

PHAS 1102
Physics of
the Universe

3 –
Magnitudes
and
distances

Brightness of Stars

- Luminosity
 - amount of energy emitted per second
 - not the same as how much we observe!
- We observe a star's **apparent brightness**
 - Depends on:
 - luminosity
 - distance
 - Brightness decreases as $1/r^2$
(as distance r increases)
 - other dimming effects
 - dust between us & star

Defining magnitudes (1)

Thus Pogson formalised the magnitude scale for brightness.

This is the brightness that a star **appears** to have on the sky, thus it is referred to as **apparent magnitude**.

Also – this is the brightness as it appears in our eyes. Our eyes have their own response to light, i.e. they act as a kind of filter, sensitive over a certain wavelength range. This filter is called the **visual band** and is centred on ~5500 Angstroms.

Thus these are

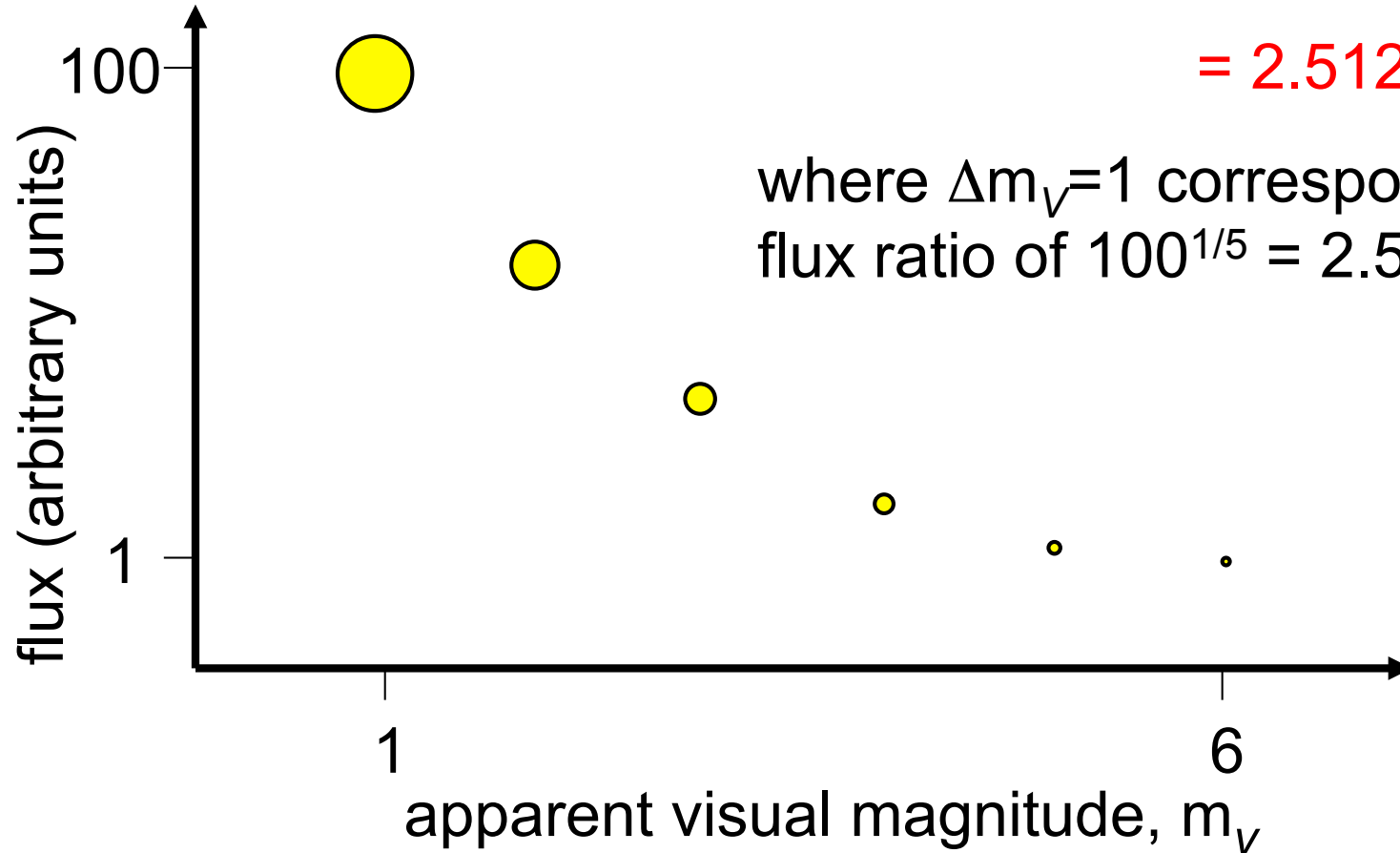
apparent visual magnitudes, m_v

Related to **flux**, i.e. energy received per unit area per unit time

Defining magnitudes (2)

For example, if star A has $m_V=1$ and star B has $m_V=6$, then

$$m_V(B)-m_V(A)=5 \quad \text{and} \quad \text{their flux ratio} \quad f_A/f_B = 100 = 2.512^5 \\ = 2.512^{m_V(B)-m_V(A)}$$



From flux to magnitude

So if you know the magnitudes of two stars, you can calculate the ratio of their fluxes using $f_A/f_B = 2.512^{m_V(B)-m_V(A)}$

Conversely, if you know their flux ratio, you can calculate the difference in magnitudes since:

$$\log_{10}(f_A/f_B) = [m_V(B)-m_V(A)] \log_{10}2.512$$

$$m_V(B)-m_V(A) = \Delta m_V = 2.5 \log_{10}(f_A/f_B)$$

$$\begin{aligned} 2.512 &= 100^{1/5} \\ &= 10^{2/5} = 10^{1/2.5} \end{aligned}$$

To calculate a star's apparent visual magnitude itself, you need to know the flux for an object at $m_V=0$, then:

$$m_S - 0 = m_S = 2.5 \log_{10}(f_0) - 2.5 \log_{10}(f_S)$$

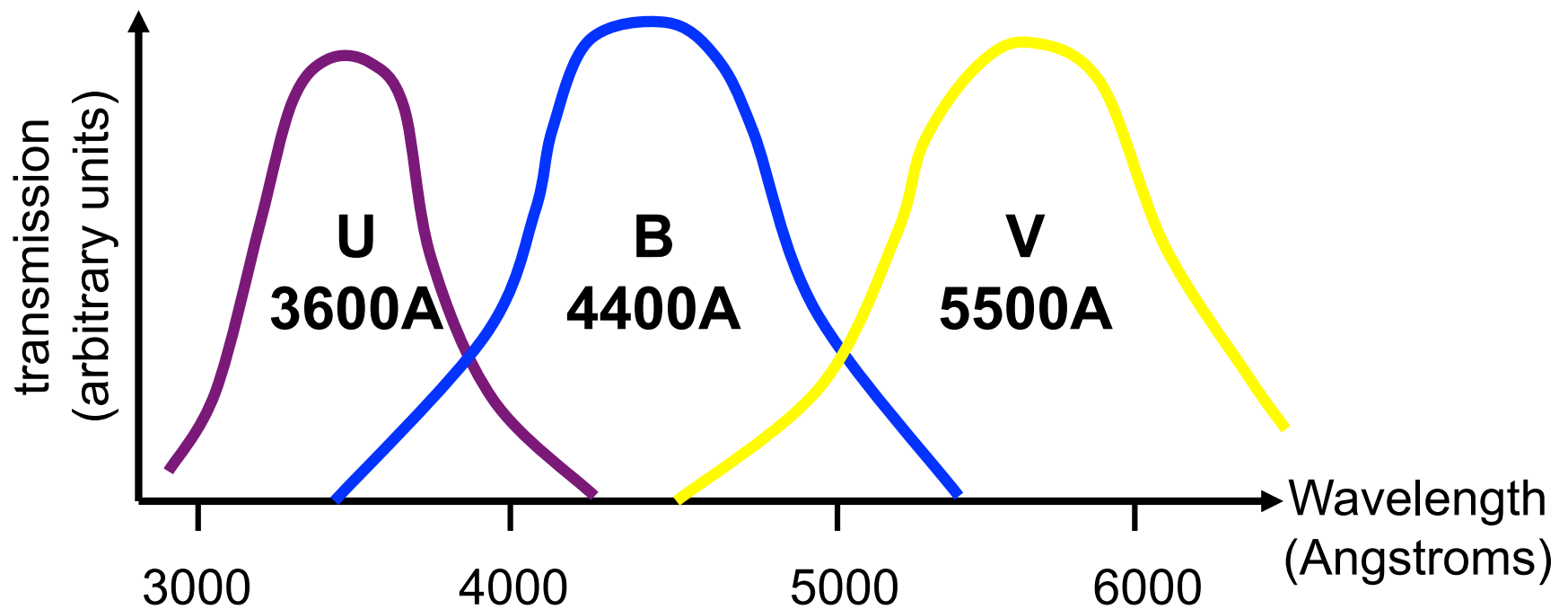
$$\Rightarrow m_S = -2.5 \log_{10}(f_S) + C$$

where C is a constant ('zero-point'), i.e. $C = 2.5 \log_{10}(f_0)$

UBV Johnson system (1)

So, different types of stars emit strongly at different wavelengths, thus will have different brightness depending on the filter (i.e. the wavelength band) used to observe them.

Harold Johnson (1921-1980) pioneered the standard UBV system of filters for measuring magnitudes in various colours.



Absolute magnitudes (1)

Knowing how bright a star is on the sky is very useful – but the stars all lie at very different distances from the Earth →

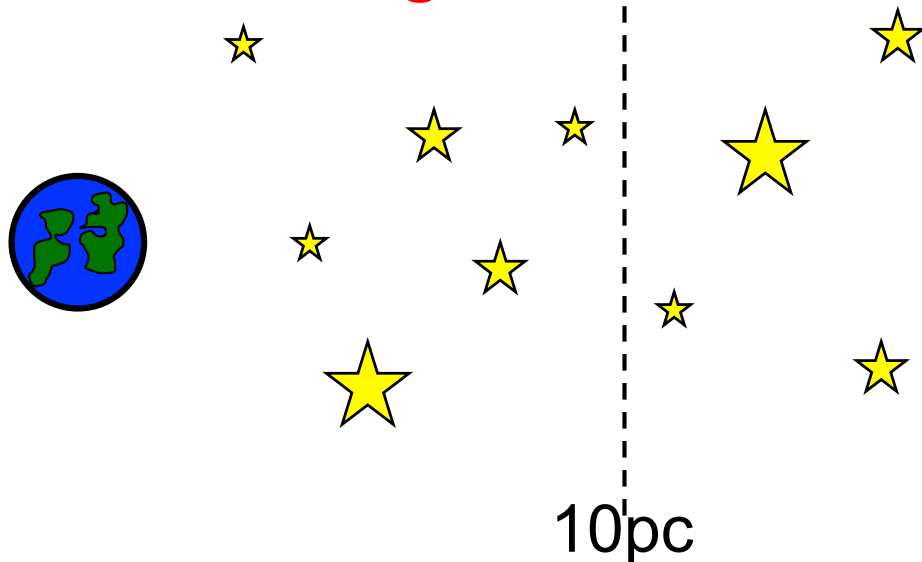
we **really** want to know a star's intrinsic brightness – i.e. its luminosity (total energy emitted per unit time, in Watt).

Astronomers have two ways of quantifying this:

Absolute magnitudes

and

Luminosities



Absolute magnitude:
magnitude a star would
have if it were placed
10 parsec = 3×10^{17} m
away from the observer

Absolute magnitudes (2)

The flux from any source falls off as the inverse square of the distance,

i.e. $\text{observed flux} \propto \frac{\text{intrinsic flux}}{\text{distance}^2}$

Recall: $f = \frac{L}{4\pi r^2}$

Example: a star lies at distance d (in parsecs) with apparent magnitude m and flux f_m . If this star was 10 parsecs away, so that its flux was f_M , then (because of the inverse square law):

$$\frac{f_m}{f_M} = \left(\frac{10}{d}\right)^2$$

But from the definition of magnitude:

$$m_B - m_A = \Delta m_V = 2.5 \log_{10} \frac{f_A}{f_B}$$

Distance modulus

So, since $m_B - m_A = \Delta m_V = 2.5 \log_{10} \frac{f_A}{f_B}$

then $m - M = 2.5 \log_{10} \frac{f_M}{f_m}$

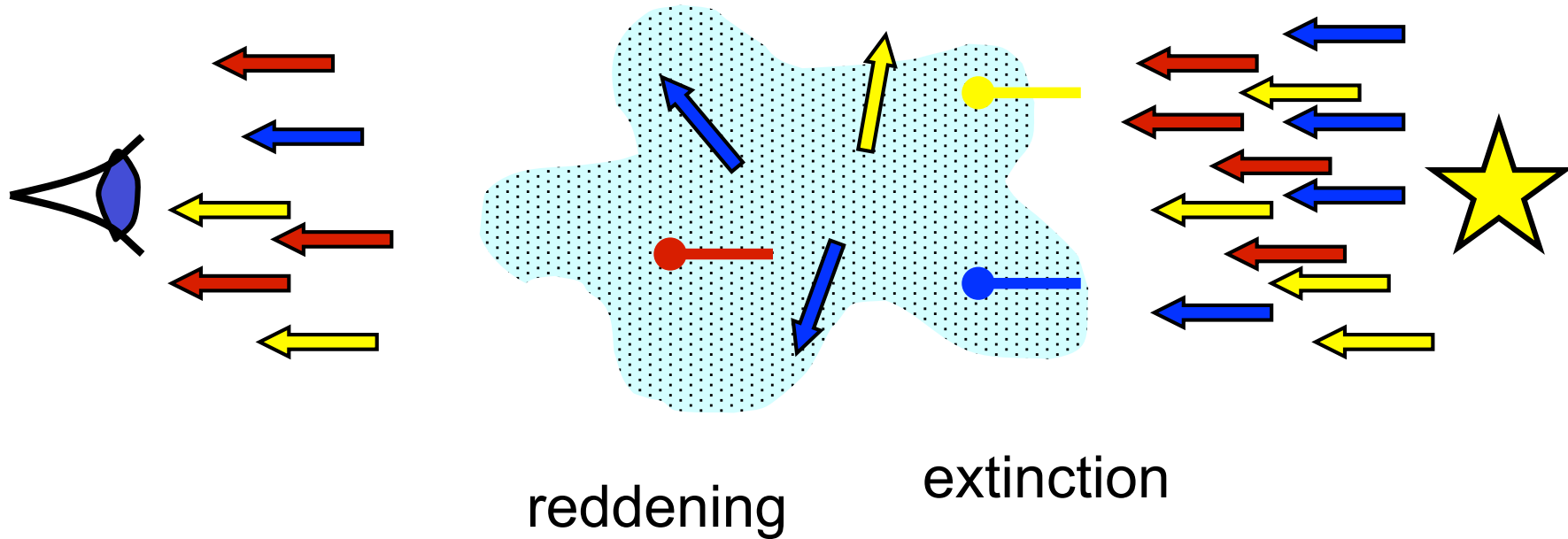
$$= 2.5 \log_{10} \left(\frac{d}{10} \right)^2 = 5 \log_{10} d - 5 \log_{10} 10$$

$$\Rightarrow m - M = 5 \log_{10} d - 5$$

where $m - M$ is known as the **distance modulus**

The absolute (V band) magnitude of the Sun is +4.82

Extinction and reddening



Any gas and dust which lie between an observer and a star will scatter and absorb the star's light, making it dimmer. This is **extinction**.

Dust scatters blue light more than red, which makes the star look redder (although, strictly speaking, 'less blue') and this is called **reddening**. This effect makes sunsets and sunrises red.

Reddening and colour excess

The effect of scattering is made easier to estimate because it is wavelength-dependent, so it will manifest itself as a colour change:

Observed colour = $(B - V)$

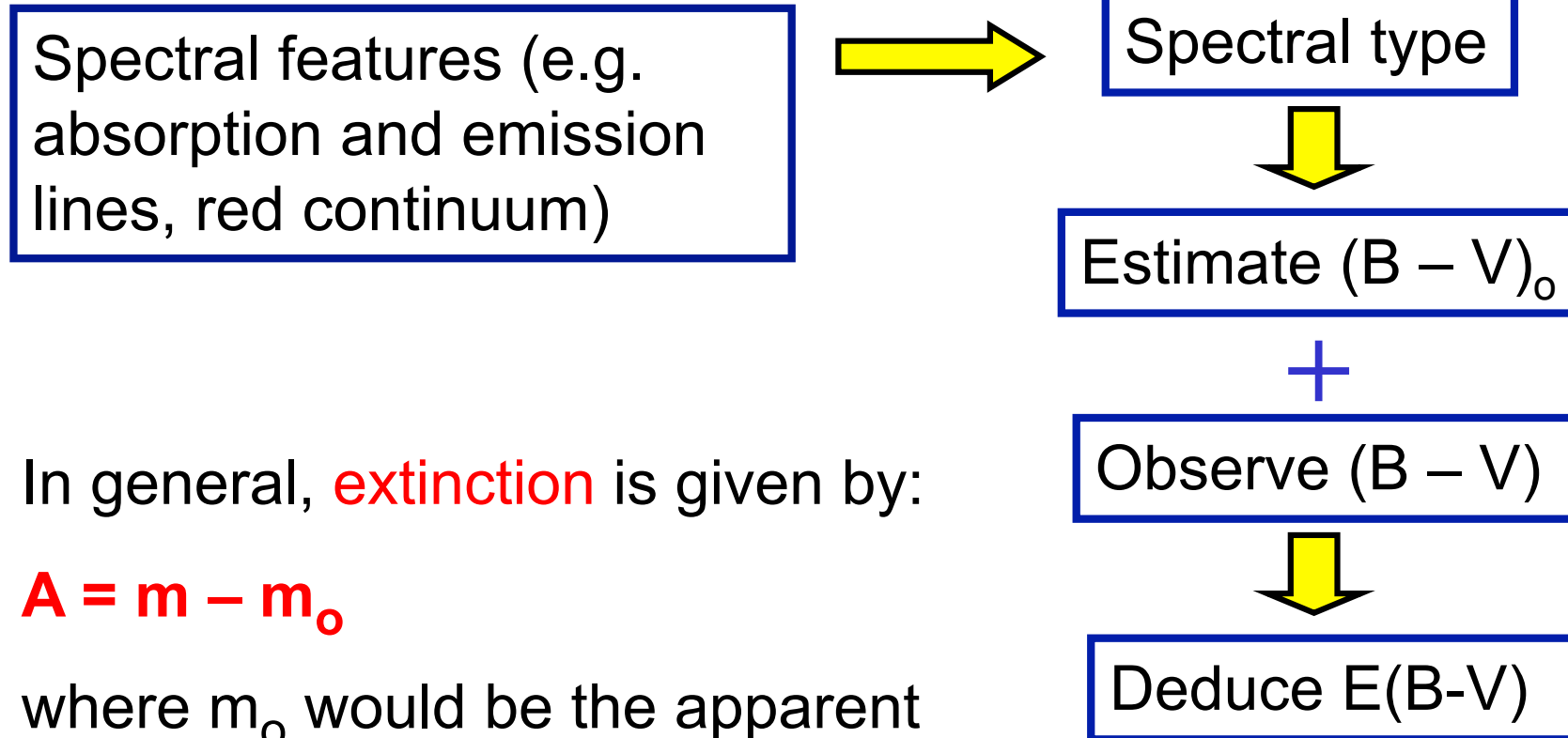
Intrinsic colour = $(B - V)_o$

Reddening is measured by the **colour excess** which is defined as:

$$E(B - V) = (B - V) - (B - V)_o$$

It is measured in magnitudes

Correcting for reddening and extinction



In general, **extinction** is given by:

$$A = m - m_o$$

where m_o would be the apparent magnitude if there was no extinction.

In the V band, studies show that

$$A_V = V - V_o \sim 3.1E(B - V)$$

Including extinction in the distance modulus

Remember the distance modulus equation:

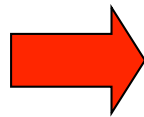
$$m - M = 5\log_{10}d - 5$$

BUT, m in this equation has been assumed to be unaffected by dust and gas, so it should read:

$$m_o - M = 5\log_{10}d - 5$$

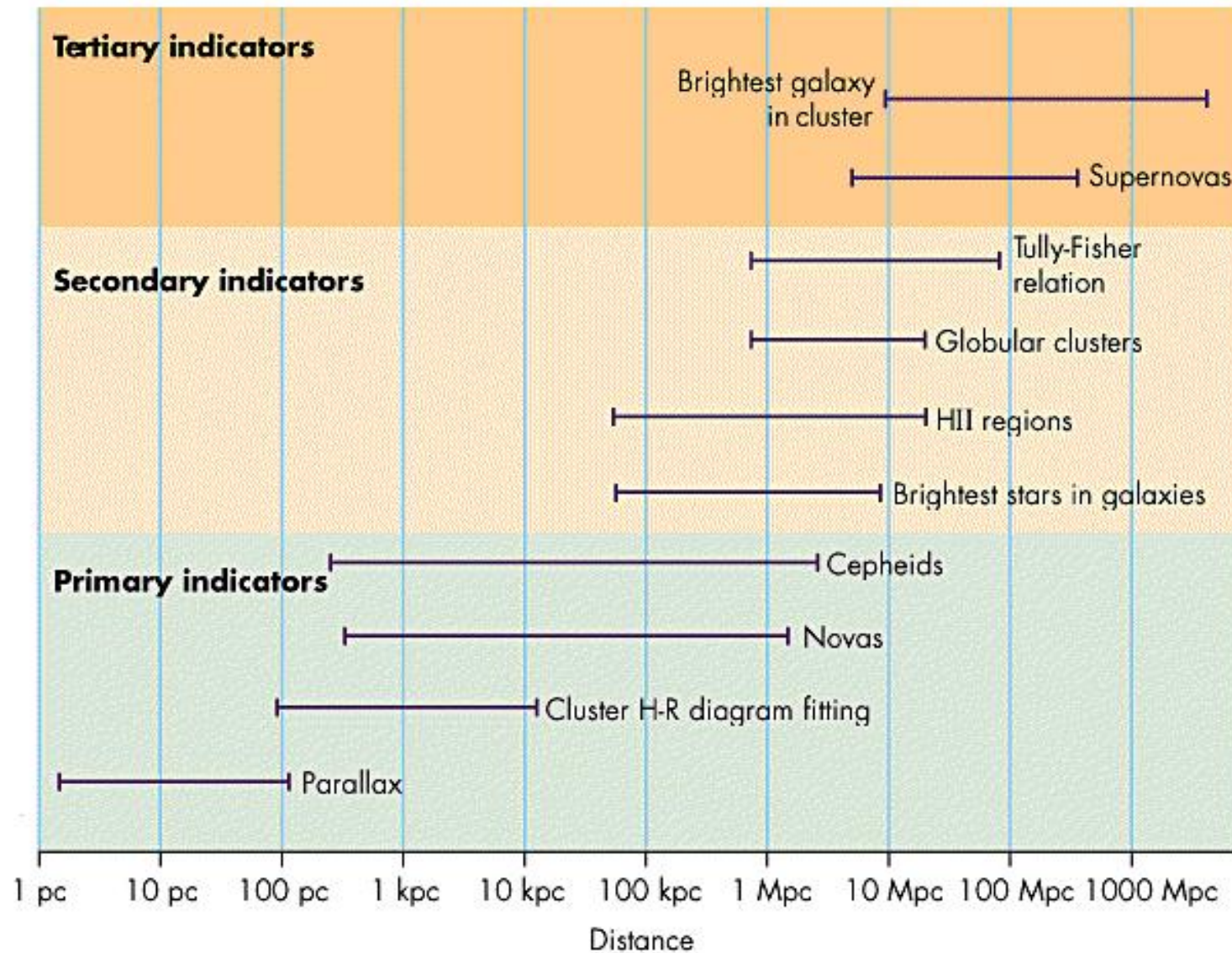
From $A = m - m_o$

$$\Rightarrow m_o = m - A$$

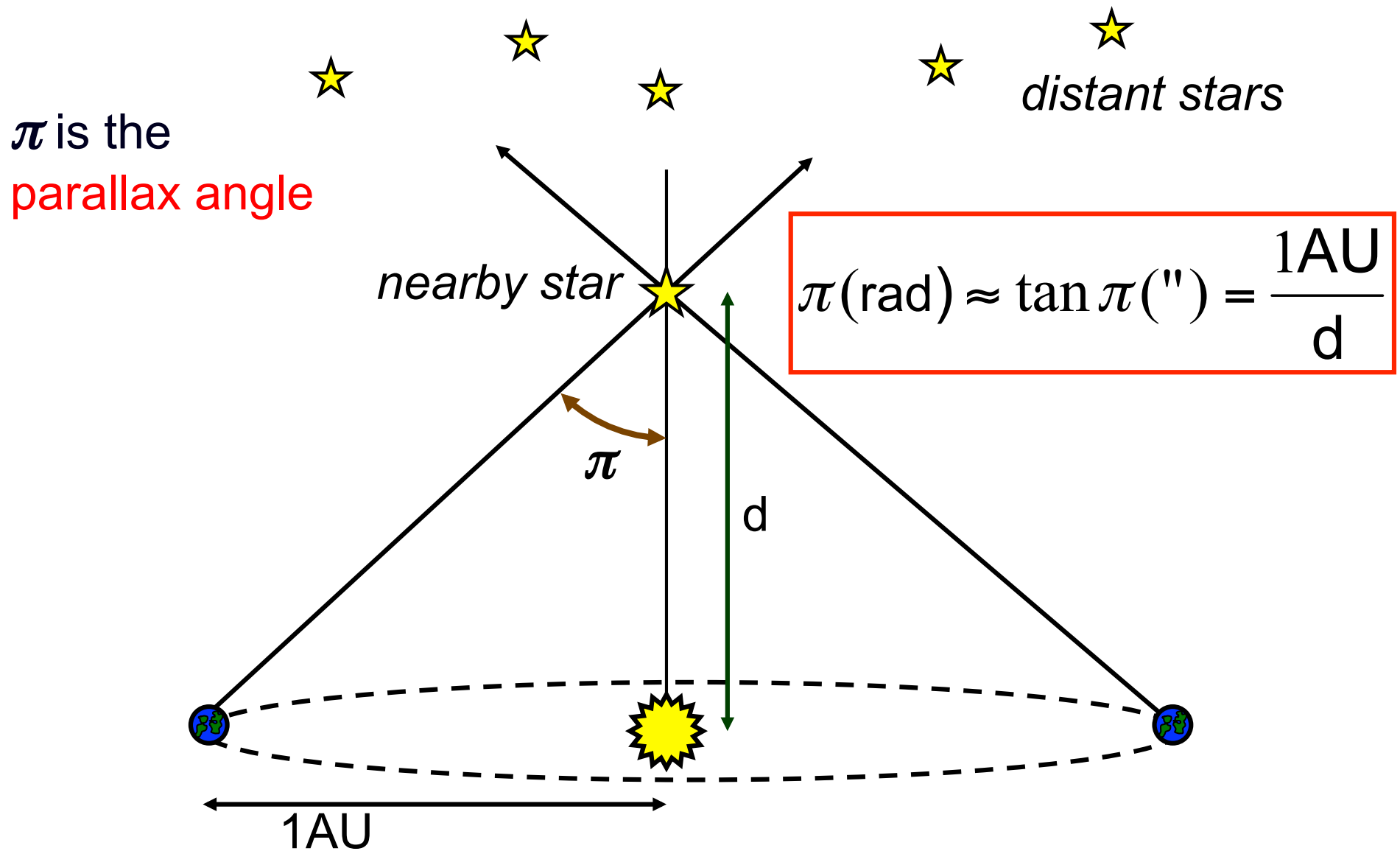


$$m - M = 5\log_{10}d - 5 + A$$

Astronomical Distance Ladder



Direct method – Trigonometric parallax (1)



Larger the distance, smaller the parallax angle.

Trigonometric parallax (2)

In one year, a nearby star will trace out an ellipse on the sky due to parallax:

Definition

1 parsec is the distance of an object for which $\pi = 1$ arcsec

$$d \text{ (parsec)} = 1/\pi(\text{''})$$

1 parsec = 206,265 AU = 3.086×10^{16} m = 3.26 light years

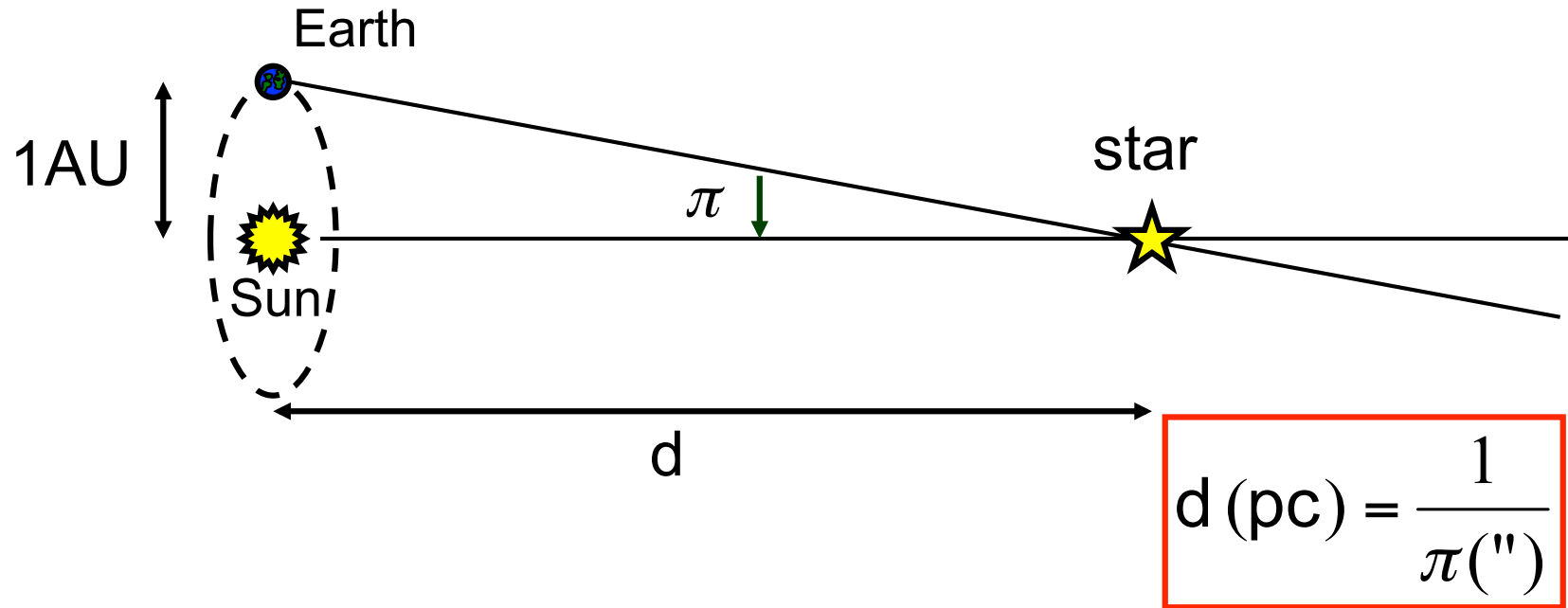
Parallax was first measured by Bessel in 1838 who found

$$\pi = 0.294'' \text{ for } 61 \text{ Cygni.}$$

Our closest star is *Proxima Centauri* (α Cen):

$$\pi = 0.764'', d = 1.31 \text{ pc}$$

Trigonometric parallax (3)



Ground-based telescopes – measure π to $\sim 0.01''$ ($d=100$ pc)

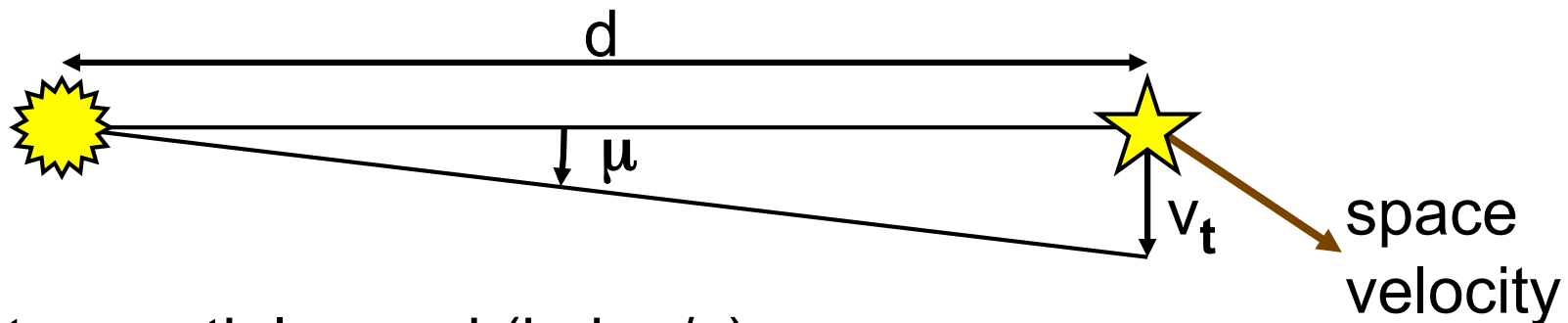
Hipparcos (High Precision PARallax COLlecting Satellite) –
measured π to $\sim 0.002''$ ($d=500$ pc) for some 120,000 stars

Gaia – will measure π to 2×10^{-5} arcsec ($d=50,000$ pc)

Proper motion

μ is measured in arcseconds per year.

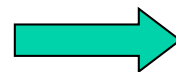
Largest proper motion known is for Barnard's Star, where $\mu = 10.34$ arcsec/year.



v_t = tangential speed (in km/s)

d = distance (in km)

$$v_t \cong \mu d \quad (\text{SI units; } \mu \text{ in radian/sec})$$

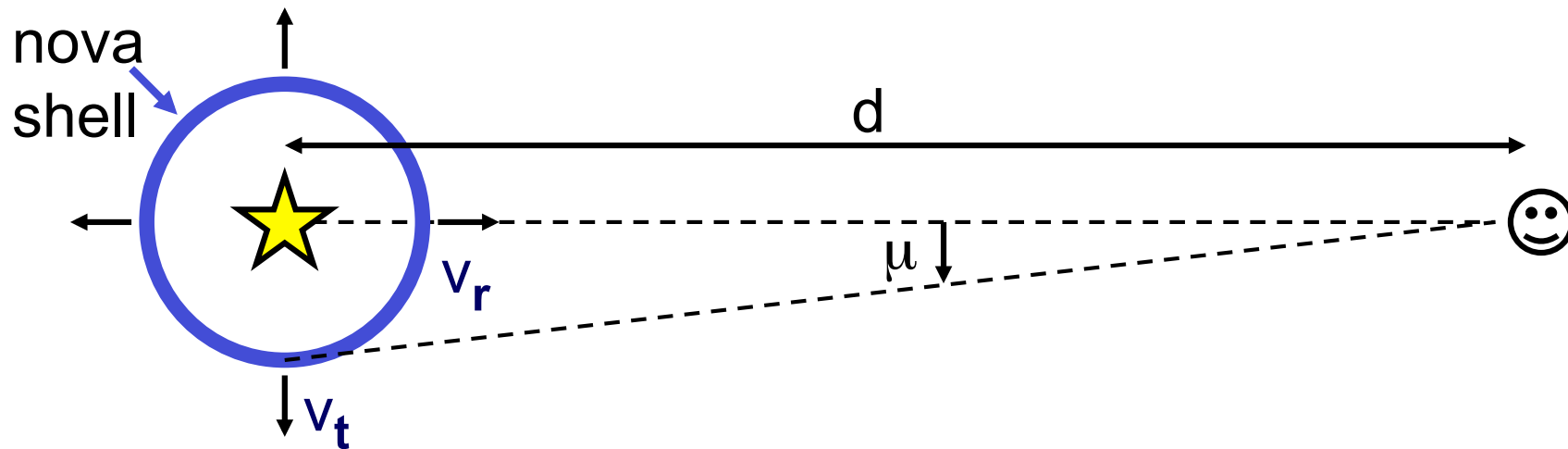


$$v_t = 4.74 \mu d$$

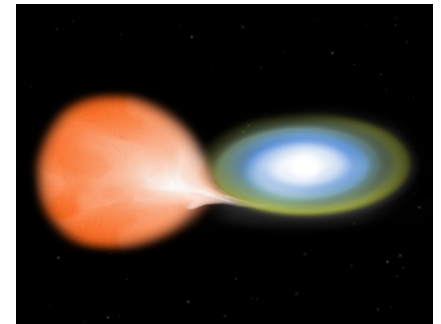
if v_t in km/s, μ in arcsec/year
and d in parsec

e.g. Nova expansion

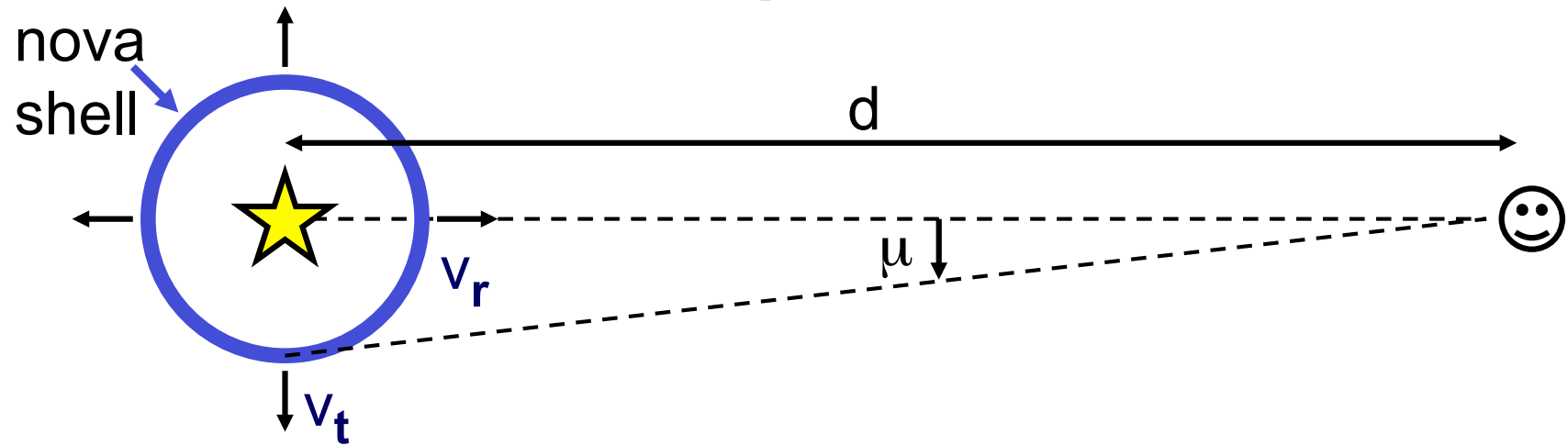
So, if a star has proper motion μ (in arcsec/year), the tangential velocity of the star is $v_t = 4.74\mu d$ (where d is in parsec and v_t in km/s).



Instead of a star, consider a **nova** – an explosion from a star. We assume that the shell thrown off is spherically-symmetric. If we can observe the expansion and measure its velocity, we can determine its distance.



Nova expansion...



Using spectroscopy and measuring the Doppler effect ($c =$ speed of light):

$$v_r = \frac{c \Delta\lambda}{\lambda}$$

If μ is the proper motion of the shell

due only to its expansion: $v_t = 4.74 \mu d$

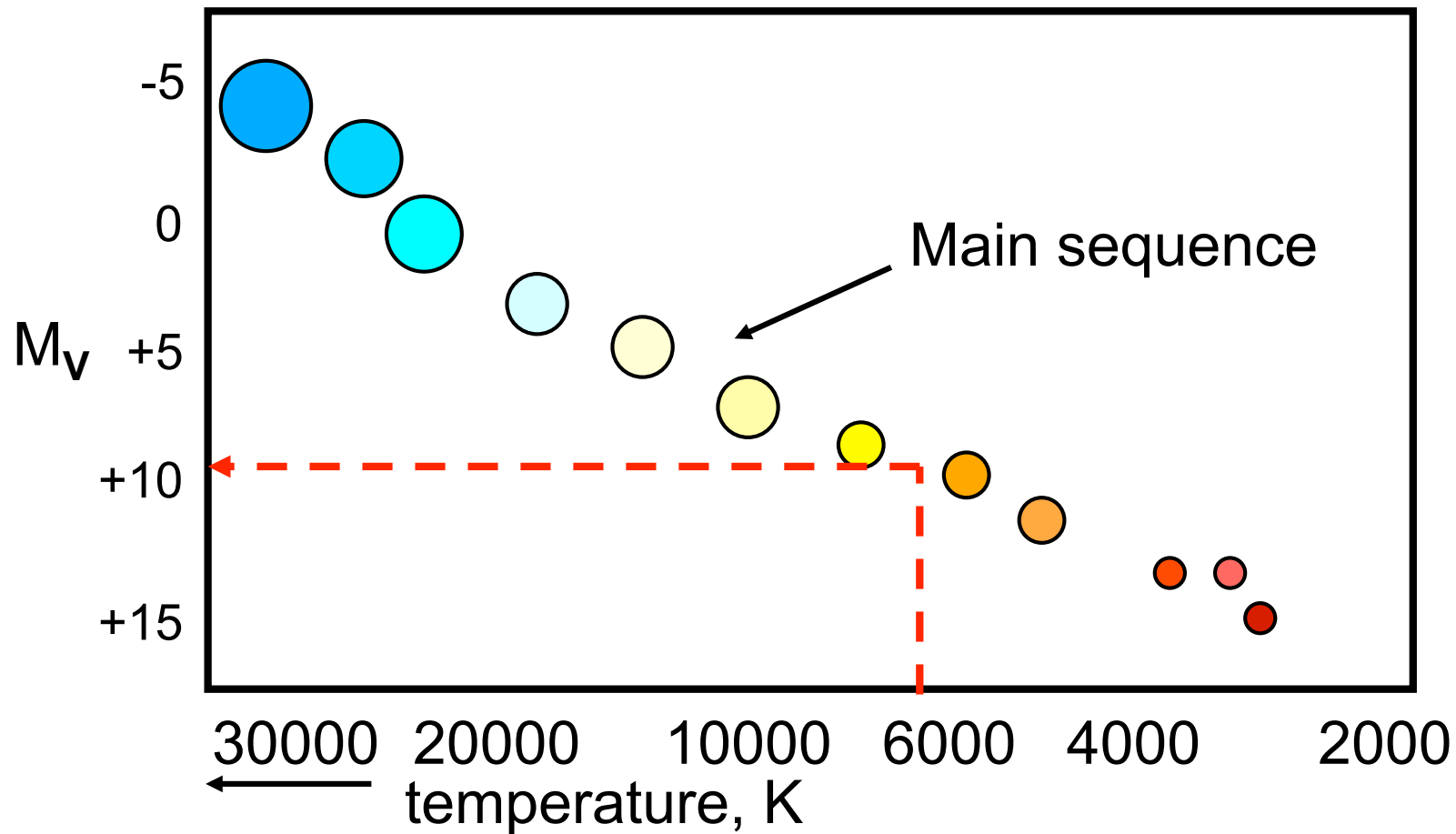
and since $v_t = |v_r|$, then

$$d = \frac{|v_r|}{4.74 \mu}$$

(in parsec, if
 v_r in km/s and
 μ in arcsec/year)

Indirect method:

Spectroscopic distances – HR diagrams (1)



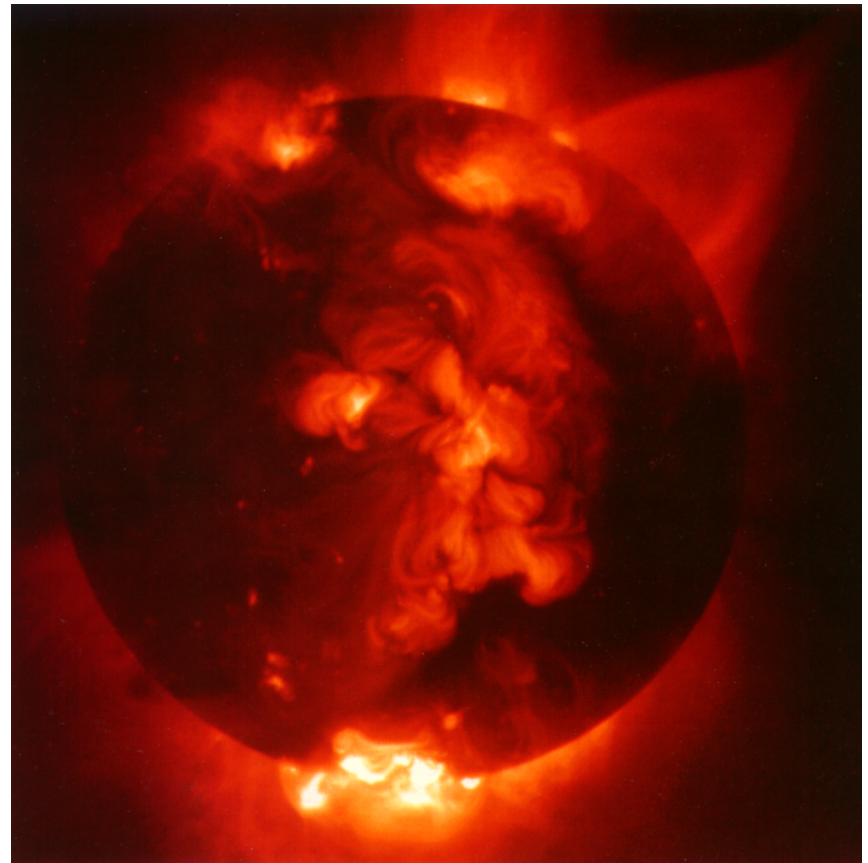
If an HR diagram is well-calibrated, the luminosity, and thus the **absolute magnitude M_V** , of any star of known colour or spectral type can be derived.

PHAS 1102

Physics of the Universe

4 - Stellar energy generation

PARTIAL notes

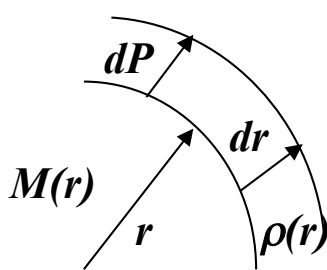


Stellar energy generation

Stars are generally very stable. Assuming that only the **inward gravitational force** and the **outward (thermal) pressure** are at work in the gas, a star is in hydrostatic equilibrium:

$$\frac{dP}{dr} = -\frac{G M(r) \rho(r)}{r^2} \quad [\text{N m}^{-3}]$$

Gravitational acceleration



where P : outward pressure (force per unit area)

r : radius from the centre of the star

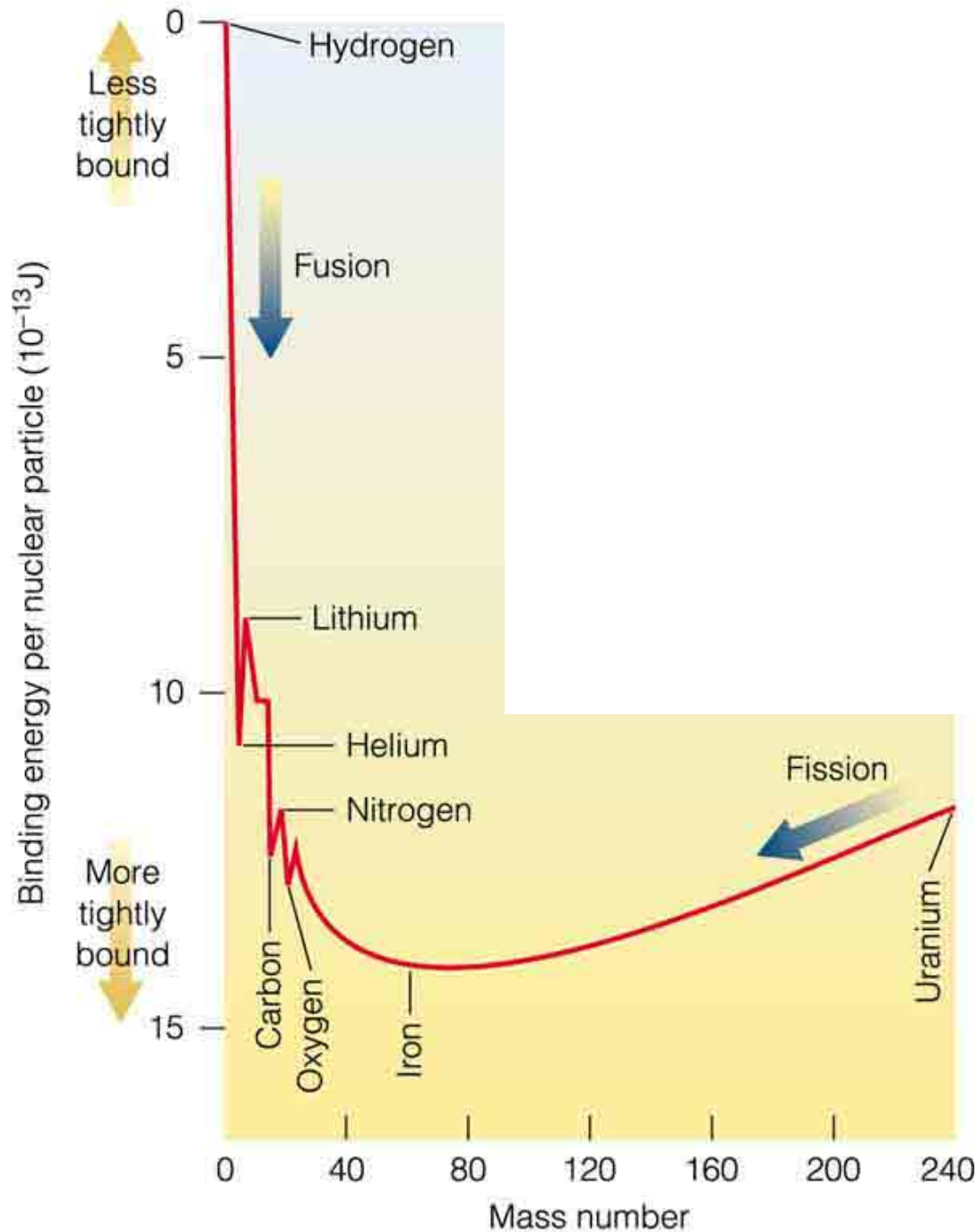
G : gravitational constant

$M(r)$: mass within radius r

$\rho(r)$: density at radius r

The four fundamental forces of Nature

<p><i>Strong nuclear</i></p>	<p>Force which holds nucleus together</p>	<p>Strength</p> <p>1</p>	<p>Range (m)</p> <p>10^{-15} (diameter of a medium sized nucleus)</p>	<p>Carrier</p> <p>gluons,</p>	<p>Particles acted on</p> <p>quarks (make up <i>p</i> and <i>n</i>)</p>
<p><i>Electro-magnetic</i></p>		<p>Strength</p> <p>$\frac{1}{137}$</p>	<p>Range (m)</p> <p>Infinite</p>	<p>Carrier</p> <p>photon mass = 0 spin = 1</p>	<p>Particles acted on</p> <p>any particle with charge</p>
<p><i>Weak nuclear</i></p>	<p>neutrino interaction induces beta decay</p>	<p>Strength</p> <p>10^{-6}</p>	<p>Range (m)</p> <p>10^{-18} (0.1% of the diameter of a proton)</p>	<p>Carrier</p> <p>Intermediate vector bosons W^+, W^-, Z_0, mass > 80 GeV spin = 1</p>	<p>Particles acted on</p> <p>quarks and leptons (<i>e</i>, <i>μ</i>, <i>τ</i>, <i>ν</i>)</p>
<p><i>Gravity</i></p>		<p>Strength</p> <p>6×10^{-39}</p>	<p>Range (m)</p> <p>Infinite</p>	<p>Carrier</p> <p>graviton? mass = 0 spin = 2</p>	<p>Particles acted on</p> <p>any particle with mass</p>



Fusion: light bind together to form heavy

Fission: break up heavy to form light

Shown is the energy released per fusion/fission event; this is called the **binding energy**.

Note that a relatively large amount is released from hydrogen to helium.

Still, it takes 10^{38} reactions per second to support the sun!

Mass deficit and binding energy

The simplest fusion reaction, becoming significant at $T \sim 10^7$ K, involves **2 protons** (H nuclei) and **2 neutrons** combined in the next stable nucleus, ${}^4\text{He}$ (α particle).

Atomic mass of proton: 1.0078 amu

Atomic mass of 4 protons: 4.0312 amu

Atomic mass of ${}^4\text{He}$ nucleus: 4.0026 amu → **mass deficit**
of 0.0286 amu

amu: atomic mass unit (1/12 of the mass of a ${}^{12}\text{C}$ atom,
 $= 1.66 \times 10^{-27}$ kg)

Mass deficit = nuclear binding energy that holds nucleus together

Mass deficit converted into energy according to Einstein's equation:
 $E = mc^2 = 0.0286 \times (1.66 \times 10^{-27}) \times (9 \times 10^{16})$ Joule
 $= 4.3 \times 10^{-12}$ Joule

Total nuclear energy in the Sun

Assume 10% of H in the Sun (temperature and density are high enough only in the core) converts into ${}^4\text{He}$.

Fraction of mass liberated into energy: $\frac{0.0286}{4.0312} = 0.0071$
(i. e. efficiency $\sim 0.7\%$)

So

$$\begin{aligned} E_{\text{total}} &= mc^2 = 0.0071 \times 0.1 \times M_{\text{Sun}} \times c^2 \\ &= 0.0071 \times 0.1 \times (2 \times 10^{30}) \times (9 \times 10^{16}) \text{ Joule} \\ &= 1.3 \times 10^{44} \text{ Joule} \end{aligned}$$

Then the Sun
can continue
to radiate for

$$\frac{E_{\text{total}}}{L_{\text{Sun}}} = \frac{1.3 \times 10^{44}}{4 \times 10^{26}} \text{ s} = 3 \times 10^{17} \text{ s} = 10^{10} \text{ yr}$$

Solar system age: 5×10^9 years \rightarrow Sun is \sim halfway through its
H-burning phase

Fusion processes for $H \rightarrow He$

Simultaneous collision of 4 protons very unlikely!

Two thermonuclear processes lead to conversion $H \rightarrow He$:

1) **Proton-proton chain** (PP)

Dominates at $T < 2 \times 10^7$ K

2) **Carbon cycle** (CNO)

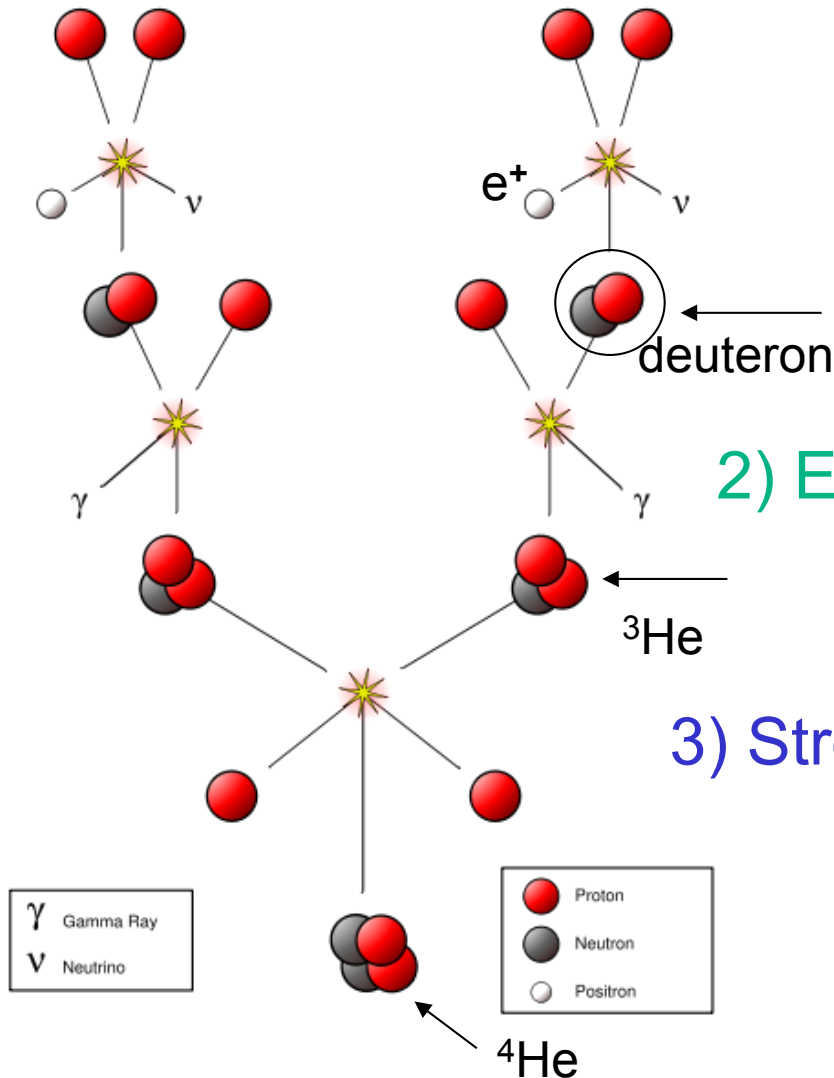
Dominates at higher temperatures
(contributes 2% of solar energy)

Particles involved: Protons, neutrons, electrons,

positrons, e^+ (= electrons, but charge = $+e$)

neutrinos, ν (very small mass, no charge,
only energy and spin)

Proton-proton chain (PP1)



1) Weak nuclear force (5×10^9 yr)
→ $0.42 + 1.02 = 1.44$ MeV

2) Electromagnetic force (1 s)
→ 5.49 MeV

3) Strong nuclear force (3×10^5 yr)
→ 12.86 MeV

Total energy produced from mass conversion: 26.7 MeV.

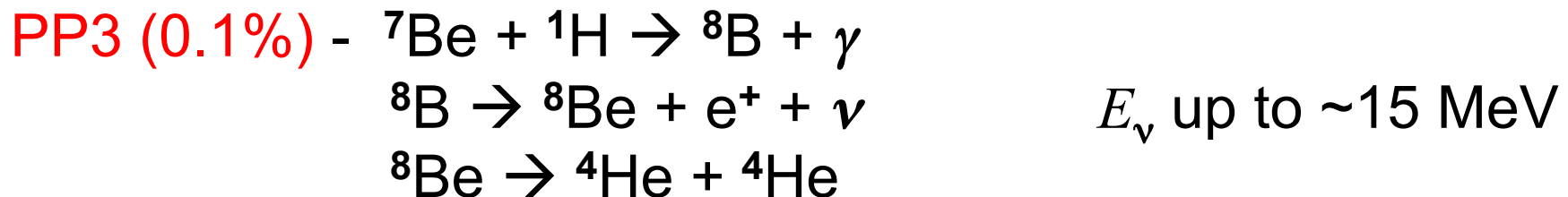
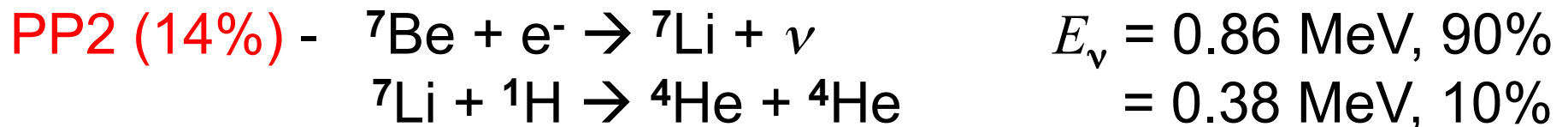
Dominates in stars **the size of the Sun, or less**. Slow step 1 ensures Sun does not exhaust its fuel too quickly!

Proton-proton chains (PP1, PP2, PP3)

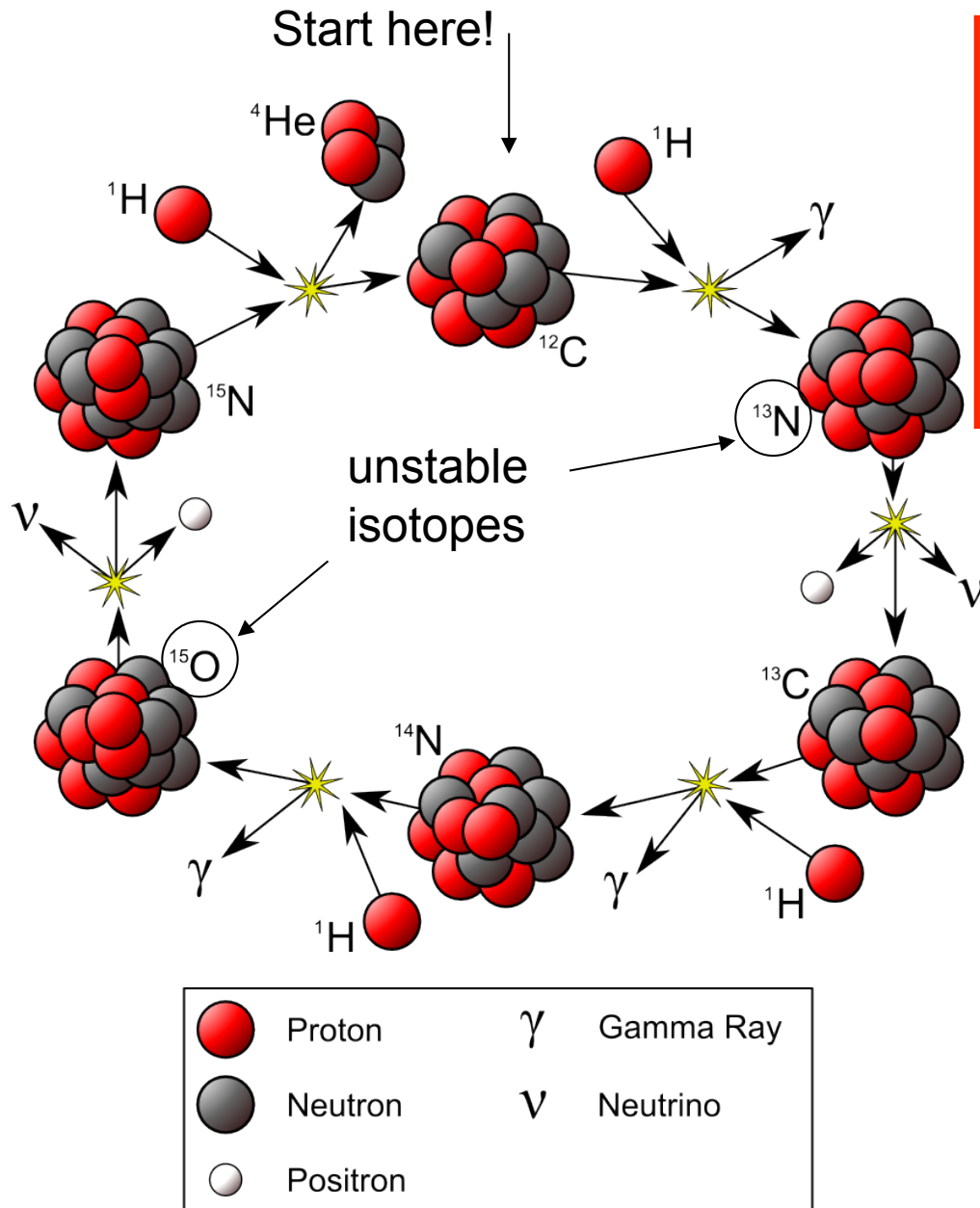
Proton-proton chain **PP1** takes place **86%** of the times.

Other PP reactions occur less frequently, thus contribute less to the Sun's luminosity.

Following first two steps of PP1,



The CNO cycle

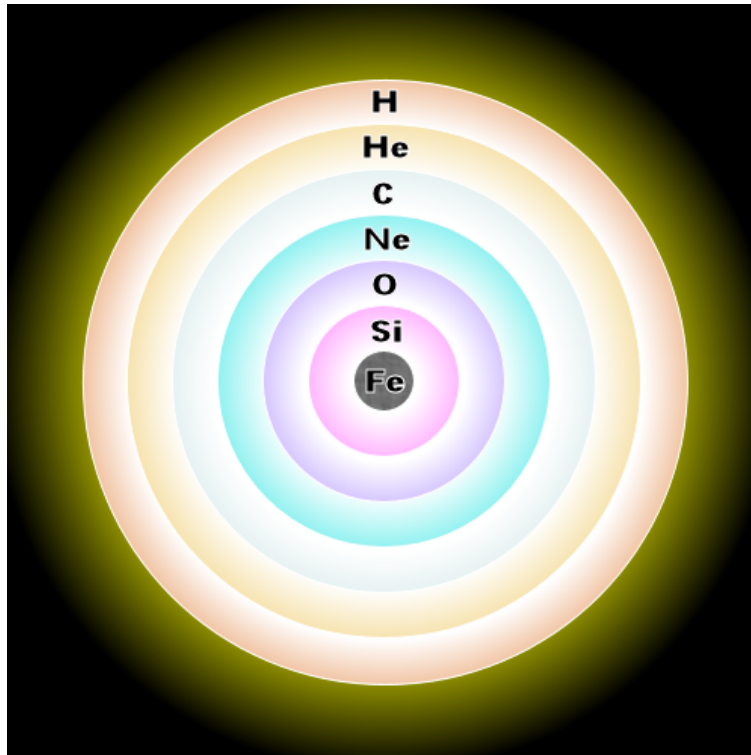


Net result is to fuse four protons into an α -particle (Helium nucleus, ^4He). C, N and O nuclei serve as **catalysts**.

CNO cycle, proposed in 1938 by Hans Bethe, is dominant source of energy in **massive stars**. Also needs **C** to be present!

Total energy production from mass conversion is ~ 25 MeV.

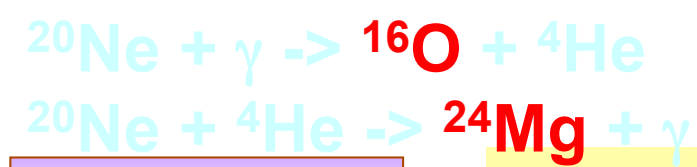
• Nucleosynthesis up to Iron →
only in **massive stars**



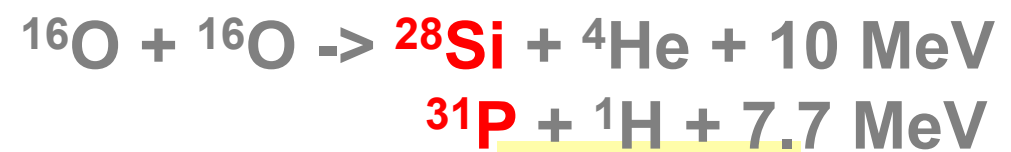
Carbon burning $T \sim 6 \cdot 10^8 \text{ K}$
 $\rho \sim 2 \cdot 10^5 \text{ g cm}^{-3}$

^{20}Ne
 ^{23}Na

Neon burning $T \sim 1.2 \cdot 10^9 \text{ K}$
 $\rho \sim 4 \cdot 10^6 \text{ g cm}^{-3}$



Oxygen burning $T \sim 1.5 \cdot 10^9 \text{ K}$
 $\rho \sim 10^7 \text{ g cm}^{-3}$



Silicon burning $T \sim 3 \cdot 10^9 \text{ K}$
 $\rho \sim 10^8 \text{ g cm}^{-3}$

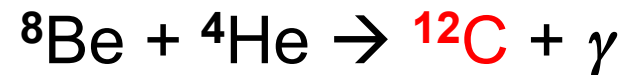
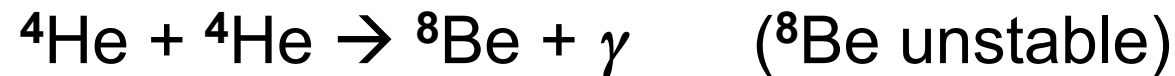
major ash: **Fe**

stars can no longer convert mass into
energy via nuclear fusion !

SUMMARY -- Further fusion processes

At $T > 10^8$ K, other reactions start transforming He into heavier elements:

Triple- α or He burning



After all He has been burnt, C, Ne, O, Mg, Si burning take place: each stage requires higher T , up to $\sim 3 \times 10^9$ K, and higher densities, thus more massive stars.

Process stops when stellar core is made up of ${}^{56}\text{Fe}$ (further fusion would absorb energy!)

→ Hydrostatic equilibrium no longer holds → star collapses

→ Supernova



Energy generation in stars → neutrinos

Only energy released as γ -rays will interact with electrons and protons and heat the interior of a star, such as the Sun. This heating supports the star and prevents it from collapsing under its own weight.

Neutrinos do not interact significantly with matter and do not help support the Sun against gravitational collapse. In a few seconds they escape.

The neutrinos in the PP1, PP2 and PP3 chains carry away 2.0%, 4.0% and 28.3% of the energy respectively.

Thus it will be possible to detect the neutrinos on Earth and verify the theory of the thermonuclear reactions occurring in the Sun (**Solar Standard Model = SSM**).

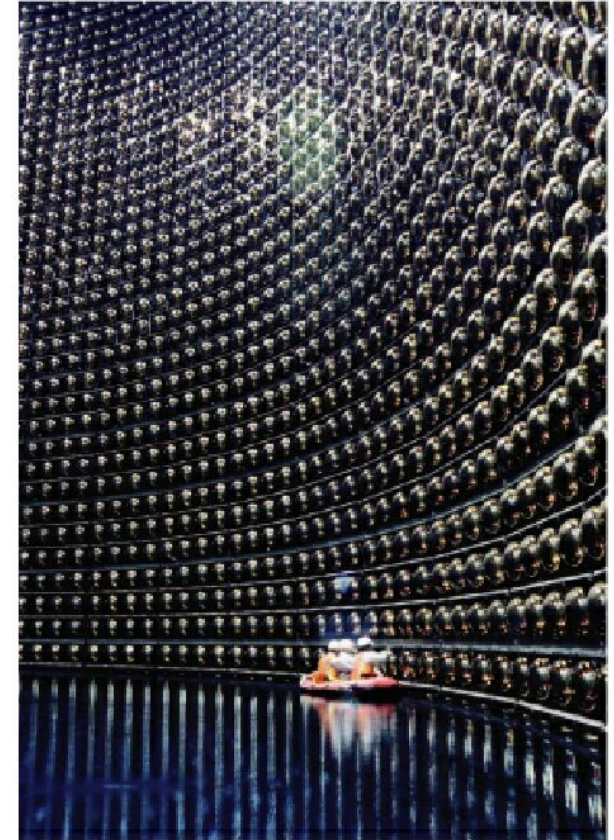
Neutrino Observatories



Homestake Neutrino Detector in South Dakota, 1.5 km underground. Neutrino detectors are placed underground to *shield them from other unwanted interaction with other cosmic ray particles.*



Sudbury Neutrino Observatory in Canada, 2 km underground. The 12 meter diameter tank contains 1,000 tons of heavy water.



Kamiokande Neutrino Detector, Japan

Three neutrino 'flavours'

Three types of neutrinos are known:

Nuclear fusion in the Sun produces only neutrinos that are associated with electrons ('**electron neutrinos**', ν_e).

Laboratory accelerators or exploding stars produce '**muon neutrinos**' (ν_μ) and '**tau neutrinos**' (ν_τ), which are associated with the muon and tau particles (leptons heavier than the electron).

Solar Neutrino Problem

From H burning in the Sun's core, $\sim 2 \times 10^{38}$ neutrinos s^{-1} expected to be produced $\rightarrow \sim 7 \times 10^{14}$ neutrinos $m^{-2} s^{-1}$ at Earth

Since the 1960s neutrino detectors have been built on the Earth to measure the flux of solar neutrinos and verify the SSM:

Mid -1960s - **Raymond Davis**, Homestake gold mine (South Dakota, USA) experiment, using a tank of 100,000 gallons of tetrachloroethylene C_2Cl_4 one mile underground:

solar neutrinos transmute $^{37}Cl \rightarrow ^{37}Ar$ (radioactive)

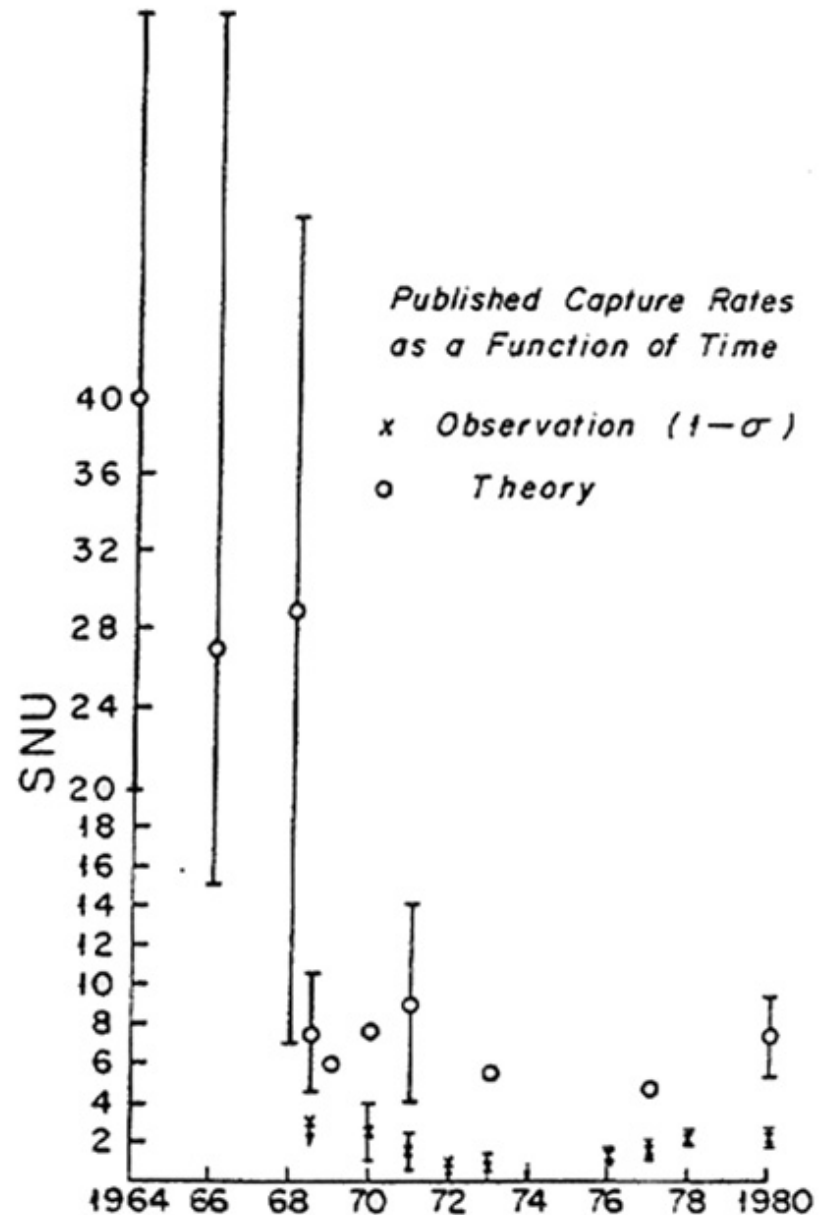
number of ^{37}Ar atoms \rightarrow solar neutrino flux

Only 1/3 of expected high-energy (PP3) neutrinos detected
 \rightarrow 'Solar Neutrino Problem' (SNP) !

Solar Neutrino Problem...

At the same time that **experiments** were improving in sensitivity, **theoretical modelling** of the energy generation in the Sun was evolving →

more and more accurate calculations (particularly by John Bahcall) were carried out to **predict** the number of expected neutrinos (very dependent on Sun's core temperature):

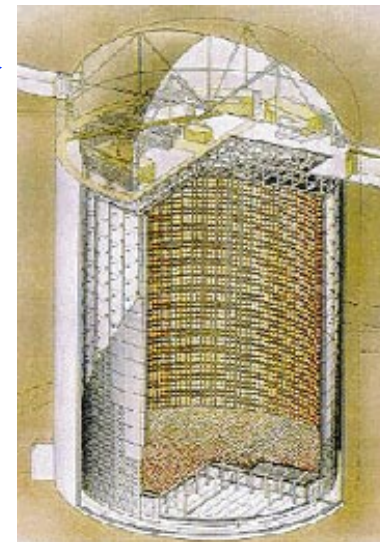


Solar Neutrino Problem...

1989, **Kamiokande** experiment (water detectors) - **only 1/2 of expected high-energy PP3 neutrinos**

Early 1990s, **GALLEX** (GALLium EXperiment), and **SAGE** (RuSsian American Gallium Experiment) detected **just over 1/2 of low-energy neutrinos from PP1** (important because dominant, and calculations more accurate – confirmed PP is the main energy production mechanism in the Sun)

Late 1990s, **Super-Kamiokande** →
(with some sensitivity to flavours other than electron neutrinos) confirmed **high-energy PP3 neutrino deficit by ~50%**



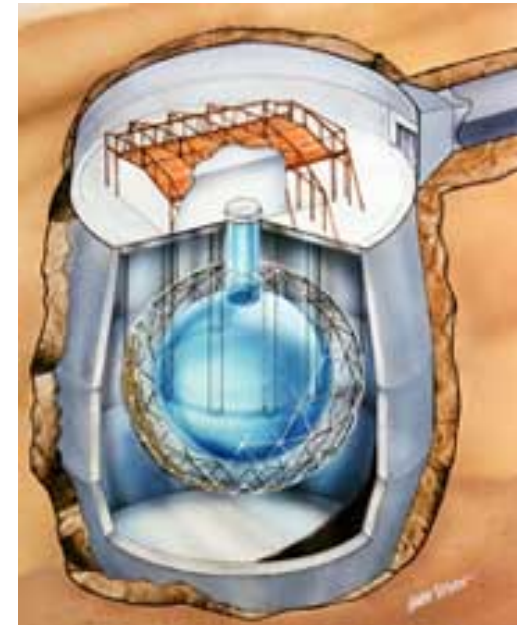
Solar Neutrino Problem

Relative sensitivity of Cl and water experiments to neutrino number and energy suggested **something was happening to neutrinos on their way from Sun to Earth.**

Meanwhile, SSM being tested, and becoming more reliable
→ **Need new neutrino physics?** (as suggested by Pontecorvo and Gribov back in 1969) → **challenge established Standard Model of Particle Physics!**

1999, **SNO** (Sudbury Neutrino Observatory) →

heavy water (D_2O) experiment came on-line with **similar sensitivity to all three types of neutrinos** → detection of ν_μ and ν_τ as well as ν_e



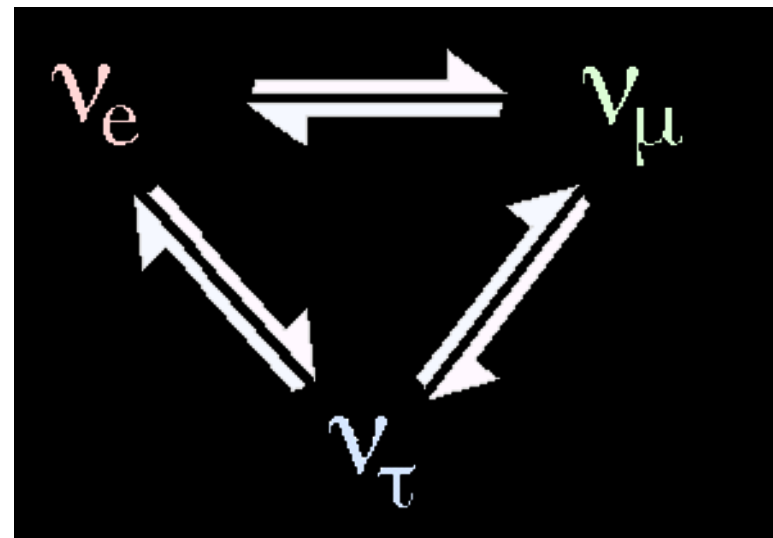
Solution of the Solar Neutrino Problem

18 June 2001, SNO collaboration announced SNP solution:
~2/3 ν_e produced in the Sun transform into ν_μ and ν_τ on their way to Earth

Total number of ν_e , ν_μ , ν_τ is = SSM predictions

Explained by the Mikheyev-Smirnov-Wolfenstein (MSW) effect of 'neutrino oscillations' (enhanced by passage through the Sun)

For neutrino oscillations to occur, neutrinos must have masses (and the Standard Model of Particle Physics has to be revised!)



The mass of neutrinos

Different flavour neutrinos have different masses, with ν_e being the lightest

From experiments, ν_e mass < 2.2 eV

From cosmology, sum of masses < 1 eV

Among current experiments, MINOS and NEMO3 (with UCL, P&A Dep.t participation) \rightarrow few 0.1 eV mass sensitivity limit

Future experiments planned may reach mass sensitivity limit ~ 0.01 eV (SUPERNEMO)

2002, [Nobel Prize in Physics](#) to Raymond Davis and Masatoshi Koshiba for the detection of cosmic neutrinos

PHAS 1102

Physics of the Universe

5 - Stellar evolution

PARTIAL notes



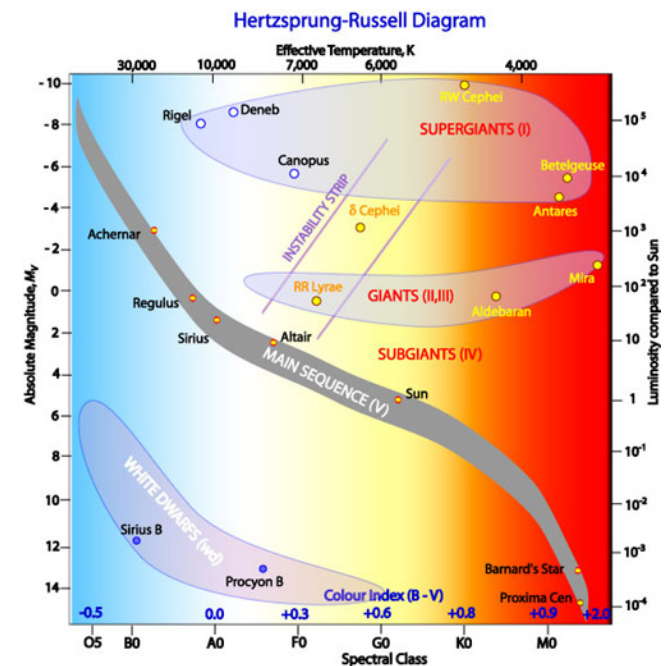
Stellar evolution

Study of physical changes taking place in stars as their composition is altered because of thermonuclear reactions.

General sequence: Protostar → Pre-Main Sequence (PMS) → Main Sequence (MS) → post-Main Sequence

Main physical parameter determining evolution: **MASS**

Evolutionary track: Plot of points showing time sequence of evolutionary stages of a star on an H-R diagram (which is collection of star snapshots - may use colour, or spectral type, instead of temperature, and magnitude in place of luminosity).



The birth and evolution of stars

Most (90%) of stars lie on the MS, where stars burning H to He (PP or CNO cycles) are in hydrostatic equilibrium.

How do stars get on to the MS, and what happens afterwards?

Stars are born from huge interstellar clouds of gas (mostly in the form of molecular H, i.e. H₂) and dust, which are massive enough to contract gravitationally: collapse starts in free-fall (particles do not collide → no internal pressure): **protostar**

As density increases, cloud's core traps (becomes opaque to) IR radiation from dust heated by collisions with molecules, collapse slows down, hydrostatic equilibrium established:

Pre-Main Sequence star

Takes ~ 1 million years to form a PMS star of 1 solar mass

A tour of star-formation...slides

From PMS to MS stars

PMS star shines by slowly contracting, while matter accretes onto its core and the central temperature raises.

Finally, central temperature high enough to start H burning, collapse halts and star is now a **real MS star**.

Hydrostatic equilibrium maintained by heat from thermonuclear reactions: **Zero-Age Main-Sequence (ZAMS) star** (before any substantial amount of H is fused to He)

Takes ~ 20 million years from initial collapse to ZAMS star

Higher mass stars arrive on MS with higher luminosity and temperature.

Main Sequence evolution (1)

Main Sequence phase: entire phase of H burning in the core
(converting H \rightarrow He via PP and CNO)

Duration of MS phase (τ_{MS}) depends on star's store of energy (amount of H, i.e. its **mass**) and the rate at which energy consumed (**luminosity**).

Evolution faster for more massive stars: more massive stars have higher central temperatures, thus nuclear reactions occur faster. So:

$\tau_{\text{MS}} \sim 10^{10}$ yr for a 1 solar mass star

$\tau_{\text{MS}} \sim 10^7$ yr for a 15 solar mass star

Main Sequence evolution (2)

For 1 solar mass star, Main Sequence lifetime 10^{10} years
(ZAMS \rightarrow MST, or Main Sequence Turnoff)

As $4 \text{ H} \rightarrow 1 \text{ He}$, number of particles falls

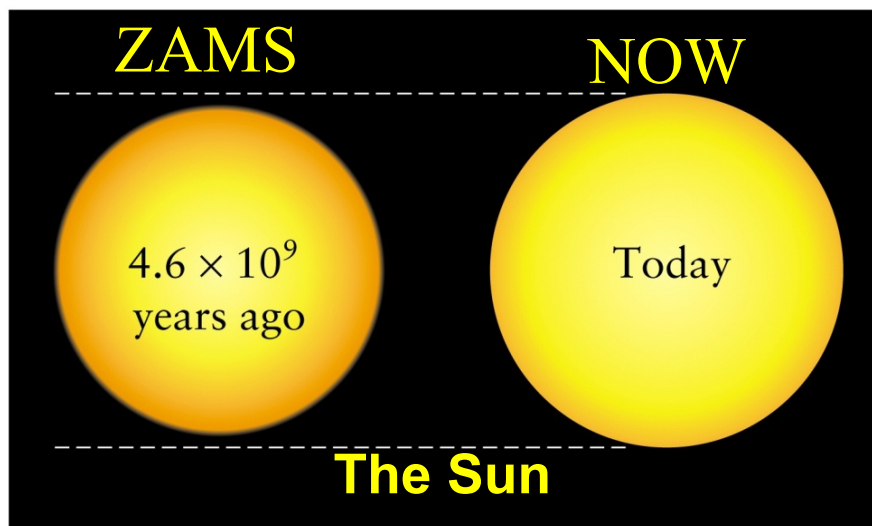
pressure drops

core contracts

core temperature rises \rightarrow pressure rises

\rightarrow increased luminosity, increased envelope radius

(‘Mirror law’: shrinking core \rightarrow expanding envelope!)

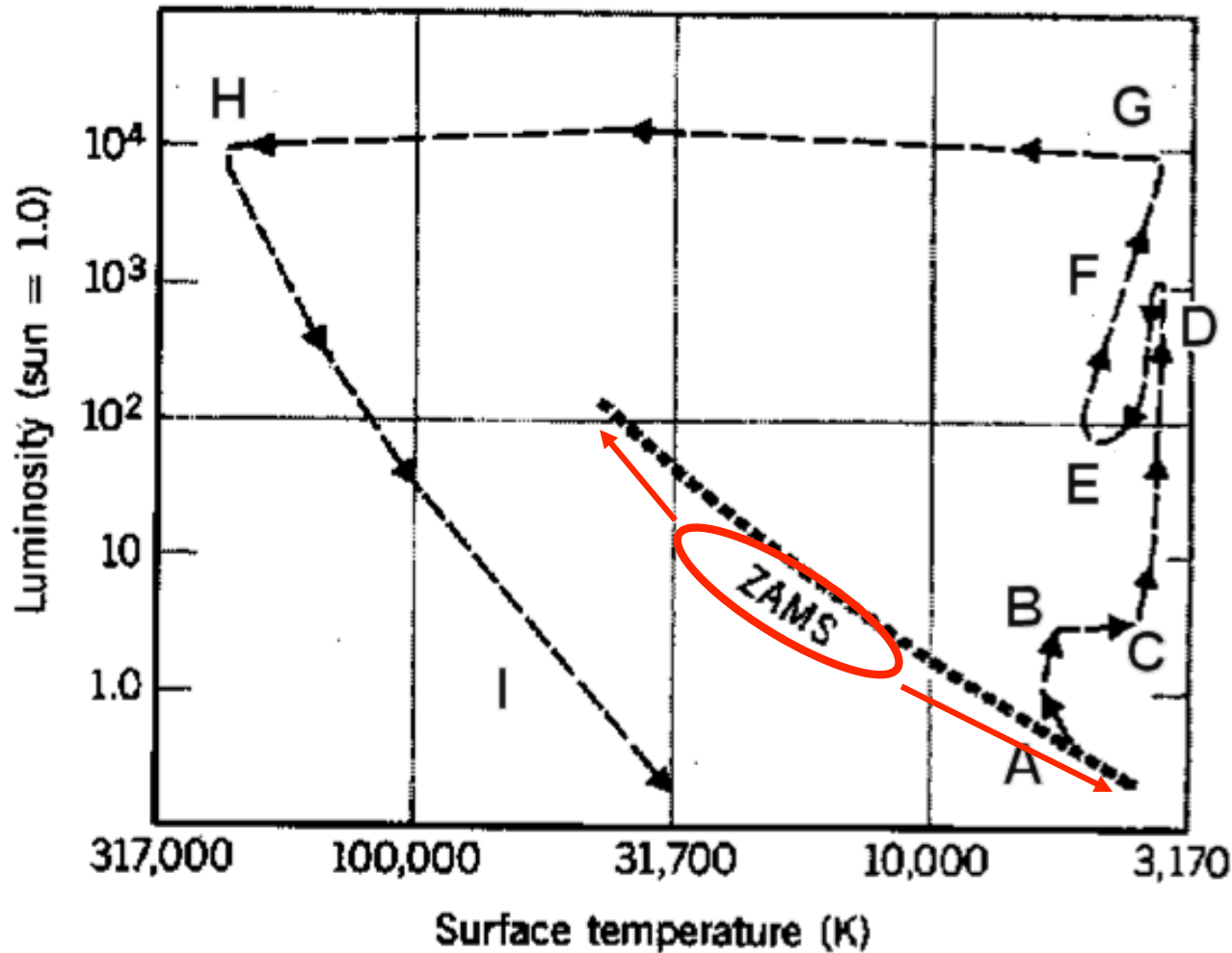


Surface temperature rise =
300K

Luminosity up by 40%
6% increase in radius

Post-Main Sequence evolution (1 solar mass star)

Evolution implies composition and size change, thus **luminosity** and **temperature** change too.

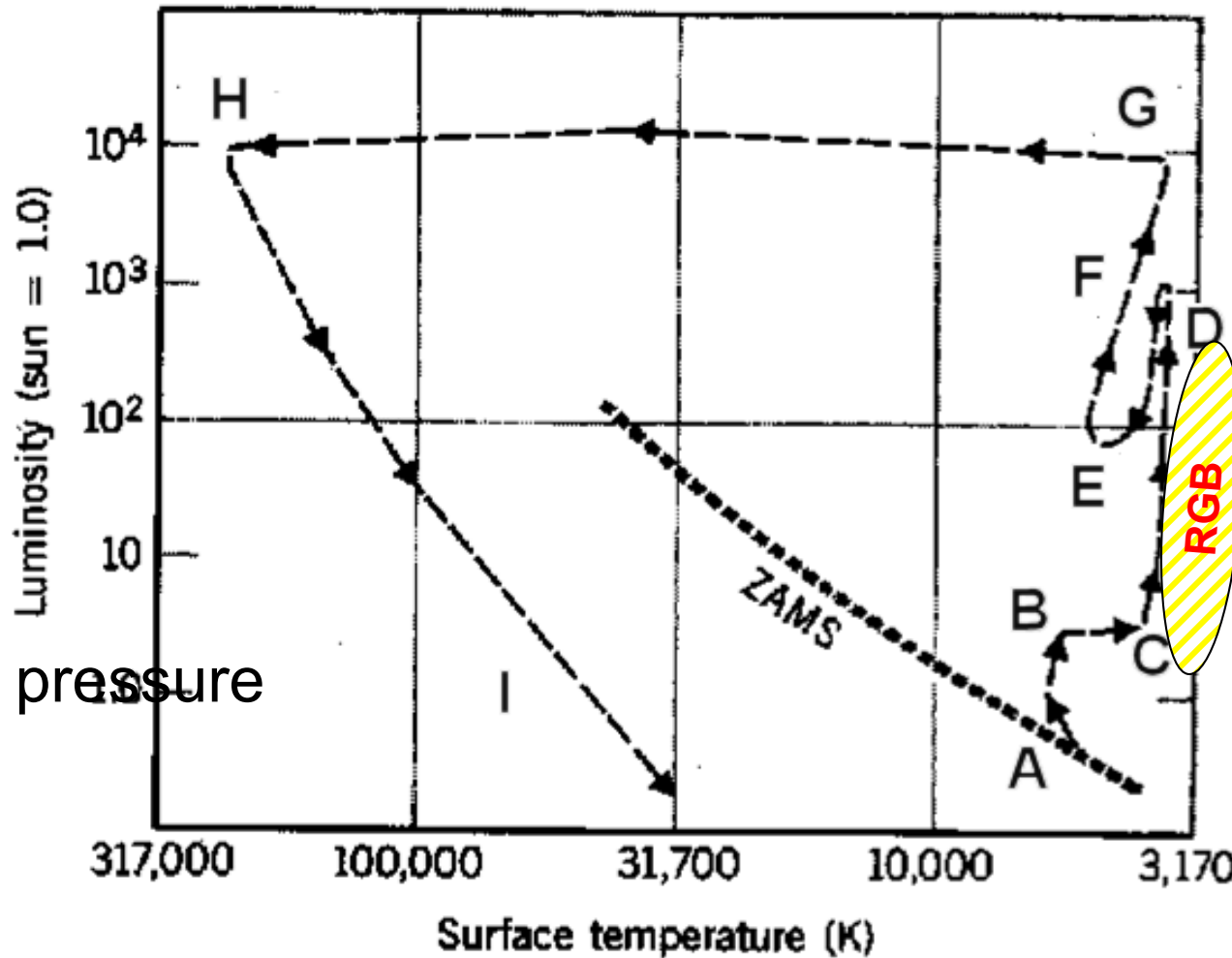


A-B: H \rightarrow He, star's core shrinks, core temperature up, luminosity up

B-C: H exhausted in core, but burns in outer shell, envelope expands, surface temperature down

Post-Main Sequence evolution (1 solar mass star)

C-D: Convection carries most energy into envelope →
Luminosity increases greatly →

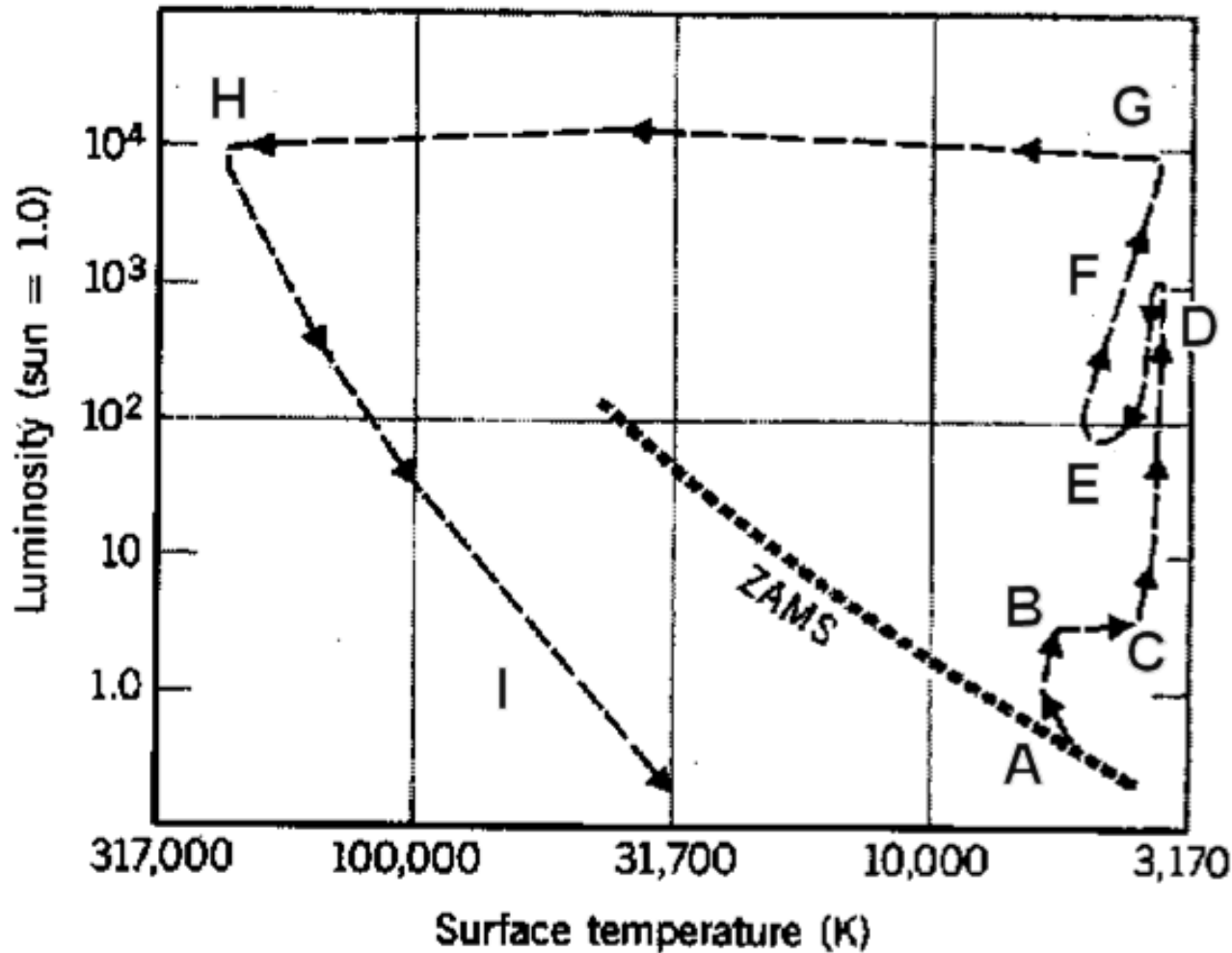


Red Giant, $R \sim 100 \times$
MS radius (star
moves along **Red
Giant Branch**, RGB)

Core density so high
that electrons form
a **degenerate gas**
(degenerate

depends on **density**,
not on temperature)
→ **balances gravity**
in place of nuclear
reactions

Post-Main Sequence evolution (1 solar mass star)

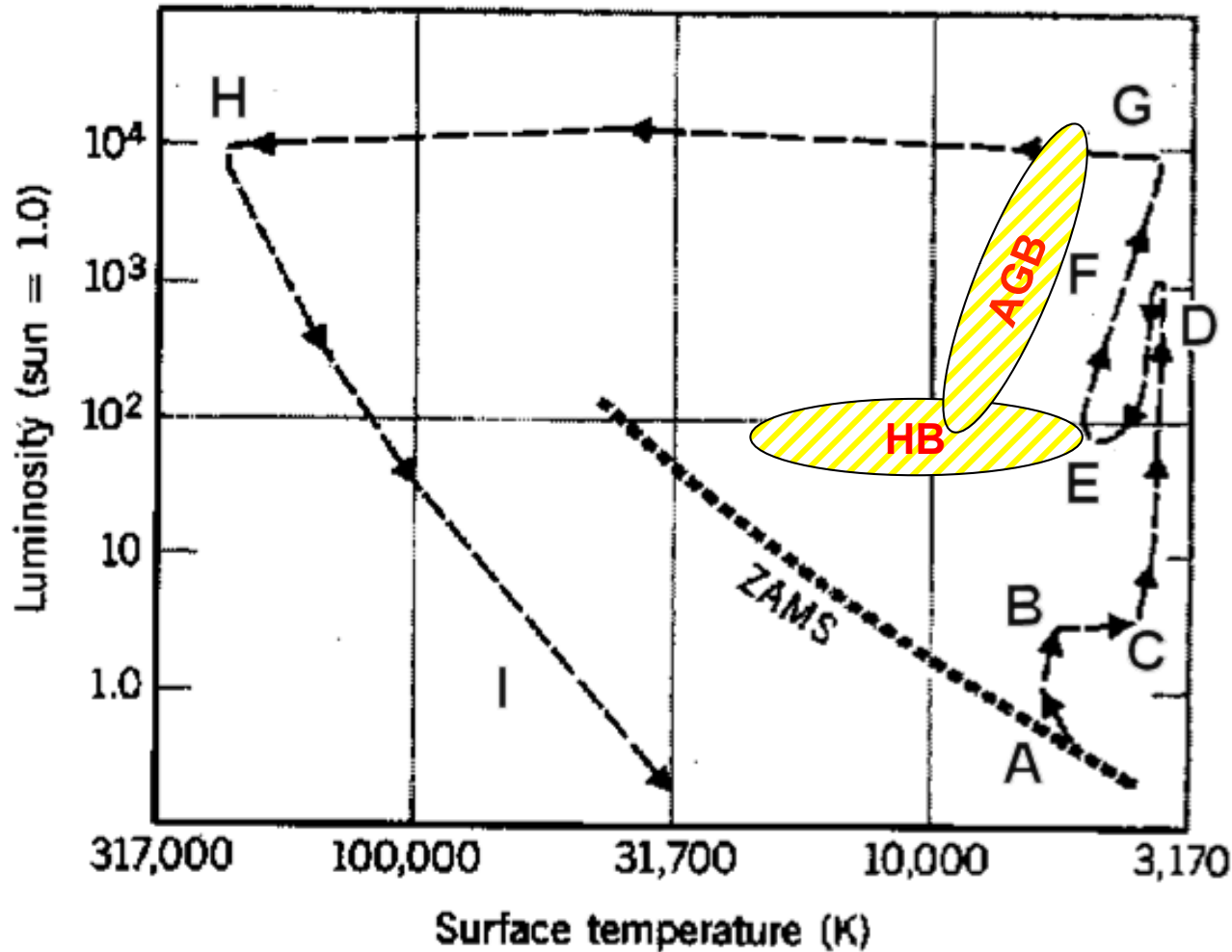


D: Core reaches a temper. of $\sim 10^8$ K
→ He burning starts
→ temper. goes up in the core, but pressure does not (degenerate gas)
→ He burning rate goes up
→ temper. goes up
→ He flash
(He burning spreads through core in few min because of gas high thermal conductivity)

Post-Main Sequence evolution (1 solar mass star)

D-E: When core gets to $\sim 3.5 \times 10^8$ K, electrons become non-degenerate, core expands and cools \rightarrow stable

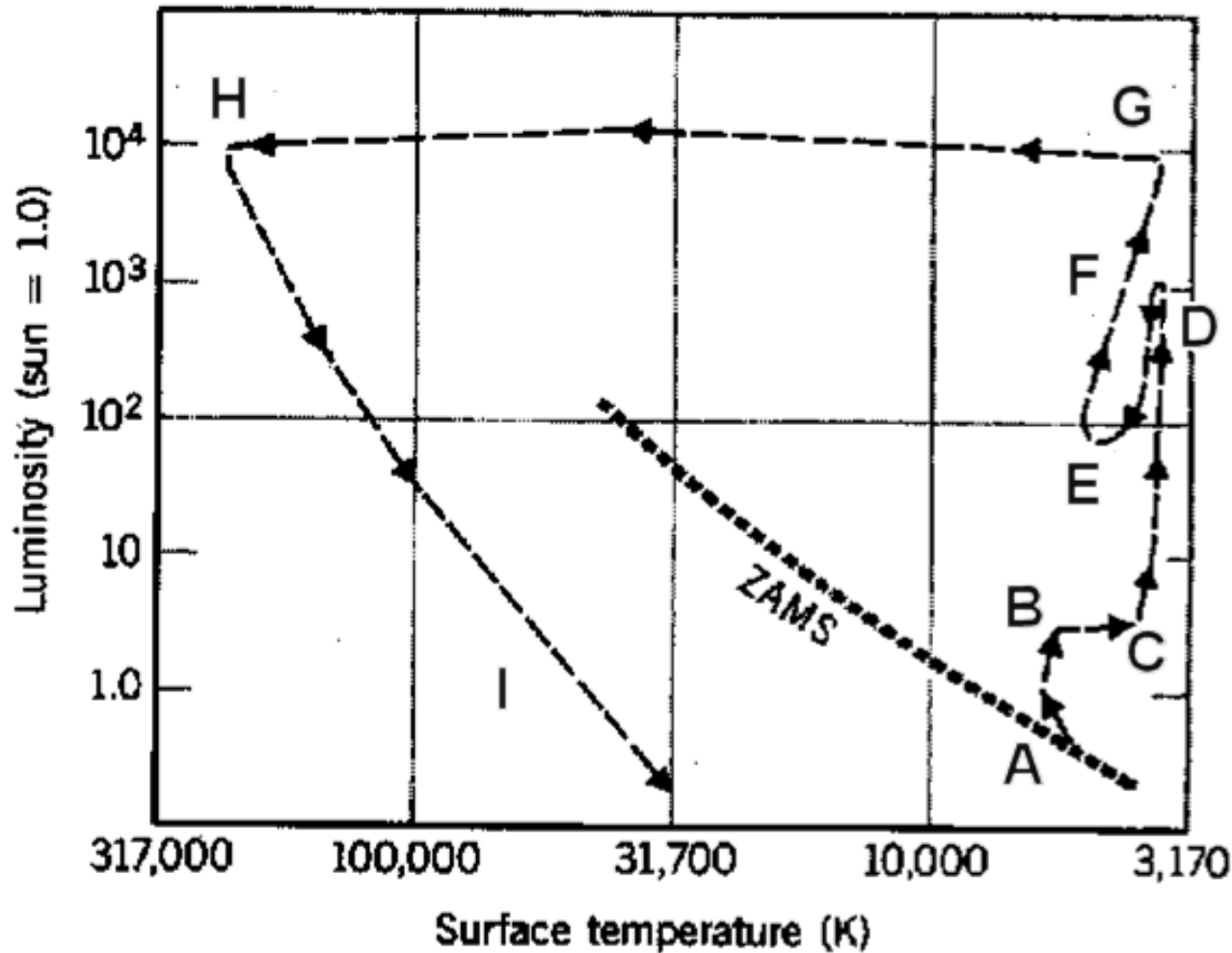
He burning phase with H shell burning (star joins **Horizontal Branch, HB**)



F: He exhaustion, C core contracts (degenerate gas) \rightarrow envelope expands, second **Red Giant** phase (**Asymptotic Giant Branch, AGB**)

Post-Main Sequence evolution (1 solar mass star)

Star not massive enough to ignite C ...

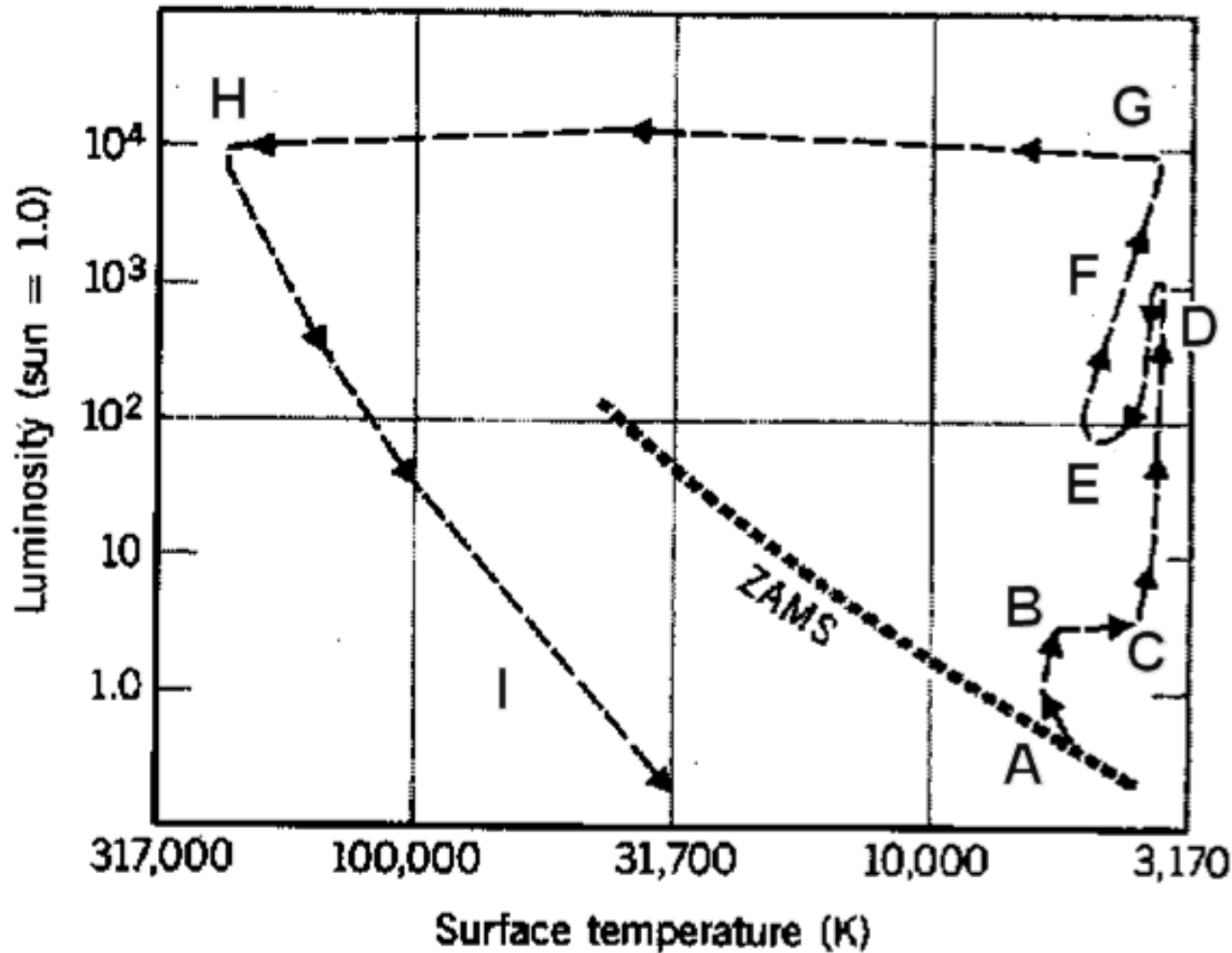


G: He burning to C (triple- α process) very sensitive to temperature \rightarrow He burning (now in a shell) causes star to become **unstable** \rightarrow star pulsates and ejects outer layers

G-H: Core exposed as a very hot star, ejected envelope forms a nebula for $\sim 10^4$ yr (Planetary Nebula phase)

Post-Main Sequence evolution (1 solar mass star)

Planetary Nebula keeps expanding until it dissipates in the Interstellar Medium.

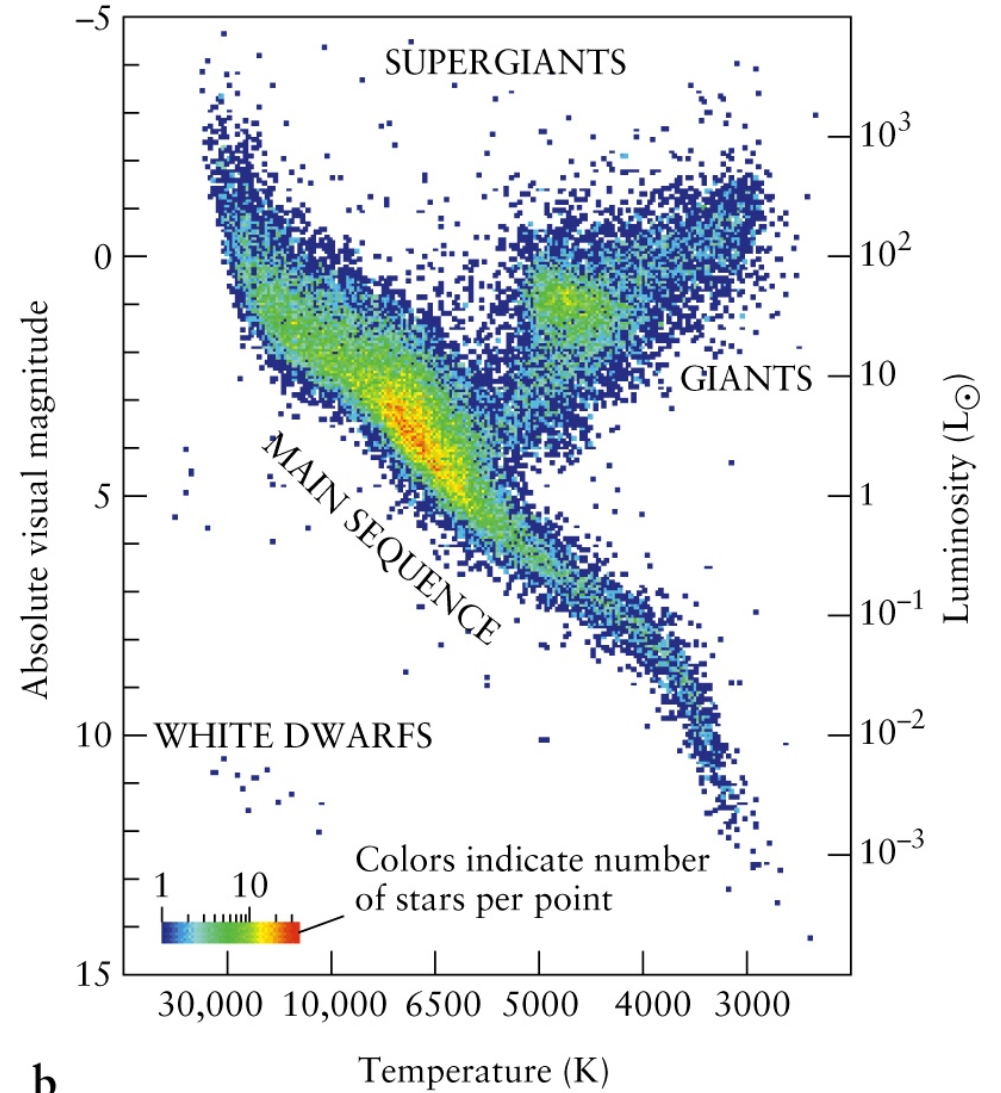
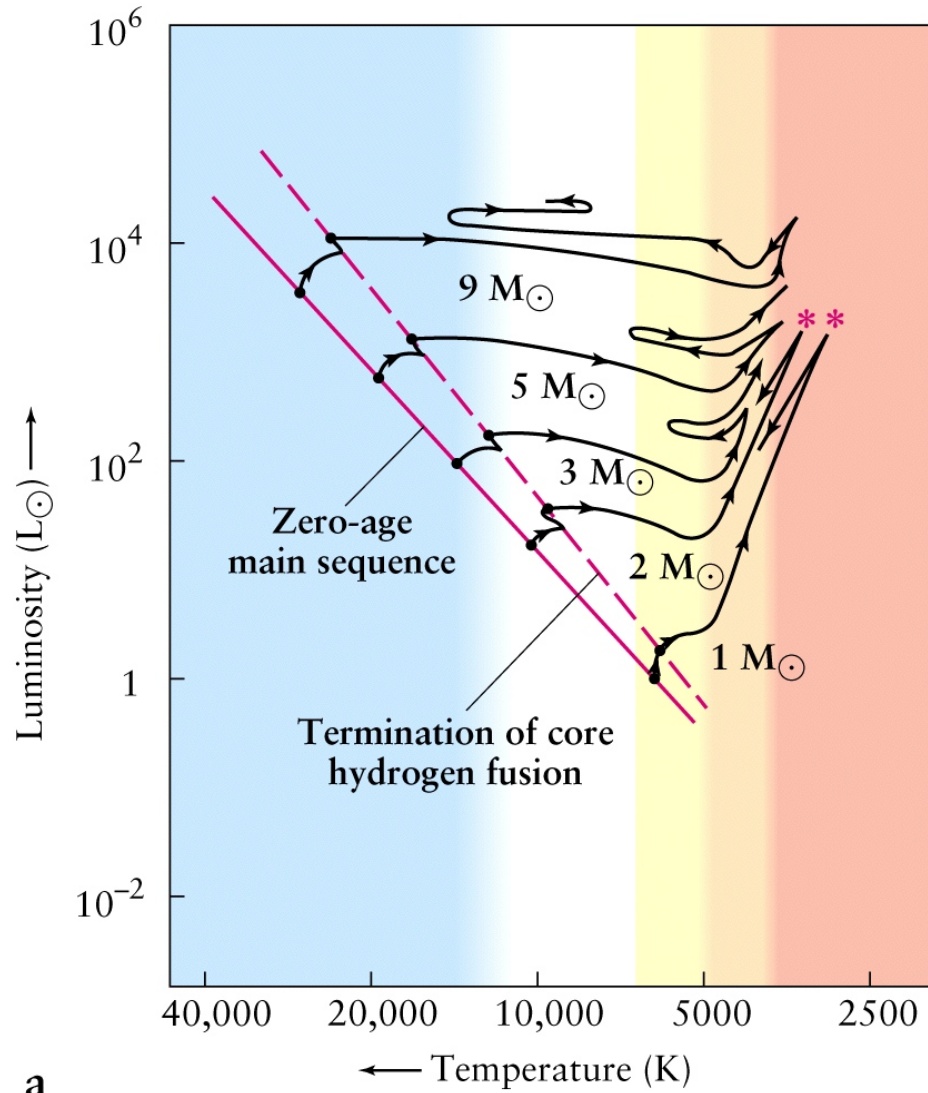


I: C core supported by electron degenerate pressure → star (~ Earth's size) never gets to C ignition temper. → C white dwarf → cools off to black dwarf in a few 10⁹ yr

...evolution...birth mass REALLY matters!

...more in the lectures...

Stellar evolution for various stellar masses



Stellar evolution of **extremely massive stars**

Extremely massive stars (50 – 100 solar masses; radiation pressure prevents formation of higher >100 masses) lose mass by **stellar winds**, which slow their evolution

Sun loses $\sim 10^{-14}$ of its mass per year in the solar wind

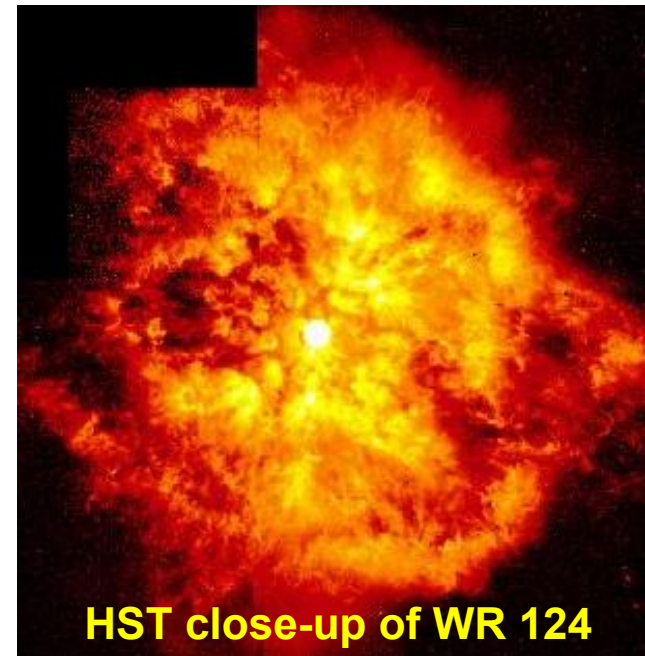
Massive O stars may lose 10^{-7} to 10^{-6} solar mass per year

Extremely massive stars lose 50-60% of their mass by end of MS phase: outer layers stripped off

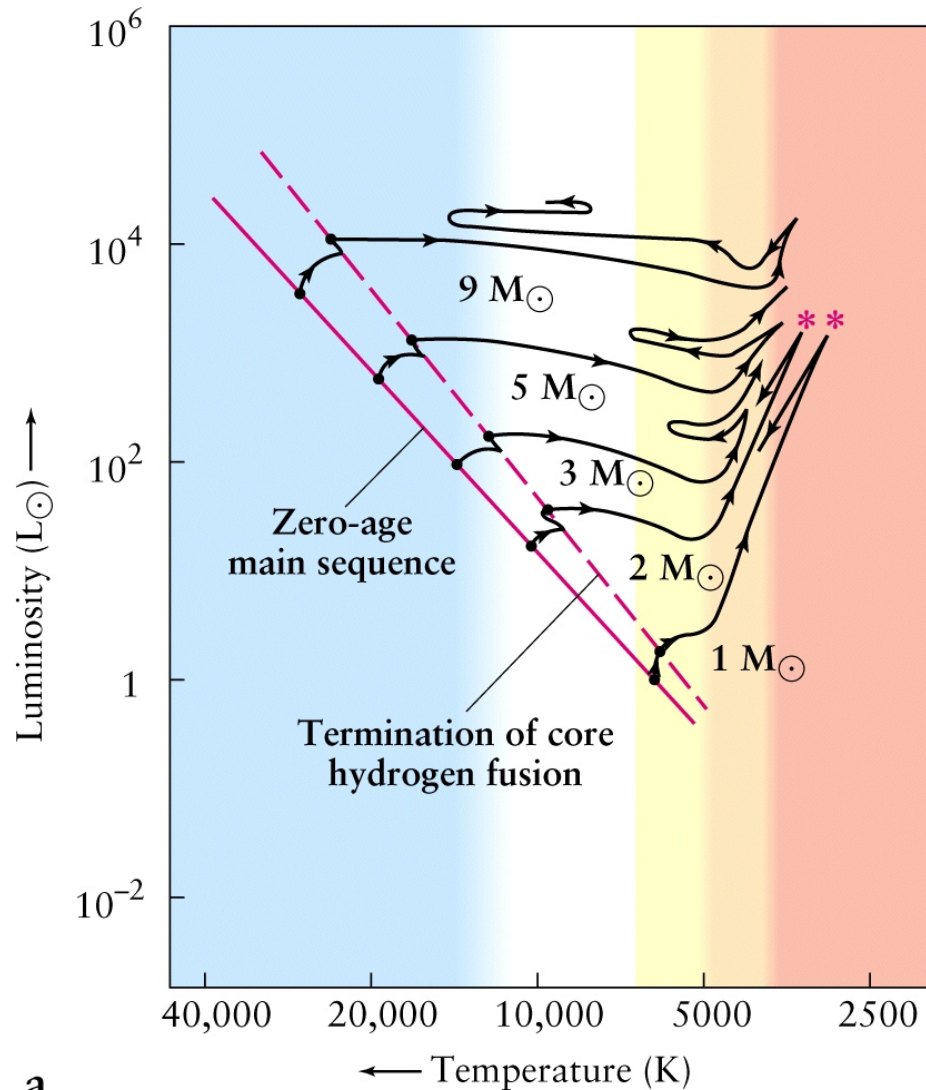
→ core is revealed, may not turn into Red Giant because no outer shell

→ **Wolf-Rayet stars** (strong N and O emission lines)

→ **Supernova** (named **Type Ib**)



Stellar evolution for >1 solar mass stars



On MS, H burning by **CNO** cycle
(higher mass, hotter core)

Post-MS, similar to 1 solar mass,
but:

Core temper. higher \rightarrow burning of
further elements occurs

No He flash, core not degenerate

Successive Red Giant phases;
after each core burning stage,
reaction continues in a shell
 \rightarrow 'onion-like' structure, shells
with different reactions

$< 8 M_{\text{Sun}}$: Evolution similar to that of 1 solar mass star

$> 8 M_{\text{Sun}}$: Nuclear burning \rightarrow **Fe core** \rightarrow collapse \rightarrow **Supernova**

Nucleosynthesis

At > 8 solar mass, Ne burning ($\sim 10^9$ K), then
O burning (2×10^9 K)
Si burning (3×10^9 K) \rightarrow S \rightarrow Fe (Ni)
Faster and faster!! (C: few hundred years; Si, a day)

Massive stars are rare, but most important: they fuse heavy elements and spread them back into the interstellar medium via Supernovae.

Red Giants play major role in nucleosynthesis:

Thermal pulses in He burning shell encourage formation of neutron-rich isotopes.

Convection pulls up elements formed in the core by H burning
(\rightarrow 'dredge-up')

The path to Supernova

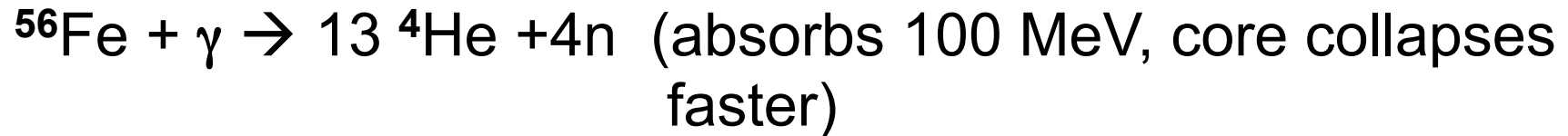
So called 'Type II Supernovae' arise from evolved stars of **> 8 solar mass** (O and B spectral type), and occur only in spiral galaxies, especially in spiral arms (regions of strong star formation).

Such massive stars can fuse elements up to Fe

- Fe core grows (Fe cannot fuse and release energy), supported by electron degeneracy pressure
- when core size reaches the **Chandrasekhar limit** (**1.44 solar mass**, or **3×10^{30} kg**) degeneracy pressure no longer sustains it
- core contracts and gets hotter
- **Catastrophic collapse** ('core collapse' supernova)

Core collapse Supernova (Type II)

At $\sim 6 \times 10^9$ K, photodissociation of Fe (in $\frac{1}{4}$ second):



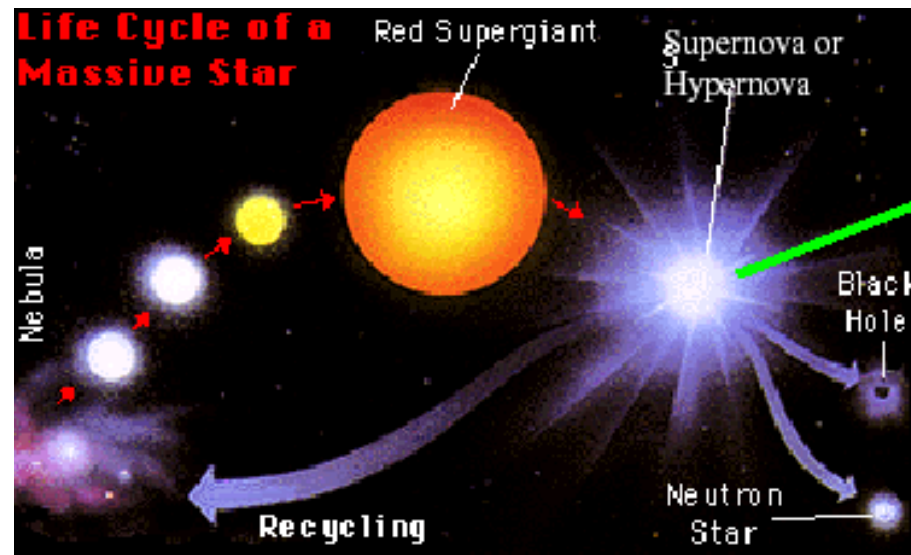
Proton and electrons 'squeezed' together to form neutrons, emitting pulse of **neutrinos** (which carry energy away, accelerate core collapse, are absorbed by outer layers, and accelerate their expulsion) in **milliseconds!**

Collapse eventually halted by short-range repulsive neutron-neutron interactions involving degenerate neutron gas pressure as well as the strong nuclear force \rightarrow **neutron star** forms

Core collapse to a black hole

Neutron stars of > 3 solar mass are unstable against further collapse to a black hole (object predicted by Einstein's General Relativity with a gravitational field so strong that nothing can escape from it - not even light)

→ Collapse of 25 - 50 solar mass stars
with a core size > 3 solar mass
can lead to formation of black holes



...birth mass matters!!

'Bounceback'

Once collapse stops, innermost core bounces back somewhat, infalling outer layers rebound, producing **shock wave** (crossing star in **a few hours**) that blows off the rest of the star's material (at speeds of 5000 – 30000 km s⁻¹)

Total energy released ~ 10⁴⁶ Joule (ν), 10⁴⁴ Joule (kinetic = energy Sun will produce over 10¹⁰ yrs)

→ **Supernova Remnant (SNR)**

Outer layers still contain fuel for nucleosynthesis (explosive)

→ flood of energetic neutrons, absorbed by heavy nuclei

For example, within several minutes



One major product of Supernova explosion is expected to be radioactive **⁵⁶Co**, with half life of 77 days → γ -rays from its decay heat expanding envelope

Supernova → Supernova Remnant

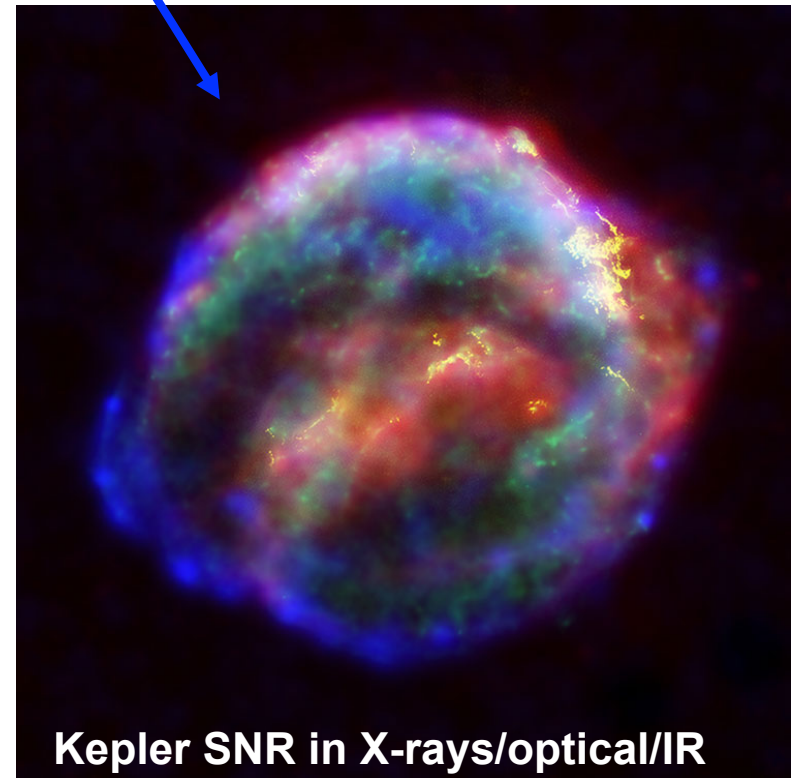
Supernovae are quite rare occurrences, ~1 per 50 – 100 yrs in our Galaxy (but none observed since 1604)

→ seen mainly in other galaxies, e.g. → SN1994D in NGC4526



Visible brightness can increase by up to $\times 10^8$, then decays over several yrs

Kinetic energy of expanding outer layers heats interstellar medium, shell of gas keeps shining in X-ray, visible and radio wavelengths for up to 100,000 yrs, with material slowly cooling off



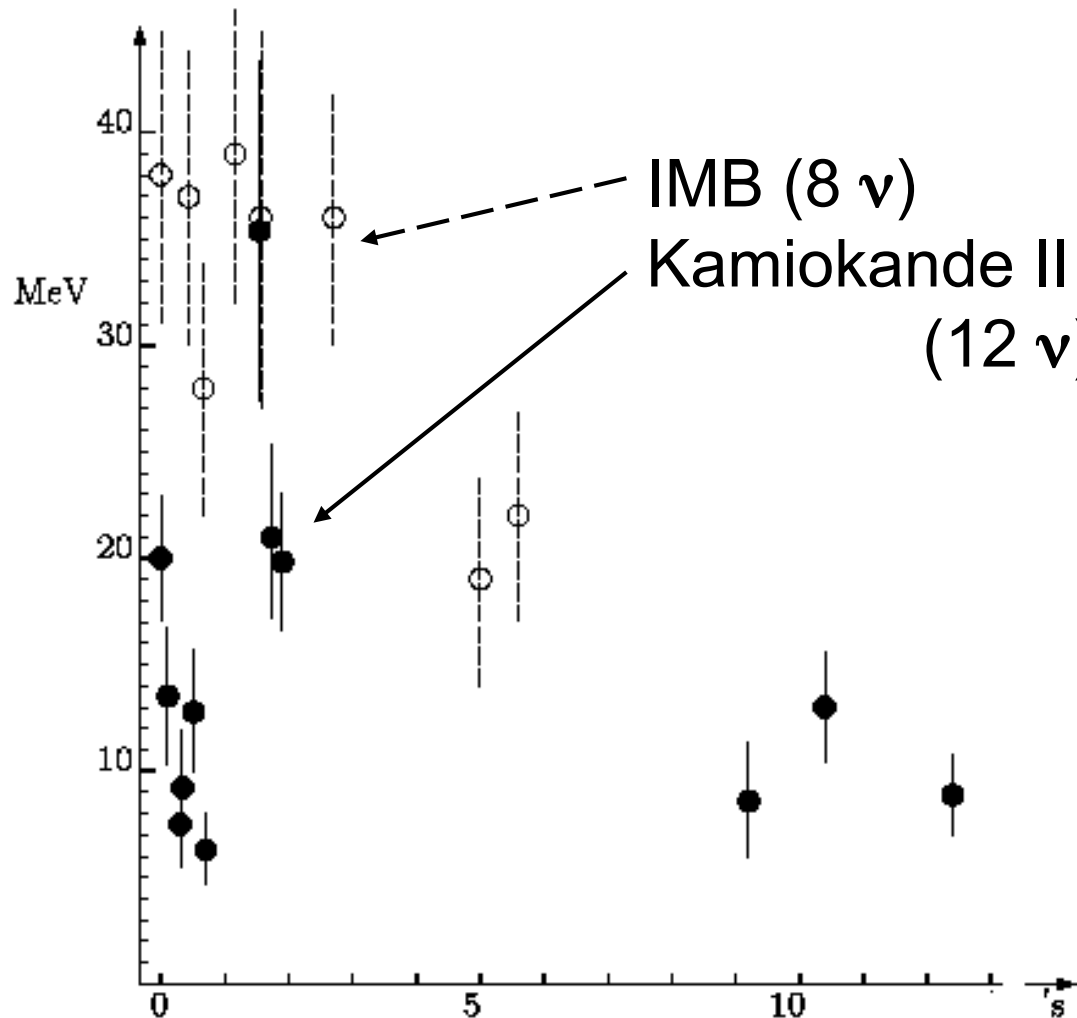
Kepler SNR in X-rays/optical/IR

(<http://apod.oa.uj.edu.pl/apod/ap041008.html>)

When SNR central density dropped sufficiently, neutron star at its core may appear (hot → X-rays, visible, radio)

Neutrinos from SN1987A

~3 hours before visible light reached Earth, burst of neutrinos (24) detected at three separate observatories

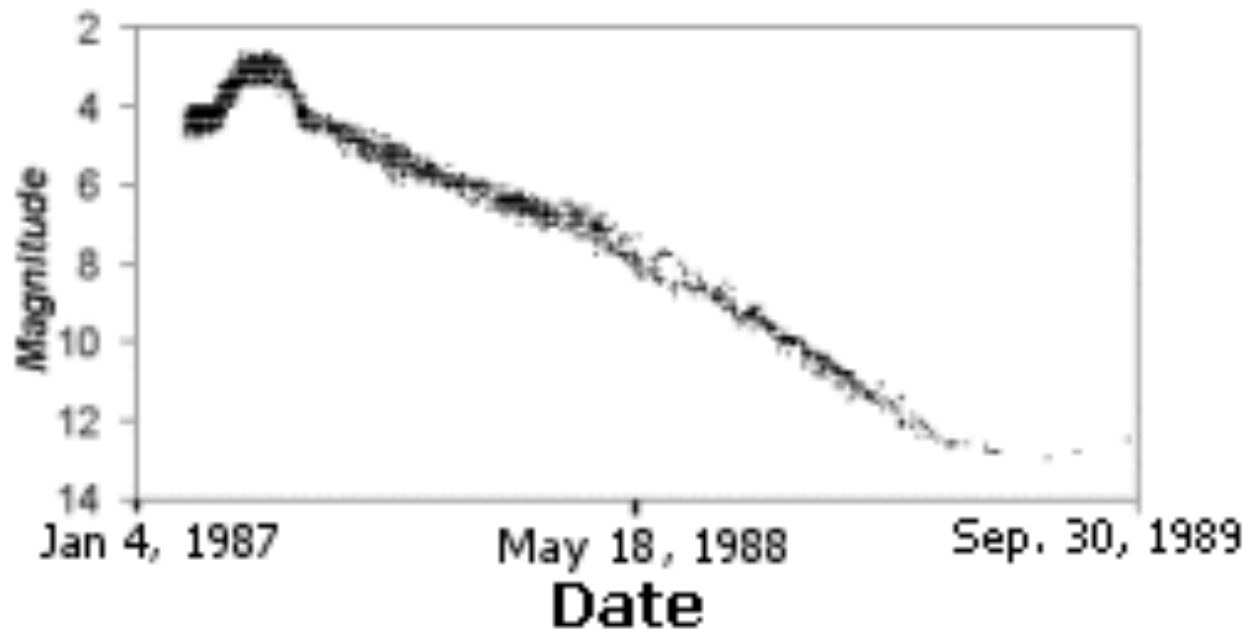


Remarkable confirmation that SN theory is correct, by observation of a neutron star formation!

Neutrino astronomy (extra-solar) was born!

The *decay* of SN1987A

Peak visible brightness in May 1987, then exponential decay from July to November exactly matches that expected for ^{56}Co , again confirming theory



Observations over subsequent ~ 20 years were to raise some surprises ...

SN1987A ring structures

Since 1990, HST has kept an attentive eye on SN 1987A, observing it at least once a year → SNR (in the centre) is surrounded by inner and outer ring structures → measured expansion speeds of 30 – 40 km s⁻¹, 100-1000x less than SN

HST has also observed ‘hot spots’ developing in the inner ring structure, which has become generally brighter with time (the two bright stars are unrelated)

SN1987A *ring expansion*

Inner ring structure also studied
in X-ray and radio band

Origin of ring structure still a
mystery: spectra show unusual
N enrichment + low speeds

→

Material expelled by progenitor
supergiant 10-20,000 yr before
SN (and now glowing because
of SN UV flash)? But why not
in all directions, rather than
puffing rings like a pipe smoker?

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Physics of the Universe

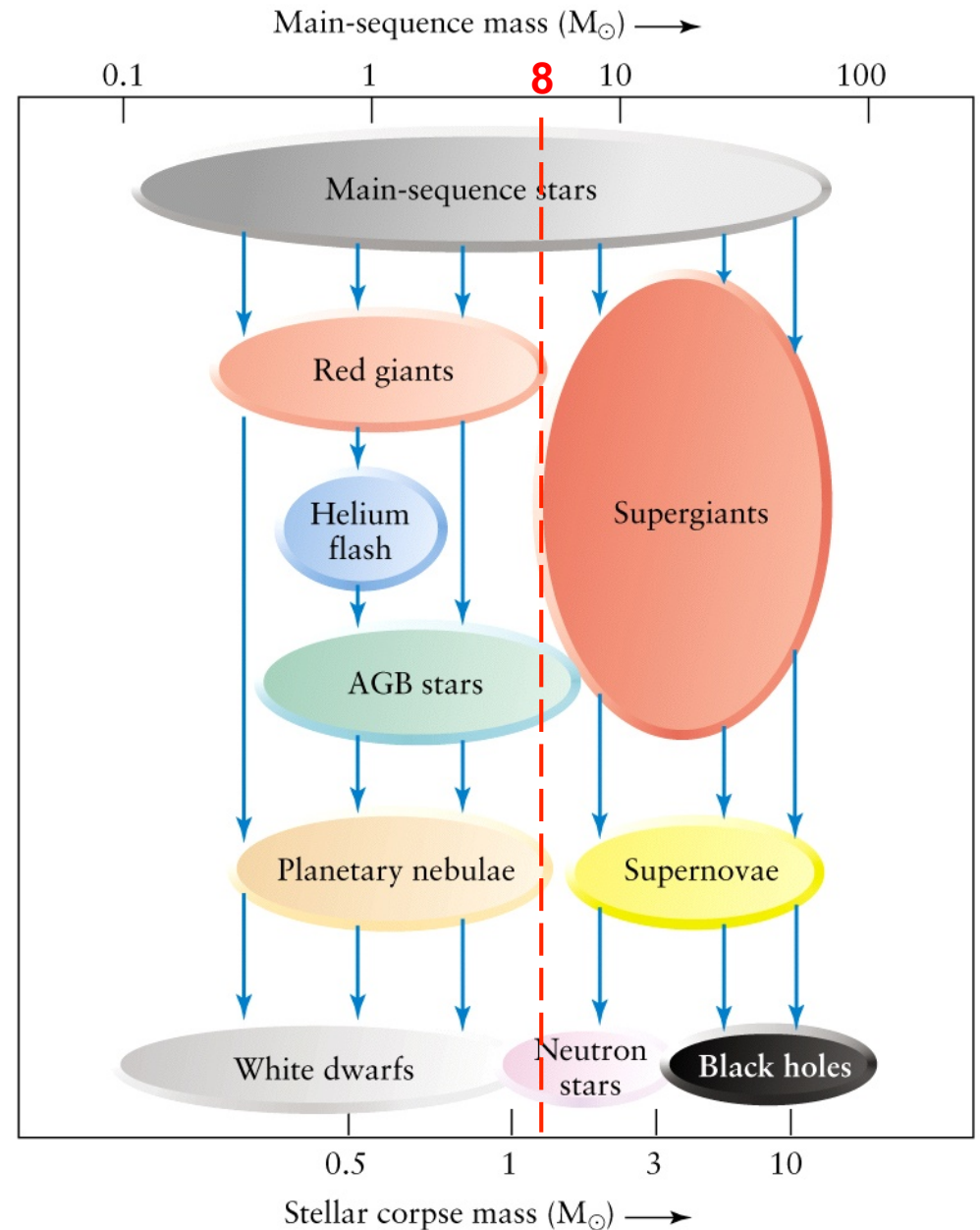
6 — End-states of Stellar Evolution PARTIAL HANDOUTS



End points of stellar evolution

Kind of stellar remnant left over after post-MS evolution depends on the **core mass at death** (which is less than star's MS mass, because of mass lost in RG phase, PN or SN):

Remnant..



White dwarfs

Planetary nebula core, after loss of outer envelope, shines as a very hot, dense star: a **white dwarf**

What kind of white dwarf?

MS mass

- | | | |
|------------------|----------------|---------------------------|
| < 0.5 solar | No He ignition | → He white dwarf |
| > 0.5, < 5 solar | No C ignition | → C - O white dwarf |
| > 5, < 8 solar | Can burn C | → O - Ne - Mg white dwarf |

Typical properties:

Mass = 0.7 solar mass

Radius = 0.01 solar radius = 7×10^6 m

Average density = 10^9 kg m⁻³

In a few 10^9 yrs , thermal energy radiated away → black dwarfs
(would be very difficult to detect, temperature just above 2.7 K
microwave background; perhaps through gravitational effects?)

Degenerate electron gas

White dwarfs supported by **electron degeneracy**

Electrons are degenerate according to **Pauli's Exclusion Principle** (law of Quantum Mechanics, 1925): Two electrons cannot occupy simultaneously the same quantum state (i.e. two things cannot be in the same place at the same time), so they get so packed together that a limit to further compression is reached.

Quantum state: Particular set of circumstances concerning locations and speeds that are available to particles

Electrons distributed more or less uniformly around nuclei, which are also tightly constrained as pressure increases, similar to crystalline lattice (like a solid rather than a gas)

Chandrasekhar limit

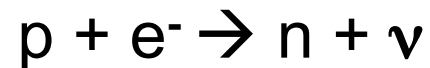
White dwarfs have peculiar properties, e.g.
as mass increases, radius decreases (mass-radius relation)

→ Ultimate mass limit for white dwarfs:

Chandrasekhar limit of ~ 1.44 solar mass = 3×10^{30} kg

In a contracting stellar remnant with > 1.44 solar mass,
degenerate electron gas pressure cannot hold gravity off

→ Matter crushed to such high densities that



Protons and electrons squeezed into neutrons →

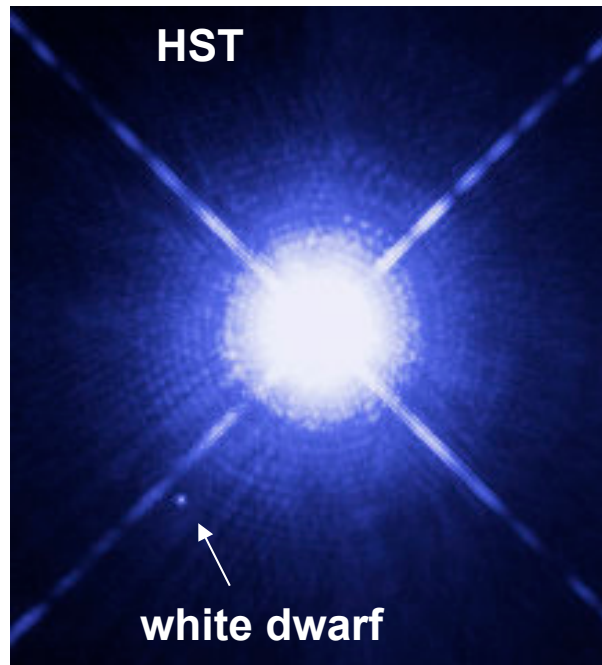
Degenerate neutron gas, which halts the collapse →

neutron star

This process is generally associated with the evolutionary end
of massive stars and Type II SN

Sirius A and B

Sirius (α **Canis Majoris**), brightest star in the night-time sky, $m_V = -1.47$; binary star system consisting of blue-white MS star (Sirius A) + faint **white dwarf** companion (**Sirius B**)



Sirius B parameters: Mass = 1.05 solar mass
Radius = 7×10^{-3} solar radius
 $T_{\text{eff}} = 29,500$ K

Supernova Type Ia

White dwarfs may also exceed the Chandrasekhar limit through **accretion** (a few white dwarfs are in binary systems with non degenerate companions)

→ This triggers thermonuclear detonation which destroys the white dwarf, producing very luminous **SN Type Ia** (from C - O white dwarf progenitors)

→ Lightcurves follow decay of ^{56}Ni and ^{56}Co

Small dispersion in maximum luminosity → good 'standard candles' for **extragalactic distance scale**

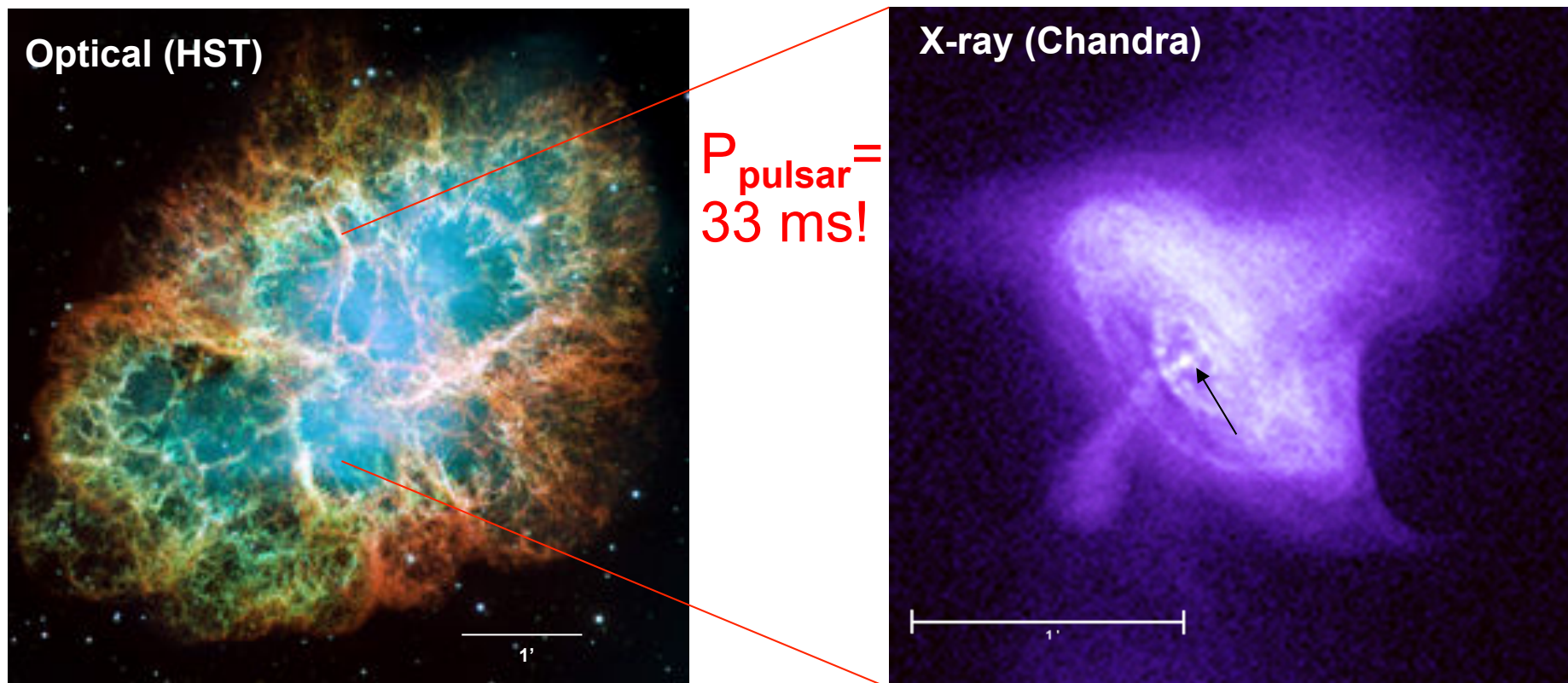
→ HST 'Key Project' to determine expansion rate and age of the Universe (see second half of the course)

Neutron star properties

A special SNR with pulsar: the Crab Nebula

SN1987A neutron star not yet observed: expected to become visible in X-rays in ~ 30 yrs (when expanding outer layers become 'optically thin').

However, most famous historical Supernova exploded in 1054 (Chinese records) to leave the **Crab SNR** and **pulsar** (thought to be the neutron star remnant of the exploded star).



The Crab Nebula

Distance (~ 2 kpc) and age (~ 950 yrs) estimated from rate of expansion of gaseous shell. Pulsar's slow down: $\sim 4 \times 10^{-6} \text{ s yr}^{-1}$

Visible line emission from filaments (gas density higher)
Nebula and pulsar are strong **radio and X-ray sources**

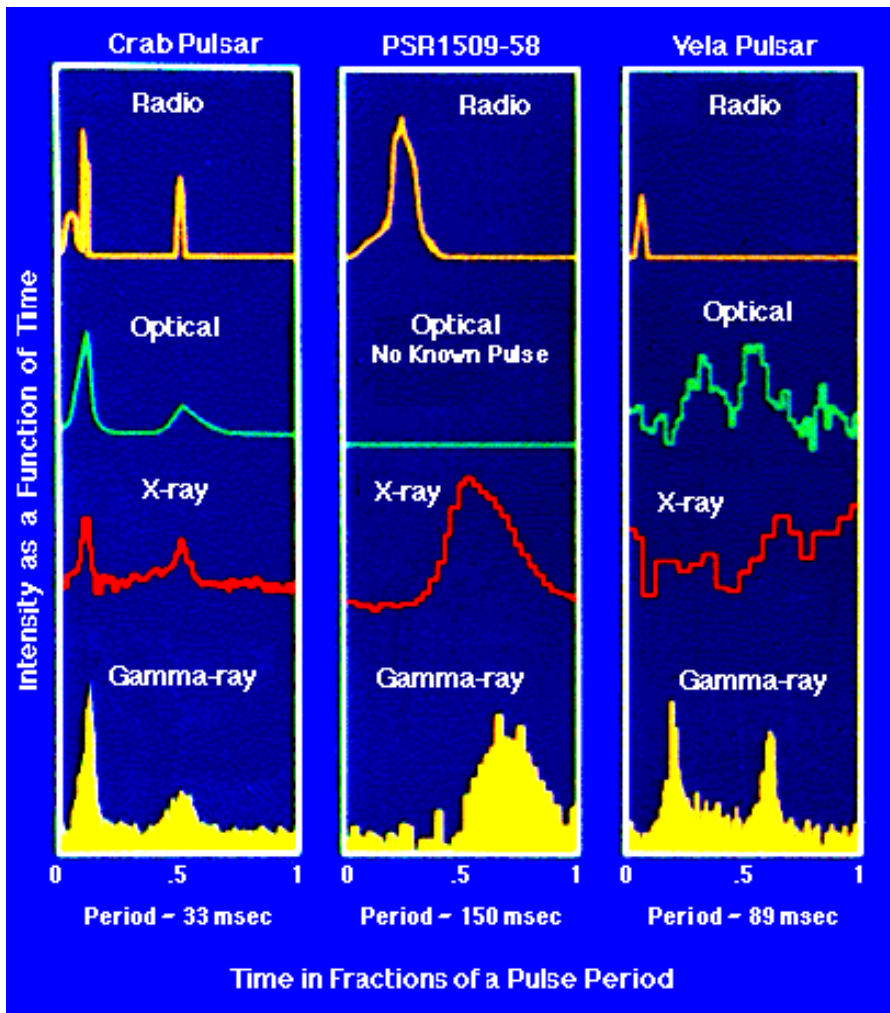
Underlying radio-to-X-ray continuum strongly polarised
→ non-thermal (i.e. non-blackbody) **synchrotron radiation** from **relativistic electrons moving in a magnetic field** (5×10^{-8} Tesla in the nebula); higher the electron energy, higher the radiation frequency

Where do relativistic electrons come from? (need powerful energy source) → The **pulsar!**

Nebula energetic output decreases in line with pulsar spin-down rate: rotational energy loss → **radiation**

Discovery of pulsars

Majority of pulsars (~1500 pulsars by 2004) discovered as radio sources (since 1967, Hewish & Bell Burnell, Cambridge → 1974 Nobel Prize)



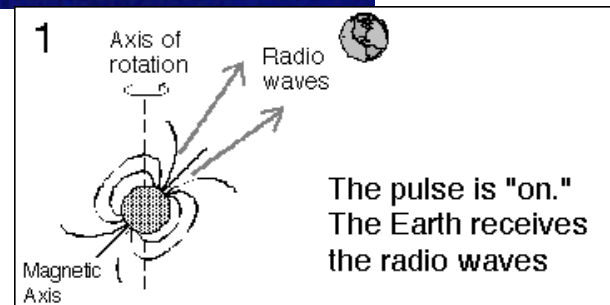
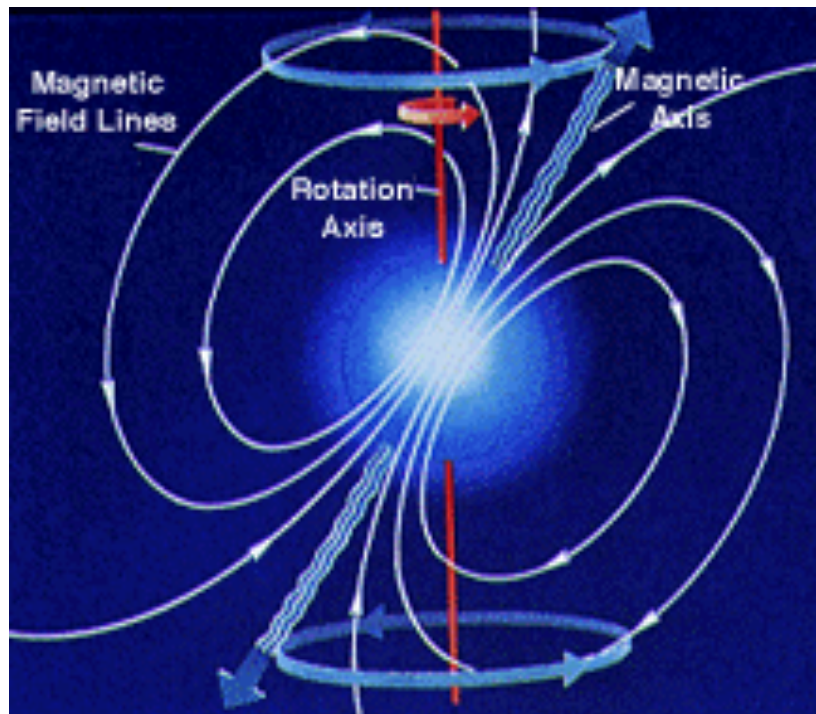
For a given pulsar, period keeps very accurately (better than 1 part in 10^8)

Amount of energy in pulses varies considerably (some pulses missing). Intensity and shape vary between pulses, average has unique shape.

Period range: $1.6 \times 10^{-3} - 4.0 \text{ s}$

Typical spin down by $10^{-8} \text{ s yr}^{-1}$
→ age from period/spin down

'Lighthouse' model for pulsars



Supernovae, Gamma-Ray Bursts and black holes

Supernovae

Type Ia – White dwarf exceeds the Chandrasekhar limit through accretion → neutron star

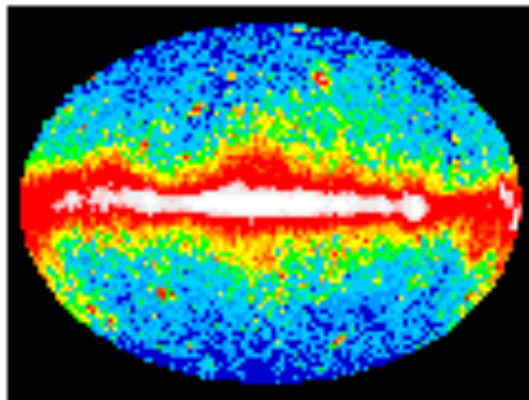
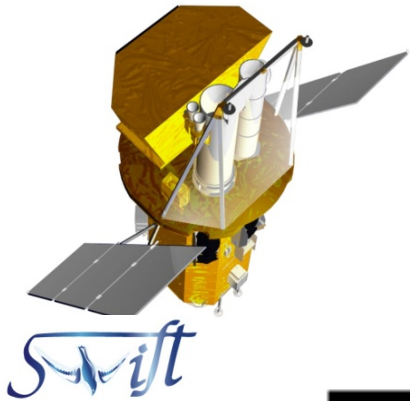
Type Ib and **Ic** – Cores of very massive stars, which have lost most of their outer layers through intense stellar winds, collapse after running out of nuclear fuel (type Ic may also be called ‘hypernovae’)

Wolf-Rayet stars → Type Ib → black holes
Some Type Ic, or even all Type Ib and Ic, may undergo a ‘collapsar’ stage: fast rotating core collapses to form a black hole, sucking in the surrounding material → precursors of long (> 2 sec) Gamma-Ray Bursts

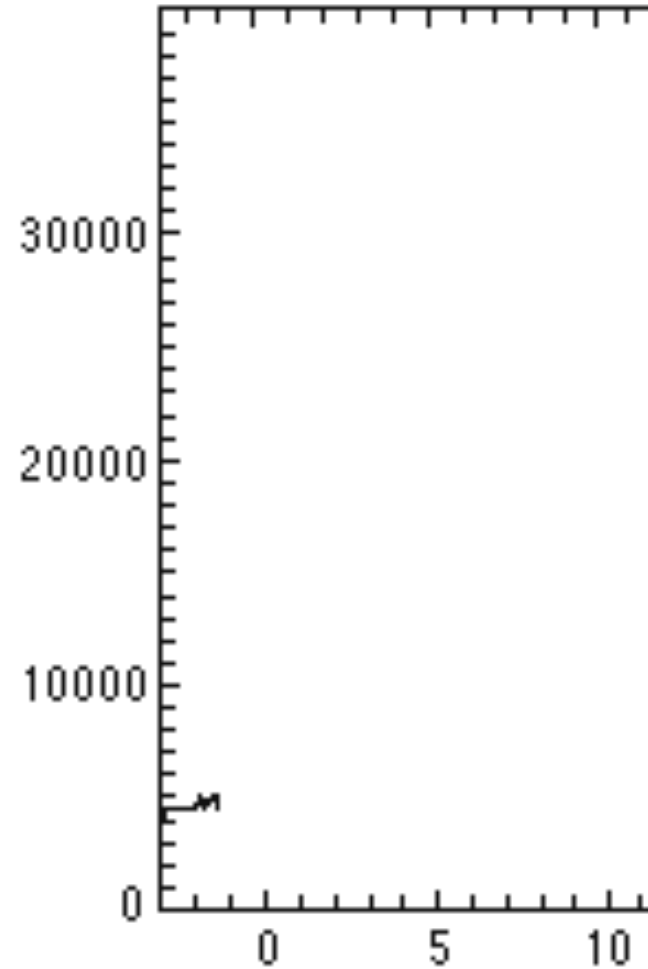
Type II – Core collapse of massive star (> 8 solar mass)
→ neutron star or black hole

What are Gamma-Ray Bursts?

Black hole births: Hypernovae (>2 s) or
coalescing neutron stars (< 2 s)



Counts per Second



$$E = 10^{44} - 10^{47} \text{ Joule}$$

Time in Seconds

Star collapse to a black hole

Similar physics applies to the collapse of neutron stars as it does to that of white dwarfs → neutron stars also obey a mass-radius relation and the upper limit to the mass is 3 solar mass →

Collapse of stars of > 3 solar mass (MS star > 20 solar mass) cannot be halted at the neutron star stage, but will go all the way to a black hole: volume decreases to zero, density becomes infinite to form a **singularity**.

A critical radius exists, called the **Schwarzschild radius**, where the escape velocity equals the speed of light (G : gravitational constant; M : black hole mass; c : speed of light)

$$R_{\text{Sch}} = \frac{2GM}{c^2}$$

Also called the **event horizon** → nothing can escape!

Black hole: Body that is all contained within its Schwarzschild radius

Observing black holes

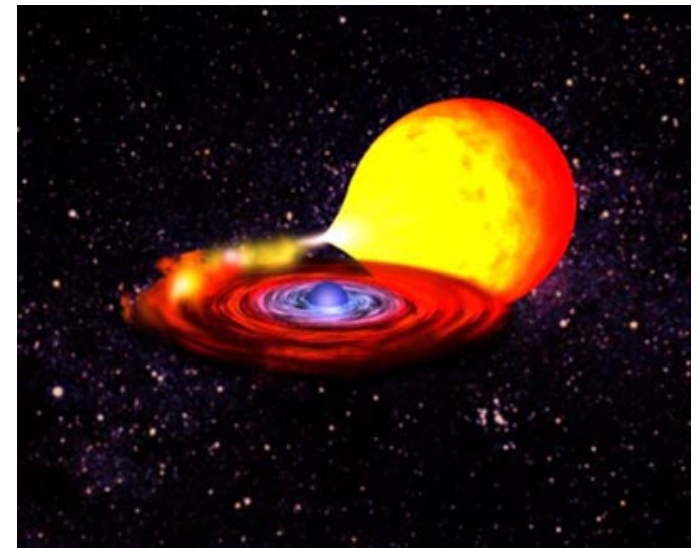
An isolated black hole cannot be observed; we can only detect its **influence** on material around it: matter falling onto a black hole gains kinetic energy and **heats up** → **ionised** → radiates

If temperature reaches few million K → **X-rays**

Most efficient if black hole has plenty of gas supply around, like in **a binary system** where the companion star fills its **'Roche lobe'** (volume controlled by the gravity of the star)

→ Black hole's strong gravity draws gas from the companion → **accretion**

If accreted material has some angular momentum, it will form an **accretion disk** around the black hole; **viscosity** in the disk heats it up → **X-rays**



Black hole candidate: Cygnus X-1

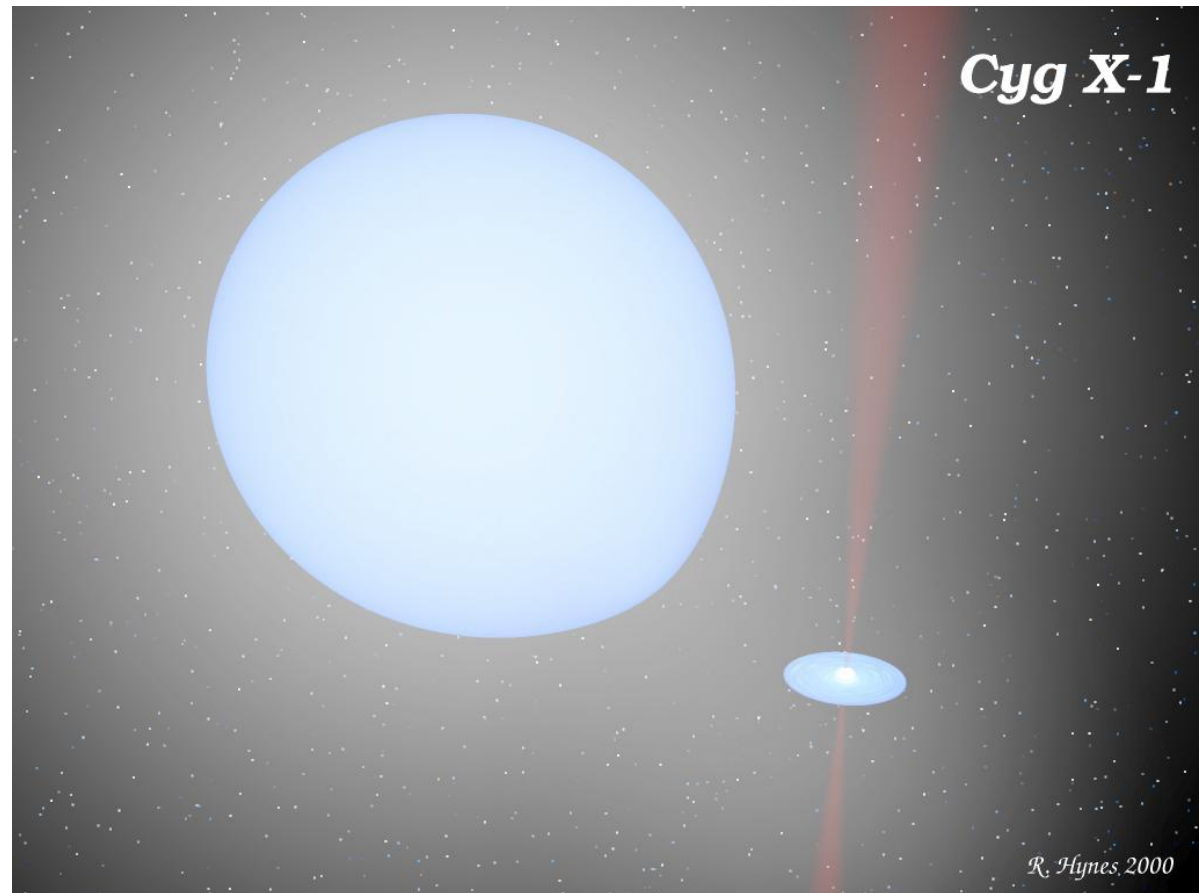
Bright X-ray source (2×10^{30} W) associated with HDE226868, an O supergiant star, in a binary with 5.6 day orbital period.

X-ray source flickers rapidly (< 0.001 s) \rightarrow compact!

Mass function of the binary \rightarrow if O star is of ~ 20 solar mass, Cyg X-1 must be $\sim 8 - 10$ solar mass (too large for neutron star)

\rightarrow black hole

A few other Galactic black hole candidates known



Supermassive black holes in Active Galactic Nuclei

... are a scaled-up version of stellar size black holes
($10^6 - 10^9$ solar mass black holes)

.....later in 'Physics of the Universe'!

