Maximum White Dwarf Mass

- once the electrons in a white dwarf become relativistic, the star <u>must</u> collapse

- critical mass is the <u>Chandrasekhar mass</u>:

$$M_{ch} = 0.21 \left(\frac{Z}{A}\right)^2 \left(\frac{hc}{Gm_p^2}\right)^{3/2} m_p$$

$$= 1.4\, M_\odot \quad \text{for} \quad \frac{Z}{A} = 0.5$$

<u>independent</u> of m_e

White Dwarf Collapse

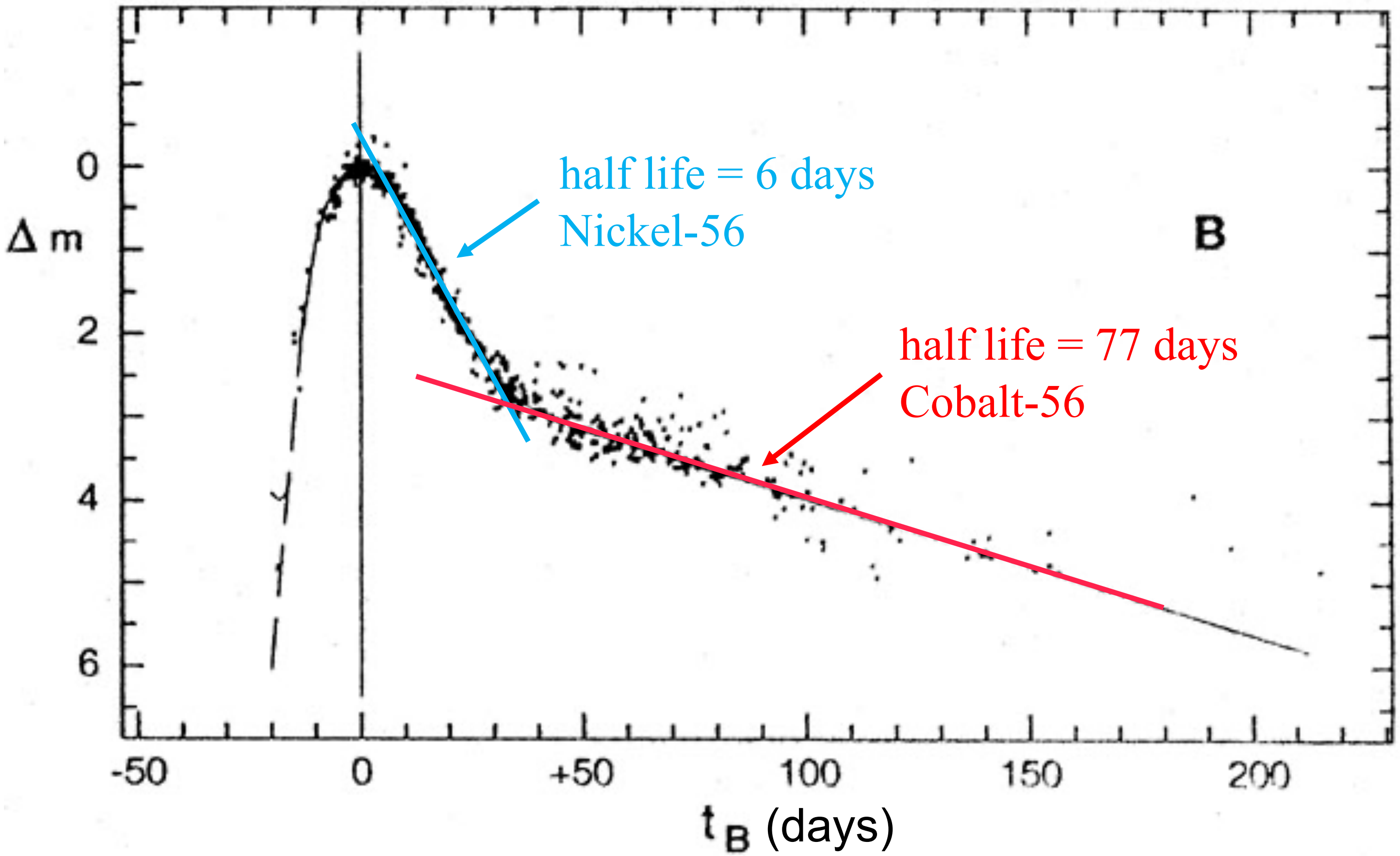
- collapse $\Longrightarrow T \uparrow \Longrightarrow C/O$ burning throughout

  $\Longrightarrow$ deflagration/explosion

  $\Longrightarrow$ supernova (Type Ia)

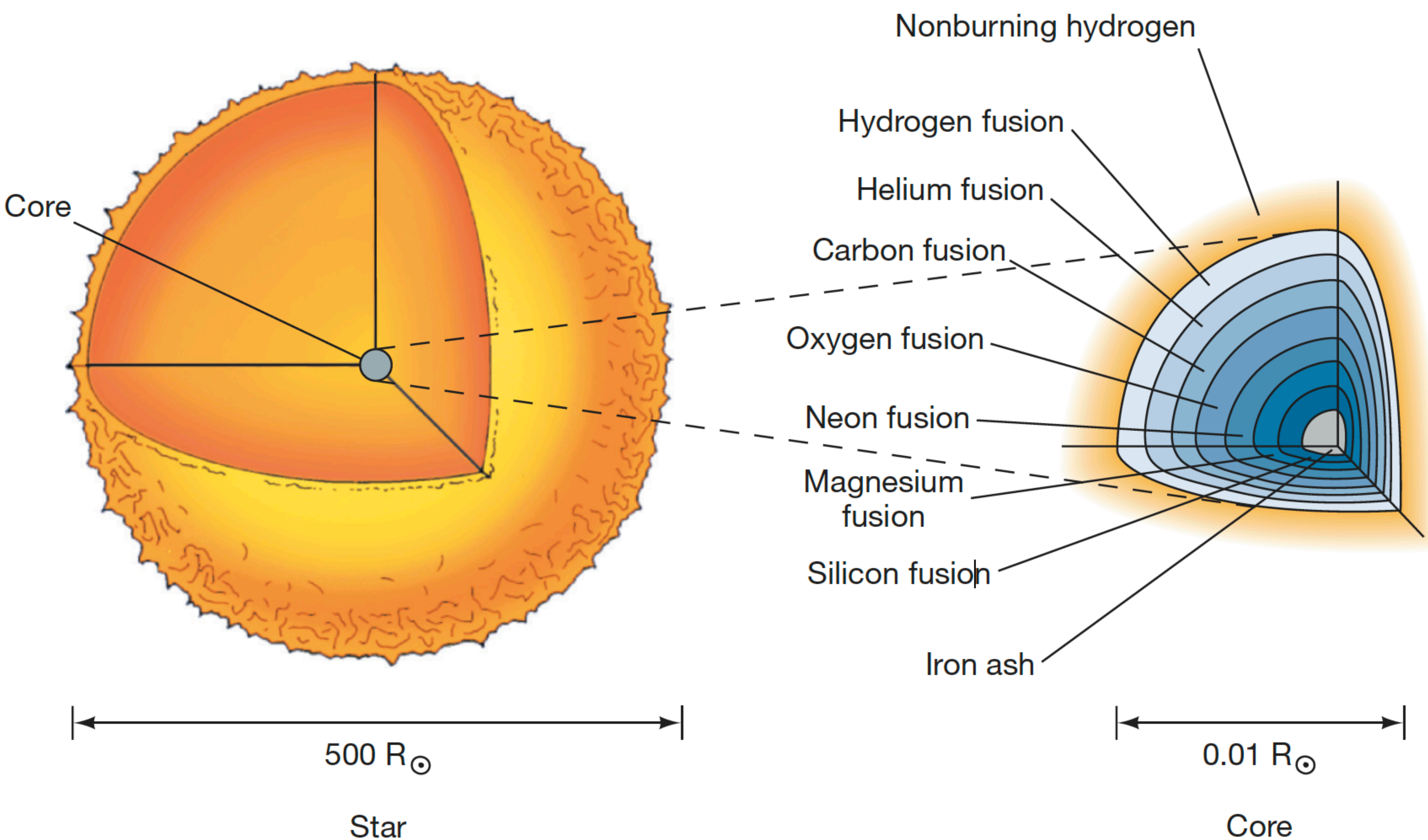
- energetics: $\sim 10^{44}$ J total $(\sim L_{\odot} \times 10^{10}$ yr$)$
- light curve: radioactive decay (Ni, Co, …)

  peak luminosity $\sim 5{\times}10^{9}\ L_{\odot}$



Cadonau 1987

NASA/Chandra X-ray Observatory/University of Texas/2MASS/University of Massachusetts/Caltech/NSF



layered core structure

High-Mass Stars

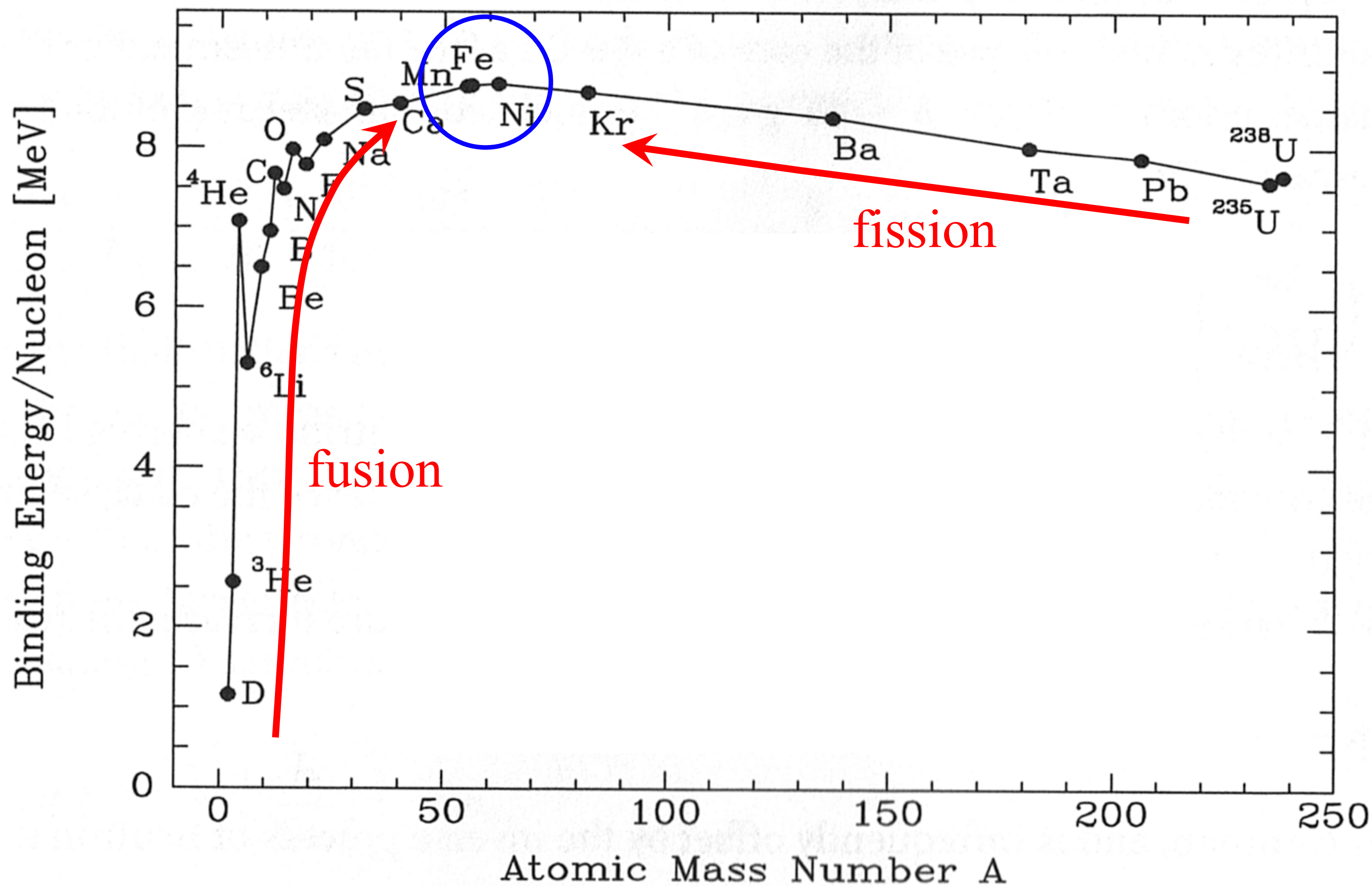
Faster and faster burning stages ($\sim 25\ M_{\odot}$ star)

$$
\begin{aligned}
H &\sim 5\times10^6 \text{ yr}\\
He &\sim 5\times10^5 \text{ yr}\\
C &\sim 500 \text{ yr}\\
Ne &\sim 1 \text{ yr}\\
Si &\sim 1 \text{ day}
\end{aligned}
$$

$$\rightarrow \quad {}^{56}Fe$$

Problem:

Iron won't fuse!


Binding Energy/Nucleon [MeV]
Atomic Mass Number A
0
2
4
6
8
0
50
100
150
200
250
D
3He
6Li
4He
Be
B
C
N
O
F
Na
S
Ca
Mn
Fe
Ni
Kr
Ba
Ta
Pb
235U
238U
fusion
fission

Core of a High-Mass Star

- Fe core grows in mass and shrinks in radius
- core is supported by electron degeneracy pressure

temperature	$T > 10^9\ K$
density	$\rho > 10^{12}\ \mathrm{kg\ m^{-3}}$
mass	$M \sim 1.2\ - 1.4\ M_{\odot} \sim M_{ch}$
radius	$R \sim 10^4\ \mathrm{km}$

- core is about to exceed M_{ch} and become unstable, but things are worse than that…

Core of a High-Mass Star

1. High $T \implies$ photodisintegration

$$\gamma + {}^{56}Fe \rightarrow 13({}^{4}He) + 4n - 124\text{ MeV}$$

$$\gamma + {}^{4}He \rightarrow 2p + 2n - 28.3\text{ MeV}$$

removes $\sim 10^{45}$ J $\approx$ core thermal energy

destabilizes the core

2. High $\rho \implies$ neutronization

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

$$e^- + {}^{56}Fe \rightarrow {}^{56}Mn + \nu_e$$

$$e^- + {}^{56}Mn \rightarrow {}^{56}Cr + \nu_e$$

removes electron pressure

neutrinos carry off energy

Collapse to a Neutron Star

- core cannot support itself, goes into free-fall
- collapses on time scale $t_{ff} \sim (G\rho)^{-1/2} \sim 0.1$ s

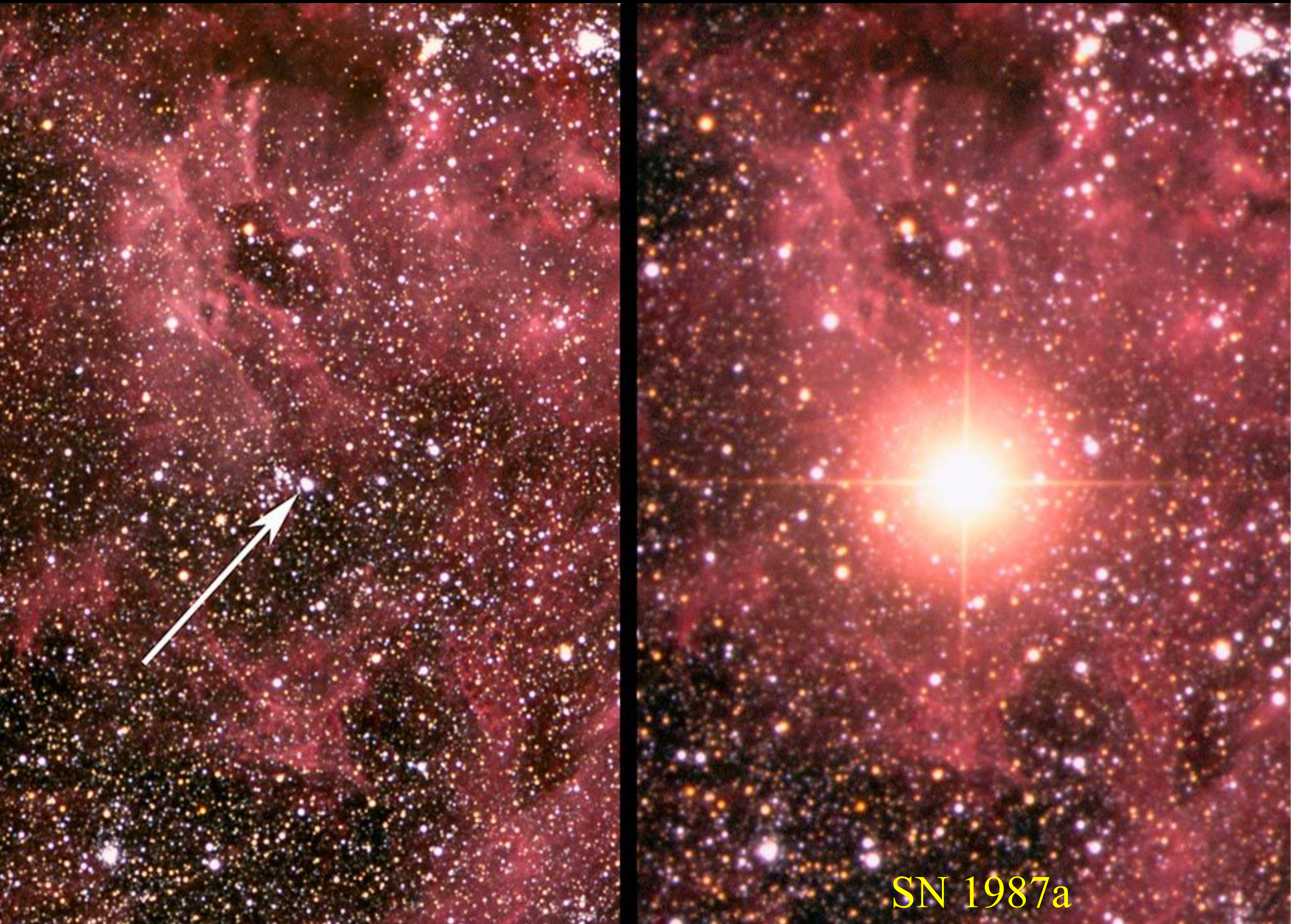
- collapse halts at nuclear density:

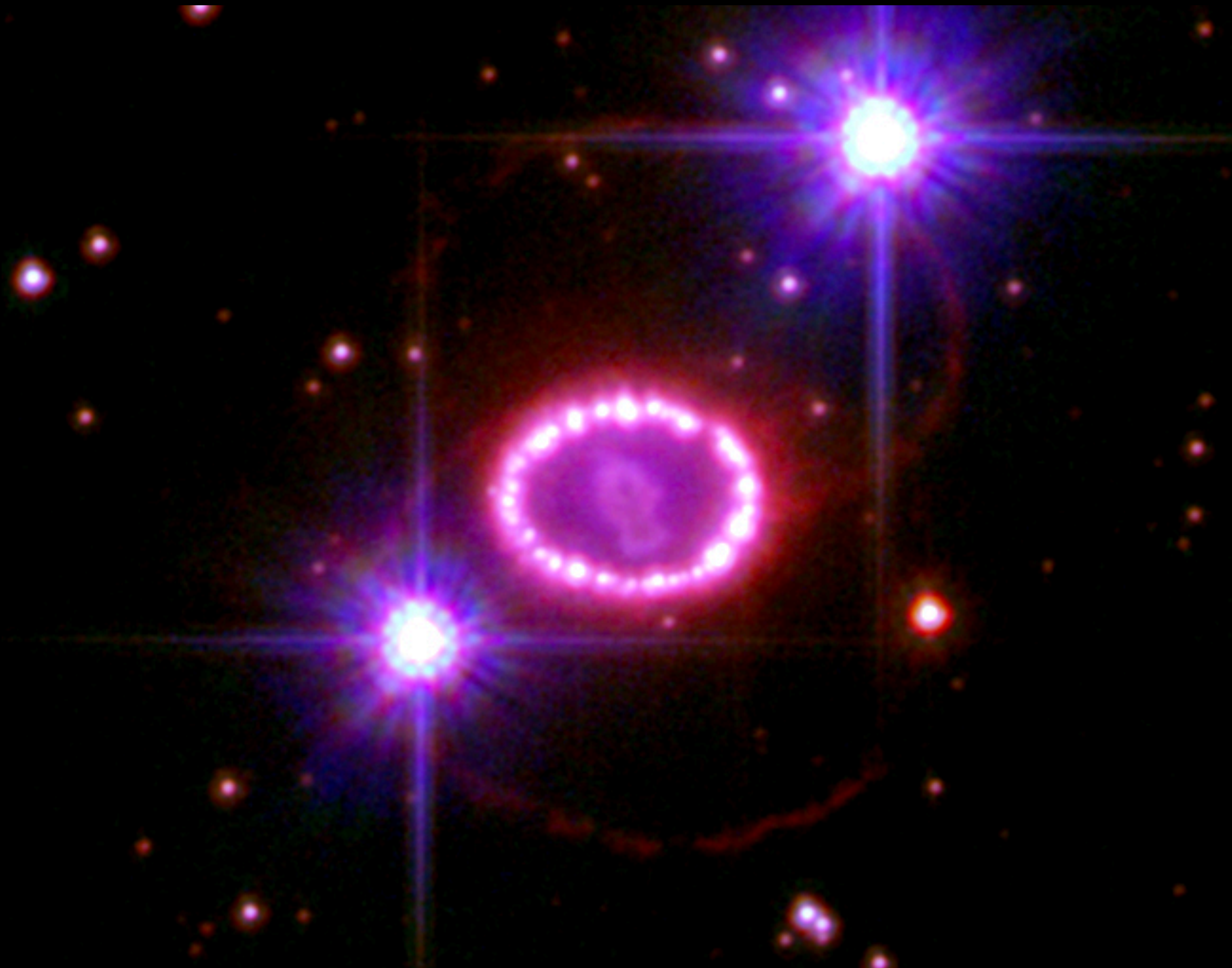
$$\rho \sim 10^{17}\ \mathrm{kg\ m^{-3}}$$

$$T \sim 10^{12} K$$

- "bounce" and resulting shock wave destroy the star

- result is a (Type II/core collapse) supernova


SN 1987a



Type II Supernova

- total energy

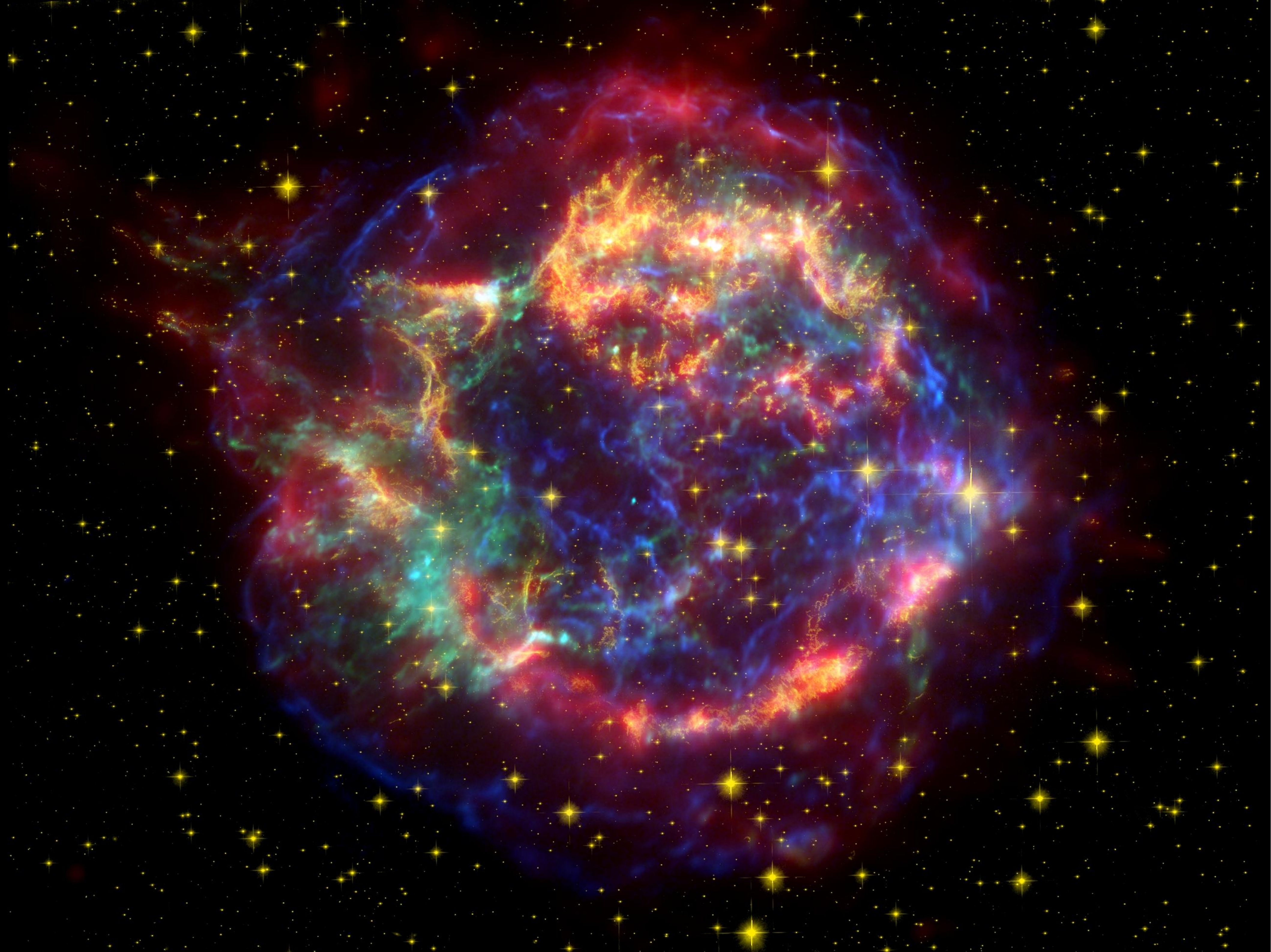
$$E_{gr} \sim \frac{GM^2}{R_{ns}} \sim 5\times10^{46} \left(\frac{M}{1.4\ M_{\odot}}\right)^2 \left(\frac{R_{ns}}{10\ \text{km}}\right)^{-1} J$$

$$T \sim 10^{12} K$$

- 99% in form of neutrinos

$$\gamma + \gamma \rightarrow e^+ + e^- \rightarrow \nu_e + \bar{\nu}_e,\ \ \nu_\mu + \bar{\nu}_\mu,\ \ \nu_\tau + \bar{\nu}_\tau$$

- 1% kinetic energy
- 0.01% radiation



Neutron Star

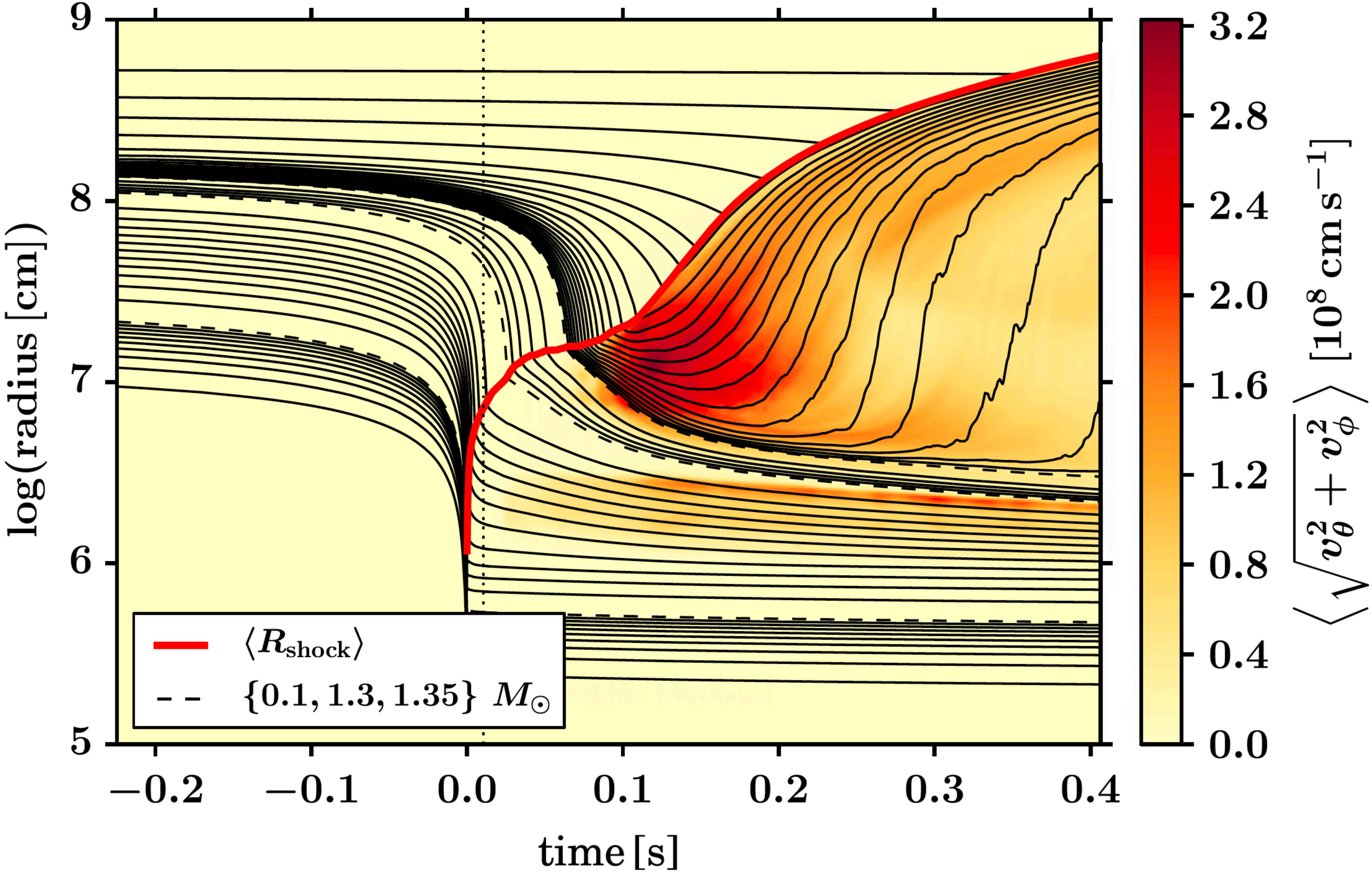
- remnant is a neutron star:

$$M \sim 1.4\ M_{\odot}, \quad R \sim 10 - 15\ \text{km}$$

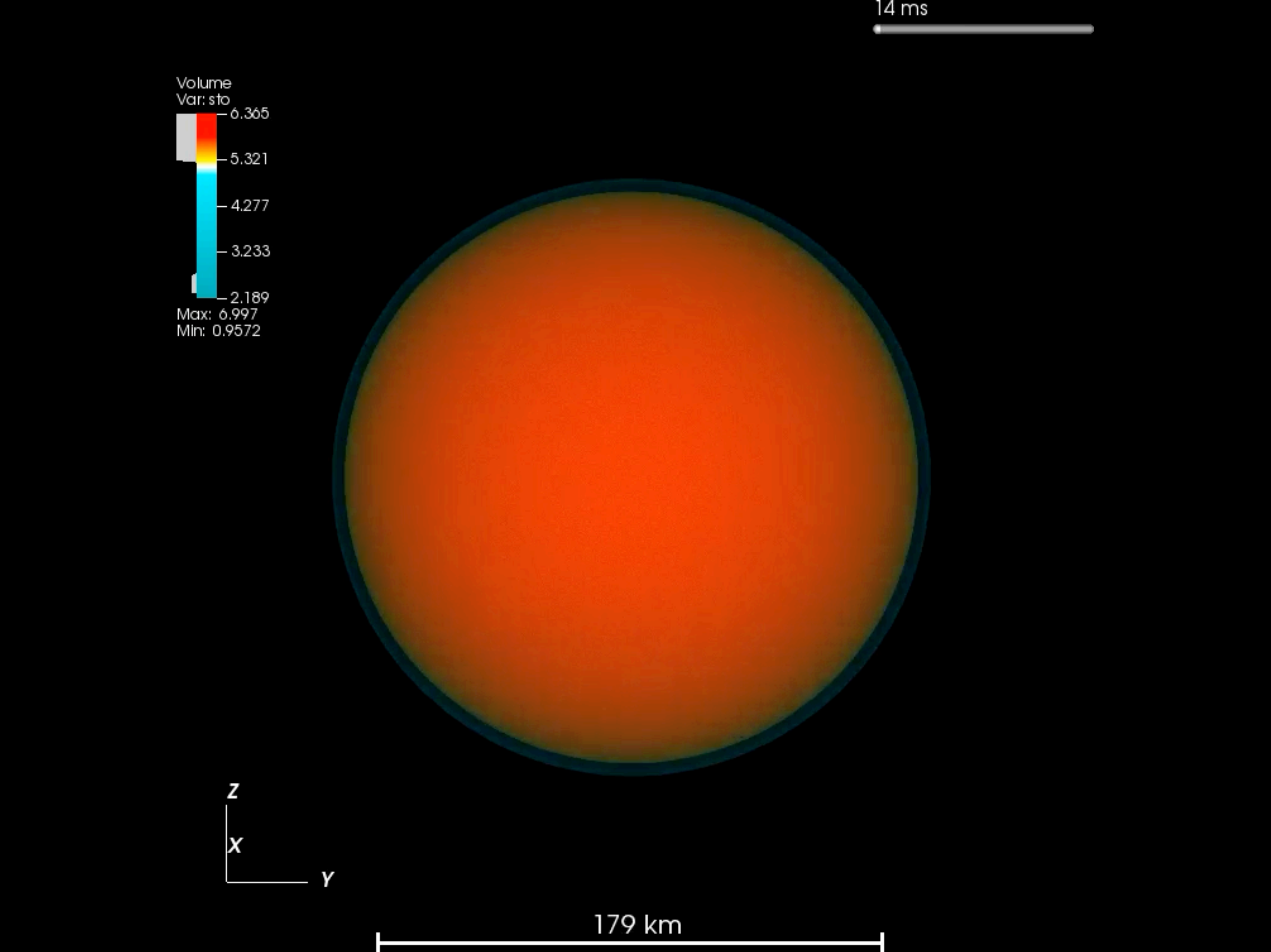
- almost entirely composed of neutrons
- supported by neutron degeneracy pressure

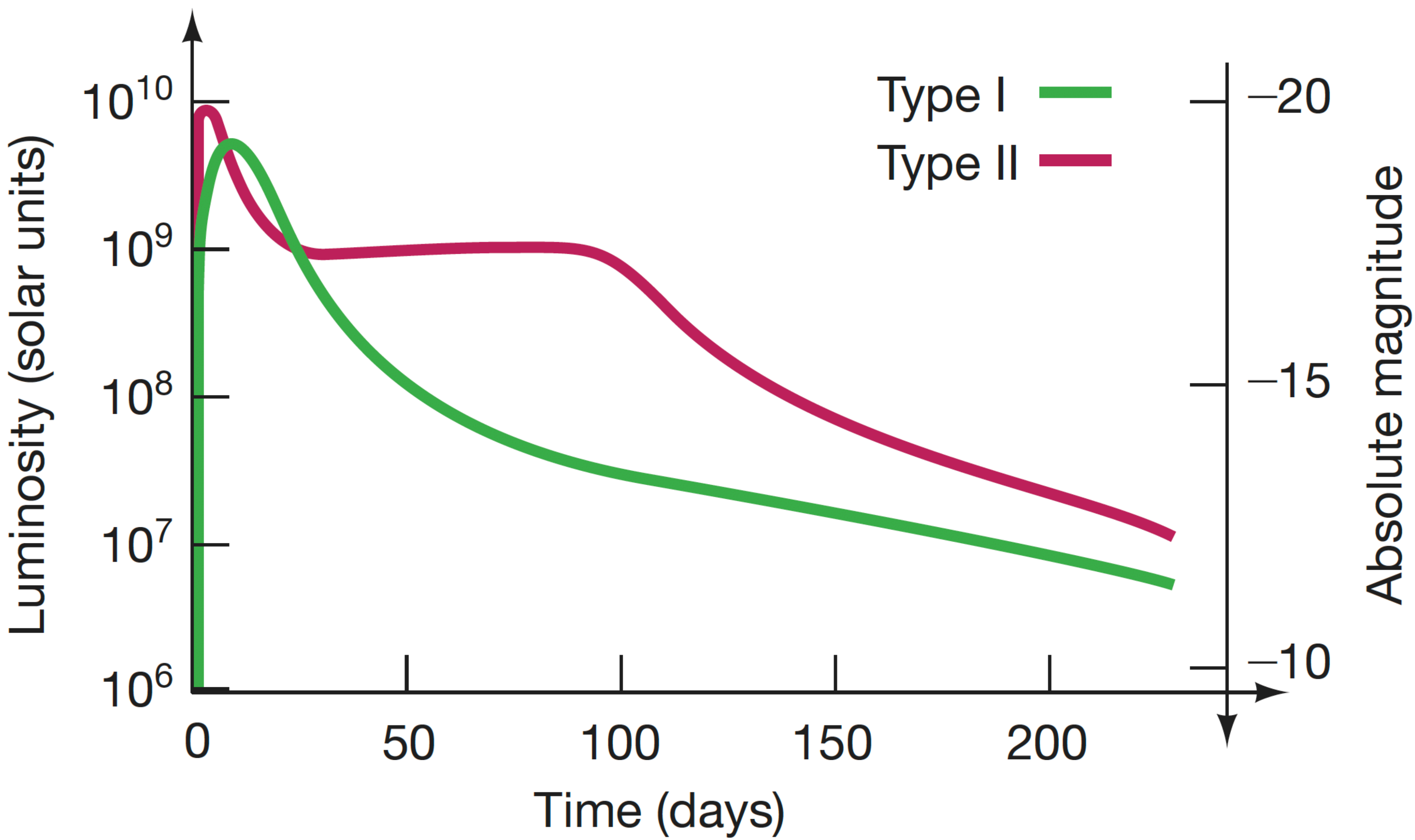
$$M_{ch} = 0.21 \left(\frac{Z}{A}\right)^2 \left(\frac{hc}{Gm_p^2}\right)^{3/2} m_p$$

$$= 5.6\ M_{\odot} \ \text{ for } \frac{Z}{A} \approx 1$$

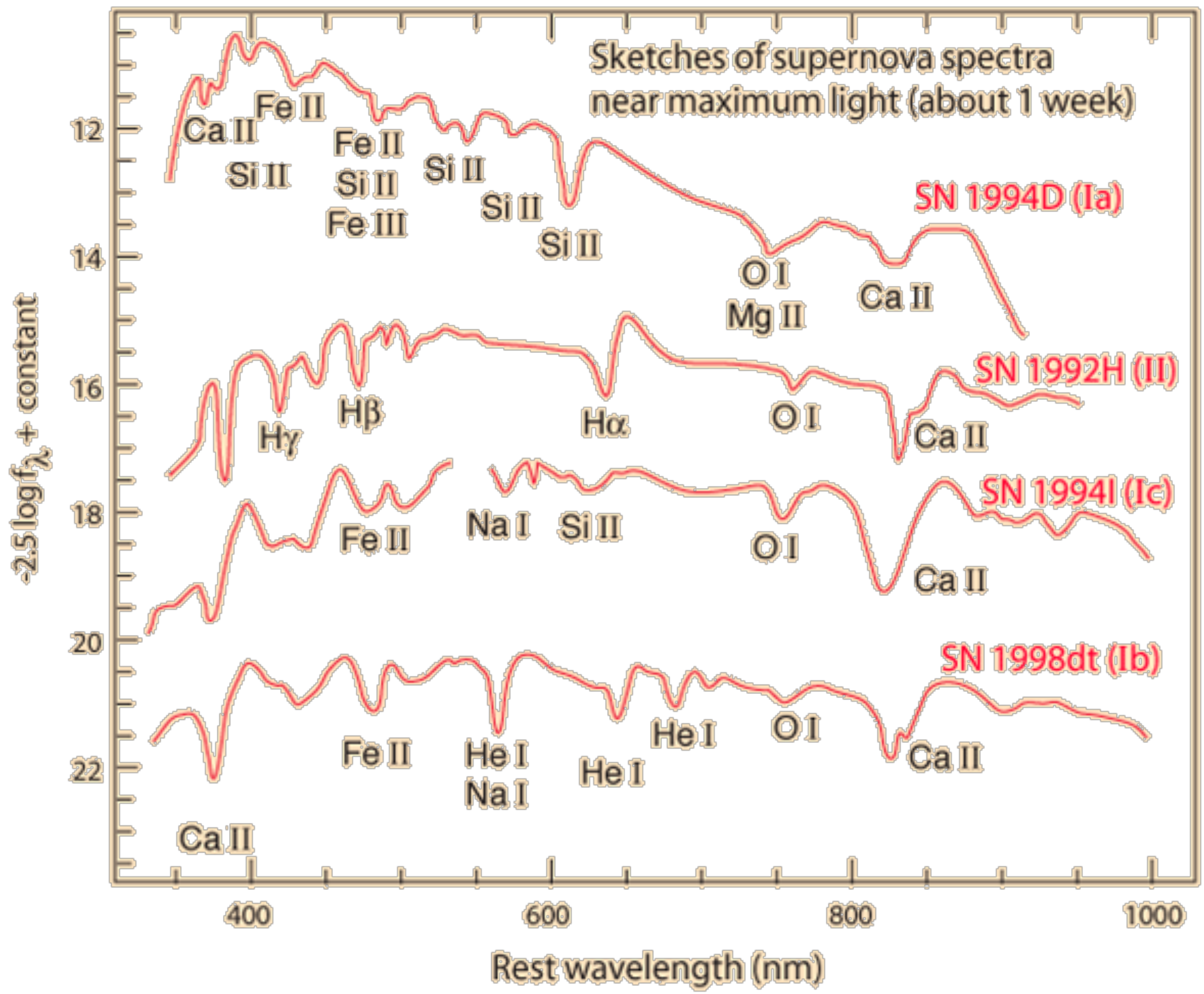


9
8
7
6
5
log(radius [cm])
−0.2
−0.1
0.0
0.1
0.2
0.3
0.4
time [s]
⟨R_shock⟩
{0.1, 1.3, 1.35} M_⊙
3.2
2.8
2.4
2.0
1.6
1.2
0.8
0.4
0.0
⟨√(v_θ² + v_φ²)⟩ [10^8 cm s^−1]

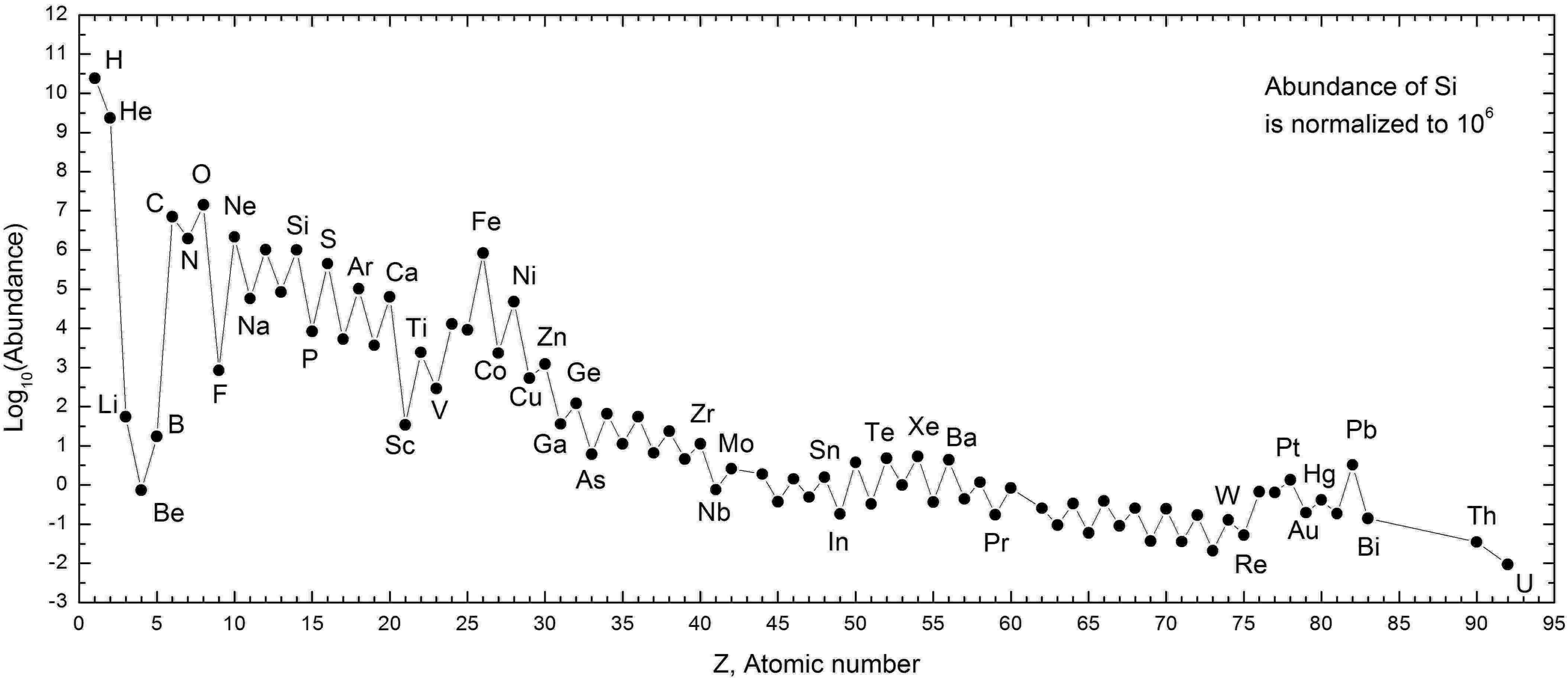

14 ms
Volume
Var: sto
6.365
5.321
4.277
3.233
2.189
Max: 6.997
Min: 0.9572
Z
X
Y
179 km

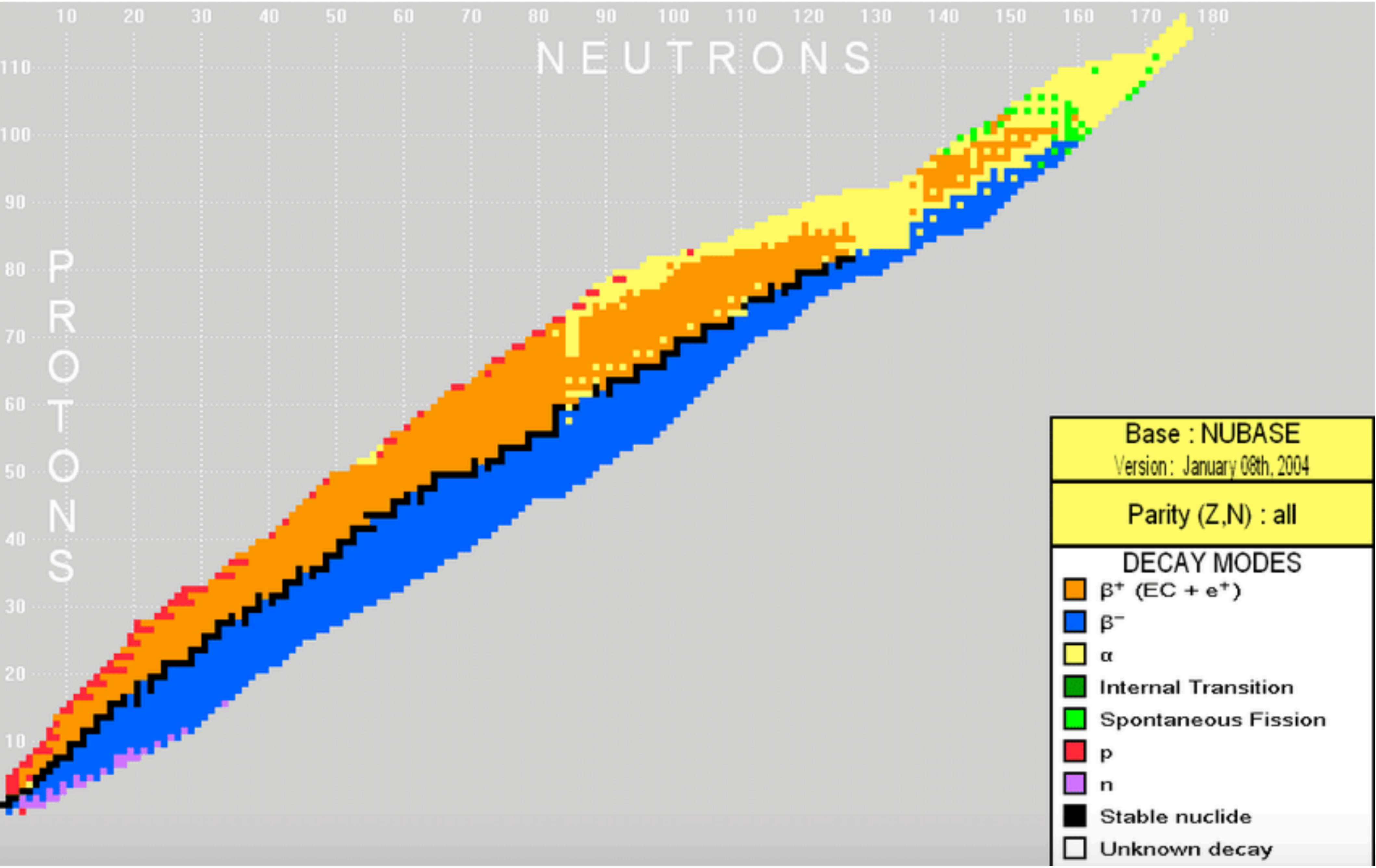


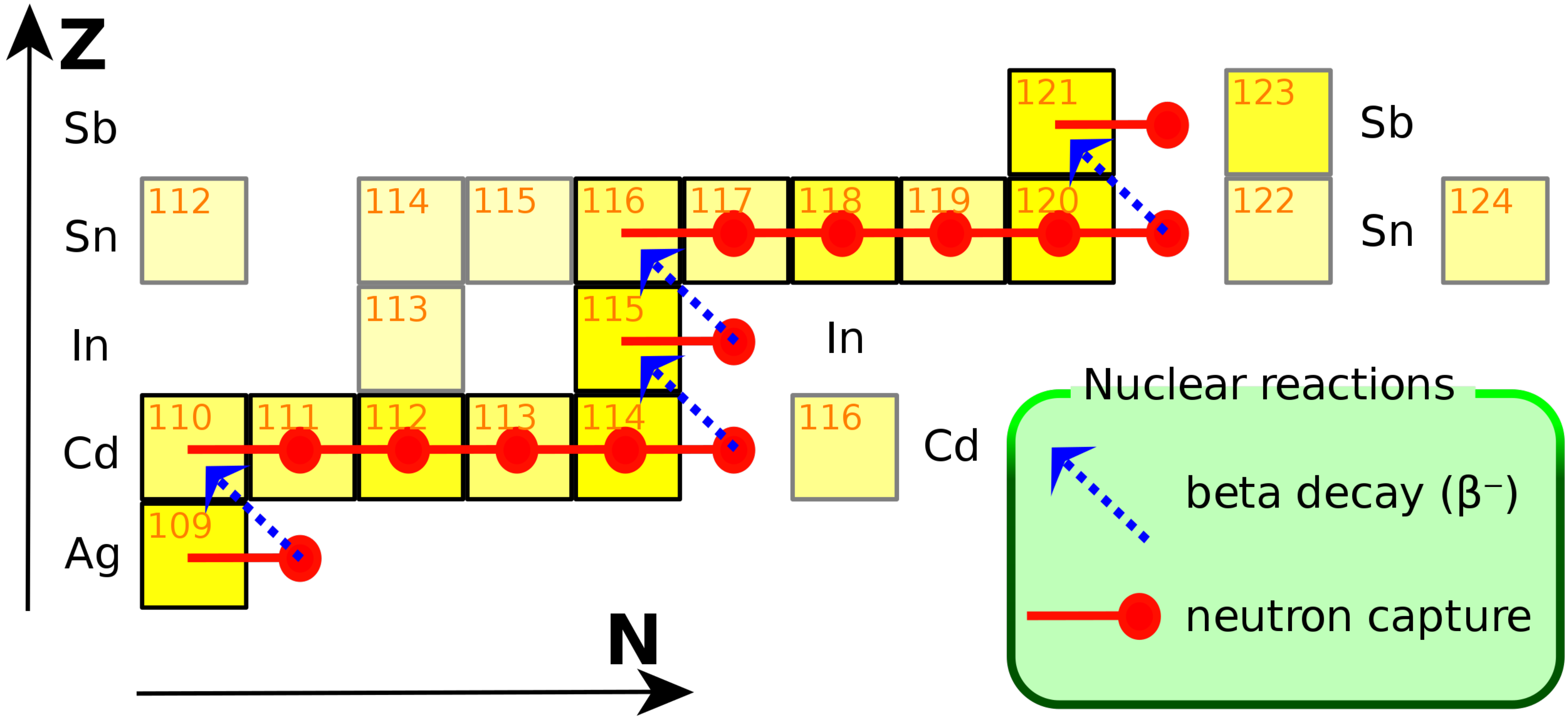
Luminosity (solar units)
10^{10}
10^{9}
10^{8}
10^{7}
10^{6}
Type I
Type II
–20
–15
–10
Absolute magnitude
0
50
100
150
200
Time (days)



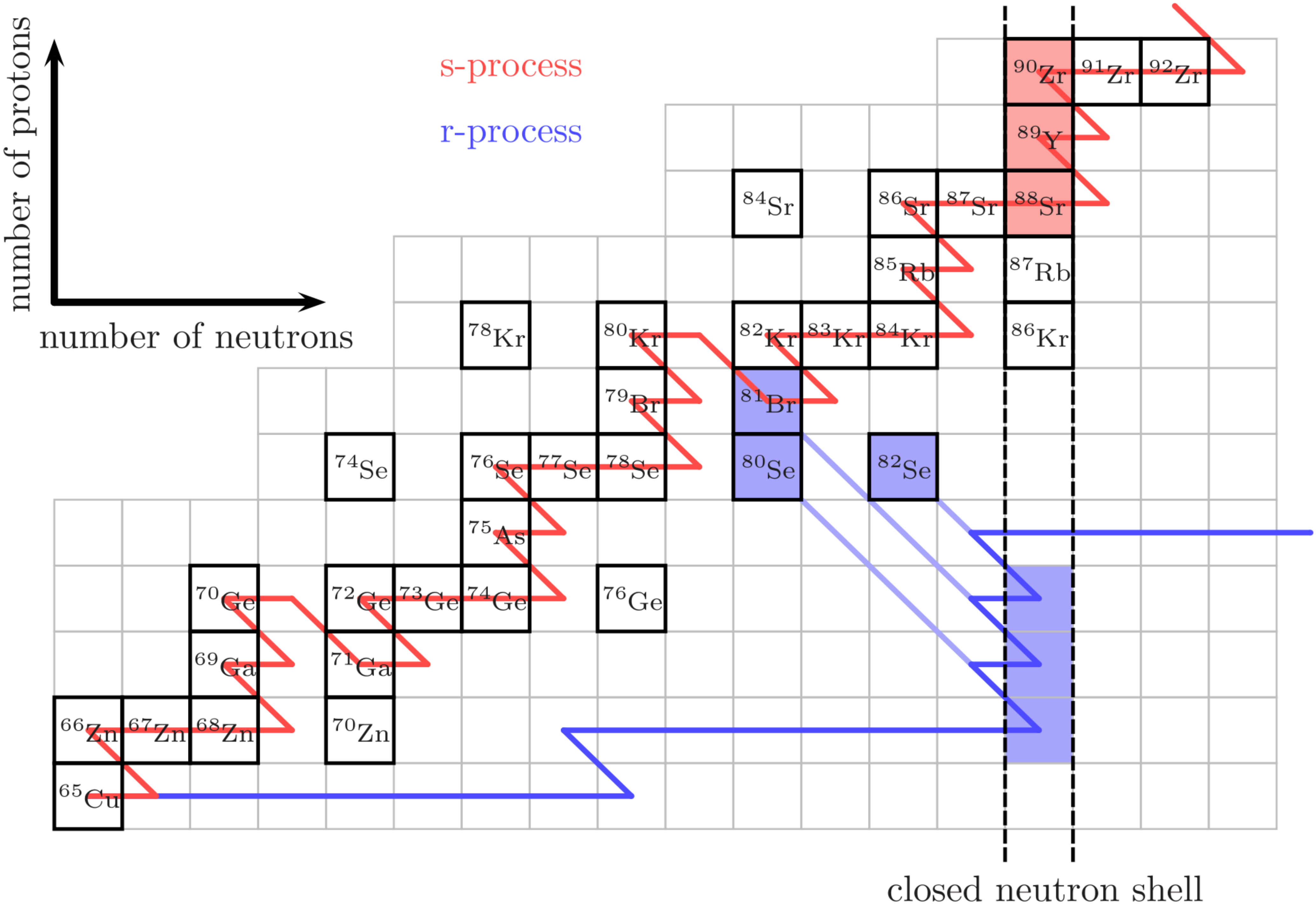
Sketches of spectra from Carroll & Ostlie, data attributed to Thomas Matheson of National Optical Astronomy Observatory.


Abundance of Si
is normalized to 10^6
Log10(Abundance)
Z, Atomic number
H
He
Li
Be
B
C
N
O
F
Ne
Na
Si
P
S
Ar
Ca
Sc
Ti
V
Fe
Co
Ni
Cu
Zn
Ga
Ge
As
Zr
Nb
Mo
Sn
In
Te
Xe
Ba
Pr
W
Re
Pt
Au
Hg
Pb
Bi
Th
U

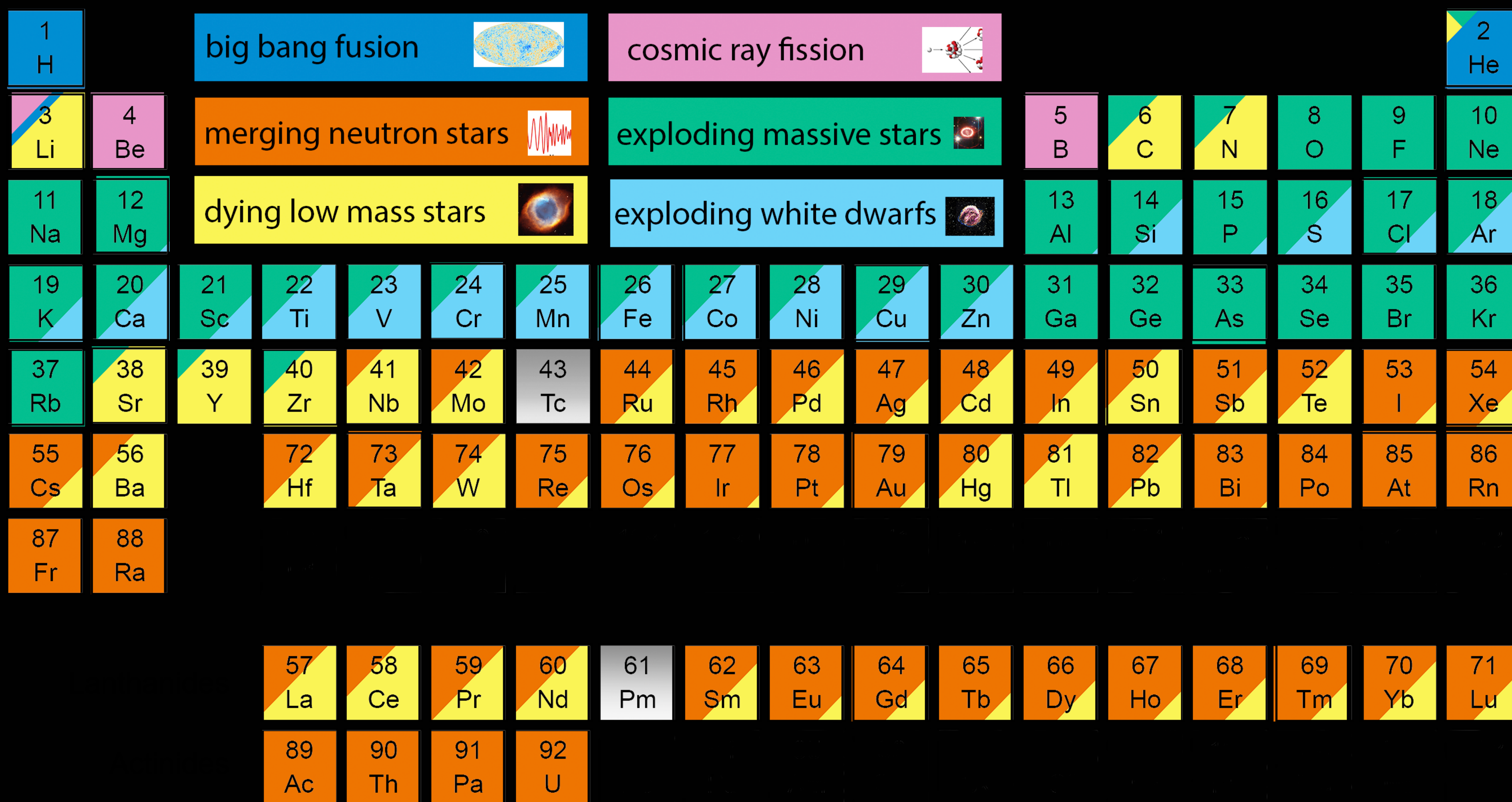

NEUTRONS
PROTONS
10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180
10 20 30 40 50 60 70 80 90 100 110
Base : NUBASE
Version : January 08th, 2004
Parity (Z,N) : all
DECAY MODES
β+ (EC + e+)
β−
α
Internal Transition
Spontaneous Fission
p
n
Stable nuclide
Unknown decay



Z
Sb
Sn
In
Cd
Ag
N
112
114
115
116
117
118
119
120
121
123
122
124
113
115
110
111
112
113
114
116
109
Sb
Sn
In
Cd
Nuclear reactions
beta decay (β⁻)
neutron capture

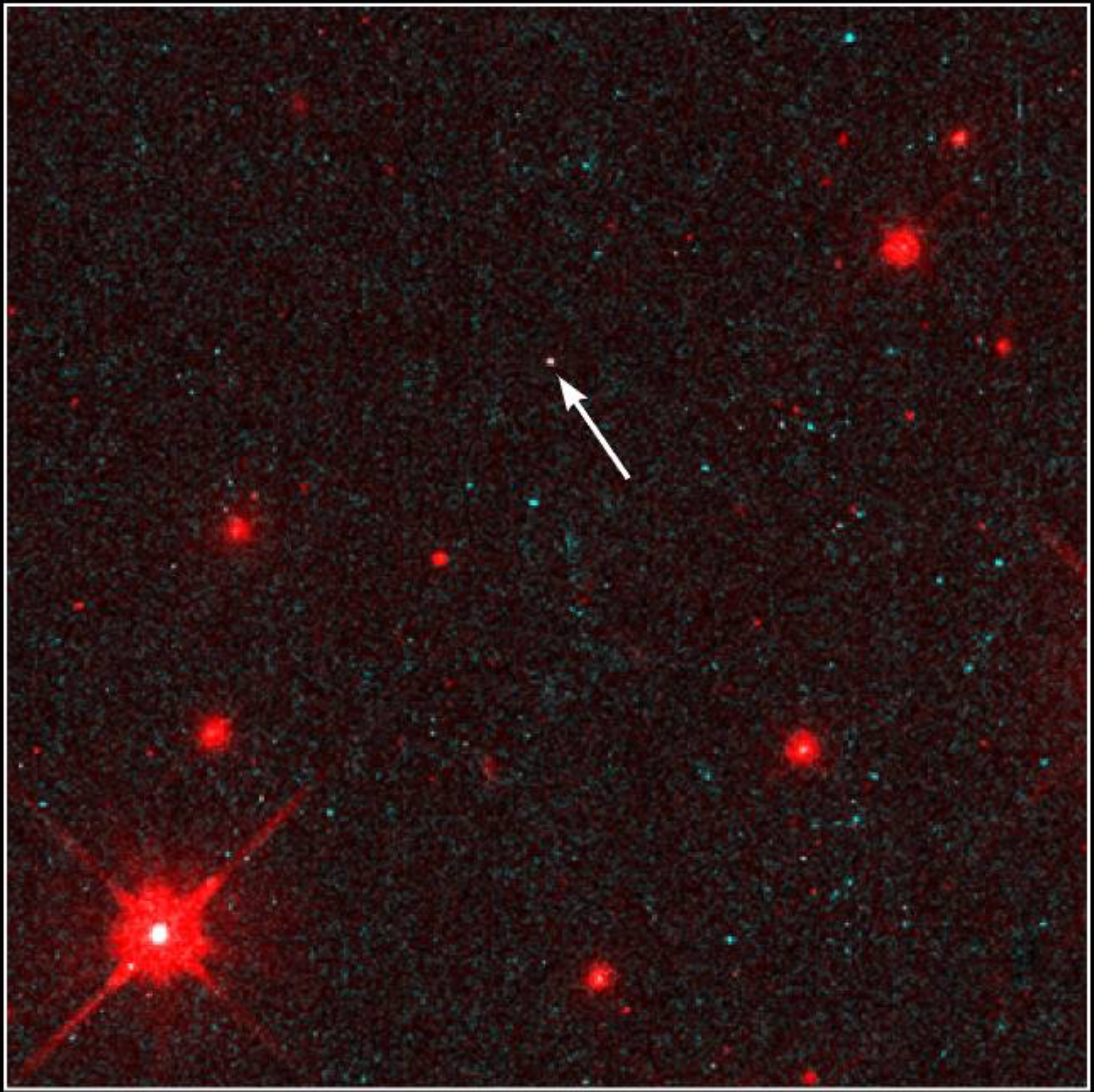

number of protons
number of neutrons
s-process
r-process
closed neutron shell
^{90}Zr
^{91}Zr
^{92}Zr
^{89}Y
^{84}Sr
^{86}Sr
^{87}Sr
^{88}Sr
^{85}Rb
^{87}Rb
^{78}Kr
^{80}Kr
^{82}Kr
^{83}Kr
^{84}Kr
^{86}Kr
^{79}Br
^{81}Br
^{74}Se
^{76}Se
^{77}Se
^{78}Se
^{80}Se
^{82}Se
^{75}As
^{70}Ge
^{72}Ge
^{73}Ge
^{74}Ge
^{76}Ge
^{69}Ga
^{71}Ga
^{66}Zn
^{67}Zn
^{68}Zn
^{70}Zn
^{65}Cu

The Origin of the Solar System Elements



Astronomical Image Credits:
ESA/NASA/AASNova

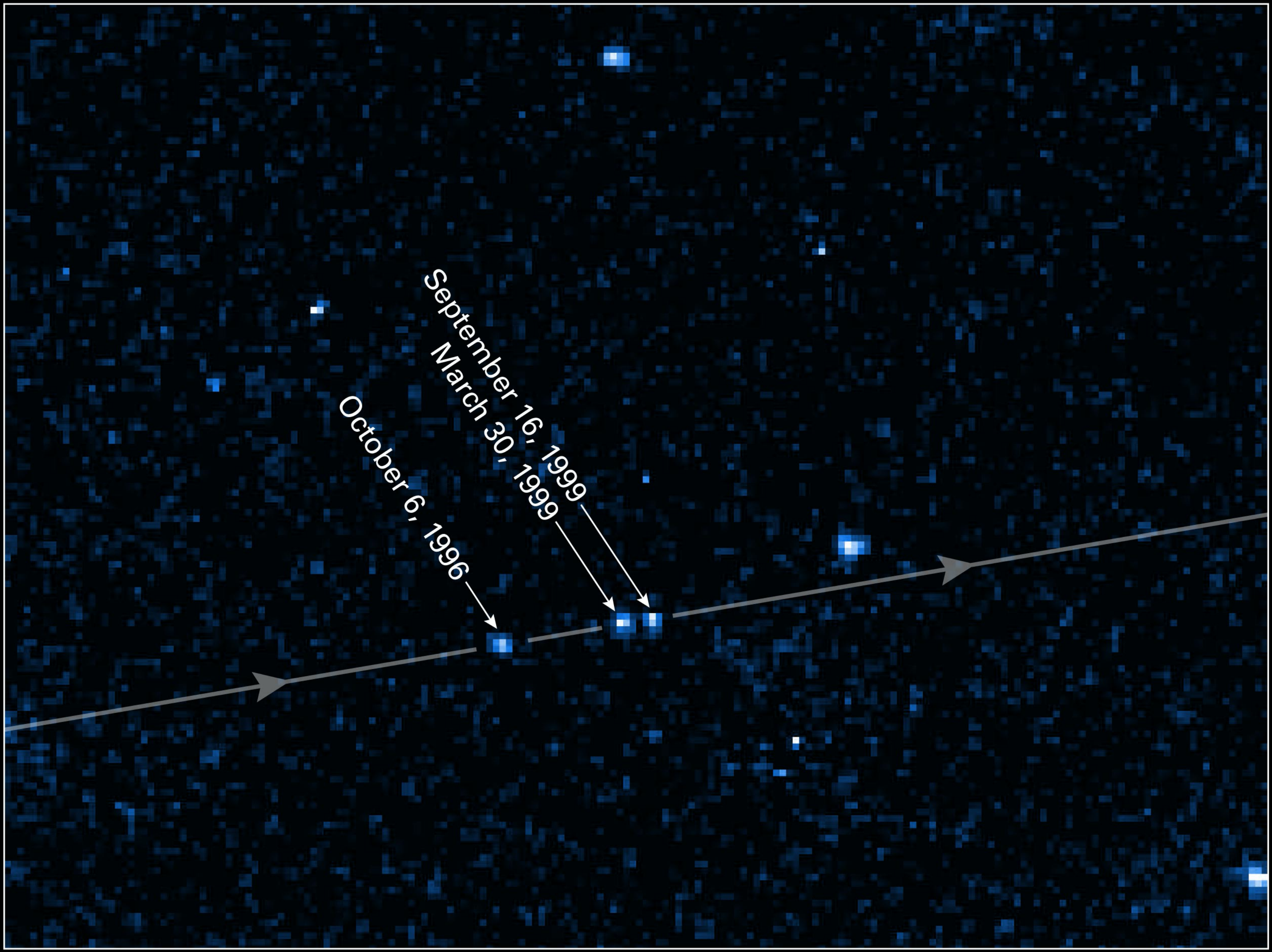
Graphic created by Jennifer Johnson



Isolated Neutron Star RX J185635-3754 HST • WFPC2

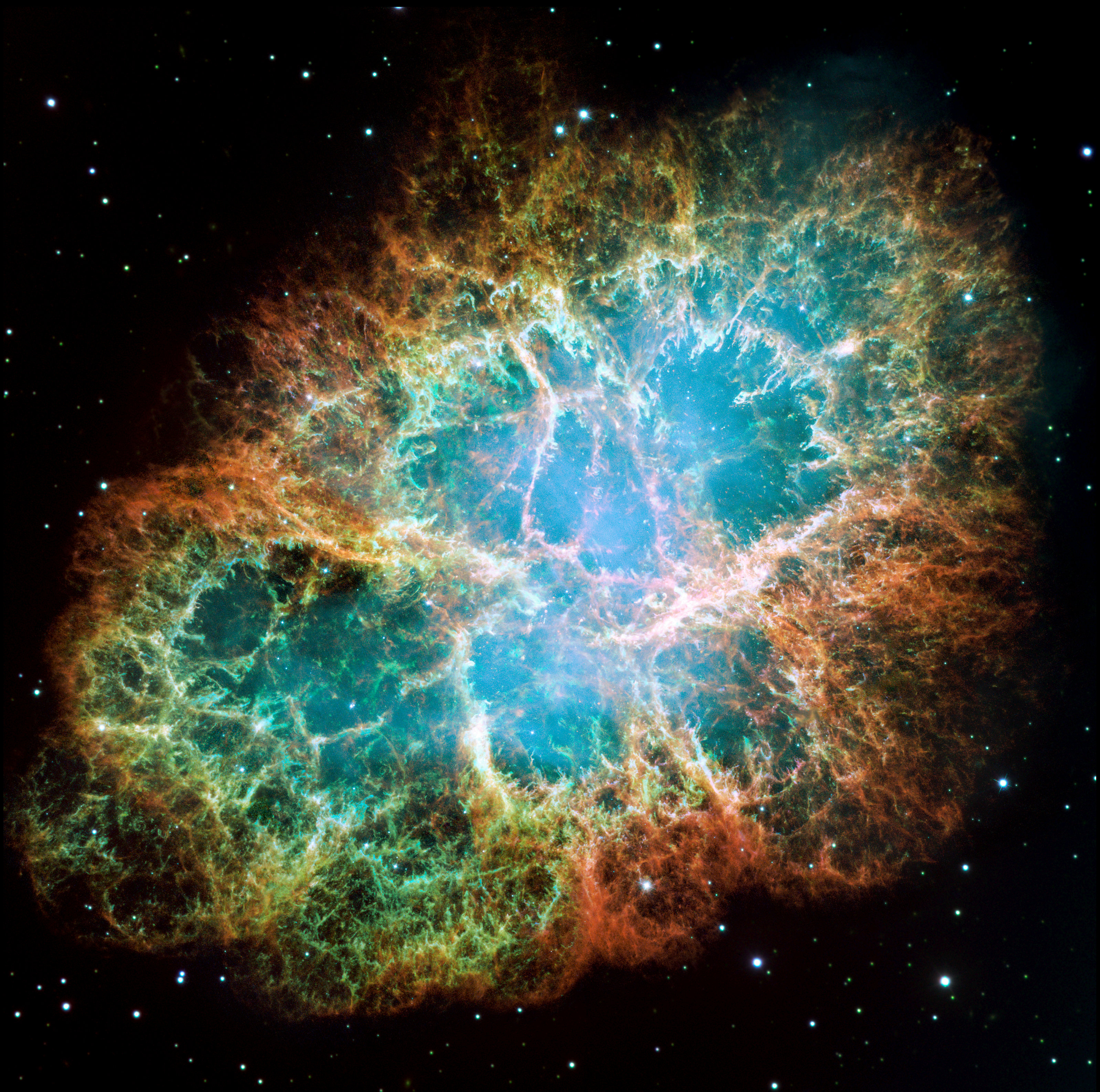
PRC97-32 • ST ScI OPO • September 25, 1997

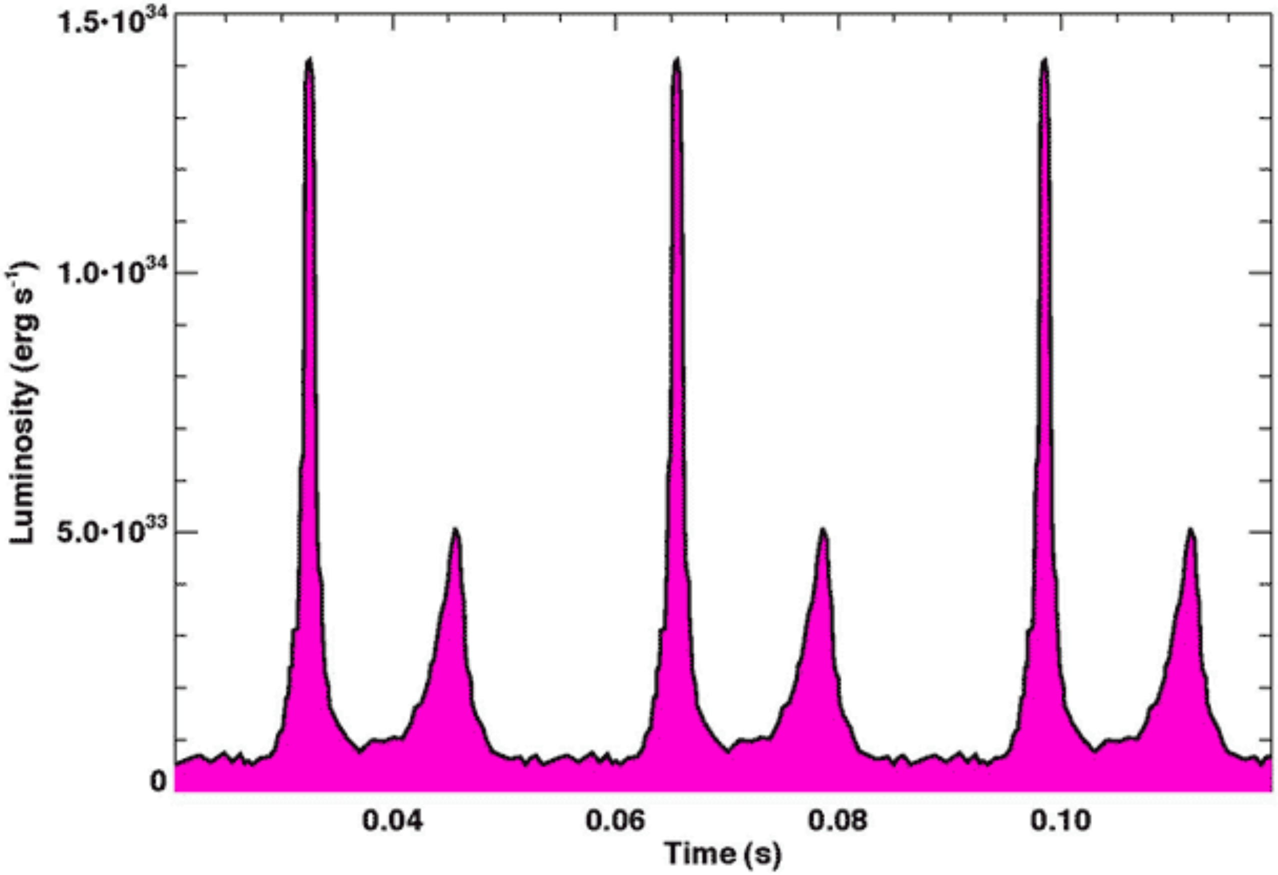
F. Walter (State University of New York at Stony Brook) and NASA



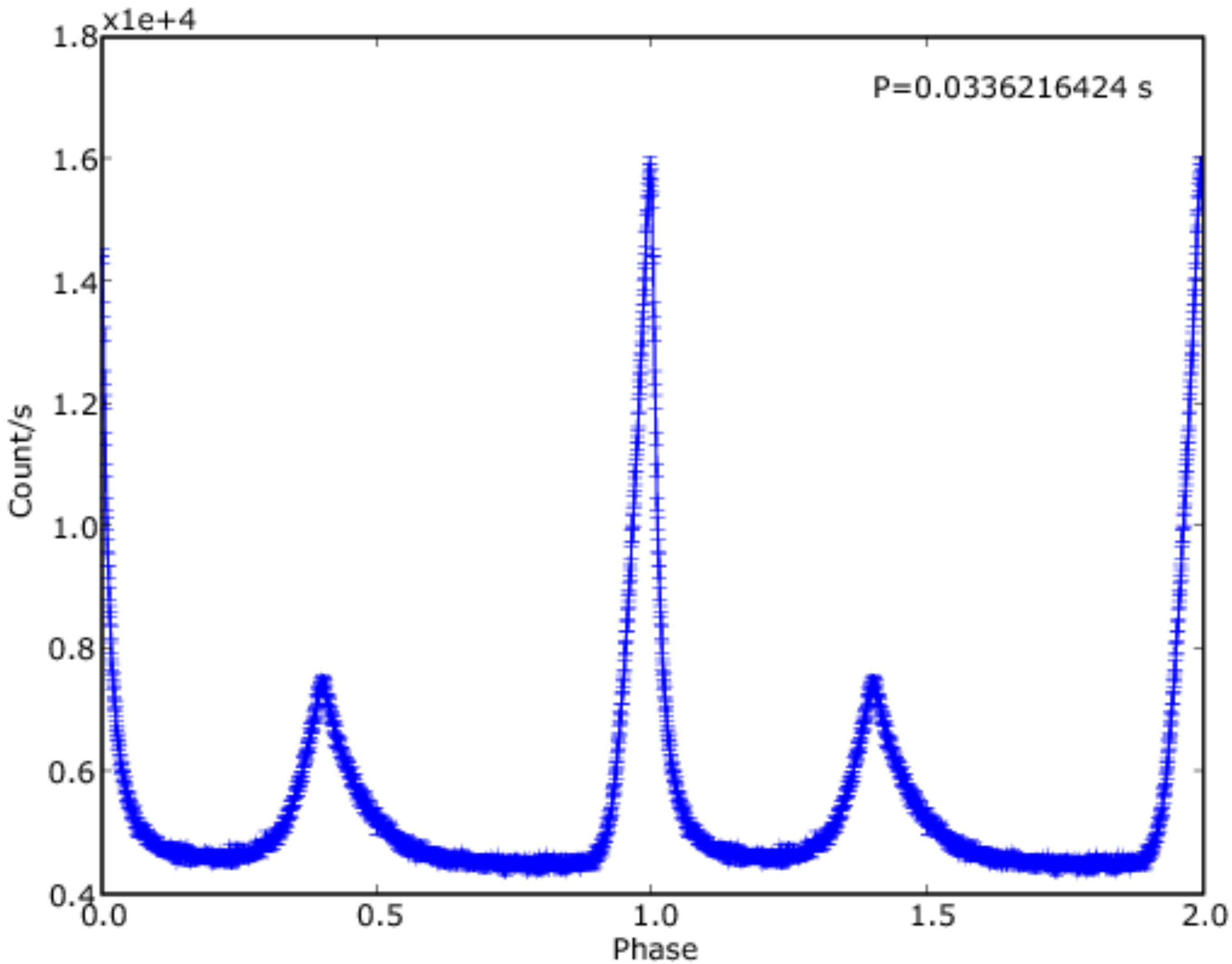
Neutron Star RX J185635-3754
Hubble Space Telescope • WFPC2

NASA and F. Walter (State University of New York at Stony Brook) • STScI-PRC00-35





1.5·10^34
1.0·10^34
5.0·10^33
0
Luminosity (erg s^-1)
0.04
0.06
0.08
0.10
Time (s)



x1e+4
P=0.0336216424 s
Count/s
Phase
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.0
0.5
1.0
1.5
2.0

Neutron Star Properties

- mass and radius

$$M \sim 1.4\, M_{\odot}, \quad R \sim 10 \text{ km}$$

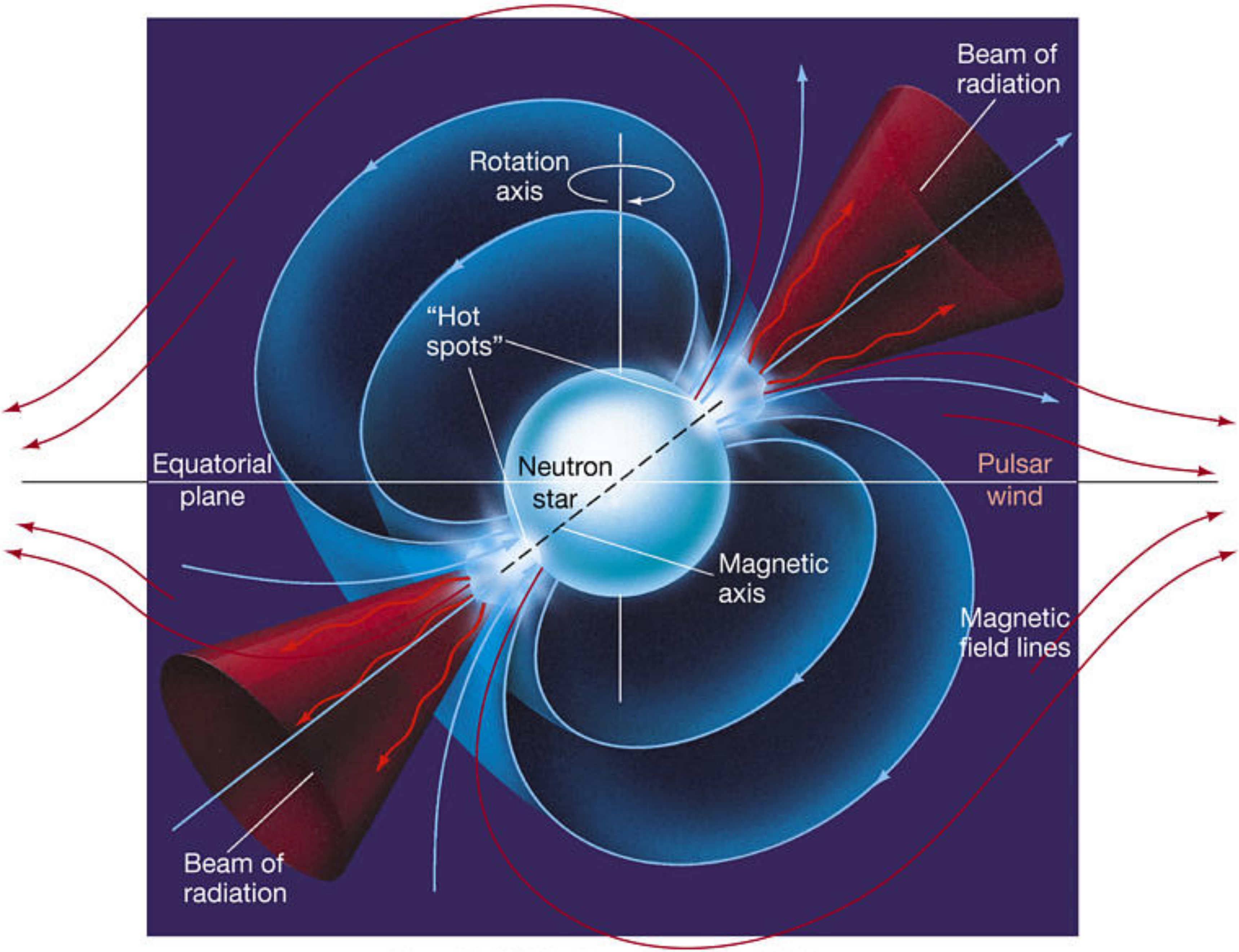
- rotation rate

$$\Omega \sim R^{-2} \rightarrow 1 - 1000 \text{ rad s}^{-1}$$

$$\frac{d\tau}{dt} \sim 10^{-13}$$

- magnetic field

$$B \sim R^{-2} \rightarrow > 10^{12} \text{ G} \quad (10^{8} \text{ T})$$


Beam of radiation
Rotation axis
"Hot spots"
Equatorial plane
Neutron star
Pulsar wind
Magnetic axis
Magnetic field lines
Beam of radiation

Neutron Star Properties

- mass and radius

$$M \sim 1.4\, M_{\odot}, \quad R \sim 10 \text{ km}$$

- rotation rate

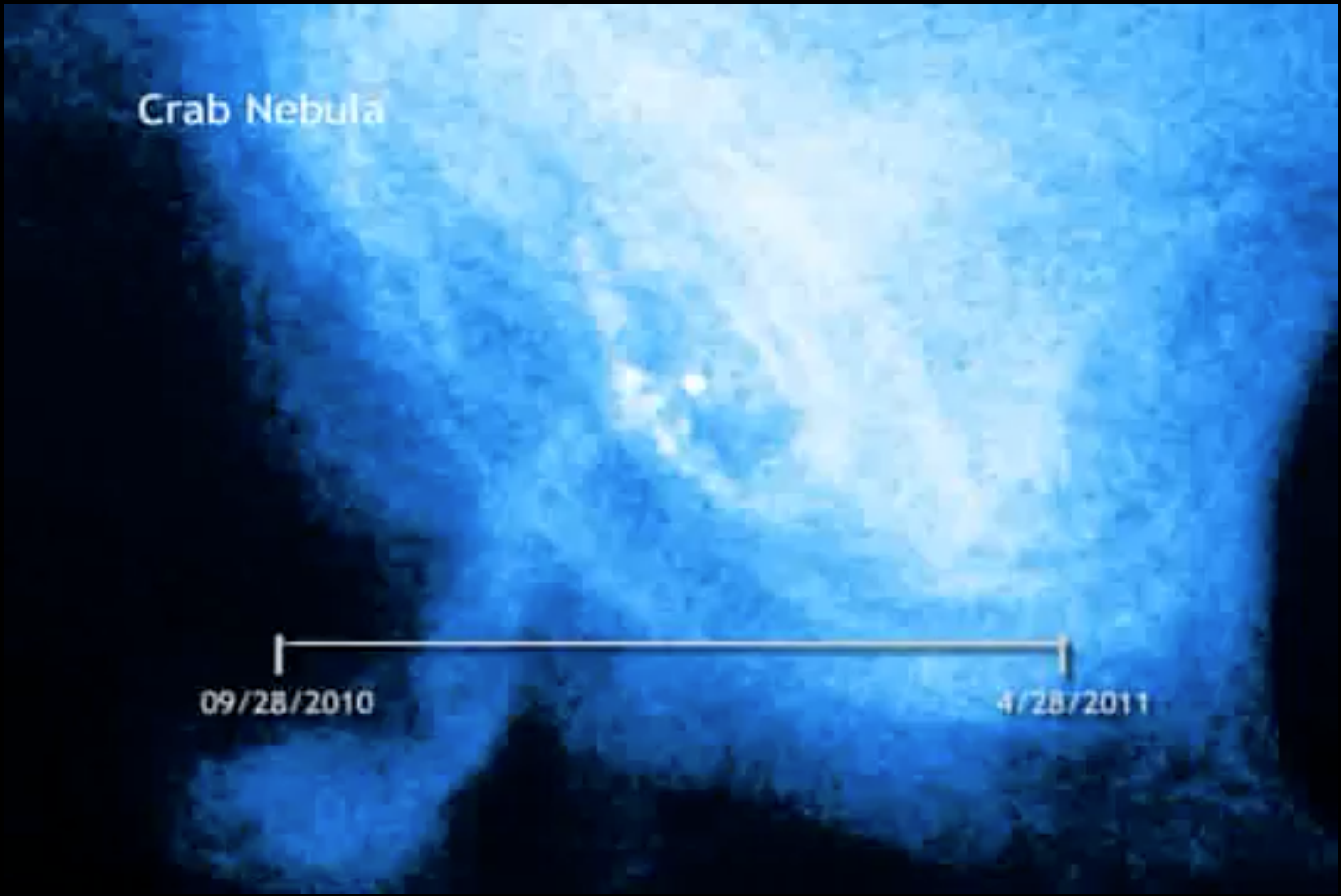
$$\Omega \sim R^{-2} \quad \rightarrow \quad 1 - 1000 \text{ rad s}^{-1}$$

$$\frac{d\tau}{dt} \sim 10^{-13}$$

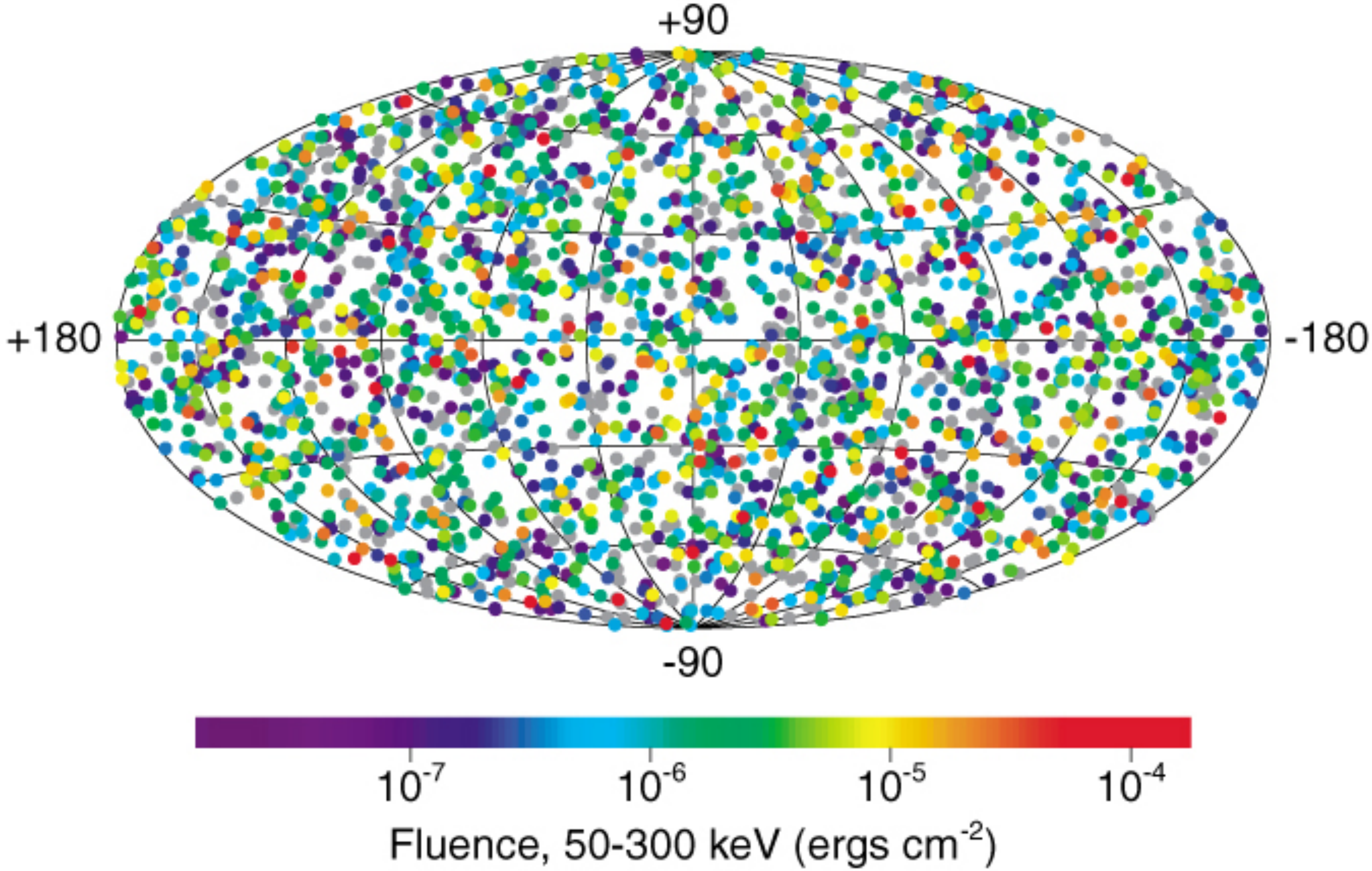
$$L = \frac{1}{6c^3} B^2 R^2 \Omega^4 \sin^2 \theta$$

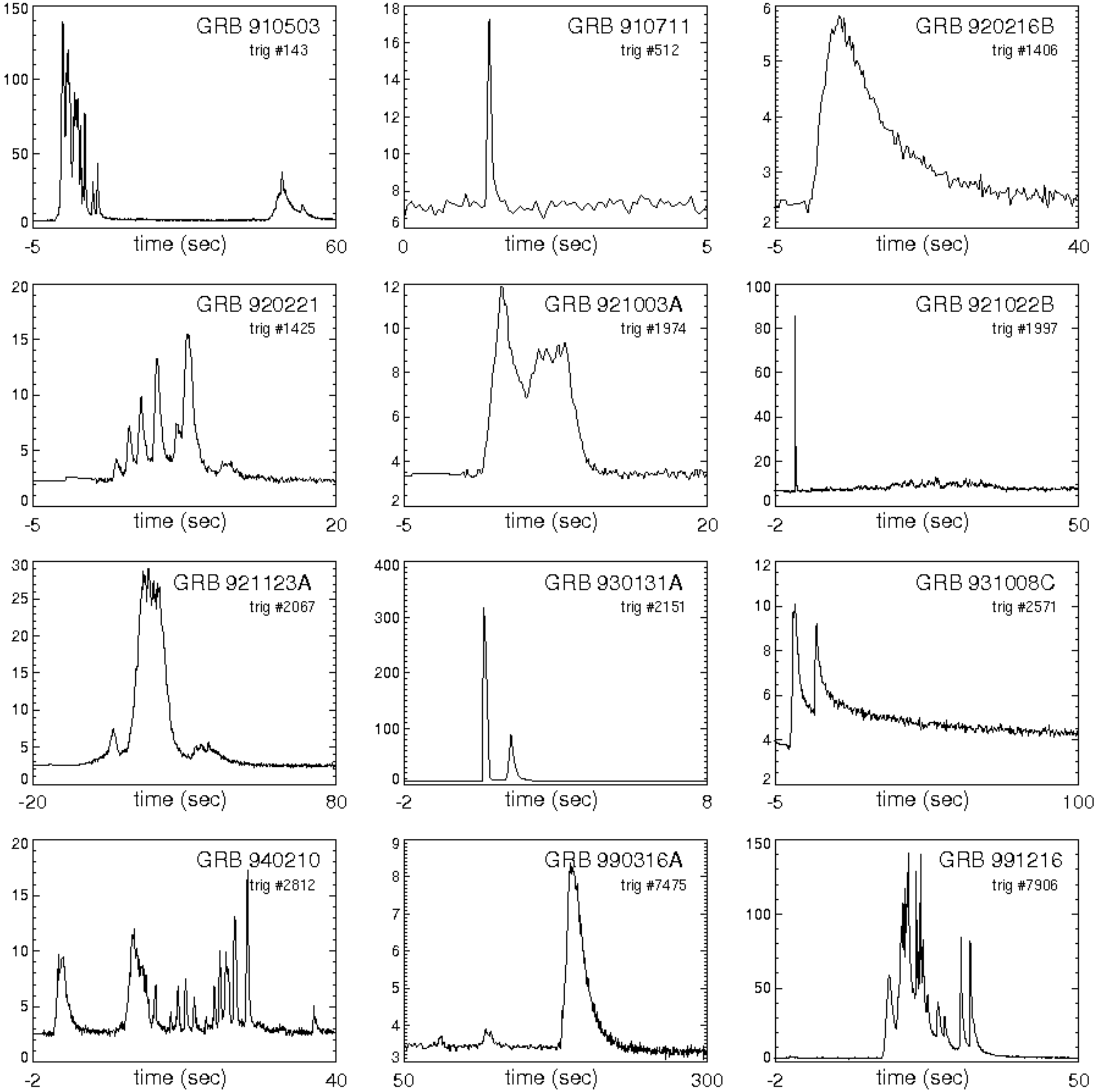
- magnetic field

$$B \sim R^{-2} \quad \rightarrow > 10^{12} \text{ G} \quad (10^8 \text{ T})$$

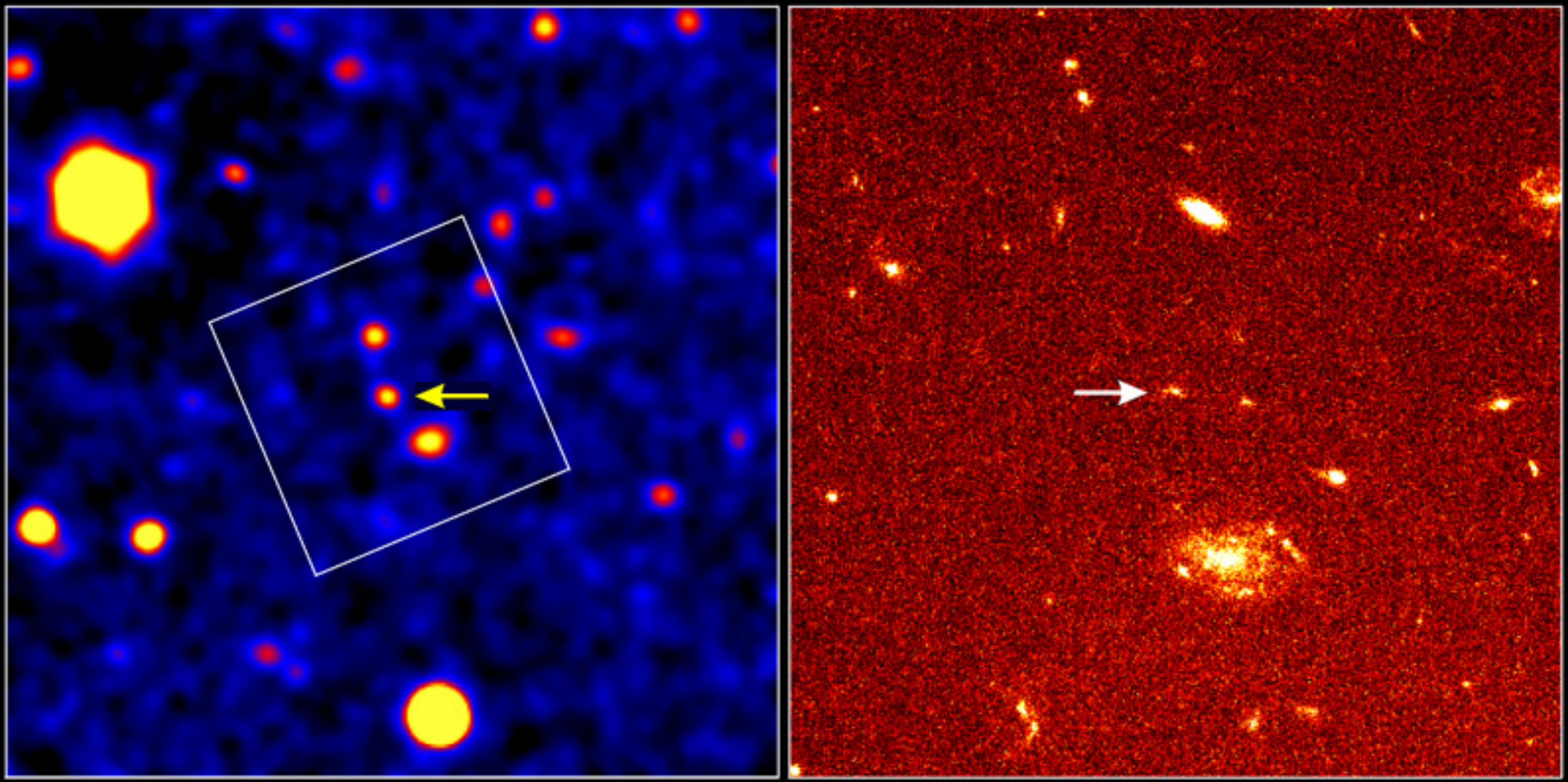

Crab Nebula
09/28/2010
4/28/2011

2704 BATSE Gamma-Ray Bursts




GRB 910503
trig #143
time (sec)
GRB 910711
trig #512
time (sec)
GRB 920216B
trig #1406
time (sec)
GRB 920221
trig #1425
time (sec)
GRB 921003A
trig #1974
time (sec)
GRB 921022B
trig #1997
time (sec)
GRB 921123A
trig #2067
time (sec)
GRB 930131A
trig #2151
time (sec)
GRB 931008C
trig #2571
time (sec)
GRB 940210
trig #2812
time (sec)
GRB 990316A
trig #7475
time (sec)
GRB 991216
trig #7906
time (sec)

Gamma Ray Burst 971214



Keck • December 1997

HST/STIS • February 1998

PRC98-17c • May 7, 1998 • ST ScI OPO
S. G. Djorgovski and S. R. Kulkarni (Caltech), the Caltech GRB Team,
W. M. Keck Observatory and NASA

Gamma-Ray Bursts (GRBs): The Long and Short of It