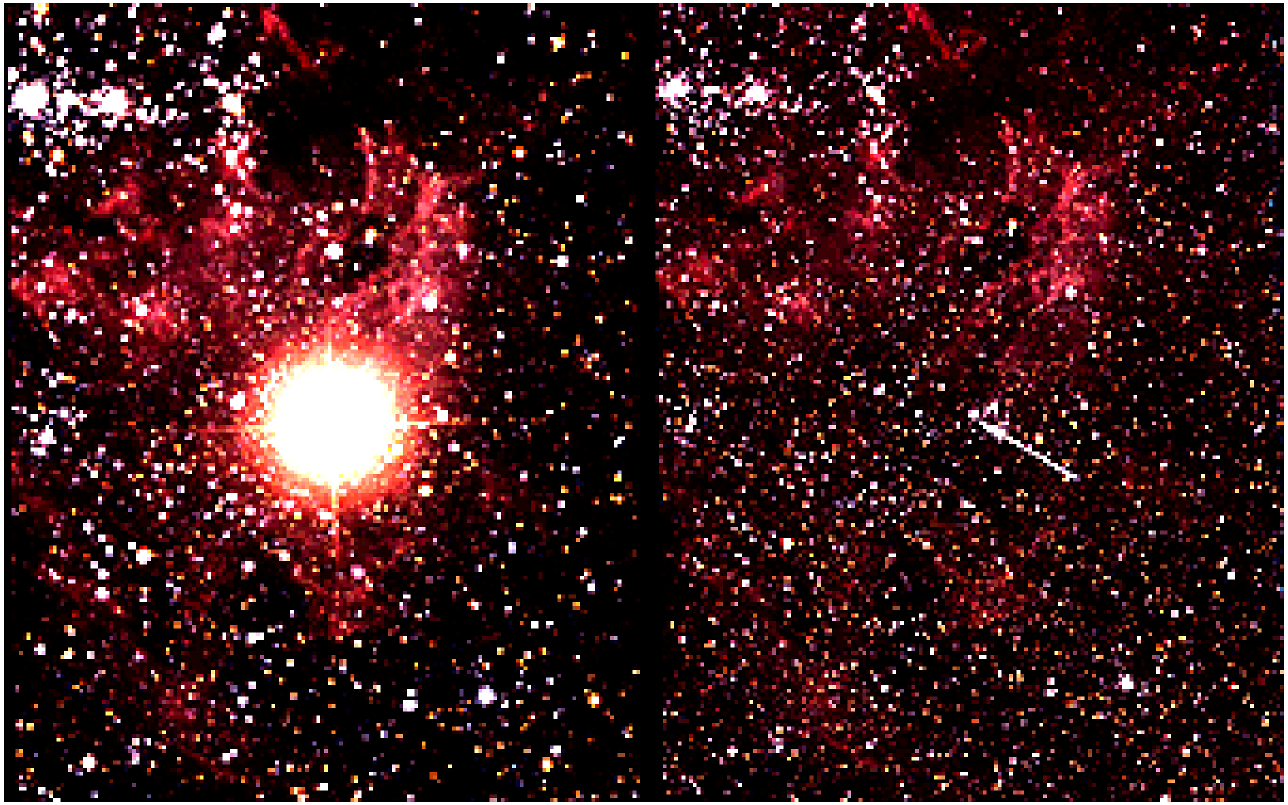


Supernova Explosion

Temperature goes up
Density goes up

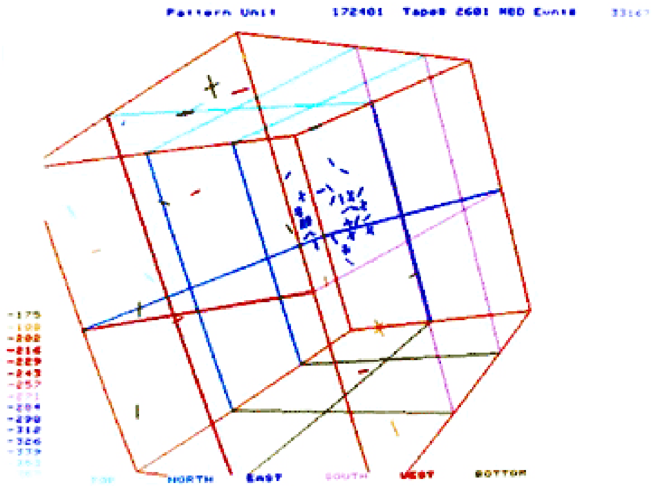
$p + e^- \rightarrow n + \nu_e$
$e^+ + e^- \rightarrow \nu + \bar{\nu}$

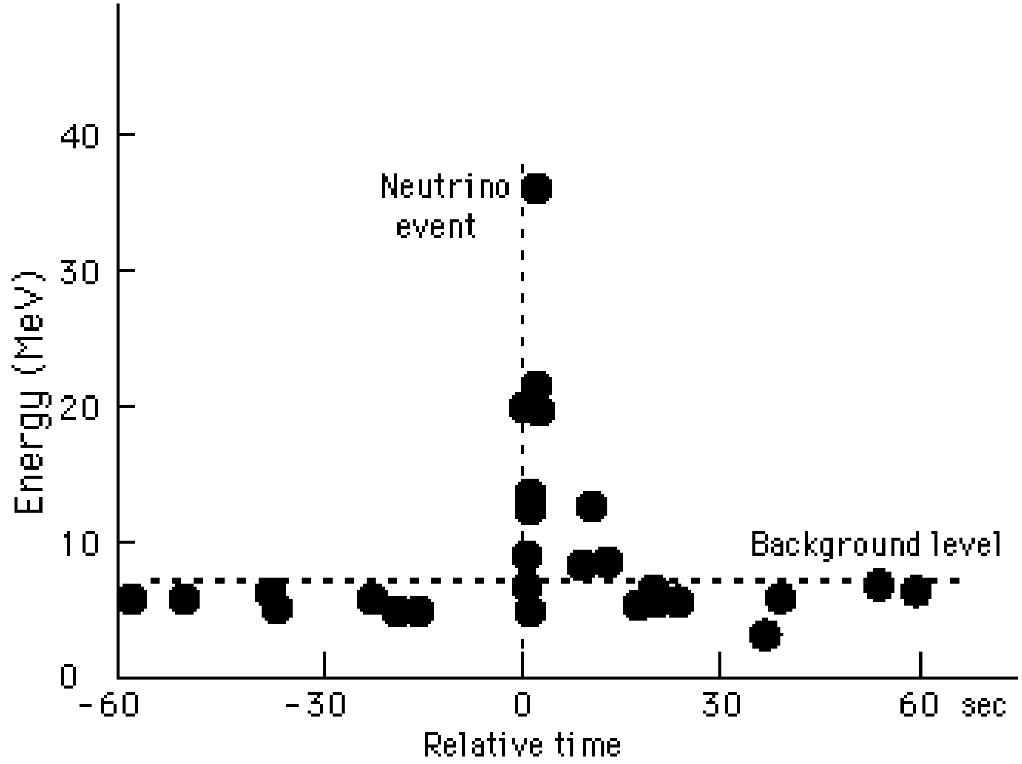
99% of SN energy comes off in neutrinos



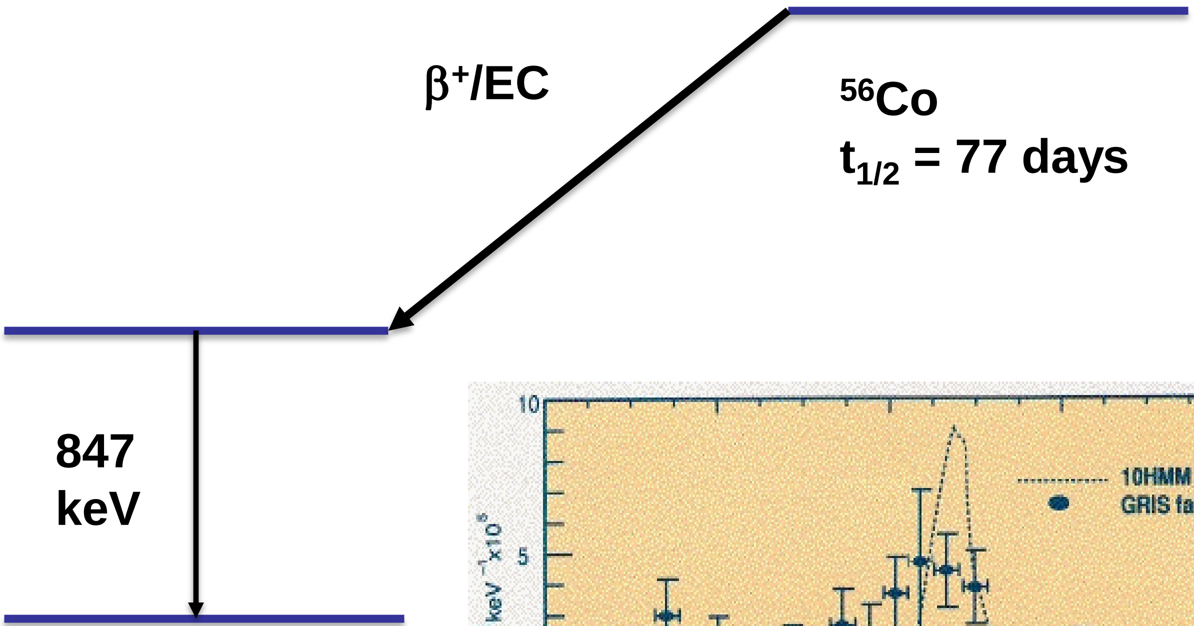
SN 1987a

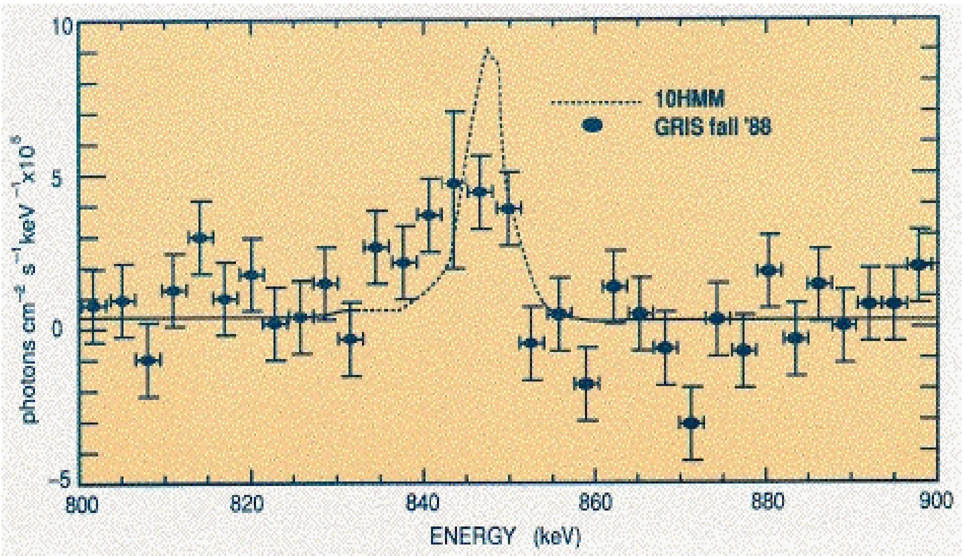
Neutrinos from SN1987a observed by Kamiokande and IMB underground telescopes





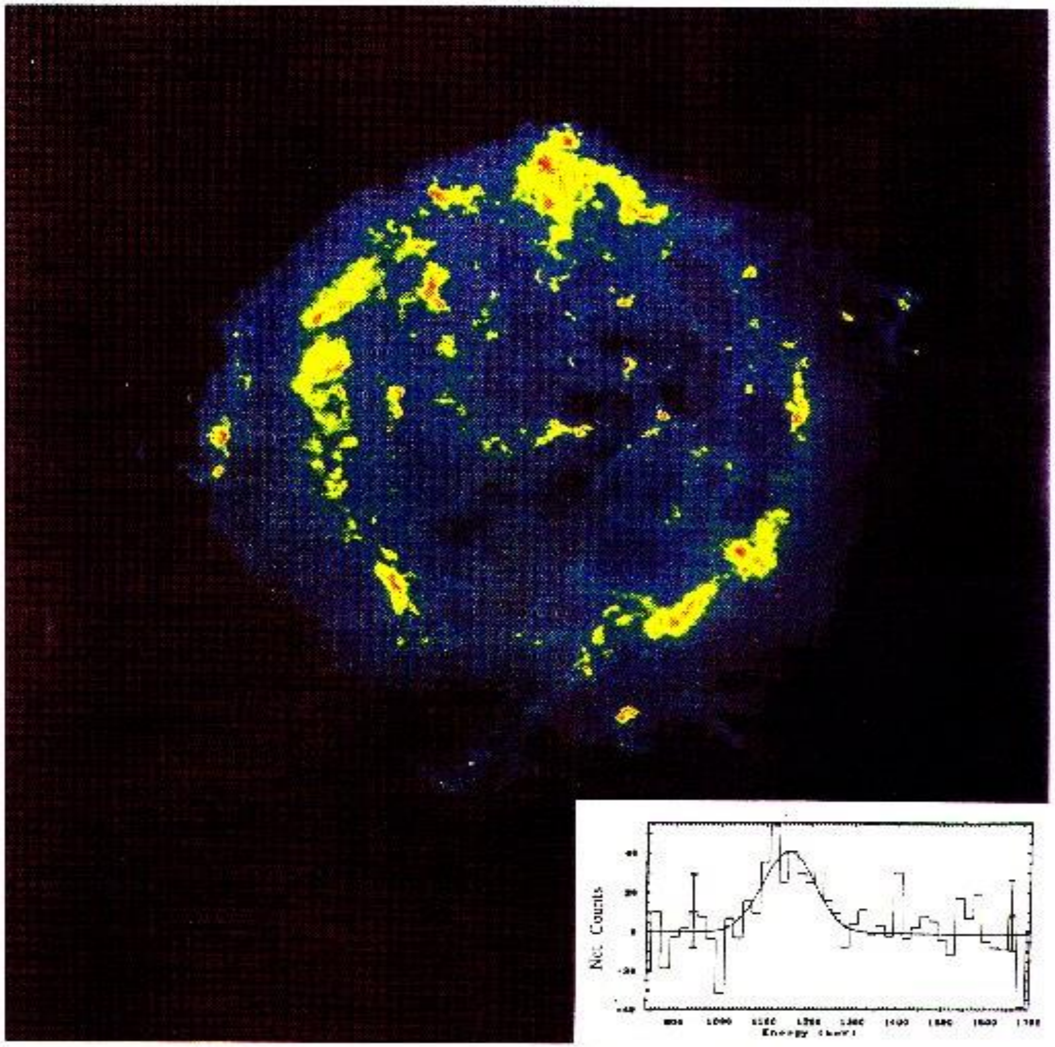
^{56}Co gamma rays observed from SN1987a

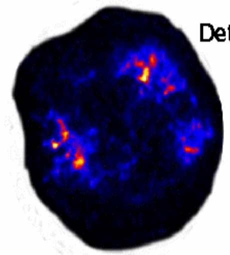




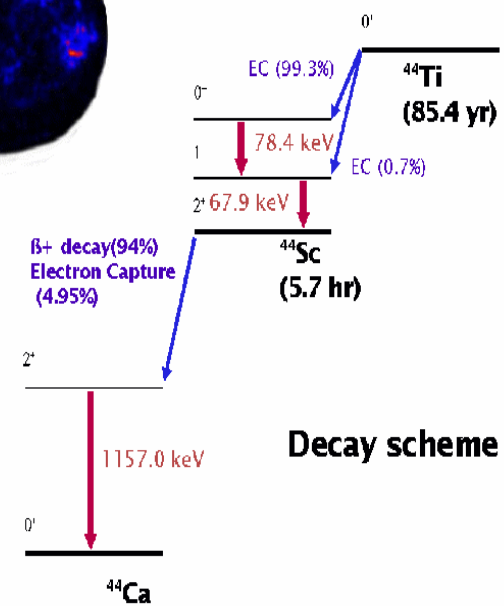
$t_{1/2}(^{56}Co)$ = 77.08±0.08 days
Lesko *et al*.
PRC **40** (1989) 445

^{44}Ti gamma rays observed from CasA





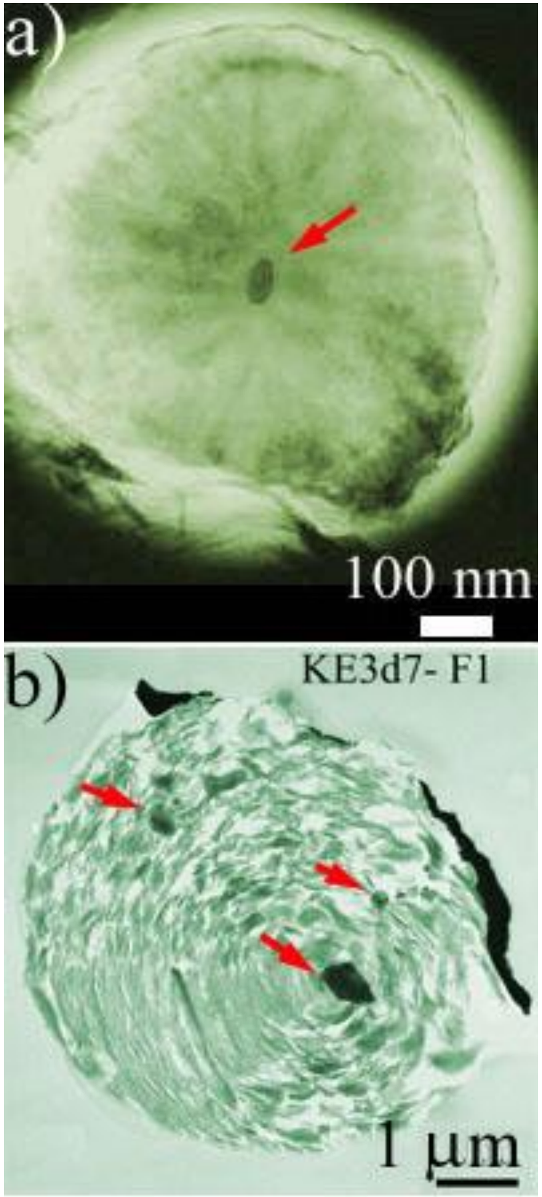
Detection of the nuclear decay lines of ^{44}Ti in Cas A
Jacco Vink (Columbia University)



Decay scheme of ^{44}Ti

$t_{1/2}(^{44}Ti) = 62 \pm 2$ years
Norman *et al.*
PRC **57**(1998) 2010

$\sigma(^{40}Ca(\alpha,\gamma)^{44}Ti$
R.D. Hoffman *et al.*
Ap. J. **715**(2010) 1383



Pre-solar graphite grains from Murchison meteorite containing TiC inclusions

E. Zinner *et al.*

Washington Univ.

Meteoritics & Planetary Science 35, 1157–1176 (2000)

Isotopic properties of silicon carbide X grains from the Murchison meteorite in the size range 0.5–1.5 μm

PETER HOPPE[1,2]*, ROGER STREBEL[1,2], PETER EBERHARDT[2], SACHIKO AMARI[3,4] AND ROY S. LEWIS[4]

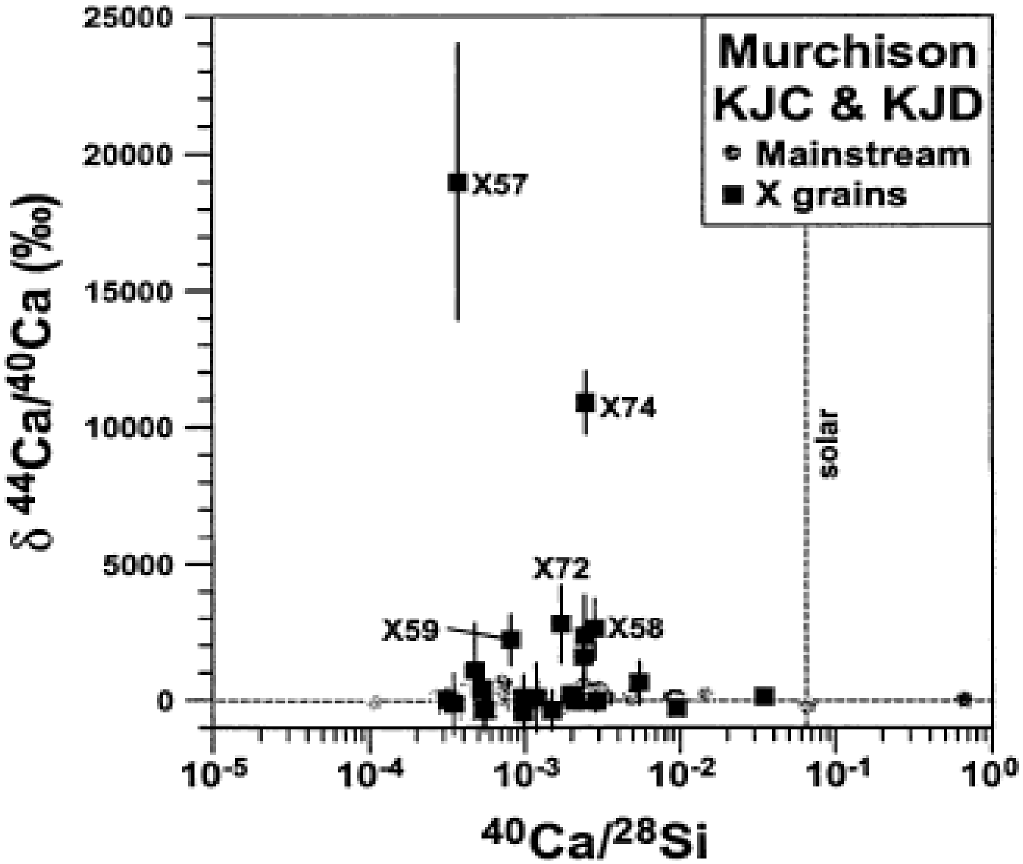


FIG. 8. Calcium-44 and Ca/Si ratios in presolar SiC grains from the Murchison separates KJC and KJD. $\delta^{44}Ca/^{40}Ca = [(^{44}Ca/^{40}Ca)/(^{44}Ca/^{40}Ca)_{\odot} - 1] \times 1000$ with $(^{44}Ca/^{40}Ca)_{\odot} = 0.0212$. Errors are 1$\sigma$. Five X grains (X57, X58, X59, X72, X74) have large excesses in ^{44}Ca by factors between 3 and 20, indicative of extinct ^{44}Ti. A few other X grains are enriched in ^{44}Ca by up to a factor of 3, but errors are large for those grains.

Supernova Remnants

- **Neutron star – supported by neutron degeneracy pressure**
  - **Upper limit on neutron star mass ~ 2.5 M_{Sun}**

Oppenheimer-Volkoff limit

Higher masses → black hole

$$R_{Schwarzschild} = 2GM/c^2$$

For 1 M_{Sun}, R_s = 3 km

Origin of Heavy elements

Neutron capture reactions

slow (s) process

produces half of nuclei from $^{56}Fe \rightarrow {}^{209}Bi$

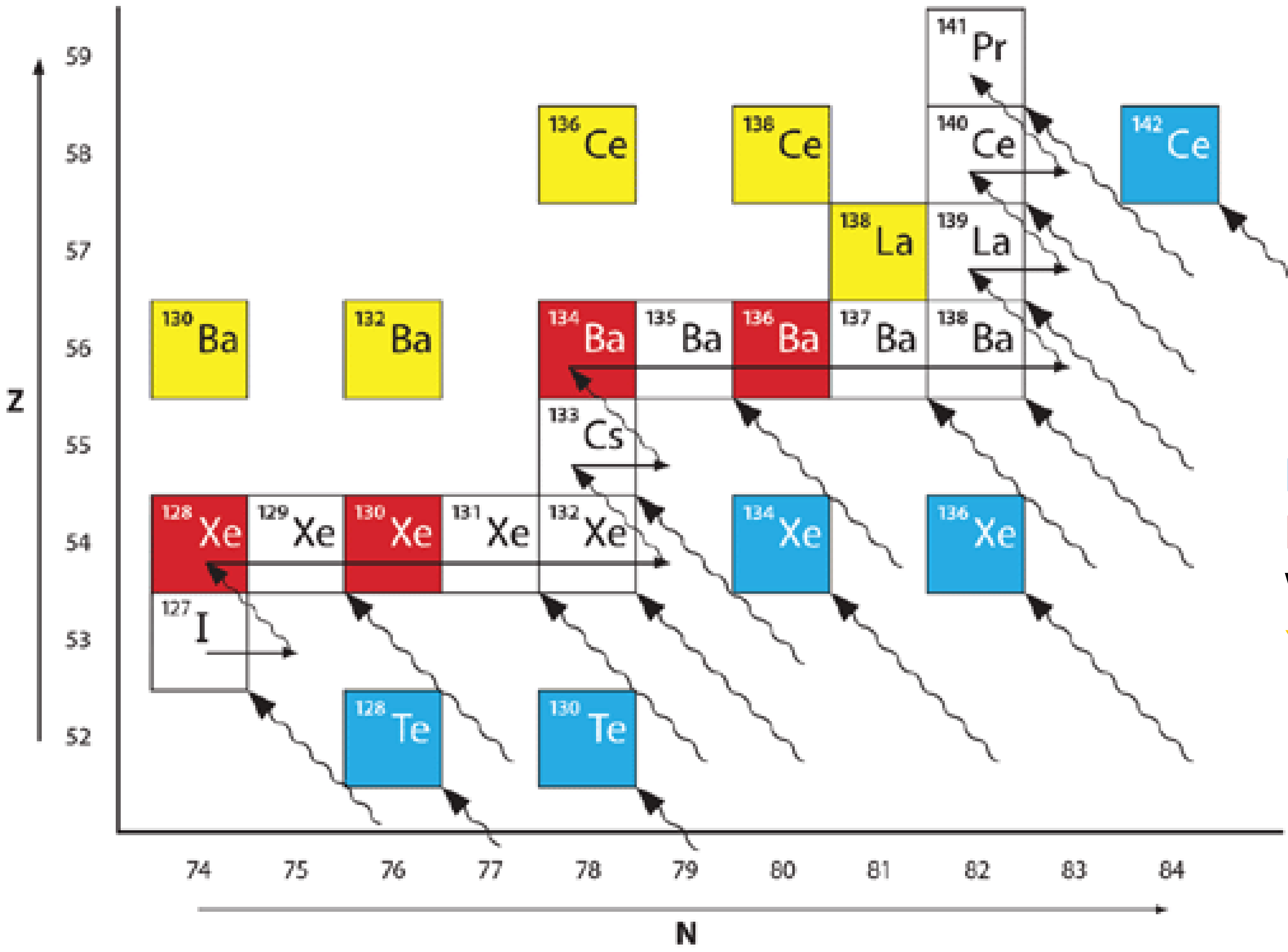
occurs during He-burning in red giant stars

rapid (r) process

produces other half of nuclei heavier than ^{56}Fe plus Th and U

occurs in supernovae, neutron star mergers ?

s and r processes



Blue – r process only
Red – s process only
White – s and r processes
Yellow – p process

s – process

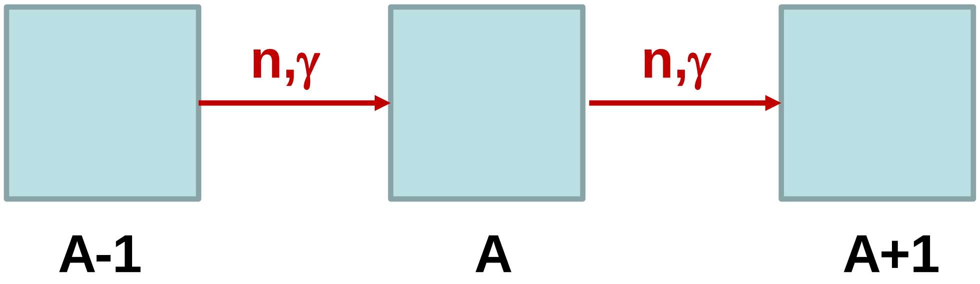
Believed to occur during He-burning in red giant stars

Neutron sources : $^{13}C(\alpha,n)^{16}O$, $^{22}Ne(\alpha,n)^{25}Mg$ reactions

at T ~ (1 – 4) x 10^8 K, $n_n \sim 10^8$ /cm^3

→ $r_{n\gamma} = n_n\langle\sigma v\rangle = (10^8/cm^3)(10^{-25}\ cm^2)(2x10^8\ cm/s) = 2 \times 10^{-9}/s$

→ $\tau_{n\gamma} \sim$ **15 years !**

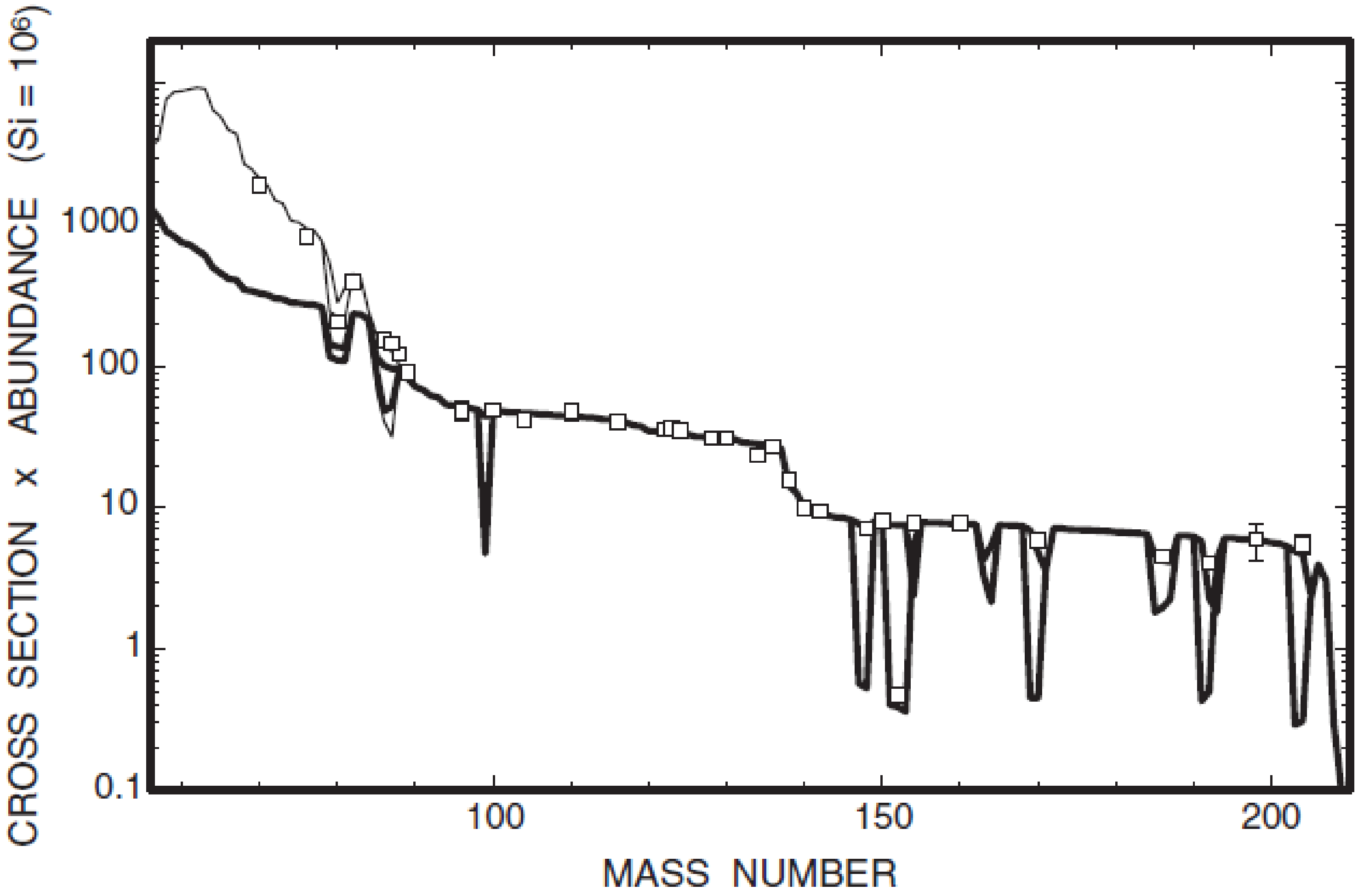


$$dN_A/dt = \sigma_{A-1}N_{A-1} - \sigma_A N_A$$

At equilibrium, $dN_A/dt = 0$

→ expect $\sigma_{A-1}N_{A-1} = \sigma_A N_A$ = constant

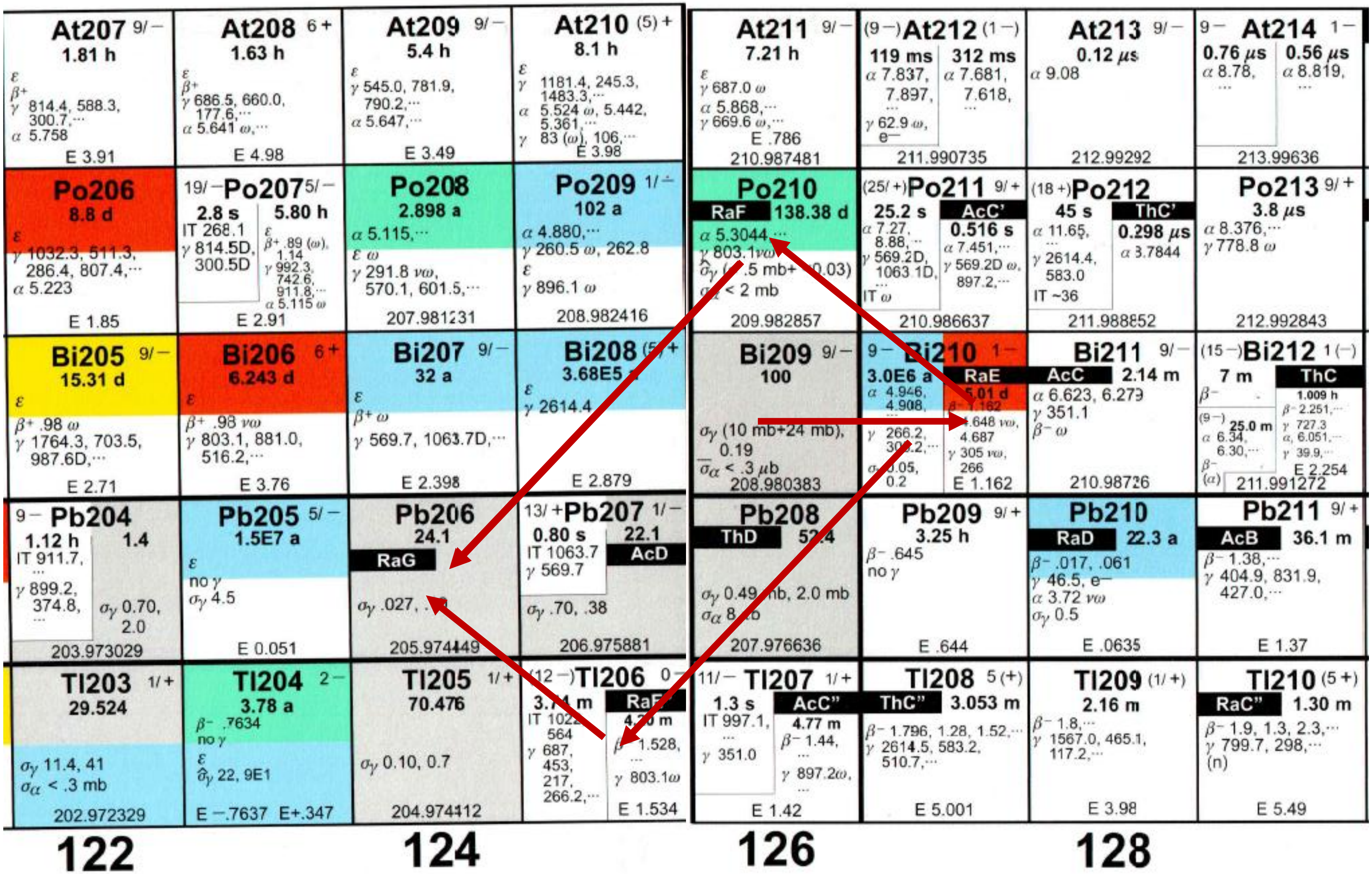
Kappeler *et al.*
Rev. Mod. Phys. 83 (2011) 157



→s-process abundance peaks for nuclei with low $\sigma(n,\gamma)$

→i.e. N = 50, 82, 126 → A ~ 90, 140, 208

Termination of s-process



r-process needed to explain Th , U

r-process path

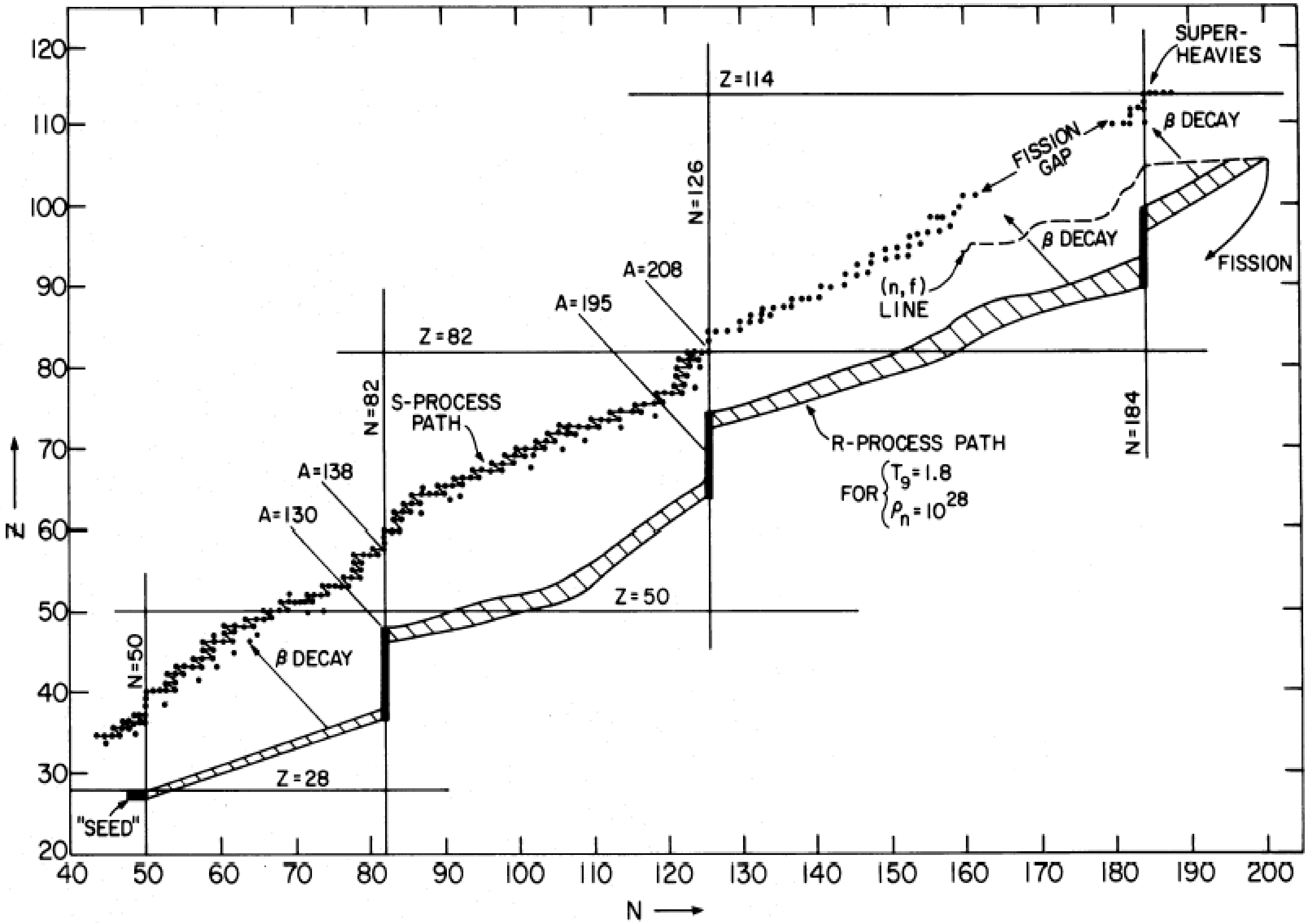
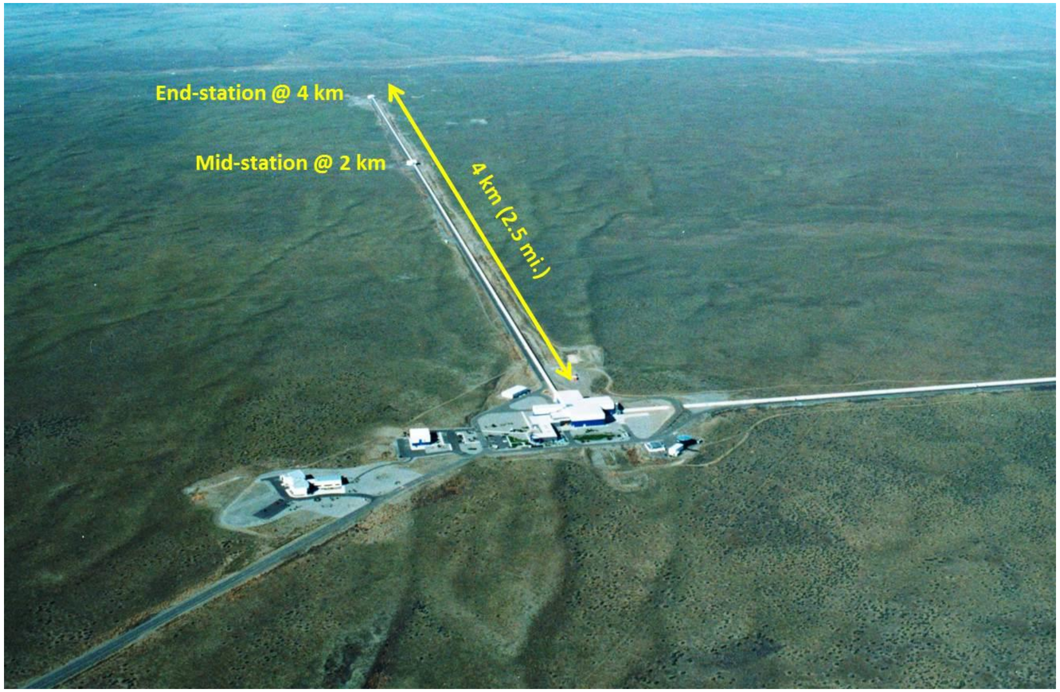


FIG. 1.—Neutron capture paths for the *s*-process and the *r*-process. The *r*-process was computed for initial conditions of $T_9 = 1.8$ and $n_n = 10^{28}$ (Schramm and Norman 1976).



GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral
LIGO, PRL **119** (2017) 161101

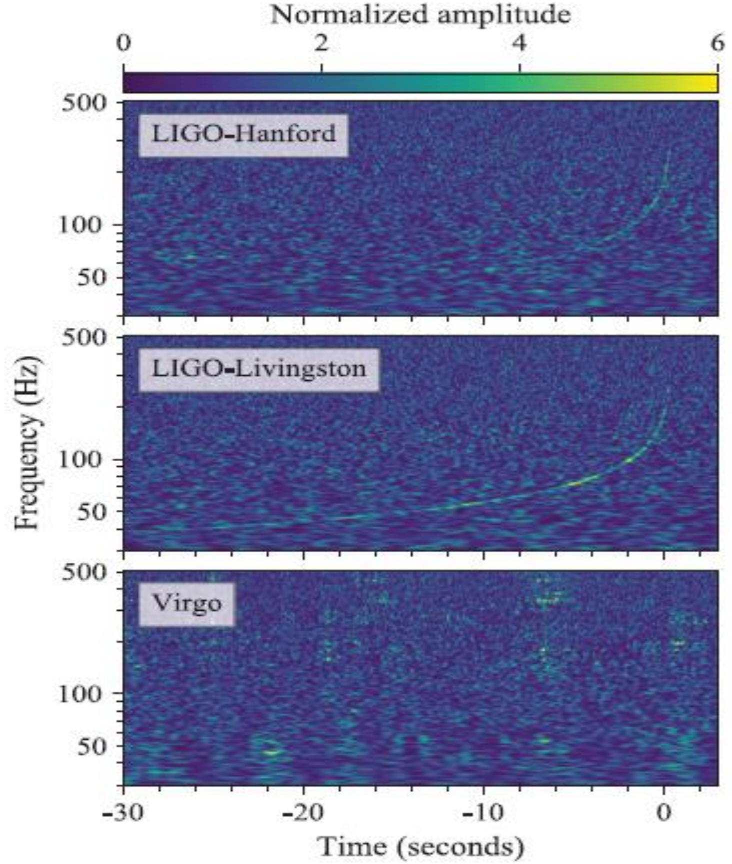
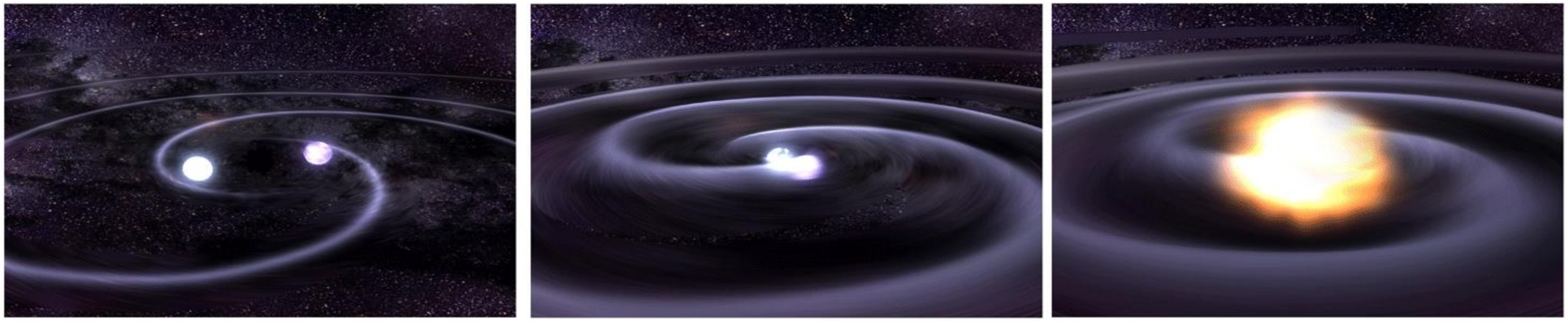
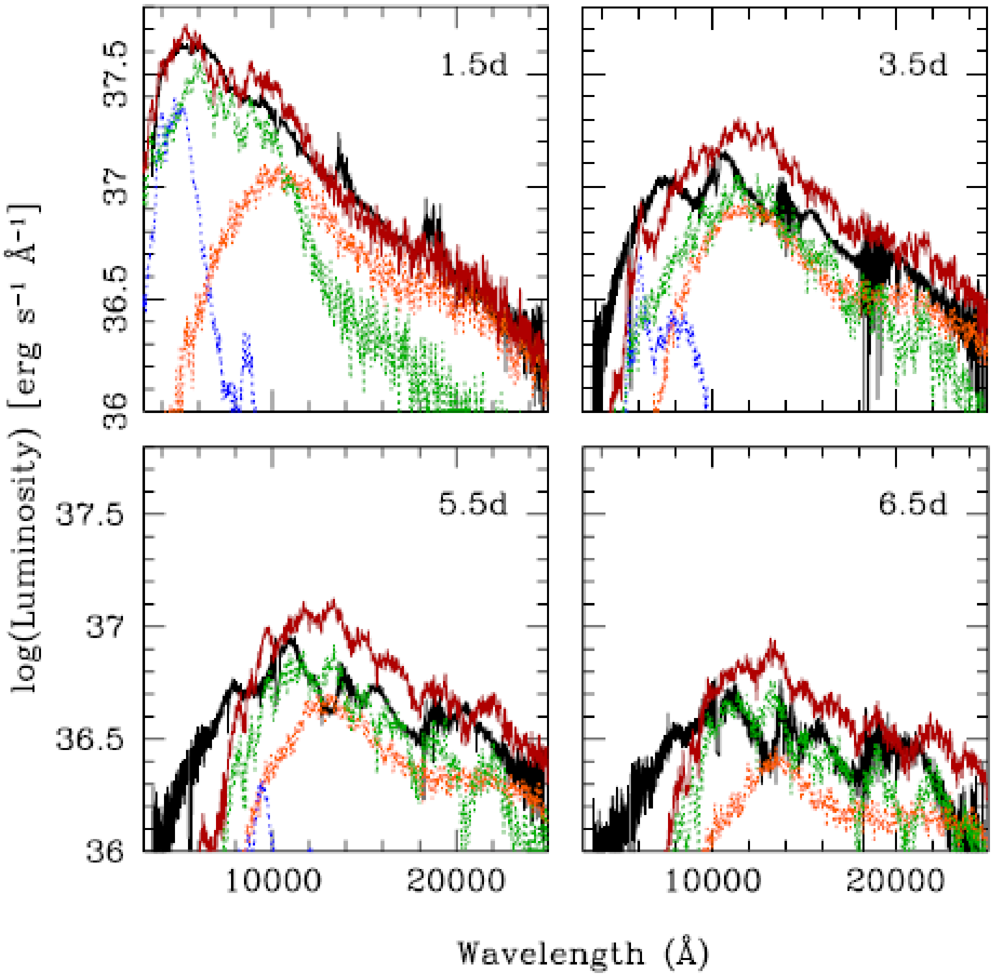


FIG. 1. Time-frequency representations [65] of data containing the gravitational-wave event GW170817, observed by the LIGO-Hanford (top), LIGO-Livingston (middle), and Virgo (bottom) detectors. Times are shown relative to August 17, 2017 12:41:04



Evidence for neutron-star mergers as a possible site for the r-process



Orange curves are rich in lanthanides (indicative of r-process)

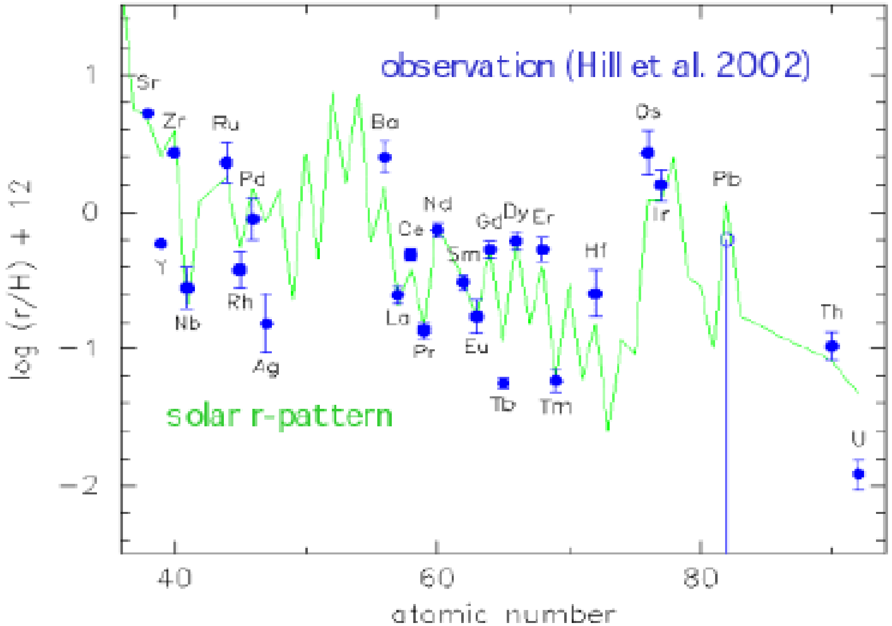
Photon spectra observed from GW170817 and GRB170817 sources

Pian *et al.*
Nature **551** (2017) 67

Discovery of U in an extremely metal-poor star !

CS 31082-001, [Fe/H] = −2.9 (Cayrel et al. 2001)

- ➲ good news: new cosmochronometer U-Th (with, e.g., Th-Eu)
- ➲ bad news: "non-universality" up to Th and U



Wanajo et al

U-Th cosmochronology

age of CS 31082-001: hard lower limit on the age of the universe

$$t^*(U/Th) = 14.1 \text{ Gyr}$$

This star may have formed too early for neutron-star mergers to explain r-process abundances. Thus, there may be more than one r-process site.

Source of stellar energies

Nuclear reactions

Origin of chemical elements