Stardust...
Nuclear astrophysics in a nuttshell

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Introduction : a bit of history

Where do we come from ?
Where was produced the matter that surrounds us ?

The answer came from astrophysics. . .

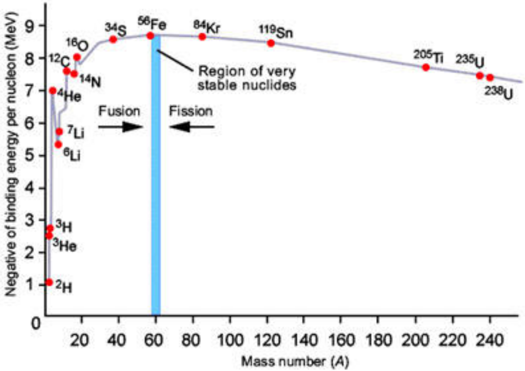
In 1920 A. Eddington : stars are nuclear powered
In 1929 R. Atkinson and F. Houtermans :
fusion of light elements produces energy
e.g. fusion of 4 protons into ^{4}He

$$4\,\mathrm{p} \to {}^4\mathrm{He} + 2\mathrm{e}^+ + 2\nu_\mathrm{e} + 26.73\ \mathrm{MeV}$$

In 1938-39, H. Bethe and C. Critchfield : pp chain and CNO cycles (H. Bethe got NP in 1967)
In 1957, seminal paper of Burbidge, Burbidge, Fowler and Hoyle on nucleosynthesis in stars [Rev. Mod. Phys. **29**, 257]

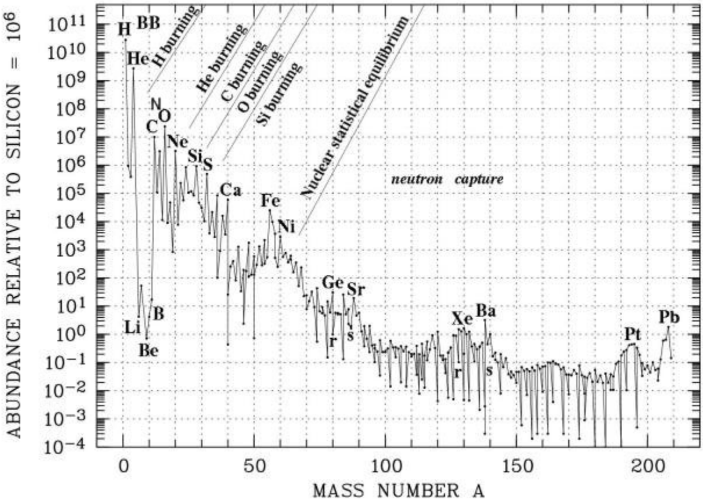
Introduction : nucleosynthesis in a nutshell

By fusion of light elements we can reach the Fe-Ni region because reactions are exoenergetic and Coulomb repulsion is small



Beyond, processes based on n or p capture lead to heavy nuclei : s, r, p, rp processes…

Abundances of elements



Abundance measured relative to Si fixed to 10^6.

pp chain $p + p \rightarrow {}^{2}_{1}H + e^{+} + \nu_e$ or $p + e^{-} + p \rightarrow {}^{2}_{1}H + \nu_e$

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

(85%) (15%)

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

ppI

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

(15%) (0.02%)

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

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

ppII

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

$${}^{8}_{5}B \rightarrow {}^{8}_{4}Be + e^{+} + \nu_e$$

$${}^{8}_{4}Be \rightarrow {}^{4}_{2}He + {}^{4}_{2}He$$

ppIII

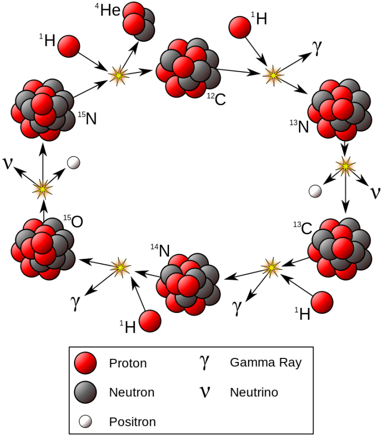
Summary : $4p \rightarrow {}^{4}_{2}He + 2e^{+} + 2\nu_e + 25\text{MeV}$

CNO cycle(s)

If the star contains C, N or O they can be used as catalyst to synthesise ^{4}He from 4 p

e.g. CNO C cycle :

$$
\begin{aligned}
{}^{12}\mathrm{C} + \mathrm{p} &\rightarrow {}^{13}\mathrm{N} + \gamma \\
{}^{13}\mathrm{N} &\rightarrow {}^{13}\mathrm{C} + \mathrm{e}^+ + \nu_e \\
{}^{13}\mathrm{C} + \mathrm{p} &\rightarrow {}^{14}\mathrm{N} + \gamma \\
{}^{14}\mathrm{N} + \mathrm{p} &\rightarrow {}^{15}\mathrm{O} + \gamma \\
{}^{15}\mathrm{O} &\rightarrow {}^{15}\mathrm{N} + \mathrm{e}^+ + \nu_e \\
{}^{15}\mathrm{N} + \mathrm{p} &\rightarrow {}^{12}\mathrm{C} + \alpha
\end{aligned}
$$



CNO C cycle

Summary : $4\mathrm{p} \rightarrow {}^4_2\mathrm{He} + 2\mathrm{e}^+ + 2\nu_e + 25\mathrm{MeV}$

Other cycles : CNO N cycle (^{14}N as catalyst), NeNaMg cycles

Reaction rate

We consider the radiative-capture reaction : $1 + 2 \rightarrow 3 + \gamma$
The reaction rate is the number of reactions occurring per unit time and volume

$$r = N_1 N_2 \, \sigma \, v$$

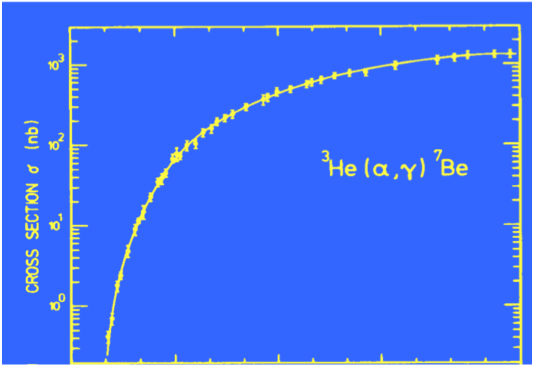
The velocity v is distributed according to Maxwell-Boltzmann

$$\begin{aligned}
\phi(\boldsymbol{v}) &\propto e^{-E/kT} \\
\Rightarrow \langle \sigma \, v \rangle &= 4\pi \int \phi(\boldsymbol{v}) \, \sigma(v) \, v^3 \, dv \\
&\propto \int e^{-E/kT} \, \sigma(E) \, E \, dE
\end{aligned}$$

$\sigma(E)$ at low energy

Due to Coulomb barrier σ plummets at low E
because reaction takes place only through tunneling

$^{3}\mathrm{He} + \alpha \rightarrow {}^{7}\mathrm{Be} + \gamma$ also noted $^{3}\mathrm{He}(\alpha, \gamma)\,{}^{7}\mathrm{Be}$



Astrophysical S factor

Due to Coulomb barrier σ plummets at low E
because reaction takes place only through tunneling
Example : ${}^3\mathrm{He} + \alpha \rightarrow {}^7\mathrm{Be} + \gamma$
also noted ${}^3\mathrm{He}(\alpha, \gamma)\,{}^7\mathrm{Be}$

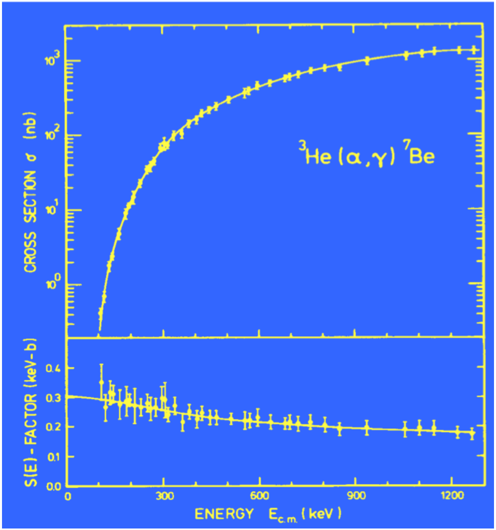
The rapid drop explained
by the Gamow factor $e^{-2\pi\eta}$,

$$\eta = \frac{Z_1 Z_2 e^2}{4\pi\epsilon_0 \hbar v}$$

is Sommerfeld parameter

$$\Rightarrow \sigma(E) = \frac{S(E)}{E} e^{-2\pi\eta}$$

The astrophysical S factor
varies smoothly with E



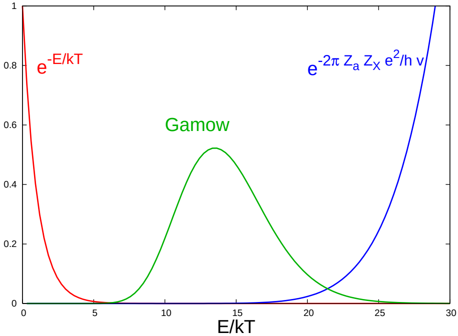
Gamow peak

$$\langle \sigma v \rangle \propto \int e^{-E/kT} \, \sigma(E) \, E \, dE$$

$$= \int e^{-E/kT} \, e^{-2\pi\eta} \, S(E) \, dE$$

$\Rightarrow S$ (i.e. σ) must be known only in the Gamow peak

$$g(E) = e^{-E/kT} \, e^{-2\pi\eta}$$



Example

For the reaction $^{3}\mathrm{He}(\alpha,\gamma)\,^{7}\mathrm{Be}$ in the sun

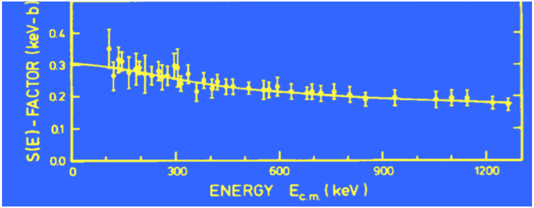
$Z_1 = 2, A_1 = 3$

$Z_2 = 2, A_2 = 4$

$T = 0.015\ T_9$

Gamow peak

at $E_0 \simeq 20$ keV



$\Rightarrow$ difficult to measure due to background.

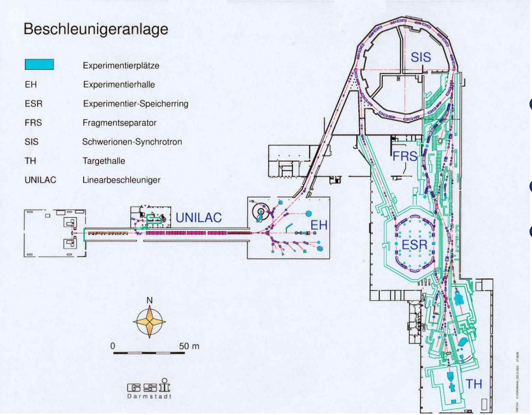
Solutions :

- Rely on theory to extrapolate down to astrophysical energies
- Go to an underground laboratory to reduce background
  e.g. LUNA collaboration
- Use indirect techniques, e.g. Coulomb breakup
  $^{8}\mathrm{B} + \mathrm{Pb} \rightarrow\ ^{7}\mathrm{Be} + \mathrm{p} \quad \leftrightarrow \quad ^{7}\mathrm{Be}(\mathrm{p},\gamma)^{8}\mathrm{B}$
- Measurement in a storage ring [Yu. Litvinov's talk on Thursday]

Storage Ring

Store heavy ions, e.g. produced at RIB facility, in a ring

Example : Experimental Storage Ring (ESR) @ GSI



- Precision measurement of nuclear masses
- Lifetime spectroscopy
- Measurement of reaction cross sections

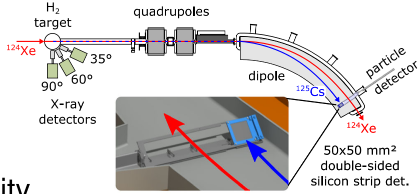
  [Yu. Litvinov's talk Thursday]

Measurement of reaction cross sections @ ESR

- ^{96}Ru(p,γ)^{97}Rh [PRC 92, 035803 (2015)]
- ^{124}Xe(p,γ)^{125}Cs [PRL 122, 092701 (2019)]

measured as proof of principle (useful in p-process model cf. infra)
Incoming beam @ 100AMeV slowed down in ESR to 5–10AMeV

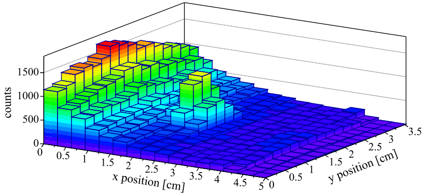
- H_2 gas-jet target
  - windowless (less background)
  - thin (no multiple collisions, but reduced luminosity)
- High revolution frequency (250–500 kHz) increases luminosity
- DSSSD in dipole detects products
- X-ray detectors to monitor luminosity

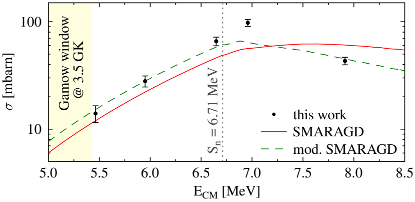


[PRL 122, 092701 (2019)]

Results for ^{124}Xe(p,γ)^{125}Cs

[PRL 122, 092701 (2019)]





- DSSSD can disentangle ^{125}Cs from scattered ^{124}Xe

- $\sigma_{(p,\gamma)}$ measured close to Gamow window
- $\Rightarrow$ constrain reaction model

He and other fusions

When enough ^{4}He has built up,
if temperature and pressure are high enough,
He fusion starts

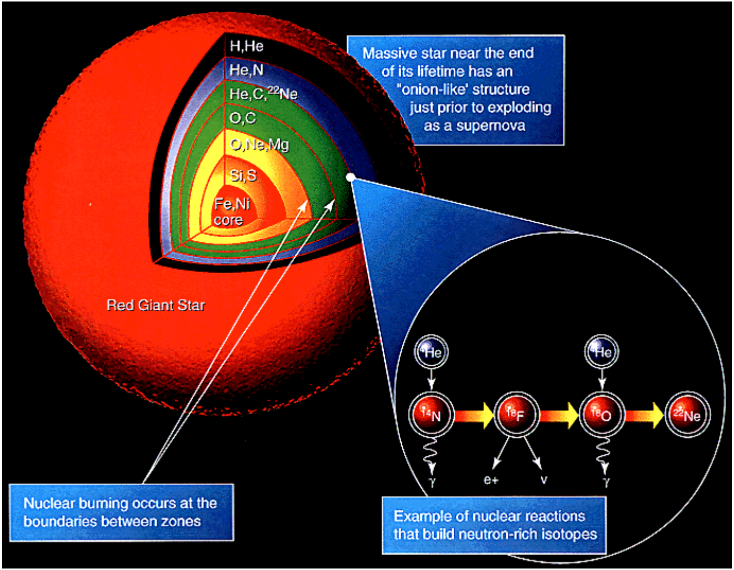
But ^{8}Be is unbound : $^8\mathrm{Be} \to {}^4\mathrm{He} + {}^4\mathrm{He}$
This $A = 8$ gap is bridged by the triple-α process

$$3\alpha \to {}^8\mathrm{Be}^* + \alpha \to {}^{12}\mathrm{C}^*$$

which occurs through the Hoyle state : $J^\pi = 0^+$ resonance in ^{12}C
predicted by F. Hoyle and observed by W. Fowler (NP in 1983)

At a later stage, C may capture α to form O
or fuse with itself to form Ne, Na or Mg
$\Rightarrow$ Onion structure of star...

The onion star



What happens next ?

Depending on the mass of the star :

- $M \lesssim 10M_\odot$:
  - ends with C-O core ($M \lesssim 8M_\odot$)
    or O-Ne-Mg core ($M \sim 8$–$10M_\odot$)
  - H outer layer is expelled → planetary nebula
  - nuclear reactions stop and what remains cools down
    → white dwarf ($M \sim M_\odot$ and $R \sim R_\oplus$)
    where gravity is compensated by the pressure of
    the electrons, which form a Fermi gas

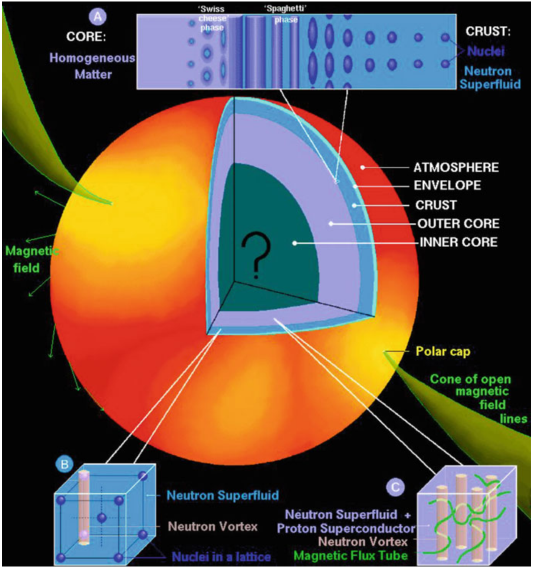
Planetary nebula : Cat's eye nebula

What happens next ?

- Massive star ($M > 10 M_\odot$)
  - C burning → Fe-Ni core
  - Gravity strikes back : gravitational collapse of the core
    → neutron star ($M \sim M_\odot$ and $R \sim 10$ km ; $\rho \sim \rho_0$)
    where gravity is compensated by
    the repulsive core of the NN interaction
    [see J. Lattimer's talk on Monday
    J. Piekarewicz's talk on Thursday]
    or black hole...
  - outer layers expelled : supernova (type II)
    [see E. O'Connor's talk on Friday]

Type II SN : Crab nebula

Neutron star



Equation of State

To understand the formation of neutron stars,
need to understand the nuclear matter

[see J. Lattimer's talk on Monday
& J. Piekarewicz's talk on Thursday]

But no need for microscopic calculations
$\Rightarrow$ (nuclear) Equation of State (EoS)
State of a perfect gas given by P, V, T, N : $\quad PV = N\,k\,T$

For nuclear matter, the state variables are
Z : proton number
N : neutron number
or in infinite matter $\alpha = (N - Z)/A$, the n-p asymmetry
ρ the density

EoS obtained from the energy of the system per nucleon ϵ

Nuclear EoS

Back to liquid-drop formula (Bethe Weizsäcker)

$$
\begin{aligned}
B(Z,N) &= a_v A - a_s A^{2/3} - a_C \frac{Z(Z-1)}{A^{1/3}} - a_{\mathrm{Sym}} \frac{(A-2Z)^2}{A} \\
\epsilon &\equiv -\frac{B(Z,N)}{A} \underset{A\to\infty}{\longrightarrow} -a_v + a_{\mathrm{Sym}}\, \alpha^2 \quad \text{with } \alpha = (N-Z)/A
\end{aligned}
$$

Liquid drop assumes constant density $\rho = \rho_0 \simeq 0.16\ \mathrm{fm}^{-3}$
We need density dependence

$$
\epsilon(\rho,\alpha) = \epsilon(\rho, \alpha = 0) + S(\rho)\alpha^2 + \ldots
$$

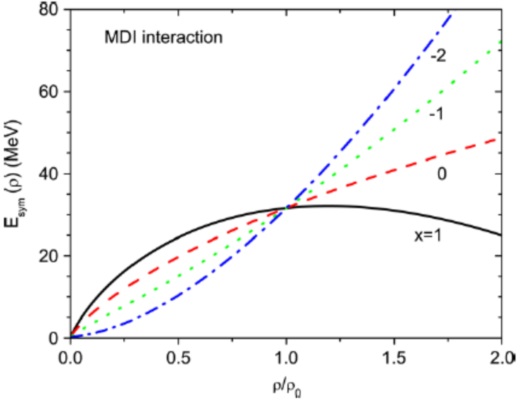
where S is the symmetry energy
Clear short review paper : [Horowitz *et al.* JPG **41**, 093001 (2014)]

Symmetry energy

S characterises the increase in energy from $N = Z$

Taylor expanded around $\rho = \rho_0$:

$$S(\rho) = S_v + \frac{L}{3}\left(\frac{\rho - \rho_0}{\rho_0}\right) + \frac{1}{18}K_{\text{sym}}\left(\frac{\rho - \rho_0}{\rho_0}\right)^2 + \dots$$



S is said

- stiff if $dS/d\rho > 0$
- soft if reaches saturation

Constraints from the lab

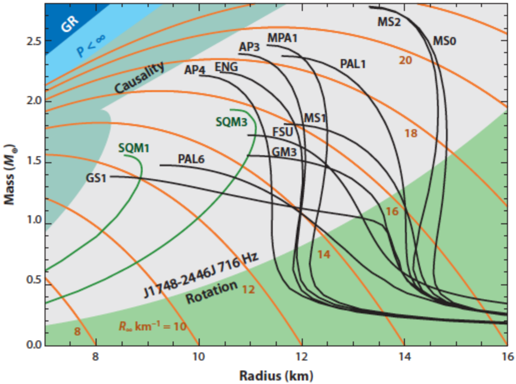
S can be constrained from nuclear experiments (laboratory) :

- neutron skin thickness (balance between surface tension and asymmetry term)
  [see J. Piekarewicz's and V. Tsaran's talks on Thursday]
- Giant Monopole Resonance (breathing mode)
- Giant Dipole Resonance (n to p oscillations)
- heavy-ion collisions (n to p ratio in emitted fragments)
  [see S. Yennello's talk on Thursday]

Constraints from the sky

from astrophysical observations [see J. Lattimer's talk on Monday]

- Mass and radii of neutron stars (existing $2\,M_\odot$)

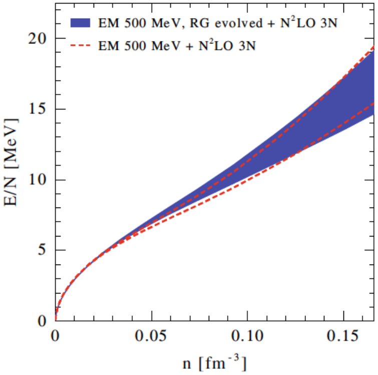


[J. Lattimer Ann. Rev. Nucl. Part. Sci. **62**, 485 (2012)]

Constraints from nuclear theory

from nuclear-structure calculation

- EFT prediction of EoS

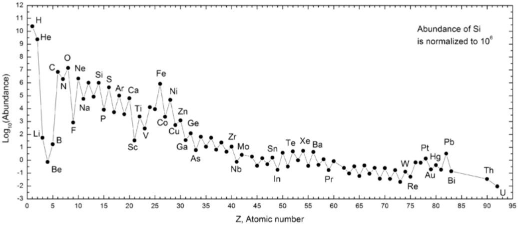


[K. Hebeler *et al.* Astrophys. J. **773**, 11 (2013)]

How do we get heavier elements ?

Increasing Coulomb barrier suppress fusion

Once Fe synthesised no more fusion



To explain formation of heavier elements

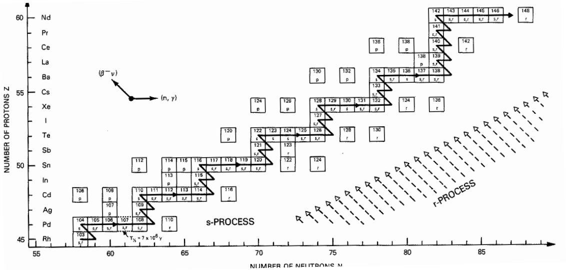
Burbidge, Burbidge, Fowler and Hoyle (B^{2}FH) suggest in 1957

successive captures of n by seed nuclei : s and r processes

s process

The s process is a *slow* process of n capture by stable nuclei
slow means slower than β decay, i.e. requires small n flux
e.g. He burning stage of AGB stars

$$^{13}\mathrm{C} + \alpha \rightarrow \ ^{16}\mathrm{O} + \mathrm{n}$$
$$^{22}\mathrm{Ne} + \alpha \rightarrow \ ^{25}\mathrm{Mg} + \mathrm{n}$$

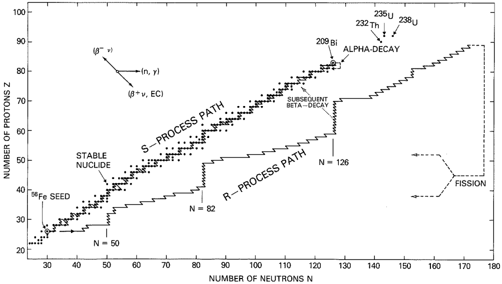


Synthesises elements close to stability ⇒ does not explain

- isotopes away from stability
- heavy elements (U, Th. . .)

r process

The r process is a *rapid* process of n capture by stable nuclei
rapid means faster than β decay, i.e. requires high n flux
e.g. core-collapse supernovæ [see E. O'Connor's talk on Friday]
n-stars mergers

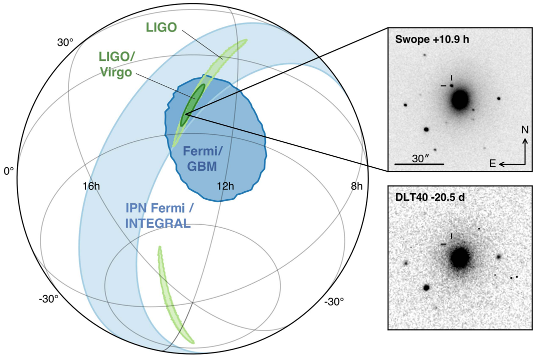


Synthesises elements far away from stability ⇒ requires

- masses of radioactive isotopes
- location of nuclear shells

Binary neutron star merger (BNS)

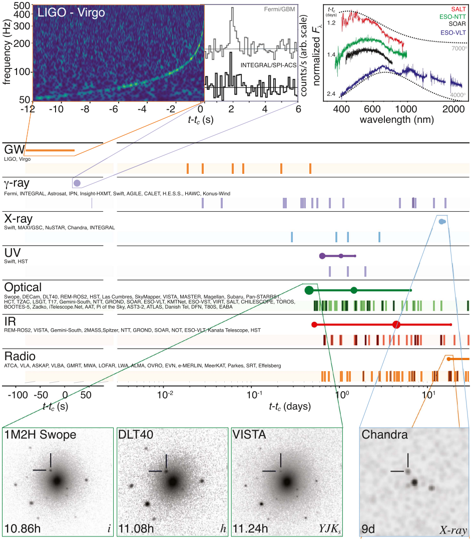
August 2017 : gravitational wave measured by LIGO and Virgo
Understood as a Binary neutron star merger (BNS)



[AJL 848, L12 (2017)]

EM signals (γ, UV, optical, IR...) have also been recorded confirming that BNS mergers are sites for r-process

Binary neutron star merger (BNS)



[AJL 848, L12 (2017)]

- GRB 2 s after GW
  $\Rightarrow v_{\mathrm{GW}} \sim c$
- EM spectrum bears signature of r-process nuclei decay
- Multi-messenger astronomy
- BNS better explains nucleosynthesis of heavy elements than SN
- Phys. Today 2017 12, 19
  Phys. Today 2018 01, 300
- Add neutrino measurement [A. Franckowiak Wednesday C. Distefano Tuesday]

p and rp processes

s and r processes synthesise only n-rich nuclei
How to explain the presence of p-rich nuclei ?

p and rp processes are similar processes
with successive p captures

p process :
Slow capture of protons
Synthesises p-rich nuclei close to stability
Possible site : O-Ne layer in supernova

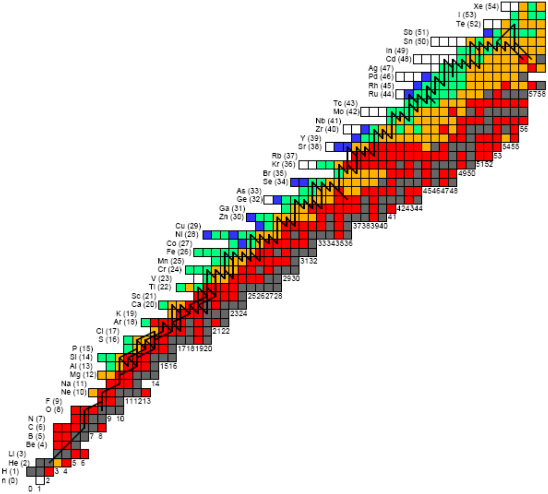
rp process

rapid p-capture reactions

synthesises elements
away from stability
cf r process

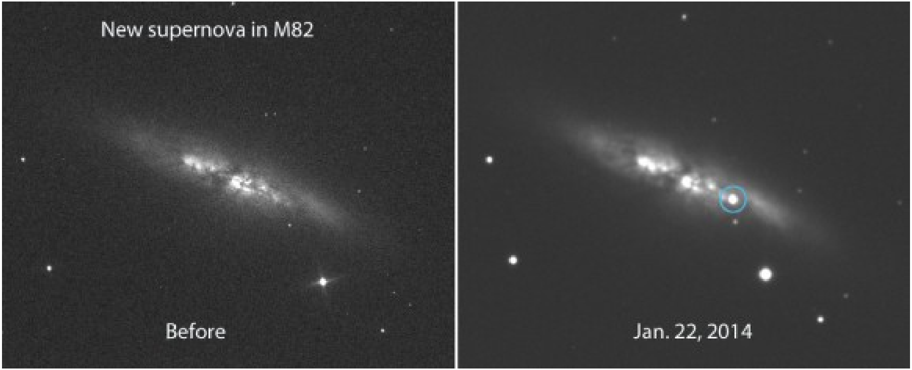
Possible sites :

- X-ray burst
  accretion by neutron star of H- and He-rich material from companion star
- type Ia supernova
  same accretion on white dwarf



[Schatz and Rehm NPA 777, 601 (2006)]

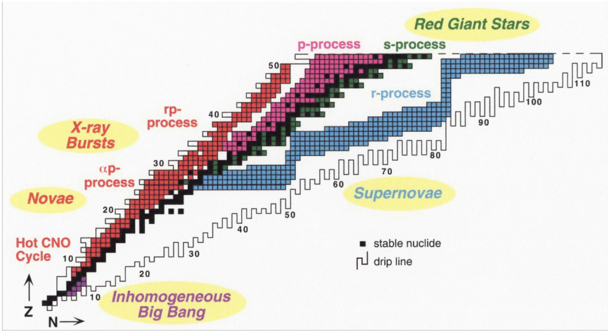
Type Ia SN : 21 January 2014



Summary

Nuclei are synthesised in stellar environments during various processes

- pp chain, CNO cycles, He burning,...
- s and r processes (n capture)
- p and rp processes (p capture)



[Smith and Rehm Annu. Rev. Nucl. Part. Sci. 51, 91 (2001)]

Stardust

Abundances of elements and production mechanisms