11. 2. 2018, KNU, KNO workshop

Black hole formation in massive stars, failed supernovae, & Neutrinos

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Core Collapse Supernova (ccSN) : Standard Scenario

- A SN occurs if the explosion energy is higher than the binding energy of the stellar envelope.
- The binding energy of the stellar envelope:

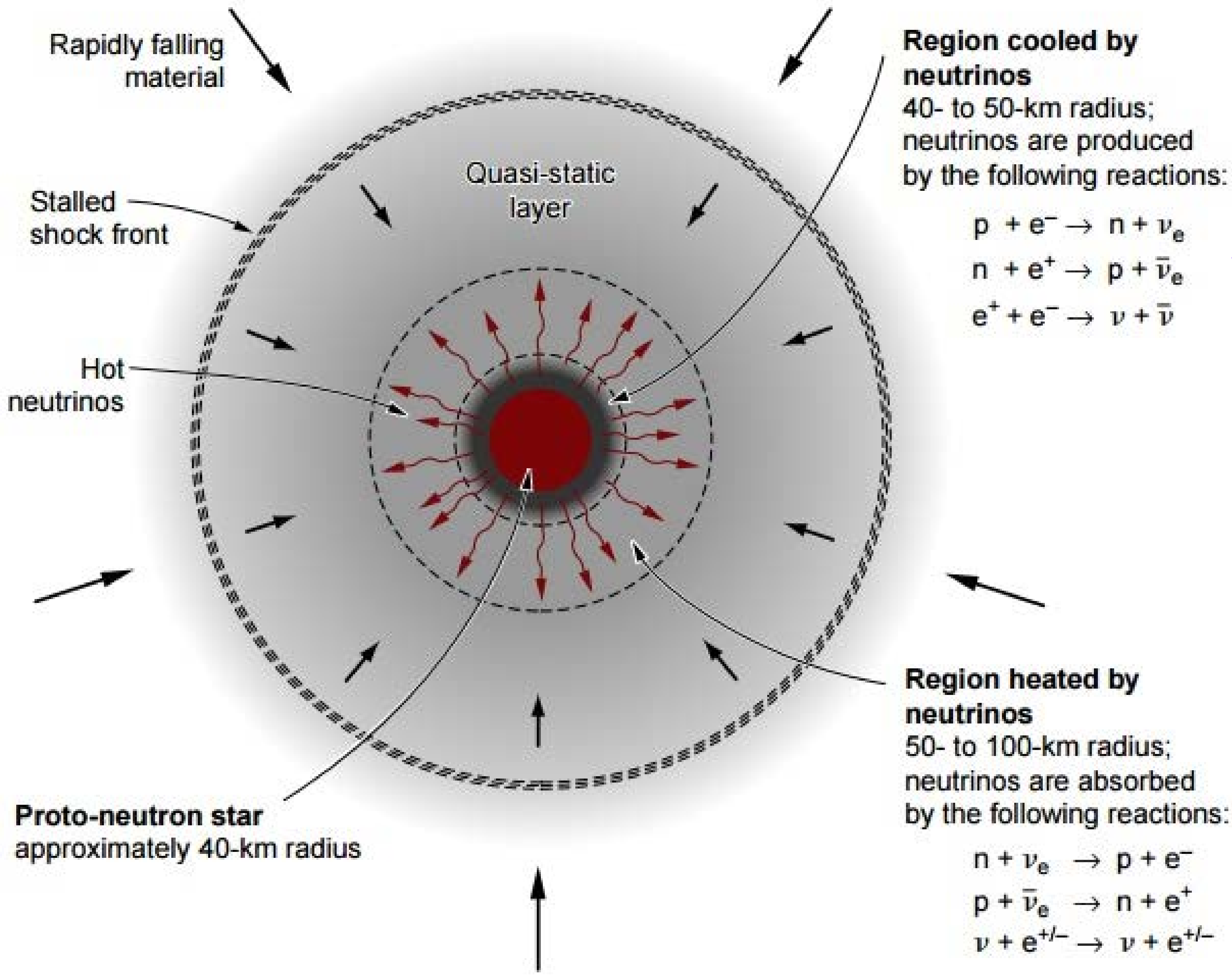
$$E_{\mathrm{b,env}} \approx \frac{GM_{\mathrm{env}}^2}{R_{\mathrm{env}}} \approx 10^{49} \sim 10^{51}\ \mathrm{erg}$$

- The energy budget for SN explosion: the difference of the binding energies of the core before and after the collapse.

$$\Delta E_{\mathrm{b,core}} \approx \frac{GM_{\mathrm{core}}^2}{R_{\mathrm{core}}} - \frac{GM_{\mathrm{NS}}^2}{R_{\mathrm{NS}}} \approx 10^{53}\ \mathrm{erg}$$

- Only 1% of this energy is enough to unbound the star.

Core Collapse Supernova (ccSN) : Standard Scenario



Neutrino emission

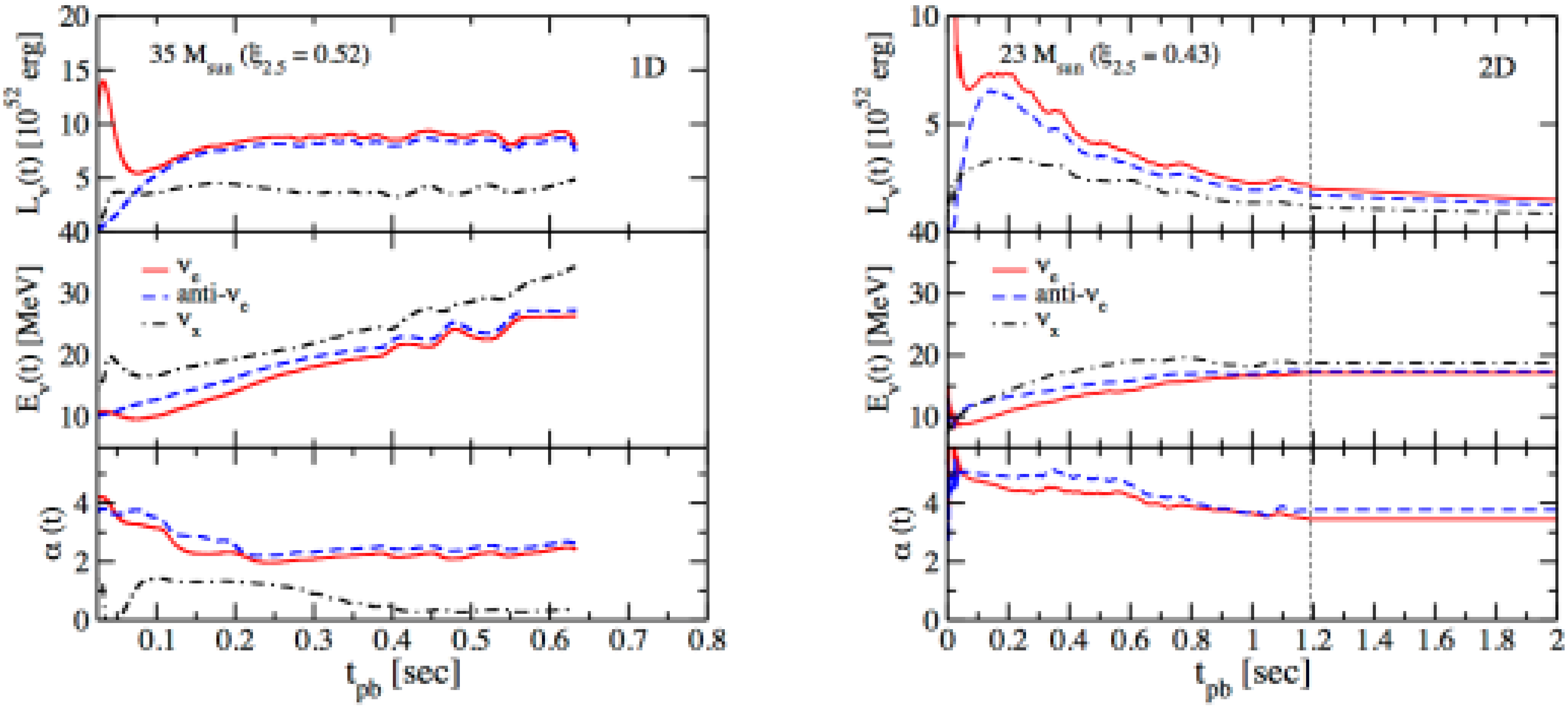
Neutrino-matter interaction

https://www.researchgate.net/figure/The-core-collapse-of-a-Type-II-Supernova_fig1_306091657

Core Collapse Supernova (ccSN) : Standard Scenario

- ***The binding energy of the core is released in the form of neutrinos during the collapse.***
- Enormous neutrino flux (~ 10^{53} erg) is thus produced. Some of them interacts with infalling matter.
- If this neutrino-matter interaction is efficient enough (~1% efficiency), a supernova explosion can occur.
- Otherwise, a SN explosion would fail → BH formation
- **Regardless of failure or success of the explosion, the neutrino energy released from the star would be about 10^{53} erg.**

Neutrino Signals from BH formation



BH formation

SN explosion

Horiuchi et al. 2018, MNRAS 475, 1363

Massive Star Evolution

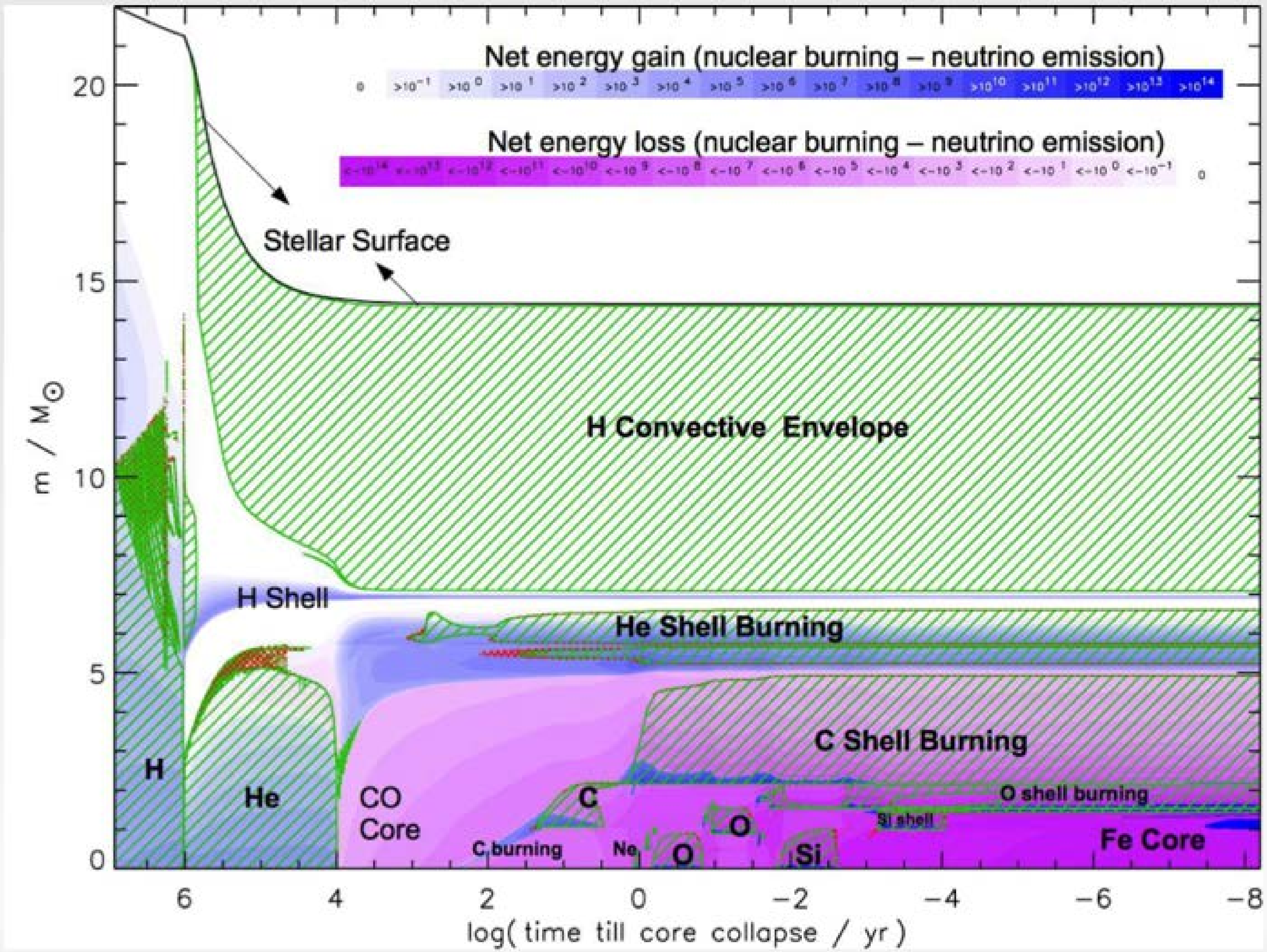


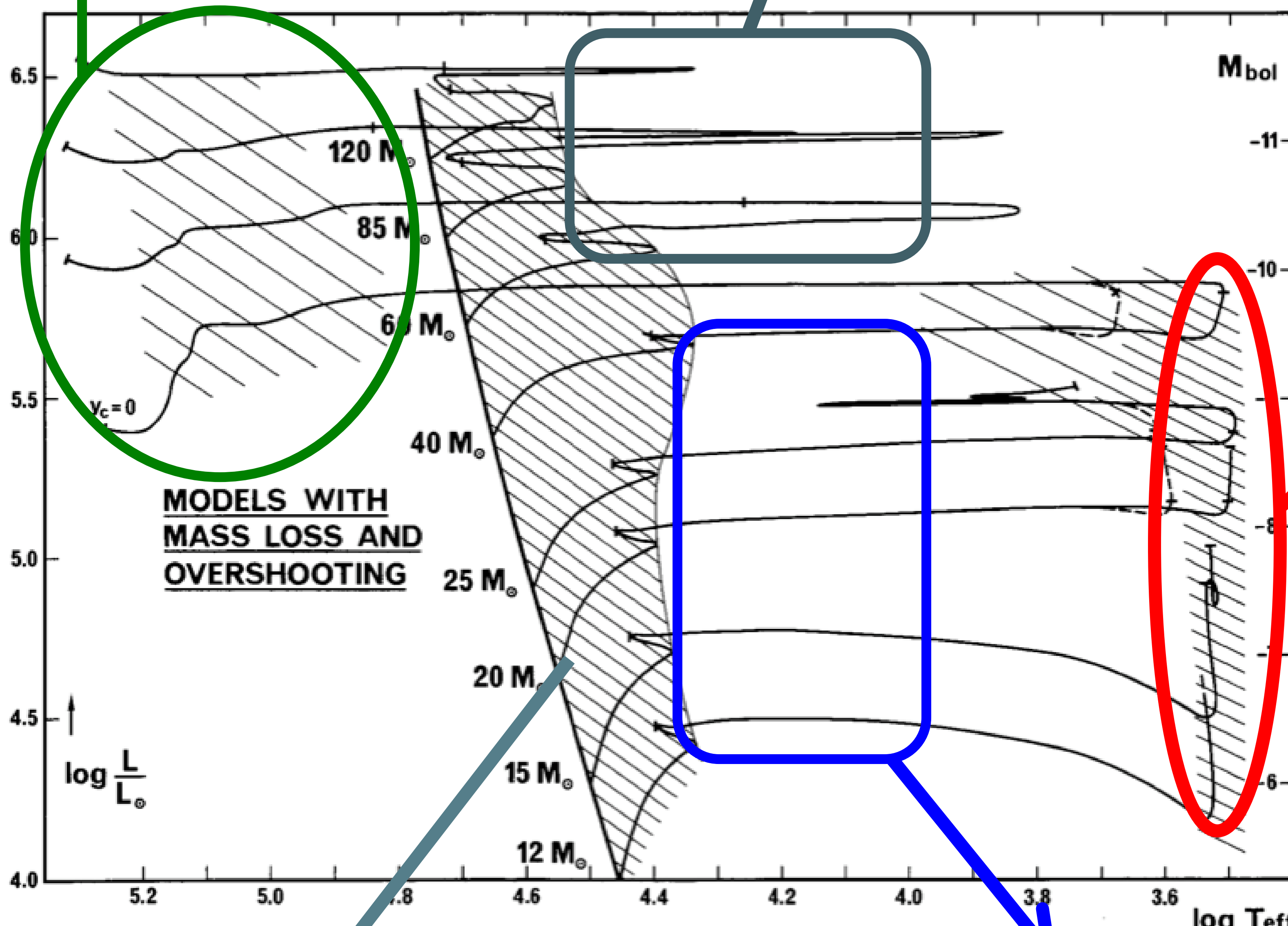
Figure from A. Heger

Which stars are BH progenitors in our Galaxy?

Wolf-Rayet Starsf
(No significant hydrogen envelope)

LBV: luminous blue variable stars

Red-Supergaint Stars



Main sequence: hatched region

Blue-Supergiant Stars

Density Profiles of Supernova Progenitor Cores

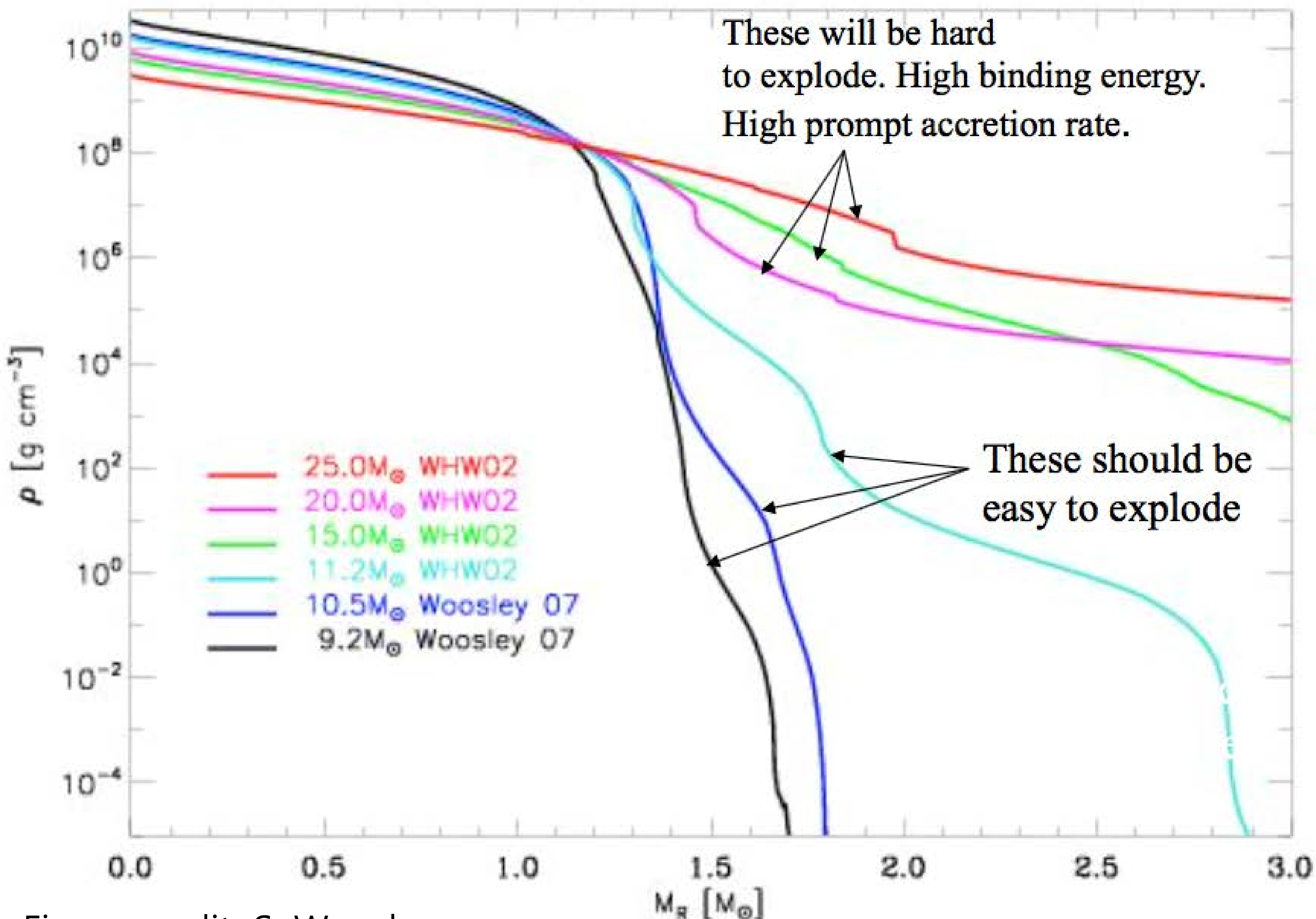
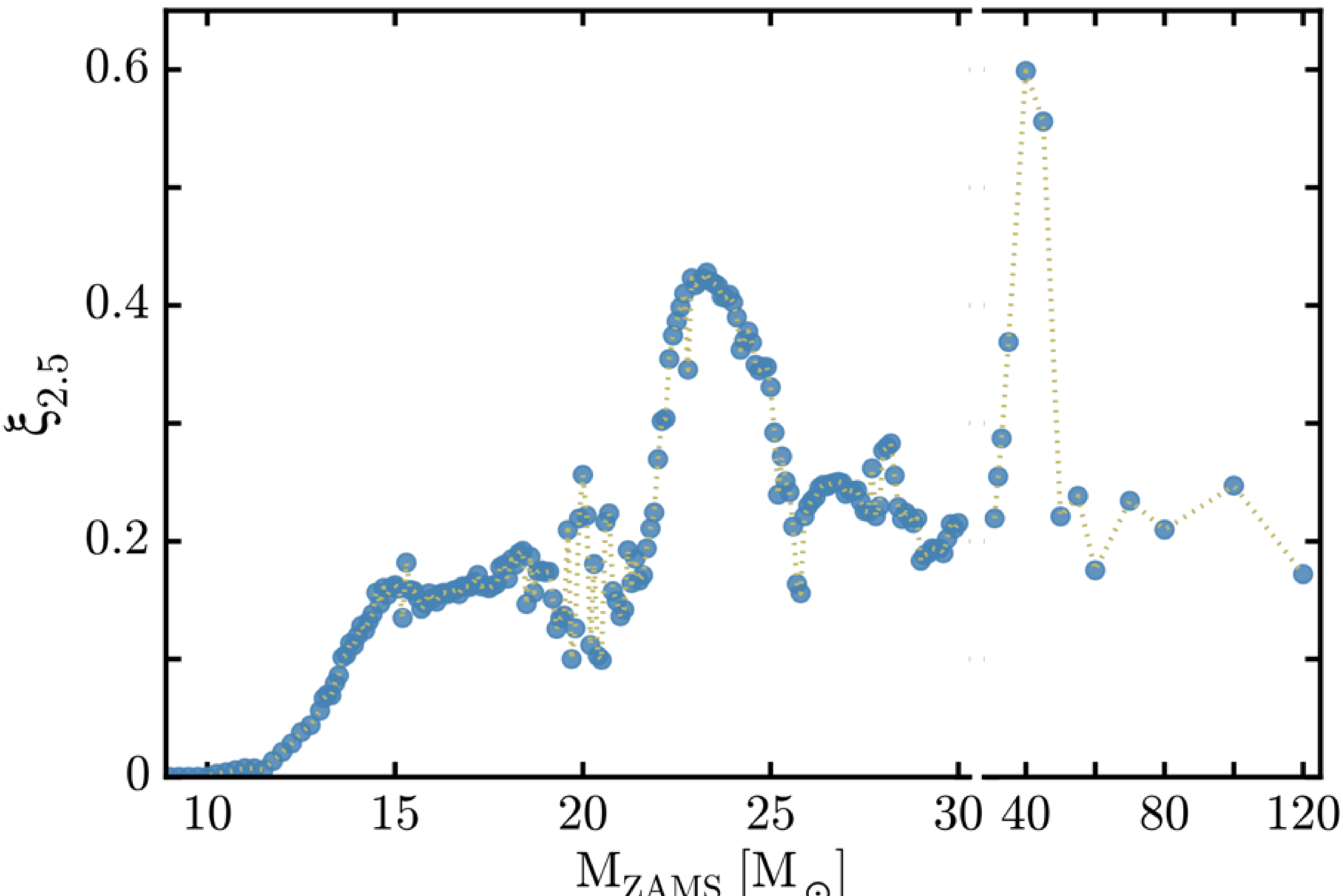
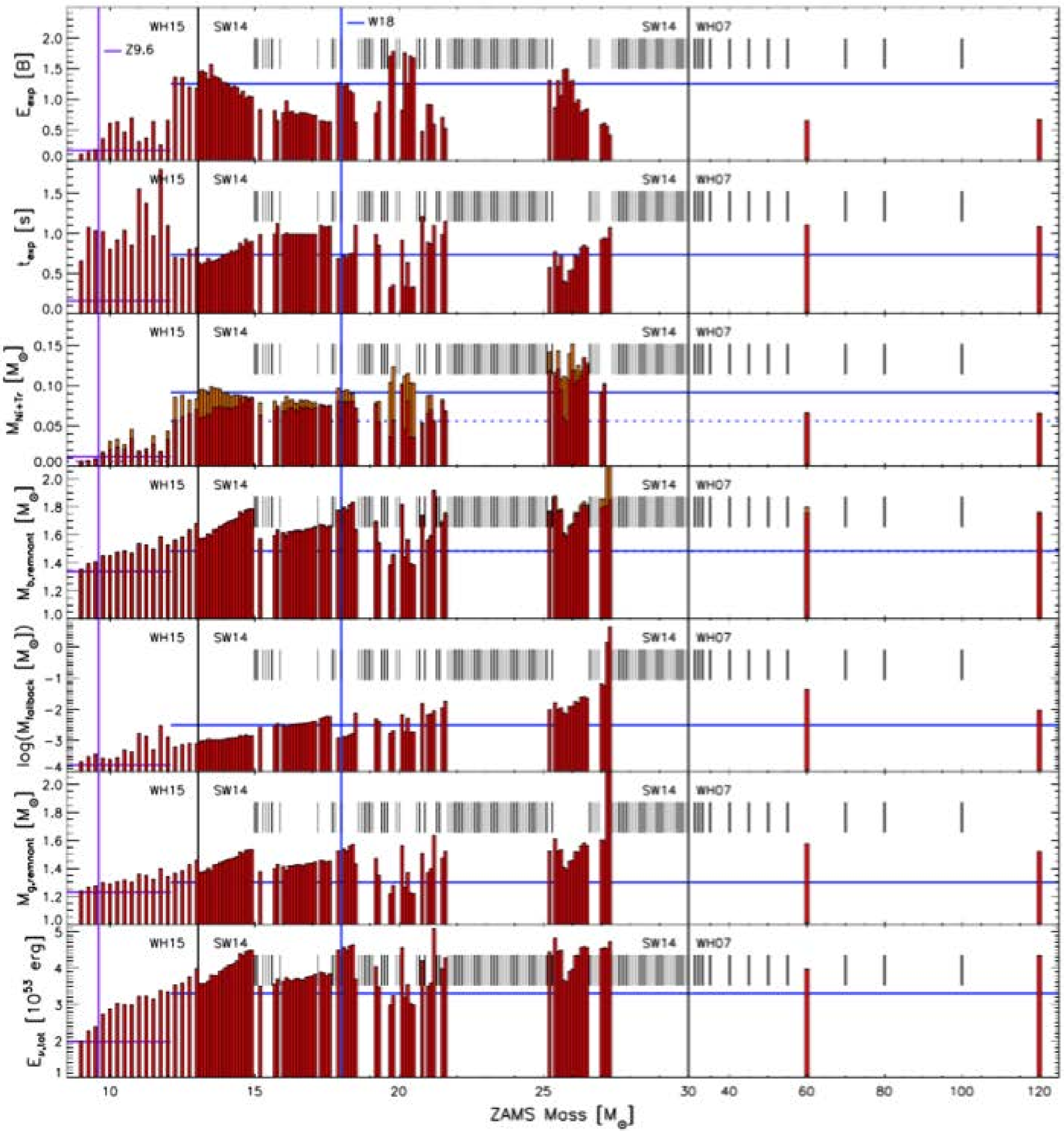


Figure credit: S. Woosley



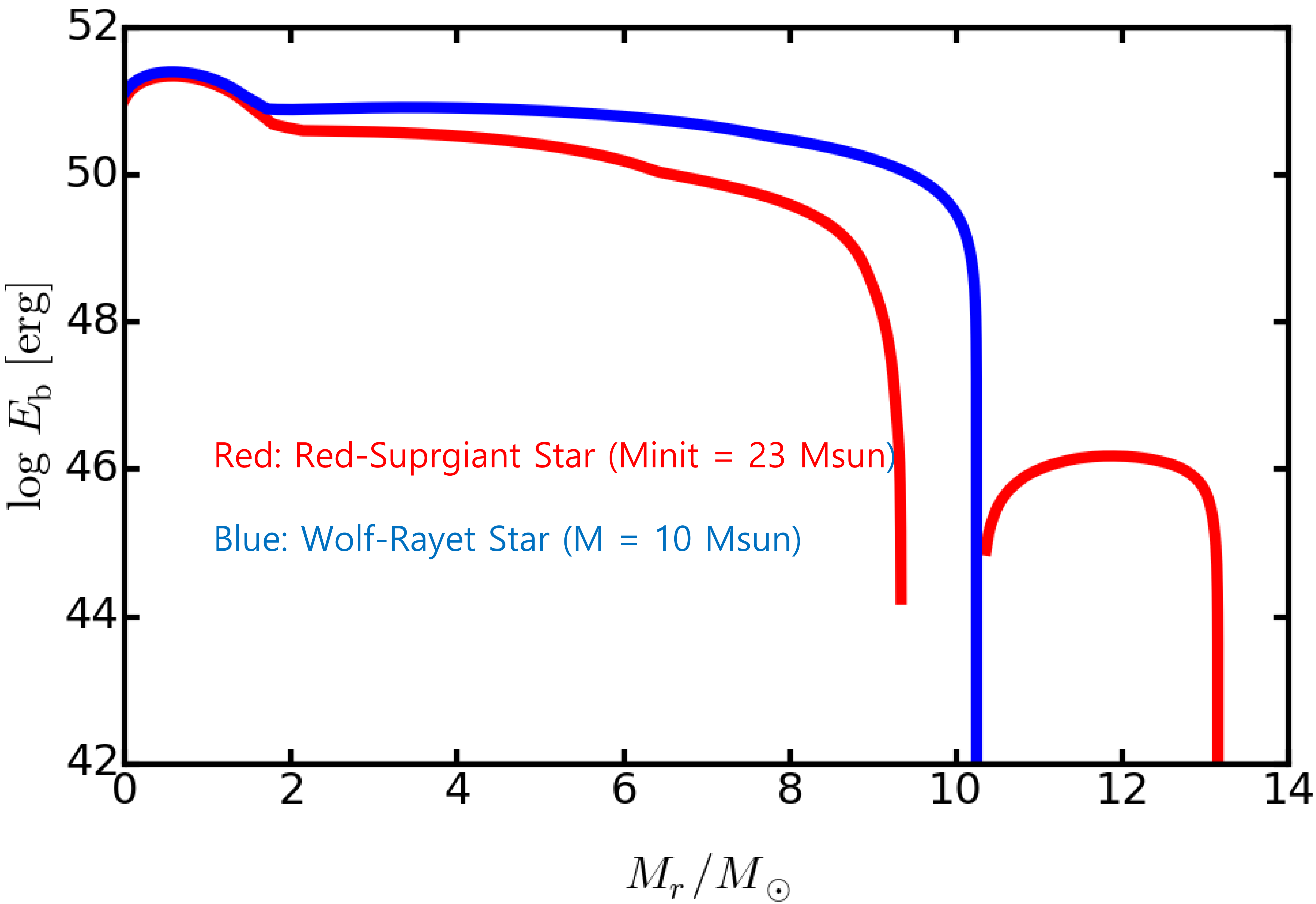
$$\xi_M = \frac{M/\mathrm{M}_\odot}{R(M)/1000\,\mathrm{km}}\bigg|_{t_{\rm bounce}}$$

Sukhbold et al. 2016

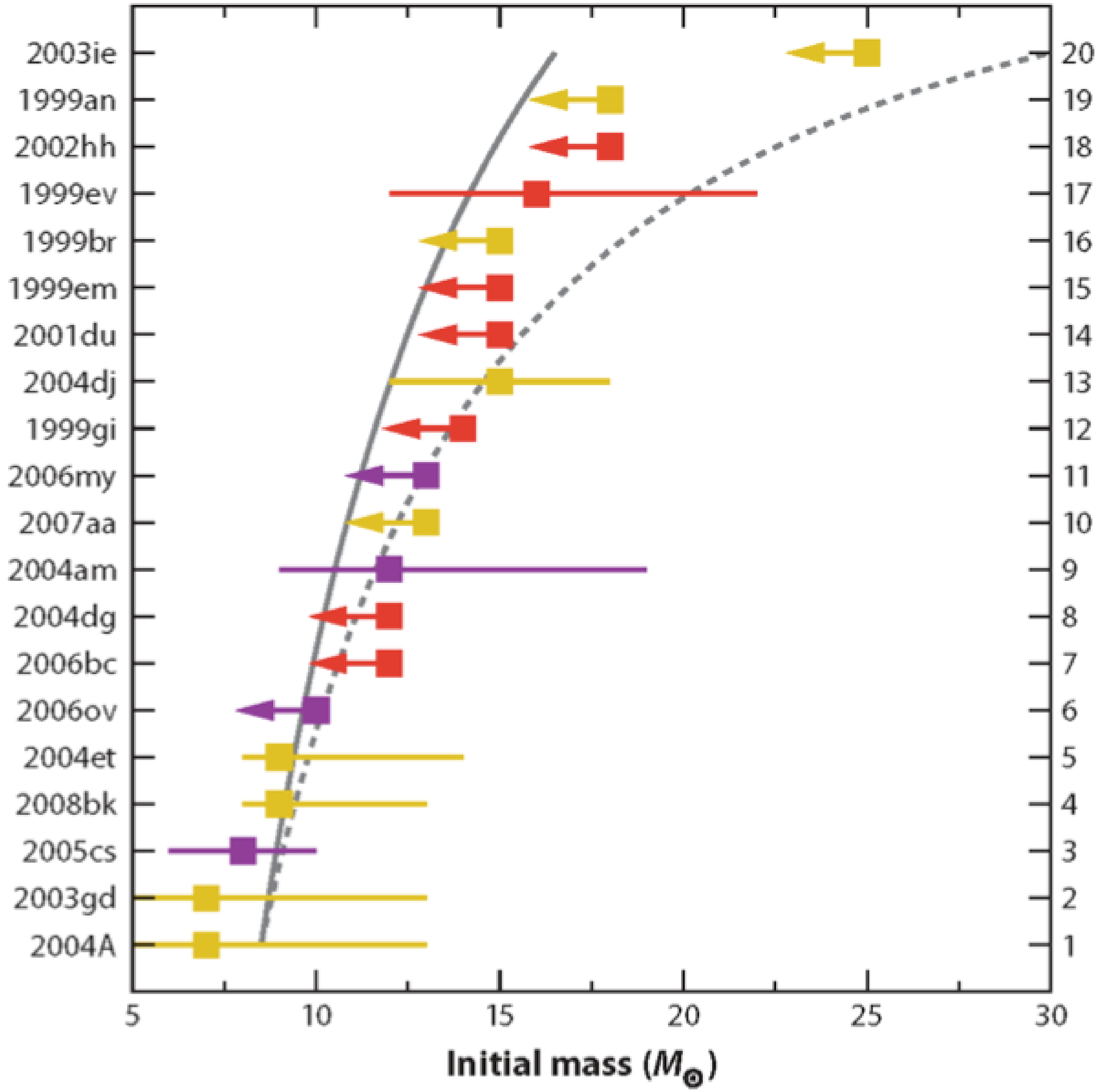


Sukhbold et al. 2016

Binding Energy in BH progenitors



Presupernova stars – Type IIp and II-L



Smartt, 2009
ARAA

Progenitors heavier than 20 solar masses excluded at the 95% condidence level.

WR stars

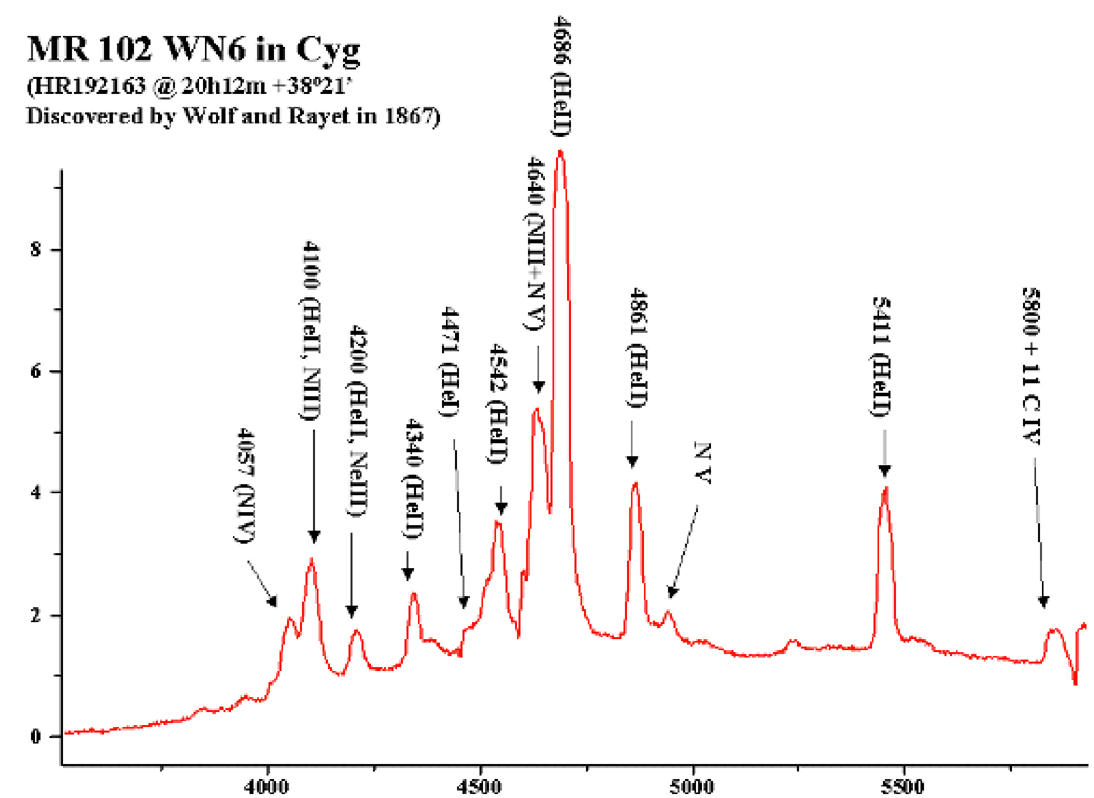
A ***Wolf-Rayet Star*** (WR star). It is a naked helium star that has lost its hydrogen envelope. A star of this kind has usually very strong winds.

WNL : Some H, strong N

WNE: No H, strong N emission

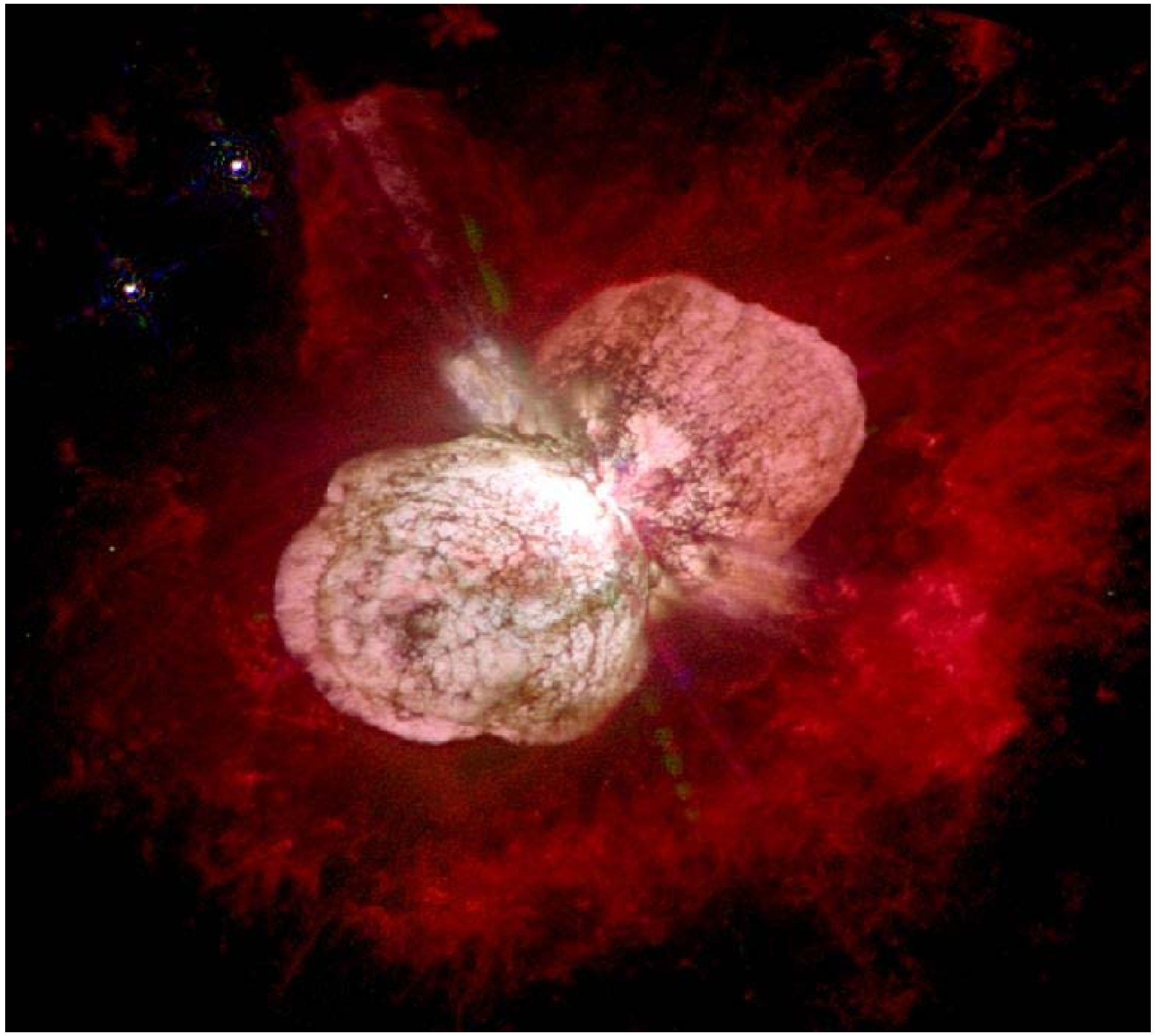
WC : strong C emission

WO : strong O emission



VMS : Very Massive Stars

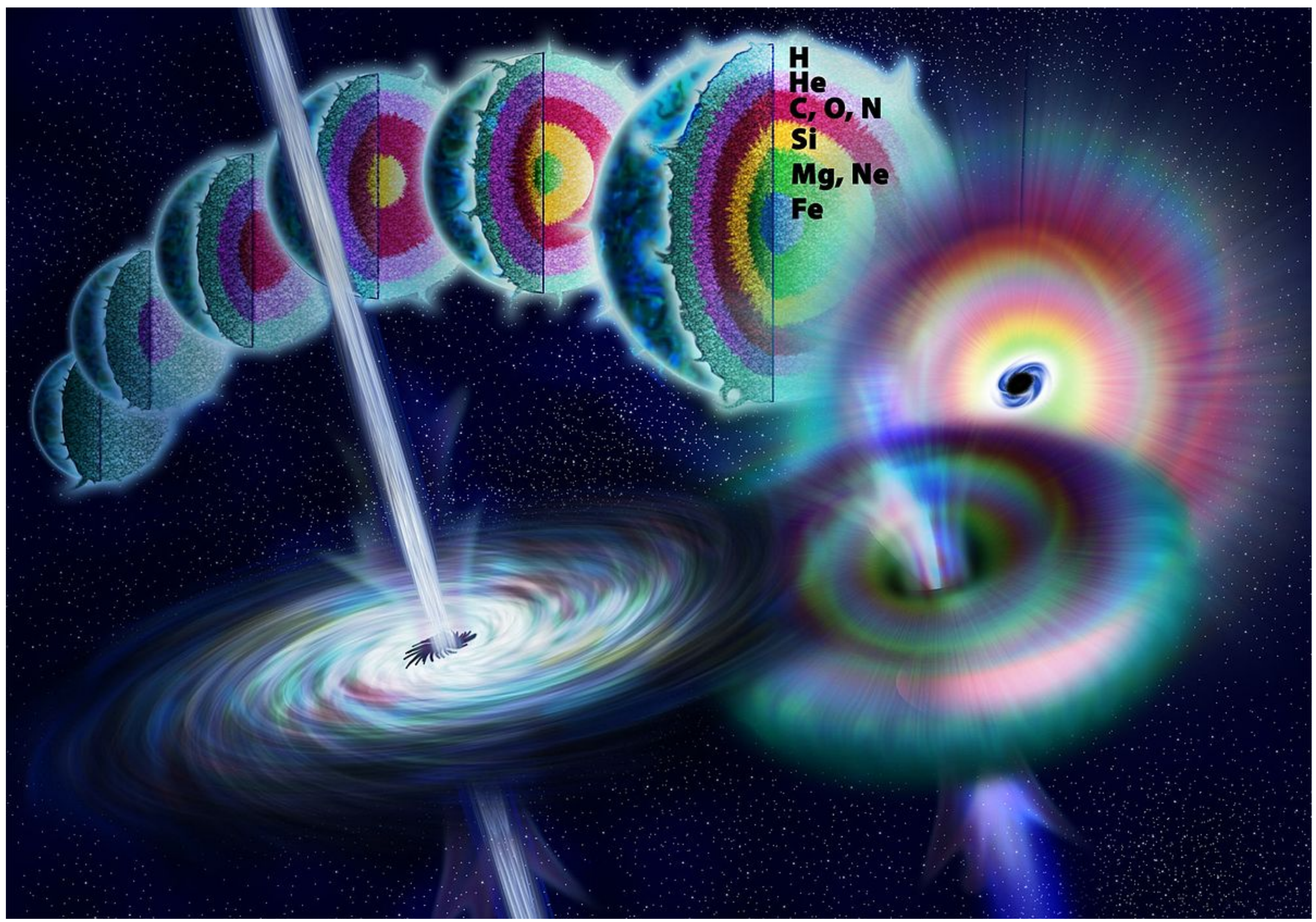
- R136a1: 265 Msun (LMC)
- R136a2: 195 Msun (LMC)
- VFTS 682 : 150 Msun (LMC)
- R136a3 : 135 Msun (LMC)
- NCG 3603-B: 132 Msun (Our Galaxy)
- Eta Carinae A: 120 Msun (Our Galaxy)



Eta Carinae nebula: The star at the center has a mass of about 100 Msun. This star underwent a great eruption in the 1840s, ejecting about 10 Msun.

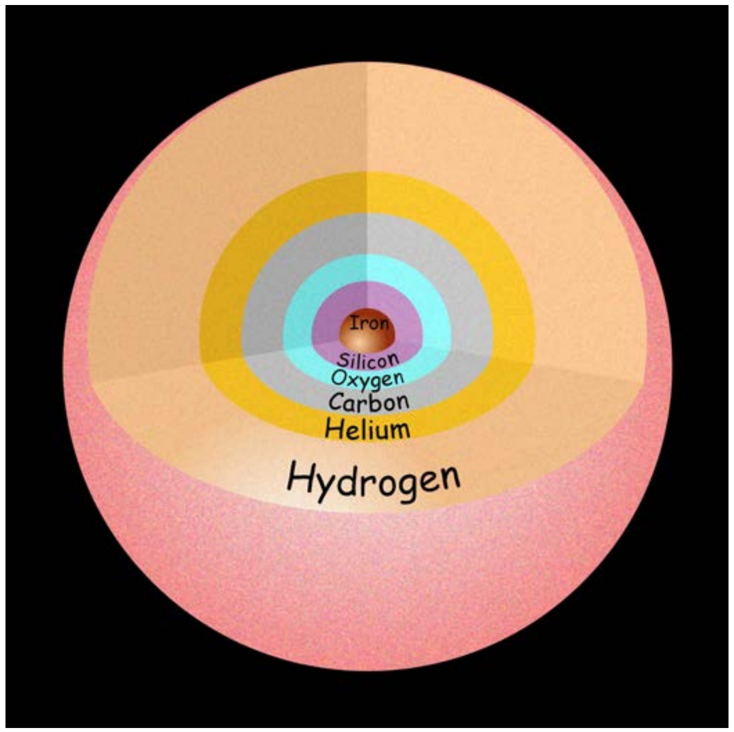
EM signals resulting from BH formation in massive stars

With rapid rotation in the core → long Gamma-ray bursts
very rare: ~1/1000 – 1/10000 SNe
Low-metallicity is preferred

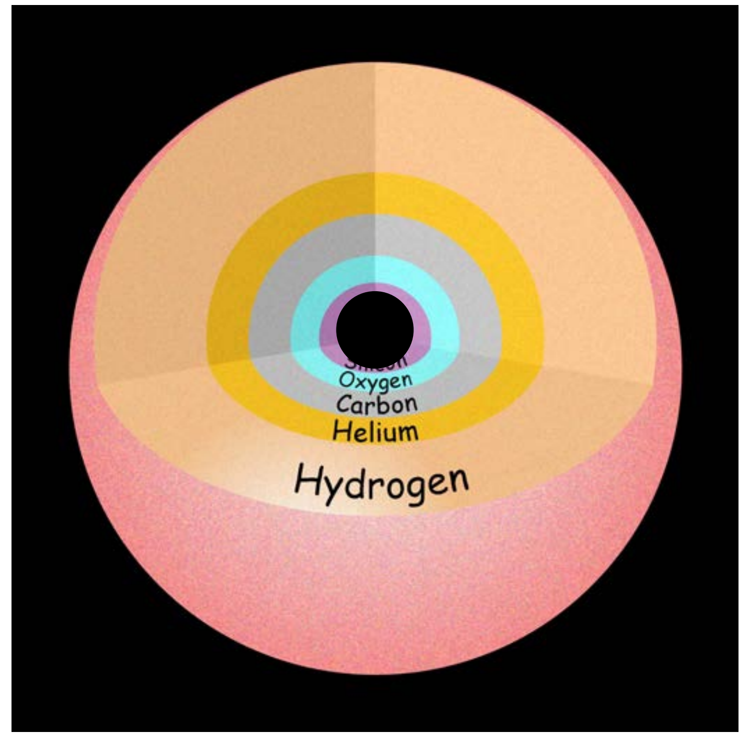


EM signals resulting from BH formation in massive stars

Without rapid rotation:

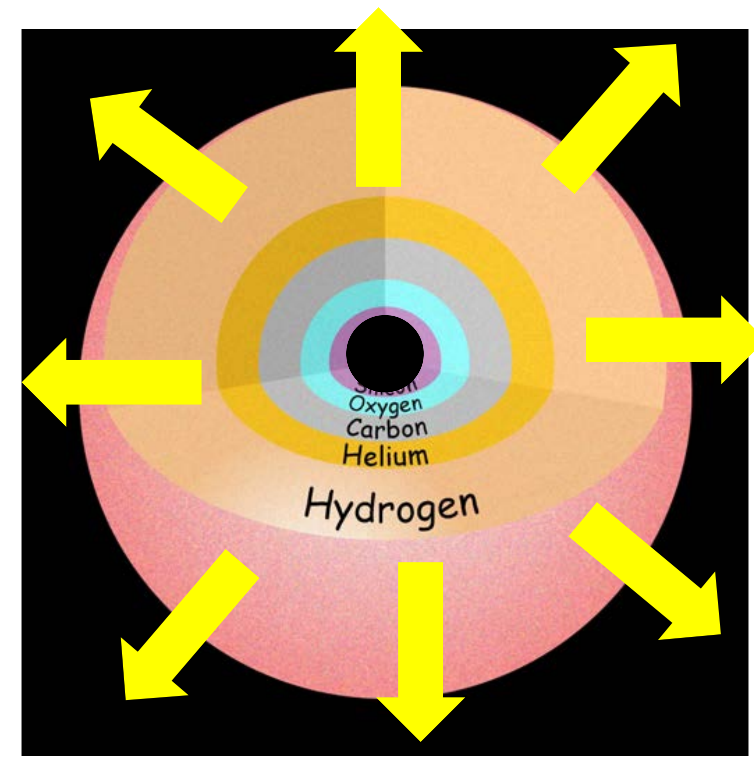


The red-supergiant star is in hydrostatic equilibrium



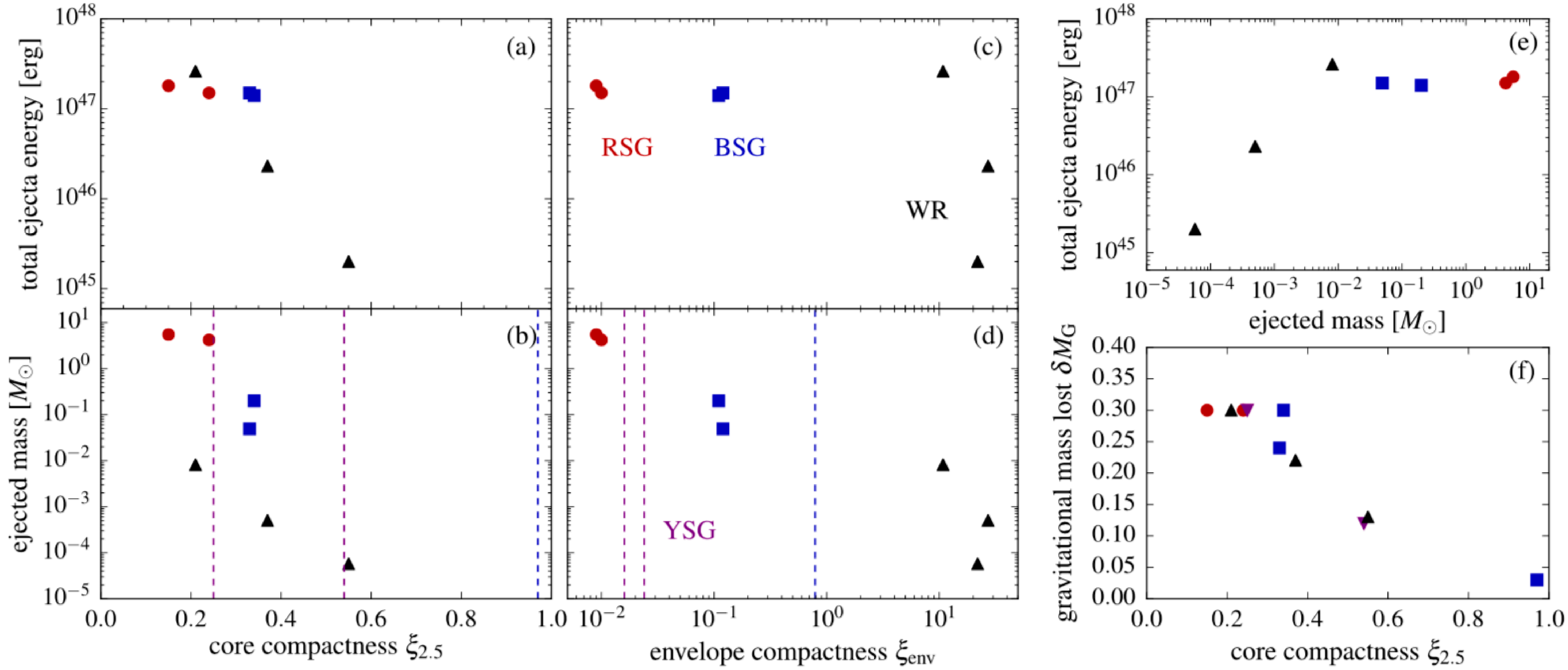
The collapse of the core to a black hole leads to mass loss via neutrino emission:
$E = mc^2 = \sim 10^{53}$ erg
→ m ~ 0.05 Msun

→ this makes the envelope out of the hydrostatic equilibrium (overpressure)



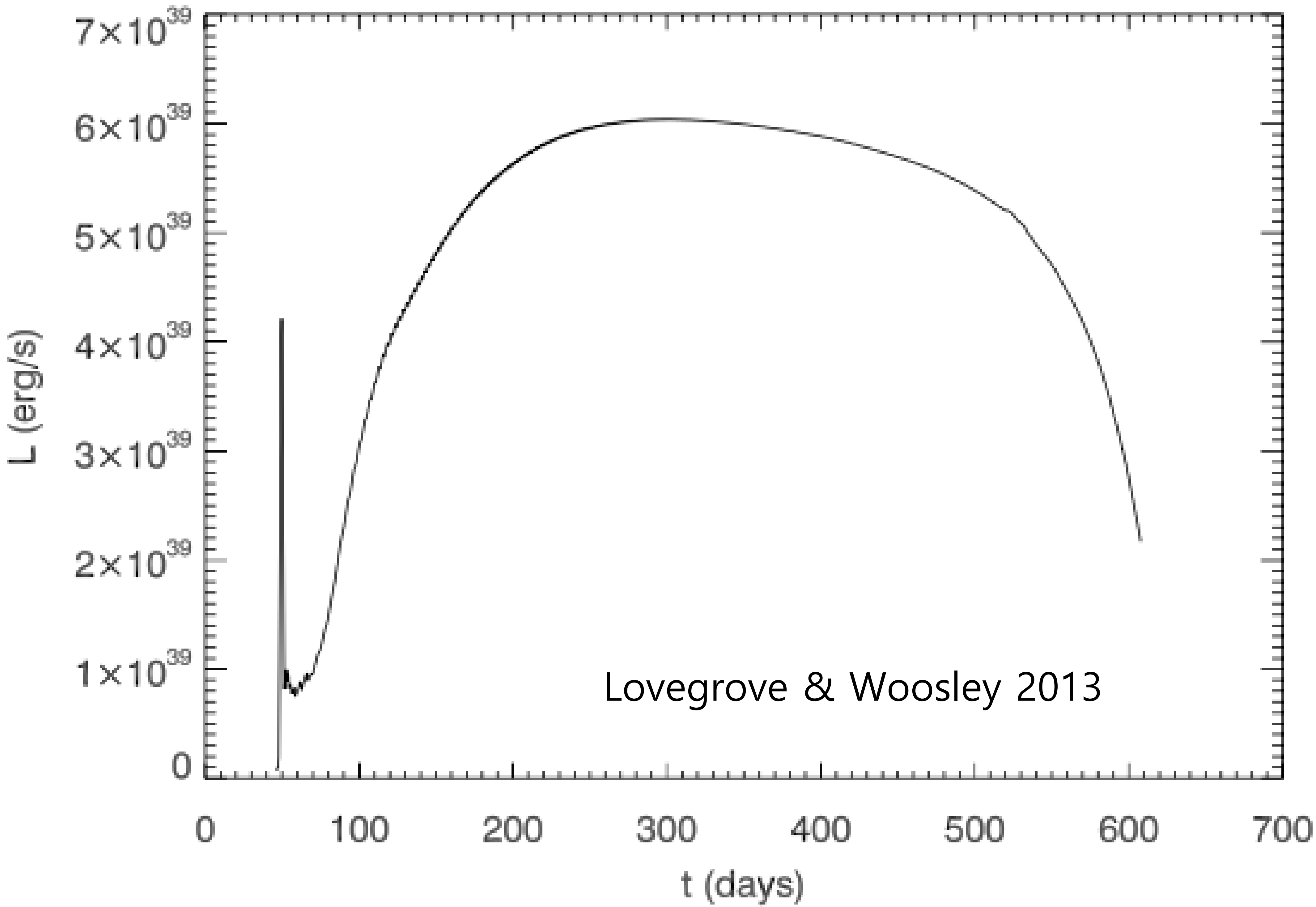
Ejection of the loosely bound envelope of the red-supergiant

Diversity of EM signals of BH formation

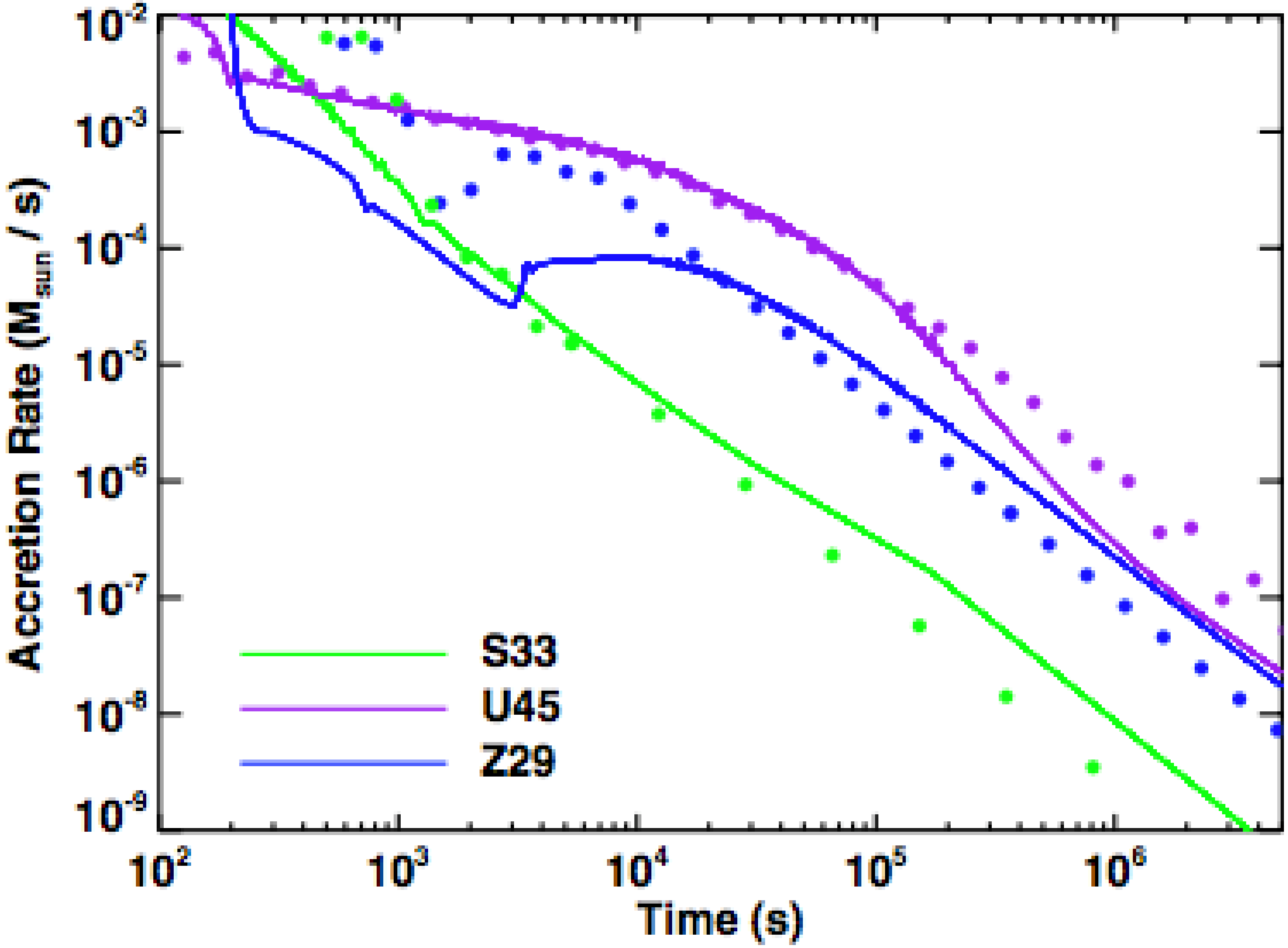


Fernandez et al. 2018

Low-luminosity but long-lasting transient due to BH formation ?



or fairly/very bright SN due to fall-back accretion?



$$\dot{E} = f\dot{M}c^2$$

Dexter & Kasen 2013

Conclusions

- The total amount of neutrino energy and neutrino luminosity from failed SN due to BH formation would be similar to those from successful SNe.
- **Neutrino signals of BH formation would be distinctively different from those of SN explosions.**
- *Possible optical signatures of BH formation*
  - If the progenitor is a red supergiant star
    - very low-luminosity, long-lasting transient (Lovegrove & Woosley 2013)
    - superluminous Type II if the accretion power is significant (Dexter & Kasen 2013)
  - If the progenitor is a Wolf-Rayet star → very short, relatively low-luminosity transient (needs future work)