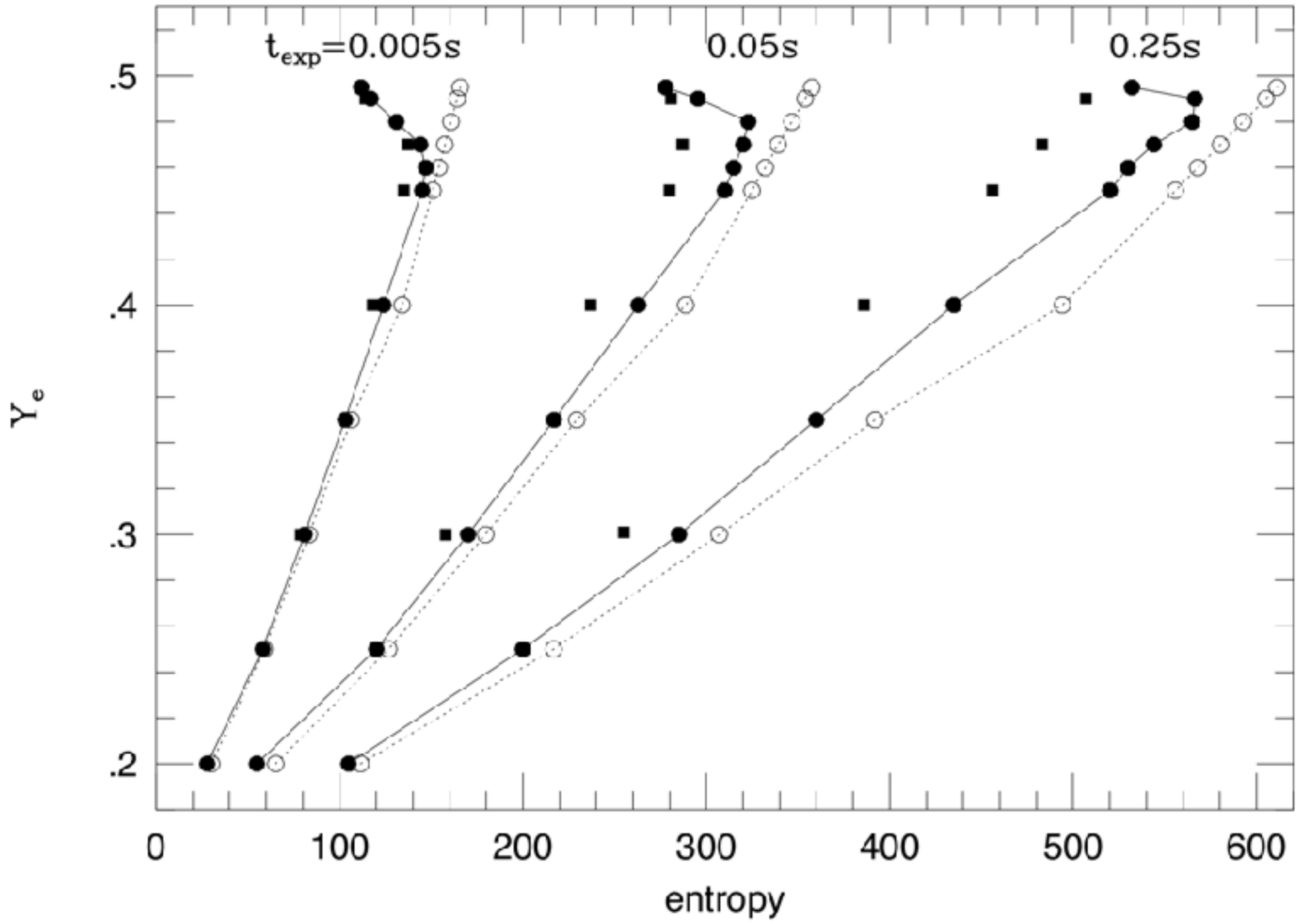
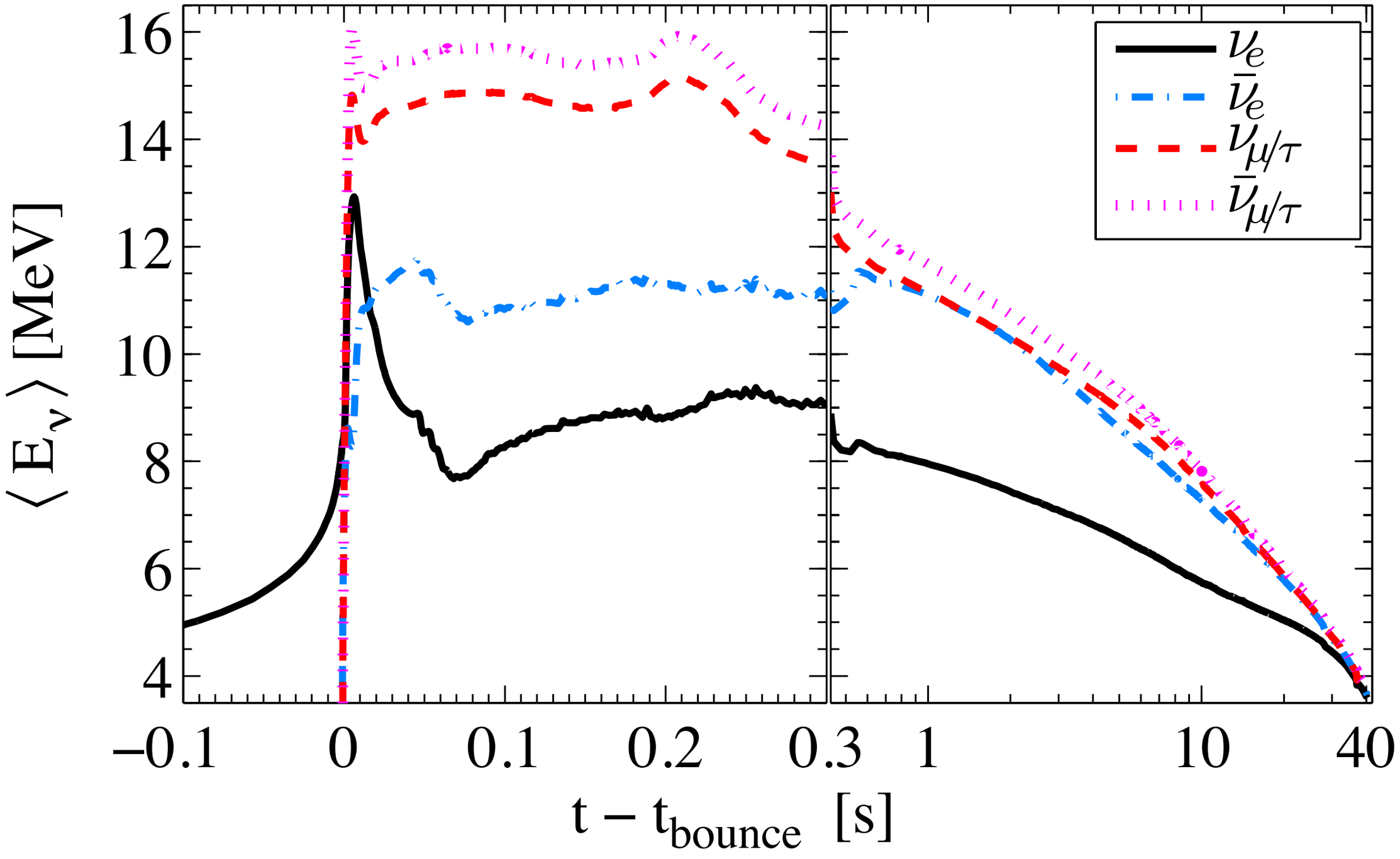
Effects of Opacity on the neutrino signal

Tobias Fischer



$$Y_e^{\rm eq} \simeq \frac{\lambda_{\nu_e n}}{\lambda_{\nu_e n} + \lambda_{\bar{\nu}_e p}}$$

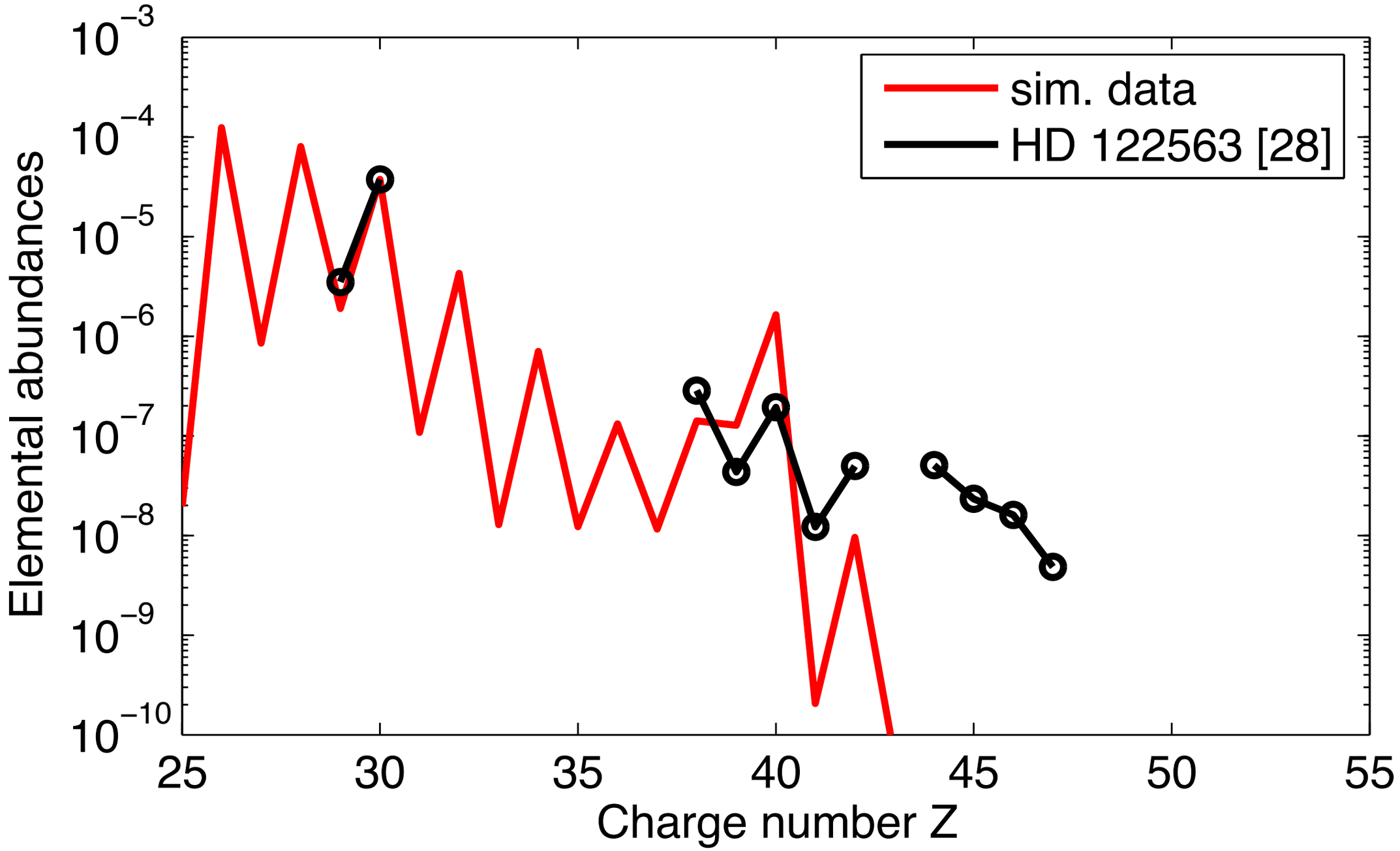
$$Y_e^{\rm eq} < 0.5 \ : \ \varepsilon_{\bar{\nu}_e} - \varepsilon_{\nu_e} \gtrsim 4\Delta \quad (\varepsilon_\nu = \langle E_\nu^2 \rangle / \langle E\nu \rangle)$$



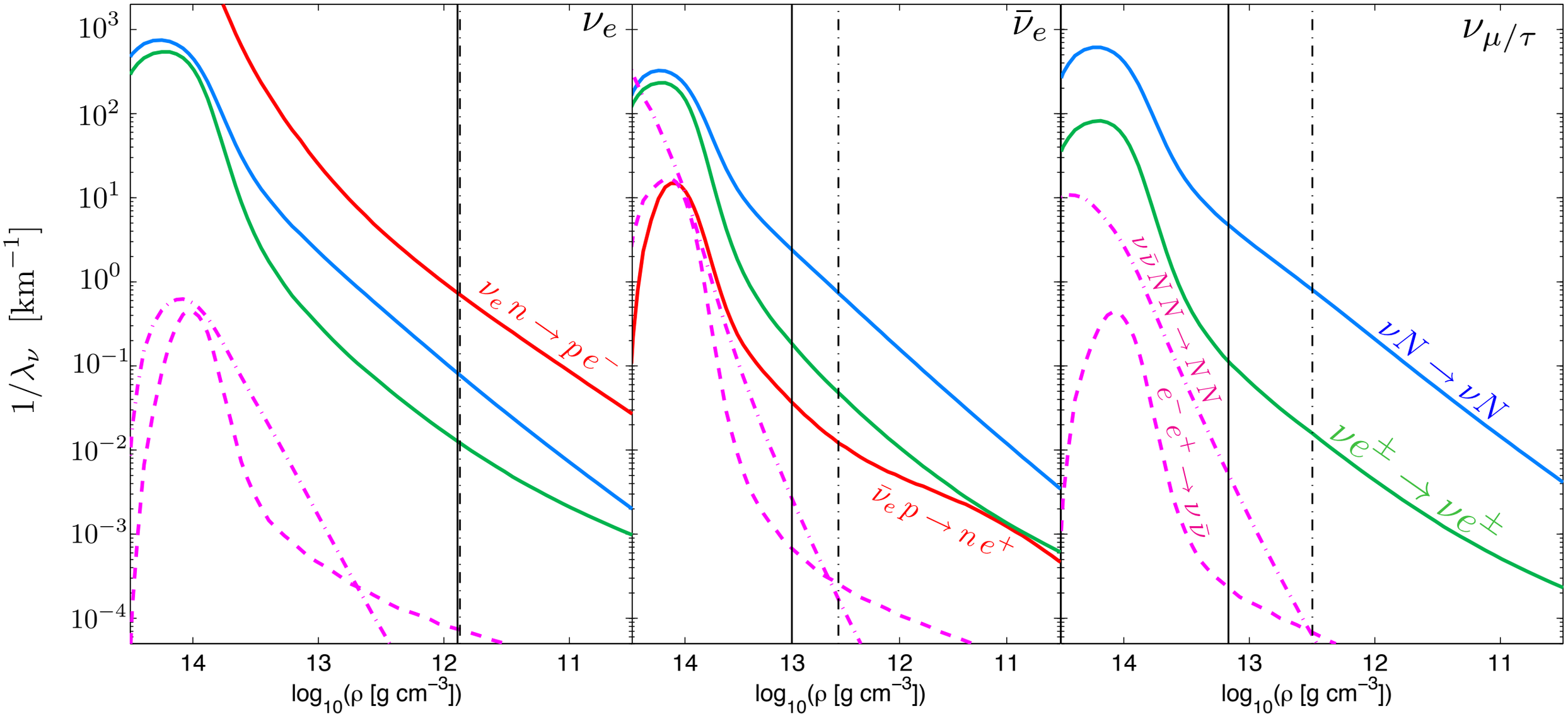
Phys. Rev. D94, 085012 (2016)

$$Y_e^{\min} \simeq 0.49 \ (t \sim 1.5 - 3 \ \mathrm{s})$$

$$Y_e > 0.5 \ (t > 4 \ \mathrm{s})$$



J. Phys. G41, 044008 (2014)



$$\nu_\mu\, n \longrightarrow p\, \mu^-$$
$$\nu_\alpha\, \mu^- \longrightarrow \mu^-\, \nu_\alpha$$
$$\nu_\mu\, e^- \longrightarrow \mu^-\, \nu_e$$
$$\nu_\mu\, \bar{\nu}_e\, e^- \longrightarrow \mu^-$$
$$\bar{\nu}_\mu\, \mu^- \longrightarrow e^-\, \bar{\nu}_e$$

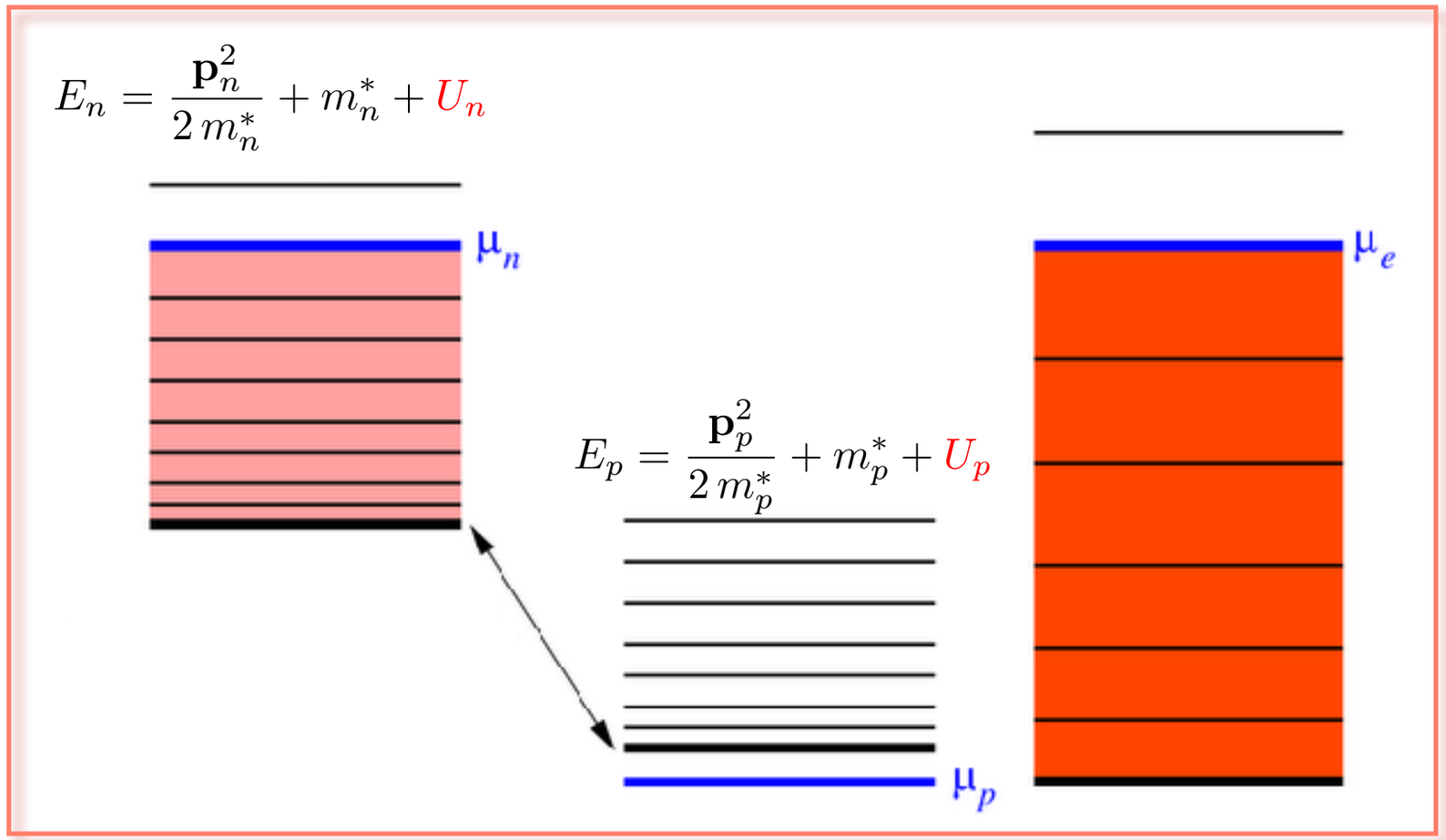
Phys. Rev. D85, 083003 (2012)

Phys. Rev. Lett. 119, 242702 (2017)

$$1/\lambda(E_{\nu_e}) = \frac{G_F^2 V_{ud}^2}{\pi\hbar c}(g_V^2 + 3g_A^2)\int \frac{d^3p_e}{(2\pi\hbar c)^3}(1 - F_e(E_e))\, S(q_0, q)$$

$$q_0 = E_\nu - E_e \ , \qquad q = \mathbf{p}_\nu - \mathbf{p}_e$$

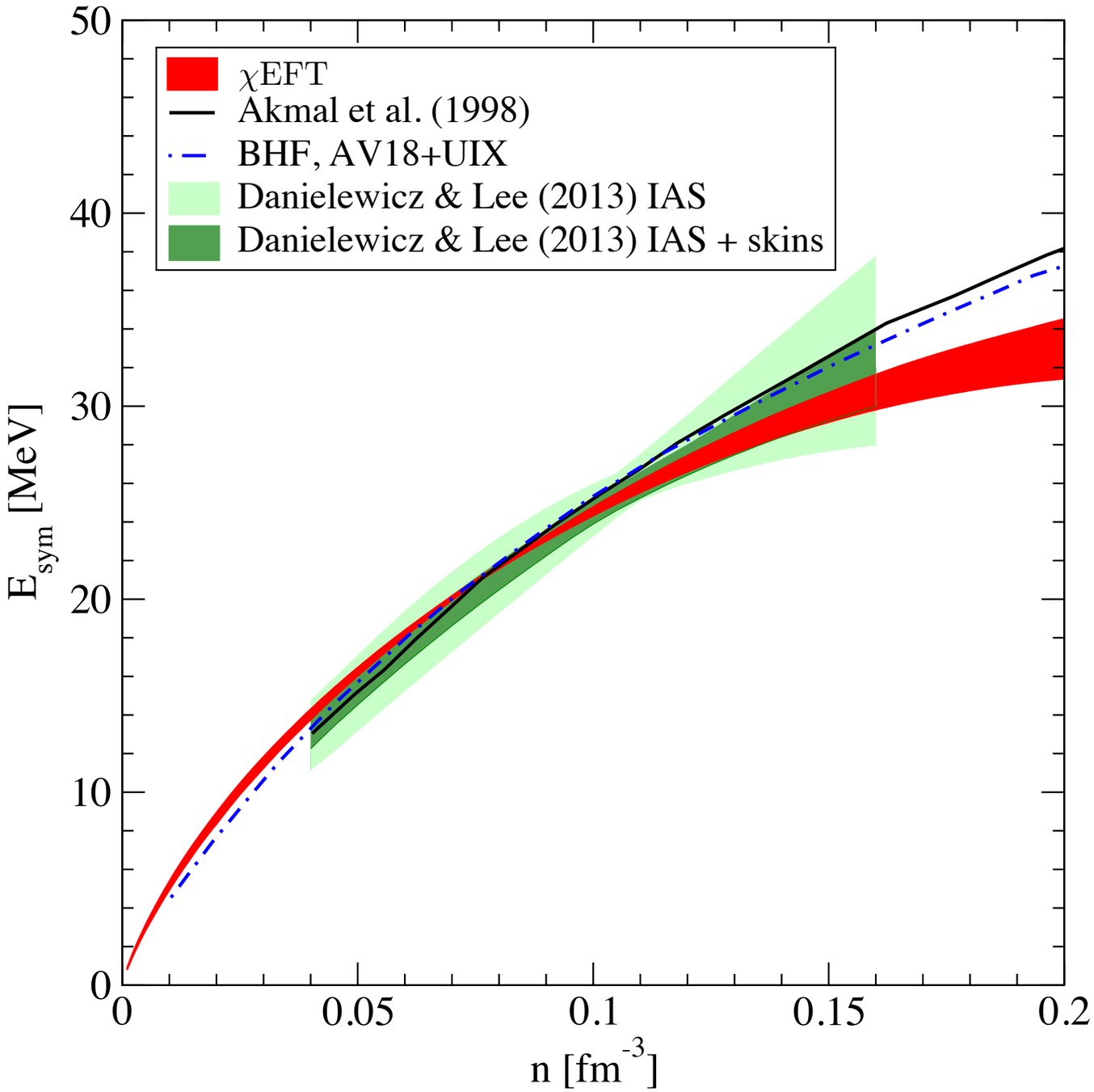
$$S(q_0, q) = 4\pi \int \frac{d^3p_n}{(2\pi\hbar c)^3}\delta(q_0 + E_n - E_p) f_n(E_n)(1 - f_p(E_p))$$

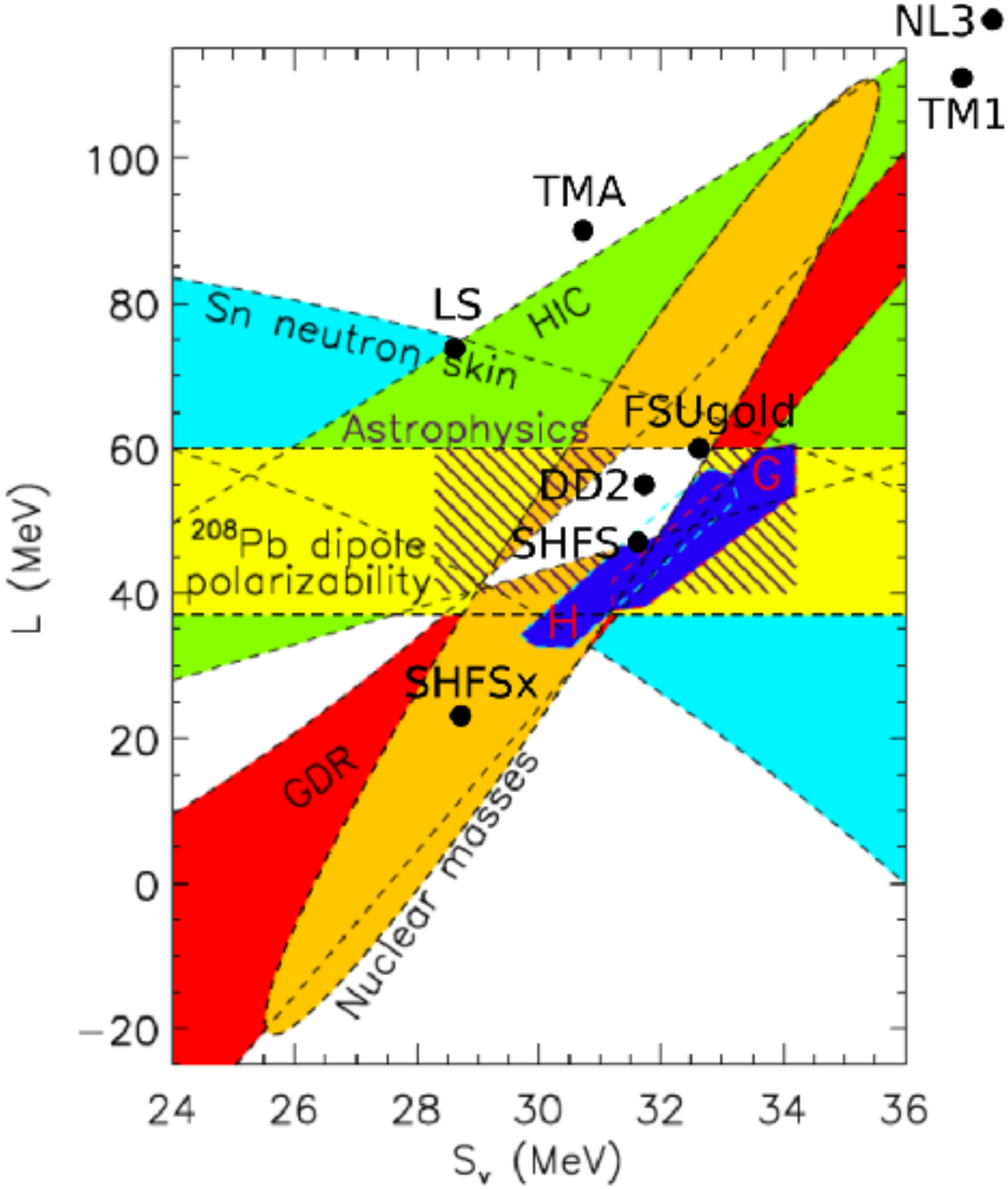


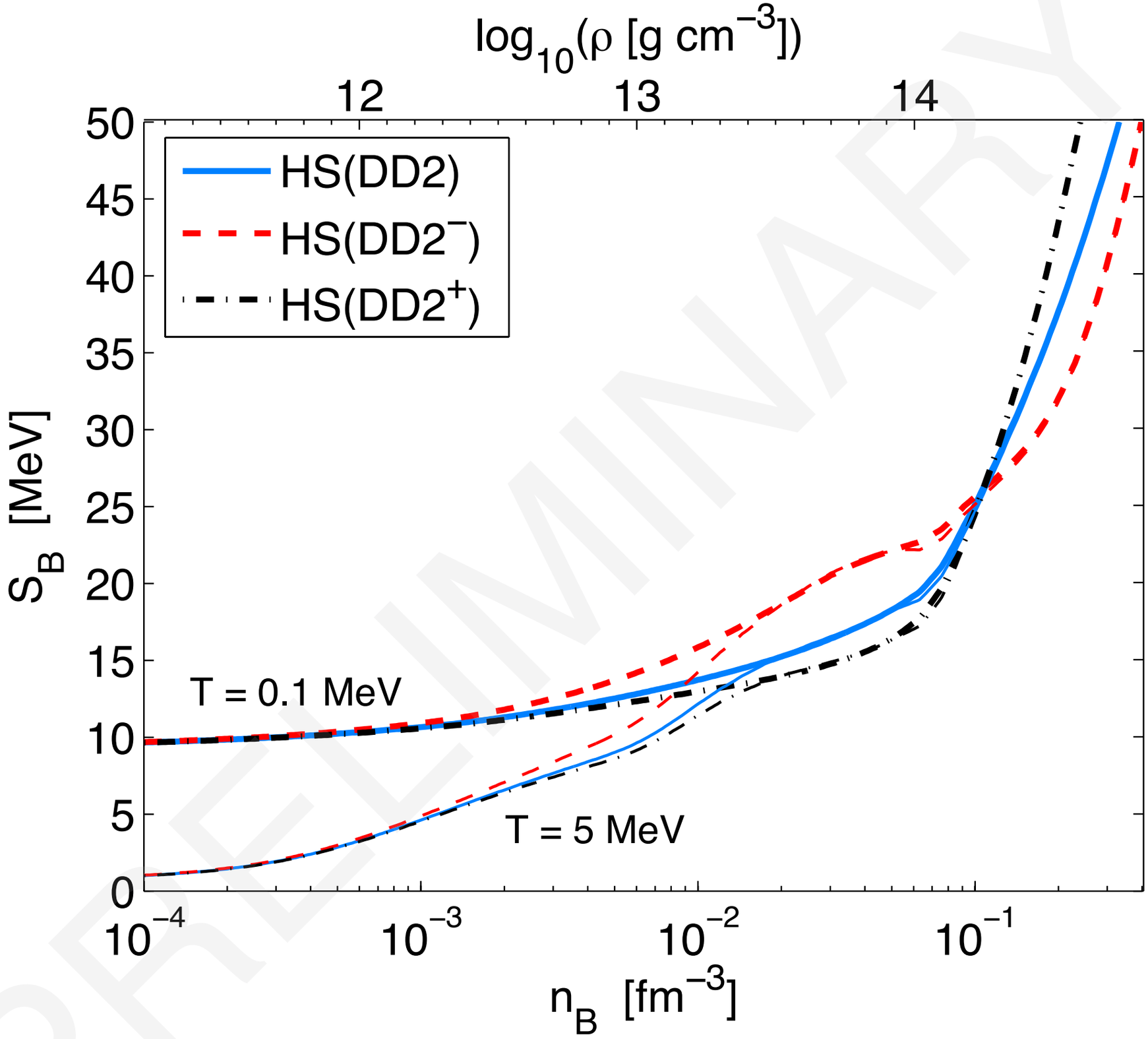
$$U_n - U_p \propto S^F(T, \rho)$$

Phys. Rev. Lett. 109, 251104 (2012)

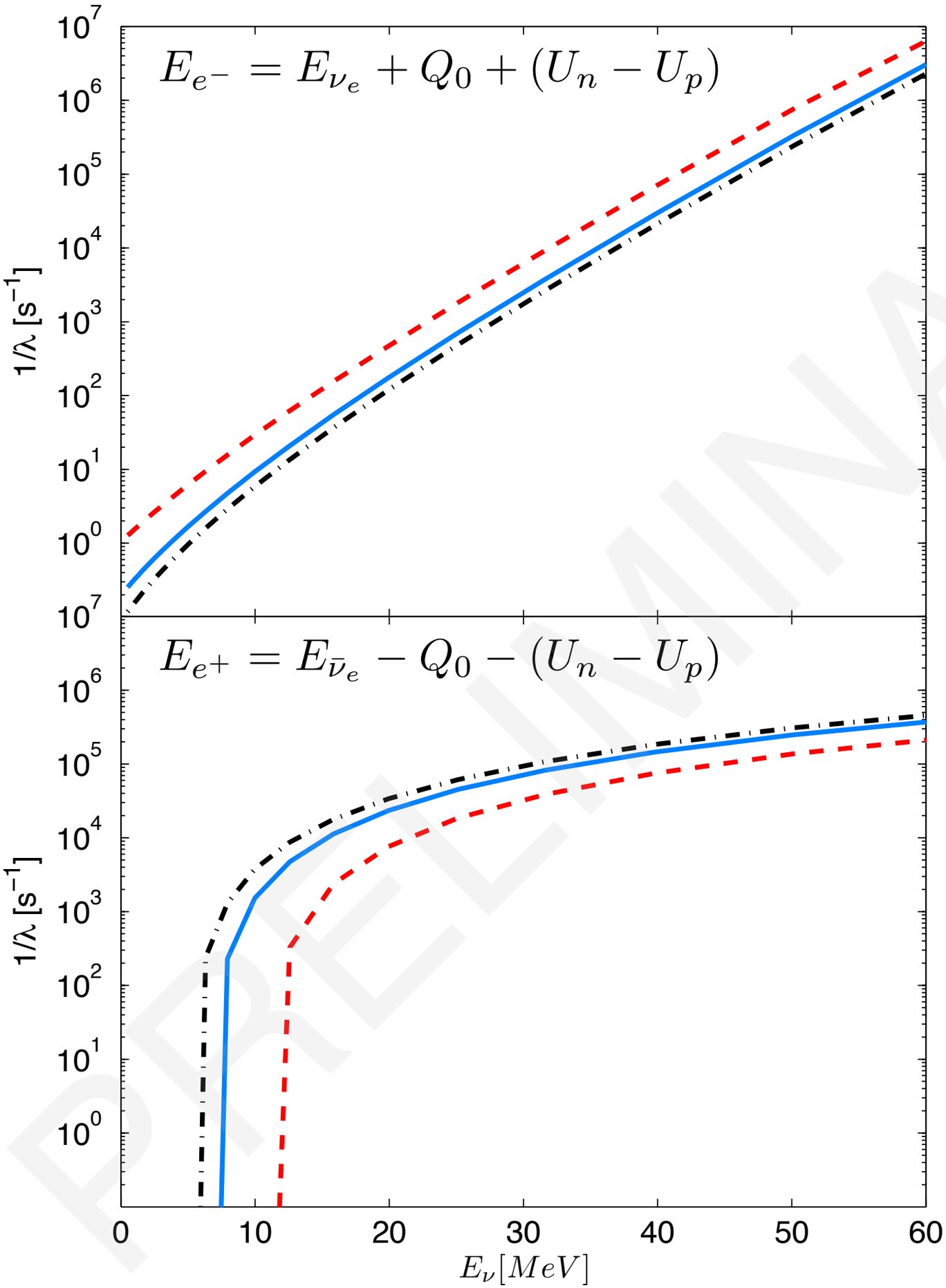
Eur. Phys. J. A50, 11 (2014)







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



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

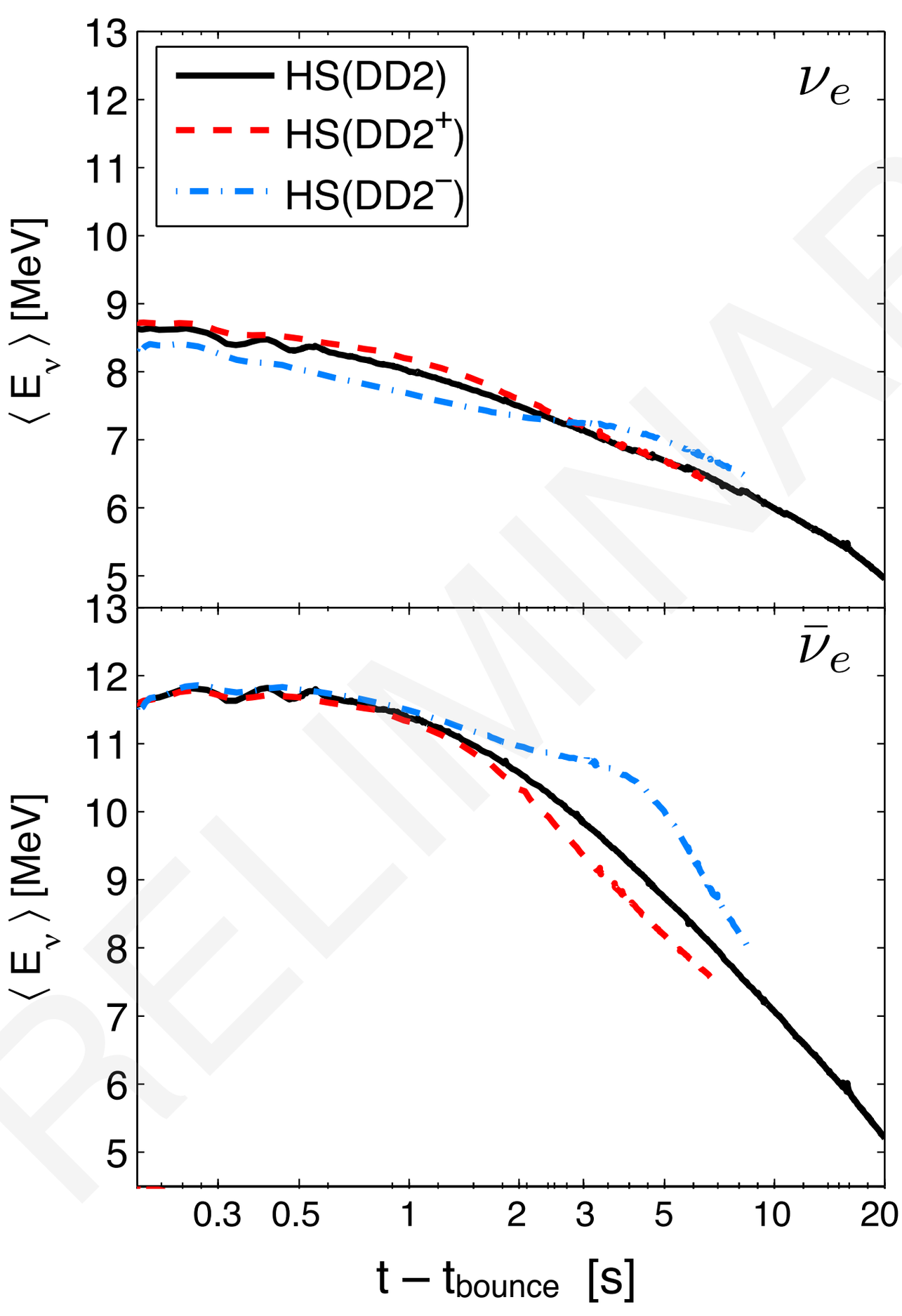
$\rho = 2 \times 10^{13}$ g cm^{-3}

$T = 5$ MeV, $Y_e = 0.2$

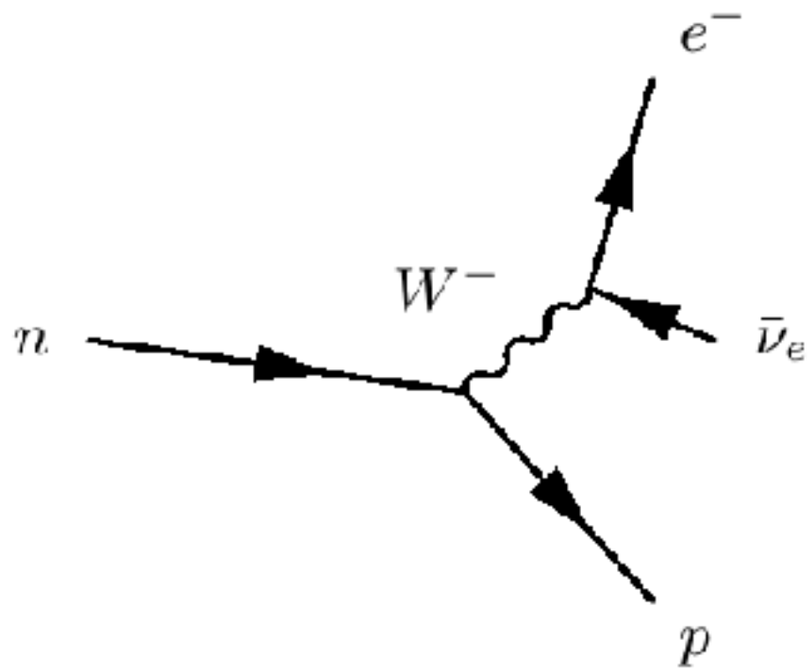
DD2$^-$: $U_n - U_p = 9.4$ MeV

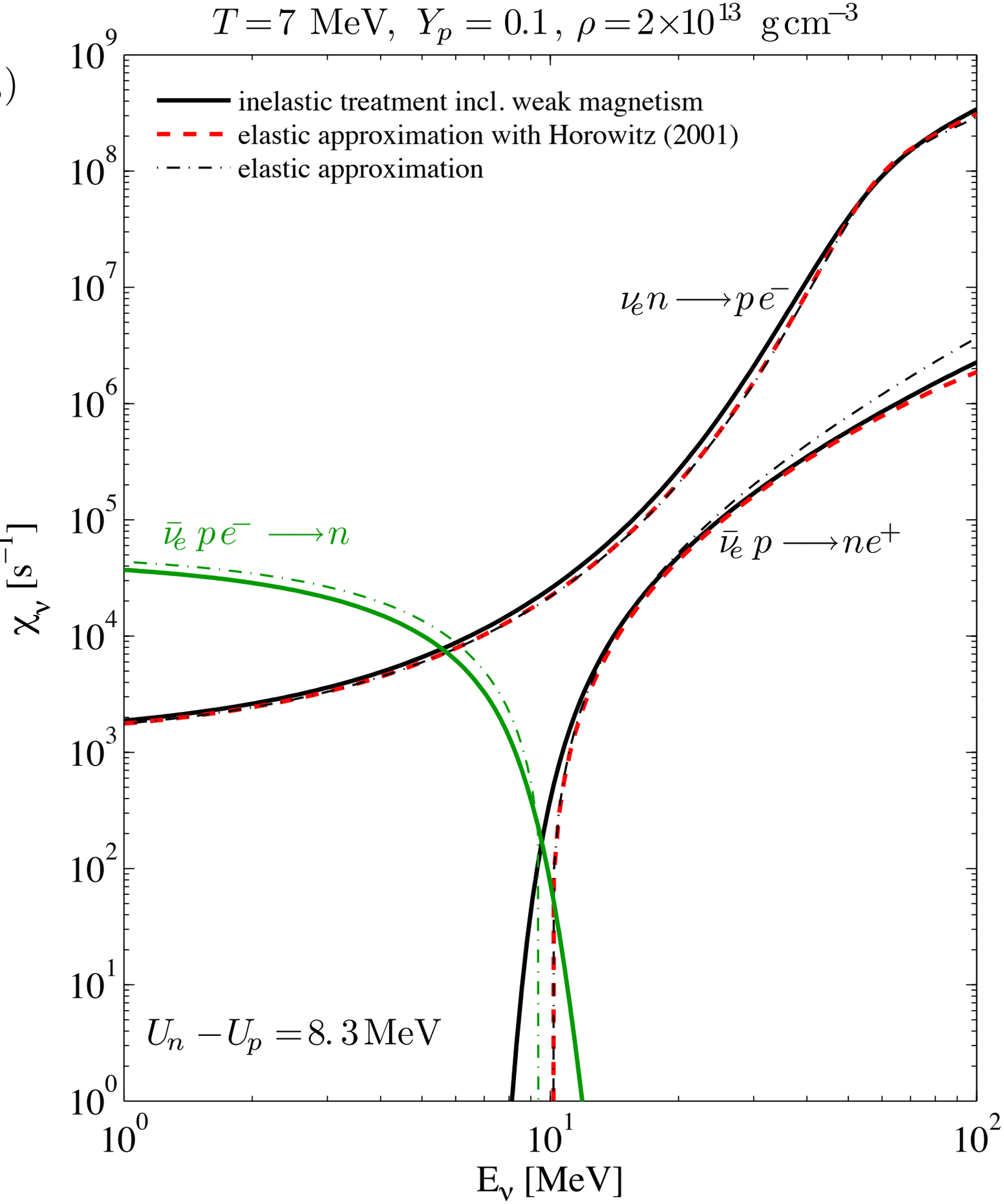
DD2 : $U_n - U_p = 5.3$ MeV

DD2$^+$: $U_n - U_p = 3.7$ MeV

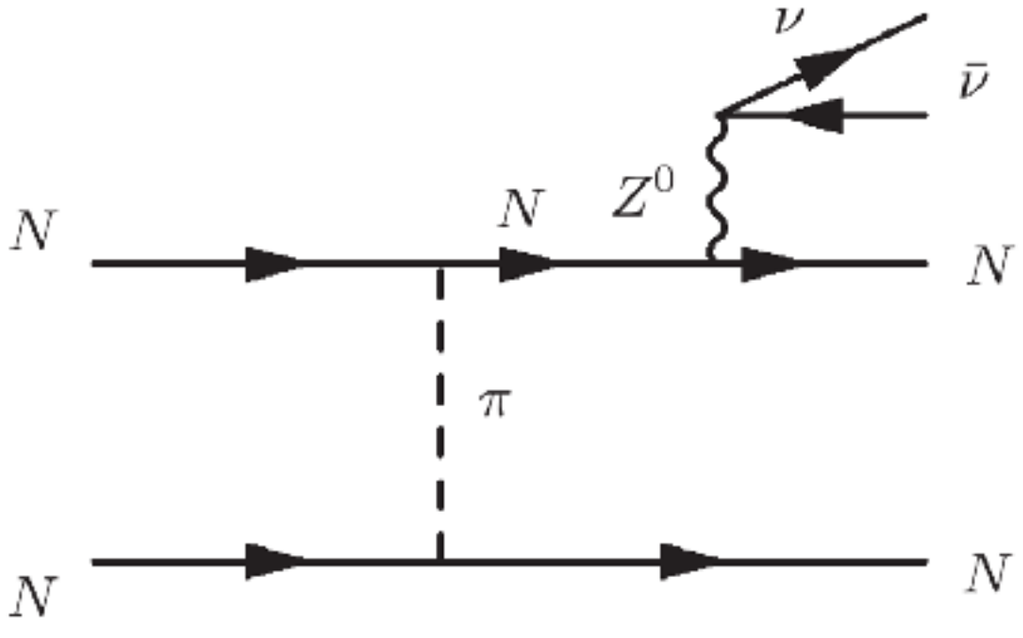

HS(DD2)
HS(DD2+)
HS(DD2−)
ν_e
$\bar{\nu}_e$
⟨ E_ν ⟩ [MeV]
13
12
11
10
9
8
7
6
5
0.3
0.5
1
2
3
5
10
20
t − t_bounce [s]

$$E_e = -E_{\bar{\nu}_e} + (m_n - m_p) + (U_n - U_p)$$

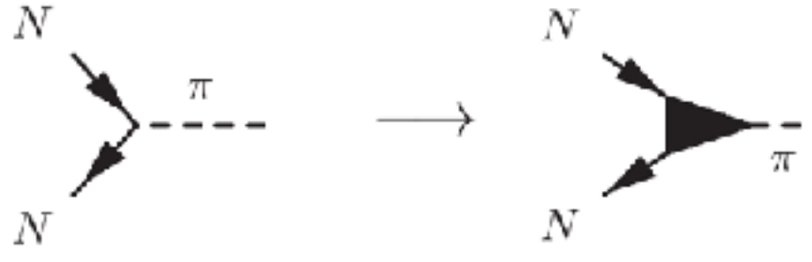


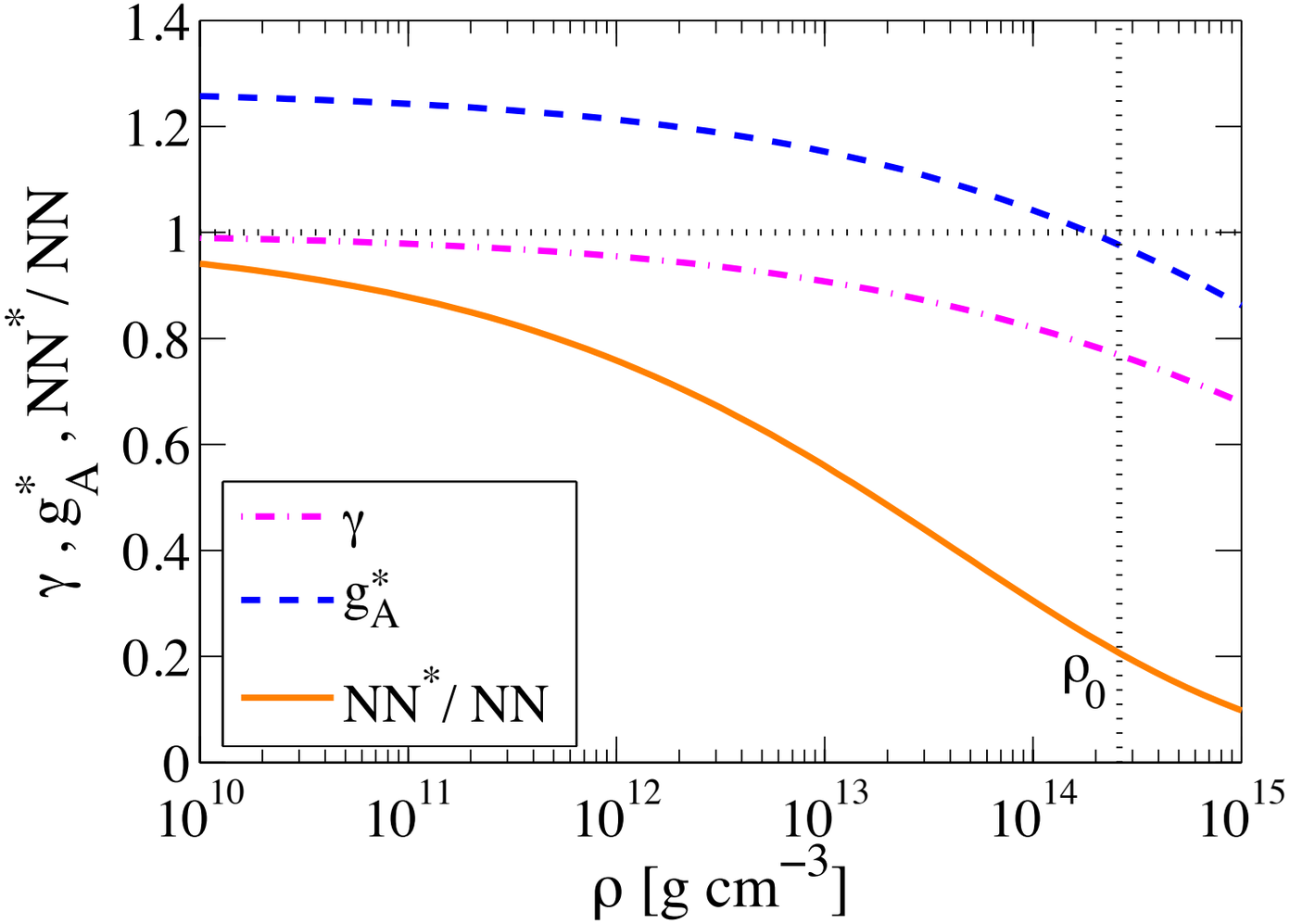


Phys. Rev. C (2018) submitted

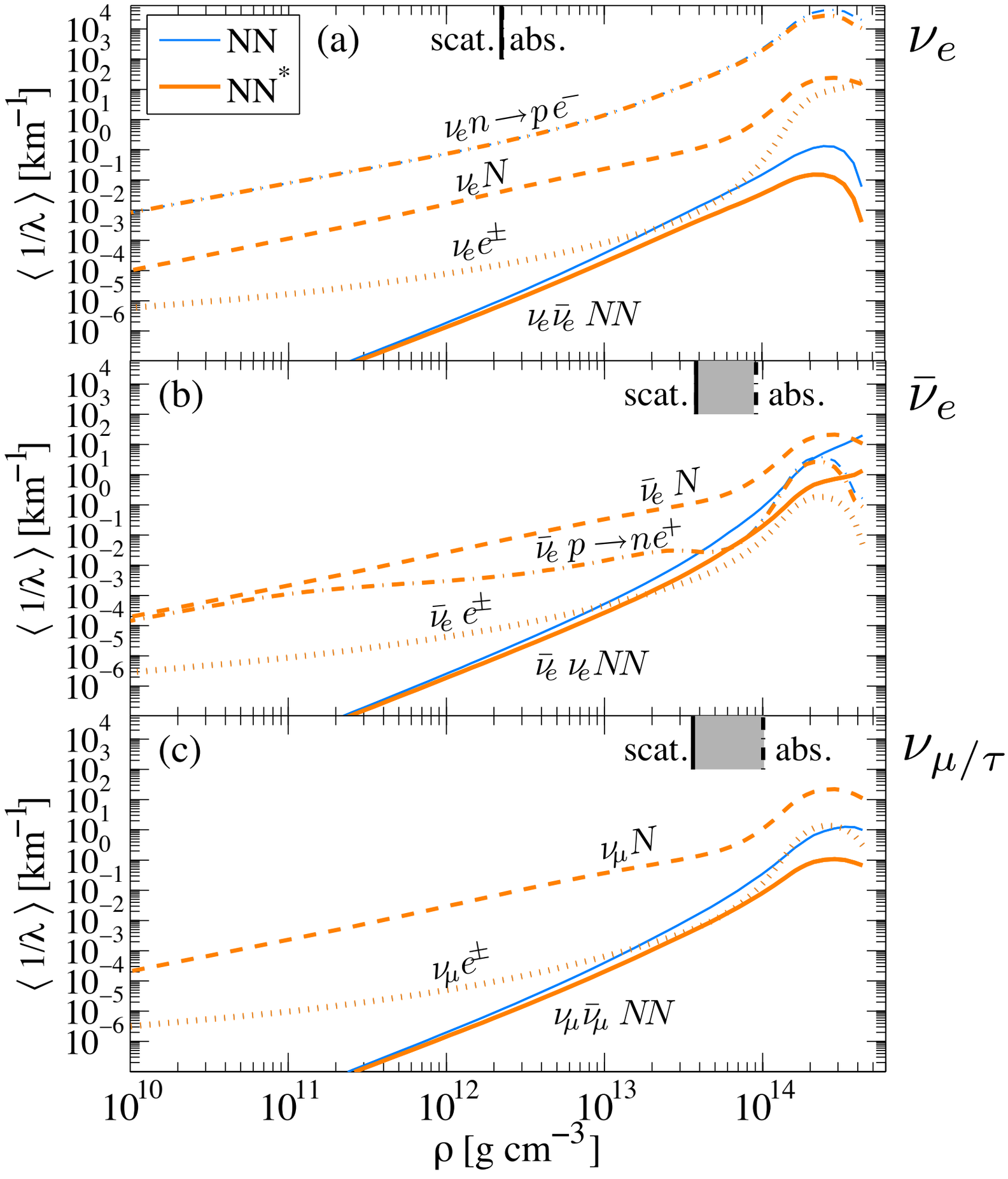


$$\gamma \simeq \left\{ 1 + \frac{1}{3} \left(\frac{m_N^*}{m_N} \right) \left(\frac{p_F(\rho)}{p_F(\rho_0)} \right) \right\}^{-1}$$



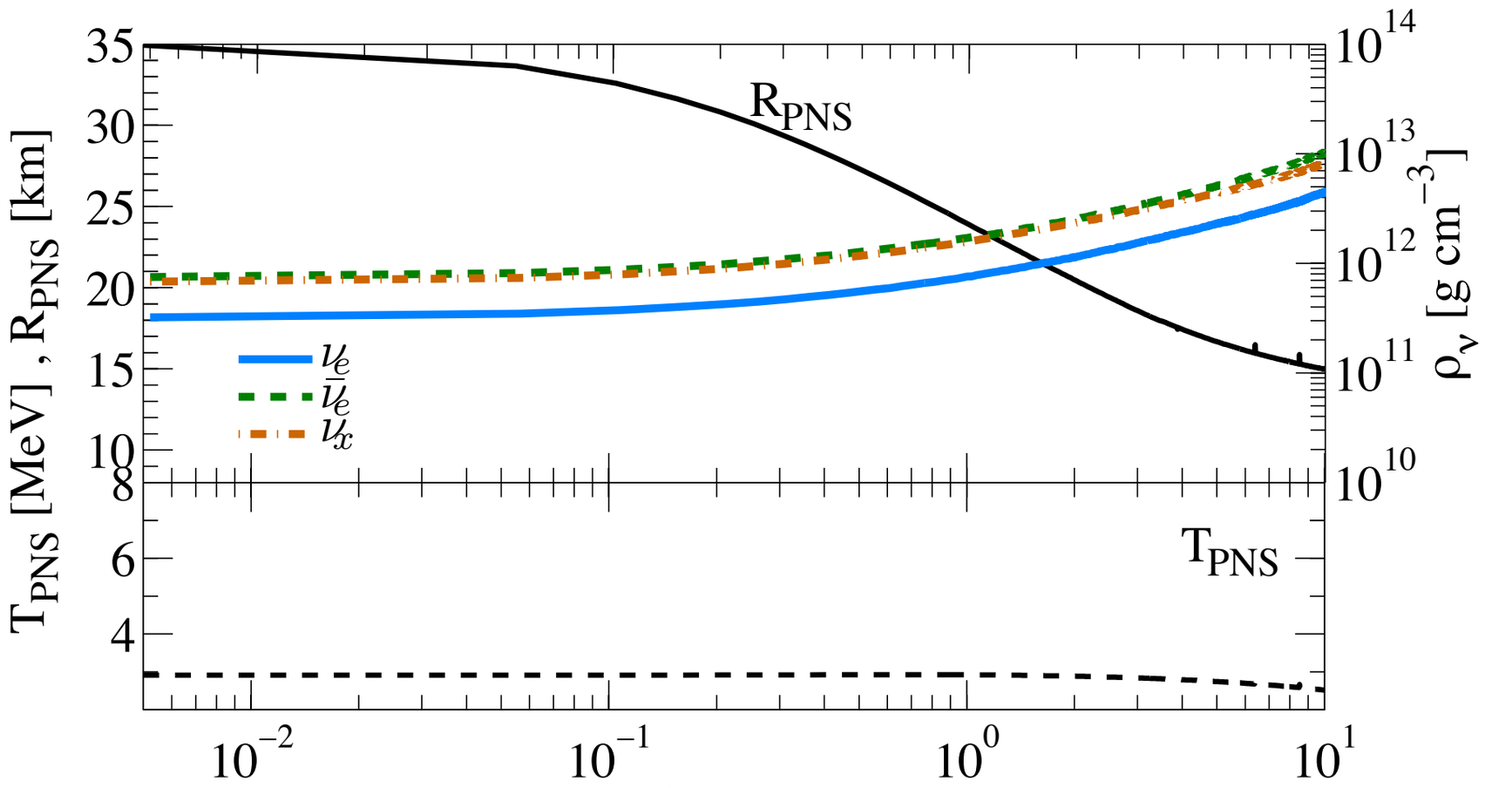


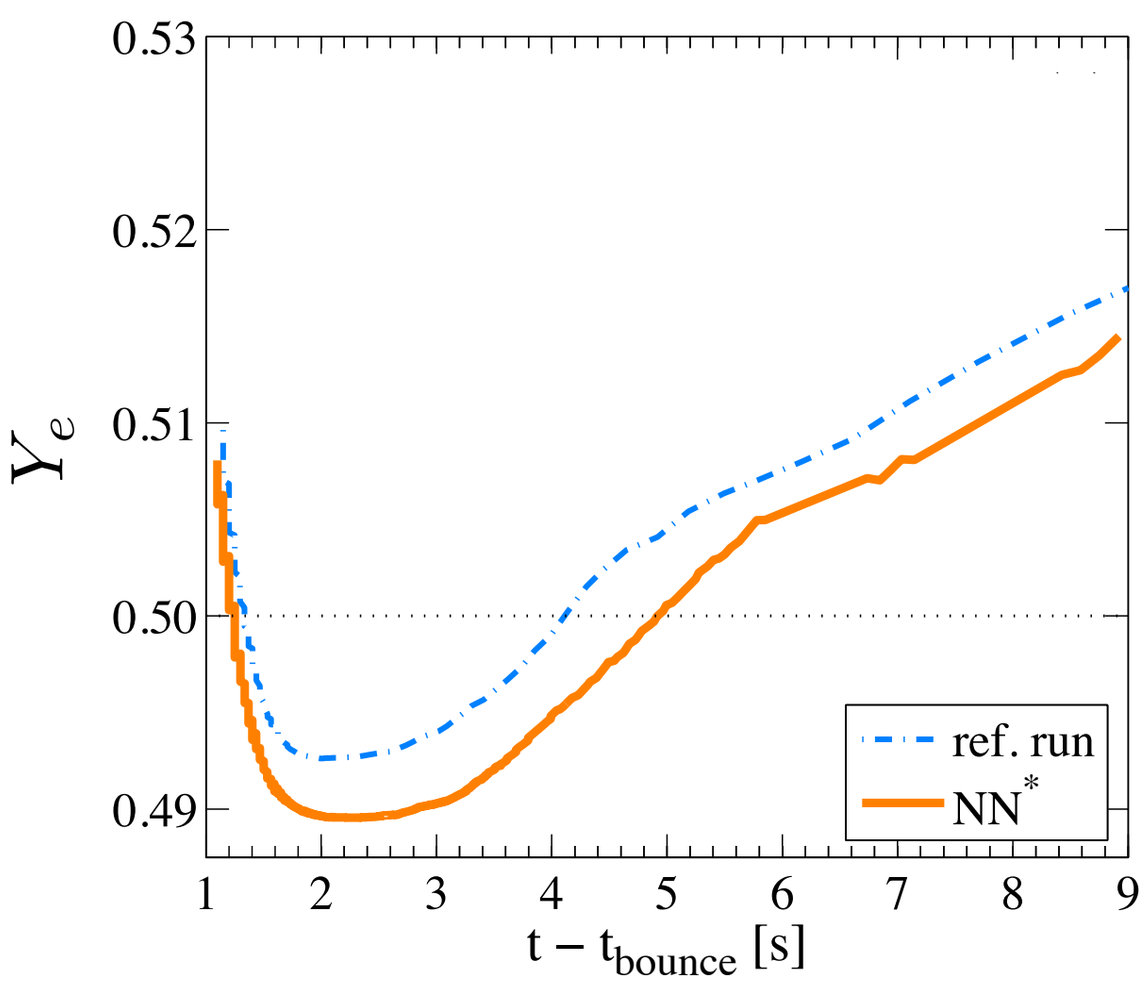
Phys. Rev. D94, 083009 (2016)
Astron. Astrophys. 593, A103 (2016)

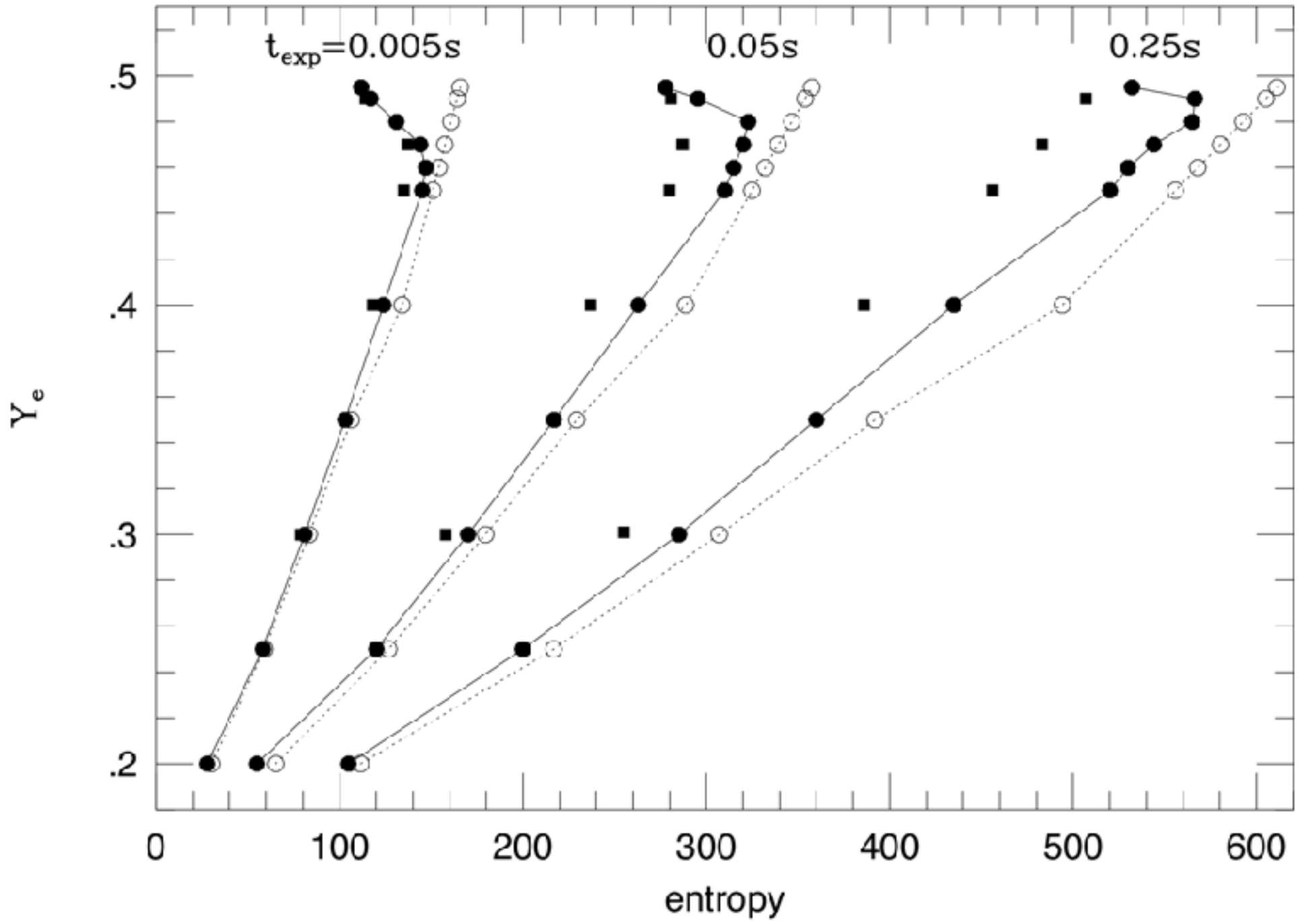


Astron. Astrophys. 593, A103 (2016)

$$M_{ZAMS} = 18\ M_\odot$$
$$M_{NS} = 1.5\ M_\odot$$



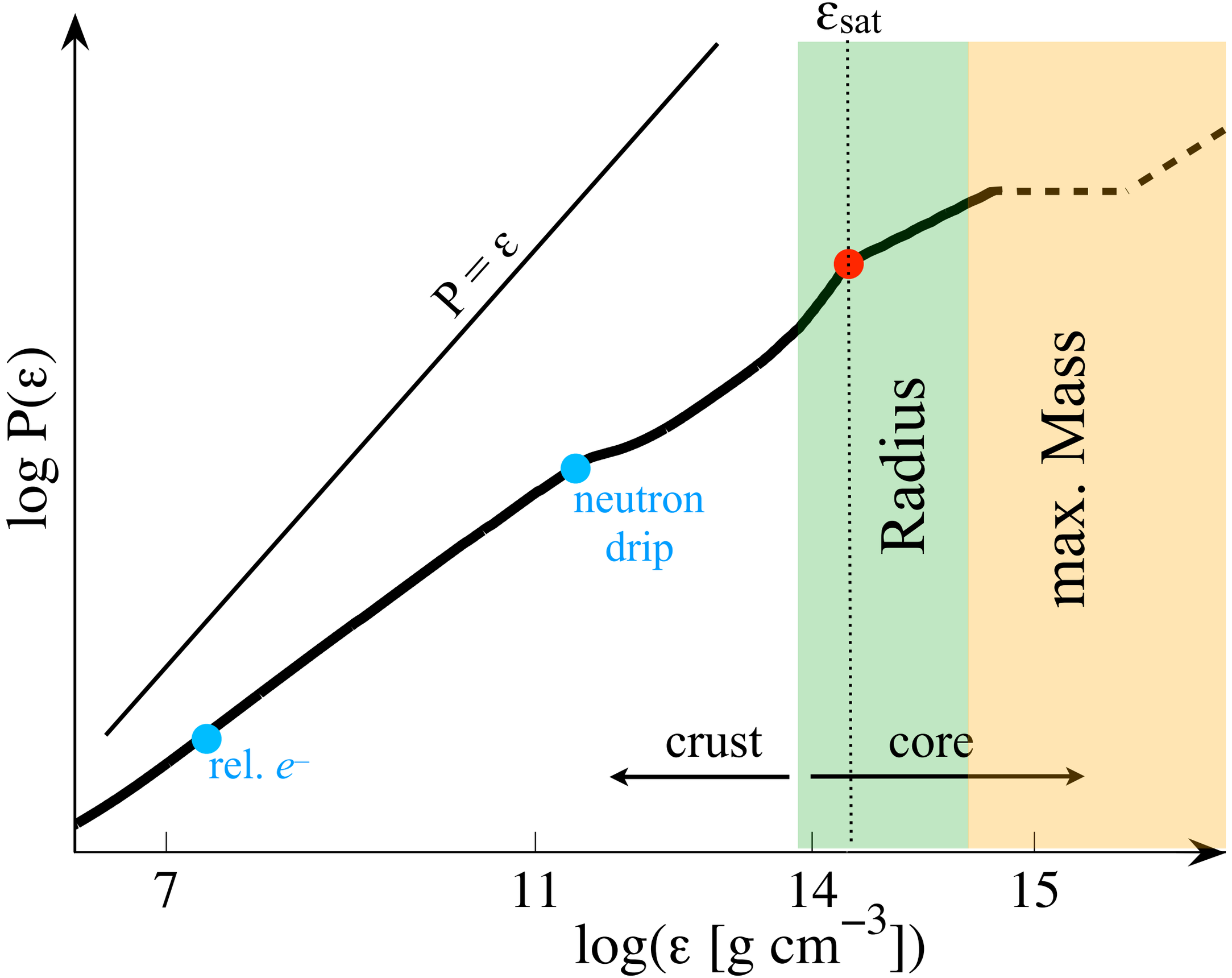


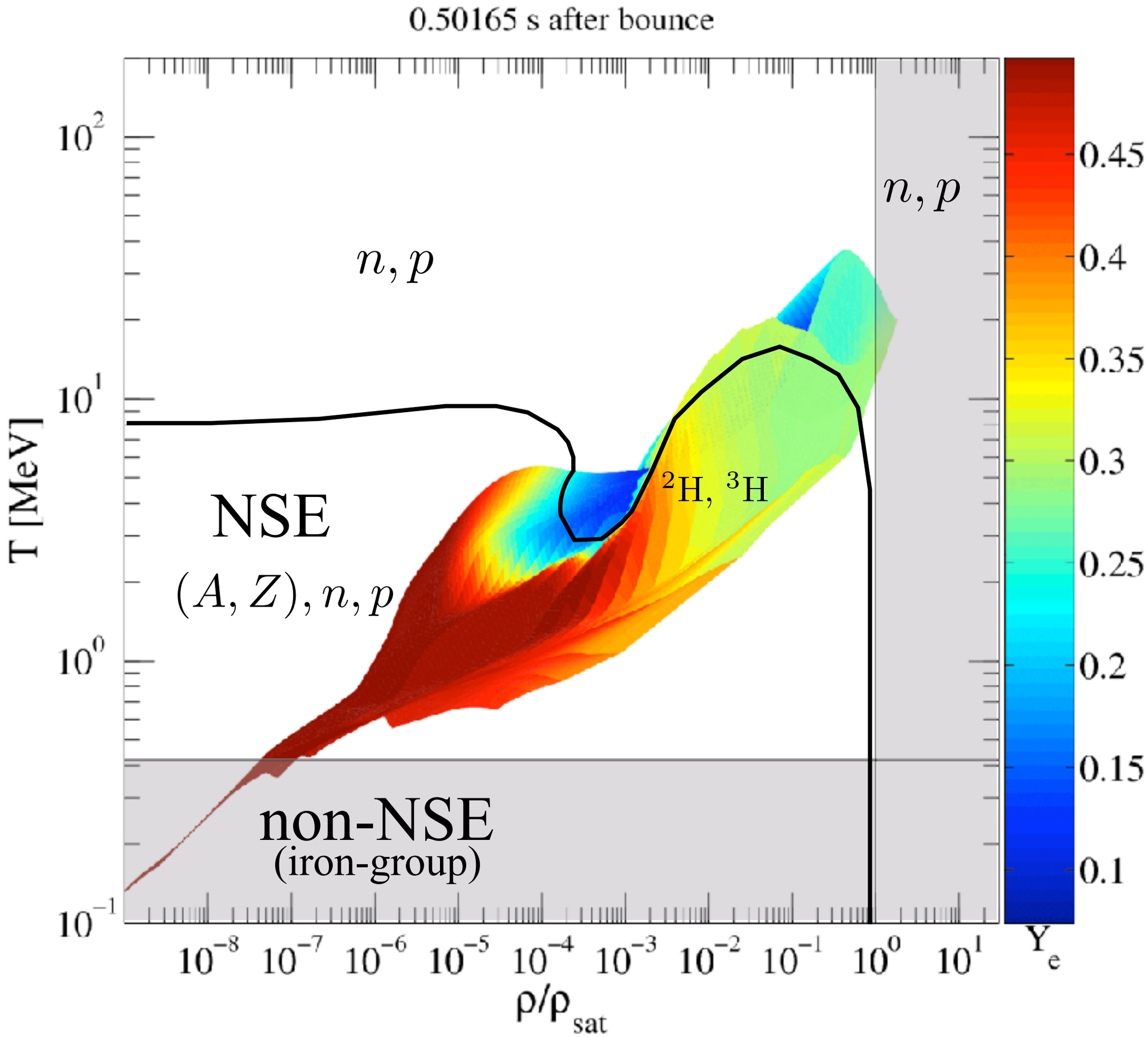


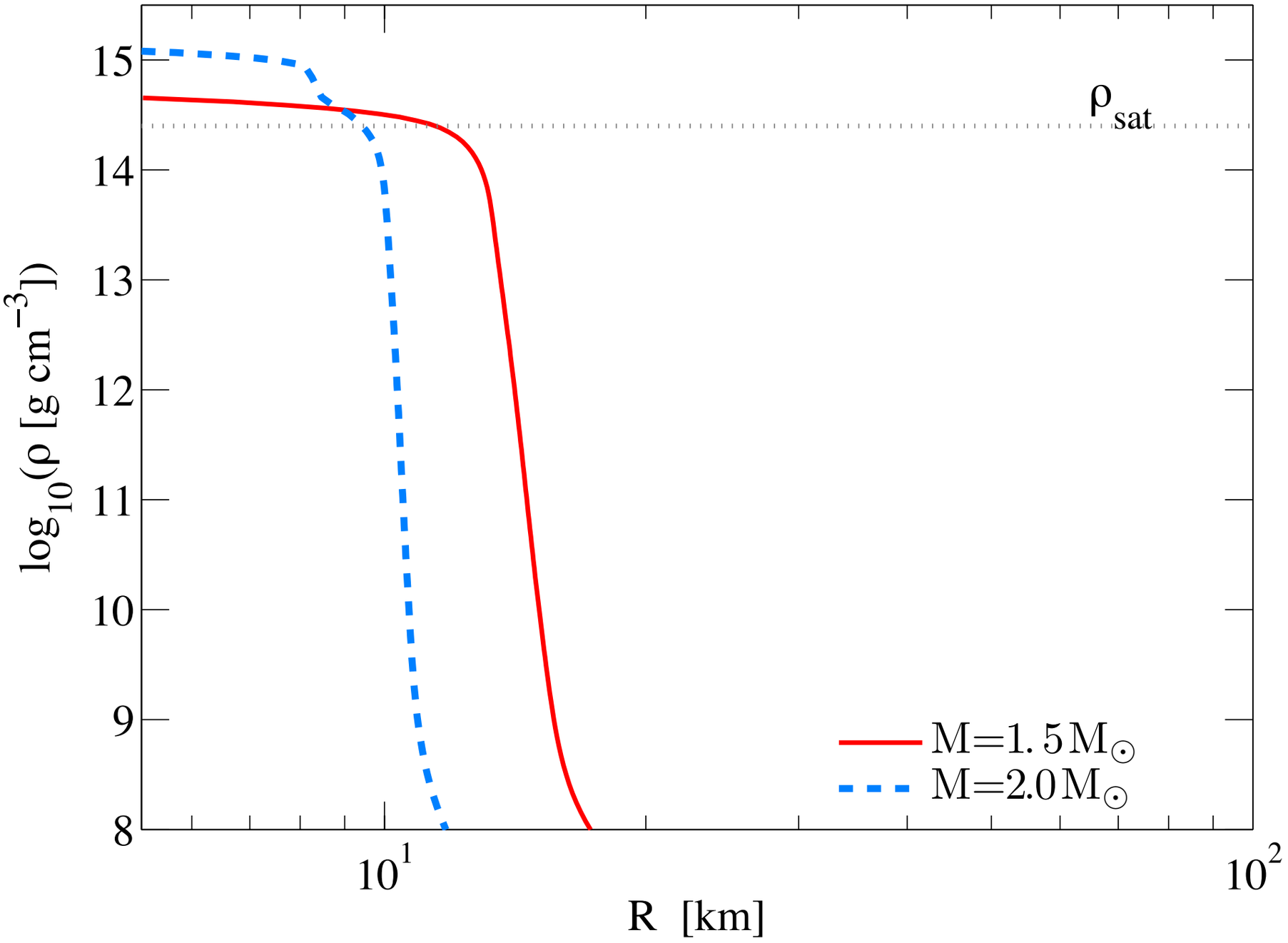
$$S \propto 50 \left(\frac{m_B}{938\ \mathrm{MeV}}\right)\left(\frac{1\ \mathrm{MeV}}{T}\right)\left(\frac{M}{1.5\ \mathrm{M}_\odot}\right)\left(\frac{40\ \mathrm{km}}{R}\right)$$

$$S \propto 100 \left(\frac{m_B}{938\ \mathrm{MeV}}\right)\left(\frac{1\ \mathrm{MeV}}{T}\right)\left(\frac{M}{2.0\ \mathrm{M}_\odot}\right)\left(\frac{27\ \mathrm{km}}{R}\right)$$

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




0.50165 s after bounce
10^2
10^1
10^0
10^{-1}
T [MeV]
n, p
NSE
$(A, Z), n, p$
^{2}H, ^{3}H
n, p
non-NSE
(iron-group)
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



$$S \propto 50 \left(\frac{m_B}{938\ \mathrm{MeV}}\right) \left(\frac{1\ \mathrm{MeV}}{T}\right) \left(\frac{M}{1.5\ \mathrm{M}_\odot}\right) \left(\frac{40\ \mathrm{km}}{R}\right)$$

$$S \propto 100 \left(\frac{m_B}{938\ \mathrm{MeV}}\right) \left(\frac{1\ \mathrm{MeV}}{T}\right) \left(\frac{M}{2.0\ \mathrm{M}_\odot}\right) \left(\frac{27\ \mathrm{km}}{R}\right)$$

$T = 0$, β–eq.

hadron

hybrid

PSR J0740+6620

GW170817

$M\,[M_\odot]$

Radius [km]

P [MeV fm^{-3}]

nucleons/ hadrons

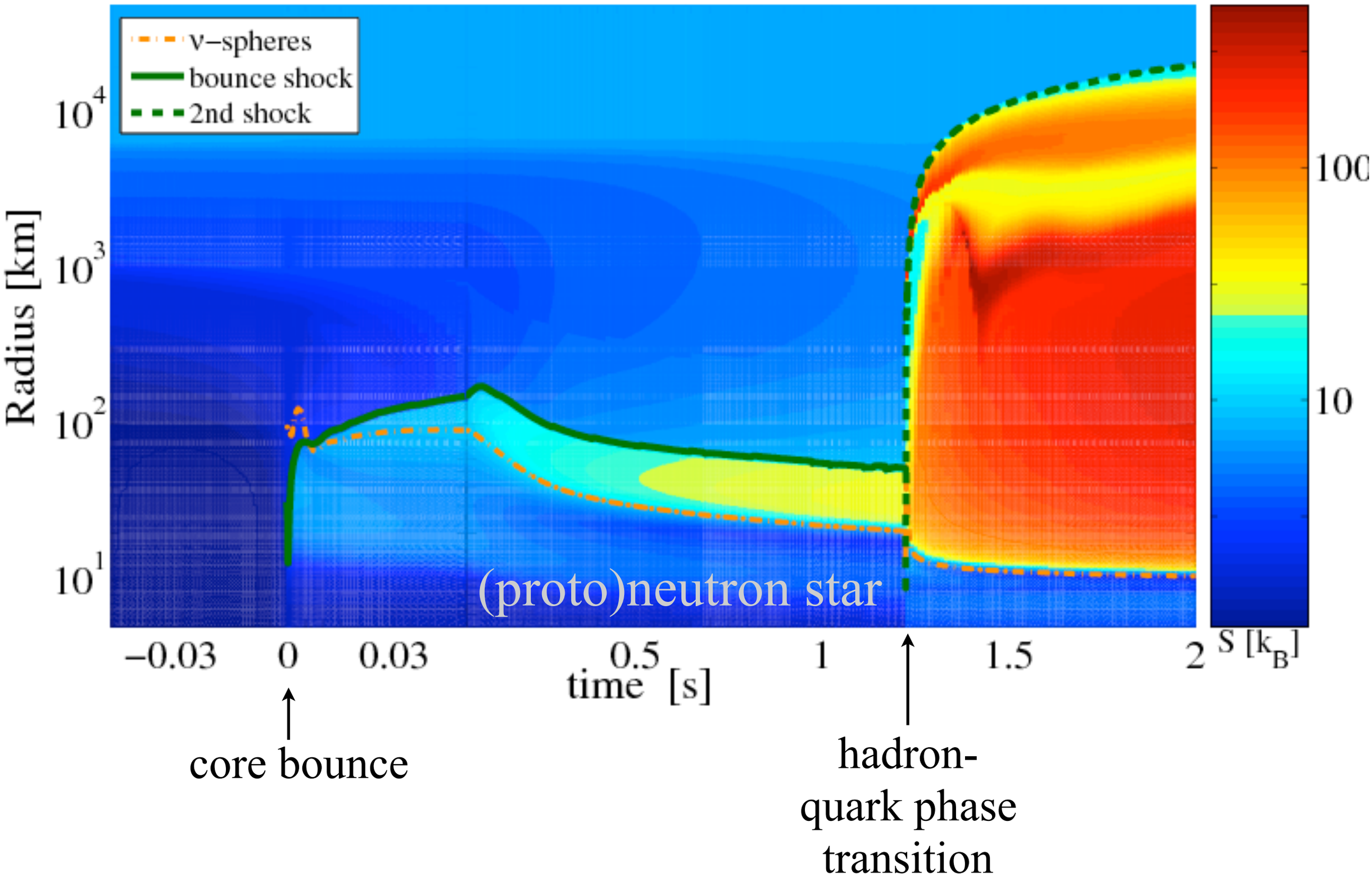
mixed phase

quarks

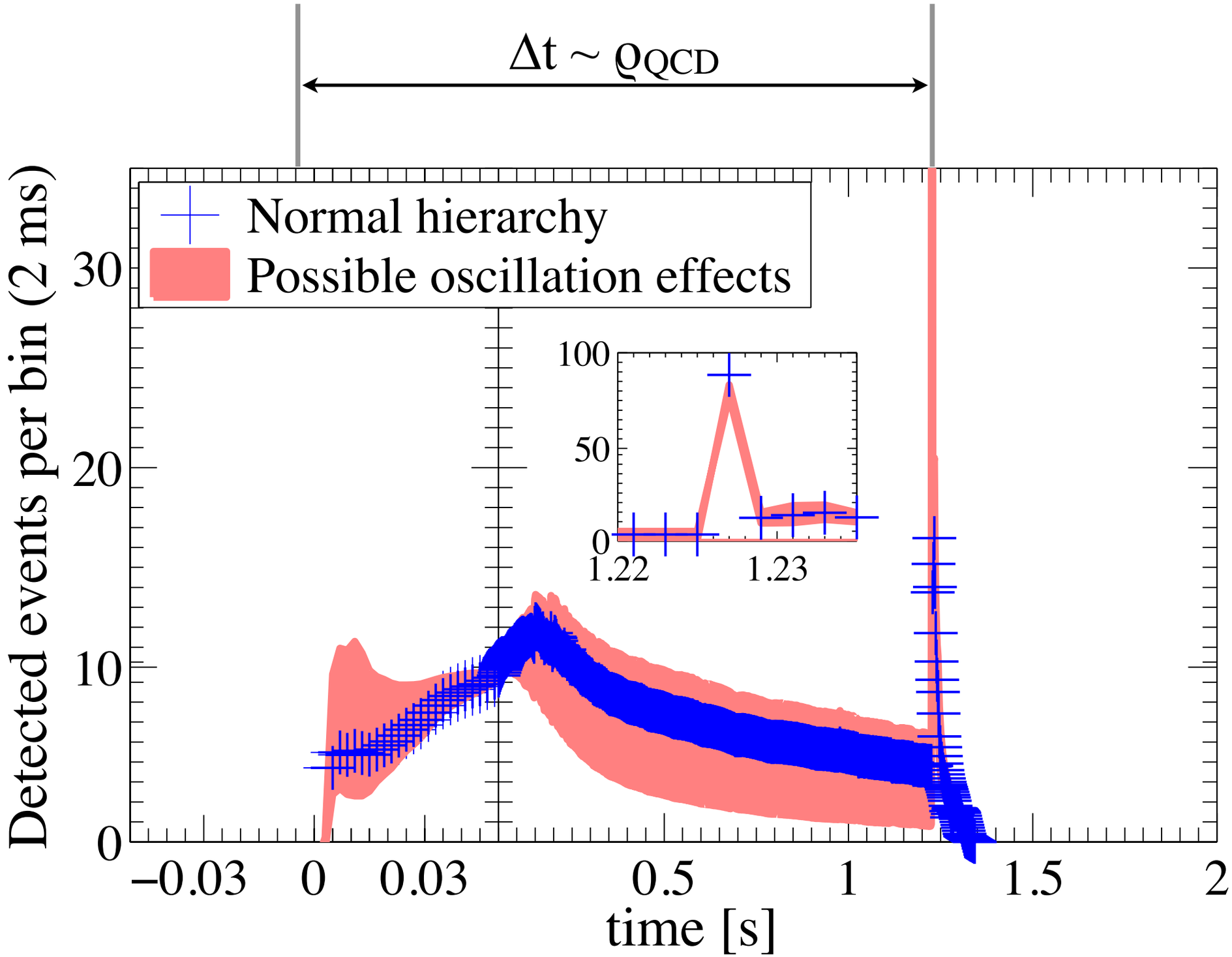
ρ/ρ_{sat}

Nature Astron. 2, 980 (2018)

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



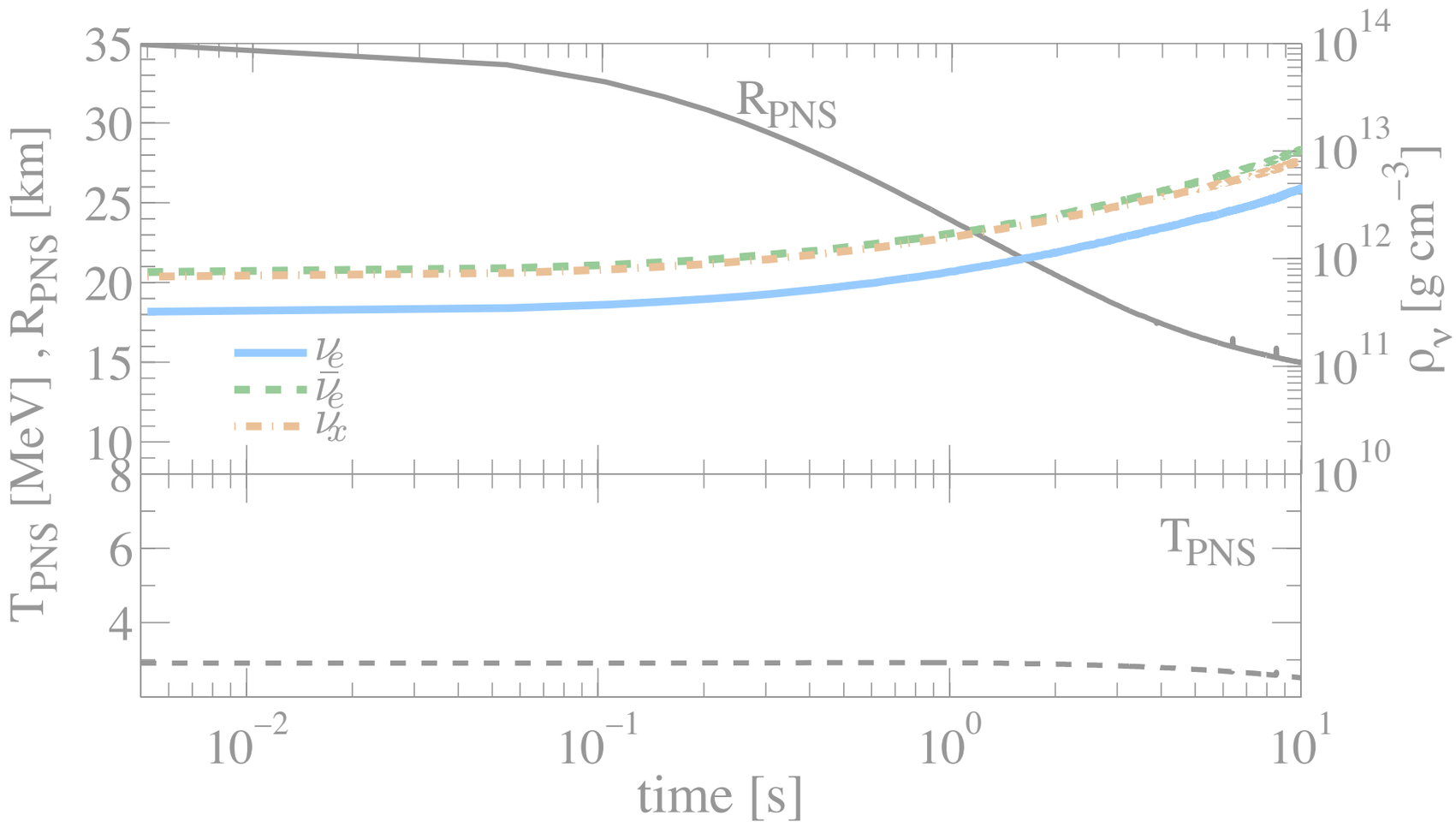
ν – signal @ Super-Kamiokande (d ~ 10 kpc)



Nature Astron. **2**, 980 (2018)

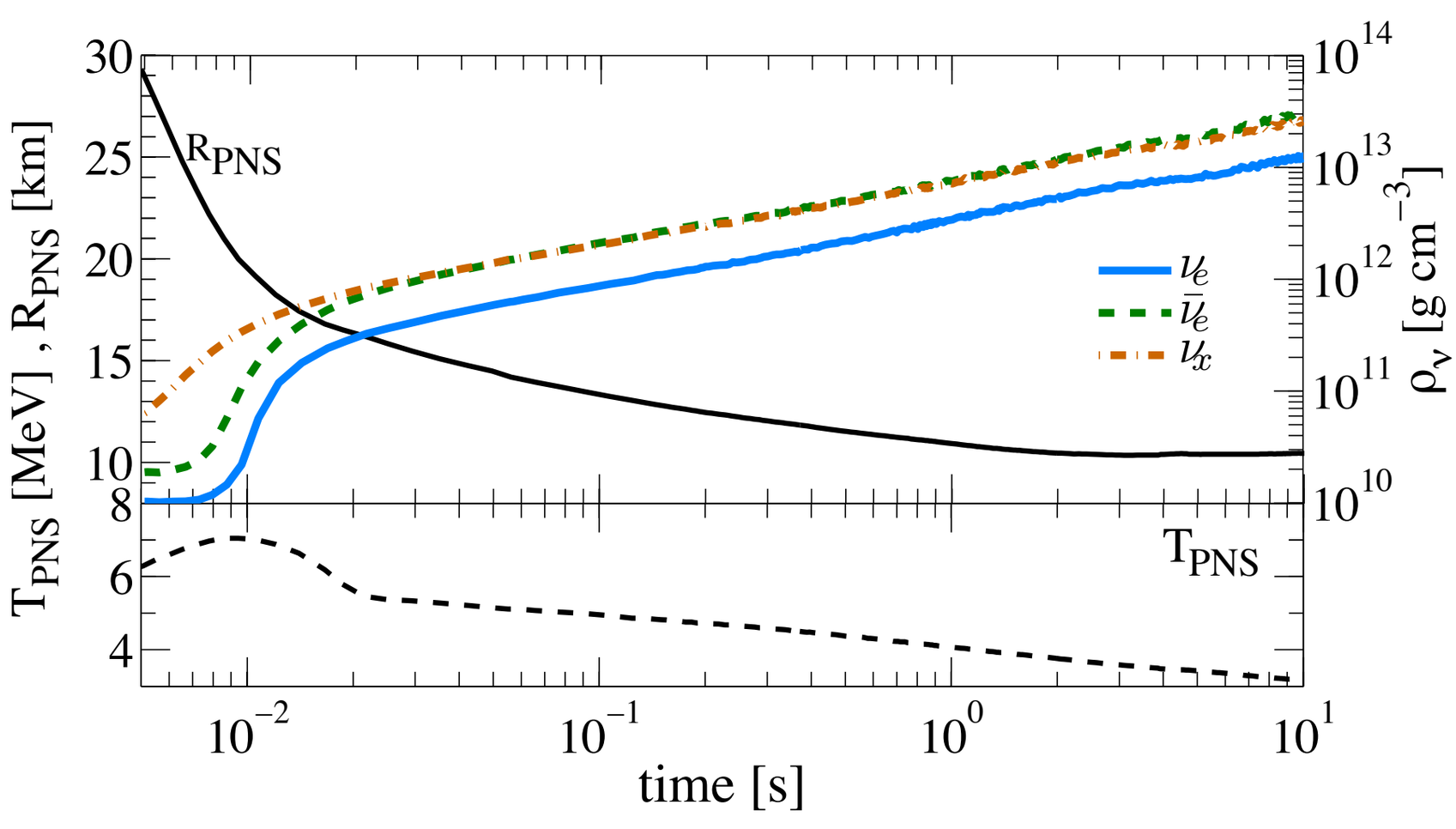
$M_{ZAMS} = 18\ M_\odot$

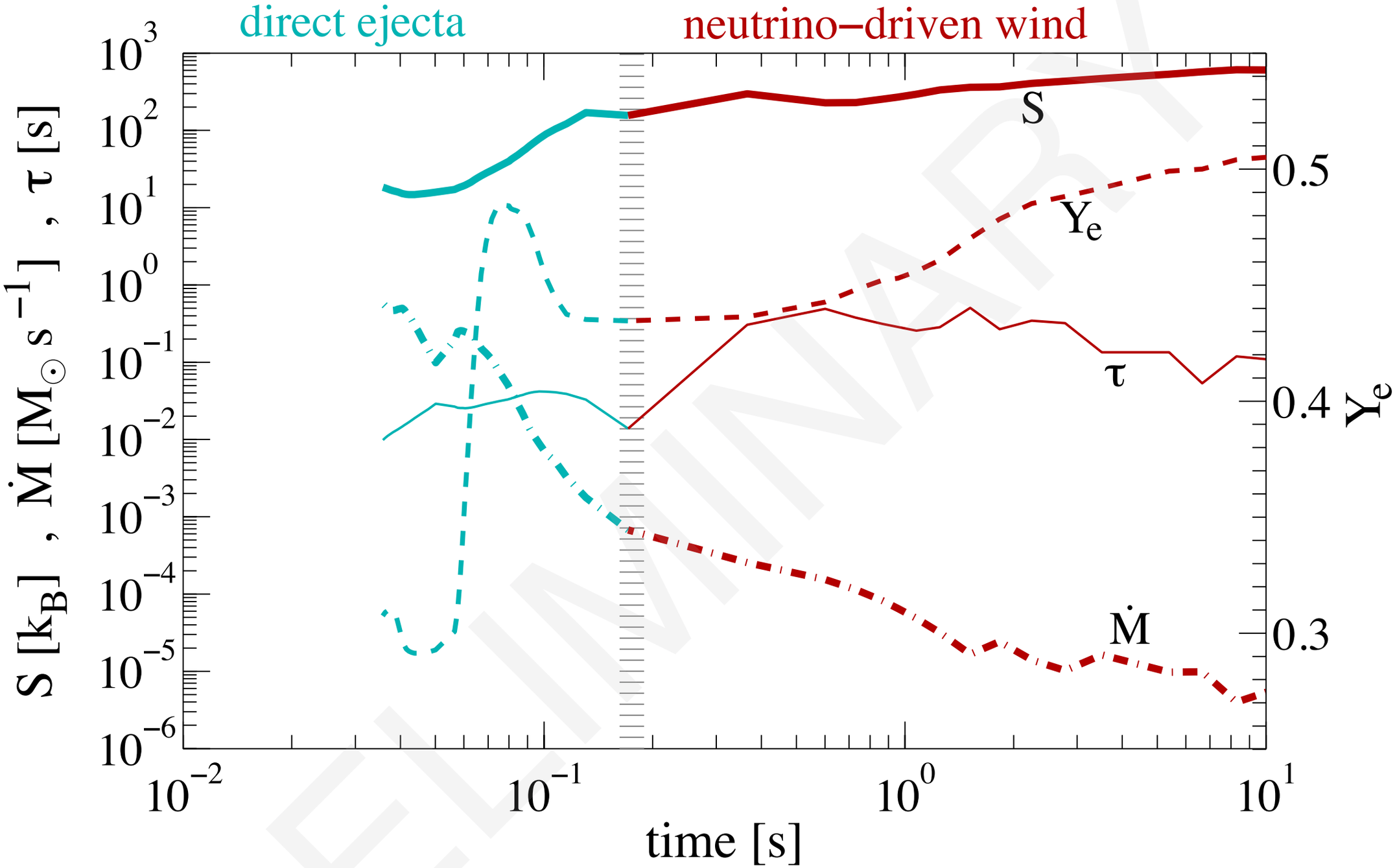
$M_{NS} = 1.5\ M_\odot$



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

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

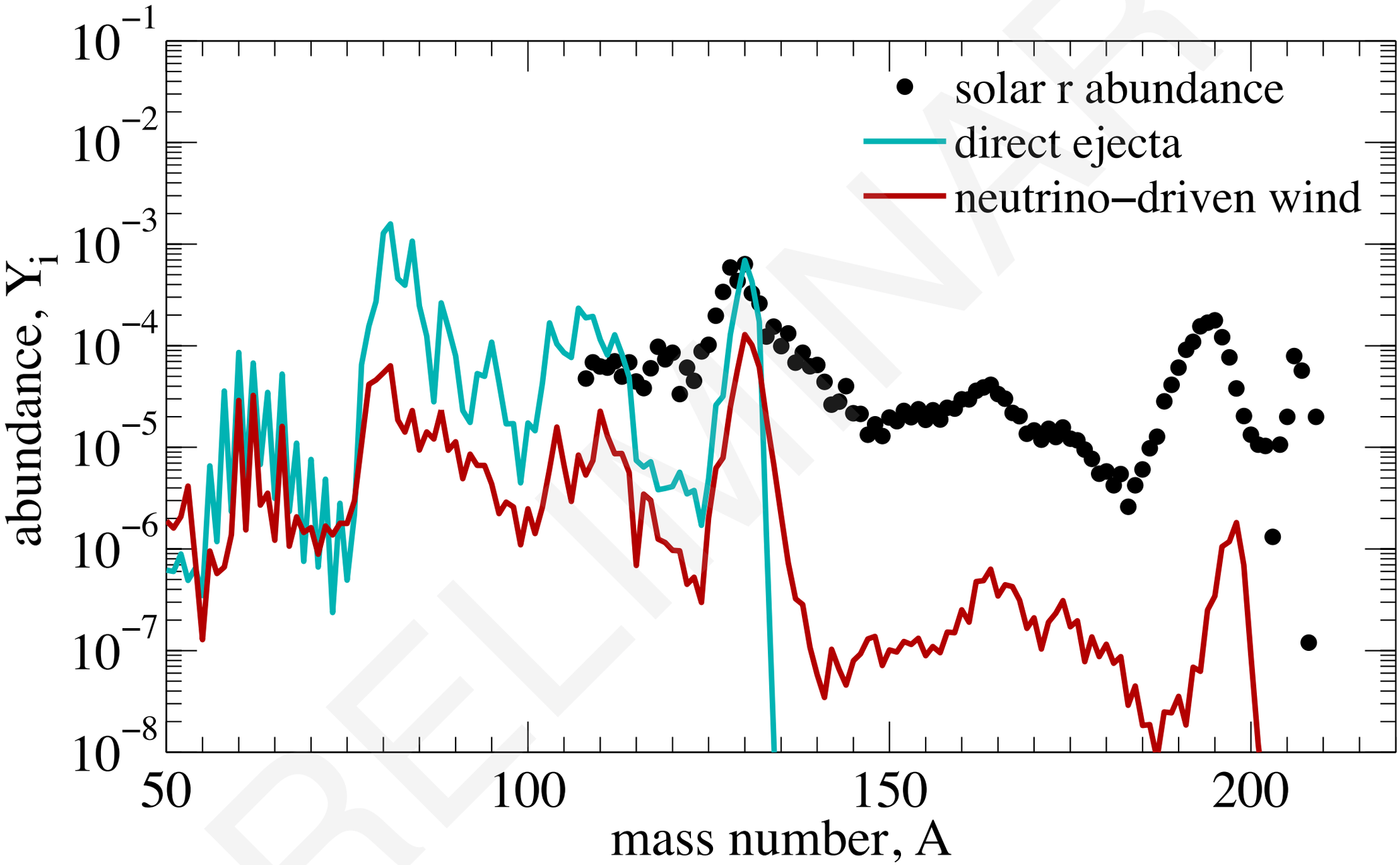




‘normal’ *ν*-driven wind

$$S \simeq 50\ k_B$$

$$Y_e \simeq 0.49 - 0.55$$



Summary

$$e^- + (A,Z) \rightleftarrows (A,Z-1) + \nu_e$$
$$\nu_\alpha + (A,Z) \rightleftarrows (A,Z) + \nu_\alpha$$
$$(A,Z)^* \rightleftarrows (A,Z) + \nu_\alpha + \bar{\nu}_\alpha$$

} nuclear structure

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

} $U_n - U_p \propto S(\rho)$
inelastic contributions
weak magnetism
$g_A \longrightarrow g_A - g_s$; $g_s \sim 0.15$

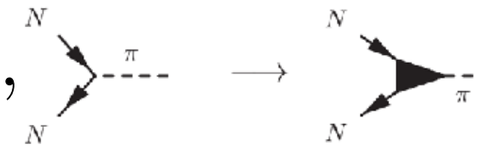
$$\nu_\alpha + N^* \rightleftarrows N^* + \nu_\alpha$$

+ nuclear correlations, $S_A < 1$

$$\nu_\alpha + e^\pm \rightleftarrows e^\pm + \nu_\alpha$$
$$\nu_\alpha + \nu_\beta \rightleftarrows \nu_\beta + \nu_\alpha$$

$$e^- + e^+ \rightleftarrows \nu_\alpha + \bar{\nu}_\alpha$$
$$NN \rightleftarrows NN + \nu_\alpha + \bar{\nu}_\alpha$$
$$\nu_\alpha + \bar{\nu}_\alpha \rightleftarrows \nu_\beta + \bar{\nu}_\beta$$

} $g_A^*(\rho)$,



$$\mu^- + p \rightleftarrows n + \nu_\mu$$
$$\mu^- \rightleftarrows e^- + \nu_\mu + \bar{\nu}_e$$
$$\nu_e + \mu^- \rightleftarrows e^- + \nu_\mu$$

Phys. Rev. Lett. 119, 242702 (2017)

Astrophys. J. 853, 170 (2018)

1	$\nu_e\, {}^2\mathrm{H} \rightleftarrows p\, p\, e^-$	charged-current absorption
2	$\bar{\nu}_e\, {}^2\mathrm{H} \rightleftarrows n\, n\, e^+$	
3	$\nu_e\, n\, n \rightleftarrows {}^2\mathrm{H}\, e^-$	
4	$\bar{\nu}_e\, p\, p \rightleftarrows {}^2\mathrm{H}\, e^+$	
5	$\bar{\nu}_e\, e^-\, {}^2\mathrm{H} \rightleftarrows n\, n$	
6	$\nu_e\, e^+\, {}^2\mathrm{H} \rightleftarrows p\, p$	
7	$\nu_e\, {}^3\mathrm{H} \rightleftarrows n\, p\, p\, e^-$	
8	$\bar{\nu}_e\, {}^3\mathrm{H} \rightleftarrows n\, n\, n\, e^+$	
9	$\nu_e\, {}^3\mathrm{H} \rightleftarrows {}^3\mathrm{He}\, e^-$	
10	$\bar{\nu}_e\, {}^3\mathrm{He} \rightleftarrows {}^3\mathrm{H}\, e^+$	
11	$\nu\, {}^2\mathrm{H} \rightleftarrows p\, n\, \nu$	scattering
12	$\nu\, {}^2\mathrm{H} \rightleftarrows {}^2\mathrm{H}\, \nu$	
13	$\nu\, {}^3\mathrm{H} \rightleftarrows {}^3\mathrm{H}\, \nu$	
14	$\nu\, {}^3\mathrm{He} \rightleftarrows {}^3\mathrm{He}\, \nu$	

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

Explosions of massive stars $\sim 50\ \mathrm{M}_\odot$

<u>Remnants</u>: massive neutron stars $\sim 2\ \mathrm{M}_\odot$

Release of 'non-standard' *ν* burst

***r*–process nucleosynthesis up to $A \sim 195$**

Wroclaw Supernova Project

In collaboration with:

A. Bauswein

N. U. Bastian

D. B. Blaschke

K. Kotake

S. Typel

B. Wehmeyer

M. R. Wu