Michela Mapelli

How do the LIGO – Virgo – KAGRA (Binary) Compact Objects form?

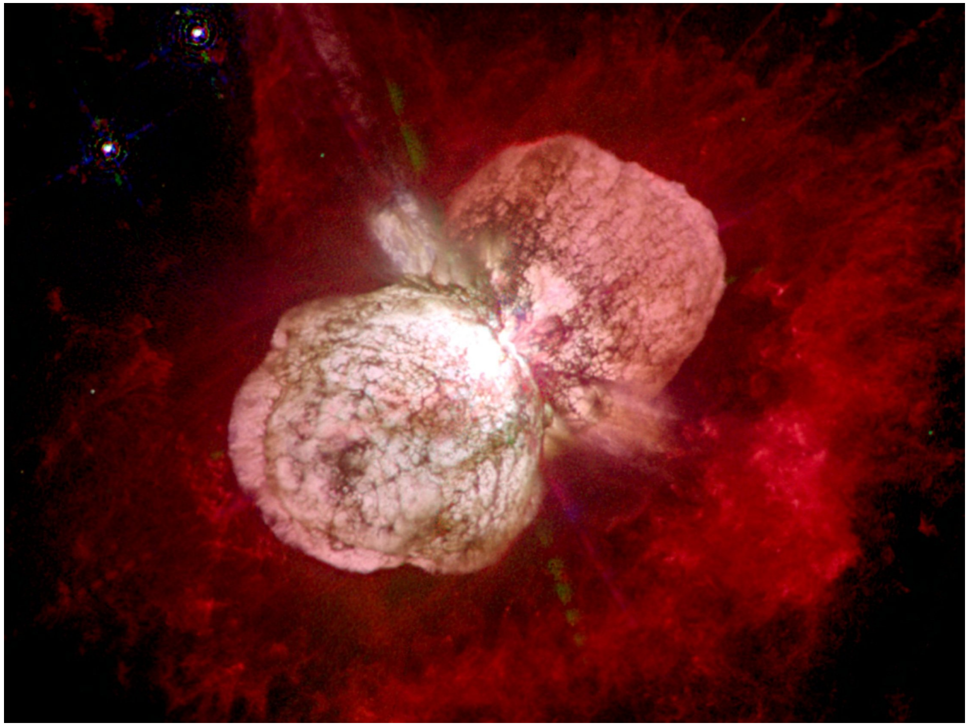
Bad Honnef, January 23rd 2026, 5th Graduate School on Astro-Particle Physics

How do compact objects form?

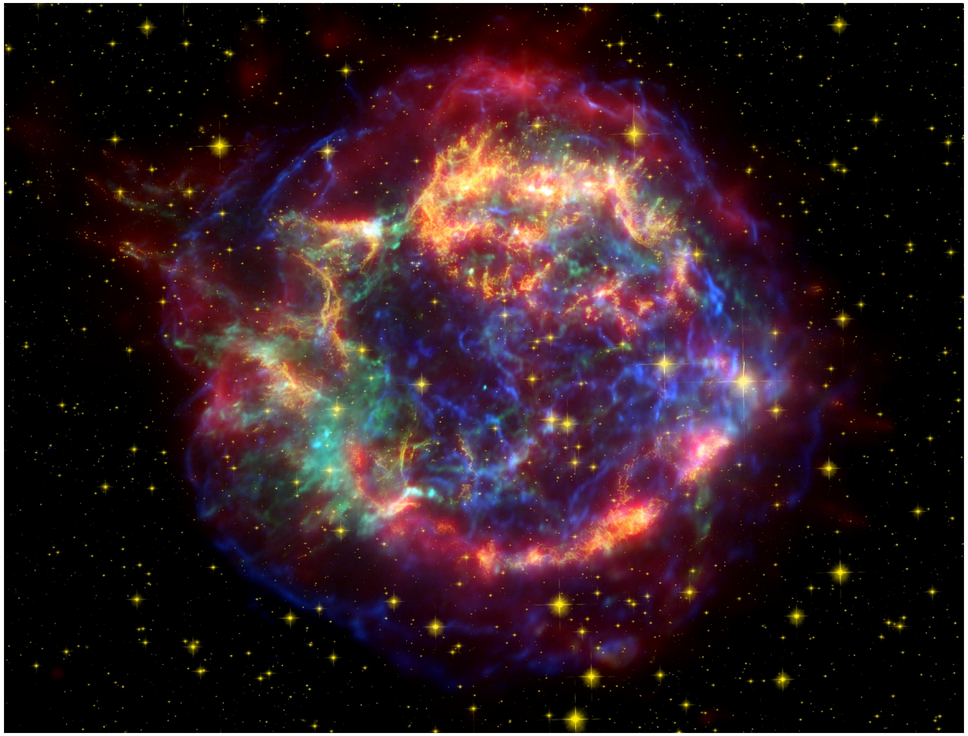
Two critical ingredients:

1) PROGENITOR STAR EVOLUTION (STELLAR WINDS)

2) SUPERNOVA (SN) EXPLOSION



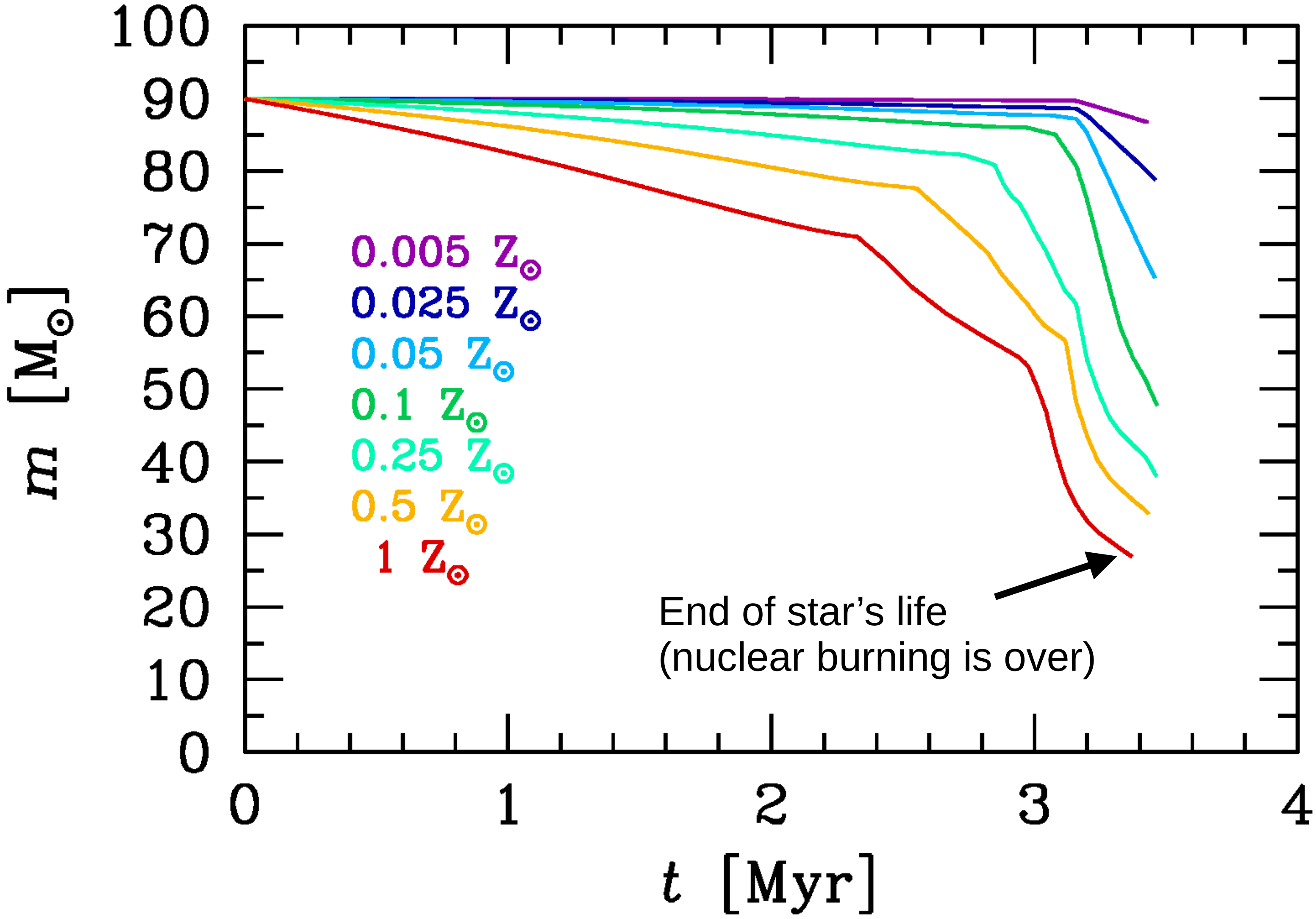
Winds ejected by Eta Carinae (HST, credits: NASA)



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

How do compact objects form? Stellar winds

Stellar winds: process that removes mass from star surface

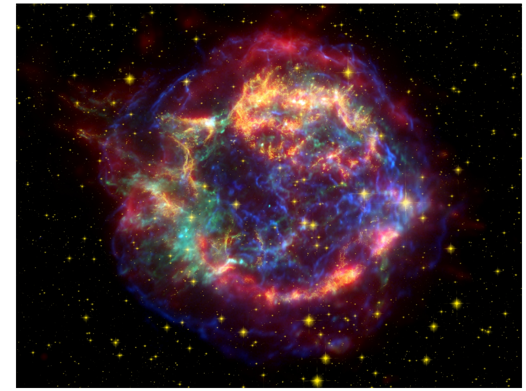


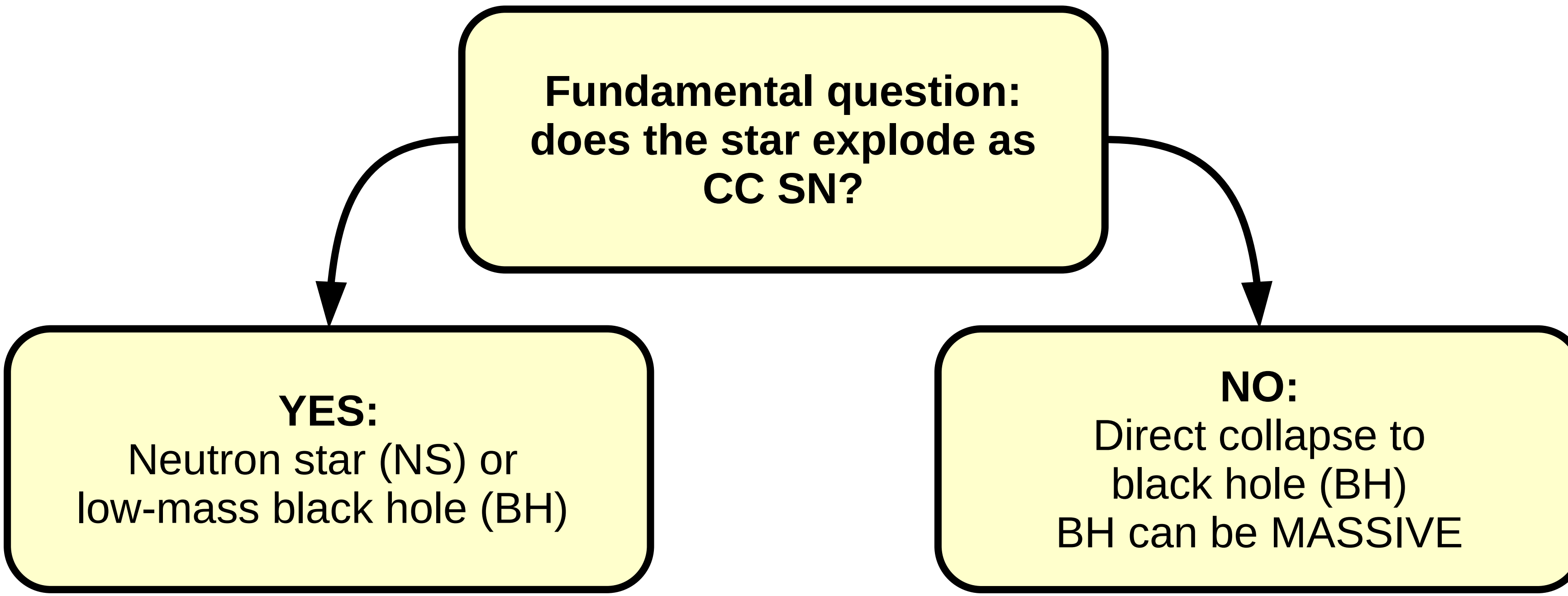
Models from PARSEC stellar evolution code (Bressan+ 2012; Tang+ 2014; Chen, Bressan+ 2015)

How do compact objects form? Core collapse (CC) supernovae

Core collapse (CC) SUPERNOVAE:

Final mass and other properties of a star
are very important,
because they affect the outcome of a
core-collapse (CC) SUPERNOVA (SN)



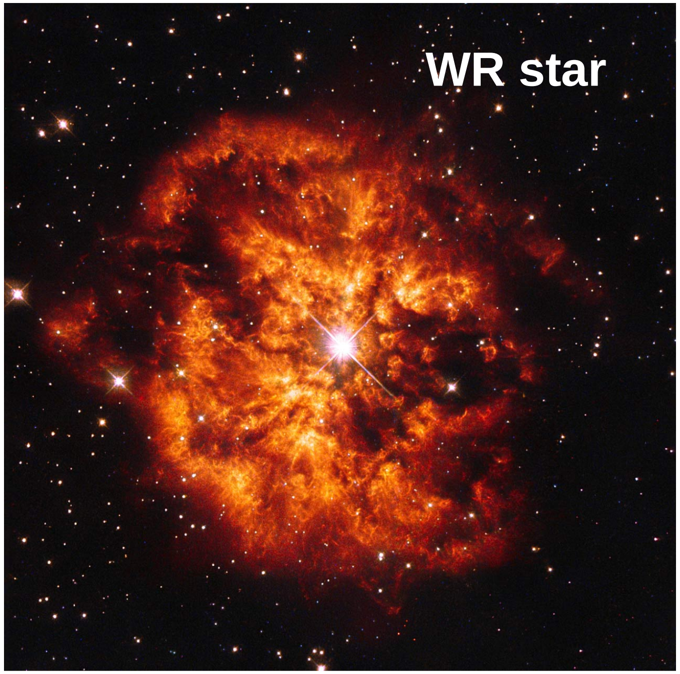


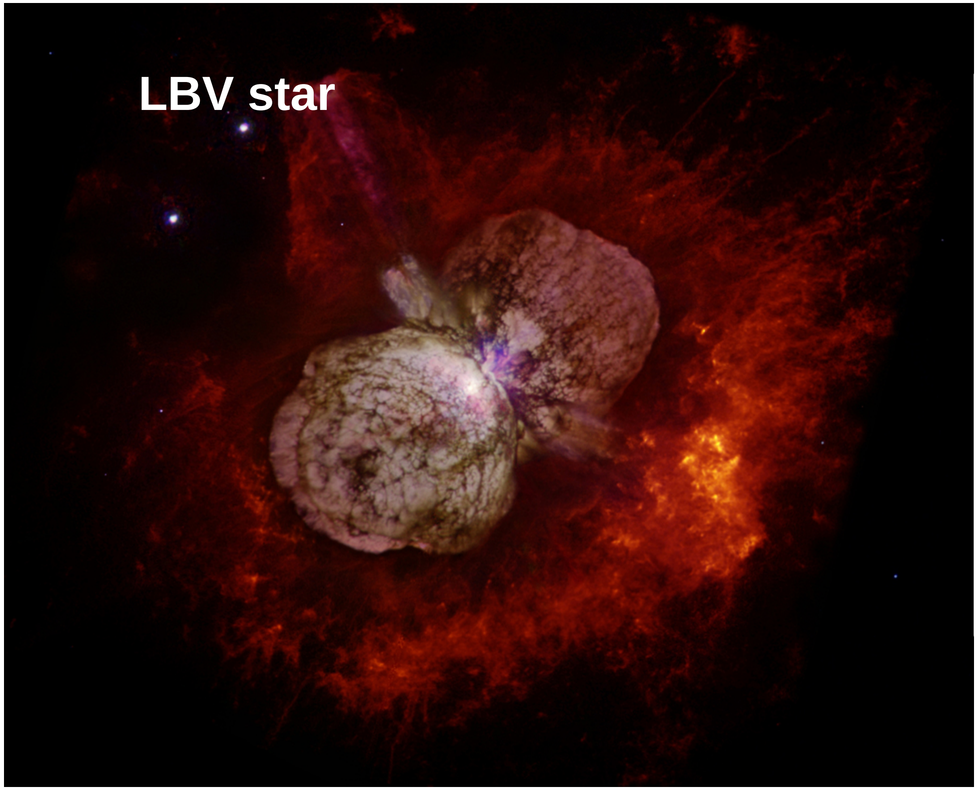
STELLAR WINDS:

We observe mass loss from massive stars

Stars with luminosity > 10^4 Lsun
lose substantial fraction of mass
by stellar winds

What is the physical process driving this?





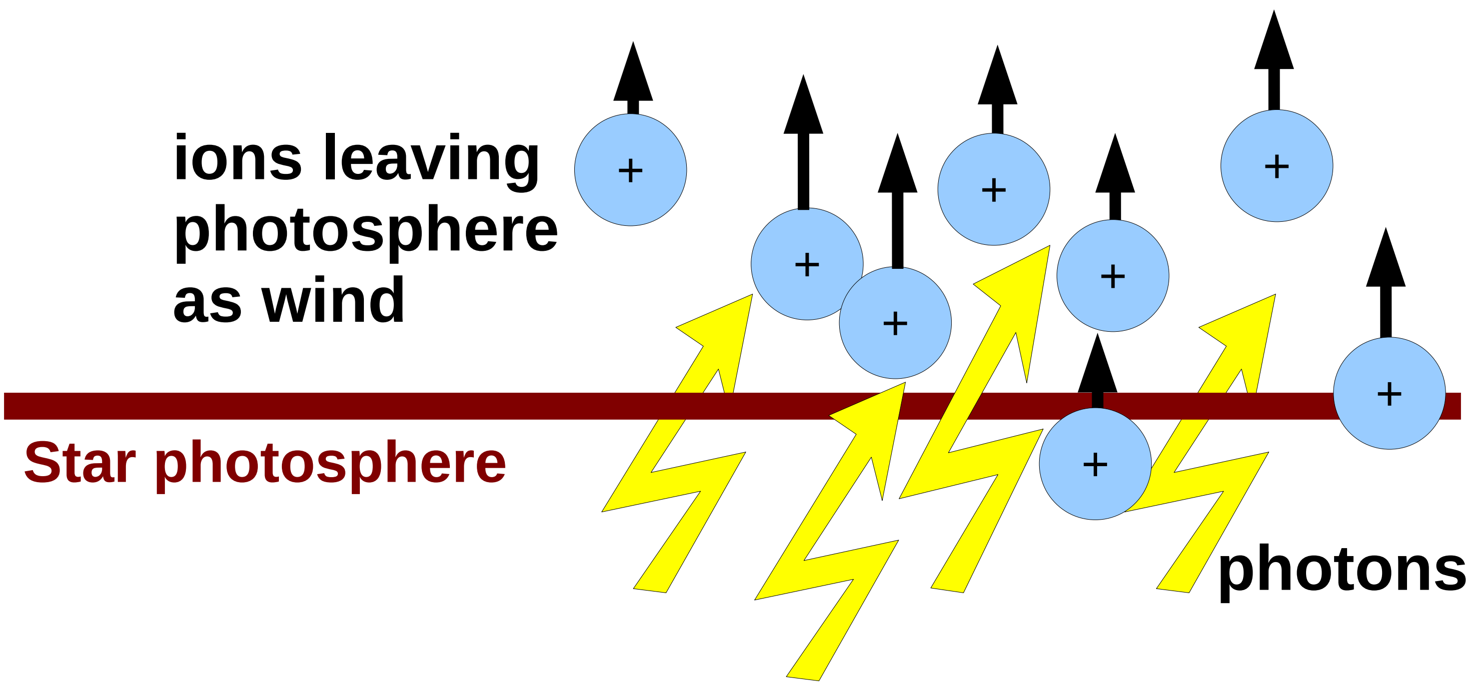
How do compact objects form? Stellar winds

Massive hot stars (>30 $M_\odot$) might lose >50% mass by winds

Stellar wind models underwent major upgrade in last ~20 yr

(Vink+ 2000, 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



STELLAR WIND THEORY, basic equation:

Local violation of mass conservation and hydrostatic equilibrium

1. Continuity equation: gives the mass loss by stellar wind

mass conservation — mass loss rate

$$\mathrm{d}m = 4\,\pi\,\rho\,r^2\,\mathrm{d}r \;\xrightarrow{\frac{1}{\mathrm{dt}}}\; \dot{m} = 4\,\pi\,\rho\,r^2\,v$$

2. Momentum equation: gives the velocity of the wind

hydrostatic equilibrium — Equation of motion

$$0 = -\frac{1}{\rho}\frac{\mathrm{d}P}{\mathrm{d}r} - \frac{G\,m(r)}{r^2} \;\longrightarrow\; \frac{\mathrm{d}v(r)}{\mathrm{d}t} = -\frac{1}{\rho}\frac{\mathrm{d}P}{\mathrm{d}r} - \frac{G\,m(r)}{r^2}$$

we have a wind if ***v(r)>0***
only if the pressure term is locally stronger than the gravity term
ONLY AT STELLAR SURFACE

How do compact objects form? Stellar winds

Massive hot stars (>30 M☉) might lose >50% mass by winds

(Vink+ 2001, 2005, 2011; see Vink+ 2016 for a short review)

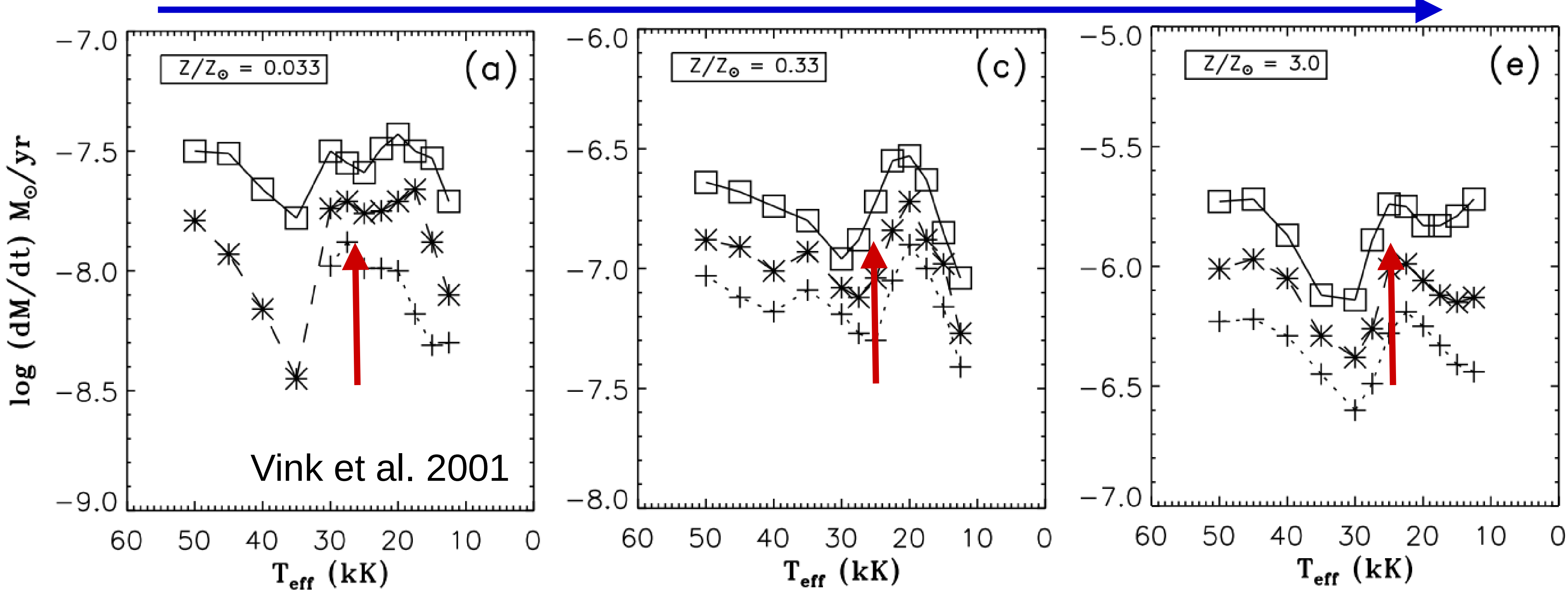
1) Line-driven winds

Coupling through atomic absorption LINES (especially Fe lines)

→ Mass loss depends on metallicity:

larger mass loss at higher metallicity

Increasing Z, increasing Mdot



Bi-stability jump: Fe IV recombines to Fe III when T<25k K → mass loss increases

How do compact objects form? Stellar winds

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(Vink+ 2001, 2005, 2011; see Vink+ 2016 for a short review)

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→ Mass loss depends on metallicity:
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the classical version of Compton scatter, when energy of photons << mass – energy of ions

2) Coupling through Thomson scatters:
electrons scatter photons and acquire linear momentum
ions are dragged away together with electrons because of Coulomb forces

→ Mass loss depends on the luminosity of the star:
the closer a star is to the Eddington limit
(radiation pressure dominates the star's physics),
the more Thomson scatters contribute to the mass loss

→ **The higher the luminosity the higher the mass loss**

→ Metallicity dependence of mass loss less important when STAR is CLOSE to electron-scattering EDDINGTON LIMIT
e.g. Graefener & Hamann 2008

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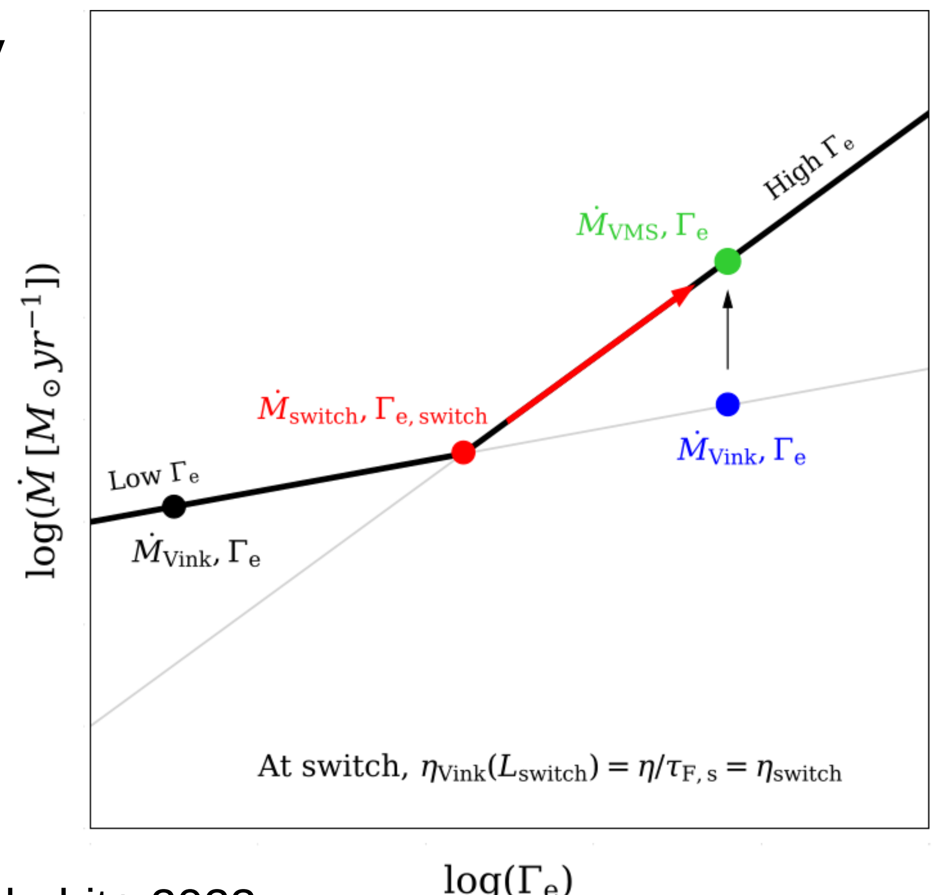
$$\Gamma = \frac{L_*}{L_{\rm Edd}}$$

$$L_{\rm Edd} = \frac{4\,\pi\,G\,M\,c}{\kappa}$$



Sabhahit+ 2023

How do we form compact objects? Stellar winds

Massive hot stars (>30 $M_\odot$) might lose >50% mass by winds

(Vink+ 2001, 2005, 2011; see Vink+ 2016 for a short review)

1) Mass loss depends on metallicity:
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2) Mass loss depends on the luminosity of the star:
the higher the luminosity the higher the mass loss

Simplest possible description (Chen, Bressan et al. 2015):

$$\dot{M} \propto Z^{\alpha}$$

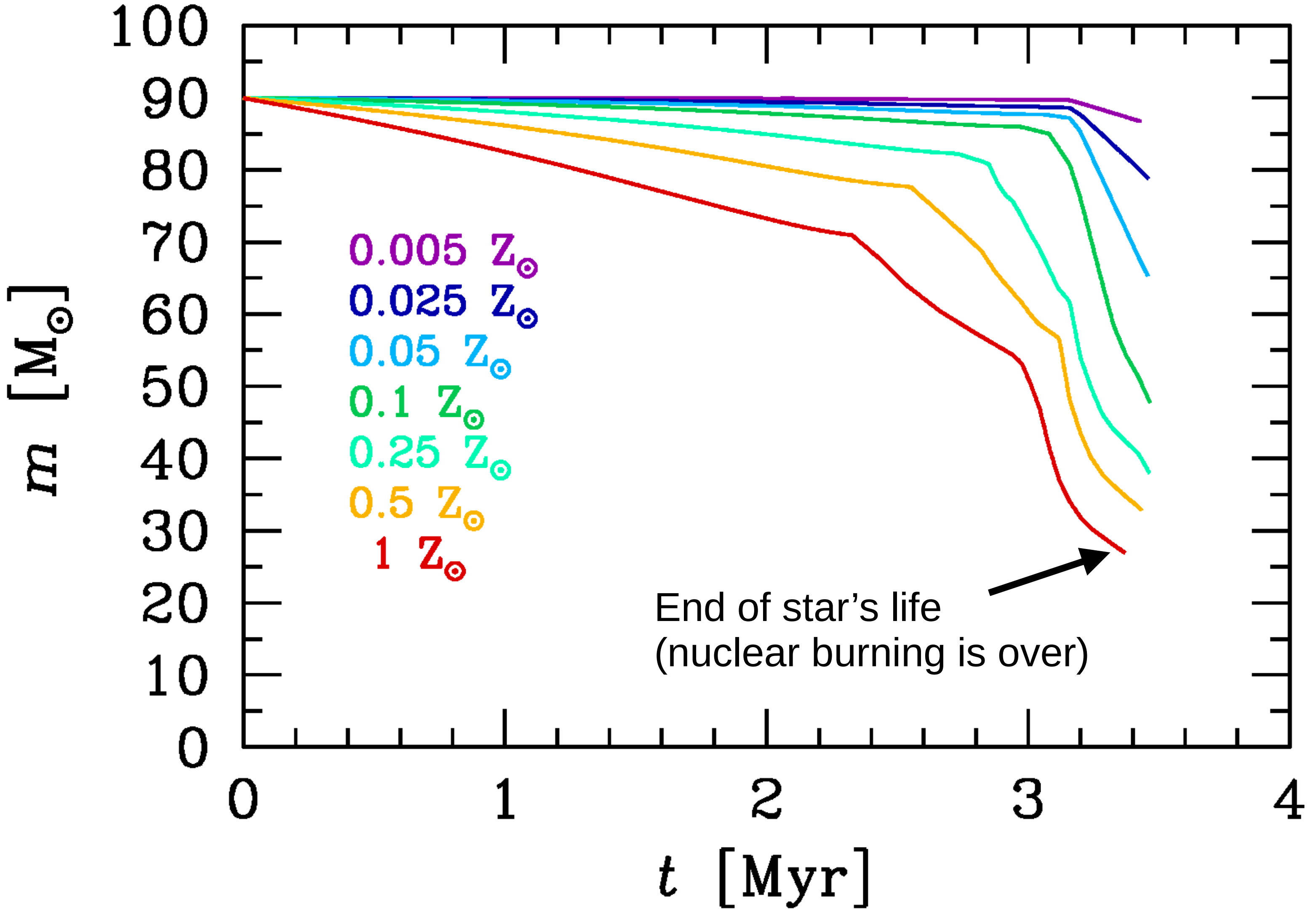
$$\begin{cases} \alpha = 0.85 & [\text{if } \Gamma < 2/3] \\ \alpha = 2.45 - 2.4\,\Gamma & [\text{if } 2/3 \leq \Gamma \leq 1] \\ \alpha = 0.05 & [\text{if } \Gamma > 1] \end{cases}$$

where $\Gamma = \frac{L_*}{L_{\rm Edd}}$ (electron-scattering Eddington ratio) and

$L_{\rm Edd} = \frac{4\,\pi\,G\,M\,c}{\kappa}$ or, for pure ionized hydrogen: $L_{\rm Edd} = \frac{4\,\pi\,G\,M\,m_{\rm p}\,c}{\sigma_{\rm T}}$

How do compact objects form? Stellar winds

Stellar winds: process that removes mass from star surface



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

Core collapse (CC) SUPERNOVAE:

Final mass and other properties of a star
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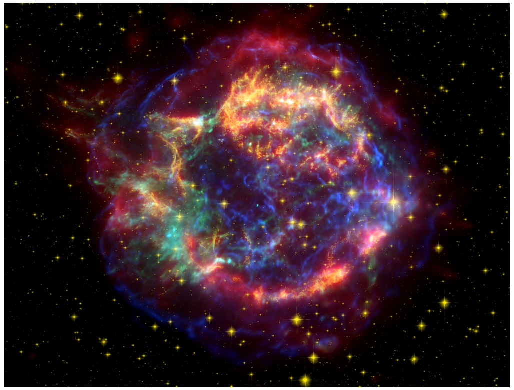
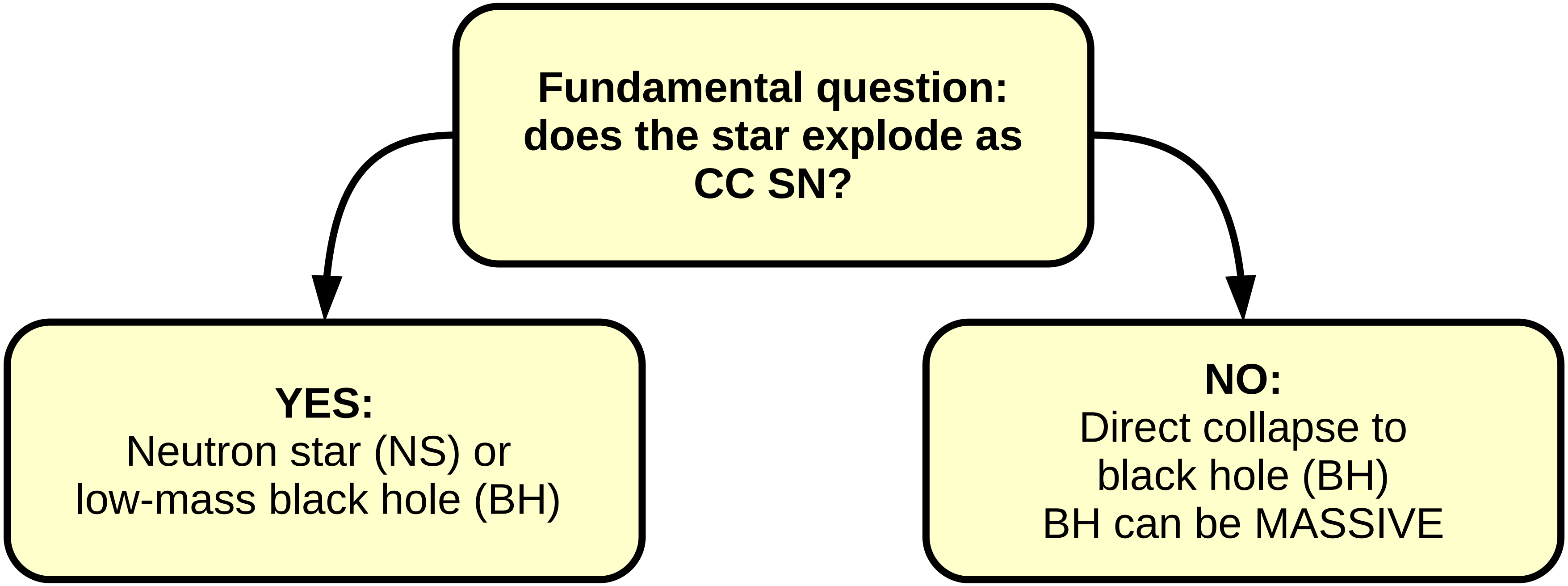




How do we form compact objects? Core collapse (CC) supernovae

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

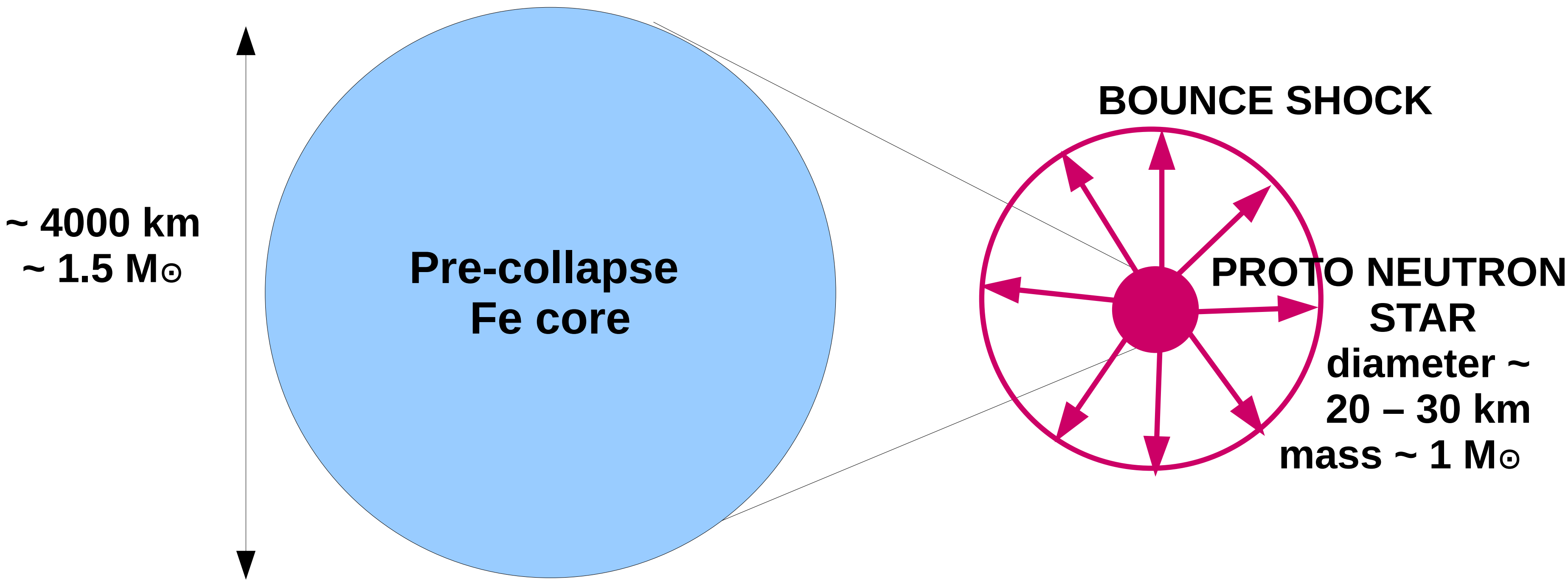
→ **COLLAPSE to NUCLEAR DENSITY (~10^{14} g cm^{-3}),**
where **neutron degeneracy pressure** stops collapse

→ **PROTO-NEUTRON STAR (PNS) FORMS**

How do we form compact objects? Core collapse (CC) supernovae

Collapse of the core produces **BOUNCE SHOCK** of the outer parts of the core on the proto-NS surface: The collapsing outer parts of the core hit the proto-NS surface and bounce back

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



How do we form compact objects? Core collapse (CC) supernovae

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SHOCK MUST REVERSE COLLAPSE OF OUTER LAYERS

But density must be sufficiently high that neutrinos interact, otherwise neutrinos leak away without transferring energy

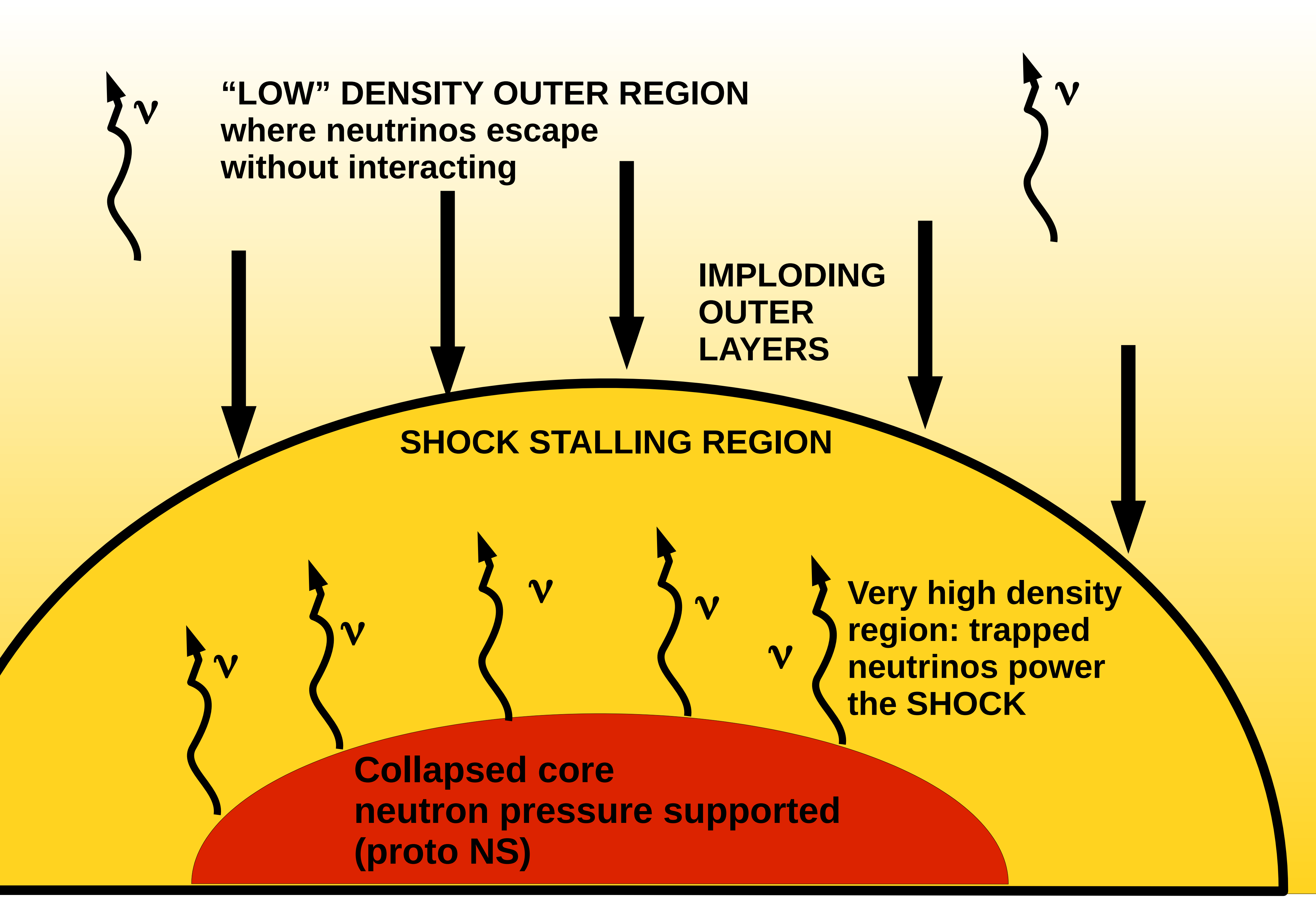
→ SHOCK MIGHT STALL
→ SN FAILS

<u>WHAT CAN REVIVE THE SHOCK?</u>

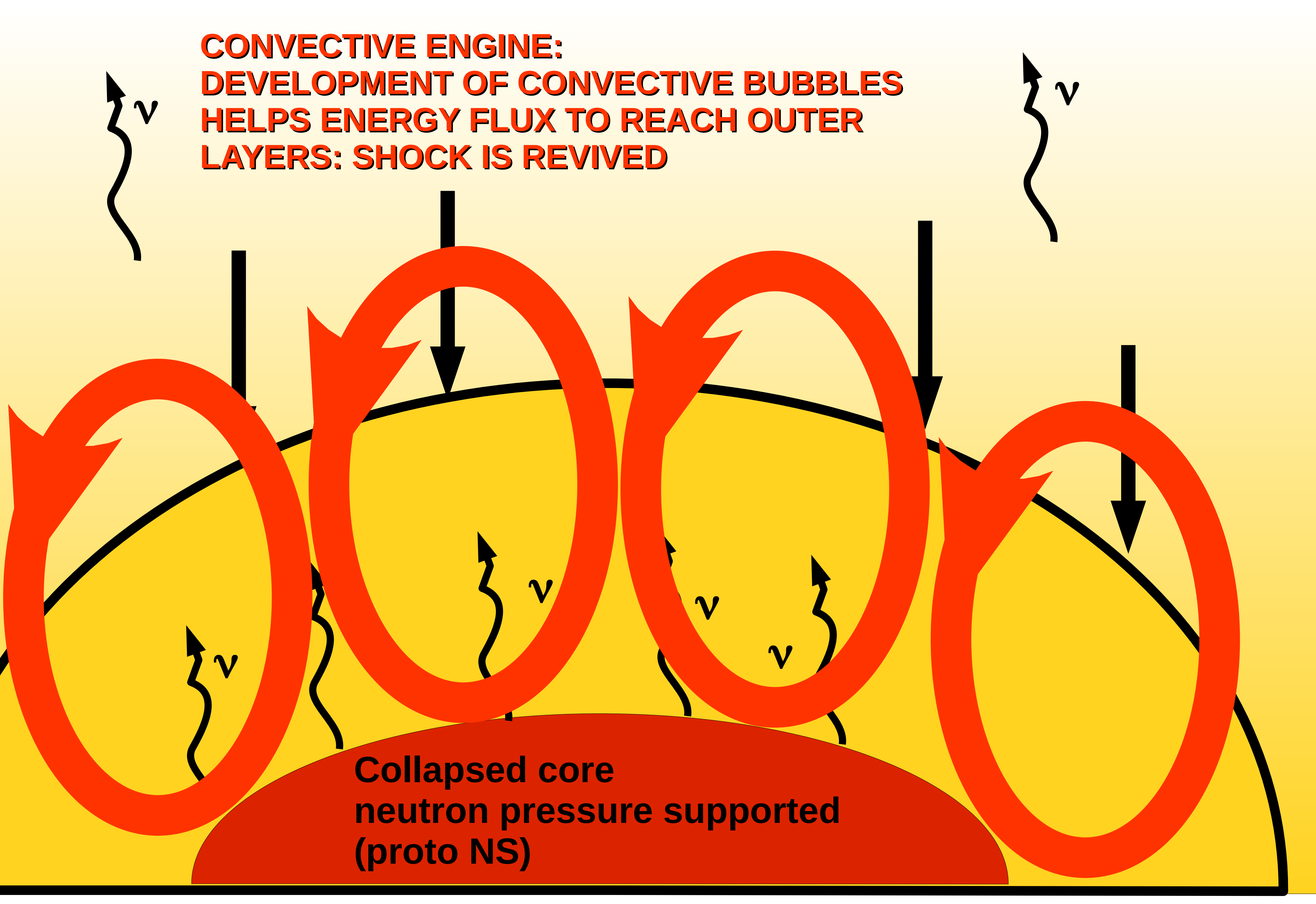
STANDARD MODEL: CONVECTIVE ENGINE

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

How do we form compact objects? Core collapse (CC) supernovae



How do we form compact objects? Core collapse (CC) supernovae



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

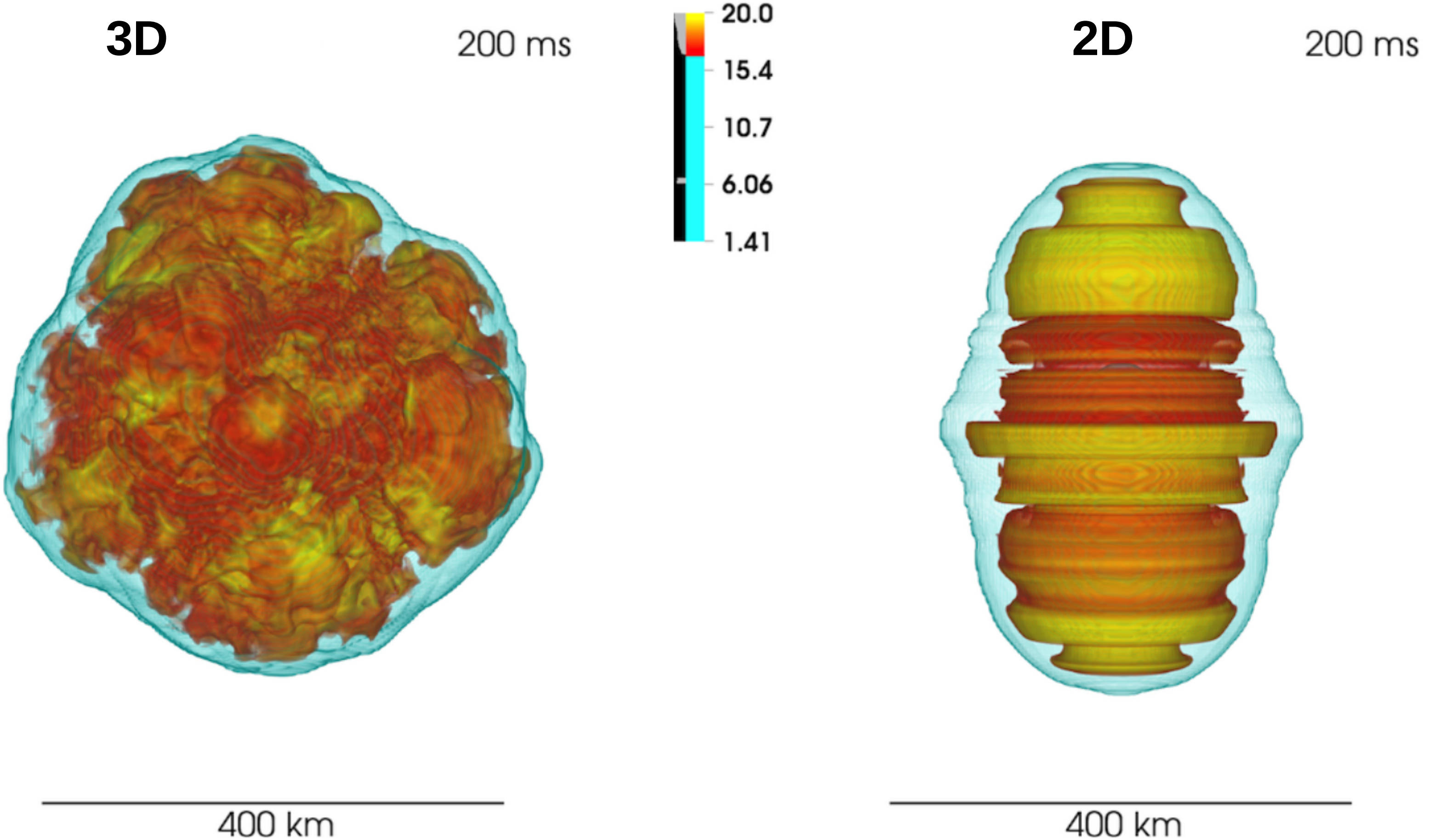
Star cannot explode if envelope binding energy > SN energy

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

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

How do we form compact objects? Core collapse (CC) supernovae

HYDRODYNAMICAL SIMULATIONS of CC SNe
Couch & O'Connor 2014



Volume renderings of **entropy**, in k_B baryon $^{-1}$

MORE REFINED CRITERIA FOR COLLAPSE VS EXPLOSION

No consensus in the SN community (Burrows et al. 2018)

1. MASS OF CARBON-OXYGEN CORE

If $M_{co} > 8 – 12$ Msun SN FAILS
(Fryer+ 1999, 2012; Belczynski+ 2010)

2. COMPACTNESS

3. More complex criteria (e.g. TWO-PARAMETER CRITERION)

How do we form compact objects? Core collapse (CC) supernovae

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 $M_\odot$ is usually adopted

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

(Ugliano+ 2012; Horiuchi+ 2012)

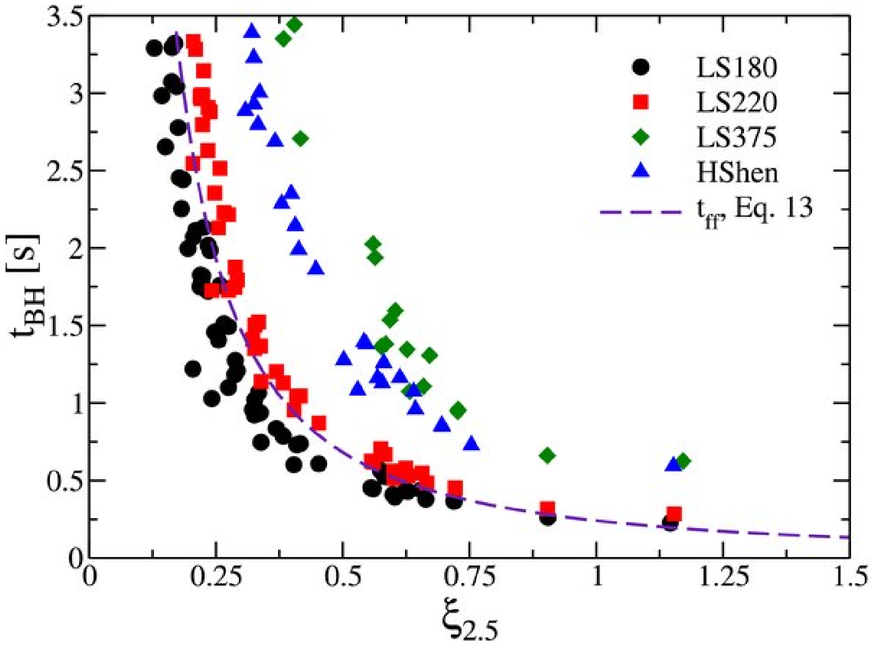


Figure from
O'Connor & Ott 2011

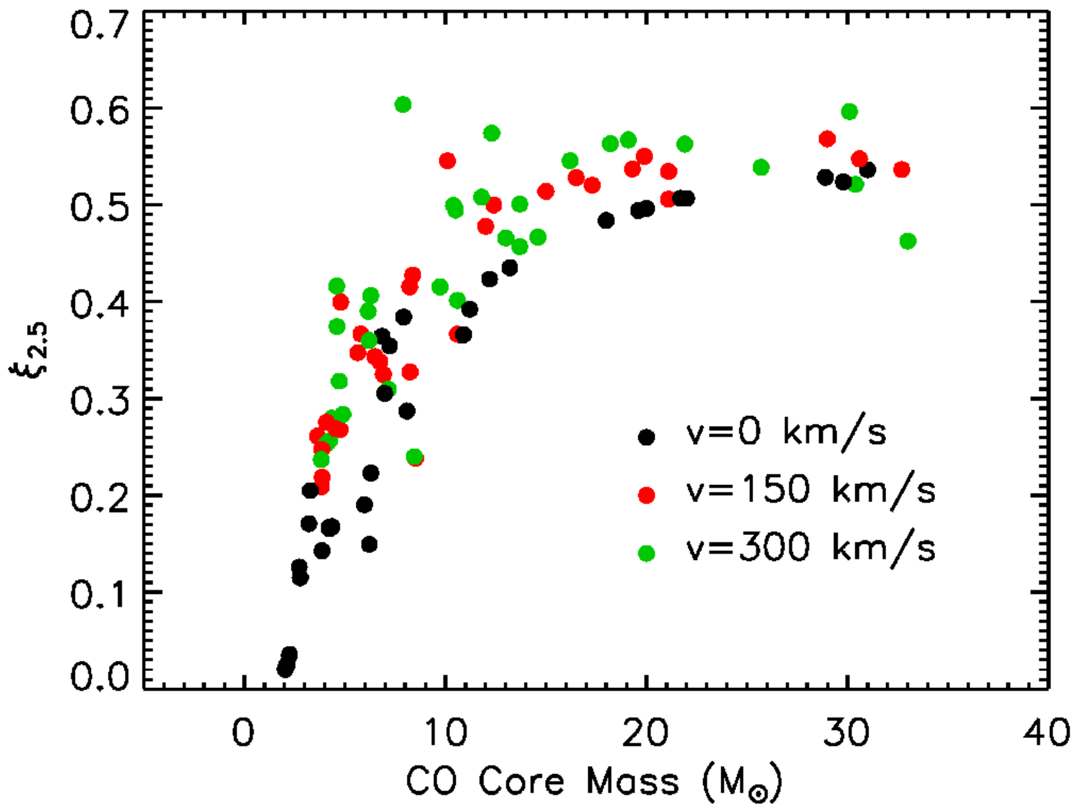
How do we form compact objects? Core collapse (CC) supernovae

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

Compactness correlates well with mass of CO core

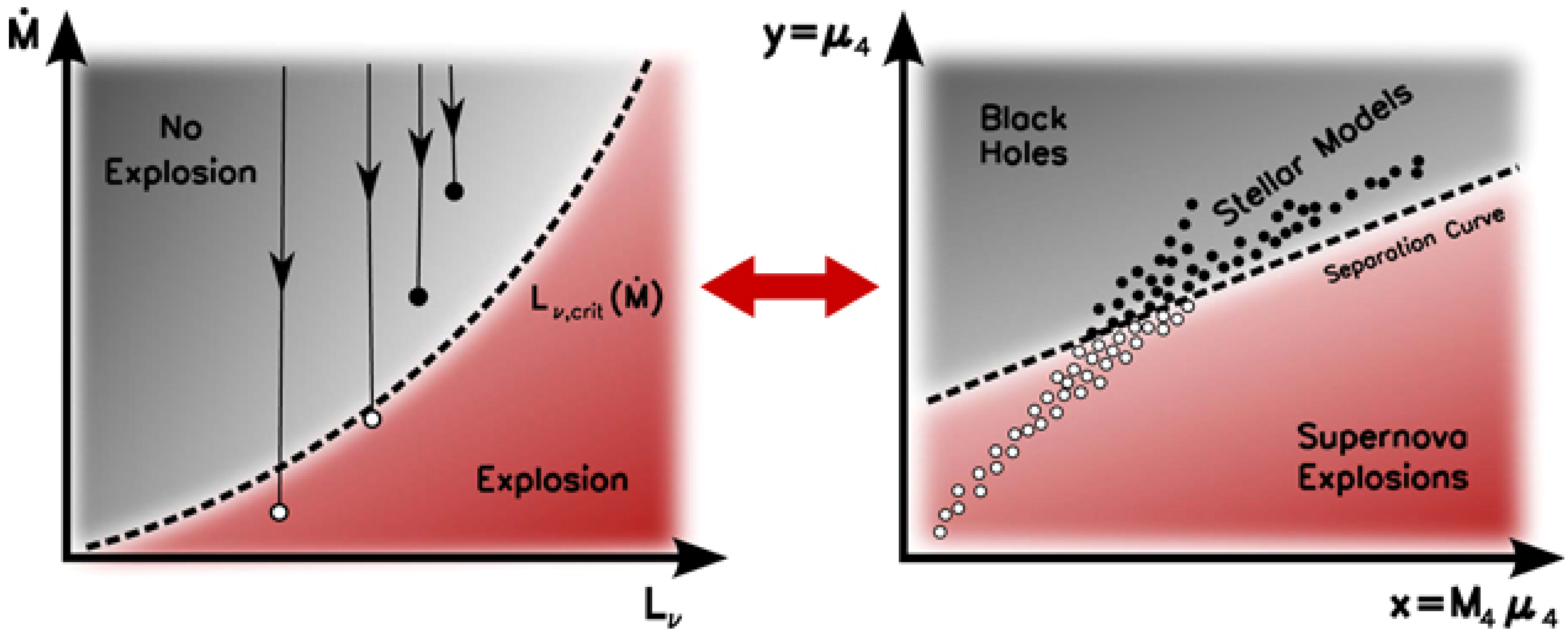
→ compactness > 0.2 corresponds to CO core > 8 M⊙

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

How do we form compact objects? Core collapse (CC) supernovae

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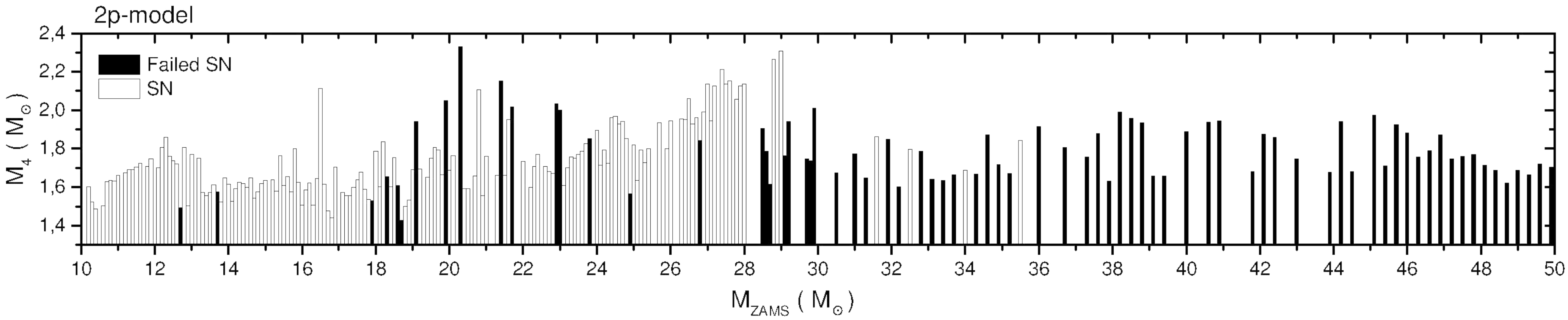


Fig. 21 Spera, MM, Bressan 2015

ISLANDS OF DIRECT COLLAPSE AND SN EXPLOSION

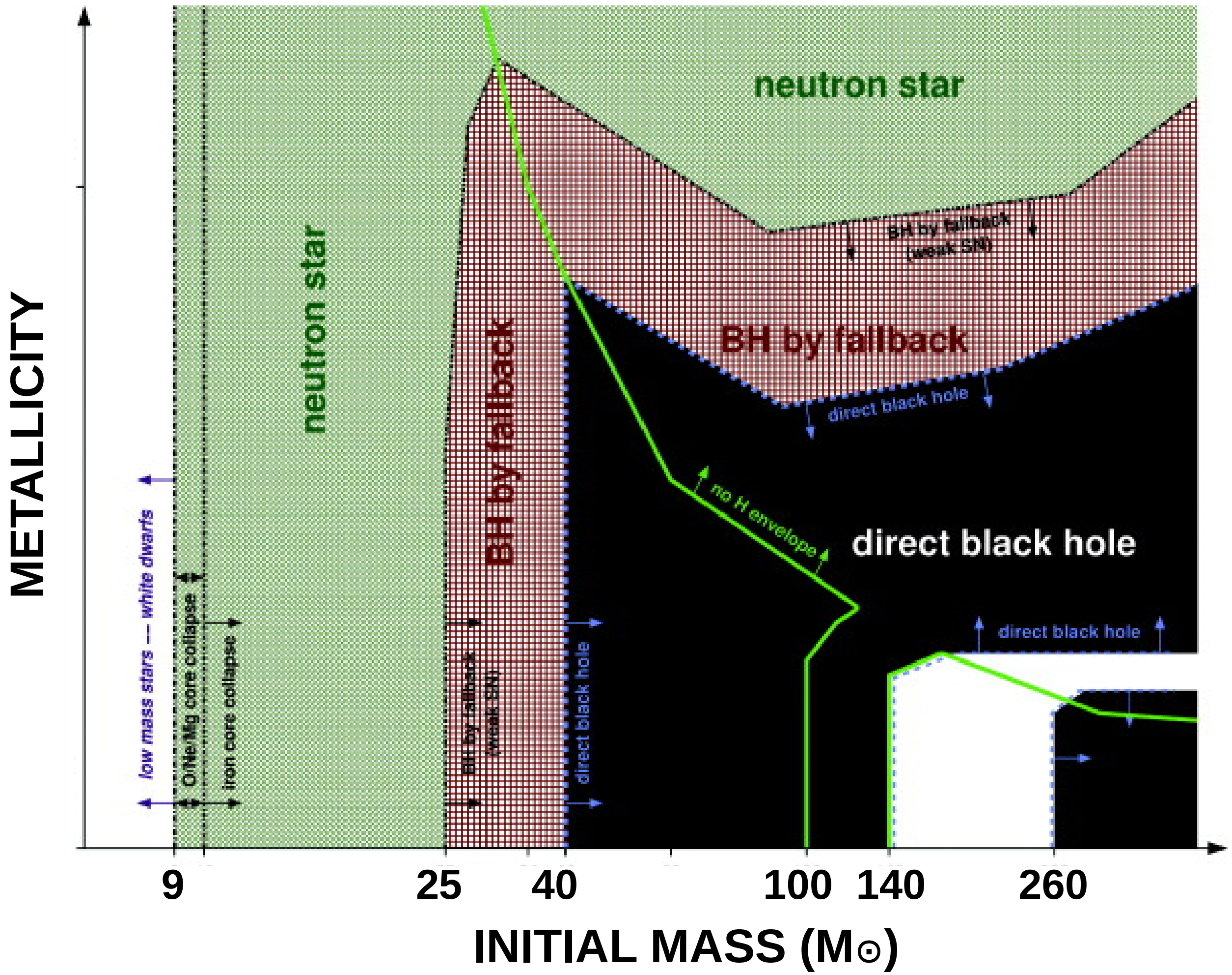
Concluding remark:
MANY MODELS of SN EXPLOSION OUTCOMES
BUT IF THE STAR IS VERY MASSIVE (>40 $M_\odot$)
THEY GIVE SIMILAR RESULT

How do we form compact objects? Core collapse (CC) supernovae

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



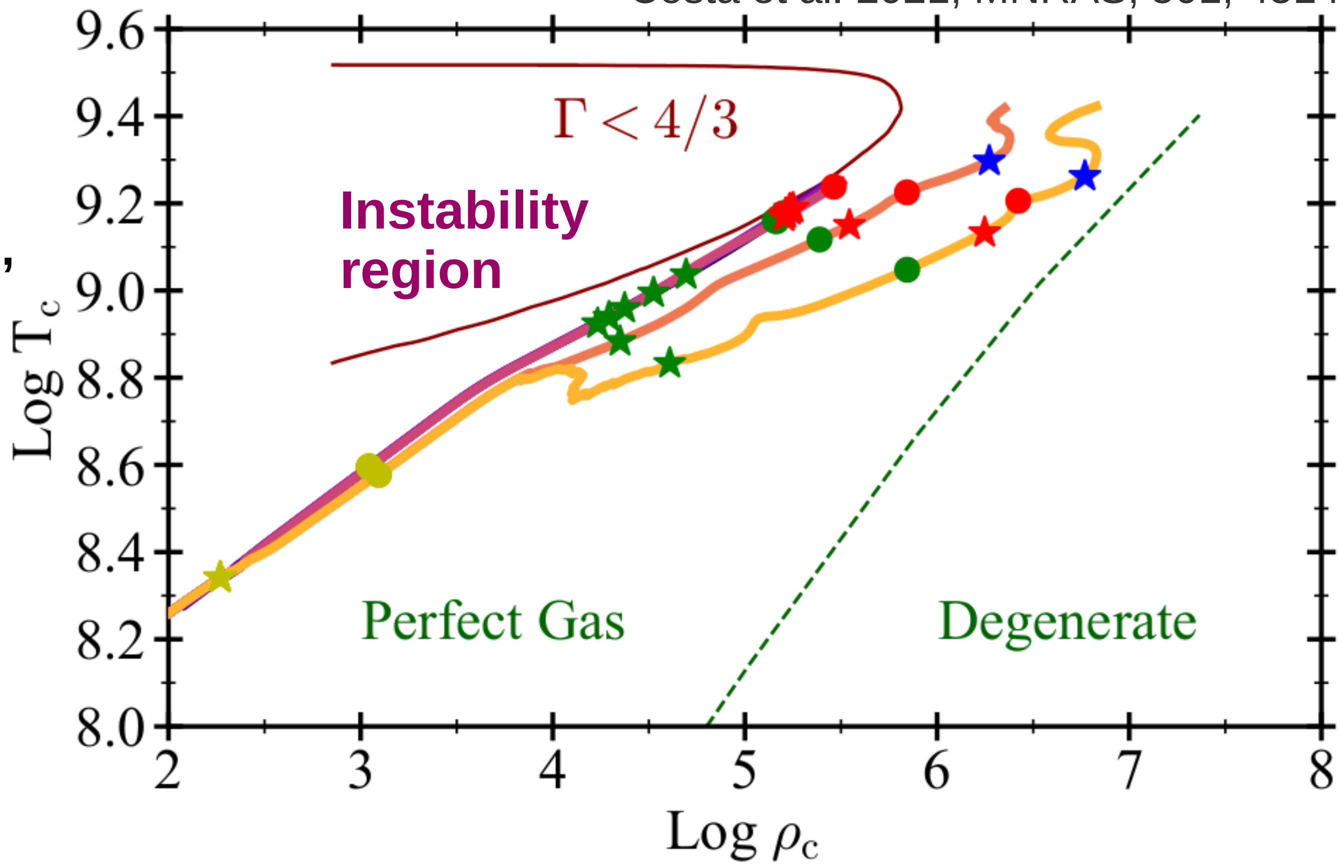
Heger et al. 2003

How do we form compact objects? Pair instability

The extreme physical conditions for pair instability
from a stellar evolution code

Costa et al. 2021, MNRAS, 501, 4514

Stars (Circles): beginning (end) of helium, carbon, neon, and oxygen burning



Γ is the first adiabatic exponent averaged over stellar core properties:

$$\Gamma = \frac{\int_{M_c} \Gamma_1 \, P \, \rho^{-1} dm}{\int_{M_c} P \, \rho^{-1} dm}$$

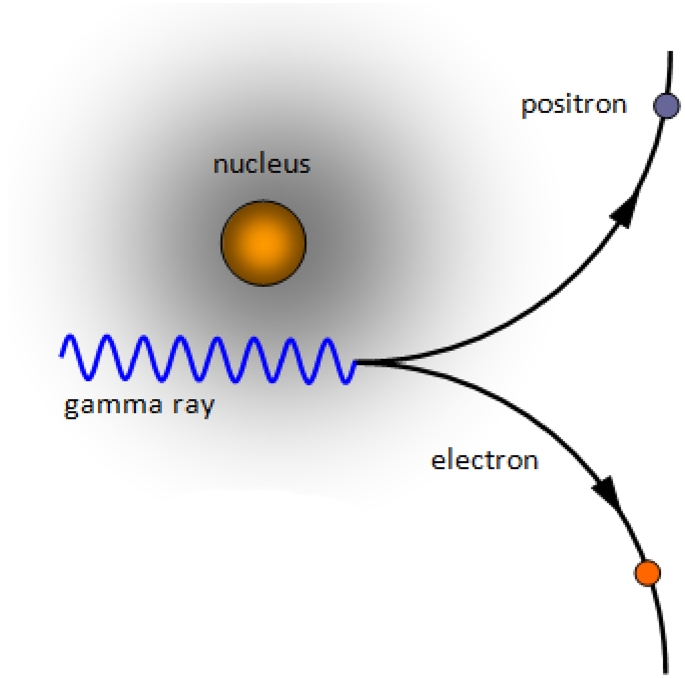
$$\Gamma_1 = \left[\frac{\partial \ln P}{\partial \ln \rho}\right]_{\mathrm{ad}}$$

How do we form compact objects? Pair instability supernovae

If star is very massive and metal poor,
135 M☉ > helium core mass > 64 M☉
after carbon 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)



$$\gamma + \gamma \rightarrow e^- + e^+.$$

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

→**high-Temperature collapse ignites all remaining species**

→ **an explosion is induced that leaves NO compact remnant (because Fe core has not formed yet)**

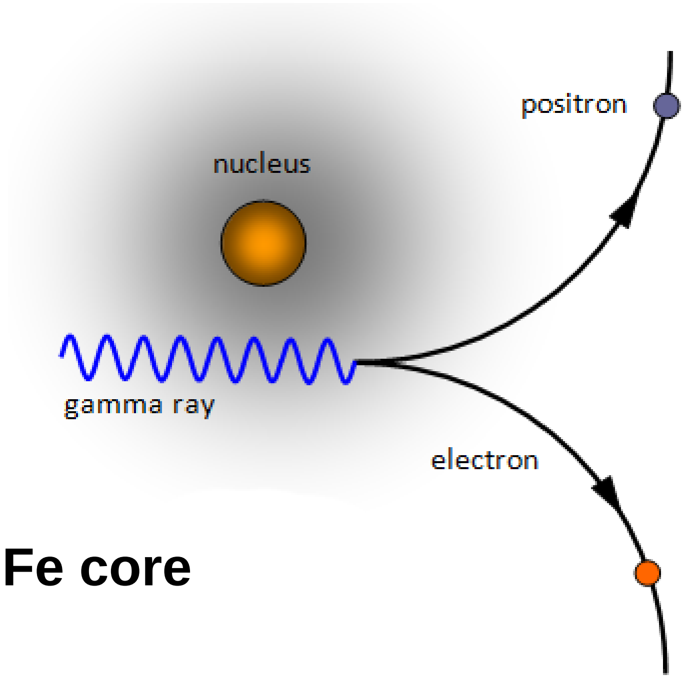
Ober, El Eid & Fricke 1983; Bond, Arnett & Carr 1984; Heger et al. 2003; Woosley, Blinnikov & Heger 2007

How do we form compact objects? Pulsational pair instability

If star is quite massive,
64 $M_\odot$ > helium core mass > 32 $M_\odot$
after C burning

→ some production of γ-ray radiation in core

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



$$\gamma + \gamma \to e^- + e^+.$$

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

→ **enhancement of nuclear reaction restores pressure**

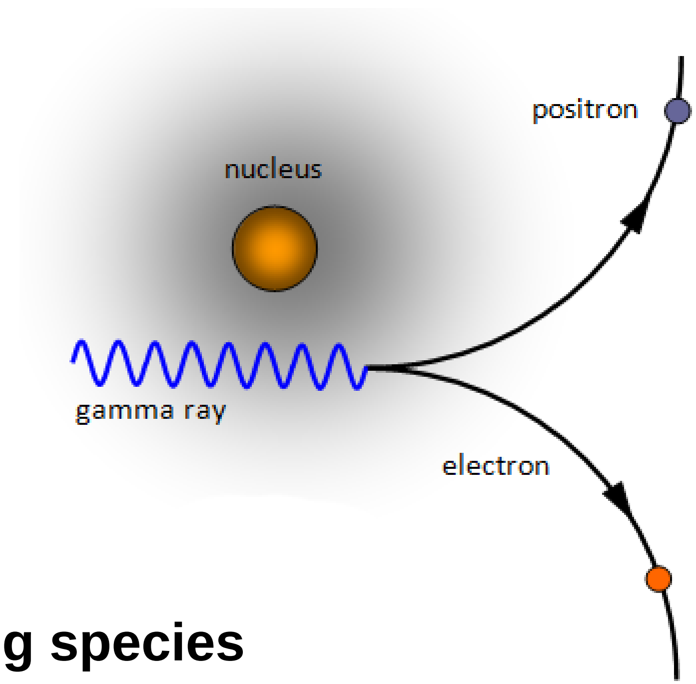
→ **star gains equilibrium after one or more oscillations**

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

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

How do we form compact objects? Pair instability triggered collapse

If star is EXTREMELY massive,
helium core mass > 135 M$_\odot$
after C burning



→ **PAIR INSTABILITY DEVELOPS**

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

→ **high-temperature collapse ignites all remaining species**

→ **central Temperature is so high that photo-disintegration of heavy atoms occurs**

$$^{56}\mathrm{Fe} + \gamma \rightarrow 13\,\alpha + 4n$$

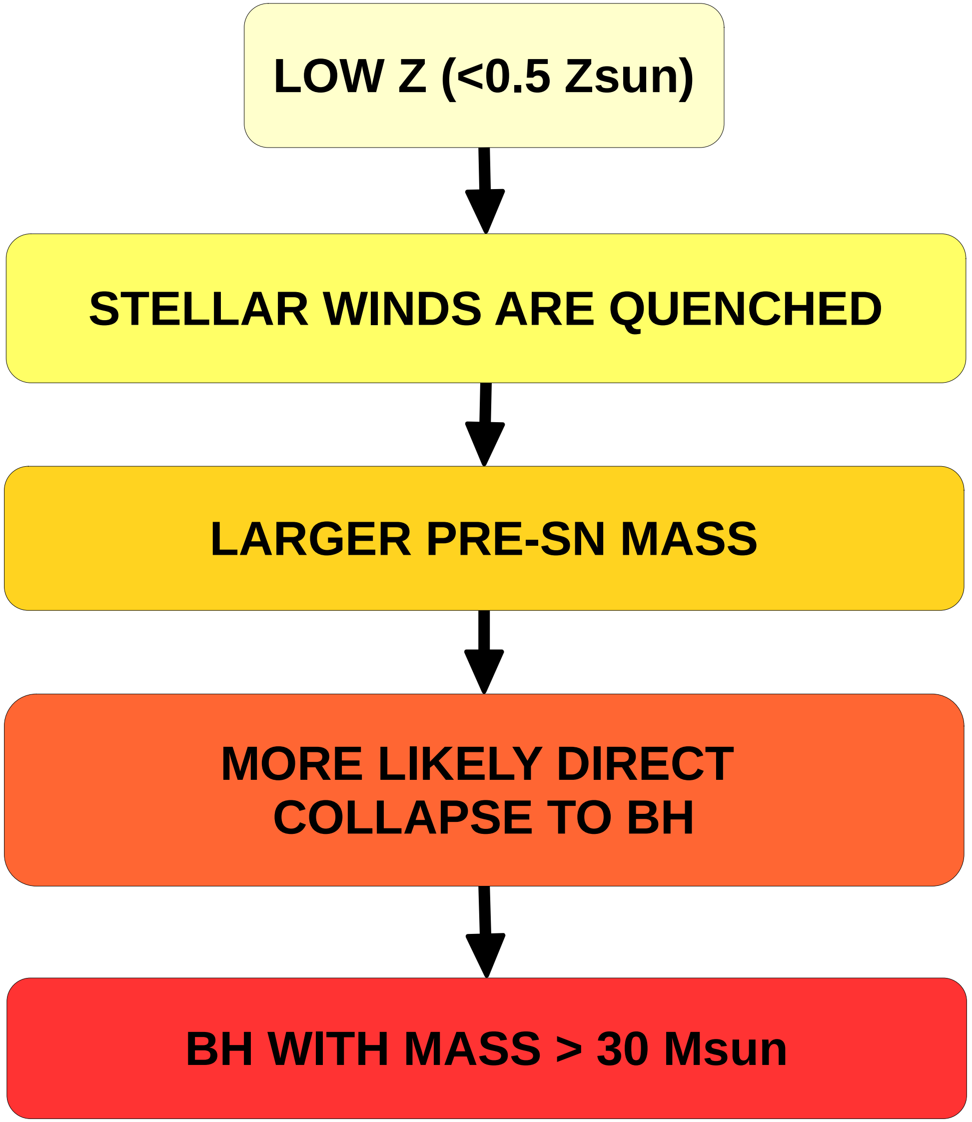
→ **this absorbs energy counteracting nuclear burning**

→ **direct collapse to a BH with mass >120 M$_\odot$**

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

How do we form compact objects? Wrap up: Masses

Very complicated problem.
However, as rule of thumb (MM+ 2009, 2010, 2013):



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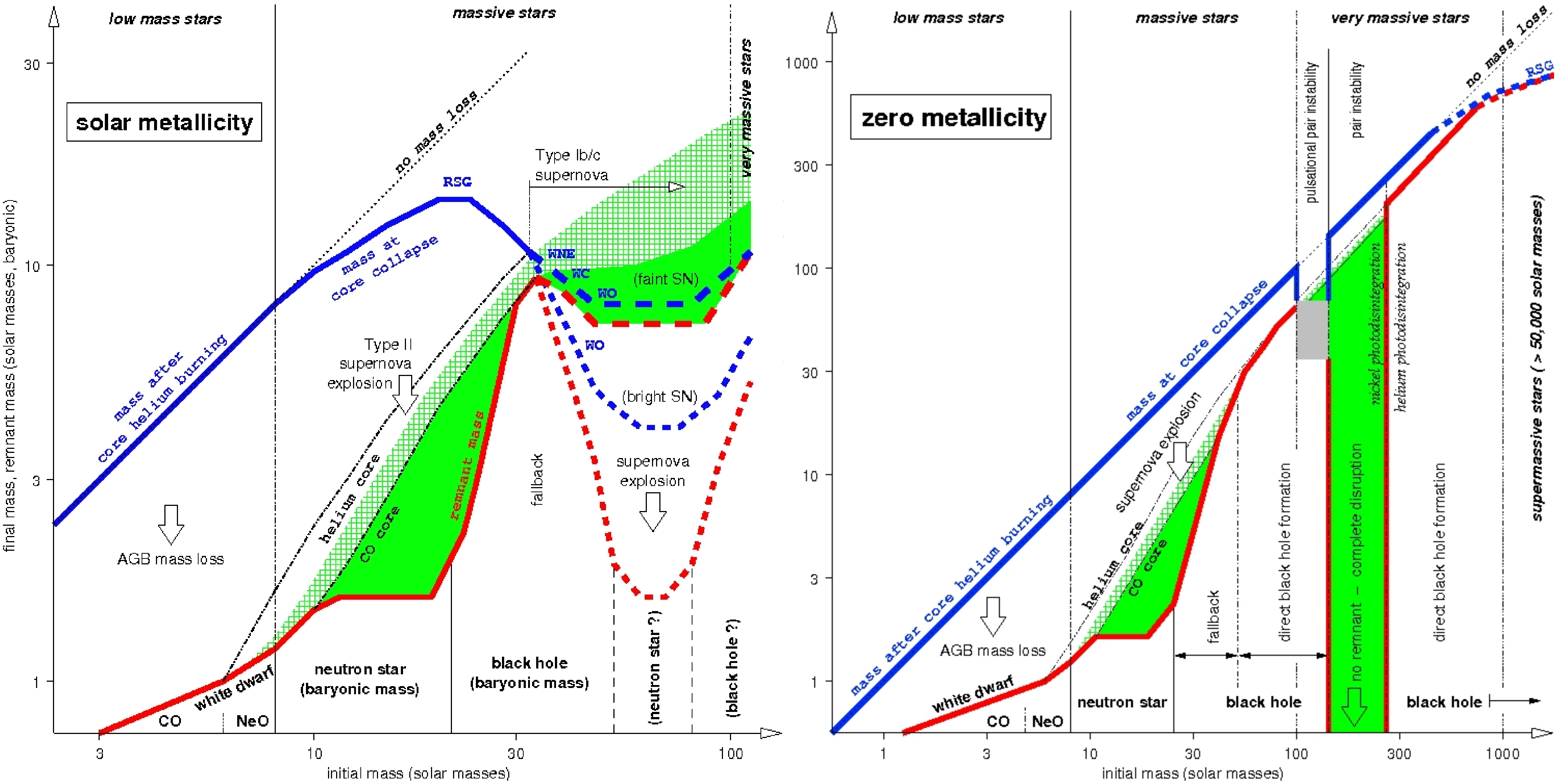
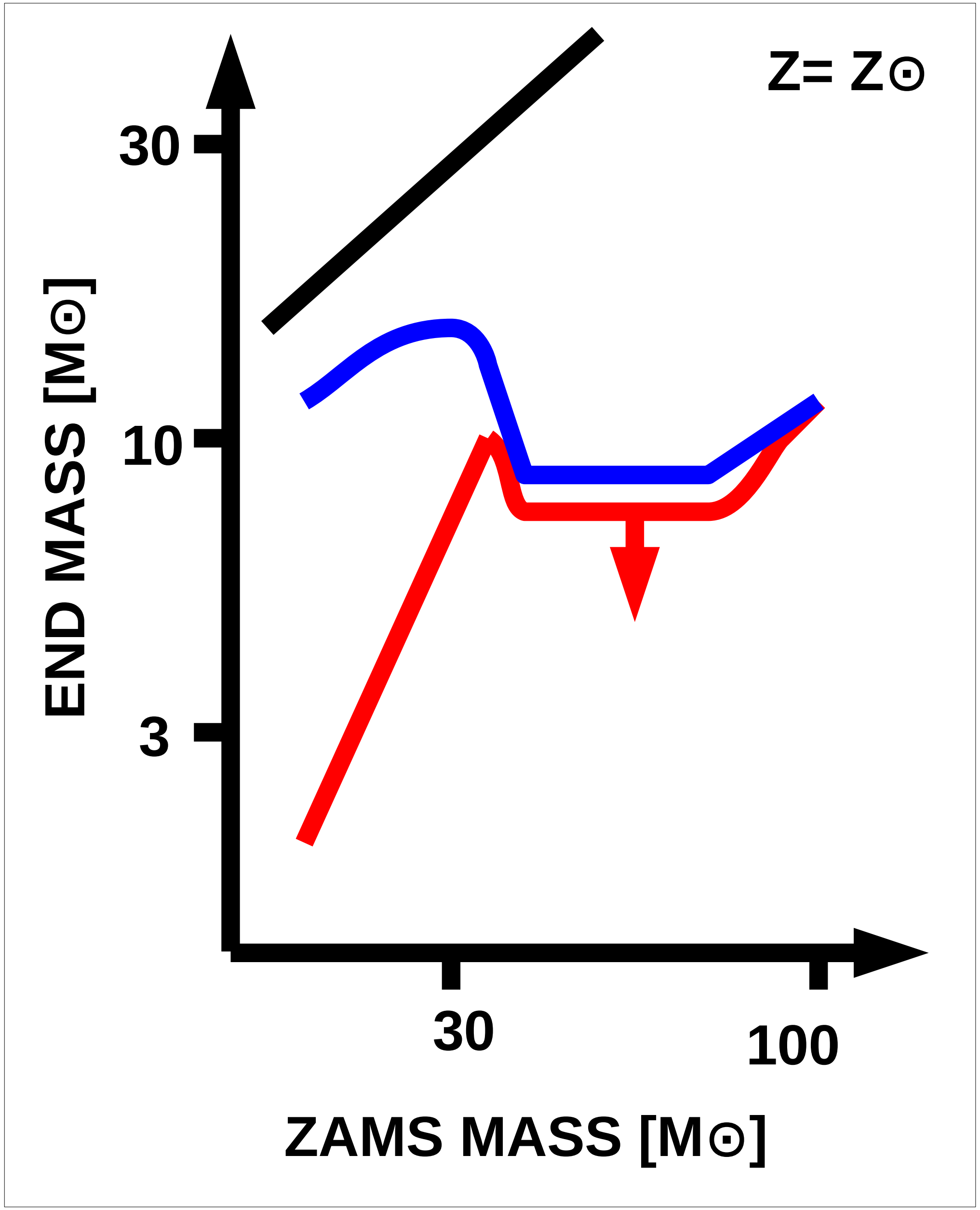
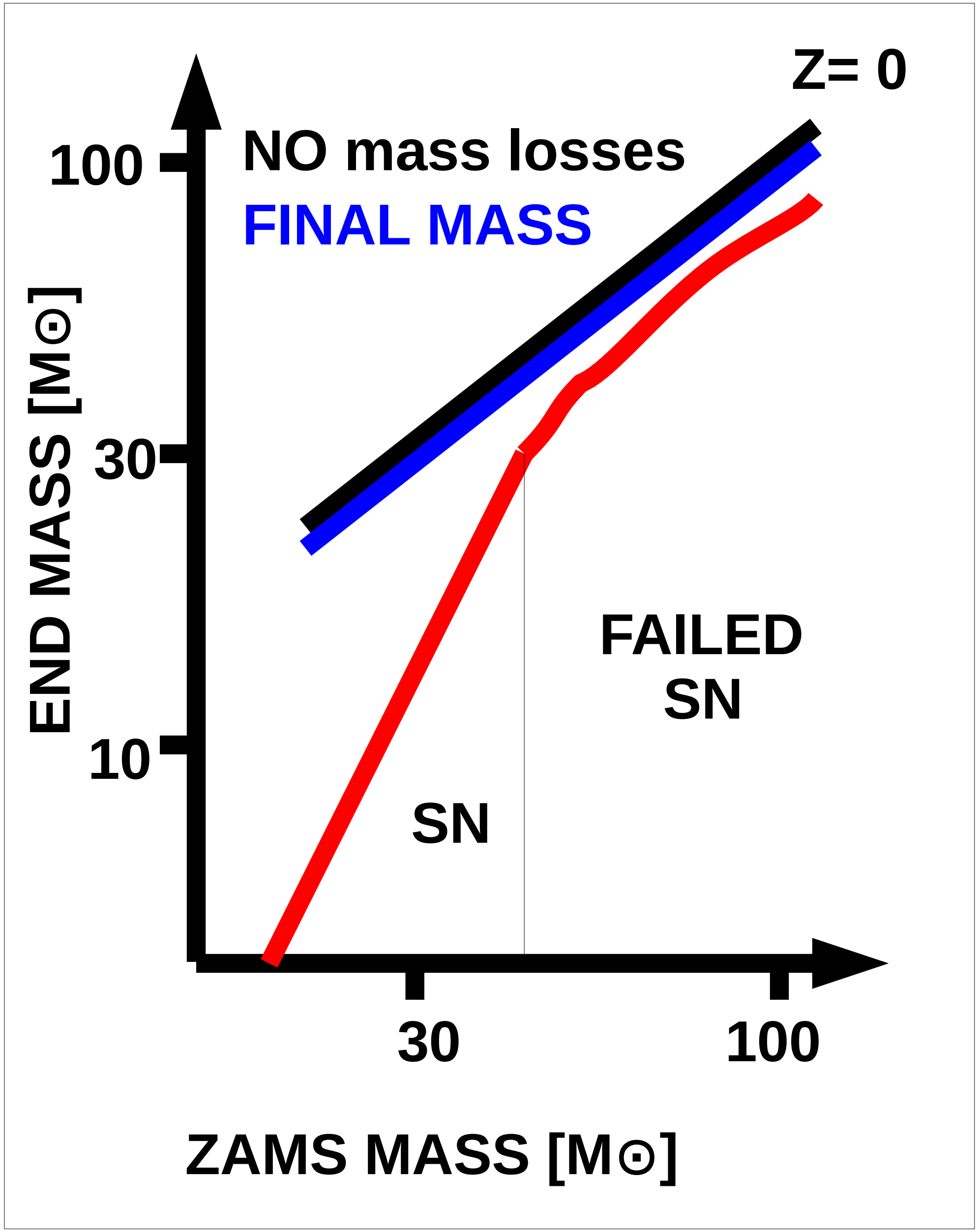


Heger et al. (2003)

How do we form compact objects? Wrap up: Masses



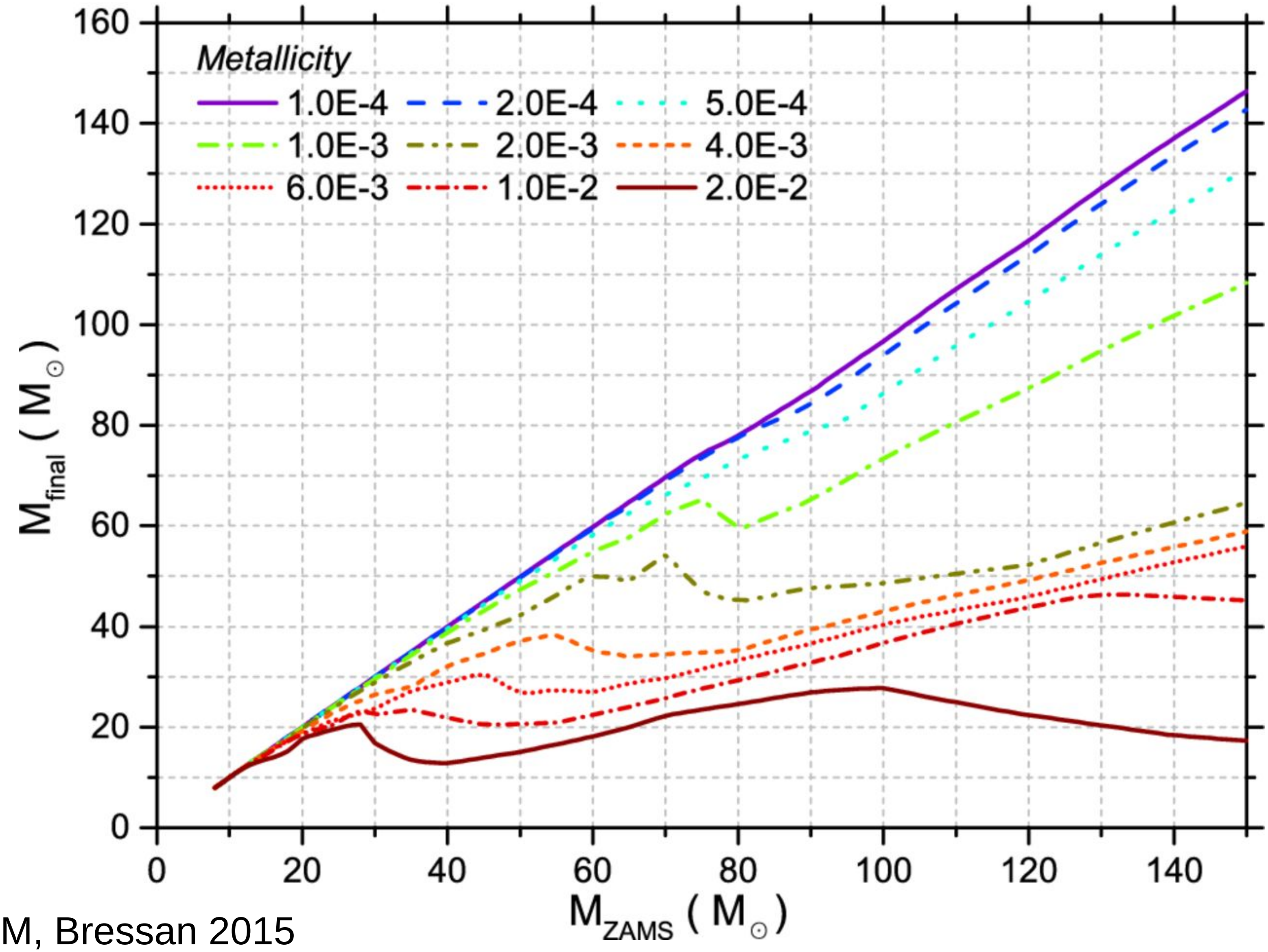


My cartoon from Heger et al. (2003)

How do we form compact objects? Wrap up: Masses

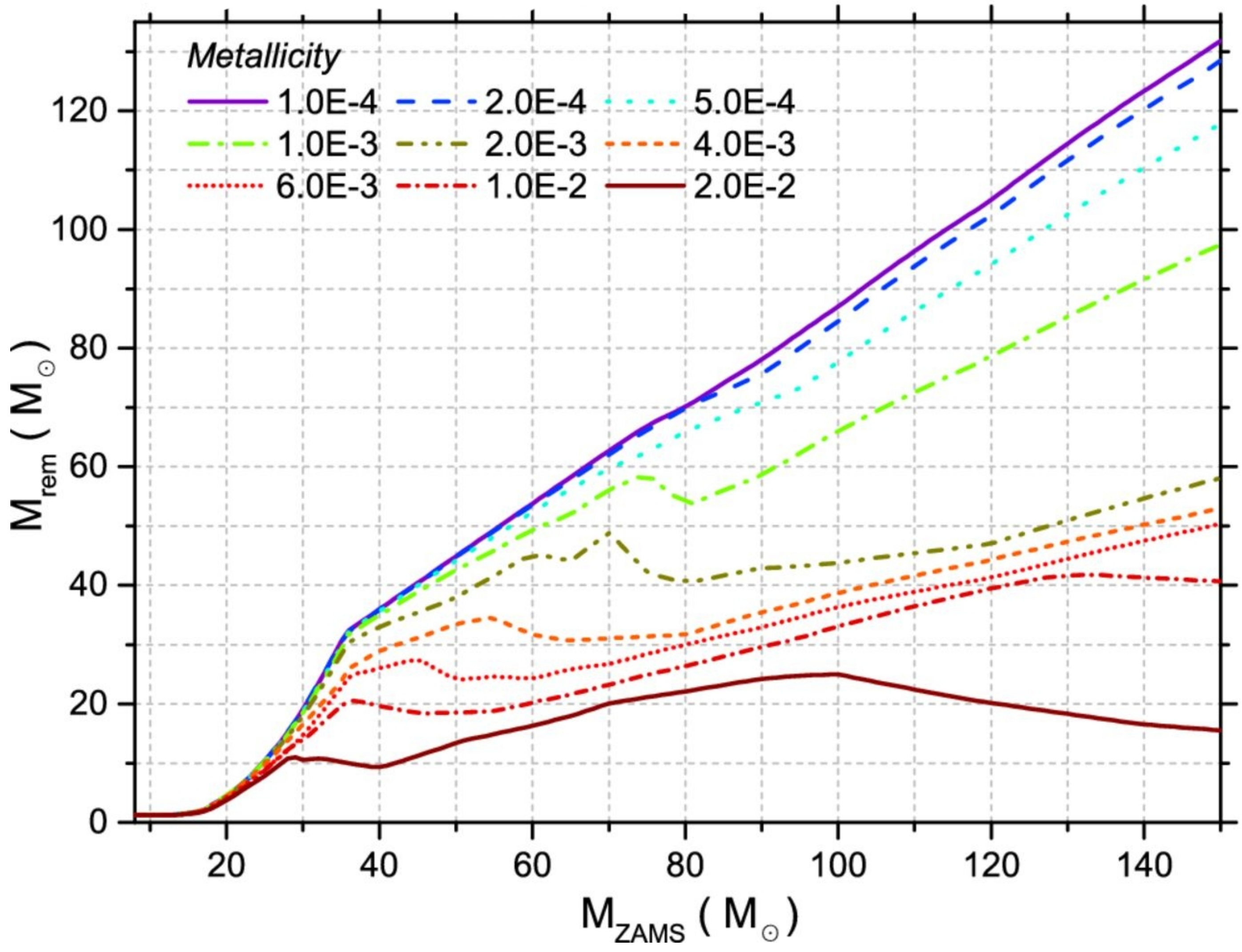
What about intermediate metallicities between 0 and solar?

- 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

How do we form compact objects? Wrap up: Masses



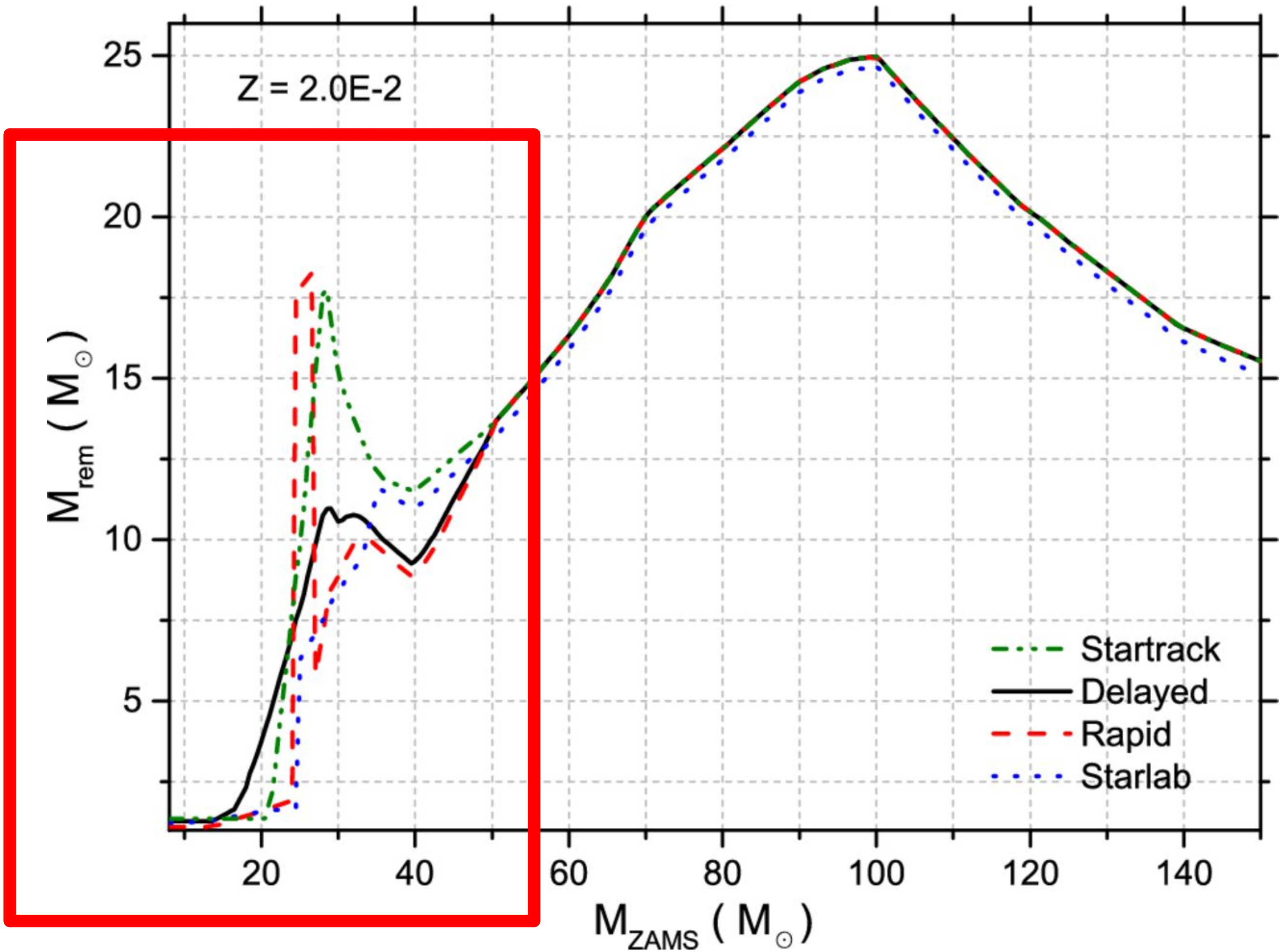
Remnant mass follows same trend as final mass → stellar winds are crucial

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

How do we form compact objects? Wrap up: Masses

Importance of supernova model for “LOW” STAR MASSES (<40 M⊙)



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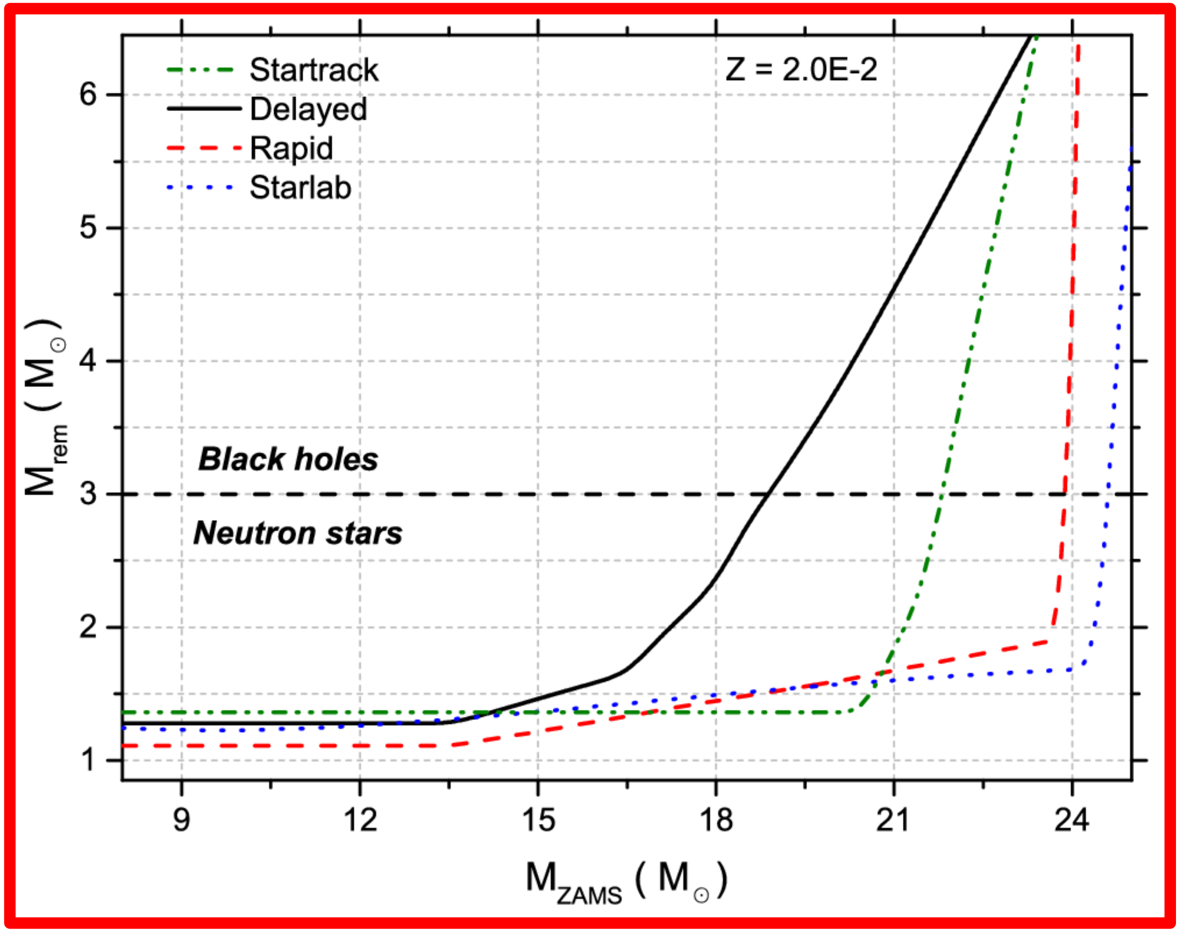
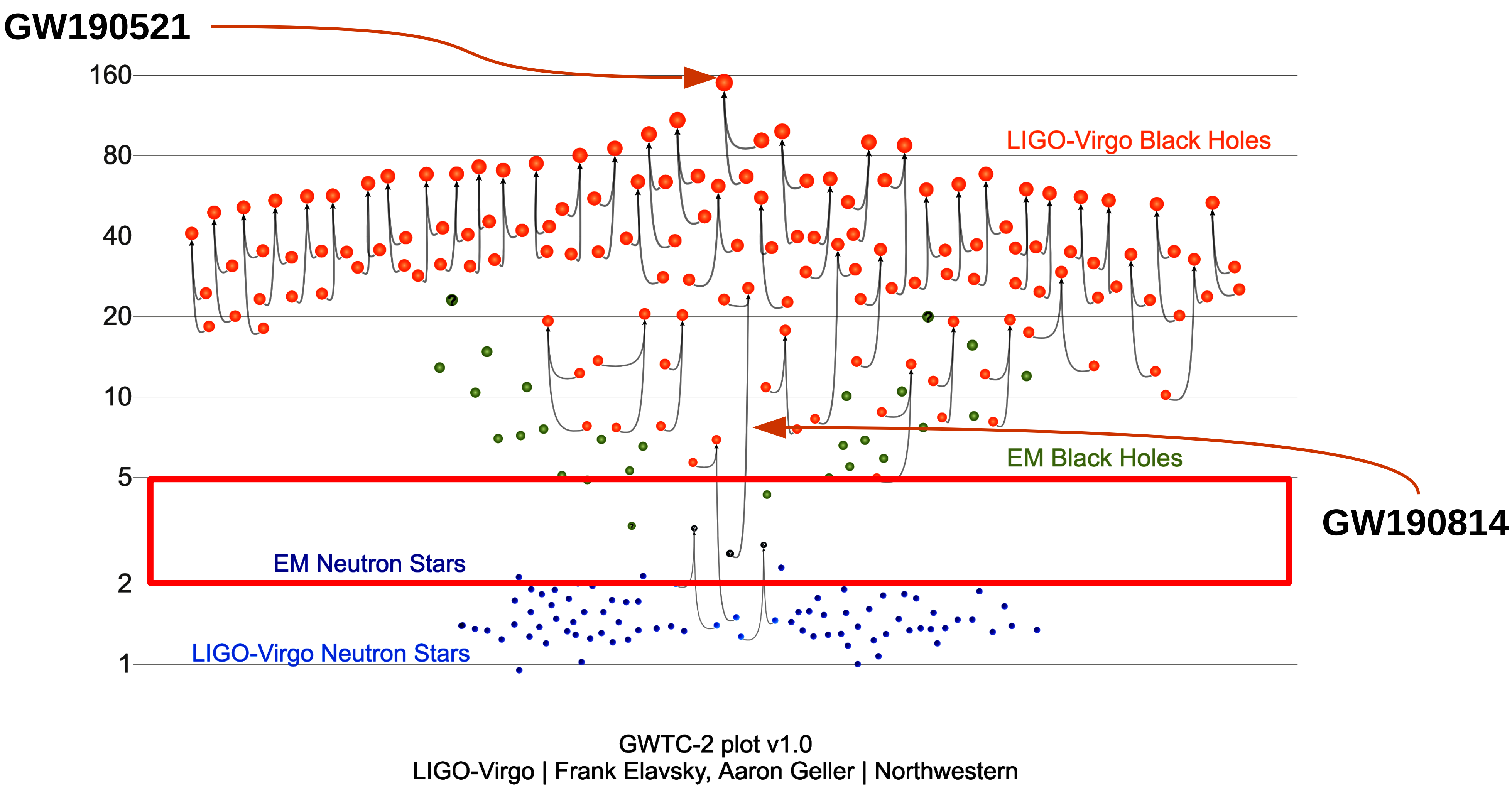


Spera, MM, Bressan 2015

Important issue: existence or not of a mass gap in the compact-object mass spectrum between ~2 and ~5 M⊙ (see e.g. Oezel et al. 2010, Farr et al. 2011, Abbott et al. 2020)

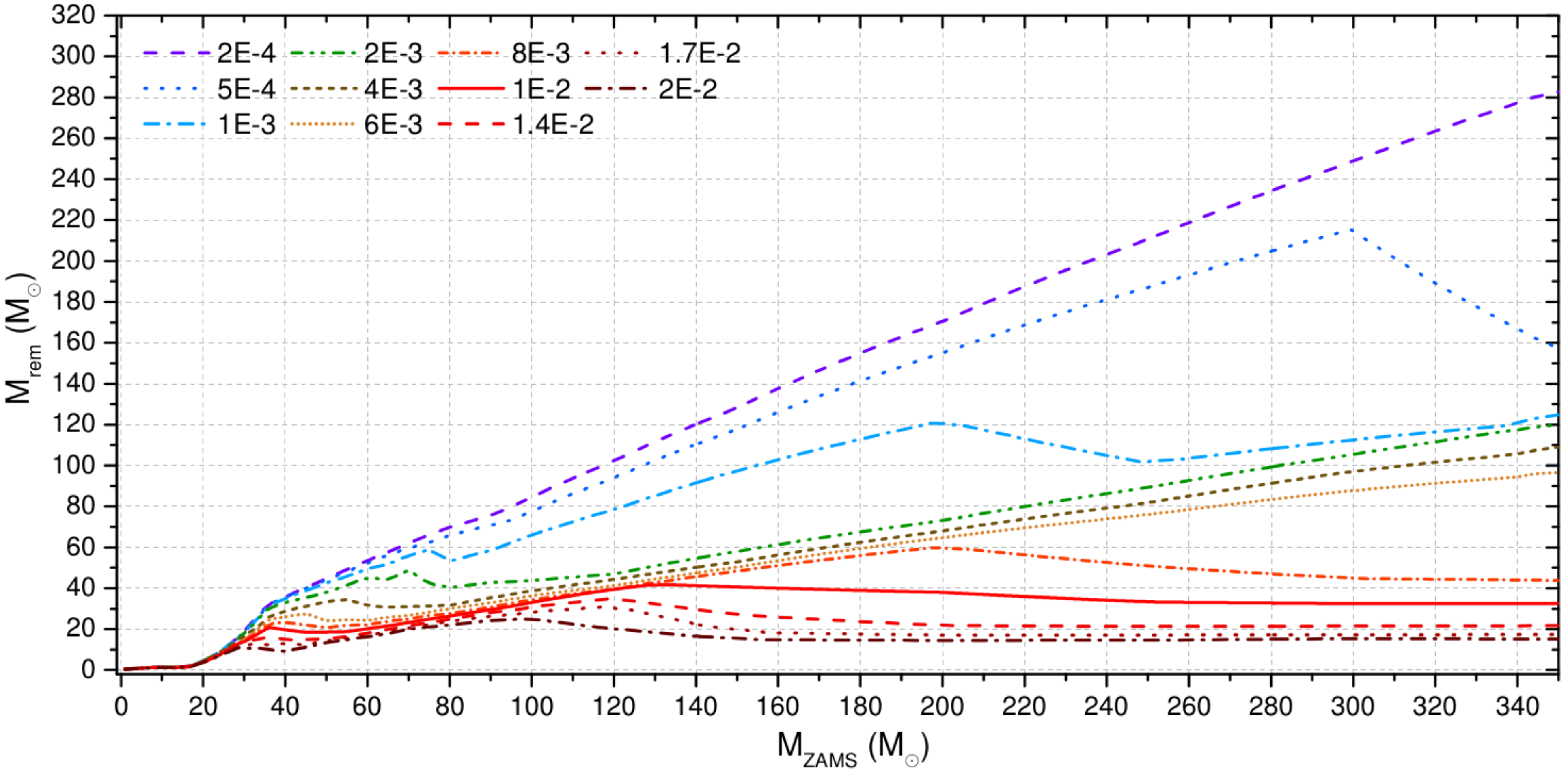
How do we form compact objects? Wrap up: Masses

A lower mass gap in BH mass spectrum?



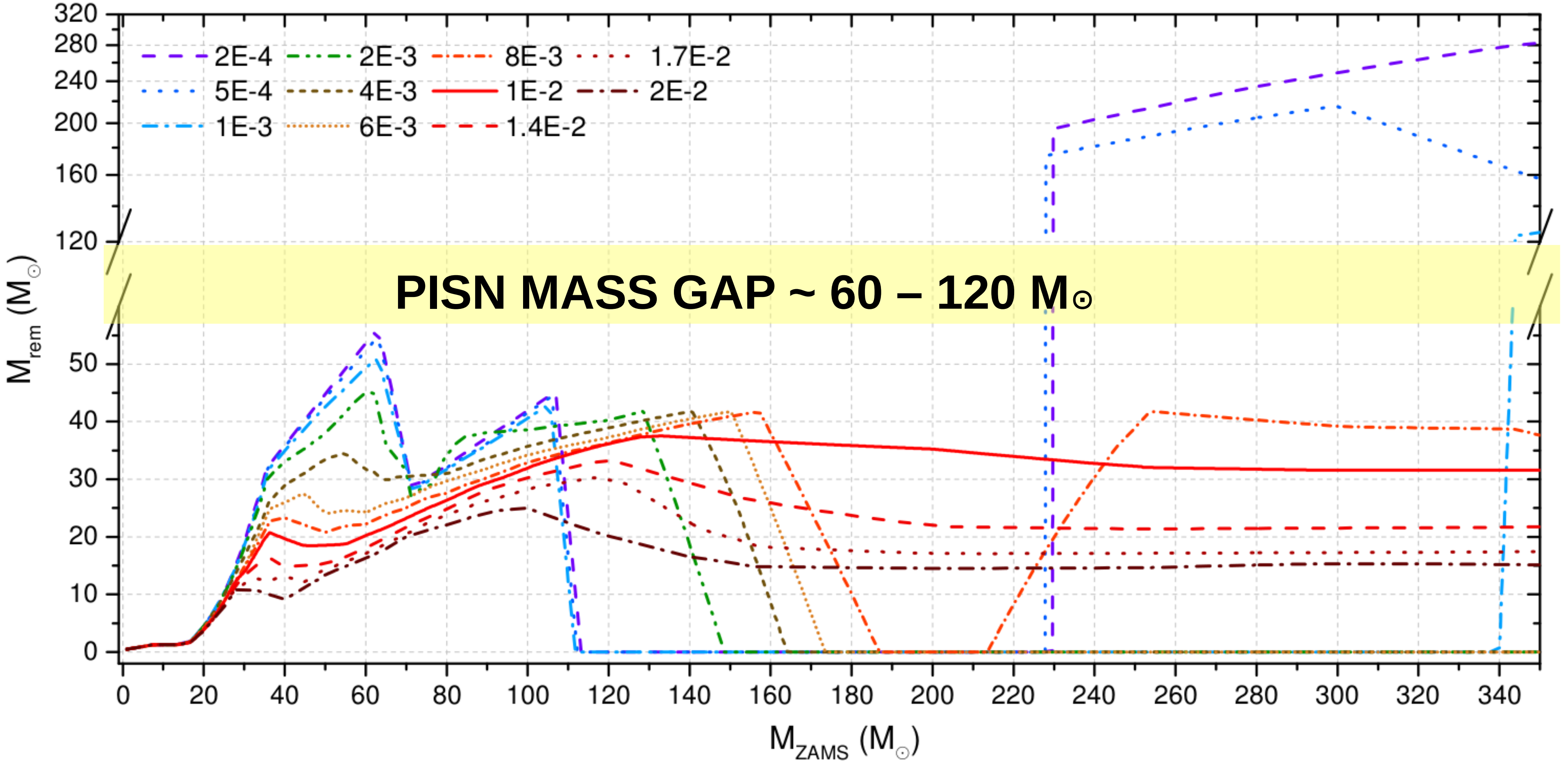
Abbott et al. 2020, GWTC-2, 2020, https://arxiv.org/abs/2010.14527

Evolution of very massive stars still uncertain
→ stellar winds are Eddington-limited rather than metallicity dependent



Spera & MM 2017

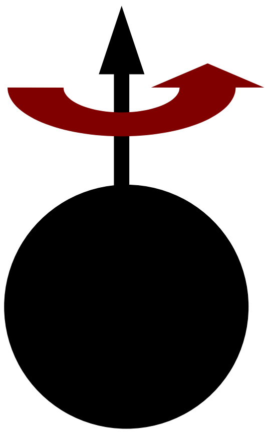
Role of pulsational pair-instability and pair-instability supernovae



Spera & MM 2017

How do we form compact objects? Wrap up: Spins

Spin of compact object usually indicated by dimensionless parameter χ:



and modulus

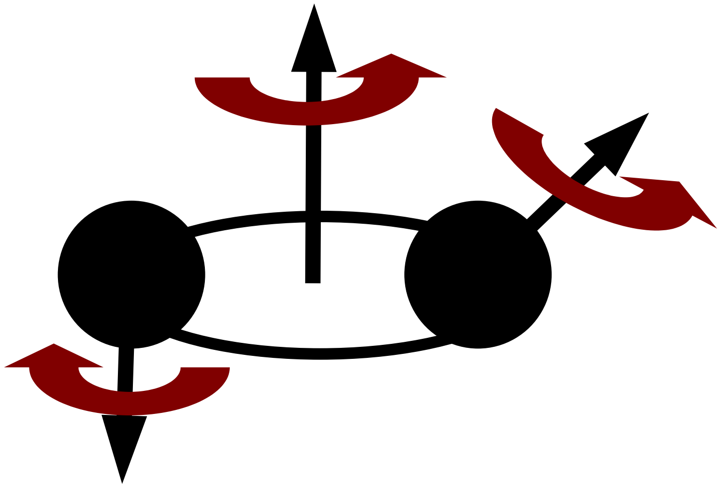
$$\vec{\chi} = \frac{\vec{J}\,c}{G\,M^2}$$

$$\chi = \frac{J\,c}{G\,M^2}$$

where *M* := compact-object mass
J := compact-object rotation angular momentum (dimensional spin)

If black hole is in binary we have 6 spin components:

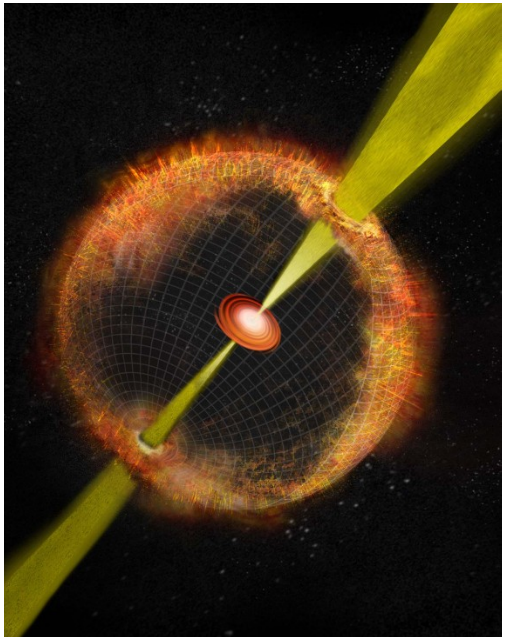
3 per each black hole



How do we form compact objects? Wrap up: Spins

Even more open question than masses

* Spin of compact object should be related to spin of the core at the end of stellar evolution



BUT:

- if supernova explosion,
  part of angular momentum is lost with the ejecta → spin is reduced

- if accretion disk or jet,
  angular momentum is transferred and spin reduced

→ **we do not know how much spin is lost during SN**

- in principle, if star collapses to black hole DIRECTLY,
  spin magnitude should be preserved

PROBLEM:

- we do not understand angular momentum transport in the stellar interior

How do we form compact objects? Wrap up: Spins

- with "classical" stellar evolution codes
(e.g. Belczynski et al. 2020; Limongi & Chieffi 2018; MM et al. 2020),
take final angular momentum of core of massive star
+ assume it collapses to BH directly

→ **gives often maximally (or nearly maximally rotating) black holes $\chi \sim 1$**

- "classical" models of stellar evolution usually neglect or simplify MAGNETIC FIELD

→ Angular momentum from stellar core efficiently dissipated via magnetic effect
e.g. magnetic **Tayler instability** (Fuller & Ma 2019, ApJ, 881, L1)

MAGNETIC LOCKING BETWEEN CORE AND ENVELOPE

→ **gives spin magnitudes $\chi < 0.2$**

References

M. Mapelli, https://arxiv.org/abs/2106.00699
and MANY references therein