Supernova progenitors and surroundings

Mathieu Renzo

FLATIRON INSTITUTE
Center for Computational Astrophysics

Collaborators: Y. Götberg, E. Zapartas, S. Justham, K. Breivik, L. van Son, R. Farmer, M. Cantiello, B. D. Metzger, C. Xin, E. Farag, S. Oey, S. de Mink, ...

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→ ARIZONA

(Postdoc position
to be announced)

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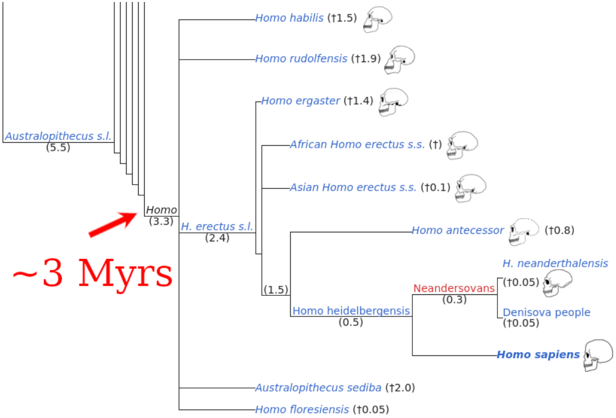
What do massive stars and humans have in common?

The most massive stars live as long as the genus *Homo* has been around



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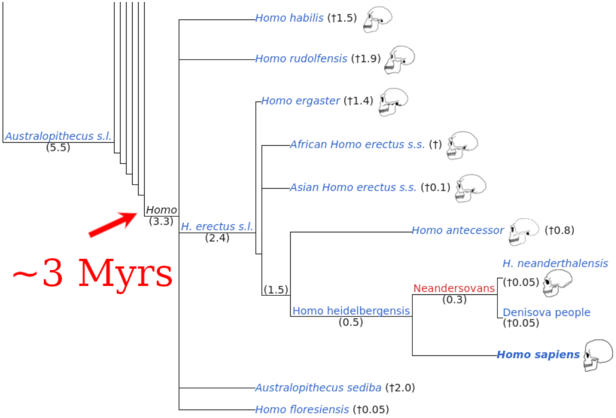
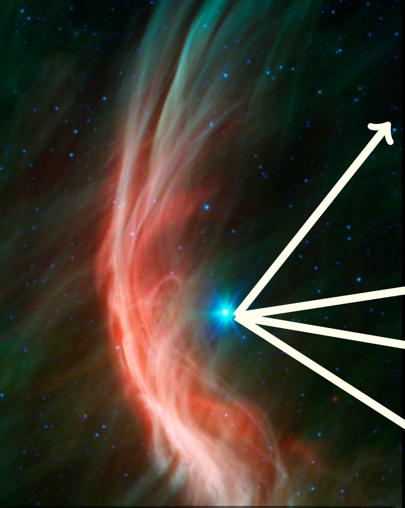


They have a *large* influence on their environment

Massive stars shape their environment & the Universe as a whole



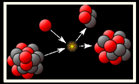
ζ Ophiuchi,
$D = 107 \pm 4\,\mathrm{pc}$
Walker *et al.* 1979, Zee *et al.* 2018, ...,
Neuhauser *et al.* 2020, **Renzo & Götberg 2021**

Compact objects
& transients

Ionizing rad.

Stellar feedback

Star Formation
& cluster evolution



Nucleosynthesis &
chemical evolution

Outline

Single-stars

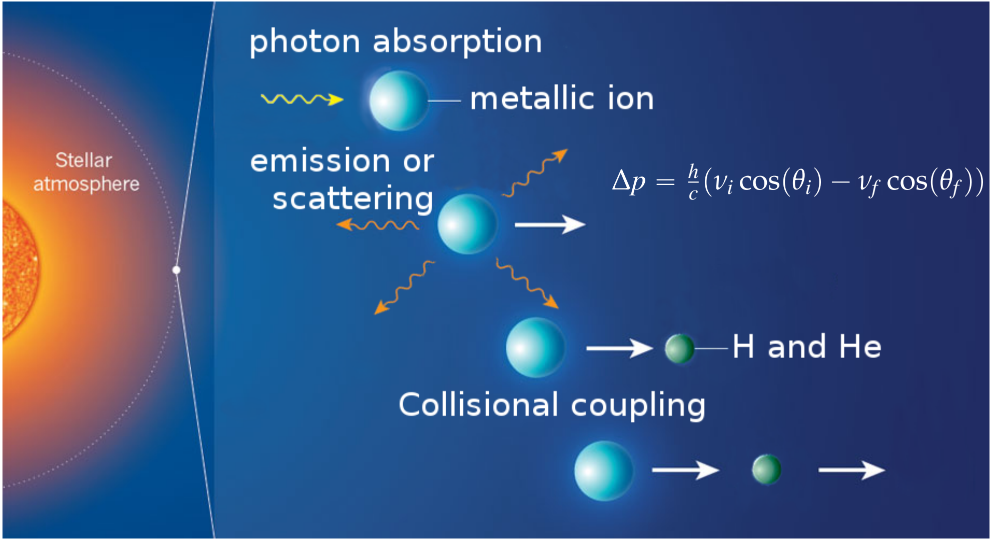
- Wind mass loss
- Eruptions/dynamical ejection

SN in a binary

- Binary interactions as CSM sources
- Asymmetric SN in asymmetric CSM
- “Widowed” companion stars

Explodability

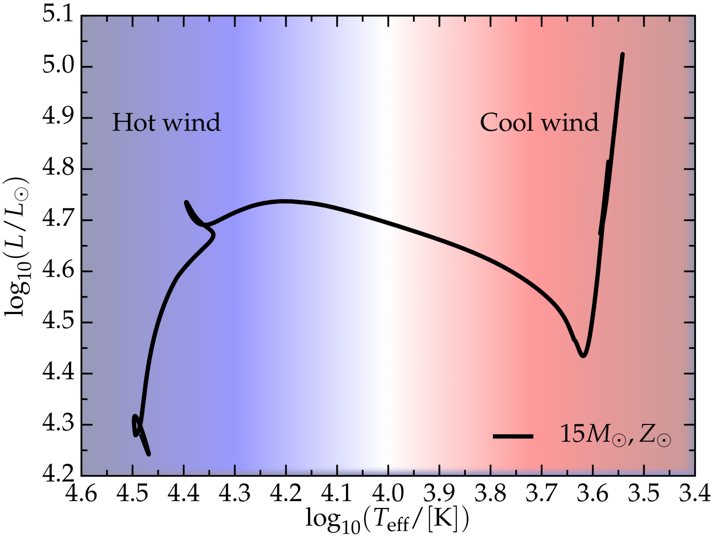
Radiatively Driven Winds in One Slide



Adapted from Offner 2013

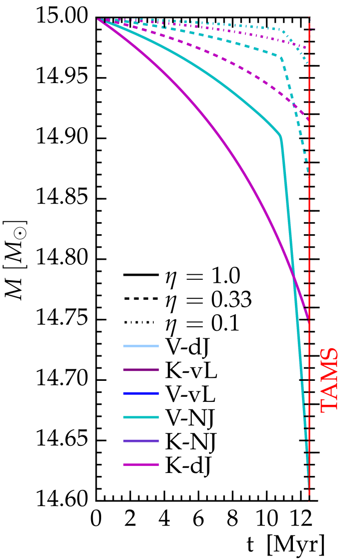
Problems: High Non-Linearity and Clumpiness

Wind driving: Hot ⇒ iron lines, Cool ⇒ pulsations+dust formation ?



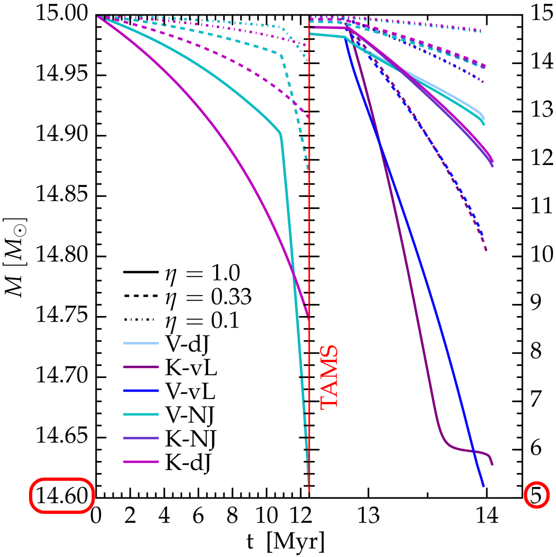
Lucy *et al.* 1970, de Jager *et al.* 1988, Kudritzski *et al.* 1989, Neuwenhuijzen *et al.* 1990, Vink (Jorick) *et al.* 2000, 2001, van Loon *et al.* 2005, Smith 2014, Tramper *et al.* 2016, **Renzo *et al.* 2017**, Beasor *et al.* 2018, 2020 Sanders *et al.* 2020, Kee *et al.* 2021, 2021, Bjorklund *et al.* 2021, 2023, Brands *et al.* 2022, ...

Uncertainties grow with M_{tot} and time



Renzo *et al.* 2017, see also Smith 2014

Uncertainties grow with $M_{\rm tot}$ and time



Renzo *et al.* 2017, see also Smith 2014

Cool winds are a major uncertainty

- Unclear driving mechanism
- Unknown functional dependence
- Only empirical "prescription"

although see Kee *et al.* 2021

- $\sim 3-10\times$ uncertainty in $\dot{M}$ (likely overestimate)

de Jager *et al.* 1988, Nieuwenhujzen & de Jager 1990, Fullerton *et al.* 2010, Smith 2014, **Renzo *et al.* 2017**, Beasor *et al.* 2018, 2020, Björklund *et al.* 2021, 2023, Vink & Sabhahit 2023

Steady and homogeneous wind profile

$$\rho_{\mathrm{CSM}}(r) = \frac{\dot{M}}{4\pi r^2 v_{\mathrm{wind}}} \propto \frac{1}{r^2}$$

Stellar winds are not steady nor homogeneous

$$\rho_{\mathrm{CSM}}(r) \neq \frac{\dot{M}}{4\pi r^2 v_{\mathrm{wind}}} \propto \frac{1}{r^2}$$

Stellar winds are clumpy

$\Longrightarrow$

Spatial and temporal variability

- Hard to infer $\dot{M}$ observationally
- Large systematic uncertainties

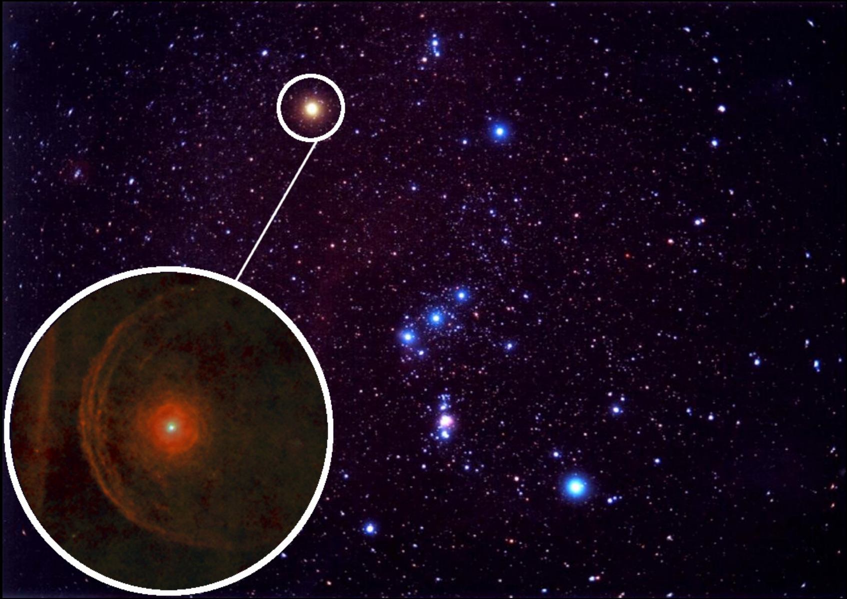
Smith 2014, Vink 2015, **Renzo *et al.* 2017**, Sanders *et al.* 2019, 2020, Beasor *et al.* 2017, 2018, 2019, 2020, 2021, Björklund *et al.* 2020, 2021, 2023, Agrawal *et al.* 2023

Single-stars

Wind mass loss

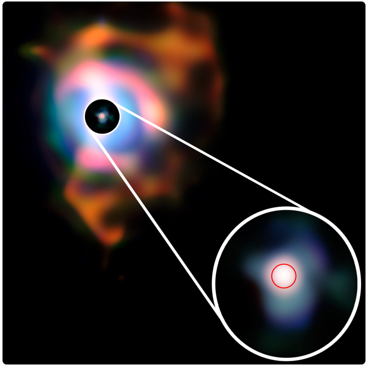
Eruptions/dynamical ejection

Betelgeuse as an example



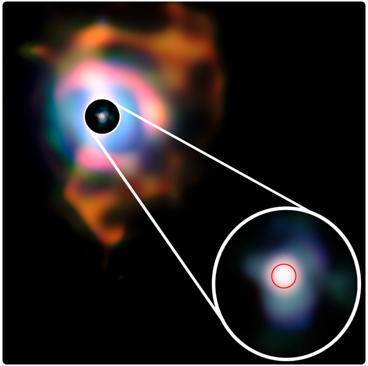
Orion

RSG environments are messy



CSM around Betelgeuse
(ESO/VLT IR)

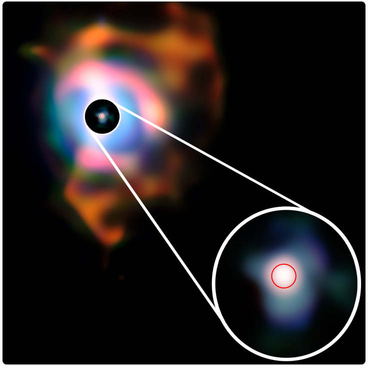
3D Radiation hydro models of RSG envelope convection



CSM around Betelgeuse
(ESO/VLT IR)

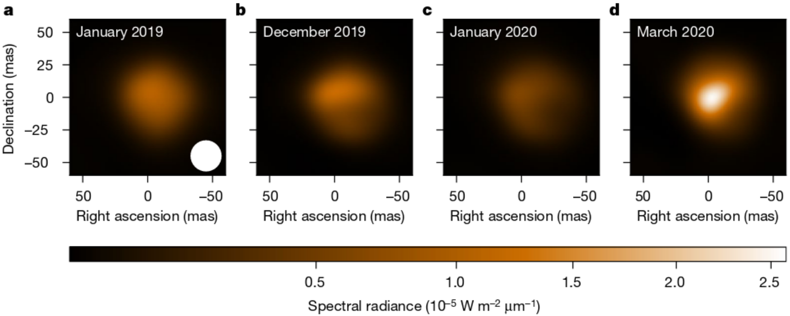
credits J. Goldberg, see Goldberg *et al.* 2022, Chiavassa *et al.* 2015, Ma *et al.* 2023

RSG mass loss is episodic



CSM around Betelgeuse
(ESO/VLT IR)

"Great Dimming": pulsation+convection in phase



Montagres *et al.* 2021

Not unique to Betelgeuse!

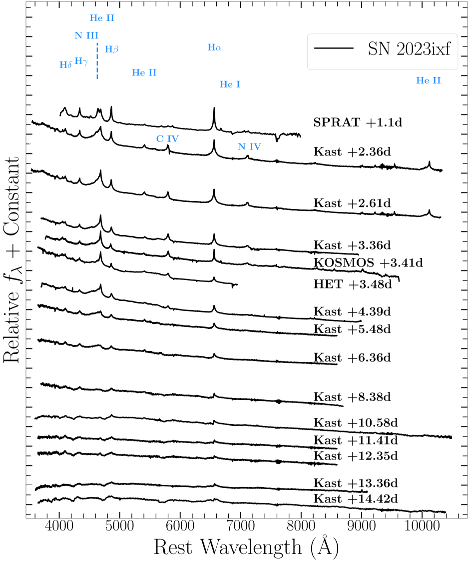
RW Ophiuchi, Anugu *et al.* 2023

SN flash spectroscopy: Hα in emission in the first hours-days

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

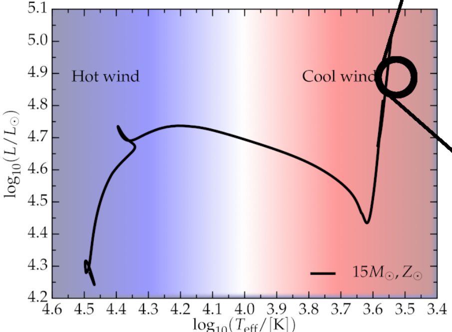


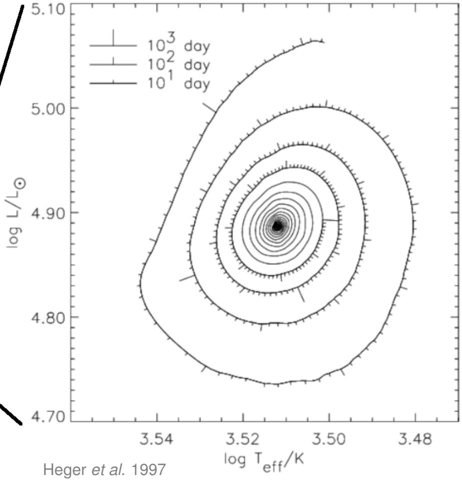
see also Igataki 2023, Jencson *et al.* 2023, Berger *et al.* 2023, Kilpatrick *et al.* 2023, Neustadt *et al.* 2023, ...

modified from Jacobson-Galan *et al.* 2023

Late pulsations during RSG

see also Gould 1968, Yoon & Cantiello 2010, Chiavassa *et al.* 2011, 2015, 2021, Goldberg *et al.* 2021, 2022, Saio *et al.* 2023, ...



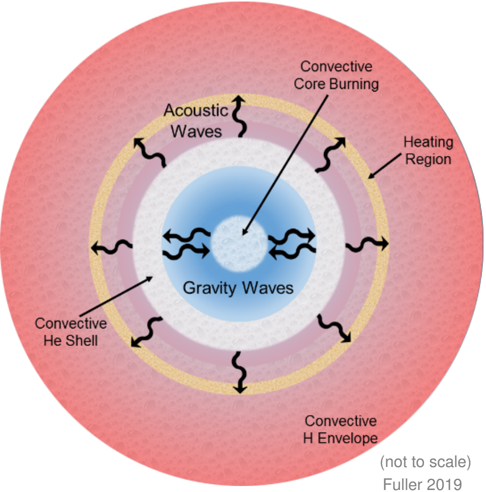


Heger *et al.* 1997

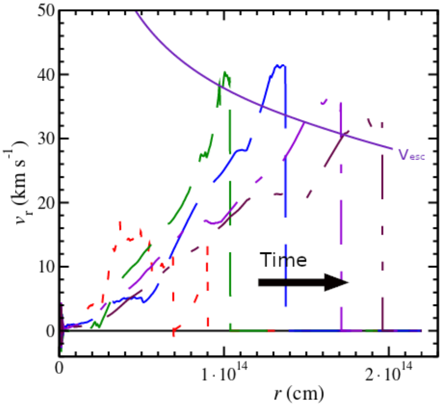
increase in L/M

$P \sim 10^3$ days
lasts $\gtrsim 10^3$ yr

C, O, Ne shell burning may excite waves driving expansion & mass loss



(not to scale)
Fuller 2019



2D hydro

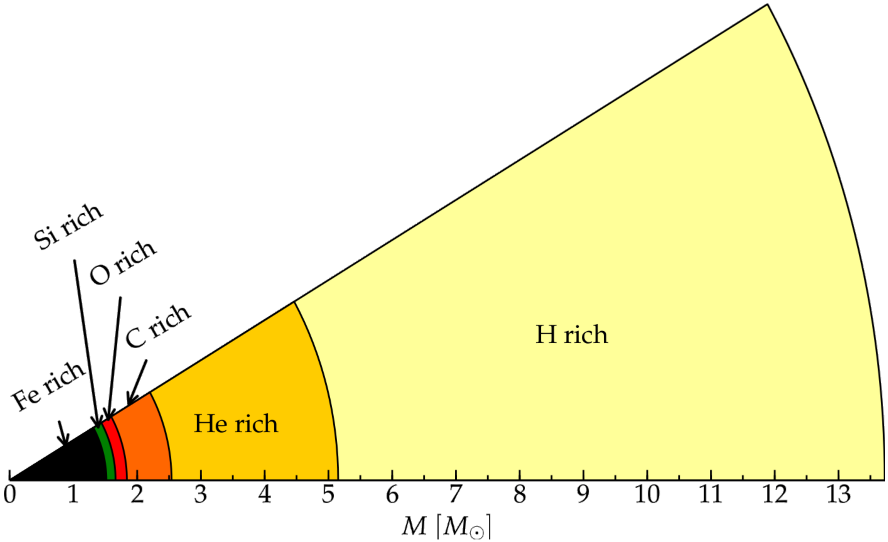
modified from Leung & Fuller 2020

Some L_{nuc} goes into waves

lasts $\lesssim 10^2$ yr small ΔM

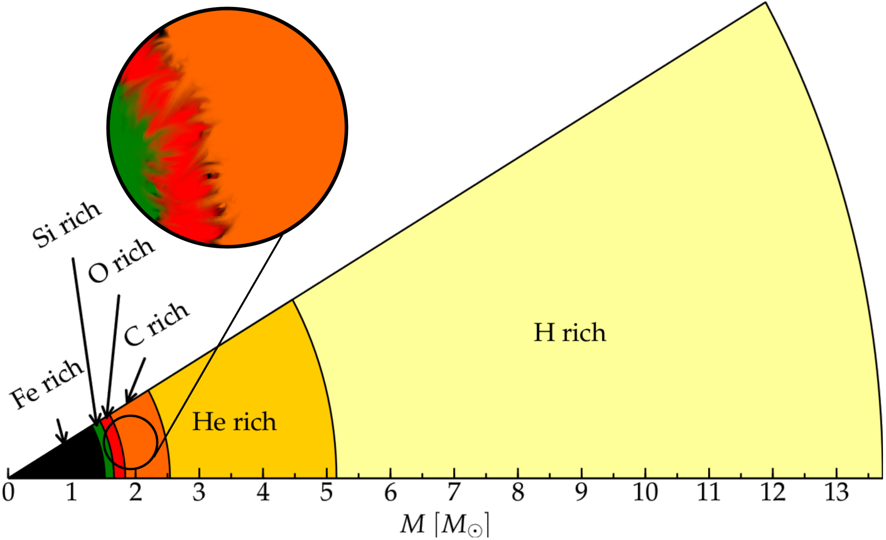
Shiode & Quataert 2012, 2014, Fuller 2018, Fuller & Ro 2019, Leung & Fuller 2020, Linial, Fuller & Sari 2021, Wu & Fuller 2021, 2022, see also Cohen & Soker 2023

Burning shells mergers



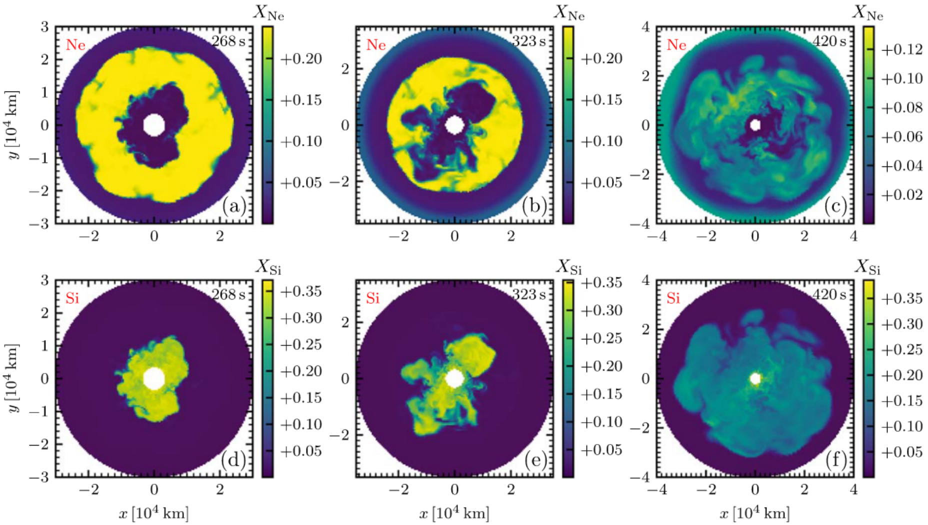
see also Heger & Woosley 2010, Woosley *et al.* 2011, Müller *et al.* 2016, Yadav *et al.* 2020, **Vartanyan *et al.* 2021, Laplace *et al.* 2021**,

Burning shells mergers



see also Heger & Woosley 2010, Woosley *et al.* 2011, Müller *et al.* 2016, Yadav *et al.* 2020, **Vartanyan *et al.* 2021, Laplace *et al.* 2021**,

Burning shell mergers: late outflows? help explosions?



Common and poorly understood

(both in 1D and 3D)

lasts $\lesssim 10\,\mathrm{yr}$

Yadav *et al.* 2020

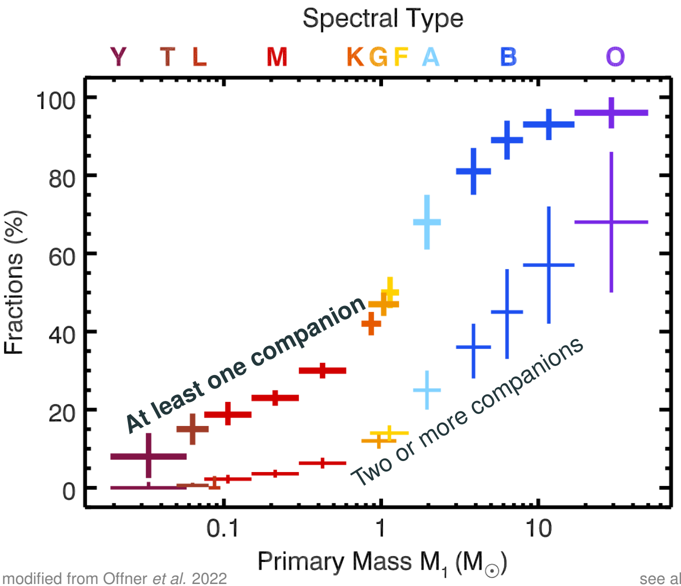
SN in a binary

Binary interactions as CSM sources

Asymmetric SN in asymmetric CSM

“Widowed” companion stars

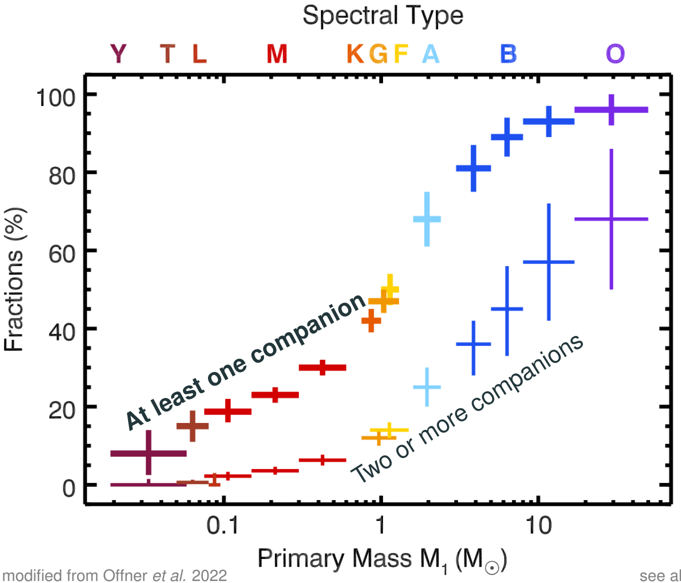
Why binaries? **Most massive stars are born with companion(s)**



modified from Offner *et al.* 2022

see also Mason *et al.* 2010, Kobulnicky & Fryer 2007, Moe & di Stefano 2017

Why binaries? Most massive stars are born with companion(s)



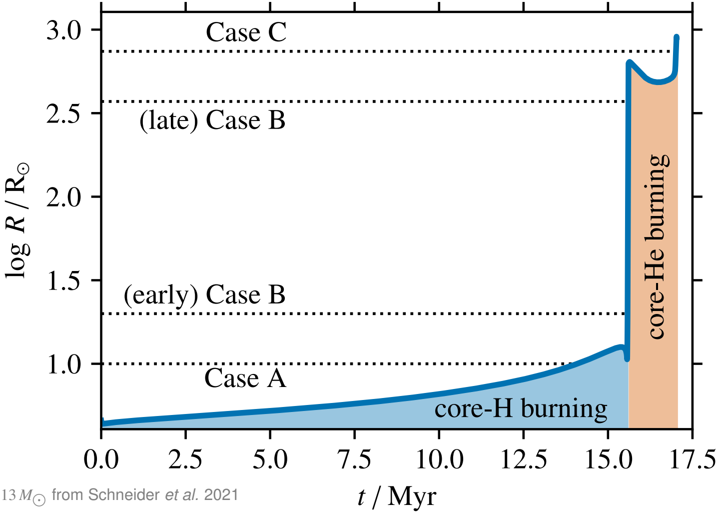
modified from Offner *et al.* 2022

Binary interactions are common

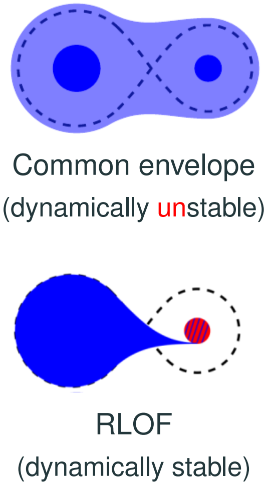
Sana *et al.* 2012

see also Mason *et al.* 2010, Kobulnicky & Fryer 2007, Moe & di Stefano 2017

Binary interaction occur $\sim 0.1 - 10$ Myr pre-collapse

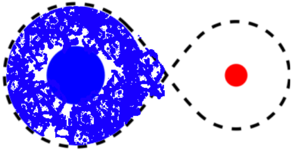


$13\,M_\odot$ from Schneider *et al.* 2021



see also Kippenhahn & Weigert 1967, Lauterborn 1970, Paczynski 1971, 1976, Ulrich & Burger 1976, Kolb *et al.* 1990, ..., Langer 2012, ..., **Renzo *et al.* 2021a,b, 2023**

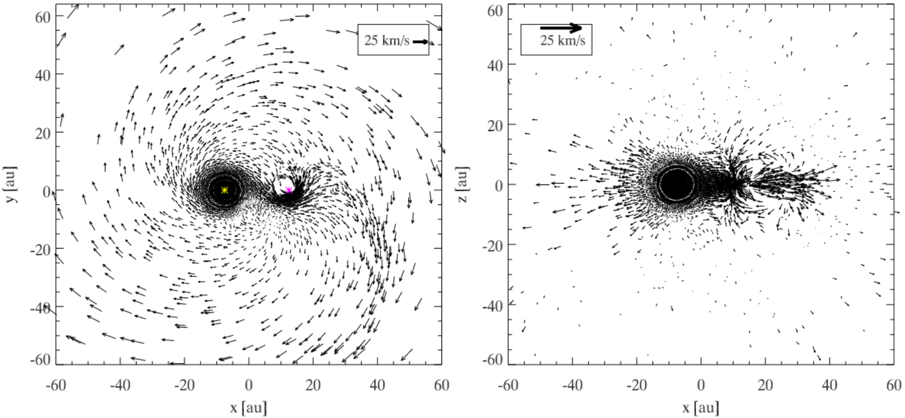
Late case C/wind-RLOF



Sensitive to wind driving mechanism

SPH simulation for Mira

(too small to explode)



see Mohamed & Podsiadlowski 2012, Abate *et al.* 2015

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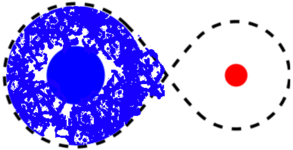

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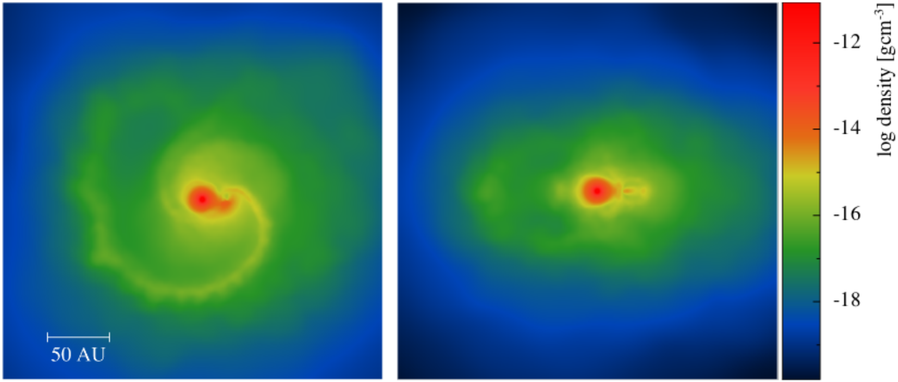


see Mohamed & Podsiadlowski 2012, Abate *et al.* 2015

SN in a binary

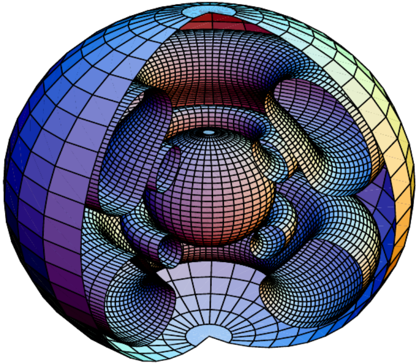
Binary interactions as CSM sources

Asymmetric SN in asymmetric CSM

"Widowed" companion stars

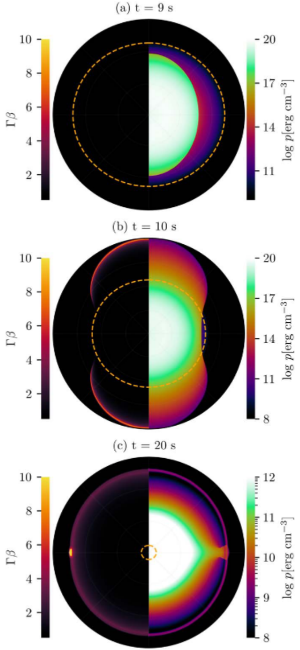
Fast-rotators are centrifugally deformed

⇒ “Ring”-like explosion



Maeder & Meynet 2000

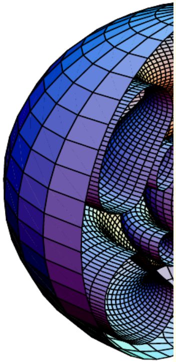
M. DuPont (NYU)

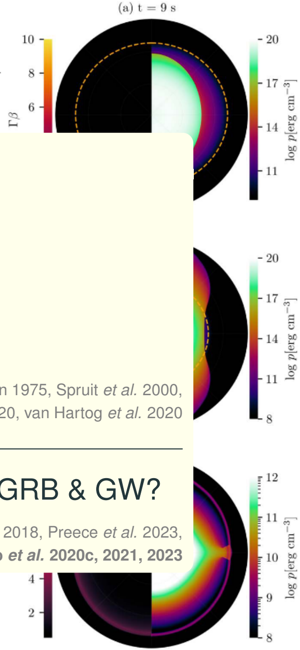


DuPont *et al.* 2022

see also Ramirez-Agudelo *et al.* 2013, 2015, Britavskiy *et al.* 2023,
Britavskiy, Renzo *et al.*, in prep.

Fast-rotators are centrifugally deformed





Difficult to hold on to rotation:

Loss: Wind mass loss (low Z helps)

Loss: Radial expansion

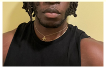
Mix: Meridional circulations

Mix: Magnetic torques

Eddington 1936, Sweet 1950, Zahn 1975, Spruit *et al.* 2000, Fuller *et al.* 2019, Ma & Fuller 2020, van Hartog *et al.* 2020

Q_{theory}: tides? accretion? mergers? lGRB & GW?

Zahn 1977, Hurley *et al.* 2002, Qin *et al.* 2018, Preece *et al.* 2023, Schneider *et al.* 2018, 2019, Chen *et al.* 2020, **Renzo *et al.* 2020c, 2021, 2023**

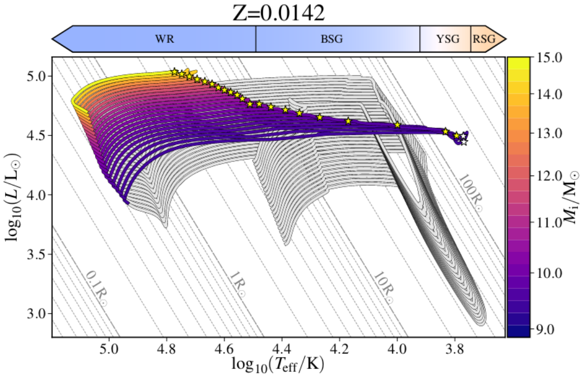


M. DuPont (NYU)

see also Ramirez-Agudelo *et al.* 2013, 2015, Britavskiy *et al.* 2023, **Britavskiy, Renzo *et al.*, in prep.**

DuPont *et al.* 2022

Stripped progenitors may be deformed at CCSN



Even larger R for lower M and Z

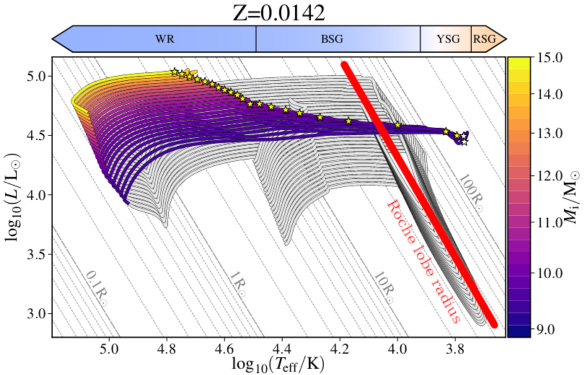
M. DuPont (NYU)

Initially spherical 10^{51} erg explosion

Laplace *et al.* 2020,

Credits: DuPont, Matzner *et al.* 2013, DuPont *et al.* in prep.

Stripped progenitors may be deformed at CCSN



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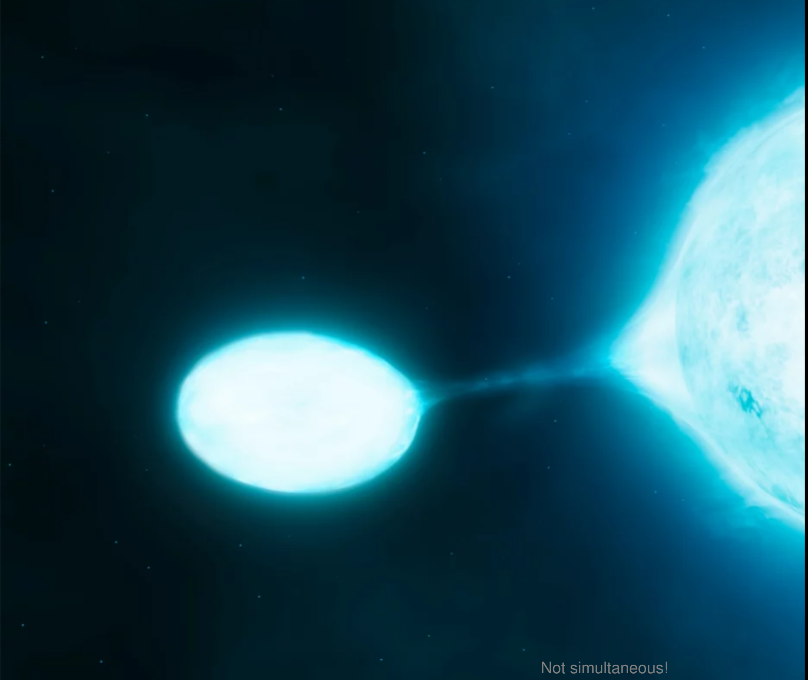
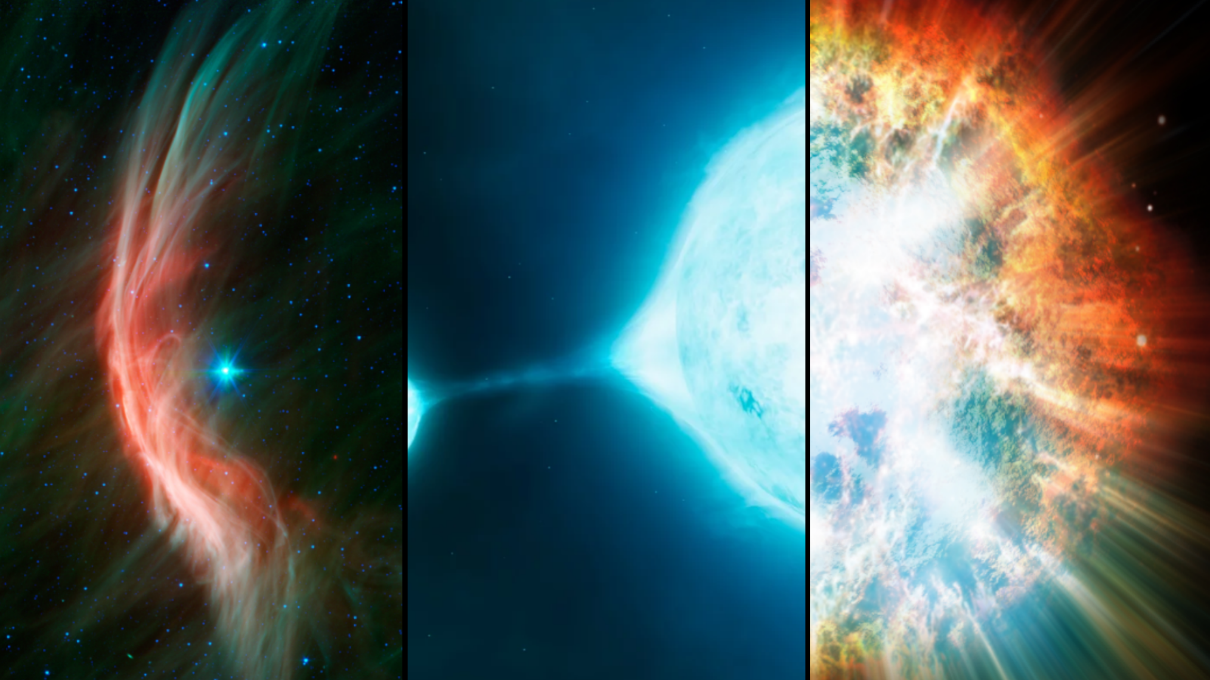
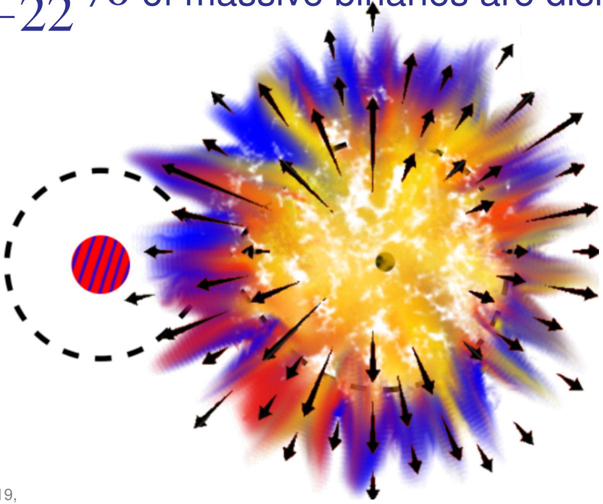


Not simultaneous!



Most massive binaries do not survive the 1st explosion

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



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

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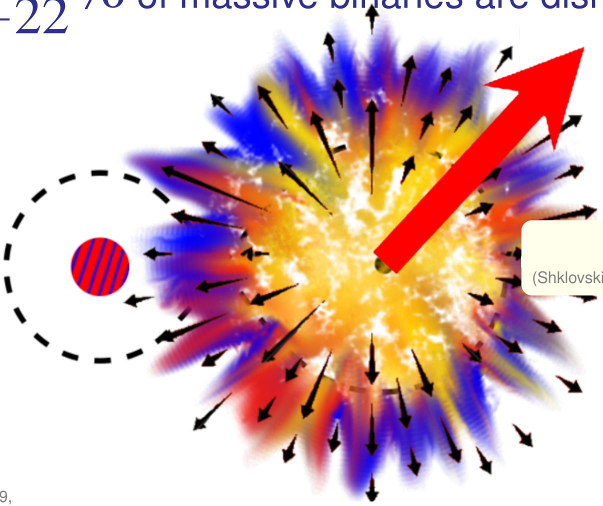


SN Natal kick

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

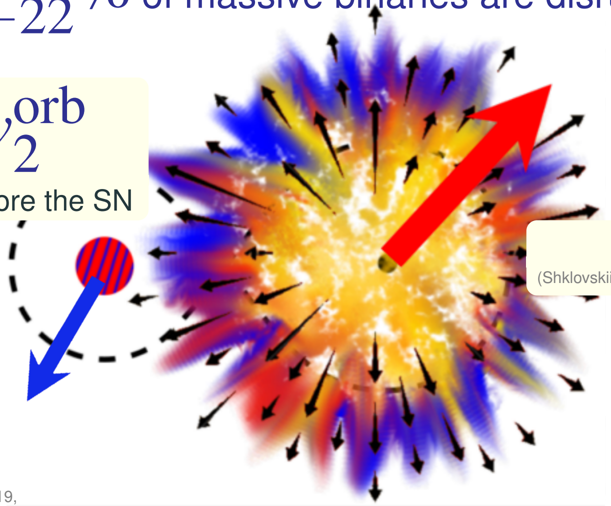
Renzo *et al.* 2019b, Kochanek *et al.* 2019, Eldridge *et al.* 2011, De Donder *et al.* 1997

Most massive binaries do not survive the 1st explosion

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

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

before the SN

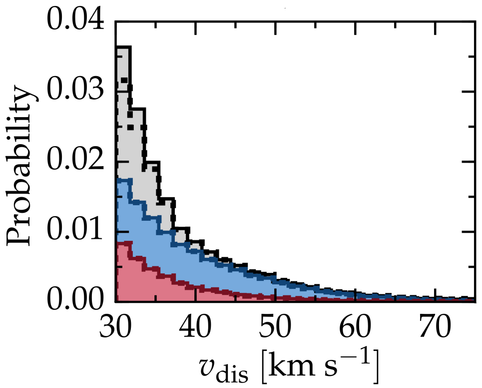


SN Natal kick

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

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

Accretor stars can be *runaways*...

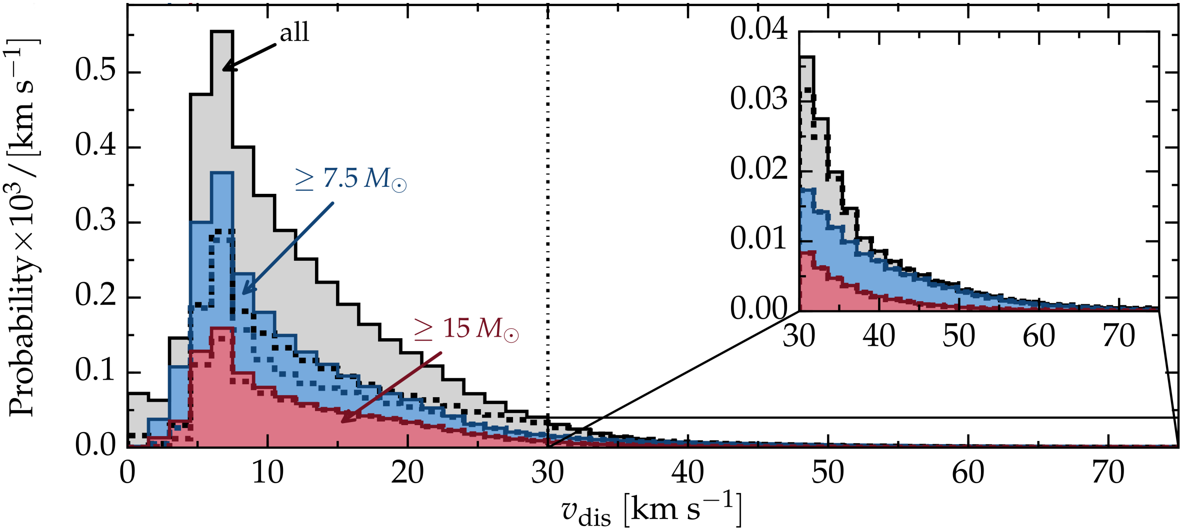


Velocity w.r.t. pre-explosion binary center of mass

Renzo *et al.* 2019b

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

...but most are only *walkaways*



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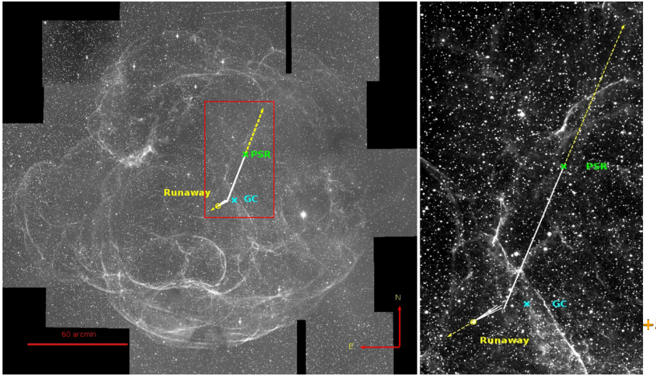
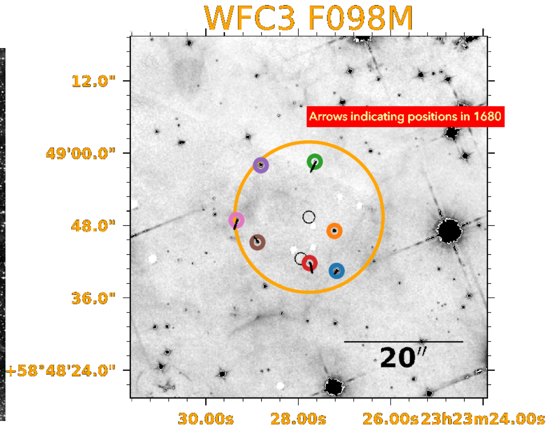
Numerical results: http://cdsarc.u-strasbg.fr/viz-bin/qcat?J/A+A/624/A66

Runaways, wakaways, and X-ray binaries in SNR



Dinçel *et al.* 2015



Kochanek *et al.* 2017, **Kerzendorf *et al.* (incl. Renzo) 2019**

SNR147

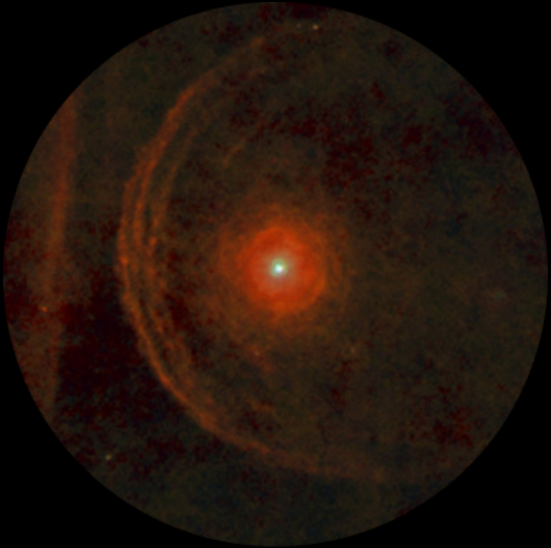
Fast runaway ⇒ post-CE stripped progenitor?

No companion in IIb ⇒ merger, WD, or low mass companion?

For X-ray binary non-detections see Kochanek *et al.* 2019

Bow shocks can also contribute to CSM structure

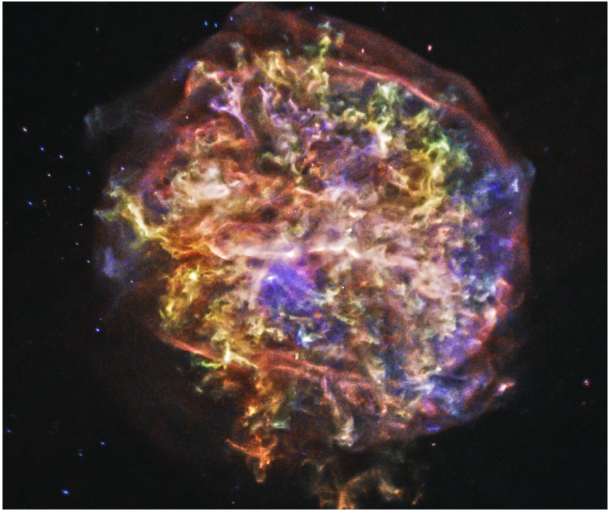
ζ Ophiuchi



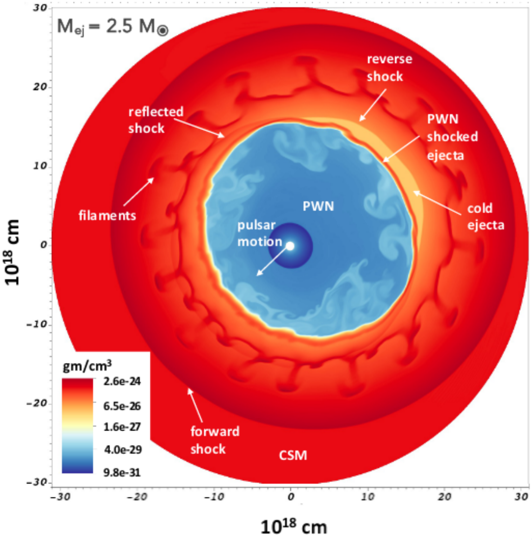
Betelgeuse

Mackey *et al.* 2014, Bodensteiner *et al.* 2018

SNR + Pulsar wind nebula + nucleosynthesis ⇒ Progenitor



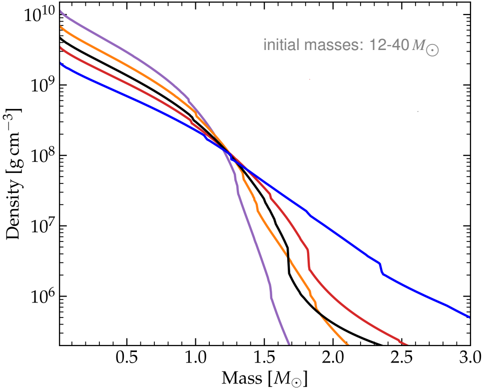
G292.0+1.8, credits *Chandra*



Temim *et al.* (incl. Renzo) 2022

Explodability

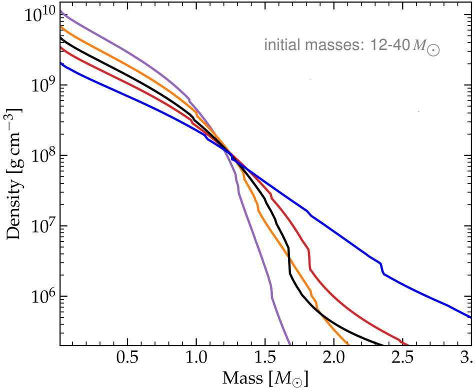
The SN success/failure is determined by the inner density profile



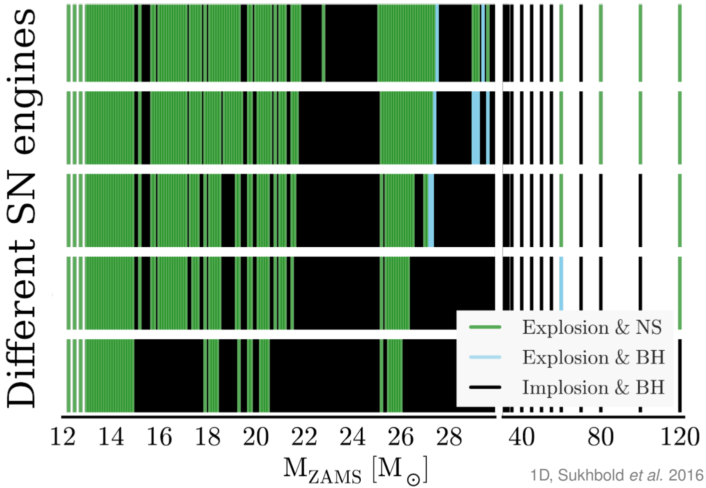
KEPLER models from Woosley *et al.* 2002, 2007
plotted in Ott *et al.* 2018

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

Non-monotonic “explodability” landscape



KEPLER models from Woosley *et al.* 2002, 2007
plotted in Ott *et al.* 2018



1D, Sukhbold *et al.* 2016

Kochanek 2009, O’Connor & Ott 2011, Sukhbold & Woosley 2014, Farmer *et al.* 2016, Ertl *et al.* 2016, 2020, **Renzo *et al.* 2017**, Davies *et al.* 2019, Patton *et al.* 2020, 2021, Mandel & Müeller 2020, **Laplace *et al.* 2021, Vartanyan *et al.* 2021, Zapartas *et al.* 2021**, Adams *et al.* 2017, Basinger *et al.* 2022, Beasor *et al.* 2023, ...

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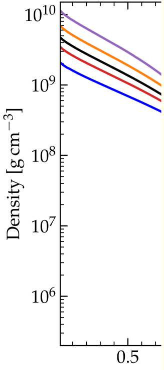
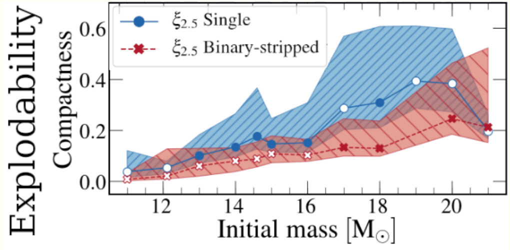


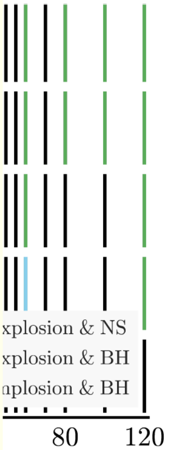
KEPLER models from
plotted in Ott *et al.* 201_

Uncertainties in progenitor evolution dominate

- wind mass loss rate — **Renzo *et al.* 2017**
- internal mixing — Davies *et al.* 2019
- RLOF (for the donor) — **Laplace *et al.* 2021, Vartanyan *et al.* 2021**, Farmer *et al.* 2022



Laplace *et al.* 2021



1D, Sukhbold *et al.* 2016

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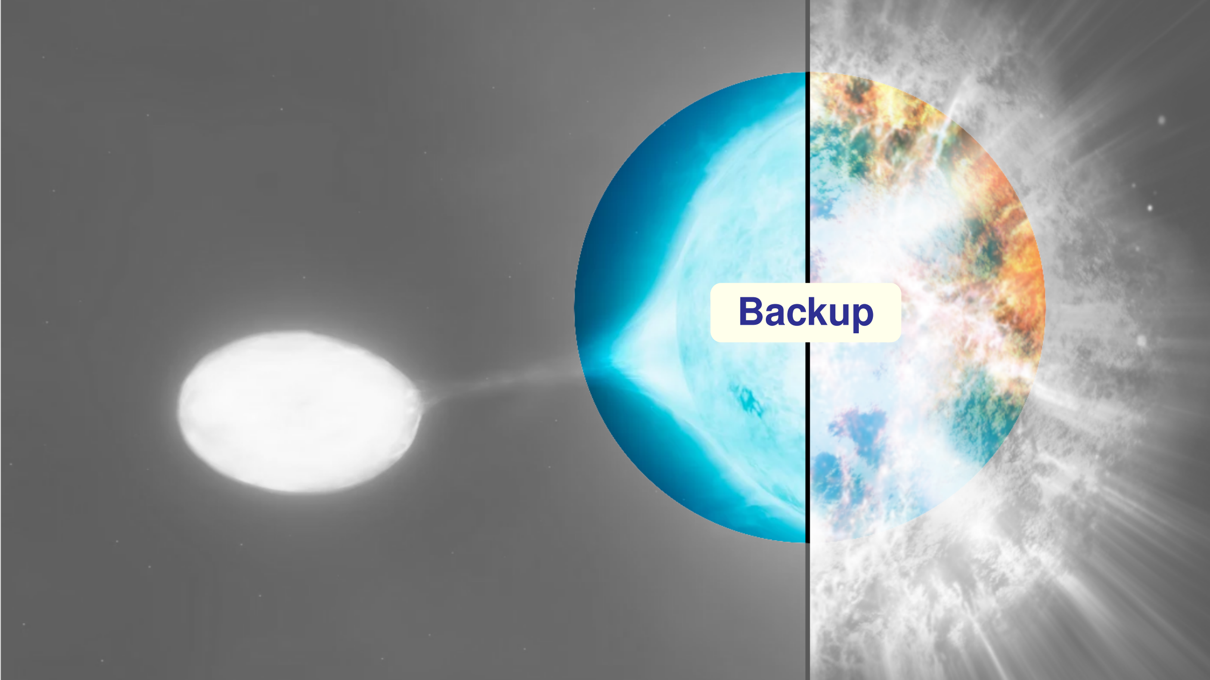
Conclusions

Take home points:

- Progenitor uncertainties dominate CCSN theory
- Mass-loss (winds/eruptions) key to CSM
- Most are in multiple systems
  - RLOF/CE typically too early for CSM[†]
  - can make aspherical exploding stars
  - can change which stars explode/collapse to BH
- Comprehensive modeling (explosion, SNR, companion) can shed light on progenitor life


Backup

What is the fate of the H-rich envelope at BH formation?

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

Possible causes for mass ejection:

- ν-driven shocks

  Nadhezin 80, Lovegrove & Woosley 13, Piro 13, Fernandez *et al.* 18, Ivanov & Fernandez 21

- Jets (even without net rotation)

  Gilkis & Soker 2014, Perna *et al.* 18, Quataert *et al.* 19, Antoni & Quataert 22

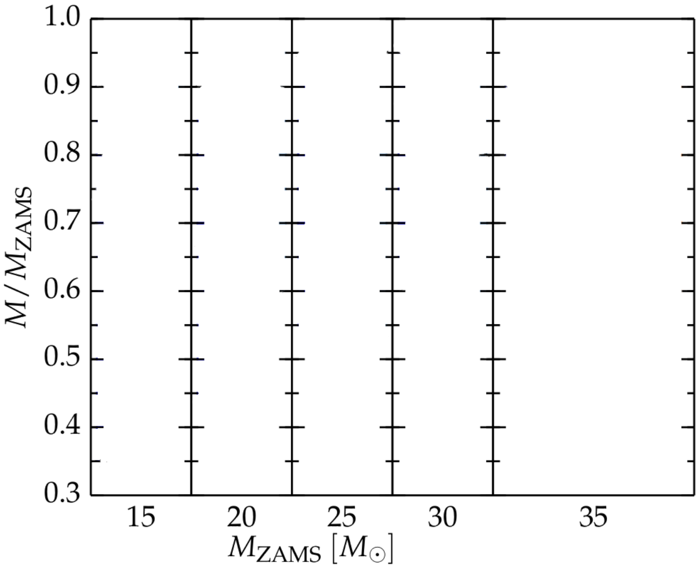
- weak fallback powered explosion

  Ott *et al.* 18, Kuroda *et al.* 18, Chan *et al.* 20, 21

Different predicted outcomes for
RSG/BSG/WR
$\Rightarrow$ Z-dependence

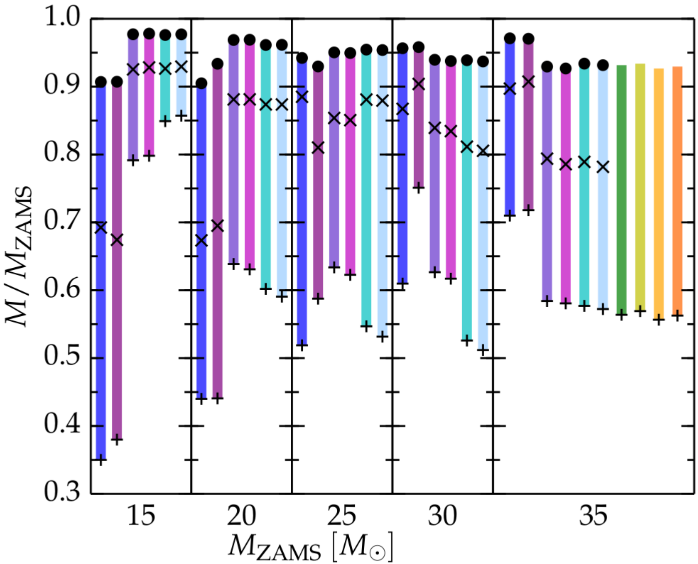
see also Adams *et al.* 17 & Basinger *et al.* 21, Neustadt *et al.* 22, Beasor *et al.* 23, Kochanek *et al.* 23

Uncertainties grow with M and as the stars evolve



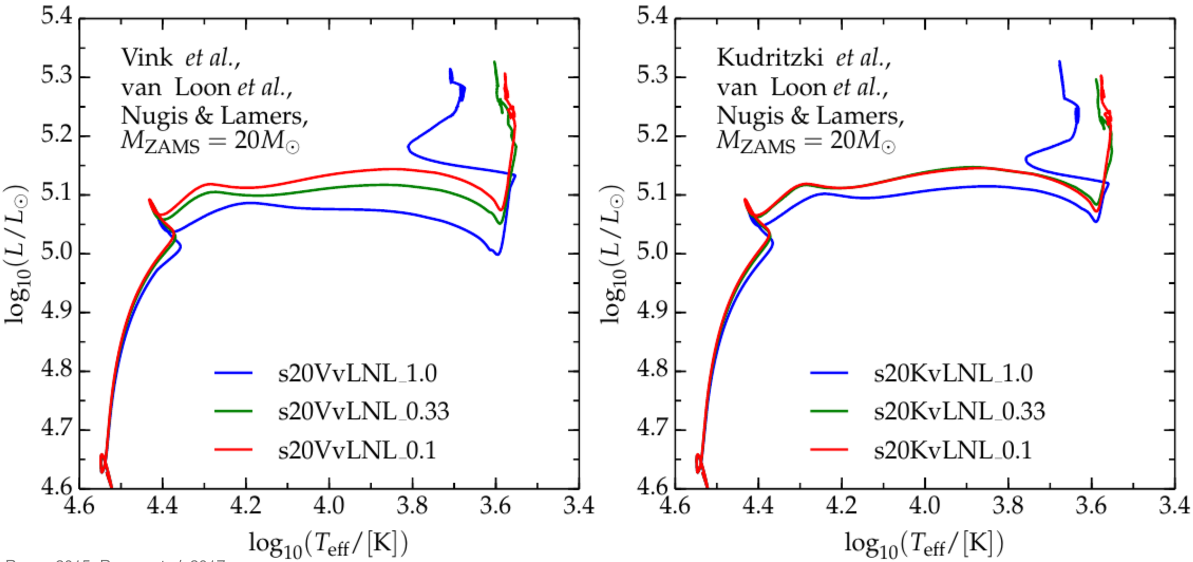
Renzo *et al.* 2017

Uncertainties grow with M and as the stars evolve



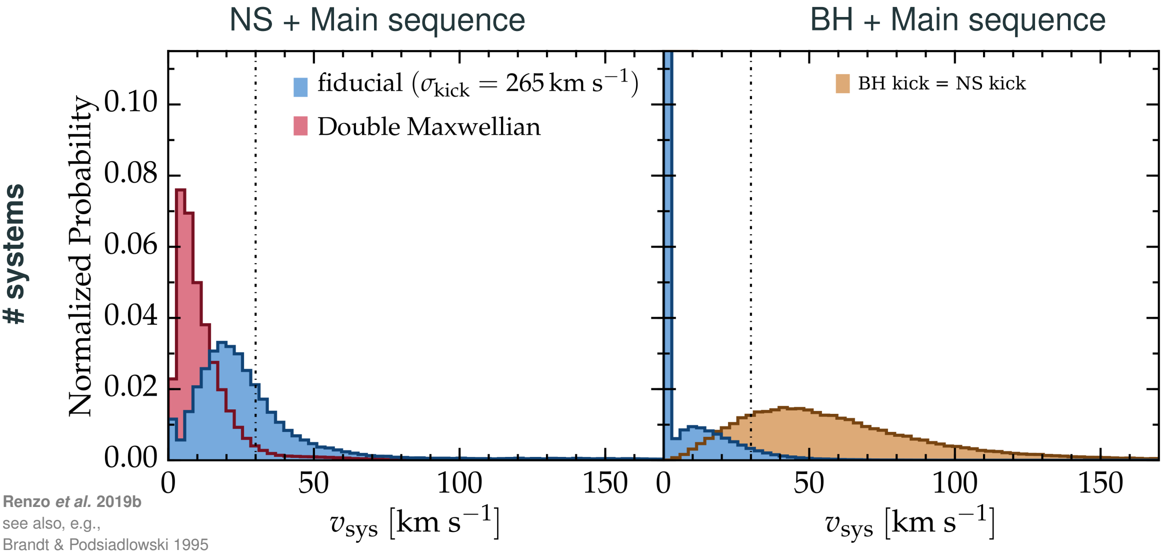
Renzo *et al.* 2017

Early mass loss is gone by core-collapse, but steers the post-MS evolution



Renzo 2015, Renzo *et al.* 2017

Post-SN velocity of surviving binaries



Velocity respect to the pre-explosion binary center of mass

Renzo *et al.* 2019b

see also, e.g.,

Brandt & Podsiadlowski 1995

Kalogera 1996

Tauris & Takens 1998

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