Astrofizyka cząstek

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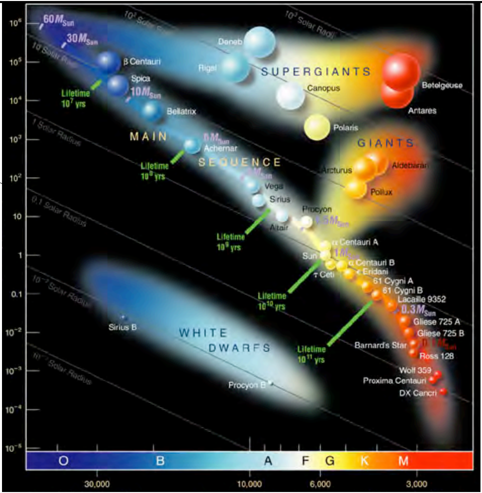
Zakład Cząstek i Oddziaływań Fundamentalnych IFD

Wykład XI

- ewolucja gwiazd
- supernowe
- błyski gamma

Luminosity



Temperature

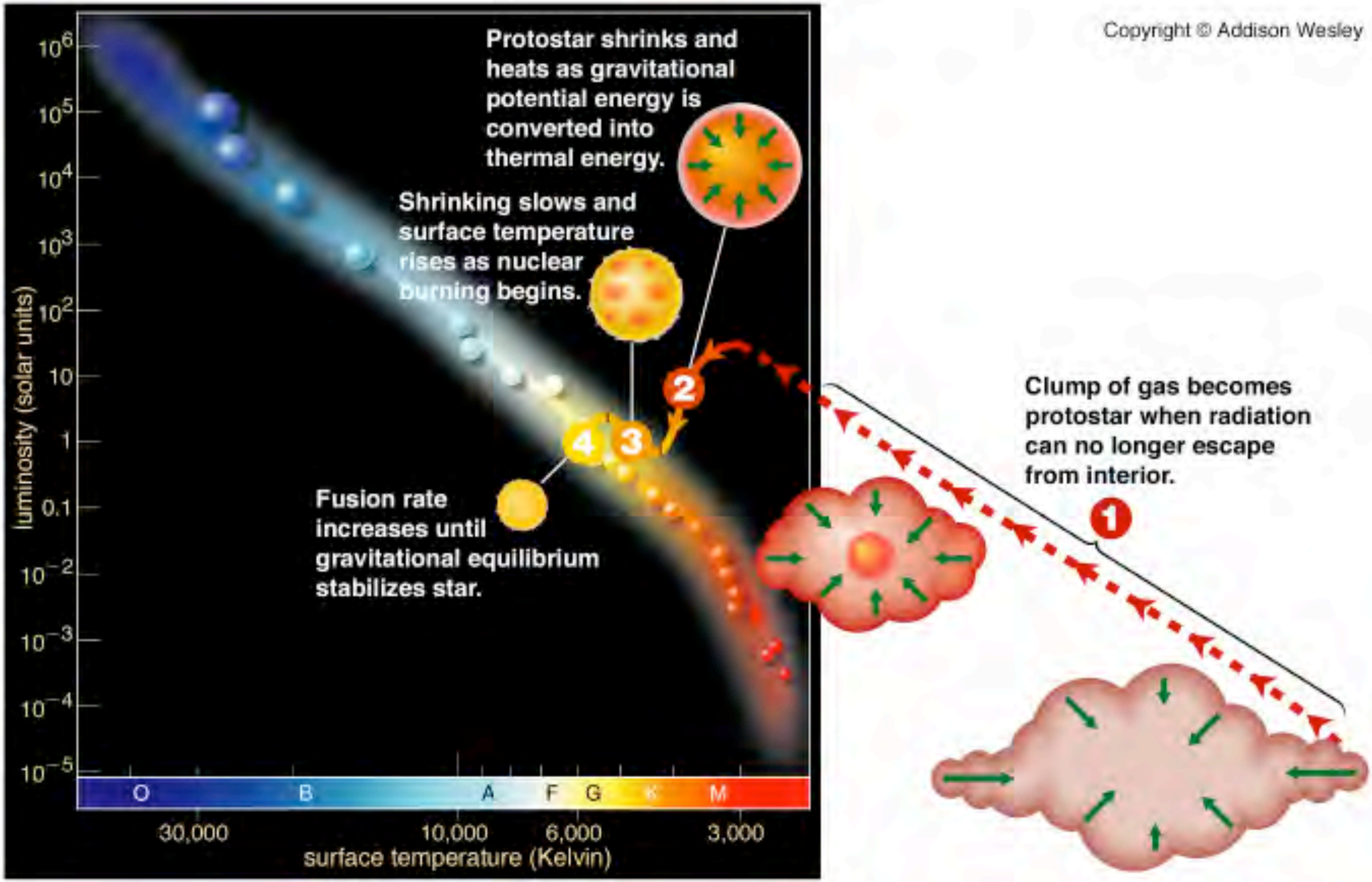
Review:
H-R diagram depicts:

X-axis: Temperature (or Color or Spectral Type)

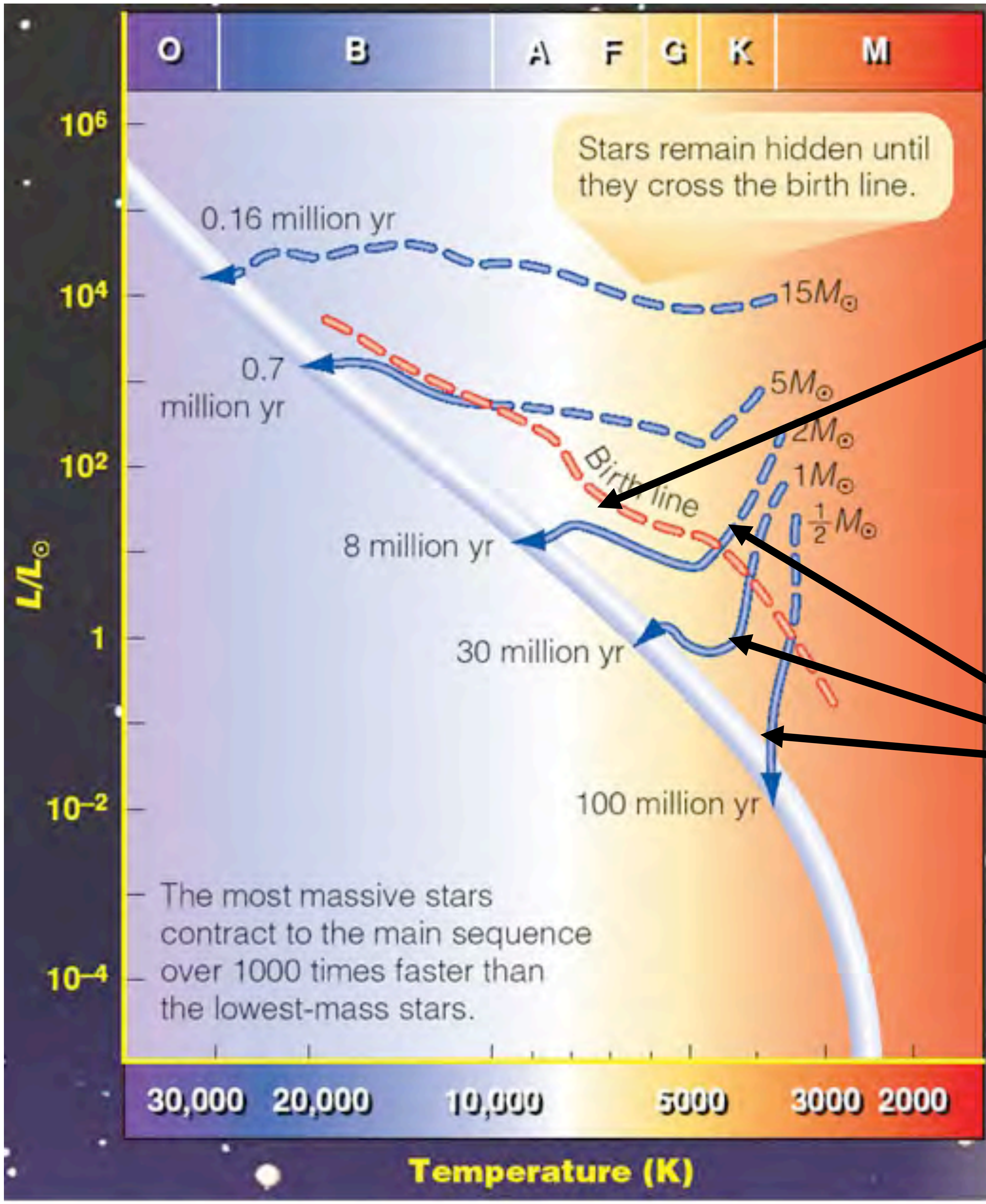
Y-axis: Luminosity

Diagonal lines: Radius

Then a Protostar is born



From Protostars to Stars



Star emerges from the enshrouding dust cocoon (T Tauri stage)

Ignition of $4\,{}^1H \rightarrow {}^4He$

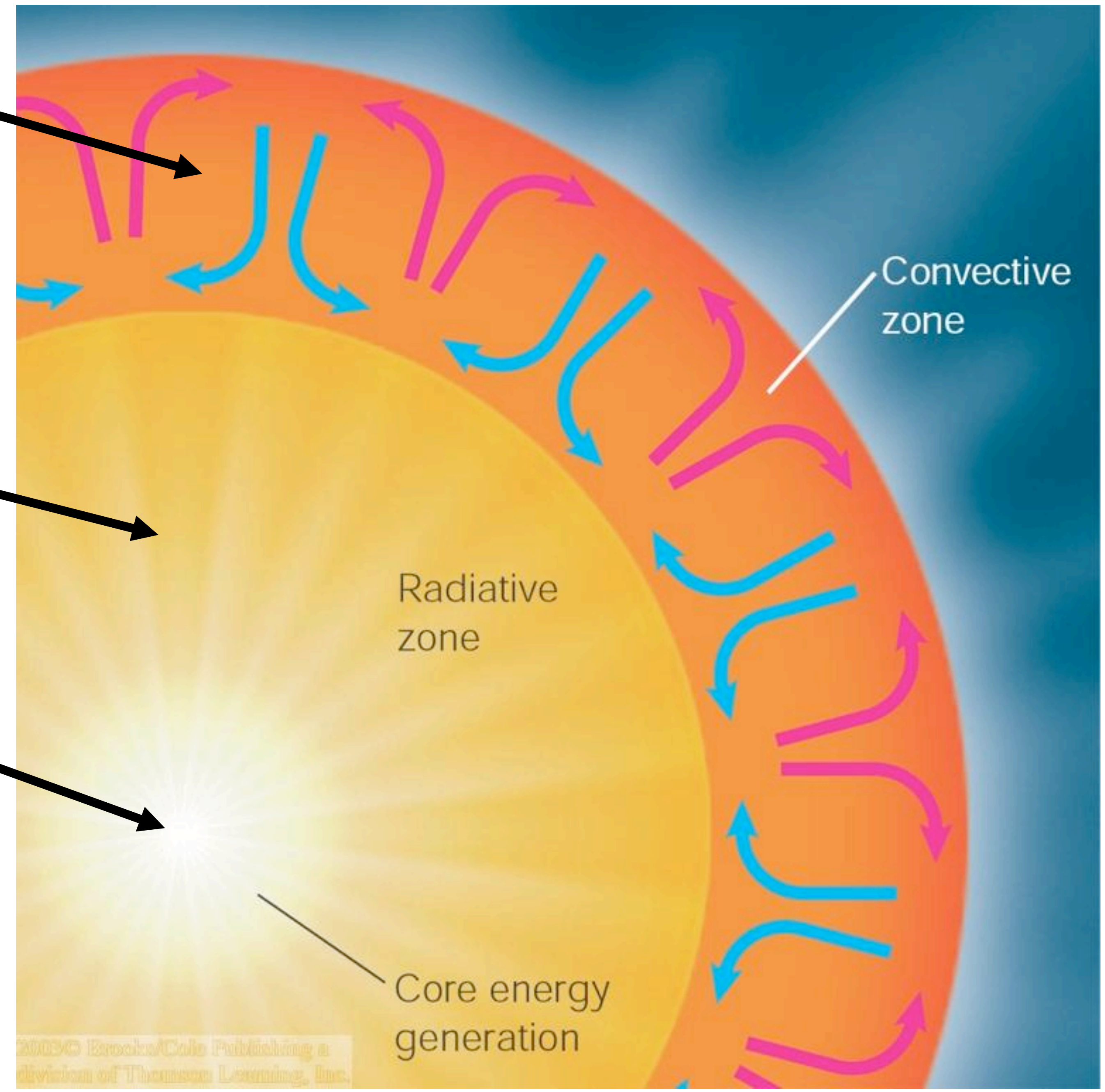
Structure of the Sun

Flow of energy

Energy transport via convection

Energy transport via radiation

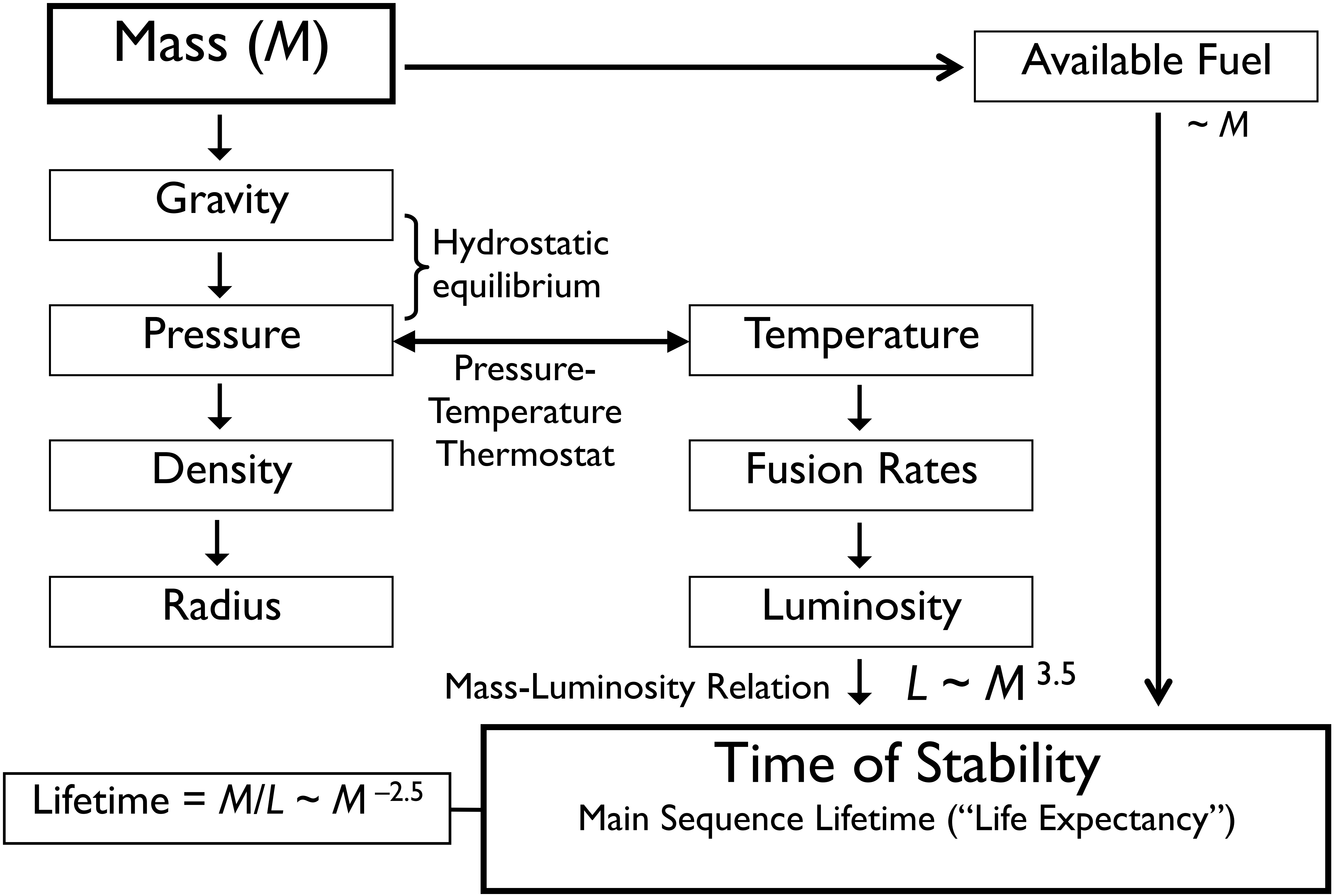
Energy generation via nuclear fusion



Temperature, density and pressure decreasing

Star's total mass determines which part of the star has convection or radiation

Modeling stellar structure

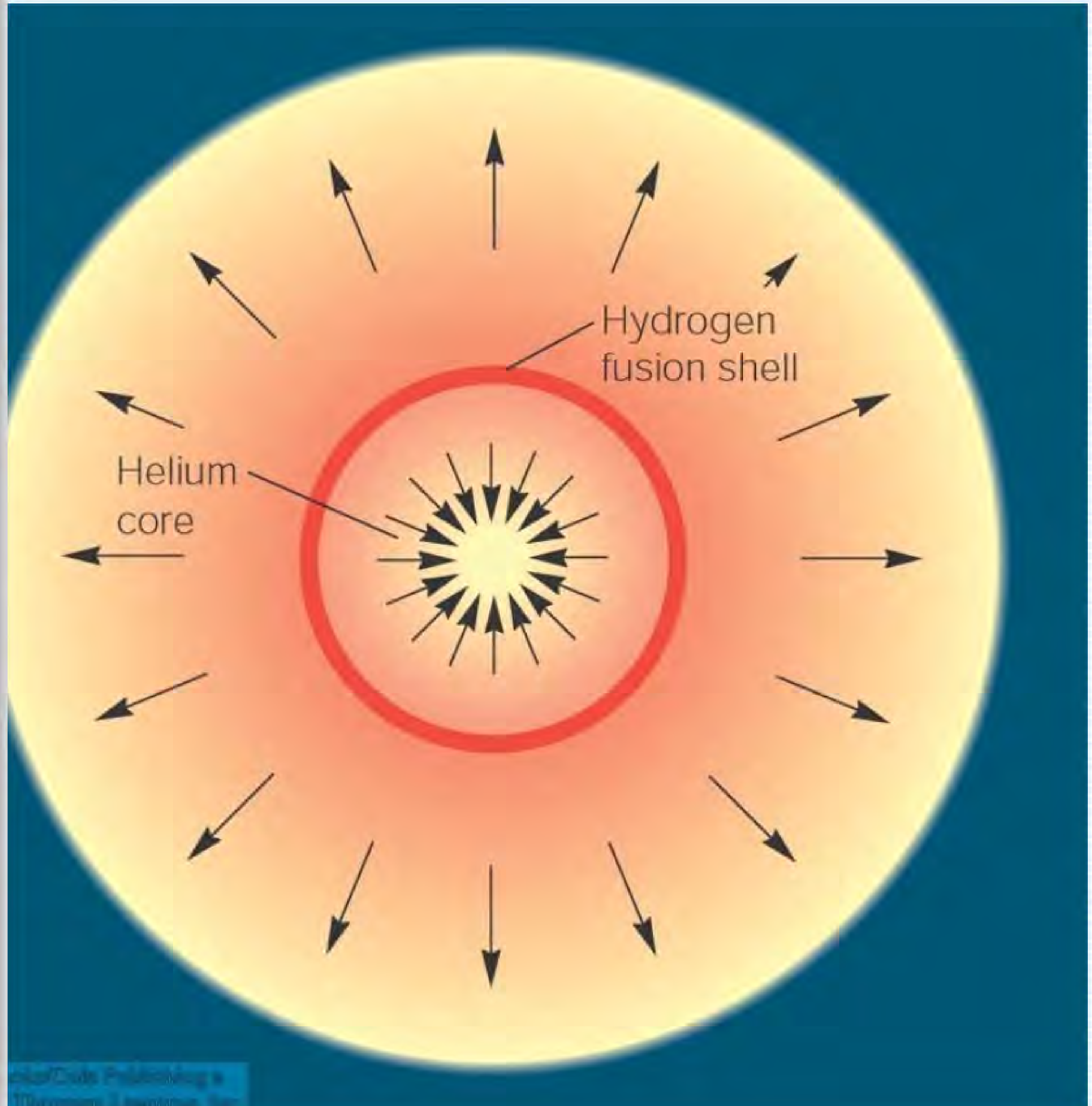


The Lifetimes of Stars

Mass ($M_\odot$)	Surface temperature (K)	Luminosity ($L_\odot$)	Time on main sequence (10^6 years)	Spectral class
25	35,000	80,000	3	O
15	30,000	10,000	15	B
3	11,000	60	500	A
1.5	7000	5	3000	F
1.0 (Sun)	6000	1	10,000	G
0.75	5000	0.5	15,000	K
0.50	4000	0.03	200,000	M

Table 12-2
Discovering the Universe, Eighth Edition

Evolution off the Main Sequence: Expansion into a Red Giant



Hydrogen in the core completely converted into He:

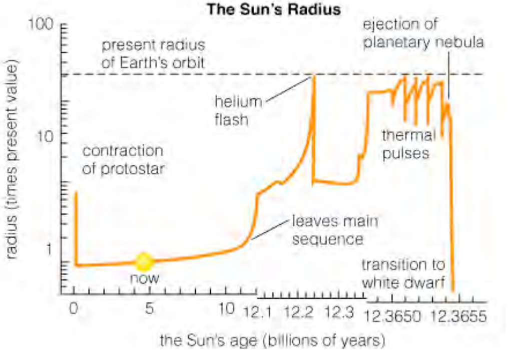
→“Hydrogen burning” (i.e. fusion of H into He) ceases in the core.

H burning continues in a shell around the core.

He Core + H-burning shell produce more energy than needed for pressure support

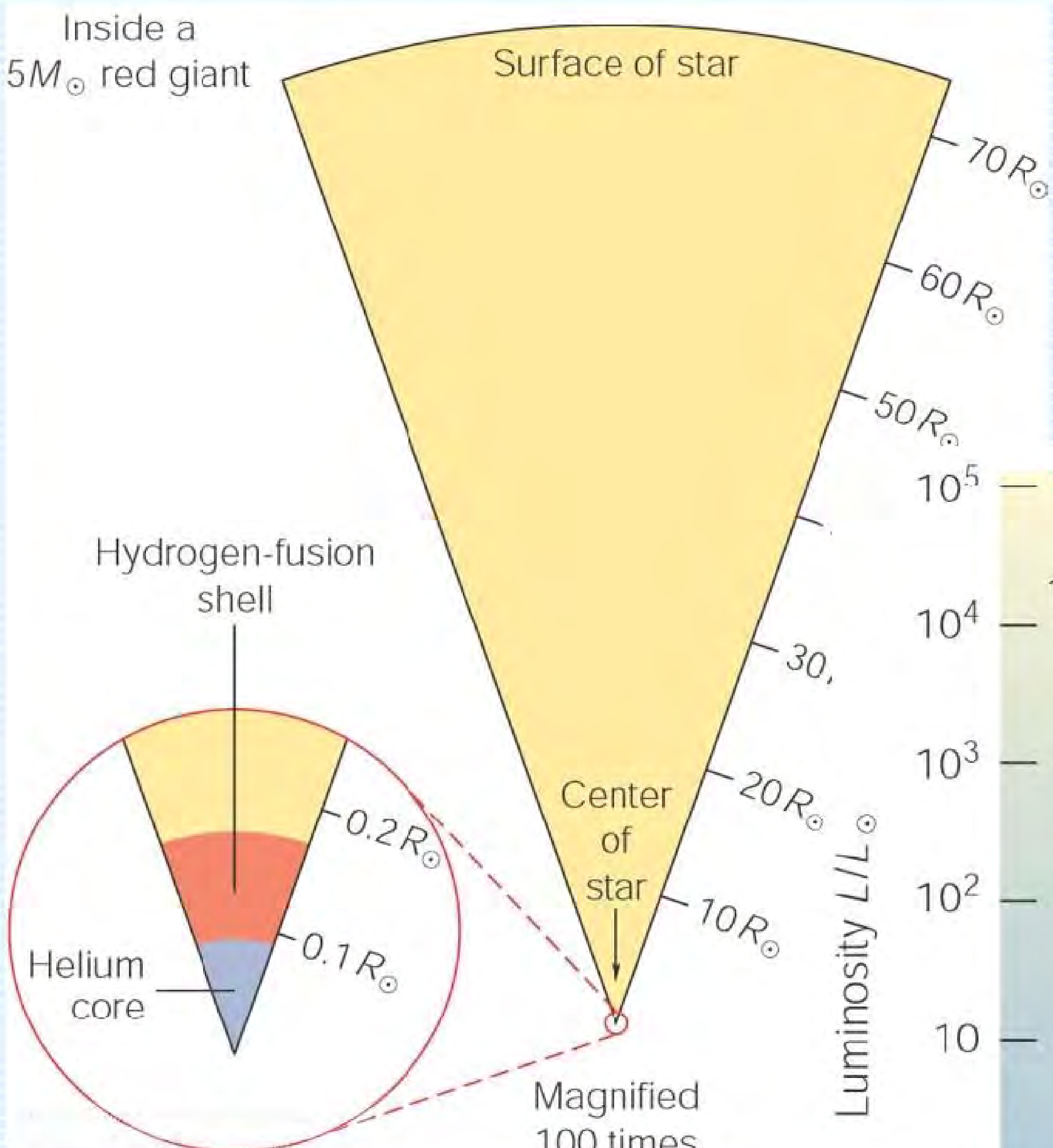
Expansion and cooling of the outer layers of the star → Red Giant

Earth's Fate

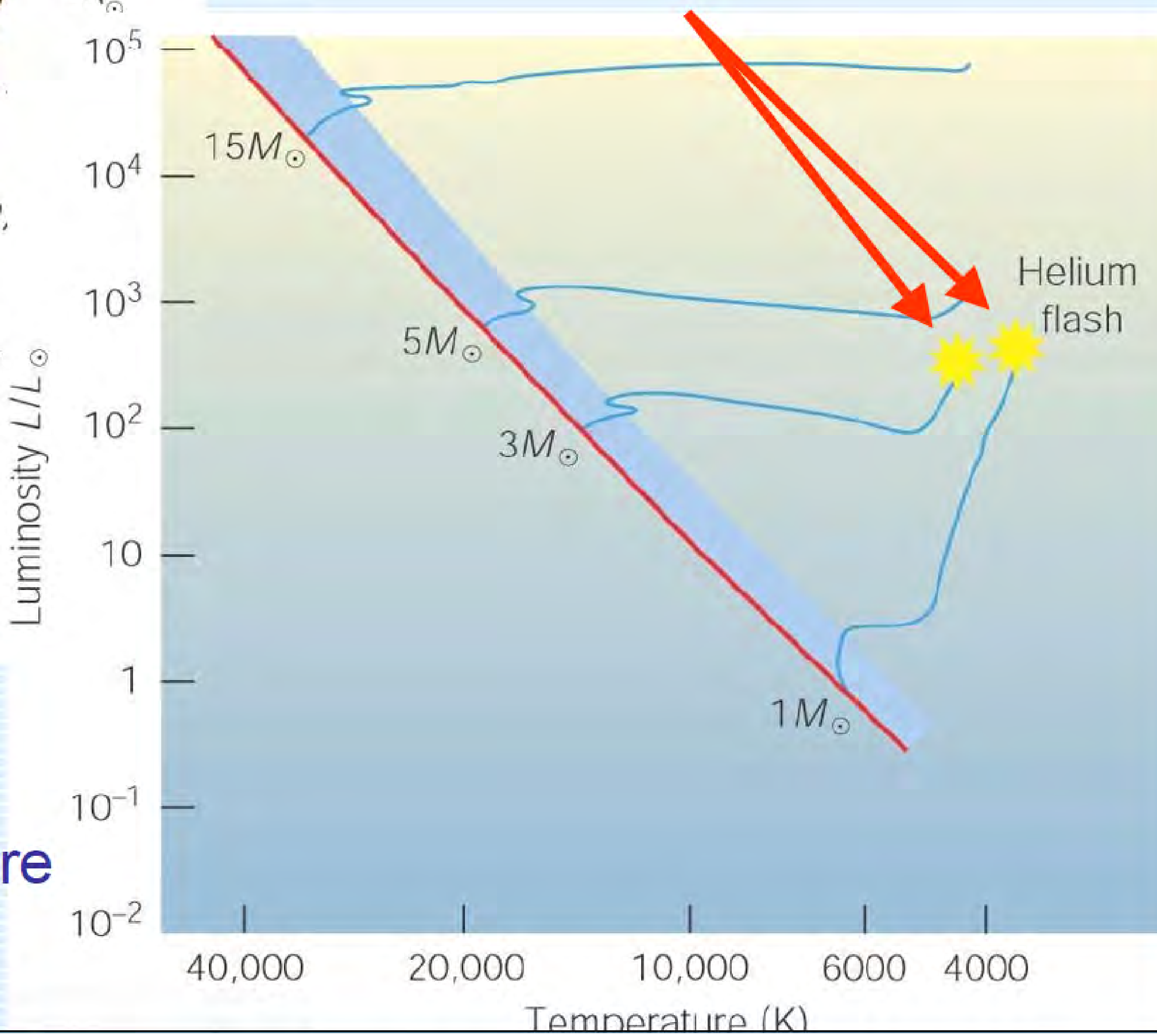


- Sun's radius will grow to near current radius of Earth's orbit

Helium Fusion

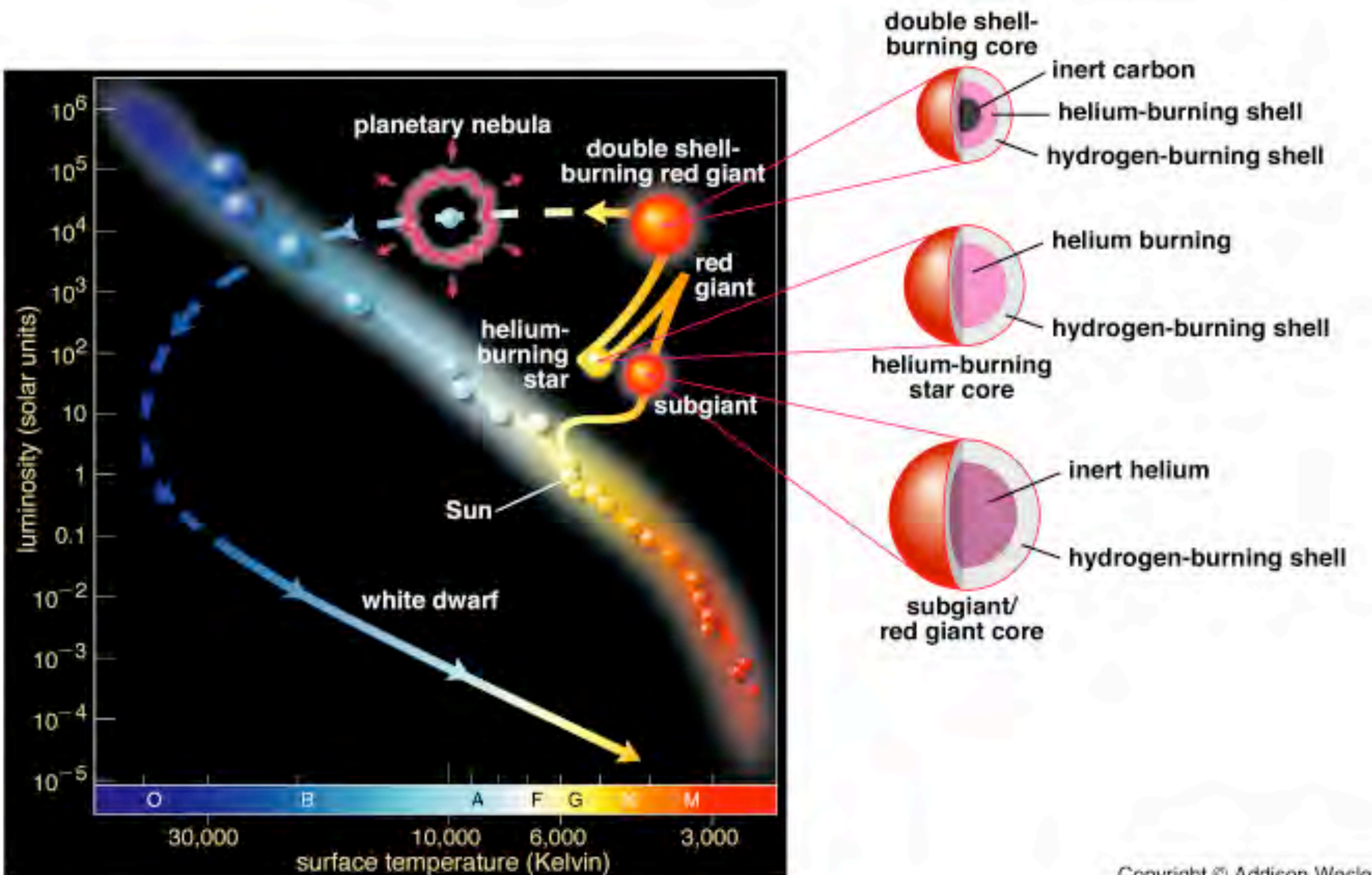


He nuclei can fuse to build heavier elements:

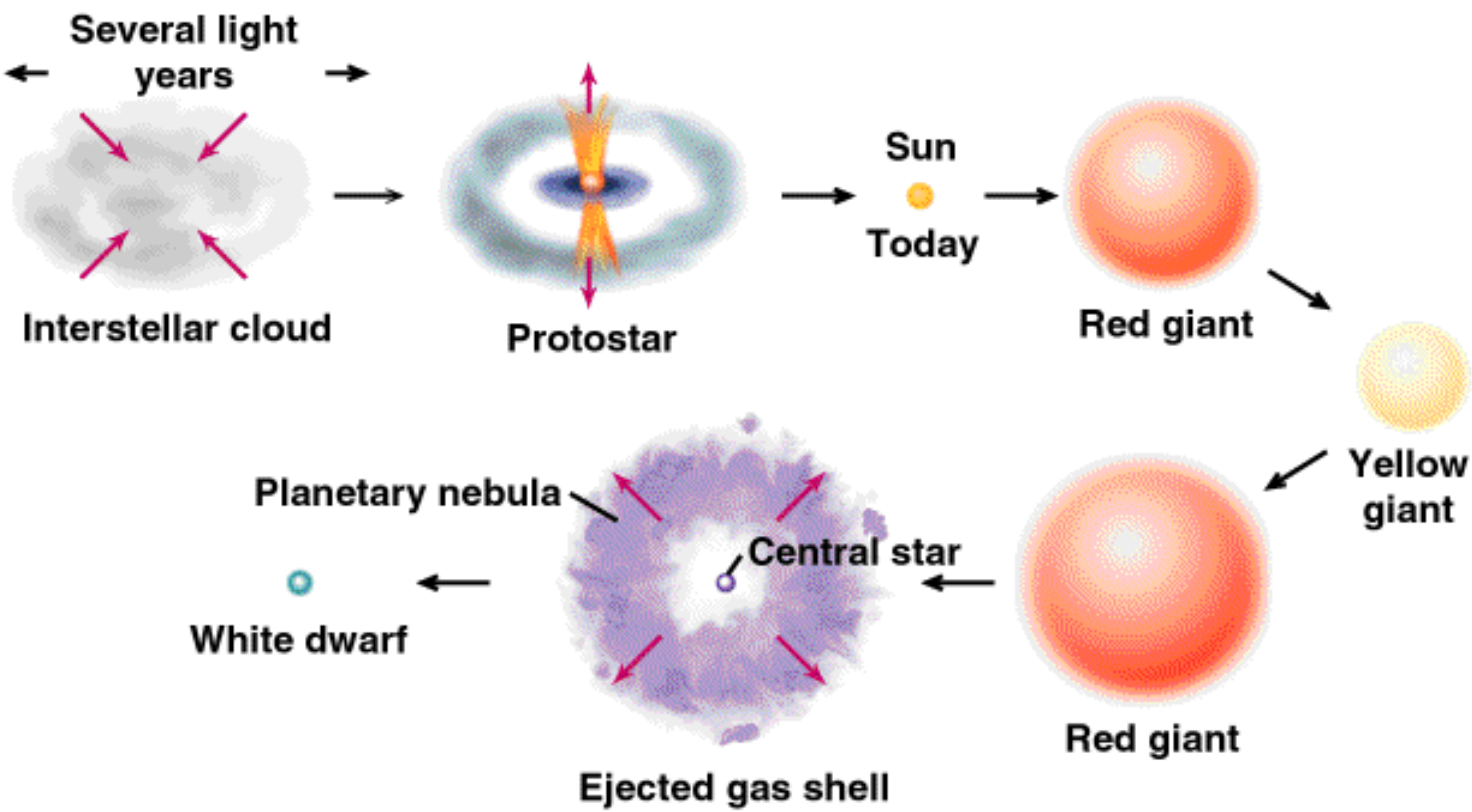


When pressure and temperature in the He core become high enough,

The life track of a Sun-like star



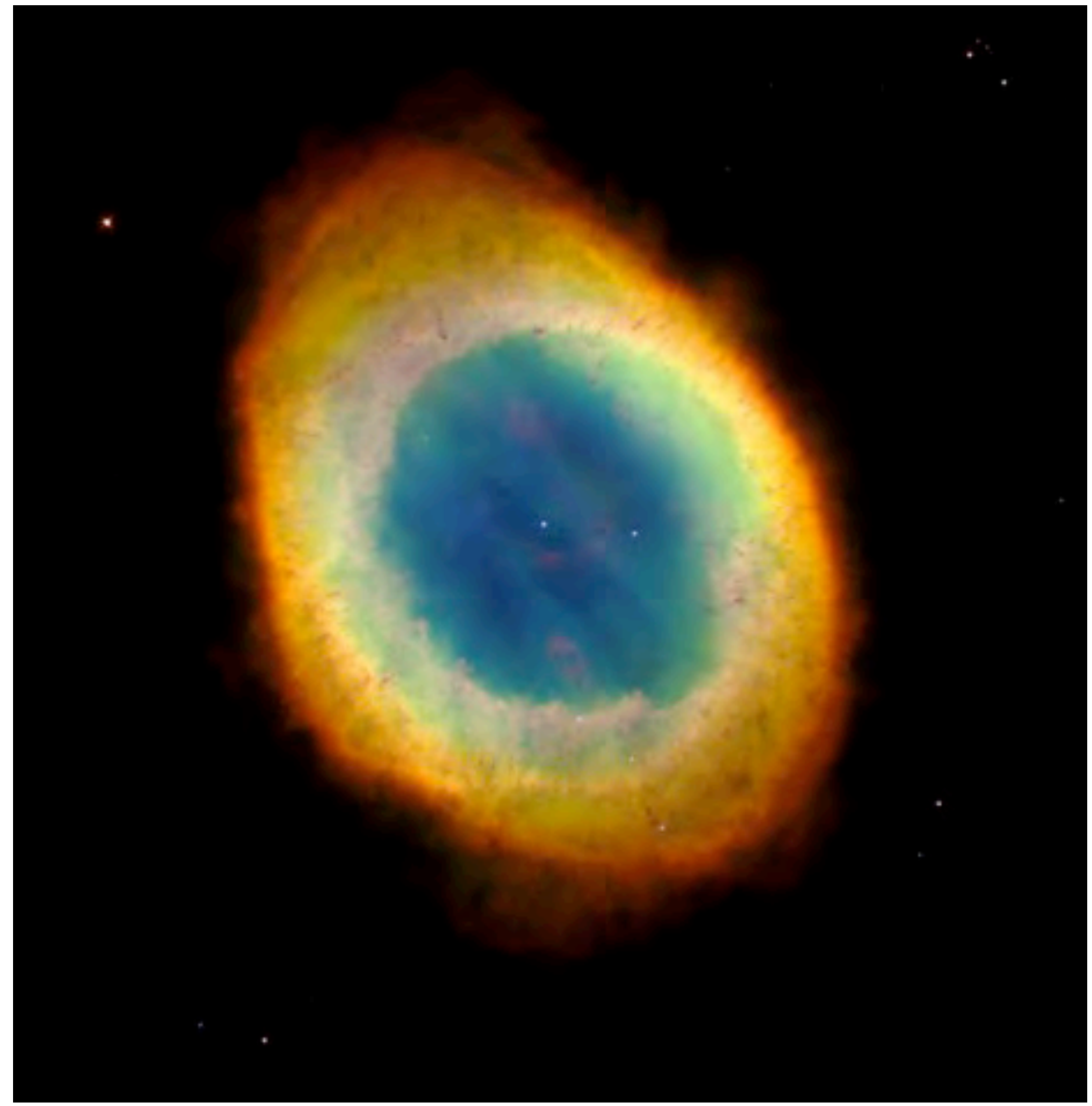
Life of the Sun



The beautiful end of the Sun

The Cat's Eye nebula

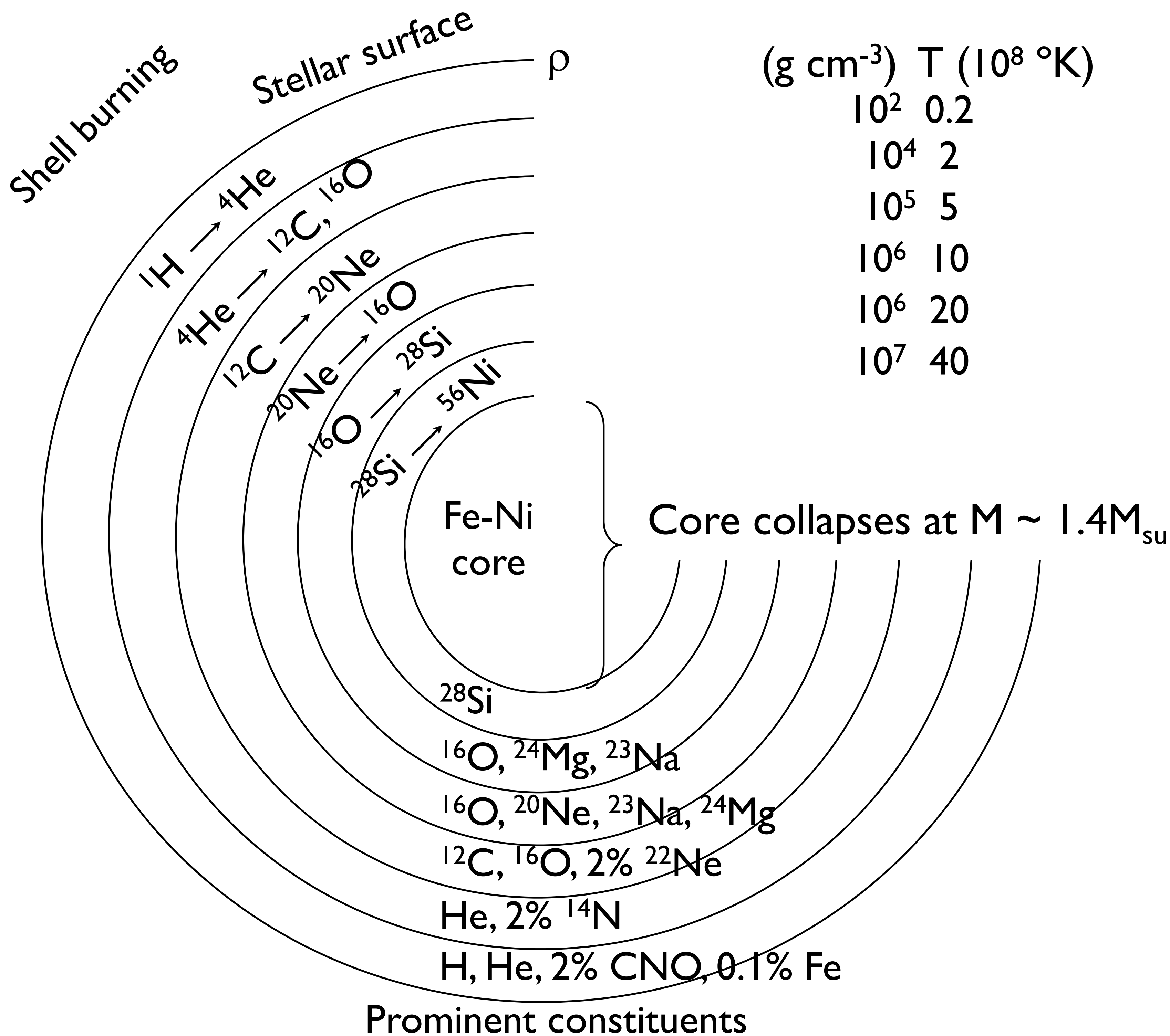
The Ring nebula



Pre-Supernova "Onion Skin" Structure

- Heavy elements settle into layers
- Shell burning at interfaces.

Composition of layers dominated by more stable nuclei (A multiple of 4)



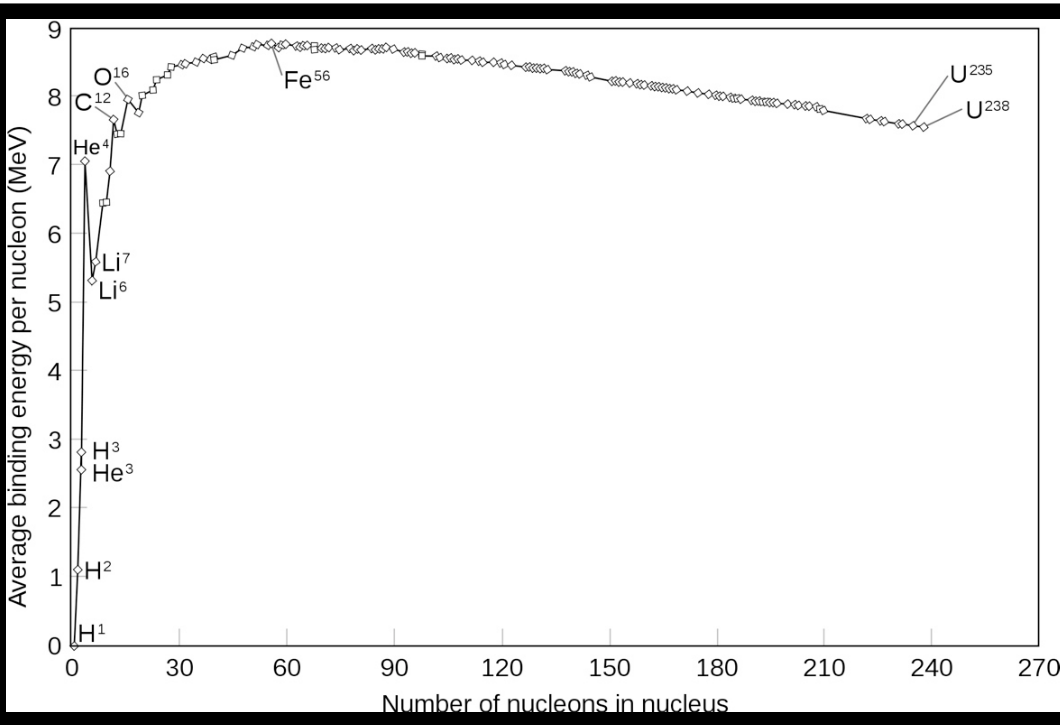
Iron core : no new possible nuclear reactions to release energy !

	H	He	C	O	Ne	Si	Fe	U
A	1	4	12	16	20	28	56	238
Z	1	2	6	8	10	14	26	92
Mass m (u.m.a)	1	4.0026	12	15.9949	19.9924	27.9769	55.9349	238.0508
Binding energy B / A (MeV / nucleon)	0	7.08	7.68	7.98	8.03	8.45	8.79	7.57

binding energy of a nucleus (Z,A) :

$$B = (Z\, m_p + (A-Z)\, m_n - m)\, c^2$$

$m_p = 1.0073$ u.m.a
$m_n = 1.0087$ u.m.a

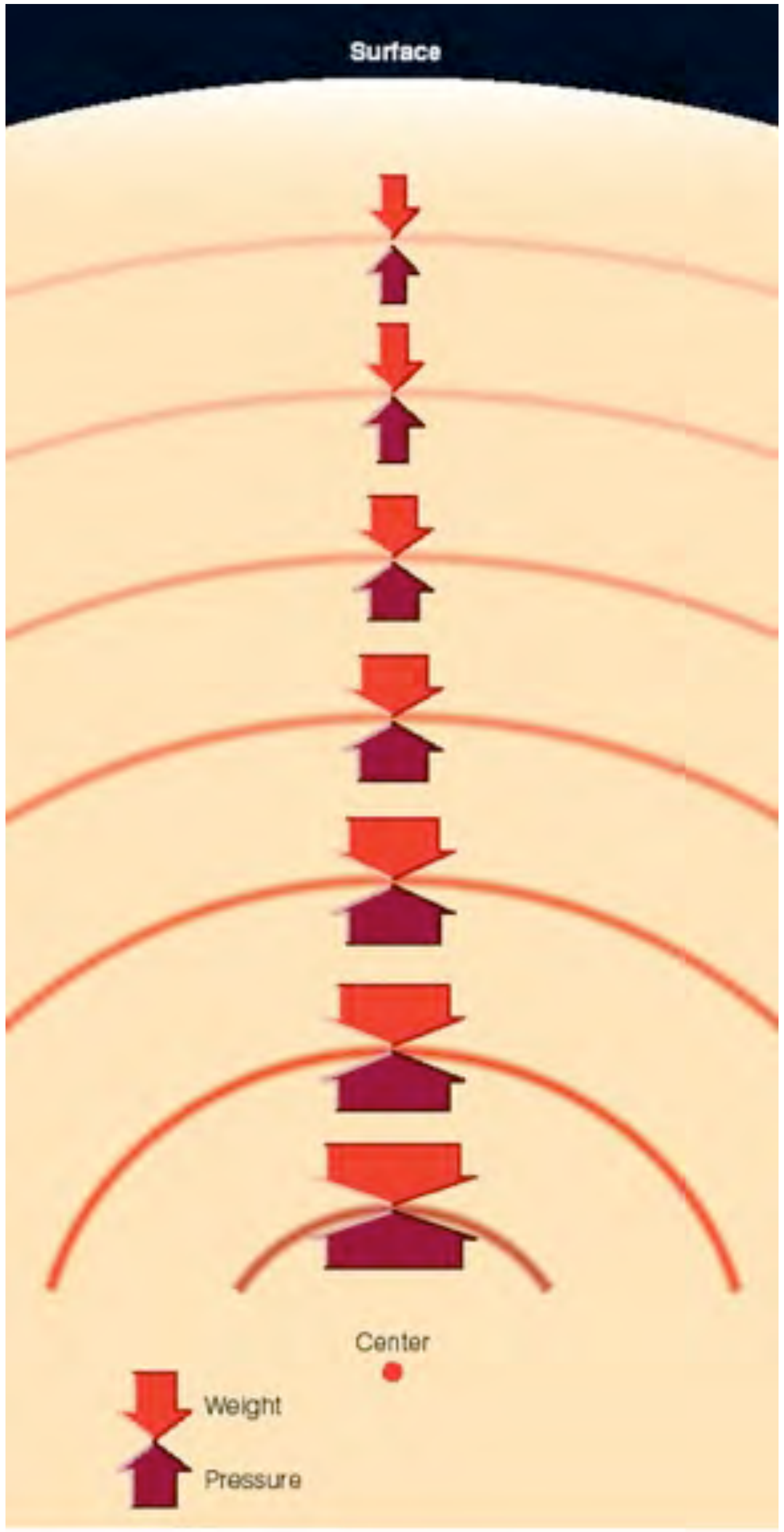


Stellar Models

"Onion skin layer model"

Four laws of stellar structure:

- Conservation of Mass
- Conservation of Energy
- Hydrostatic Equilibrium
- Energy Transport

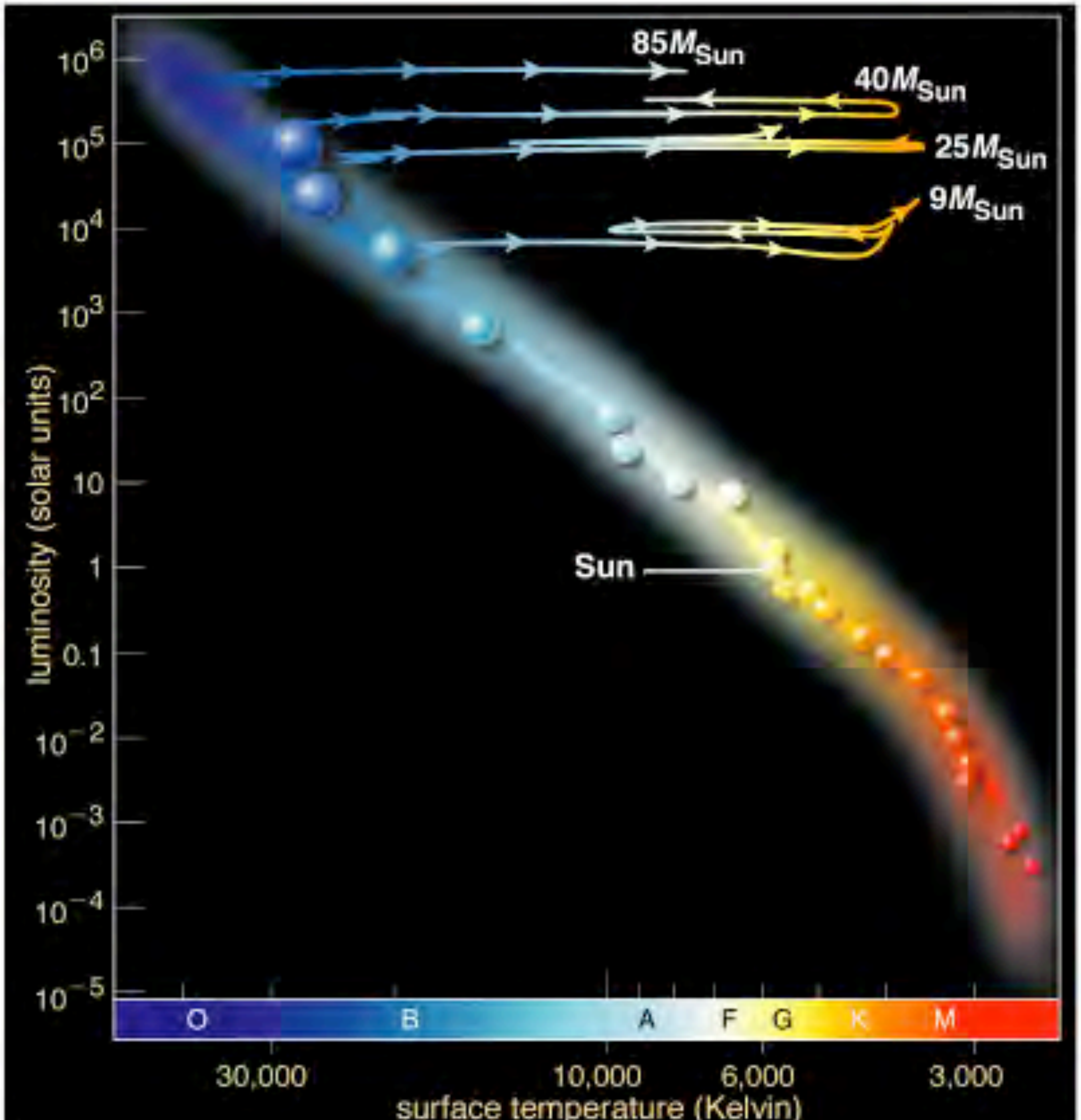


Stellar Nucleosynthesis

Evolutionary Time Scales for a 15 M_{sun} Star

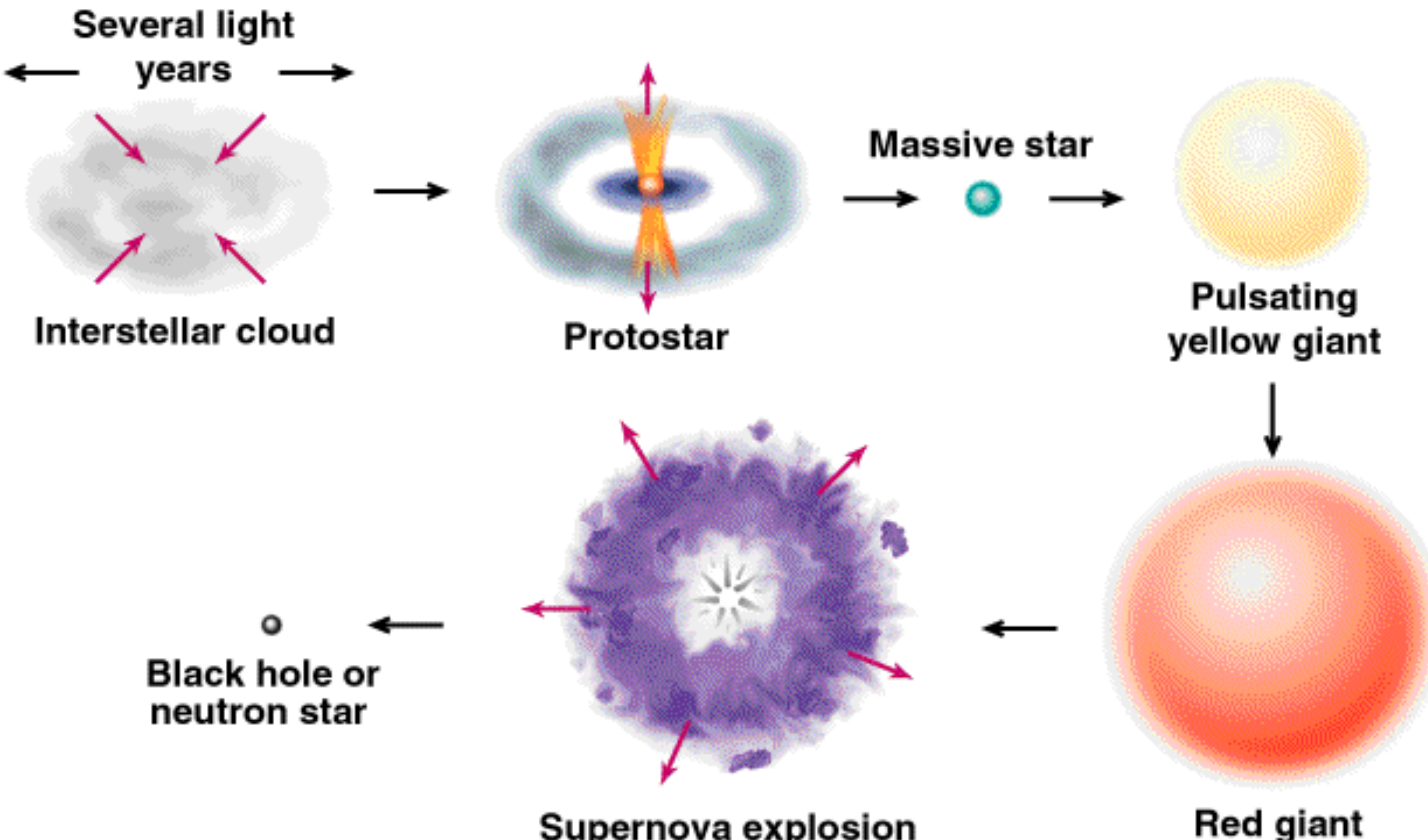
Fused	Products	Time	Temperature
H	^{4}He	10^{7} yrs.	4×10^{6} K
^{4}He	^{12}C	Few X 10^{6} yrs	1×10^{8} K
^{12}C	^{16}O, ^{20}Ne, ^{24}Mg, ^{4}He	1000 yrs.	6×10^{8} K
^{20}Ne +	^{16}O, ^{24}Mg	Few yrs.	1×10^{9} K
^{16}O	^{28}Si, ^{32}S	One year	2×10^{9} K
^{28}Si +	^{56}Fe	Days	3×10^{9} K
^{56}Fe	Neutrons	< 1 second	3×10^{9} K

The life track of massive stars



- Massive stars reach main sequence fast, ~0.1 Myr
- More massive stars evolve faster: O-stars explode only after ~ few Myr only!

Life of a High Mass Star



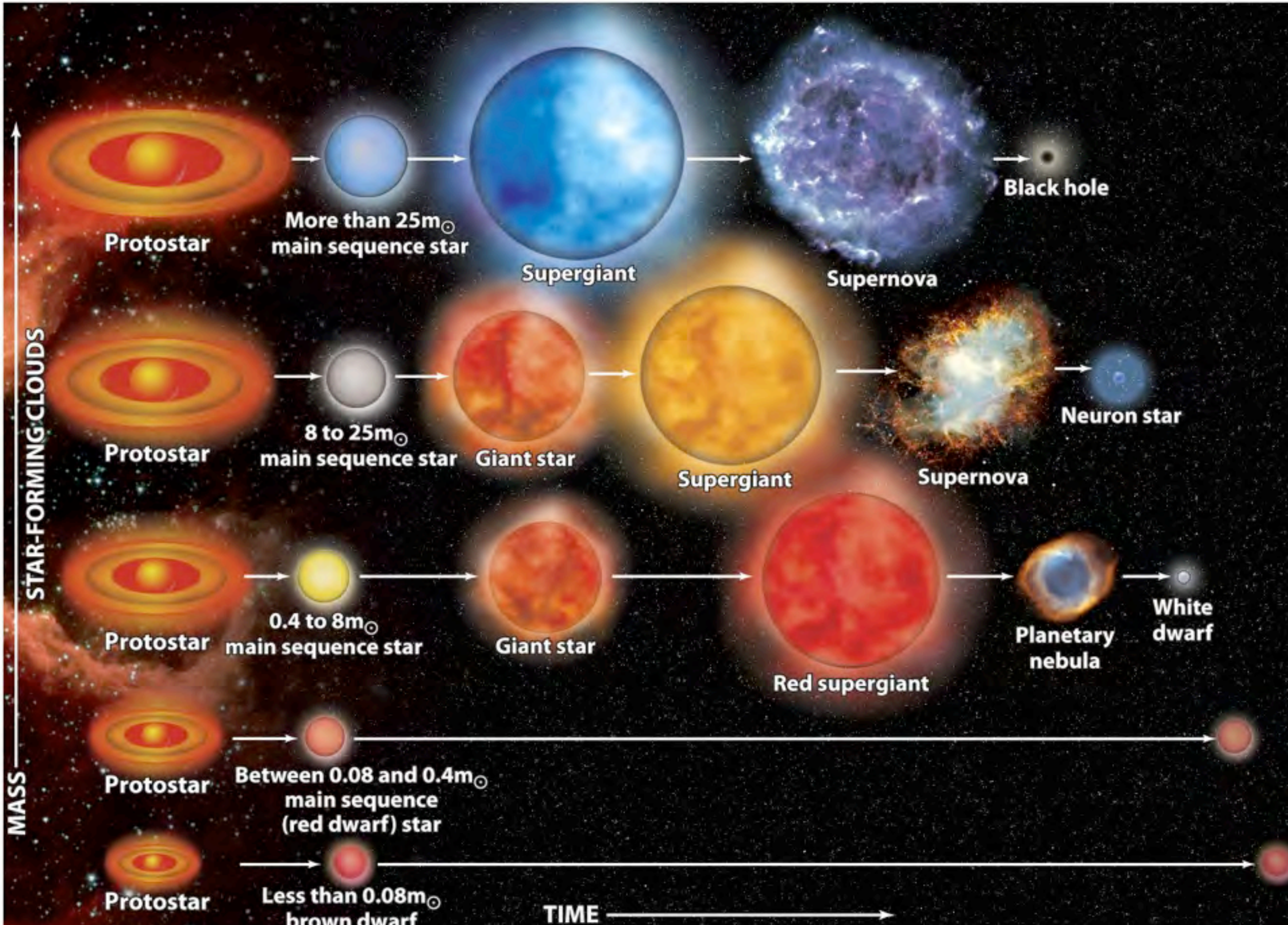


Figure 13-28a
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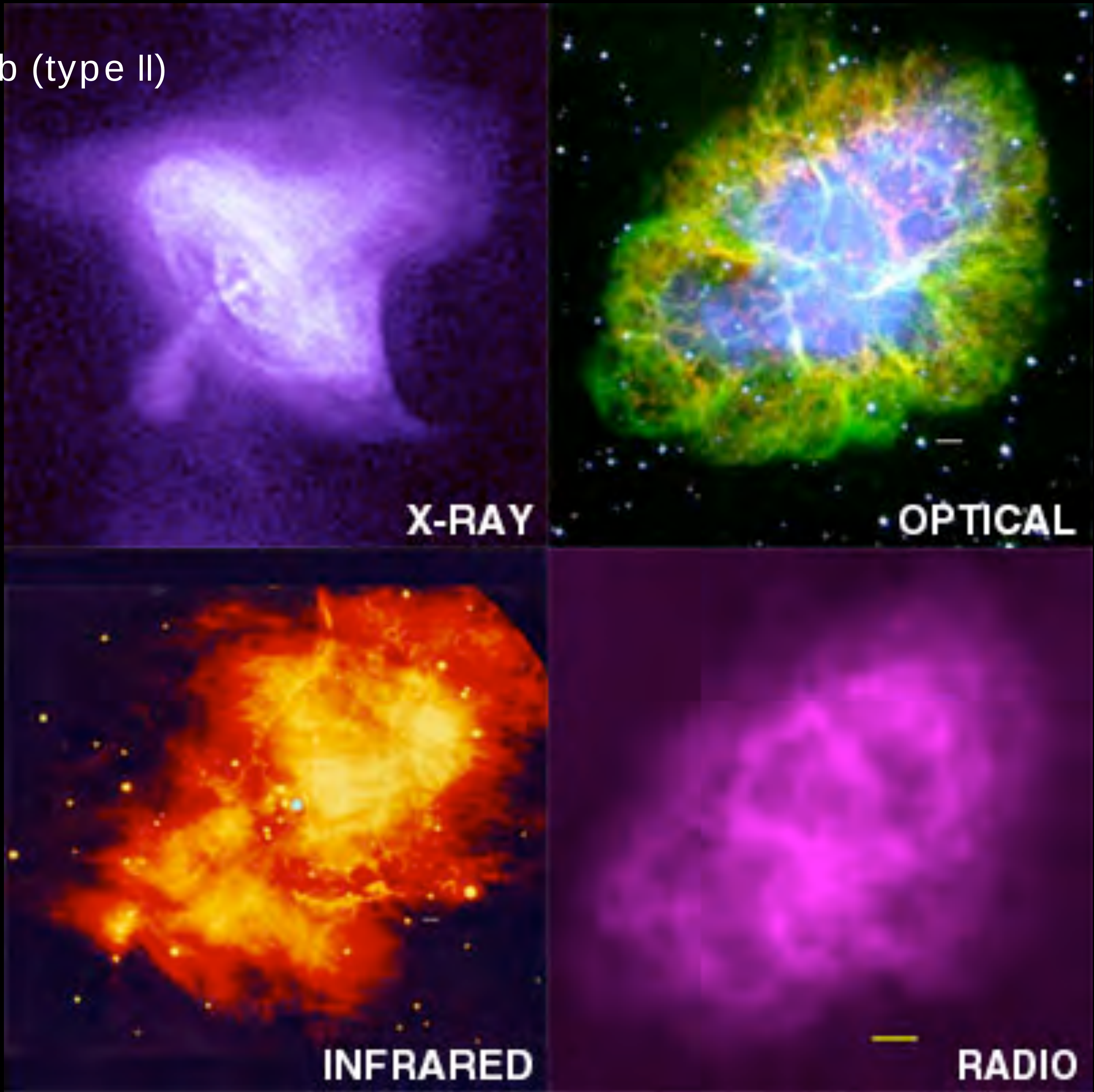
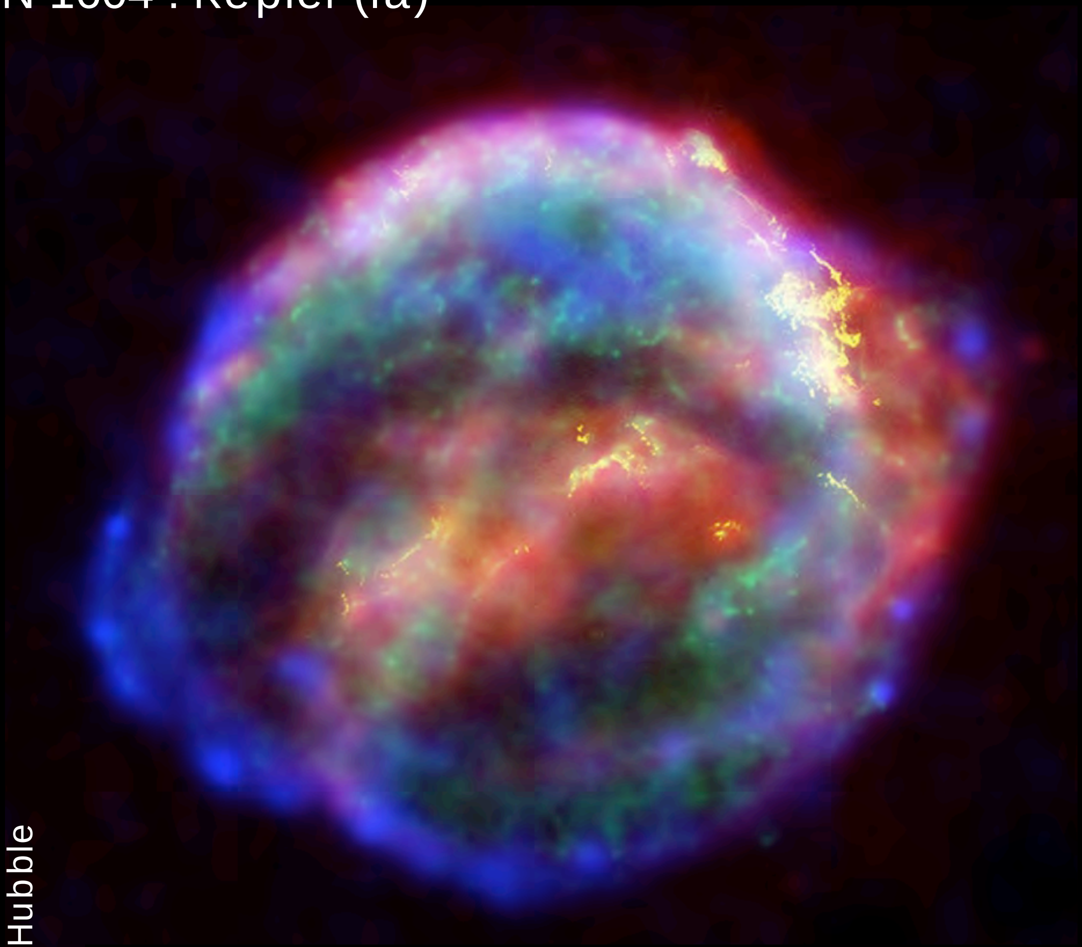
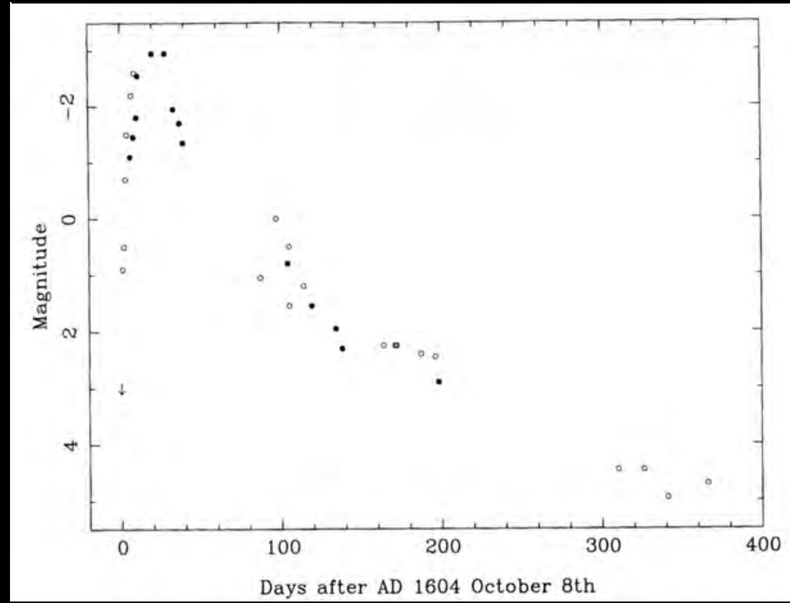
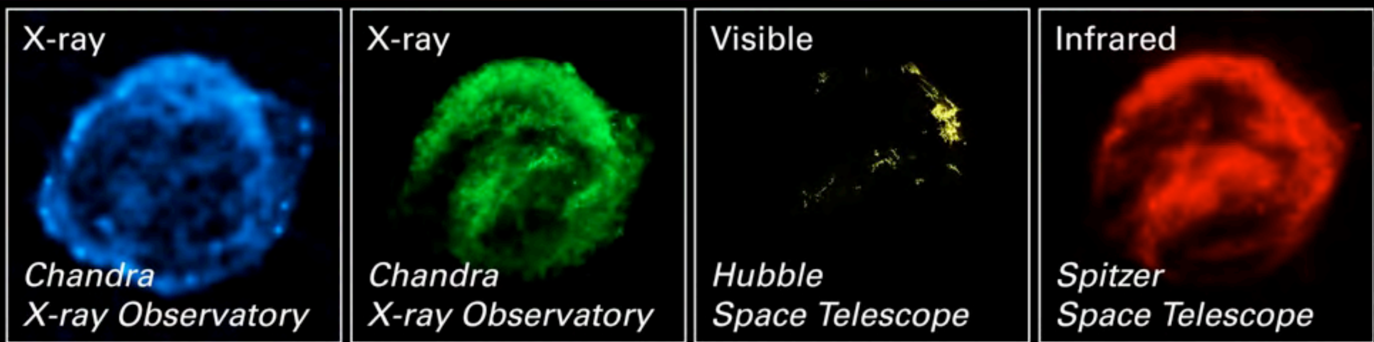
SN 1054 : Crab (type II)

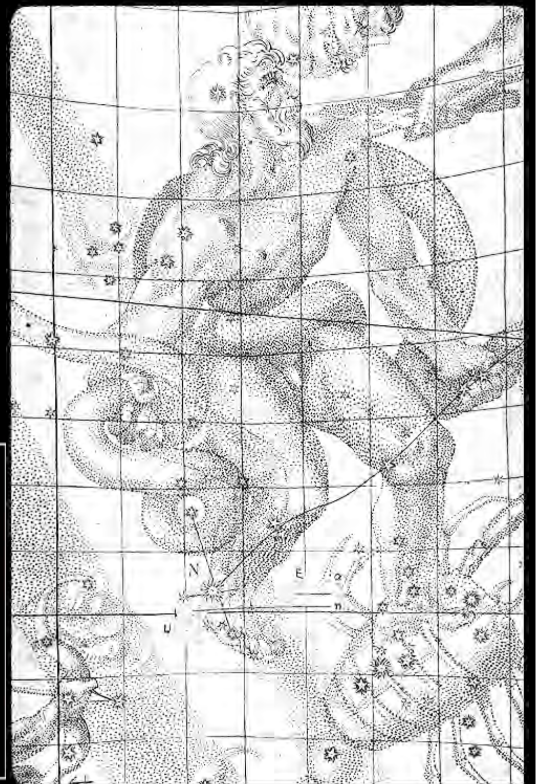


SN 1604 : Kepler (Ia)









Chandra - Spitzer - Hubble

All these stars are in still on the main sequence

Initial mass		Final state
$\sim 0.1\text{-}9\ M_\odot$ Nuclear burning stops before the production of an iron core.	$\sim 0.1\text{-}0.8\ M_\odot$	WD He
	$\sim 0.8\text{-}8\ M_\odot$	WD C,O
	$\sim 8\text{-}9\ M_\odot$	WD O,Ne,Mg
$\gtrsim 9\ M_\odot$ Production of an iron core	$\sim 8\text{-}25\ M_\odot$	NS + SN
	$\sim 8\text{-}40\ M_\odot$?	NS→BH + SN ?
	$\gtrsim 40\ M_\odot$?	BH ?

From the gravitational collapse to the bounce and the explosion : summary

1. Triggering the collapse
   - pressure in the iron core is dominated by degenerate electrons
   - gravitational instability when M = Chandrasekhar mass $M_{Ch} = 1.457\ (Y_e / 0.5)^2\ M_\odot$
     (Y_e = number of free electrons per nucleon ; here $Y_e < 0.5$)

From the gravitational collapse to the bounce and the explosion : summary

1. Triggering the collapse
2. Neutron enrichment

- Normal matter : balance between β and inverse β decay

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

-Collapsing core : neutron production is favored by the degeneracy of electrons
(β decay necessitates to produce a very energetic electron above the Fermi energy)
-This leads to neutron enrichment by electron capture

$$^{56}Fe + e^- \to ^{56}Mn + \nu_e$$
$$^{56}Mn + e^- \to ^{56}Cr + \nu_e$$
$$\dots$$

-Exotic chemical composition with neutron rich nuclei
-Emission of electronic neutrinos ν_e that escape the star

-A few details... evolution of the chemical composition

Masse volumique ρ (kg.m^{-3})	Energie de Fermi des électrons libres E_F (MeV)	Caractéristiques moyennes des noyaux A	Z	Nombre d'électrons libres par nucléon Y_e
10^{13}	8.2	69	29 (Cu)	0.42
$10^{13.5}$	11.9	71	30 (Zn)	0.418
10^{14}	17.5	76	31 (Ga)	0.41
$10^{14.5}$	25	86	34 (Se)	0.389
10^{15}	36	105	37 (Rb)	0.358

From the gravitational collapse to the bounce and the explosion : summary

1. Triggering the collapse
2. Neutron enrichment
3. Gravitational collapse
   - Pressure in the core is dominated by the pressure of ultra-relativistic degenerate electrons (adiabatic index $\gamma = 4/3$)
   - Due to the neutron enrichment, the number of free electrons per nucleon Y_e decreases
   - Then the Chandrasekhar mass decreases : $M_{Ch} = 1.457\ (Y_e / 0.5)^2\ M_\odot$ which favors the collapse
     - In such conditions, the collapse is homologous (self-similar profiles for velocity, density, ...)
     - The collapse lasts for a dynamical time, i.e. free fall timescale ~ 100 ms !
   - A few details...
     - Dynamical time (free fall) : $t_{\rm dyn} \simeq \frac{1}{\sqrt{G\rho}} \simeq 0.07\,{\rm s} \left(\frac{\rho}{3\times 10^{12}\,{\rm kg/m^3}}\right)^{-1/2}$
     - Sound speed : $c_{\rm S} \simeq 0.05c \left(\frac{\rho}{3\times 10^{12}\,{\rm kg/m^3}}\right)^{1/6}$
     - Sonic time : $t_{\rm son} \simeq t_{\rm dyn}$
     - The inner part of the collapsing core can always communicate internally with sound waves : homologous collapse (Goldreich & Weber 1980) : collapse duration t_0 ~ 0.2 s

$$v(r,t) \simeq -\frac{2}{3}\frac{r}{t_0 - t}$$

     - The external part cannot adjust fast enough : free fall

From the gravitational collapse to the bounce and the explosion : summary

1. Triggering the collapse
2. Neutron enrichment
3. Gravitational collapse
4. Evolution of the equation of state - gravitational collapse stops - formation of a neutron star

- Due to the collapse, the density in the core increases rapidly

  - At very large densities, individual nuclei do not exist anymore : neutron-rich mixture of n,p,e
  - The neutron enrichment goes on (neutronization) by direct inverse β decay

$$p + e^- \rightarrow n + \nu_\mathrm{e}$$

  -When the density becomes of the order of the nuclear density (2.6×10^{17} kg/m3 ~ 0.16 n / fm^3), the E.O.S. evolves due to the repulsive nature of the nuclear force (strong interaction) at short distances : a new dominant pressure appears

  - the collapse stops (if the mass of the core is not too large, otherwise a BH will form...)
  - the core becomes a neutron star

- A few details...
  - Binding energy of the new born neutron star :

$$B_{NS} \simeq -6 \times 10^{44}\,\mathrm{J} \left(\frac{f}{0.1}\right)\left(\frac{Y_\mathrm{e}}{0.36}\right)^2\left(\frac{\rho}{\rho_\mathrm{nuc}}\right)$$

  - Details are highly uncertain ...
  - Initially the NS oscillate, but very rapidly it stabilizes
  - The NS will cool, which can contribute to the next steps of the scenario

From the gravitational collapse to the bounce and the explosion : summary

1. Triggering the collapse
2. Neutron enrichment
3. Gravitational collapse
4. Evolution of the equation of state - gravitational collapse stops - formation of a neutron star
5. Neutrino trapping

- At the end of the collapse, the density in the central region is so high that neutrinos are trapped ! (very unique conditions, usually not found in the Universe except just after the Big Bang ($t < 10^{-12}$ s))

- Neutrino adopt a thermal distribution in equilibrium with the other species
  - The core cools by emitting neutrino thermal radiation (photons cannot escape) $\gamma\gamma \to e^+e^- \to \nu\bar{\nu}$
    = a neutrino « black body»
  - The neutrinosphere as a radius of a few 10 km. The rest of the star is transparent.
  - Neutrinos and anti-neutrinos of the 3 flavors are emitted !
    (cf. detection of electronic anti-neutrino SN1987A)
  - Electron captures stop : $Y_e = 0.36$; Final Chandrasekhar mass : $M_{Ch} = 0.75\ (Y_e\ /\ 0.36)^2\ M_\odot$

- A few details...
  - For $\varrho_c < 10^{15}$ kg/m^3 : the core is transparent for the neutrinos produced by electron captures
  - Dominant interaction : elastic scattering on nuclei
  - Cross section : $$\sigma_{\nu,el} \simeq 9 \times 10^{-47}\,\mathrm{m}^2\, A^2\, (1 - Y_\mathrm{e})^2 \left(\frac{\epsilon_\nu}{15\,\mathrm{MeV}}\right)^2$$
  - Mean free path :

$$\ell_\nu \simeq \frac{1}{(\rho/Am_u)\,\sigma_{\nu,\mathrm{el}}} \simeq 4.3 \times 10^3 \left(\frac{A}{69}\right)^{-1} \left(\frac{1-Y_\mathrm{e}}{1-0.42}\right)^{-2} \left(\frac{\epsilon_\nu}{15\,\mathrm{MeV}}\right)^{-2} \left(\frac{\rho_\mathrm{c}}{10^{13}\,\mathrm{kg/m^3}}\right)^{-1}$$

  - Collapse of an initial core R = 2 000 km and $\varrho = 3\times10^{12}$ kg/m^3 : $\varrho_c = 10^{15}$ kg/m^3 when R = 300 km
  - At this stage : $\ell_{\nu,el}$ = 23 km << R
    The diffusion time is $t_{\nu,el} \sim R^2\ /\ (\ c\ \ell_{\nu,el}\ )$ ~ 15 ms comparable to the dynamical time
  - When R ~ 10 km : $t_{\nu,el} >> t_{dyn}$: neutrinos are trapped !

From the gravitational collapse to the bounce and the explosion : summary

1. Triggering the collapse
2. Neutron enrichment
3. Gravitational collapse
4. Evolution of the equation of state - gravitational collapse stops - formation of a neutron star
5. Neutrino trapping
6. Bounce - Formation and propagation of a shock wave

    - As the dynamical timescale for the gravitationnal collapse of the core is very short (< 1 s) The enveloppe cannot react immediately

    - When the neutron star forms, the still infalling external region of the core bounces on it

    - This triggers the formation of a shock wave propagating outwards
      $R > R_{shock}$: the medium is still infalling (v<0)
      $R < R_{shock}$: the medium is moving outwards (v>0) and has been heated

      Huge discontinuity for the velocity : 100 000 km/s !

    - The kinetic energy carried by the shock is $E_{SN} \sim -B_{NS} \sim 6 \times 10^{44}$ J

    - The shock wave deposits kinetic and thermal energy in the shocked medium (equipartition as it is a strong shock)

From the gravitational collapse to the bounce and the explosion : summary

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6. Bounce - Formation and propagation of a shock wave
7. Photo-disintegration of iron - Shock stops
   - The close vicinity of the new-born neutron star (where the shock initially propagates) is made of iron and other heavy elements
   - Most of the energy of the shock is lost by photo-disintegration of iron

$$\gamma + {}^{56}Fe \rightarrow 13\,{}^{4}He + 4n$$
$$\gamma + {}^{4}He \rightarrow 2p + 2n$$

   - Energetic cost :
     124 MeV per Fe nucleus (2.2 MeV/nucleon) and 28.3 MeV per He nucleus,
     i.e. 8.8 MeV / nucleon (binding energy of iron)

   - This is equivalent to 1.7×10^{45} J/M$_\odot$: a few 0.1 M$_\odot$ of iron is enough to stop the shock
     ~ 0.4 M$_\odot$ is enough to stop the shock if photo-disintegration is complete
     ~ 0.7 M$_\odot$ if photo-disintegration stops at He
   - The shock becomes an accretion shock at a radius of ~ 150-300 km
   - Without a new process to deposit more energy in the shocked region so that the shock can start again, in ~ 1s, the new-born neutron star will accrete enough mass (mass flux >> 1 M$_\odot$/s) to reach the maximum mass and collapse into a black hole : the supernova has failed !

- A few details...
  - energy per nucleon deposited by the initial shock (discontinuity of velocity 100 000 km/s)
    kinetic energy = thermal energy ~ 1/2 (100 000 km/s)^2 ~ 26 MeV / nucleon
  - temperature is large enough to produce a large number of photons above 10 MeV which allows iron photo-disintegration
  - what is the available mass of iron ? 1.2 (initial) - 0.8 (inner core: NS formation) ~ 0.4 M$_\odot$

From the gravitational collapse to the bounce and the explosion : summary

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5. Neutrino trapping
6. Bounce - Formation and propagation of a shock wave
7. Photo-desintegration of iron - Shock stops
8. Shock starts again and crosses the whole star : explosion !
    - In reality, massive stars do explode as supernovae. However, the mechanism at work to help the shock to start again remains unclear...

    - Candidates which are currently investigated :
        - Realistic microphysics (equation of state, electron captures, ...)
        - Neutrino heating (Bethe & Wilson, 1985)
        - Hydrodynamic instabilities / convection
        - Magneto-rotational driving
        - ?

    - A few details...
        - The neutrino luminosity of the core is :

$$L_\nu \simeq 4\pi R^2 \left(\frac{7}{2}\sigma\right) T^4 \simeq 7 \times 10^{46}\,\mathrm{W} \left(\frac{R}{50\,\mathrm{km}}\right)^2 \left(\frac{T}{5\,\mathrm{MeV}}\right)^4$$

        - If ~ 1 % of this pwer is deposited in the shocked matter, the shock can start to propagate again

        - Hydrodynamics : a lot of discussion around SASI - Bonus : explosion is asymetric (pulsar kick)

Energetics of the explosion

1. Radiated energy : $E_{ph} \sim 10^{42}$ J
2. Kinetic energy : $E_{kin} \sim 10^{44}$ J
3. Gravitational energy released by the collapse : $\Delta E \sim 3 \times 10^{46}$ J
4. Energy emitted as neutrinos : $E_{\nu} \sim 3 \times 10^{46}$ J

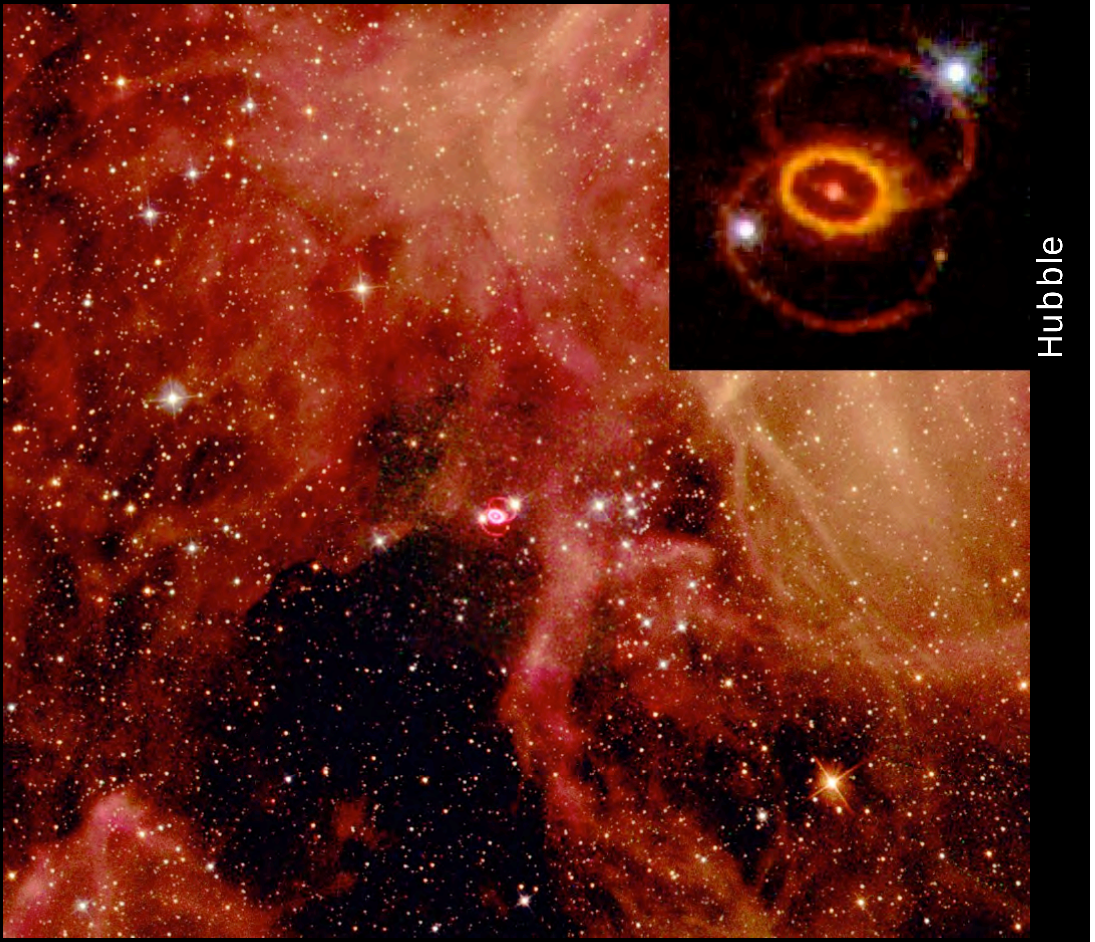
The proposed scenario for core-collapse supernovae is very well supported by observations :

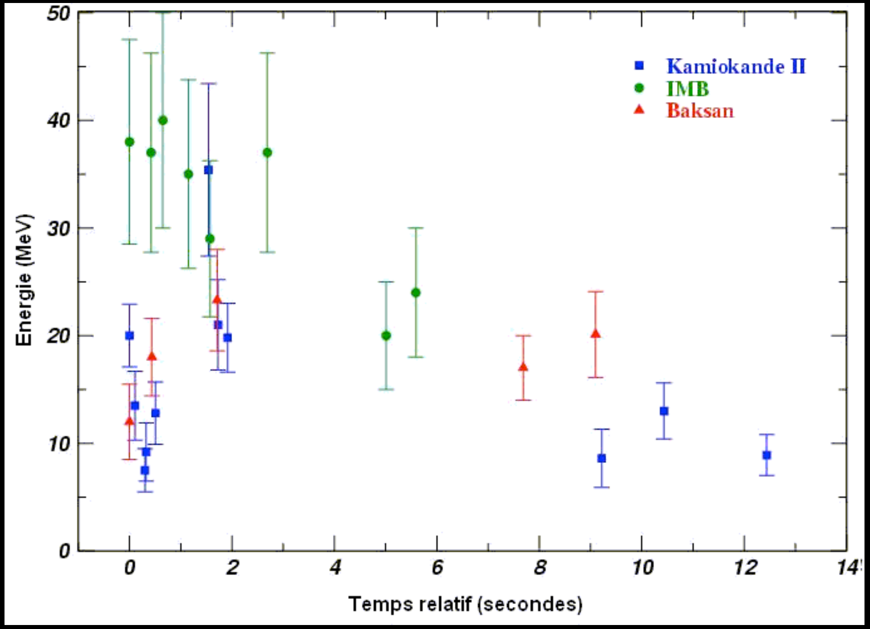
- SN1054 (in Taurus) reported by Chinese and Japanese astronomers in 1054
- Centuries later : the Crab nebula is discovered
- 1968 : discovery of the Crab pulsar
- The age of the Crab pulsar is ~ 950 yr
- The link massive stars - supernovae - neutron stars is demonstrated !

- SN1987A : the detection of electronic anti-neutrinos proves that a very dense region is formed (dense enough to be opaque for neutrinos) : gravitational collapse
- The duration and mean energy of neutrinos coincide well with the theoretical estimate of the size and temperature of this central region
- The estimate of the energy emitted as neutrinos is comparable to the energy release by the gravitational collapse of an iron core into a neutron star

But the details of the mechanism are still unclear ...

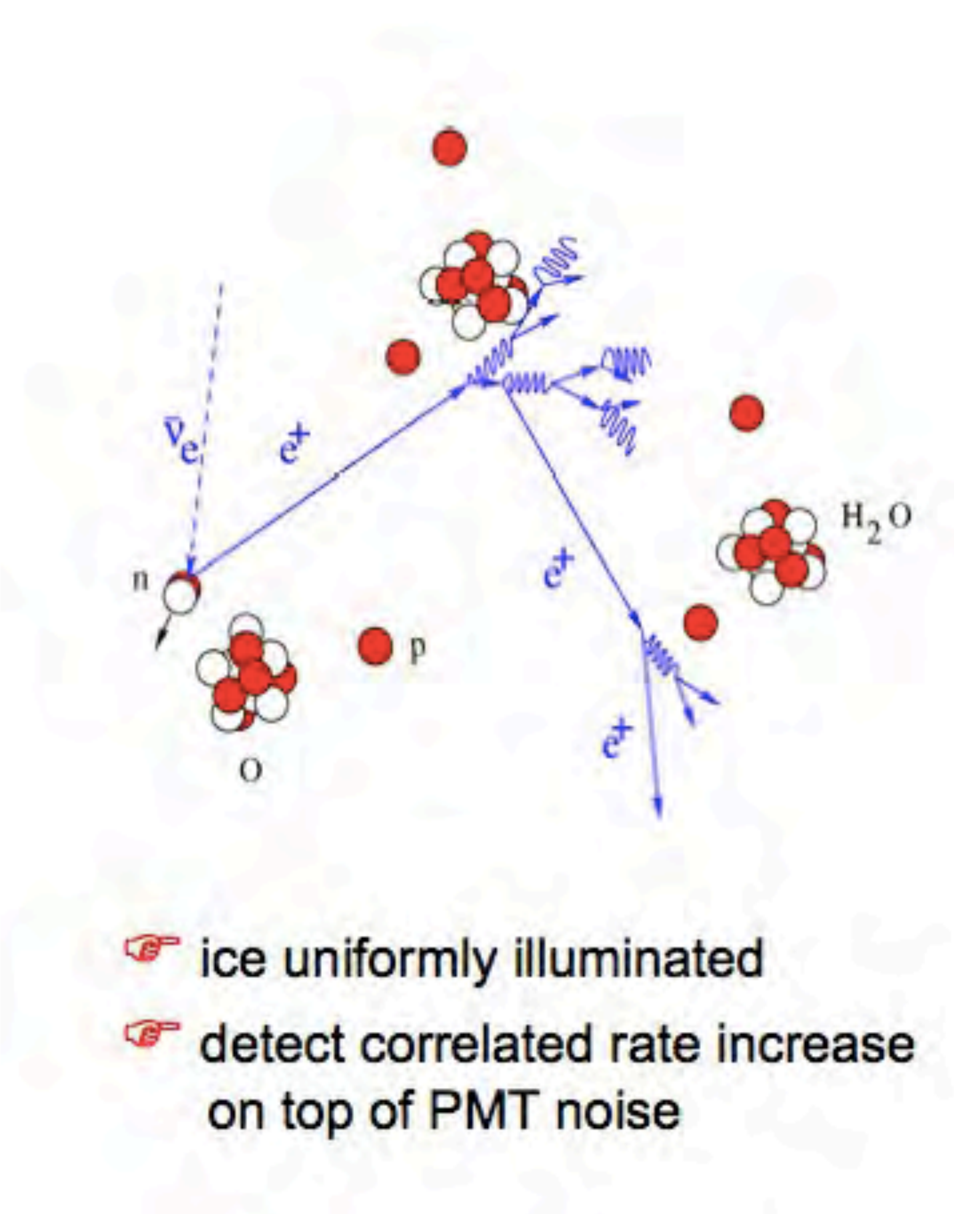
SN 1987A : type II





Anti-neutrinos :
11 (Kamiokande II) + 8 (IMB) + 5 (Baksan)
duration : 13 s, neutrino-light delay : about 3 hours

5) Neutrino telescopes: core collapse SN



IceCube can also detect large numbers of MeV neutrinos by observing a collective rise in all photomultiplier rates on top of the dark noise. With **2 ms timing resolution**, IceCube can track subtle features in the temporal development of the supernova neutrino burst. For a supernova at the galactic center, its sensitivity matches that of a background-free megaton-scale supernova search experiment. The sensitivity decreases to 20 standard deviations at the galactic edge (30 kpc) and 6 standard deviations at the Large Magellanic Cloud (50 kpc).

http://arxiv.org/pdf/1106.6225v1.pdf

Two Types of Supernova

Massive star supernova:

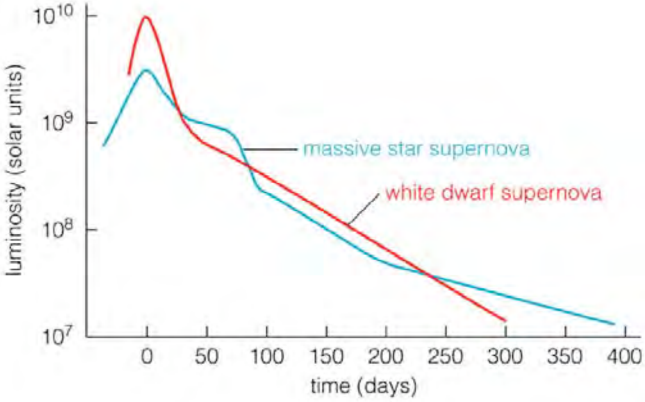
Iron core of massive star reaches white dwarf limit and collapses into a neutron star, causing explosion

White dwarf supernova:

Carbon fusion suddenly begins as white dwarf in close binary system reaches white dwarf limit, causing total explosion

or

the merging of two white dwarf binaries.



One way to tell supernova types apart is with a ***light curve*** showing how luminosity changes with time

The Evolution of Binary-Star Systems

If the stars in a binary-star system are relatively widely separated,

- **Their evolution proceeds much as it would have if they were not companions**

If they are closer,

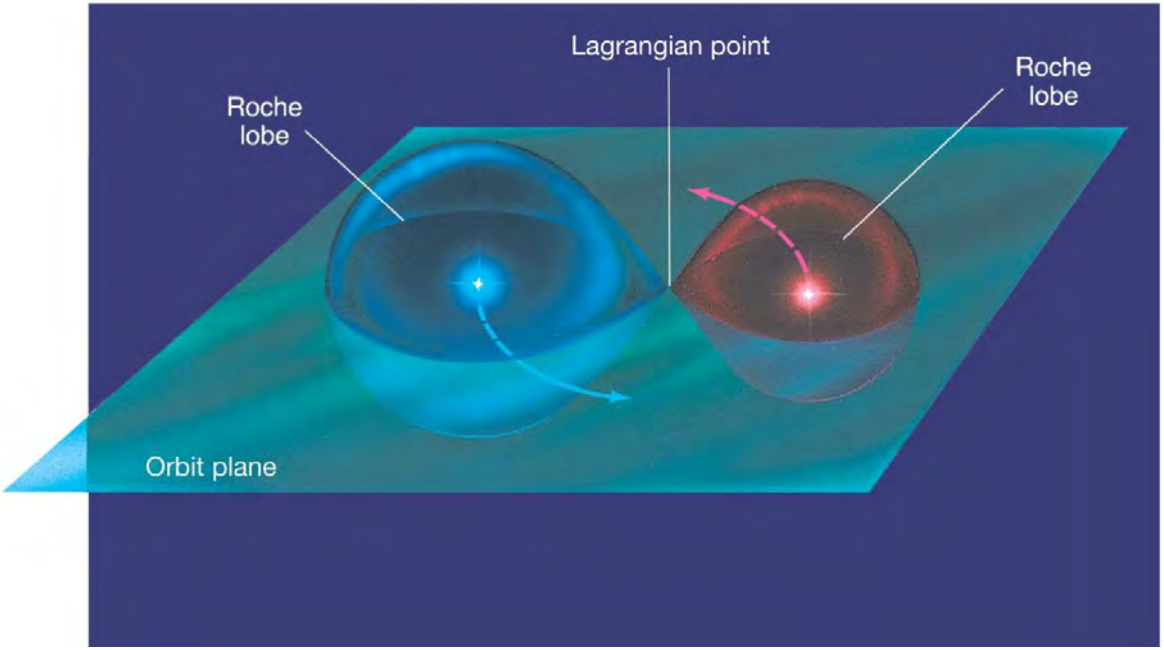
- **It is possible for material to transfer from one star to another,**
- **Leading to unusual evolutionary paths**

The Evolution of Binary-Star Systems

Each star is surrounded by its own Roche lobe

Particles inside the lobe belong to the central star

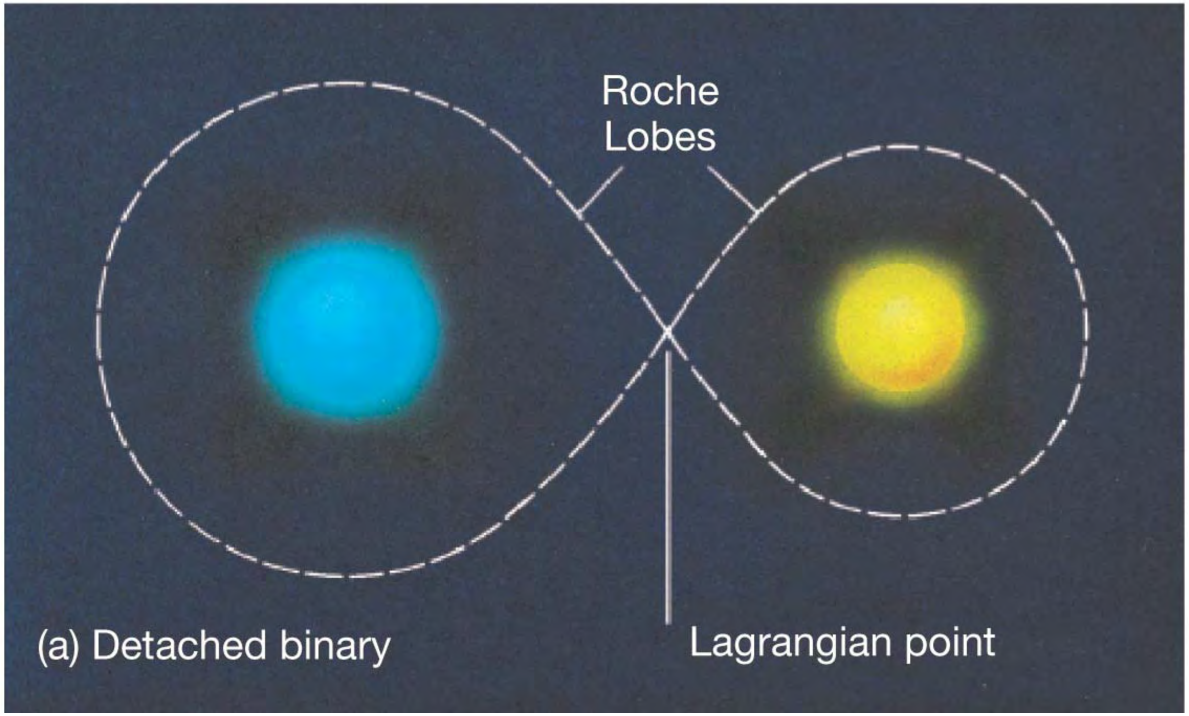
The Lagrangian point is where the gravitational forces are equal



The Evolution of Binary-Star Systems

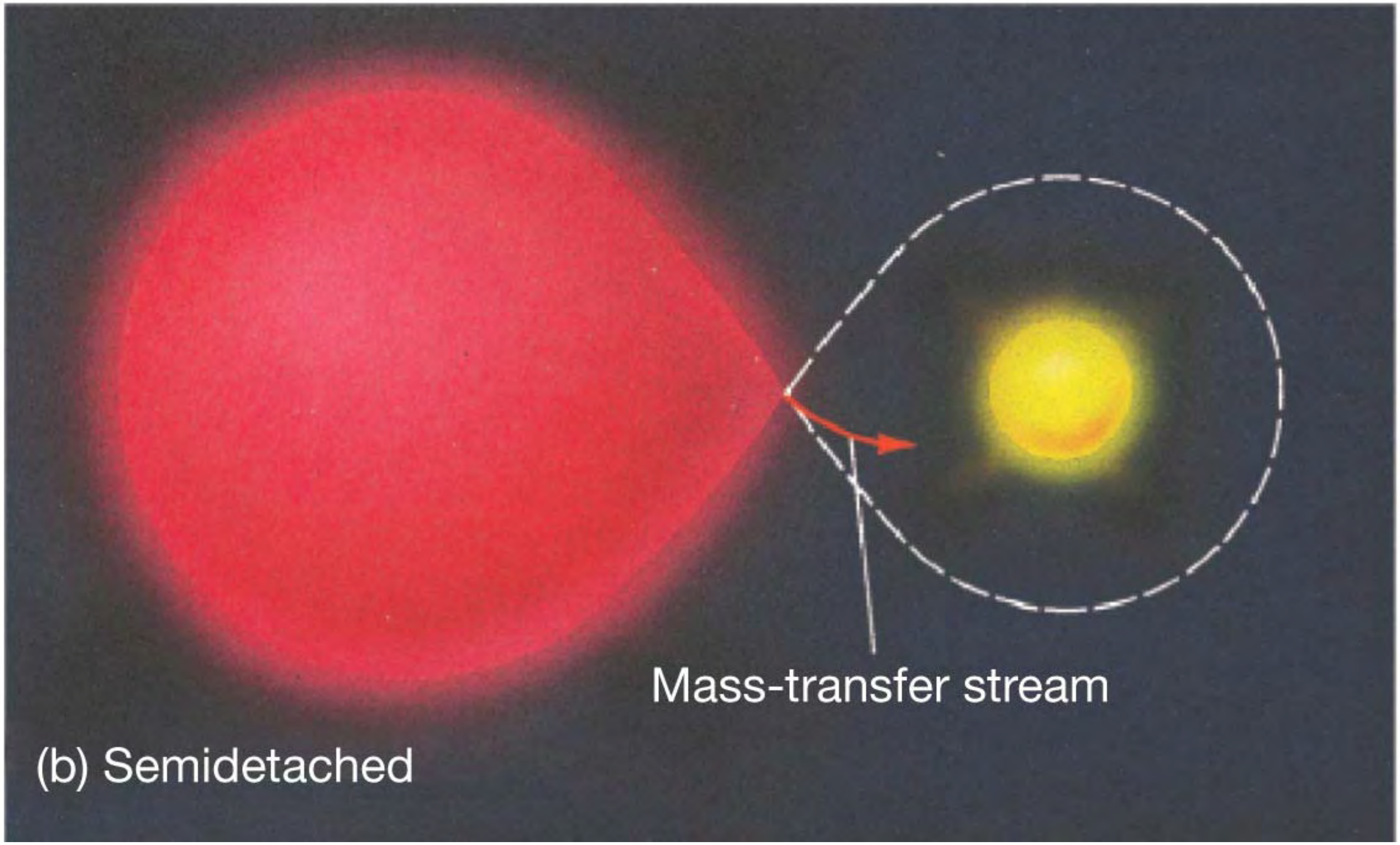
There are different types of binary-star systems, depending on how close the stars are

In a **detached binary**, each star has its own Roche lobe



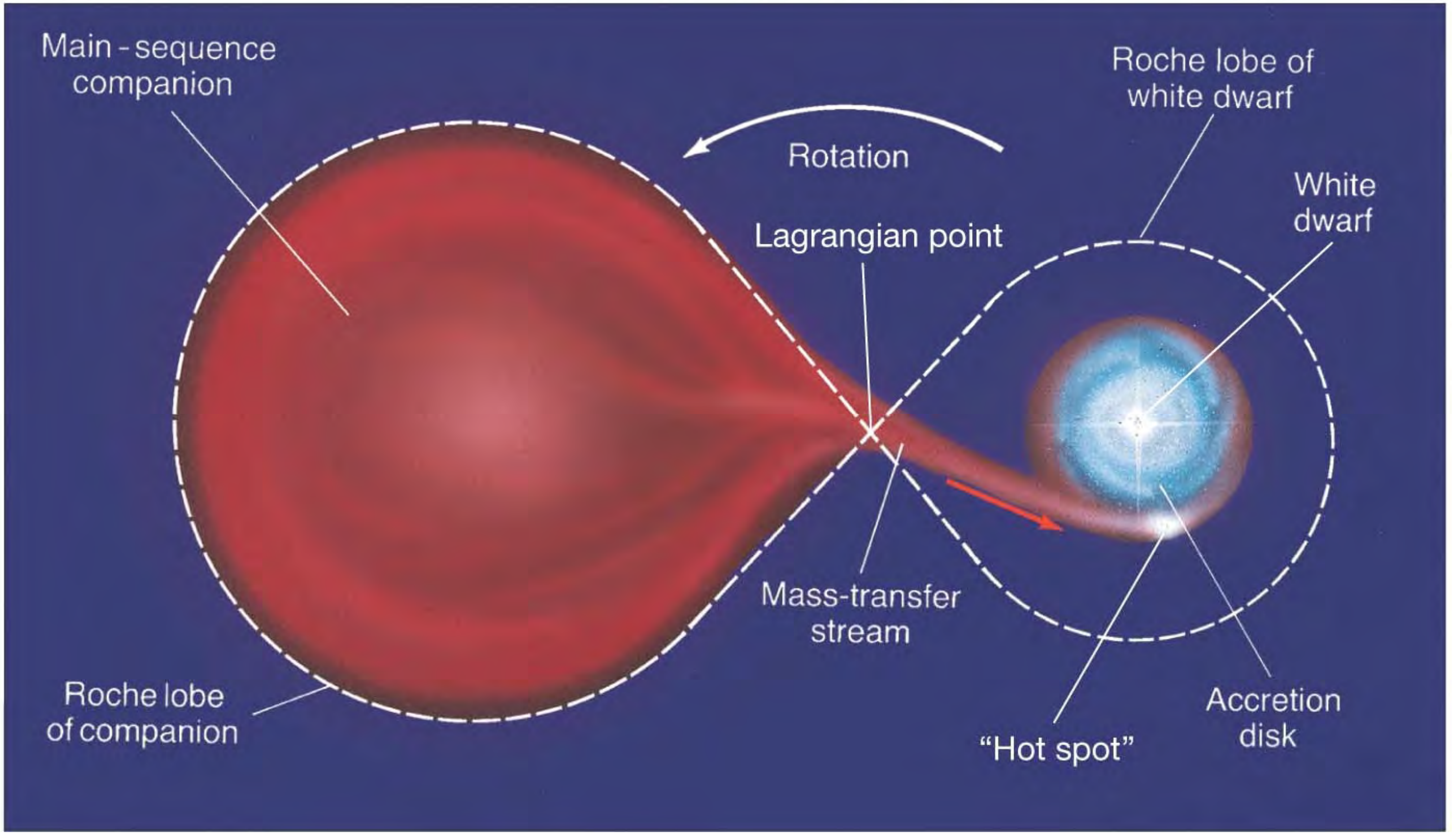
The Evolution of Binary-Star Systems

In a semidetached binary, one star can transfer mass to the other

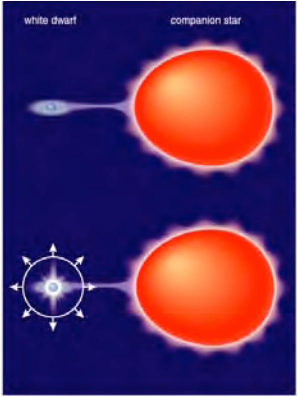


Life after Death for White Dwarfs

A white dwarf that is part of a semidetached binary system can undergo repeated novas



Nova



- The temperature of accreted matter eventually becomes hot enough for hydrogen fusion

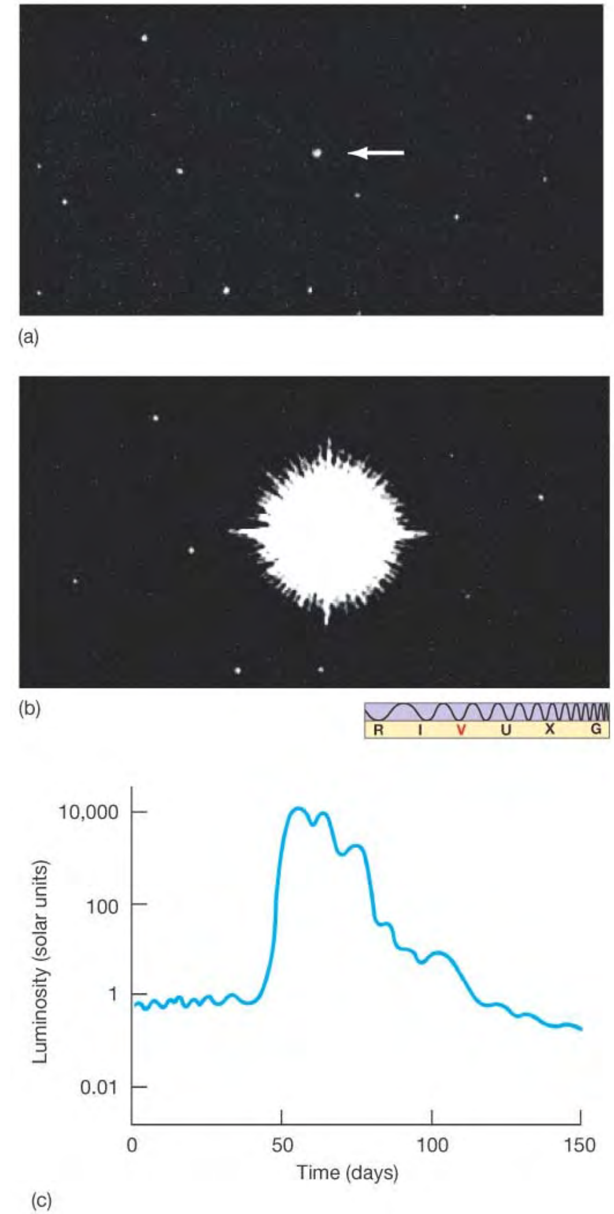
- Fusion begins suddenly and explosively, causing a *nova*

Life after Death for White Dwarfs

Nova

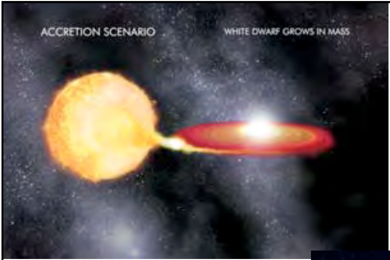
Star that flares up very suddenly

Then returns slowly to its former luminosity



Nova or White Dwarf Supernova?

- Supernovae are MUCH MUCH more luminous!!! (about 10 million times)
- Nova: H to He fusion of a layer of accreted matter, white dwarf left intact
- Supernova: complete explosion of white dwarf, nothing left behind



Triggering White Dwarf Supernova

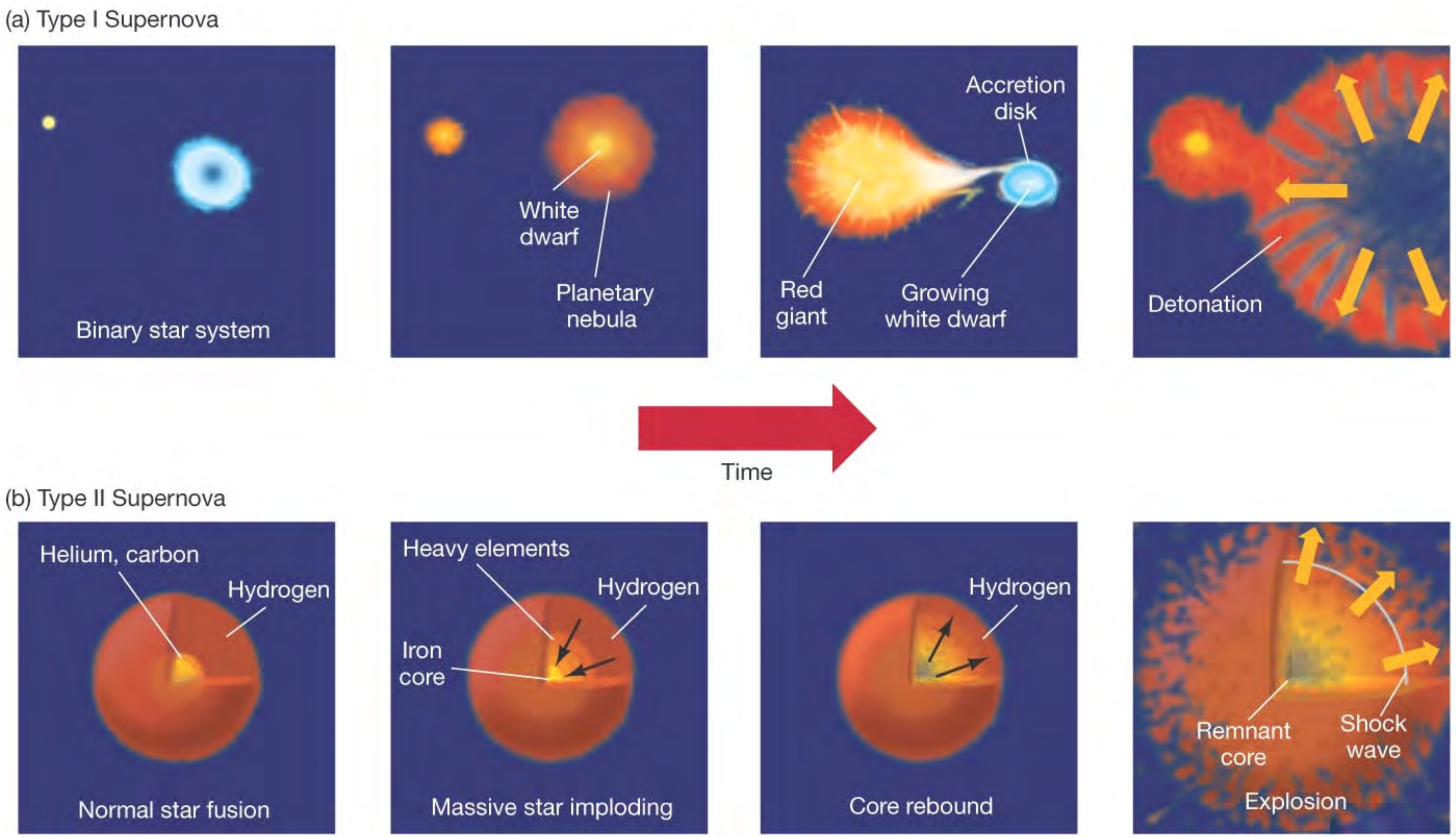
White dwarf fed by accretion disk until it exceeds 1.4 solar masses

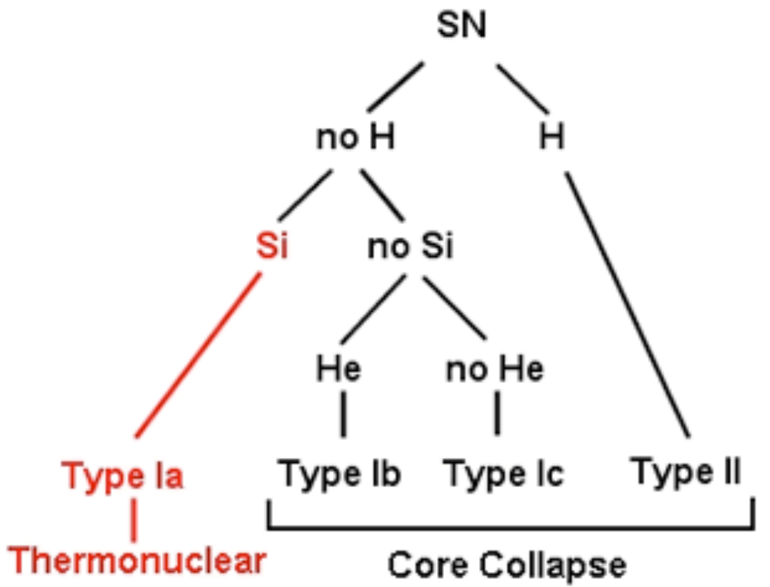
White dwarf binary combines and exceeds 1.4 solar masses

http://chandra.harvard.edu/photo/2010/type1a/animations.html

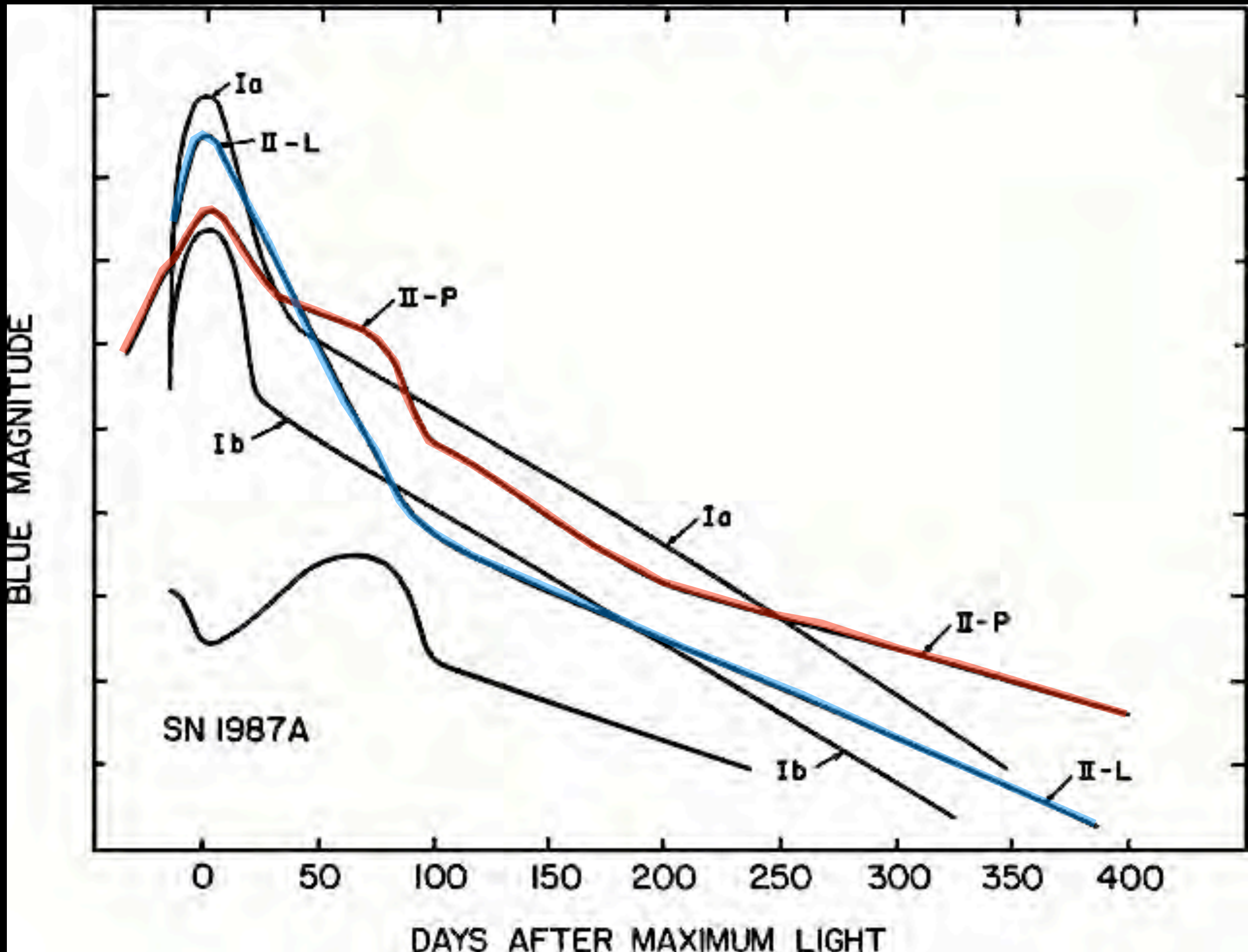
Supernovae

This graphic illustrates the two different types of supernovae




SN
no H
H
Si
no Si
He
no He
Type Ia
Type Ib
Type Ic
Type II
Thermonuclear
Core Collapse

Type II SNe: additional classification based on the light curve (type II-P vs type II-L)



How often do SN happen?

- The rate of Supernovae is

  ~ 1 SN / Galaxy / 50 years

- But there hasn't been one seen in our galaxy in over 390 years!

Historical (Naked Eye) Supernovae

Date (A.D.)	Constellation	Apparent Mag./Dist	Where Observed
1006	Lupus	-5 (> Venus) 3 kpc	Many Places
1054	Taurus (Crab Nebula)	-5 (> Venus) 2 kpc	China, SW America
1572	Cassiopeia (Tycho's SN)	-4 (< Venus) 5 kpc	Many Places
1604	Ophiucus (Kepler's SN)	-2 (> Sirius) 6 kpc	Many Places
1987	LMC	+3 (Avg. Star) 50 kpc	Southern Hemisphere

Two different mechanisms

	Supernova rate (SNU) (from Allen's astrophysical quantities, A.N. Cox Editors)		
Host galaxy	Ia	Ib / Ic	II
Elliptical E	0.11		
Lenticular SO	0.15		
Spirals SOa, Sa, Sab, Sb	0.20 ± 0.07	0.11 ± 0.06	0.40 ± 0.19
Spirals Sbc, Scd, Sc, Sdm, Im	0.24 ± 0.09	0.16 ± 0.08	0.88 ± 0.37

1 SNU = 1 supernova per century per $10^{10}\ L_\odot$

Type Ia supernovae = thermonuclear destruction of a white dwarf

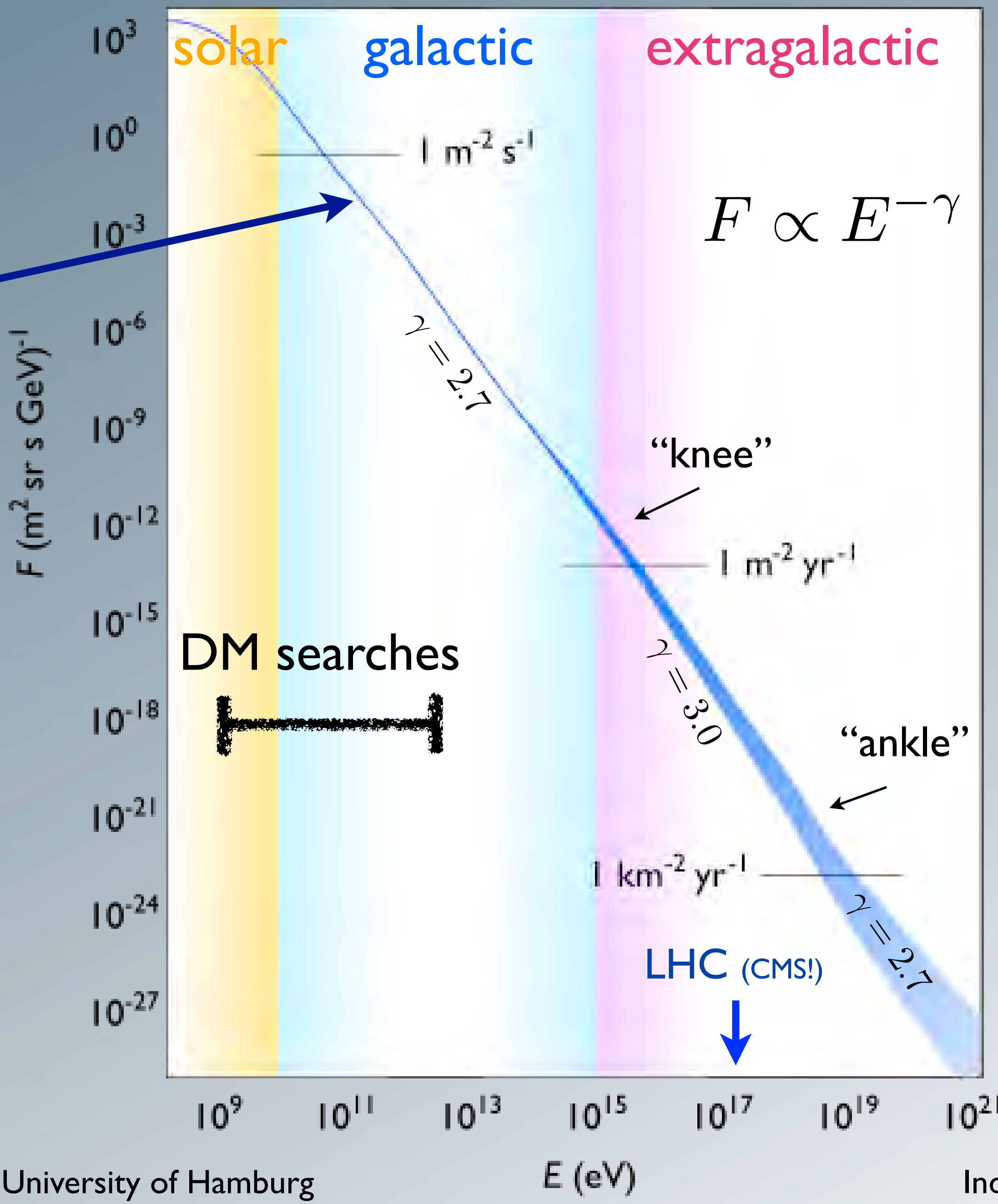
- explanation for the host statistics : long delay between star formation and explosion (progenitor is not a massive star)
- explanation for the spectrum : no H in white dwarfs, observed products of CO nuclear burning

Type Ib/Ic and II supernovae = gravitational collapse of a massive star

- explanation for the host statistics : short delay between star formation and explosion (progenitor is a massive star)
- explanation for the spectrum : depending on the progenitor mass, H or He enveloppe can be expelled

Spectrum and origin of CRs

mostly protons!



Summarizing:

SNRs are good candidate sources for CRs because:

- they can provide the right amount of energy in form of CRs (if **~10% efficiency**)
- they inject CRs in the ISM with (roughly) the spectrum needed to explain CR observations (**~ $E^{-2.1...2.4}$**)
- they can accelerate CRs (at least) up to the energy of the CR knee (**~5 x 10^{15} eV**)

(patrz wykład 7)

The Formation of the Elements

The last nucleus in the alpha-particle chain is nickel-56

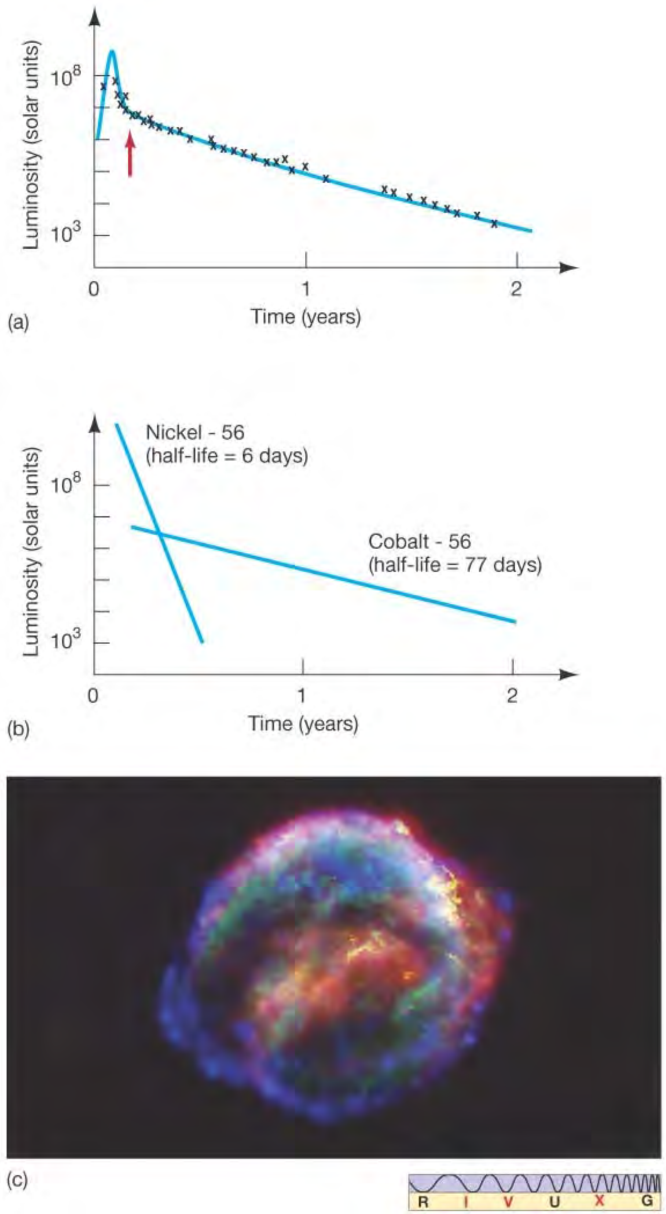
Nickel-56 is unstable and quickly decays to cobalt-56 which subsequently decays into iron-56

Iron-56 is the most stable nucleus, so it neither fuses nor decays

Within the cores of the most massive stars, neutron capture can create heavier elements, all the way up to bismuth-209

The heaviest elements are made during the first few seconds of a supernova explosion

The Formation of the Elements



This theory of formation of new elements in supernova explosions produces a light curve that agrees quite well with observed curves

Results of explosions

- Explosions put the processed stellar material back into the interstellar medium for the next generation of stars to use!

- In a Supernova, neutrons bombard nuclei and build up very heavy elements, e.g. Gold, Uranium, etc.

The Cycle of Stellar Evolution

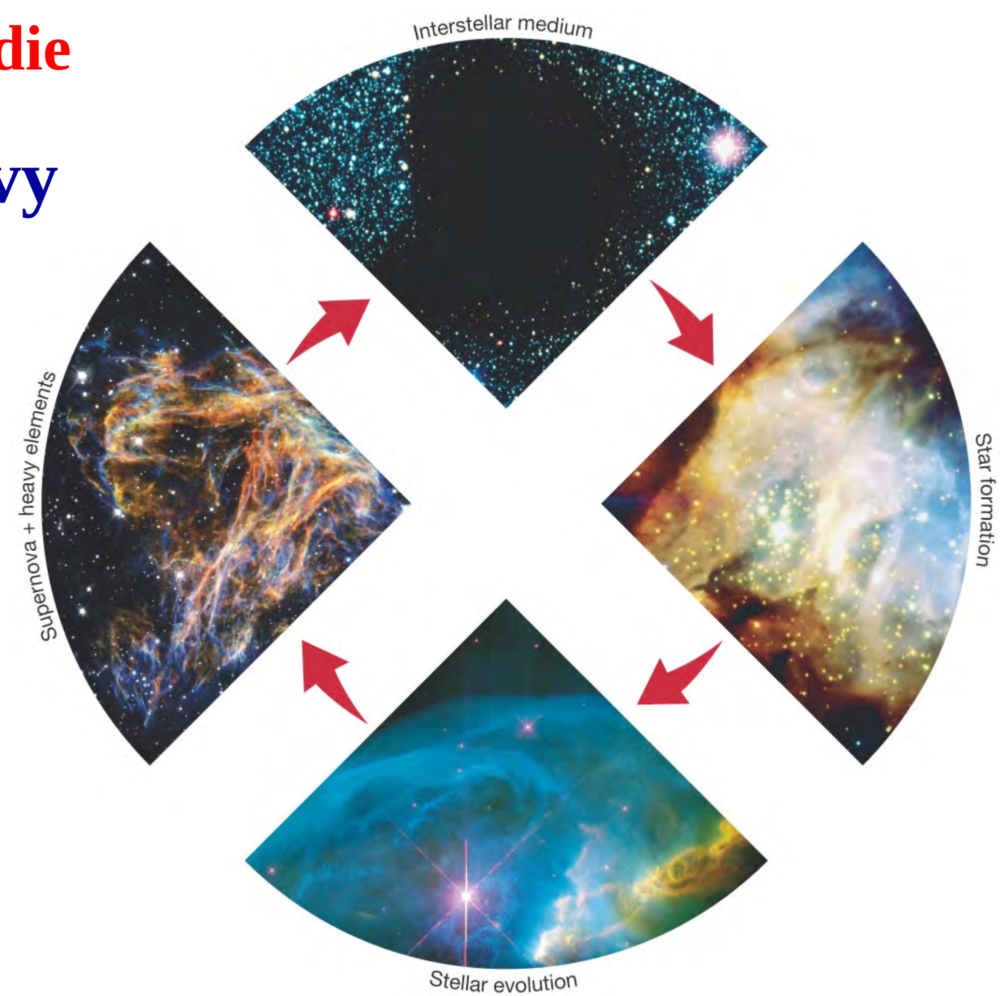
Star formation is cyclical

Stars form, evolve, and die

In dying, they send heavy elements into the interstellar medium

These elements then become parts of new stars.

And so it goes



Stars explode!

- Mild Explosion $\rightarrow$ Planetary Nebula
  - Ejection of the outer layers of the red giant.
- Strong Explosion $\rightarrow$ Nova
  - Eruptions in a binary star system
- Catastrophic Explosion $\rightarrow$ Supernova
  - Blasting away of the outer parts of a star

1963 – Treaty banning nuclear weapon tests in space

Military satellites VELA launched

- **equipped with γ-ray detectors**
- **orbit R=100 000 km, period=4.5 days**
- **could detect nuclear explosion at the other side of the Moon**

1958 – USA planned nuclear tests at the other side of the Moon

(uncovered in 2000)

THE ASTROPHYSICAL JOURNAL, 182:L85–L88, 1973 June 1

OBSERVATIONS OF GAMMA-RAY BURSTS OF COSMIC ORIGIN

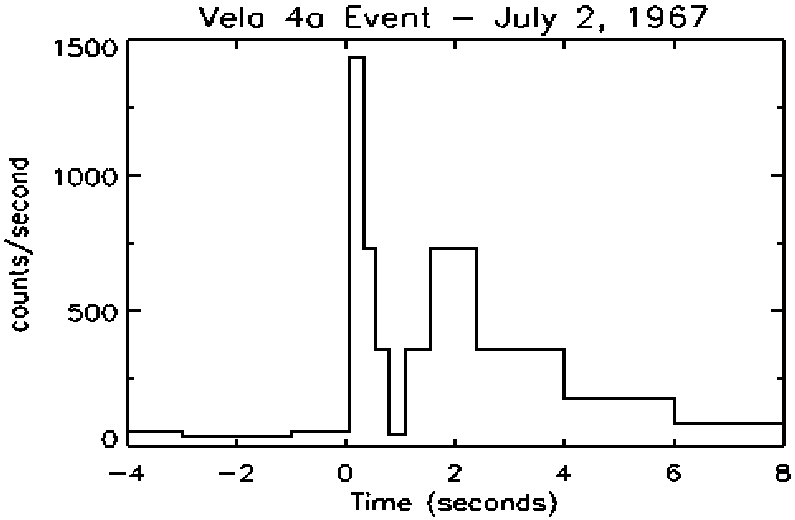
RAY W. KLEBESADEL, IAN B. STRONG, AND ROY A. OLSON

University of California, Los Alamos Scientific Laboratory, Los Alamos, New Mexico
Received 1973 March 16; revised 1973 April 2

ABSTRACT

Sixteen short bursts of photons in the energy range 0.2–1.5 MeV have been observed between 1969 July and 1972 July using widely separated spacecraft. Burst durations ranged from less than 0.1 s to $\sim$30 s, and time-integrated flux densities from $\sim 10^{-5}$ ergs cm^{-2} to $\sim 2 \times 10^{-4}$ ergs cm^{-2} in the energy range given. Significant time structure within bursts was observed. Directional information eliminates the Earth and Sun as sources.

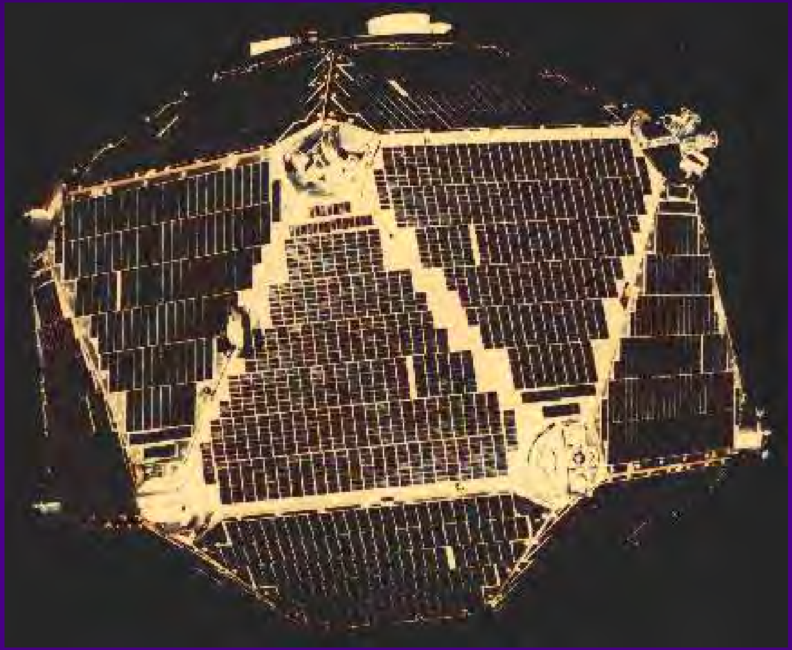
Subject headings: gamma rays — X-rays — variable stars



1969 – Launch of VELA 5 i 6

- time resolution 1/64 s
- direction (~5°) & distance estimate

1969-73 – 16 γ bursts detected



1973 – publication

- distance > 1 mln km
- directions exclude Sun and planets
- distribution ~isotropic
- journalists suspect nuclear war between E.T.'s
- astronomers got excited

Status in 1990

>95% astronomers: galactic origin

Ed Fenimore, Martin Rees, Donald Lamb, ...

- **GRB in Magellanic Cloud in place of old SN**
- **spectral lines**
- **small energy enough to explain**
- **optical flashes found at old photo-plates**
- **compactness problem** (γ >1MeV $\Rightarrow$ e^+e^-)

<5% astronomers: extragalactic origin

Bohdan Paczyński, ...

- **deficit of weak bursts**
- **izotropic distribtion**

Today we know that all the arguments were irrelevant or false ...

Burst And Transient Source Experiment

1973 – Gerald Fishman heard the talk on VELA results and started to work on new γ detectors

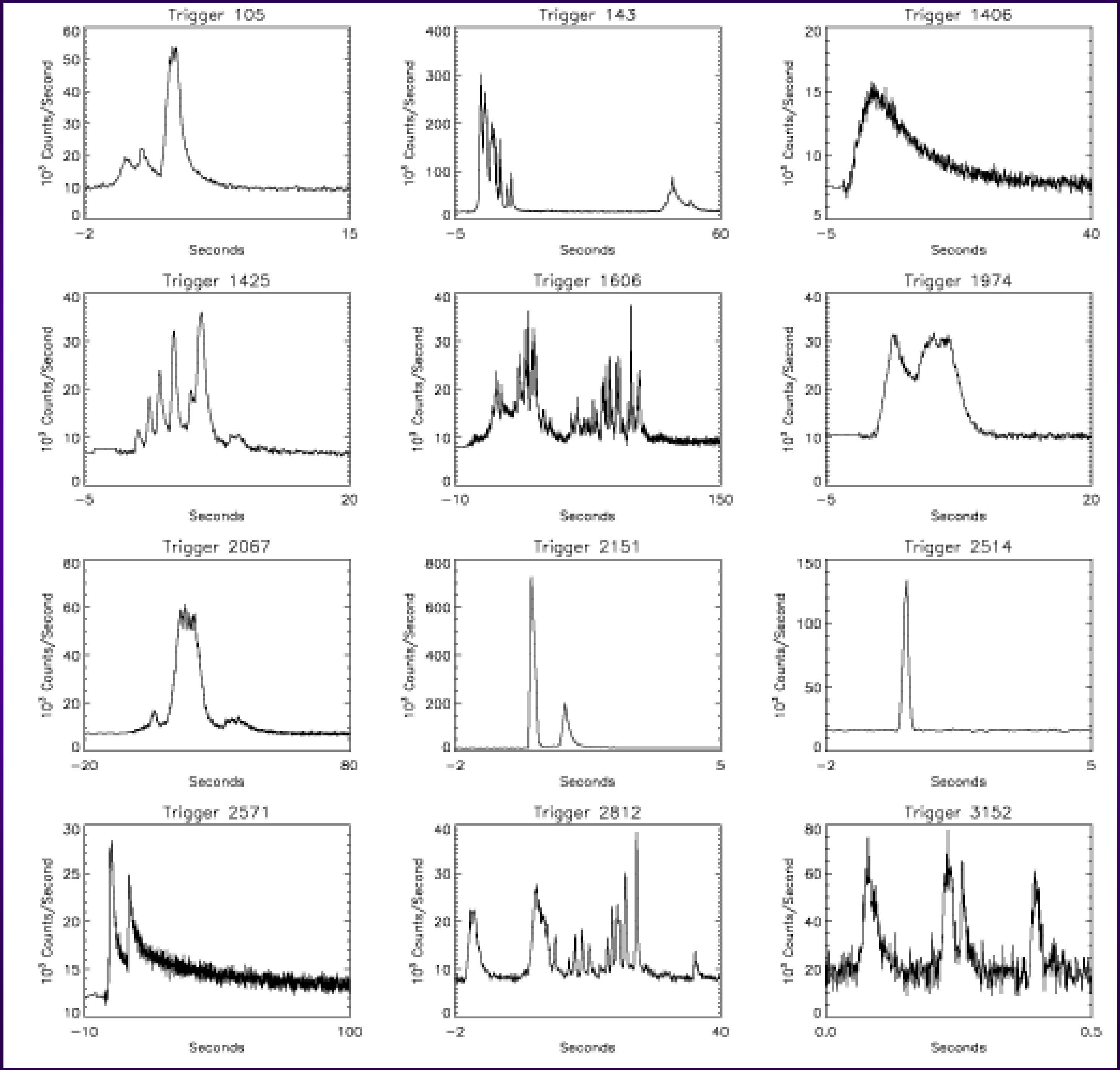
1975 – 2 baloon flights of 12h: only solar γ

1980, 82 – flights 19+48h: 1 GRB / 40 expected

1978 – BATSE planned for GRO satellite in 1985

1991 – in orbit!

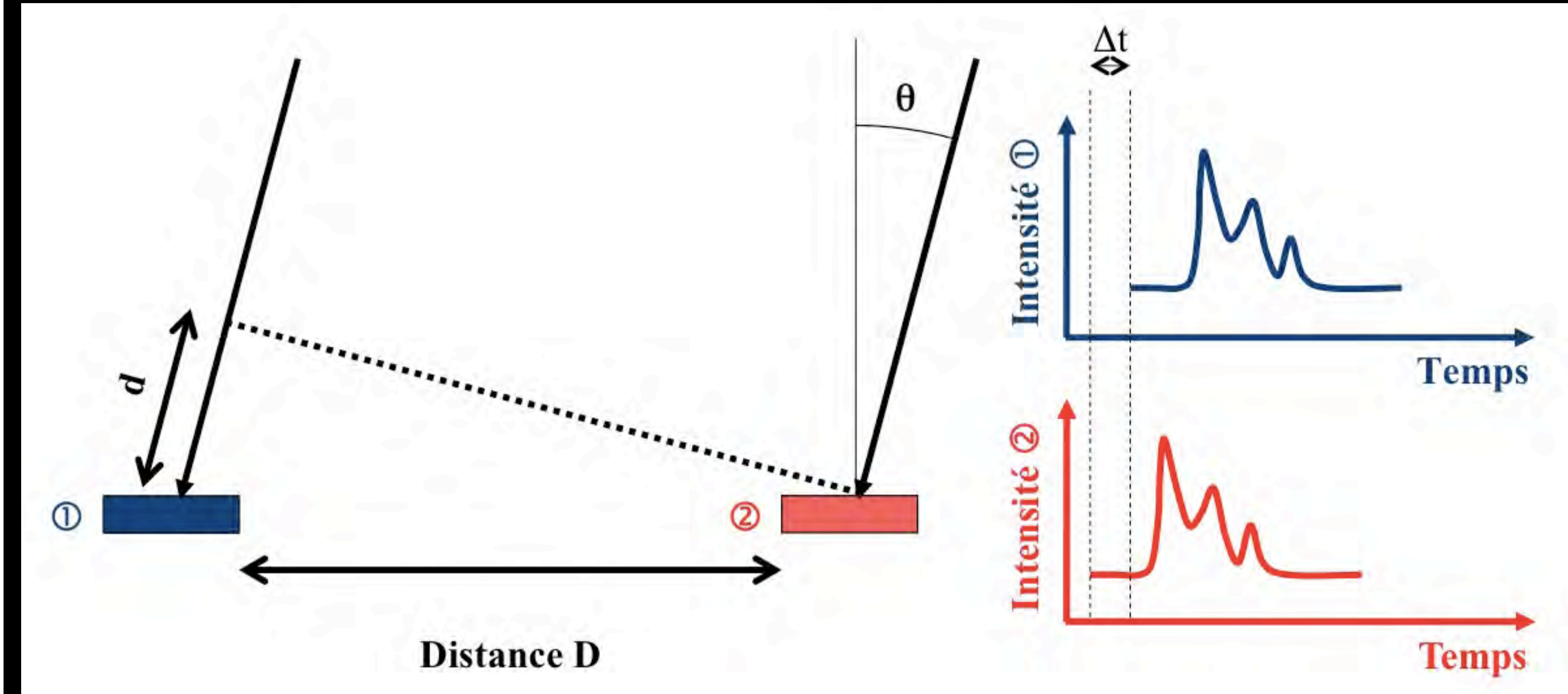
- **cost 12M$**
- **+ 400 manyear**
- **18 years preparation**
- **6 years delay**

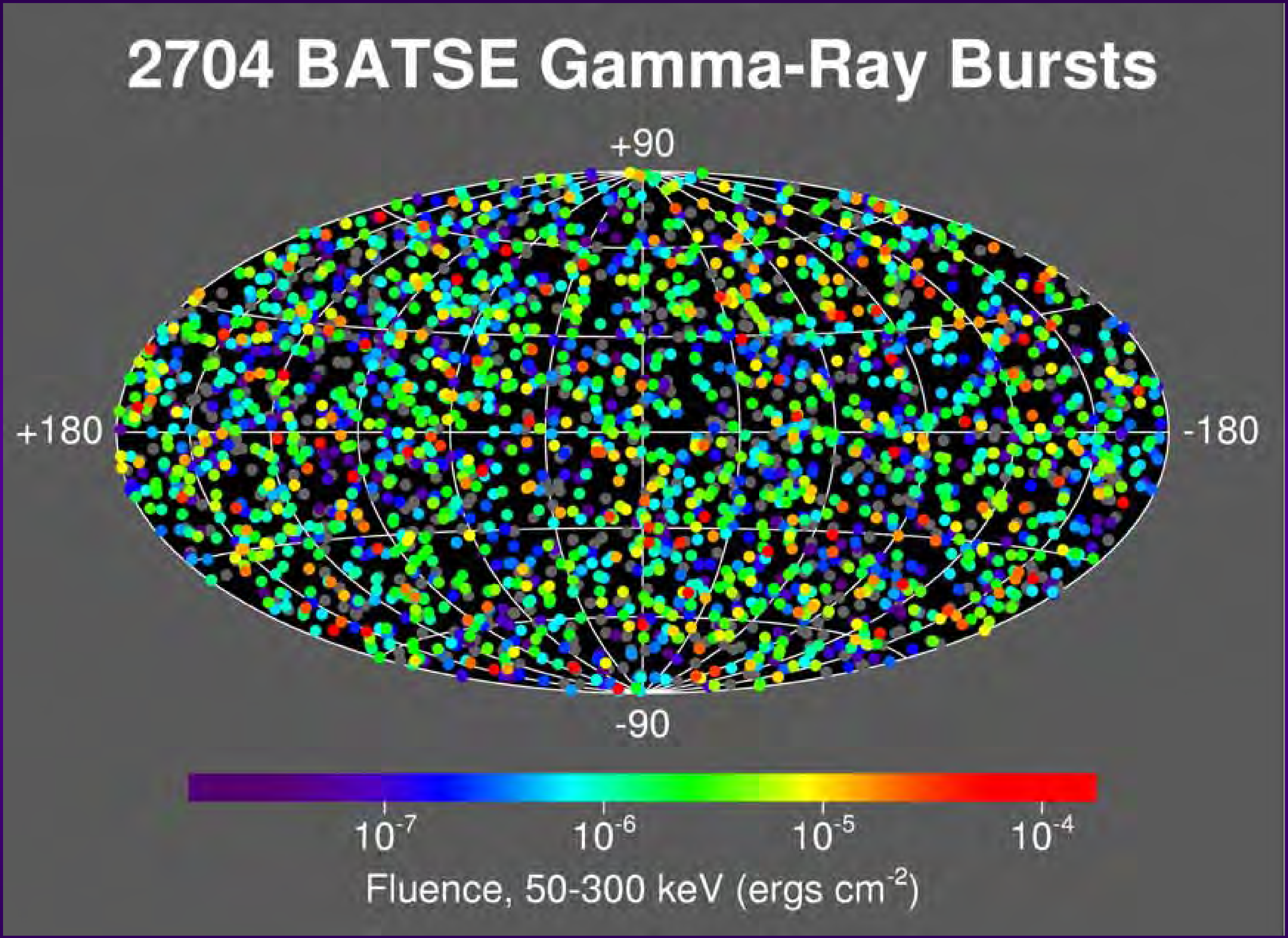


Different shapes

Time: 0.01-100s

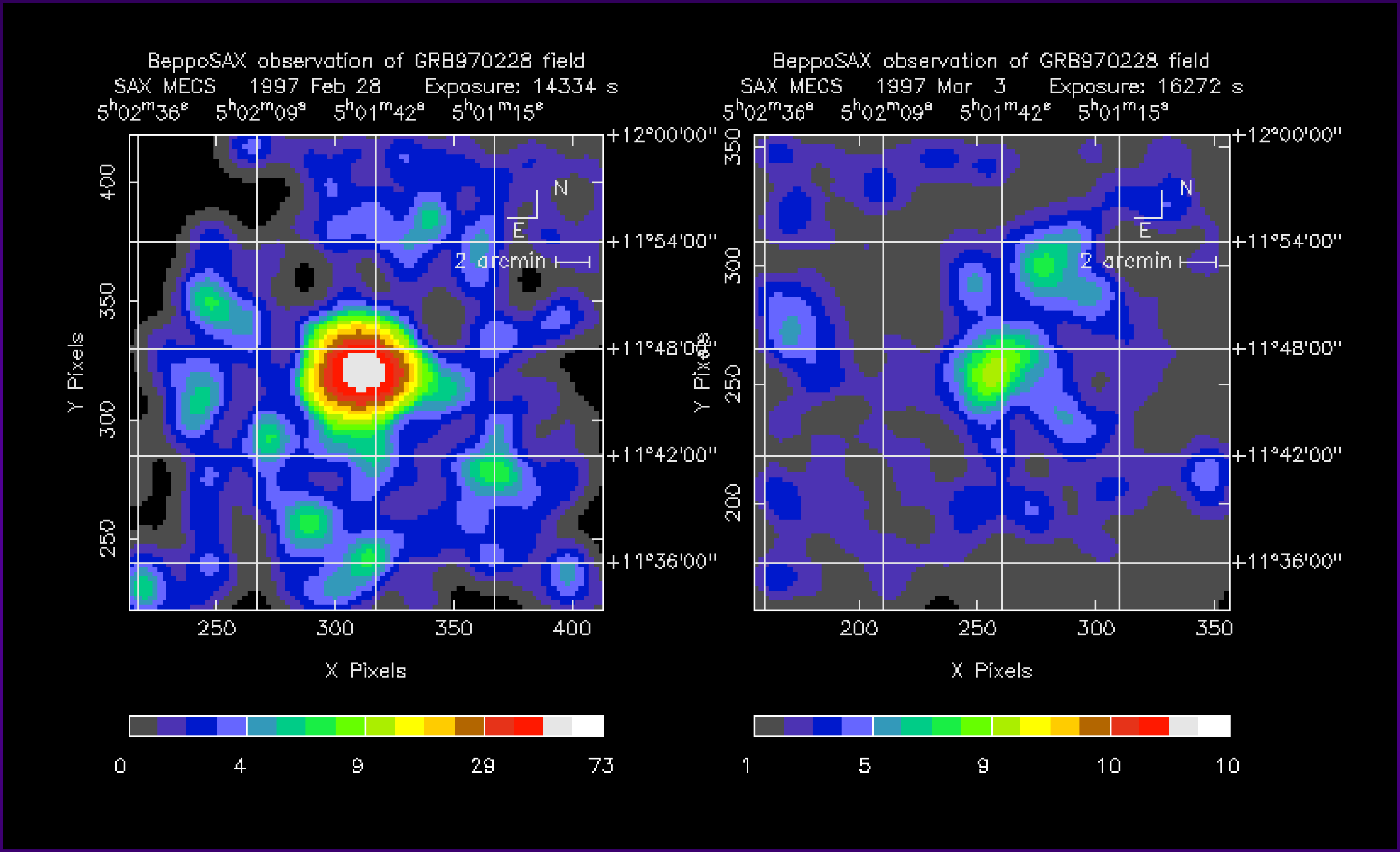
Gamma-ray bursts : localization





Izotropic distribution in galactic coordinates

First afterglows

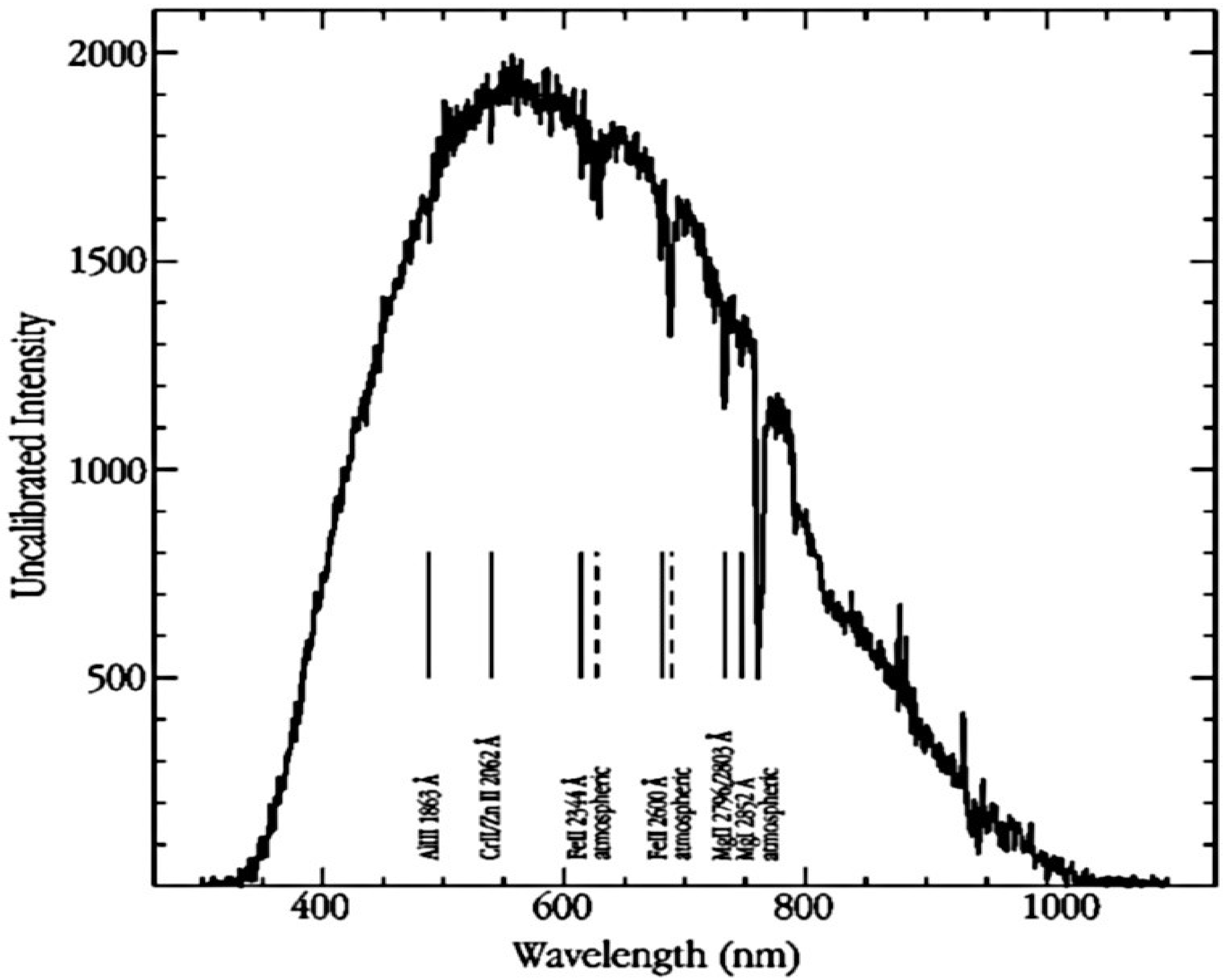


1997.02.28 – GRB observed in X-rays

21 h later – optical observation

William Herschel Telescope, 4.2m, La Palma

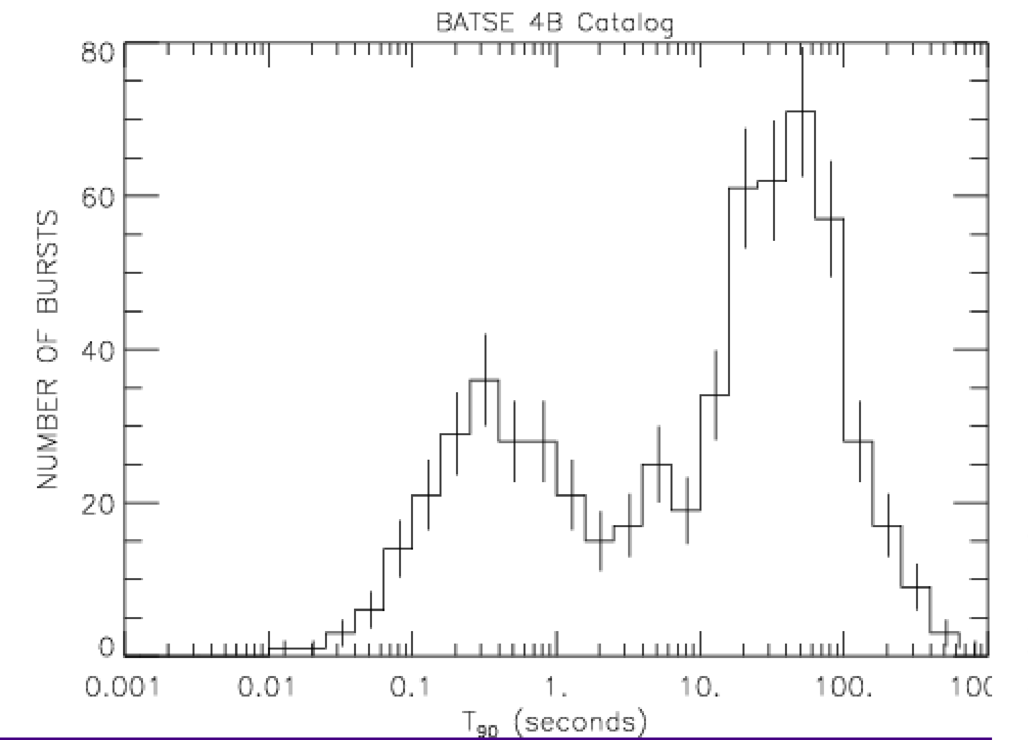
optical afterglow detection: red-shift determination possible



Spectrum of GRB 990510 Afterglow
(VLT/ANTU + FORS1)

ESO PR Photo 22f/99 (18 May 1999)

„Short” and „long” bursts



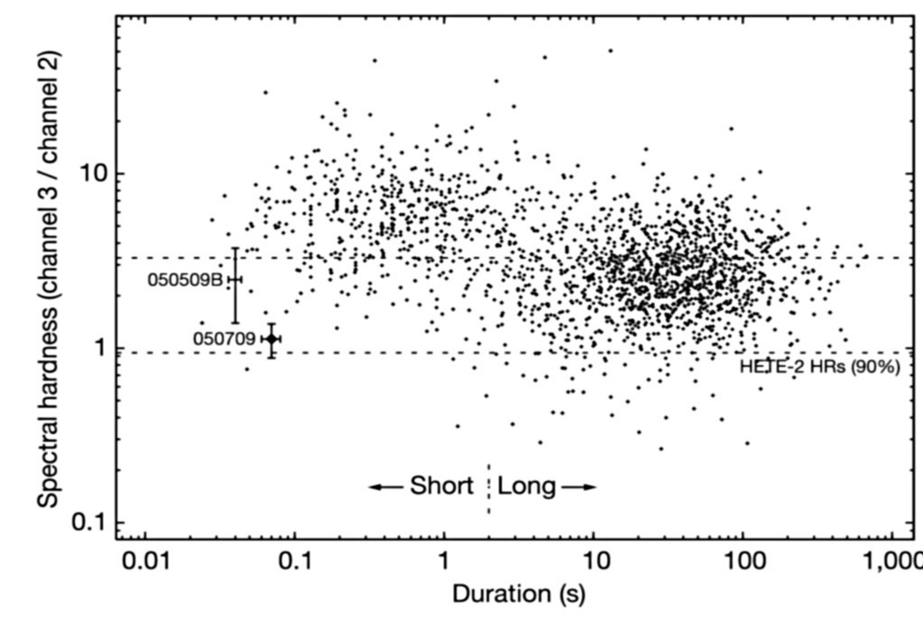
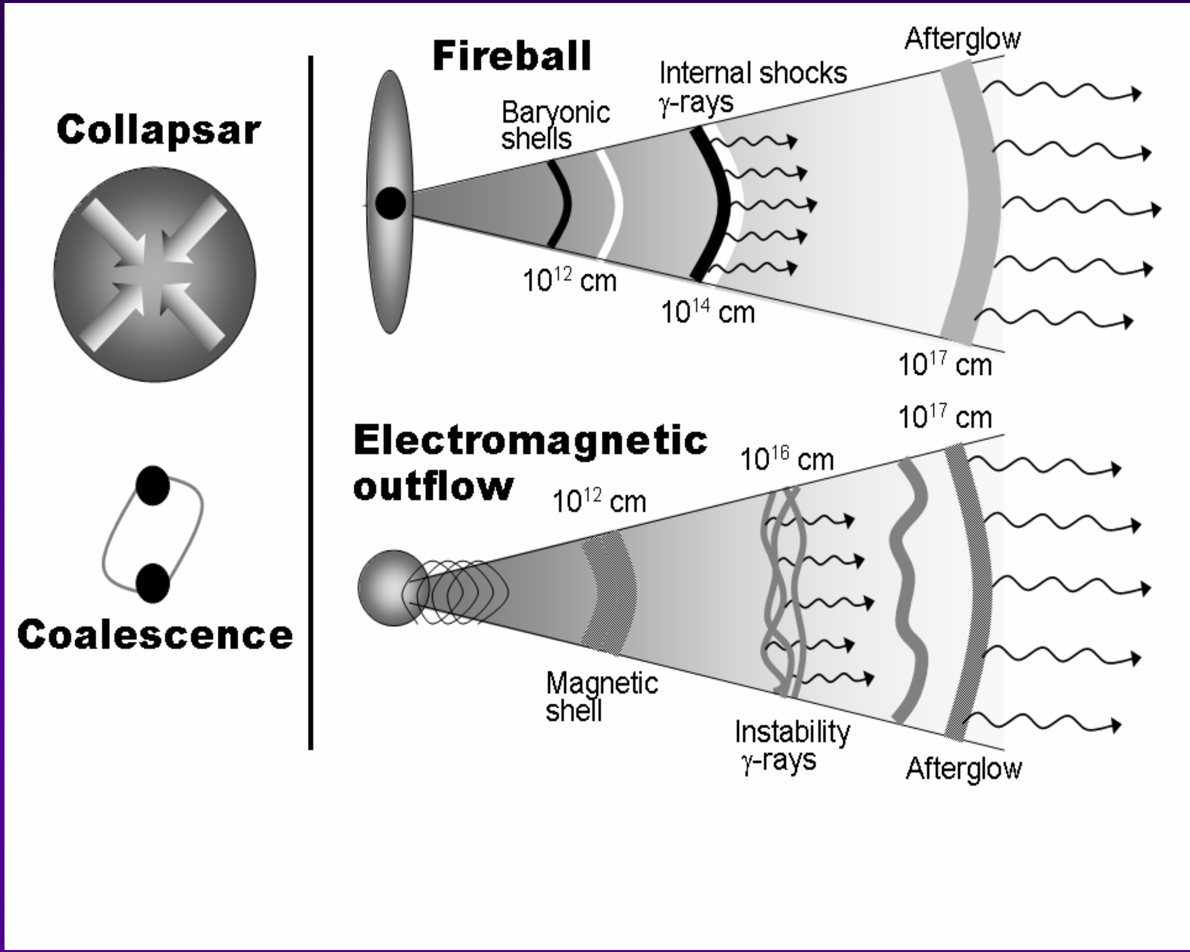


Figure 1 | The classic BATSE duration–spectral hardness diagram[1].

Central engines

Collapsar (hypernova)
big, rotating star collapsing to neutron star and/or black hole
(long bursts?)

Coalescence (merger)
of two neutron stars or NS and BH
(short burts?)



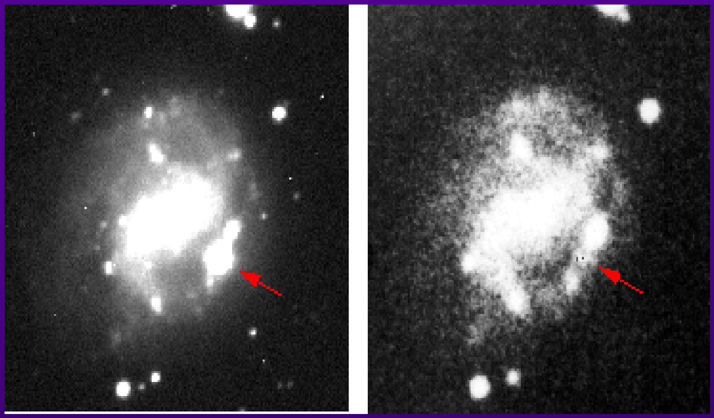
Engine → energy transport → conversion to γ–rays → afterglow

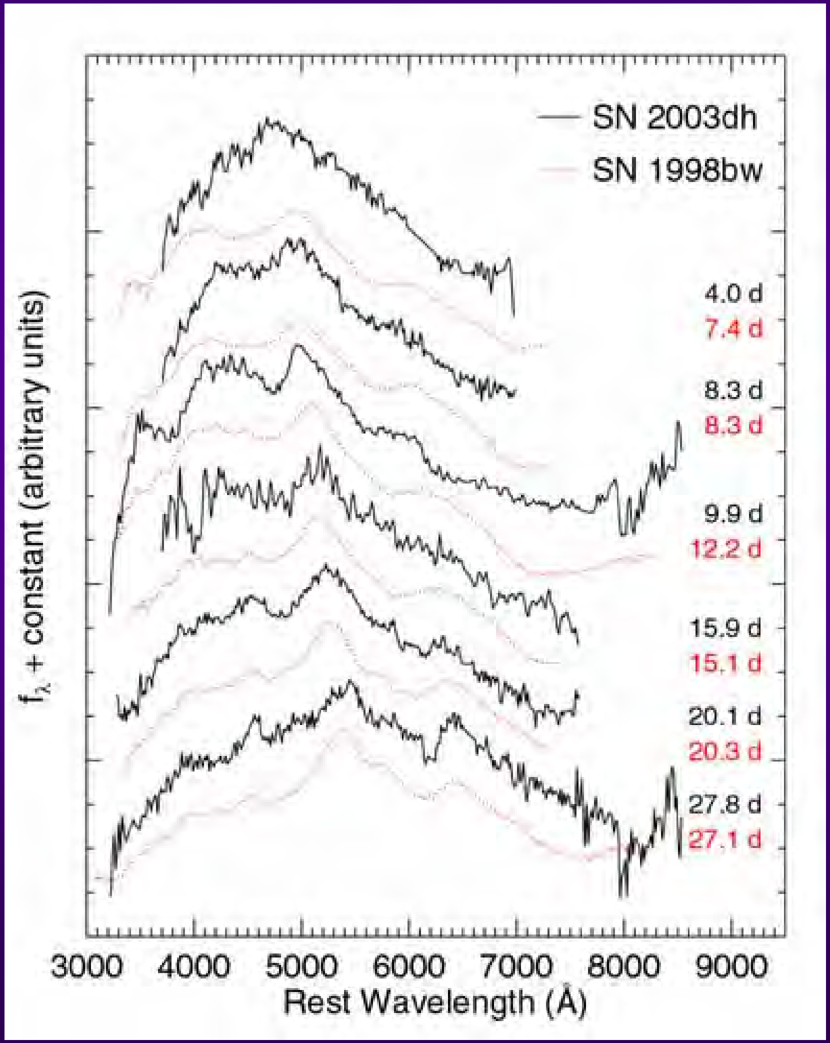
Collapsar Coalescence	Baryonic Magnetic	Internal Shocks Magnetic instability	External Shock

Supernowa SN1998bw

1998.04.25 – GRB discovered by BeppoSAX

- **very bright afterglow – 14^m**
  (all so far $>20^m$)
- **SN-like spectrum**
- **max. after 2 weeks**





Several GRB-SN pairs found so far

Swift

Autonomous slew
Low earth orbit
Launch Vehicle: Delta
Mass: 1271 kg
Power: 1650 W
Launch Date: September 2004

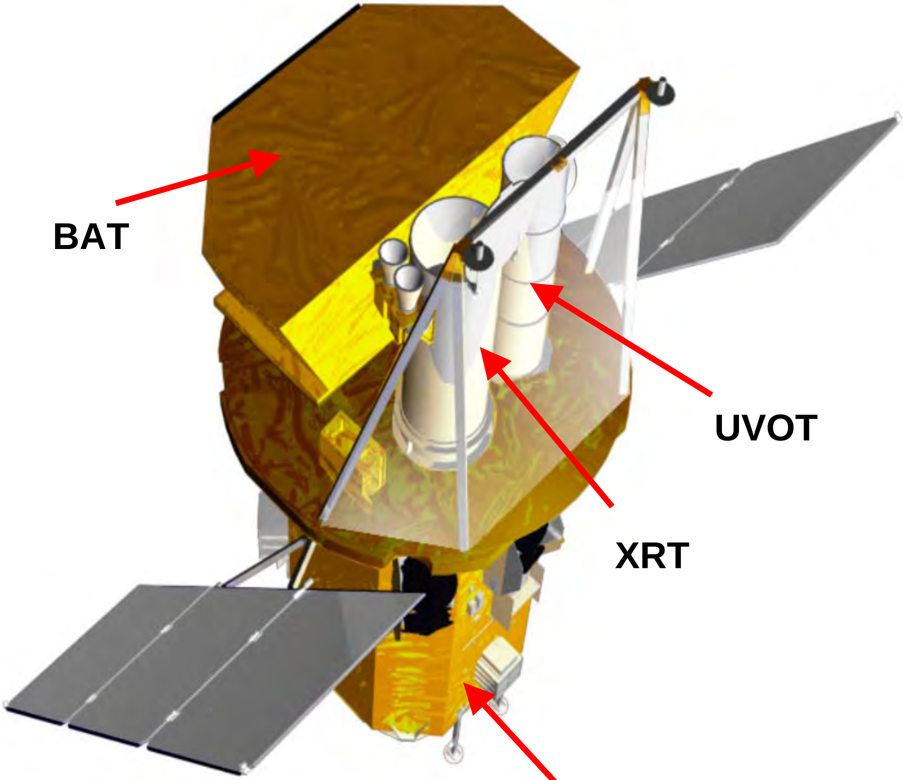
Swift Instruments

Instruments

- Burst Alert Telescope (BAT)
  - New CZT detectors
  - Detect >100 GRBs per year
  - Most sensitive gamma-ray imager ever
- X-Ray Telescope (XRT)
  - Arcsecond GRB positions
  - CCD spectroscopy
- UV/Optical Telescope (UVOT)
  - Sub-arcsecond imaging
  - 6 filters
  - 24^{th} mag sensitivity (1000 sec)

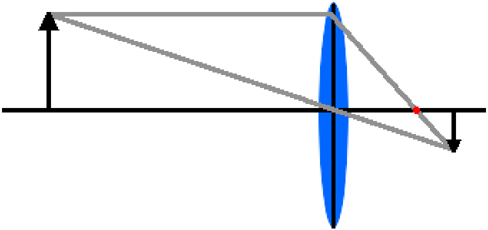
Spacecraft

- Autonomous re-pointing, 20 - 70 sec
- Onboard and ground triggers

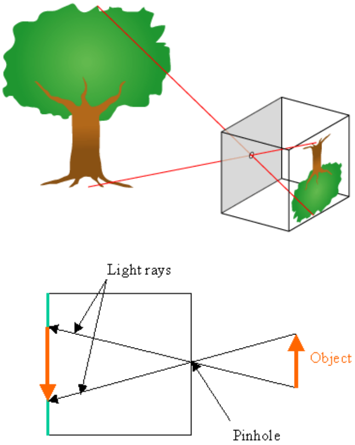


Producing an image

- Different imaging techniques exists
- Most common way: Focusing of light (lenses/mirrors)
- Creates a 1-to-1 correspondence between object and detector

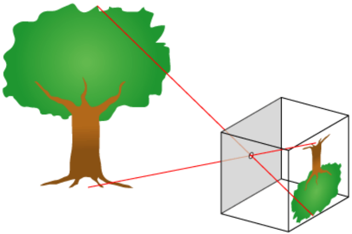


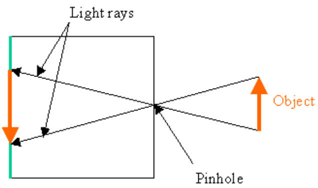
Producing an image



- Alternative imaging method: Pinhole camera
- Keeps 1-to-1 correspondence between object and detector
- Many drawbacks, but no focusing needed

Producing an image

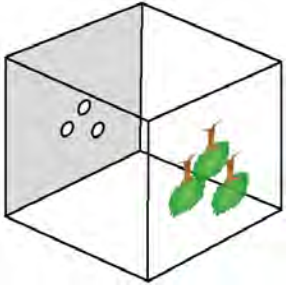


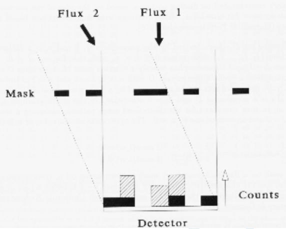


- Hard X- & γ-rays: Hard to focus
- Pinhole camera is interesting, but inefficient
- Solution: More holes!

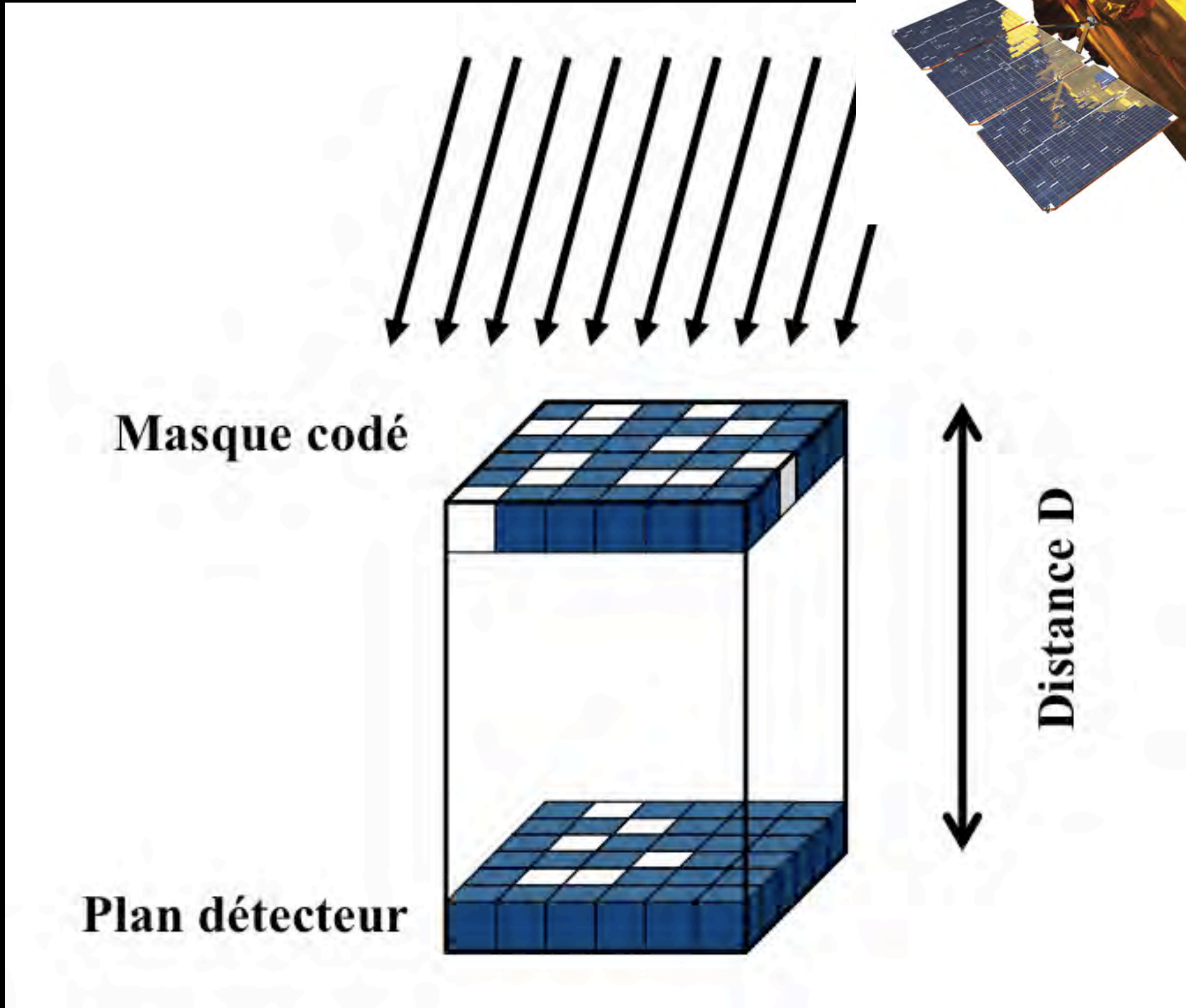
Producing an image

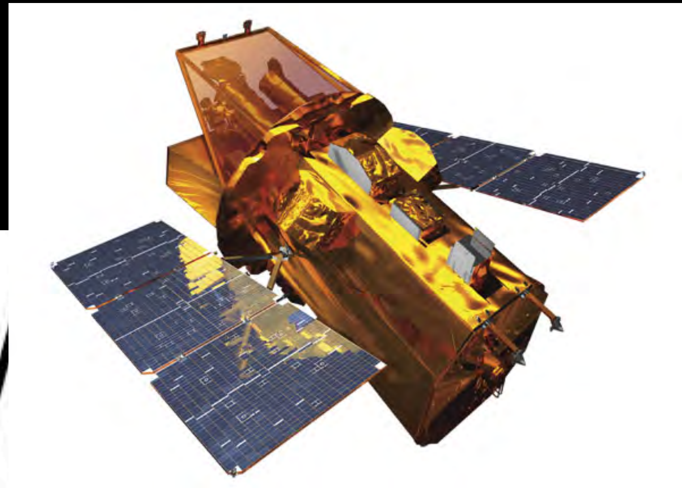
- Now detecting superposition of many images
- New problems introduced..
- Software needed to reconstruct original image
- More noice introduced per pixel, but gathering much more photons





Gamma-ray bursts : localization





Mask patterns

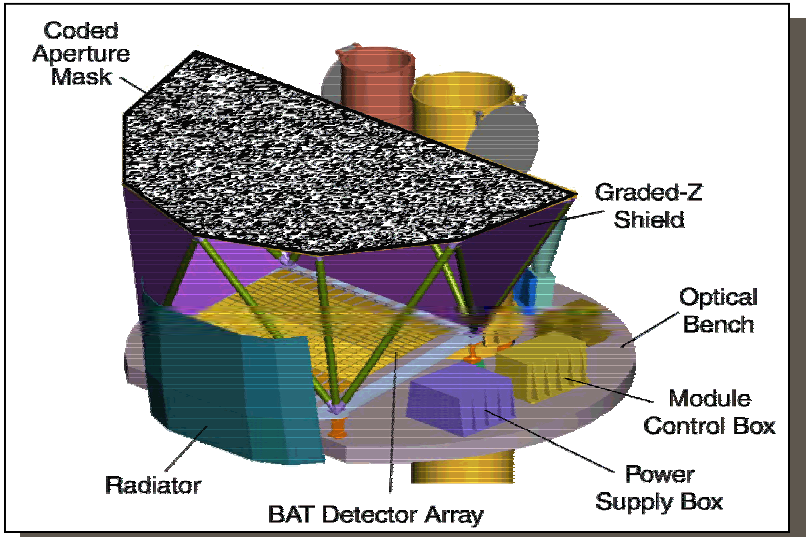
- Non-redundant arrays (NRAs)
- Uniformly redundant arrays (URAs)
- Random pattern

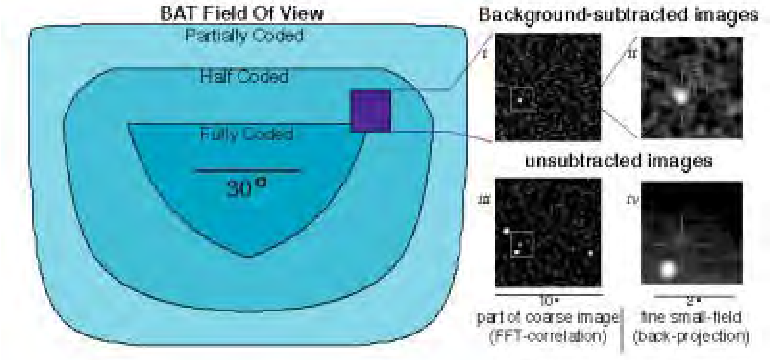
Suitable for different image deconvolution techniques

The coded mask of Swift

Burst Alert Telescope Instrument

- **Real time gamma ray burst positions**
  - Half coded 1.4 steradian FOV
  - Pattern: completely random
  - 5200 cm^2 CdZnTe pixel array
  - 15 - 150 keV band
  - 5 times more sensitive than BATSE
  - Several bursts per week detected
  - Angular resolution of 1 - 4 arcmin
  - Energy resolution of $\Delta E/E \sim 0.05$ @60keV
  - Onboard processing to provide prompt arcminute position to satellite and to the ground (~8-15 s)

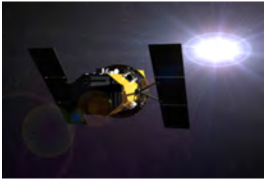


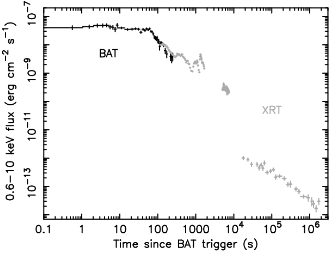


What makes Swift unique?

- Wide FOV of BAT (1/6 of the sky)
- Rapid localization and slewing capabilities (50 degrees in 20-75 s)
- Integrated X-Ray, UV and optical telescopes, for fast follow-up and position determination
- Exellent for catching transient objects!

A typical observation



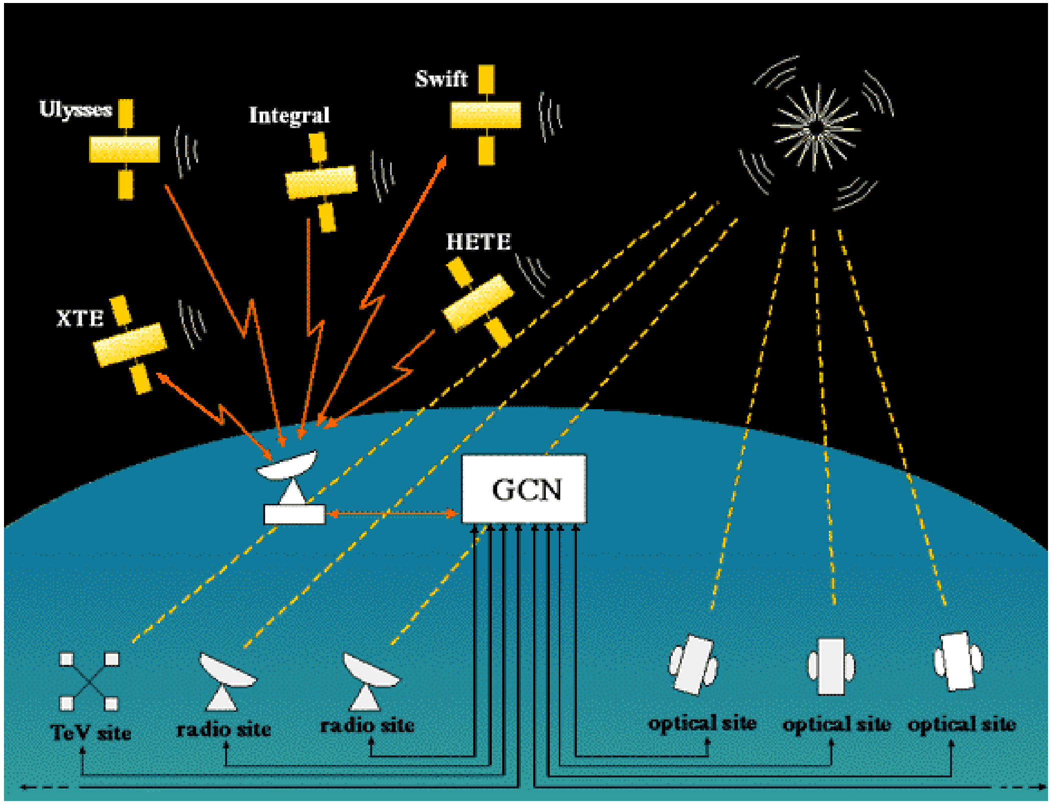


Timeline of Burst Detection Events

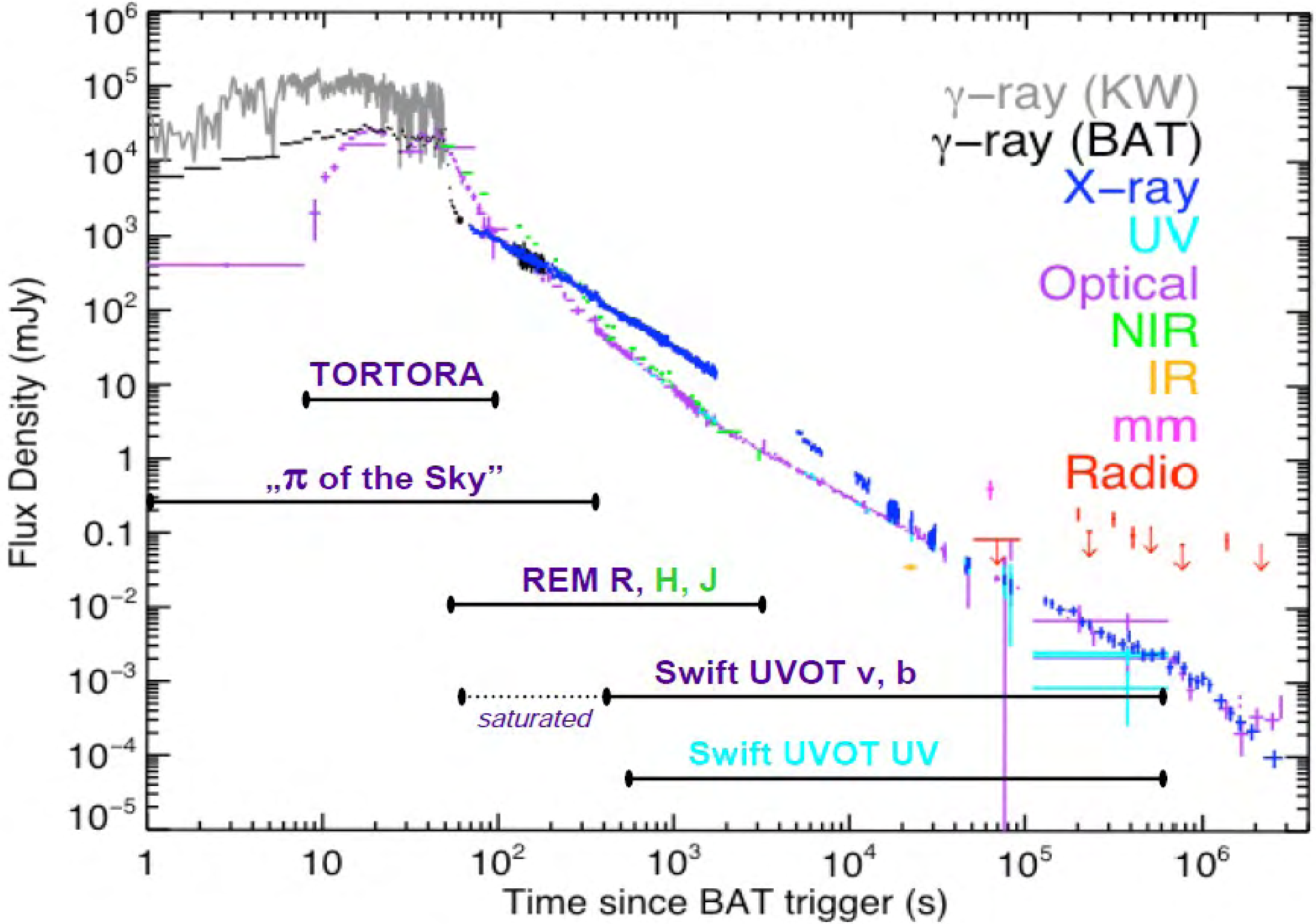
Time (sec)	Event
0	GRB detection
20	Slew begins
20	BAT approx. location distributed
~ 50	GRB acquired
70	XRT location distributed
240	UVOT finding chart distributed
300	XRT lightcurve distributed
1200	XRT spectrum distributed
~ 60,000	All automated observations complete (20,000 sec exposure)

The GRB Coordinates Network

After a burst is detected, its coordinates and light curve are sent to the GCN

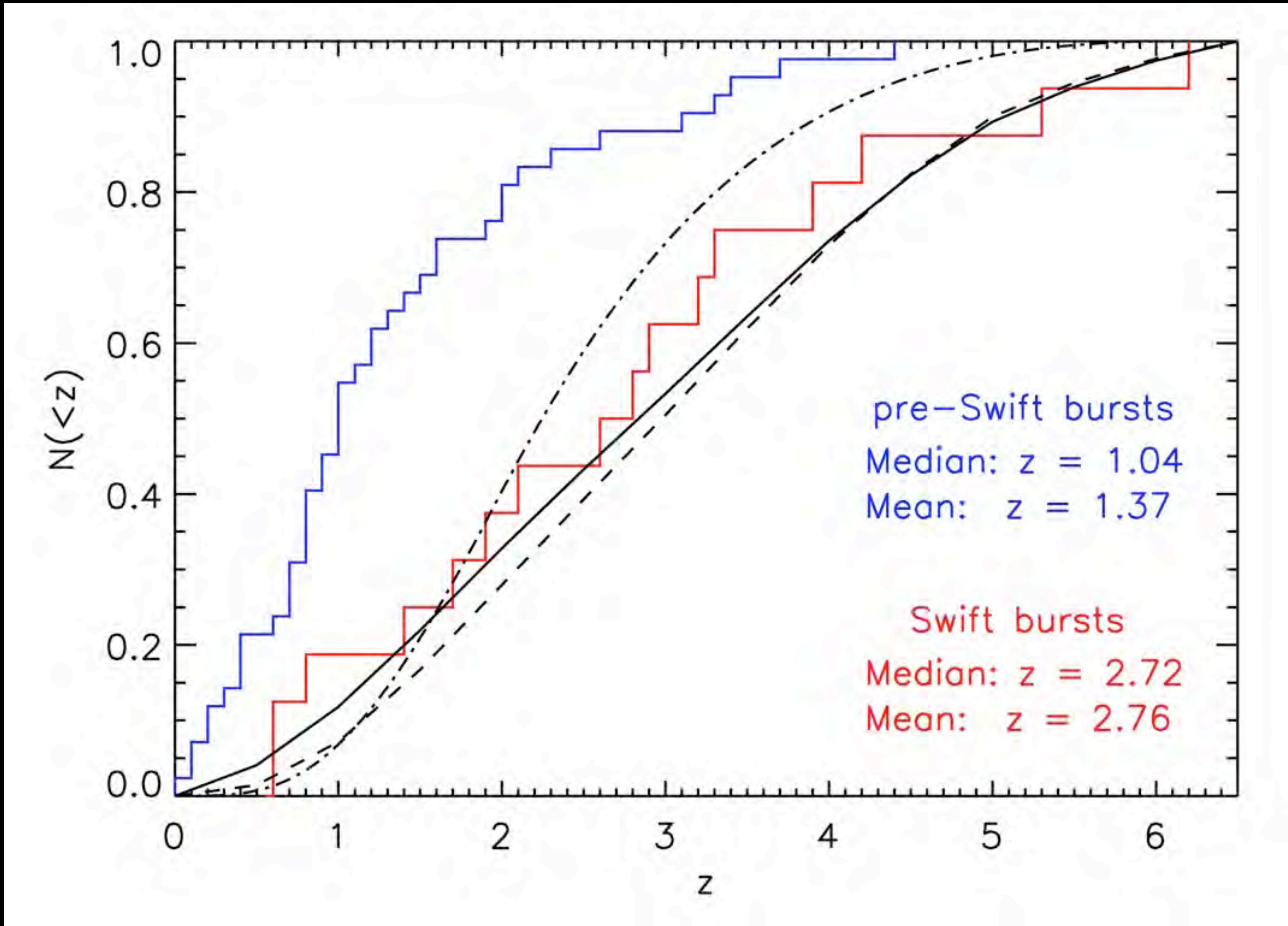


GRB080319B



γ–ray (KW)
γ–ray (BAT)
X–ray
UV
Optical
NIR
IR
mm
Radio
TORTORA
„π of the Sky"
REM R, H, J
Swift UVOT v, b
saturated
Swift UVOT UV
Flux Density (mJy)
Time since BAT trigger (s)

Gamma-ray bursts : redshift distribution (Swift)



Theory (1) Necessity of a compact source

1. Cosmological distance : z = 0.0085 to 9.4 [z =9.4, Universe is 524 Myr old]

Prompt emission

2. Huge release of gamma-rays : $E_{\gamma,iso} \sim 10^{41} \rightarrow 10^{48}$ J
   For comparison :
   - Supernova : $E_{\nu} \sim 3\times10^{46}$ J ; $E_{kin} \sim 10^{44}$ J ; $E_{\gamma} \sim 10^{42}$ J
   - rest-mass energy of the sun : $M_{\odot} c^2 = 1.8 \times 10^{47}$ J

3. Short timescale variability : $t_{var} \sim 1$ - 10 ms

Compact source ($R < c\, t_{var} \sim$ 300-3000 km)
+
Huge energy release
$\Rightarrow$
Catastrophic event leading to the formation of a stellar mass compact object

4. Non-thermal spectrum
   - MeV photons are detected in most GRBs
   - GeV photons have been detected in a few GRBs by Fermi

Afterglow + host galaxy

5. Long GRBs are most probably associated with the gravitational collapse of some massive stars

6. Short GRBS seem to occur in any types of galaxies : no correlation with star formation

-Long GRBs : association with massive stars $\Rightarrow$ gravitational collapse
 Collapsar scenario (Woosley, 1993)

-Short GRBs : best candidate = NS+NS (or NS+BH) mergers (no direct evidence)

GRB Theory

1. Initial event = formation of a compact object
   Central engine =
   - accreting stellar mass black hole
   - magnetar ?

2. Relativistic ejection

3. Photospheric radius : first emission of photons

4. Internal dissipation in the relativistic outflow : prompt emission

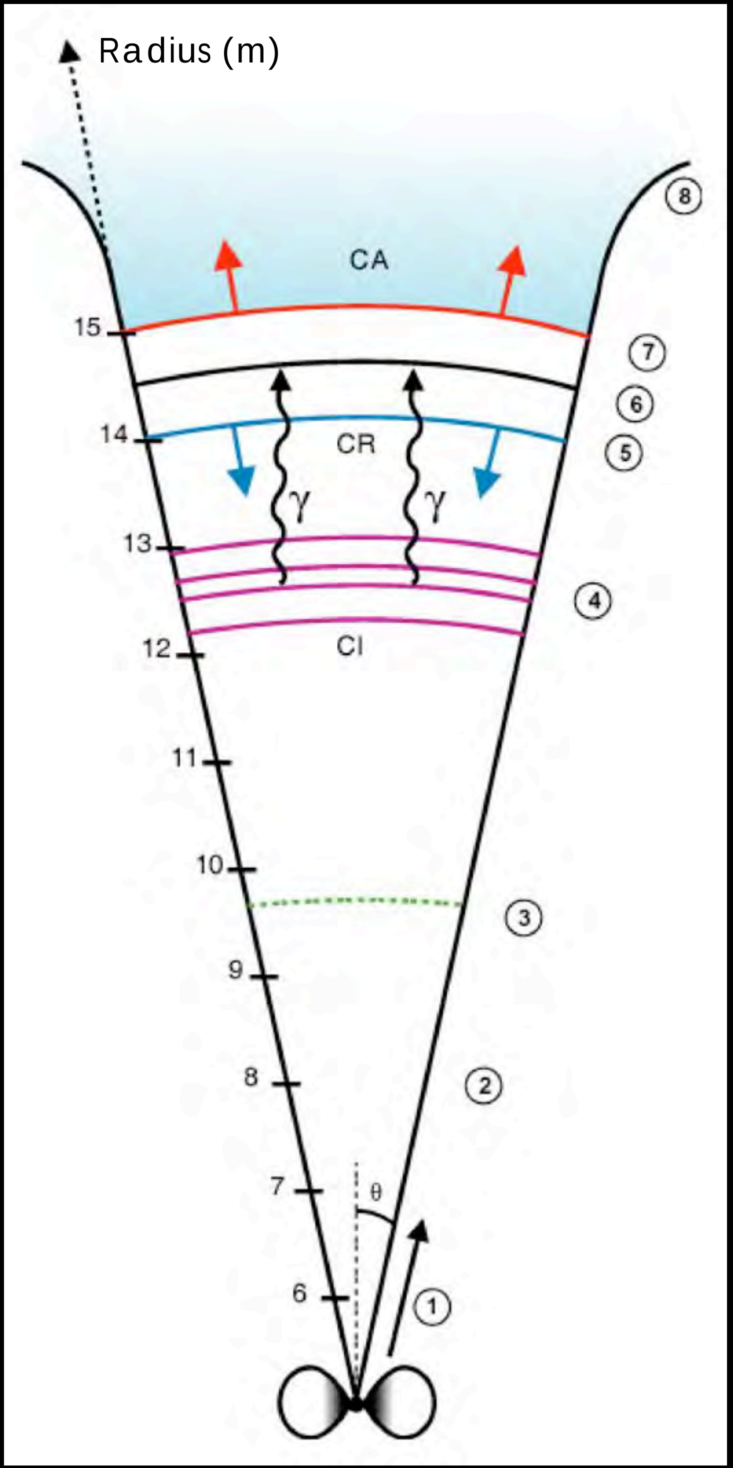
Next steps are related to the deceleration by the external medium

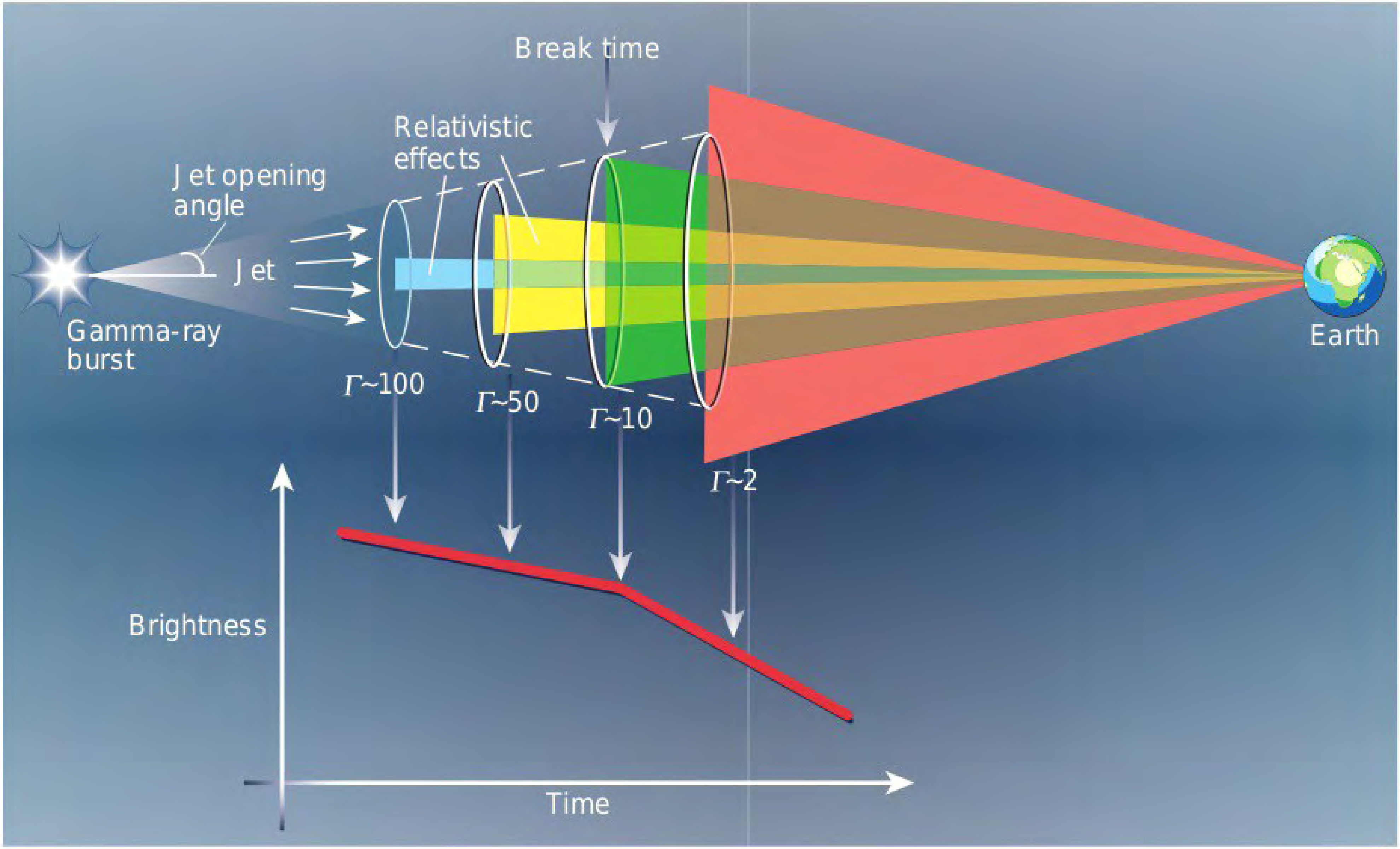
5. Reverse shock : contribution to the emission is unclear
   (prompt optical / early afterglow emission ? X-rays ? ...)

6. Contact discontinuity

7. Forward shock : strong ultra-relativistic shock : afterglow

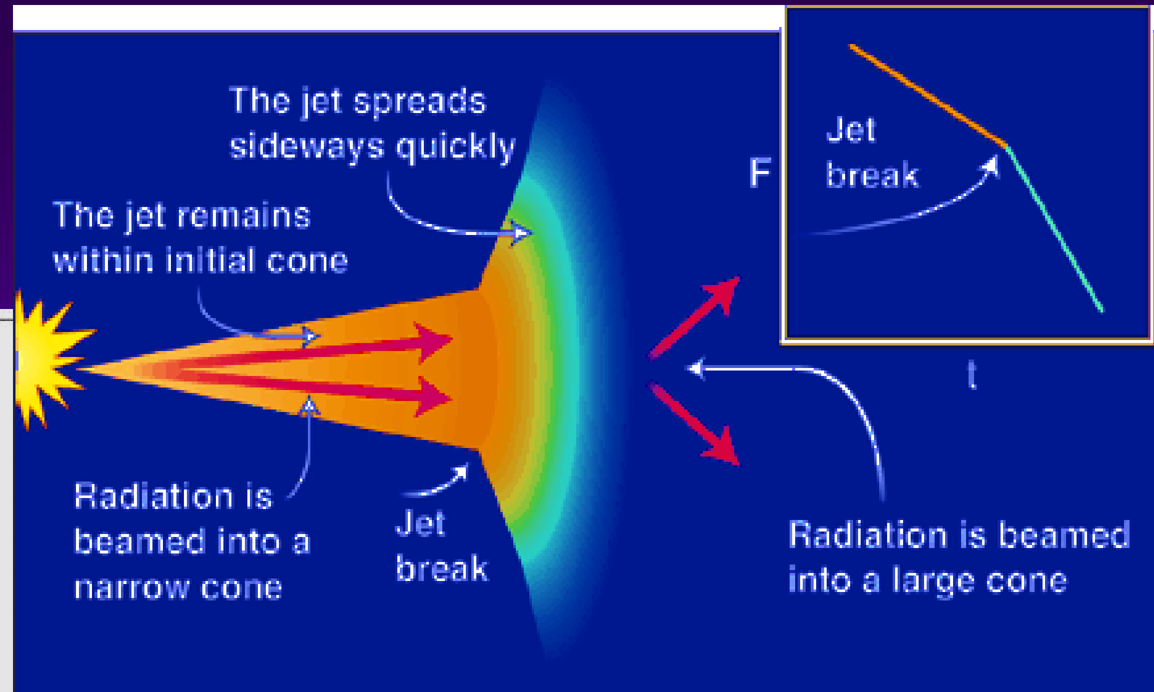
8. Late evolution : Newtonian motion + lateral expansion
   A GRB remnant should look like a SN remnant after a few 10^4 yr

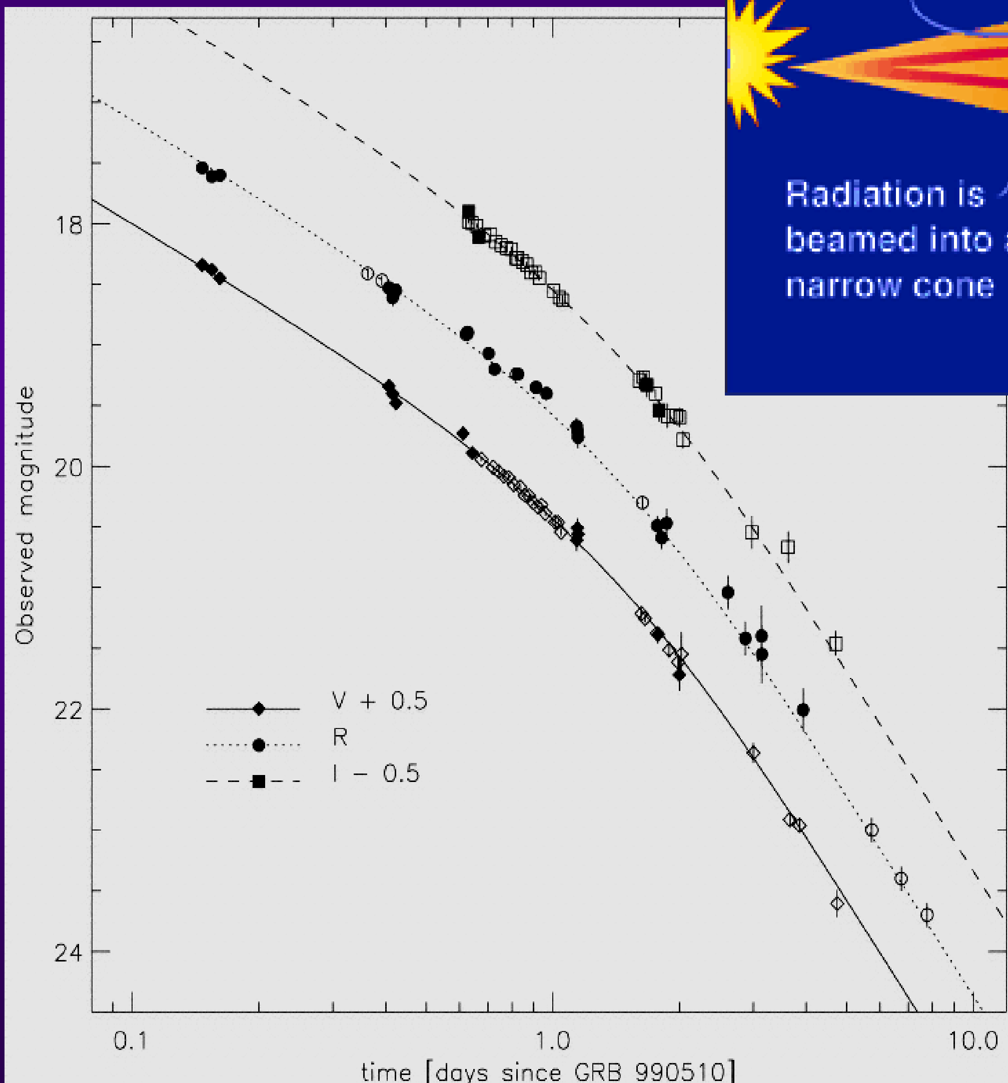


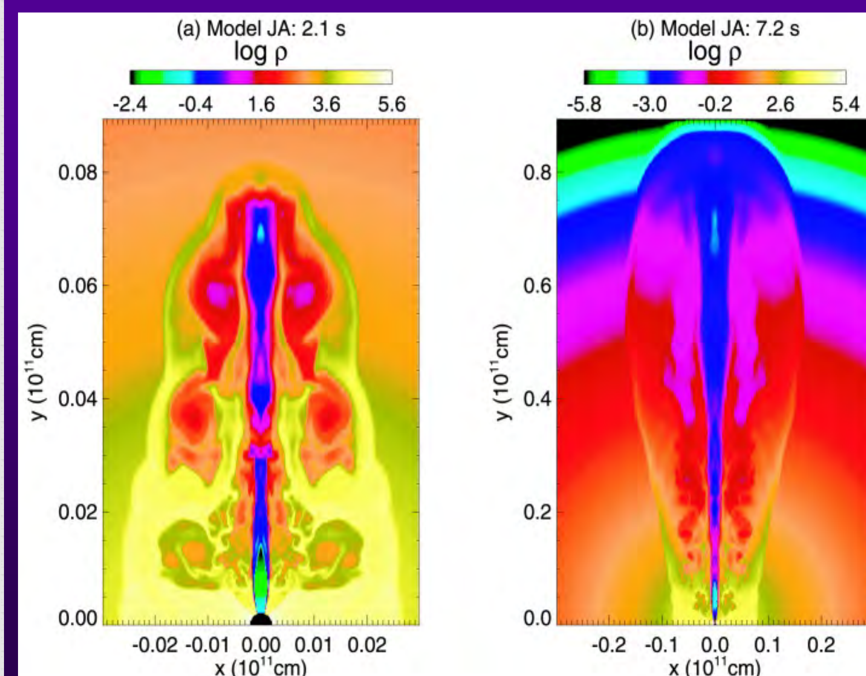


Break time
Relativistic
effects
Jet opening
angle
Jet
Gamma-ray
burst
Γ~100
Γ~50
Γ~10
Γ~2
Earth
Brightness
Time

Jets


The jet spreads sideways quickly
The jet remains within initial cone
Radiation is beamed into a narrow cone
Jet break
Radiation is beamed into a large cone
F
Jet break
t


Observed magnitude
18
20
22
24
V + 0.5
R
I − 0.5
0.1
1.0
10.0
time [days since GRB 990510]


(a) Model JA: 2.1 s
log ρ
-2.4 -0.4 1.6 3.6 5.6
y (10^11 cm)
0.00 0.02 0.04 0.06 0.08
-0.02 -0.01 0.00 0.01 0.02
x (10^11 cm)
(b) Model JA: 7.2 s
log ρ
-5.8 -3.0 -0.2 2.6 5.4
y (10^11 cm)
0.0 0.2 0.4 0.6 0.8
-0.2 -0.1 0.0 0.1 0.2
x (10^11 cm)

GRBs as cosmic accelerators

1. Outflow is made of leptons + hadrons
   (not a electron-positron jet)

2. Mildly or relativistic shocks are present
   (do they accelerate particles ?)
   or magnetic reconnection regions

3. Electrons are accelerated to high Lorentz factors
   (GeV emission detected by Fermi)

4. No evidence yet for proton acceleration
   (radiation too inefficient to contribute in LAT range)

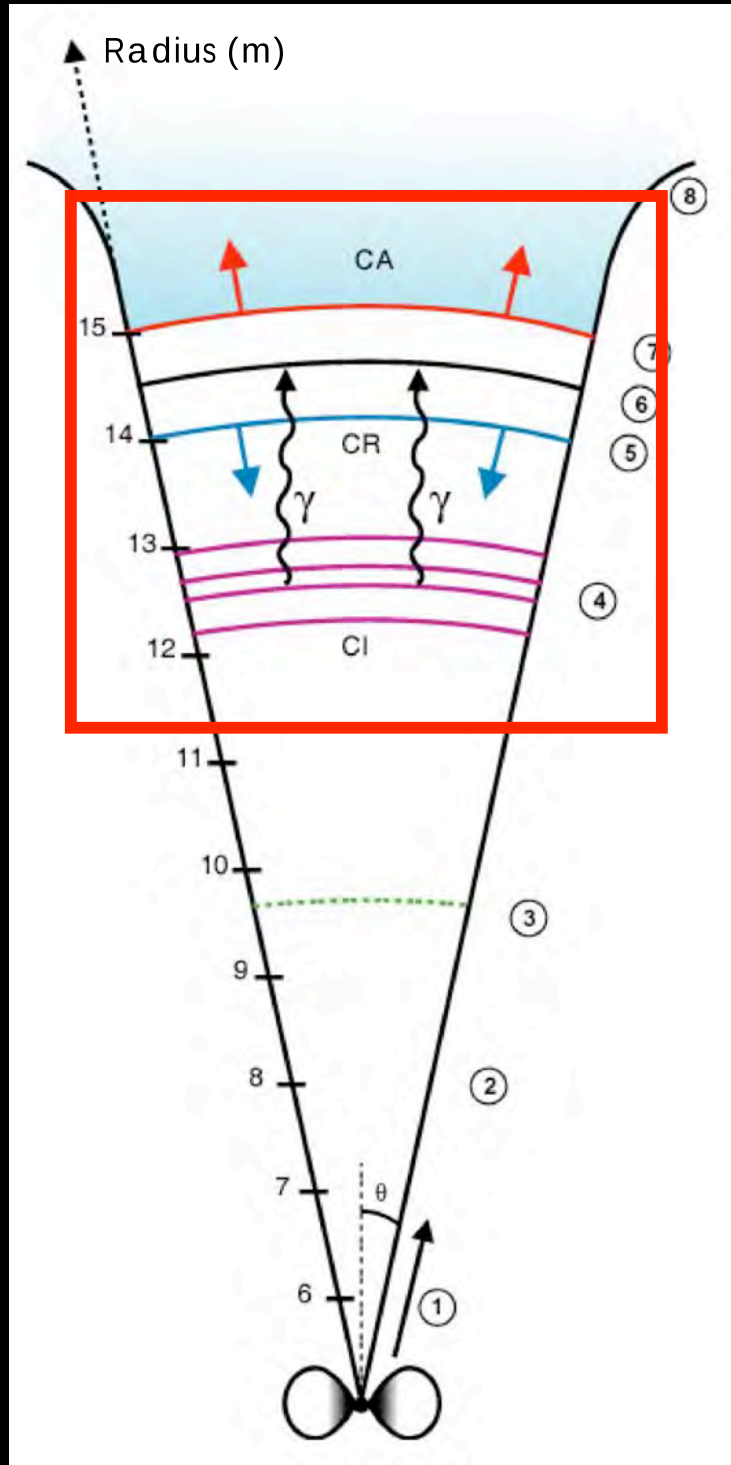
   TeV ?

5. If the same energy is deposited in accelerated protons and
   electrons : HE neutrino emission is expected

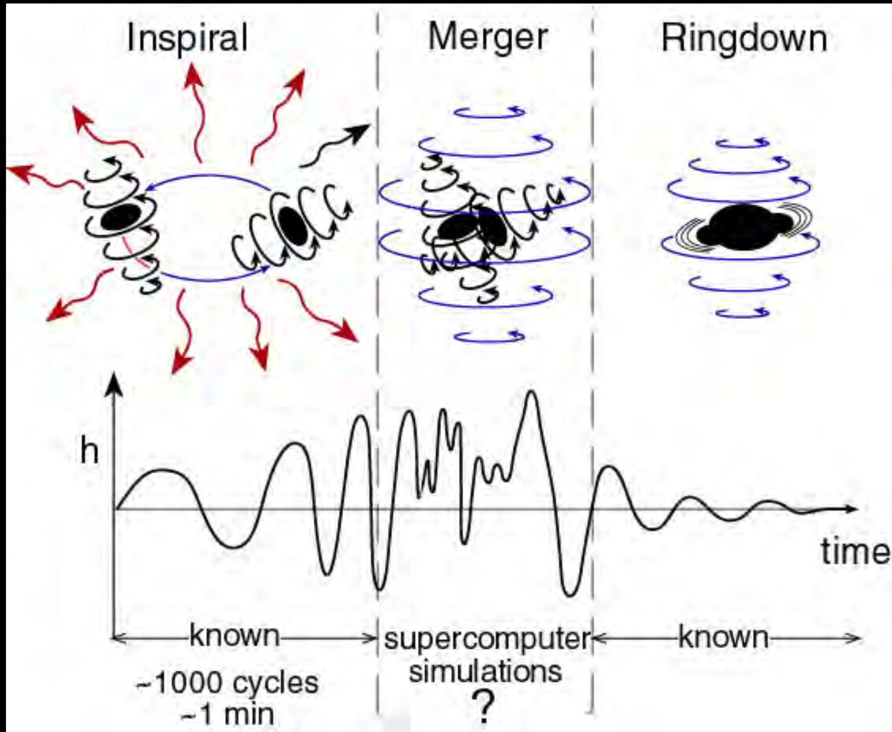
   (ICECUBE : sensitivity has reached the most optimistic models...)

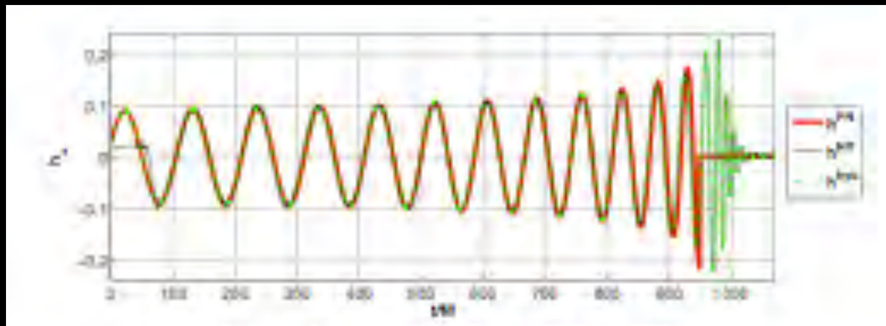
   Note : this is the case even if protons are not accelerated above 10^{18} eV

6. Acceleration in relativistic shocks is highly uncertain but GRBs
   may have the capacity to acceleration hadrons above 10^{20} eV



Gravitational waves ? Best candidate = short GRBs if associated to NS-NS mergers



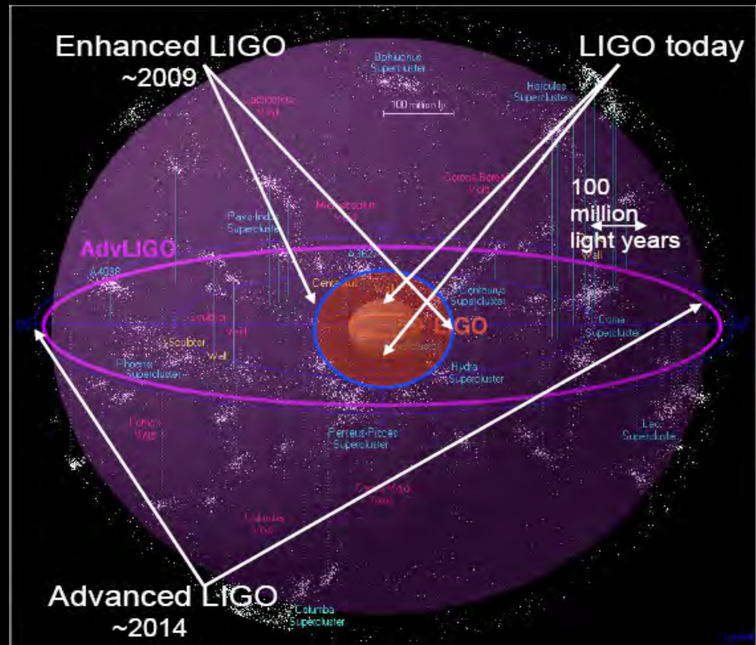


Ajith et al, CQG 24, S689 (2007)

Proof of the formation of black hole, mesure of its mass and spin...

Gravitational waves ? Best candidate = short GRBs if associated to NS-NS mergers

Horizon	NS-NS	NS-BH
LIGO I / Virgo	15 Mpc	30 Mpc
Advanced LIGO / Advanced Virgo	200 Mpc	420 Mpc



Rate	NS-NS	NS-BH
LIGO I / Virgo	0.02 yr^{-1} (0.0002 to 0.2)	0.004 yr^{-1} (0.000 07 to 0.1)
Advanced LIGO / Advanced Virgo	40 yr^{-1} (0.4 to 400)	10 yr^{-1} (0.2 to 300)

The population of NS-NS or NS-BH binaries is not well known...

population synthesis (highly uncertain)

Only a few systems are observed :
e.g. PSR B 1913+16 (merger in ~ 100 Myr)