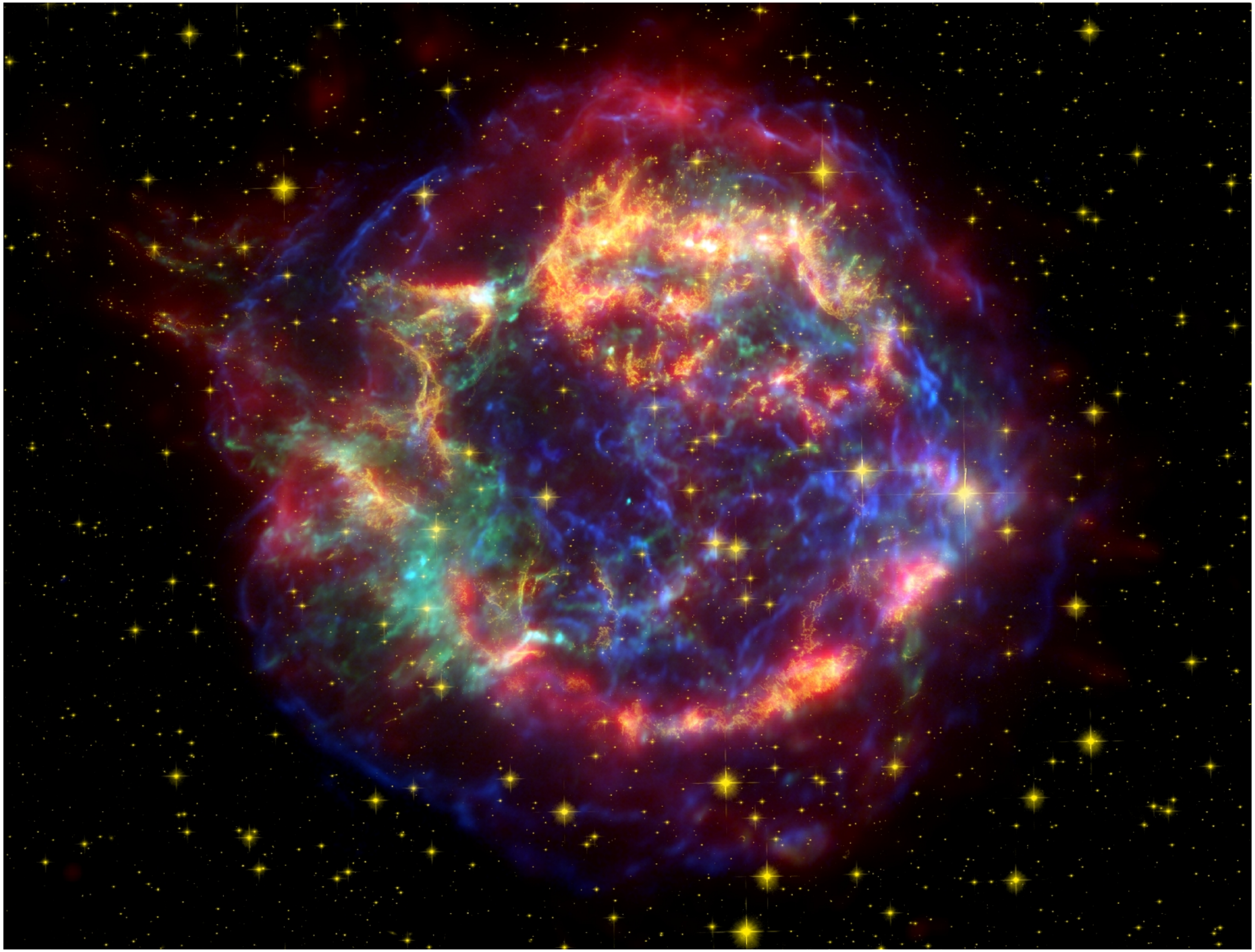
Supernova or direct collapse?

Supernova explosions and black hole mass

Core-collapse 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,
where neutron degeneracy pressure stops collapse

→ PROTO-NEUTRON STAR FORMS

Fraction of binding energy of core (Eb,c ~10^{53} erg)

$$W \sim 5 \times 10^{53}\,\mathrm{erg}\,\left(\frac{M_{\rm PNS}}{1.4\,M_\odot}\right)^2\,\left(\frac{10\,\mathrm{km}}{R_{\rm PNS}}\right)$$

used to launch a SHOCK : = supernova explosion

MECHANISM that converts binding energy into shock is UNKNOWN

Convective engine?

Rotational instability?

Magnetically driven explosion?

STANDARD MODEL: CONVECTIVE ENGINE

Potential energy is converted into thermal energy (mostly thermal energy of neutrinos) and core bounces driving shocks

SHOCK MUST REVERSE COLLAPSE OF OUTER LAYERS

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

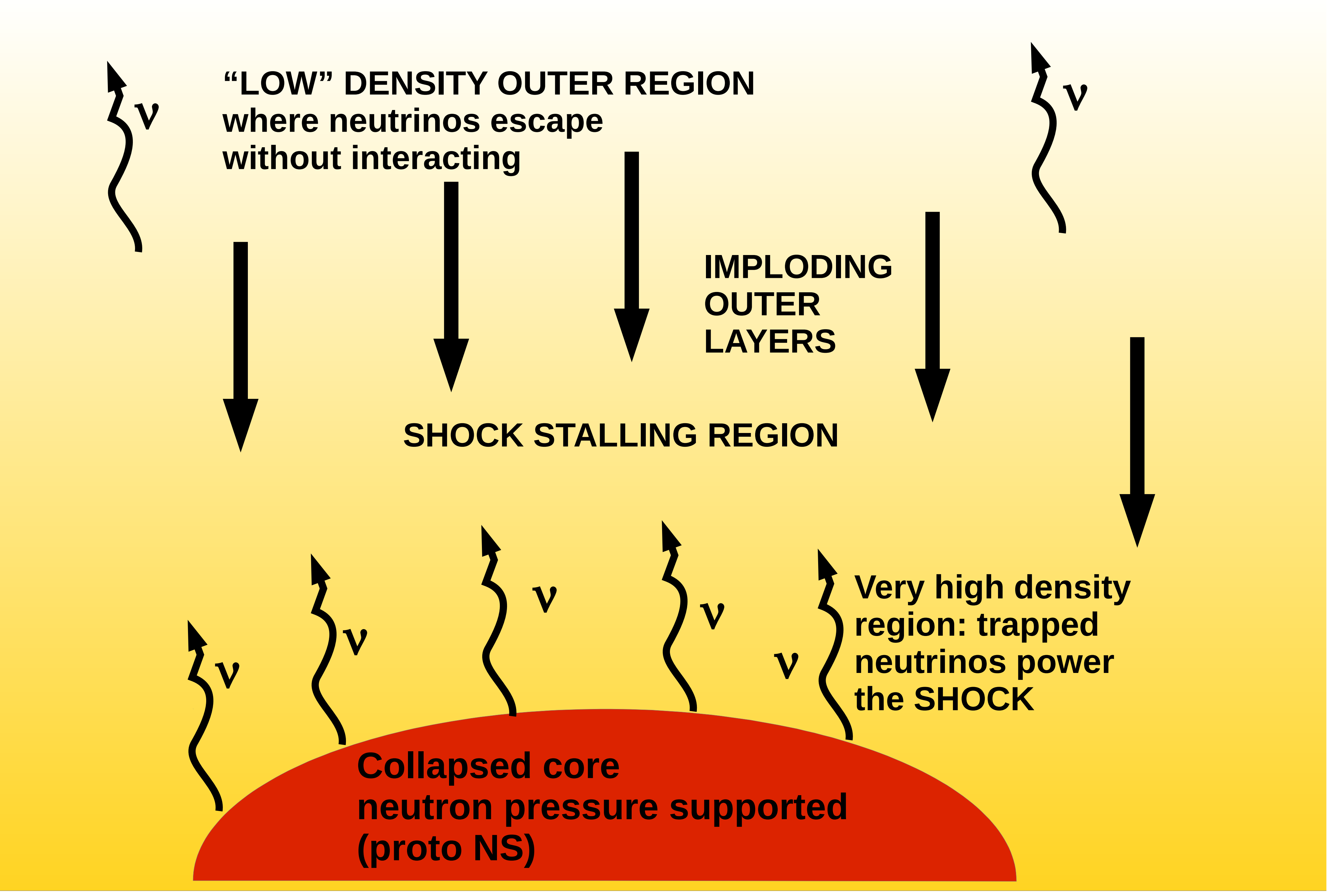
→ SHOCK MIGHT STALL

→ SN FAILS

WHEN DOES THE SHOCK STALL and the SN FAILS?

Convective region below shock where neutrino transfer is enhanced by convection

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


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

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 might contain wrong physics

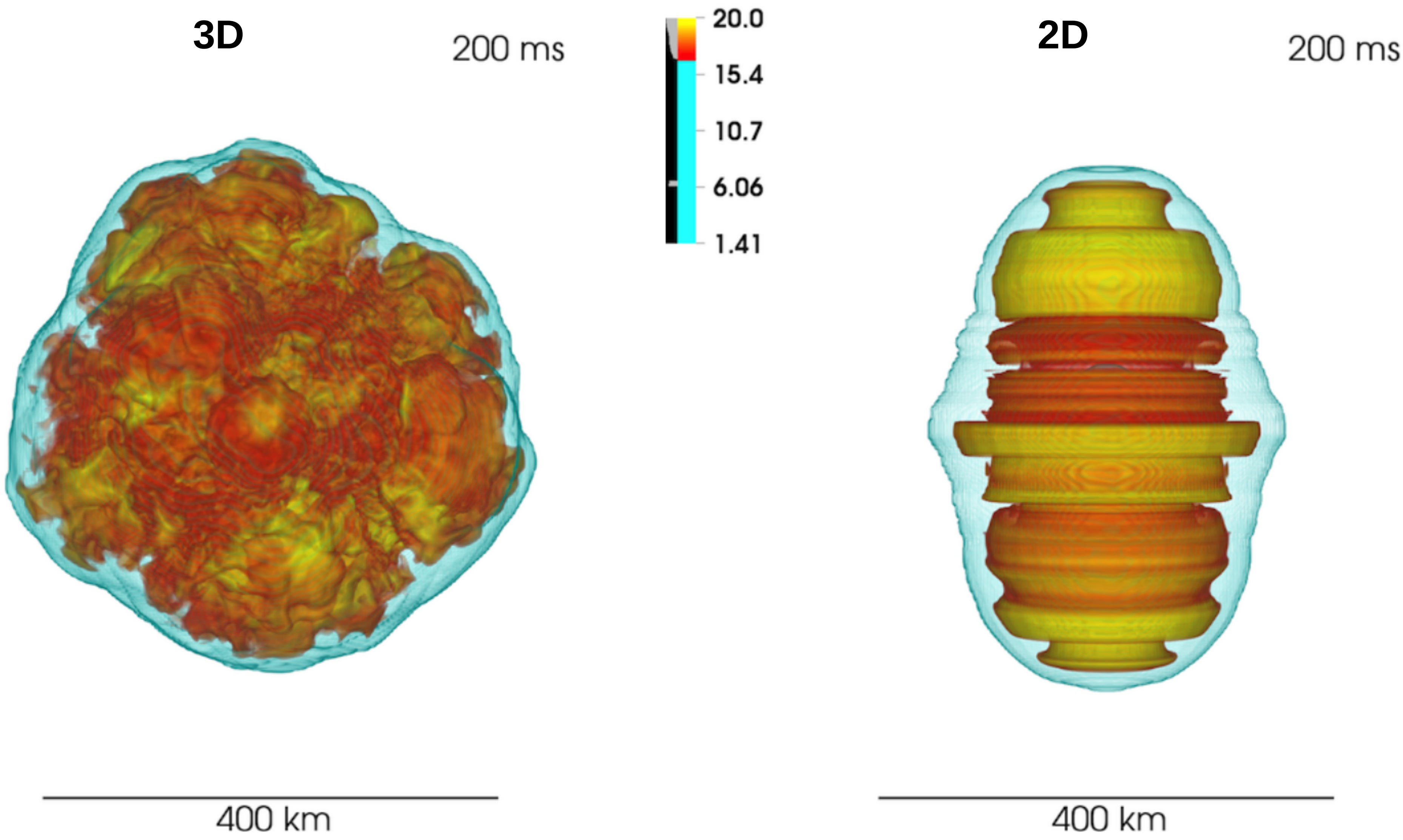
(Marek & Janka 2009; Mueller et al. 2012a, 2012b)

3D: computationally expensive, explode slowly

(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)



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

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

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

envelope mass

proto-NS ~ 1 Msun

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 Msun this SN fails and star collapses to a BH!

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 > 7 – 8 Msun SN FAILS

(Fryer+ 1999, 2012; Belczynski+ 2010)

2. COMPACTNESS

3. TWO-PARAMETER CRITERION

2. COMPACTNESS (= ratio between mass and radius) of a given portion of the stellar core at the onset of collapse

(O'Connor & Ott 2011, Ugliano et al. 2012)

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

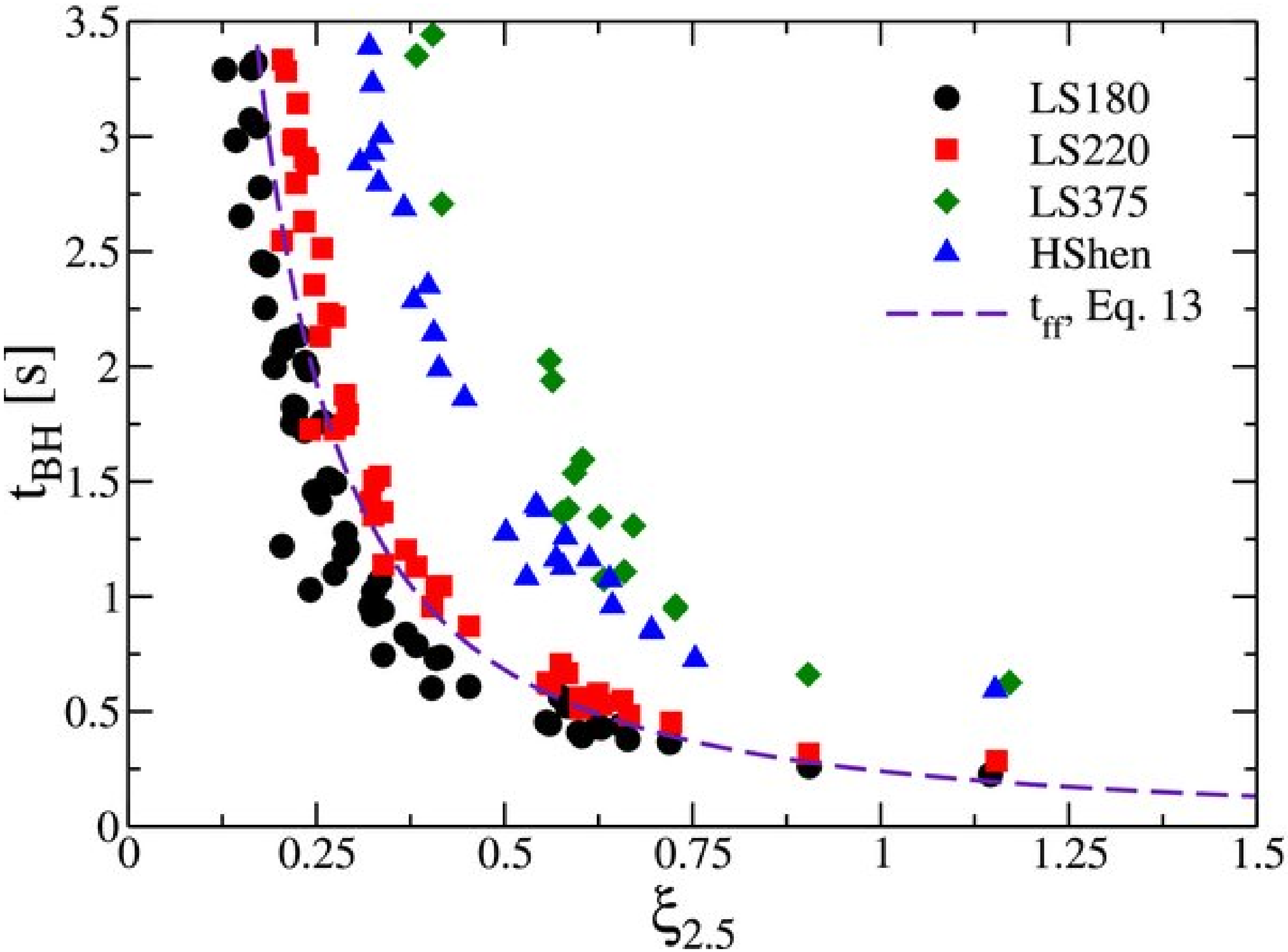
$M = 2.5\ \mathrm{M}_\odot$ is usually adopted

Time for BH formation strong function of compactness at 2.5 Msun

Star collapses if

$$\xi_{2.5} > 0.2$$

(Horiuchi et al. 2014)



2. COMPACTNESS

Compactness criterion and CO core criterion agree

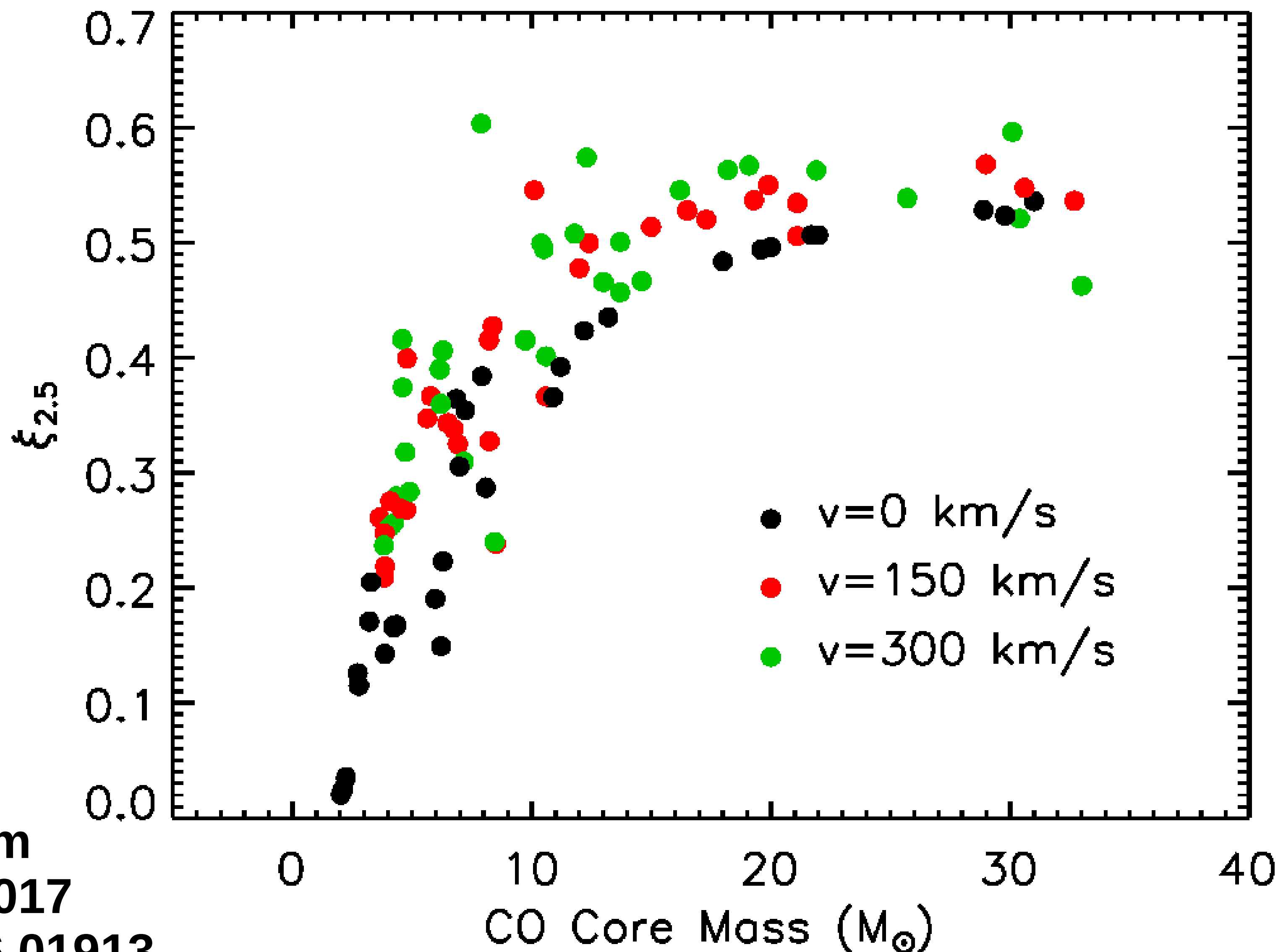
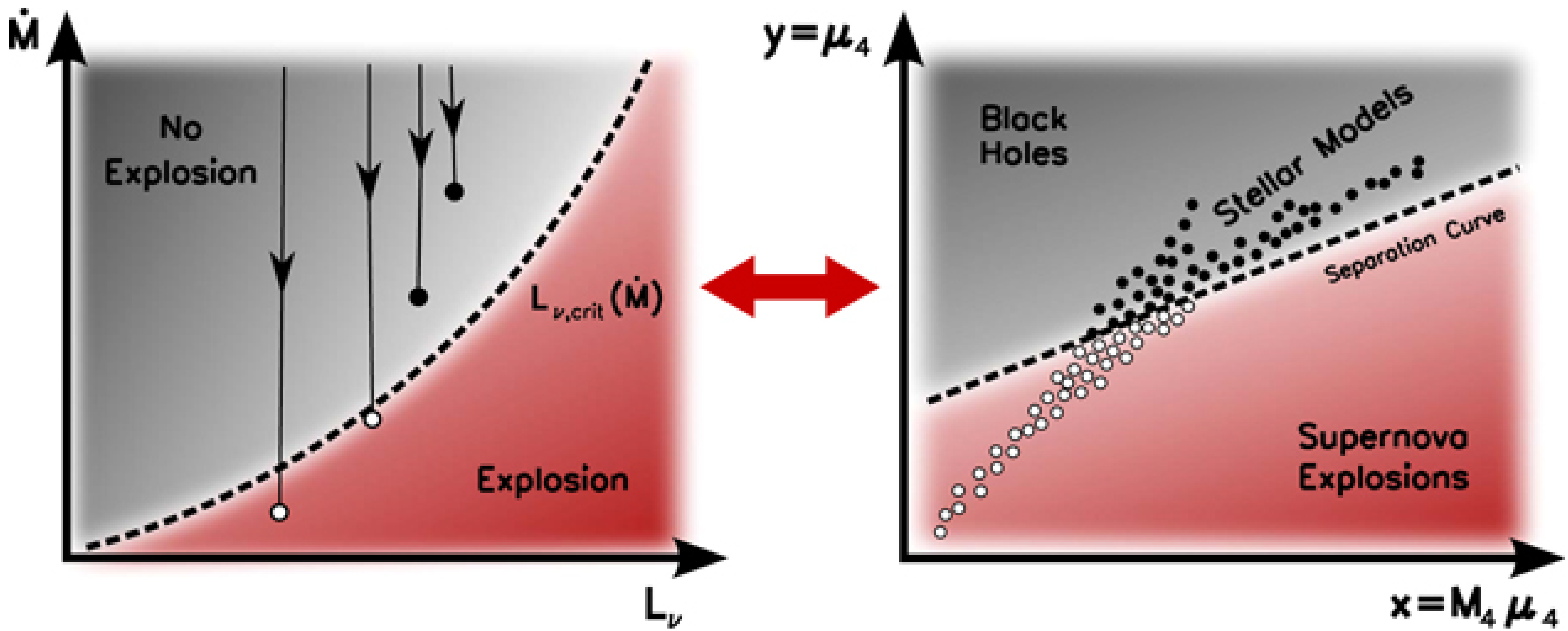


Figure from Limongi 2017 arXiv:1706.01913

3. 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

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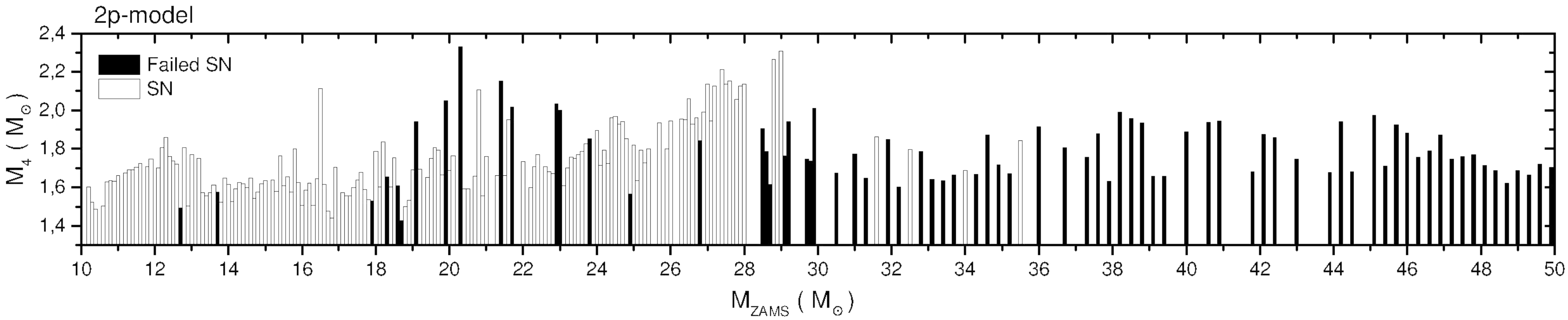
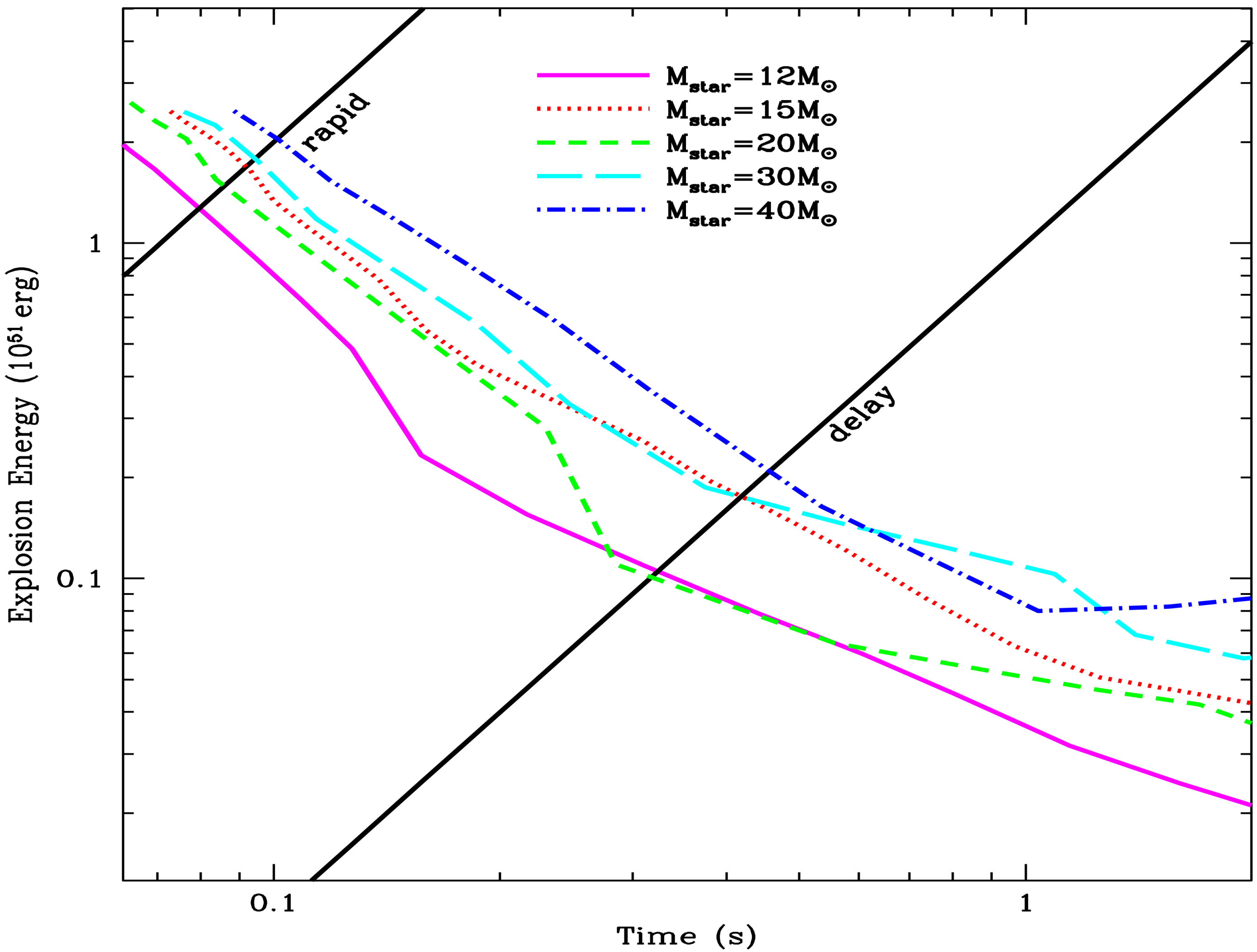


Fig. 21 **Spera, MM, Bressan 2015**

ISLANDS OF DIRECT COLLAPSE AND SN EXPLOSION

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

SN outcome depends on the "rapidity" of the explosion
(e.g. Fryer+ 2012; Fryer 2014)



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

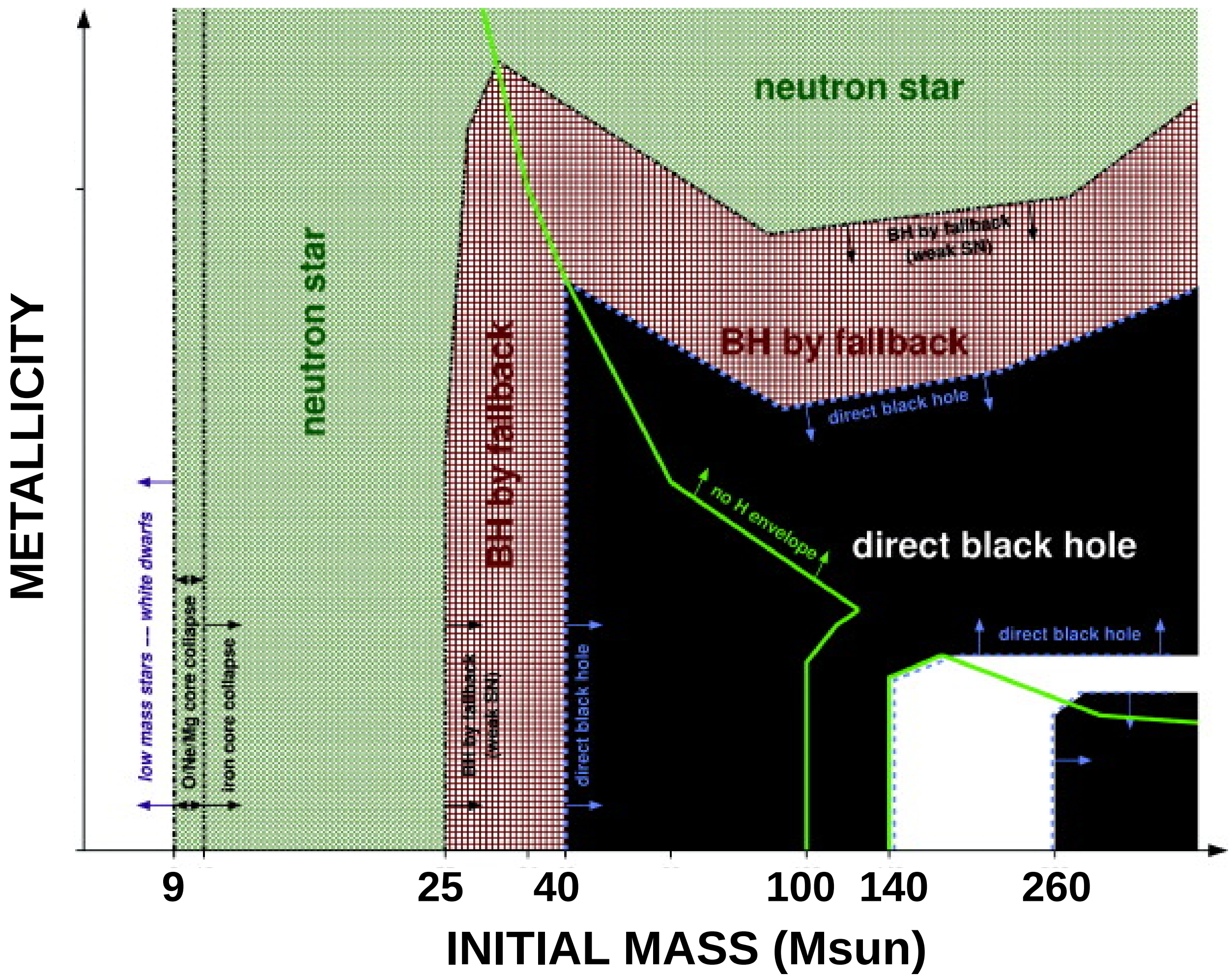
DELAYED (>200 ms after bounce): explosion energy <10^51 erg/s)

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

SN outcome depends on the "fallback" of the outer layers:

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

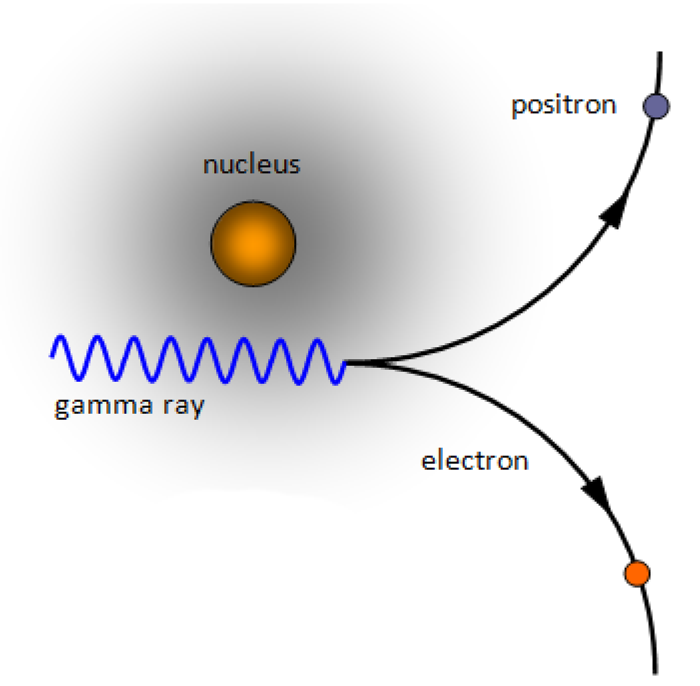
Barely constrained – depends on explosion energy,
angular momentum,
progenitor's mass/metallicity



Heger 2003

PAIR-INSTABILITY SUPERNOVAE

If star is very massive
(=produces γ–ray radiation in core)
γ-ray photons scattering atomic nuclei produce electron-positron pairs (1 Mev)



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 remnant

!! Strongly depends on progenitor mass/metallicity and neutrino physics (eg Belczynski+ 2016)

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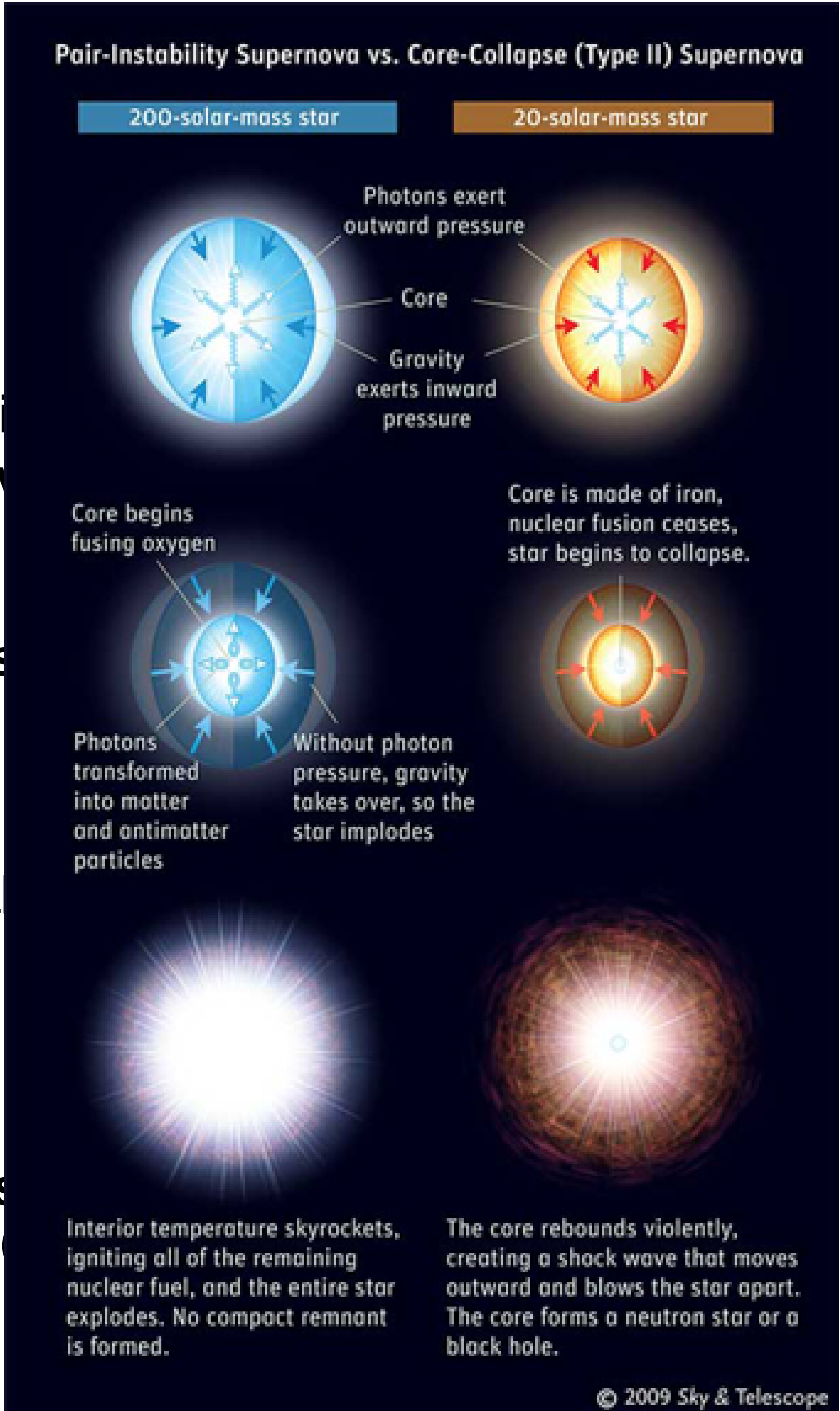


ELECTRON-CAPTURE SUPERNOVAE

Collapse of ONe core triggered by electron capture in 5 – 10 Msun stars

* **stars which should produce white dwarfs**

* **if > 1.4 Msun ONe core is developed, electron capture is efficient onto Mg and Ne**

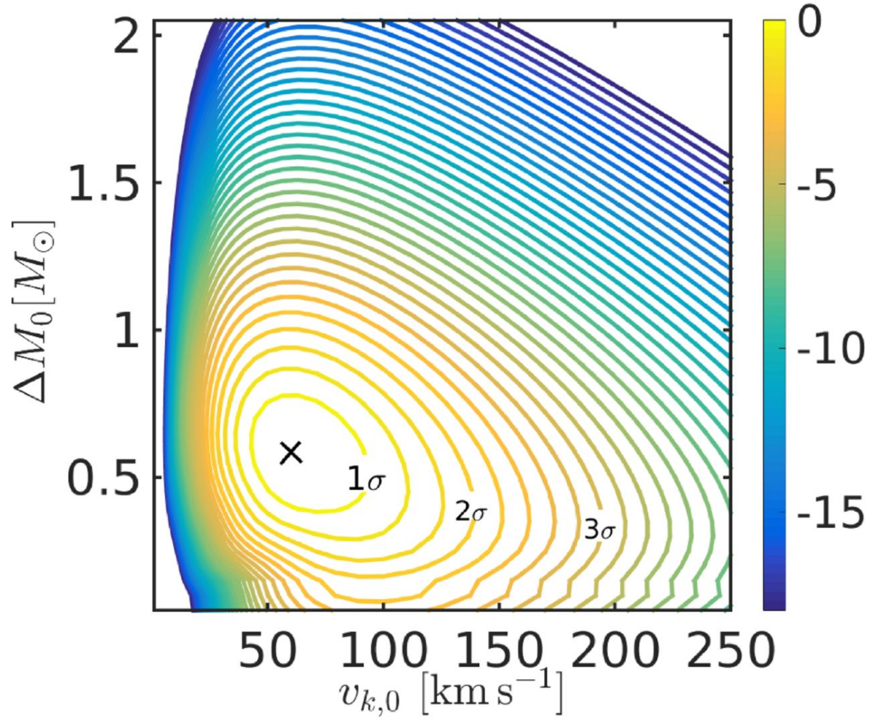
* **removes pressure leading to core collapse**
  (Nomoto 1984; Jones+ 2016)

* **thought to happen mostly in binaries**

* **smaller NS masses (~ 1.2 Msun)**

* **lower kicks**
(van den Heuvel 2007; Beniamini & Piran 2016)

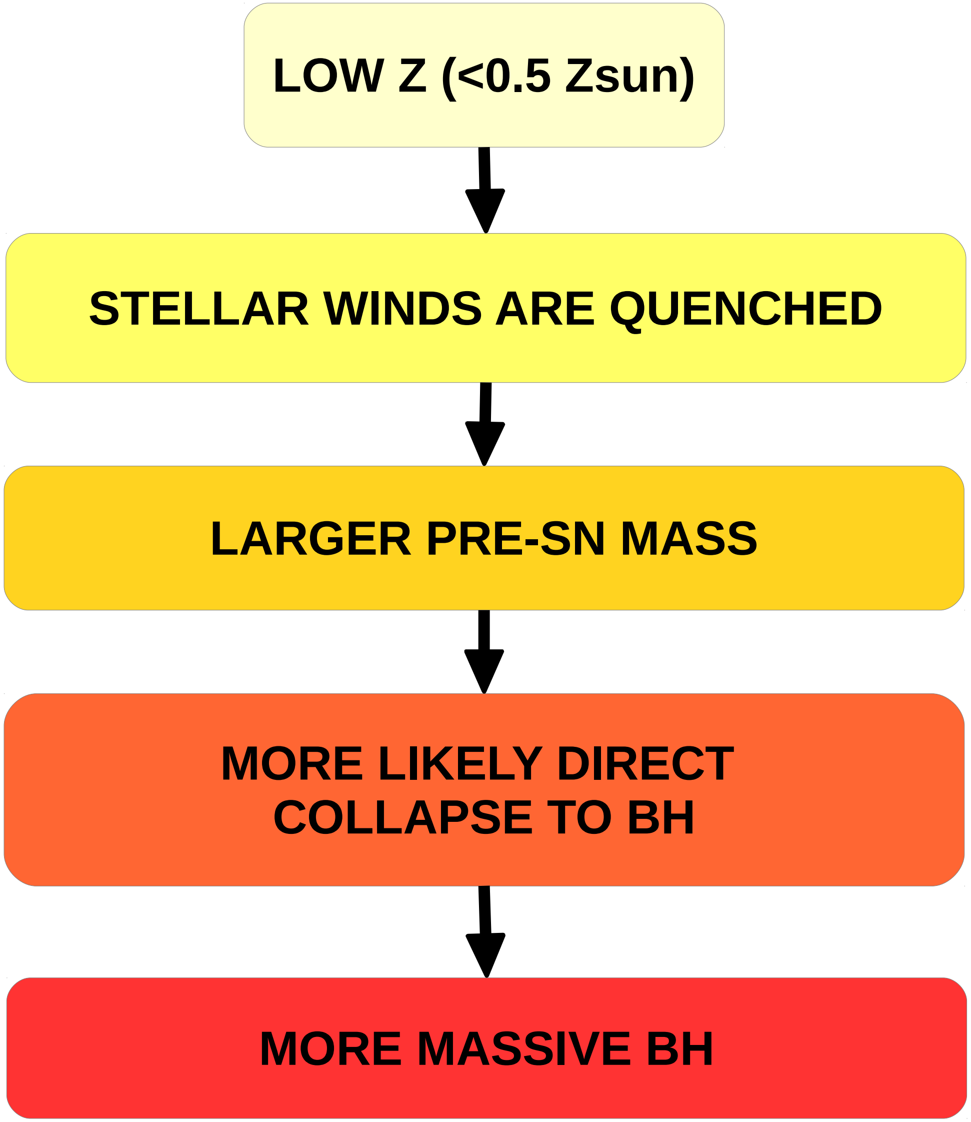
10 NS binaries

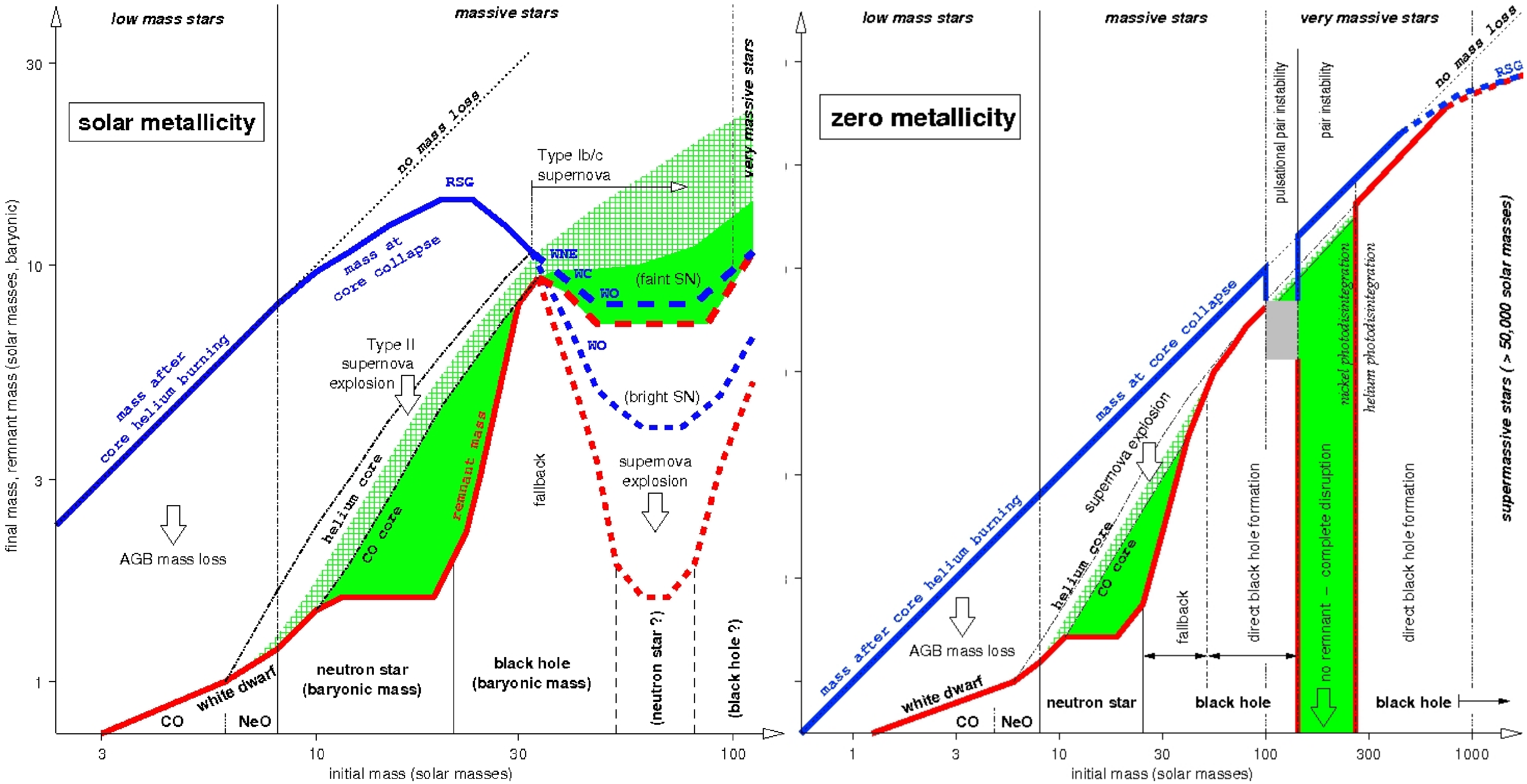


Beniamini & Piran 2016

The formation of compact remnants: wrap up

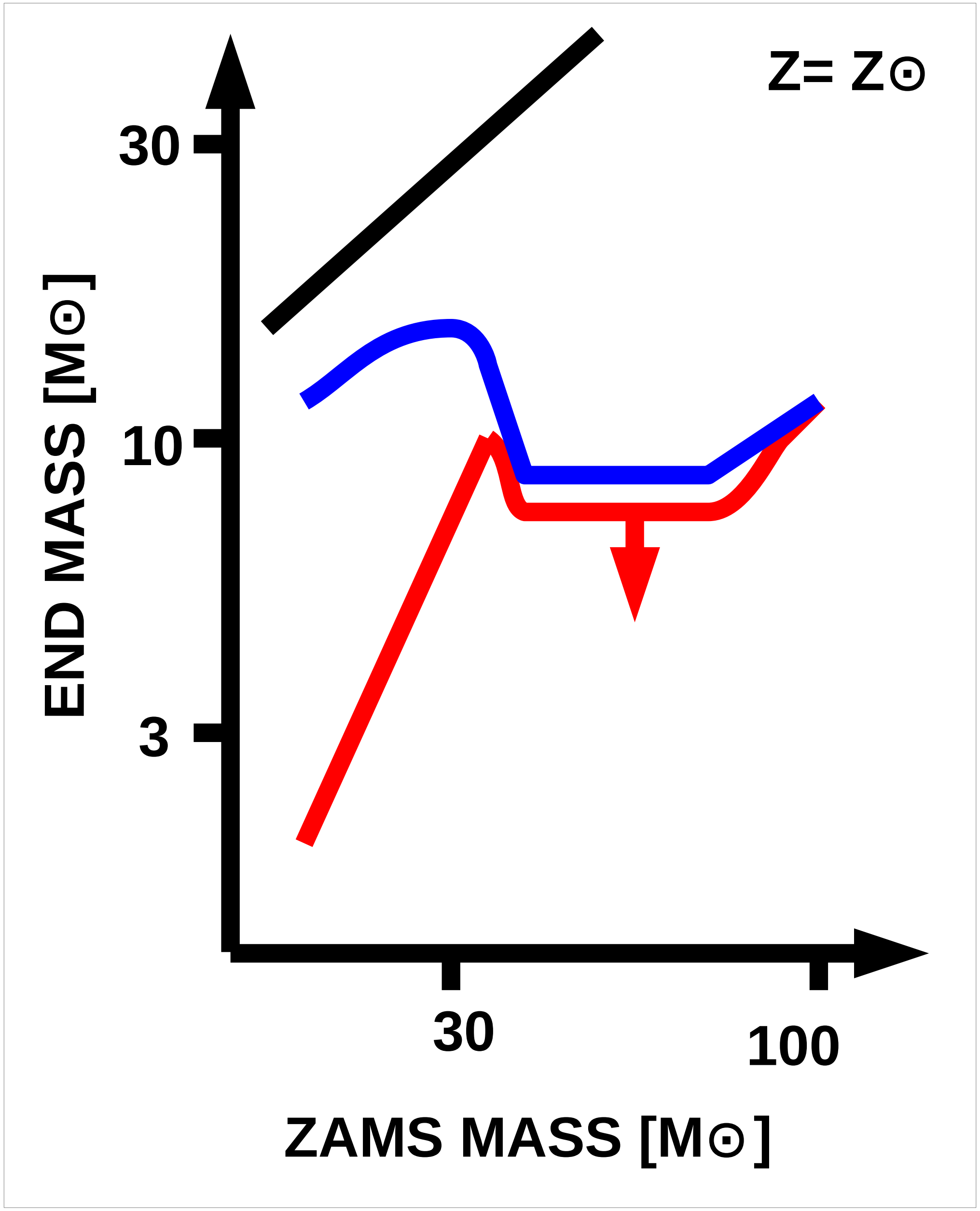
Very complicated. However, as rule of thumb (MM+ 2009, 2013):

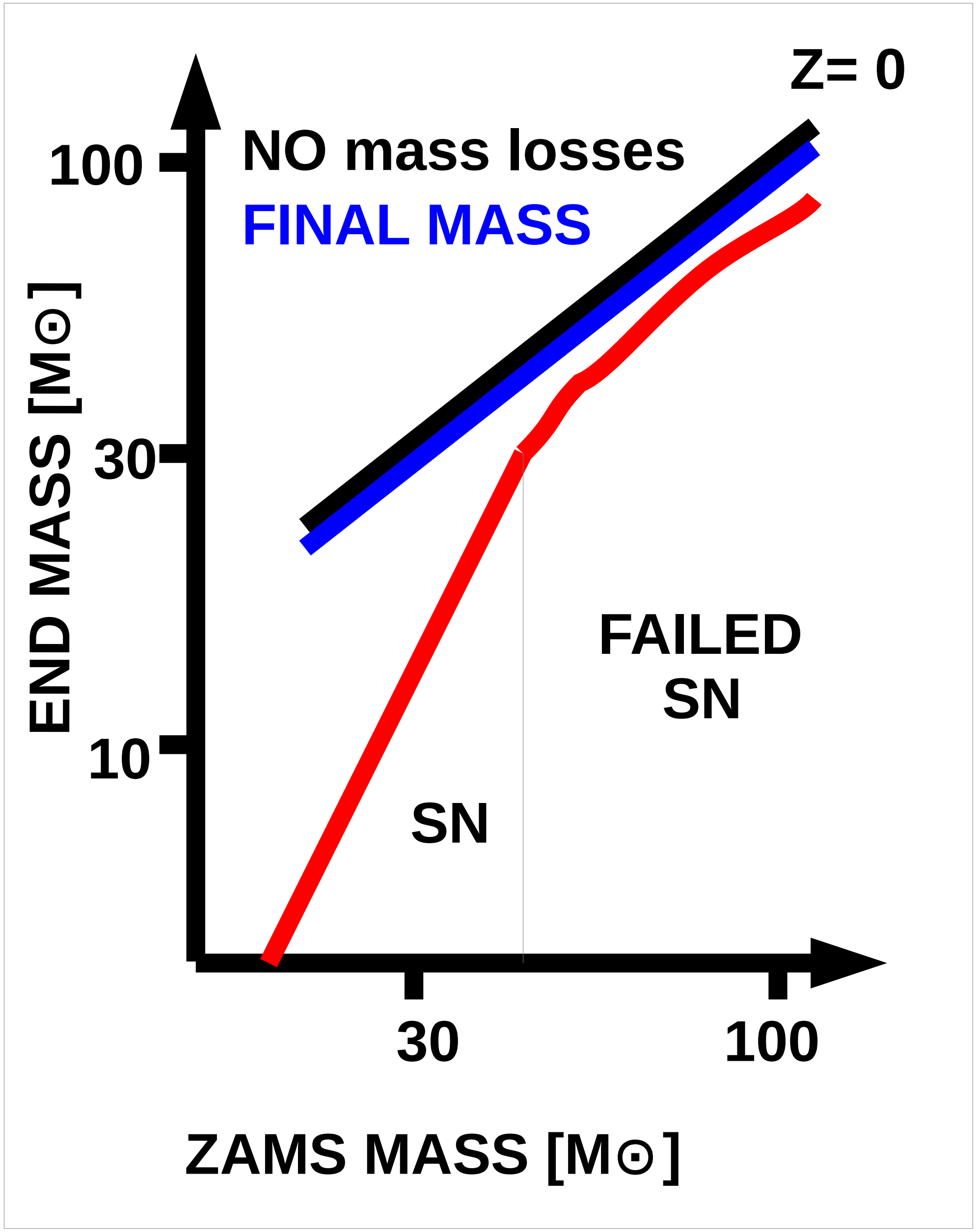




Heger et al. (2003)

Michela Mapelli





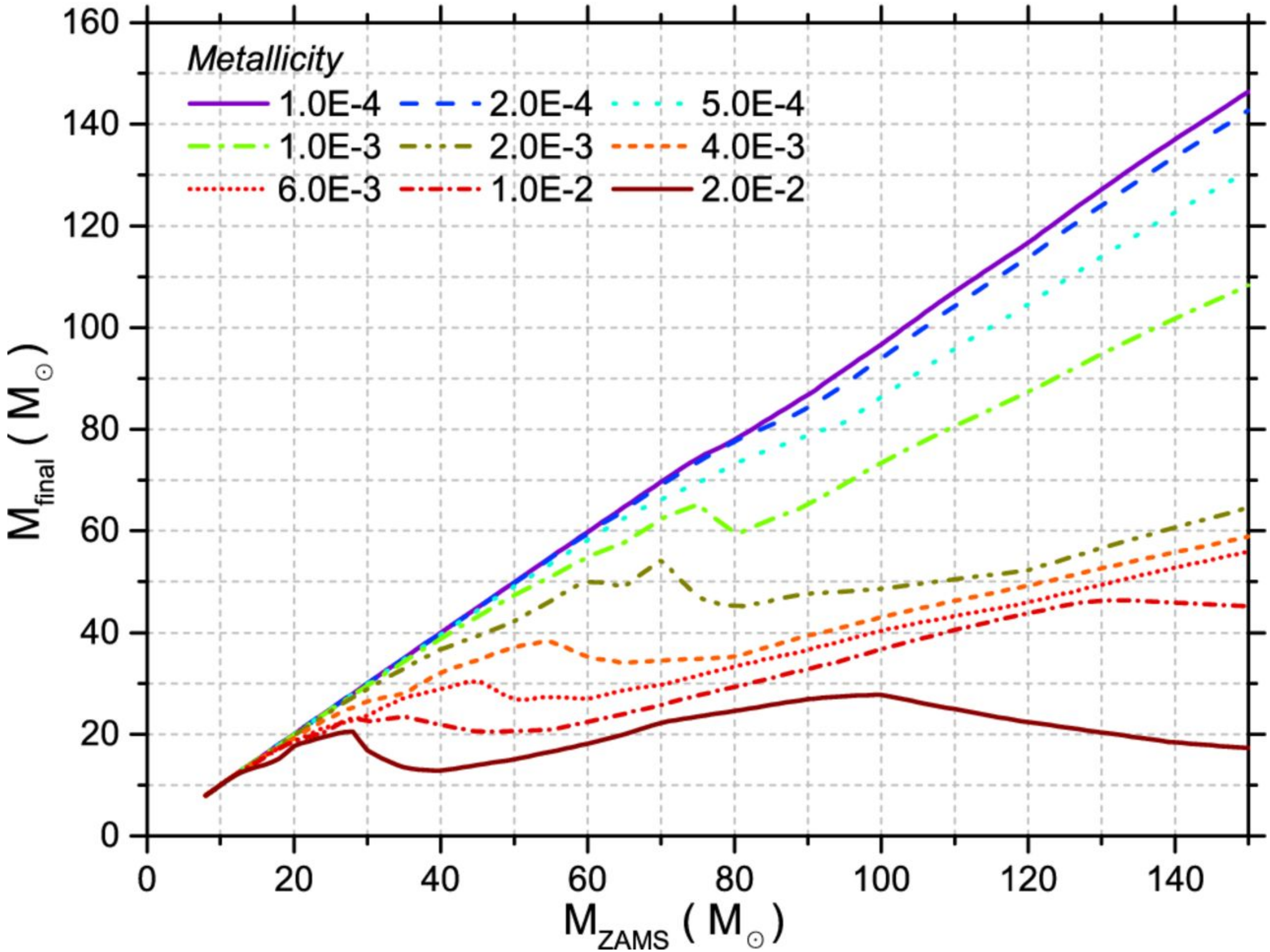
My cartoon from
Heger et al. (2003)

What about intermediate metallicities between 0 and solar?
- more difficult because stellar winds are uncertain

Remnant Model	Stellar Evolution	Supernova Model	Max. BH mass at Z~0.01 Zsun
MM+ 2009	Maeder+ 1992	Fryer+ 1999	~50 Msun
MM+ 2010	Portinari+ 1998	Fryer+ 1999	~80 Msun
Belczynski+ 2010	Hurley+ 2000 and Vink+ 2001	Fryer+ 1999	~80 Msun
Fryer+ 2012	Hurley+ 2000 and Vink+ 2001	Fryer+ 2012	~80 Msun
MM+ 2013,2014	SeBa (Portegies Zwart+ 2001) and Vink+ 2001		~85 Msun
Spera, MM & Bressan 2015; Spera, Giacobbo & MM 2016	PARSEC (Bressan+ 2012; Tang, Bressan+ 2014; Chen, Bressan+ 2015)	O'Connor+2011 Fryer+ 2012 Ertl+ 2015 (6 different SN models compared)	~130 Msun

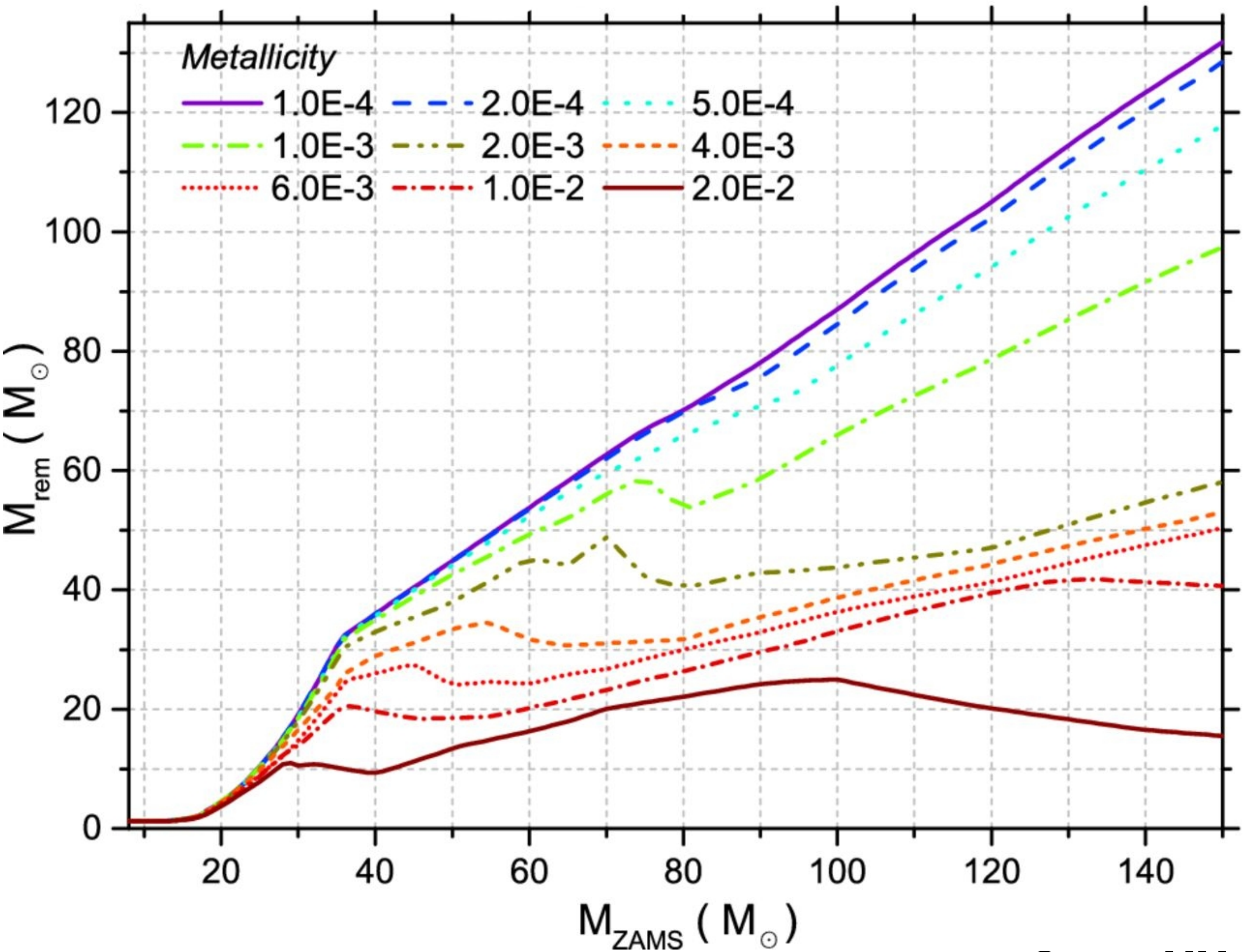
What about intermediate metallicities between 0 and solar?

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



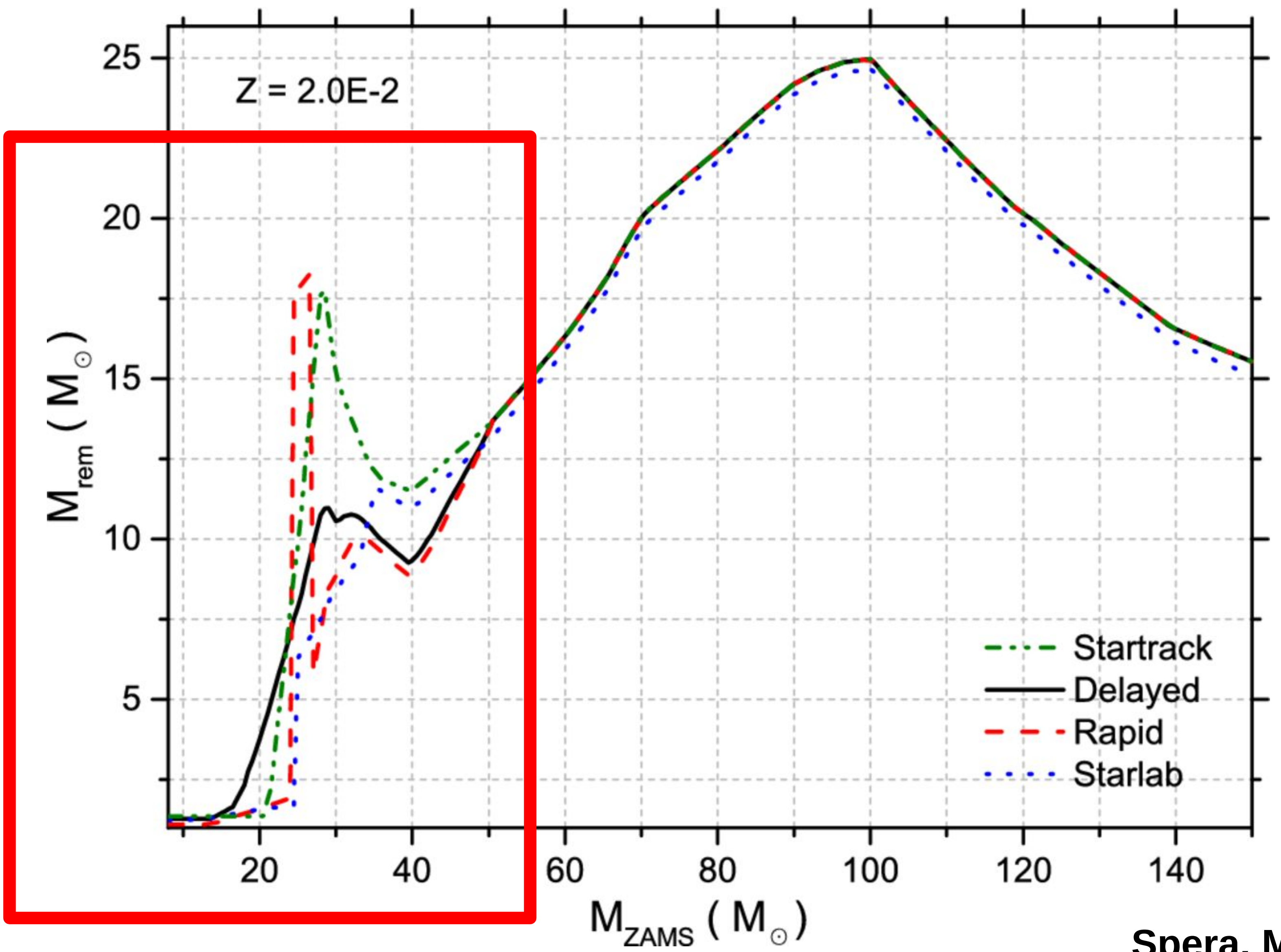
Spera, MM, Bressan 2015

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



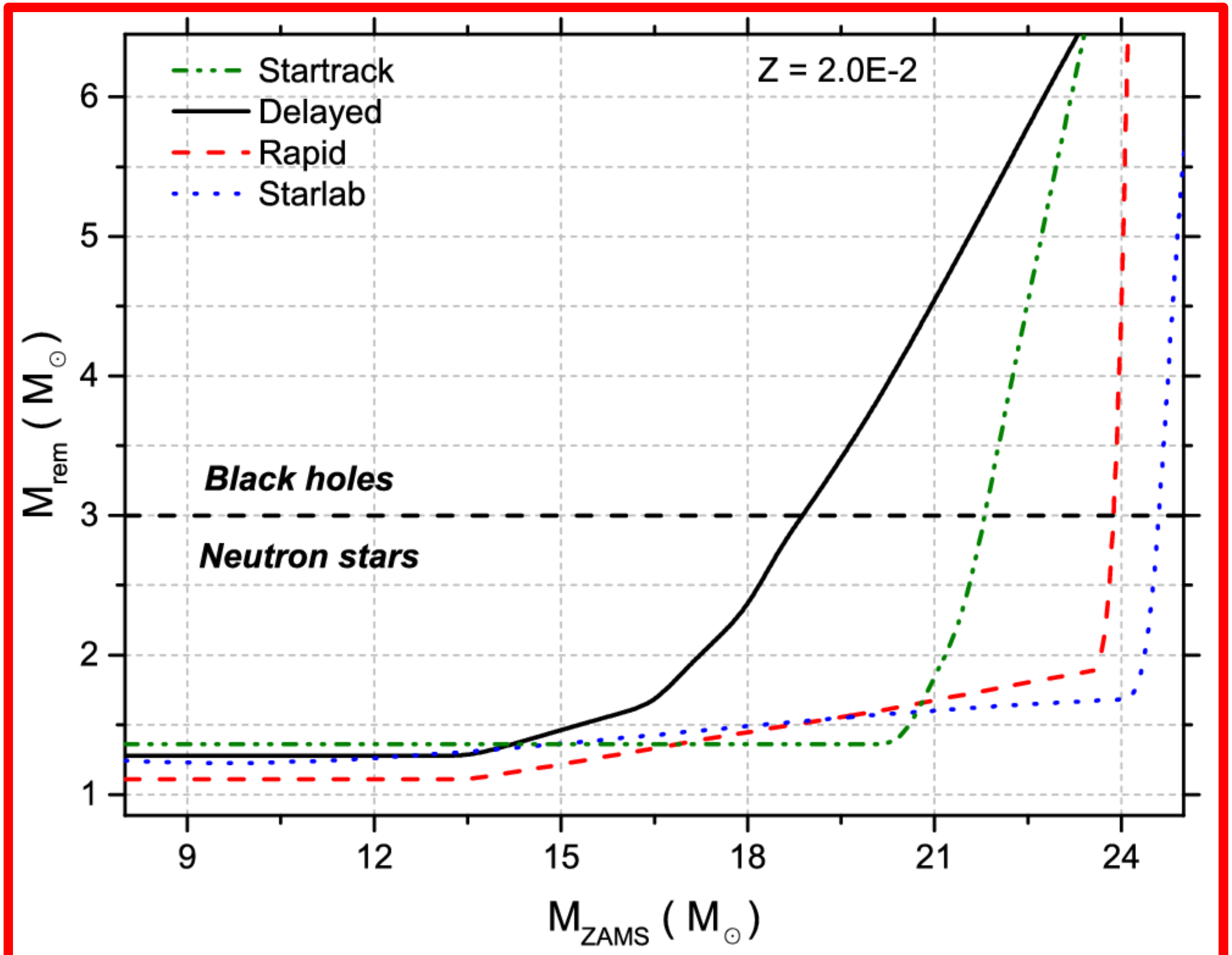
Spera, MM, Bressan 2015

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



Spera, MM, Bressan 2015

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



Spera, MM, Bressan 2015

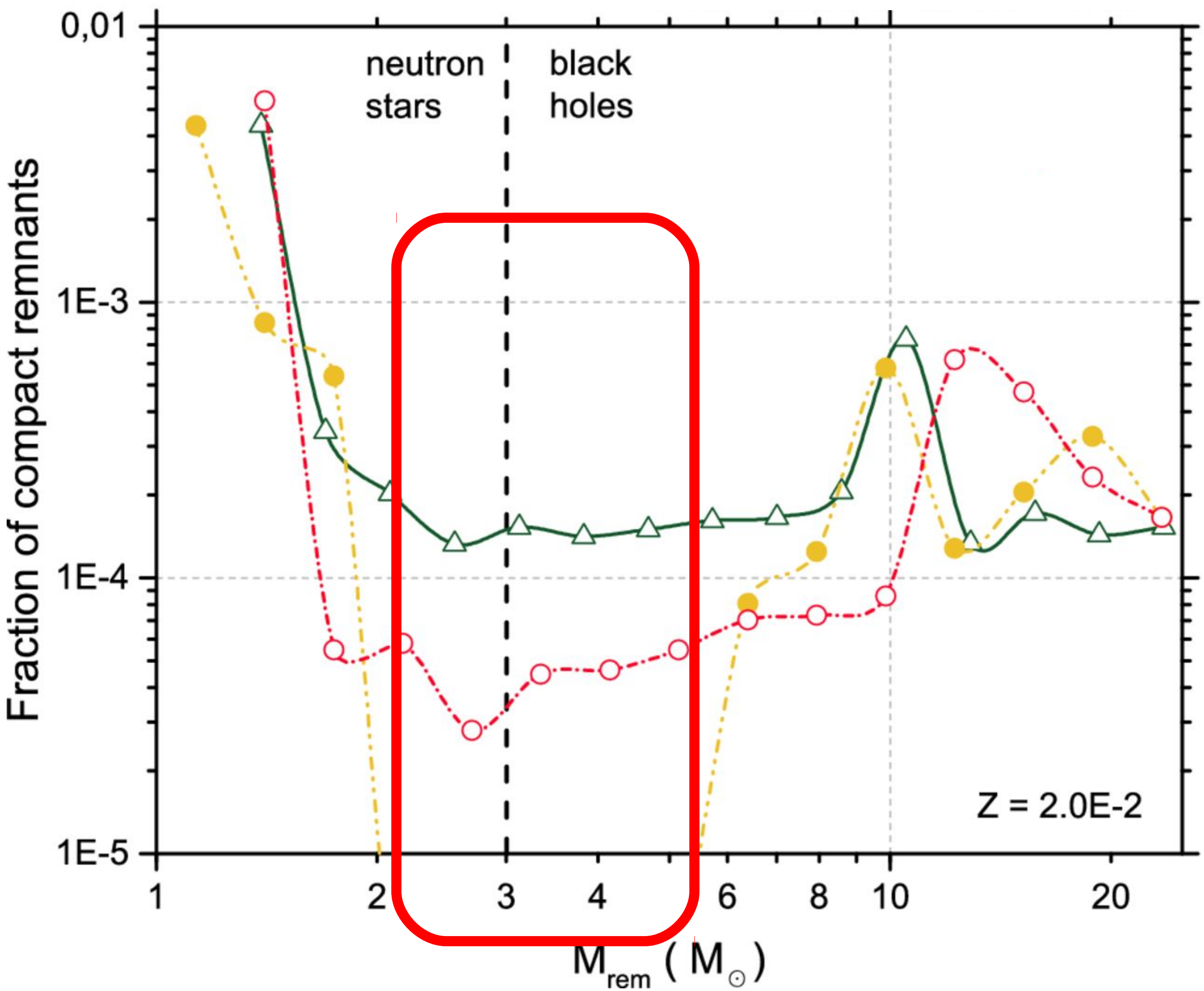
Importance of supernova model for LOW STAR MASSES (<40 M⊙)

Solar metallicity

GREEN:
DELAYED
SN (Fryer+ 2012)

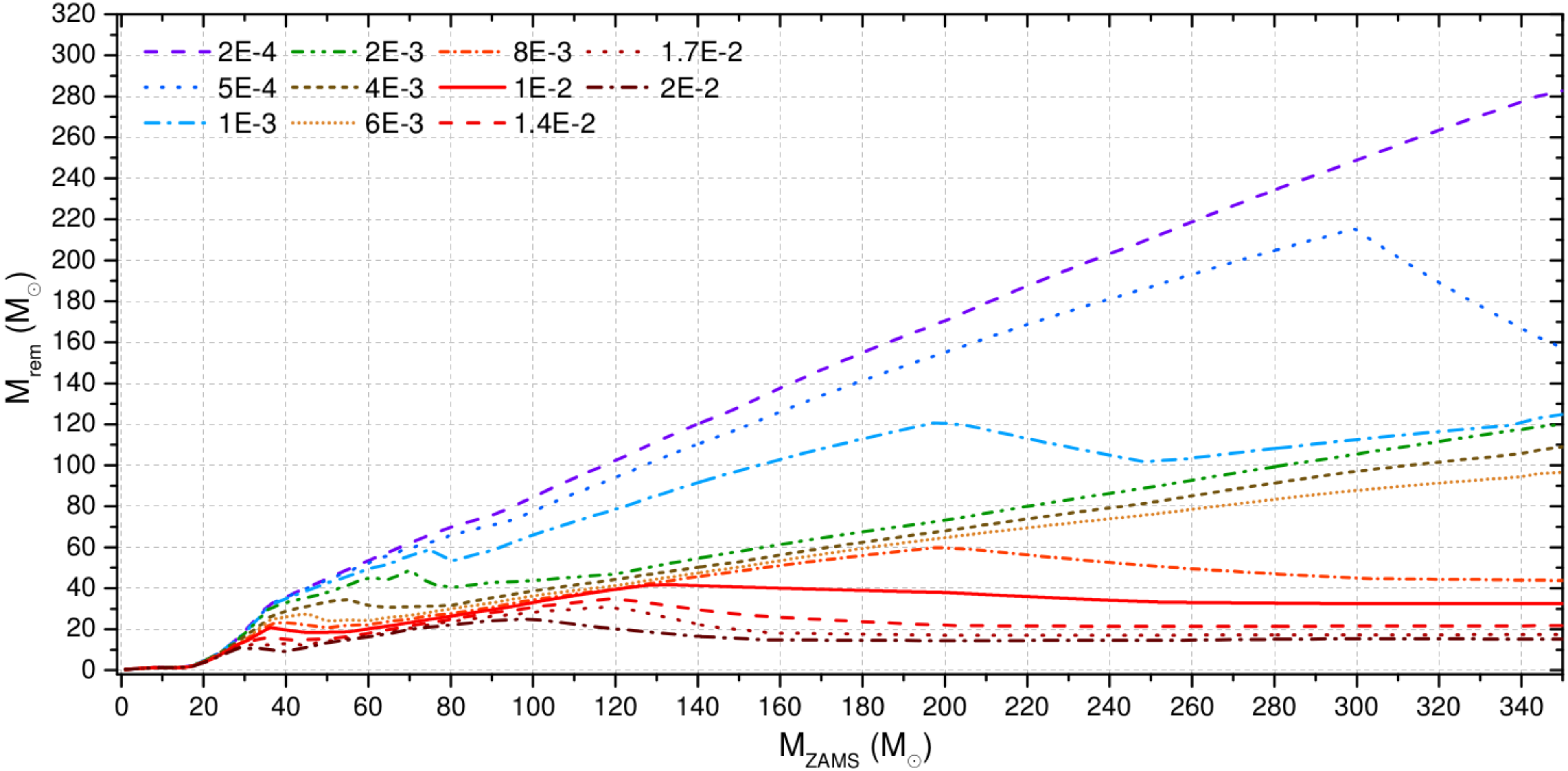
RED:
DELAYED
SN (MM+ 2013)

YELLOW:
PROMPT SN
(Fryer+ 2012)



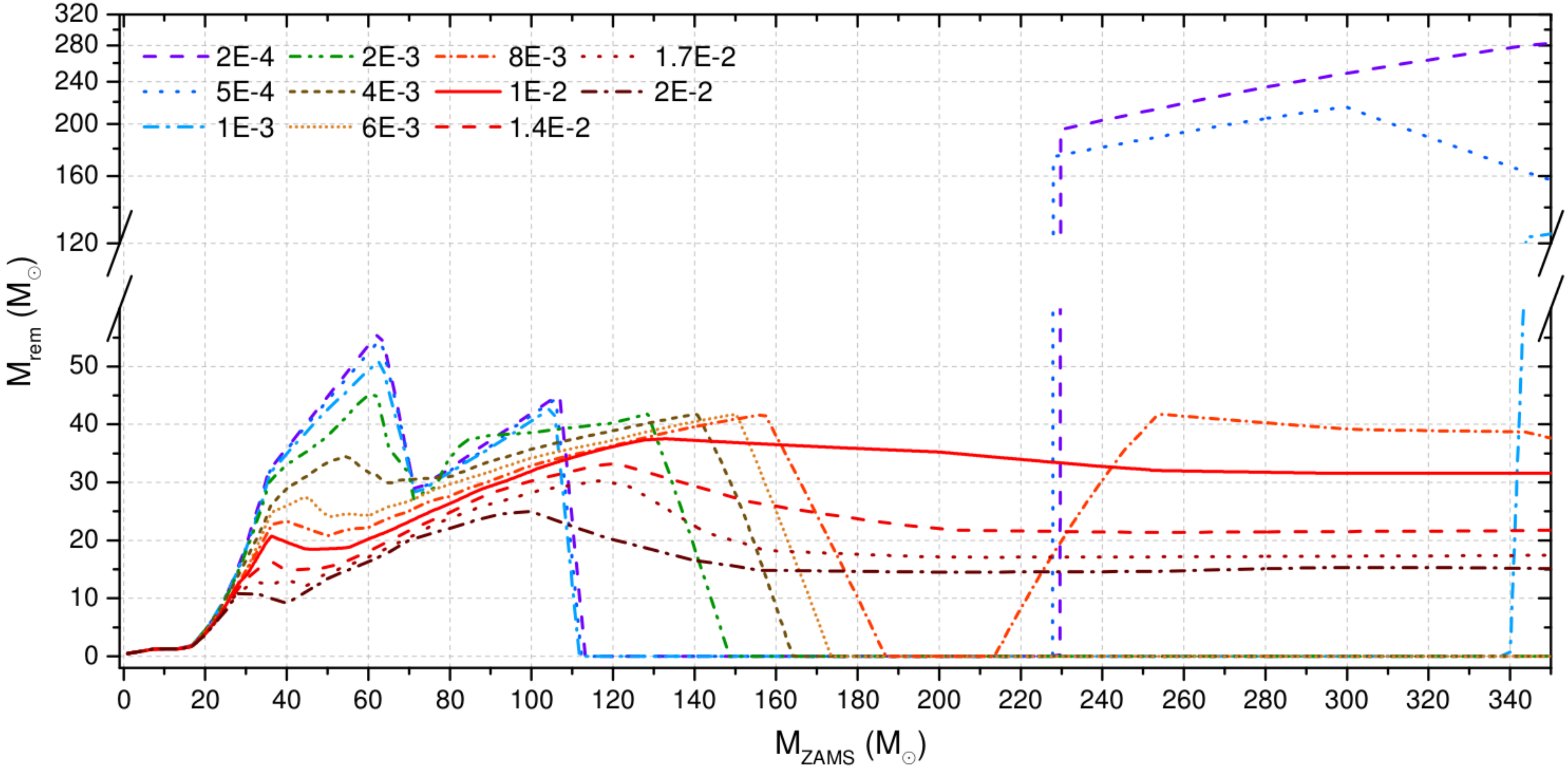
Spera, MM, Bressan 2015

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 (still missing in most models)



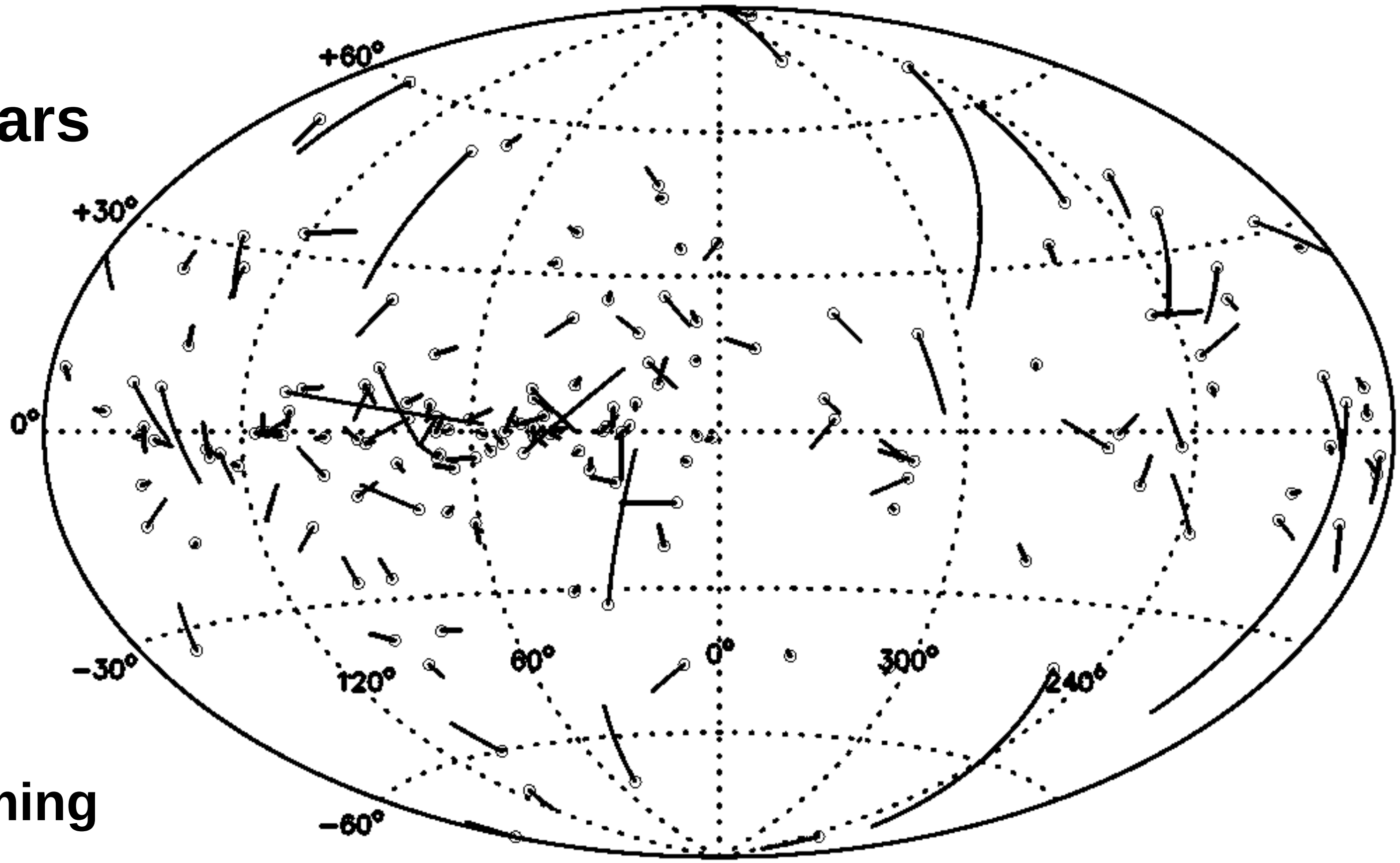
Spera & MM 2017

Supernova kicks and compact-object binaries:

A massive-star binary can become a compact-object binary only if it is not unbound by SN kicks

SN kicks for NSs constrained from velocity of PULSARS

Hobbs+ (2005):
sample of 233 pulsars with proper motion measurements



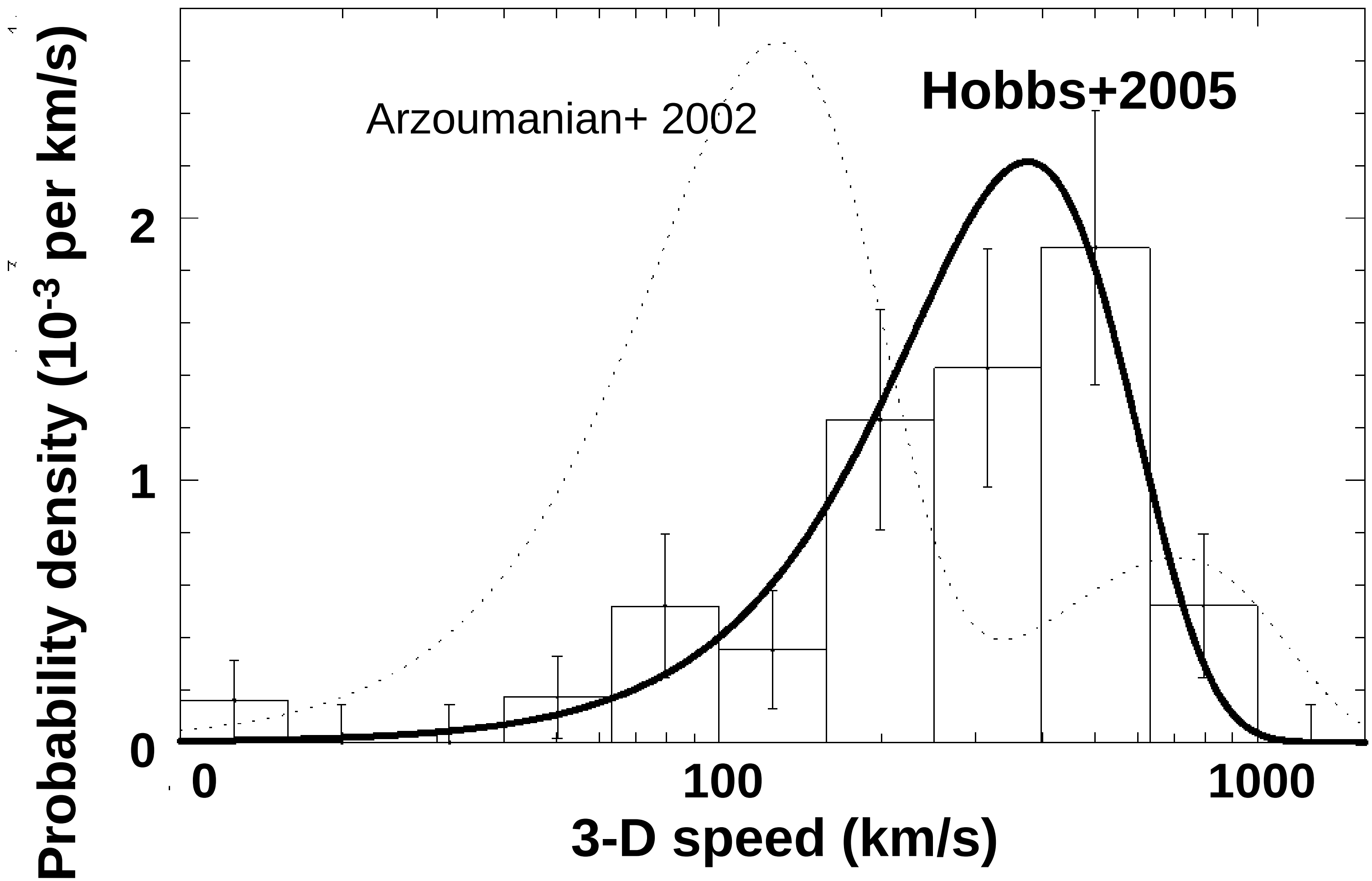
A pulsar is currently at the position indicated by a circle

The track is its motion for the last 1 Myr assuming no radial velocity.

Supernova kicks and compact-object binaries:

Hobbs+ (2005): **3-D velocity distribution of pulsars obtained from the observed 2-D distributions of pulsars**

→ Maxwellian distribution with sigma ~ 265 km/s

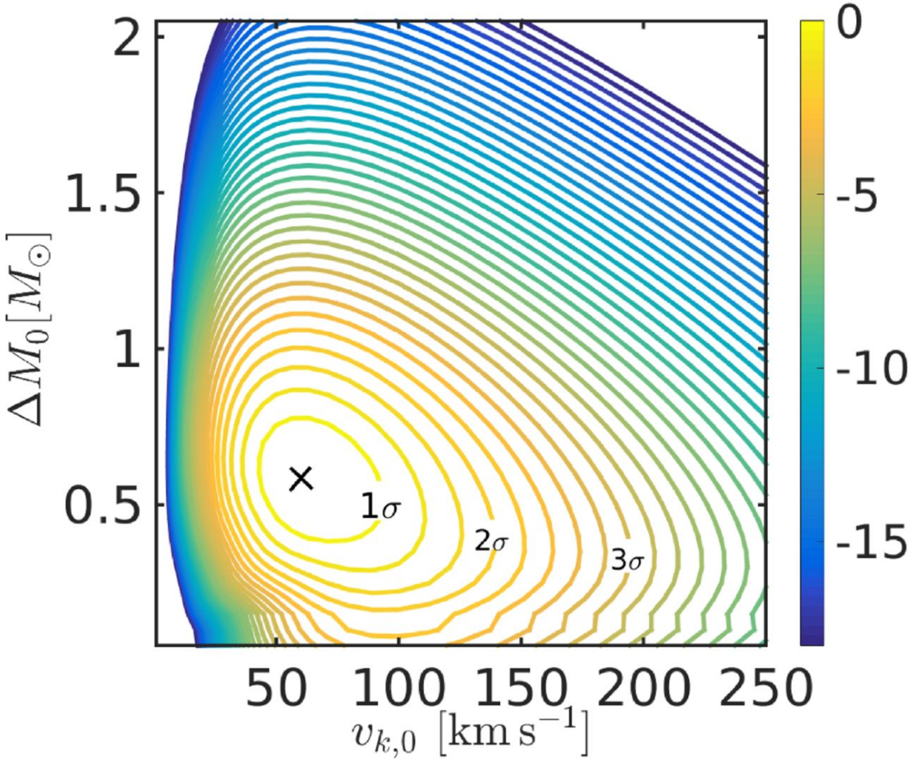


Supernova kicks and compact-object binaries:

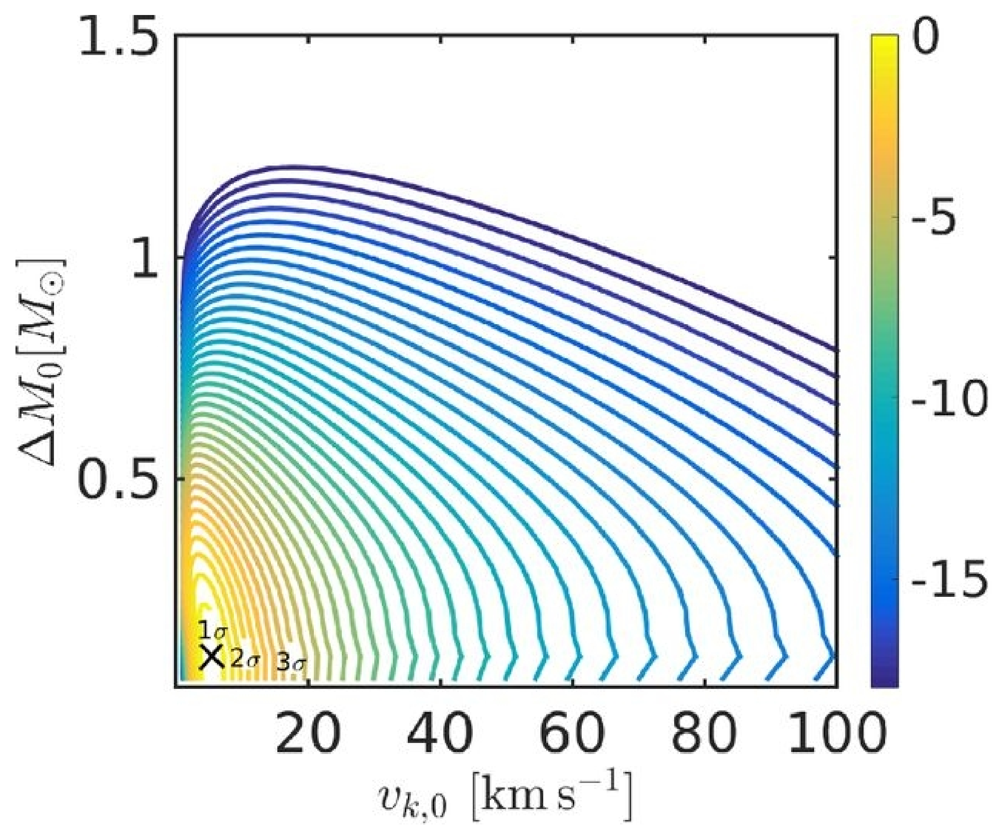
Beniamini & Piran 2016:
Estimate kick of double neutron stars only

Maximum likely-hood of ejected mass and kick from conservation of energy and angular momentum

10 NS binaries



6 NS binaries with small eccentricity



Supernova kicks and black hole binaries:

WHAT ABOUT black holes?

No reliable methods to measure. Then people assume

1. conservation of linear momentum

$$v_{\rm kick,\,BH} = \frac{m_{\rm NS}}{m_{\rm BH}}\,v_{\rm kick,\,NS}$$

2. BHs formed without SN (failed or direct collapse) get NO KICK + kick modulated by FALLBACK

$$v_{\rm kick,\,BH} = (1 - f_{\rm fb})\,v_{\rm kick,\,NS}$$

THANK YOU