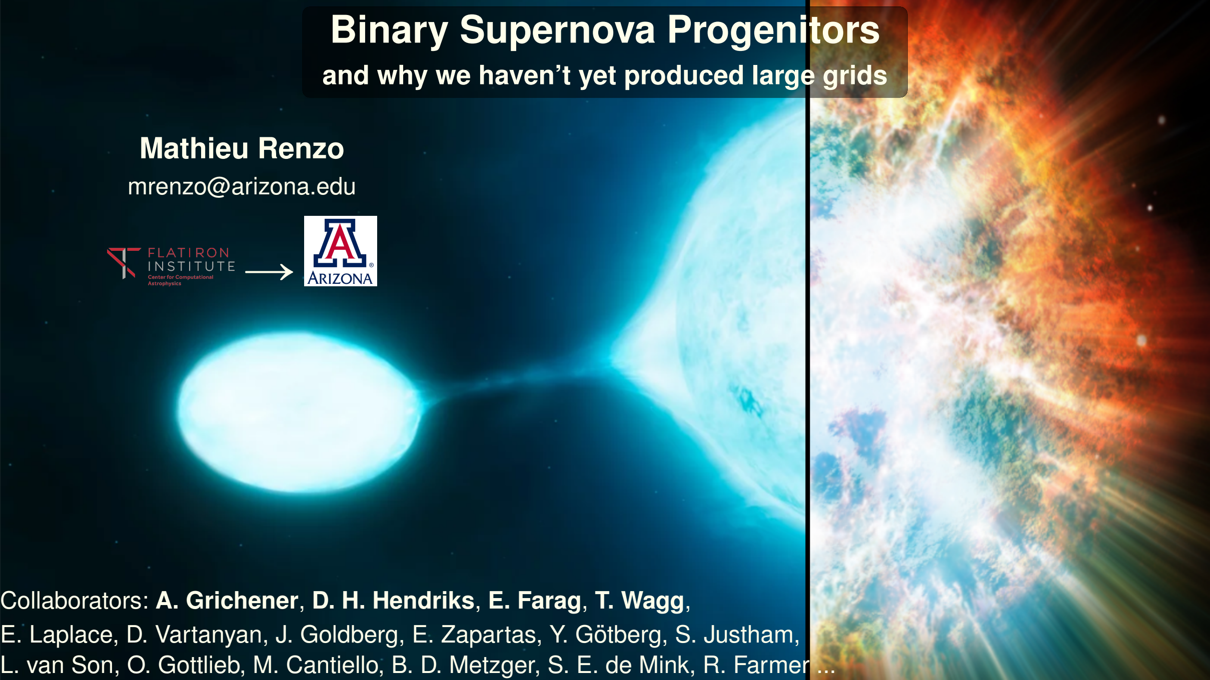

Binary Supernova Progenitors

and why we haven’t yet produced large grids

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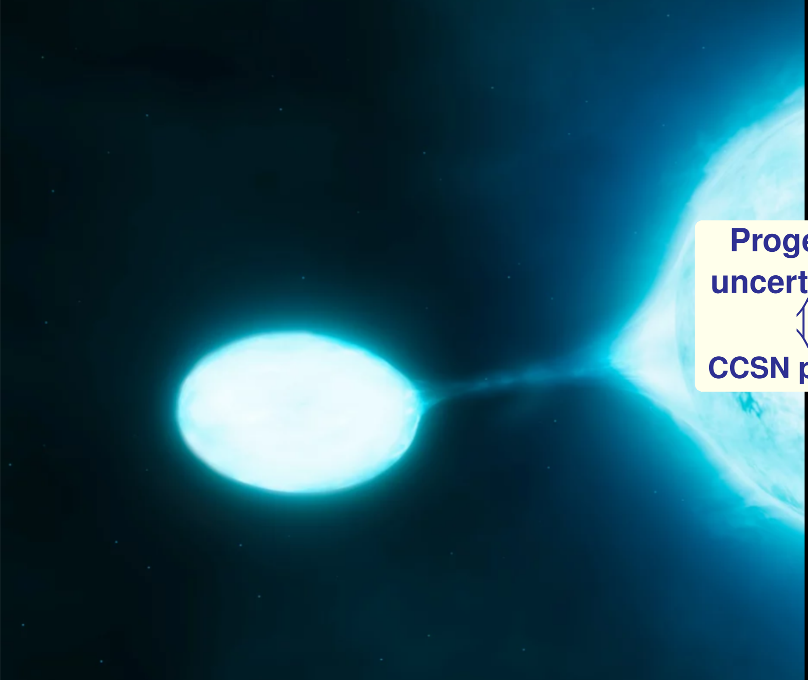
Center for Computational Astrophysics
→
ARIZONA

Collaborators: **A. Grichener**, **D. H. Hendriks**, **E. Farag**, **T. Wagg**,
E. Laplace, D. Vartanyan, J. Goldberg, E. Zapartas, Y. Götberg, S. Justham,
L. van Son, O. Gottlieb, M. Cantiello, B. D. Metzger, S. E. de Mink, R. Farmer ...

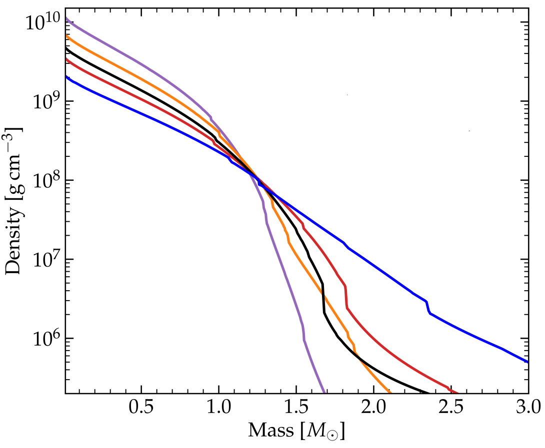


Progenitor uncertainties

⇕

CCSN problem

KEPLER $12-40\,M_{\rm ZAMS}$ single stars



from Woosley *et al.* 2002, 2007 as shown in Ott *et al.* 2018

Progenitor uncertainties

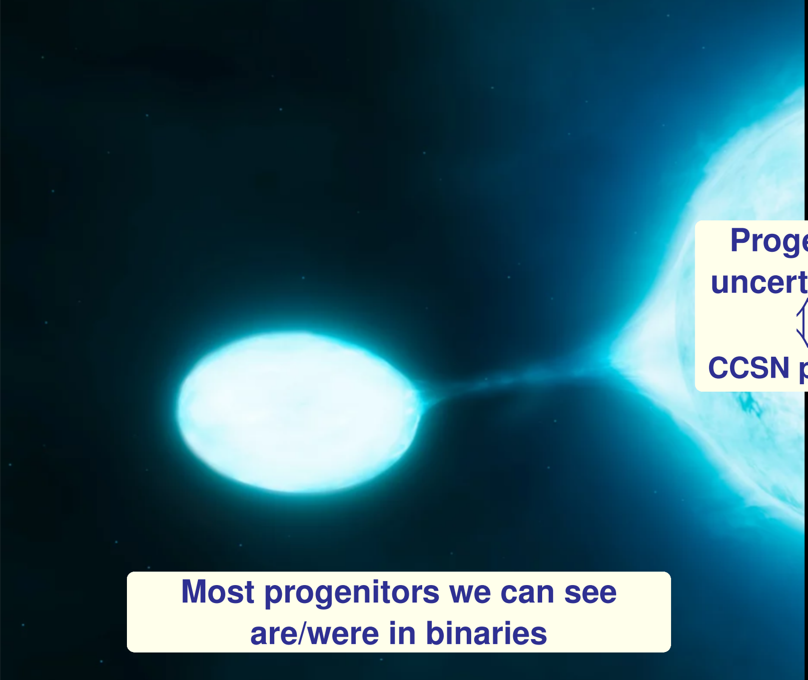
$\Updownarrow$

CCSN problem

Core structure is set by late core burning

$(\rho, Y_e) \Rightarrow (\dot{M}, L_{\nu_e}) \Rightarrow$ "explodability"

Kochanek 2009, O'Connor & Ott 2011, Ugliano *et al.* 2012, Sukhbold & Woosley 2014, Farmer *et al.* 2016, Ertl *et al.* 2016, 2020, Sukhbold *et al.* 2016, **Renzo *et al.* 2017**, Ott *et al.* 2018, Davies *et al.* 2019, Patton *et al.* 2020, 2021, Mandel & Müeller 2020, **Laplace *et al.* 2021, Vartanyan *et al.* 2021**, 2023a, b, **Zapartas *et al.* 2017, 2019a,b, 2021**, Boccioli *et al.* 2022, Adams *et al.* 2017, Basinger *et al.* 2022, Beasor *et al.* 2023, Burrows *et al.* 1994, 2005, 2023, ...



Progenitor uncertainties

⇕

CCSN problem

Most progenitors we can see are/were in binaries

Binaries and binary products
are unavoidable at population level

Binary interactions create unique pre-SN structures

Podsiadlowski *et al.* 1989, 1990, 1991, Cantiello *et al.* 2007, Justham *et al.* 2014,
Renzo *et al.* 2020c, Schneider *et al.* 2020, 2021, 2023, Chatzopoulos *et al.* 2020, 2023,
Renzo & Götberg 2021,**Laplace *et al.* 2021**, 2023, **Renzo *et al.* 2023**, Henneco *et al.* 2023, ...

CCSN progenitors from binaries

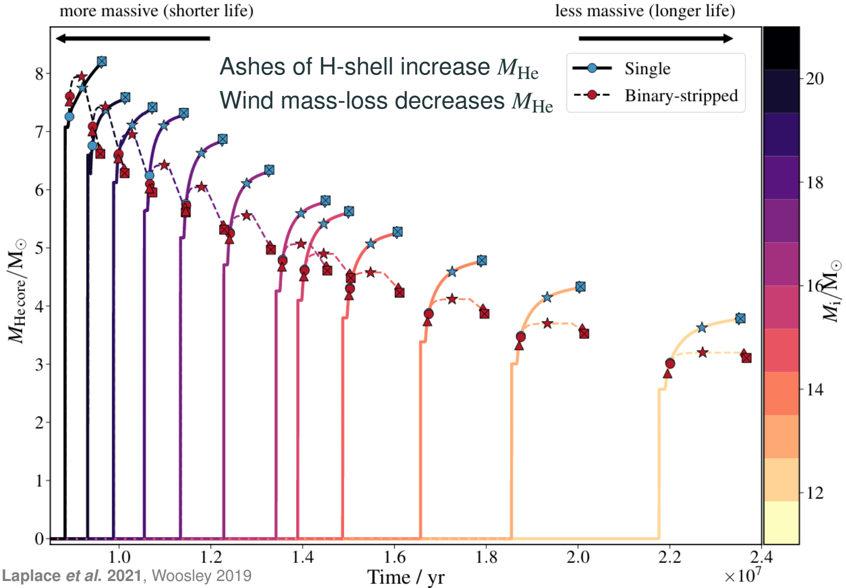
Donor

Accretor

Mergers (very massive ones)

Why no comprehensive answer (yet)

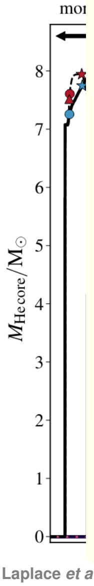
Donor: $M(t)$, $J(t)$ influence He core burning ... and following phases



Laplace *et al.* 2021, Woosley 2019

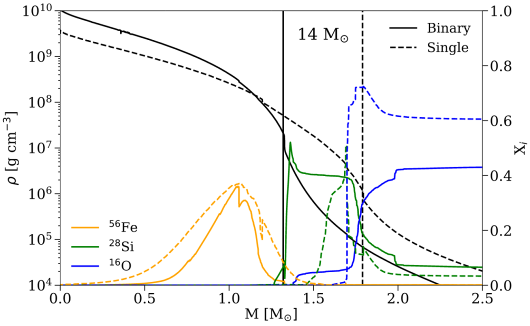
Donor vs. single

Donor: $M(t)$, $J(t)$ influence He core burning ... and following phases

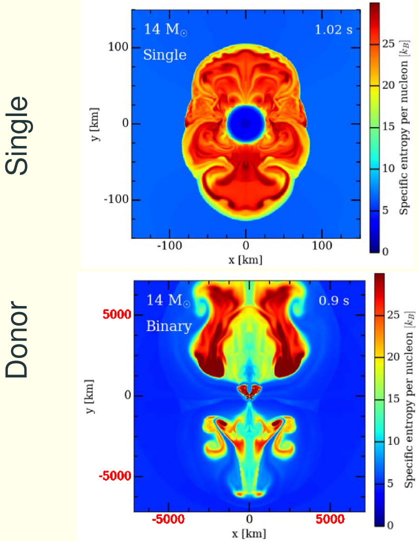


11 pairs of 2D explosion models

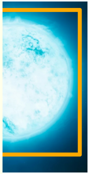
Donor slightly more explodable, unclear trends



Vartanyan *et al.* 2021



gle



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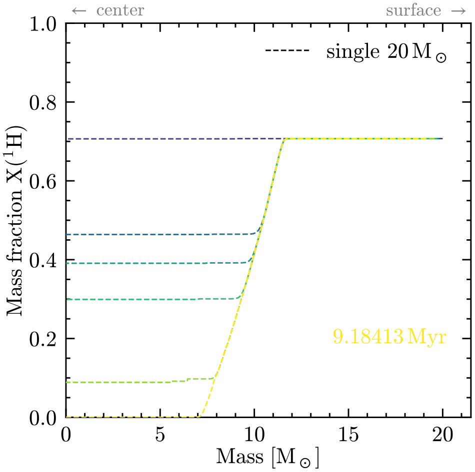

Accretor vs. single

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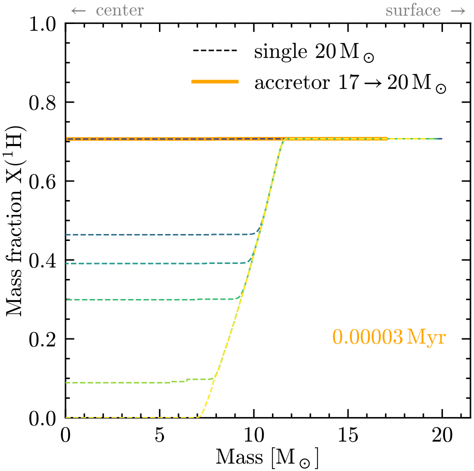

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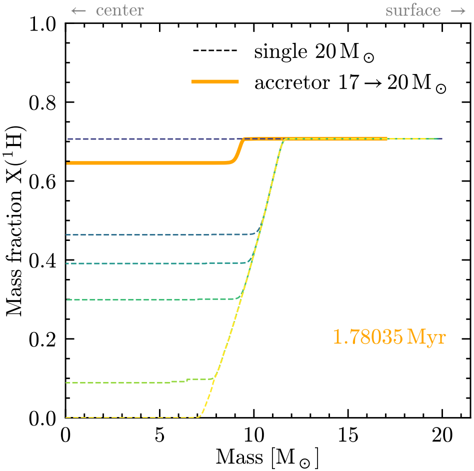

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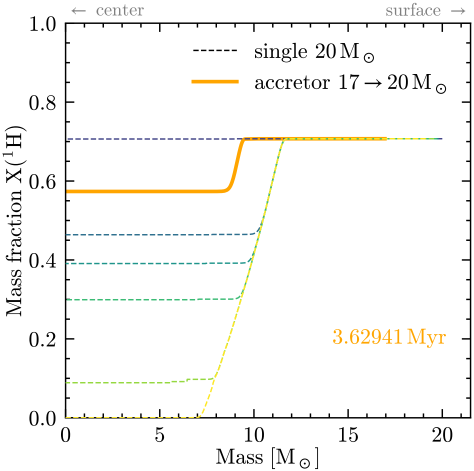

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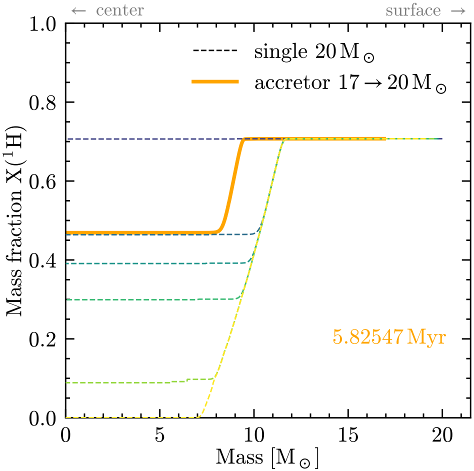

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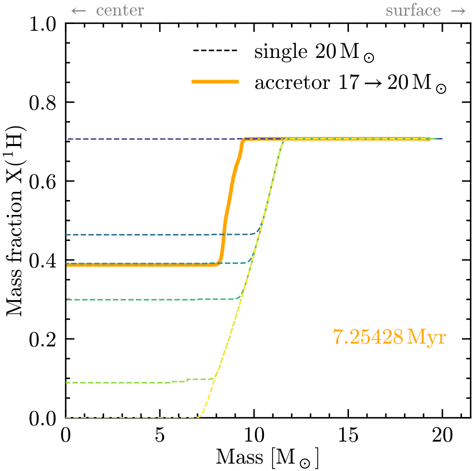

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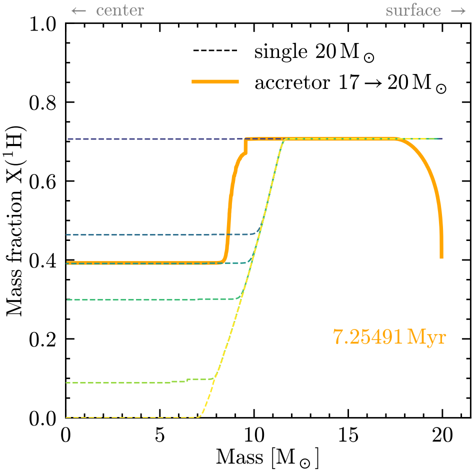

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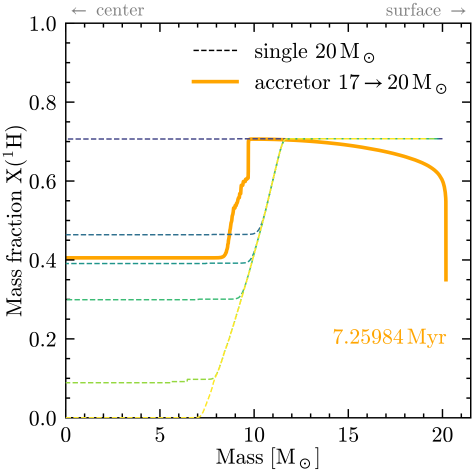

Accretor vs. single

Consequences

- Blue loops — **Renzo *et al.* 2023**
- Lower envelope binding E — **Renzo *et al.* 2023**
- long-GRB — Cantiello *et al.* 2007

Neo *et al.* 1977, Hellings 1983, 1864, Braun & Langer 1995, Cantiello *et al.* 2007, **Renzo & Götberg 2021, Renzo *et al.* 2023, Landri, Ricker, Renzo, in prep.**

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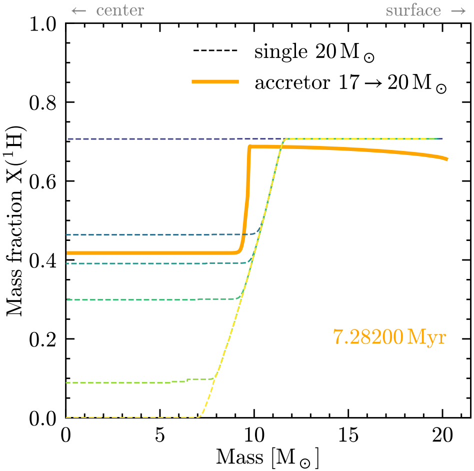

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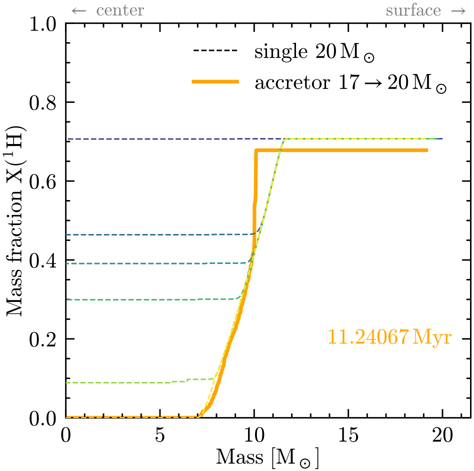

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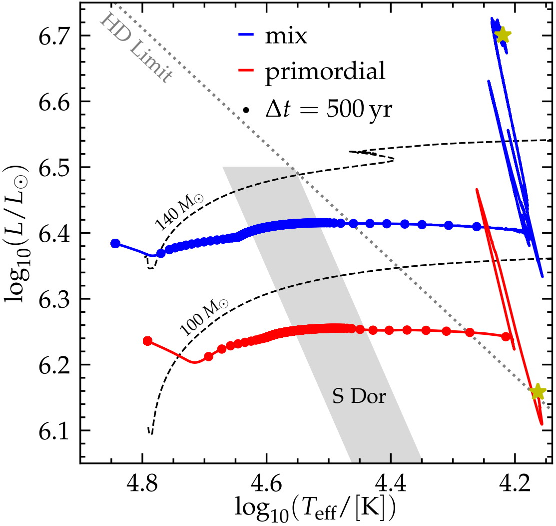
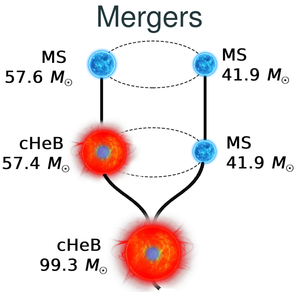
Mergers: $M(t)$, $J(t)$ influence He core burning ... and following phases





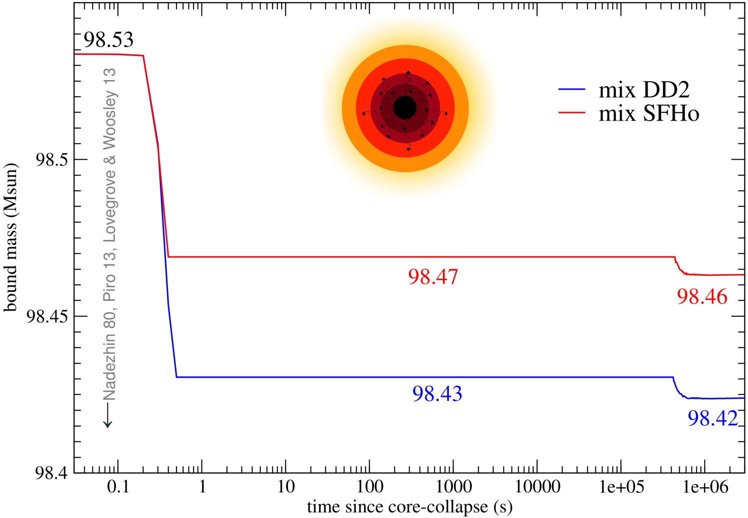
BH progenitors in the PISN gap?

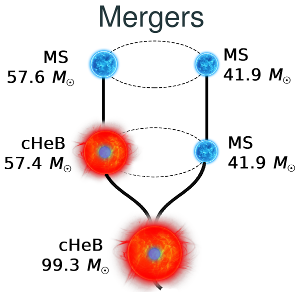
Renzo *et al.* 2020c

Spera *et al.* 2019, di Carlo *et al.* 2019, 2020b, see also Kremer *et al.* 2020, Mapelli *et al.* 2020, **Renzo *et al.* 2020c**, Costa *et al.* 2023, Ballone *et al.* 2023

Mergers: $M(t)$, $J(t)$ influence He core burning ... and following phases

MESA → GR1D+FLASH credits: R. Fernàndez





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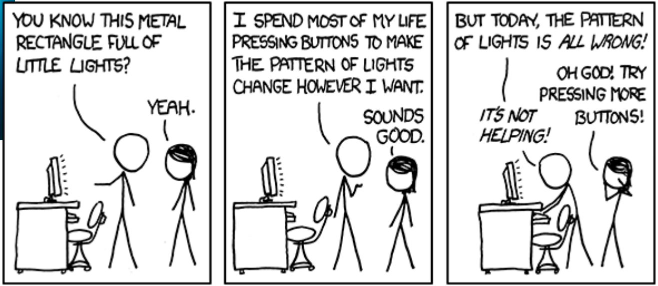
Exploration of binary "explodability" landscape not yet possible

Variety of evolutionary paths

- Orbital architecture M_1, M_2, P, e
- Z, winds, rotation, overshooting, ...
- Pre-/post-main sequence interactions
- Donors, Accretors, Mergers, Reversed-mergers

Getting one model to the onset of collapse:



xkcd.com/722

Numerical challenges

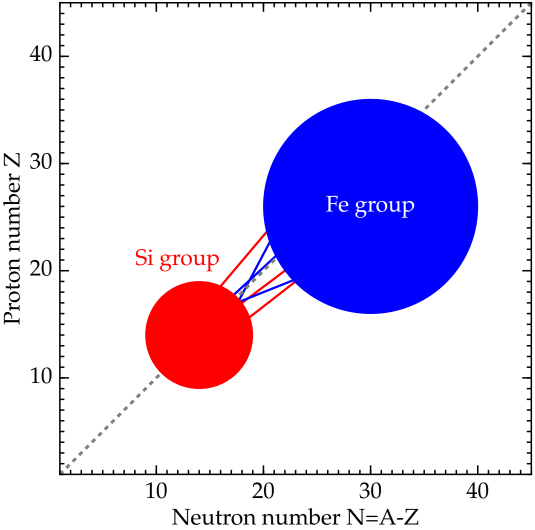
(for single & binary progenitors)

Nuclear reaction networks

Input physics ⇒ C/O ratio

Spurious envelope velocities

Limiting factor: Post-carbon burning stiffness and numerical stability



Numerical techniques:

- “Compound” reactions

e.g., MESA code, Timmes *et al.* 1996

- Sub-timestep integration

e.g., MESA code, Paxton *et al.* 2011-2019, Jermyn *et al.* 2022

- Co-processing

e.g., KEPLER code **???**, Weaver et al. 1976,
FRANEC code**???**, Limongi & Chieffi 2013, 2018

- “Quasi” statistical equilibrium

Hix & Thielemann 1996, José & Iliadis 2011

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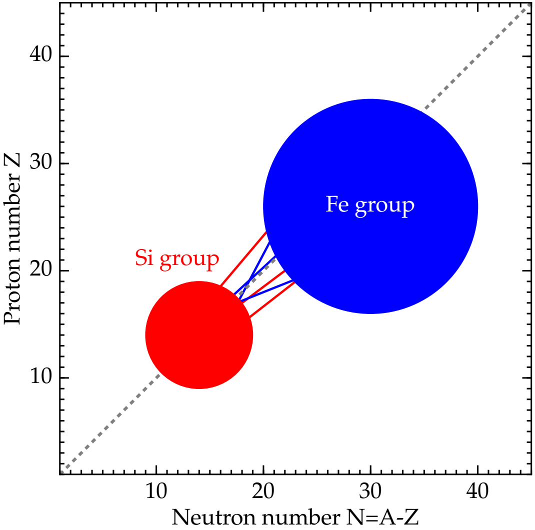

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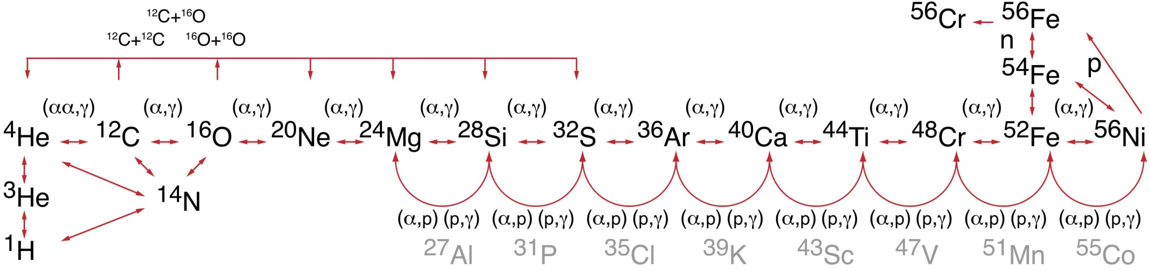
“Compound” reactions: α-chain nuclear reaction networks



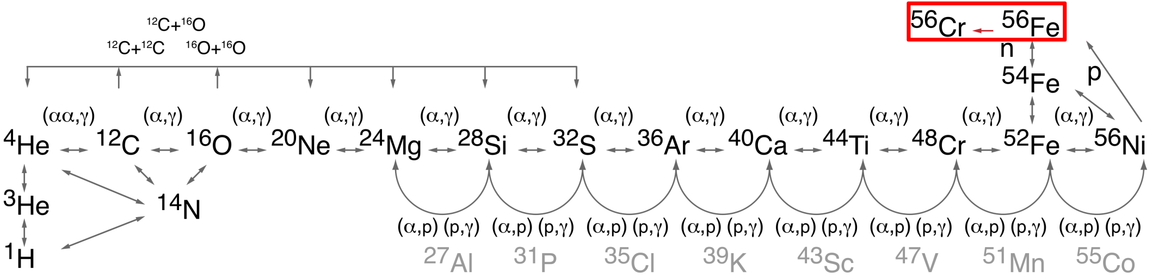
default in MESA

`approx21.net` $\Rightarrow N_{\rm iso} = 21$

cost $\propto (N_{\rm mesh} \times N_{\rm iso})^2 \times N_{\Delta t}$

Fig. from **Marchant, Renzo *et al.* 2019**, see also Timmes *et al.* 1996, Farmer *et al.* 2016, **Renzo *et al.* 2017**, **Grichener, Renzo *et al.*, in prep.**

"Compound" reactions: α-chain nuclear reaction networks



The only weak reaction included

$$^{56}\mathrm{Fe} + 2e^{-} \rightarrow {}^{56}\,\mathrm{Cr} + 2\nu_e$$

$$\Downarrow$$

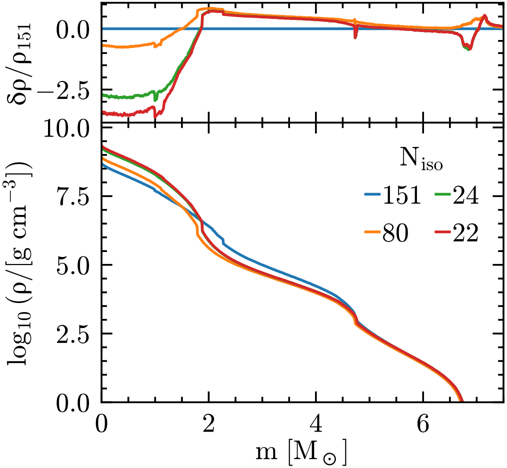
The core Y_e is pre-determined:

$$Y_e(r=0) \equiv Y_e(^{56}\mathrm{Cr}) = 0.428$$

Fig. from **Marchant, Renzo *et al.* 2019**, see also Timmes *et al.* 1996, Farmer *et al.* 2016, **Renzo *et al.* 2017**, **Grichener, Renzo *et al.*, in prep.**

Different nuclear network ⇒ different progenitor

same $20\,M_\odot$ except for $N_{\rm iso}$



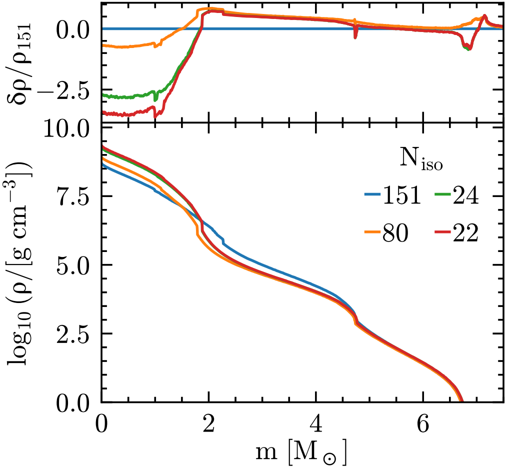
Aldana Grichener
(Technion)

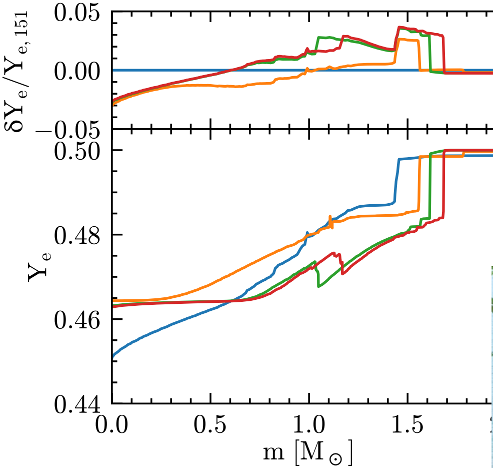
N.B.: not yet converged with increasing $N_{\rm iso}$

Grichener, Renzo *et al.*, in prep.

Different nuclear network ⇒ different progenitor

same $20\,M_\odot$ except for N_iso





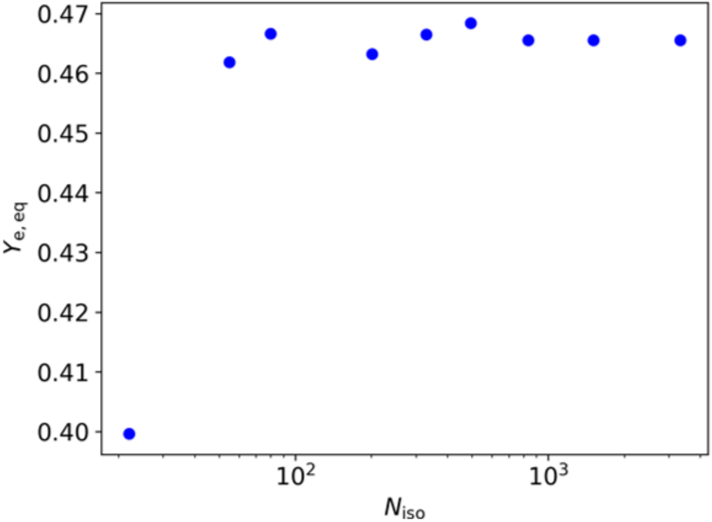
Aldana Grichener (Technion)

N.B.: not yet converged with increasing N_iso

Grichener, Renzo *et al.*, in prep.

How many (and which) isotopes do we need?

Standalone MESA one-zone burner at fixed $\log_{10}(T/K) = 9.84$, $\log_{10}(\rho/[\mathrm{g\ cm^{-3}}]) = 8.47$



Aldana Grichener
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Farmer *et al.* 2016, **Renzo *et al.* 2017, Grichener, Renzo *et al.*, in prep.**

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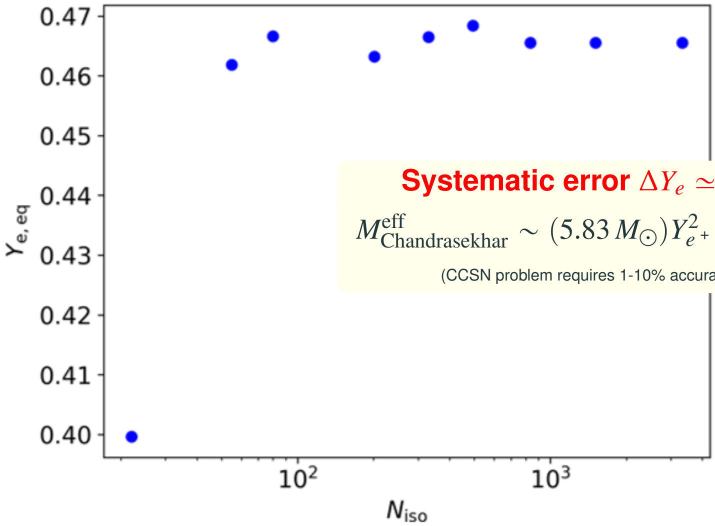

Systematic error $\Delta Y_e \simeq 15\%$

$$M^{\mathrm{eff}}_{\mathrm{Chandrasekhar}} \sim (5.83\,M_\odot)Y_e^2 + \{\text{thermal corr.}\}$$

(CCSN problem requires 1-10% accuracy)

Aldana Grichener
(Technion)

Farmer *et al.* 2016, **Renzo *et al.* 2017, Grichener, Renzo *et al.*, in prep.**

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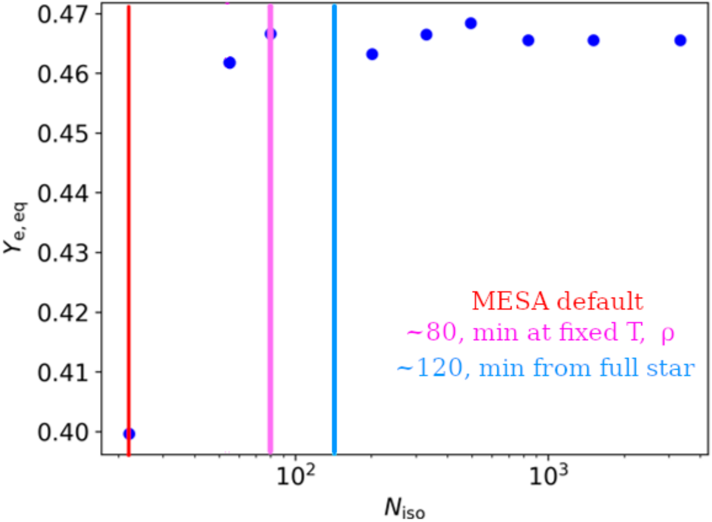


CCSN progenitor are expensive!

cost $\propto (N_{\mathrm{mesh}} \times N_{\mathrm{iso}})^2 \times N_{\Delta t}$

Aldana Grichener
(Technion)

Farmer *et al.* 2016, **Renzo *et al.* 2017, Grichener, Renzo *et al.*, in prep.**

Nuclear reaction networks
are the computational bottleneck but
not the dominant uncertainty[†]

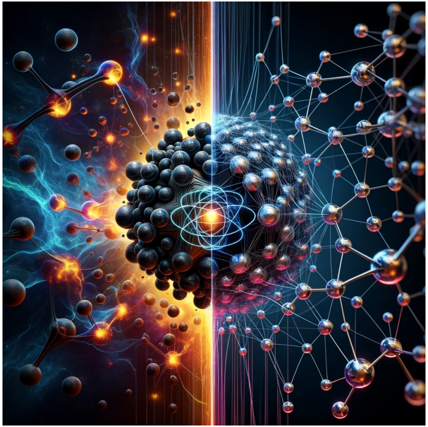
[†] cf. binary interactions, wind mass loss, rotation, convective boundary mixing, ...

e.g., Farmer *et al.* 2016, **Renzo *et al.* 2017**, Davies *et al.* 2019, **Laplace *et al.* 2021, Vartanyan *et al.* 2021**, Anders *et al.* 2021, 2022, 2023, **Johnston *et al.*, submitted**

Neural Nuclear Network: emulate away the nuclear reaction network

- ✓ Training set standalone MESA one-zone burner at fixed (T,ρ)
- Design and train neural-network to emulate $f:\mathbb{R}^{\sim 123}\rightarrow\mathbb{R}^{\sim 121}$

$$(\{X_i\}\times T\times\rho\times\Delta\mathrm{t})\rightarrow(\{X_i\}\times\varepsilon_{\nu,\mathrm{nuc}})$$

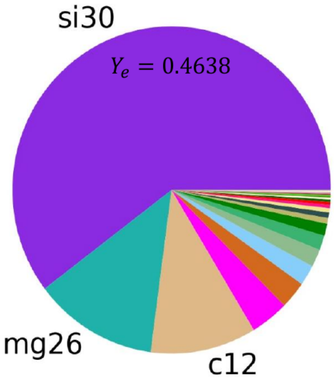


Dall-E generated by K. Wong

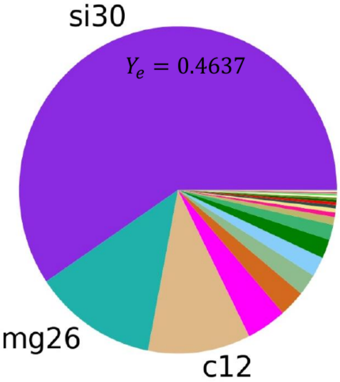
Aldana Grichener
(Technion)

Grichener, Renzo, Kerzendorf *et al.*, in prep.

Neural Nuclear Network: work in progress



Standalone MESA
one-zone burner



NNN `v.0.1`
neural network

Error: $\sim 4 - 131\%$

Aim: NNN for 1-,2-,3-D

Aldana Grichener
(Technion)

Grichener, Renzo, Kerzendorf *et al.*, in prep.

Numerical challenges

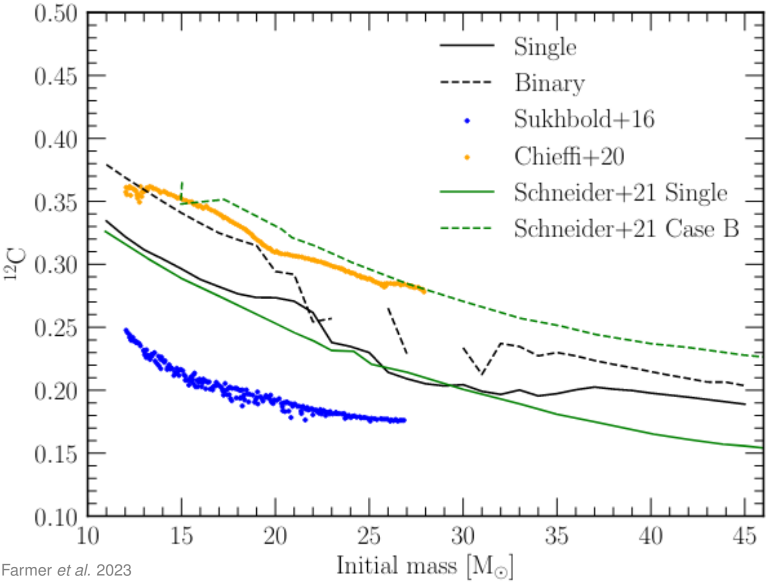
(for single & binary progenitors)

Nuclear reaction networks

Input physics ⇒ C/O ratio

Spurious envelope velocities

Core C/O ratio varies across models



Farmer *et al.* 2023

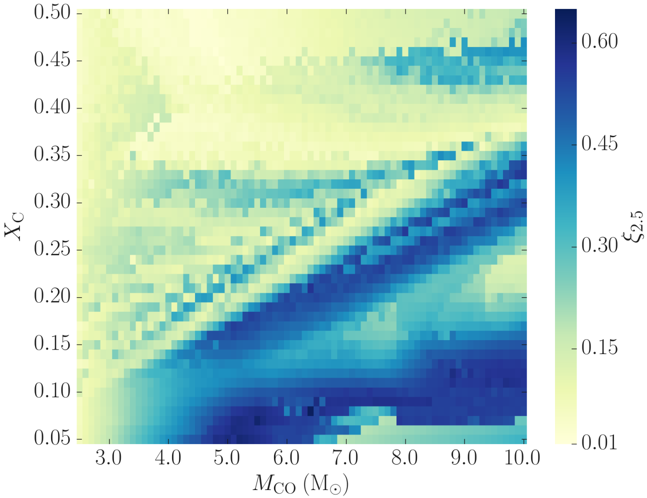
Set by T_c during (late) He core burning

- Code assumptions:
  - H/He core boundary
  - Wind mass loss
  - Rotational mixing
  - Nuclear rates
- Mass loss/accretion
  - case A/B RLOF

Adam may be right **not** to believe CO core masses from nebular spectra

C/O ratio important for “explodability”

Pure CO cores evolved to pre-core-collapse



KEPLER pure CO cores from Patton & Sukhbold 2020, see also Clausen *et al.* 2015, Spera *et al.* 2017, Patton *et al.* 2021, **Laplace *et al.* 2021**, Farmer *et al.* 2023

C/O ratio important for "explodability"

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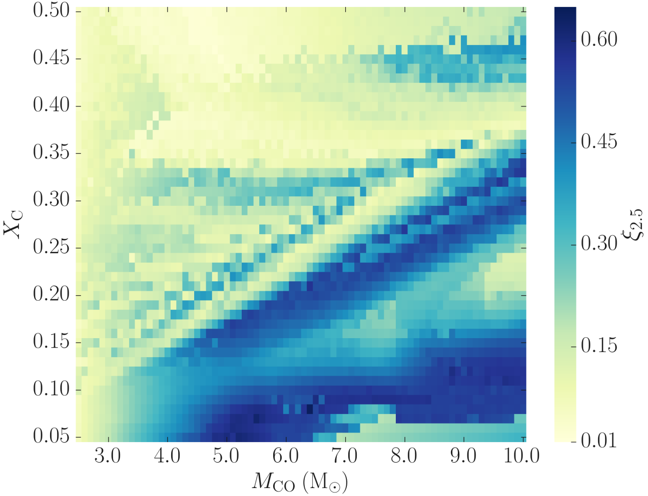


No stripped-envelope SNe from single stars:

Massive enough for wind self-stripping

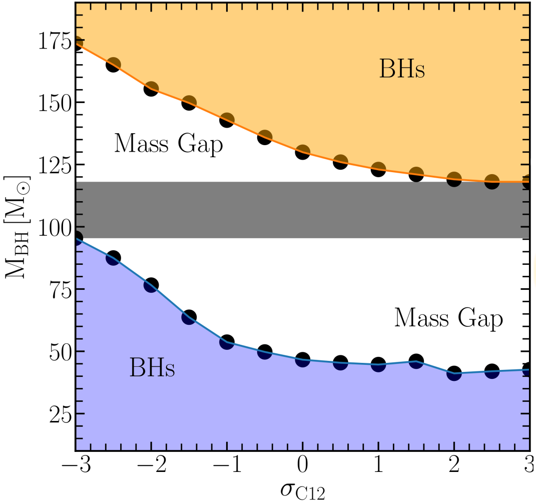
⇕

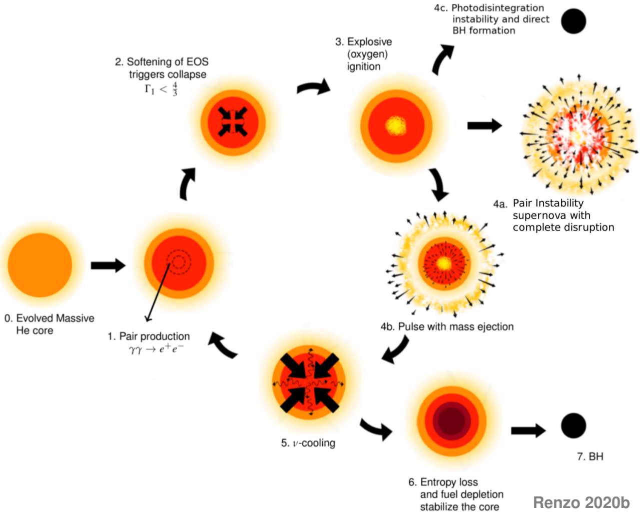
Too massive to explode

POSYDON (MESA)+KEPLER, **Zapartas, Renzo, *et al.* 2021**

KEPLER pure CO cores from Patton & Sukhbold 2020, see also Clausen *et al.* 2015, Spera *et al.* 2017, Patton *et al.* 2021, **Laplace *et al.* 2021**, Farmer *et al.* 2023

$^{12}\mathrm{C}(\alpha,\gamma)^{16}\mathrm{O}$ reaction rate key for (Pulsational) Pair Instability



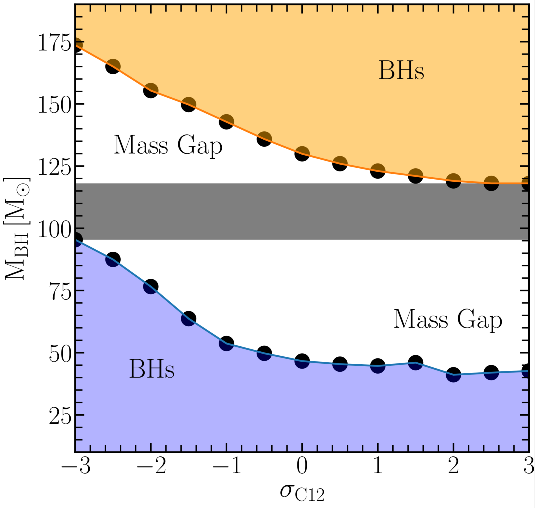


Renzo 2020b

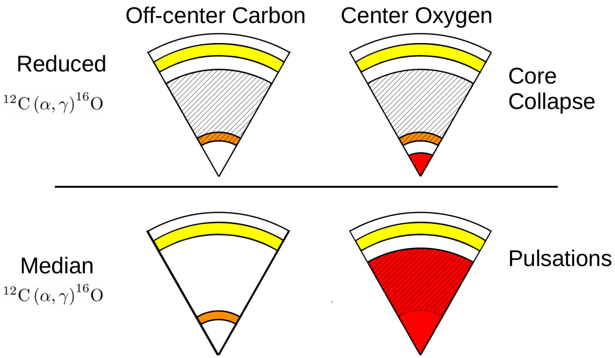
⇐ **lower** **Rate** **higher** ⇒

Farmer, Renzo *et al.* 2020, see also **Farmer, Renzo *et al.* 2019**, Costa *et al.* 2021, Woosley & Heger 2021, **Farag, Renzo *et al.* 2022**

Higher C/O ⇒ thicker C shell ⇒ stabilizing effect



⇐ **lower** **Rate** **higher** ⇒


Off-center Carbon

Center Oxygen

Reduced $^{12}C\,(\alpha,\gamma)^{16}O$

Core Collapse

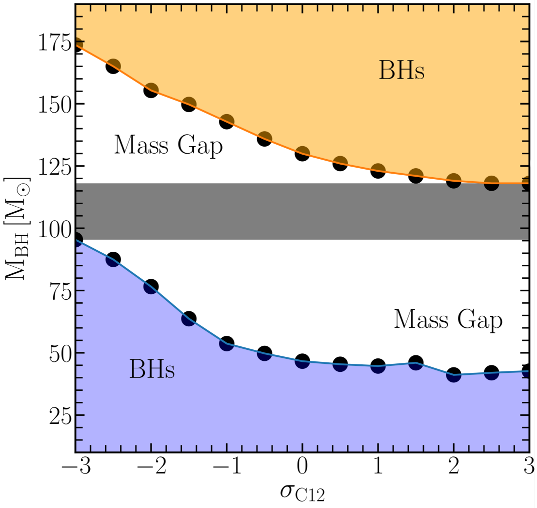
Median $^{12}C\,(\alpha,\gamma)^{16}O$

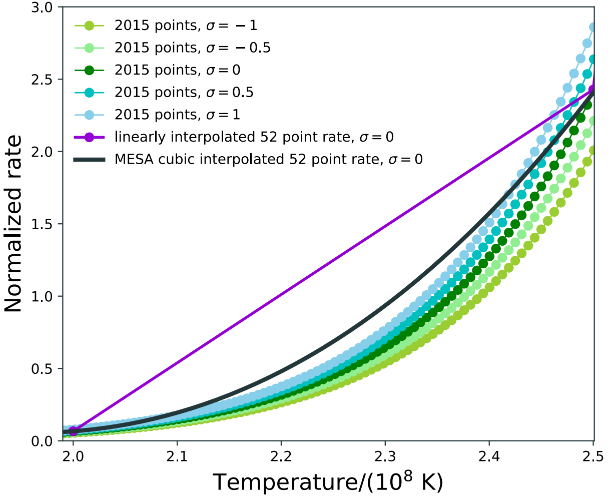
Pulsations

Farmer, Renzo *et al.* 2020, Woosley & Heger 2021
Qualitatively similar for CCSN progenitors
see also Sukhbold & Woosley 2014, Schneider *et al.* 2020, 2023

Farmer, Renzo *et al.* 2020, see also **Farmer, Renzo *et al.* 2019**, Costa *et al.* 2021, Woosley & Heger 2021, **Farag, Renzo *et al.* 2022**

$^{12}C(\alpha,\gamma)^{16}O$ reaction rate was undersampled in publicly available tables



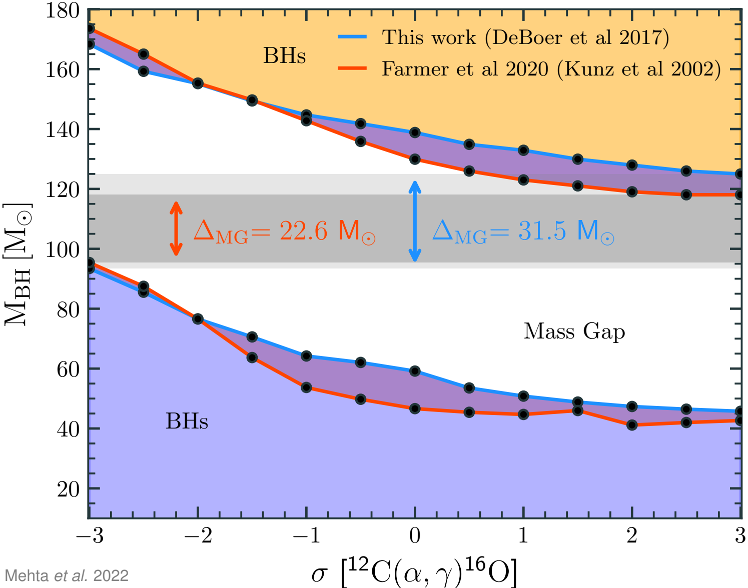


⇐ **lower** **Rate** **higher** ⇒

Farmer, Renzo *et al.* 2020, see also **Farmer, Renzo *et al.* 2019**, Costa *et al.* 2021, Woosley & Heger 2021, **Farag, Renzo *et al.* 2022**

Mehta *et al.* 2022

BH mass gap from single He cores with updated $^{12}\mathrm{C}(\alpha,\gamma)^{16}\mathrm{O}$ rate



Mehta *et al.* 2022

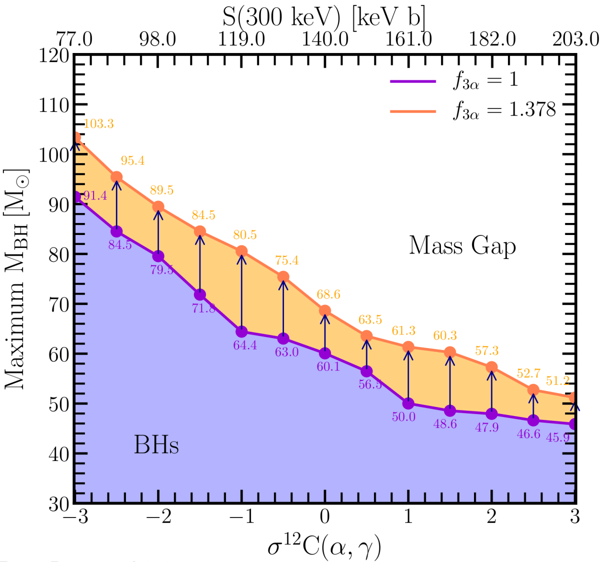
✓ Open science success!

- Open-source codes and SDK
- Input & output files on `zenodo.org`
- Refine tabulated input physics
- Community-driven improvements

Ebraheem “Eb” Farag

Arizona State Univ.

3α rate uncertainties



Farag, Renzo *et al.* 2022

New edges of the gap:

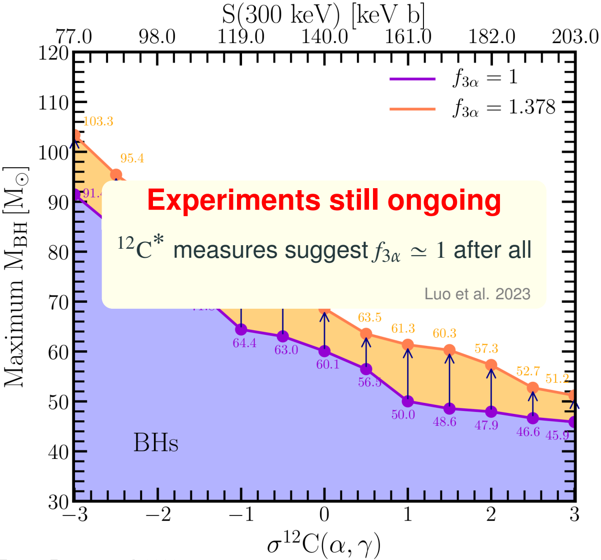
$\max(M_{\rm BH})$ below the gap: $69^{+34}_{-18}\,M_\odot$

$\min(M_{\rm BH})$ above the gap: $139^{+30}_{-14}\,M_\odot$

Ebraheem “Eb” Farag

Arizona State Univ.

3α rate uncertainties: ongoing debate!



Experiments still ongoing

$^{12}C^*$ measures suggest $f_{3\alpha} \simeq 1$ after all

Luo et al. 2023

Farag, Renzo *et al.* 2022

New edges of the gap:

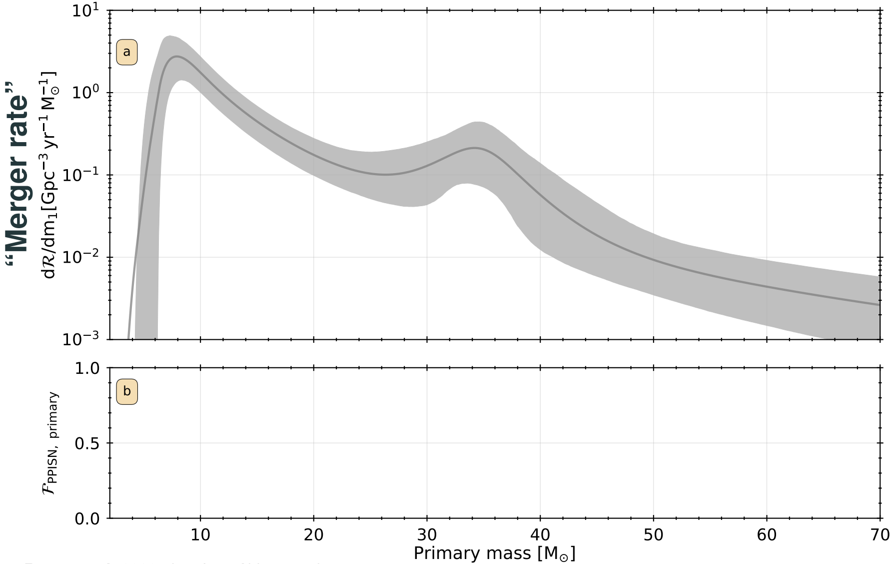
$\max(M_{BH})$ below the gap: $69^{+34}_{-18}\, M_\odot$

$\min(M_{BH})$ above the gap: $139^{+30}_{-14}\, M_\odot$

Ebraheem “Eb” Farag

Arizona State Univ.

GW detected BHs: feature at $\sim 35\,M_\odot$ and tail "in the gap"

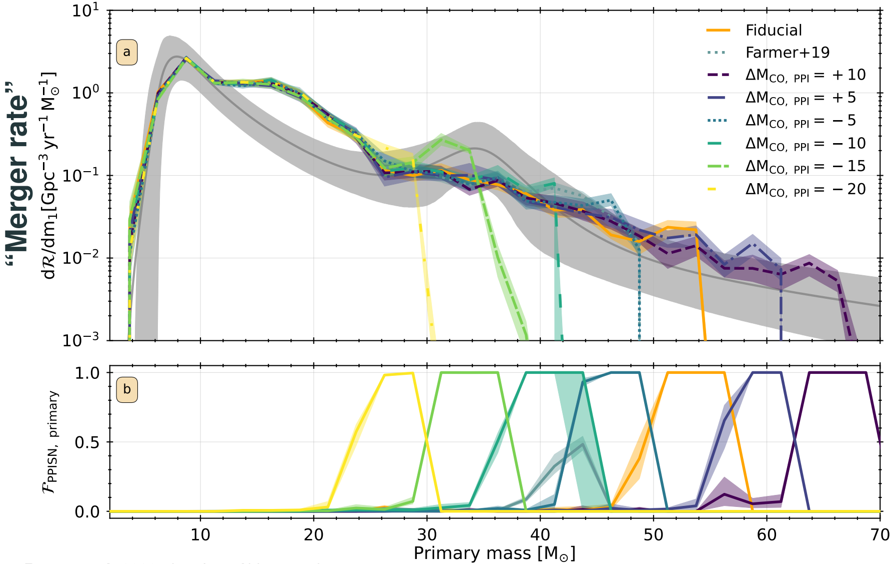


David D. Hendriks

Univ. Surrey

Hendriks, van Son, Renzo *et al.*, 2023, data from Abbott *et al.* 2022

For $\sim 35\,M_\odot$ feature to be related to (P)PISN requires $\Delta \min\{M_{\mathrm{CO,PPI}}\} \simeq 15\,M_\odot$



David D. Hendriks

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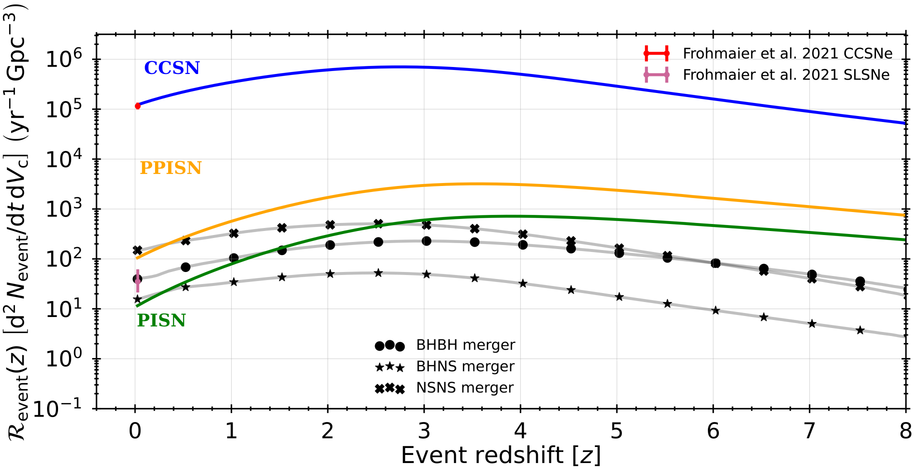
Hendriks, van Son, Renzo *et al.*, 2023, data from Abbott *et al.* 2022

Combining GW and EM constraints increases the tension



David D. Hendriks

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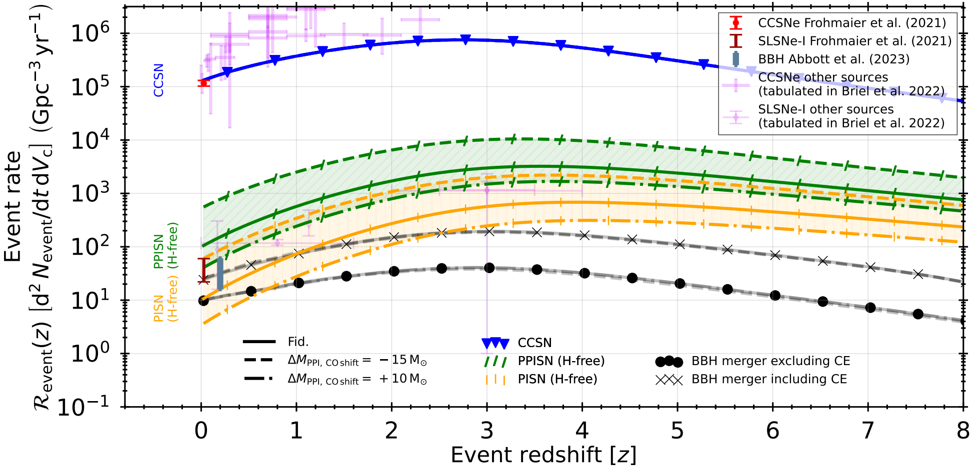
Hendriks, van Son, Renzo *et al.* 2023

Combining GW and EM constraints increases the tension



David D. Hendriks

Univ. Surrey

Hendriks, van Son, Renzo *et al.* 2023

Numerical challenges

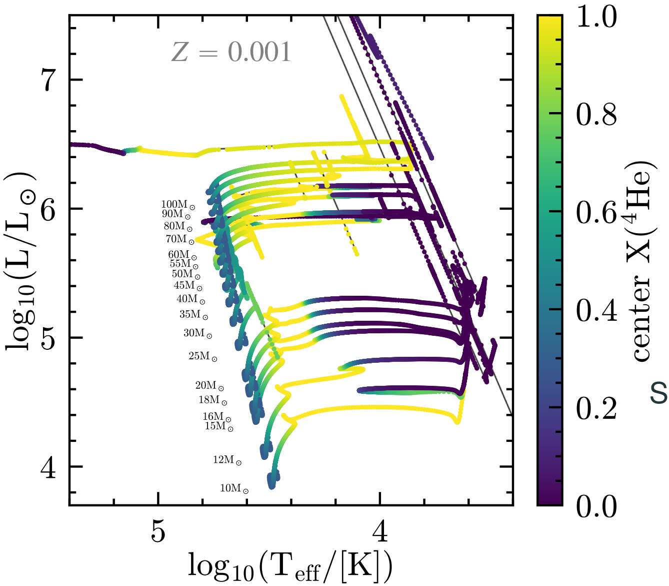
(for single & binary progenitors)

Nuclear reaction networks

Input physics ⇒ C/O ratio

Spurious envelope velocities

Late evolution results in $v/\dot{v} \ll \tau_{\mathrm{dyn}}$ across the Hertzsprung-Russell diagram



Stellar engineering solutions:

- Damp/expunge “outer” v

e.g., Farmer *et al.* 16, **Renzo *et al.* 17**, Aguilera-Dena *et al.* 18

- “stellar lid” by increasing P_{surf}

KEPLER/FRANEC **???**

Conclusions

Progenitor uncertainties dominate the CCSN problem

- Most progenitors are born in binaries

  and

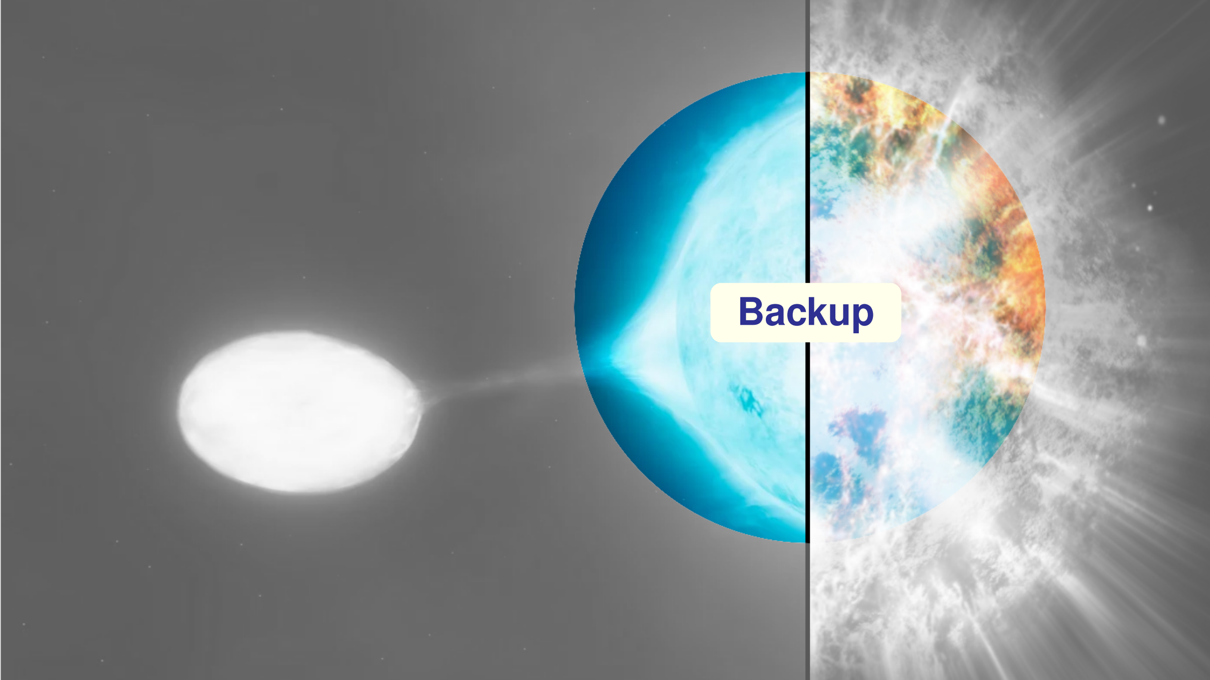
  Binary products are unavoidable in observations
- Binary evolution produces unique progenitors:
  - $M_{\rm core}/M_{\rm env}$, $J(m)$ → explodability, BH/NS, jets, obs. diagnostic, yields
  - RSG vs. BSG vs. WR
  - delay time, location relative to SFR
  - ...

✗ Computational challenges prevent exploring the parameter space
  - Core structure → leverage ML
  - Envelope stability → "stellar engineering"

    missing relevant physics?

- $\sim 35\,M_\odot$ feature in BH mass from GWs **not** from (P)PISN

Hendriks, van Son, Renzo et al. 2023



Backup

Formal definition of “stiffness”

A set of **O**rdinary **D**ifferential **E**quations is “stiff” if:

$$\frac{\max\left(\mathbb{E}(\mathcal{J})\right)}{\min\left(\mathbb{E}(\mathcal{J})\right)} \in \mathbb{C}$$

and

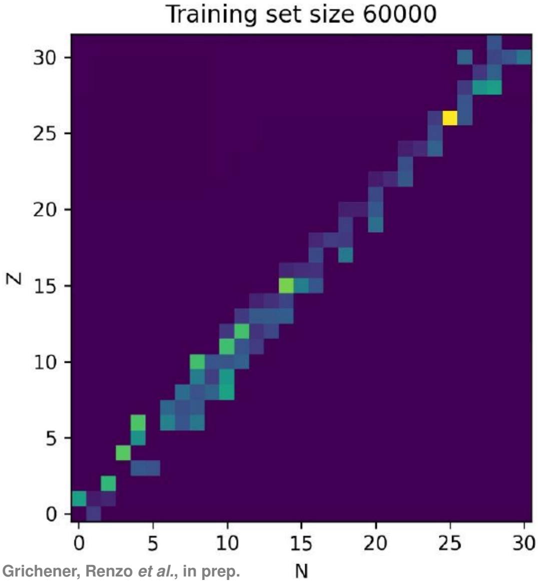
$$\frac{|\max\left(\mathbb{E}(\mathcal{J})\right)|}{|\min\left(\mathbb{E}(\mathcal{J})\right)|} \gg 1$$

where $\mathbb{E}(\mathcal{J})$ are the eigenvalues of the Jacobian matrix of the system:

$$\mathcal{J}_{ij} = \frac{\partial f_i}{\partial x_j}$$

Timmes 1999

NNN normalized abundance losses: not equally good for every isotope



Grichener, Renzo *et al.*, in prep.

Yellow is worse

Aldana Grichener
(Technion)

Do BHs form via a failed, weak, or full blown SN explosion?

$$\Delta E_\nu \simeq 10^{53}\ \mathrm{erg}$$

Possible causes for mass ejection at BH formation:

- ν-driven shocks

  Nadhezin 1980, Lovegrove & Woosley 2014, Fernandez *et al.* 2018, Ivanov & Fernandez 2021

- Jets and disk wind

  (even without net rotation)

  Gilkis & Soker 2014, Perna *et al.* 2018, Quataert *et al.* 2019

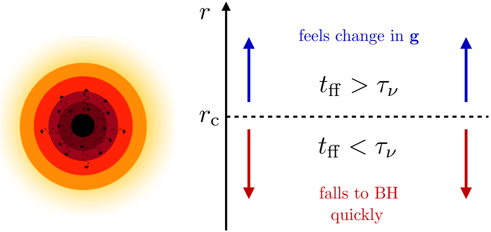
- (weak) fallback powered explosion

  Ott *et al.* 2018, Kuroda *et al.* 2018, Chan *et al.* 2020, Powell *et al.* 2021

see also Adams *et al.* 2017 for possible EM counterpart to BH formation

Accretion disks and ν-driven shocks remove little mass for BSG

$$M_{\rm BH,0} \simeq M_{\rm core} - E_\nu/c^2$$



r

feels change in $\mathbf{g}$

$t_{\rm ff} > \tau_\nu$

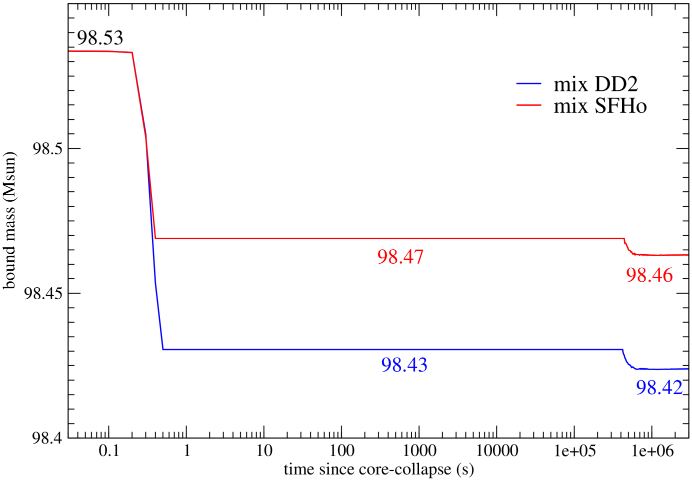
$r_{\rm c}$

$t_{\rm ff} < \tau_\nu$

falls to BH quickly

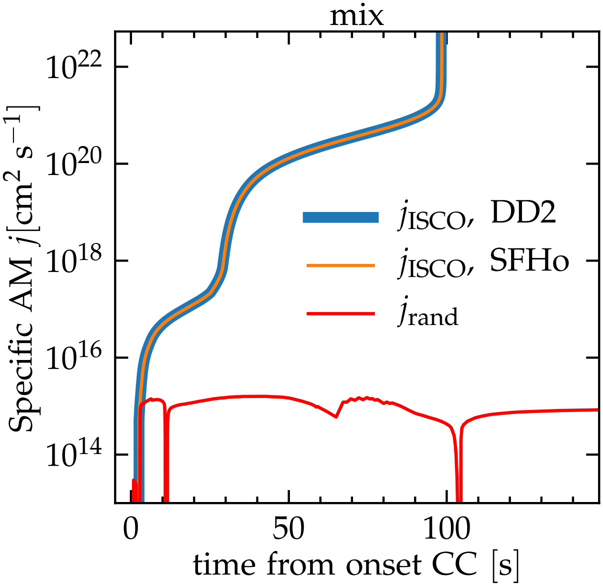
Fernàndez *et al.* 2018

MESA → GR1D+FLASH credits: R. Fernàndez



Nadhezin 1980, Lovegrove & Woosley 2013, Piro *et al.* 2013, Coughlin *et al.* 2018, Fernàndez *et al.* 2018, Ivanov & Fernàndez 2021

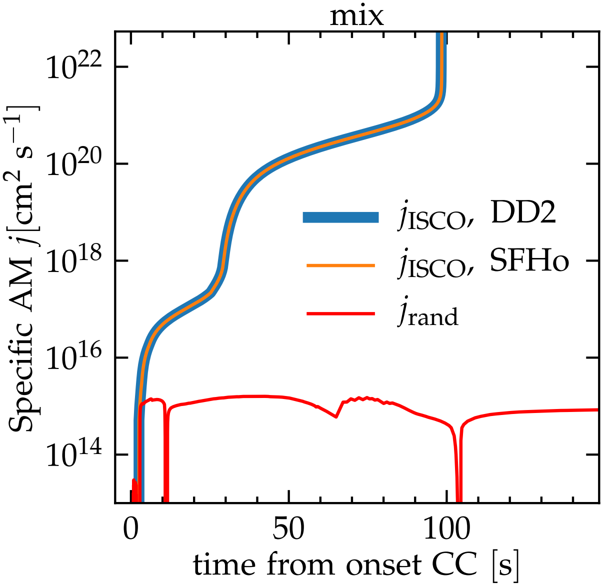
Can convective random motion cause disk formation and collapsar?



$$j_{\mathrm{rand}} = \frac{H_p v_{\mathrm{conv}}}{\sqrt{4\pi}}$$

c.f. Gilkis & Soker *et al.* 2014, Quataert *et al.* 2019, Coughlin *et al.* 2020

Can convective random motion cause disk formation and collapsar?



$$j_{\rm rand} = \frac{H_p v_{\rm conv}}{\sqrt{4\pi}}$$

Not enough in non-rotating models

But the merger process might inject AM

c.f. Gilkis & Soker *et al.* 2014, Quataert *et al.* 2019, Coughlin *et al.* 2020

EM transients from (P)PISN

Approximate supernova type
(mass-loss dependent, Sec. 7)

Pulse delay to core-collapse
(Sec. 6)

Thermonuclear ignition
(Sec. 5.1)

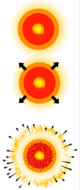
Radial expansion
max $R(v < v_{\rm esc})$ (Sec. 5.2)

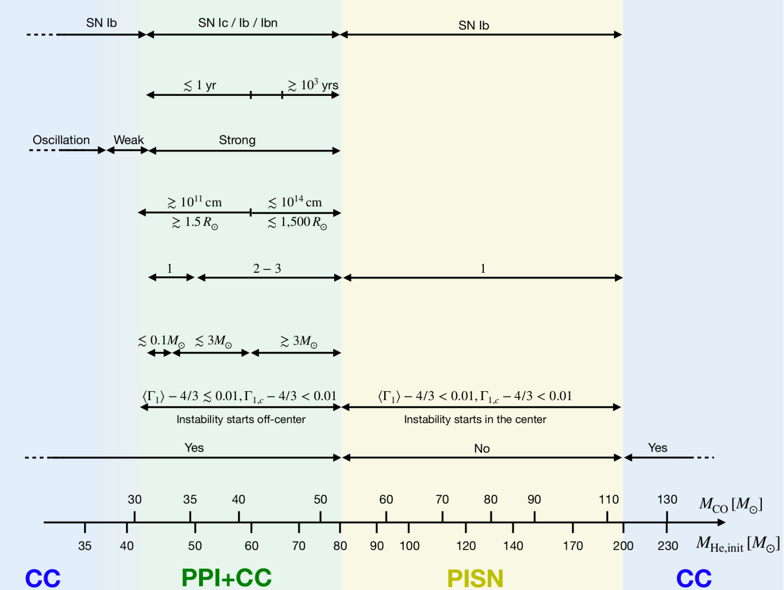
Number of mass ejections
(Sec. 5.3)

$M_{\rm CSM}$ He-rich
(Sec. 6)

Thermal stability
(Sec. 5.1.1)

BH remnant
(Sec. 3)

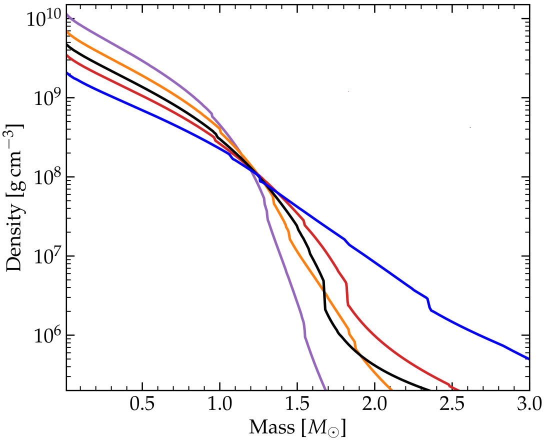




Renzo, Farmer *et al.* 2020b

SN success/failure is determined by progenitor core profile

KEPLER $12-40\,M_{\rm ZAMS}$ models



from Woosley *et al.* 2002, 2007 as shown in Ott *et al.* 2018

Core structure is set by late core burning

- $Y_e = \sum_i Z_i/(Z_i+N_i) \Rightarrow \nu$ flux
- $\rho \Rightarrow (\dot{M}, L_{\nu_e}) \Rightarrow$ "explodability"

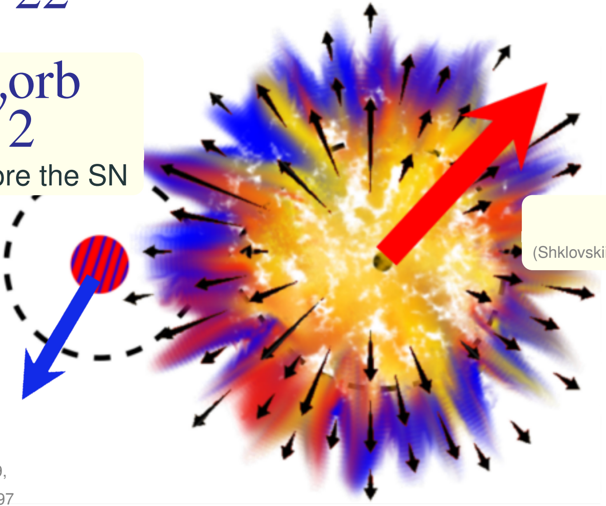
Kochanek 2009, O'Connor & Ott 2011, Ugliano *et al.* 2012, Sukhbold & Woosley 2014, Farmer *et al.* 2016, Ertl *et al.* 2016, 2020, Sukhbold *et al.* 2016, **Renzo *et al.* 2017**, Ott *et al.* 2018, Davies *et al.* 2019, Patton *et al.* 2020, 2021, Mandel & Müeller 2020, **Laplace *et al.* 2021, Vartanyan *et al.* 2021**, 2023a, b, **Zapartas *et al.* 2017, 2019a,b, 2021**, Boccioli *et al.* 2022, Adams *et al.* 2017, Basinger *et al.* 2022, Beasor *et al.* 2023, Burrows *et al.* 1994, 2005, 2023, ...

Accretors may live alone, but they are *not* single stars

$86^{+11}_{-22}\%$ of massive binaries are disrupted

$$v_{\rm dis} \simeq v_2^{\rm orb}$$

before the SN



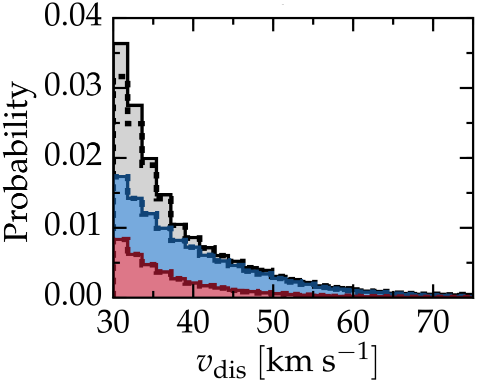
SN Natal kick

(Shklovskii 1970, Katz 1975, Janka 2013, 2017)

Renzo *et al.* 2019b, Kochanek *et al.* 2019, Eldridge *et al.* 2011, De Donder *et al.* 1997

Kinematics of the widowed stars

Accretor stars can be *runaways*...

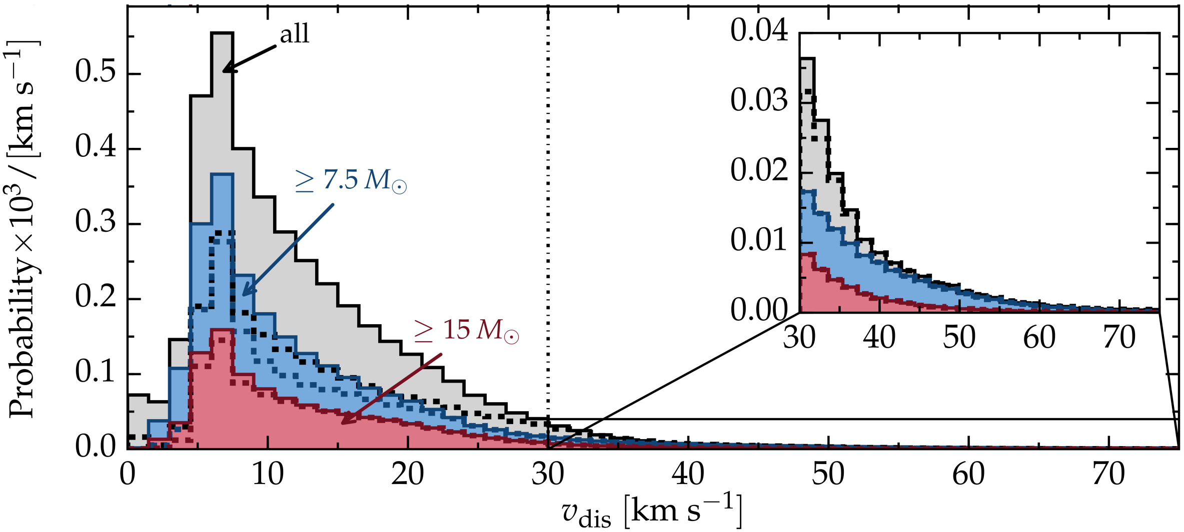


Velocity w.r.t. pre-explosion binary center of mass

Renzo *et al.* 2019b

Numerical results: http://cdsarc.u-strasbg.fr/viz-bin/qcat?J/A+A/624/A66

...but most are only *walkaways*



Velocity w.r.t. pre-explosion binary center of mass

Renzo *et al.* 2019b

Numerical results: http://cdsarc.u-strasbg.fr/viz-bin/qcat?J/A+A/624/A66

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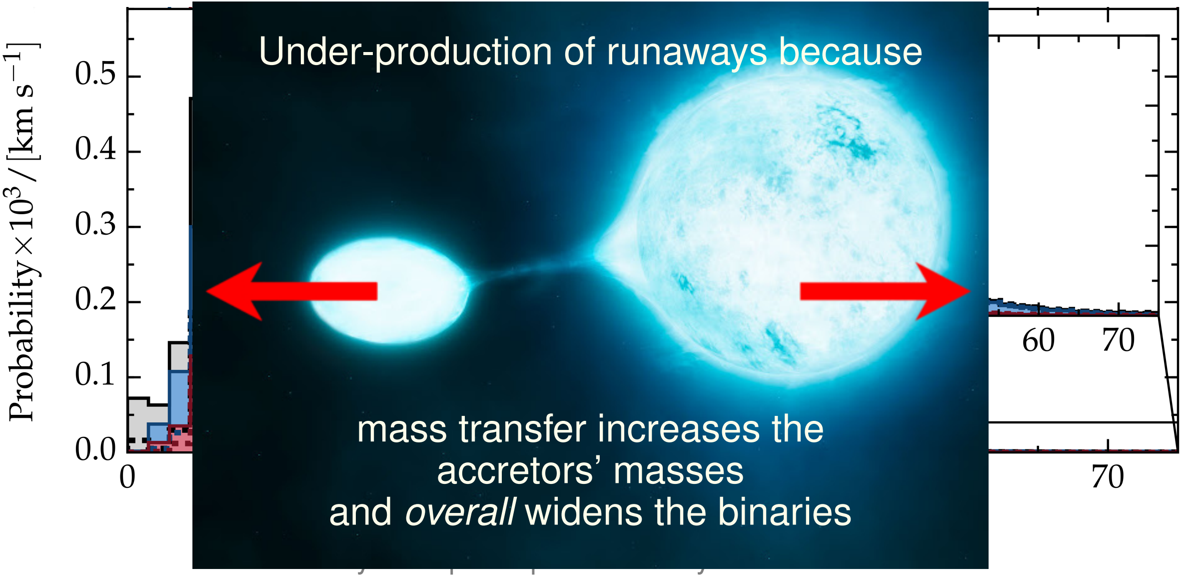


Under-production of runaways because

mass transfer increases the accretors' masses
and *overall* widens the binaries

Renzo *et al.* 2019b

Numerical results: http://cdsarc.u-strasbg.fr/viz-bin/qcat?J/A+A/624/A66

Structure of accretors

- Spin-up

  Packet 1981, Cantiello *et al.* 2007, de Mink *et al.* 2013, **Barker, Renzo *et al.*, in prep.**

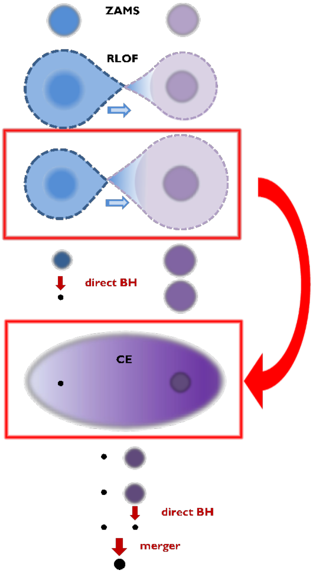
- Pollution

  Blaauw 1993, **Renzo & Götberg 2021**

- Rejuvenation

  Hellings 1983, 1985, **Renzo *et al.* 2023**

The common envelope in GW progenitors is initiated by the accretor

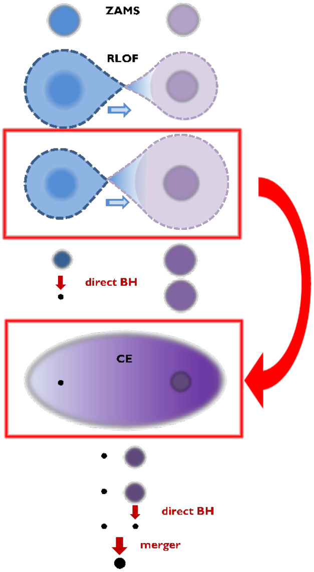


Belczynski *et al.* 16

Does RLOF rejuvenation impact how easy it is to remove the envelope ?

Renzo *et al.* 2023

The common envelope in GW progenitors is initiated by the accretor



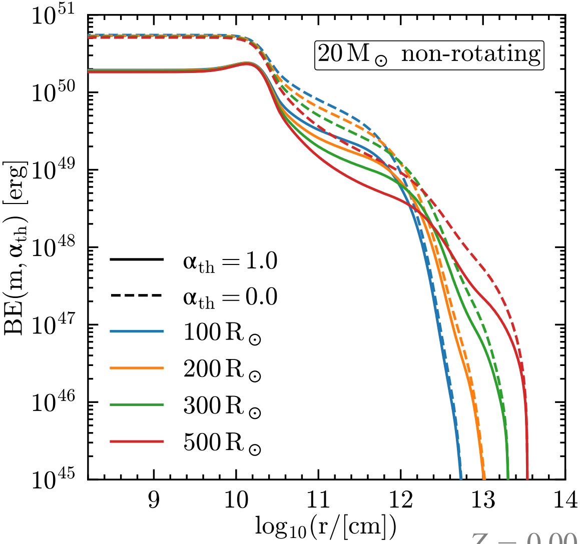
Belczynski *et al.* 16

Does RLOF rejuvenation impact how easy it is to remove the envelope ?

Renzo *et al.* 2023

1. Binary evolution until detachment
2. Continue evolution of accretors as single stars
3. Compare binding energy of accretors and single stars of same total mass at given R

The binding energy is the cost to “dig” into the star



$$BE(m, \alpha_{\mathrm{th}}) = -\int_m^M dm' \left(-\frac{Gm'}{r(m')} + \alpha_{\mathrm{th}} u(m') \right)$$

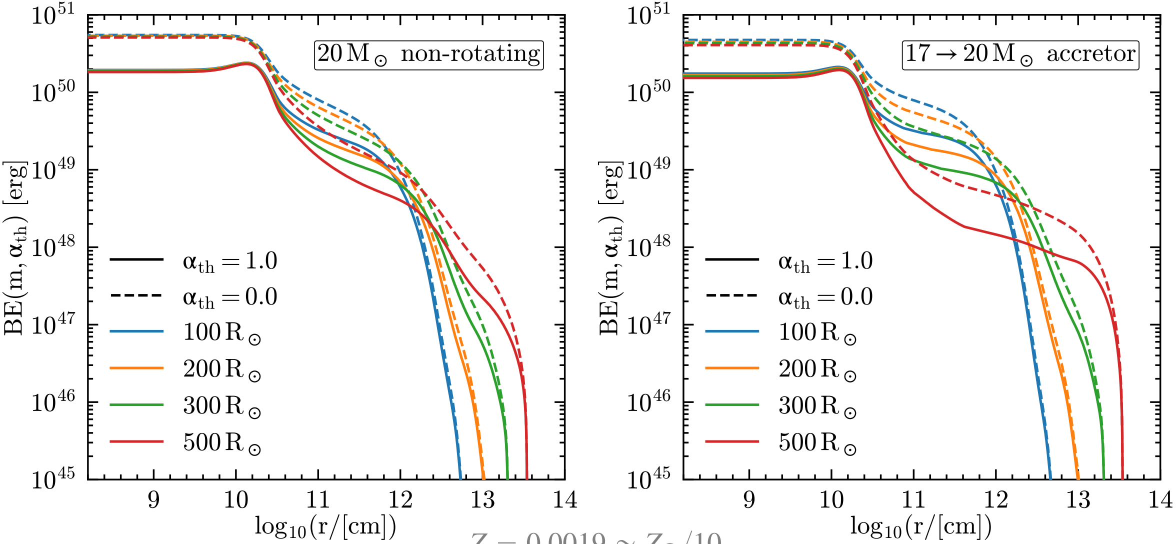
- Gravitational potential energy
- Internal energy
- α_{th} free parameter

fraction of internal energy usable to eject envelope

$Z = 0.0019 \simeq Z_\odot/10$

Renzo *et al.* 2023

Comparing $20\,M_\odot$ non-rotating single star vs. accretor



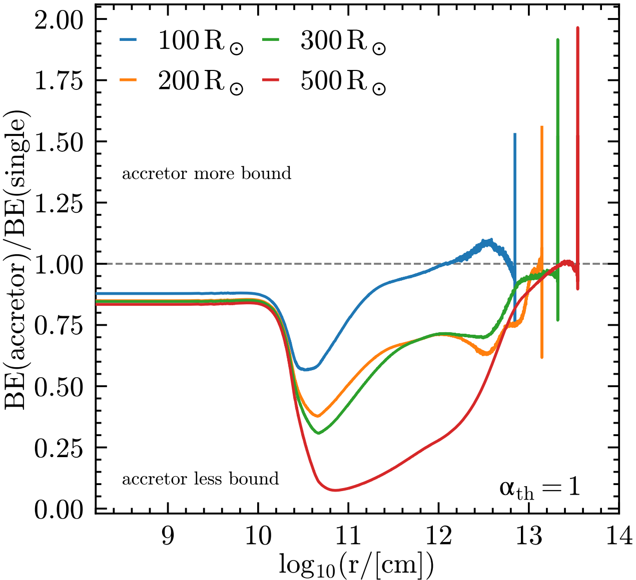
$Z = 0.0019 \simeq Z_\odot/10$

Renzo *et al.* 2023

Taking the ratio: accretors are easier to unbind

NS progenitor

$15 \rightarrow 17\,M_{\odot}$

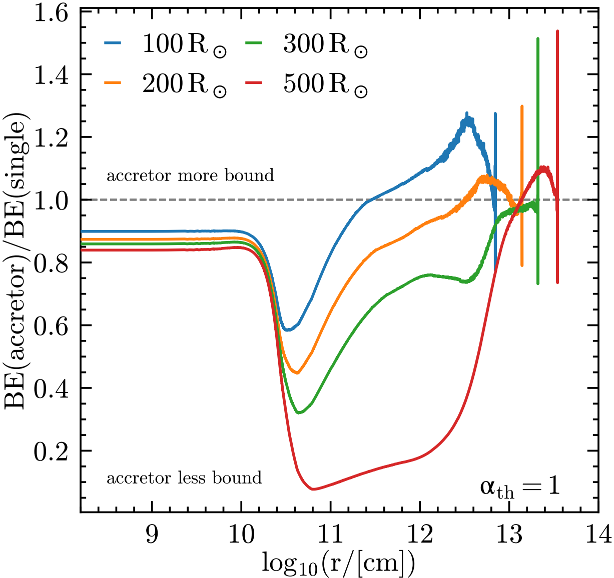


Renzo *et al.* 2023

Taking the ratio: accretors are easier to unbind

NS or BH progenitor

$17 \to 20\,M_\odot$

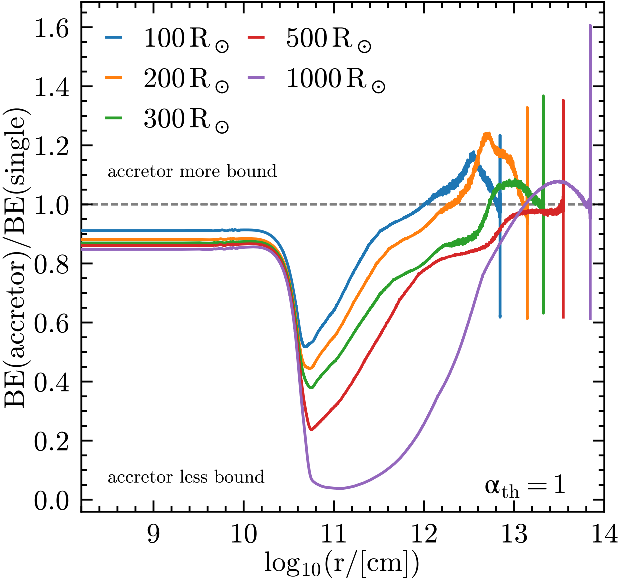


Renzo *et al.* 2023

Taking the ratio: accretors are easier to unbind

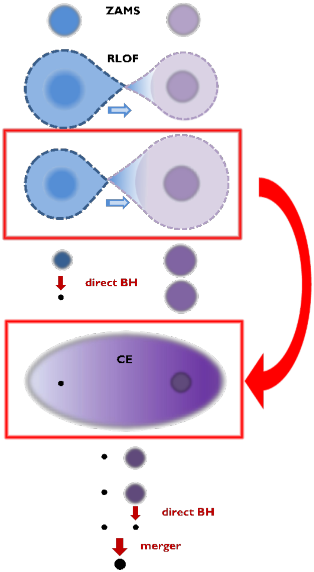
BH progenitor

$30 \rightarrow 36\,M_\odot$



Renzo *et al.* 2023

If the common-envelope donor is a former accretor

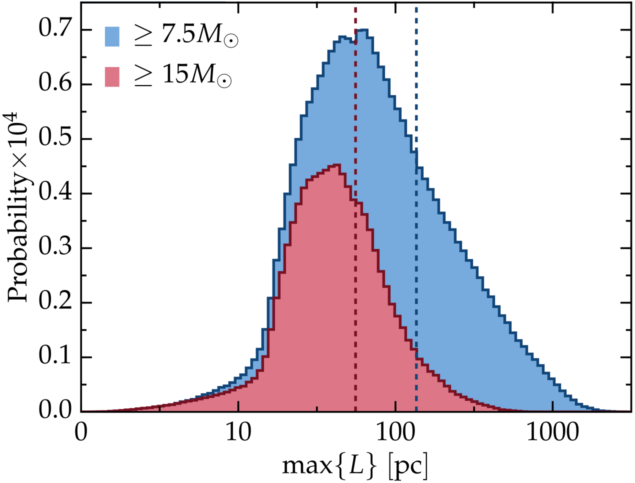


Belczynski *et al.* 16

Implications for common-envelope

- Fewer “reverse” stellar merger
- Wider post-CE separation
- Mass-dependent (?) impact on GW merger rates

How far do they get?

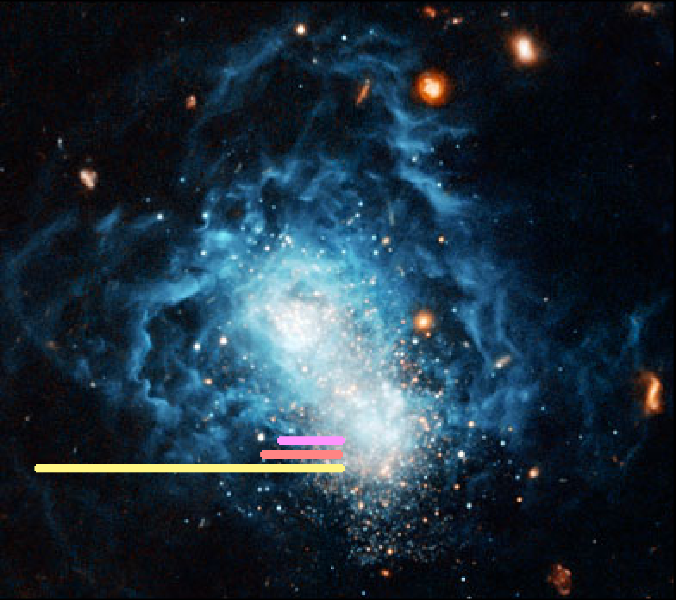


“Distance traveled”

(No potential well)

Renzo *et al.* 19b

Nevertheless: widowed stars can escape local dust clouds



for $M \geqslant 7.5\,M_\odot$:

$\langle D\rangle = 128\,\mathrm{pc}$

$\langle D_\mathrm{run}\rangle = 525\,\mathrm{pc}$

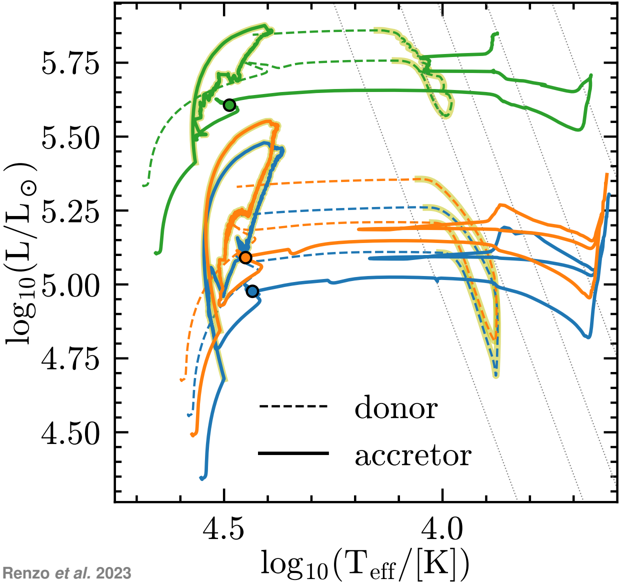
$\langle D_\mathrm{walk}\rangle = 103\,\mathrm{pc}$

Renzo *et al.* 19b

I Zw18

Credits: ESA/Hubble & Nasa, A. Aloisi

Low-Z massive accretors



$Z = 0.0019 \simeq Z_\odot/10$

(to focus on GW merger progenitors)

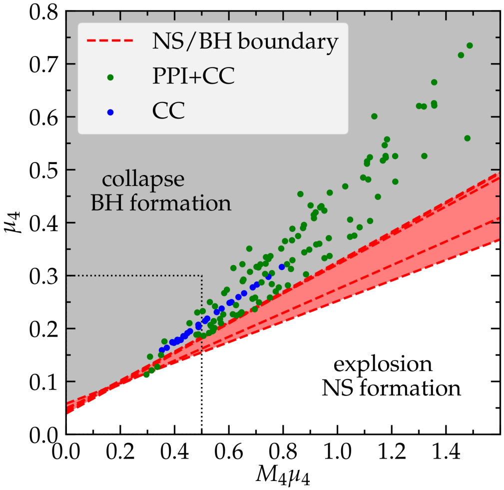
Renzo *et al.* 2023

PPISN explodability

Population synthesis implementation

Can the final core-collapse result in an explosion?

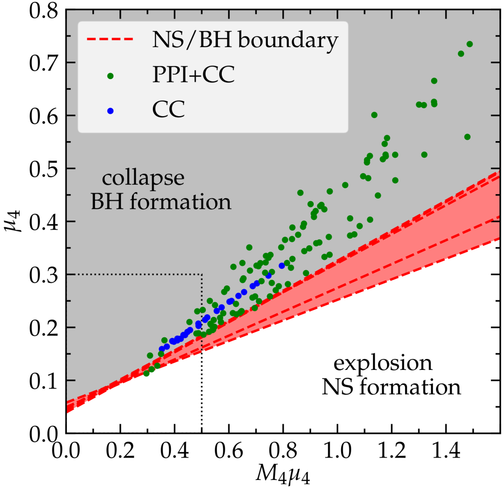
Parametric 1D explodability criteria
are not really applicable.

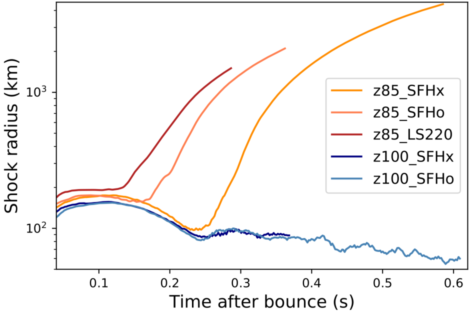


Renzo, Farmer, *et al.* 2020b, see also Ertl *et al.* 2016,2020, O'Connor & Ott 2011, Müller & Mandel 2020, Couch *et al.* 2020

Can the final core-collapse result in an explosion?

Parametric 1D explodability criteria
are not really applicable.





Powell, Muëller, Heger 2021

$$\max \Delta M_{\rm CC} \lesssim 3.5\,M_\odot$$

from ν-driven engines

Rahman *et al.* 2021

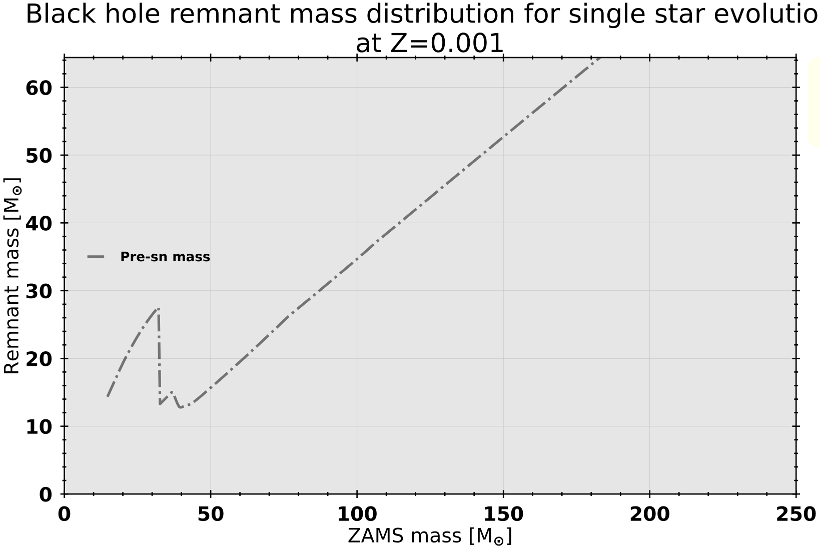
Renzo, Farmer, *et al.* 2020b, see also Ertl *et al.* 2016,2020, O'Connor & Ott 2011, Müller & Mandel 2020, Couch *et al.* 2020

PPISN explodability

Population synthesis implementation

Population synthesis: $M_{\text{initial}} \underset{\dagger}{\rightarrow}$ CO core mass† → BH mass

†and composition! (Patton & Sukhbold 2020)



“Initial mass”

Hendriks, van Son, Renzo *et al.* 2023

Fryer *et al.* 2012

see also Fryer *et al.* 22, Olejak *et al.* 22

see also:
Belczynski *et al.* 2016, Spera & Mapelli 2017, Stevenson *et al.* 2019, Mandel & Müller 2020, **van Son *et al.* 2021**, **Renzo *et al.* 2022, Farag *et al.* 2022** ...

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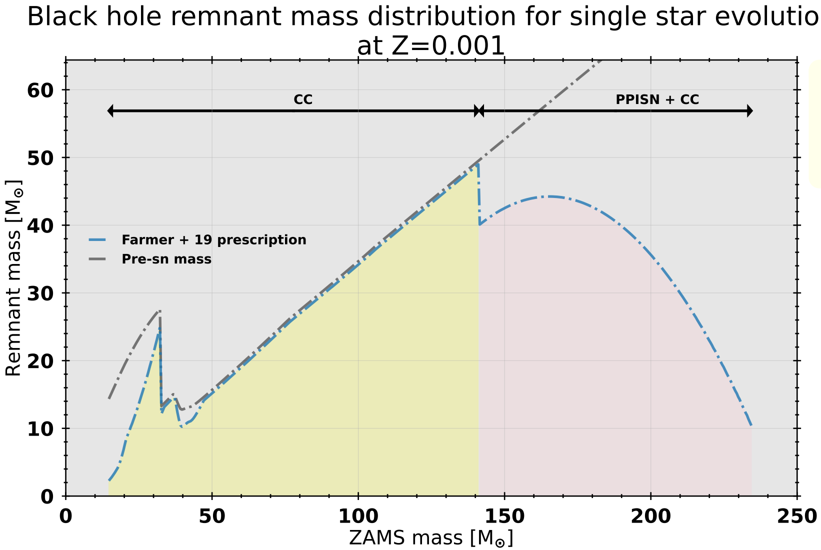
Population synthesis: $M_{\mathrm{initial}} \rightarrow$ CO core mass† $\rightarrow$ BH mass

†and composition! (Patton & Sukhbold 2020)



"Initial mass"

Hendriks, van Son, Renzo *et al.* 2023

Fryer *et al.* 2012

+

Farmer *et al.* 2019

see also:
Belczynski *et al.* 2016, Spera & Mapelli 2017, Stevenson *et al.* 2019, Mandel & Müller 2020, **van Son *et al.* 2021**, **Renzo *et al.* 2022**, **Farag *et al.* 2022** ...

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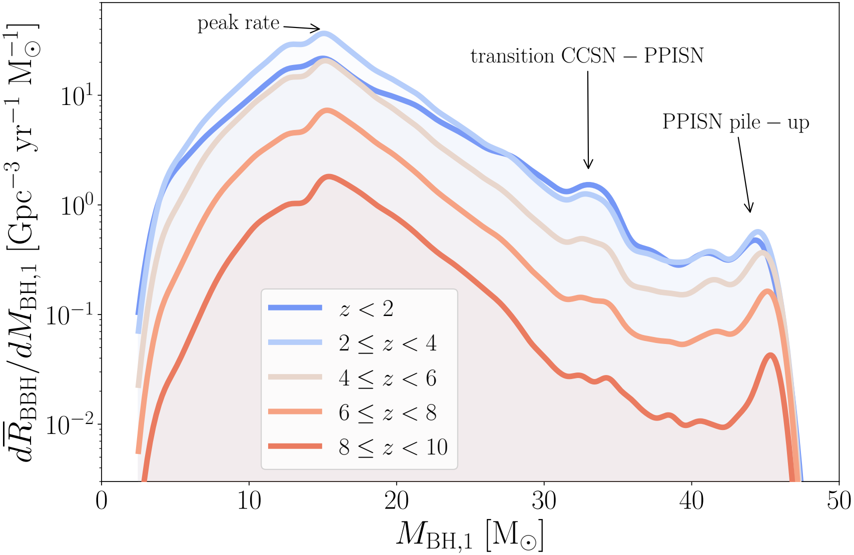
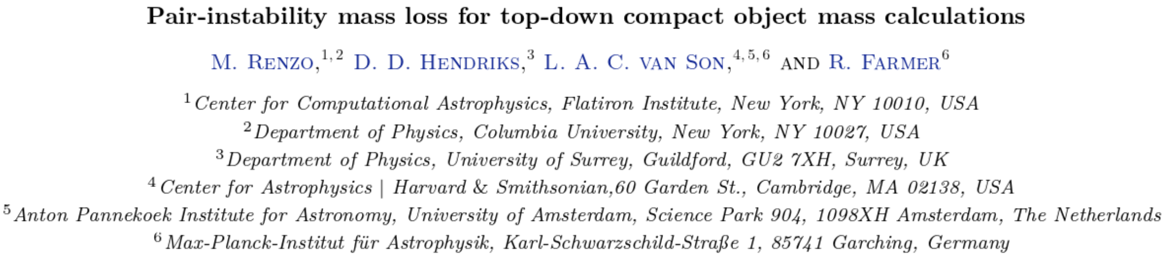
Using “recipes” out-of-the-box leads to artificial features

“Binary BH merger rate”



“biggest BH mass”

van Son *et al.* (incl. MR) 2021



Pair-instability mass loss for top-down compact object mass calculations

M. Renzo,[1,2] D. D. Hendriks,[3] L. A. C. van Son,[4,5,6] and R. Farmer[6]

[1] Center for Computational Astrophysics, Flatiron Institute, New York, NY 10010, USA
[2] Department of Physics, Columbia University, New York, NY 10027, USA
[3] Department of Physics, University of Surrey, Guildford, GU2 7XH, Surrey, UK
[4] Center for Astrophysics | Harvard & Smithsonian,60 Garden St., Cambridge, MA 02138, USA
[5] Anton Pannekoek Institute for Astronomy, University of Amsterdam, Science Park 904, 1098XH Amsterdam, The Netherlands
[6] Max-Planck-Institut für Astrophysik, Karl-Schwarzschild-Straße 1, 85741 Garching, Germany

$$M_{\mathrm{BH}} = M_{\mathrm{proto-NS}} + M_{\mathrm{fallback}}$$

(e.g., Fryer *et al.* 2012, 2022)

$$\Downarrow$$

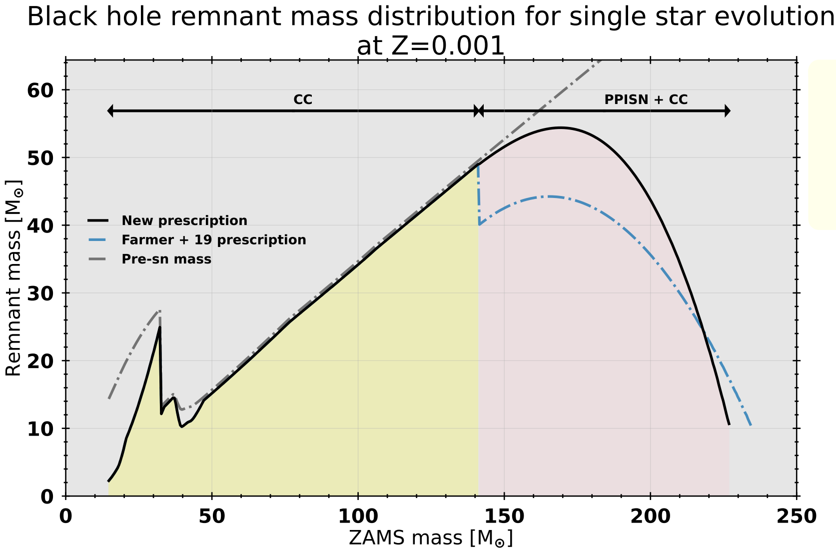
$$M_{\mathrm{BH}} = M_{\mathrm{pre-explosion}} - \left(\Delta M_{\mathrm{SN}} + \Delta M_{\nu,\mathrm{core}} + \Delta M_{\mathrm{env}} + \Delta M_{\mathrm{PPI}} + \cdots\right)$$

New fit to **Farmer, Renzo *et al.* 2019**

Renzo *et al.* 2022

Population synthesis: $M_{\rm initial} \rightarrow$ CO core mass† → BH mass

† and composition! (Patton & Sukhbold 2020)



“Initial mass”

Fryer *et al.* 2012

\+

~~**Farmer *et al.* 2019**~~

Renzo *et al.* 2022

David D. Hendriks

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Hendriks, van Son, Renzo *et al.* 2023

Population synthesis: $M_{\rm initial}$ → CO core mass† → BH mass

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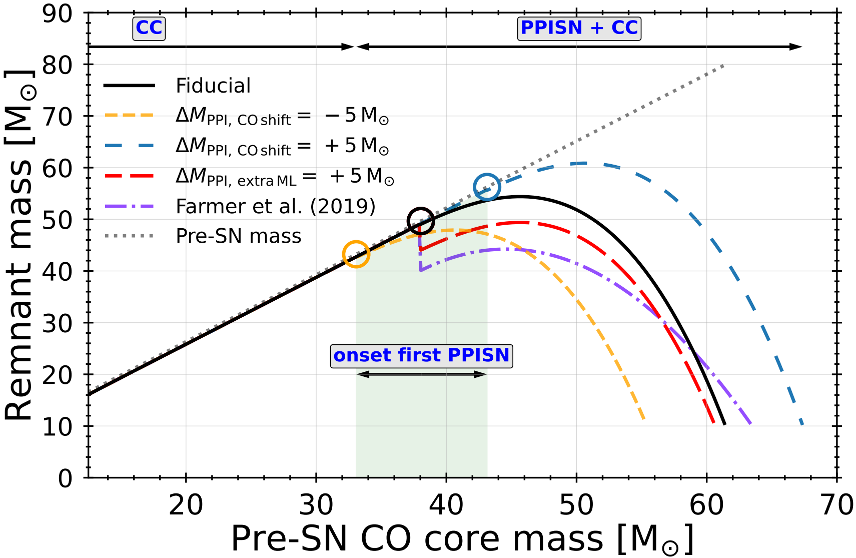


Fryer *et al.* 2012

+

~~**Farmer *et al.* 2019**~~

Renzo *et al.* 2022

David D. Hendriks

Univ. Surrey

Hendriks, van Son, Renzo *et al.* 2023

“Classical” wisdom: core and envelope decouple late in the evolution

$$L_{\nu,\mathrm{cooling}} \gg L_{\gamma}$$

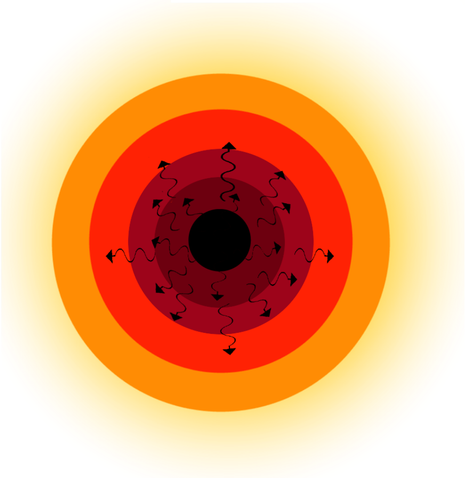
e.g., Fraley 1968

$$\Downarrow$$

$$\tau_{\mathrm{nuc}}(m \leqslant M_{\mathrm{core}}) \ll \tau_{\mathrm{KH}}$$

$$\Downarrow$$

“Frozen-envelope”



Observational evidence that core and envelope do not decouple

$$L_{\nu,\mathrm{cooling}} \gg L_{\gamma}$$

e.g., Fraley 1968

$$\Downarrow$$

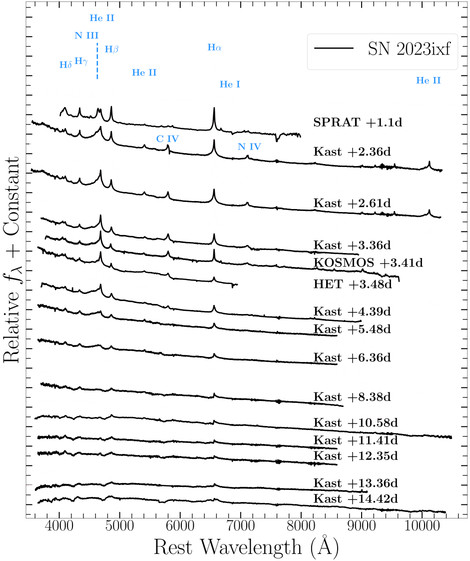
$$\tau_{\mathrm{nuc}}(m \leqslant M_{\mathrm{core}}) \ll \tau_{\mathrm{KH}}$$

Late mass-ejection episodes are common

- $\gtrsim 36\%$ and possibly up to $\sim 50\%$ of type II SNe
- $\dot{M} \gtrsim 10^{-3}\, M_{\odot}\ \mathrm{yr}^{-1}$ within 10^{2-3} days pre-explosion
- Later SN looks "normal"

Bruch *et al.* 2023, see also, e.g., Kochanek 2012, Khazov *et al.* 2016

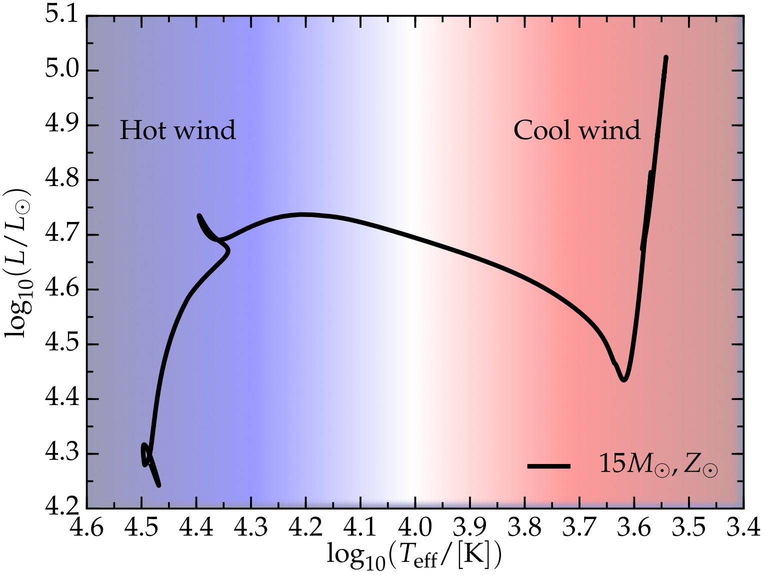
see also Igataki 2023, Jencson *et al.* 2023, Berger *et al.* 2023,
Kilpatrick *et al.* 2023, Neustadt *et al.* 2023, ...



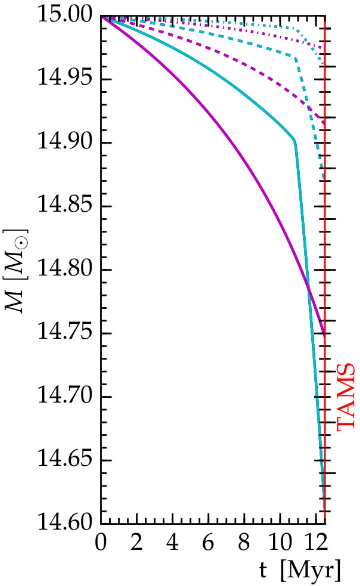
modified from Jacobson-Galan *et al.* 2023

Single star wind uncertainties

Combination of algorithms



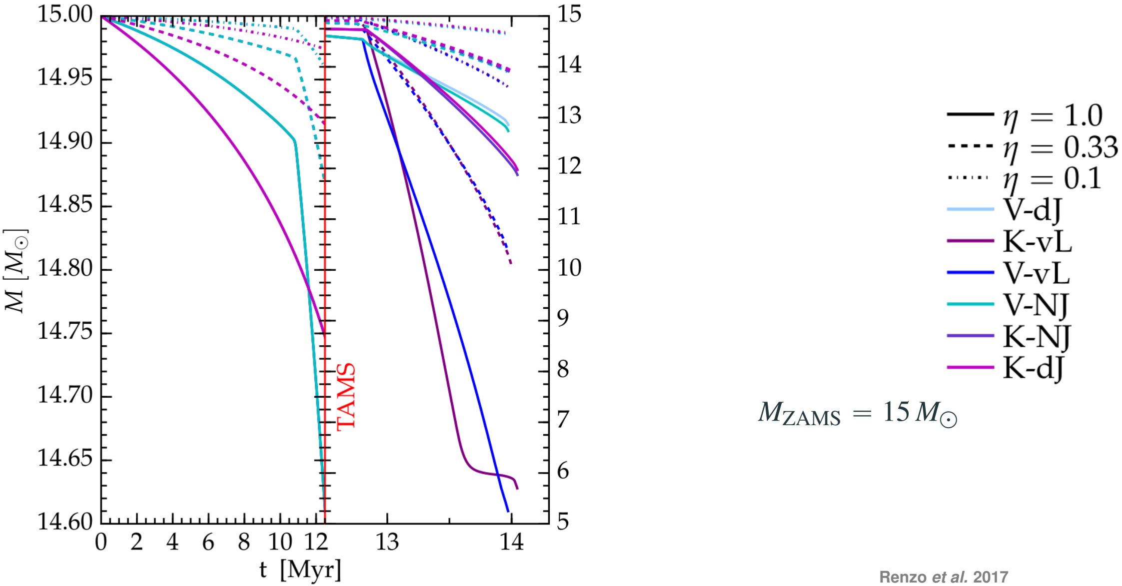
Wind mass loss history



$$M_{\rm ZAMS} = 15\,M_\odot$$

Renzo *et al.* 2017

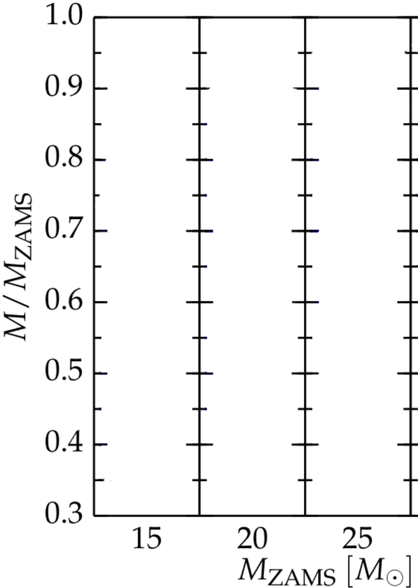
Wind mass loss history



$M_{\mathrm{ZAMS}} = 15\,M_\odot$

Renzo *et al.* 2017

Impact on the final mass



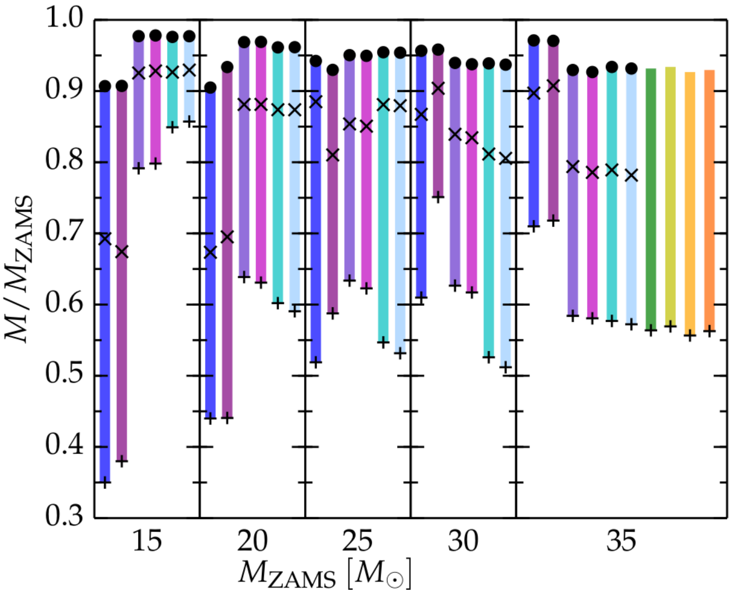
MESA

Legend:

- ● $\eta = 0.1$
- x $\eta = 0.33$
- + $\eta = 1.0$

Renzo *et al.* 2017

Impact on the final mass



MESA

Legend:

- ● $\eta = 0.1$
- **x** $\eta = 0.33$
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Renzo *et al.* 2017