Radiation from supernovae and neutron star mergers

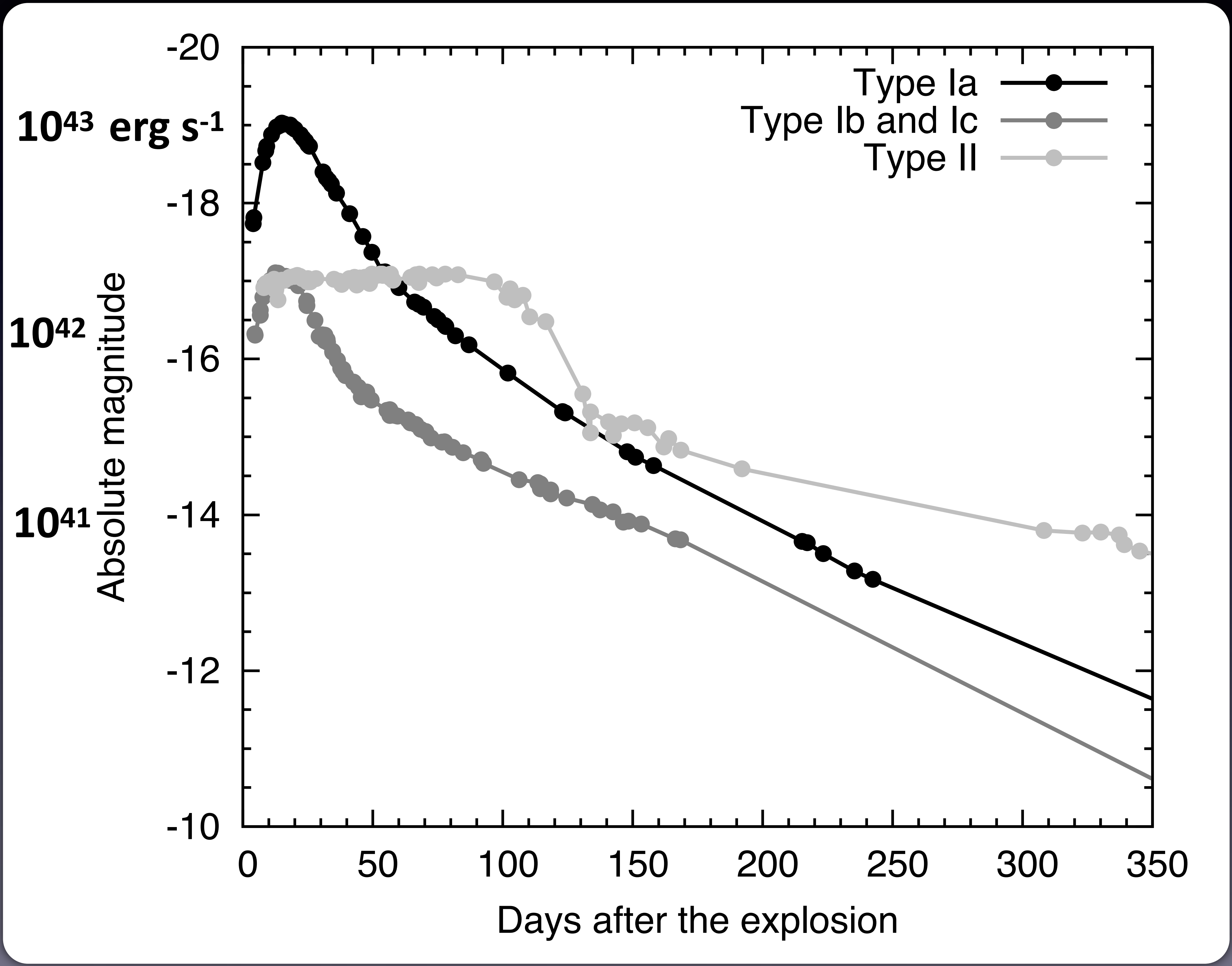
Masaomi Tanaka
(Tohoku University, Japan)

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?

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**

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)

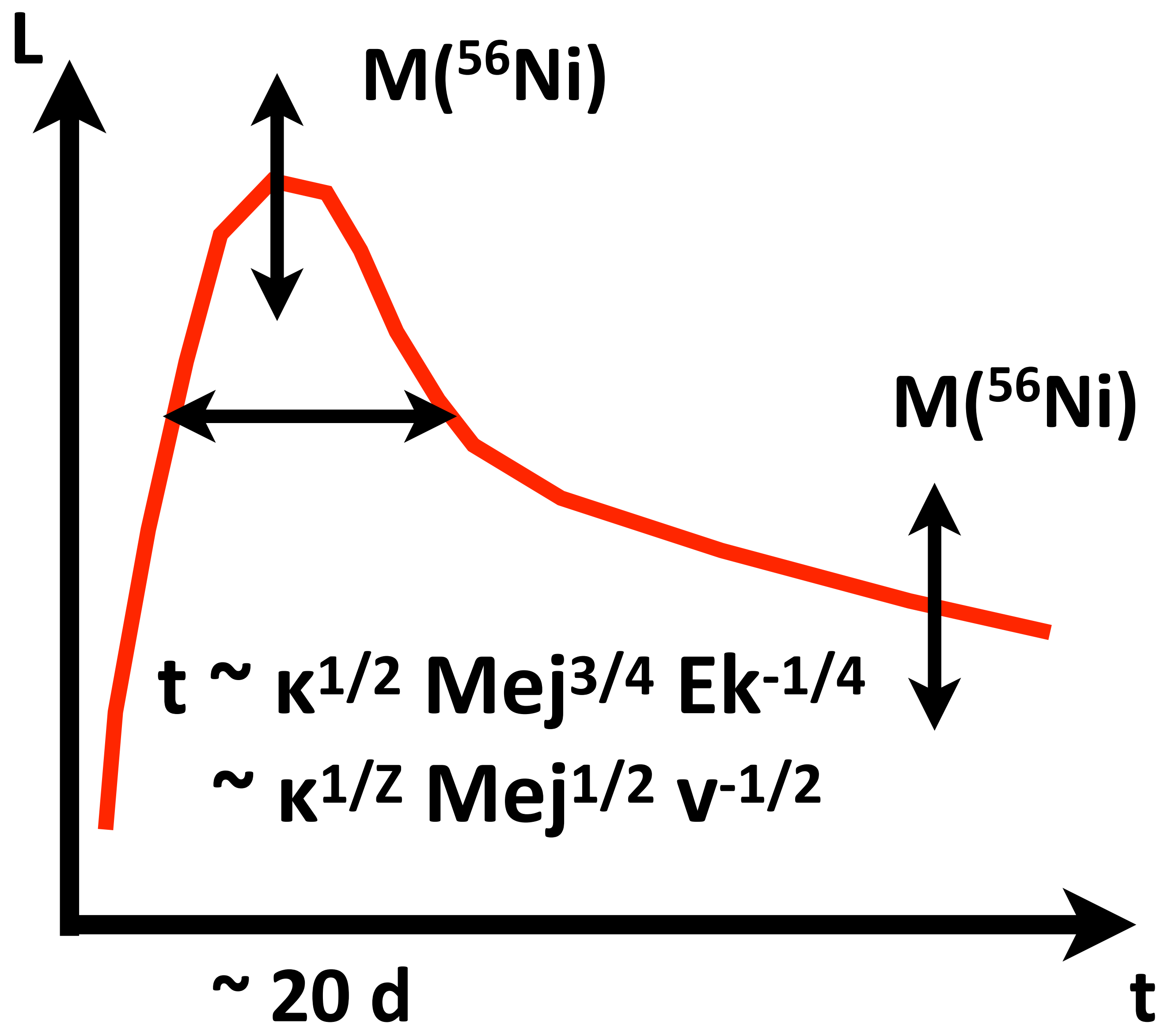
3. **Interaction with CSM**
   Ekin => Eth (Type IIn)

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 $t \sim \kappa^{1/2} Mej^{3/4} Ek^{-1/4}$
    $\sim \kappa^{1/2} Mej^{1/2} v^{-1/2}$

Observations <=> physical quantities

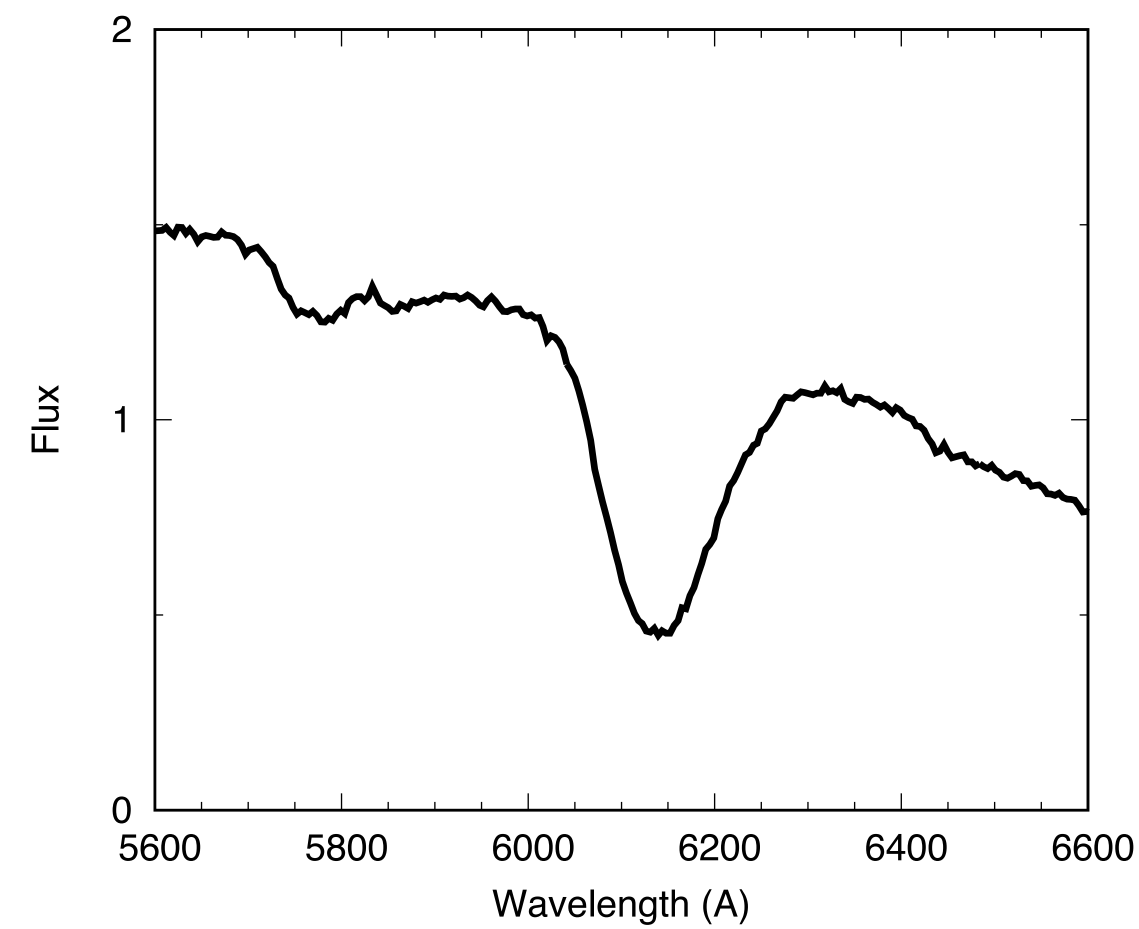
Light curves



Spectra

$v \sim E^{1/2} Mej^{-1/2}$

+ chemical composition

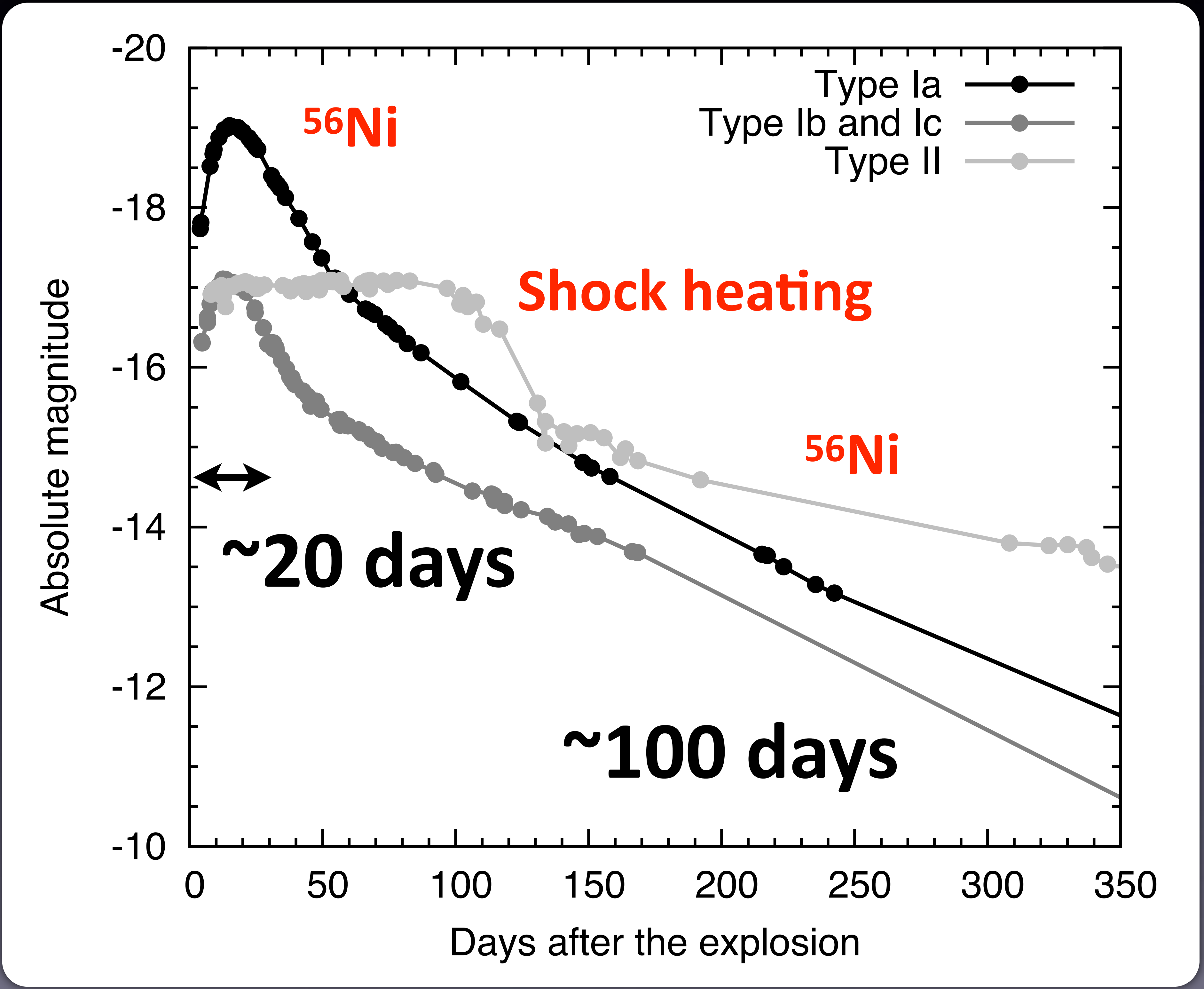


E, Mej, M(56Ni), X (element)

Lessons from supernova observations

1. Thermonuclear supernovae
2. Core-collapse supernovae
3. Gamma-ray bursts and supernovae

Light curves

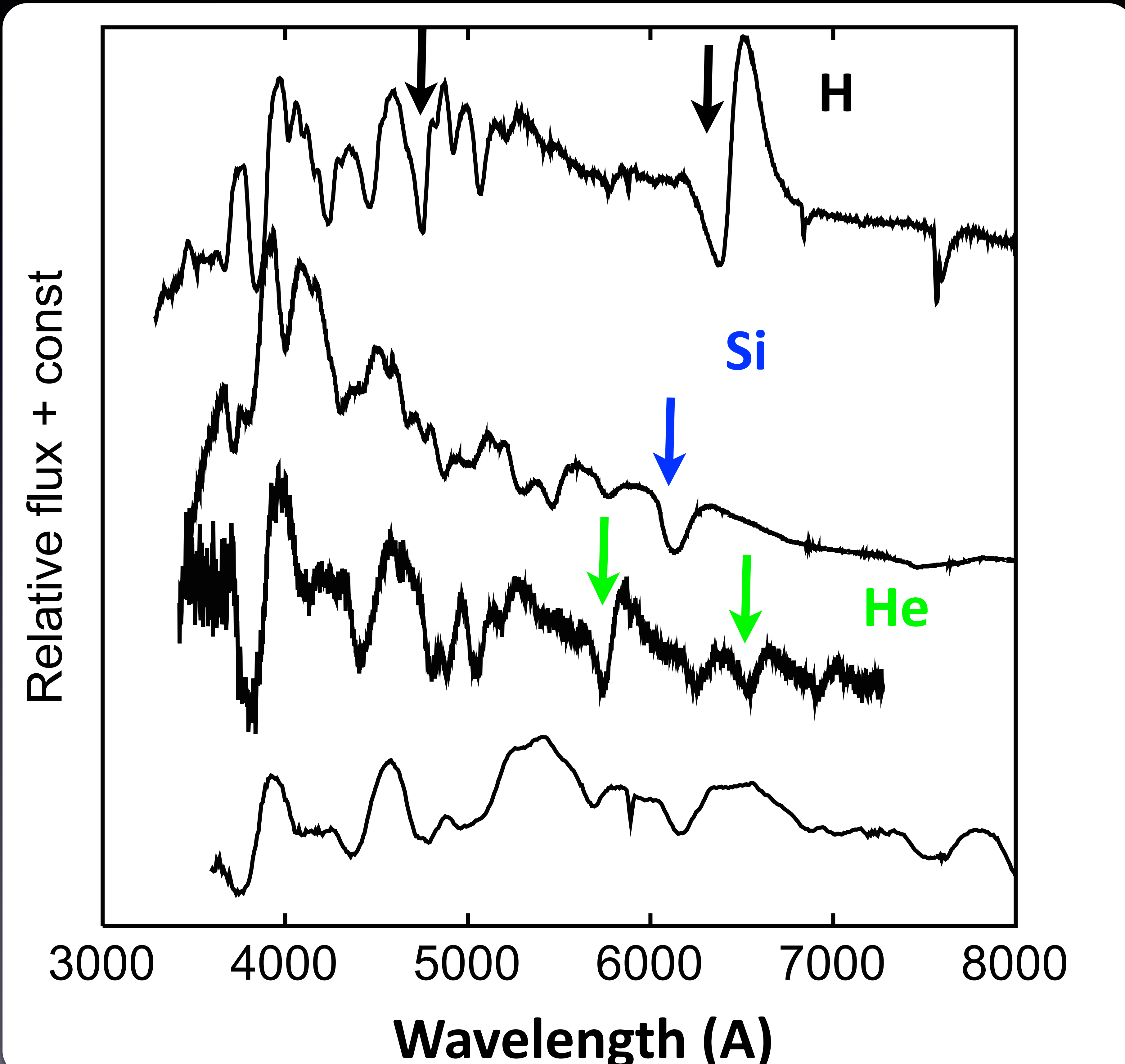


10^{43} erg s^{-1}

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

Type Ia SNe eject more ^{56}Ni

4 types of supernovae



Type II

Type I

Ia

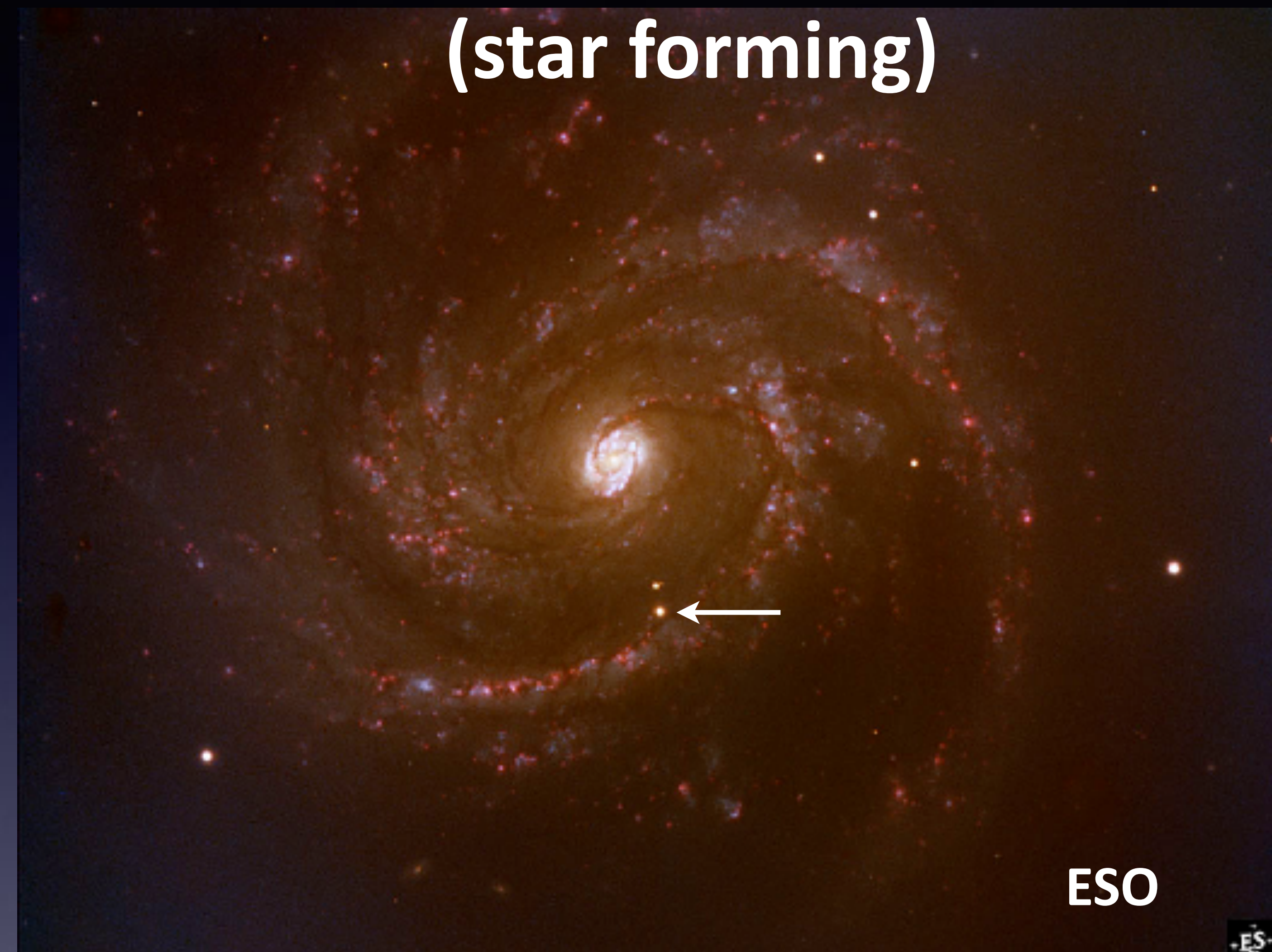
Ib

Ic

Host galaxies of supernovae

Elliptical galaxy

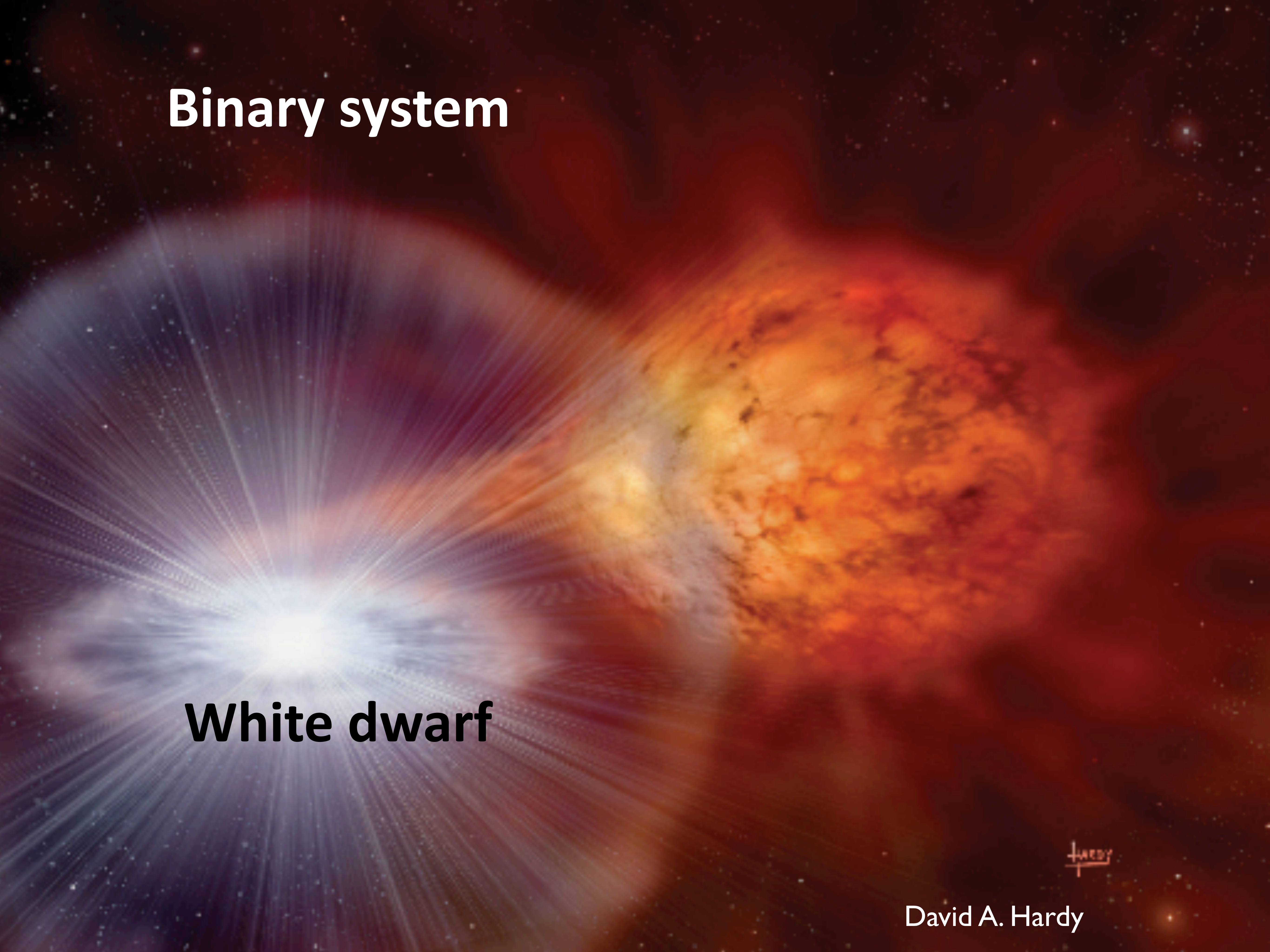
Spiral galaxy (star forming)



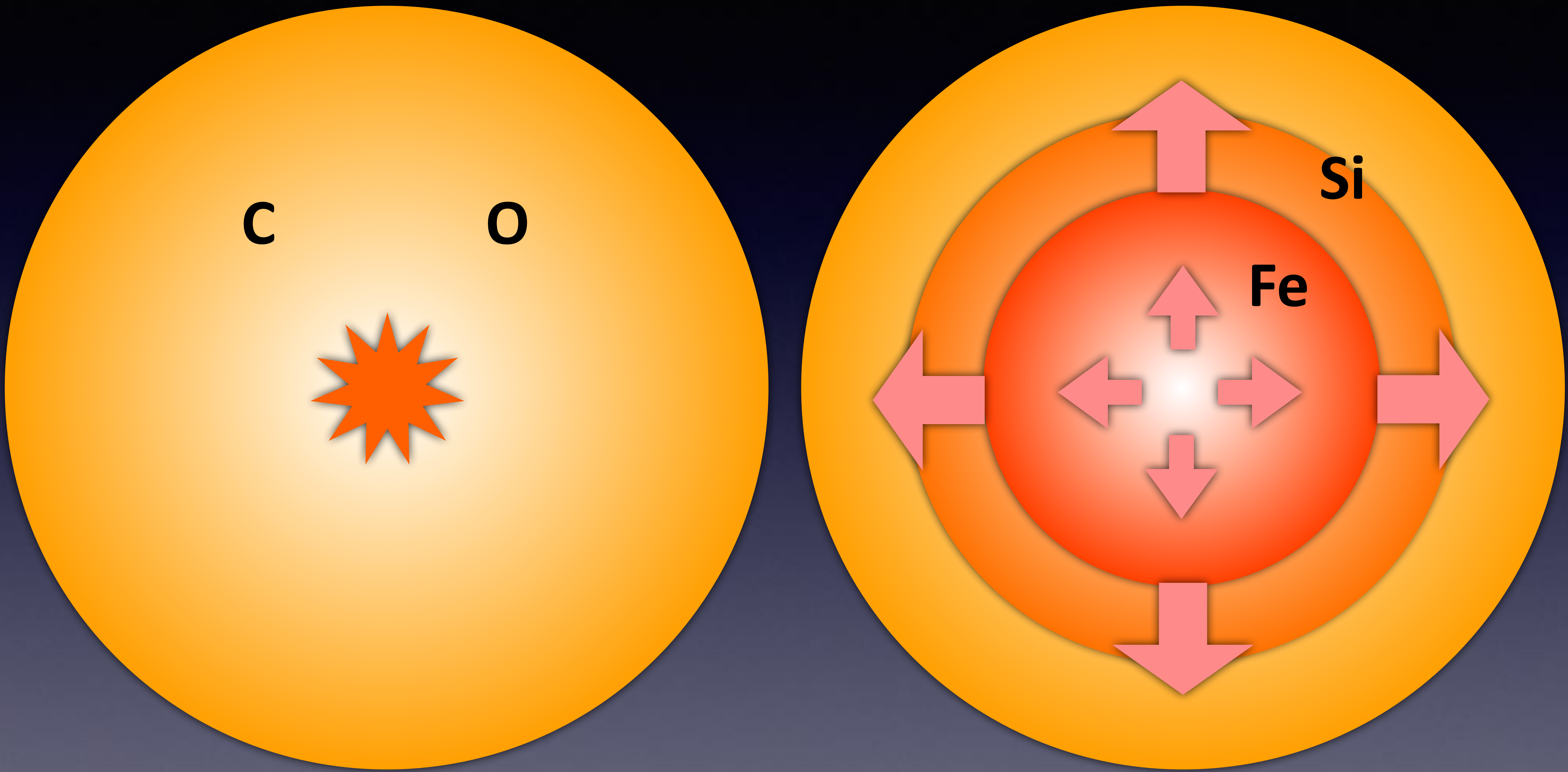
Type Ia | **Type Ia** | **Type Ib, Ic, II**

→ **II, Ib, Ic: Young stars (massive stars)**

Ia: Old stars (low-mass stars)


Binary system
White dwarf
David A. Hardy

Thermonuclear explosion



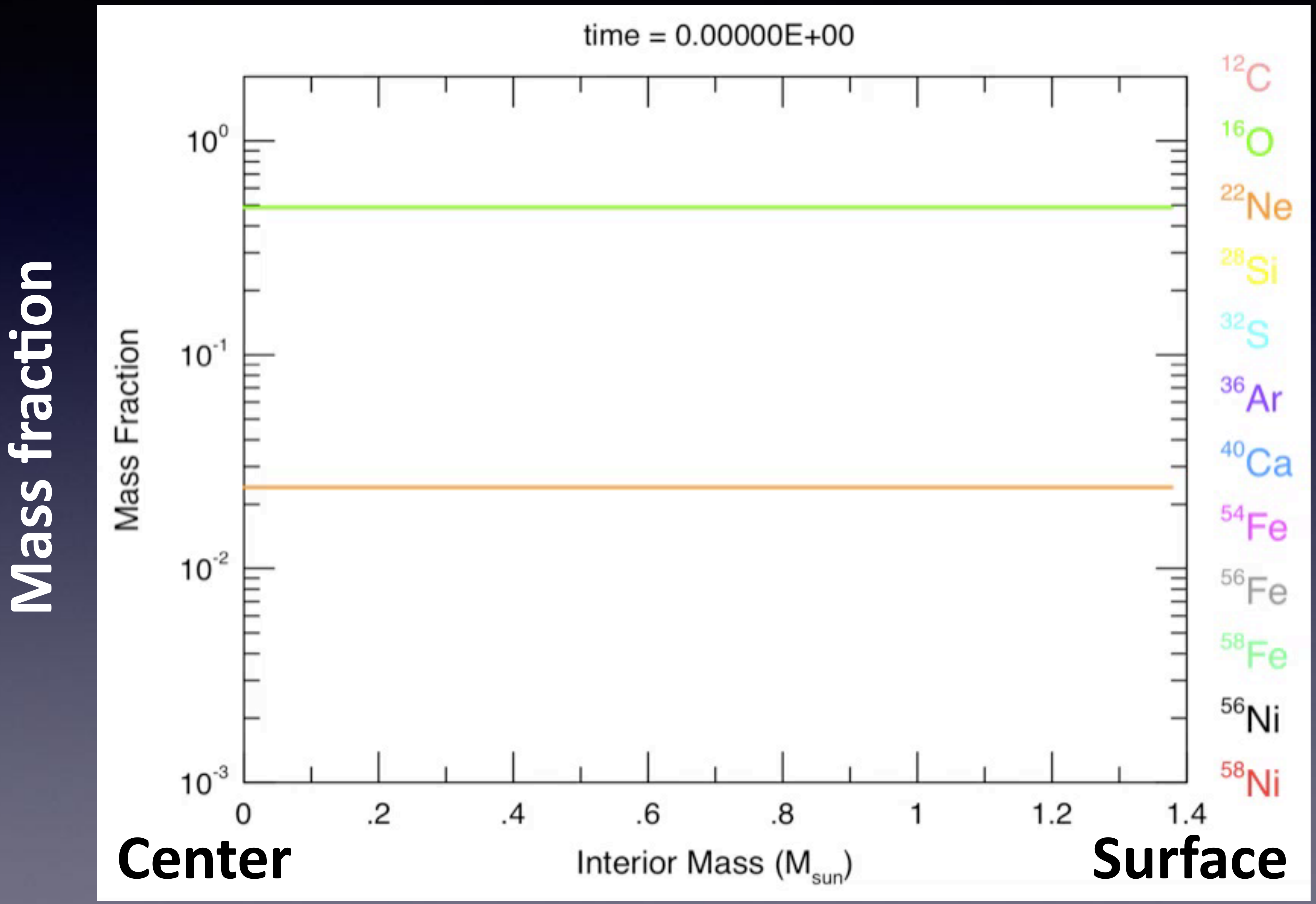
Supernova!

Thermonuclear supernovae

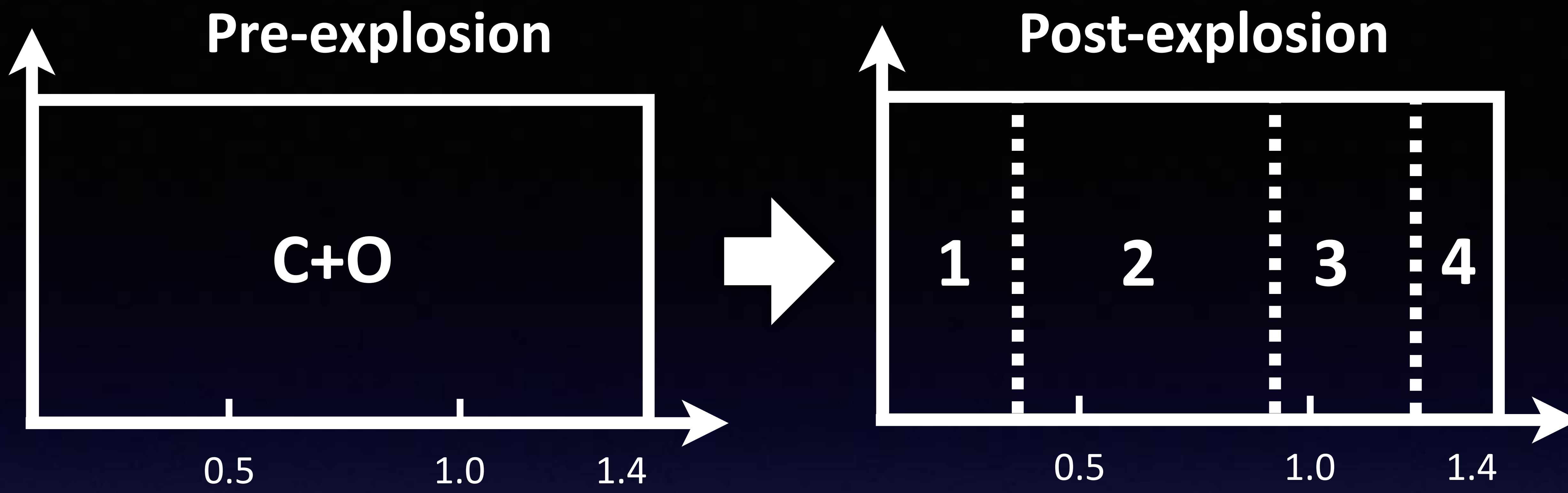
Normal stars are stable with nuclear burning

Why do white dwarfs explode by nuclear burning?

Explosion of white dwarf

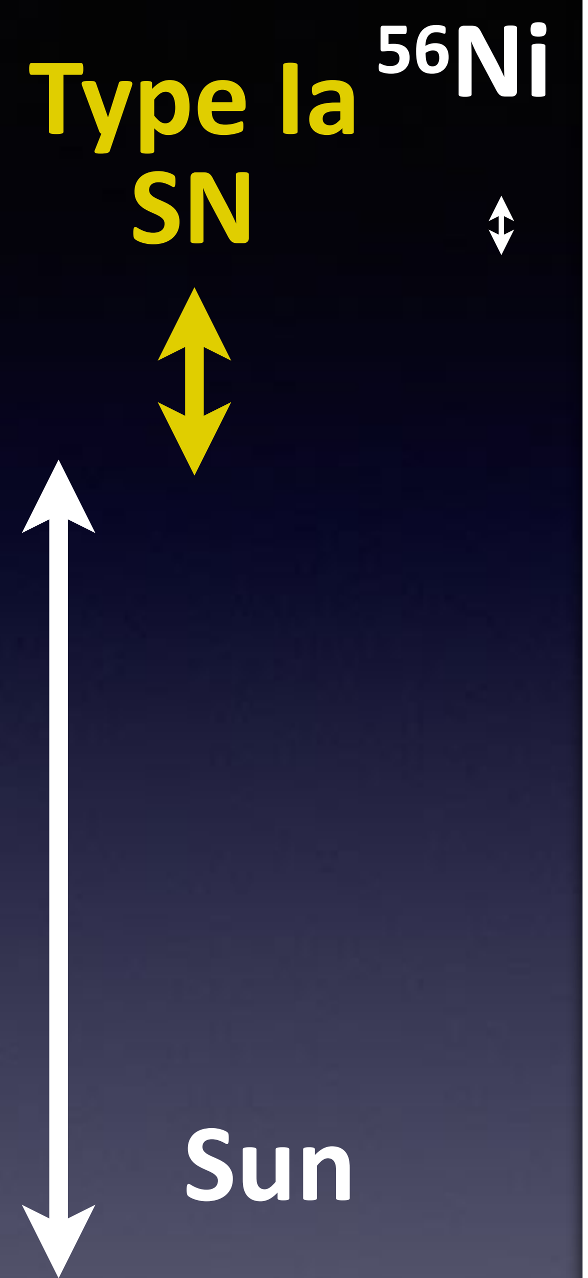


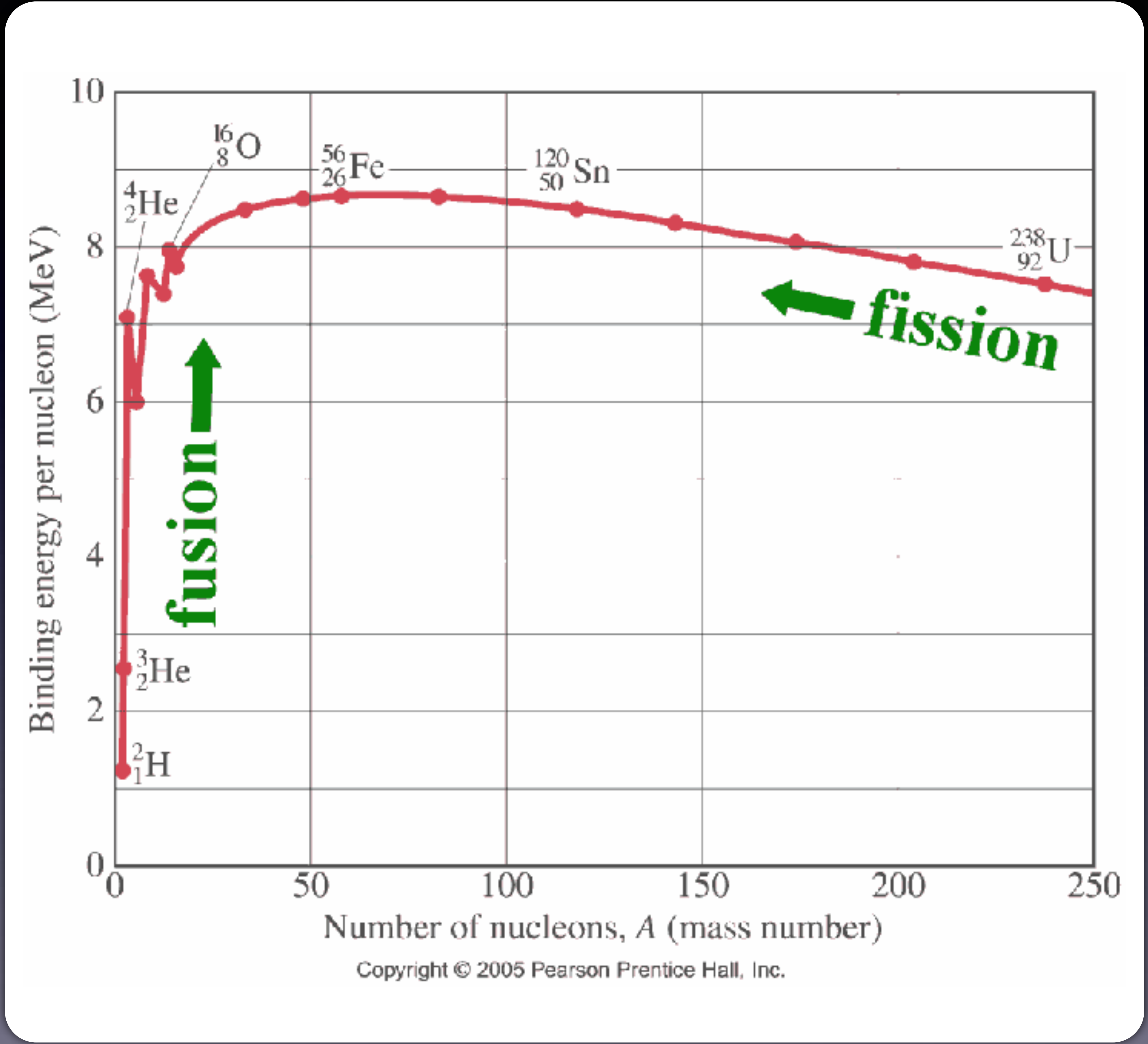
Nomoto+84, Timmes+



*NSE = nuclear statistical equilibrium

zone	T (K)	P (g cm^{-3})		Elements
1	(7-9) x 10^9	10^{8-9}	NSE + e-capture	^{56}Fe, ^{54}Fe, ^{58}Ni
2	(5-7) x 10^9	10^{7-8}	NSE	^{56}Ni
3	(4-5) x 10^9	<10^7	Incomplete Si burning	^{28}Si, ^{32}S, ^{40}Ca
4	< 4 x 10^9	<10^7	Incomplete O burning	^{16}O, ^{24}Mg


Type Ia SN
56Ni
Sun


10
8
6
4
2
0
0
50
100
150
200
250
Binding energy per nucleon (MeV)
Number of nucleons, A (mass number)
2 1 H
3 2 He
4 2 He
16 8 O
56 26 Fe
120 50 Sn
238 92 U
fusion
fission
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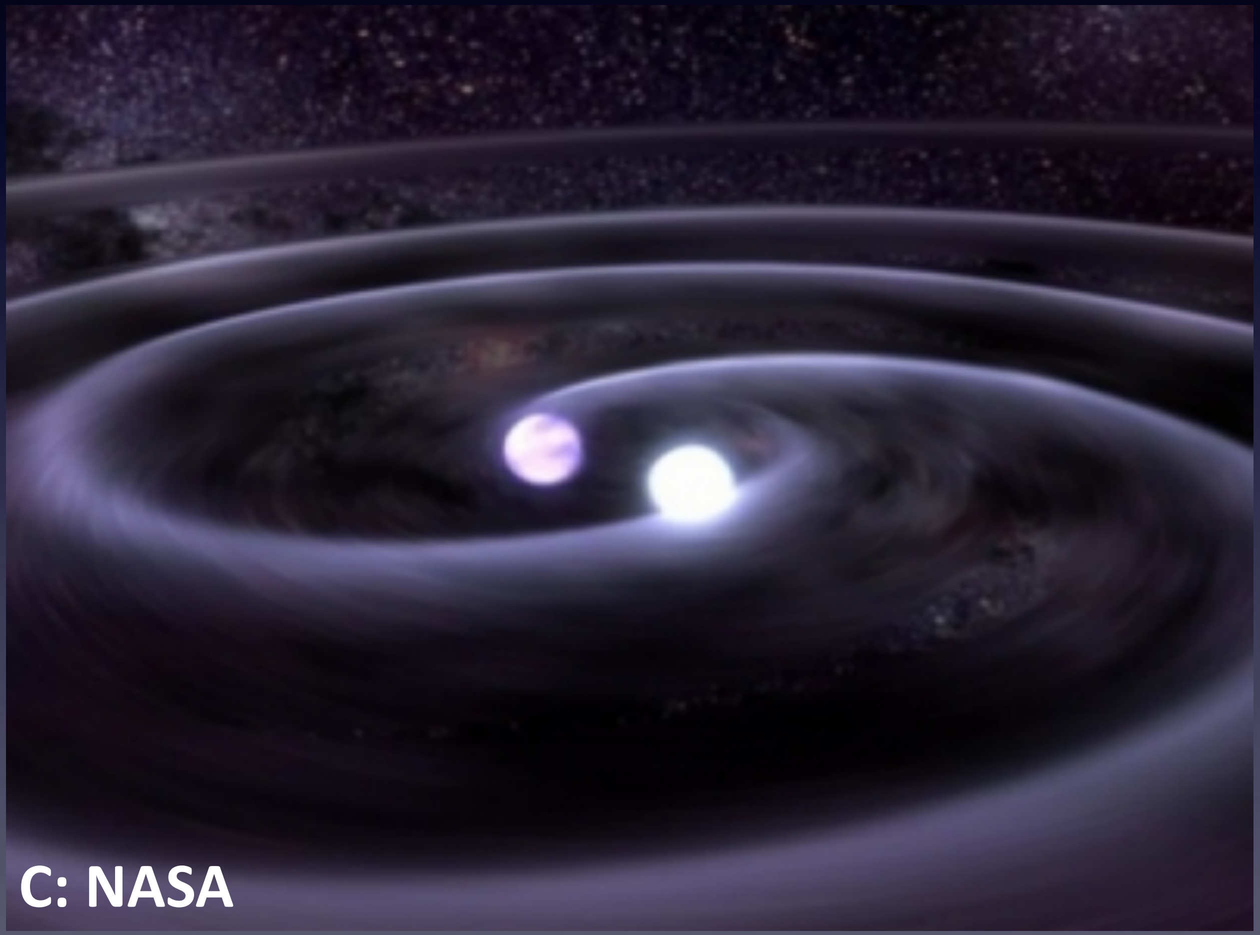
How to trigger explosion (progenitor scenarios)

Accretion from
non degenerate star

single degenerate

Merger of two white dwarfs



double degenerate

Which is correct or dominant? Not yet understood

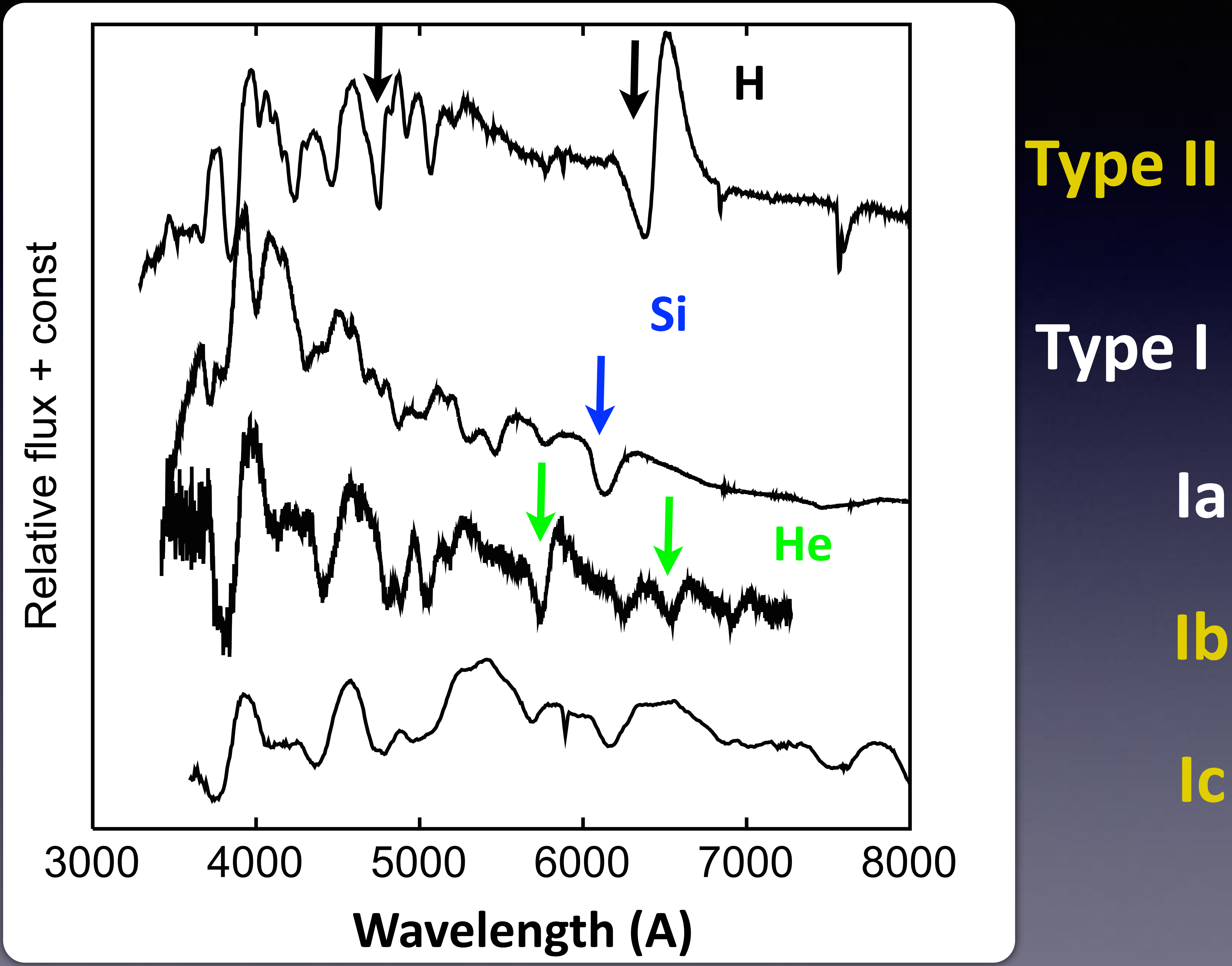
Summary: Thermonuclear supernovae

- **Classified as Type Ia SNe**
  - No H line, strong Si line
  - Discovered in all types of galaxies
- **Thermonuclear explosion of white dwarf in binary**
  - Thermonuclear runaway
    triggered when mass reaches Chandrasekhar limit
    => Homogeneous properties (standard candle)
  - Explosive nucleosynthesis
- **Progenitor system is still not clear**

Lessons from supernova observations

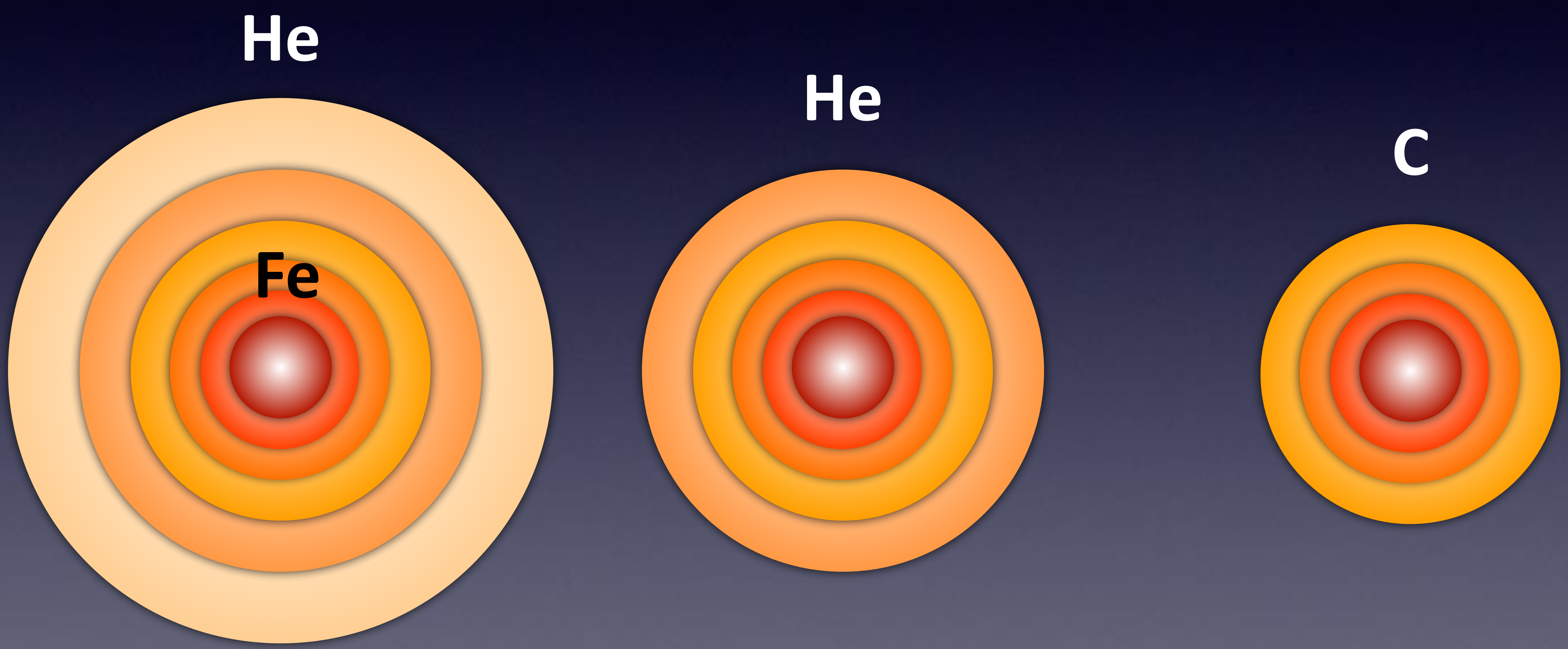
1. Thermonuclear supernovae
2. Core-collapse supernovae
3. Gamma-ray bursts and supernovae

4 types of supernovae



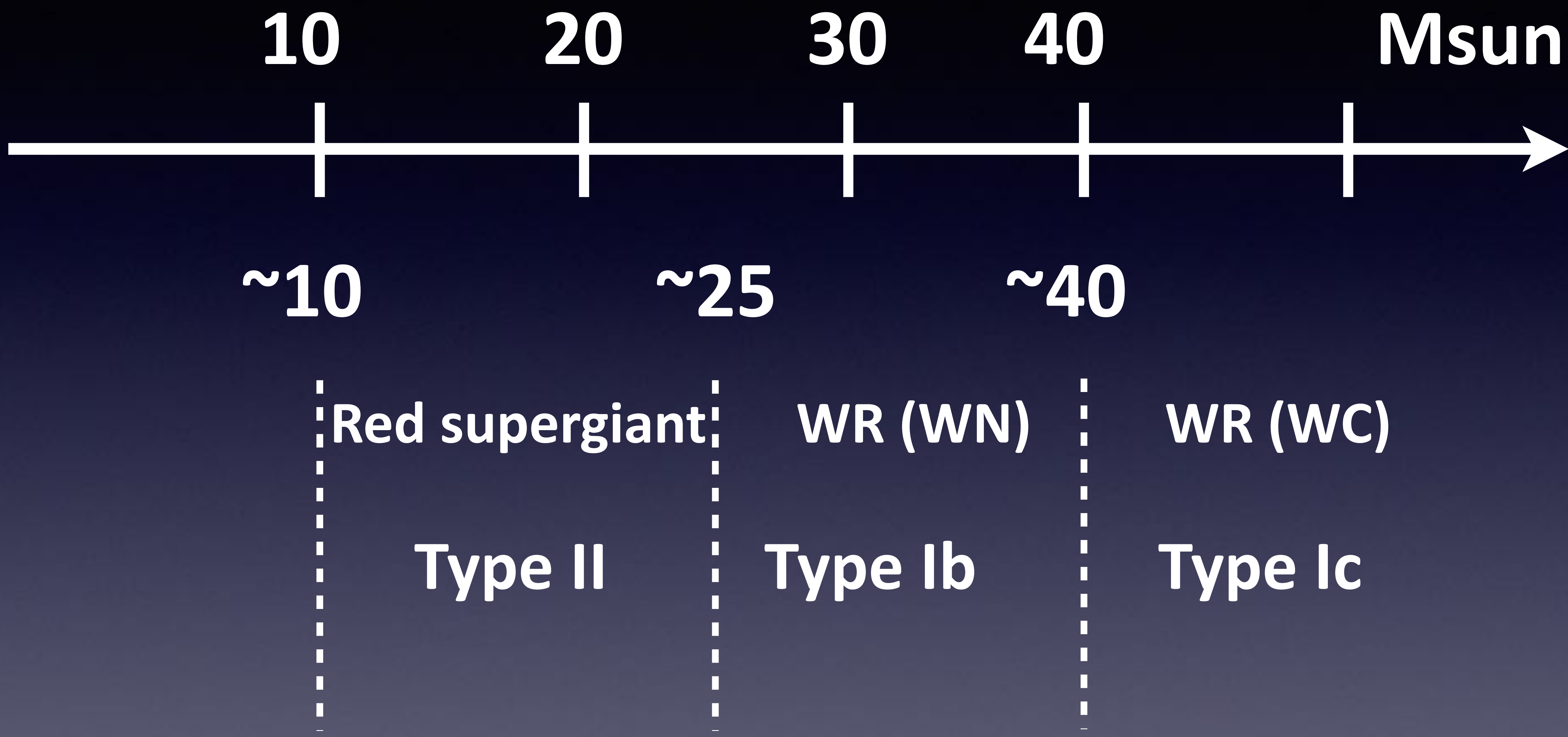
Core-collapse SNe and their progenitors

Type II | Type Ib | Type Ic



Mass loss due to stellar wind

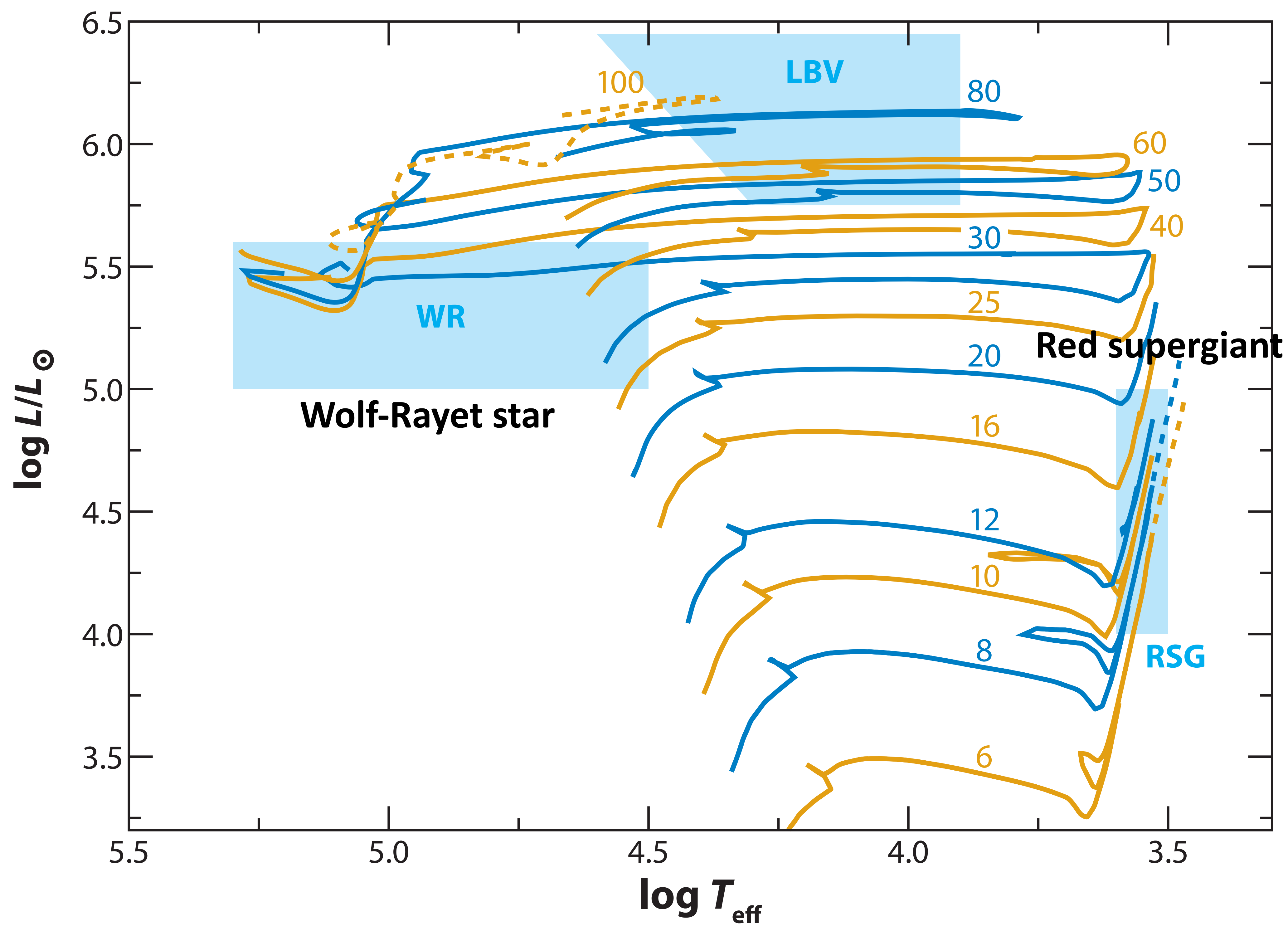
Initial mass and supernova types



Is this really correct??

=> We need observational tests

SN progenitors in HR diagram

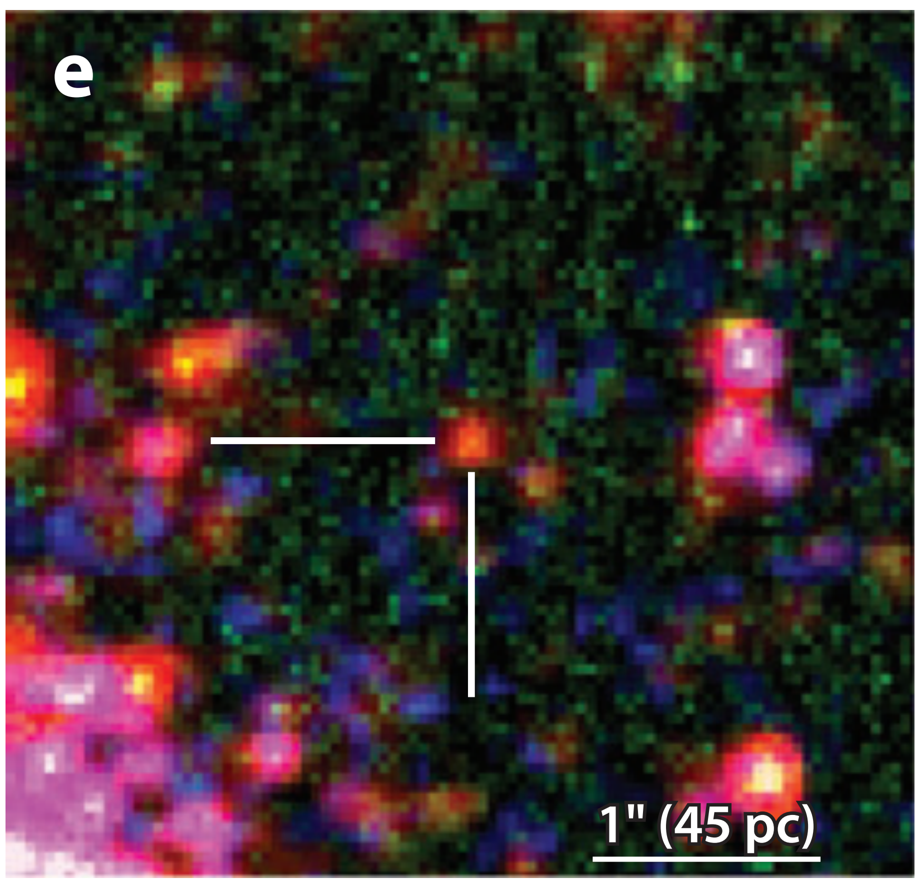


Smartt 09

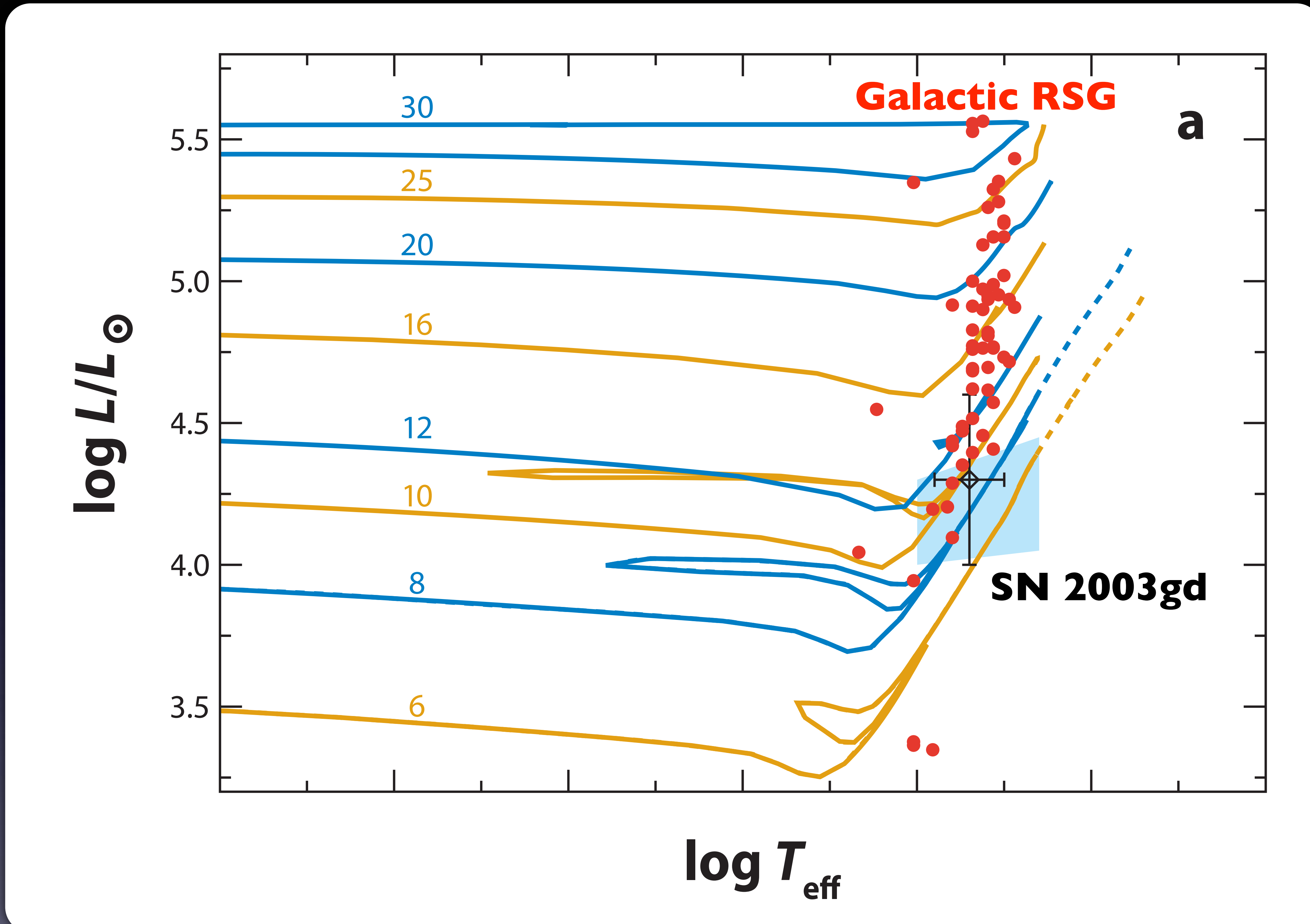
Direct observations (only up to ~< 20 Mpc)

SN 2003gd in
M74 (10 Mpc)

WFPC2 F300W, F606W, F814W

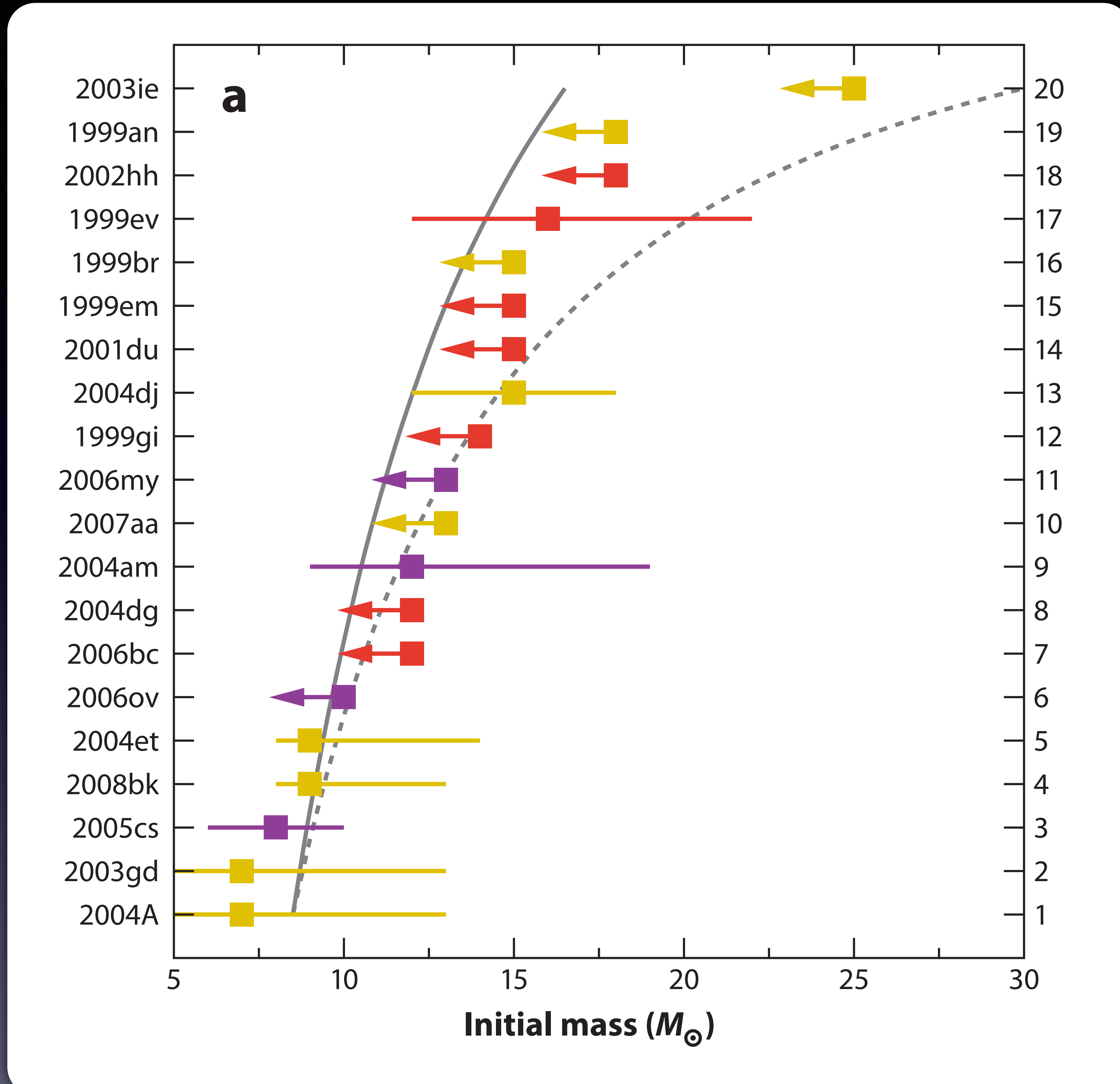


Smartt+04, Van Dyk+03



Smartt 09

Red supergiant => Type II SN!!

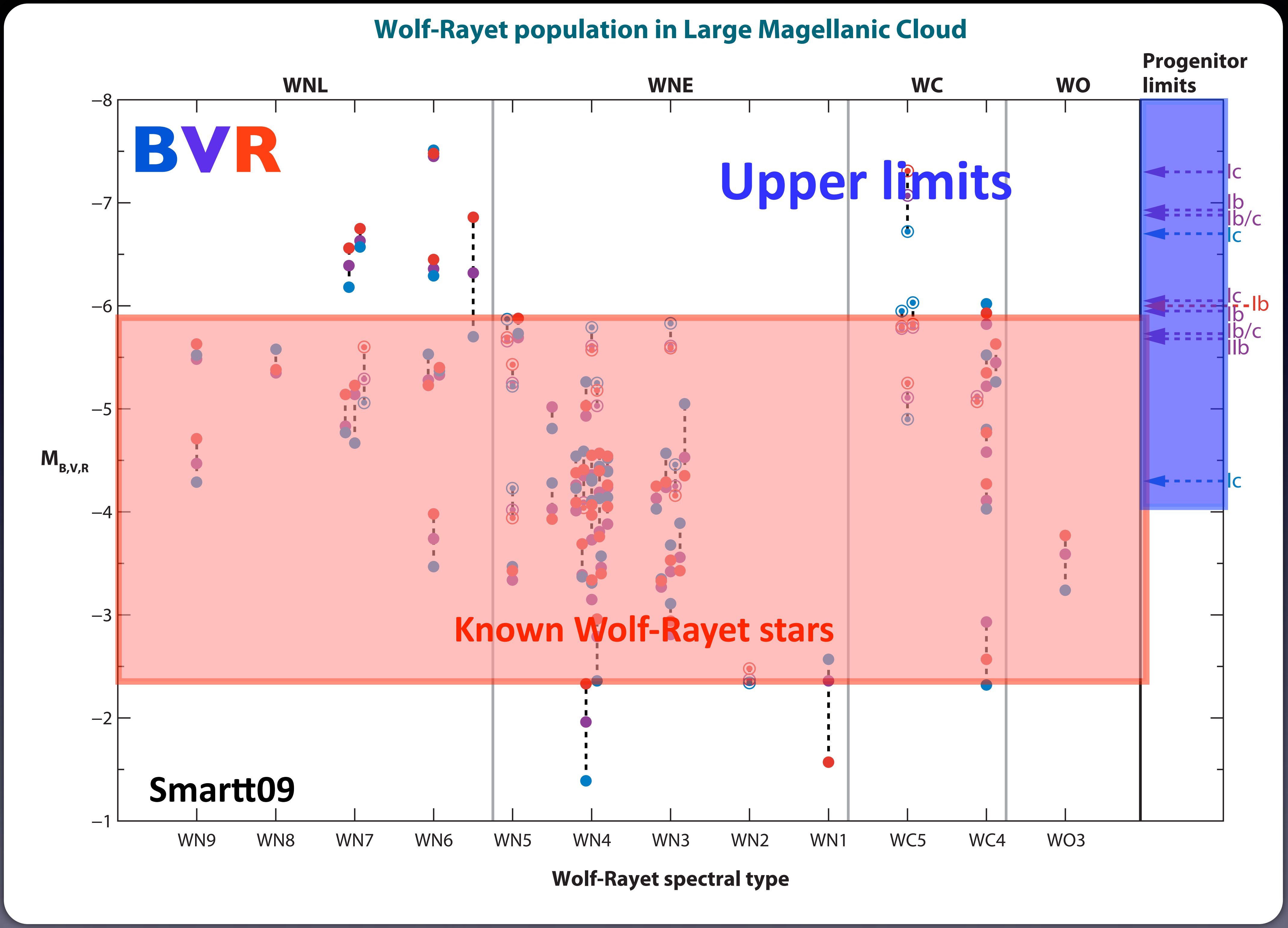


Smartt 09

Red supergiant => Type II SN!!

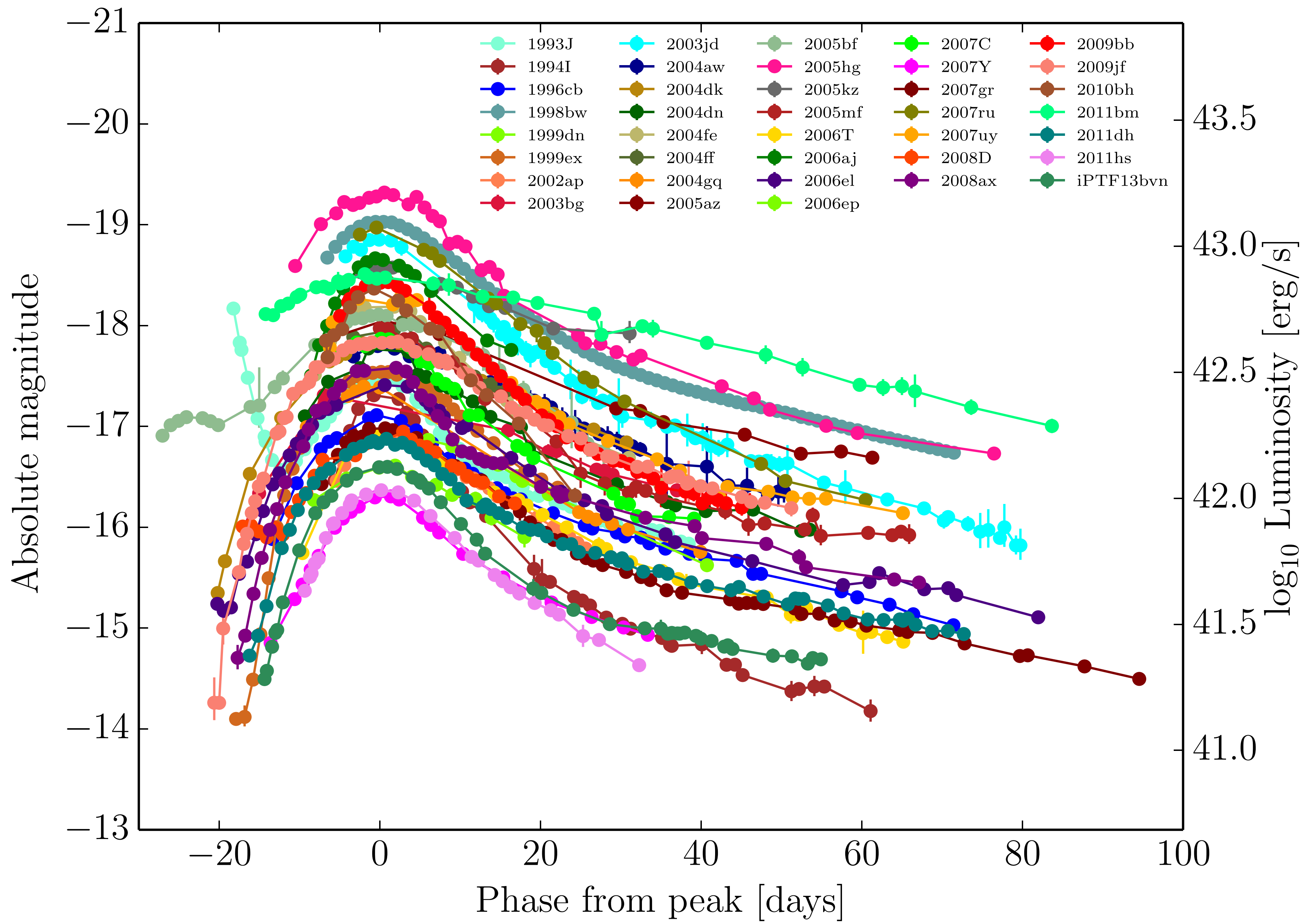
~ 10-20 Msun

Wolf-Rayet stars => Type Ib/Ic??



No direct evidence

Light curves of Type Ib/Ic supernovae



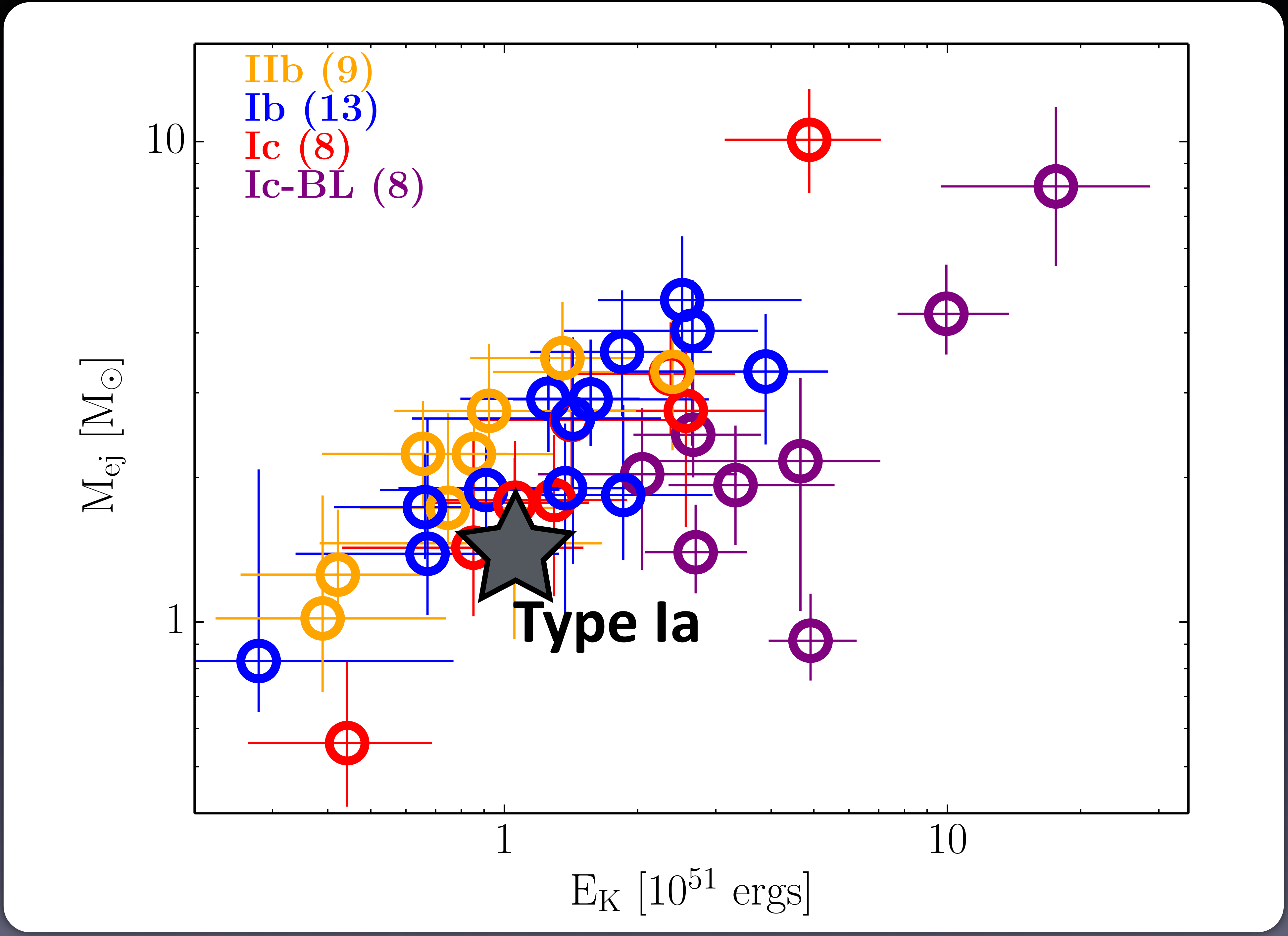
Type Ia

Lyman+16

Timescale ~ 20 days (similar to Type Ia)

velocity ~ 10,000 km/s (similar to Type Ia)

Physical quantities for Type Ib/Ic SNe

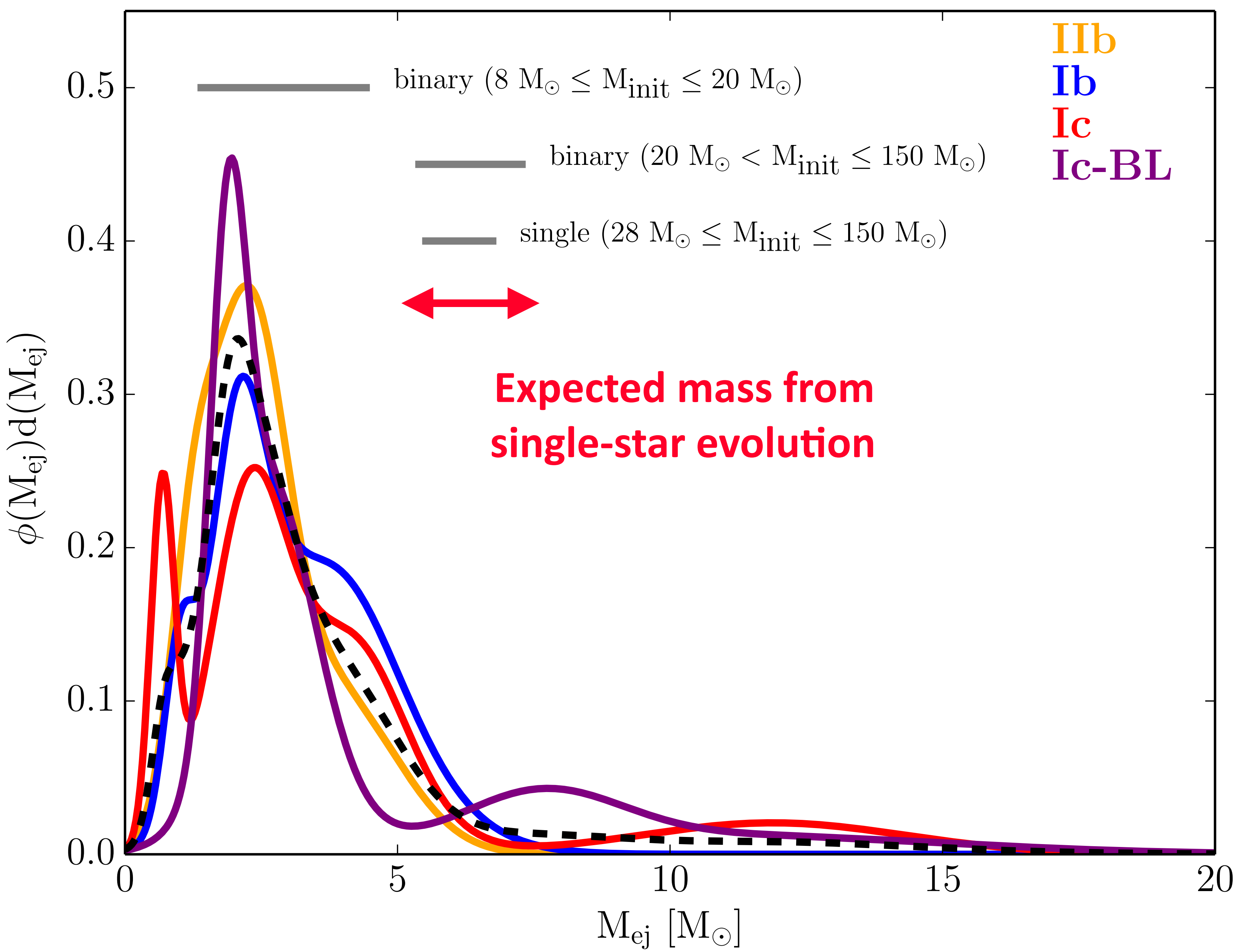


Mej ~ 1-3 Msun

Ek ~ (0.5-5) x 10^{51} erg

Lyman+16

Ejecta mass of Type Ib/Ic SNe



Lyman+16

Binary evolution plays an important role

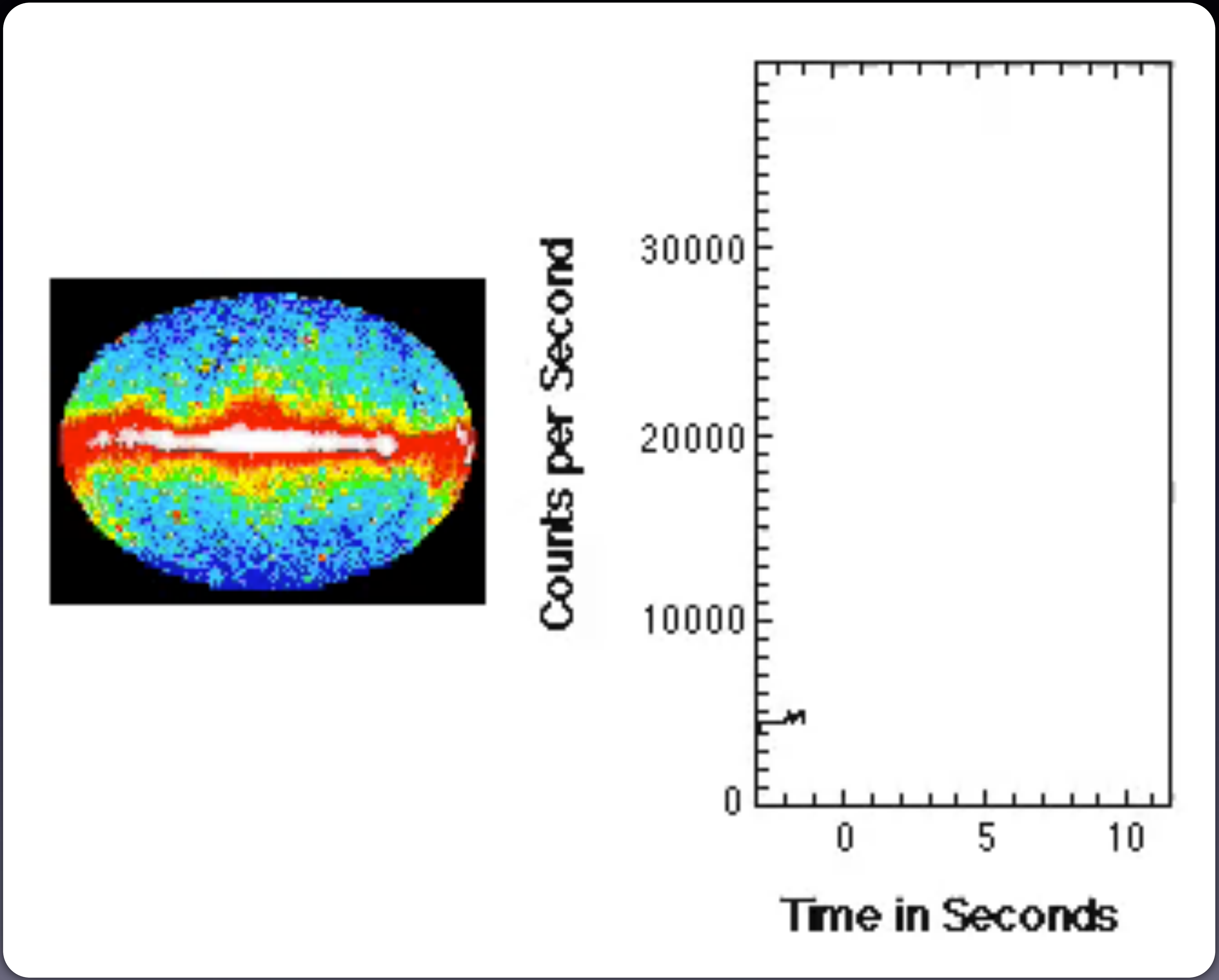
Summary: Core-collapse supernovae

- **Type II supernovae**
  - Explosion of red supergiants
  - Tested with direct progenitor observations
- **Type Ib/Ic supernovae**
  - Explosion of stripped-envelope massive stars
  - Ejecta mass is relatively small (3-5 Msun)
  - Binary evolution may be a key

Lessons from supernova observations

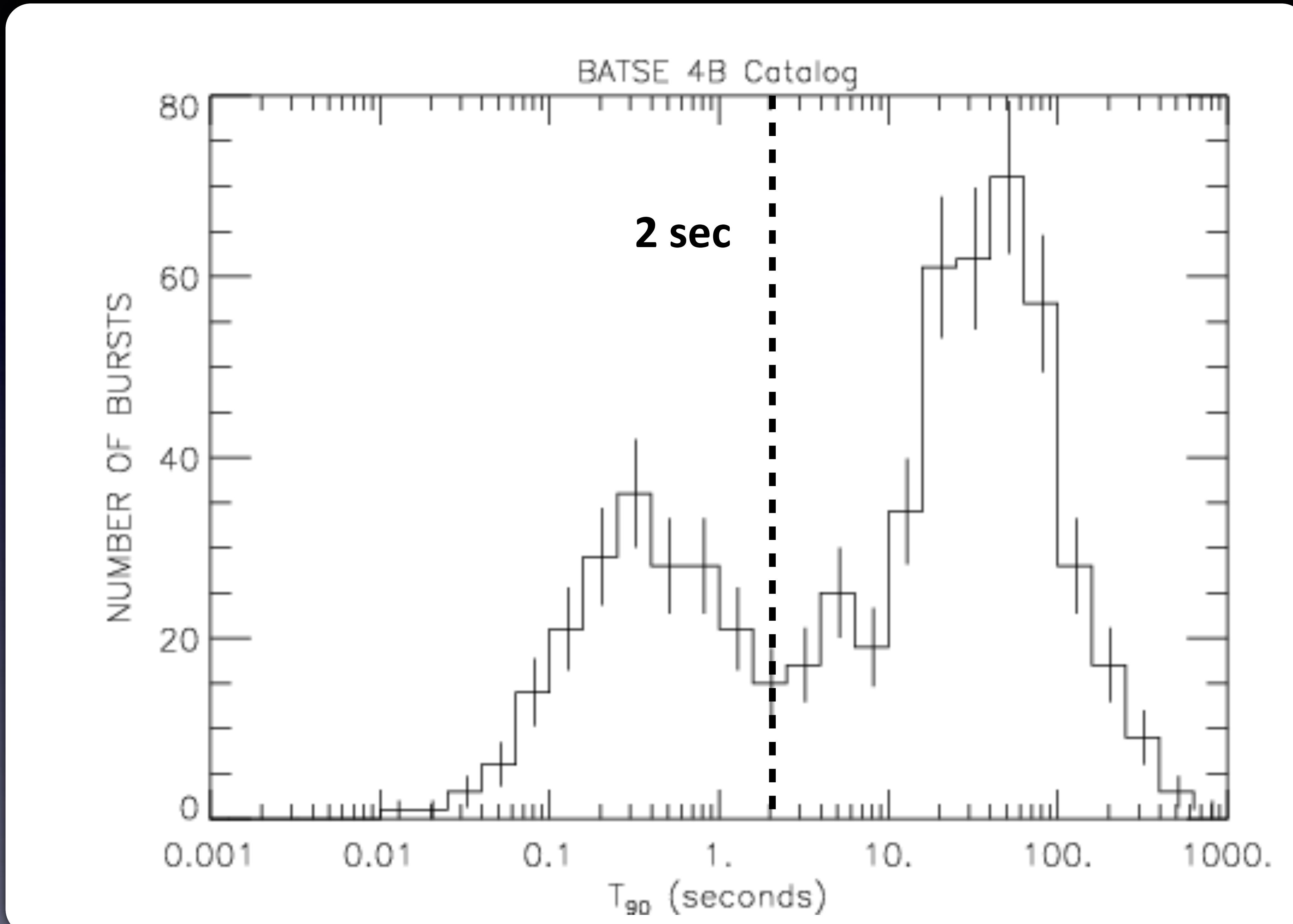
1. Thermonuclear supernovae
2. Core-collapse supernovae
3. Gamma-ray bursts and supernovae

Gamma-ray bursts (GRBs)



https://science.nasa.gov/science-news/science-at-nasa/2008/16oct_grboverview/

Duration of GRBs



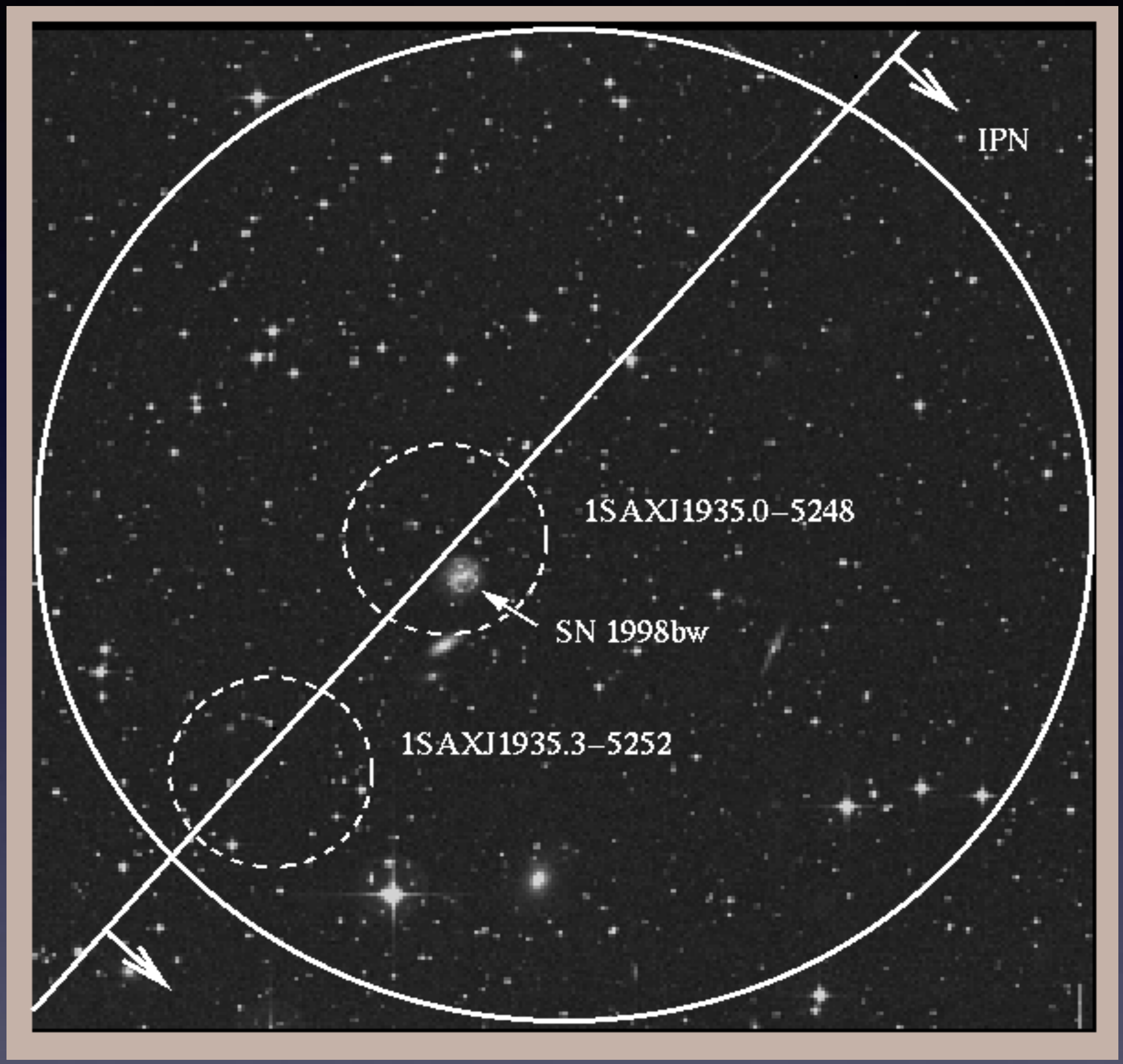
Short GRBs

Long GRBs

Long GRBs - supernova association

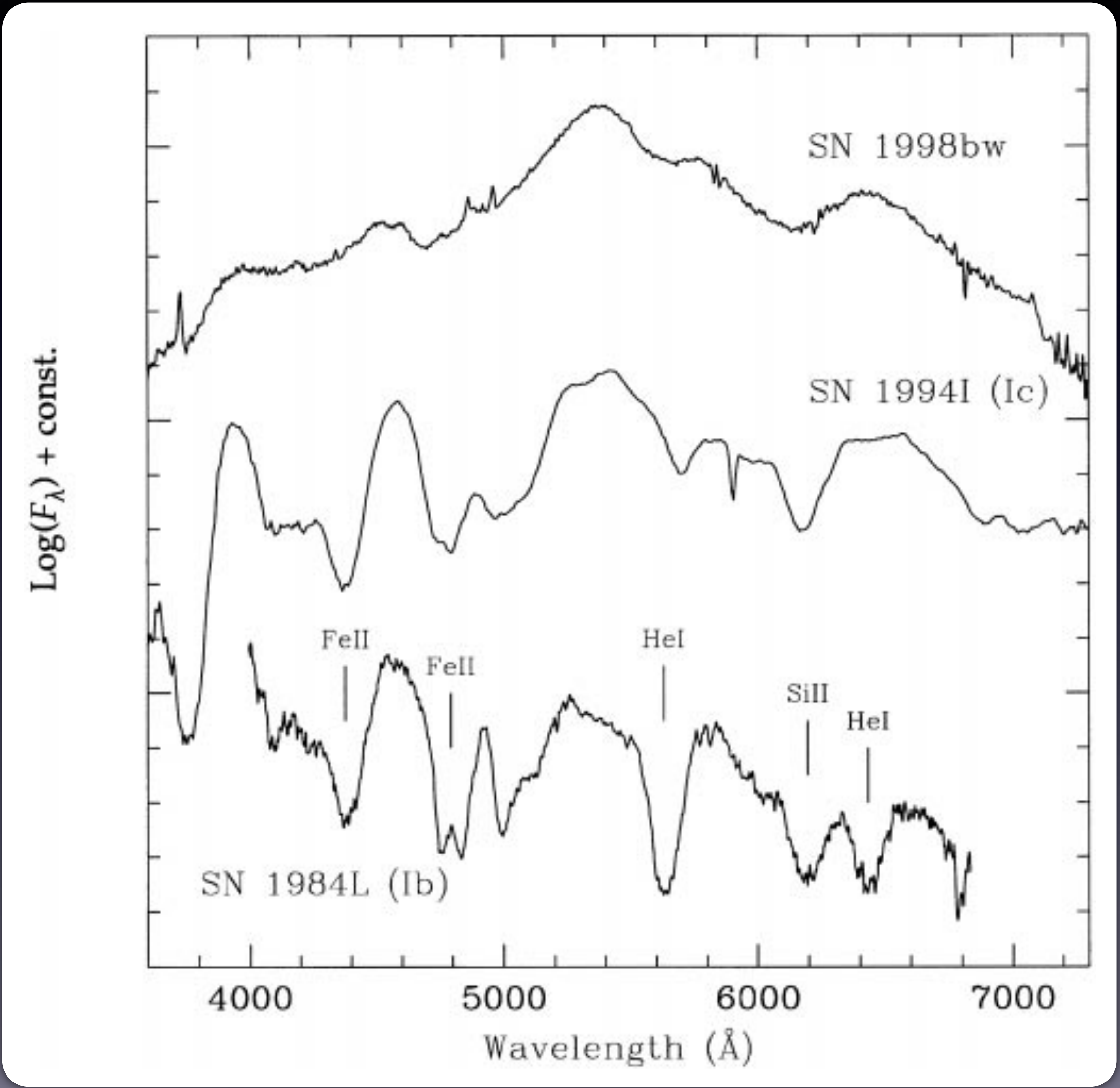
First observations in 1998

(long)
GRB 980425/SN 1998bw



Galama+98

GRB 980425/SN 1998bw

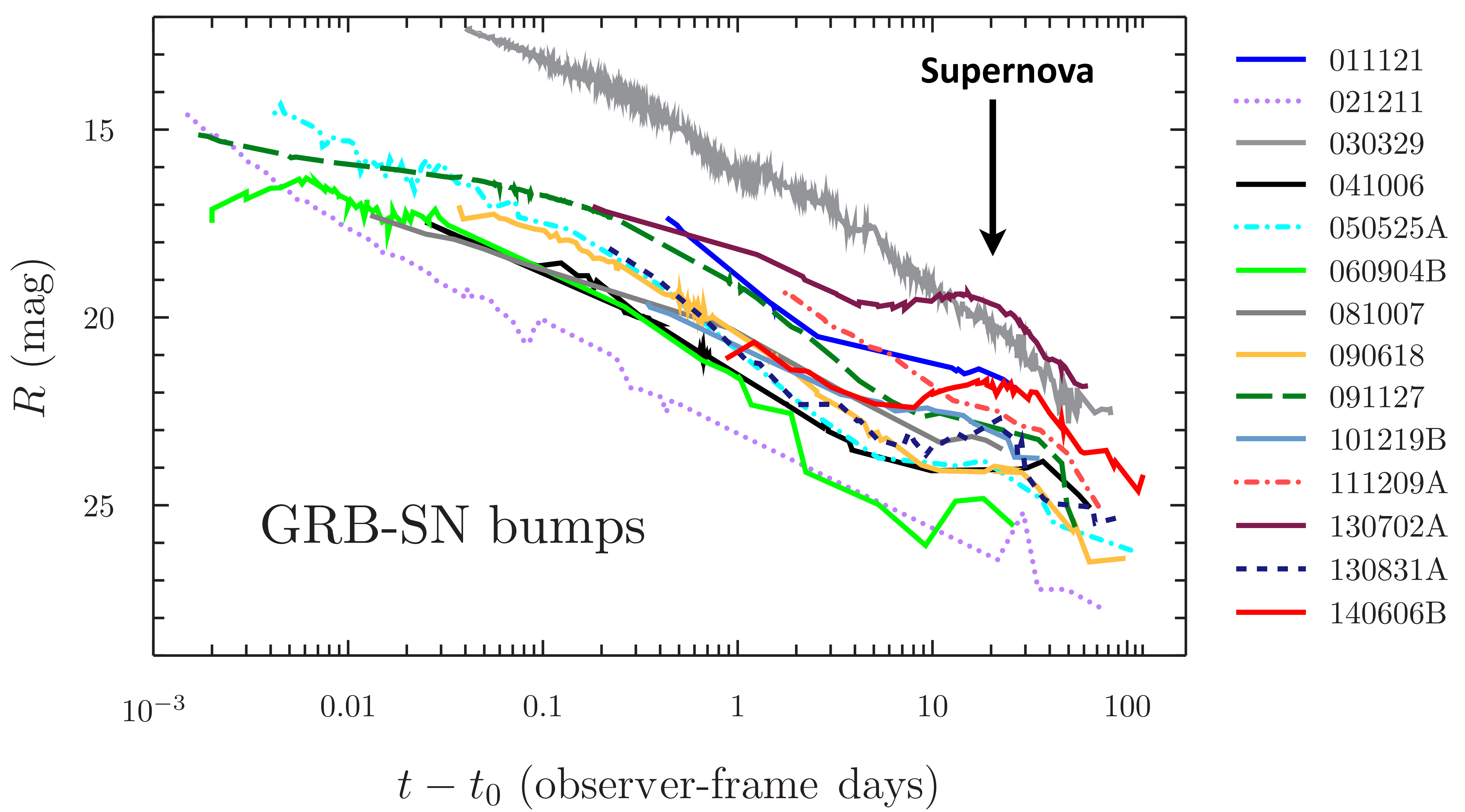


- Type Ic (no H, He)

- Broad line
=> High expansion velocity

Galama+98

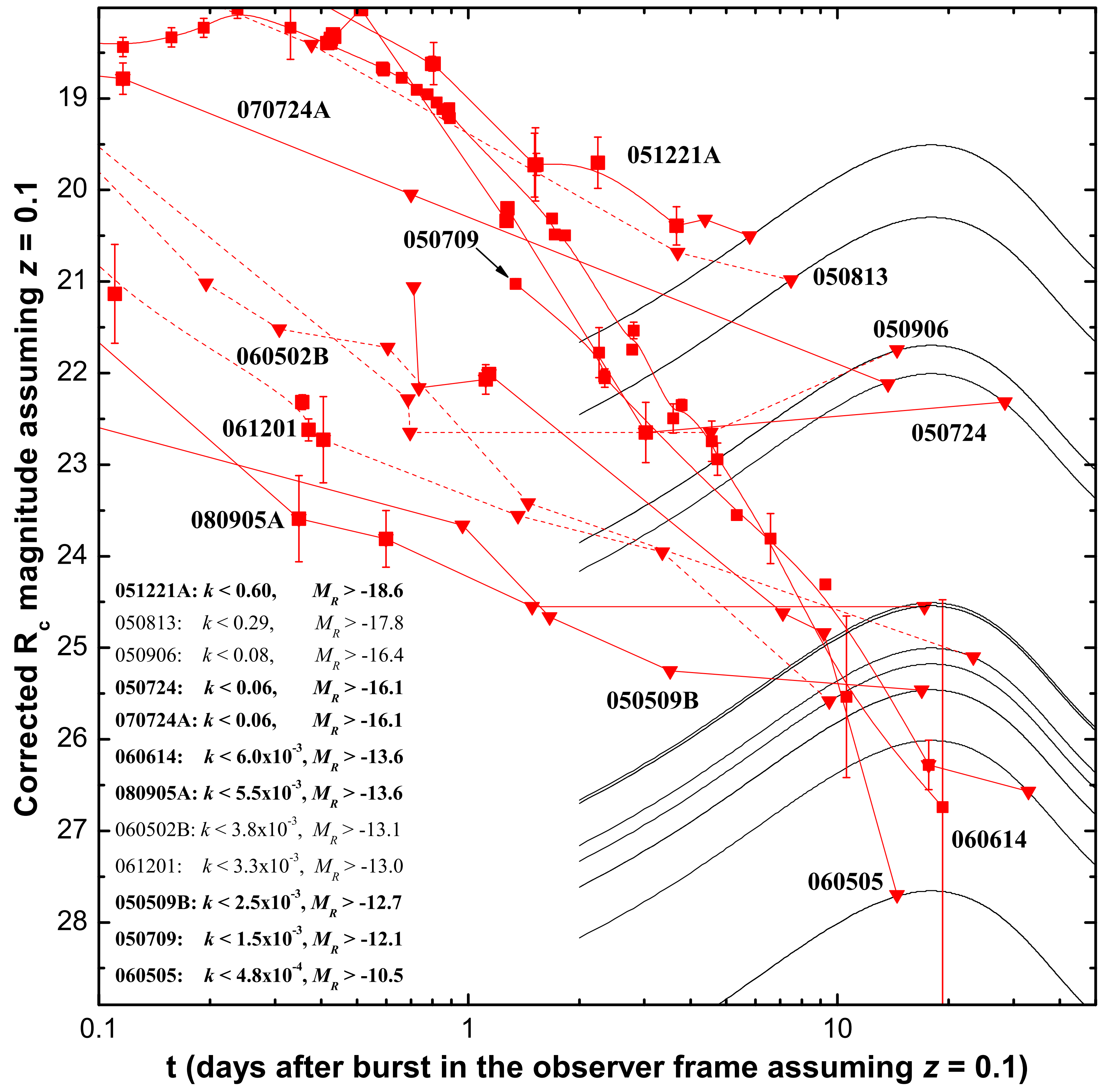
Long GRB - supernovae



Cano et al. 2016

Short GRBs

No SN association

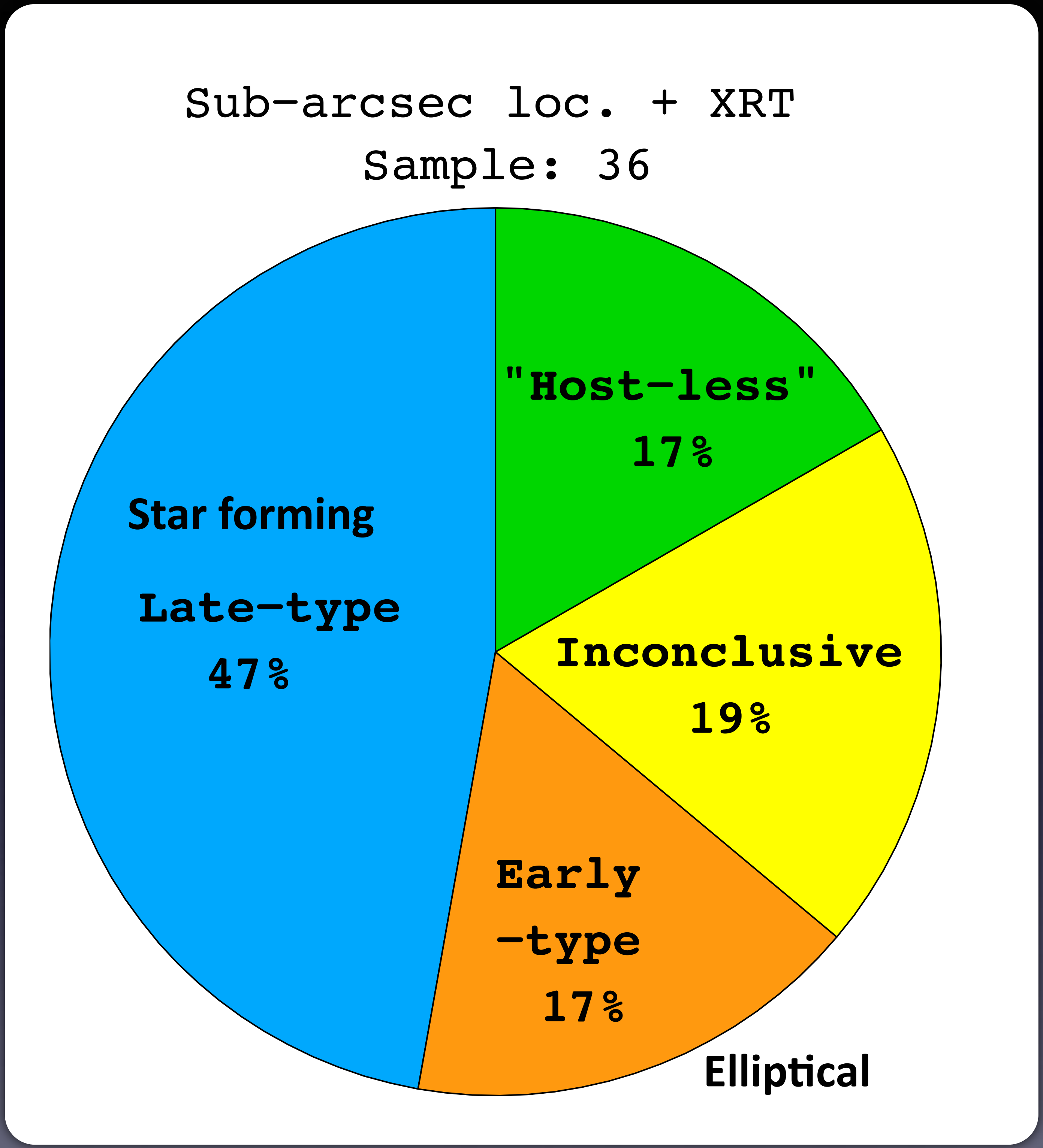


Kann+11

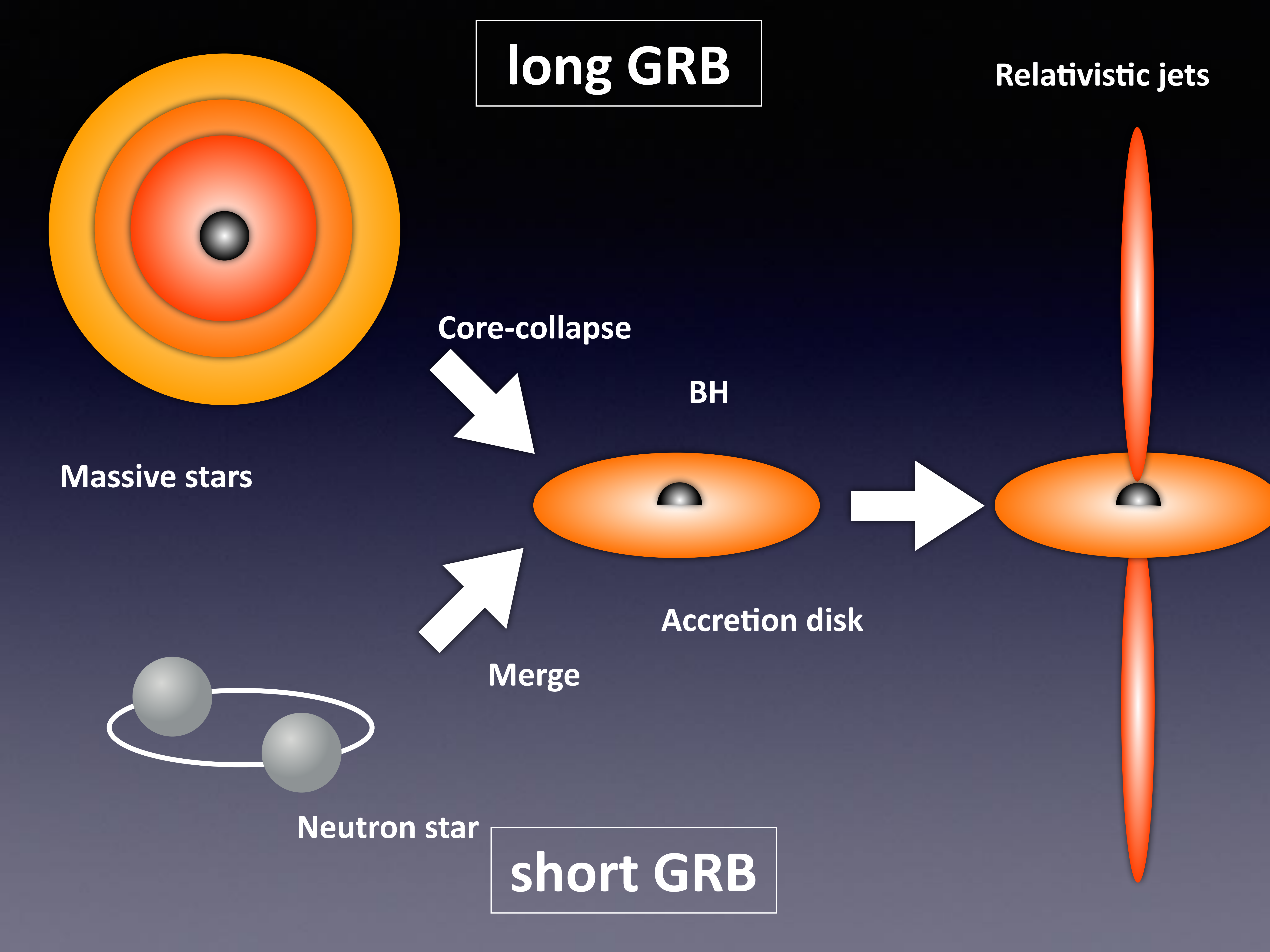
Host galaxies of short GRBs

Discovered also in elliptical galaxies

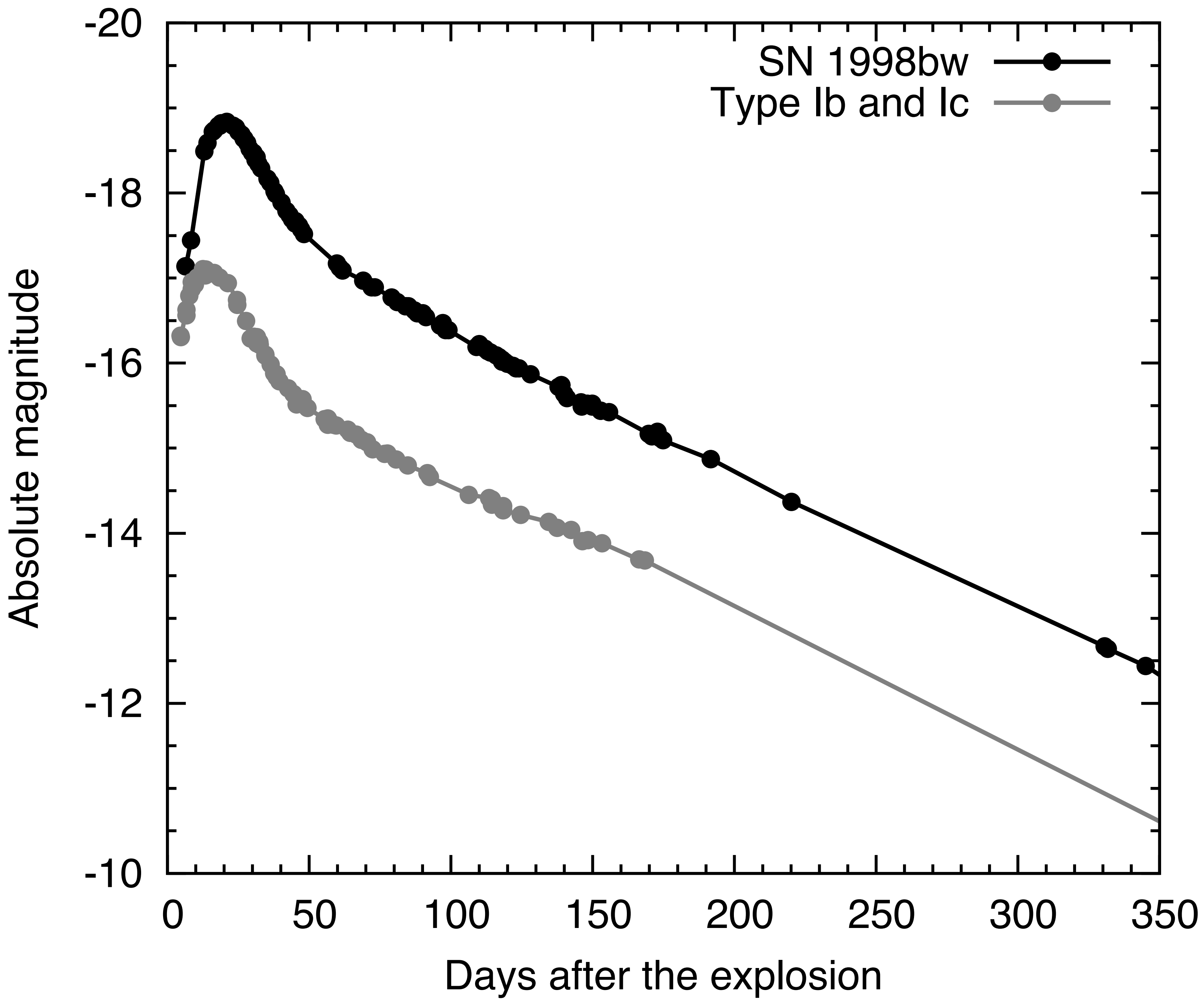
c.f. Similar to Type Ia SNe



Berger 04


long GRB
Relativistic jets
Core-collapse
BH
Massive stars
Accretion disk
Merge
Neutron star
short GRB

Light curves of GRB-SN

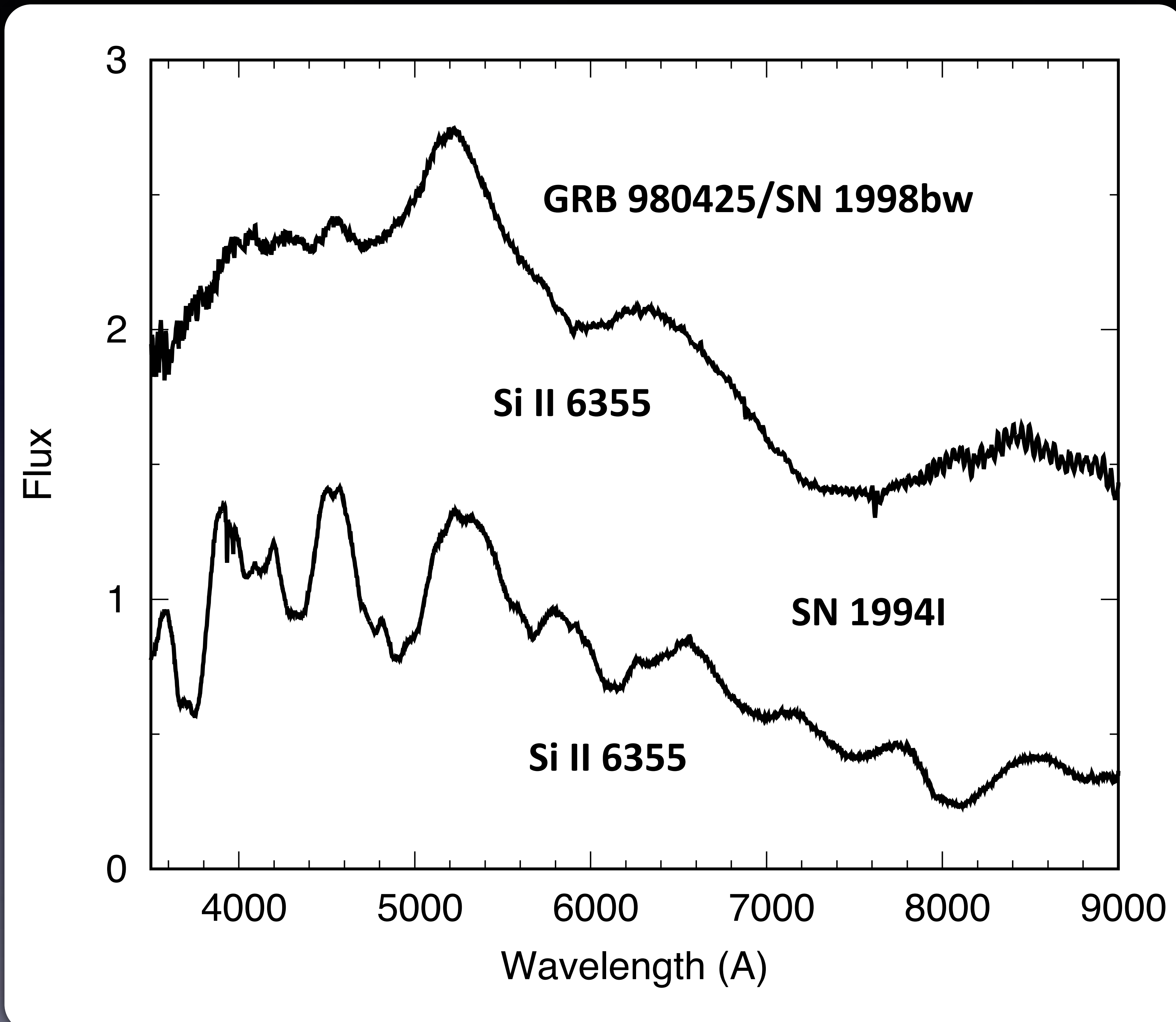


Brighter than normal SNe
=>
M(^{56}Ni) ~ 0.5 Msun

Timescale
$t \sim \kappa^{1/2} E^{-1/4} Mej^{3/4}$

Longer than normal SNe

Spectra of GRB-SNe



Type Ic

No H, He

“broad-line” Ic

v ~ 20,000 km/s!

Higher than normal SNe by a factor of 2-3

	Timescale	Velocity	Ejecta mass	Kinetic energy
Ic	~15 d	8,000 km/s	~ 3 Msun	10^{51} erg
GRB-SN	~20 d	20,000 km/s		

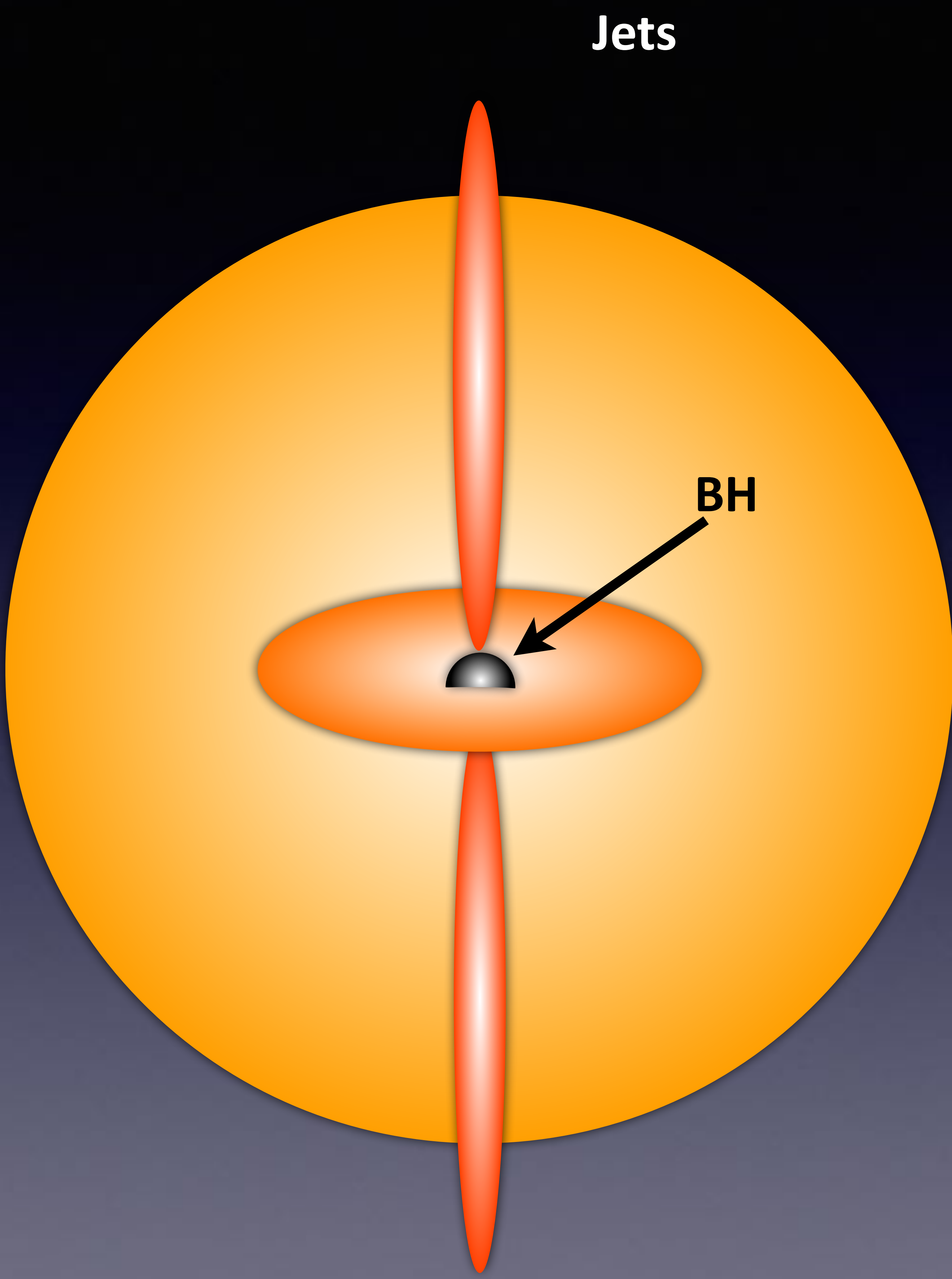
Summary: GRB-SN

- Kinetic energy ~ 10^{52} erg

  Neutrino-driven explosion is difficult?? => BH

- Relativistic jets
  - BH＋accretion disk

  Rapid rotation may be a key



Summary: explosive transients

	Spectrum	Galaxy	Progenitor	Ejecta mass	Kinetic energy
Type Ia	No H	Elliptical Spiral	White dwarfs	~ 1.4 Msun	10^{51} erg
Type II	H	Spiral	Massive stars	~10 Msun	10^{51} erg
Type Ib/Ic	No H/He	Spiral	Massive stars	~3-5 Msun	10^{51} erg
Long GRBs	Type Ic Broad line	Spiral	Massive stars (rotating?)	~10 Msun	10^{52} erg
Short GRBs	??	Elliptical Spiral	Neutron stars?	??	??