Nucleosynthesis in Explosive Astrophysical Sites

Lecture 1

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Opening paragraph in the astrophysics section of NuPECC LRP

From the first few seconds of the Big Bang which created the seed material for our universe, through to the present energy generation in our Sun which keeps us alive, nuclear physics has shaped the evolution of the universe and our place in it.

Along the way, nuclear reactions have controlled the evolution and death of stars forming the most compact objects in the Universe, determined the chemical evolution of galaxies and produced the elements from which we ourselves are built.

Our understanding of this complex evolution has developed as a result of nuclear physicists working closely with cosmologists, astrophysicists and astronomers in a hugely productive collaborative effort to understand the development of the universe and our place in it.

What is nuclear astrophysics and how do nuclear physicicists contribute?

The aim of nuclear astrophysics is to:

Identify and study the nuclear reactions that occur in stars and other astrophysical sites

Understand how these give rise to the energy generation which powers these objects

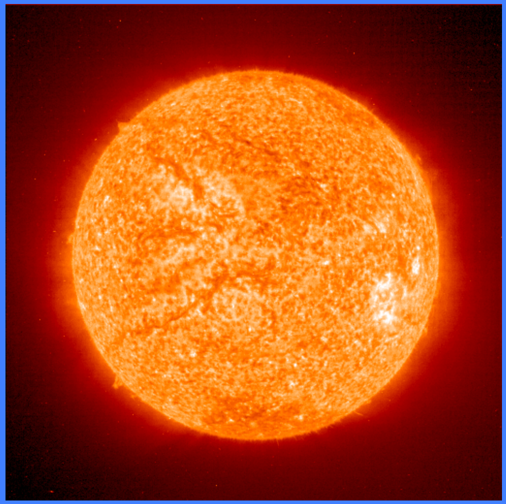
Understand how these processes lead to the abundances of the elements that we see around us

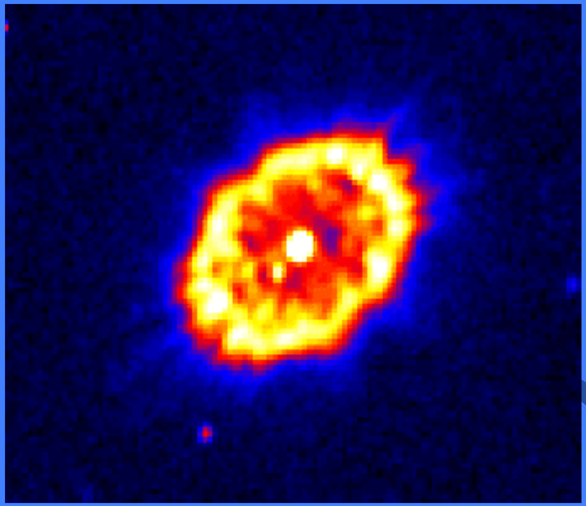
This effort requires an effective collaboration between different scientific fields

Astronomers
Observe astrophysical sites and measure energy output and element abundances

Astrophysicists
Develop models of the sites in terms of the material dynamics and nuclear reactions

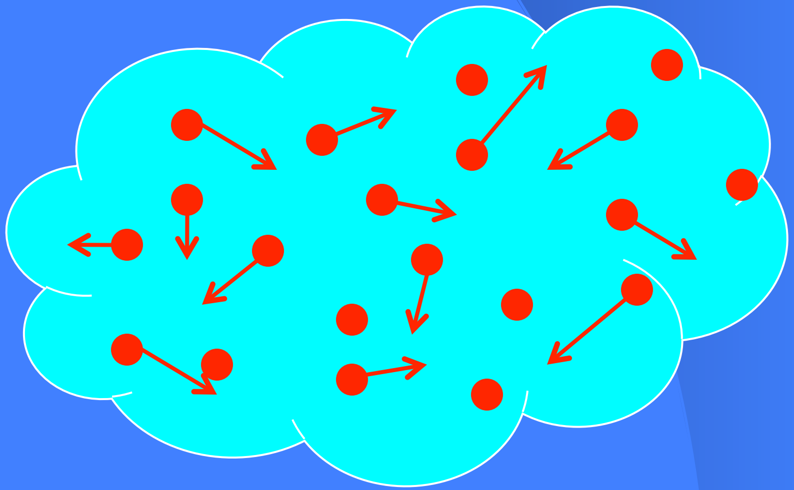
Nuclear Physicists
Measure (experimentalists) or calculate (theorists) the necessary reaction rates or decay rates





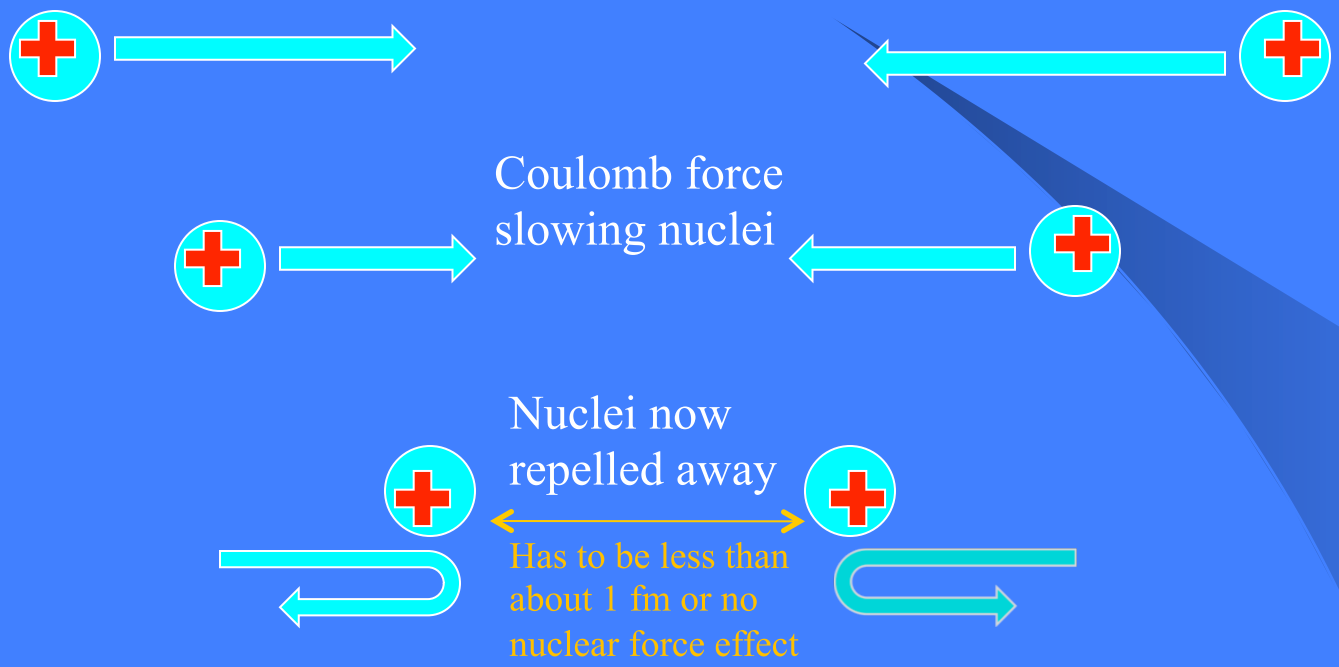
Any astrophysical site contains a hot, gaseous mix

In this the nuclei are moving with a spread of velocities (energies) and continually colliding (billions of times per second).



So why don't we get nuclear reactions happening all the time?

Because even though the temperatures seem very hot (10^7-10^9K), the velocities (and so kinetic energy) of the nuclei are still fairly low ($E = kT$)



Only the very fastest collisions are energetic enough to overcome the Coulomb repulsion so that the nuclei get close enough for nuclear reactions to occur – these release energy and cause new elements to be created

You will do a calculation during the break to show this

How could we model this?

Assume a mix of different nuclei (from spectroscopic measurements)

Assume a distribution of energies (Maxwell-Boltzmann)

Carry out nuclear physics experiments to measure the reaction probability (cross section) at all energies for all nuclei

Fold these distributions to get the average reaction rate

Set up a set of coupled equations which track how the number of each type of nuclei changes as the reactions occur and which also determine the rate at which energy is released in these nuclear reactions.

Simple example

Start with large gas of N_p hydrogen nuclei at temperature T

Step 1 Calculate how many collisions happen in given time step
Use cross sections to calculate how many reactions occur that produce new nuclei like d
Calculate how much energy is released in these reactions and how much this will heat the gas

Now have a gas of N_p hydrogen nuclei and N_d deuterium nuclei and higher temperature

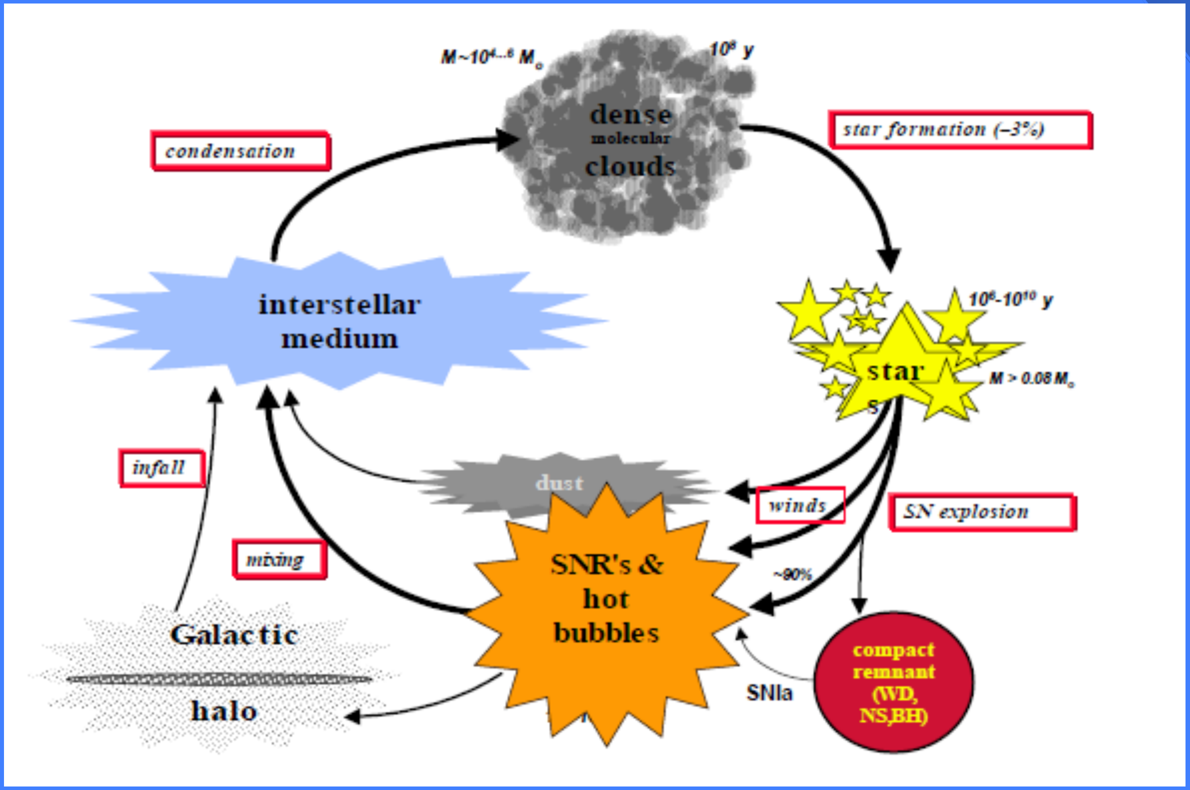
Step 2 Calculate how many collisions happen in given time step
Use cross sections to calculate how many reactions occur that produce new nuclei like d, t, ^{3}He and ^{4}He
Calculate how much energy is released in these reactions and how much this will heat the gas

And keep repeating.......

So as time goes on, heavier and heavier nuclei are elements are created in a star

Stars that have reached the end of their lives often explode, which blows these newly created heavy elements out into the universe

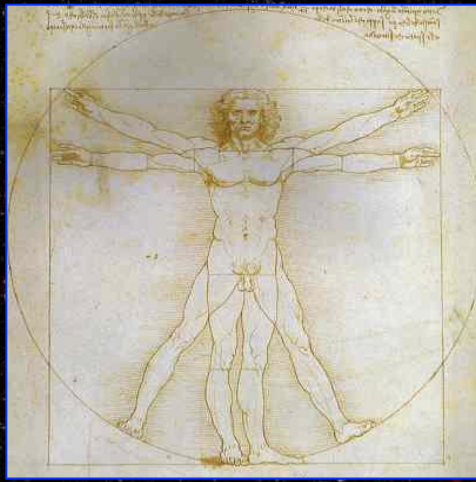
These get collected into the next generation of stars that form and so over time the universe gets enriched in heavy elements

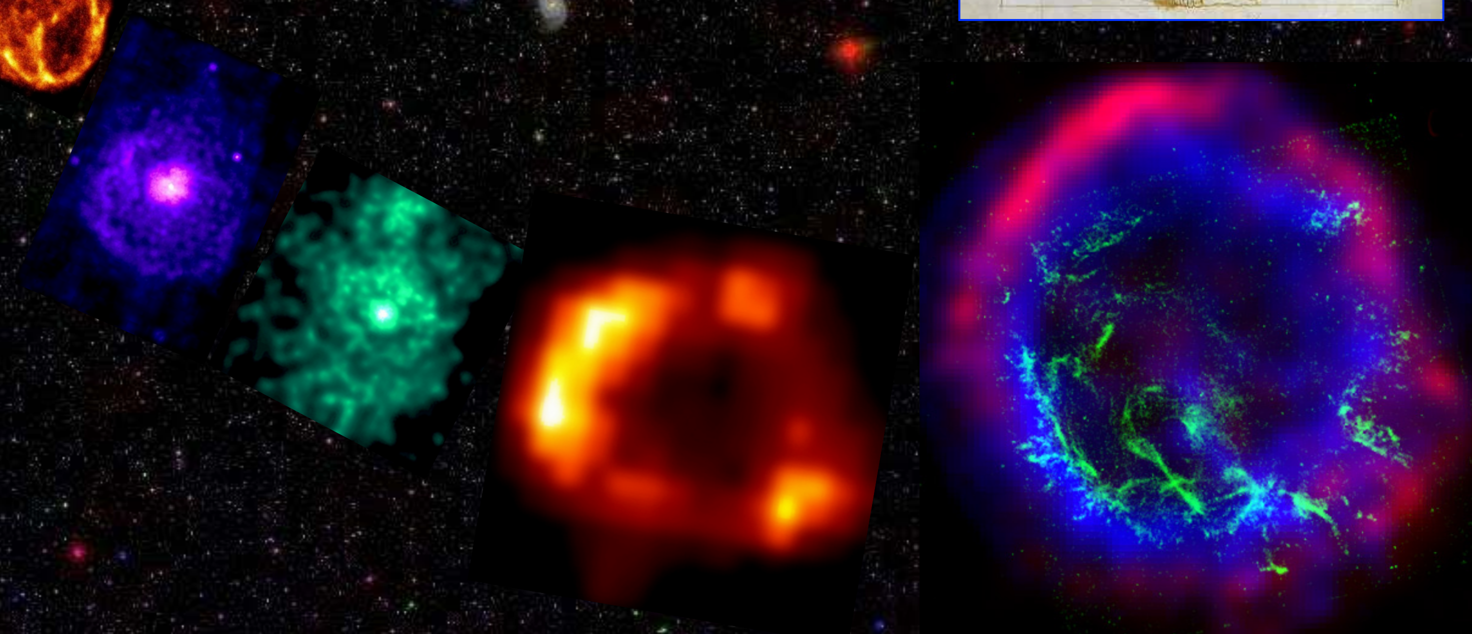


Each heavy atom in our body was build and processed through ~100-1000 star generations since the initial Big Bang event!

We are made of star stuff

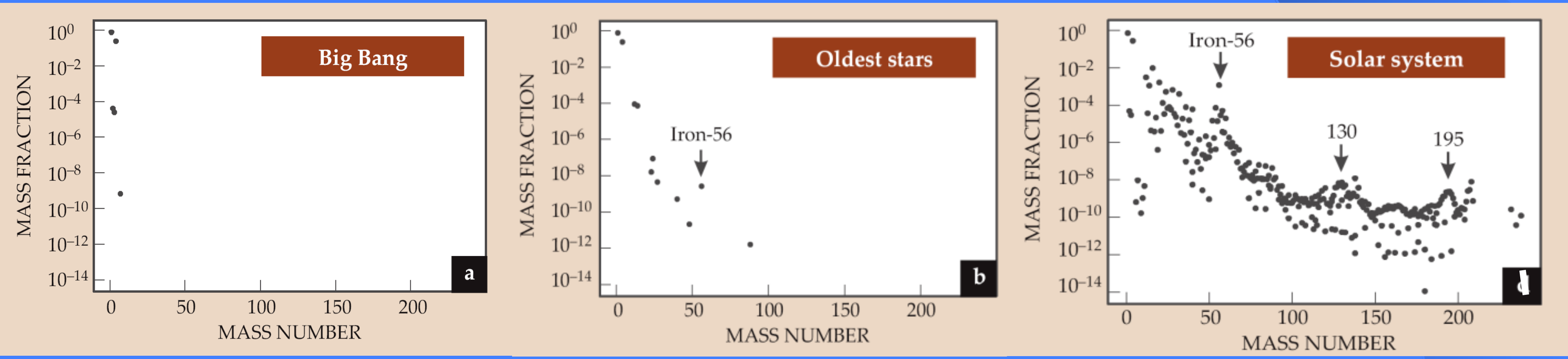
Carl Sagan



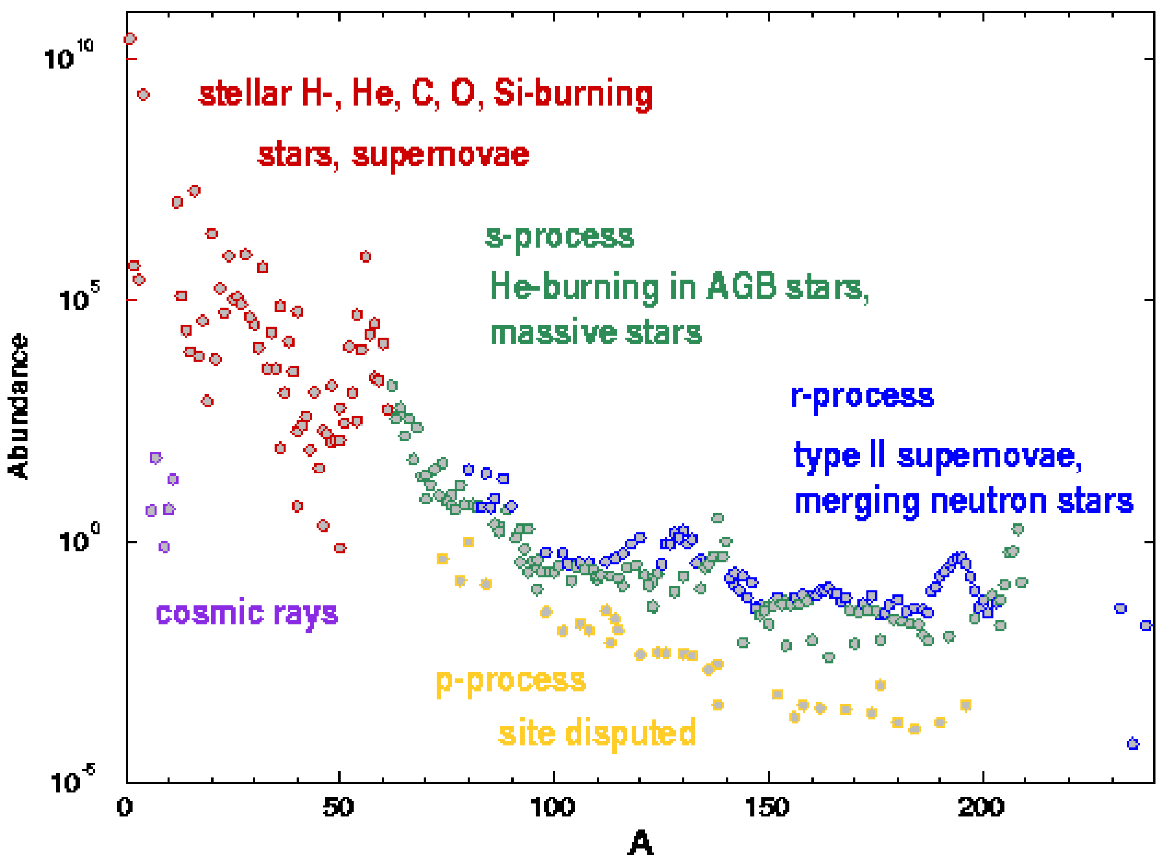


THE CHEMICAL EVOLUTION OF THE UNIVERSE

The Big Bang created a universe filled with Hydrogen and Helium – a fairly boring place and one not conducive to life. Over the last 13-14 Billion years, different types of nucleosynthesis in various astrophysical sites has transformed that primordial H and He to create the heavier elements

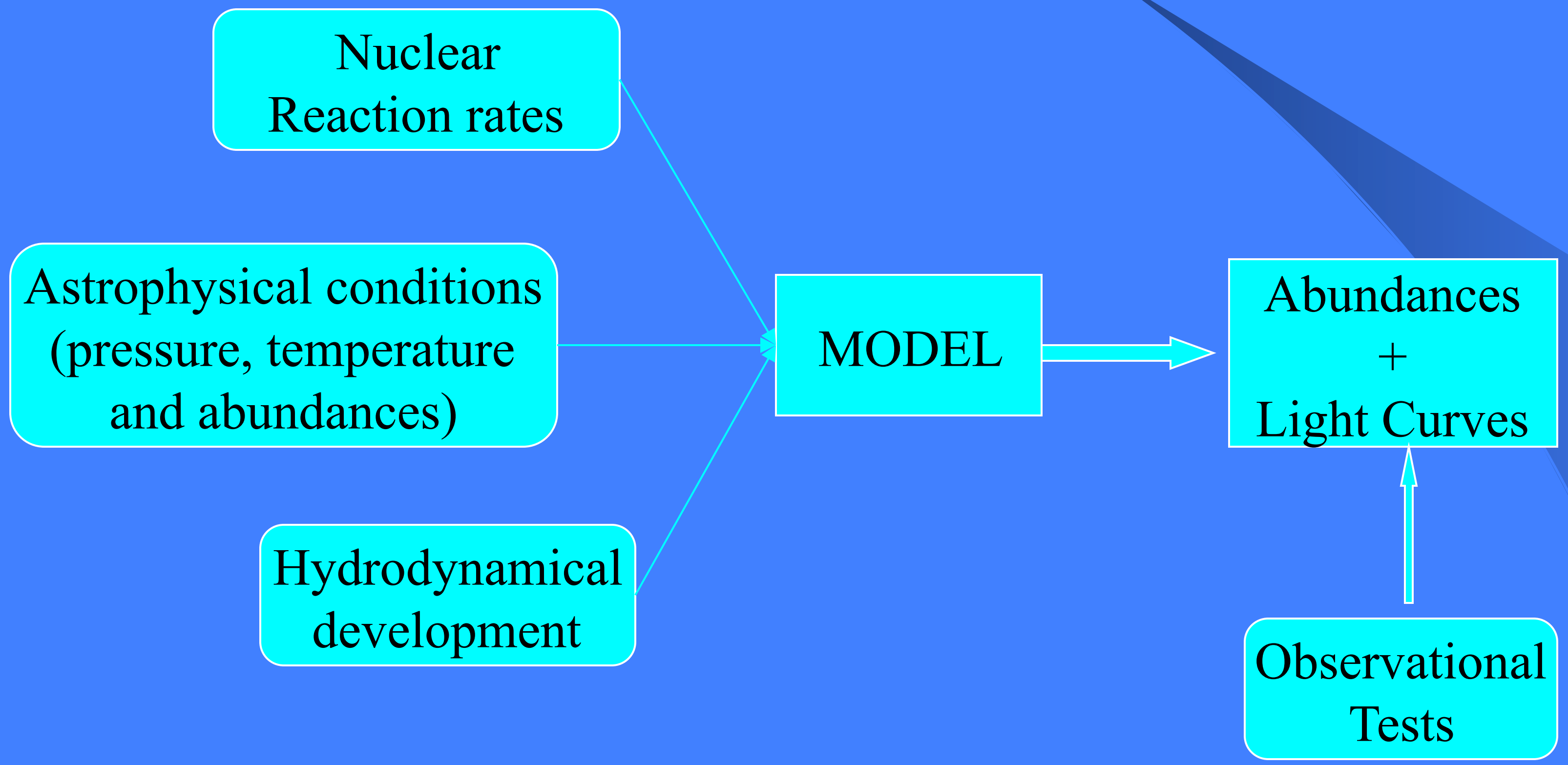


The different elements are formed in different classes on nucleosynthesis which occur in different astrophysical sites



Big Bang Nucleosynthesis (H, He and small amounts of Li,Be)
Nucleosynthesis in stars (Nuclei up to Fe and about half of heavier elements)
Explosive nucleosynthesis (the rest of the heavy elements)
(Novae, X-ray Bursters, Supernovae...)

Modelling nucleosynthesis in a start (or other astrophysical site)

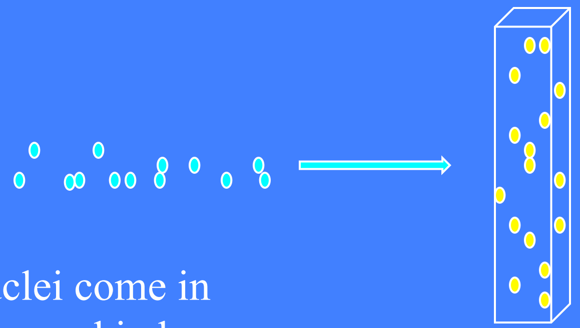


Measuring the reaction rate

If nucleus A collides with nucleus B, what is the probability that a nuclear reaction will occur and produce a new nucleus?

The convention is to quote this reaction probability not as a probability, but as a cross section – no new physics here, just a different definition.

Why confuse things in this way? Partly historical, but partly because it helps use picture the collisions using classical ideas that our brains can understand



N_B nuclei come in per second in beam

N_T nuclei per unit area in target

If each target nucleus "looks like" it has a cross sectional area σ, then

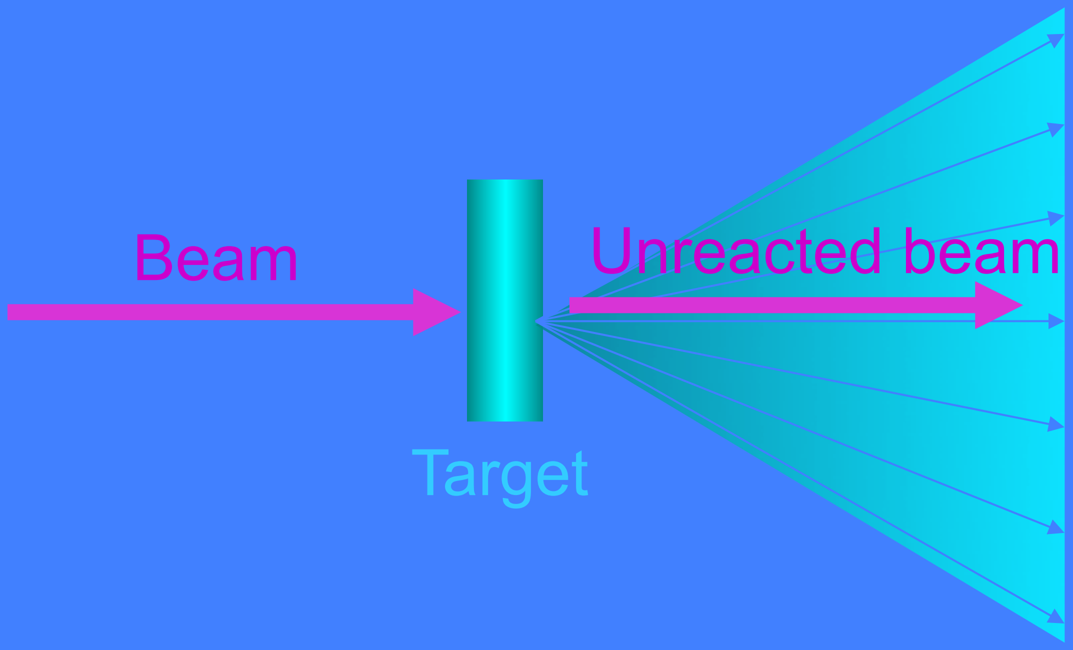
Probability of reaction

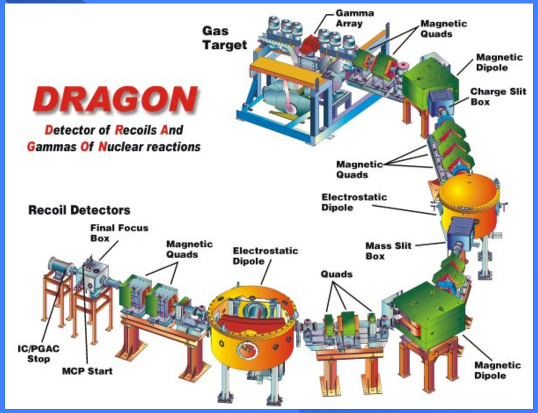
$\propto N_B$

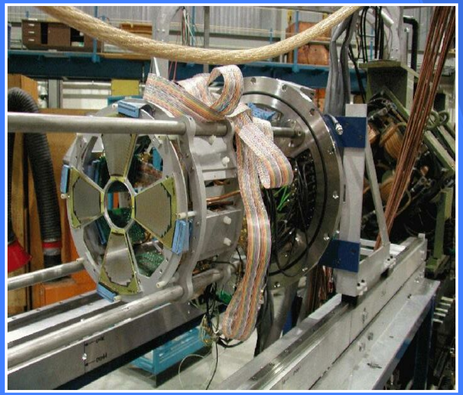
$\propto N_T$

$\propto \sigma$

Measuring the cross section



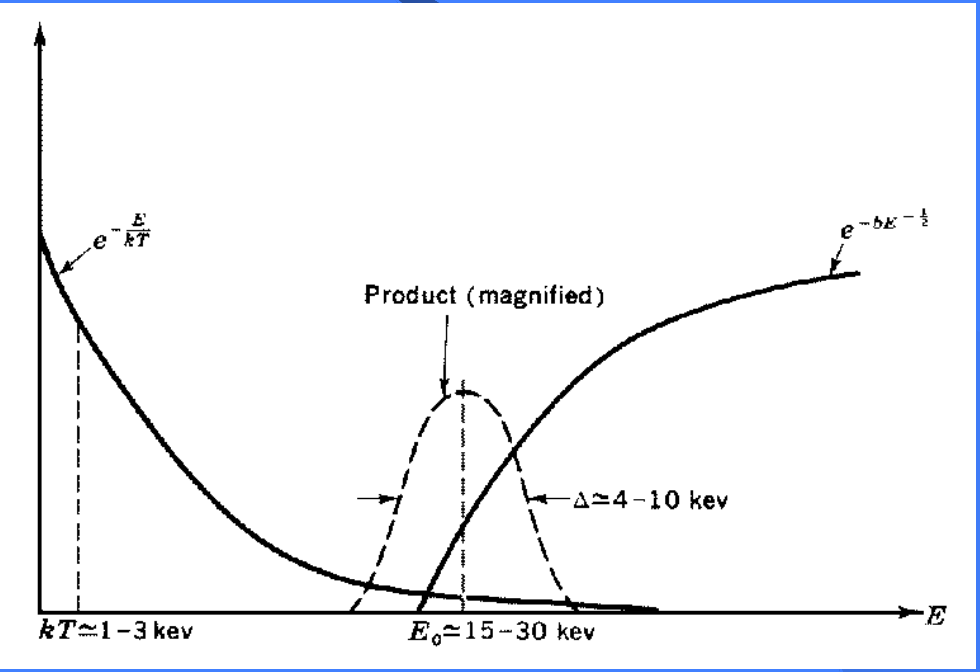




Know number of beam particles
Know number of target nuclei
Measure number of nuclei created
Probability > Cross section

Fortunately we don't have to measure the cross section at all energies

The combination of the falling number of particles at high energy (tail of Maxwell Boltzmann) with the low probability of penetrating the Coulomb barrier means the bulk of reactions occur in a narrow range of energies

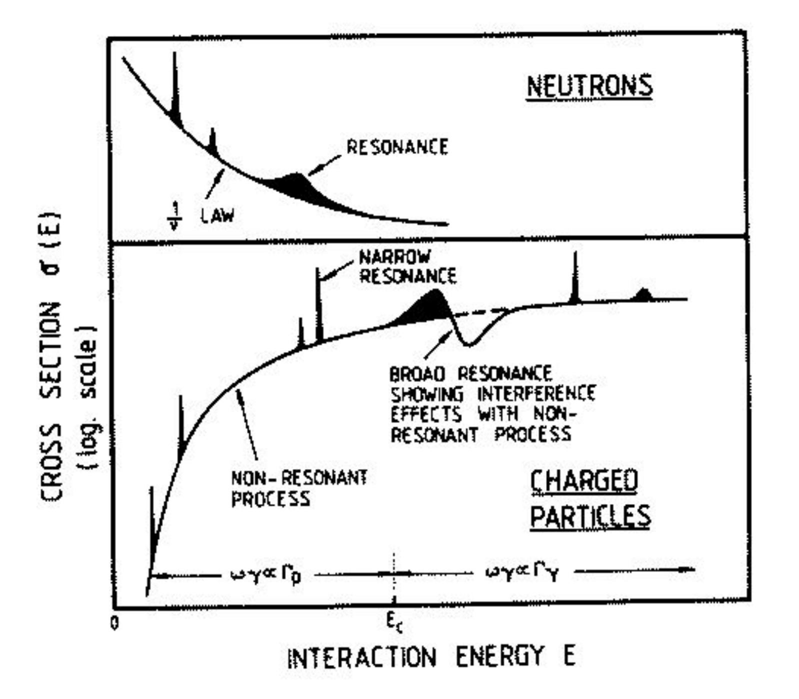


Gammow Window

However we have to be careful as Nature can be cunning

As well as direct reactions, there can be resonant reactions if the collision energy matches that needed to excite a state in one of the nuclei.

In this case the cross section is greatly enhanced



There are basically three “classes” of nucleosynthesis

Nucleosynthesis in the Big Bang

Nucleosynthesis in stars

Nucleosynthesis in explosive sites (Novae, X-ray Bursters, SN etc)

Nucleosynthesis in the Big Bang

Fairly "textbook" stuff

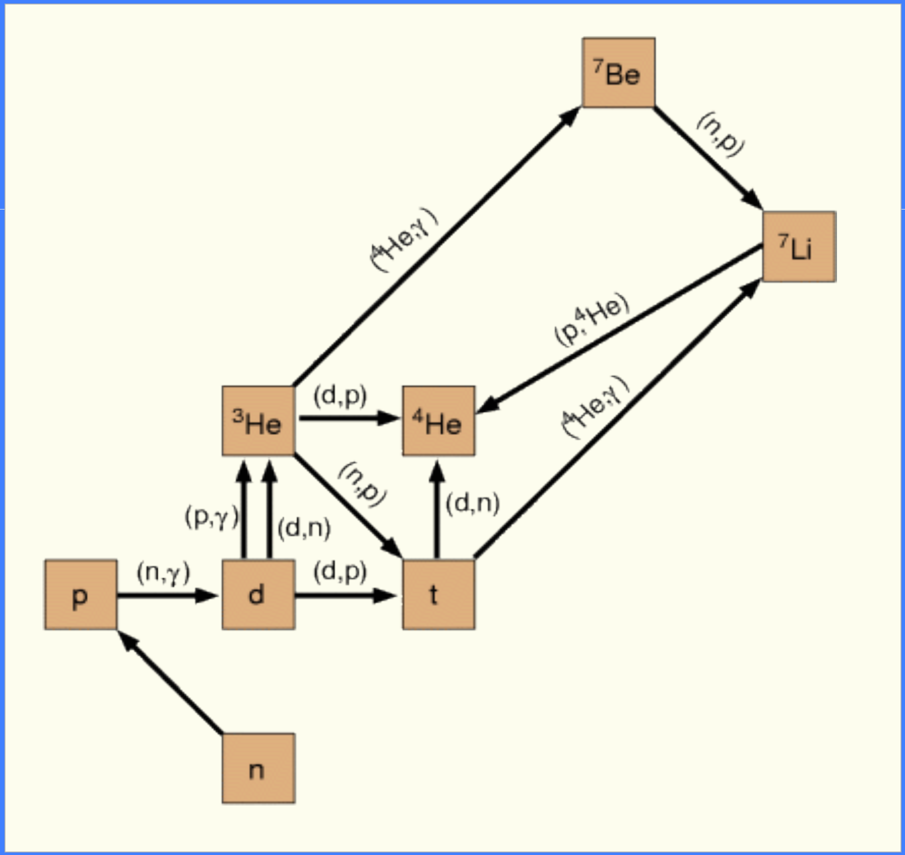
Few, light nuclei (p, d, t, ^{3}He, α) involved

High(!) temperature so energies well above barrier and so cross sections large

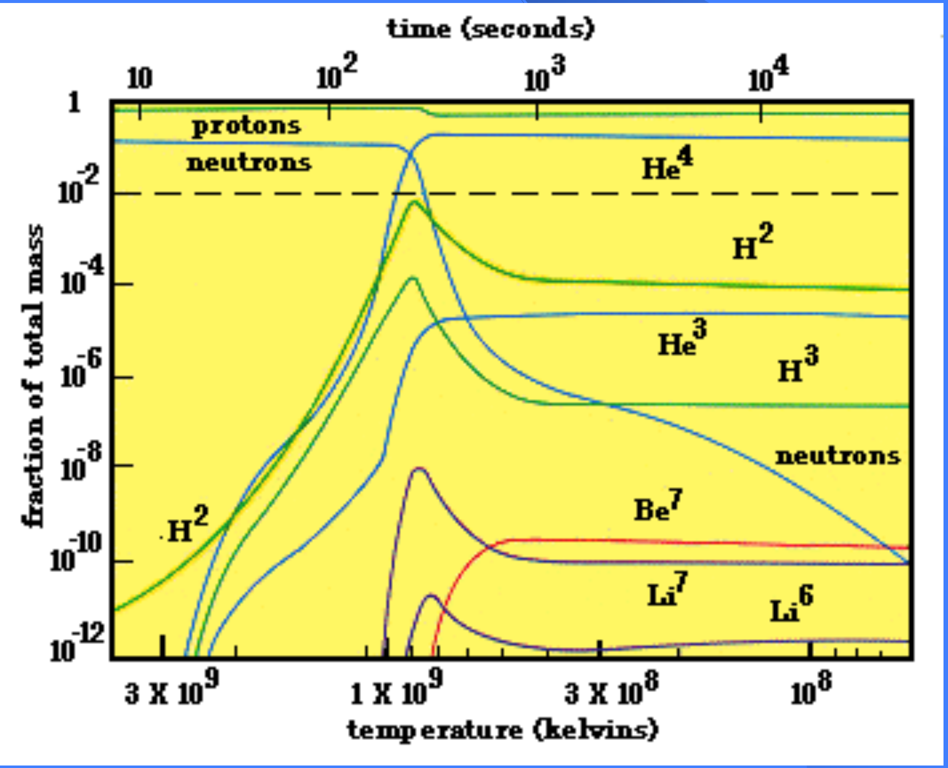
$$p + n \longleftrightarrow d + \gamma$$

$$d + n \longrightarrow H^3 + \gamma$$
$$H^3 + p \longrightarrow He^4 + \gamma$$
$$d + p \longrightarrow He^3 + \gamma$$
$$He^3 + n \longrightarrow He^4 + \gamma$$

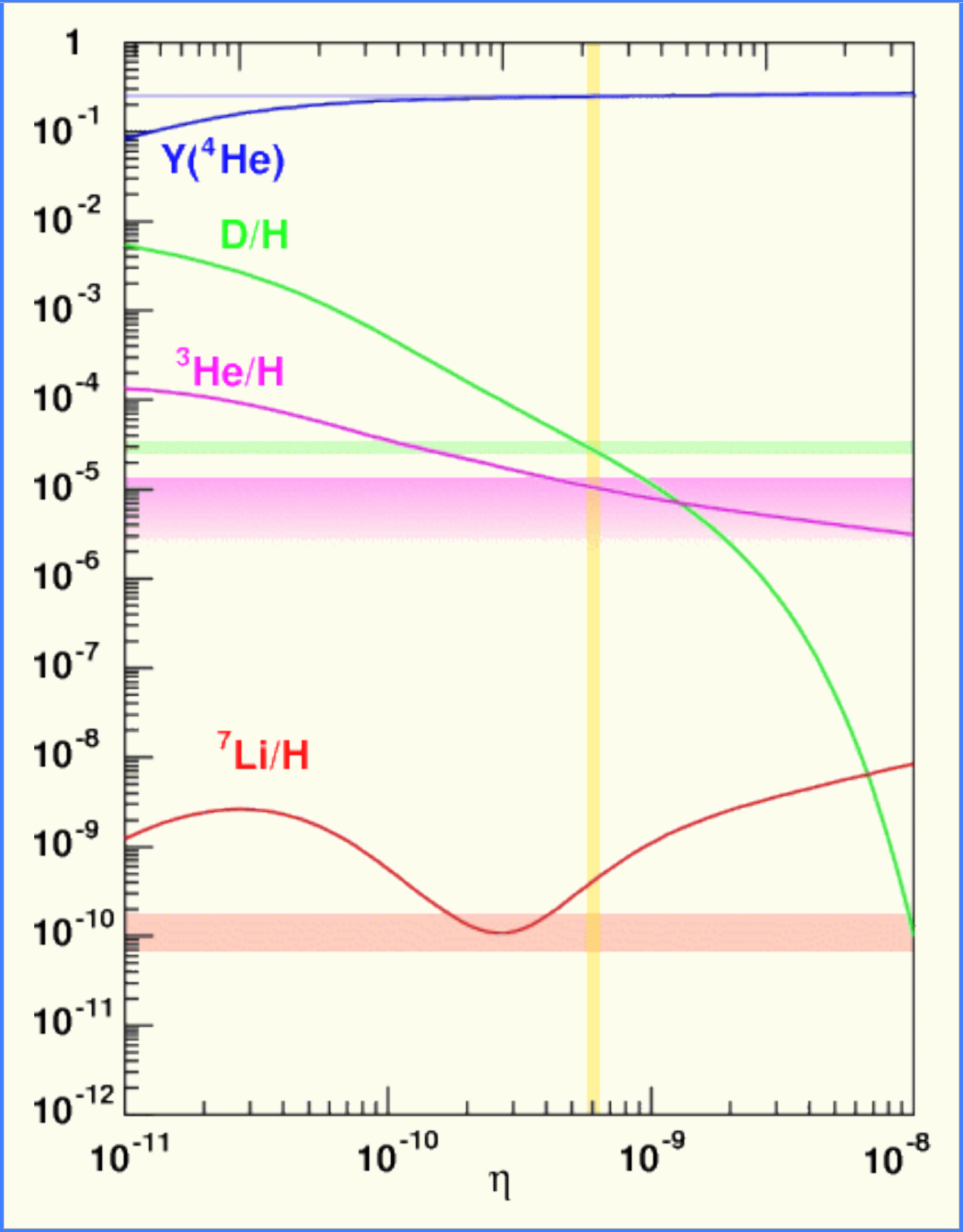
$$d + d \longrightarrow He^3 + n$$
$$d + d \longrightarrow H^3 + p$$
$$H^3 + d \longrightarrow He^4 + n$$
$$He^3 + d \longrightarrow He^4 + p$$



7Be
(n,p)
7Li
(4He,γ)
(p,4He)
3He
(d,p)
4He
(4He,γ)
(n,p)
(p,γ)
(d,n)
(d,n)
p
(n,γ)
d
(d,p)
t
n



time (seconds)
10
10^2
10^3
10^4
1
protons
neutrons
He^4
10^-2
H^2
10^-4
He^3
H^3
10^-6
neutrons
10^-8
Be^7
H^2
10^-10
Li^7
Li^6
10^-12
3 X 10^9
1 X 10^9
3 X 10^8
10^8
temperature (kelvins)
fraction of total mass



Still some discrepancies to track down – the Lithium anomaly

Are these a problem with the reaction cross section measurements (probably not), or do they indicate a problem with the standard model of the BB (maybe) or with the Li astronomy measurements (probably)?

Nothing else on this topic at the workshop, but ask me if you are interested

Nucleosynthesis in stars

A much more complex situation, with many different types of reactions occurring at different stages in the star's lifecycle:

Proton burning (like BB nucleosynthesis)

Helium burning (producing C and O nuclei)

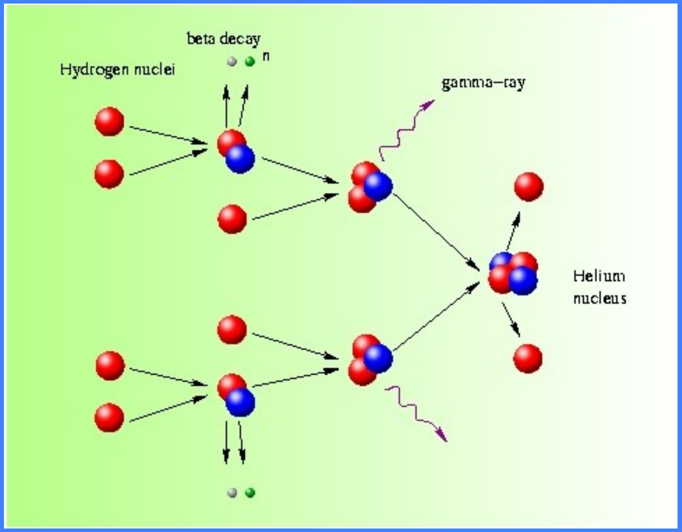
CNO-cycle (catalytic processing of H > He)

Reactions with heavier nuclei (C, O, Ne Mg, Si)

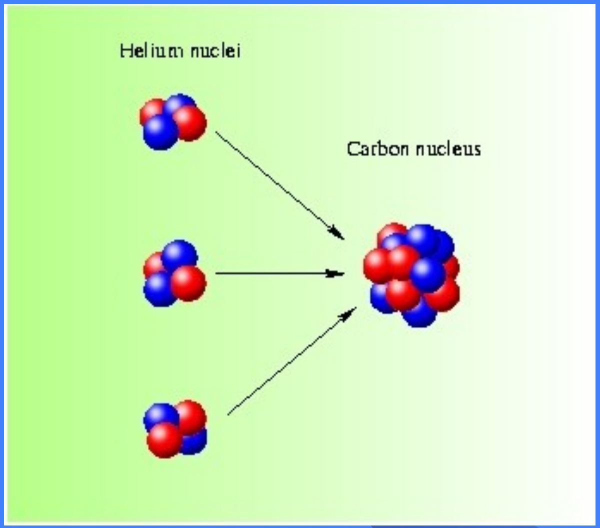
Neutron induced reactions (s-process)

More on these from Professor Iliadis and Professor Gialanella

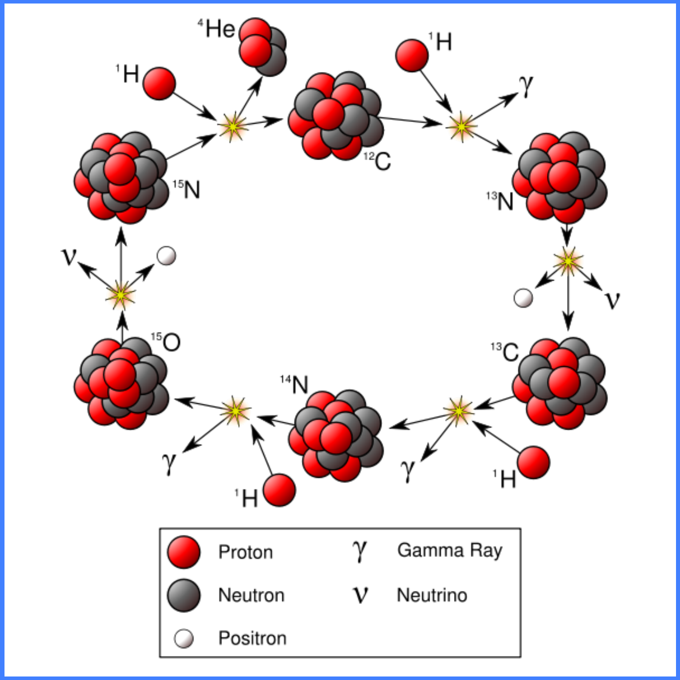
Hydrogen burning

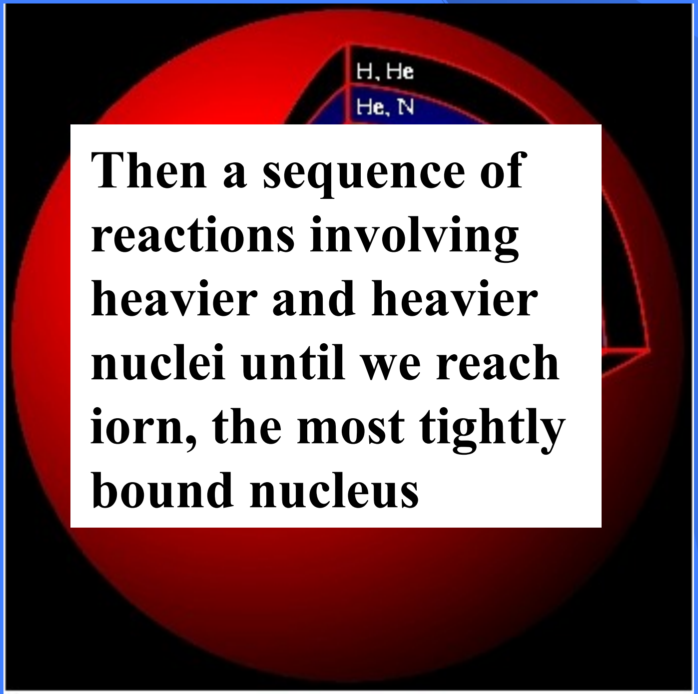


Helium burning



CNO-cycle





Then a sequence of reactions involving heavier and heavier nuclei until we reach iorn, the most tightly bound nucleus

Professor Iliadis will describe each of these in more detail in his lectures

What are the experimental problems?

Firstly, although these are “hot” sites, the energies of the particles are still very low (<< 1 MeV/u) and so well below the Coulomb barrier.

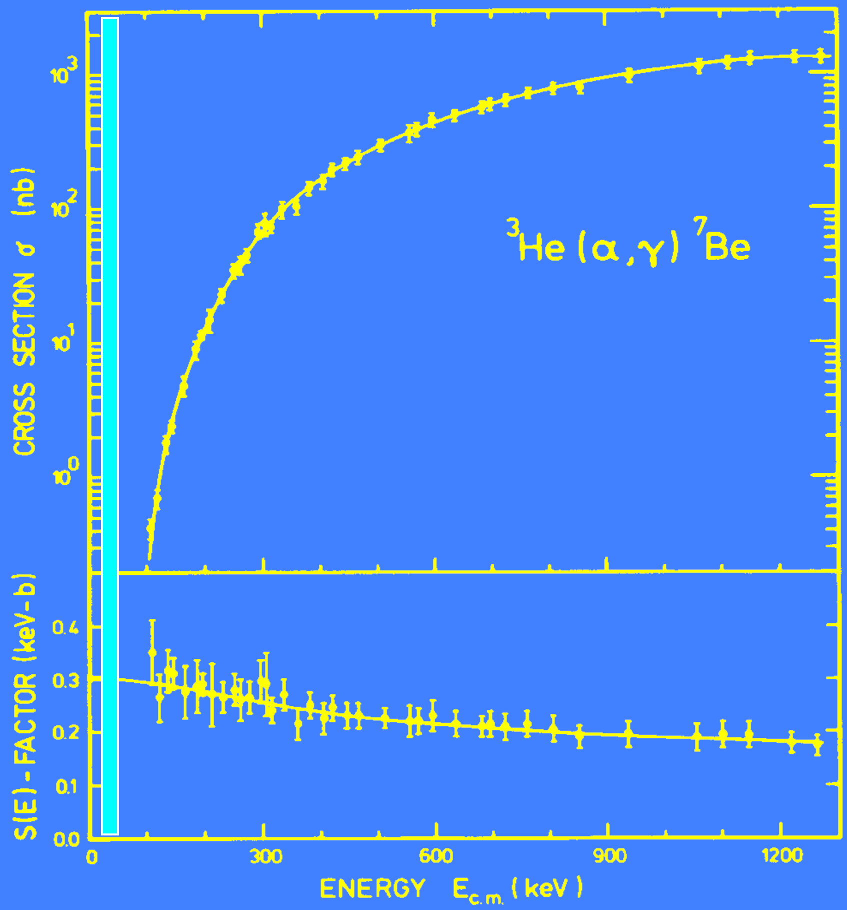
Typical temperatures: T ~10^6-10^8 K ⇒ typical interaction energies: E~10-300 keV (i.e. sub-Coulomb energies)

So the reactions only proceed through quantum mechanical tunnelling and the cross sections are extremely low.

This in turn makes the measurements very long and we run into problems because of background events in the detector systems.

1 event/ 3000 y ⇐ 10^{-18} barn < σ < 10^{-9} barn ⇒ 35 events/h

Often you can't even get close to the Gamow window and have to extrapolate from higher energies



$$\sigma(E) = S(E) \cdot \exp(-2\pi\eta)/E$$

$$S(E) = E \cdot \sigma(E) \cdot \exp(2\pi\eta)$$

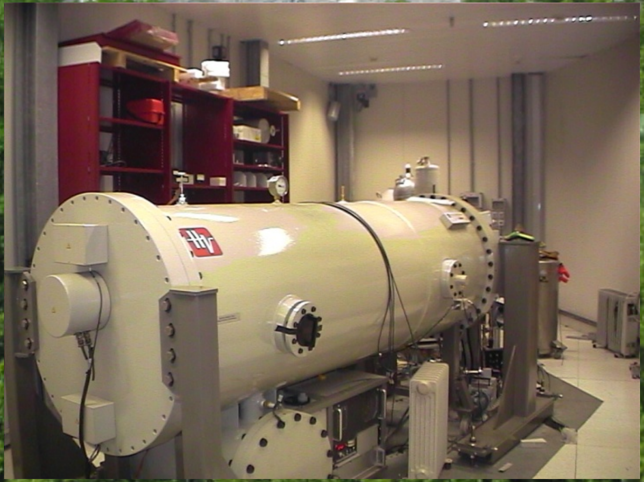
$$2\pi\eta = 31.29\, Z_1 Z_2 (\mu/E)^{0.5}$$

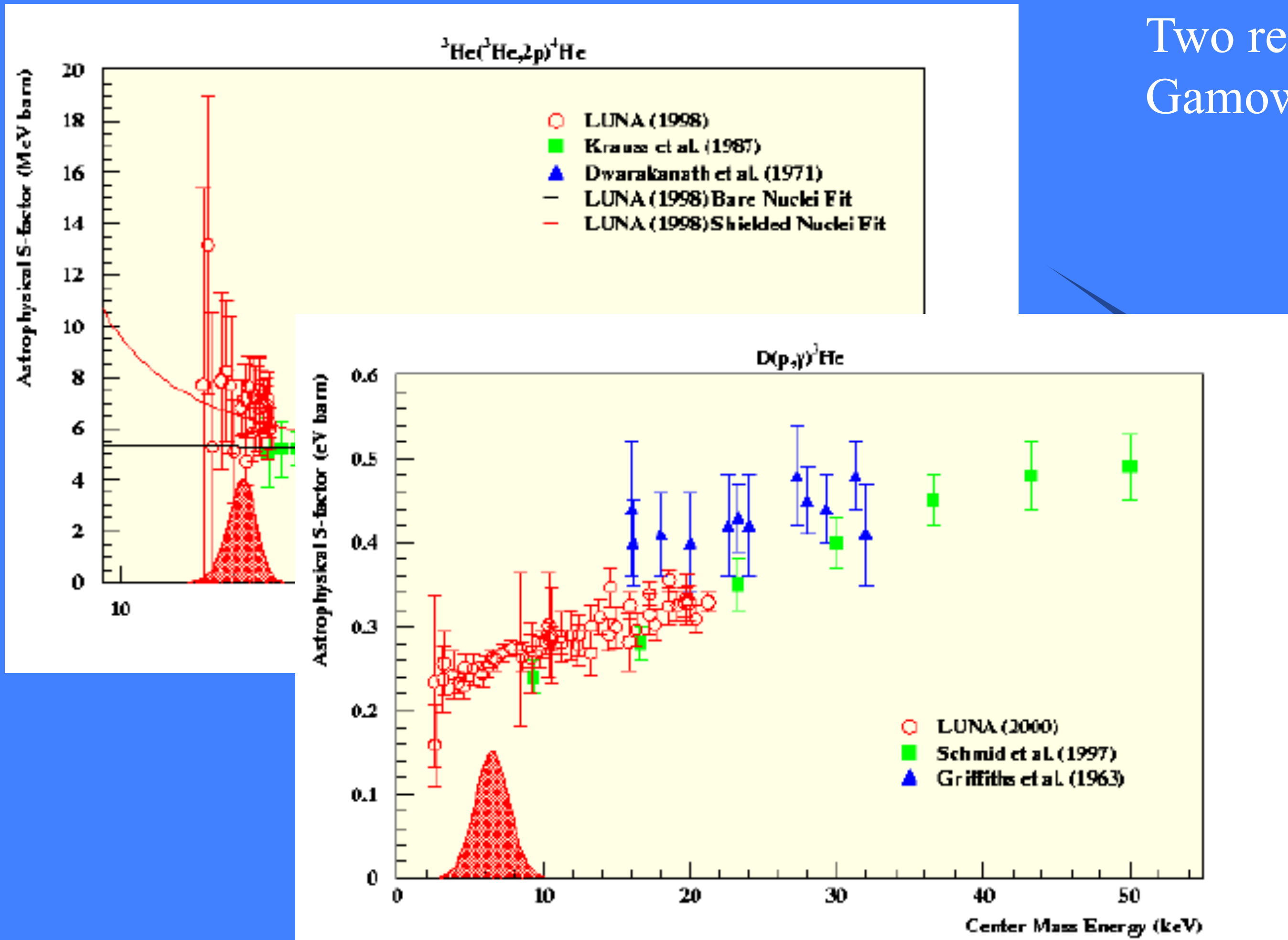
More on this reaction from Professor Gialanella

Can't get any lower because the natural background counts in our detectors mask the few counts we see from the reactions

The solution? Take your accelerator underground to a low background laboratory

LUNA accelerator facility in the Gran Sasso Laboratory





Two reactions measured into Gamow range

^{3}He(α, γ)^{7}Be

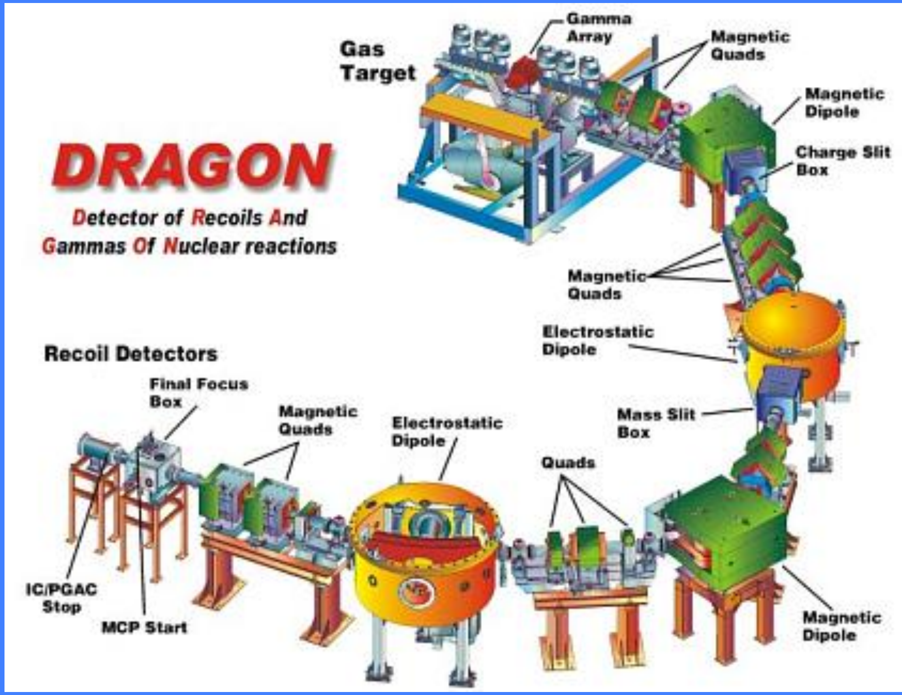
^{3}He(^{3}He,2p)α

More recently, with LUNA-II the ^{14}N(p,γ) ^{15}O rate has been measured

You will hear more about this approach Professor Iliadis' lecture tomorrow

If you can't go underground, you can try and reduce backgrounds by using various coincidence techniques

Example: DRAGON spectrometer at TRIUMF for measuring radiative capture reactions like (p,γ) and α,γ)



$^{21}Na(p,\gamma)\,^{22}Mg$

Windowless gas target

Detect capture gamma ray in high efficiency detector array around the target

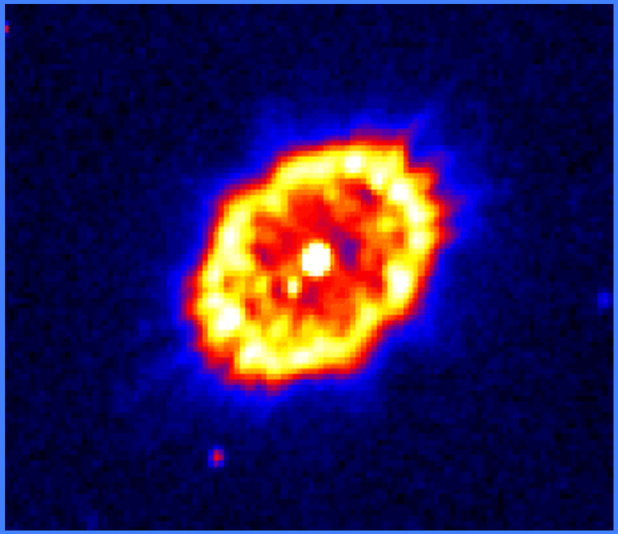
Allow beam and reaction nuclei (which are at zero degrees) to enter high dispersion separator (E and B fields) where reaction nucleus selected

Only record gammas if also detect a ^{22}Mg recoil nucleus

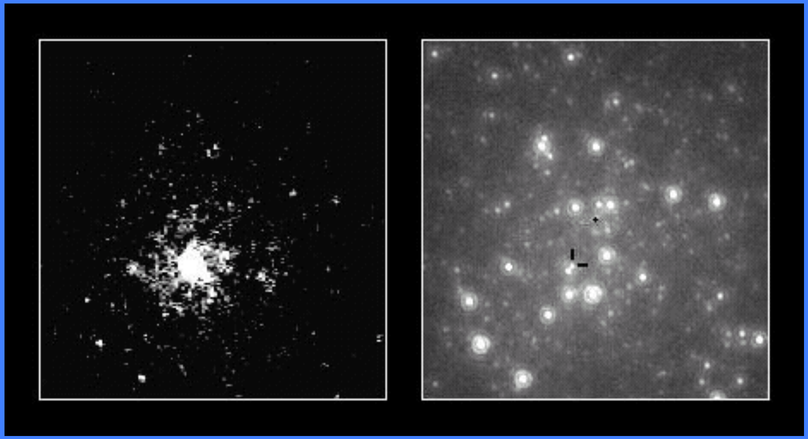
Other examples such as DRS at Oak Ridge, ERNA in Bochum etc.

More information on separators in Professor Gialanella's lectures

Nucleosynthesis in explosive sites



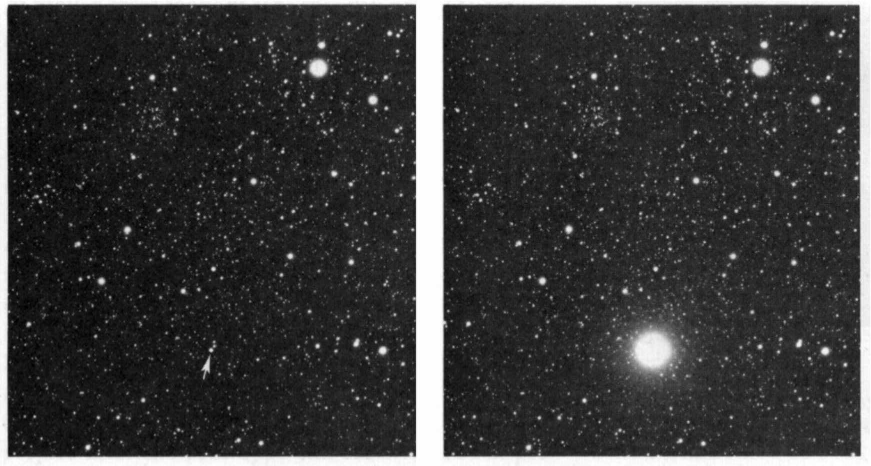
Nova Herculis 1934: AAT



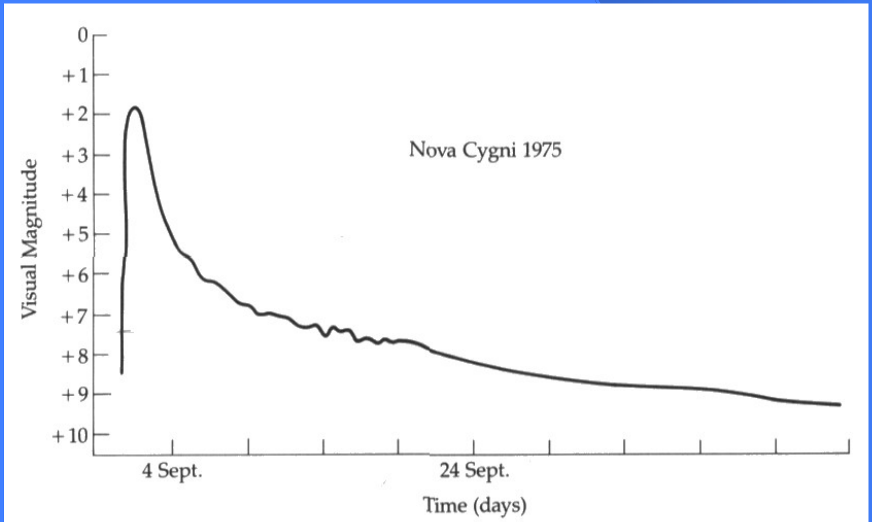
X-ray burster in NGC 6624: HST

SN1999BE: CGCG 089-013
One week after outburst

NOVAE



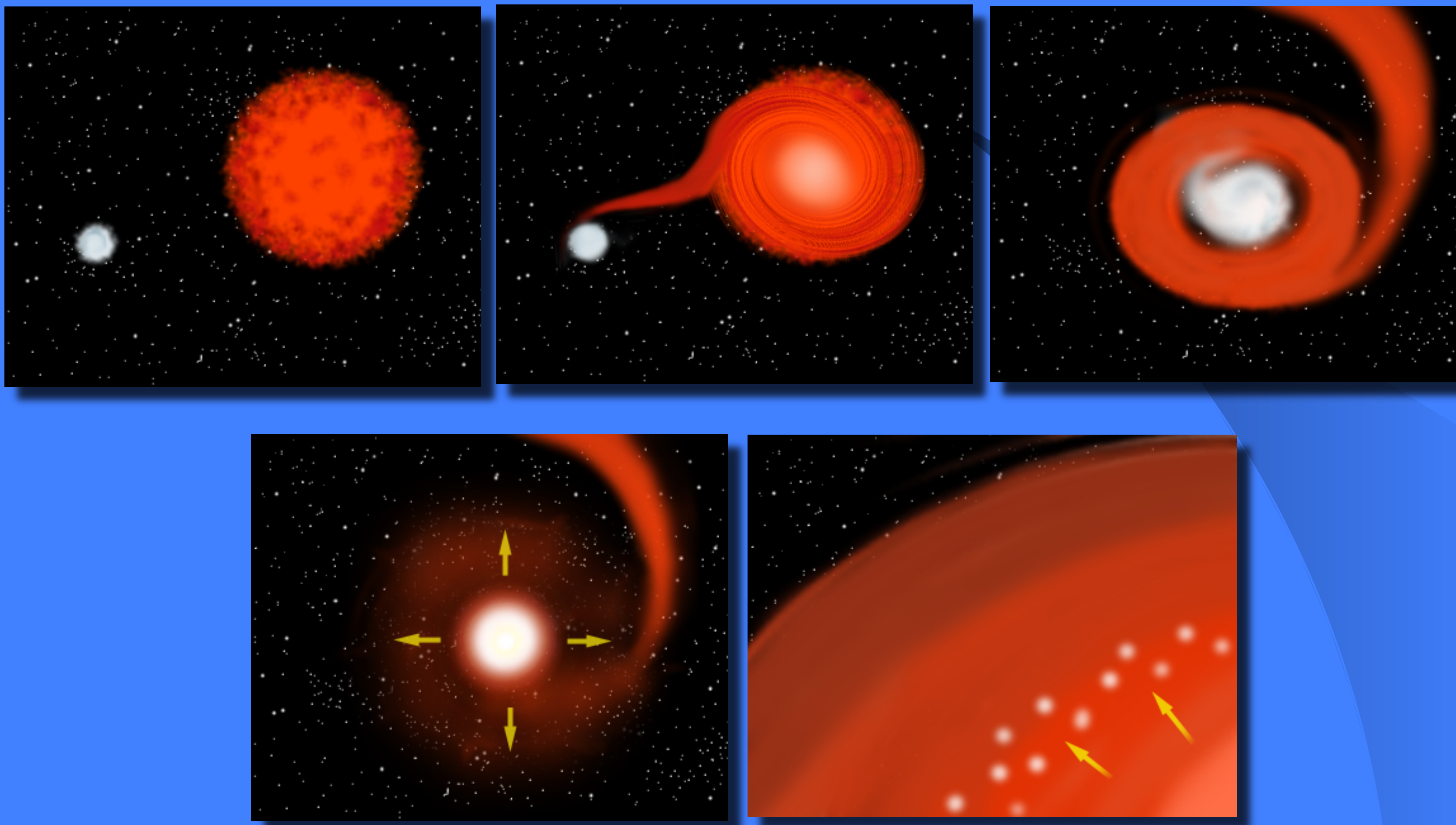
Humans have been seeing novae ("new stars") in the sky for hundreds of thousands of years
(20-60 per year in Milky Way)



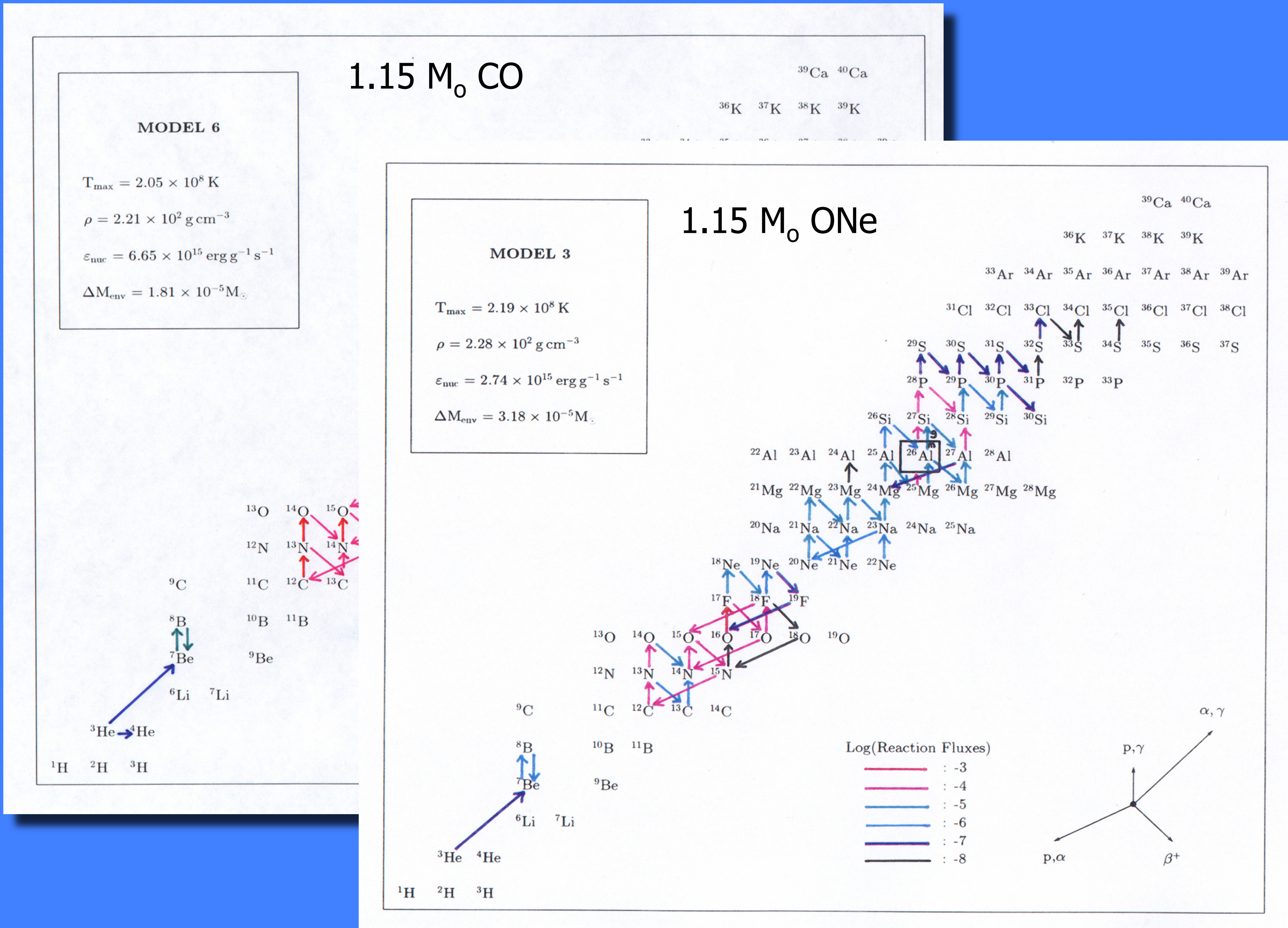
From light curve we can estimate the peak temperature ($3x10^8$K) and duration (hours) of the outburt

We can also determine the element abundance from spectroscopic measurements

Artists impression of a nova outburst



The nucleosynthesis depends on the type of White Dwarf



X-RAY BURSTER

Also binary system, but evolved star is a neutron star and not a white dwarf. Hotter temperatures and reactions run further up in mass.

SUPERNOVA - Type-1

Also accretion onto a white dwarf in a binary system, but this time the WD grows in mass above the Chandrasaker limit and it collapses gravitationally, heating the material.

SUPERNOVA Type-2

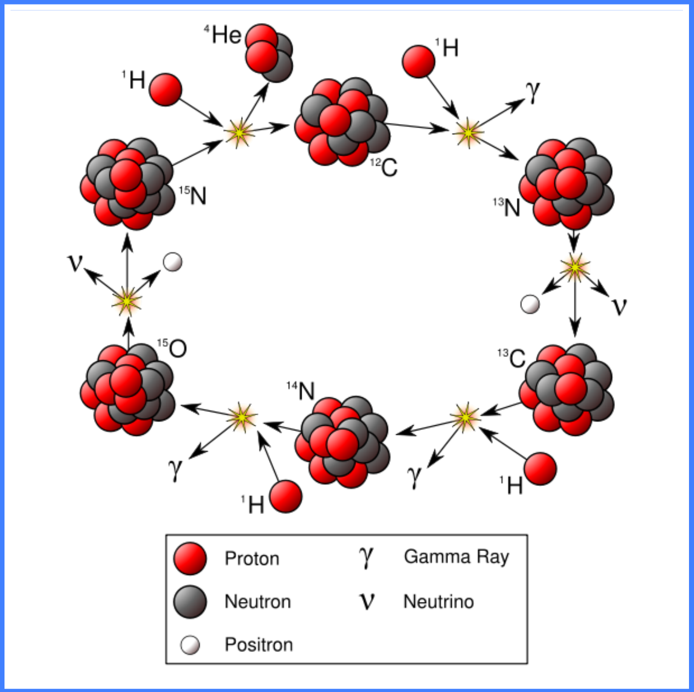
End of life of a massive star when it runs out of nuclear fuels and gravity takes over to collapse it into a neutron star or black hole, again heating the material.

What's different between these astrophysical sites?

Main different is that they are much hotter and have higher density of matter (we will see why later on)

This means collisions occur more frequently and the cross sections are higher, so reactions occur much more frequently

CNO-cycle in a star



Note how beta decays occur in this reaction sequence in a star

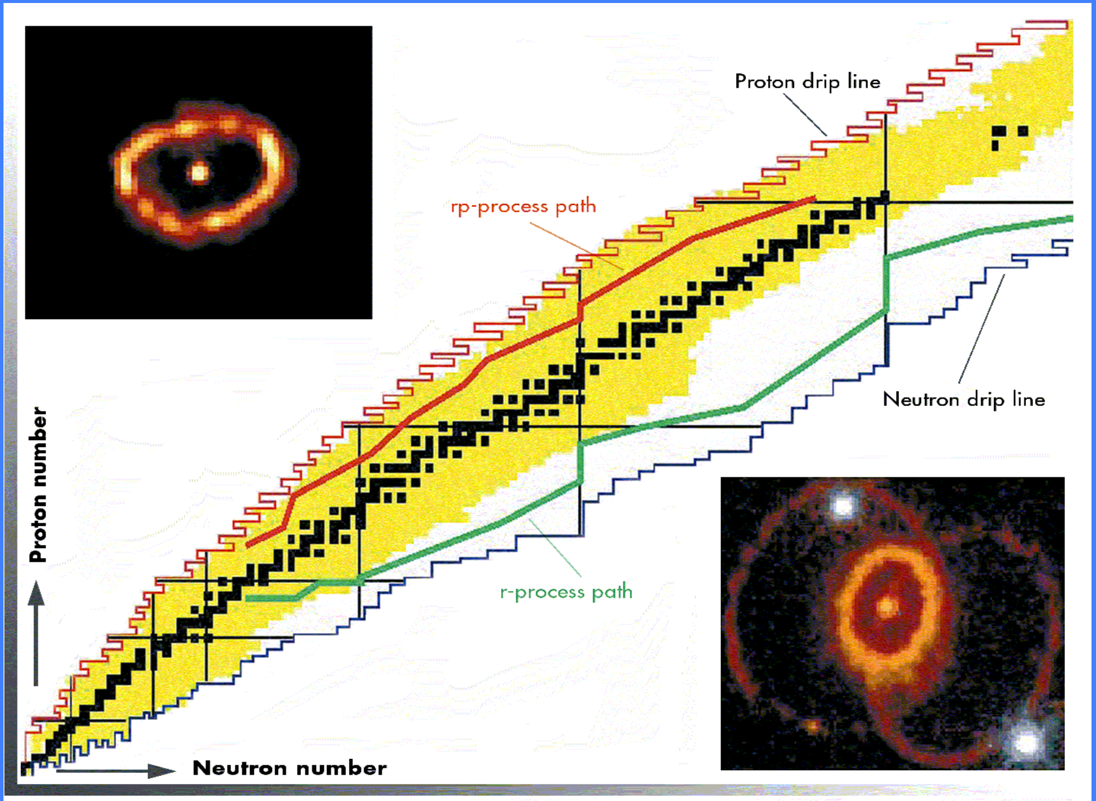
Even though each nucleus undergoes millions of collision per second, only very very rarely does a nuclear reaction occur

So any unstable nuclei created in a reaction have time to decay before they undergo another reaction

Always dealing with reactions between stable nuclei

By contrast, in the explosive sites the reactions occur so frequently that the unstable nuclei don't have time to decay between reactions

These nuclei then undergo further reactions – indeed the reactions involving these “exotic” nuclei dominate the process.



But this creates a problem for us – these nuclei don’t live long enough for us to make a target out of them to use to measure the cross sections

Primary accelerator → Target → Separator + Ion Source → Accelerator

High intensity stable beam

The technology required to solve this problem was developed in the last decade – accelerator facilities where short lived nuclei can be produced and then accelerated quickly in a second accelerator to provide a beam of radioactive nuclei.

END OF PART 1

However, you have homework for the break!

You have probably heard many times that astrophysical reactions rates are very small because they occur below the Coulomb barrier.

.........have you ever checked this?

Let’s think of a typical reaction, say alpha burning on carbon

$$\alpha + {}^{12}C > {}^{16}O + \gamma$$

As the nuclei approach they run up against the Coulomb barrrier

So how close do the nuclei get?

$z_1 z_2 e^2/4\pi\varepsilon_0 r_{close}$ = E (the kinetic energy)

But the kinetic energy is related to the temperature

$E \sim kT$

So what is r_{close} if T is, say, 10^9K?

And how close are the nuclear surfaces?

$r = 1.2\ A^{1/3}$ fm

How does this compare with the range of the nuclear force?

$\varepsilon_0 = 8.85 \times 10^{-12}$ $e = 1.6 \times 10^{-19}$ $k = 1.38 \times 10^{-23}$