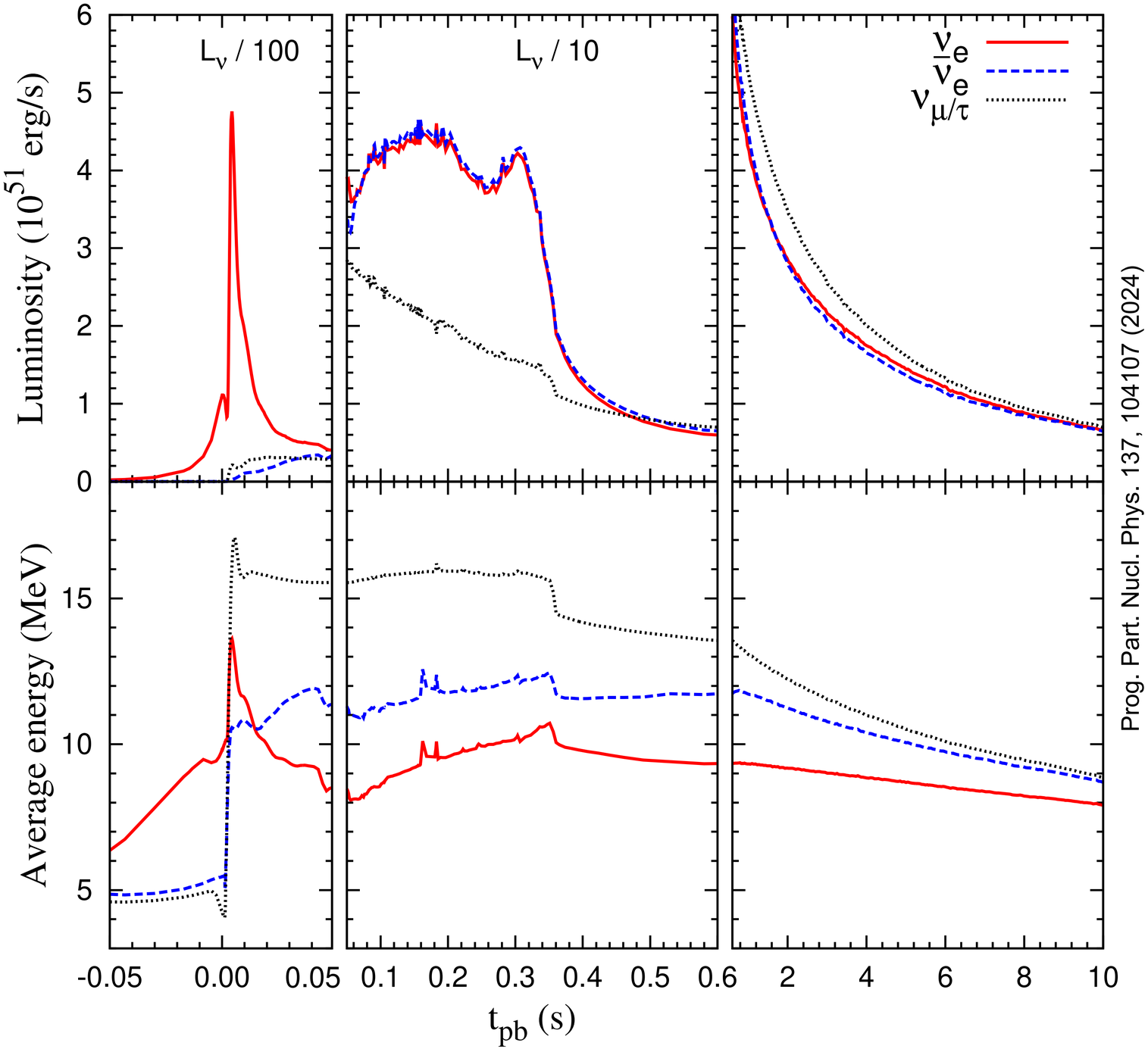
An attempt to (critically) understand *the* supernova neutrino signal

Wrocław University of Science and Technology

SILESIAN UNIVERSITY IN OPAVA

National Science Centre Poland


Luminosity (10^{51} erg/s)
L_ν / 100
L_ν / 10
ν_e
$\bar{\nu}_e$
$\nu_{\mu/\tau}$
Average energy (MeV)
t_{pb} (s)
Prog. Part. Nucl. Phys. 137, 104107 (2024)

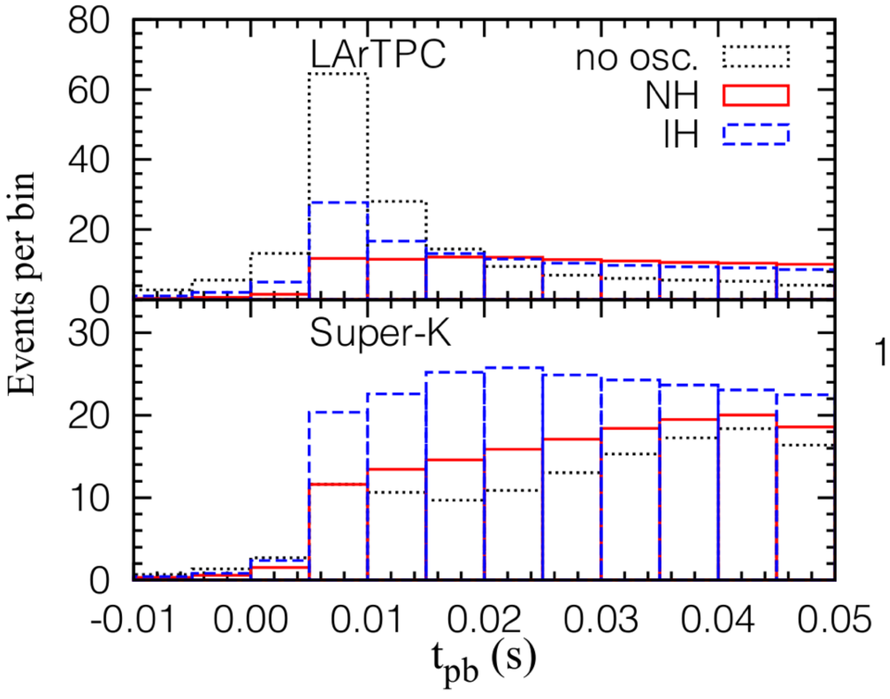
LArTPC (fictive 34 kton liquid argon time projection chamber)

$$\nu_e + {}^{40}\mathrm{Ar} \longrightarrow {}^{40}\mathrm{K}^* + e^-$$
$$\bar{\nu}_e + {}^{40}\mathrm{Ar} \longrightarrow {}^{40}\mathrm{Cl}^* + e^+$$
$$\nu_\alpha + e^- \longrightarrow \nu_\alpha + e^-$$

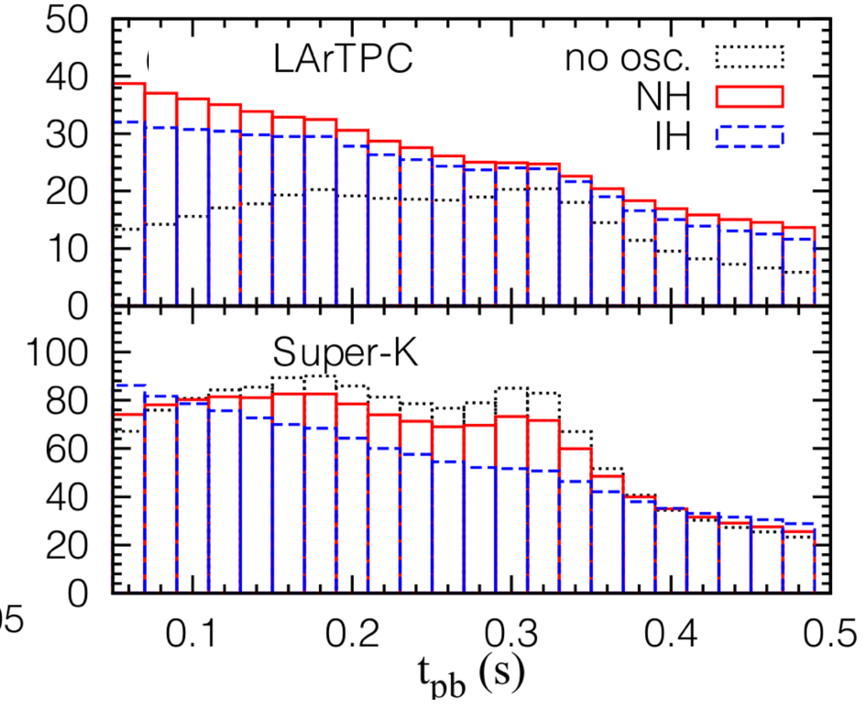
Super-K (50 kton ultra-pure water)

$$\bar{\nu}_e + p \longrightarrow n + e^+$$
$$\nu_e + {}^{16}\mathrm{O} \longrightarrow {}^{16}\mathrm{F}^* + e^-$$
$$\bar{\nu}_e + {}^{16}\mathrm{O} \longrightarrow {}^{16}\mathrm{N}^* + e^+$$
$$\nu_\alpha + {}^{16}\mathrm{O} \longrightarrow {}^{16}\mathrm{O} + \nu_\alpha$$
$$\nu_\alpha + e^- \longrightarrow \nu_\alpha + e^-$$

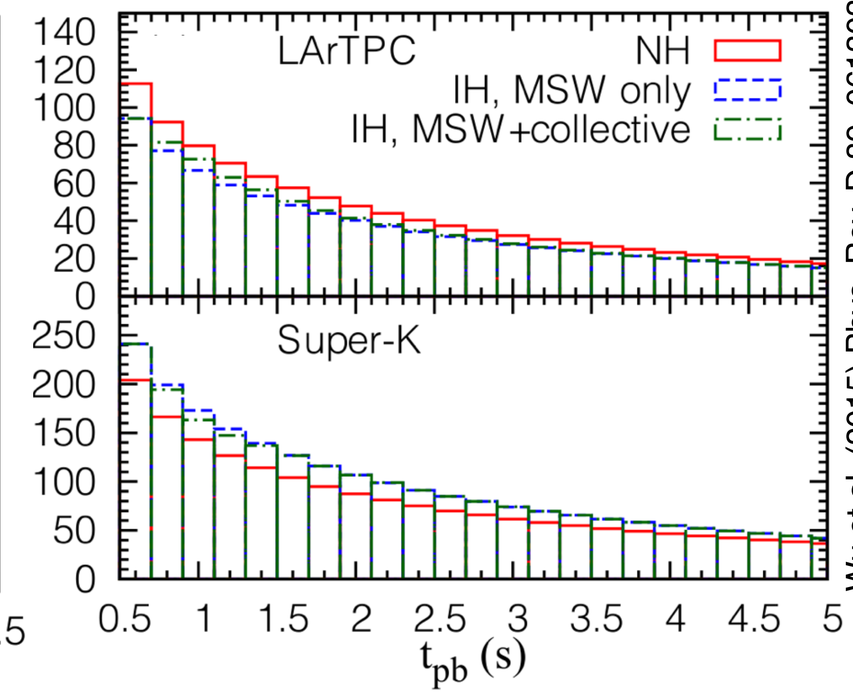
ν_e–burst



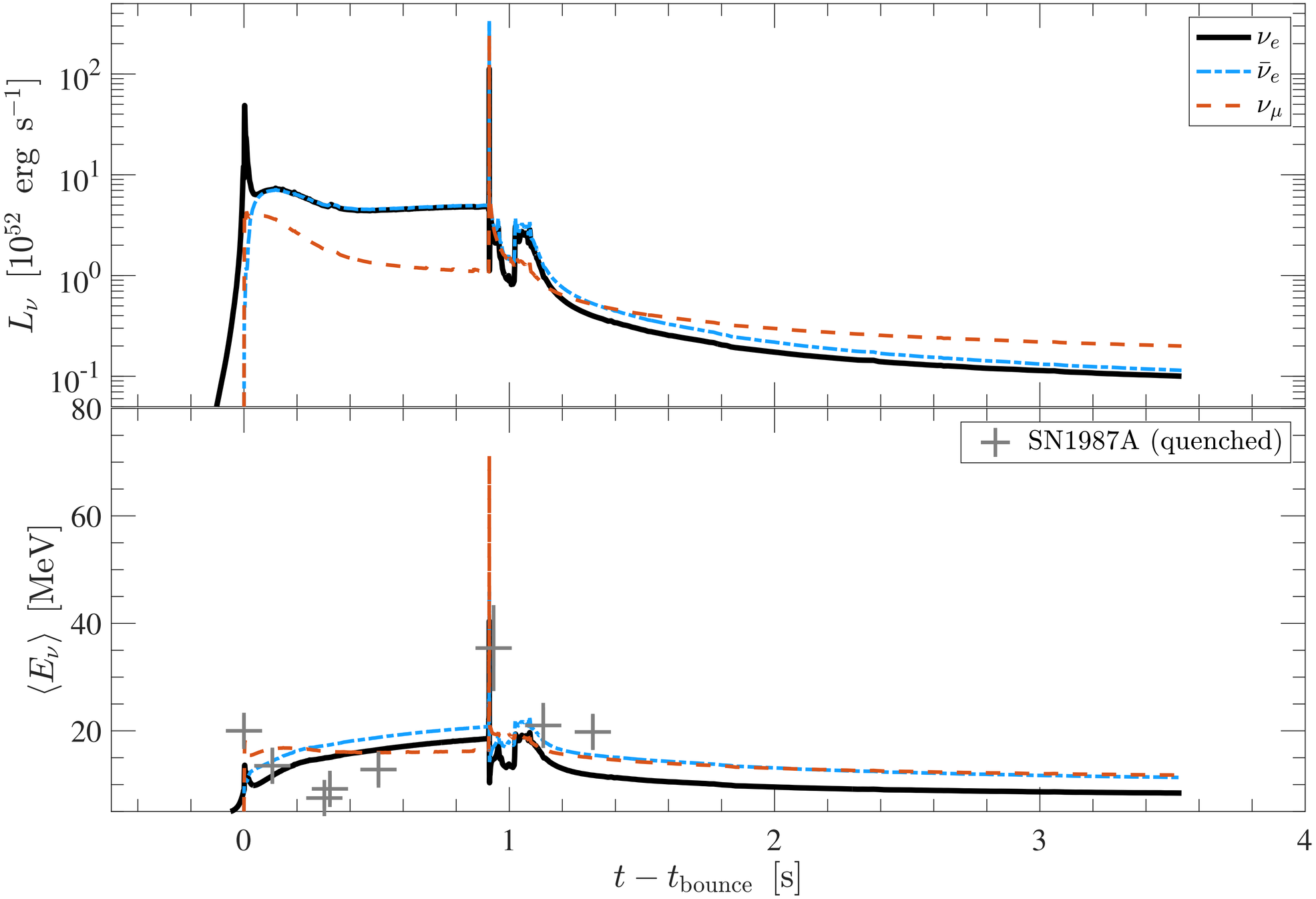
accretion phase



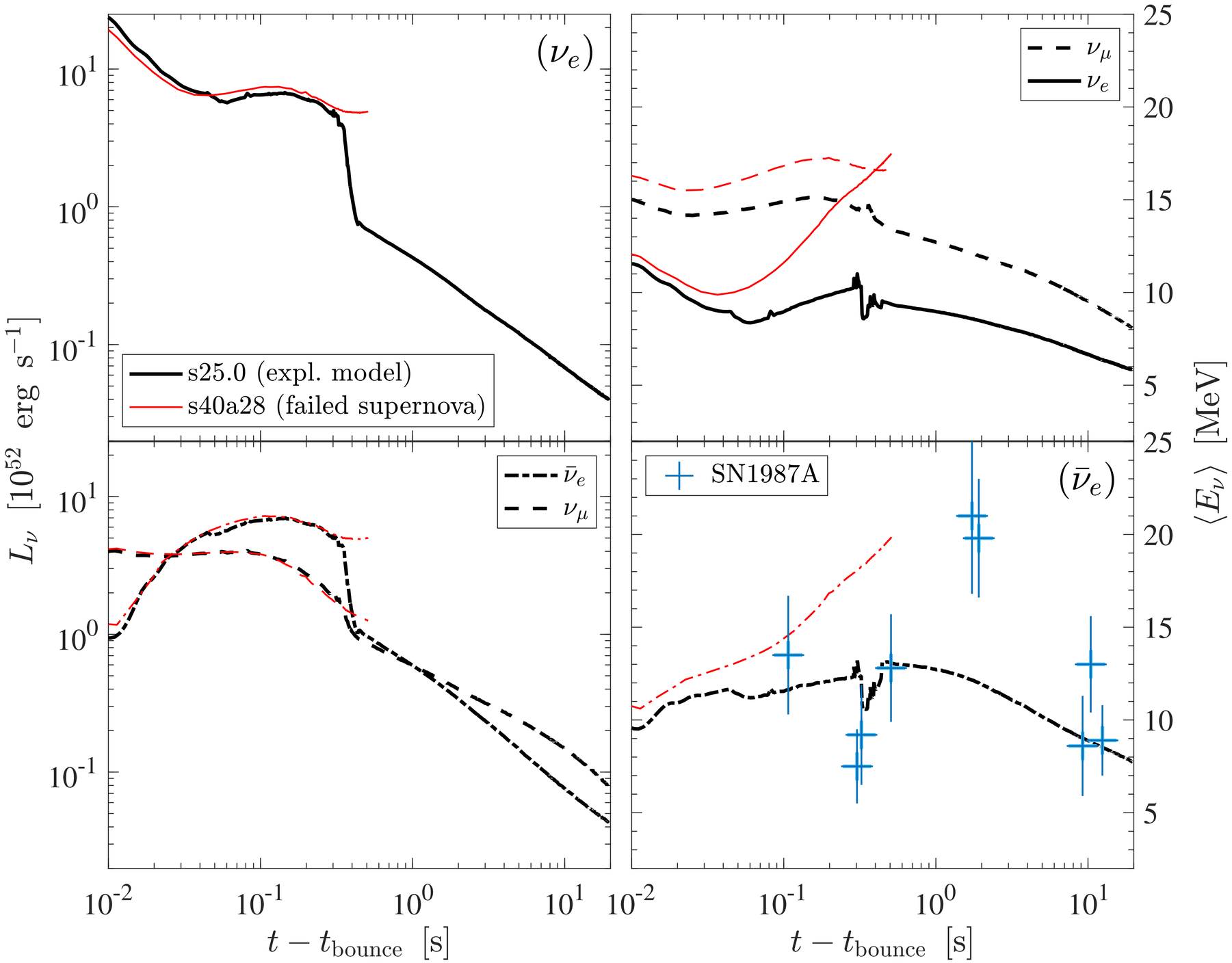
deleptonization



Wu et al.,(2015) Phys. Rev. D 89, 061303



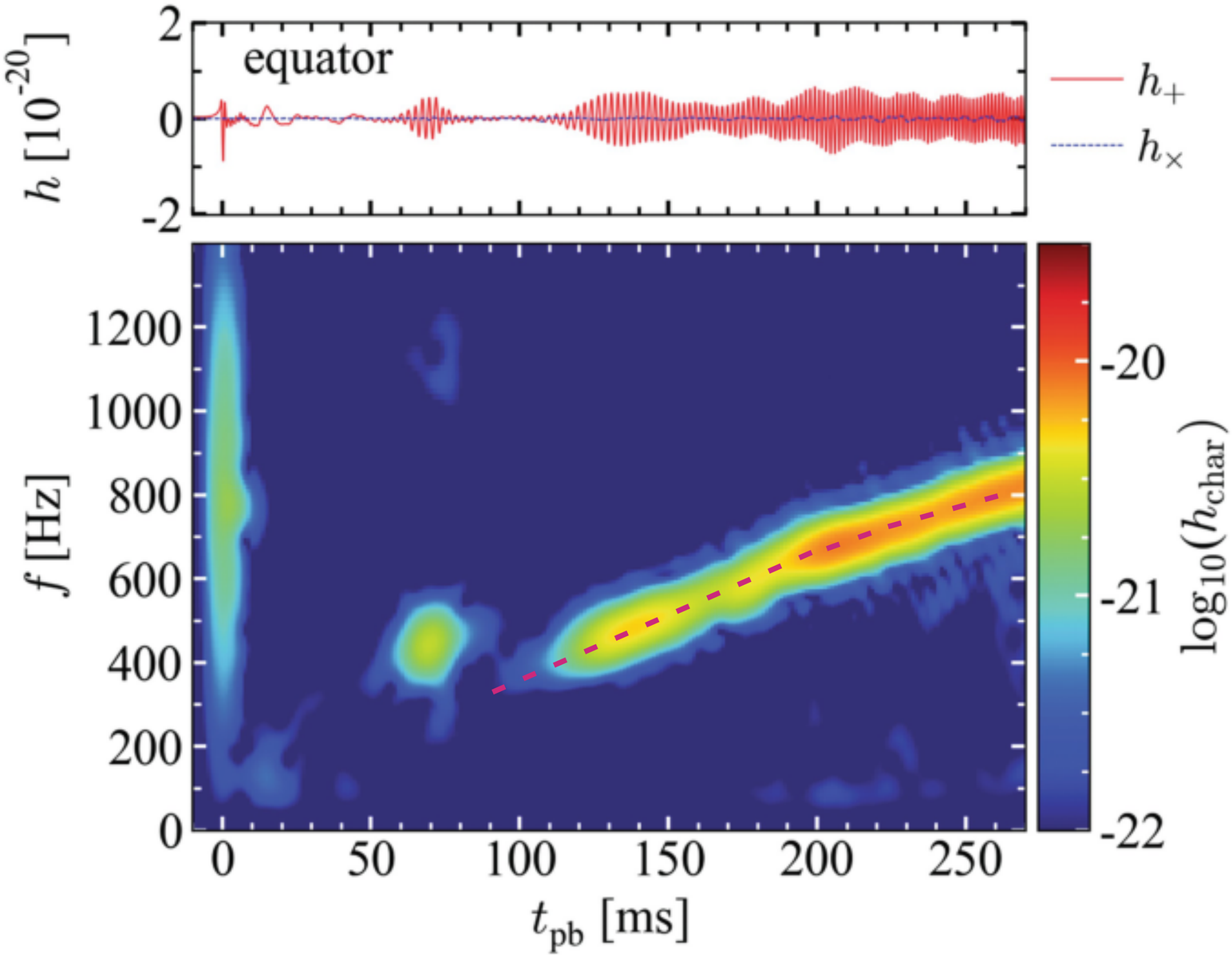
Talk by Noshad Khosravi Largani



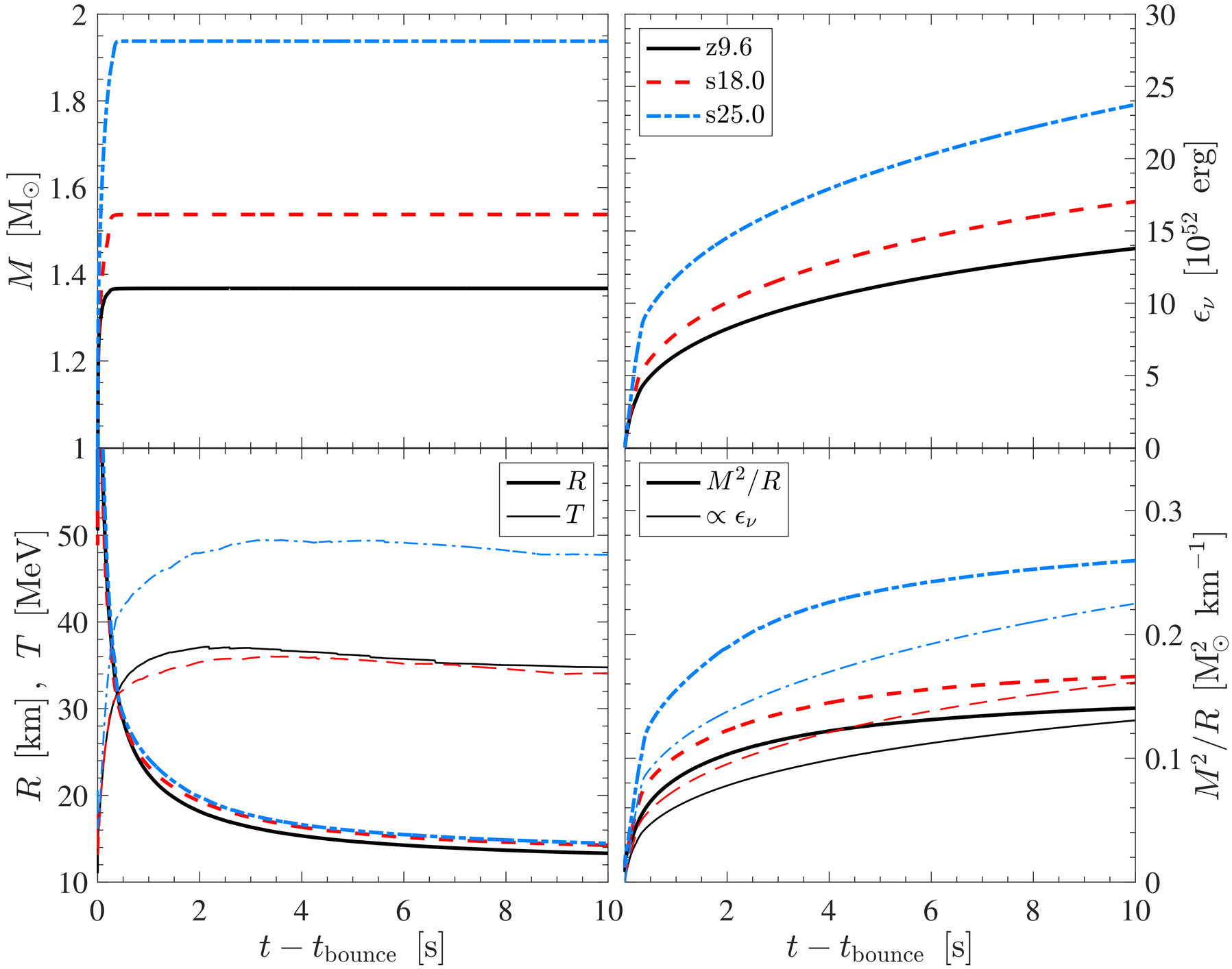
Talk by John Beacom

Yüksel & Beacom, Phys. Rev. D 76, 083007 (2007)
Olsen et al, Phys. Rev. D 104, 123020 (2021)
Fiorillo et al., Phys. Rev. D 108, 083040 (2023)
Li et al., Phys. Rev. D 109, 083025 (2024)

Abdiakamalov et a., Handbook of Gravitational Wave Astronomy (2022)

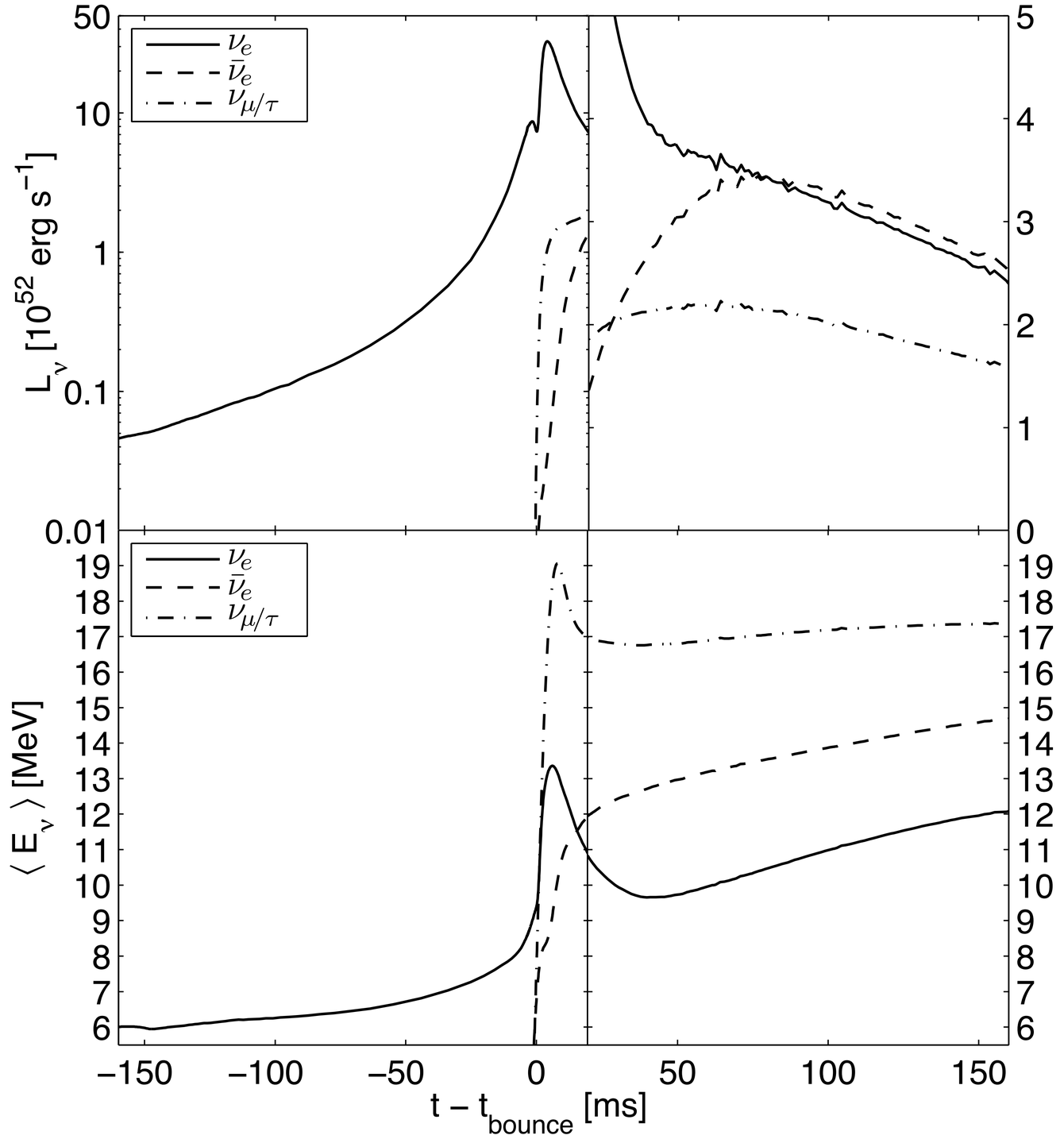


$$\propto \sqrt{\frac{M}{R^3}}$$



$$\epsilon_{\rm bind} \simeq \frac{3}{5}\frac{GM^2}{R} \simeq \epsilon_\nu$$

Gallo Rosso et al., J. Cosm. Astroart. Phys. 006 (2018)
Nagakura & Vartanyan, Mon.Not. Roy. Astron. Soc. 512, 2806 (2022)



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

Juodagalvis et al., Nucl. Phys. A848, 454 (2010)

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

$$l^- + p \leftrightarrows \nu_l + n$$

$$l^+ + n \leftrightarrows \bar{\nu}_l + p$$

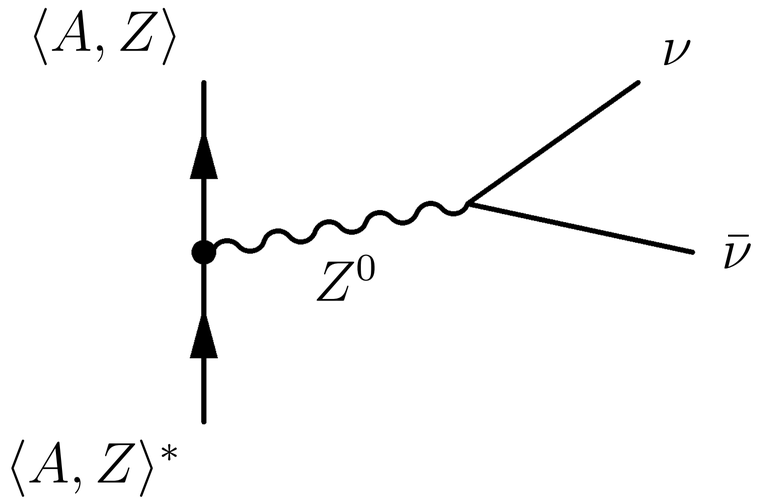
$$\nu + N \leftrightarrows \nu' + N$$

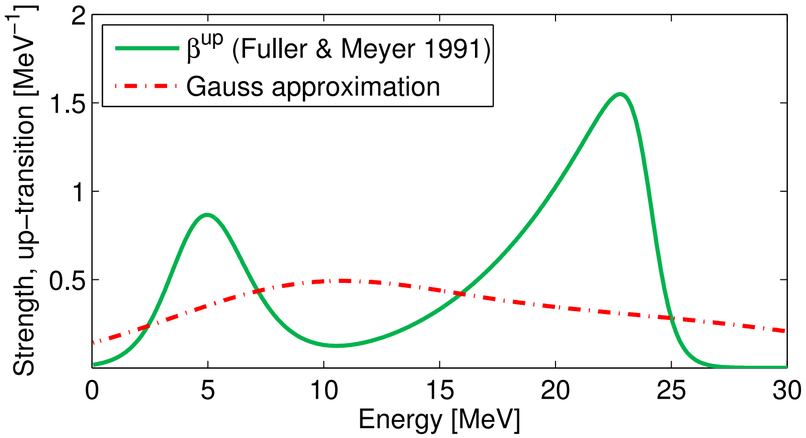
$$\nu + l^\pm \leftrightarrows \nu' + l^\pm$$

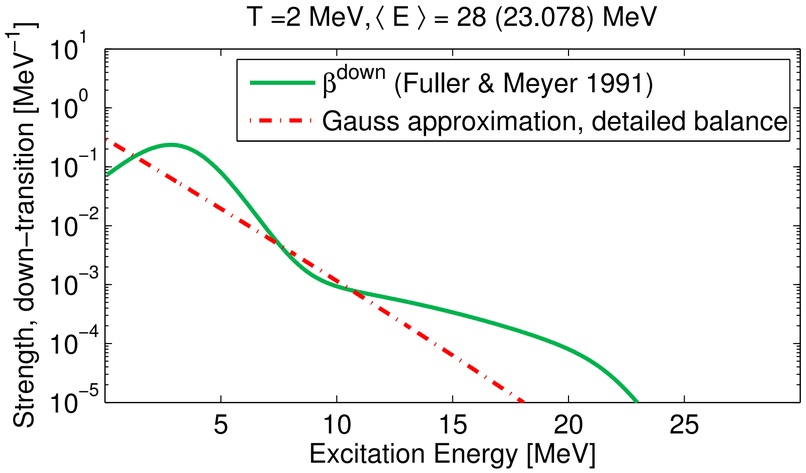
$$e^- + e^+ \leftrightarrows \nu + \bar{\nu}$$

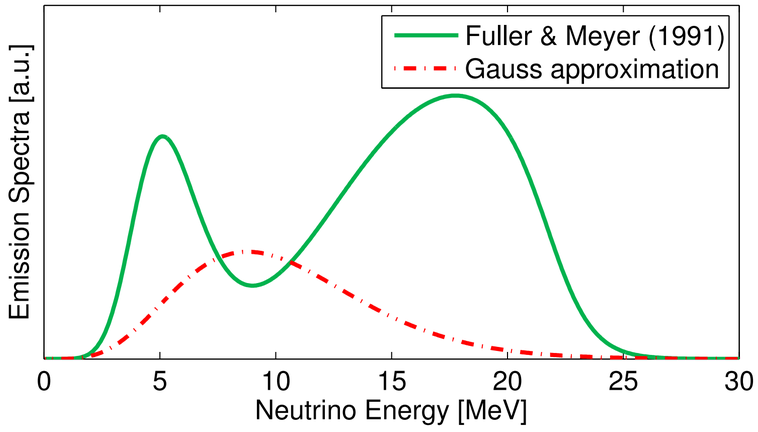
$$N + N \leftrightarrows N + N + \nu + \bar{\nu}$$

$$\nu_\alpha + \bar{\nu}_\alpha \leftrightarrows \nu_\beta + \bar{\nu}_\beta$$

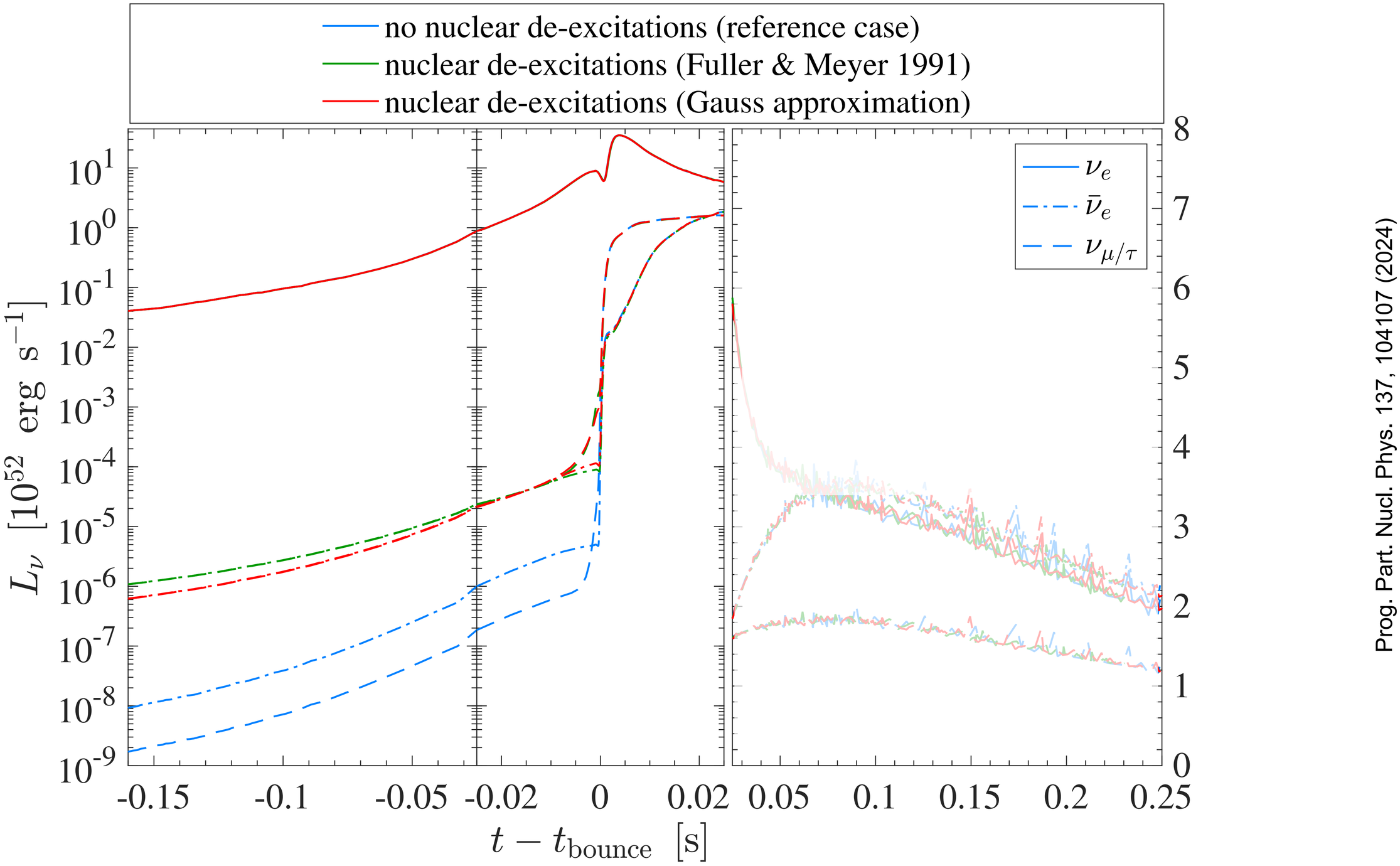




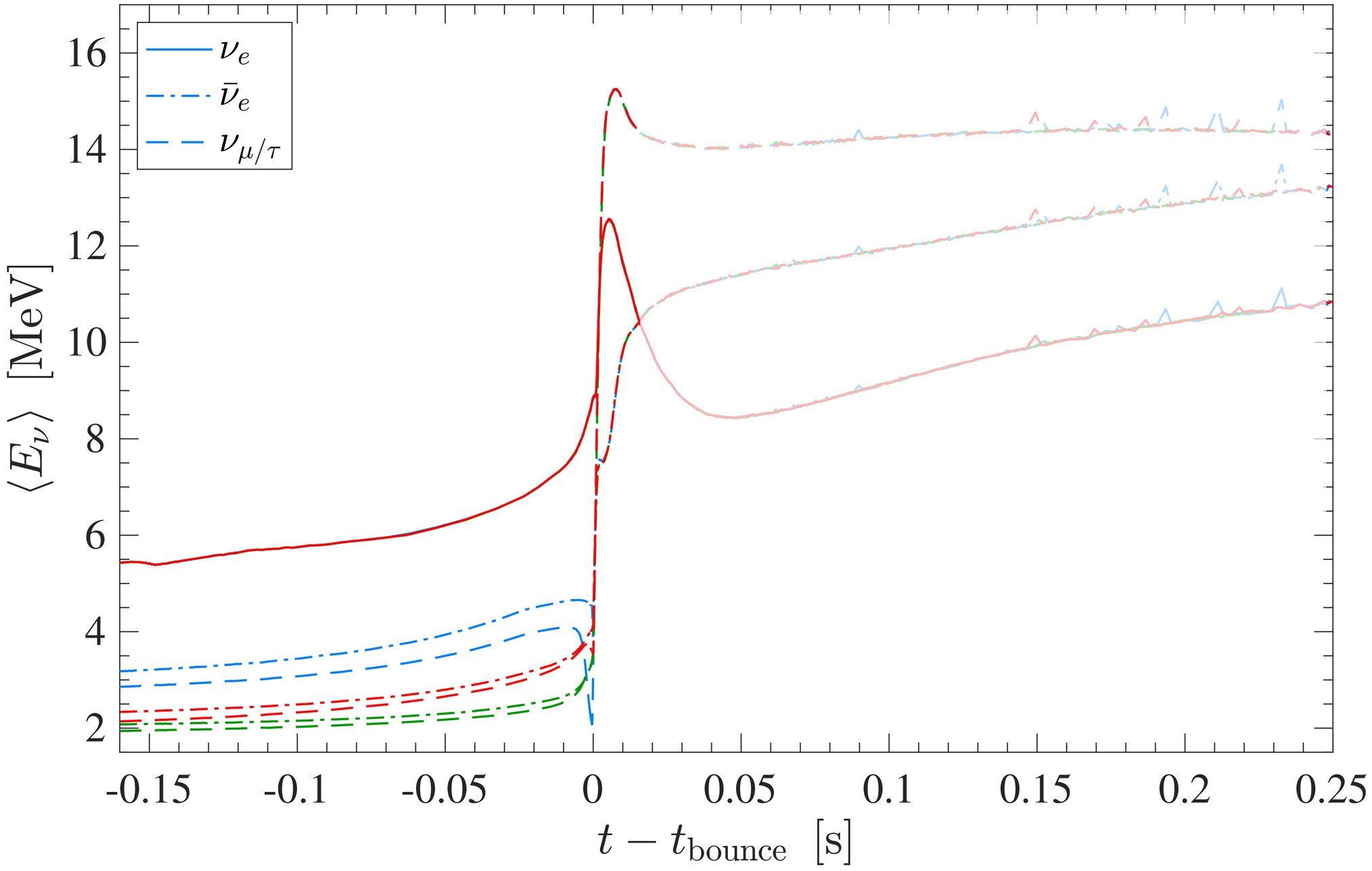




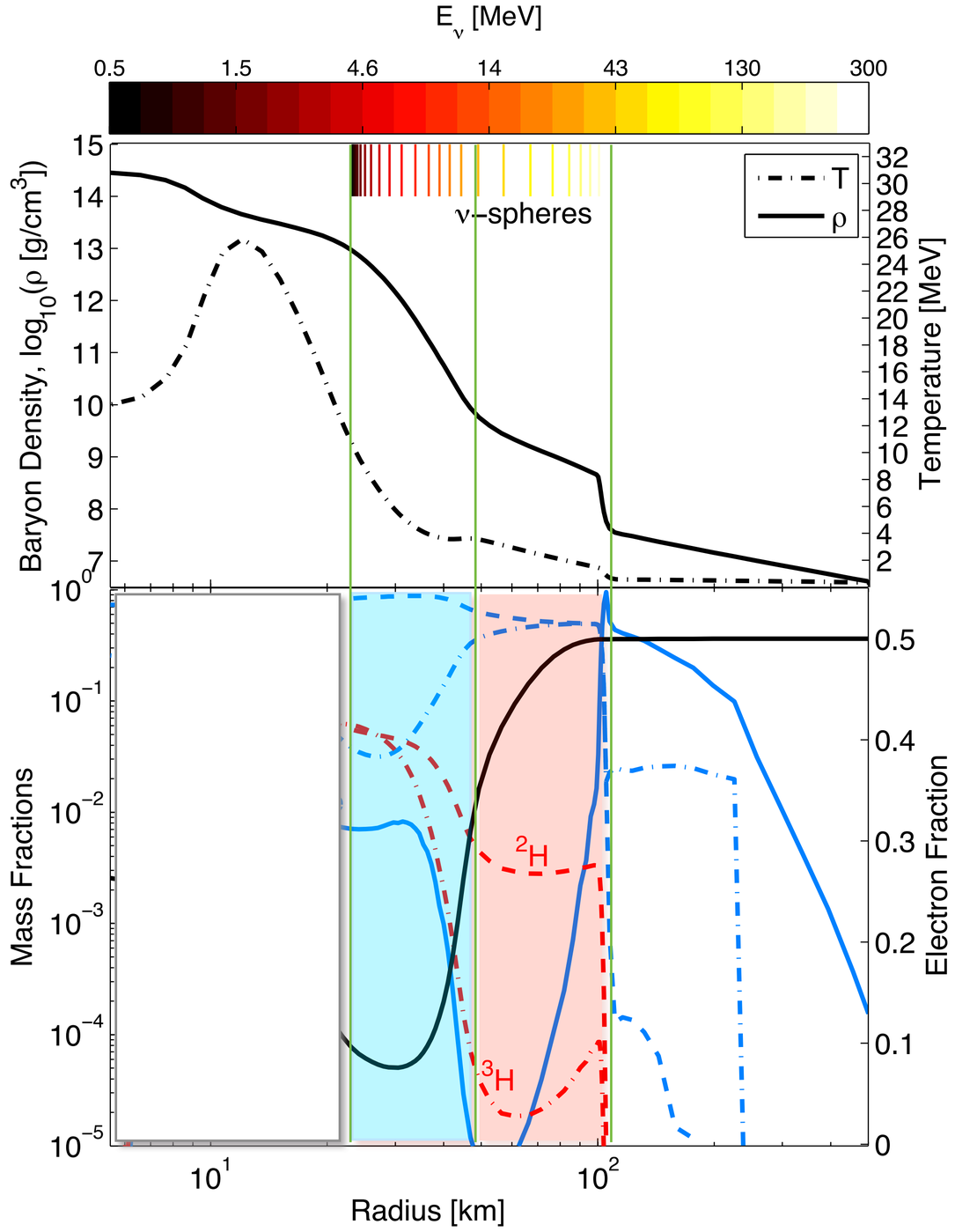
Fuller & Meyer, ApJ 376, 701 (1991)
Fischer et al., Phys. Rev. C88, 06504 (2013)



Prog. Part. Nucl. Phys. 137, 104107 (2024)



Prog. Part. Nucl. Phys. 137, 104107 (2024)



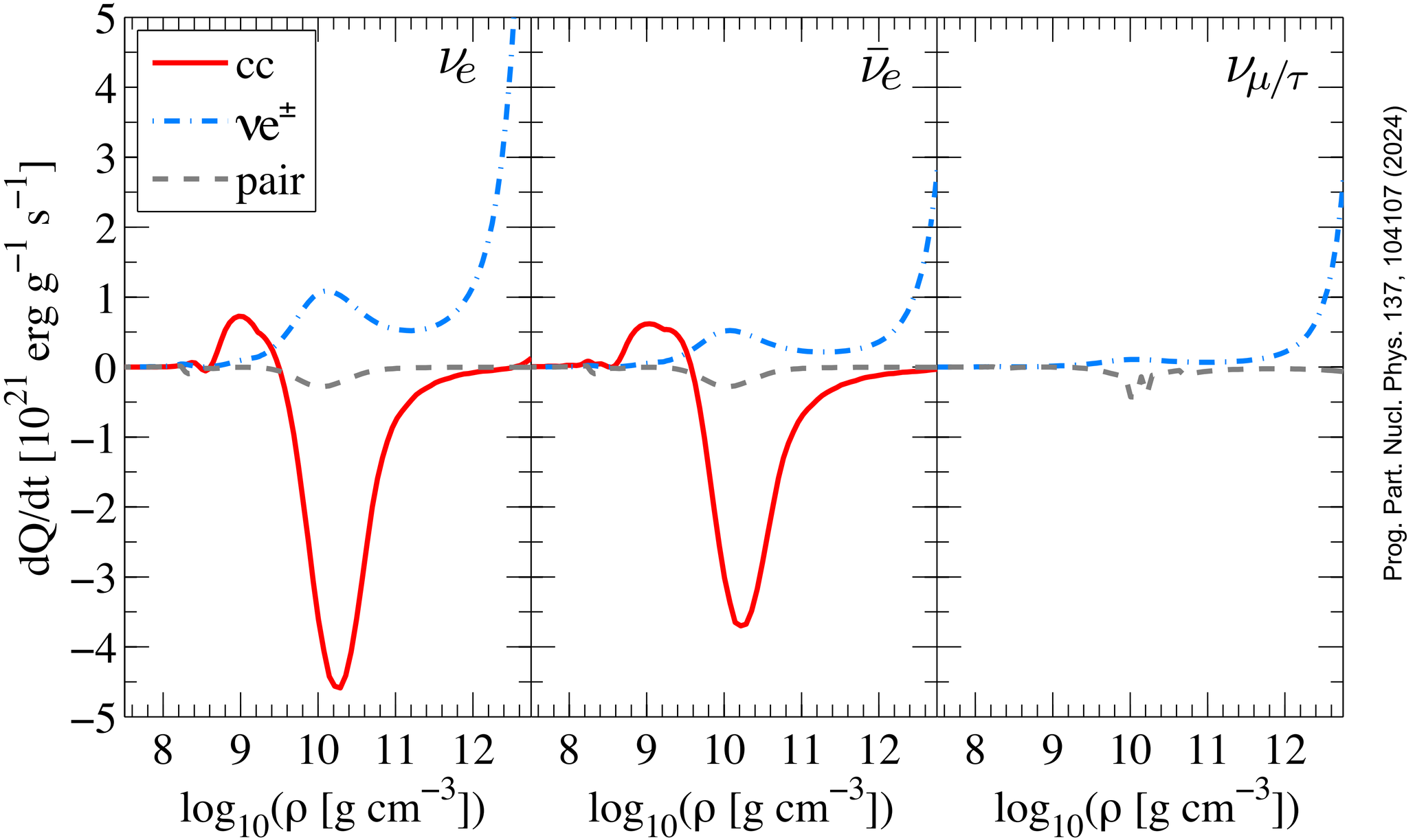
Prog. Part. Nucl. Phys. 137, 104107 (2024)

$$p^\alpha \frac{\partial f}{\partial x^\alpha} - \Gamma^\alpha_{\beta\delta}\, p^\beta p^\delta \frac{\partial f}{\partial p^\alpha} = \Omega(f)$$

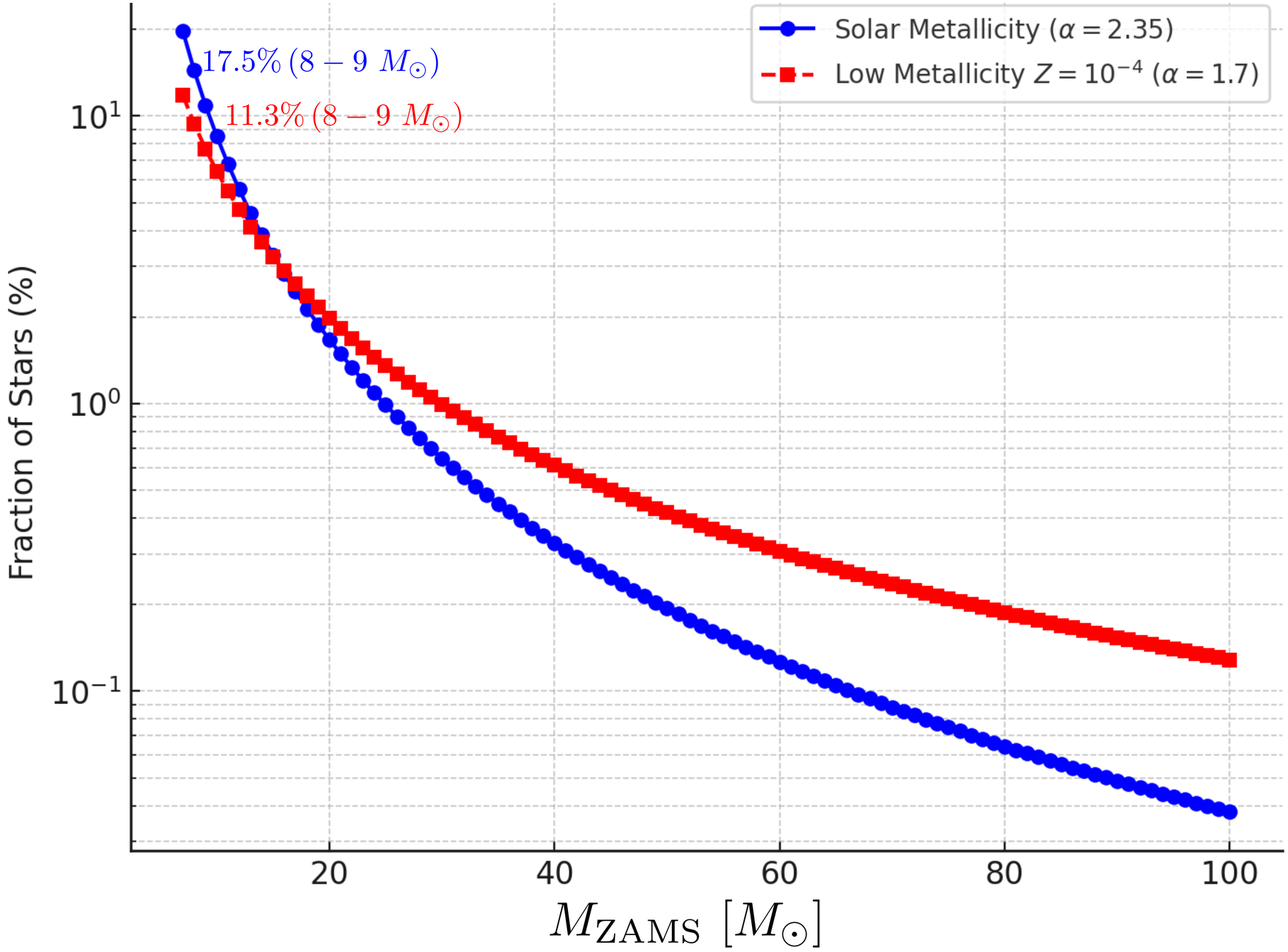
$$(x^\mu, p_\alpha) \longrightarrow (t, a, \cos\theta, \varepsilon \equiv |\mathbf{p}|)$$

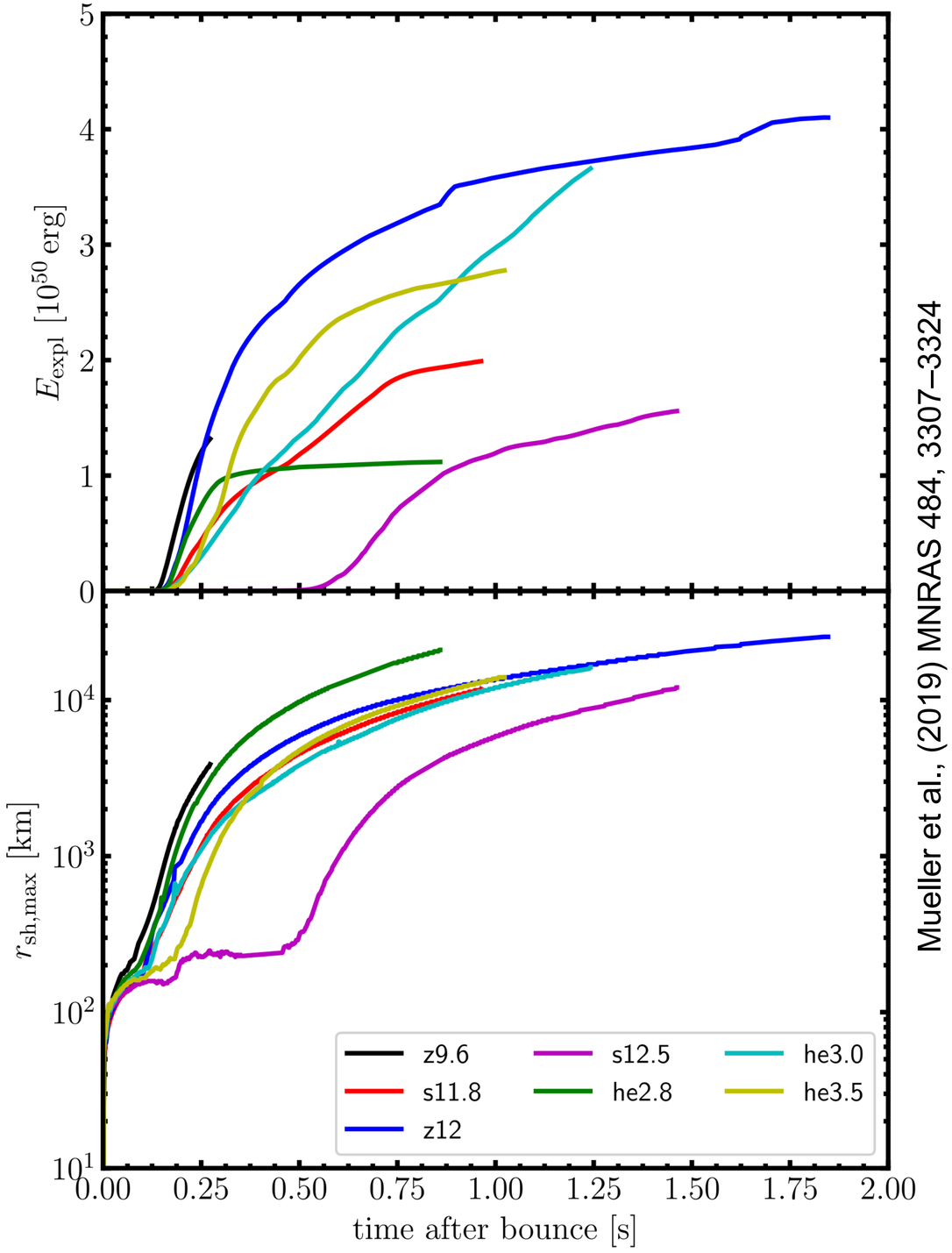
$$f(t, a, \cos\theta, \varepsilon)$$

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

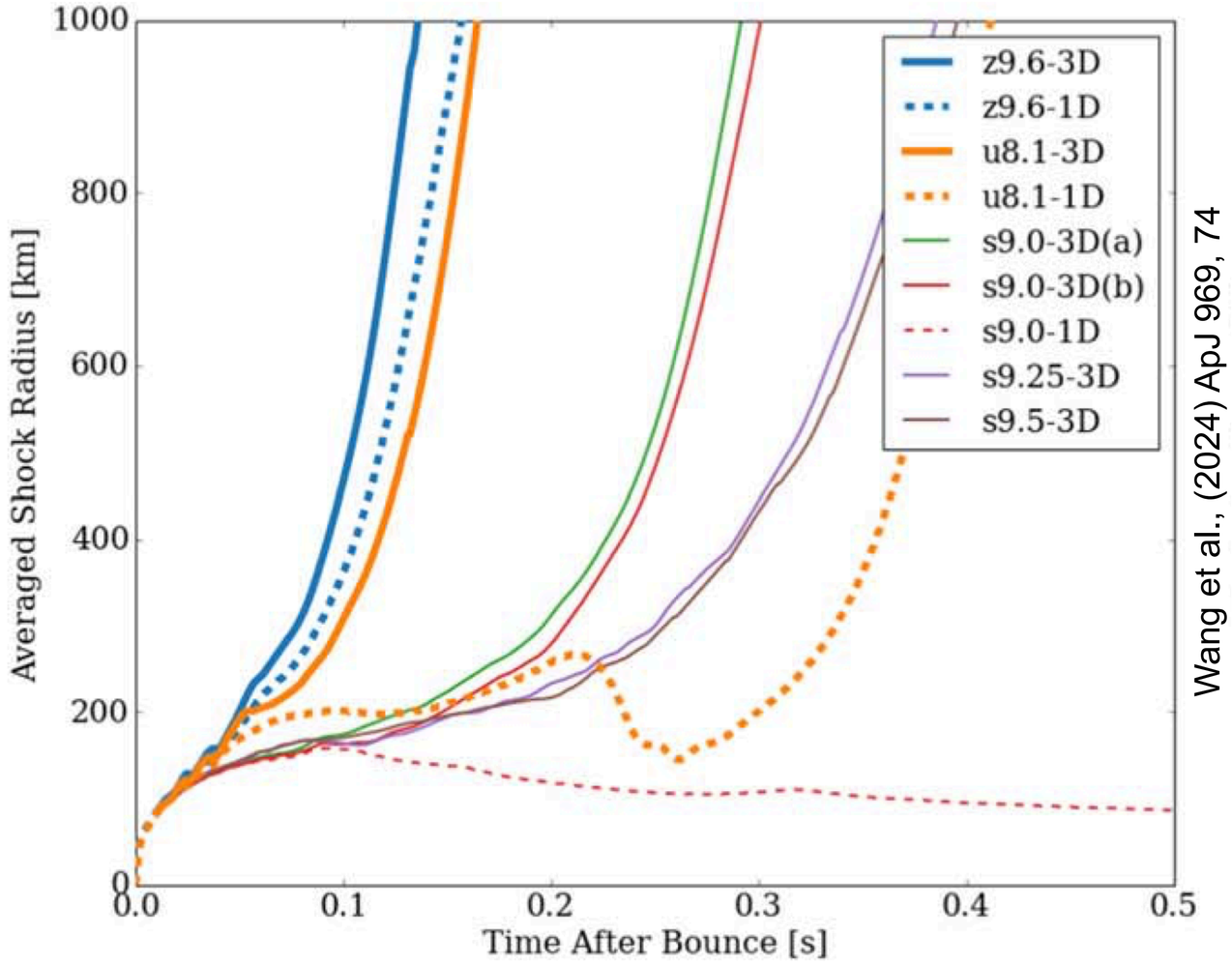


Prog. Part. Nucl. Phys. 137, 104107 (2024)

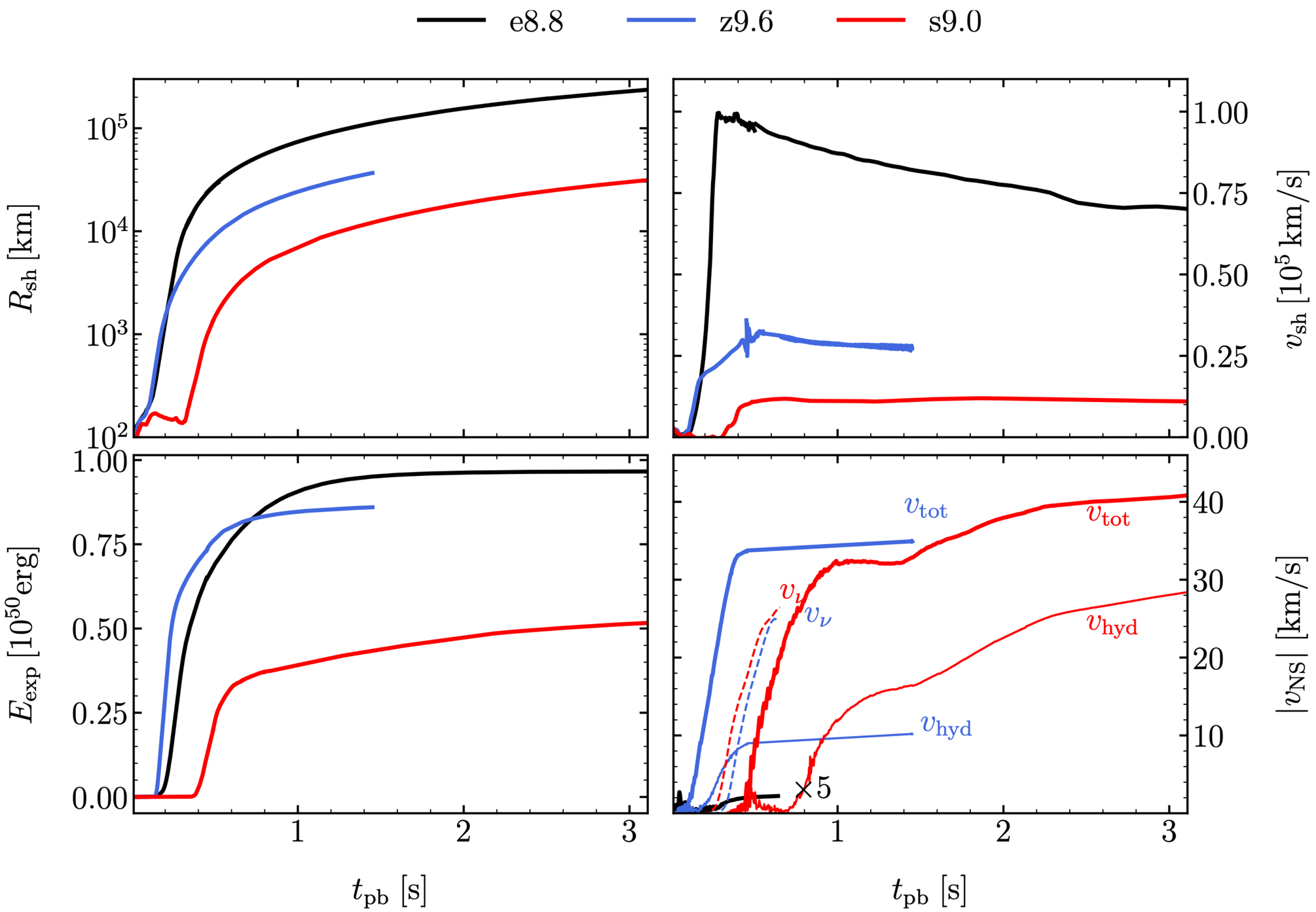

Solar Metallicity ($\alpha = 2.35$)
Low Metallicity $Z = 10^{-4}$ ($\alpha = 1.7$)
$17.5\%\,(8-9\ M_\odot)$
$11.3\%\,(8-9\ M_\odot)$
Fraction of Stars (%)
10^1
10^0
10^{-1}
20
40
60
80
100
$M_{\rm ZAMS}\ [M_\odot]$

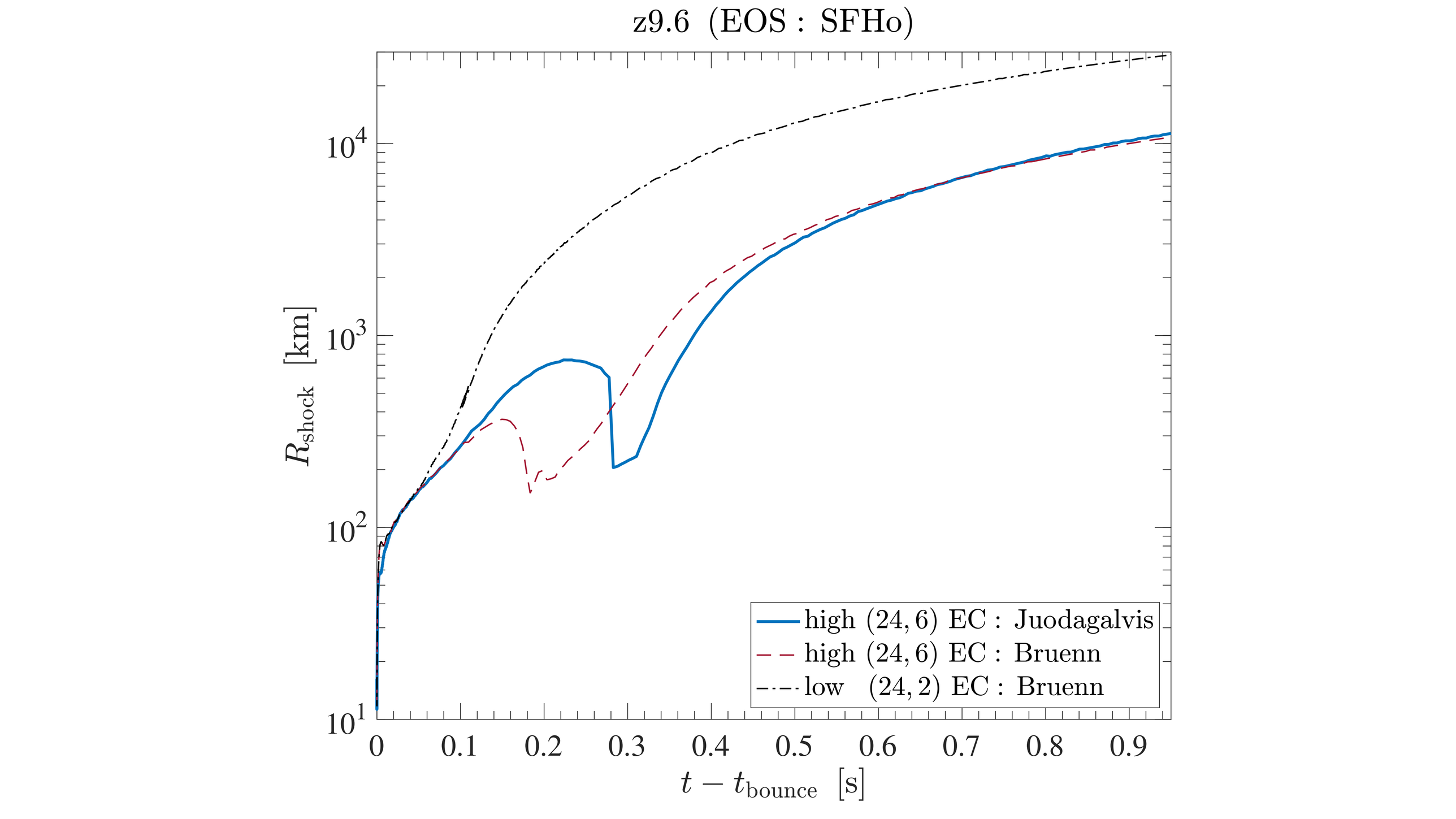


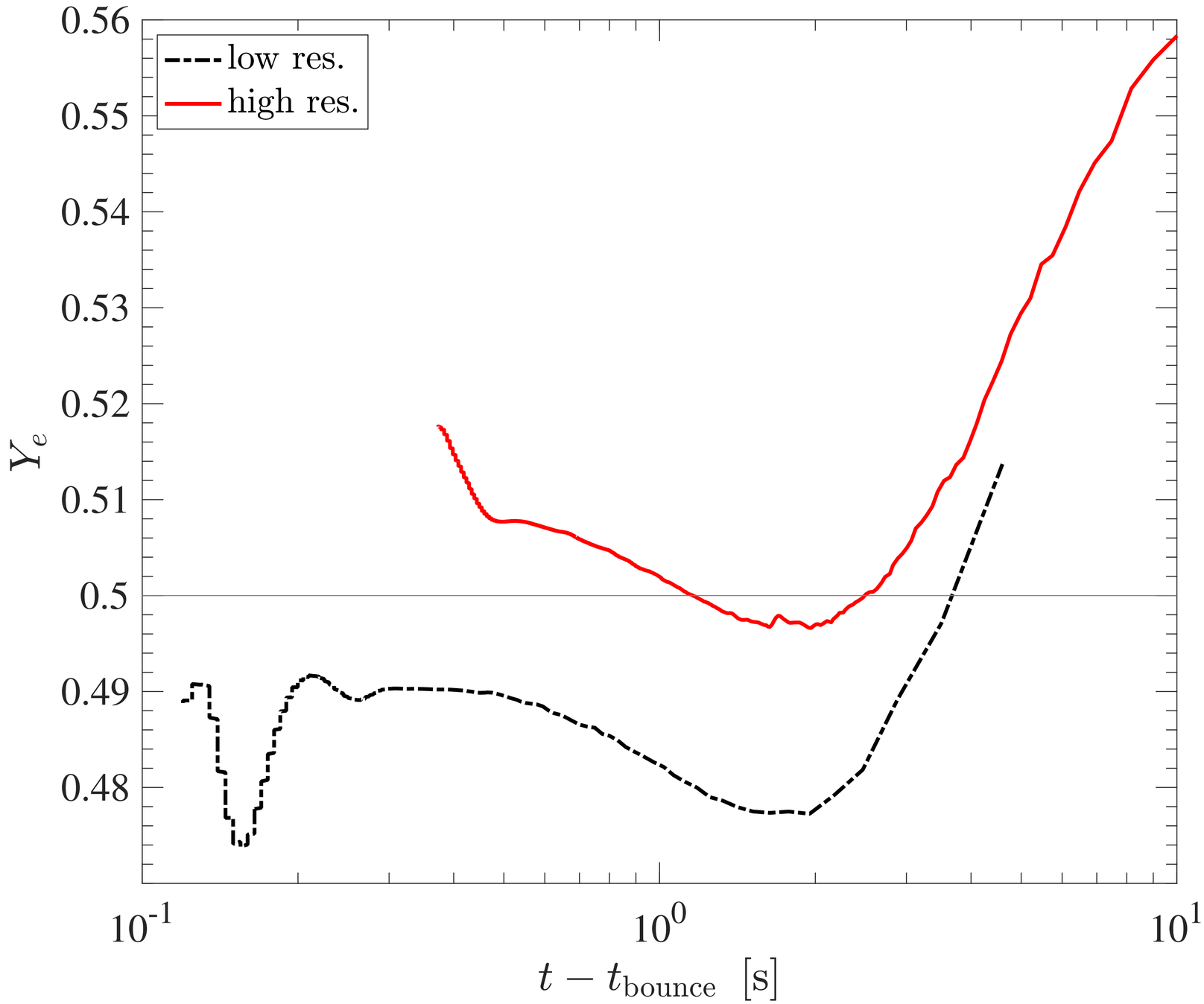
Mueller et al., (2019) MNRAS 484, 3307–3324

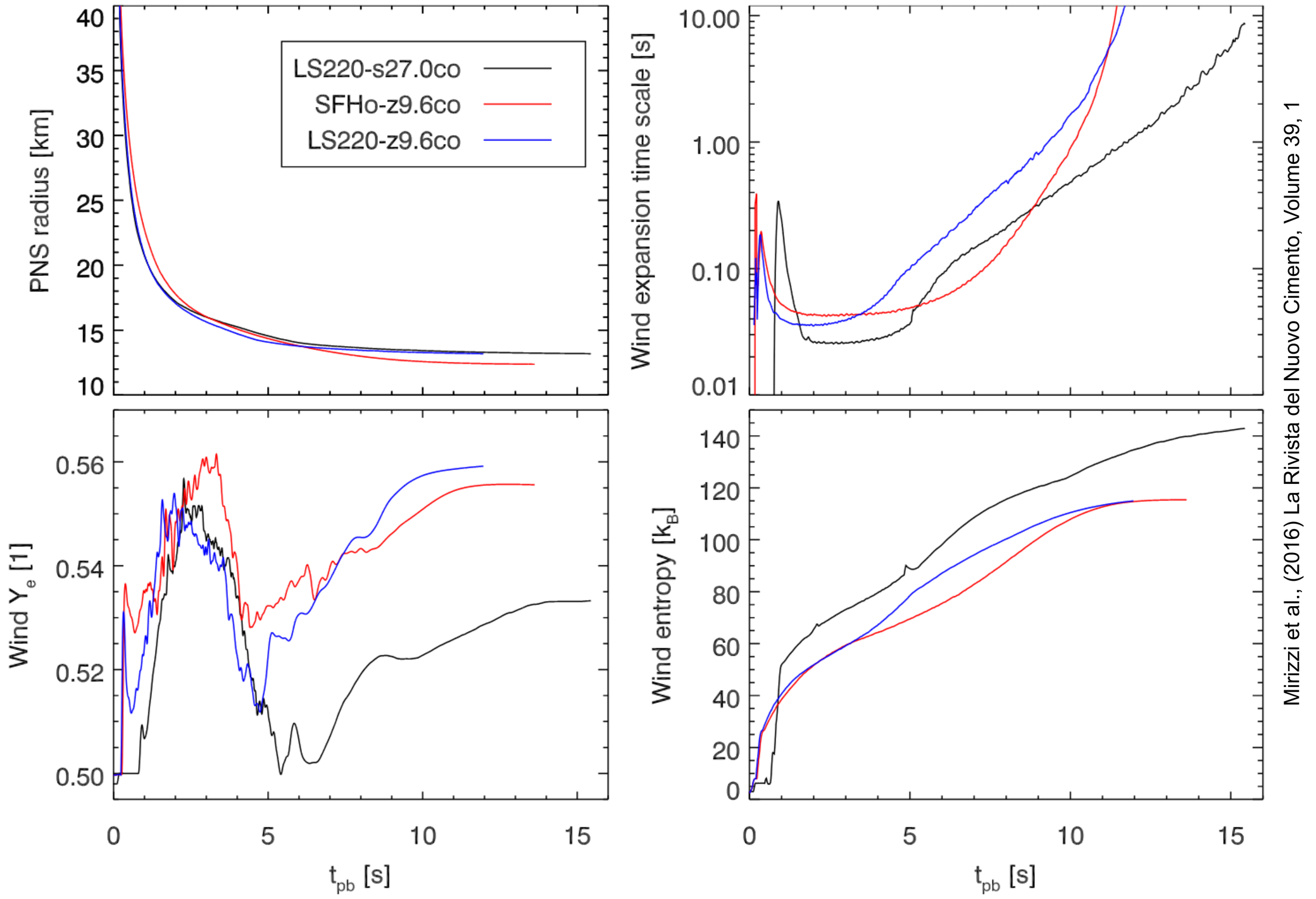


Wang et al., (2024) ApJ 969, 74




z9.6 (EOS : SFHo)
R_{shock} [km]
10^4
10^3
10^2
10^1
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
$t - t_{\mathrm{bounce}}$ [s]
high (24, 6) EC : Juodagalvis
high (24, 6) EC : Bruenn
low (24, 2) EC : Bruenn


z9.6 (EOS : SFHo)
low res.
high res.
0.56
0.55
0.54
0.53
0.52
0.51
0.5
0.49
0.48
Y_e
10^{-1}
10^{0}
10^{1}
$t - t_{\rm bounce}$ [s]



Mirizzi et al., (2016) La Rivista del Nuovo Cimento, Volume 39, 1

The Astrophysical Journal, 852:40 (20pp), 2018 January 1

Nucleosynthesis in the Innermost Ejecta of Neutrino-driven Supernova Explosions in Two Dimensions

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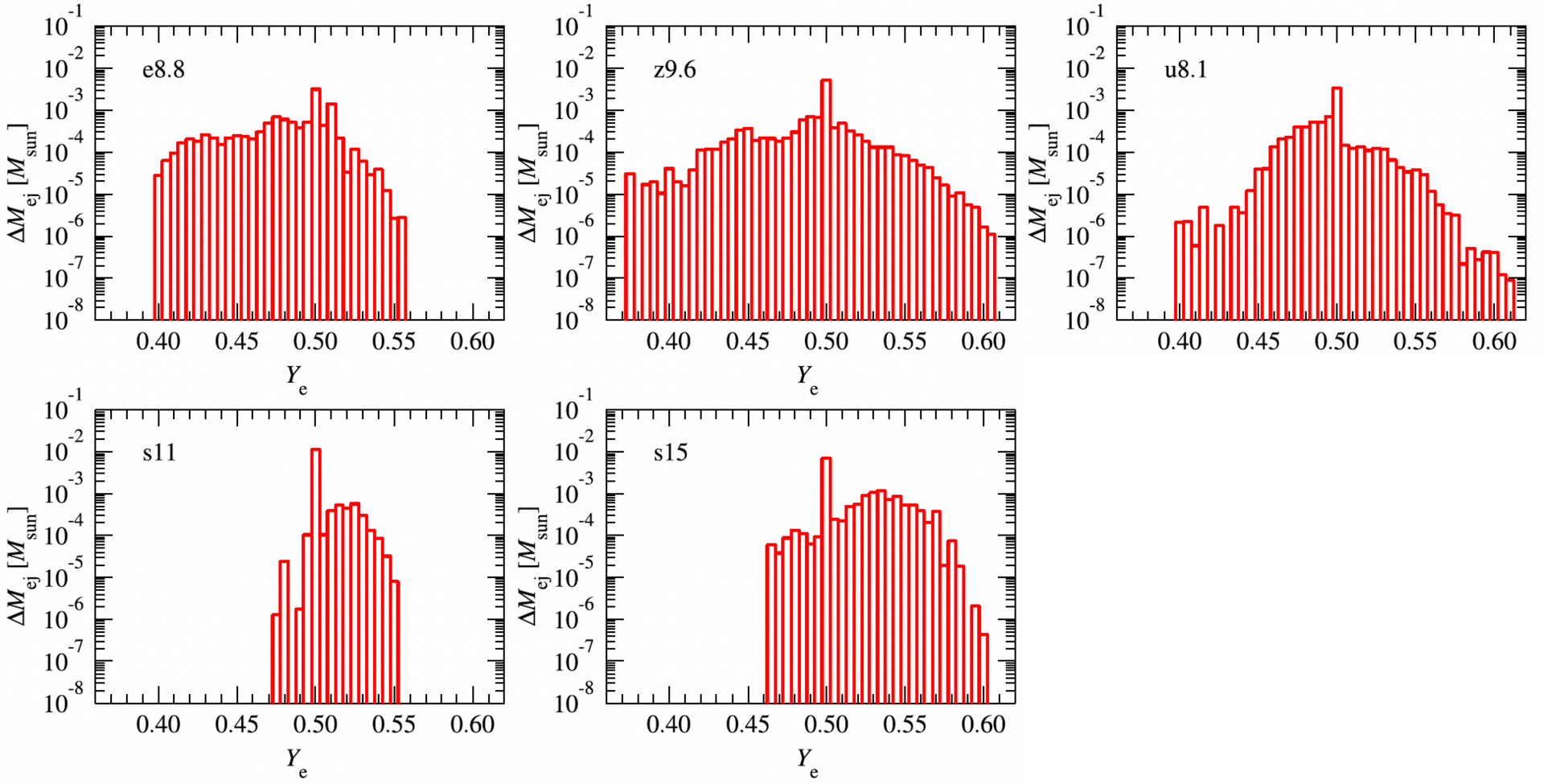
Abstract

We examine nucleosynthesis in the innermost neutrino-processed ejecta (a few $10^{-3}\,M_{\odot}$) of self-consistent two-dimensional explosion models of core-collapse supernovae (CCSNe) for six progenitor stars with different initial masses. Three models have initial masses near the low-mass end of the SN range of $8.8\,M_{\odot}$ (e8.8; electron-capture SN), $9.6\,M_{\odot}$ (z9.6), and $8.1\,M_{\odot}$ (u8.1), with initial metallicities of 1, 0, and 10^{-4} times the solar metallicity, respectively. The other three are solar-metallicity models with initial masses of $11.2\,M_{\odot}$ (s11), $15\,M_{\odot}$ (s15), and $27\,M_{\odot}$ (s27). The low-mass models e8.8, z9.6, and u8.1 exhibit high production factors (nucleosynthetic abundances relative to the solar abundances) of 100–200 for light trans-Fe elements from Zn to Zr. This is associated with an appreciable ejection of neutron-rich matter in these models. Remarkably, the nucleosynthetic outcomes for the progenitors e8.8 and z9.6 are almost identical, including interesting productions of ^{48}Ca and ^{60}Fe, irrespective of their quite different (O–Ne–Mg and Fe) cores prior to collapse. In the more massive models s11, s15, and s27, several proton-rich isotopes of light trans-Fe elements including the *p*-isotope ^{92}Mo (for s27) are made, up to production factors of ∼30. Both electron-capture SNe and CCSNe near the low-mass end can therefore be dominant contributors to the Galactic inventory of light trans-Fe elements from Zn to Zr and probably ^{48}Ca and live ^{60}Fe. The innermost ejecta of more massive SNe may have only subdominant contributions to the chemical enrichment of the Galaxy except for ^{92}Mo.

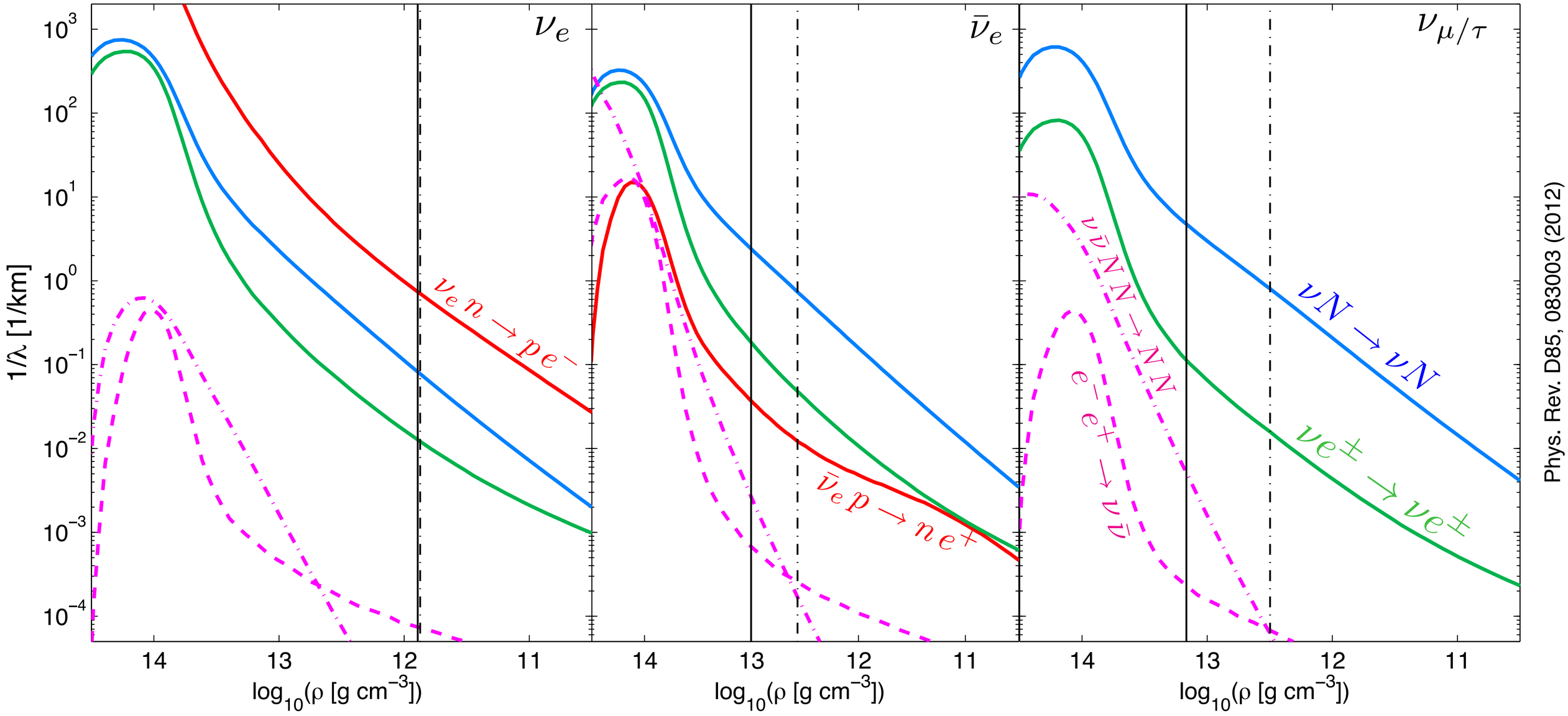
Properties of Innermost SN Ejecta

Model	Type	$M_{\rm PNS}$[a] ($M_\odot$)	$M_{\rm ej}$[b] ($10^{-3}\,M_\odot$)	$M_{\rm ej,n}$[c] ($10^{-3}\,M_\odot$)	$Y_{\rm e,min}$[d]	$Y_{\rm e,max}$[e]	$S_{\rm min}$[f] ($k_{\rm B}$ nuc^{-1})	$S_{\rm max}$[g] ($k_{\rm B}$ nuc^{-1})
e8.8	ECSN	1.36	11.4	5.83	0.398	0.555	9.80	383
z9.6	CCSN	1.36	12.4	4.94	0.373	0.603	12.6	27.8
u8.1	CCSN	1.36	7.69	3.24	0.399	0.612	9.83	29.9
s11	CCSN	1.36	14.1	0.133	0.474	0.551	6.64	34.7
s15	CCSN	1.58	15.9	0.592	0.464	0.598	6.78	36.7



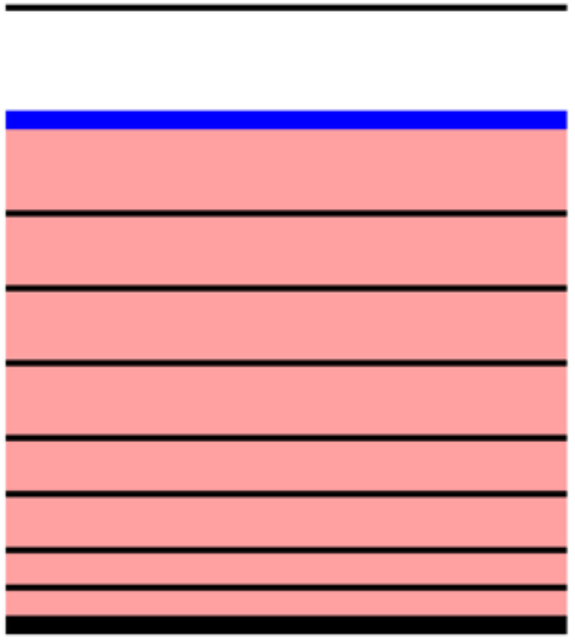
Weak rates

$$\frac{1}{\lambda_\nu} = \frac{1}{n_\nu} \int \frac{d^3k}{(2\pi)^3} \frac{1}{\lambda_\nu}(\mathbf{k})\, f_\nu(\mathbf{k})$$



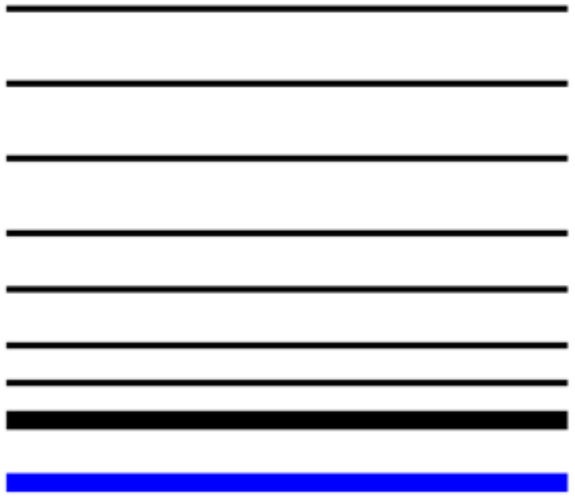
Phys. Rev. D85, 083003 (2012)

$$E_n = \sqrt{p^2 + (m_n^*)^2} + U_n$$

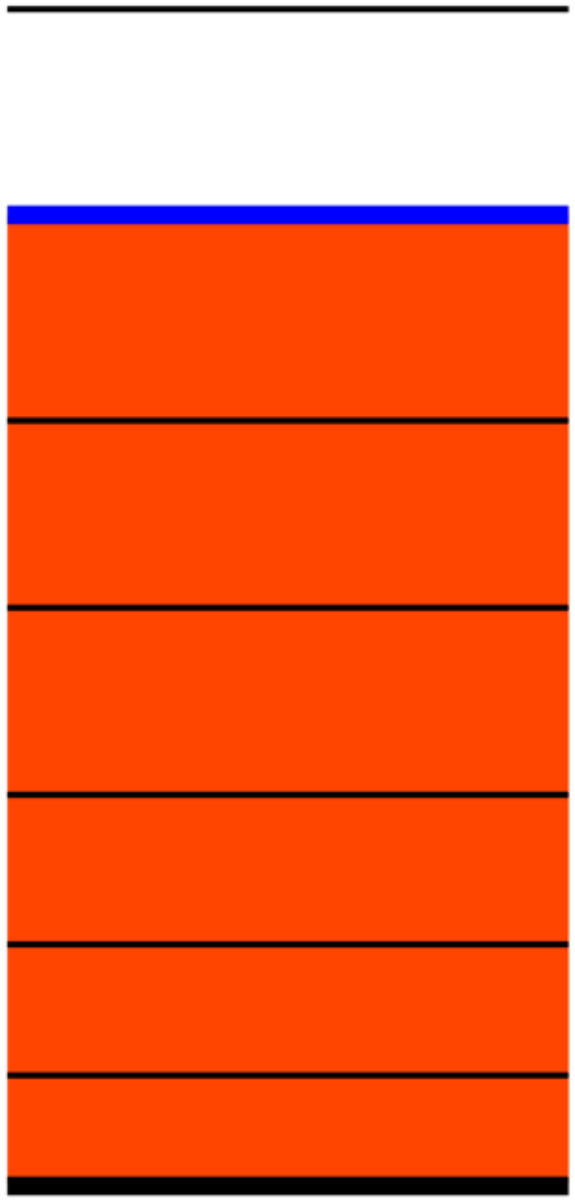


μ_n

$$E_p = \sqrt{p^2 + (m_p^*)^2} + U_p$$



μ_p



μ_e

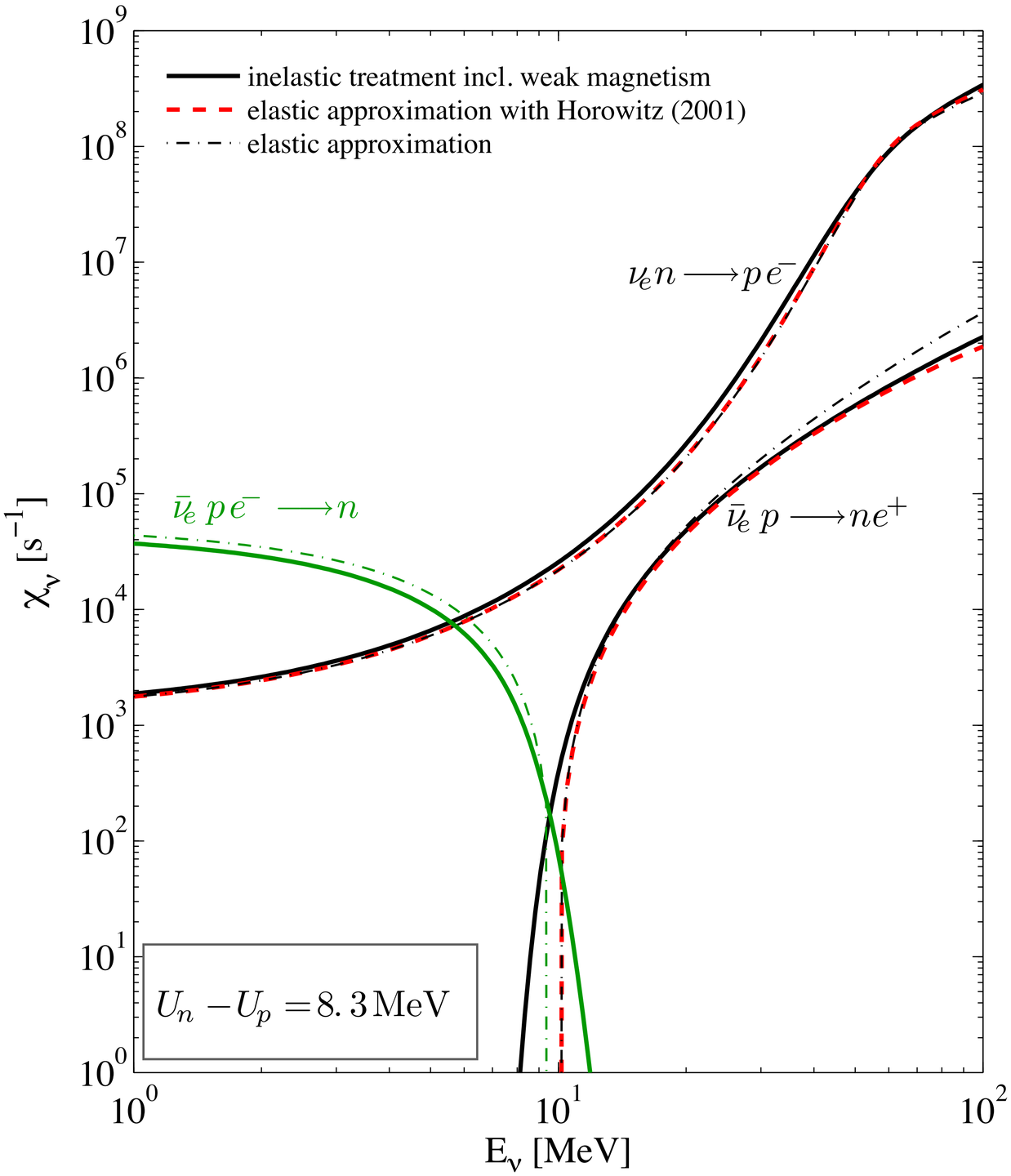
Phys. Rev. C95, 045807 (2017)

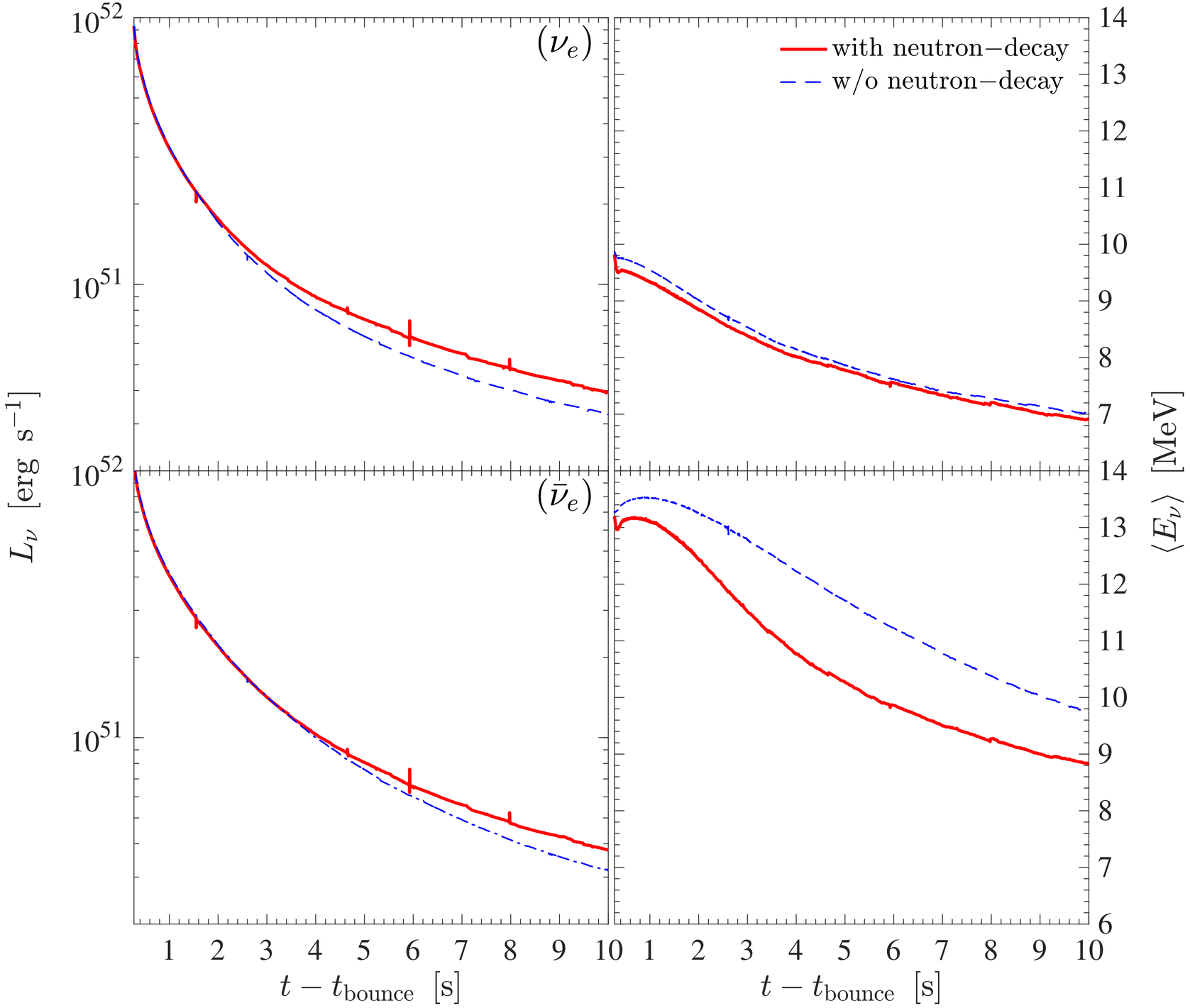
Phys. Rev. C 101, 025804 (2020)

Phys. Rev. C 102, 023037 (2020)

$$
\begin{aligned}
T &= 7\ \mathrm{MeV}\ , \\
Y_p &= 0.1\ , \\
\rho &= 2\times 10^{13}\ \mathrm{g\ cm^{-3}}
\end{aligned}
$$

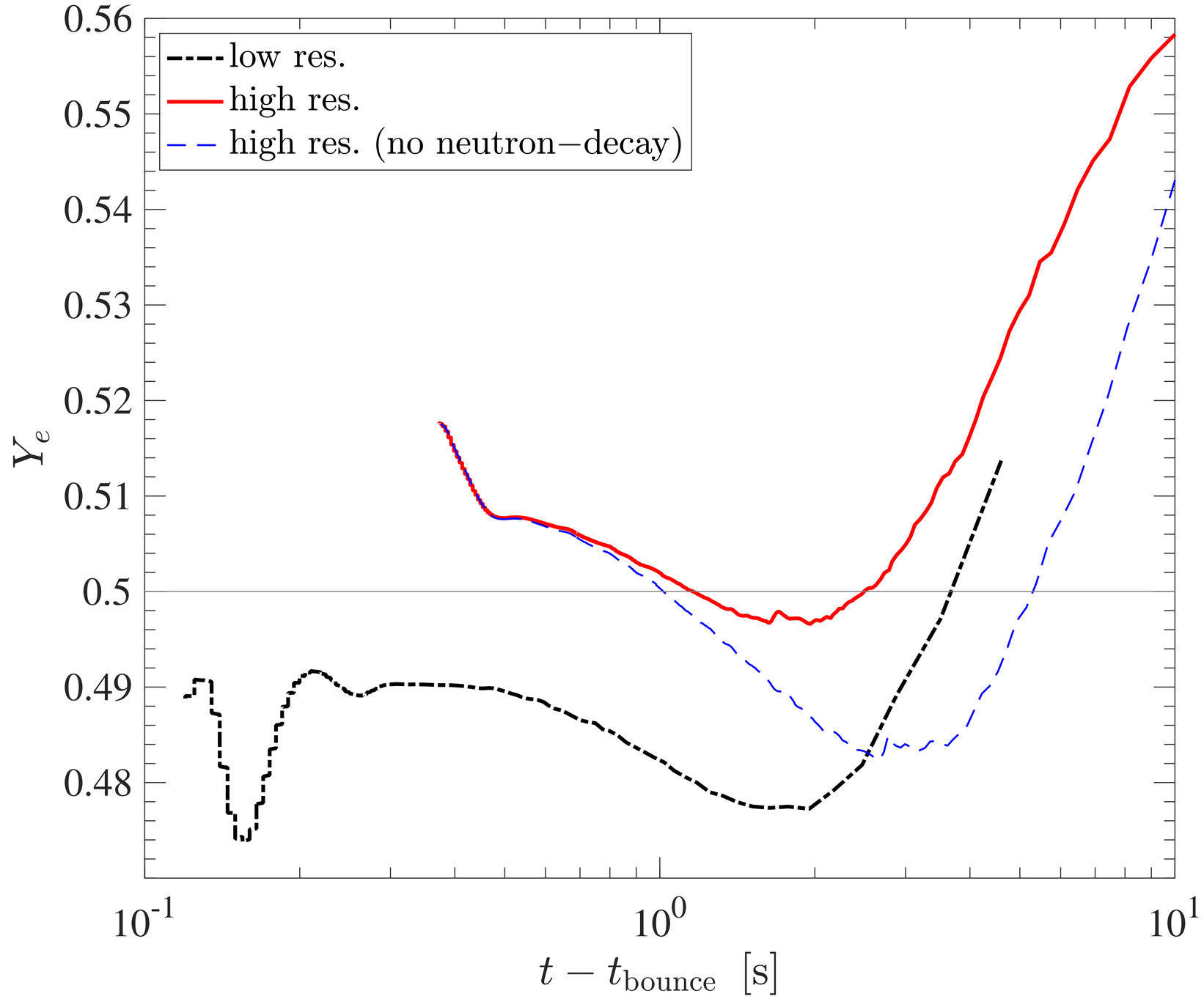
$$
\begin{aligned}
E_{e^-} &= E_{\nu_e} + (E_n - E_p) \\
E_{e^+} &= E_{\bar{\nu}_e} - (E_n - E_p) \\
E_{e^-} &= -E_{\bar{\nu}_e} + (E_n - E_p)
\end{aligned}
$$

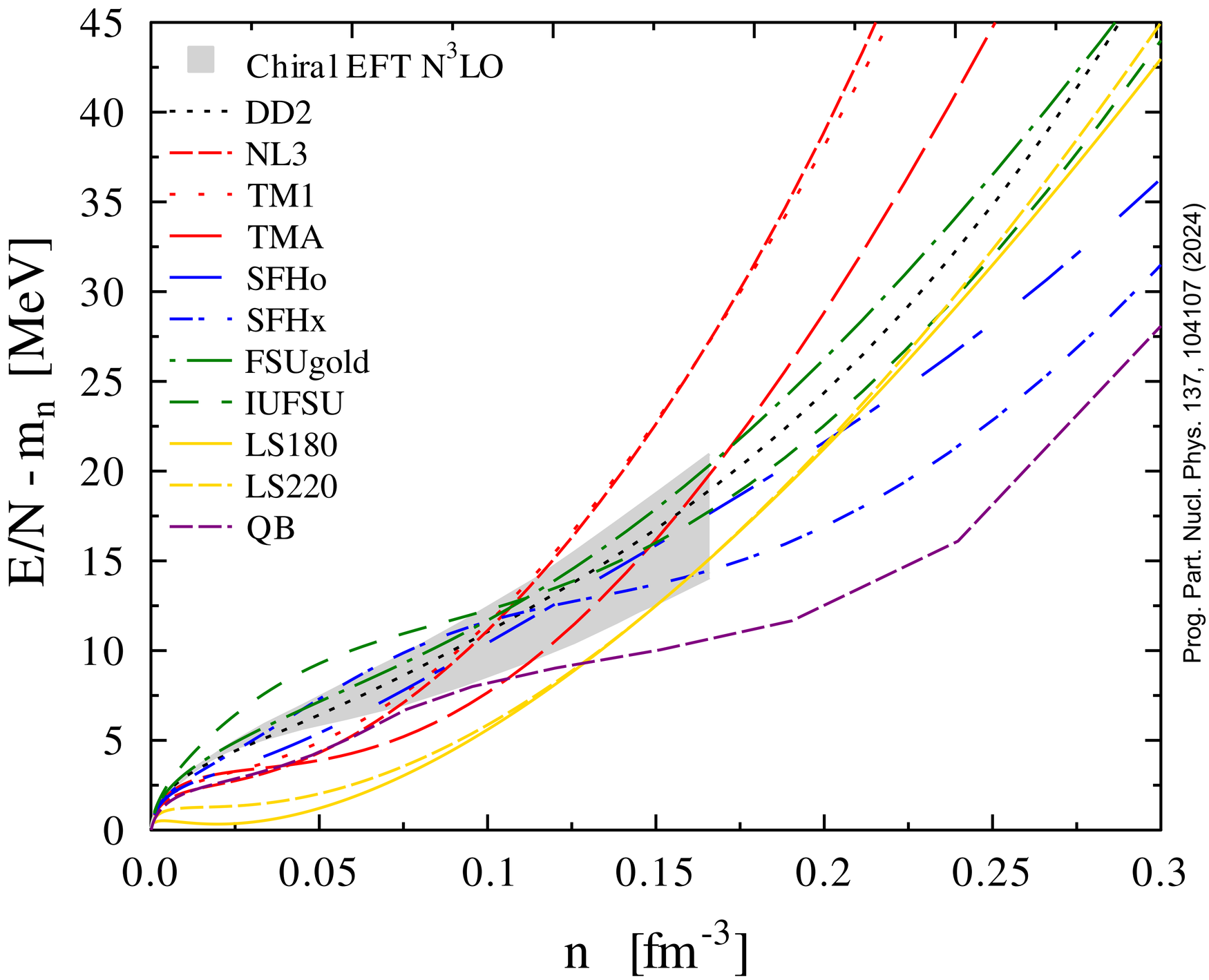



(ν_e)
$(\bar{\nu}_e)$
with neutron−decay
w/o neutron−decay
L_ν [erg s^{-1}]
$\langle E_\nu \rangle$ [MeV]
$t - t_{\rm bounce}$ [s]
$t - t_{\rm bounce}$ [s]
10^{52}
10^{51}
10^{52}
10^{51}
1 2 3 4 5 6 7 8 9 10
1 2 3 4 5 6 7 8 9 10
14 13 12 11 10 9 8 7
14 13 12 11 10 9 8 7 6

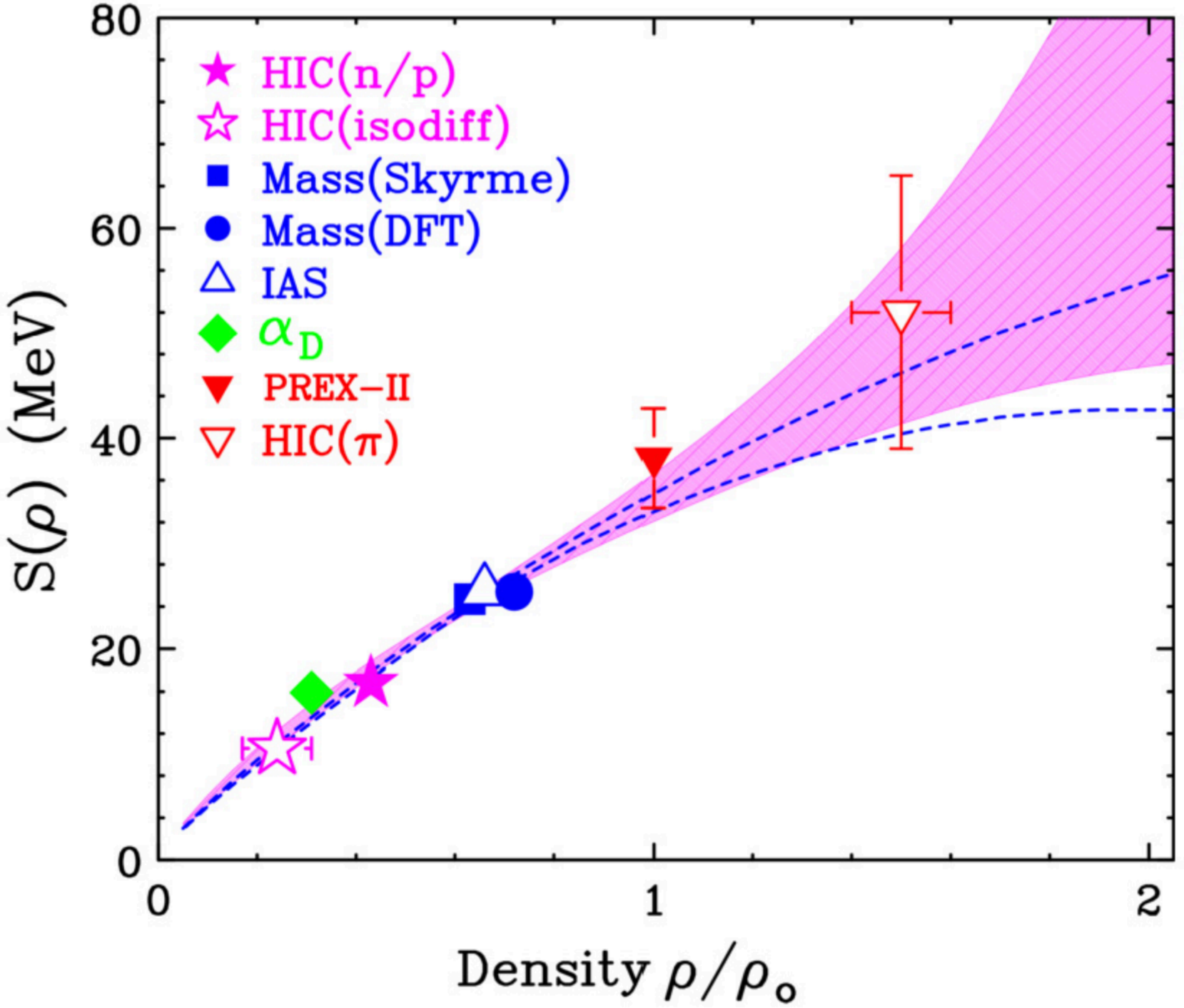
z9.6 (EOS : SFHo)

z9.6 (EOS : SFHo)


low res.
high res.
high res. (no neutron−decay)
0.56
0.55
0.54
0.53
0.52
0.51
0.5
0.49
0.48
Y_e
10^{-1}
10^{0}
10^{1}
$t - t_{\rm bounce}$ [s]



Prog. Part. Nucl. Phys. 137, 104107 (2024)

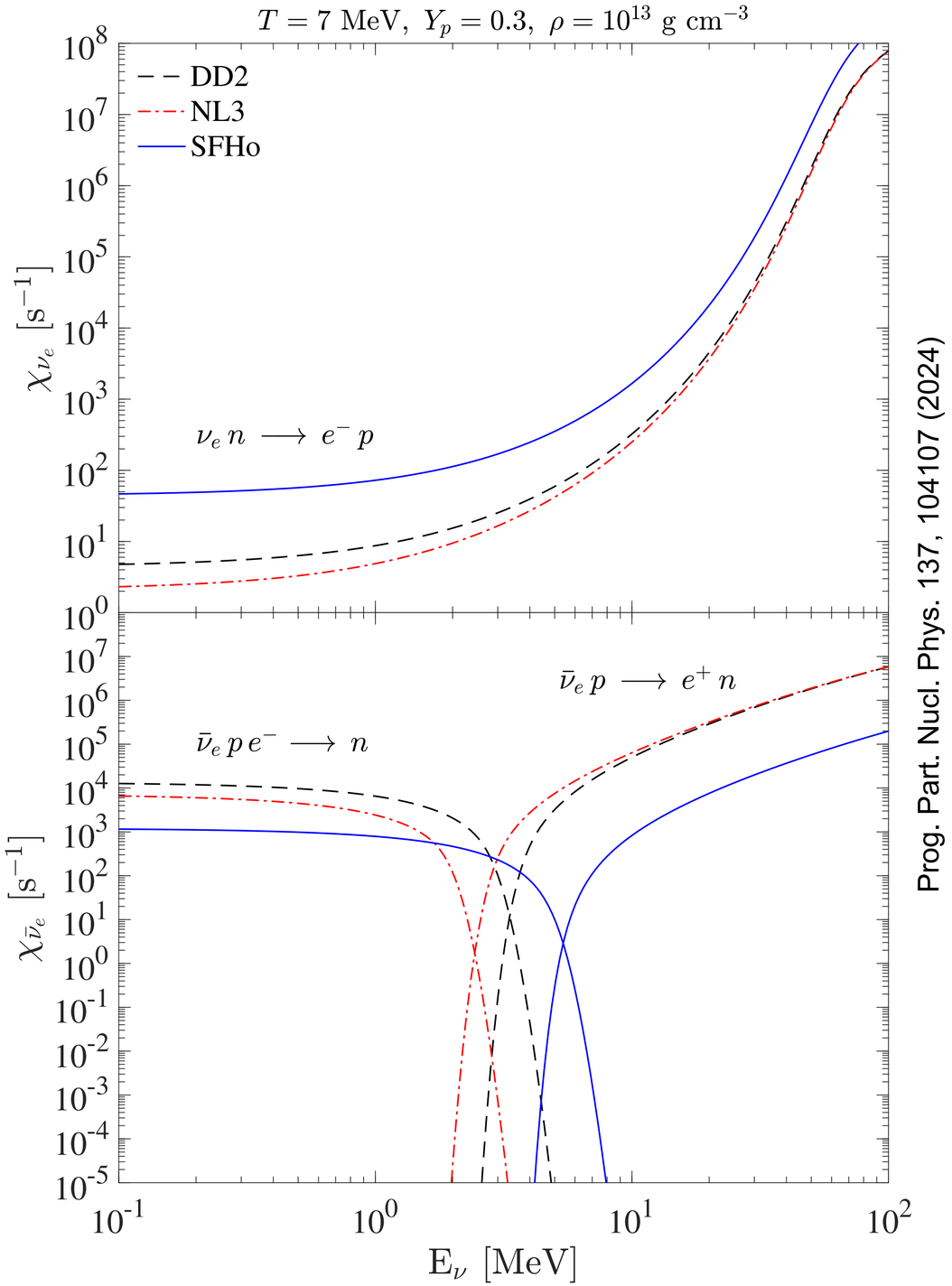


Phys. Lett. B 830, 137098 (2024)

$$G_V(q^2) - \gamma^5 G_A(q^2)$$

$$+ \frac{iF_2(q^2)}{2M_N} \sigma^{\mu\nu} q^*_\nu$$

$$- \frac{2M_N}{m_\pi^2 - q^2} \gamma^5 G_A(q^2) q^{*\mu}$$



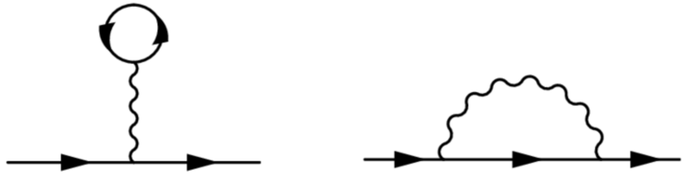
Prog. Part. Nucl. Phys. 137, 104107 (2024)

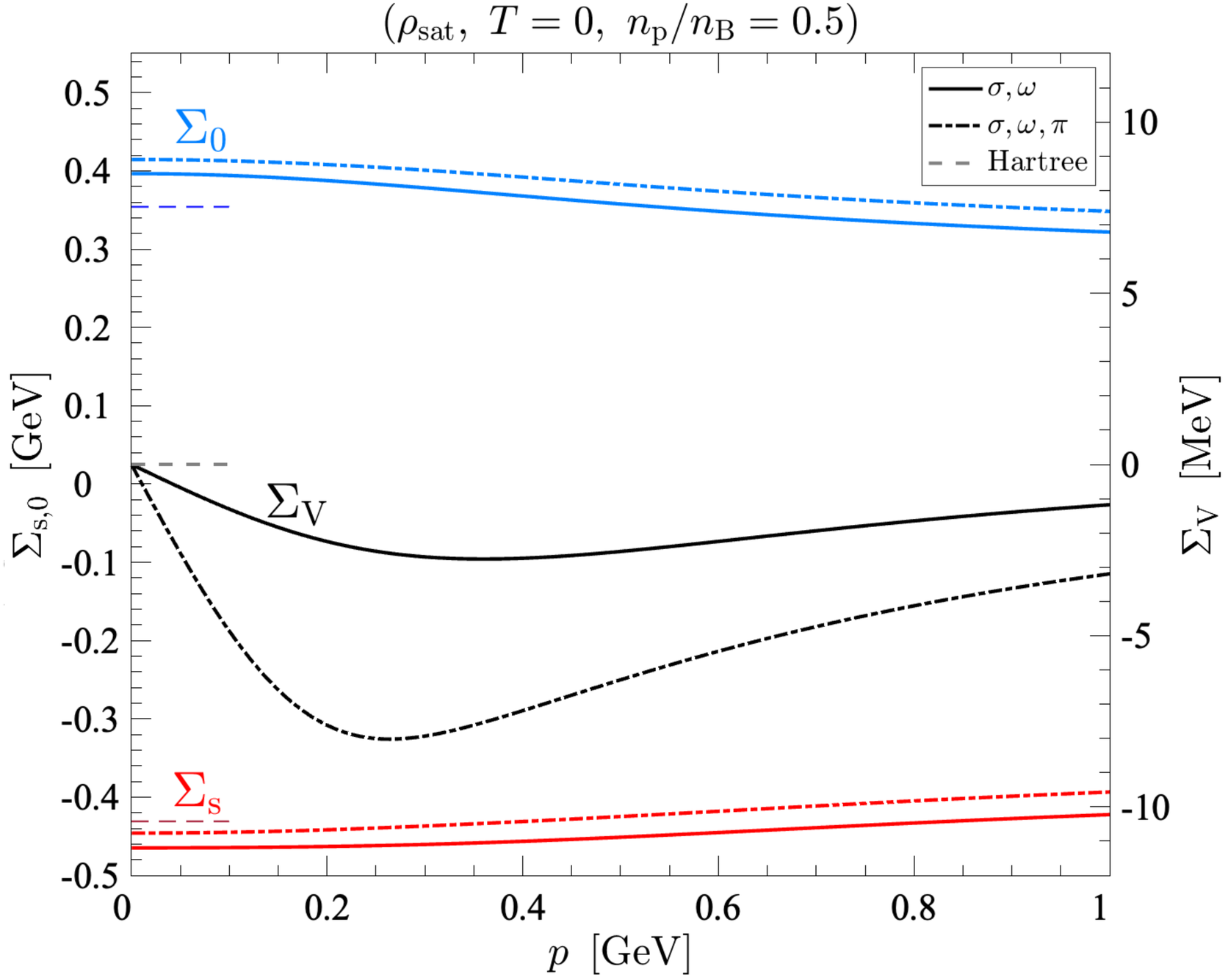
Neutrinos from core-collapse supernovae

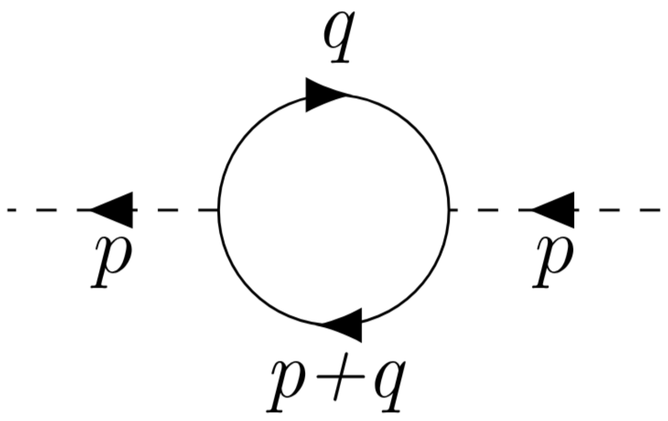
Summary and conclusions

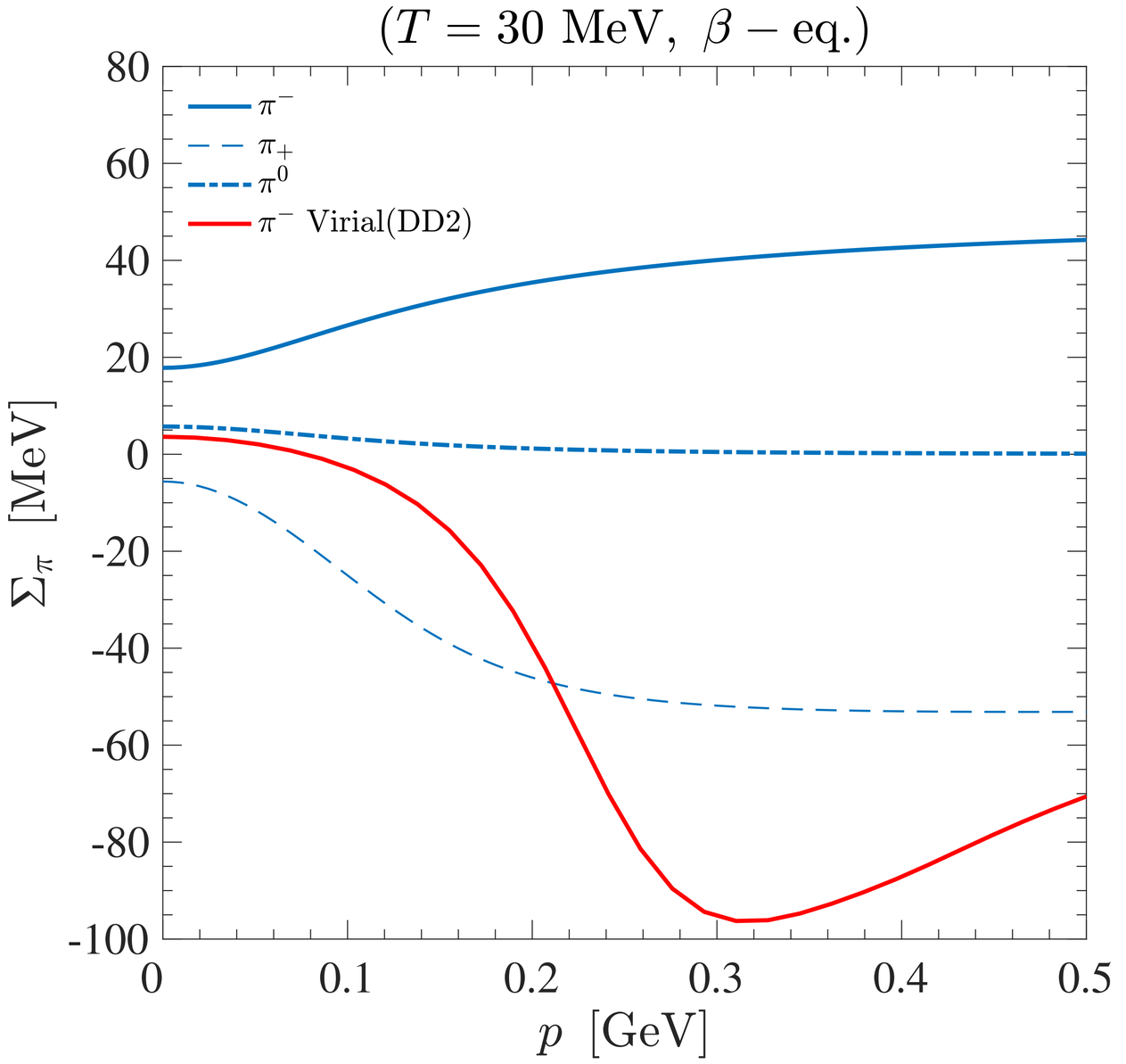
What's to be done:

- **EOS & weak rates**

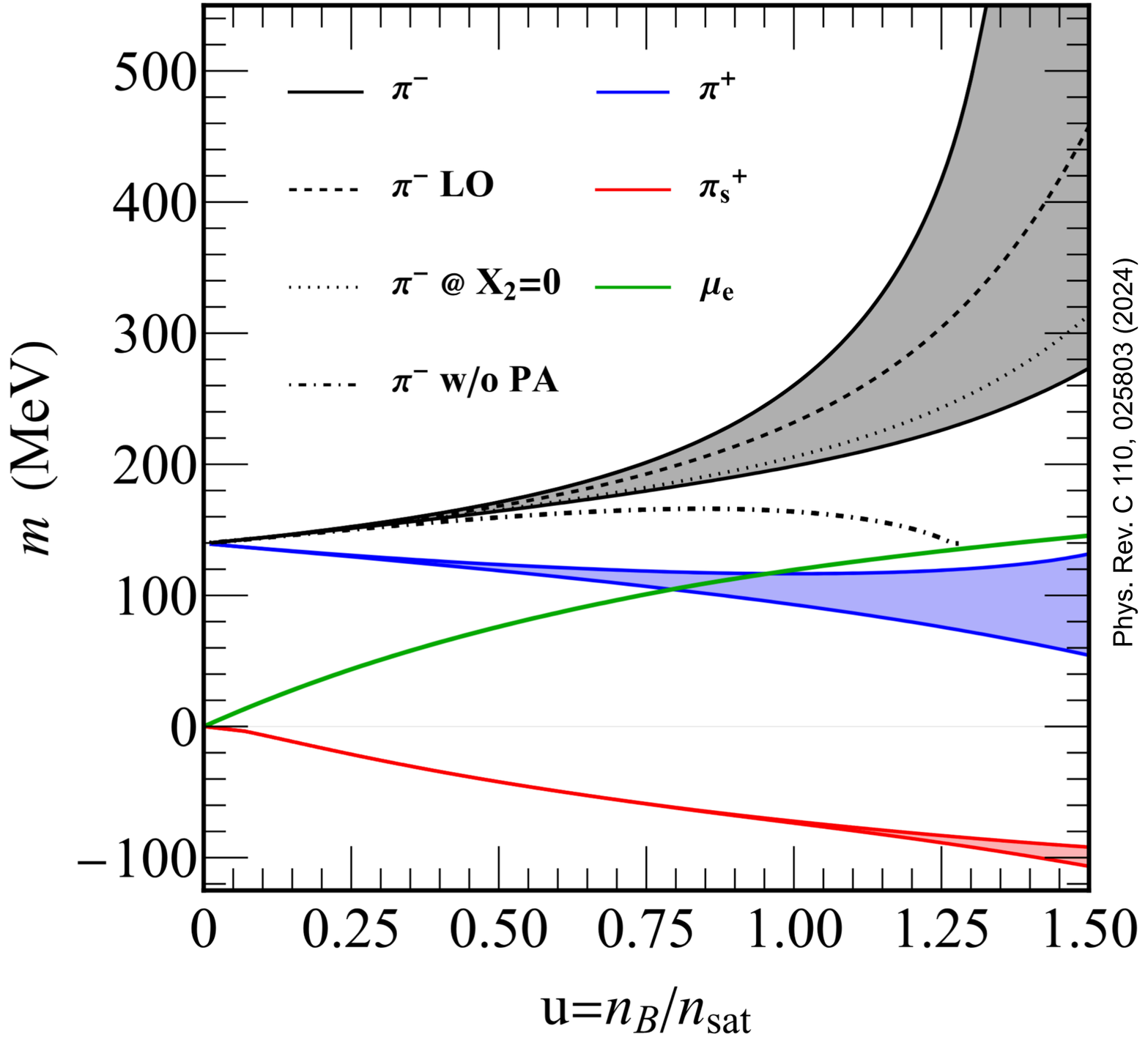




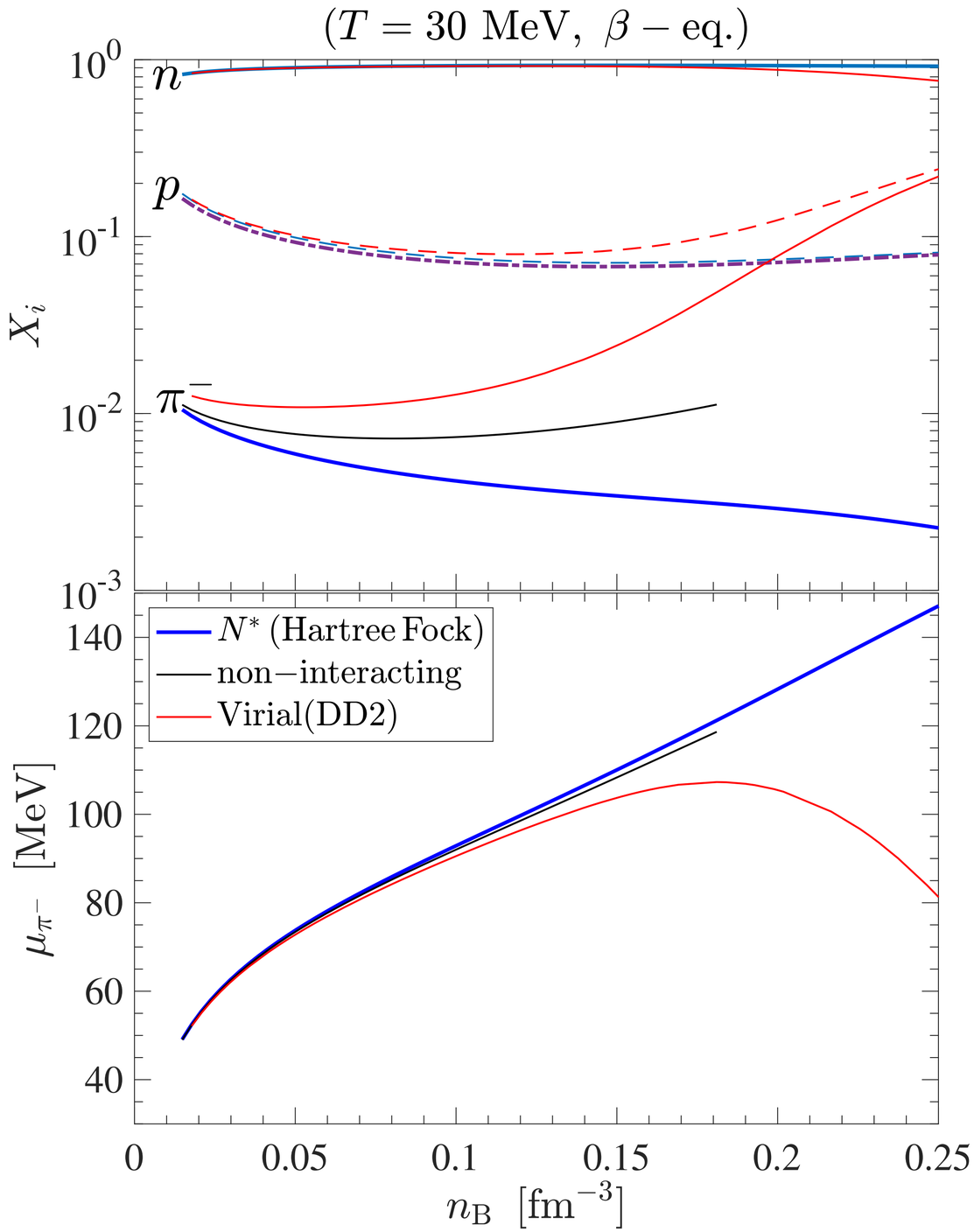




$$\Pi(p) = -i\left(\frac{f_\pi}{m_\pi}\right)^2 \int \frac{d^4q}{(2\pi)^4}\,\mathrm{Tr}\left[\not{p}\gamma^5 G(p+q)\not{p}\gamma^5 G(q)\right]$$



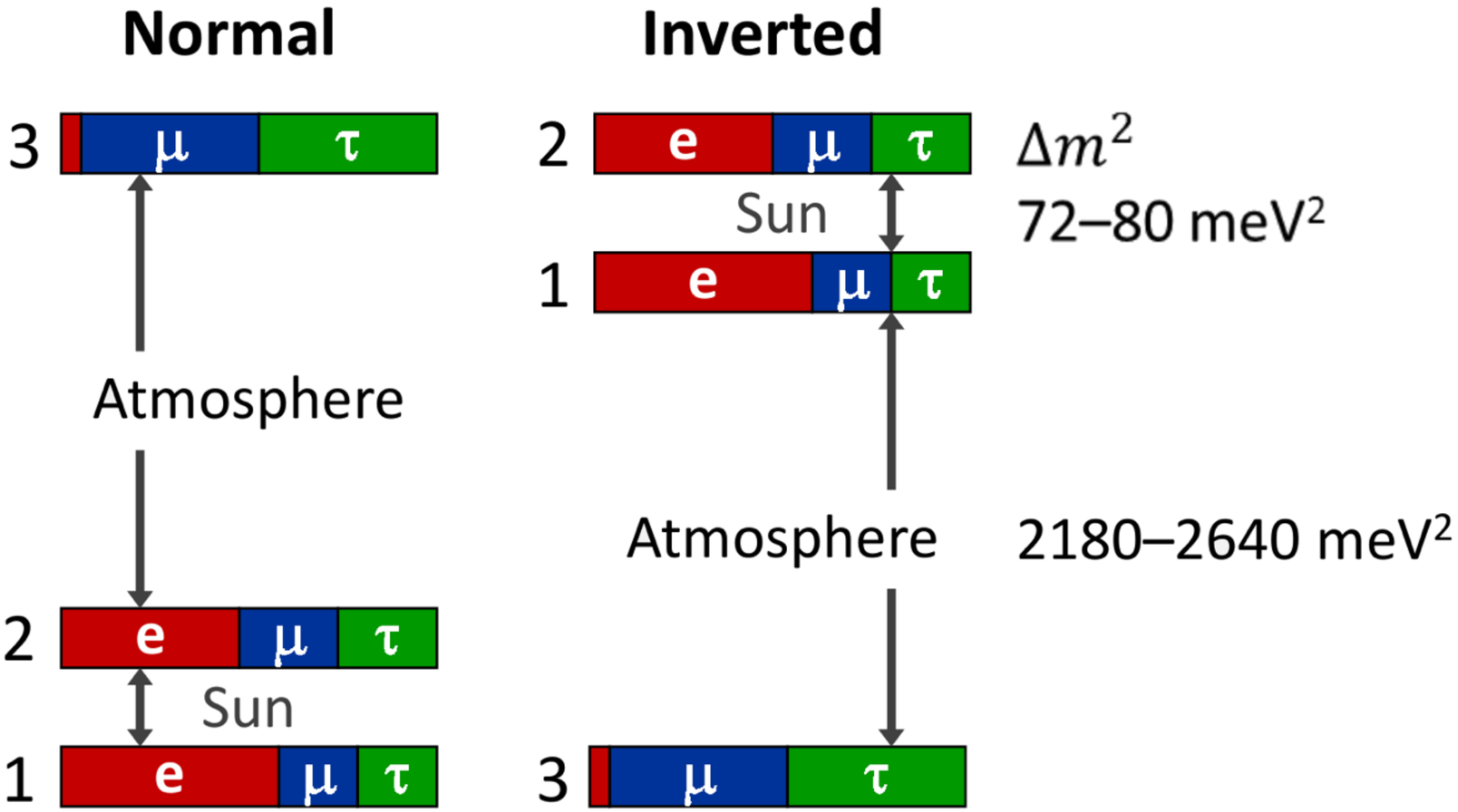
Phys. Rev. C 110, 025803 (2024)


$(T = 30\ \mathrm{MeV},\ \beta - \mathrm{eq.})$
10^0
10^{-1}
10^{-2}
10^{-3}
X_i
n
p
π^-
N^* (Hartree Fock)
non−interacting
Virial(DD2)
140
120
100
80
60
40
μ_{π^-} [MeV]
0
0.05
0.1
0.15
0.2
0.25
n_B [fm^{-3}]

What's to be done:

- EOS & weak rates
- **Neutrino oscillations**

Talks by:
Masamichi Zaizen, Hiroki Nagakura



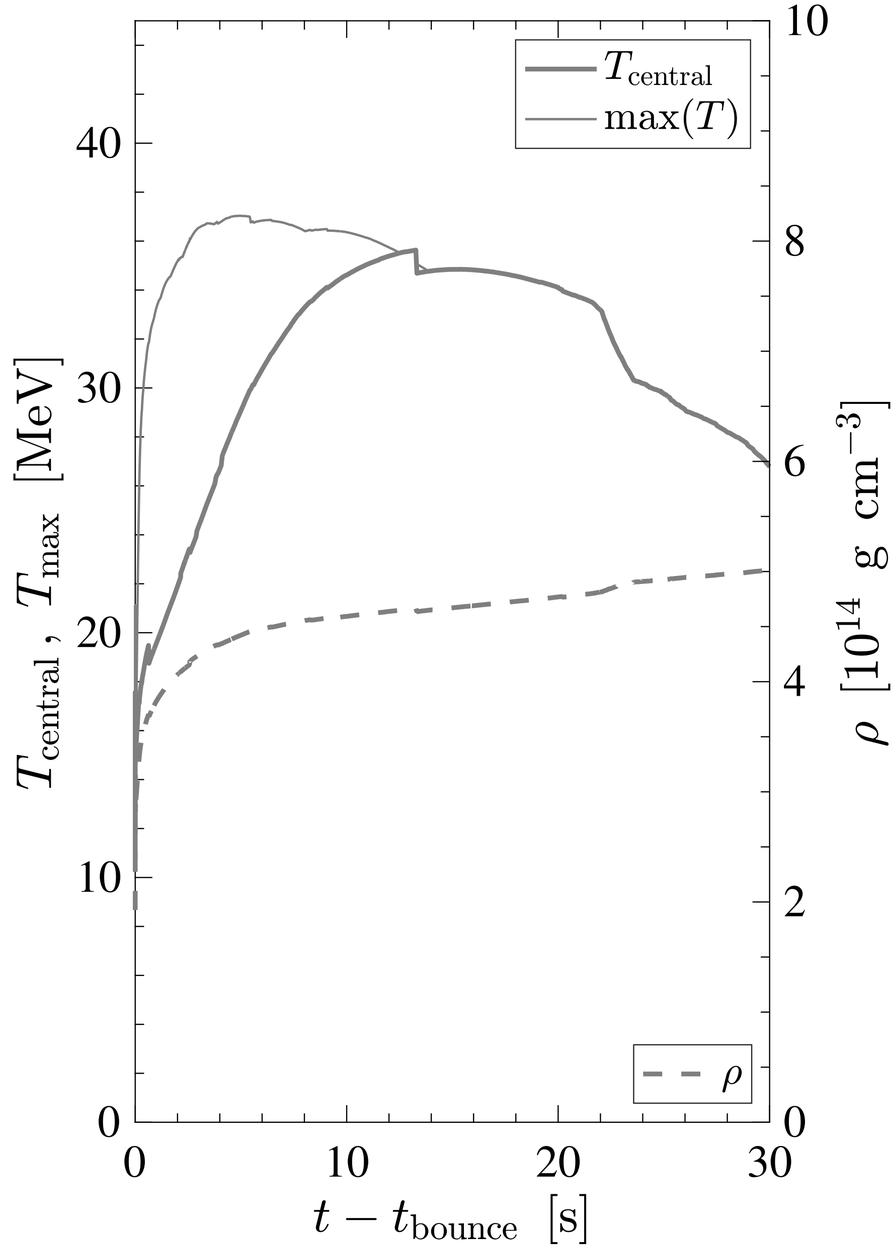
What's to be done:

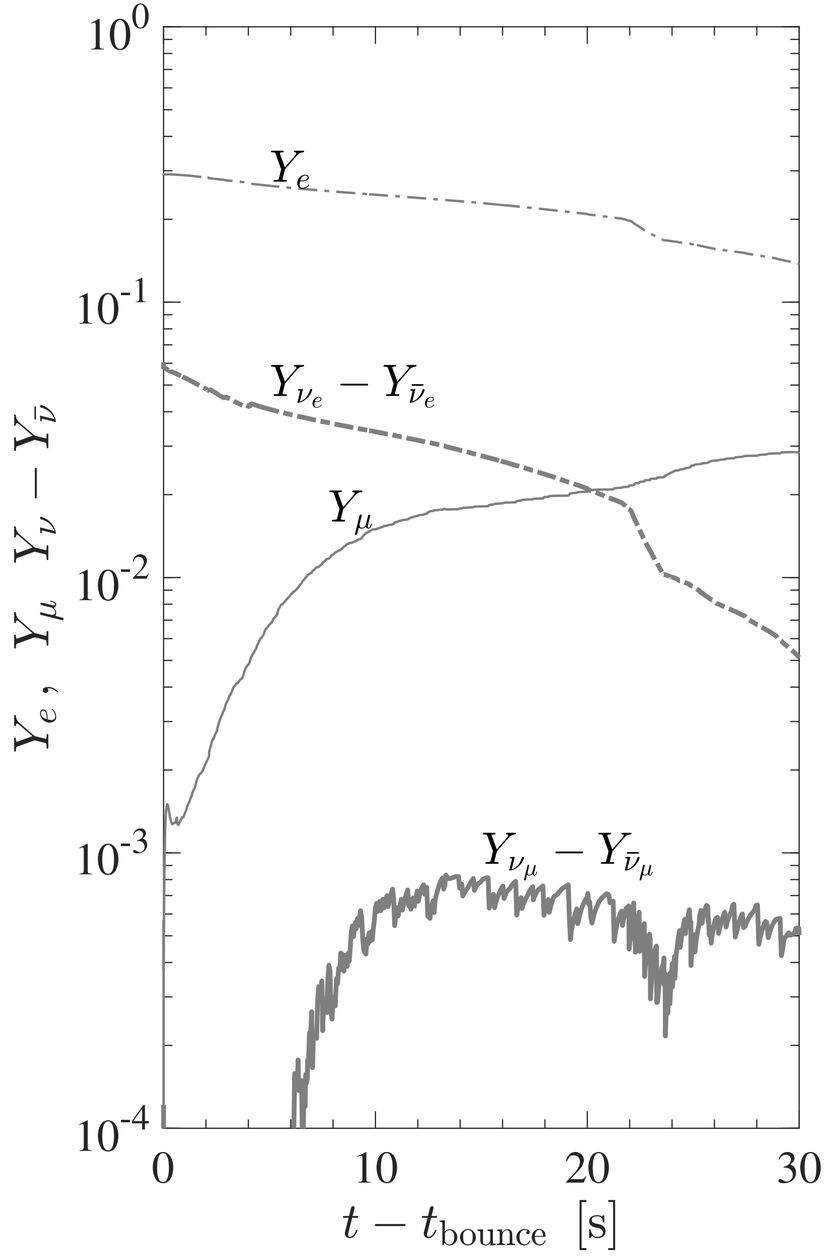
- EOS & weak rates
- Neutrino oscillations
- **Other degrees of freedom (μ, . . .)**

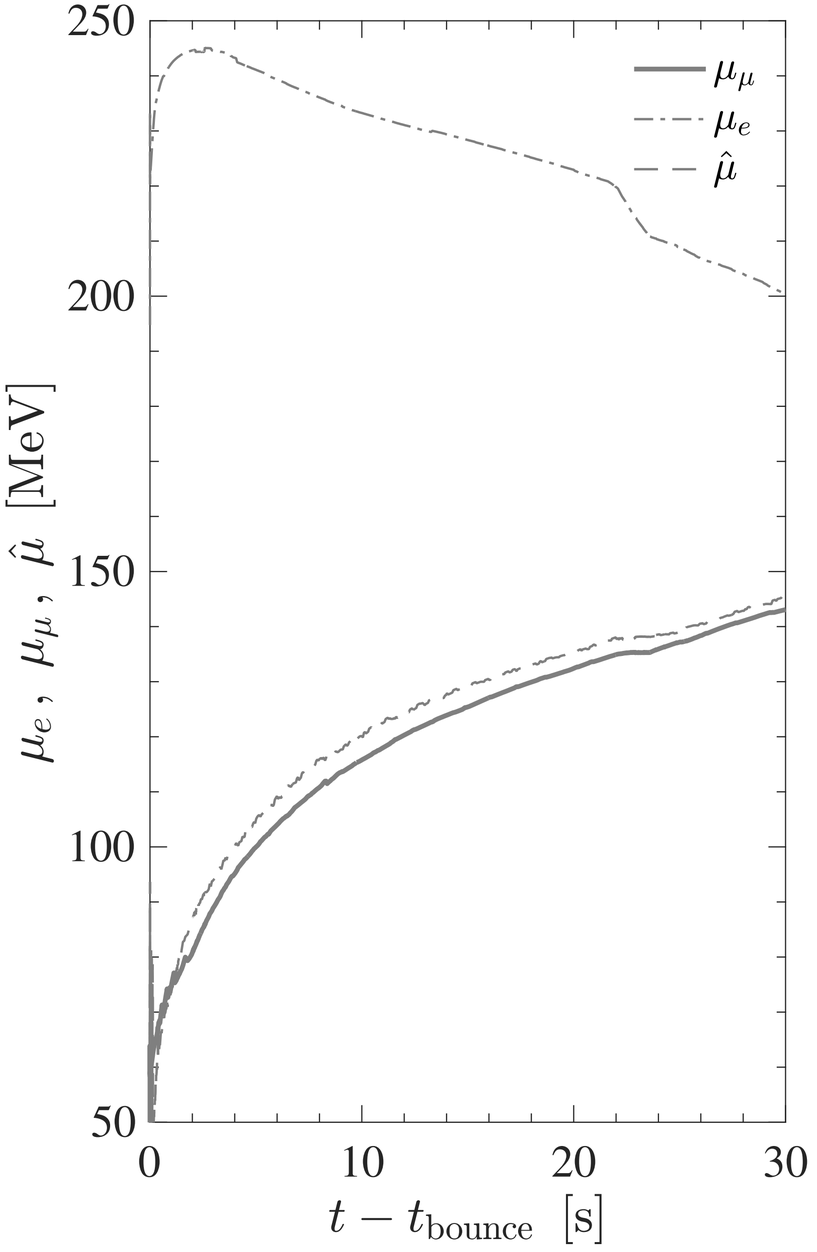
$$\begin{aligned}
\nu_\mu + n &\leftrightarrows \mu^- + p \\
\nu_\alpha + \mu^- &\leftrightarrows \nu_\alpha + \mu^- \\
\nu_\mu + e^- &\leftrightarrows \nu_e + \mu^- \\
\bar{\nu}_\mu + e^+ &\leftrightarrows \bar{\nu}_e + \mu^+ \\
\nu_\mu + \bar{\nu}_e + e^- &\leftrightarrows \mu^- \\
\bar{\nu}_\mu + \mu^- &\leftrightarrows \bar{\nu}_e + e^- \\
&\vdots
\end{aligned}$$

Phys. Rev. Lett. 119, 242702 (2017)
Phys. Rev. D 102, 023027 (2020)
Phys. Rev. D 102, 123001 (2020)
Phys. Rev. D 104, 103012 (2021)
J. Cosm. Astropart. Phys. 01, 061 (2025)

Phys. Rev. D 104, 103012 (2021)







What's to be done:

- EOS & weak rates
- Neutrino oscillations
- **Other degrees of freedom (μ, light cluster, . . .)**

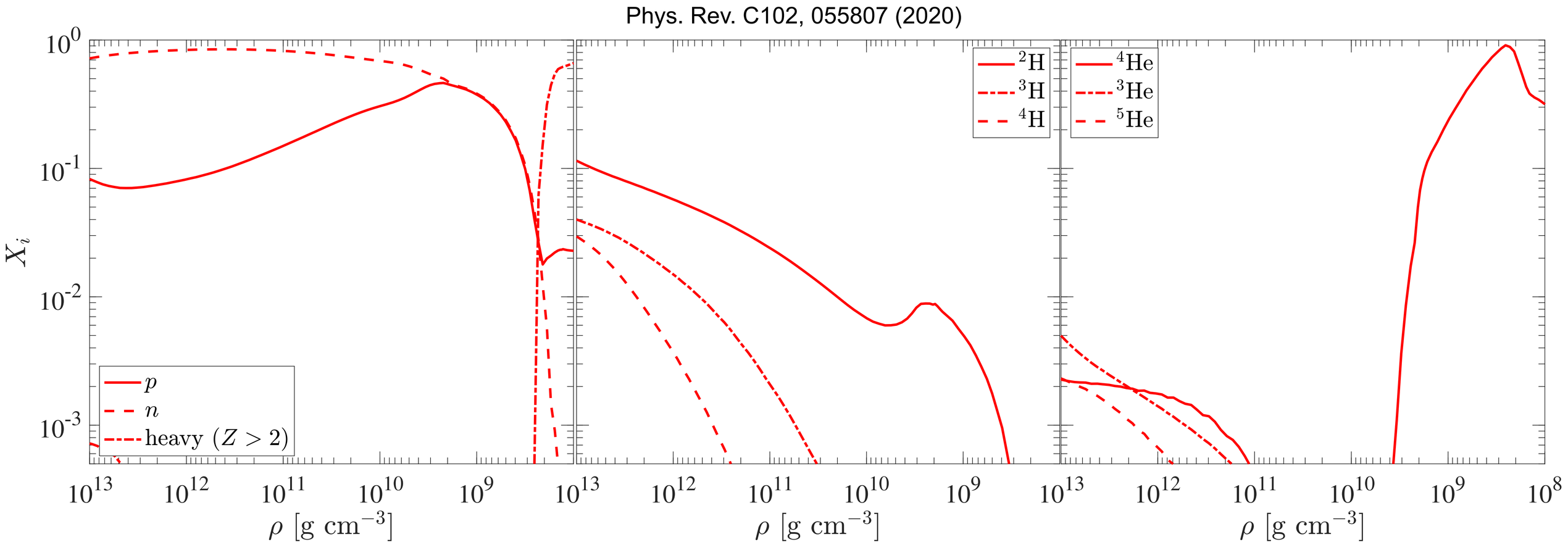
Phys. Rev. C102, 055807 (2020)

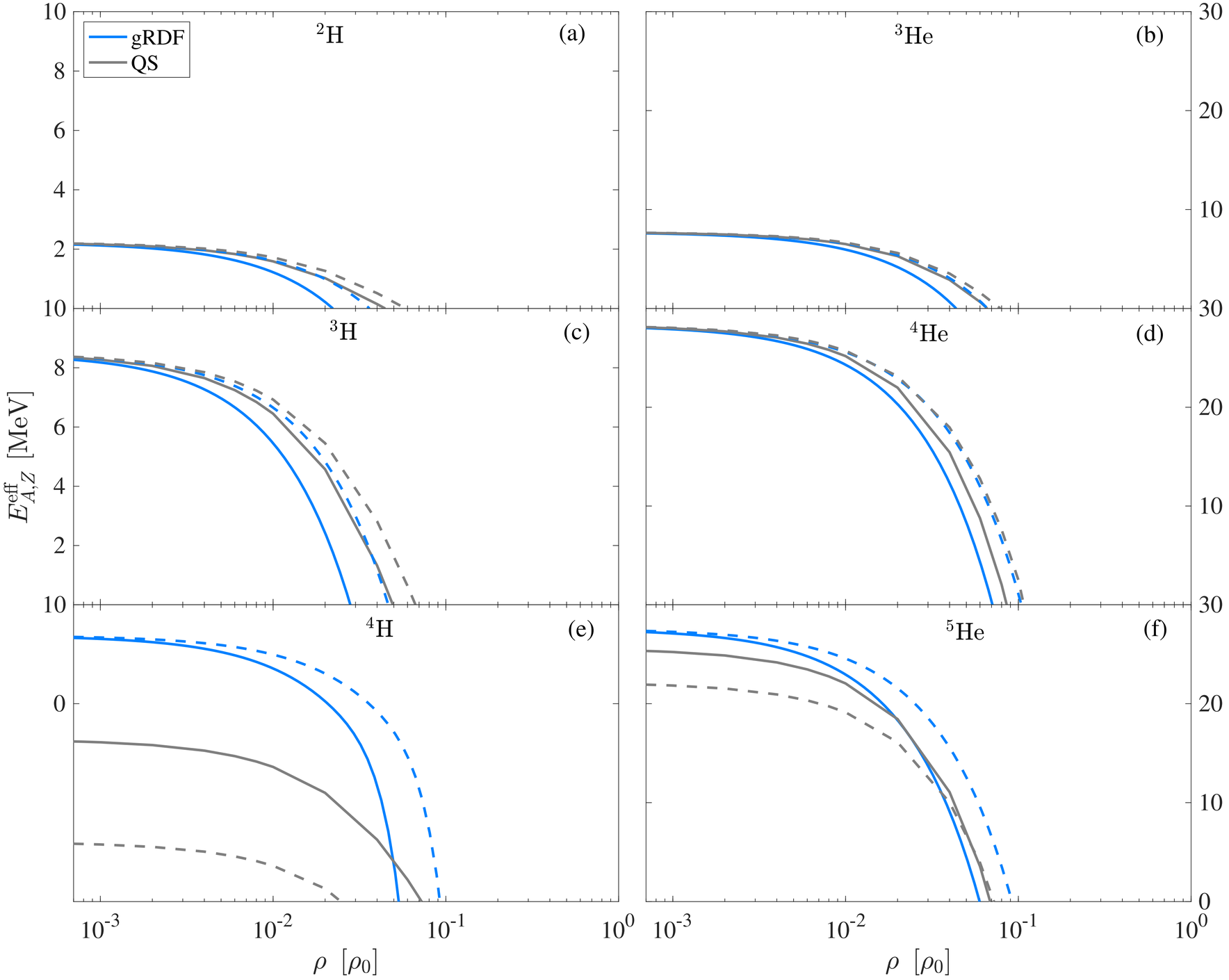
$$\nu_e\, {}^2\mathrm{H} \rightleftarrows p\, p\, e^-$$
$$\bar{\nu}_e\, {}^2\mathrm{H} \rightleftarrows n\, n\, e^+$$
$$\nu_e\, n\, n \rightleftarrows {}^2\mathrm{H}\, e^-$$
$$\bar{\nu}_e\, p\, p \rightleftarrows {}^2\mathrm{H}\, e^+$$
$$\bar{\nu}_e\, e^-\, {}^2\mathrm{H} \rightleftarrows n\, n$$
$$\nu_e\, e^+\, {}^2\mathrm{H} \rightleftarrows p\, p$$
$$\nu_e\, {}^3\mathrm{H} \rightleftarrows n\, p\, p\, e^-$$
$$\bar{\nu}_e\, {}^3\mathrm{H} \rightleftarrows n\, n\, n\, e^+$$
$$\nu_e\, {}^3\mathrm{H} \rightleftarrows {}^3\mathrm{He}\, e^-$$
$$\bar{\nu}_e\, {}^3\mathrm{He} \rightleftarrows {}^3\mathrm{H}\, e^+$$

$$\nu\, {}^2\mathrm{H} \rightleftarrows p\, n\, \nu$$
$$\nu\, {}^2\mathrm{H} \rightleftarrows {}^2\mathrm{H}\, \nu$$
$$\nu\, {}^3\mathrm{H} \rightleftarrows {}^3\mathrm{H}\, \nu$$
$$\nu\, {}^3\mathrm{He} \rightleftarrows {}^3\mathrm{He}\, \nu$$

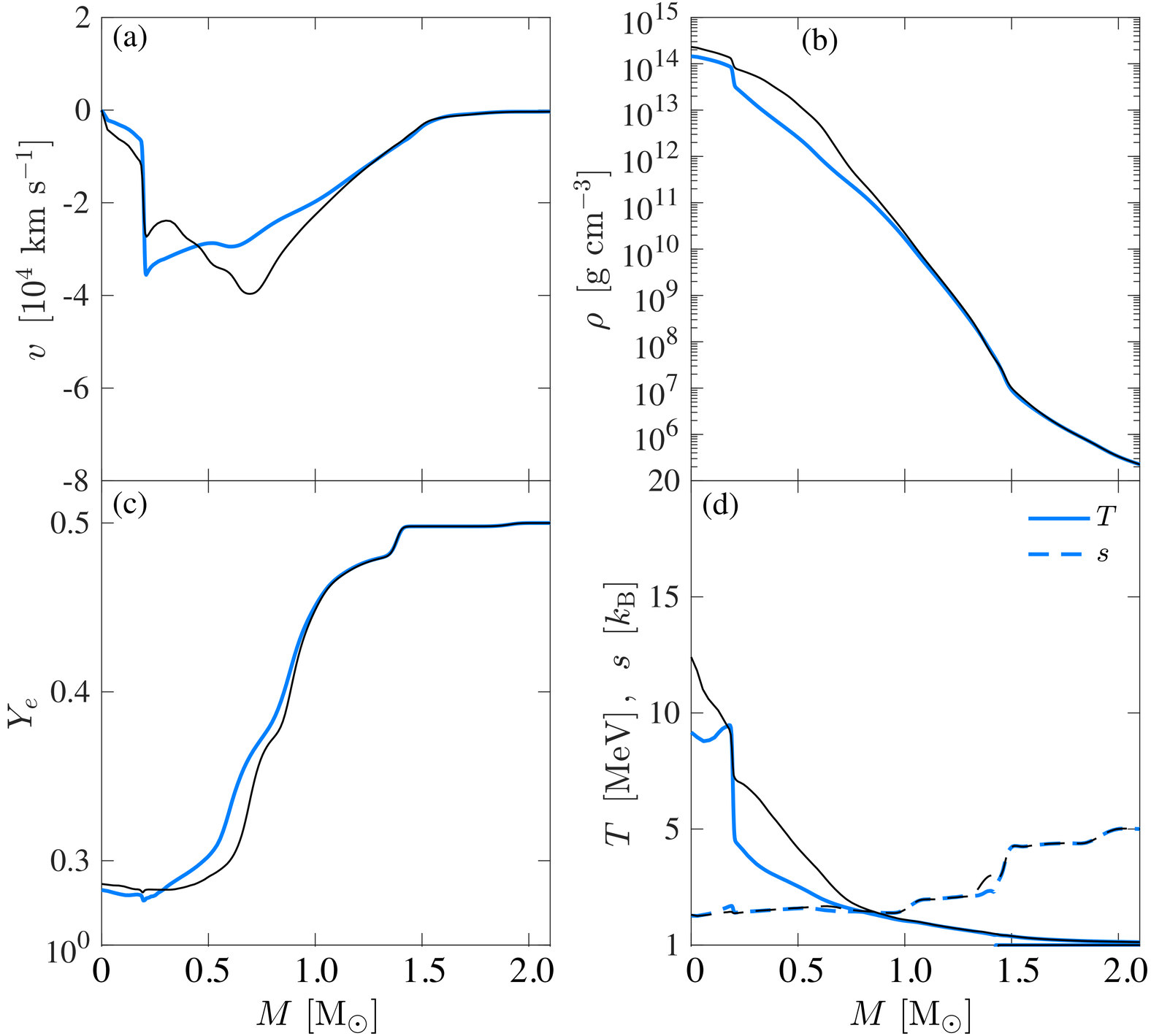
What's to be done:

- EOS & weak rates
- Neutrino oscillations
- **Other degrees of freedom (μ, light cluster, . . .)**

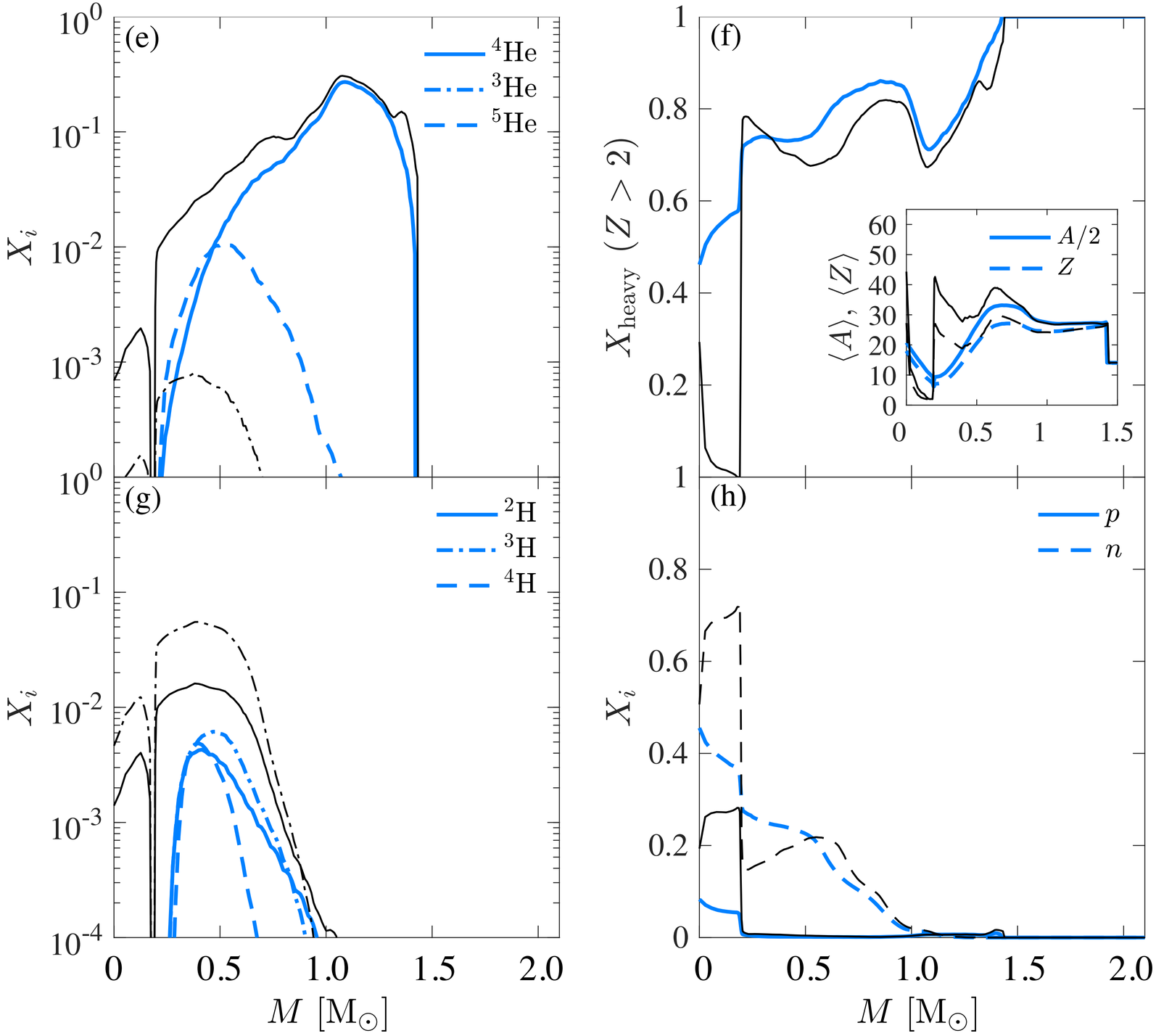




Phys. Rev. C102, 055807 (2020)



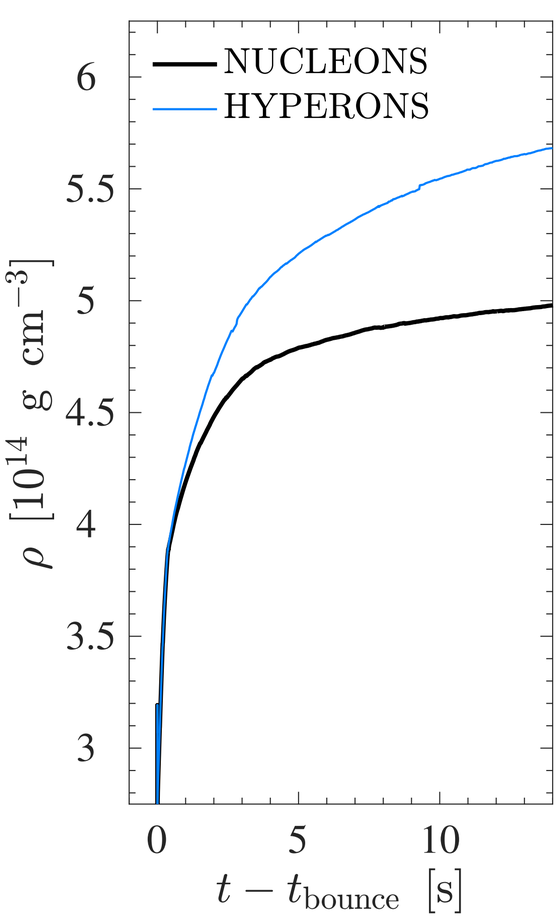
Phys. Rev. C102, 055807 (2020)

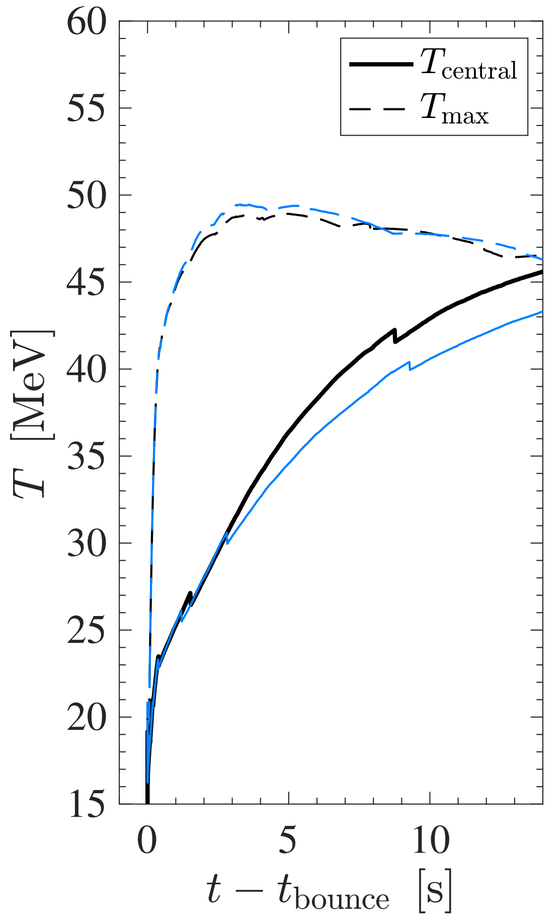


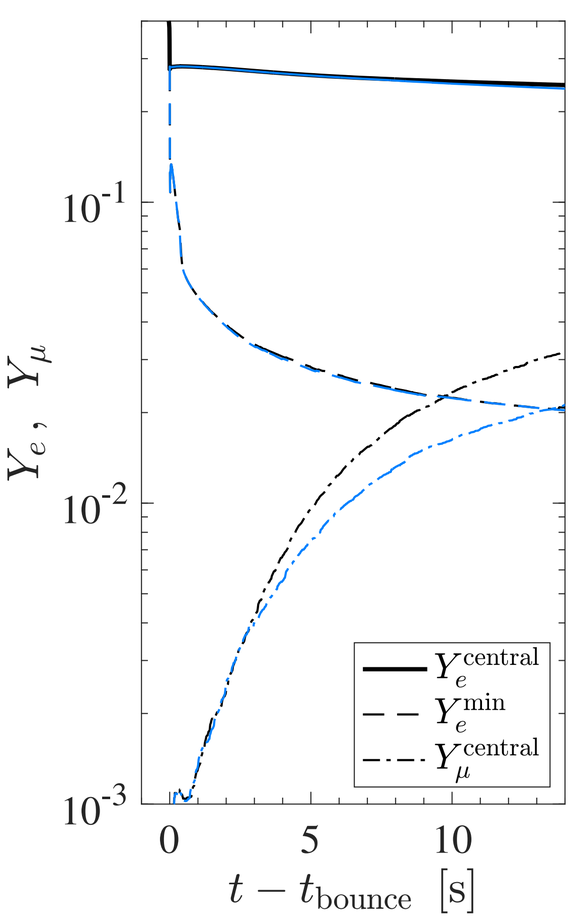
Phys. Rev. C102, 055807 (2020)

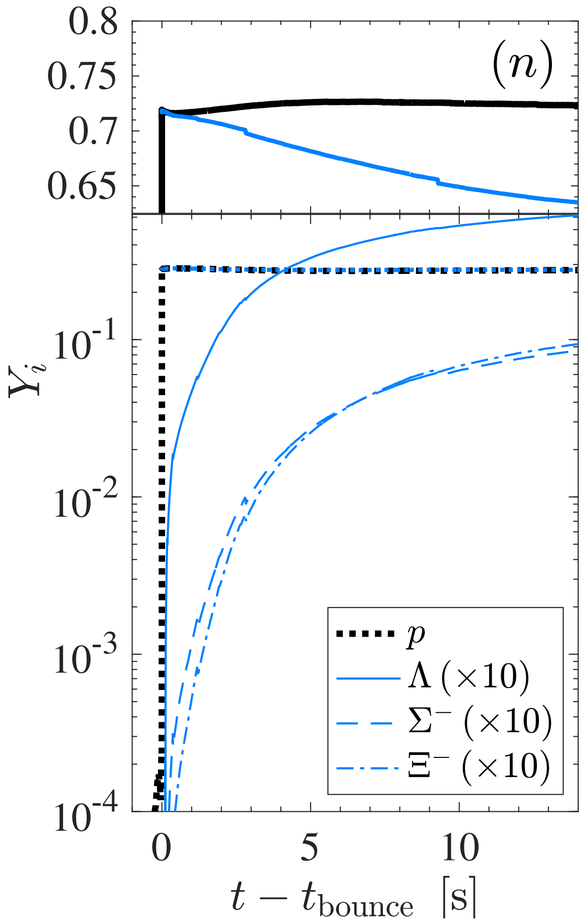
What's to be done:

- EOS & weak rates
- Neutrino oscillations
- **Other degrees of freedom (μ, light cluster, hyperons)**









J. Cosm. Astropart. Phys. 01, 061 (2025)

Thanks for your attention

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