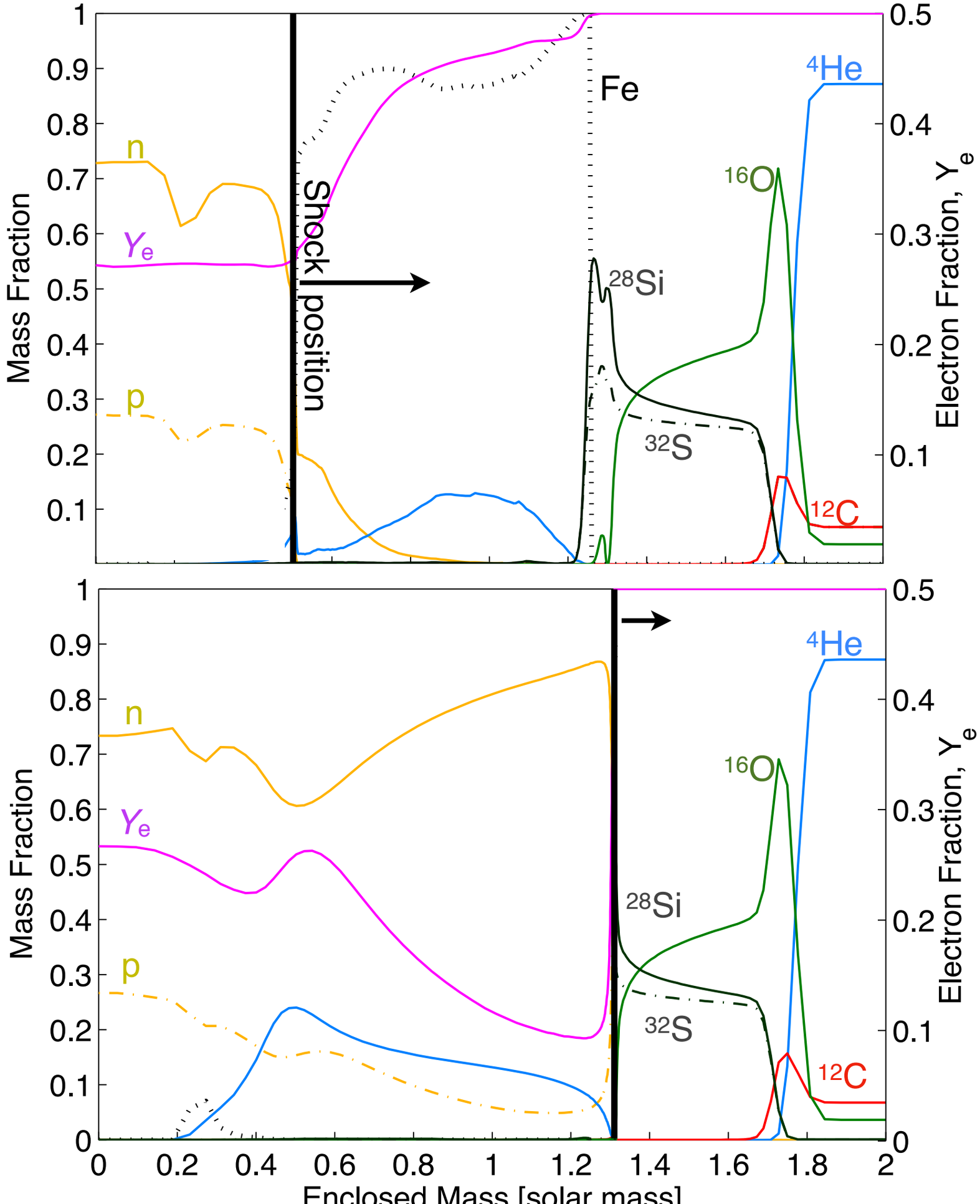
<u>The difficult relationship between:</u>

massive star explosions

and

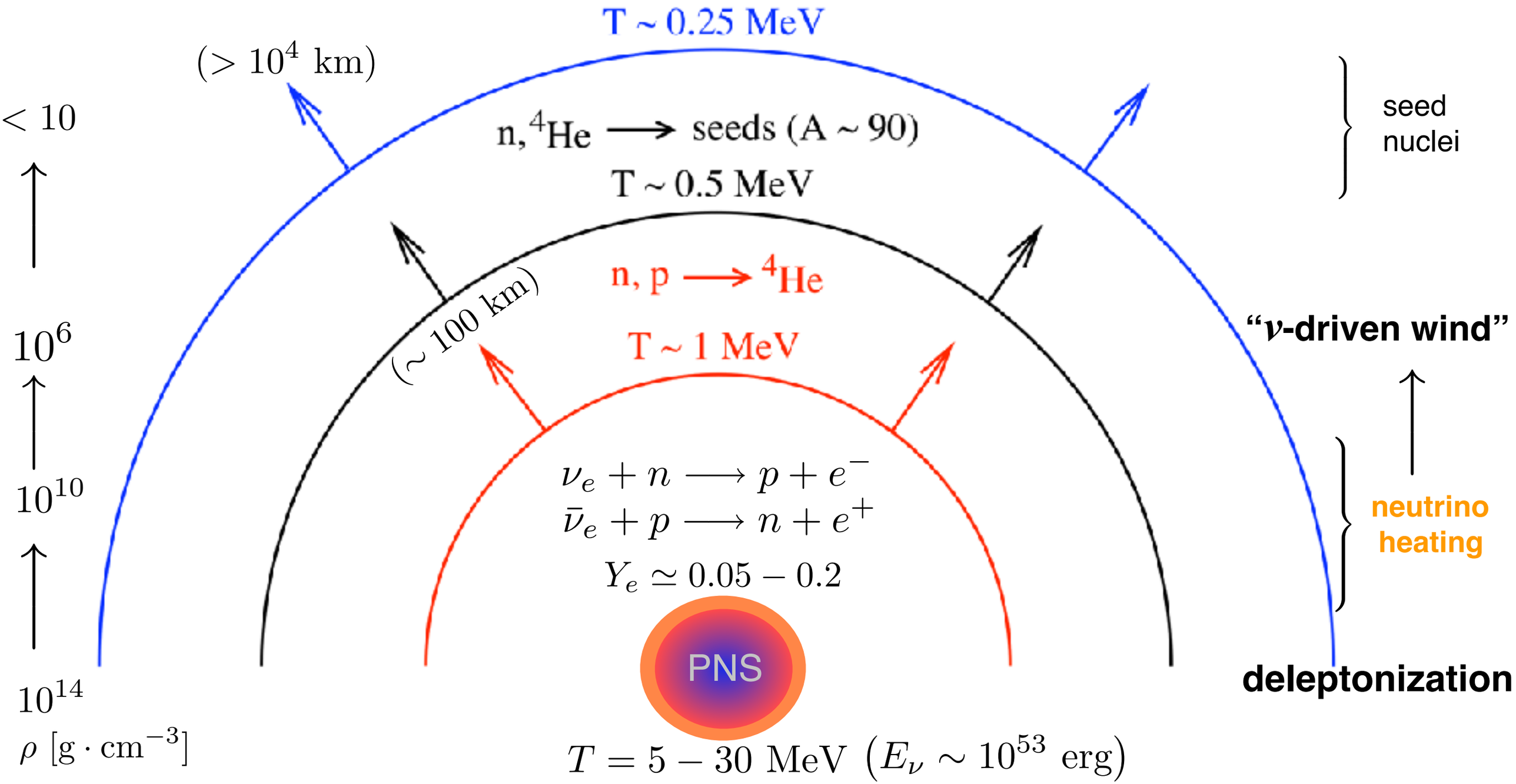
the *r* process


Mass Fraction
Electron Fraction, Y_e
Enclosed Mass [solar mass]
n
Y_e
p
Shock position
Fe
^{4}He
^{16}O
^{28}Si
^{32}S
^{12}C
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0.2
0.4
0.6
0.8
1.2
1.4
1.6
1.8
2

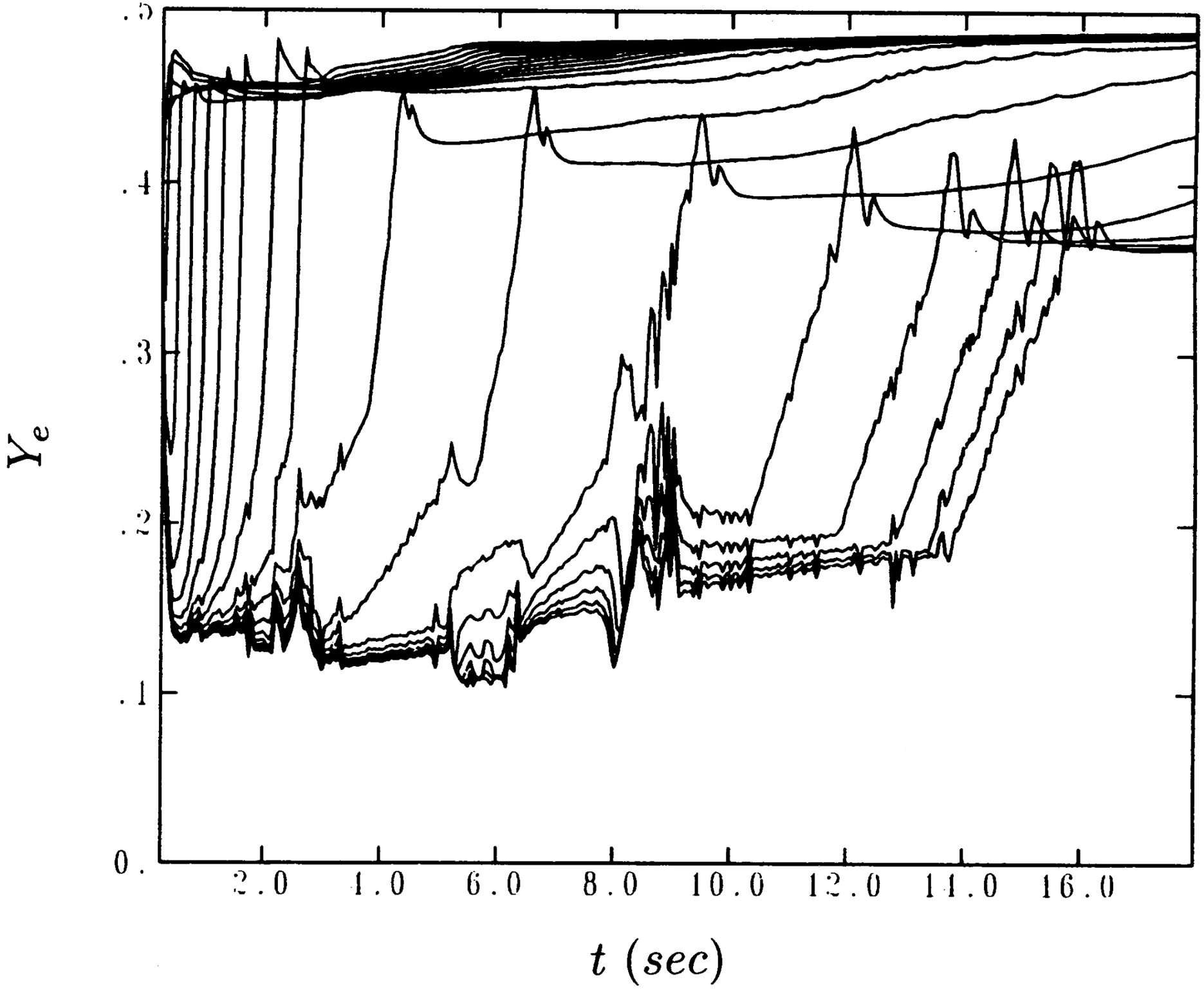
proton rich ($Y_e > 0.5$)
ν*p* process

neutron rich ($Y_e < 0.5$)
neutron-capture process

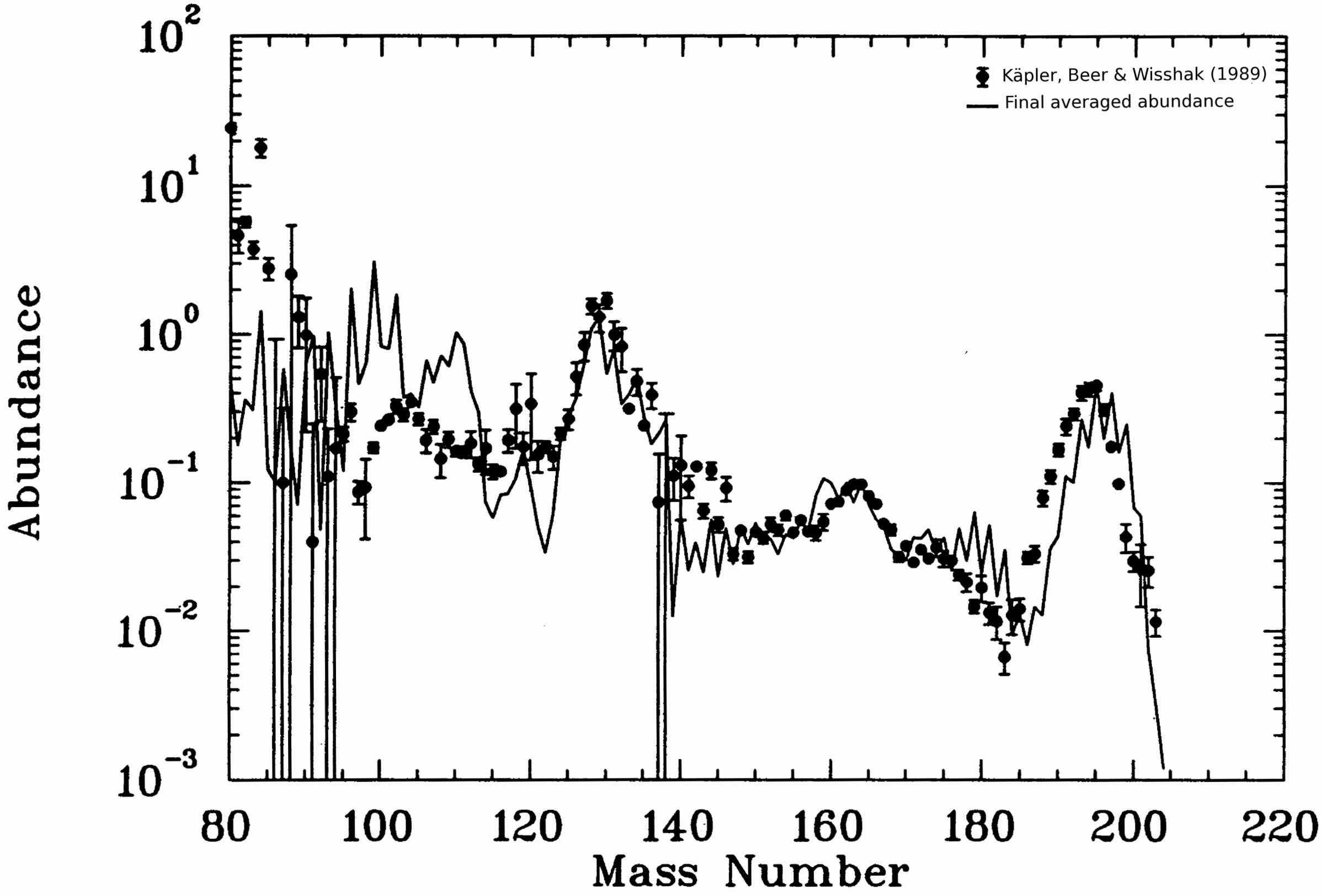
formation of heavy nuclei



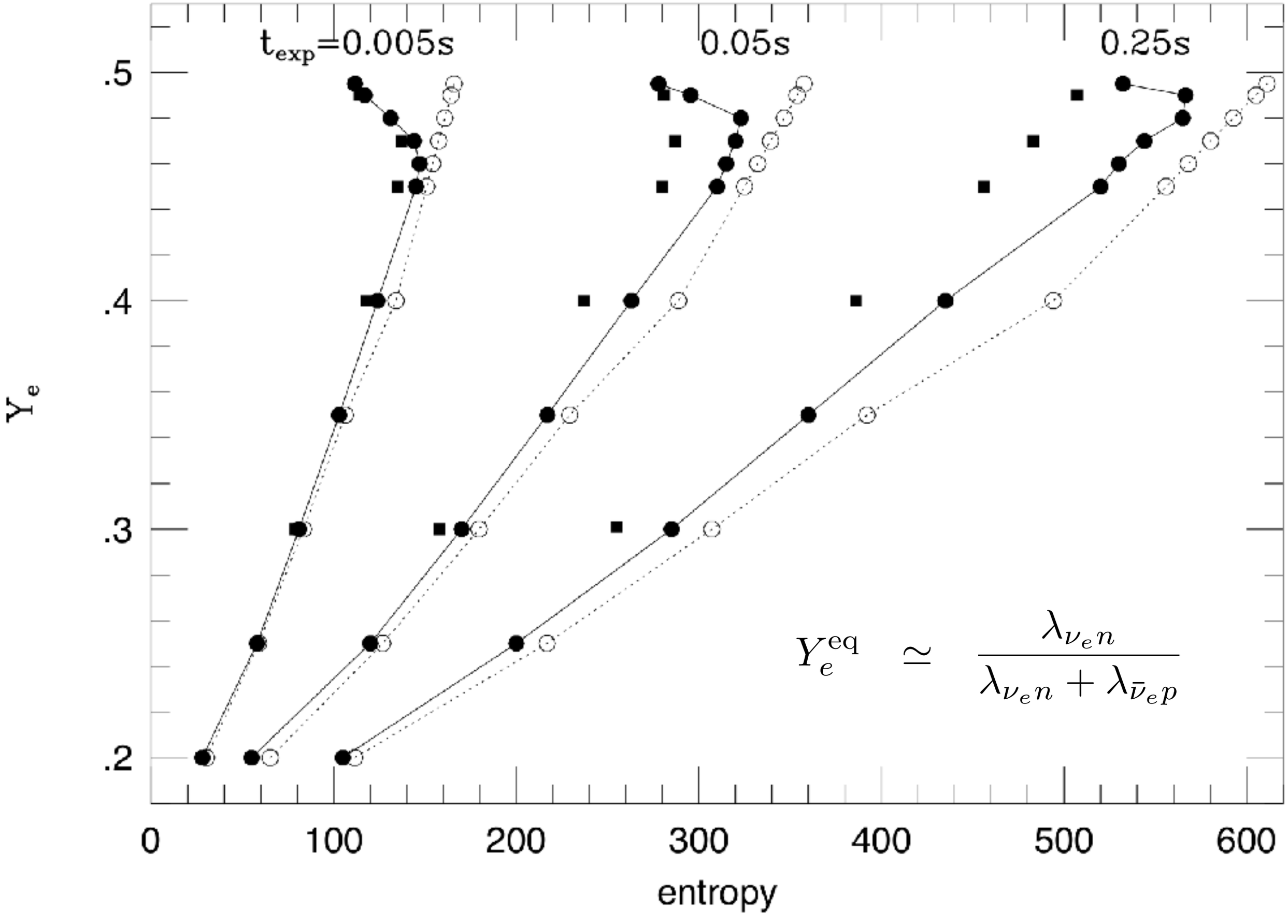
$$S \simeq 100 - 300\ \mathrm{k_B}$$

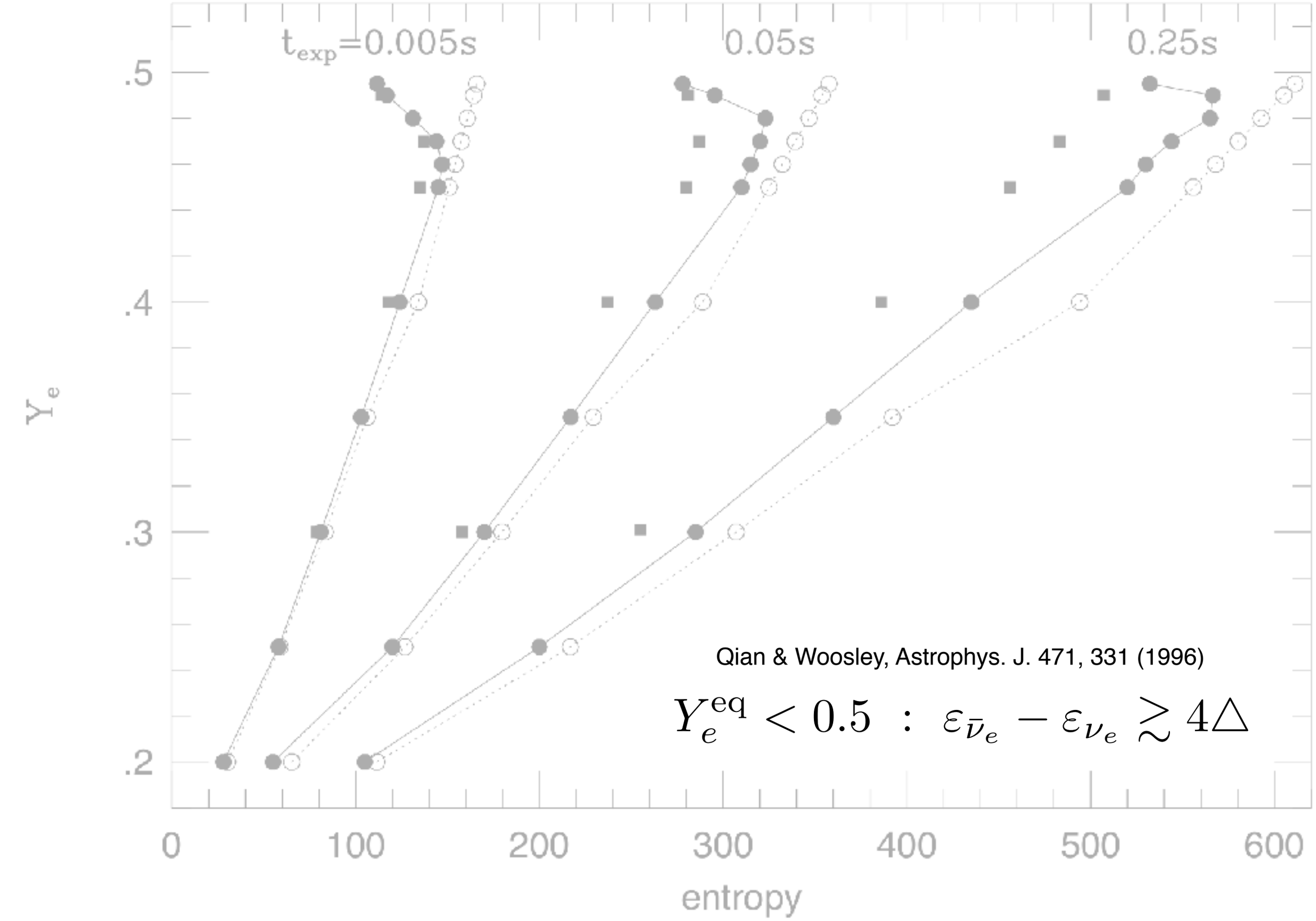


Woosley et al., Astrophys. J., 433, 229 (1994)


Käpler, Beer & Wisshak (1989)
Final averaged abundance
Abundance
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
80
100
120
140
160
180
200
220
Mass Number

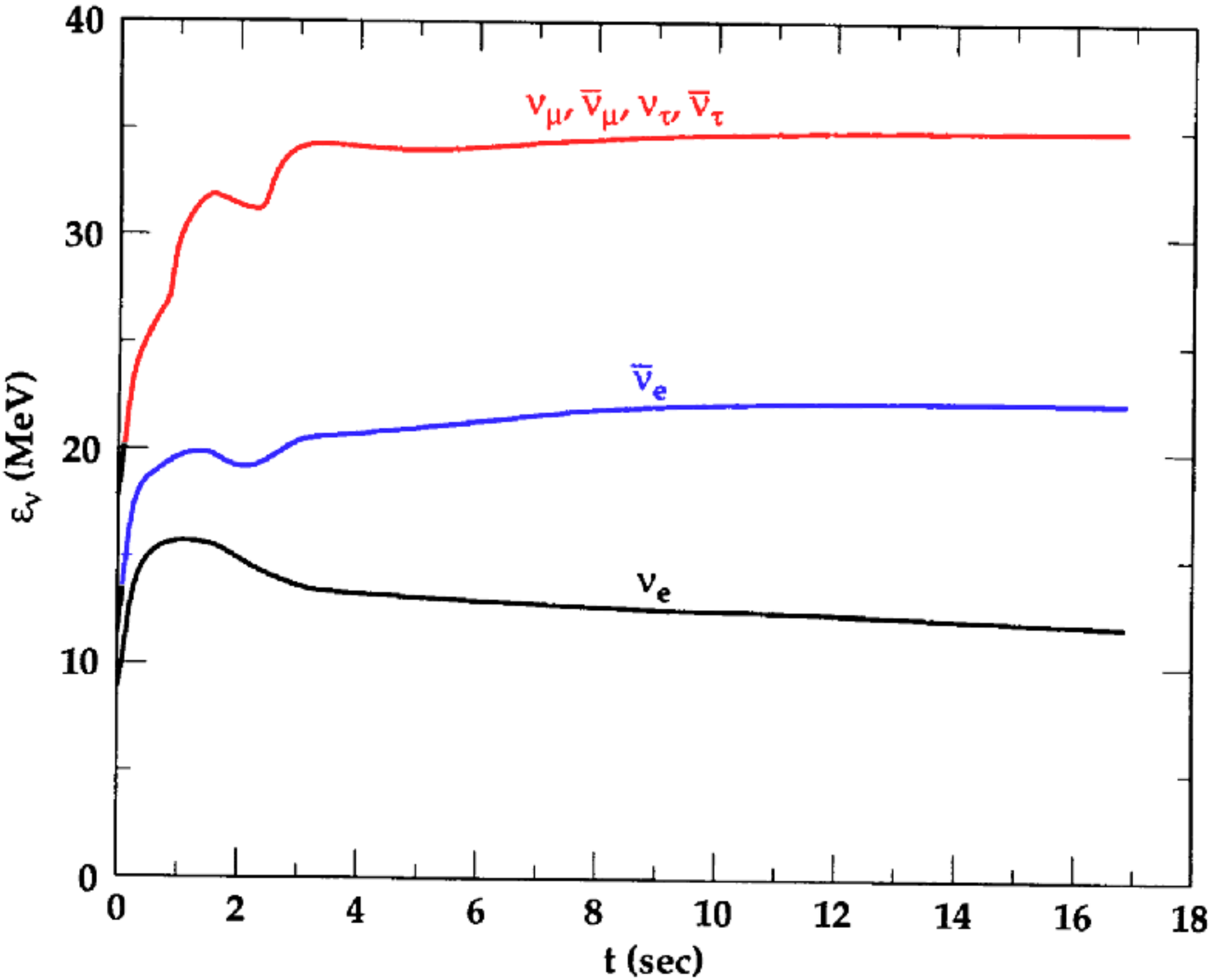
Hoffmann et al., Astrophys. J. 842, 951 (1997)





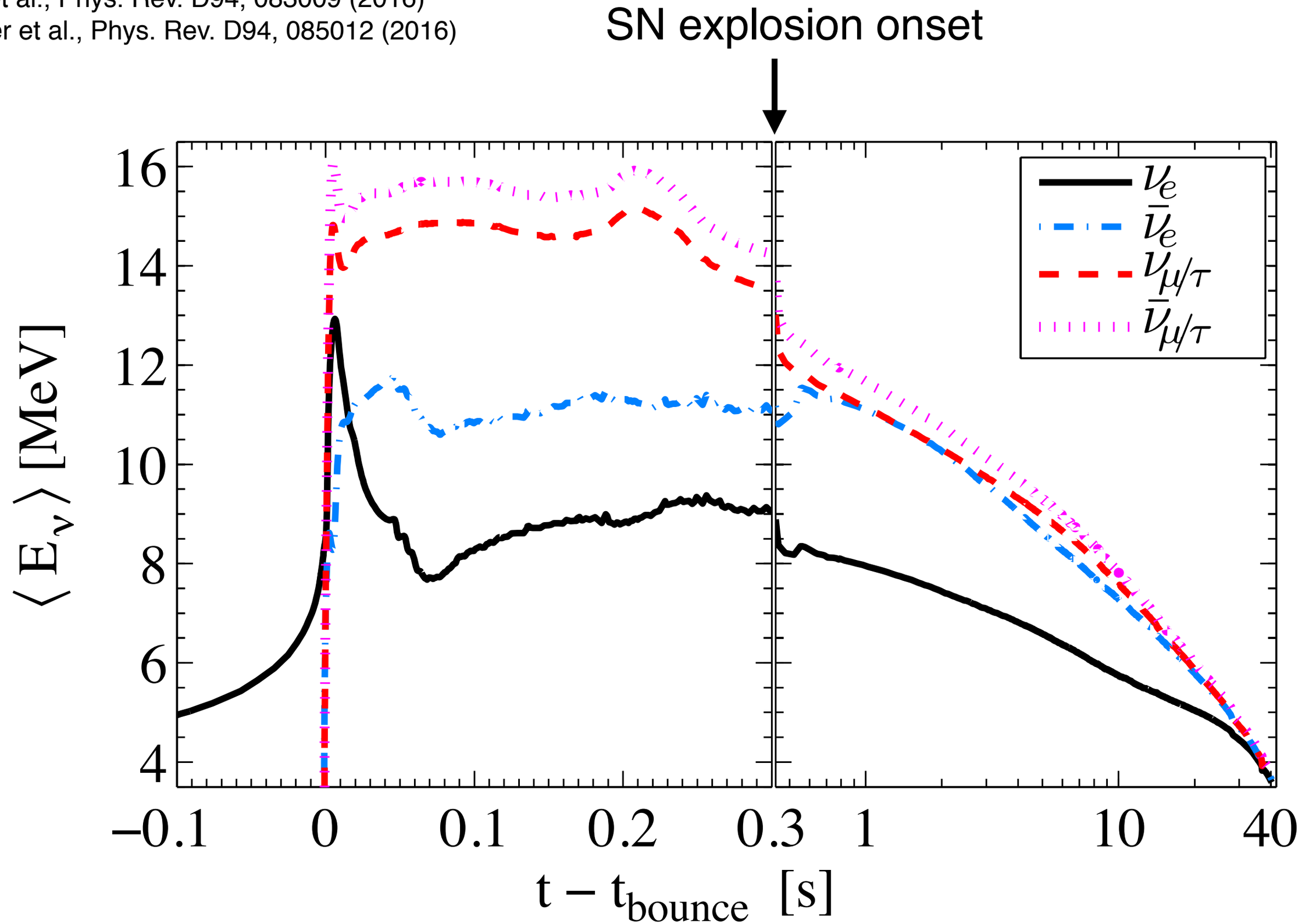
Qian & Woosley, Astrophys. J. 471, 331 (1996)

$$Y_e^{\rm eq} < 0.5 \ : \ \varepsilon_{\bar{\nu}_e} - \varepsilon_{\nu_e} \gtrsim 4\triangle$$



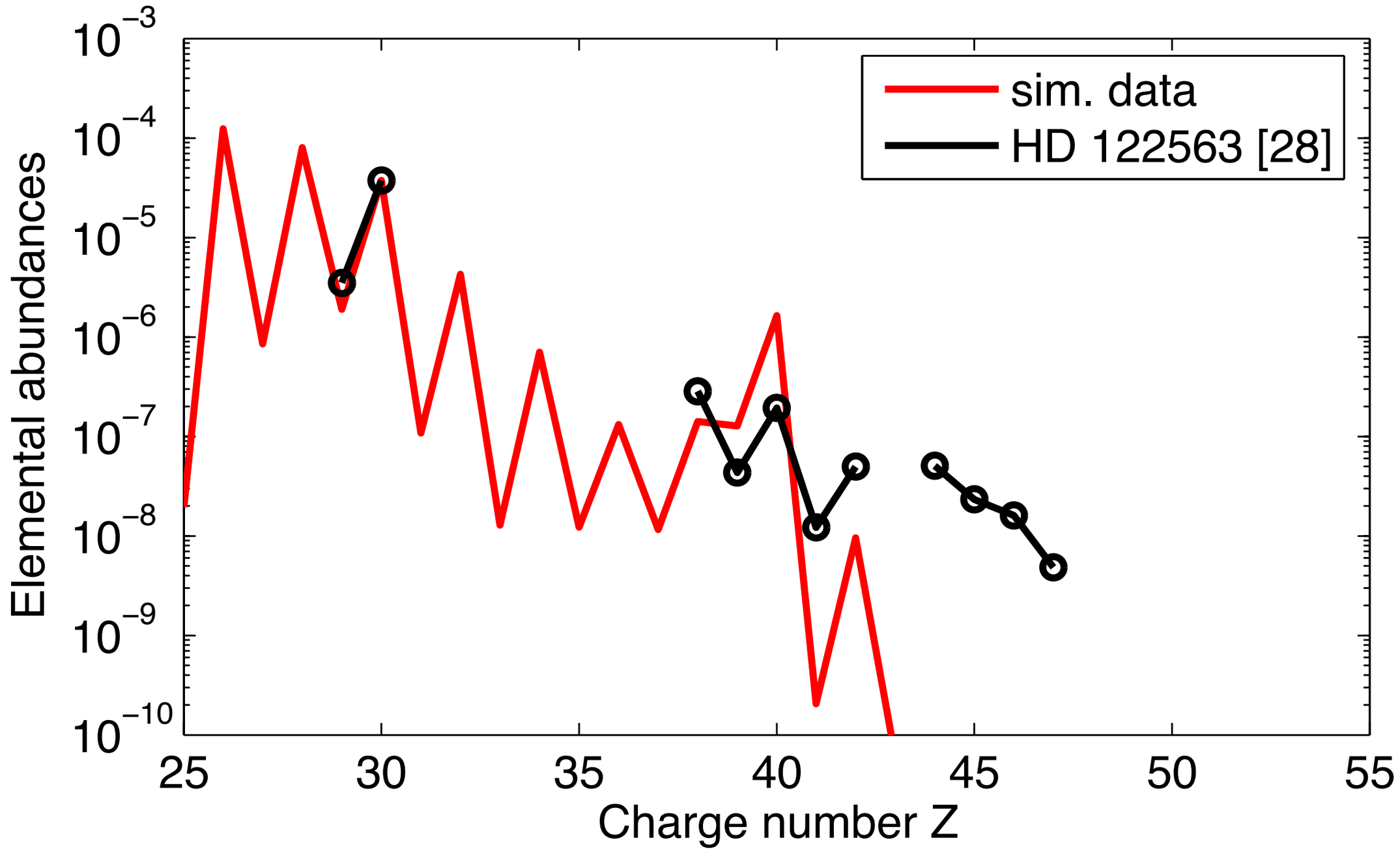
Woosley et al., Astrophys. J. , 433, 229 (1994)

Fischer et al., Astron. Astrophys. 517, A80 (2010)
Hüdepohl et al., Phys. Rev. Lett. 104, 251101 (2010)
Roberts et al., Phys. Rev. D86, 065803 (2012)
Bartl et al., Phys. Rev. D94, 083009 (2016)
Fischer et al., Phys. Rev. D94, 085012 (2016)
. . . .

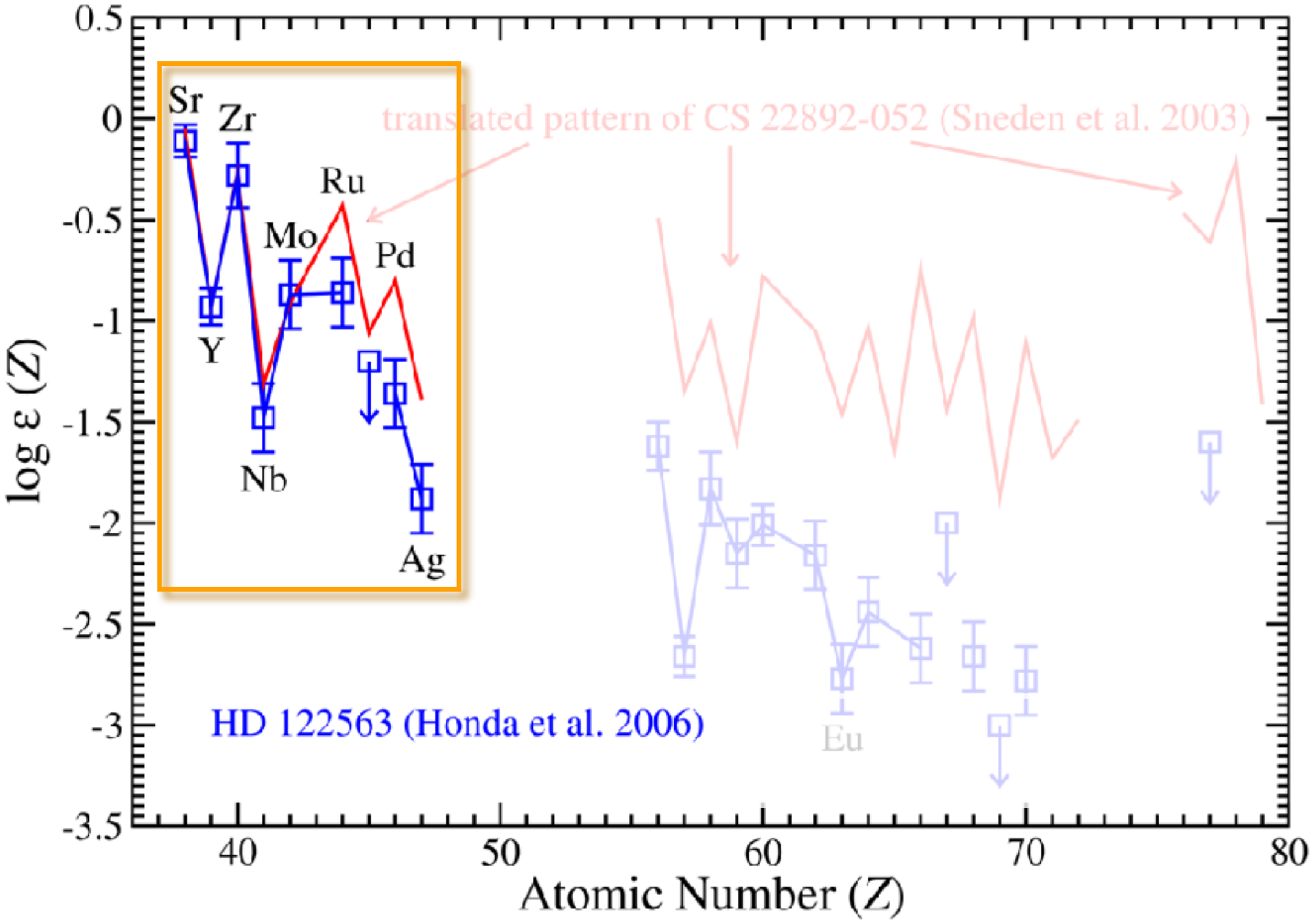


$$Y_e^{\min} \simeq 0.49 \ (t \sim 1.5 - 3 \ \mathrm{s})$$

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



Martinez-Pinedo et al., J. Phys. G41, 044008 (2014)



"Weak component" of the r process

ν_e

$\bar{\nu}_e$

$\nu_{\mu/\tau}$

$1/\lambda_\nu$ [km^{-1}]

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

$\nu_e n \to p e^-$

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

$\nu N \to \nu N$

$\nu e^\pm \to \nu e^\pm$

$\nu\bar{\nu} NN \to NN$

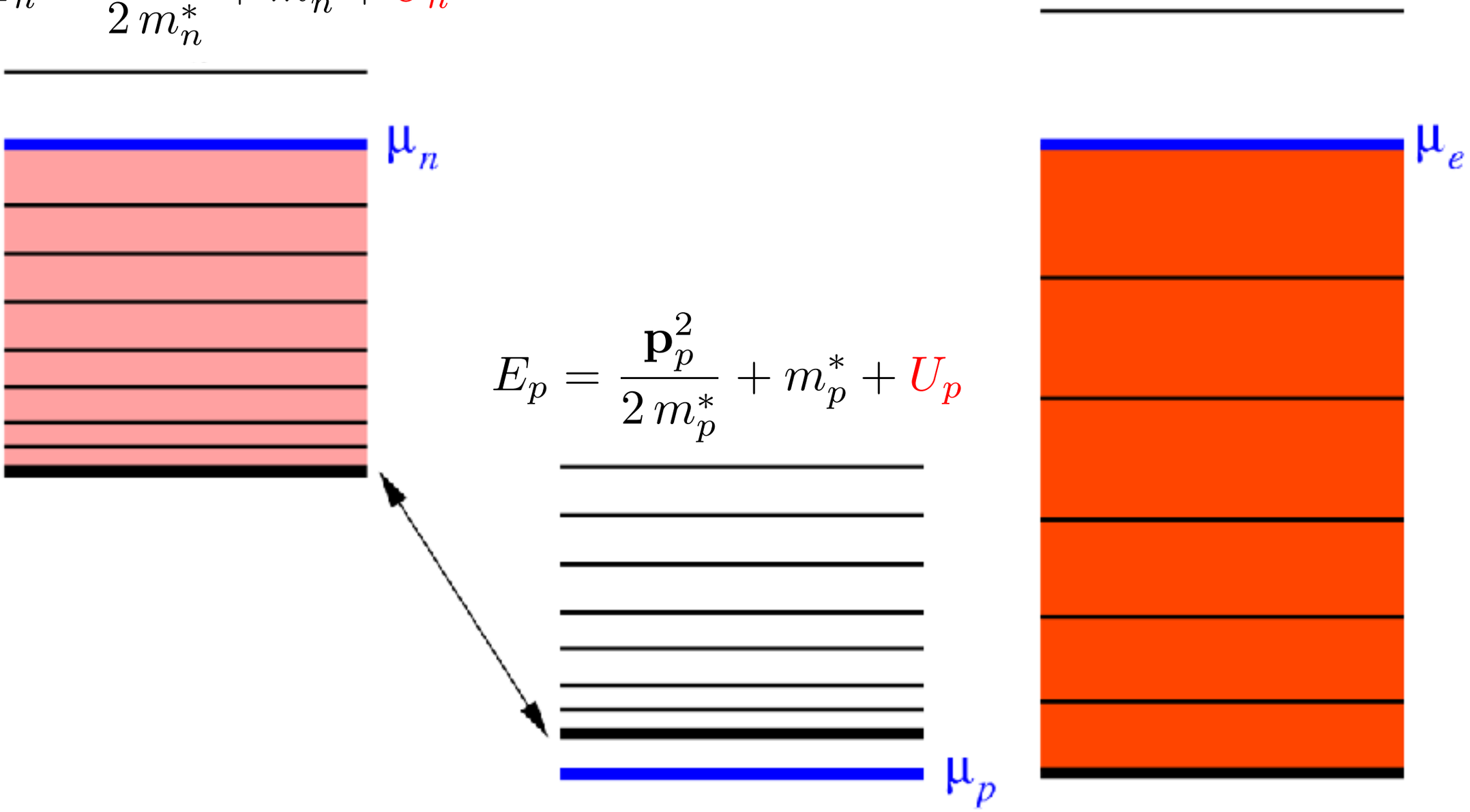
$e^- e^+ \to \nu\bar{\nu}$

14 13 12 11

$\log_{10}(\rho$ [g cm^{-3}])

$$\nu_e\, n \rightarrow p\, e^-$$

$$E_n = \frac{\mathbf{p}_n^2}{2\, m_n^*} + m_n^* + U_n$$

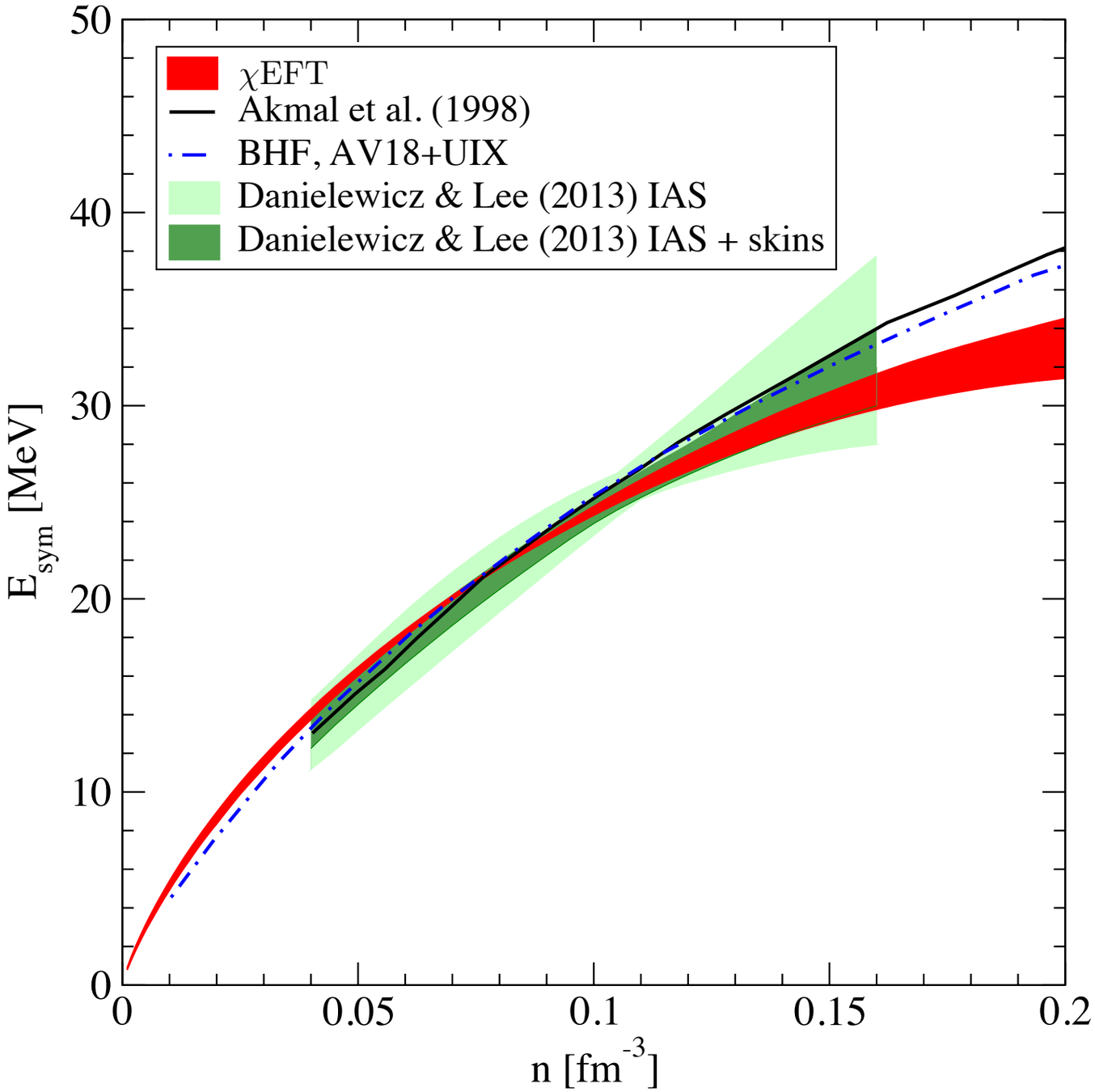


$$E_p = \frac{\mathbf{p}_p^2}{2\, m_p^*} + m_p^* + U_p$$

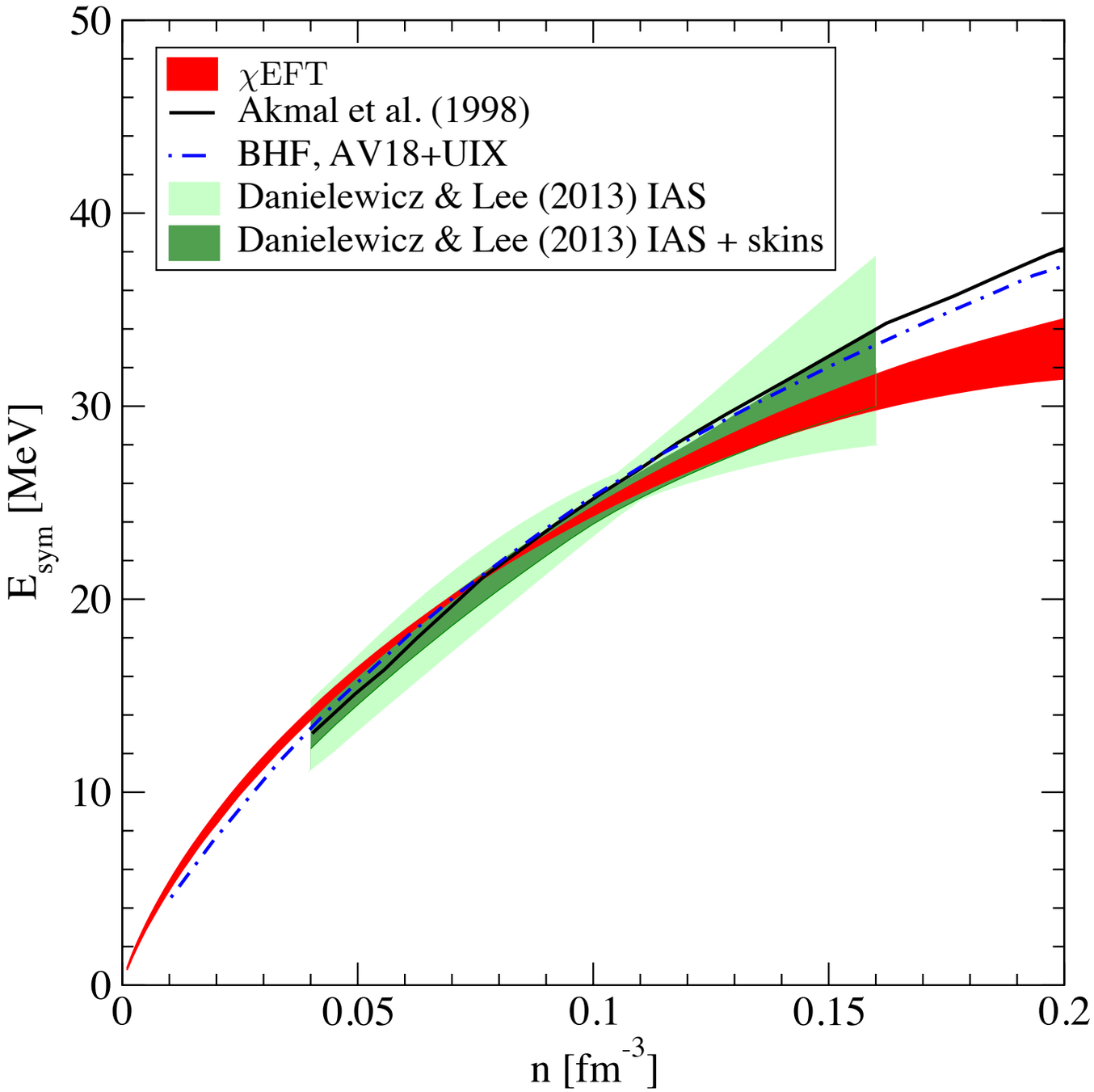
$$U_n - U_p \propto S^F(T, \rho)$$

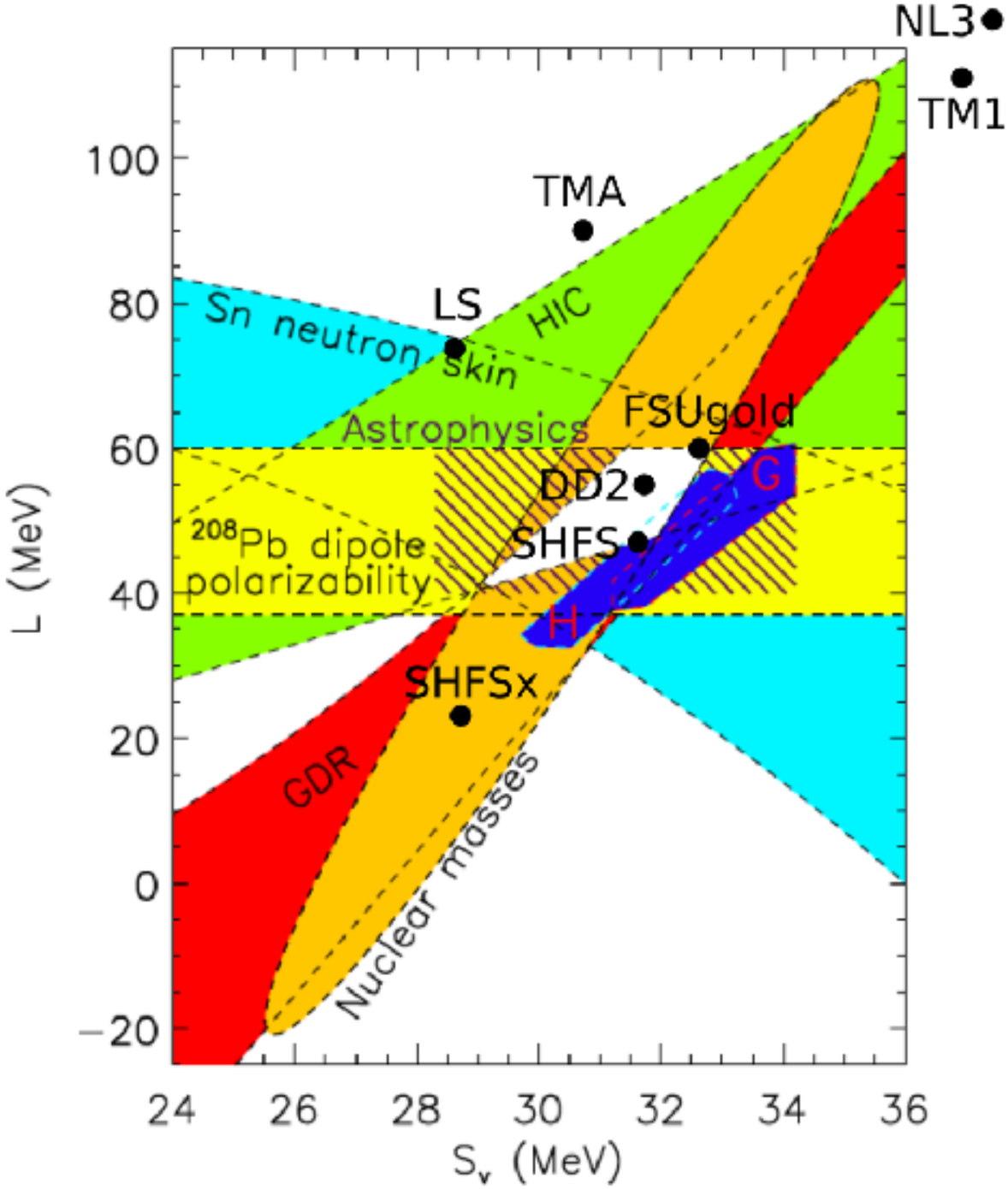
Martinez-Pinedo et al., Phys. Rev. Lett. 109, 251104 (2012)

Lattimer & Lim, Eur. Phys. J. A50, 11 (2014)



Lattimer & Lim, Eur. Phys. J. A50, 11 (2014)

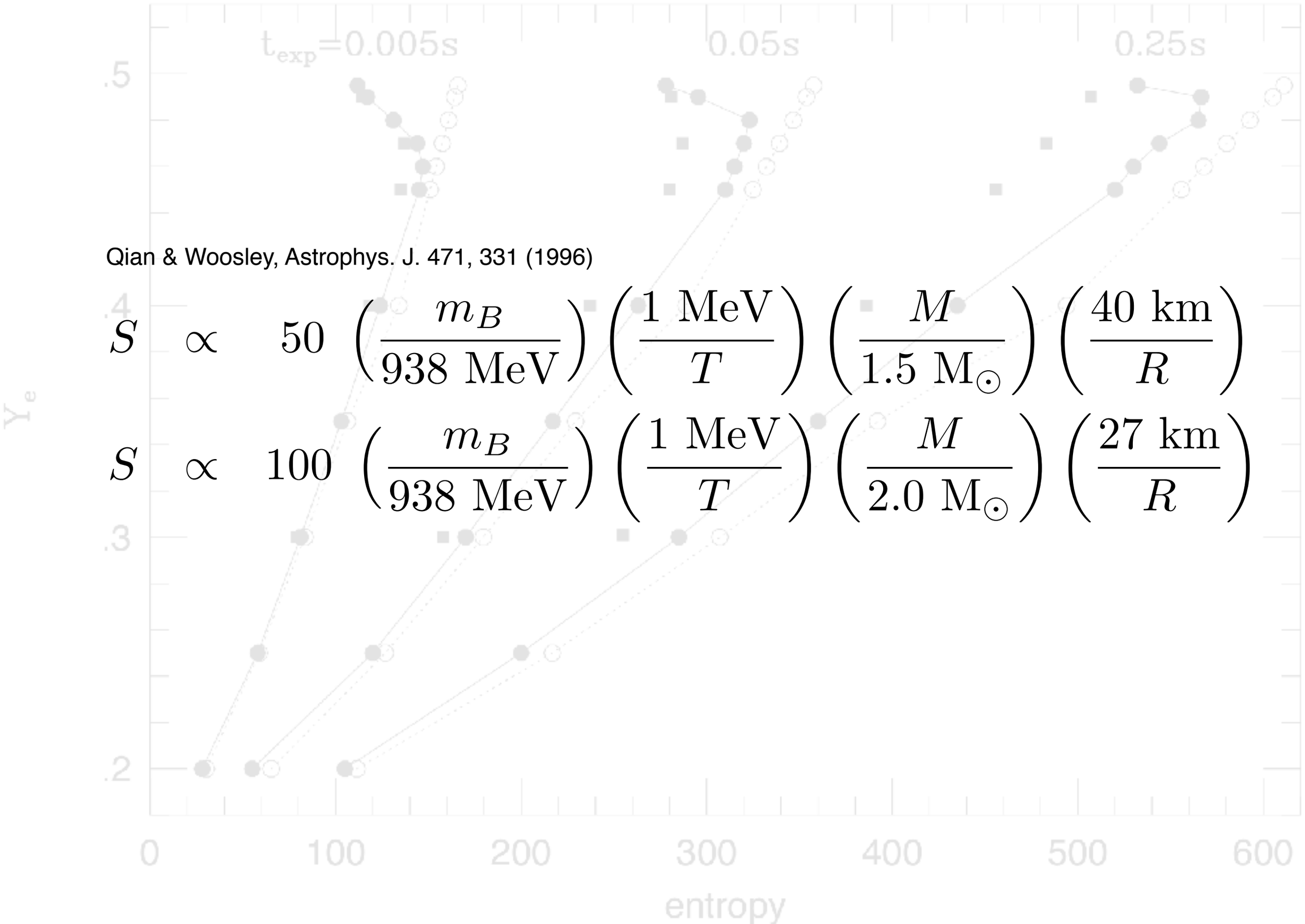


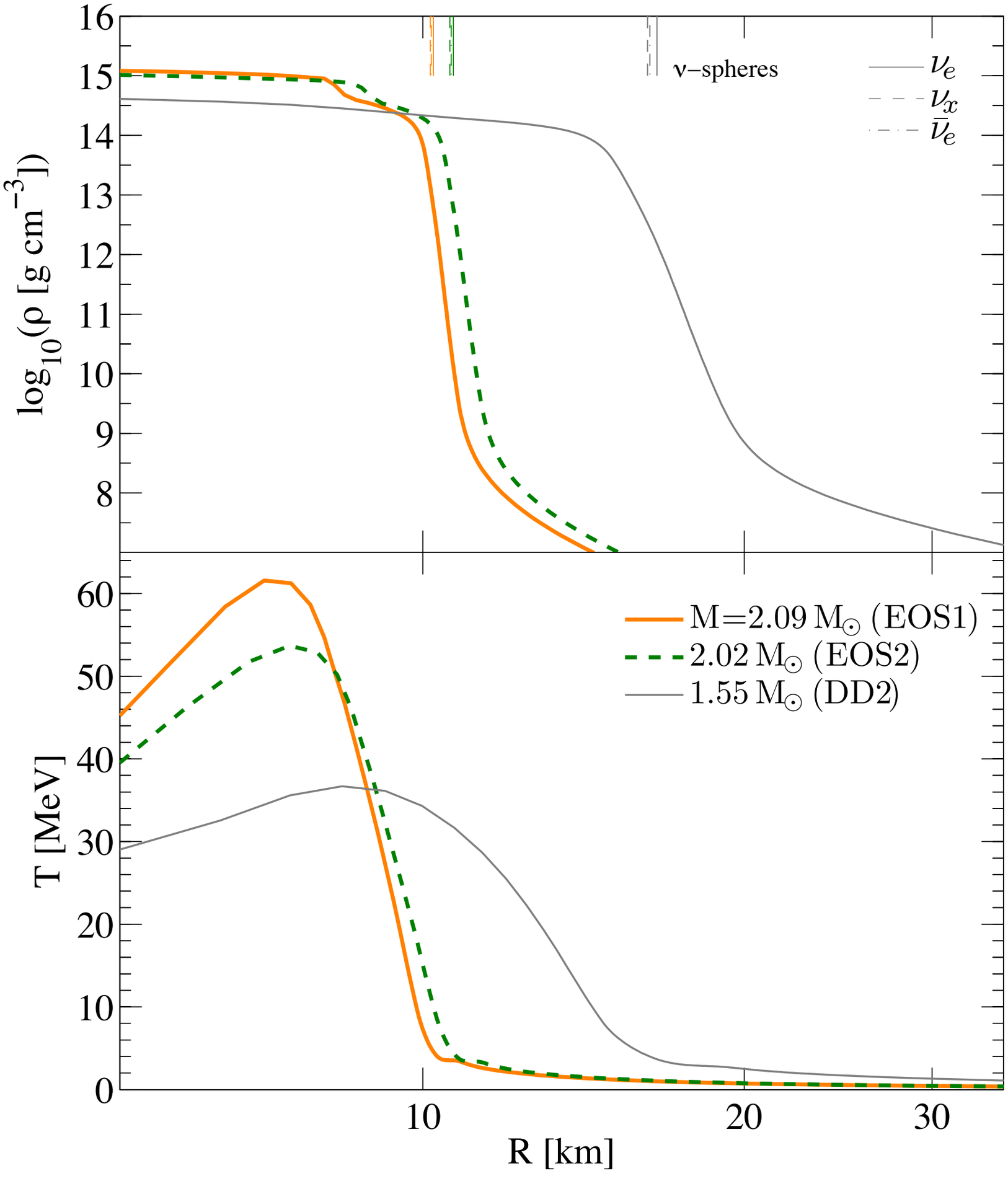


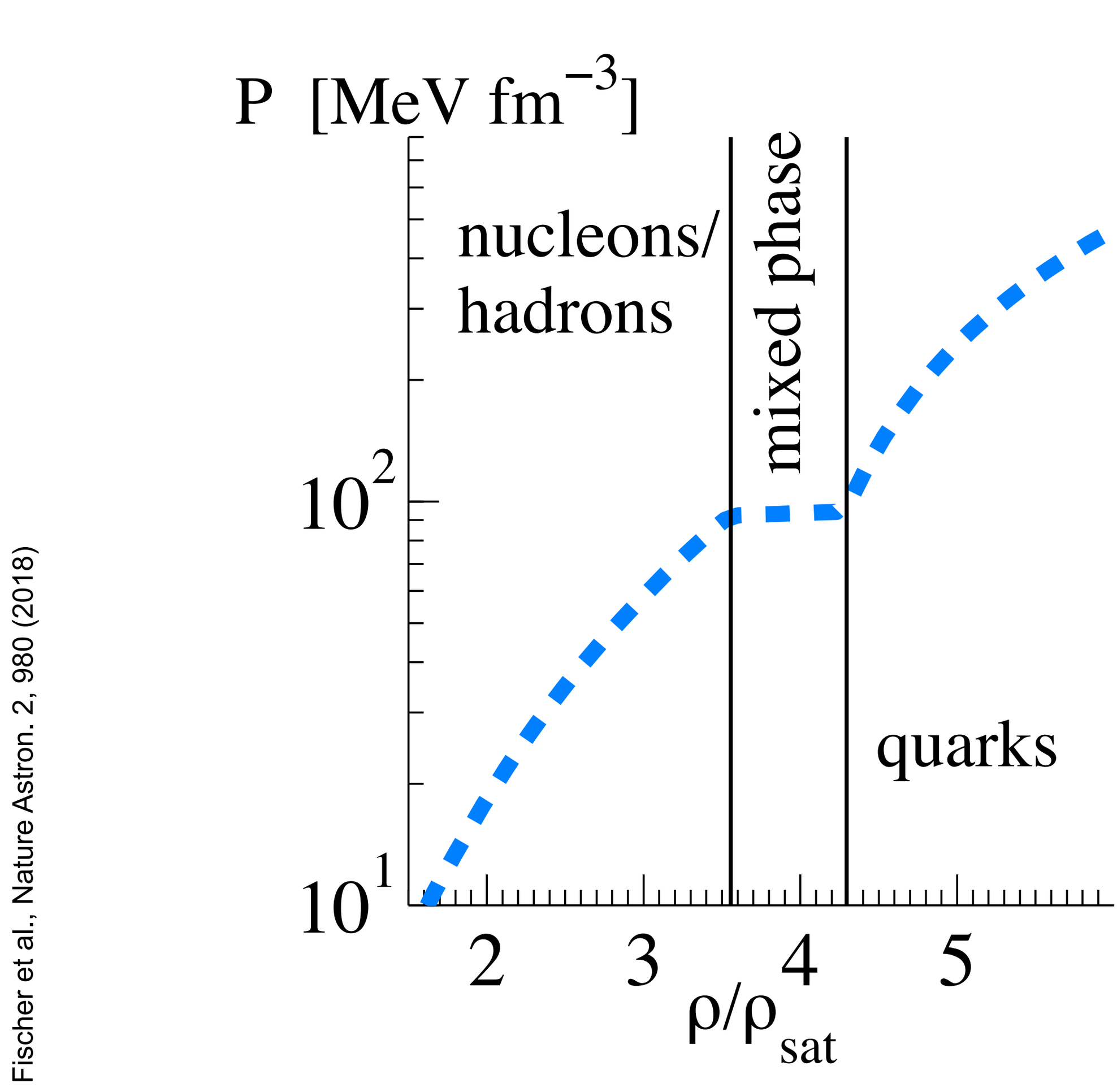
Qian & Woosley, Astrophys. J. 471, 331 (1996)

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

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




ν−spheres
ν_e
ν_x
$\bar{\nu}_e$
$\log_{10}(\rho\ [\mathrm{g\ cm^{-3}}])$
16
15
14
13
12
11
10
9
8
M=2.09 M$_\odot$ (EOS1)
2.02 M$_\odot$ (EOS2)
1.55 M$_\odot$ (DD2)
T [MeV]
60
50
40
30
20
10
0
10
20
30
R [km]



Fischer et al., Nature Astron. 2, 980 (2018)

$T = 0$, β–eq.

hadron

hybrid

PSR J0740+6620

GW170817

$M\,[M_\odot]$

Radius [km]

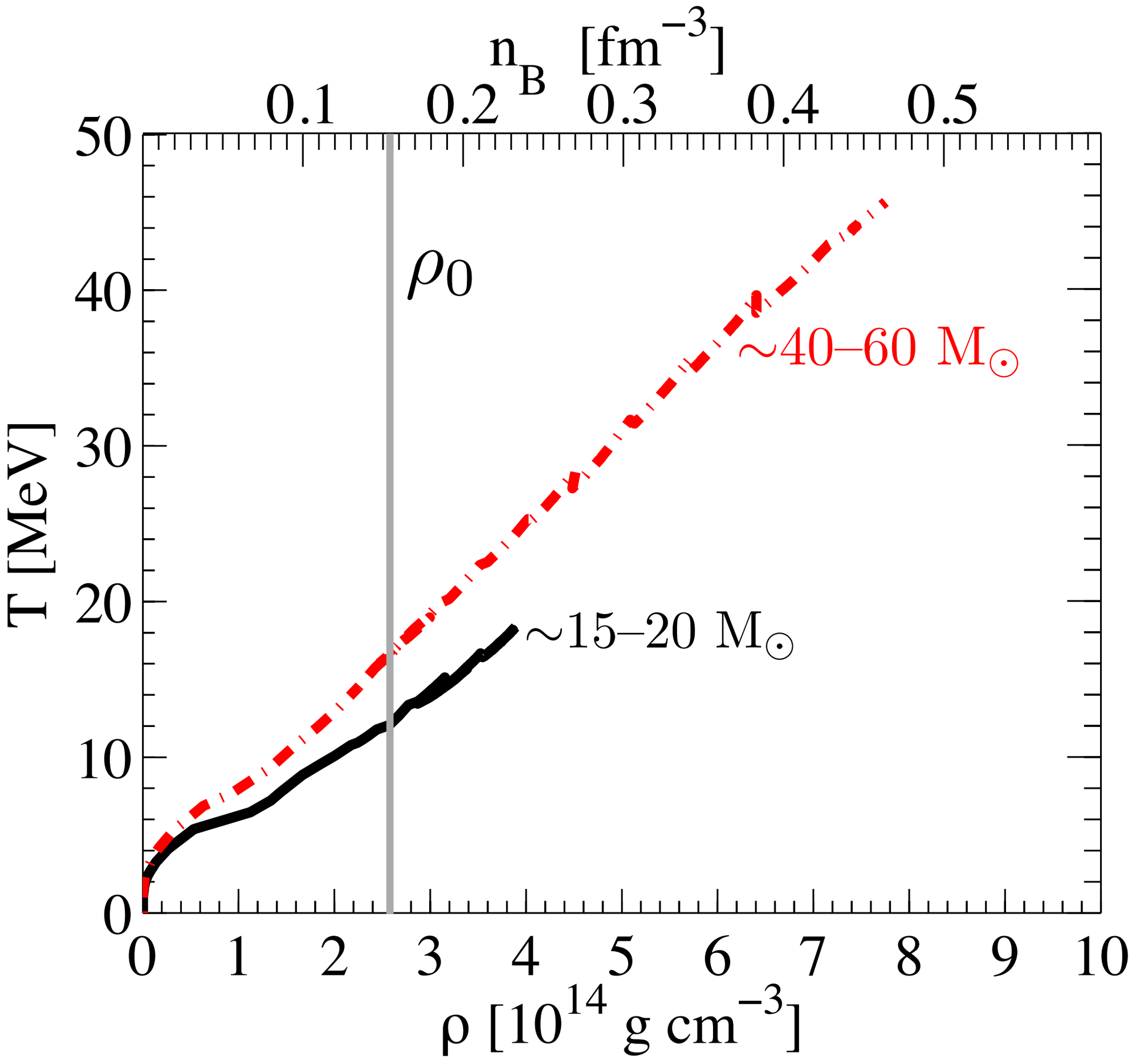
P [MeV fm^{-3}]

nucleons/ hadrons

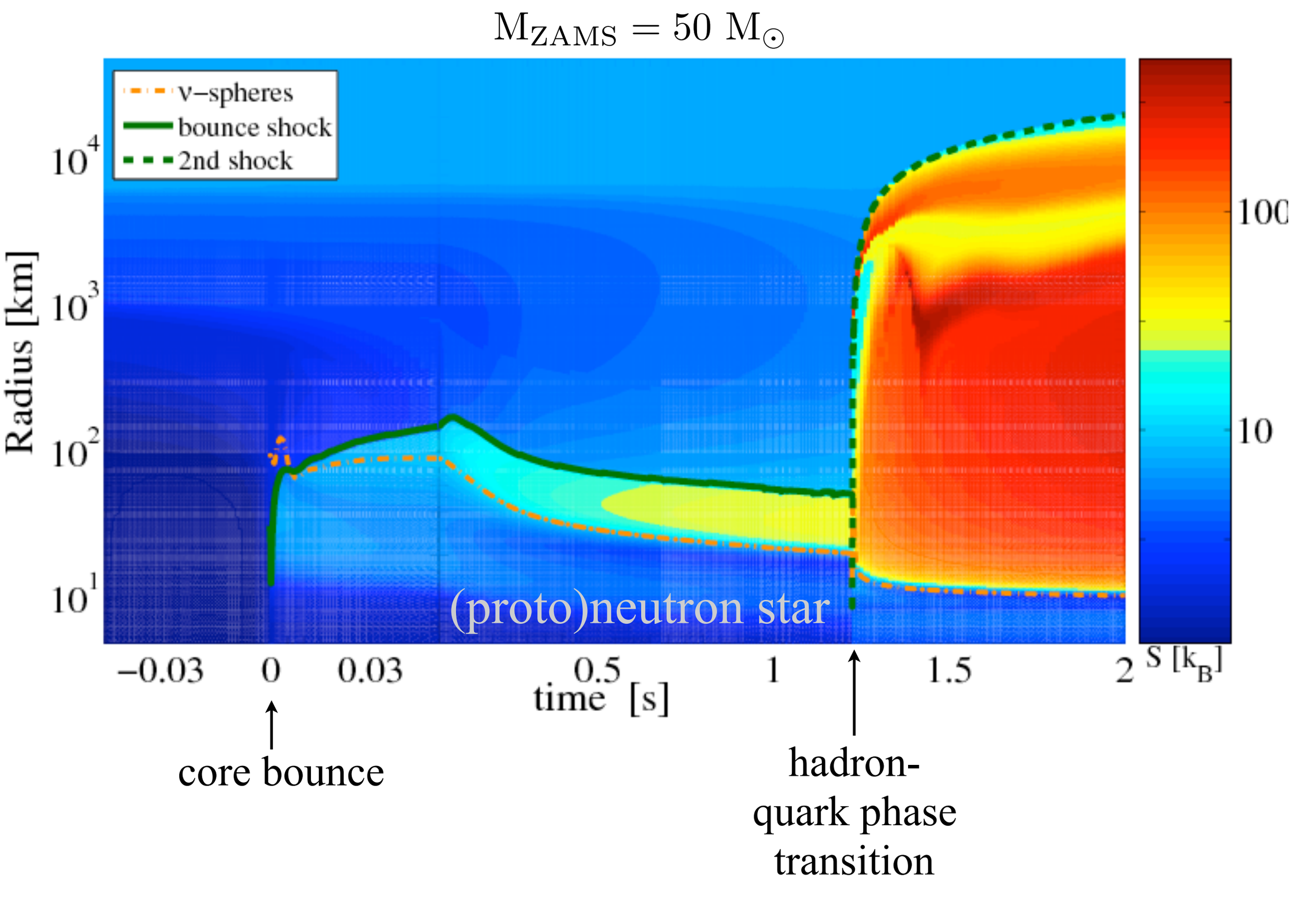
mixed phase

quarks

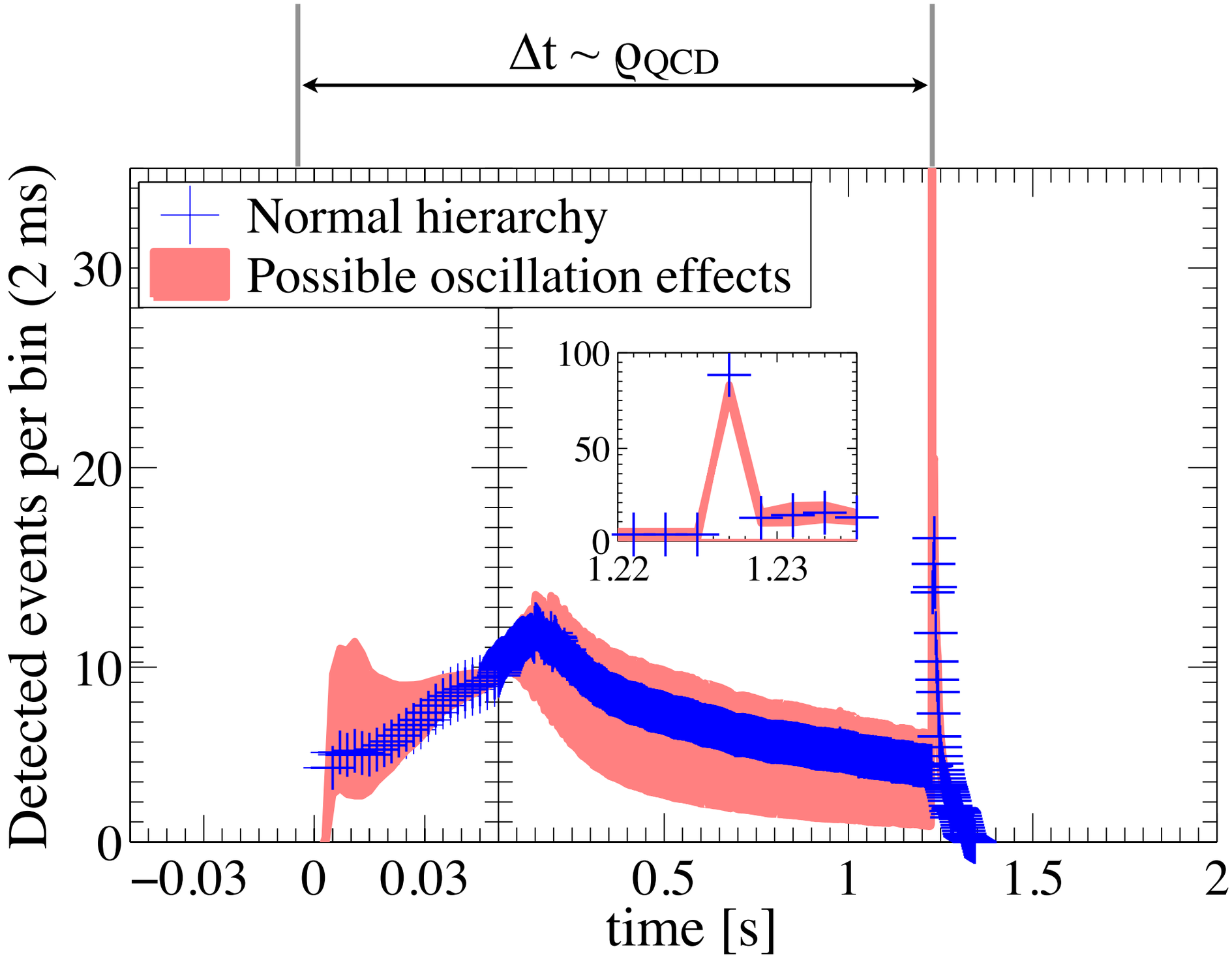
ρ/ρ_{sat}


n_B [fm^-3]
0.1
0.2
0.3
0.4
0.5
50
40
30
20
10
0
T [MeV]
ρ0
~40–60 M⊙
~15–20 M⊙
0
1
2
3
4
5
6
7
8
9
10
ρ [10^14 g cm^-3]

Fischer et al., Nature Astron. 2, 980 (2018)

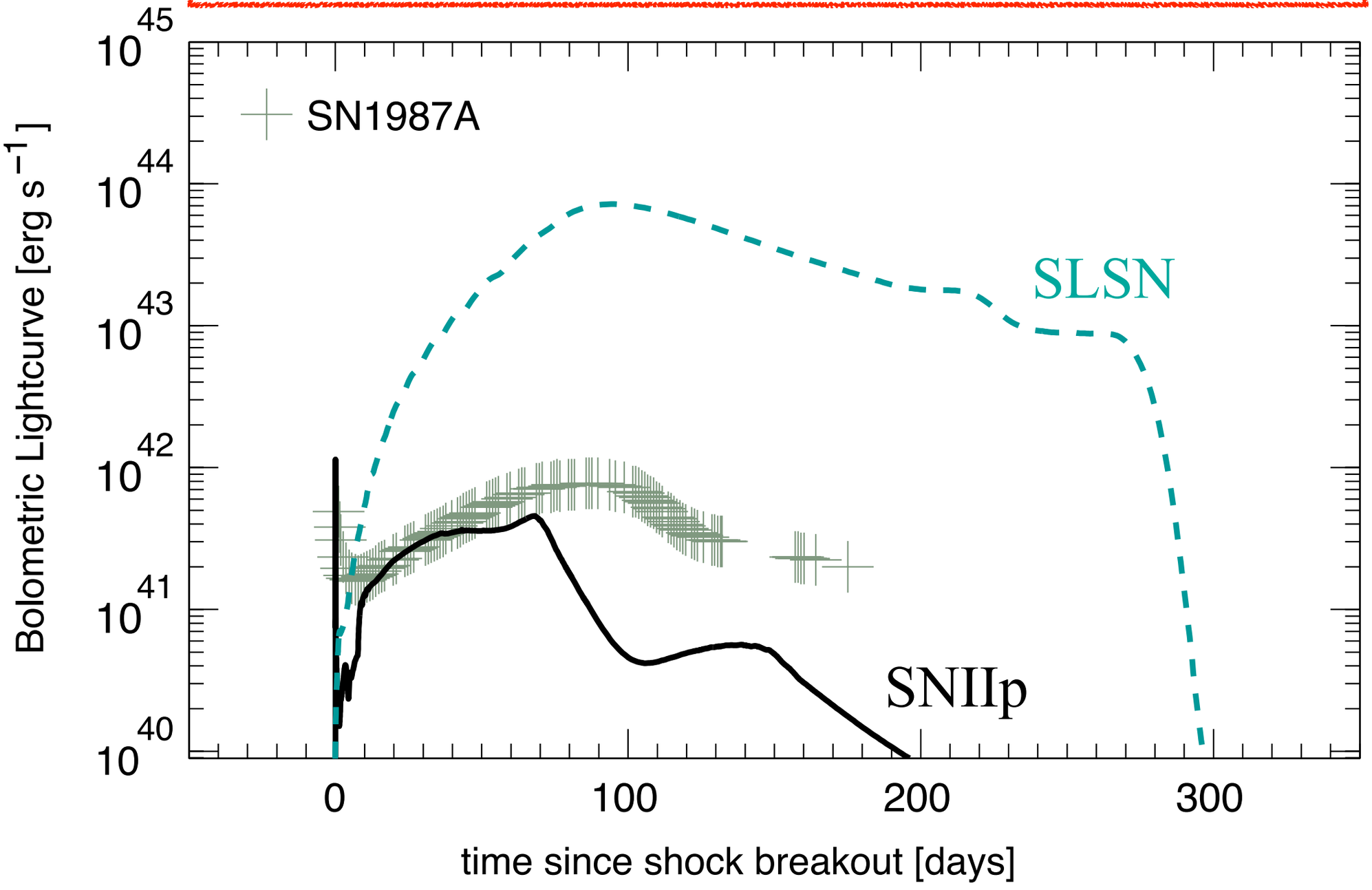


ν – signal @ Super-Kamiokande (d ~ 10 kpc)

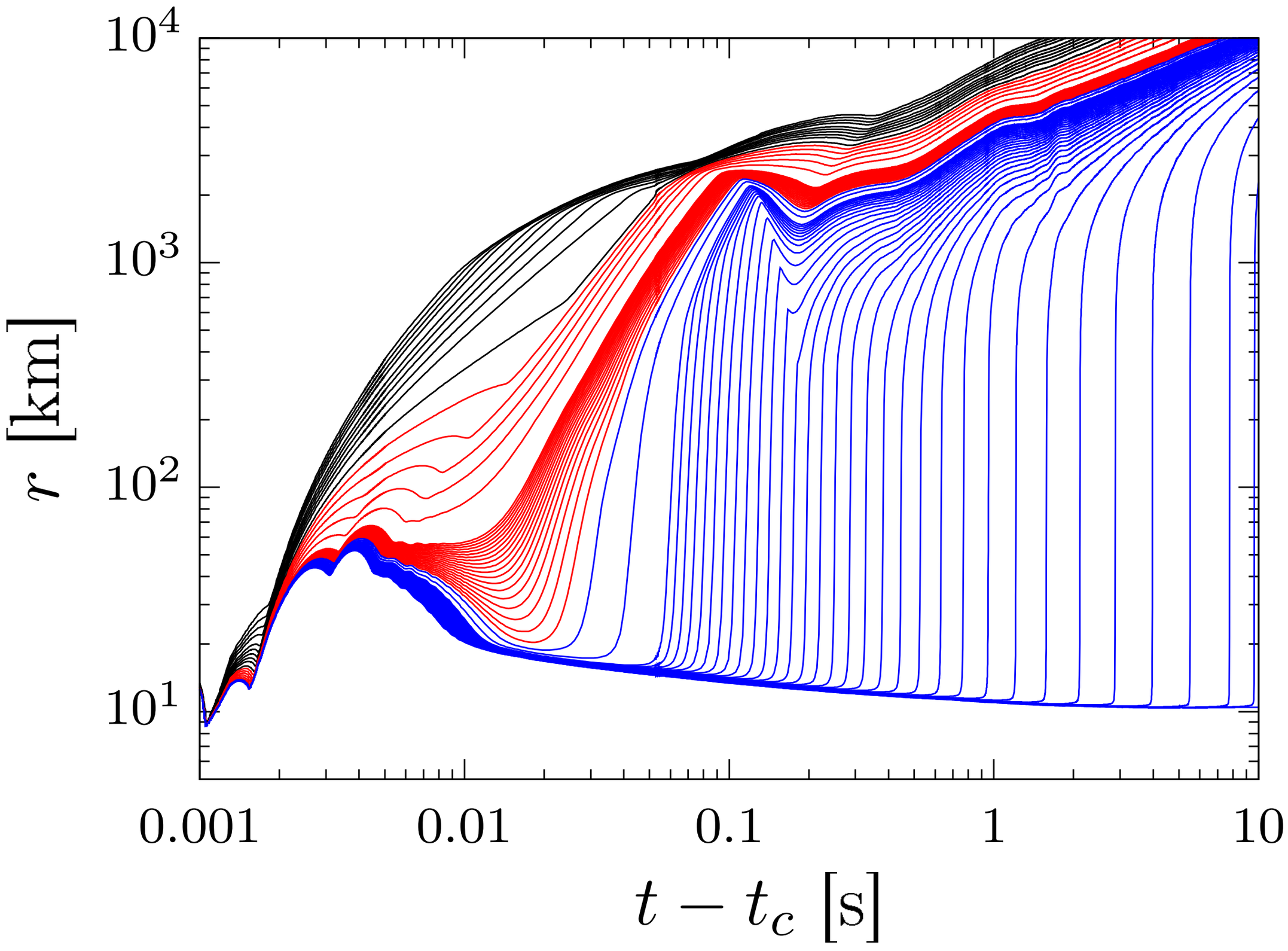


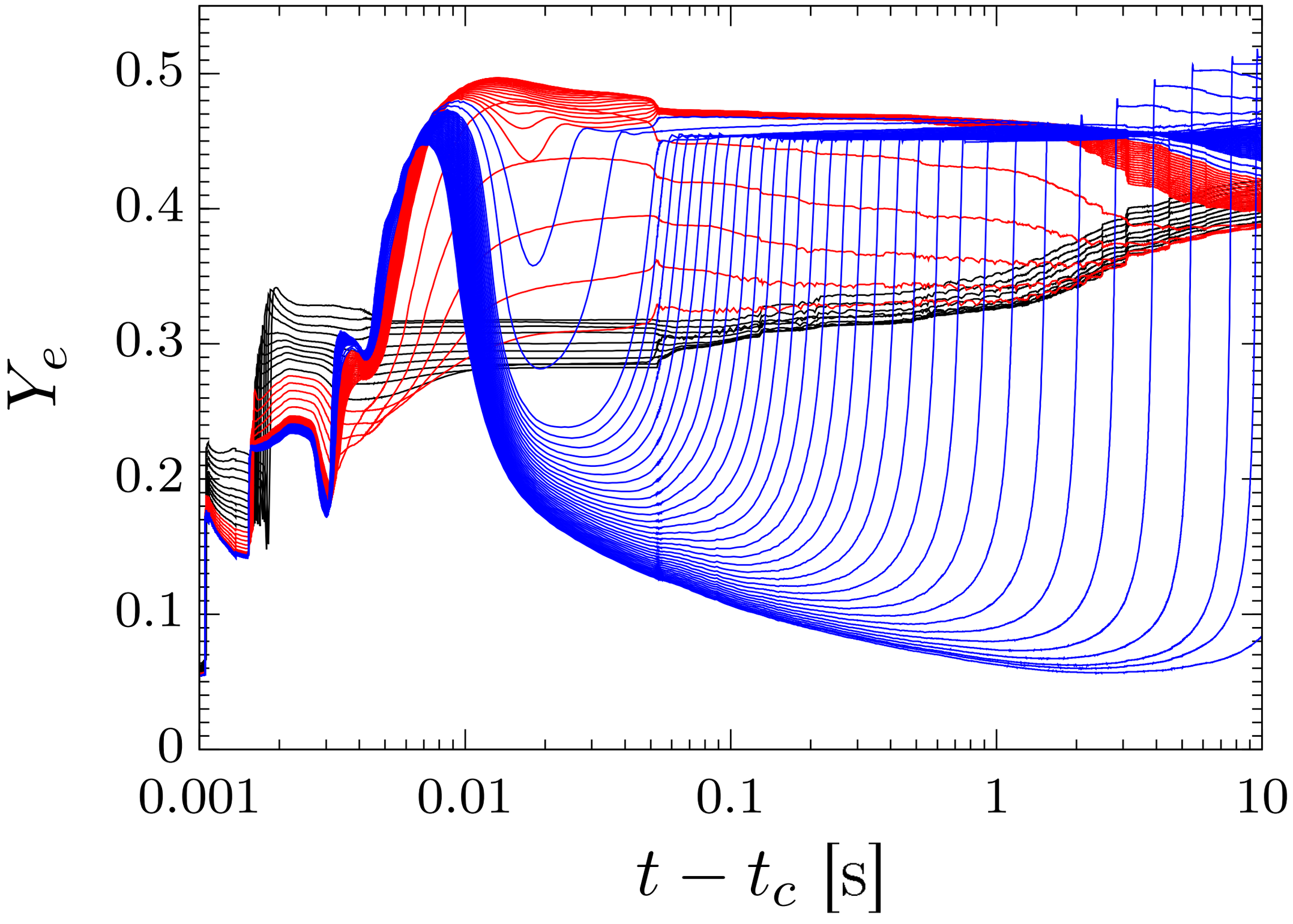
Fischer et al., Nature Astron. 2, 980 (2018)

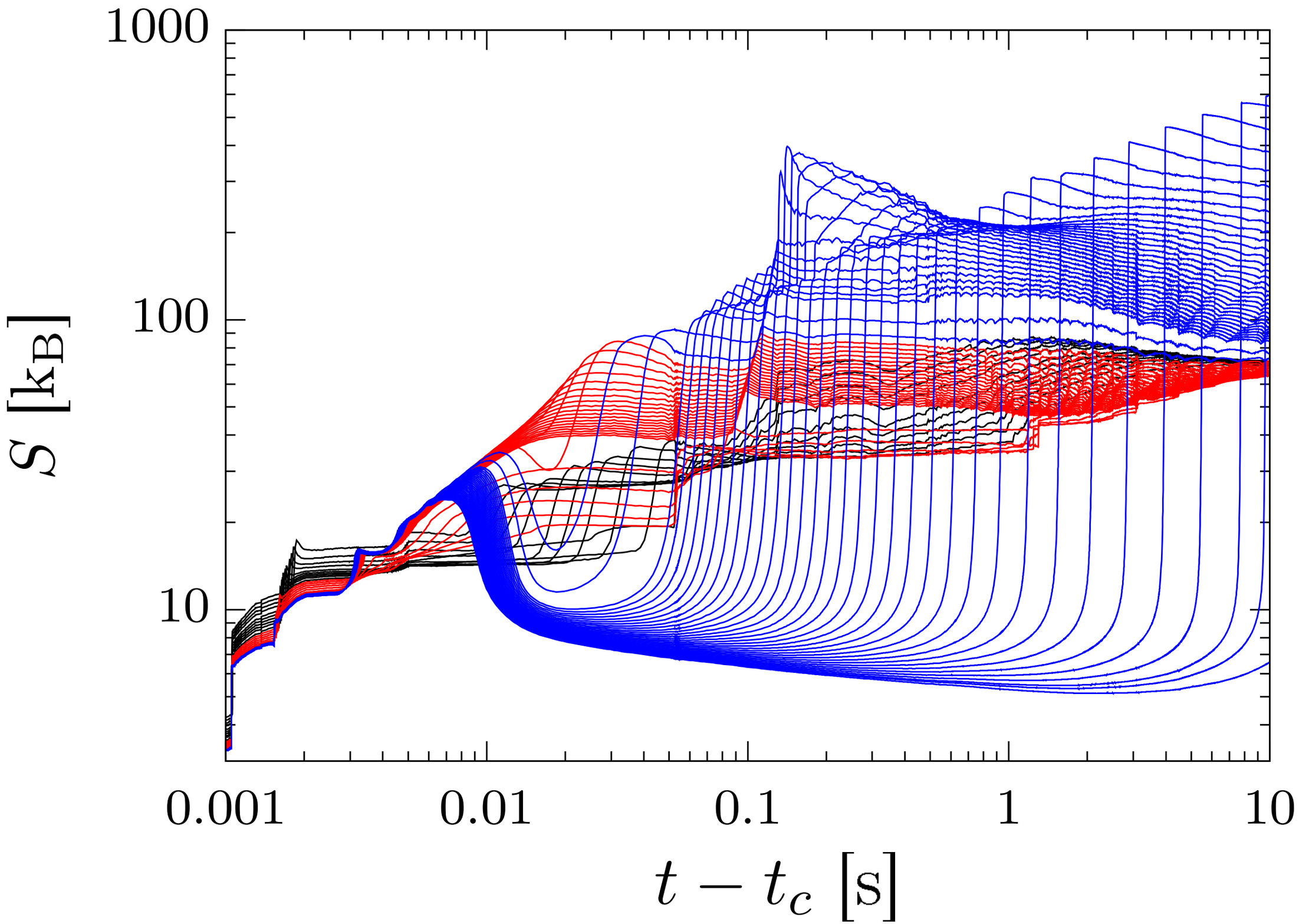
$$
\begin{aligned}
E_{expl} &= 3 \times 10^{51}\ \mathrm{erg} \\
M_{NS} &\simeq 2\ M_\odot \\
M_{Ni} &\simeq 0.024\ M_\odot
\end{aligned}
$$



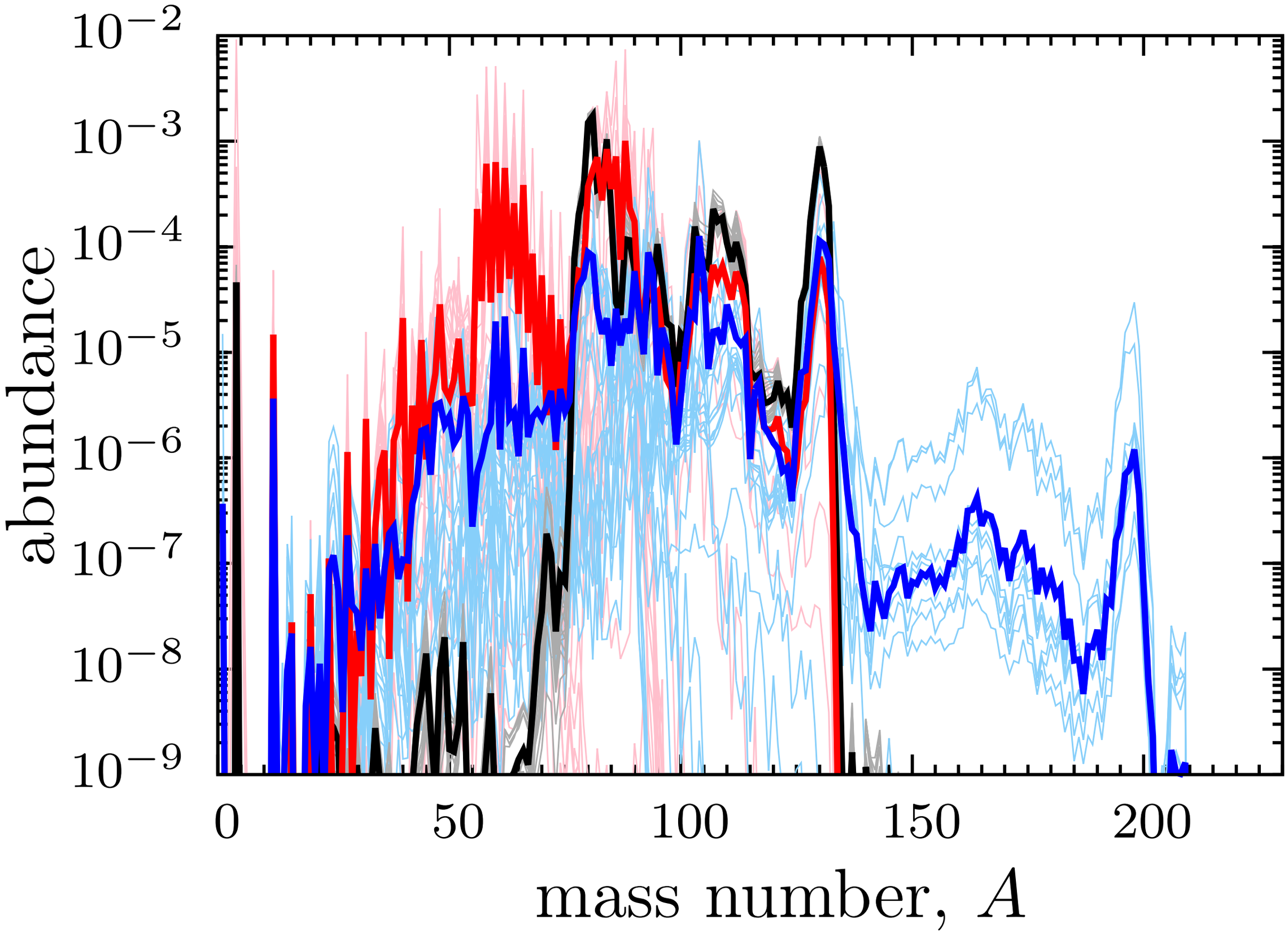
Fischer et al., Nature Astron. 2, 980 (2018)


10^4
10^3
10^2
10^1
r [km]
0.001
0.01
0.1
1
10
$t - t_c$ [s]


Y_e
0.5
0.4
0.3
0.2
0.1
0
0.001
0.01
0.1
1
10
$t - t_c$ [s]


1000
100
10
S [k_B]
0.001
0.01
0.1
1
10
$t - t_c$ [s]

10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
$S[\mathrm{k_B}],\ \dot{M}[\mathrm{M_\odot\ s^{-1}}],\ \tau[\mathrm{s}]$
0.55
0.5
0.45
0.4
0.35
0.3
0.25
Y_e
S
Y_e
τ
$\dot{M}_\odot$
0.01
0.1
1
10
$t(r = 500\ \mathrm{km}) - t_c\ [\mathrm{s}]$


10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
abundance
0
50
100
150
200
mass number, A

10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
$Y(A)$
solar r abun.
50 $M_\odot$, EOS 1
50 $M_\odot$, EOS 2
40 $M_\odot$, EOS 2
40 60 80 100 120 140 160 180 200
mass number, A

No strong *r* process for "normal" ν-driven winds

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

} nuclear structure

$$U_n - U_p \propto S(\rho)$$

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

} inelastic contributions
weak magnetism

$$g_A \to g_A - g_S \ , \quad g_S \simeq 0.1 - 0.12$$

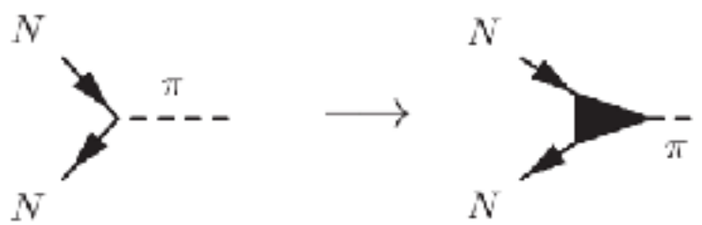
+ nuclear correlations $S_A < 1$

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

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

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

} $g_A^*(\rho)$,



Kotake et al., Astrophys. J. 853, 170 (2018)

No strong *r* process for "normal" *ν*-driven winds

What's possibly missing:

- **Multi-dimensional effects; late-time accretion may power higher *ν*–luminosities/energies**

- **Neutrino oscillations**

- ***μ* neutrinos**

$$\nu_\mu\, n \longrightarrow p\, \mu^-$$

$$\nu_\alpha\, \mu^- \longrightarrow \mu^-\, \nu_\alpha$$

$$\nu_\mu\, e^- \longrightarrow \mu^-\, \nu_e$$

$$\nu_\mu\, \bar{\nu}_e\, e^- \longrightarrow \mu^-$$

$$\bar{\nu}_\mu\, \mu^- \longrightarrow e^-\, \bar{\nu}_e$$

Bollig et al., Phys. Rev. Lett. 119, 242702 (2017)

No strong *r* process for "normal" ν-driven winds

Explosions of massive stars $\sim 35 - 50\ \mathrm{M}_\odot$

<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

Thanks for your attention

In collaboration with:

A. Bauswein
N. U. Bastian
D. B. Blaschke
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S. Typel
B. Wehmeyer
M. R. Wu