Radiation from supernovae and neutron star mergers

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Goals of this lecture

- Why do supernovae (SNe) emit huge luminosity?
- Why does emission from SNe evolve with time?
- What can we learn from observations of SNe?

- Why do NS mergers emit electromagnetic emission?
- What can we learn from observations of NS merger?

Lecture material

https://www.astr.tohoku.ac.jp/~masaomi.tanaka/sochi2019

Schedule

* White board (~ half)
  Slides (~ half)

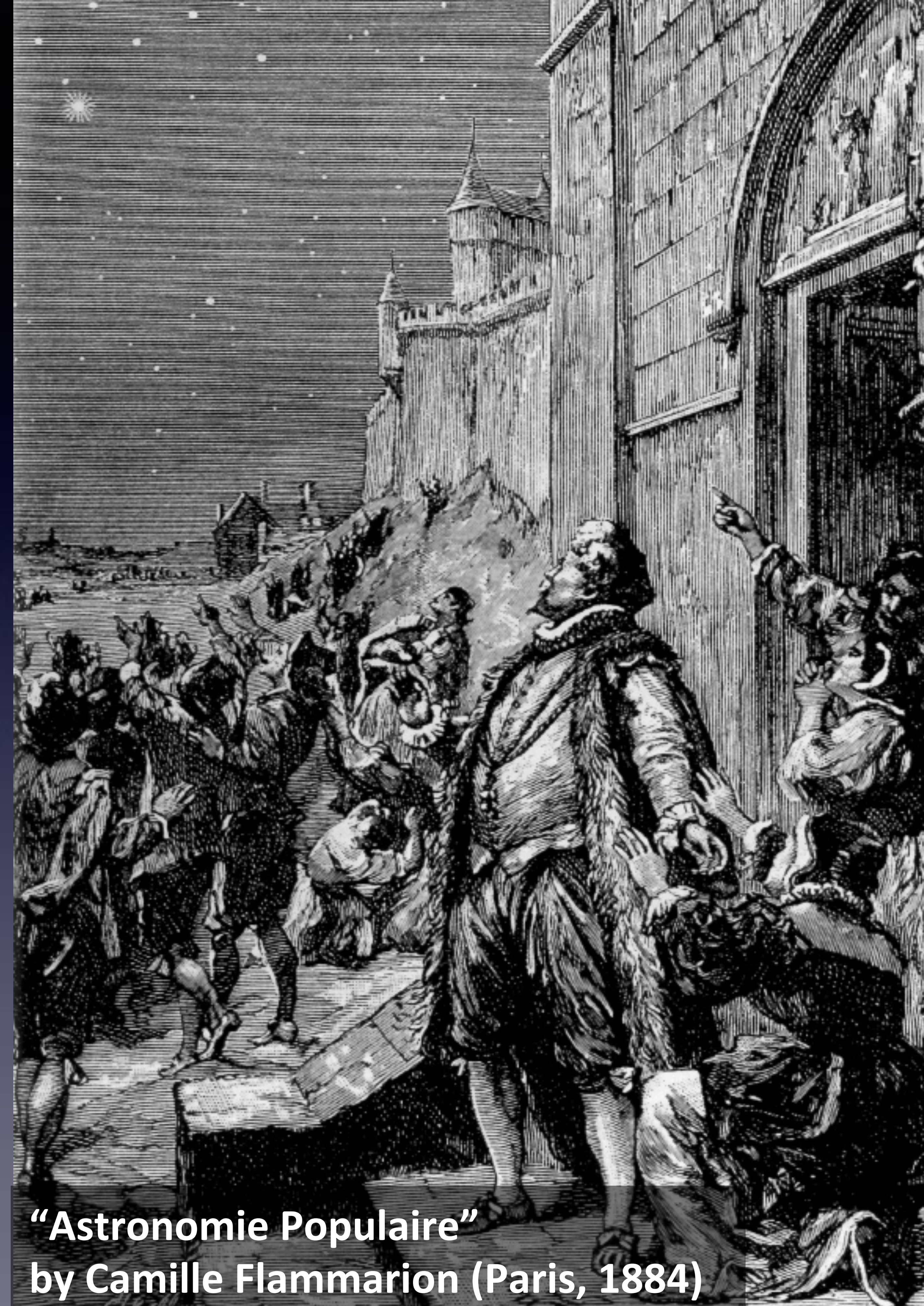
- Wednesday
  - Basic of radiation from supernovae - 1
  - Basic of radiation from supernovae - 2
- Friday
  - Lessons from supernova observations
  - Neutron star mergers

Basic of radiation from supernovae

1. Observations of supernovae
2. Power source of supernovae
3. Light curves of supernovae

1572
Tycho Brahe
"Stella Nova"

1604
Johannes Kepler

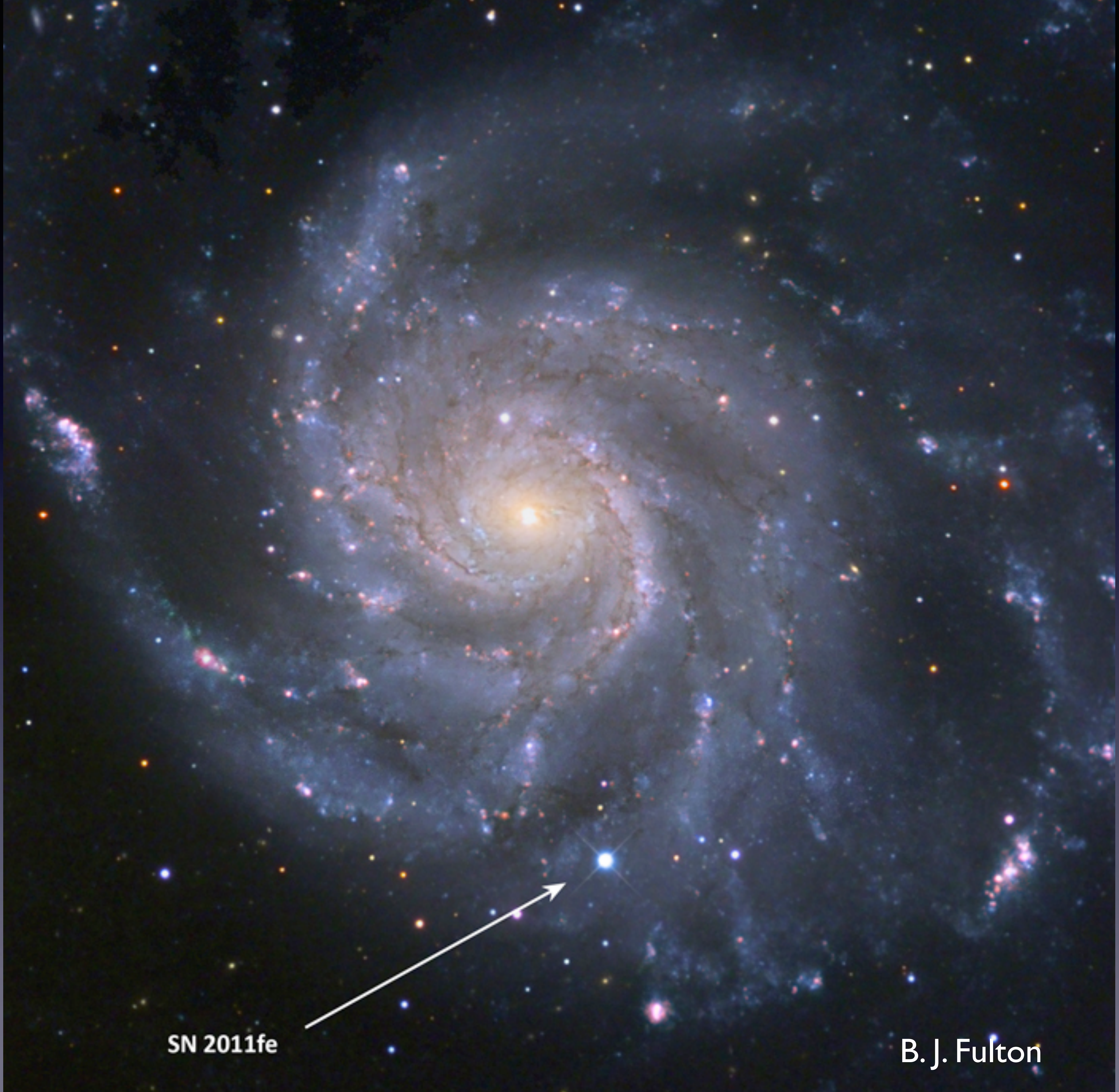


"Astronomie Populaire"
by Camille Flammarion (Paris, 1884)

Historical supernovae

Name	Location	Year	Magnitude
SN 185	Galactic	185	-8?
SN 1006	Galactic	1006	-9?
Crab	Galactic	1054	-4?
SN 1181	Galactic	1181	0
Tycho	Galactic	1572	-4
Kepler	Galactic	1604	-3
SN 1987A	LMC	1987	3

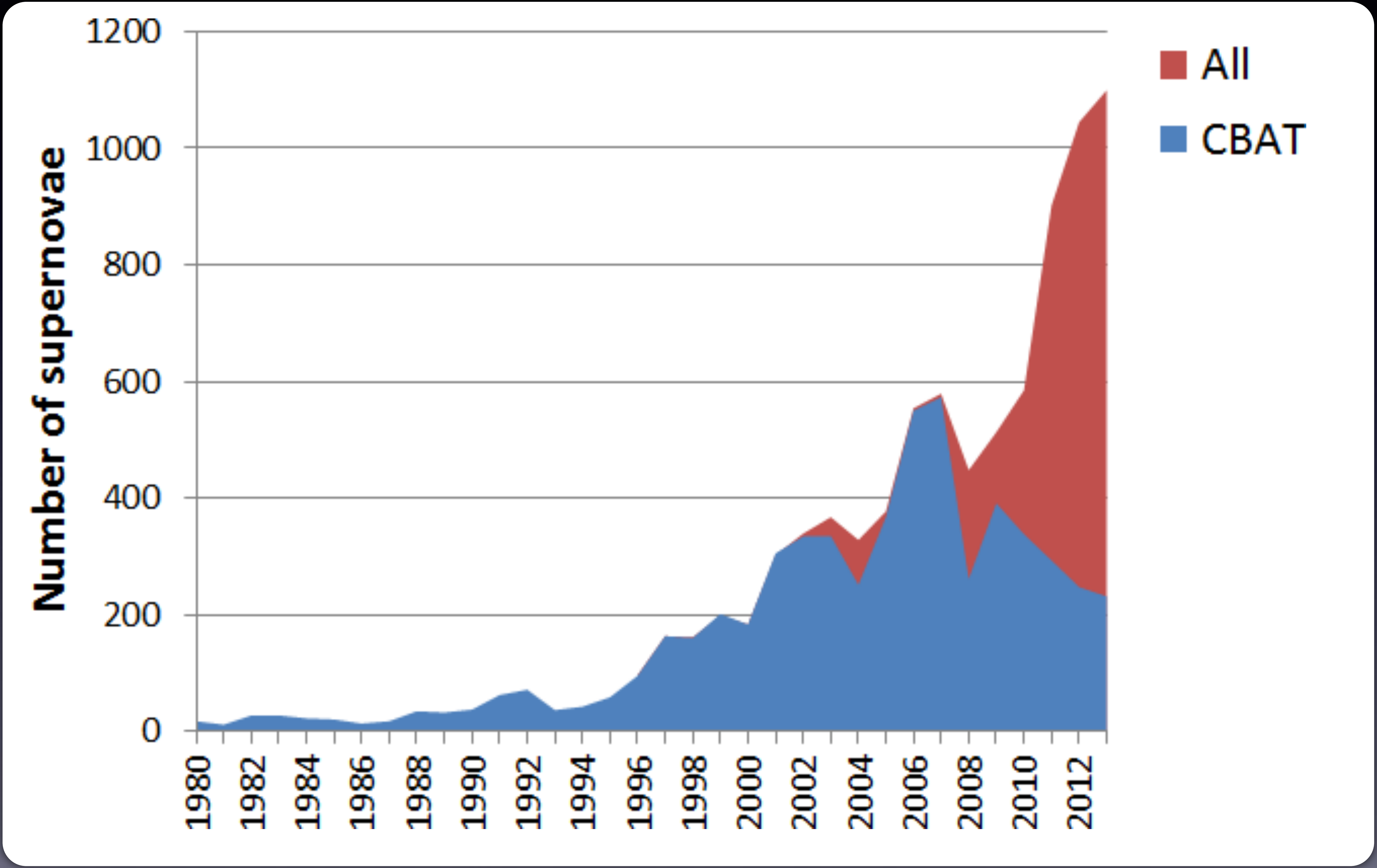
~ 1 supernova every 100-200 years


SN 2011fe
B. J. Fulton


SN 2011dh

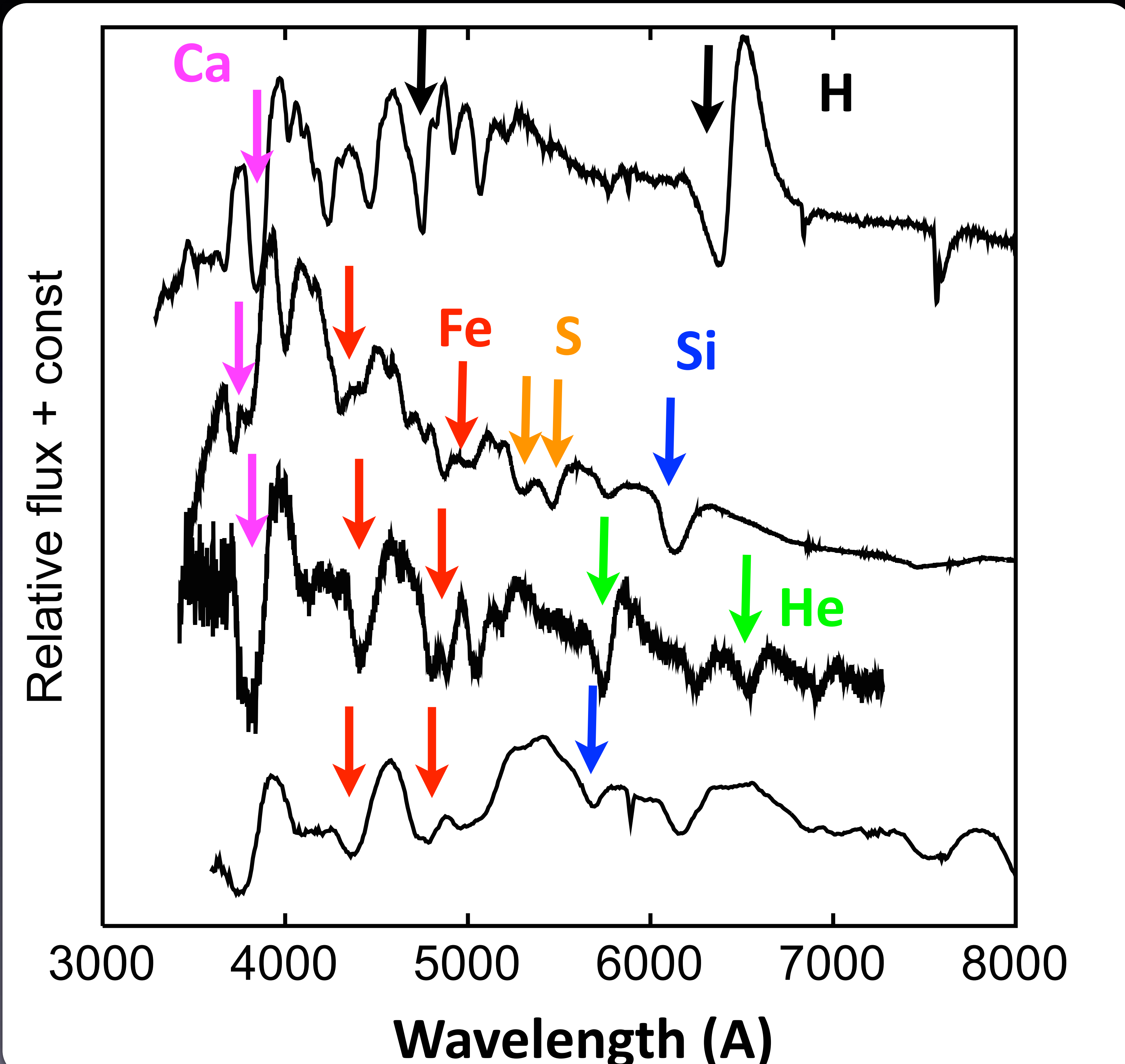

SDSS

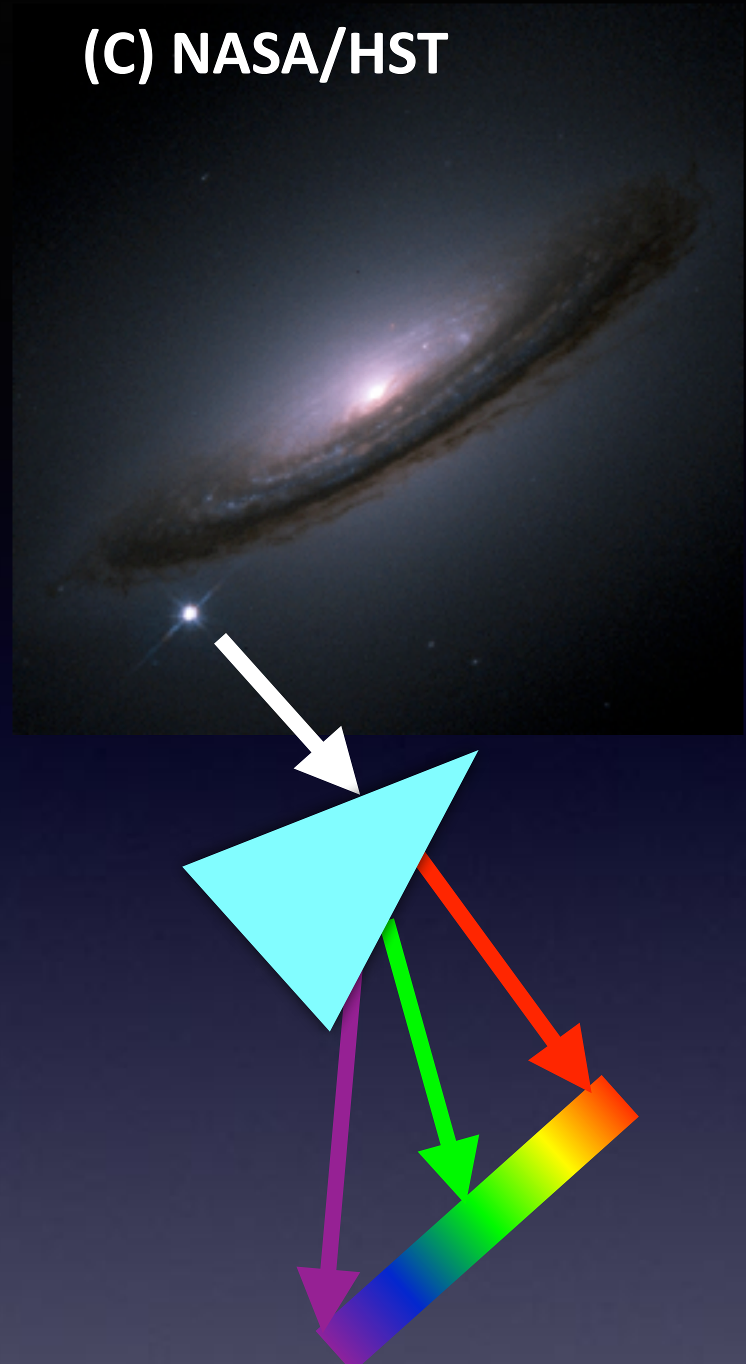
History of SN discovery



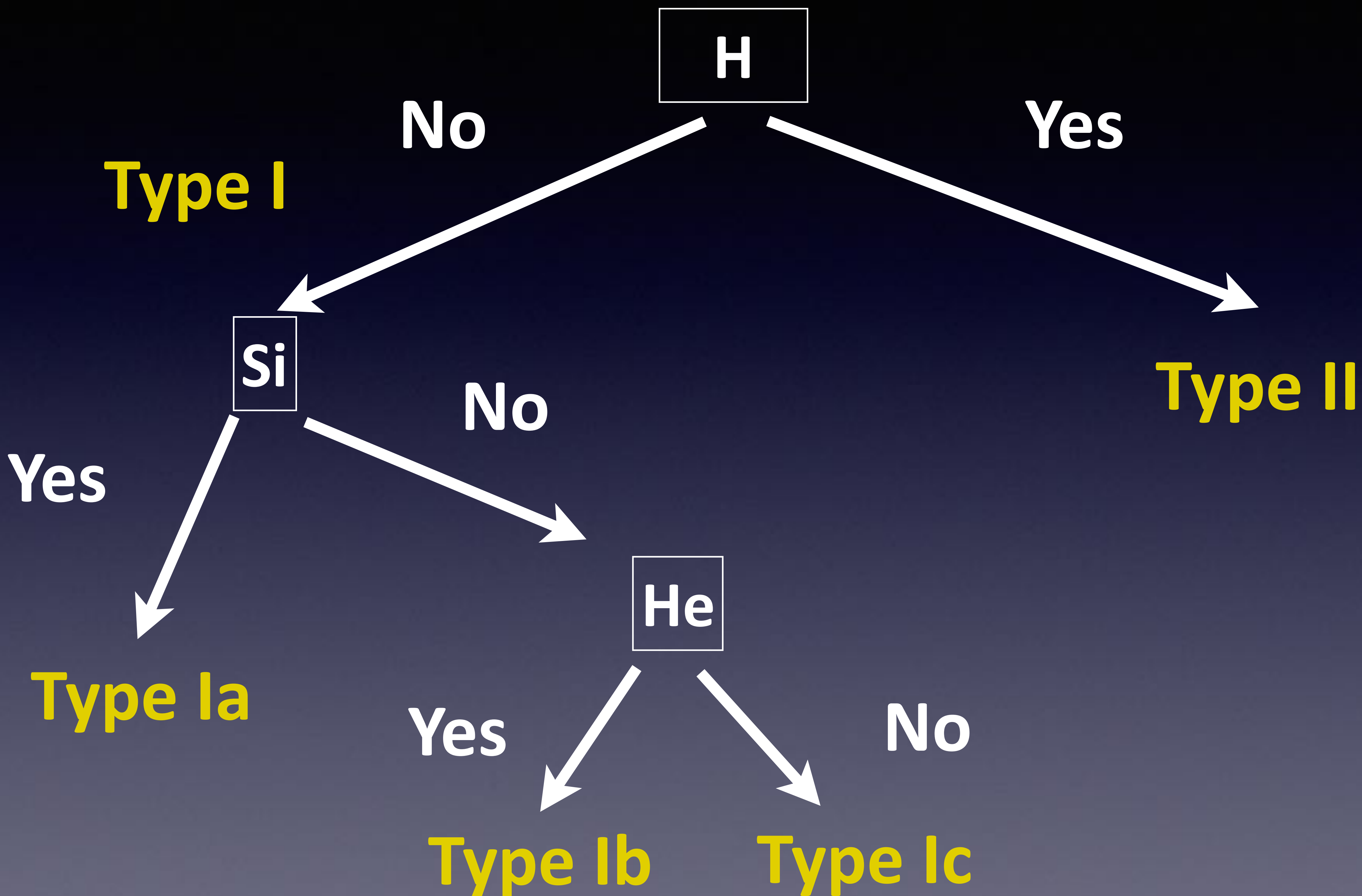
http://proftimobrien.com/2014/02/supernova-2014j-in-m82/

Spectroscopic classification

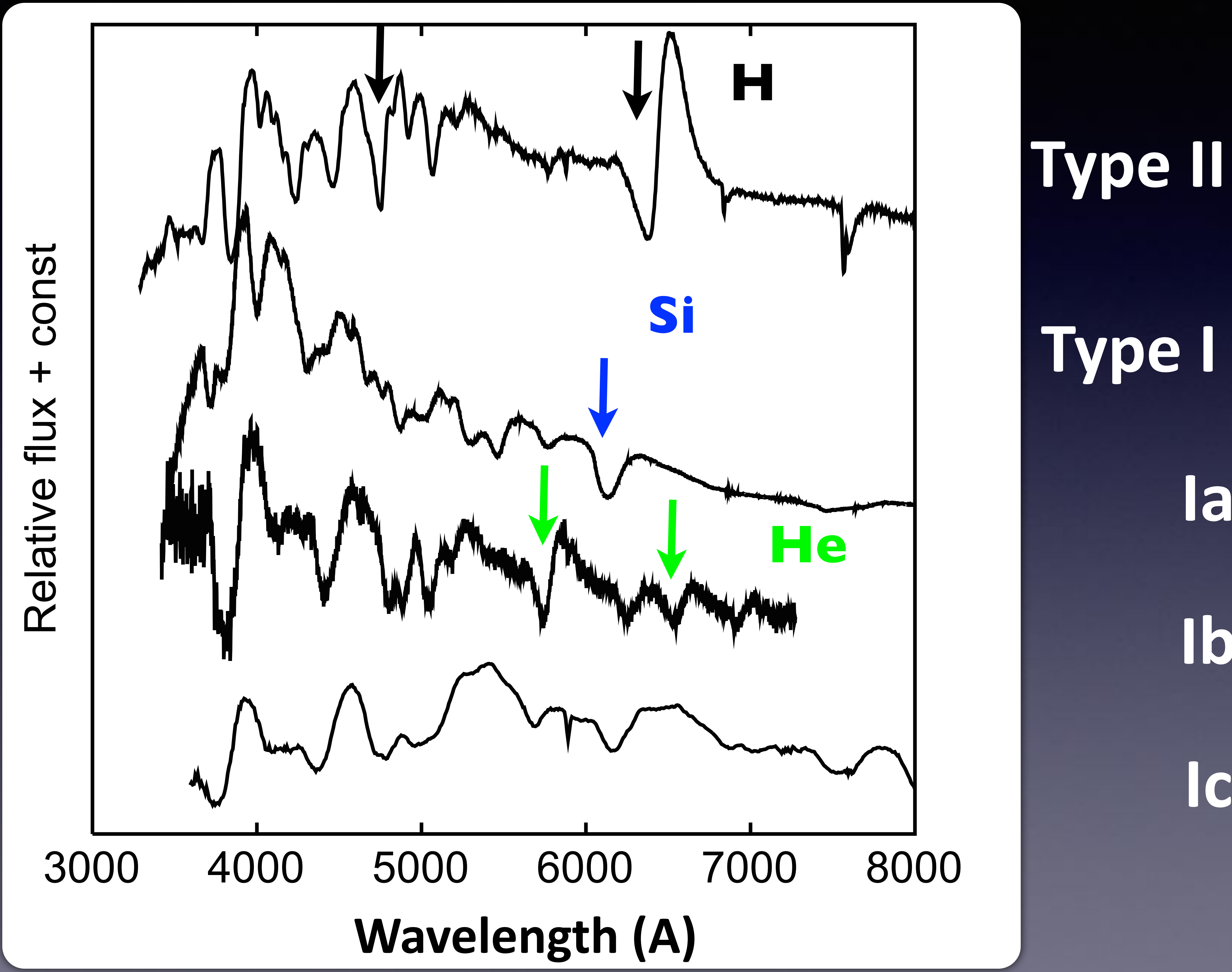




4 types of supernovae



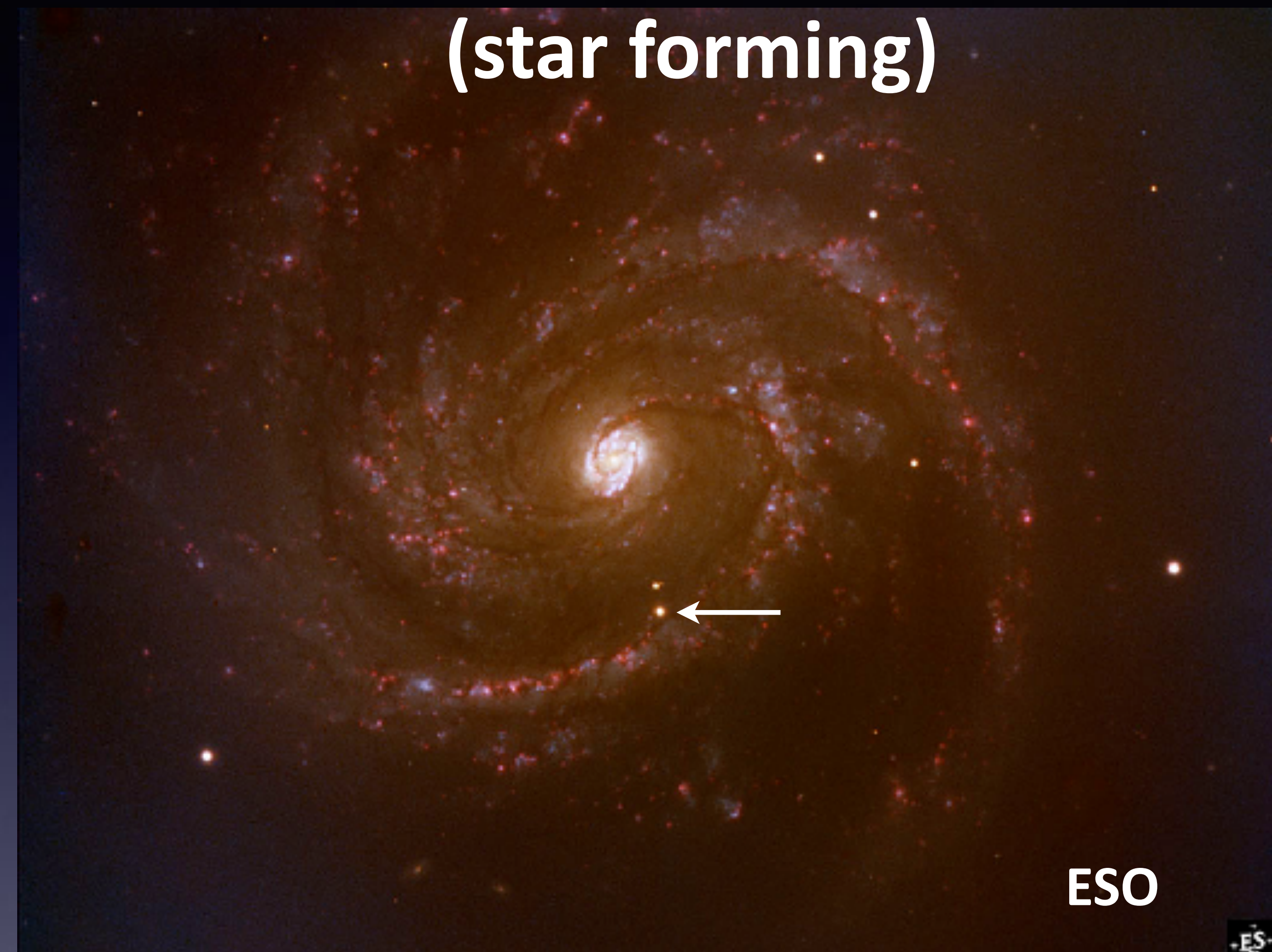
4 types of supernovae



Host galaxies of supernovae

Elliptical galaxy

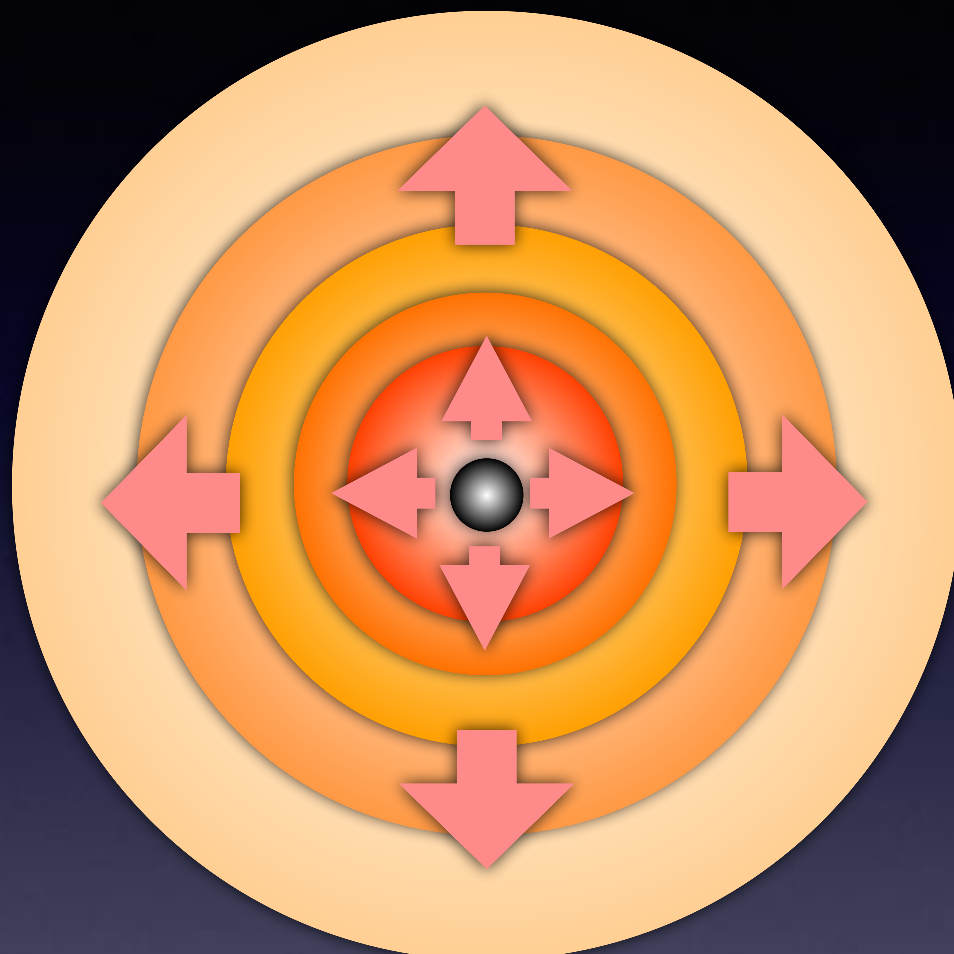
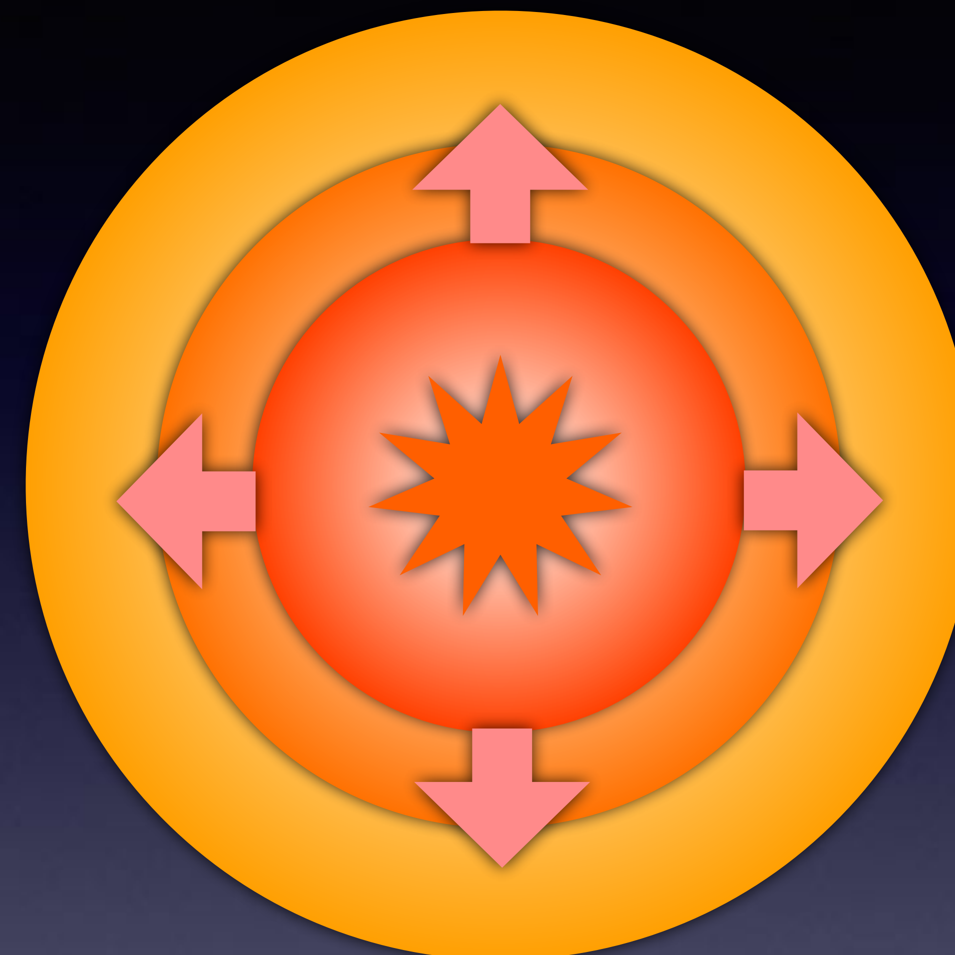
Spiral galaxy (star forming)



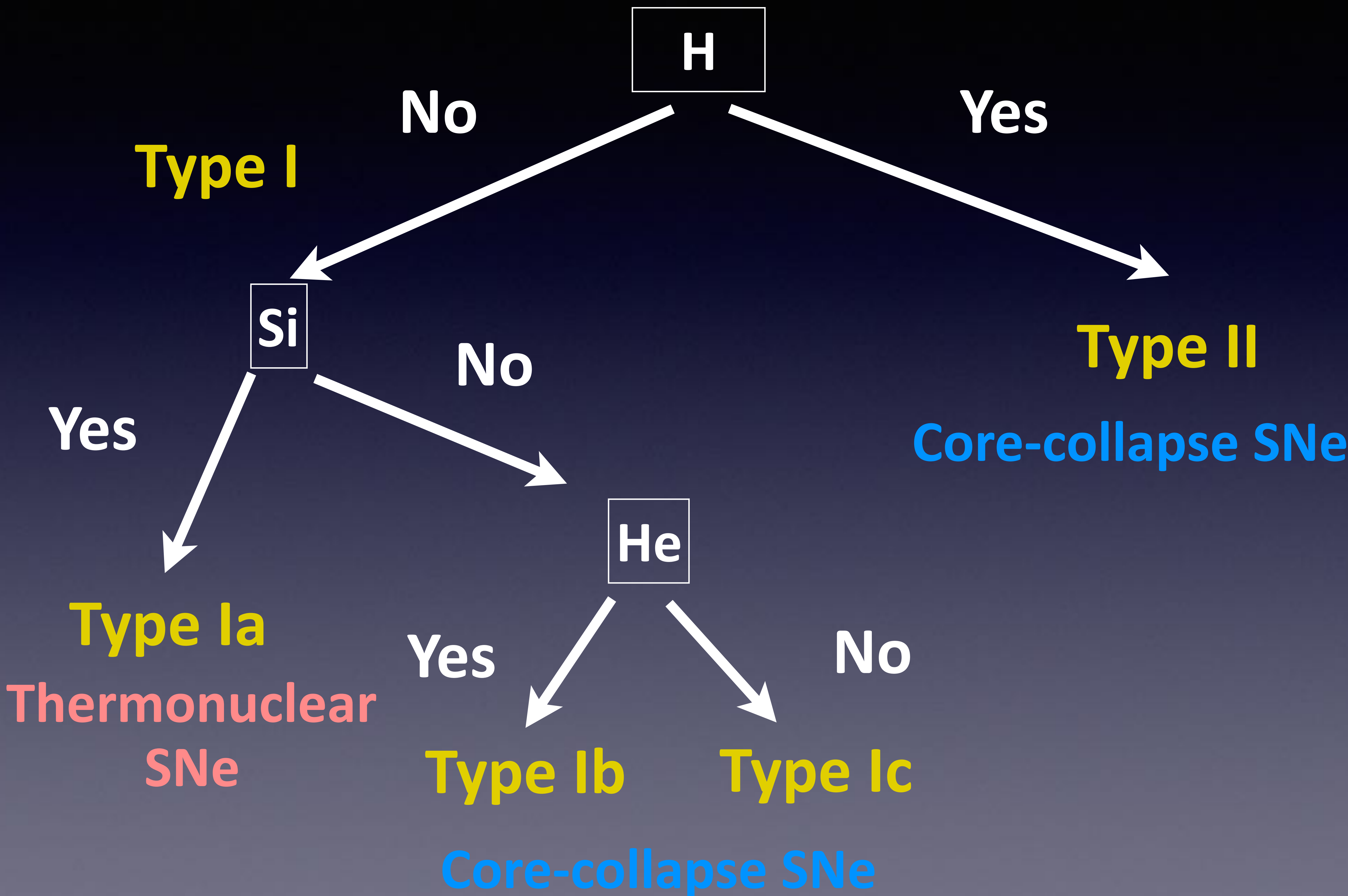
Type Ia (elliptical galaxy)

Type Ia **Type Ib, Ic, II** (spiral galaxy)

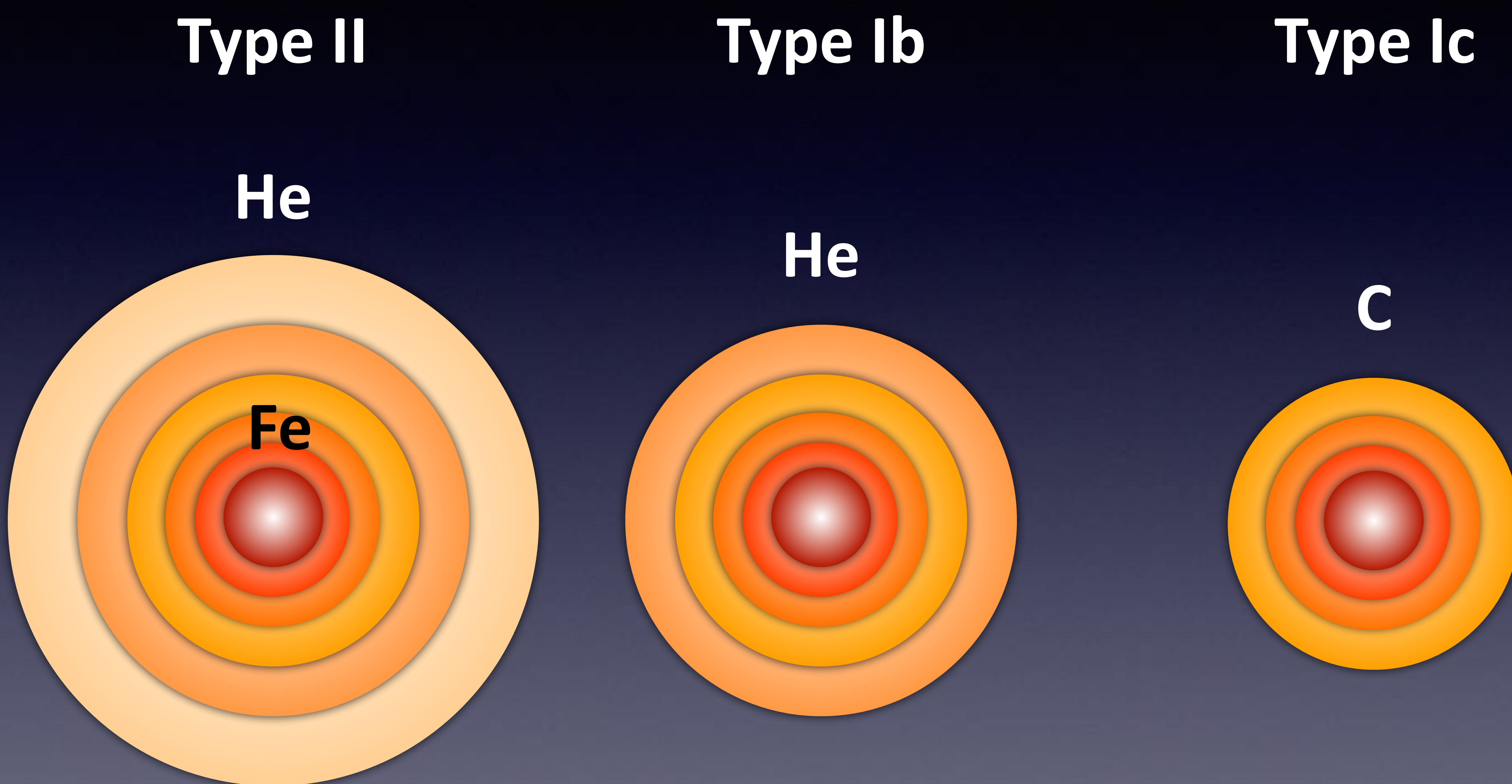
II, Ib, Ic: Young stars (massive stars)
Ia: Old stars (low-mass stars)

	Core-collapse SNe	Thermonuclear SNe
		
Progenitor	**Massive stars** Short lifetime	**Low-mass stars (in binary)** Long lifetime
Elements	**O, Mg, Ca, …** (progenitor star)	**Si, Ca, Fe, …** (explosion)

4 types of supernovae

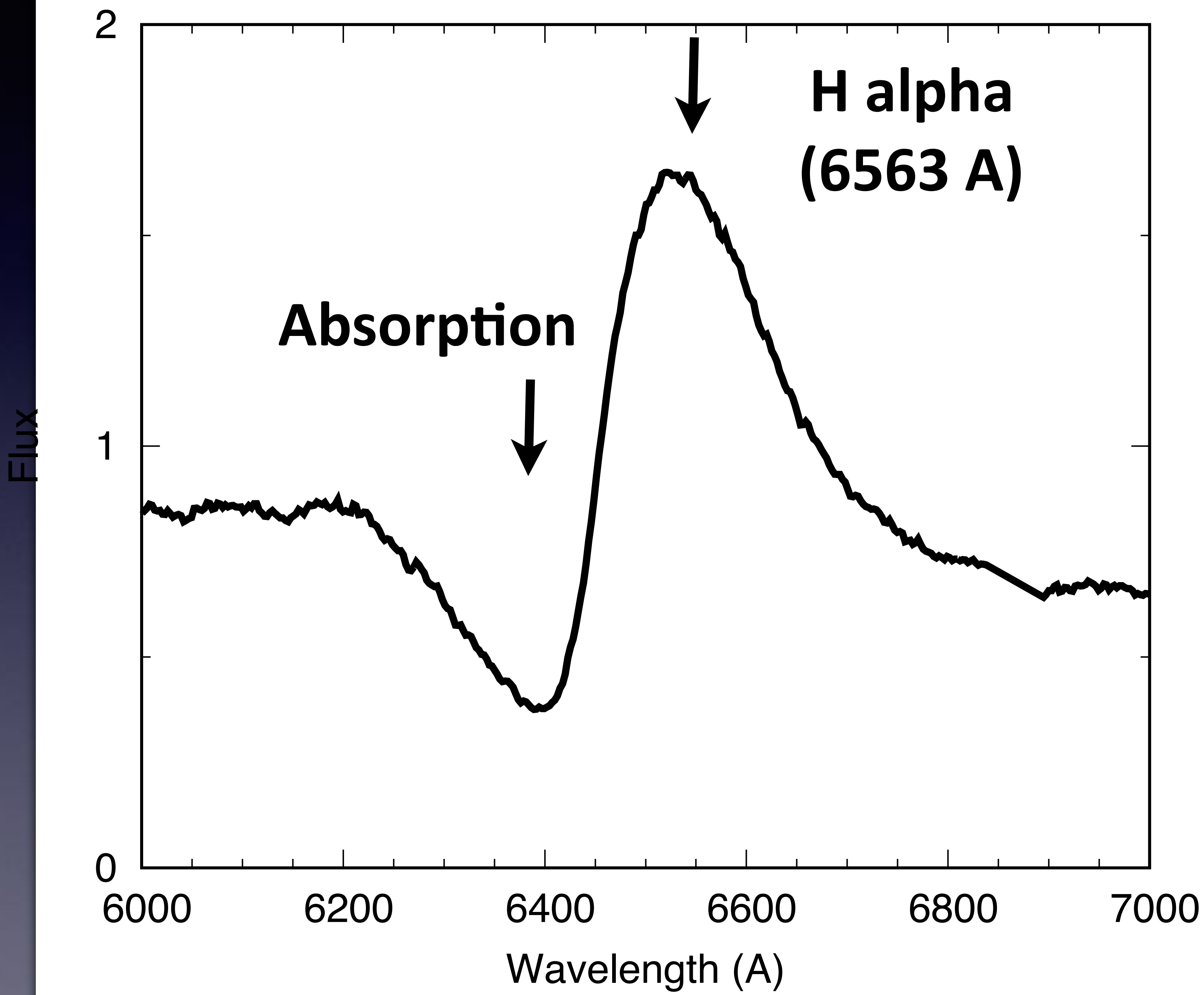


Core-collapse SNe and their progenitors



Mass loss due to stellar wind

Line profile

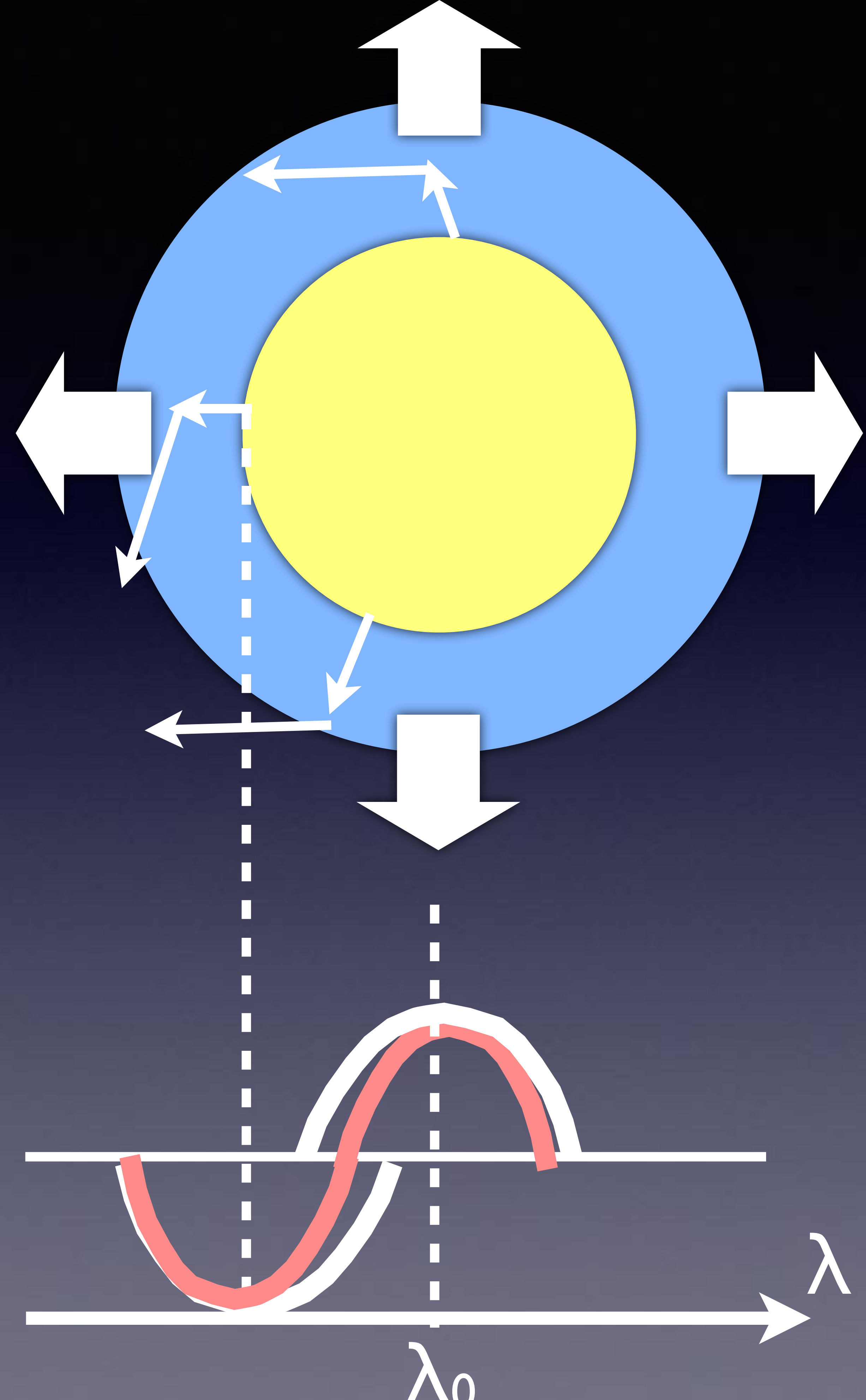


"P-Cygni" Profile

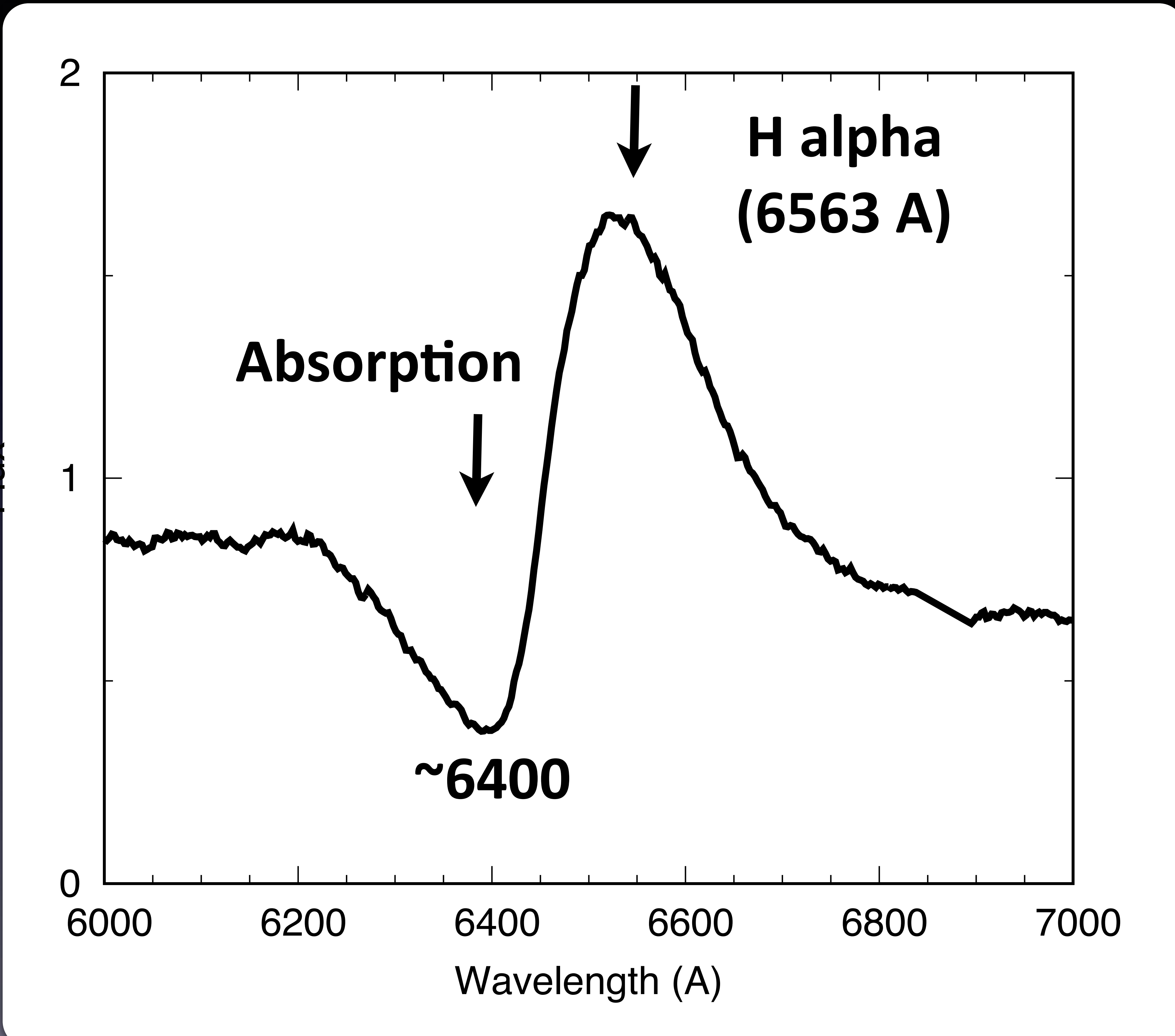
Doppler effects

$$\lambda = \left(\frac{c - v}{c}\right) \lambda_0$$

$$\frac{v}{c} = \frac{(\lambda_0 - \lambda)}{\lambda_0}$$



Line profile



v/c = 163/6563

=>

v = 0.025 x c

~ 7,000 km/s

Q. How large is the kinetic energy?

$$E = \frac{1}{2} M v^2$$

Mass ~ 5 Msun

Msun $= 2 \times 10^{33}$ g

Velocity ~ 5000 km/s

Ekin $=$ 1/2 x Mass x $(\text{Velocity})^2$

$= 1/2 \times (5 \times 2 \times 10^{33}\ \text{g}) \times (5 \times 10^{8}\ \text{cm/s})^2$

~ 10^{51} erg

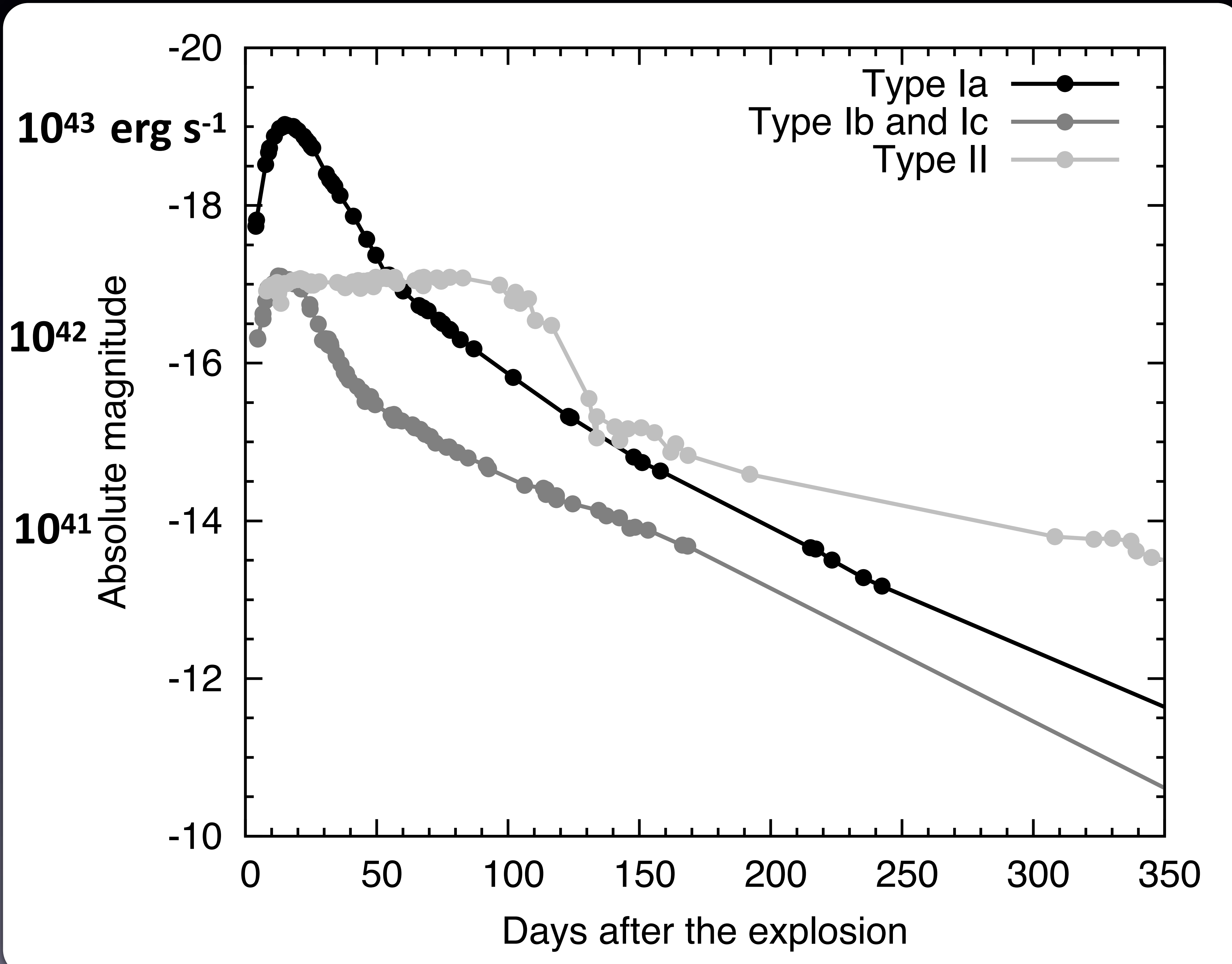
Summary: Observations of supernovae

- **Supernova observations**
  - Modern observations discover > 1000 extragalactic SNe/yr
- **Spectral classification**
  - Core-collapse supernovae = Type II, Type Ib/Ic
  - Thermonuclear supernovae = Type Ia
- **Supernova explosions**
  - V ~ 5,000 - 10,000 km/s (Doppler shift)
  - Ekin ~10^{51} erg << Egrav (~ 10^{53} erg)

Basic of radiation from supernovae

1. Observations of supernovae
2. Power source of supernovae
3. Light curves of supernovae

Light curve (brightness as a function of time)



Luminous!
(decay of ^{56}Ni)

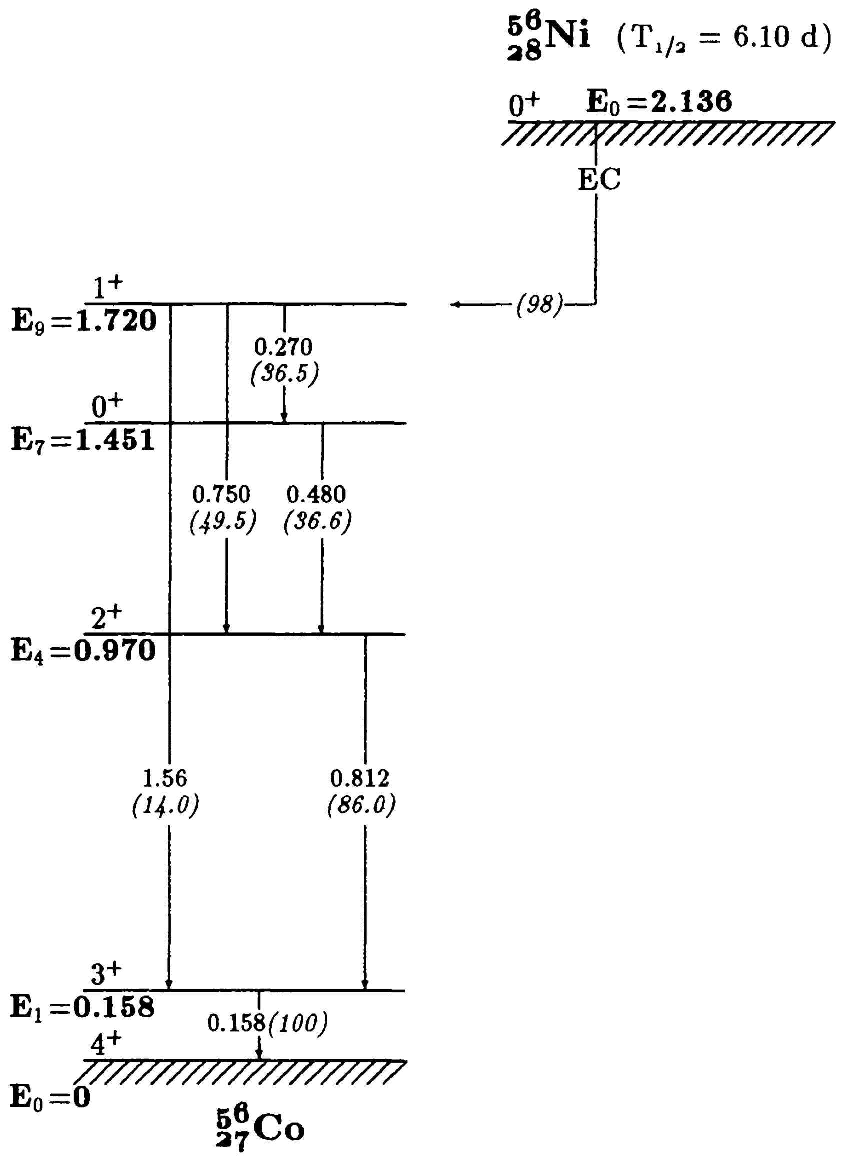
Type I
- Has a peak
- Ia > Ib, Ic

Type II
- Has a plateau

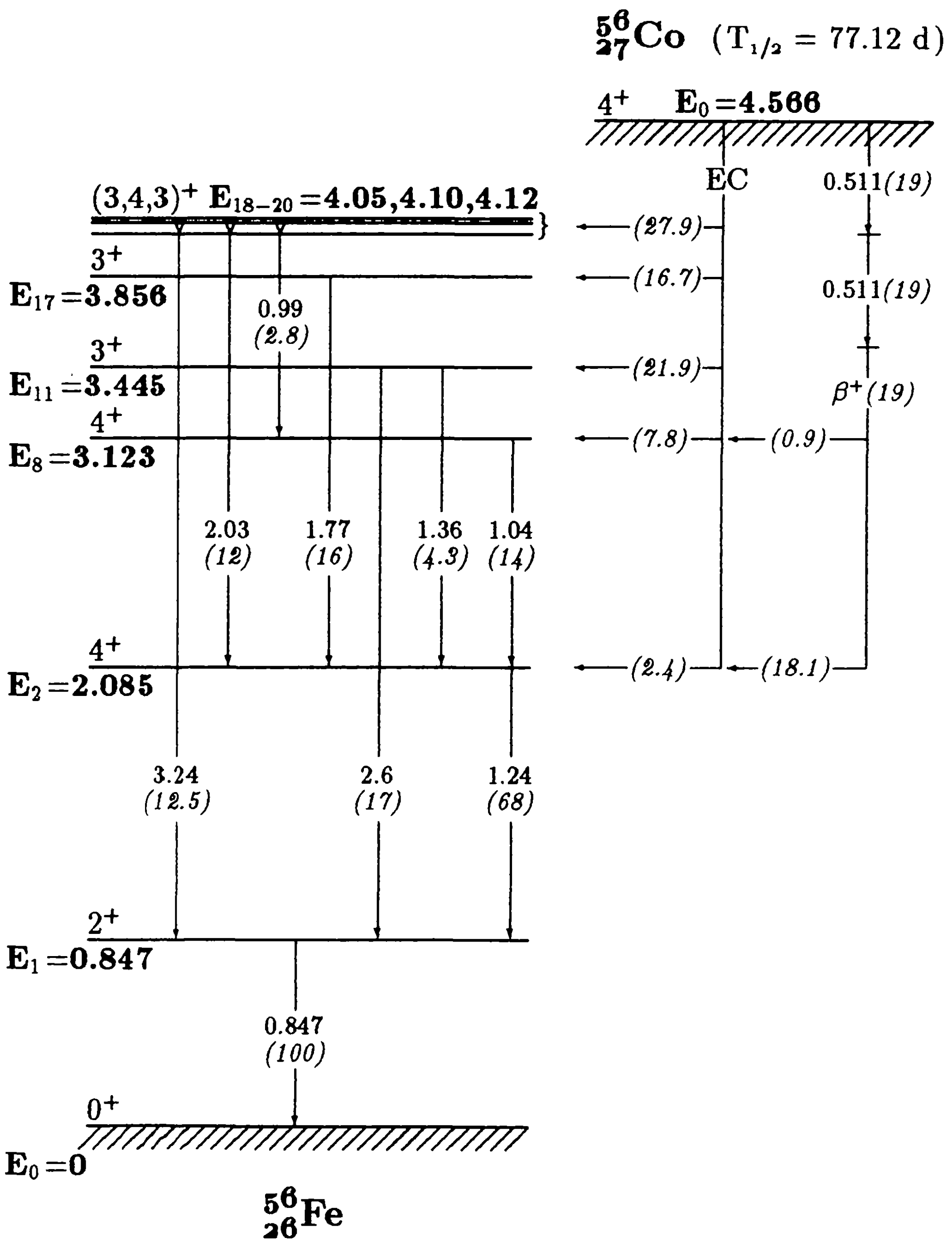
Various types of explosive transients

What determines
their luminosity and timescale?

^{56}Ni

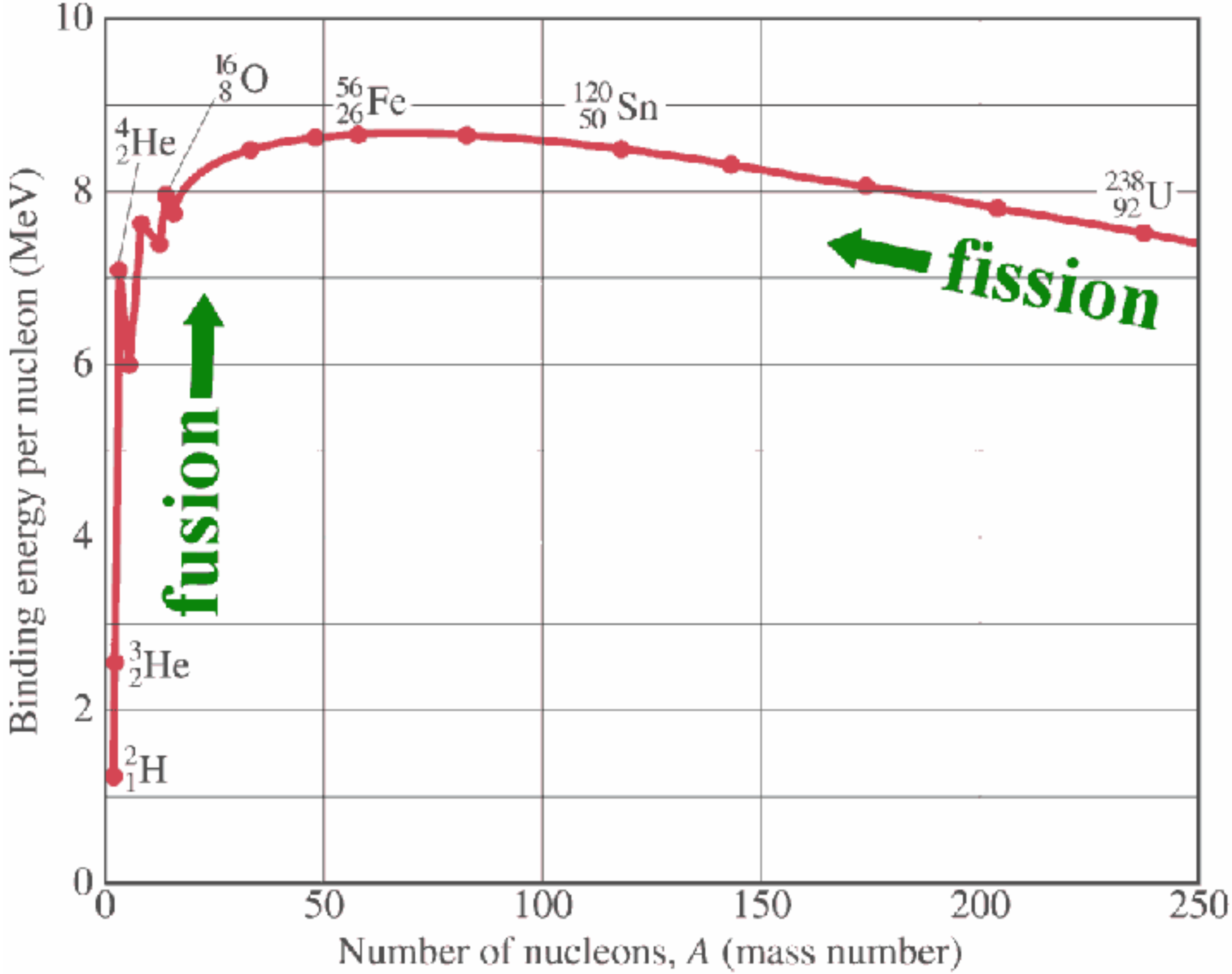


^{56}Co



Nadyozhin 94

^{56}Ni

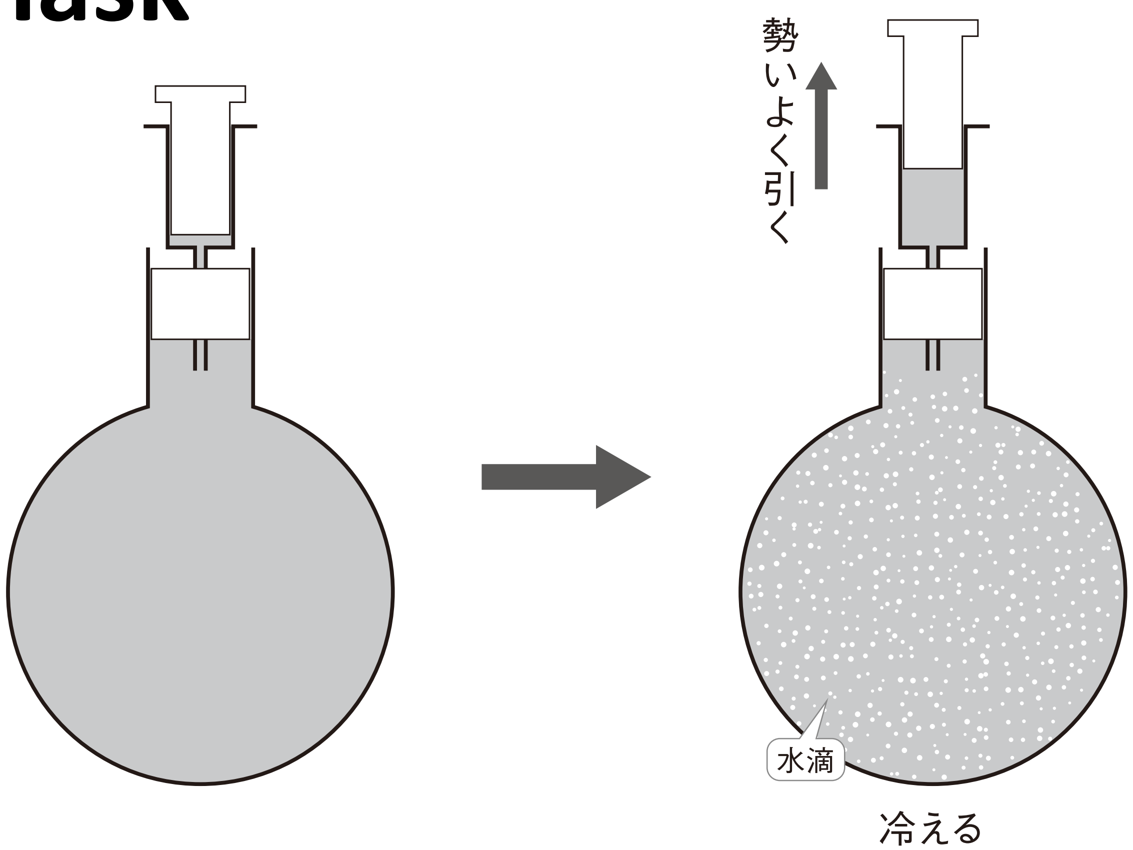


10
8
6
4
2
0
Binding energy per nucleon (MeV)
$^{16}_{8}$O
$^{56}_{26}$Fe
$^{120}_{50}$Sn
$^{4}_{2}$He
$^{238}_{92}$U
fission
fusion
$^{3}_{2}$He
$^{2}_{1}$H
0
50
100
150
200
250
Number of nucleons, A (mass number)

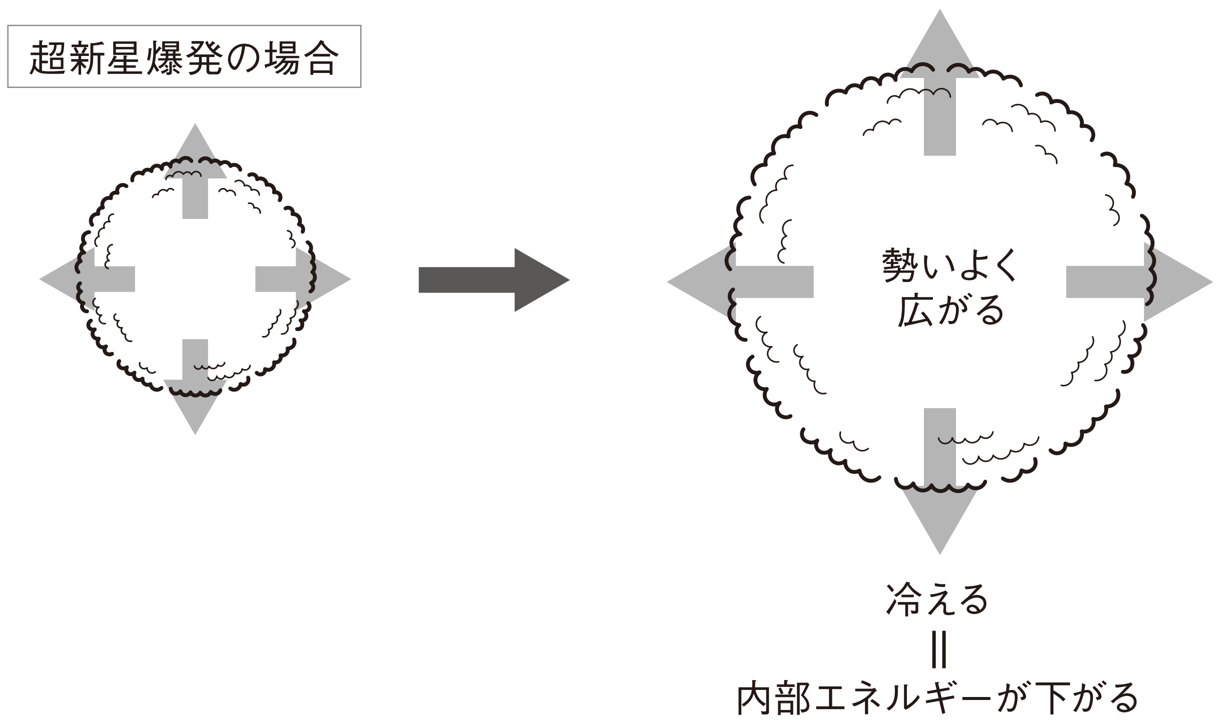
Sun

Adiabatic expansion

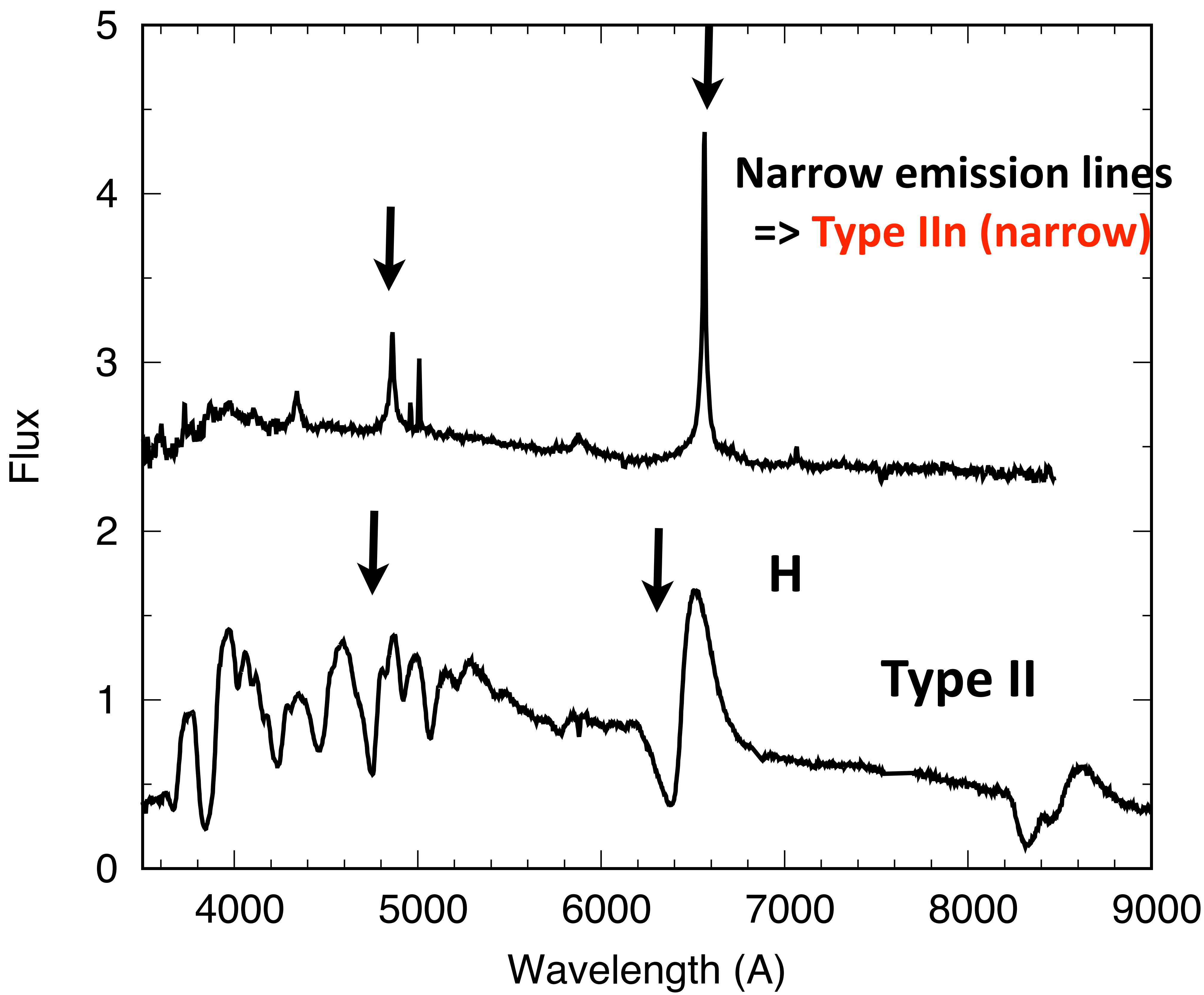
Flask



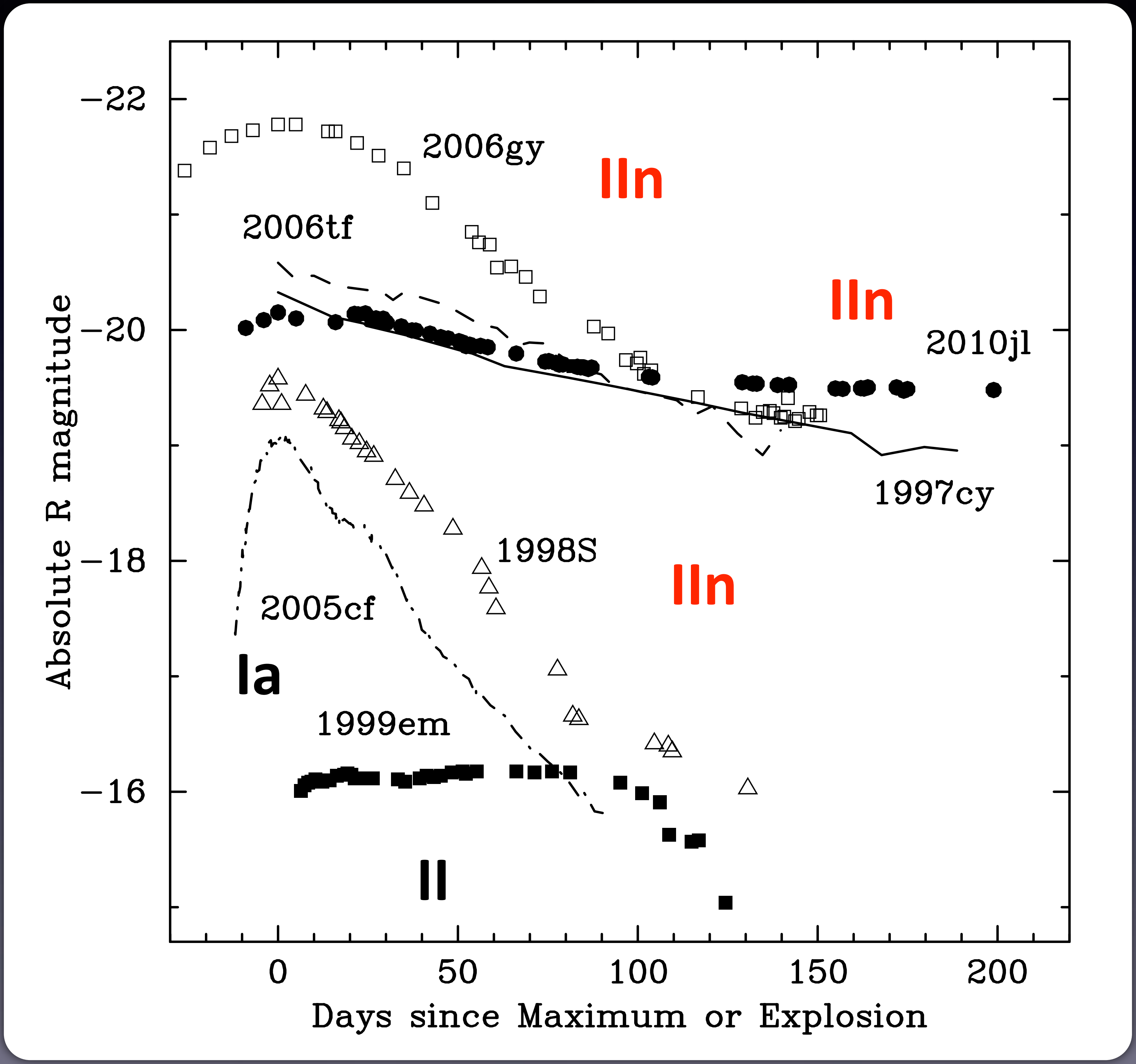
Supernovae



Supernova interacting with circumstellar material



Supernova interacting with circumstellar material



Type IIn SN

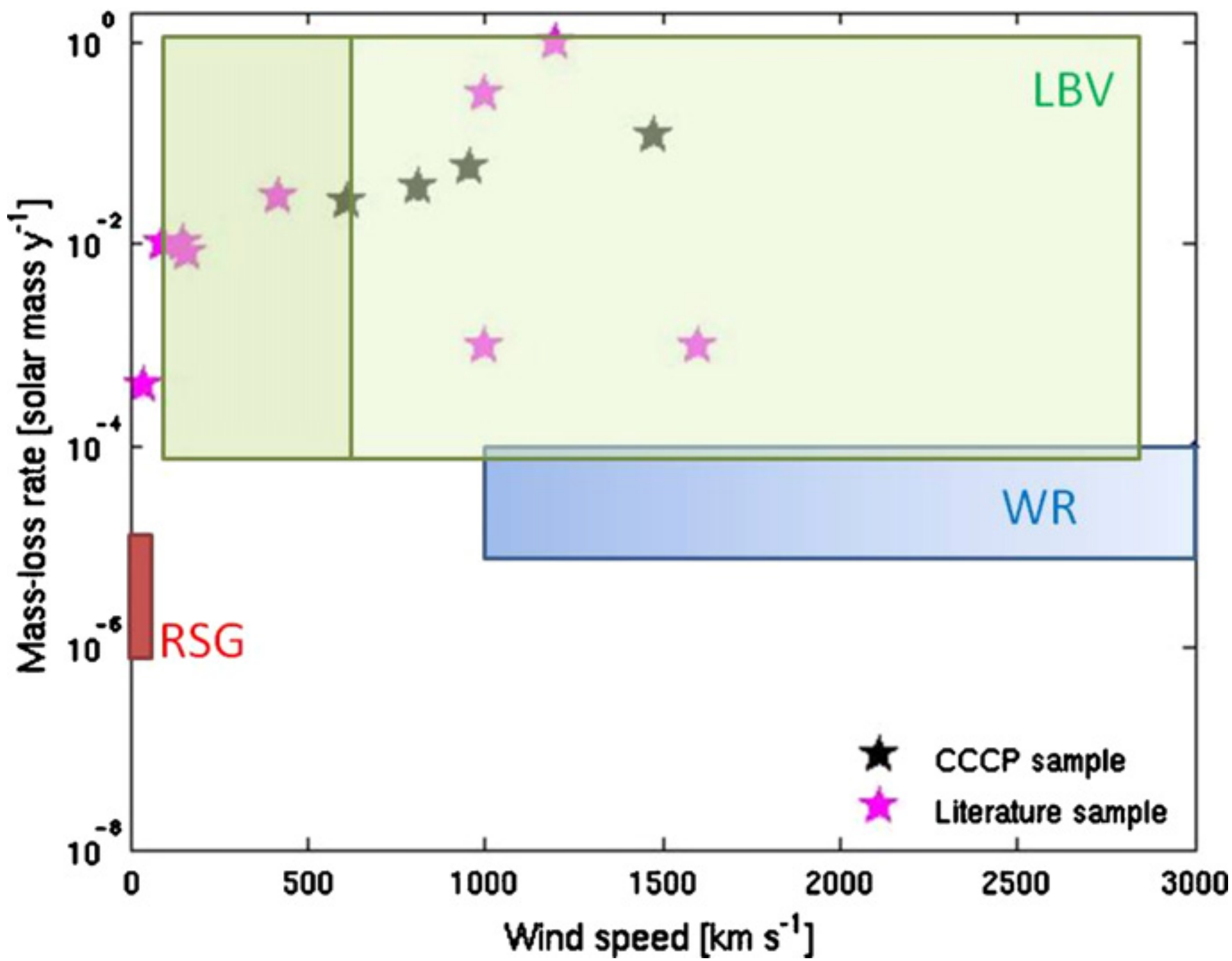
- Brighter than Type II

- Longer than Type II
  but sometimes faster

- Large variation

Zhang+12

Stellar mass loss probed by Type IIn supernovae



Kiewe+2012

Intensive mass loss just before the explosion

Summary: Power source of supernovae

- **Erad ~ 10^{49} erg**
  << Ekin (10^{51} erg) << Egrav (10^{53} erg)

- **Power source**

1. **Radioactivity (^{56}Ni)**
   Important in all the types
   Type Ia > Core-collapse

2. **Shock heating**
   Important for large-radius star (Type II)

3. **Interaction with CSM**
   Ekin => Eth (Type IIn)

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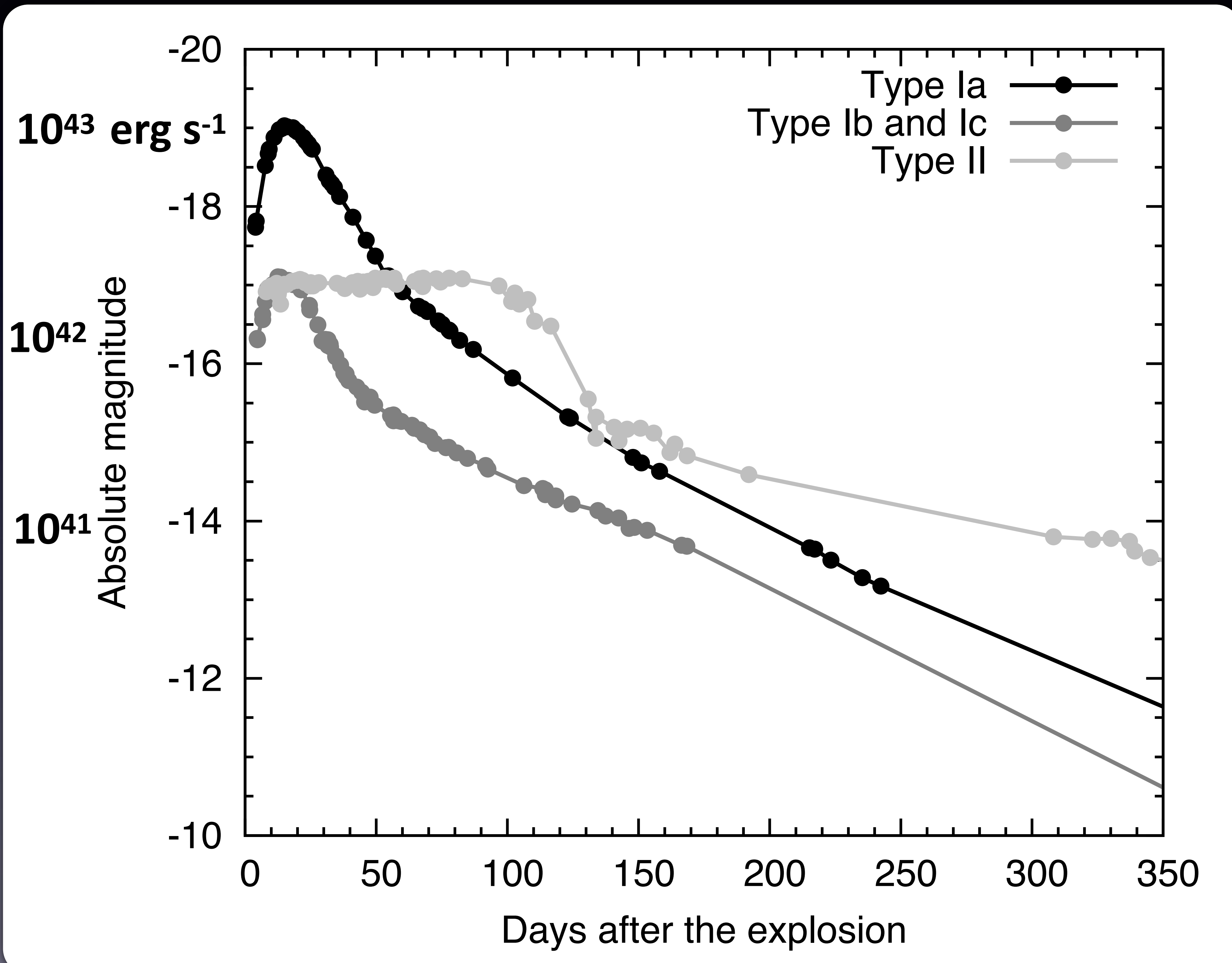
Light curves



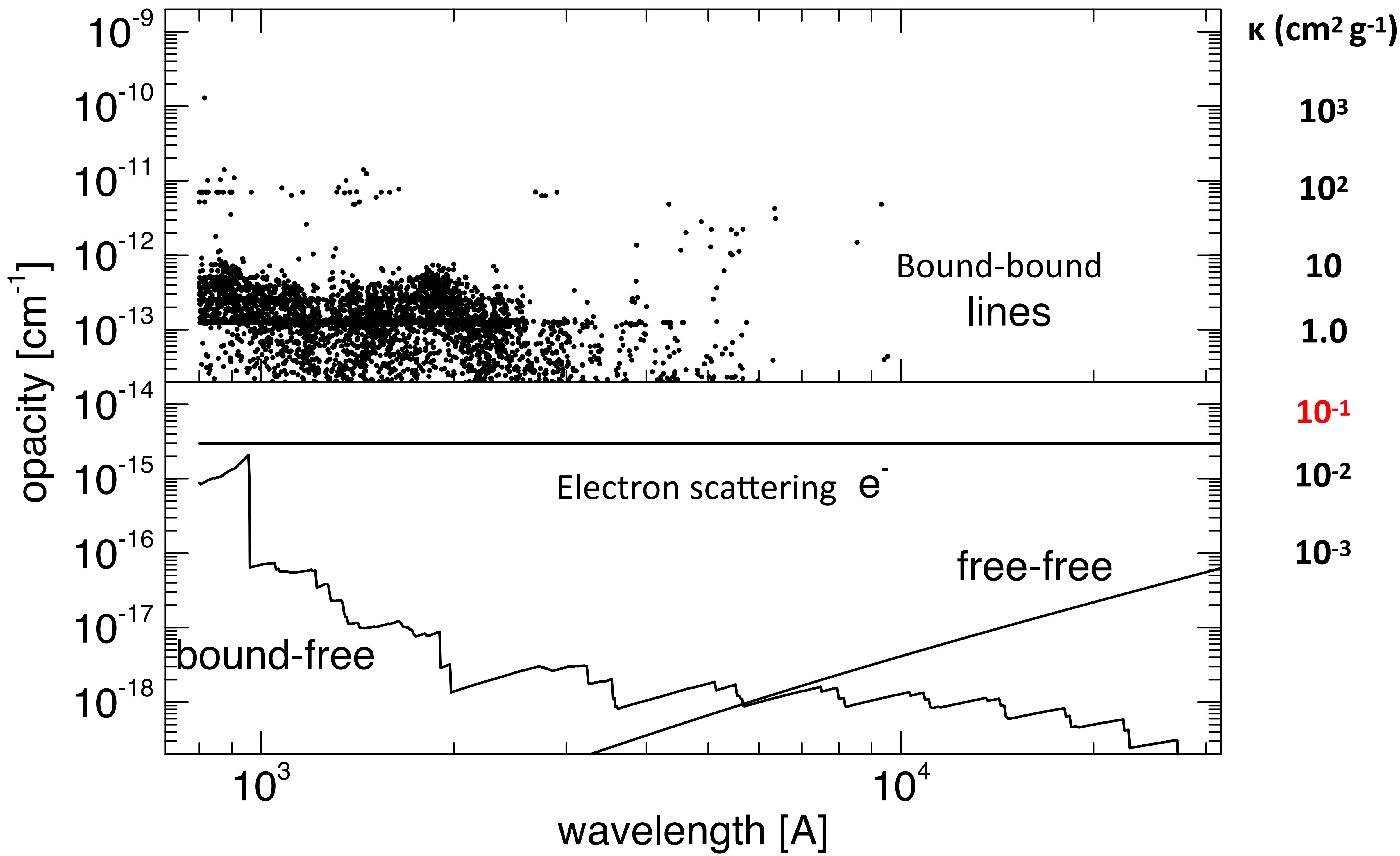
Type I
- Peak
- L(Ia) > L(Ib, Ic)

Type II
- plateau
- L(Ia) > L(II)

Various types of explosive transients

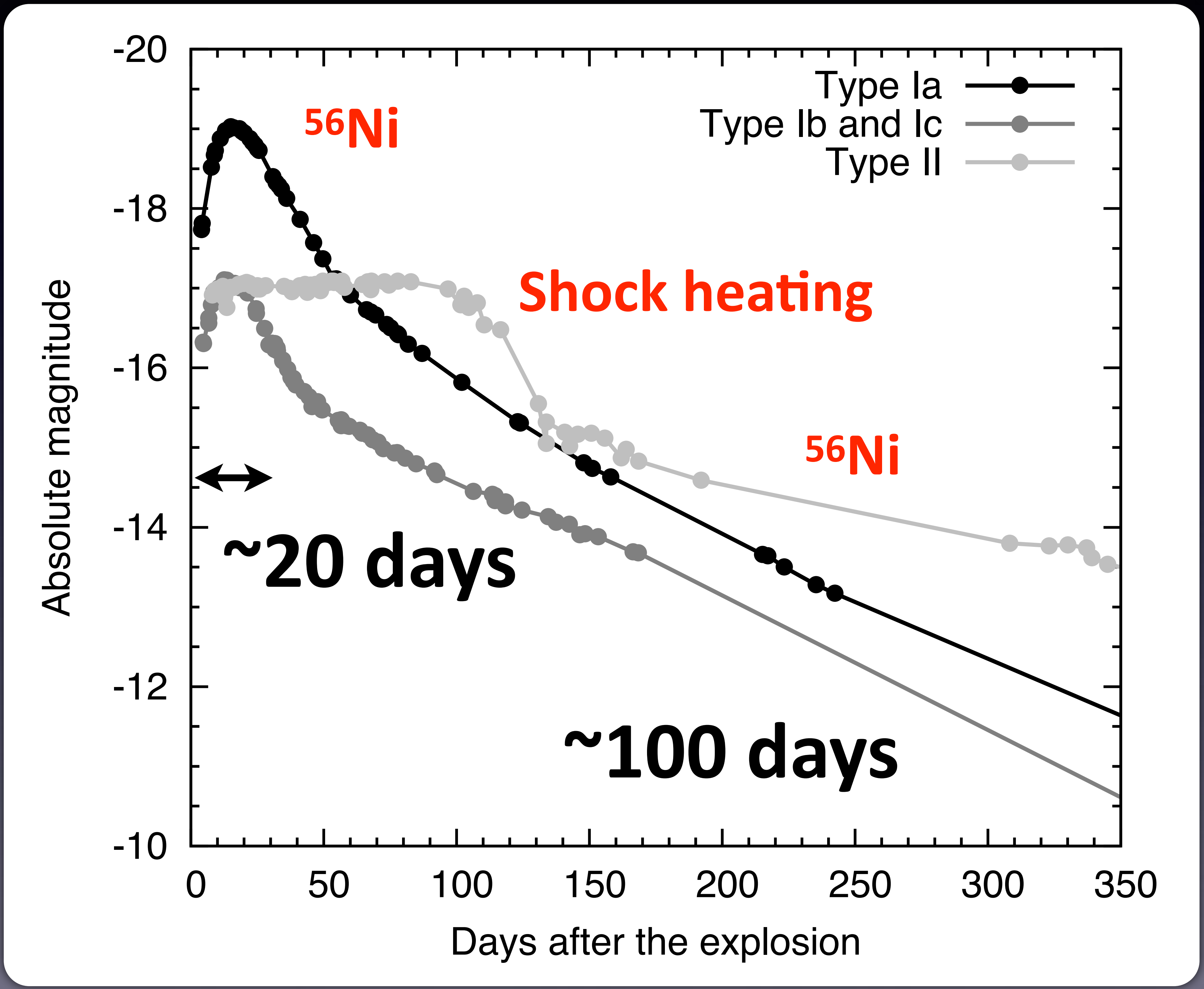
What determines
their luminosity and timescale?

Opacity in supernova ejecta (Type Ia SN, $\rho = 10^{-13}$ g cm^{-3})



Pinto & Eastman 2000

Light curves



10^{43} erg s^{-1}

10^{42} erg s^{-1}

Type Ia SNe eject more ^{56}Ni

Summary: Light curves of supernovae

- **Timescale of emission**
  - SN ejecta are initially optically thick
  - Optical depth decreases with time
  - Photons diffuse out from SN ejecta
  - Source of opacity:
    bound-bound transitions and e-scattering
  - Typical timescale $t \sim \kappa^{1/2}\, M_{ej}^{3/4}\, E_k^{-1/4}$
    $\sim \kappa^{1/2}\, M_{ej}^{1/2}\, v^{-1/2}$