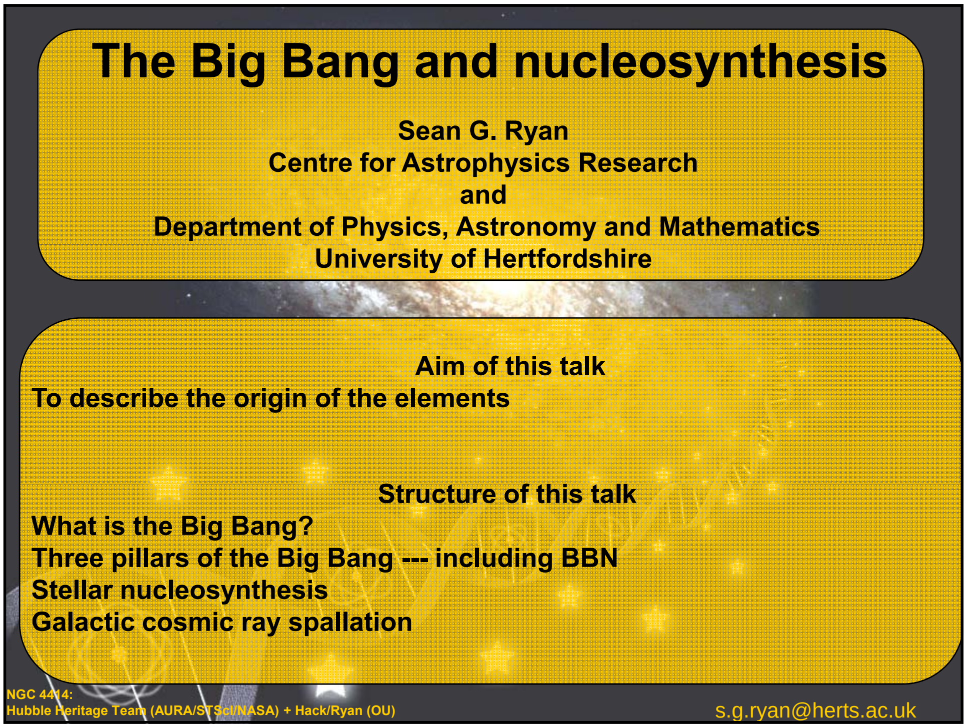

The Big Bang and nucleosynthesis

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Aim of this talk

To describe the origin of the elements

Structure of this talk

What is the Big Bang?
Three pillars of the Big Bang --- including BBN
Stellar nucleosynthesis
Galactic cosmic ray spallation

NGC 4414:
Hubble Heritage Team (AURA/STScI/NASA) + Hack/Ryan (OU)

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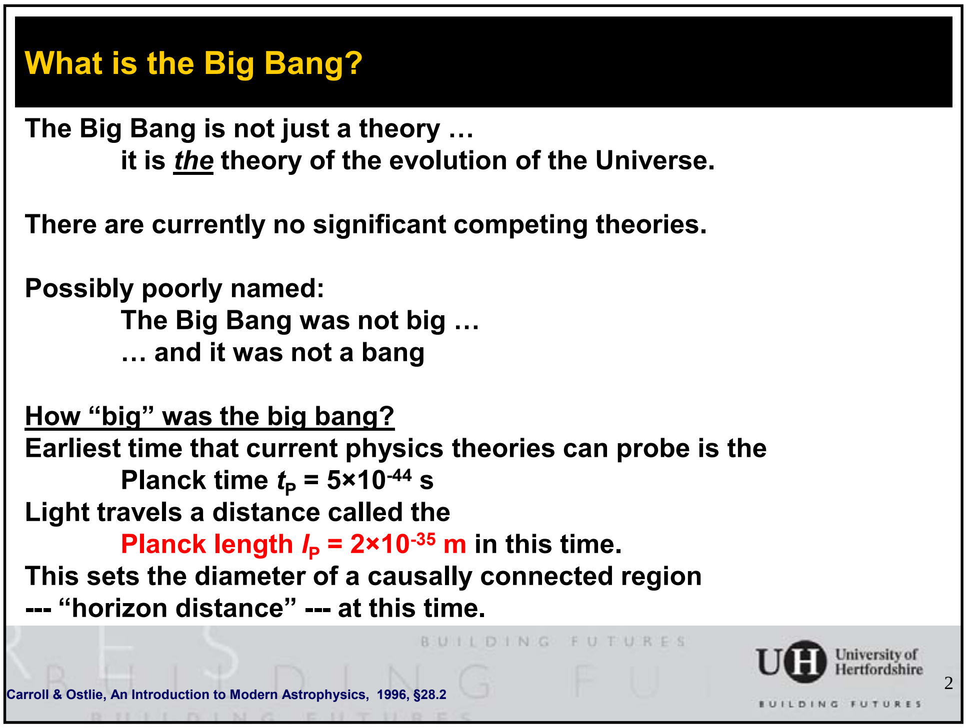


What is the Big Bang?

The Big Bang is not just a theory …
it is ***the*** theory of the evolution of the Universe.

There are currently no significant competing theories.

Possibly poorly named:
The Big Bang was not big …
… and it was not a bang

How "big" was the big bang?
Earliest time that current physics theories can probe is the
Planck time $t_P = 5\times10^{-44}$ s
Light travels a distance called the
Planck length $l_P = 2\times10^{-35}$ m in this time.
This sets the diameter of a causally connected region
--- "horizon distance" --- at this time.

Carroll & Ostlie, An Introduction to Modern Astrophysics, 1996, §28.2

What is the Big Bang?

Was there a bang?
There was no explosion.
Matter did not rush outwards through space.

Rather space itself expanded,
carrying the matter along with it…
(or more strictly, spacetime expanded)
Astronomers talk of the scale factor *R*,
not the radius,
of the Universe.

R increases with time, describing the expansion of the Universe.
$R_{\text{today}} \equiv R_0 = 1$.

Rate of expansion has varied significantly and in some ways unexpectedly (inflation, acceleration), over the history of the Universe.

Carroll & Ostlie, An Introduction to Modern Astrophysics, 1996, §27.2

What is the Big Bang?

Historical note:

Q: If the observable Universe was small and there was no explosion,
why is its early phase called the Big Bang?

A: It was so named by Fred Hoyle in a BBC radio interview,
and Hoyle was a major opponent of the theory, not a supporter!

What is the Big Bang?

Emergence of the Big Bang theory

Expansion of the Universe discovered observationally:

(1) vast majority of galaxies are moving away [Slipher 1914 et seq.]

(2) galaxies that are further away are receding faster [Hubble 1929]

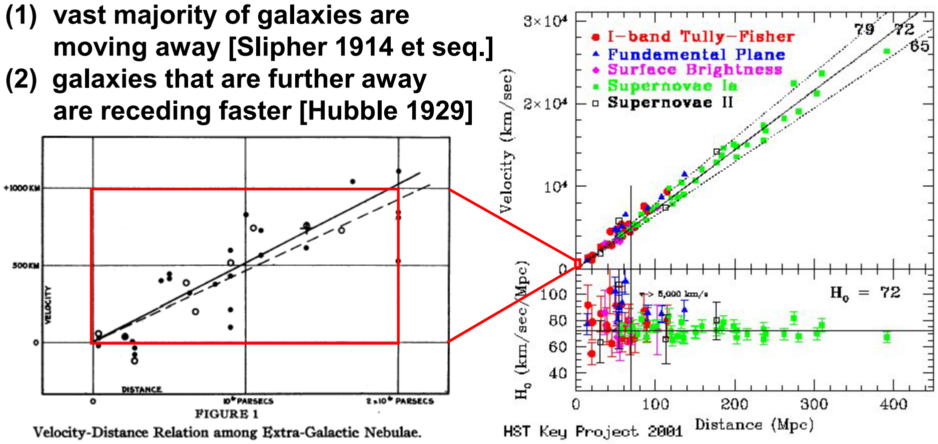


FIGURE 1

Velocity-Distance Relation among Extra-Galactic Nebulae.

HST Key Project 2001

Hubble, E., "A Relation between Distance and Radial Velocity among Extra-Galactic Nebulae" (1929) *Proceedings of the National Academy of Sciences of the United States of America*, Volume 15, Issue 3, pp. 168-173
Huchra, J. http://cfa-www.harvard.edu/~huchra/hubble/

Big Bang nucleosynthesis

Expansion implies during early phase, Universe was dense and hot

Particles disassemble at high temperatures:

molecules disassociate -	atoms are separated
atoms ionise -	electrons are removed
nuclei disassemble -	nucleons are removed
nucleons disassemble -	quarks (sub-nuclear particles)

Idea grew that, in an expanding and cooling Universe,
nucleons would assemble to produce *all* of the elements
→ Big Bang nucleosynthesis [Alpher, Bethe & Gamow 1946/48 αβγ]

Idea was optimistic:
lack of stable nuclei with atomic mass 5 and 8 prevented easy formation of nuclei heavier than ^{4}He [Alpher & Herman]
Big bang nucleosynthesis produces ^{1}H, ^{2}H, ^{3}He, ^{4}He and ^{7}Li only

Carroll & Ostlie, An Introduction to Modern Astrophysics, 1996, §27.2 & 28.1

Big Bang nucleosynthesis

Start story of BBN at $t \sim 2\times10^{-6}$ s, when $T \sim 10^{13}$ K,
and hence characteristic energy of particles $kT \sim 1$ GeV,
comparable to mass-energy of proton and neutron:
$E_p = m_p c^2 \sim 938.3$ MeV and $E_n = m_n c^2 = 939.6$ MeV
[Note: $\Delta E = 1.3$ MeV]

Universe has cooled to point at which quarks assemble into stable protons and neutrons. u u d → p   u d d → n
Protons and neutrons produced in almost identical numbers.

p's and n's continually interchanging with one another:

$n \leftrightarrow p + e^- + \text{anti-}\nu_e$ n ↔ p + - + ν_e

$n + e^+ \leftrightarrow p + \text{anti-}\nu_e$

$n + \nu_e \leftrightarrow p + e^-$

Ratio of n's to p's, n_n/n_p, decreases as Universe cools,
due to higher mass of neutrons: $m_n = m_p + 1.3\ \text{MeV}/c^2$.

Carroll & Ostlie, An Introduction to Modern Astrophysics, 1996, §28.1

Big Bang nucleosynthesis

Universe expands and cools (at $t \sim 2$ s) to $T \sim 10^{10}$ K, $kT \sim 1$ MeV:

(1) comparable to mass-energy difference of proton and neutron,
(2) comparable to energy required to form e^- and e^+ via $\gamma \rightarrow e^+ + e^-$.

(1) conversion of protons to neutrons ceases.
(2) e^- and e^+ cease to be produced, most annihilate; few e^-'s remain
When conversion of protons and neutrons ceases, n_n/n_p ratio =0.22.

🟢🔴🔴🔴🔴🔴

Neutrons decay with half-life 10.3 minutes … $n \rightarrow p + e^- + \text{anti-}\nu_e$

Now we wait for the Universe to cool down some more …
tick, tock, tick, tock, …
for about 4 minutes …
during which time n_n/n_p runs down to about 0.16

🟢🔴🔴🔴🔴🔴🔴

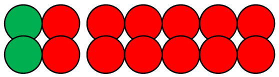
Carroll & Ostlie, An Introduction to Modern Astrophysics, 1996, §28.1

Big Bang nucleosynthesis

At $t \sim 230$ s and $T \sim 10^9$ K ($kT \sim 0.1$ MeV),
first compound nucleus can form and *survive*:

$p + n \rightarrow d + \gamma$ d = ^{2}H

Binding energy of d (deuteron) is 2.2 MeV.



Successive reactions form ^{3}He, ^{4}He and ^{7}Li:

e.g. $d + n \rightarrow t + \gamma$ $d + p \rightarrow {}^3He + \gamma$
$d + d \rightarrow t + p$ $d + d \rightarrow {}^3He + n$
$t + p \rightarrow {}^4He + \gamma$ ${}^3He + n \rightarrow {}^4He + \gamma$
$t + d \rightarrow {}^4He + n$ ${}^3He + d \rightarrow {}^4He + p$
plus ${}^4He + t \rightarrow {}^7Li + \gamma$ ${}^3He + {}^4He \rightarrow {}^7Be + \gamma$
${}^7Be + n \rightarrow {}^7Li + p$ ${}^7Be + e^- \rightarrow {}^7Li + \nu_e$

At $t \sim 20$ minutes, BBN ends:
density too low,
too cool (particle energies too low to tunnel through Coulomb barrier),
too few neutrons to have further nucleosynthesis.

Carroll & Ostlie, An Introduction to Modern Astrophysics, 1996, §28.1
Nollett 2008, Physics World, Testing the elements of the Big Bang, p. 20-26
Jones & Lambourne 2004, An Intro to Galaxies and Cosmology, §6.4.1 (CUP/OU)

Big Bang nucleosynthesis

Big Bang nucleosynthesis (BBN)
Why doesn't $p + n \rightarrow d + \gamma$ d = ^{2}H
proceed earlier at $t < 230$ s and $T > 10^9$ K ($kT > 0.1$ MeV),
since binding energy of d (deuteron) is 2.2 MeV?

Photons outnumber baryons ~ 10^9:1
so even when the "typical" photon energy is less than 2.2 MeV,
there are still more than enough 2.2 MeV photons to dissociate the d's.

Fraction of photons with $E > 2.2$ MeV falls below 10^{-9} only once $T < 10^9$ K
At higher T, energetic and abundant photons dissociate d's

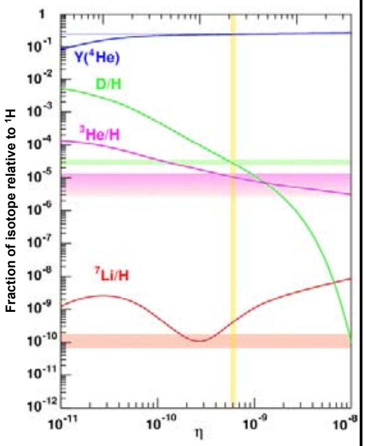
Carroll & Ostlie, An Introduction to Modern Astrophysics, 1996, §28.1
Jones & Lambourne 2004, An Intro to Galaxies and Cosmology, §6.4.1 (CUP/OU)

Big Bang nucleosynthesis

Big Bang nucleosynthesis (BBN)
Production of ^{2}H, ^{3}He, ^{4}He and ^{7}Li calculated as a function of the baryon to photon ratio, η.

Treat η as a (the) free parameter in BBN.
Obtain reasonable consensus between ^{2}H, ^{4}He and ^{7}Li and a small range of values of η.
Note, however, that ^{4}He is not a very sensitive test!

Since 2003, observations of the angular power spectrum of the cosmic microwave background radiation provide a better measure of η.



http://www.einstein-online.info/en/spotlights/BBN/index.html, citing E. Vangioni-Flam

Cosmic microwave background radiation

Recombination
After t ~ 400 000 yrs, T ~ 4000 K, kT ~ few eV
kT comparable to the ionisation energy of hydrogen (13.6 eV)
(Recall: H is dominant product of BBN).

p's and (free) e^-'s can combine to form neutral H atoms

This epoch is called recombination.

Before recombination, Universe was largely opaque to photons due to the high opacity of free electrons, which scatter photons.
[electron scattering; Thomson scattering]

After recombination, Universe becomes much more transparent as few free electrons remain.

Cosmic microwave background radiation

Cosmic microwave background radiation

Recombination

→ more transparent Universe
→ matter and radiation no longer interact closely
→ temperature of matter and temperature of radiation evolve separately

Photons which existed as the Universe became transparent then continued to travel through the Universe, little affected by matter.

However, increasing scale factor of Universe, R, results in these old photons being stretched over time: $\lambda_t/\lambda_0 = R_t/R_0$

$E = h\nu = hc/\lambda \sim 2.7kT$, **so** $T \propto 1/\lambda \propto 1/R$ **, i.e.** $T_0 = T \times R/R_0$

Recombination led to prediction that redshifted radiation would be observable with $T_0 \sim 5$K **[Alpher & Herman 1948]**

Carroll & Ostlie 1996, Intro to Modern Astrophysics, §27.2
Phillips, A. 1999, The Physics of Stars, §2.3

Cosmic microwave background radiation

Detection

Recombination led to prediction that redshifted radiation would be observable with $T_0 \sim 5$K **[Alpher & Herman 1948]**

10K radiation independently predicted by Dicke & Peebles (1964).

5-10 K corresponds to microwave region of electromagnetic spectrum

Wein's law: $\lambda_{peak} T = 2.9$ **mm K**

so for $T = 5$-10 K, $\lambda_{peak} = 0.3$-0.6 **mm**

Penzias & Wilson detected it as an unexpected microwave noise source, essentially uniform across the sky, with a temperature of 2.7 K.

Carroll & Ostlie, An Introduction to Modern Astrophysics, 1996, §28.1
Jones & Lambourne 2004, An Intro to Galaxies and Cosmology, §6.5 (CUP/OU)
http://www.bell-labs.com/project/feature/archives/cosmology/

Cosmic microwave background radiation

Uniform to better than 1 part in 10^5.

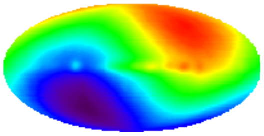
All sky map

Range 0 K to 4 K

Implications

Highly uniform microwave background radiation is consistent only with the epoch of recombination when the Universe became transparent at a high temperature, and redshifted the radiation via expansion.

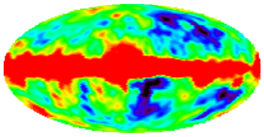
Range 2.721-2.729 K



Shows dipole anisotropy due to motion of Earth ***through*** space relative to the rest frame (not origin) of the expansion ***of*** space

With dipole anisoptropy removed

Range 0.2 mK



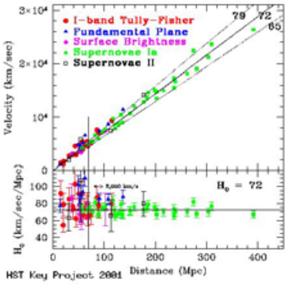
finer structure emerges.

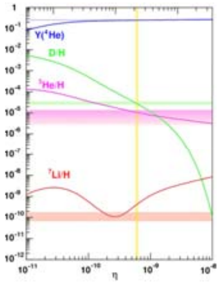
http://map.gsfc.nasa.gov/m_uni/uni_101Flucts.html

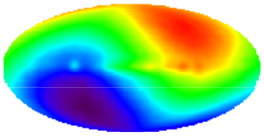
The three pillars of the Big Bang theory

The three observational pillars of the big bang theory are, therefore:

- The measured expansion of the Universe (redshift of Galaxies);
- The agreement of observed and calculated fractions of ^{2}H, ^{4}He and ^{7}Li;
- The detection of an almost uniform microwave background radiation.







Carroll & Ostlie, An Introduction to Modern Astrophysics, 1996, §28.1
Jones & Lambourne 2004, An Intro to Galaxies and Cosmology, §6.5 (CUP/OU)

The three pillars of the Big Bang theory

Implications

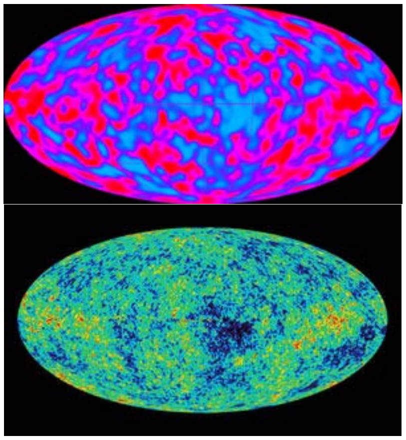
Study of CMBR non-uniformities is of major importance.

Two competing effects produce acoustic oscillations:

- **Pressure of photons on matter, which tends to smooth out the distribution of matter**
- **Gravity, which tends to make matter clump**

This produces structure in the temperature maps.

COBE and WMAP maps



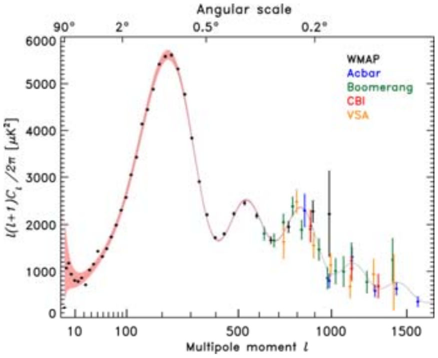
http://en.wikipedia.org/wiki/COBE

The three pillars of the Big Bang theory

Implications of acoustic oscillations

Useful to measure the angular power spectrum of temperature fluctuations.

Structure which is due to acoustic oscillations affects ratio of second peak to first peak, provides a precise measurement of the baryon density of the Universe, Ω_B.
$\Omega_B h^2 = 0.0224 \pm 0.0009$
[Spergel et al. 2003]



Baryon density Ω_B translates into baryon-to-photon ratio η, which *previously* was the *free* parameter in BBN.

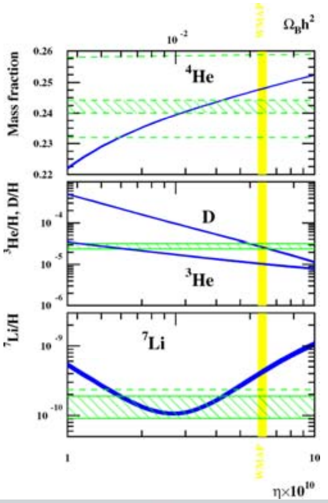
http://en.wikipedia.org/wiki/Cosmic_Microwave_Background_Radiation#Primary_anisotropy

Updating BBN

Big Bang nucleosynthesis (BBN)
WMAP observations of the angular power spectrum of the cosmic microwave background radiation show excellent agreement with amount of ^{2}H from observations,
but rather less good agreement with ^{4}He or ^{7}Li.

Currently unclear whether the small discrepancy is because:

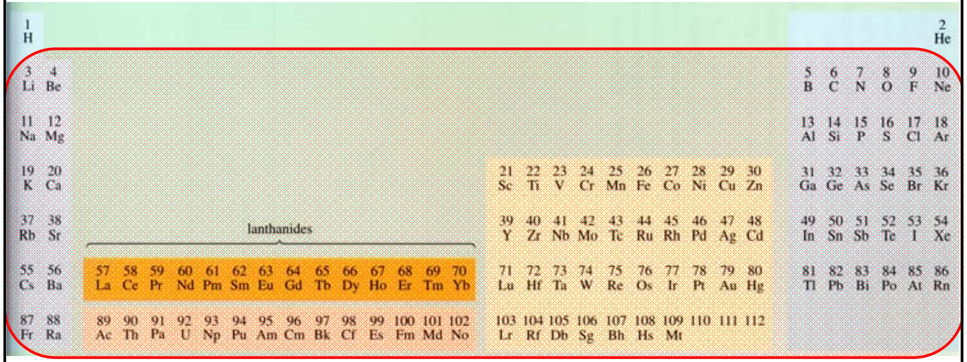
- measured abundances of light isotopes are imperfect, or
- BBN is set to reveal more fundamental physics



Coc, A. & Vangioni, E. 2005, IAU Symp. 228, 13

Stellar nucleosynthesis

BBN explains origin of light isotopes ^{1}H, ^{2}H, ^{3}He, ^{4}He and ^{7}Li,
but not the ~100 other elements and their ~280 stable isotopes.



1 H																															2 He
3 Li	4 Be																									5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg																									13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca															21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr	lanthanides														39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba	57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra	89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110	111	112						

To continue nucleosynthesis beyond He and Li, need some way to bridge the lack of stable isotopes at mass 5 and 8.

Stellar nucleosynthesis

<u>Lack of stable isotopes at mass 5 and 8.</u>

Dominant isotopes are ^1H and ^4He, but …

hypothetical combination $^1H + ^4He$ leads to mass 5, which is unstable;
hypothetical combination $^4He + ^4He$ leads to mass 8, which is unstable.

The solution was identified as the triple alpha-process,
occurring in evolved stars,
… but first need to see why stars are good sites for fusion.

Q: What makes stars hot?

Stellar nucleosynthesis

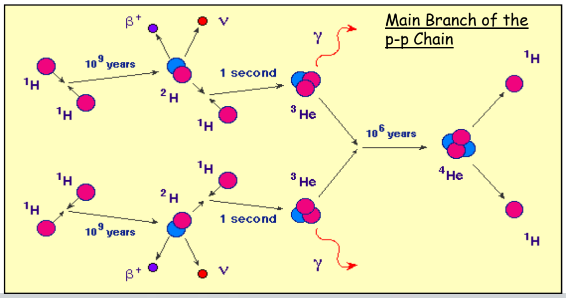
Q:	**What makes stars hot?**
A:	**Gravity (not fusion)**

Sun (and other main sequence dwarf stars) convert ^1H to ^4He via process called proton-proton (pp) chain.

Process not identical to production of ^4He from ^1H in BBN.
Comes in three sequences ("branches").

Branch I of PP chain:

$^1H + ^1H \rightarrow ^2H + e^+ + \nu_e$ ×2
$e^+ + e^- \rightarrow \gamma_{ee} + \gamma_{ee}$ ×2
$^1H + ^2H \rightarrow ^3He + \gamma_{pd}$ ×2
$^3He + ^3He \rightarrow ^4He + 2^1H$



Stellar nucleosynthesis

Net result of branch I of pp chain is conversion of $4\,{}^{1}\mathrm{H}$ and $2e^{-}$ into ${}^{4}\mathrm{He}$.

${}^{4}\mathrm{He}$ nucleus mass < mass of 4 protons and 2 electrons,
so net effect is the conversion of nuclear mass (energy) into
the kinetic energy of the reaction products,
and gamma rays which are quickly absorbed by the stellar matter.

Mass defect
(i.e. the difference in mass between reactants and products)
and equivalent energy *Q* that is released
can be calculated for each reaction.

Stellar nucleosynthesis

Overall: $4p + 2e^{-} \rightarrow {}^{4}\mathrm{He} + 2\nu_e + 6\gamma$

Mass defect $= [4\times1.00728 + 2\times0.00055 - (4.00260 - 2\times0.00055)]$ amu
$= 0.02872$ amu

$$
\begin{aligned}
Q &= mc^2 \\
&= 0.02872 \text{ amu} \times 1.661\times10^{-27} \text{ kg amu}^{-1} \times (2.998\times10^{8} \text{ m s}^{-1})^2 \\
&= 4.288\times10^{-12} \text{ J} \\
&= 26.76 \text{ MeV}
\end{aligned}
$$

This energy is released into the star,
except for the escape of some energy carried away by neutrinos.

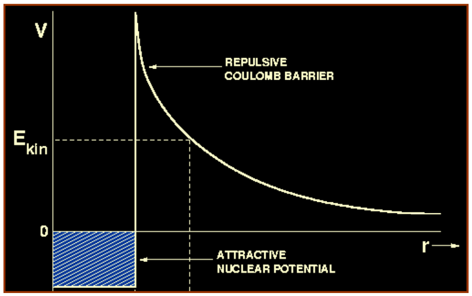
This energy is just enough to replenish energy radiated from the star's surface… structure of star adjusts to keep this balance.

Such fusion reactions happen because the star is hot, not vice versa.

Stellar nucleosynthesis

For two nuclei to fuse, they must be brought close enough for attractive strong nuclear force to bind nucleons together.

Range of strong force is only ~ 10^{-15} m, i.e. ~ 1 fm, so two nuclei must be brought to within this distance.



However, at such small separations, electrostatic repulsion (Coulomb barriers) is very high.

Hence particles need high kinetic energies (high temperatures) in order to fuse.
Even then, they don't overcome the Coulomb barrier, they quantum tunnel through it.

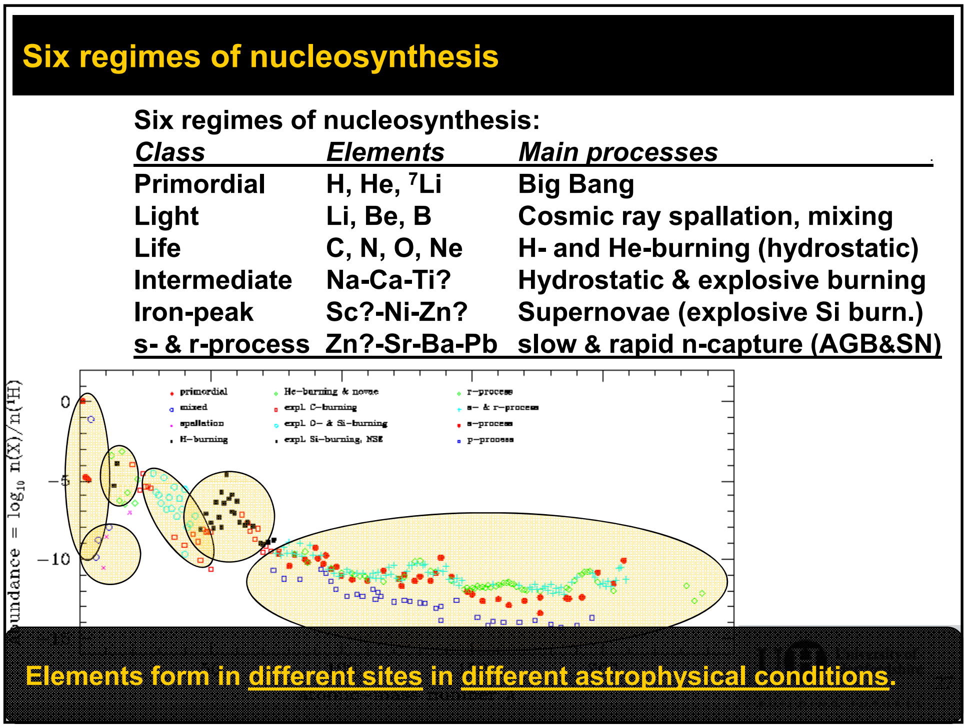
Stellar nucleosynthesis

Probability of tunnelling though Coulomb barrier depends on ratio of particle kinetic energy *E* to the potential energy (height) of the Coulomb barrier, which depends on atomic number *Z*.

If nuclei with higher atomic number (high *Z*) are to be fused, then higher particle energies *E* (and hence higher temperatures *T*) are required.

For this reason, ^{4}He nuclei will not fuse at the temperatures required to fuse ^{1}H.

Fusion in stars therefore proceeds in stages, always beginning with the lowest atomic numbers (H) and working progressively to higher atomic numbers, but only if sufficiently high temperatures are attained.



Six regimes of nucleosynthesis

Six regimes of nucleosynthesis:

Class	*Elements*	*Main processes*
Primordial	H, He, ^{7}Li	Big Bang
Light	Li, Be, B	Cosmic ray spallation, mixing
Life	C, N, O, Ne	H- and He-burning (hydrostatic)
Intermediate	Na-Ca-Ti?	Hydrostatic & explosive burning
Iron-peak	Sc?-Ni-Zn?	Supernovae (explosive Si burn.)
s- & r-process	Zn?-Sr-Ba-Pb	slow & rapid n-capture (AGB&SN)

Elements form in <u>different sites</u> in <u>different astrophysical conditions</u>.