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 (Lecture 1)

1: SN from observational side

2: SN from theoretical side

3: SN engine: Neutrino heating

4: Progenitor and remnant property

Outline (Lecture 2)

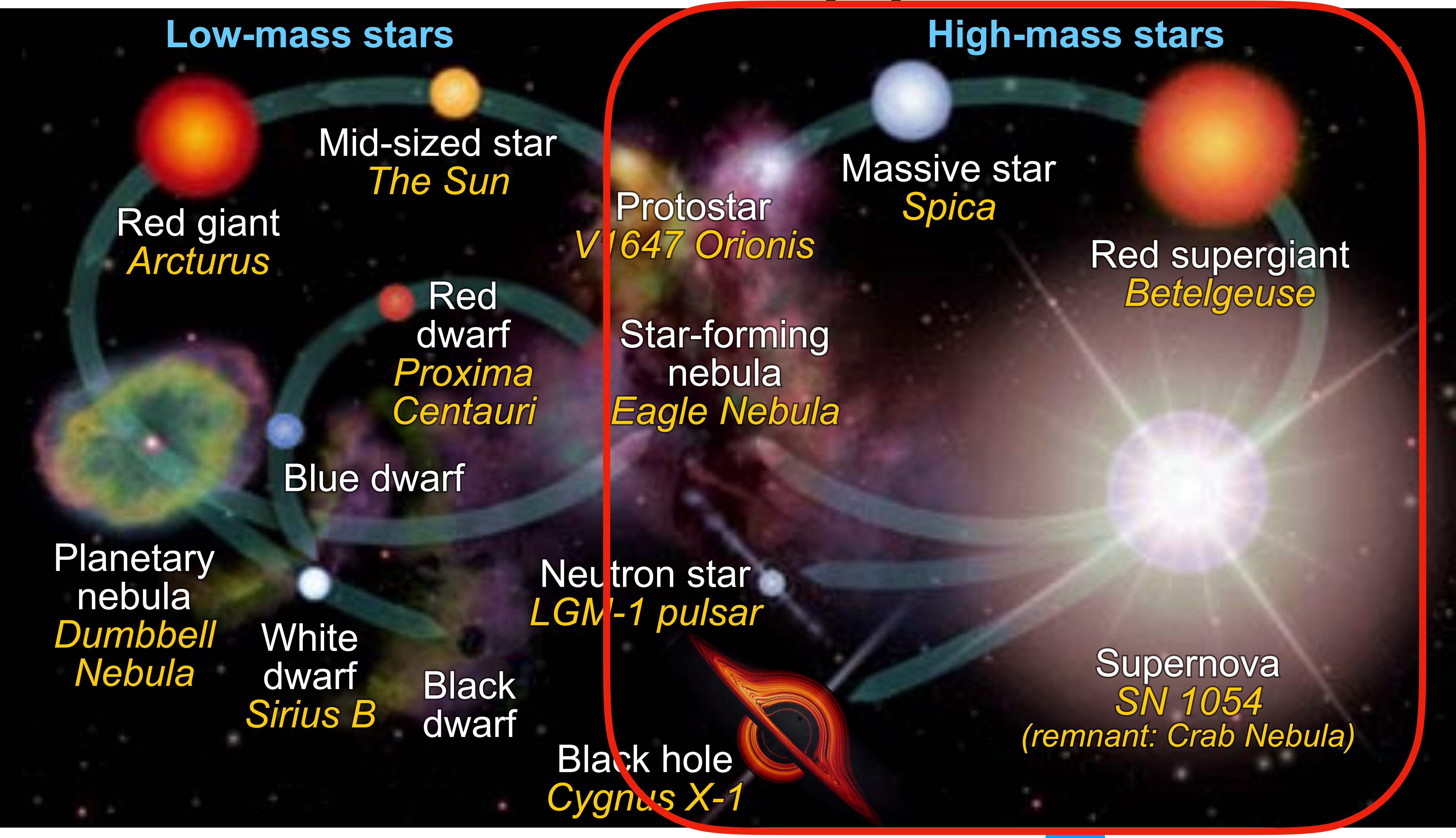
(1: Recap of Lecture 1)

2: Hadron-quark phase transition in supernova

3: How to probe it?

4: Summary

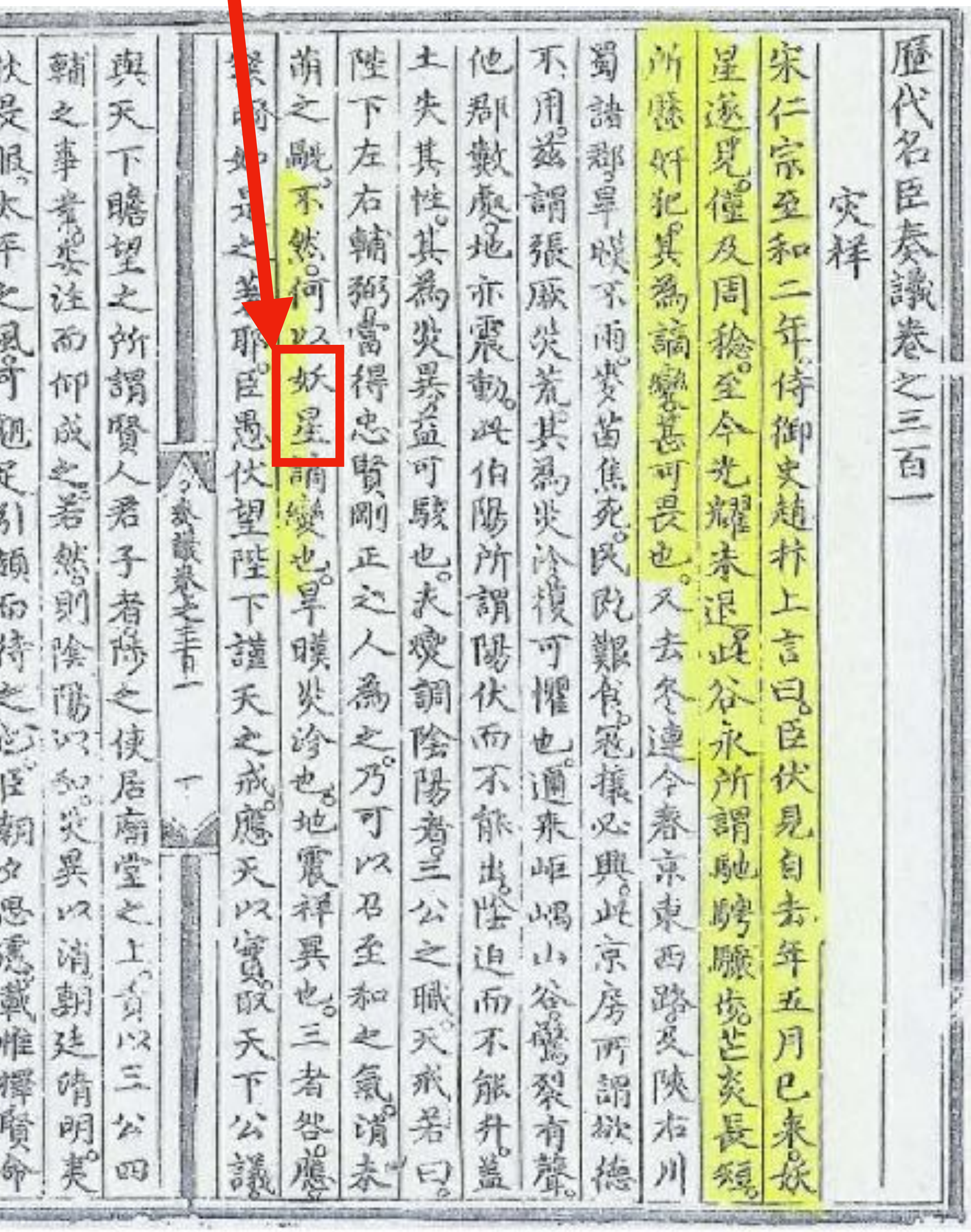
Stellar evolutionary cycles



In this lecture I will focus only on this high-mass ($\sim 10M_{sun} < M < \sim 100M_{sun}$) branch.

A historical Supernova: SN1054

A “guest star” reported by Chinese astronomers in 1054.



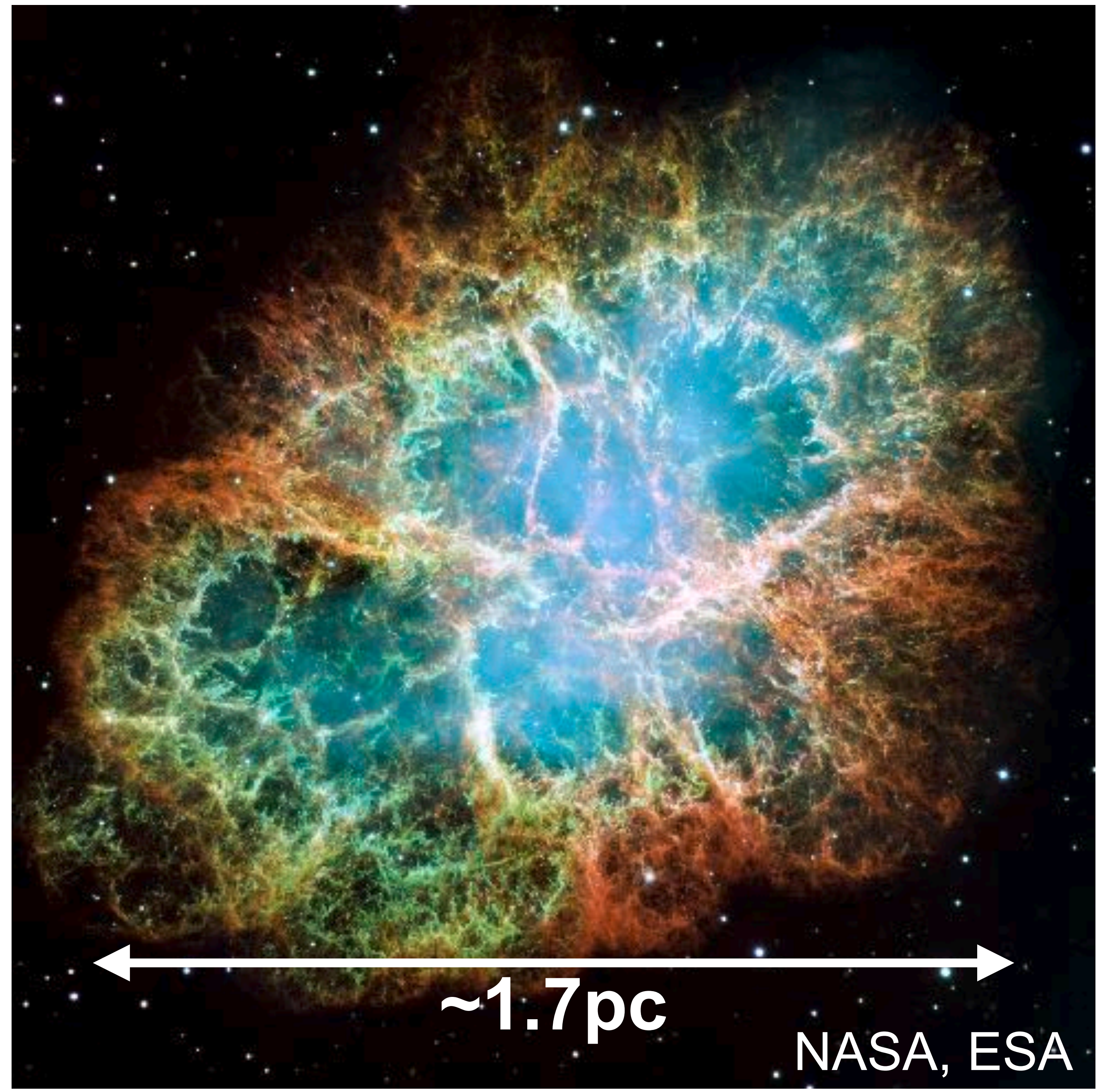
歷代名臣奏議卷之三百一

災祥

宋仁宗至和二年侍御史趙抃上言曰臣伏見自去年五月已來妖
星遂見僅及周歲至今光耀未退此谷永所謂馳騁驟歩芒炎長緩
所鍾奸宄其為譴變甚可畏也又去冬連今春京東西路及陝右川
蜀諸郡旱暵不雨麥苗焦死民阻艱食寇攘必興此京房所謂欲德
不用茲謂張厥災荒其為災沴模可懼也通來恆嶋山谷震裂有聲
他郡數處地亦震動此伯陽所謂陽伏而不能出陰迫而不能升蓋
土失其性其為災異益可駭也夫燮調陰陽者三公之職天戒若曰
陛下左右輔弼當得忠賢剛正之人為之乃可以召至和之氣消未
萌之亂不然何以妖星譴變也旱暵災沴也地震祥異也三者咎應
如是之著耶臣愚伏望陛下謹天之戒應天以實敢天下公議

Pankenier, David W. 2006. Journal of Astronomical History and Heritage* 9(1): 77-82.

The Crab Nebula: now the remnant of SN1054



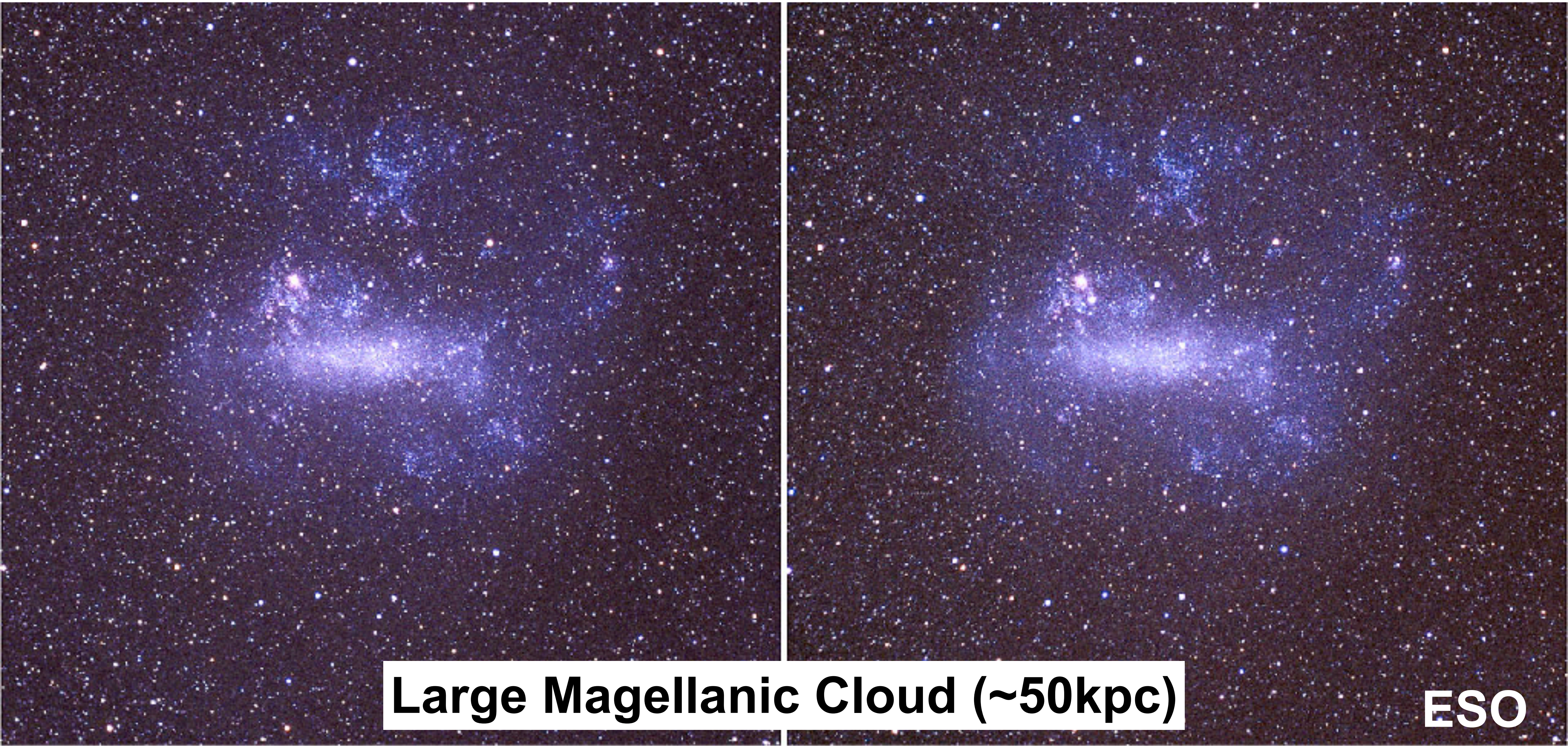
1pc=3.26ly

A historical Supernova: SN1054

The Crab pulsar

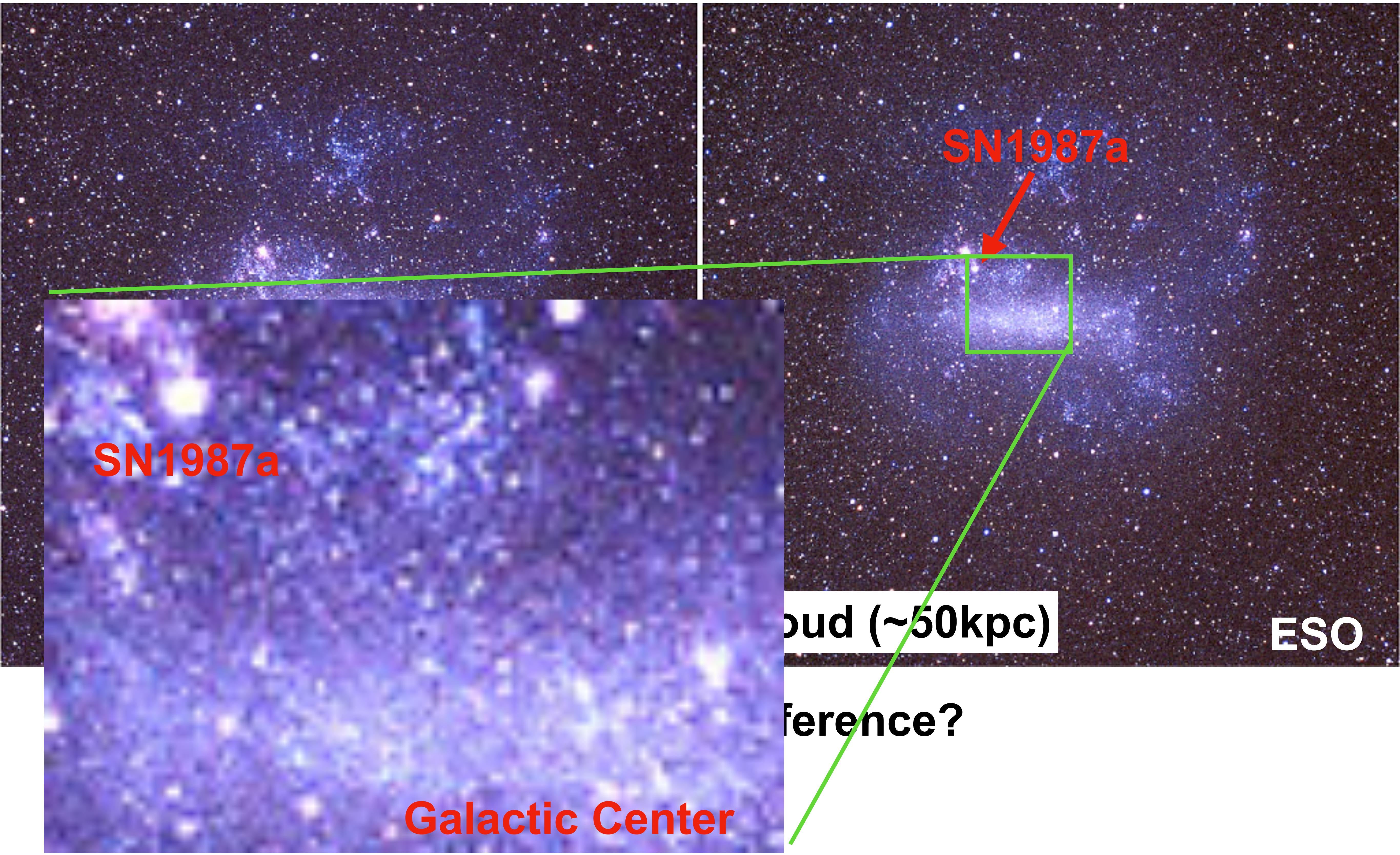
Optical: NASA/HST/ASU/J. Hester et al.
X-Ray: NASA/CXC/ASU/J. Hester et al.

Another example: SN1987a

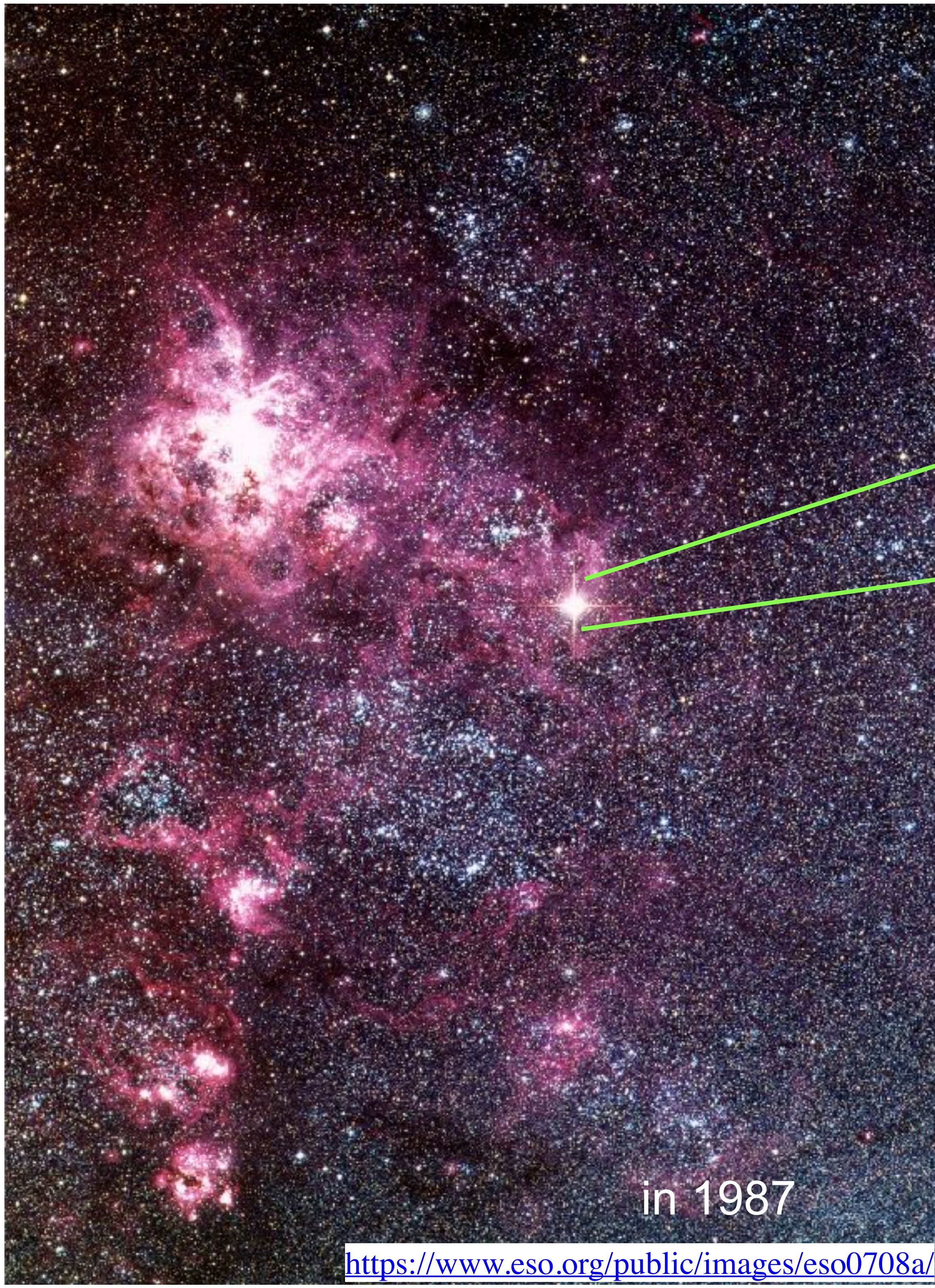


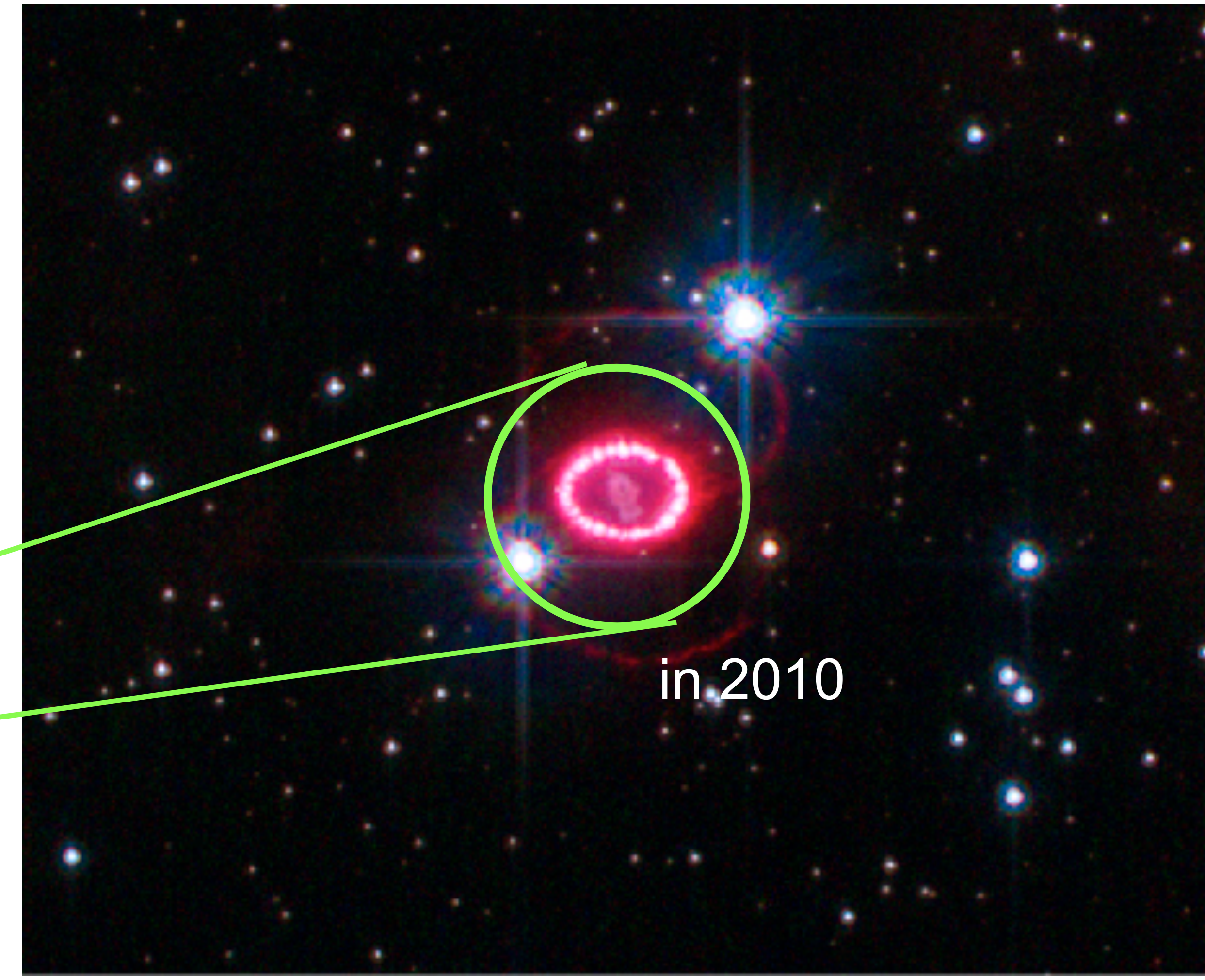
Can you find difference?

Another example: SN1987a



Another example: SN1987a



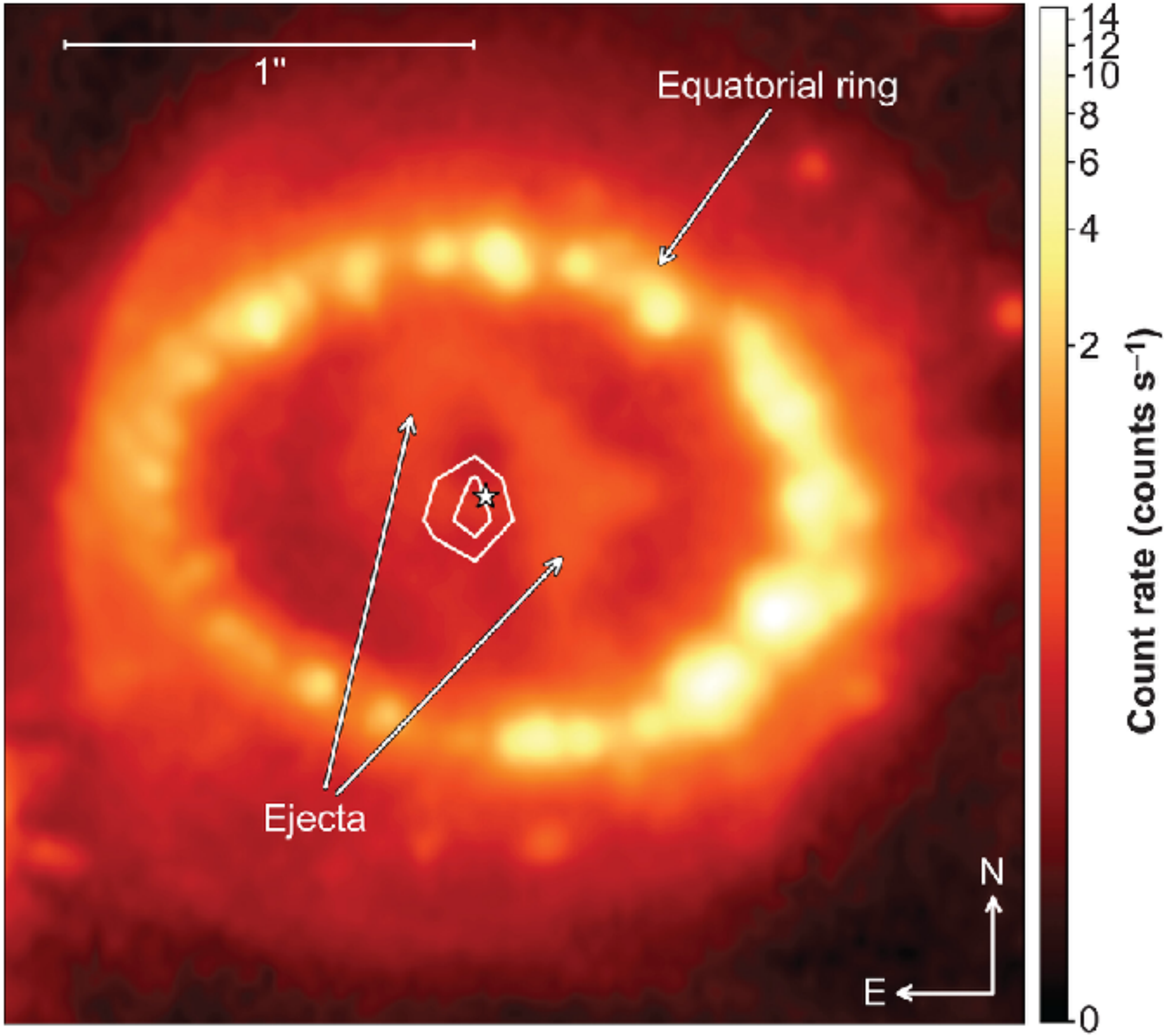


NASA Goddard Space Flight Center

SN1987a was expected to leave a NS (not BH) behind. But so far no evidence of NS……

This *__was__* one of mysteries in the SN theory.

Another example: SN1987a



Fransson+, 2024, Science

But recently…

An evidence of neutron star in the remnant of SN1987a(!?)

Short summary of SNe

from observational side

1. **Huge explosion of massive stars.**
   * **Their brightness 1SN~1Galaxy.**
2. **SNe leave behind a compact star.**
   * **NS or BH or some exotic stars(?)**

There are indeed more observable properties such as:

- various optical spectrums to classify the SN type
- neutrinos(SN1987a)
- GWs(yet-to-be-detected)

Outline

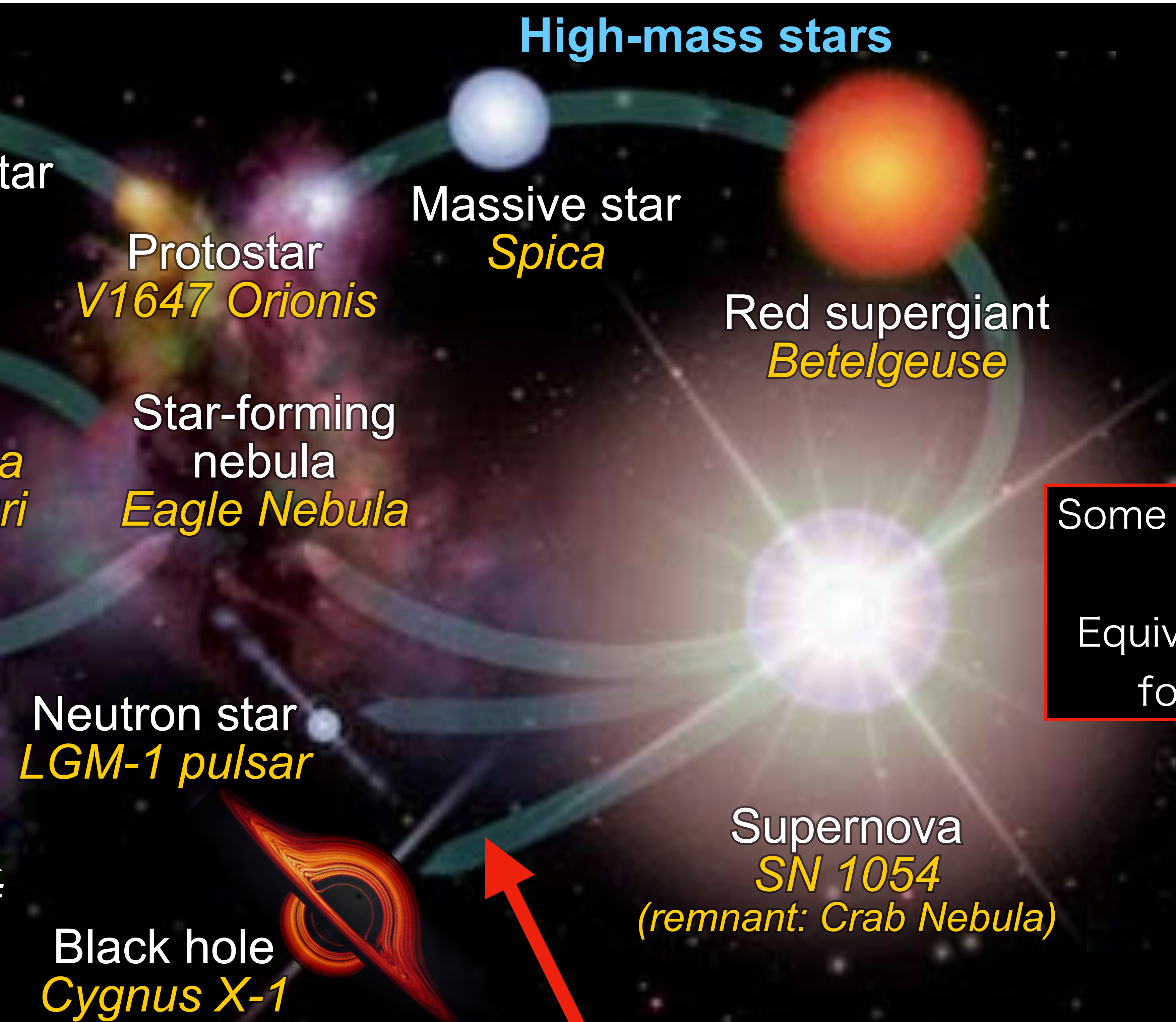
1: SN from observational side

2: SN from theoretical side

3: SN engine: Neutrino heating

4: Progenitor and remnant property

The remnant *mass* of massive stars

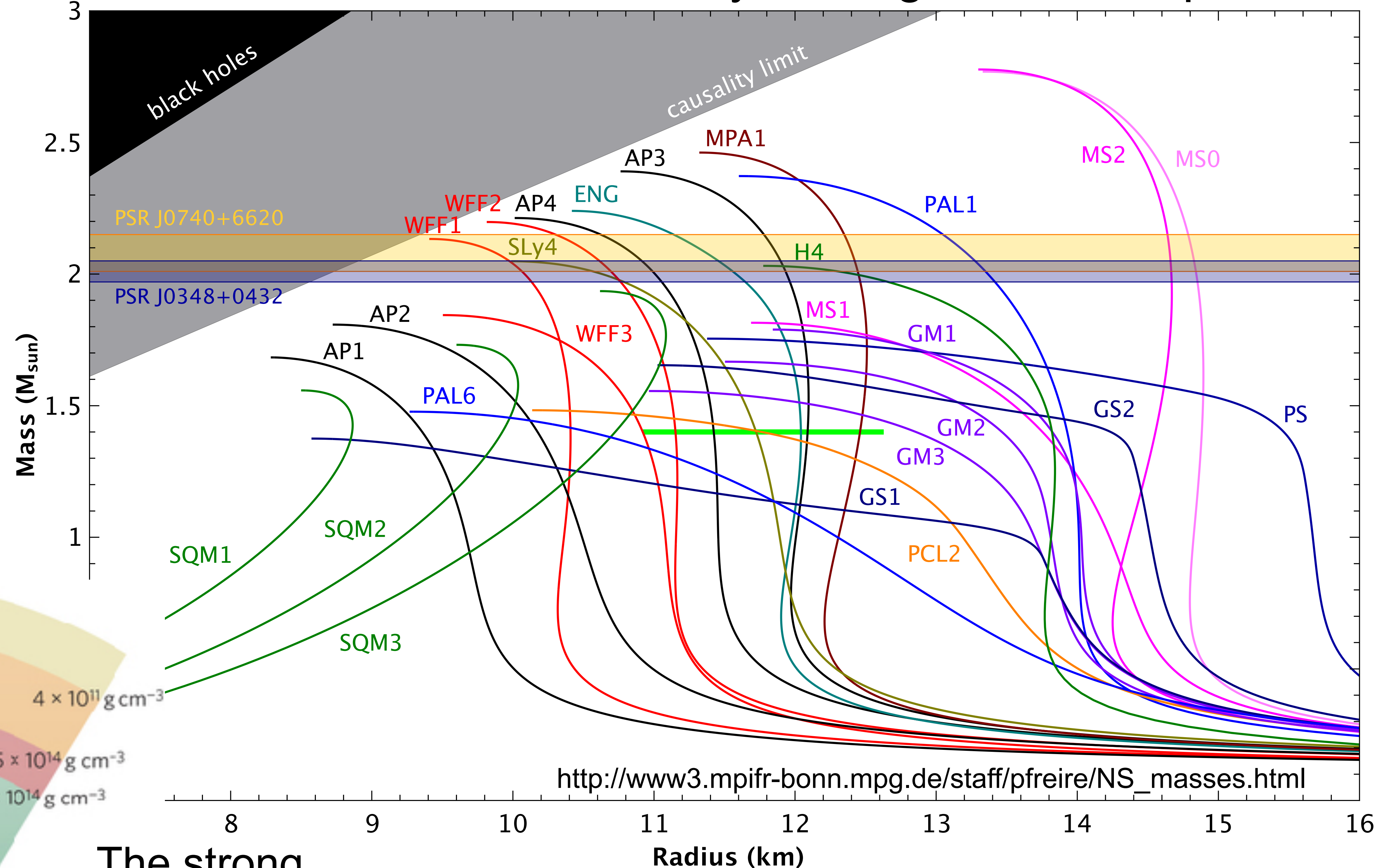


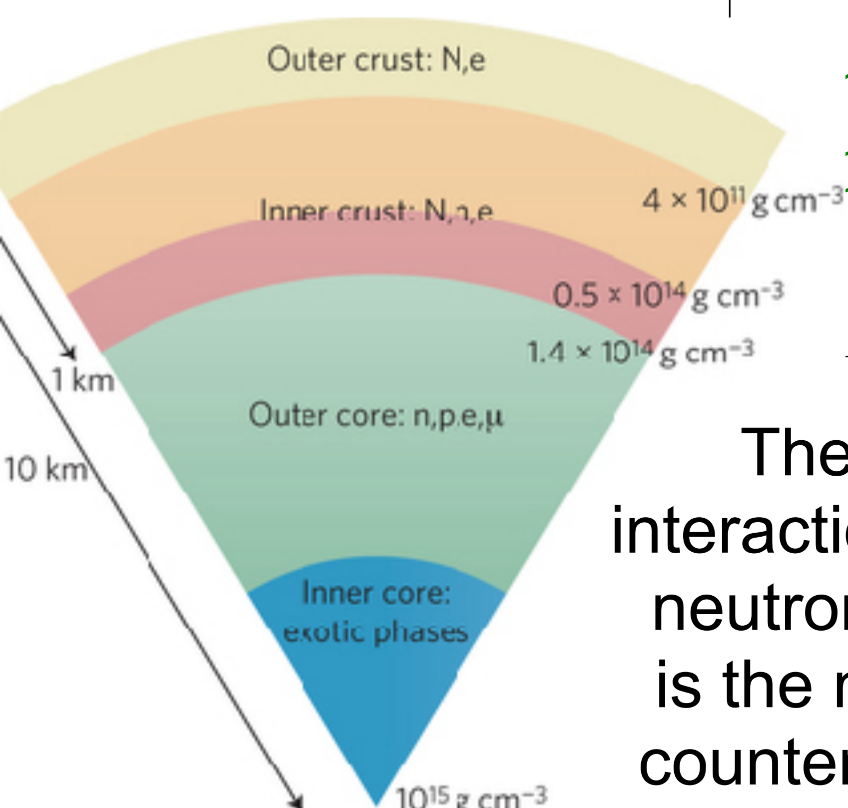
Some fractions (from 0 to <100%) of the star are ejected.
Equivalently, the remaining matters form the remnant: NS or BH.

C.f. WD (Type Ia SN) and very massive stars (>a few 100Msun) can explode the entire star, i.e. 100% mass ejection.

But what determines the BH or other branch?

The MR relation obtained by solving the TOV equation



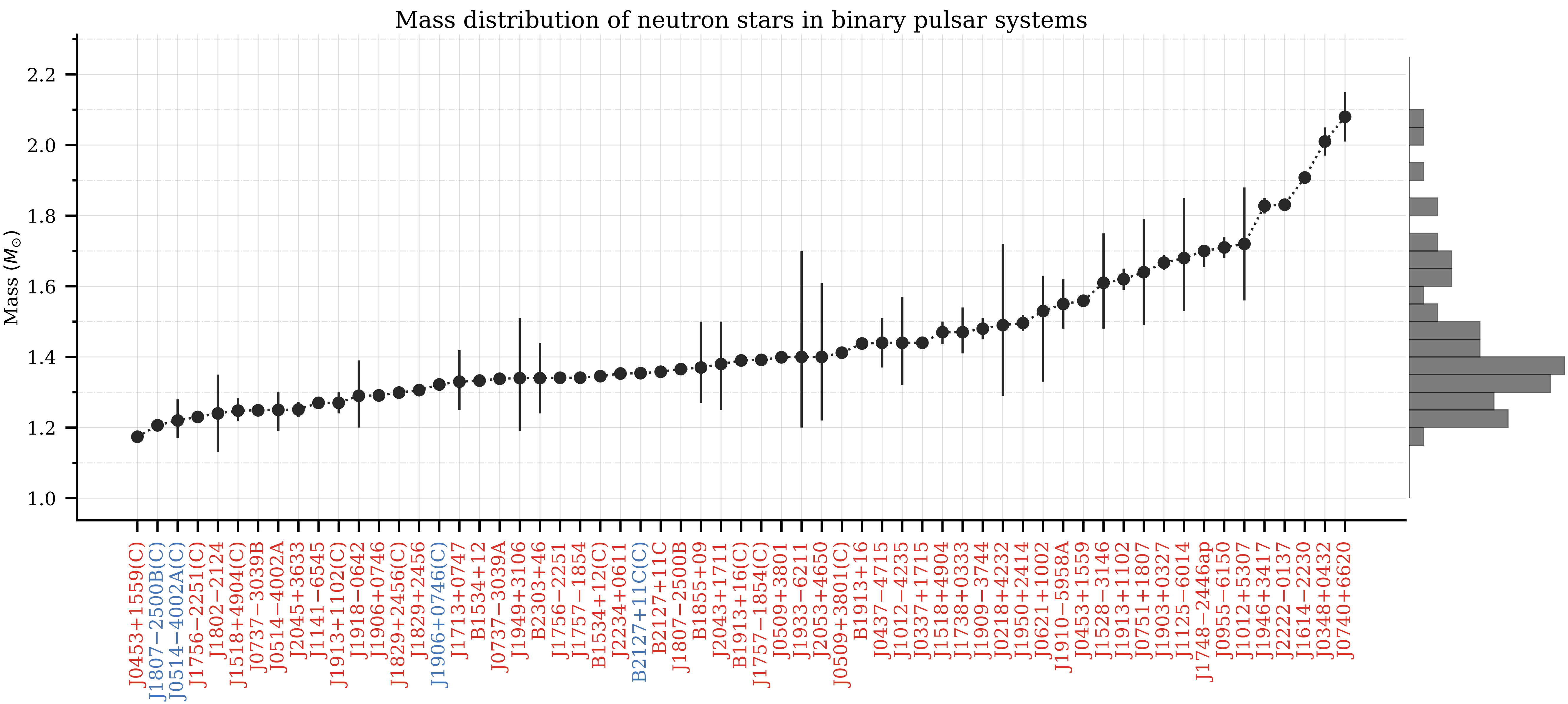


Caplan&Horowitz, 2017

The strong interaction between neutron & proton is the main force countervailing the gravitational force.

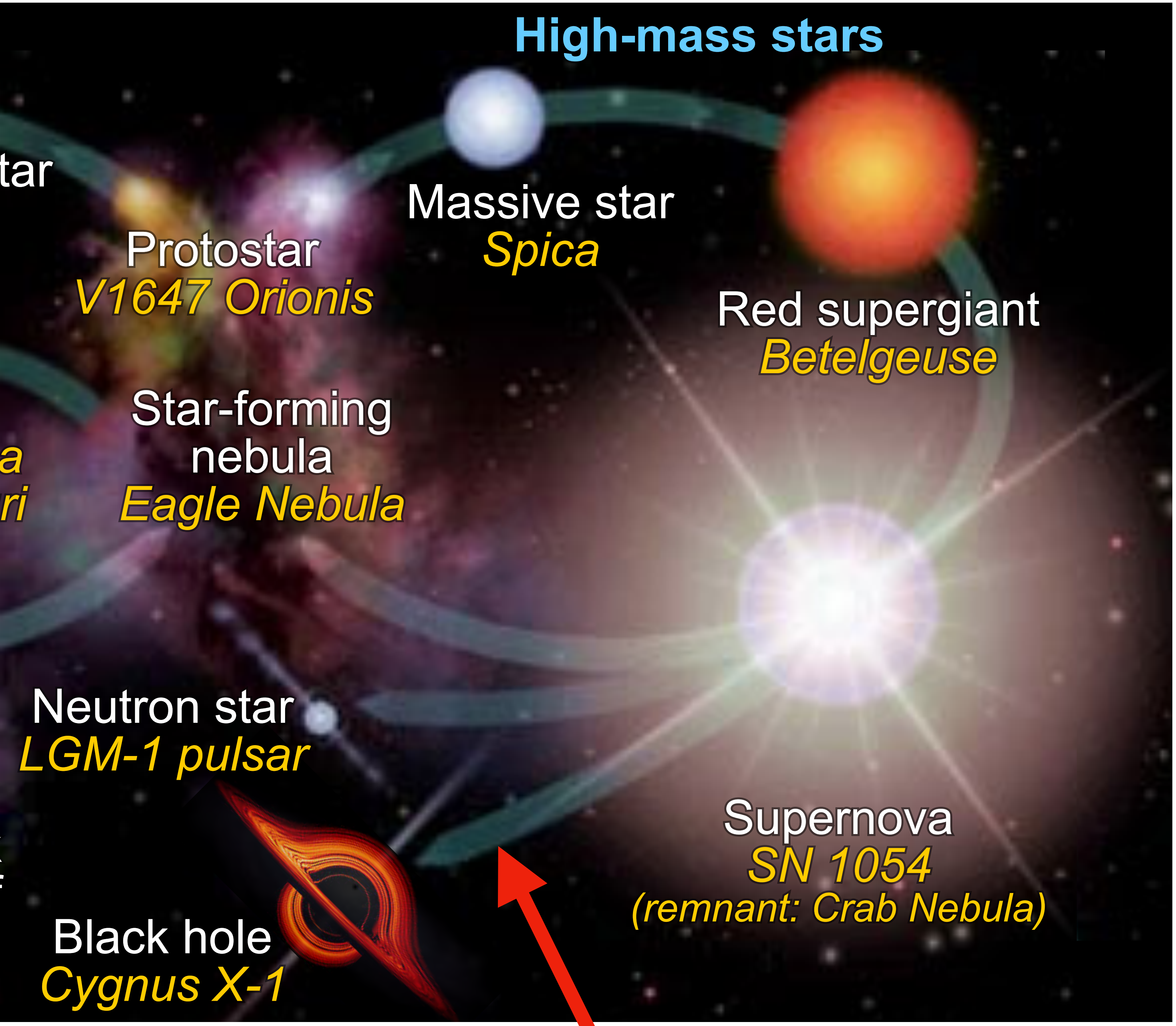
The maximum NS mass is likely to be ~3M_{sun}.

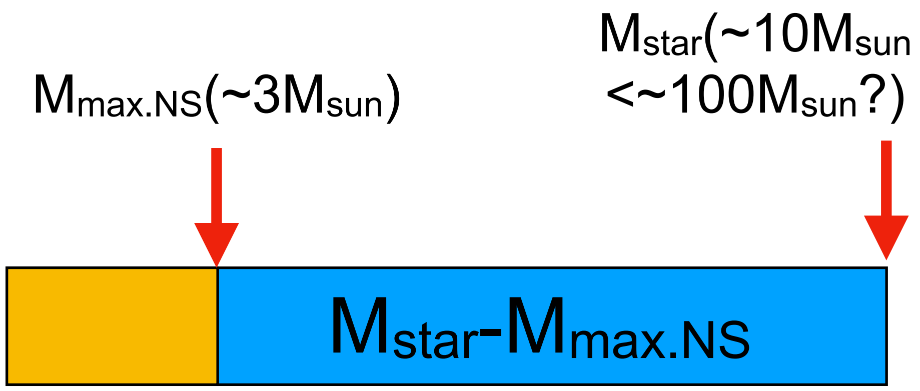
I.e. if the remnant mass exceeds that threshold, the remnant becomes BH.



Source: https://www3.mpifr-bonn.mpg.de/staff/pfreire/NS_masses.html

The remnant *mass* of massive stars





The remnant is NS, if M_{star}-$M_{max.NS}$ can be ejected. Otherwise BH.

But what determines the NS or BH branch?

Short summary of SNe

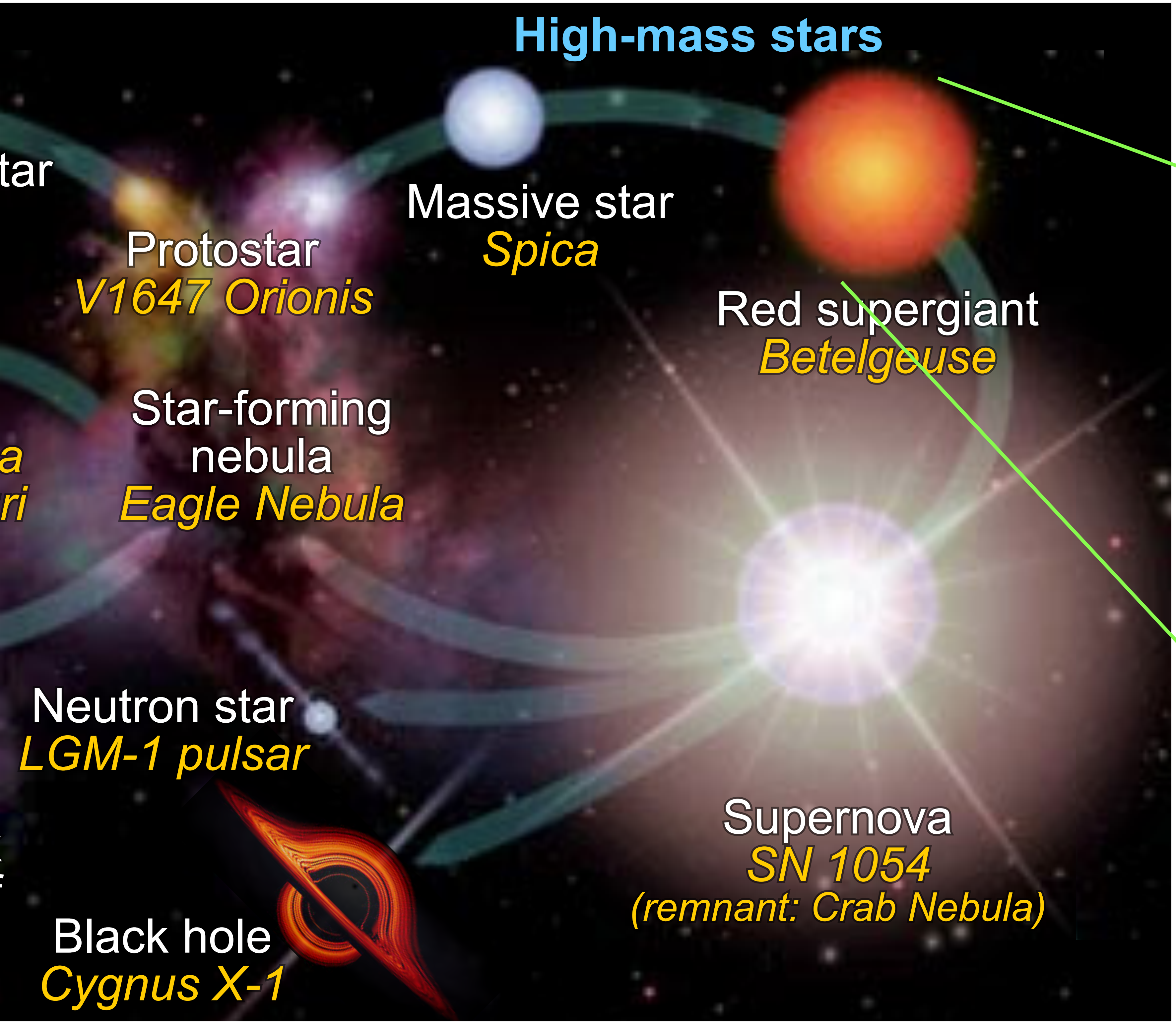
from observational side

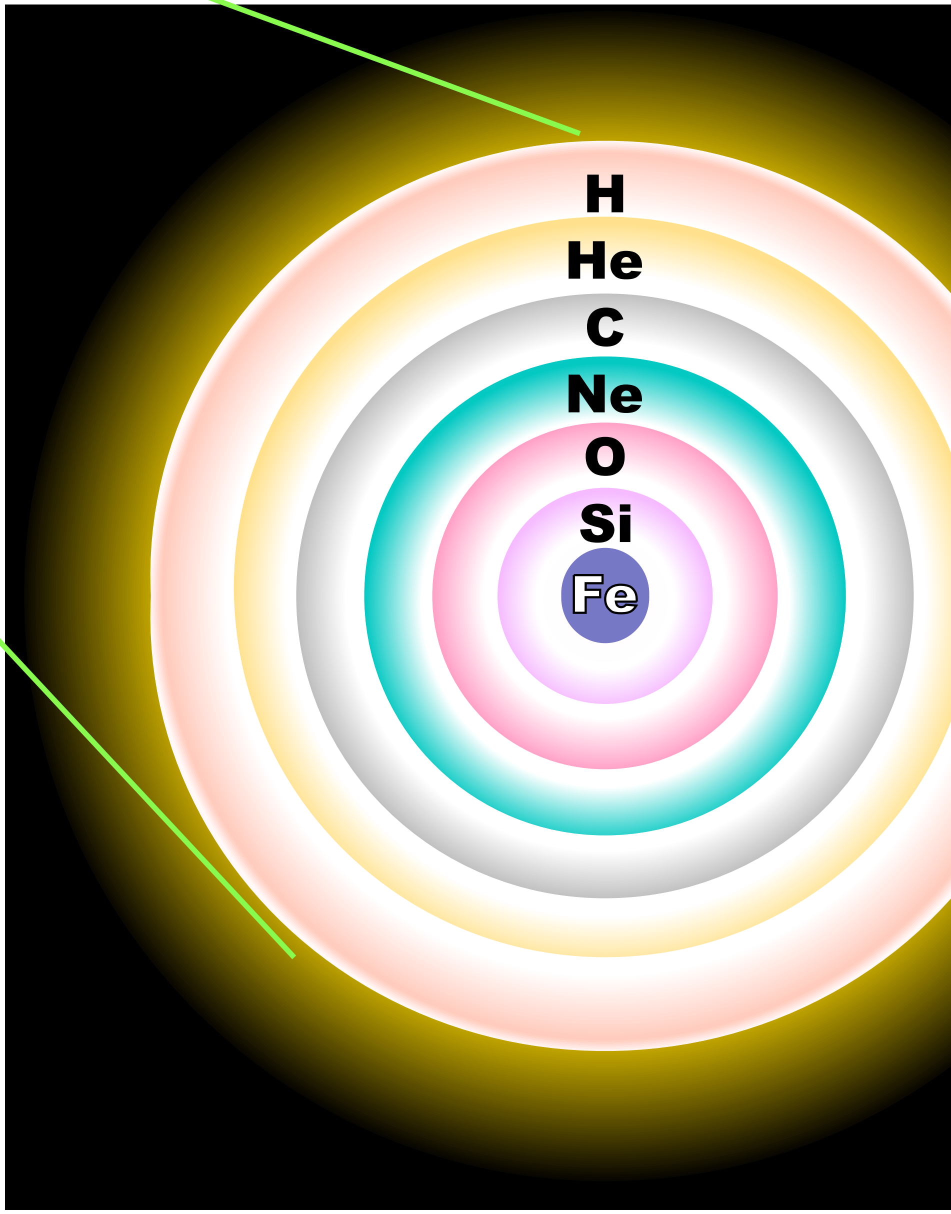
1. Huge explosion of massive stars.
   * Their brightness 1SN~1Galaxy.
2. SNe leave behind a compact star.
   * NS or BH or some exotic stars(?)

from theoretical side

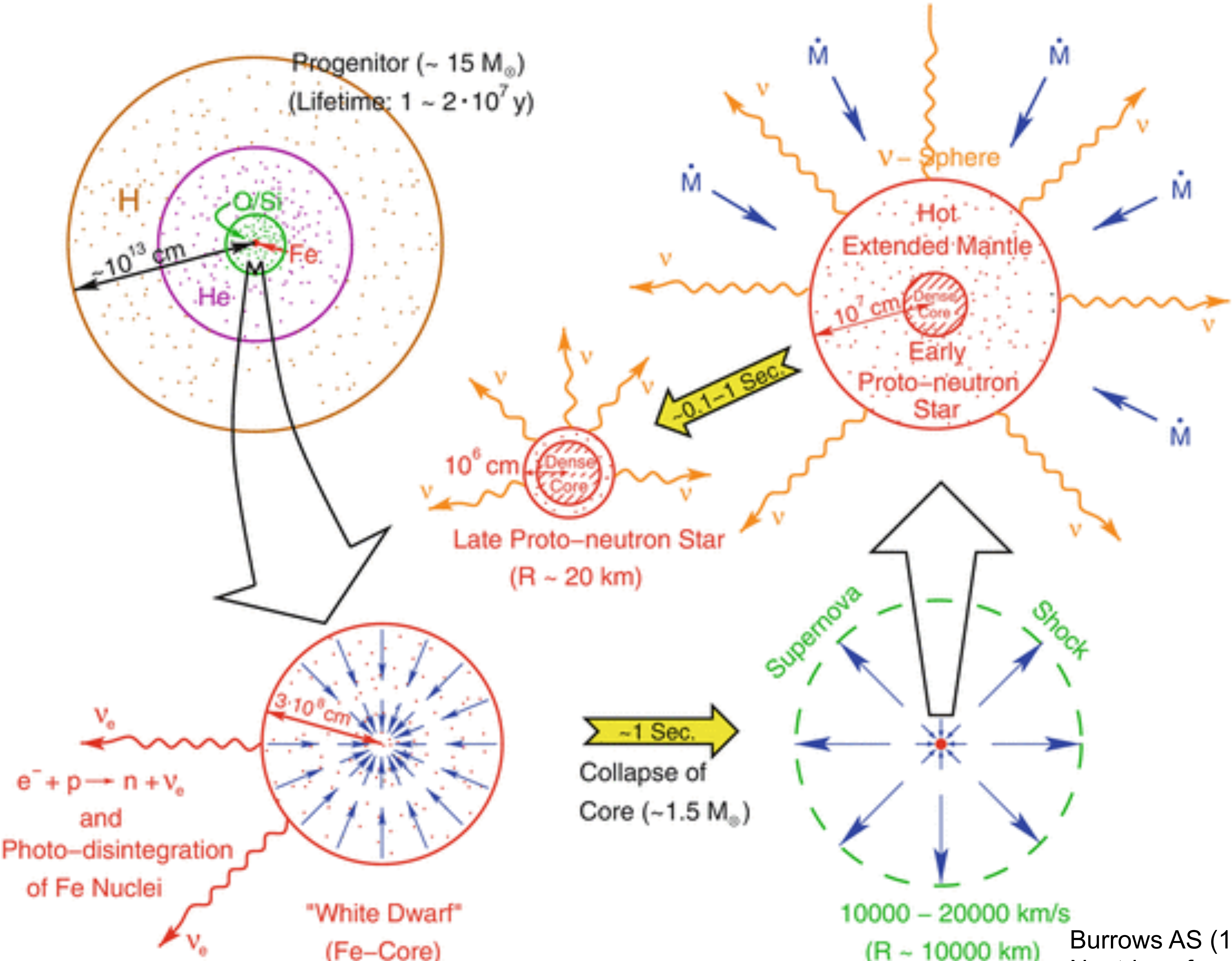
3. The explosion should blow off "M_{star}-$M_{max.NS}$" to explain the NS formation branch.
4. If fails, the BH formation.

The fate of massive stars

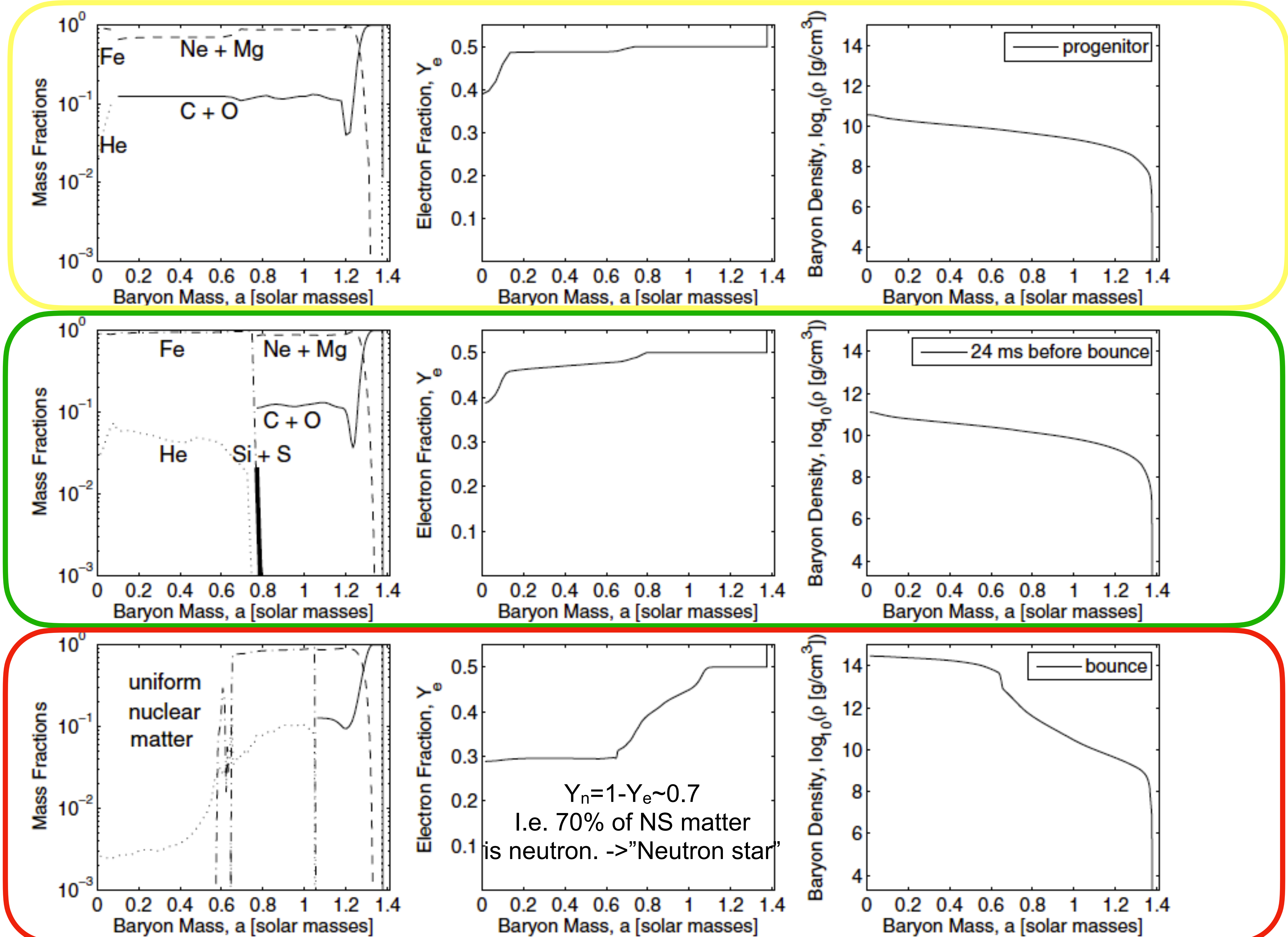




The fate of massive stars (>~10M_{sun})



Burrows AS (1990b)
Neutrinos from supernovae.

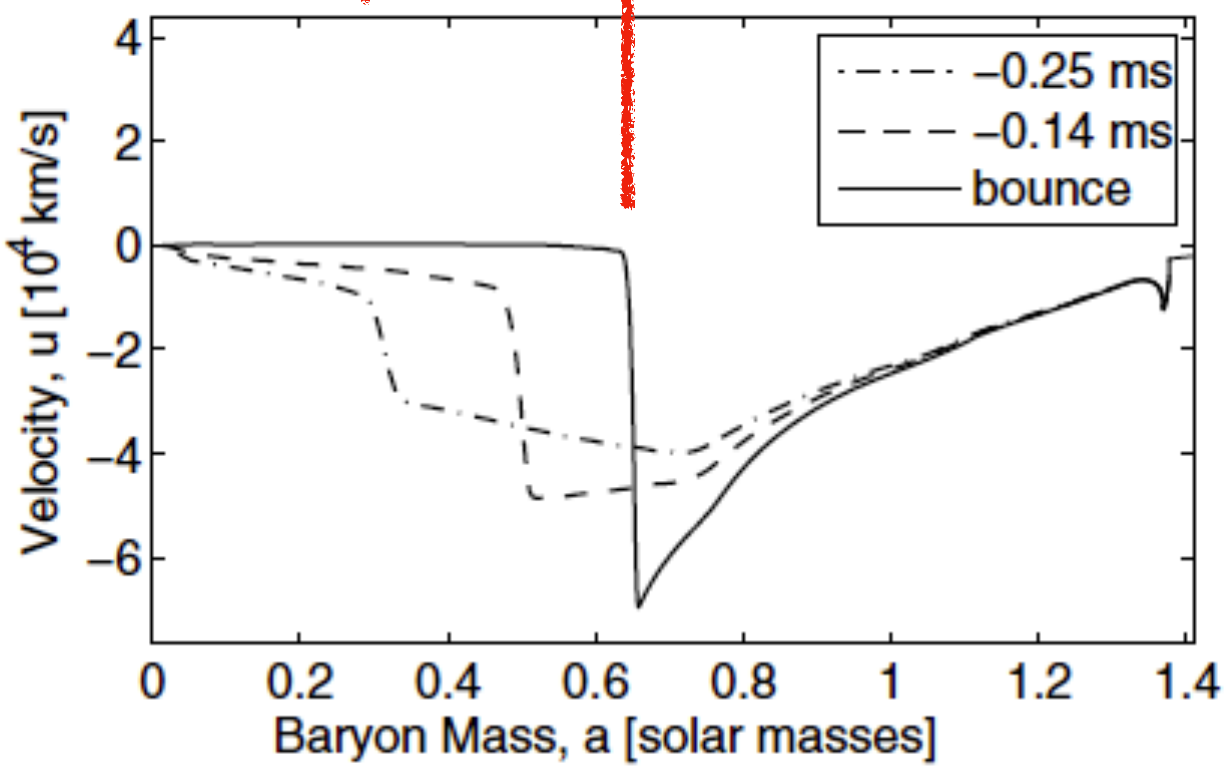


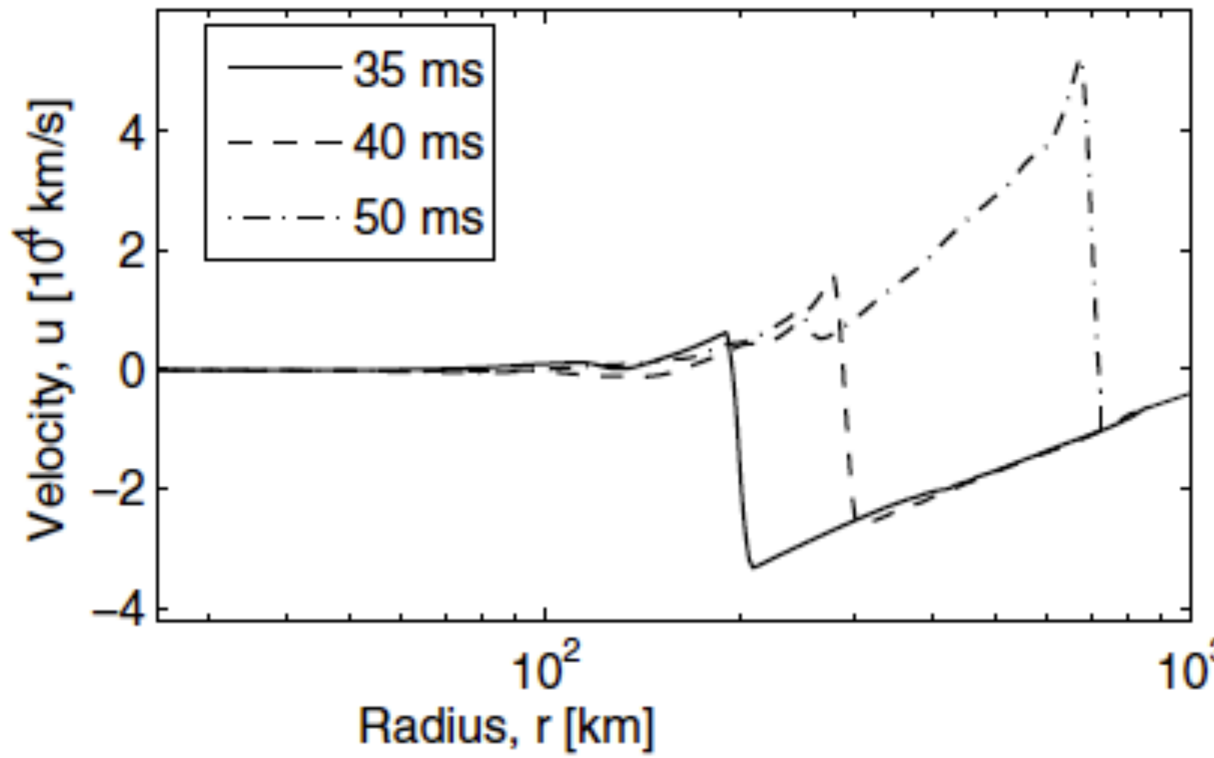
Mass Fractions
Fe
Ne + Mg
C + O
He
Electron Fraction, Y_e
Baryon Density, $\log_{10}(\rho\ [g/cm^3])$
progenitor
Baryon Mass, a [solar masses]
Fe
Ne + Mg
C + O
He
Si + S
24 ms before bounce
uniform
nuclear
matter
bounce
$Y_n = 1 - Y_e \sim 0.7$
I.e. 70% of NS matter
is neutron. ->"Neutron star"

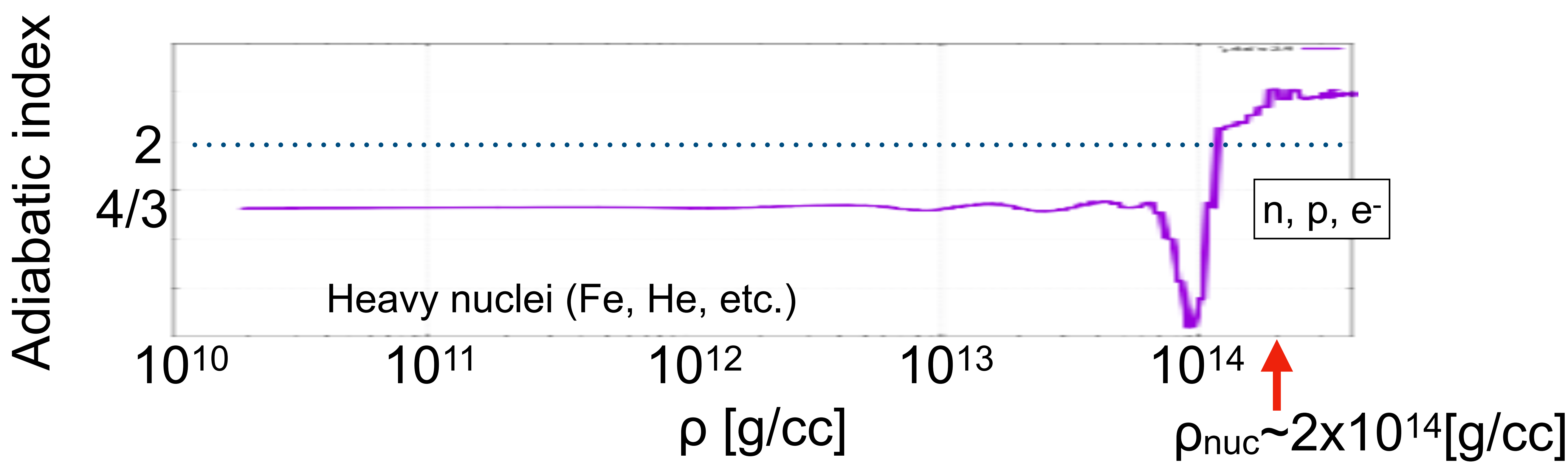
Fischer+,'10

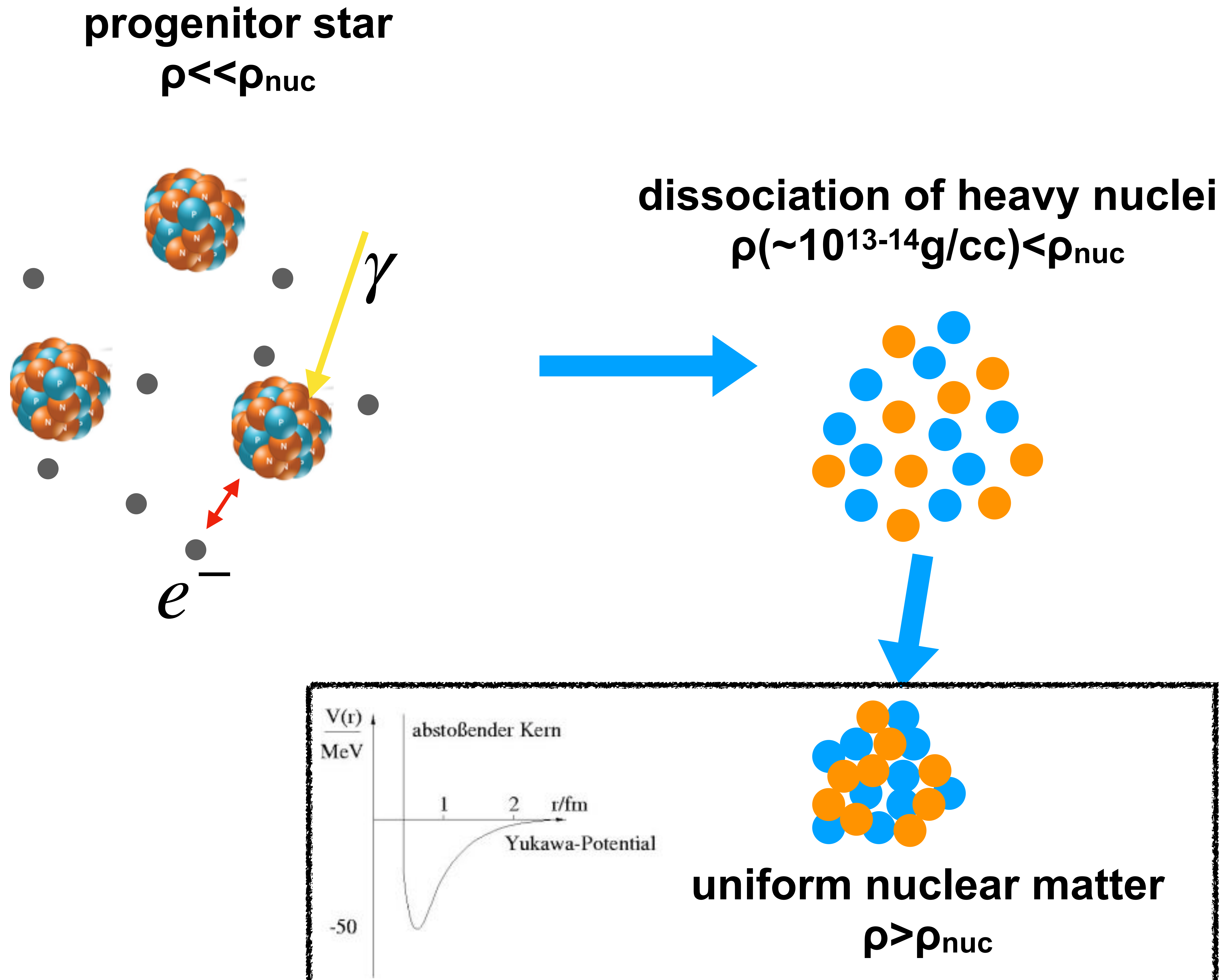
uniform nuclear matter
i.e. n, p, e- & neutrinos

8.8M$_{sun}$ of Fischer+,'10

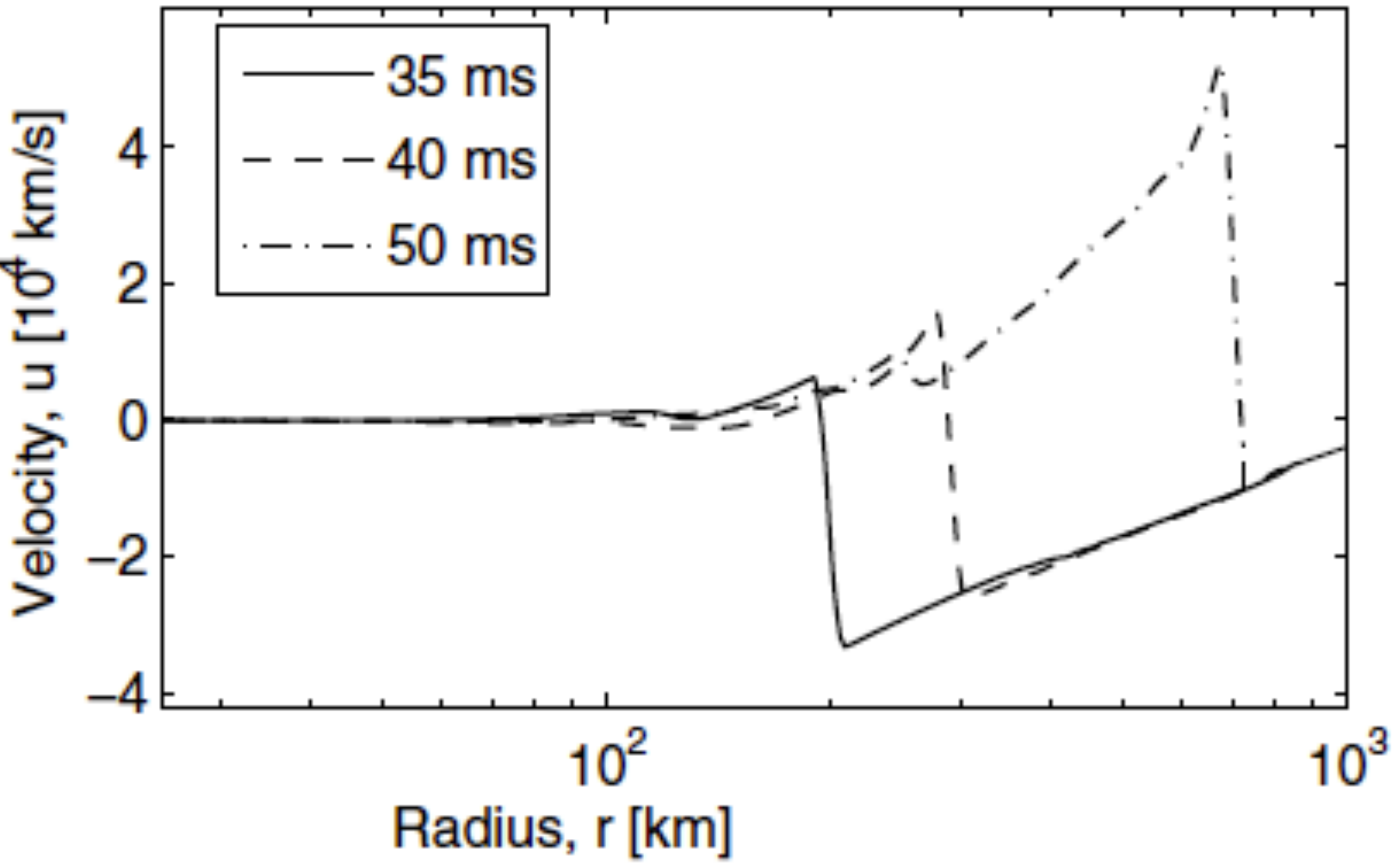







progenitor star
ρ<<ρnuc
γ
e−
dissociation of heavy nuclei
ρ(~10^13-14 g/cc)<ρnuc
V(r)
MeV
abstoßender Kern
1
2
r/fm
Yukawa-Potential
-50
uniform nuclear matter
ρ>ρnuc

8.8M_{sun} of Fischer+,'10

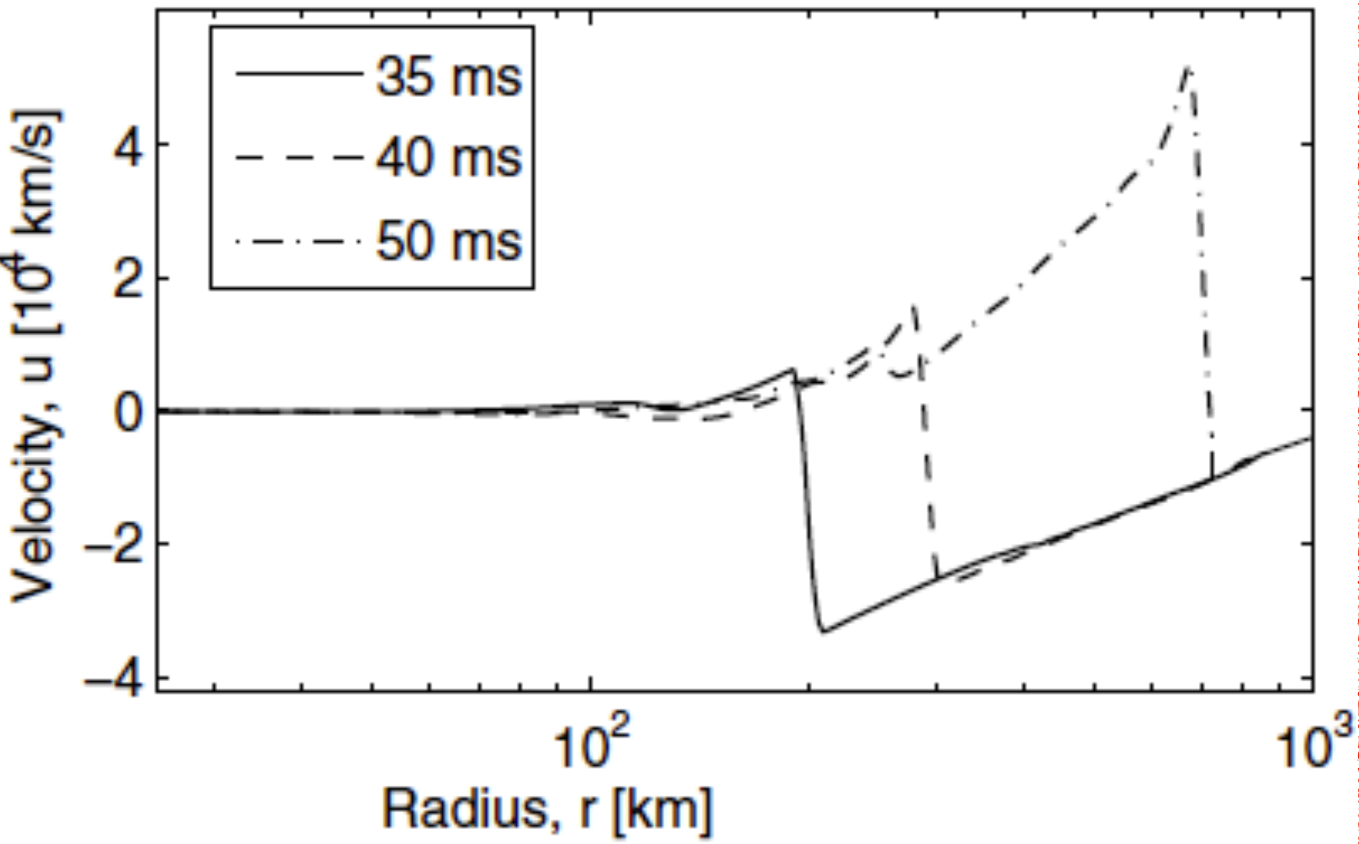


The explosion driven
by the elastic bounce of NS.

However, this mechanism works
only for light progenitor stars.
E.g., ~8.8M_{sun} (Kitaura&Janka, '05)

light progenitor stars

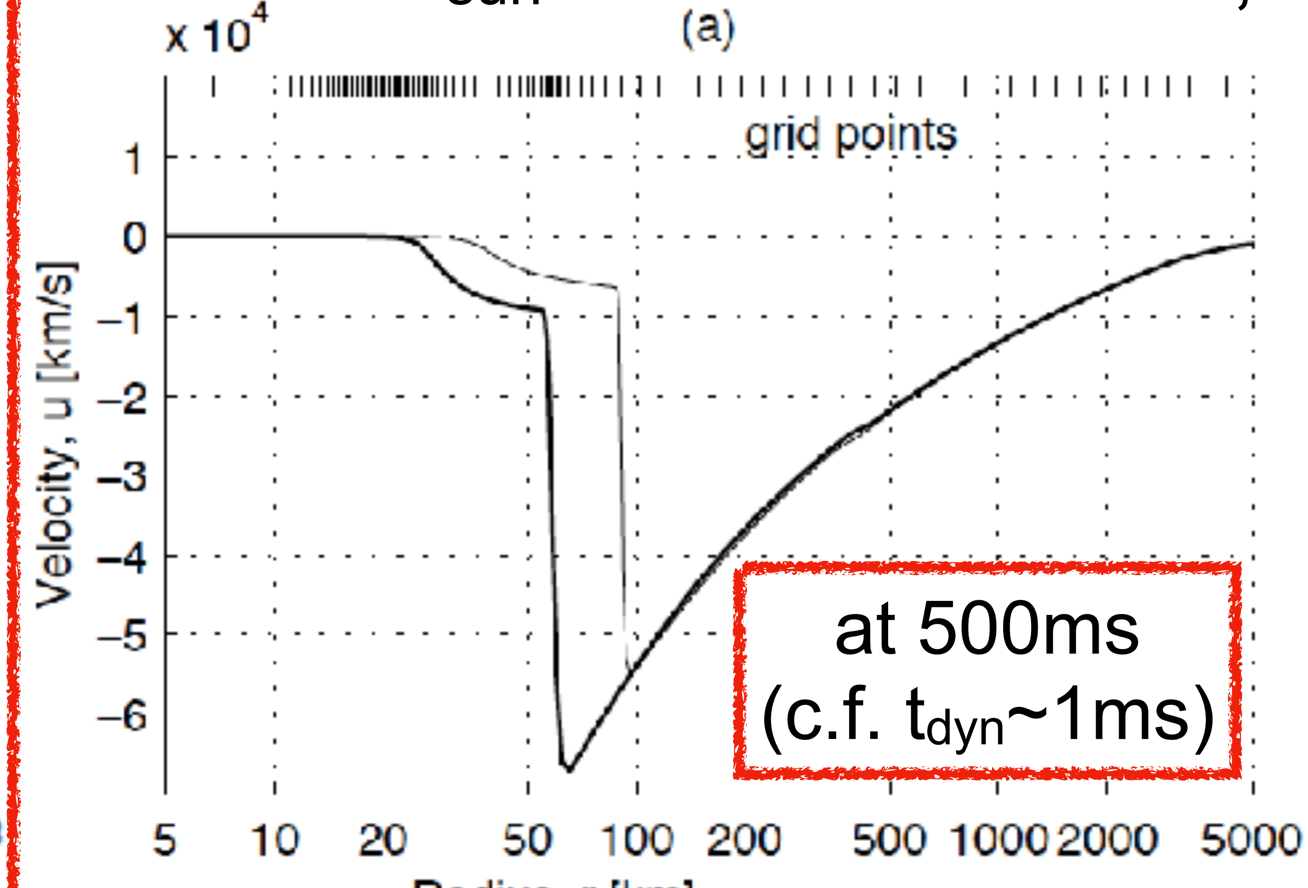
$8.8M_{sun}$ of Fischer+,'10

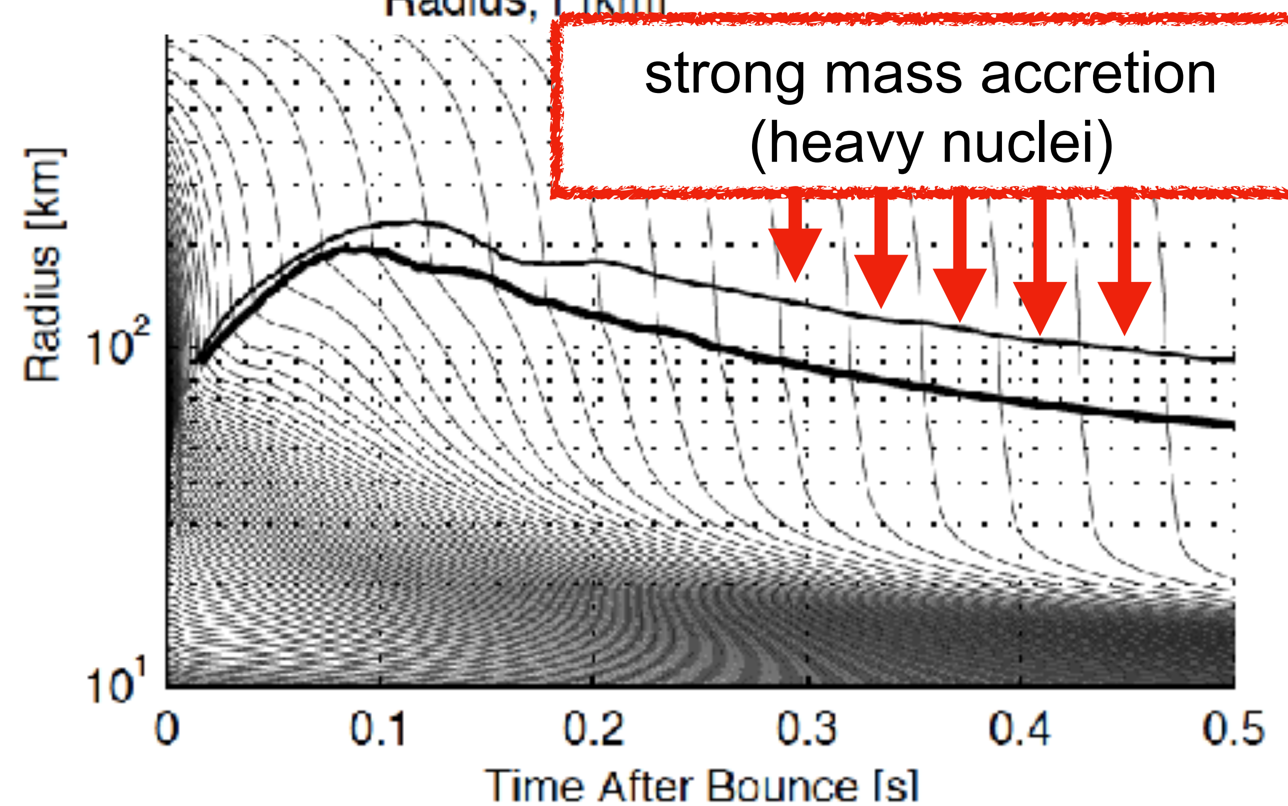


- **The elasticity of NS (i.e. a gigantic nuclei) alone cannot explode all massive stars.**
- ***Prompt explosion*** **may work only for some low mass stars (~8-10M_{sun})**

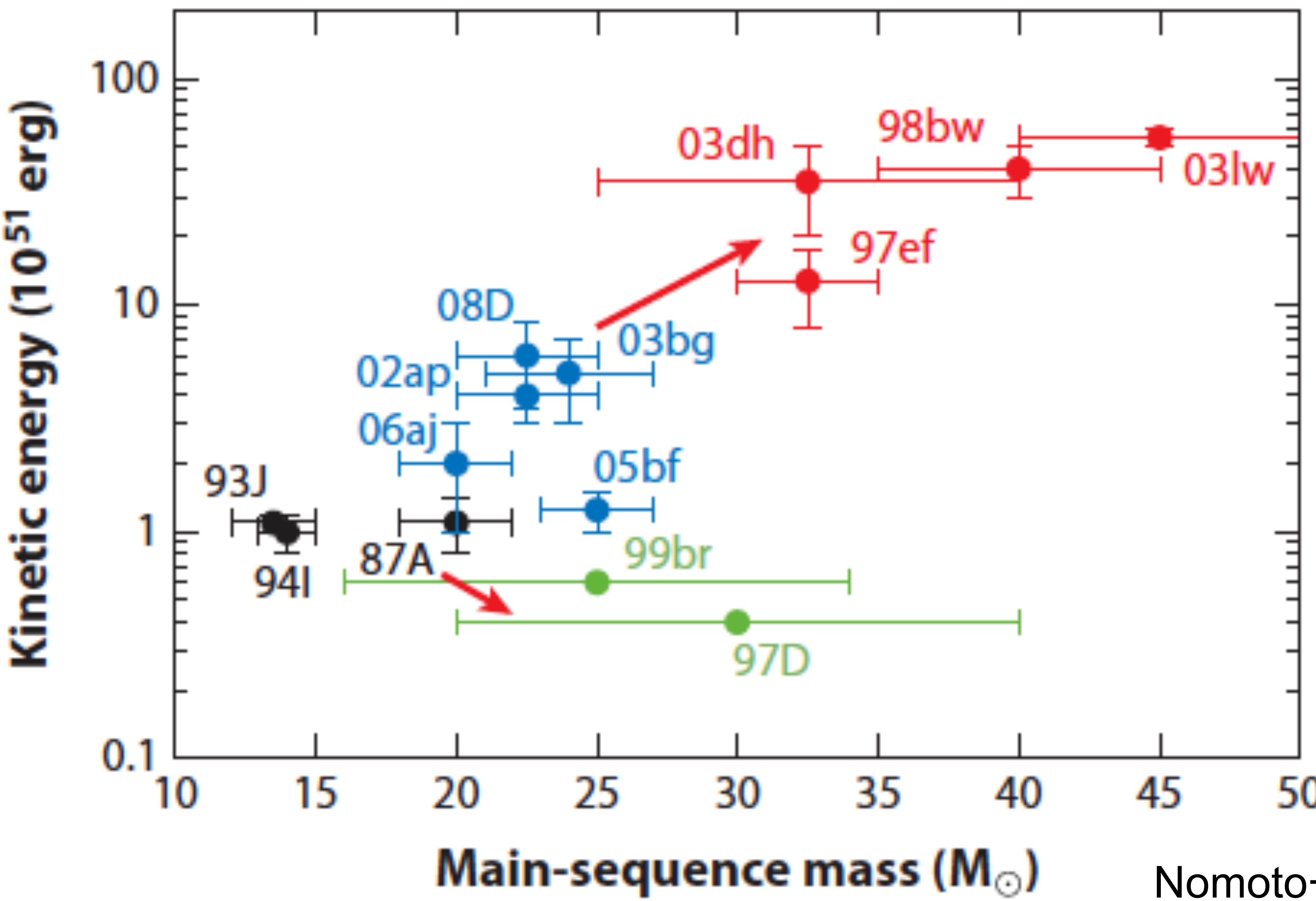
heavy progenitor stars

$13M_{sun}$ of Liebendörfer+,'01





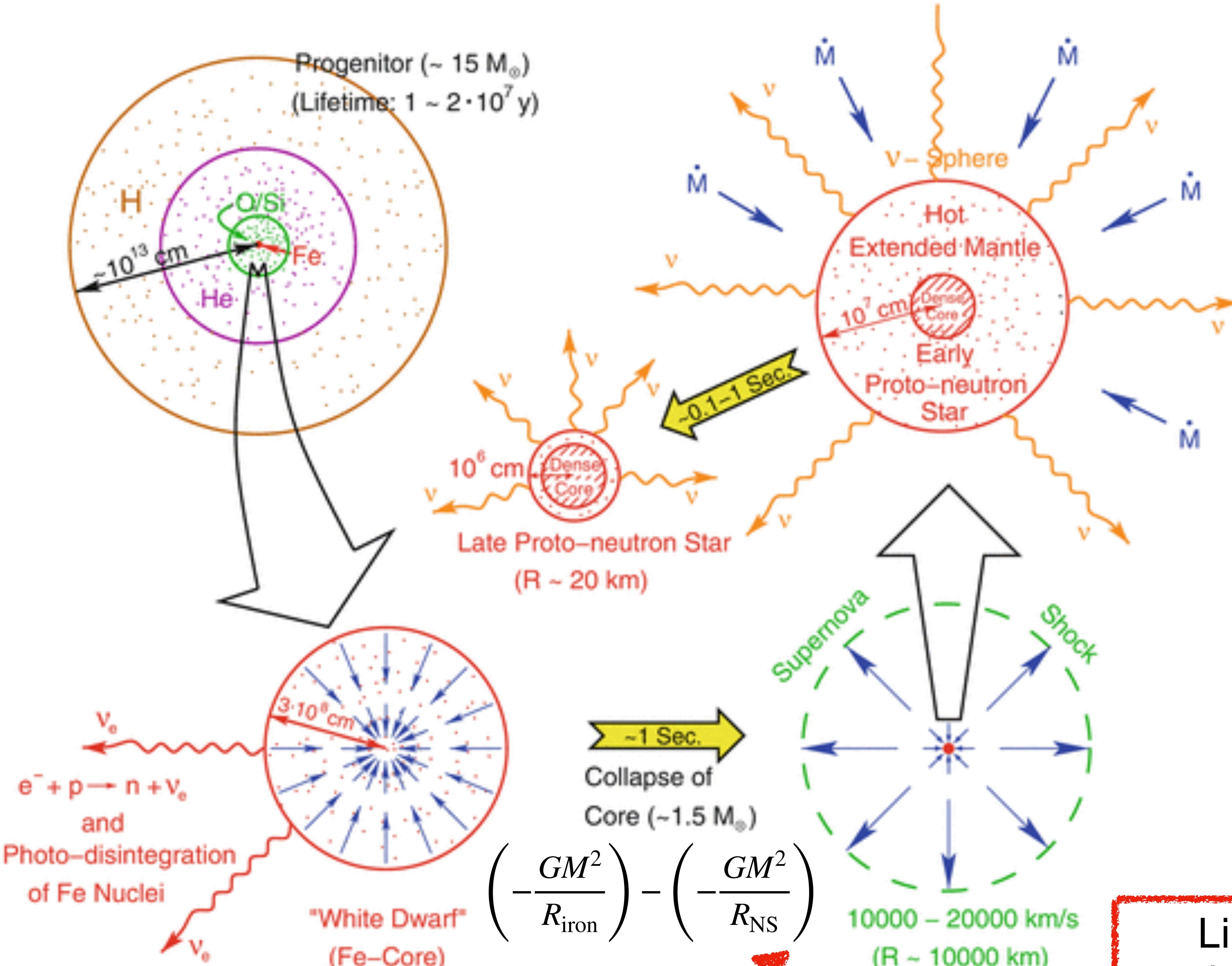
But there are many SNe with $M>10M_{sun}$



Nomoto+, '13

How can we explain these observations?

What is the ultimate energy source of SNe?



$$\left(-\frac{GM^2}{R_{\rm iron}}\right) - \left(-\frac{GM^2}{R_{\rm NS}}\right)$$

Liberation of gravitational binding energy of ~10^{53} erg

Burrows AS (1990b) Neutrinos from supernovae.
In: Petschek AG (ed) Supernovae. Springer, New York, pp 143–181

The breakdown of energies in the proto-neutron star

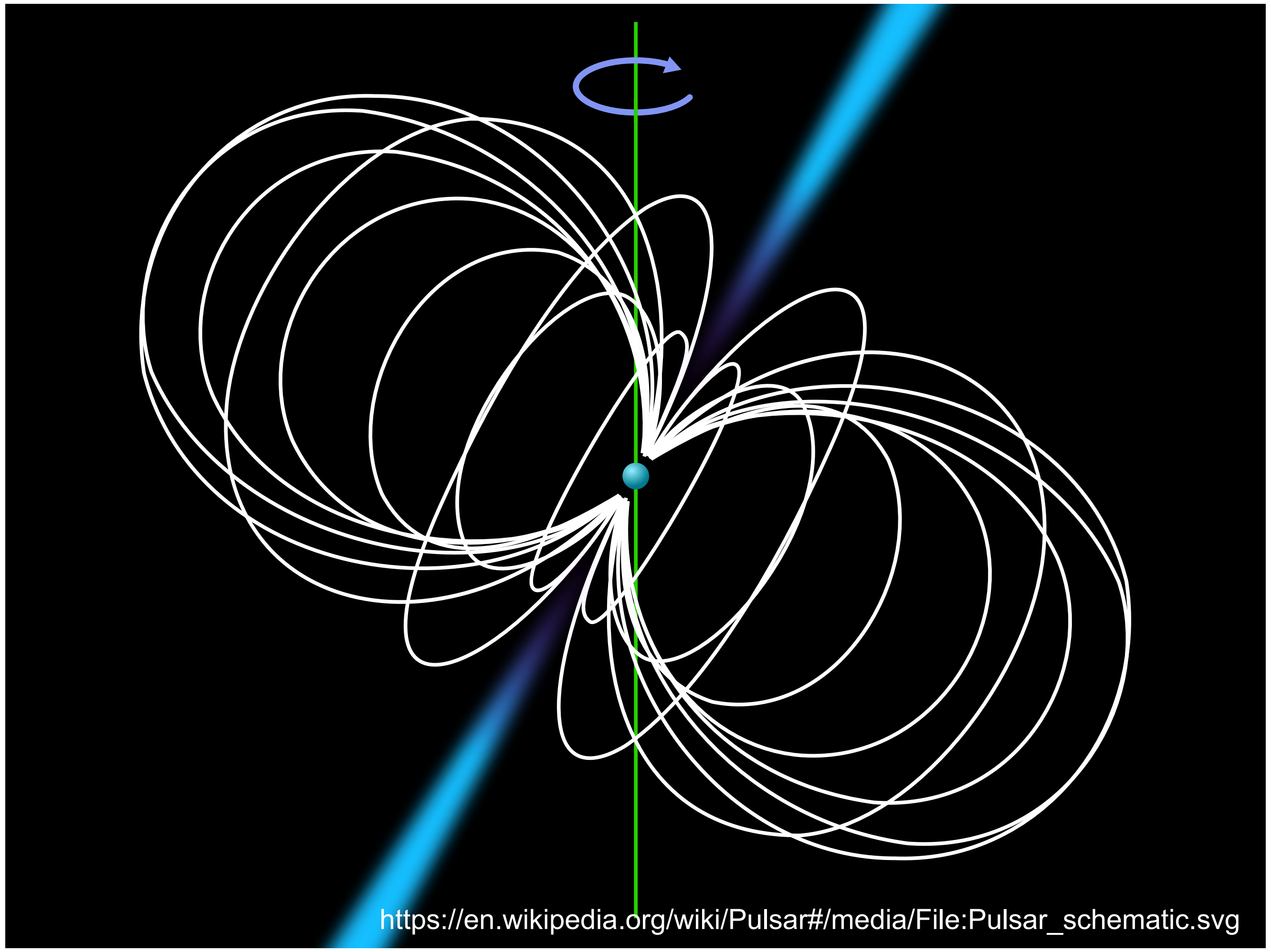
$$\left(-\frac{GM^2}{R_{\rm iron}}\right)-\left(-\frac{GM^2}{R_{\rm NS}}\right) \approx \text{ a few} \times 10^{53} \text{ ergs}$$

$$M \approx M_\odot$$
$$R_{\rm iron} \approx 10^8 \text{ cm}$$
$$R_{\rm NS} \approx 10^6 \text{ cm}$$

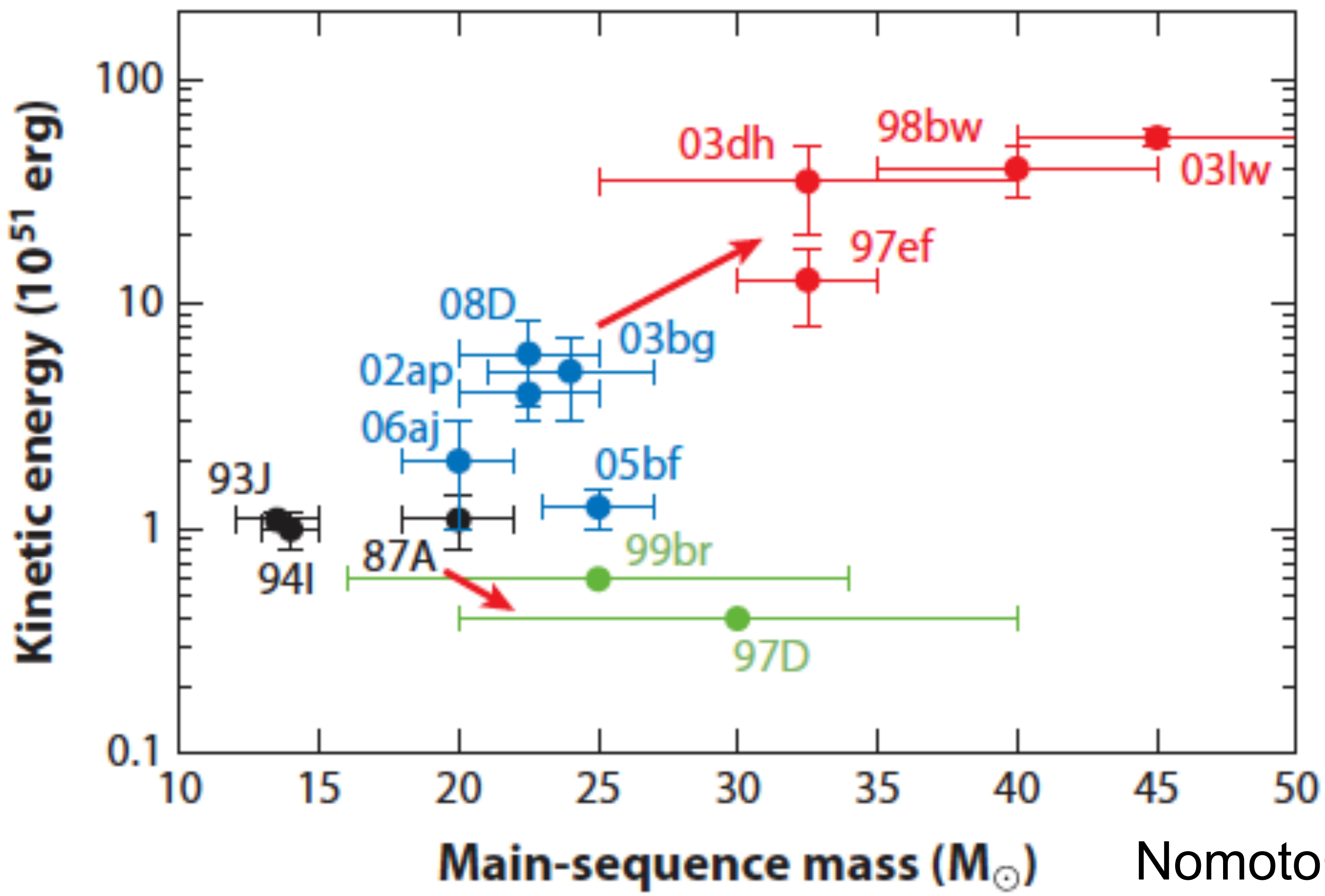
Liberation of gravitational binding energy of ~10^{53} erg

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

What we can use to explode the star are these three energy sources.



The fundamental question: What mechanisms drive SNe?



Nomoto+, '13

The observed explosion energies are $\sim 10^{49-52}$ergs.
But hereafter we are focusing on the canonical explosion energy of 10^{51} ergs

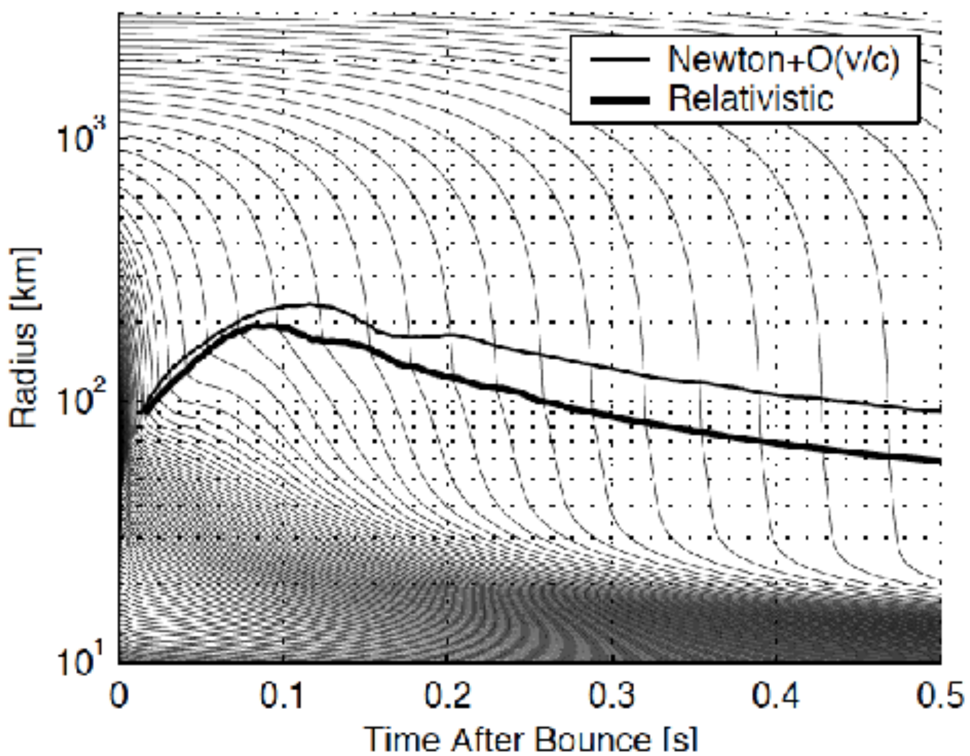
Possible SN explosion mechanisms

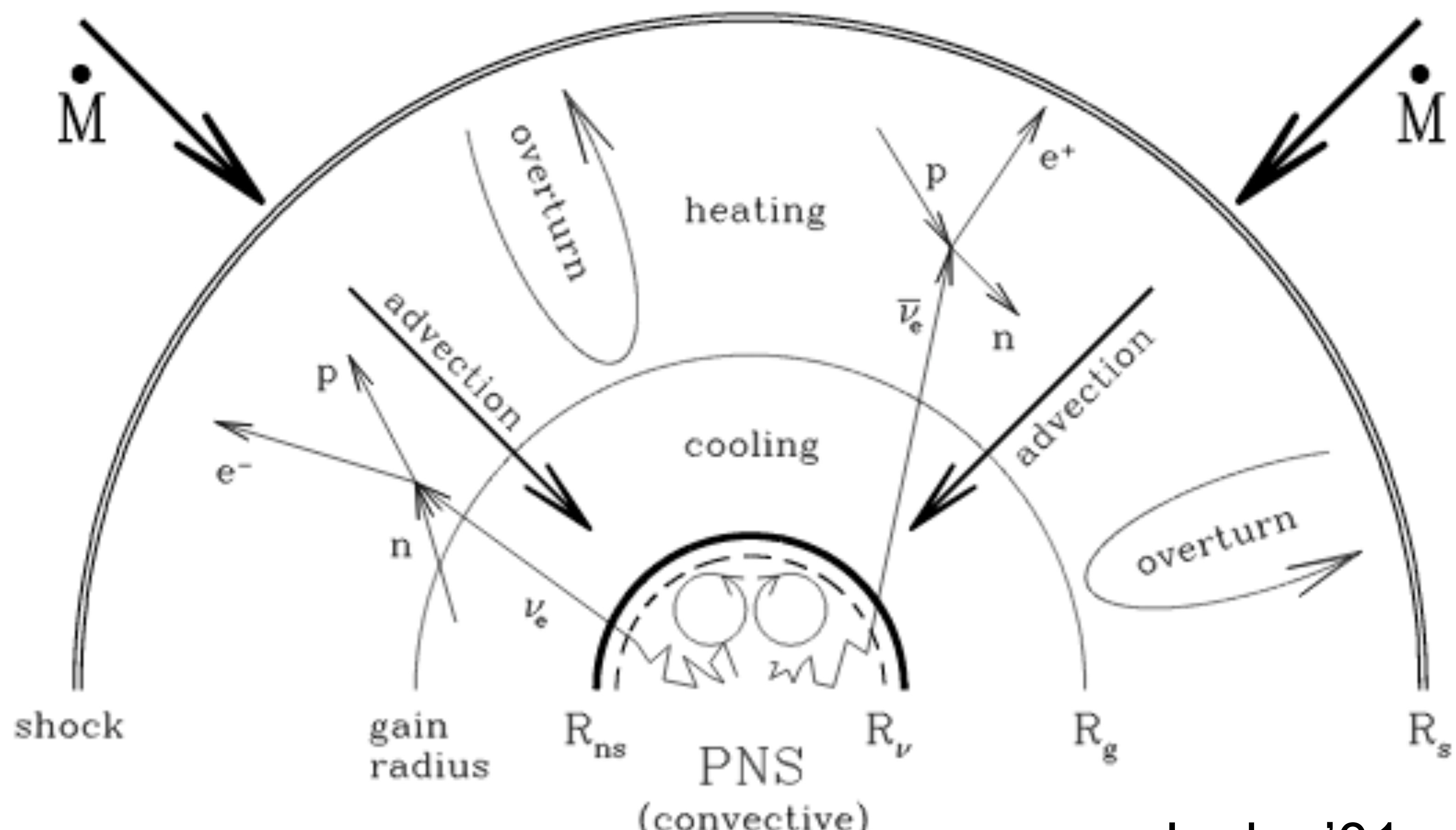
1.Neutrino driven explosion (ν-driven) For reviews, Janka'12, Kotake+,'12, Burrows+,'13

~99% of internal energy
is radiated away via neutrinos (~10^{53}ergs)

A fraction of them deposit energy behind the
stalled shock

13M_{sun} of Liebendörfer+,'01



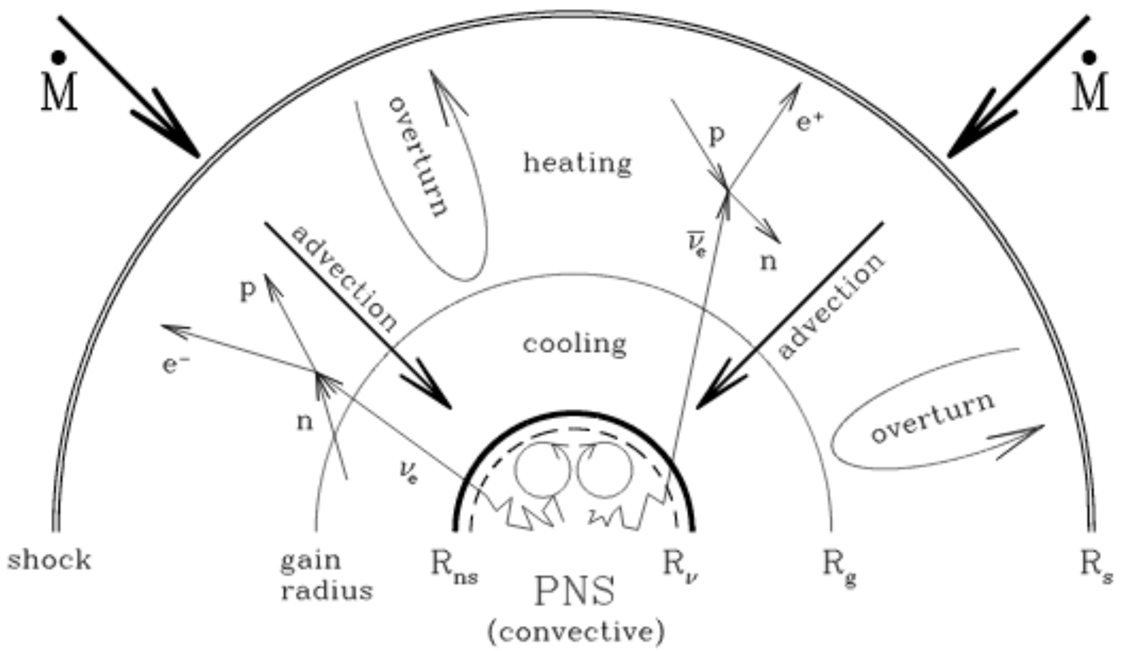


Janka,'01

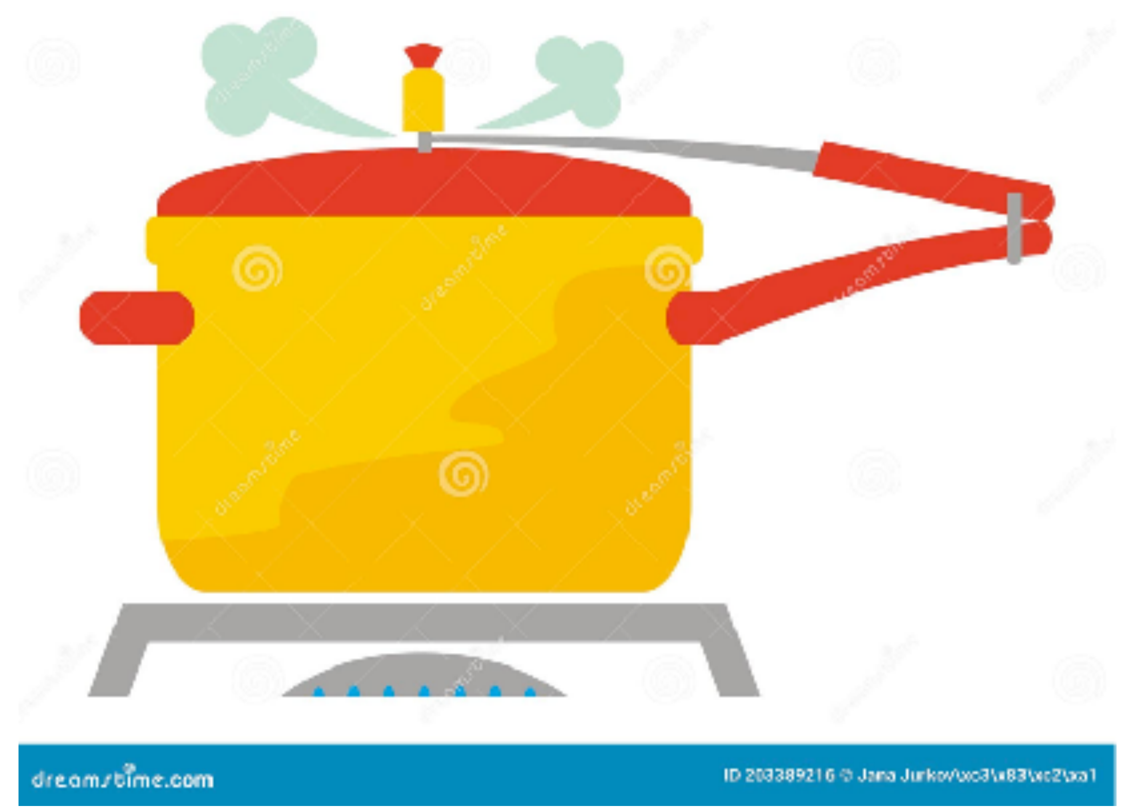
1.Neutrino driven explosion (ν-driven) For reviews, Janka'12, Kotake+,'12, Burrows+,'13

The PNS temperature is T~20MeV(~10^{11}K) !

Enormous amount of neutrinos (~10^{56} /s) are radiated away from PNS.



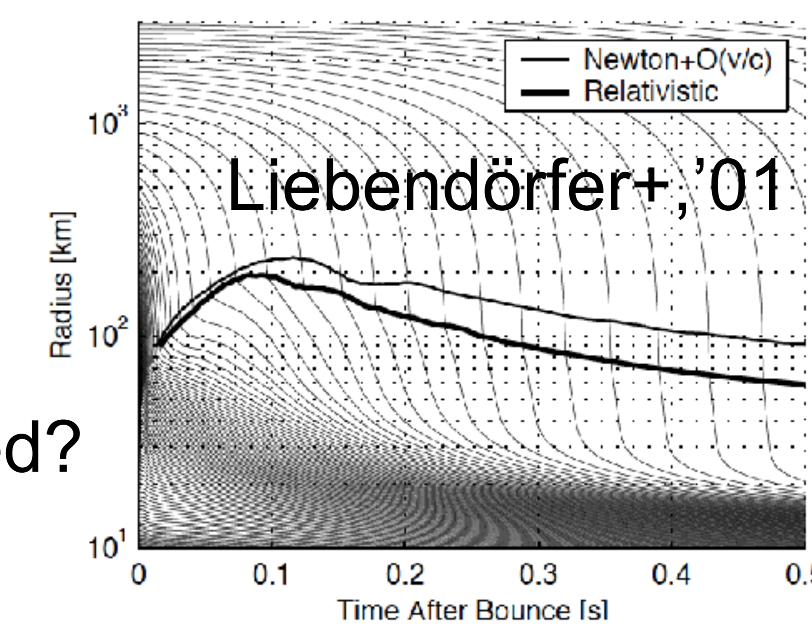
$\approx$



Although neutrinos are known to ***weakly*** interact with ordinal matters, some of them can still interact with SN matters mainly via:

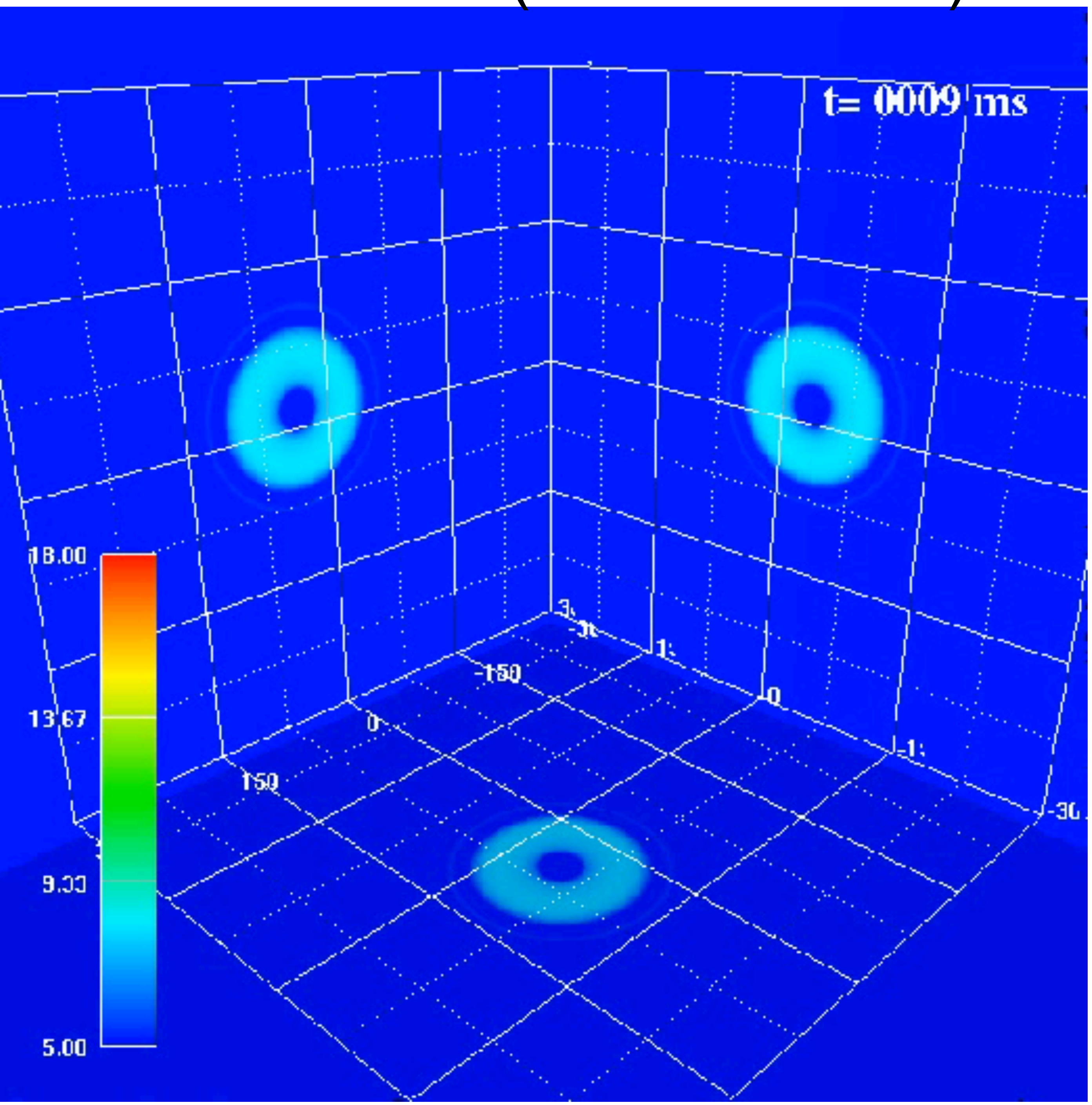
$$\nu_e n \leftrightarrow e^- p$$
$$\bar{\nu}_e p \leftrightarrow e^+ n$$

But why failed?

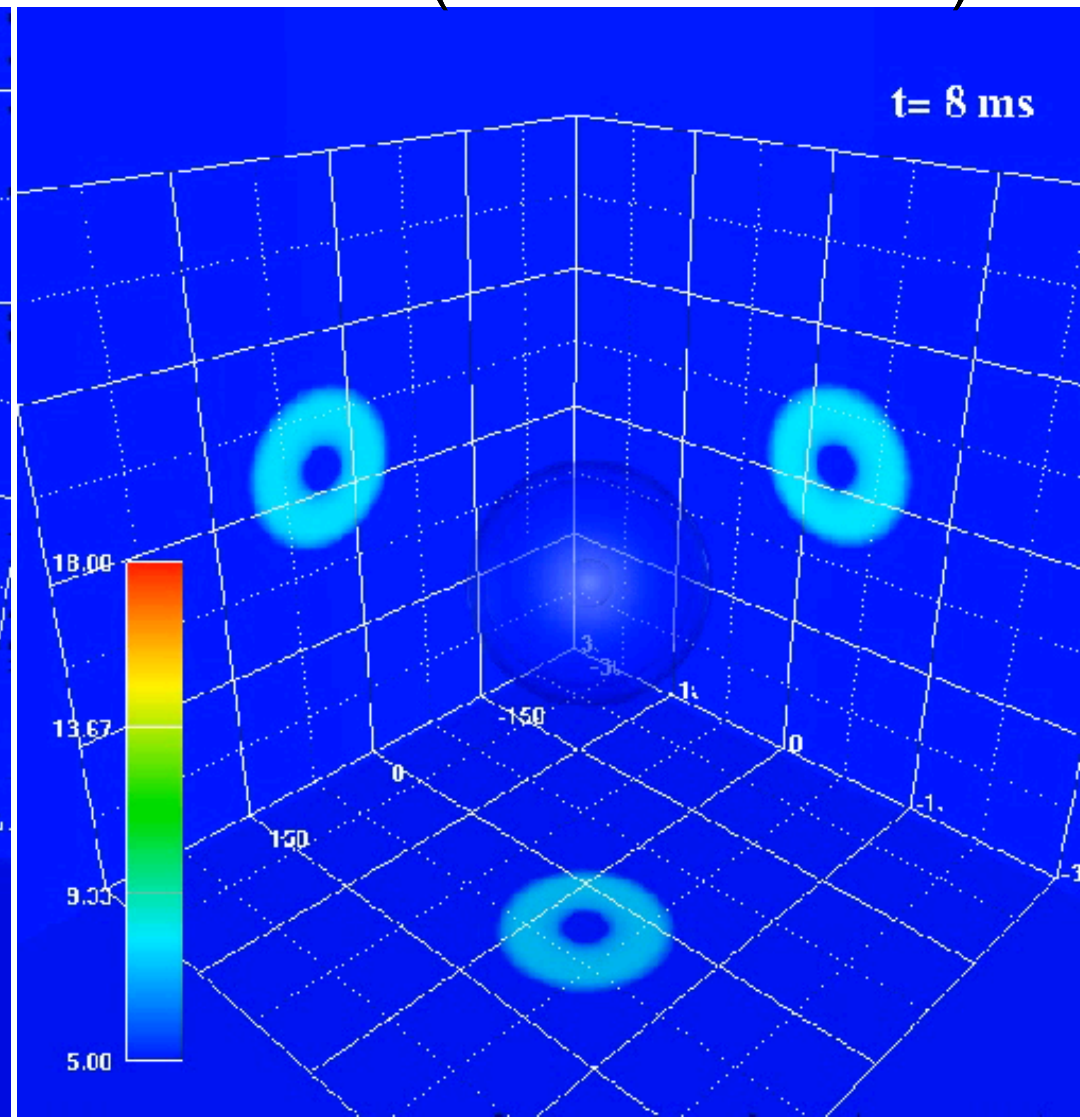


Convection motions facilitate the explosion.

3D model (w. convection)



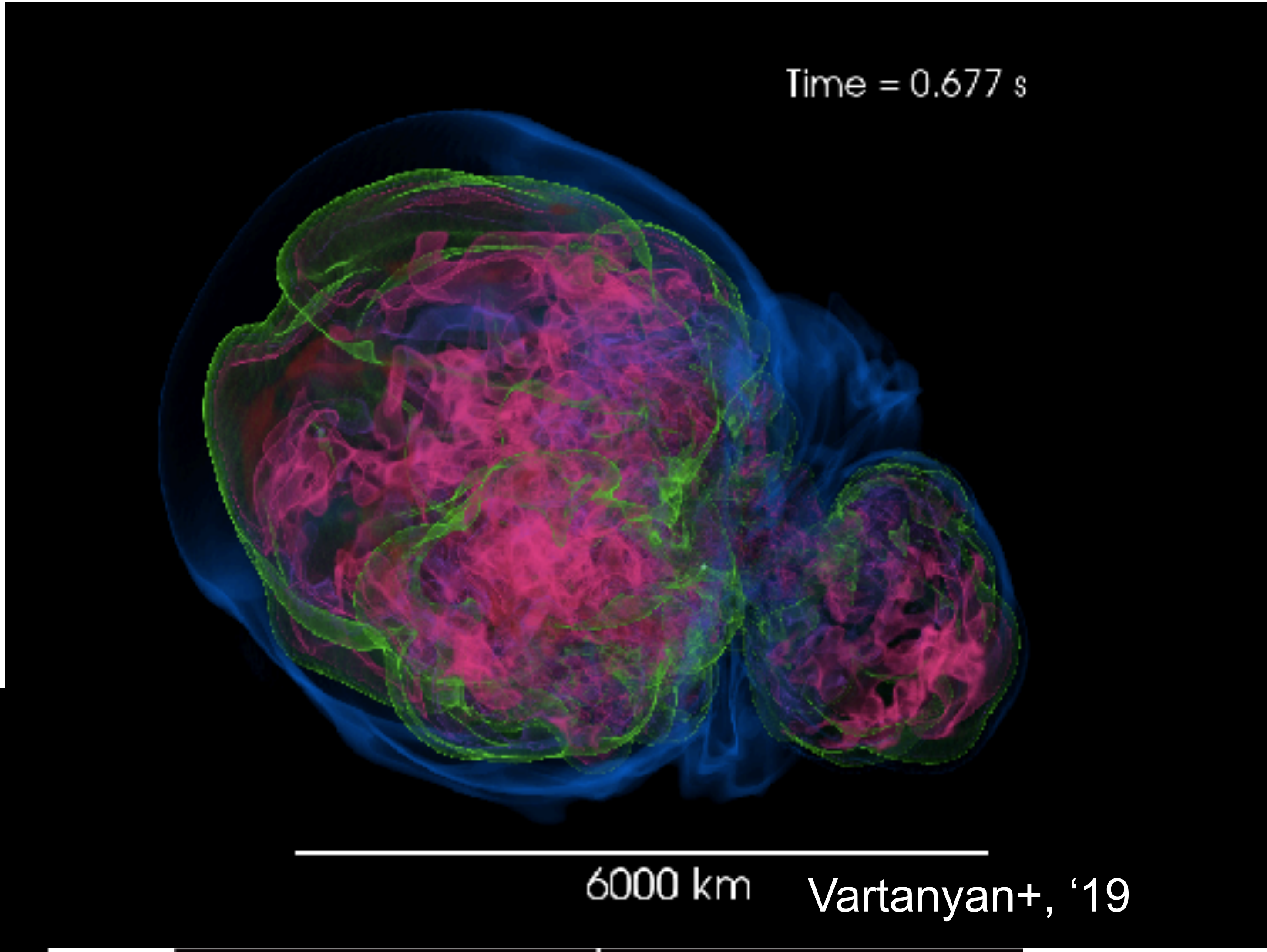
1D model (w./o. convection)



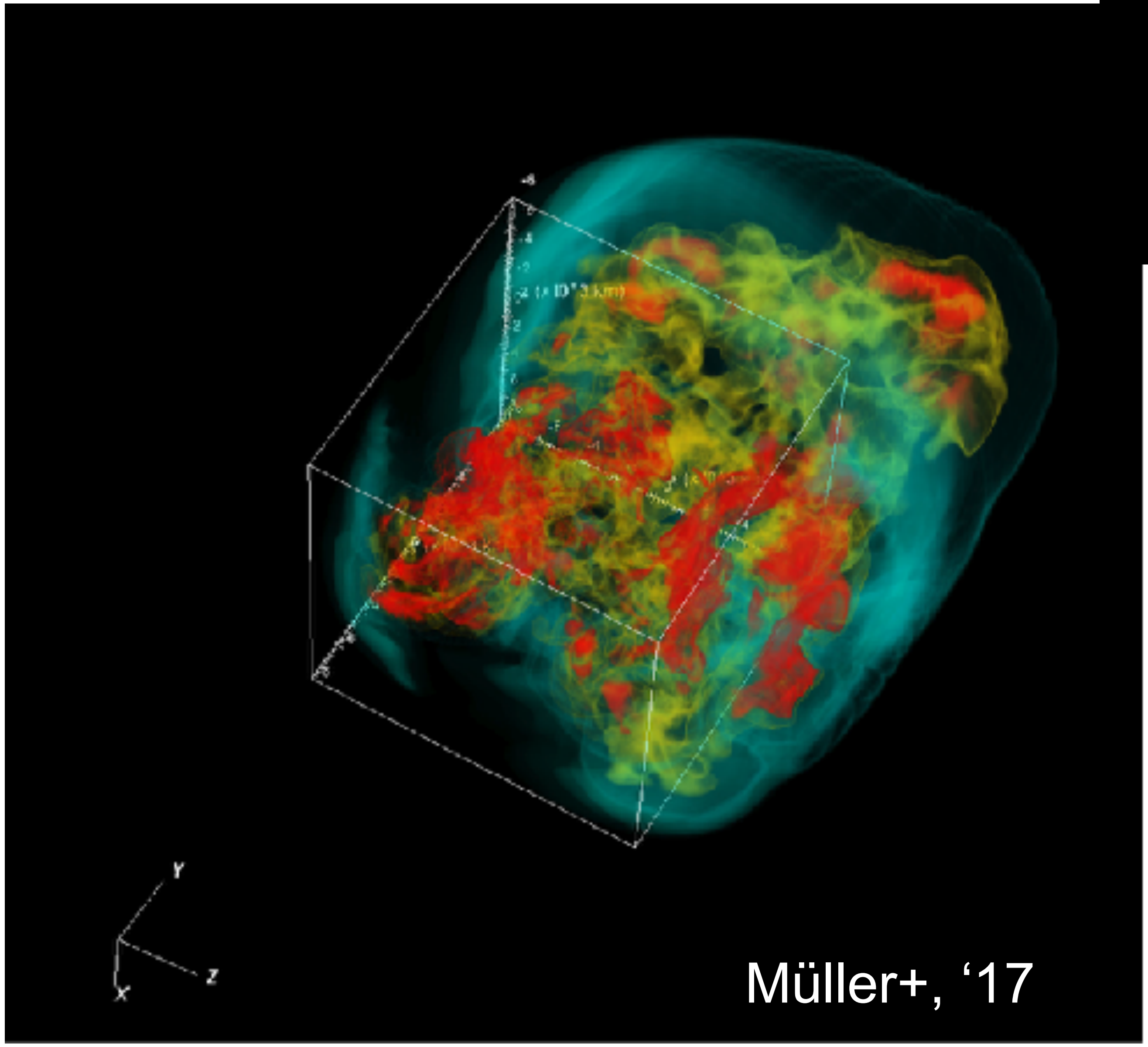
600km^3

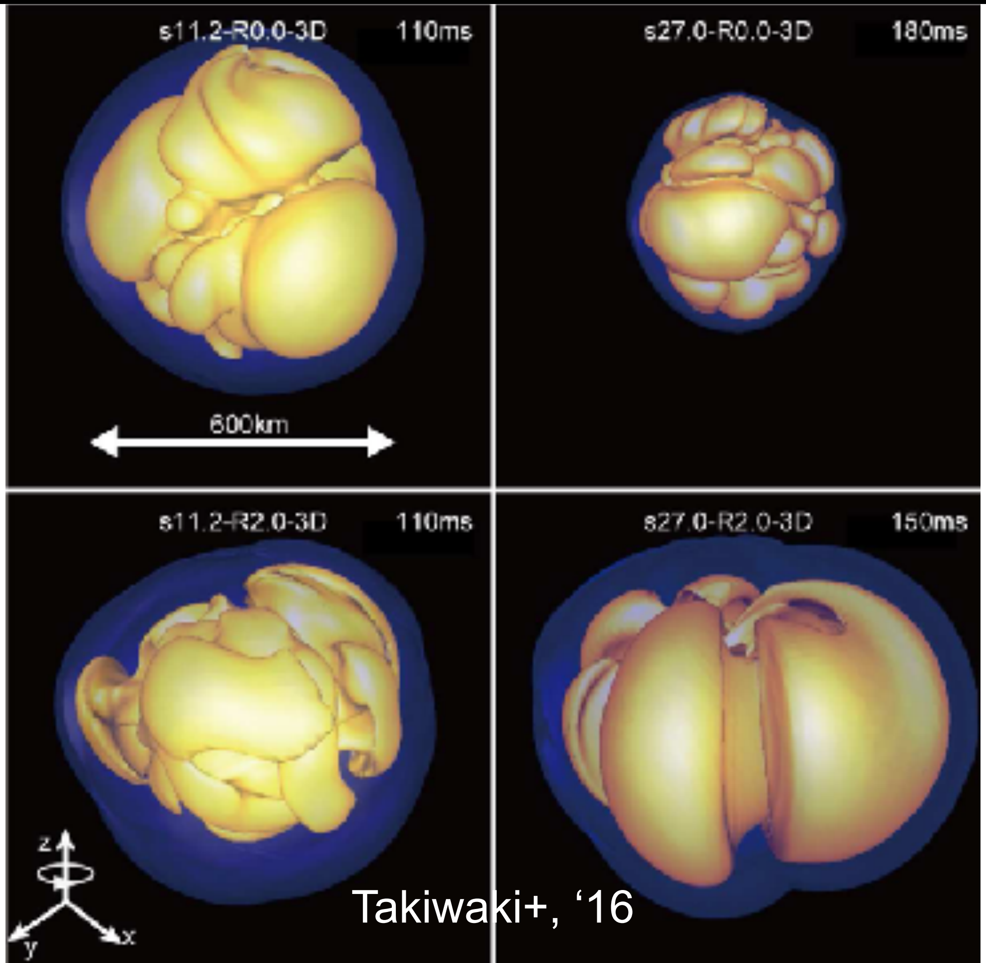
Takiwaki+,’18

Now there are several successful SN explosion models driven by <u>neutrino-heating</u> in full 3D.



Vartanyan+, '19


Müller+, '17



Takiwaki+, '16

Outline

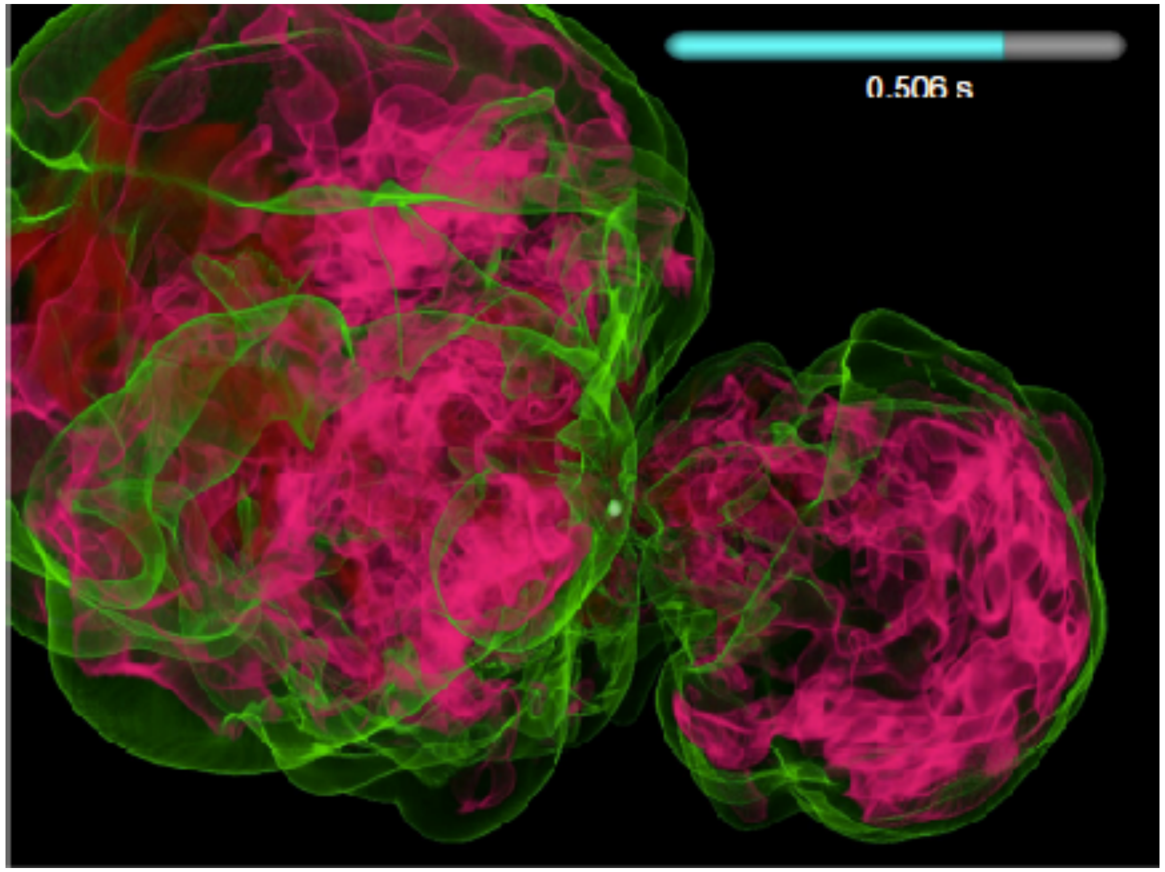
1: SN and NS formation from observational side

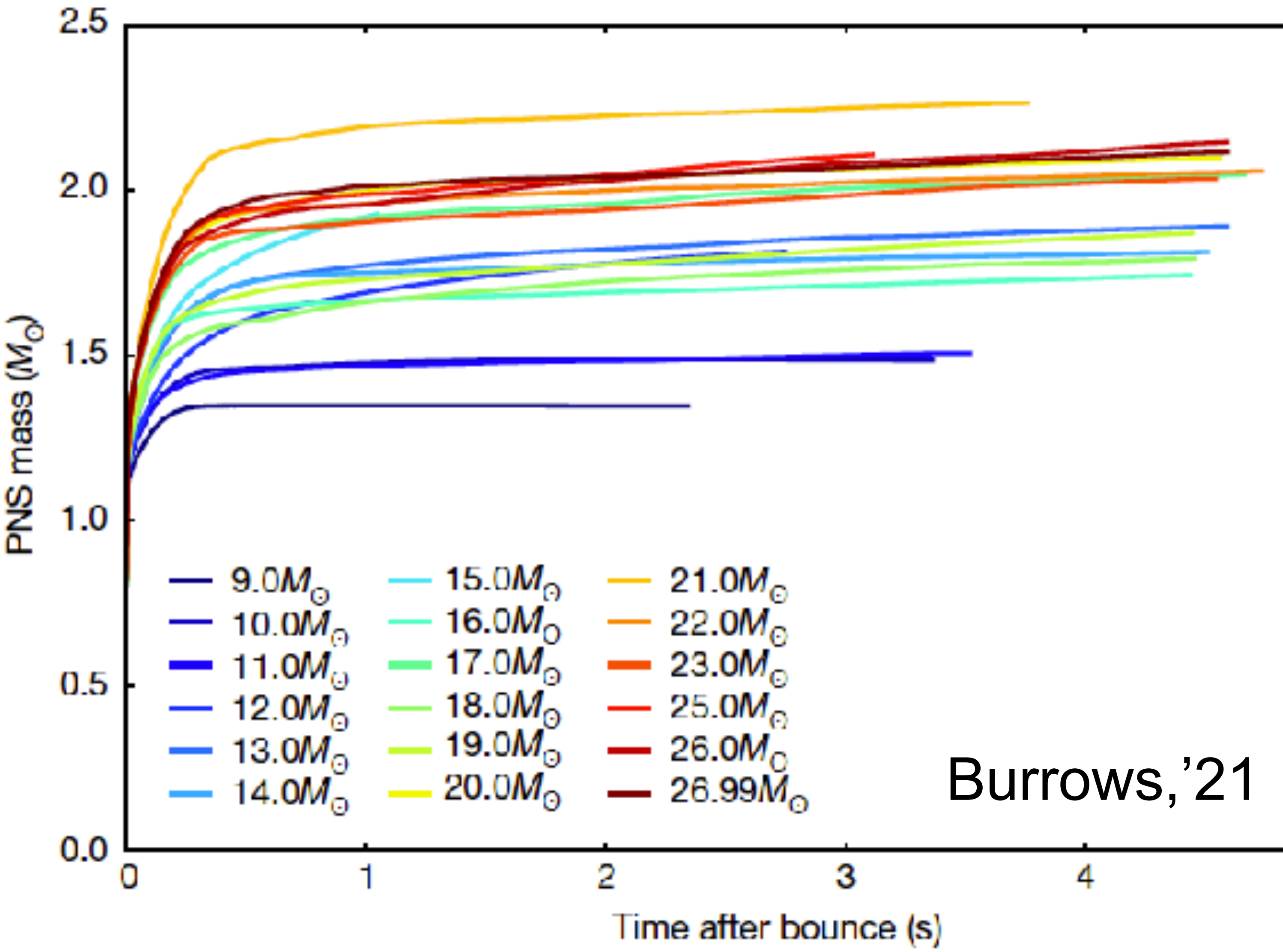
2: SN and NS formation from theoretical side

3: SN dynamics

4: Progenitor and remnant property

NS formation





Burrows,'21

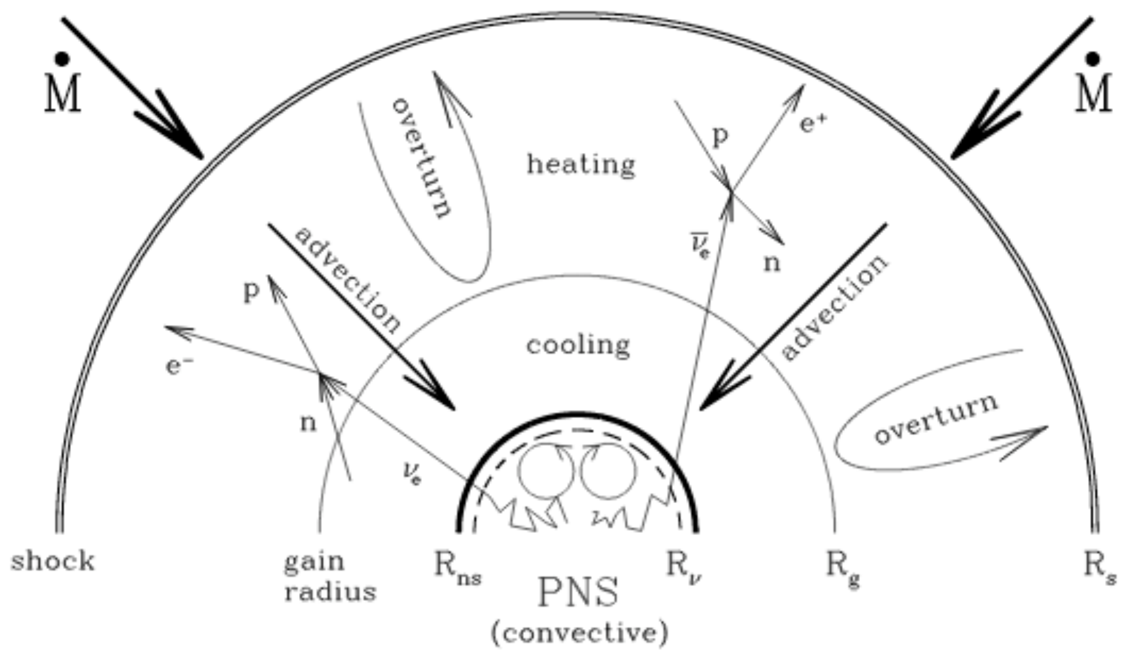
Among the SN progenitors (~10M_{sun}<M< ~100M_{sun}),
less massive stars (~10M_{sun}<M< ~30M_{sun}) may explode
by neutrino heating and leave behind a NS.

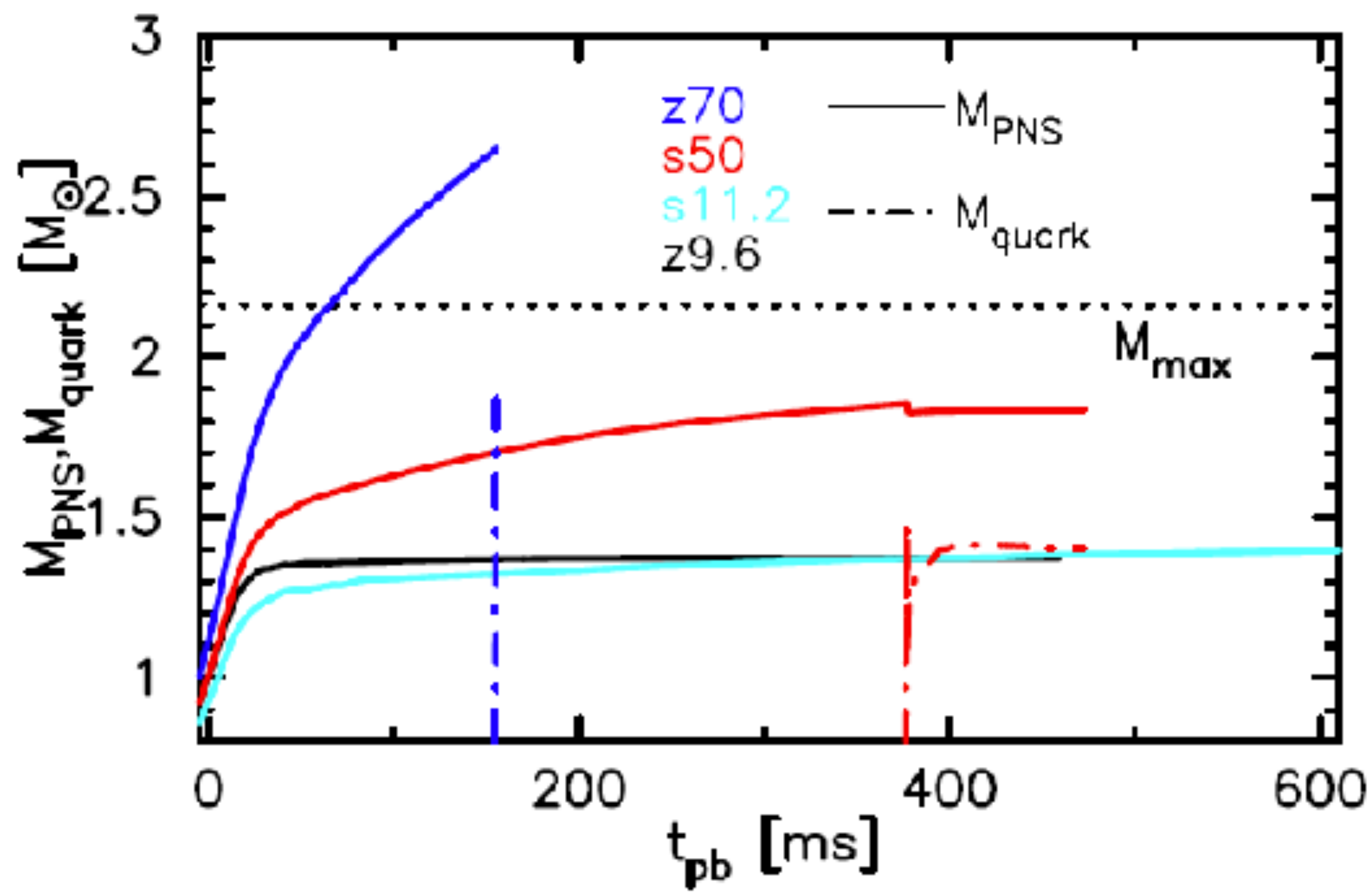
consistent

- A plausible progenitor model of SN1987a:
  ~18M_{sun} in a binary system (Podsiadlowski, '92)

An evidence of NS(?) by
Fransson+, 2024, Science

BH formation

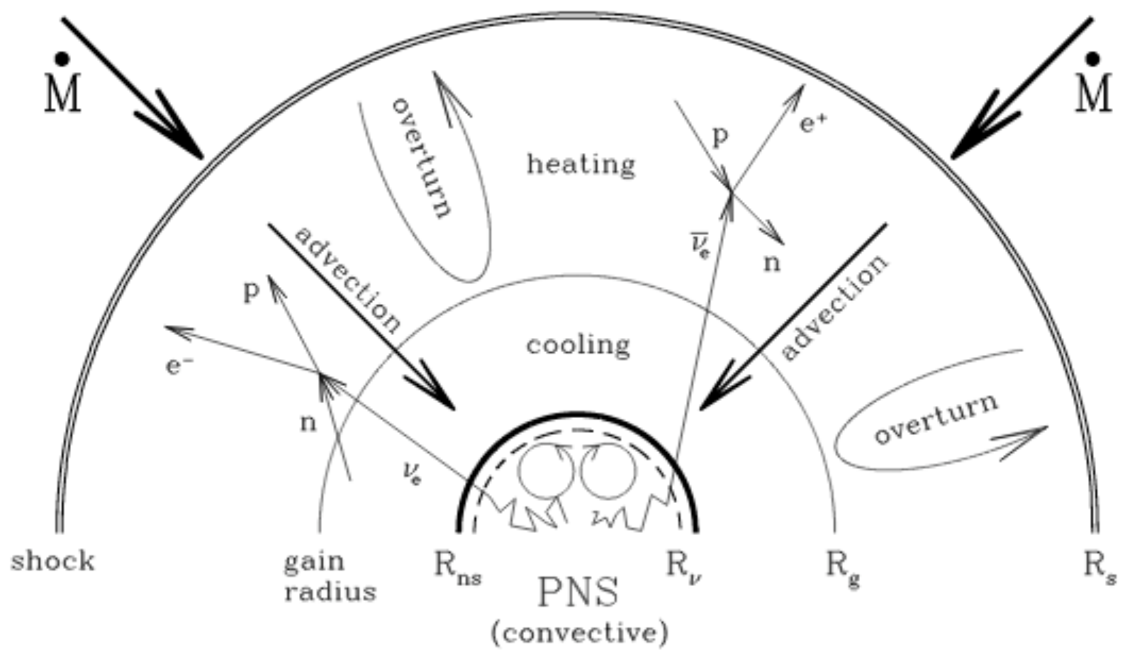




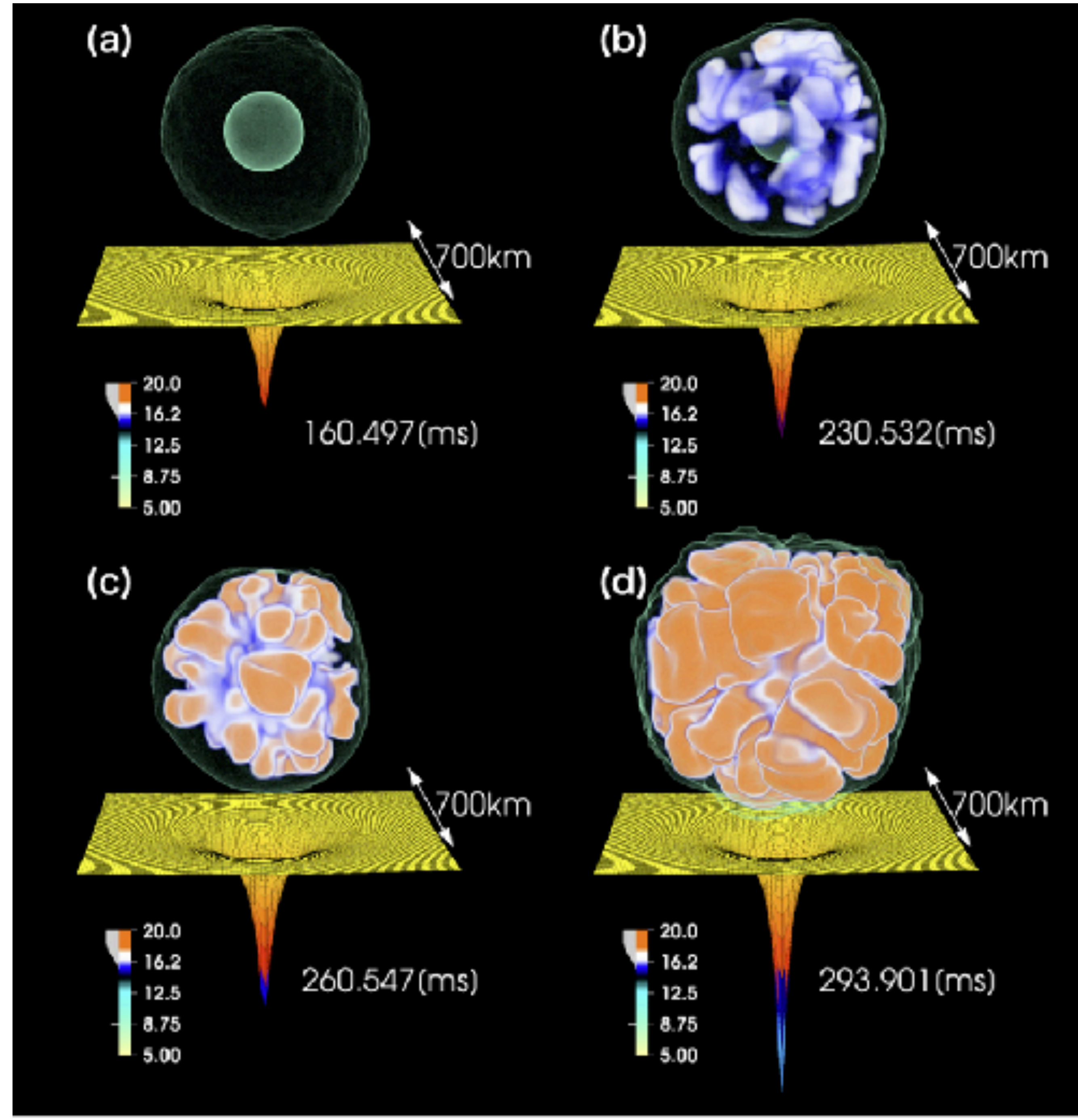
TK, Fischer+,'21

PNS mass increases rapidly for more massive stars ($\sim$40-70M_{sun}<M< $\sim$100M_{sun}).
Resulting in a failed SN explosion, i.e. *BH formation*.

BH formation



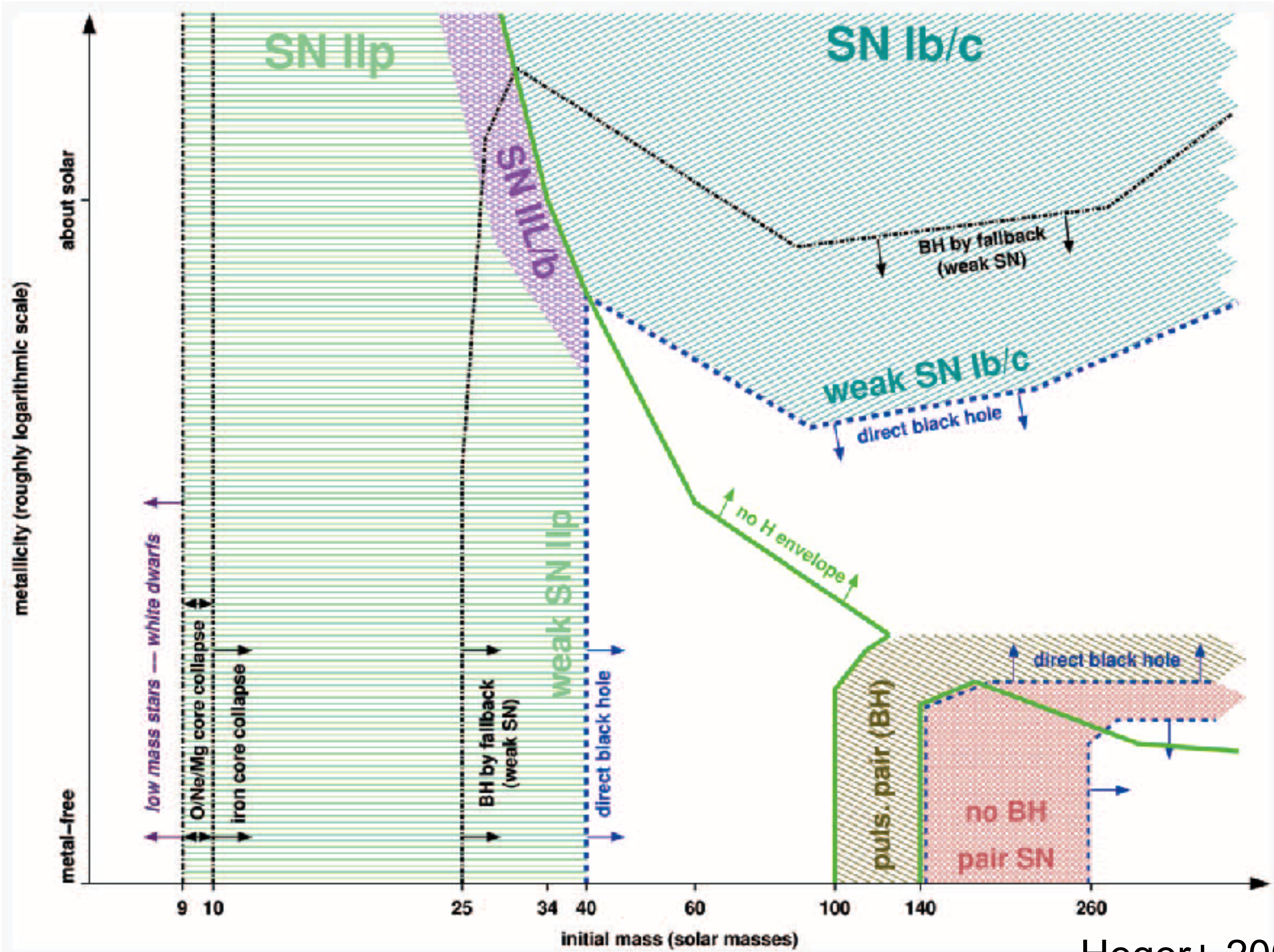
$70M_{sun}$



TK+,'18

More massive stars ($\sim 40M_{sun} < M < \sim 100M_{sun}$) cannot explode solely by neutrino heating.

The NS/BH formation branch and its progenitor mass dependence



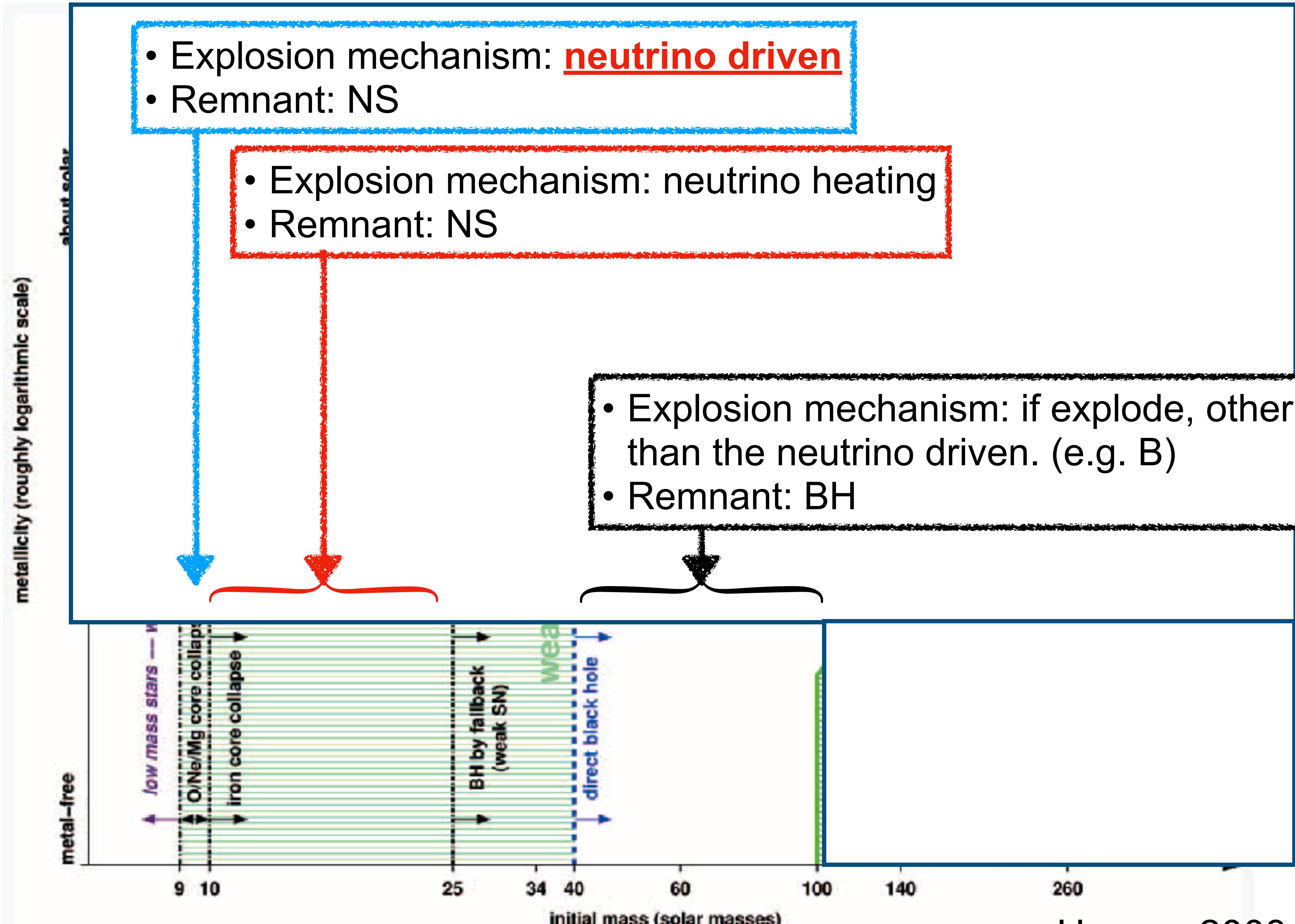
Heger+,2003

The NS/BH formation branch and its progenitor mass dependence

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

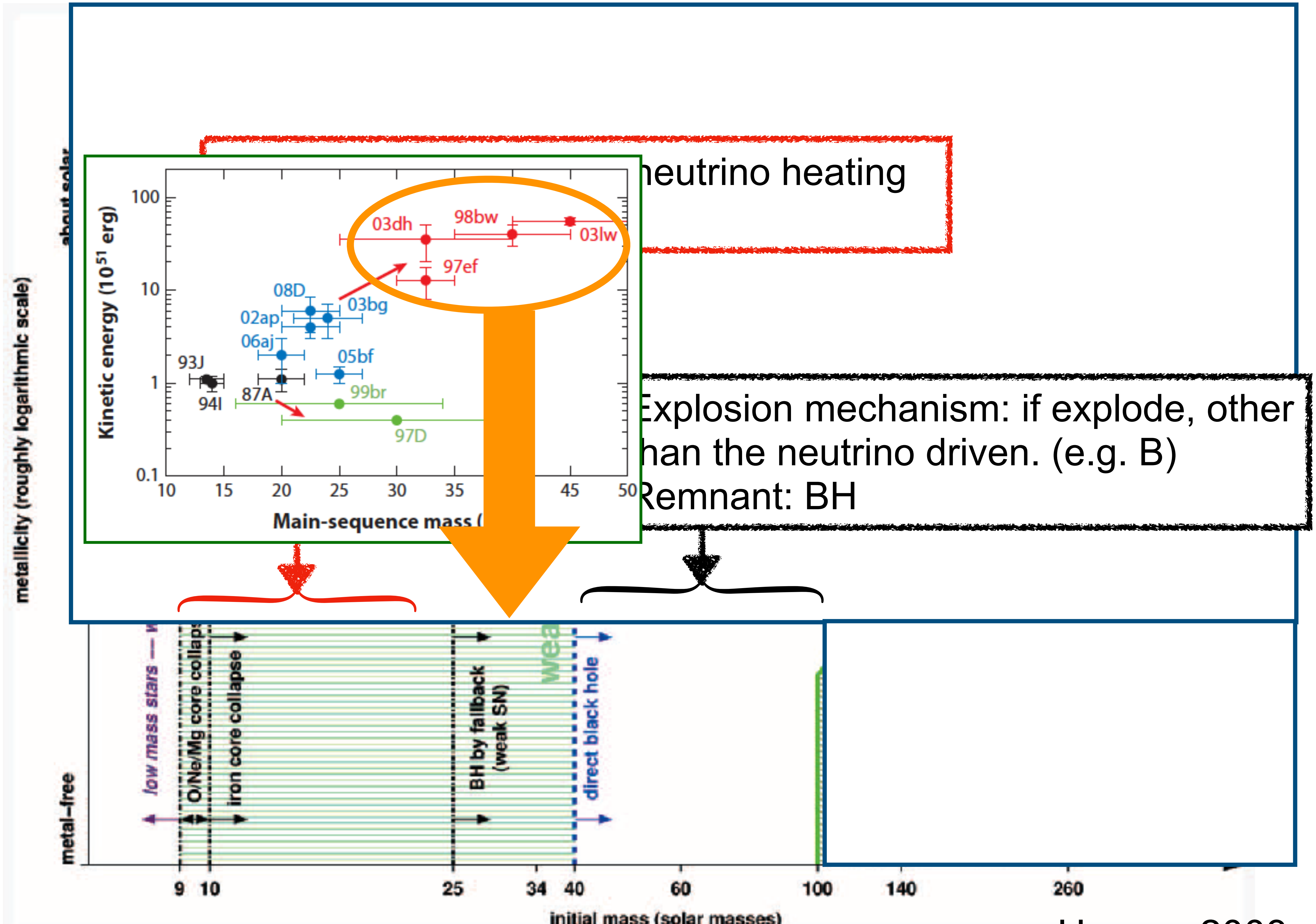
- Explosion mechanism: neutrino heating
- Remnant: NS

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



Heger+,2003

The NS/BH formation branch and its progenitor mass dependence

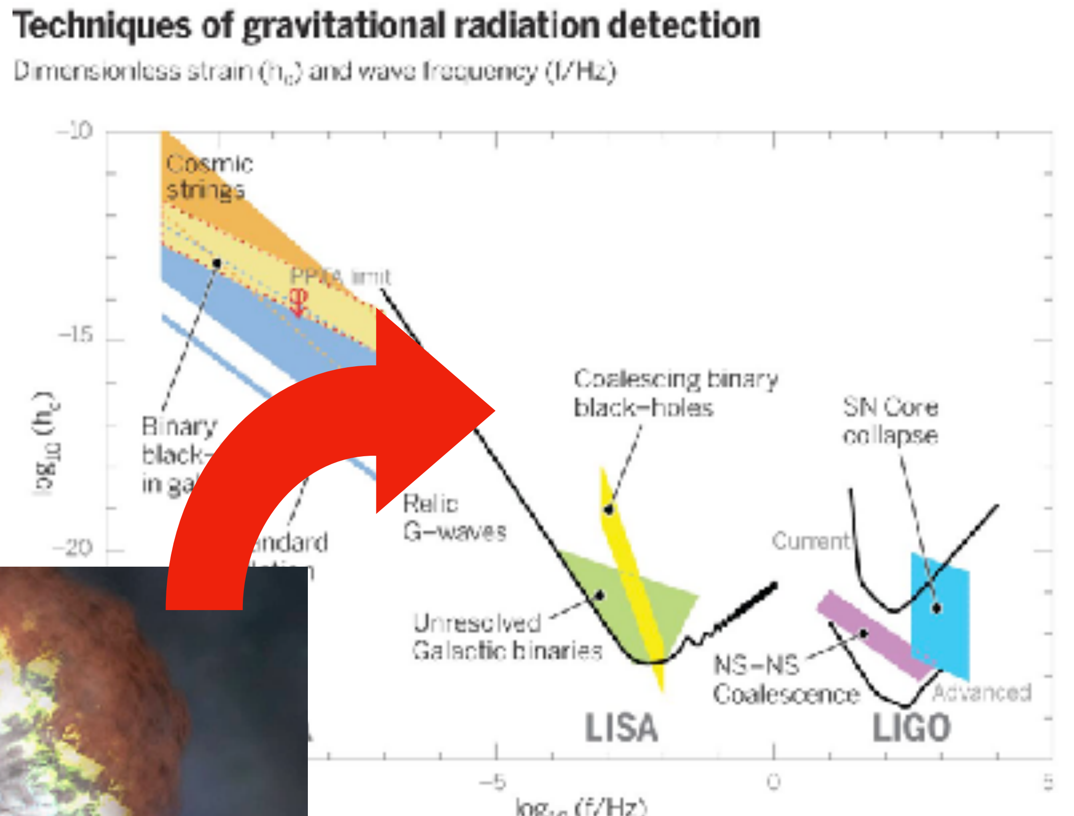


Heger+,2003

Why are SNe important?

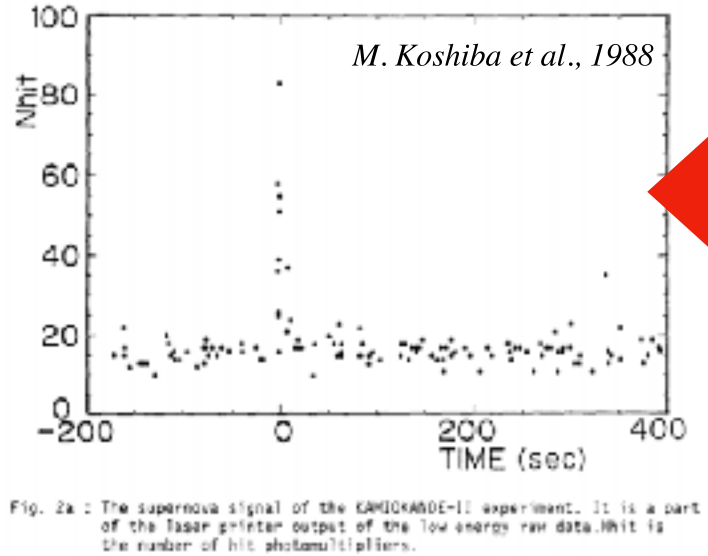
They are the source/origin of:

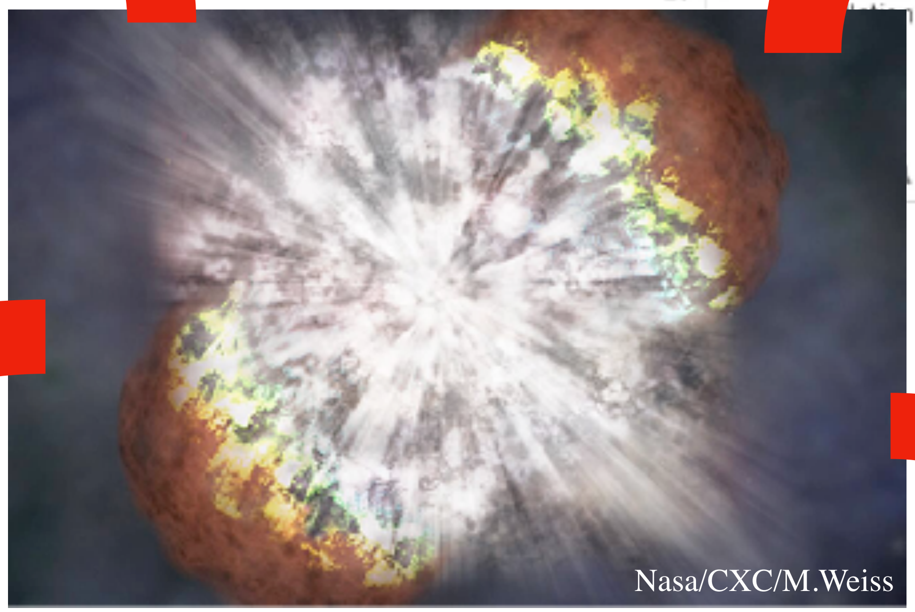
GWs



R. N. Manchester, The Twelfth Marcel Grossmann Meeting on General Relativity (2012)

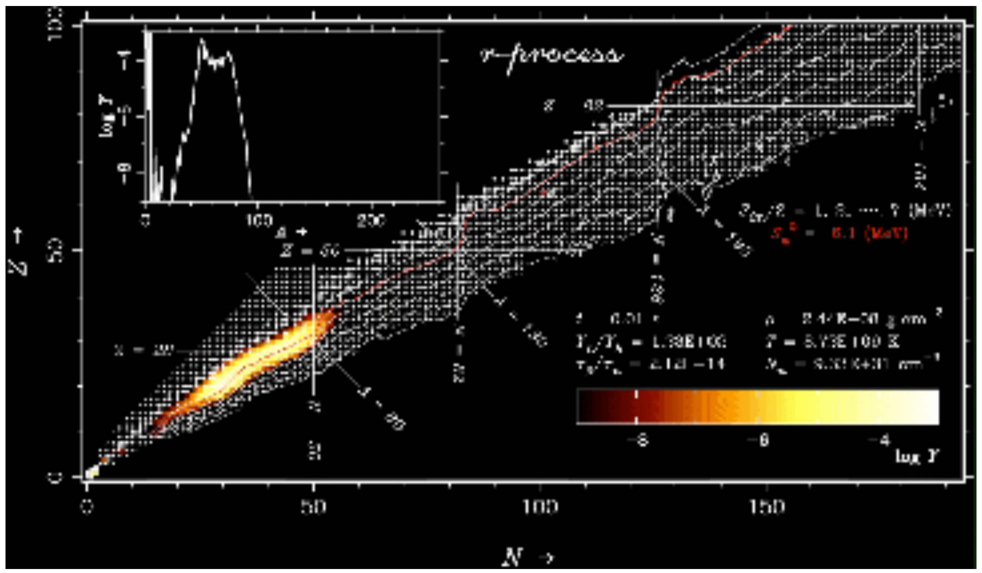
Neutrinos





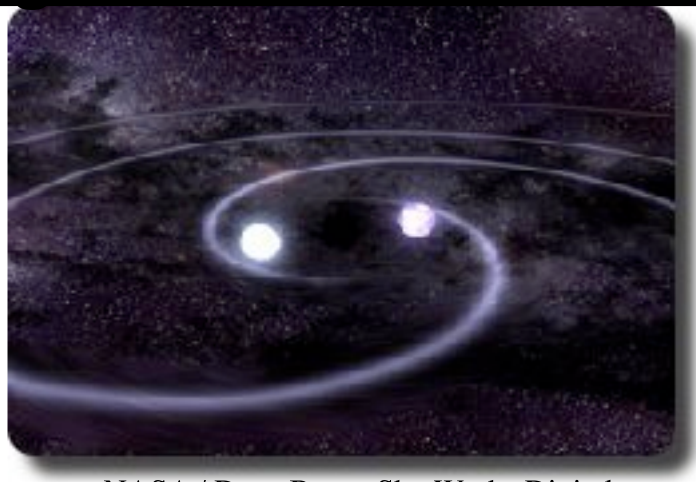
Nasa/CXC/M.Weiss

Heavy elements



Wanajo+,'04

NSs, BHs, magnetars, exotic stars,,,,



NASA / Dana Berry, Sky Works Digital