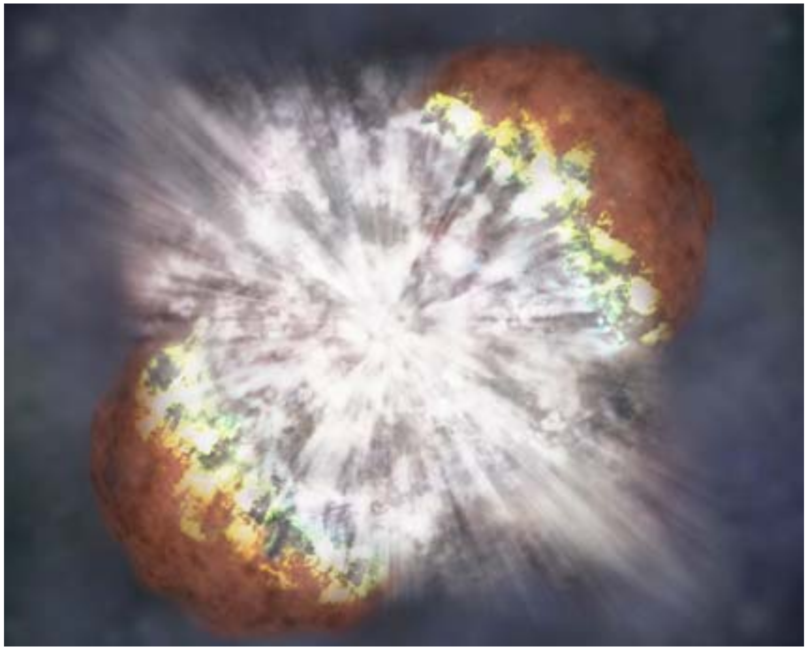


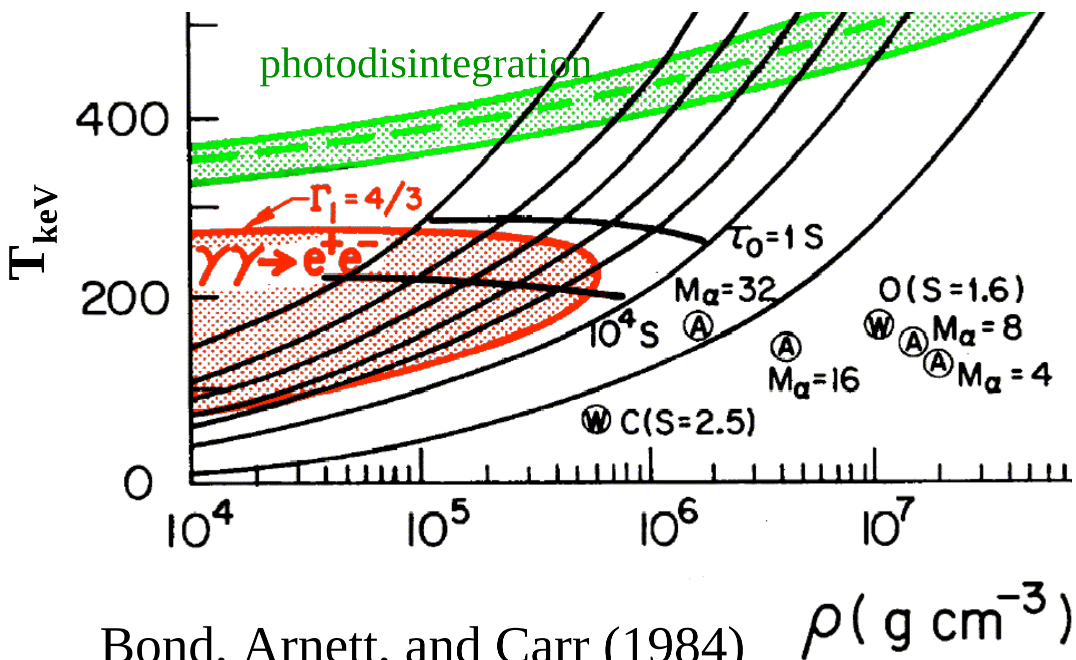
PAIR INSTABILITY SUPERNOVAE

WHAT DO THEY MAKE?

Stan Woosley, Alex Heger,
Dan Kasen

Pair Instability

Stars of sufficiently high mass (central entropy) encounter a structural instability ($\Gamma < 4/3$) and collapse following the end of helium burning. Explosive C, O, Si burning can reverse the implosion and make a thermonuclear explosion



Bond, Arnett, and Carr (1984)

$$\mathrm{BE} \sim \frac{GM^2}{R}$$

Nuclear energy $\sim f\ M$

Above some mass

hard to explode

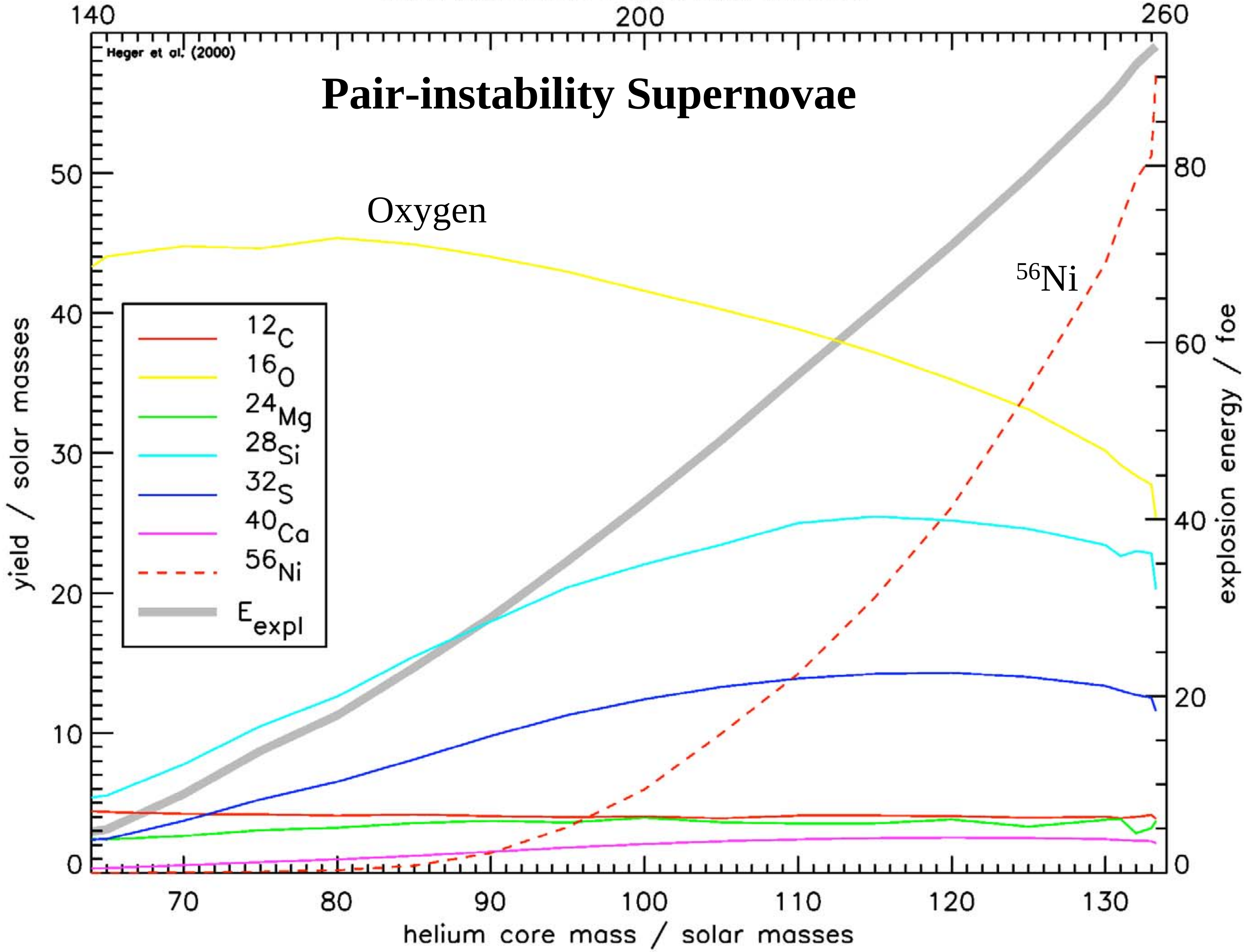
PAIR-INSTABILITY SUPERNOVAE

(Rakavy, Shaviv, and Zinamon (1967);
Barkat, Rakavy and Sack (1967))

He Core	Main Seq. Mass	Supernova Mechanism
$2 \le M \le 40$	$10 \le M \le 95$	Fe core collapse to neutron star or a black hole
$40 \le M \le 63$	$95 \le M \le \sim 150$	Pulsational pair instability followed by Fe core collapse
$63 \le M \le 133$	$\sim 150 \le M \le 260$	Pair instability supernova
$M \ge 133$	$M \ge 260$	Black hole. Possible GRB

Umeda and Nomoto (2001); Heger and Woosley (2002);
Woosley et al (2007)

Heger and Woosley (2002)



Complications:

- Did they, do they ever exist and what was the heaviest?
- Mass loss: Eta Carina or $\dot{M} \propto Z^n \rightarrow 0$ as $Z \rightarrow 0$
- Convection and convective dredge up. Primary nitrogen production leads to red supergiant, otherwise blue. RSG may lose mass even at Z = 0.
- Rotation - increases He core mass, increases mixing and mass loss and may dominate the explosion mechanism in some mass range
- Binary - lose envelope?

Consequences:

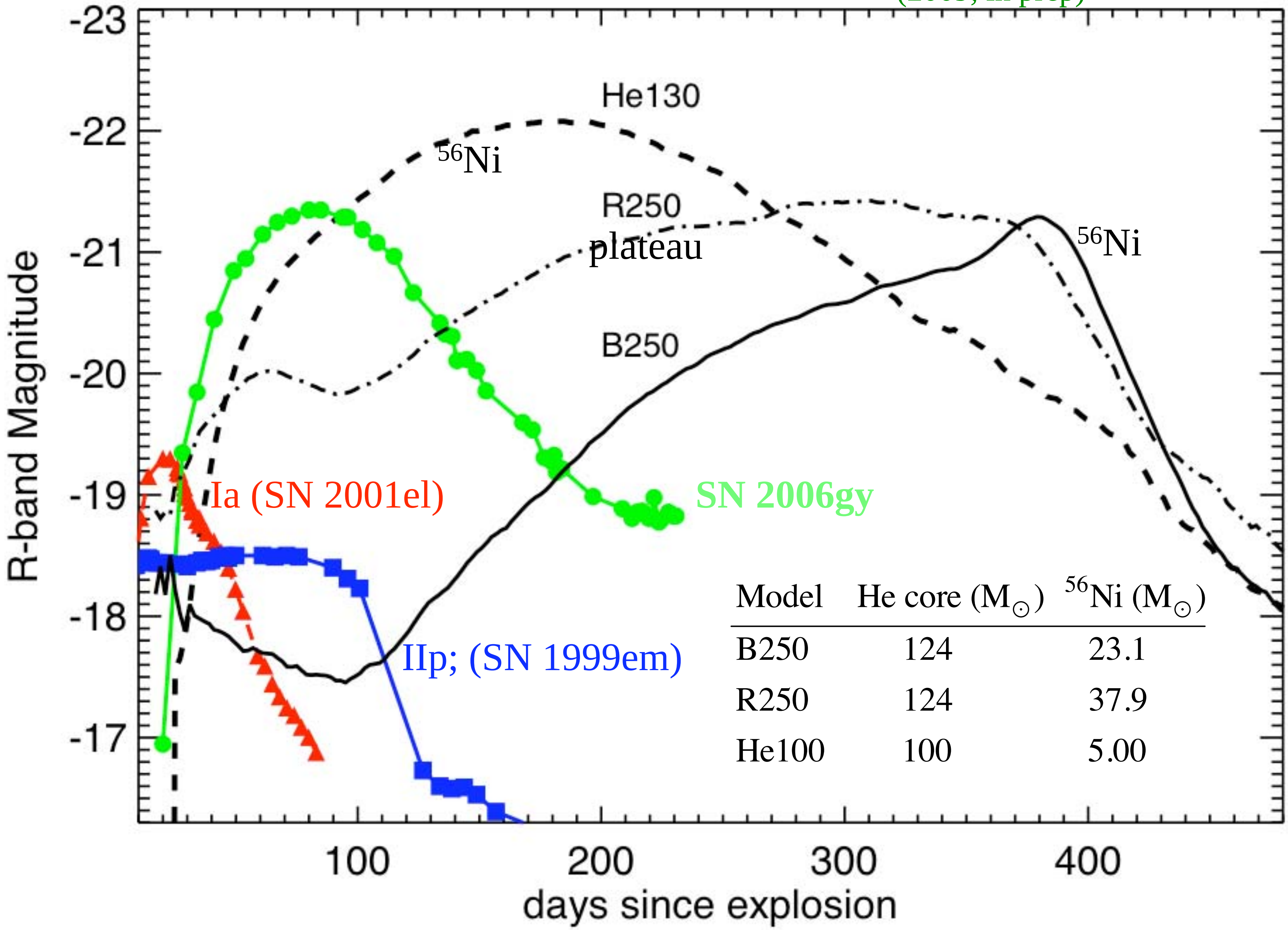
- Both IMF and mass function at death (FMF) are uncertain

- PreSN stars may be RSG, BSG, or stripped cores (for any Z)

- Rotation may or may not be adequate to explode any gravitationally bound residual of e.g. a pulsational pair SN

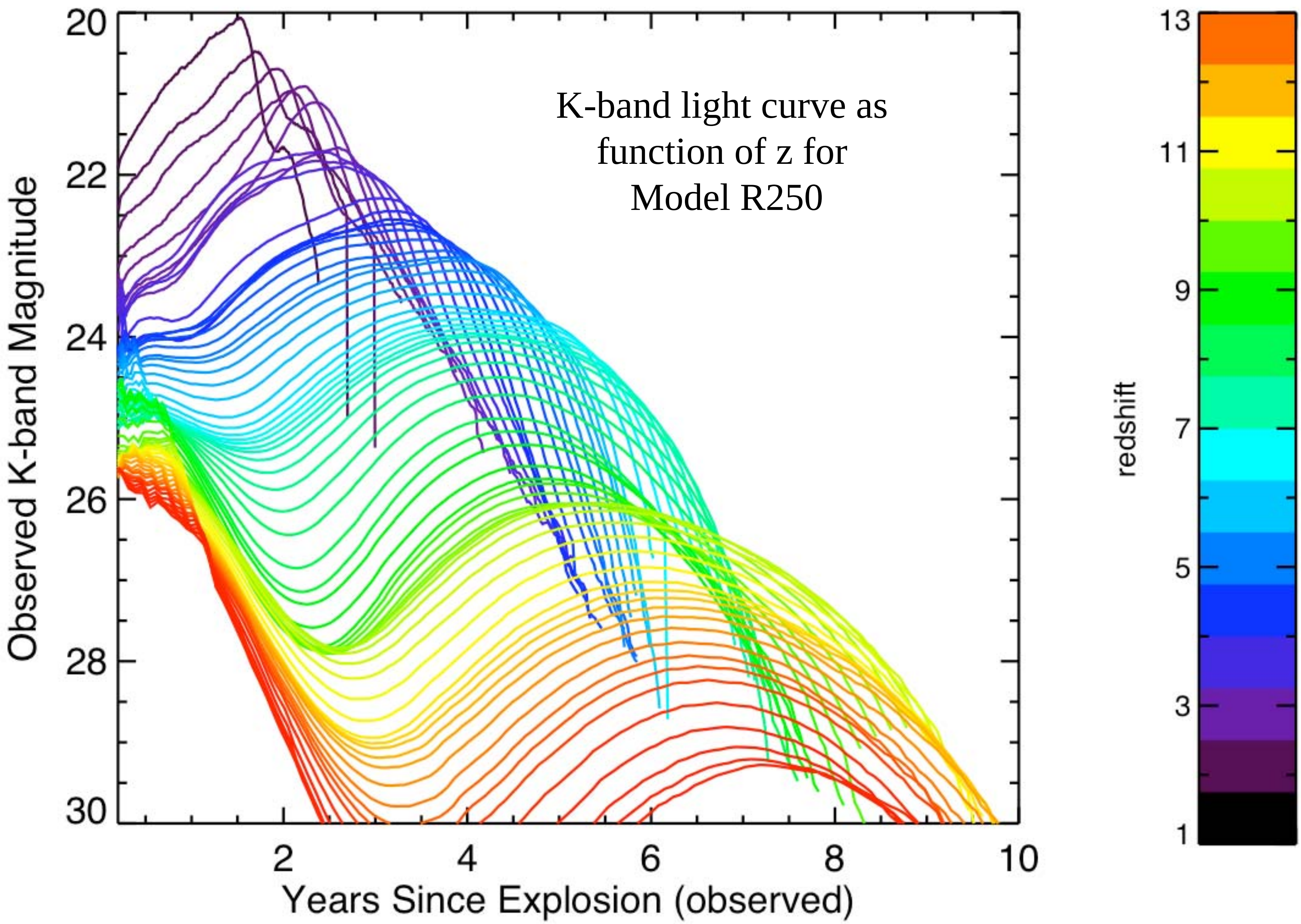
Light Curves and spectra

Kasen, Woosley and Heger
(2009, in prep)



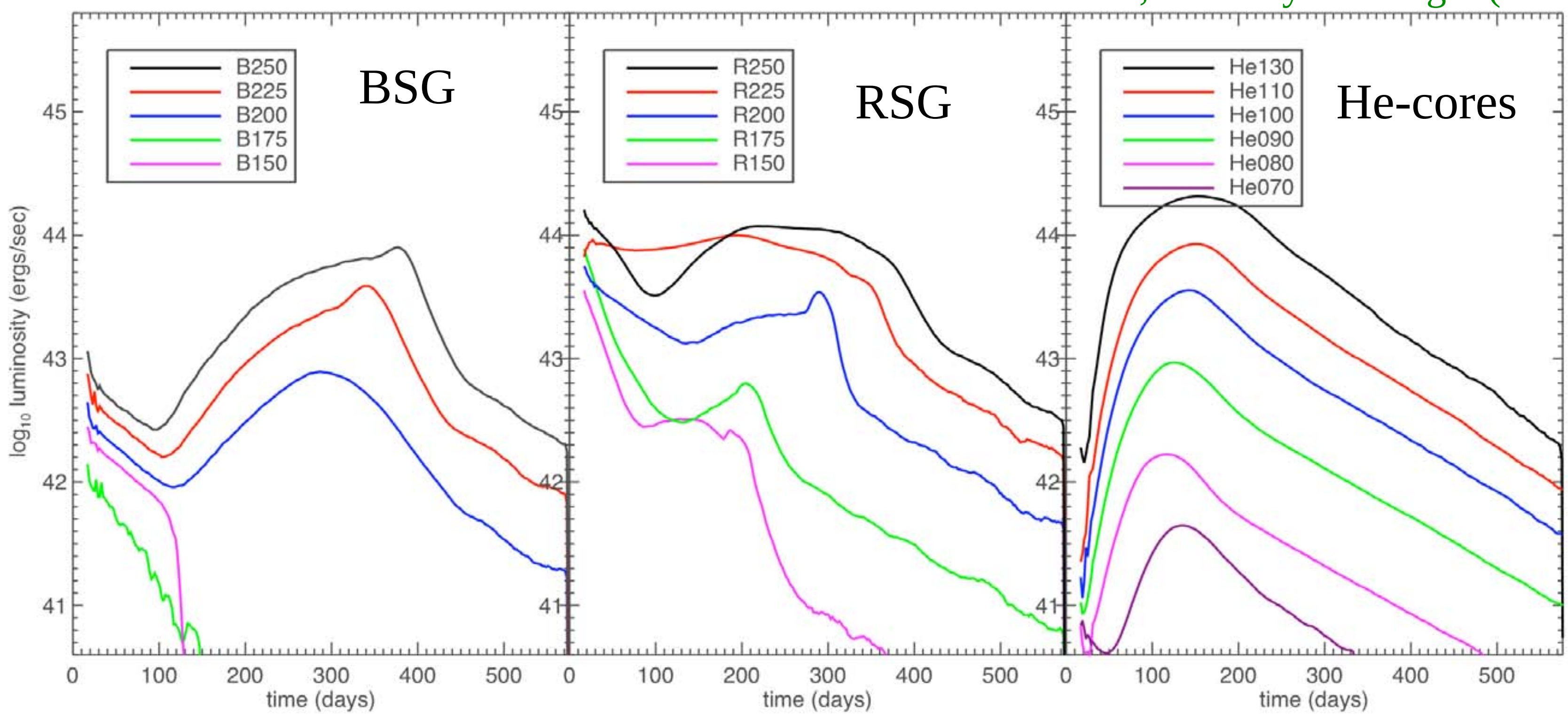
Model	He core ($M_\odot$)	^{56}Ni ($M_\odot$)
B250	124	23.1
R250	124	37.9
He100	100	5.00

Kasen, Woosley, and Heger (2009)

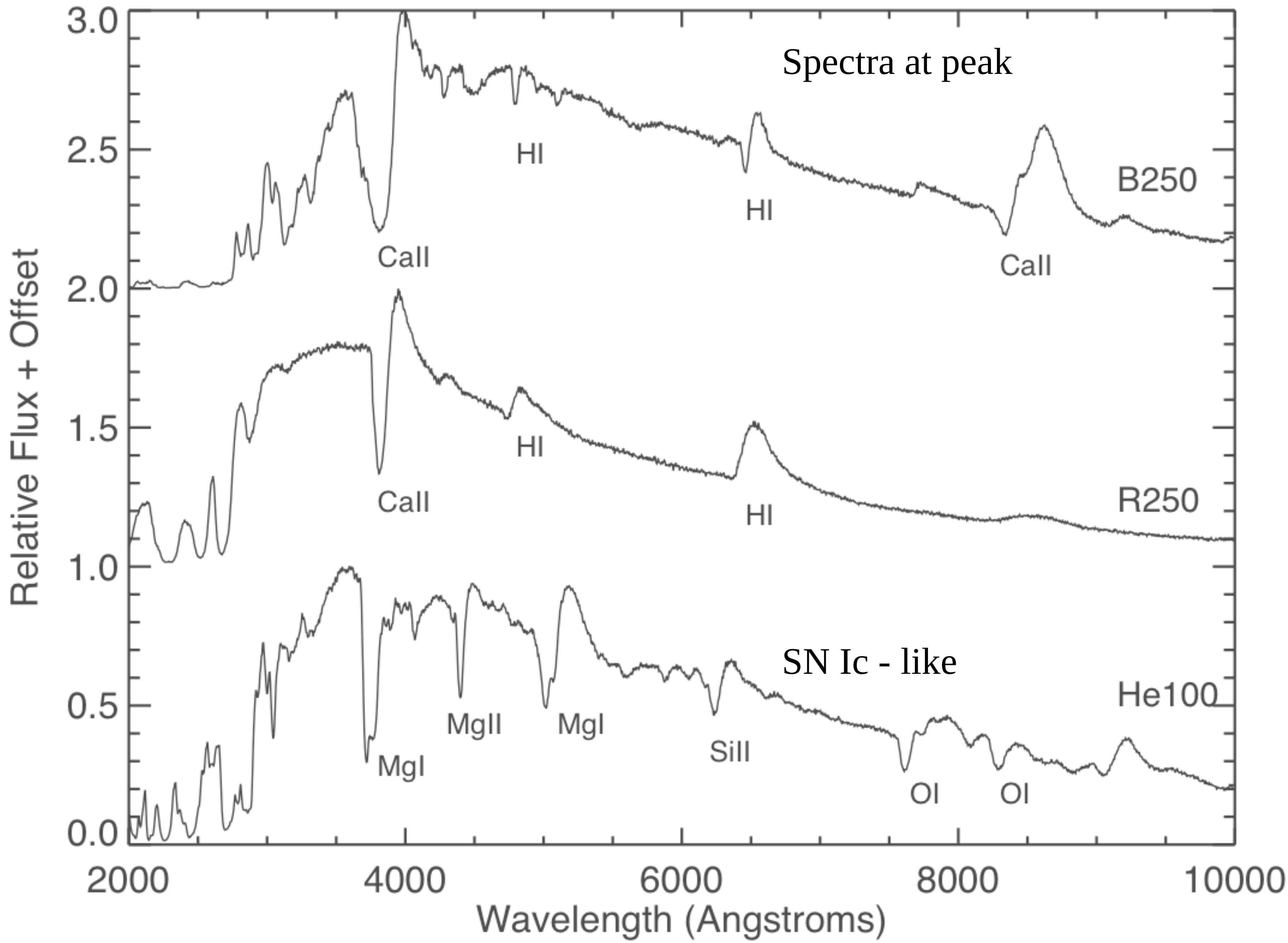


A wide variety of transients are possible depending on the mass of the progenitor (amount of ^{56}Ni made in the explosion), the mass, if any, of the presupernova hydrogen envelope and its radius

Kasen, Woosley and Heger (2009)



The most common variety (lower mass RSGs) may in fact resemble ordinary SN IIp. Spectra will differ if metals are absent. v ~ 5000 km s^{-1}. Long plateaus in some.

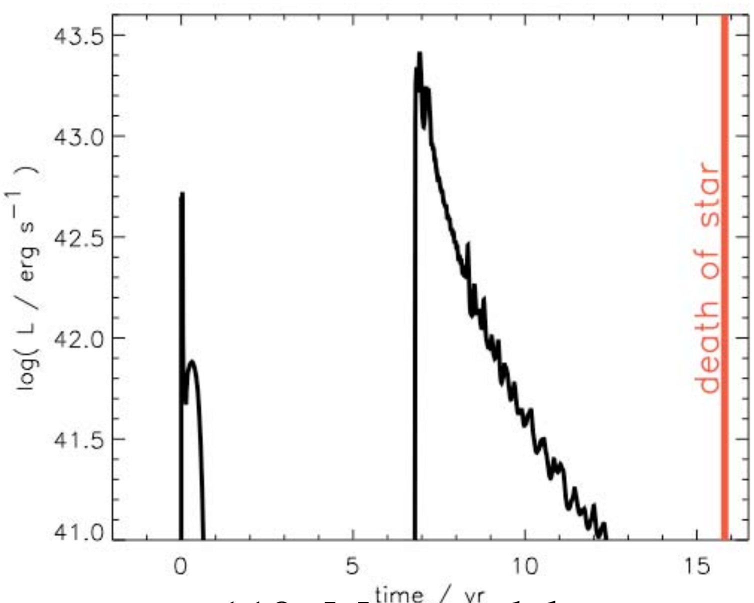


Spectra at peak
SN Ic - like
B250
R250
He100
CaII
HI
HI
CaII
CaII
HI
HI
MgI
MgII
MgI
SiII
OI
OI
Relative Flux + Offset
Wavelength (Angstroms)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
2000
4000
6000
8000
10000

Pulsational Pair Instability Supernovae

Woosley, Blinnikov, and Heger (Nature, 2007)

- Pulsational pair instability (95 - 130* solar masses):



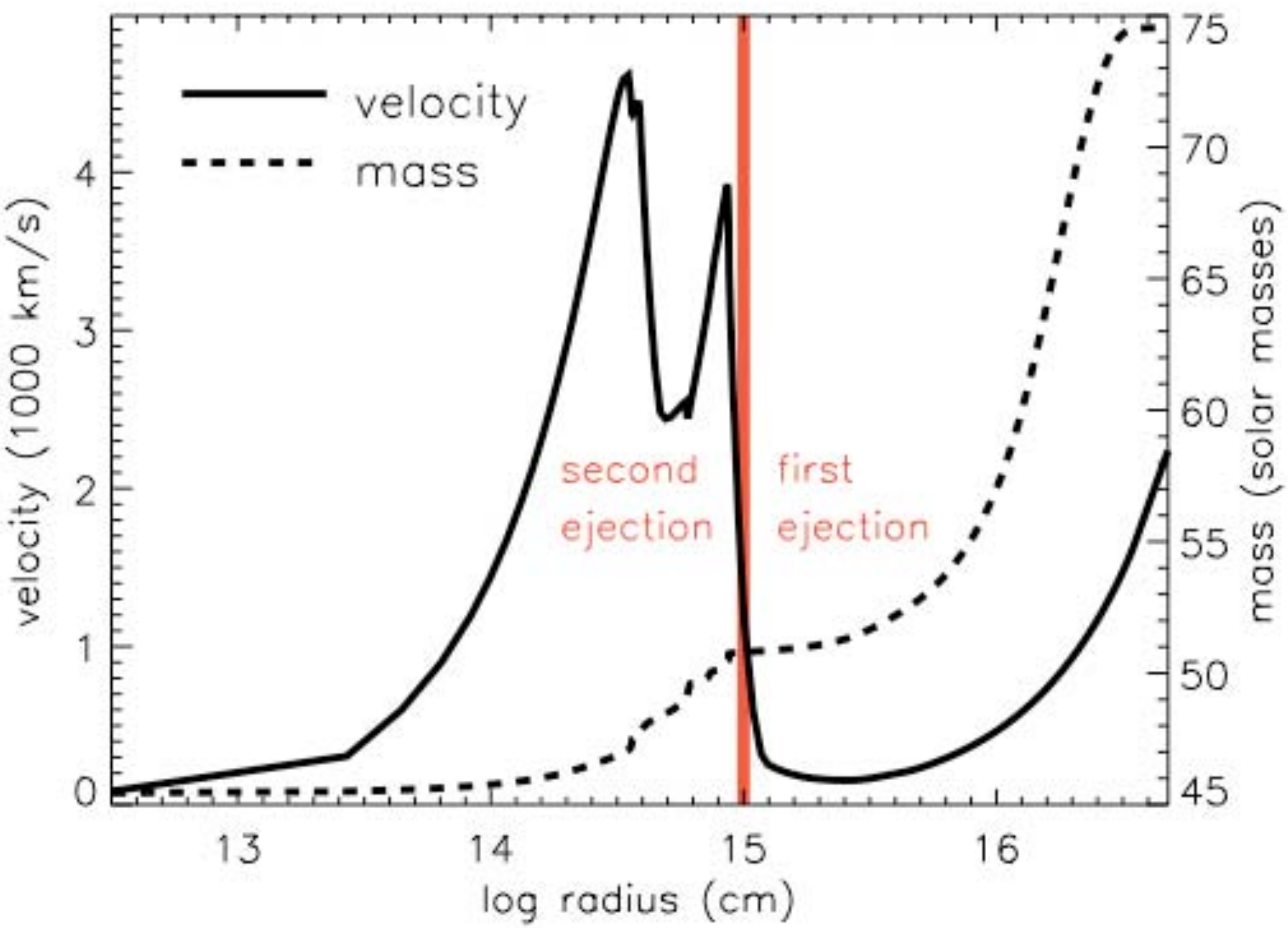
110 $M_\odot$ model

50 $M_\odot$ helium core

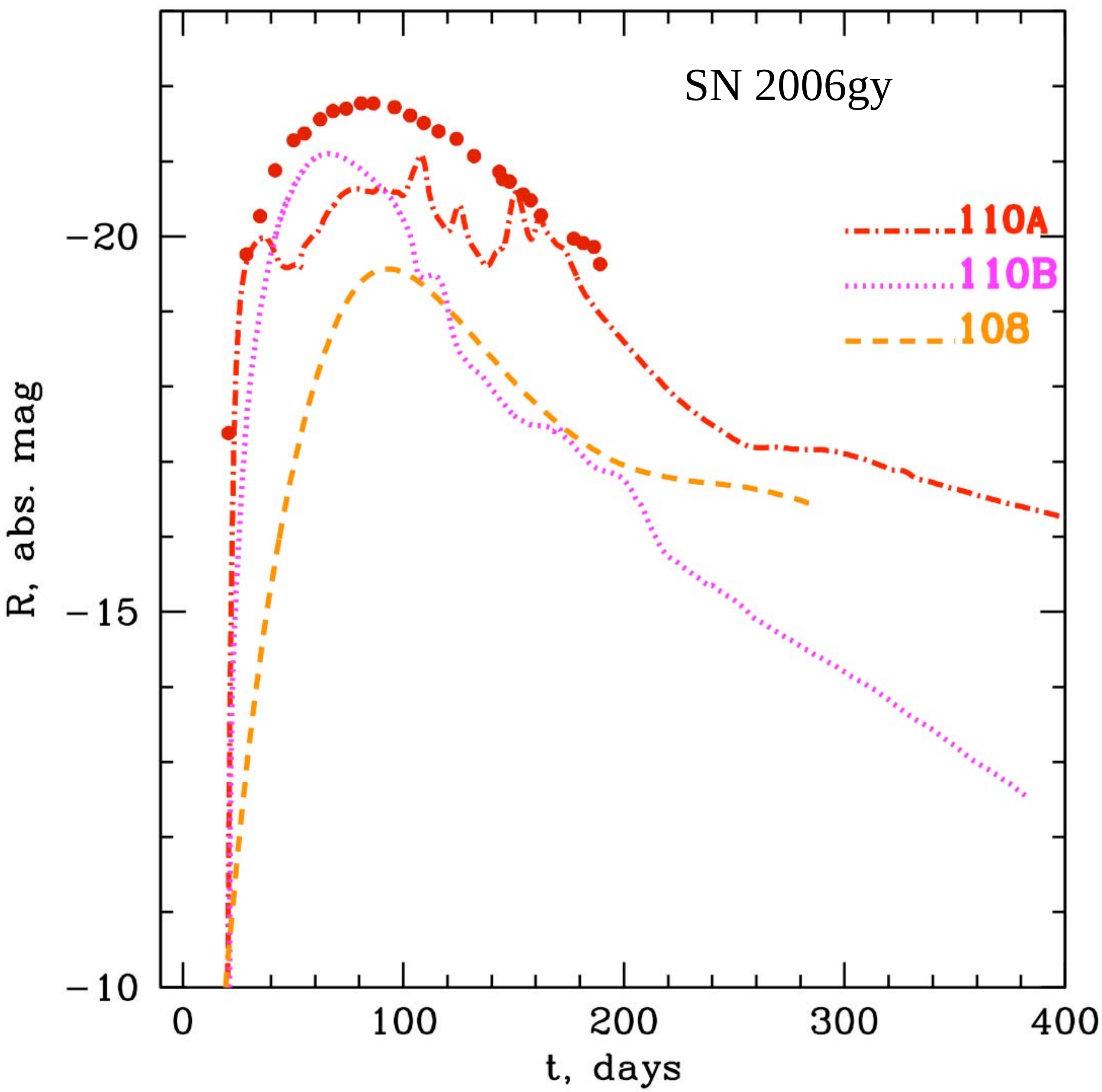
Helium Core	Number Pulses	Energy Range	Interval Range
M_{sun}		10^{51} erg	years
48	6	.11- 2.4	.02 - 0.26
51	4	.44 - 3.7	0.09 - 0.9
52	4	.94 - 3.1	.01 - 3.0
54	3	2.1 - 3.2	0.03 - 12
56	3	1.3 - 3.3	.01 - 110

•main sequence masses ignoring rotation, smaller mass limit with rotation

All mass external to ~40 solar masses is ejected, then pulsations cease and some time later, the remaining (40 solar masses) probably becomes a black hole



Should see low velocity circumstellar lines whose characteristic speed increases with time.


SN 2006gy
110A
110B
108
R, abs. mag
−20
−15
−10
0
100
200
300
400
t, days

Pulsational Pair Instability Supernovae:

Depending on the IMF, pulsational pair instability may be (probably are) the most common variety of pair instability supernovae.

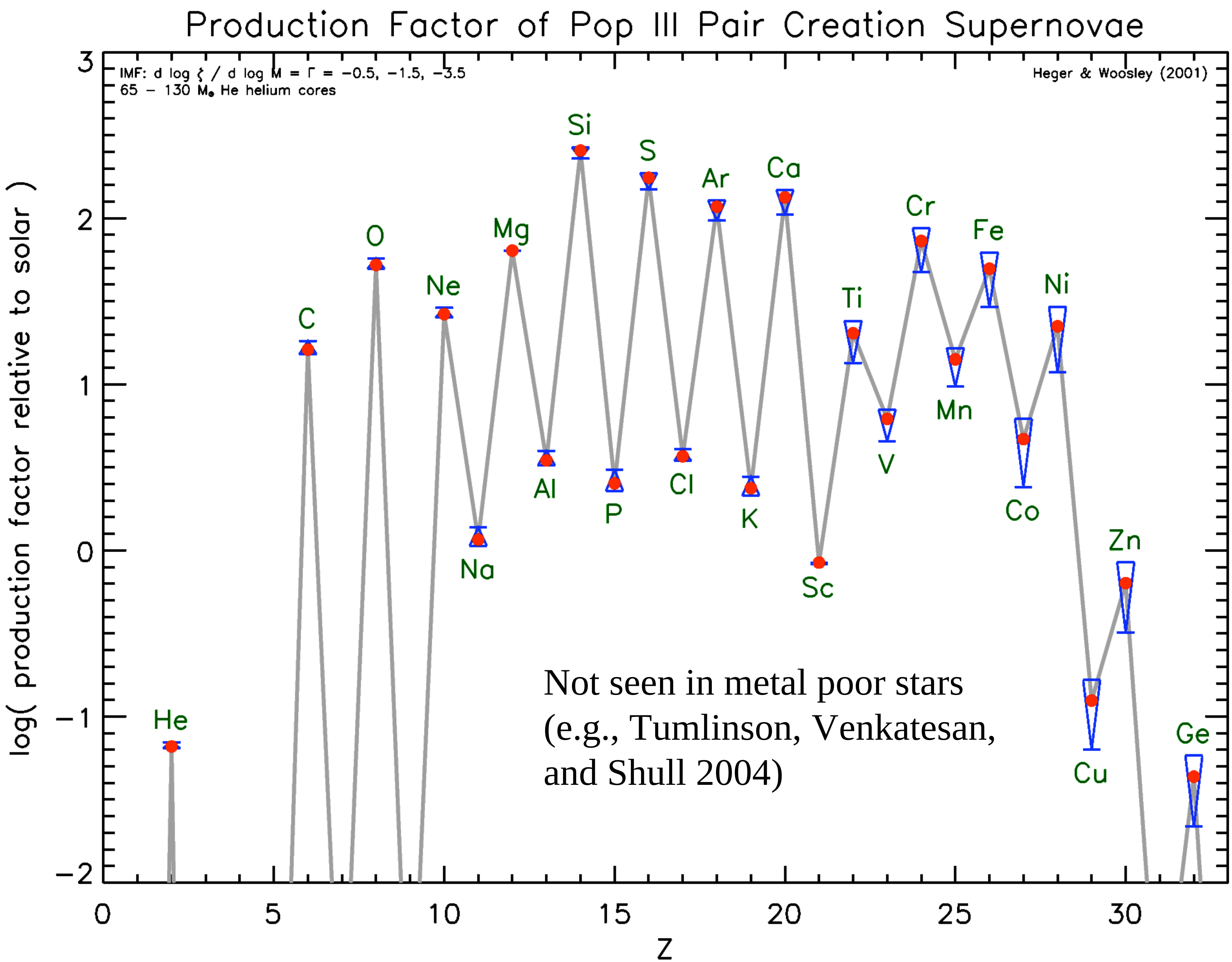
They could even be the most common kind of supernova in the early universe (if the IMF was truncated at ~ 20 - 30 M_{sun} (Tan and McKee 2004, 2008)

Depending on uncertain mass loss they may also be common in modern times.

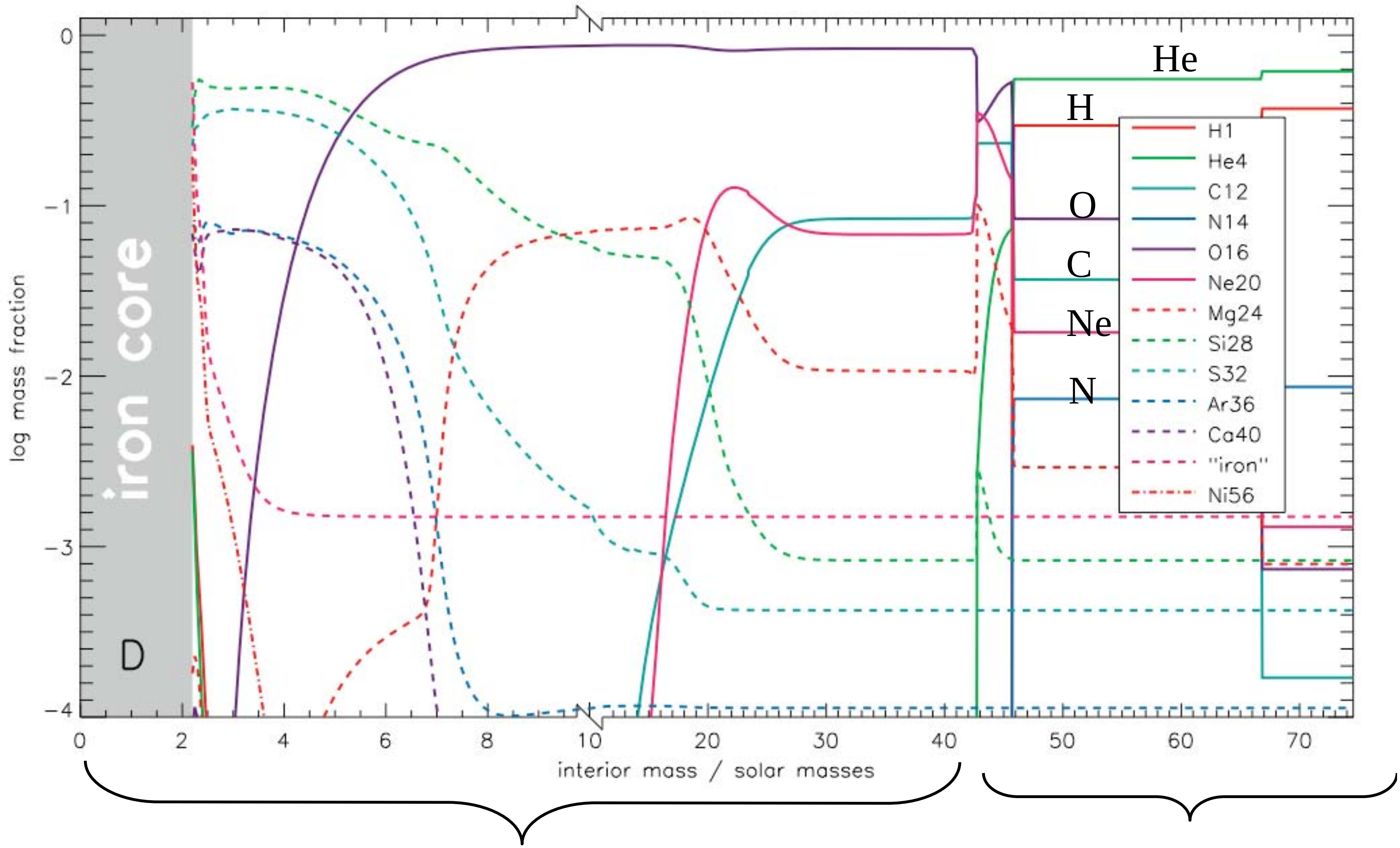
They could be part of the supernova imposter sample.

Can make SN I as well as II.

Nucleosynthesis


Production Factor of Pop III Pair Creation Supernovae
IMF: d log ζ / d log M = Γ = −0.5, −1.5, −3.5
65 − 130 M⊙ He helium cores
Heger & Woosley (2001)
log(production factor relative to solar)
Z
He
C
O
Ne
Na
Mg
Al
Si
P
S
Cl
Ar
K
Ca
Sc
Ti
V
Cr
Mn
Fe
Co
Ni
Cu
Zn
Ge
Not seen in metal poor stars
(e.g., Tumlinson, Venkatesan,
and Shull 2004)

However…

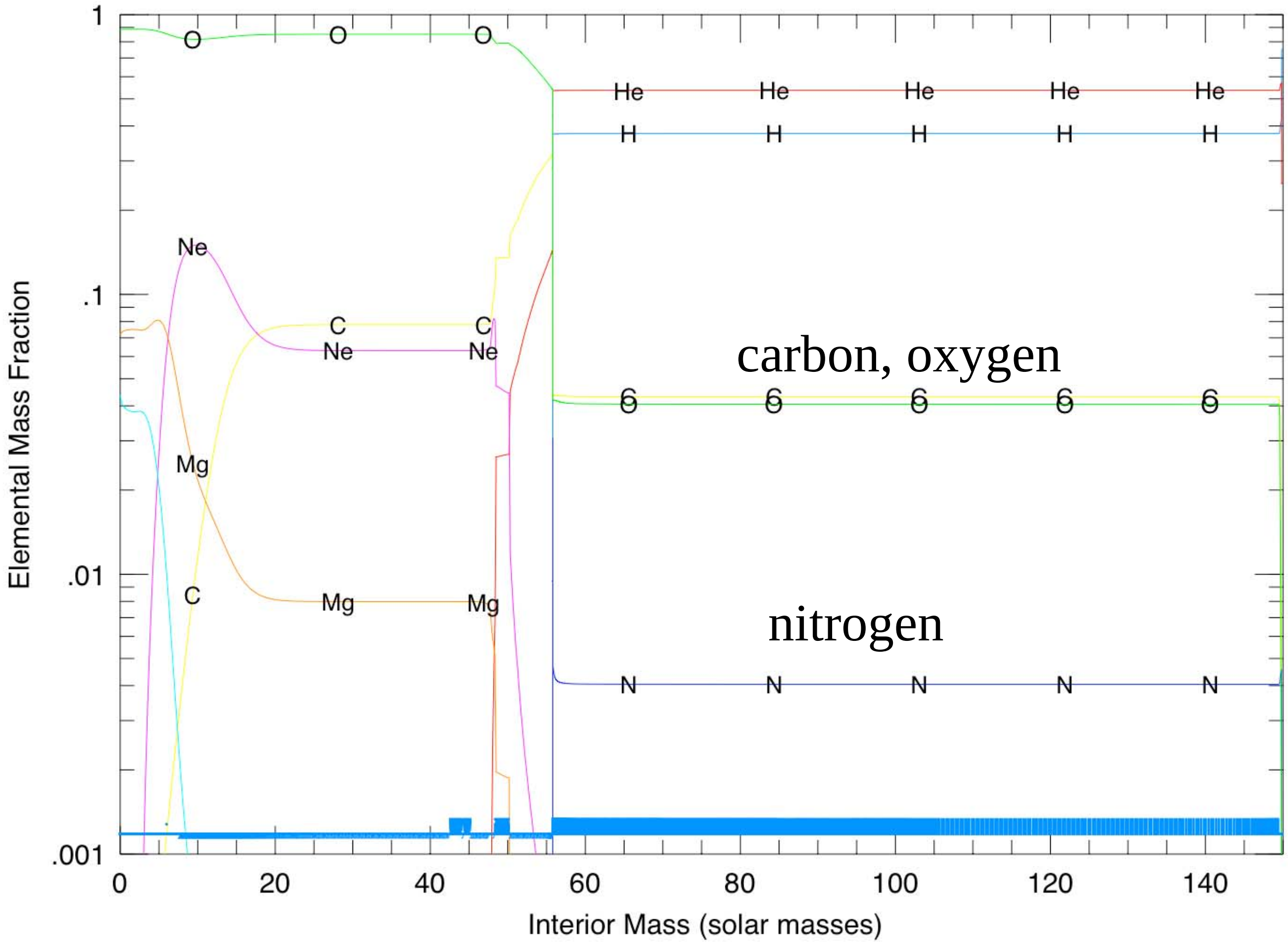


BE ~ 2.5 B

May be too big to explode with neutrinos and too slowly rotating to explode with rotation

Ejected in pulses

A 150 solar mass zero metallicity model at the time it encounters the first pulsational instability.

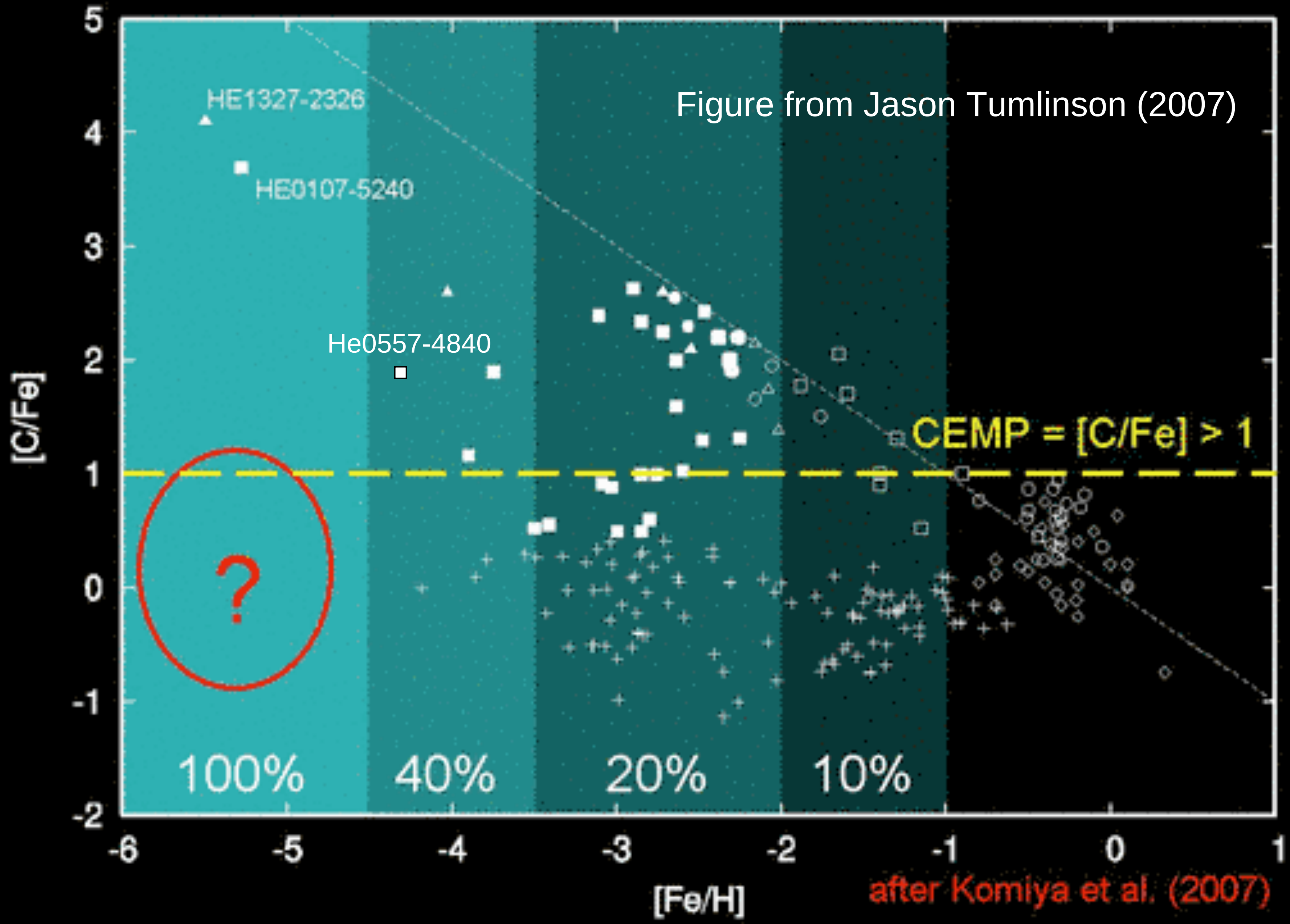


External to
45 solar masses

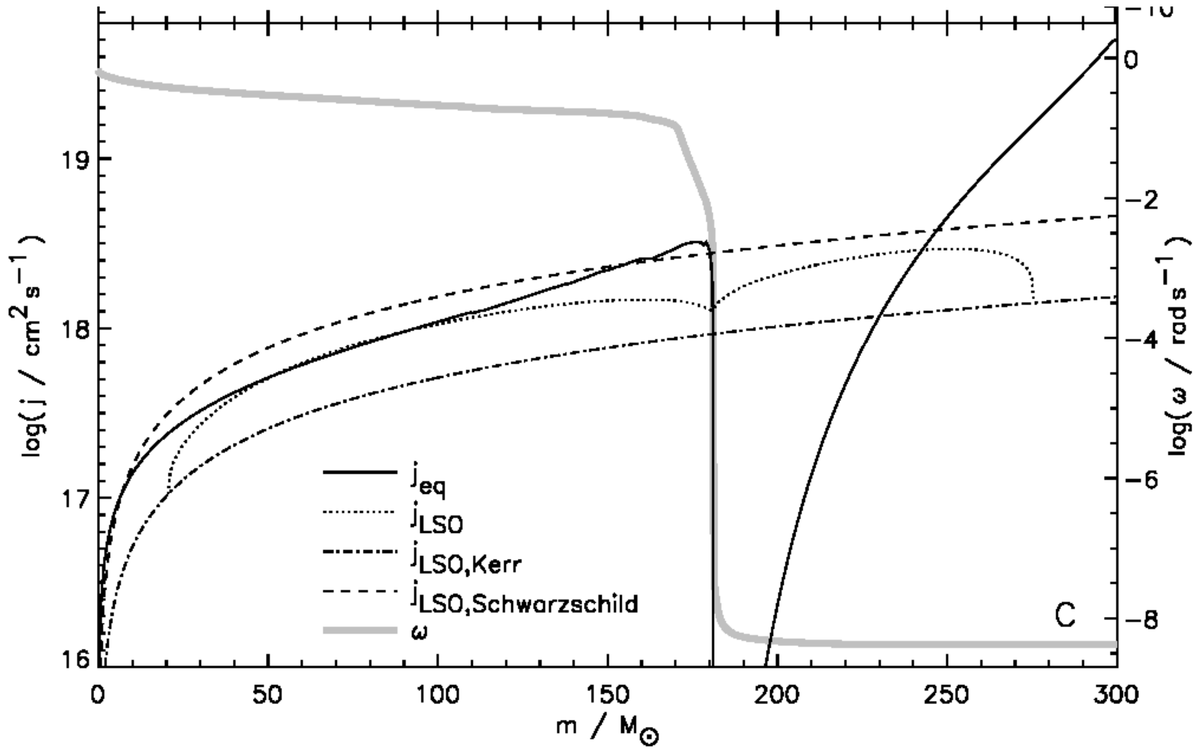
O - 11.7 Msun
C - 5.9
N - 0.4
Si, Fe, etc - 0

The principal outcome of pair-instability SNe below about 150 - 170 solar masses and above 90 solar masses may be CNO and 40 solar mass black holes

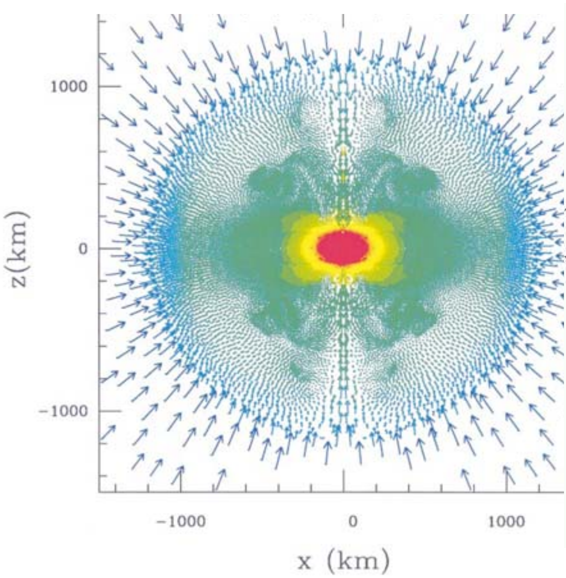
Carbon-Enhanced Metal-Poor Stars (CEMPs):

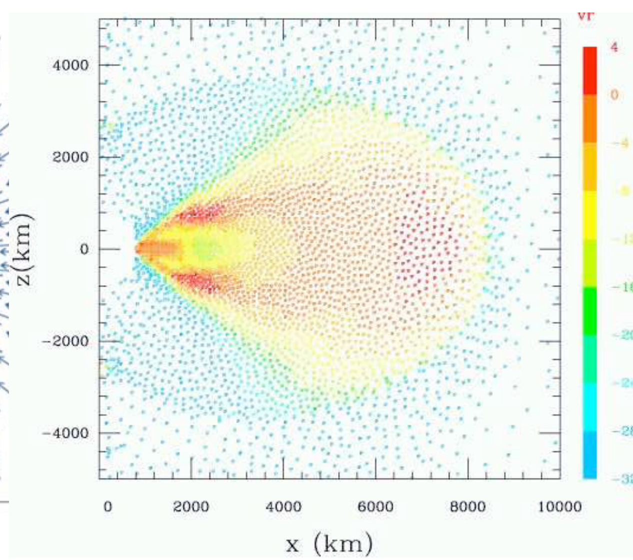


Gamma-Ray Bursts



Fryer, Woosley, and Heger (2001)



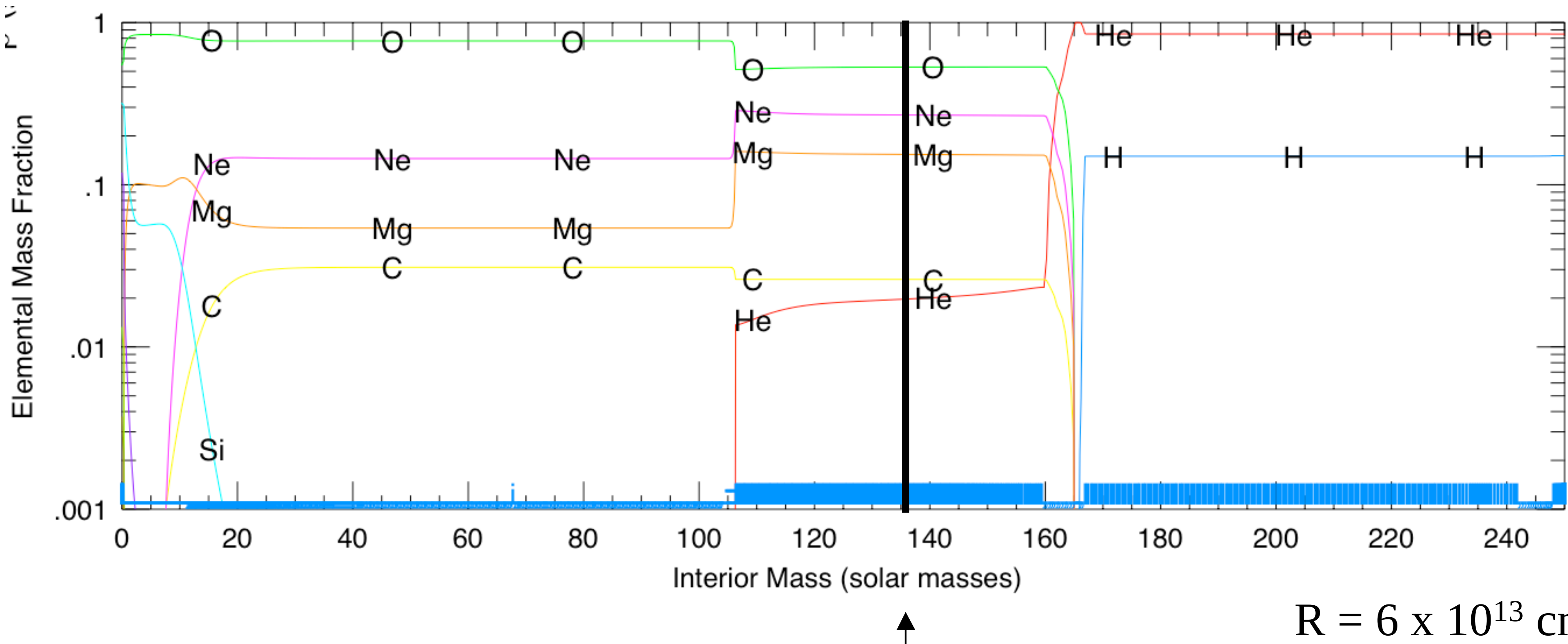


Black hole of ~140 solar masses accretes 20 solar masses at 1 - 10 solar masses per second.

Long, energetic GRB?

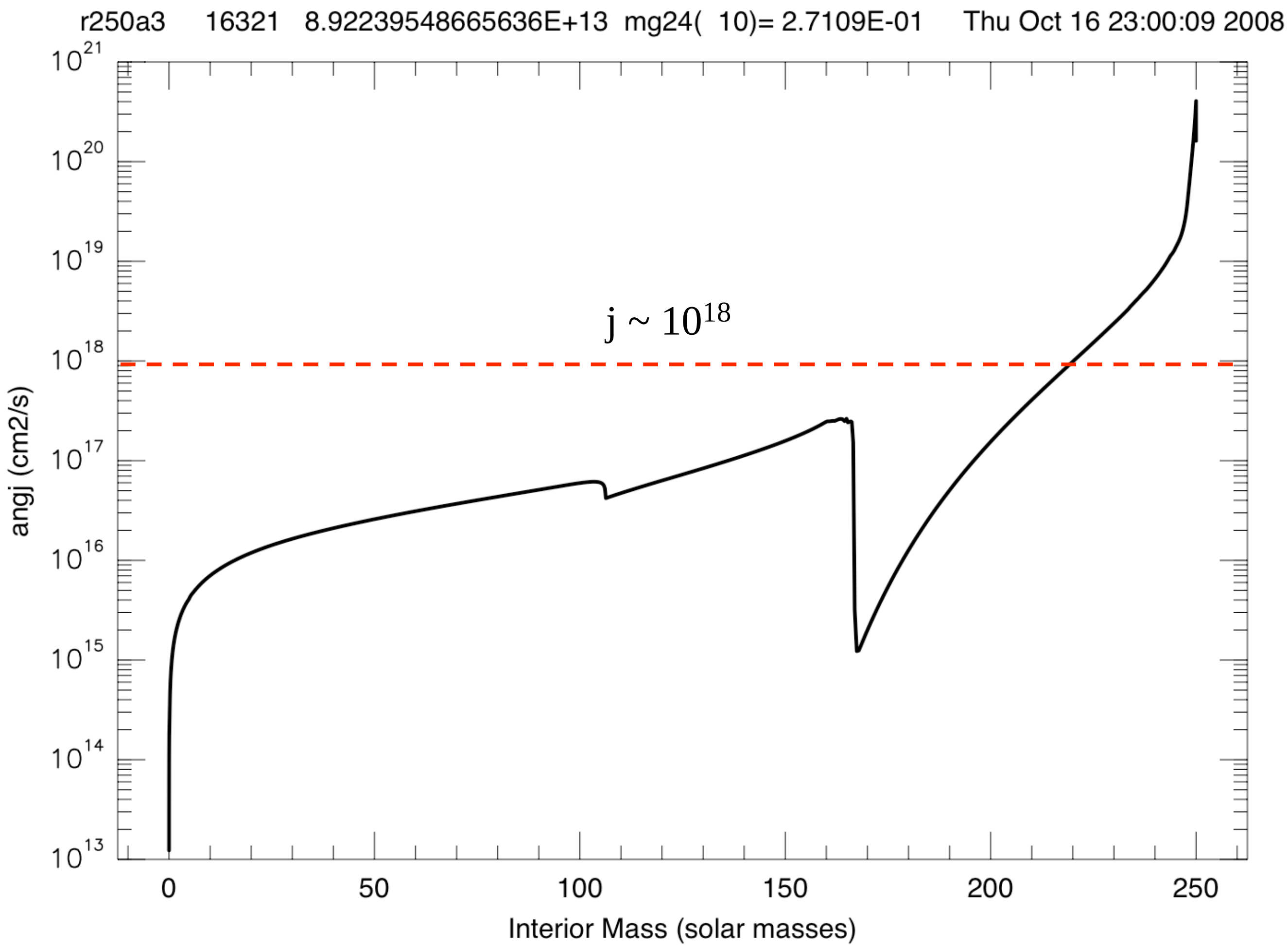
Pair-instability black hole formation

Rotating 250 solar mass model; Include B-torques, Spruit (2001)
v_{rot} = 220 km/s on main sequence



R = 6 x 10^{13} cm

critical helium core mass for BH formation



Entire helium core collapses to black hole without (initially) forming a disk. Makes the problem simple.

If the core of a very massive star collapsed to a black hole, could it simply disappear?

$$j_{LSO} = 2\sqrt{3}\ GM/c = 2.3\times10^{18}\ M_{BH}/150\,M_\odot\ \mathrm{cm^2\ s^{-1}} \qquad \text{non-rotating}$$

$$j_{LSO} = 2/\sqrt{3}\ GM/c = 7.7\times10^{17}\ M_{BH}/150\,M_\odot\ \mathrm{cm^2\ s^{-1}} \qquad \text{Kerr}\quad a = 1$$

Even with mild rotation the outer ~10 solar masses will be hung up in a disk around a 240 solar mass black hole - new kind of transient.

Free fall times scale from $10^{12} - 10^{13}$ cm is hours to days *(1+z)

$$E \sim 0.01\,Mc^2 \sim 2\times10^{53}\ \mathrm{erg}$$

$$L_{jet} \sim 10^{48-49}\ \mathrm{erg\ s^{-1}}$$

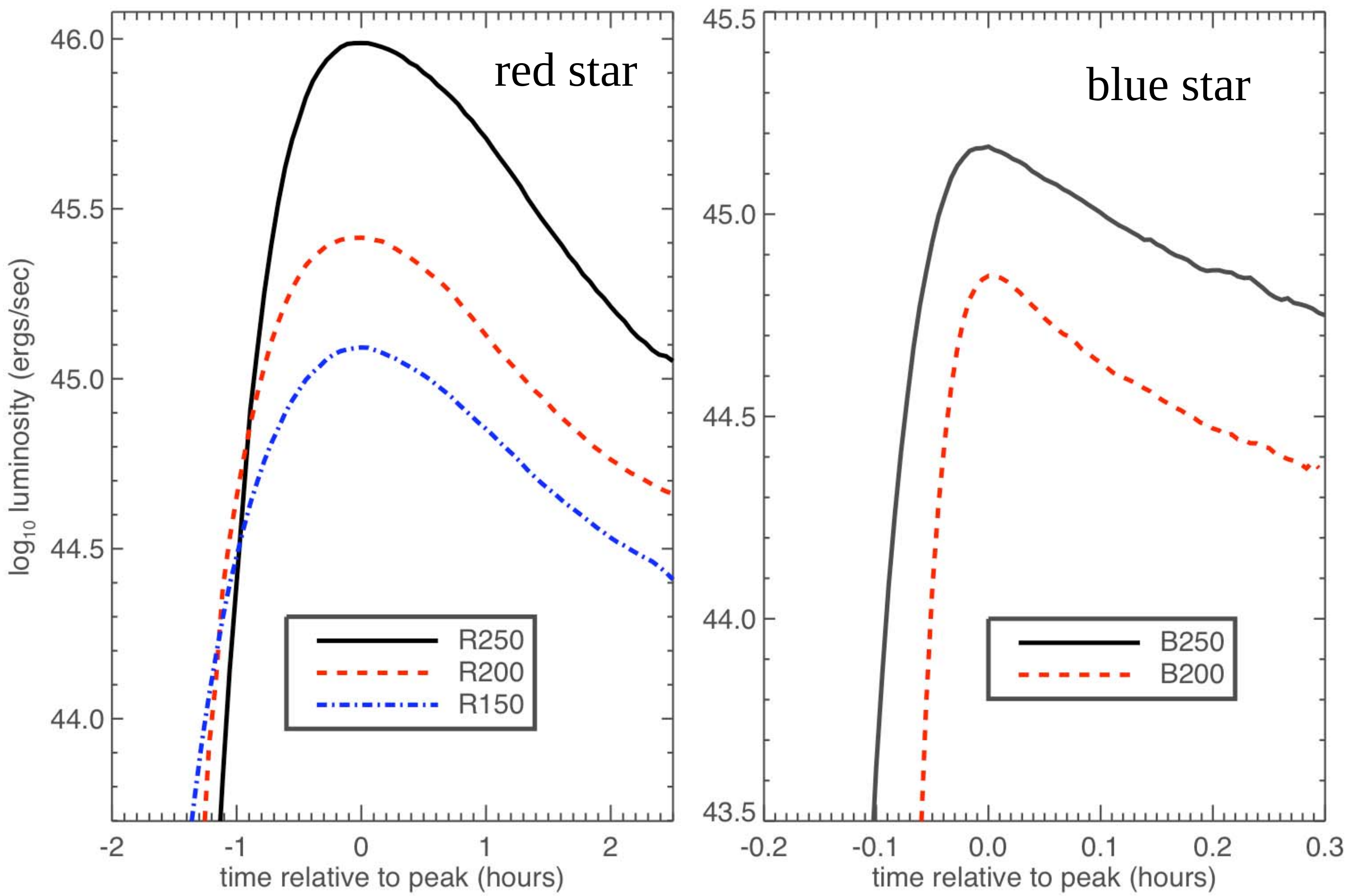
brighter still with beaming?

Gamma-ray Blazar?

Shock

Break out

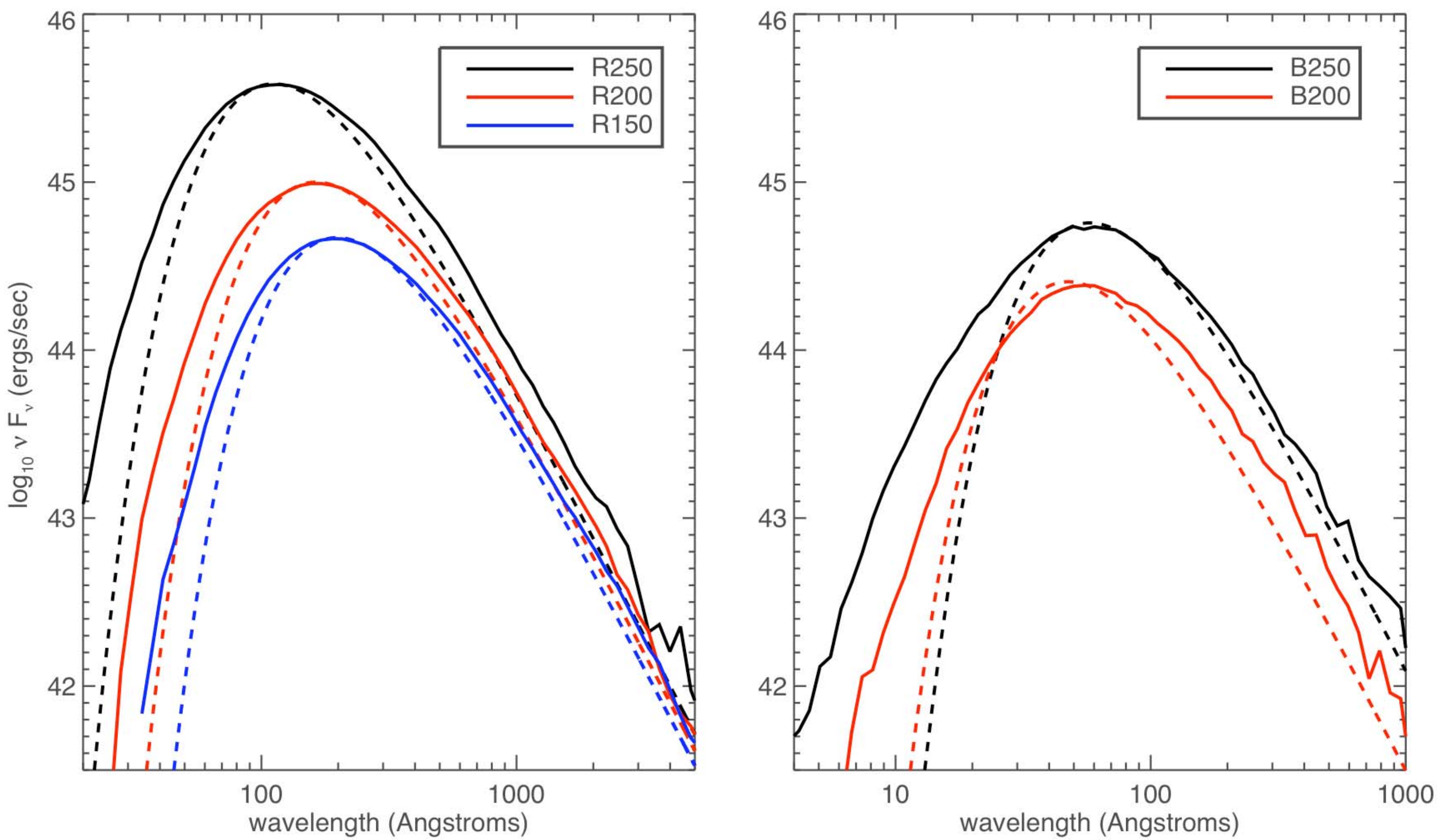
Typical break out transients for pair-instability supernovae that retain hydrogen envelopes are 10^{45} - 10^{46} erg s^{-1} for several hours in the waveband 30 - 170 A (fainter and shorter for BSG progenitors)



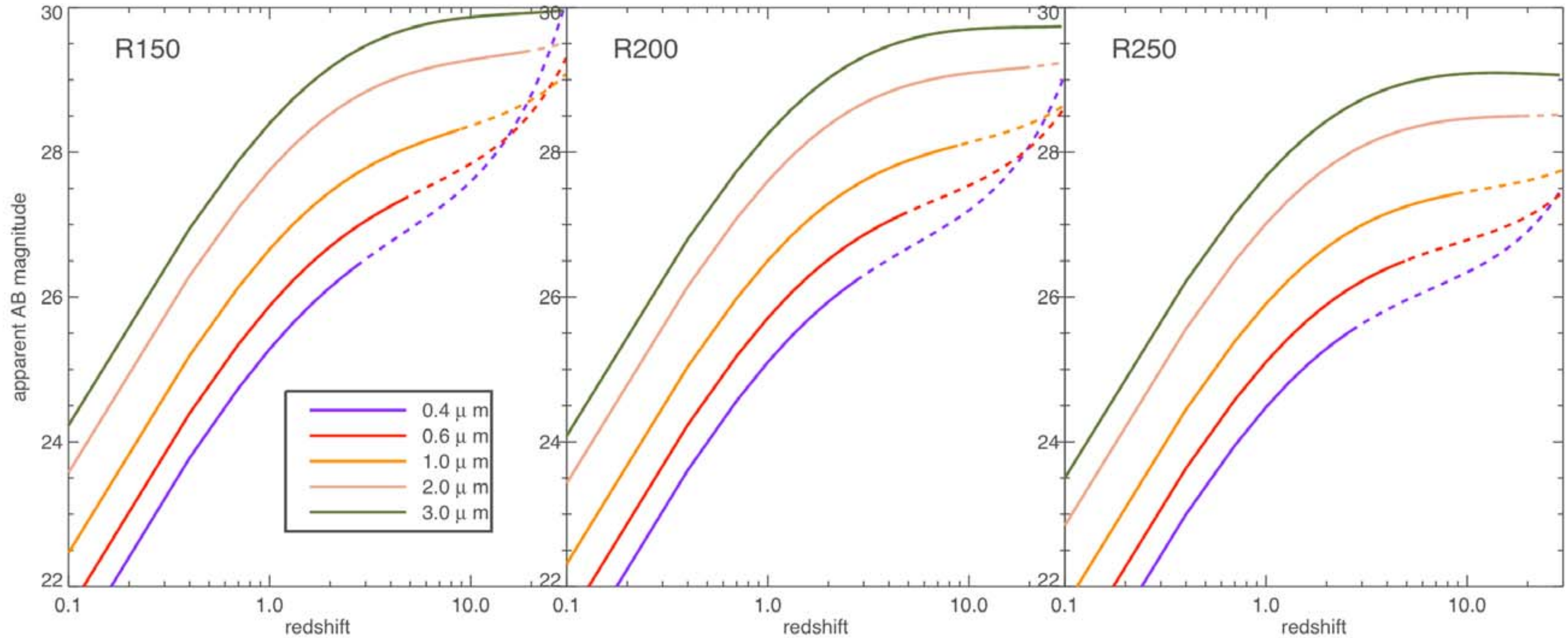
problem with absorption if studied from objects at high redshift

Kasen and Woosley (2009, in prep)

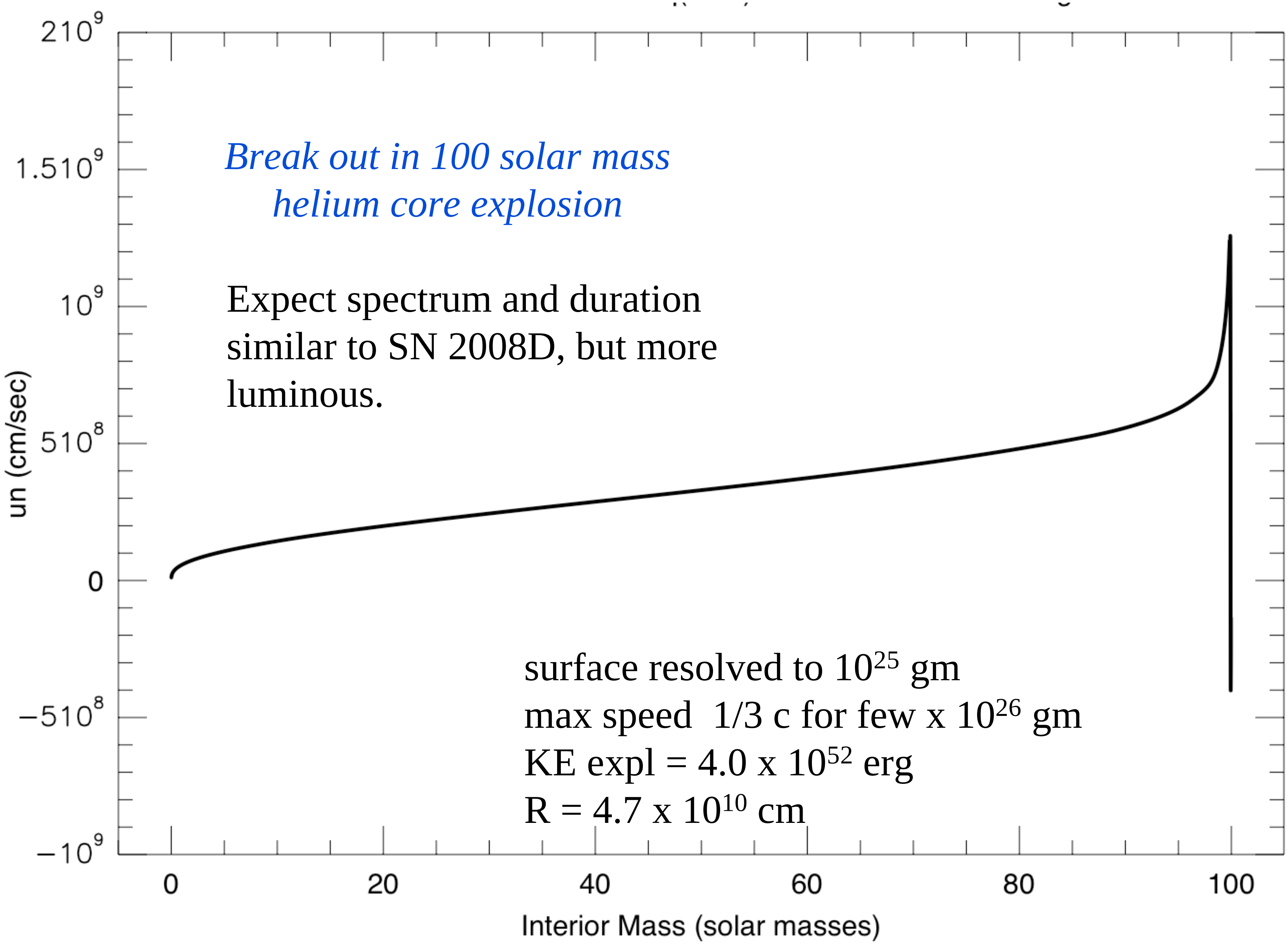
Spectra at peak (rest frame)



Were it not for intervening hydrogen, optical surveys could probe break out to redshifts as high as z = 30, but ….



Spectrum of the break out transient for the red and blue supergiant models will be heavily absorbed in the ultraviolet (λ < 1215 A) by intervening hydrogen. Best observational strategy may be the longer wavelength tail. The blue giant models are harder to observe.


Break out in 100 solar mass
helium core explosion
Expect spectrum and duration
similar to SN 2008D, but more
luminous.
surface resolved to 10^{25} gm
max speed 1/3 c for few x 10^{26} gm
KE expl = 4.0 x 10^{52} erg
R = 4.7 x 10^{10} cm
$2 10^9$
$1.5 10^9$
10^9
$5 10^8$
0
$-5 10^8$
-10^9
un (cm/sec)
0
20
40
60
80
100
Interior Mass (solar masses)

Some Conclusions

- Pair instability supernovae can produce a large range of transient phenomena from bright “hypernovae” to faint “supernova imposters”

- Depending on assumptions (IMF, rotation, mixing, mass loss) pulsational pair SNe may have played an important role in Pop III nucleosynthesis

- The first generation may have produced mostly CNO and 40 solar mass black holes

- Break out in pair instability supernovae can produce bright x-ray and uv-transients that are potentially observable.

- Black hole formation may produce unusual transients