Supernova explosions of
massive blue-supergiant stars

triggered by the QCD phase transition

—

on the origin of massive neutron stars

From protoneutron stars to hybrid stars
Exploring the QCD phase transition in core collapse supernovae

Tobias Fischer

Department of Physics, University Basel, Switzerland

CSQCD II, May 2009

PRL **102,** 081101 (2009) PHYSICAL REVIEW LETTERS week ending 27 FEBRUARY 2009

Signals of the QCD Phase Transition in Core-Collapse Supernovae

I. Sagert,[1] T. Fischer,[3] M. Hempel,[1] G. Pagliara,[2] J. Schaffner-Bielich,[2] A. Mezzacappa,[4] F.-K. Thielemann,[3] and M. Liebendörfer[3]

[1]*Institut für Theoretische Physik, Goethe-Universität, Max-von-Laue-Str. 1, 60438 Frankfurt am Main, Germany*
[2]*Institut für Theoretische Physik, Ruprecht-Karls-Universität, Philosophenweg 16, 69120 Heidelberg, Germany*
[3]*Department of Physics, University of Basel, Klingelbergstr. 82, 4056 Basel, Switzerland*
[4]*Physics Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831, USA*
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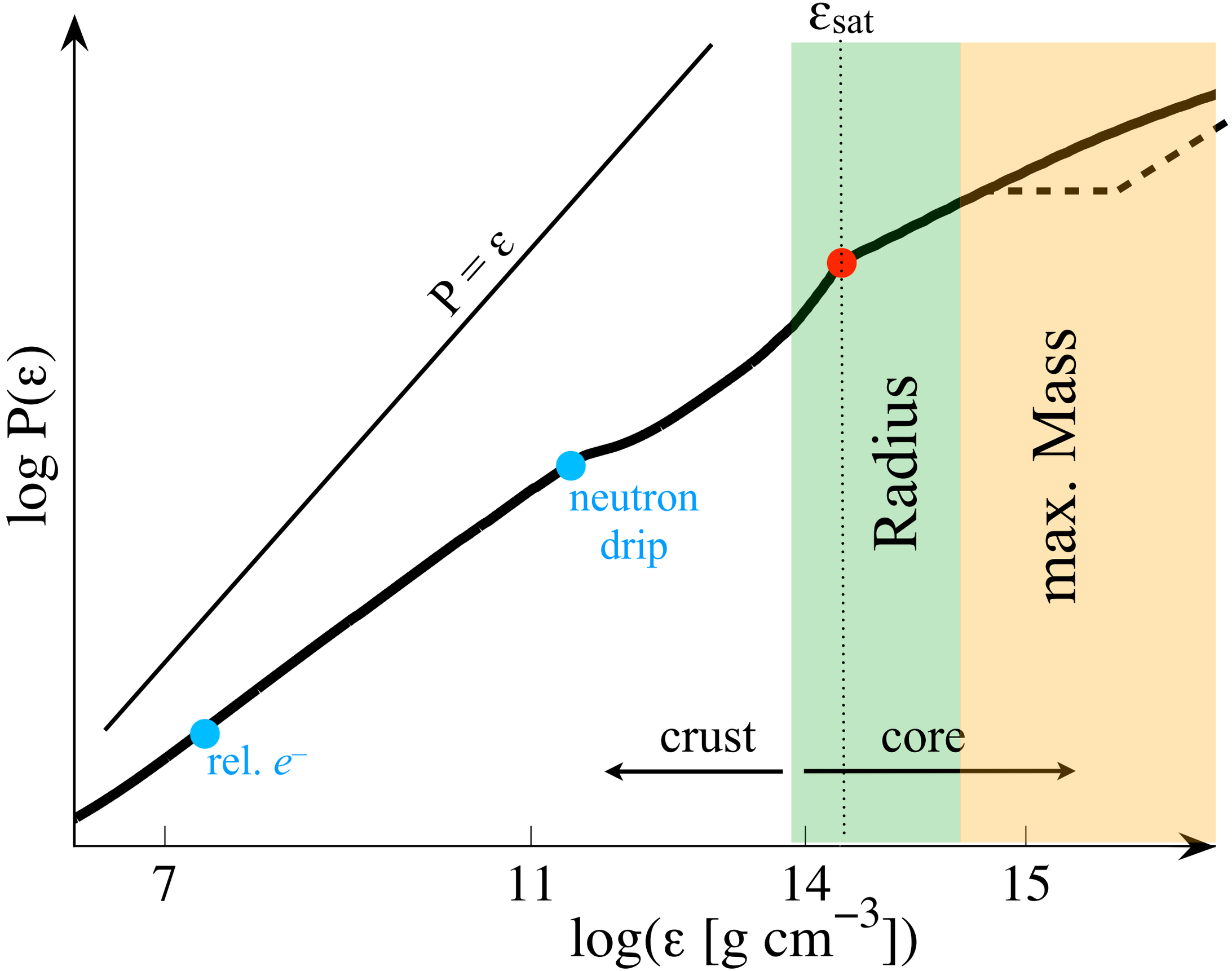
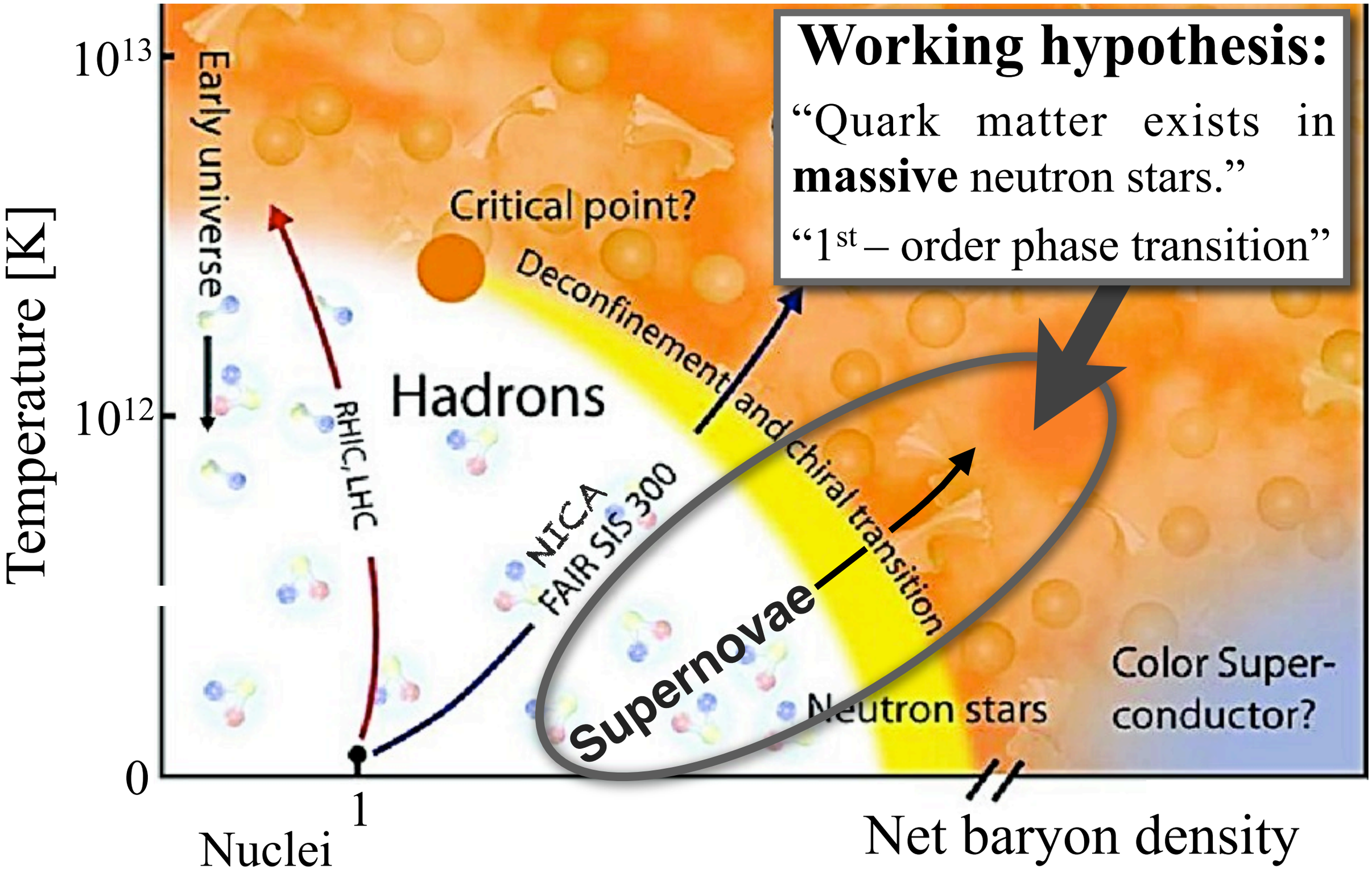
We explore the implications of the QCD phase transition during the postbounce evolution of core-collapse supernovae. Using the MIT bag model for the description of quark matter, we model phase transitions that occur during the early postbounce evolution. This stage of the evolution can be simulated with general relativistic three-flavor Boltzmann neutrino transport. The phase transition produces a second shock wave that triggers a delayed supernova explosion.

$$\rho_{\mathrm{transition}} \simeq \rho_{\mathrm{sat}} \ , \quad M_{\mathrm{max}} < 2\ \mathrm{M}_{\odot}$$

$P(\varepsilon_{sat}) = 2.5 \pm 1$ MeV fm^{-3}

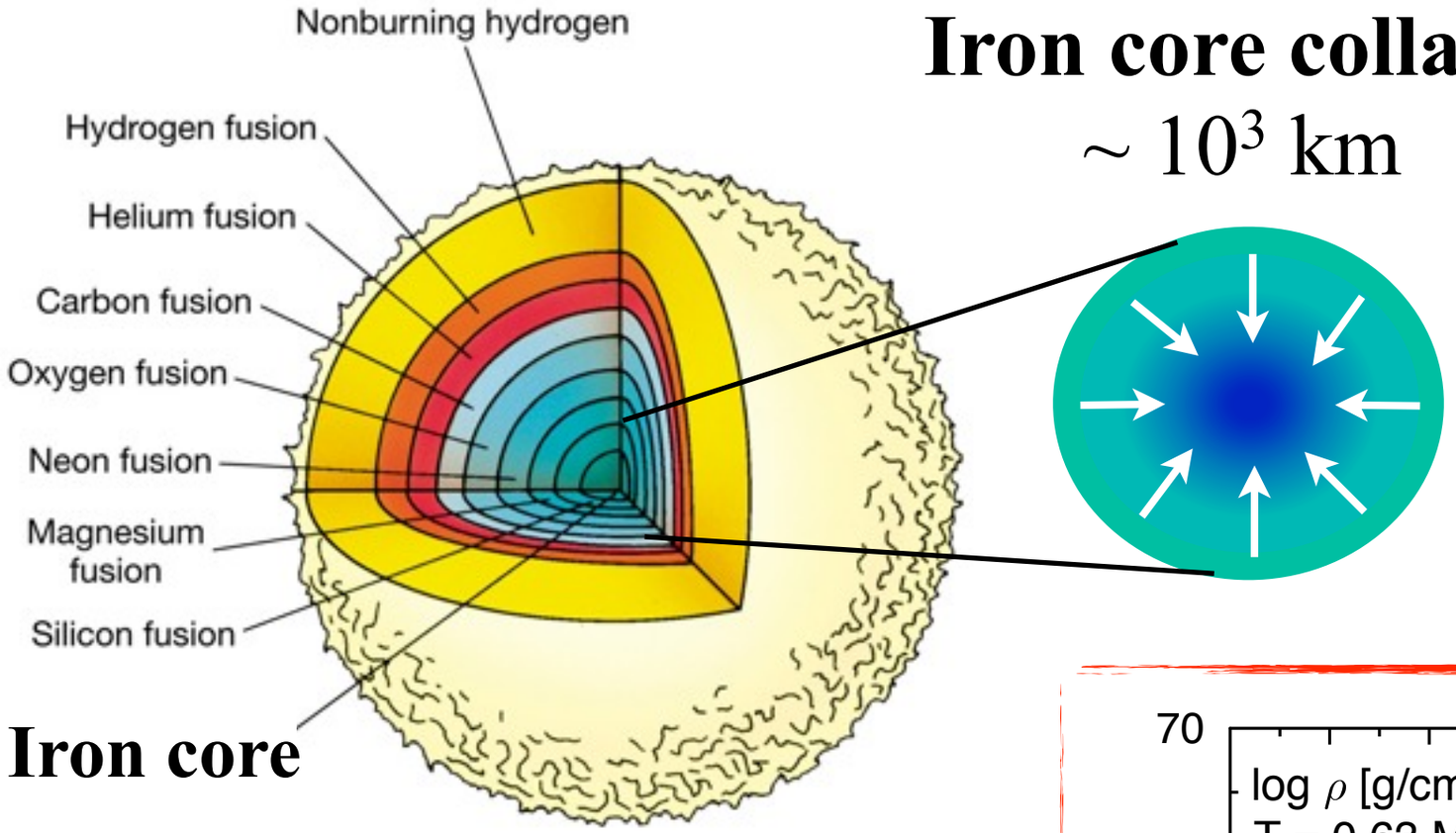


Inaccessible in heavy-ion collisions



Iron core collapse

$\sim 10^3$ km

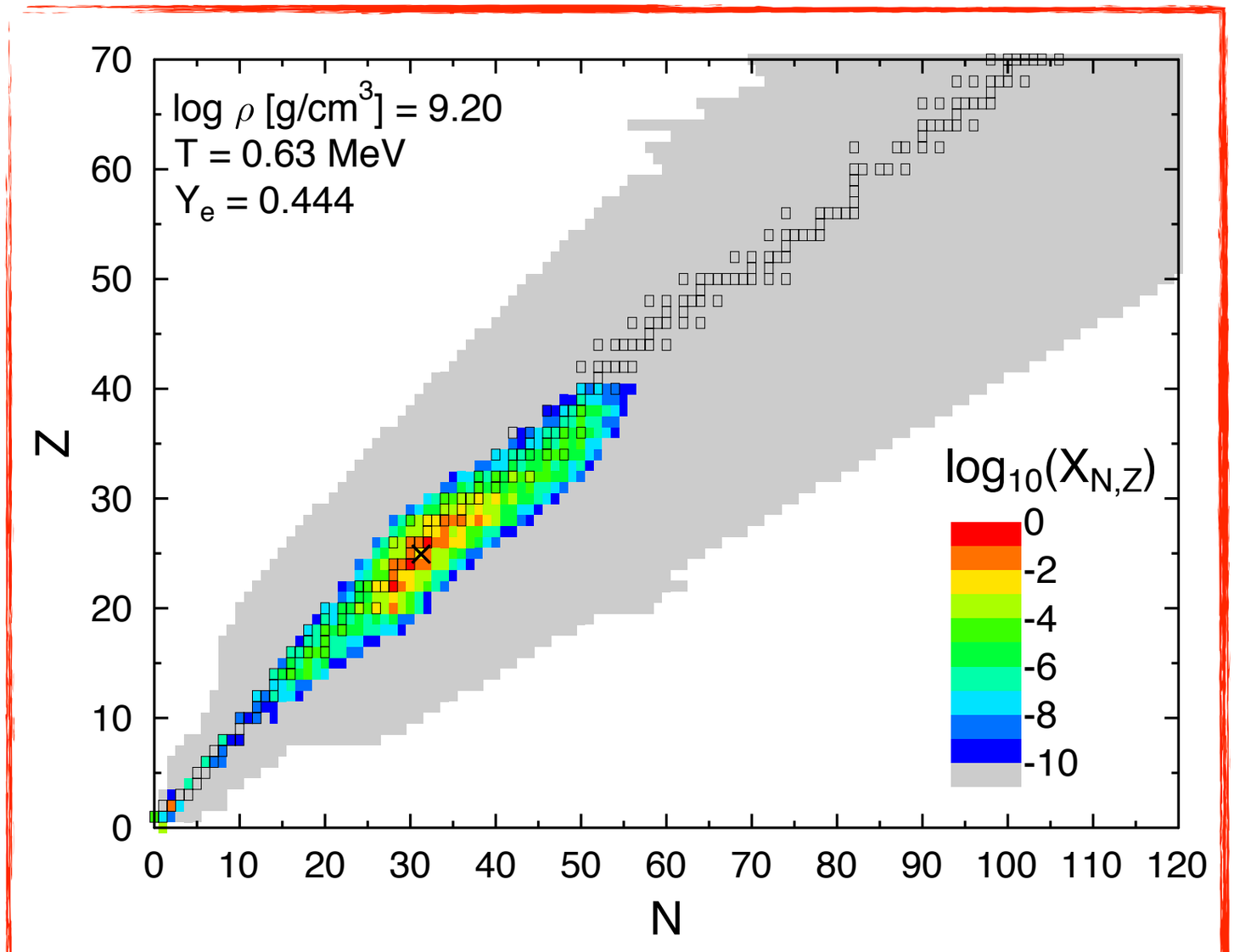


$$E_{\rm gain} \simeq 3 - 6 \times 10^{53}\ {\rm erg}$$

$$M_{\rm ZAMS} > 8\ {\rm M}_\odot$$

$$e^- + {}^{56}{\rm Mn} \longrightarrow {}^{56}{\rm Fe} + \nu_{\rm e}$$
$$e^- + {}^{56}{\rm Fe} \longrightarrow {}^{56}{\rm Co} + \nu_{\rm e}$$
$$e^- + {}^{56}{\rm Co} \longrightarrow {}^{56}{\rm Ni} + \nu_{\rm e}$$

.....



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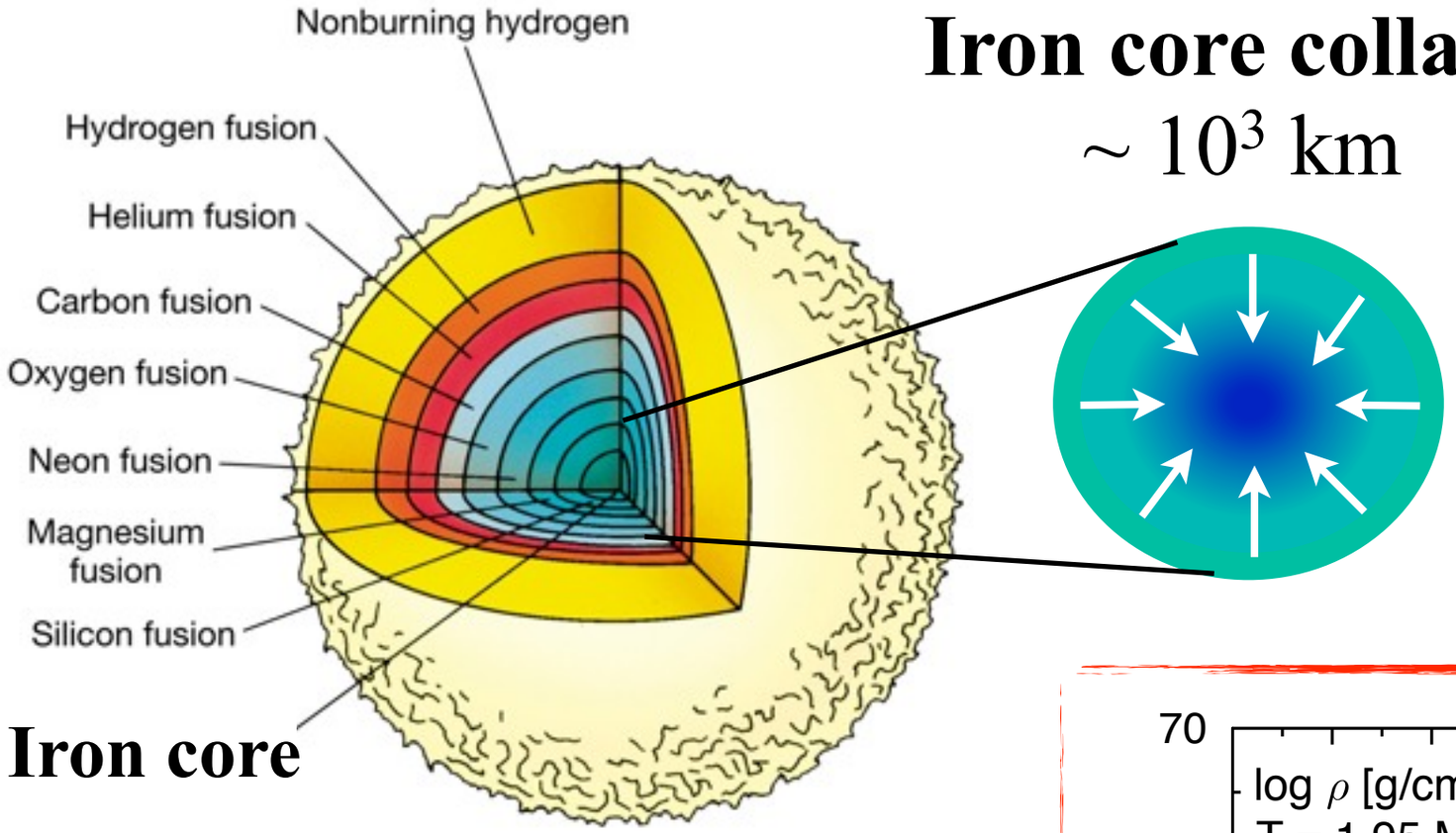

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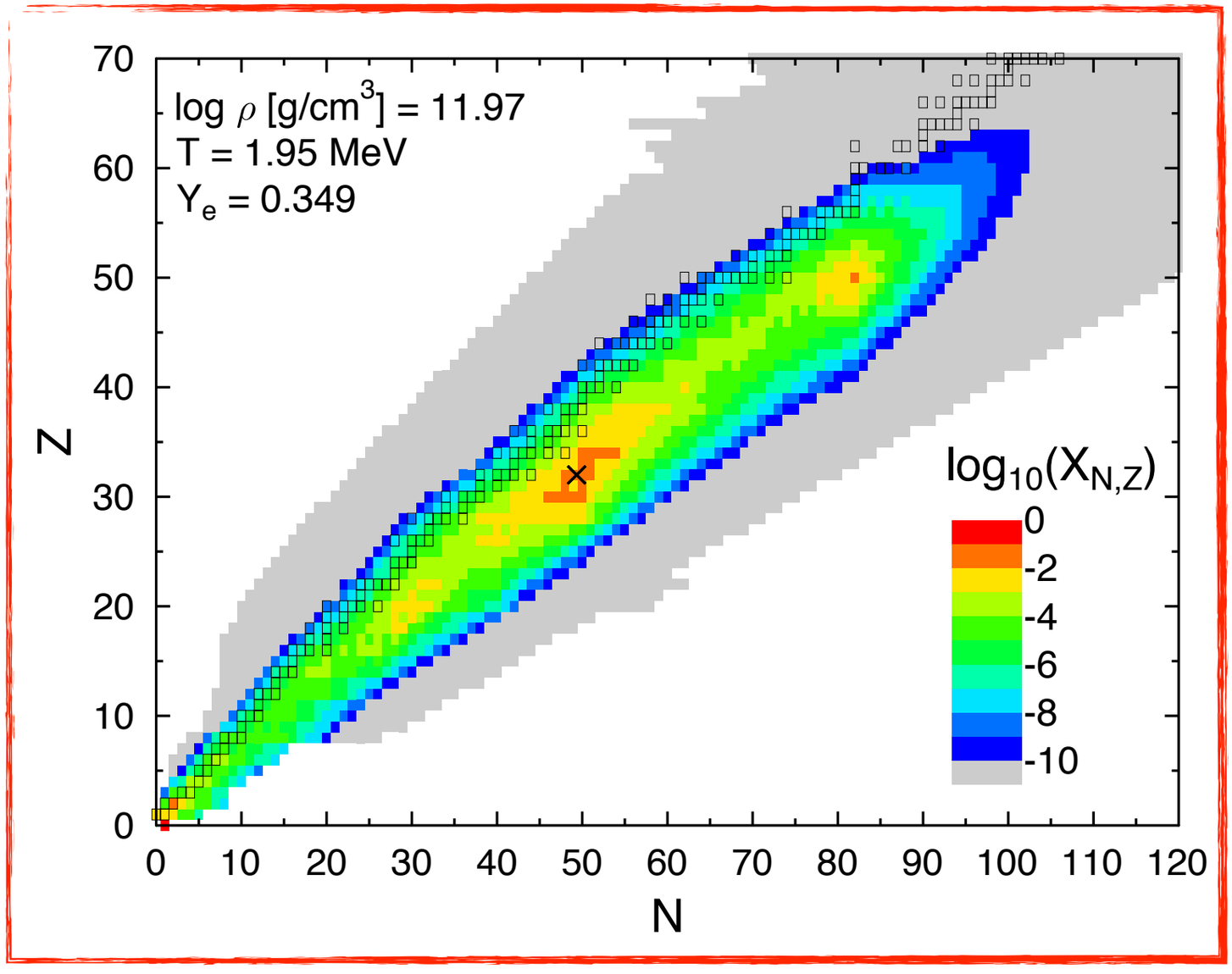

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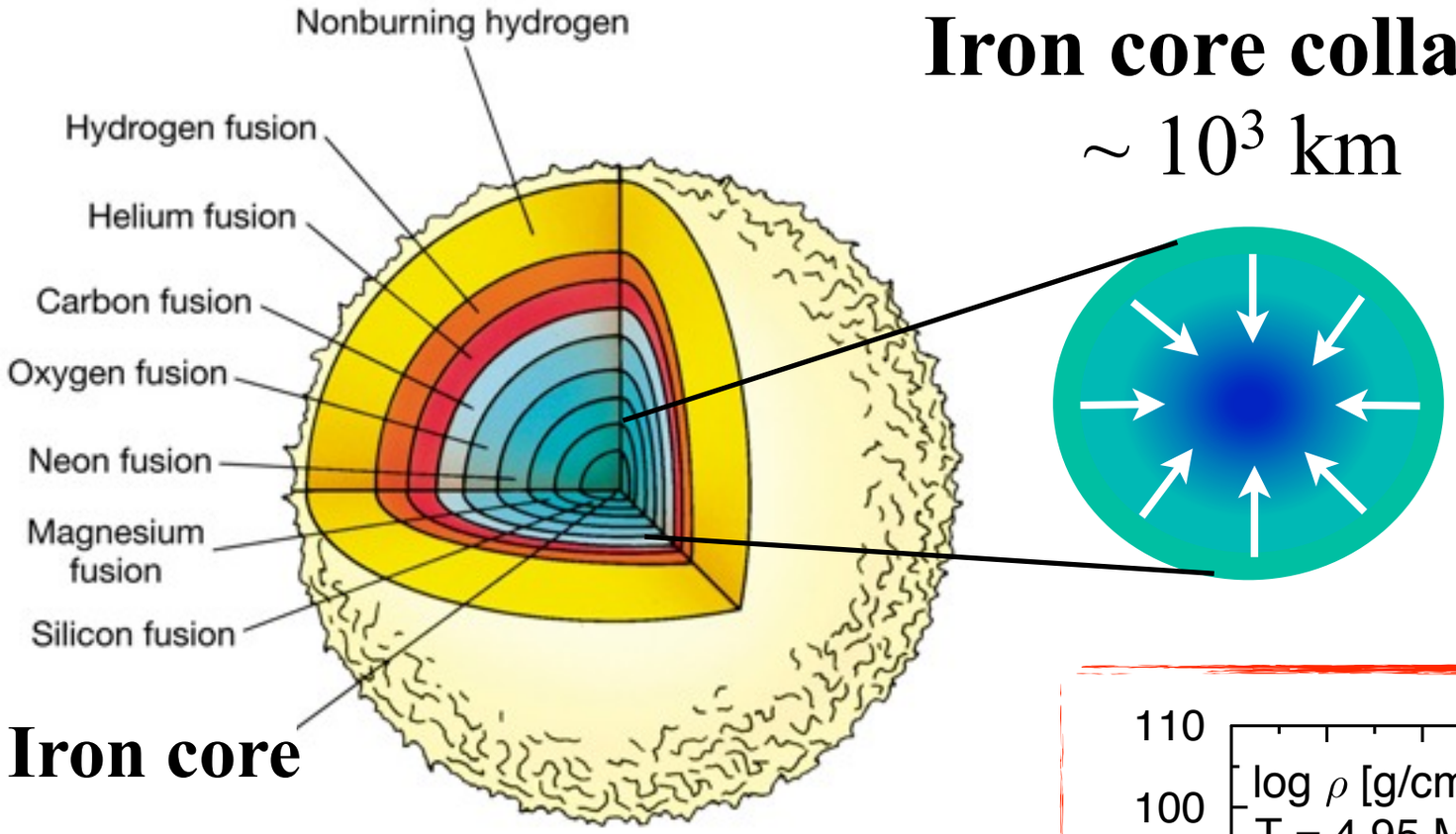

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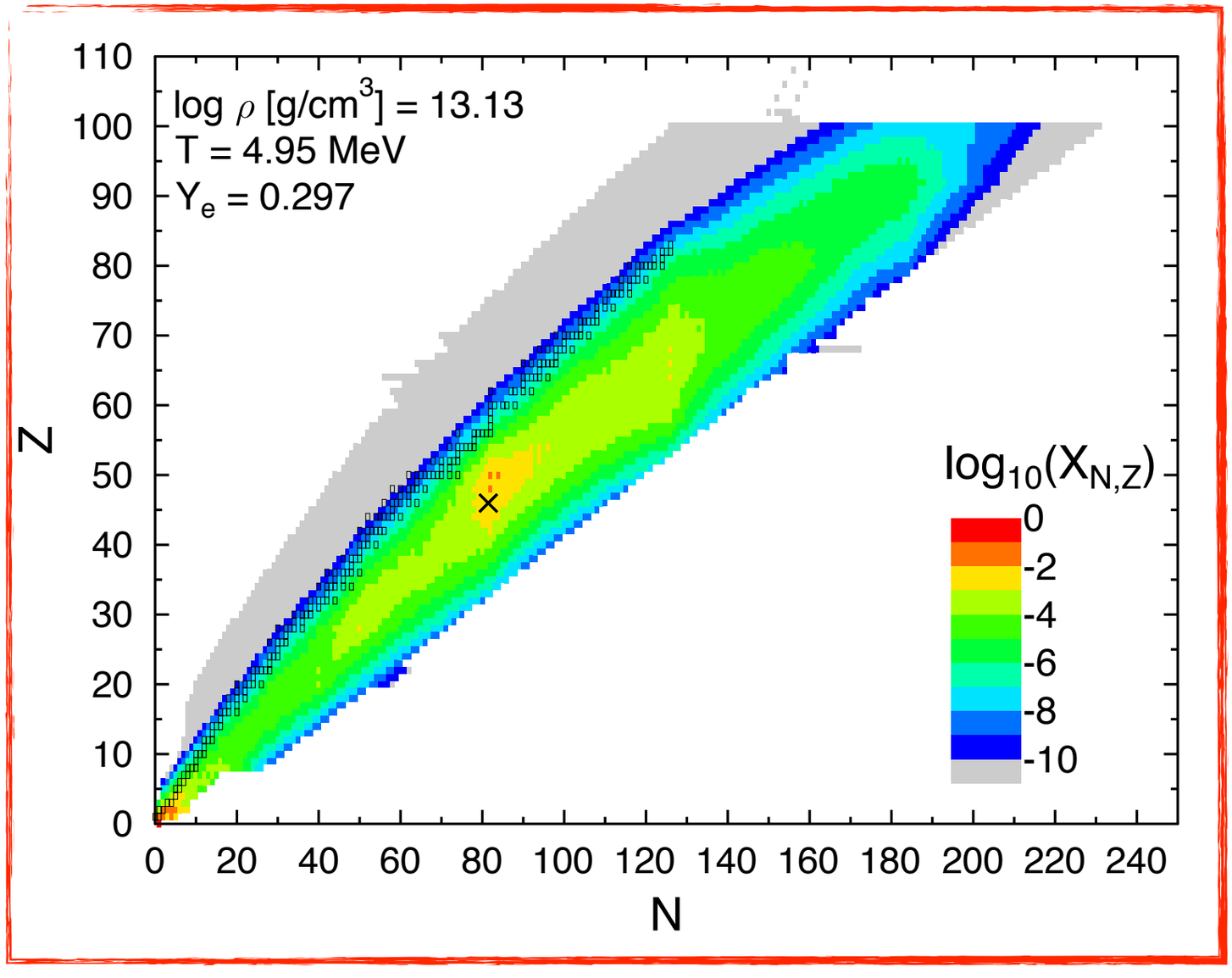
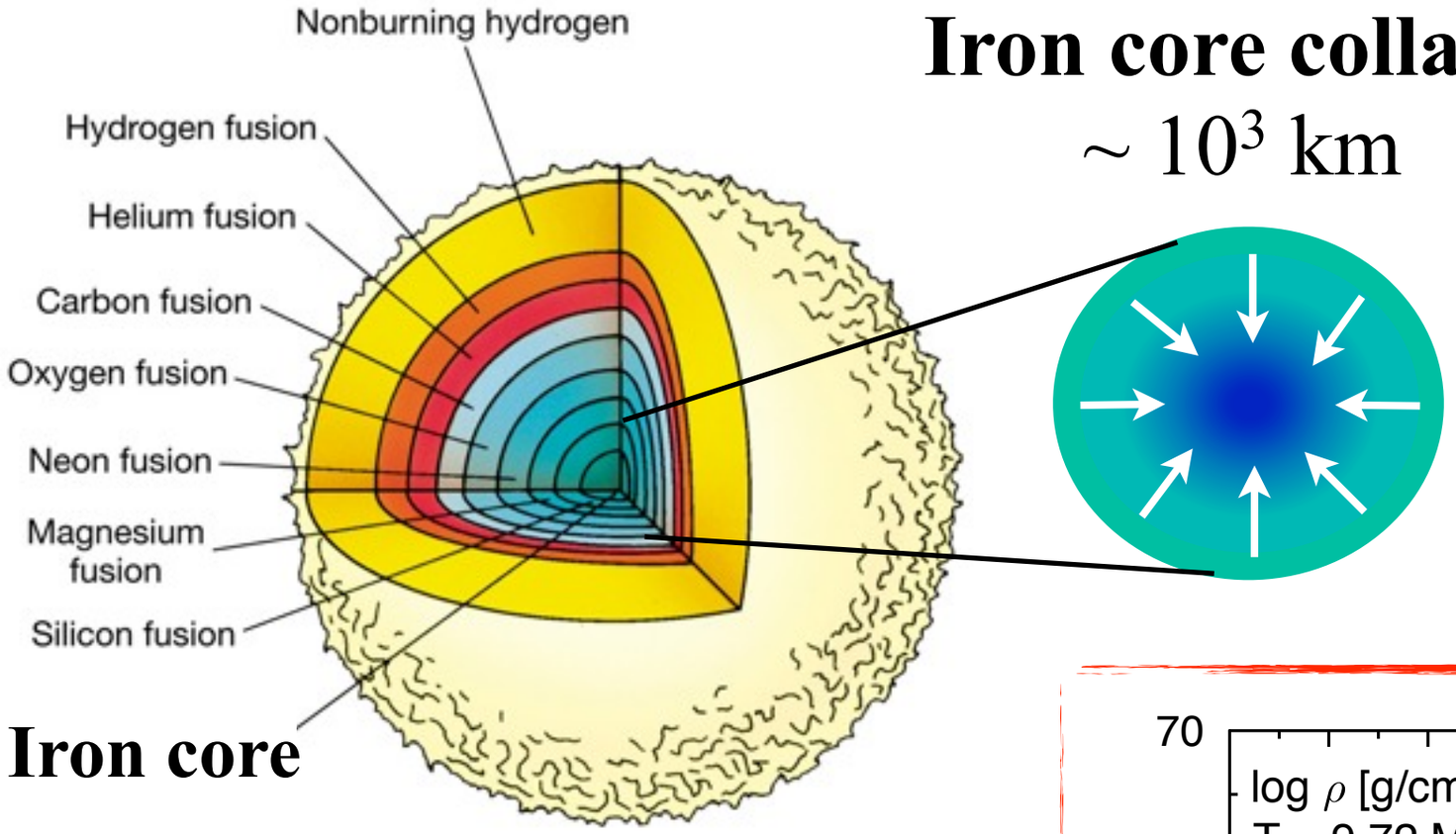


Iron core collapse

$\sim 10^3$ km



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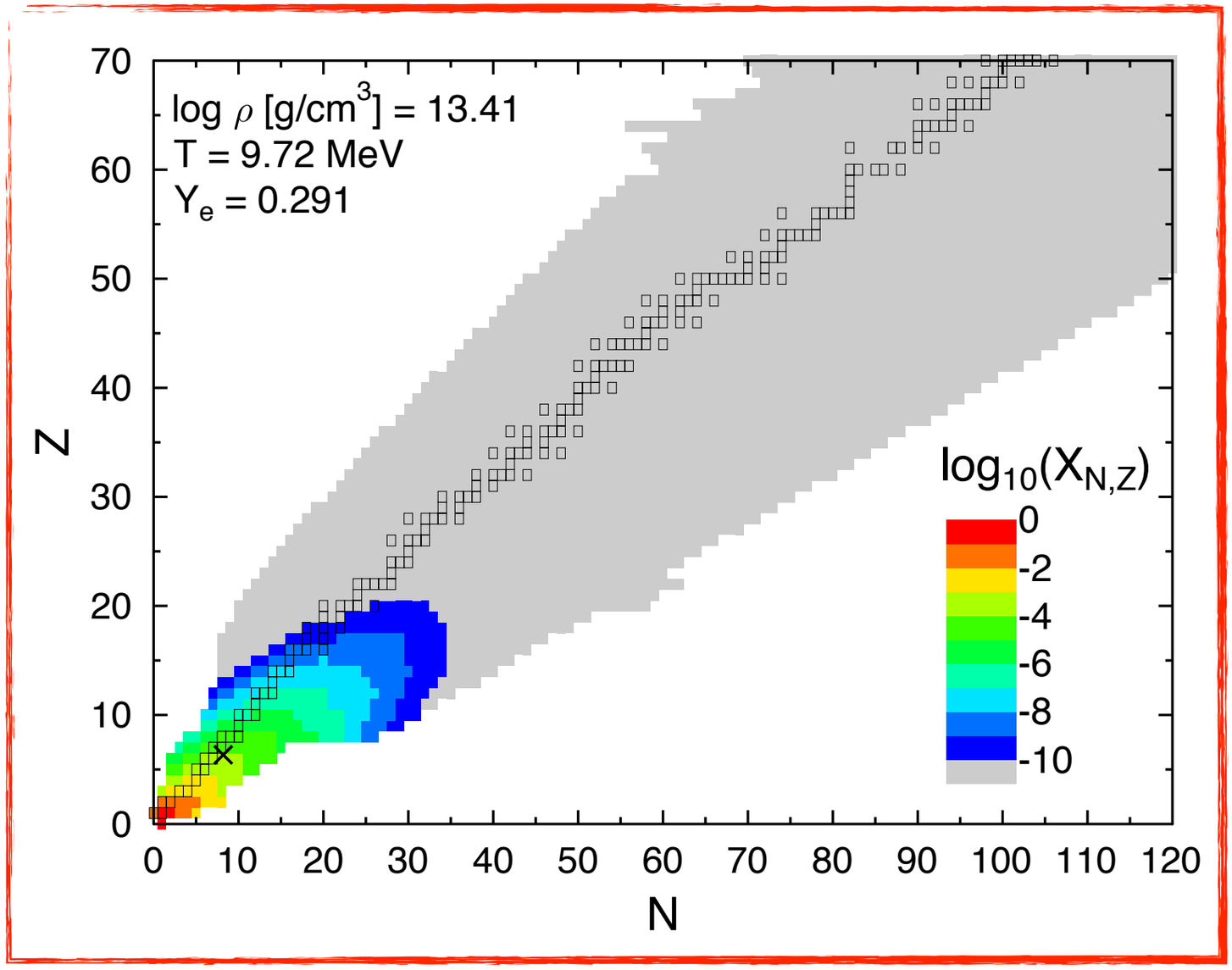
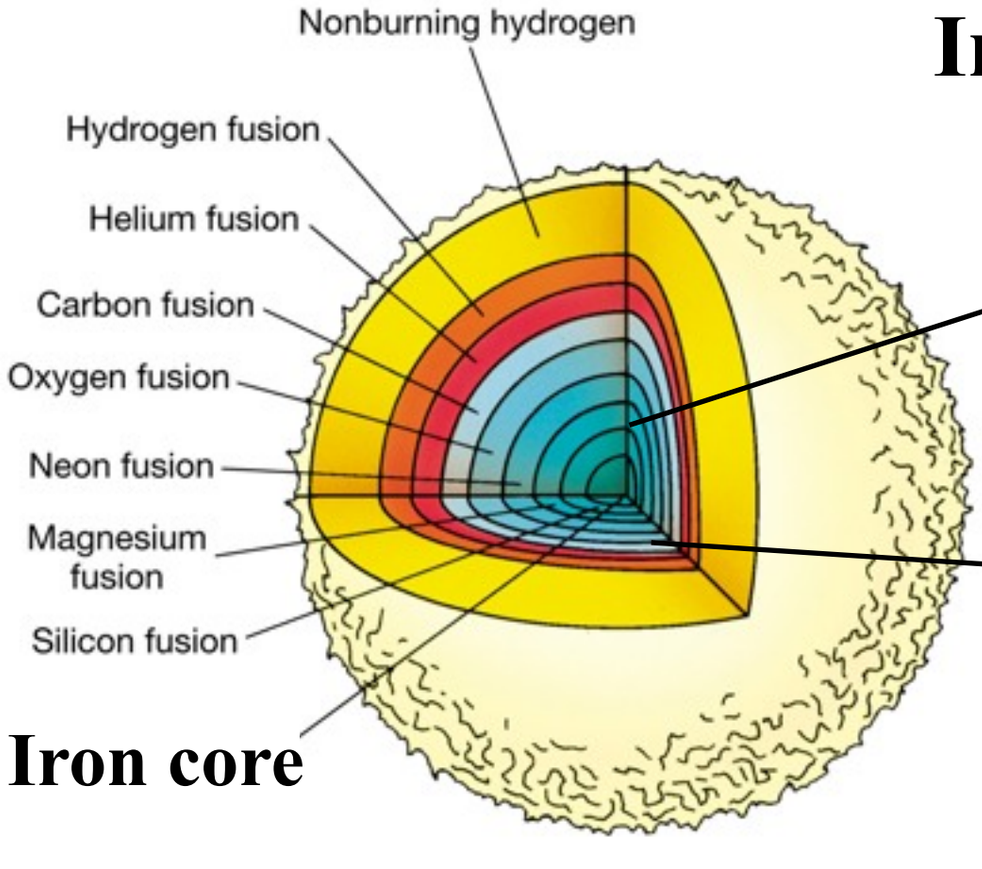
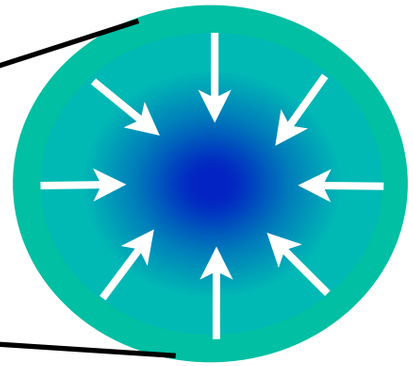




Iron core collapse

$\sim 10^3$ km

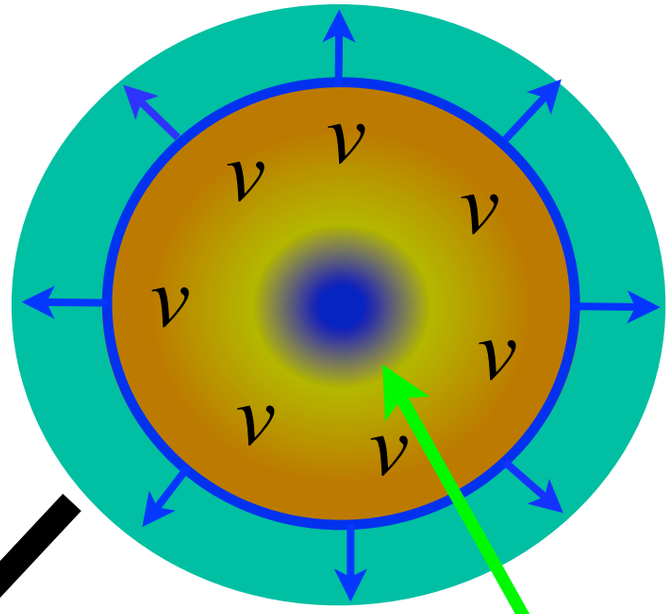


$E_{\rm gain} \simeq 3 - 6 \times 10^{53}$ erg

"Supernova problem"

(ejection of stellar mantle)

$E_{\rm expl} \simeq 10^{50} - 10^{51}$ erg



proto-neutron star (PNS)

$\sim$ 40–80 km

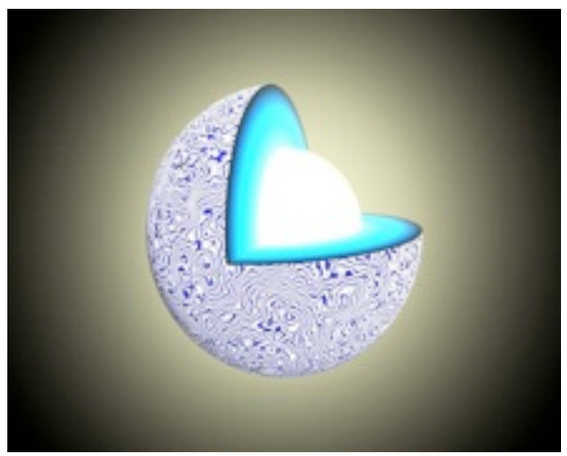
T $\sim$ 10–50 MeV

$8 - 25\ \mathrm{M}_\odot$

neutron star

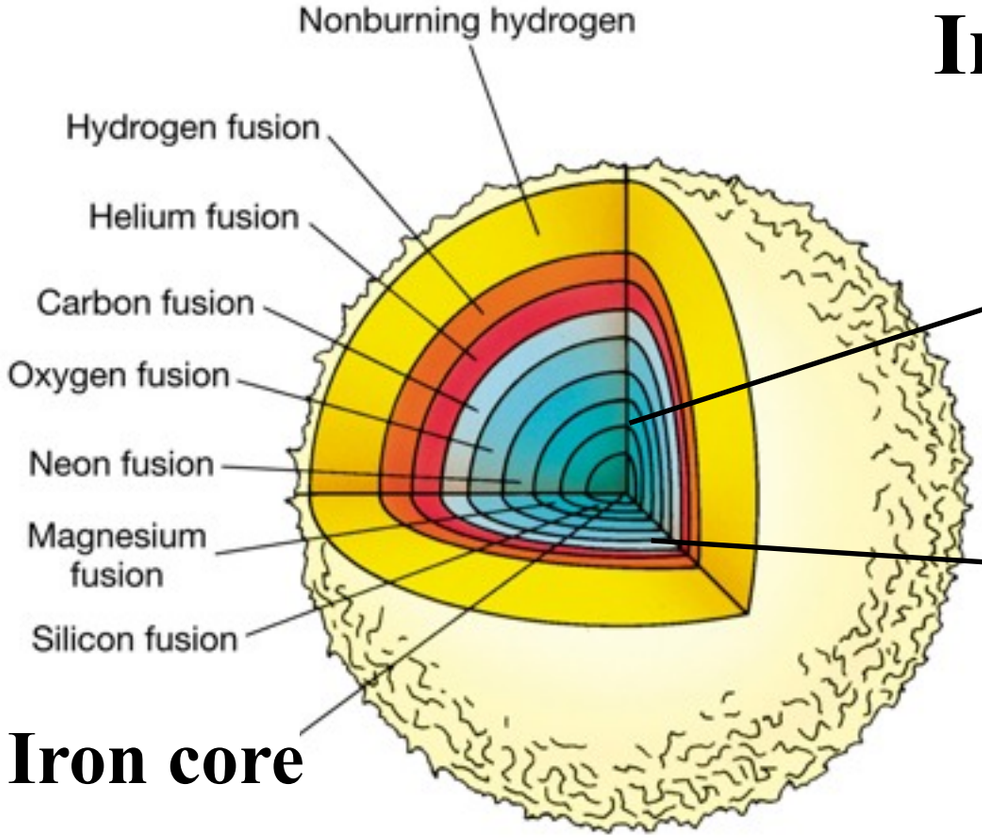
$\sim$ 12–14 km

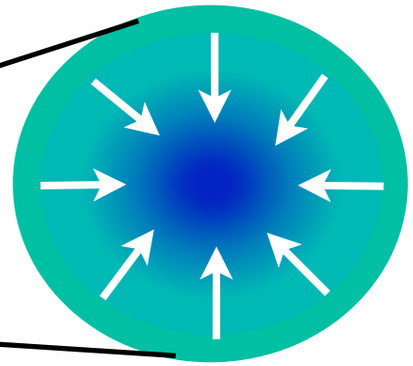
T = 0



Iron core collapse

$\sim 10^3$ km





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~~**"Supernova problem"**~~

~~(ejection of stellar mantle)~~

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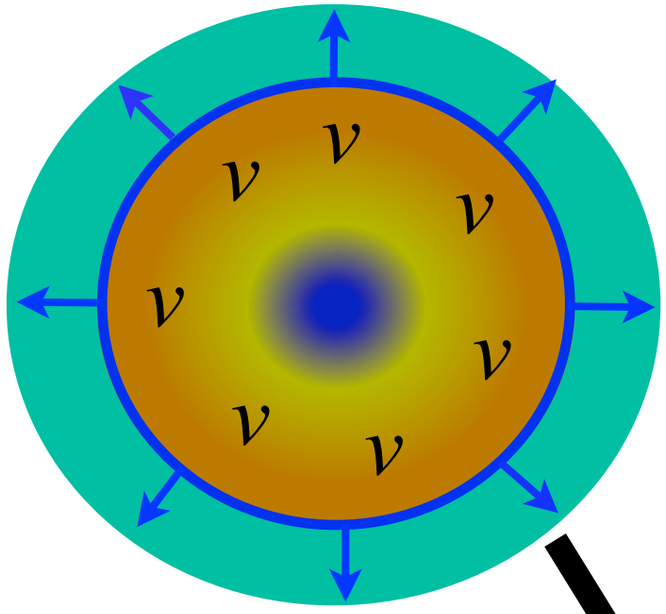
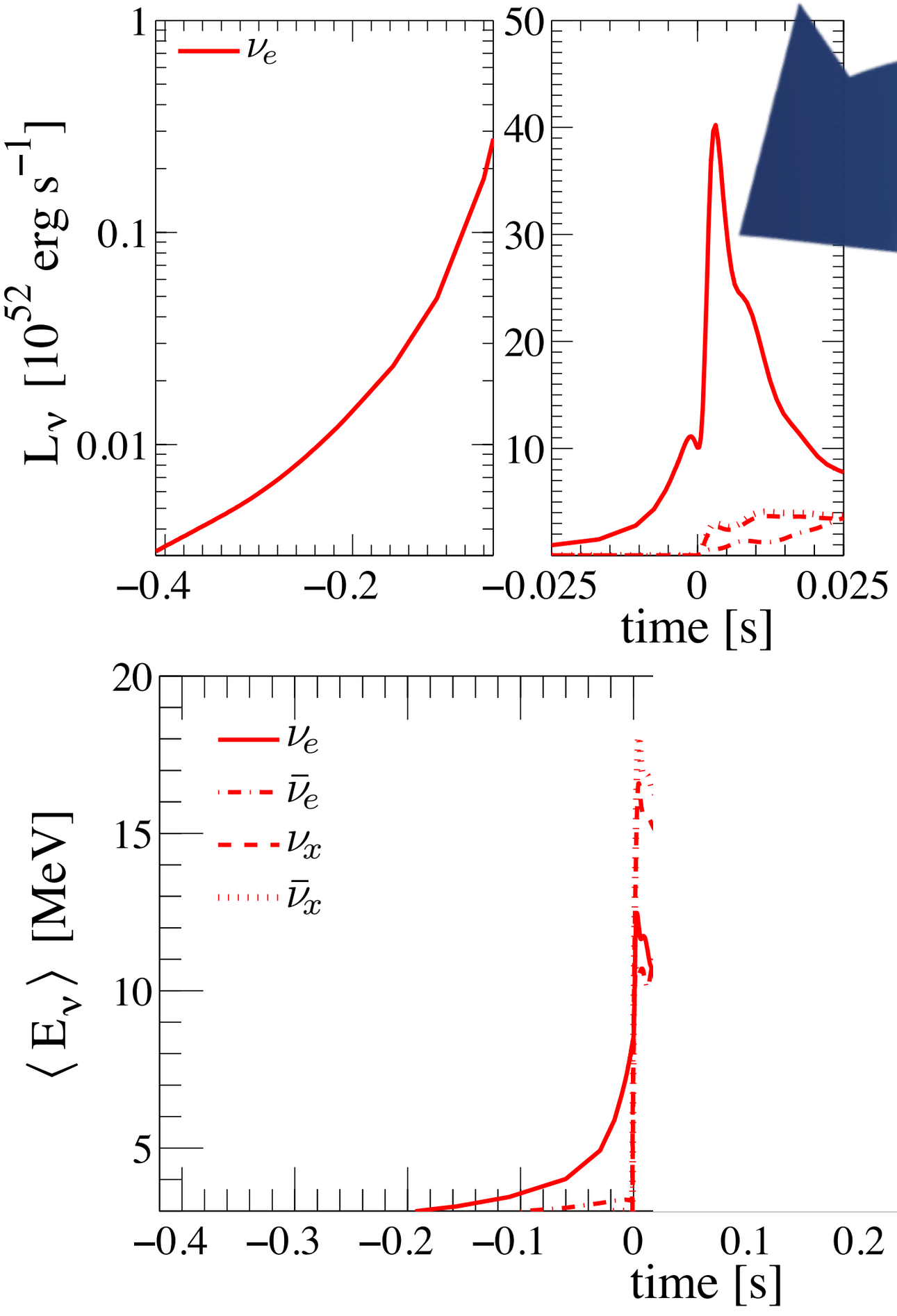
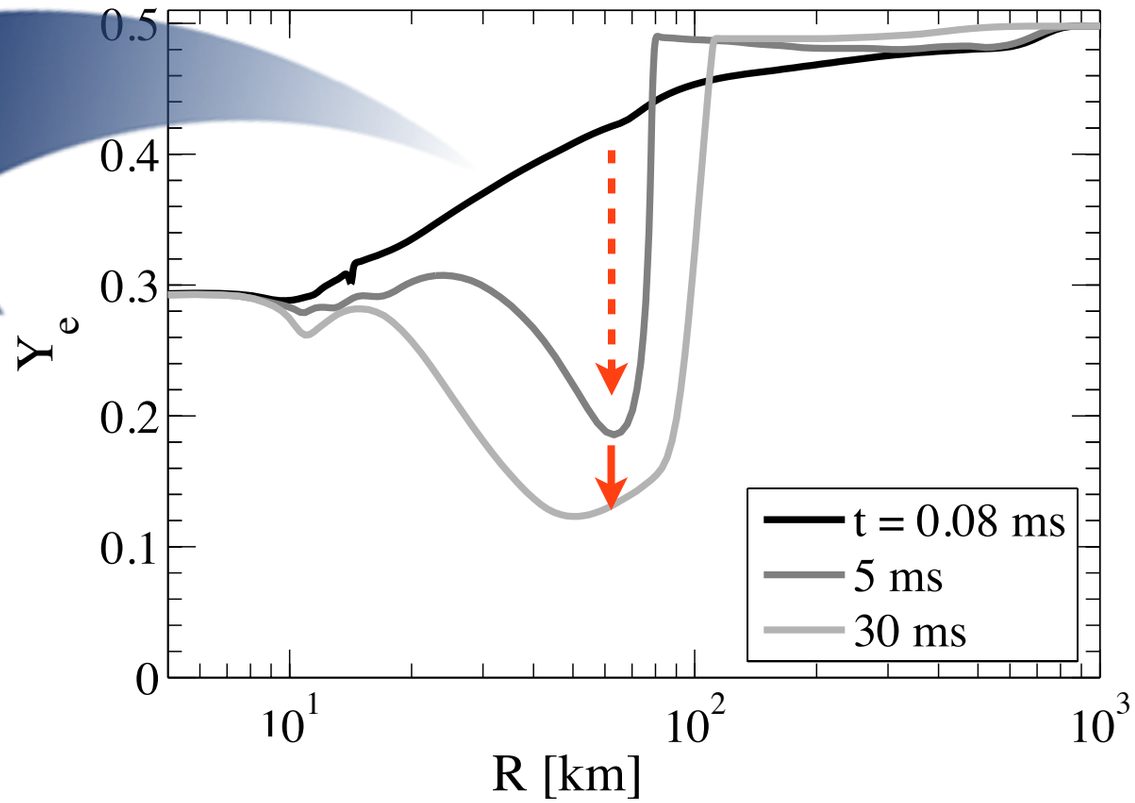
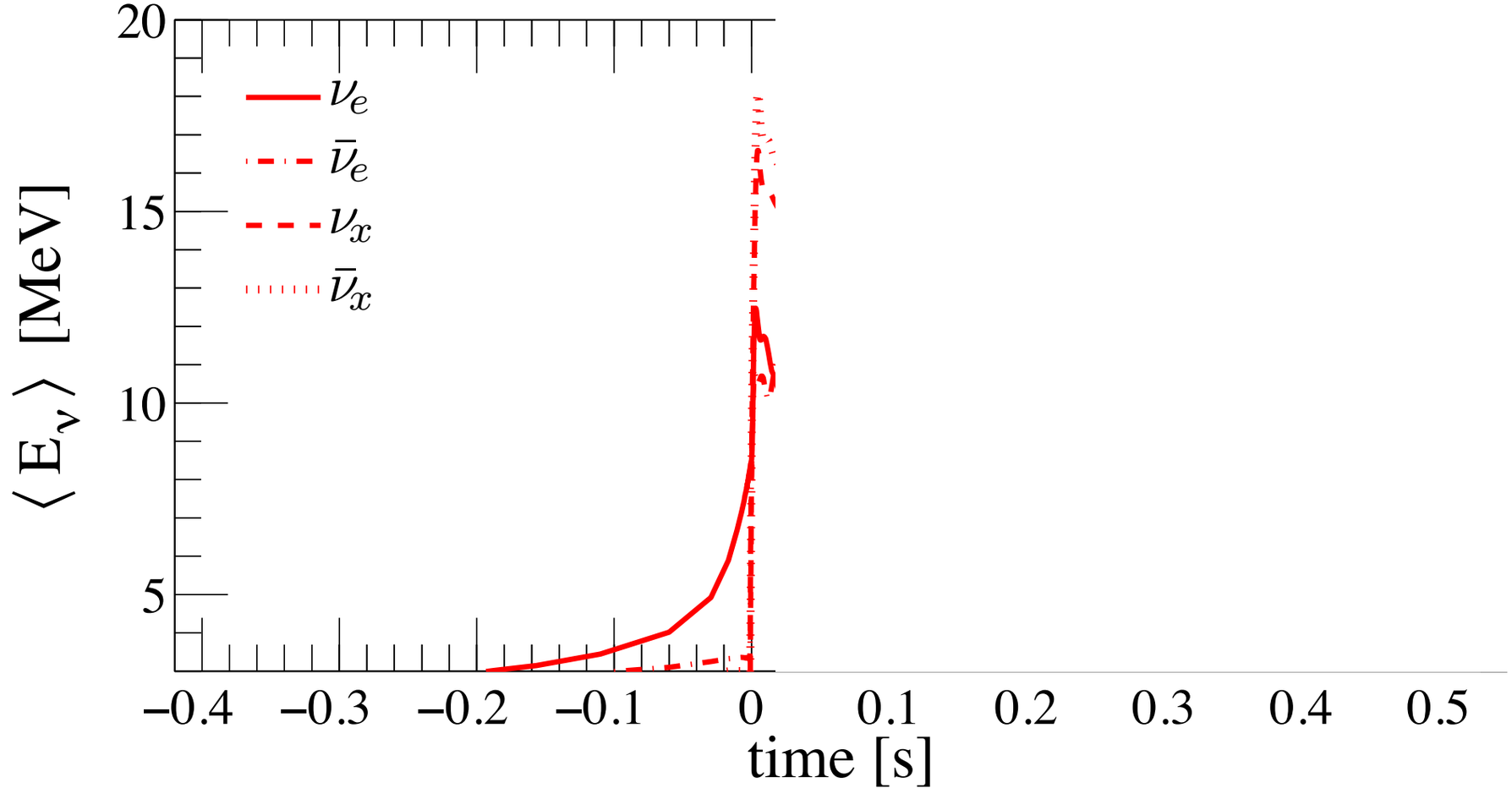


$\gtrsim 30$ $\mathrm{M}_\odot$ (?)

black hole







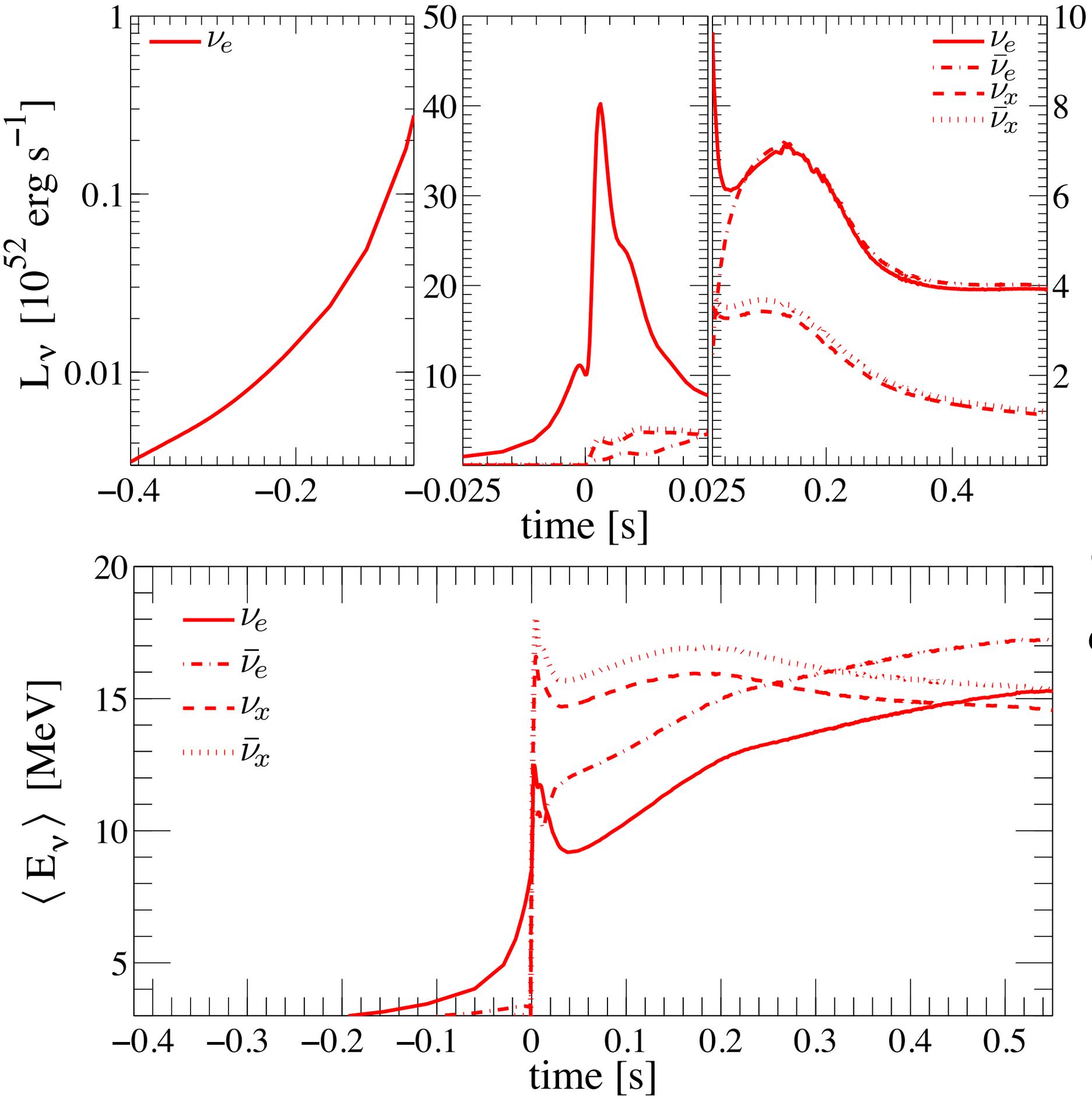
$$e^- + p \leftrightarrows n + \nu_e$$

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

$$\nu + N \leftrightarrows N + \nu'$$

$$\nu + e^\pm \leftrightarrows e^\pm + \nu'$$

$$\nu\bar{\nu}$$



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$$\nu + N \leftrightarrows N + \nu'$$

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$$\nu\bar{\nu}$$

Entropy [k_B]

2 4 6 8 10 12 14

10^5

^{4}He

10^4

^{12}C

^{16}O

infalling heavy nuclei

$\simeq 1 - 0.01\ M_\odot\ s^{-1}$

10^3

^{28}Si, ^{32}S

Radius [km]

R_{ν_e}

$(n, p, {}^4\mathrm{He}, e^\pm)$

Fe - core

Shock

ν ν ν ν

$(n, p, e^\pm)$

10^2

10^1

(proto)neutron star

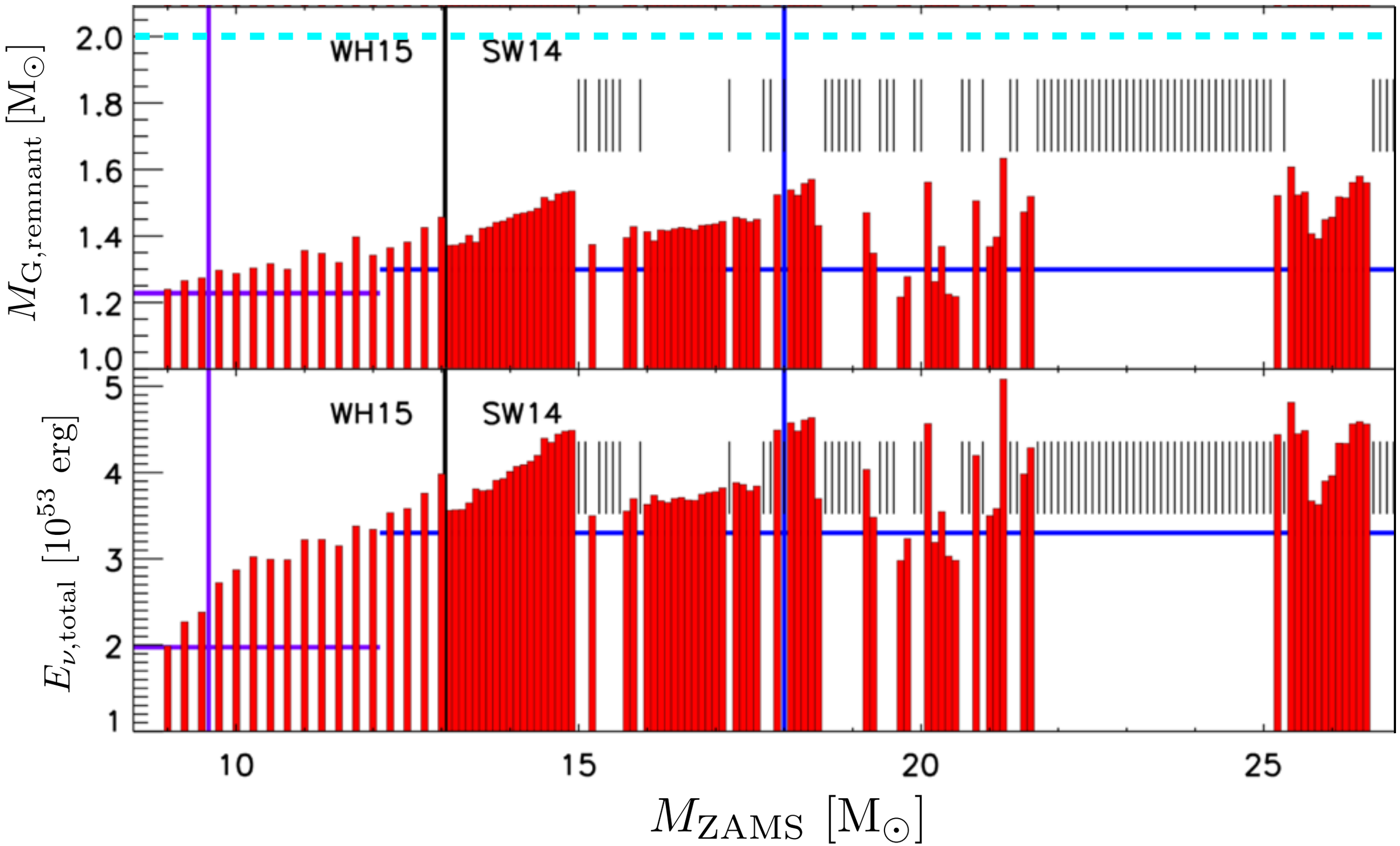
-0.1 0 0.1 0.2

time [s]

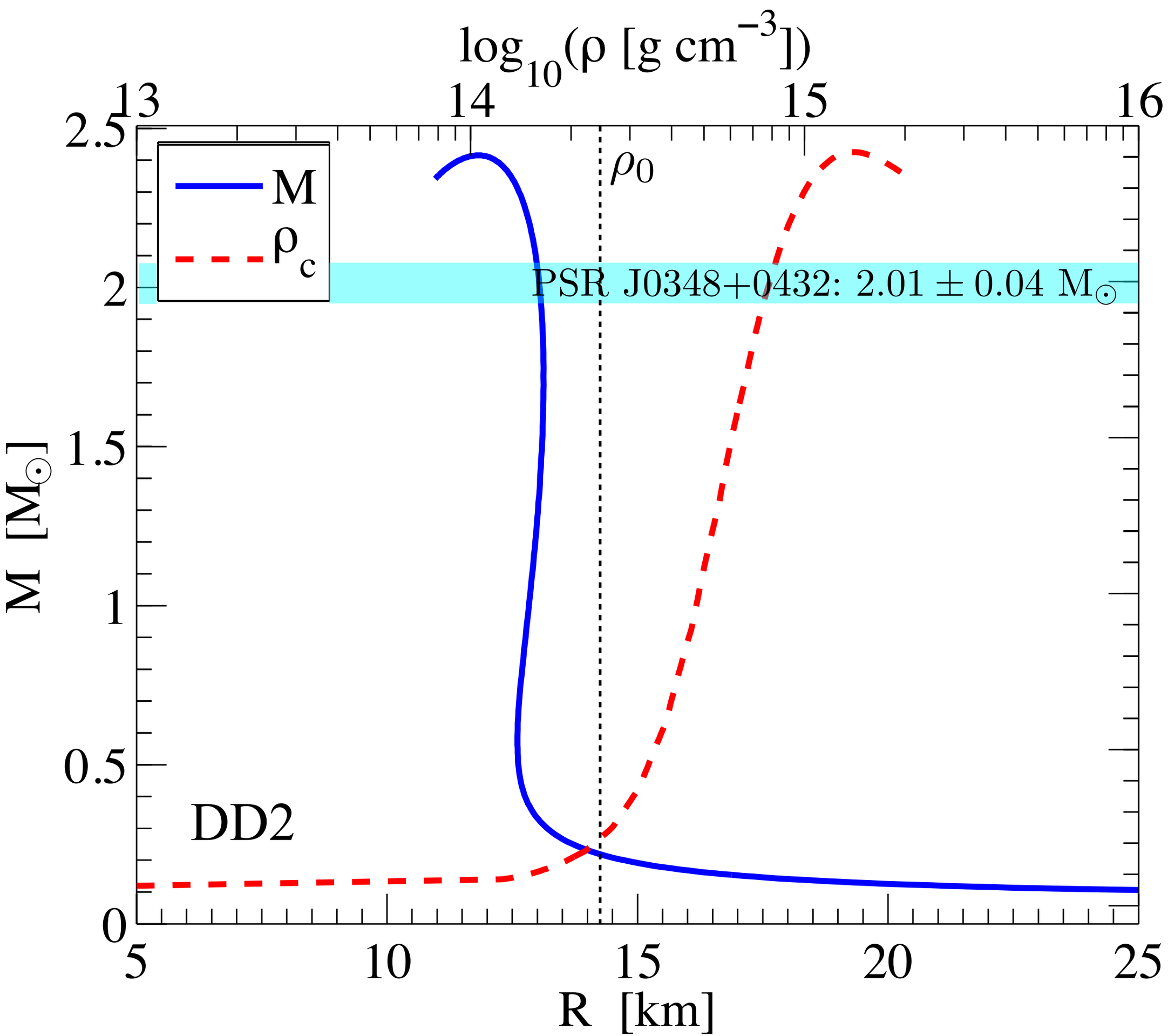
e^- capture supernovae

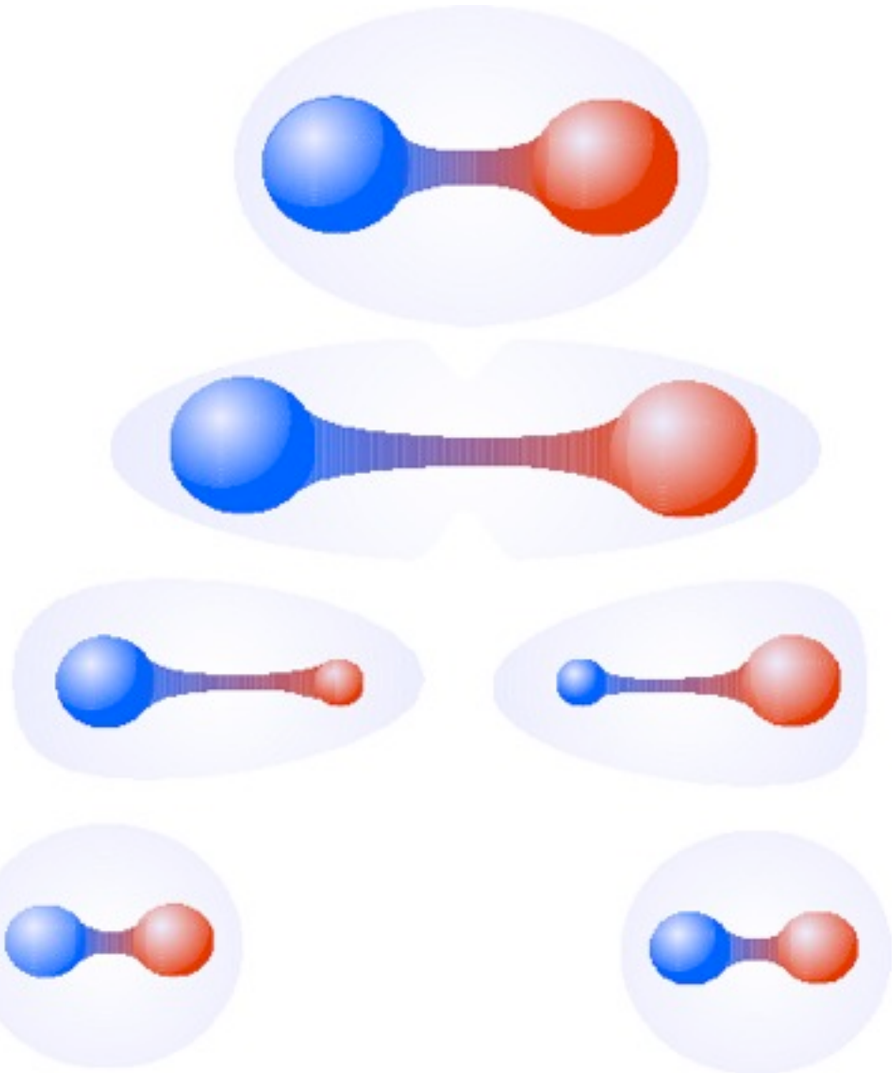
SN1987A

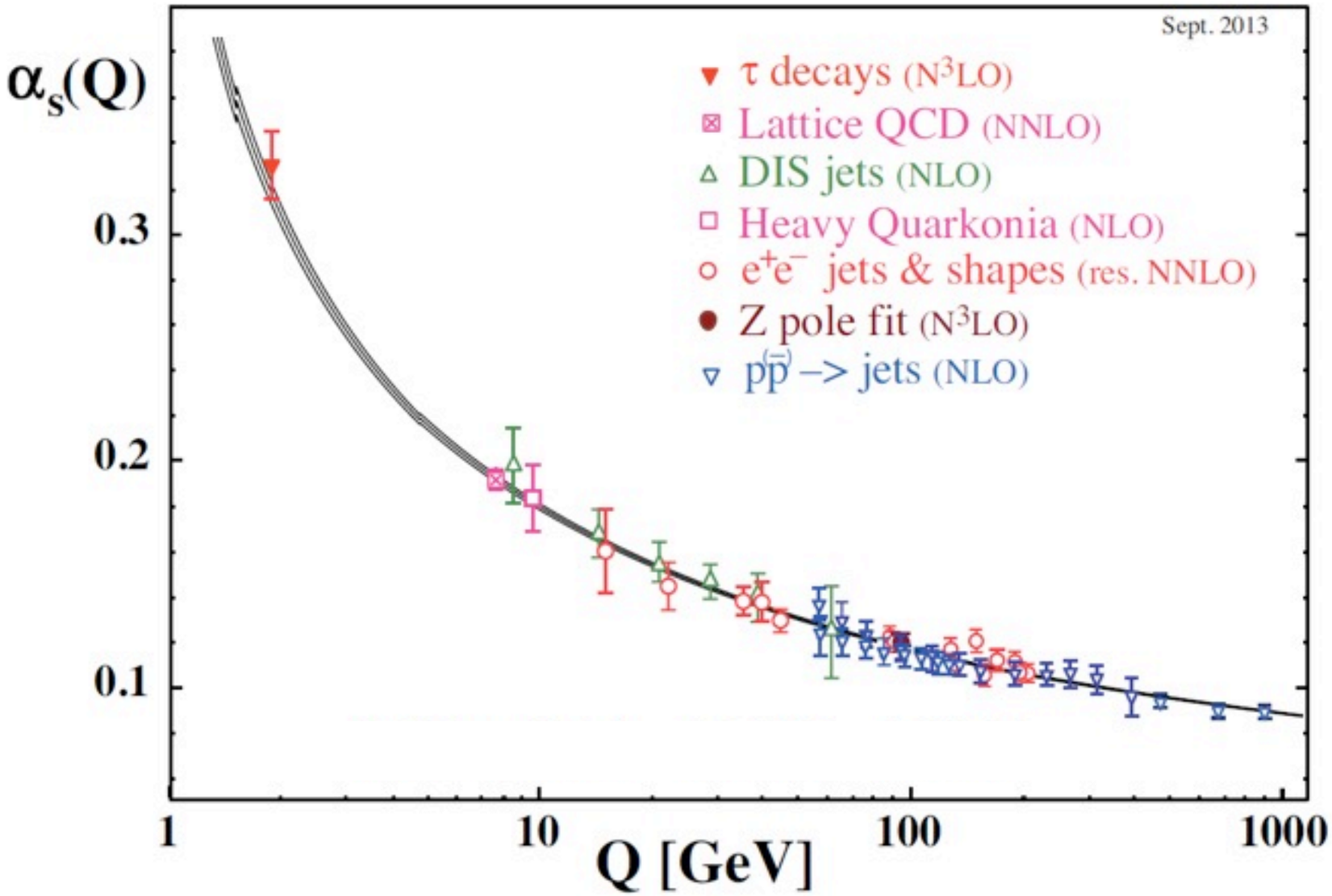
$M_{\rm G,remnant} < 1.65\ {\rm M}_\odot$



ApJ 821:38, 45 (2016)

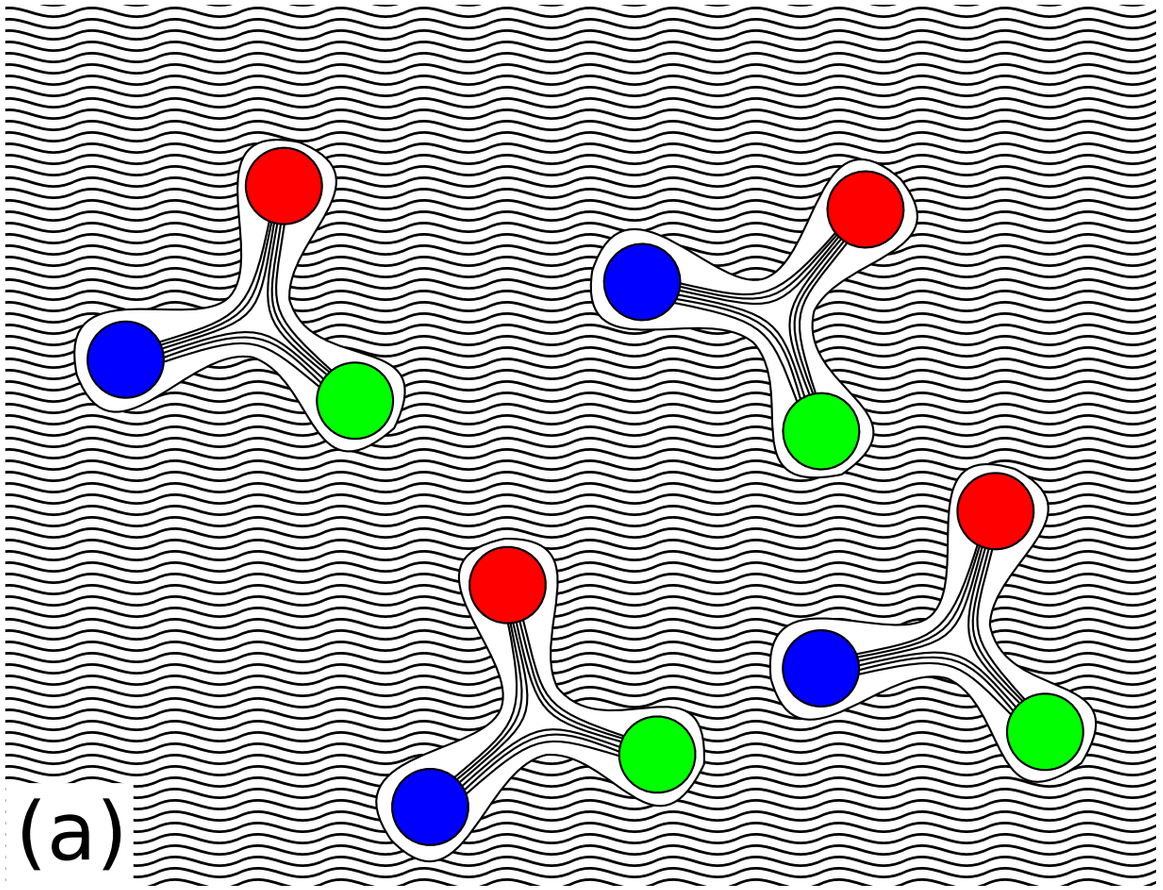

log10(ρ [g cm−3])
13
14
15
16
2.5
2
1.5
1
0.5
0
M [M⊙]
M
ρc
ρ0
PSR J0348+0432: 2.01 ± 0.04 M⊙
DD2
5
10
15
20
25
R [km]



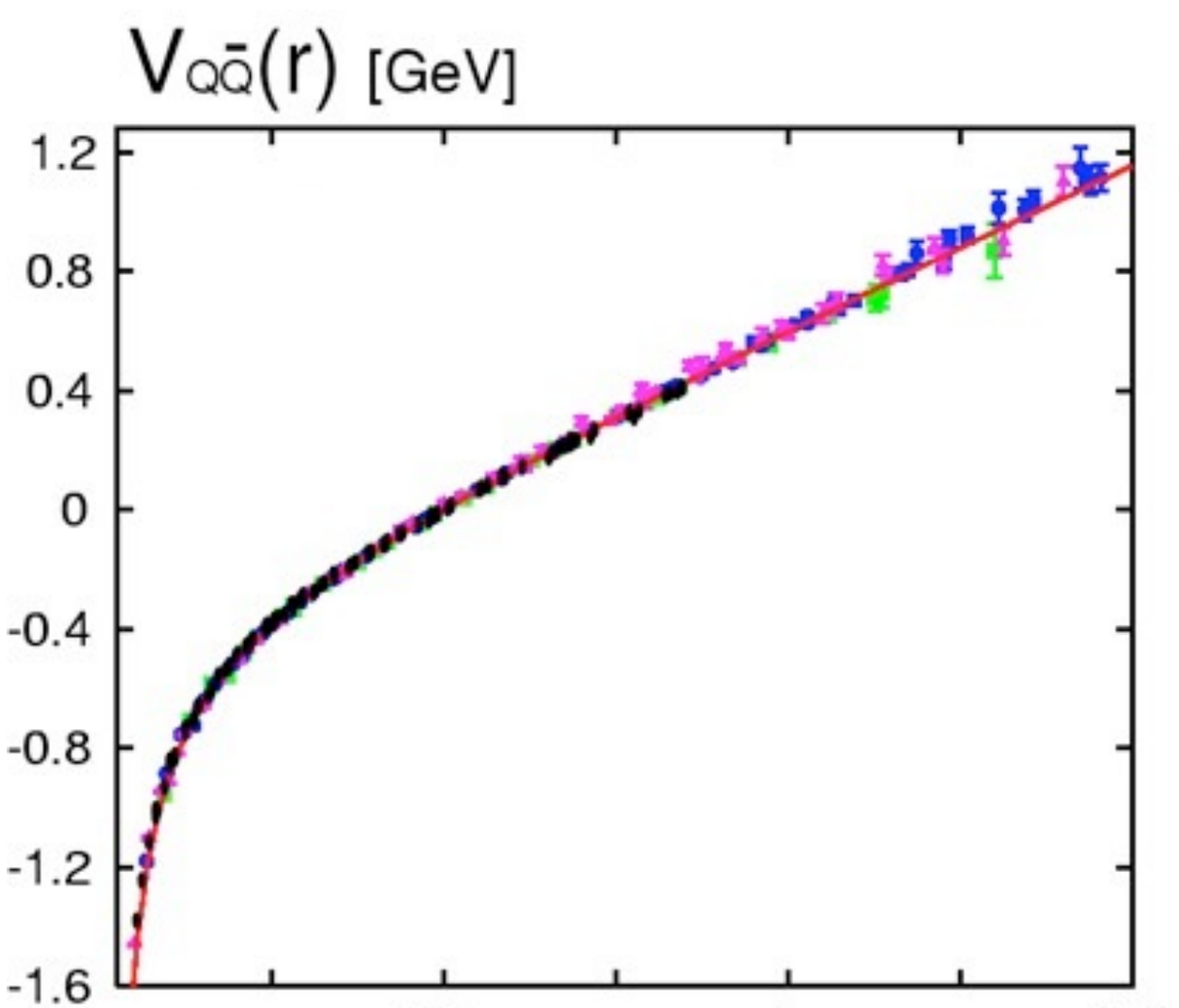


see talk by Niels-Uwe Bastian

vacuum



$$D = D_0$$



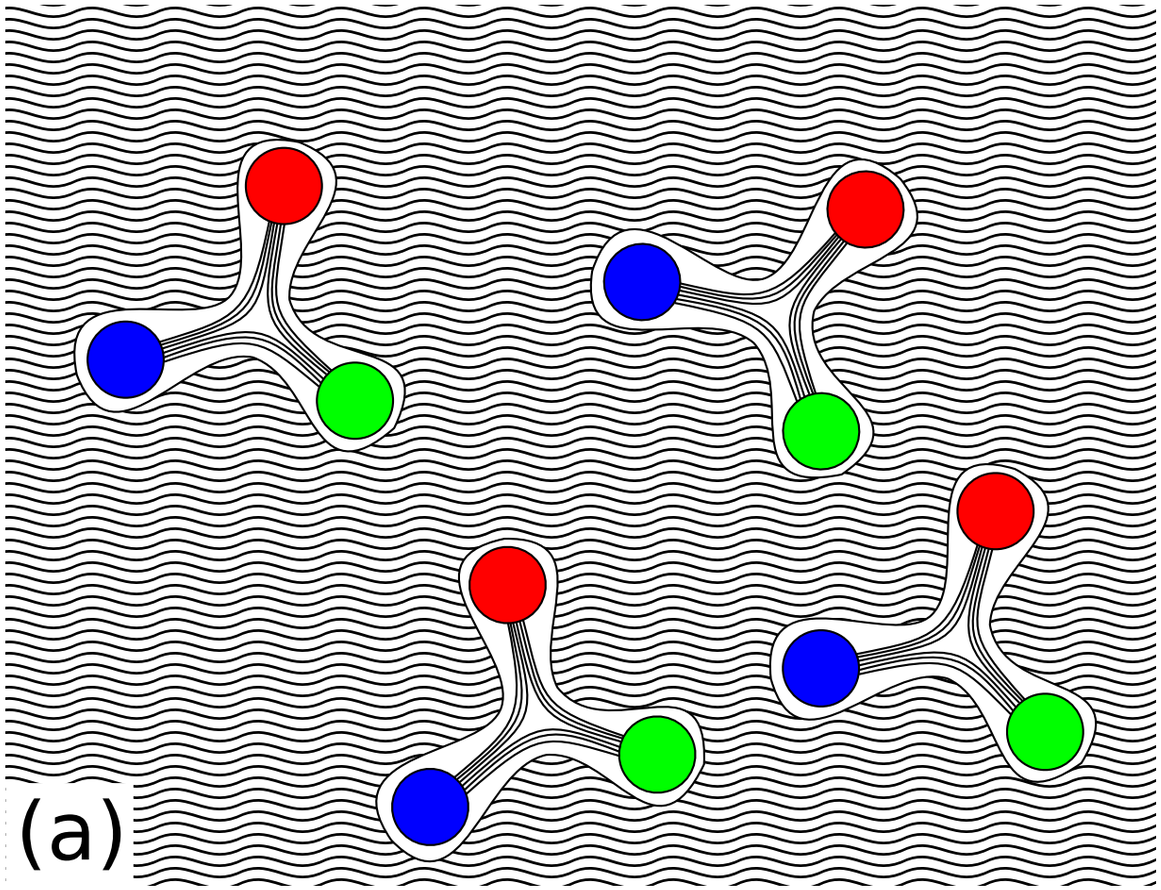
$$V_{QQ}(r) \propto D_0\, r - \frac{A}{r}$$

$$D_0 = 1 \text{ GeV fm}^{-1}$$

NPA 536, 669 (1992)

PRD 96, 056024 (2017)

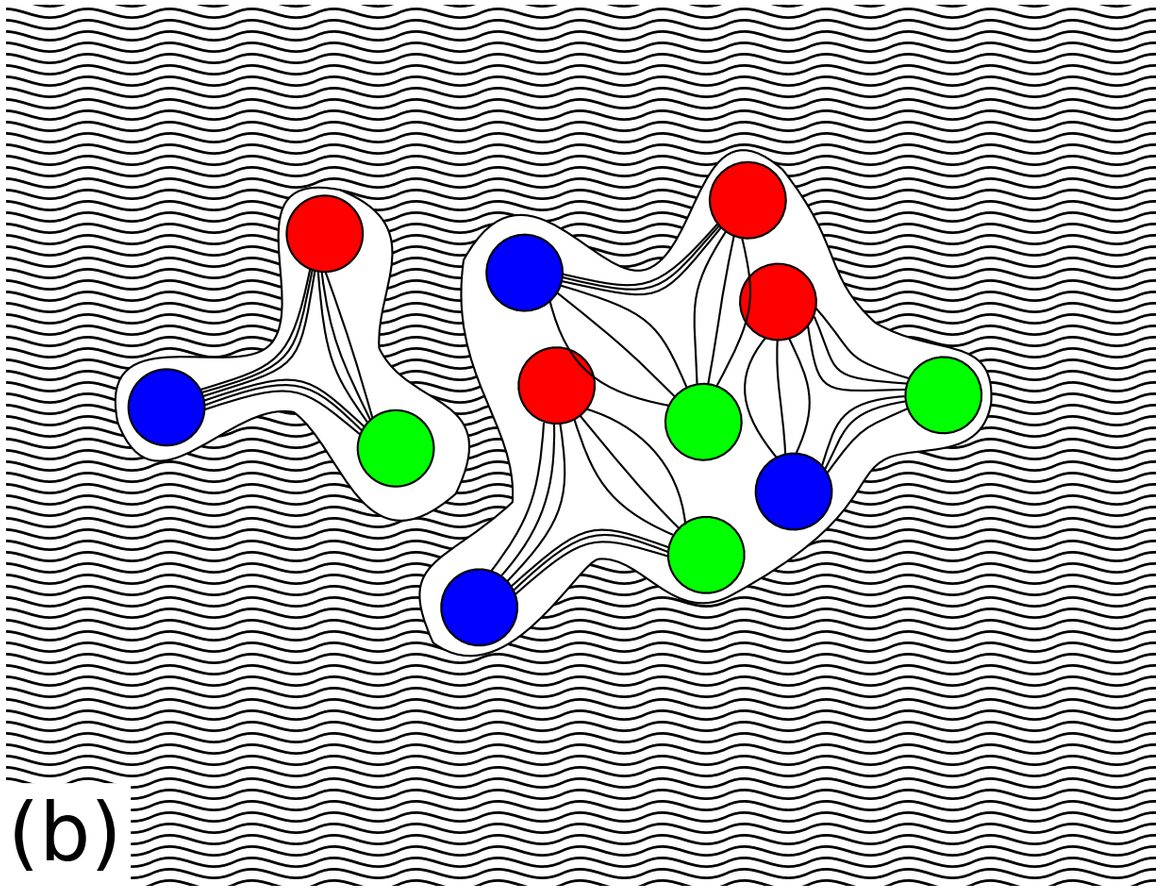
vacuum



$$D = D_0$$

(see talk by Aleksandr Nikolaev)

medium dependence



$$D(\rho) = D_0\,\Phi(\rho)$$

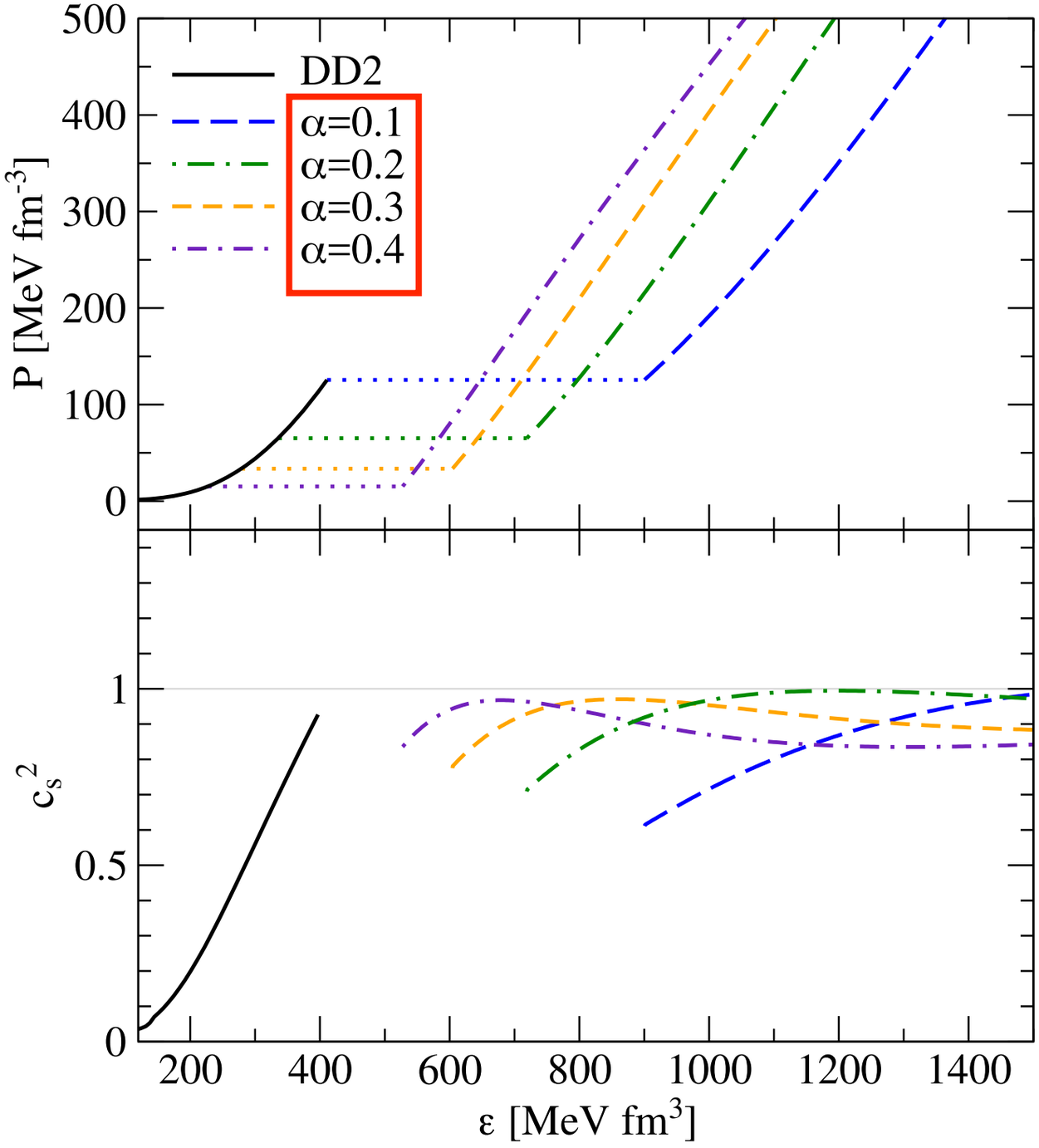
$$\Phi(\rho) = \exp\left\{-\alpha(\rho-\rho_0)^2\right\}$$

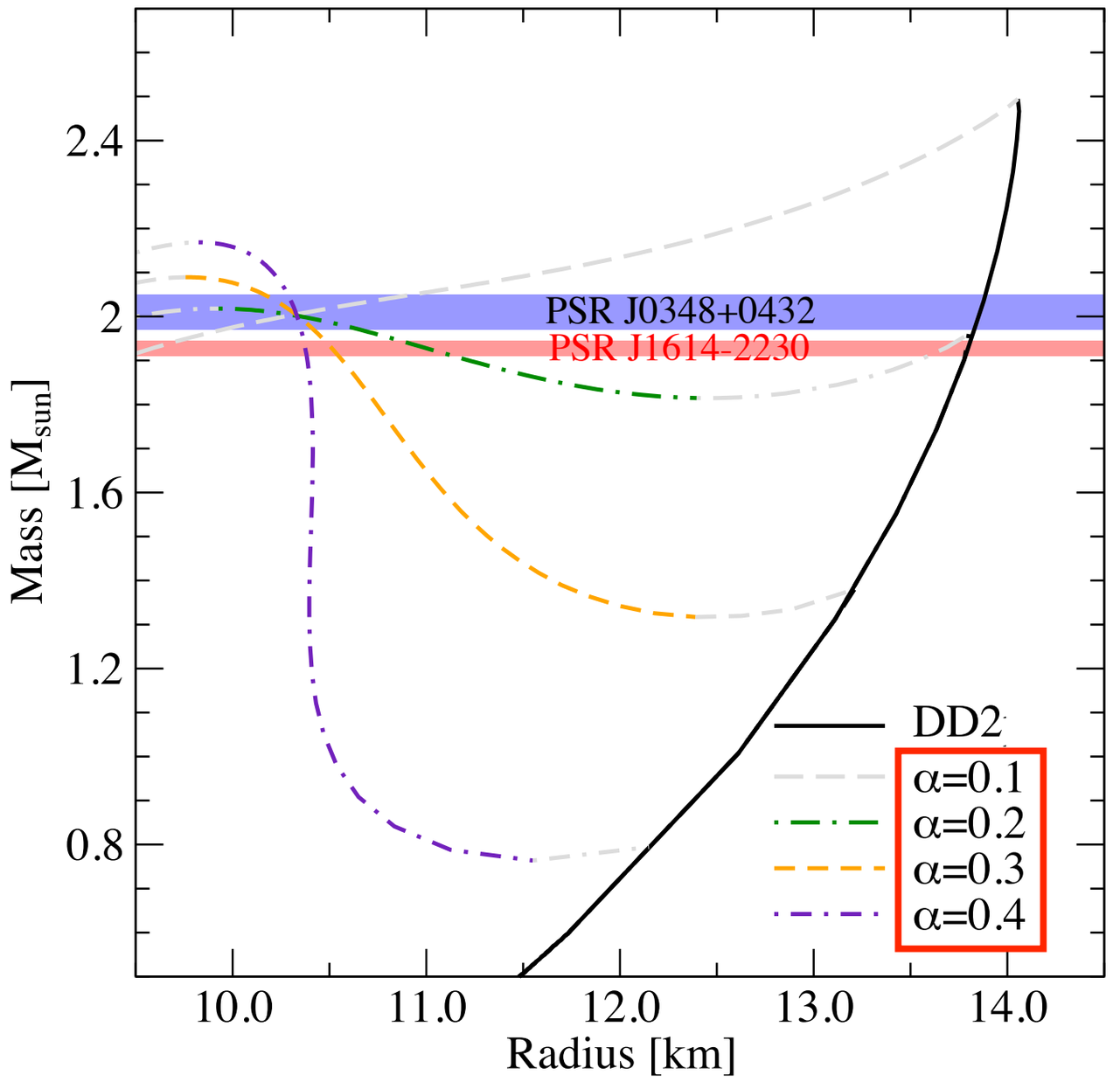
repulsive vector interaction:

$$\mu^* = \mu - a\,\rho - \mathcal{O}\left(\rho^3\right)$$

A&A 577, 40 (2015)

ApJ 810, 134 (205)





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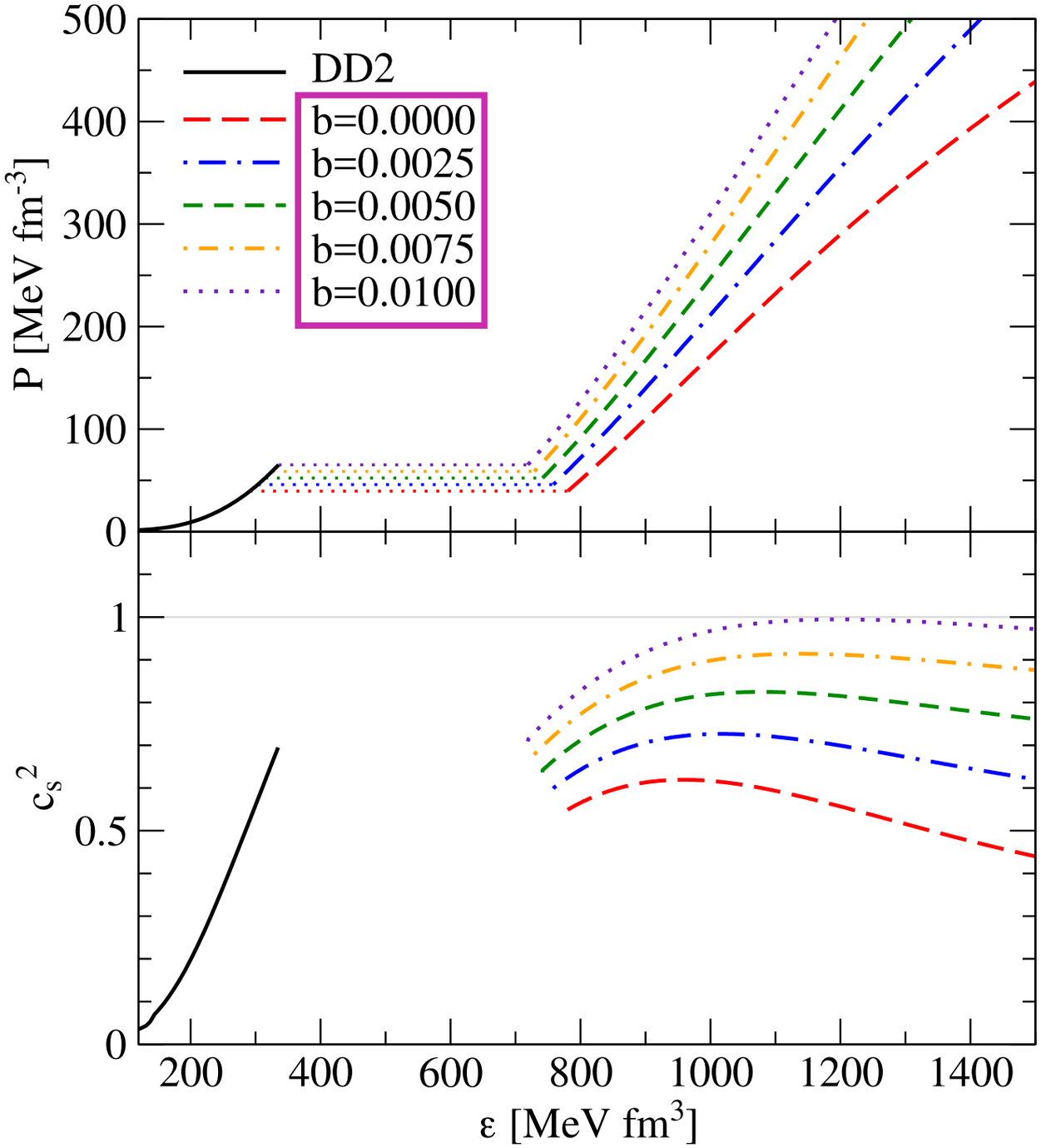

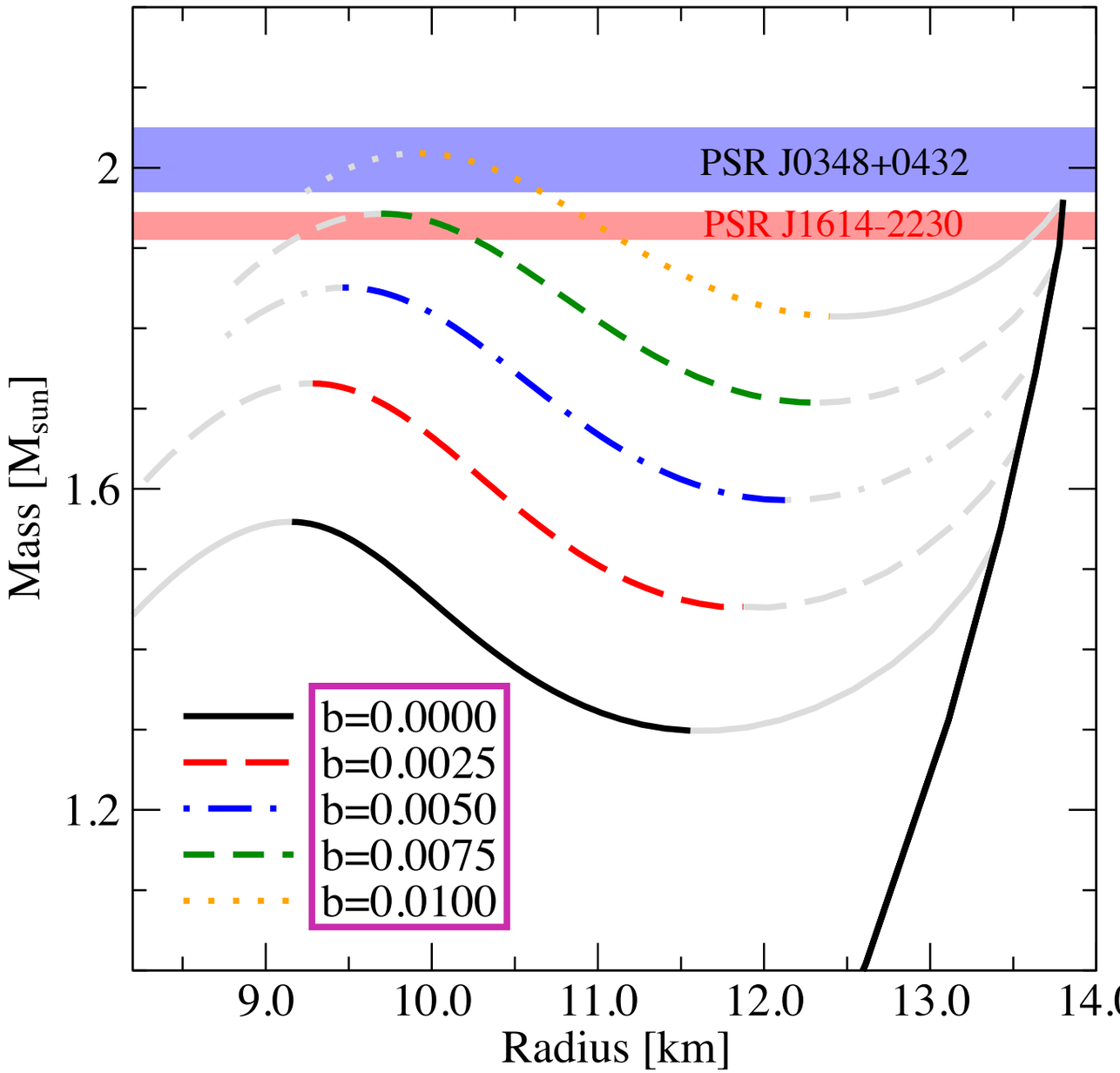

repulsive vector interaction:

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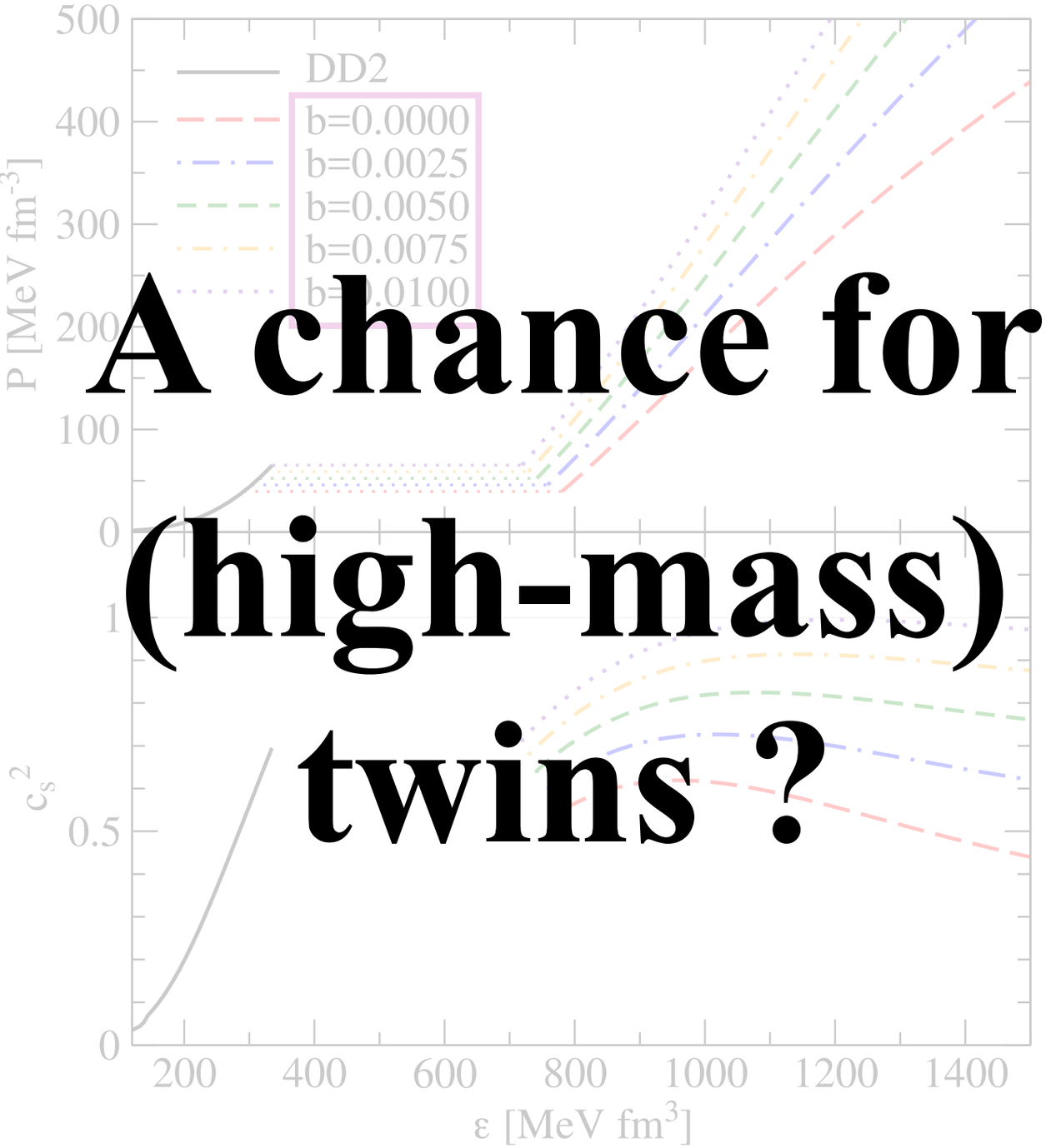
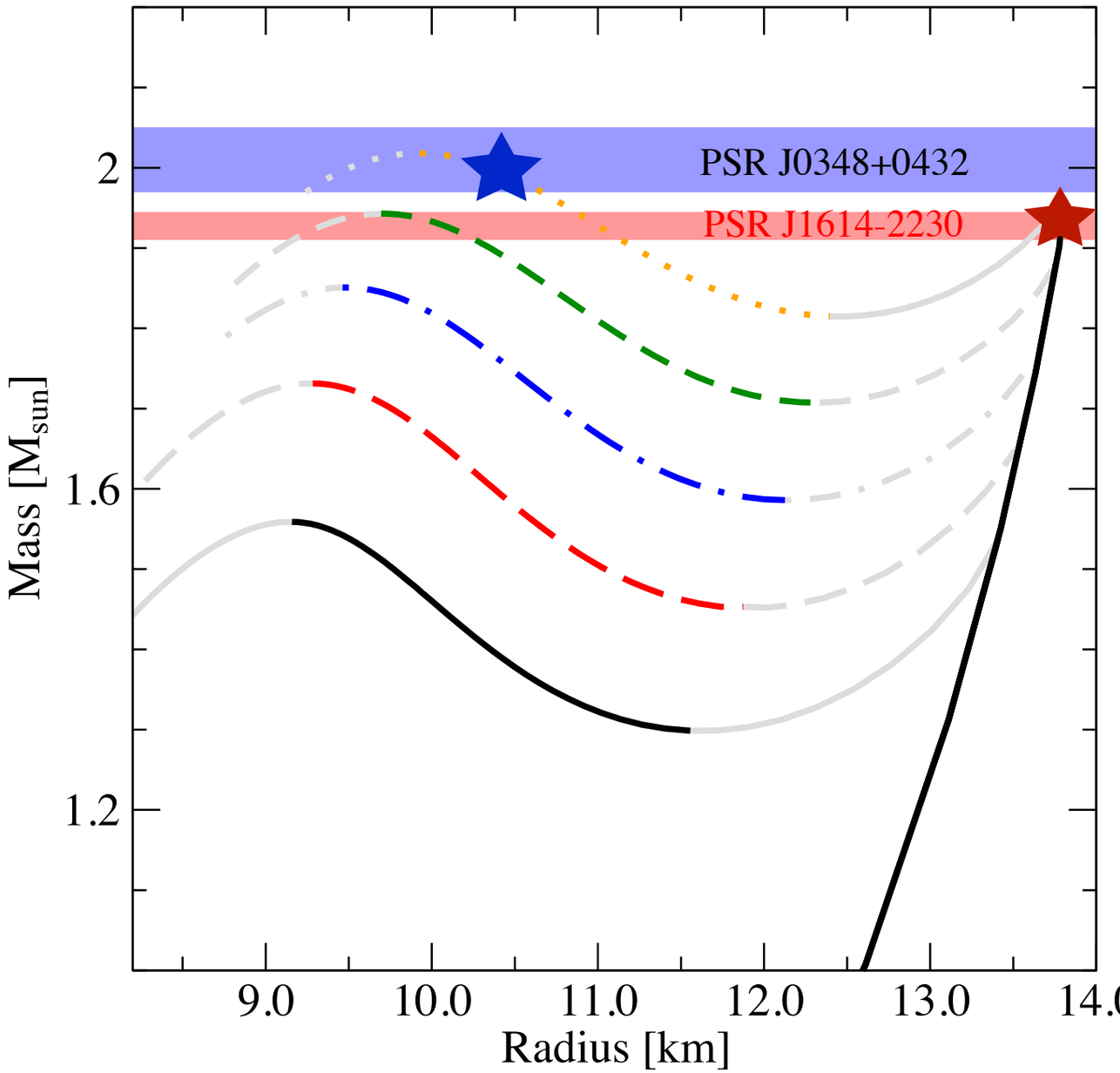
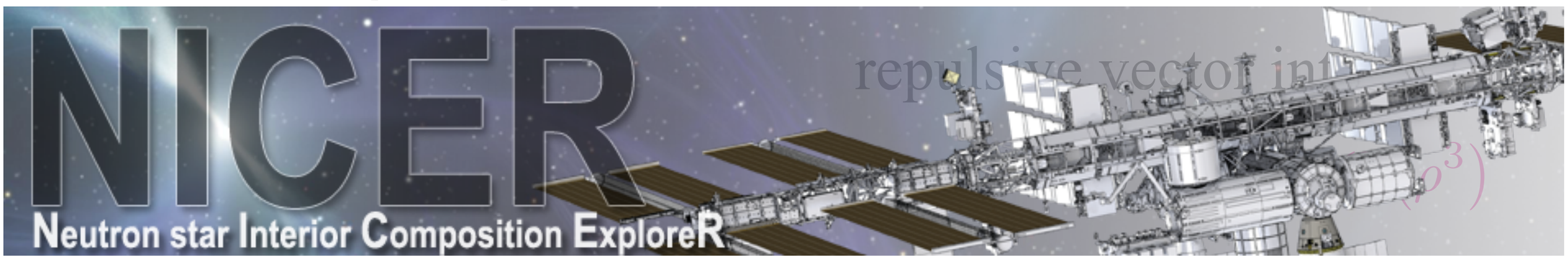
A chance for (high-mass) twins ?







repulsive vector int

(ω^3)

T = 0, β–eq.

hadron

hybrid

$R_{1.5\,\mathrm{M}_\odot} = 12.2$ km

$M_{\max} = 2.15\ \mathrm{M}_\odot$

M [$M_\odot$]

Radius [km]

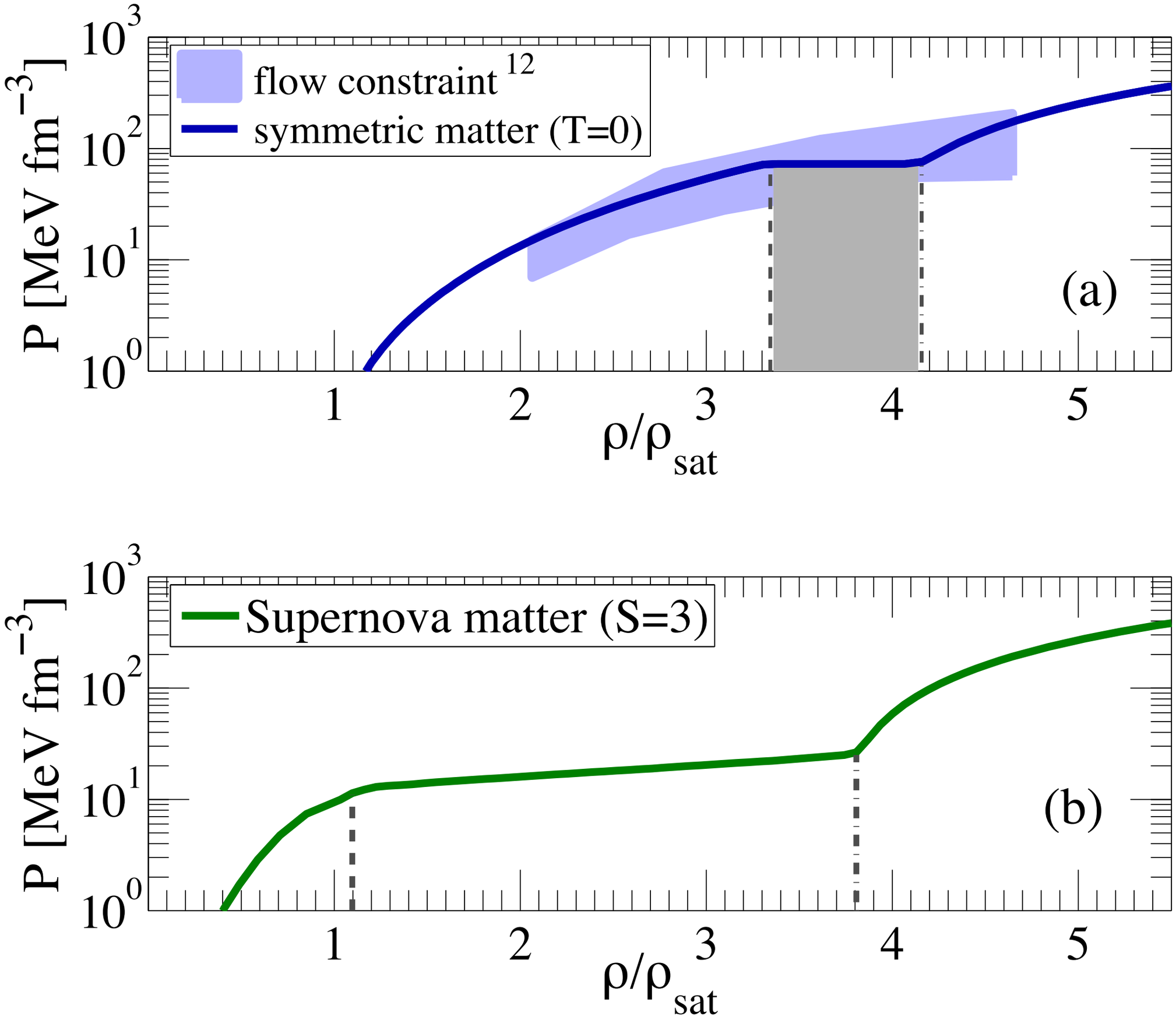
P [MeV fm^{-3}]

nucleons/ hadrons

mixed phase

quarks

ρ/ρ_{sat}


flow constraint [12]
symmetric matter (T=0)
P [MeV fm^{-3}]
10^3
10^2
10^1
10^0
1
2
3
4
5
ρ/ρ_{sat}
(a)
Supernova matter (S=3)
P [MeV fm^{-3}]
10^3
10^2
10^1
10^0
1
2
3
4
5
ρ/ρ_{sat}
(b)

T/T_c

$12\,M_\odot$: no phase transition

$50\,M_\odot$: no phase transition

quark-gluon plasma

1

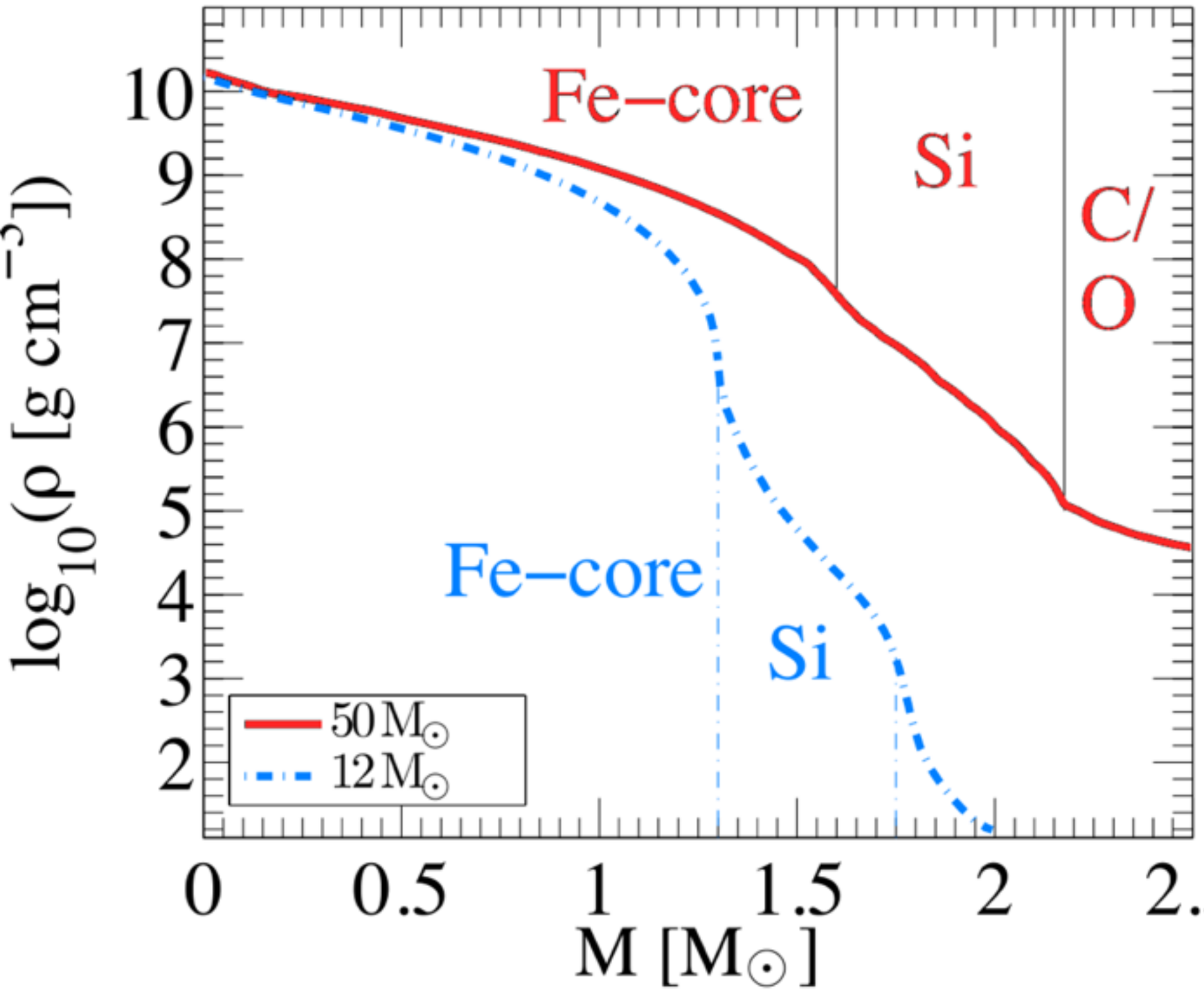
hadron-quark mixed phase

black-hole formation

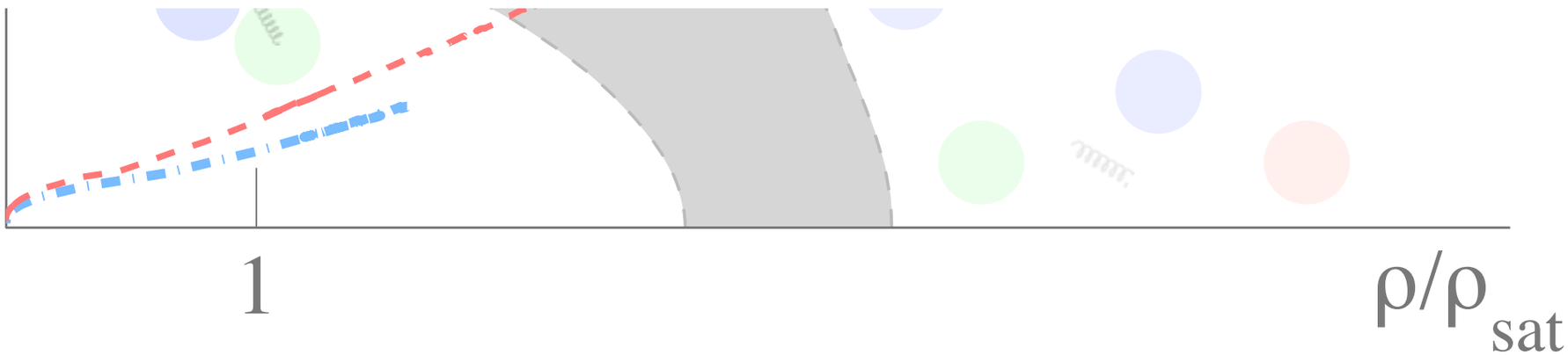
1

ρ/ρ_{sat}

o phase transition
o phase transition



black-hole
formation



T/T_c

1

quark-gluon plasma

hadron-quark mixed phase

$12\,M_\odot$: no phase transition

$50\,M_\odot$: no phase transition

$50\,M_\odot$: **with phase transition**

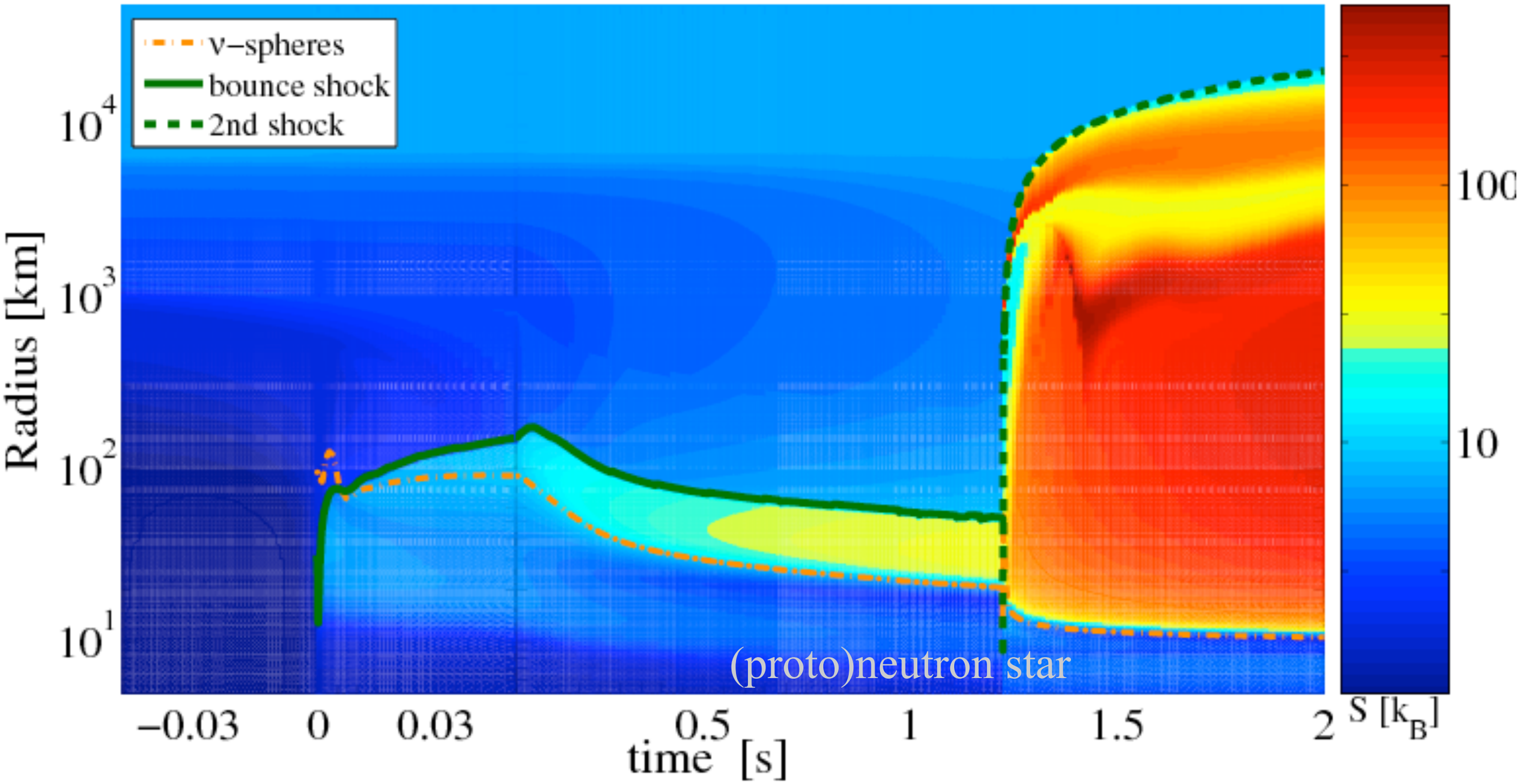
black-hole formation

$\tau \sim 1$ ms

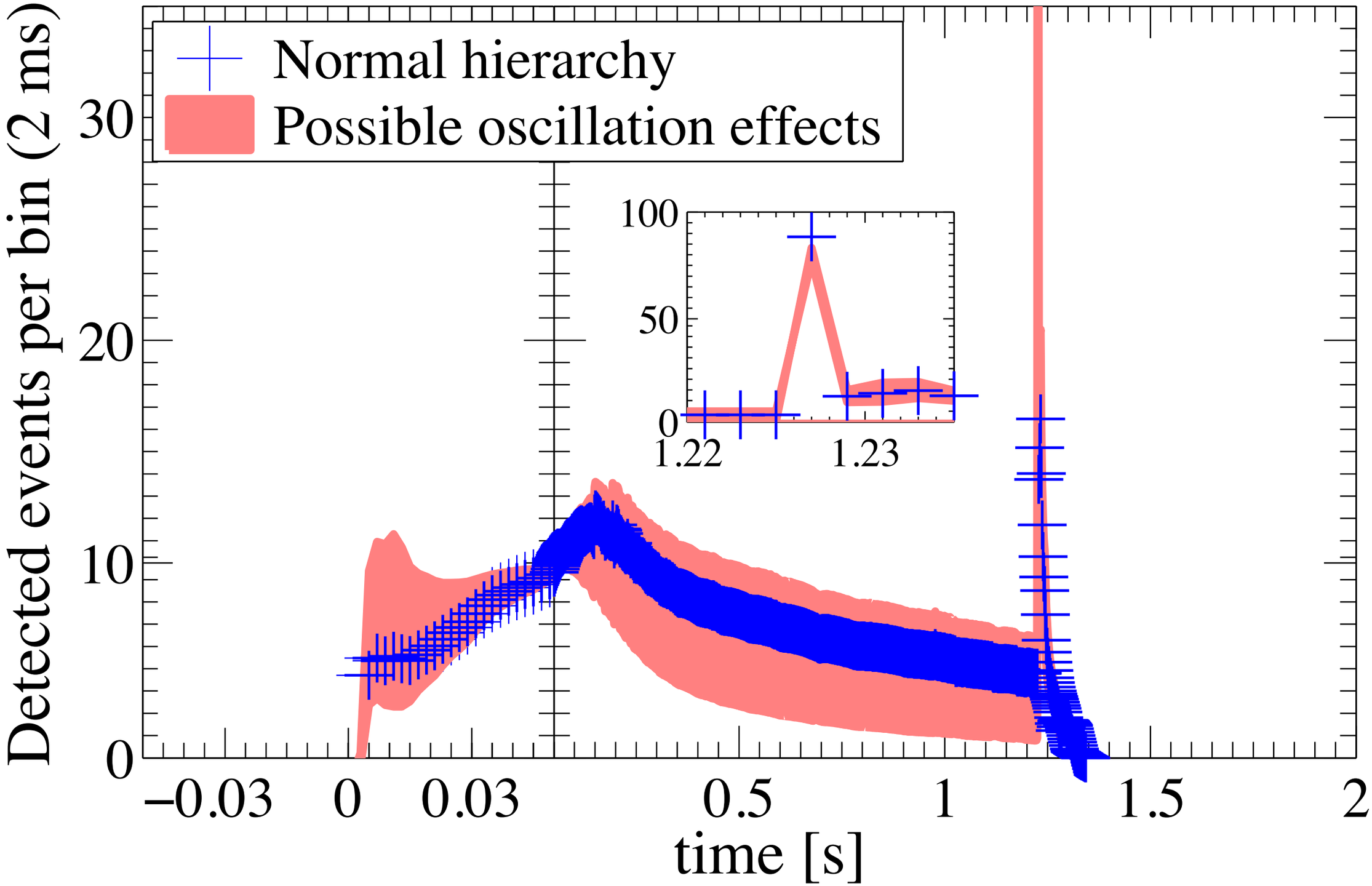
POW!

1

ρ/ρ_{sat}

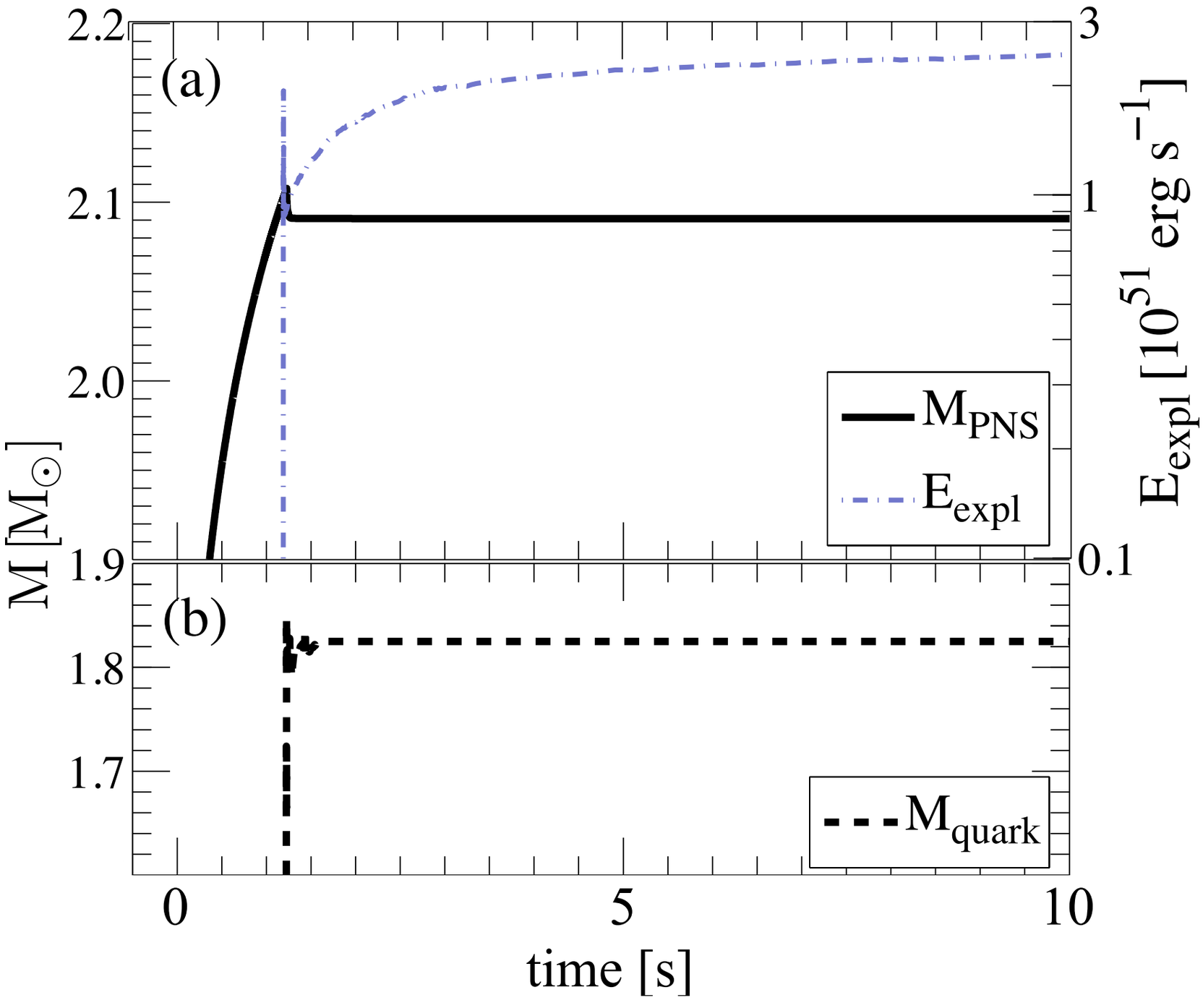


ArXiv astro-ph.HE/1712.08778



ArXiv astro-ph.HE/1712.08778

$$E_{expl} = 3 \times 10^{51} \text{ erg s}^{-1}$$
$$M_{NS} \simeq 2\ M_\odot$$

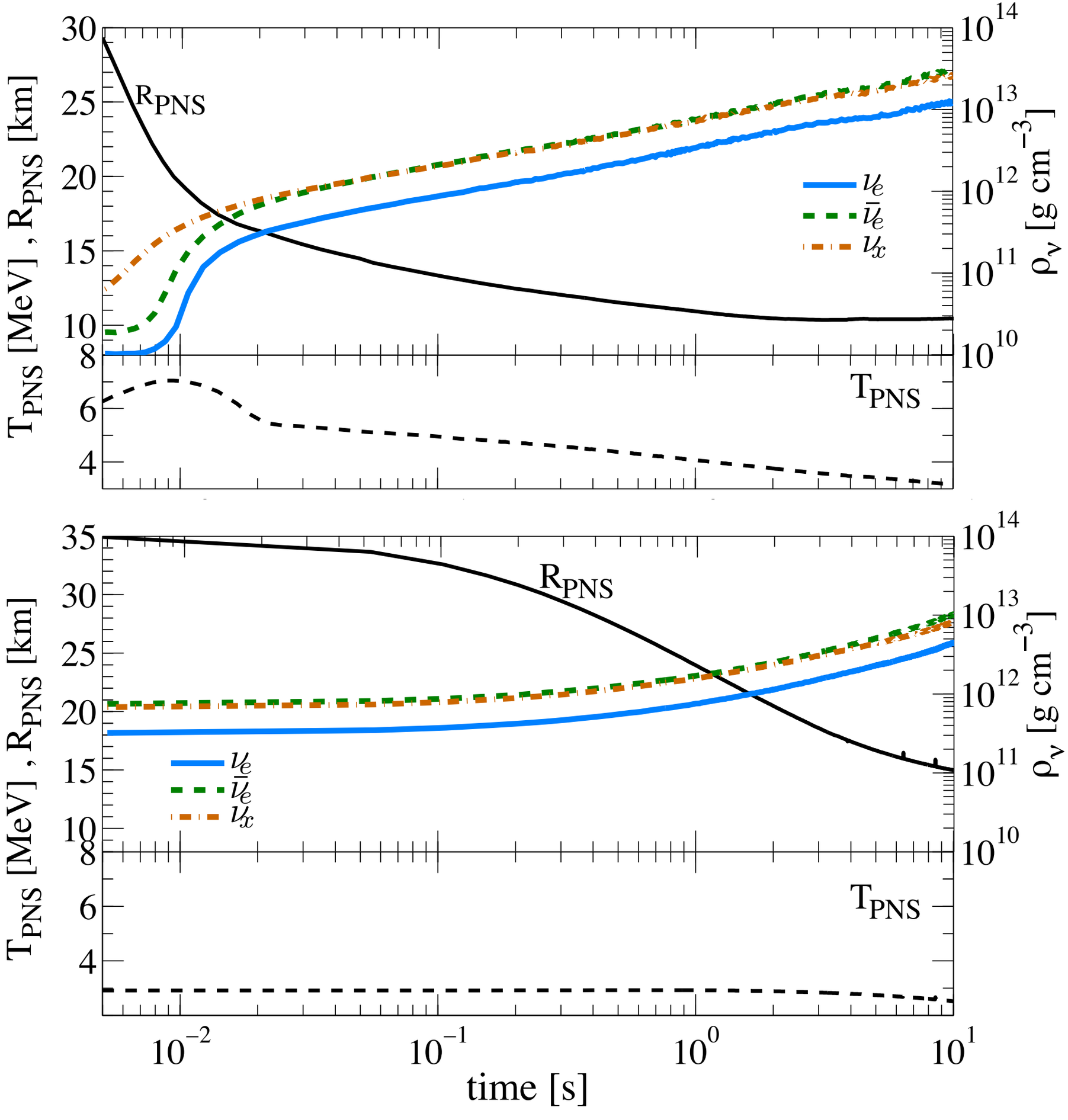


ArXiv astro-ph.HE/1712.08778

hadron-quark phase transition (this work)

$M_{ZAMS} = 50\ M_\odot$

$M_{NS} = 2.0\ M_\odot$



ν-driven explosion (ref. model)

$M_{ZAMS} = 18\ M_\odot$

$M_{NS} = 1.5\ M_\odot$

direct ejecta

neutrino−driven wind

S

Y_e

τ

Ṁ

0.5

0.4 Y_e

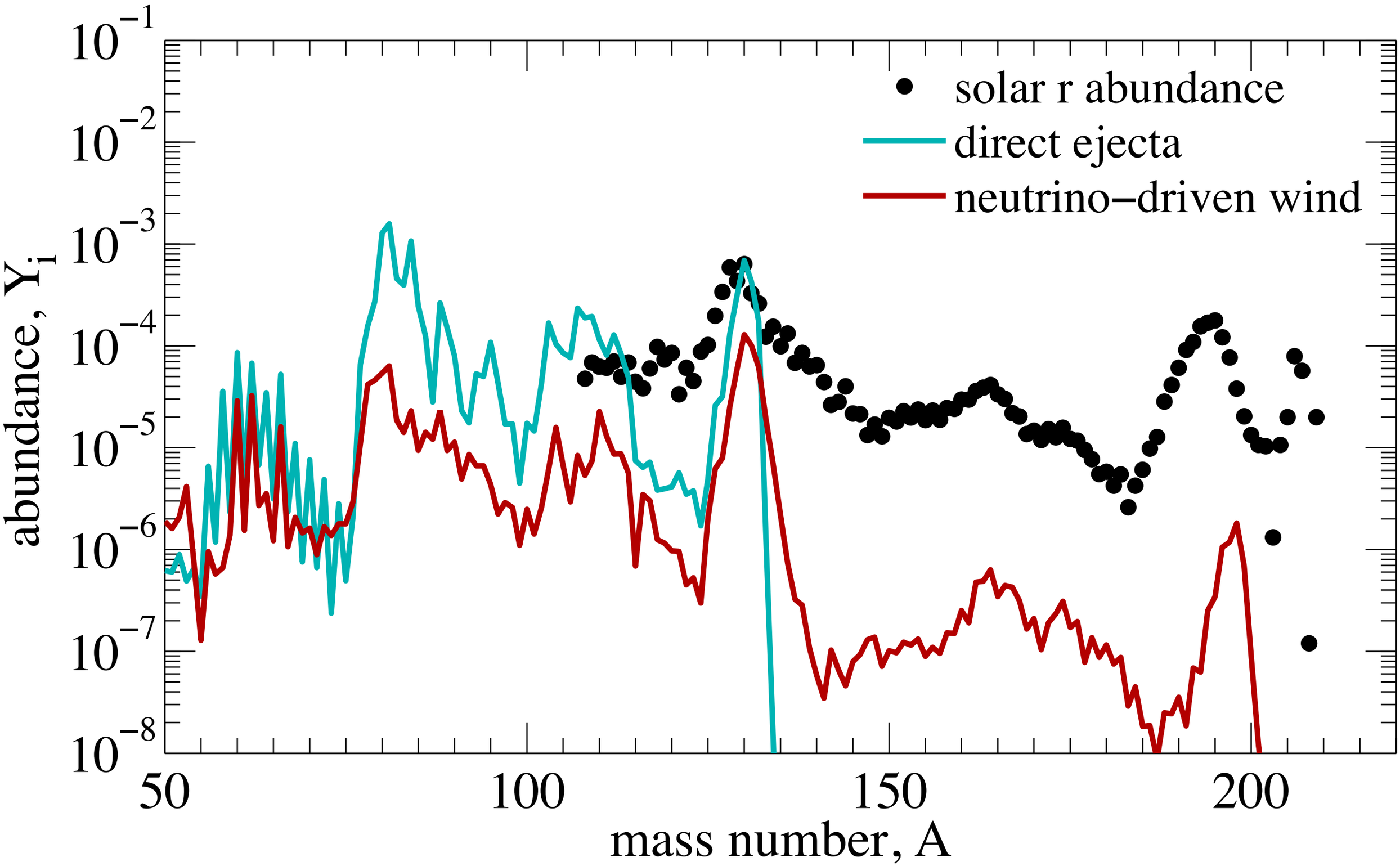
0.3

10^{3}
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}

$S\ [k_B]$, $\dot{M}\ [M_\odot\ s^{-1}]$, τ [s]

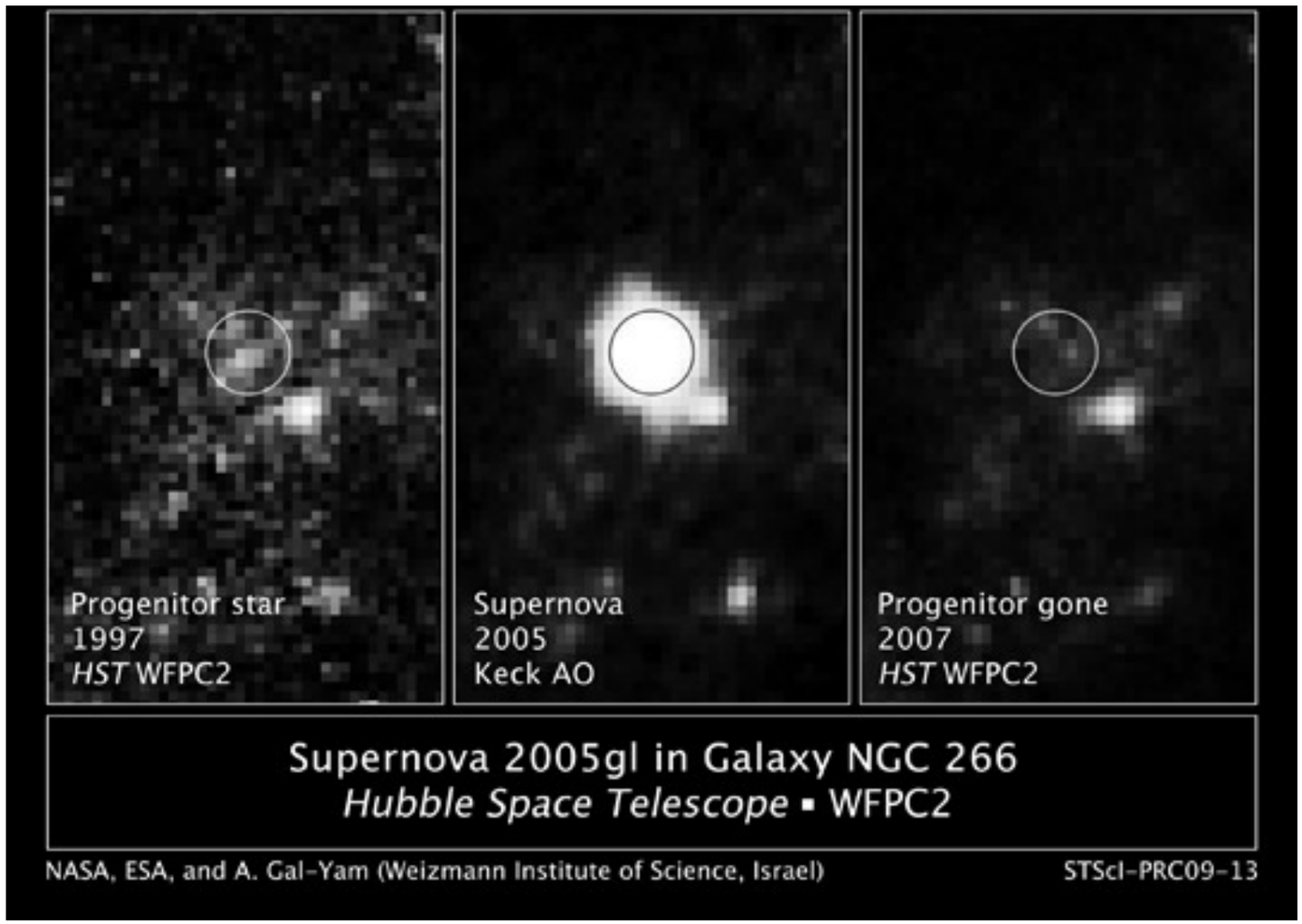
10^{-2} 10^{-1} 10^{0} 10^{1}

time [s]


solar r abundance
direct ejecta
neutrino−driven wind
abundance, Y_i
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
50
100
150
200
mass number, A

Novel road to explosions of very massive stars $\gtrsim 40 - 50\ \mathrm{M}_\odot$

"The progenitor was so bright that it probably belonged to a class of stars called Luminous Blue Variables (LBVs)"



remnants: massive neutron stars $\sim 2\ \mathrm{M}_\odot$

r process nucleosynthesis

Wroclaw Supernova Project

Thanks for your attention

In collaboration with:

N. U. Bastian
D. Blaschke
M. Cierniak
T. Klähn
S. Typel
M. R. Wu