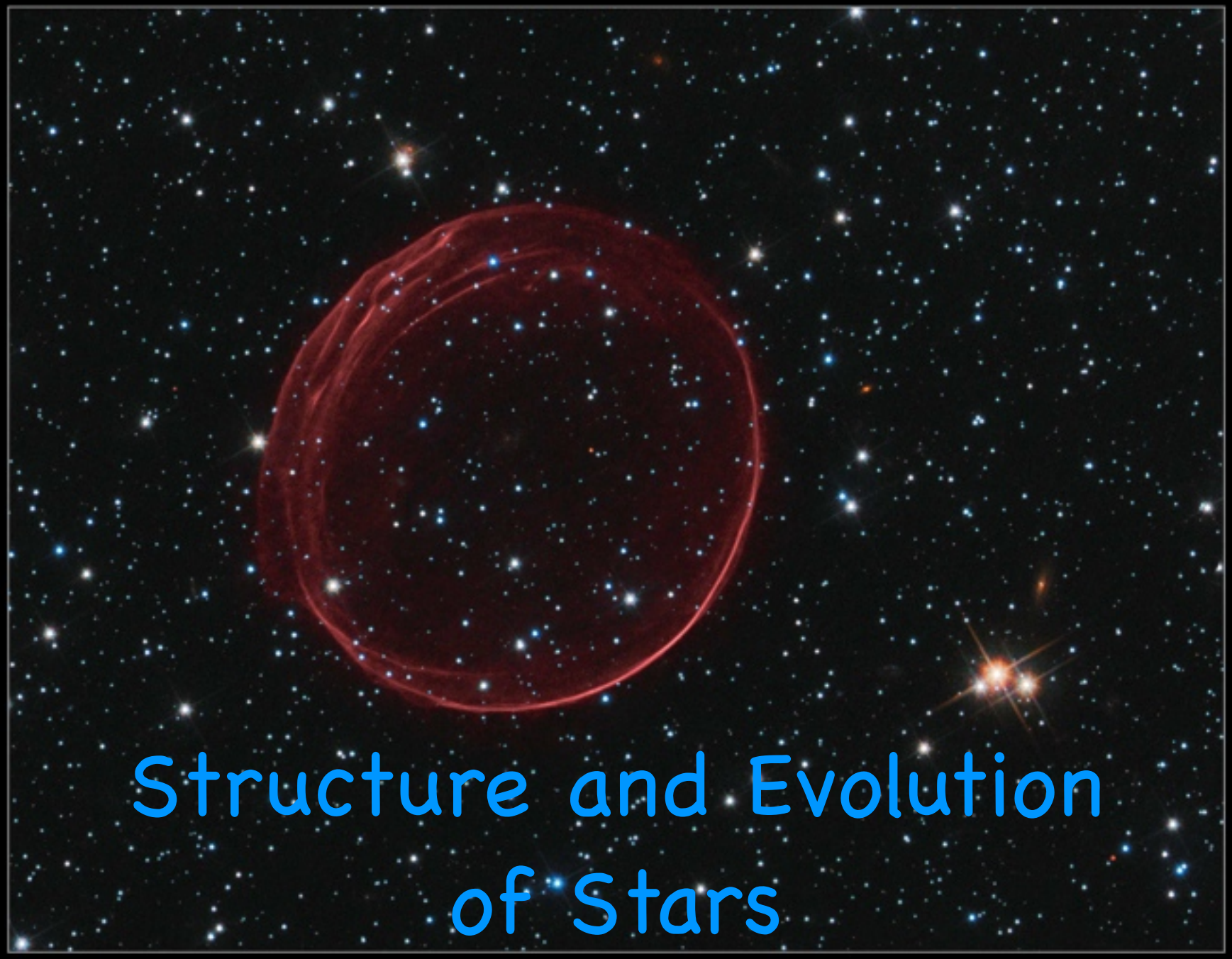
Supernova Remnant 0509-67.5



# Structure and Evolution of Stars

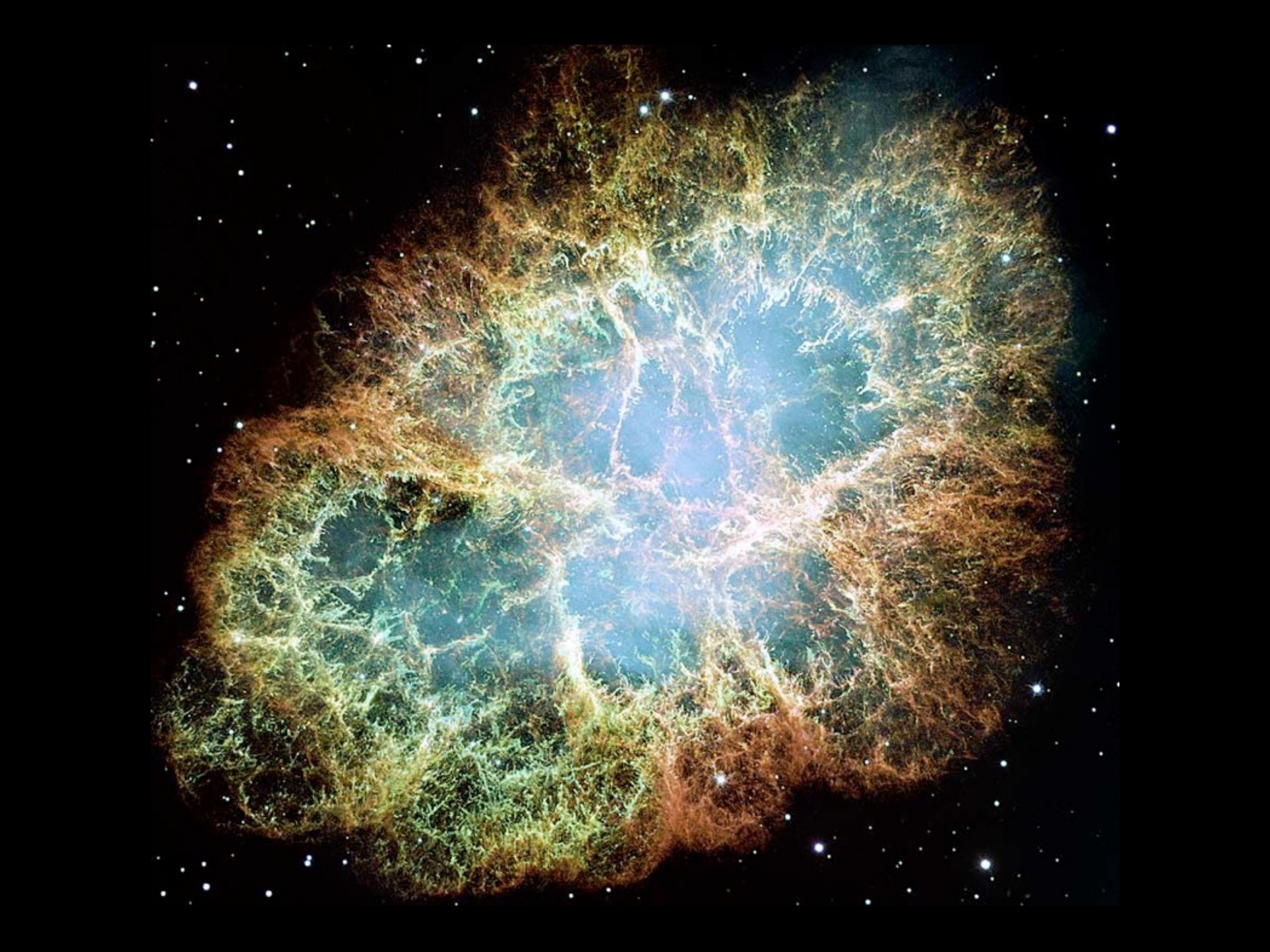
## Lecture 16

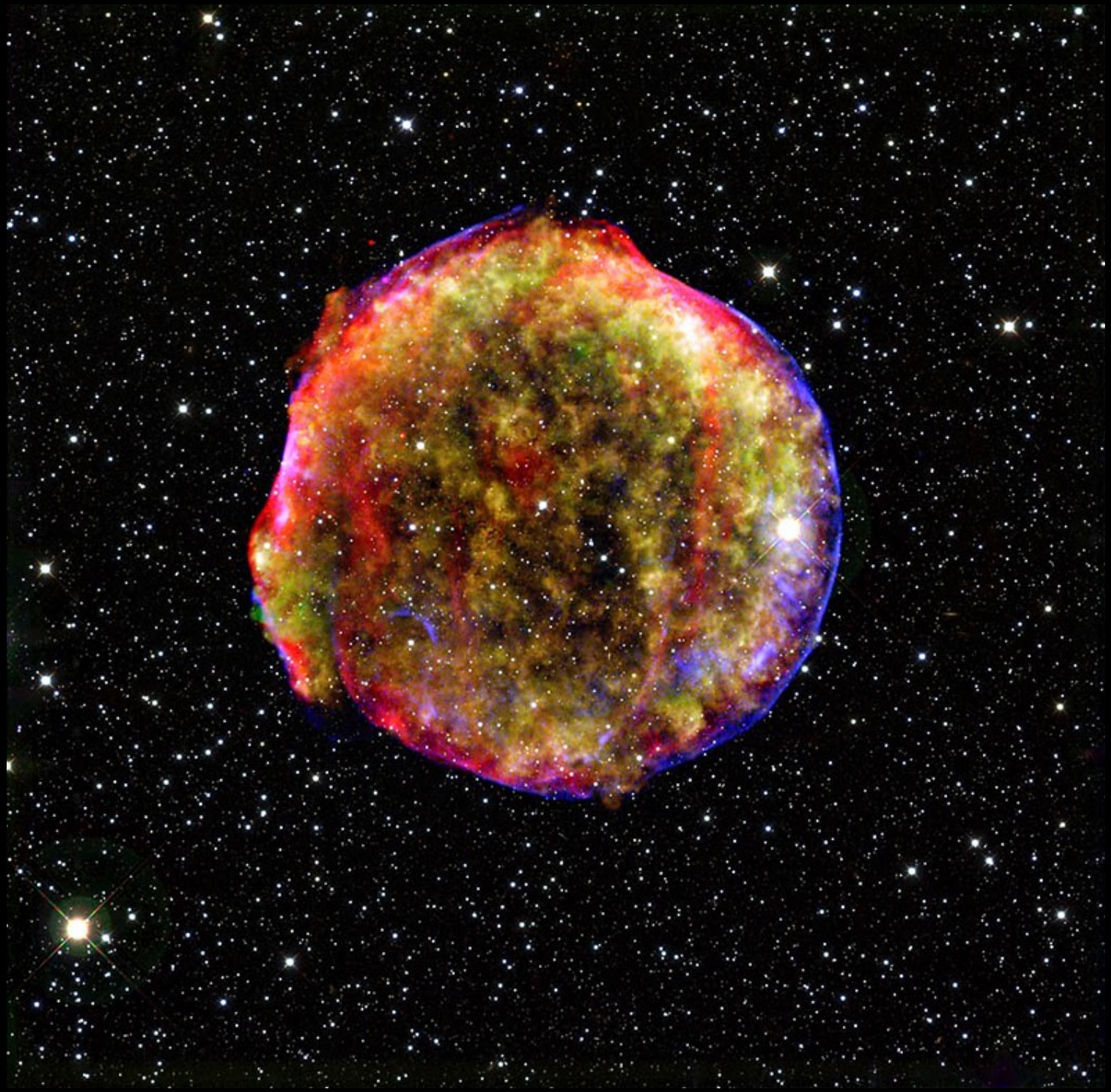
Hubble Heritage

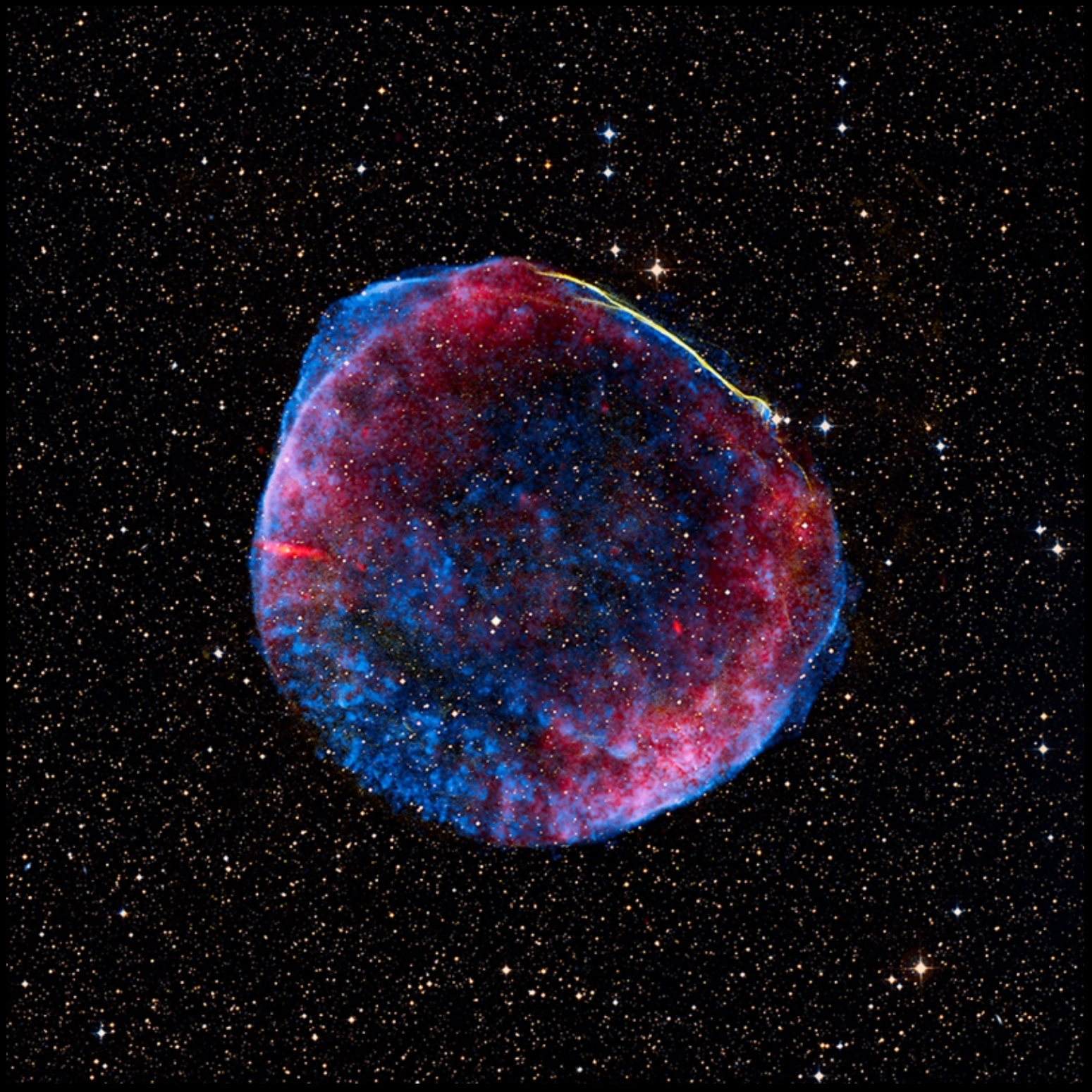

2005ed
2005ef
2005ei
2005ez
2005fa
2005fd
2005ff
2005fv
2005gj
2005hc
2005ij
2005ir
2005js
2005ku
2005lk
2006fs
2006gf
2006hr
2006hx
2006jz
2006kd
2006ne
2006nz
2006ob
2007jh
2007jt
2007jw
2007la
2007lr
2007mi
2007mn
2007ol
2007om
2007pd
2007rs
2007sn

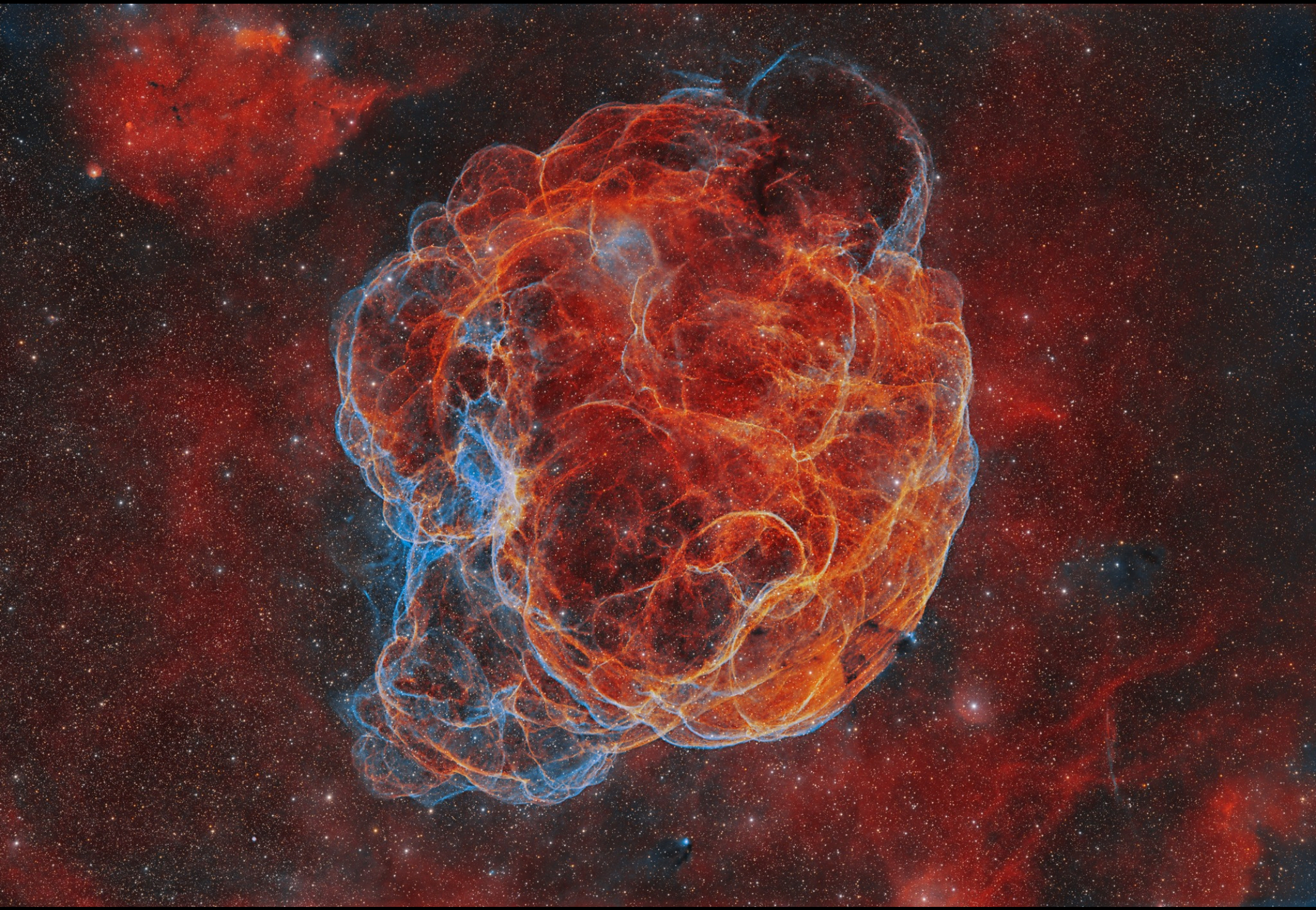
**Table 16.1.** Historical supernovae.

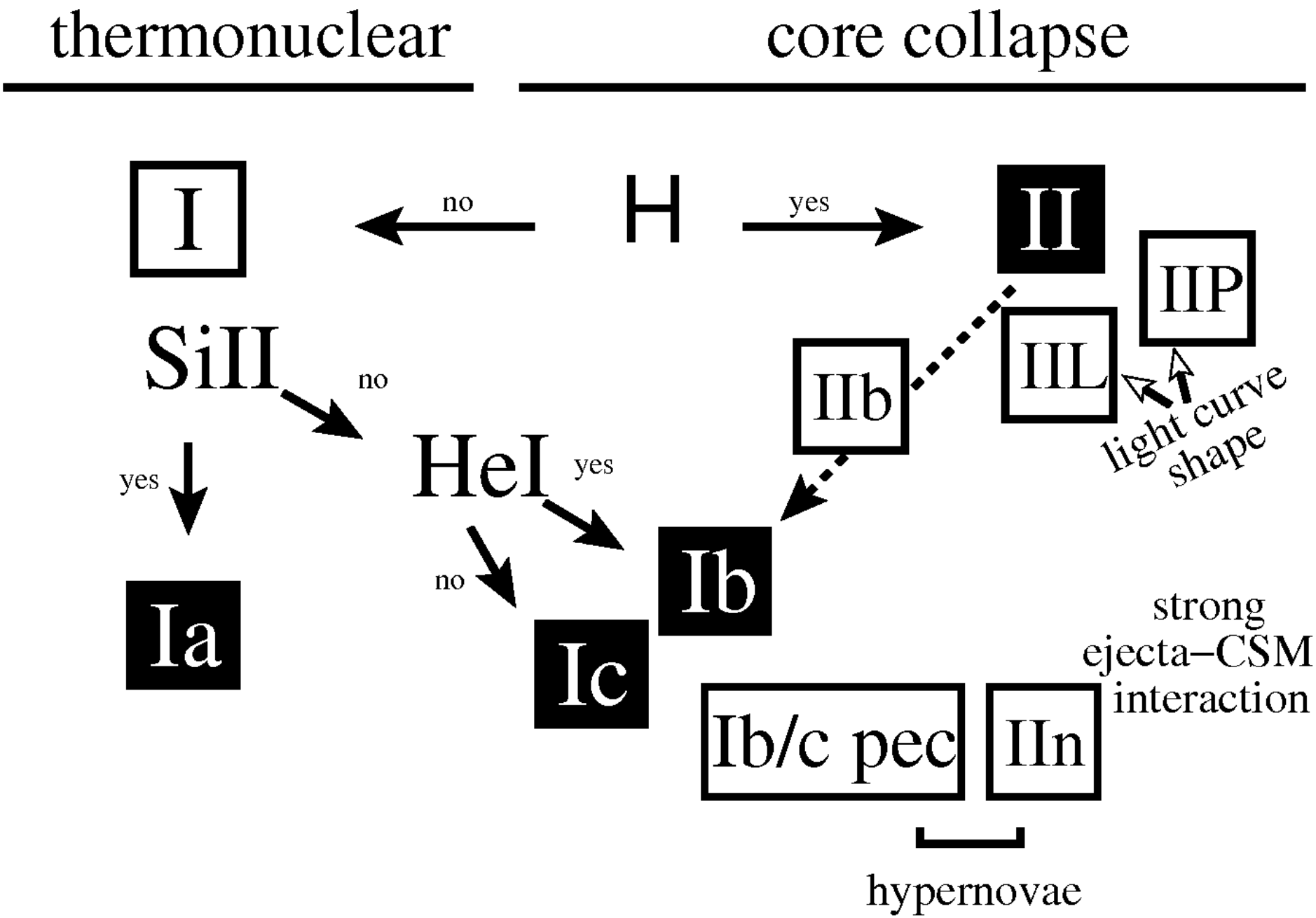
| year (AD) | $V$ (peak) | SN remnant | SN type | compact object |
|---|---|---|---|---|
| 185 | −2 | RCW 86 | Ia? | – |
| 386 | | ? | ? | |
| 393 | −3 | ? | ? | |
| 1006 | −9 | PKS 1459-41 | Ia? | – |
| 1054 | −6 | Crab nebula | II | NS (pulsar) |
| 1181 | −1 | 3C 58 | II | NS (pulsar) |
| 1572 | −4 | 'Tycho' | Ia | – |
| 1604 | −3 | 'Kepler' | Ia? | – |
| ∼1667 | $\gtrsim$+6 | Cas A | IIb | NS |



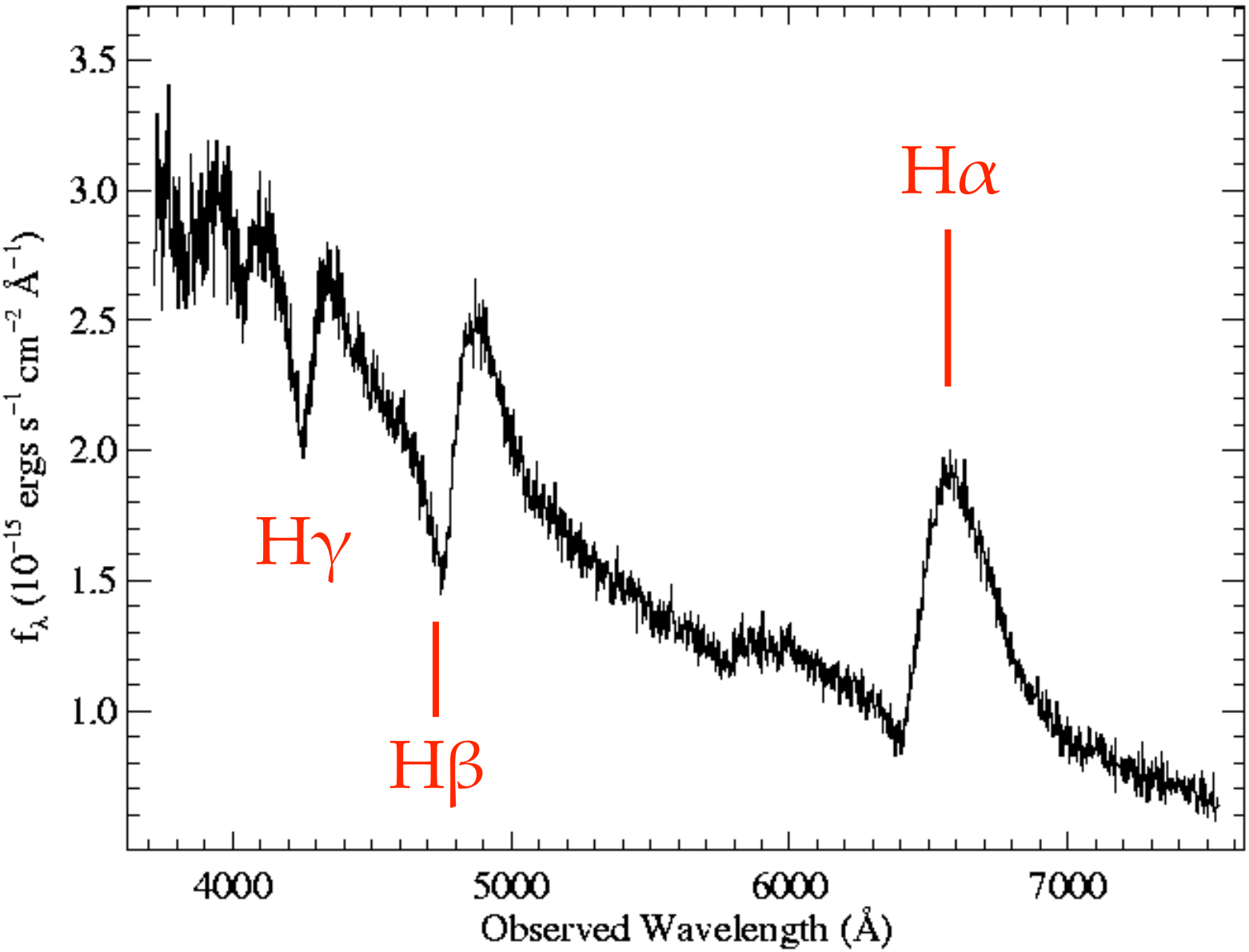




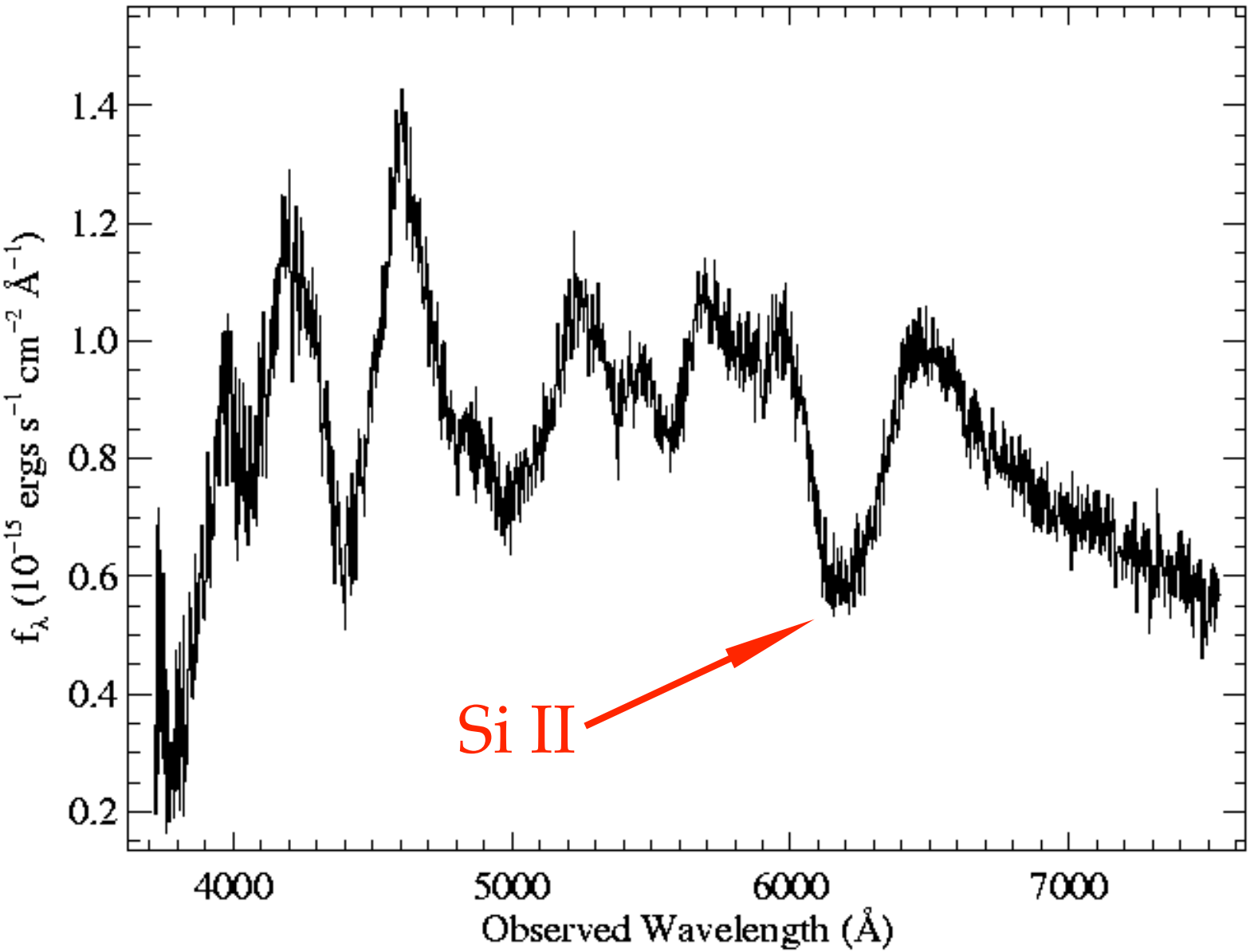


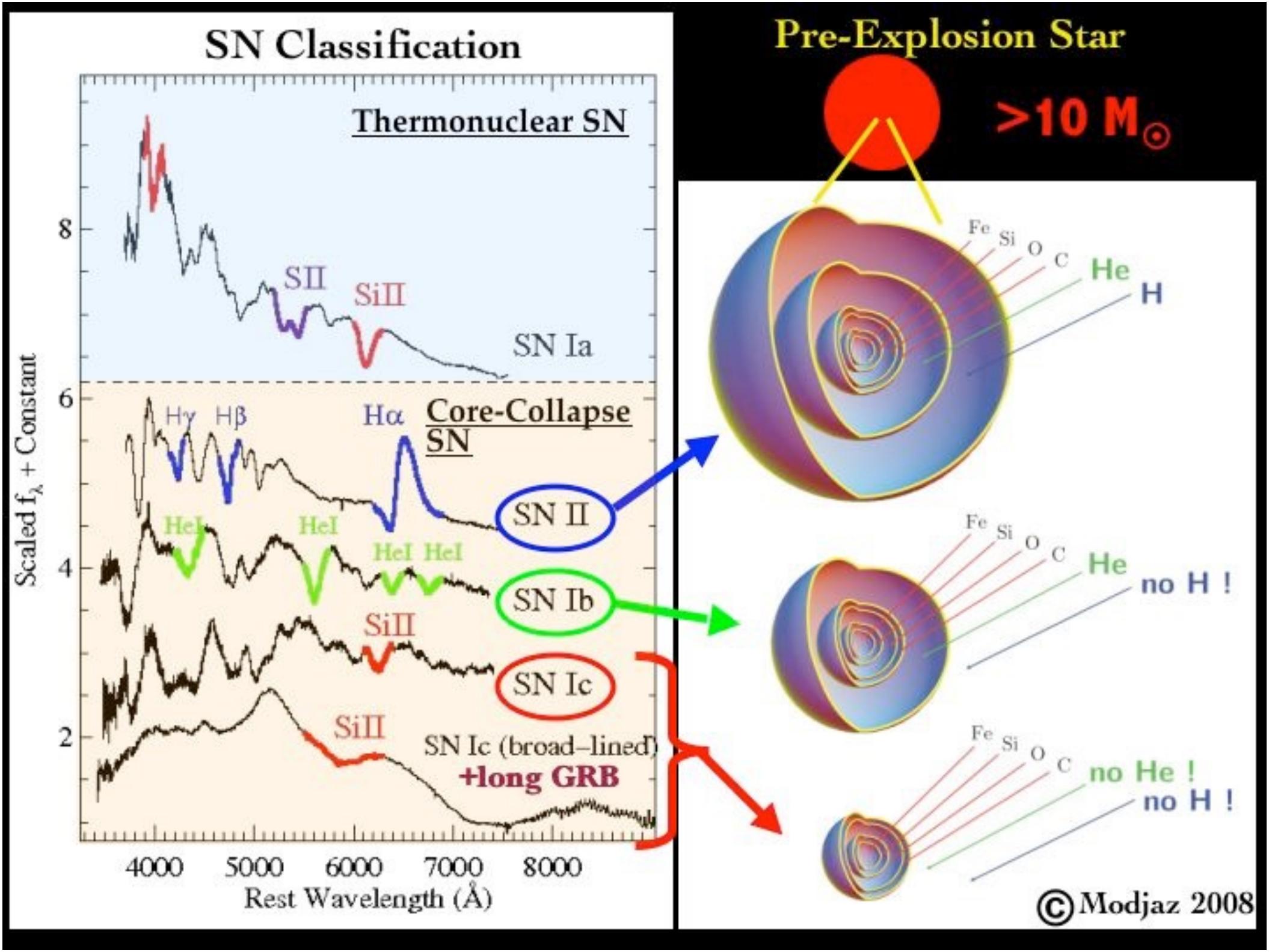

thermonuclear
core collapse
I
no
H
yes
II
IIP
IIL
IIb
light curve shape
SiII
no
yes
HeI
yes
no
Ia
Ib
Ic
strong ejecta–CSM interaction
Ib/c pec
IIn
hypernovae

# Type II SN 2001cm

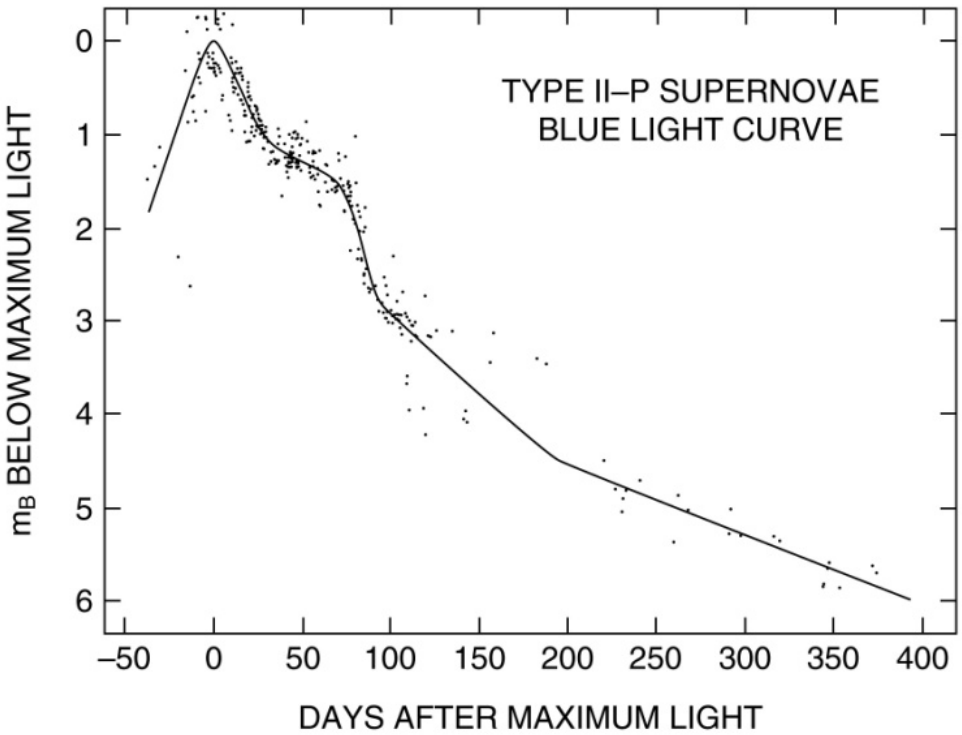


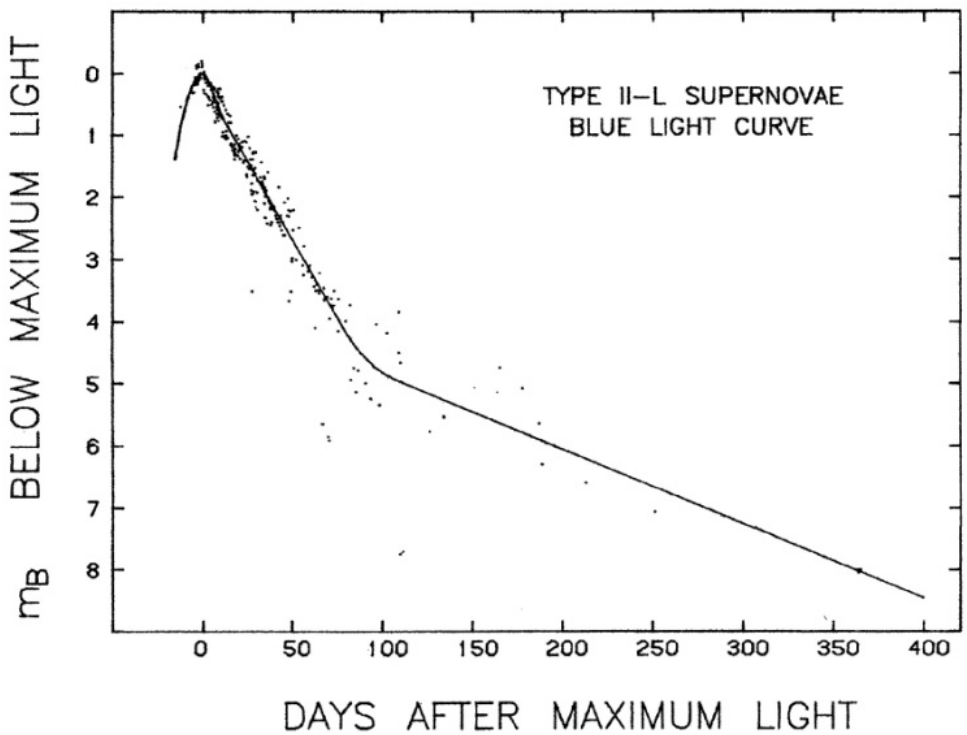
# Type Ia SN 2001N



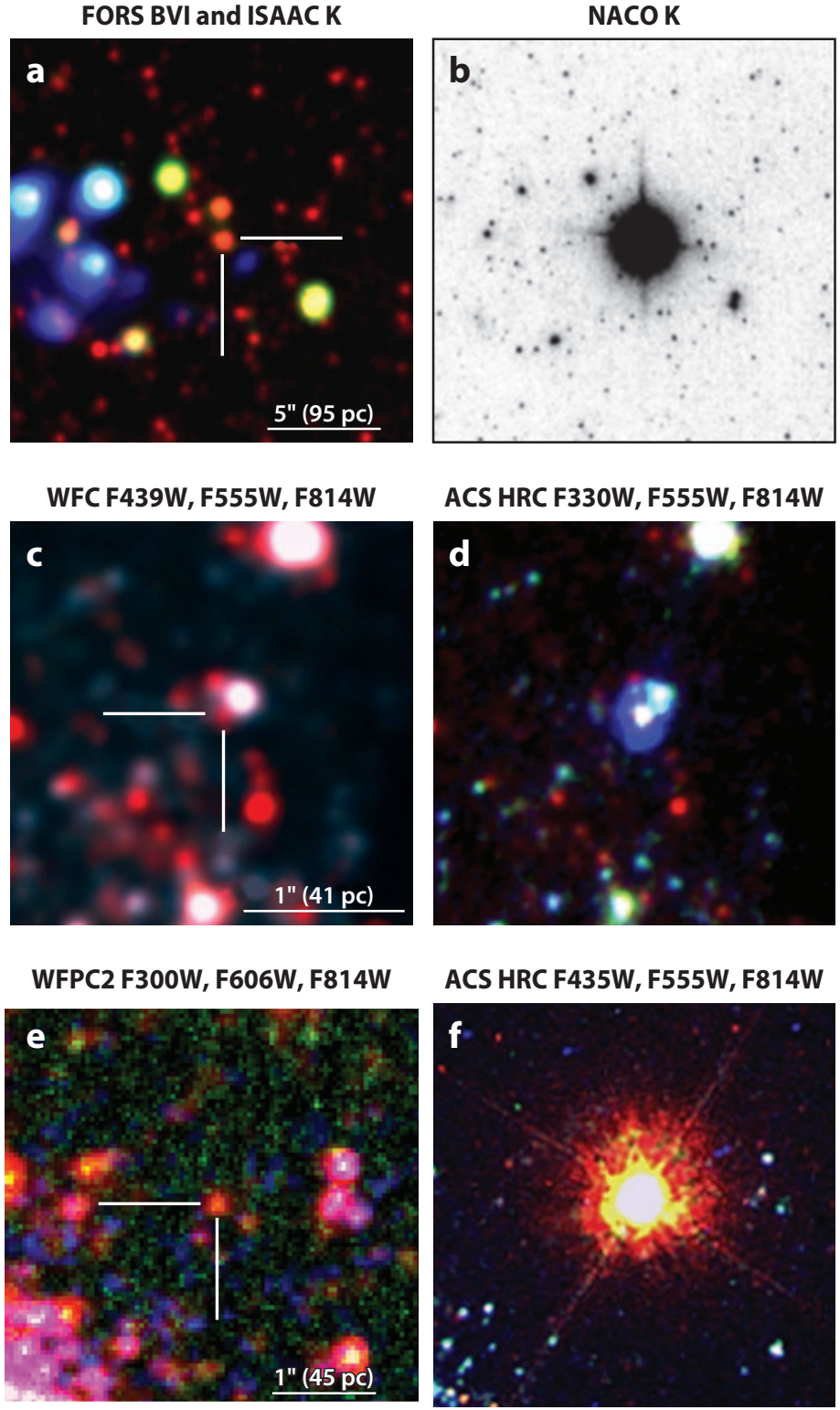

SN Classification
Thermonuclear SN
SII
SiII
SN Ia
Core-Collapse SN
Hγ
Hβ
Hα
HeI
HeI
HeI
HeI
SN II
SN Ib
SiII
SN Ic
SiII
SN Ic (broad–lined)
+long GRB
Scaled $f_\lambda$ + Constant
Rest Wavelength (Å)
4000
5000
6000
7000
8000
2
4
6
8
Pre-Explosion Star
>10 M⊙
Fe
Si
O
C
He
H
no H !
no He !
© Modjaz 2008

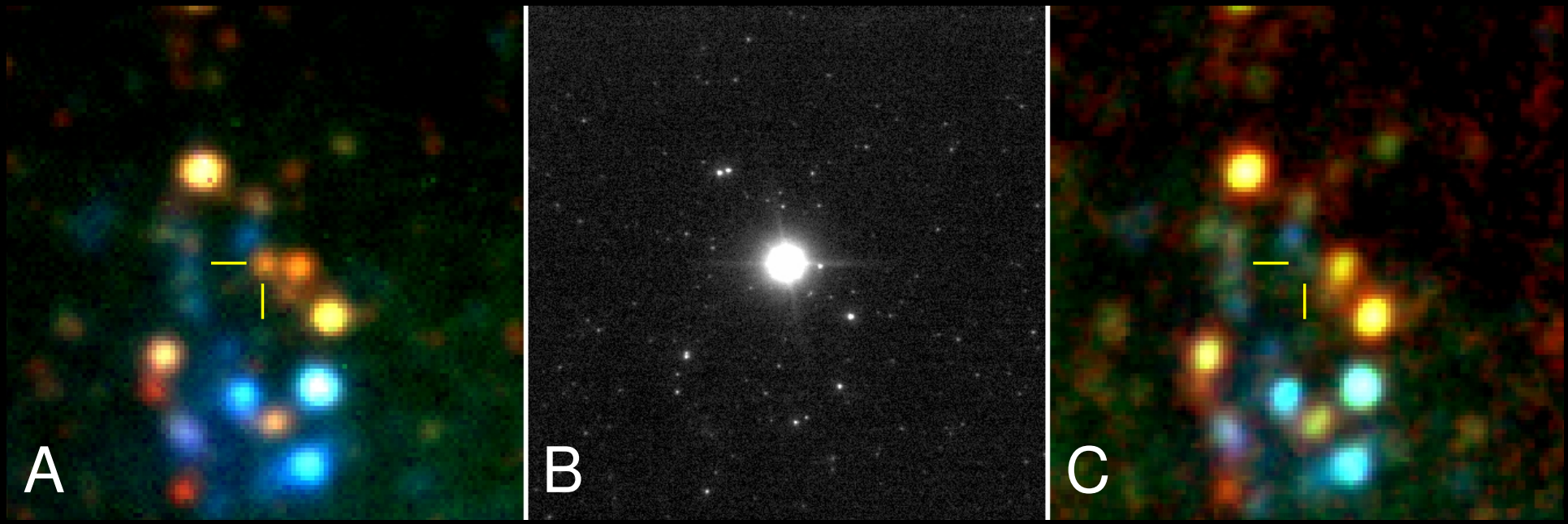
# Typical Light Curves of Type II SNe

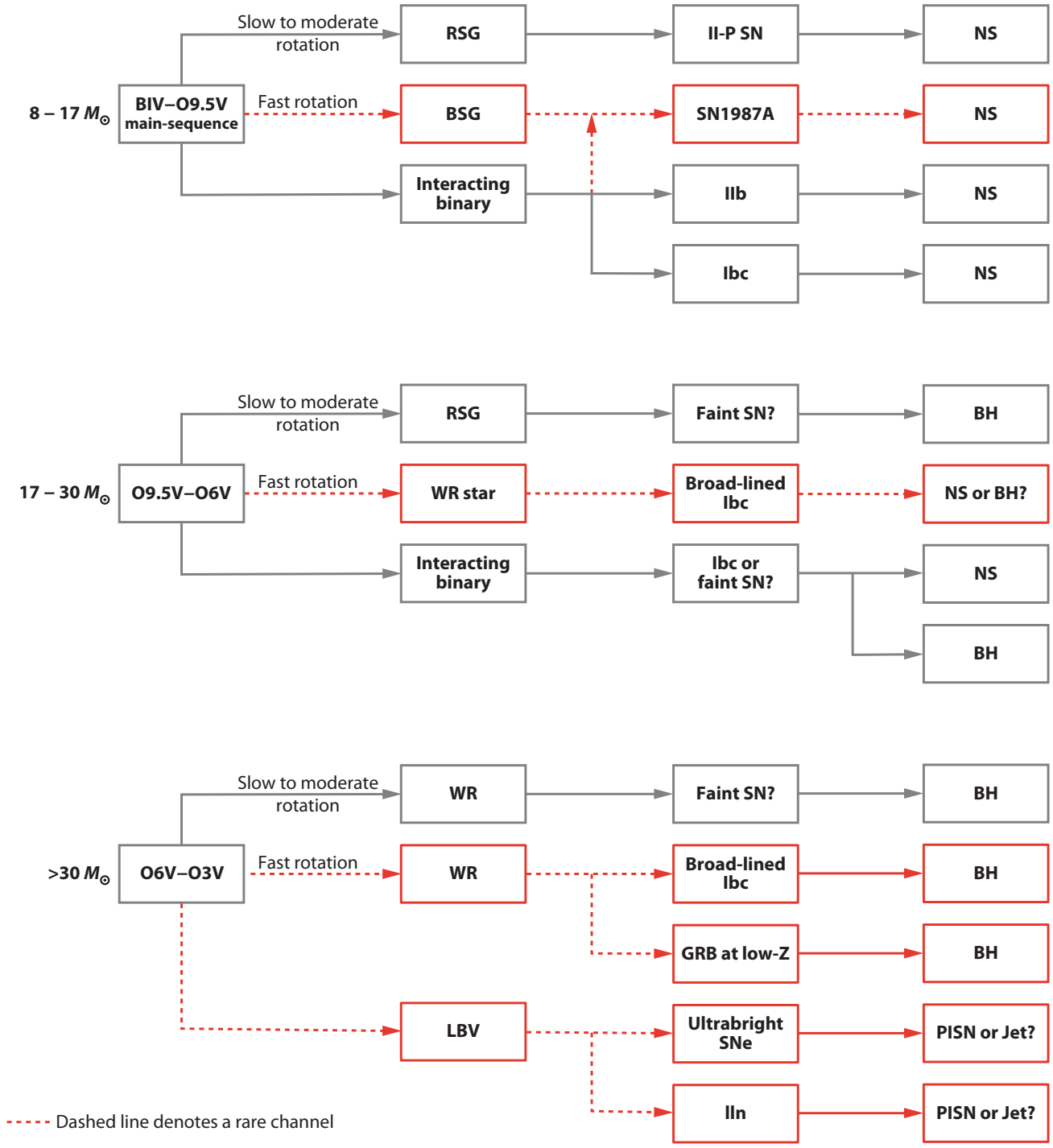


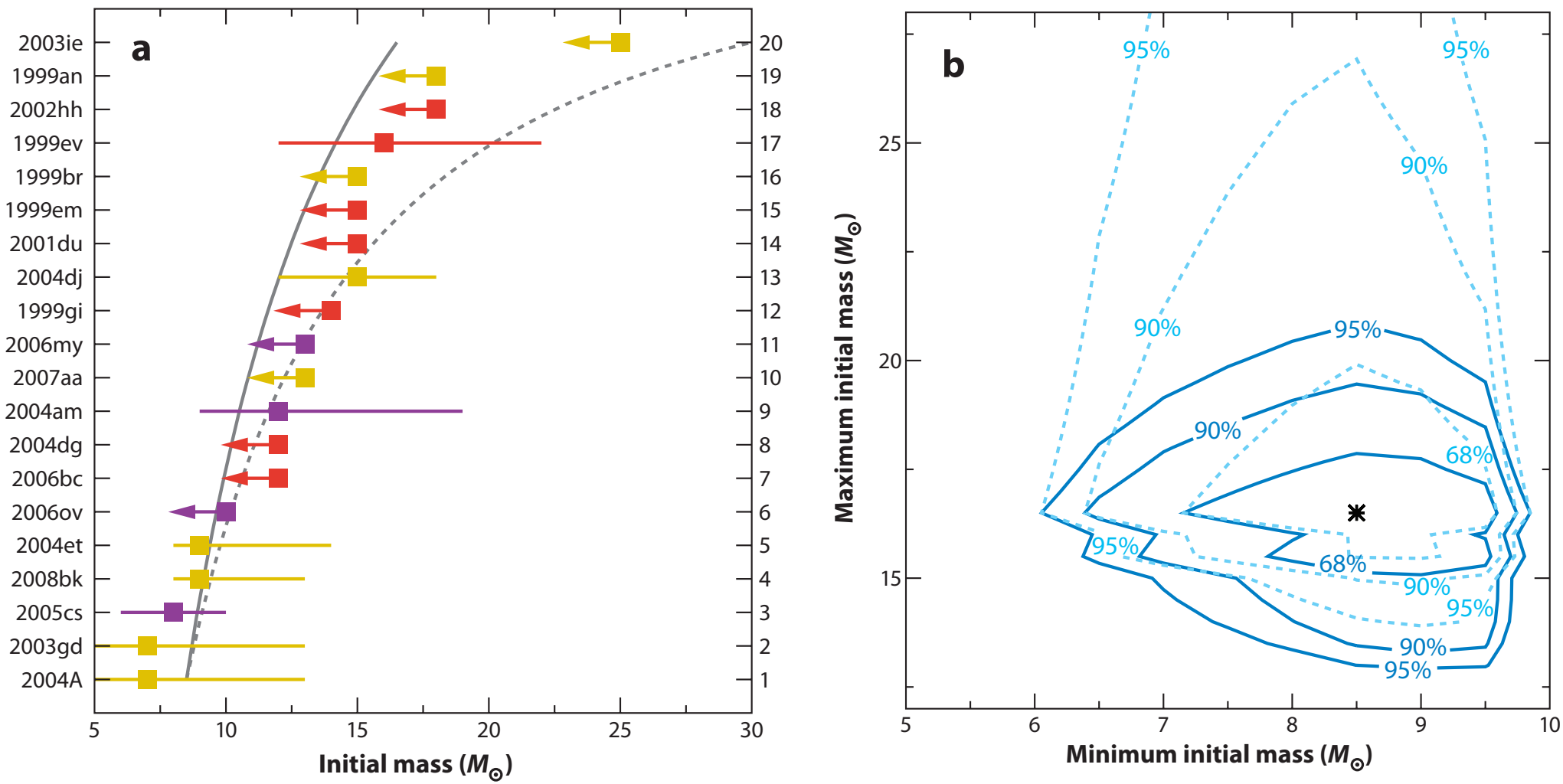



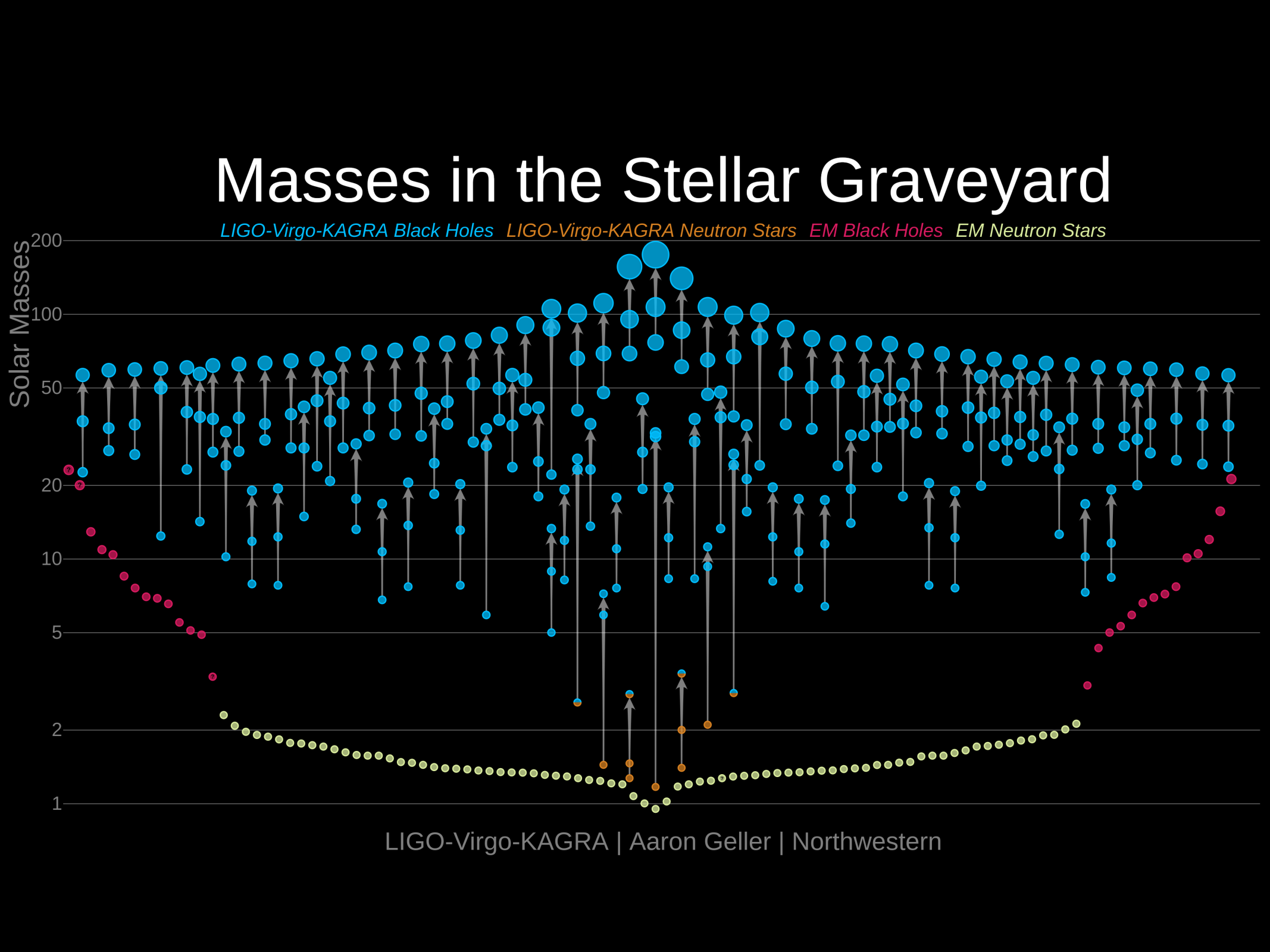

Doggett & Branch 1985

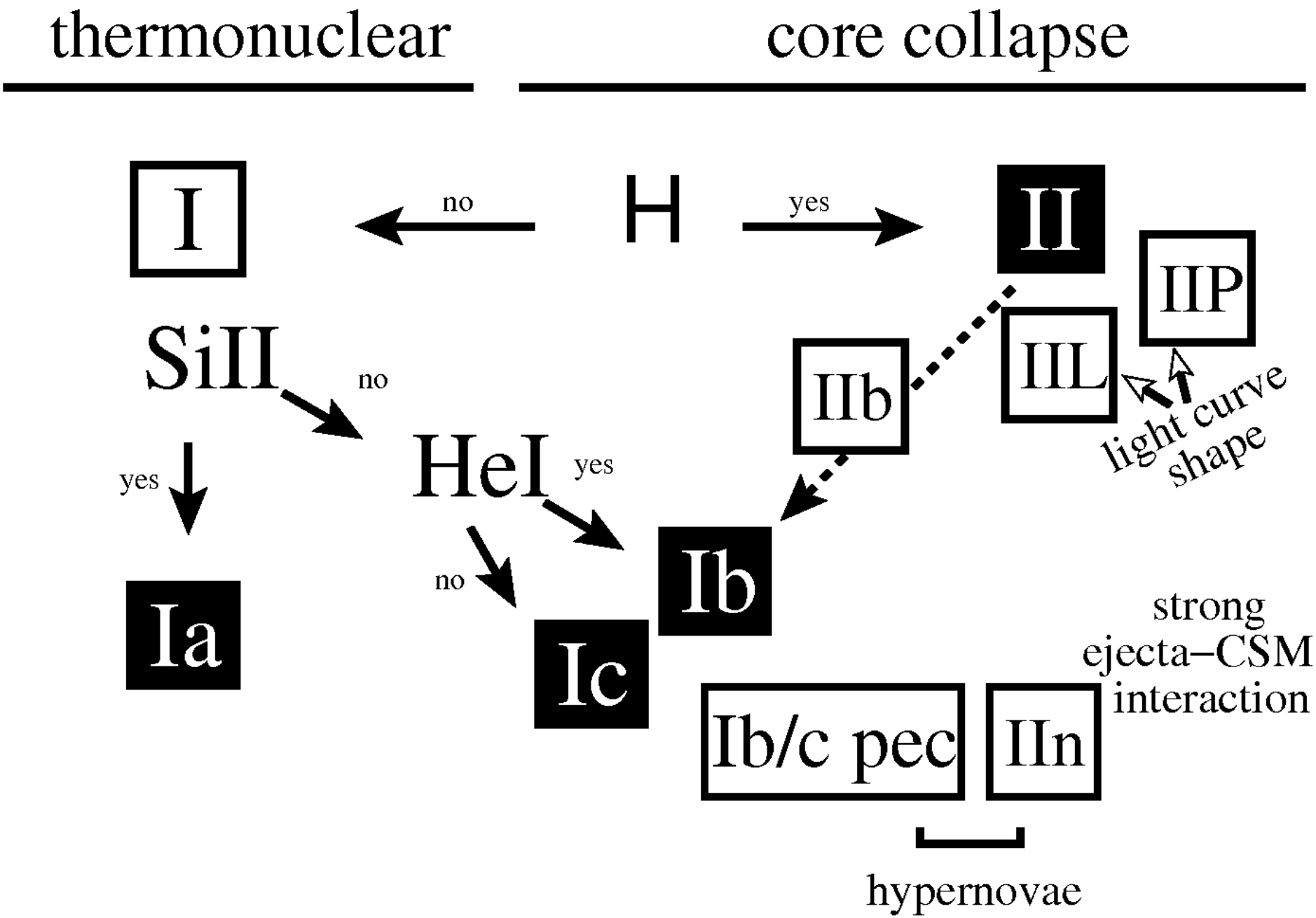

FORS BVI and ISAAC K
NACO K
a
b
5" (95 pc)
WFC F439W, F555W, F814W
ACS HRC F330W, F555W, F814W
c
d
1" (41 pc)
WFPC2 F300W, F606W, F814W
ACS HRC F435W, F555W, F814W
e
f
1" (45 pc)

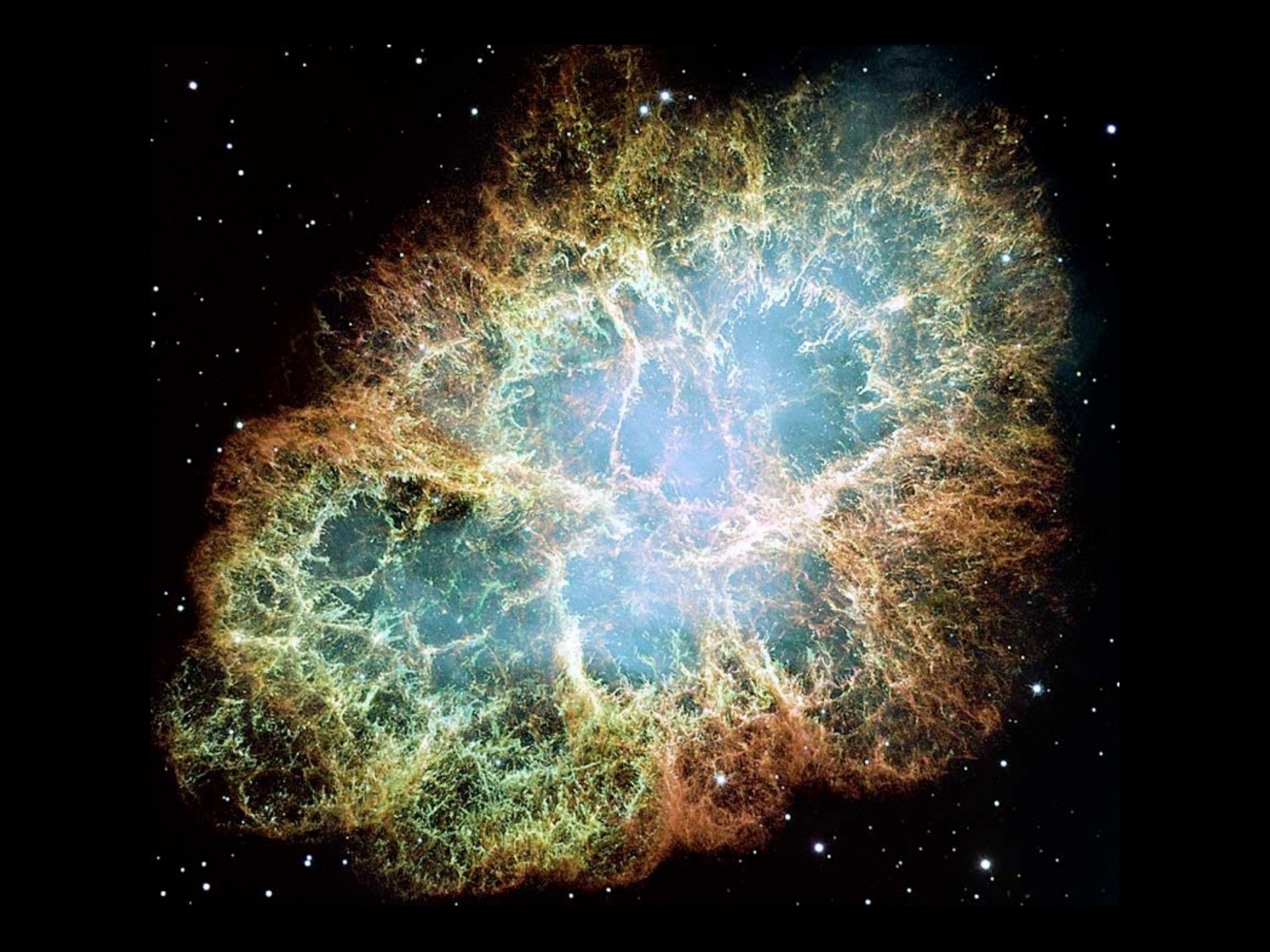

A
B
C

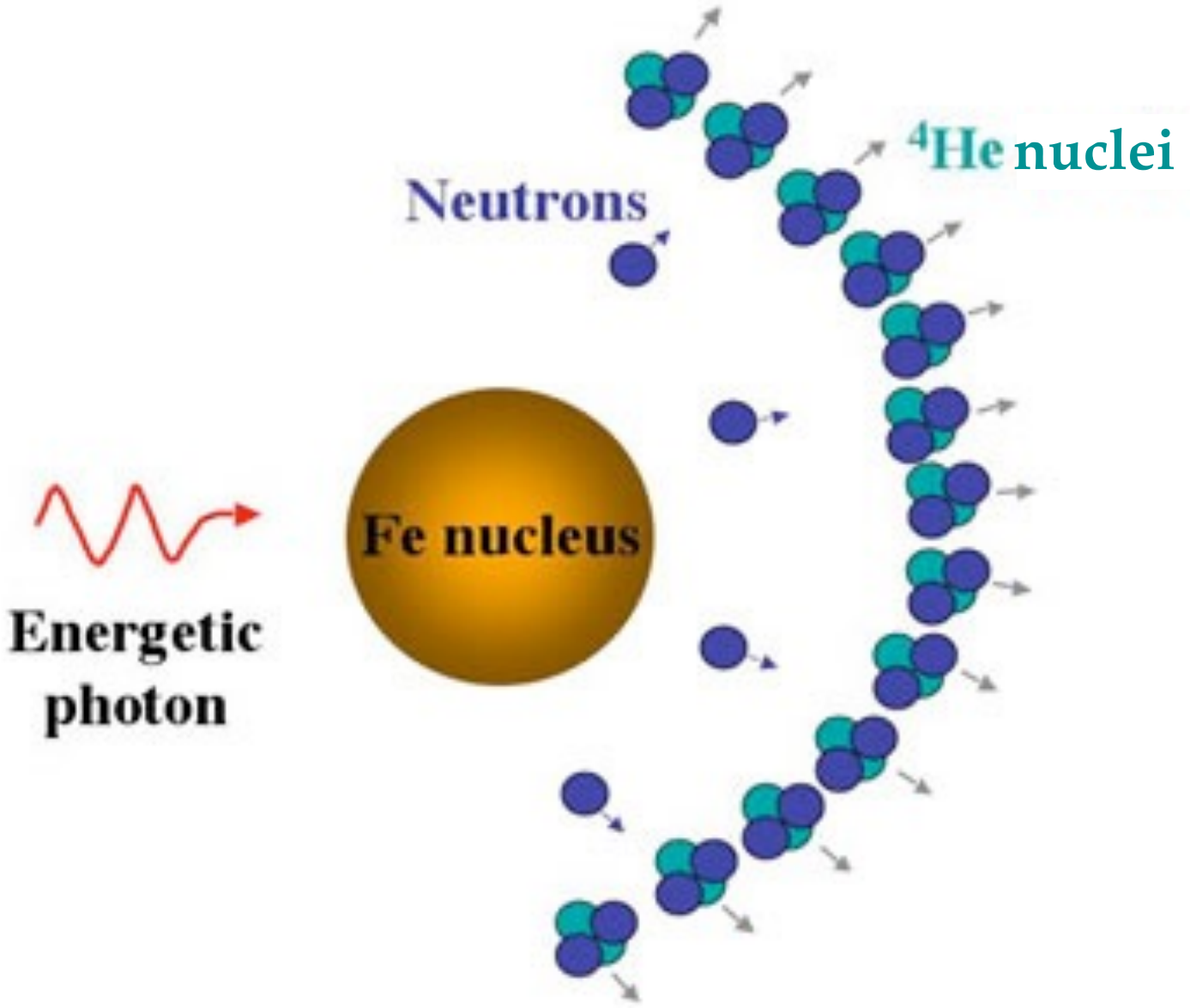

8 – 17 $M_\odot$
BIV–O9.5V main-sequence
Slow to moderate rotation
Fast rotation
RSG
BSG
Interacting binary
II-P SN
SN1987A
IIb
Ibc
NS
NS
NS
NS
17 – 30 $M_\odot$
O9.5V–O6V
Slow to moderate rotation
Fast rotation
RSG
WR star
Interacting binary
Faint SN?
Broad-lined Ibc
Ibc or faint SN?
BH
NS or BH?
NS
BH
>30 $M_\odot$
O6V–O3V
Slow to moderate rotation
Fast rotation
WR
WR
LBV
Faint SN?
Broad-lined Ibc
GRB at low-Z
Ultrabright SNe
IIn
BH
BH
BH
PISN or Jet?
PISN or Jet?
Dashed line denotes a rare channel

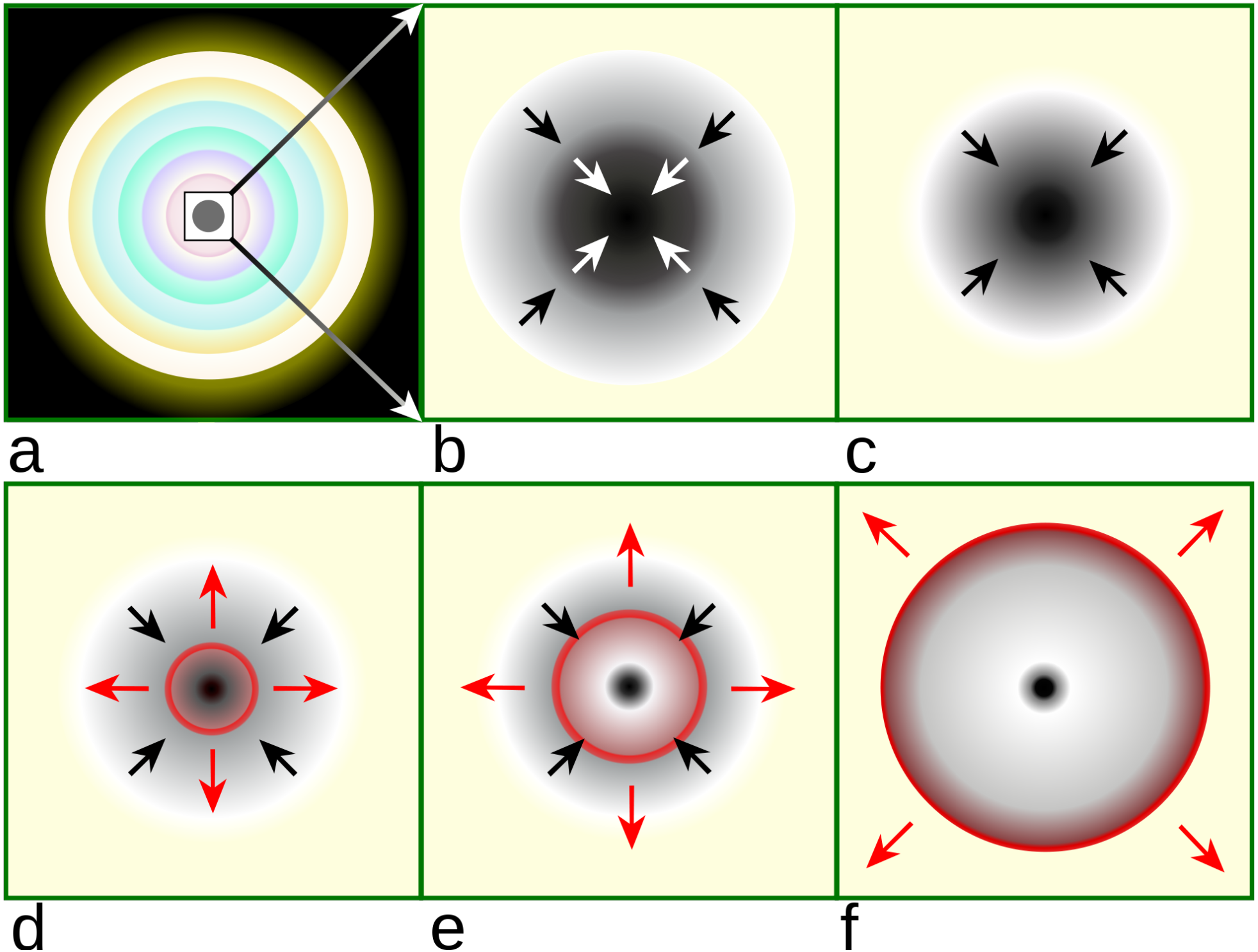

a
2003ie
1999an
2002hh
1999ev
1999br
1999em
2001du
2004dj
1999gi
2006my
2007aa
2004am
2004dg
2006bc
2006ov
2004et
2008bk
2005cs
2003gd
2004A
20
19
18
17
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
5
10
15
20
25
30
Initial mass ($M_\odot$)
b
95%
90%
95%
90%
95%
90%
68%
95%
68%
90%
95%
90%
95%
25
20
15
5
6
7
8
9
10
Maximum initial mass ($M_\odot$)
Minimum initial mass ($M_\odot$)

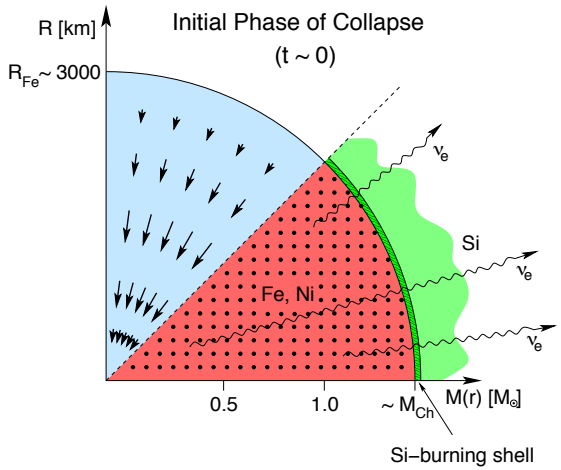

Masses in the Stellar Graveyard
LIGO-Virgo-KAGRA Black Holes
LIGO-Virgo-KAGRA Neutron Stars
EM Black Holes
EM Neutron Stars
Solar Masses
200
100
50
20
10
5
2
1
LIGO-Virgo-KAGRA | Aaron Geller | Northwestern

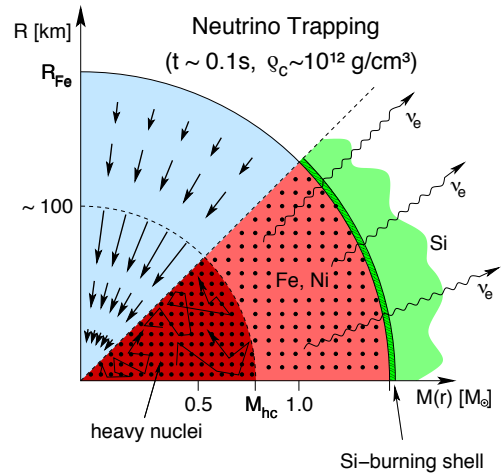

thermonuclear
core collapse
I
no
H
yes
II
IIP
IIL
IIb
light curve shape
SiII
no
yes
HeI
yes
no
Ia
Ib
Ic
strong ejecta–CSM interaction
Ib/c pec
IIn
hypernovae

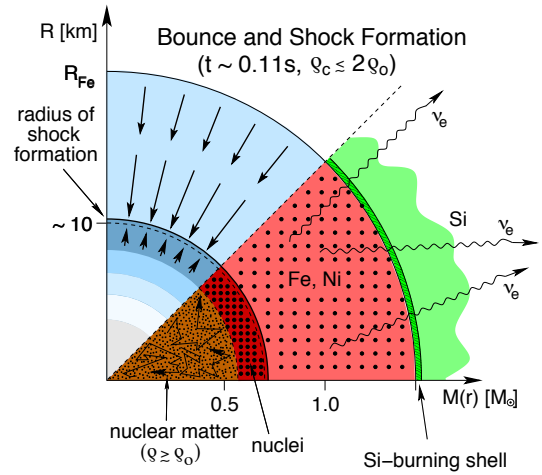


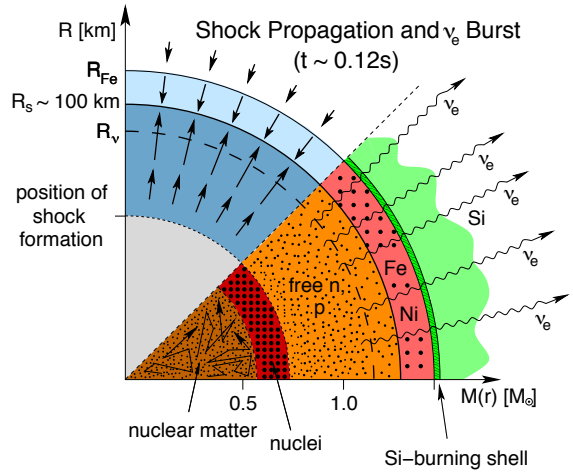

Neutrons
$^4$He nuclei
Fe nucleus
Energetic photon

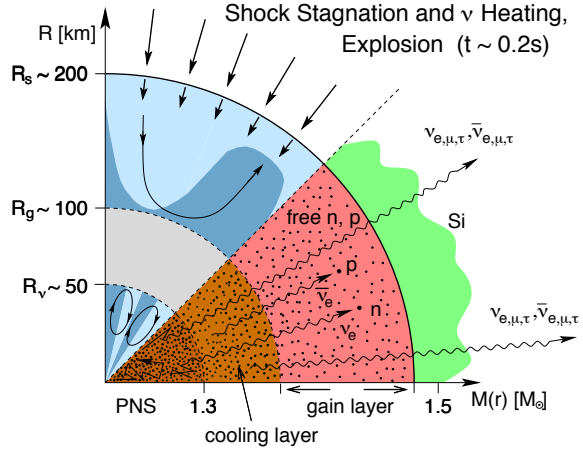

a
b
c
d
e
f

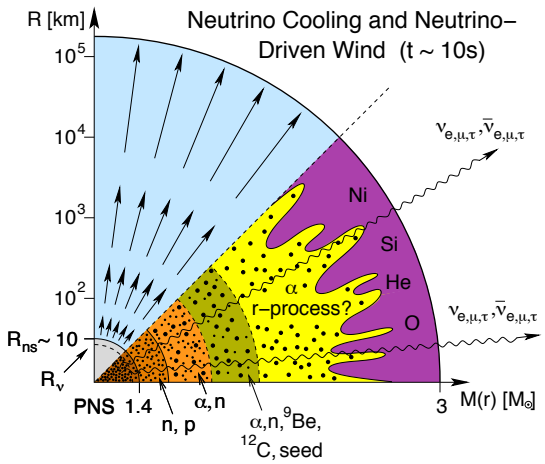

Initial Phase of Collapse
(t ~ 0)
R [km]
R_Fe ~ 3000
Si
Fe, Ni
0.5
1.0
~ M_Ch
M(r) [M⊙]
Si–burning shell

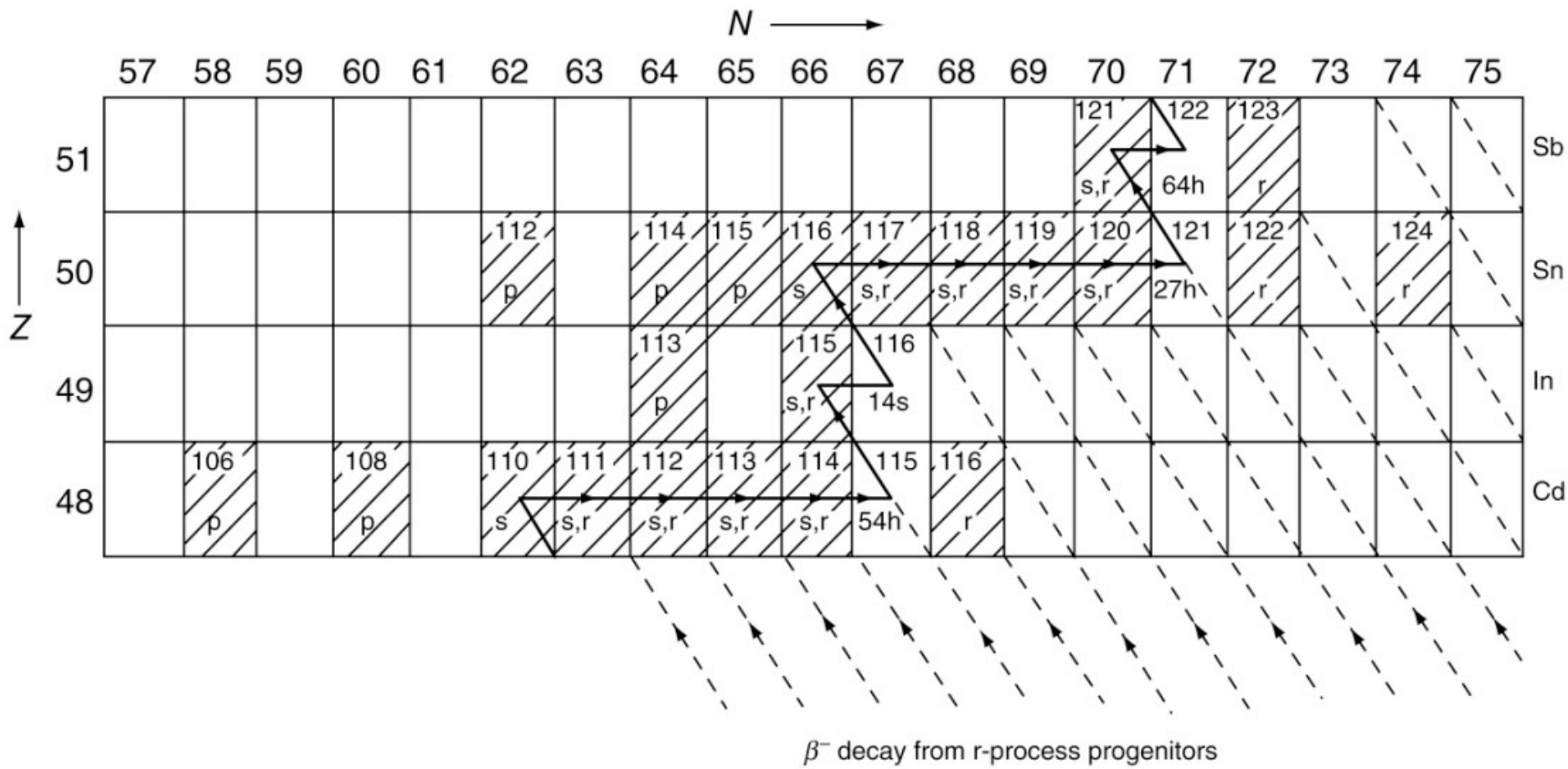

Neutrino Trapping
(t ~ 0.1s, ϱc ~ 10^12 g/cm^3)
R [km]
R_Fe
~ 100
Si
Fe, Ni
0.5
M_hc
1.0
M(r) [M⊙]
heavy nuclei
Si–burning shell


Bounce and Shock Formation
(t ~ 0.11s, ϱc ≤ 2ϱ0)
R [km]
R_Fe
radius of shock formation
~ 10
Si
Fe, Ni
0.5
1.0
M(r) [M⊙]
nuclear matter
(ϱ ≥ ϱ0)
nuclei
Si–burning shell

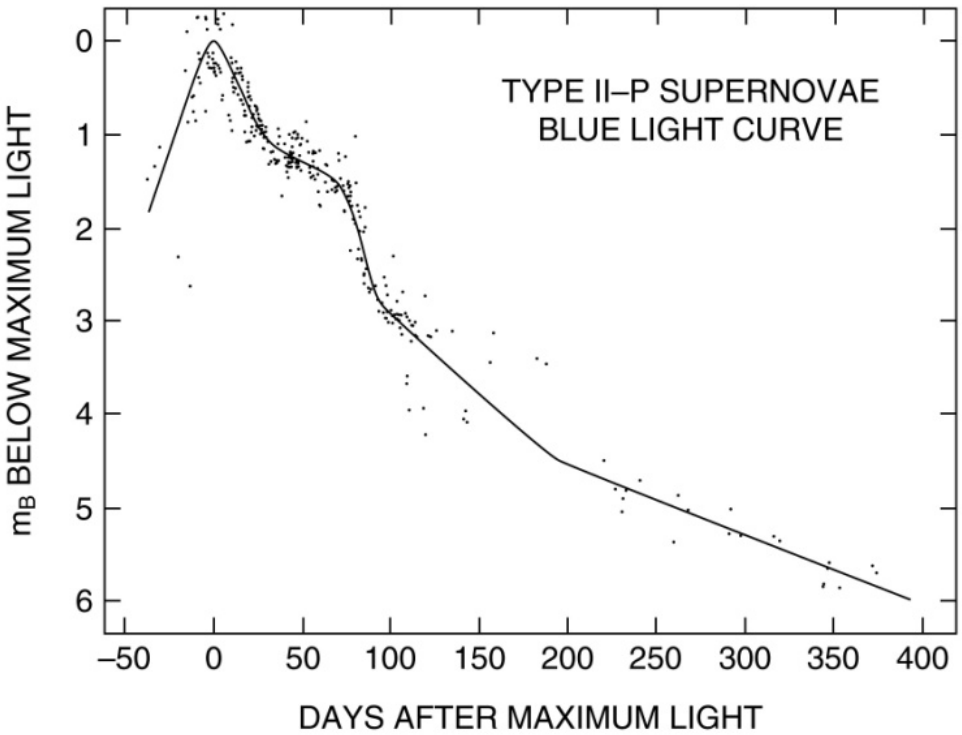

Shock Propagation and ν_e Burst
(t ~ 0.12s)
R [km]
R_Fe
R_s ~ 100 km
R_ν
position of shock formation
Si
free n, p
Fe
Ni
0.5
1.0
M(r) [M⊙]
nuclear matter
nuclei
Si–burning shell

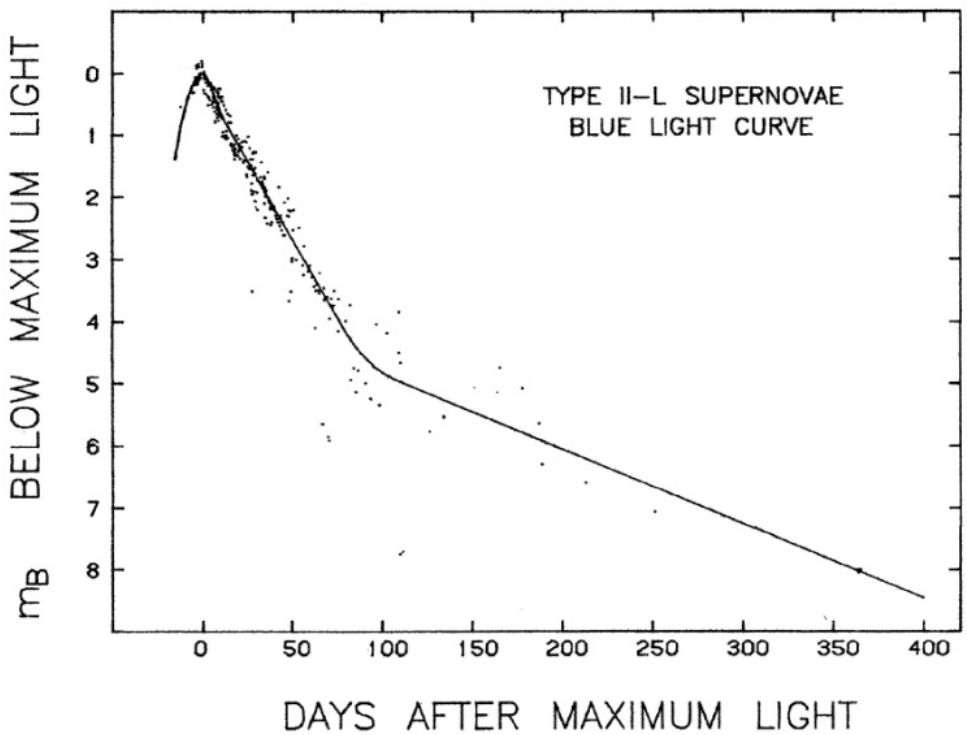

Shock Stagnation and ν Heating,
Explosion (t ~ 0.2s)
R [km]
R_s ~ 200
R_g ~ 100
R_ν ~ 50
Si
free n, p
p
n
PNS
1.3
gain layer
1.5
M(r) [M⊙]
cooling layer


Neutrino Cooling and Neutrino–
Driven Wind (t ~ 10s)
R [km]
10^5
10^4
10^3
10^2
Ni
Si
He
O
α
r–process?
R_ns ~ 10
R_ν
PNS
1.4
n, p
α, n
α, n, 9Be,
12C, seed
3
M(r) [M⊙]

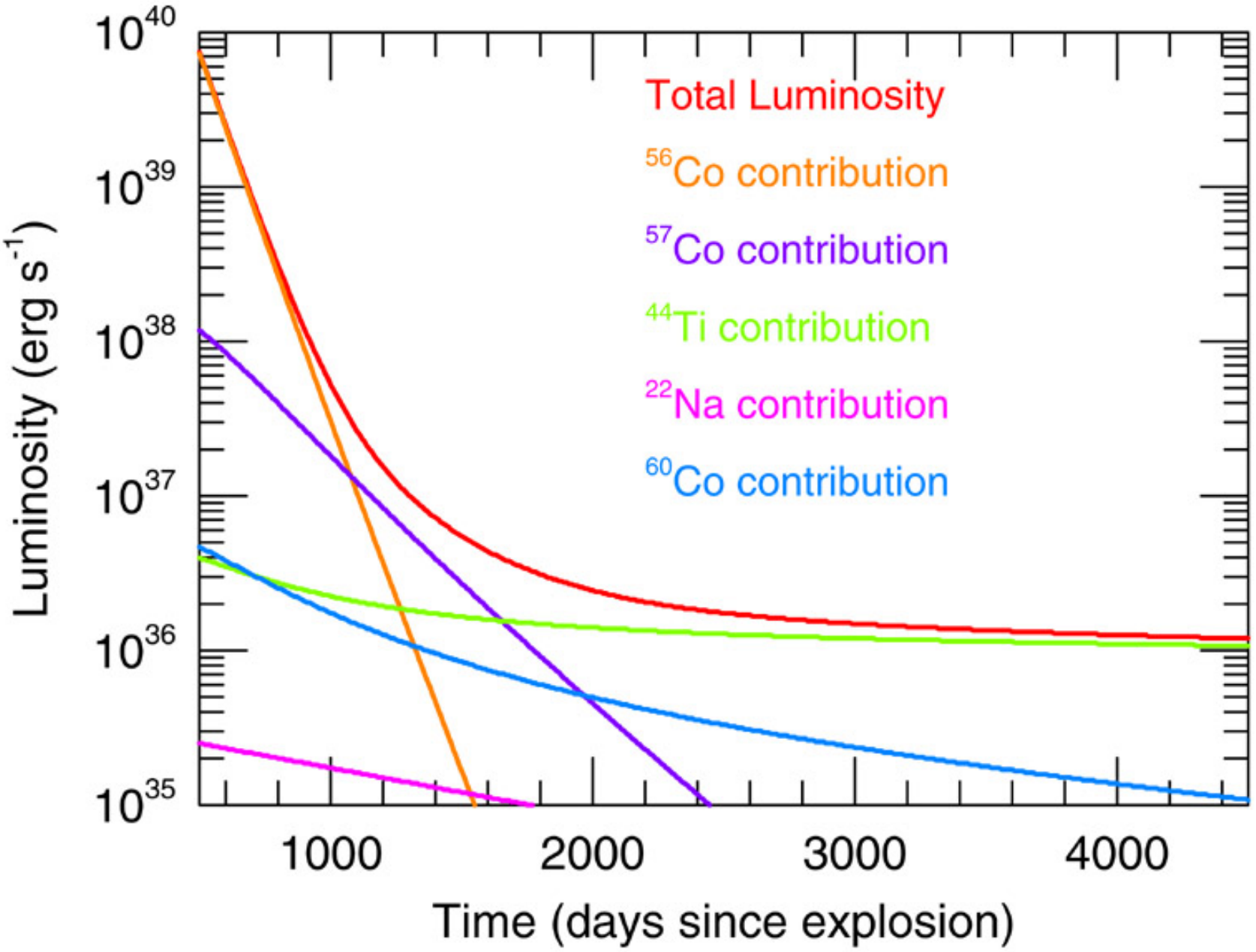

N
57 58 59 60 61 62 63 64 65 66 67 68 69 70 71 72 73 74 75
Z
51
50
49
48
Sb
Sn
In
Cd
121 s,r
122 64h
123 r
112 p
114 p
115 p
116 s
117 s,r
118 s,r
119 s,r
120 s,r
121 27h
122 r
124 r
113 p
115 s,r
116 14s
106 p
108 p
110 s
111 s,r
112 s,r
113 s,r
114 s,r
115 54h
116 r
β⁻ decay from r-process progenitors

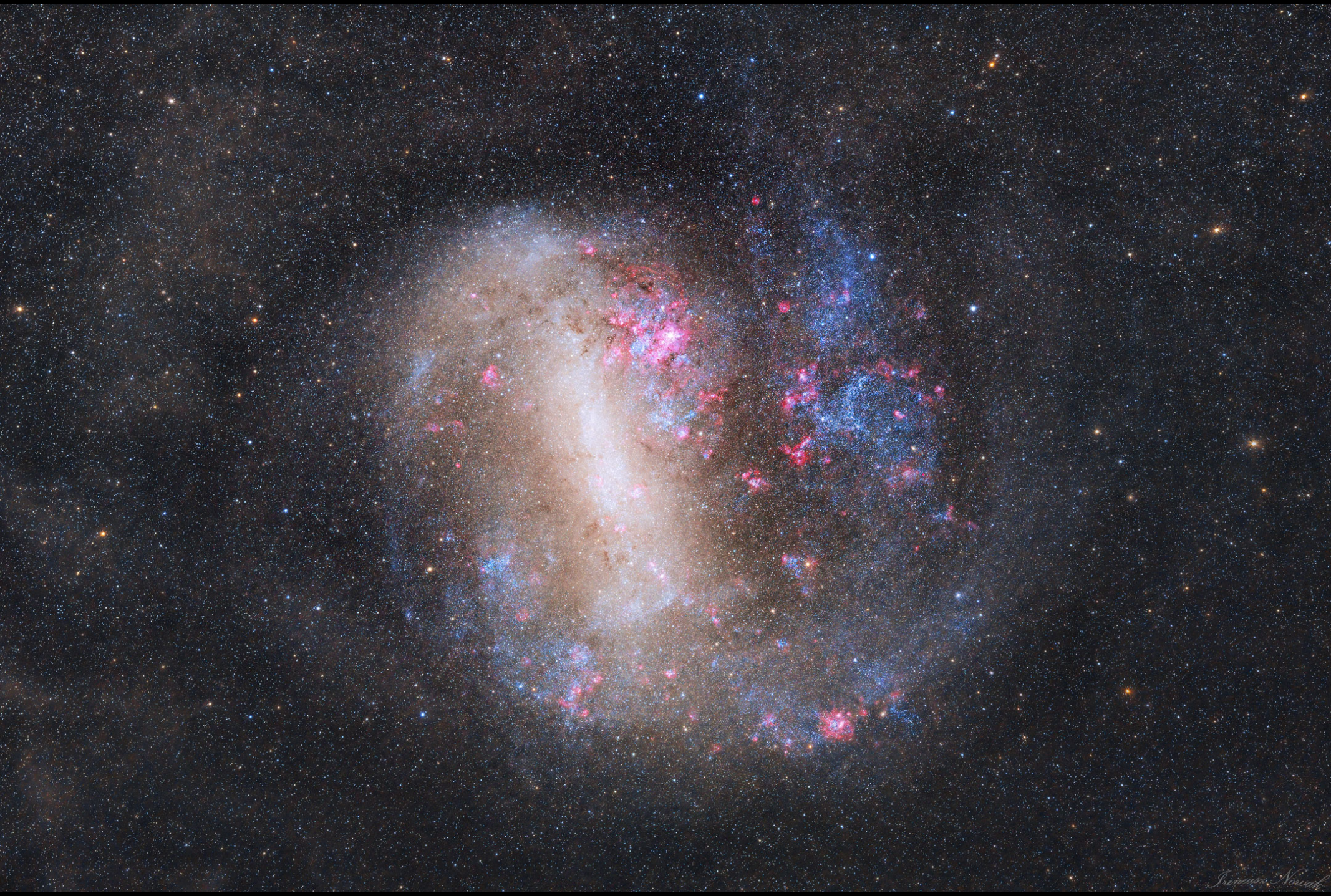
# Typical Light Curves of Type II SNe



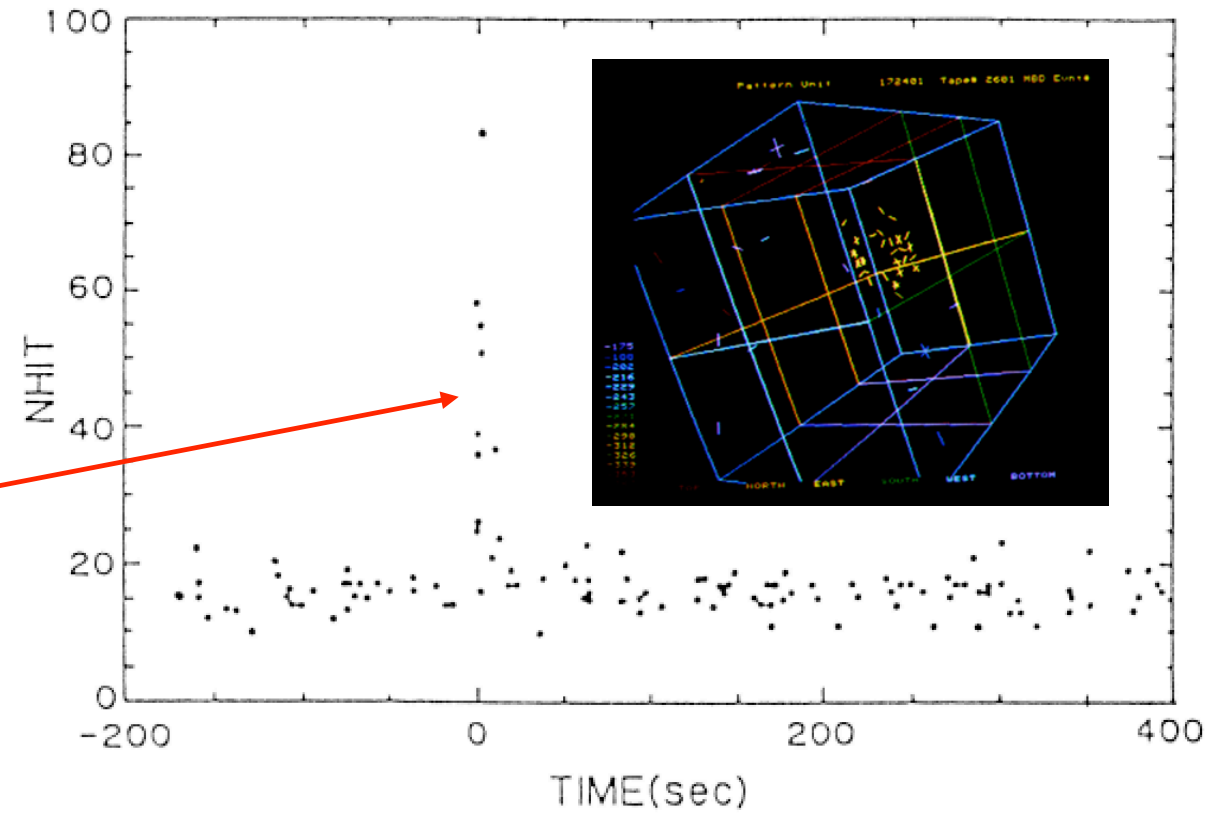



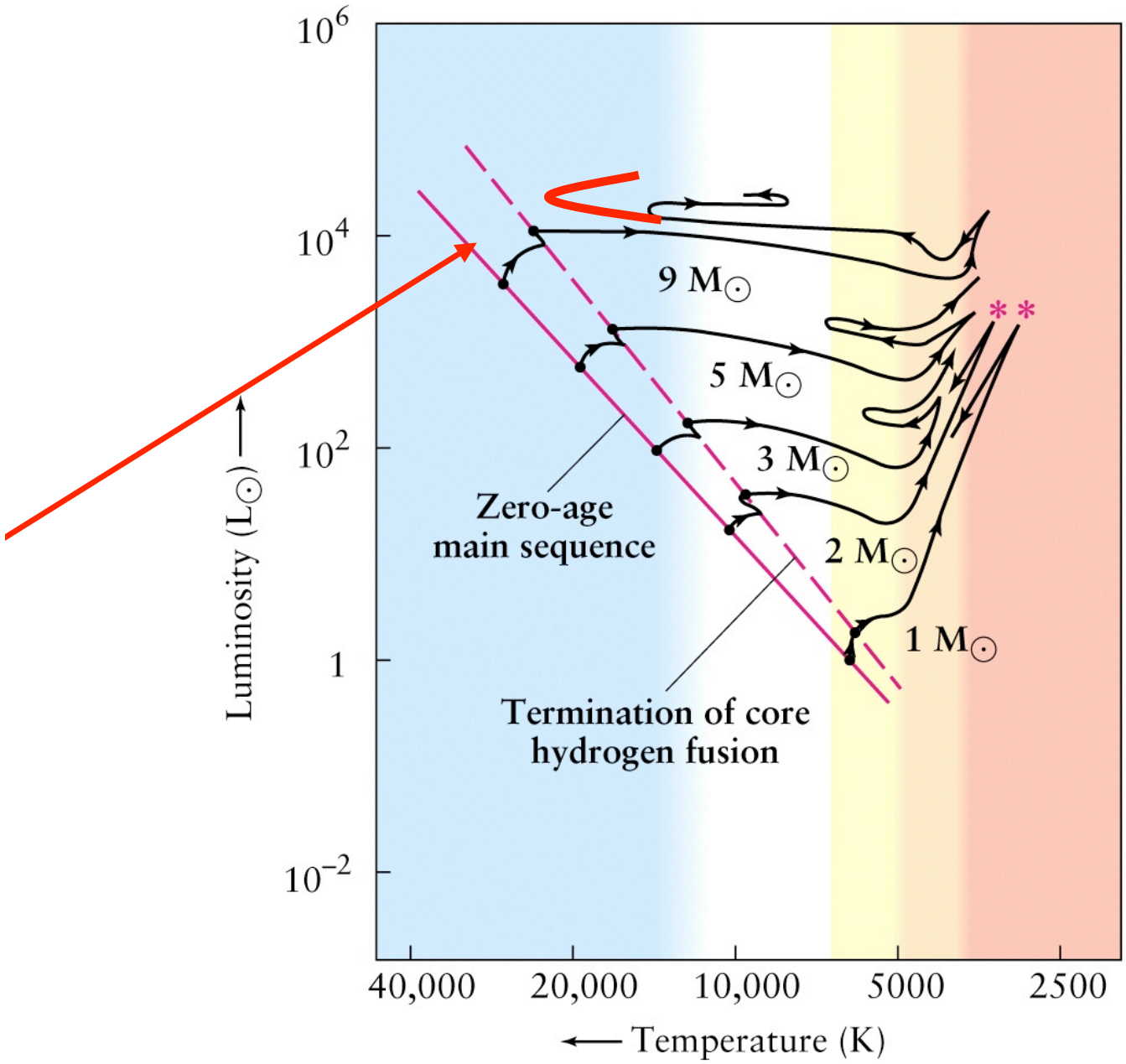

Doggett & Branch 1985

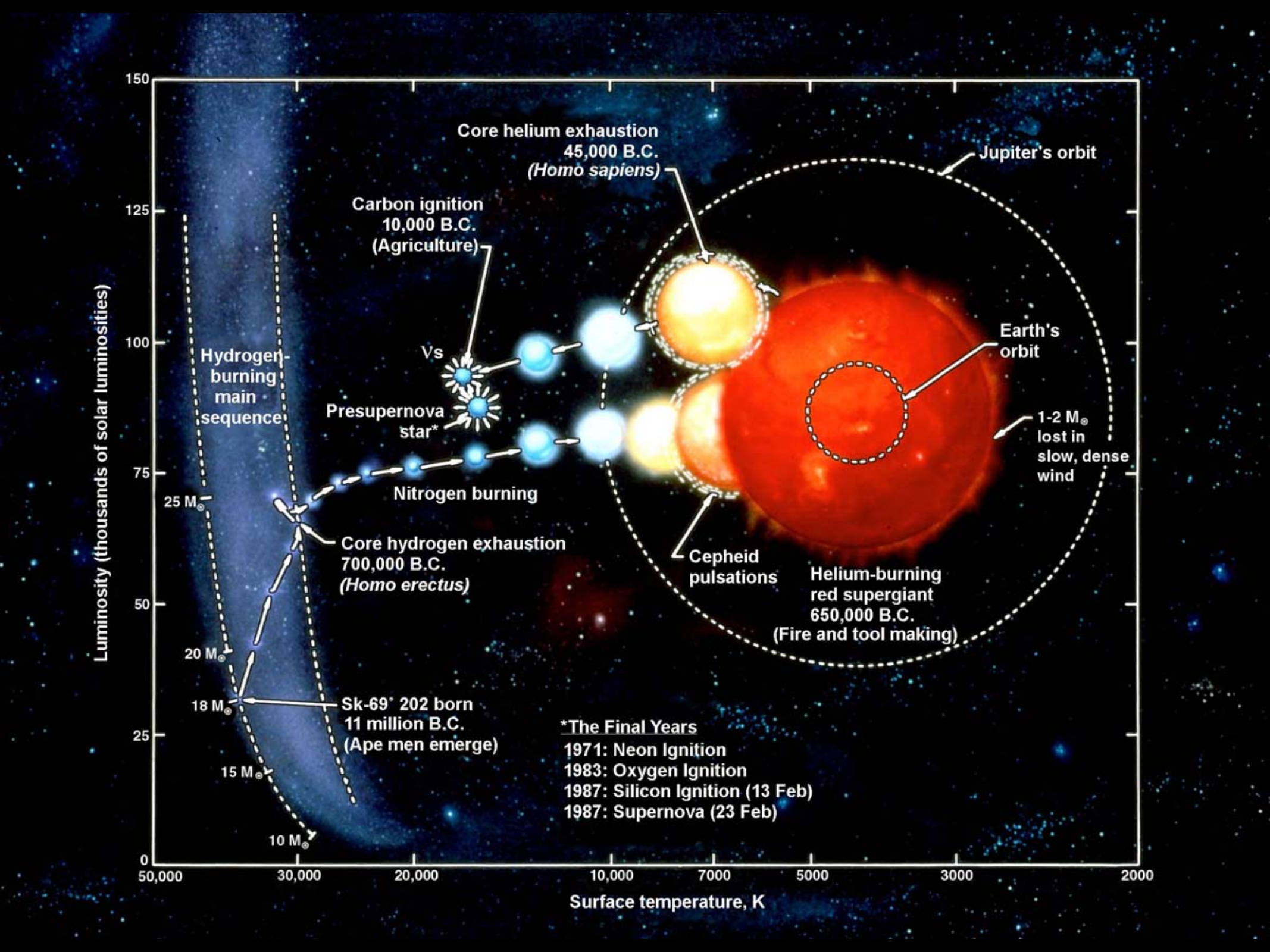

Total Luminosity
56Co contribution
57Co contribution
44Ti contribution
22Na contribution
60Co contribution
Luminosity (erg s-1)
10^40
10^39
10^38
10^37
10^36
10^35
1000
2000
3000
4000
Time (days since explosion)

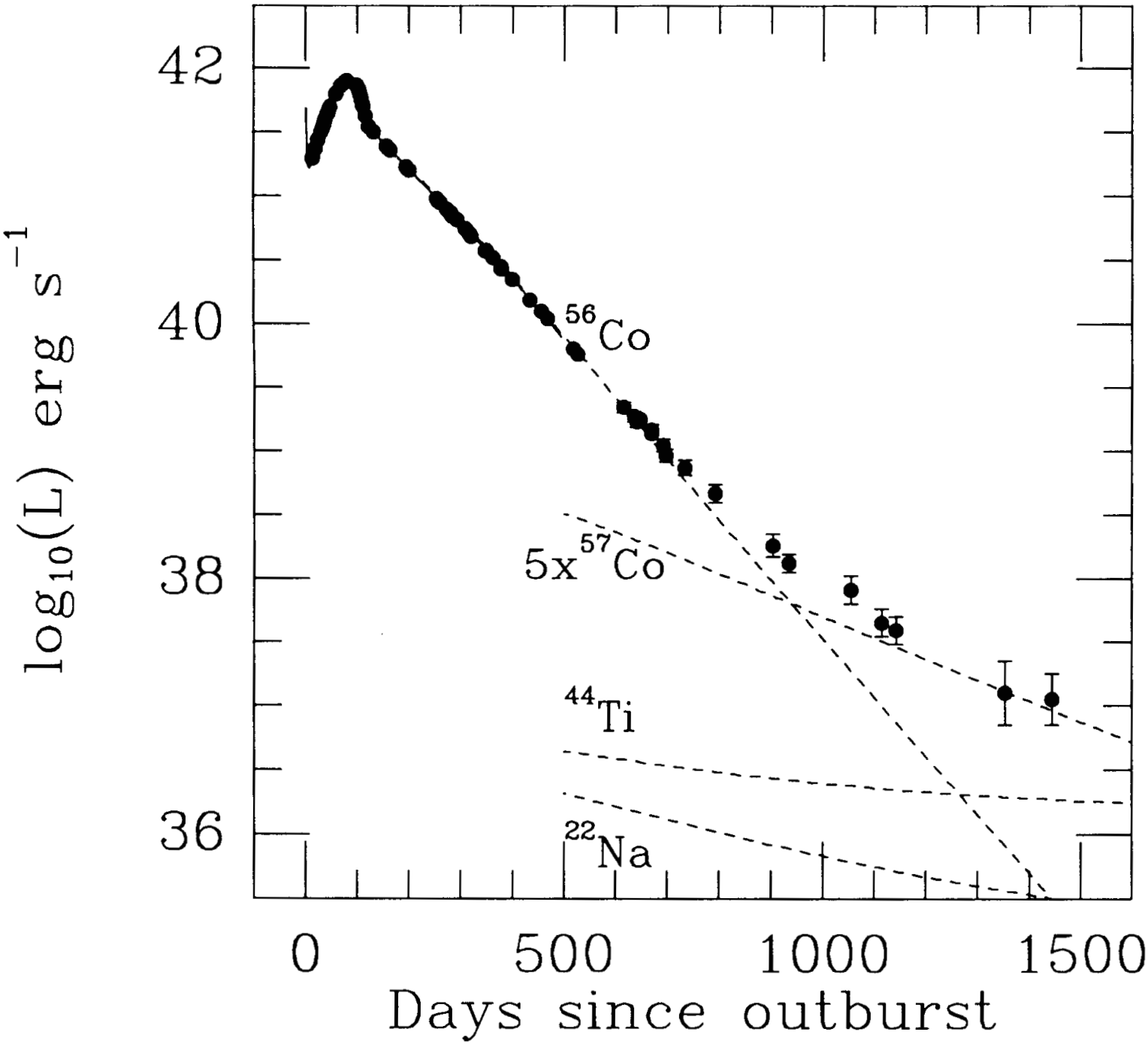

Ireneusz Nowak

Detection of neutrino burst by Super-K (~12). IMB saw 8 (out of est. $10^{20}$ entering detector!!!)

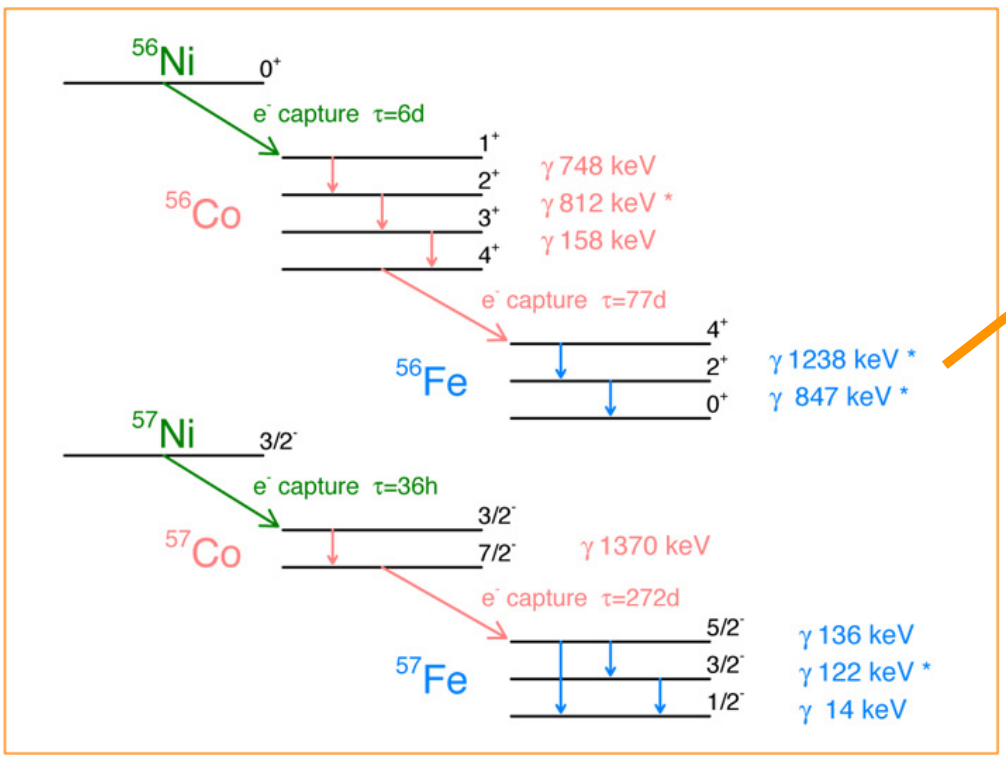


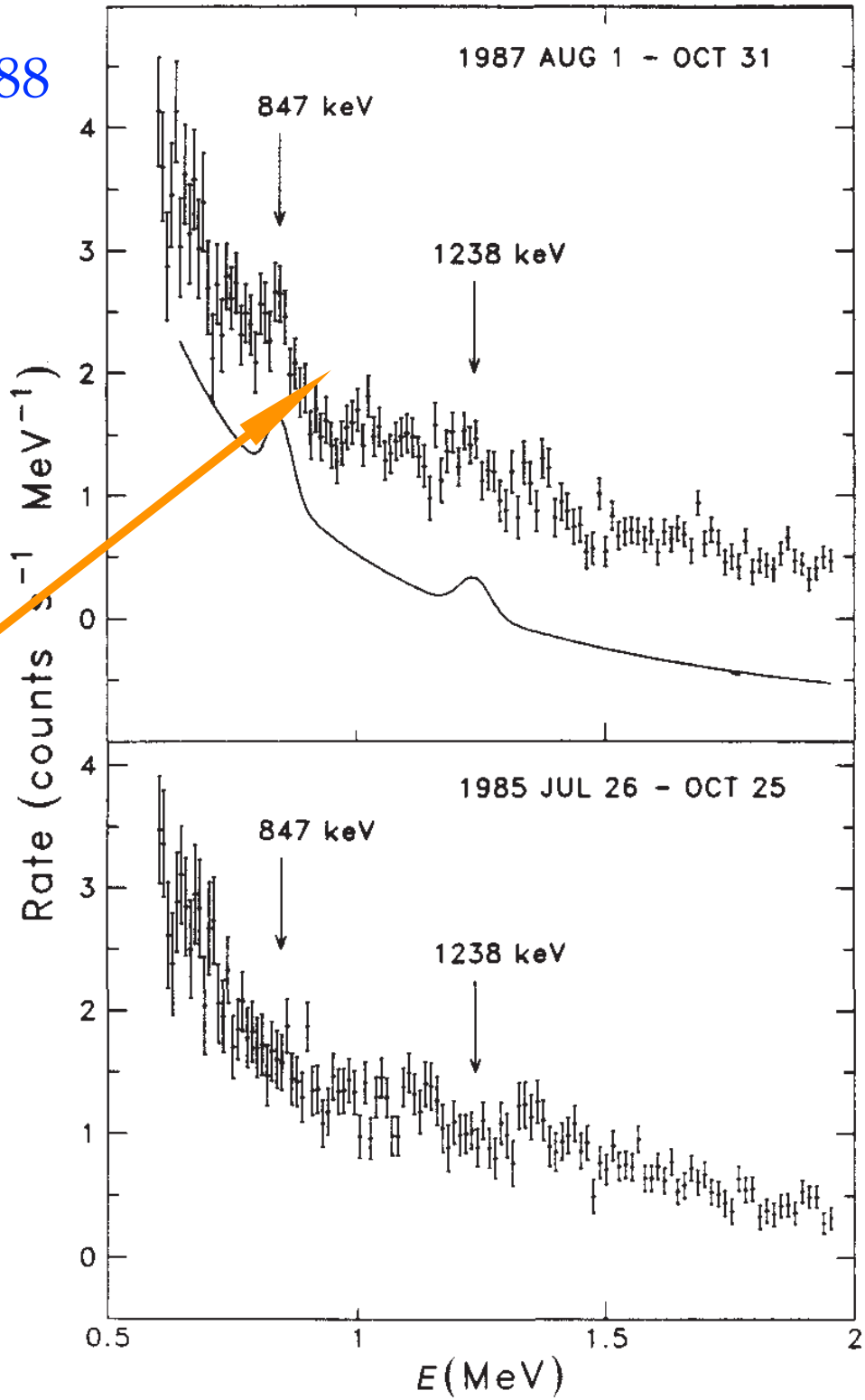

$10^6$
$10^4$
$10^2$
1
$10^{-2}$
Luminosity ($L_\odot$)
9 $M_\odot$
5 $M_\odot$
3 $M_\odot$
2 $M_\odot$
1 $M_\odot$
Zero-age
main sequence
Termination of core
hydrogen fusion
40,000
20,000
10,000
5000
2500
Temperature (K)

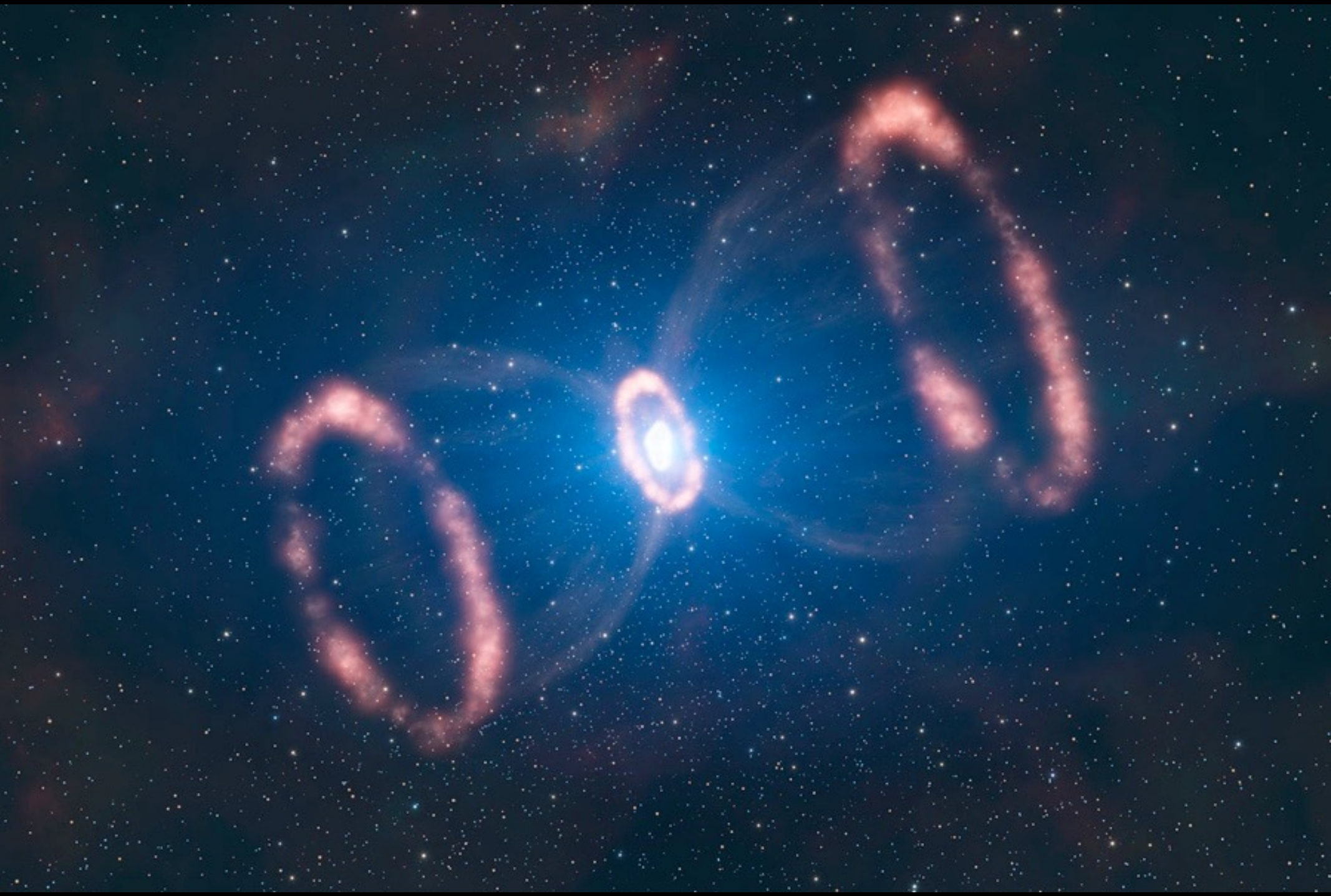

Core helium exhaustion
45,000 B.C.
(Homo sapiens)
Jupiter's orbit
Carbon ignition
10,000 B.C.
(Agriculture)
Earth's
orbit
Hydrogen-
burning
main
sequence
Vs
Presupernova
star*
1-2 M⊙
lost in
slow, dense
wind
Nitrogen burning
25 M⊙
Core hydrogen exhaustion
700,000 B.C.
(Homo erectus)
Cepheid
pulsations
Helium-burning
red supergiant
650,000 B.C.
(Fire and tool making)
20 M⊙
18 M⊙
Sk-69° 202 born
11 million B.C.
(Ape men emerge)
15 M⊙
10 M⊙
*The Final Years
1971: Neon Ignition
1983: Oxygen Ignition
1987: Silicon Ignition (13 Feb)
1987: Supernova (23 Feb)
Luminosity (thousands of solar luminosities)
150
125
100
75
50
25
0
50,000
30,000
20,000
10,000
7000
5000
3000
2000
Surface temperature, K

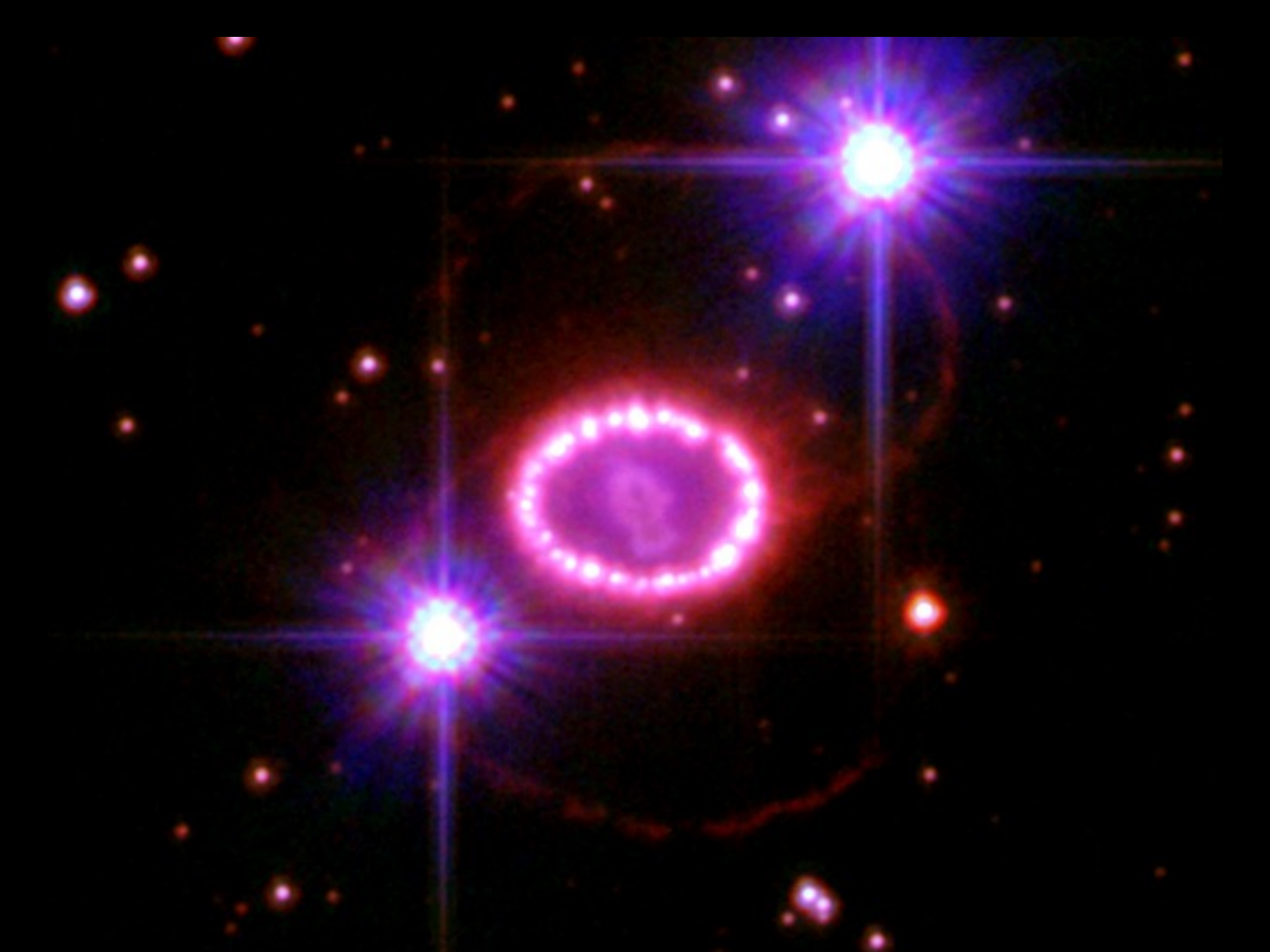

42
40
38
36
$\log_{10}(L)$ erg $s^{-1}$
$^{56}$Co
5x $^{57}$Co
$^{44}$Ti
$^{22}$Na
0
500
1000
1500
Days since outburst

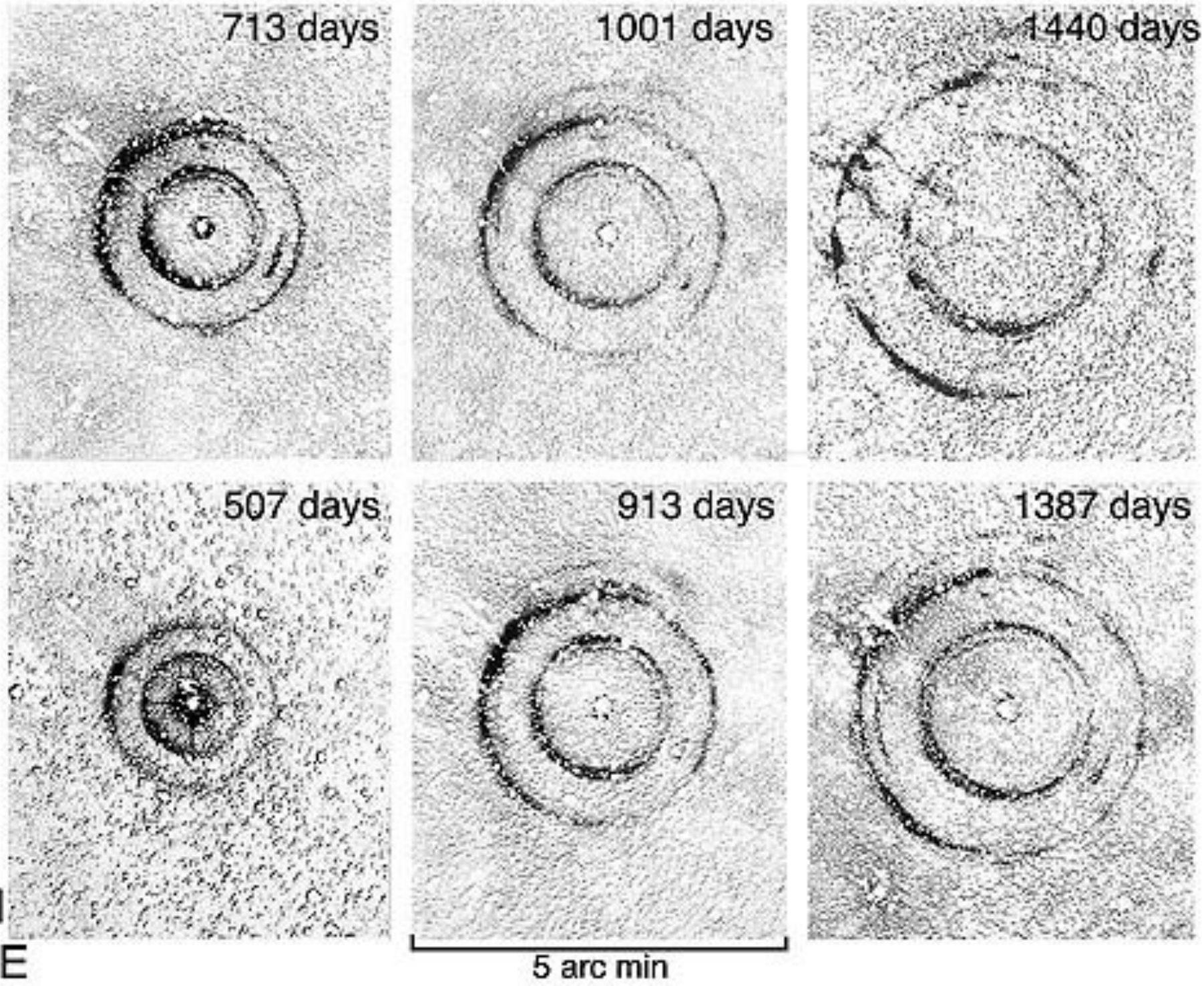
# Matz et al. 1988 (SMM)

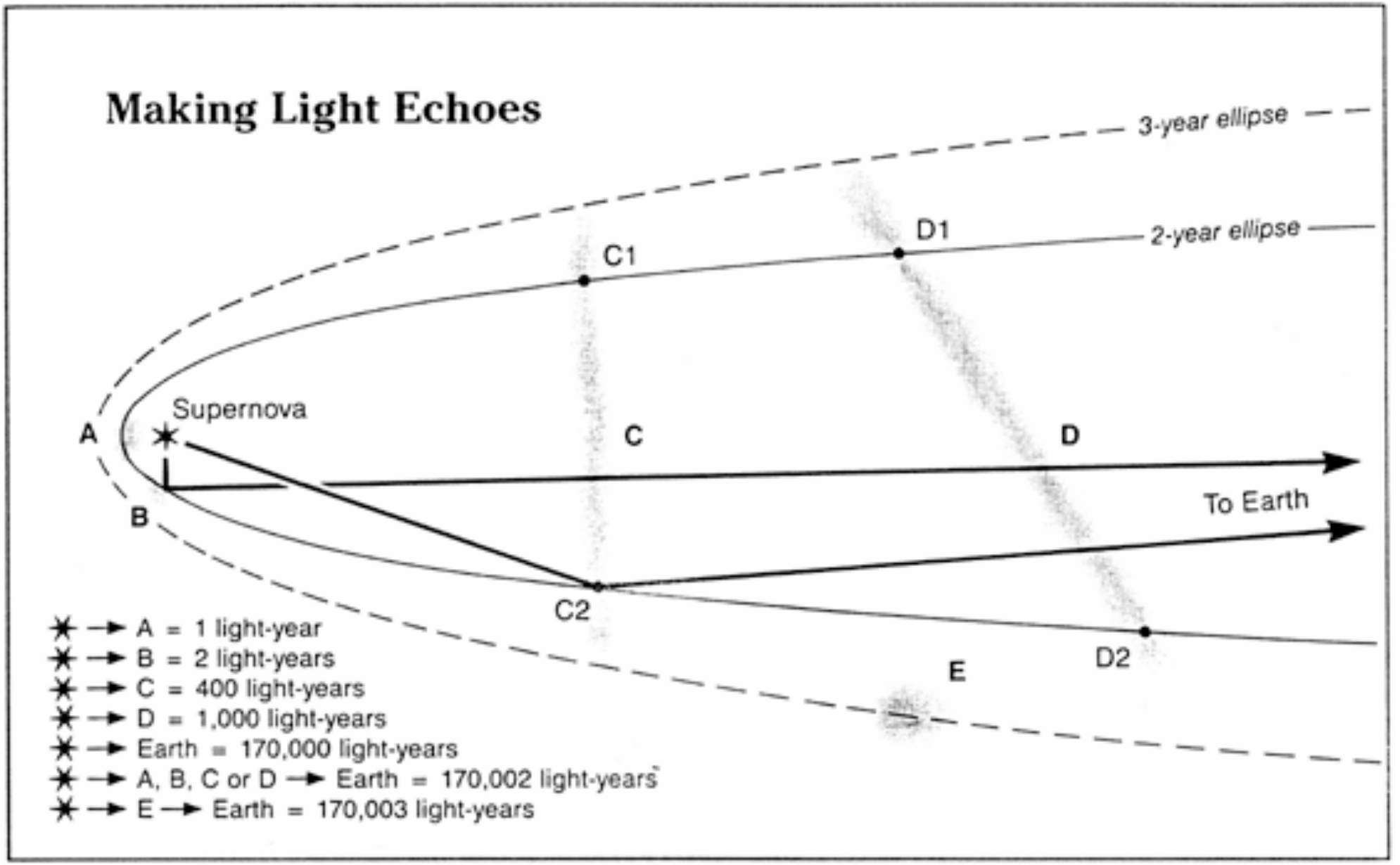


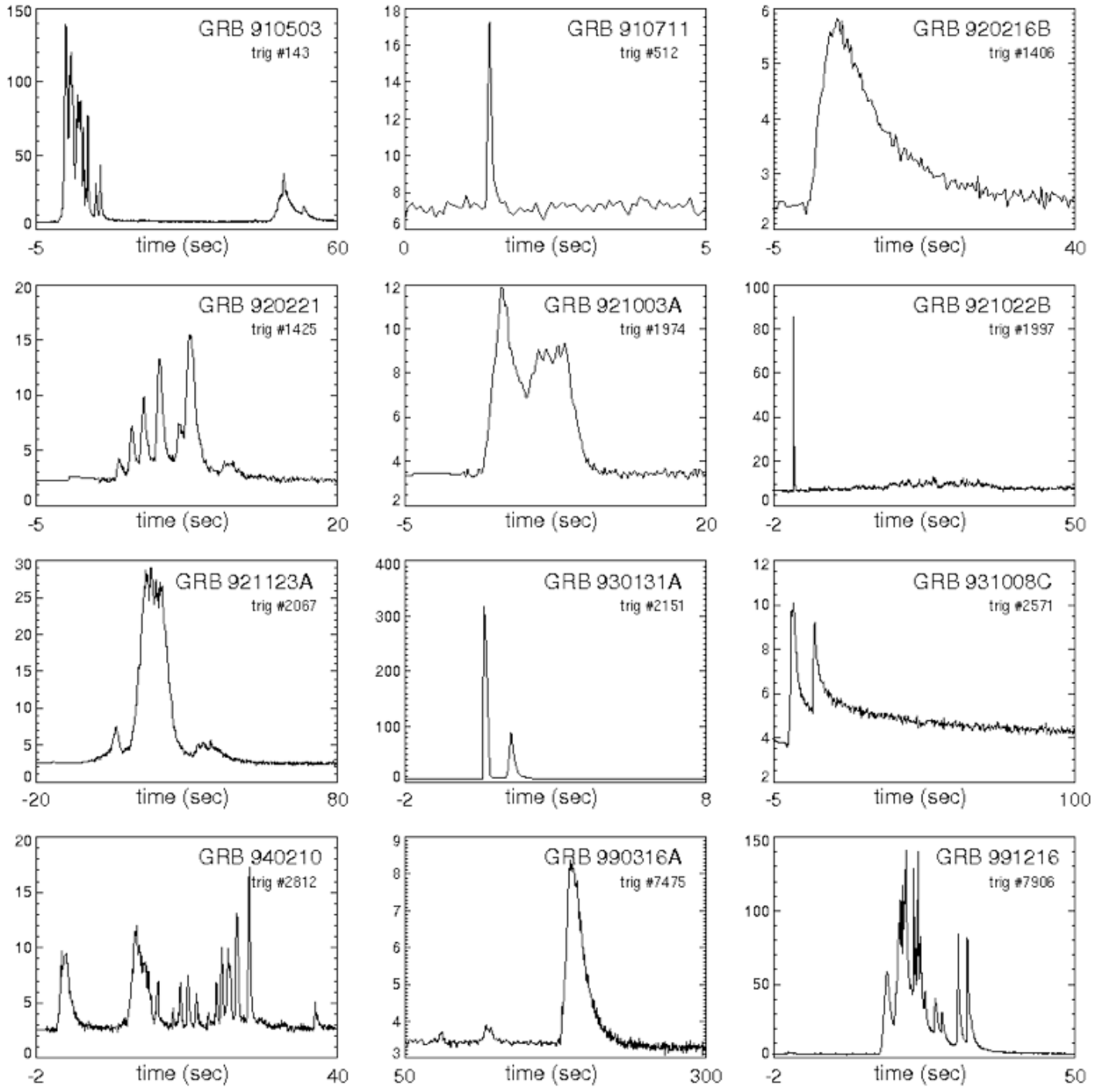



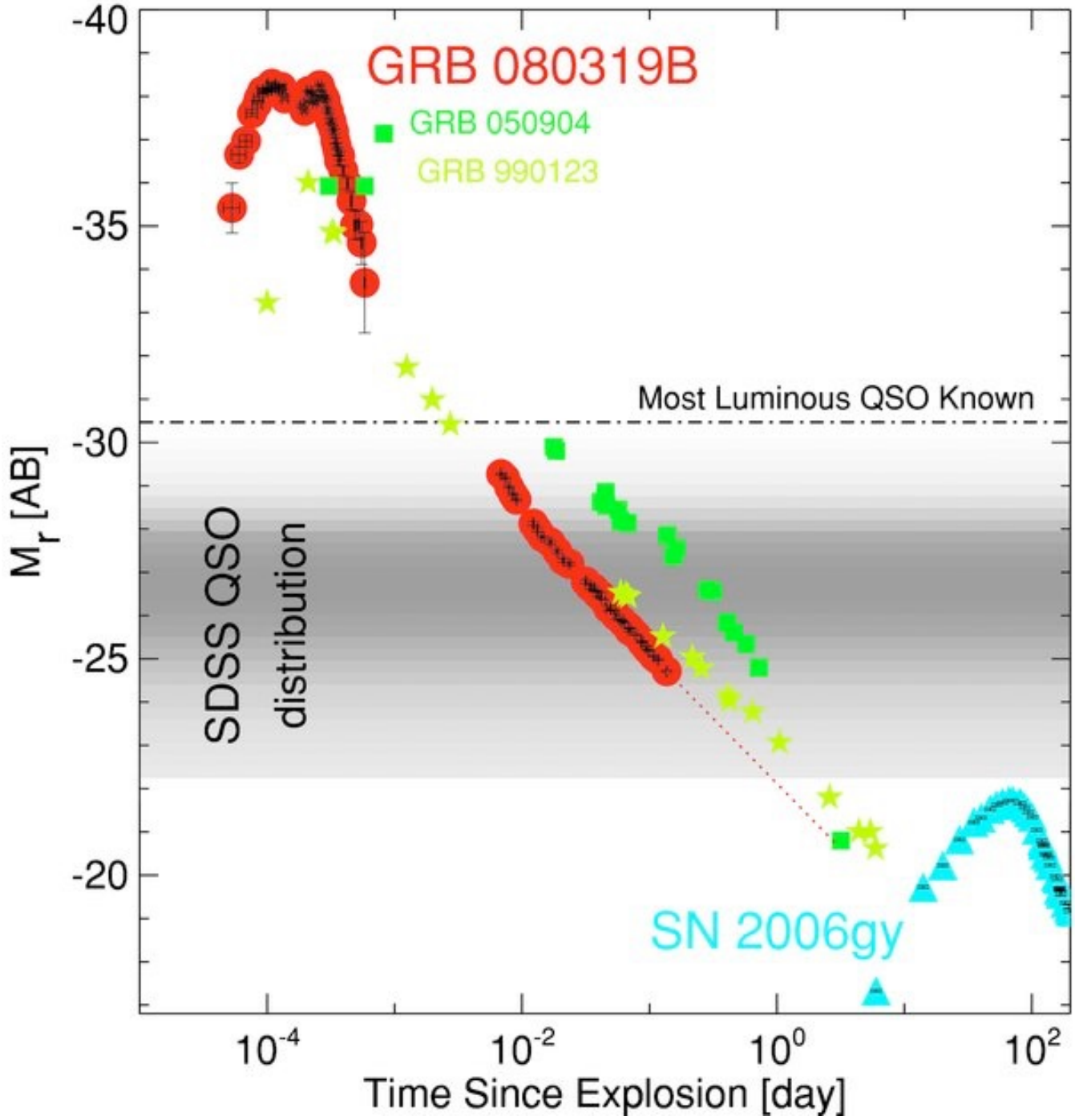




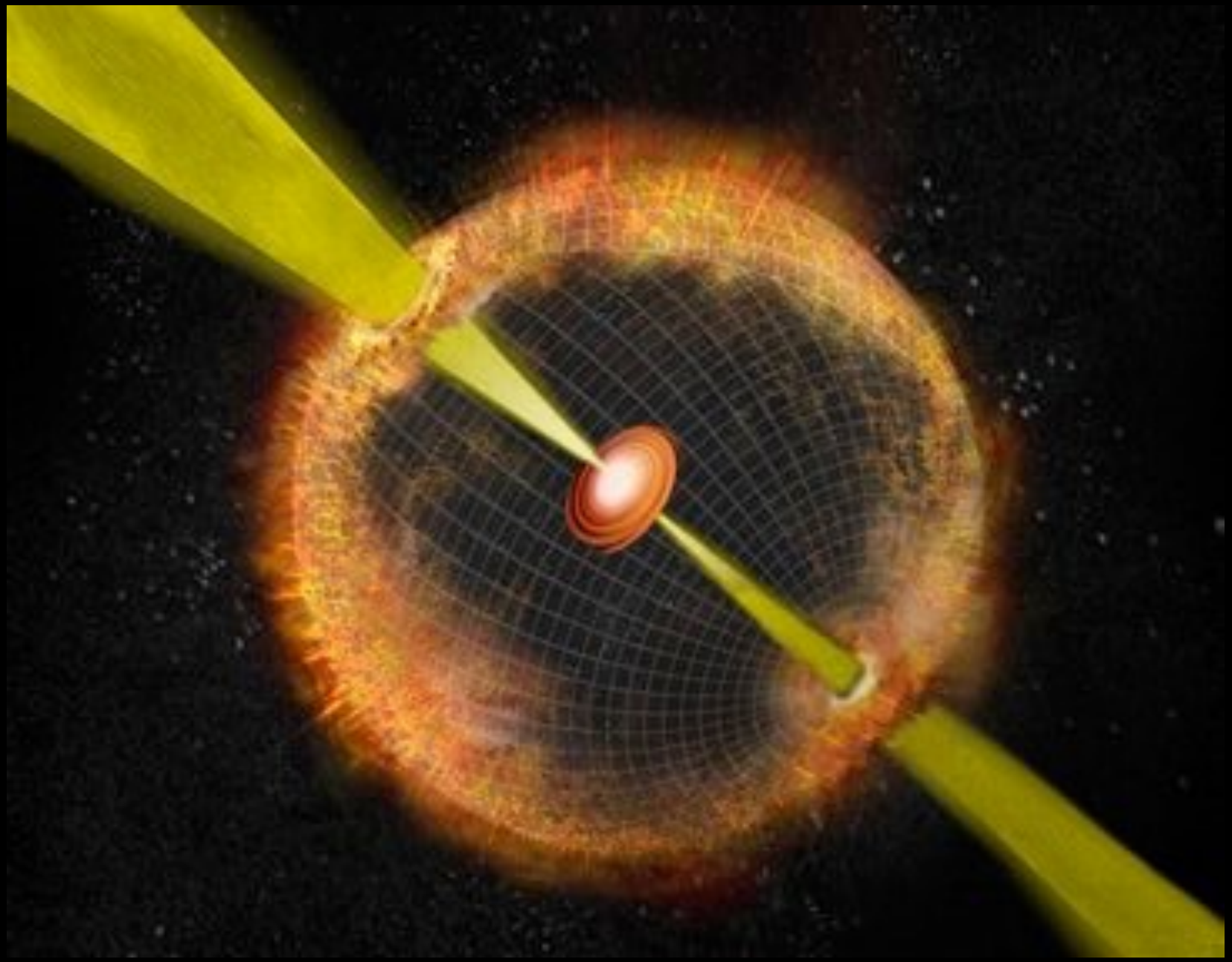

713 days
1001 days
1440 days
507 days
913 days
1387 days
N
E
5 arc min

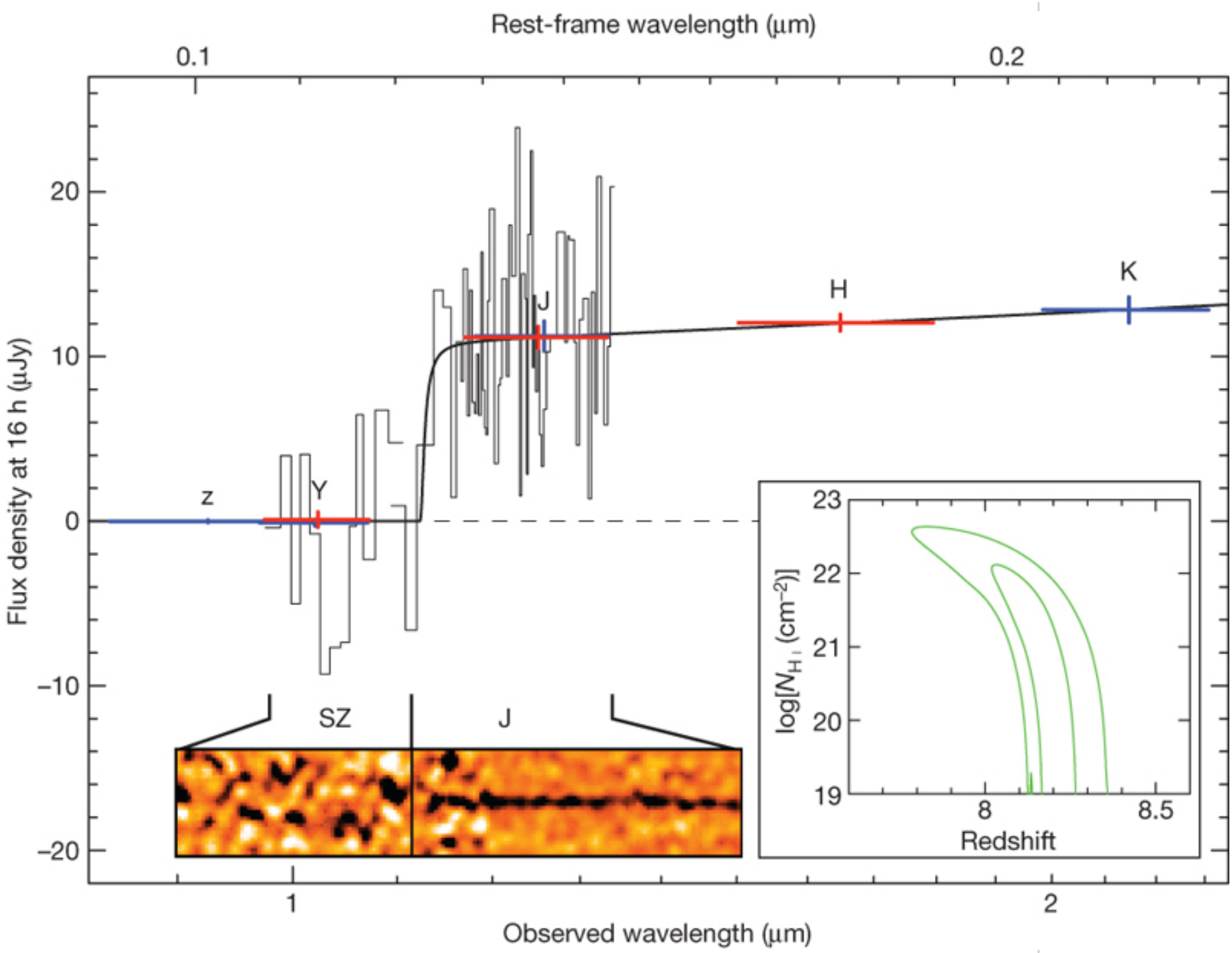

Making Light Echoes
3-year ellipse
2-year ellipse
D1
C1
Supernova
A
C
D
B
To Earth
C2
D2
E
A = 1 light-year
B = 2 light-years
C = 400 light-years
D = 1,000 light-years
Earth = 170,000 light-years
A, B, C or D → Earth = 170,002 light-years
E → Earth = 170,003 light-years


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




Bloom et al. 2009




Rest-frame wavelength (μm)
0.1
0.2
20
10
0
−10
−20
Flux density at 16 h (μJy)
z
Y
J
H
K
SZ
J
23
22
21
20
19
log[$N_{H\,I}$ (cm$^{-2}$)]
8
8.5
Redshift
1
2
Observed wavelength (μm)

Quasar

Intergalactic “Clouds”