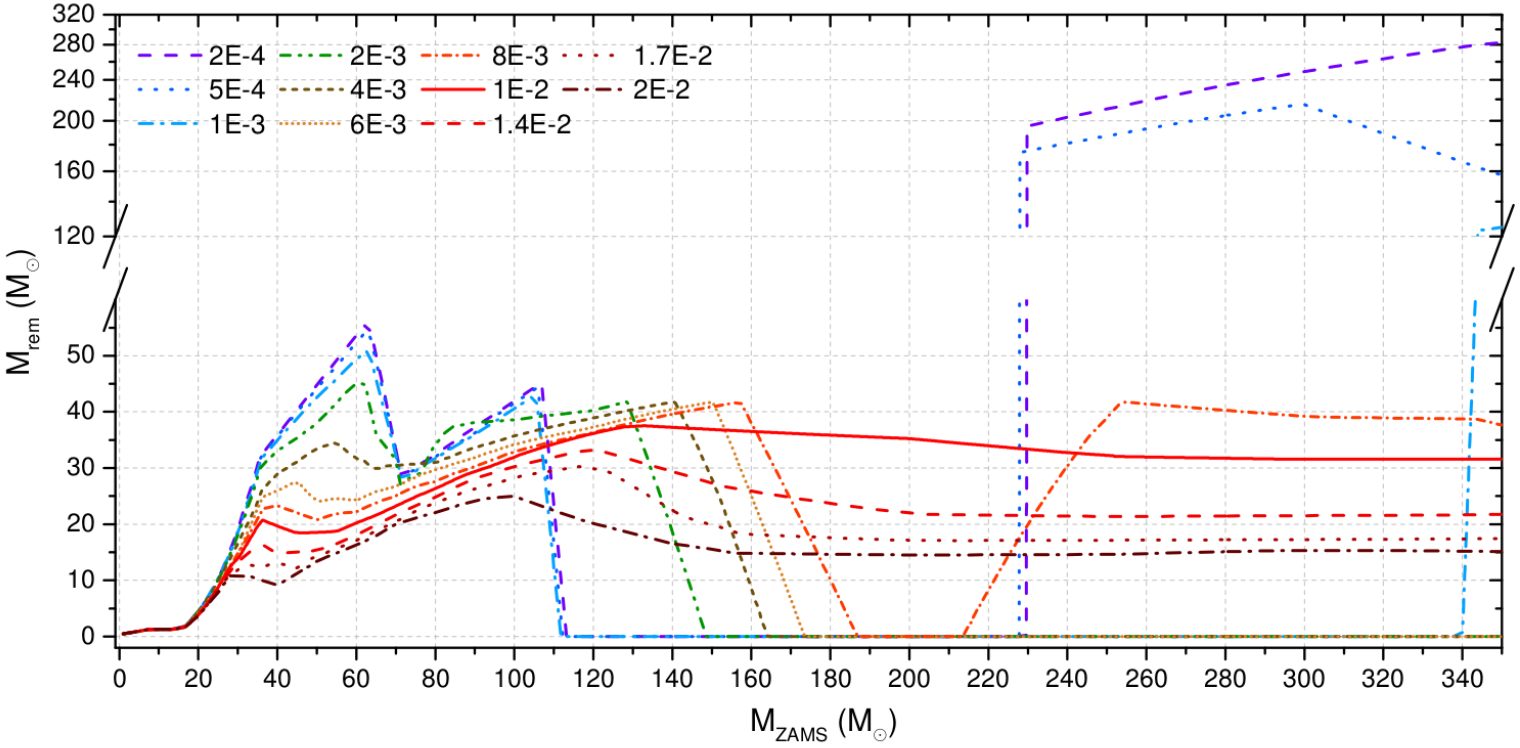
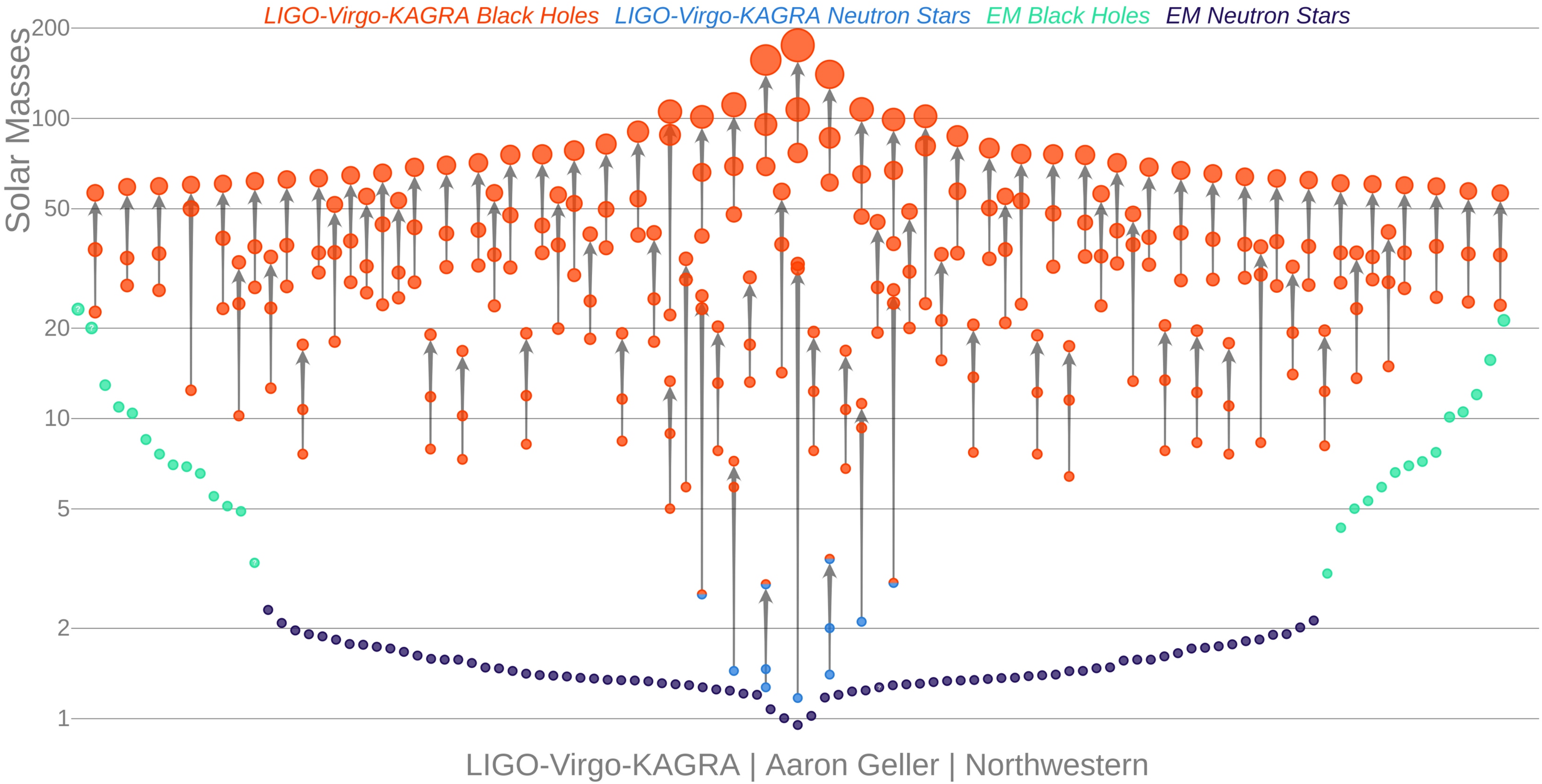
The formation of compact objects from single star evolution



Masses in the Stellar Graveyard



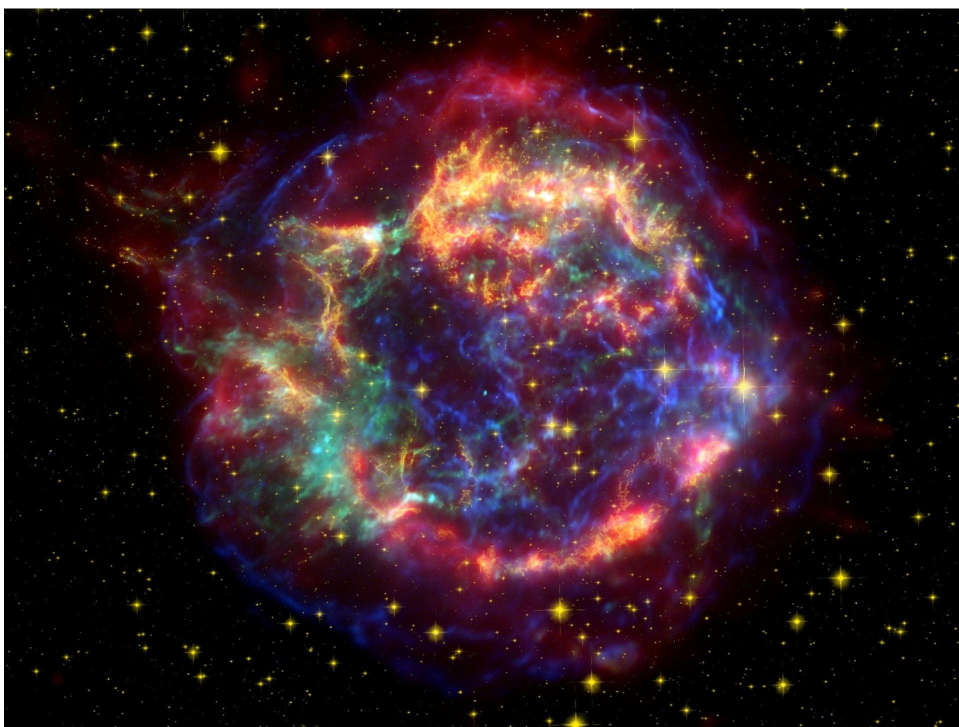
Abbott et al. 2022, GWTC-3

Two critical ingredients:

1) PROGENITOR STAR EVOLUTION (STELLAR WINDS)

2) SUPERNOVA (SN) EXPLOSION

Winds ejected by Eta Carinae (HST, credits: NASA)



Chandra + HST + Spitzer Image of the SN remnant Cassiopeia A

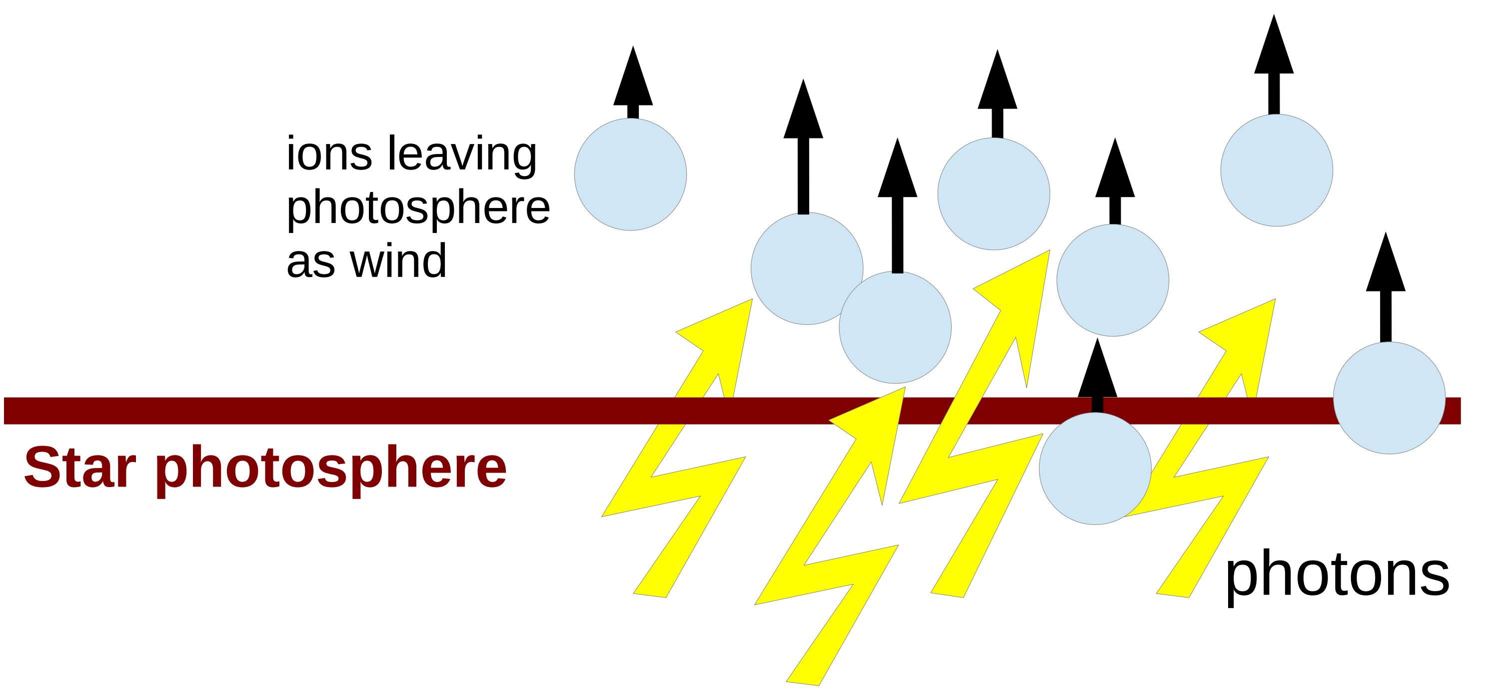
Stellar winds

Massive stars (>30 $M_\odot$) might lose >50% mass by winds
(Vink+ 2001, 2005, 2011; see Vink+ 2016 for a short review)

Photons in atmosphere of a star couple with ions
→ **transfer linear momentum to the ions and unbind them**

Coupling through resonant METAL LINES (especially Fe lines)
→ **MASS LOSS DEPENDS ON METALLICITY**

If star radiation pressure dominated, coupling through electron scattering
→ **MASS LOSS DEPENDS ON LUMINOSITY**



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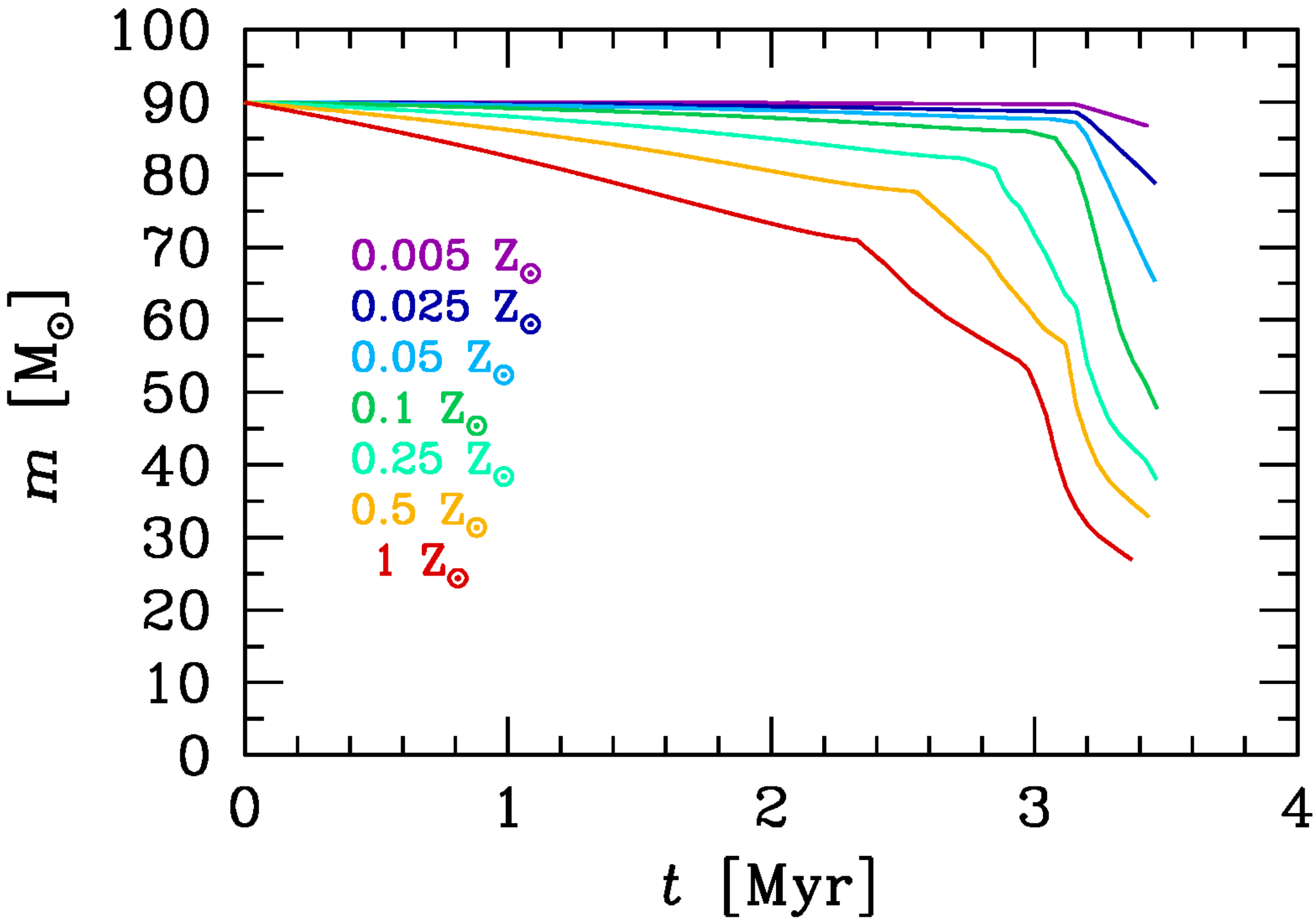
$$\boxed{\dot{M} \propto Z^{\alpha}} \qquad \alpha \sim 0.5 - 0.9$$

$$\begin{cases} \alpha = 0.85 & [\text{if } \Gamma < 2/3] \\ \alpha = 2.45 - 2.4\,\Gamma & [\text{if } \Gamma > 2/3] \end{cases}$$

$$\boxed{\Gamma = \frac{L_*}{L_{\rm Edd}}}$$

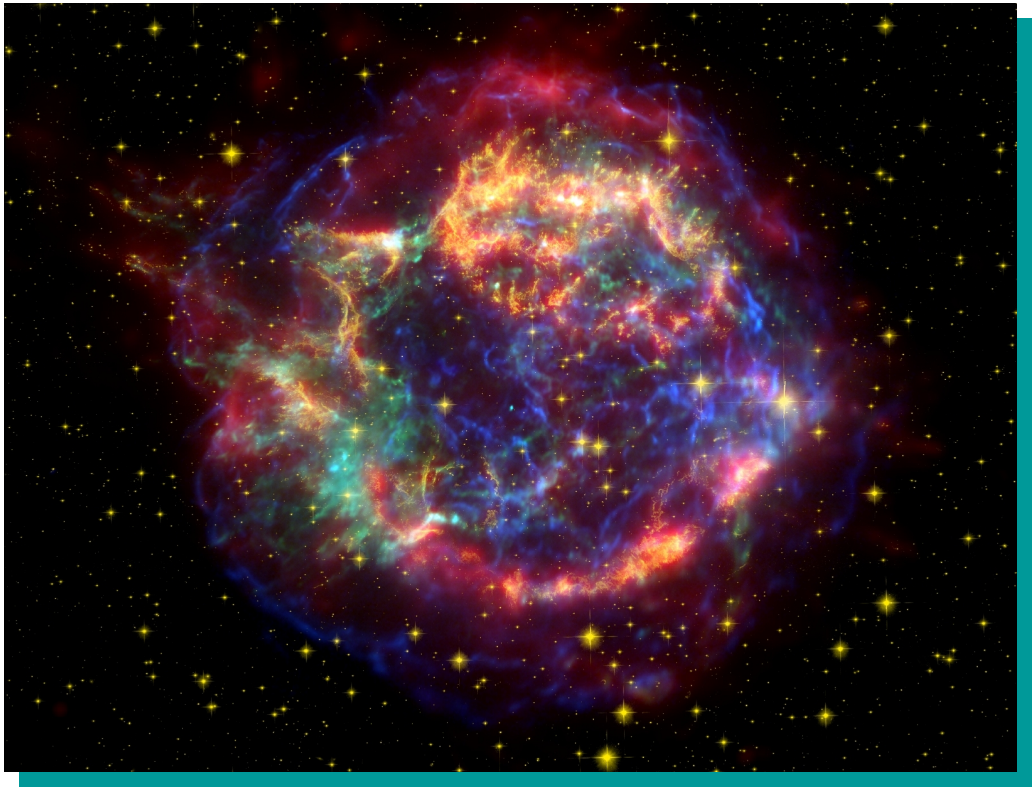
Stellar winds



Models from PARSEC stellar evolution code (Bressan+ 2012; Tang+ 2014; Chen, Bressan+ 2015)

Core-collapse supernovae

Final mass of a star is very important,
because it affects the outcome of a
core-collapse (CC) SUPERNOVA



When Fe core forms in a massive (> 8 Msun) star

1) Fe-group atoms (Ni-62, Fe-58, Fe-56) have maximum binding energy: no more energy released by fusion
→ stellar core starts collapsing because pressure drops

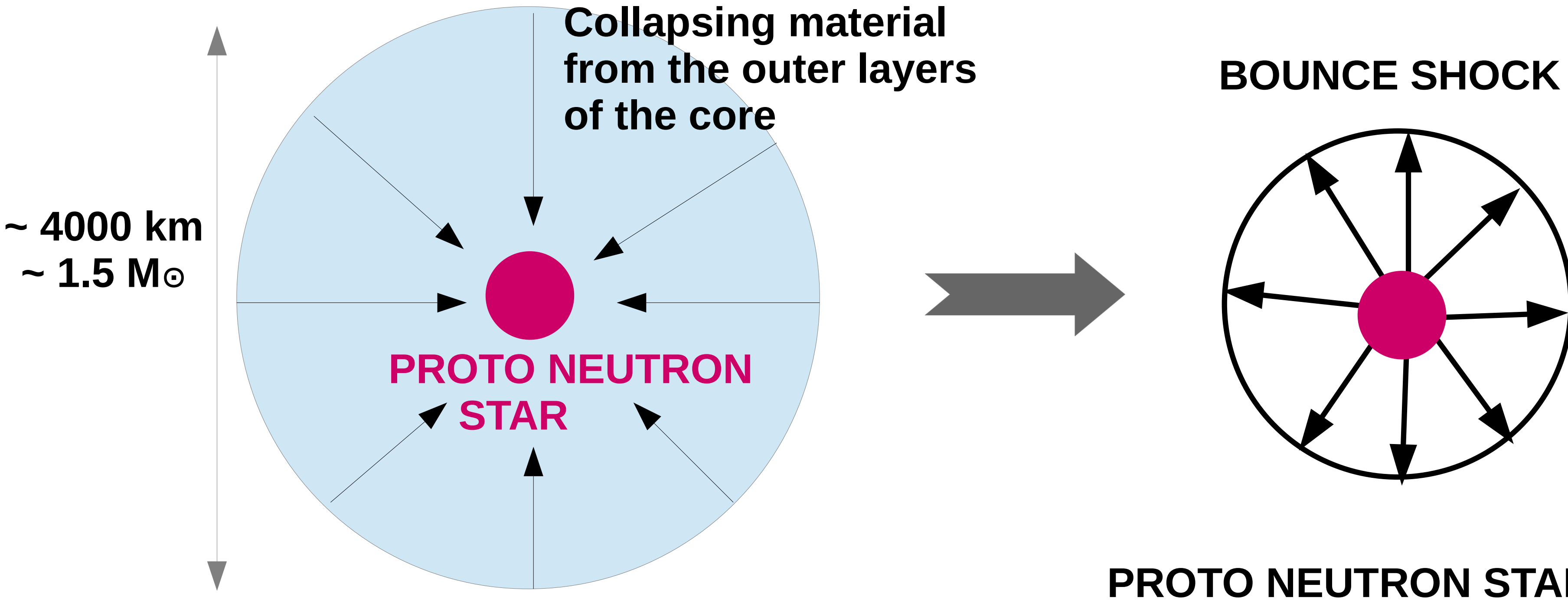
2) electron degeneracy pressure tries to stop collapse but if core mass > Chandrasekhar mass (~1.4 Msun)
electron + proton capture removes electrons
→ electron pressure decreases

→ COLLAPSE to NUCLEAR DENSITY (~10^{17} kg m^{-3}), where neutron degeneracy pressure stops collapse

→ PROTO-NEUTRON STAR (PNS) FORMS

Collapse of the core to nuclear density produces BOUNCE SHOCK

Fraction of binding energy of core (Eb,c $\sim 10^{53}$ erg)
is converted into thermal energy (mostly of neutrinos)



PROTO NEUTRON STAR
diameter ~ 20 – 30 km
mass ~ 1 M⊙

Collapse of the core to nuclear density produces BOUNCE SHOCK

Fraction of binding energy of core (Eb,c ~10^{53} erg)
is converted into thermal energy (mostly of neutrinos)

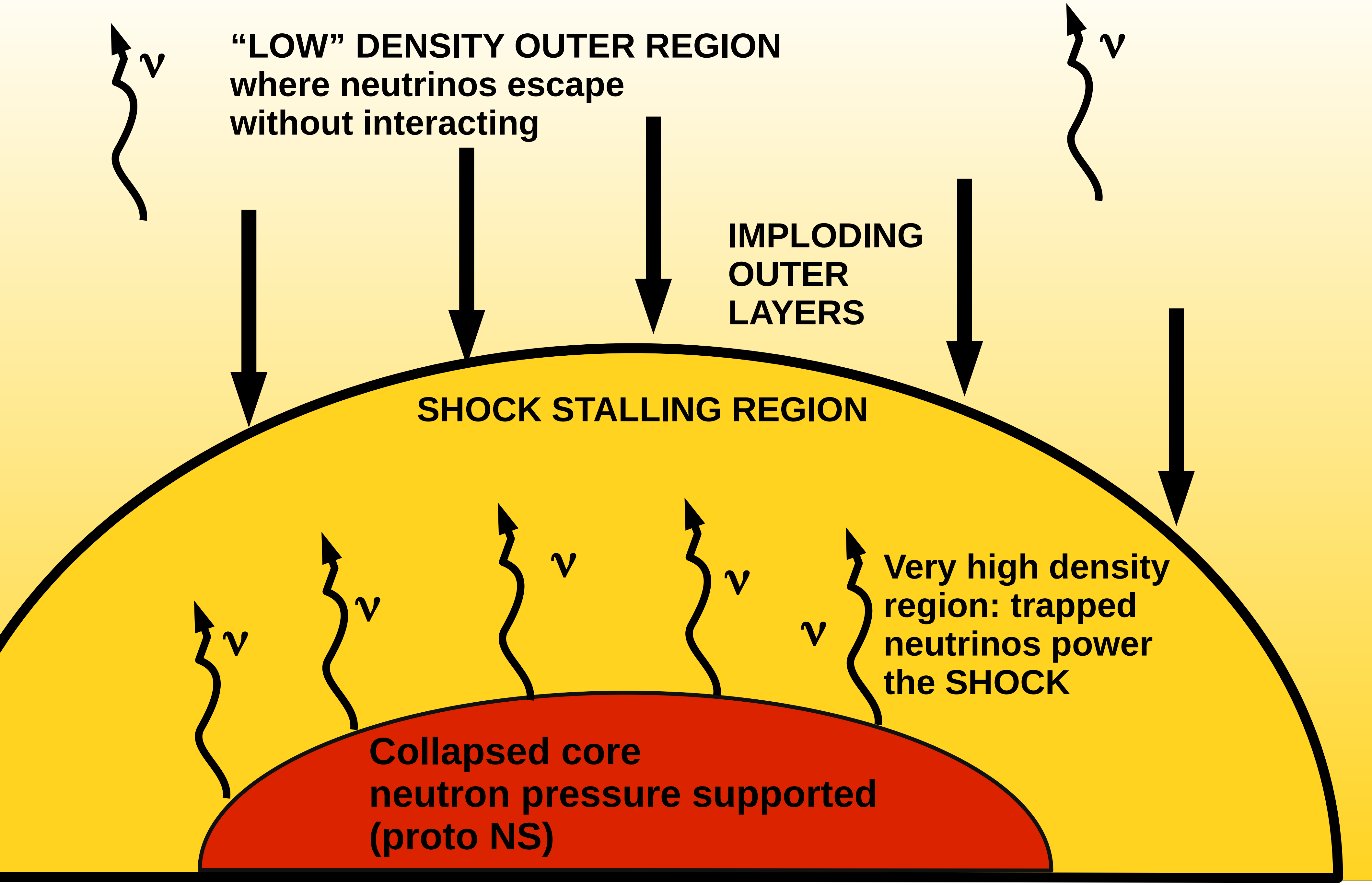
SHOCK MUST REVERSE COLLAPSE OF OUTER LAYERS

But density must be sufficiently high that neutrinos interact, otherwise neutrinos leak away without transferring energy
→ SHOCK MIGHT STALL
→ SN FAILS

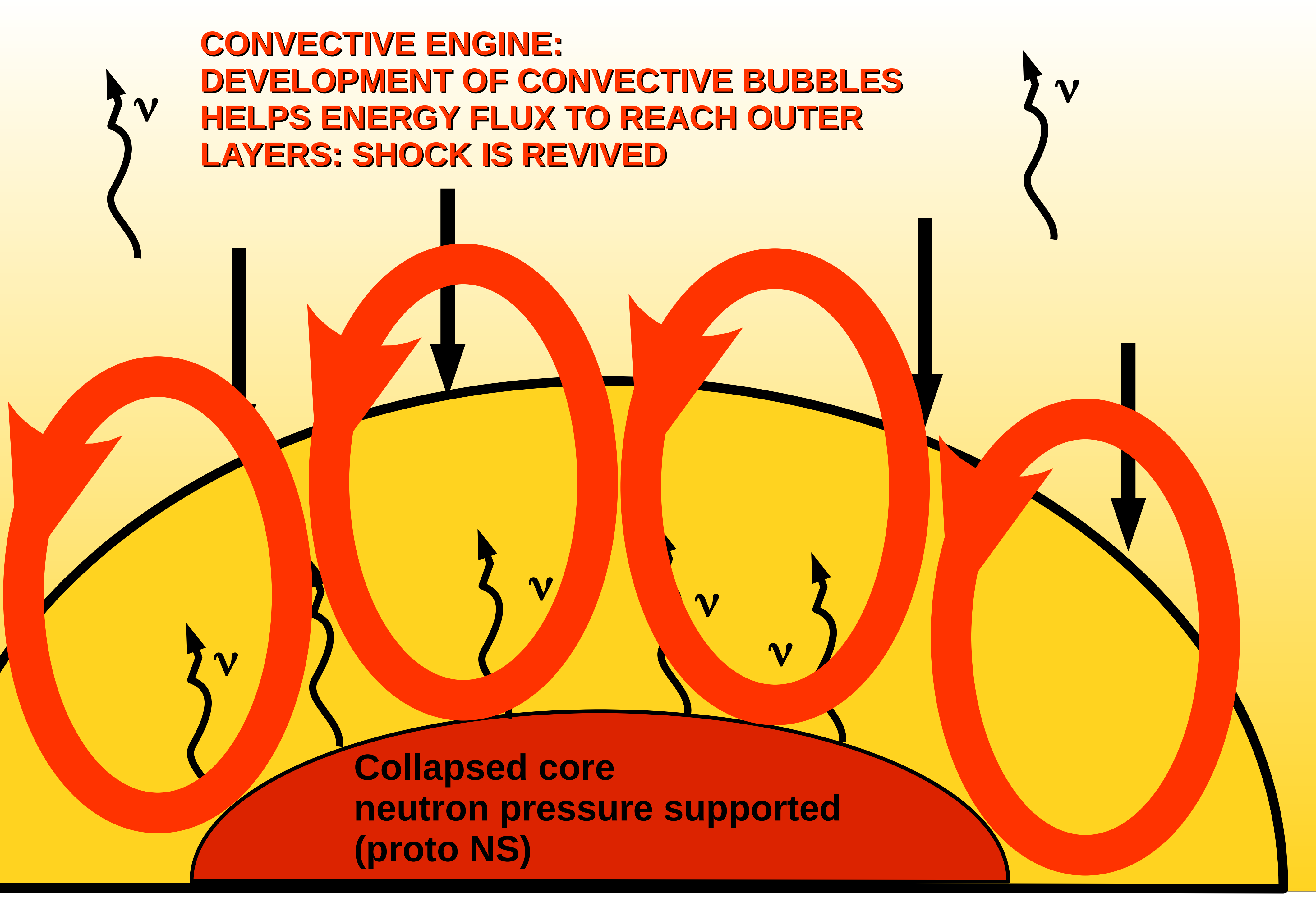
WHAT CAN REVIVE THE SHOCK?

STANDARD MODEL: CONVECTIVE ENGINE

Fryer 2014, http://pos.sissa.it/archive/conferences/237/004/FRAPWS2014_004.pdf



“LOW” DENSITY OUTER REGION
where neutrinos escape
without interacting
ν
ν
IMPLODING
OUTER
LAYERS
SHOCK STALLING REGION
ν
ν
ν
ν
ν
Very high density
region: trapped
neutrinos power
the SHOCK
Collapsed core
neutron pressure supported
(proto NS)


CONVECTIVE ENGINE:
DEVELOPMENT OF CONVECTIVE BUBBLES
HELPS ENERGY FLUX TO REACH OUTER
LAYERS: SHOCK IS REVIVED
ν
ν
ν
ν
ν
ν
Collapsed core
neutron pressure supported
(proto NS)

Supernova shock stops anyway if BOUND MASS is too LARGE (Fryer 1999; Fryer & Kalogera 2001)

Back-of-the-envelope calculation to connect direct collapse and pre-supernova mass:

envelope mass

proto-NS ~ 1 Msun

$$E_{\rm SN} = \frac{G\,M_{\rm env}\,(M_{\rm env} + M_{\rm core})}{R_{\rm env}}$$

envelope radius

Star cannot explode if envelope binding energy > SN energy

$$M_{\rm env} \sim 50\,M_\odot \left(\frac{E_{\rm SN}}{10^{51}{\rm erg}}\right)^{1/2} \left(\frac{R_{\rm env}}{10\,R_\odot}\right)^{1/2}$$

If M_{fin}> 50 M$_\odot$ this SN fails and star collapses to a BH

How to study a core-collapse supernova (SN)?

HYDRODYNAMICAL SIMULATIONS

!!CAVEAT: only stars with mass 8 – 11 Msun explode easily!!

1D: large statistics (hundreds of models), approximate neutrino transfer (often kinetic bombs or thermal bombs to artificially induce explosion even in more massive stars)

(O'Connor & Ott 2011; Ugliano et al. 2012; Ertl et al. 2016)

2D: explode easily but often contain less physics than 1D and we cannot run large sets

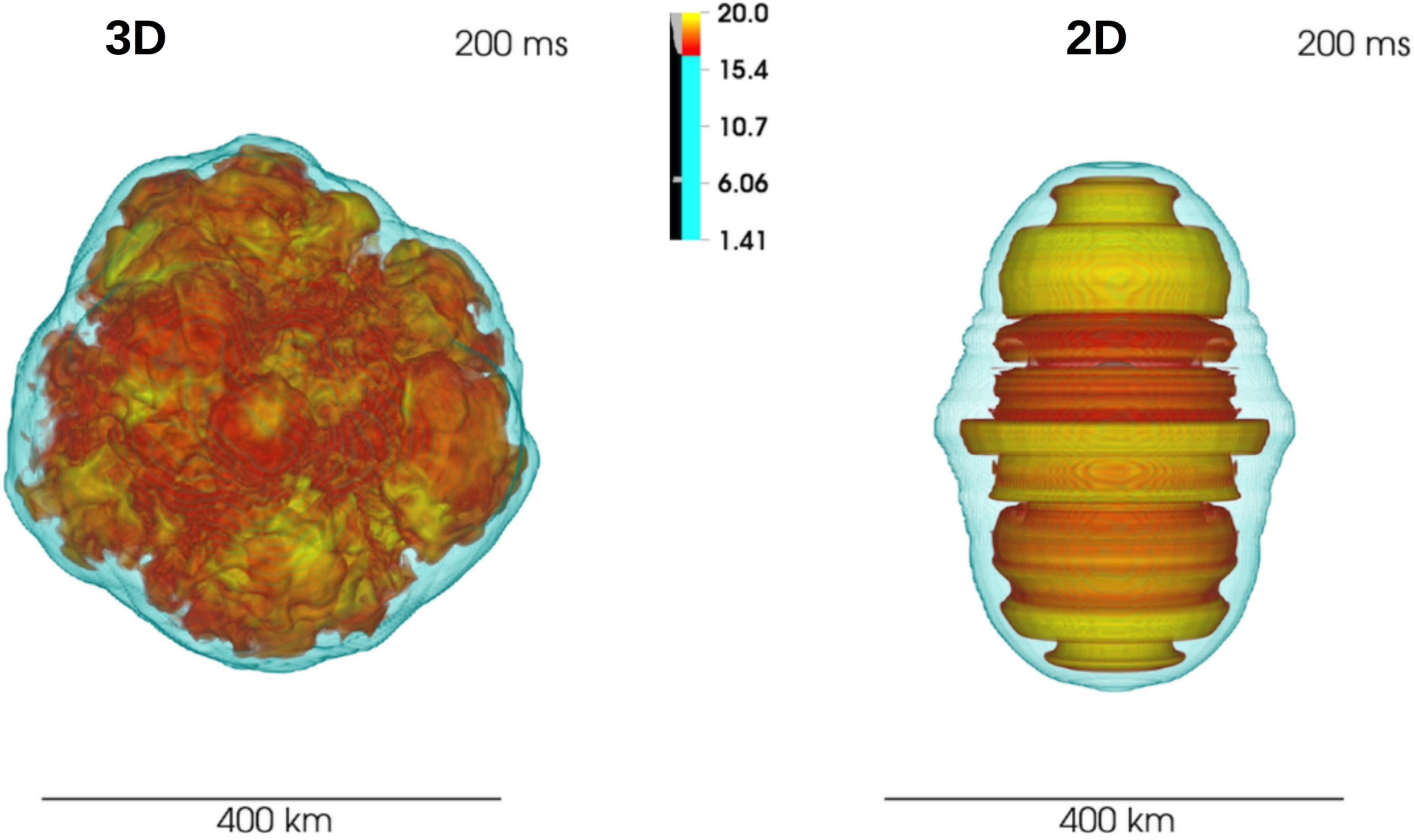
(Marek & Janka 2009; Mueller et al. 2012a, 2012b)

3D: computationally expensive (see 2D)

(Ott et al. 2005; Bondin & Mezzacappa 2007; Couch 2013; Couch & O'Connor 2014)

How to study a core-collapse supernova (SN)?

HYDRODYNAMICAL SIMULATIONS (Couch & O'Connor 2014)



CRITERIA FOR COLLAPSE TO A REMNANT

depends on the "compactness" of the inner layers of the star

1. MASS OF CARBON-OXYGEN CORE

If Mco > 8 – 12 Msun SN FAILS
(Fryer+ 1999, 2012; Belczynski+ 2010)

2. COMPACTNESS

3. TWO-PARAMETER CRITERION

Core-collapse (CC) SN depends on the "compactness" of the inner layers

COMPACTNESS (= ratio between mass and radius) of a given portion of the stellar core at the onset of collapse
(O'Connor & Ott 2011)

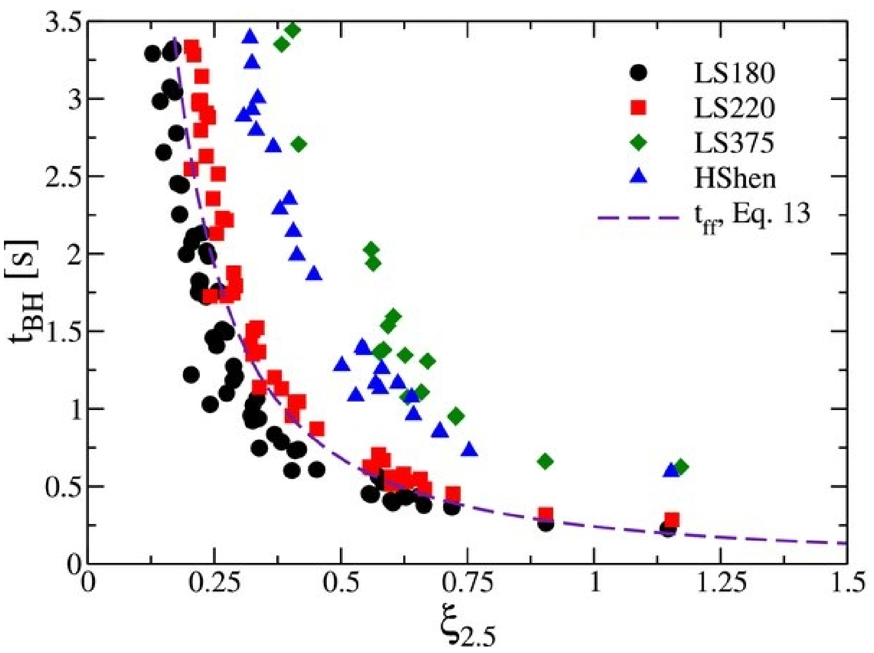
$$\xi_M \equiv \frac{M/\,\mathrm{M}_\odot}{R\,(M)\,/1000\,\mathrm{km}}$$

***M* = 2.5 M⊙ is usually adopted**

Star collapses if $\xi_{2.5} > 0.2$

(Ugliano+ 2012; Horiuchi+ 2012)

Figure from
O'Connor & Ott 2011

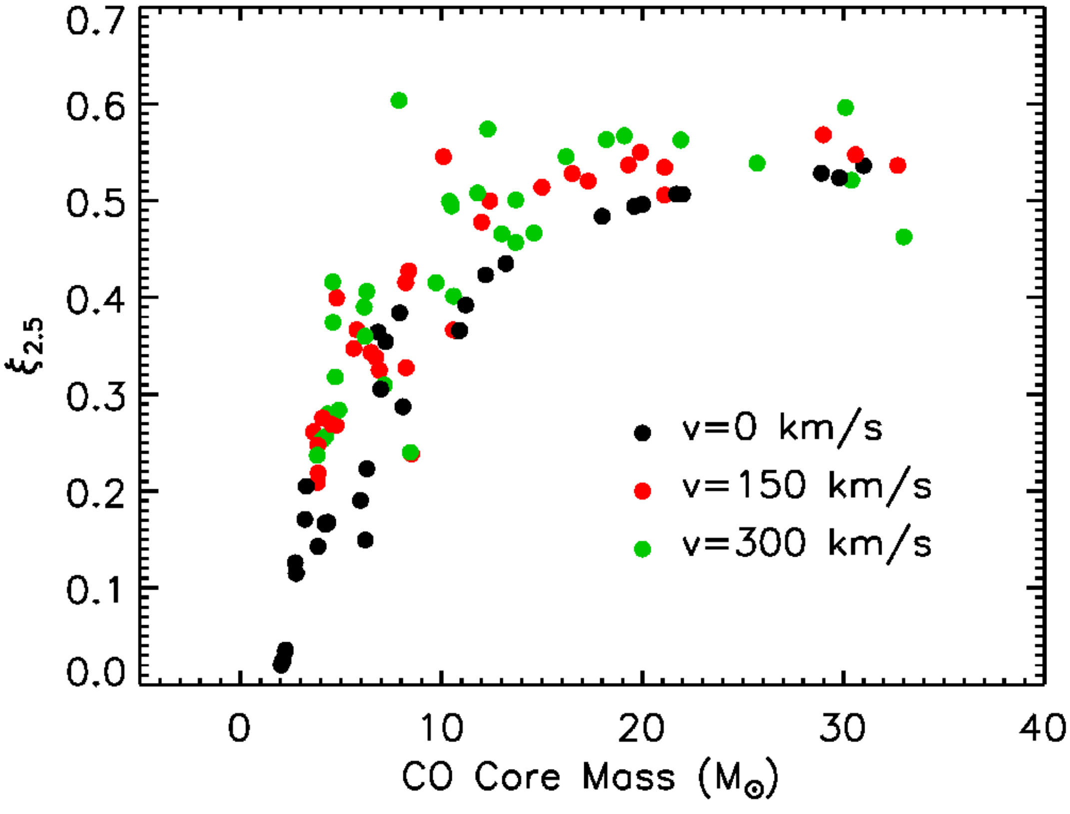


Core-collapse (CC) SN depends on the "compactness" of the inner layers

Compactness correlates well with mass of CO core

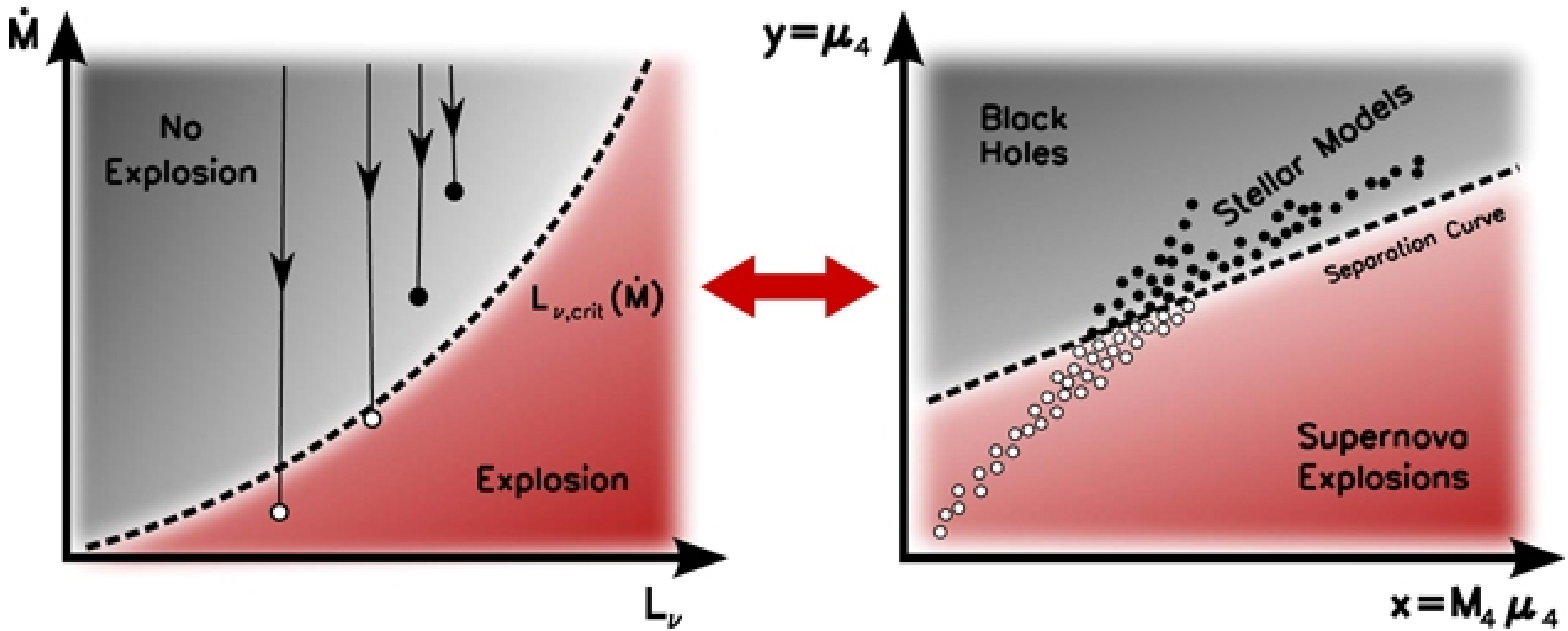
→ **compactness > 0.2 corresponds to CO core > 8 M⊙**

Figure from Limongi 2017 arXiv:1706.01913



Core-collapse (CC) SN depends on the enclosed mass (M_4) and mass gradient (μ_4) at a dimensionless entropy per nucleon *s* = 4

$$M_4 = m(s=4)/M_\odot \qquad \mu_4 = \left[\frac{dm/M_\odot}{dr/1000\,\mathrm{km}}\right]_{s=4}$$



Ertl et al. 2016

Core-collapse (CC) SN depends on the enclosed mass (M_4) and mass gradient (μ_4) at a dimensionless entropy per nucleon s = 4

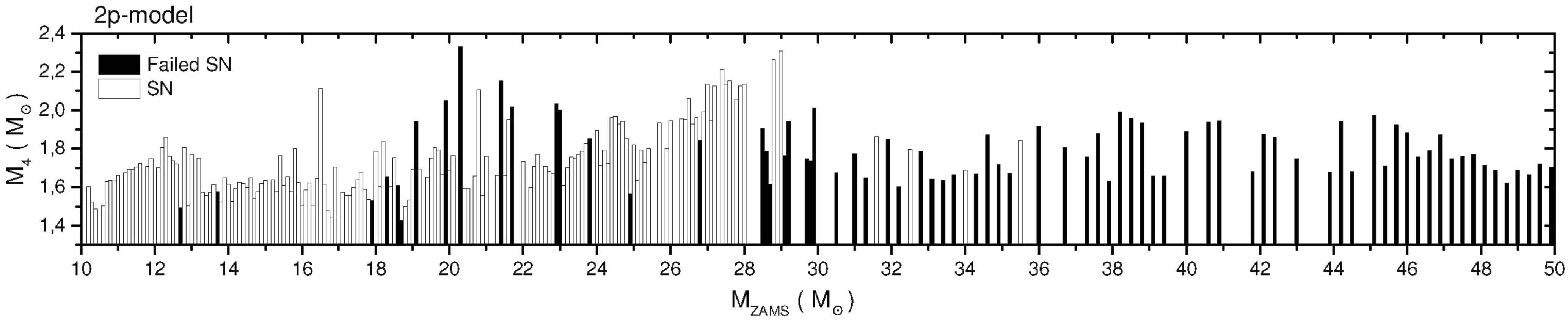


Fig. 21 Spera, MM, Bressan 2015

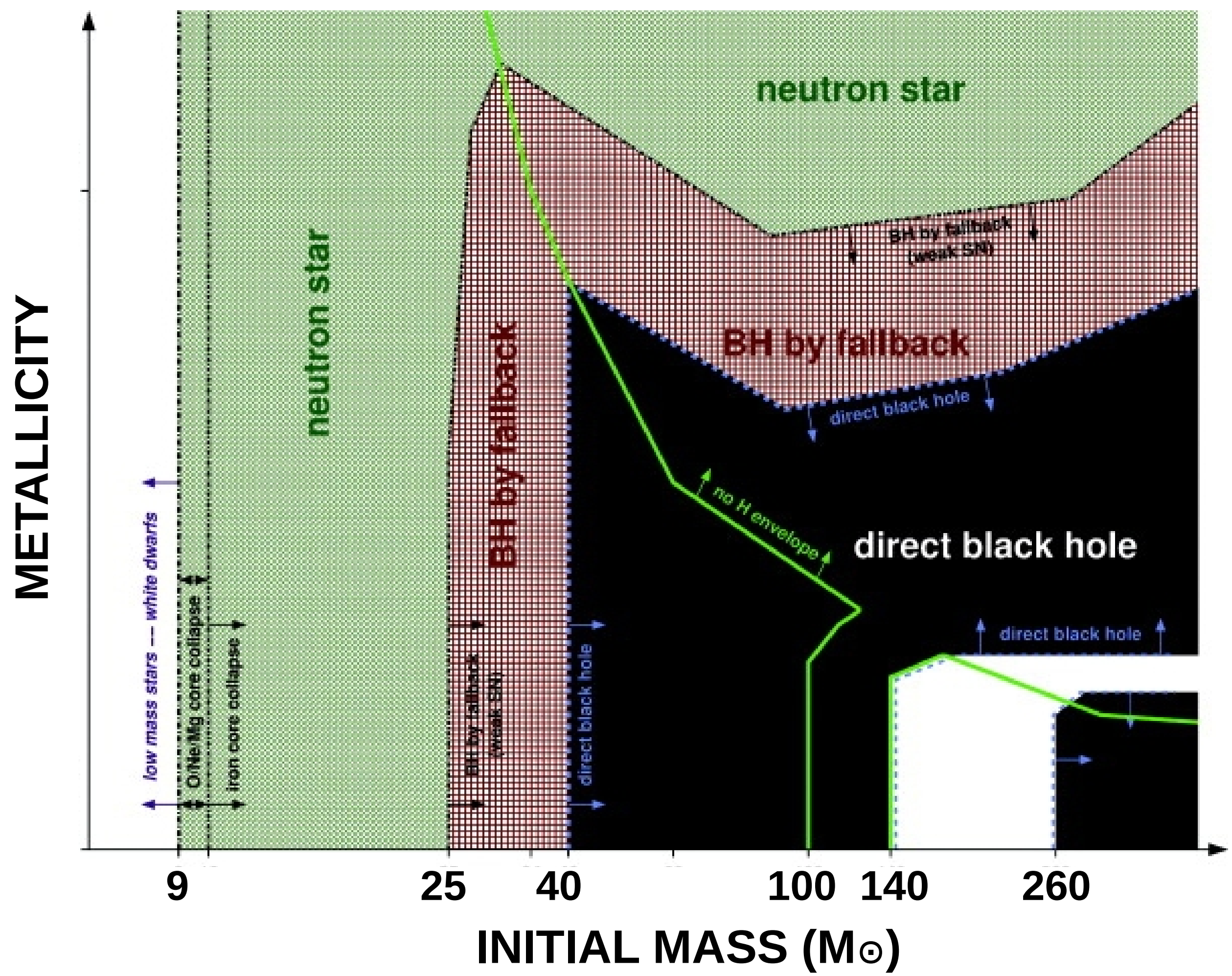
ISLANDS OF DIRECT COLLAPSE AND SN EXPLOSION

Concluding remark:
MANY MODELS of SN EXPLOSION OUTCOMES
BUT IF THE STAR IS VERY MASSIVE (>40 $M_\odot$)
THEY GIVE SIMILAR RESULT

CC SN depends on the "fallback" of the outer layers of the star:

How much material falls back to the proto-NS after the SN

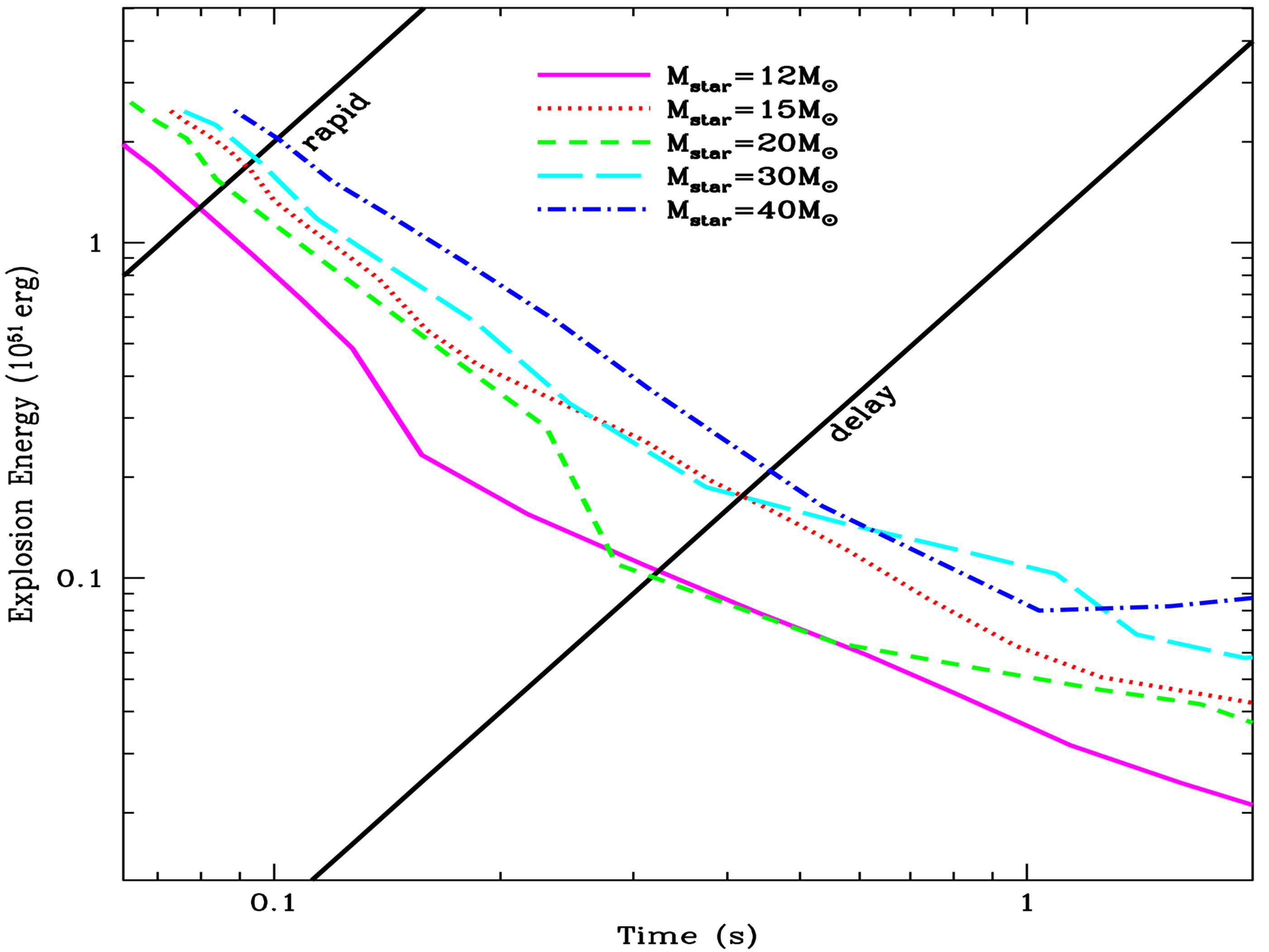
Barely constrained – depends on explosion energy,
angular momentum,
progenitor's mass/metallicity



Heger et al. 2003

CC SN depends on the rapidity of the explosion:

(e.g. Fryer+ 2012; Fryer 2014)



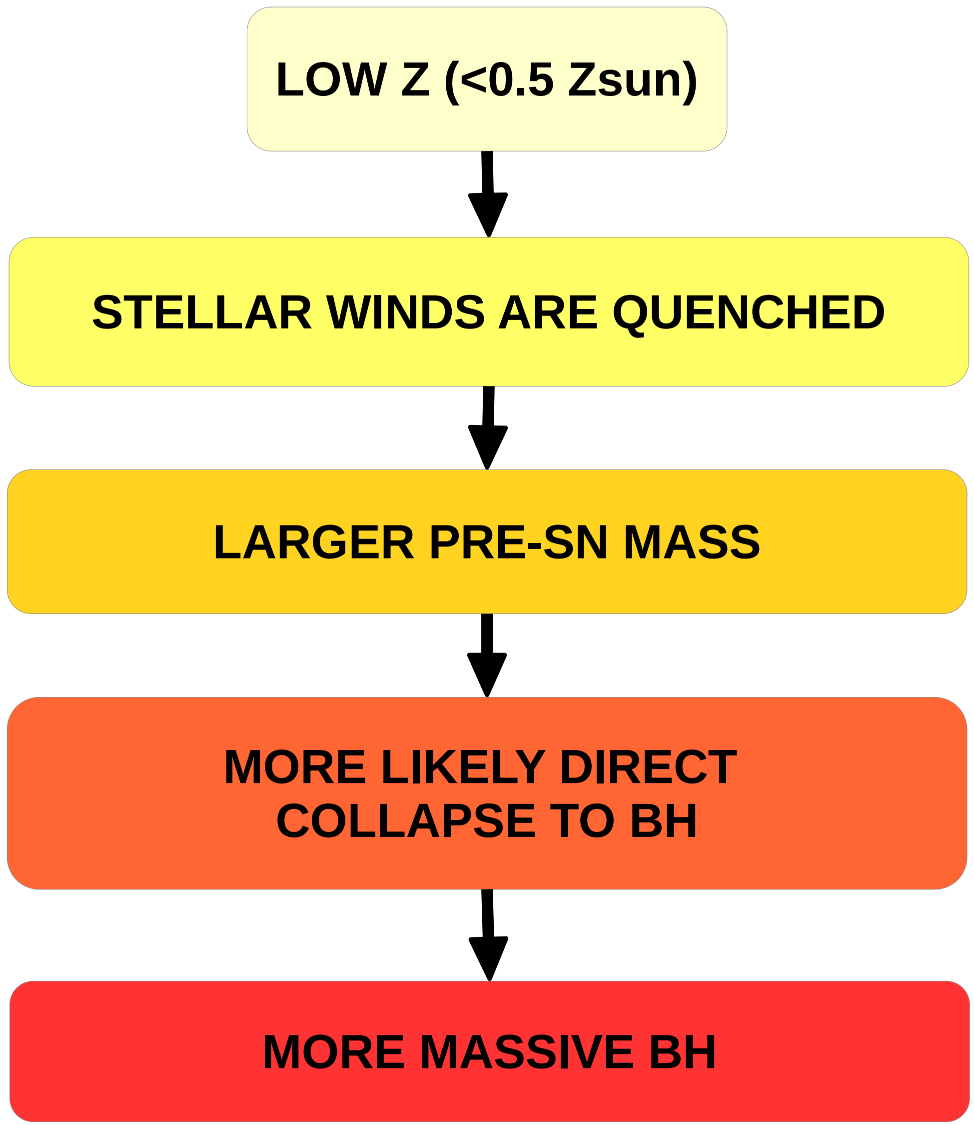
RAPID
(<200 ms
after bounce):
explosion
energy >10^51 erg/s

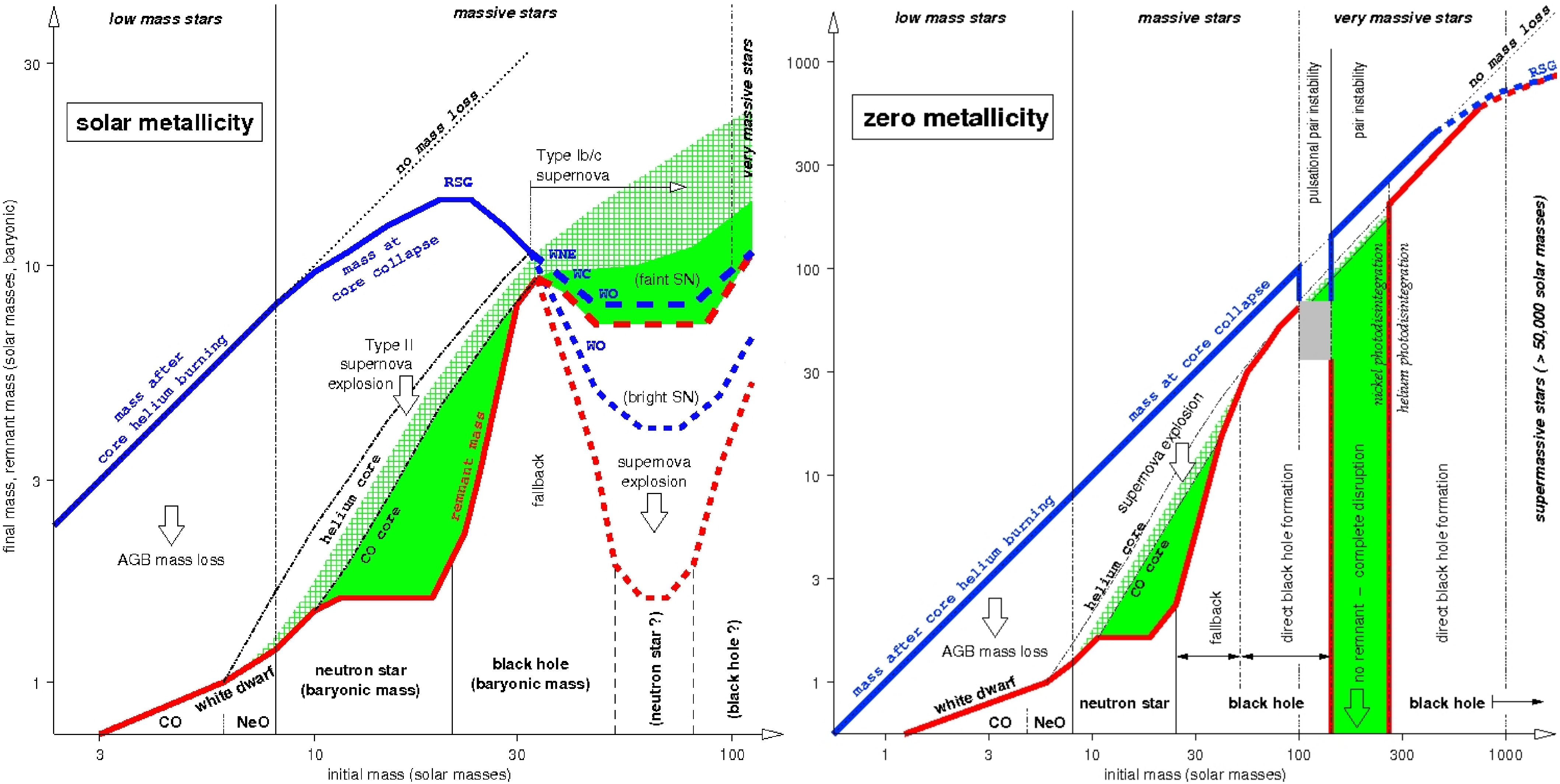
DELAYED
(>200 ms
after bounce):
explosion
energy <10^51 erg/s)

From Fryer 2014,
http://pos.sissa.it/archive/conferences/237/004/FRAPWS2014_004.pdf

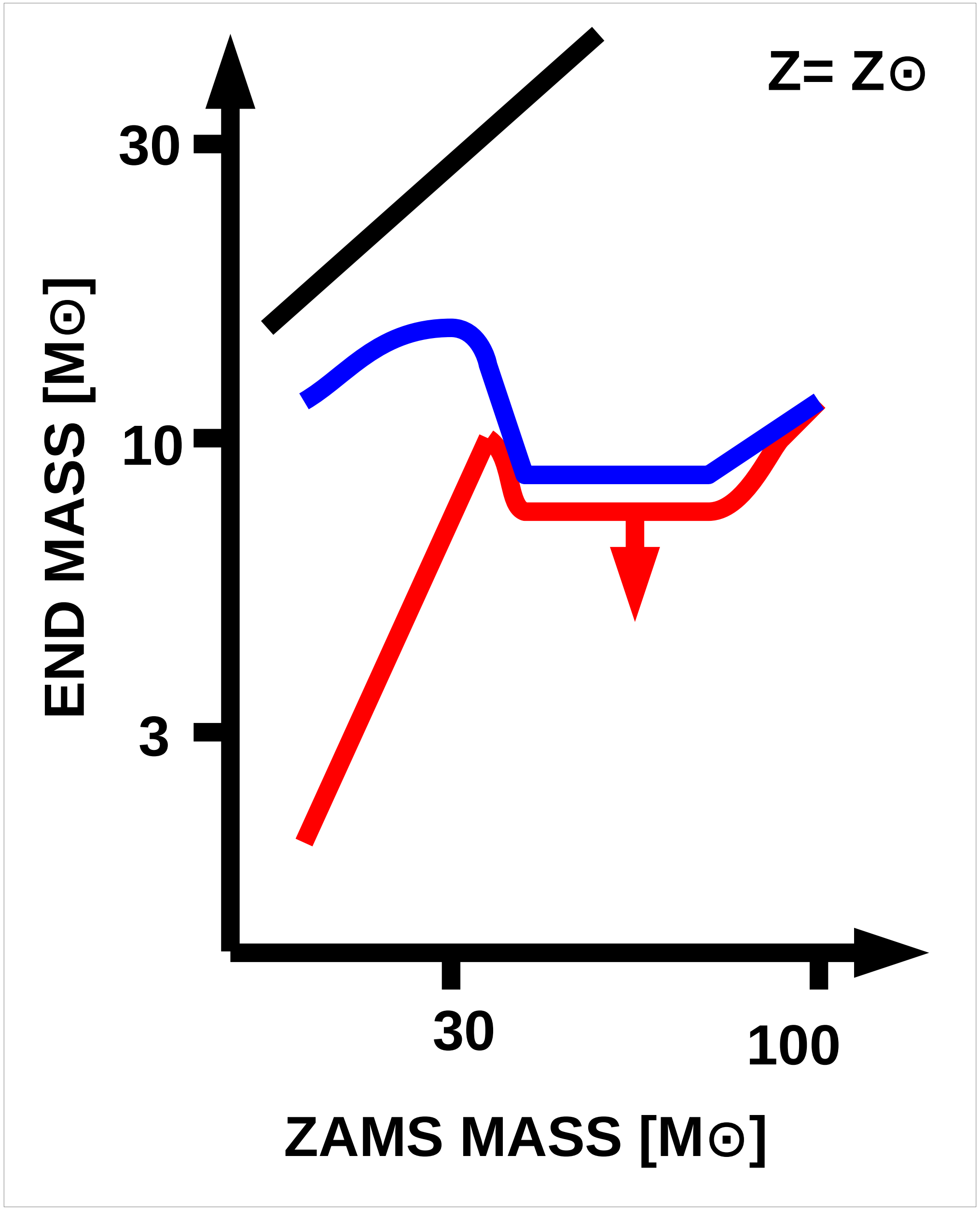
The formation of compact remnants: wrap up

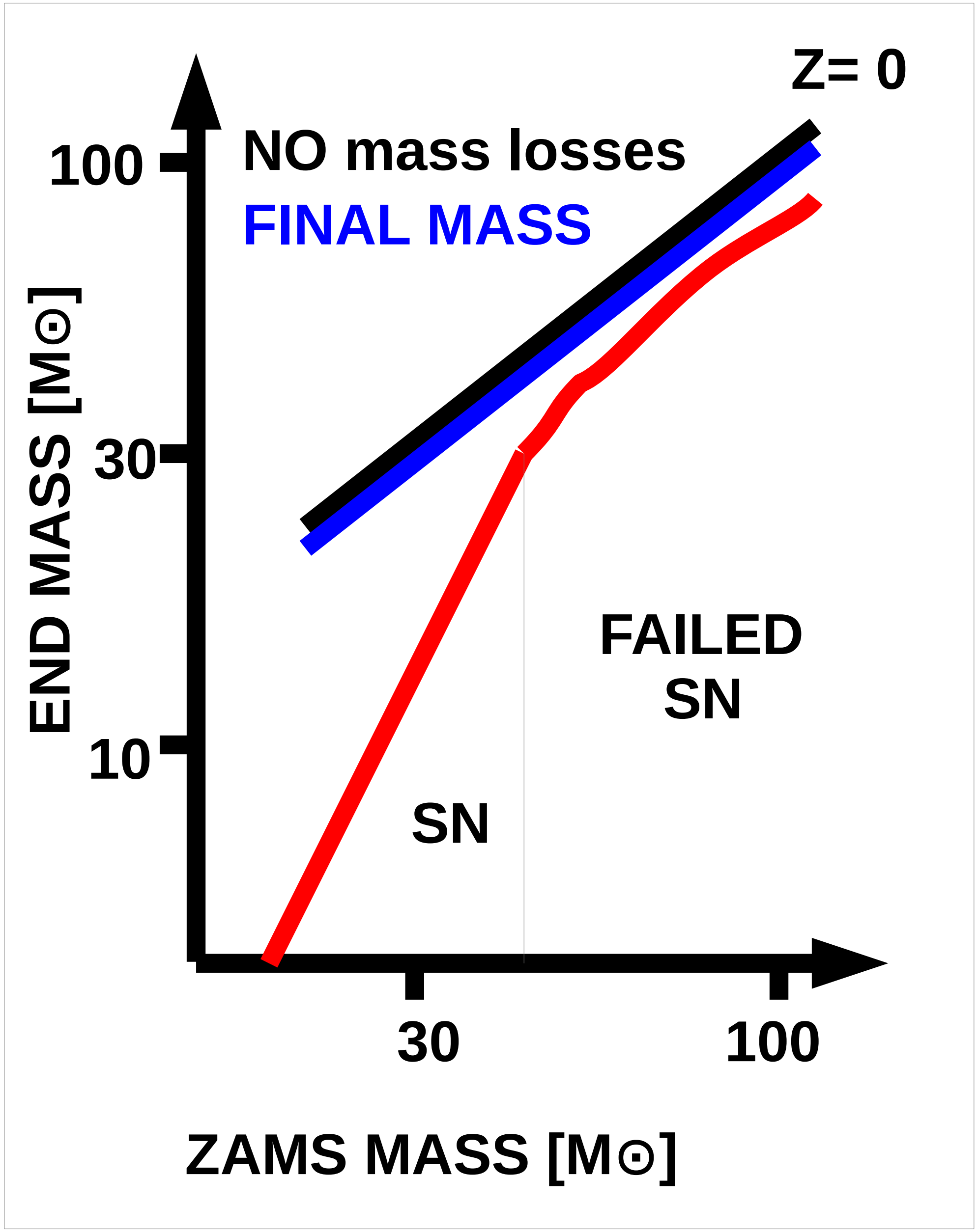
Very complicated. However, as rule of thumb (MM+ 2009, 2013):





Heger et al. (2003)

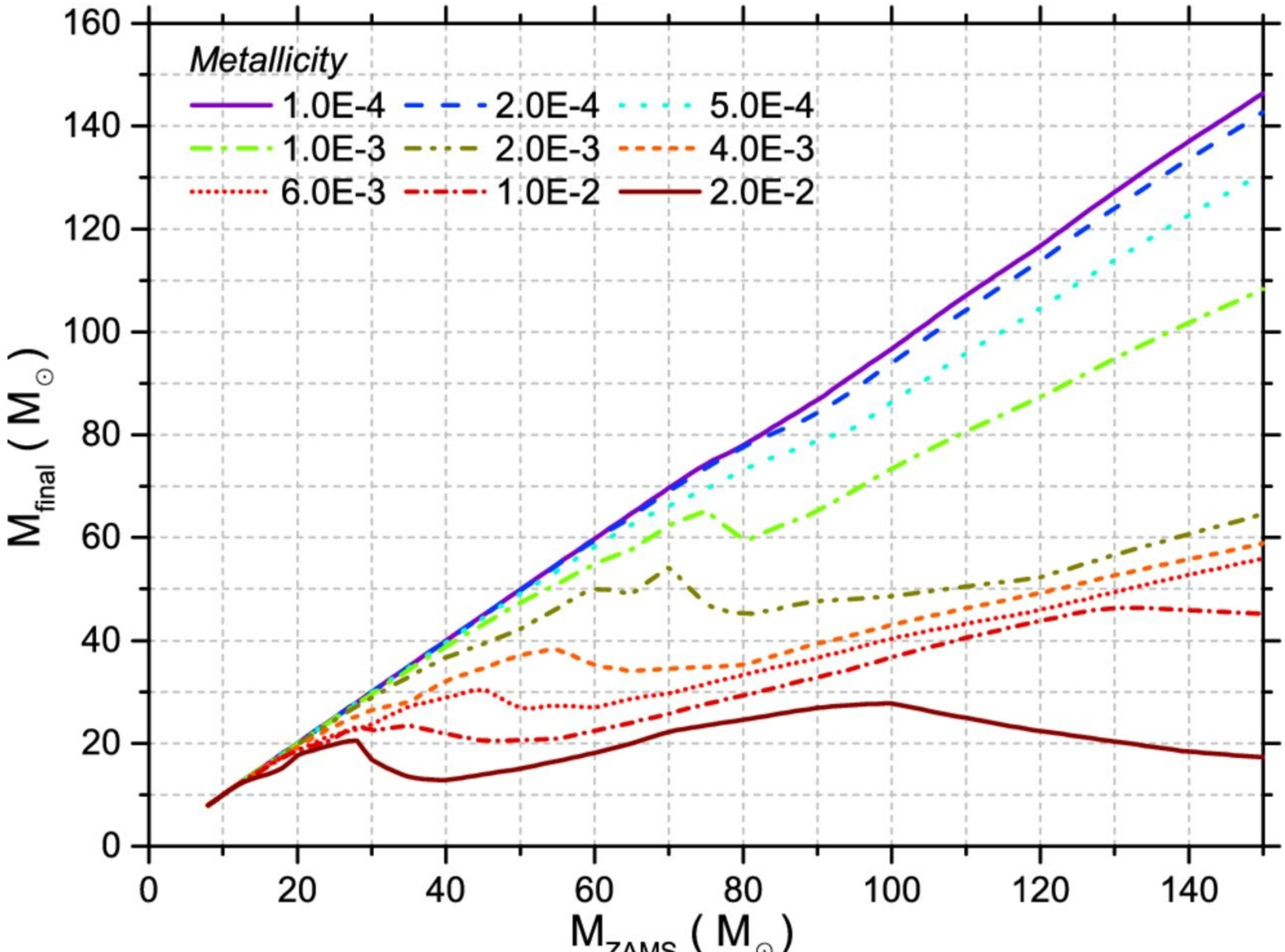




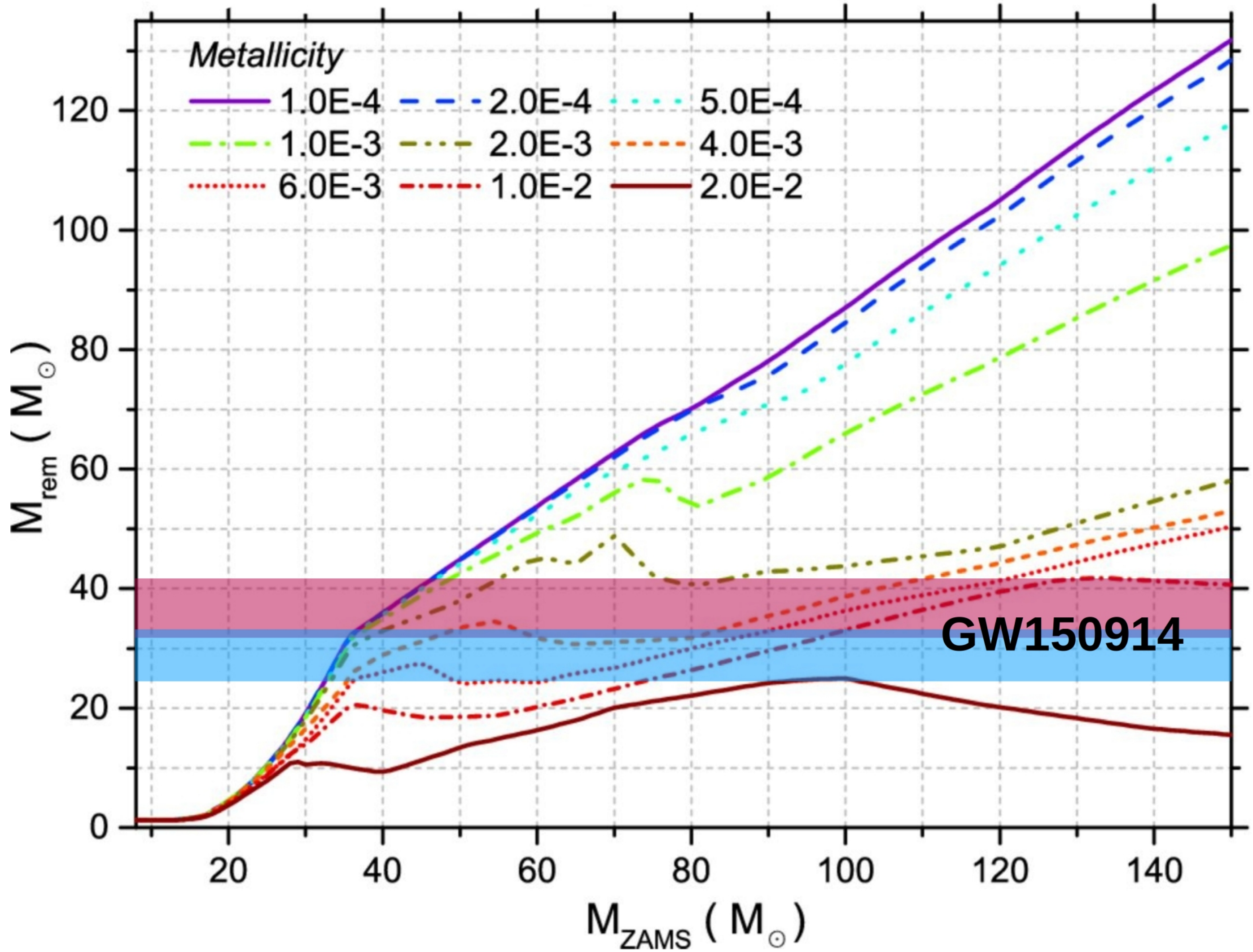
My cartoon from Heger et al. (2003)

What about intermediate metallicities between 0 and solar?

- more difficult because stellar winds are uncertain
- importance of final mass: pre-supernova mass of the star (when CO core built)



Spera, MM, Bressan 2015

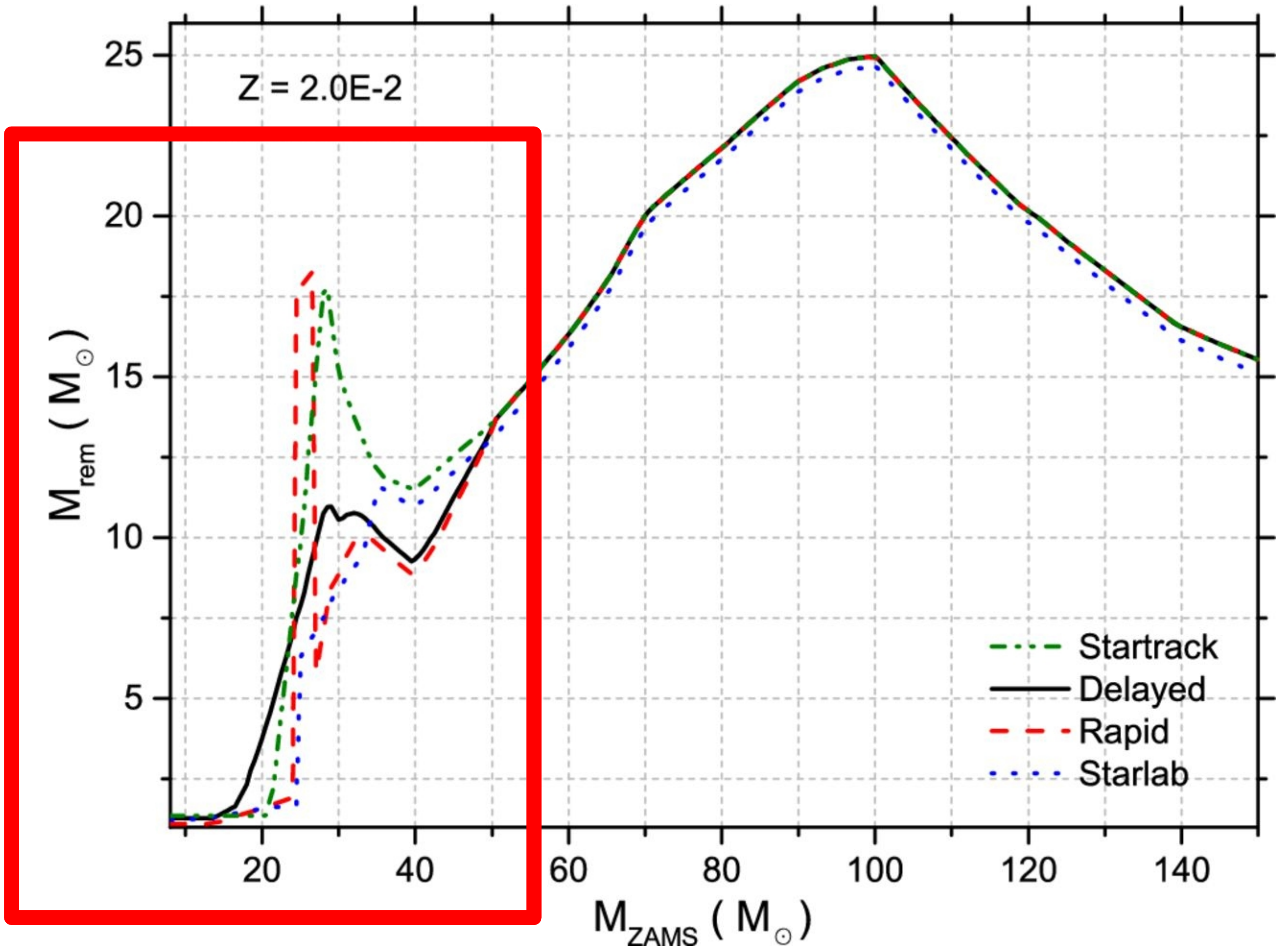


Remnant mass follows same trend as final mass → stellar winds are crucial

From Spera, MM & Bressan 2015, MNRAS, 451, 4086

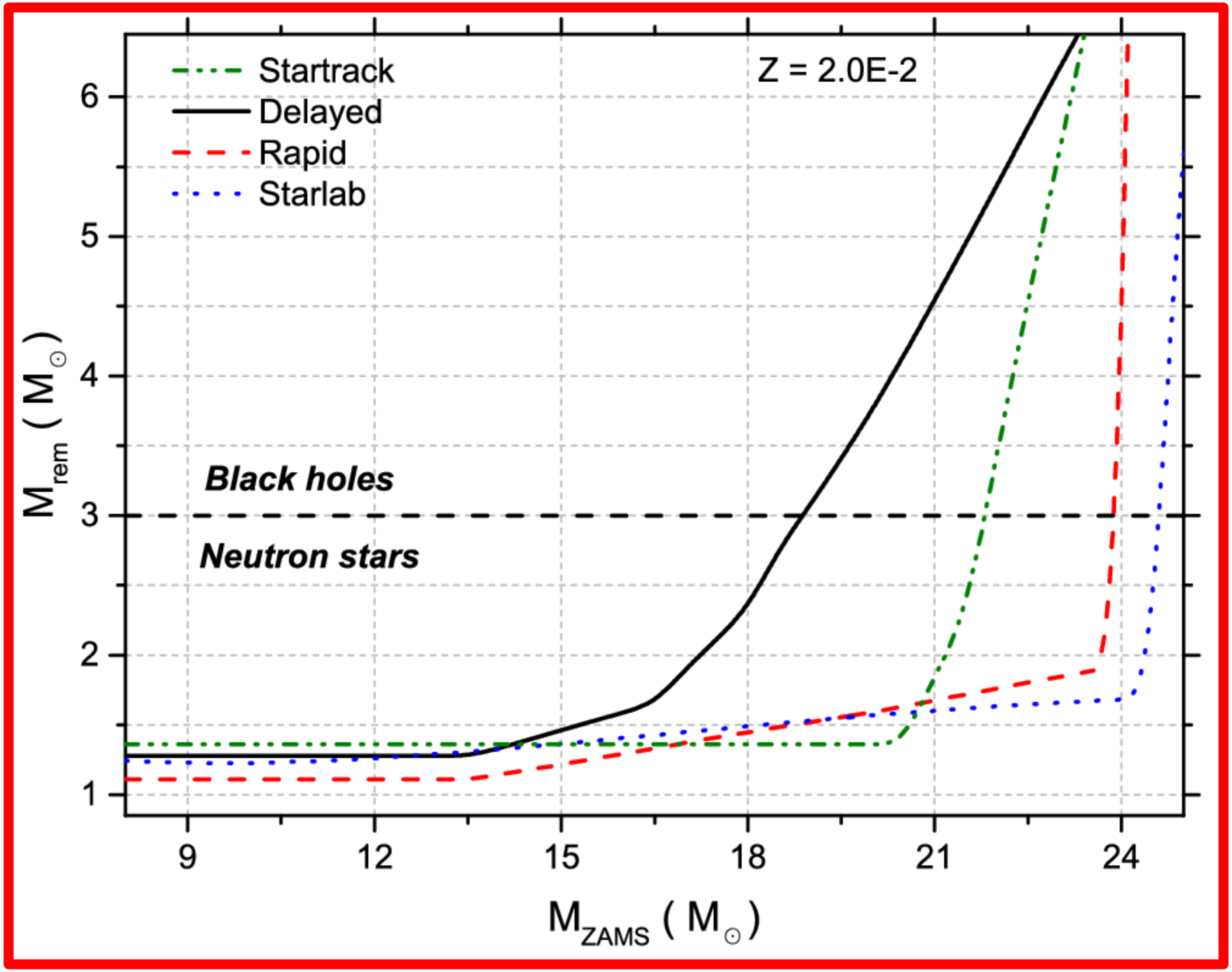
See also MM+ 2009, MNRAS, 395, L71; MM+ 2010, MNRAS, 408, 234; Belczynski+ 2010, ApJ, 714, 1217; Fryer+ 2012, ApJ, 749, 91; MM+ 2013, MNRAS, 429, 2298; Belczynski+ 2016, A&A, 594, 97; Spera & MM 2017, MNRAS, 470, 4739

Importance of supernova model for "LOW" STAR MASSES (<40 M$_\odot$)



Spera, MM, Bressan 2015

A lower mass gap in BH mass spectrum?



Spera, MM, Bressan 2015

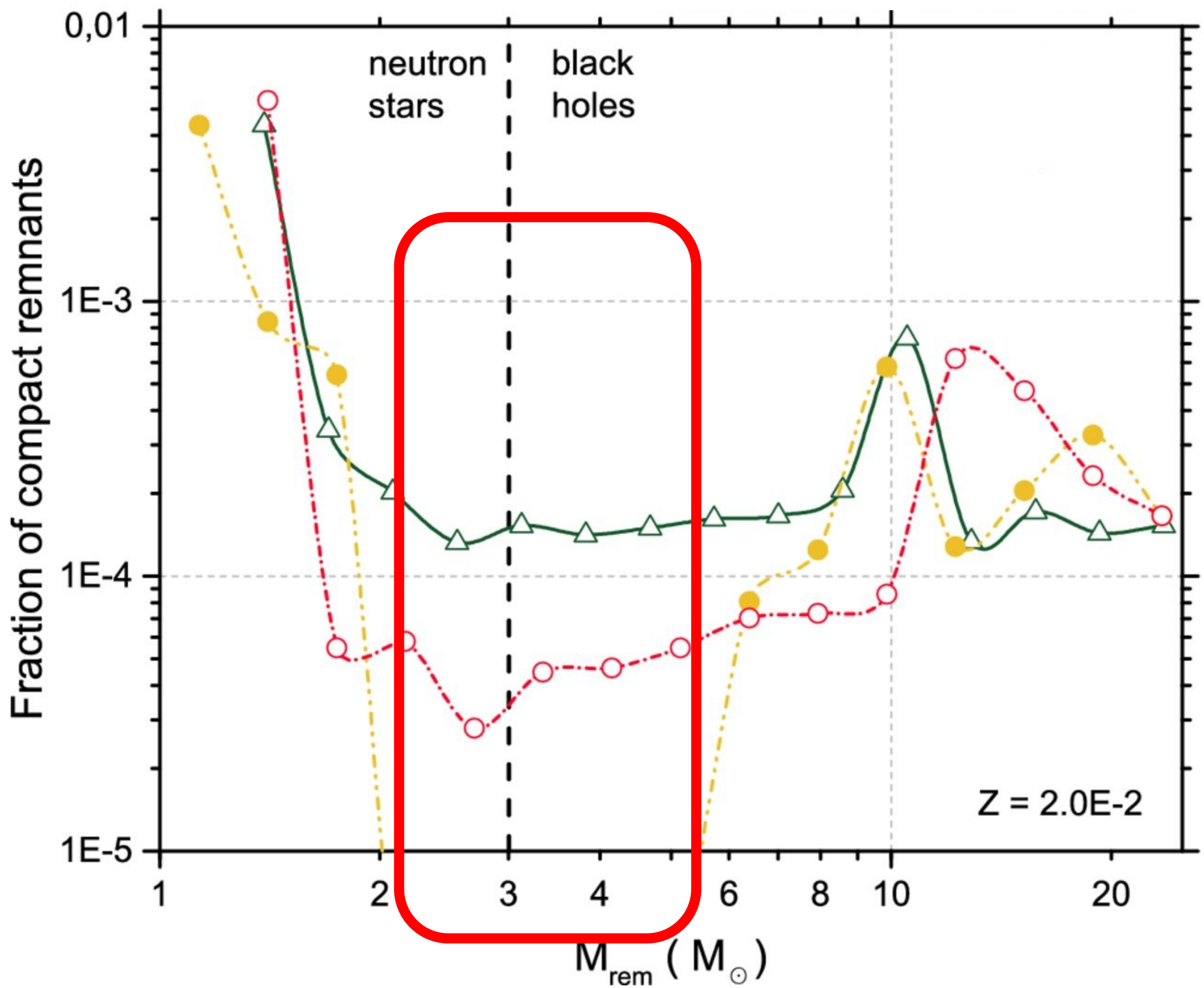
A lower mass gap in BH mass spectrum?

Solar metallicity

GREEN:
DELAYED
SN (Fryer+ 2012)

RED:
DELAYED
SN (MM+ 2013)

YELLOW:
PROMPT SN
(Fryer+ 2012)



Spera, MM, Bressan 2015

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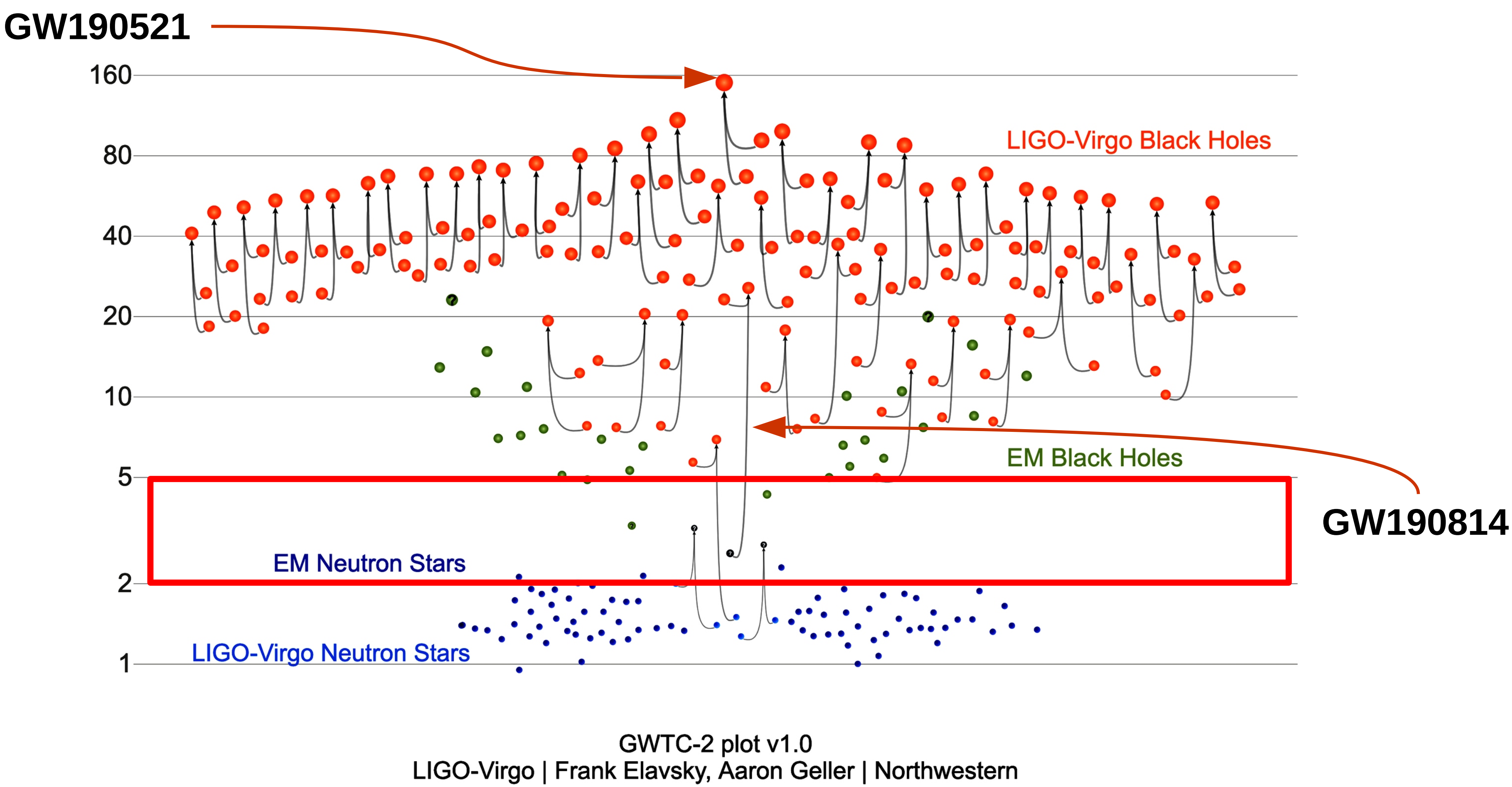
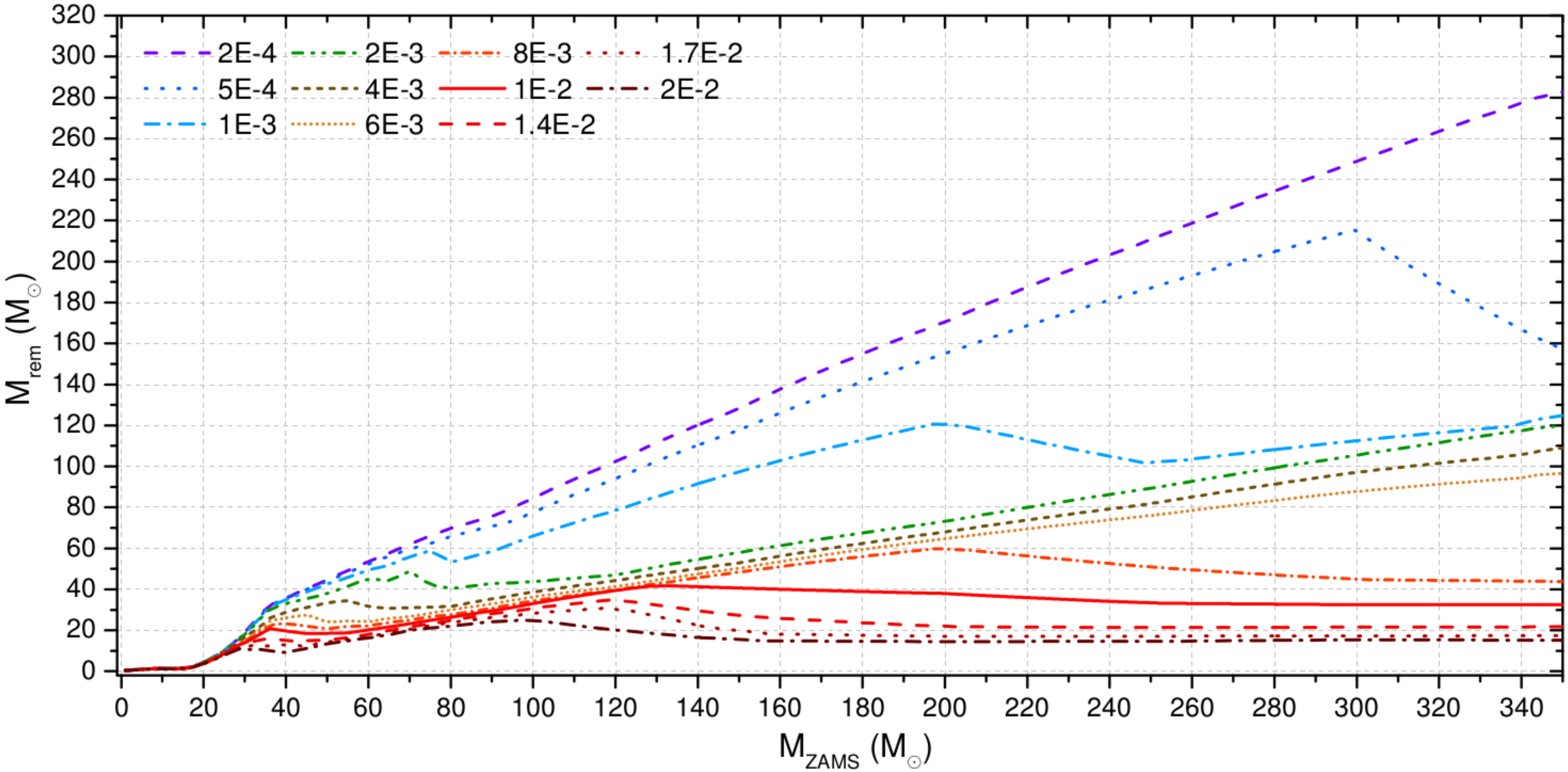


Abbott et al. 2020, GWTC-2, 2020, https://arxiv.org/abs/2010.14527

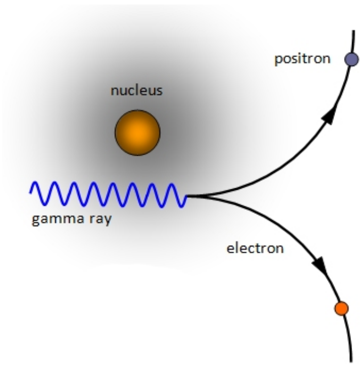
Evolution of very massive stars still uncertain

→ stellar winds are Eddington-limited rather than metallicity dependent



Spera & MM 2017

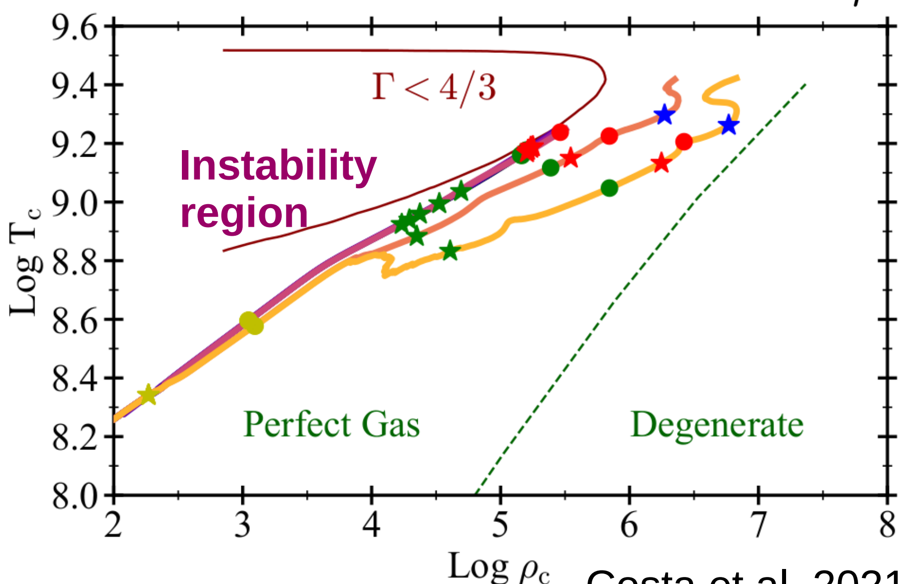
PAIR-INSTABILITY SUPERNOVAE (PISNe)



$$\Gamma = \frac{\partial \ln P}{\partial \ln \rho}$$

If star is very massive,
helium core mass > 64 M⊙ at end of C burning
→ central temperature > 7 x 10^8 K
→ efficient production of γ-ray radiation in core

→ γ-ray photons scattering atomic nuclei produce electron-positron pairs (1 Mev, nearly at rest)



Costa et al. 2021

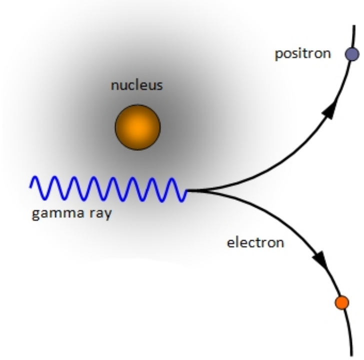
The missing pressure of γ-ray photons produces dramatic collapse during O burning, without Fe core

→ Temperature increase during collapse ignites all remaining species

→ an explosion is induced that leaves NO remnant

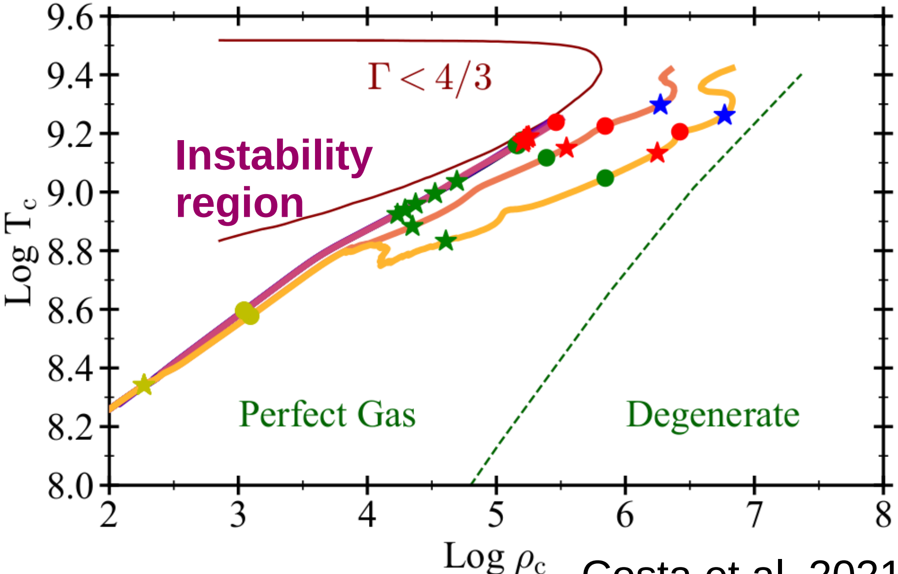
Ober, El Eid & Fricke 1983; Bond, Arnett & Carr 1984; Heger et al. 2003; Woosley, Blinnikov & Heger 2007

PULSATIONAL PAIR INSTABILITY (PPI)



If star is quite massive,
64 M⊙> Helium core mass > 32 M⊙
→ some production of γ-ray radiation in core

$$\Gamma = \frac{\partial \ln P}{\partial \ln \rho}$$



Costa et al. 2021

➔ γ-ray photons scattering atomic nuclei produce electron-positron pairs (1 Mev, nearly at rest)

The missing pressure of γ-ray photons produces contraction during O burning, without Fe core

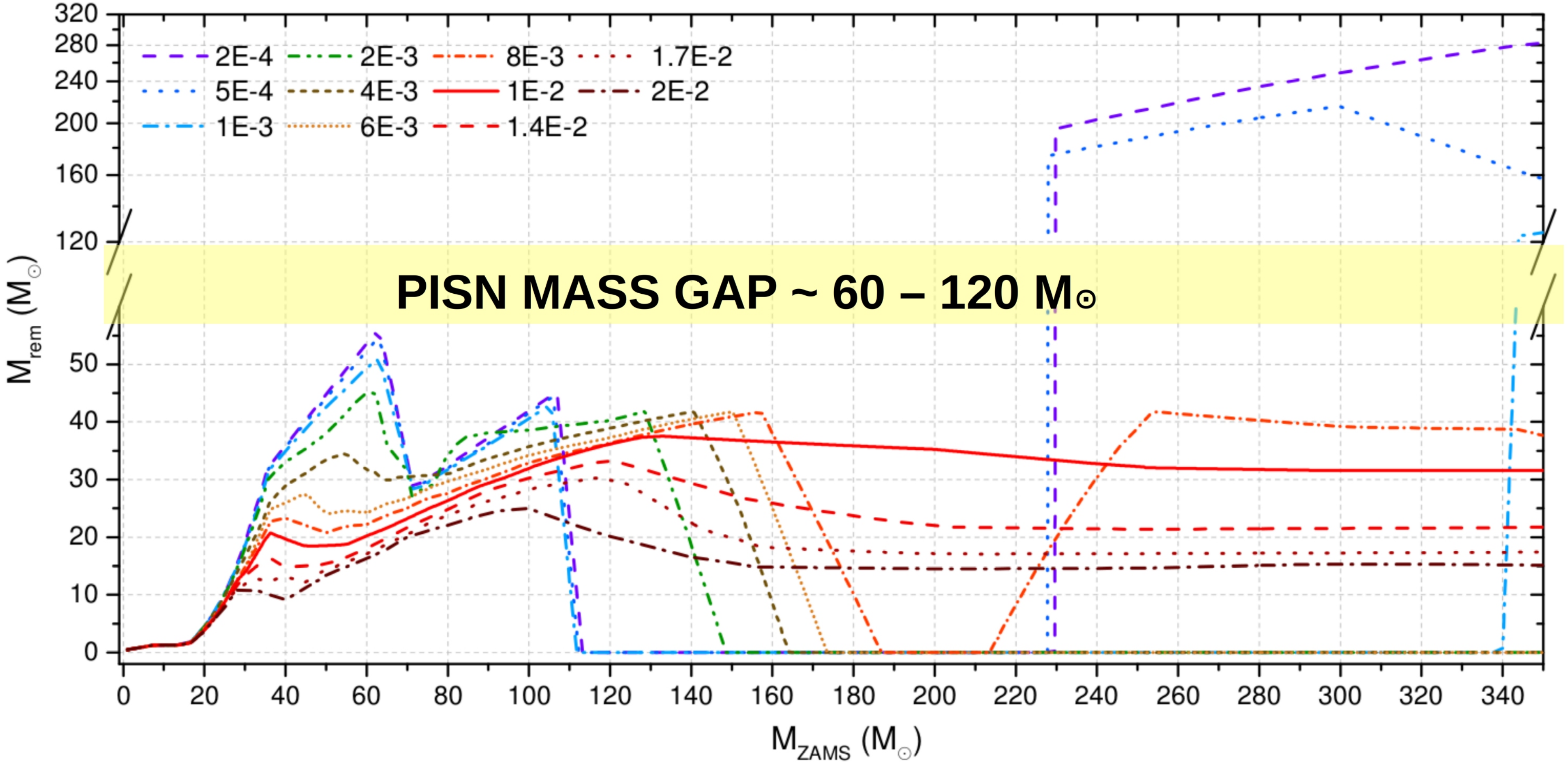
→ enhancement of nuclear reactions restores pressure

→ star gains equilibrium after one or more oscillations

→ **oscillations enhance mass loss and final mass is lower**

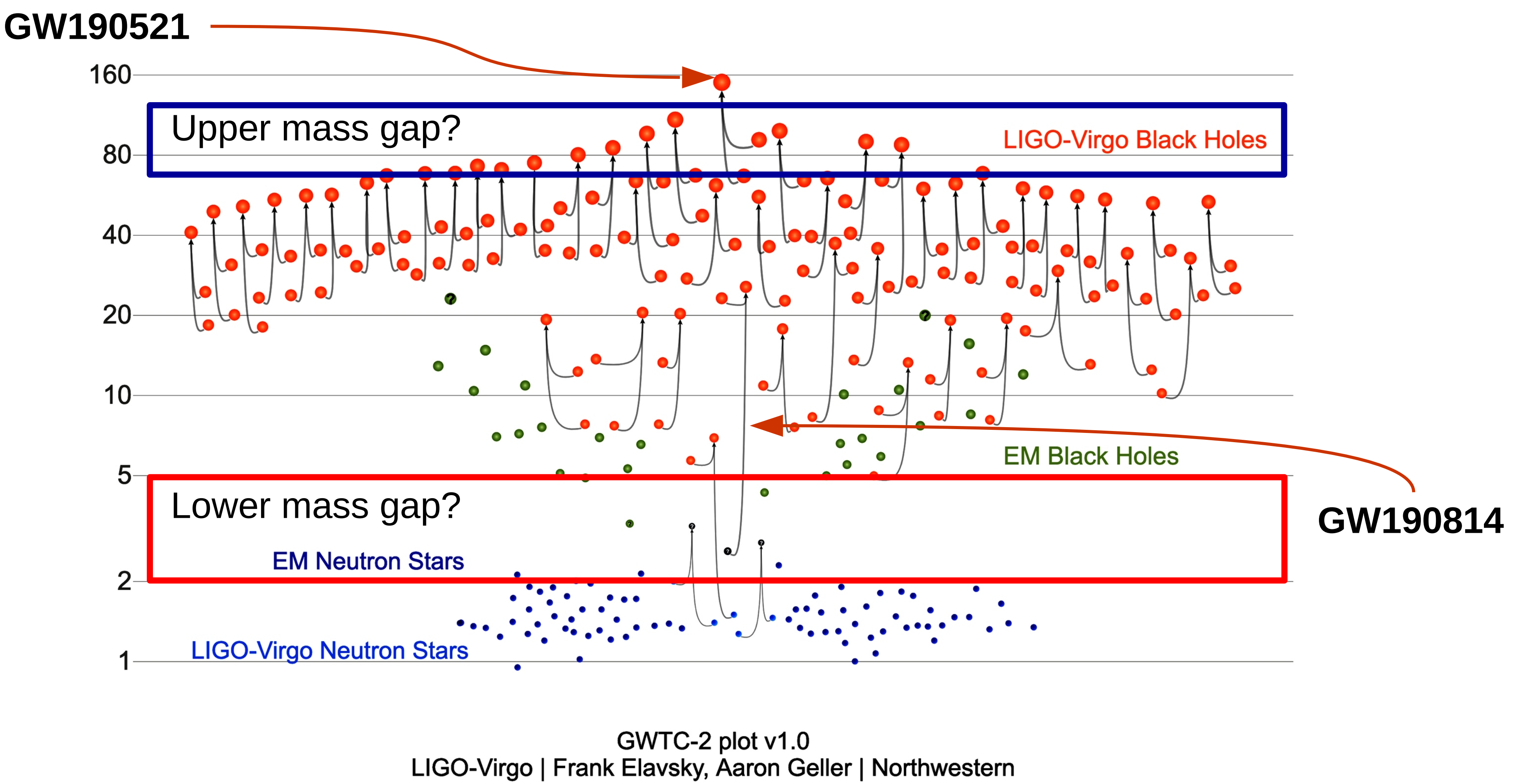
Barkat, Rakavy & Sack 1967; Woosley, Blinnikov & Heger 2007; Yoshida et al. 2016; Woosley 2017, 2019; Marchant et al. 2019

An upper mass gap because of (pulsational) pair instability?



Spera & MM 2017

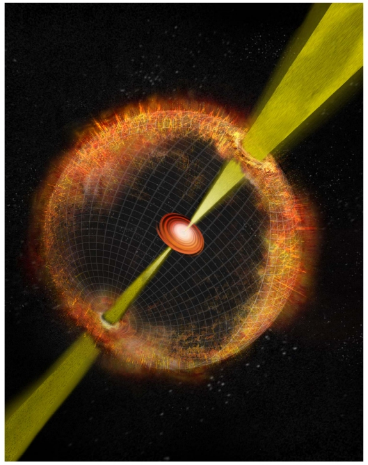
A un upper mass gap in BH mass spectrum?



Abbott et al. 2020, GWTC-2, 2020, https://arxiv.org/abs/2010.14527

WHAT ABOUT THE SPIN? Spin magnitude is OPEN ISSUE

Spin of compact object should be related to spin of the core at the end of stellar evolution (if ang. mom. is conserved)



BUT:

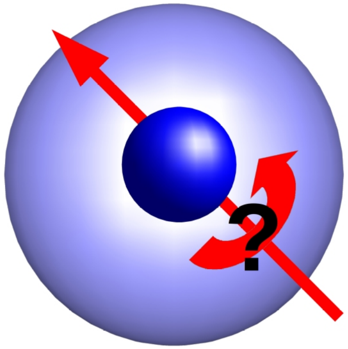
- if **supernova explosion**, part of spin is lost
- if **accretion disk or jet**, angular momentum is transported outward/away
- if star collapses to **black hole DIRECTLY**, angular momentum should be conserved

PROBLEM:

- large uncertainties on **angular momentum transport in the stellar interior**

→ **we do not know spin of the core at the end of stellar evolution**

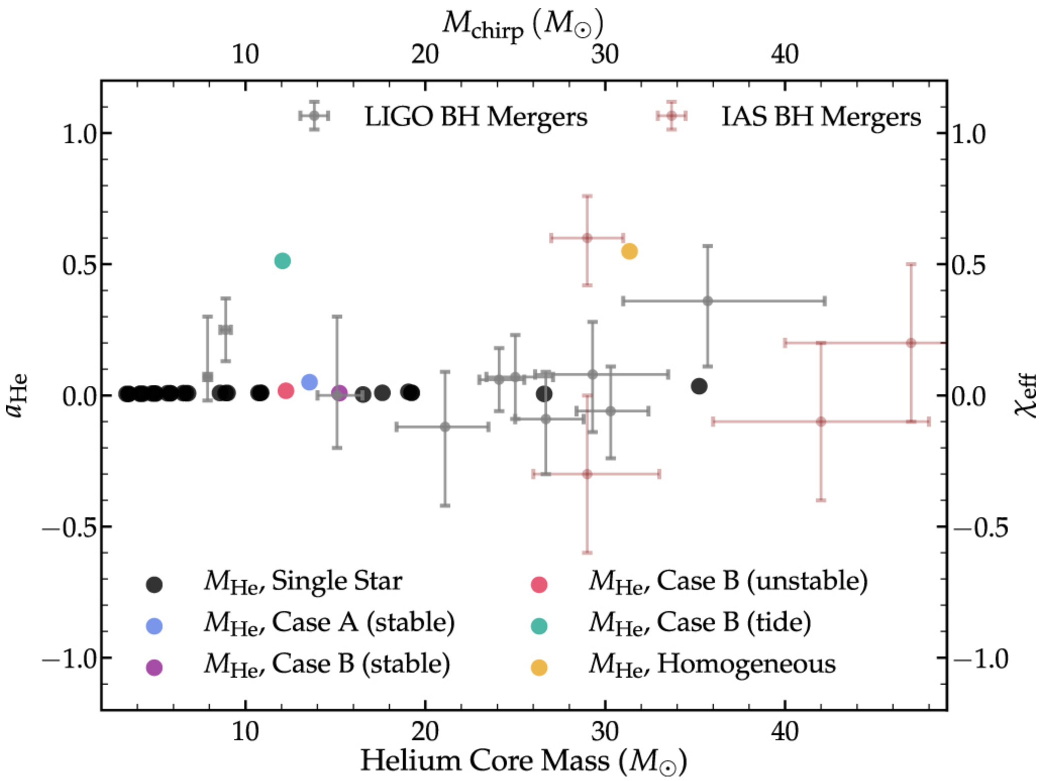
(e.g. Belczynski et al. 2020; Limongi & Chieffi 2018; MM et al. 2020)



WHAT ABOUT THE SPIN? Spin magnitude is OPEN ISSUE

Models of stellar evolution usually neglect or simplify MAGNETIC FIELD

→ Angular momentum from stellar core efficiently dissipated via magnetic effect - e.g. **Tayler-Spruit dynamo** (Spruit 2002)



Final core spins are close to zero with Tayler-Spruit dynamo

Fuller & Ma 2019, ApJ, 881, L1

Does it work for some / all stars?

References:

* M. Mapelli, Formation channels of Single and Binary Stellar-Mass Black Holes, Chapter of the Book "Handbook of Gravitational Wave Astronomy", 2021, Springer, https://ui.adsabs.harvard.edu/abs/2021hgwa.bookE...4M/abstract

and MANY references therein