Pulsational Pair Instability Supernovae

Woosley (2017)

How do massive stars evolve?

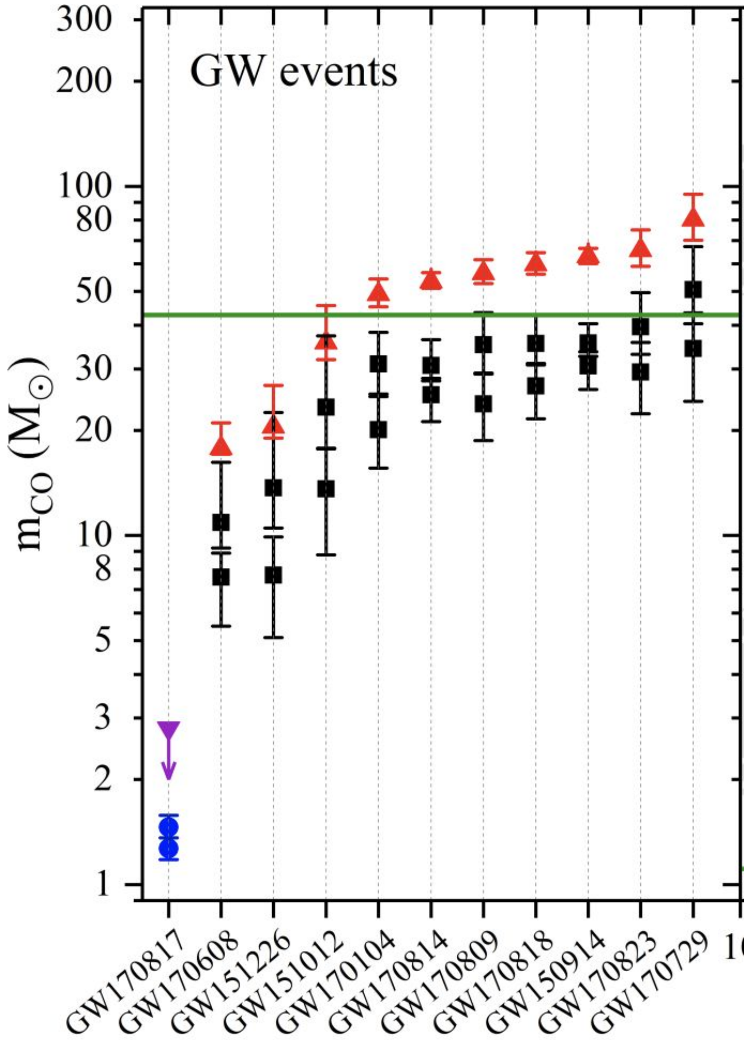
→ Black hole mass distribution

→ Pop III evolution

→ Superluminous supernovae?

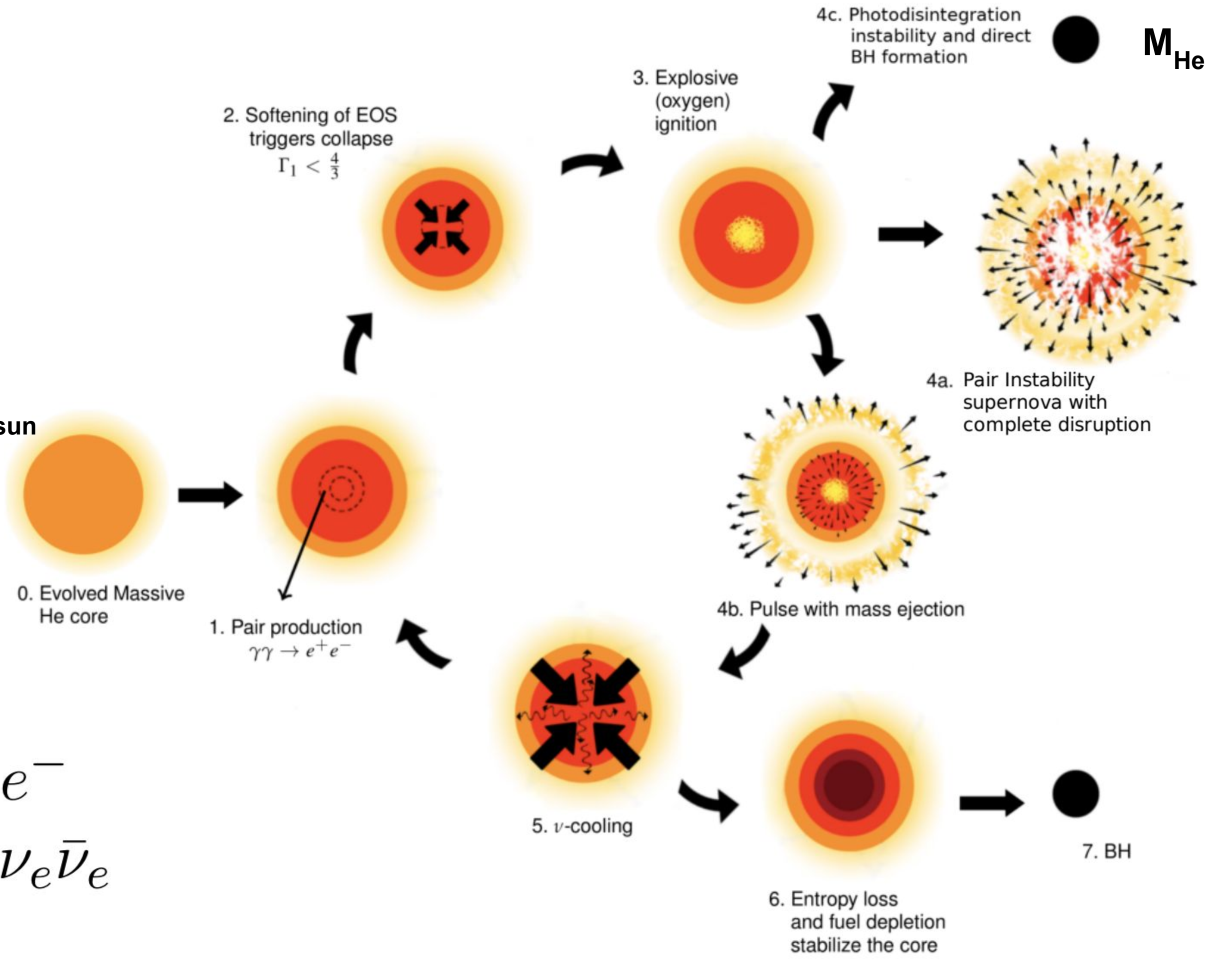
→ Other weird transients?

Ligo 2018



Renzo+2020

$M_{He} > 30\text{-}40\ M_{sun}$



$M_{He} > 125\ M_{sun}$

$M_{He} > 65\ M_{sun}$

$M_{He} < 65\ M_{sun}$

$T \sim 10^{8\text{-}9}$ K

$$\gamma\gamma \longrightarrow e^+e^-$$
$$e^+e^- \longrightarrow \nu_e\bar{\nu}_e$$

Outline

Jean

- The simplest case: a pure He core, no nuclear burning
- More realistic models of He core, no envelope

Viraj

- Models of red supergiants (i.e., H envelope, no rotation)
- Models of bright blue stars
- The effects of rotation
- Superluminous supernovae

Dillon

- Eta Carinae
- GW 150914
- The nucleosynthetic signatures of PPISN
- Conclusions

Code

KEPLER code

- Stellar evolution/explosion
- Implicit hydrodynamics
- Nuclear reactions complete up to germanium

Biggest uncertainties:

- Mass loss! (they fiducially assume 0.1 Z, and test varying assumptions)
- 1D code → no mixing/overturn → artifacts (spikes in density)
- Possible opacity uncertainties

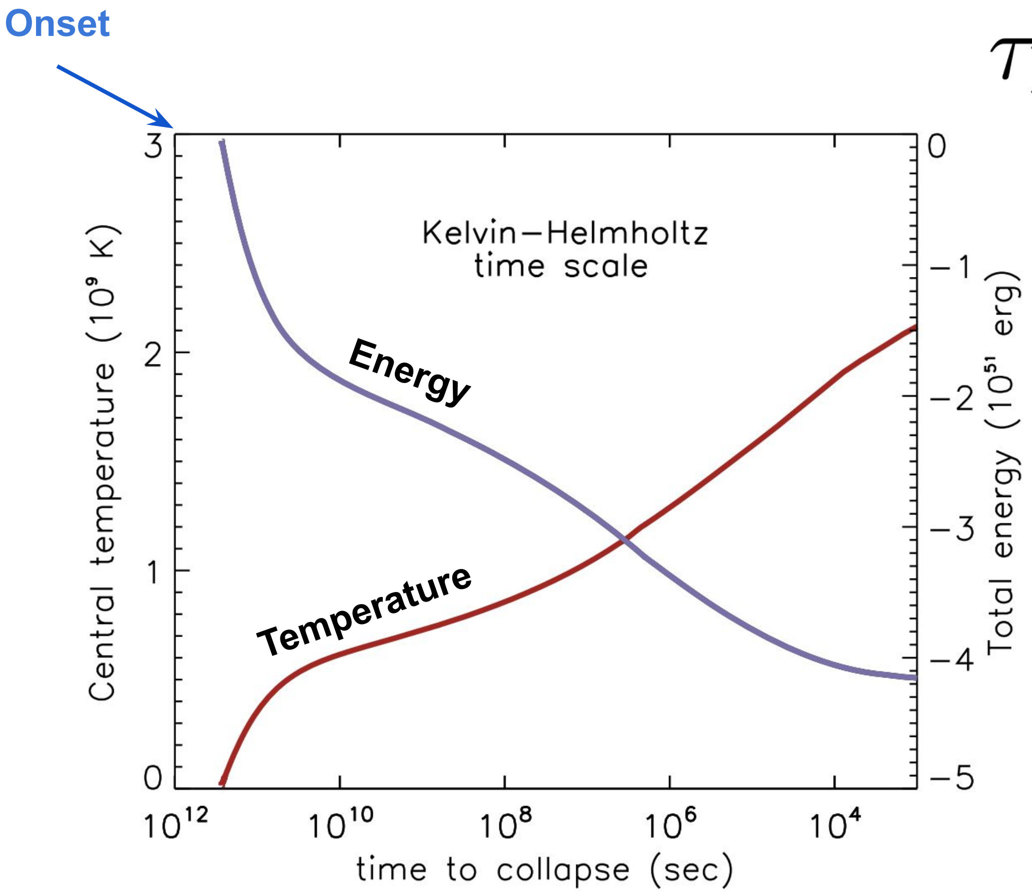
$$\dot{M} = 9.63 \times 10^{-15} \left(\frac{L}{L_\odot}\right)^{1.24} \left(\frac{M}{M_\odot}\right)^{0.16} \left(\frac{R}{R_\odot}\right)^{0.81} M_\odot \ \mathrm{yr}^{-1}.$$

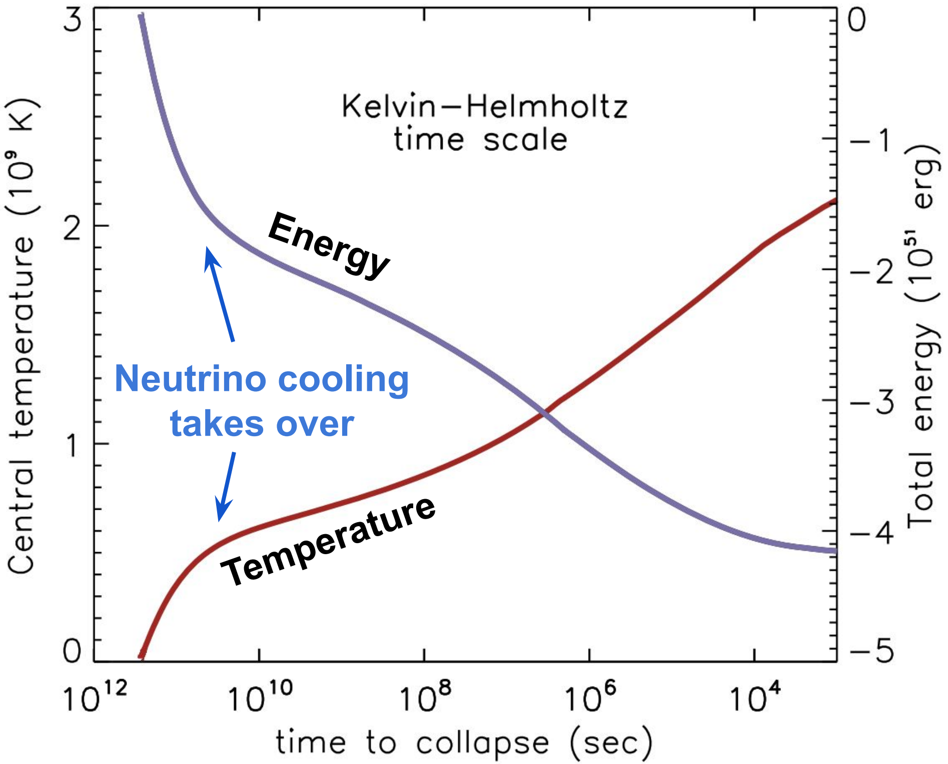
$$\Delta M = (8\, M_{100}^{2.83} + 55\, R_{14}^{0.81} M_{100}^{1.40}) \left(\frac{Z}{Z_\odot}\right)^{1/2}$$

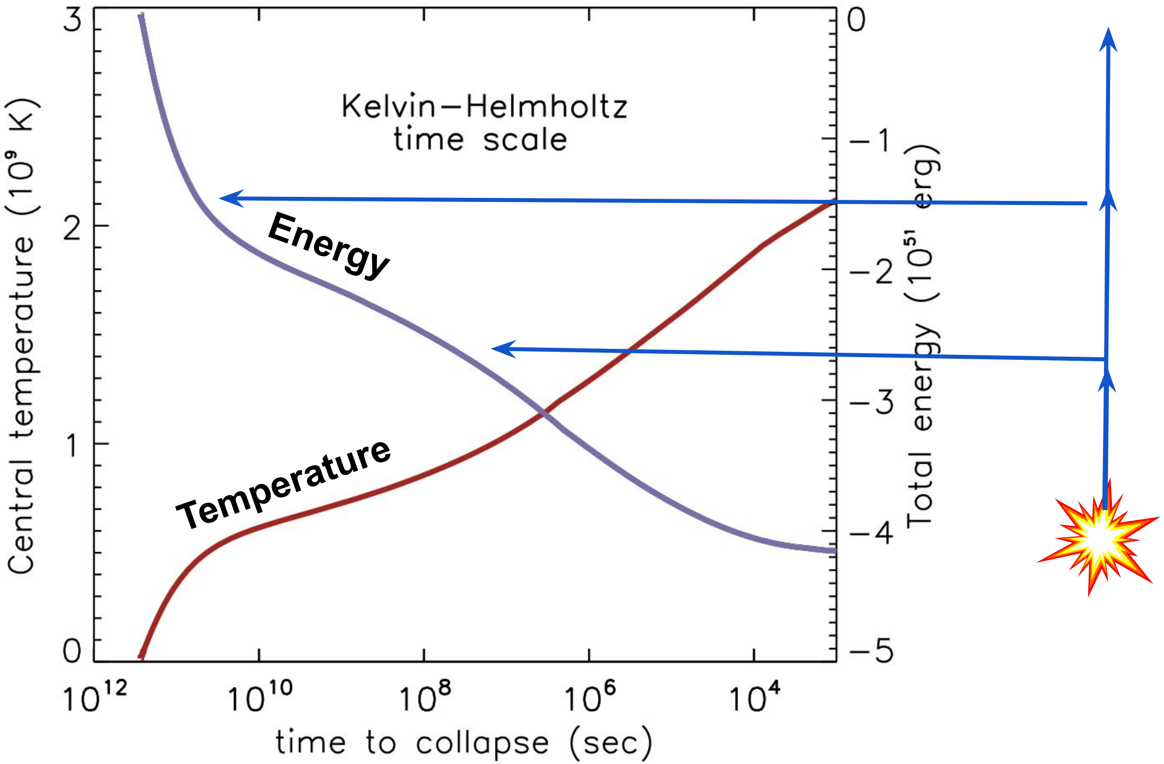
A toy model - a pure He core, no nuclear burning

M_{He} = 40 M_{sun}

$$\tau_{\mathrm{KH}} \sim \frac{GM}{RL}$$




Kelvin–Helmholtz
time scale
Energy
Temperature
Neutrino cooling
takes over
Central temperature (10^9 K)
Total energy (10^{51} erg)
time to collapse (sec)
3
2
1
0
0
−1
−2
−3
−4
−5
10^{12}
10^{10}
10^{8}
10^{6}
10^{4}



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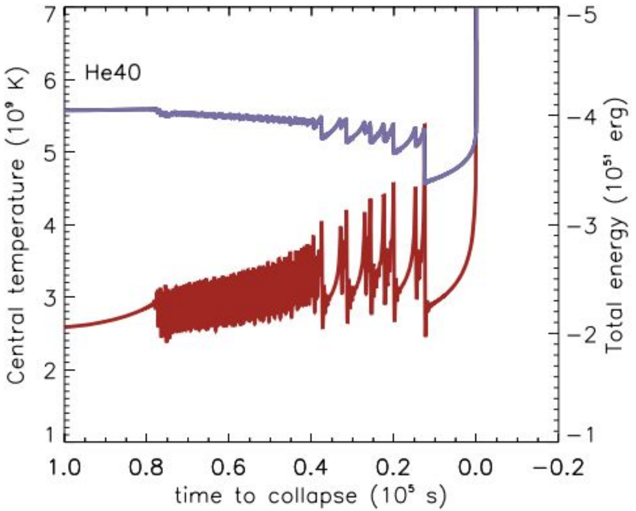
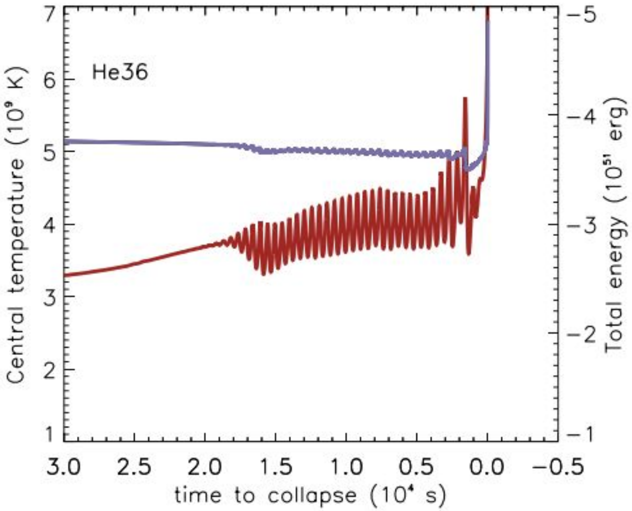
Linear regime

- Increased mass → more weak pulses which start earlier
- Each pulse is only a small perturbation on the core structure
  (relatively small temperature increase, only small mass ejection)





Linear regime
Increased mass → more, earlier pulses

Mass ($M_\odot$)	M_{CO} ($M_\odot$)	Pulses	Duration (s)	KE-pulse (10^{51} erg)	M_{Fe} ($M_\odot$)	M_{eject} ($M_\odot$)	$M_{remnant}$ ($M_\odot$)
30	24.65	stable	⋯	⋯	2.34	⋯	30.00
32	26.30	stable	⋯	⋯	2.38	⋯	32.00
34	28.01	5 weak	2.3(3)	0.0012	2.51	0.13	33.87
36	29.73	33 weak	1.8(4)	0.0037	2.53	0.18	35.82
38	31.40	>100 weak	4.2(4)	0.0095	2.65	0.34	37.66
40	33.05	9 strong	7.8(4)	0.066	2.92	0.97	39.03
42	34.77	18	2.0(5)	0.26	2.68	2.65	39.35
44	36.62	11	7.7(5)	0.83	3.18	5.02	38.98
46	38.28	11	1.2(6)	0.77	2.40	5.51	40.49
48	40.16	8	3.8(6)	0.94	2.53	6.65	41.35
50	41.83	6	1.2(7)	0.86	2.76	6.31	43.69
51	42.59	6	1.9(7)	1.00	2.37	7.80	43.20
52	43.52	5	1.4(8)	0.99	2.47	7.87	44.13
53	44.34	4	7.8(8)	0.86	2.68	4.73	46.70
54	45.41	4	4.7(9)	0.94	2.16	6.85	47.15
56	47.14	3	3.4(10)	0.56	2.04	7.99	48.01
58	48.71	3	8.0(10)	1.1	2.00	12.14	45.86
60	50.54	3	8.5(10)	0.75	1.85	12.02	47.98
62	52.45	7	2.2(11)	2.3	3.19	27.82	34.18
64	54.14	1	⋯	4.0	⋯	64	⋯

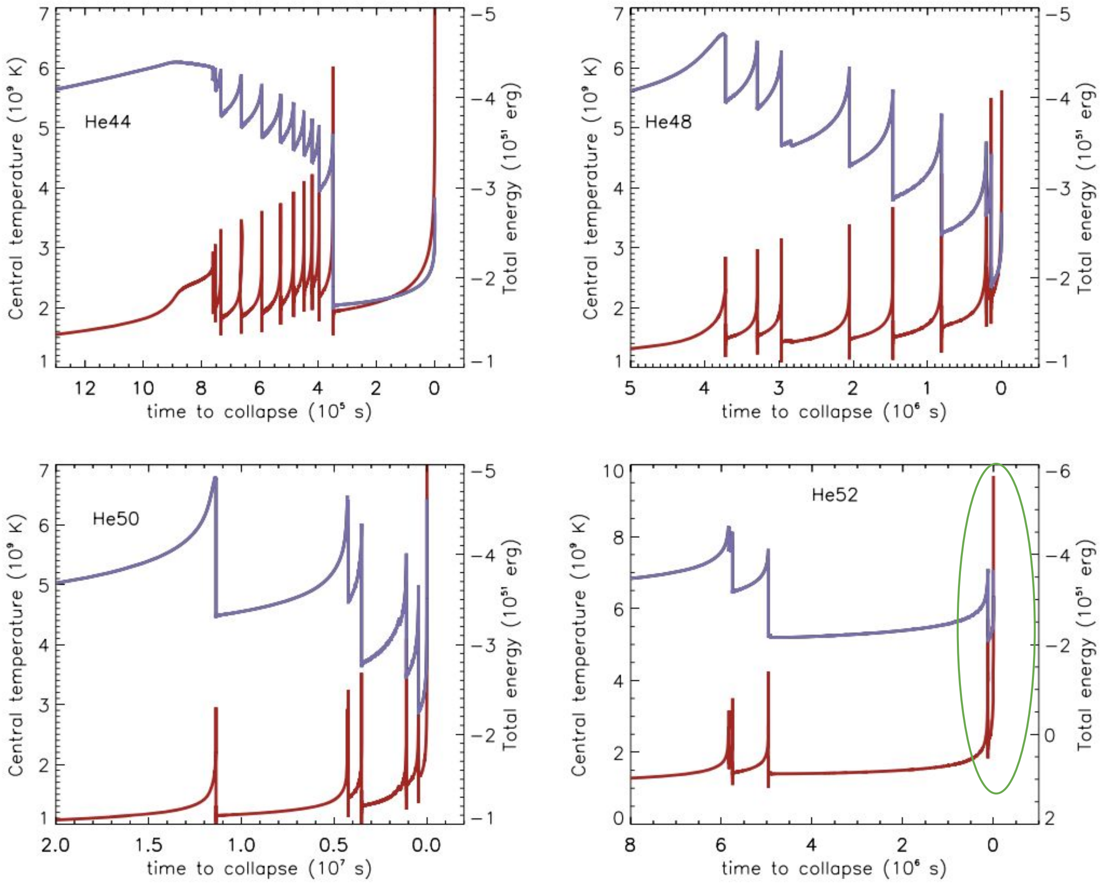
Strong regime

- Fewer, stronger pulses
- “Discrete explosive events”

- Above 52 M_{sun}, a couple fast pulses before collapse

- At highest masses, the remnant is barely bound after each pulse → will appear as the remnant of a faint supernova with a bright Wolf-Rayet star at the center (“dormant/zombie” supernovae)

- The final result is a massive iron core with dense Si/O shells → hard to explode → most likely will form BH
- BH mass range: ~35-50 M_{sun}



Strong regime
Increased mass → fewer, more powerful pulses

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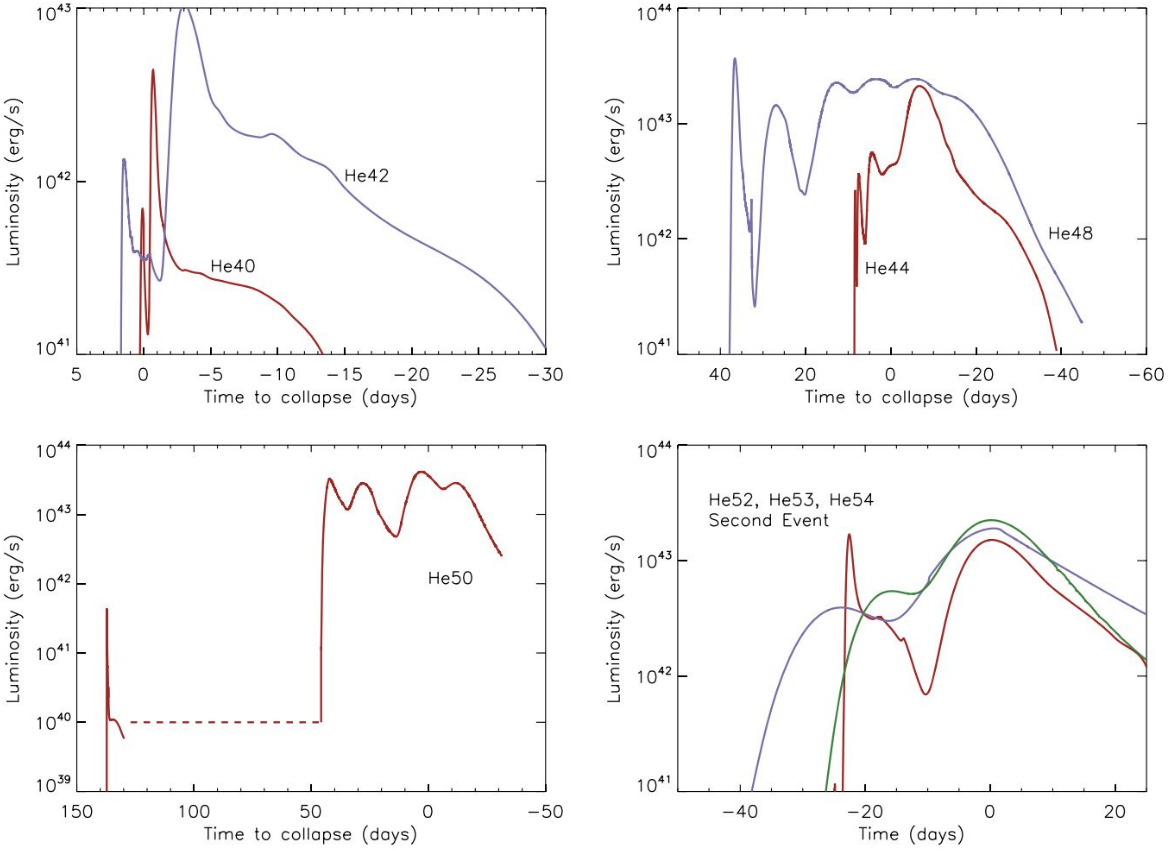
Wide variety of possible lightcurves

- Many will be characterized as SNe Ibn/Icn
- Heavier masses show faint, brief transients from the first, powerful pulse. Followed by brighter event caused by second pulse + collision of ejected material from two pulses
- Nothing extremely bright



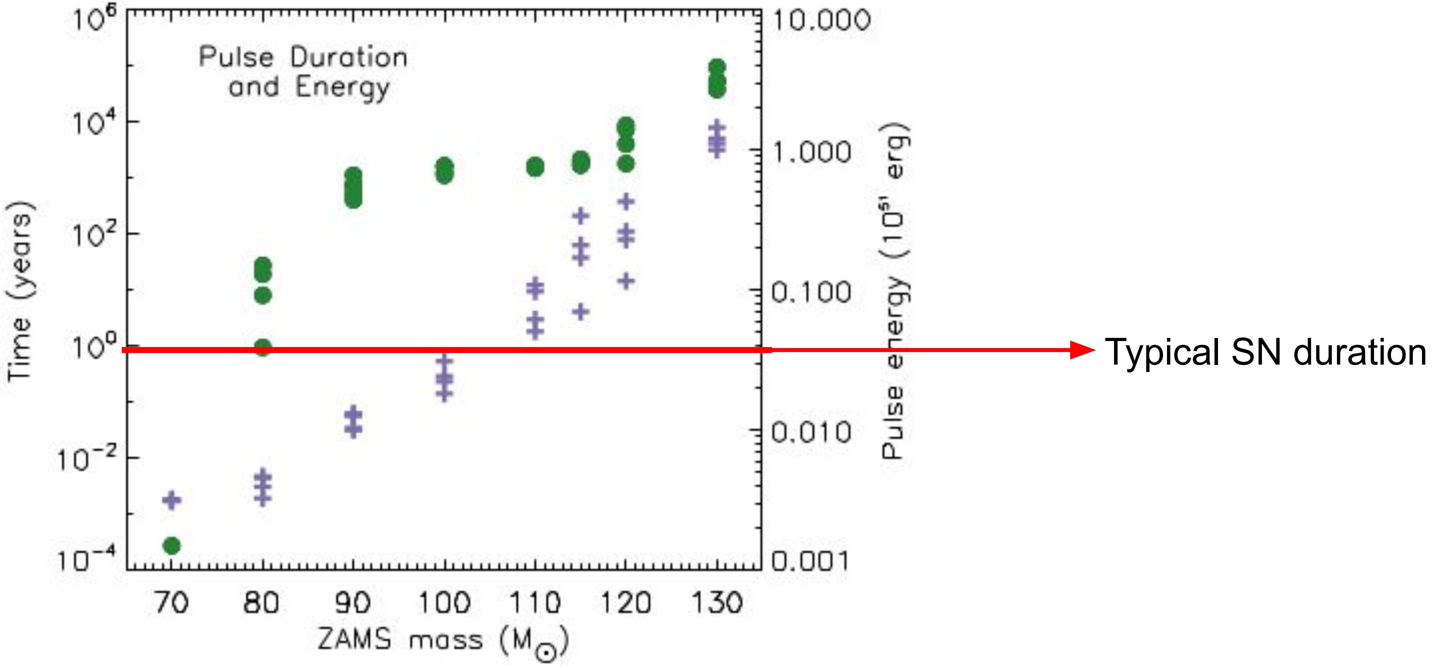
RSGs (adding H envelope, no rotation)

Adding H envelope :

- First pair-instability same as before
- Envelope “tamps” expansion of core, more core falls back
- Increases mass of remnant core
- Shortens interval between pulses, increases max energy slightly
- H envelope available for ejection, interaction

RSGs (adding H envelope, no rotation)

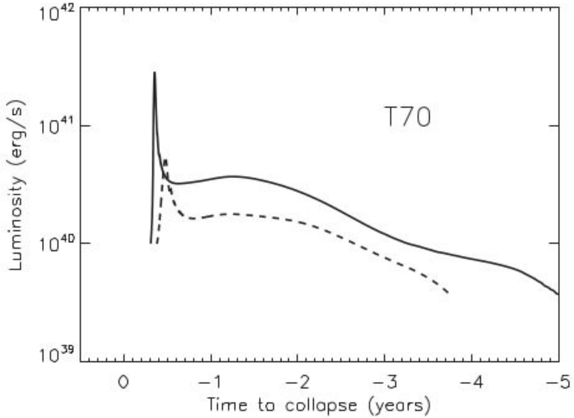
He core : 30-70 Msun -> ZAMS ~ 70-150 Msun , Z ~ 0.1 Zsun



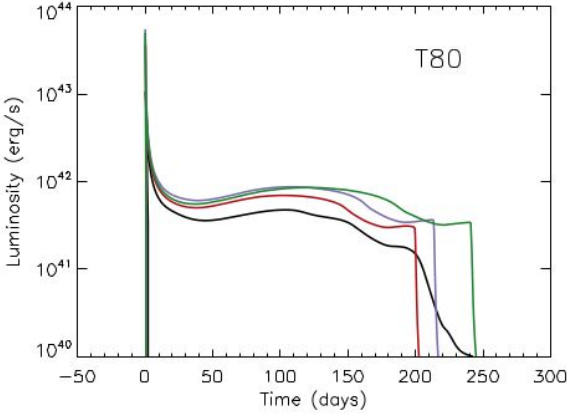
Explosions from RSG

Mechanism :

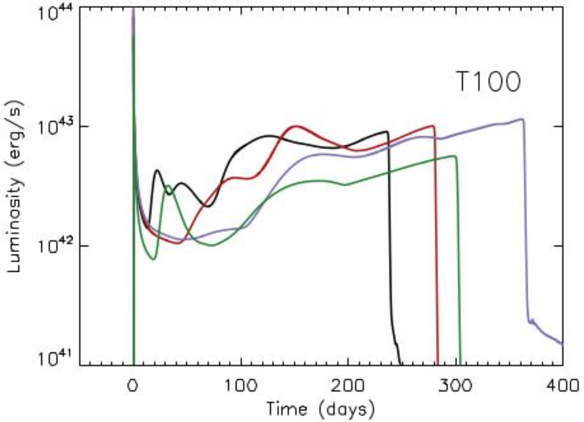
- First pulse ejects maximum mass (including H envelope) at ~1000 km/s
- Most of the radiation comes from recombination in this ejecta
- Subsequent pulses eject more mass, that collides with the pre-existing outflows radiating through shocks
- Similar to SN IIp or SN IIn
- No radioactive Ni ejected



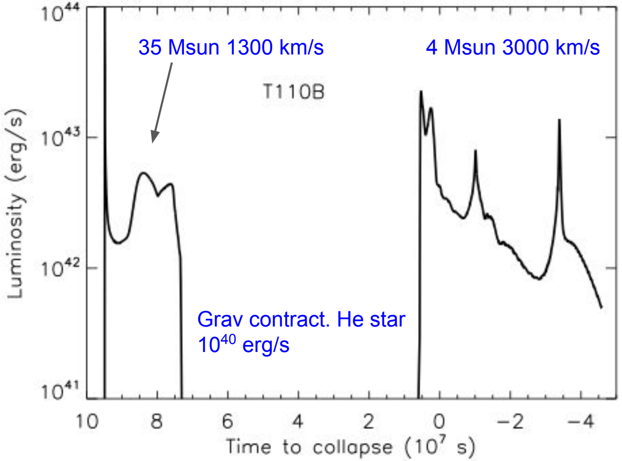
Faint, cold (red) SN IIp, 100 km/s

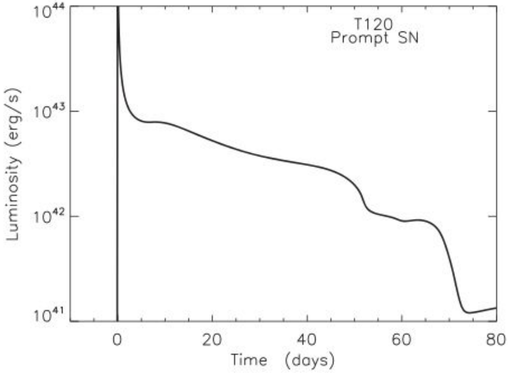


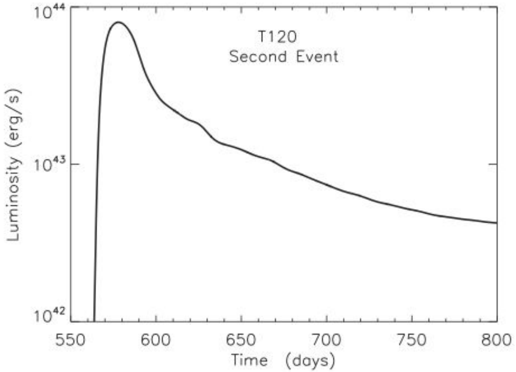
~Ordinary* SN IIp



~Long irregular SN IIp







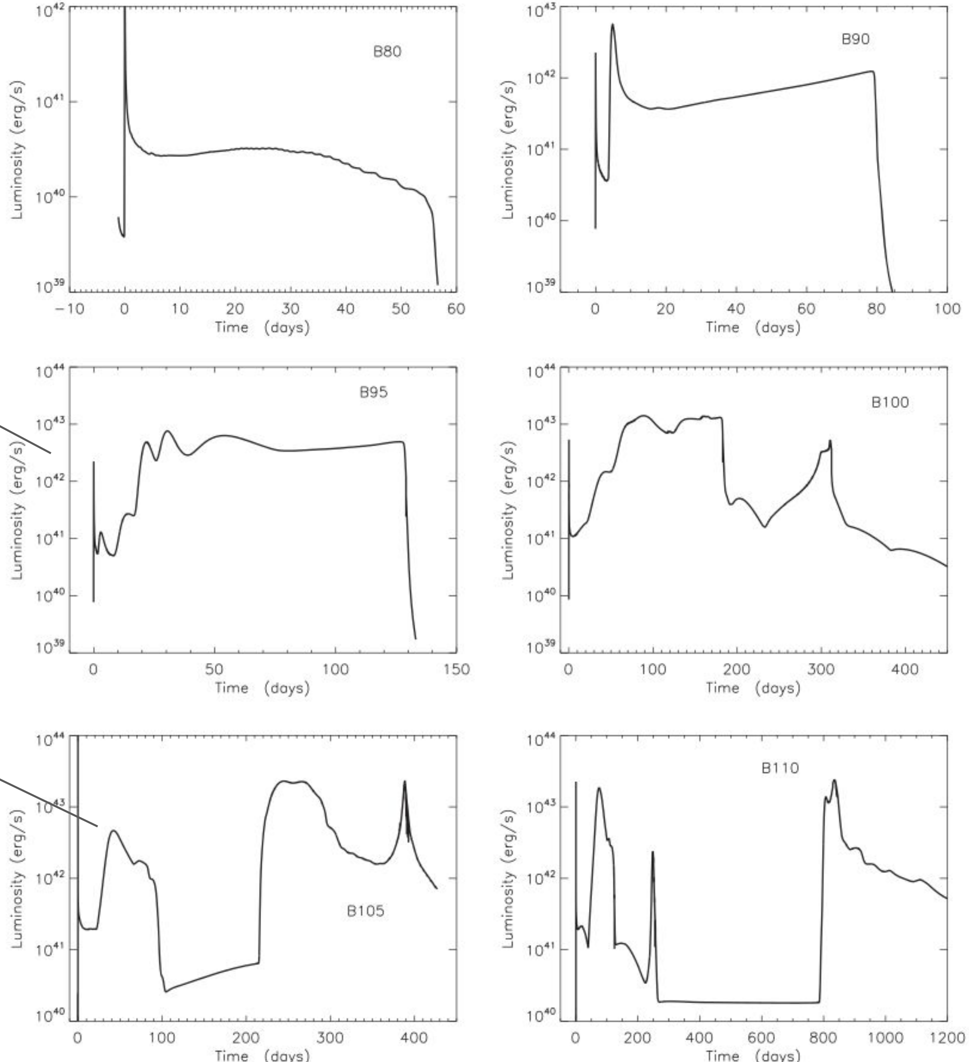
BSGs / bright blue stars

- LBVs could be progenitors of peculiar type IIn SN
- Photospheric radii : RSG ~10^{14} cm, BSG ~10^{12} cm, Teff 25000-30000 K
- First outburst is significantly fainter than RSG case.
- Lower pulsational mass loss as the star is more tightly packed

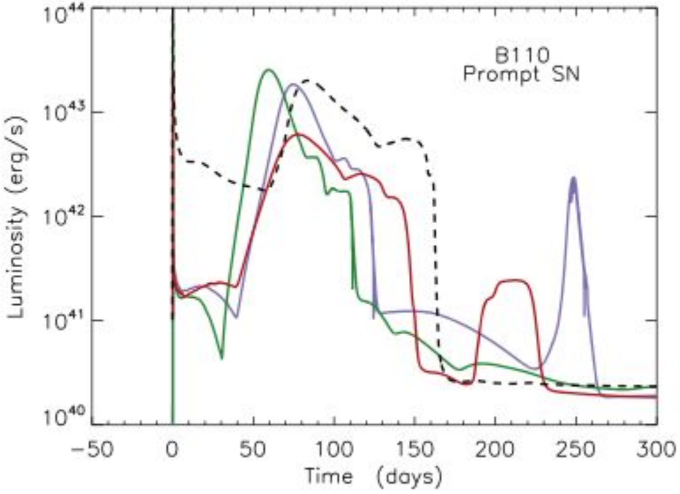
No mass ejection below 80 Msun

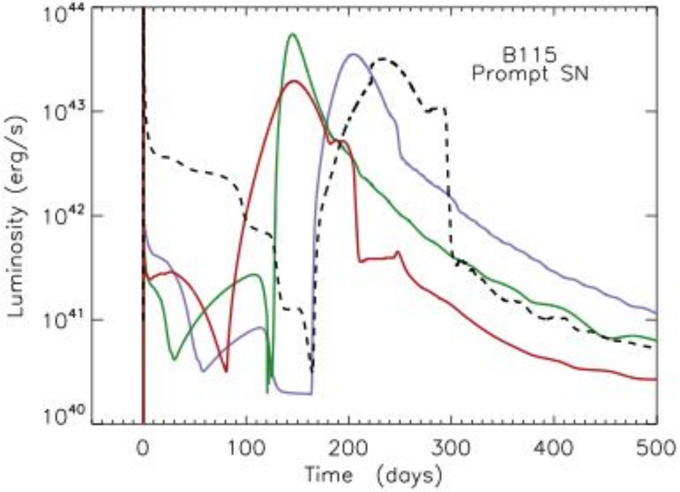
Shock breakout

Faint first peak



The second increase in luminosity is caused by subsequent mass ejections at ~3000 km/s that collide with previously ejected mass





110-120 Msun, very faint first peak for few weeks -> dramatic rebrightening

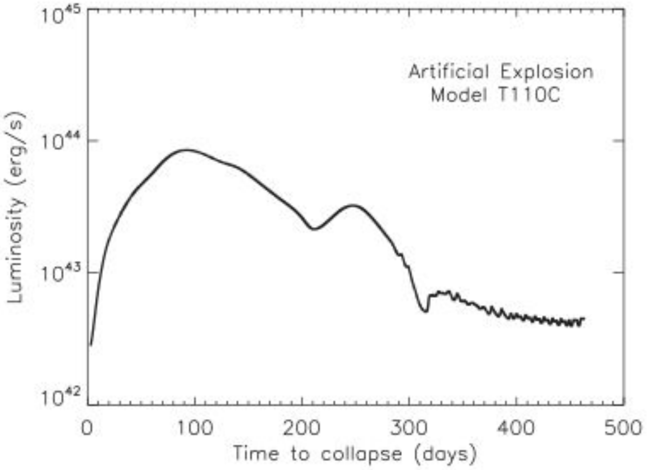
Observed in some SN IIn
SN1961v, SN20009ip, SN2010mc
Thought to come from LBVs

Rotation

- Rotation -> chemical mixing -> increases He core mass
- Rotation reduces ZAMS threshold for PPI
- Once PPI happens, evolution is similar to non-rotating counterparts

Can PPI explain SLSNe?

- No, L_{PPI}~< 10^{43} erg/s, L_{SLSN} ~ 10^{44} erg/s
- Iron core collapse -> Rotation!
- BH with an accretion disk, or a millisecond magnetar?
- Bipolar outflows during the formation of a BH, interacting with previous PPI shells



Eta Carinae as a PPISN progenitor?

- Great eruption (1840s)
- Tail of CSM velocities observed to be 3500-6000 km/s (explosive)
- Can reproduce timing of multiple eruptions. But model is too bright / ejecta not naturally asymmetric

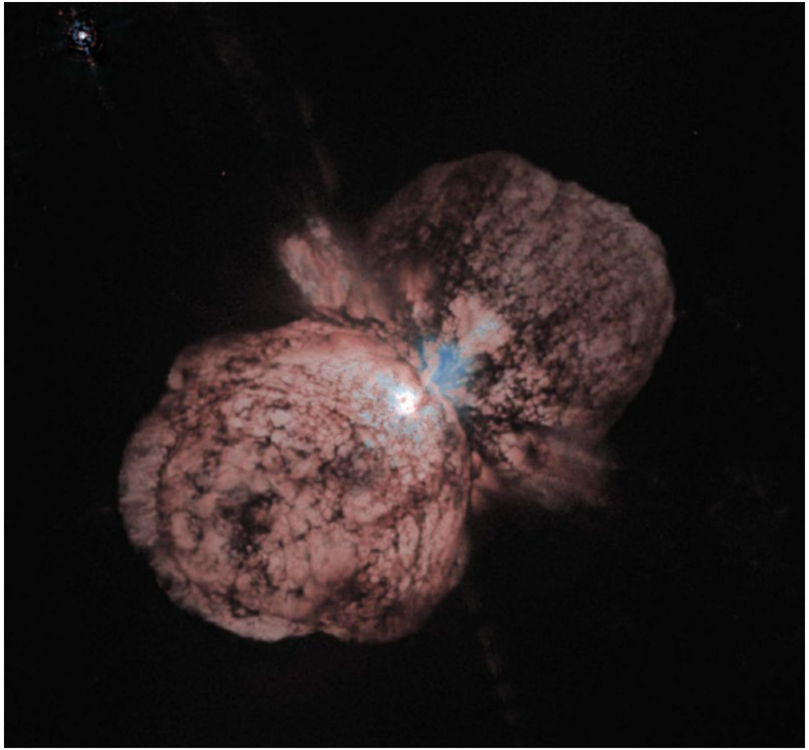


Table 6
125 $M_\odot$ Models for Eta Carinae

Model	M_{ej1}	E_1	t_{1-2}	M_{ej2}	E_2	$t_{\rm PreSN}$	$M_{\rm now}$
T125A	22.5	8.3	70	7.1	8.0	2650	51.8
T125B	34.0	9.6	470	7.4	5.8	1100	58.2

GW 150914 & BH production

- 36 + 29 $M_\odot$ BH's →

90 + 70 $M_\odot$ ZAMS (non rotating, low Z)

70 + 60 $M_\odot$ ZAMS (rotating, low Z)

- Initial masses in the **pulsational** pair instability range. Final outcome of **P**PISNe = massive black holes (as opposed to nothing for PISNe)

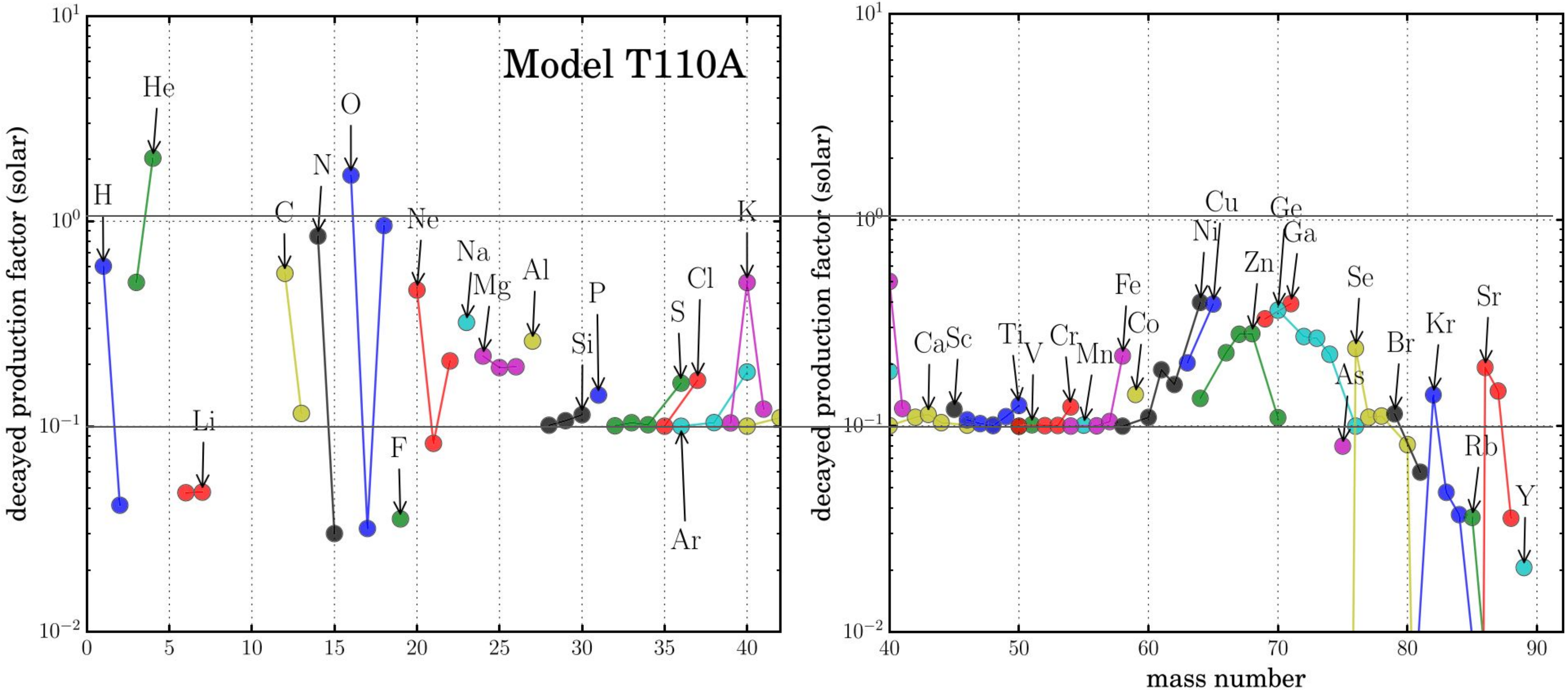
- Many (most?) PPISNe produce black holes of ~30$M_\odot$

- BH's can be produced up to ~52 $M_\odot$. Above that mass, nothing gets left behind

Model ($M_\odot$)	M_{preSN} ($M_\odot$)	M_{rem} ($M_\odot$)
R60A	46.58	46.6
R70A	54.41	37.0
R80A	62.20	43.6
R80Ar	62.47	47.8
R90A	68.84	48.1
R100A	75.32	44.8
R110A	80.91	0
C60A	26.30	26.3
C60B	35.40	35.3
C60C	46.45	41.2
C70A	28.35	28.4
C70B	40.72	38.1
C70C	53.24	41.7
C80A	30.46	30.5
C80B	44.88	40.4
C80C	59.69	46.3
C90A	31.43	31.4
C90B	49.39	43.4
C90C	65.81	0

Nucleosynthesis

Mostly He and CNO produced, very few iron peak elements. Implications for lightcurve? Weird element ratios in early stars perhaps?



Conclusions (1): What is a PPISN?

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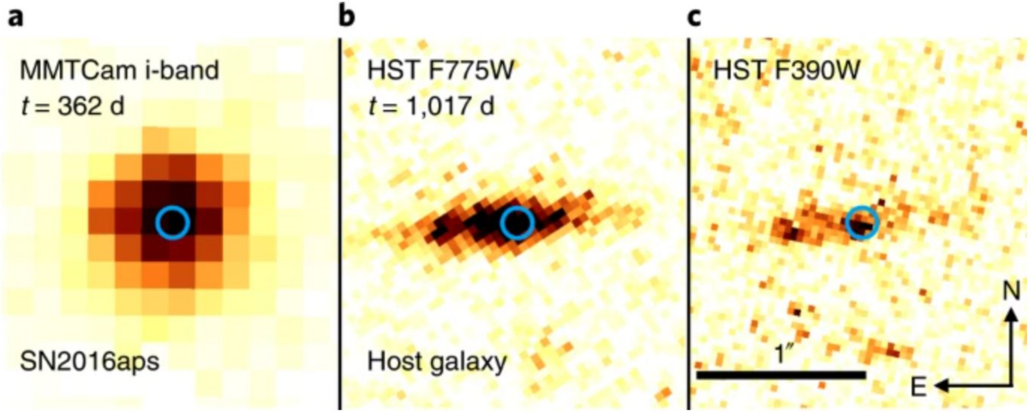
- Pulsations can last from ~hours to ~10,000 years
- Afterwards, the star finishes its nuclear fusion and undergoes core collapse as normal
- Major production channel for LIGO black holes?

Conclusions (2): What might a PPISN look like?

- Low metallicity host
- **Rare** (< 3% of CCSNe)
- He cores can be surrounded by envelopes (RSG, BSG, LBV) or not (WR) leading to a **wide range of explosion types**
- CSM interaction important in identifying these events
- Possible exotic behaviors (e.g. SN imposters followed by SN, multi-peak SNe), but many uncertainties remain

Fig. 1: Ground-based and HST images of SN2016aps and its host galaxy.



A claimed PPISN: 2016aps (Nicholl et al. 2020)