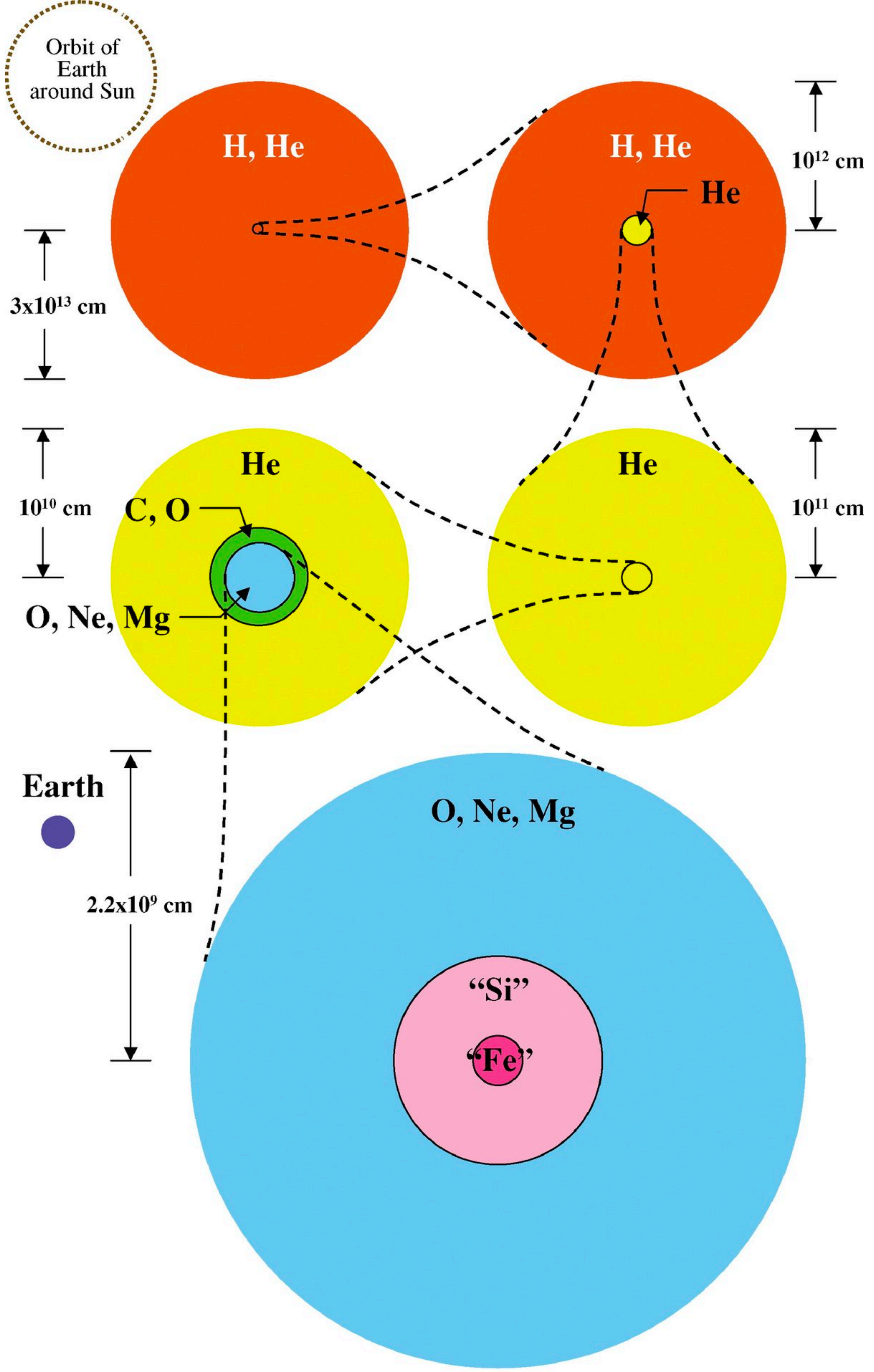
Supernovae and the birth of neutron stars

Lluís Galbany (RyC fellow, ICE-CSIC)

Neutron stars, black holes & gravitational waves, Feb 9th 2022

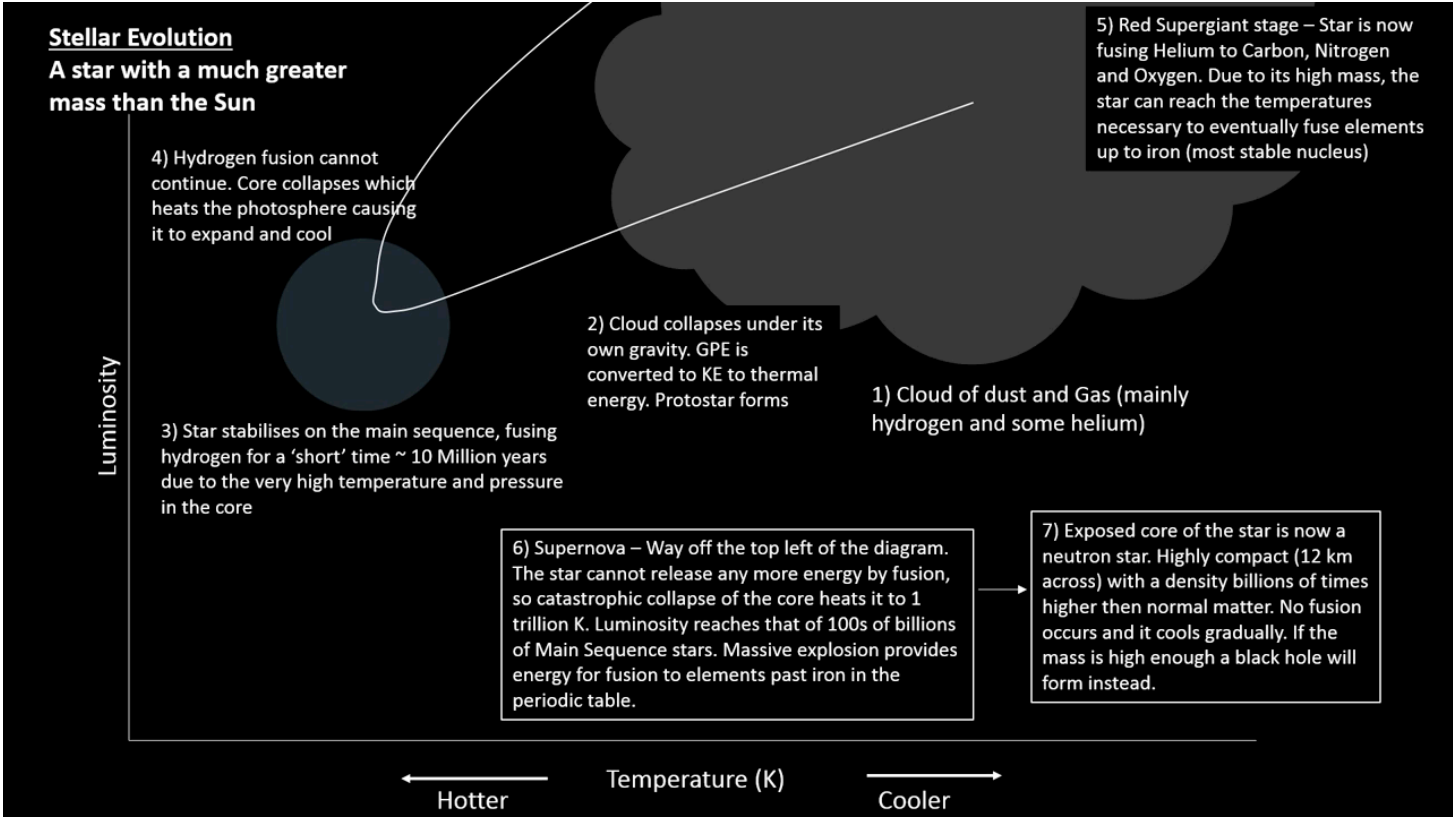
Core-collapse supernovae

- Resulting from massive stars M > 8 Msun
- Nuclear reactions in their interiors produce new and heavier elements. Onion structure (but mixing…)
- Once Fe is reached in their interiors, nuclear reactions stop at the core, and gravity is not countered by pressure. The core of the star collapse
- Different subtypes differ on the composition and structure of the star envelopes
- Binarity or stellar metallicity-driven winds could cause the envelope striping
- Type II SNe also useful for cosmology!



Mezzacappa A. 2005.
Annu. Rev. Nucl. Part. Sci. 55:467–515

Stellar evolution stars M > 8 Msun



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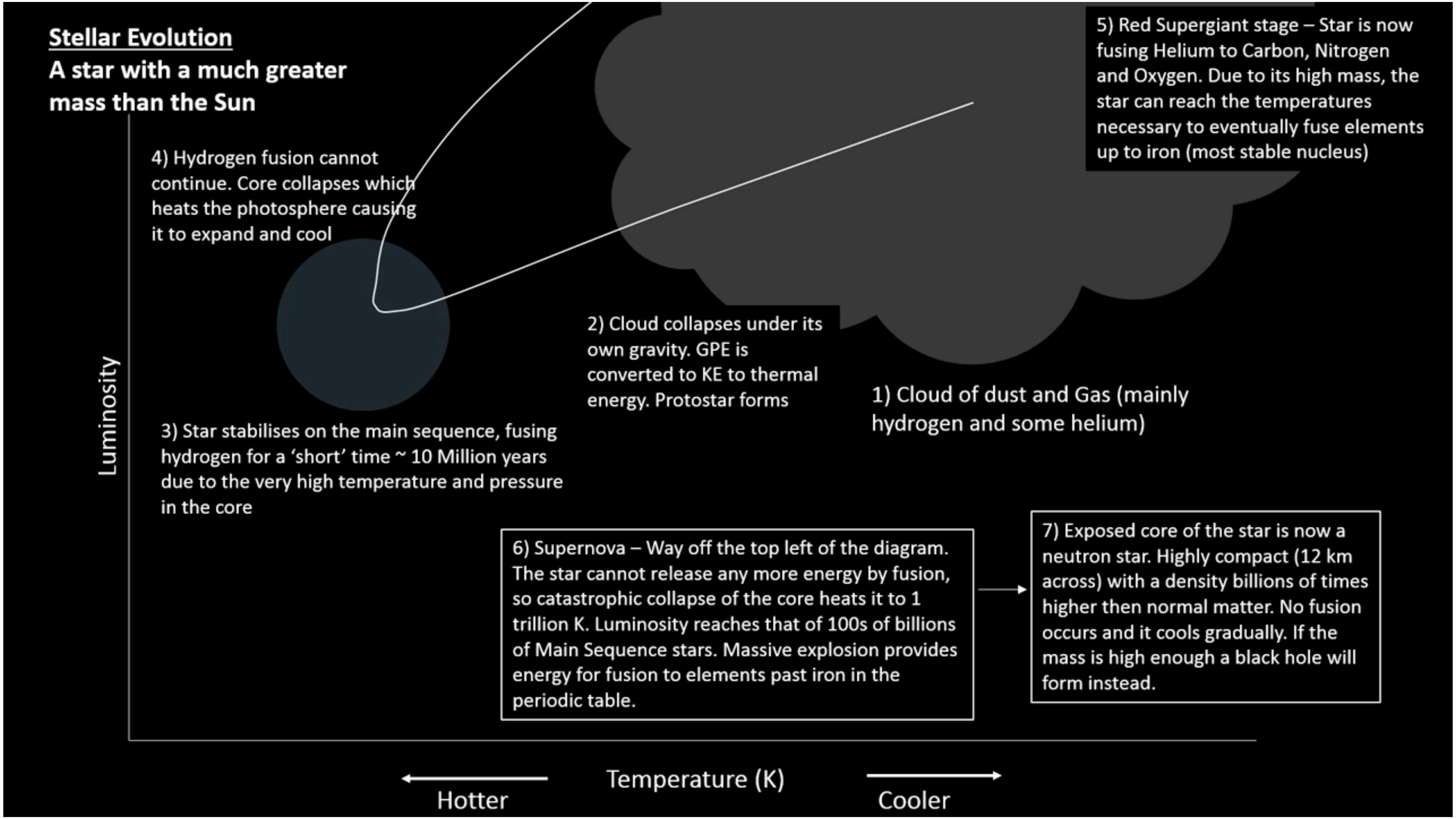
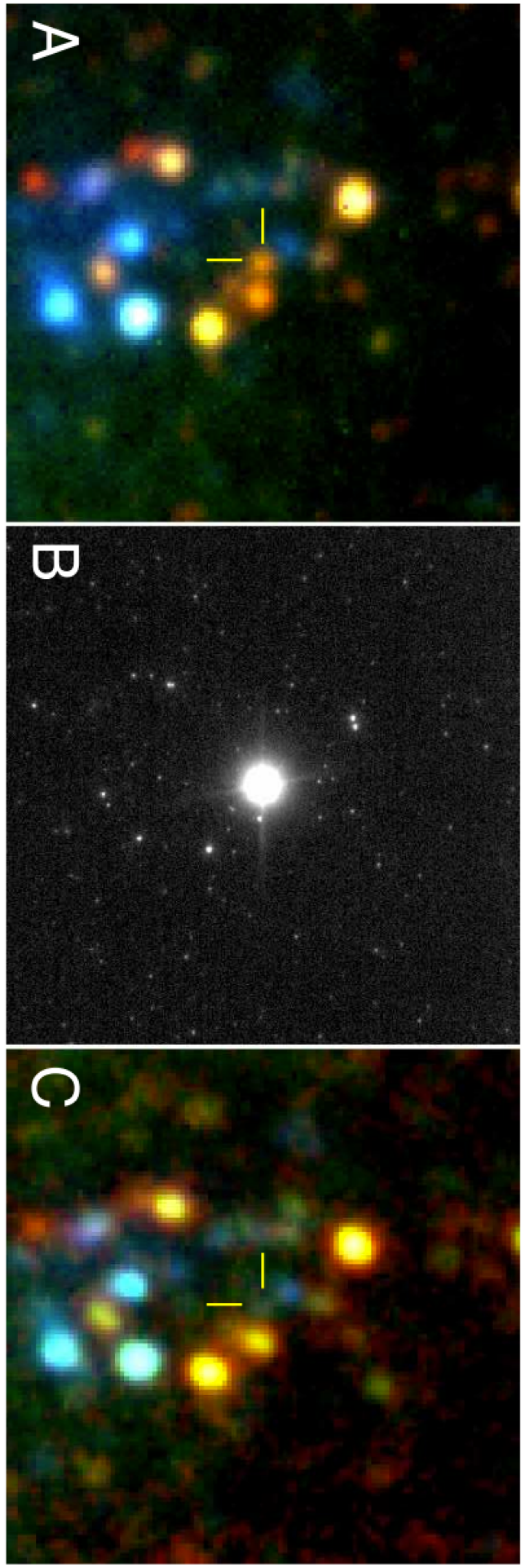


Mattila+10
Smartt+15
Van Dik+17

Direct progenitor detection

- More knowledge compared to SNe Ia
- Around ~30 progenitor detection (+ some more upper limits) in HST archival images
- All CCSNe (~80% SNII) and no SNIa
- Low statistics, but RSG at all SNII locations, YSG at SNIb and SNIIb
- Envelope stripped for SNIb and SNIc (binarity, winds)
- RSG problem



pre-x

x

post-x

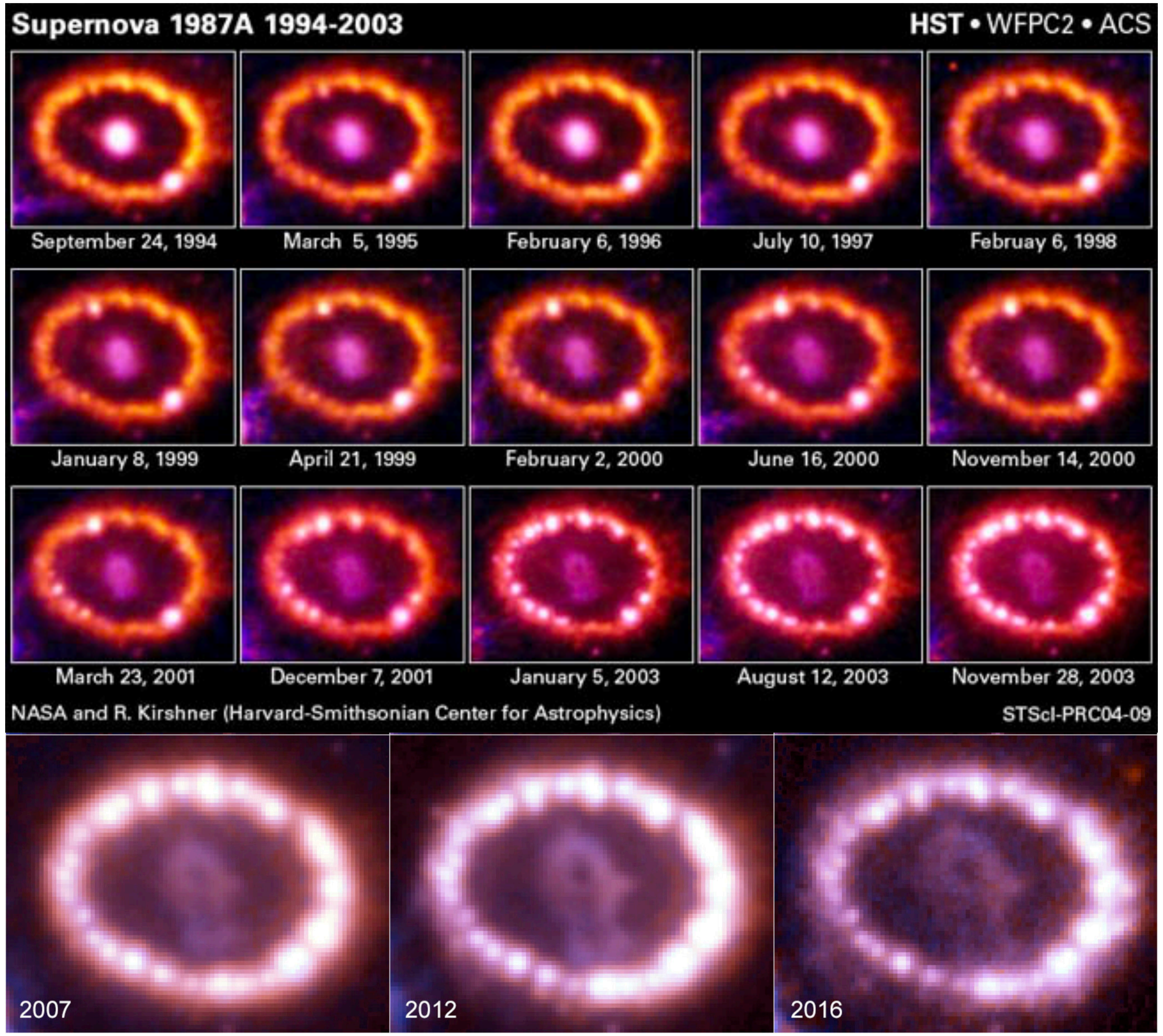
Table 1. Direct SN progenitor detections to date.

SN	type	source	SN	type	source
1961V	IIn?	[7,8]	2009hd	II-L?	[36]
1978K	IIn	[9]	2009ib	II-P	[37]
1987A	II-P(pec)	[10–12]	*2009ip*	IIn?	[38,39]
1993J	IIb	[13,14]	~~2009kr~~	II-L?	[34,40,41]
1996al	IIL?	[15]	~~2009md~~	II-P	[15,34,42]
1997bs	IIn?	[16]	*2011dh*	IIb	[43,44]
~~1999ev~~	II-P?	[17–19]	2012A	II-P	[45,46]
2003gd	II-P	[20,21]	*2012aw*	II-P	[47,48]
2004A	II-P	[22]	2012ec	II-P	[49]
2004et	II-P	[23,24]	2013df	IIb	[1]
2005cs	II-P	[25,26]	*2013ej*	II-L?	[50]
2005gl	IIn	[27,28]	*iPTF13bvn*	Ib	[51]
2006my	II-P	[19,29,30]	2014C	Ib/IIn	[52]
~~2006ov~~	II-P	[24,29]	ASASSN-14ha	II-P	—
2008ax	IIb	[31]	2015bh	IIn	[53,54]
2008bk	II-P	[32,33]	2016bkv	IIn?	—
2008cn†	II-P	[34,35]	2016gkg	IIb	[55,56]

Table 2. Upper limits to SN progenitor detections to date.

SN	type	source	SN	type	source
1994I	Ic	[58]	2004gt	Ic	[71,72]
1999an	II-P	[17,18]	2005V	Ib/c	[67]
1999br	II-P	[17,18]	2005at	Ic	[67]
1999em	II-P	[59]	2006bc	II-P	[66]
1999ga	II-L	[60]	2007aa	II-P	[66]
1999gi	II-P	[61]	2007gr	Ic	[73]
2000ds	Ib	[17,18]	2009H	II-P	—
2000ew	Ic	[17,18]	2009N	II-P	—
2001B	Ib	[17,18]	2009jf	Ib	—
2001du	II-P	[62,63]	2010O	Ib	[74]
2002ap	Ic-bl	[64,65]	2010P	Ib	[74]
2002hh	II-P	[66]	2010br	Ib/c	[67]
2003ie	II-P(pec?)	[66]	2010jl	IIn	[75]
2003jg	Ic	[67]	2011am	Ib	[67]
2004am	II-P	[68]	2011hp	Ic	[67]
2004cc	Ic	[67]	2012P	IIb	[76]
2004dg	II-P	[66]	2013dk	Ic	[77]
2004dj	II-P	[69,70]	2016adj	??	—
2004gn	Ic	[67]	2016cok	II-P	[78]

SN1987A



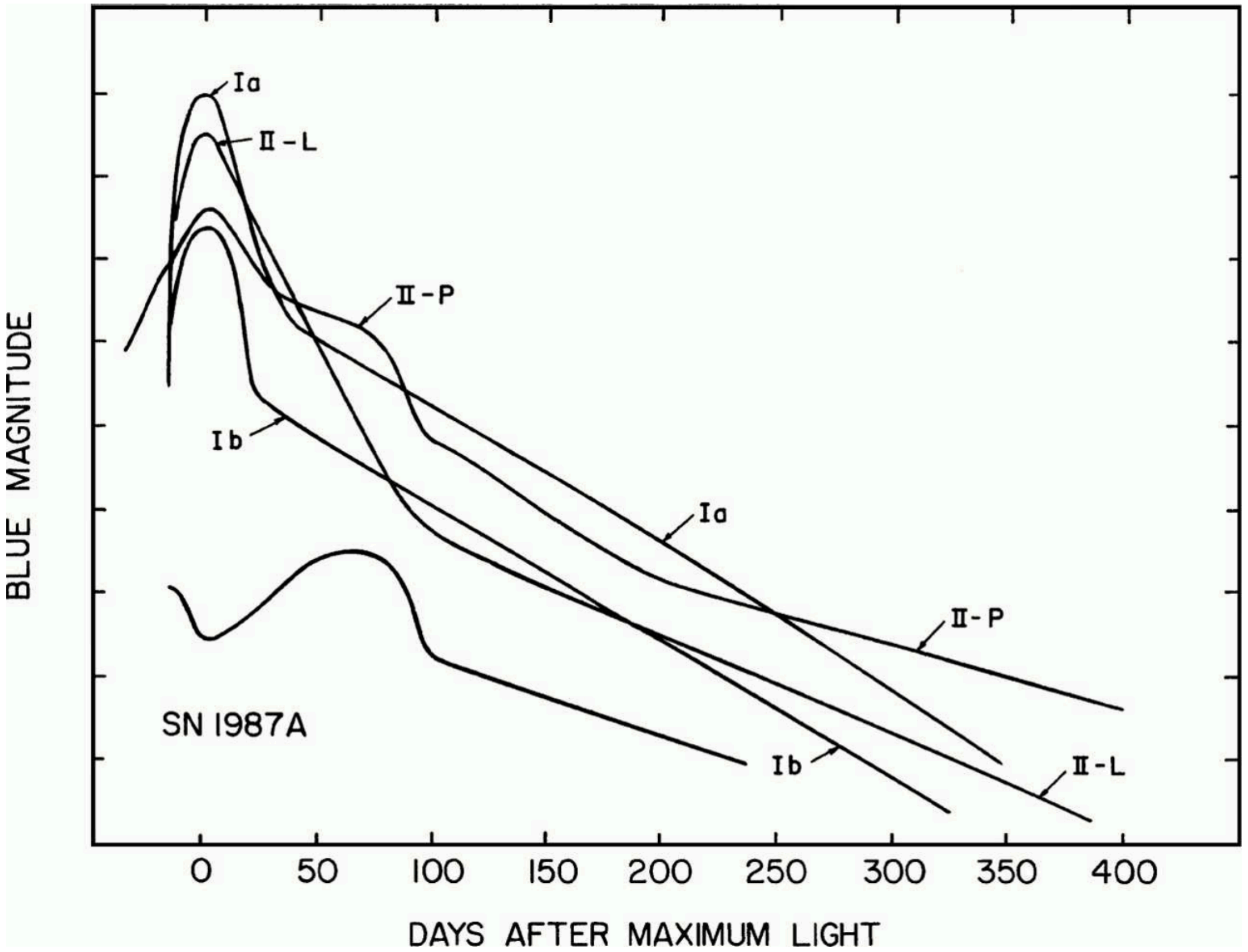


Figure 1.4: Schematic supernova light curves for different classes and subclasses (Filippenko 1997).

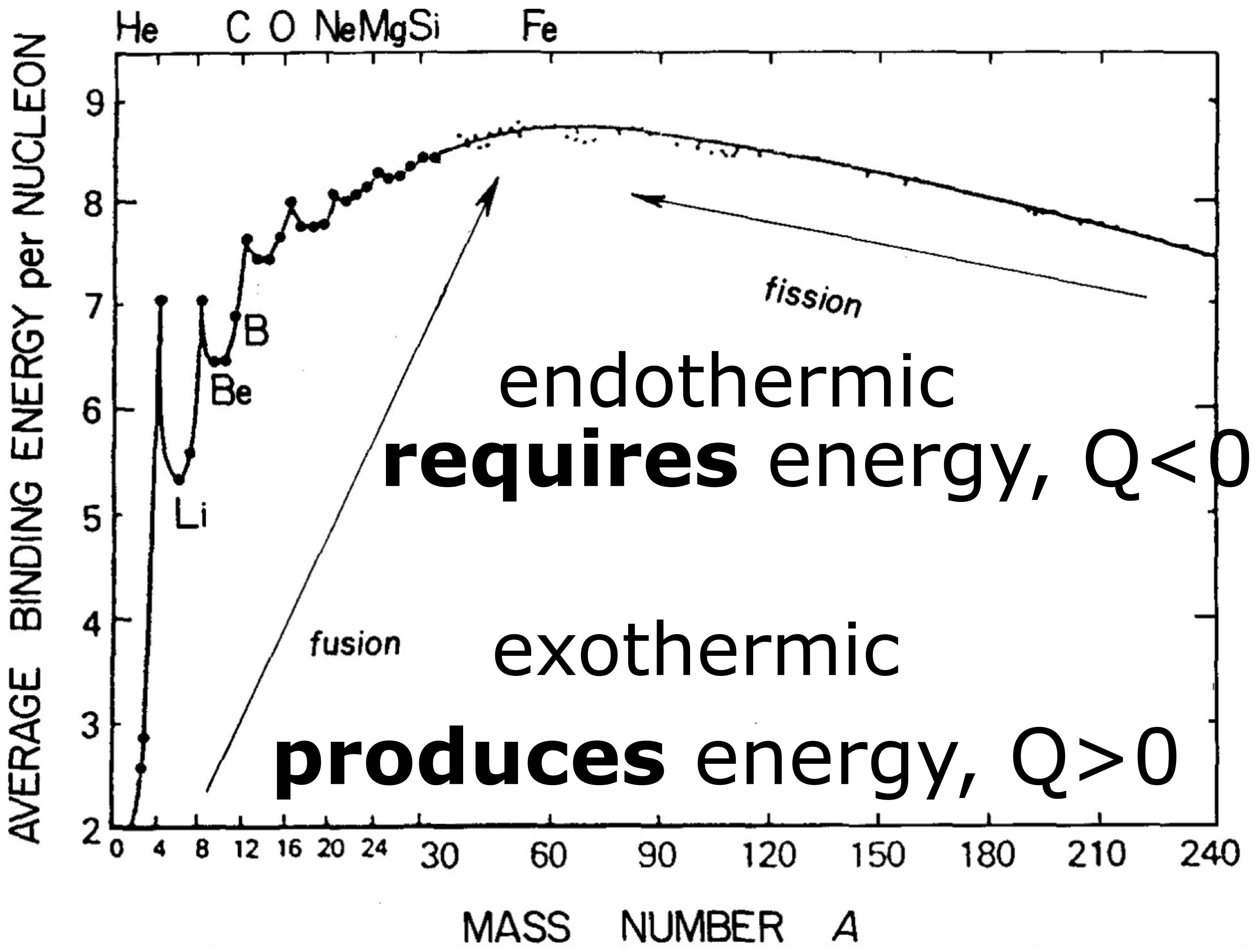
Discovered on Feb 24th 1987
From Las Campanas (Chile) at the LMC
35 ago in 2 weeks!
Peculiar SNII
Blue supergiant

Binding energy per nucleon E_B/A

Atomic masses

element	Z	A	M/m_u	element	Z	A	M/m_u	element	Z	A	M/m_u
n	0	1	1.008665	C	6	12	12.000000	Ne	10	20	19.992441
H	1	1	1.007825		6	13	13.003354	Mg	12	24	23.985043
	1	2	2.014101	N	7	13	13.005738	Si	14	28	27.976930
He	2	3	3.016029		7	14	14.003074	Fe	26	56	55.934940
	2	4	4.002603		7	15	15.000108	Ni	28	56	55.942139
Li	3	6	6.015124	O	8	15	15.003070				
	3	7	7.016003		8	16	15.994915				
Be	4	7	7.016928		8	17	16.999133				
	4	8	8.005308		8	18	17.999160				

$$\frac{E_B}{A}$$



^{56}Fe fusion is endothermic

It is the natural endpoint of the stellar nuclear reaction cycles

The decrease is due to the increase in the number of protons *Z,* which experience a repulsive Coulomb force

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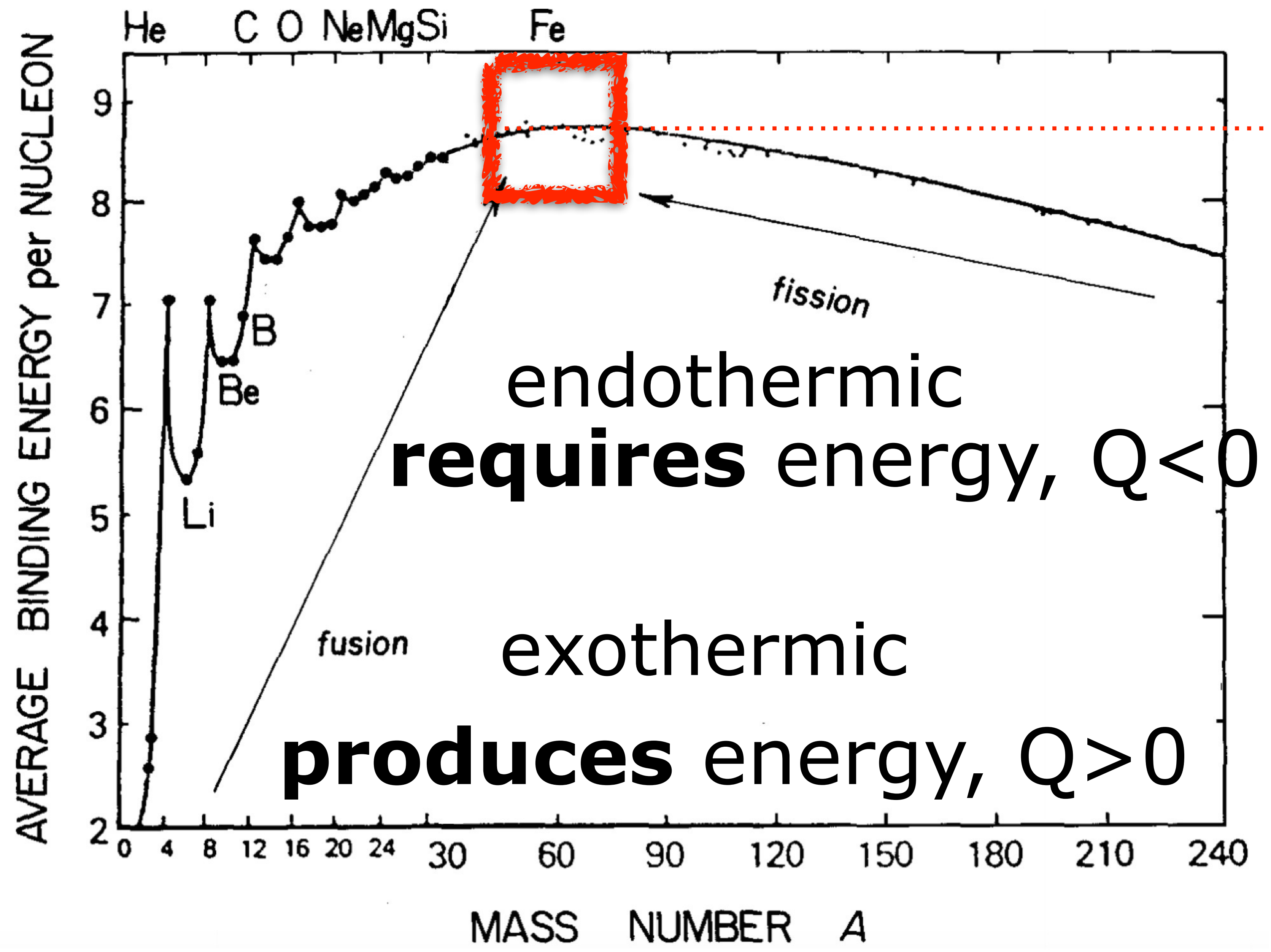

8.79 MeV

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Main nuclear burning cycles

In principle, many different nuclear reactions can occur simultaneously in a stellar interior.

But for the calculation of the structure and evolution of a star usually a much simpler procedure is sufficient

- nuclear fusions of different possible fuels are well separated by substantial *T* differences. The evolution of a star therefore proceeds through several distinct *nuclear burning cycles*
- For each nuclear burning cycle, only a handful of reactions contribute significantly to the energy production
- In a chain of subsequent reactions, often one reaction is by far the slowest and determines the rate of the whole chain

H burning

Net reaction: $4\,^1\mathrm{H} \rightarrow {}^4\mathrm{He} + 2\mathrm{e}^+ + 2\nu + 2\gamma$

The total energy release is $Q = 26.734\ \mathrm{MeV}$

in order to create 1 ***He*** nucleus,
2 ***p*** have to be converted into ***n*** -
> 2 neutrinos are released

$$p \rightarrow n + e^+ + \nu$$

Since a simultaneous reaction between four ***p*** is extremely unlikely, a chain of reactions is always necessary for ***H*** burning.

p-p chain & ***CNO cycle***

$(5 \times 10^6 < T < 15 \times 10^6\ \mathrm{K})$ $(T > 15 \times 10^6\ \mathrm{K})$

He burning

Helium burning into ^{12}C and ^{16}O occurs at $T>10^8$ K

- Coulomb barrier for He is higher than that of H
- No stable ion with A=8, so 2 steps are needed:

$$^4\mathrm{He} + {}^4\mathrm{He} \rightarrow {}^8\mathrm{Be}$$

^{8}Be lifetime ~3×10^{-16} s!

$$^8\mathrm{Be} + {}^4\mathrm{He} \rightarrow {}^{12}\mathrm{C}^* \rightarrow {}^{12}\mathrm{C} + \gamma$$

The second reaction takes place because ^{12}C has a resonant energy level precisely at the Gamow peak of the ^{8}Be + ^{4}He reaction

$$\epsilon_{3\alpha} = q_{3\alpha} X_4^3 \rho^2 \lambda_{3\alpha}$$

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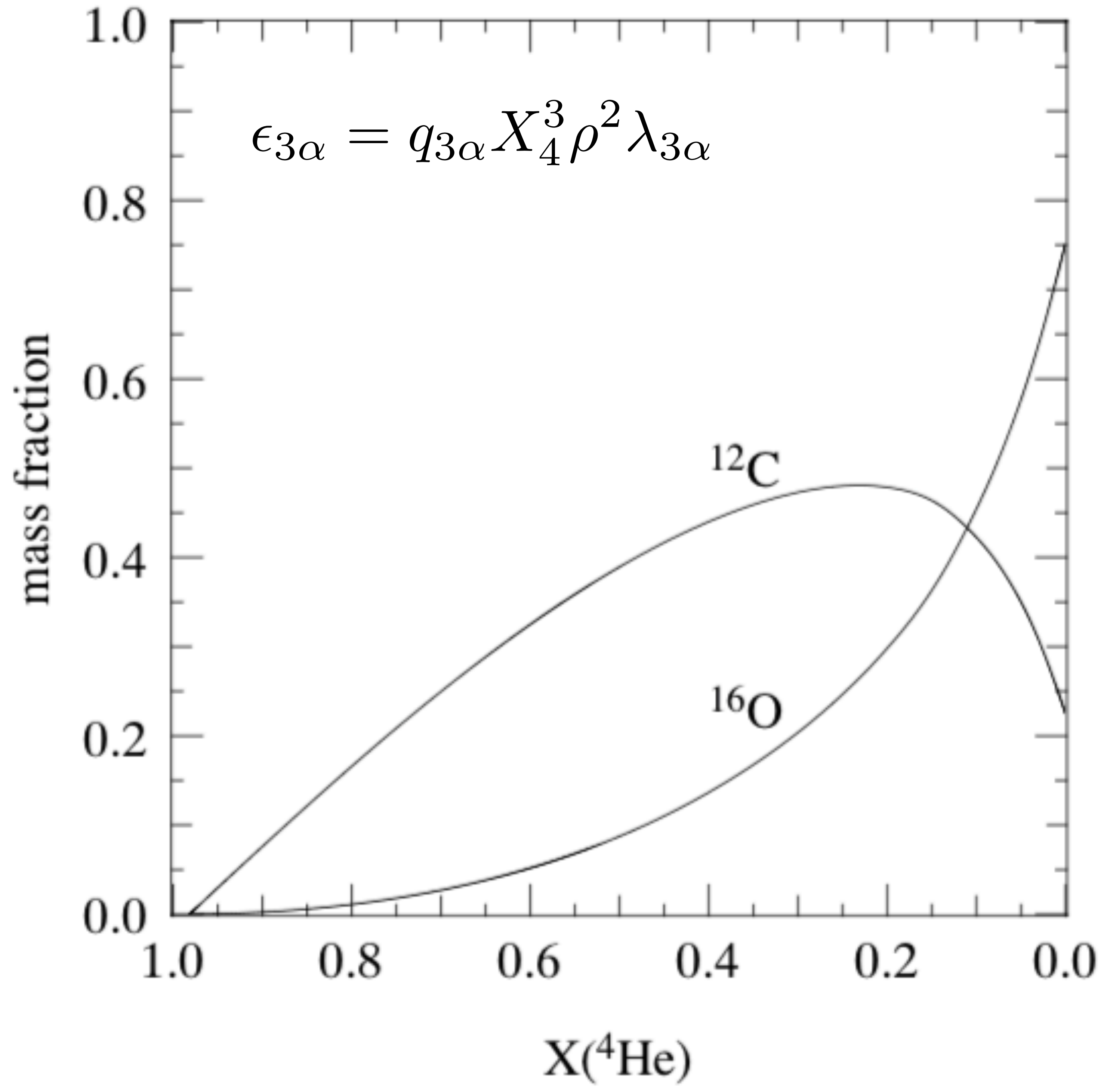


The effect of the 2 reactions is called the triple-α process

$$3\,{}^4\mathrm{He} \to {}^{12}\mathrm{C} + \gamma$$ Q=7.275 MeV

Once a sufficient amount of ^{12}C is created (near the end of the He-fusion phase) we get:

$$^{12}\mathrm{C} + {}^4\mathrm{He} \to {}^{16}\mathrm{O} + \gamma$$ Q=7.162 MeV

C burning and beyond

At T > 5×10^8 K the $^{12}C+^{12}C$ Coulomb barrier can be overcome

$$^{12}\mathrm{C} + {}^{12}\mathrm{C} \rightarrow {}^{24}\mathrm{Mg} + \gamma \begin{cases} \rightarrow {}^{20}\mathrm{Ne} + {}^{4}\mathrm{He} & Q = 4.616 \text{ MeV } (\sim 50\%) \\ \rightarrow {}^{23}\mathrm{Na} + p & Q = 2.238 \text{ MeV } (\sim 50\%) \end{cases}$$

At T > 1.5×10^9 , *Neon burning* (Net reaction: $2^{20}\mathrm{Ne} \rightarrow {}^{16}\mathrm{O} + {}^{24}\mathrm{Mg}$)

$$^{20}\mathrm{Ne} + \gamma \rightarrow {}^{16}\mathrm{O} + {}^{4}\mathrm{He} \qquad Q = -4.73 \text{ MeV}$$

$$^{20}\mathrm{Ne} + {}^{4}\mathrm{He} \rightarrow {}^{24}\mathrm{Mg} + \gamma \qquad Q = 9.31 \text{ MeV}$$

At T > 2×10^9 , *Oxygen burning*

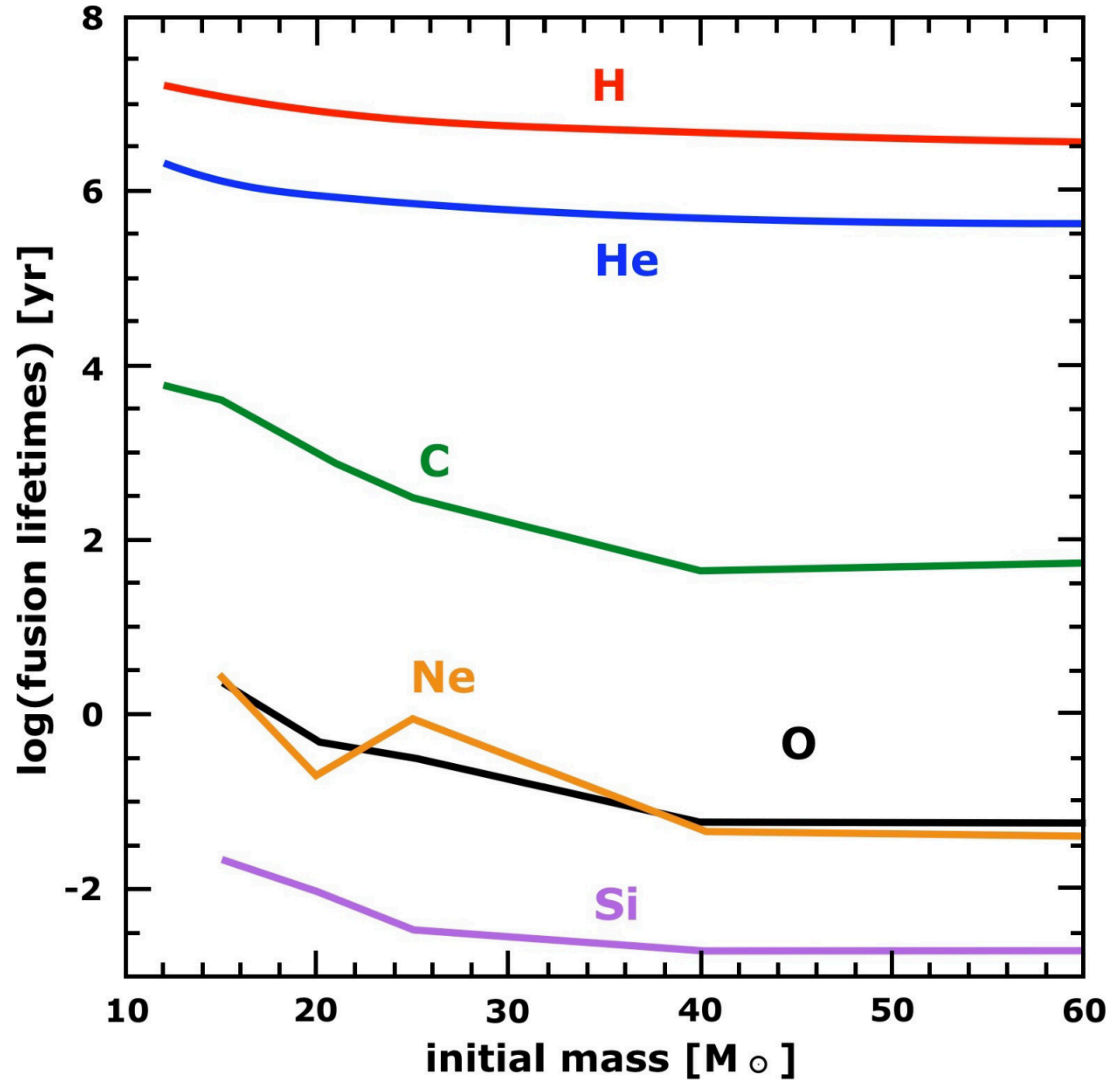
$$^{16}\mathrm{O} + {}^{16}\mathrm{O} \begin{cases} \rightarrow {}^{28}\mathrm{Si} + {}^{4}\mathrm{He} & Q = 9.59 \text{ MeV } (\sim 60\%) \\ \rightarrow {}^{31}\mathrm{P} + p & Q = 7.68 \text{ MeV } (\sim 40\%) \end{cases}$$

and many other secondary reactions ending up with lots of ^{28}Si and ^{32}S

At T > 3×10^9 , *Silicon burning*, but Coulomb barrier is very high. Instead,

Photo-desintegration $\quad ^{28}\mathrm{Si}(\gamma,\alpha)\ {}^{24}\mathrm{Mg}(\gamma,\alpha)\ {}^{20}\mathrm{Ne}(\gamma,\alpha)\ {}^{16}\mathrm{O}(\gamma,\alpha)\ {}^{12}\mathrm{C}(\gamma,\alpha)\ {}^{8}\mathrm{Be}(\gamma,\alpha)\ 2\alpha$

α-capture $\quad ^{28}\mathrm{Si}(\alpha,\gamma){}^{32}\mathrm{S}(\alpha,\gamma){}^{36}\mathrm{Ar}(\alpha,\gamma){}^{40}\mathrm{Ca}(\alpha,\gamma){}^{44}\mathrm{Ti}(\alpha,\gamma)...{}^{56}\mathrm{Ni}$ which is unstable and decay:



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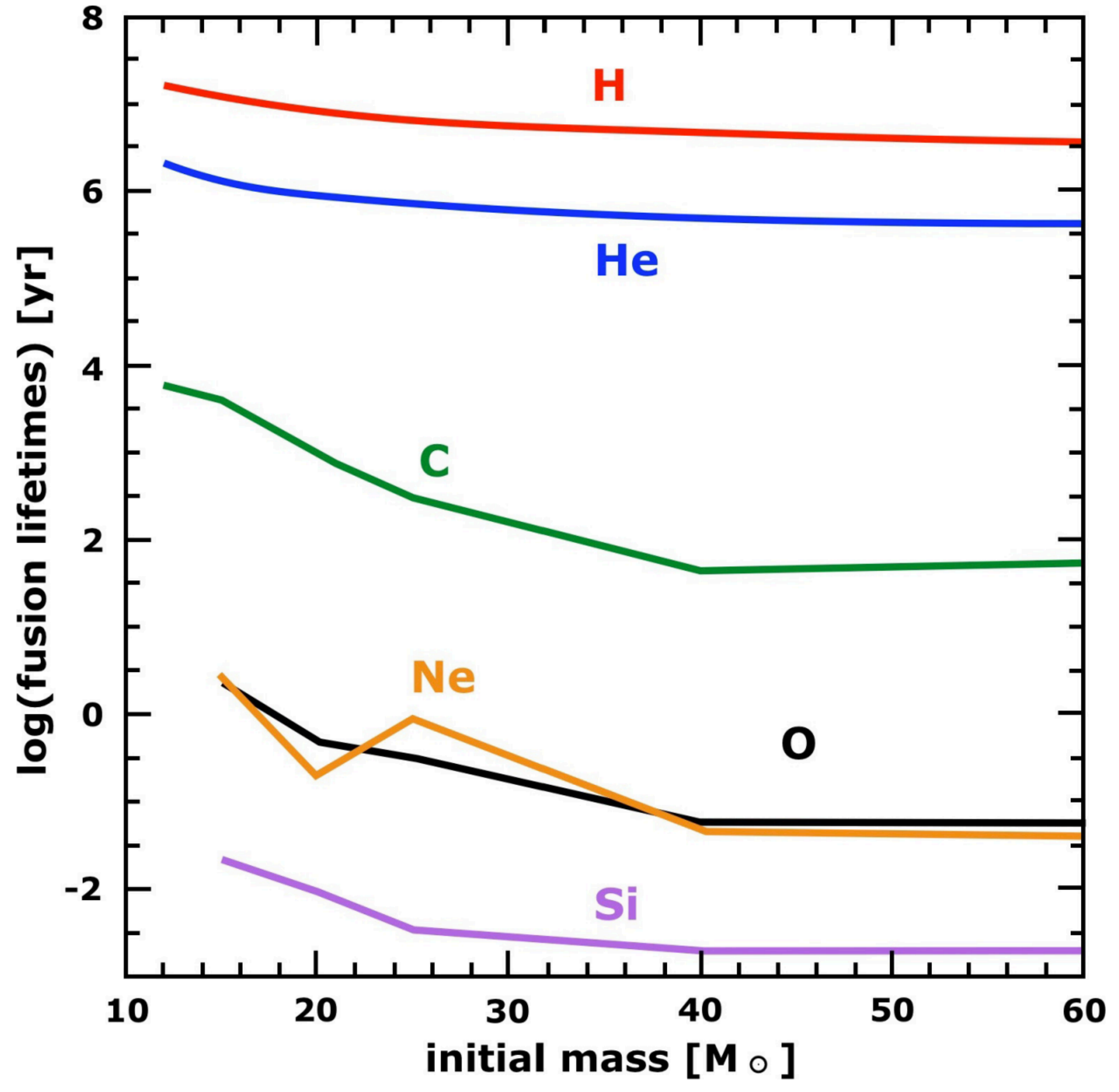

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α-capture $^{28}\mathrm{Si}(\alpha,\gamma){}^{32}\mathrm{S}(\alpha,\gamma){}^{36}\mathrm{Ar}(\alpha,\gamma){}^{40}\mathrm{Ca}(\alpha,\gamma){}^{44}\mathrm{Ti}(\alpha,\gamma)...{}^{56}\mathrm{Ni}$ which is unstable and decay: $\boxed{^{56}\mathrm{Ni} \rightarrow {}^{56}\mathrm{Co} \rightarrow {}^{56}\mathrm{Fe}}$

Nuclear fusion

Summary of the most important reaction rates in stars

*for 15M$_\odot$ star

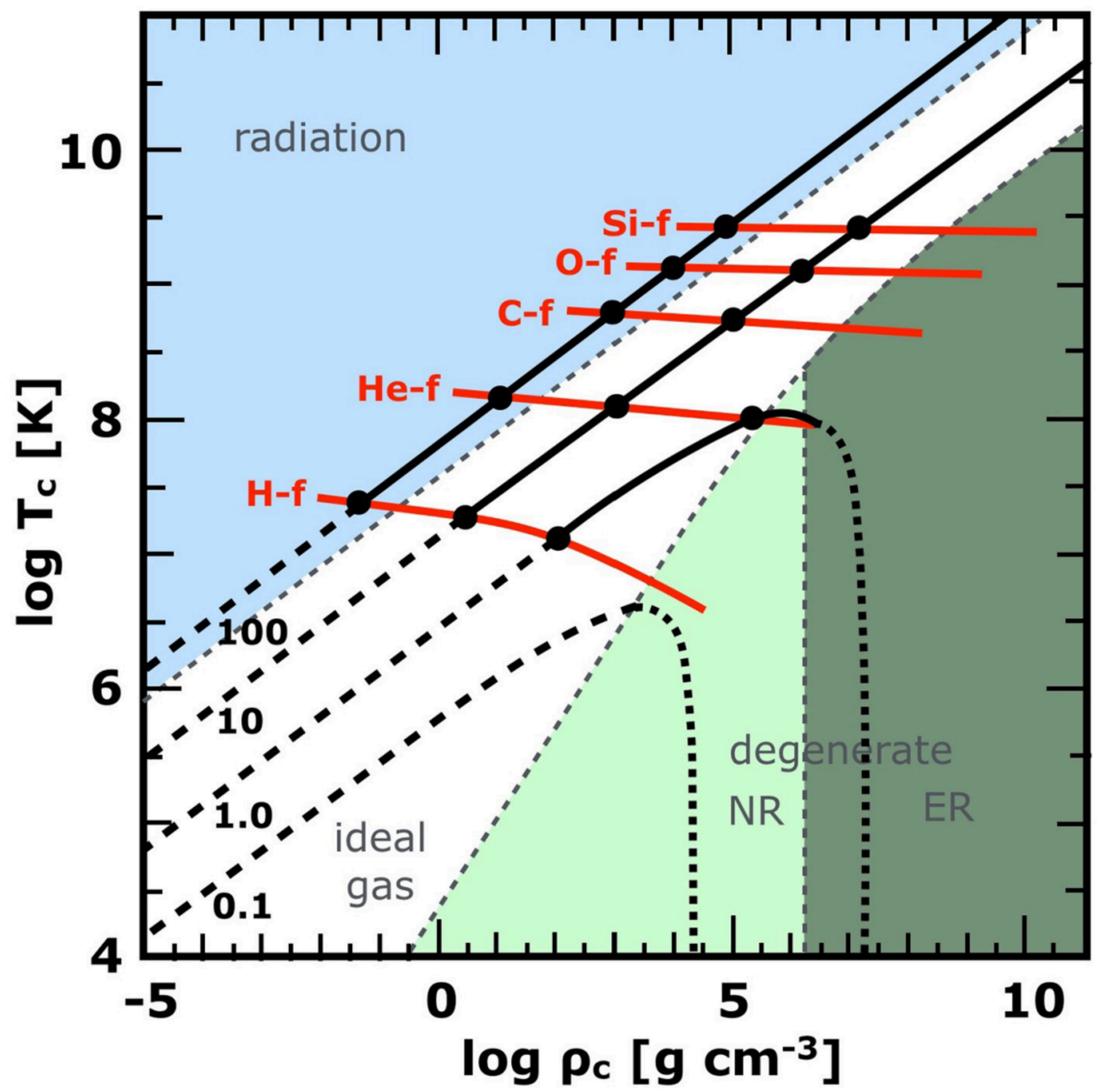
Fuel (1)	Process (2)	T_{thresh} 10^6 K (3)	Product (4)	E_{net} MeV/nucl (5)	T_c 10^6 K (6) *	L_{net}/L (7) *	Duration yr (8) *
H	p-p chain	4	He	6.55	–	–	–
H	CNO cycle	15	He	6.25	35	0.94	1.1×10^7
He	3-α fusion	100	C,O	0.61	180	0.96	2.0×10^6
C	C-fusion	600	Ne,Mg,Na,O	0.54	810	0.16	2.0×10^3
Ne	Ne photdis	900	O,Mg,Si		1600	5.3×10^{-4}	0.7
O	O-fusion	1000	S,Si,P,Mg	0.30	1900	8.2×10^{-5}	2.6
Si	Si nucl equil.	3000	Fe,Ni,Cr,Ti	<0.18	3300	5.8×10^{-7}	0.05

Results: - neutronization of the core
- E loss by neutrino emission
- collapse of the core down to nuclear densities, $\rho \sim 10^{14}$ g/cm^3

Neutron stars

Stellar remnants of stars 8<M<25 Msun

- The Fe core (no nuclear reactions, supported by deg. P) grows until it reaches MCh and can no longer support itself against gravitational collapse.
- The core collapses and the first steps of a *CC SN* are initiated.
- Iron nucleus starts to be compressed, reaching very high densities (~nuclear, 10^{17} kg m^{-3})
- The rotation of the core increases as a result of conservation of angular momentum
- As T increases, protons and electrons combine to form neutron and neutrinos.



(electron capture)

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

Neutron stars

Stellar remnants of stars 8<M<25 Msun

- At such densities a strong nuclear force repulsion abruptly halts the collapse leading to a shock wave that propagates out through the still collapsing outer core (->SN)
- NS are partially supported against further collapse by *neutron degeneracy pressure*
- The (now) NS keeps compressing, cooling and shrinking until its roughly ~10 km wide.
- If the mass > 2 Msun (Tolman–Oppenheimer–Volkoff limit), neutron degeneracy and nuclear forces are insufficient to support the NS collapses to a BH.
- If aligned with the Earth: Pulsar (Jocelyn Bell 1967)
- If highly magnetised: Magnetar
- If in binaries, they can merge and produce short GRBs and GW.

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Remnants of stellar evolution

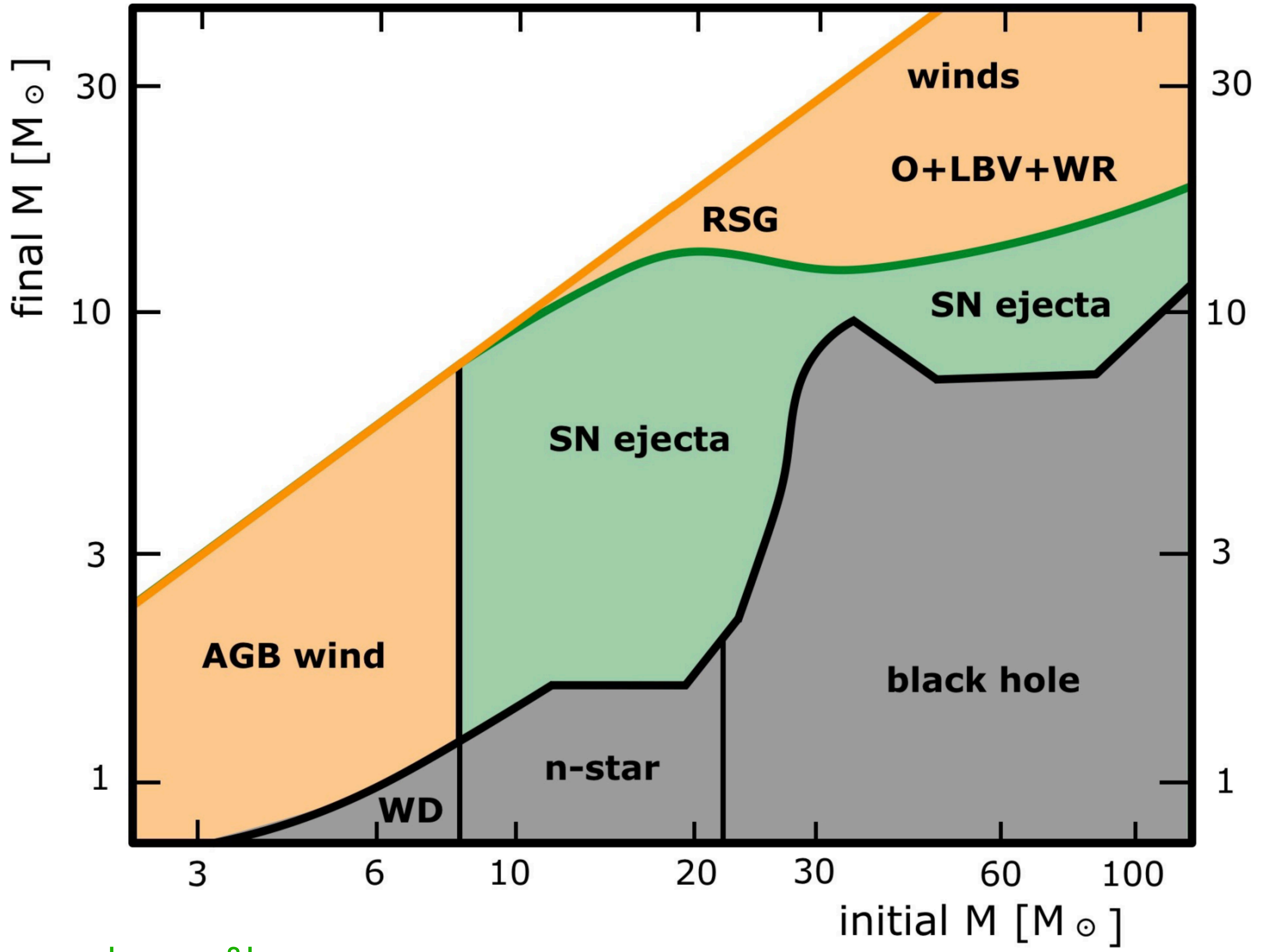
(for a solar Z star…)

- Stars with Mi ~8 Msun lose a large fraction of their M in the AGB wind and end their lives as WD

- Stars with 8≲Mi≲25 Msun lose a small fraction of their M in the RSG wind, eject a substantial fraction of their M in a SN explosion, and leave a NS behind

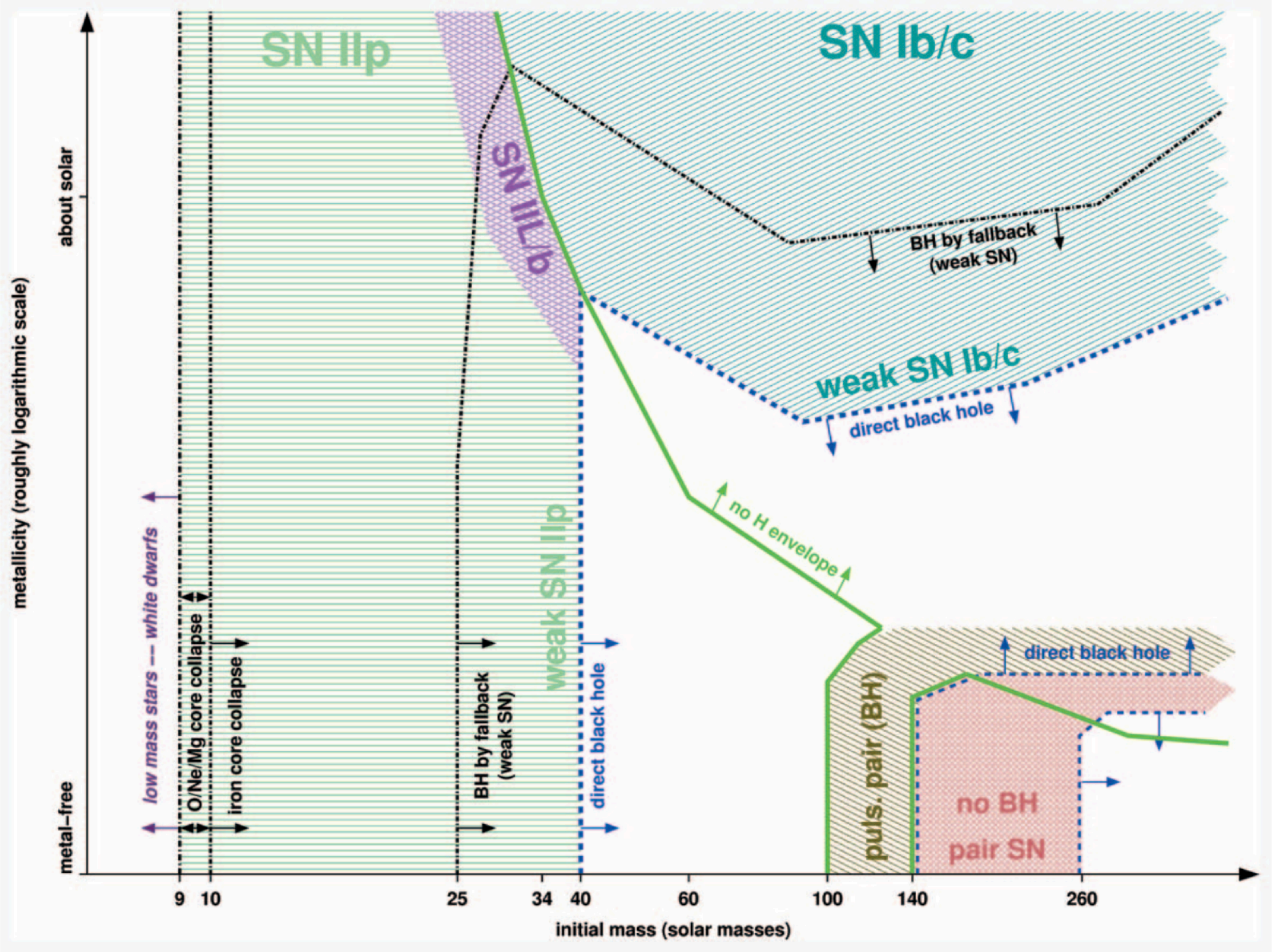
- Stars with 25≲Mi≲100 Msun lose a substantial fraction of their mass in winds, eject a small fraction of their mass in the SN explosion, and leave a BH behind

- For stars with M>20 Msun their fate depends both on mass and metallicity



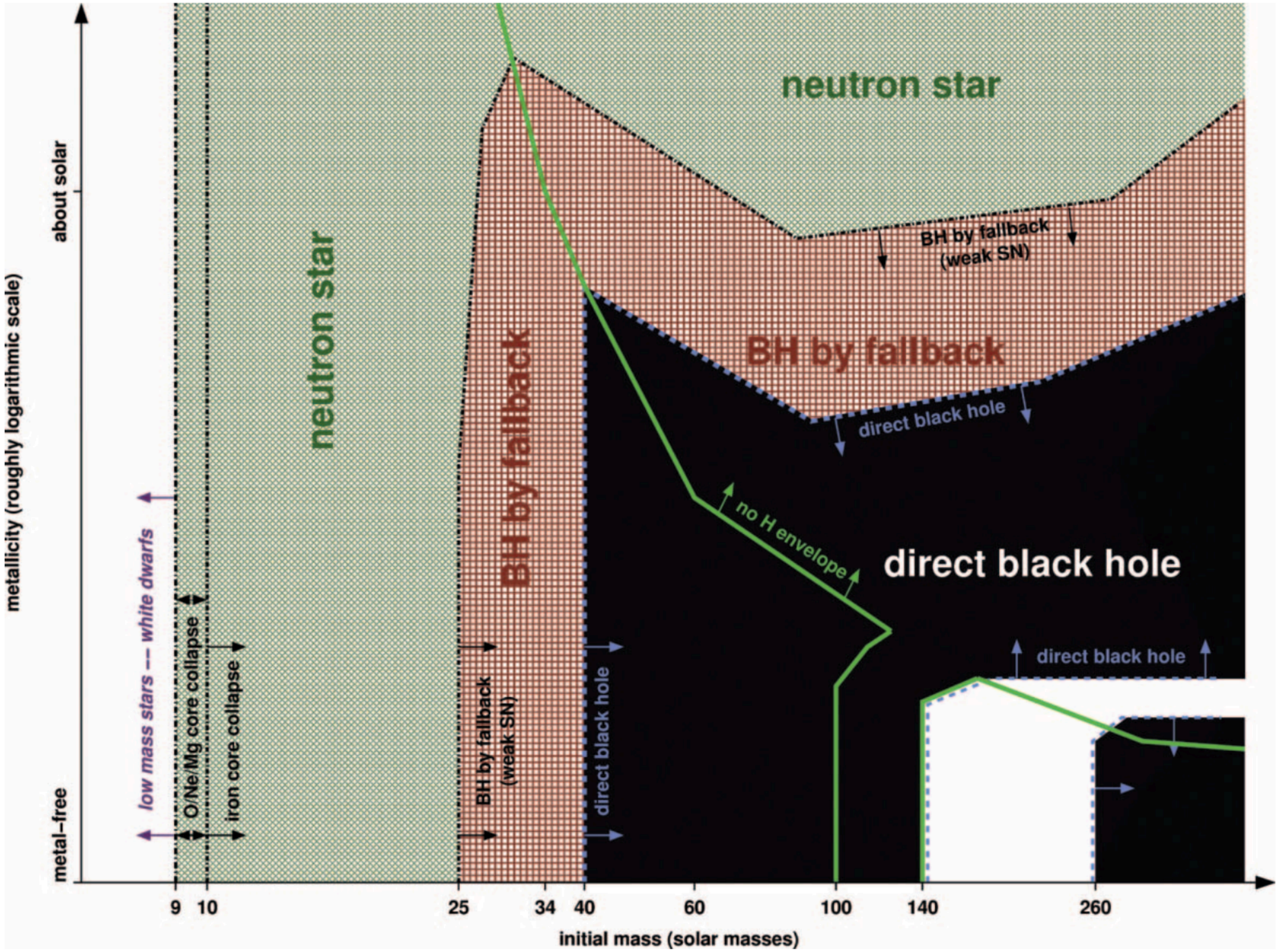
Lamers&Levesque

Remnants of stellar evolution



Heger+03

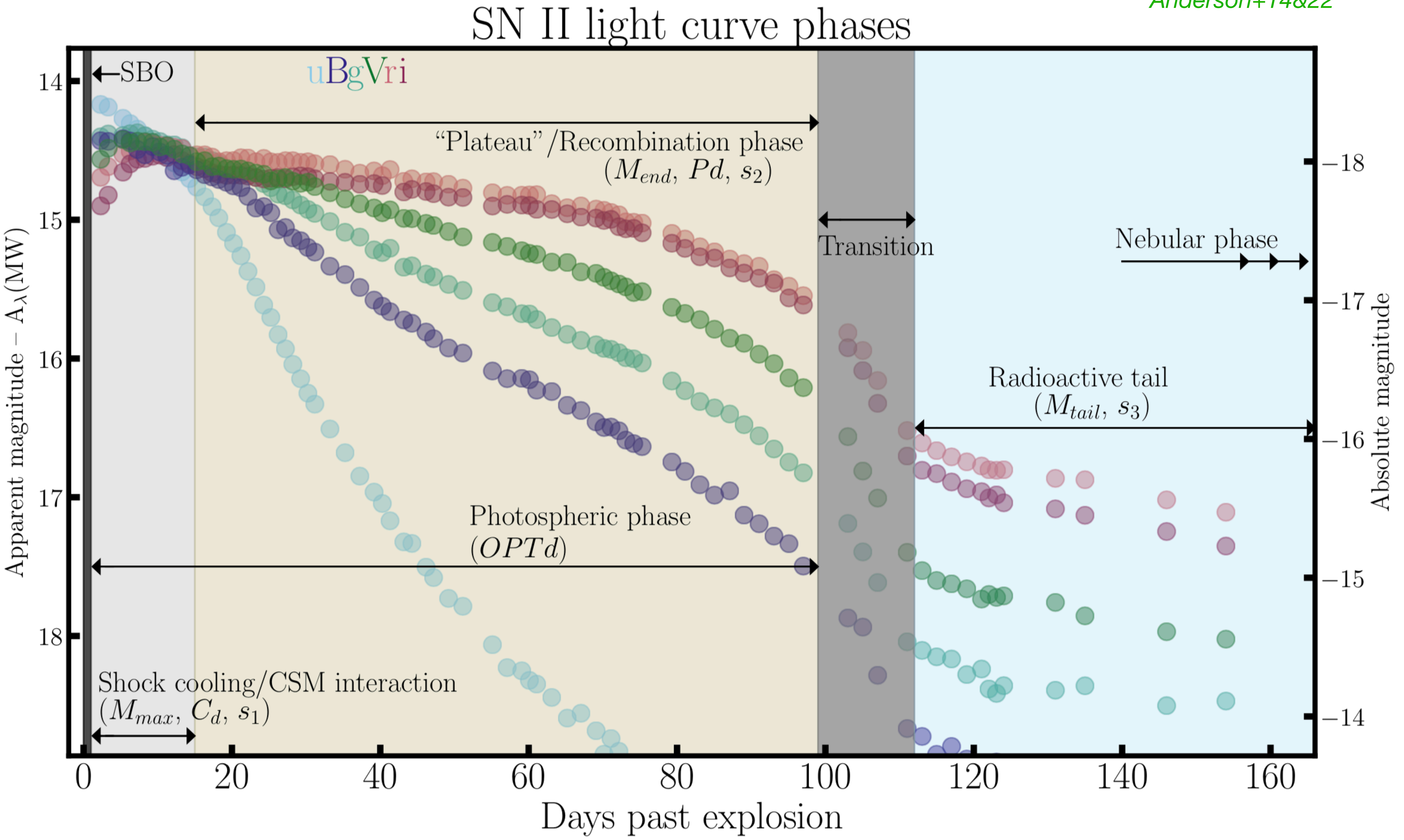
Remnants of stellar evolution



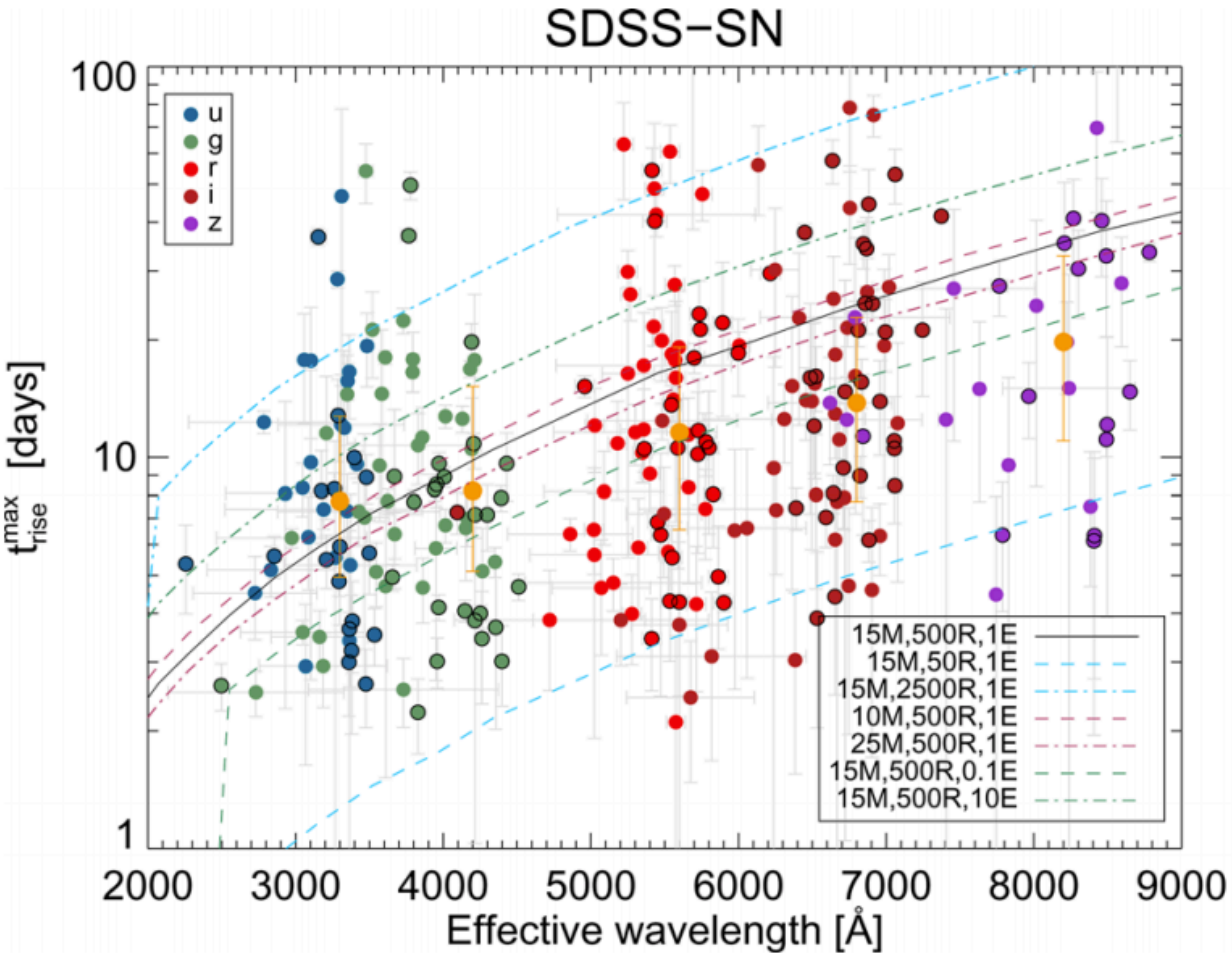
Heger+03

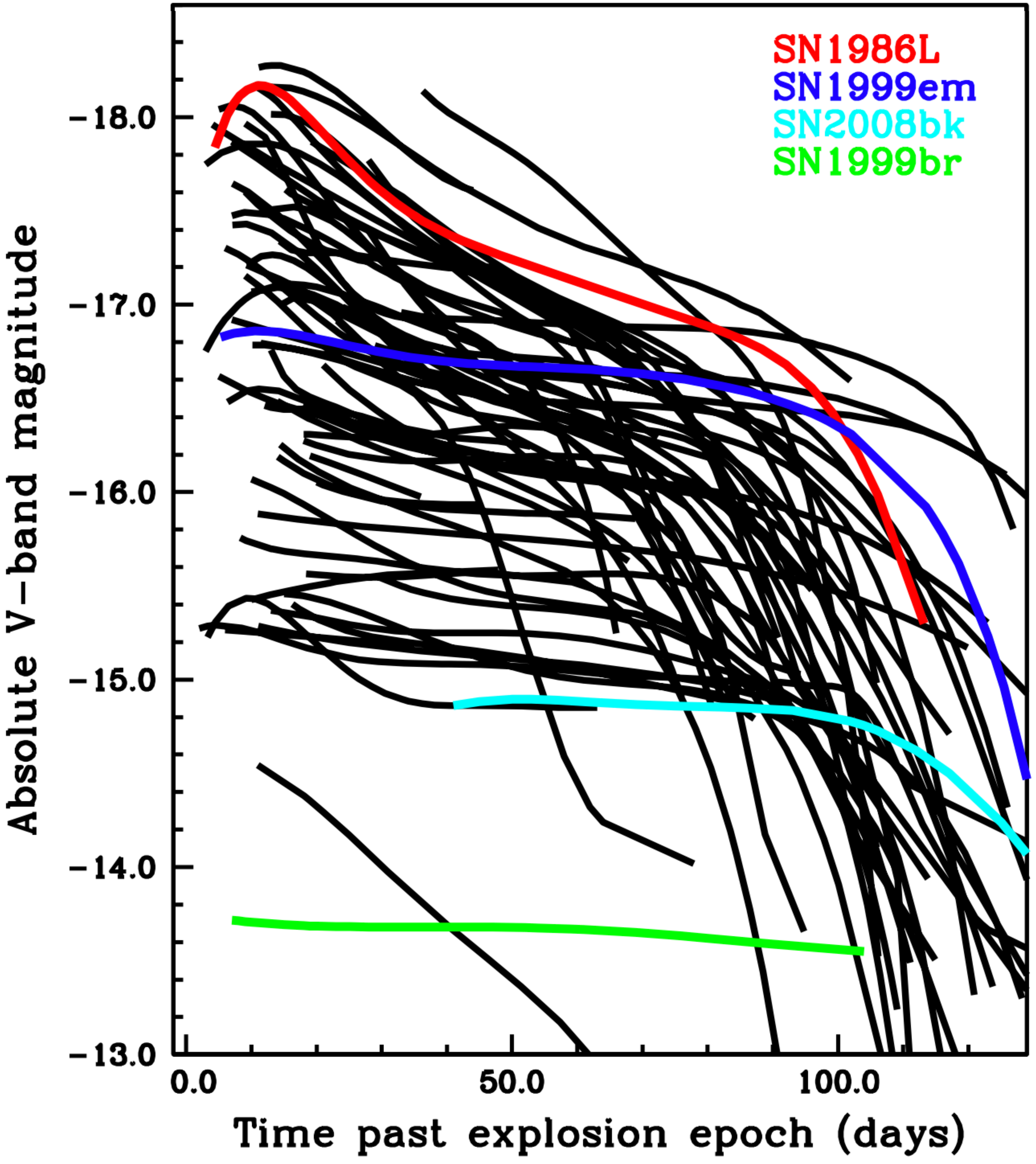
SNe II light curves

Anderson+14&22

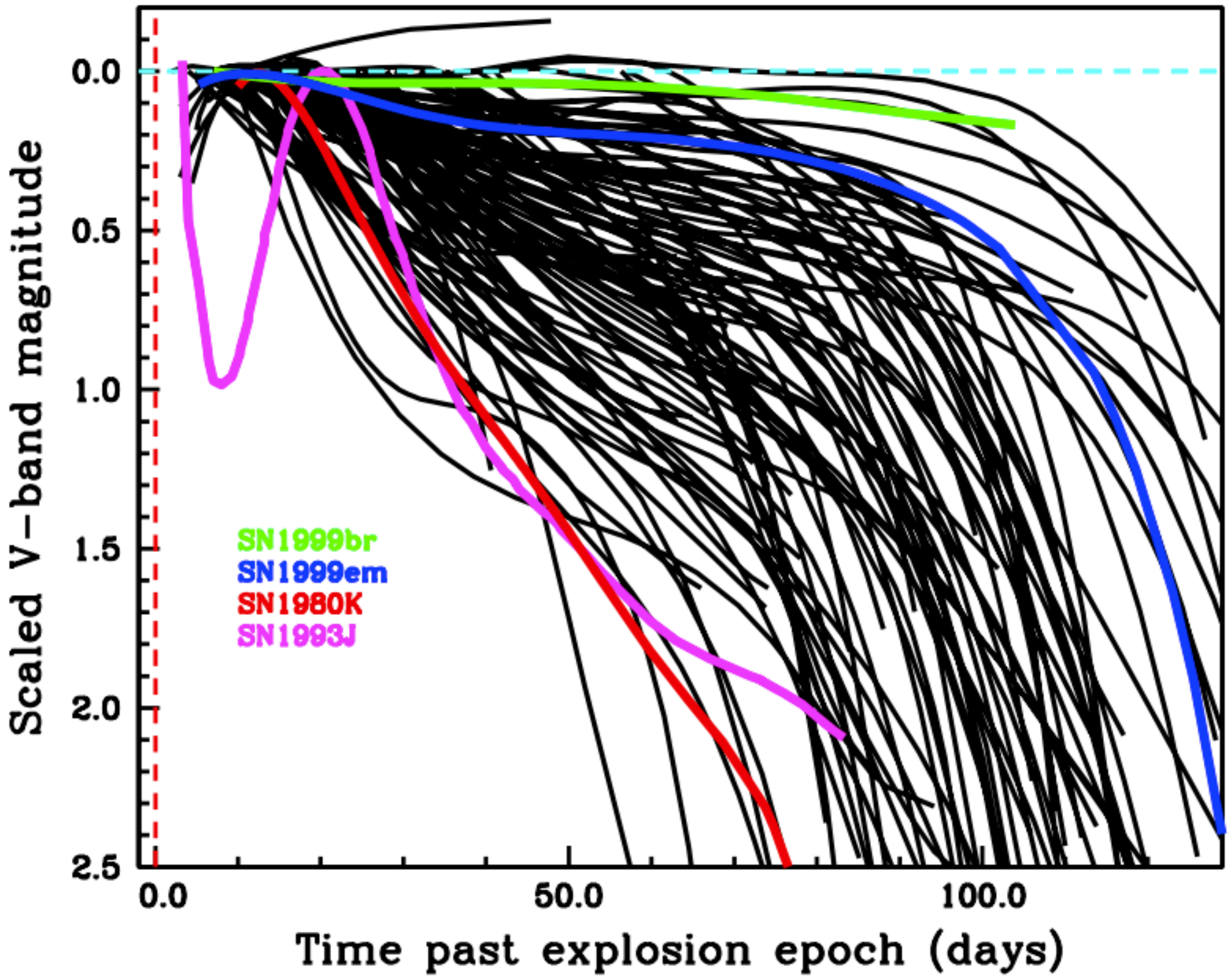


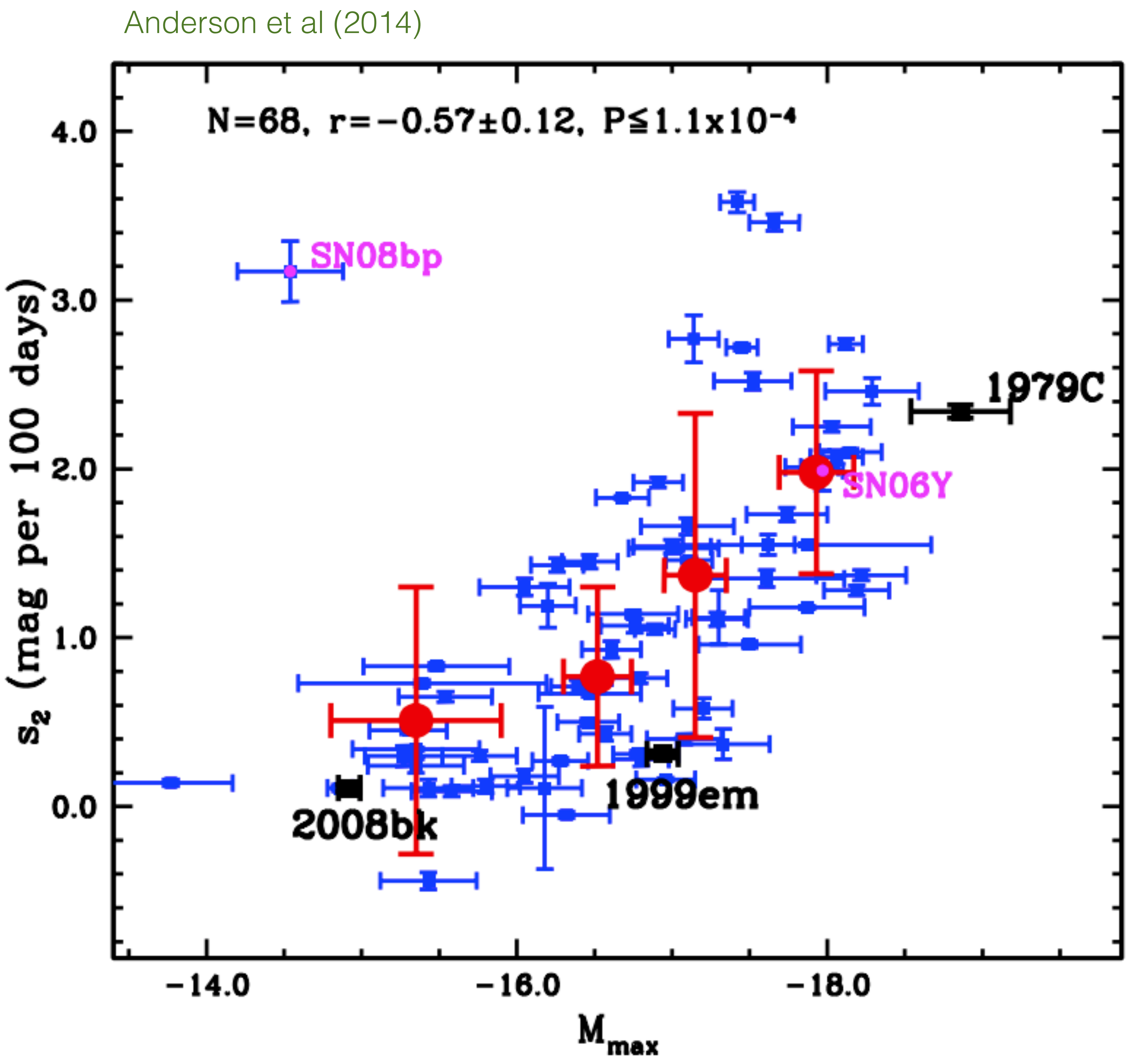
González-Gaitán+14

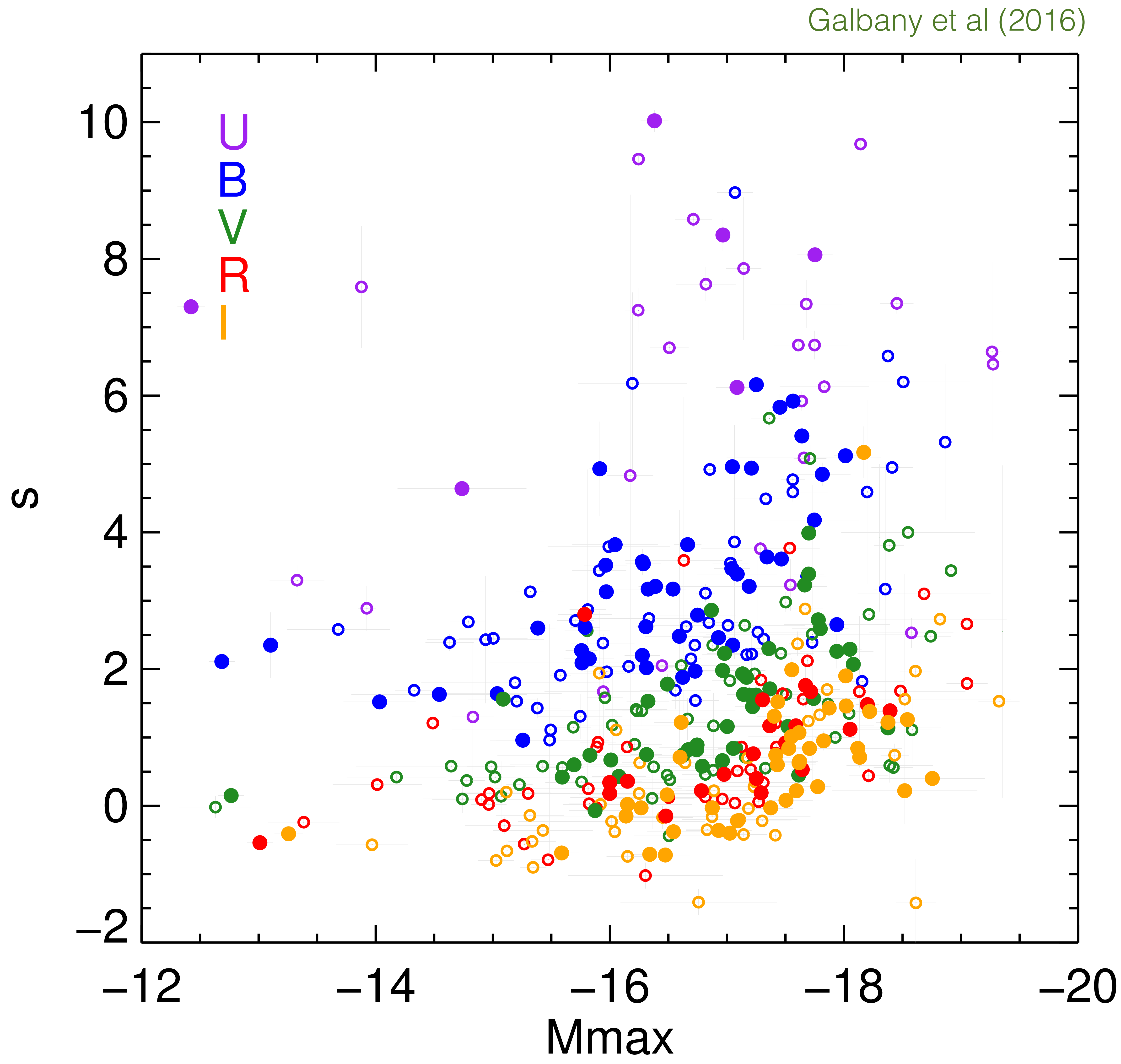



SN1986L
SN1999em
SN2008bk
SN1999br
Absolute V-band magnitude
-18.0
-17.0
-16.0
-15.0
-14.0
-13.0
0.0
50.0
100.0
Time past explosion epoch (days)

Anderson+14


SN1999br
SN1999em
SN1980K
SN1993J
Scaled V-band magnitude
0.0
0.5
1.0
1.5
2.0
2.5
0.0
50.0
100.0
Time past explosion epoch (days)



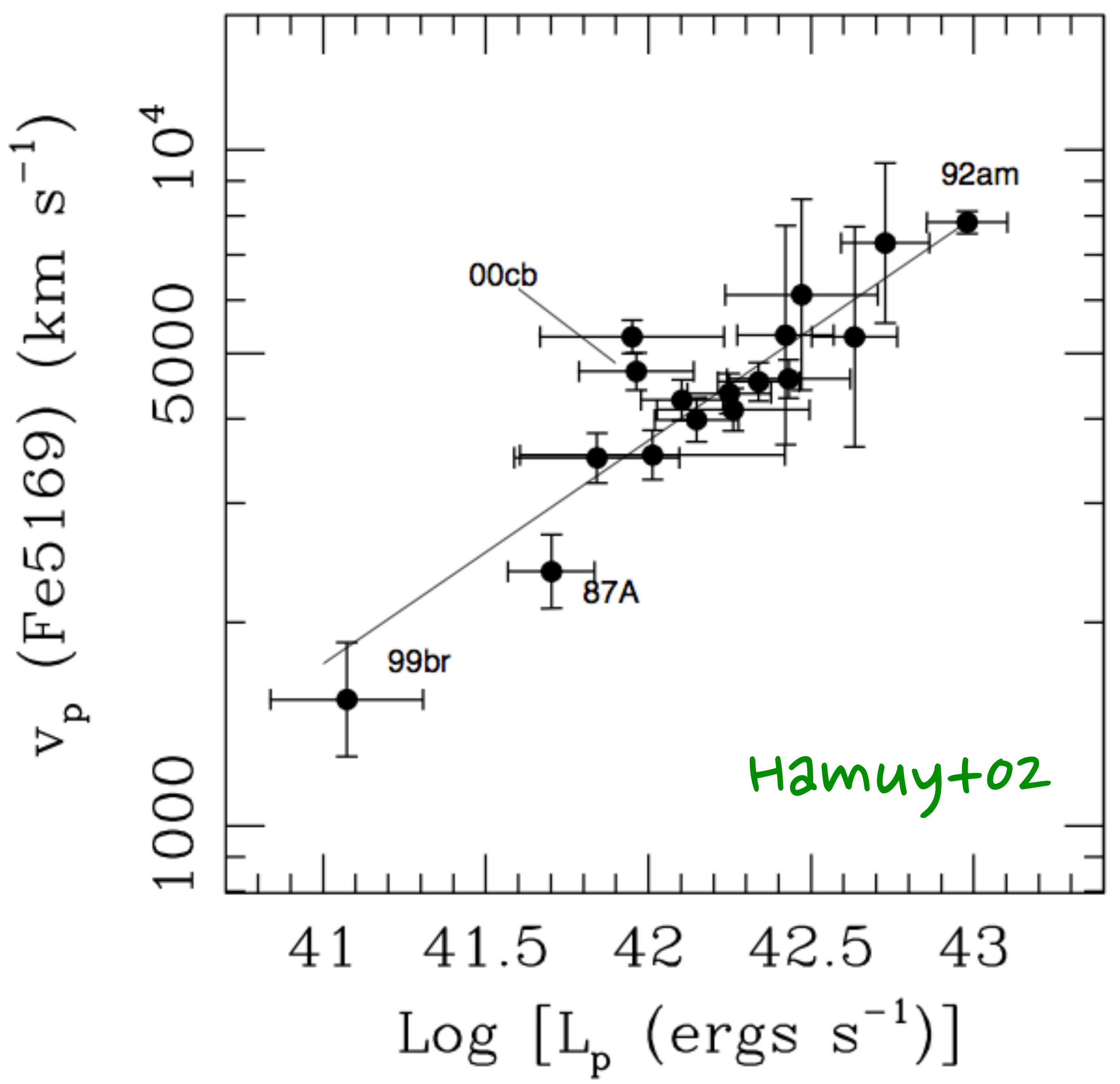


Redder bands flatter

Cosmology

Expanding photosphere method (EPM)
Spectral-fitting Expanding Atmosphere Method (SEAM)
Standard Candle Method (SCM)
Photospheric Magnitude Method (PMM)

All of them require 1 SN spectrum (at least)



Luminosity and expansion velocity are correlated during the plateau phase.

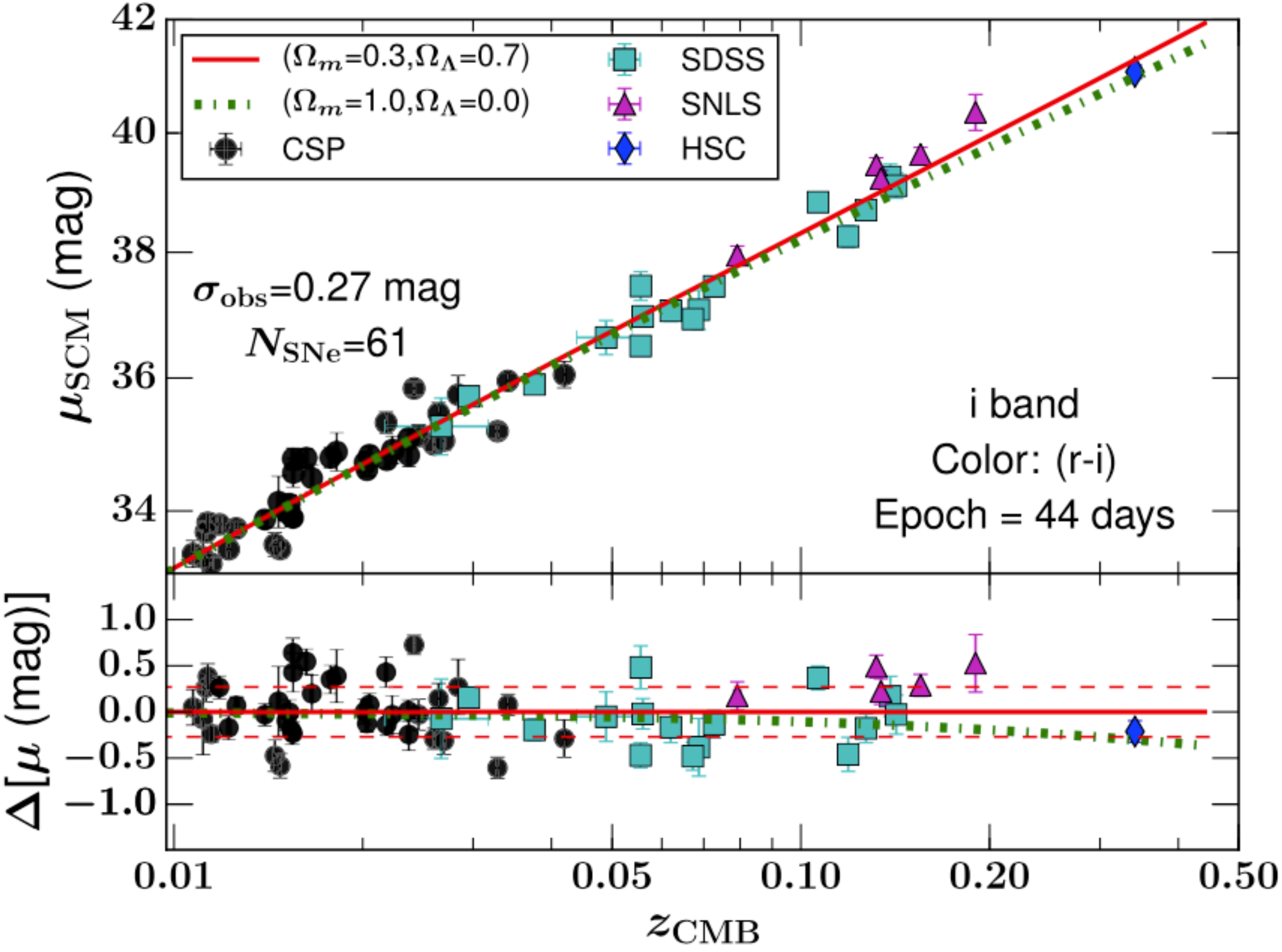
Velocity of Fe 5169A feature as a proxy for exp. vel.

Nugent et al. (2006) added a color term that further reduced the scatter.

$$m_{\lambda 1}^{model} = \mathcal{M}_{\lambda 1} - \alpha log_{10}\left(\frac{v_{H\beta}}{5000\ km\ s^{-1}}\right) + \beta_{\lambda 1}(m_{\lambda 2} - m_{\lambda 3}) \ +5log_{10}(\mathcal{D}_L(z_{CMB}|\Omega_m, \Omega_\Lambda))$$

SCM

Standard
Candle
Method



de Jaeger et al. 2017
de Jaeger et al. 2020

SCM

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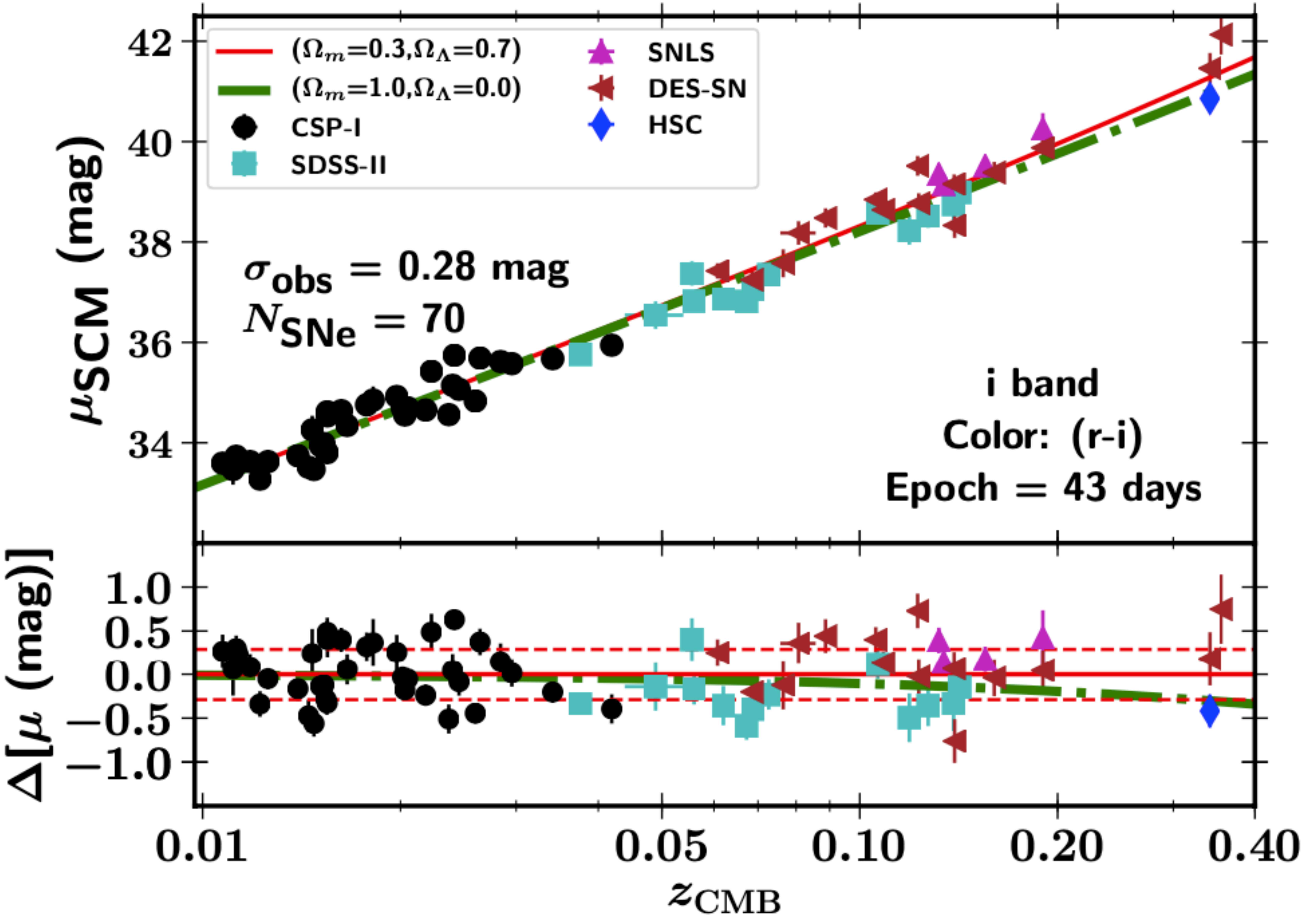
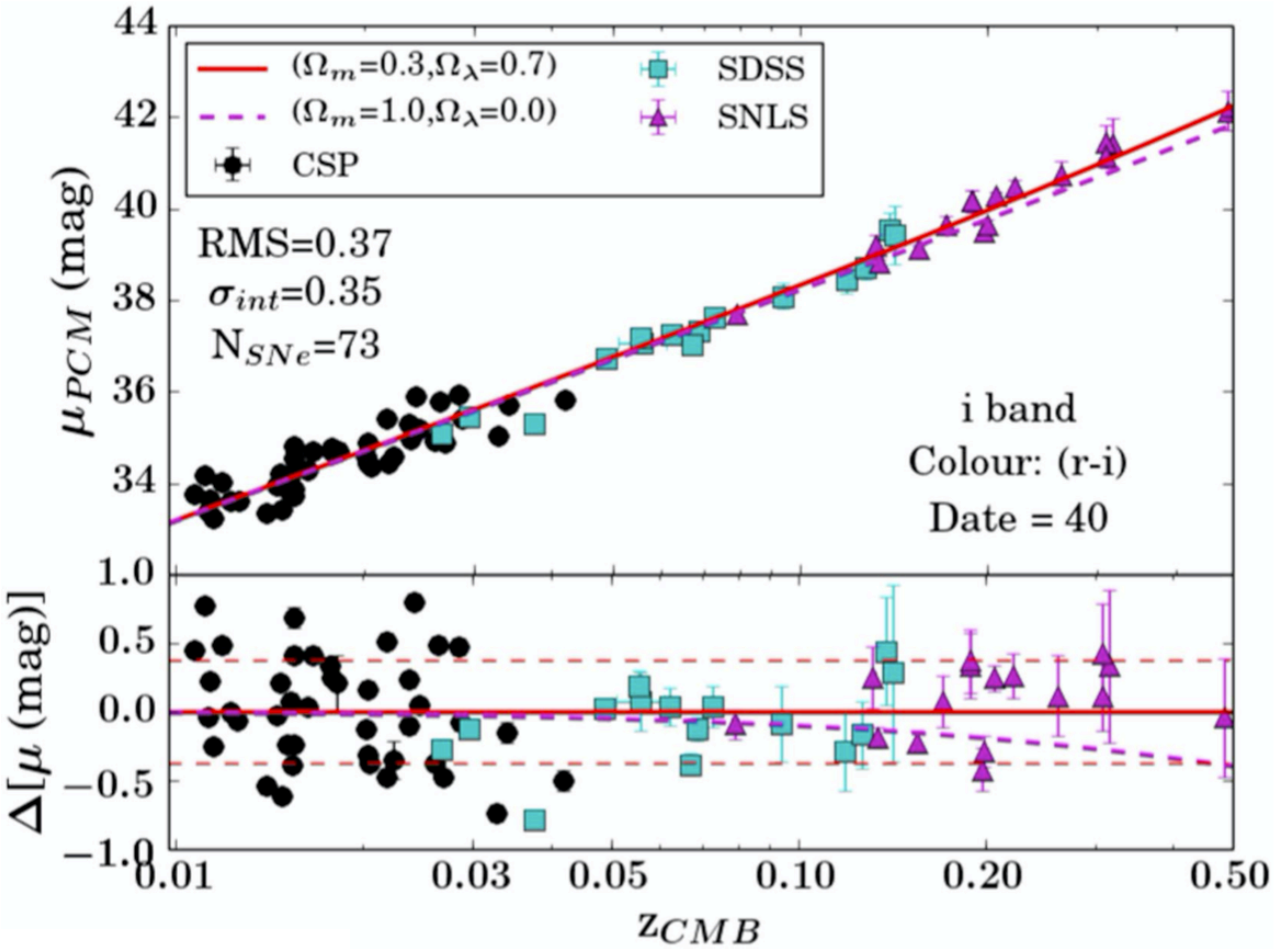


de Jaeger et al. 2017
de Jaeger et al. 2020

PCM

Photometric
Color
Method

de Jaeger et al. 2017
de Jaeger et al. 2020



$$m_{\lambda 1}^{\text{model}} = \mathcal{M}_{\lambda 1} - \alpha s_2 + \beta_{\lambda 1}(m_{\lambda 2} - m_{\lambda 3}) + 5\log_{10}(\mathcal{D}_L(z_{\text{CMB}}|\Omega_m, \Omega_\Lambda)).$$

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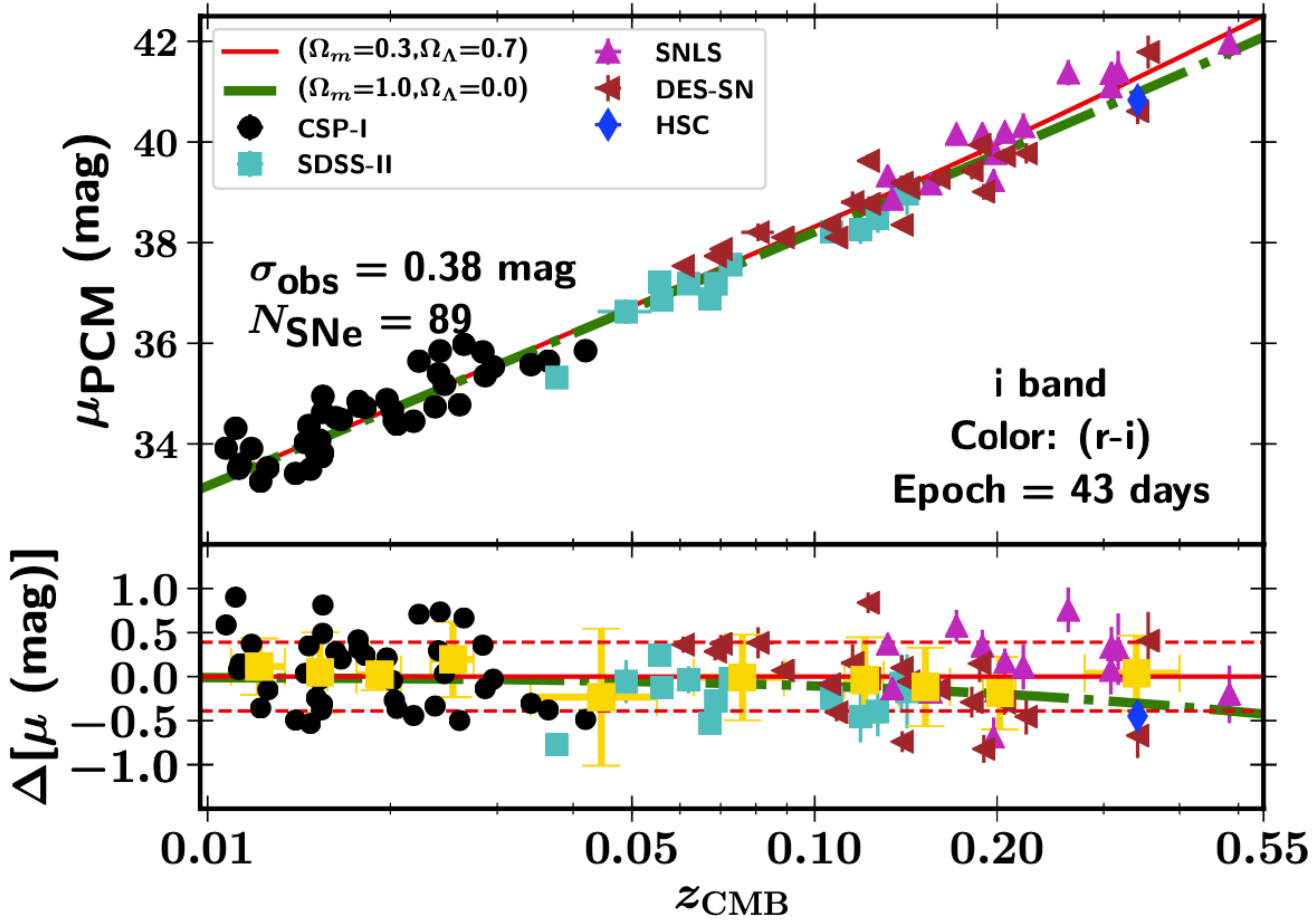

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