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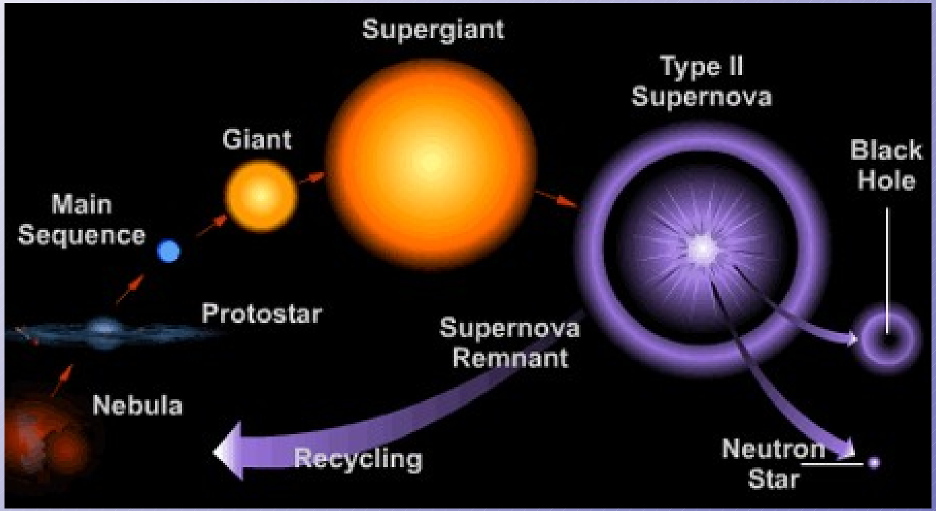
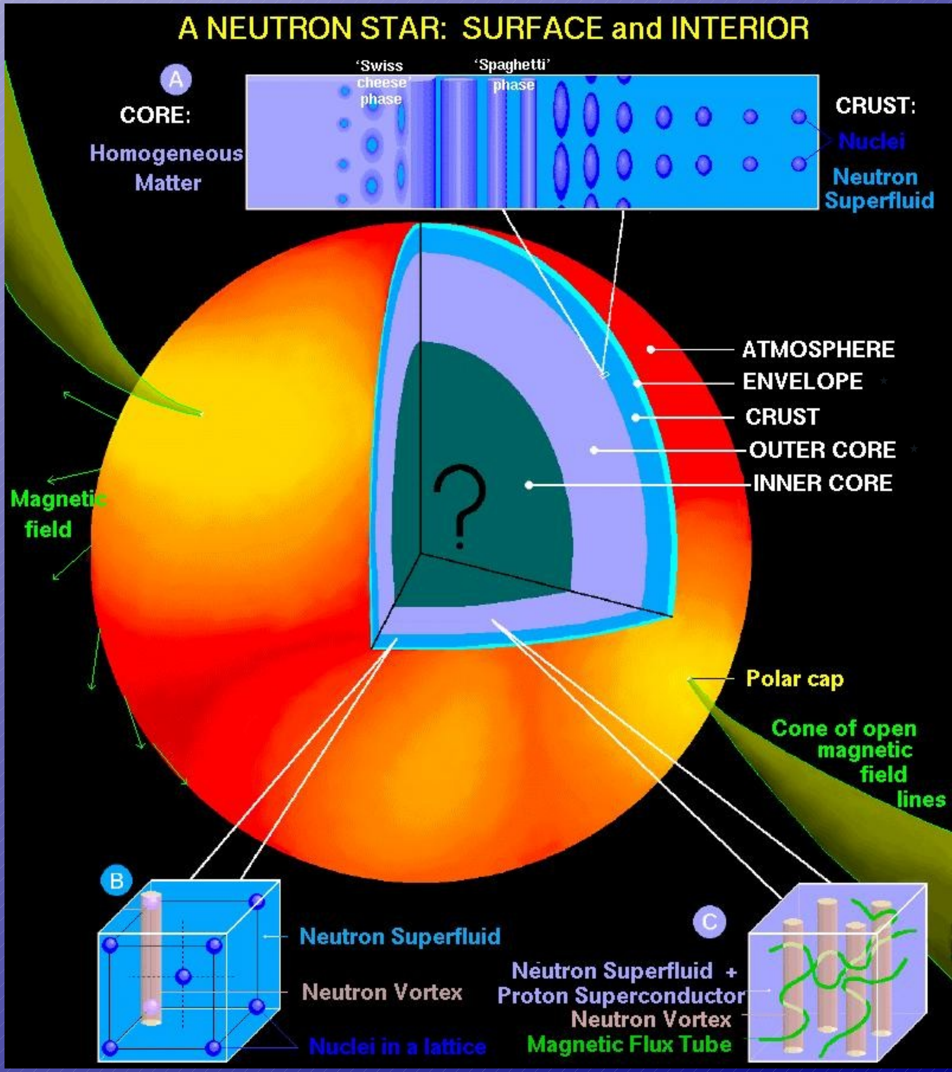
THERMONUCLEAR EXPLOSIONS ON NEUTRON STARS OBSERVED WITH JEM-X

Jérôme Chenevez, DTU Space

What is a neutron star?

Cadavres exquis (Star corpses...)





Angular momentum conservation
$\Rightarrow$ rapid rotation.

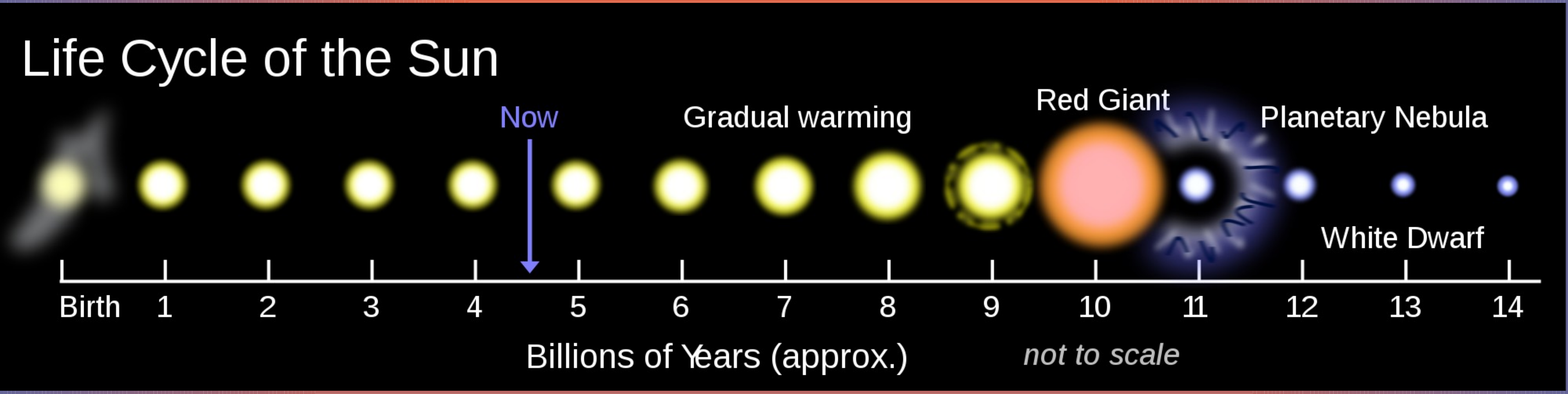
Magnetic field conservation $\Rightarrow$ high **B**.

NS crust is the strongest imaginable material

INTRODUCTION

Life and depth of the stars

The Sun case



The main sequence

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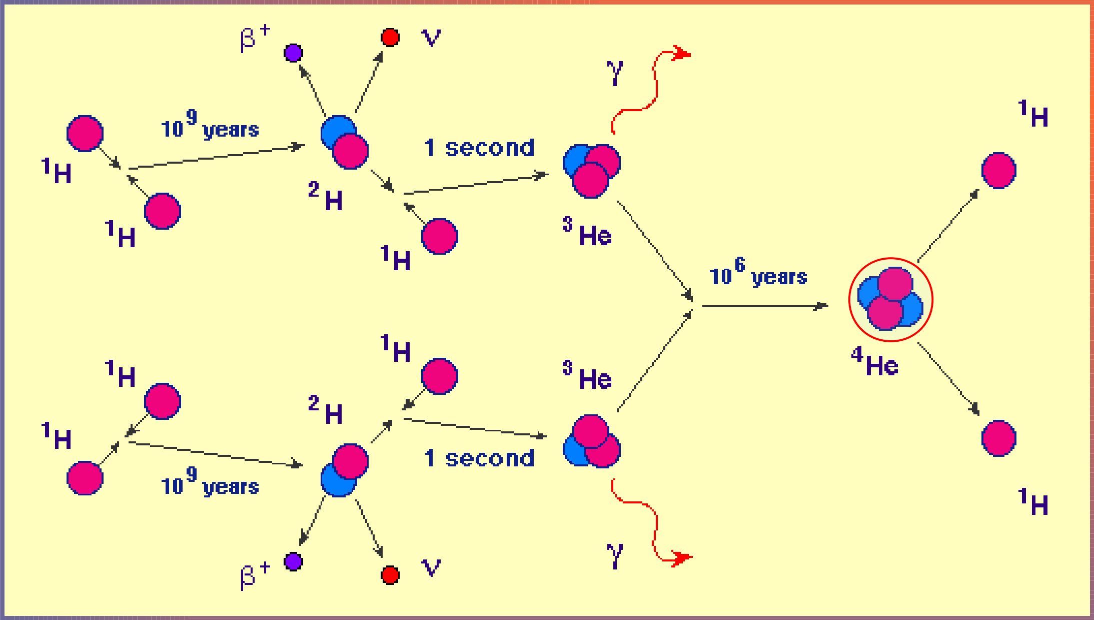
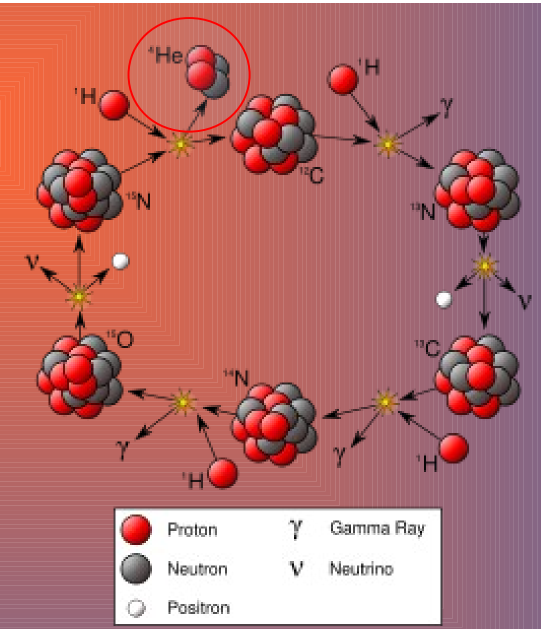
4 H → He

Mass ($M_\odot$)	Surface temperature (K)	Spectral class	Luminosity ($L_\odot$)	Main-sequence lifetime (10^6 years)
25	35,000	O	80,000	4
15	30,000	B	10,000	15
3	11,000	A	60	800
1.5	7000	F	5	4500
1.0	6000	G	1	12,000
0.75	5000	K	0.5	25,000
0.50	4000	M	0.03	700,000

The main-sequence lifetimes were estimated using the relationship $t \propto 1/M^{2.5}$ (see Box 19-2).



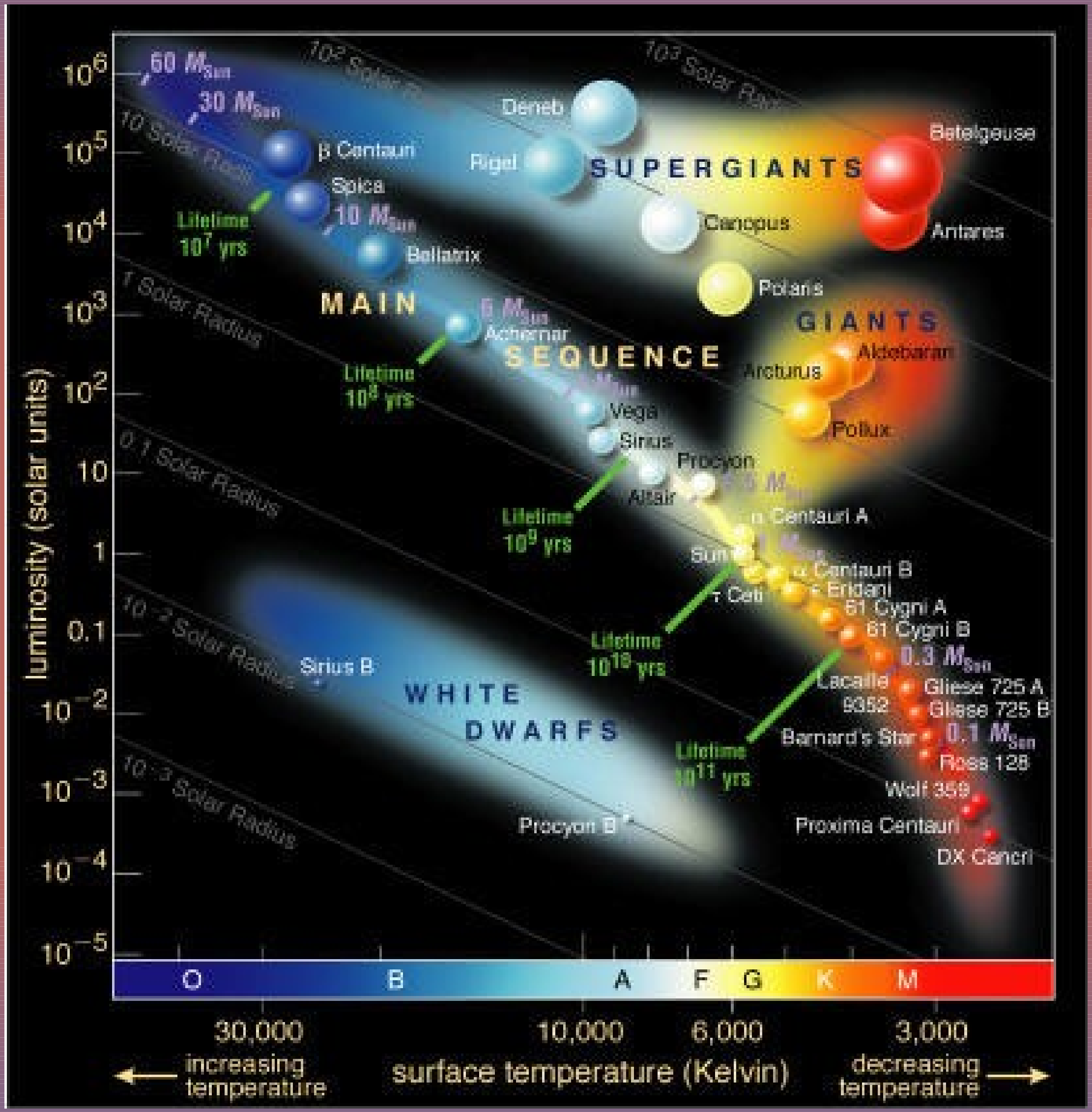
p-p chain ($M \leq \approx M_\odot$)



CNO cycle ($M \geq 1.5 M_\odot$)

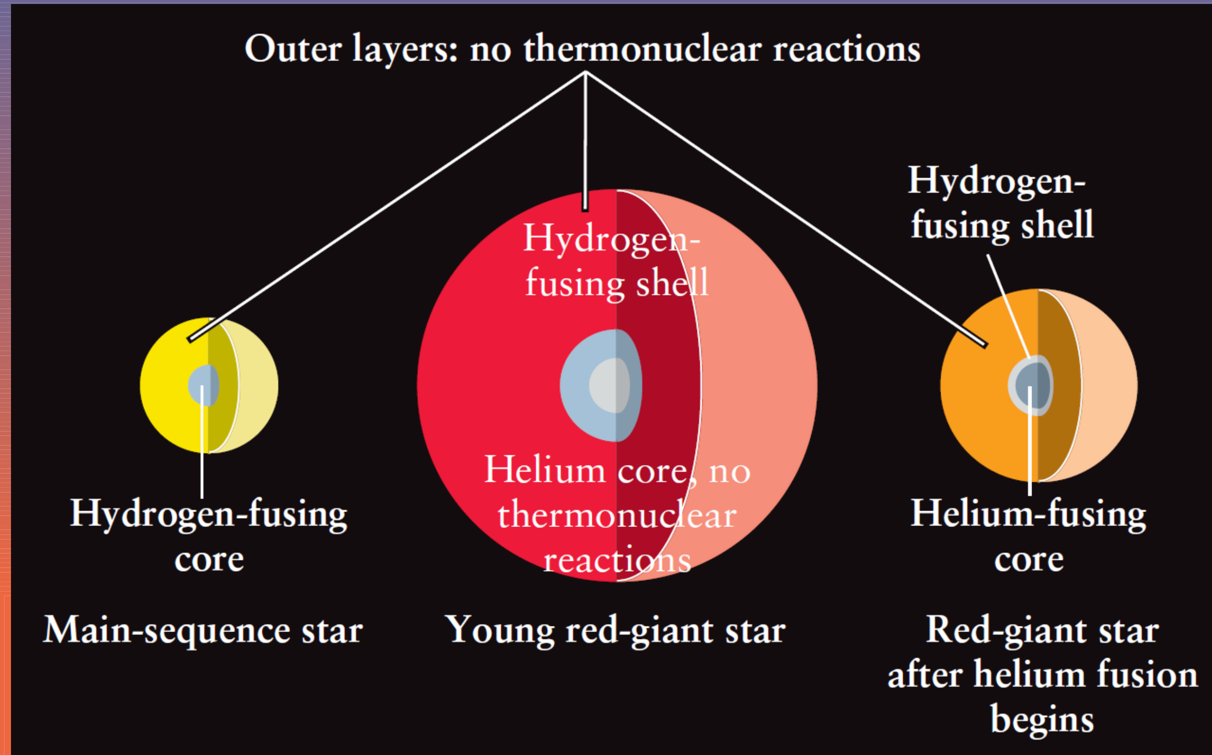
The main sequence

H-R diagrams

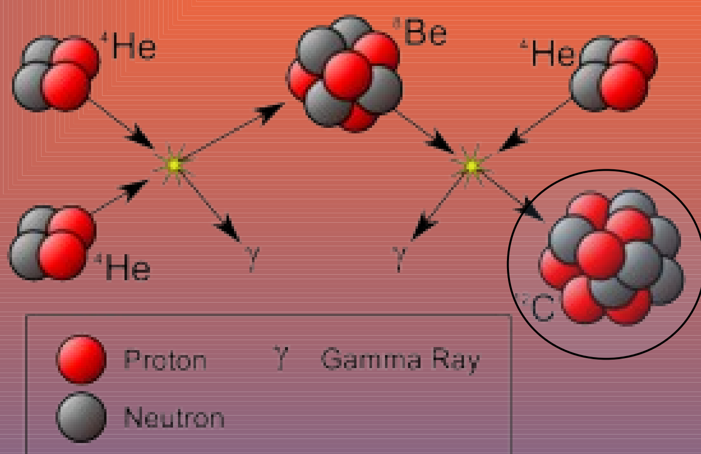


Stellar evolution

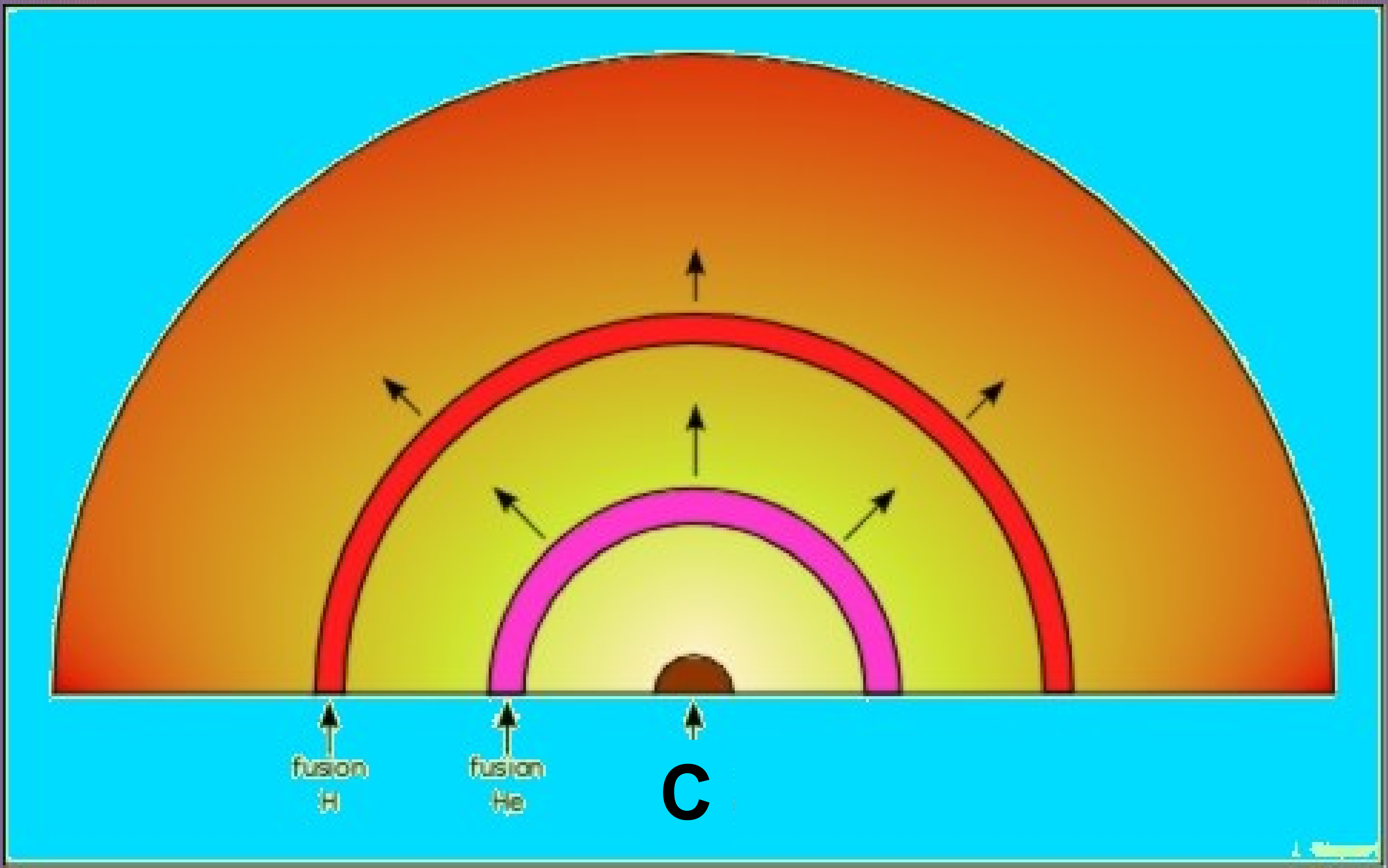
Thermonuclear cycles in red giants



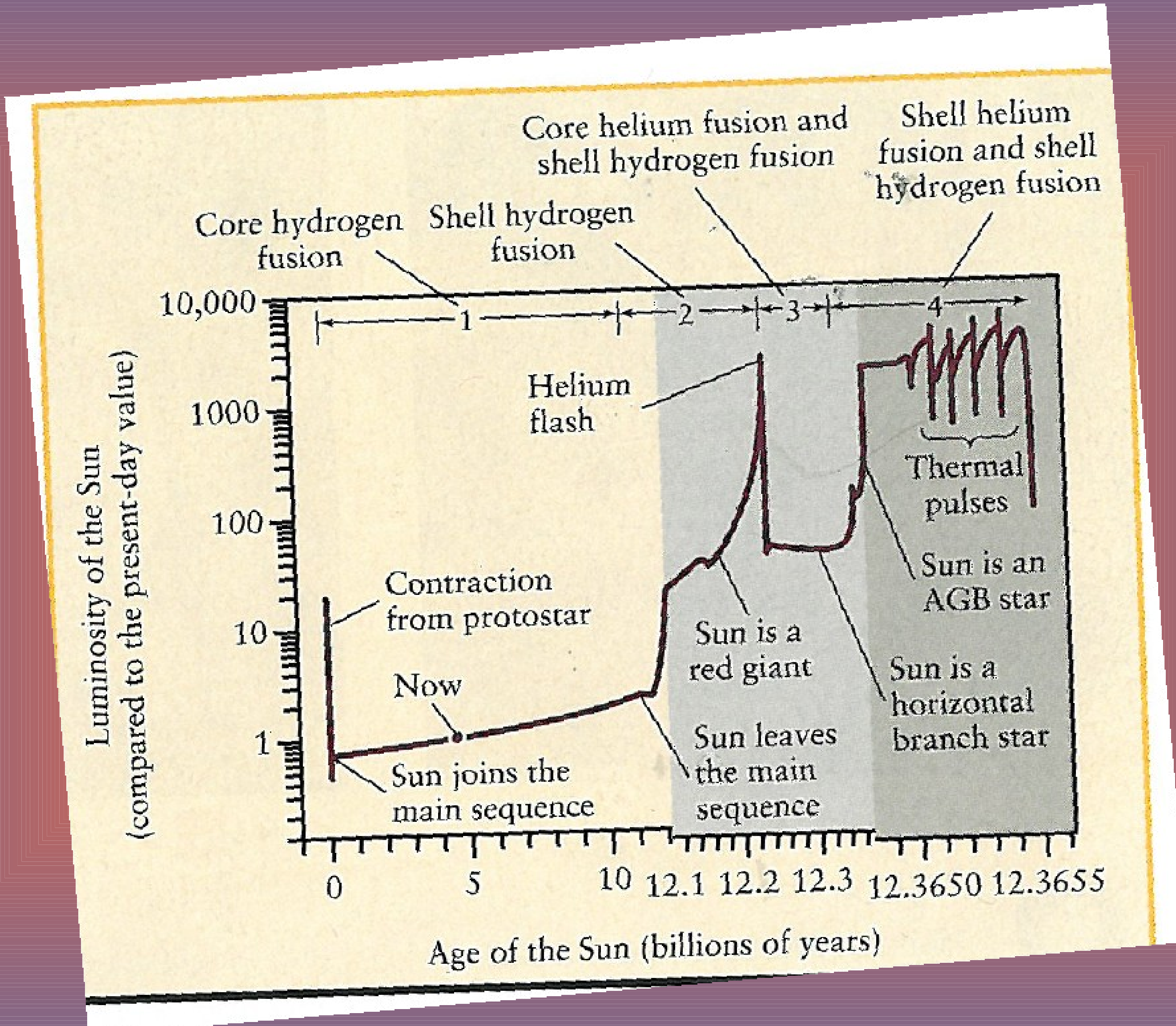
3- α



Shell fusion

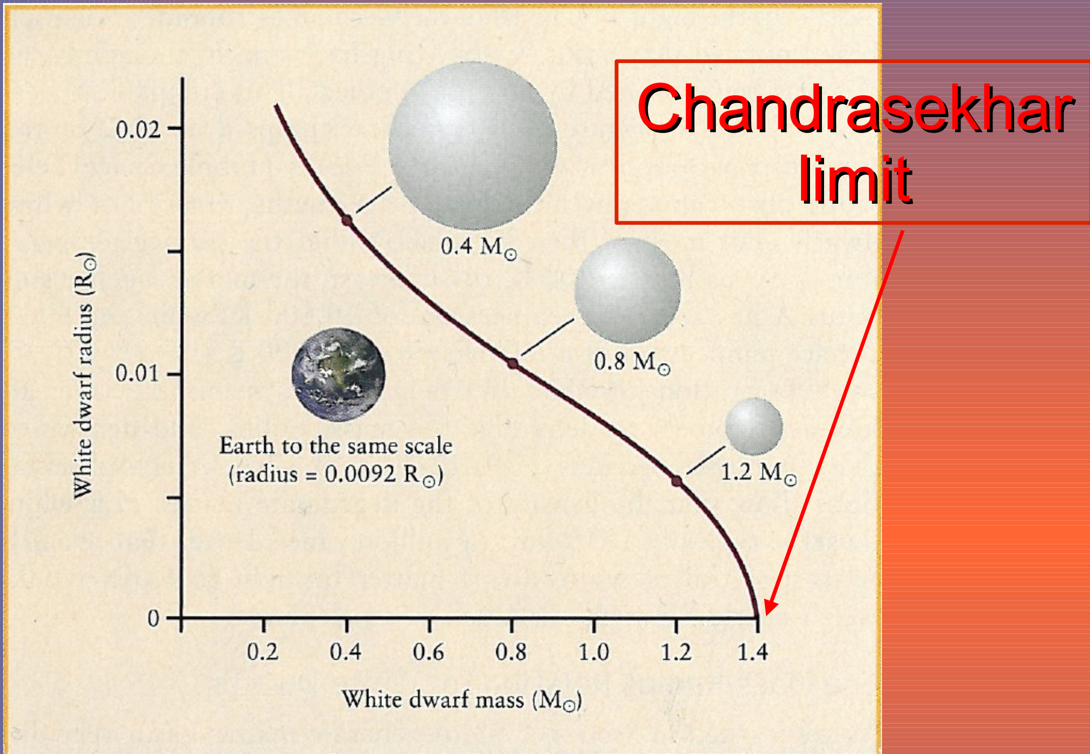


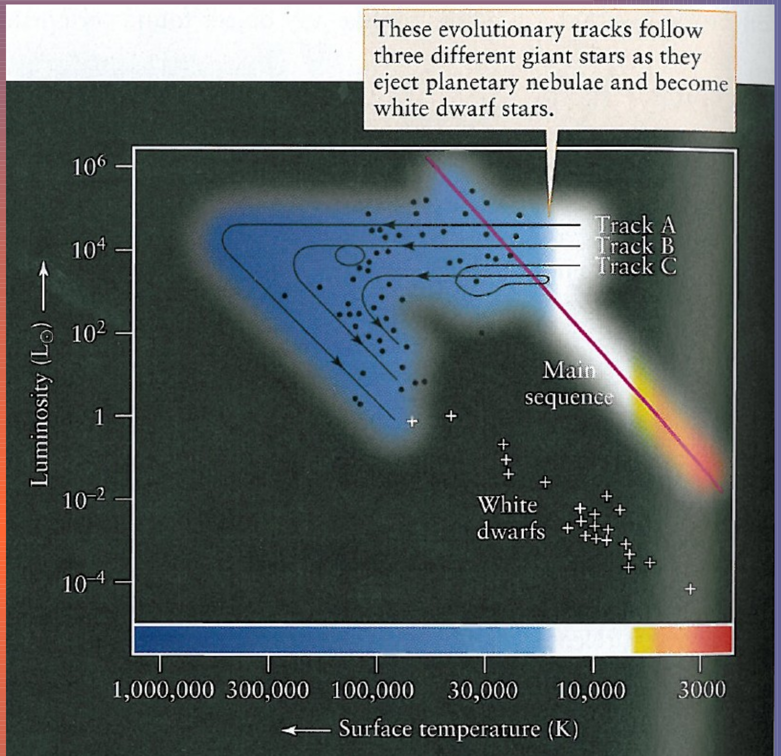
The Sun life (II)



Stellar evolution

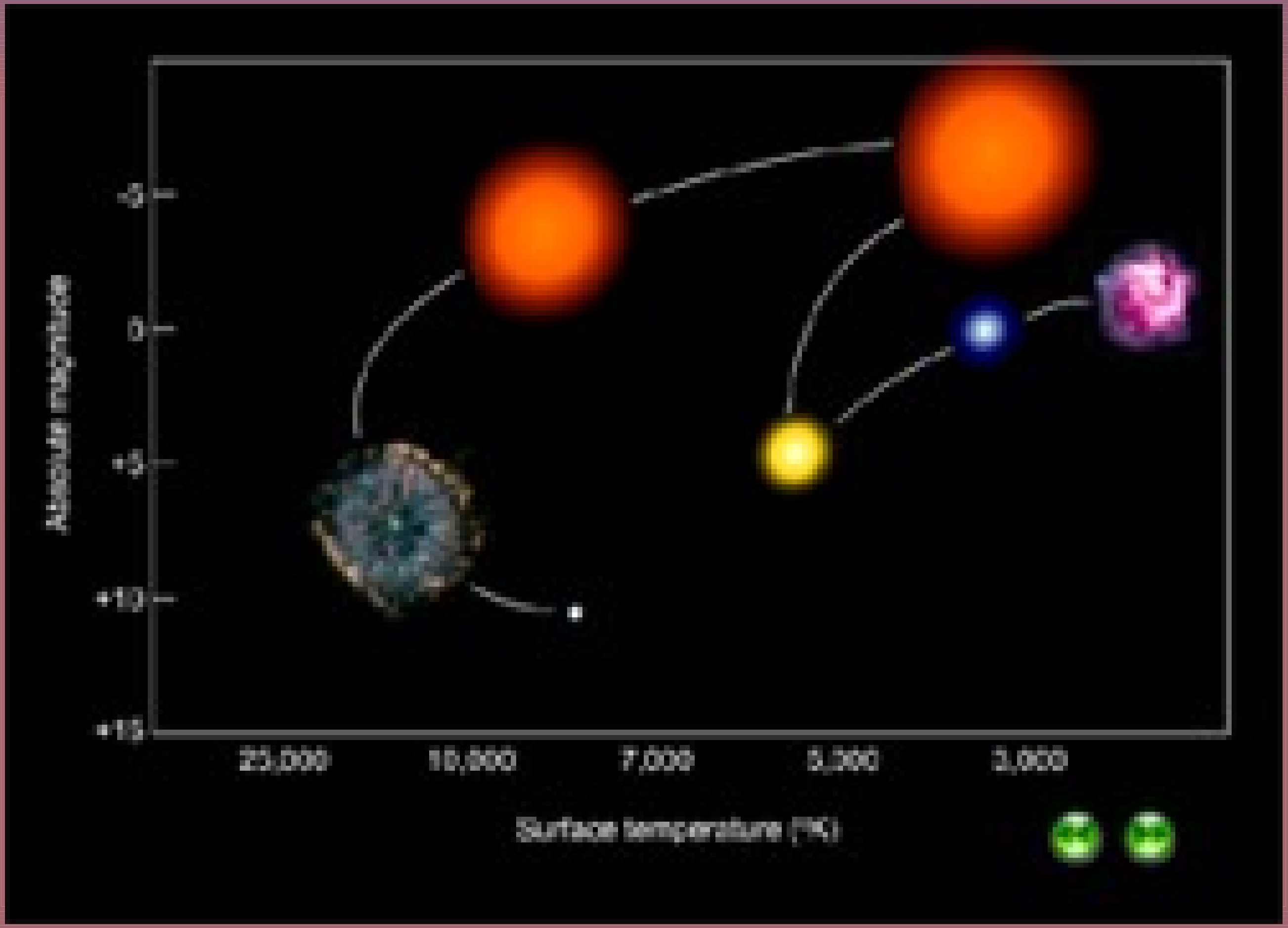
White dwarfs





Evolutionary track	Mass ($M_\odot$) Giant star	Ejected nebula	White dwarf
A	3.0	1.8	1.2
B	1.5	0.7	0.8
C	0.8	0.2	0.6

Summary

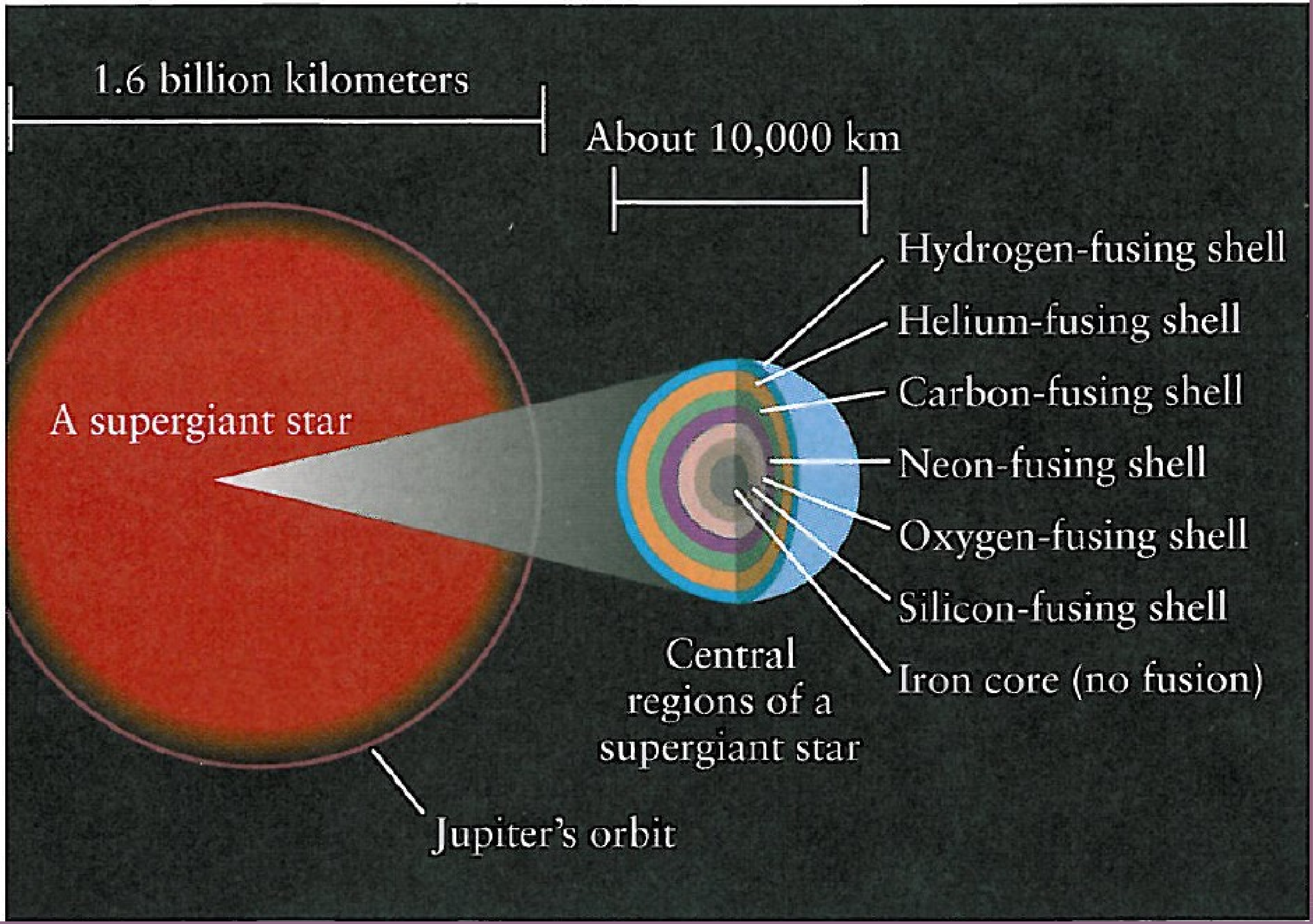


Low-mass star evolution in the HR-diagram

High-mass stars

$M > 8\ M_{\odot}$

Further nucleosynthesis



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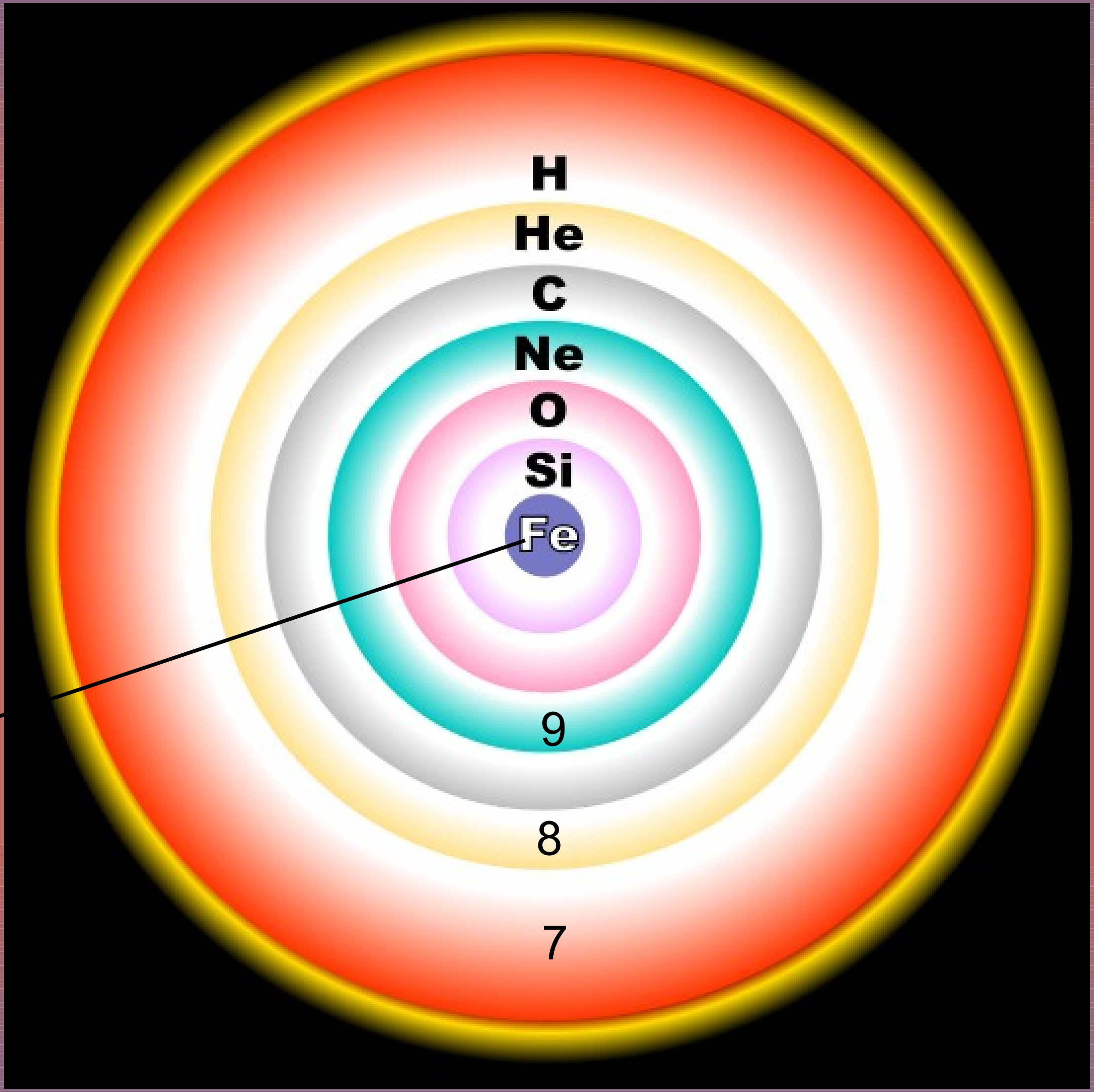
Nuclear onion

Star's core
R≈10.000 km

Massive stars only



LogT: 10

Stage before star's death

Stellar evolution

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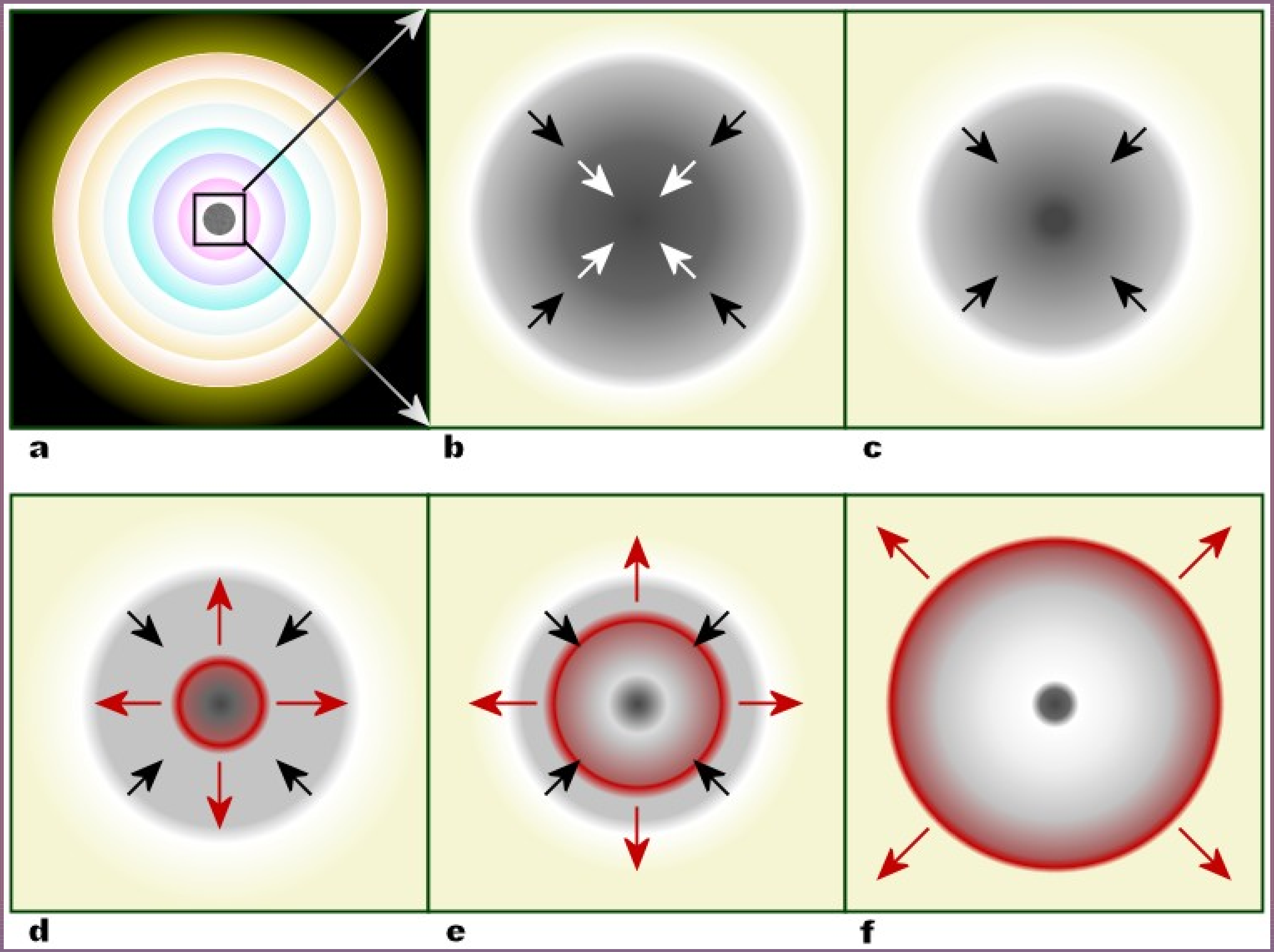
The explosion engine

$M_{core} > 1.4\ M_{\odot}$



Stellar evolution

Photodisintegration

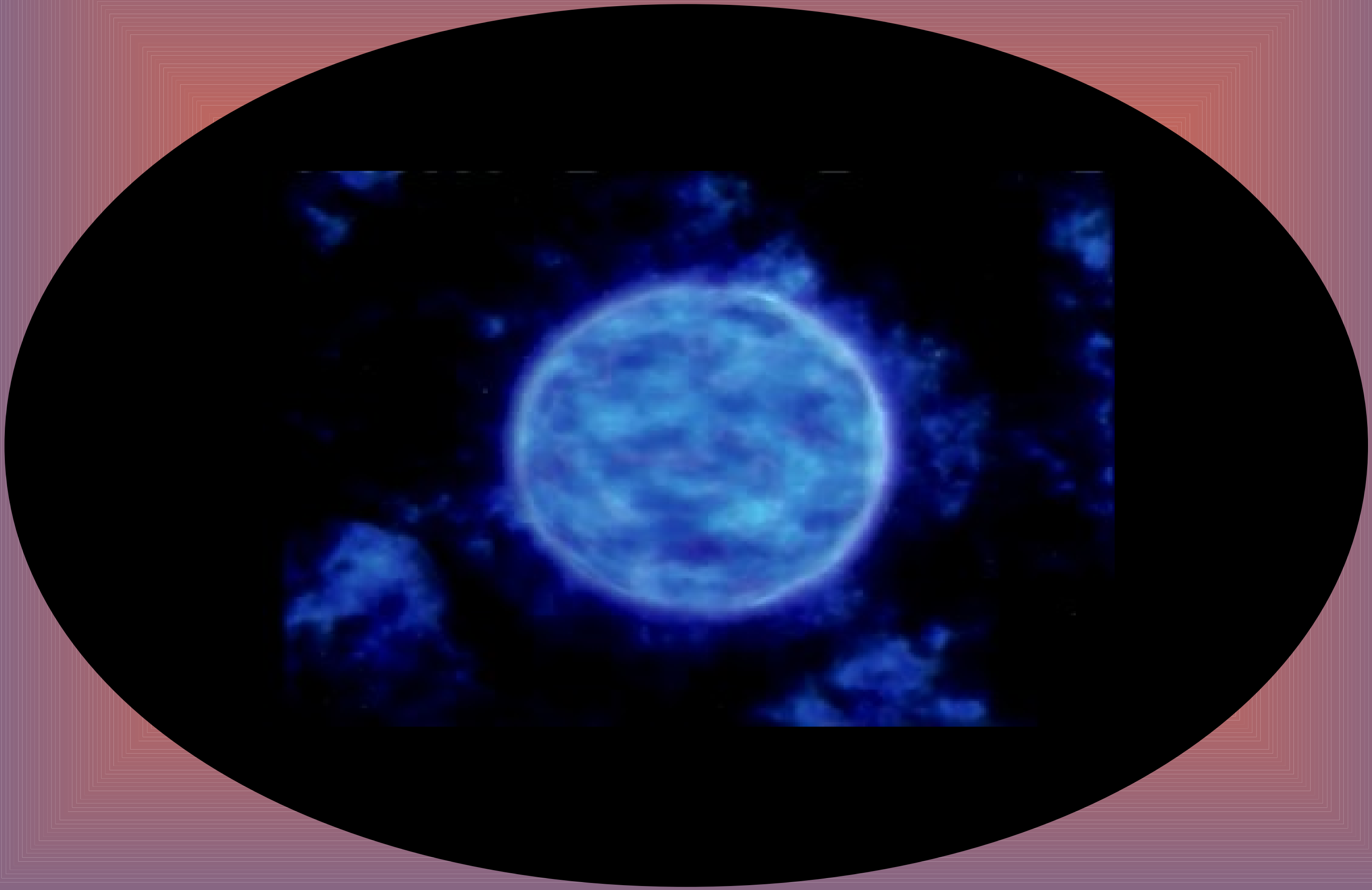
ν + neutrons

Towards the neutron star

Table 20-1 Evolutionary Stages of a 25-$M_\odot$ Star

Stage	Core temperature (K)	Core density (kg/m^3)	Duration of sta
Hydrogen fusion	4×10^7	5×10^3	7×10^6 years
Helium fusion	2×10^8	7×10^5	7×10^5 years
Carbon fusion	6×10^8	2×10^8	600 years
Neon fusion	1.2×10^9	4×10^9	1 year
Oxygen fusion	1.5×10^9	10^{10}	6 months
Silicon fusion	2.7×10^9	3×10^{10}	1 day
Core collapse	5.4×10^9	3×10^{12}	¼ second
Core bounce	2.3×10^{10}	4×10^{15}	milliseconds
Explosive (supernova)	about 10^9	varies	10 seconds

The black hole case



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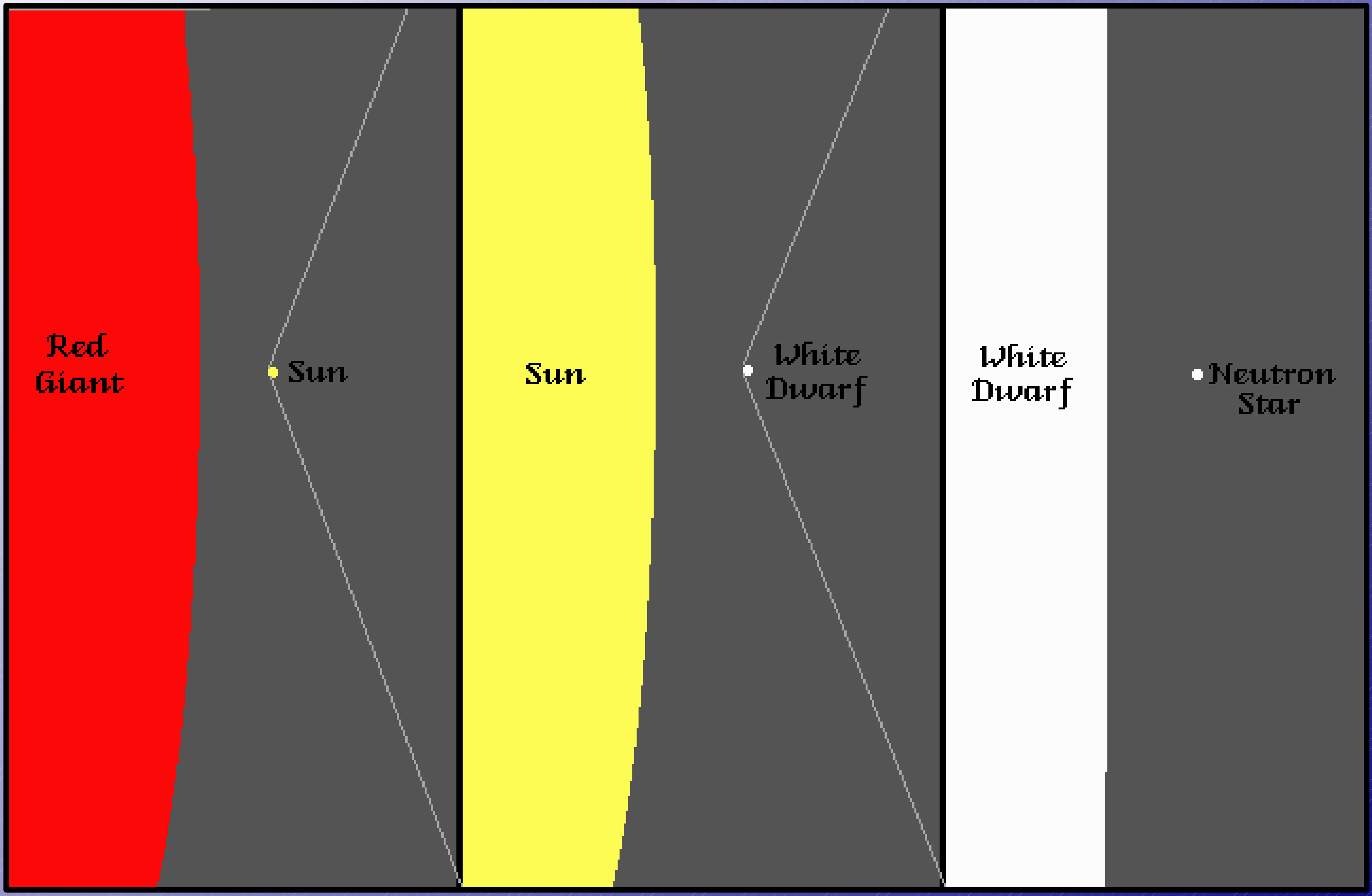
Comparative sizes



Ratio ~10^8

A star the size of Copenhagen...

T ~10^6 K

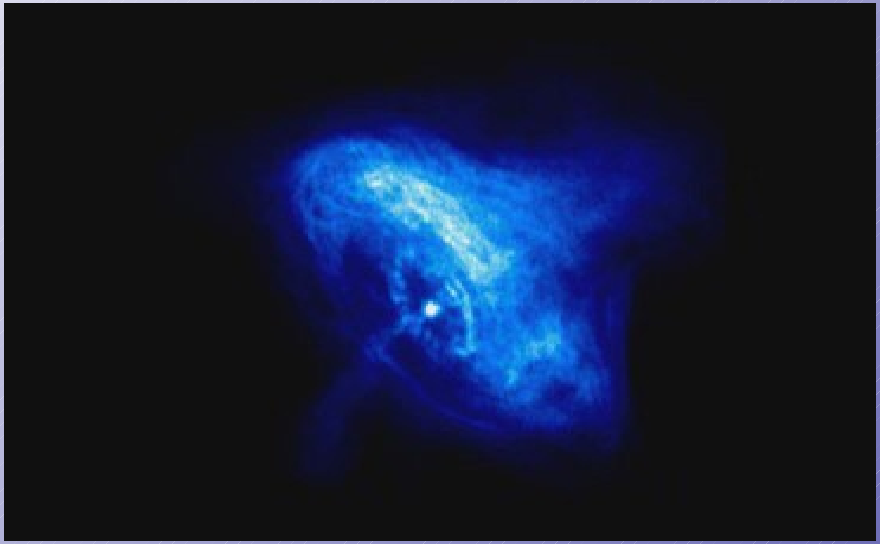
R ≈10 km

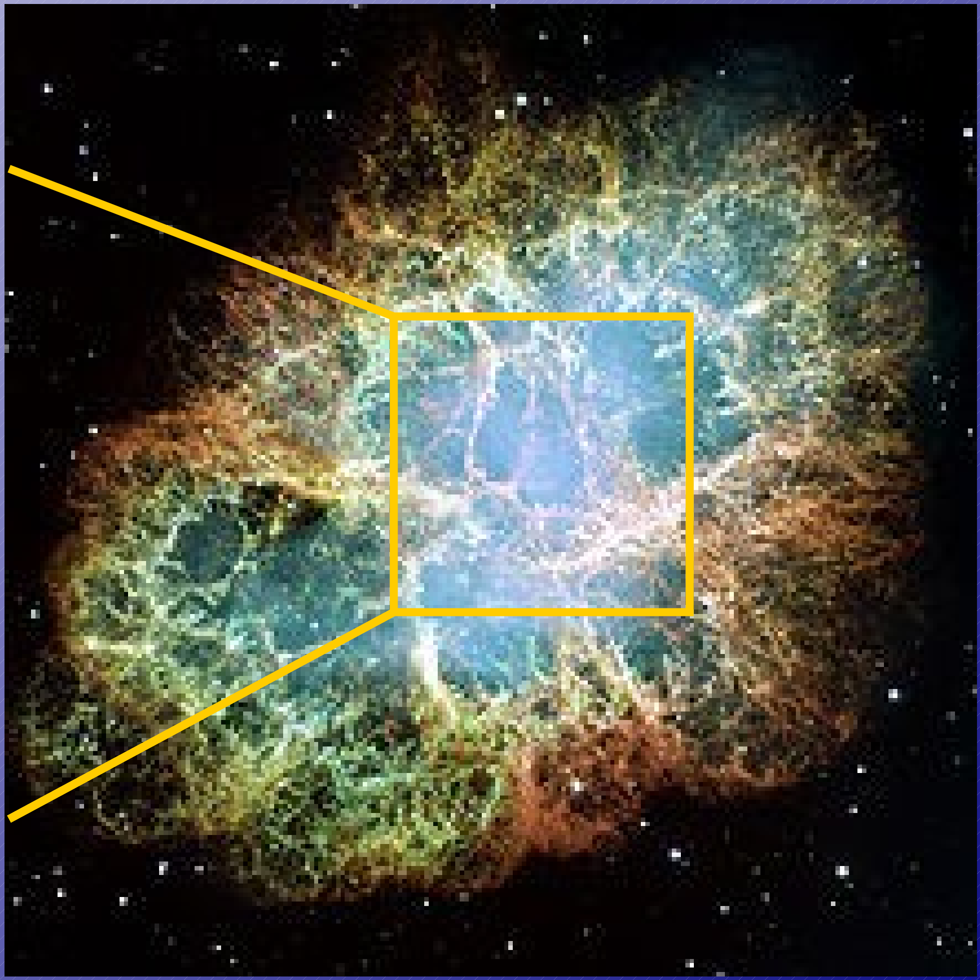
$$L = 4\pi R^2 \sigma T^4$$

… but 1.5–2 × the mass of the Sun

The Crab pulsar and nebula

X-ray pulsar





30 Hz radio emission

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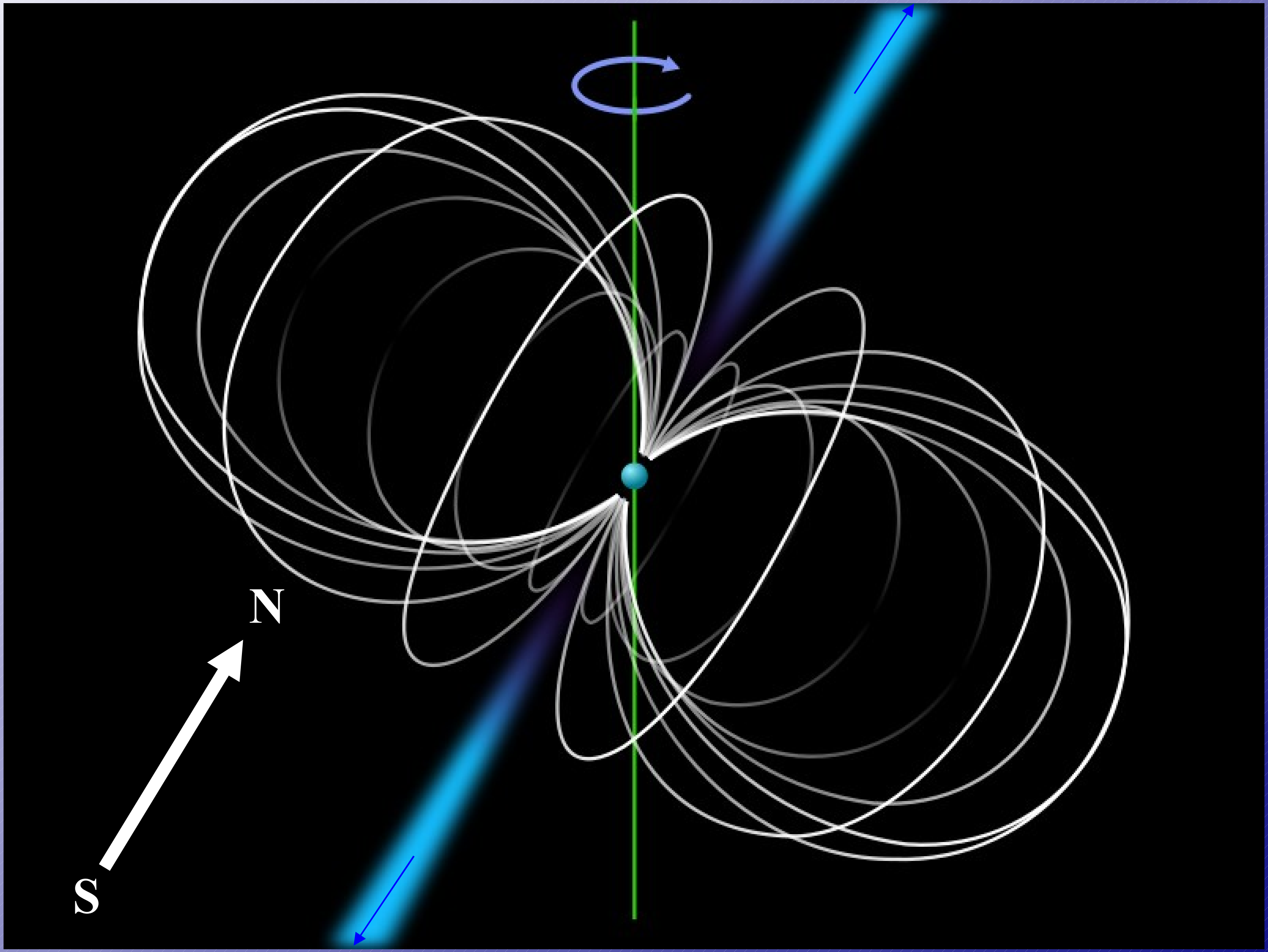
A stellar dynamo

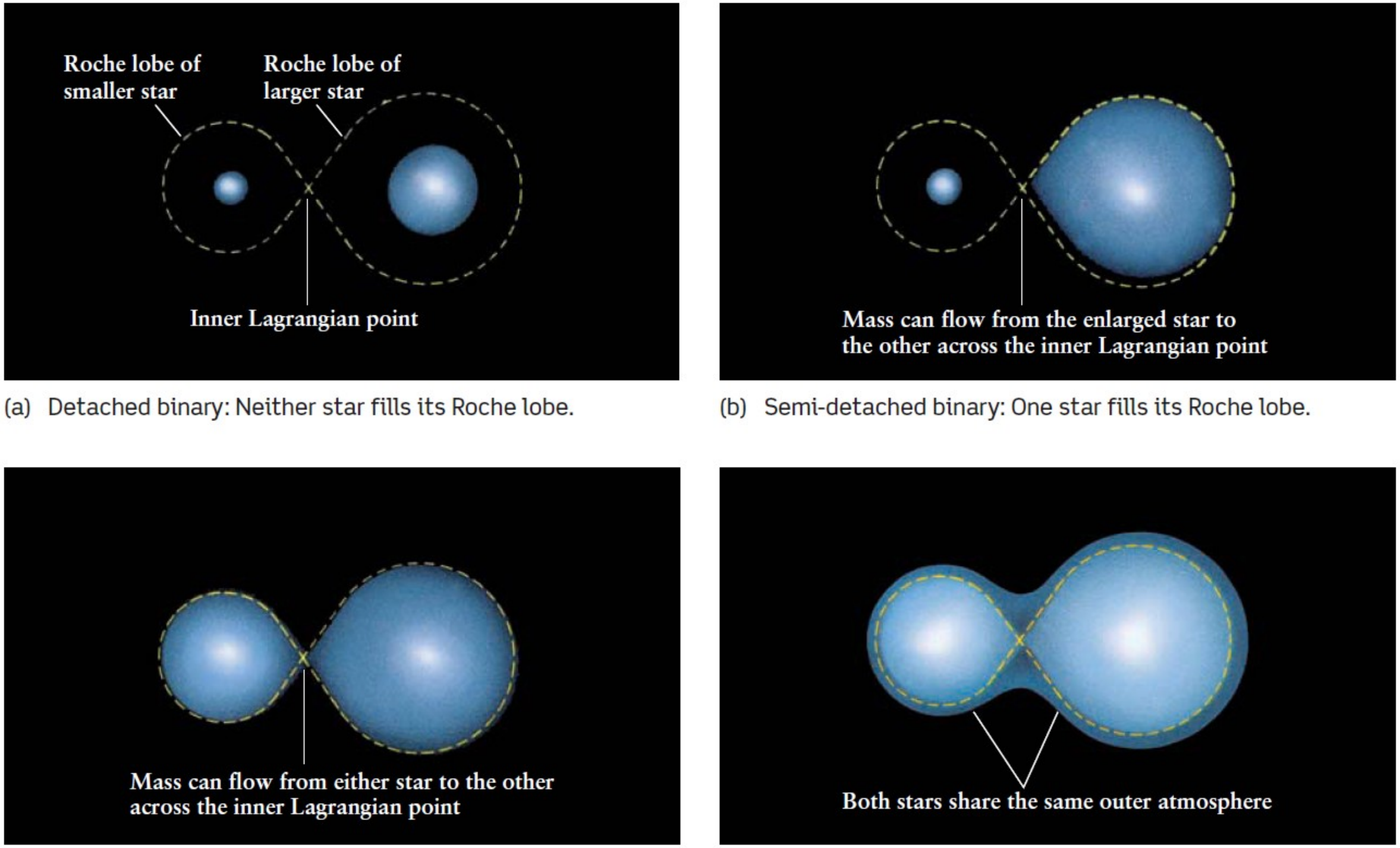


B~10^{12} – 10^{15} Gauss

End of the story?

… Not if the stars live in pair…

Mass transfer in close binaries



(a) Detached binary: Neither star fills its Roche lobe.

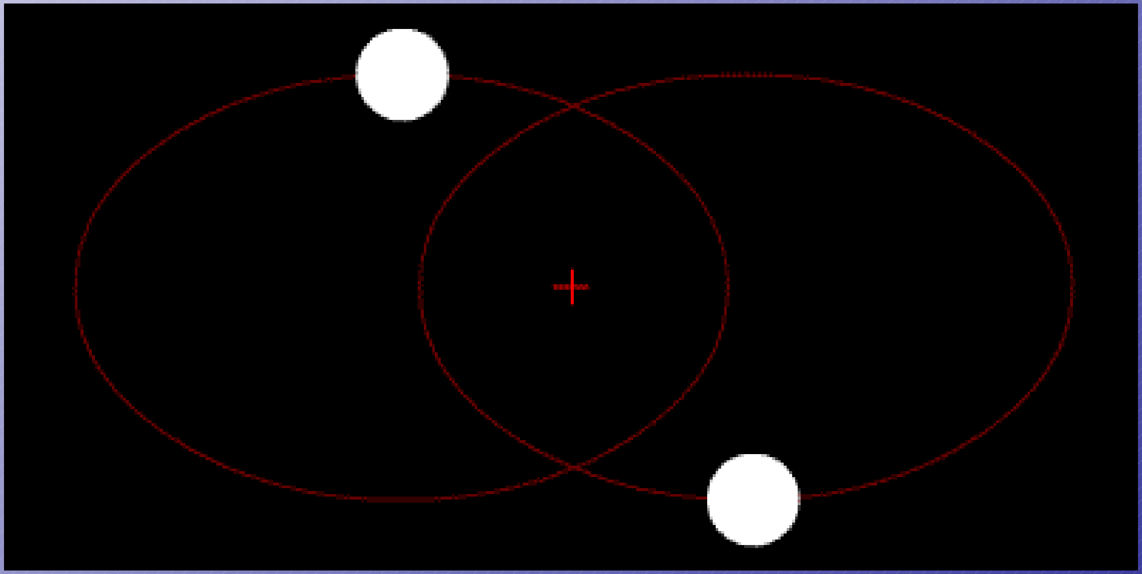
(b) Semi-detached binary: One star fills its Roche lobe.

(c) Contact binary: Both stars fill their Roche lobes.

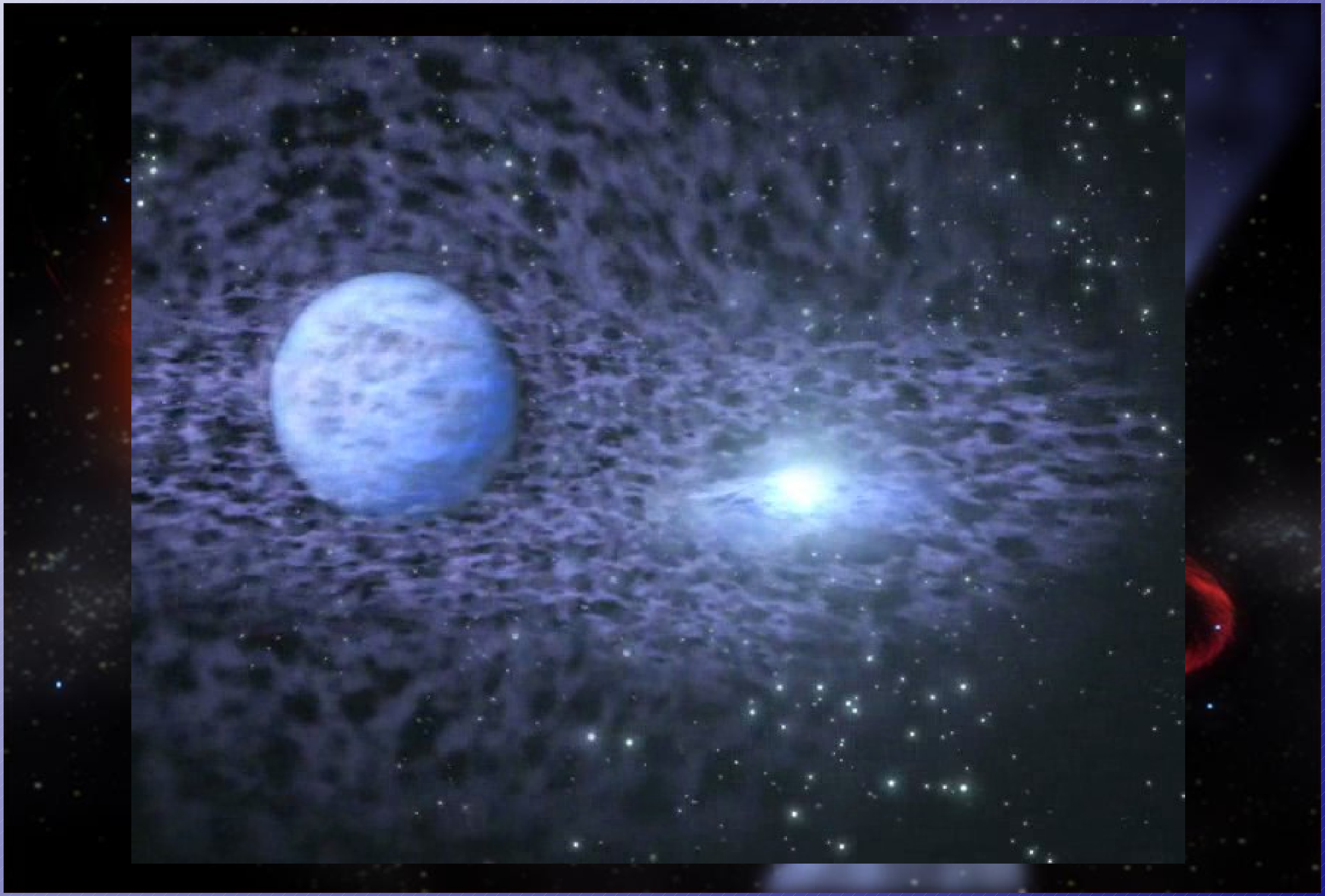
(d) Overcontact binary: Both stars overfill their Roche lobes.

Symbiotic binaries

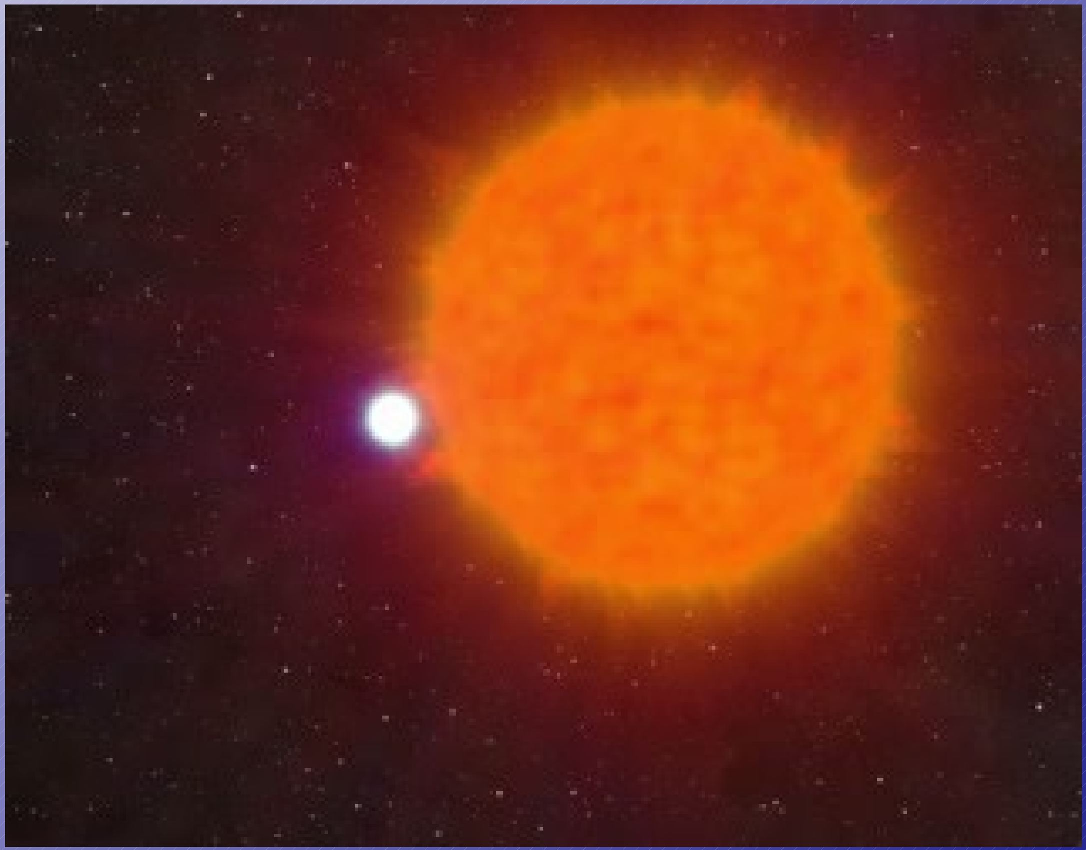
Binary systems

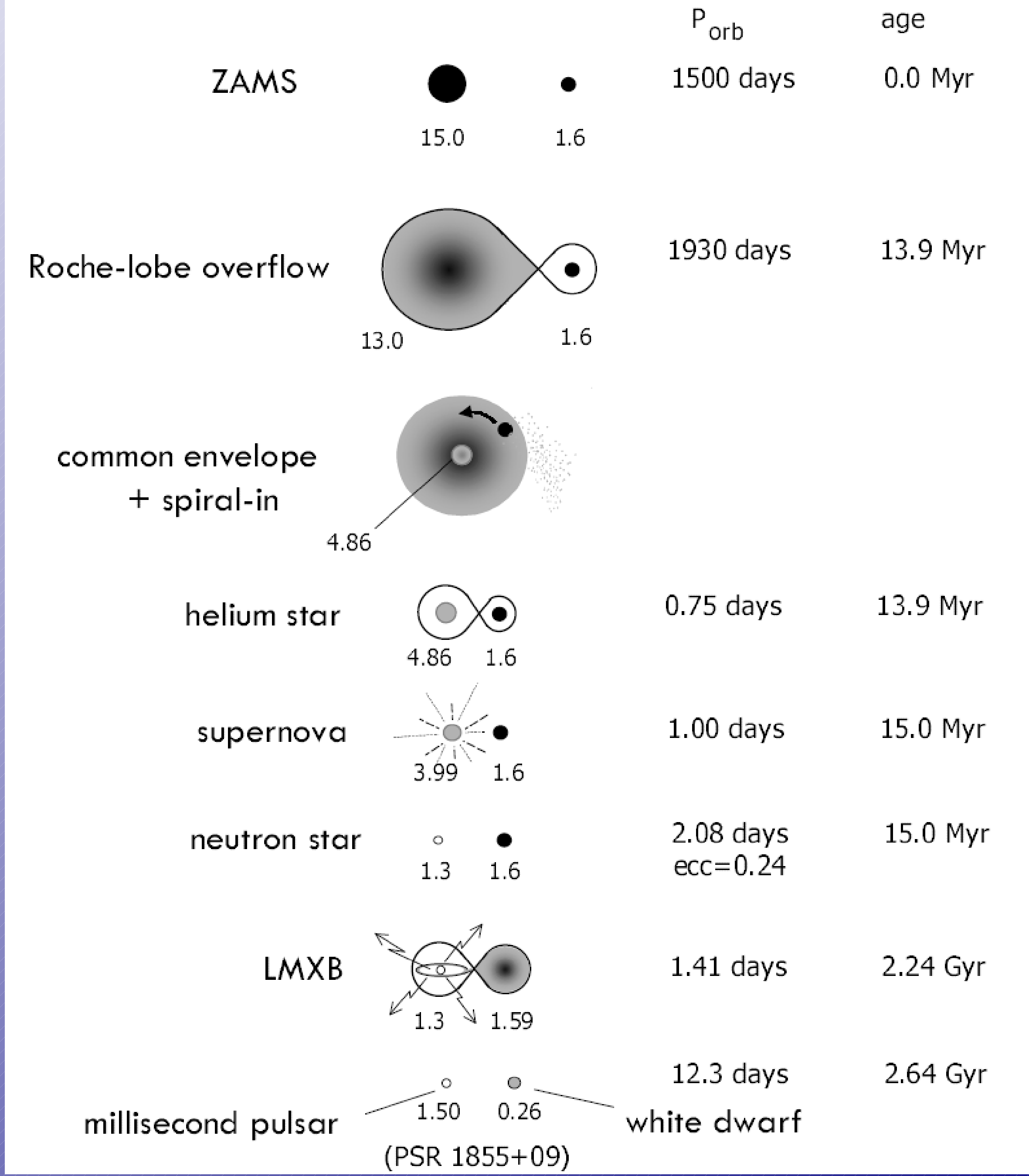


X-ray binaries



Binary evolution to double pulsar




P orb
age
ZAMS
15.0
1.6
1500 days
0.0 Myr
Roche-lobe overflow
13.0
1.6
1930 days
13.9 Myr
common envelope
+ spiral-in
4.86
helium star
4.86
1.6
0.75 days
13.9 Myr
supernova
3.99
1.6
1.00 days
15.0 Myr
neutron star
1.3
1.6
2.08 days
ecc=0.24
15.0 Myr
LMXB
1.3
1.59
1.41 days
2.24 Gyr
12.3 days
2.64 Gyr
millisecond pulsar
1.50
0.26
white dwarf
(PSR 1855+09)

Classification after the mass of the companion

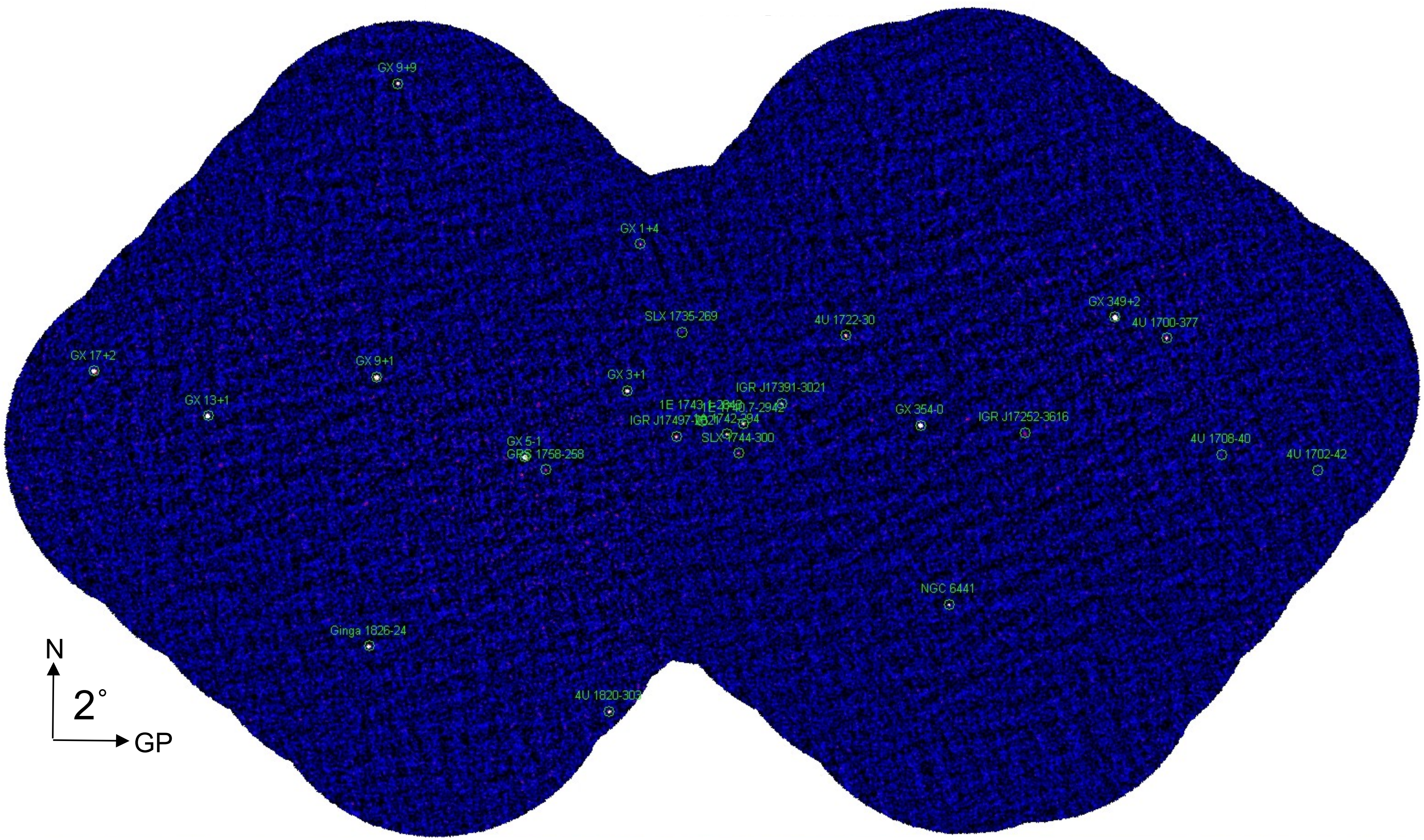
Characteristics

	HMXB	LMXB
X-ray spectra:	$kT \geq 15$ keV (hard)	$kT \lesssim 10$ keV (soft)
Type of time variability:	regular X-ray pulsations no X-ray bursts	only a very few pulsars often X-ray bursts
Accretion process:	wind (or atmos. RLO)	Roche-lobe overflow
Timescale of accretion:	10^5 yr	10^7–10^9 yr
Accreting compact star:	high **B**-field NS (or BH)	low **B**-field NS (or BH)
Spatial distribution:	Galactic plane	Galactic center and spread around the plane
Stellar population:	young, age $< 10^7$ yr	old, age $> 10^9$ yr
Companion stars:	luminous, $L_{opt}/L_x > 1$ early-type O(B) stars $> 10\,M_\odot$ (Pop. I)	faint, $L_{opt}/L_x \ll 0.1$ blue optical counterparts $\lesssim 1\,M_\odot$ (Pop. I and II)

$M_{Comp} > M_{CO}$ $\quad$ $M_{Comp} < M_{CO}$

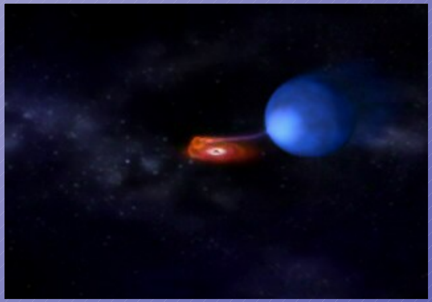
JEM-X – The X-ray Monitor onboard INTEGRAL

The Galactic Center region as seen by JEM-X



>90 X-ray bursters known to date; ~2/3 located in the Galactic Bulge

X-ray bursters



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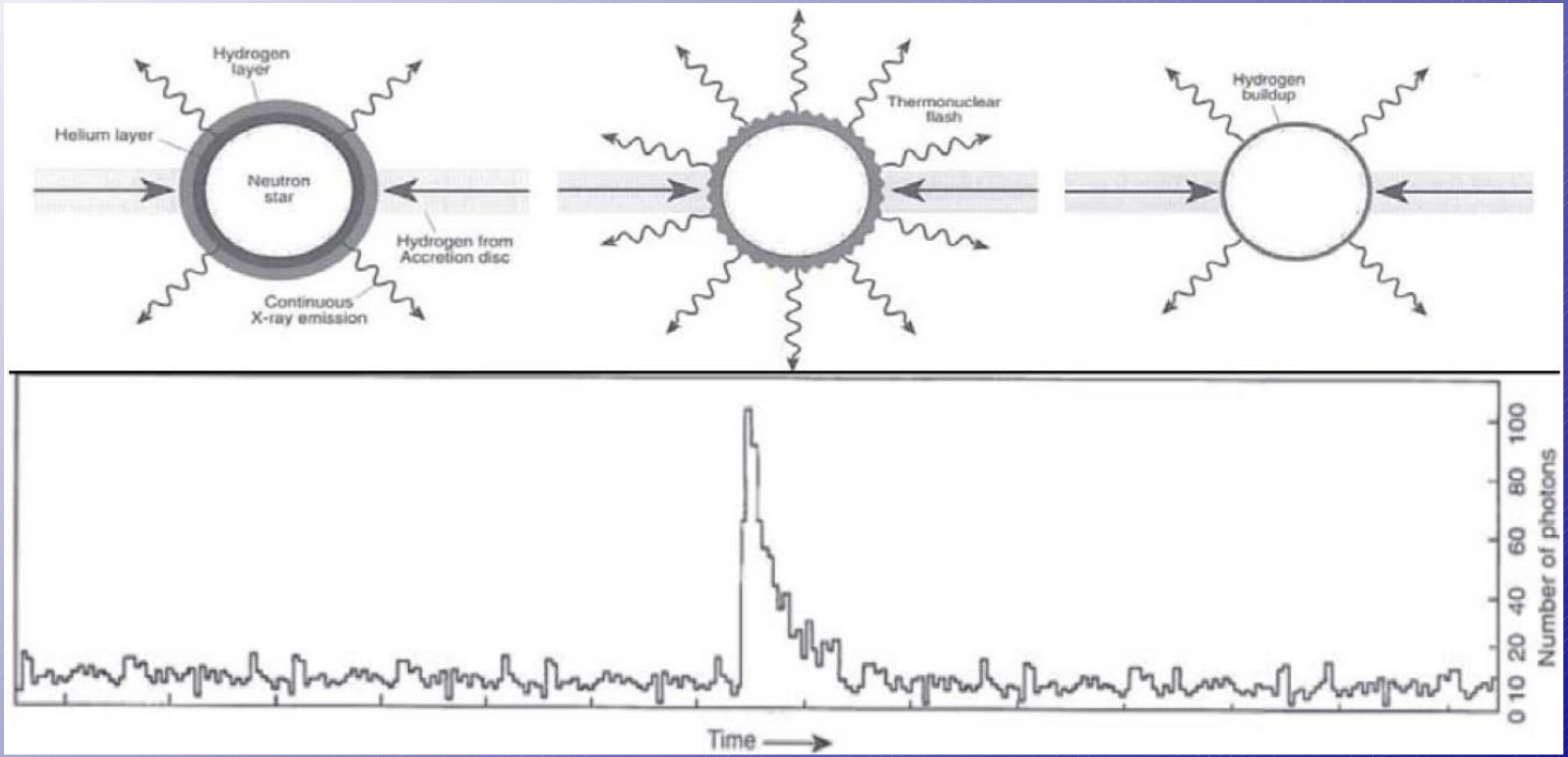
X-ray bursts



X-ray bursts are thermonuclear explosions in the surface layers of a neutron star accreting H and/or He from the envelope of a companion star. Their emission is described by blackbody radiation with peak temperature ≈2 keV and X-ray softening during the decay.

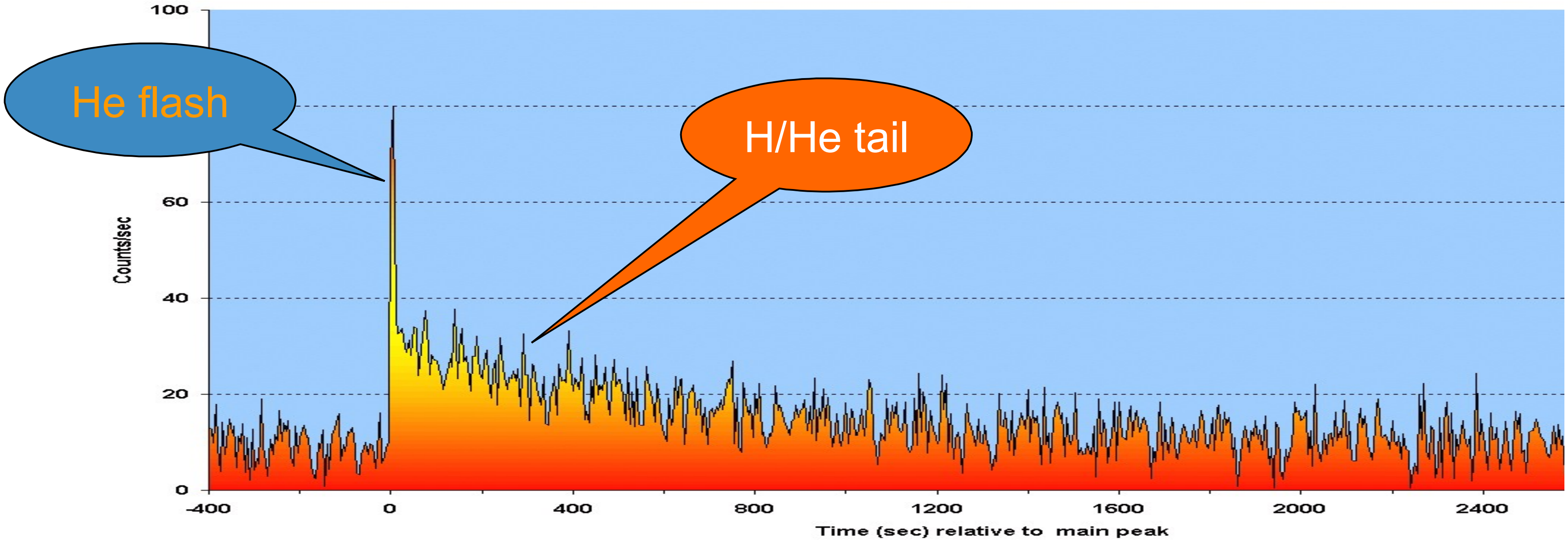
OBSERVATIONS

esa ASTROPHYSICS

INTEGRAL

Picture of the Month

February 2006



An unusual thermonuclear flash from a common burster...

GX 3+1 is a bright and well-known low-mass X-ray binary. Normally, a few times per day it shows short (less than 10 sec duration) and strong bursts. INTEGRAL detected on August 31, 2004 an unusual type I X-ray burst. Its duration was about 30 minutes. The peculiar burst is characteri short spike of ~6 sec, similar to the normal type I X-ray bursts, followed by a remarkable extended decay of cooling emission. The discovery is re astro-ph/0512559). Although it seems most probable that the burst is due to unstable burning of a mixed hydrogen/helium layer involving an unu: other scenario's (involving unstable burning of either pure helium or carbon) cannot be ruled out.

Data displayed in the figure are from JEM-X in the 3-20 keV range and plotted with 5 s bins. The main peak (t = 0 s) occurred at UTC 18:

Credits: J. Chenevez (DNSC, Copenhagen) et al.

Download the picture.
Download caption
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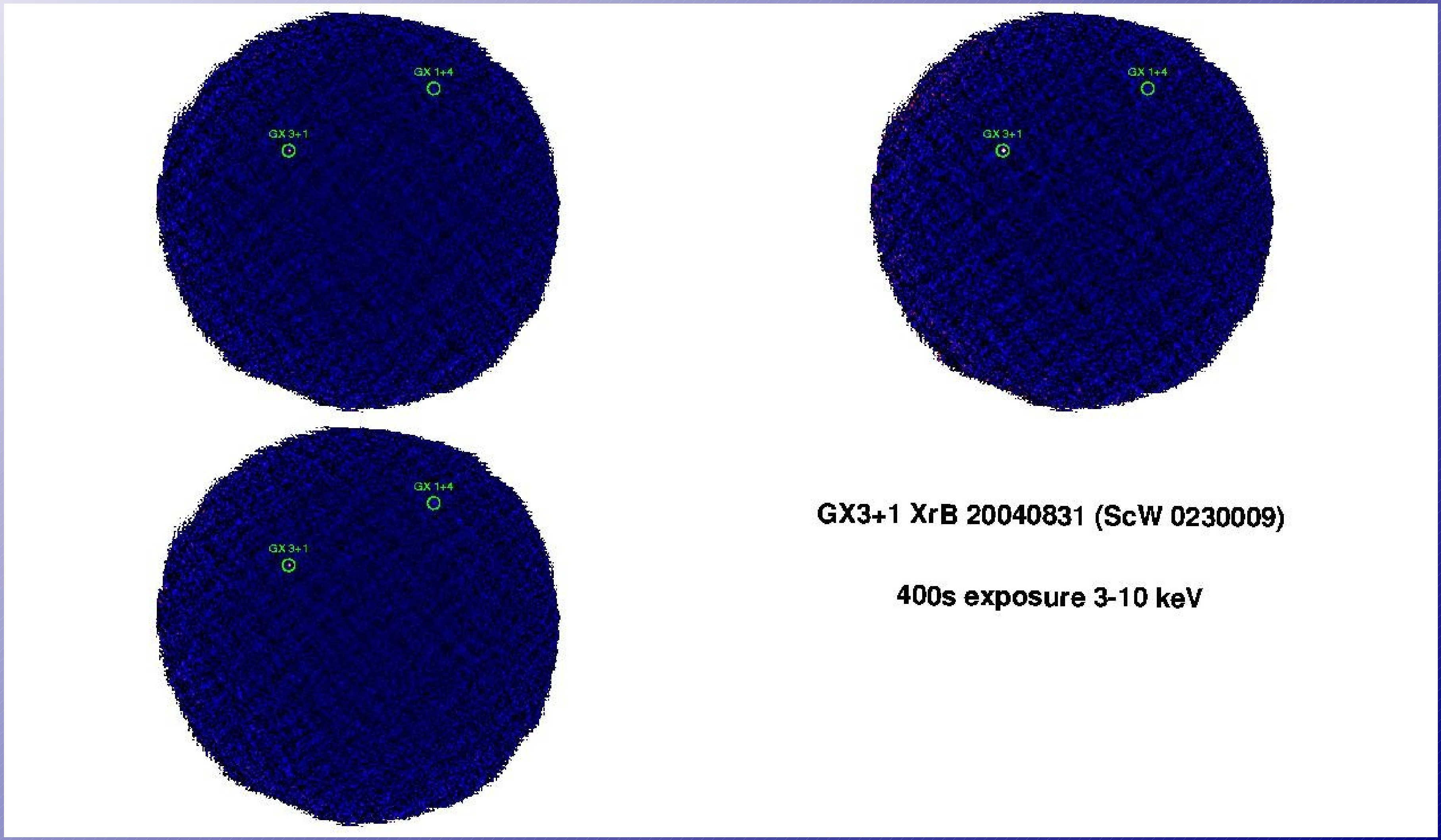
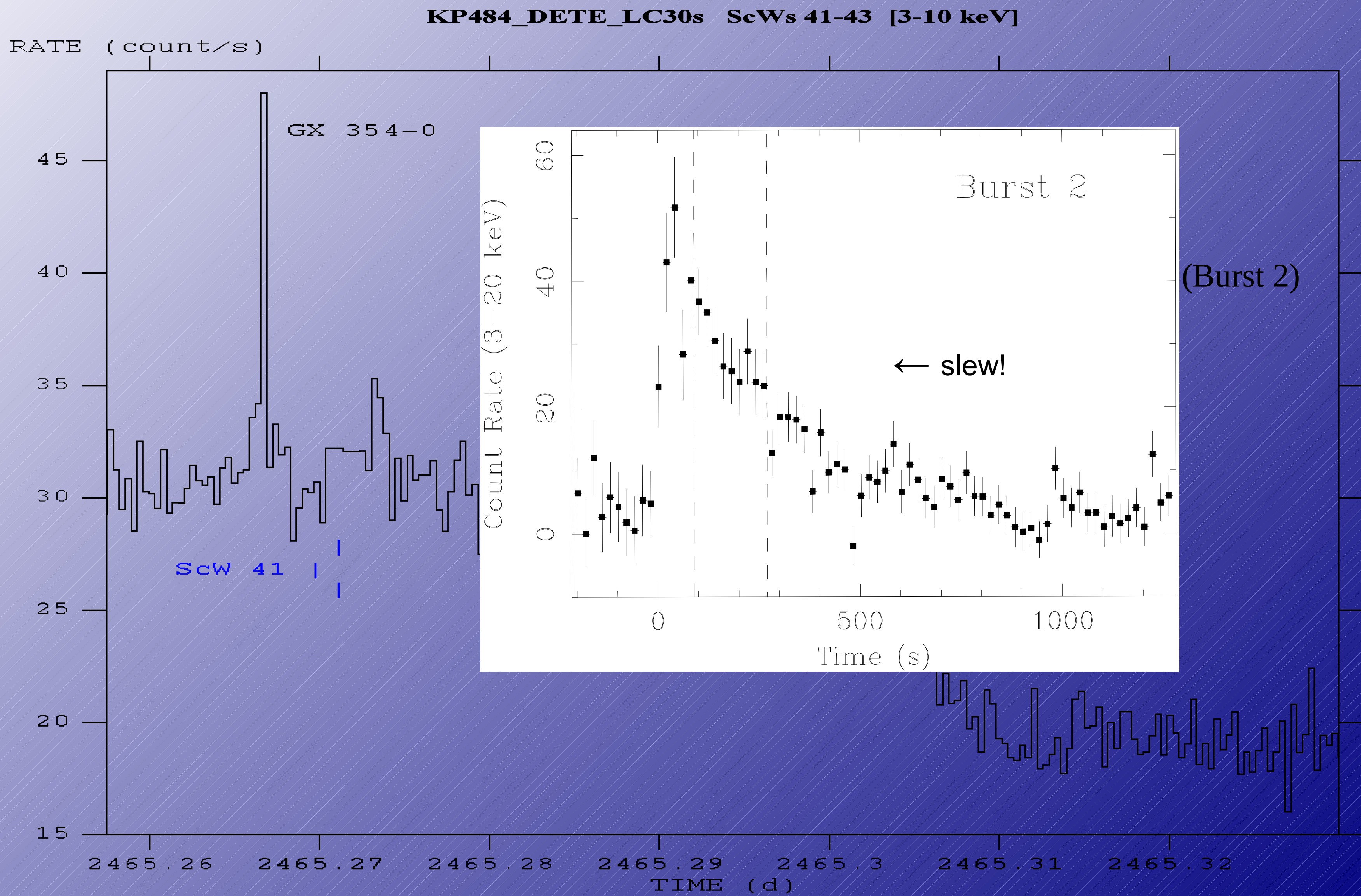
Example 1: X-ray burst detection in JEM-X <u>images</u>




KP484_DETE_LC30s ScWs 41-43 [3-10 keV]
RATE (count/s)
GX 354-0
ScW 41
TIME (d)
45
40
35
30
25
20
15
2465.26
2465.27
2465.28
2465.29
2465.3
2465.31
2465.32
Burst 2
Count Rate (3-20 keV)
Time (s)
0
20
40
60
500
1000
← slew!
(Burst 2)

Investigation method

Time resolved spectral analysis

Standard method: cut the burst in short time intervals
and model the burst emission by black-body spectra

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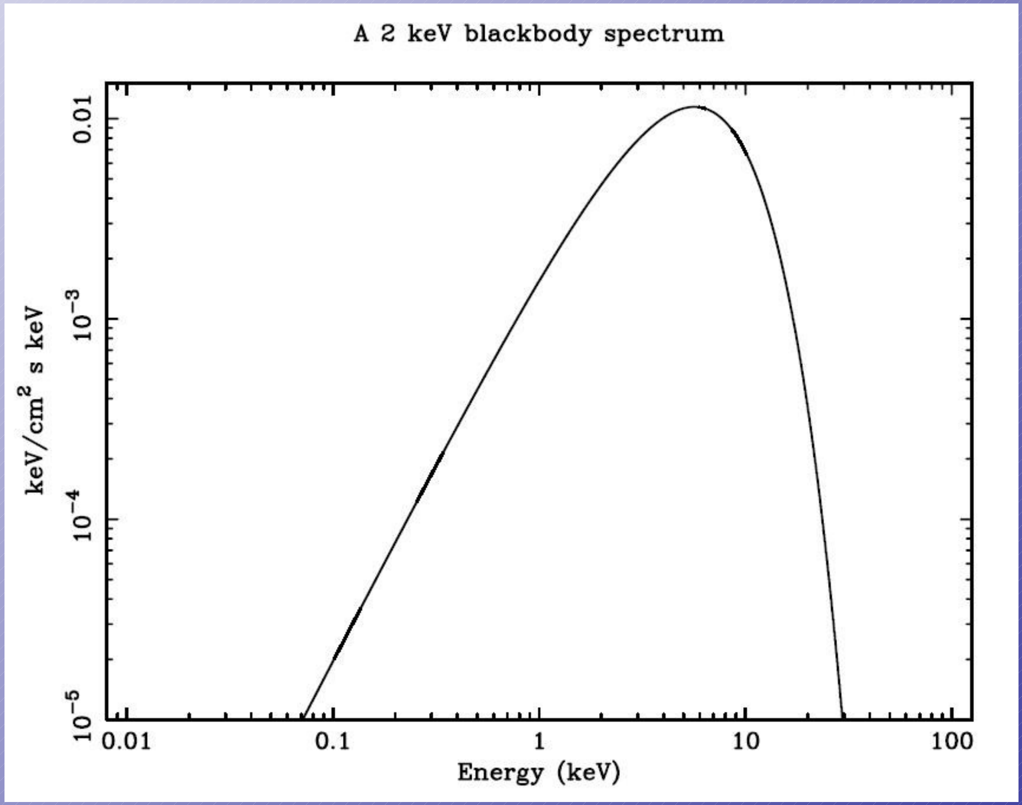
Thermonuclear explosions

X-ray bursts are characterized by a ≈2 keV (T ≈ $25 \cdot 10^6$ K) blackbody emission and exponential decay with cooling.

Blackbody radiation



Spectral intensity ≡ Planck Function:

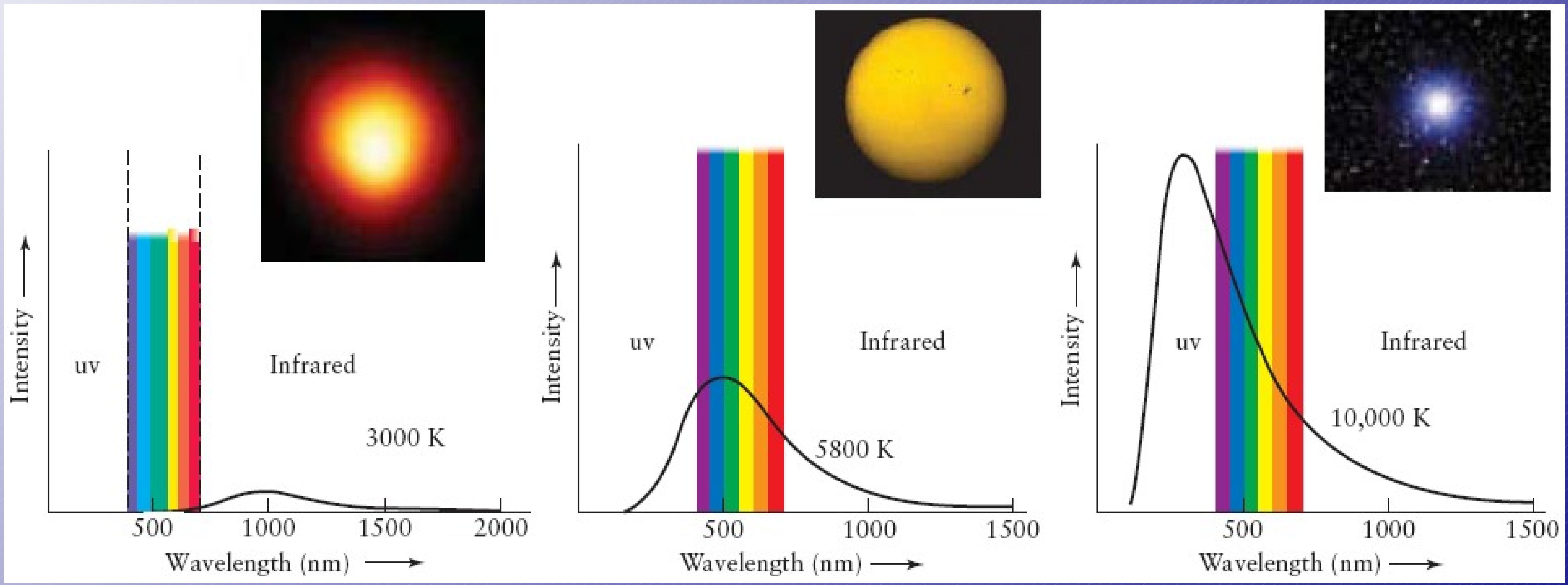
$$I_\nu = \frac{2h\nu^3}{c^2} \frac{1}{e^{h\nu/kT} - 1}$$

Wien displacement law: $h\nu_{Max} = 2.82\ kT$

⇓

Maximum burst emission (5-6 keV) in JEM-X

Blackbody emission



$$I_\nu = \frac{2h\nu^3}{c^2}\frac{1}{e^{h\nu/kT}-1}$$

$$\overset{\iint \cdot}{\Rightarrow}$$

$$L = 4\pi R^2 \sigma T^4$$

Neutron stars

Blackbody emission from a neutron star

Flux conservation: $\mathrm{L} = \Phi$

$$\Leftrightarrow \; 4\pi \; R_{BB}^2 \, \sigma \; T_{eff}^4 = 4\pi \; d^2 F_{BB}$$

(Stefan's law)

$$\Leftrightarrow \; R_{BB} = \frac{\mathbf{d}}{T_{eff}^2} \sqrt{\frac{F_{BB}}{\sigma}}$$

The distance **d** is typically that to the centre of the Galaxy ≈ 25.000 l.yr.
The measured radius is ≈ 10 km.

So the ratio is ≈1/23.000.000.000.000.000

Application

Flux conservation: L = Φ

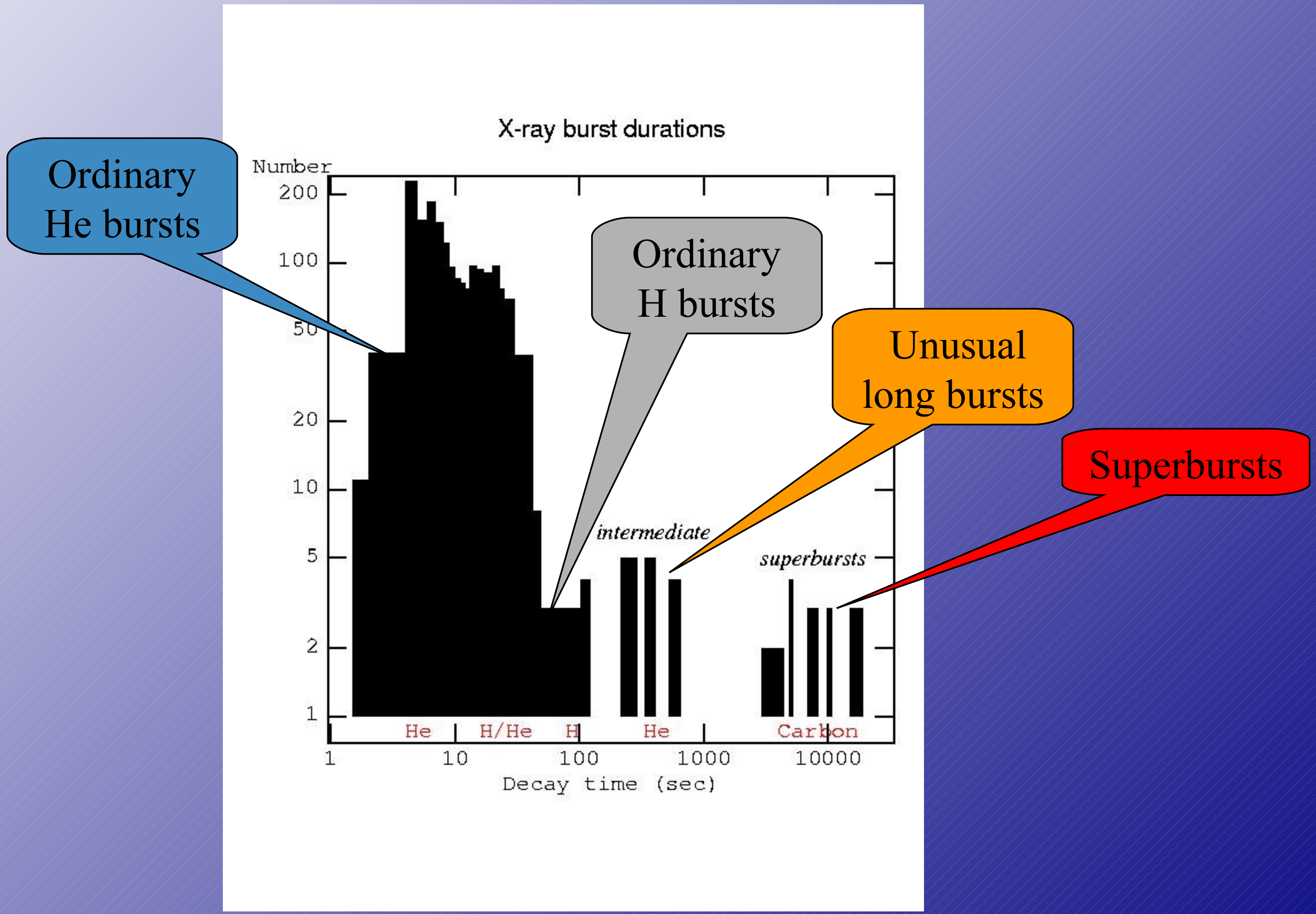
X-ray bursts as standard candles: if L= L_{Edd} ⇒ distance

$$L \leq L_{Edd} \Leftrightarrow 4\pi \; d^2 \; F \leq L_{Edd}$$

$$\Leftrightarrow \; d \leq \sqrt{\frac{L_{Edd}}{4\pi \; F}}$$

: upper limit to distance

More or less long bursts



Distribution of the X-ray bursts as a function of their exponential decay time

Neutron stars

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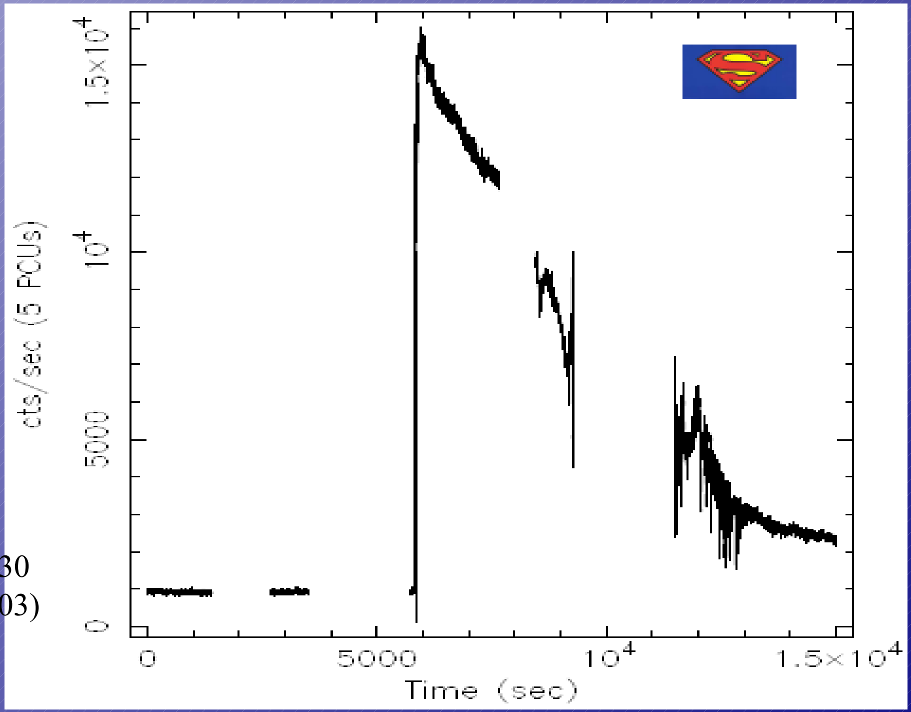
Superbursts

Compared to normal type I X-ray bursts, superbursts are ~1000 times more energetic ($E_b \approx 10^{42}$ ergs), ~1000 times longer (from hours to half a day), and have recurrence times of the order of years. They are very rare, only 15 such events having been found from 8 sources.

Superbursts display the same properties as usual X-ray bursts.
They are thought to arise from Carbon shell flashes in the sub-layers where heavy elements have previously been produced through the occurrence of H/He bursts. Their long duration is explained by their depth below the surface.



Superburst from 4U 1820-30 on 9/9/1999 (Kuulkers, 2003)

Intermediate long bursts

Only 14 bursts have shown a duration of a few tens of minutes

6 of them have been observed by JEM-X!

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THE END ?

Suggested literature: “Dragon’s egg” by Robert Forward