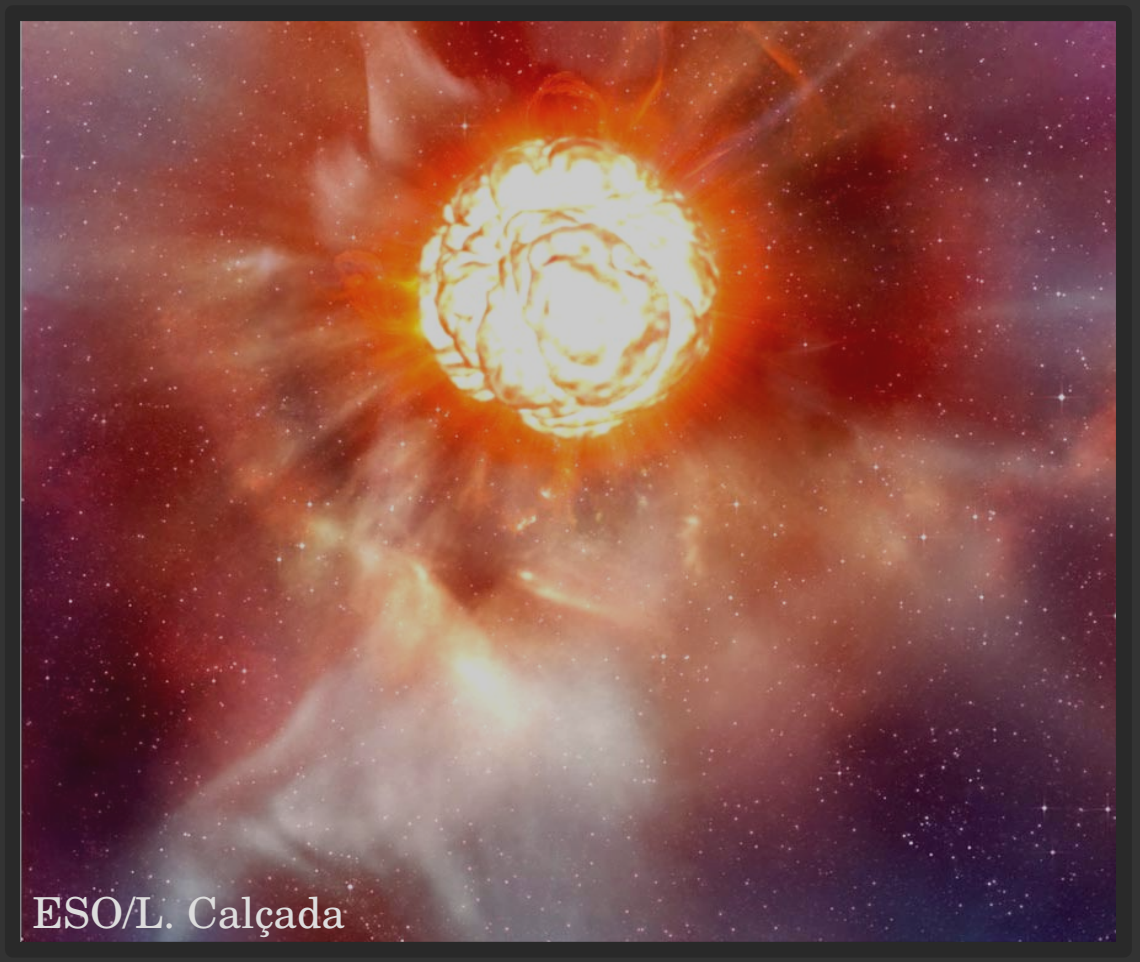


Missing Red Supergiants and Carbon Burning

by

Tuguldur Sukhbold

based on

Sukhbold & Adams 2019, submitted to MNRAS

Collaborators:

Stan Woosley	(UC Santa Cruz)
Thomas Ertl	(Max Planck IA)
Thomas Janka	(Max Planck IA)
Alex Heger	(Monash)

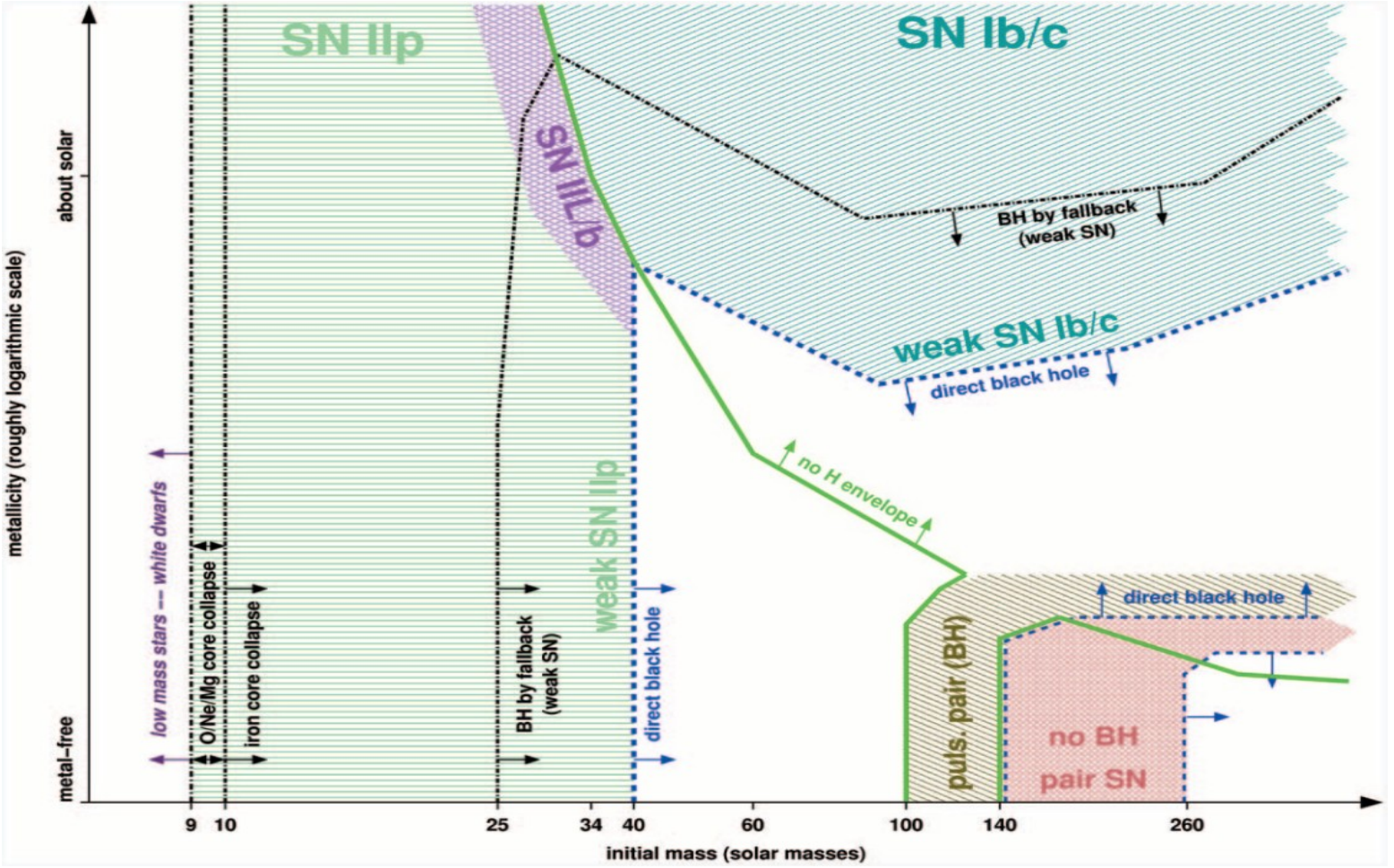
Ohio Supercomputer Center

FOE19, NCSU, 23 May, 2019

Which Massive Stars Explode?

$\sim 8 < M_{\mathrm{ZAMS}} < \sim 30 \;\; [M_\star] \quad \text{at solar } Z$

Older picture, until ~ 2010



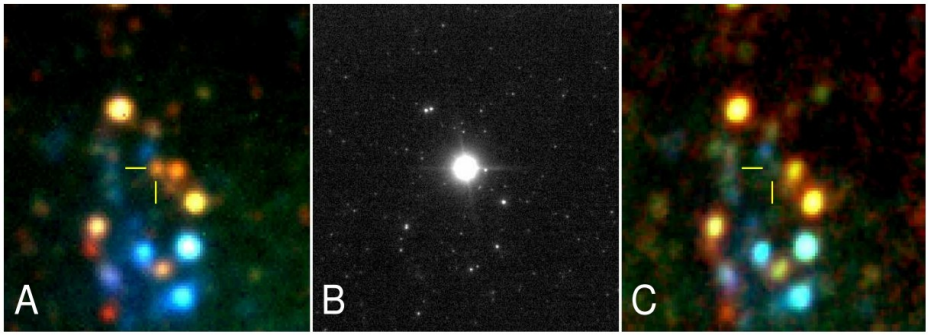
Heger et al. (2003)

All stars explode as SN in ~8 < M_{ZAMS} < ~30 [$M_\star$]

New evidence: Missing Red Supergiants

Smartt (2009, 2015)

Direct Progenitor Imaging



before SN
(HST archival)

after SN

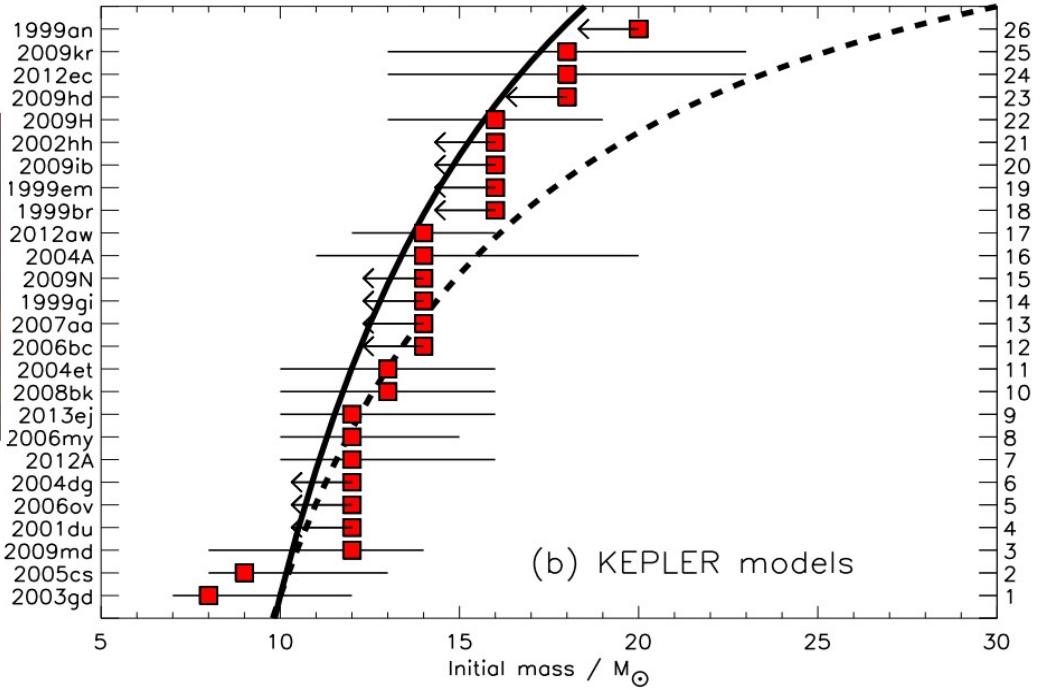
$F_{PROG} = F_A - F_C$

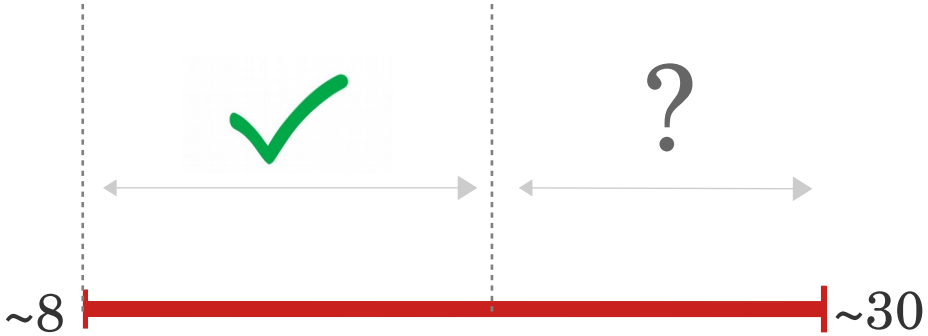
distance

L_{PROG}

$L\,(M)$

M_{ZAMS}





initial mass range of
RSG in local group

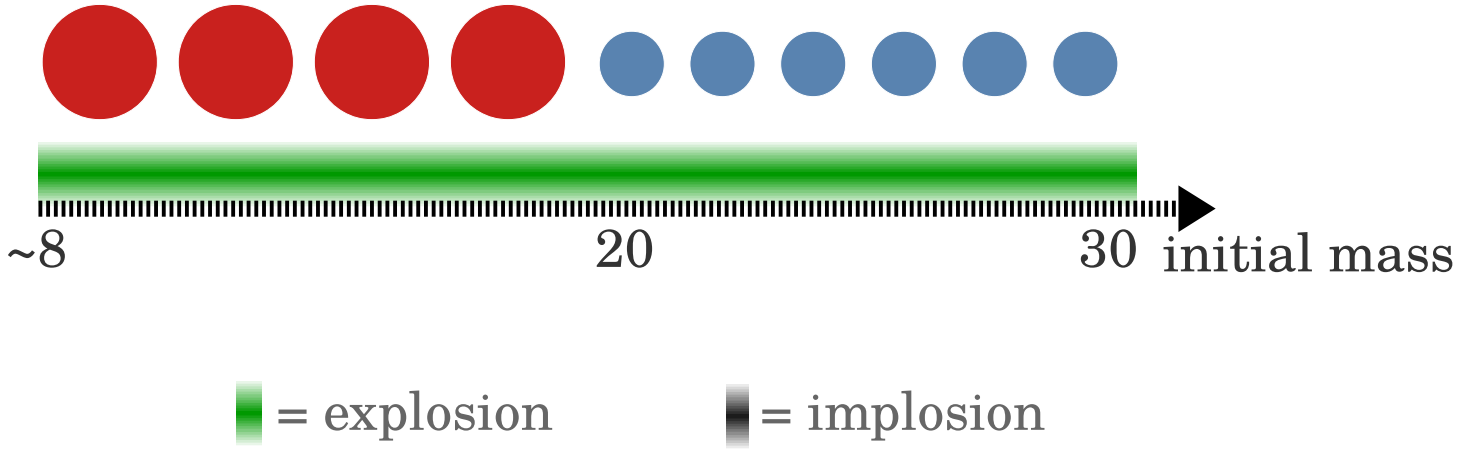
Theory:

1. do not die as luminous RSG:

(ignore explosion physics, edit stellar evolution)

e.g.,

Yoon & Cantiello (2010)
Chieffi & Limongi (2013)
Groh et al. (2013)
Limongi & Chieffi (2018)



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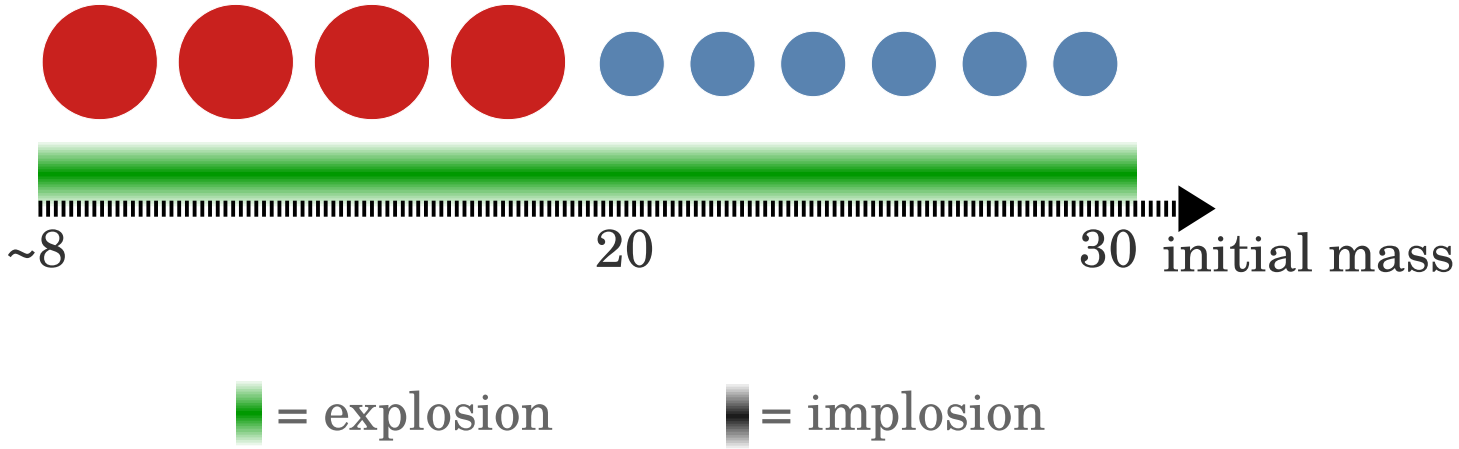

- ✗ - light curves of Type I b/c SN
- ✗ - ratio of Red/Blue SGs
- ✗ - mass distribution of BHs
- ✗ - direct imaging of implosion candidate

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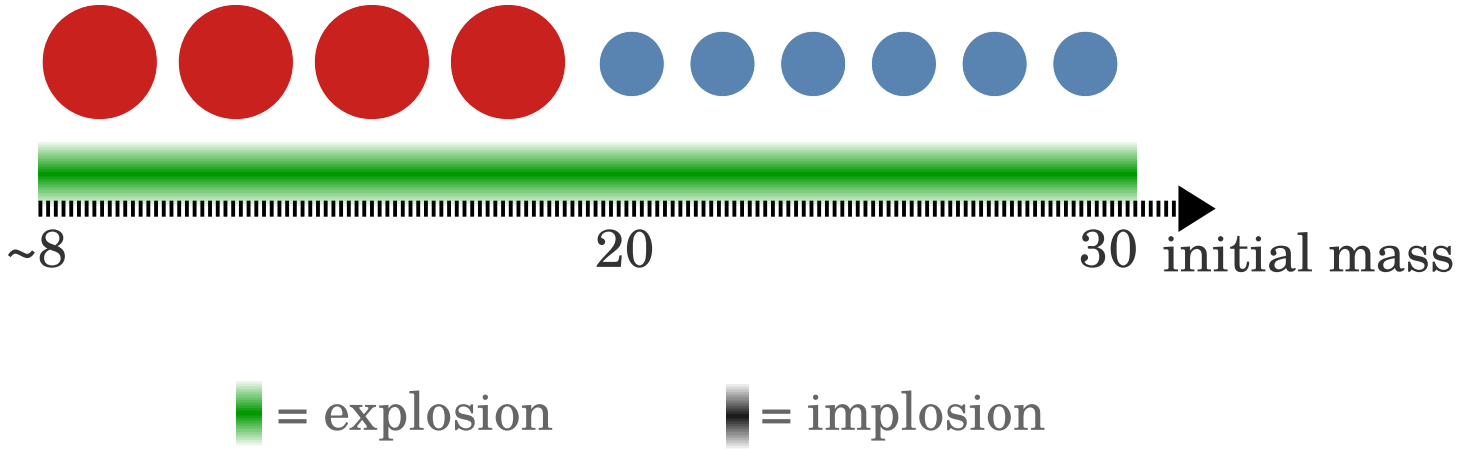
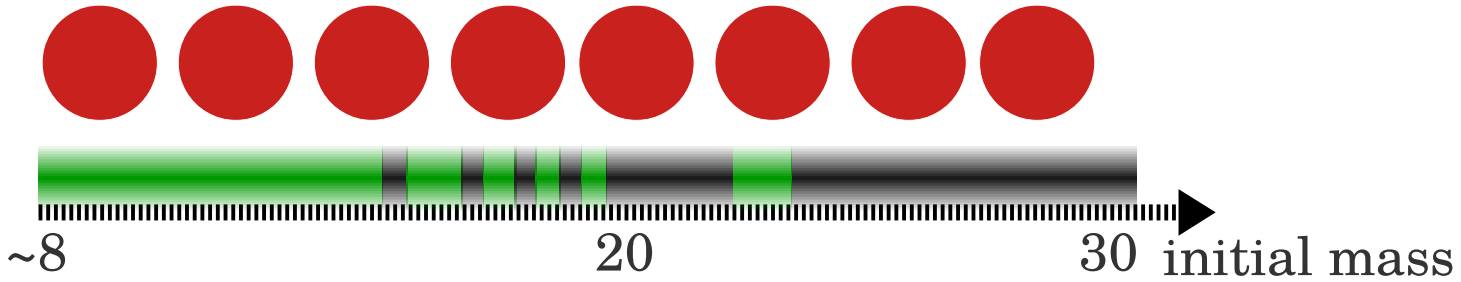


2. luminous RSG don't explode:

(keep stellar evolution, include explosion physics)

e.g.,

O'Connor & Ott (2011)
Ugliano et al. (2012)
Sukhbold & Woosley (2014)
Ertl et al. (2016)
Sukhbold et al. (2016)
Müller et al. (2016)
Sukhbold et al. (2018)

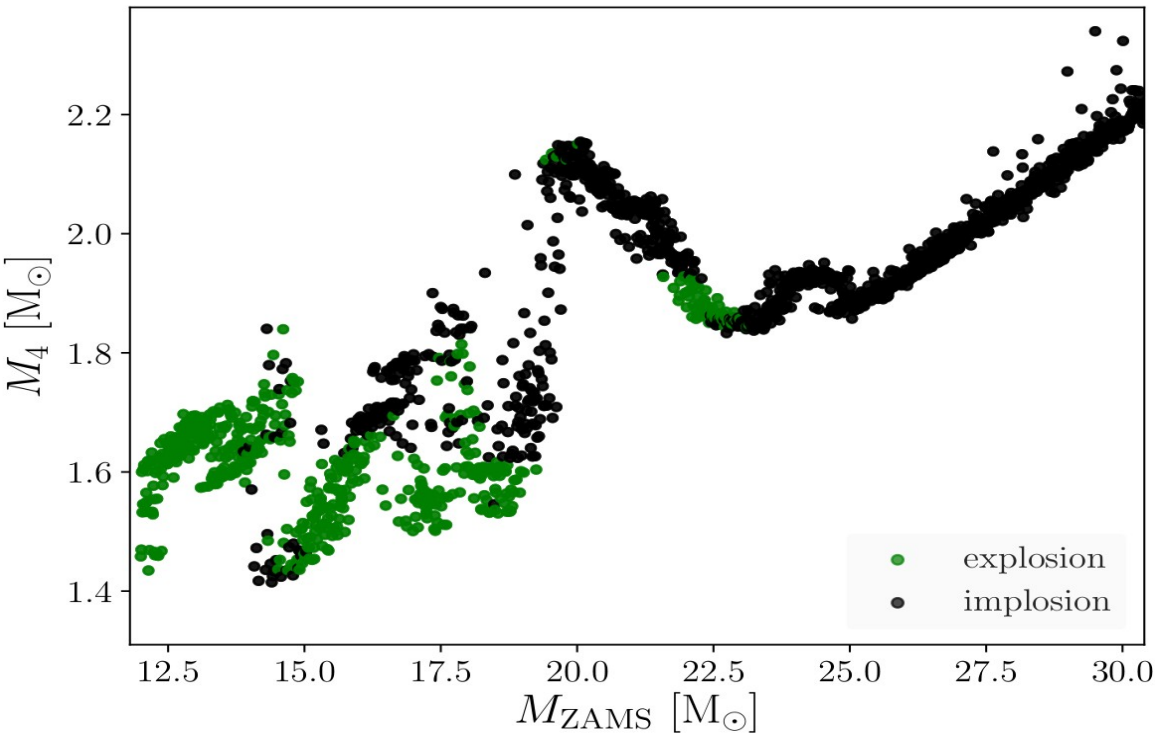


Non-monotonic Final Core Structure

less massive O-core
compact final core structure
stars mostly **explode**

massive O-core
extended final core structure
stars mostly **implode**

mass location of O-shell ≈



evolution:
KEPLER
explosion:
P-HOTB

C-burning Transition: Convective vs Radiative

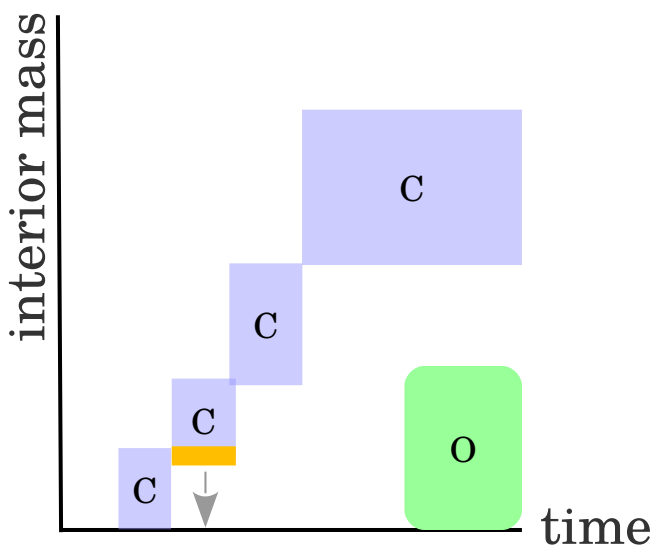
e.g., Barkat & Marom (1990) Weaver & Woosley (1993) Timmes et al. (1996)

energy generation rate: $\epsilon_{\rm n} \sim X_{\rm C}^2 \rho T^{23}$
(C-burning)

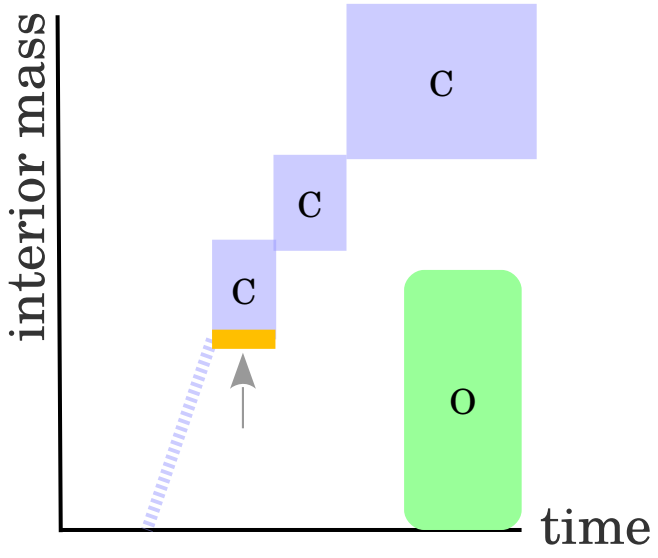
energy loss rate: $\epsilon_\nu \sim T^{12} \rho^{-1}$
(neutrinos)

To drive convection:
$\epsilon_{\rm n}/\epsilon_\nu > 1$

lower initial mass
(i.e., ~ 15 $M_\star$)



higher initial mass
(i.e., ~ 25 $M_\star$)



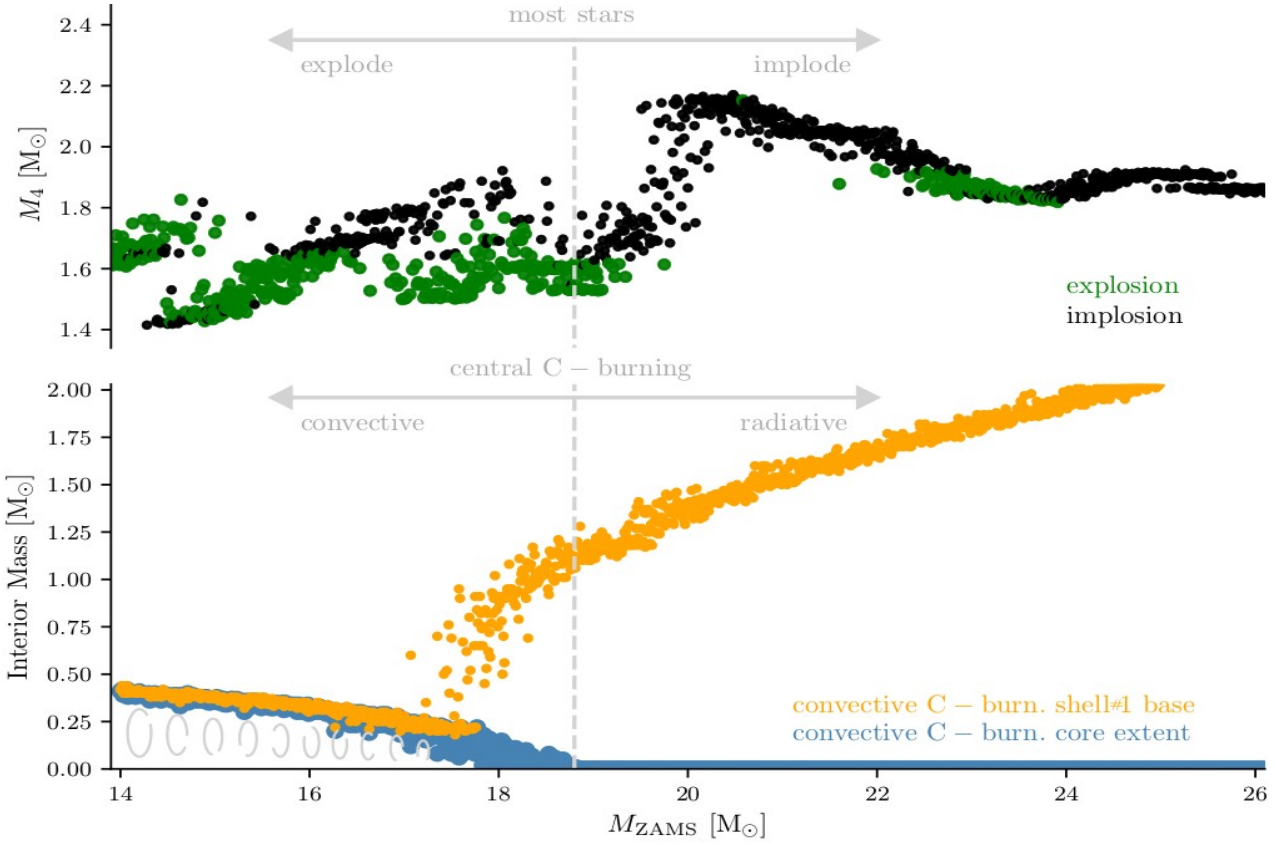
Transition and Explodability

central C-burn is convective

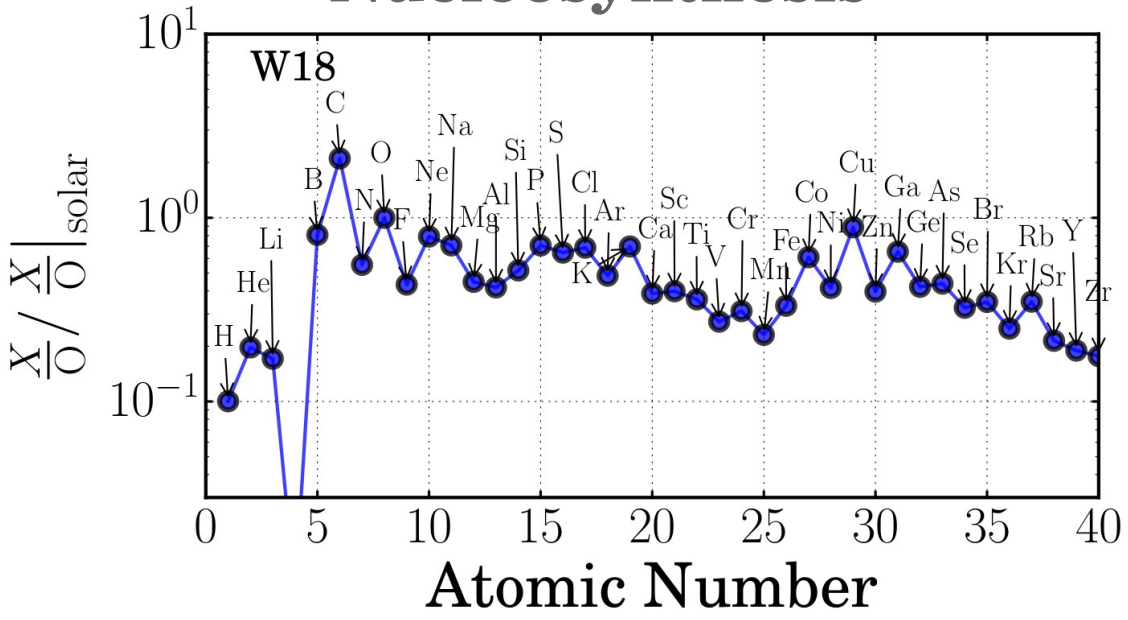
- less massive O-core
- compact core structure
- stars mostly **explode**

central C-burn is radiative

- massive O-core
- extended core structure
- stars mostly **implode**



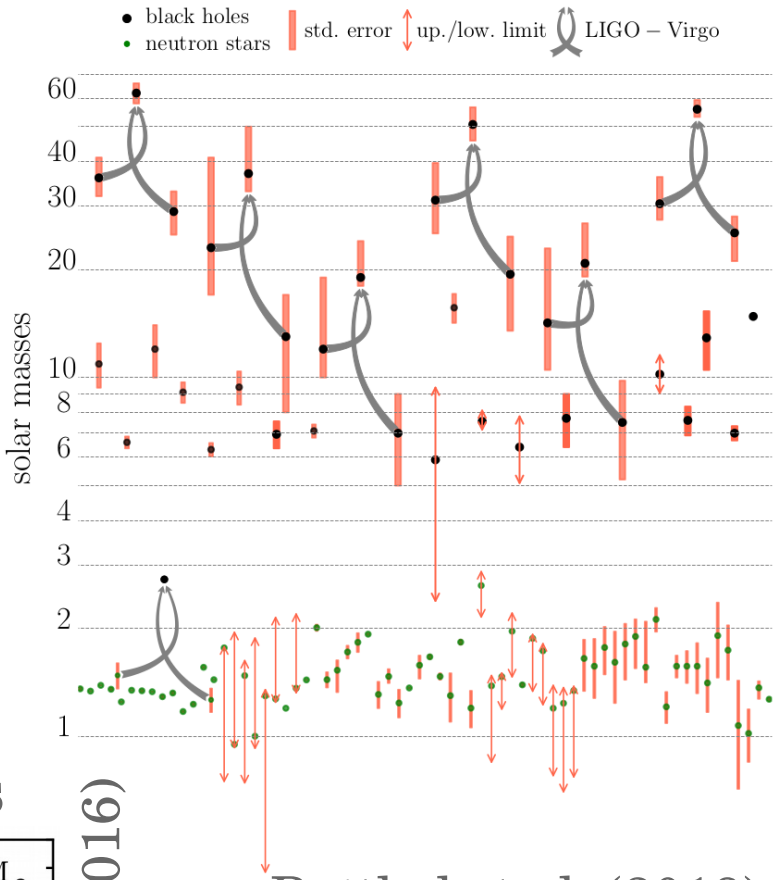
Nucleosynthesis



Sukhbold et al. (2016)

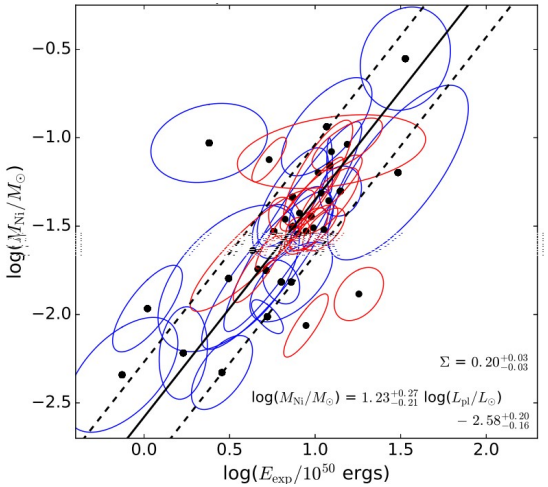
Brown & Woosley (2013)

Compact Remnants



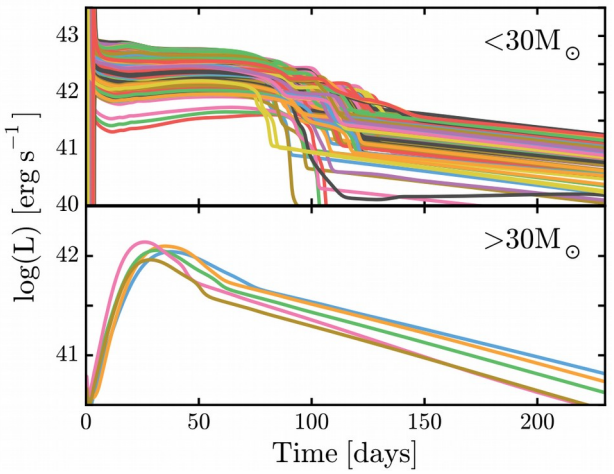
Raithel et al. (2018)

Explosion



Müller et al. (2017)

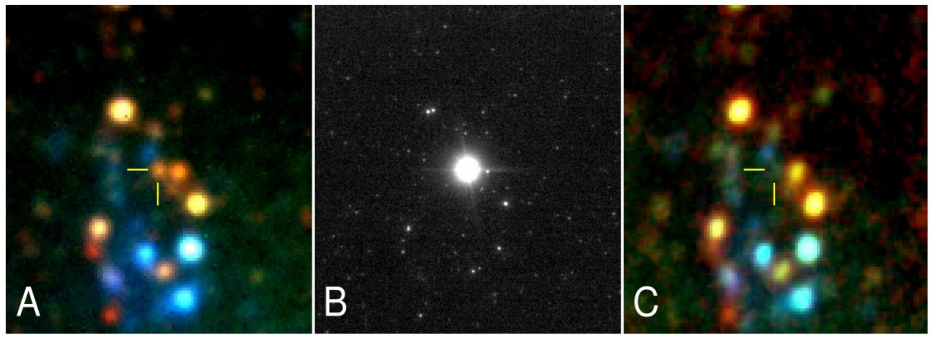
Light Curves



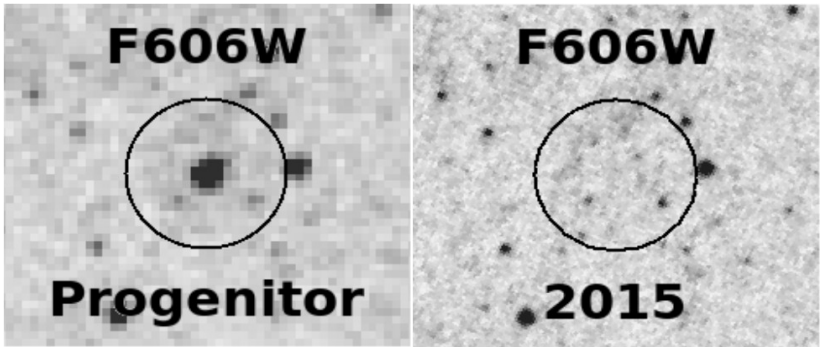
Sukhbold et al. (2016)

First Detection of Implosion

Smartt (2015)

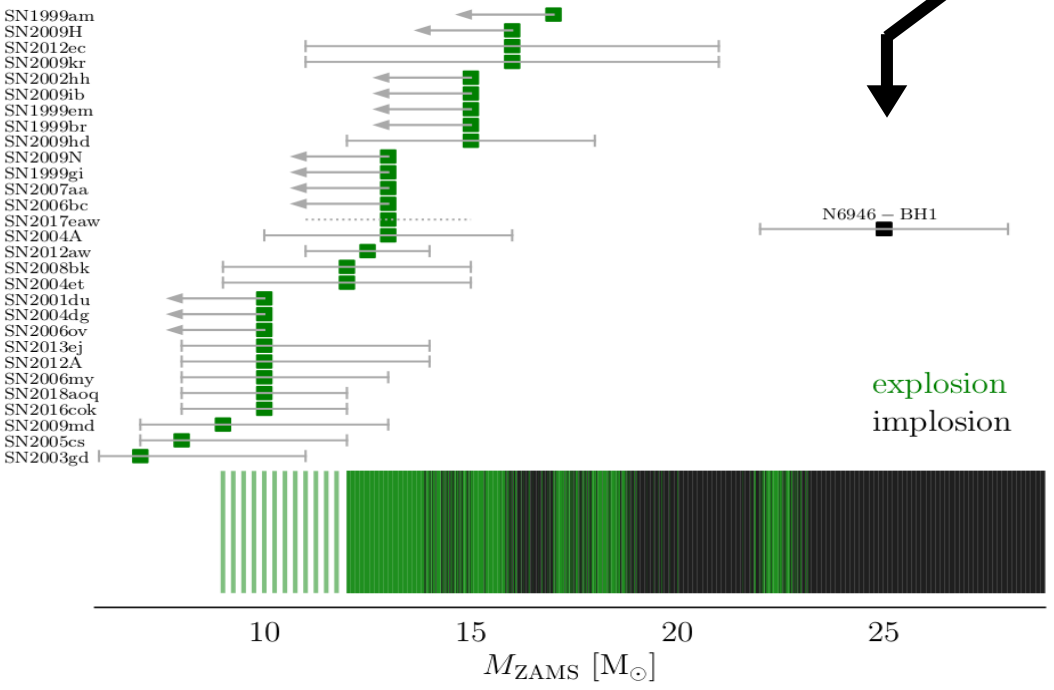


Search for Progenitors of SN



Adams et al. (2016)

Search for Disappearing Stars
(Kochanek et al. 2008)

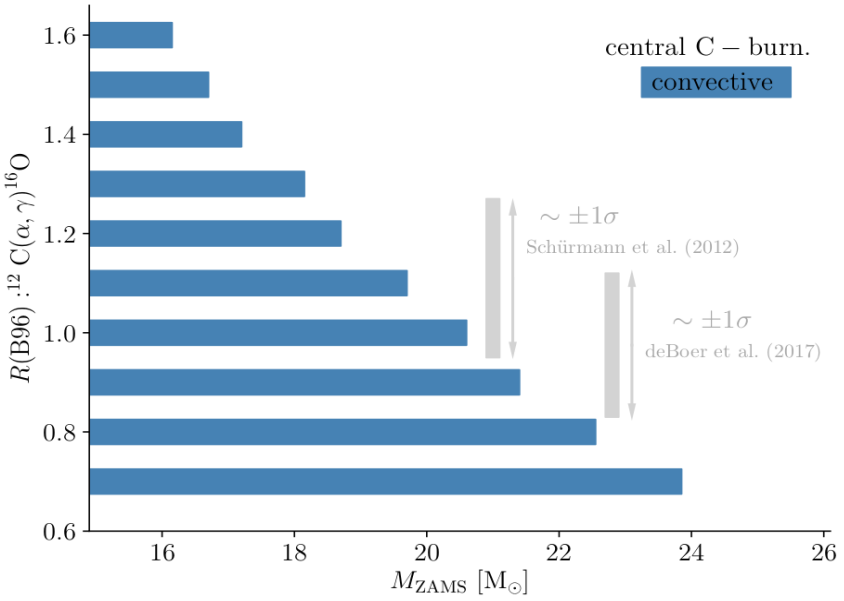


First candidate N6946-BH1:

- initial mass ~ 25 (+/-3) $M_\star$
- Observed transient consistent with envelope ejection (Lovegrove & Woosley 2013)

Constrain Massive Stellar Models?

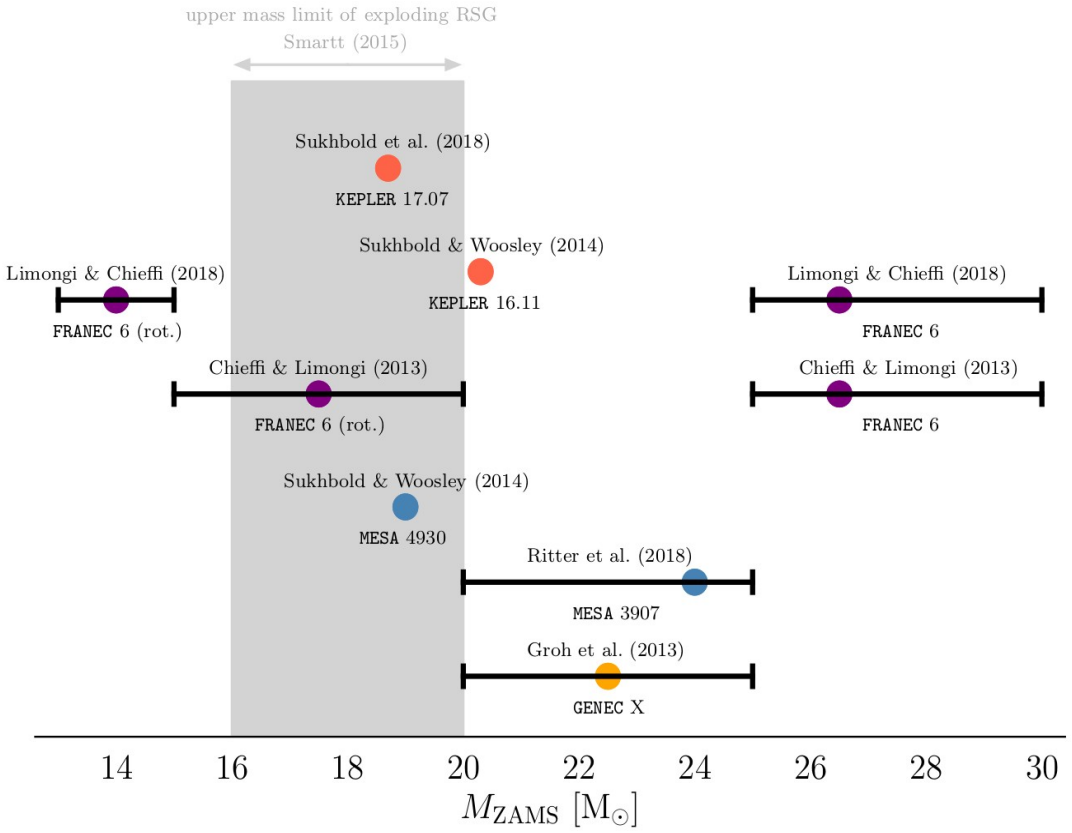
sensitivity to $^{12}C(\alpha,\gamma)^{16}O$:



- overshooting
- rotation
- semi-convection
- mass loss

...

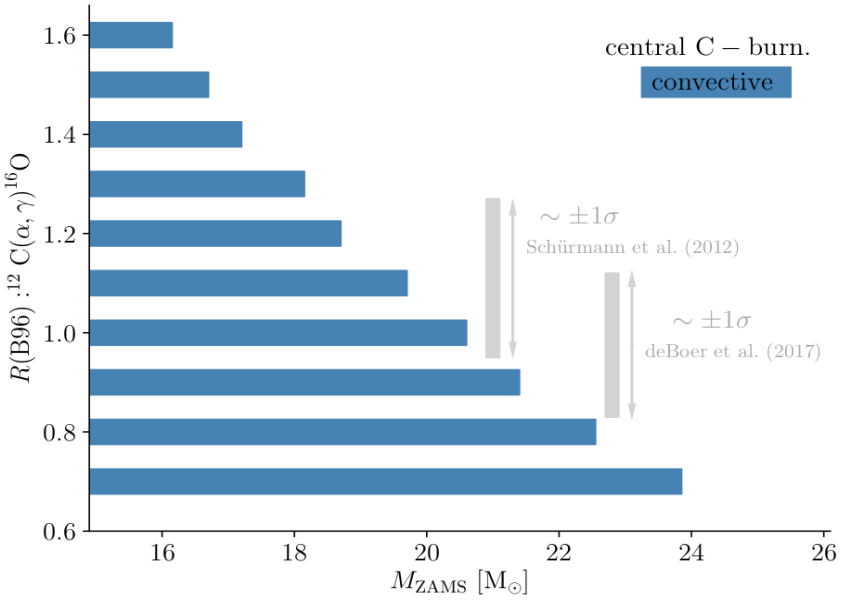
C-burn. transition mass in literature:



Constrain Massive Stellar Models?

"Sometimes speculation advances science." Stan Woosley (in response to referee)

sensitivity to $^{12}C(\alpha,\gamma)^{16}O$:



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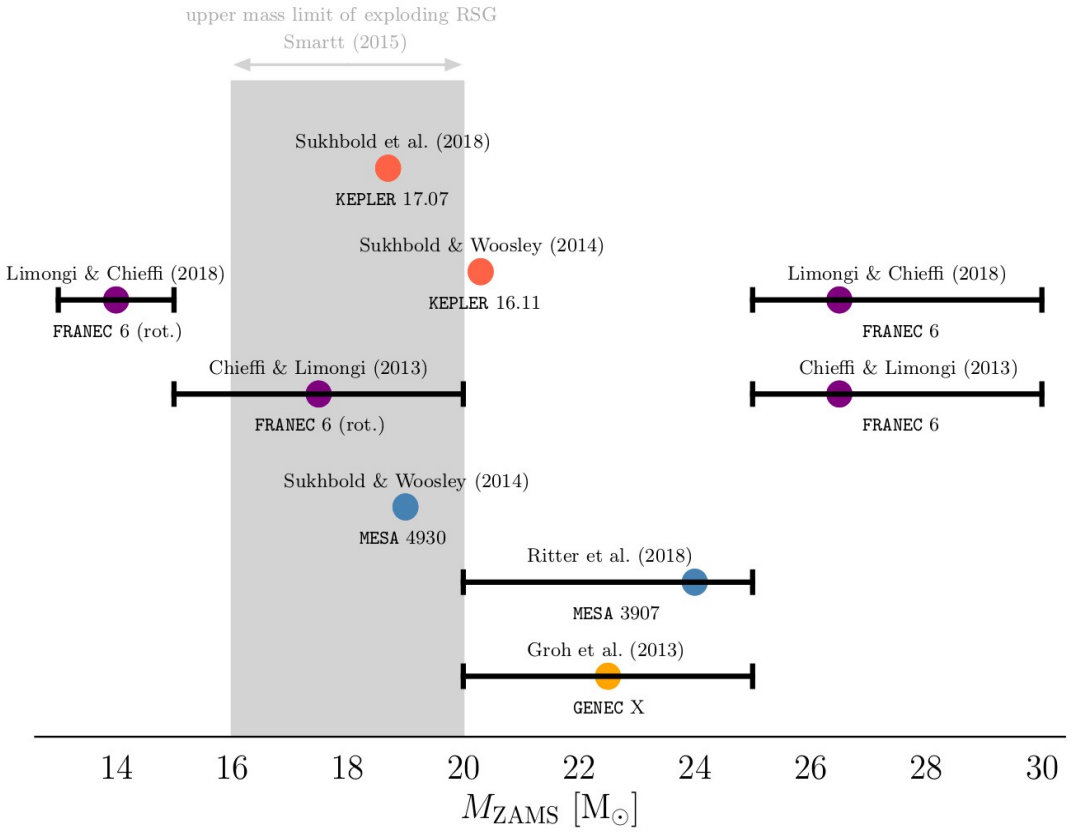

Possible Caveats

Observations:

RSG really missing?

- bias due to circumstellar dust extinction?
  Walmswell & Eldridge (2012) and Beasor & Davies (2016)
  probably a small effect
  Kochanek et al. (2012)

- bias due to improper bolometric correction?
  Davies & Beasor (2018)
  maybe improper statistical analysis
  Kochanek 2019, in prep

Theory:

robust and reproduced?

- stellar evolution results with **KEPLER**:
  MESA ✓
  e.g., **FRANEC** ? **GENEC** ? **HONGO** ?

- explosion results with **P-HOTB**:
  GR1D ✓
  Müller et al. (2016) ✓
  1D turbulence based models?
  e.g., Couch et al. 2019
  Mabanta et al. 2019
  (but see Mueller 2019)

To sum up:

fairly clear that luminous RSG stars (M_{ZAMS} > 16-20) do not result in SN

consistent with stellar evolution + calibrated ν-driven explosion results

currently observed upper limit of exploding RSG could be the signature of central C-burning transition