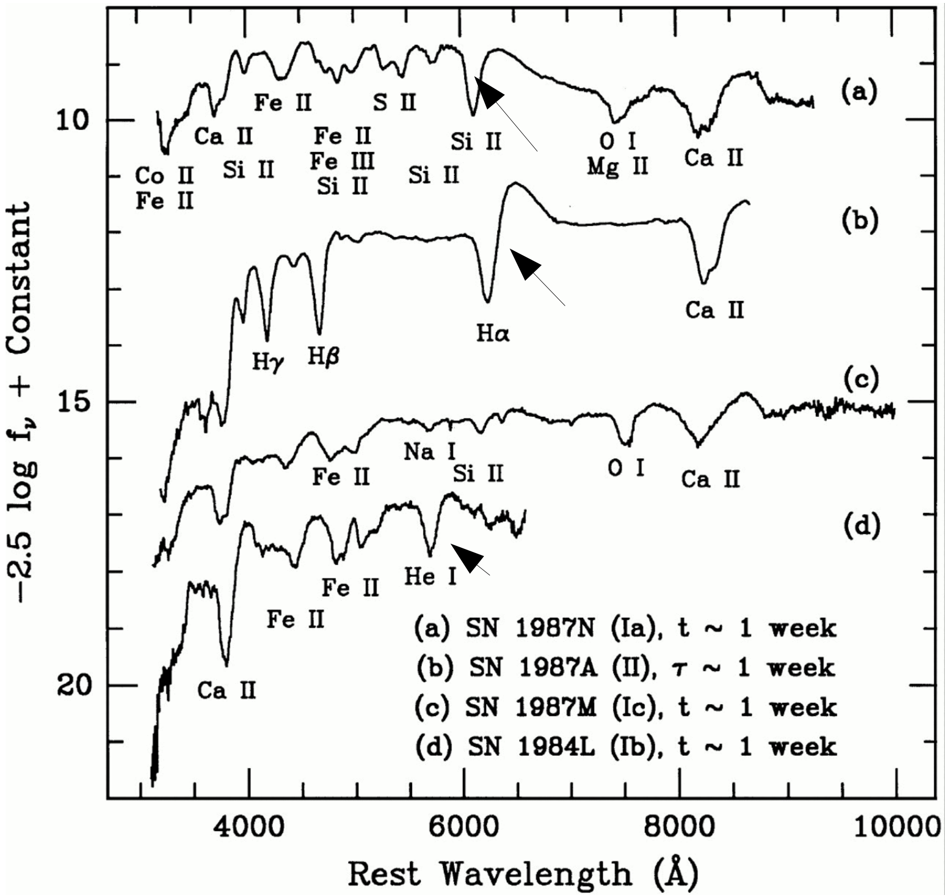
SN classification

Early spectra



Type I: no H

Type II: H

Ia: Si 6150 line

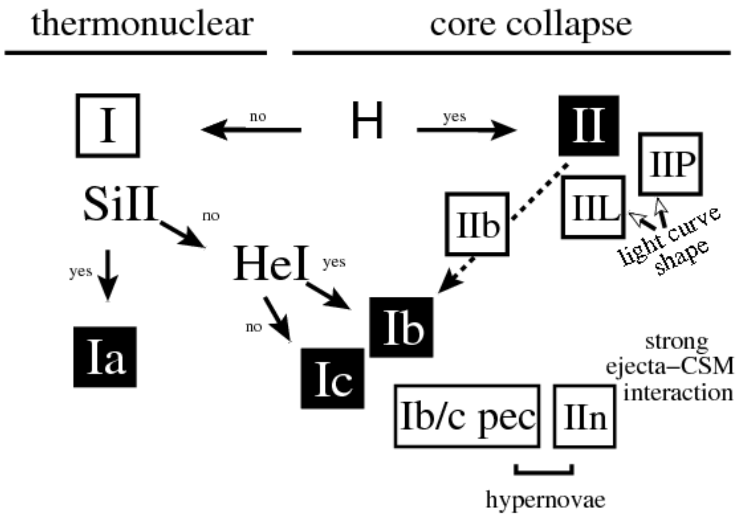
Ib/c no Si line

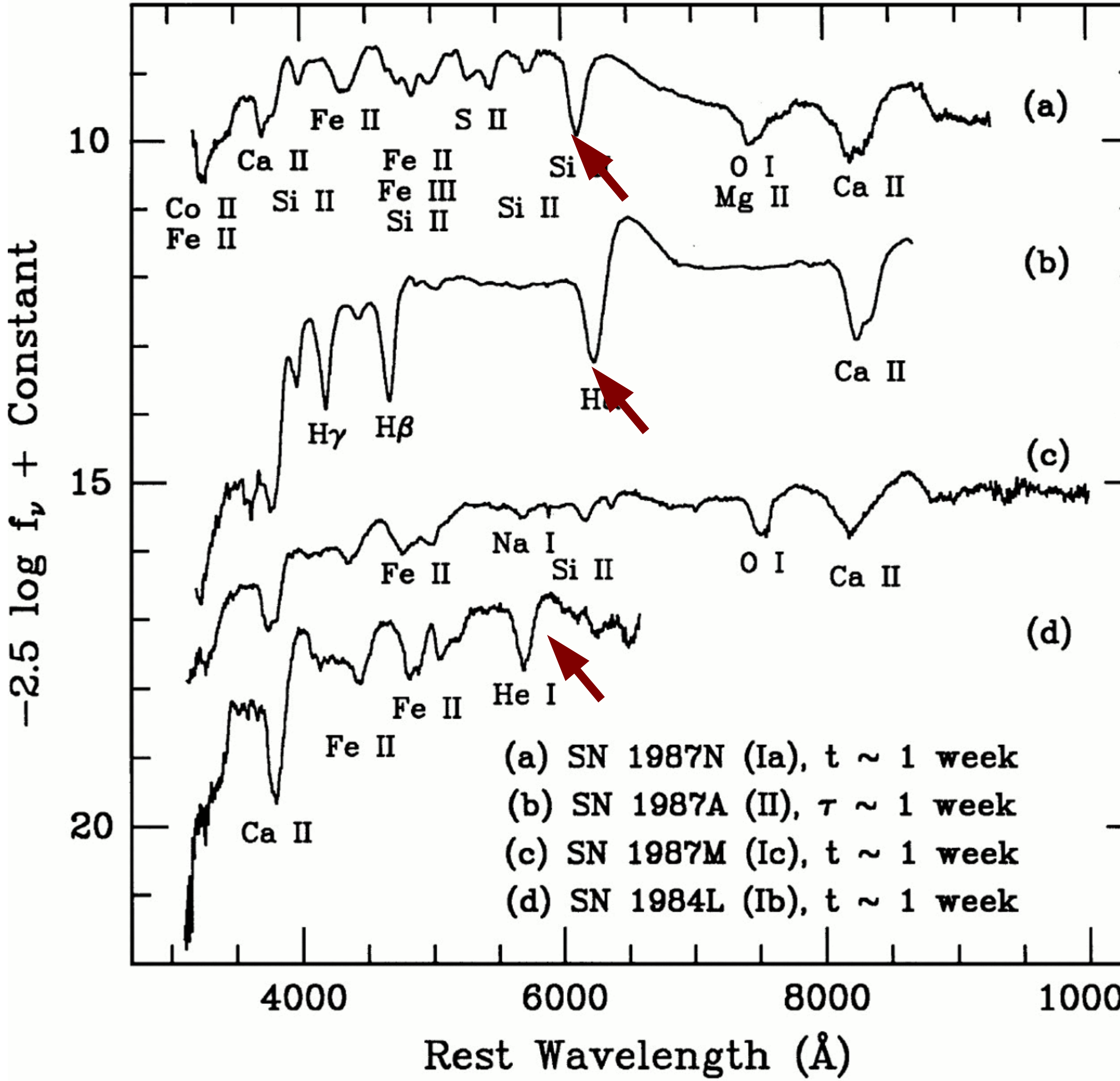
Ib He

Ic no He

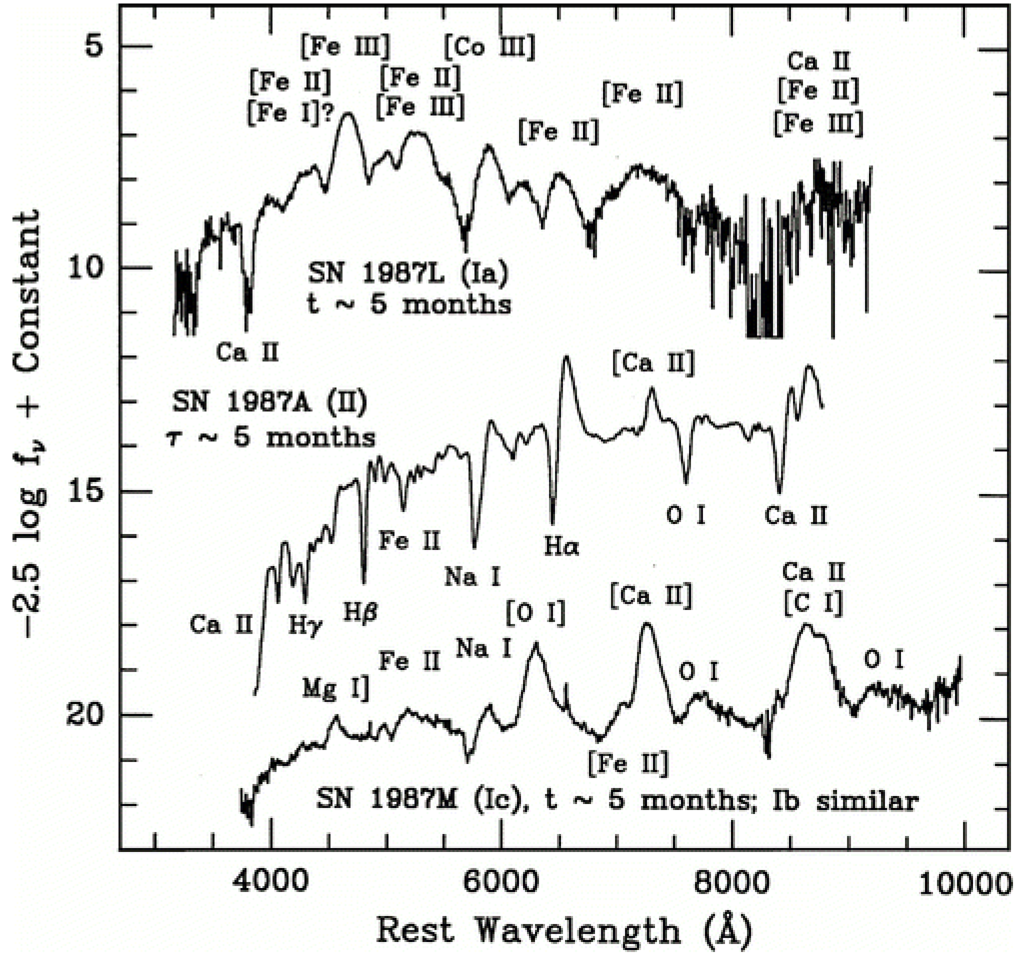
SN classification

Early spectra



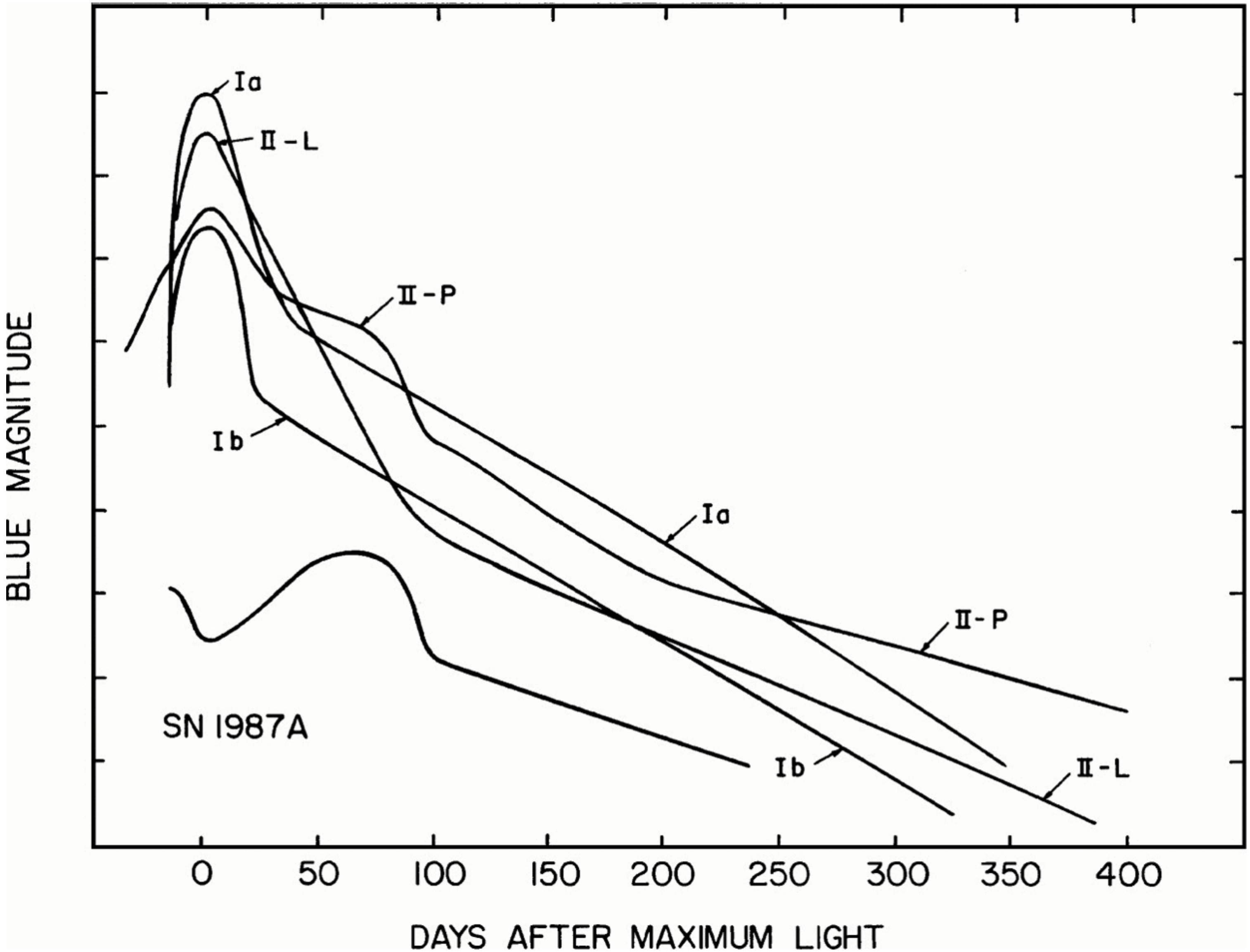


Late spectra



Type Ia: Strong Fe II-III lines

Ib/c: strong O I, Ca II, Mg I



Type IIP: Plateau ~ 100 days IIL: Linear decline

Shock break-out

$$E_{th} \approx E_{tot}/2$$

$$\epsilon V = a T^4 \frac{4\pi}{3} R^3$$

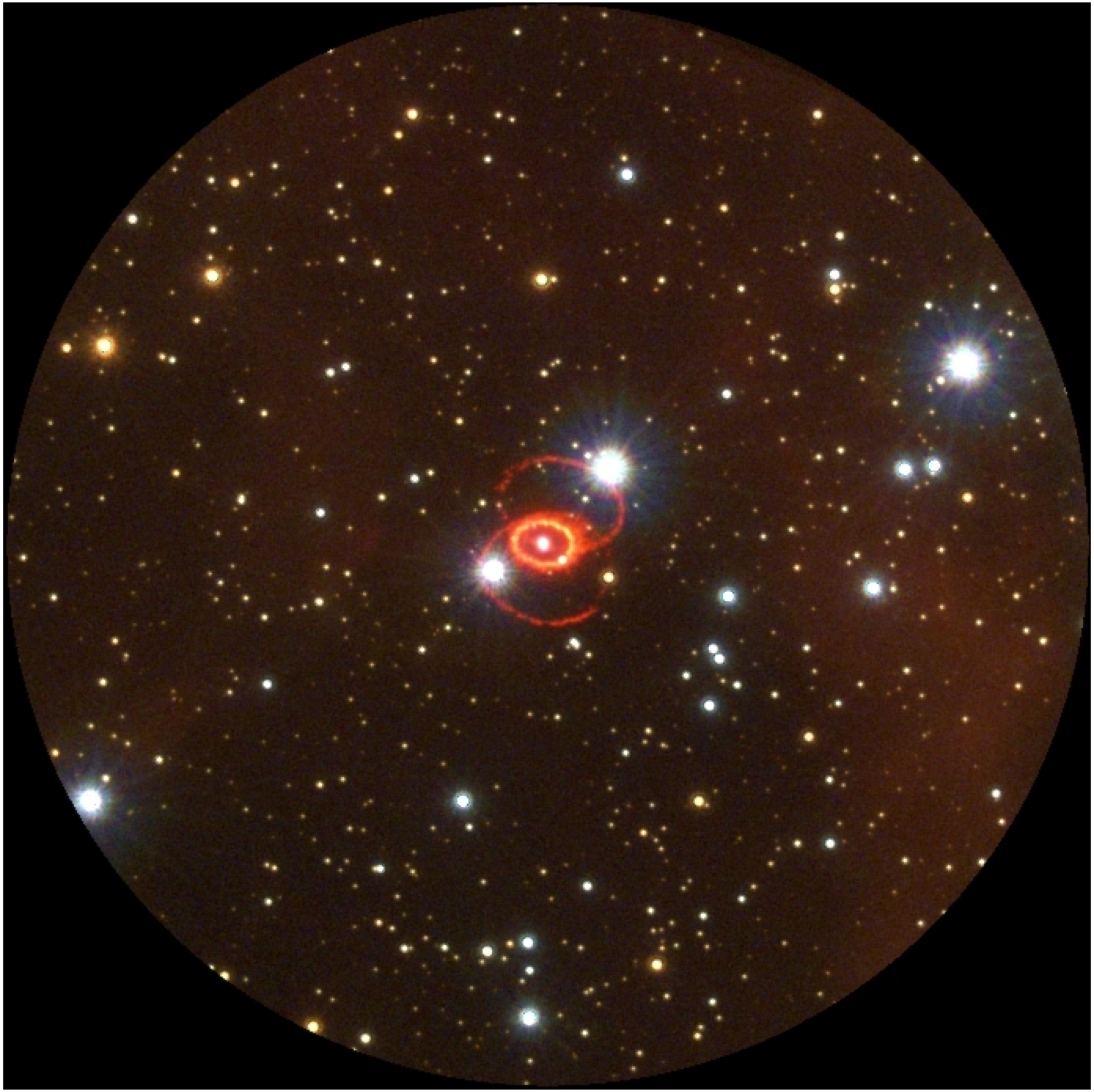
$$T_{eff} \approx 2 \times 10^5 E_{51}^{1/4} R_{13}^{-3/4}$$

Scatterings $\Rightarrow$ $T_{color} \sim 2\ T_{eff}$

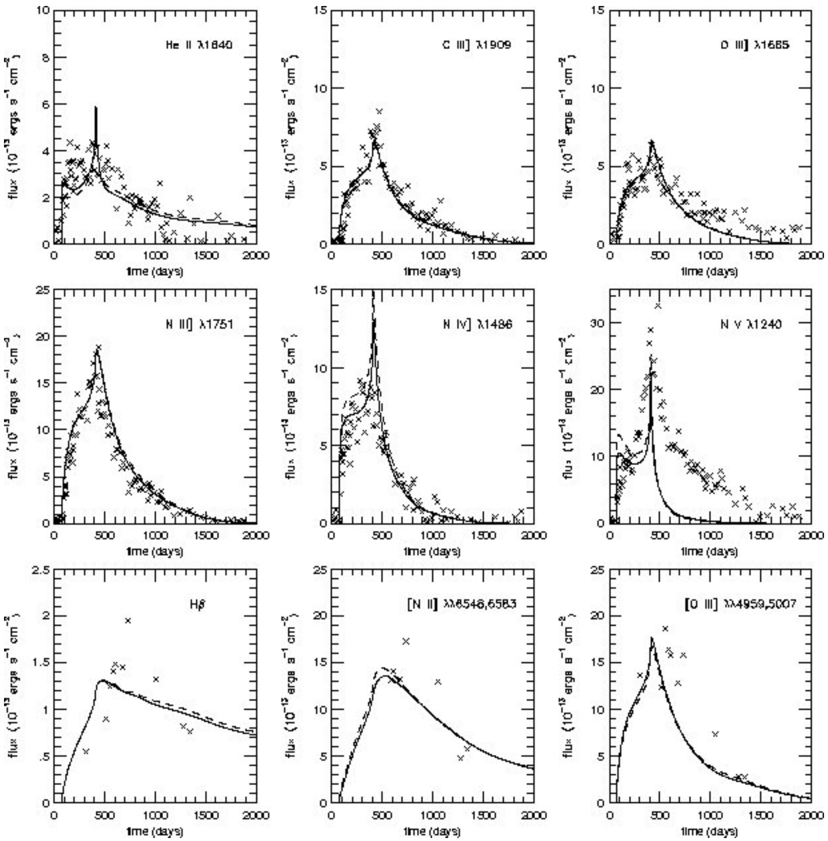
RSG R ~ 10^{13}-10^{14} cm T < 5×10^4 K

WR R ~ 10^{11} cm T ~ 5×10^6 K

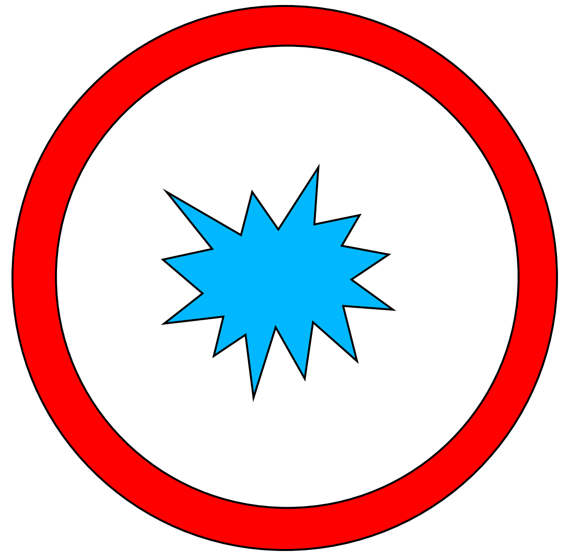
The Ring



What makes the rings glow?



P. Lundqvist + CF 96



X-ray flash at shock breakout

during first hour + recombination

+ light echo of ring

Radius ~ 190 light days

Shock break-out in SN 1987A

BSG R ~ 2×10^{12} cm E ~ 1.5×10^{51} ergs T_{eff} ~ 4×10^{5} K

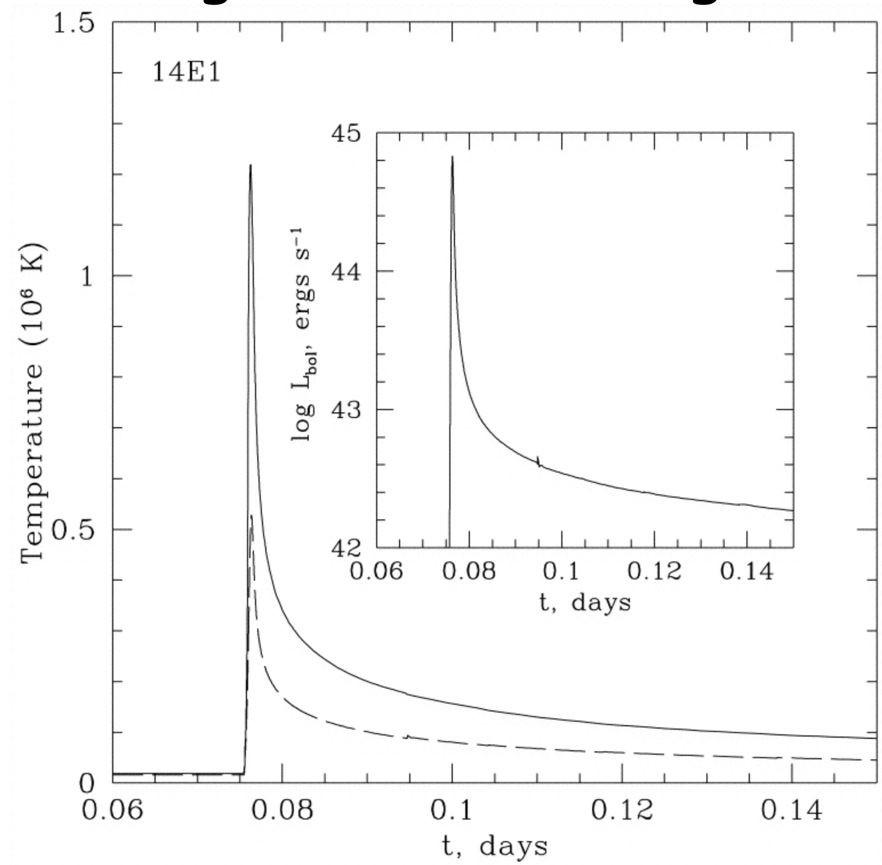
T_{color} ~ 10^{6} K τ ~ 3-4 min L ~ 10^{45} erg s^{-1} E ~ 10^{47} ergs

Ionization and heating of rings of SN 1987A

Observe N III-N V

Needs T_{color} ~ 10^{6} K !

Break-out confirmed years later!



Diffusion phase

$$t_{diff} \approx \frac{R^2 \rho \kappa}{3 \pi^2 c}$$

$$t_{\exp} \approx \frac{R}{V}$$

$$\frac{t_{diff}}{t_{\exp}} \approx 0.2 \frac{M}{M_O} \frac{V}{10^4 \, km \, s^{-1}} \left(\frac{R^2}{10^{15} \, cm} \right)^{-2}$$

$M \sim 10 \, M_O$ $R_{peak} \sim 10^{15}$ cm

Up to R_{peak} radiation is trapped $\Rightarrow$ adiabatic expansion

from R_O to R_{peak}

Diffusion phase

$$E_{int} = (\gamma - 1)\, p V = \frac{1}{3} K \rho^{4/3} V \propto R^{-1}$$

Small R_o $\Rightarrow$ most internal energy lost in adiabatic expansion $\Rightarrow$ faint SN!

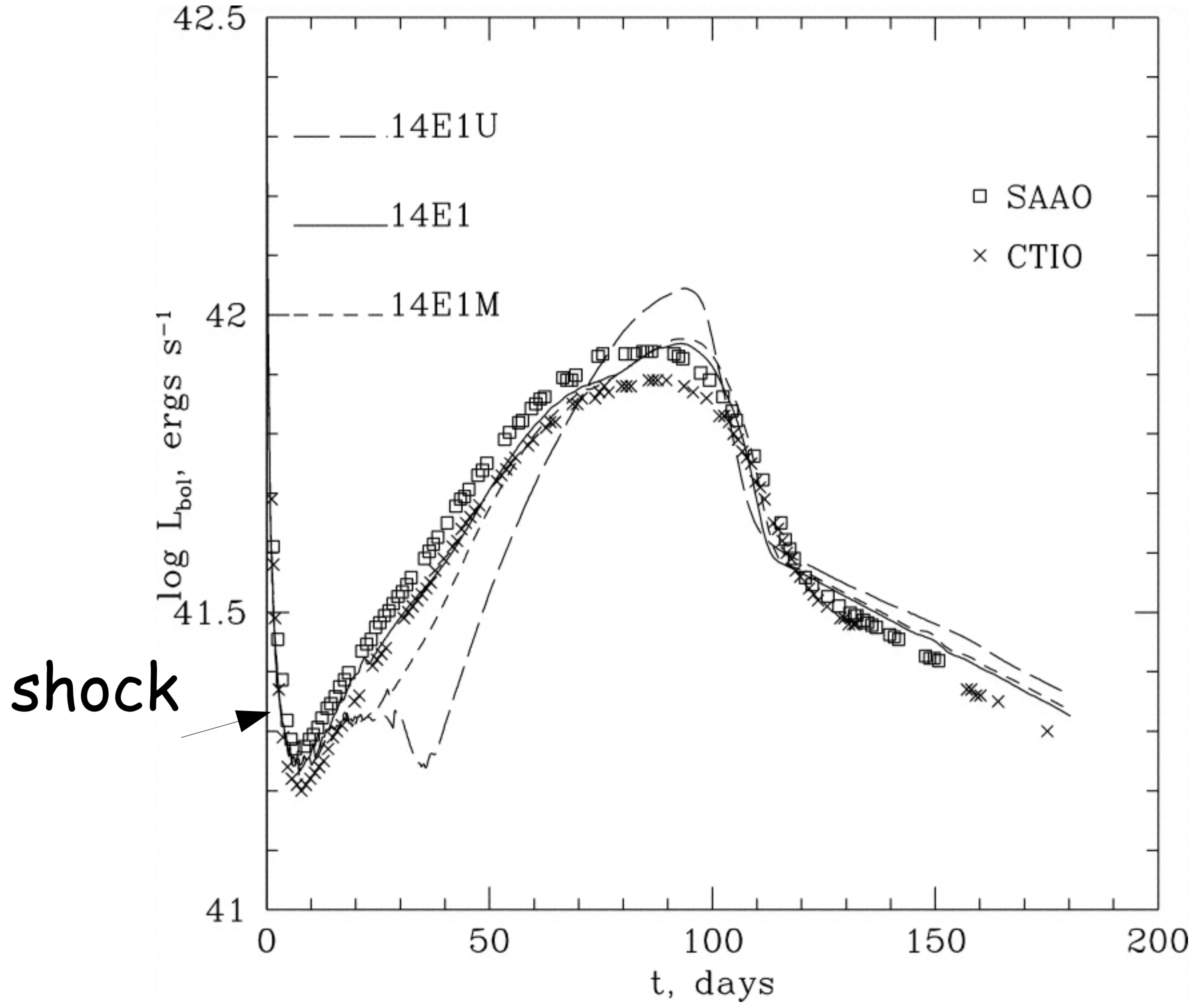
RSG progenitors: Shock energy may power LC for ~ 100 days

BSG progenitors, WR stars: Shock energy lost

Need other energy source

SN 1987A

progenitor BSG   R ~ 10^{12} cm

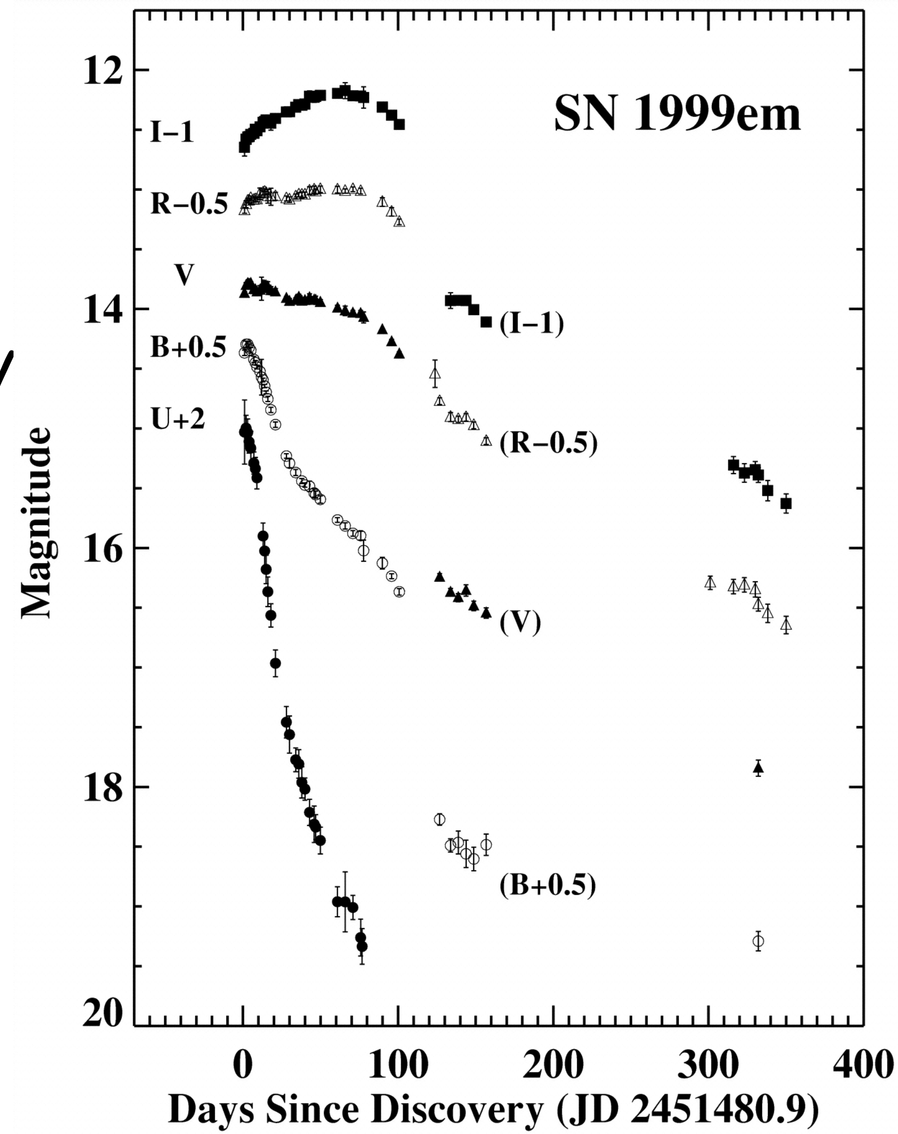


Plateau phase

$R_0 \sim 10^{14}$ cm $\Rightarrow$ adiabatic expansion not important

$\Rightarrow$ diffusive release of shock energy

$t_{diff} \sim 100$ days $\Rightarrow$ plateau



Radioactivity

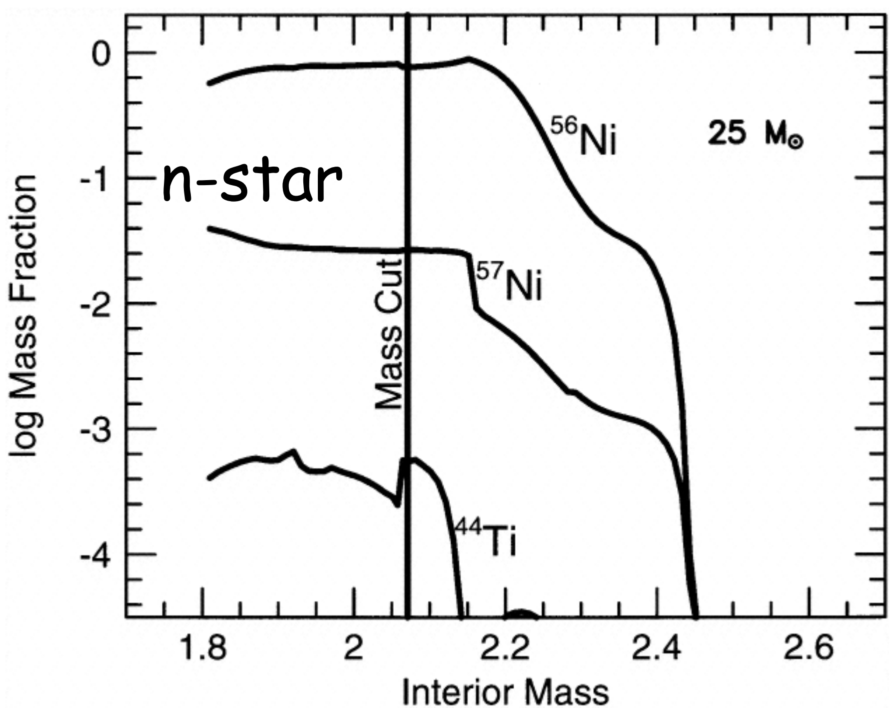
$^{56}Ni \rightarrow\rightarrow {}^{56}Co + \gamma \rightarrow {}^{56}Fe + \gamma \qquad \tau = 111$ days

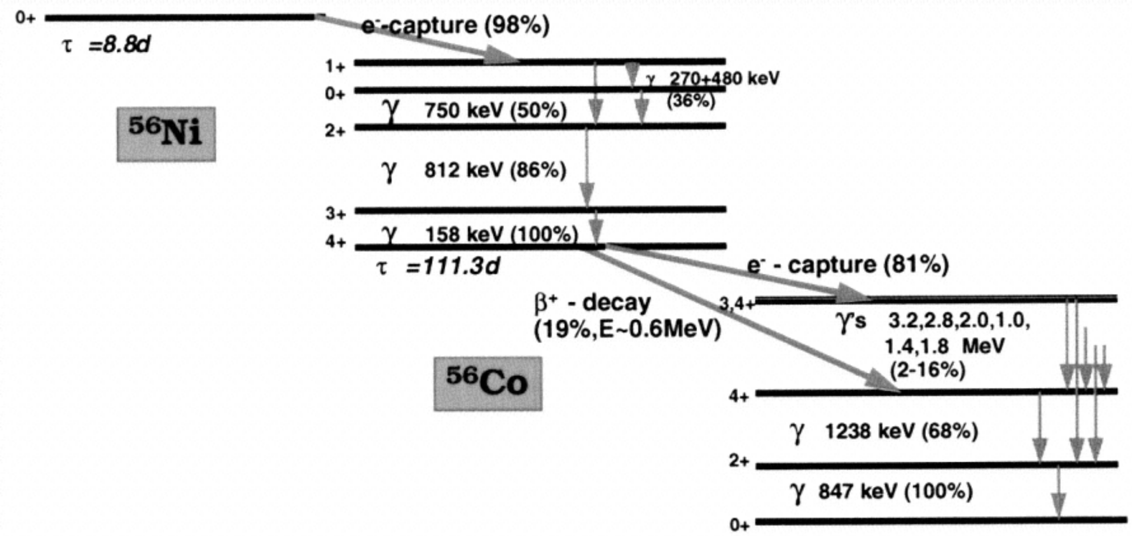
$+ e^{+}$

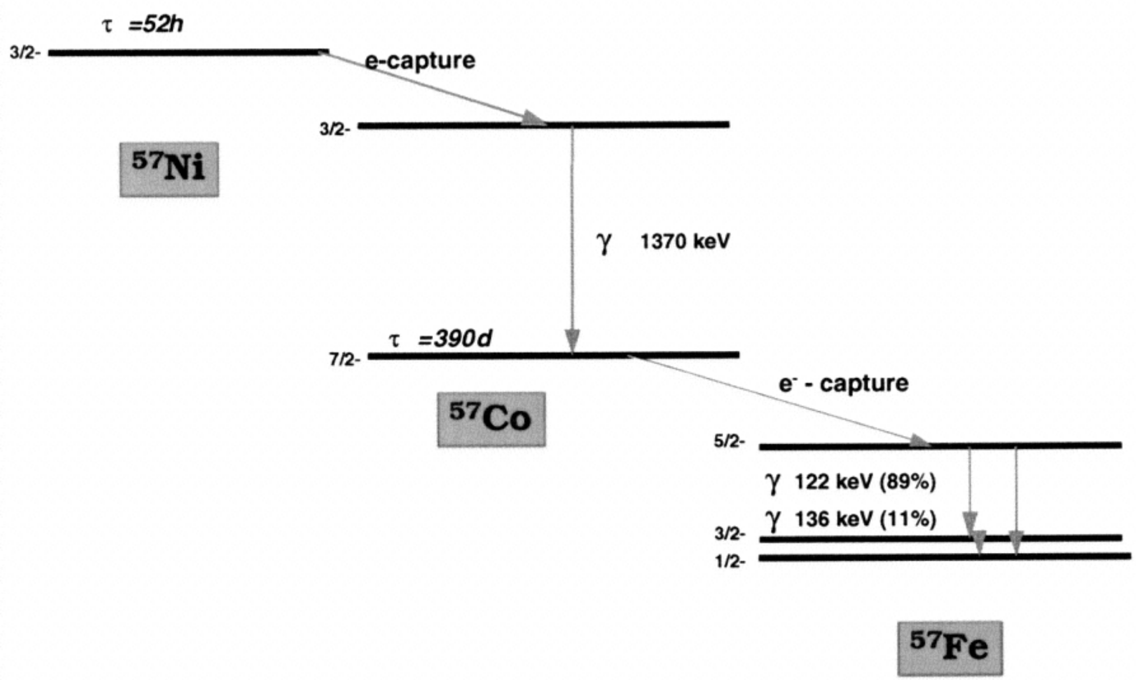
$^{57}Ni \rightarrow {}^{57}Co + \gamma \rightarrow {}^{57}Fe + \gamma \qquad \tau = 395$ days

$^{44}Ti \rightarrow\rightarrow {}^{44}Sc + \gamma \rightarrow {}^{44}Ca + \gamma \qquad \tau = 78$ years

$+ e^{+}$




0+
τ =8.8d
e⁻-capture (98%)
1+
0+
2+
γ 270+480 keV
(36%)
γ 750 keV (50%)
56Ni
γ 812 keV (86%)
3+
γ 158 keV (100%)
4+
τ =111.3d
e⁻ - capture (81%)
β⁺ - decay
(19%,E~0.6MeV)
3,4+
γ's 3.2,2.8,2.0,1.0,
1.4,1.8 MeV
(2-16%)
56Co
4+
γ 1238 keV (68%)
2+
γ 847 keV (100%)
0+


τ =52h
3/2-
e-capture
3/2-
57Ni
γ 1370 keV
τ =390d
7/2-
57Co
e⁻ - capture
5/2-
γ 122 keV (89%)
γ 136 keV (11%)
3/2-
1/2-
57Fe

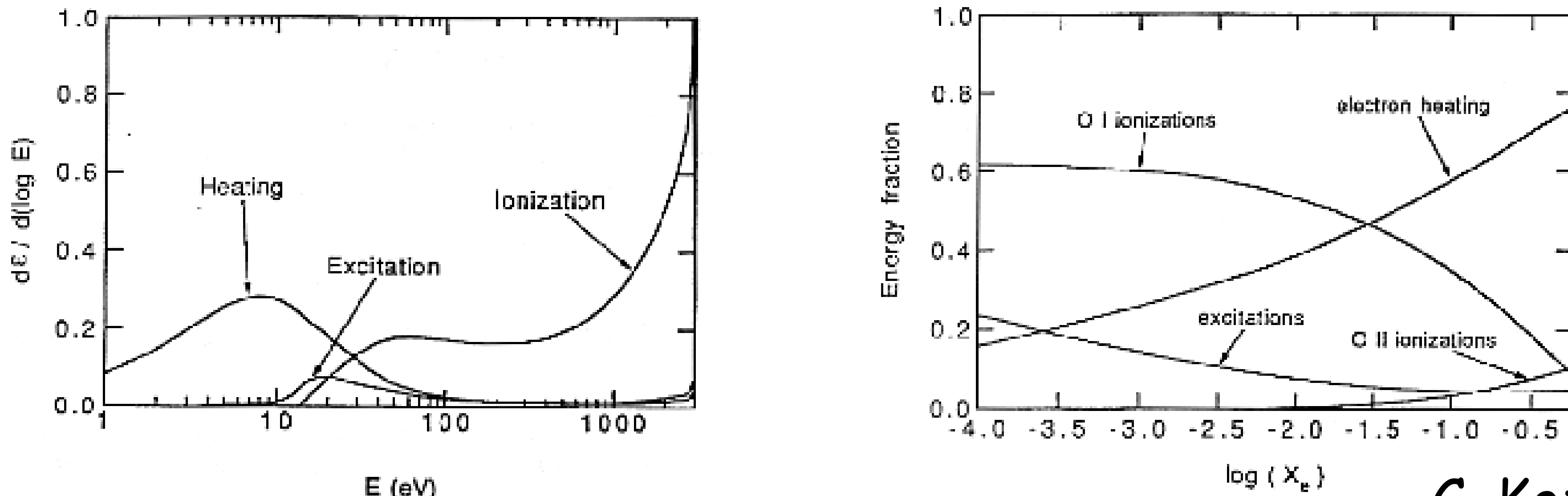
Gamma-ray thermalization

Gamma-rays -> non-thermal electrons (10 eV – 100 keV)

non-thermal electrons -> ionizations, excitations, heating

ionizations -> recombinations, excitations -> rad. decays,

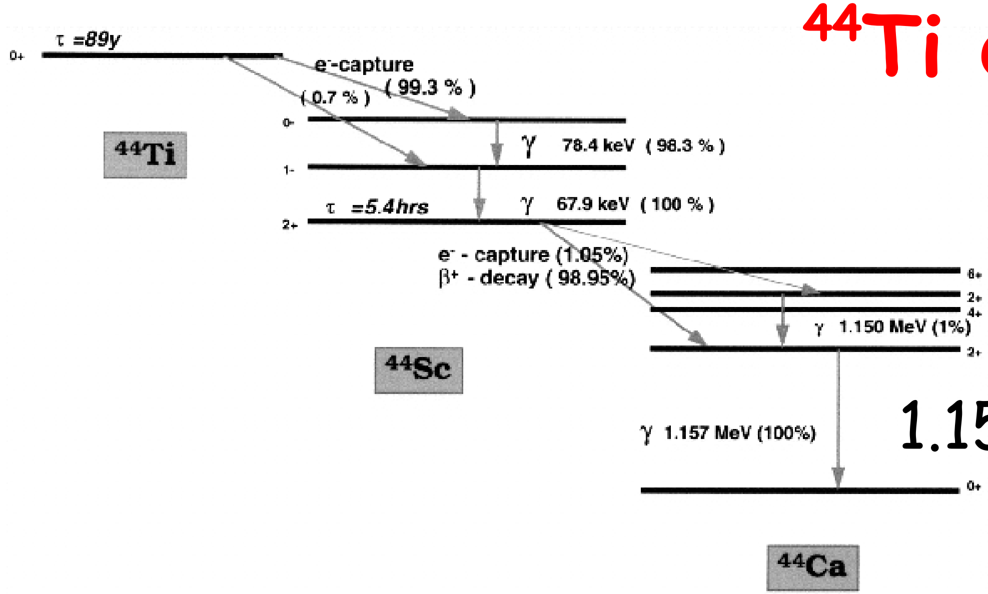
heating -> coll. excit. -> rad. decays



C. Kozma

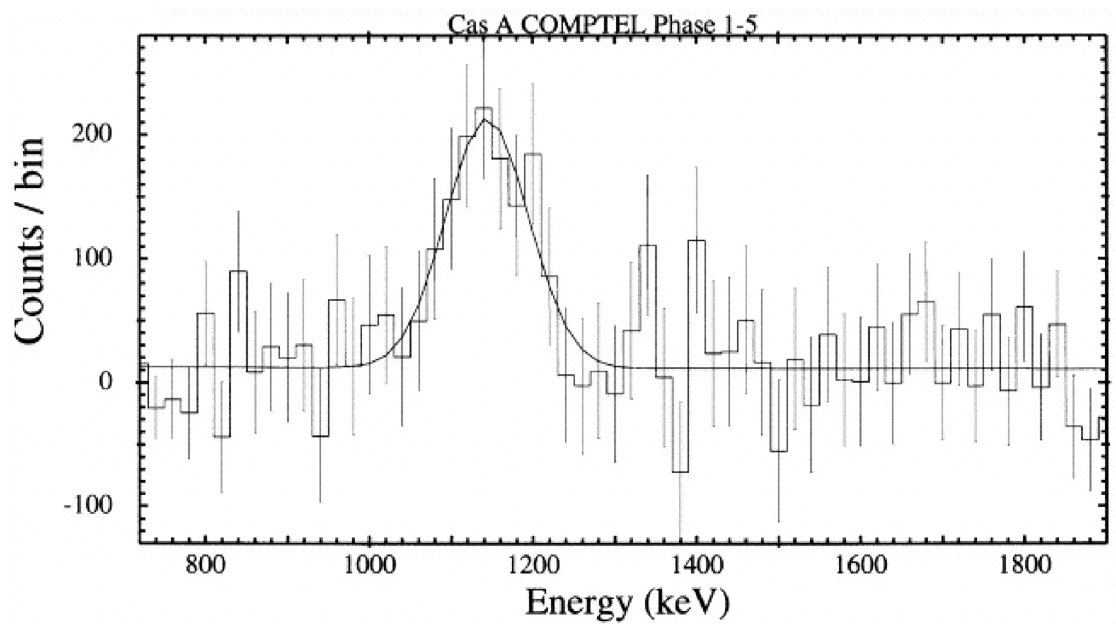
Gamma-rays thermalized to UV/optical/IR photons

^{44}Ti decay



1.157 MeV

Cas A



Radioactivity

$^{56}Ni \rightarrow\rightarrow {}^{56}Co + \gamma \rightarrow\rightarrow {}^{56}Fe + \gamma$ 81 % 96.4 % energy

$+ e^+$ 19 % 3.6 %

τ = 8.8 days τ = 111 days

Gammas

$$L_\gamma = 1.27\times 10^{42}\left(\frac{M(^{56}Ni)}{0.1\ M_{sun}}\right) e^{-t/111.3d}$$

positrons

$$L_+ = 4.44\times 10^{40}\left(\frac{M(^{56}Ni)}{0.1\ M_{sun}}\right) e^{-t/111.3d}$$

positrons trapped (large cross section)

gammas scattered

$$L_{bol} = L_\gamma[(1-e^{-\tau_\gamma})+0.035]\quad erg\ \ s^{-1}$$

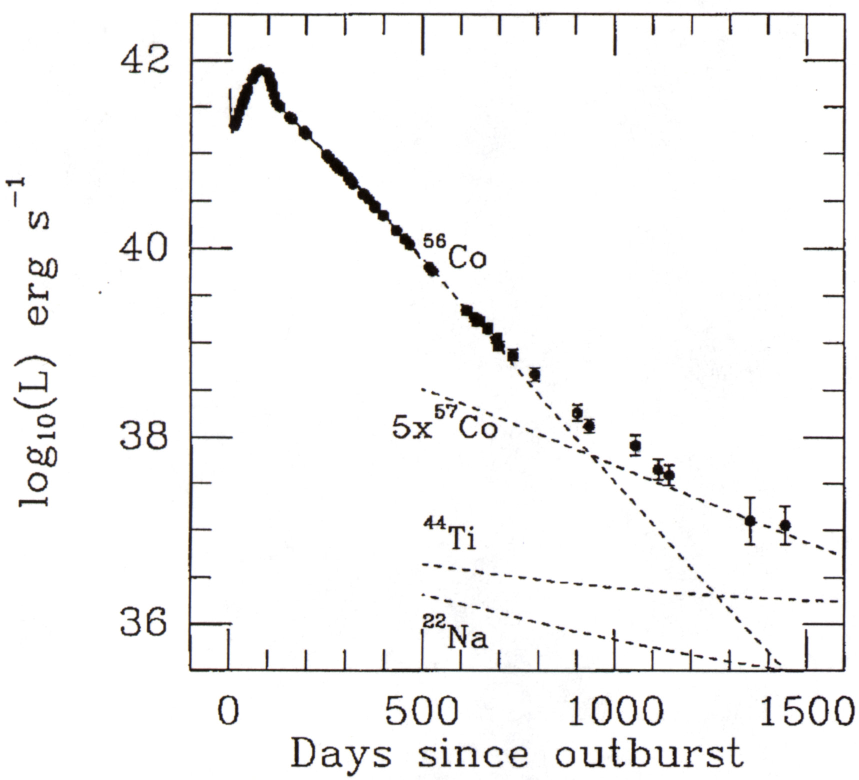
$$\tau_\gamma = \kappa_\gamma \rho R = \kappa_\gamma \frac{3}{4\pi}\frac{M}{V^2 t^2} = 0.38\frac{Z}{A}\left(\frac{M}{M_{sun}}\right)\left(\frac{V}{10^4\ \ km\ \ s^{-1}}\right)^{-2}\left(\frac{t}{100\ \ days}\right)^{-2}$$

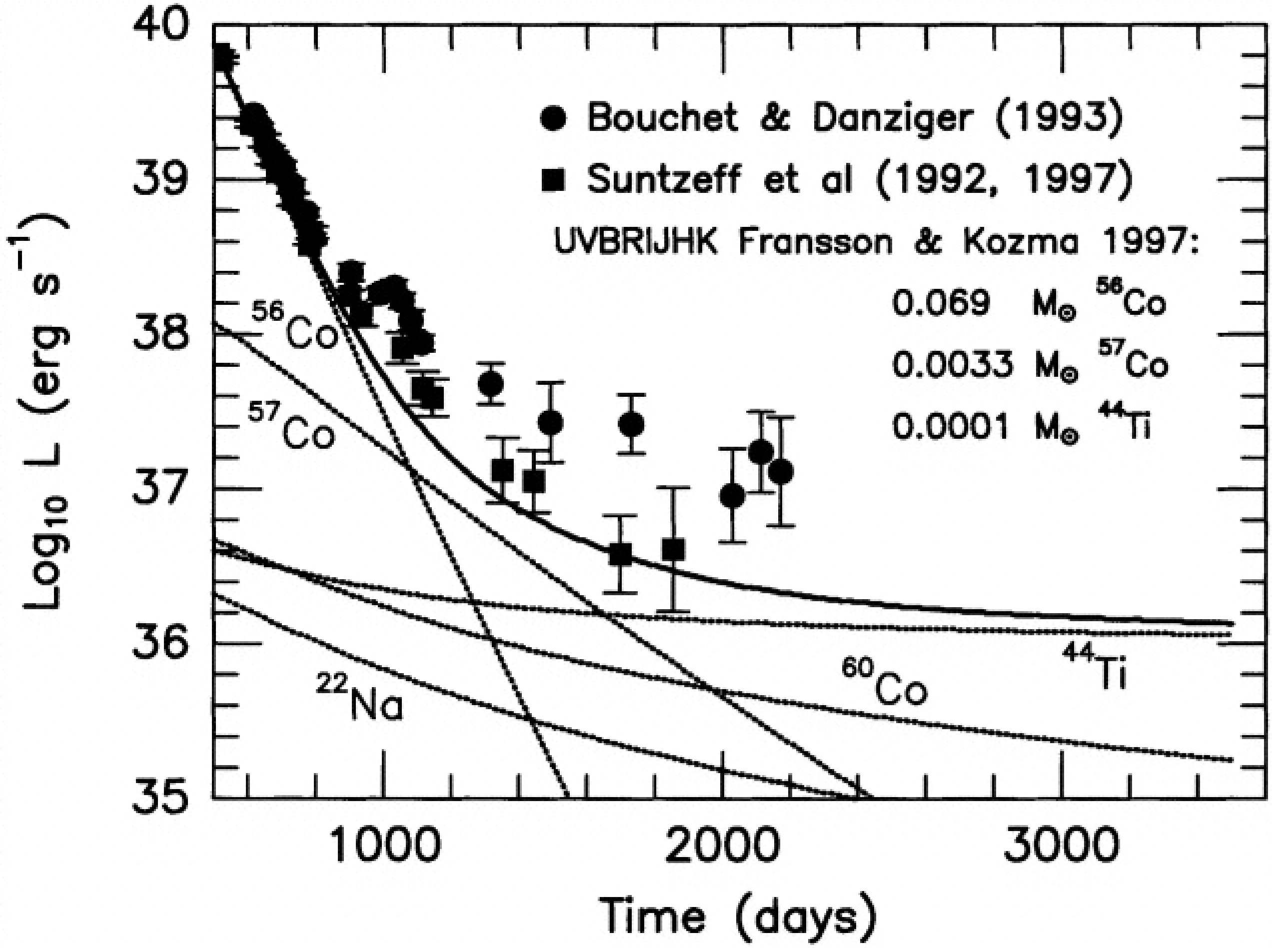
SN 1987A

$M_{core} \approx 4 \quad M_{sun} \qquad V_{core} \approx 2000 \quad km \quad s^{-1}$

$$\tau_{\gamma} \approx 40 \left(\frac{t}{100 \quad days} \right)^{-2}$$

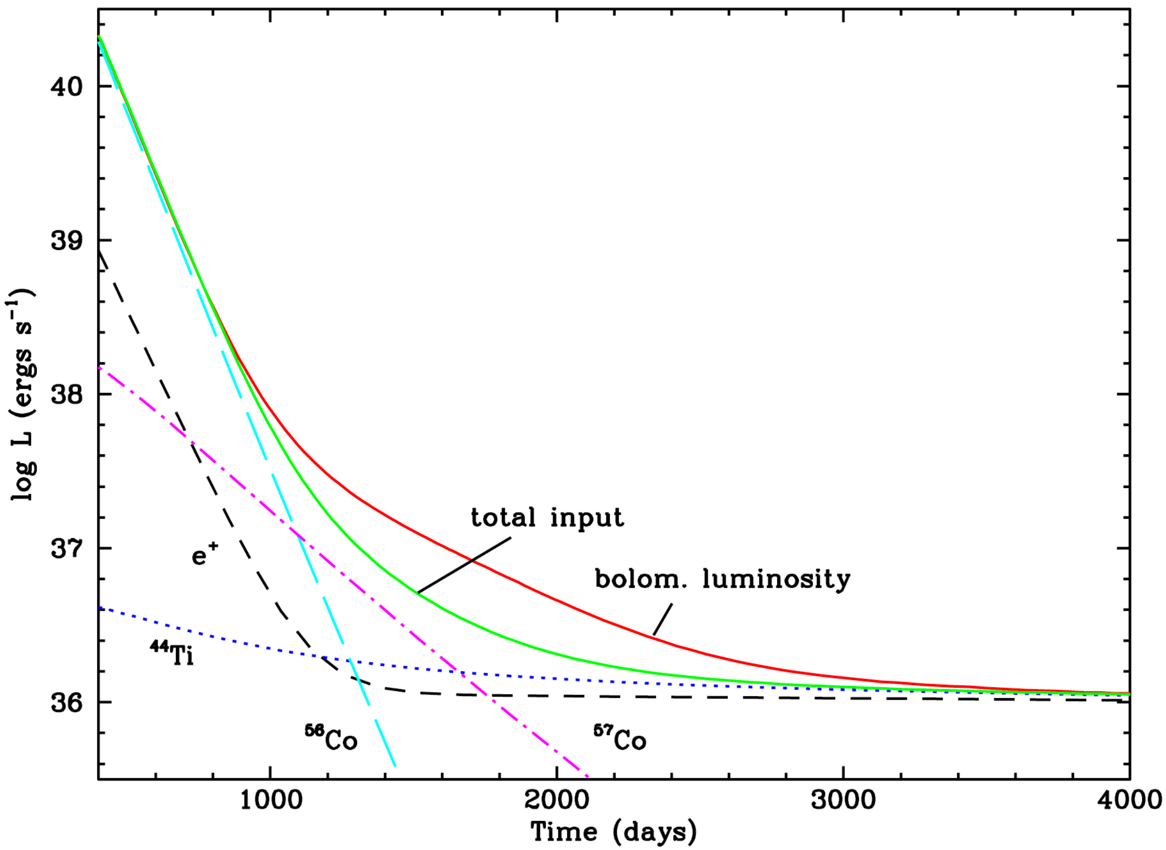
$$M_{bol} = -t \frac{2.5 \log e}{11.3 \quad days} + const = -\frac{t}{102.5 \quad days} + const$$




Bouchet & Danziger (1993)
Suntzeff et al (1992, 1997)
UVBRIJHK Fransson & Kozma 1997:
0.069 M⊙ 56Co
0.0033 M⊙ 57Co
0.0001 M⊙ 44Ti
56Co
57Co
22Na
60Co
44Ti
Log10 L (erg s−1)
Time (days)
40
39
38
37
36
35
1000
2000
3000

SN 1987A radioactivities

C. Kozma + CF

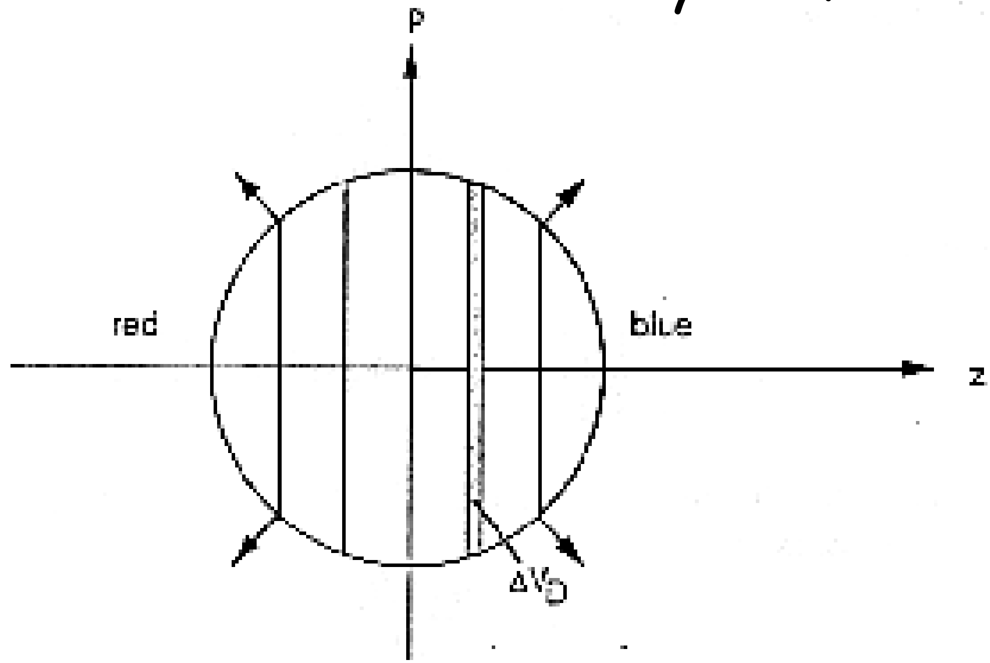


$M(^{56}Ni) = 0.07\ M_O$, $M(^{57}Ni) = 3\times10^{-3}\ M_{O,}$ $M(^{44}Ti) = 1\times10^{-4}\ M_O$

Sobolev approximation

$$\frac{\nu-\nu_0}{\nu_0}=\frac{V_z}{c}=\frac{z}{r}V\frac{(r)}{c}= \text{ constant}$$

constant velocity surface



Homologous exp. $V(r)=V_0\frac{r}{R_0}=\frac{r}{t}$

$$\frac{z}{R_0}=\frac{ct}{R_0}\frac{(\nu-\nu_0)}{\nu_0}$$

$$\tau_\nu=\sigma_\nu n_1 \delta l$$

$$\sigma_\nu=\frac{\pi e^2}{mc}\frac{f_{12}}{\Delta\nu_D}$$

$$\delta l=\frac{\partial r}{\partial V}\Delta V_D=\left[\frac{\partial}{\partial r}\left(\frac{V_0}{R_0}r\right)\right]^{-1}\Delta V_D = \frac{R_0}{V_0}\Delta V_D = \frac{\Delta\nu_D}{\nu}ct$$

$$\tau = \frac{A_{21} \lambda^3 g_2}{8 \pi g_1} \left(n_1 - \frac{g_1}{g_2} n_2 \right) t.$$

$$\beta = \frac{1}{2} \tau \int_0^{\tau} \int_{-1}^{1} e^{-\tau'} d\mu \quad d\tau' = \frac{1 - e^{-\tau}}{\tau}.$$

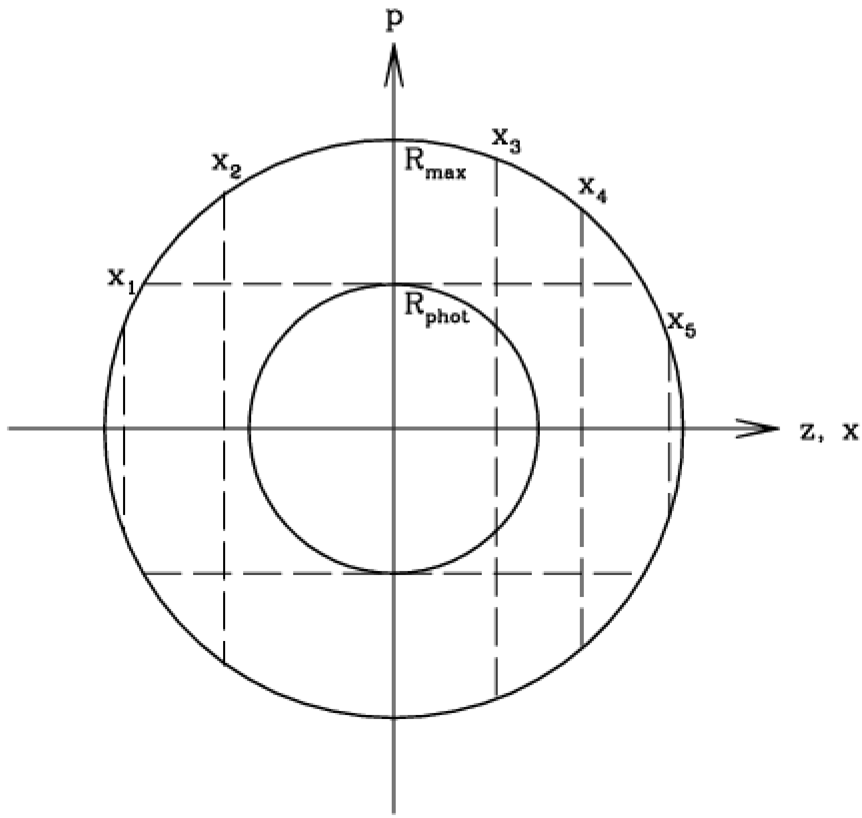
= Sobolev approx

$$S = \frac{2 h \nu^3}{c^2 (n_2 g_1 / n_1 g_2 - 1)}$$

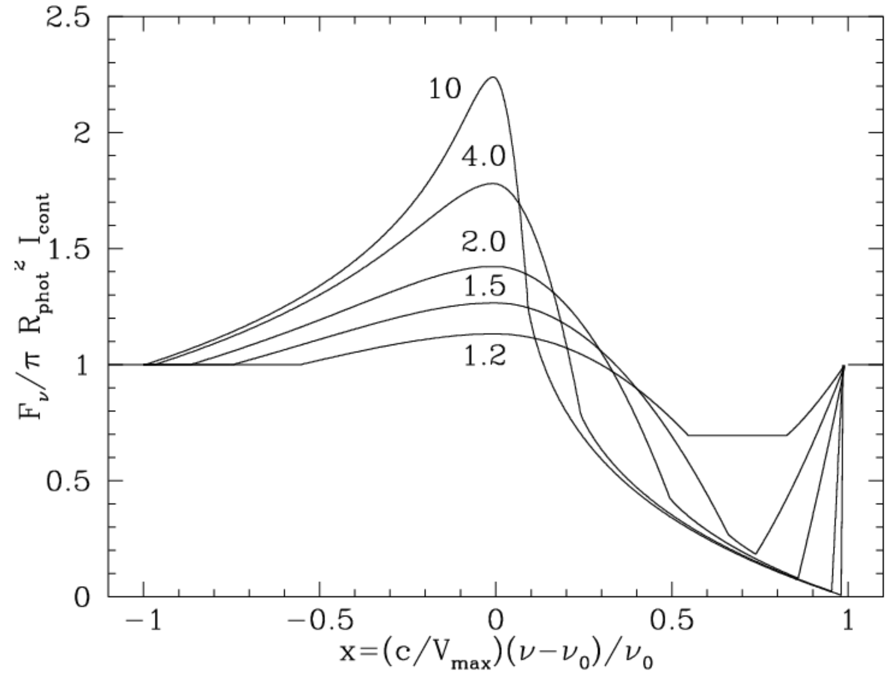
$$F_x = 2\pi \int_{p_{min}}^{p_{max}} [S(p, z = xR)(1 - e^{-\tau}) + e^{-\tau} I_{cont}] \, p \, dp$$

$$p \quad dp = r \quad dr \qquad for\ constant\ z \quad (i.e., constant\ x)$$

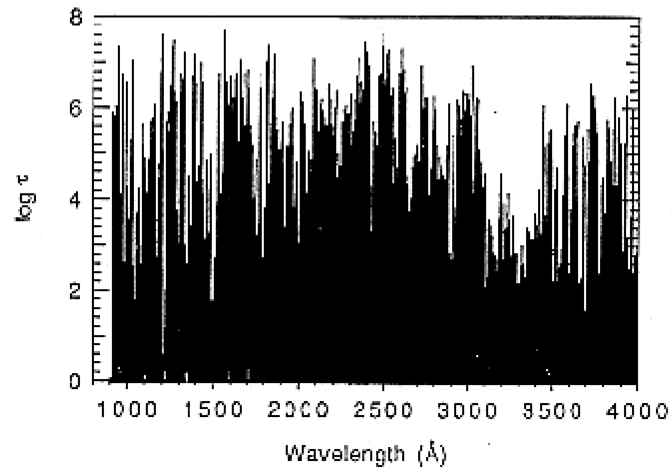
$$F_x = 2\pi \int_{r_{min}}^{R} [S(r)(1 - e^{-\tau}) + e^{-\tau} I_{cont}] r \, dr$$

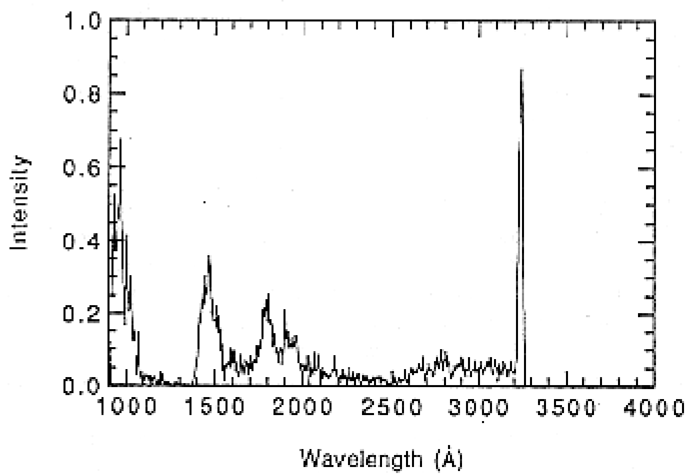


p
z, x
R_{max}
R_{phot}
x_1
x_2
x_3
x_4
x_5

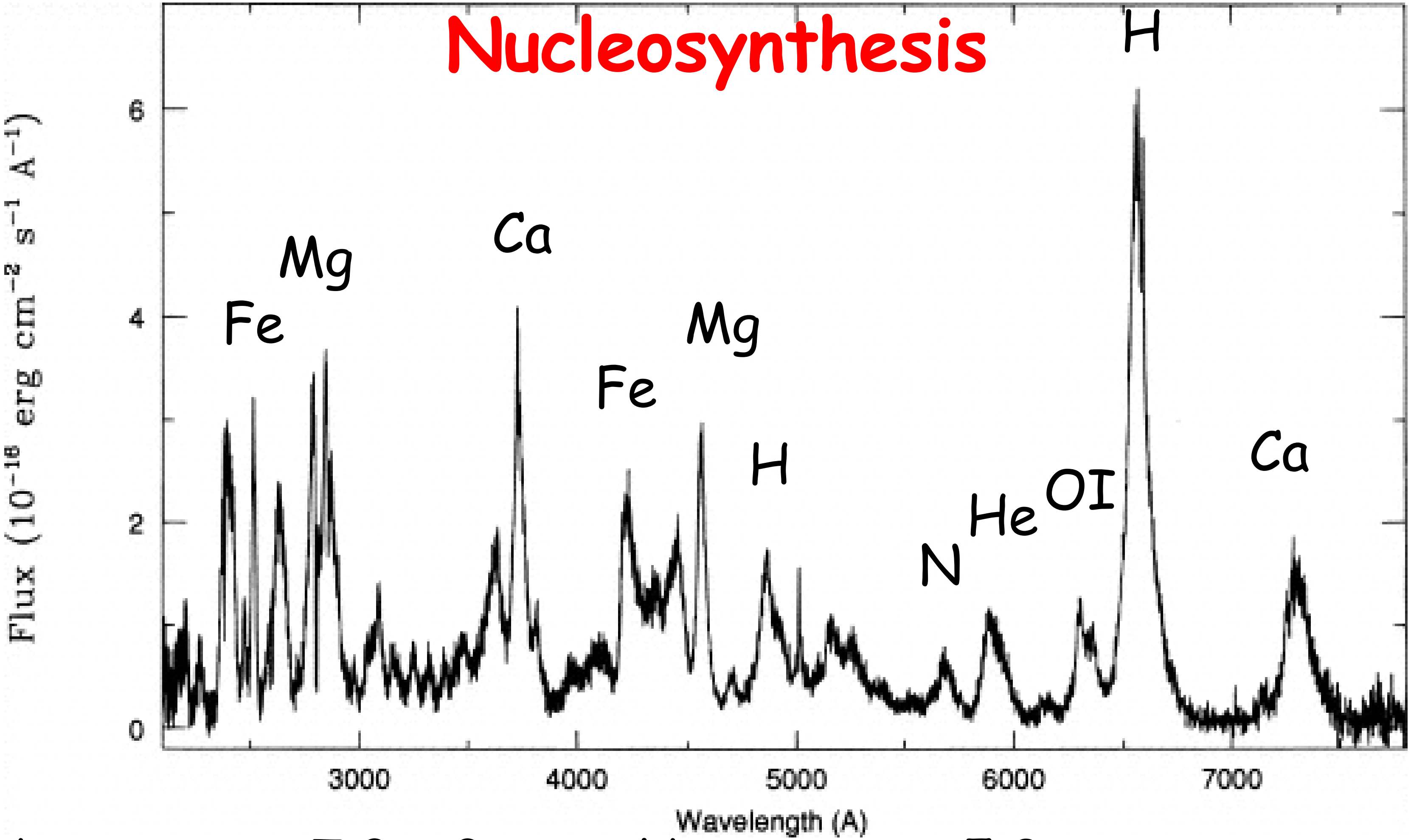


$F_\nu/\pi\ R_{phot}{}^2\ I_{cont}$
$x=(c/V_{max})(\nu-\nu_0)/\nu_0$
2.5
2
1.5
1
0.5
0
−1
−0.5
0
0.5
1
10
4.0
2.0
1.5
1.2


8
6
4
2
0
log τ
1000
1500
2000
2500
3000
3500
4000
Wavelength (Å)


1.0
0.8
0.6
0.4
0.2
0.0
Intensity
1000
1500
2000
2500
3000
3500
4000
Wavelength (Å)

Nucleosynthesis



H	7.2 ± 2	He	5.8
N	3.4×10^{-2}	O	1.9 ± 1
Ne	6.0×10^{-2}	Mg	2.2×10^{-2}
^{44}Ti ($\rightarrow ^{44}$Ca)	1.0×10^{-4}	^{56}Ni($\rightarrow ^{57}$Fe)	0.07
^{57}Ni ($\rightarrow ^{57}$Fe)	$3\text{X}10^{-3}$	^{58}Ni + ^{60}Ni	6.0×10^{-3}

$M_{initial} \sim 20\ M_{O}$

C. Kozma + CF 2002

$$F_x = 2\pi \int_{r_{min}}^{R} [S(r)(1 - e^{-\tau}) + e^{-\tau} I_{cont}] r\, dr$$

$$S = \frac{(1-\epsilon)\beta W I_{rm\, cont} + \epsilon B_\nu}{(1-\epsilon)\beta + \epsilon}$$

$$W(r) = \frac{1}{2}[1 - \sqrt{1 - (R_{phot}/r)^2}]$$