GW170817

Binary neutron star merger

A LIGO / Virgo gravitational wave detection with associated electromagnetic events observed by over 70 observatories.

Distance
130 million light years

Discovered
17 August 2017

Type
Neutron star merger

12:41:04 UTC

gravitational waves detected

+2 seconds

γ –ray burst detected

+10 hours 52 min

bright source of light detected in NGC4993

“kilonova”

+11 hours 36 min: infrared emission
+15 hours: ultra-violet emission
+ 9 days: X-ray emission

+ 16 days

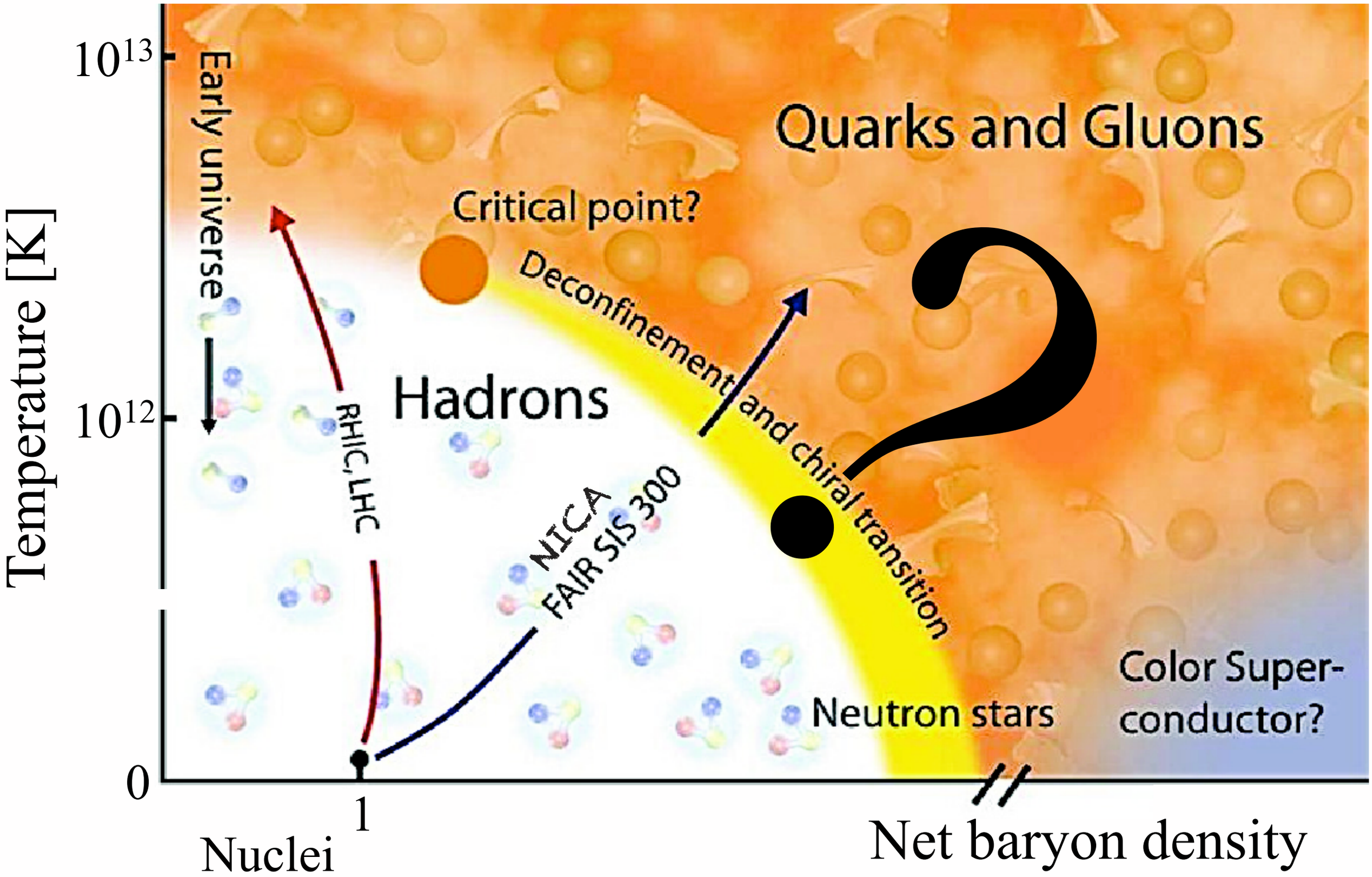
radio emission detected

Accurate prediction of **observable** signal(s)

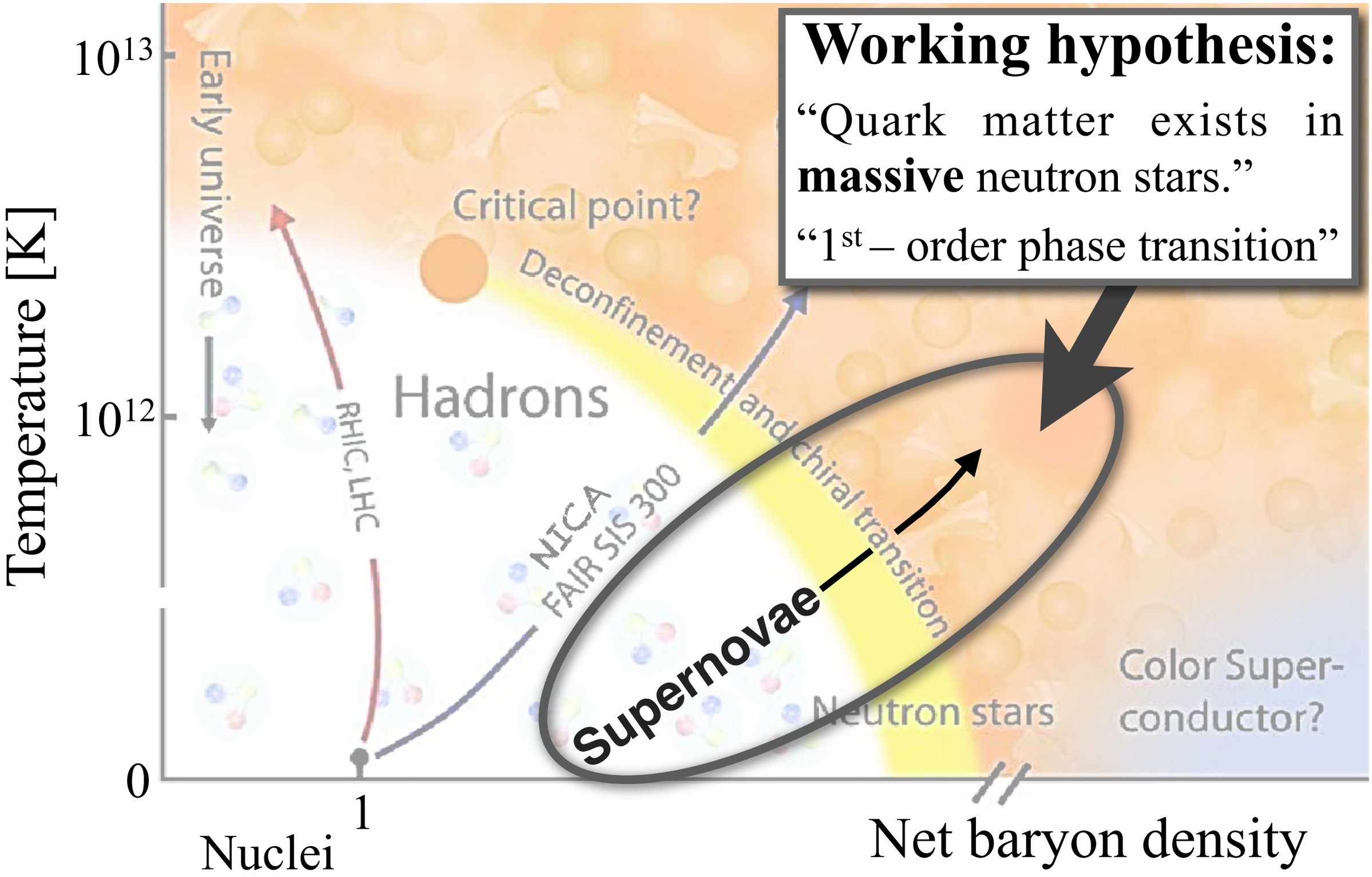
Relation to microscopic models of strongly-interacting matter

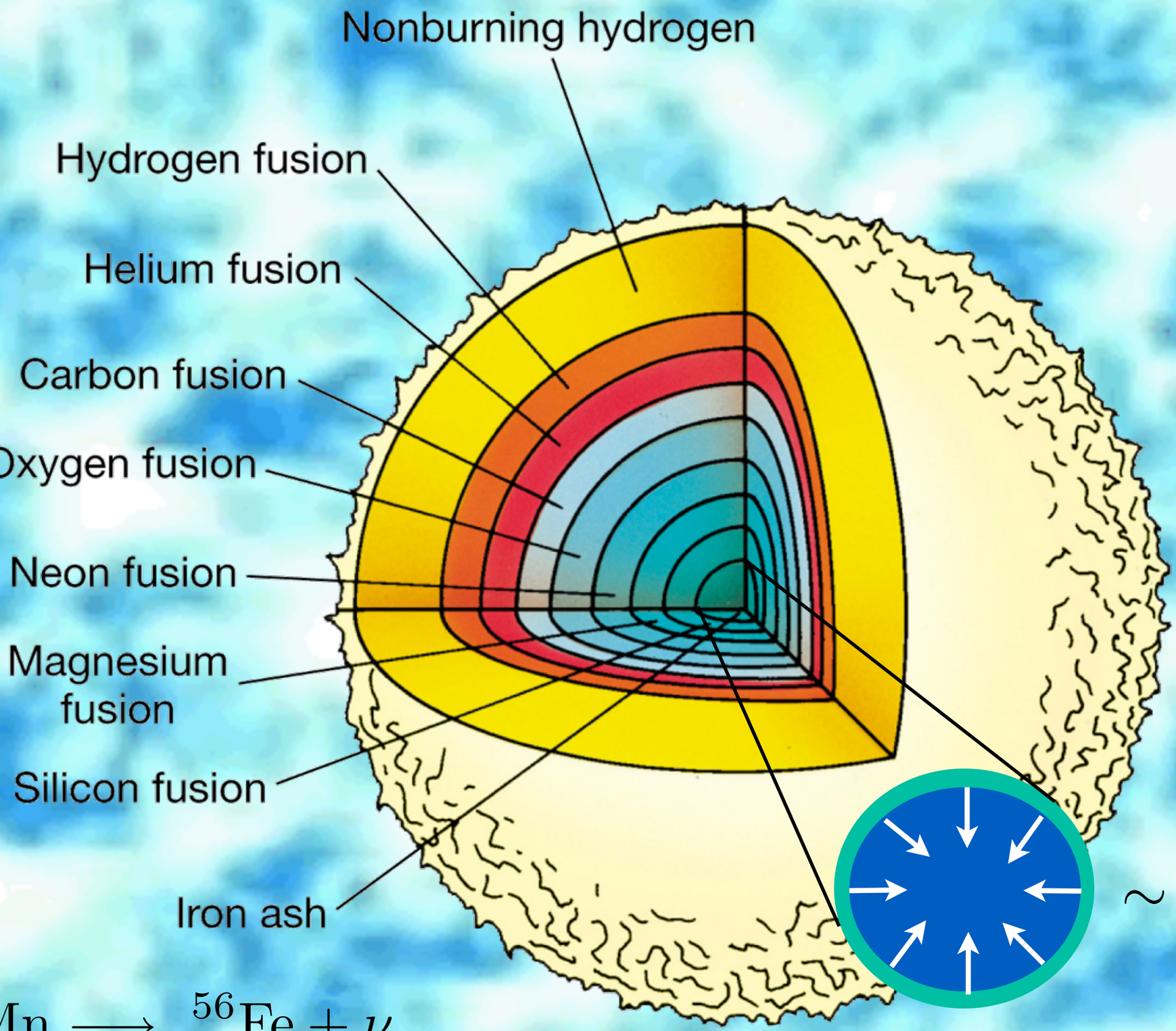
Astrophysics probes phase of hot and dense matter ?

Hot and dense phases of matter ?



Inaccessible in heavy-ion collisions





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

$\sim 10^3$ km

Iron core collapse

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

$\left(\nu_e, \bar{\nu}_e, \nu_{\mu/\tau}, \bar{\nu}_{\mu/\tau}\right)$

Rapid deleptonization
during shock passage
across neutrinosphere:

$Y_e = 0.28 \longrightarrow 0.1$

Mass accretion

Expanding shock

post-shock region
(high entropy)
n,p,^{4}He

Low-entropy region
^{56}Fe, ^{56}Ni

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

Entropy per Baryon, s [k_B]

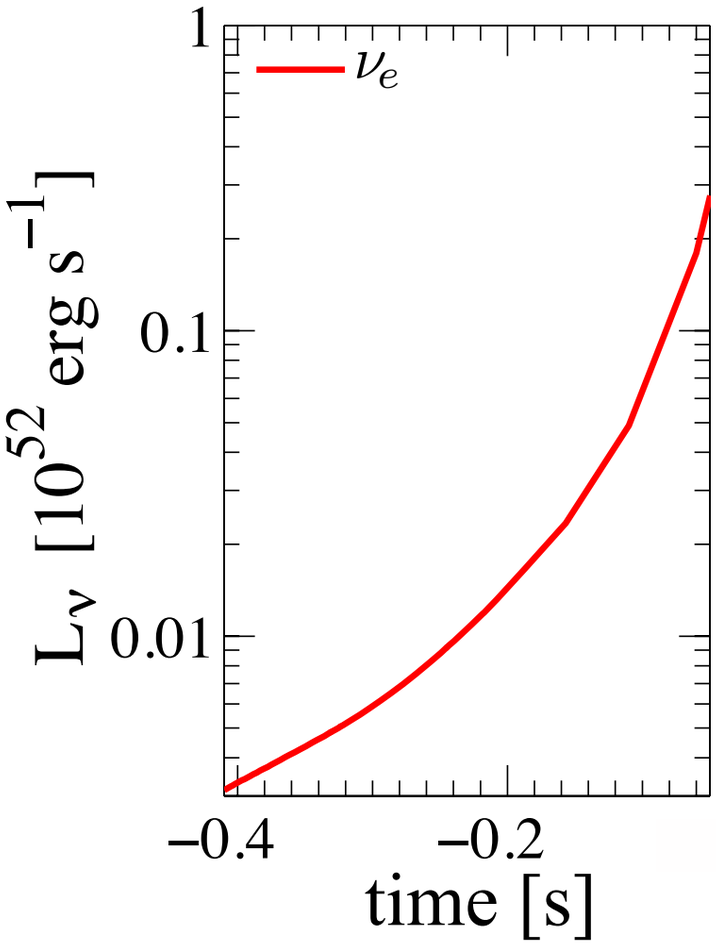
Electron Fraction, Y_e

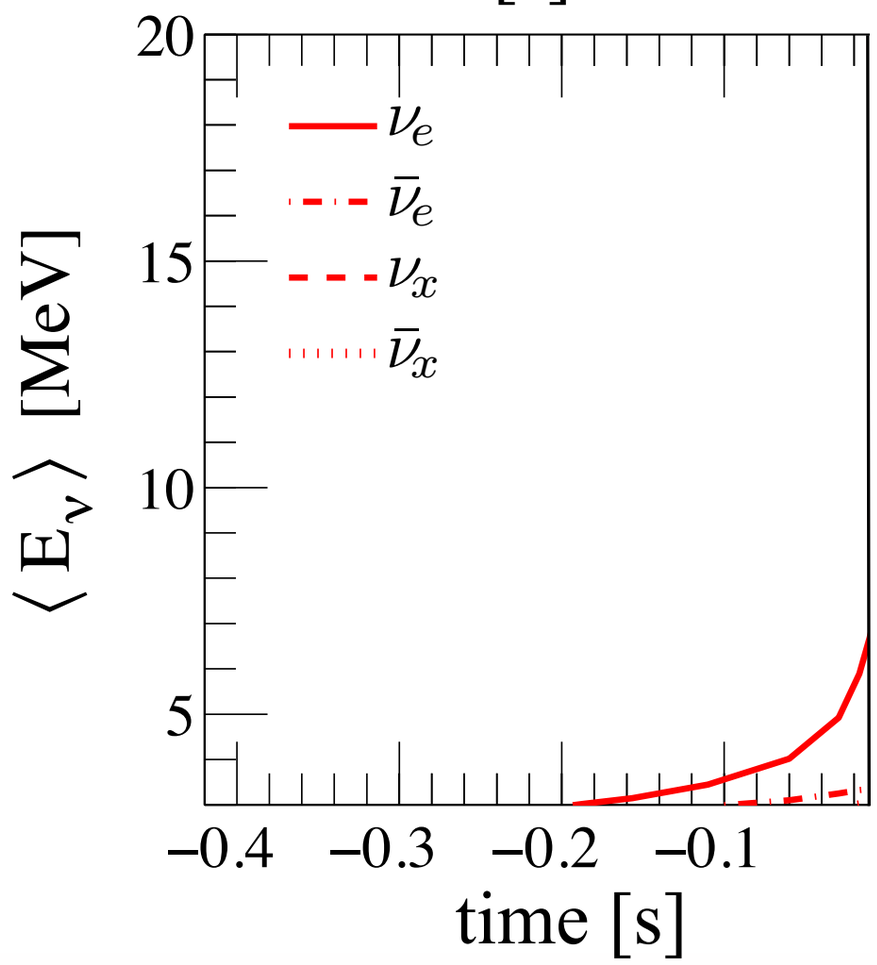
0 2 4 6 8 10

0 0.1 0.2 0.3 0.4 0.5

-500 -400 -300 -200 -100 0 100 200 300 400

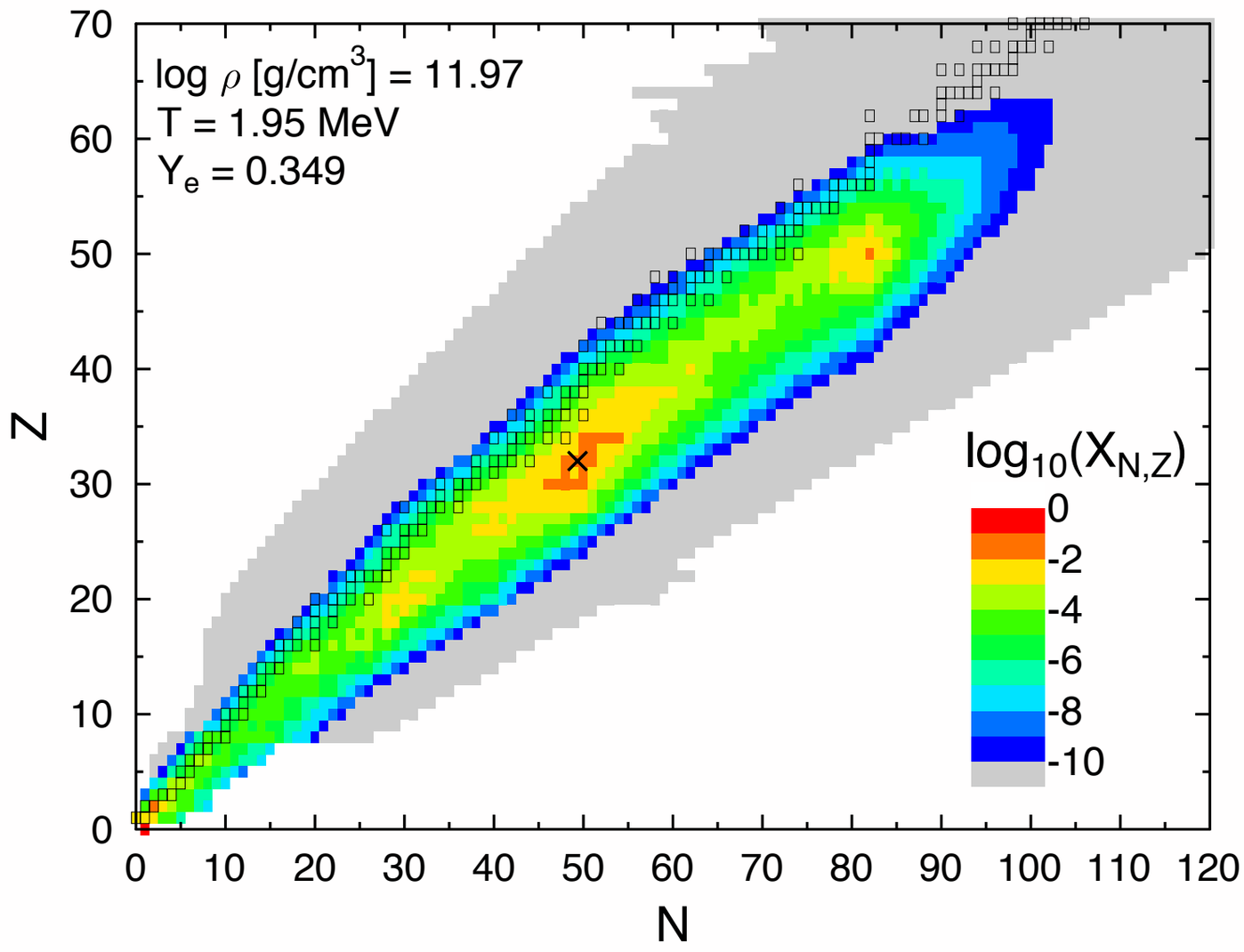
(X,Y) – plane

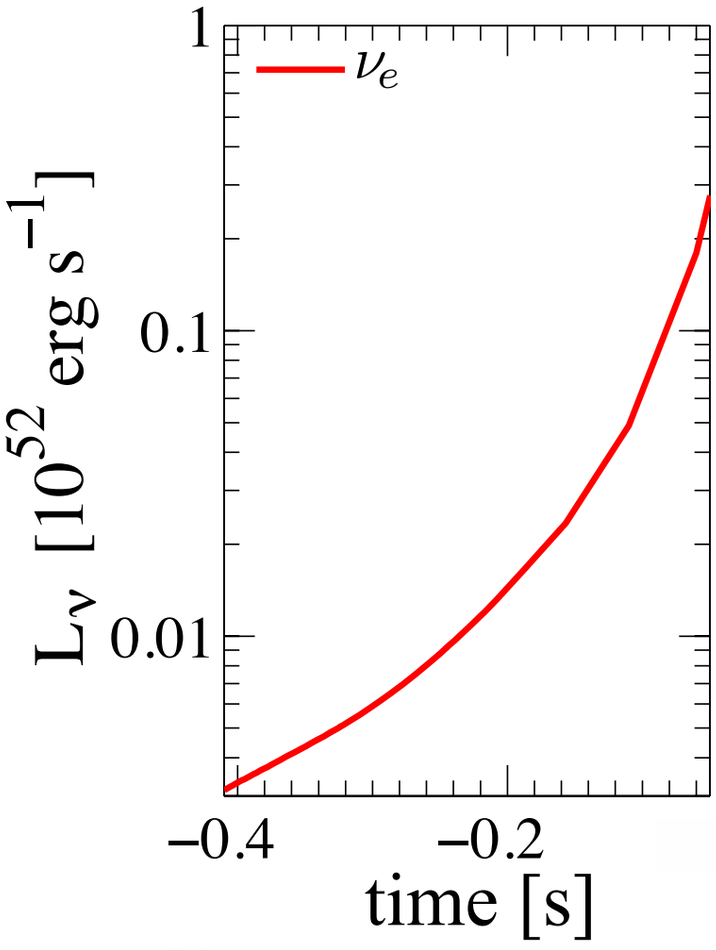




$$e^- + \langle A, Z \rangle \leftrightarrows \langle A, Z-1 \rangle + \nu_e$$

$$\nu_e + \langle A, Z \rangle \leftrightarrows \langle A, Z \rangle + \nu'_e$$



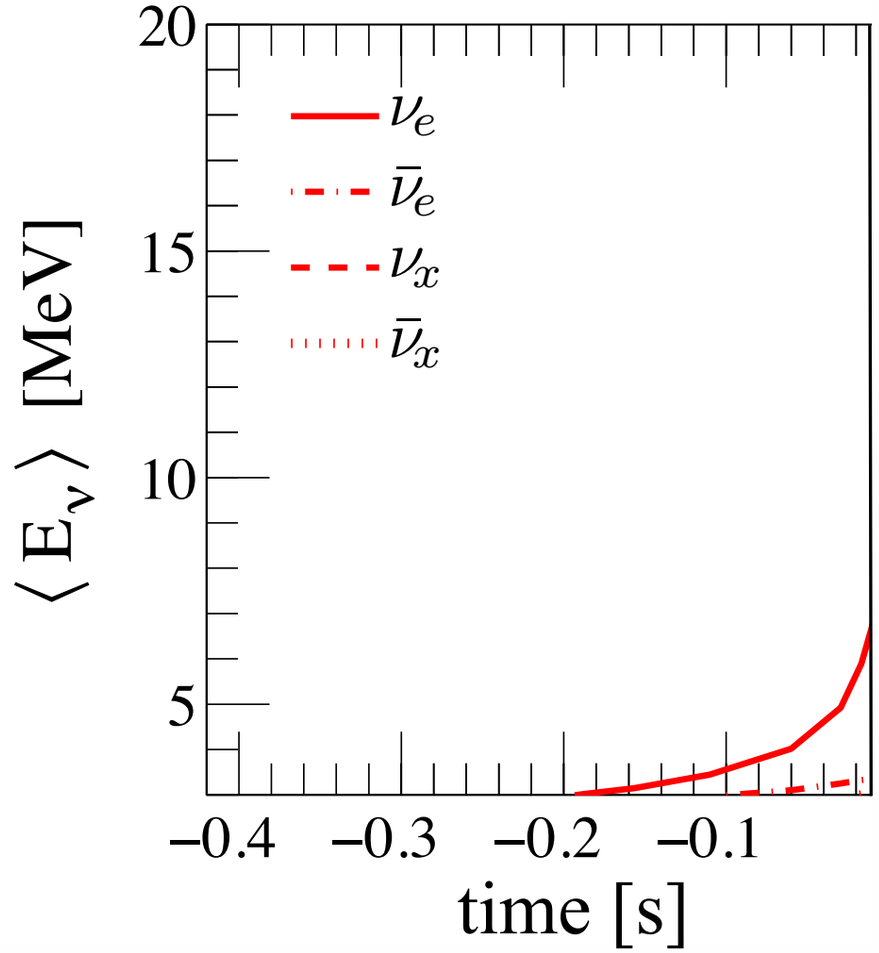


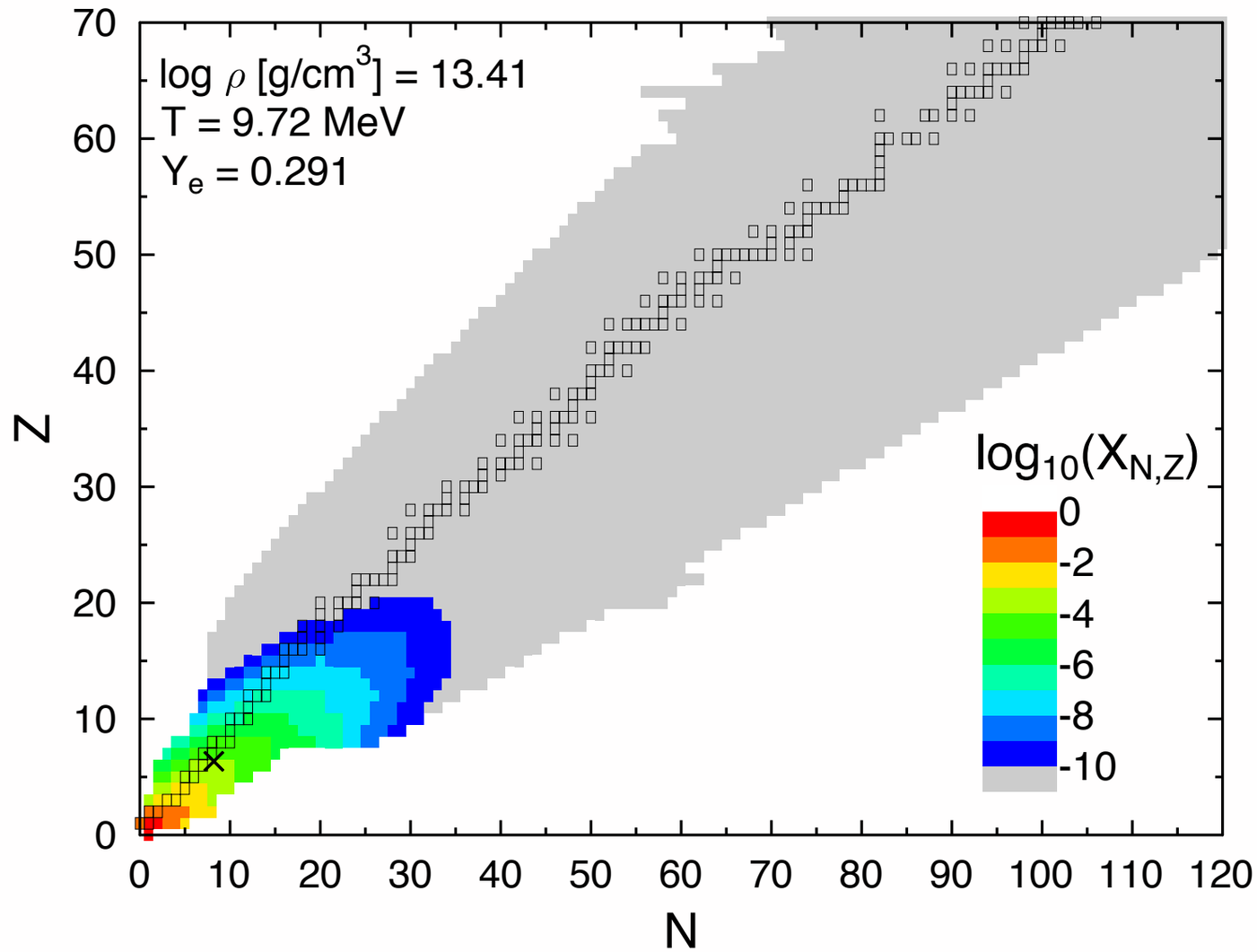
$$e^- + \langle A, Z \rangle \leftrightarrows \langle A, Z-1 \rangle + \nu_e$$

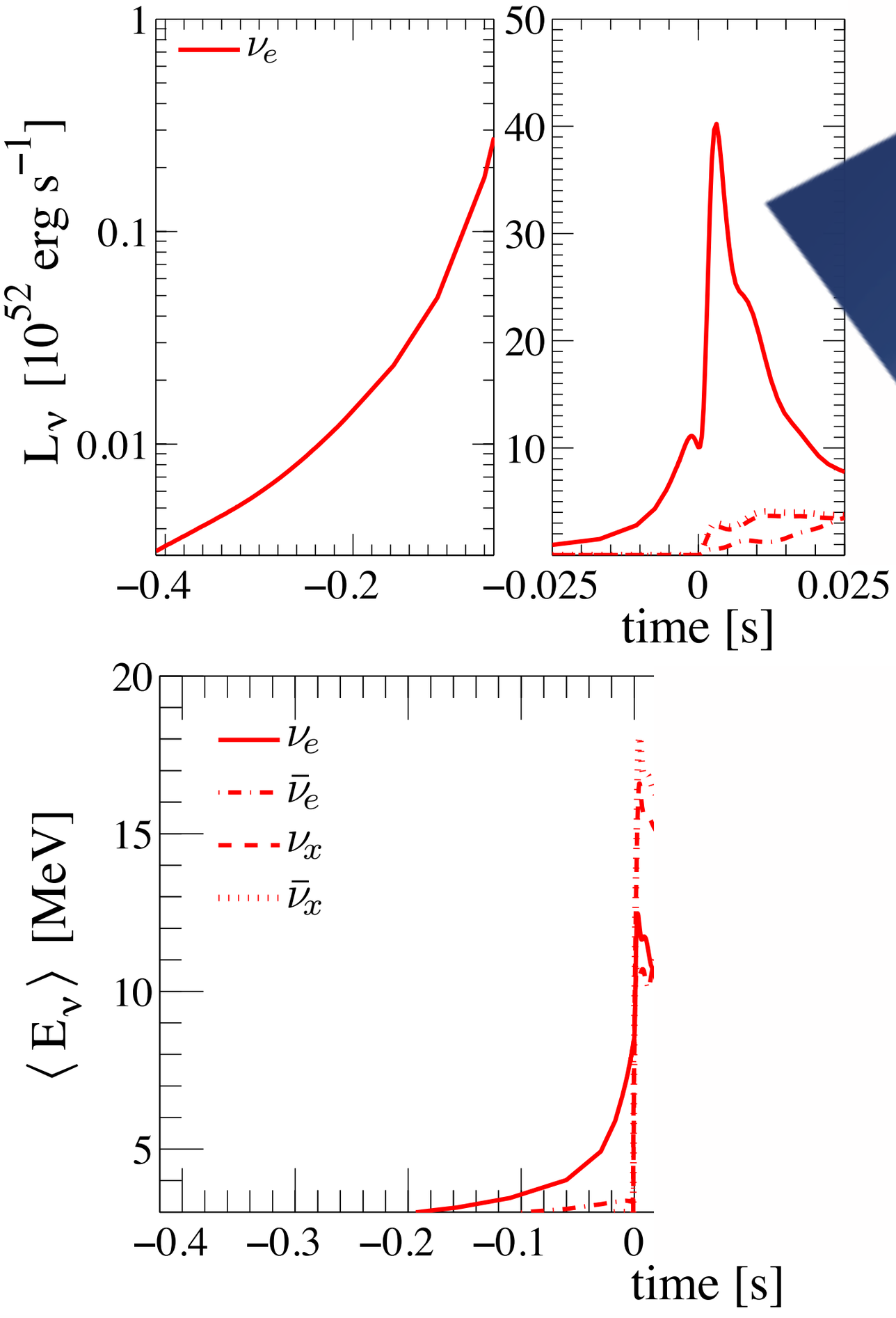
$$\nu_e + \langle A, Z \rangle \leftrightarrows \langle A, Z \rangle + \nu_e'$$

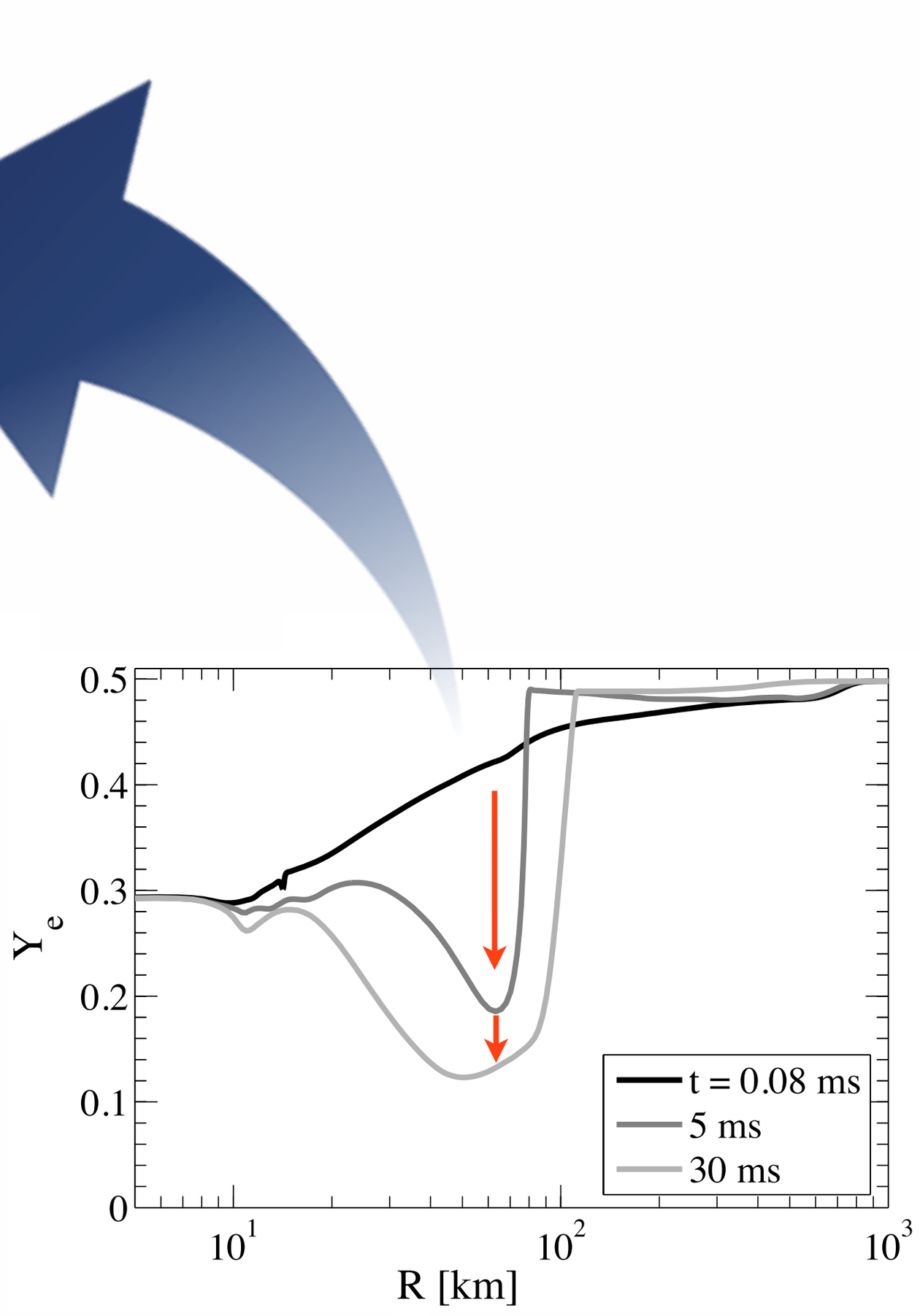
$$e^- + p \leftrightarrows n + \nu_e$$

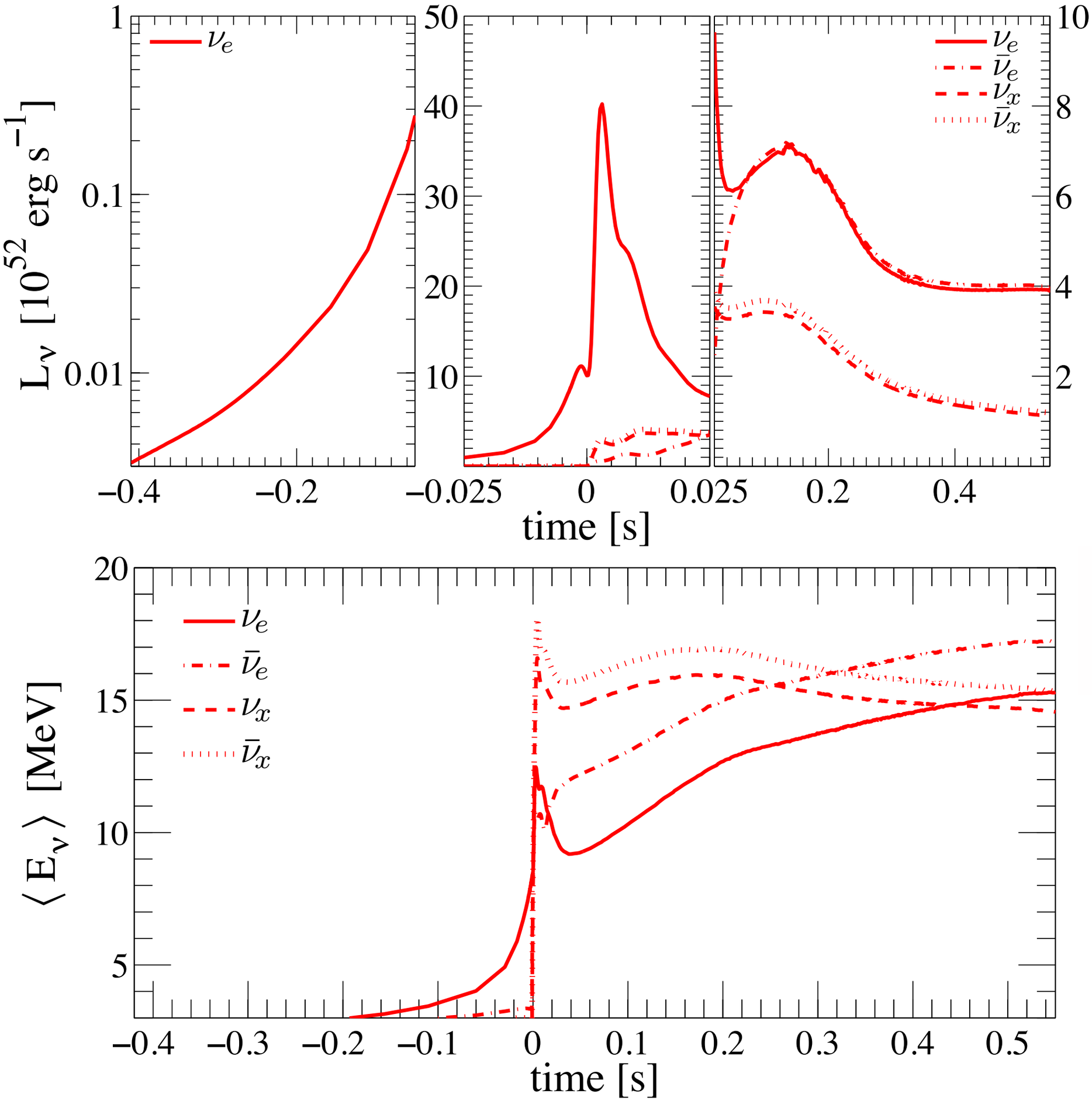
$$\nu + N \leftrightarrows N + \nu'$$






ν_e
L_ν [10^{52} erg s^{-1}]
1
0.1
0.01
50
40
30
20
10
−0.4
−0.2
−0.025
0
0.025
time [s]
ν_e
$\bar{\nu}_e$
ν_x
$\bar{\nu}_x$
$\langle E_\nu \rangle$ [MeV]
20
15
10
5
−0.4
−0.3
−0.2
−0.1
0
time [s]


Y_e
0.5
0.4
0.3
0.2
0.1
0
10^1
10^2
10^3
R [km]
t = 0.08 ms
5 ms
30 ms



$$e^- + p \leftrightarrows n + \nu_e$$
$$e^+ + n \leftrightarrows p + \bar{\nu}_e$$
$$\nu + N \leftrightarrows N + \nu'$$
$$\nu + e^\pm \leftrightarrows e^\pm + \nu'$$
$$\nu\bar{\nu}$$

High density

Low density

Electron Flavor

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

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

Thermal Equilibrium

Free Streaming

Neutrino Sphere

Other Flavors

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

$e^- + e^+ \leftrightarrows \bar{\nu} + \nu$

$N + N \leftrightarrows \bar{\nu} + \nu + N + N$

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

Thermal Equilibrium

Diffusion

Free Streaming

Energy Sphere (ES)

sphere of last energy exchange

Transport Sphere

sphere of last elastic scattering

Raffelt (2001), ApJ 561, 890

0.50165 s after bounce

n, p

n, p

NSE

$(A, Z), n, p$

non-NSE

(iron-group)

T [MeV]

10^2

10^1

10^0

10^{-1}

10^{-8} 10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 10^0 10^1

ρ/ρ_{sat}

0.45

0.4

0.35

0.3

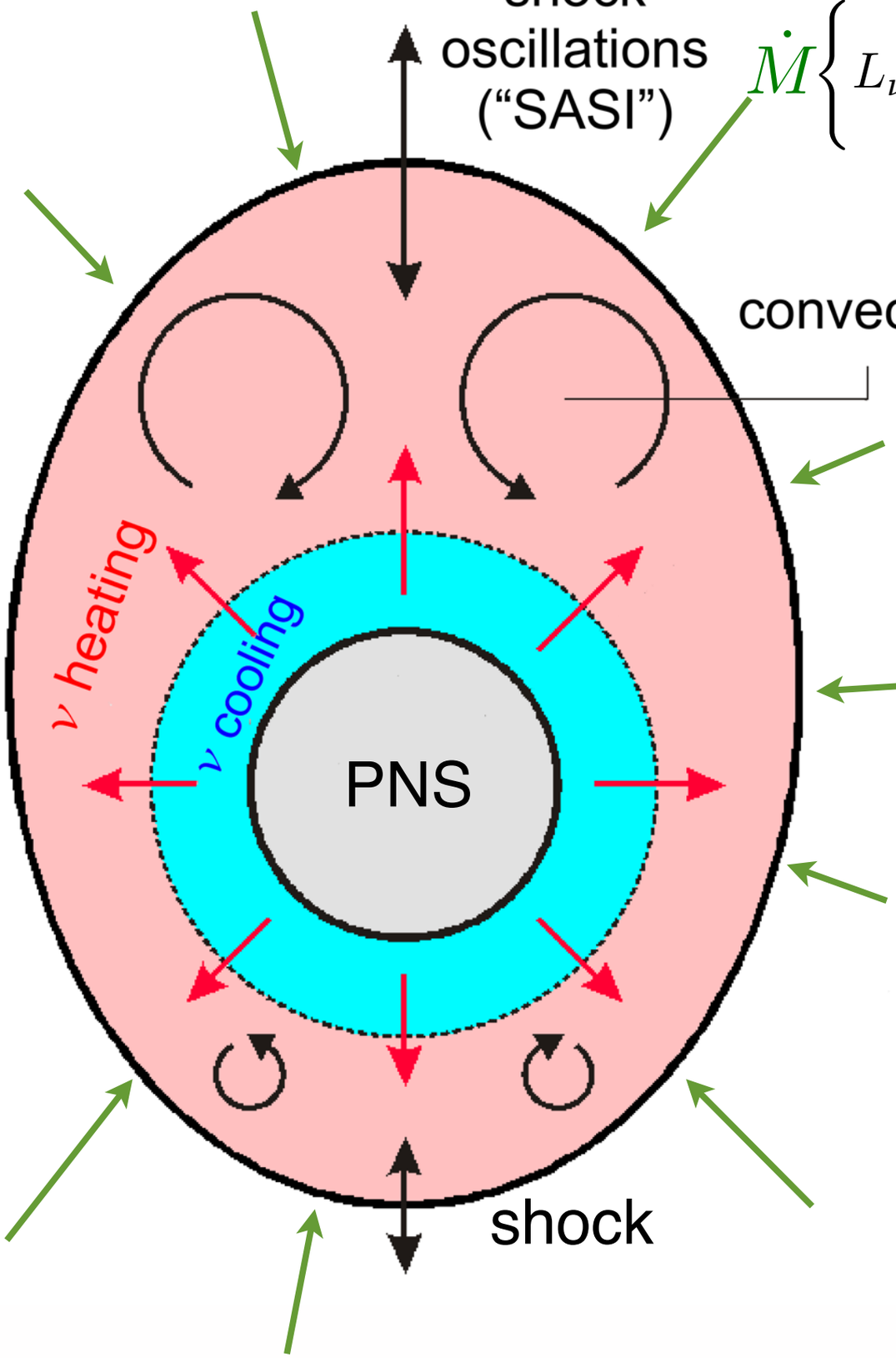
0.25

0.2

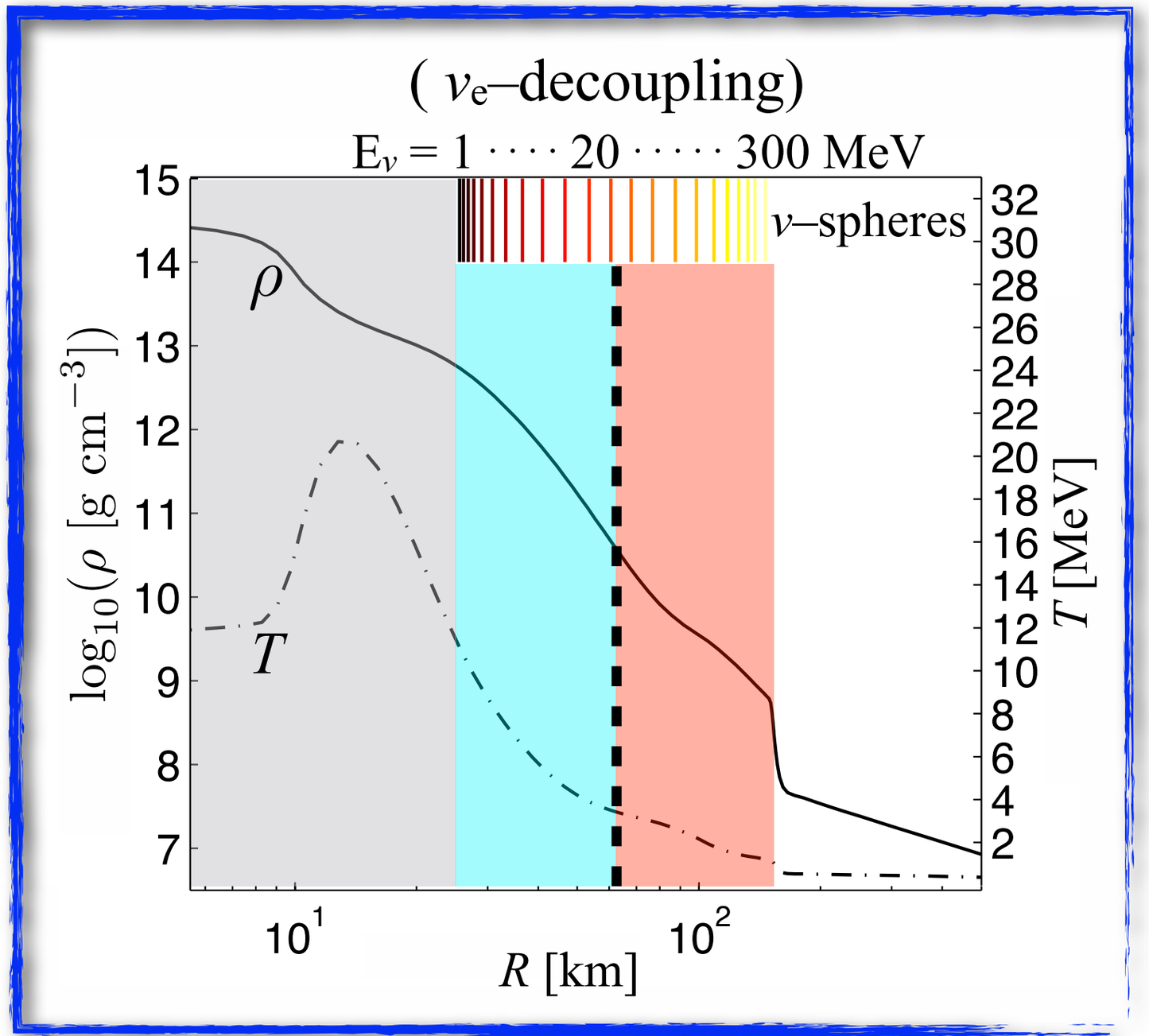
0.15

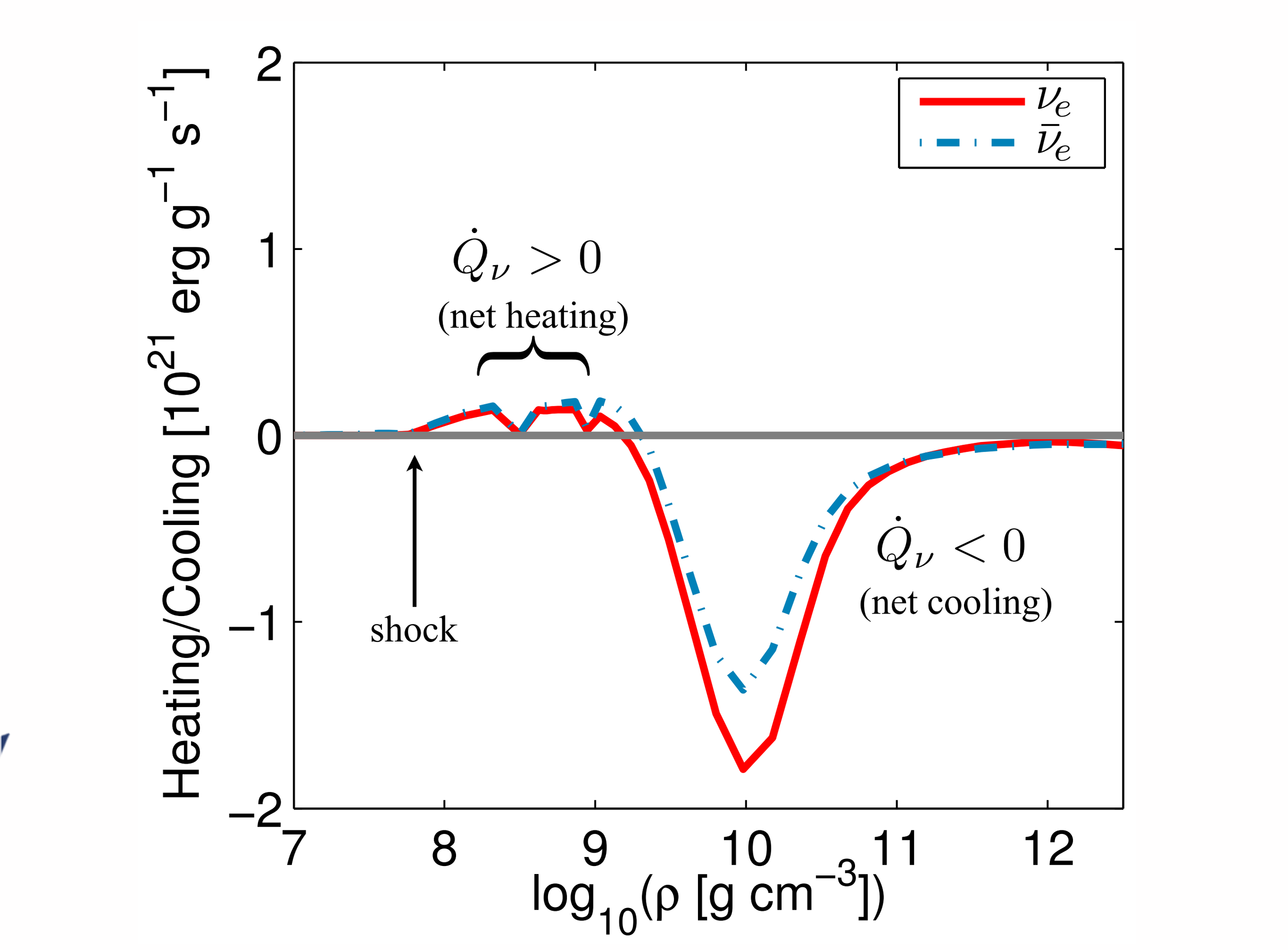
0.1

Y_e



$$\dot{M}\left\{ L_{\nu_e} \propto 10^{52} \left(\frac{M}{1.5\ \mathrm{M}_\odot}\right) \left(\frac{\dot{M}}{0.4\ \mathrm{M}_\odot\ \mathrm{s}^{-1}}\right) \left(\frac{100\ \mathrm{km}}{R}\right)\ \mathrm{erg\ s}^{-1} \right.$$

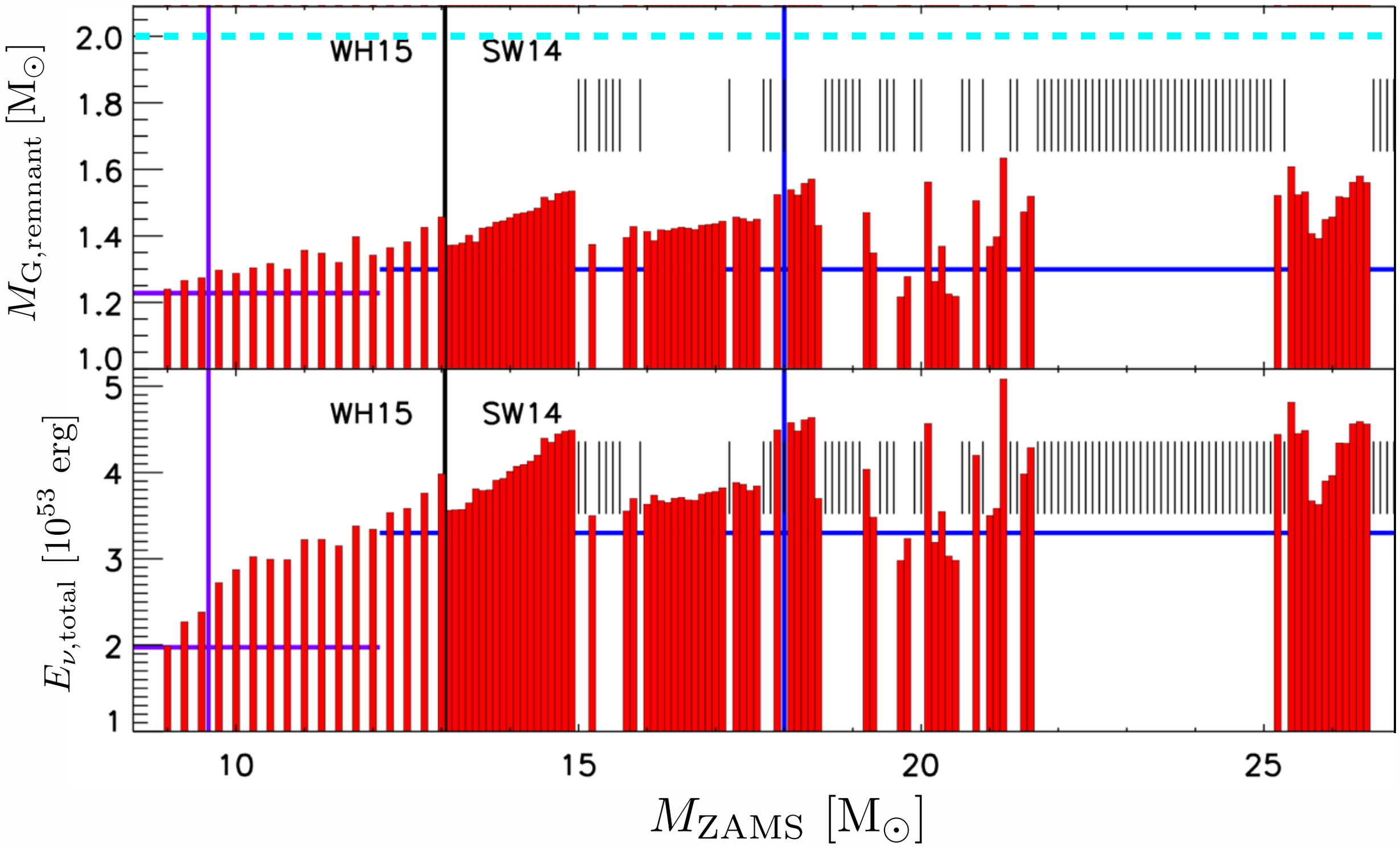



ν_e
$\bar{\nu}_e$
$\dot{Q}_\nu > 0$
(net heating)
shock
$\dot{Q}_\nu < 0$
(net cooling)
Heating/Cooling [10^{21} erg g^{-1} s^{-1}]
$\log_{10}(\rho$ [g cm^{-3}])
2
1
0
−1
−2
7
8
9
10
11
12

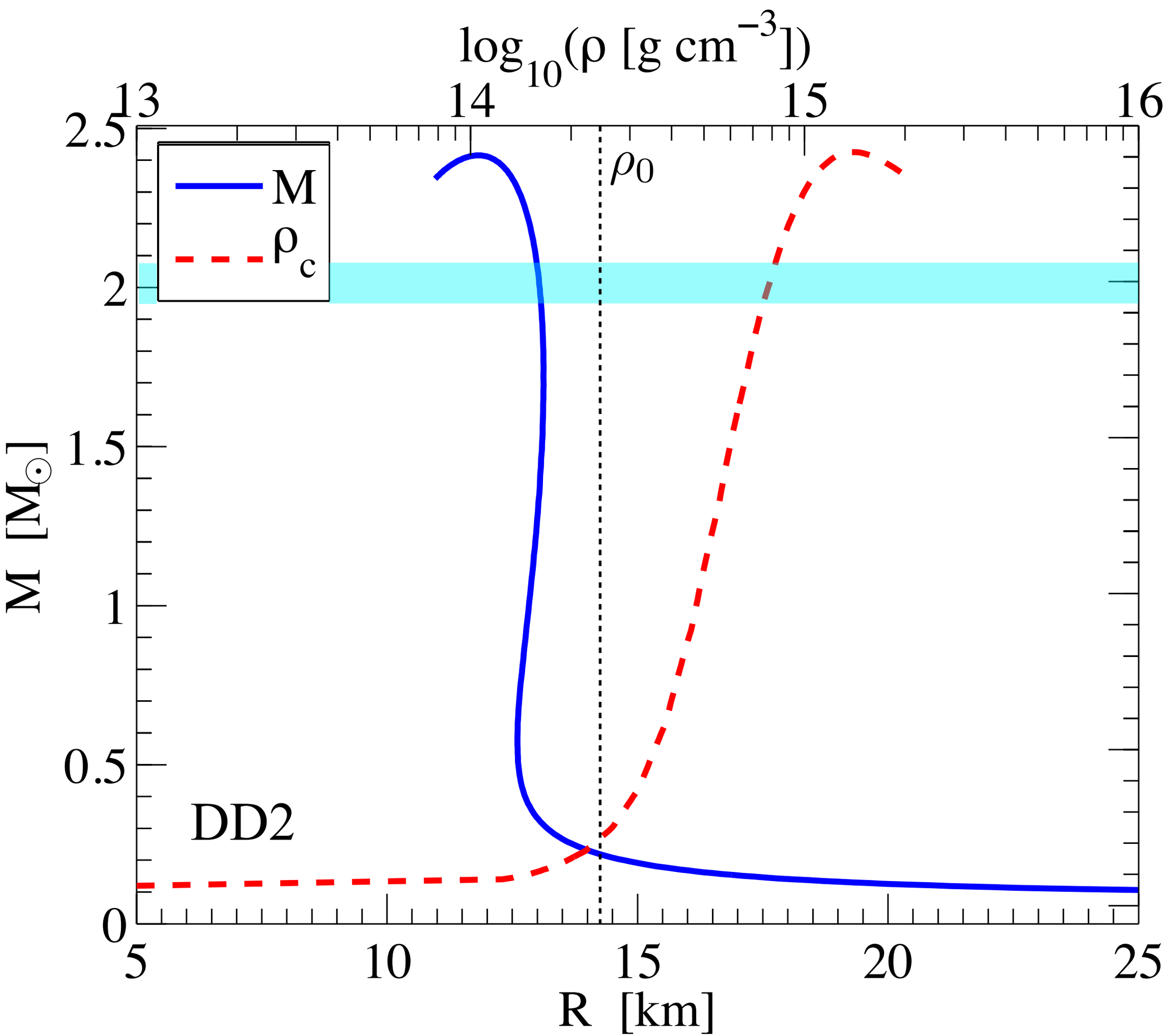
e^- capture supernovae

SN1987A

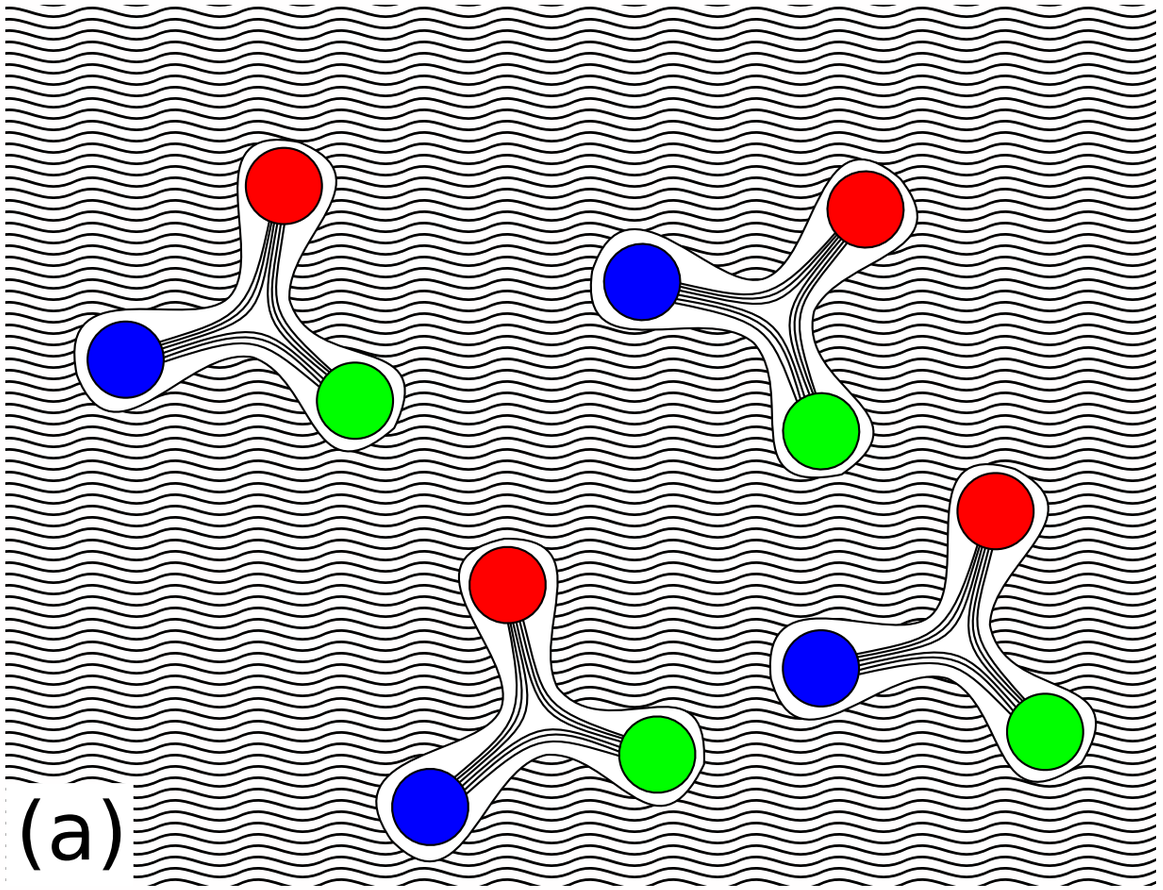
$M_{\mathrm{G,remnant}} < 1.65\ \mathrm{M}_\odot$



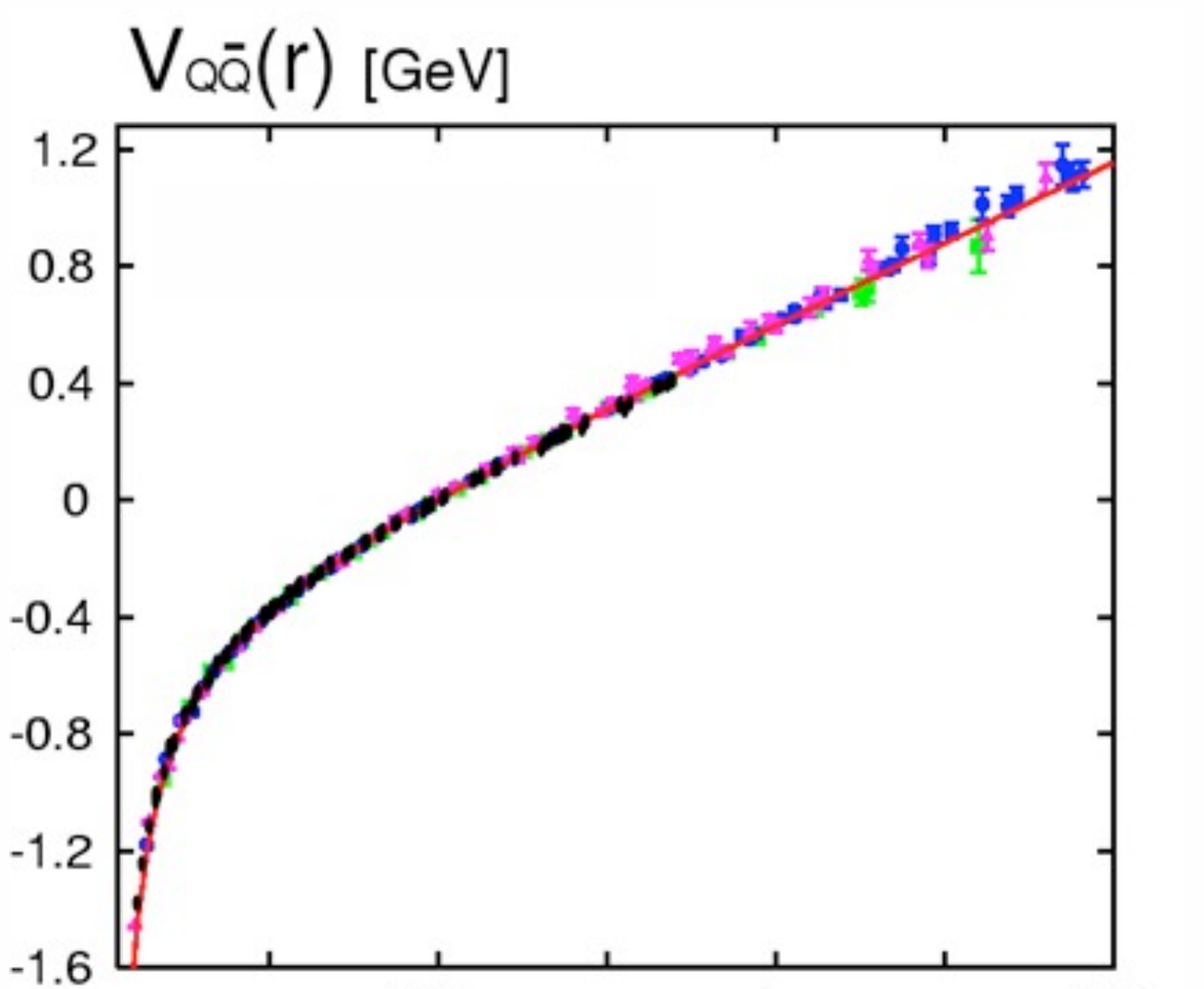
ApJ 821:38, 45 (2016)


log10(ρ [g cm−3])
13
14
15
16
2.5
2
1.5
1
0.5
0
M [M⊙]
M
ρc
ρ0
DD2
5
10
15
20
25
R [km]

vacuum



$$D = D_0$$

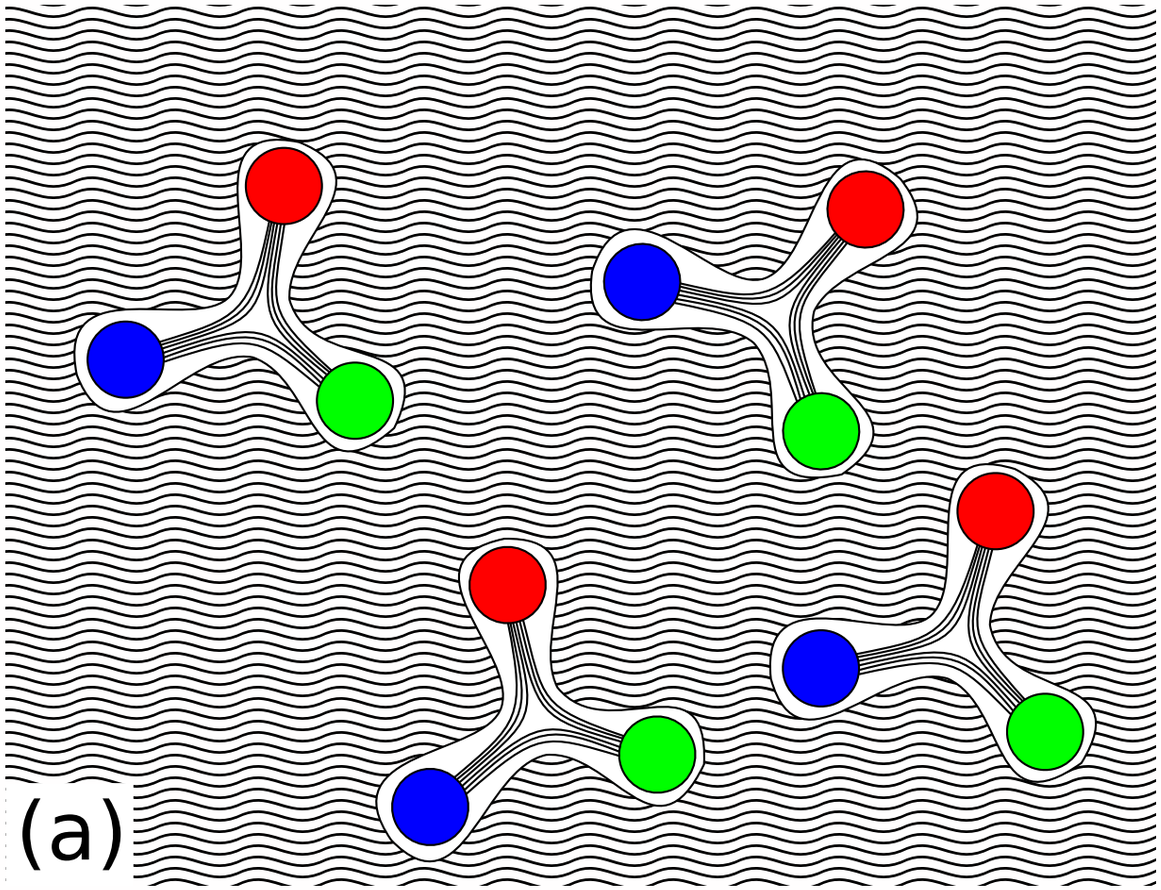


$$V_{QQ}(r) \propto D_0\, r - \frac{A}{r}$$

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

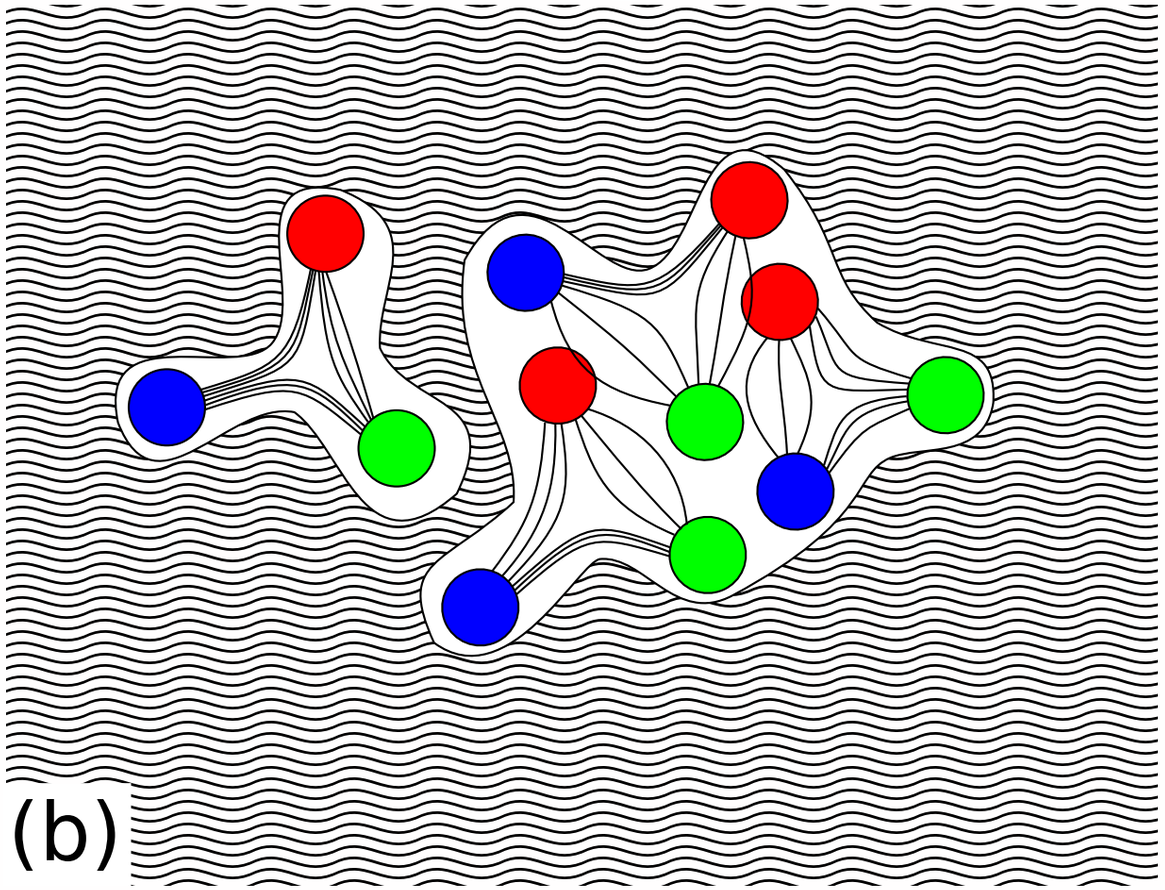
NPA 536, 669 (1992)

vacuum



$$D = D_0$$

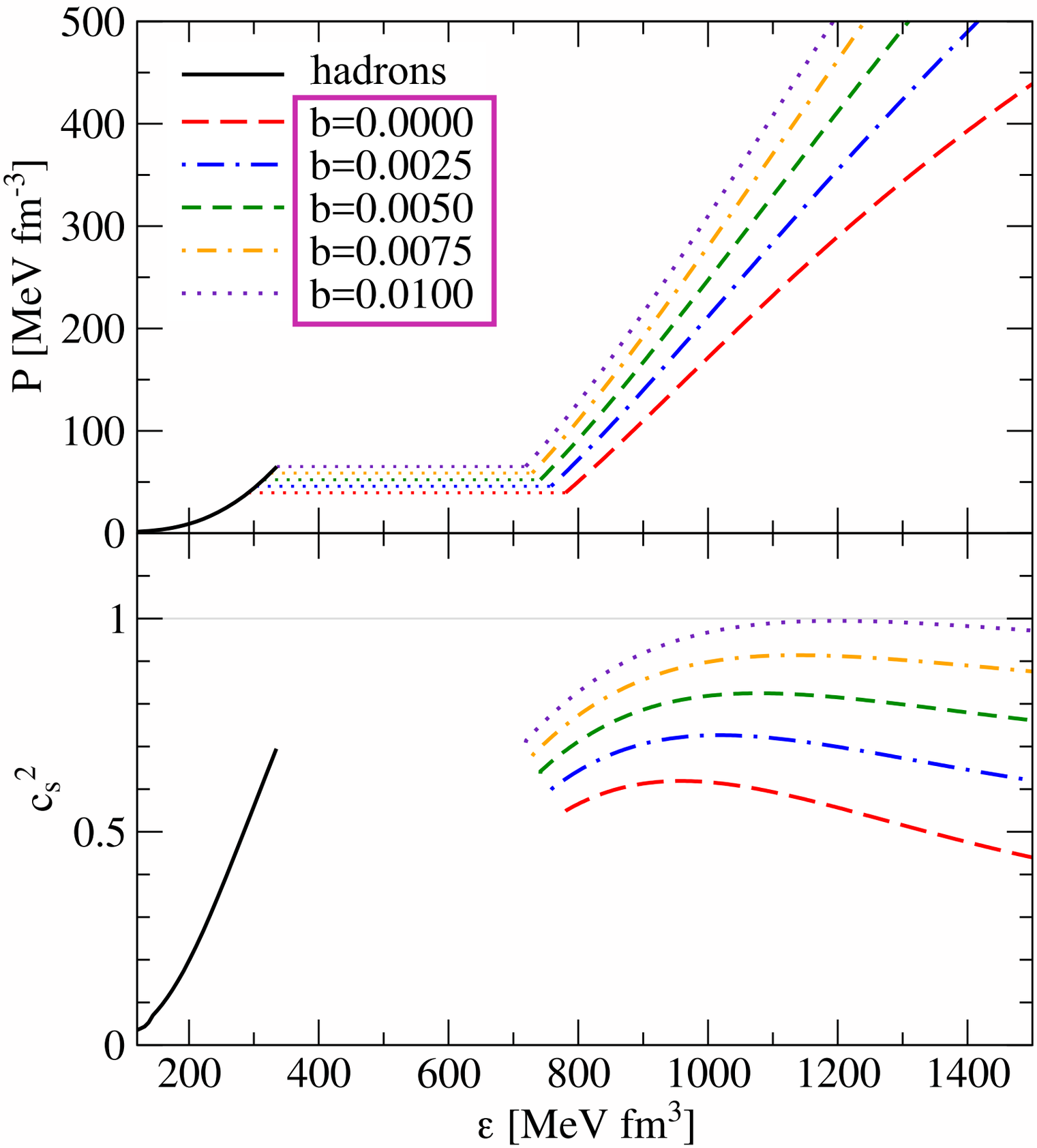
medium dependence



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

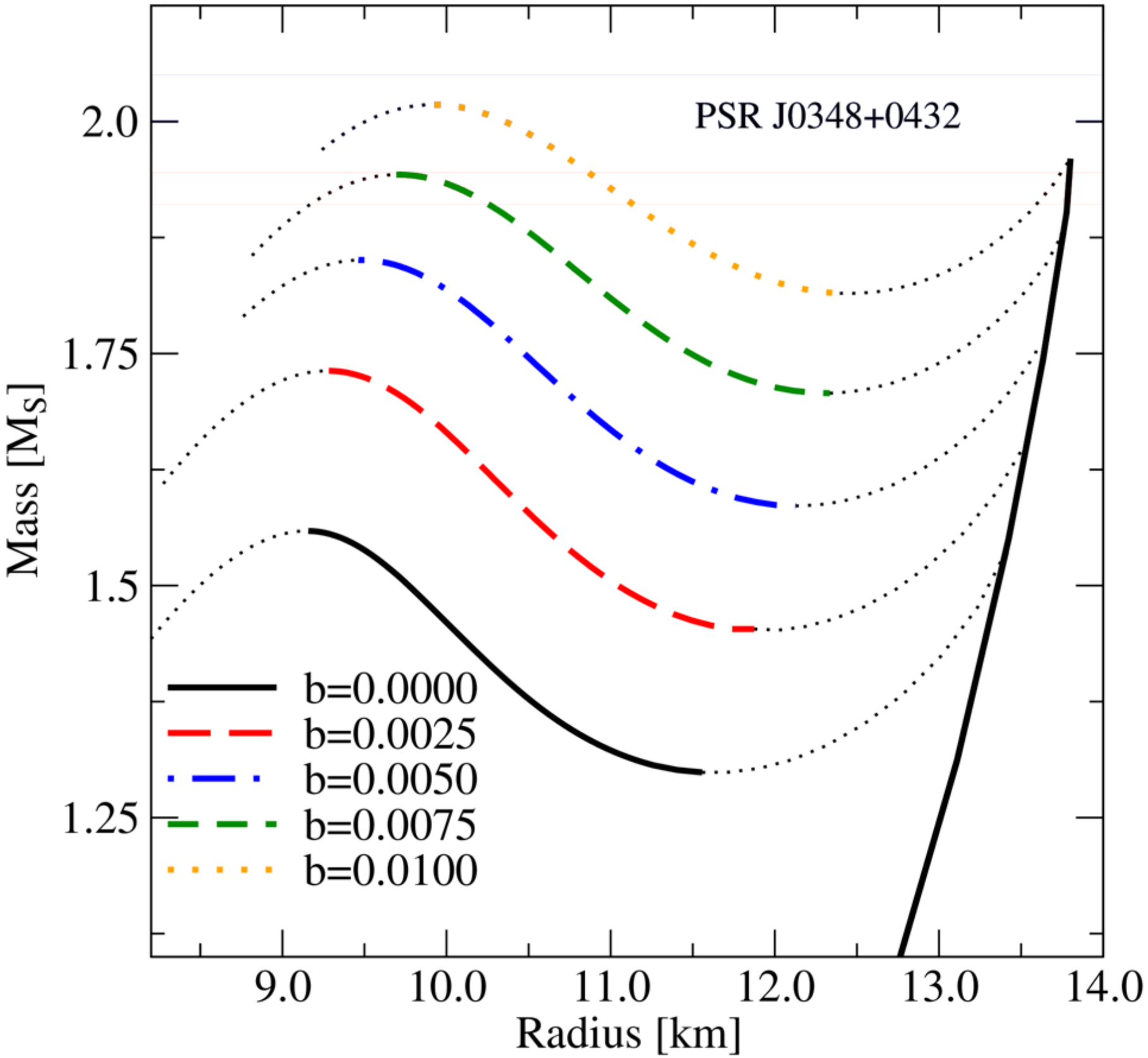
$$\Phi(\rho) = \exp\left\{-\alpha(\rho-\rho_0)^2\right\}$$

PRD 96, 056024 (2017)

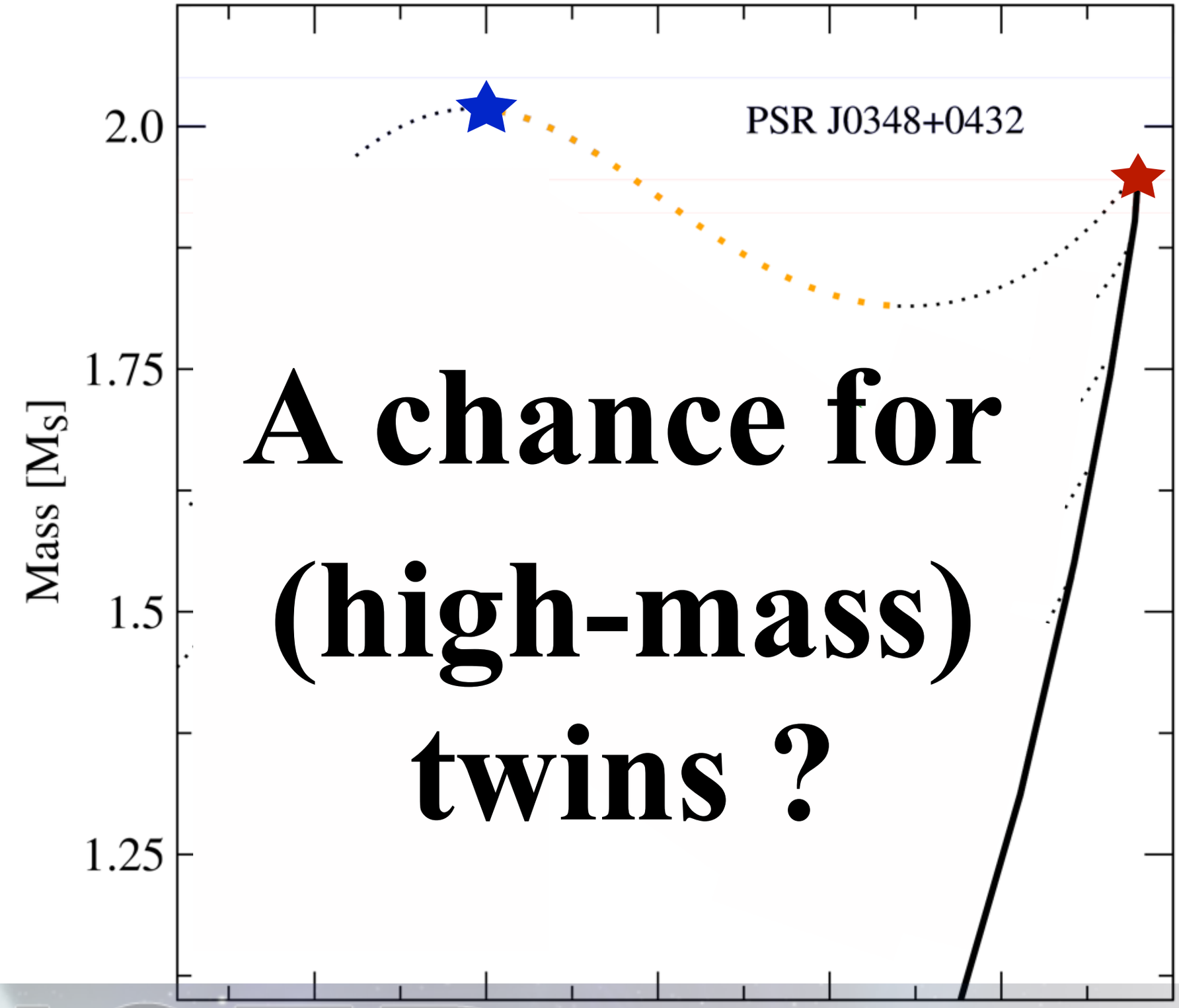


repulsive vector interaction: $\mu^* = \mu - a\,\rho - \mathcal{O}\left(\rho^3\right)$

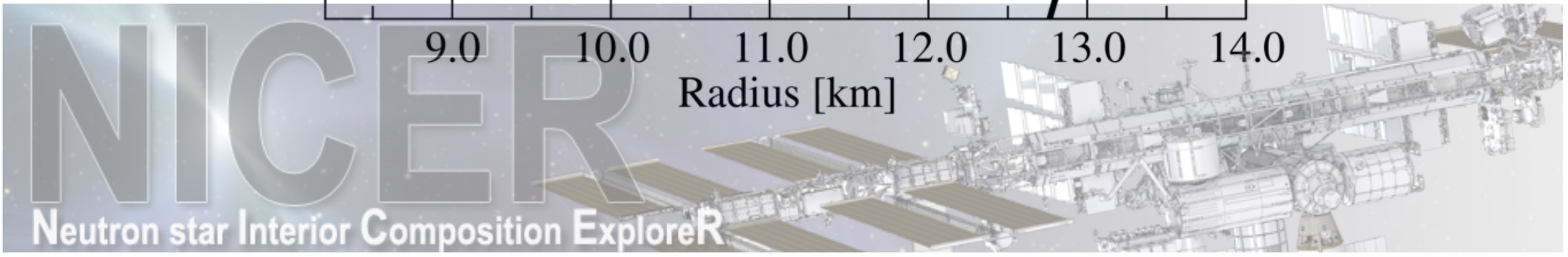
A&A 577, 40 (2015); ApJ 810, 134 (2015)

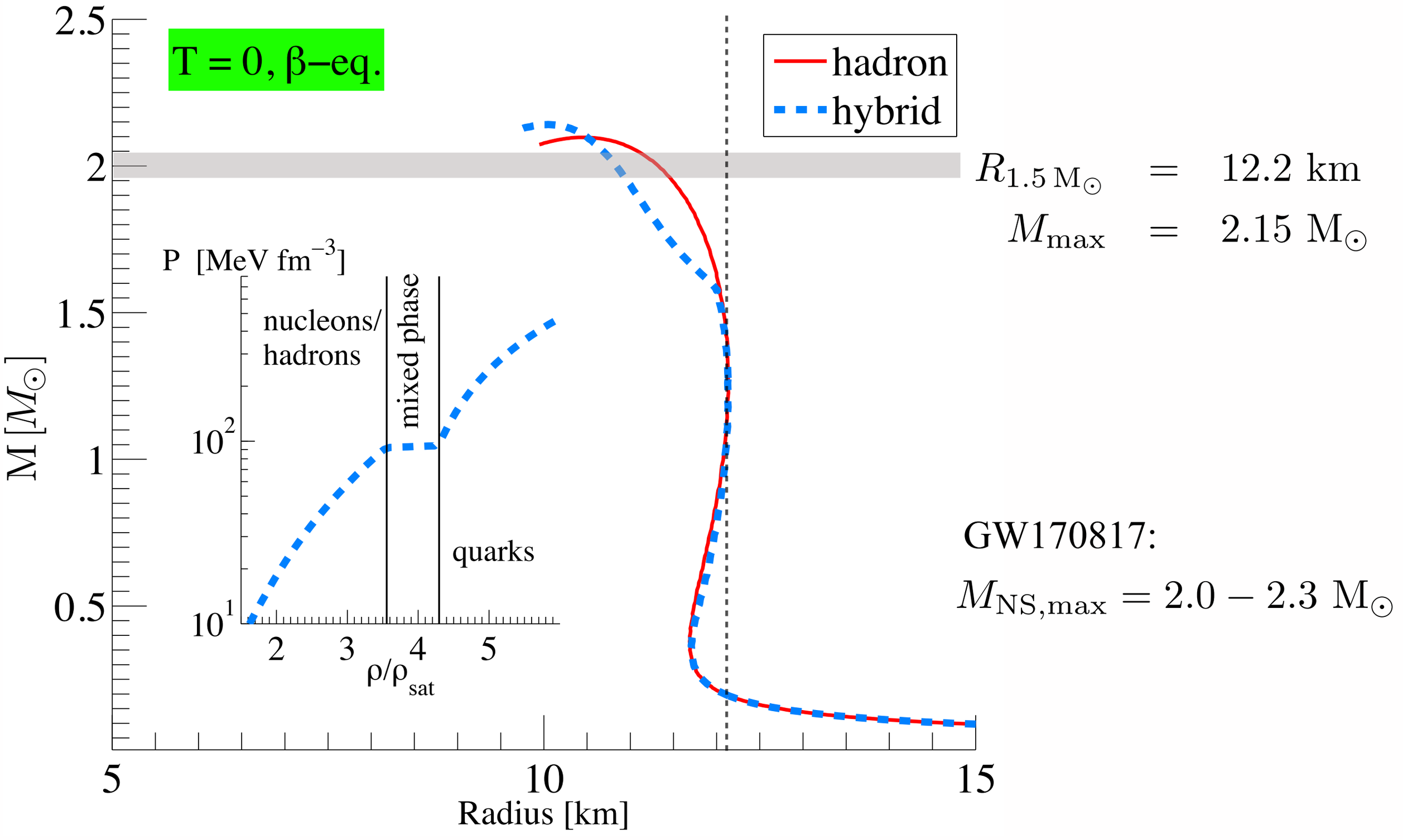


repulsive vector interaction: $\mu^* = \mu - a\,\rho - \mathcal{O}\left(\rho^3\right)$

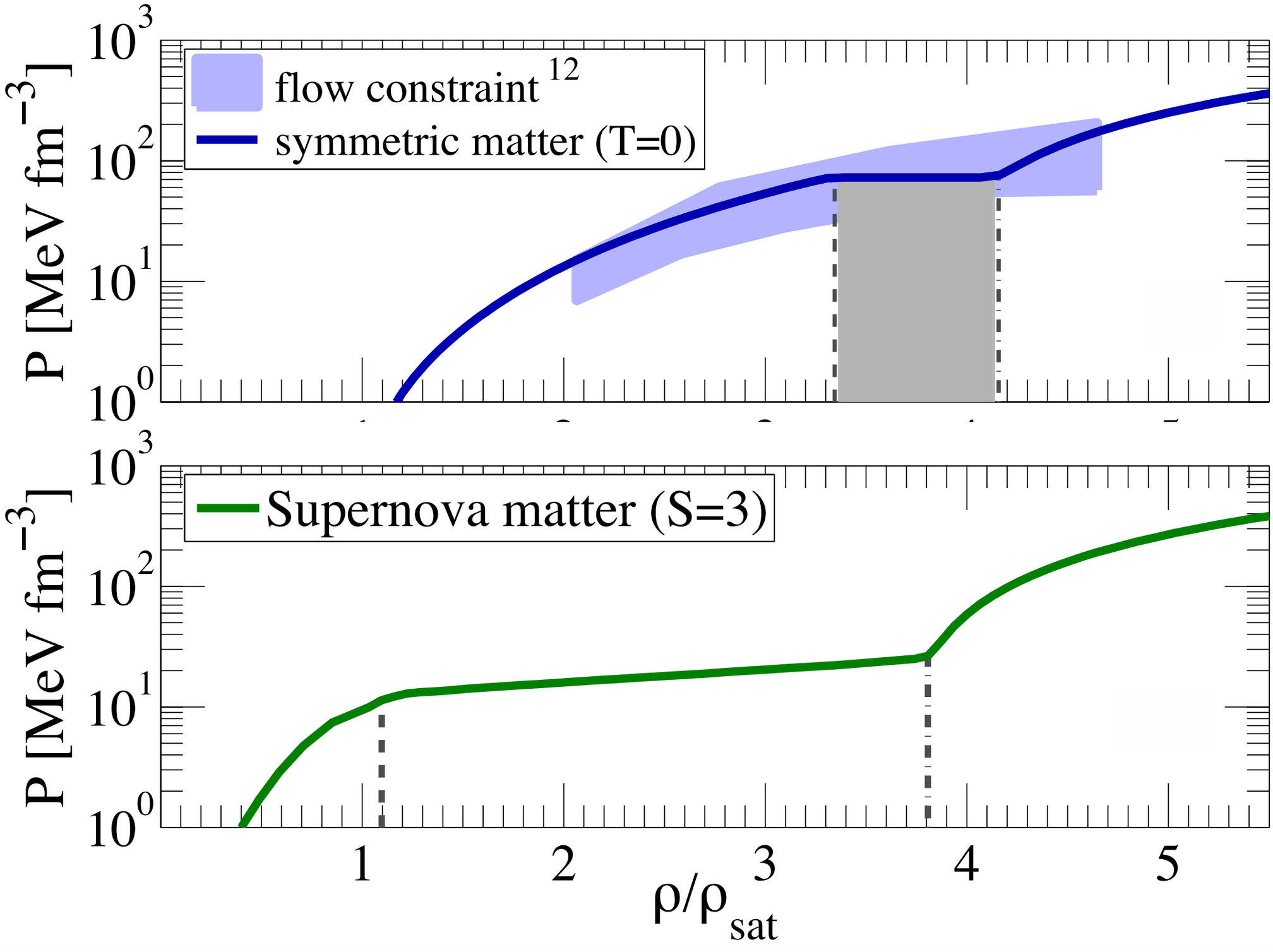


A chance for (high-mass) twins ?





Margalit & Metzger (2017) ApJ 850, L19
Shibata et al., (2017) PRD 96, 123012
Rezzolla et al., (2018) ApJ 852, L25
Ruiz et al., (2018) PRD 97



Nature Astron.2 (2018)

T/T_c

1

quark-gluon plasma

hadron-quark mixed phase

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

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

black-hole formation

1

ρ/ρ_{sat}

T/T_c

1

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

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

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

quark-gluon plasma

hadron-quark mixed phase

black-hole formation

$\tau \sim 1$ ms

POW!

1

ρ/ρ_{sat}

entropy per particle [k_B]

1 10 100

50 $M_\odot$

Radius [km]

10^4 10^3 10^2 10^1

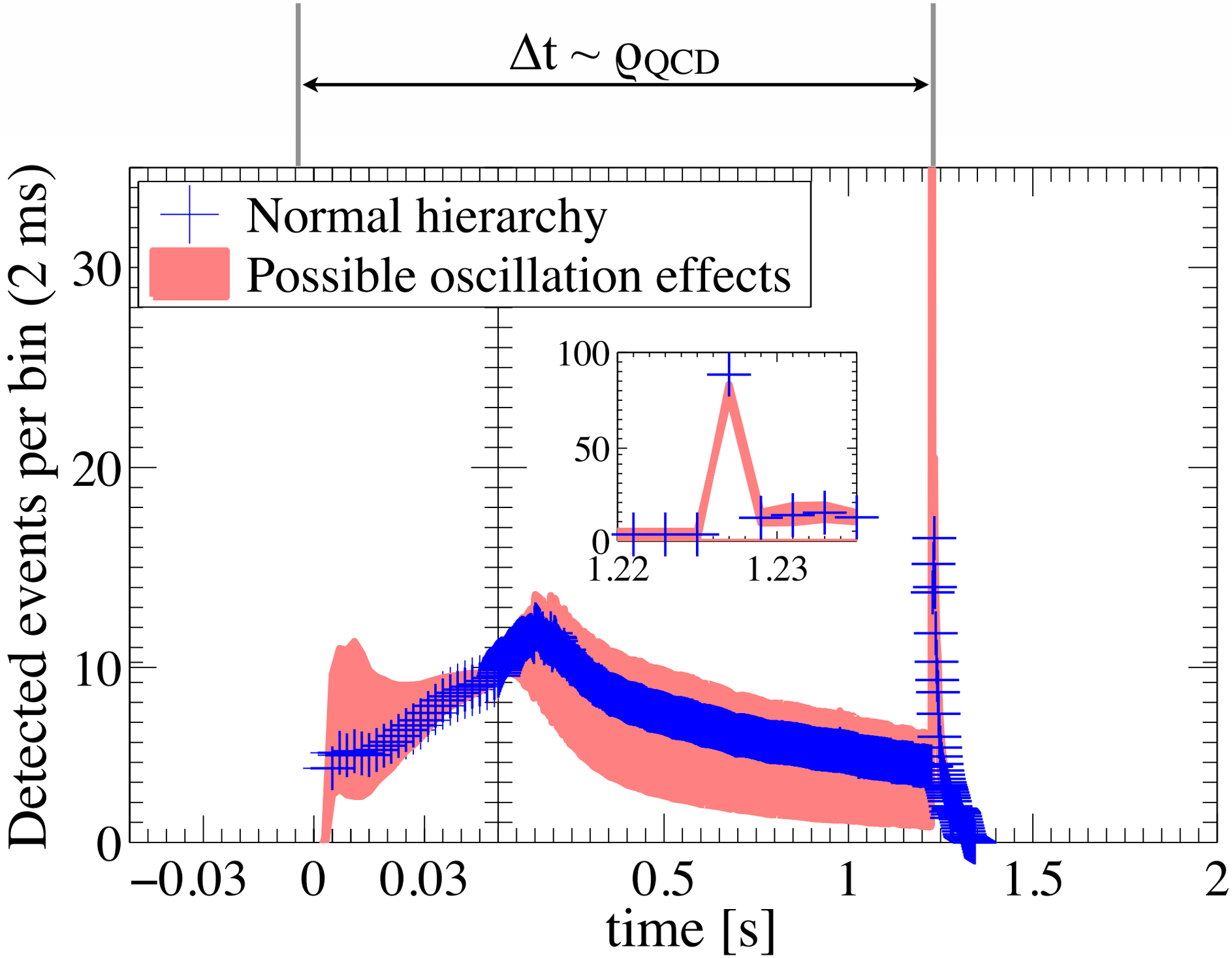
(proto)neutron star

0 0.5 1.0 1.5 2.0

time [s]

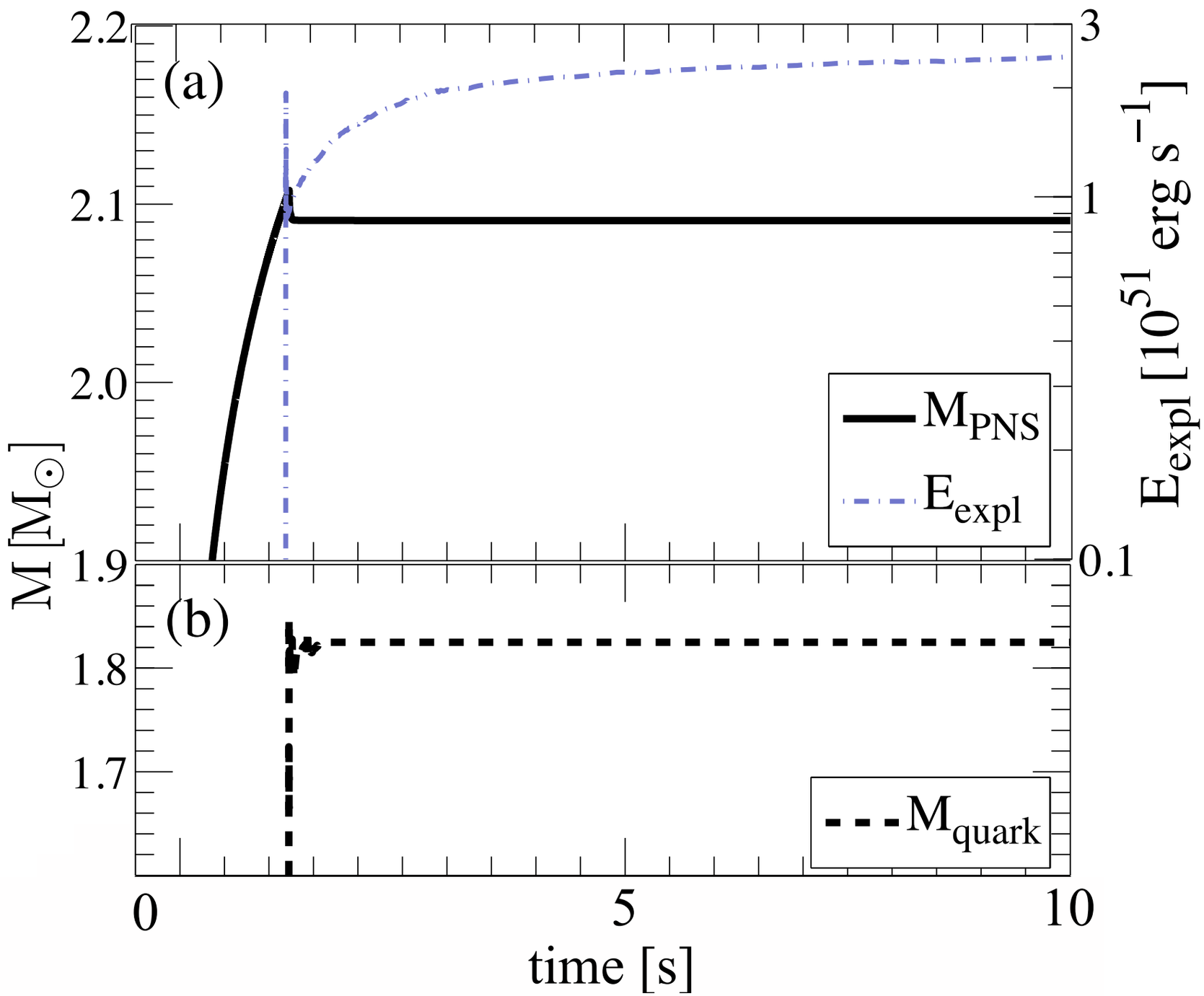
Nature Astron.2 (2018)

ν – signal @ Super-Kamiokande (d ~ 10 kpc)



Nature Astron.2 (2018)

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

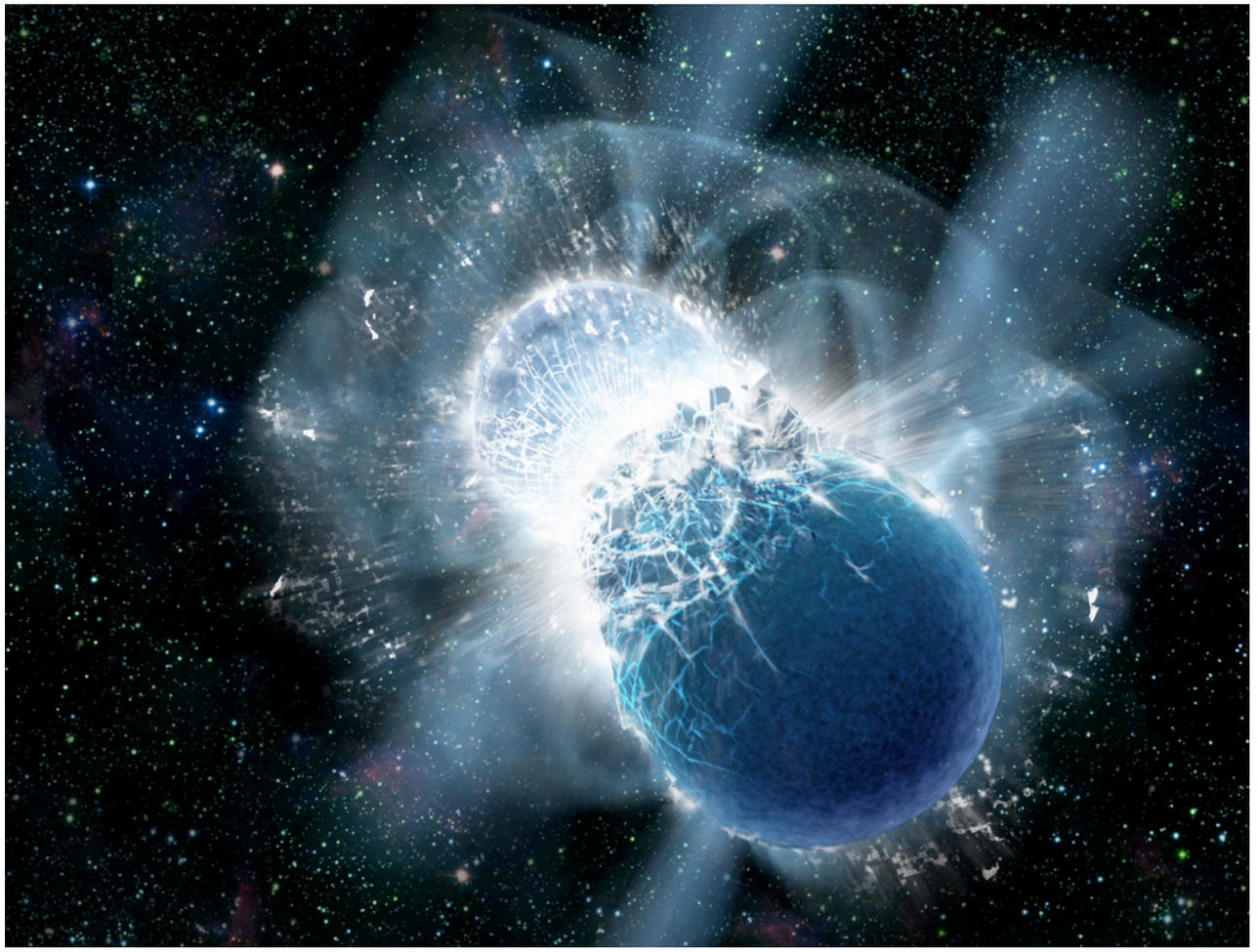


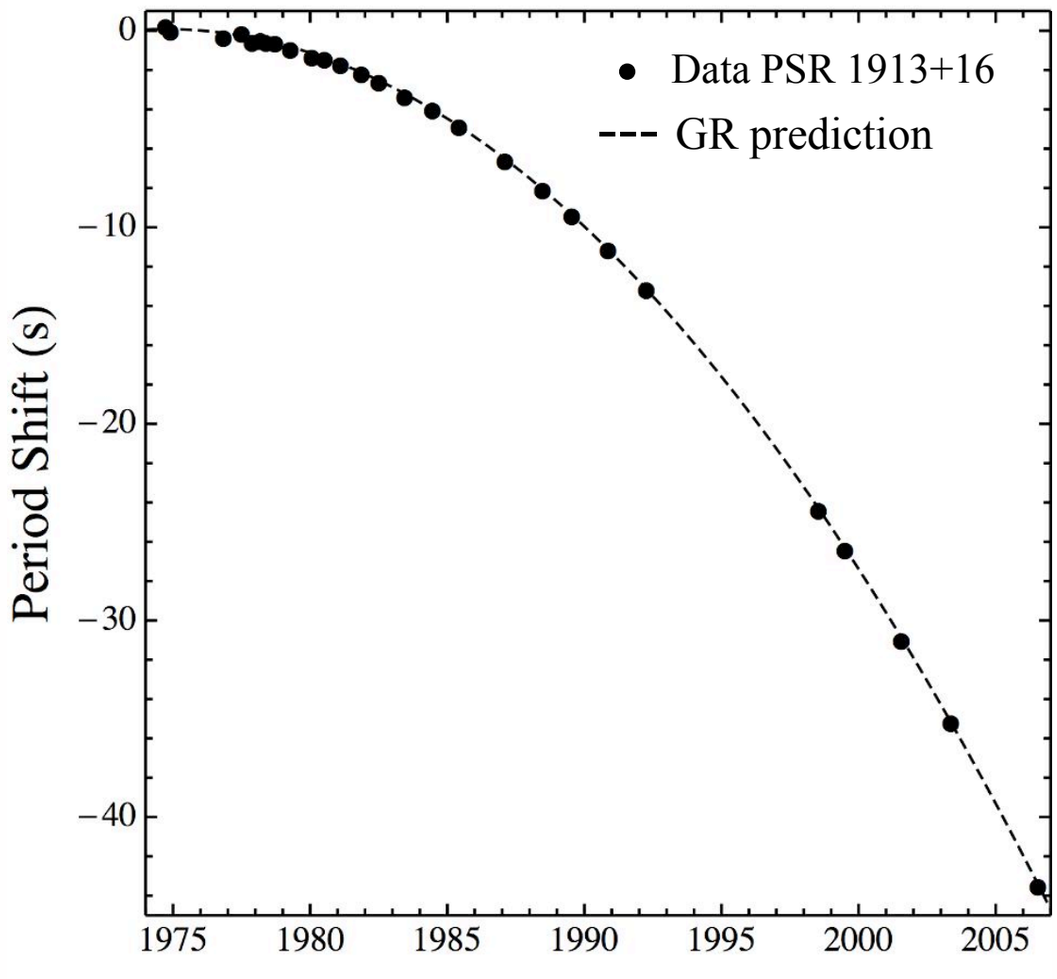
Nature Astron.2 (2018)

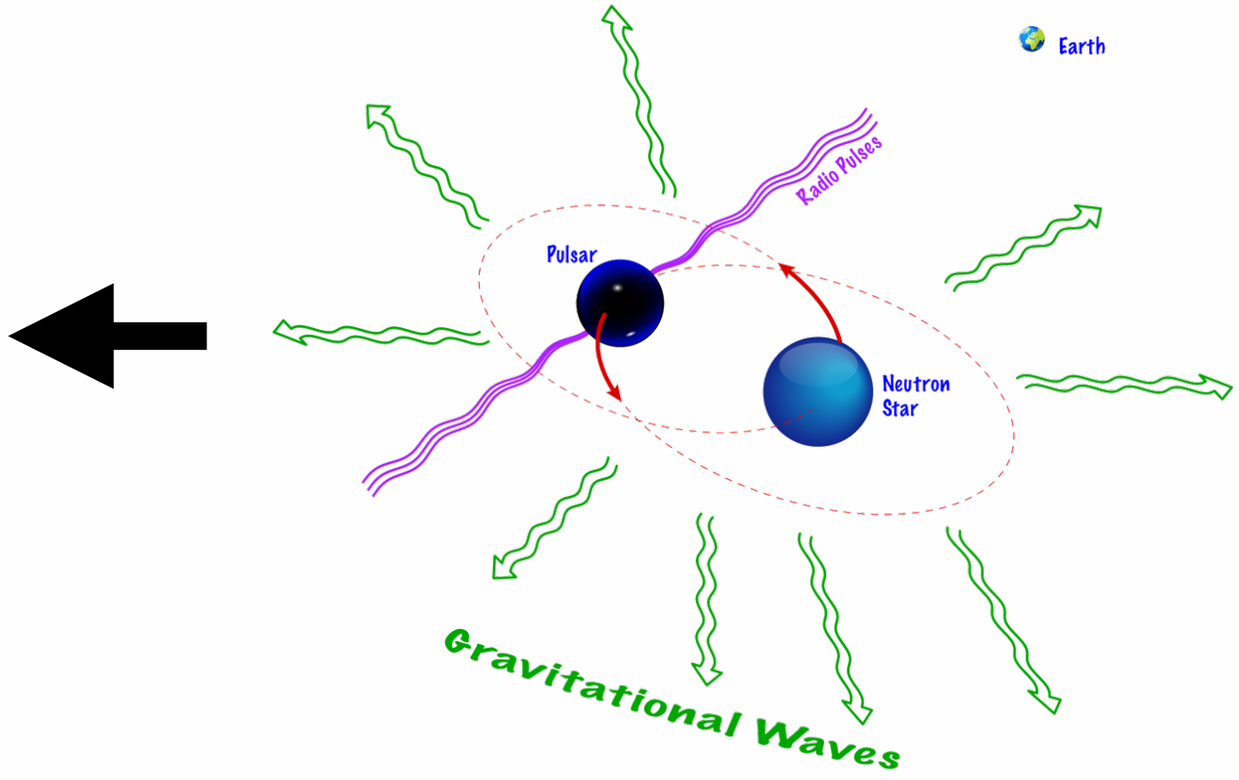
The Nobel Prize in Physics 1993

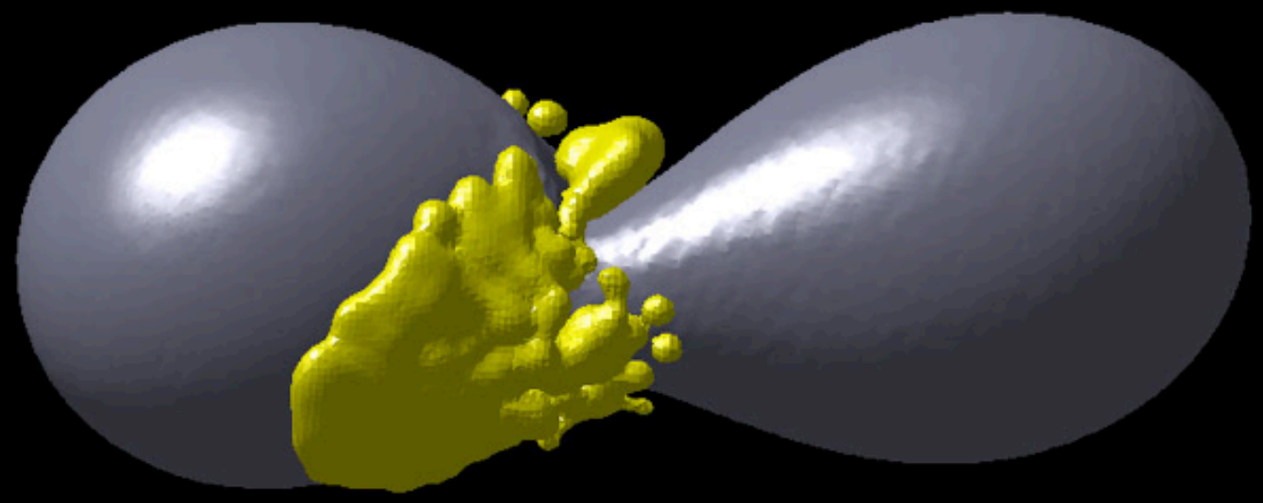
Russell A. Hulse, Joseph H. Taylor Jr.

"for the discovery of a new type of pulsar, a discovery that has opened up new possibilities for the study of gravitation"







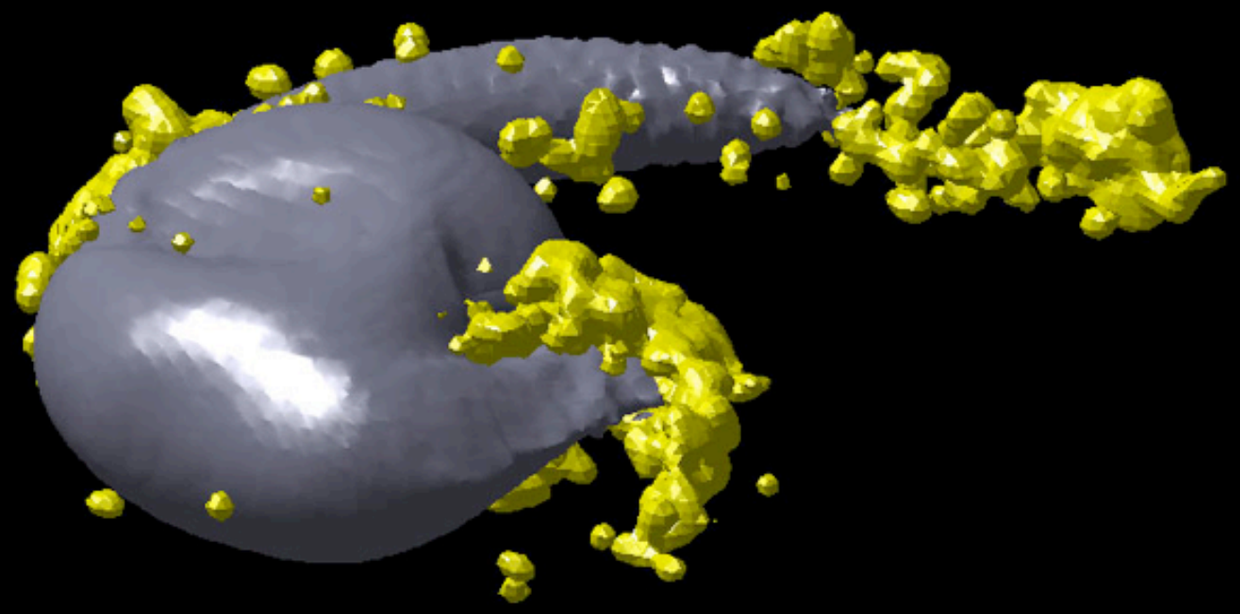


Goriely et al.,(2011) ApJ 738, L32
Bauswein & Janka (2010) PRD 82, 084043

Baiotti et al.,(2008) PRD 78, 084033
Freiburghaus et al.,(1999) ApJ 525, L121
Lattimer et al.,(1974) ApJ 192, L145

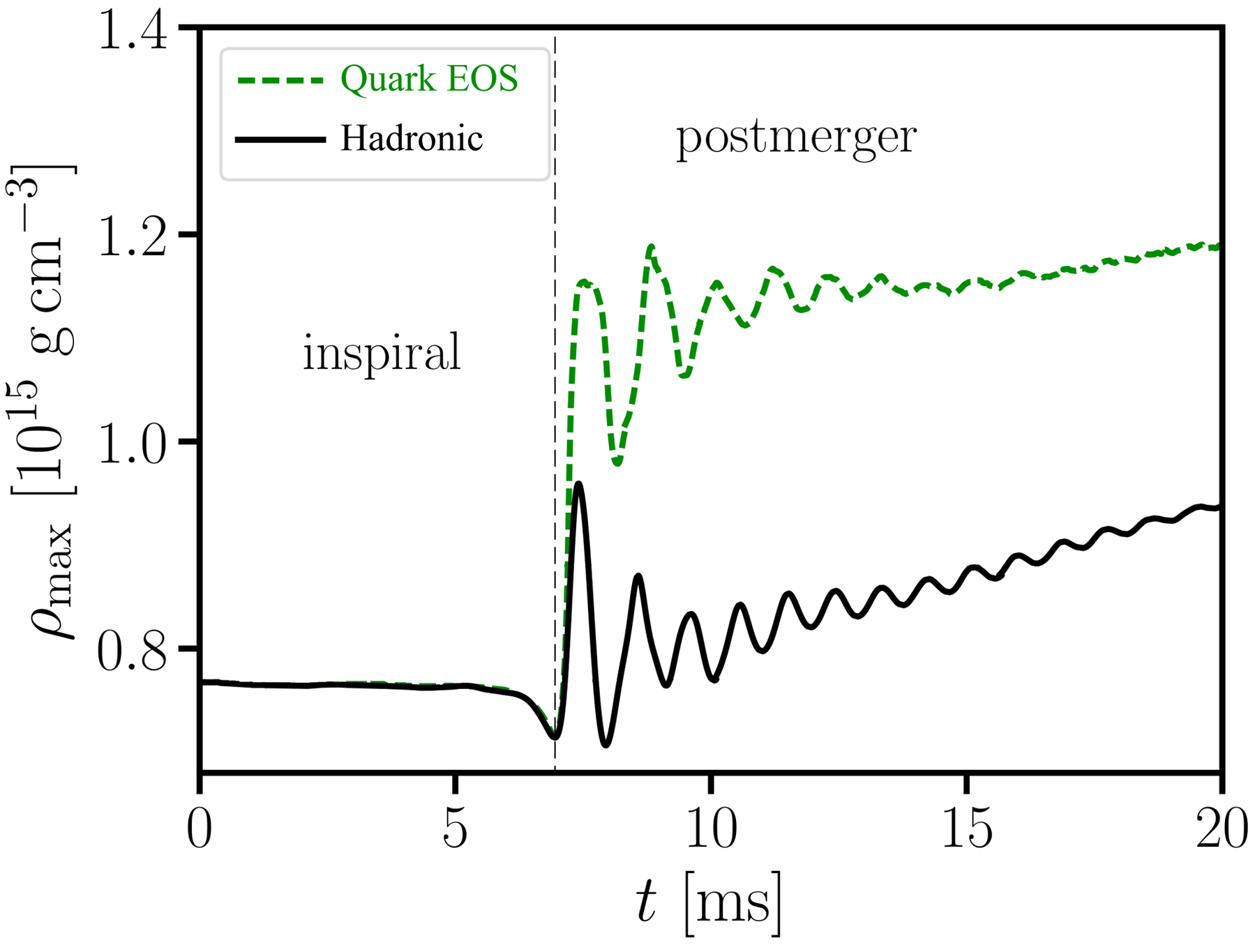
Rezzolla et al,(2016) PRD 93, 124051
Goriely et al.,(2015) MNRAS 452, 894
Bauswein et al.,(2015) PRC 92, 055805
Eichler et al.,(2015) ApJ 808, 13
Perego et al.,(2014) MNRAS 443, 3134
Korobkin et al.,(2012) MNRAS 426, 1940

1st binary neutron star merger detection: **GW170817**



Binary neutron star merger : $1.35 - 1.35\ M_\odot$ (GW170817)

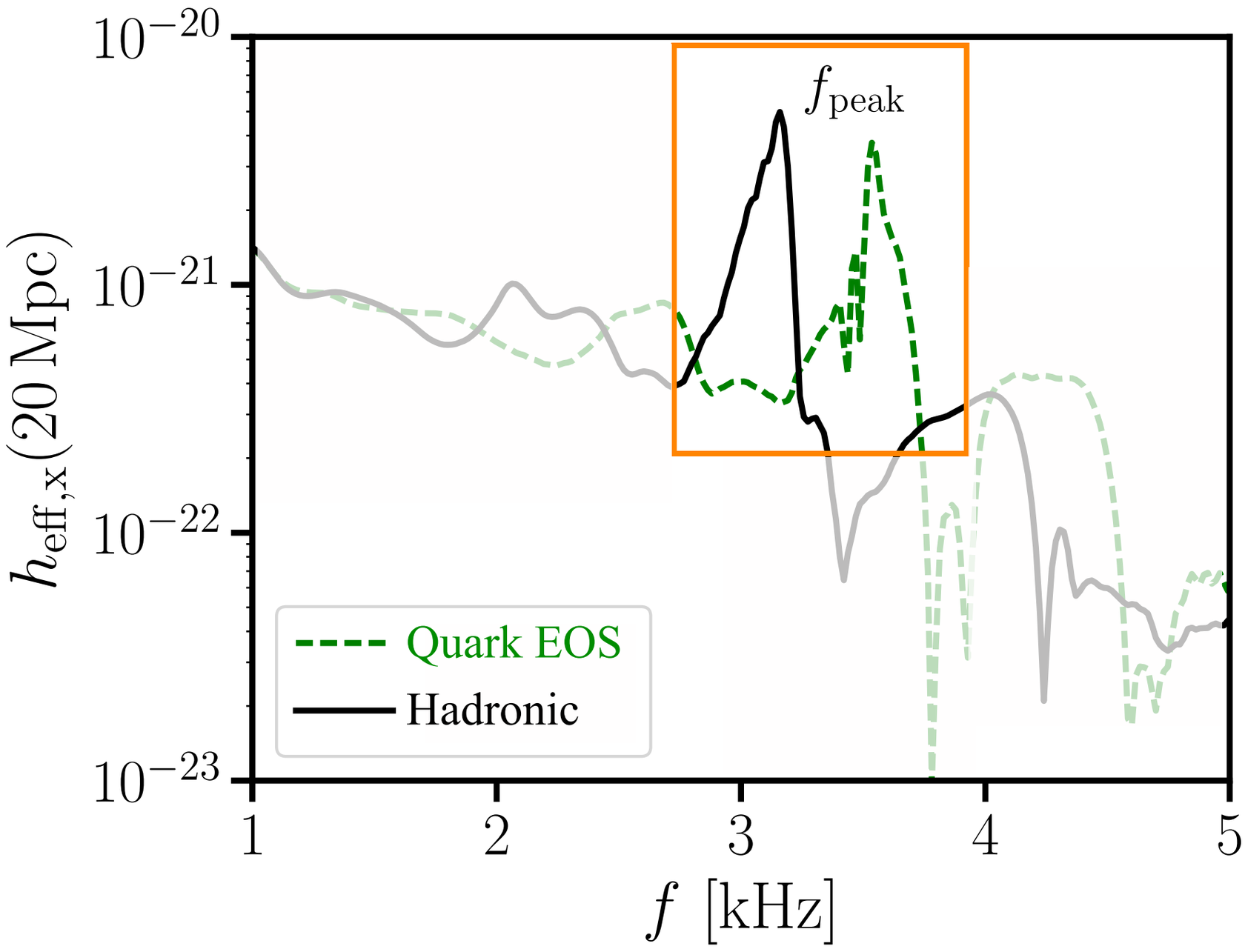
1st–order phase transition



ArXiv astro-ph.HE/1809.01116

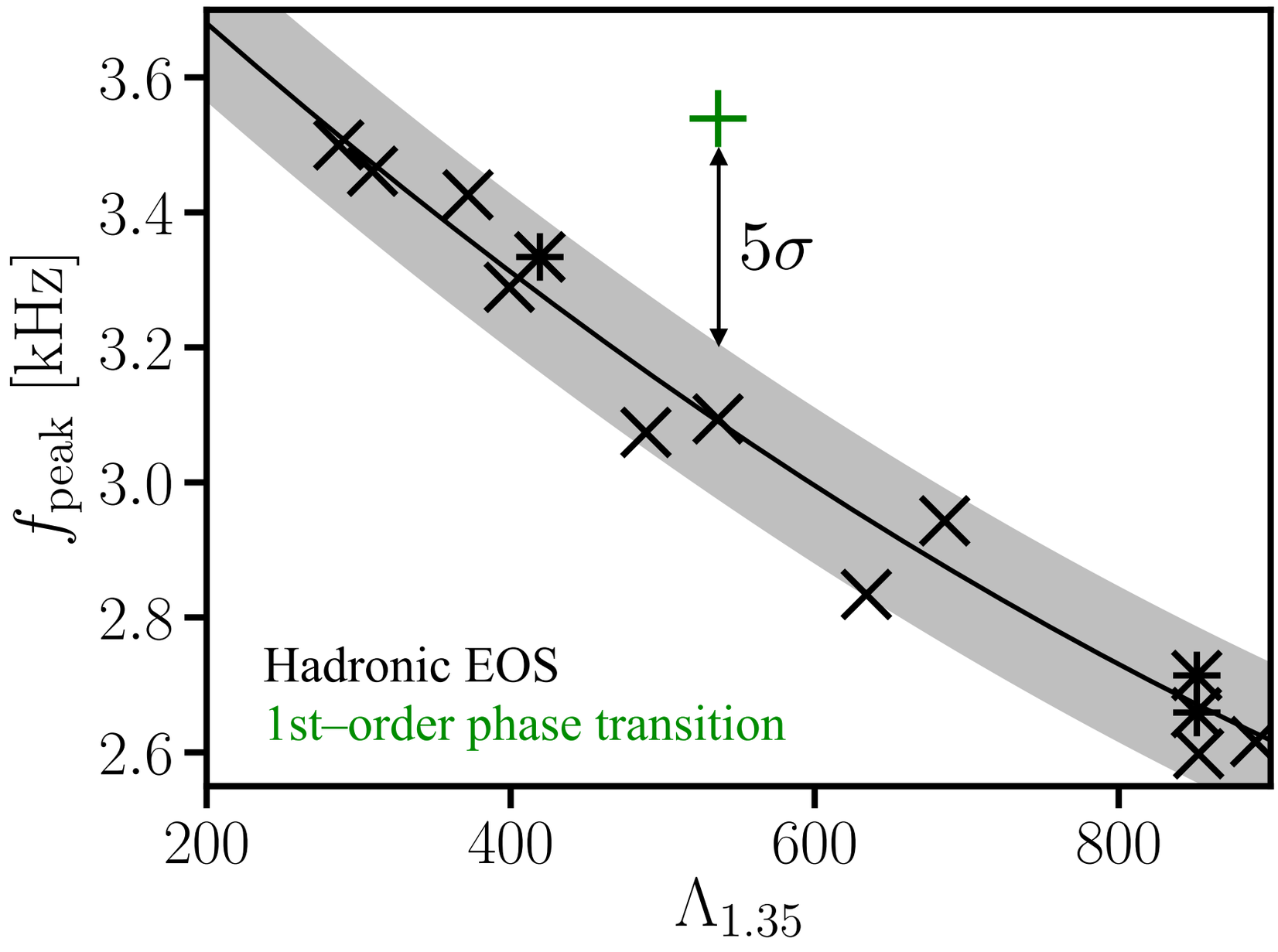
Binary neutron star merger : $1.35 - 1.35\ \mathrm{M}_\odot$ (GW170817)

1st–order phase transition



ArXiv astro-ph.HE/1809.01116

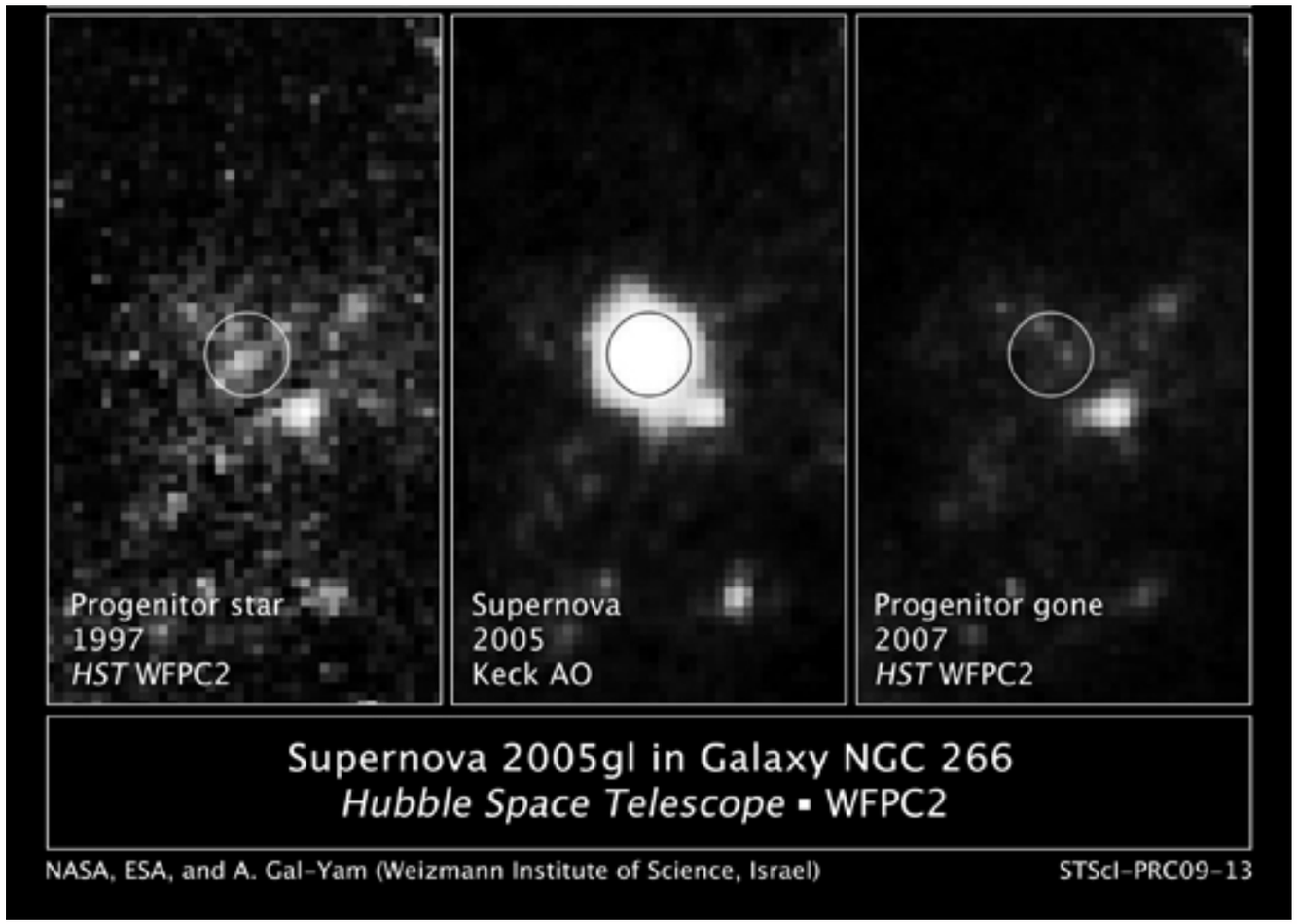
$$f_{\rm peak} \neq \left(6.486 \times 10^{-7}\Lambda^2 - 2.231 \times 10^{-3}\Lambda + 4.1\right)\ \text{Hz}$$



ArXiv astro-ph.HE/1809.01116

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 $\sim 2\ \mathrm{M}_\odot$

Additional neutrino burst

GW-signal from neutron-star mergers

Wroclaw Supernova Project

Thanks for your attention

In collaboration with:

A. Bauswein
N. U. Bastian
D. Blaschke
M. Cierniak
T. Klähn
K. Kotake
S. Typel
M. R. Wu