Quark deconfinement in supernova explosions: How to probe it ?

ESO - https://www.eso.org/public/images/eso0708a/

Max-Planck-Institut für Gravitationsphysik
ALBERT-EINSTEIN-INSTITUT

• Takami Kuroda (MPI Potsdam)
Karpacz Winter School, 23.5.2024

Outline (Day 2)

(1: Recap of Day 1)

2: Hadron-quark phase transition in supernova

3: How to probe it?

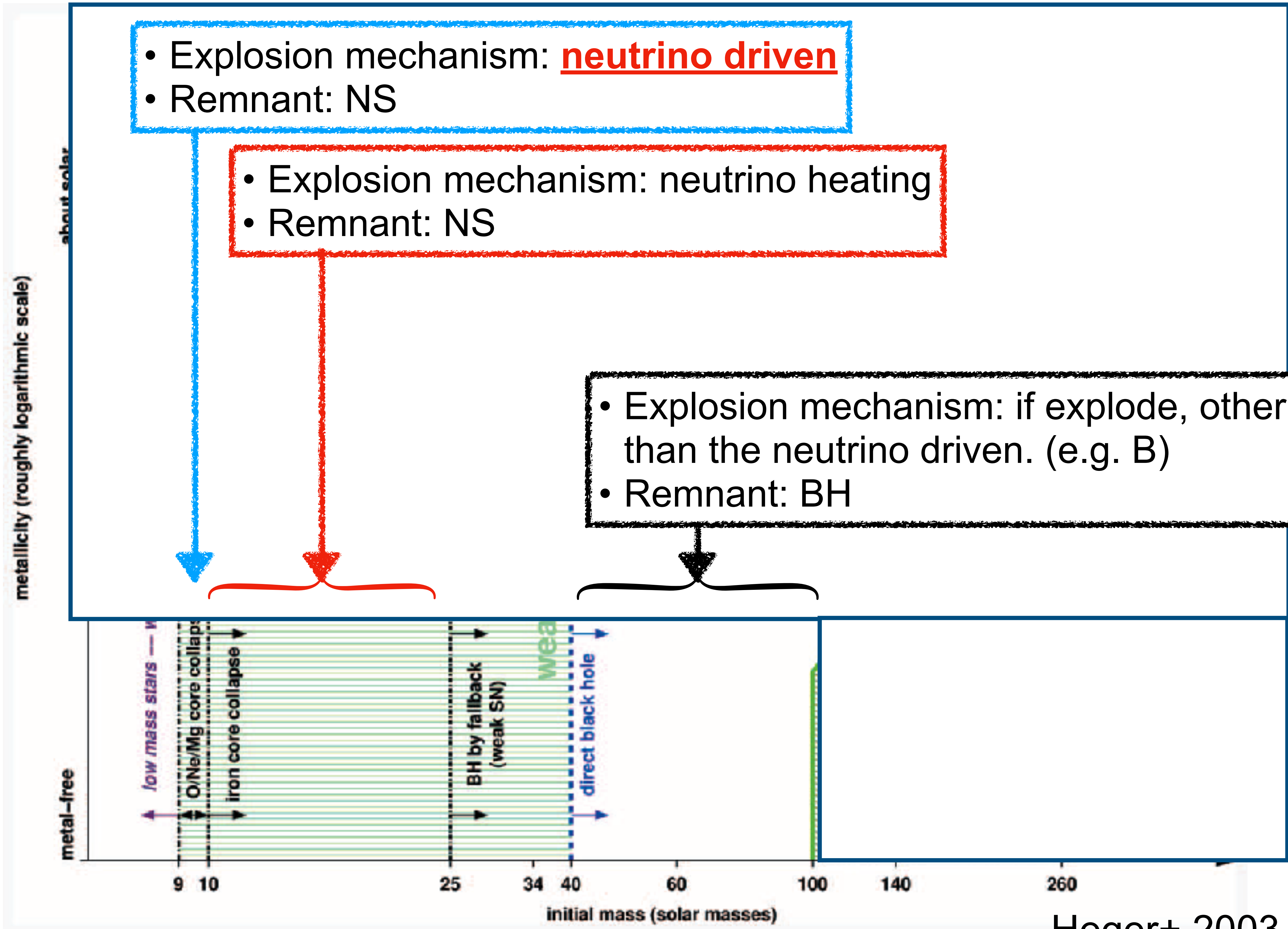
4: Summary

The NS/BH formation branch and its progenitor mass dependence

- Explosion mechanism: **neutrino driven**
- Remnant: NS

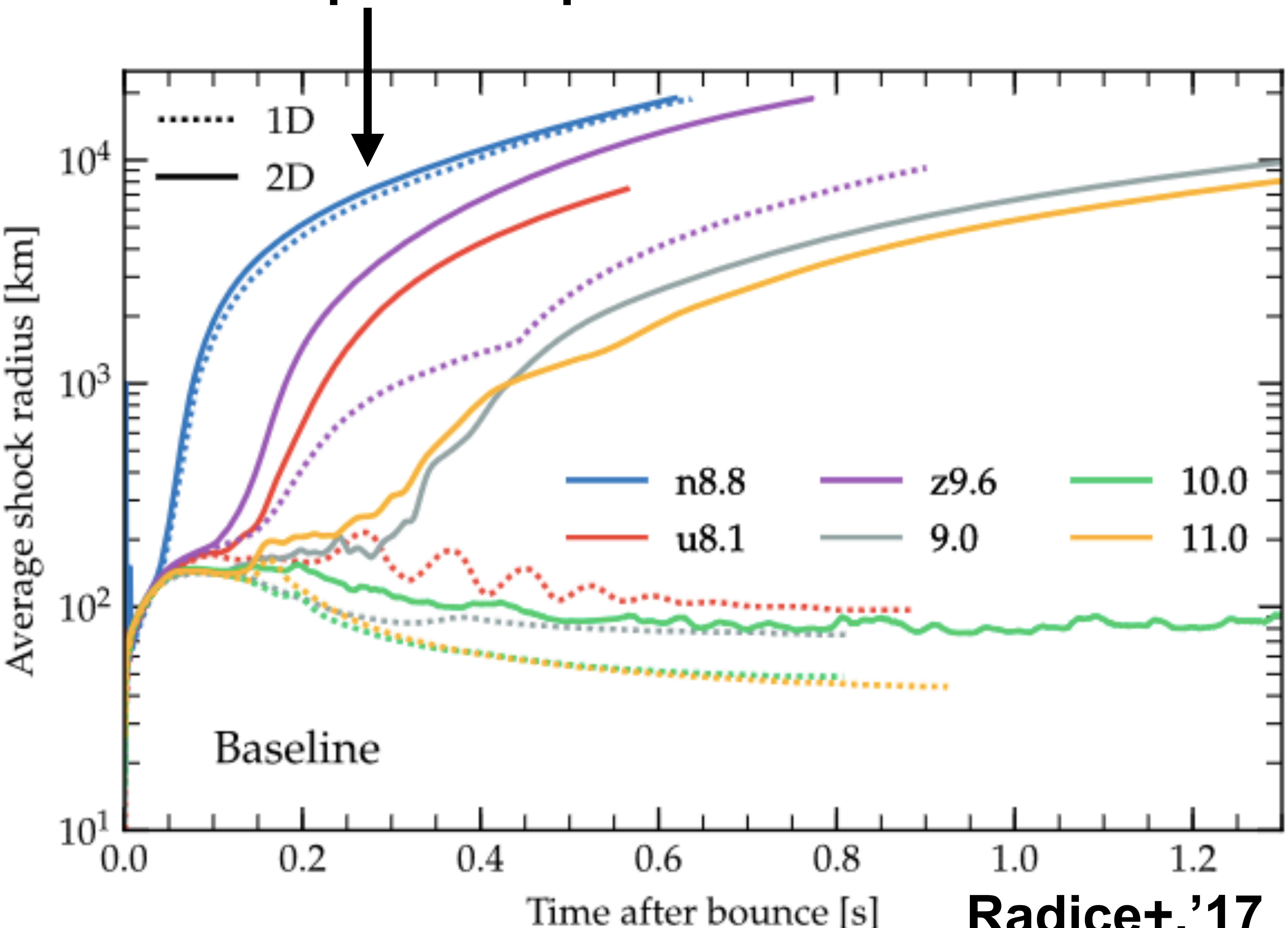
- Explosion mechanism: neutrino heating
- Remnant: NS

- Explosion mechanism: if explode, other than the neutrino driven. (e.g. B)
- Remnant: BH



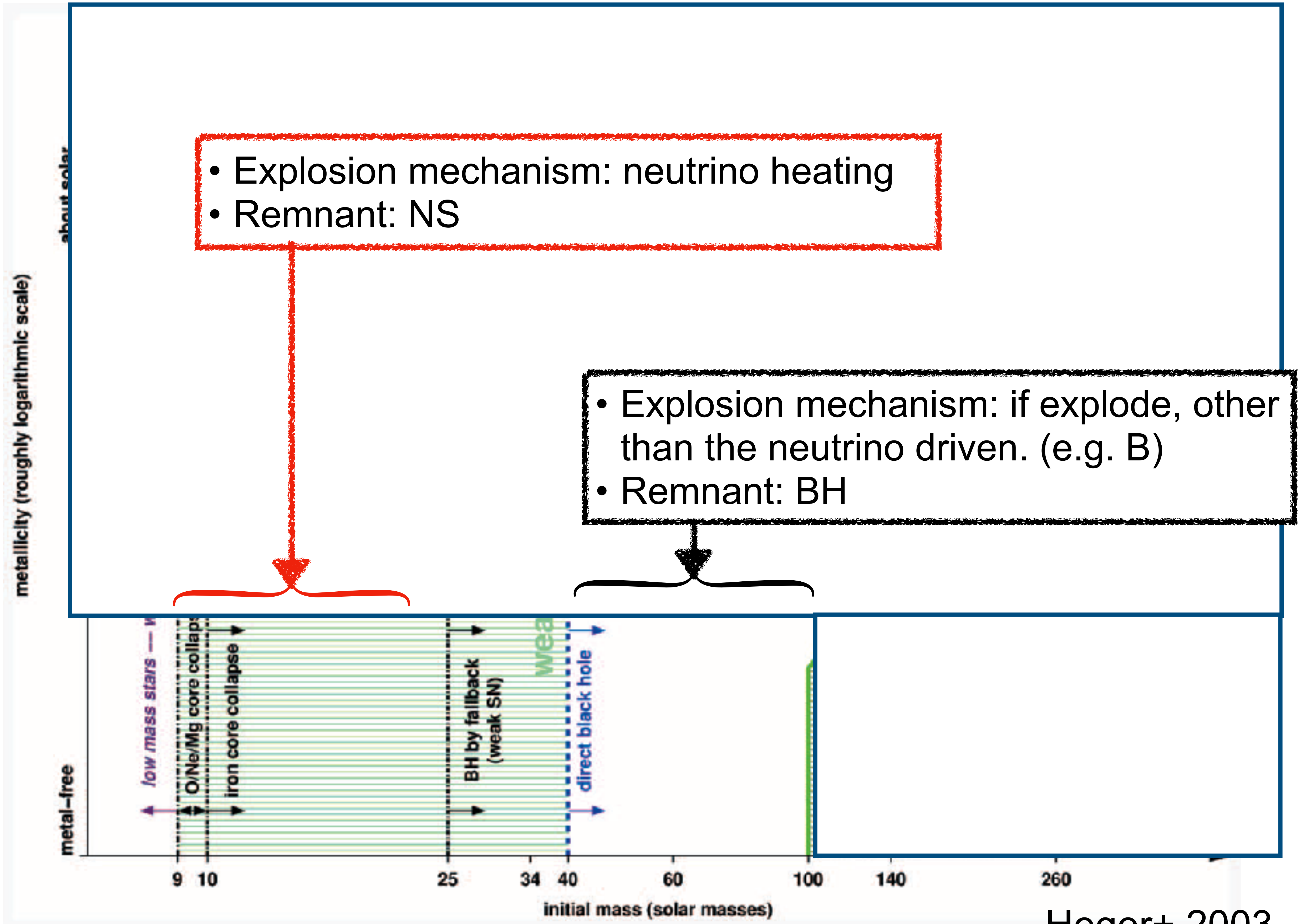
Heger+,2003

Prompt-*like* explosion



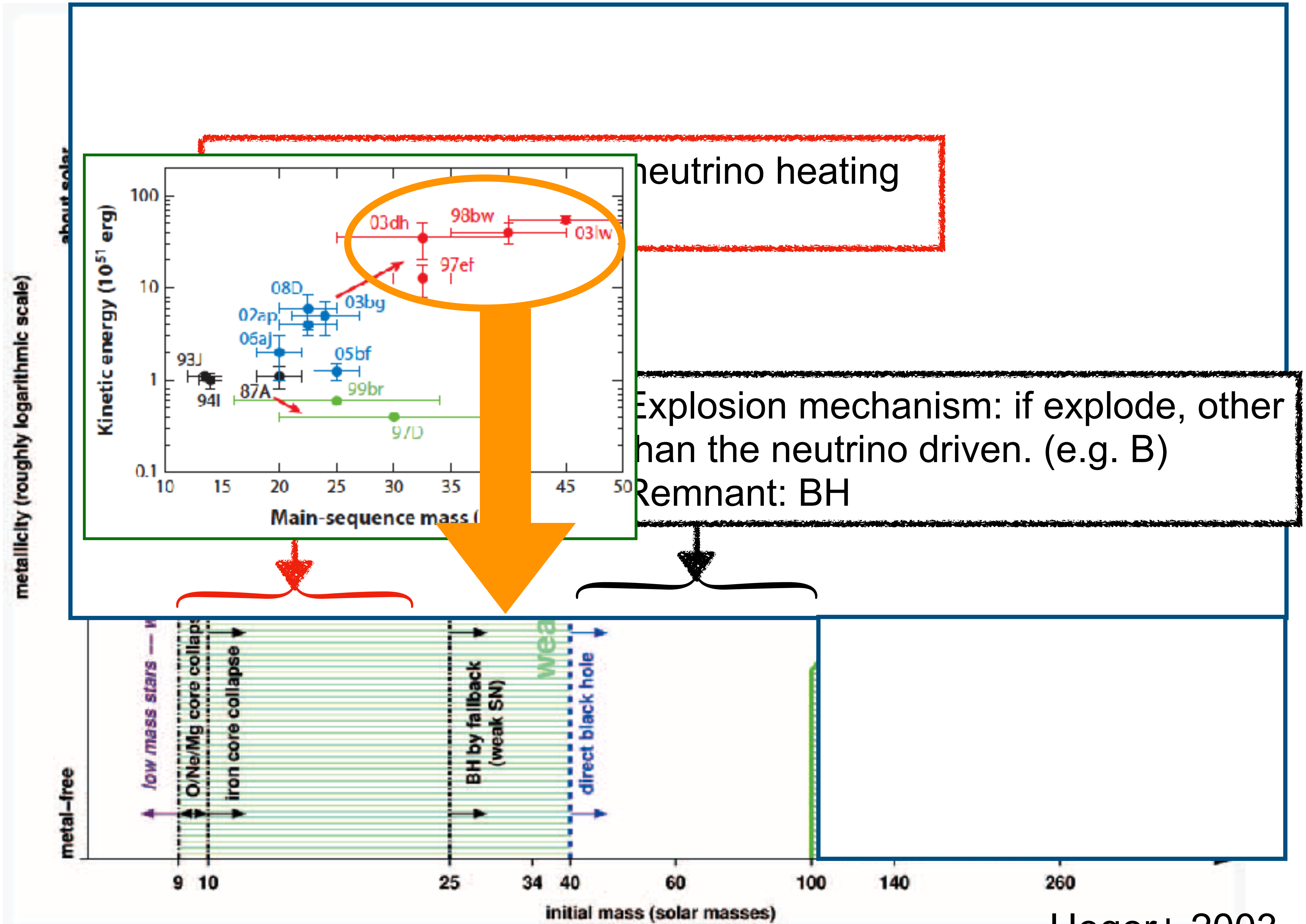
Radice+,'17

The NS/BH formation branch and its progenitor mass dependence



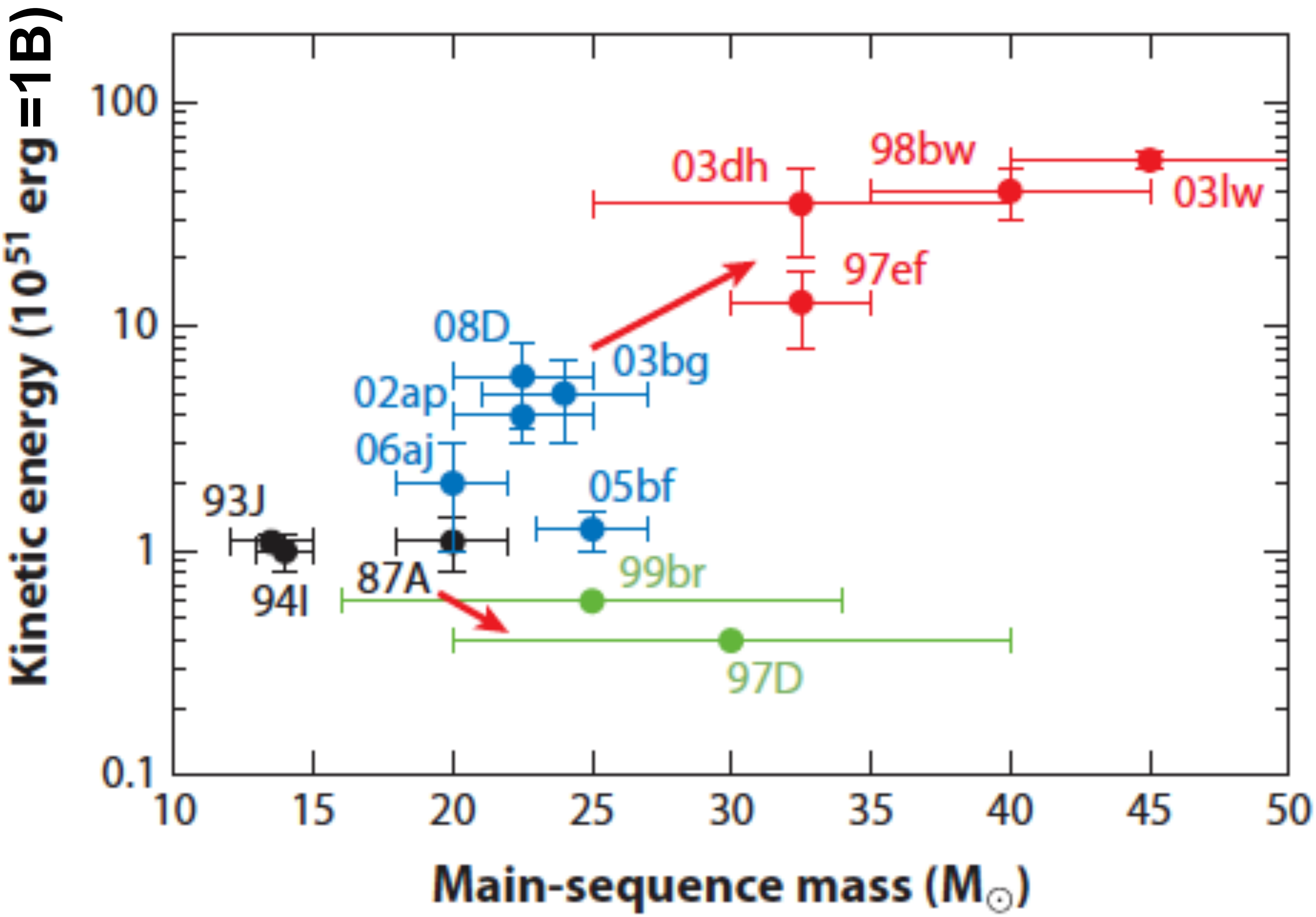
Heger+,2003

The NS/BH formation branch and its progenitor mass dependence



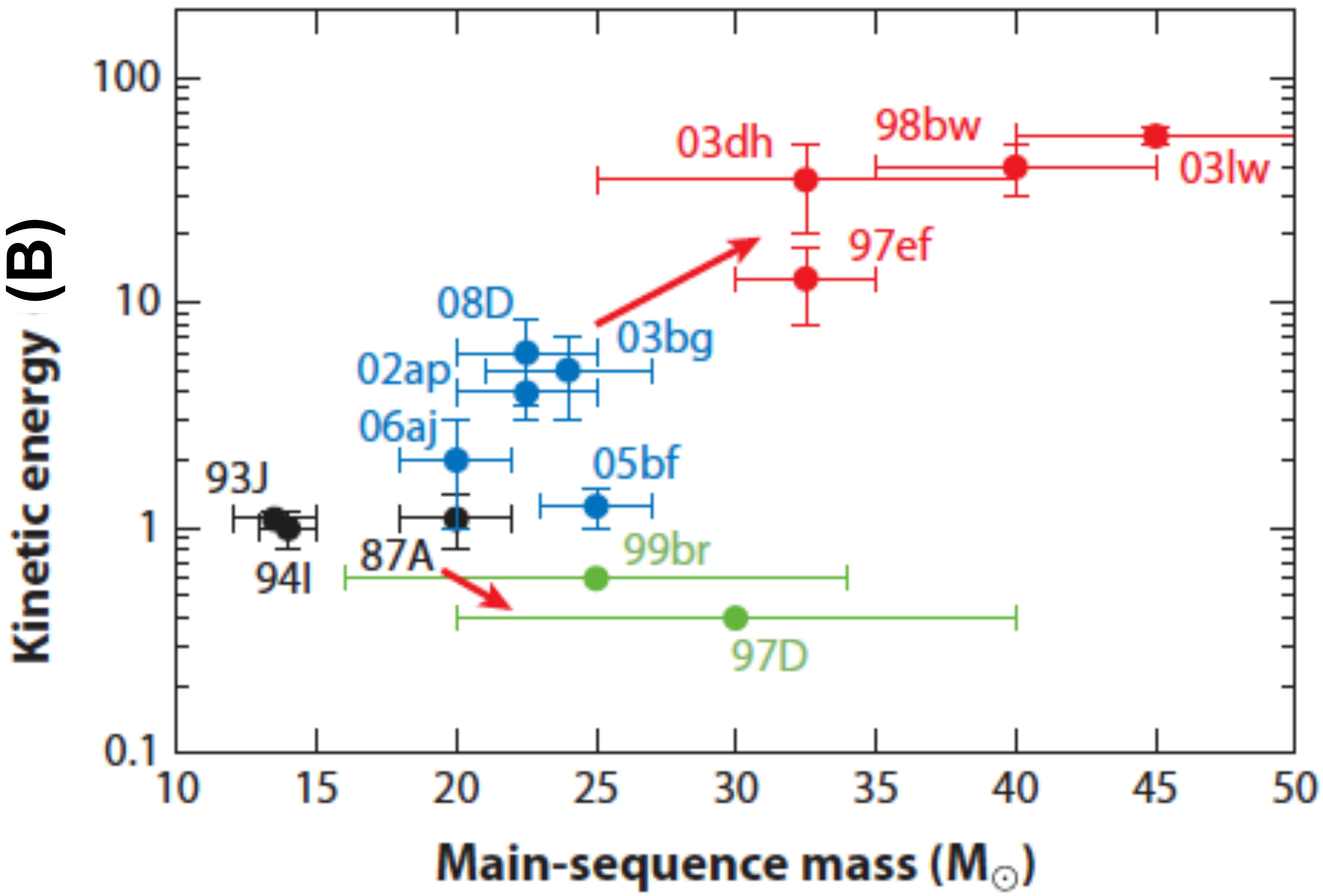
Heger+,2003

Note



In this lecture I simply focus on whether such intermediate mass progenitor stars can explode or not. I omit detailed discussion about its explosion energy.

Note

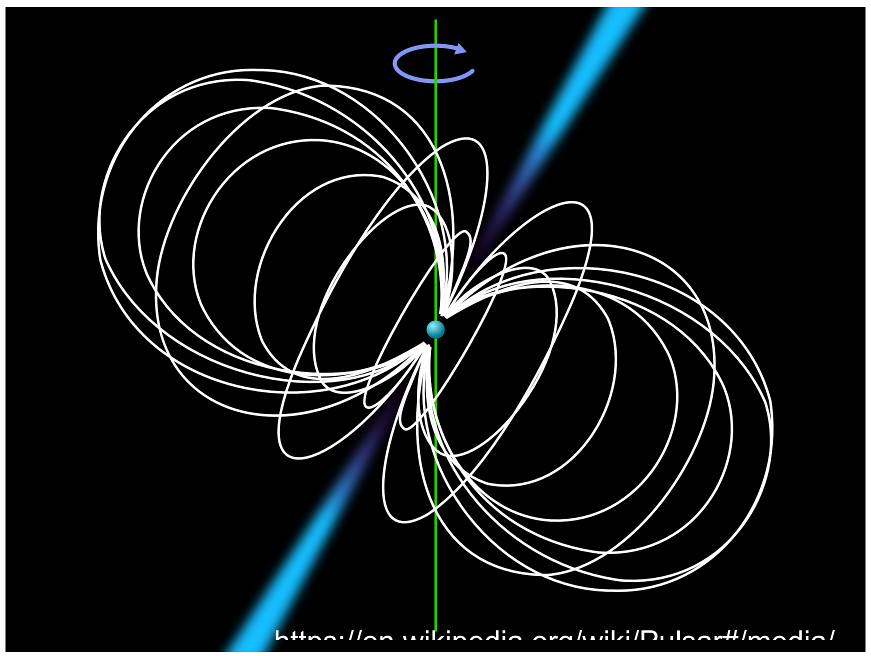


Possible mechanisms of, e.g. super luminous SN2006gy, according to:

- **Type II SN with a few times 10^{51}erg (Moriya+'13, and can be models by $50M_{sun}$ star w./ QCD transition Fischer+,'17)**
- **Pulsational Pair instability SN (Wooslwy+,'07)**
- **Type Ia SN (Jerkstand+,'20)**

There could be possible explosion scenarios for intermediate mass progenitors ($\sim 30M_{sun} < M < \sim 50M_{sun}$?)

The standard neutrino heating mechanism utilizes the internal energy.

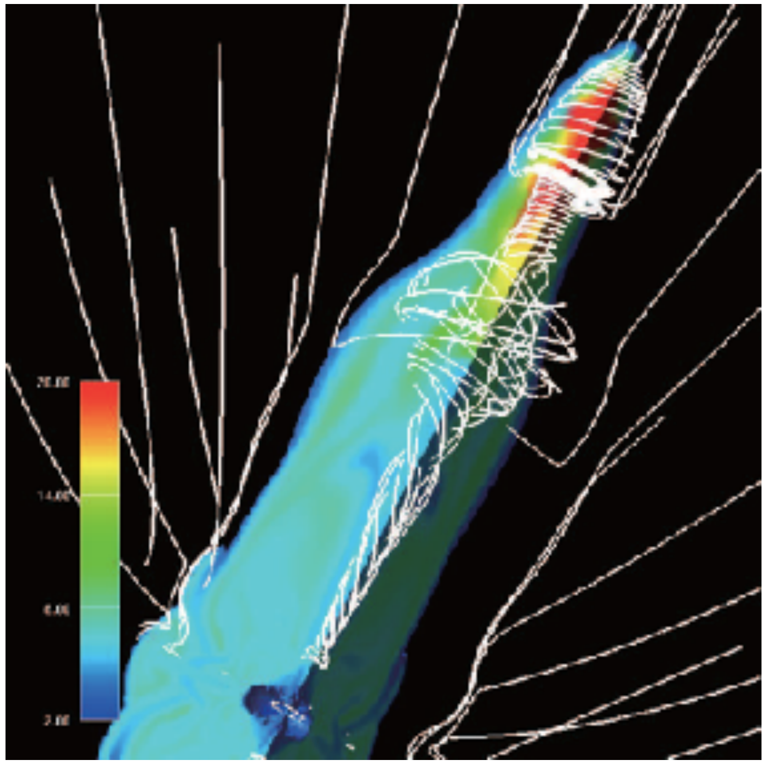


- $E_{int} \sim 10^{53}$ergs
- $E_{rot} < 10^{52}$ergs
- $E_{mag} < 10^{51}$ergs

If the PNS is strongly magnetized (i.e. magnetar) and rapidly rotates….

(1)The standard explosion mechanism
Neutrino driven explosion,

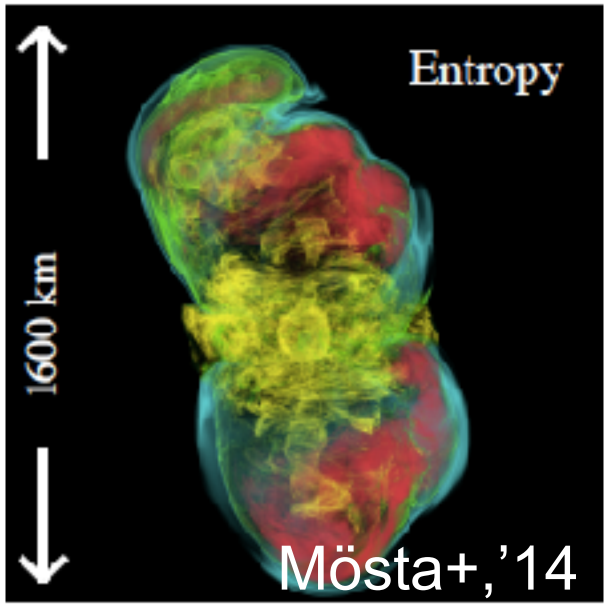
Colgate&White'66, Bethe&Wilson'85
For reviews, Janka'12, Kotake+,'12, Burrows+,'13

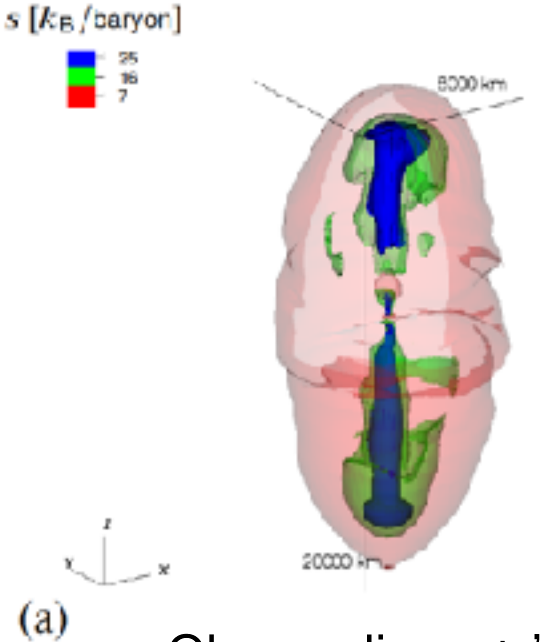


(2)If the magnetic field is strong enough
Magneto-rotational explosion (MRE) takes place,

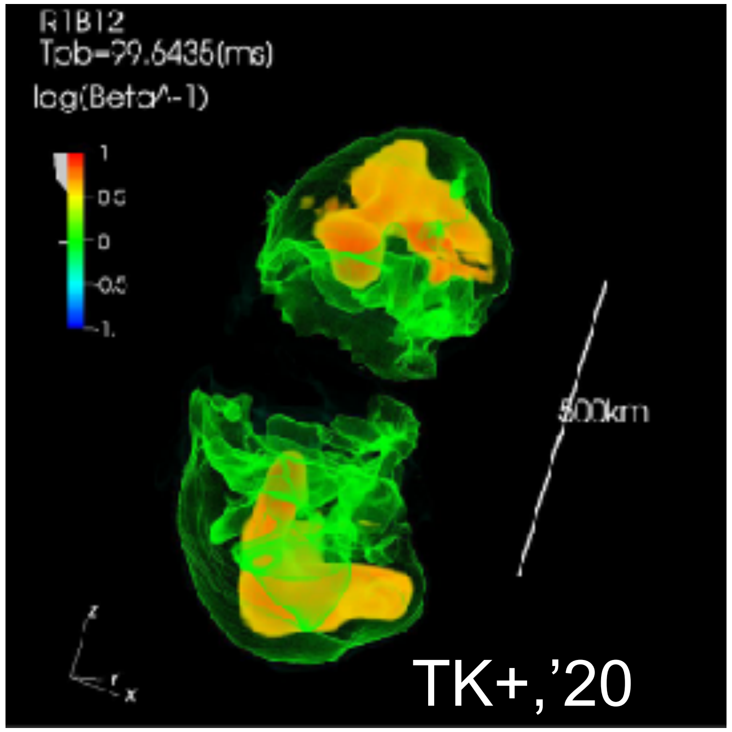
2D: Ardeljan+,'00, Kotake+,'04, Obergaulinger+,'06,'17, Burrows+,'07, Takiwaki+,'09,

3D: Mikami+, '08; Newtonian, no neutrino, Polytropic EOS
Mösta+,'14; full GR but very simplified neutrino transport
Obergaulinger+,'19,'20; SR with M1 neutrino transport
Kuroda+,'20a(b); full GR with M1 neutrino transport





Obergaulinger+,'20



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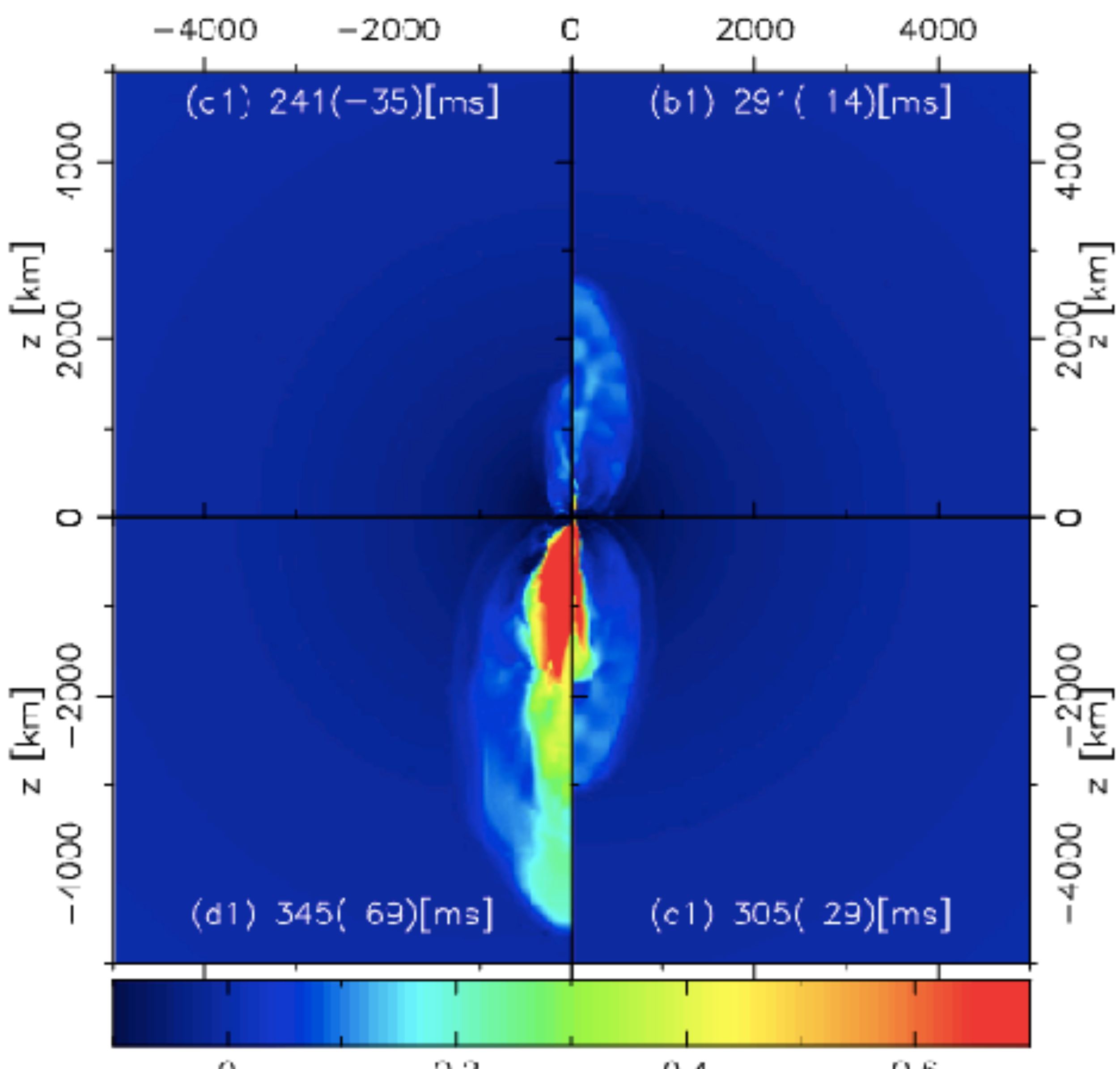


TK&Shibata, arXiv:2404.02792

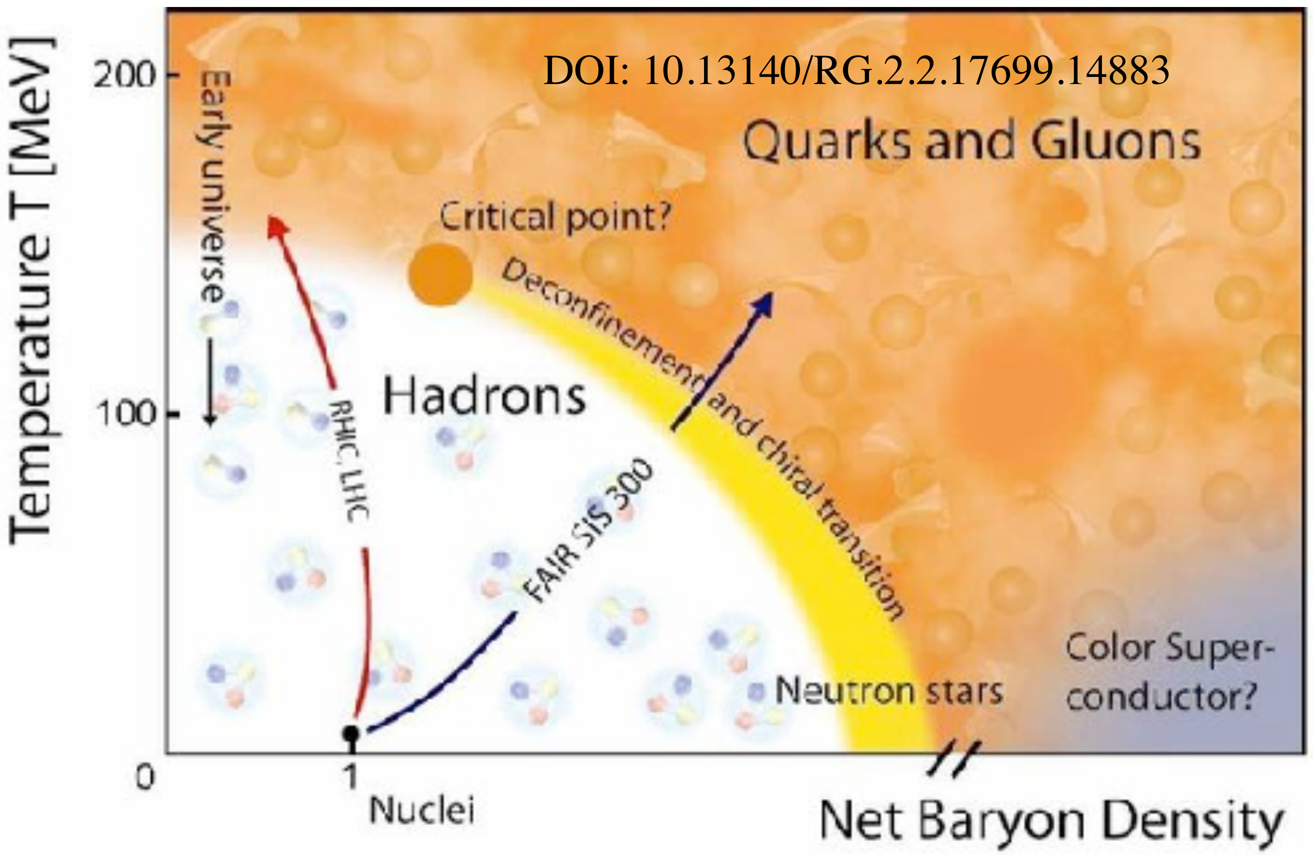
The first self-consistent SN model exploded by the Blandford-Znajek mechanism

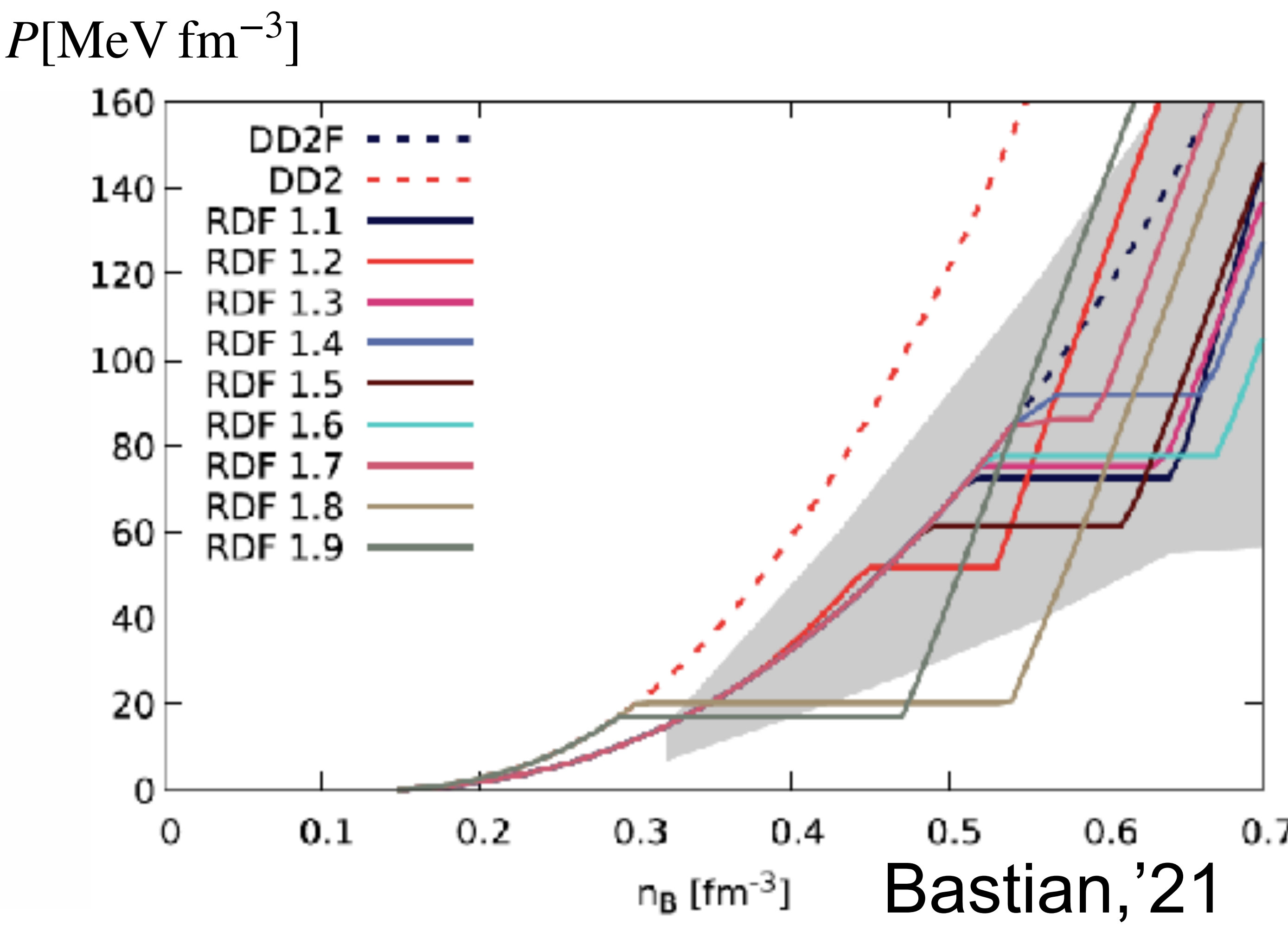
In MRE(or BZ) model, extraction of total rotational energy ($\sim 10^{52\text{-}53}$erg) is ***unavoidable!***

Too high explosion energy(?)

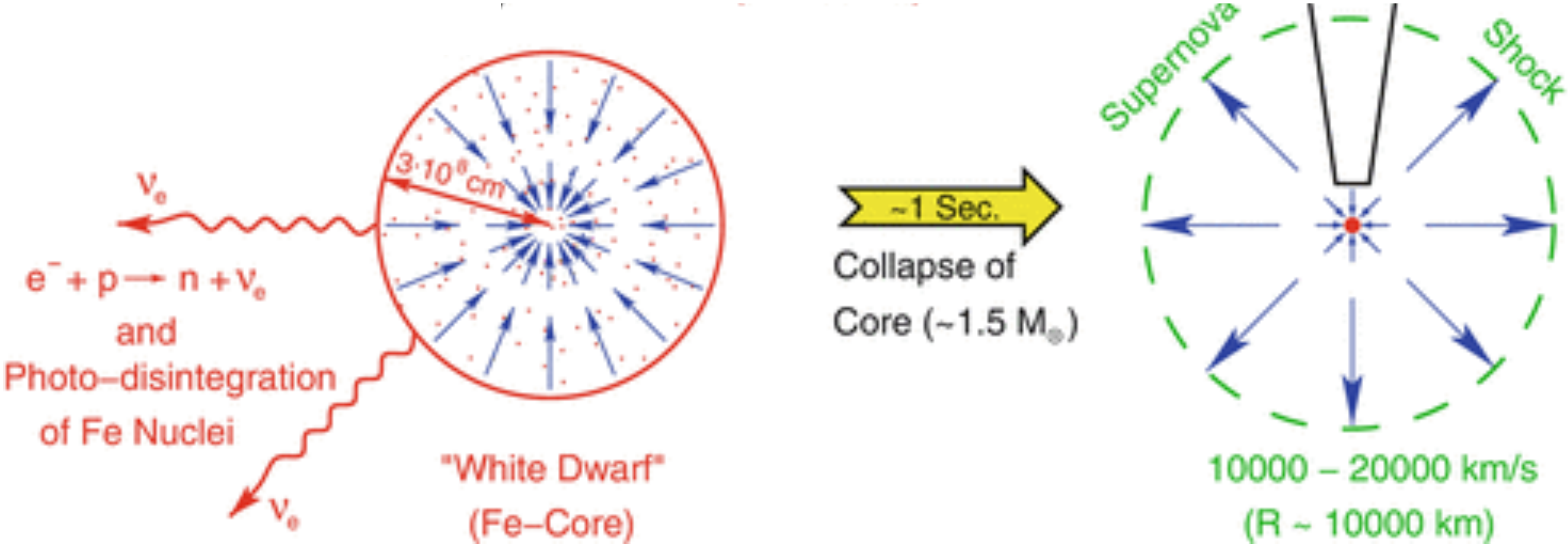
Possible SN explosion mechanisms

1. Neutrino driven explosion (ν-driven) (10-20M_{sun})
2. Magneto rotational explosion (MRE) (30~100(?)M_{sun})
3. Other mechanisms (30-50(?)M_{sun})
   (e.g. phase transition (PT) from hadronic to quark matters)

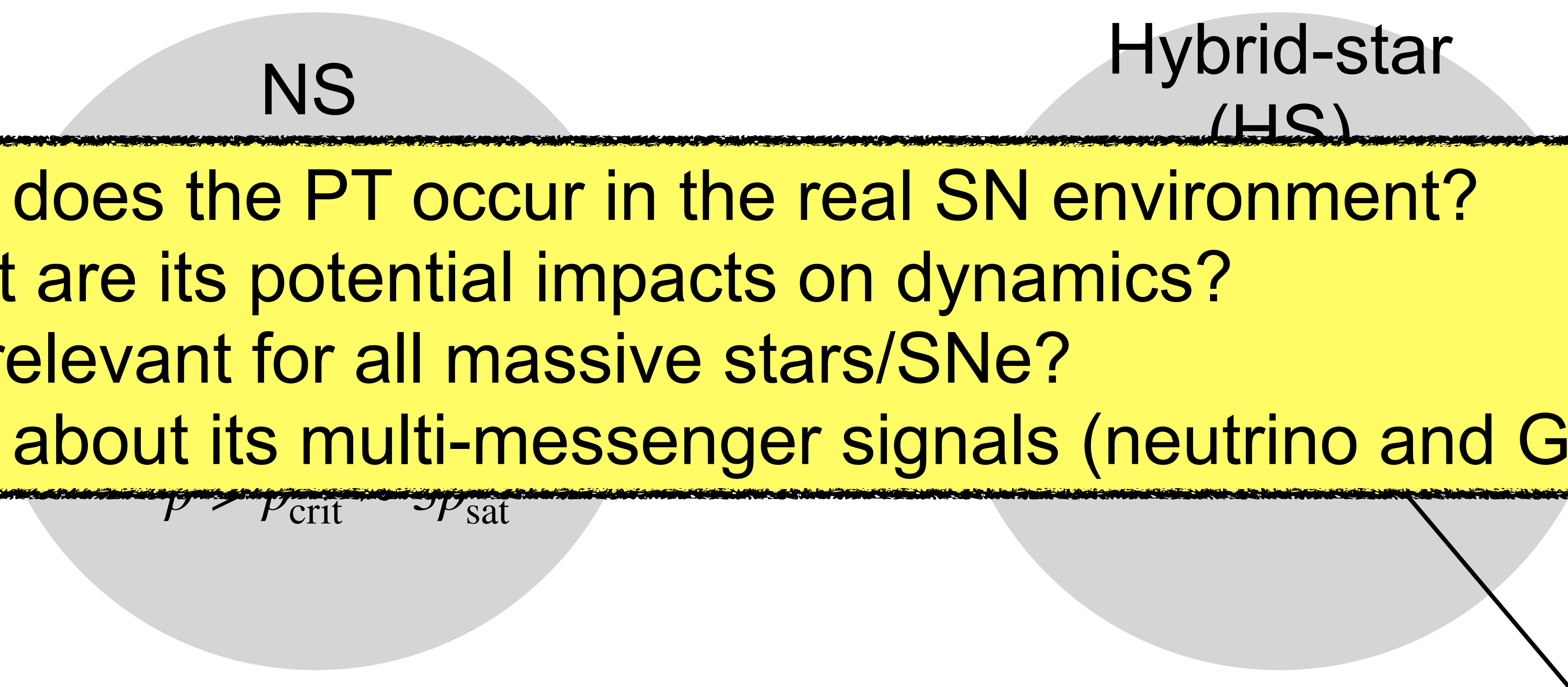




Bastian,'21



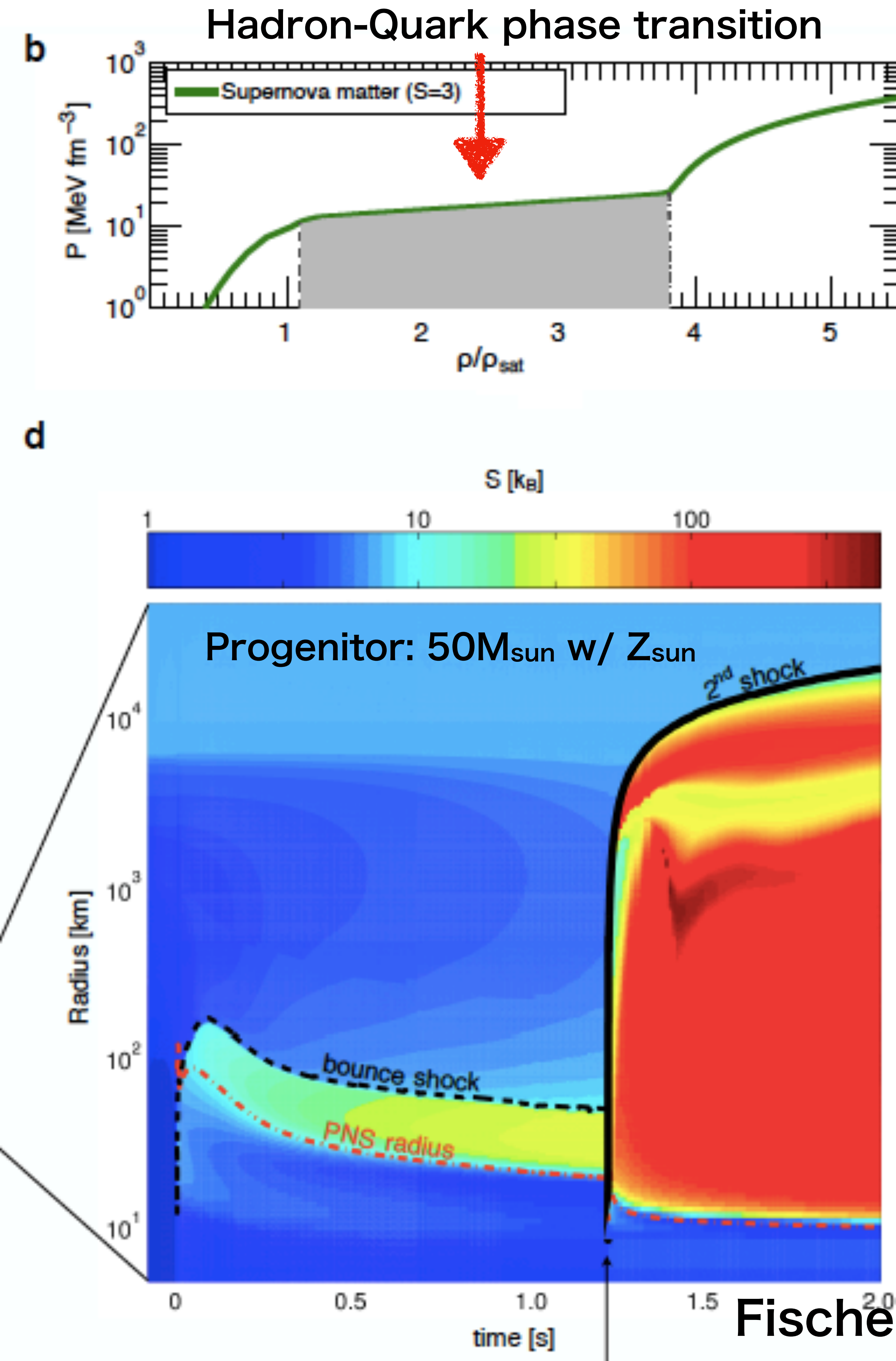
1st collapse: stellar (Fe) core transforms itself into NS

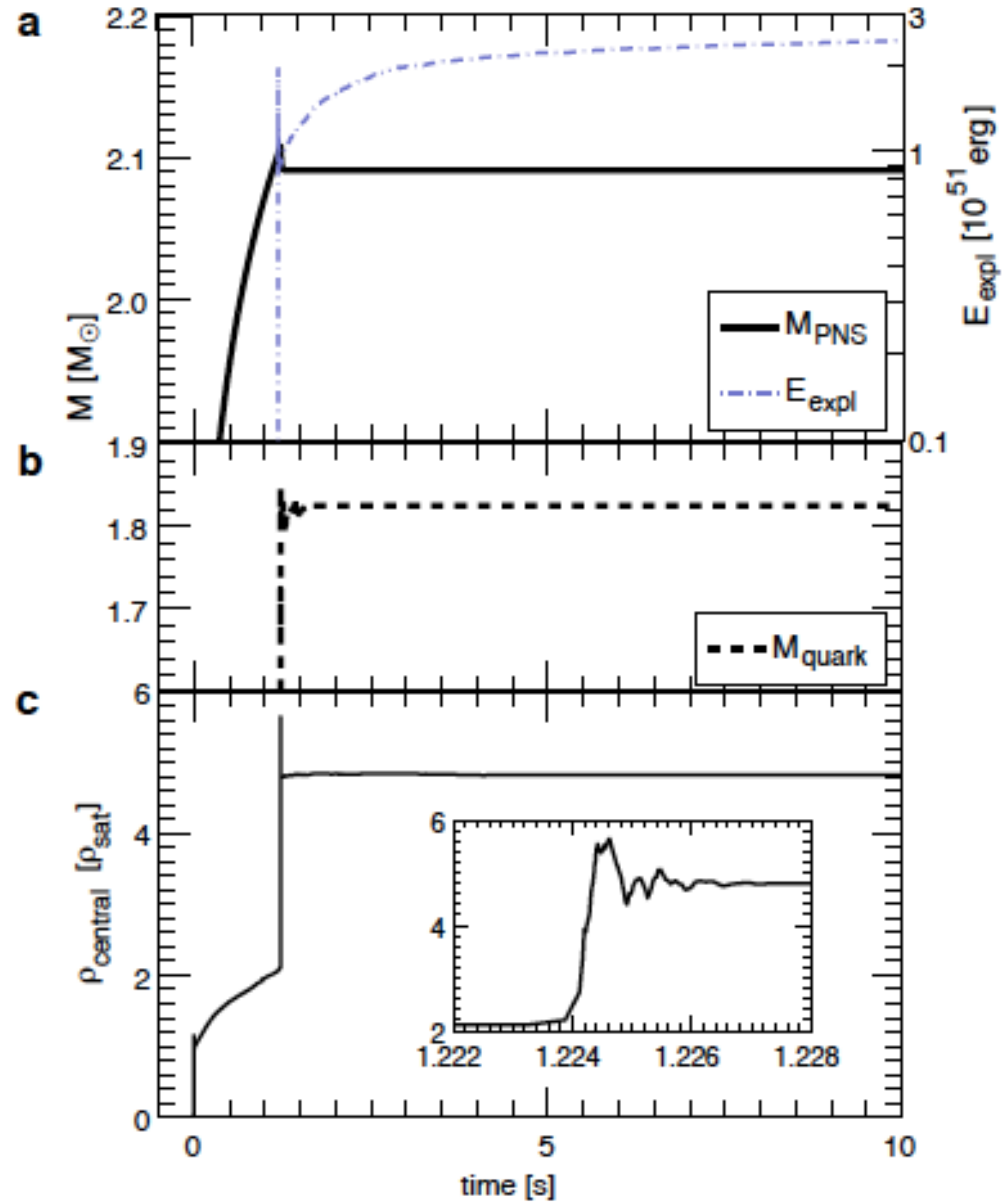


- How does the PT occur in the real SN environment?
- What are its potential impacts on dynamics?
- Is it relevant for all massive stars/SNe?
- How about its multi-messenger signals (neutrino and GW)?

2nd collapse: Neutron star core transforms itself into quark-core

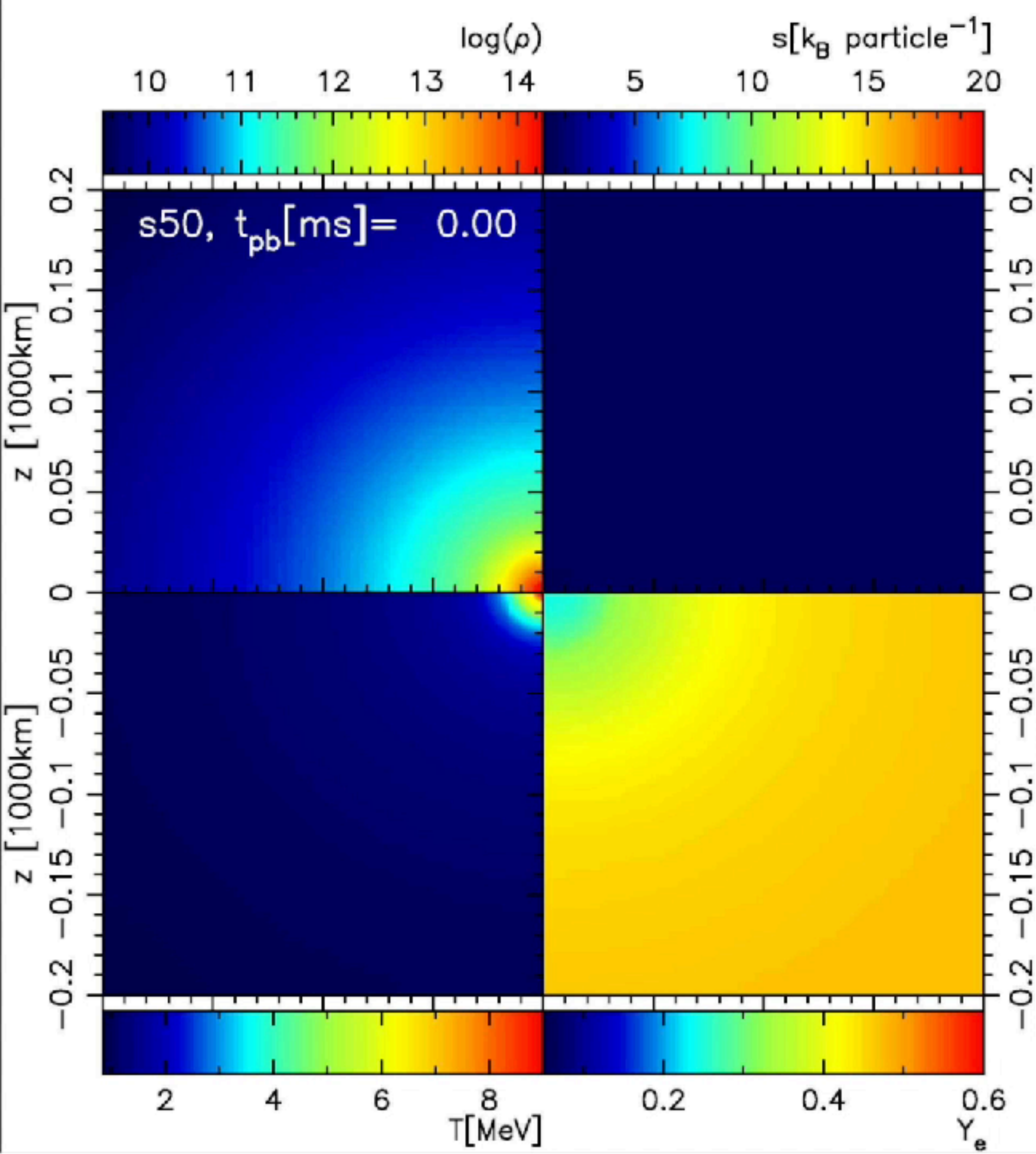
PNS contraction and formation of HS in 1D.

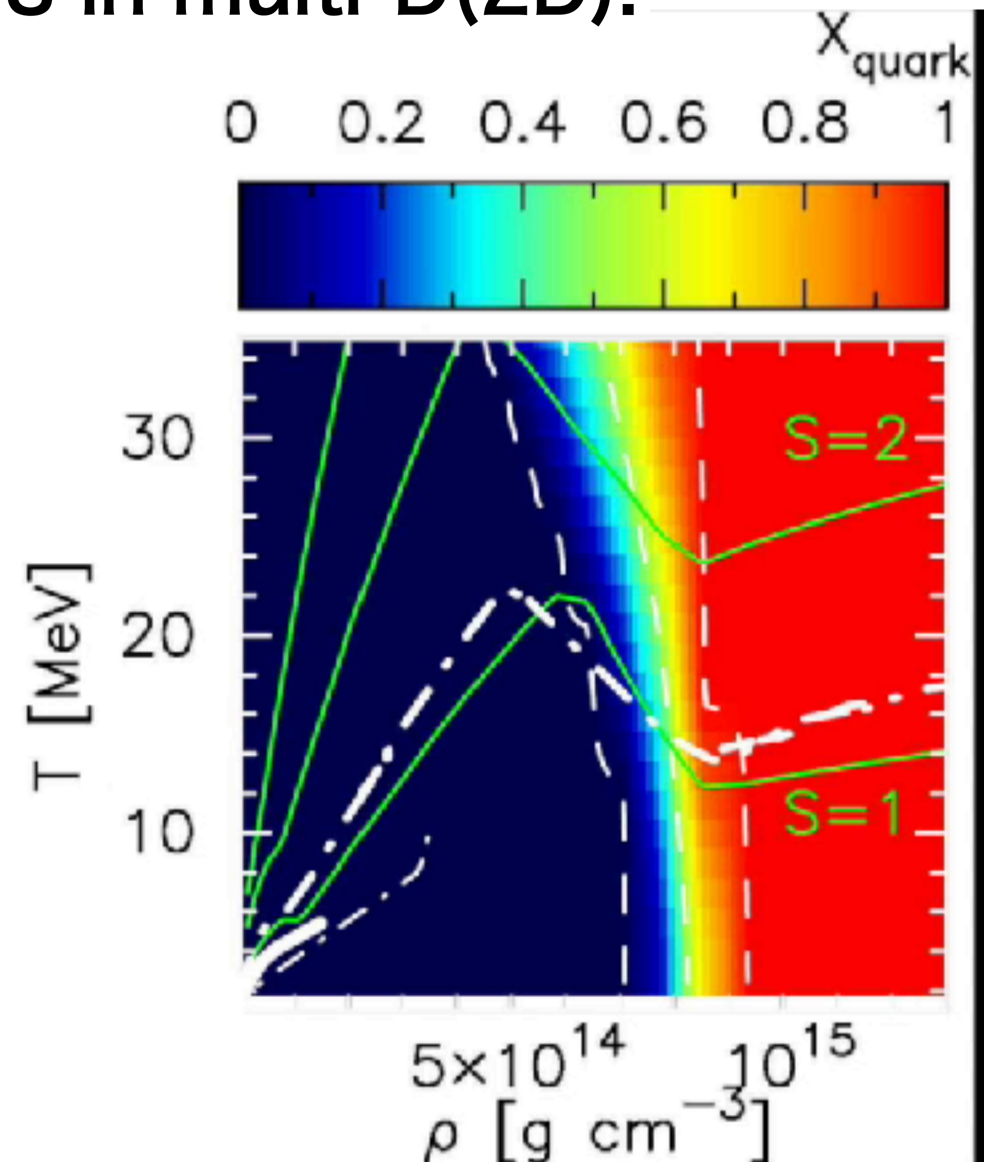




Fischer+,'17 (See also Sagert+,'09, Khosravi+,'24)

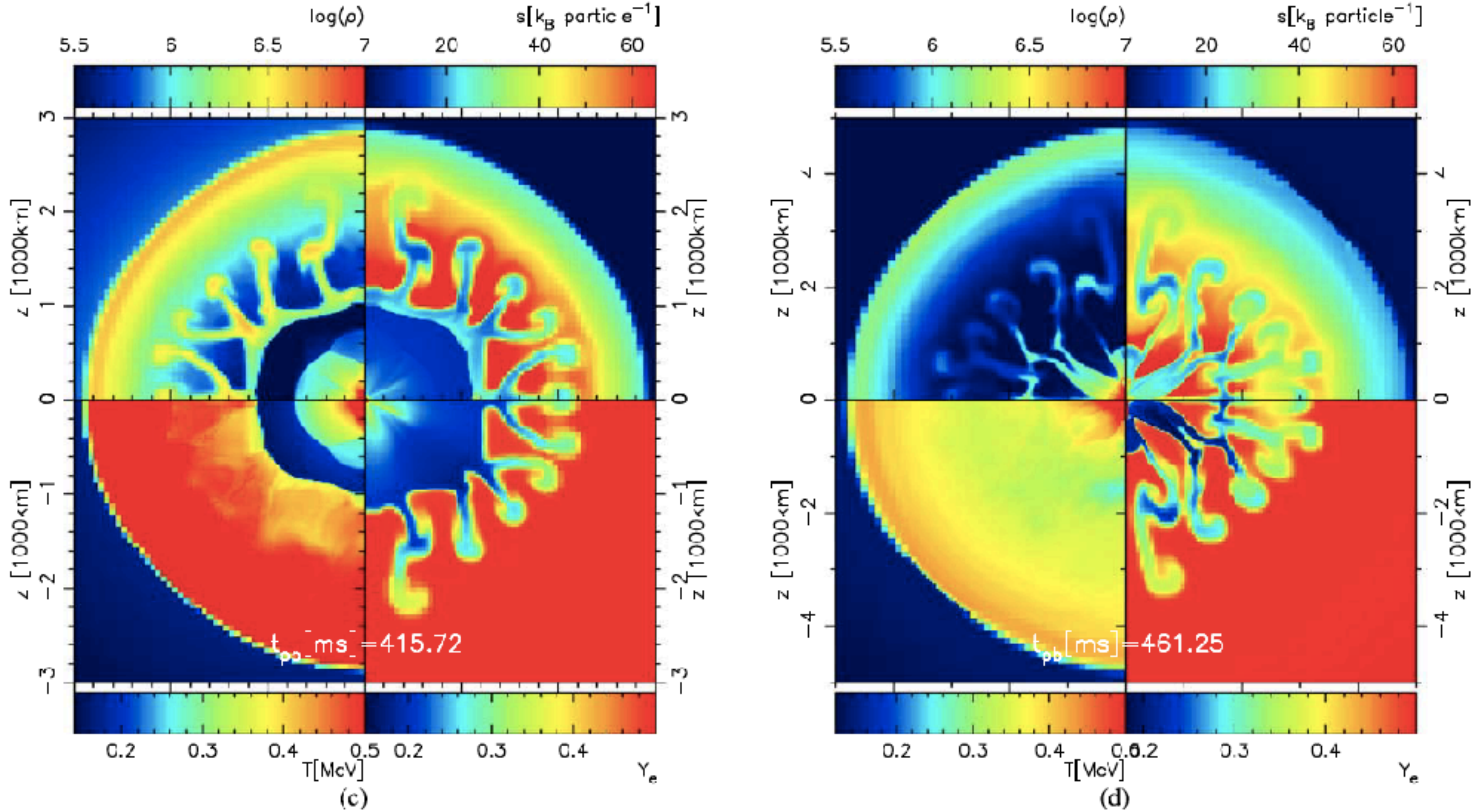
PNS contraction and formation of HS in multi-D(2D).





TK, Fischer+,’21

Strong aspherical explosion!



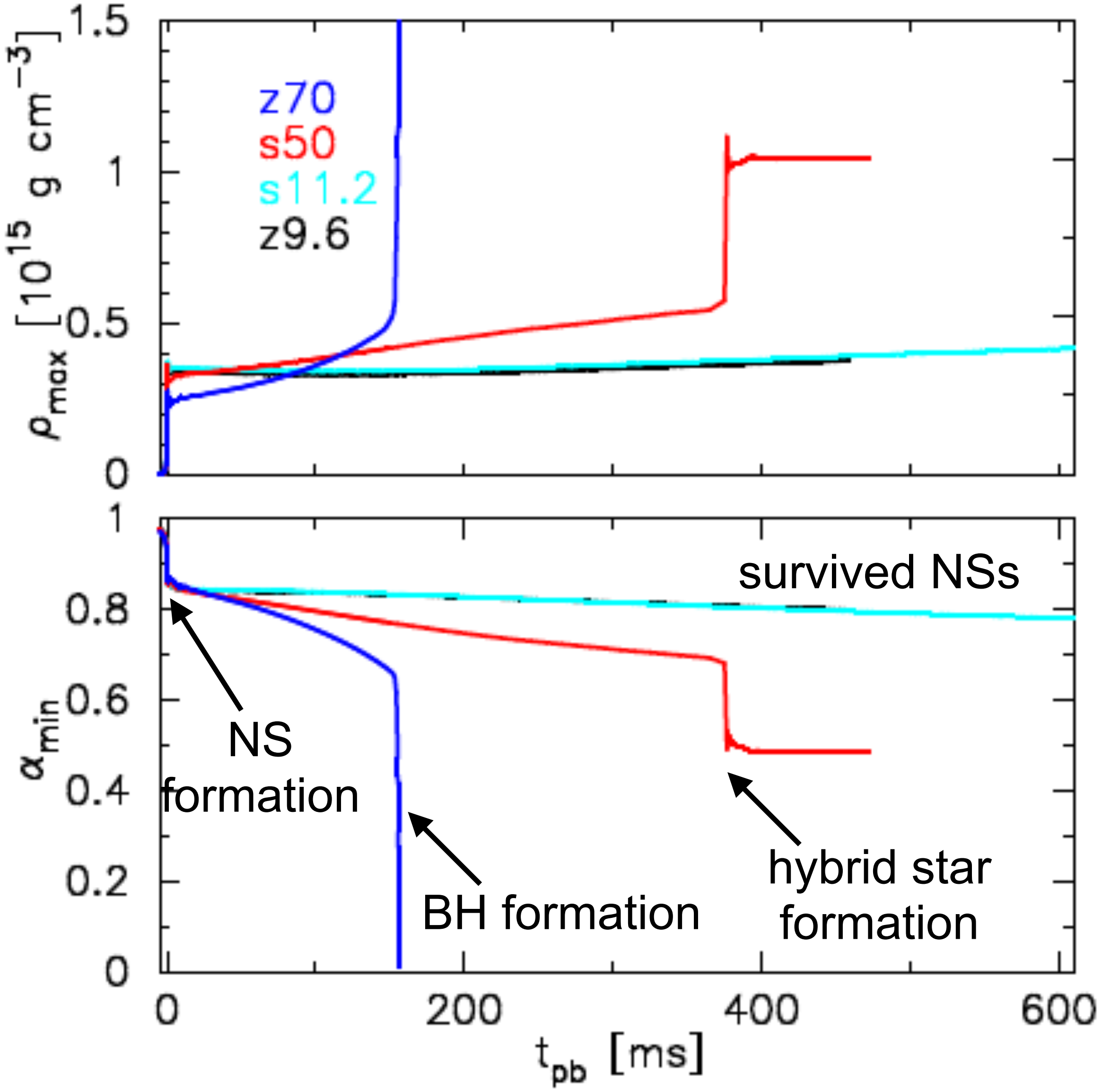
~30ms after PT

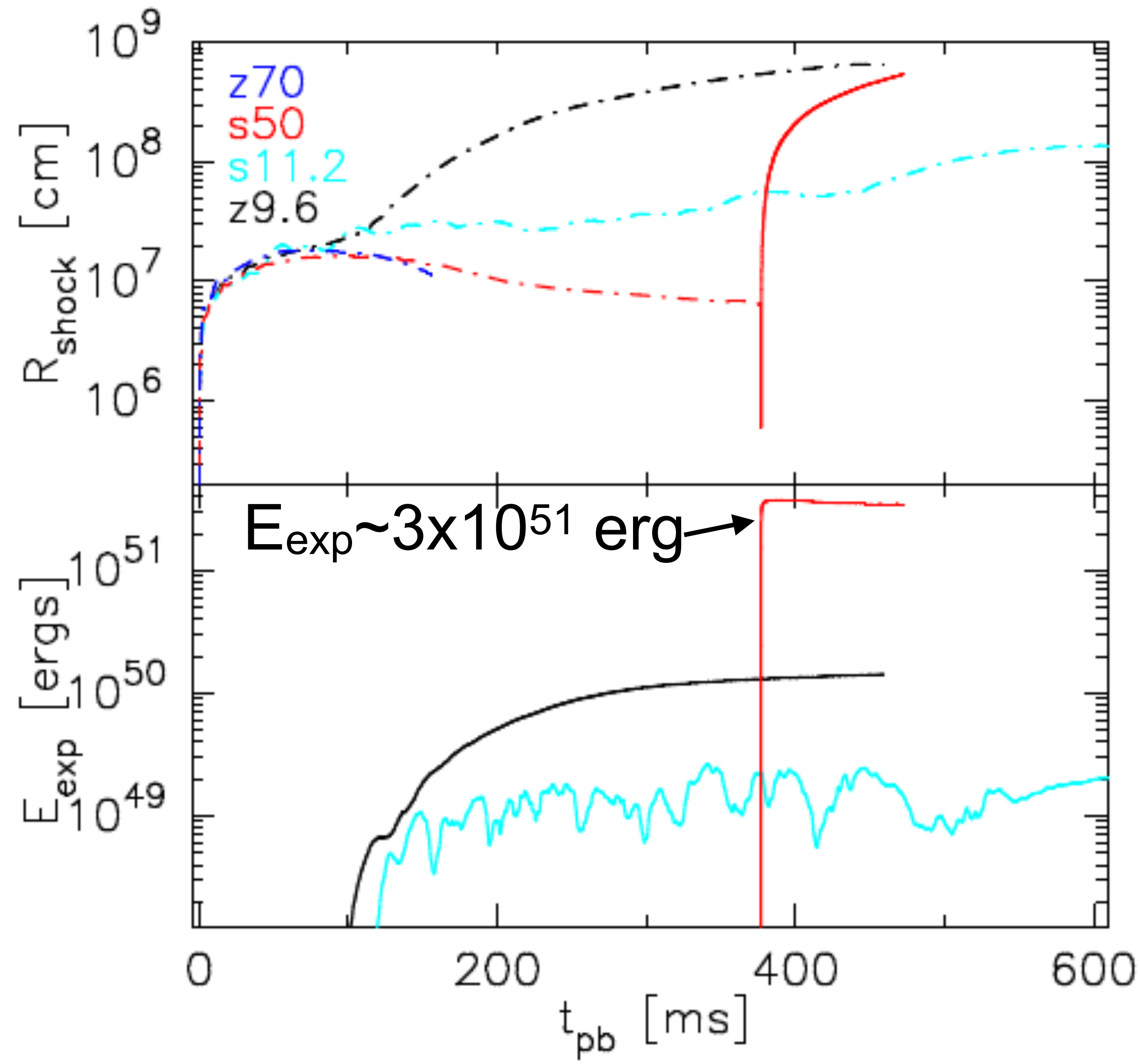
~80ms after PT

(Impact on the r-process, see Fischer+,'20)

• Is it relevant for all massive stars/SNe?

Various post (1st-)bounce evolutions





TK, Fischer+,'21

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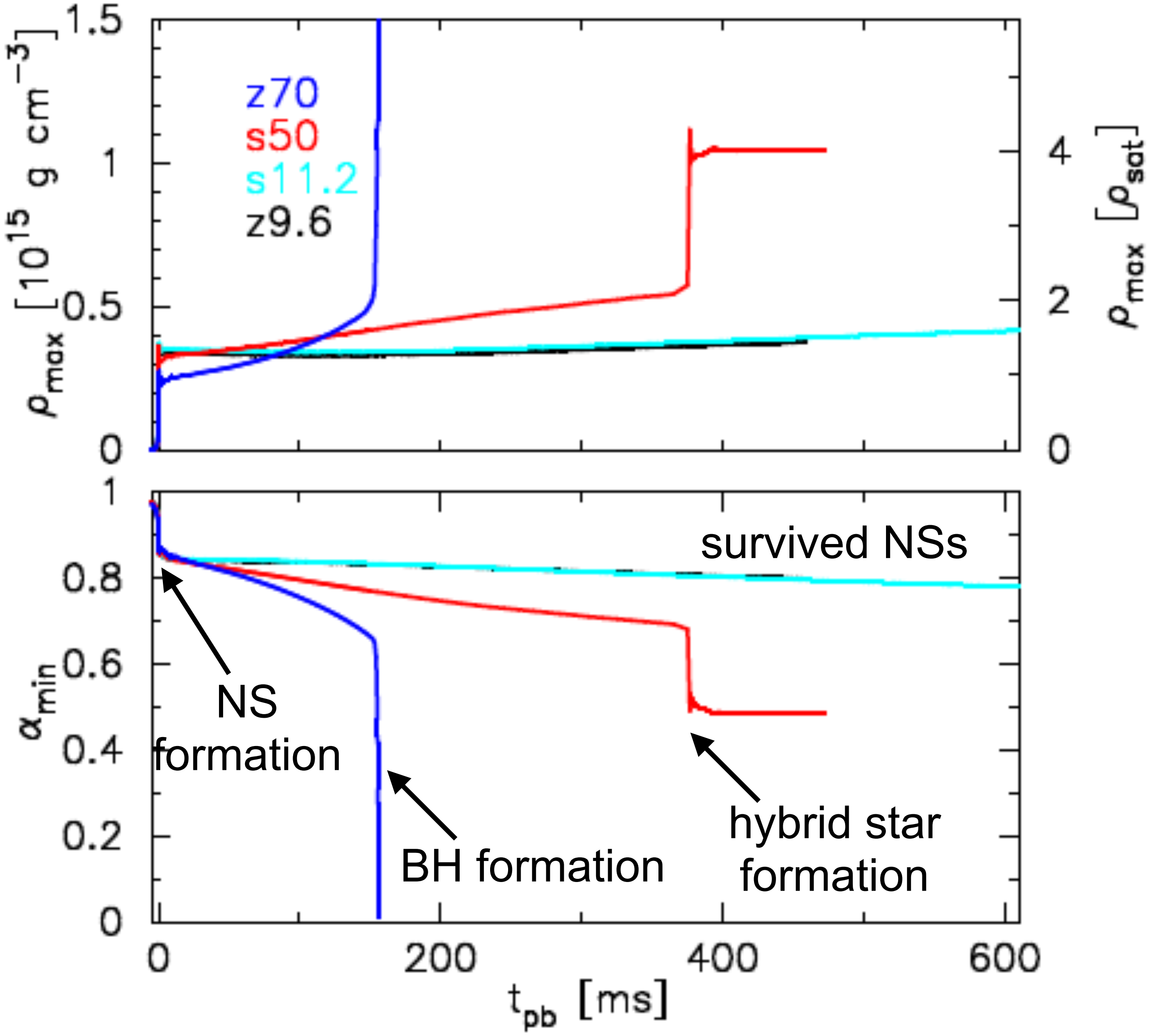
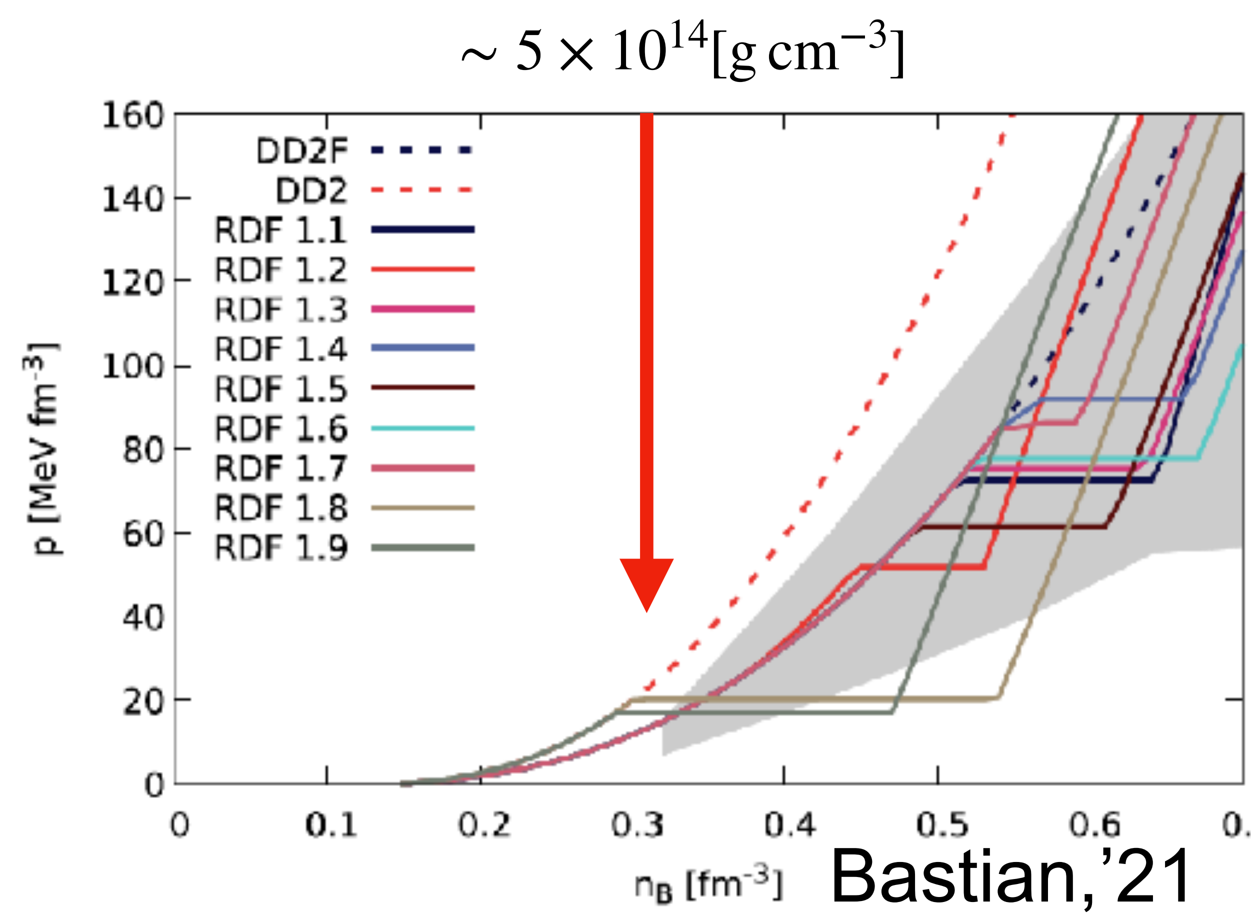


TK, Fischer+,'21



Bastian,'21

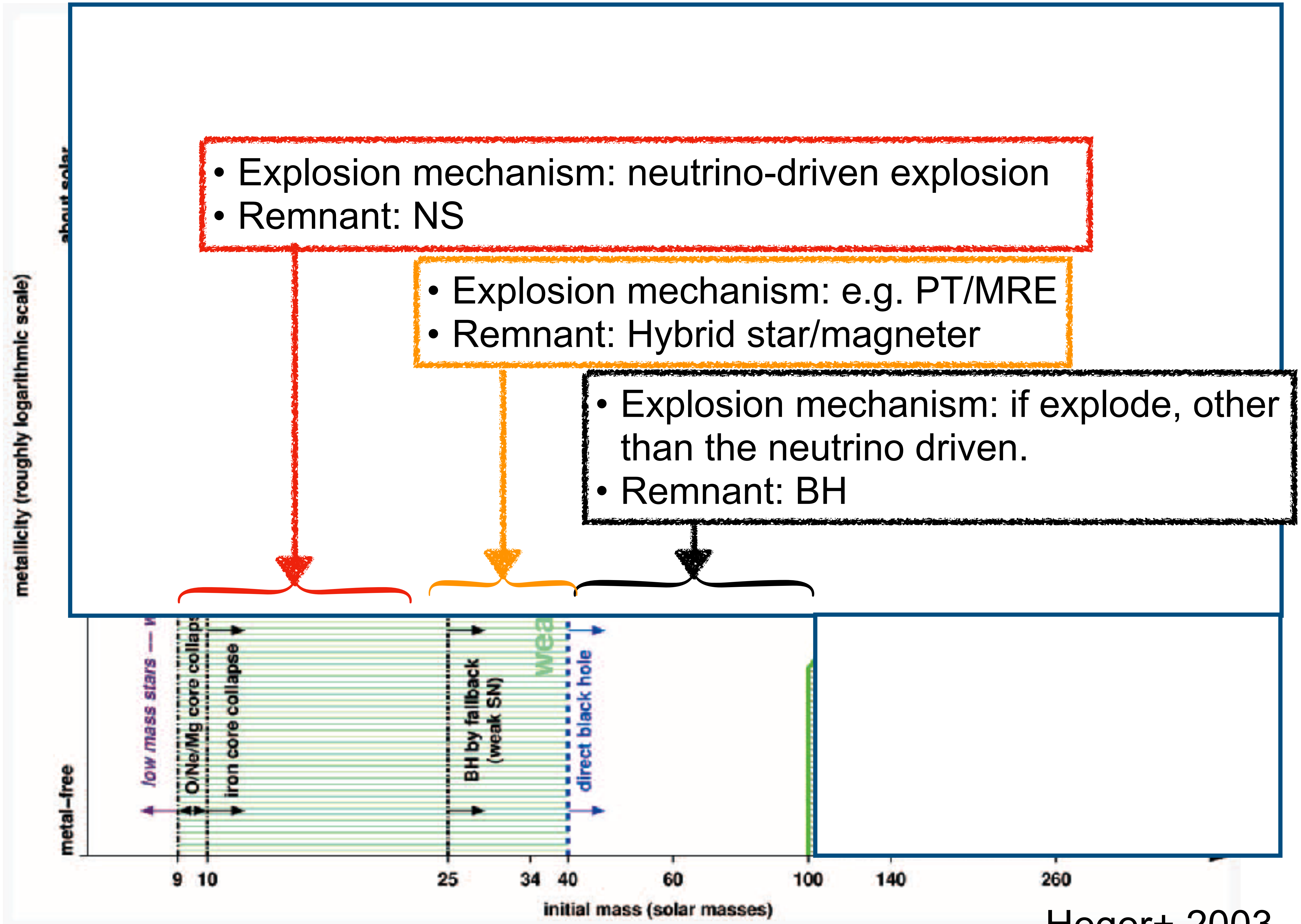
- Less massive stars, *no*, as explosion (e.g. by neutrino) likely happens.
- More massive stars, practically *no*, as it immediately becomes BH.
- Currently only for moderate massive stars (~40-50 M_{Sun}(?)), *yes*.

The NS/BH formation branch and its progenitor mass dependence

- Explosion mechanism: neutrino-driven explosion
- Remnant: NS

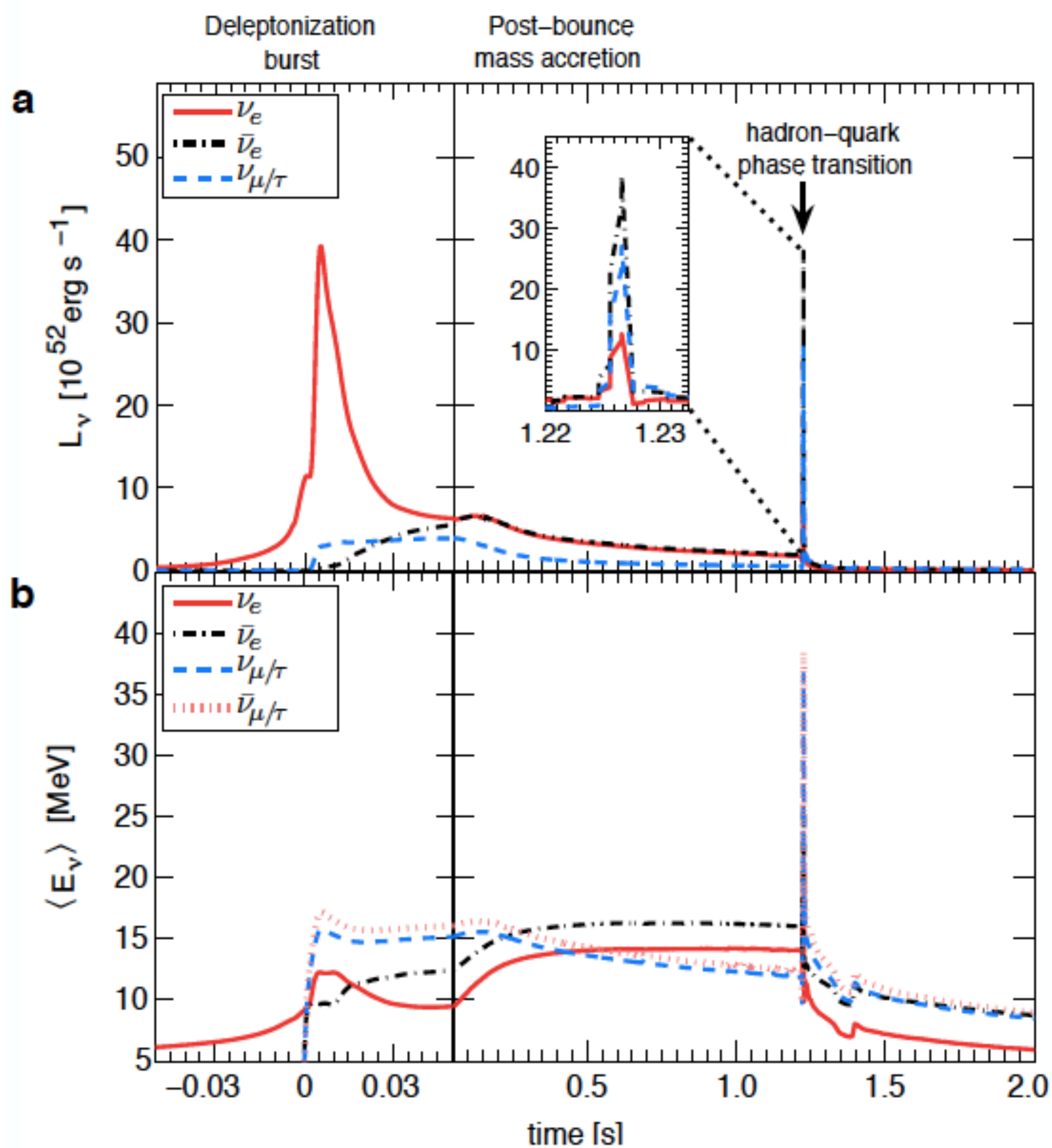
- Explosion mechanism: e.g. PT/MRE
- Remnant: Hybrid star/magneter

- Explosion mechanism: if explode, other than the neutrino driven.
- Remnant: BH



Heger+,2003

• Their multi-messenger signals



Fischer+,'17

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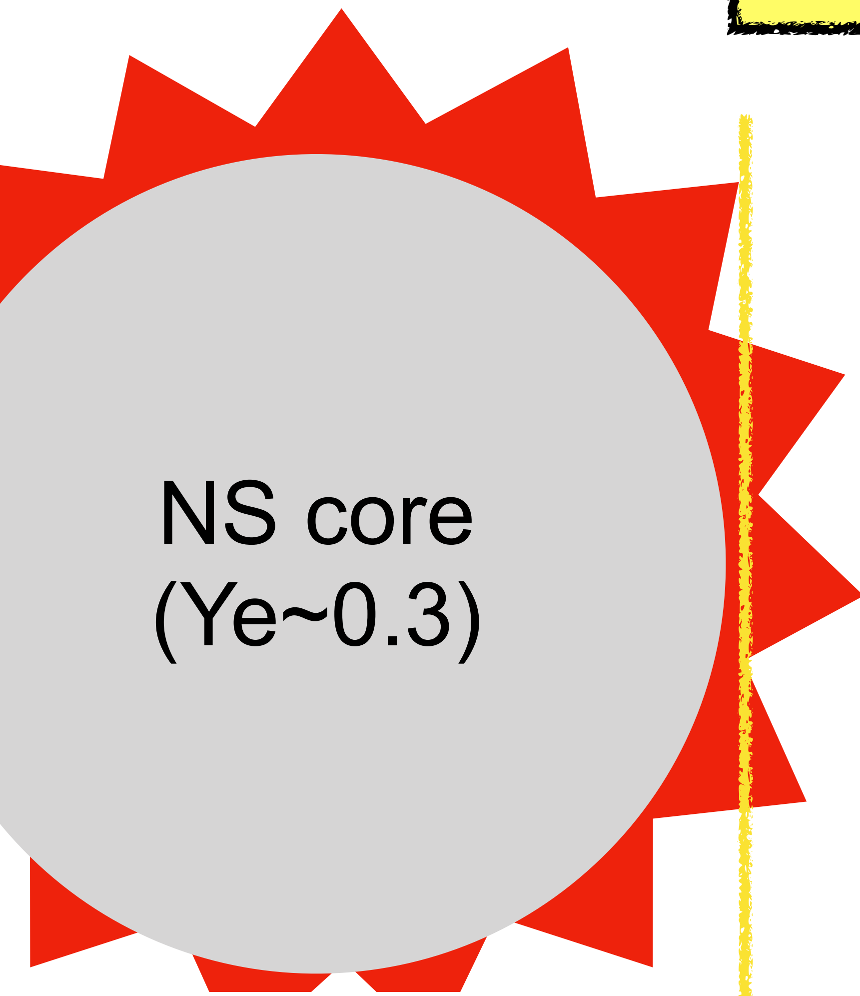
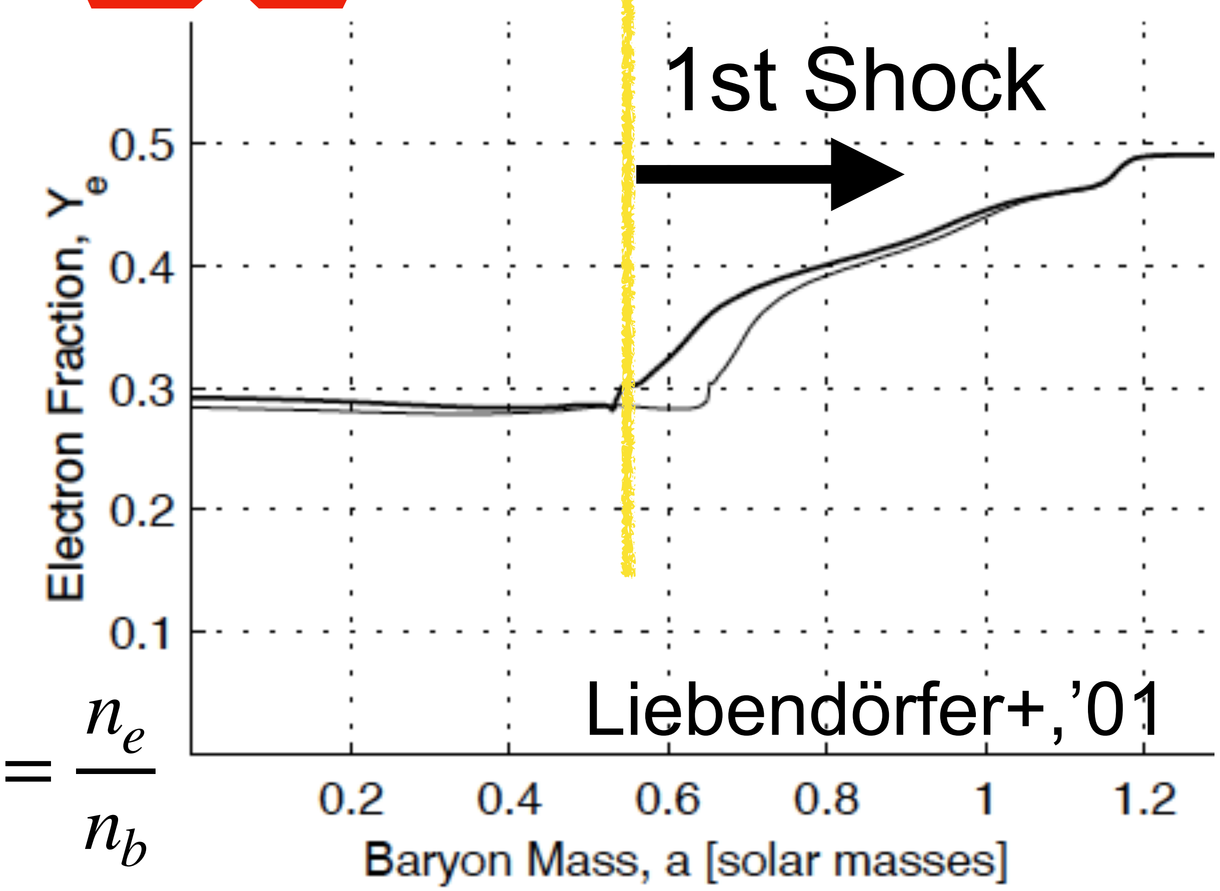


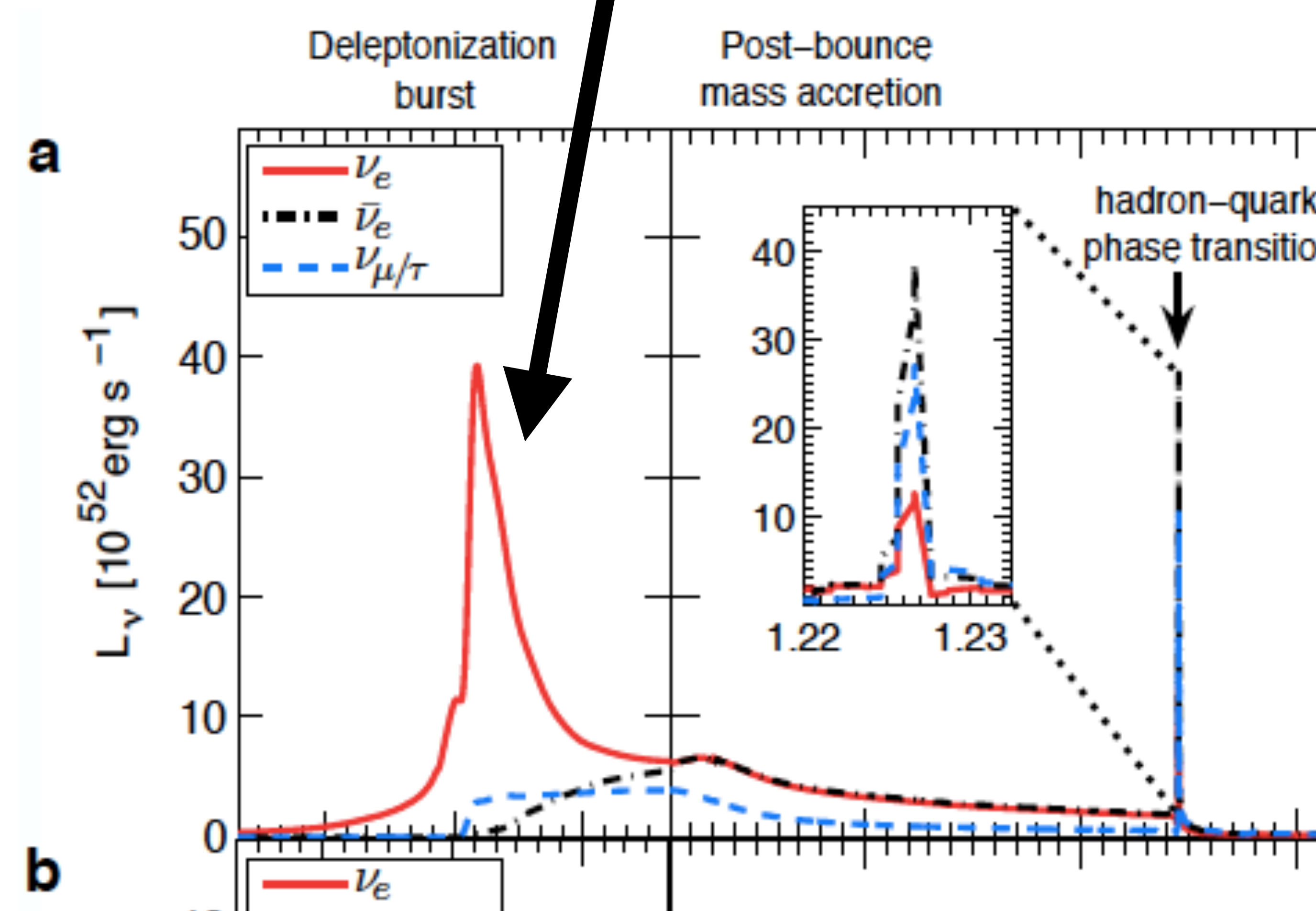
Dominant process (electron capture)

$$e^{-}p \rightarrow \nu_e n$$

produces the neutrino (ν_e) burst



$$Y_e = \frac{n_e}{n_b}$$

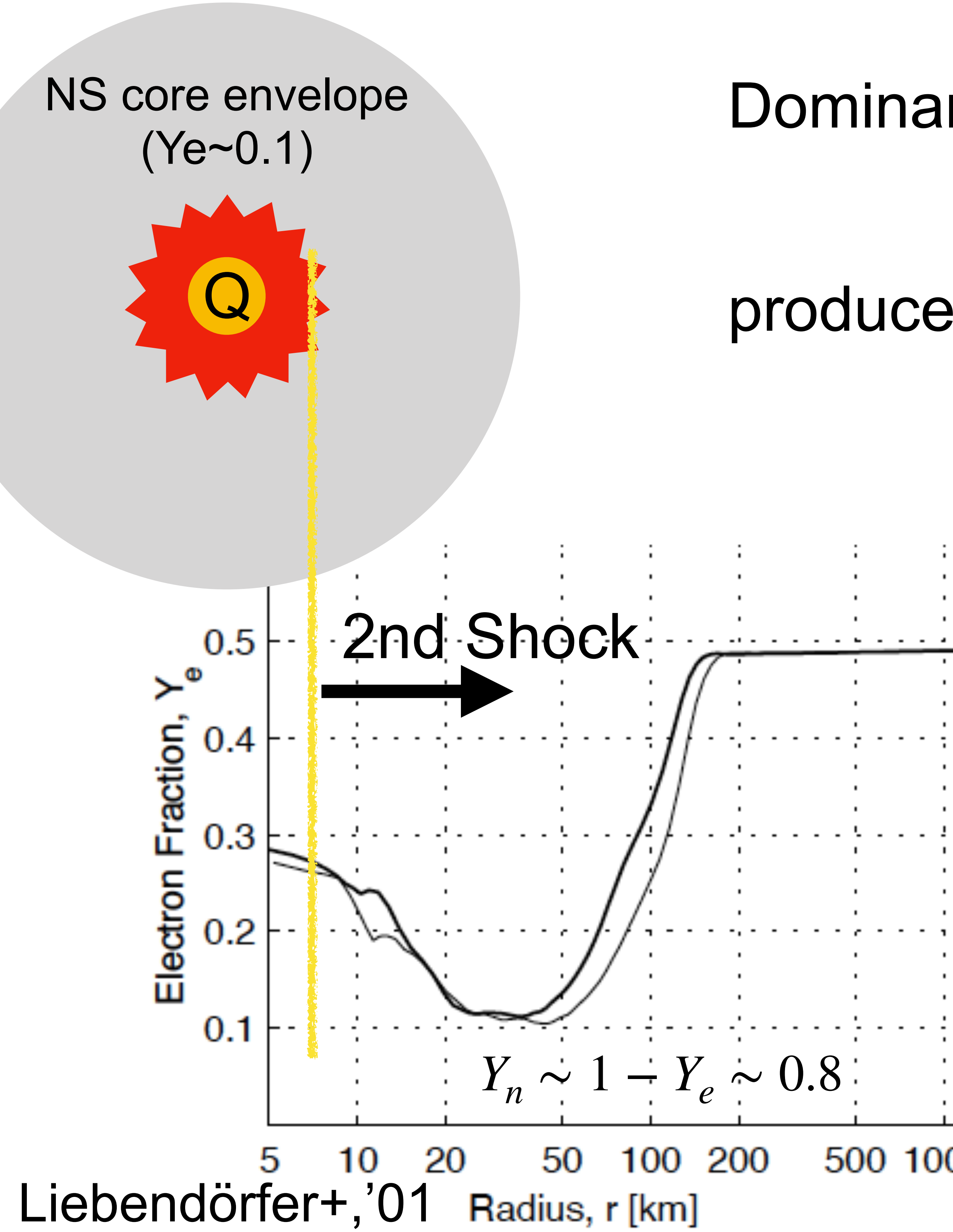


• Their multi-messenger signals

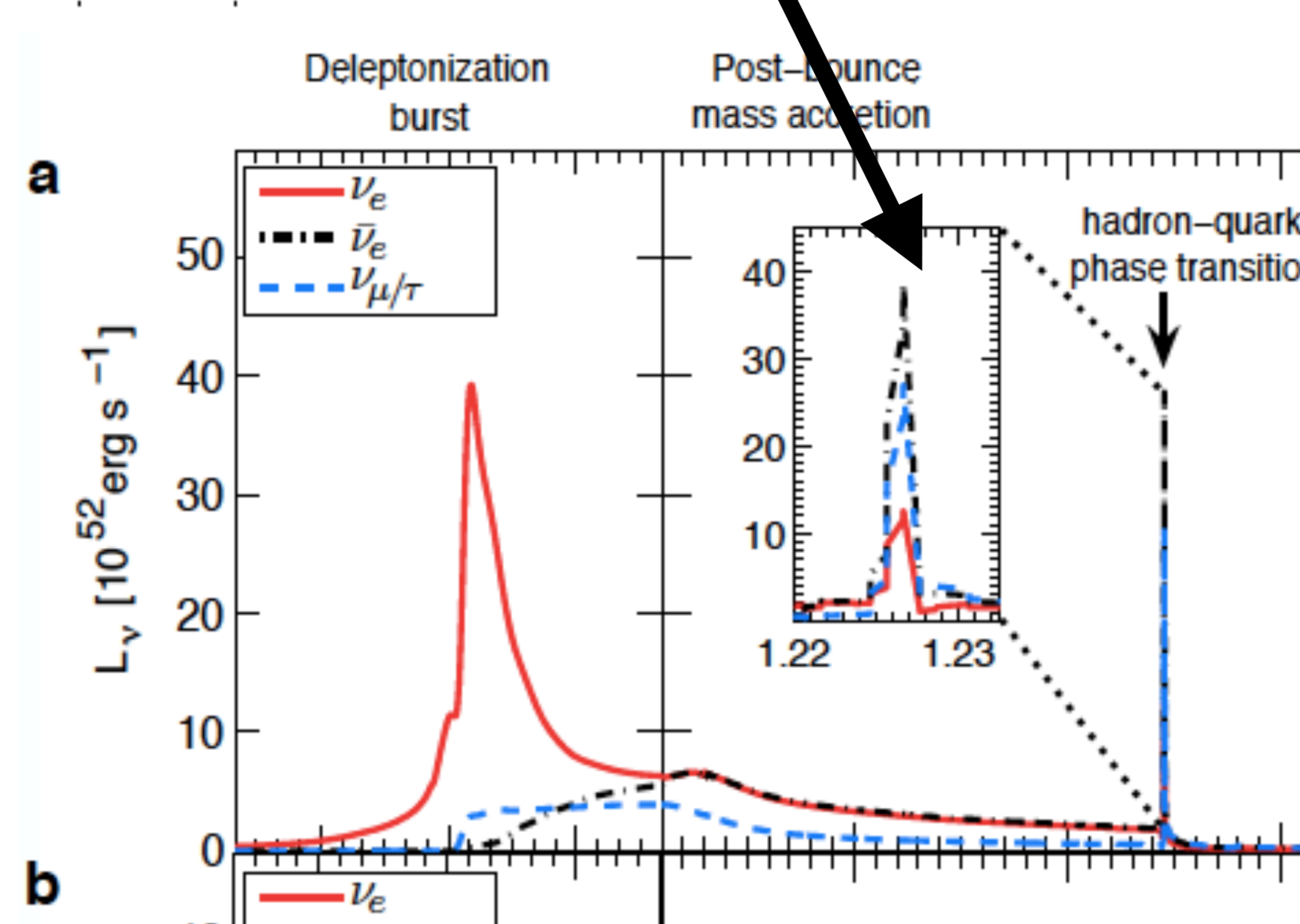
Dominant process (positron capture)

$$e^{+}n \rightarrow \bar{\nu}_e p$$

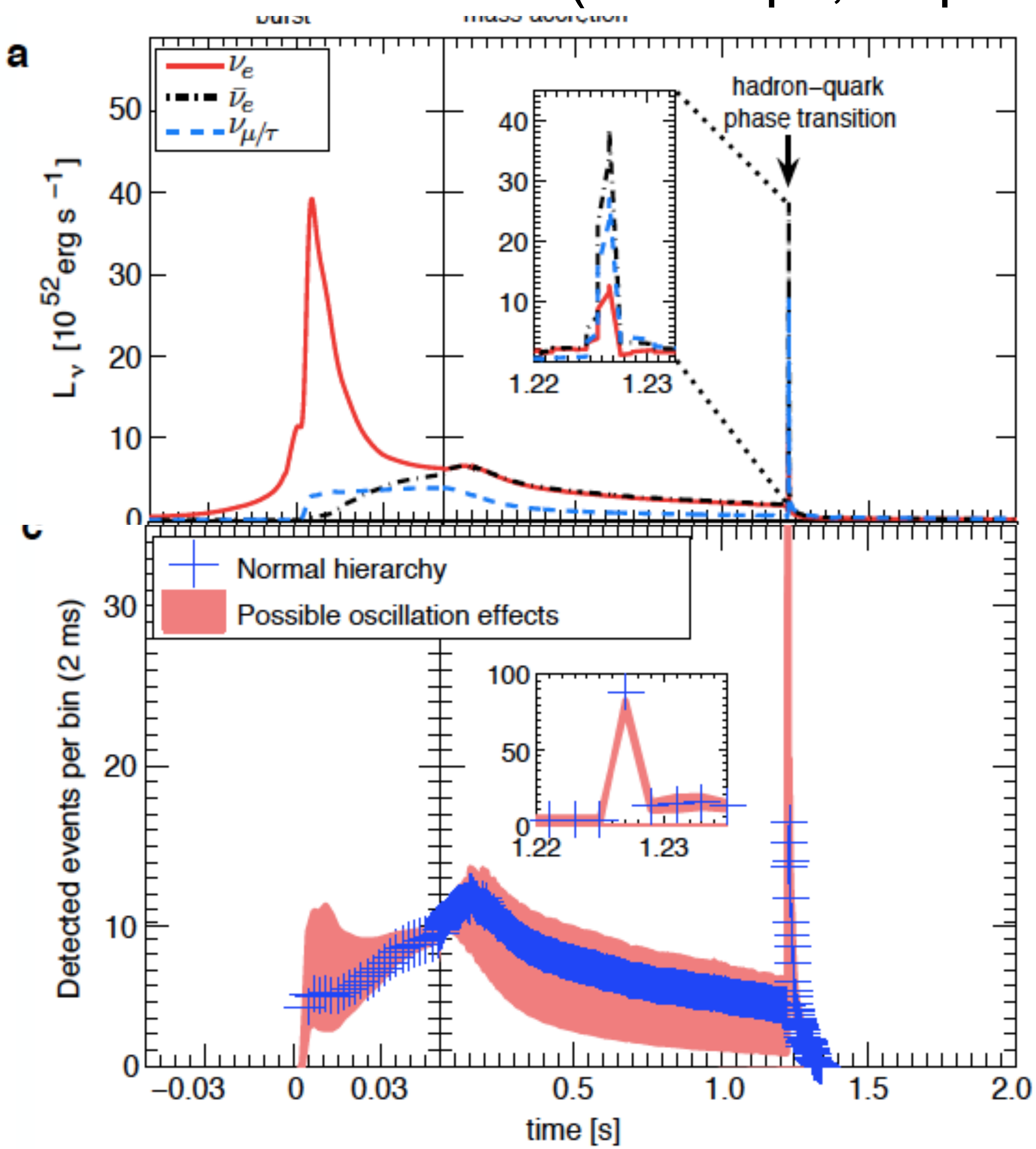
produces the anti-neutrino ($\bar{\nu}_e$) burst



Liebendörfer+,'01



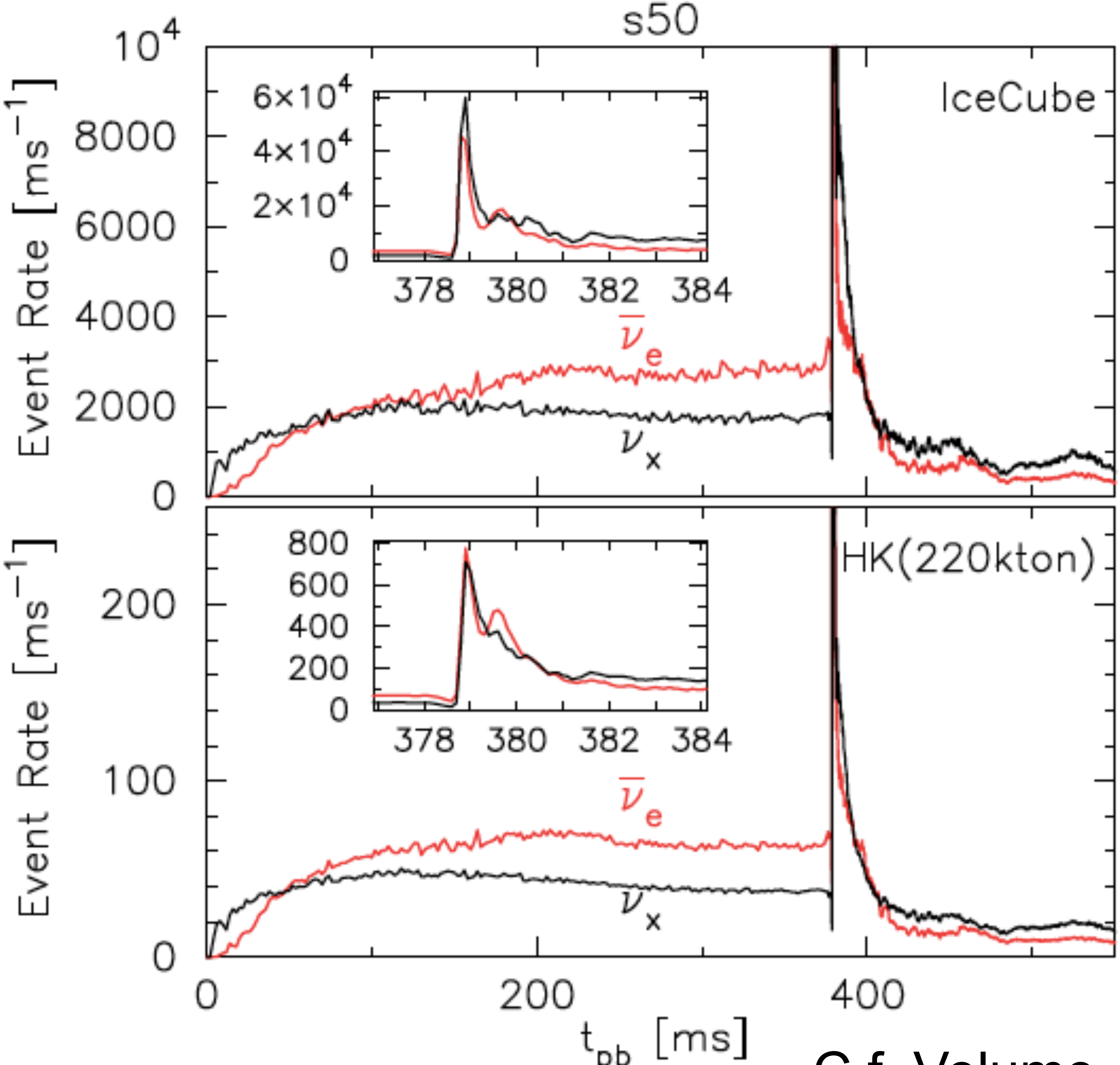
Expected neutrino detection (D=10kpc, Super Kamiokande)



Fischer+,'17

$$\bar{\nu}_e p \to e^+ n$$

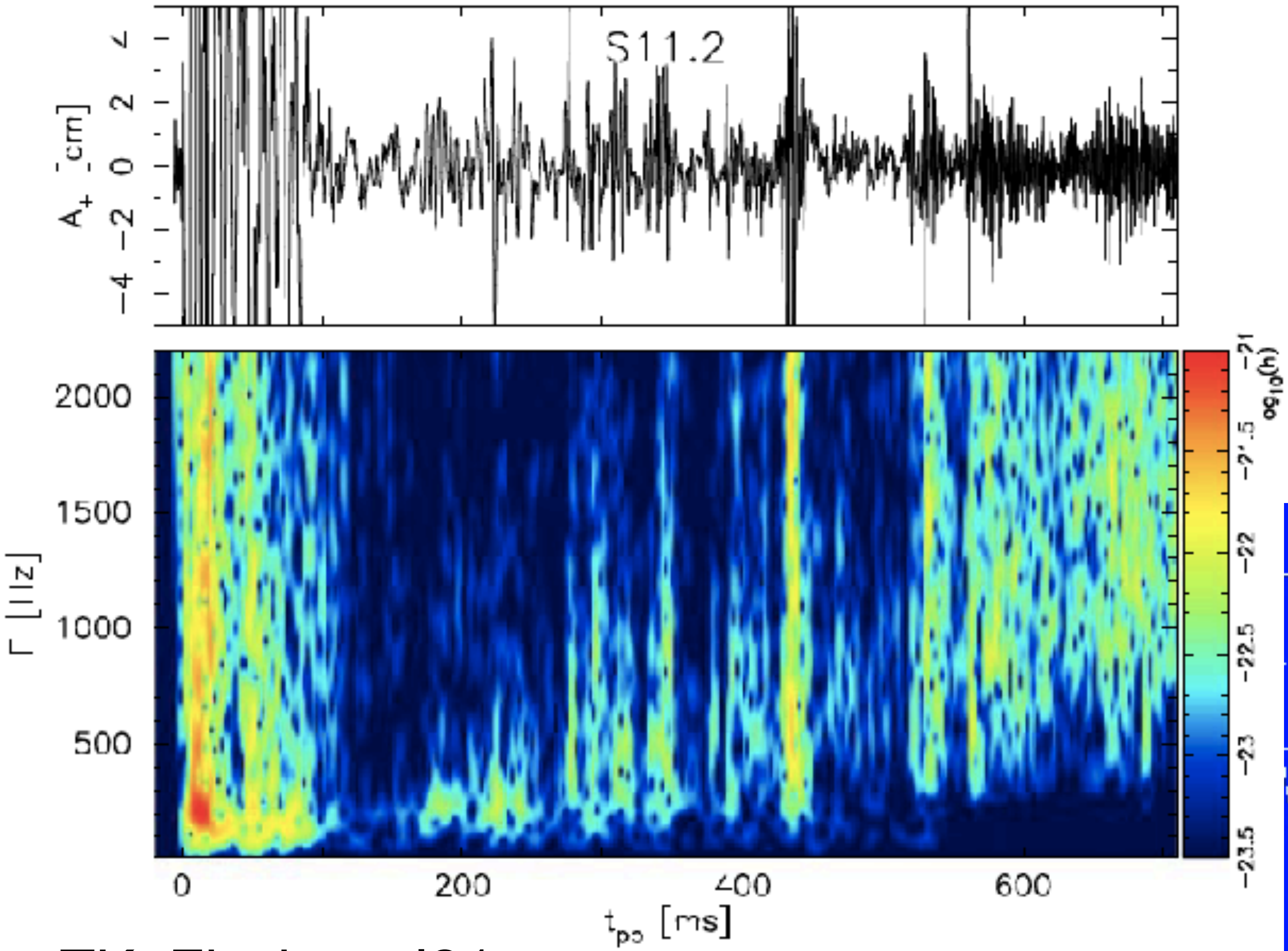
Expected neutrino detection (D=10kpc, IceCube & HyperK)



TK, Fischer+,'21

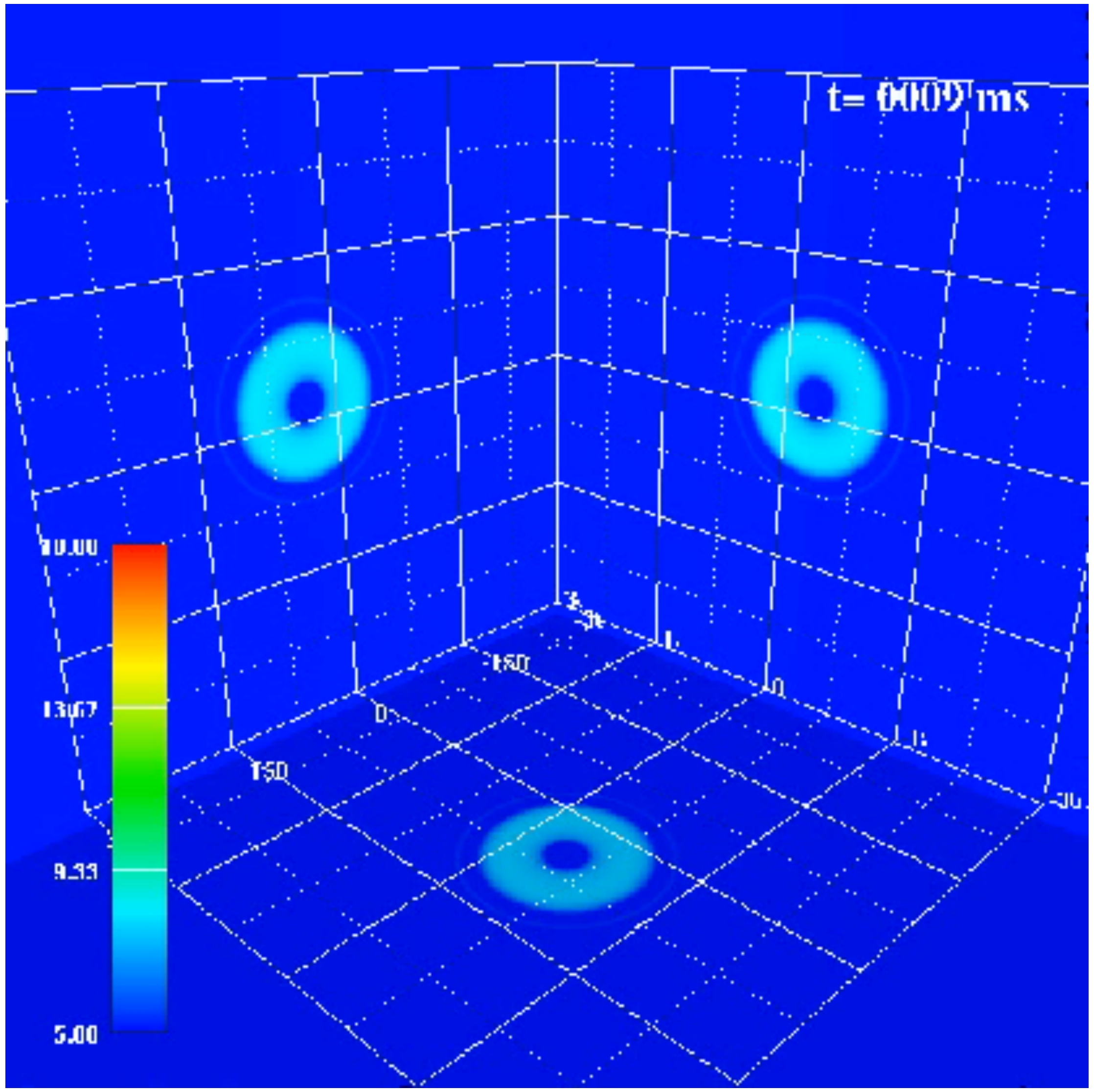
C.f. Volume_{HK}~$4\mathrm{Volume}_{SK}$

GW signals (typical case: 11.2M_{sun})

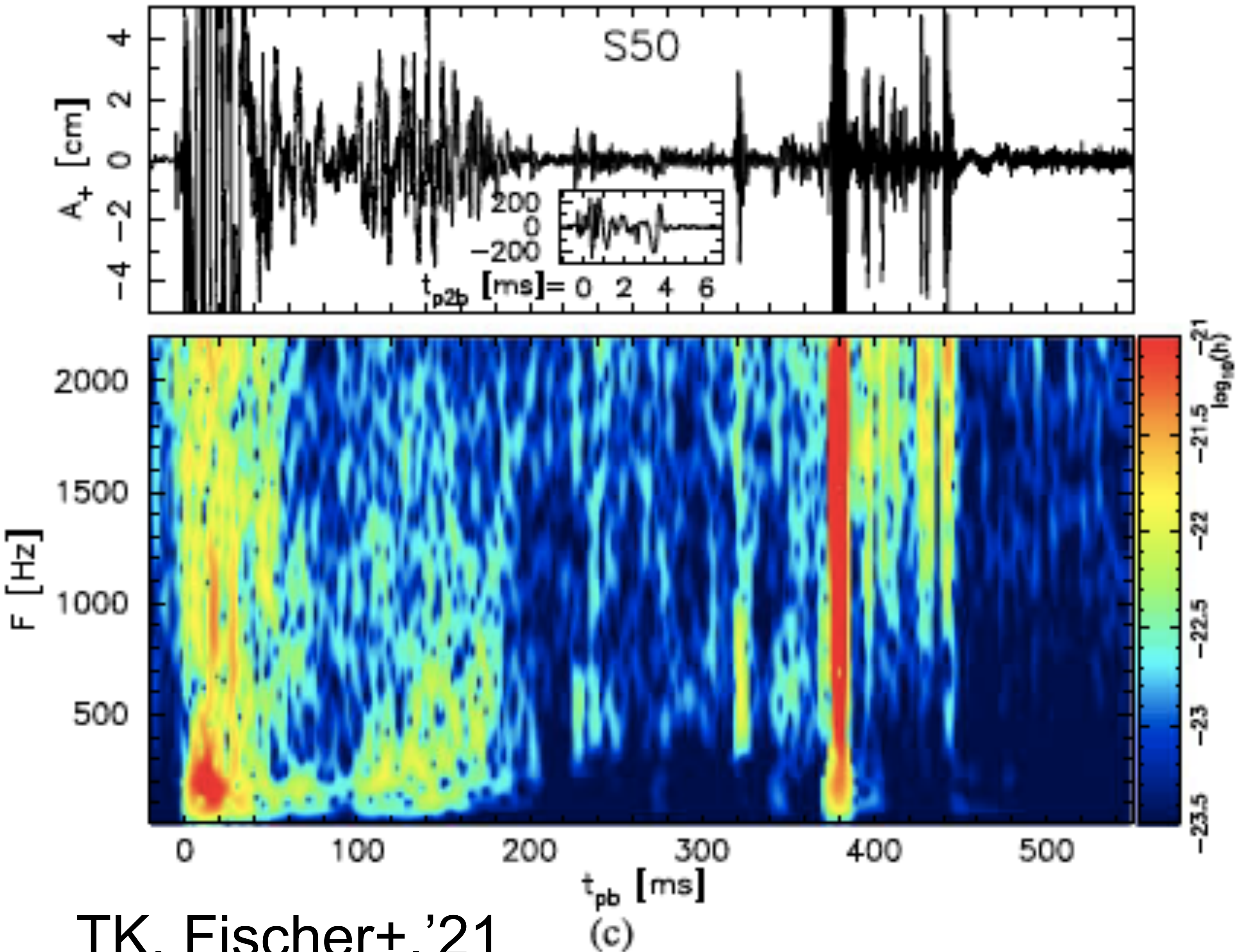


TK, Fischer+,'21

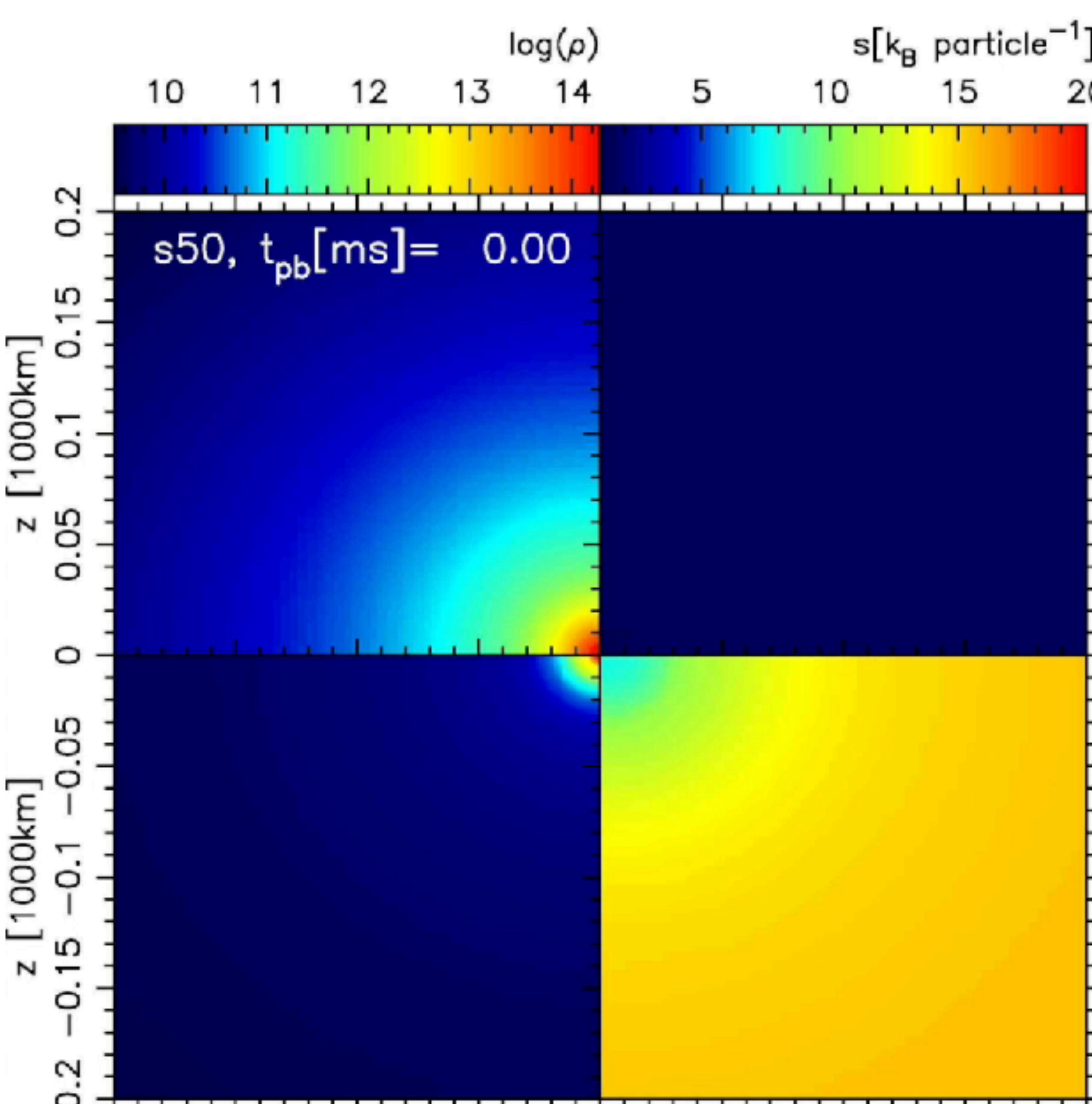
Takiwaki+,'18



GW signals (PT case: $50M_{sun}$)



TK, Fischer+,'21
(see also Zha+,'20)



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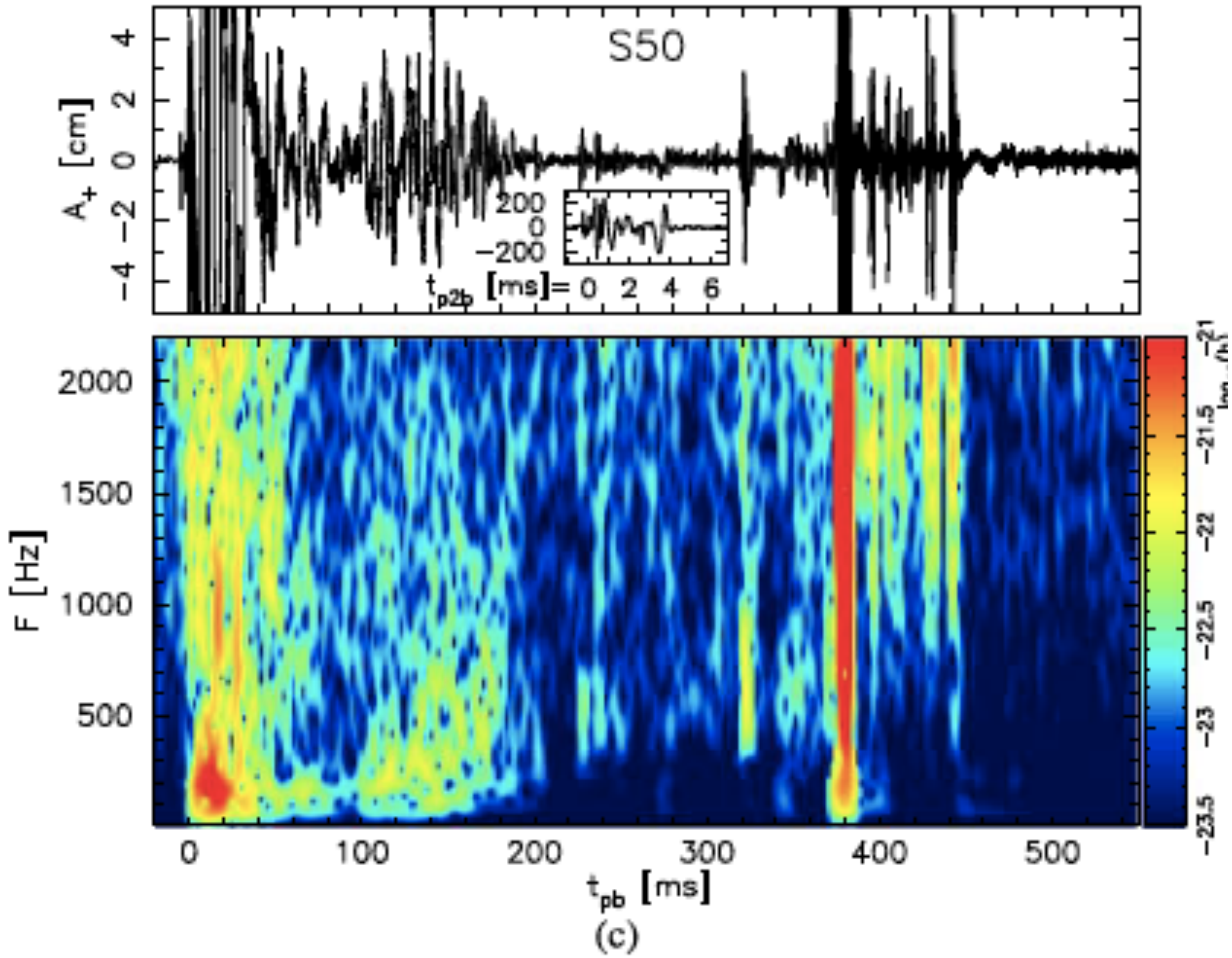
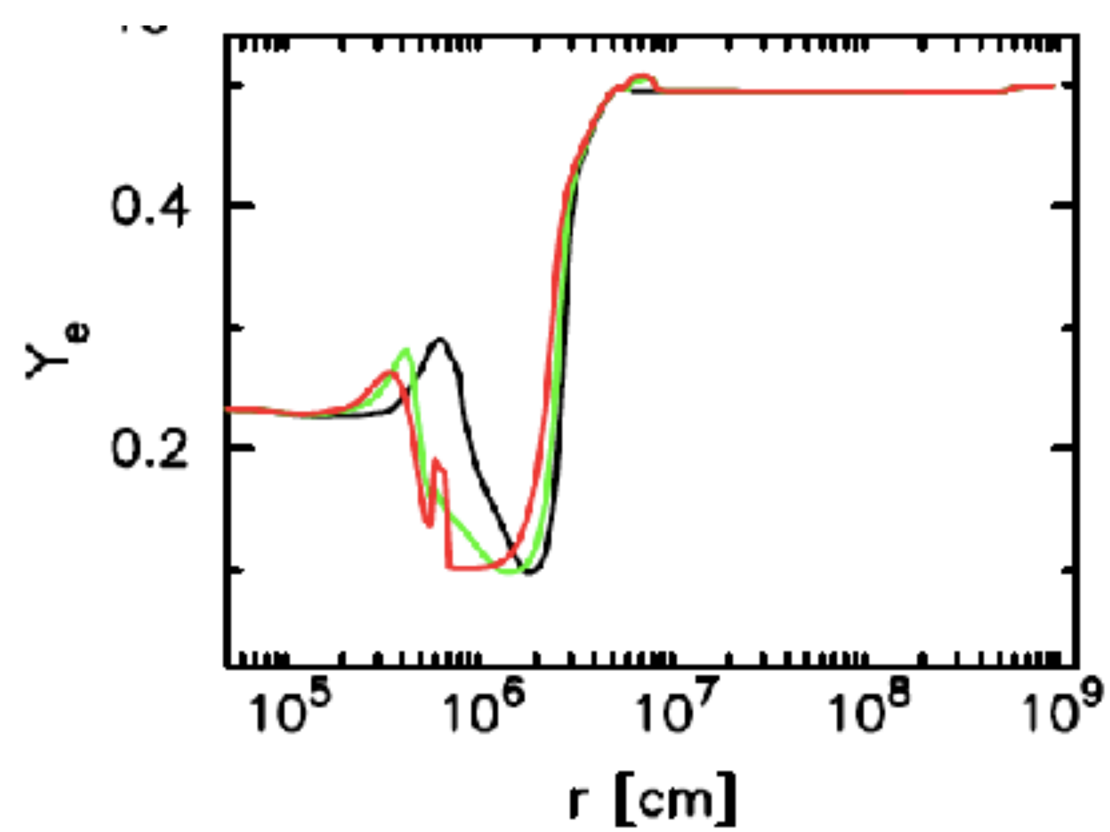
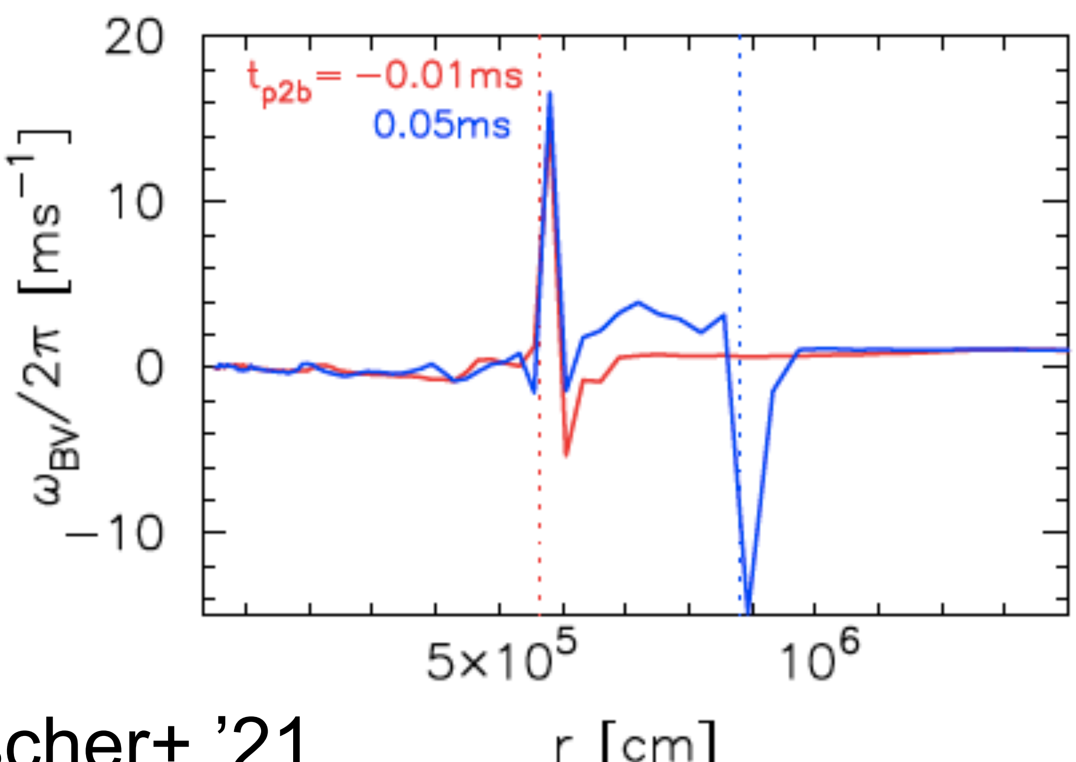


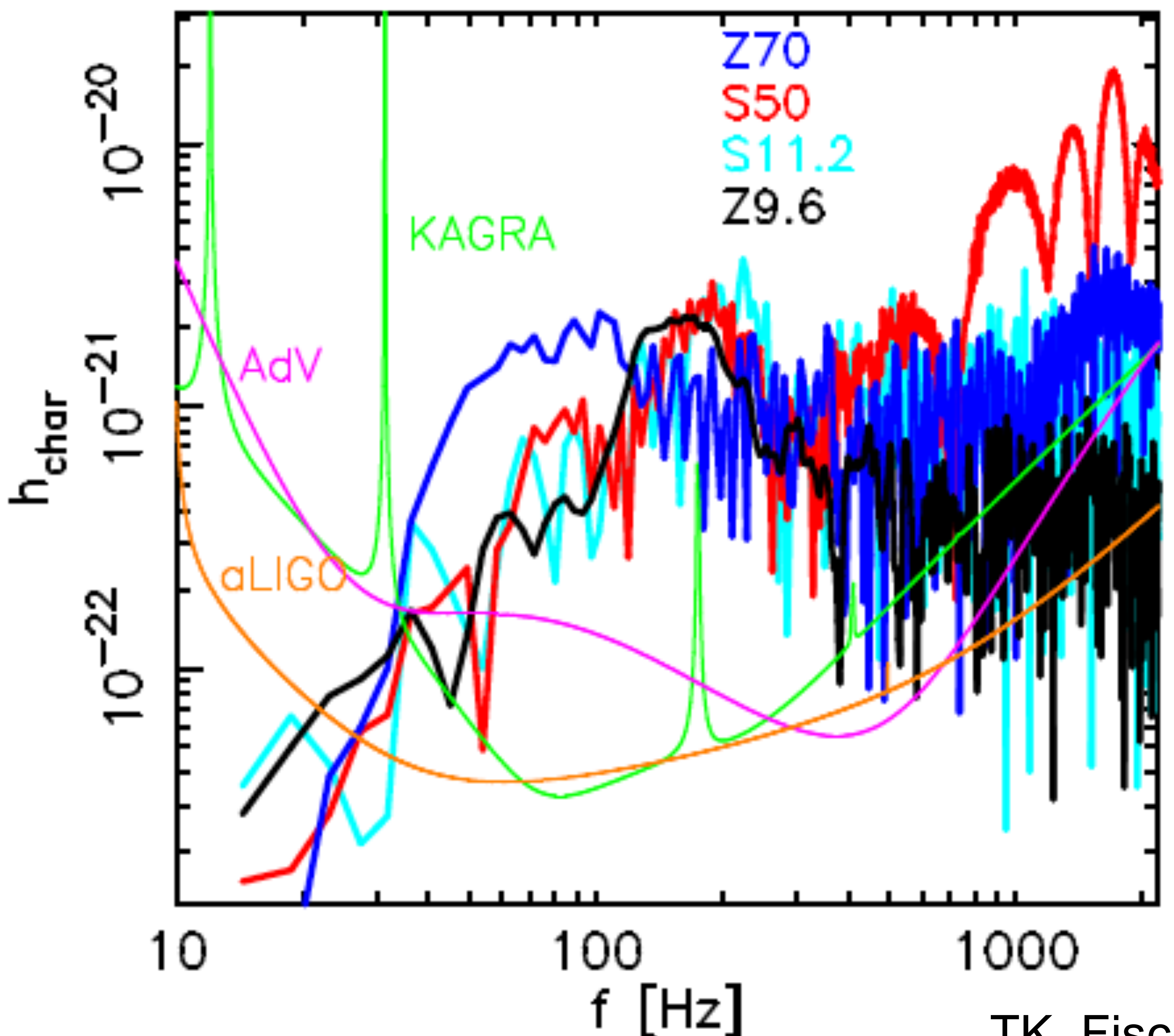




<u>Strong convection motions are generated via the shock passage similar to the 1st core bounce.</u>

TK, Fischer+,'21

GW signals



TK, Fischer+,'21

Summary

Our understanding of the SN explosion physics
and of the formation process of various compact stars
is still remaining patchy but gradually deepened.

In SN physics, all the *four fundamental forces* play substantial roles.

- General relativity (GR) governs the overall dynamics.
- The nuclear force (i.e. strong force) determines structure of compact stars.
- SN explosion is driven by the neutrino heating (weak force)
  or sometimes by magnetic (B-)fields (electromagnetic force).

The current status of SN theory		
progenitor mass	explosion mechanism	remnant type
~10-20M_{sun}	Neutrino driven explosion (ν-driven)	neutron star (NS)
~30-40M_{sun}	Magneto rotational explosion (MRE)	magnetar, black hole (BH)
~50M_{sun}	Explosion by the hadron-quark phase transition (PT)	quark star (QS)
>~70M_{sun}	Failed explosion	BH

Various properties of progenitor stars: mass, spin, magnetic fields, etc.

→

Various explosion mechanisms:

- ν-driven
- MRE
- PT
- ???

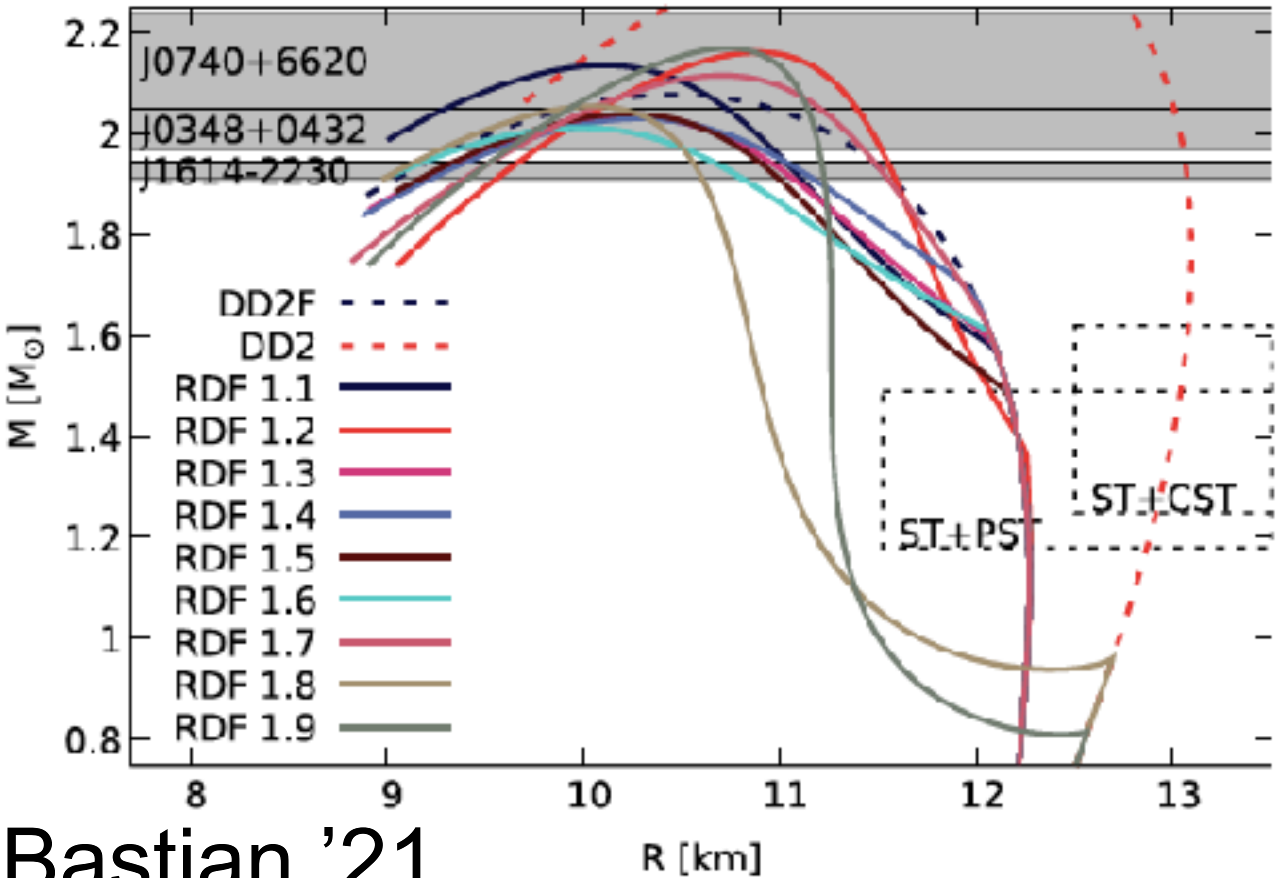
→

Various remnants:

- NSs
- BHs
- magnetars
- QSs

Exercise

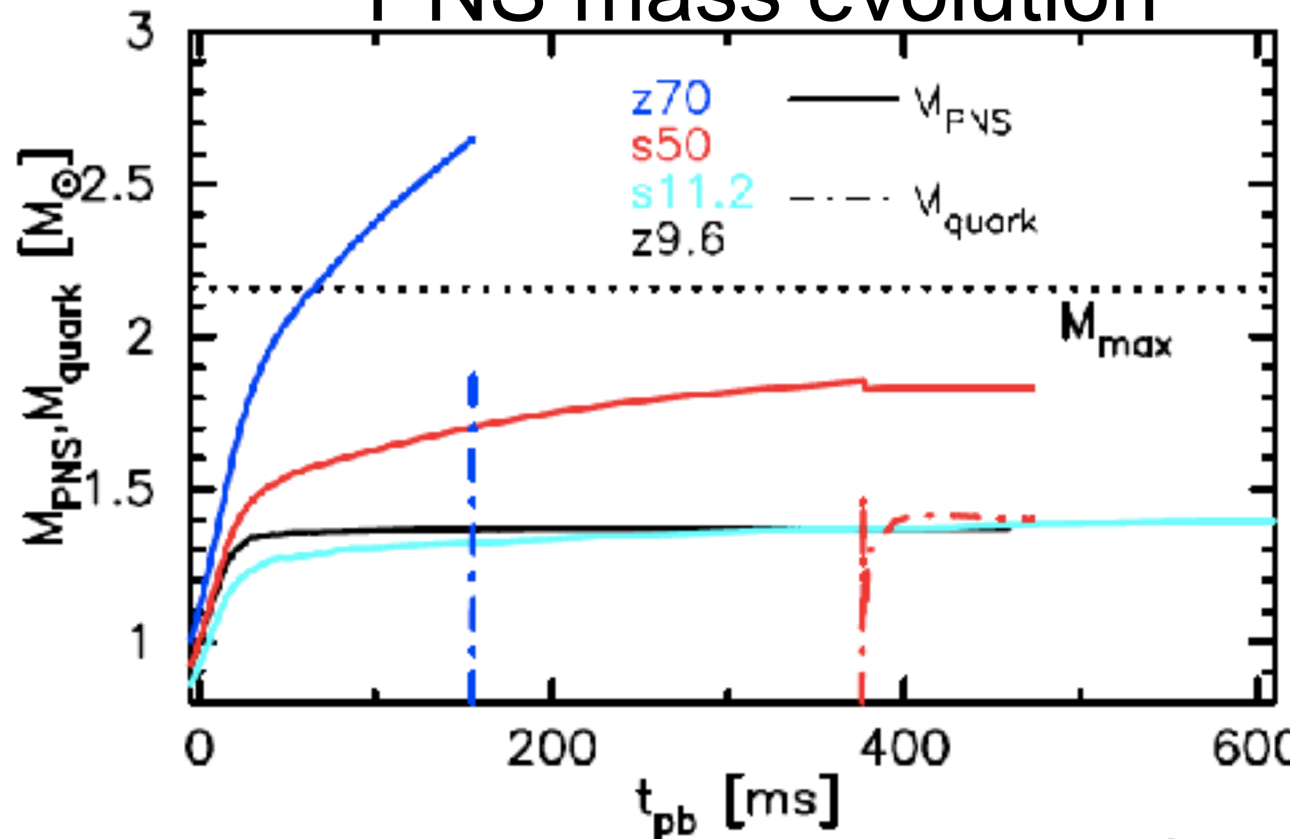
MR relation



Bastian,’21

FIG. 6. Mass-radius relations $M(R)$ for cold neutron star configurations for each parameter set including the two hadronic reference EOSs. Also shown are the experimental constraints of precise high mass measurements and the recent NICER results.

PNS mass evolution



TK, Fischer+,’21

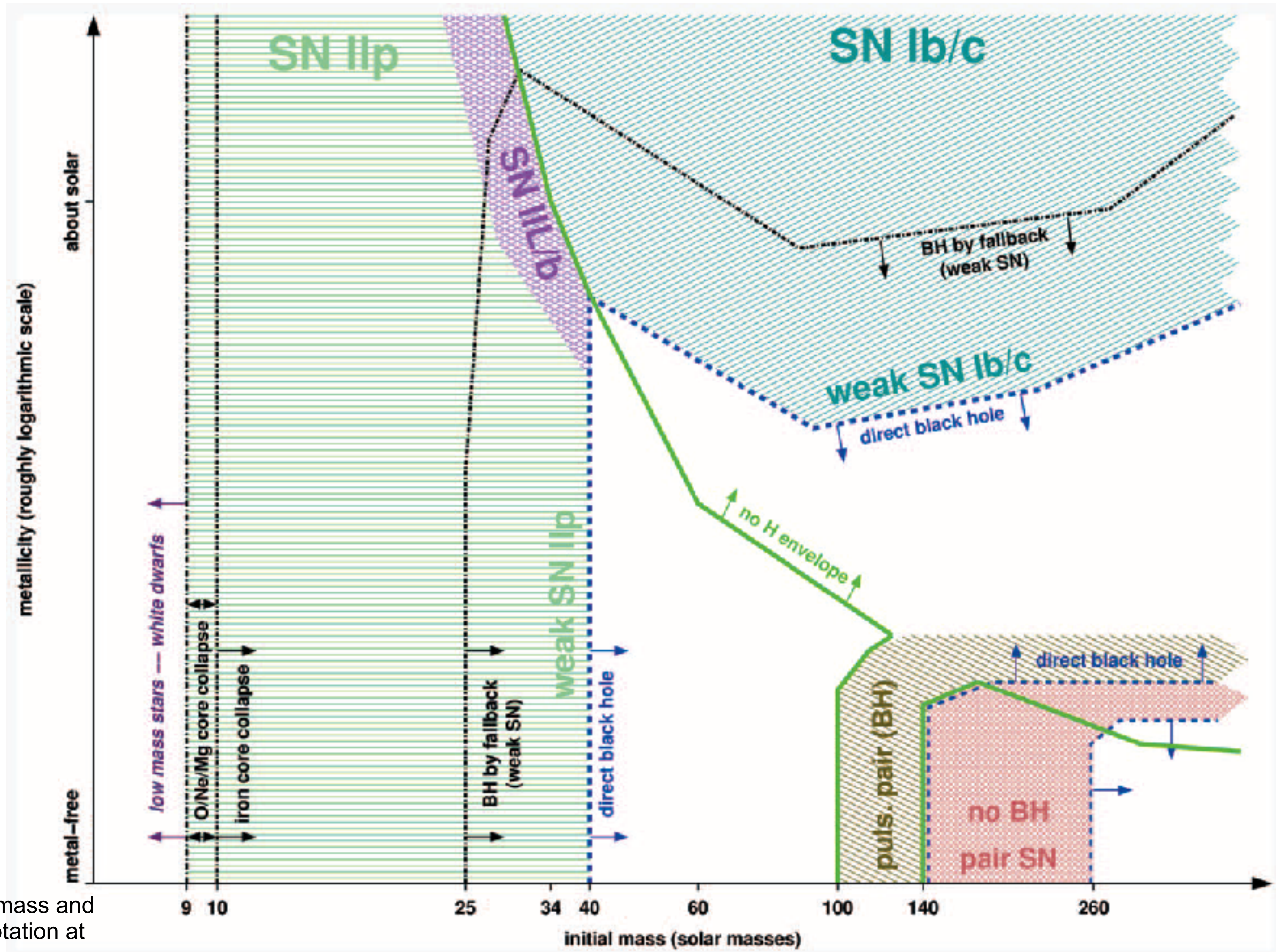
Hadronic eos is based on DD2F

1. **From these figures, estimate the available energy budget for explosion.**

2. **Why does the PT mechanism succeed, while the prompt mechanism does not.**

Progenitor mass dependence

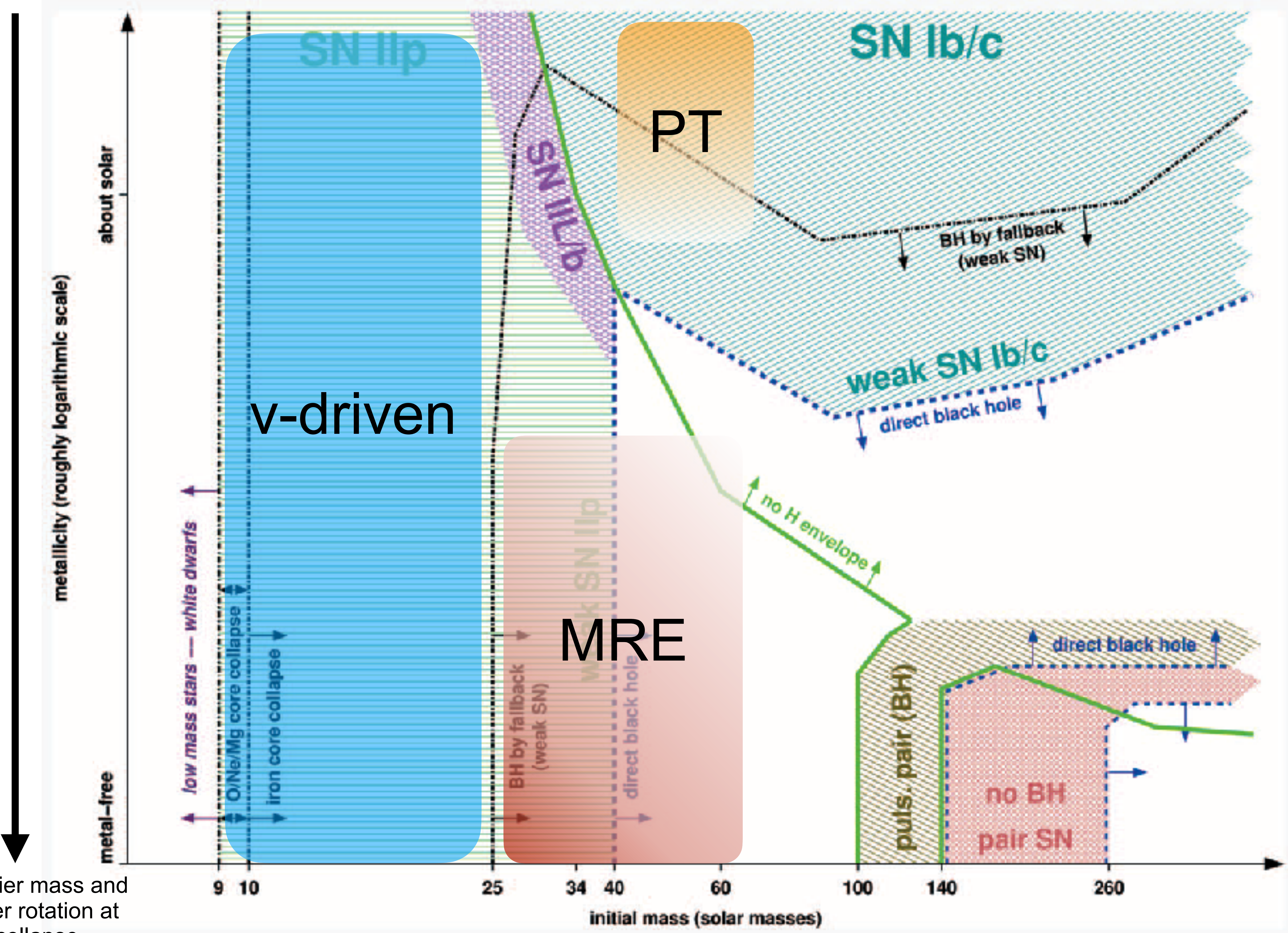
Heger+,2003



Heavier mass and faster rotation at collapse

Progenitor mass dependence

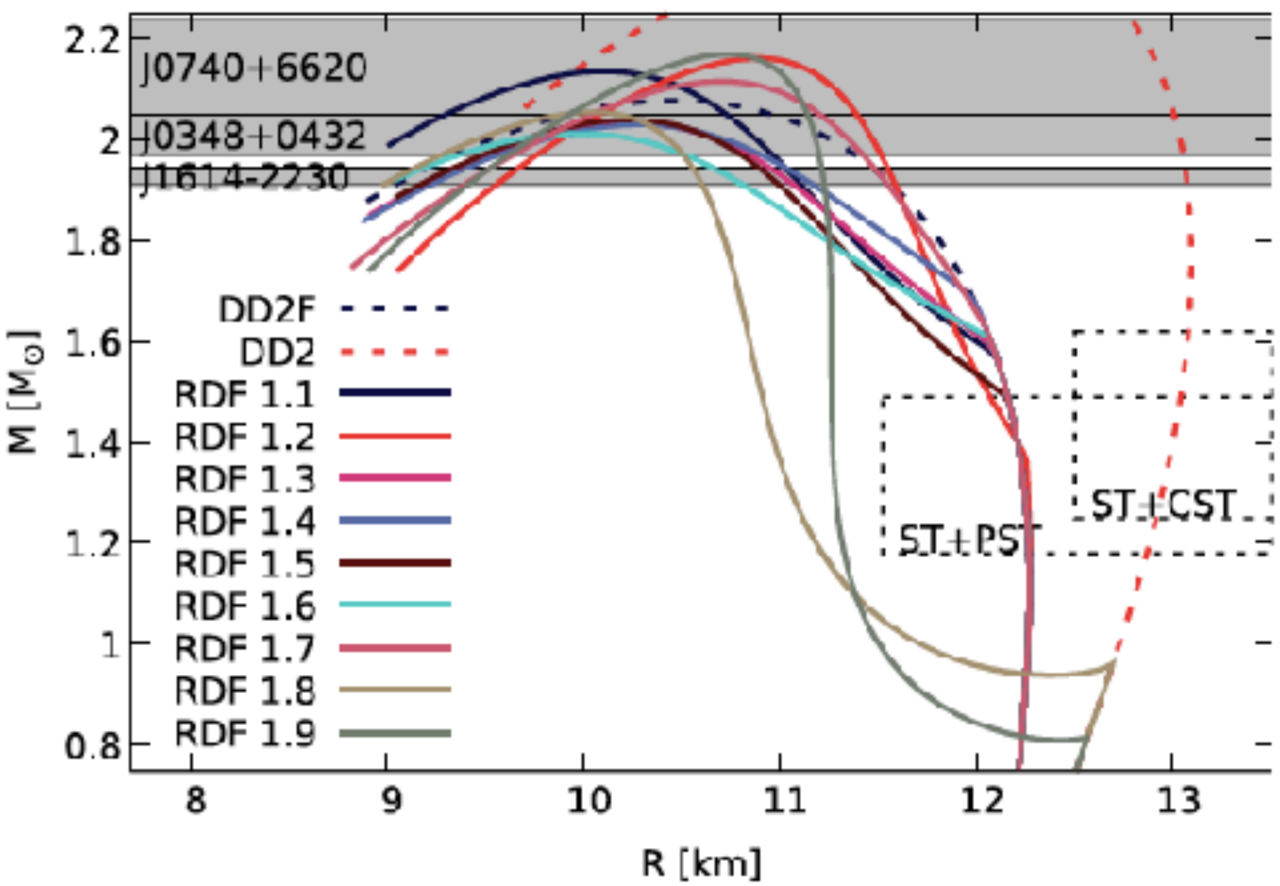
Heger+,2003



Heavier mass and faster rotation at collapse

Exercise

MR relation



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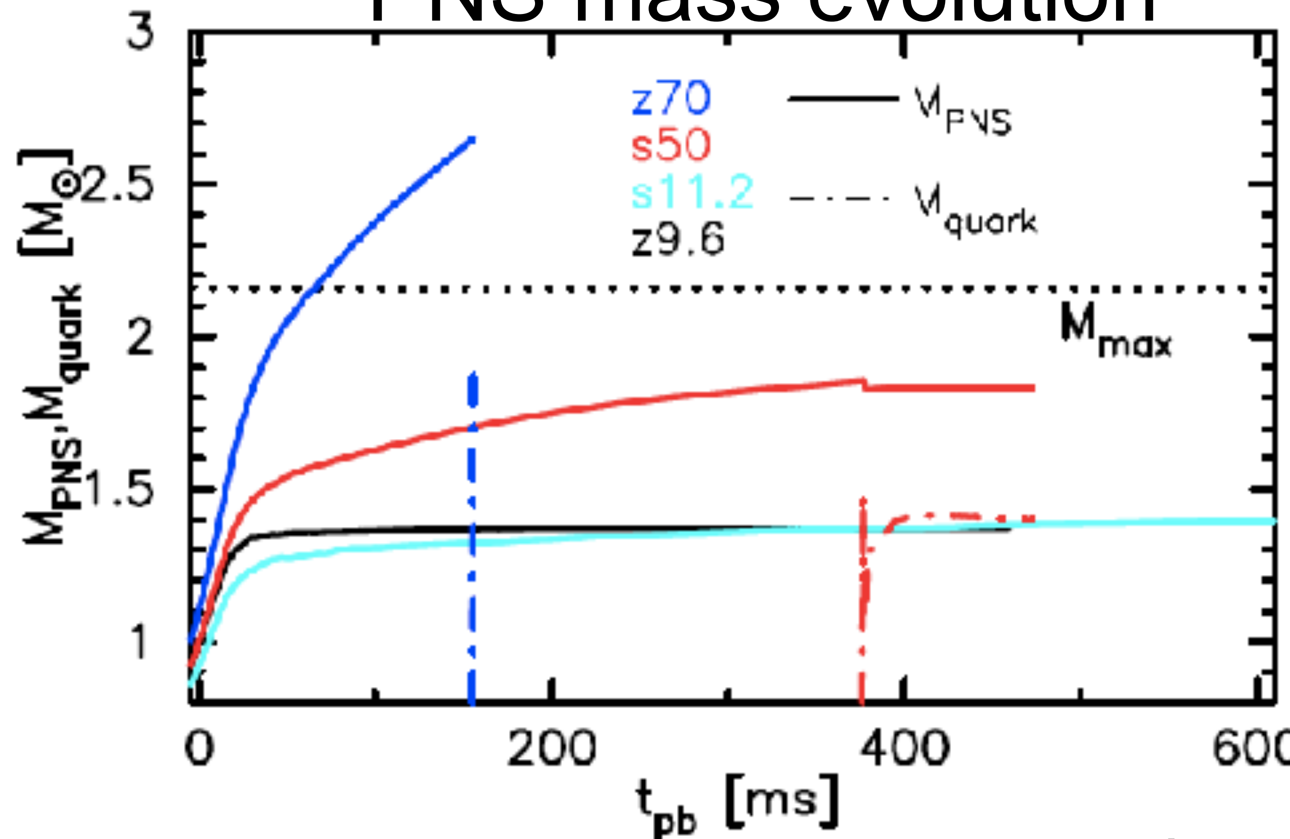
Bastian,'21

PNS mass evolution



TK, Fischer+,'21

Hadronic eos is based on DD2F

1. Estimate the available energy budget for explosion

$$-G * M^2 * \left(\frac{1}{R_{\rm PNS}} - \frac{1}{R_{\rm HS}}\right) \sim 6 \times 10^{52}\,\mathrm{erg}$$

for M~1.8M_{sun}, R_{PNS}~12km, R_{HS}~11km

Exercise

2. **Why does the PT mechanism succeed, while the prompt mechanism does not.**

At the first bounce the shock propagates through heavy nuclei media.
—-> photodissociation of iron (heat absorbing process) causes the shock stalling

At the second bounce the shock propagates through n&p media.
—-> no photodissociation, thus no shock stalling