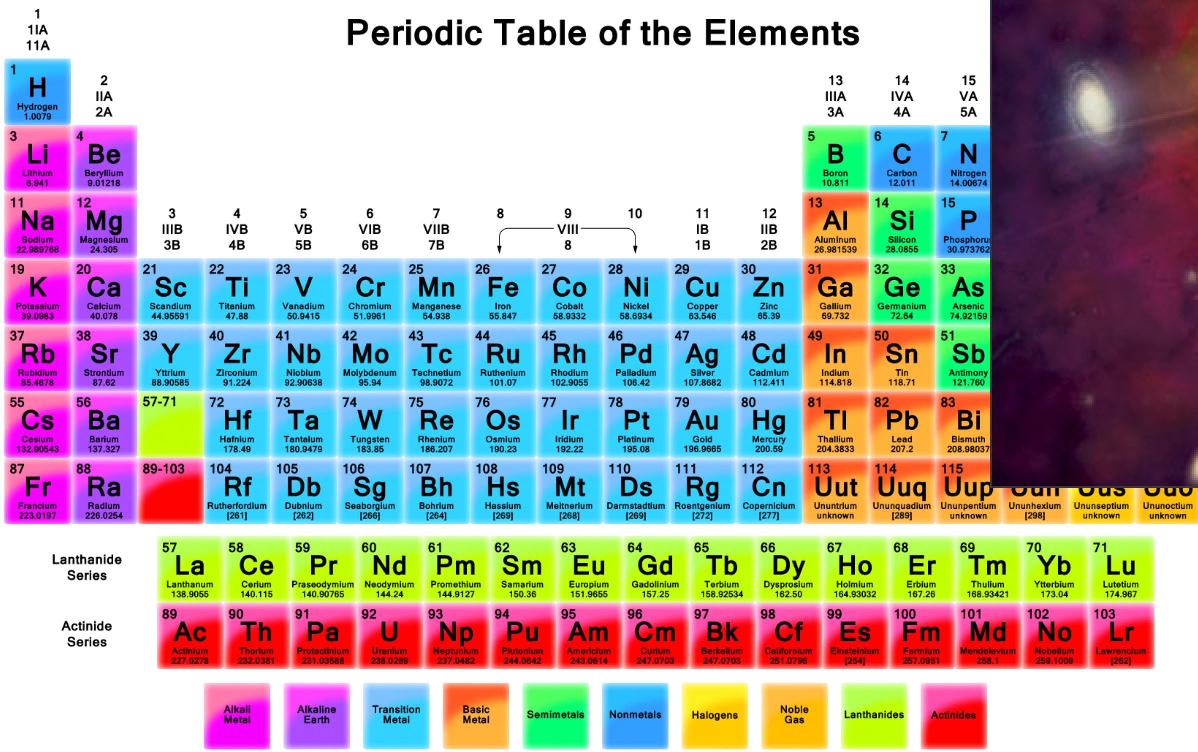
Nucleosynthesis



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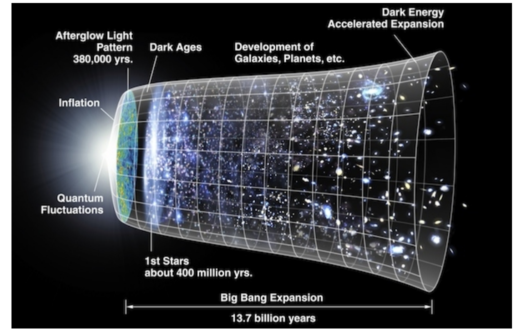
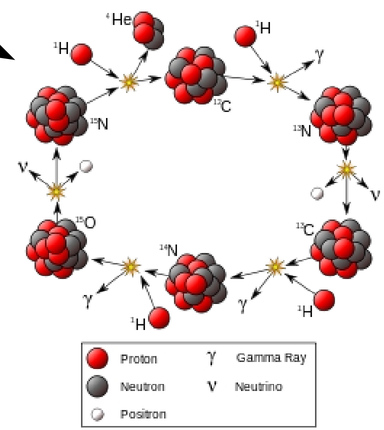
Overview



- Big Bang Nucleosynthesis (BBN)
- Hydrostatic burning in stars:
  - PP-Chain
  - CNO-Cycle



- Explosive burning
- Neutron-captures

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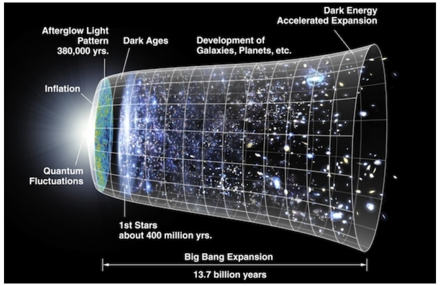
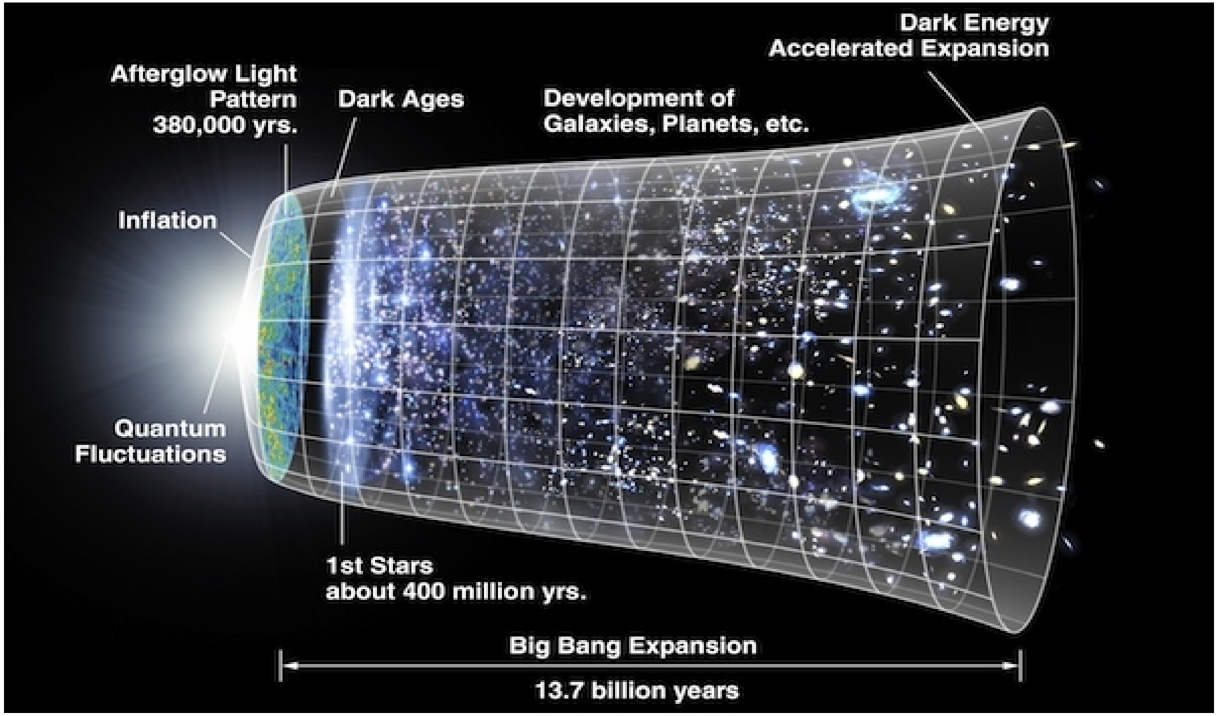
Big Bang Nucleosynthesis – BBN



- From quark soup to lithium
- Time line
- Cooling
- Reactions
- BBN
- Which nuclei can and cannot be made



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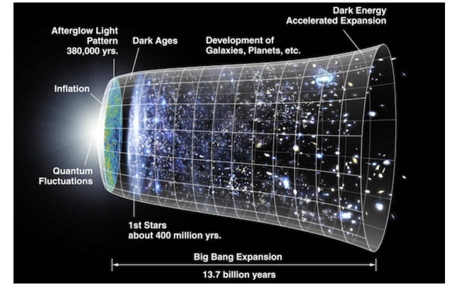
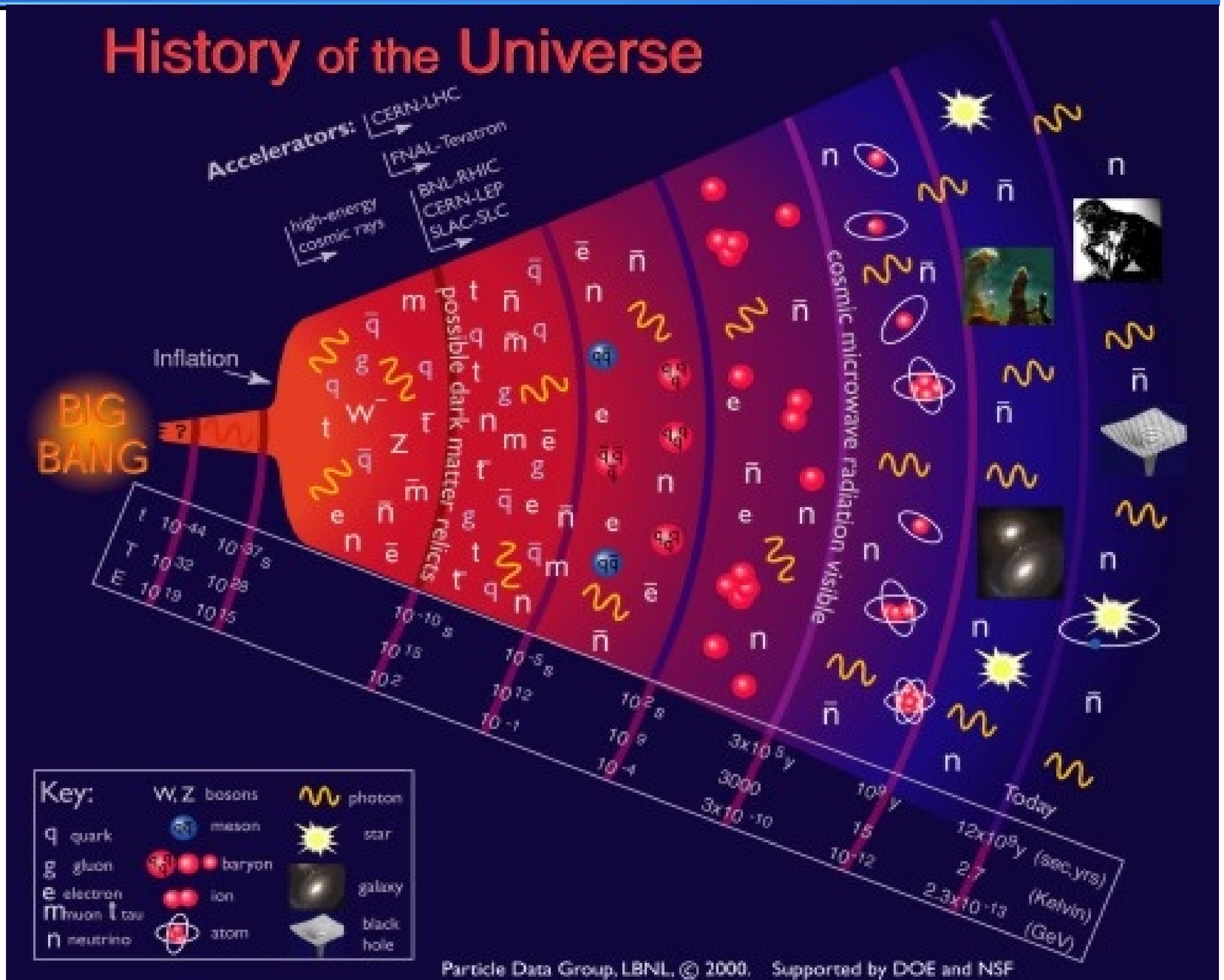
Early evolution – A quark soup





The number of:

Photons >> baryons >> anti-matter

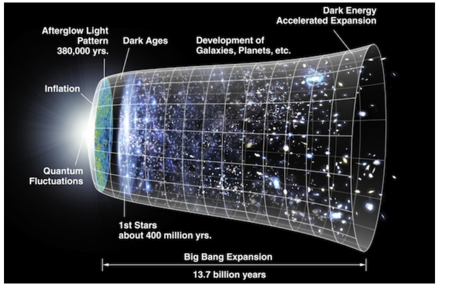
↓

BBN produced:

H, ^{2}H(D), ^{3}H, ^{3}He, ^{4}He, ^{6}Li, ^{7}Li, ^{7}Be –

but how?

From the CMB to Deuterium



- We will focus on what happens after t=1s
- The particles in the soup are now free neutrons (n), protons (p), electrons (e), neutrinos (ν), and photons (γ)
- General notation: A = Z + N (atomic mass= #p + #n)
- And 1H = p, 2H = D (deuterium), 3H = 'T' (tritium)
- What happens at t > 1s:

$n + e^+ \rightleftharpoons p + \bar{\nu}_e$ and $p + e^- \rightleftharpoons n + \nu_e$

Equilibrium stops (t~0.1s or <1s), as the temperature drops (due to expansion) the neutrinos, which interact via the weak force, will find it harder to react with n and p, and decouple from n, p (and e) and freeze their ratios. At low T protons are favoured – #p > #n

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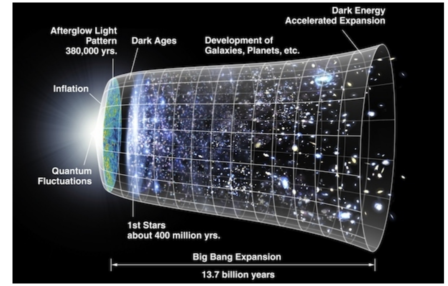
After the first second



- At the frozen n/p-ratio, there will be 1 n for every 5 p.

t ~ 2s

- These can now react with each other:
- p + p ──► D + e^+ + ν_e (a neutrino enters ──► weak interaction ──► low cross section = low probability)
- n+n ──► D + e^- + $\bar{\nu}_e$ (again low probability)
- p+n ──► D + γ (strong interaction = high probability)
- The energy (E) released in this reaction (2.22MeV) is carried away by the photon – this E is high and might dissociate H
- Need to continue fast because n decays in ~ 15min (890s)

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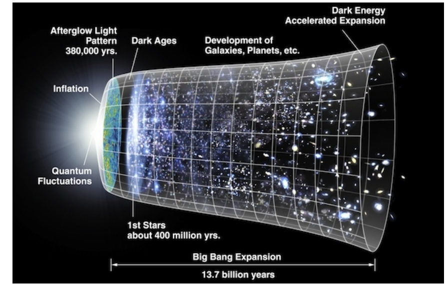
Deuterium



At high temperatures the very energetic photons will dissociate H, and only as the universe cools the conditions will allow D to form:

t ~ 200s

This happens around t ~ 200s, a very low baryon-to-photon ratio (η) ~ 5.5*10^-10 and T has dropped below 10^9K (7.6*10^8K)

At this point the n:p-ratio will be 1:7. Then D is formed via p-n reactions:

- p+n ⟶ D + γ   But D is not tightly bound (binding energy per nucleon = B/A is 2.22MeV)
- A n-D equilibrium will end once a significant amount of D formed. D will then fuse to become helium or tritium

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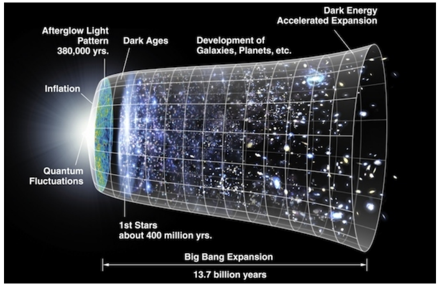
Fusing D and creating He



- D + p ↔ ^{3}He +γ
- D + n ↔ ^{3}H + γ (tritium is unstable – decays in 18 yrs – considered stable during BBN)
- D + D ↔ ^{4}He + γ
- D + D ↔ ^{3}H + p (most likely)
- D + D ↔ ^{3}He + n (most likely)
  - ^{3}H + p ↔ ^{4}He + γ
  - ^{3}He + n ↔ ^{4}He + γ
  - ^{3}H + D ↔ ^{4}He + n
  - ^{3}He + D ↔ ^{4}He + p

Once D fusion starts basically all is converted to ^{4}He, since this nuclei is strongly bound and energetically favourable!

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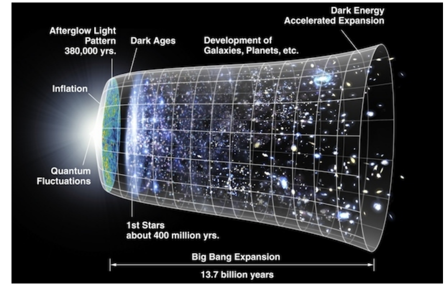
Helium



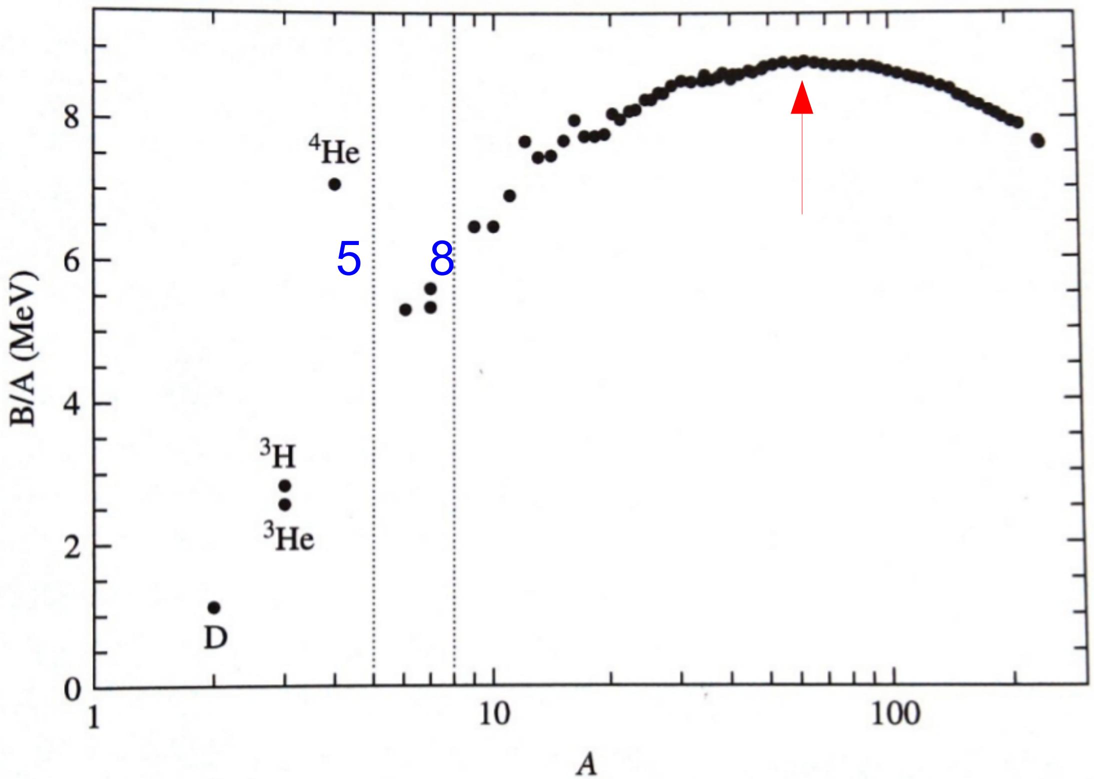


FIGURE 10.1 The binding energy per nucleon (B/A) as a function of the number of nucleons (protons and neutrons) in an atomic nucleus. Note the absence of nuclei at $A = 5$ and $A = 8$.

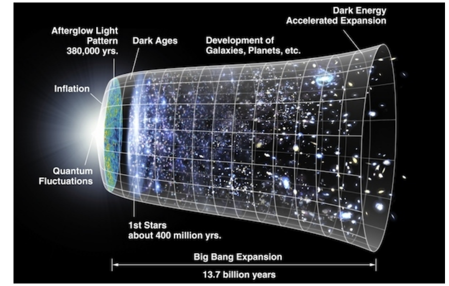
B/A (^{4}He) = 7.07MeV

^{4}He is the tightest bound lighter nuclei

B/A (^{56}Fe) = 8.8MeV

(=Maximum binding energy... See arrow)

No stable A = 5 and 8 nuclei



- Since ^4He is the tightest bound nuclei, further fusion is slowed down, and because there are no stable nuclei with atomic number 5 and 8 ^4He will resist reacting with n or p.
- The way to proceed is for ^4He to react with D:
- $^4He + D \leftrightarrow \; ^6Li + \gamma$ or $^4He + {}^3H \leftrightarrow \; ^7Li + \gamma$
- Small amounts of Be are made via:
- $^4He + {}^3He \leftrightarrow \; ^7Be + \gamma$
- While $^4He + {}^4He \rightarrow \; ^8Be$ which in t~10^-16s will decay back to $^4He + {}^4He$

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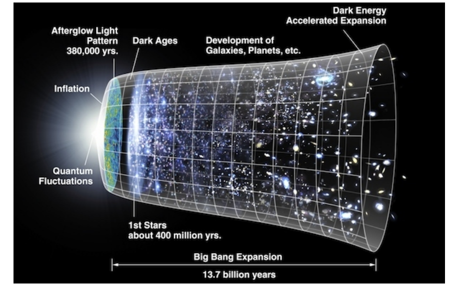
It all happened in ~ 10min.



- The elements up to Li (Be) were all created within 10 minutes

10min

- Within 15 minutes the neutrons will decay (if they are not bound in nuclei) $n \rightarrow p + e^- + \bar{\nu}_e$

- The final amount yielded by the BBN will depend on the baryon-to-photon ratio (η)

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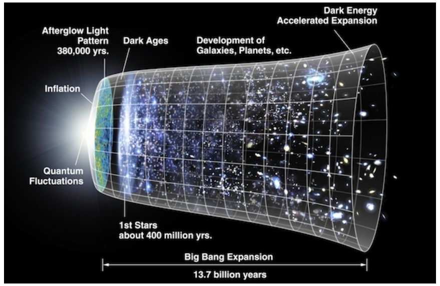
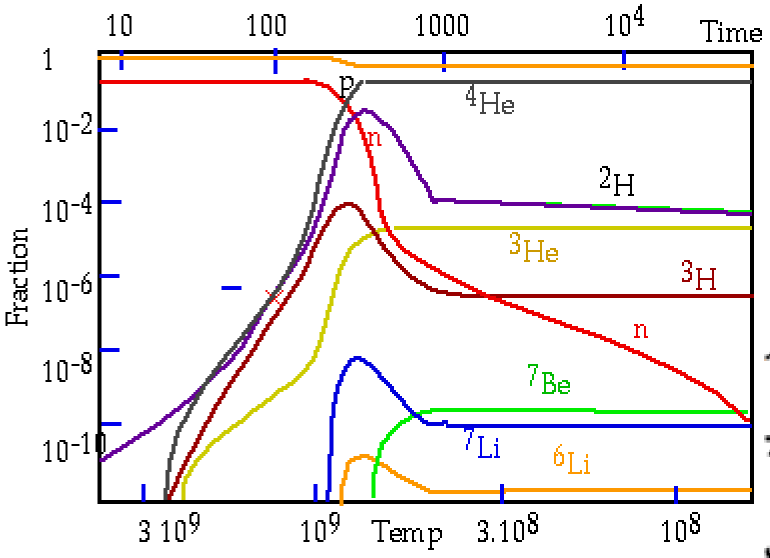
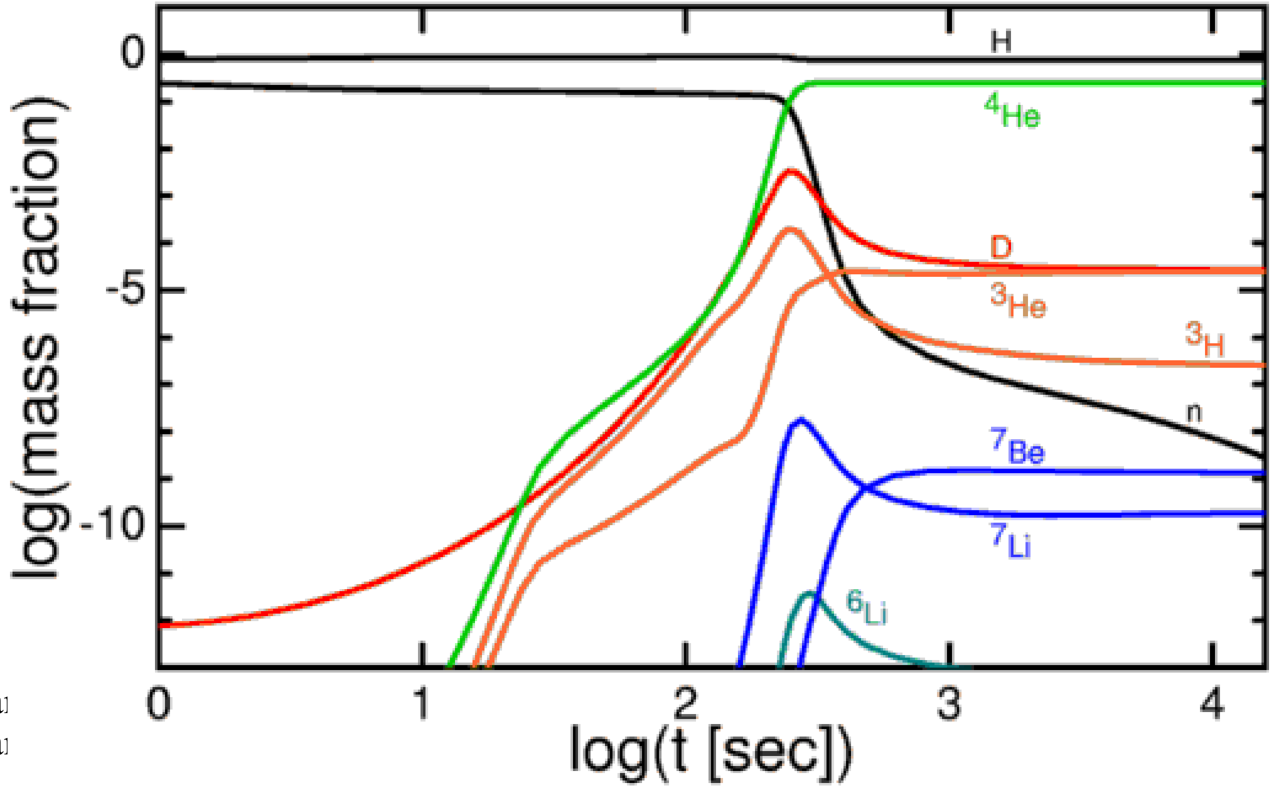
Mass distribution of BBN reactions



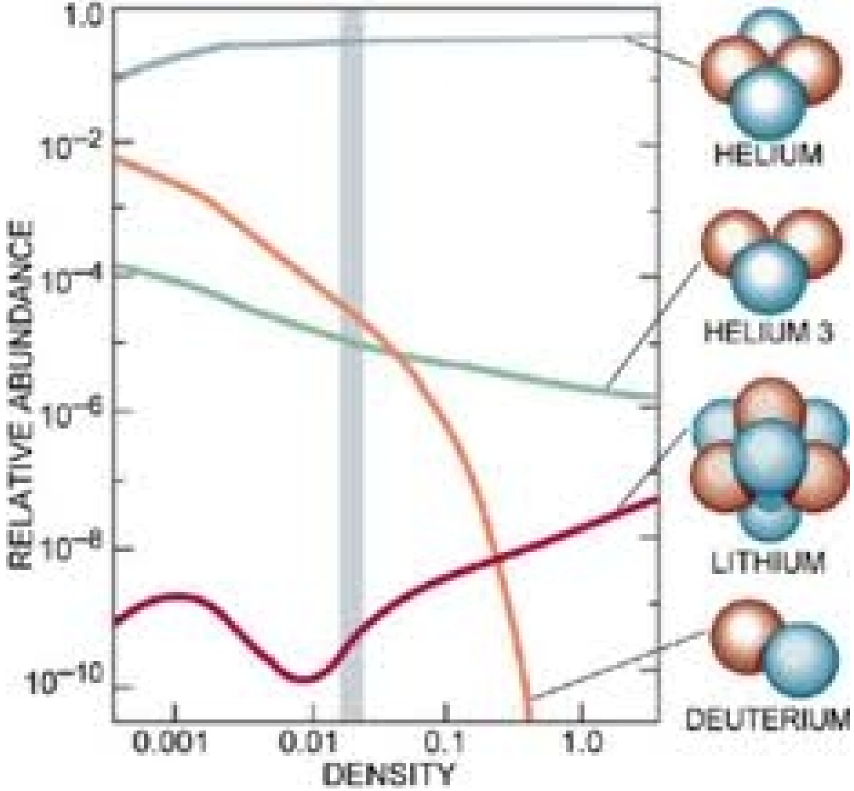


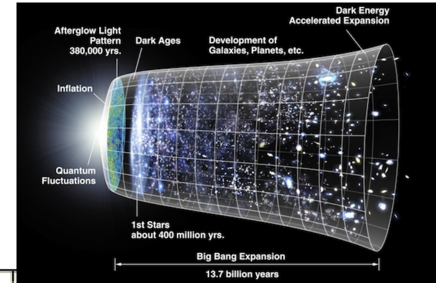
X=H → ~75%
Y=He → ~25 %
Z = all heavier elements < 1%

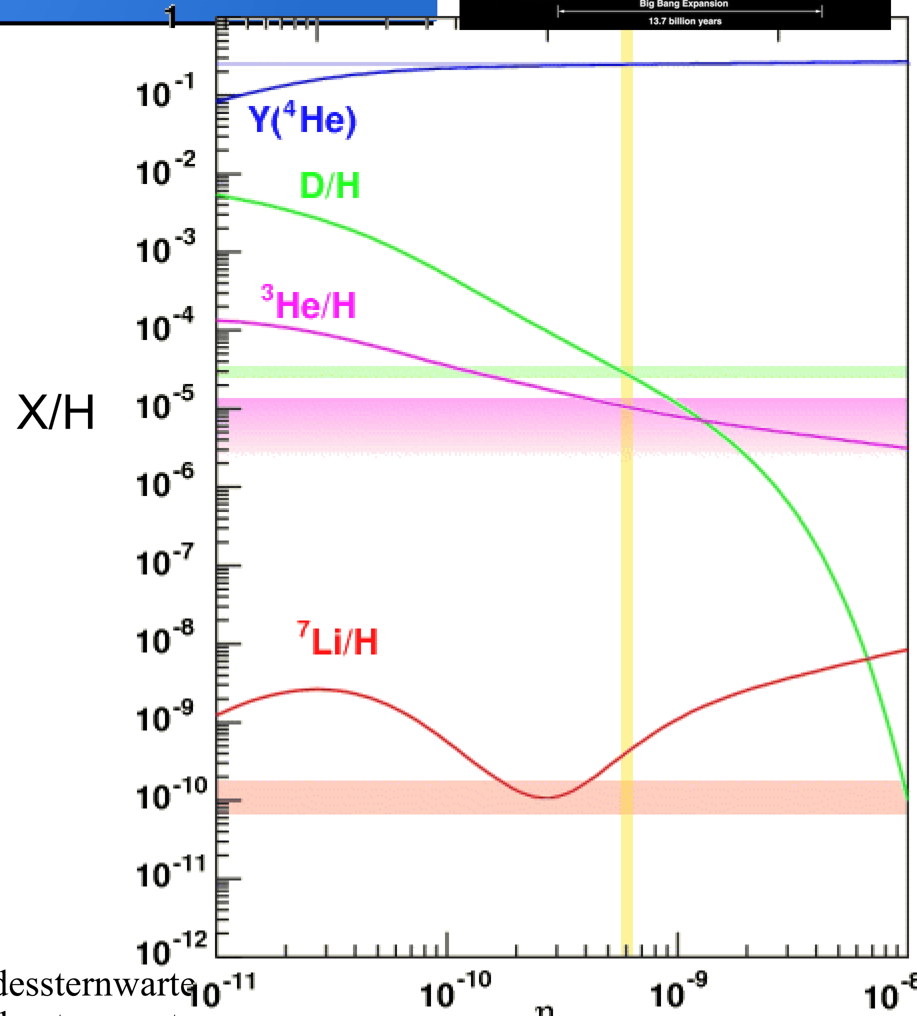


Ca
Ca

Observations vs theory







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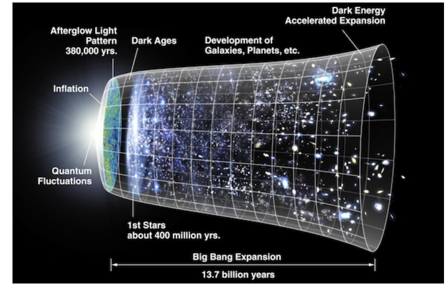
BBN observations



- We can measure the light elements in stellar interiors (H, He, Li) if the stars are cool
- But D is easily destroyed in stars – therefore D is measured in intergalactic clouds through Ly α absorption caused by a quasar
- WMAP obtained an η ~ 6.1 * 10^-10 (yellow line)
- Li problem

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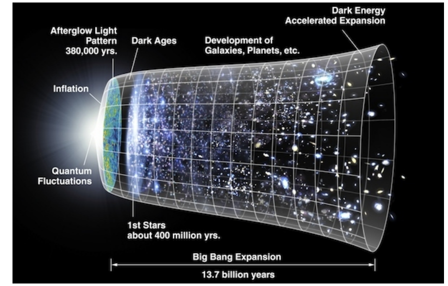
Summary of reactions



$$n^0 \longrightarrow p^+ + e^- + \bar{\nu}_e$$

$$^2_1D + p^+ \longrightarrow ^3_2He + \gamma$$

$$^2_1D + ^2_1D \longrightarrow ^3_1T + p^+$$

$$^3_2He + ^4_2He \longrightarrow ^7_3Li + \gamma$$

$$^3_2He + ^2_1D \longrightarrow ^4_2He + p^+$$

$$^7_3Li + p^+ \longrightarrow ^4_2He + ^4_2He$$

Ex. 1 $$p^+ + n^0 \longrightarrow ^2_1D + \gamma$$

Ex. 2 $$^2_1D + ^2_1D \longrightarrow ^3_2He + n^0$$

Ex. 3 $$^3_1T + ^2_1D \longrightarrow ^4_2He + n^0$$

$$^3_2He + n^0 \longrightarrow ^3_1T + p^+$$

$$^3_2He + ^4_2He \longrightarrow ^7_4Be + \gamma$$

$$^7_4Be + n^0 \longrightarrow ^7_3Li + p^+$$

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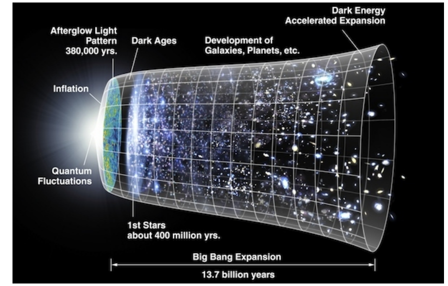
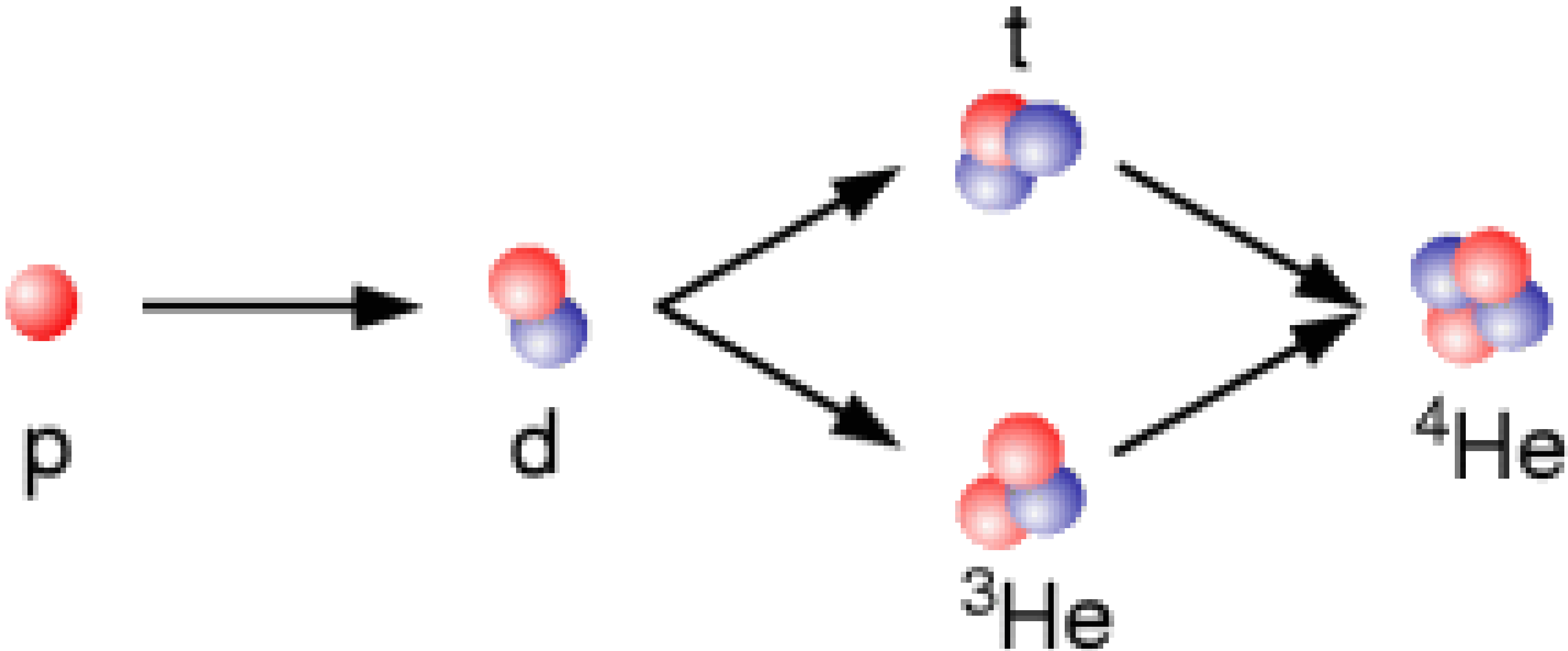
The most likely way to He, Ex. 1





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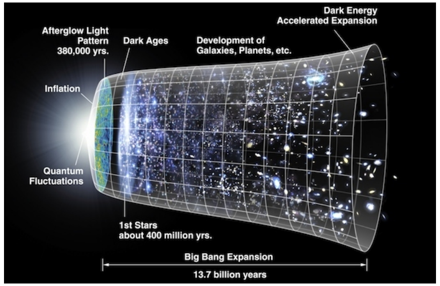
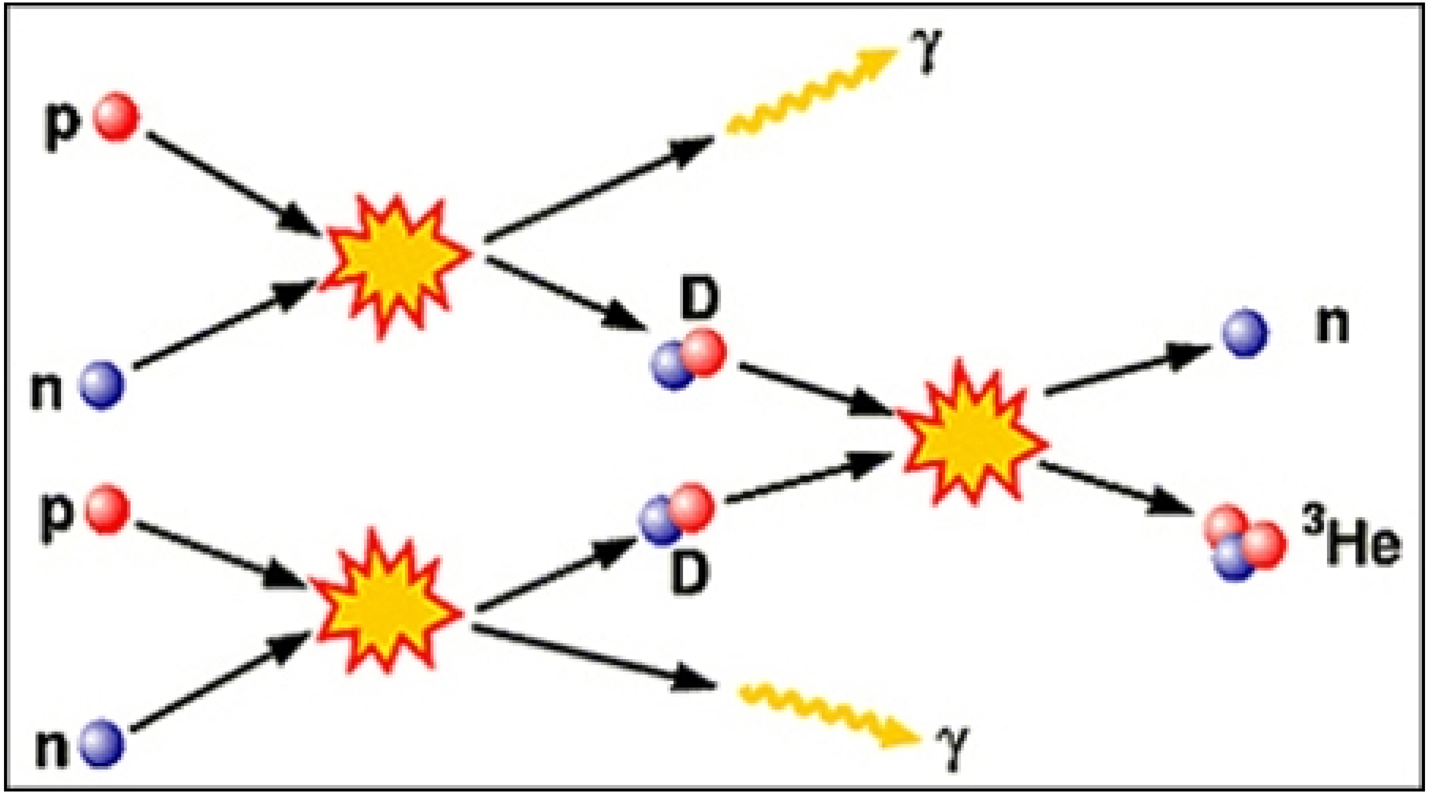
Creating He, Example 2





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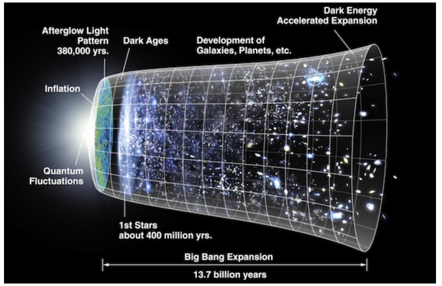
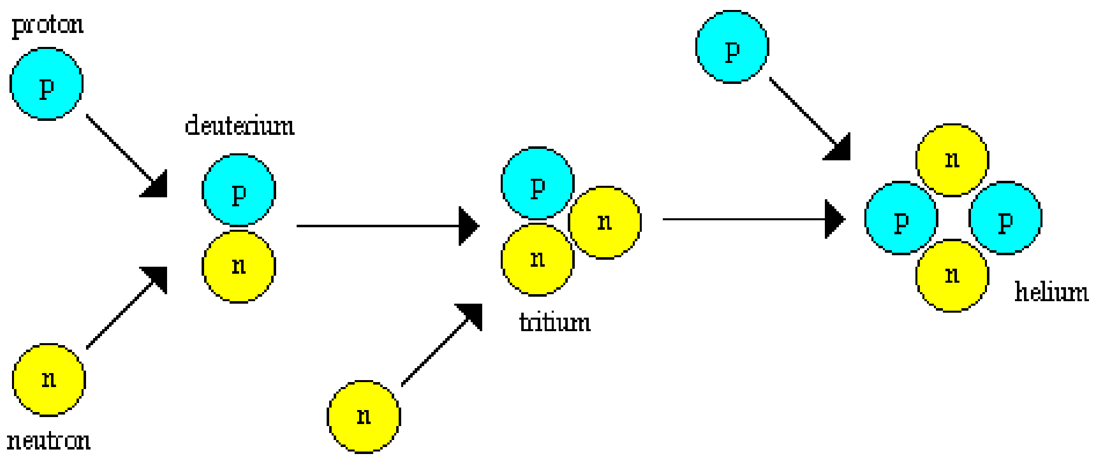
Creating He, Example 3



Nucleosynthesis

as the Universe cools, protons and neutrons can fuse to form heavier atomic nuclei



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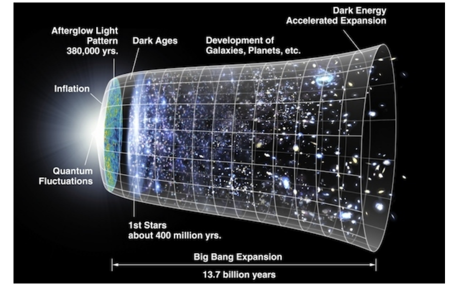
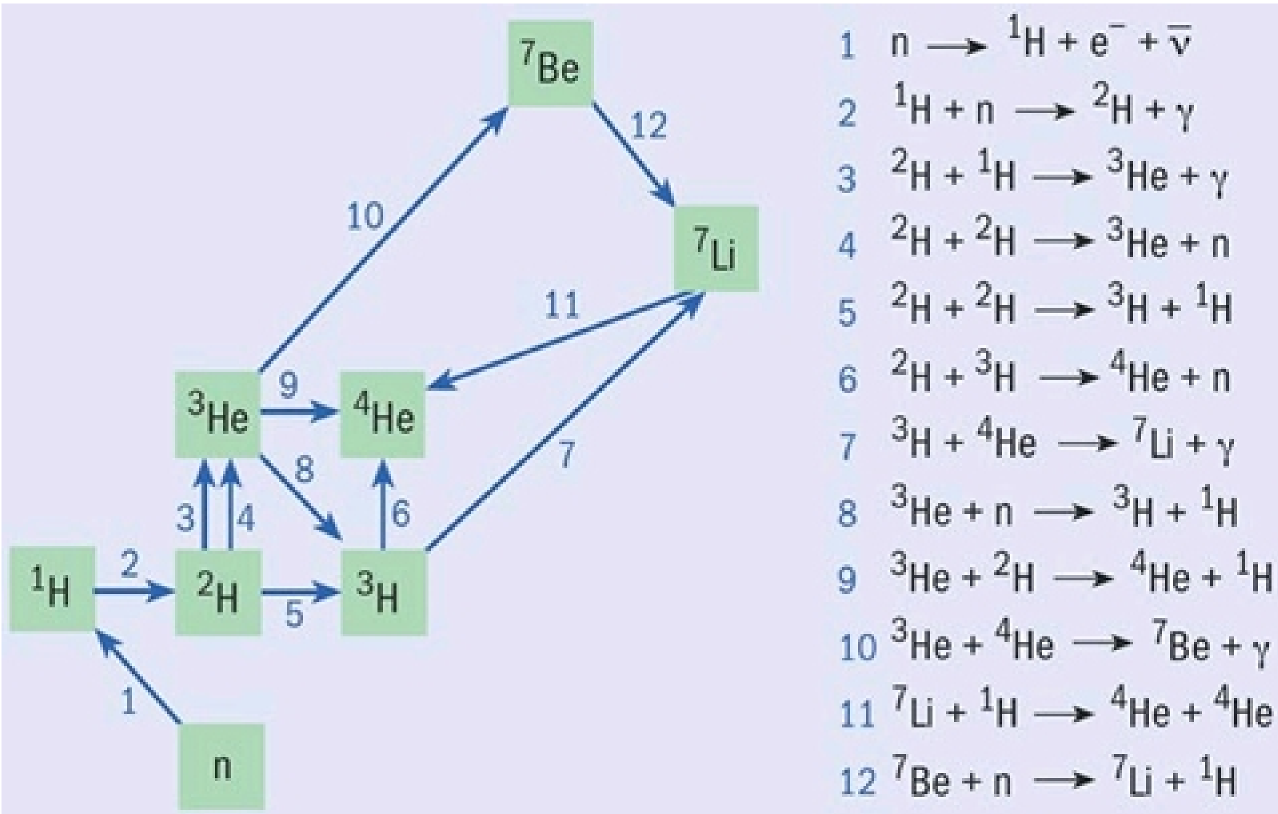
Nuclei of 7 particles





Later on tritium will decay to He, and Be to Li

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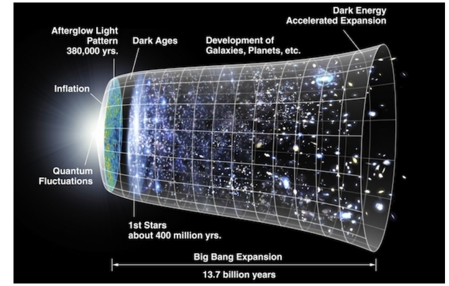
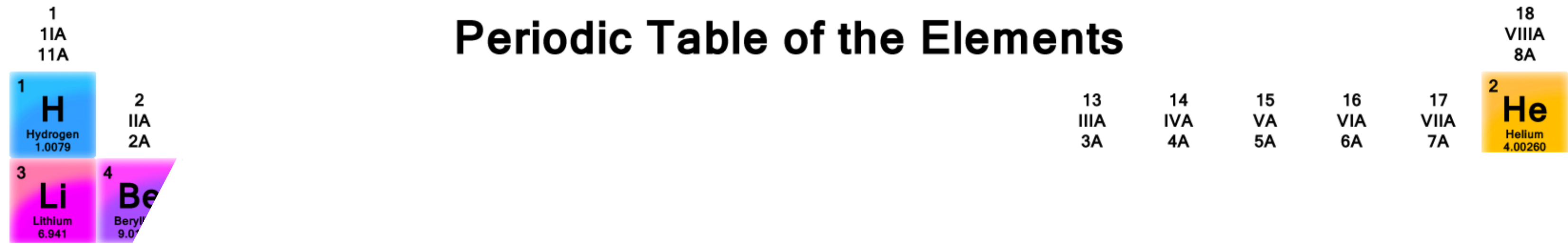
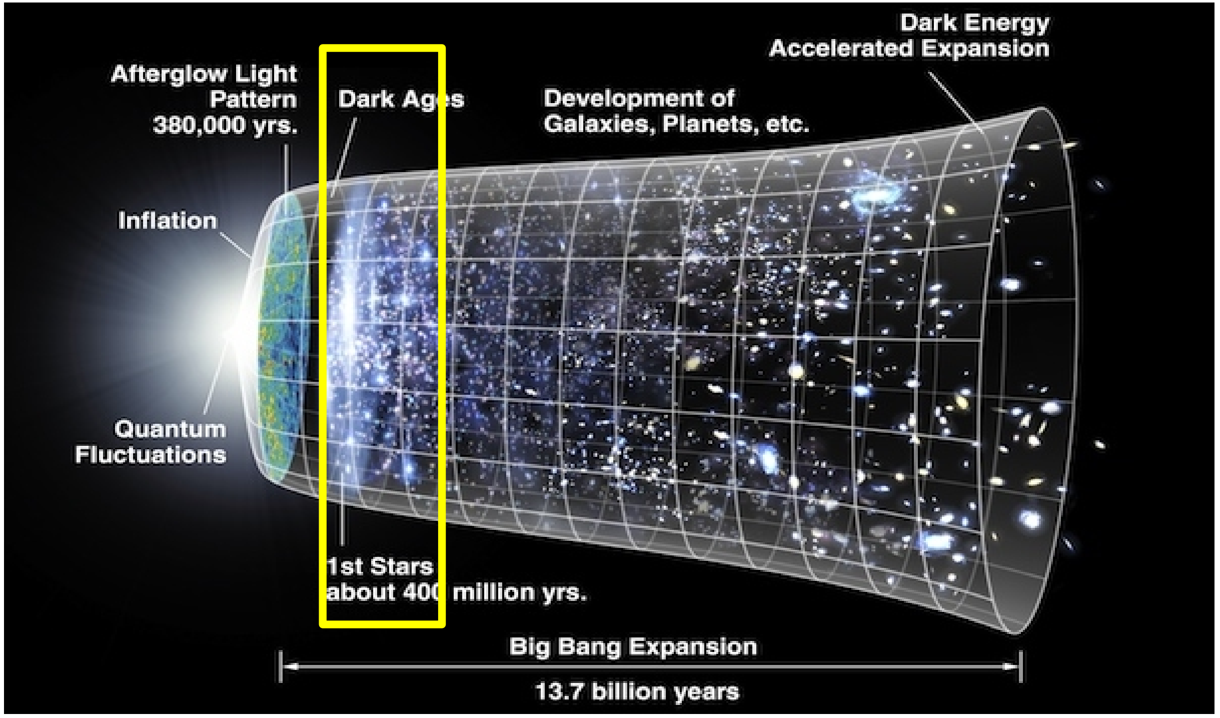
Outcome of BBN





Stellar Nucleosynthesis

We now fast forward over the next 400.000,000 yrs – aka the dark ages



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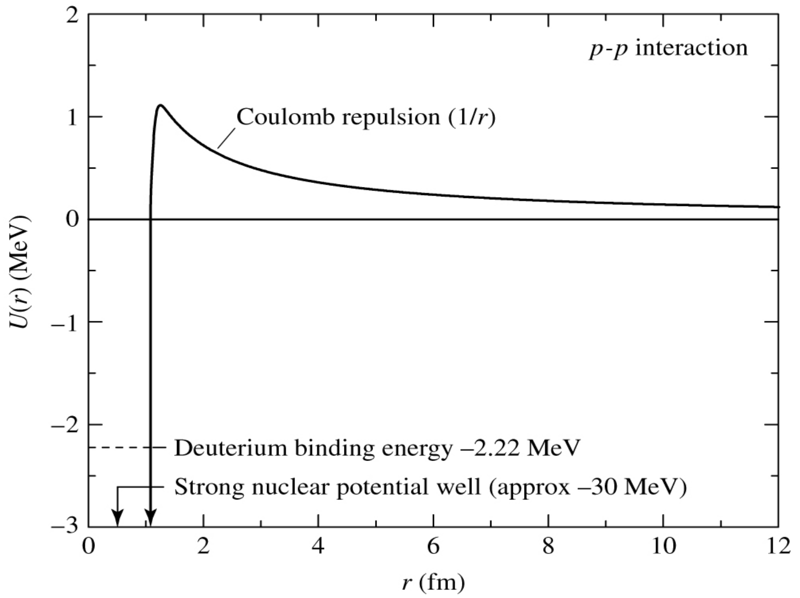
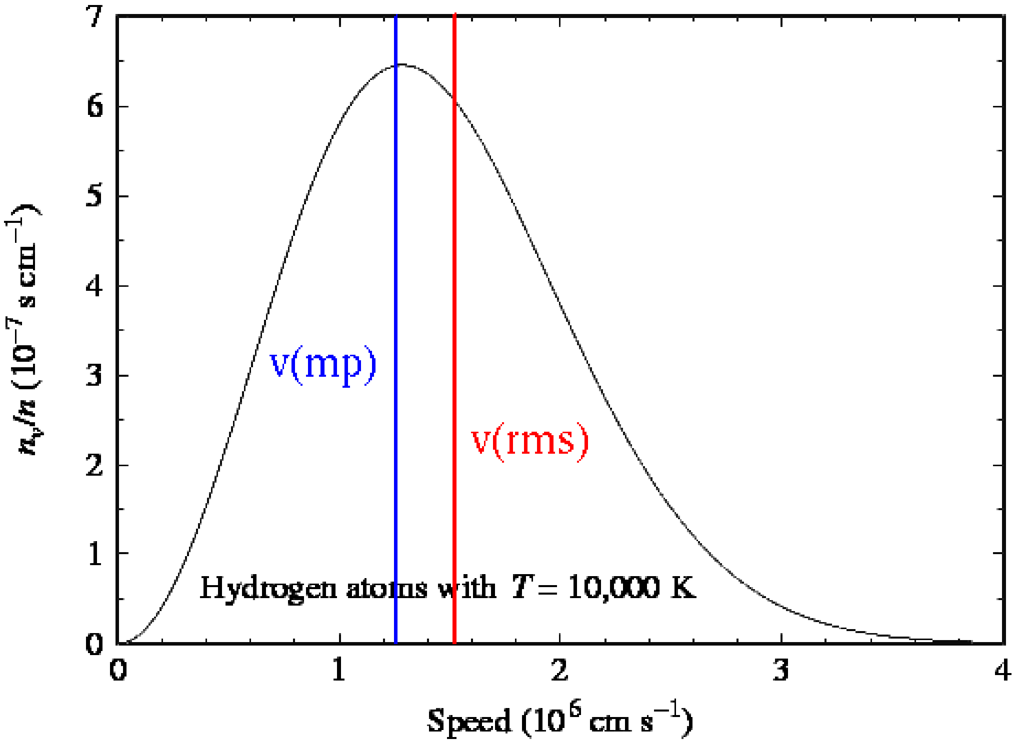
Why can these reactions take place?

Charged particles repelled by nuclei



Maximum kinetic energy; Maxwell Boltzmann



Ecoulomb ~ Z1*Z2e^2/r → MeV

Ekin ~ 3/2kBT → KeV

Ecoul >> Ekin !

Etail ~ exp^(-E/kBT)

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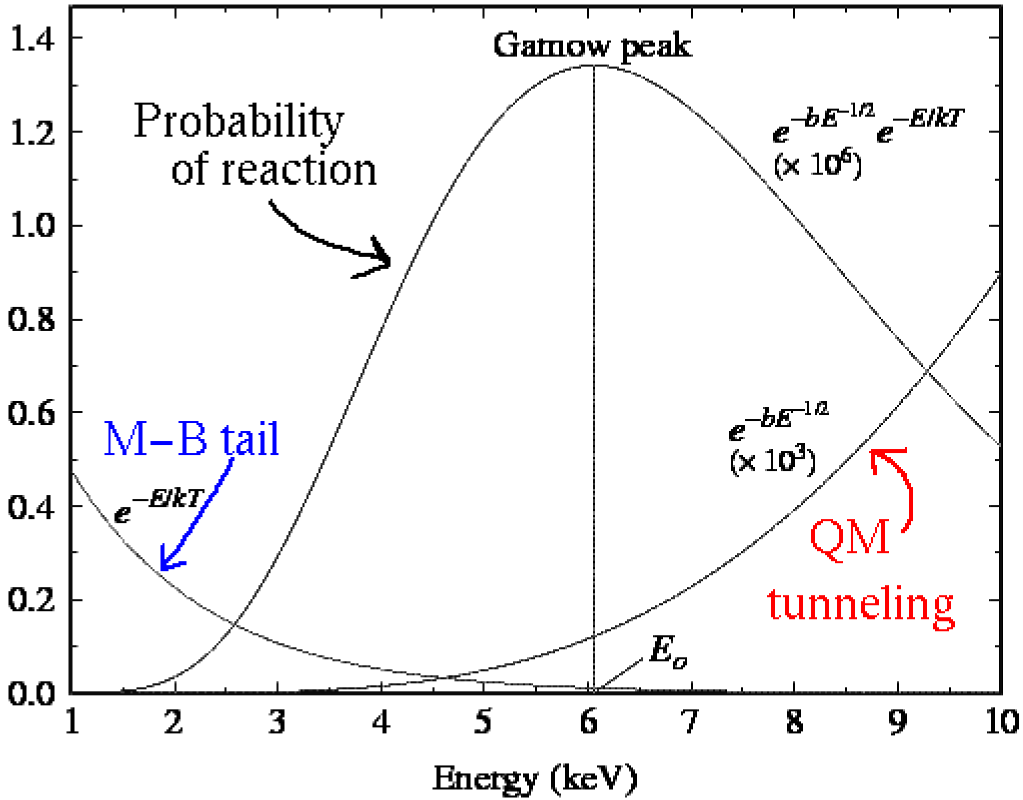
Why can these reactions take place?

Maxwell Boltzmann (MB) – Gamov Peak = Max. possibility – Tunneling



The likelihood of a reaction taking place is maximum at the Gamov peak, which is the product of the fast particles described by MB ~ exp(-E/kT) and the possibility of penetrating the coulomb barrier exp (-const.*E^-1/2) i.e. particles with high E and cross section →

Gamov peak: The E-region where reactions will take place because there are enough high energy particles (in the MB tail) which have a high enough cross section to react (tunneling).

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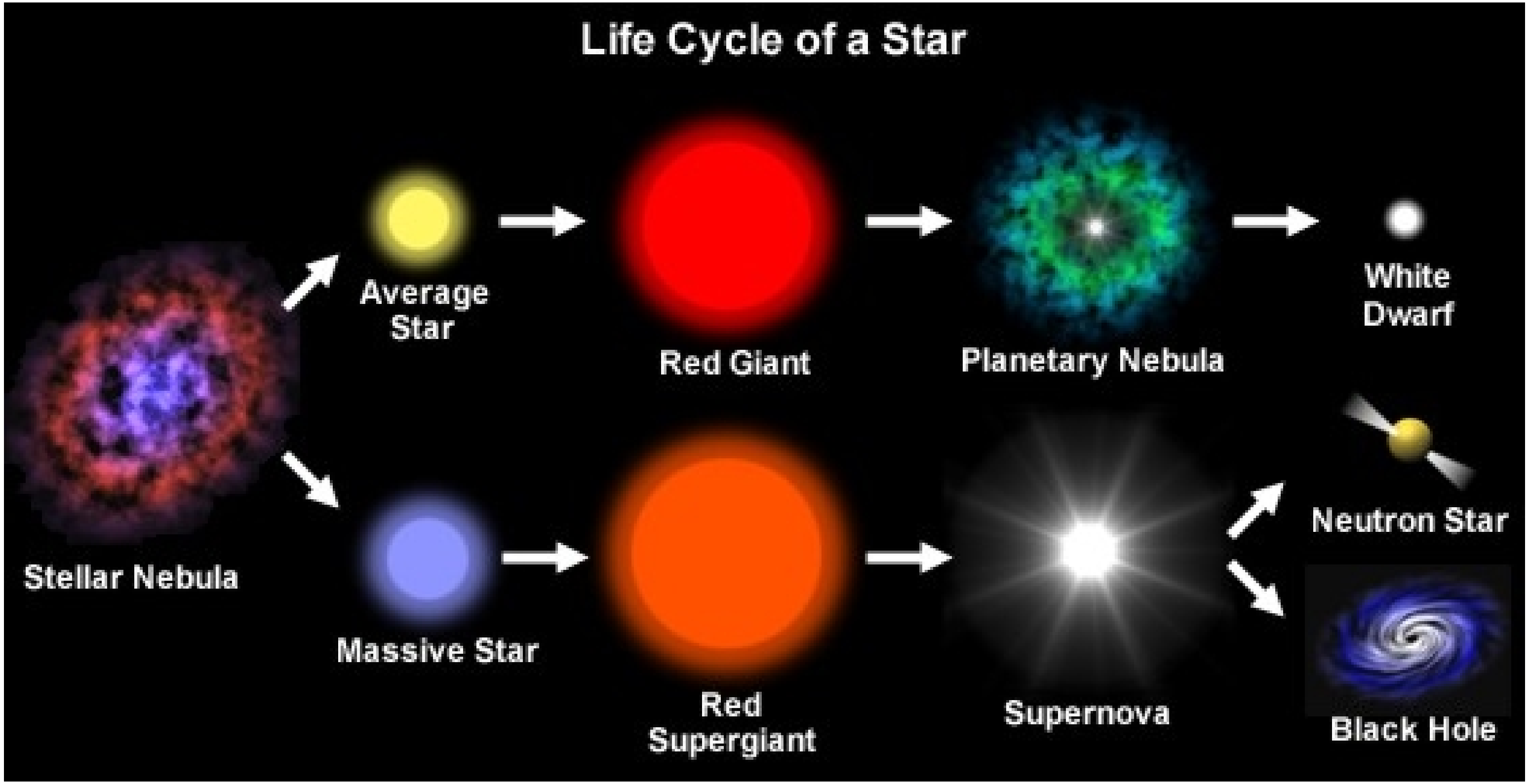
A star's fate depends on its mass



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PP-chain – formulas

- The First stars created He via the pp-chain since no C, N, O were present.
- Stellar fusion (to He) is much slower than the He synthesised in BBN. This is mainly due to p $\rightarrow$ n which is a weak interaction (a neutrino is included)
- $H(H,e^{+}\nu)D(H,\gamma)^{3}He(^{3}He,2H)^{4}He$, where

  $H(H,e^{+}\nu)D$ equals writing $H + H \rightarrow D + e^{+} + \nu$
- Energy generated: $E = Eo\ X^{2}\rho T^{n}$, where n=4 if T~ 1.5*10^6K
- Energy output: Q ~ 26.2 MeV (incl. Neutrino E)

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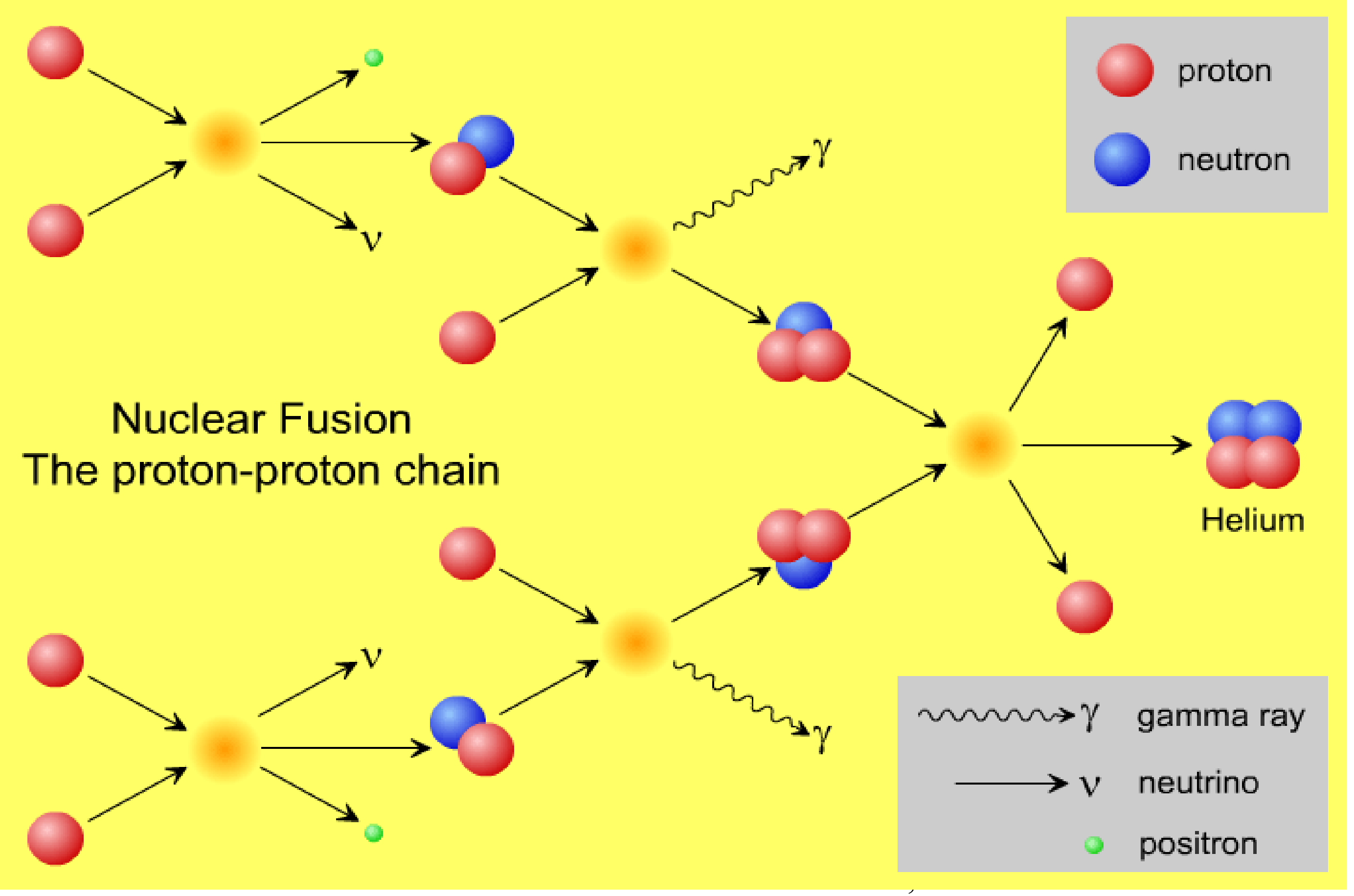
Low mass stars - PP-chain



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The most common PPI Chain

PP is the dominant reaction at low T and M

H burning lasts billions of years

Low mass stars - PP-chain

$$^1_1\mathrm{H} + {}^1_1\mathrm{H} \rightarrow {}^2_1\mathrm{H} + e^+ + \nu_e$$

$$^2_1\mathrm{H} + {}^1_1\mathrm{H} \rightarrow {}^3_2\mathrm{He} + \gamma$$

69%

$$^3_2\mathrm{He} + {}^3_2\mathrm{He} \rightarrow {}^4_2\mathrm{He} + 2\,{}^1_1\mathrm{H}$$

(PP I)

31%

$$^3_2\mathrm{He} + {}^4_2\mathrm{He} \rightarrow {}^7_4\mathrm{Be} + \gamma$$

99.7%

$$^7_4\mathrm{Be} + e^- \rightarrow {}^7_3\mathrm{Li} + \nu_e$$

$$^7_3\mathrm{Li} + {}^1_1\mathrm{H} \rightarrow 2\,{}^4_2\mathrm{He}$$

(PP II)

0.3%

$$^7_4\mathrm{Be} + {}^1_1\mathrm{H} \rightarrow {}^8_5\mathrm{B} + \gamma$$

$$^8_5\mathrm{B} \rightarrow {}^8_4\mathrm{Be} + e^+ + \nu_e$$

$$^8_4\mathrm{Be} \rightarrow 2\,{}^4_2\mathrm{He}$$

(PP III)

All PP chains

Q(PPI) ~26Mev
Q(PPII)~25MeV
Q(PPIII)~ 19MeV

PPIII has the largest energy loss due to neutrinos (7.2MeV). For this reason: Neutrino experiments often try to measure this reaction

Low mass star never burn further than C or O

Low-mass vs high-mass stars

- High mass stars are convective in the centre,low mass stars in the outer parts

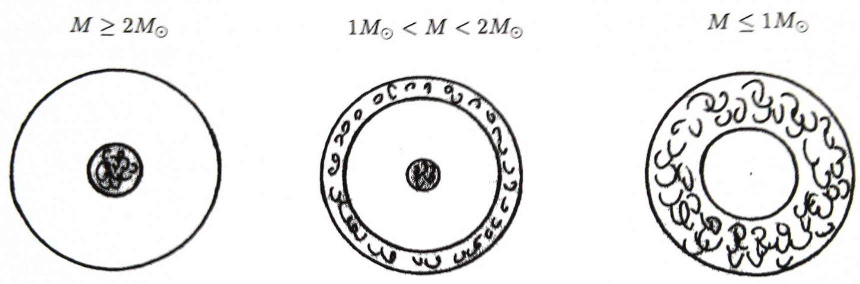
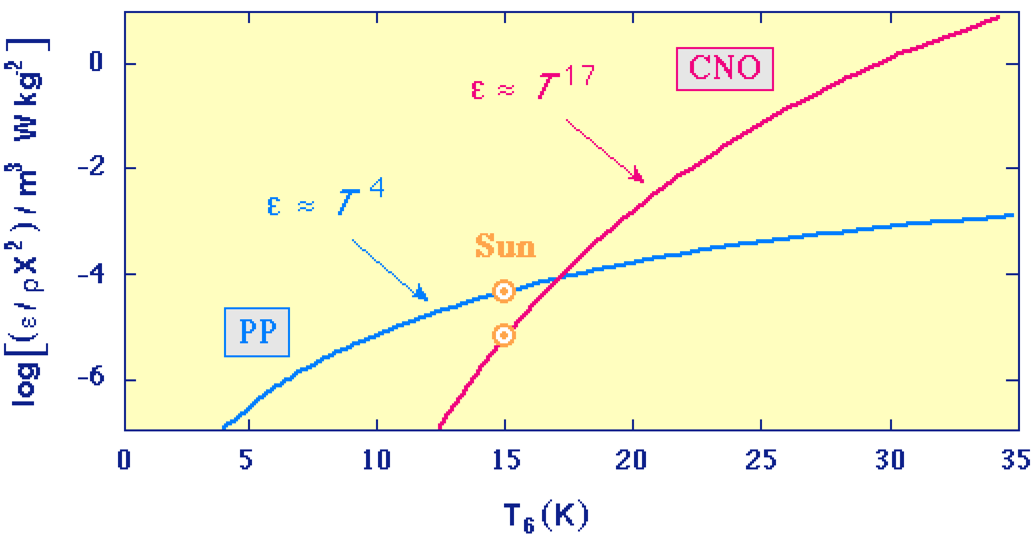


Figure 6.2. The typical occurrence of convection zones in main-sequence stars. In relatively massive stars there is a convective core, whereas in relatively light stars on the main sequence, and in general in stars with low effective temperature, there is an outer convection zone. In red giants this convection zone occupies by far the largest fraction of the stellar radius, and a substantial fraction of the stellar mass.



J. Christensen-Dalsgaard

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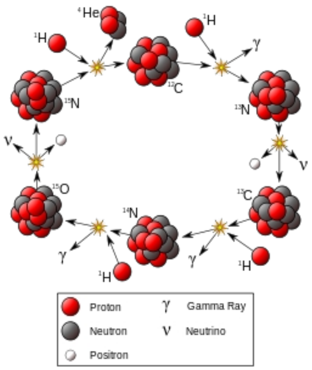
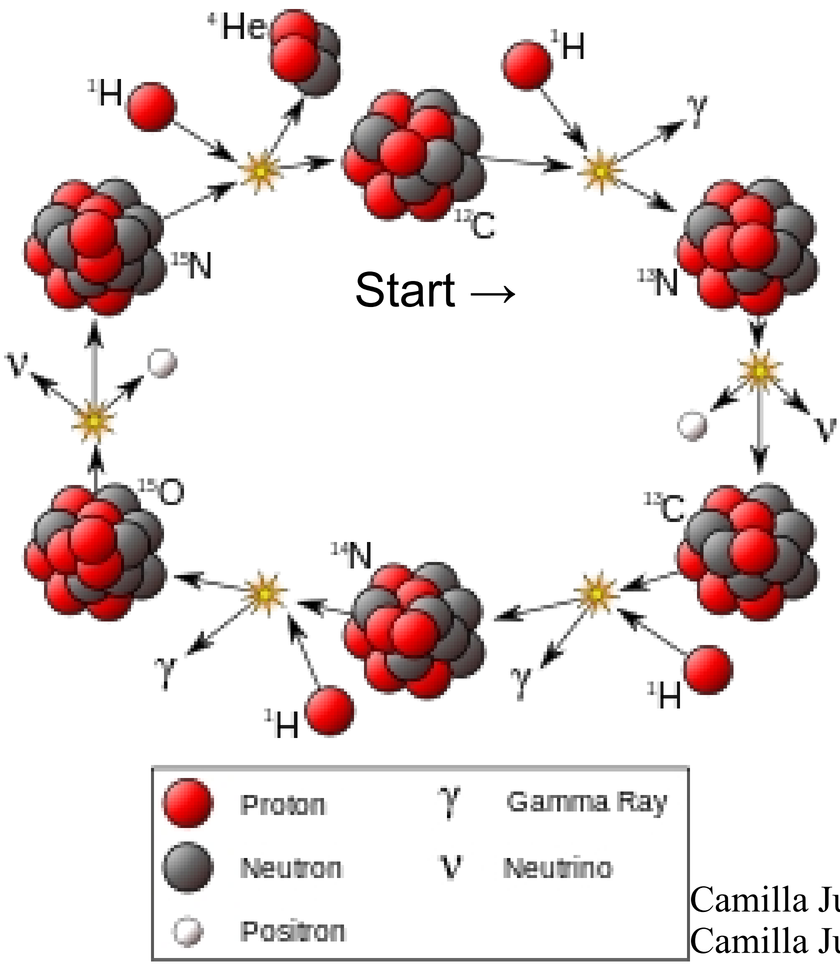
CNO – Cycle – massive stars





In stars more massive than 1.5Msun, the CNO can take place.

$^{12}C(H,\gamma)^{13}N(e^{+}\nu)^{13}C(H,\gamma)^{14}N(H,\gamma)^{15}O(e^{+}\nu)$
$^{15}N(H,4He)^{12}C$

^{12}C is very reactive, while the ^{14}N has the smallest probability

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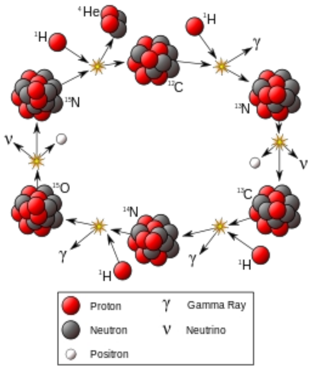
CNO-cycle – Formulas



- CNO reactions will dominate at high T and M
- $E = E_o Z X \rho T^n$, where n~20 if T>> 1.5*10^6K, and Z= heavy element abundance
- Q ~ 25MeV (neutrino loss ~ 1.7MeV)
- The next elements in line to be created would be B and Be, however, there are no stable A=8 nuclei. Therefore these elements are made via spallation processes.

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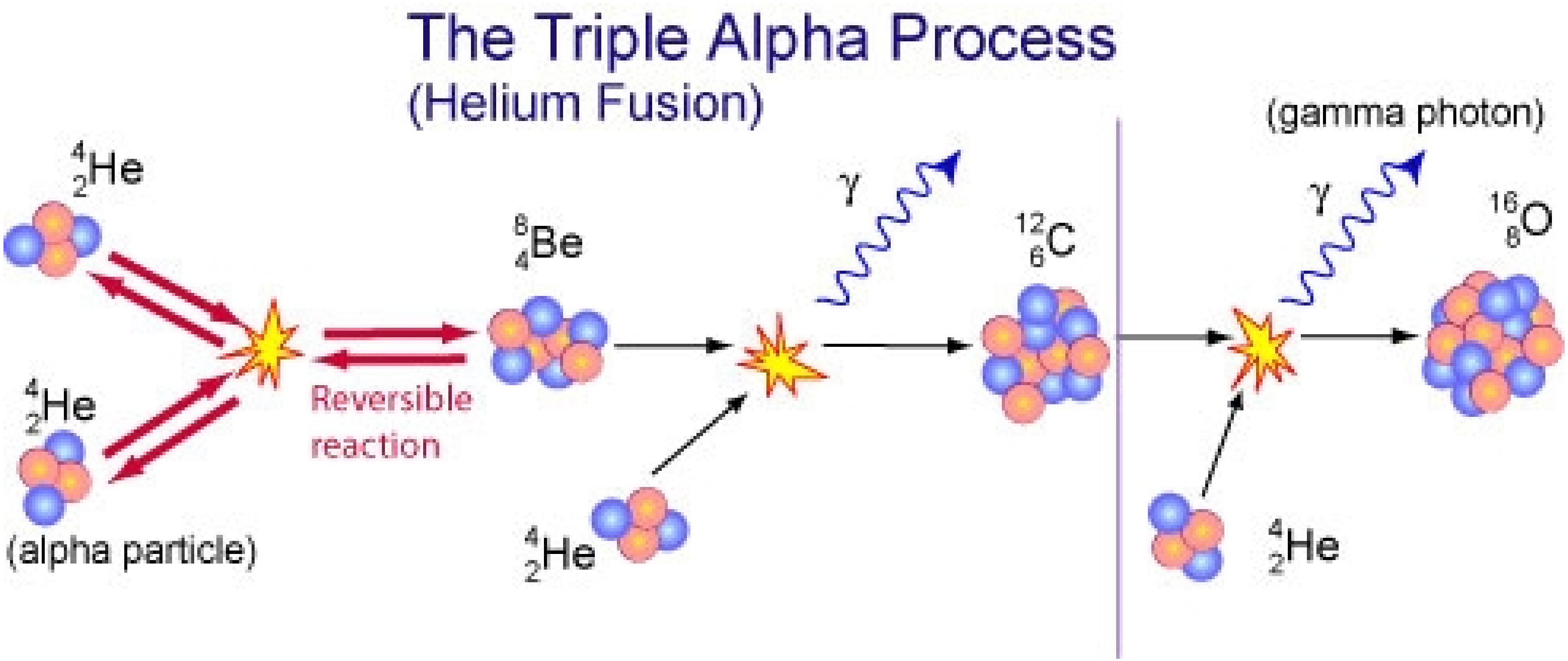
Heavier than He – triple alpha



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Triple alpha

At sufficiently high temperatures and densities, a 3-body reaction called the triple alpha process can occur:

Two helium nuclei ("alpha particles") fuse to form unstable beryllium. If another helium nucleus can fuse with the beryllium nucleus before it decays, stable carbon is formed along with a gamma ray.

The processes take place ~10^8 K,

$E = E_o Y^3 \rho T^{30}$

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Massive stars

C burning (at 1-10*10^8 K): & O burning (at 10^9 K):

$$
\begin{aligned}
{}^{12}C + {}^{12}C &\rightarrow {}^{16}O + 2\,{}^{4}He \\
&\rightarrow {}^{20}Ne + {}^{4}He \\
&\rightarrow {}^{23}Na + p^{+} \\
&\rightarrow {}^{23}Mg + n \\
&\rightarrow {}^{24}Mg + \gamma
\end{aligned}
$$

$$
\begin{aligned}
{}^{16}O + {}^{16}O &\rightarrow {}^{24}Mg + 2\,{}^{4}He \\
&\rightarrow {}^{28}Si + {}^{4}He \\
&\rightarrow {}^{31}P + p^{+} \\
&\rightarrow {}^{31}S + n \\
&\rightarrow {}^{32}S + \gamma
\end{aligned}
$$

6 months

Then ^{12}C reactions follow owing to their low coulomb barrier, but at these high T the photons are very energetic and can photodisintegrate the nuclei and alpha captures will follow before the ^{16}O reactions will take place.

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Alpha-elements: Mg, Si,..,Ca, Ti

- Photodisintegration of Ne followed by *Ne-burning*
- $^{20}Ne + \gamma \rightarrow {}^{16}O + {}^{4}He$ – α-capture: $^{20}Ne + {}^{4}He \rightarrow {}^{24}Mg$
- A lot of α-captures will follow due to the large coulomb barrier of the heavier elements
- In the most massive stars (M>10Msun), the final hydrostatic burning phase will be *Si-burning* which lasts 1 day

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Si-burning

$$^{32}\mathrm{S} + \gamma \rightarrow {}^{28}\mathrm{Si} + {}^{4}\mathrm{He}\ . \qquad (14.3)$$

The ^{4}He released in this process may then be captured in other nuclei, including the ^{28}Si. Hence in fact the reaction (14.3) may go both ways, and should therefore be expressed as

$$^{28}\mathrm{Si} + {}^{4}\mathrm{He} \rightleftarrows {}^{32}\mathrm{S} + \gamma\ . \qquad (14.4)$$

It follows from Figure 14.2, and is indicated by the location of the γ in equation (14.4), that energy is released in the reaction $^{28}\mathrm{Si} + {}^{4}\mathrm{He}$. Thus it is energetically favourable to shift the equilibrium in equation (14.4) towards the right, so that the equation should *really* be written

$$^{28}\mathrm{Si} + {}^{4}\mathrm{He} \rightleftharpoons {}^{32}\mathrm{S} + \gamma\ . \qquad (14.5)$$

Furthermore, given the continuing photo-dissociation of the nuclei and hence presence of ^{4}He, there is a possibility of similar reactions involving the subsequent nuclei, such as

$$\begin{aligned} {}^{32}\mathrm{S} + {}^{4}\mathrm{He} &\rightleftharpoons {}^{36}\mathrm{Ar} + \gamma\ , \\ {}^{36}\mathrm{Ar} + {}^{4}\mathrm{He} &\rightleftharpoons {}^{40}\mathrm{Ca} + \gamma\ , \\ &\vdots \\ {}^{52}\mathrm{Fe} + {}^{4}\mathrm{He} &\rightleftharpoons {}^{56}\mathrm{Ni} + \gamma\ . \end{aligned} \qquad (14.6)$$

J. Christensen-Dalsgaard

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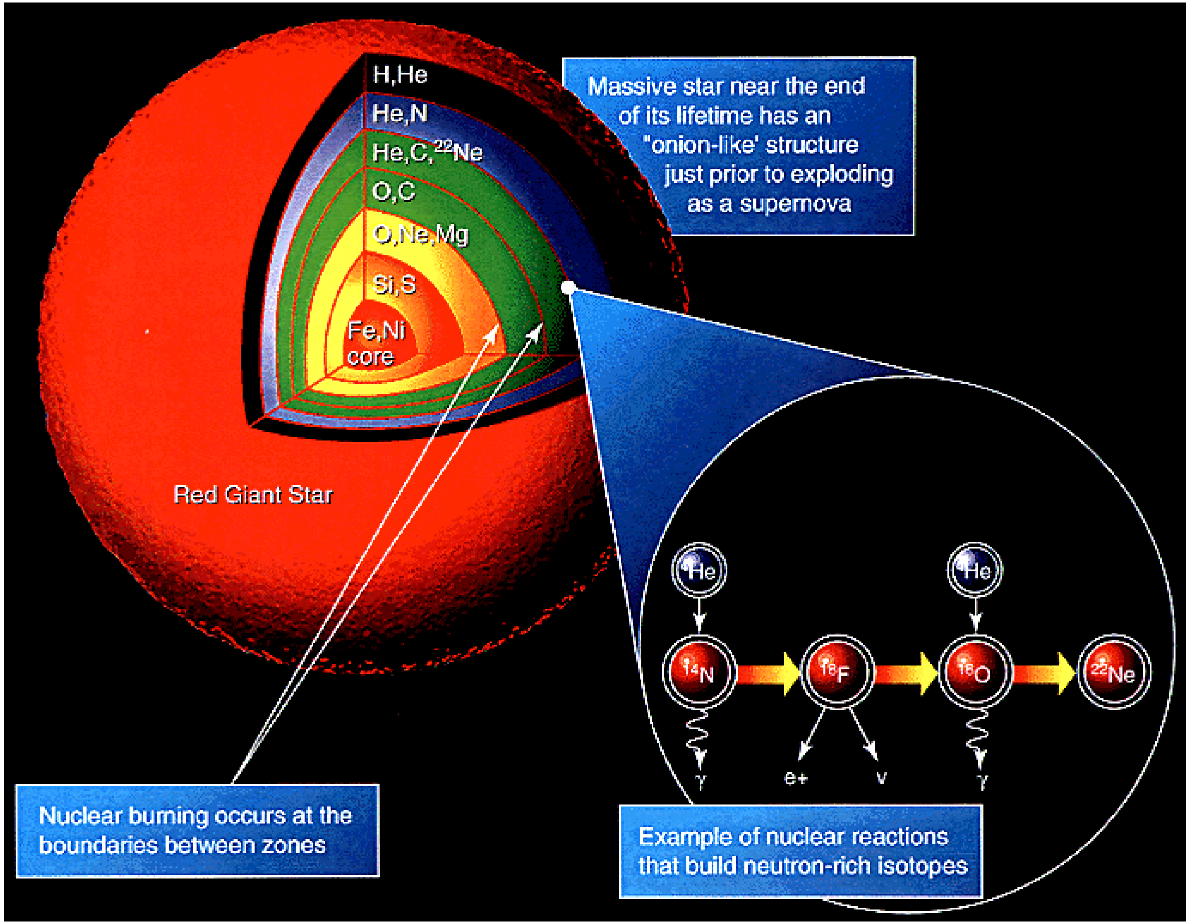
Stellar burning



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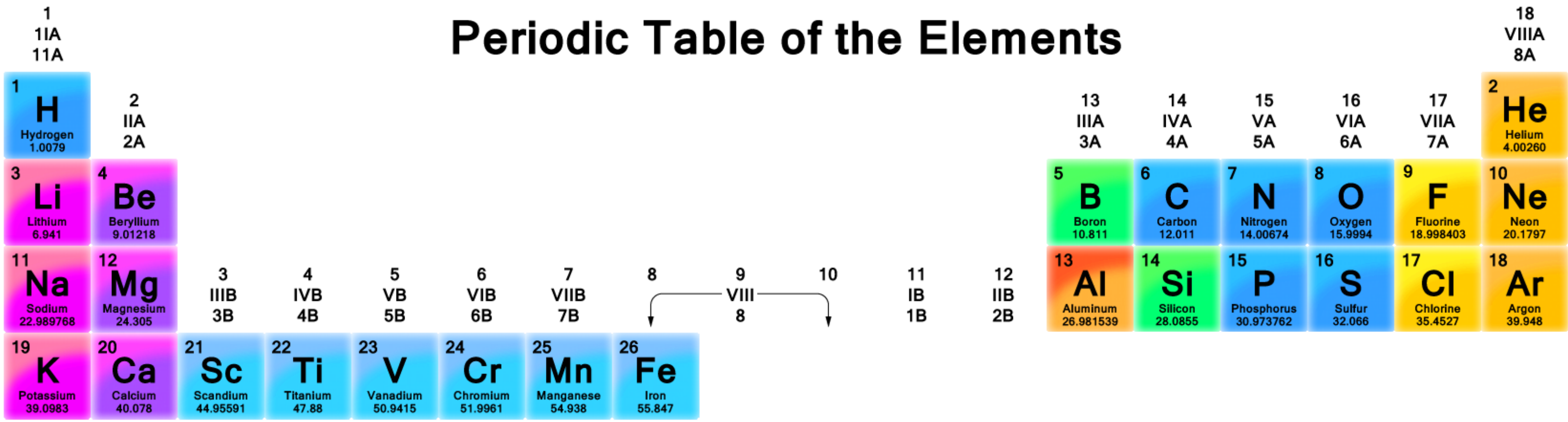
J. Bornak

Outcome of stellar burning



Stellar explosion - simplified

The star can no longer produce energy by fusion processes, and can only generate energy in the core by contracting. An outgoing electron pressure will try to counteract the collapse, however, electron-capture processes will set in and thereby decrease the outgoing e-pressure. Meanwhile neutrinos will carry energy away from the collapsing stars and maintain a relatively low temperature. The electron gas becomes degenerate and cannot sustain the gravitational pressure, so the density increases by two orders of magnitude at which point the core cannot contract anymore, and the collapse is turned into and outgoing shock → A supernova explosion

Matter outside O-burning shell is little or not affected by the explosion

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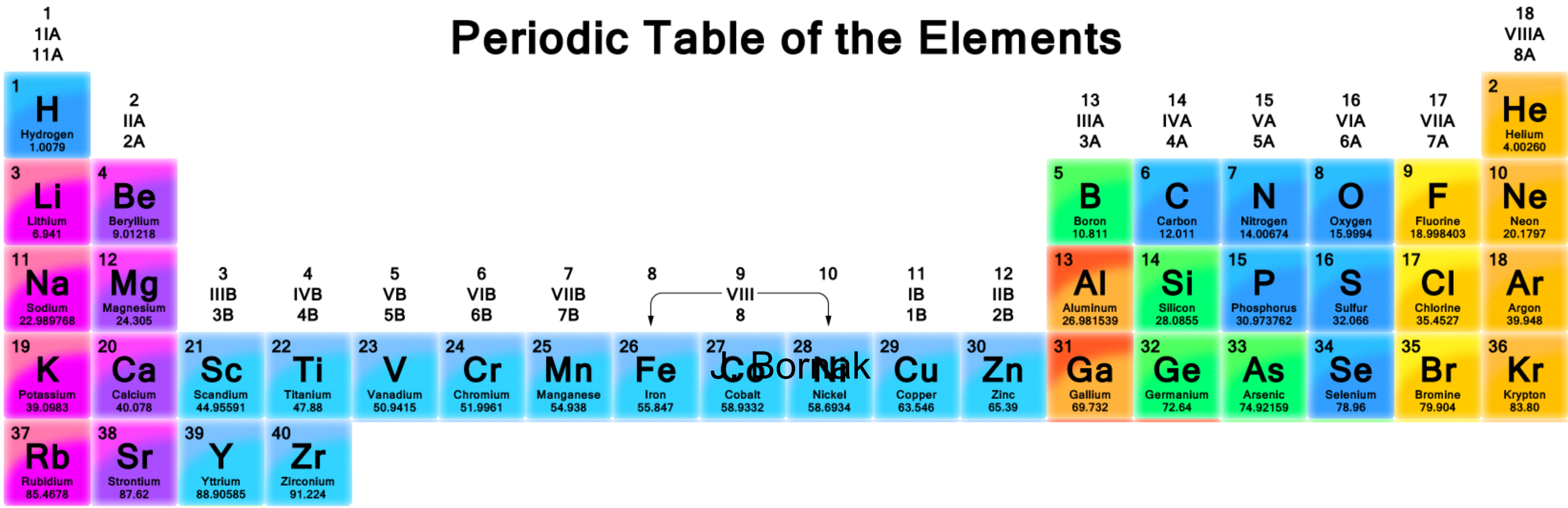
Explosive burning



J. Bornak

Heavy element formation

- Outline for part 2
- Neutron captures – beta-decay (majority)
- Proton processes (nu-p, spallation,... - minority)
- Theory – models for SN winds, mergers etc.
- Applications: Observations
- Galactic chemical evolution

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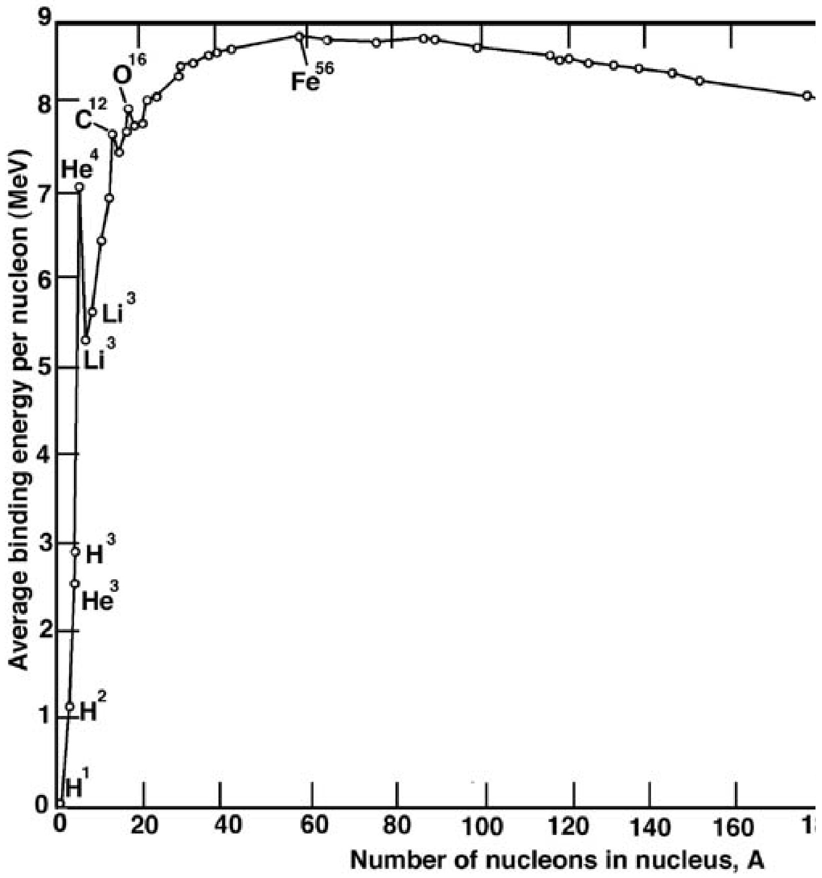
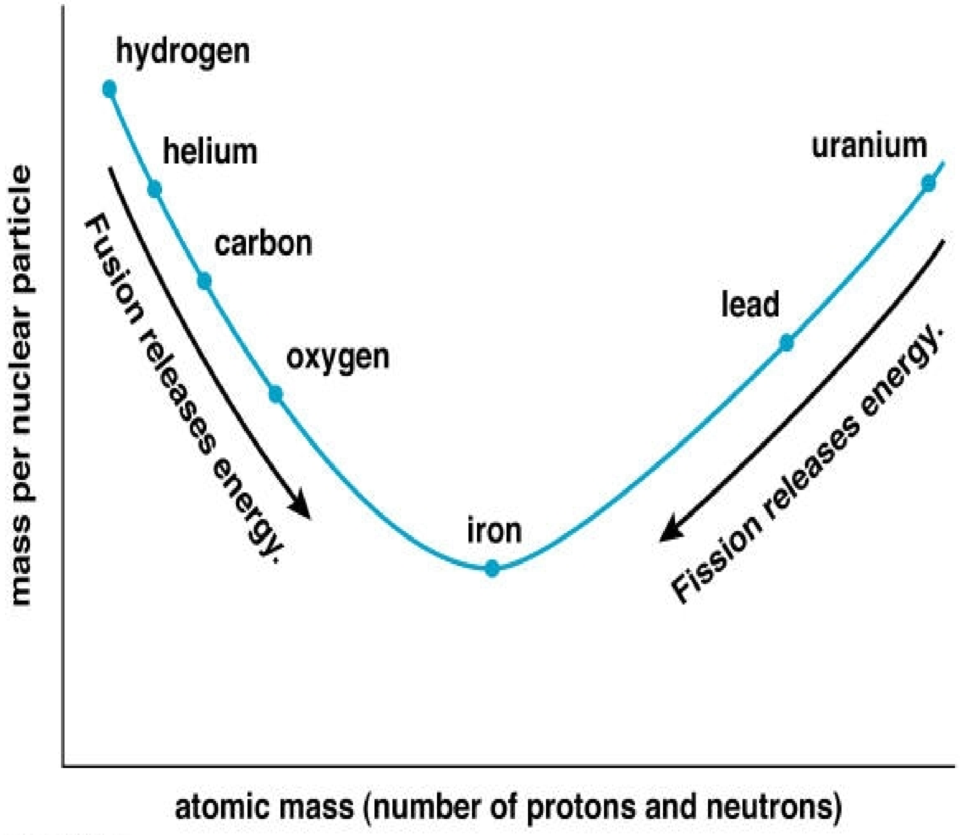
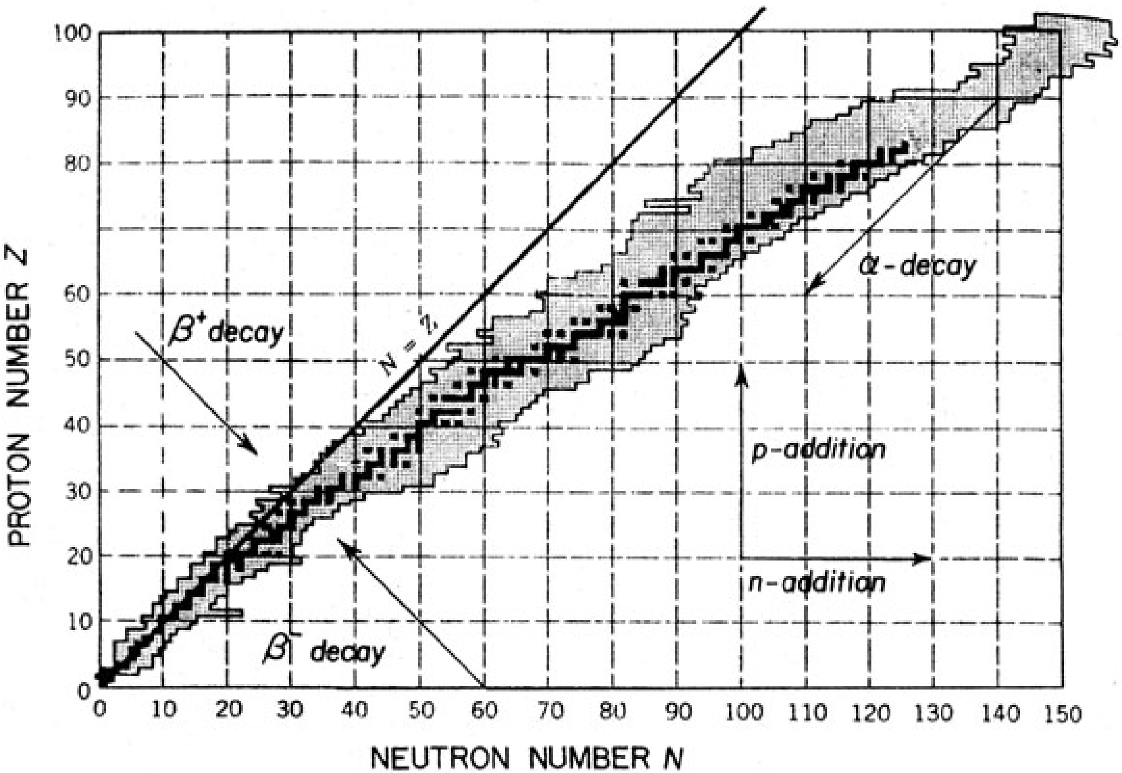
How to proceed...

- Max. binding energy reached at Fe

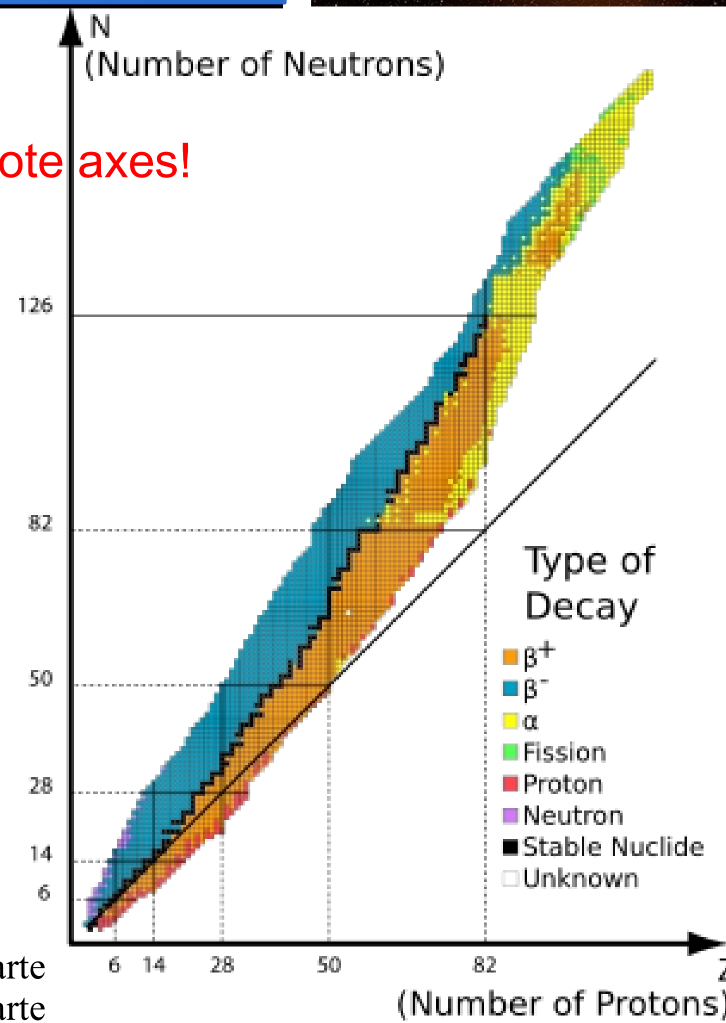




Creating the heavy elements



Note axes!



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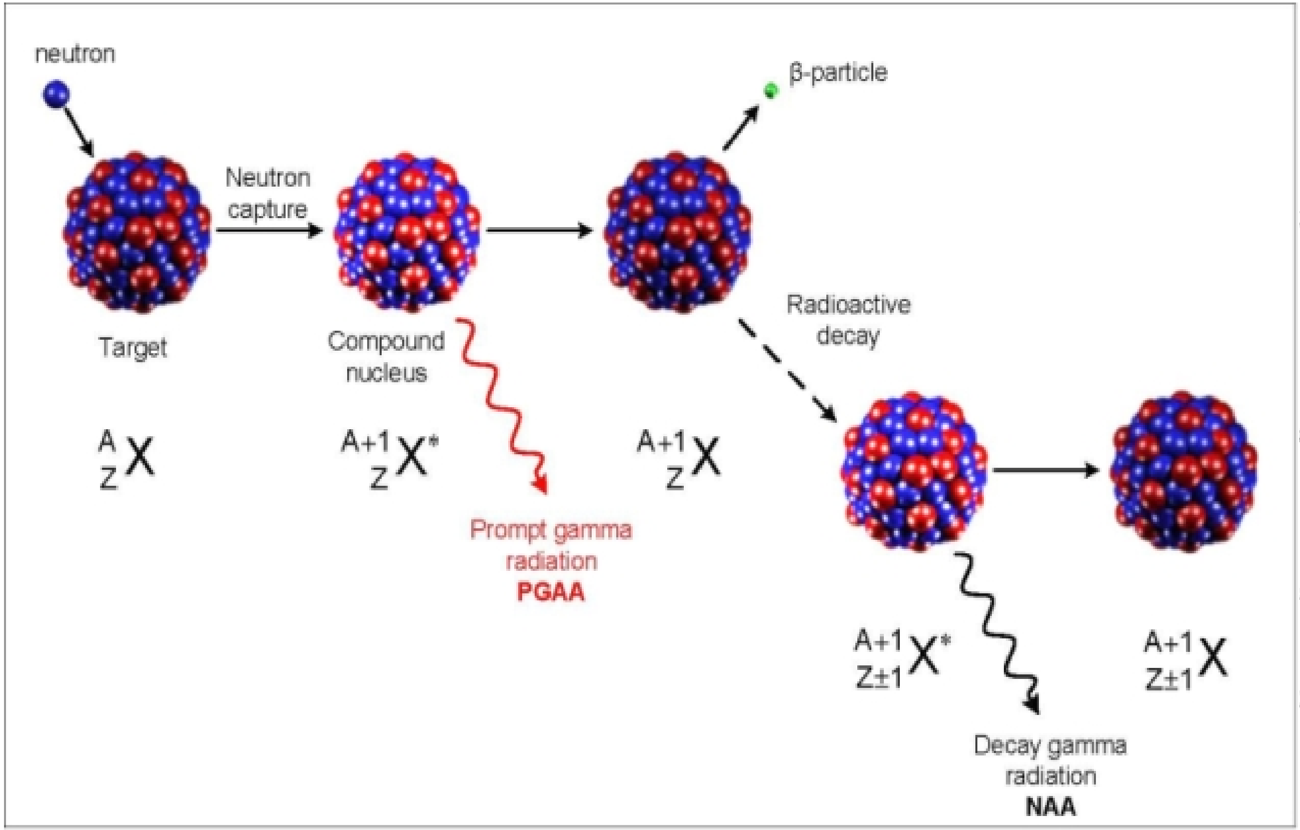
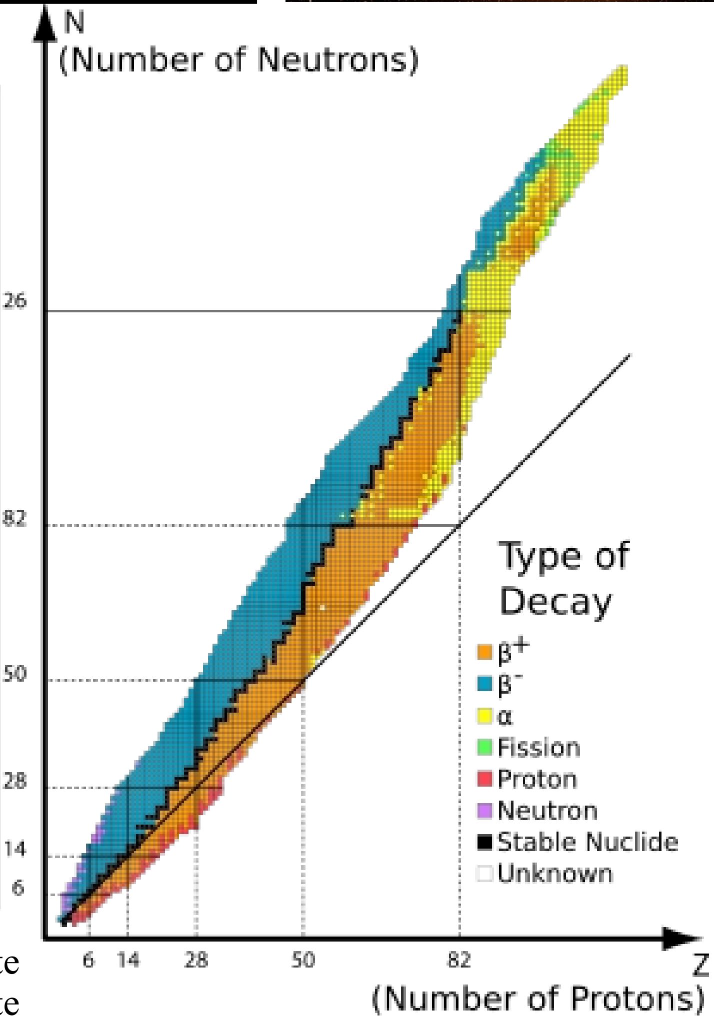
Creating the heavy elements





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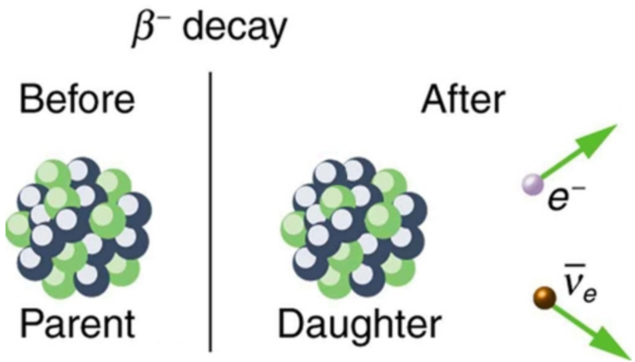
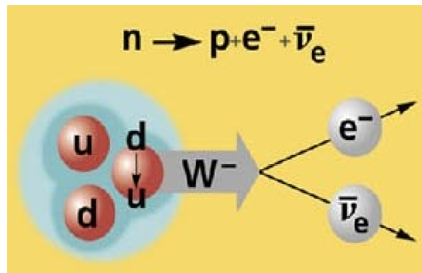
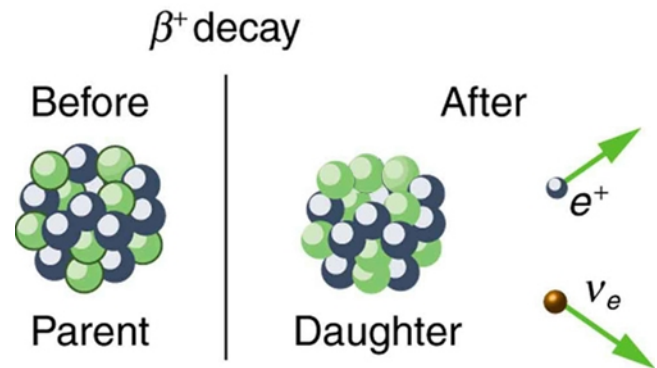
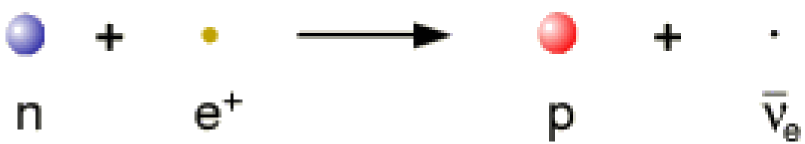
What else affects n-captures?



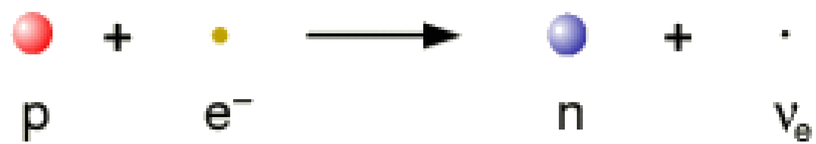






A lot of anti-neutrinos will react with the protons and produce neutrons

Meanwhile, a lot of neutrinos will convert the neutrons to protons



BUT – how can these particles be captured in the first place?

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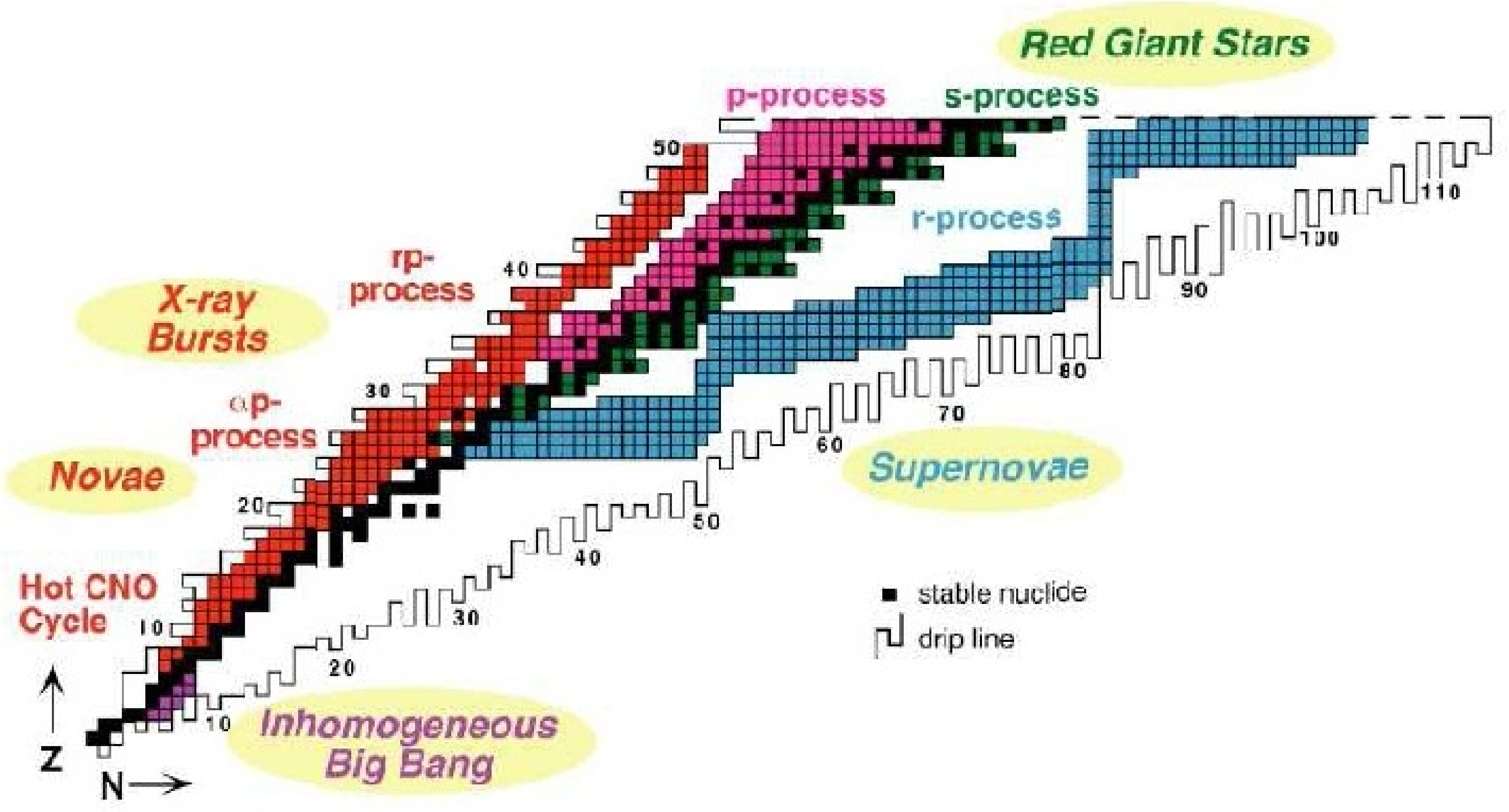
Possible formation sites



Heavy element formation

- P-processes (p, nu-p, spallation) → 35 nuclei
- The majority of heavy nuclei are created via:
- Rapid neutron-capture (r-)processes (1/3 – ½)
  - Weak r (Sr – Cd or Sn) range undertain
  - Main r (> Ba)
- Slow neutron-capture (s-)processes (½ – 2/3)
  - Weak s-process (A < 90)
  - Main s-process (A>90)
  - (strong?)

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The two main formation processes

Most heavy isotopes are created by n-capture processes which are out of equilibrium (NSE).

The 2 main processes are:

R-process	s-process
Primary	Secondary
High Nn ~ 10^26	lower Nn ~ 10^8
(Kratz et al, 2007)	(Busso et al, 1999)
Energetic/explosive (SN)	RGB/AGB stars
	13C or 22Ne reactions
~1/3 - ½	~1/2 - 2/3
N-cap. >> β-decay	N-cap. ~ β-decay

The isotopes are radio active and decay to become the stable isotopes we can measure abundances of

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The main r-process

- This process creates the heaviest most n-rich unstable nuclei
- Conditions:
- High energy
- Many seeds and free neutrons – i.e. a low Ye
- Ye = 1 – Yn and Ye=Yp
- Possibly high entropy
- Due to the high neutron flux this process moves far from stability

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Main r-process sites

- Massive supernovae (SN)
- X-ray binaries
- Novae
- Neutron star / Black hole mergers
- But – site remains unknown

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Massive supernovae

- An early possible site, which due to its high mass will have a short life ending with an explosion. This object may very well be the first to produce heavy elements after the Big Bang Nucleosynthesis.
- Happen frequently
- Can create all heavy r-nuclei (if conditions allow)
- Conditions may vary → very different outcome

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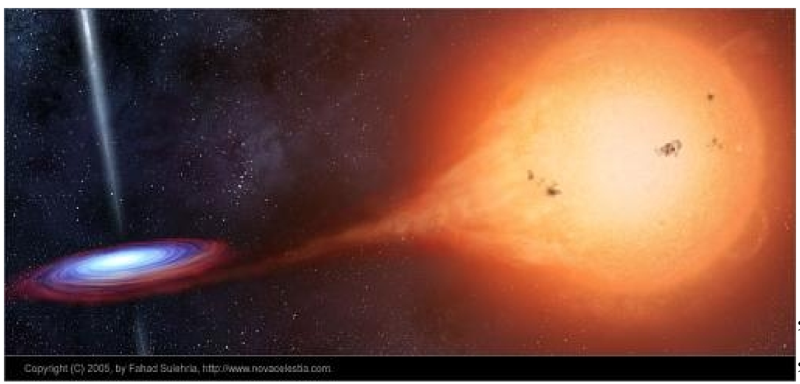
X-ray binaries

- An accreting binary system of, e.g., a neutron star + companion (giant), but the system can have various secondaries.
- Energetic environment, fueled by H-burning
- But: Models and observations do NOT match



In a High Mass X-ray Binary (HMXB) the primary accretes matter from the secondary's stellar wind. The secondary is usually an early type (young and massive) star with a strong stellar wind. In a Low Mass X-ray Binary (LMXB) the secondary is larger than its Roche Lobe, the surface of gravitational equipotential inside of which material is bound to the star. Material overflowing the Roche Lobe is attracted by the primary, again a compact object.
In both types of X-ray binaries material attracted to the accretor forms (by conservation of angular momentum) an accretion disk around it. Viscous processes in the disk serves to heat the material in the disk to millions of degrees (emitting X-rays as a black body) and redistribute angular momentum such that material migrates to the inner part of the disk. Material loses gravitational potential energy as it falls toward the accretor and emits X-rays. J. Bornak

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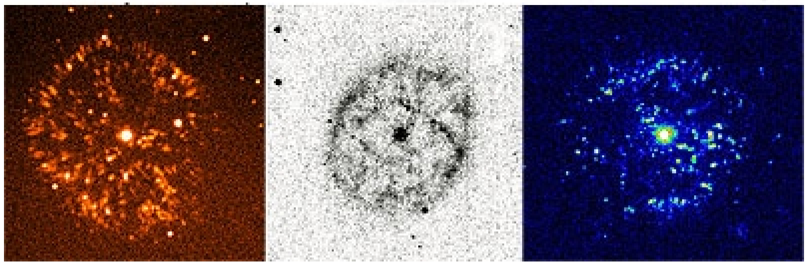
Novae

- A binary system of a white dwarf +giant/MS star
- Not frequent (1 in 10000 yrs)
- Lower energy



Classical Novae
A classical nova is thought to occur in a binary system consisting of a white dwarf accreting from a main sequence (or late type giant) via Roche Lobe overflow. The accreted material builds up as a layer on the surface of the white dwarf until the base temperature increases to the point when a thermonuclear runaway occurs, dominated by CNO reactions. This shell burning continues at Edddington luminosity for the white dwarf. Material is ejected at speeds from a few hundred to a thousand km/s. The shell starts as an optically thick fireball and expands and cools to be optically thin. Novae are classified by the speed at which they decrease in brightness. Classical novae are thought to recur every 10,000 years or so. J. Bornak

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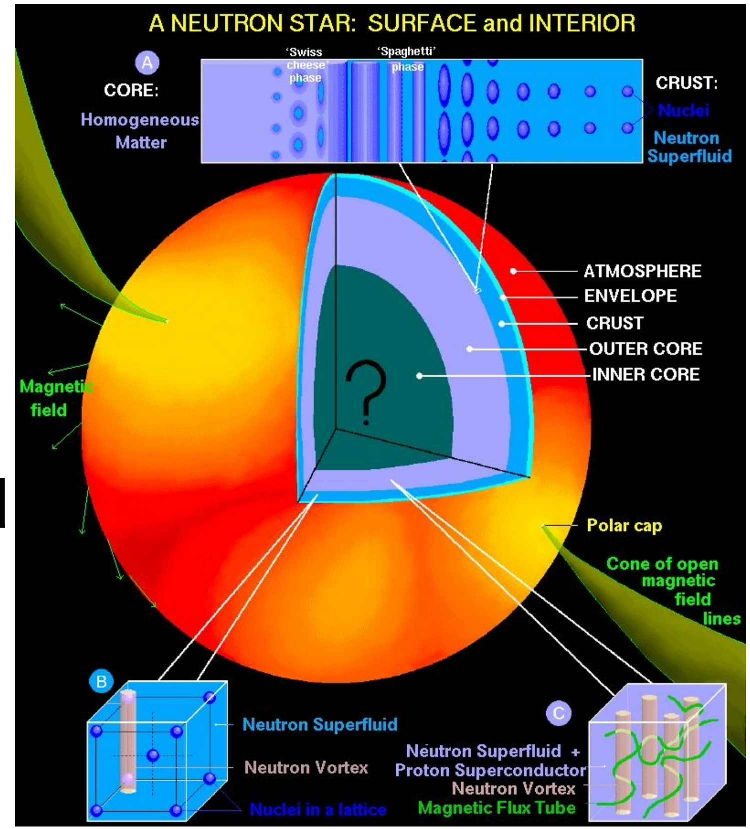
Neutron star (NS) mergers

- Rare events
- Low entropy
- Low Ye

  (Ye~0.2-0.3 – I.e. many neutrons)
- Large mass of heavy elements ejected – 10^-4 to 10^-2Msun
- Full main r-process



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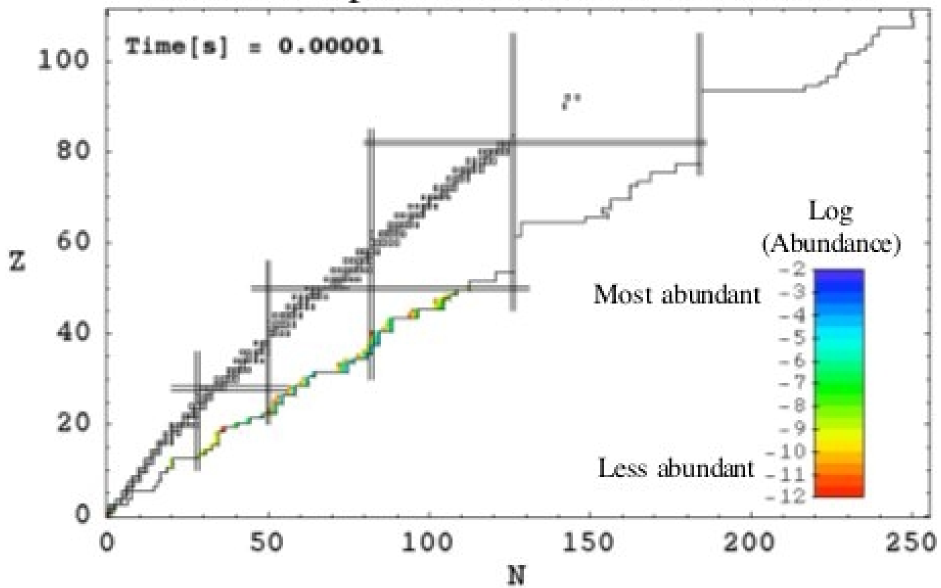
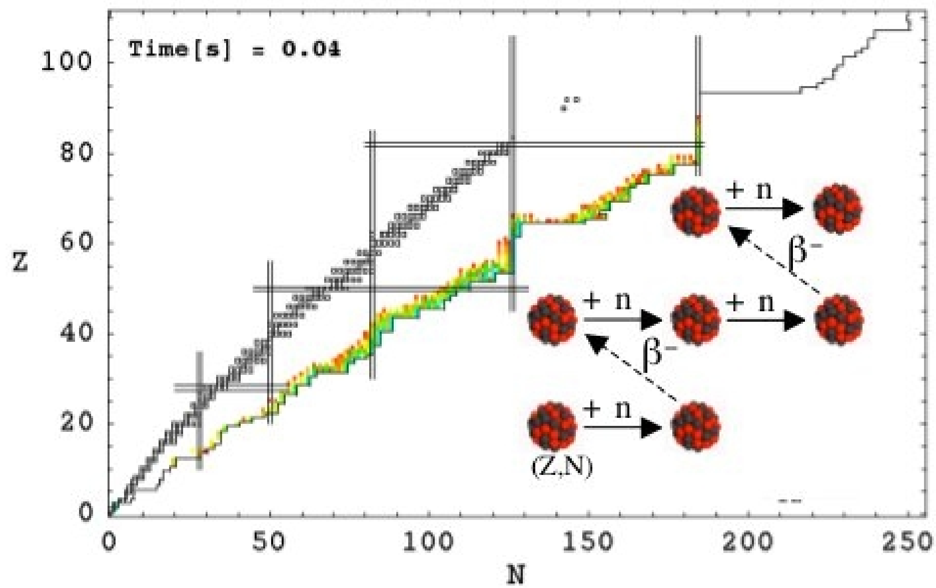
M. Colemann Miller

Initial composition of neutron star crust

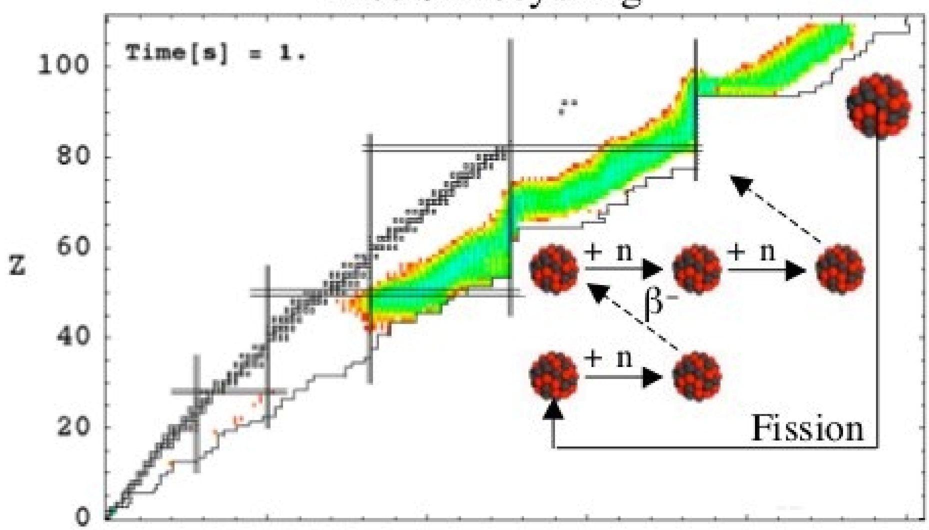


Sequence of neutron captures and β-decays

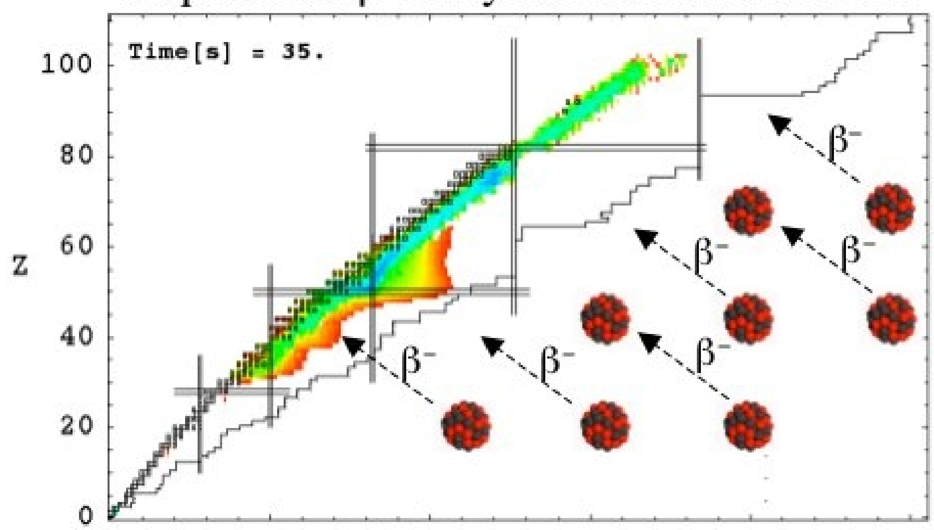


Model predictions of NS mergers

Fission recycling



Sequence of β-decays back to stable nuclei



The weak r-process

- Still a rapid process, but closer to stability
- Lower neutron density
- Higher Ye
- Less massive/energetic objects
- Does not create a full range of elements, but seems constrained to the regions Sr - Sn

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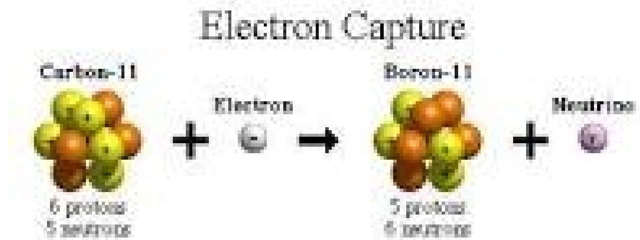
The weak r-process sites



- Faint O-Ne-Mg CC SN – M ~ 8-10Msun
- Ye ~ 0.4 (minimum 0.3)
- Supernova model problems (1D – 2D – 3D)
- Neutrino-driven winds
- Ejecta mass of heavy elements: 10^-7-10^-4Msun
- Parameters not well constrained, and the model cannot create the heavier elements
- Both models can produce up to Ag-Cd in their current state

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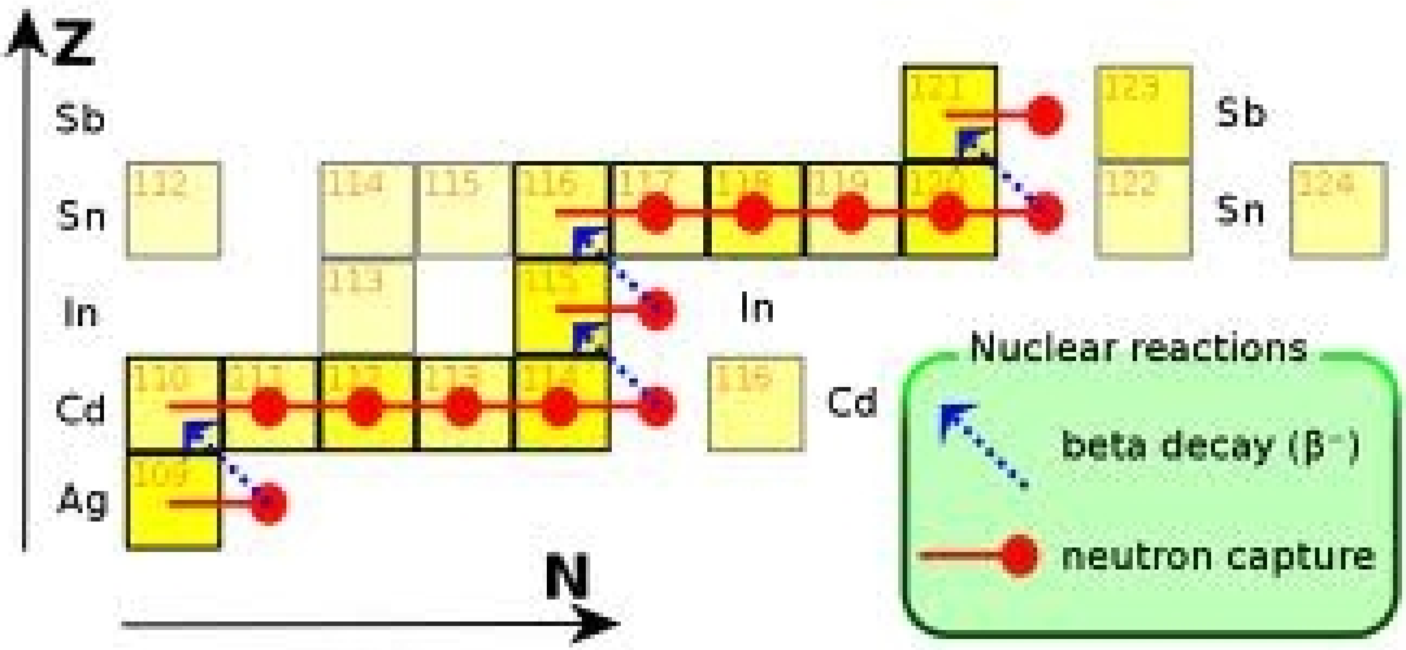
Zooming in on the weak r-process



The weak r-process might create elements in the range Sr – Sn (or at least Cd).

Observational indications follow

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The weak/main s-process

- Neutron sources in massive stars: $^{22}Ne(\alpha,n)^{25}Mg$,

  T> 2.5*10^8K,
- Thermal pulse, nn~10^10cm−3
- Neutron soure in AGB stars:

  $^{12}C(p,\alpha)^{13}N(\beta+)^{13}C(\alpha,n)^{16}O$,
- T~9*10^7K, interpulse in He-intershell, nn~10^7cm−3

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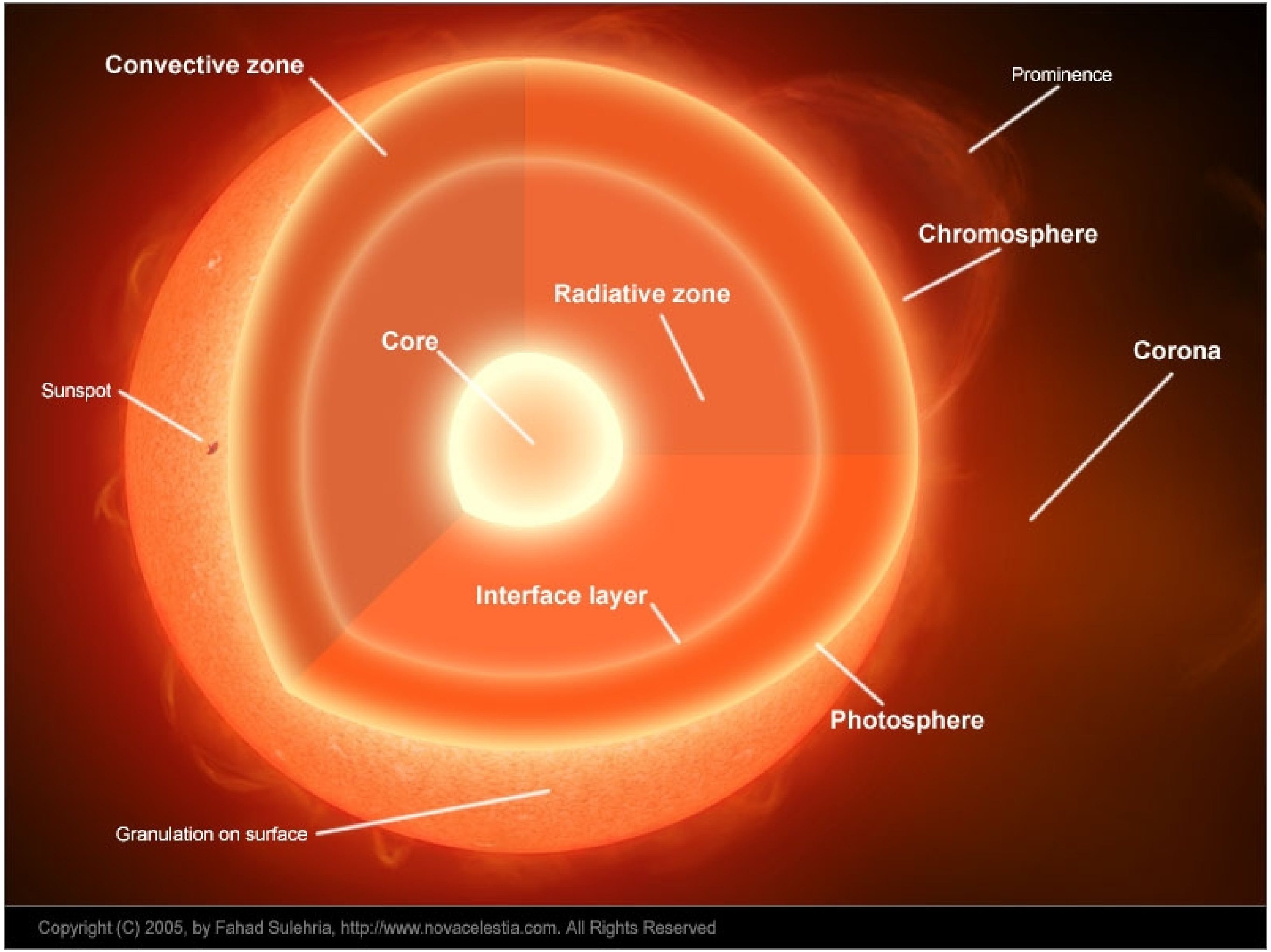
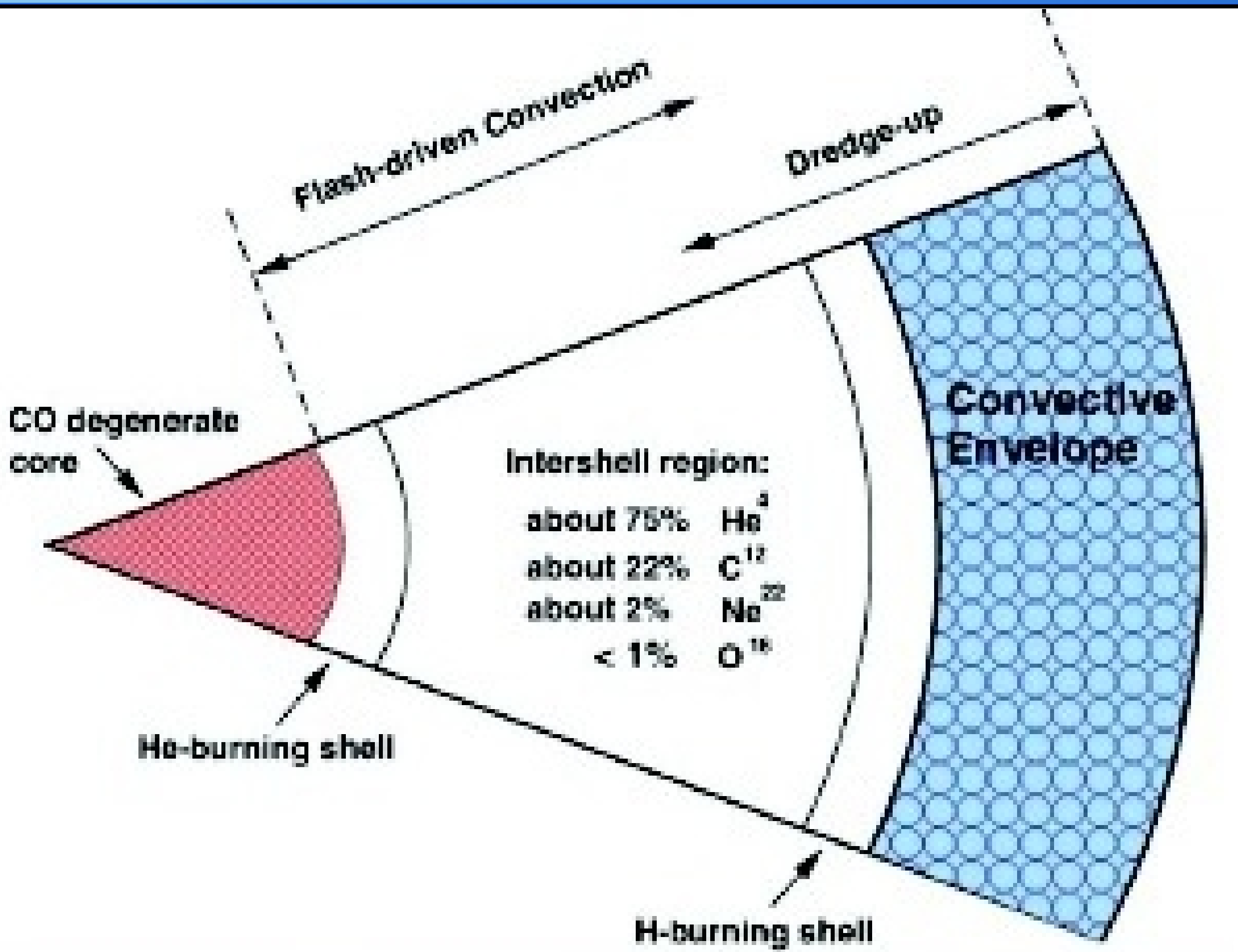
Core and shell burning



Main s-process



Structure of a very evolved asymptotic giant branch (AGB) star

Unstable double shell burning leads to thermal pulses, followed by a 3rd dredge-up !
s-process in 13C-pockets (Karakas et al, 2002)

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Main s-process

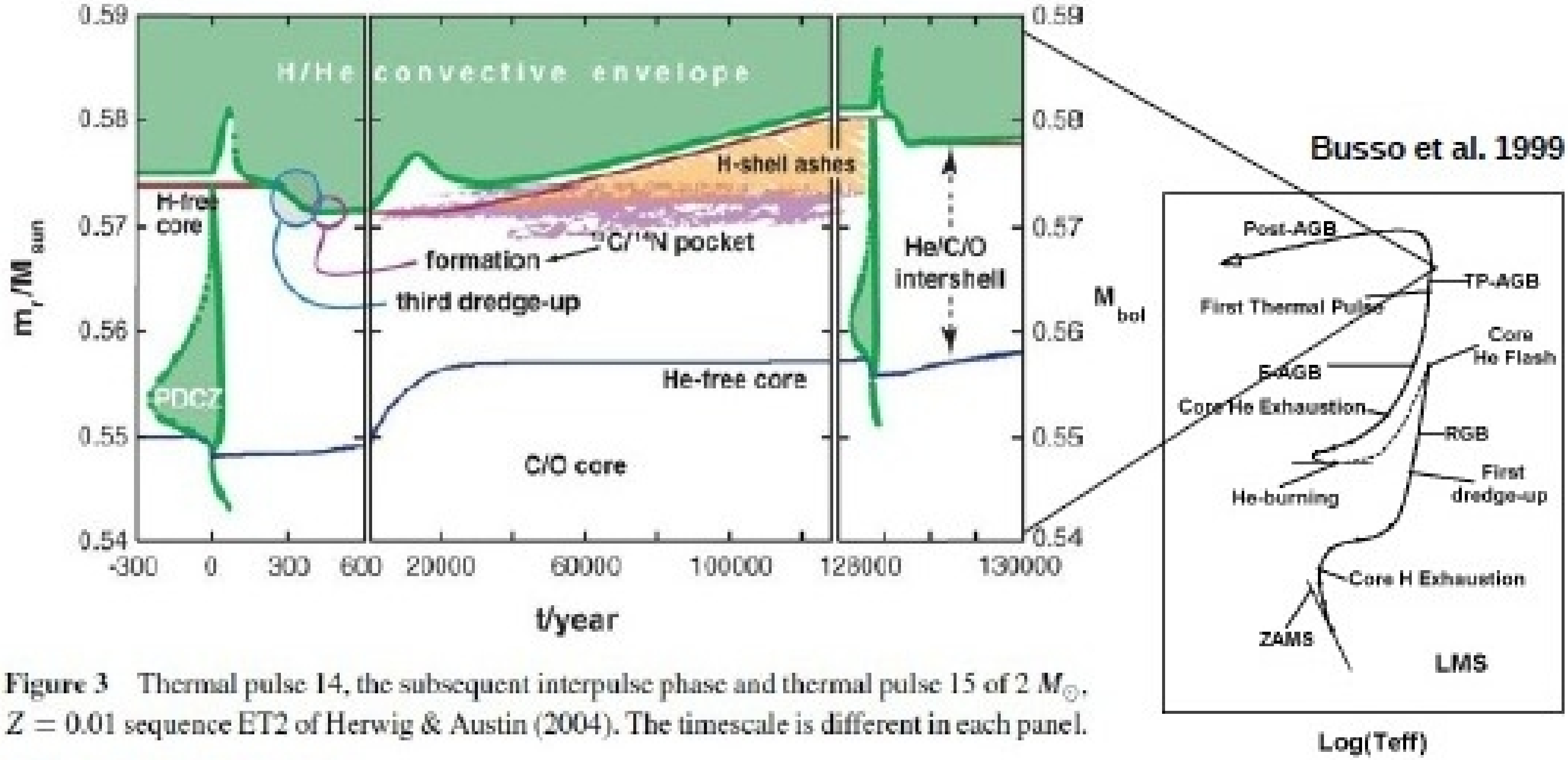

Figure 3 Thermal pulse 14, the subsequent interpulse phase and thermal pulse 15 of 2 $M_{\odot}$, $Z = 0.01$ sequence ET2 of Herwig & Austin (2004). The timescale is different in each panel.

Herwig 2005, ARAA 43

Problems with each process

- Nuclear physics (reaction rates etc.) needs to be improved (but hard to measure...)
- Model uncertainties such as 13C-pockets
- Weak s – tends to need rotating stars, but how fast should they rotate?
- S-process sites known, r-process site unknown

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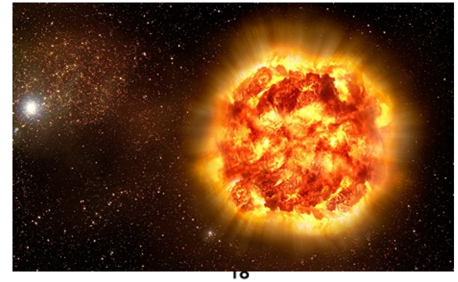
The complete table



Periodic Table of the Elements

1 1IA 11A	2 IIA 2A	3 IIIB 3B	4 IVB 4B	5 VB 5B	6 VIB 6B	7 VIIB 7B	8	9 VIII 8	10	11 IB 1B	12 IIB 2B	13 IIIA 3A	14 IVA 4A	15 VA 5A	16 VIA 6A	17 VIIA 7A	18 VIIIA 8A
1 H Hydrogen 1.0079																	2 He Helium 4.00260
3 Li Lithium 6.941	4 Be Beryllium 9.01218											5 B Boron 10.811	6 C Carbon 12.011	7 N Nitrogen 14.00674	8 O Oxygen 15.9994	9 F Fluorine 18.998403	10 Ne Neon 20.1797
11 Na Sodium 22.989768	12 Mg Magnesium 24.305											13 Al Aluminum 26.981539	14 Si Silicon 28.0855	15 P Phosphorus 30.973762	16 S Sulfur 32.066	17 Cl Chlorine 35.4527	18 Ar Argon 39.948
19 K Potassium 39.0983	20 Ca Calcium 40.078	21 Sc Scandium 44.95591	22 Ti Titanium 47.88	23 V Vanadium 50.9415	24 Cr Chromium 51.9961	25 Mn Manganese 54.938	26 Fe Iron 55.847	27 Co Cobalt 58.9332	28 Ni Nickel 58.6934	29 Cu Copper 63.546	30 Zn Zinc 65.39	31 Ga Gallium 69.732	32 Ge Germanium 72.64	33 As Arsenic 74.92159	34 Se Selenium 78.96	35 Br Bromine 79.904	36 Kr Krypton 83.80
37 Rb Rubidium 85.4678	38 Sr Strontium 87.62	39 Y Yttrium 88.90585	40 Zr Zirconium 91.224	41 Nb Niobium 92.90638	42 Mo Molybdenum 95.94	43 Tc Technetium 98.9072	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.9055	46 Pd Palladium 106.42	47 Ag Silver 107.8682	48 Cd Cadmium 112.411	49 In Indium 114.818	50 Sn Tin 118.71	51 Sb Antimony 121.760	52 Te Tellurium 127.6	53 I Iodine 126.90447	54 Xe Xenon 131.29
55 Cs Cesium 132.90543	56 Ba Barium 137.327	57-71	72 Hf Hafnium 178.49	73 Ta Tantalum 180.9479	74 W Tungsten 183.85	75 Re Rhenium 186.207	76 Os Osmium 190.23	77 Ir Iridium 192.22	78 Pt Platinum 195.08	79 Au Gold 196.9665	80 Hg Mercury 200.59	81 Tl Thallium 204.3833	82 Pb Lead 207.2	83 Bi Bismuth 208.98037	84 Po Polonium [208.9824]	85 At Astatine 209.9871	86 Rn Radon 222.0176
87 Fr Francium 223.0197	88 Ra Radium 226.0254	89-103	104 Rf Rutherfordium [261]	105 Db Dubnium [262]	106 Sg Seaborgium [266]	107 Bh Bohrium [264]	108 Hs Hassium [269]	109 Mt Meitnerium [268]	110 Ds Darmstadtium [269]	111 Rg Roentgenium [272]	112 Cn Copernicium [277]	113 Uut Ununtrium unknown	114 Uuq Ununquadium [289]	115 Uup Ununpentium unknown	116 Uuh Ununhexium [298]	117 Uus Ununseptium unknown	118 Uuo Ununoctium unknown

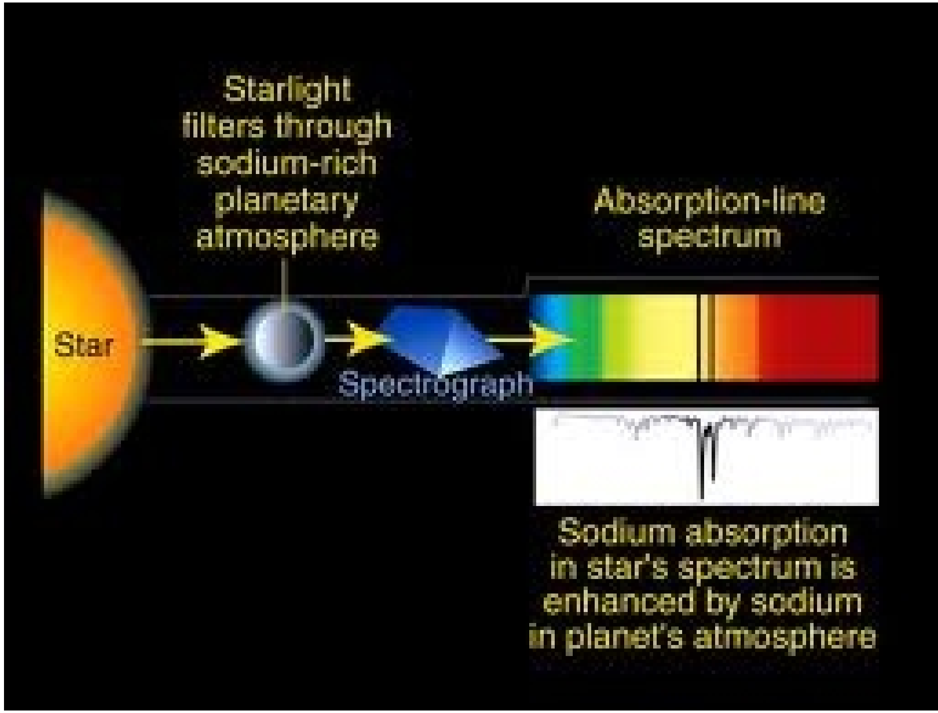
Series															
Lanthanide Series	57 La Lanthanum 138.9055	58 Ce Cerium 140.115	59 Pr Praseodymium 140.90765	60 Nd Neodymium 144.24	61 Pm Promethium 144.9127	62 Sm Samarium 150.36	63 Eu Europium 151.9655	64 Gd Gadolinium 157.25	65 Tb Terbium 158.92534	66 Dy Dysprosium 162.50	67 Ho Holmium 164.93032	68 Er Erbium 167.26	69 Tm Thulium 168.93421	70 Yb Ytterbium 173.04	71 Lu Lutetium 174.967
Actinide Series	89 Ac Actinium 227.0278	90 Th Thorium 232.0381	91 Pa Protactinium 231.03588	92 U Uranium 238.0289	93 Np Neptunium 237.0482	94 Pu Plutonium 244.0642	95 Am Americium 243.0614	96 Cm Curium 247.0703	97 Bk Berkelium 247.0703	98 Cf Californium 251.0796	99 Es Einsteinium [254]	100 Fm Fermium 257.0951	101 Md Mendelevium 258.1	102 No Nobelium 259.1009	103 Lr Lawrencium [262]

Alkali Metal | Alkaline Earth | Transition Metal | Basic Metal | Semimetals | Nonmetals | Halogens | Noble Gas | Lanthanides | Actinides

Applications – comparison to observations

- The nuclear physics which is the input for astrophysical models is often compared to observationally derived stellar abundances
- [X/Fe] = log (Nx/NH) – log(Nx/NH)Sun – [Fe/H],

  where x is an element
- From this we will be able to determine the abundance of an element that is present in the star



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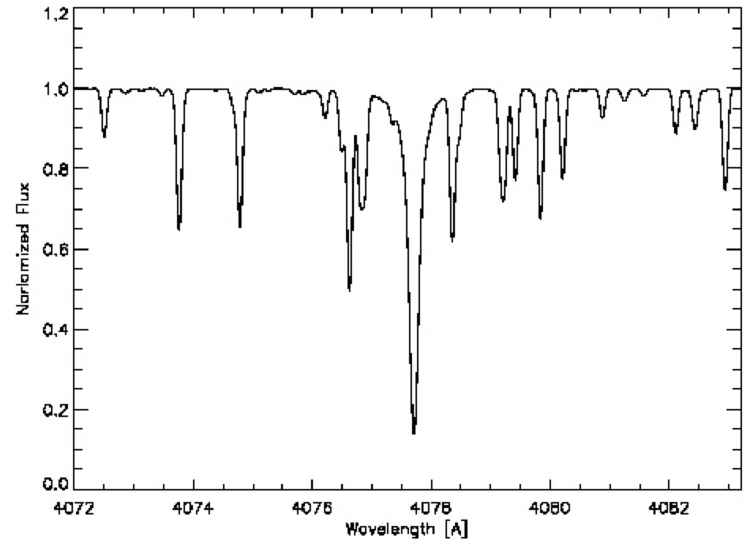
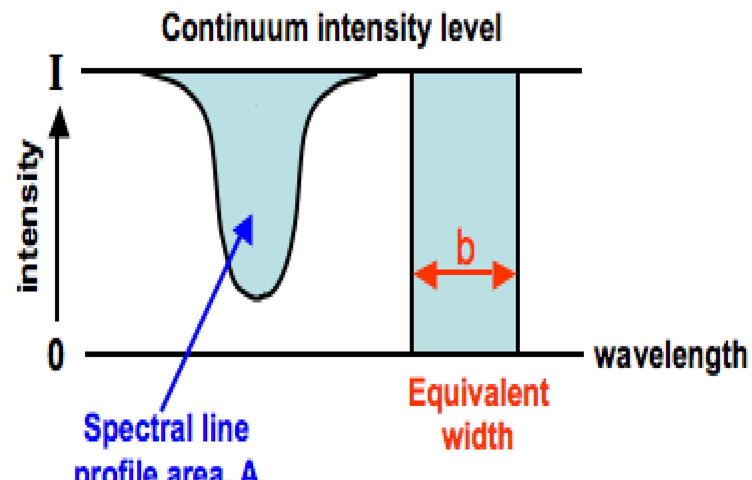
Absorption lines & abundances

- Stellar spectra carry information on the star's composition which can be obtained via their absorption lines
- From the integrated area of an absorption line we can learn how abundant the star is in the element the line transition corresponds to
- In order to calculate the elemental abundances we first need to:
  - Reduce the spectra
  - Determine the stellar parameters -
  - Then we can derive the abundances





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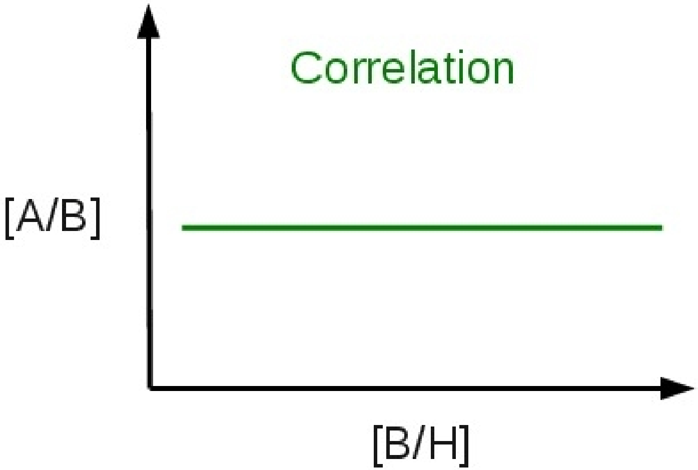
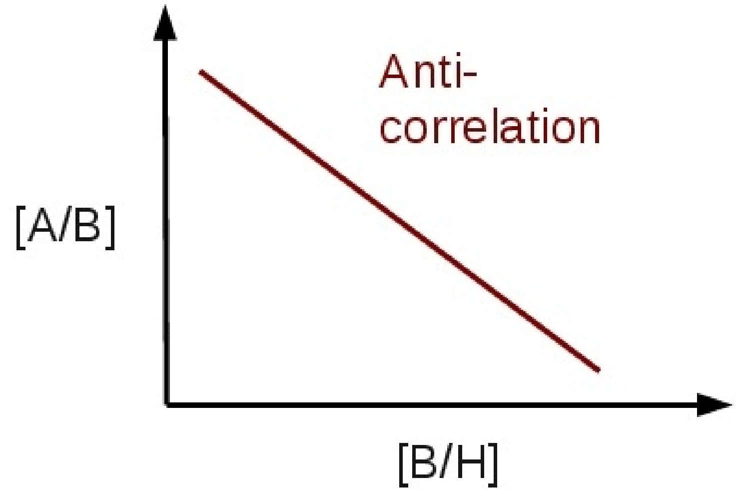
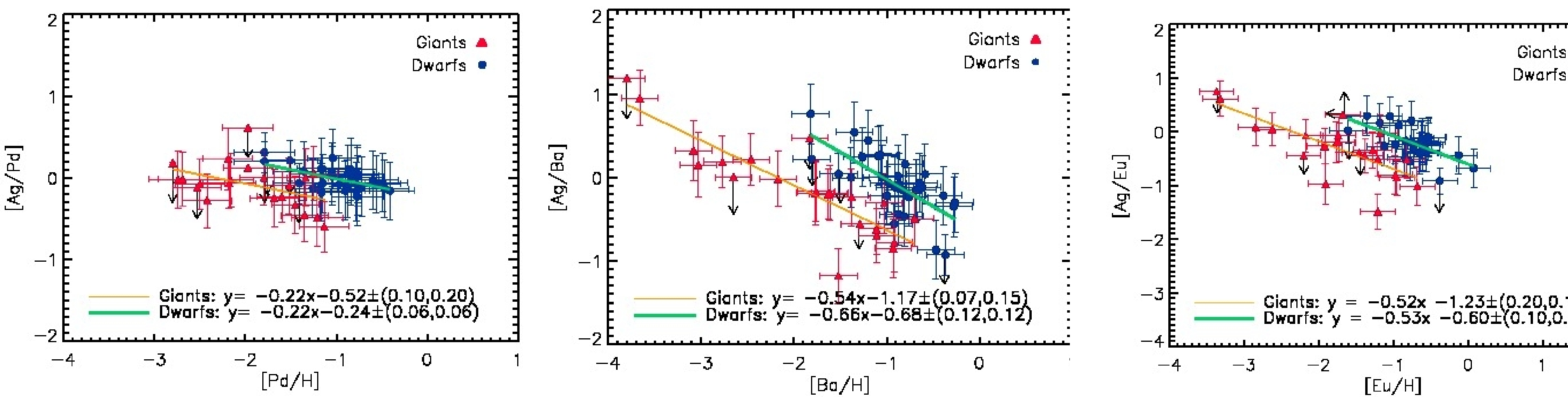
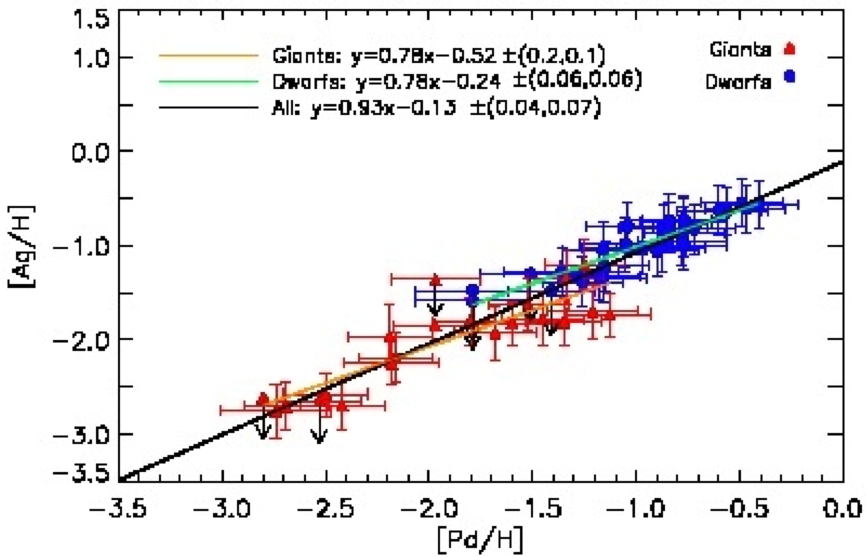
Tracing formation processes







Tracing formation processes



Pd and Ag correlate → they are produced in the same process

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A record holding star

- CS31082-001 (Siqueira Mello et al. 2013)
- 37 heavy elements

Table 1. LTE abundances in CS 31082-001 as derived from previous works, from the present paper, and our adopted final abundances.

El.	Z	A(X) (1)	A(X) (2)	A(X) (3)	A(X) This Work	A(X) adopted	[X/Fe] adopted
Ge	32	—	—	—	+0.10	+0.10±0.21	-0.55
Sr	38	+0.72	—	—	—	+0.72±0.10	0.73
Y	39	-0.23	—	—	-0.15	-0.19±0.07	0.53
Zr	40	+0.43	—	—	+0.55	+0.49±0.08	0.84
Nb	41	-0.55	—	—	-0.52	-0.54±0.12	0.97
Mo	42	—	—	—	-0.11	-0.11±0.13	0.90
Ru	44	+0.36	—	—	+0.36	+0.36±0.12	1.45
Rh	45	-0.42	—	—	-0.42	-0.42±0.12	1.39
Pd	46	-0.05	—	—	-0.09	-0.09±0.07	1.18
Ag	47	-0.81	—	—	-0.84	-0.84±0.21	1.15
Ba	56	+0.40	—	—	—	+0.40±0.14	1.16
La	57	-0.60	-0.62	—	—	-0.62±0.05	1.17
Ce	58	-0.31	-0.29	—	-0.31	-0.29±0.05	1.03
Pr	59	-0.86	-0.79	—	—	-0.79±0.05	1.38
Nd	60	-0.13	-0.15	—	-0.21	-0.15±0.05	1.33
Sm	62	-0.51	-0.42	—	-0.42	-0.42±0.05	1.51
Eu	63	-0.76	-0.72	—	-0.75	-0.72±0.05	1.69
Gd	64	-0.27	-0.21	—	-0.29	-0.21±0.05	1.61
Tb	65	-1.26	-1.01	—	-1.00	-1.01±0.05	1.64
Dy	66	-0.21	-0.07	—	-0.12	-0.07±0.05	1.73
Ho	67	—	-0.80	—	—	-0.80±0.06	1.62
Er	68	-0.27	-0.30	—	-0.31	-0.30±0.05	1.67
Tm	69	-1.24	-1.15	—	-1.18	-1.15±0.05	1.64
Yb	70	—	-0.41	—	—	-0.41±0.11	1.66
Lu	71	—	—	—	-1.08	-1.08±0.13	1.73
Hf	72	-0.59	-0.72	—	-0.73	-0.72±0.05	1.33
Ta	73	—	—	—	-1.60	-1.60±0.23	1.47
W	74	—	—	—	-0.90	-0.90±0.24	0.92
Re	75	—	—	—	-0.21	-0.21±0.21	2.45
Os	76	+0.43	—	+0.18	—	+0.18±0.07	1.72
Ir	77	+0.20	—	+0.20	—	+0.20±0.07	1.72
Pt	78	—	—	+0.30	—	+0.30±0.23	1.46
Au	79	—	—	-1.00	—	-1.00±0.34	0.89
Pb	82	—	—	-0.65	—	-0.65±0.19	0.25
Bi	83	—	—	-0.40	—	-0.40±0.33	1.83
Th	90	-0.98	—	—	—	-0.98±0.13	1.84
U	92	-1.92	—	—	—	-1.92±0.17	1.68

References. (1) Hill et al. (2002), (2) Sneden et al. (2009), (3) Barbuy et al. (2011).

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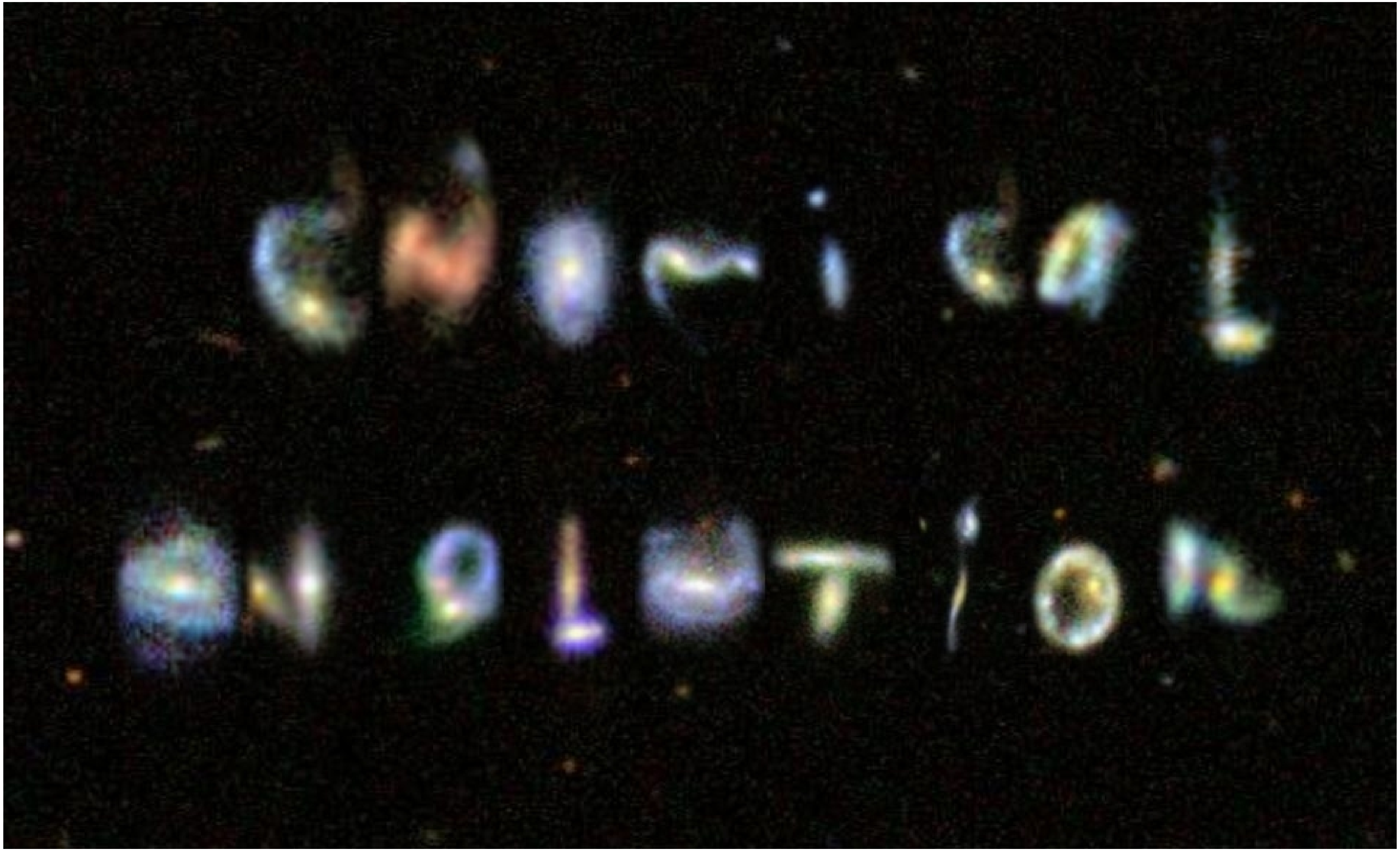
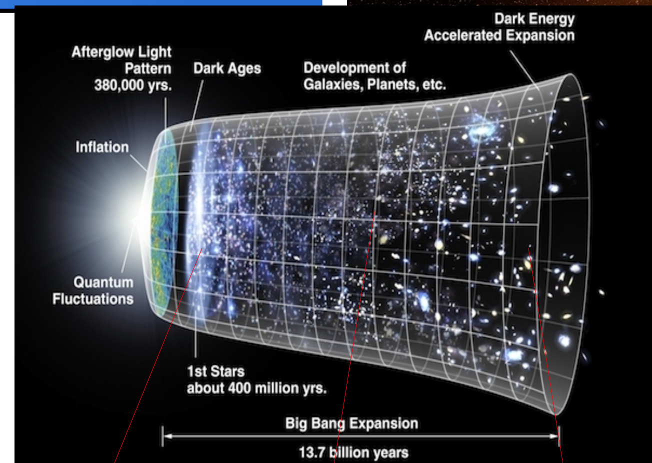
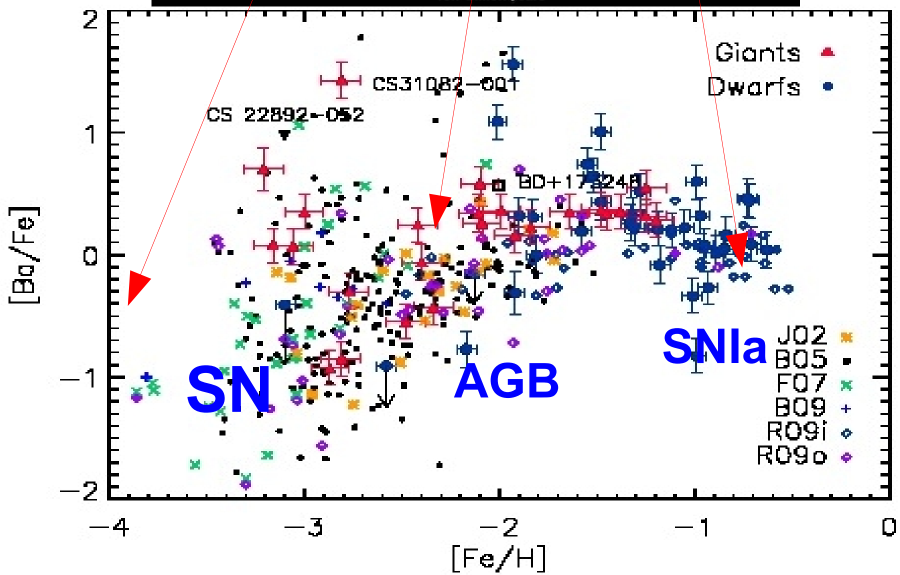
Galaxify



Young and old stars - together



- When we observe the sky today, we will see a mixture of very old stars (maybe the first) but also young recently formed stars
- Heavy stars evolve faster → they will be the first ones to explode as SN II (M>8Msun)
- Then asymptotic giant branch stars follow (1-8Msun)
- Binary stars are the last to explode as SN Ia



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Galactic chemical evolution

- When we look as many stars together, with a variety of ages, we can determine how the chemistry of our Galaxy evolved (Galactic chemical evolution)
- Therefore we study abundances in stars
- These can be compared to BBN nucleosynthesis, SN, and AGB yields

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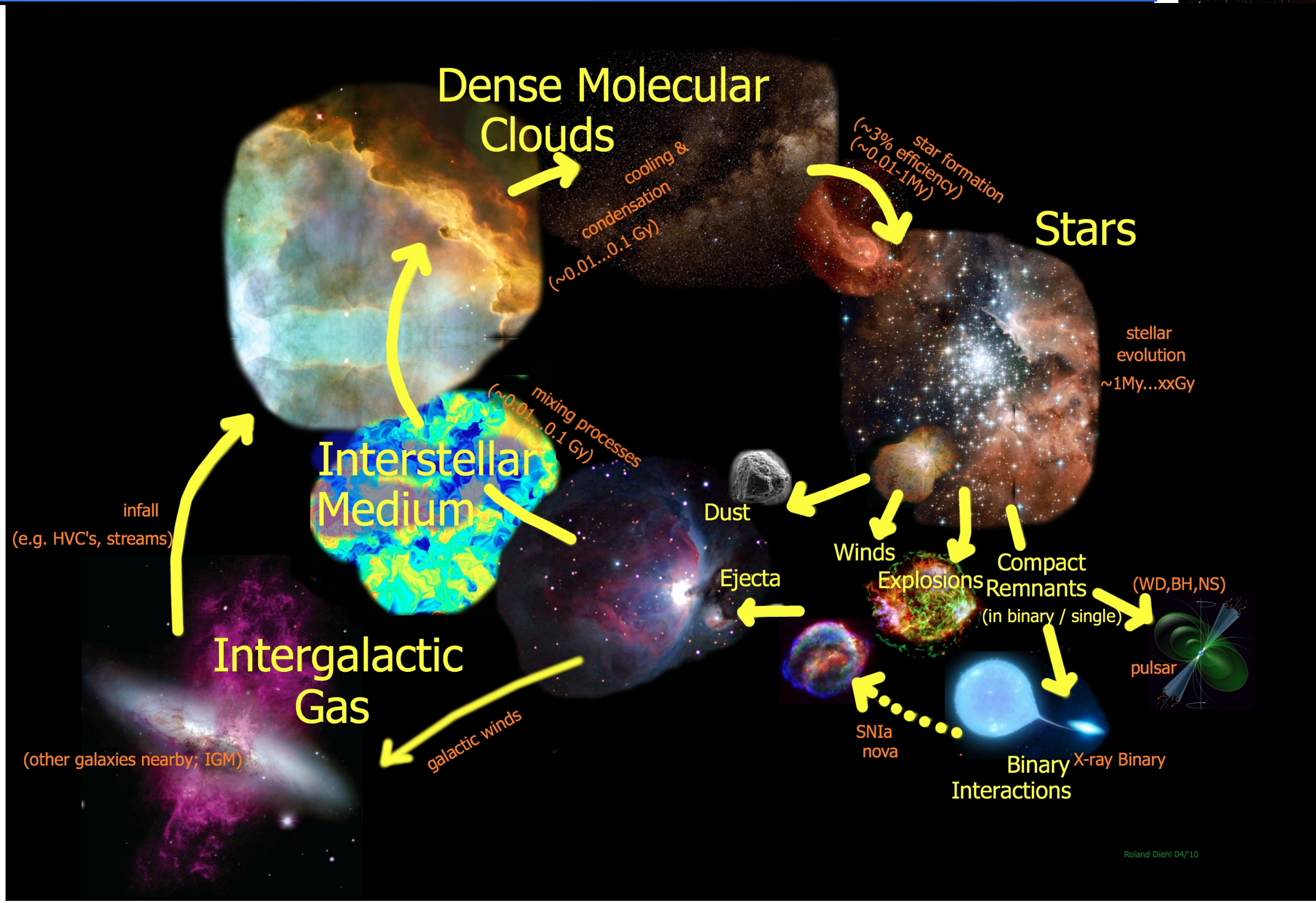
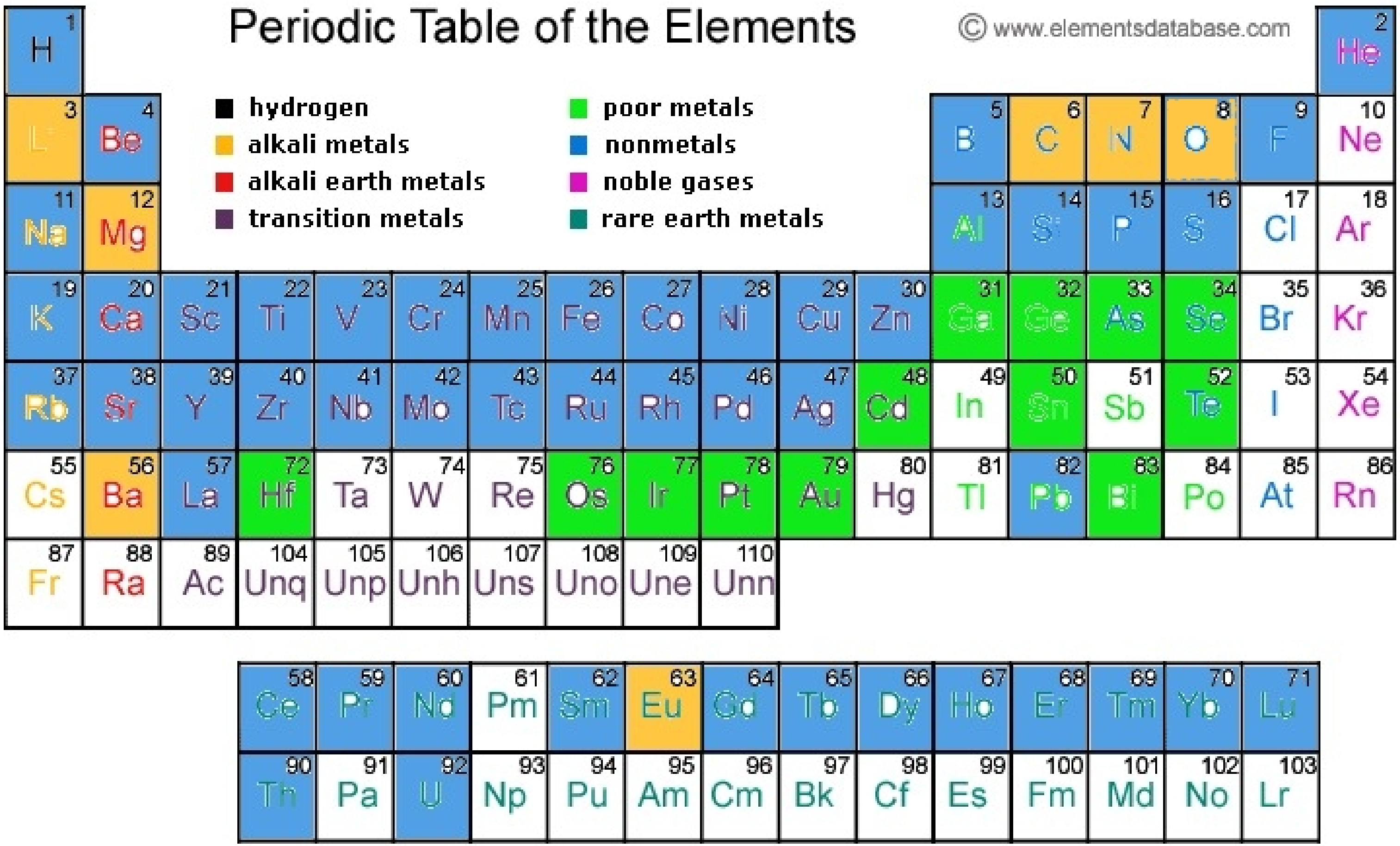
The cycle of matter



Observable elements



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Galaxify

Generally: Google images

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