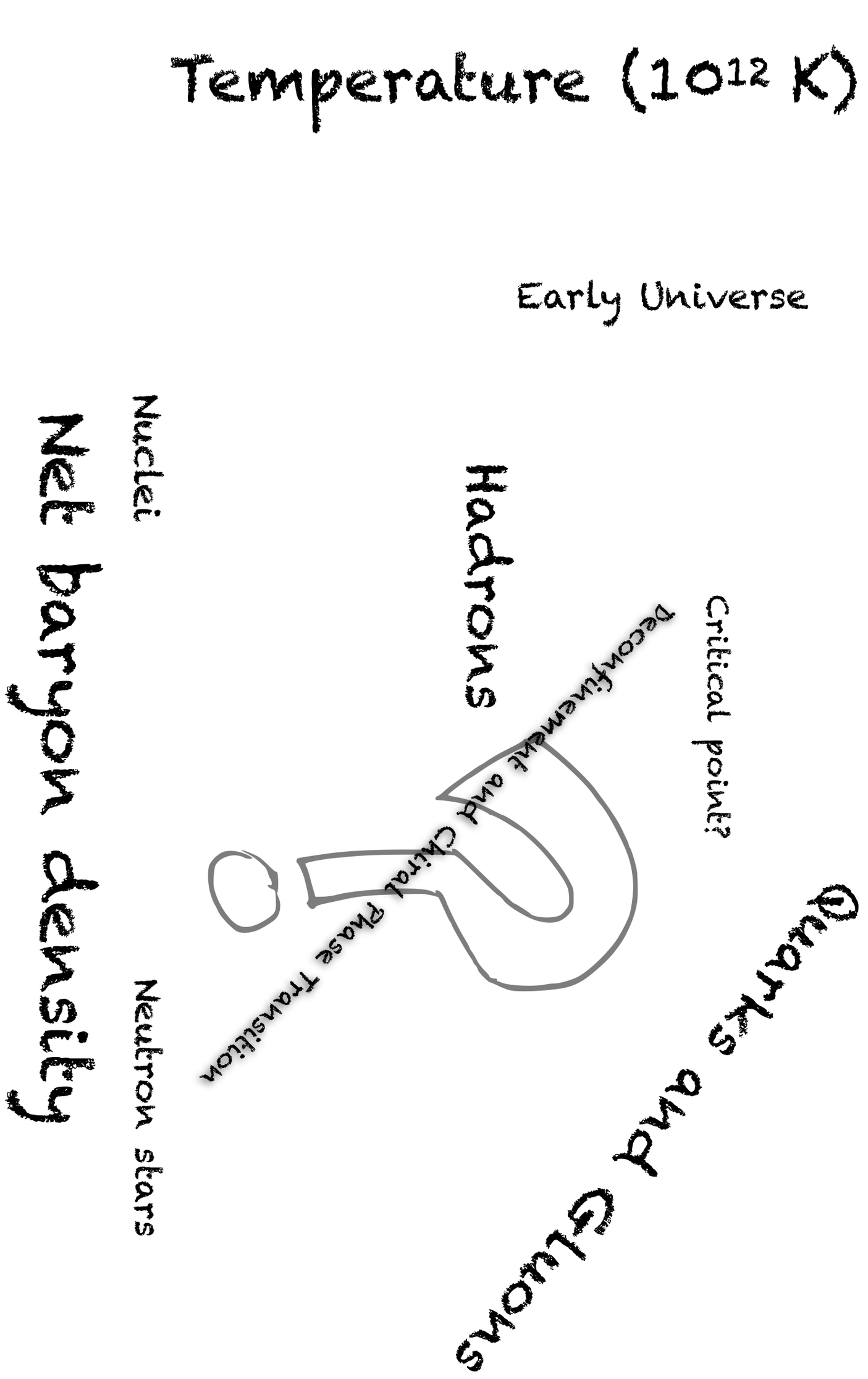
Simulations of Core-Collapse Supernova Featuring a first order QCD phase transition



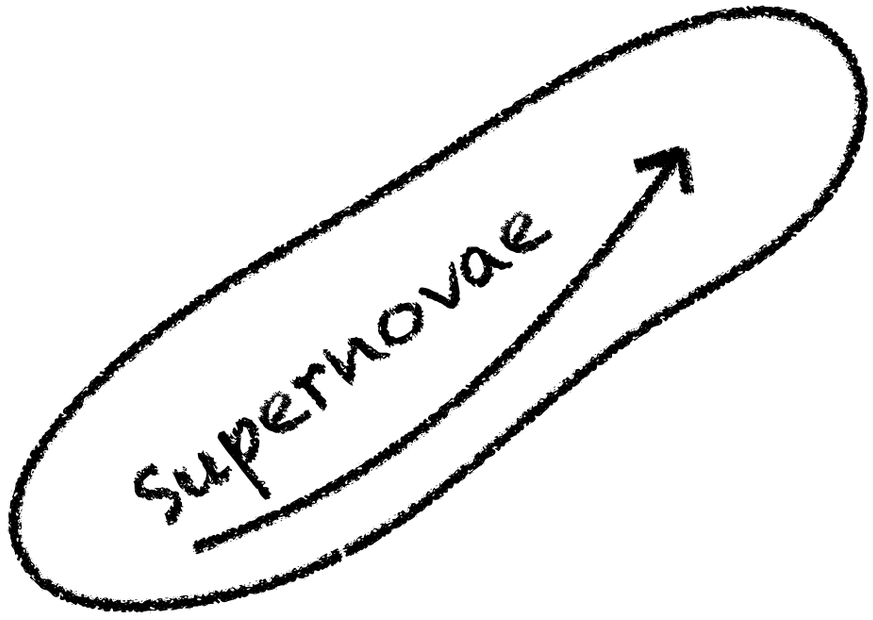


Redrawn and adapted from GSI Helmholtz Centre, Darmstadt

Objective:

"Quark matter exists in massive neutron stars"

"1st – order phase transition"



Redrawn and adapted from GSI Helmholtz Centre, Darmstadt

(d) Cubic spline

$c_s^2(n)$ $\pm 1\sigma$

pQCD
(N^{2}LO)

χEFT
(N^{3}LO)

$x_0 = 0.9$ fm^{-3}

$x_0 = 0.49$ fm^{-3}

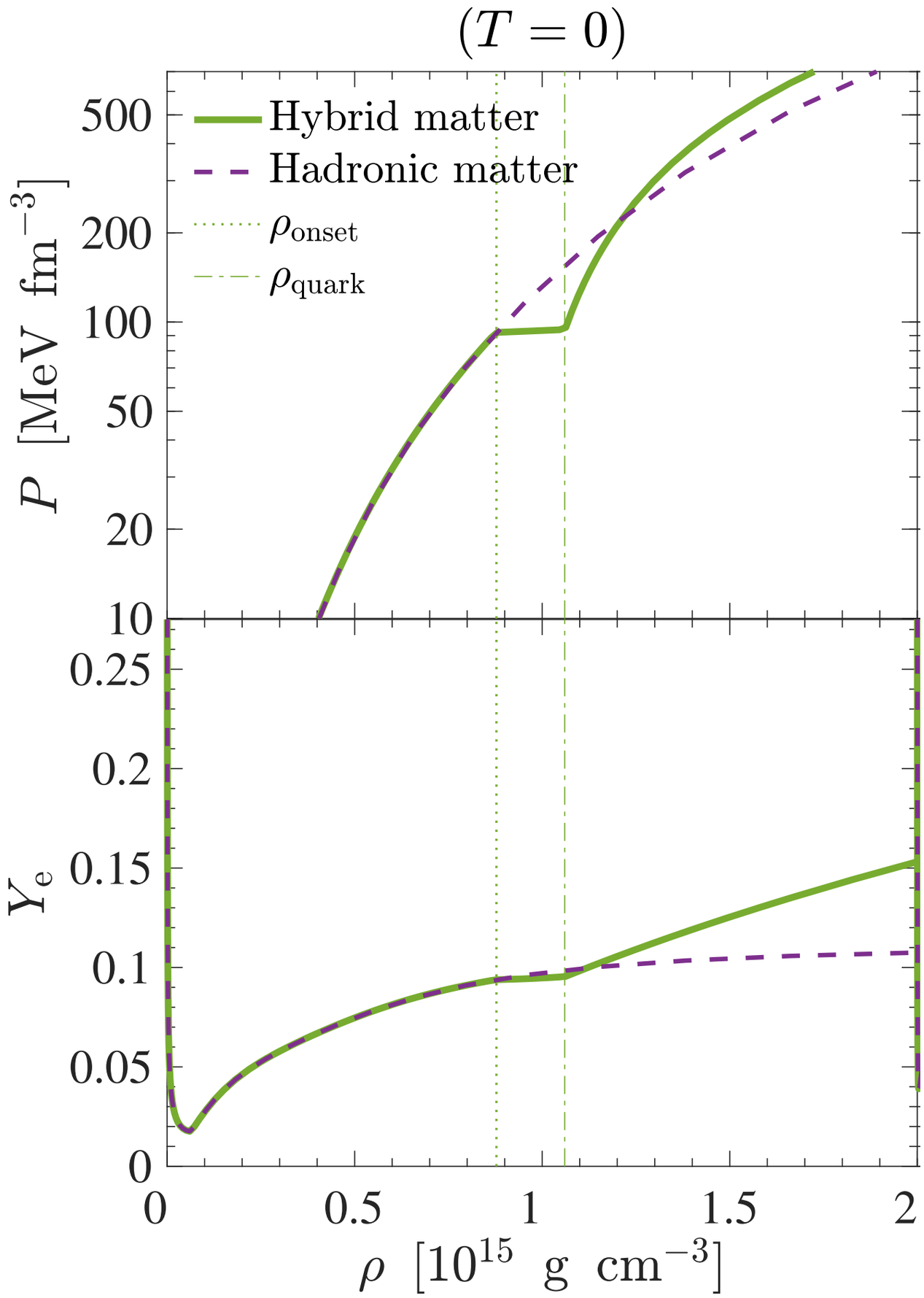
$x_0 = 0.49$ fm^{-3}

1.0
0.8
0.6
0.4
0.2
0.0

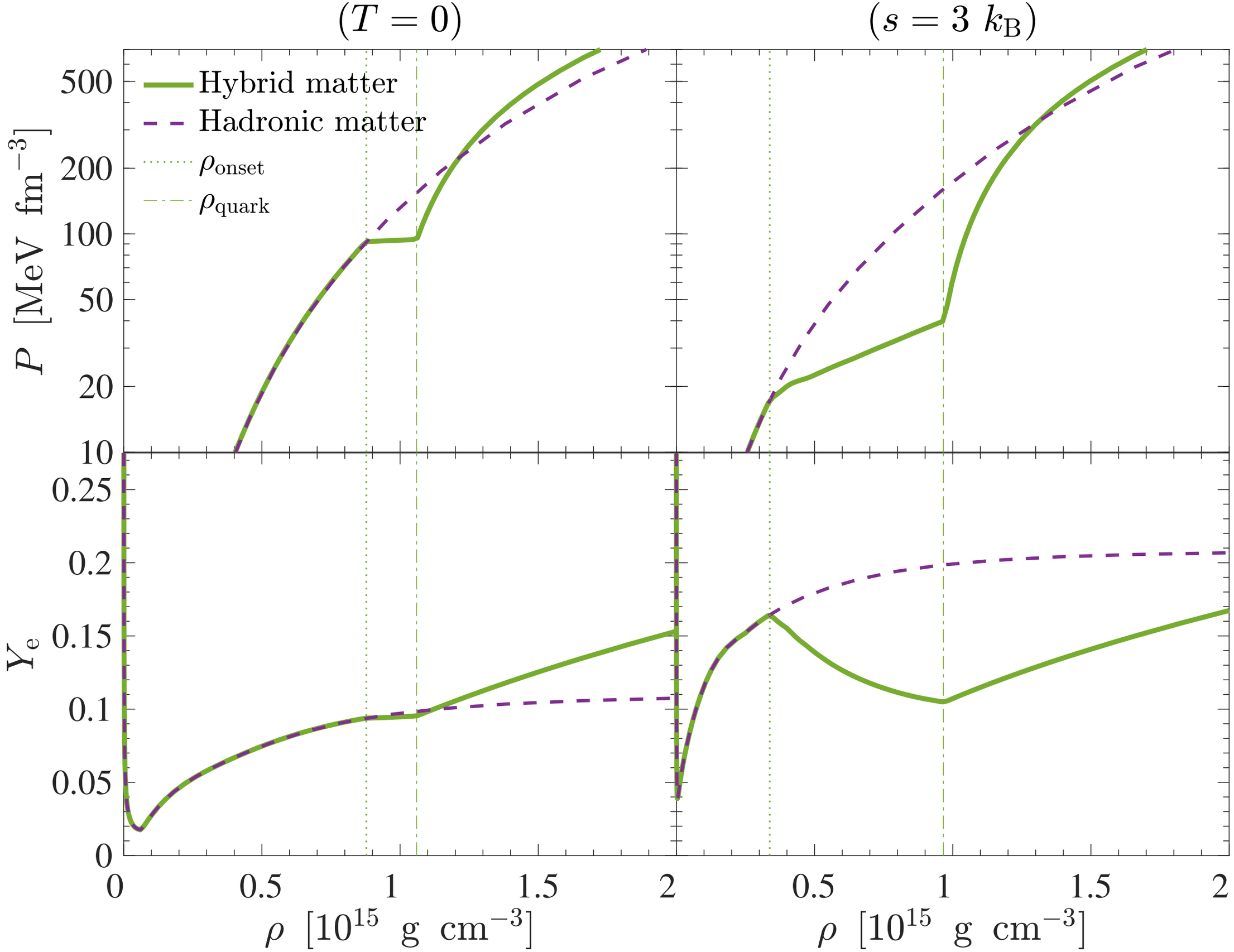
10^0
10^1
10^2

Scaled density n_B/n_0

A. C. Semposki et al., Phys. Rev. C, 113, 015808 (2026)

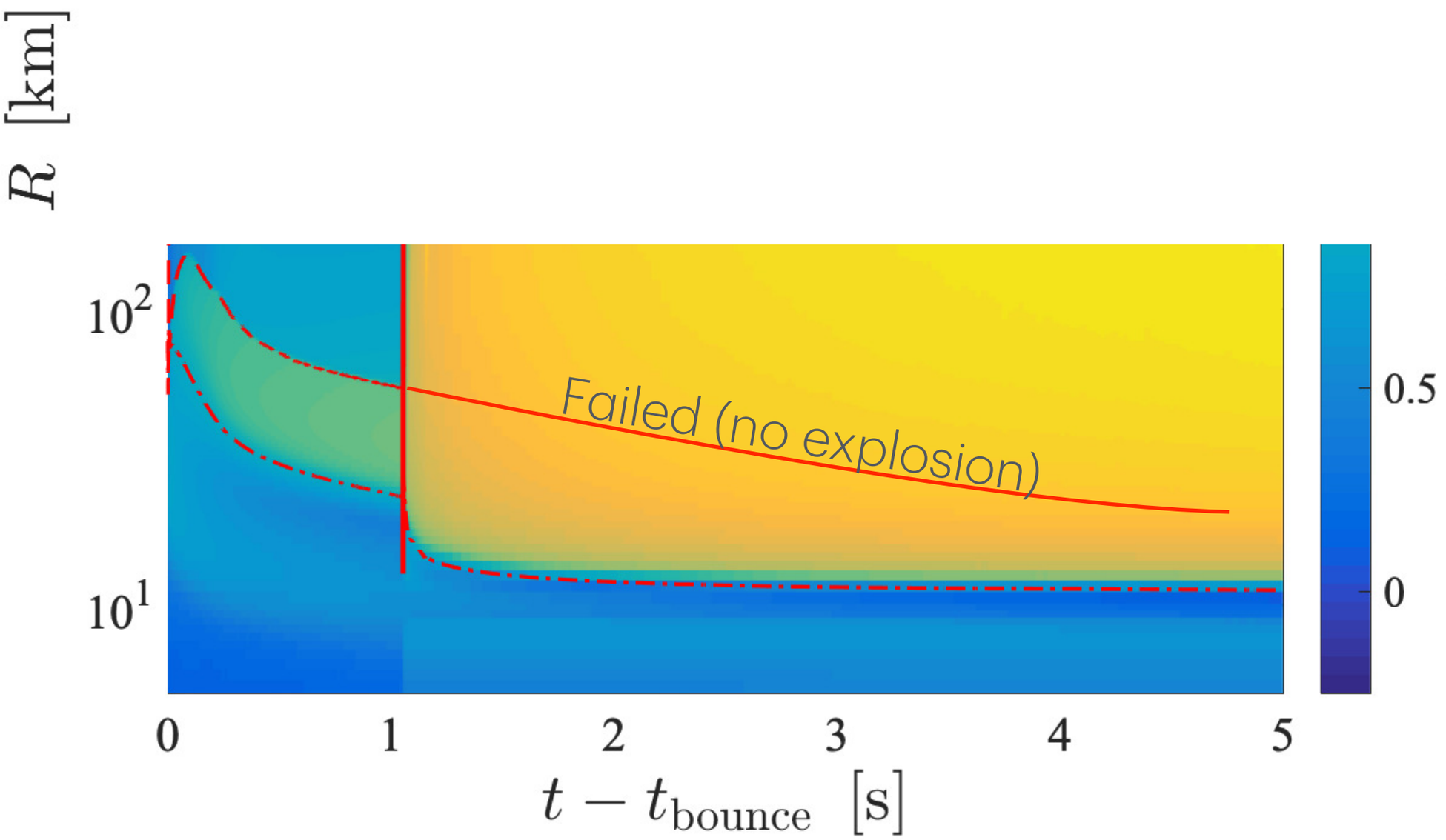


Bastian, Phys. Rev. D, 103, 023001 (2021)

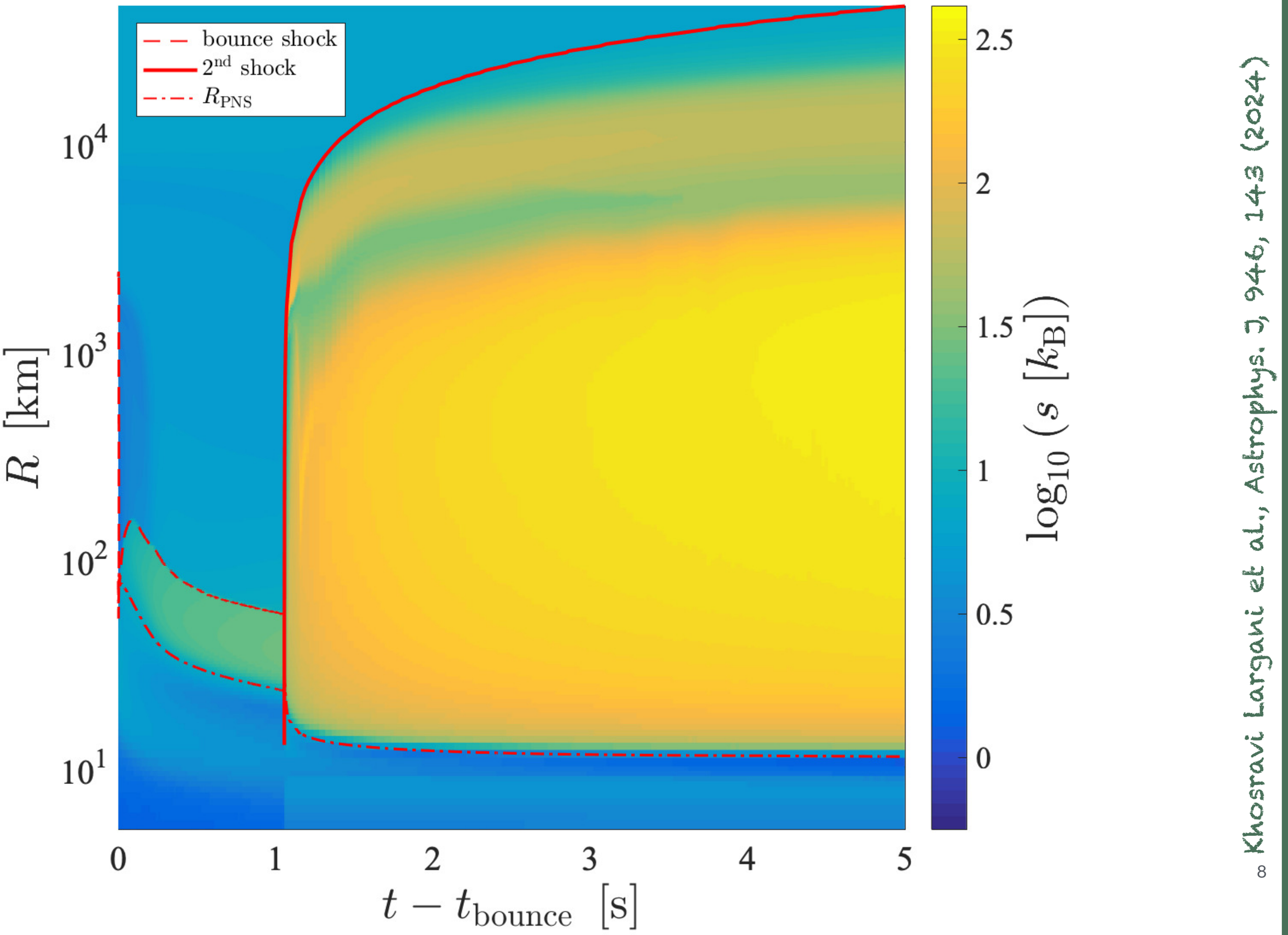


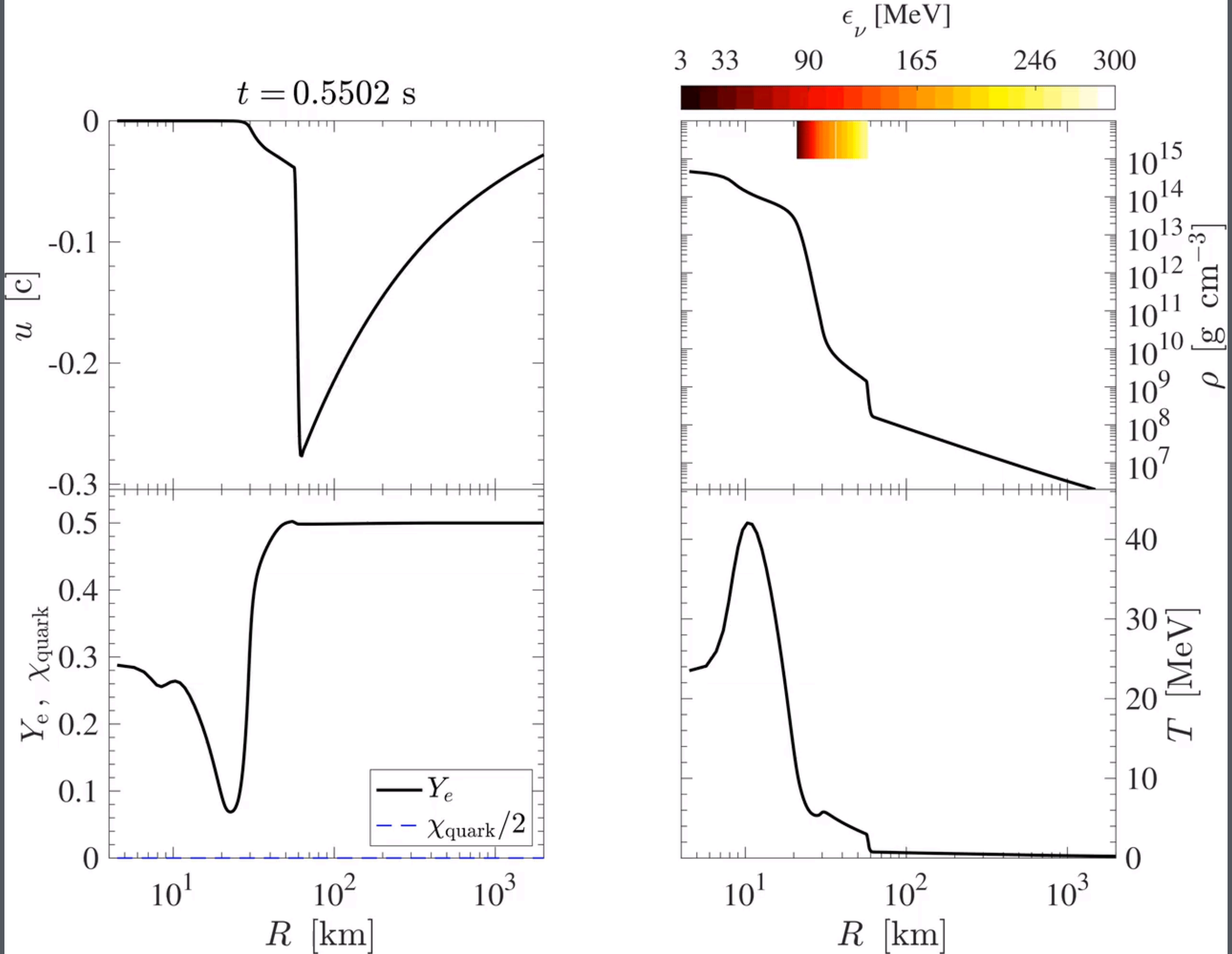
Bastian, Phys. Rev. D, 103, 023001 (2021)

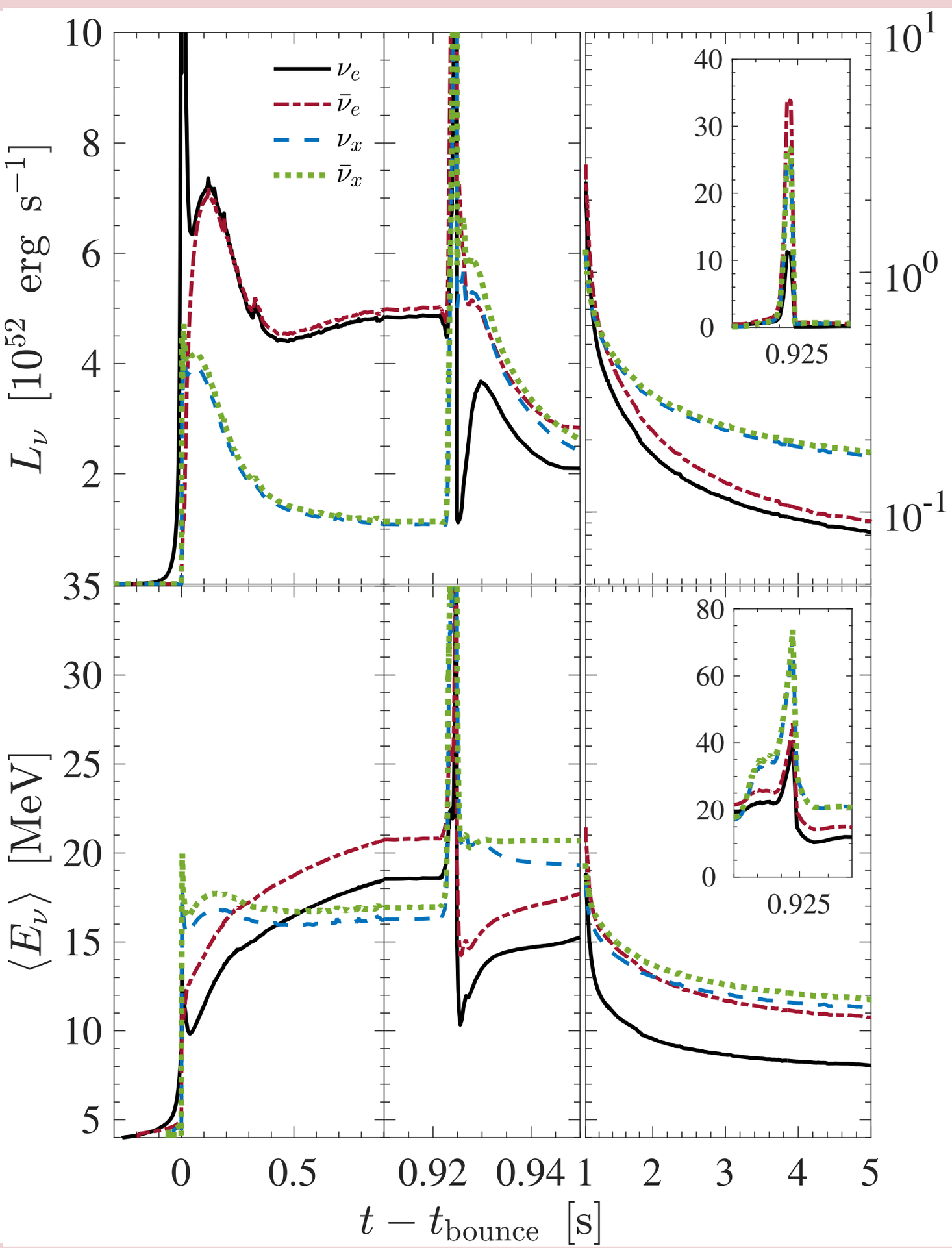
General relativistic neutrino radiation hydrodynamics

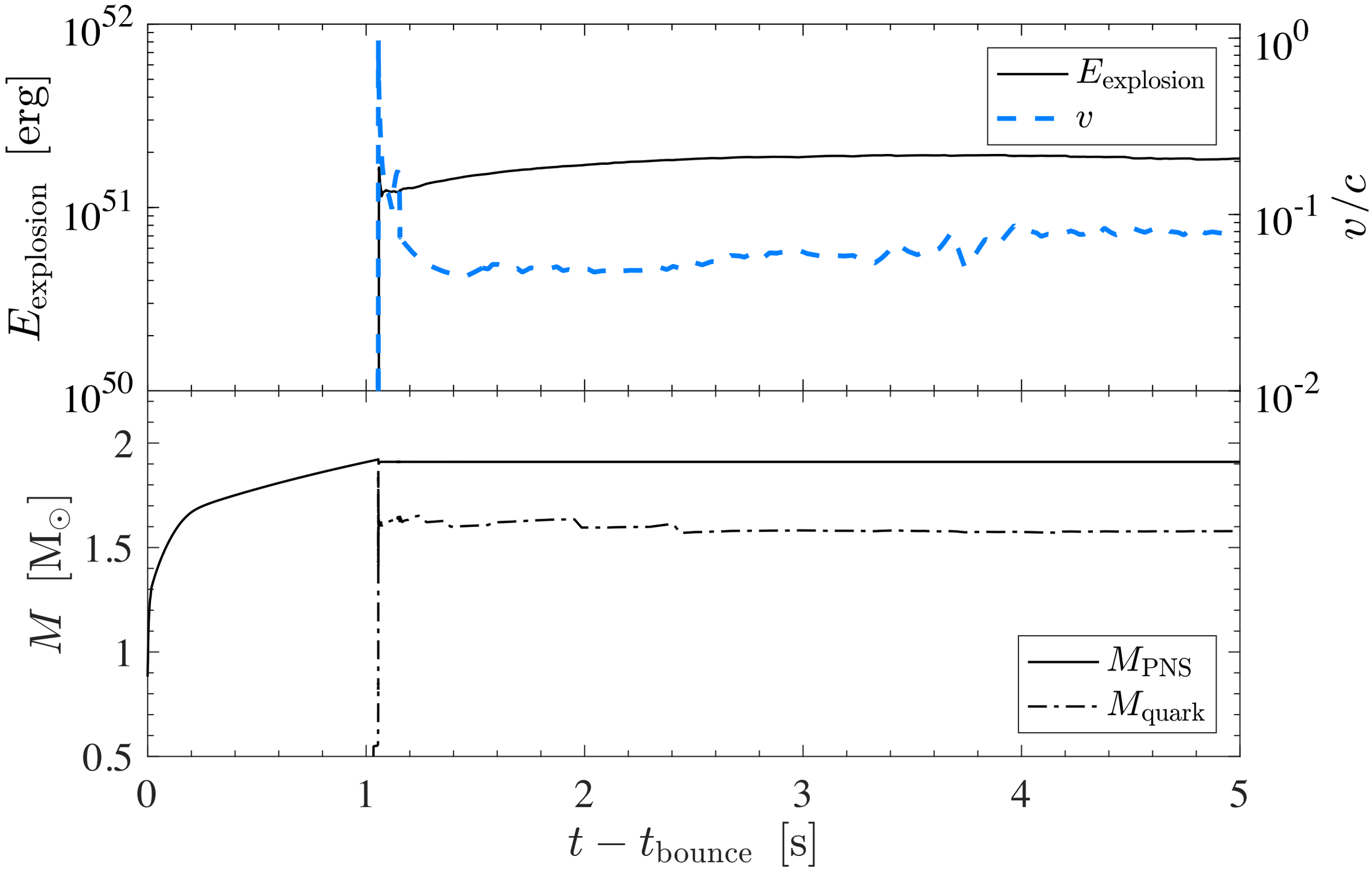


Khosravi Largani et al., Astrophys. J, 946, 143 (2024)


bounce shock
2nd shock
$R_{\rm PNS}$
10^4
10^3
10^2
10^1
R [km]
0
1
2
3
4
5
$t - t_{\rm bounce}$ [s]
2.5
2
1.5
1
0.5
0
$\log_{10}(s\ [k_{\rm B}])$

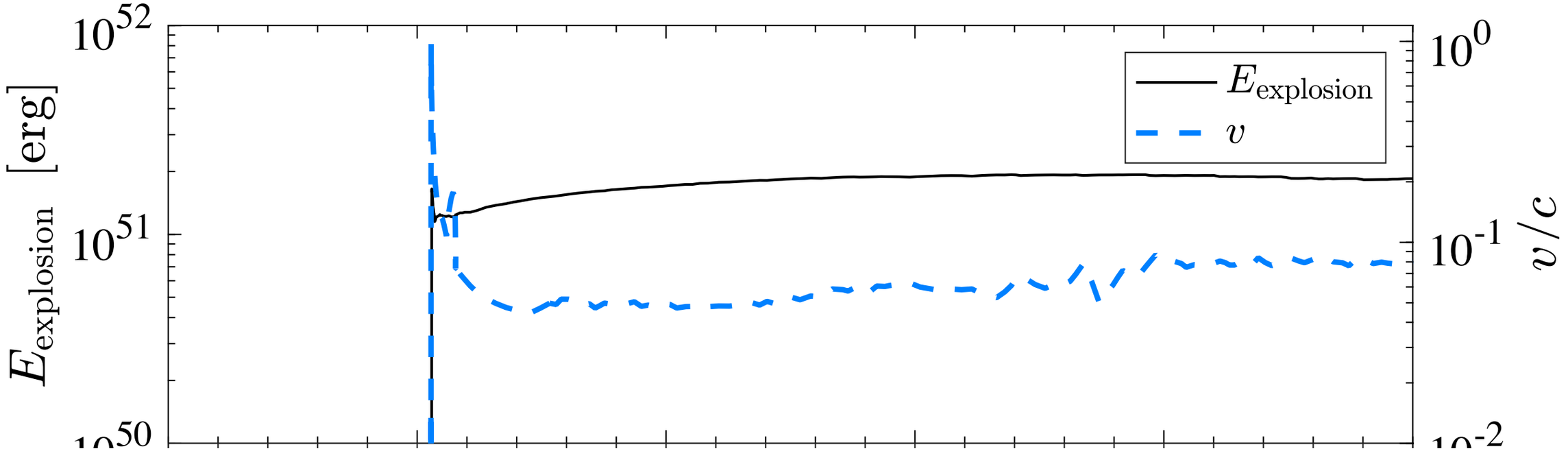

$t = 0.5502$ s
u [c]
Y_e , $\chi_{\rm quark}$
Y_e
$\chi_{\rm quark}/2$
R [km]
ϵ_ν [MeV]
3 33 90 165 246 300
ρ [g cm^{-3}]
T [MeV]
R [km]


ν_e
$\bar{\nu}_e$
ν_x
$\bar{\nu}_x$
L_ν [10^{52} erg s^{-1}]
$\langle E_\nu \rangle$ [MeV]
$t - t_{\rm bounce}$ [s]
0.925
0.925

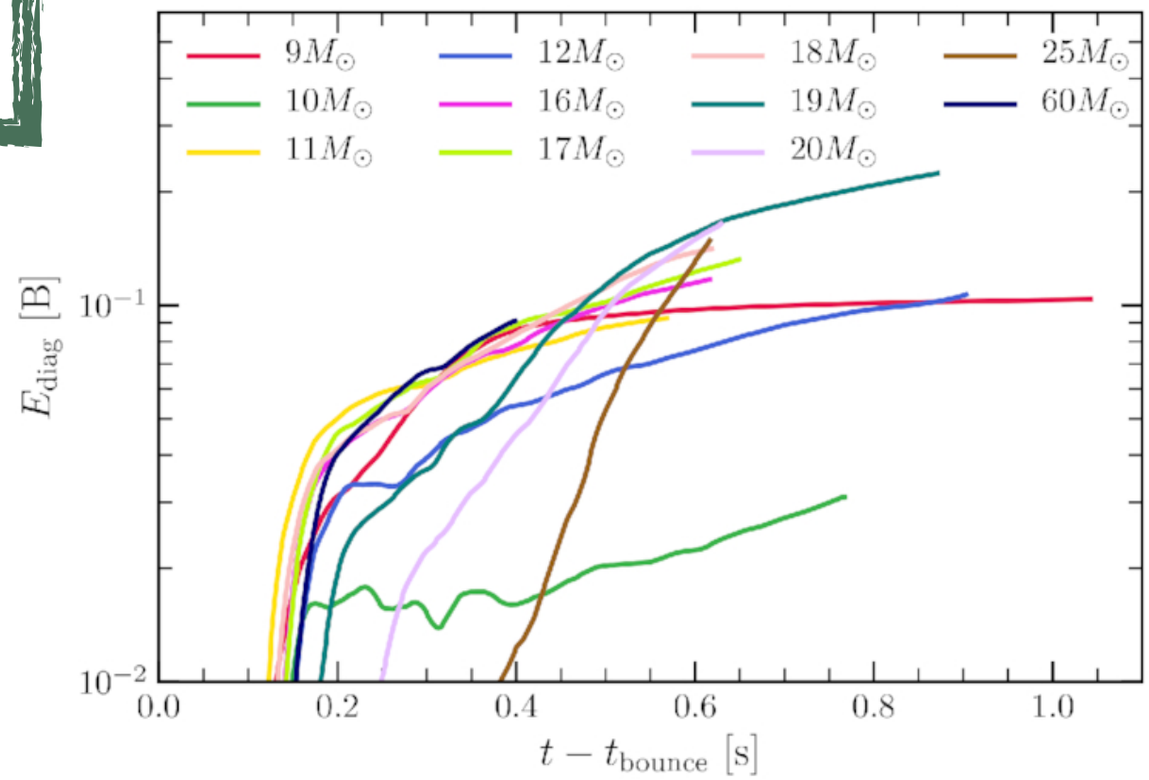


$$\mathrm{E_{expl}} = 3 \times 10^{51}\ \mathrm{erg}$$
$$\mathrm{M_{NS}} \simeq 2\ \mathrm{M_\odot}$$

Khosravi Largani et al., Astrophys. J. 946, 143 (2024)



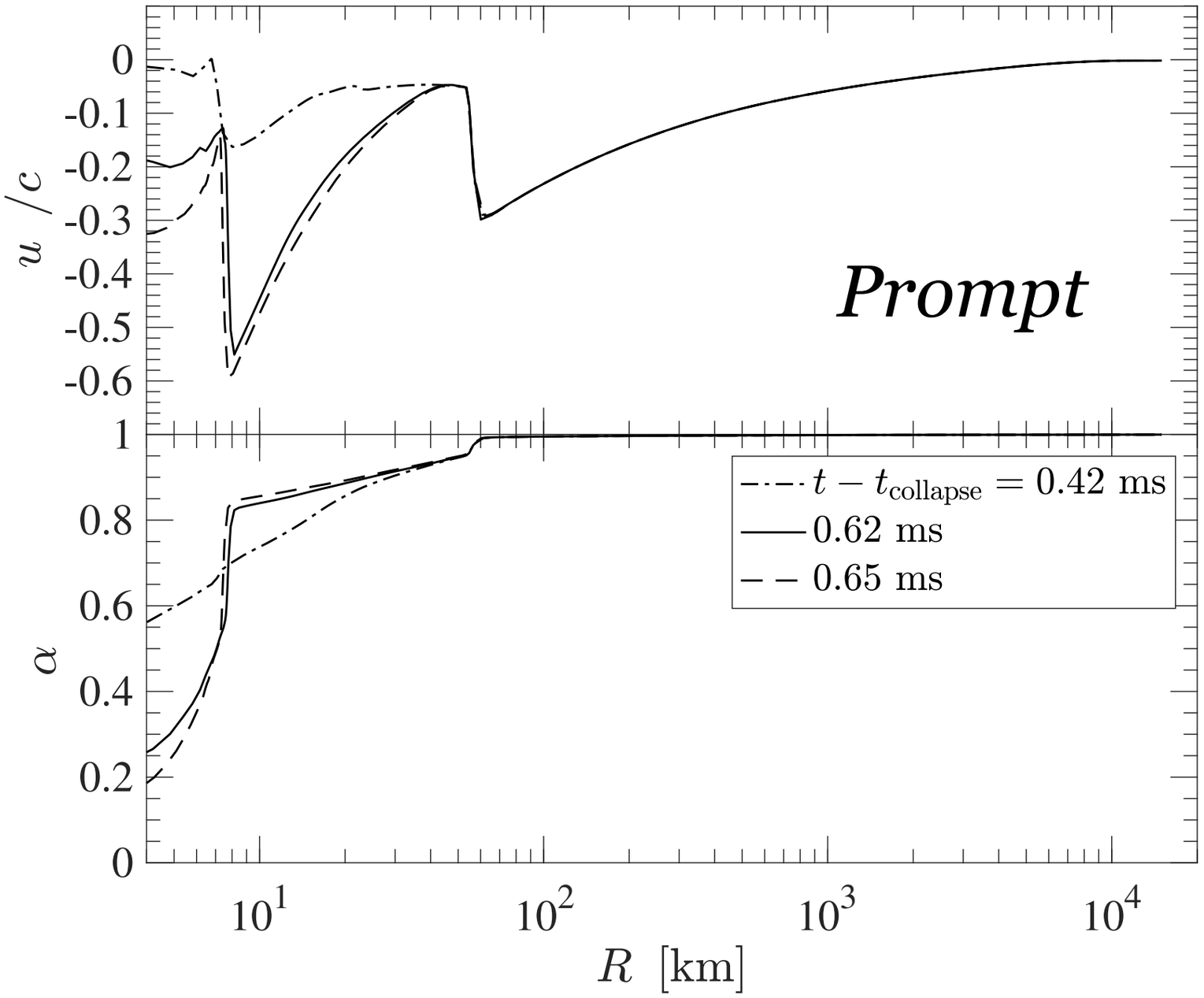
$$\mathrm{E_{expl}} = 3 \times 10^{51}\ \mathrm{erg}$$
$$\mathrm{M_{NS}} \simeq 2\ \mathrm{M_\odot}$$



Burrows et al., Mon. Not. R. Astron. Soc.,491,2 (2020)

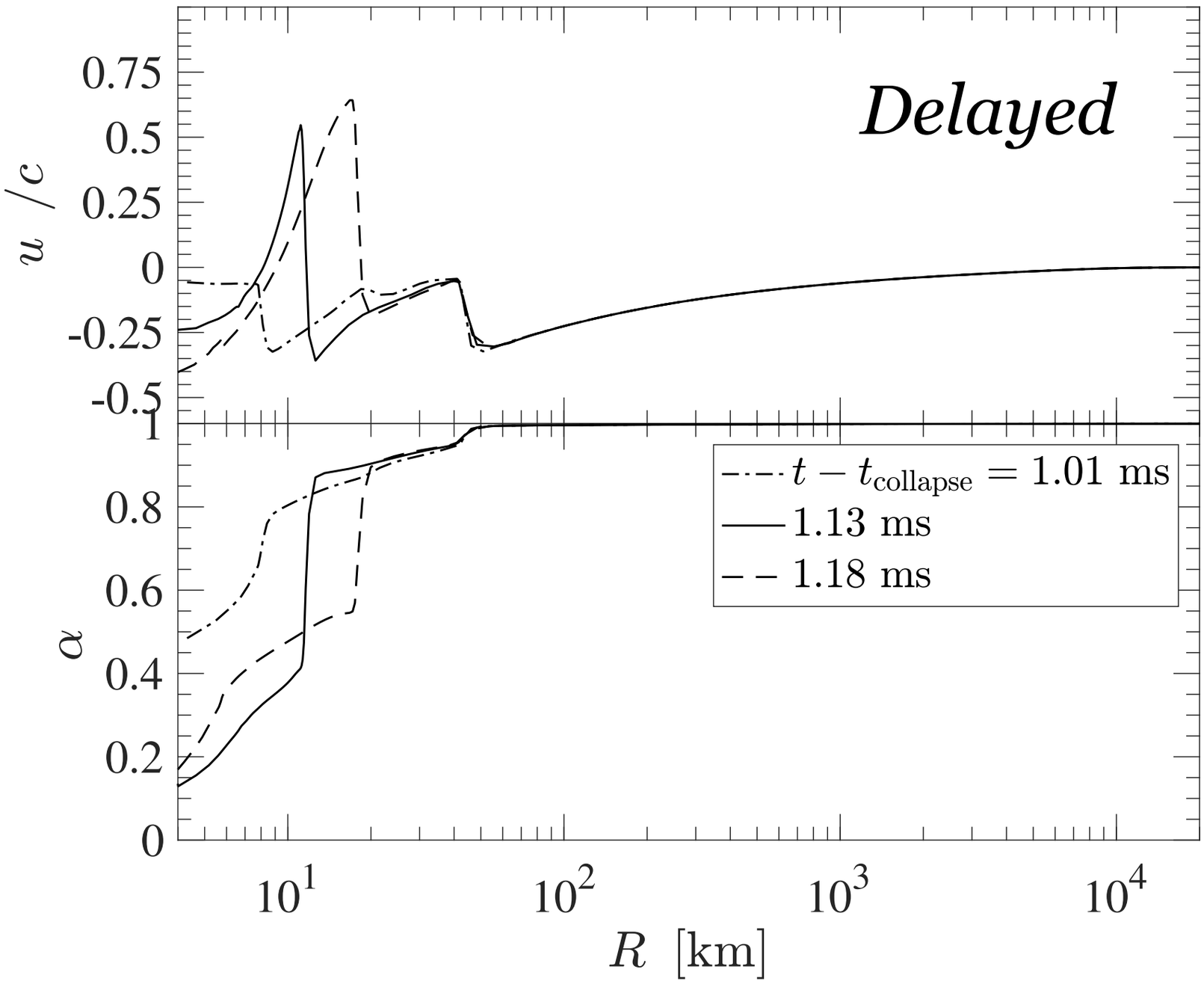
Khosravi Largani et al., Astrophys. J, 946, 143 (2024)

Black-hole formation: Two distinct scenarios



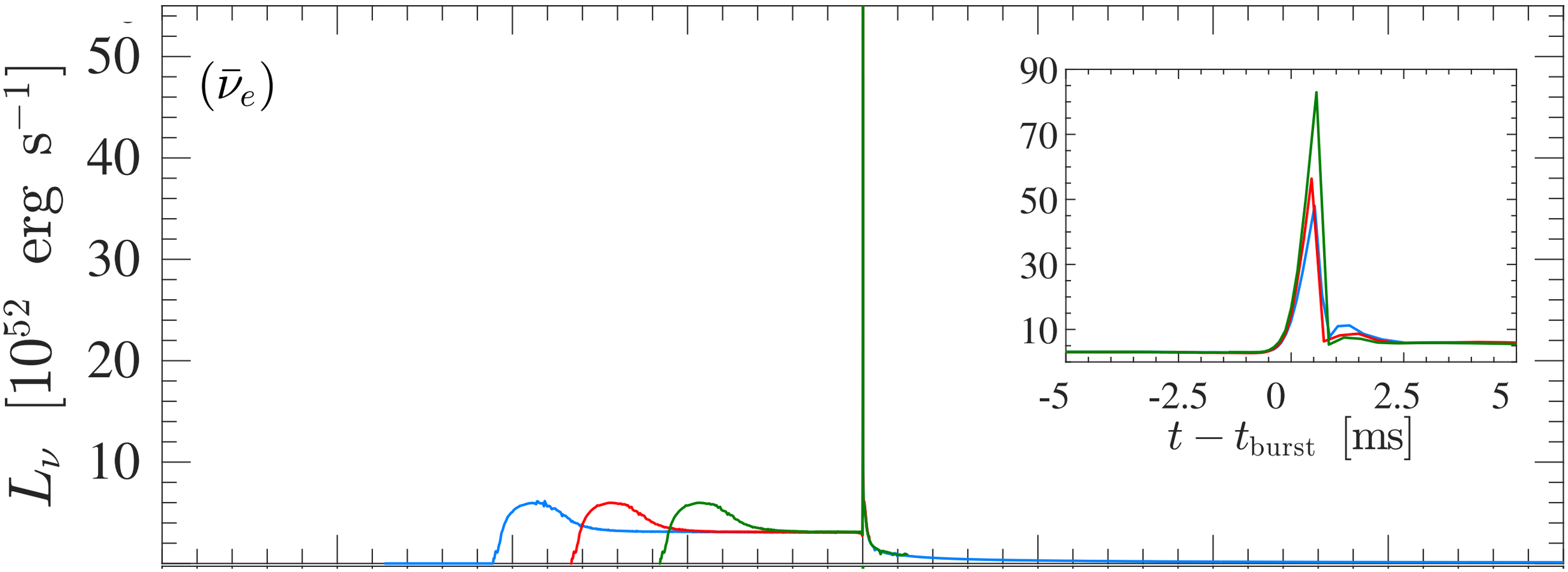
Jakobus et al., MNRAS, 516, 2554 (2022)
Khosravi Largani et al., ApJ 946, 143 (2024)

Black-hole formation: Two distinct scenarios



Jakobus et al., MNRAS, 516, 2554 (2022)

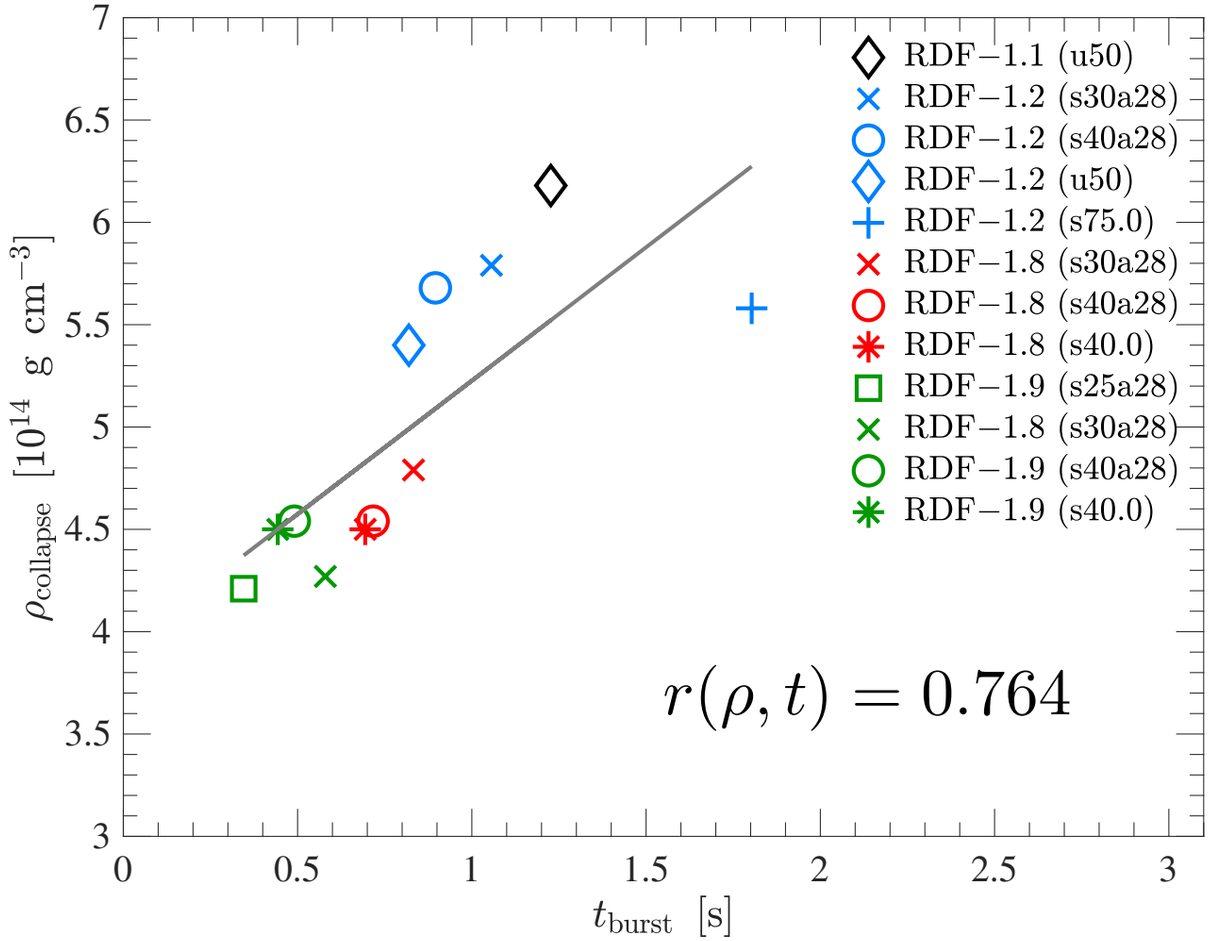
Khosravi Largani et al., ApJ 946, 143 (2024)

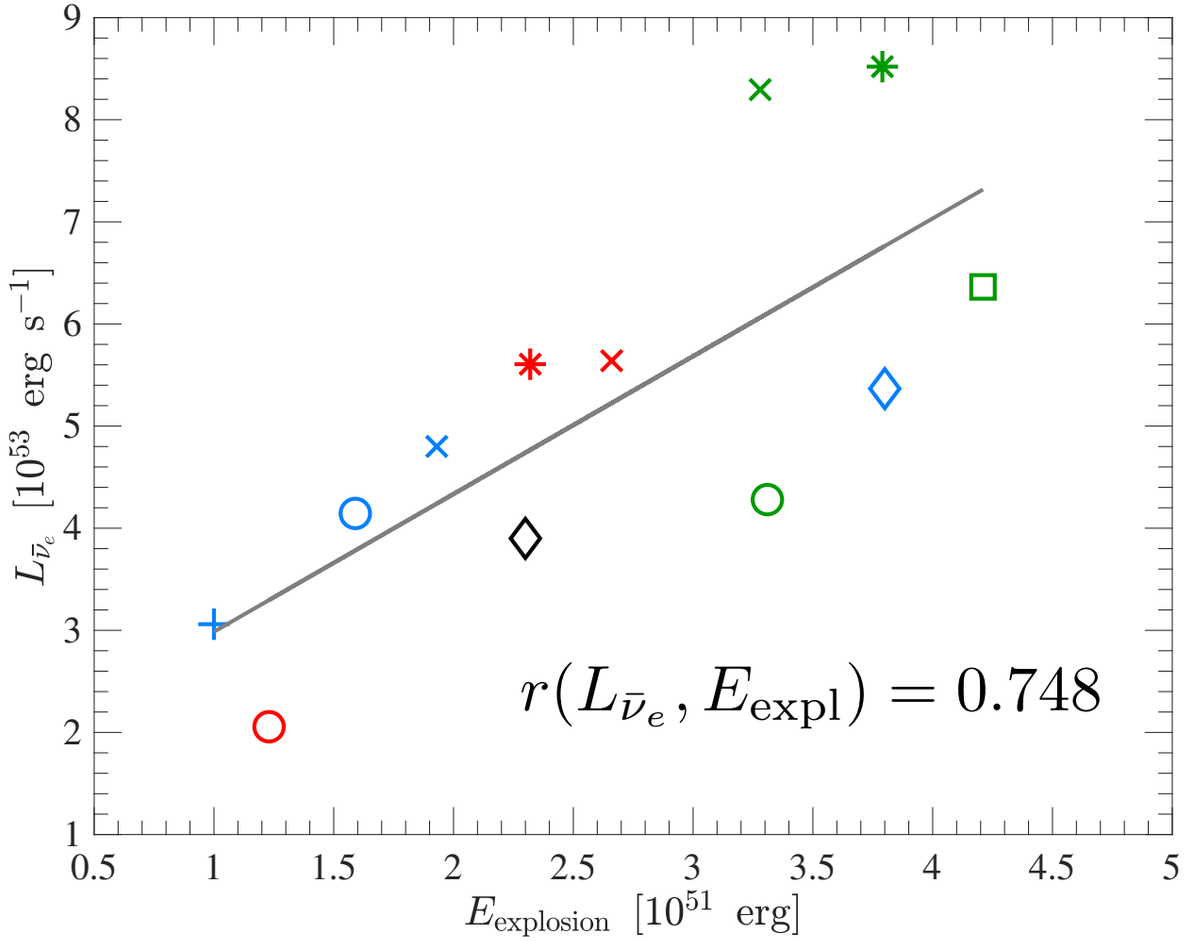


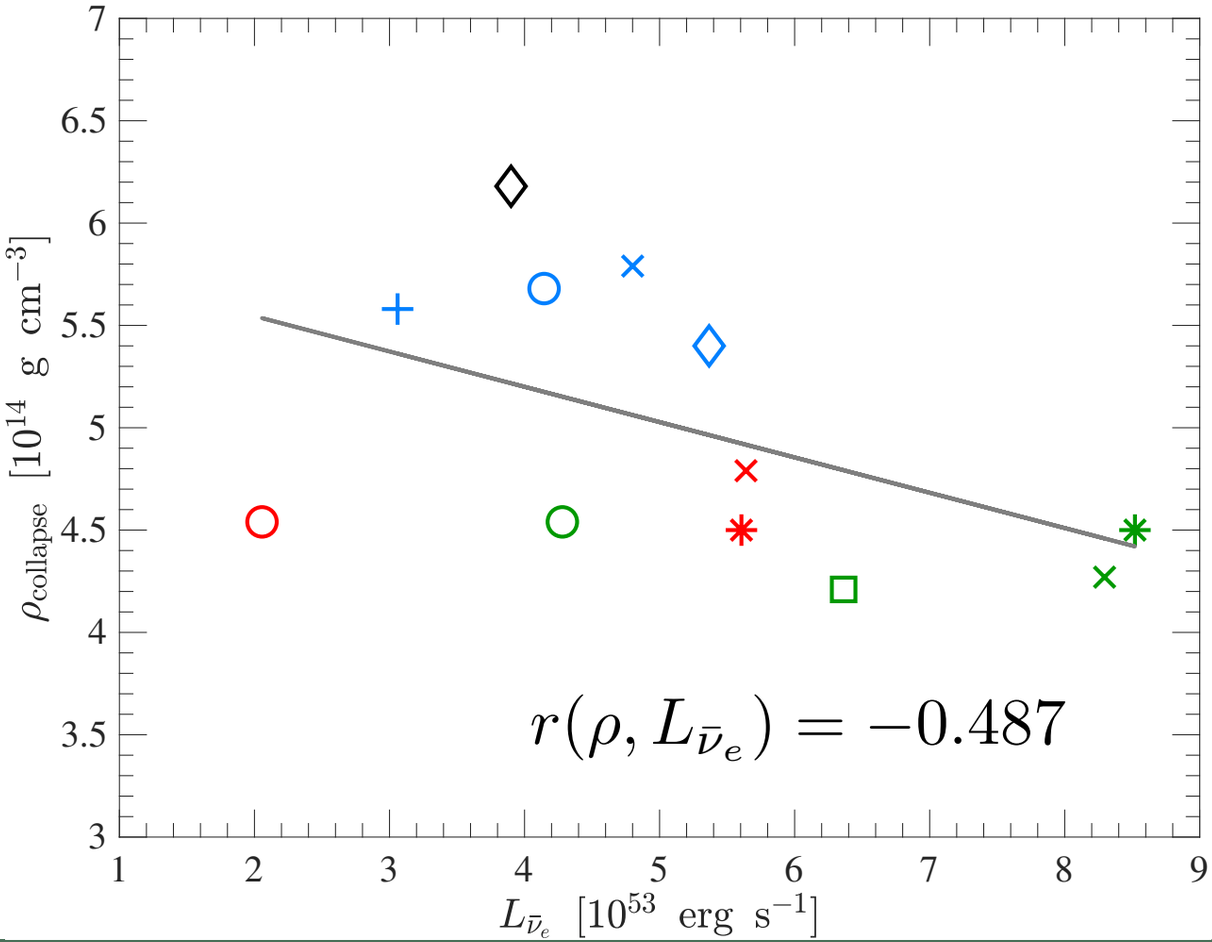
These systematic distinctions may put a constraint on the hybrid EoS

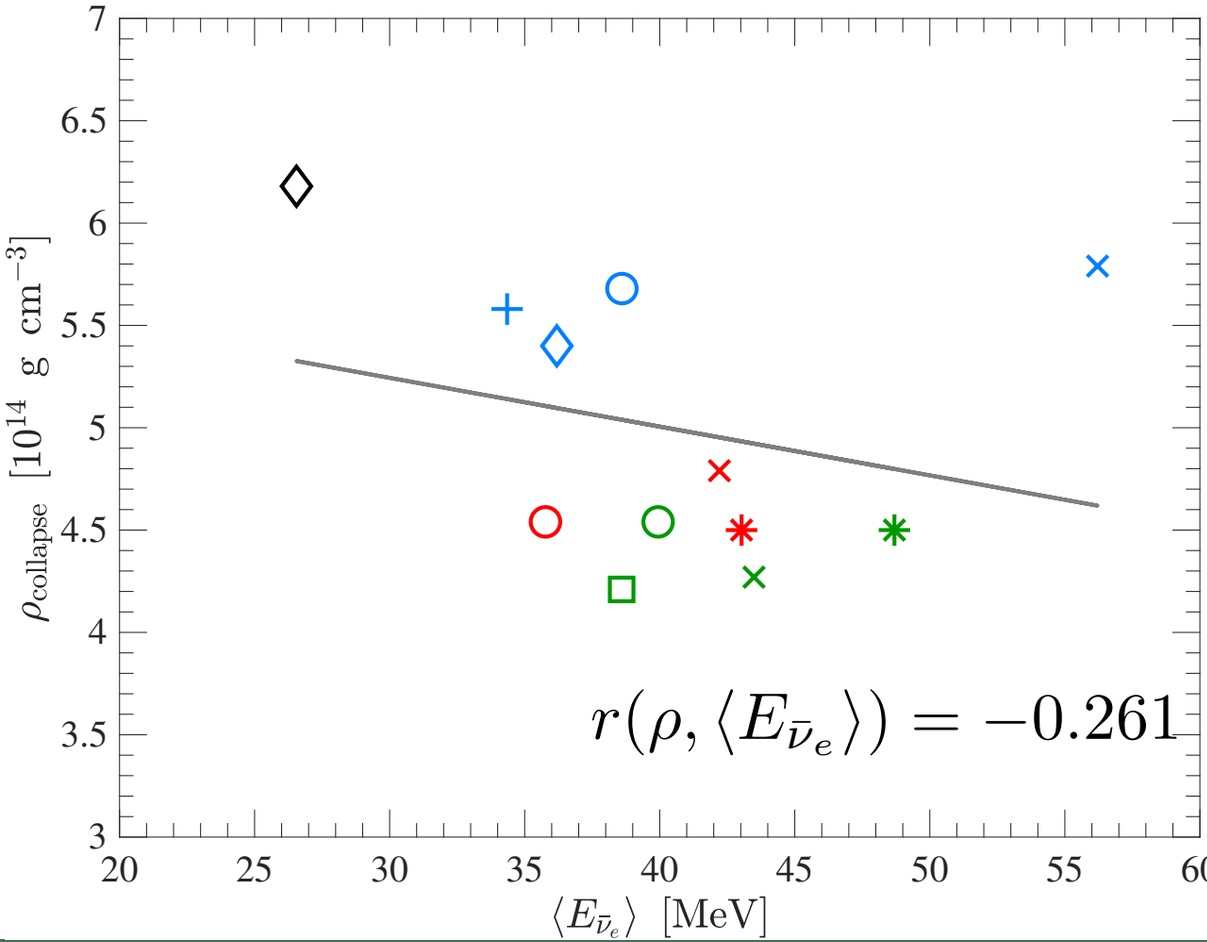
Progenitor	EOS RDF	$t_{\rm burst}$ [s]	$L_{\bar{\nu}_e,{\rm peak}}$ [10^{53} erg s^{-1}]	$\langle E_{\bar{\nu}_e}\rangle$ [MeV]	$E_{\rm expl}$ [10^{51} erg]

Khosravi Largani et al., ApJ 946, 143 (2024)



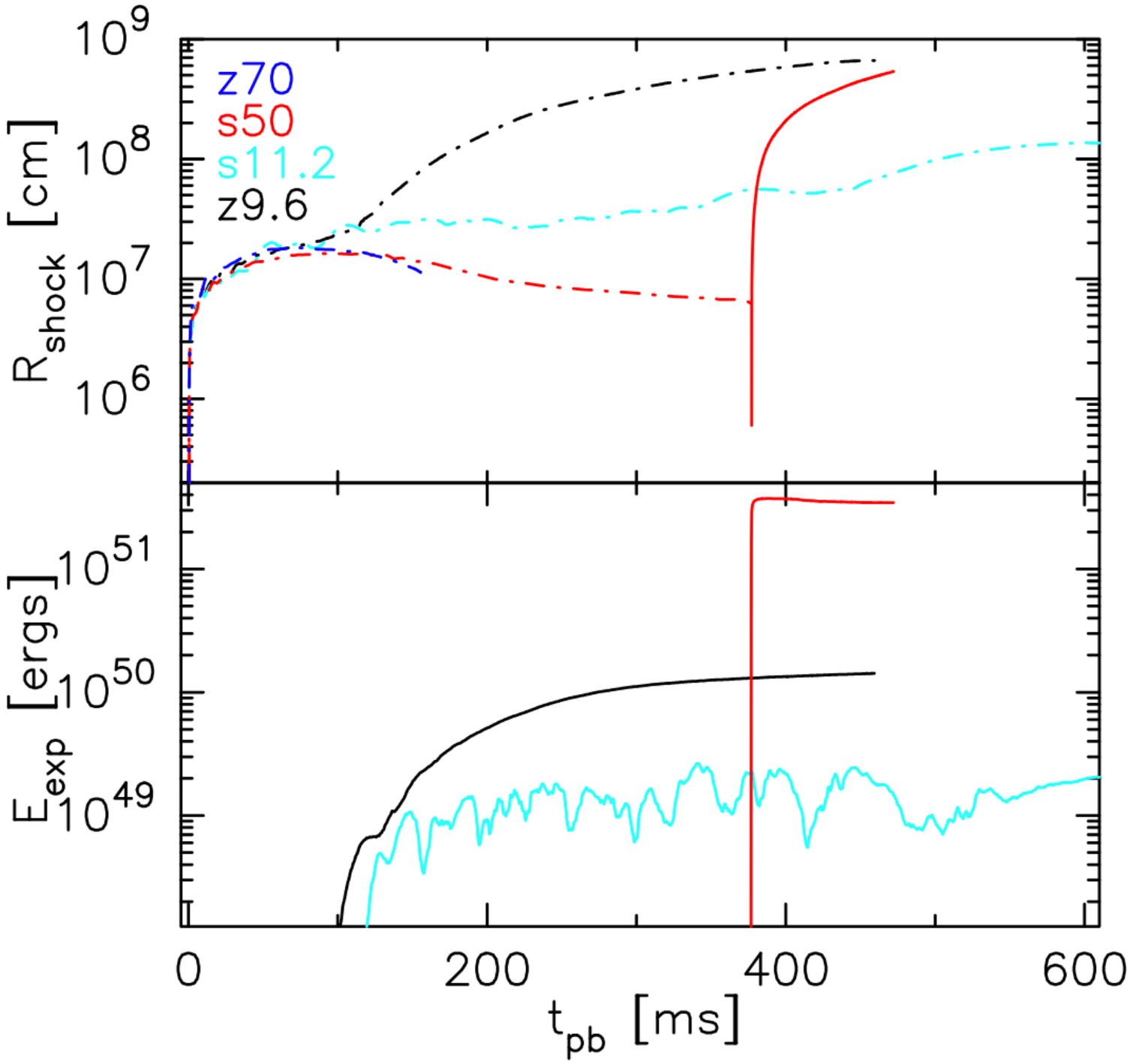






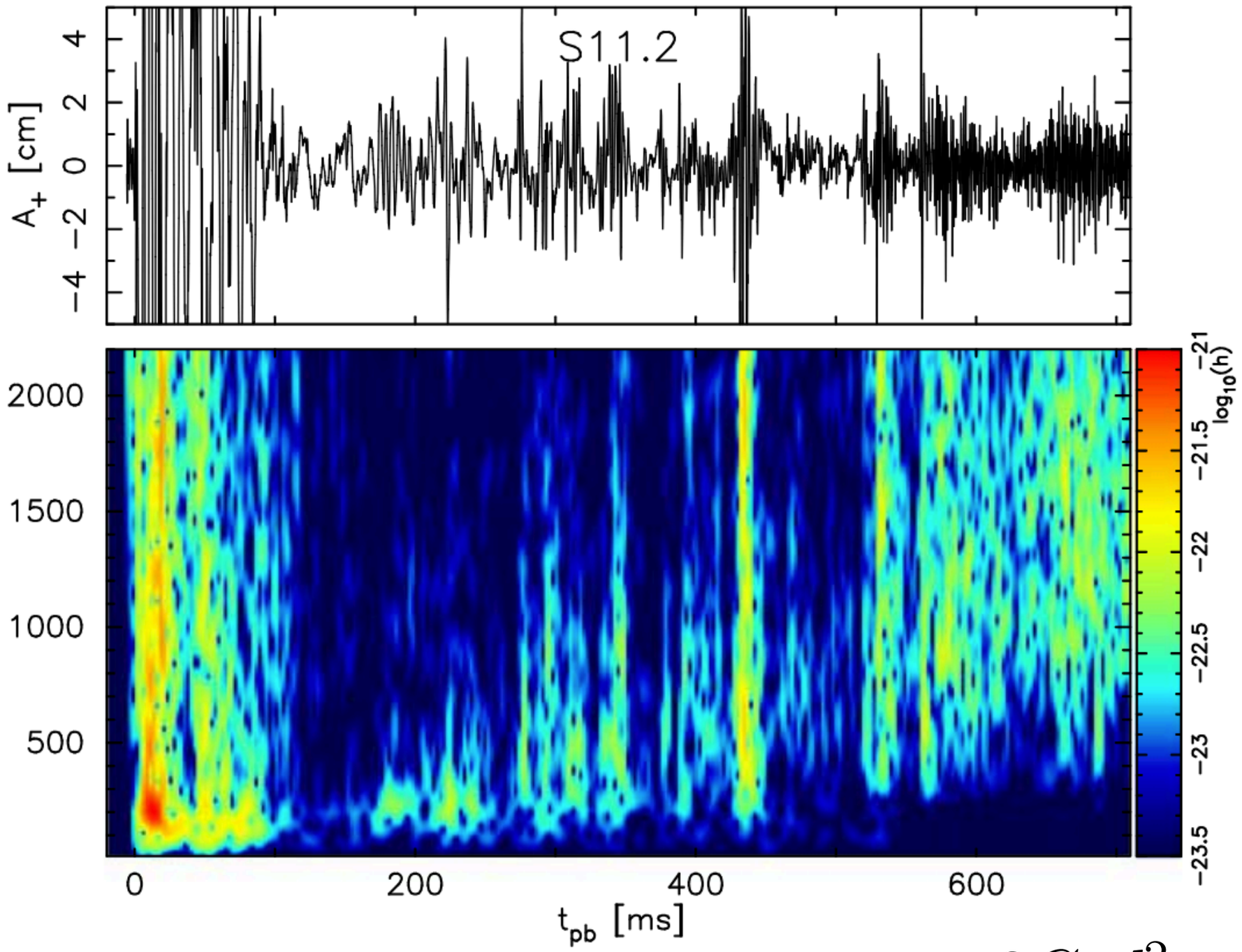
Khosravi Largani et al., Astrophys. J. 946, 143 (2024)

Multi dimensional simulations



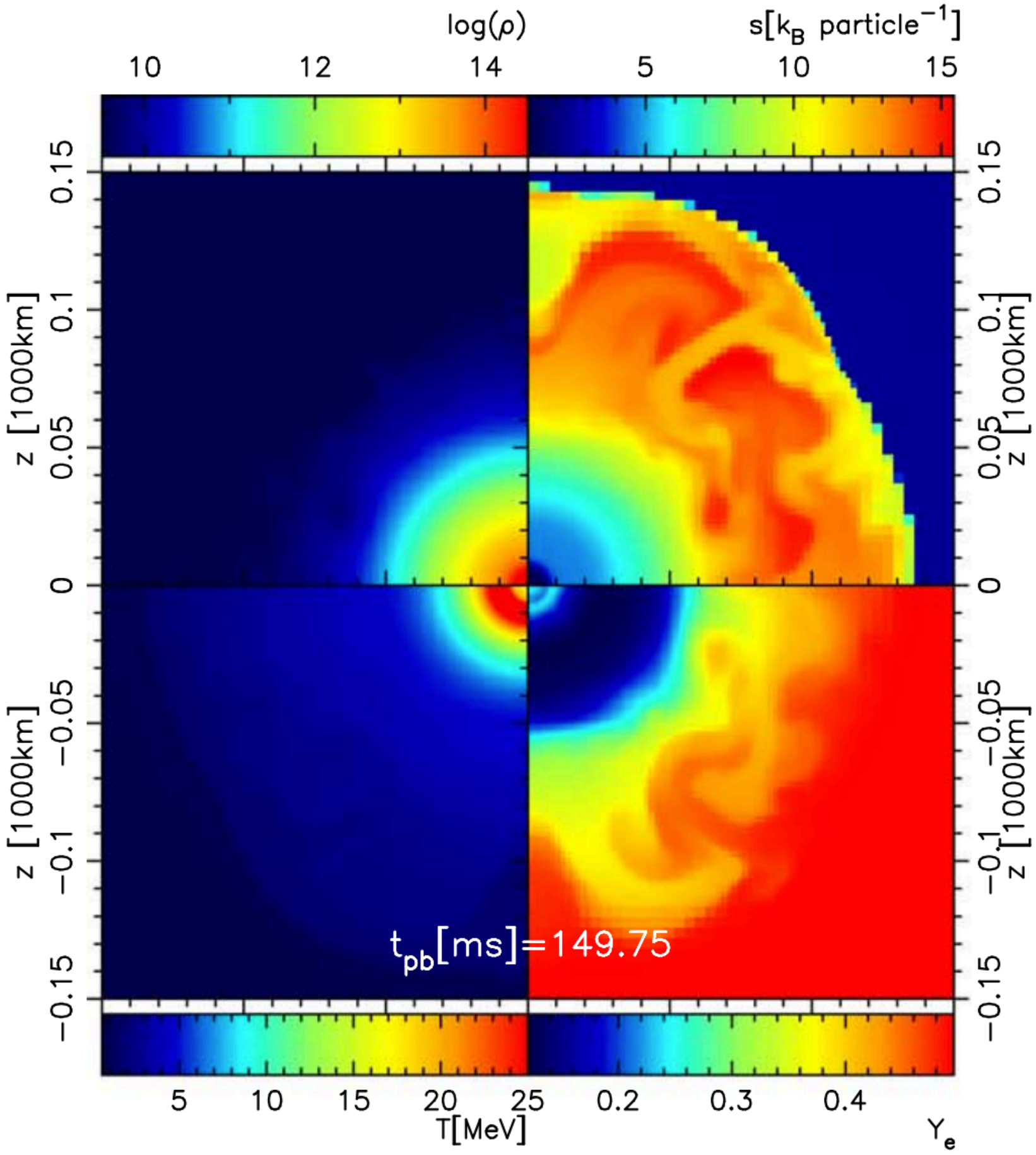
Kuroda et al., Astrophysical J., 924, 38 (2022)

Gravitational waves

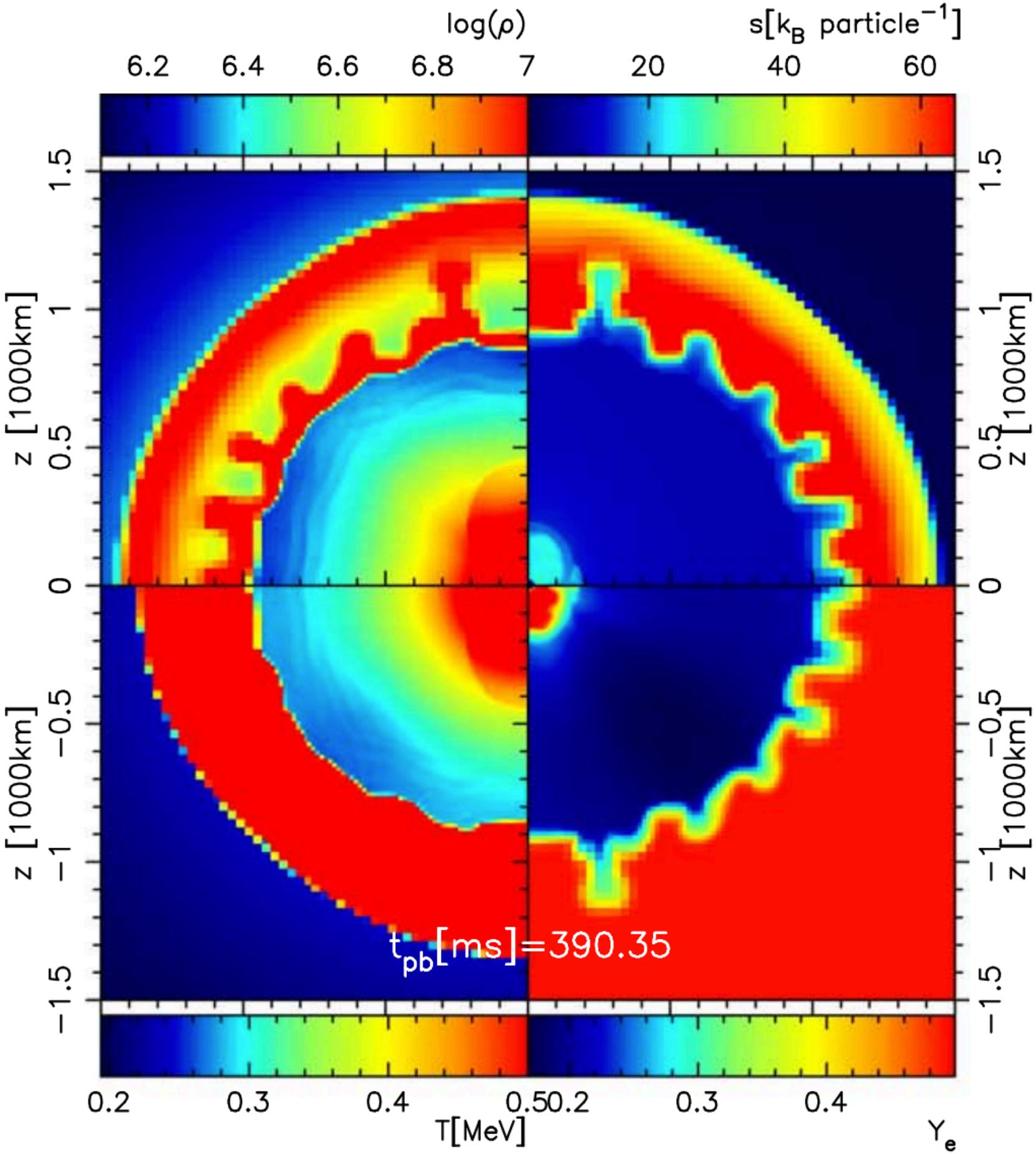


Kuroda et al., Astrophysics. J., 924, 38 (2022)

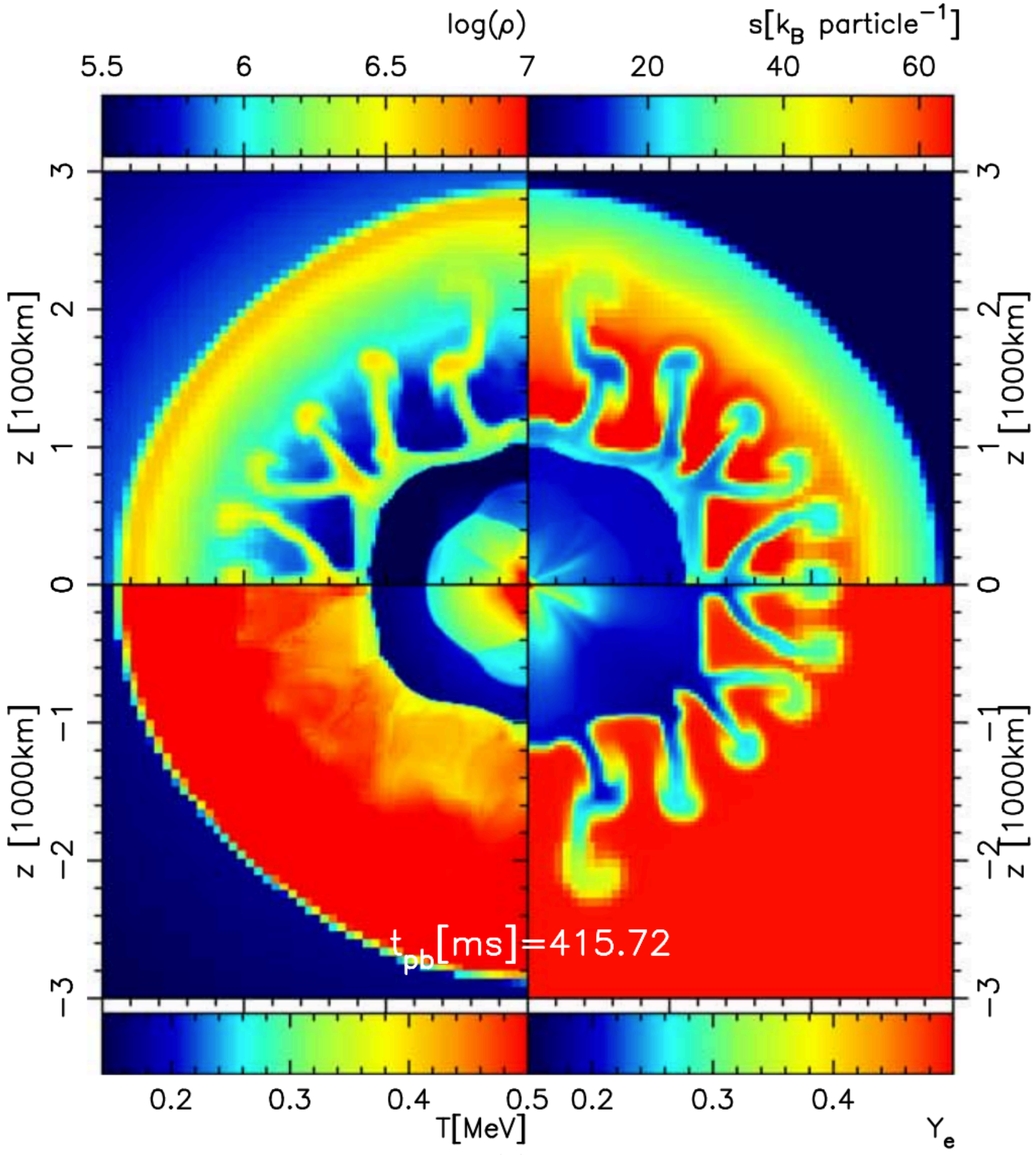
$$Q_{ij} = \int \rho(r)(3r_i r_j - |\vec{r}|^2 \delta_{ij}) d^3 r \qquad h_{ij} = \frac{2G}{c^4 r} \frac{d^2}{dt^2} Q_{ij}$$



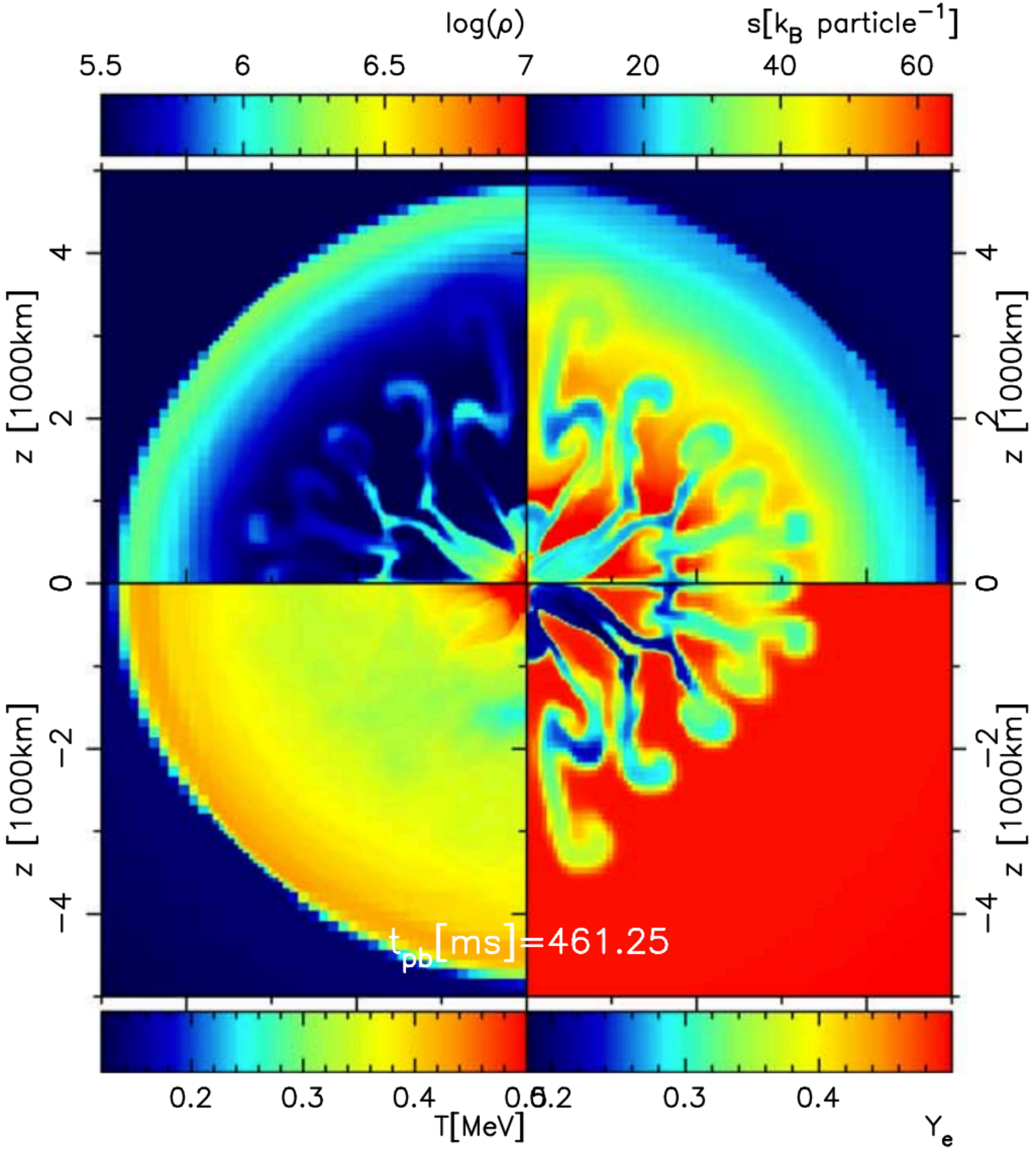
Kuroda et al., Astrophysics. J., 924, 38 (2022)



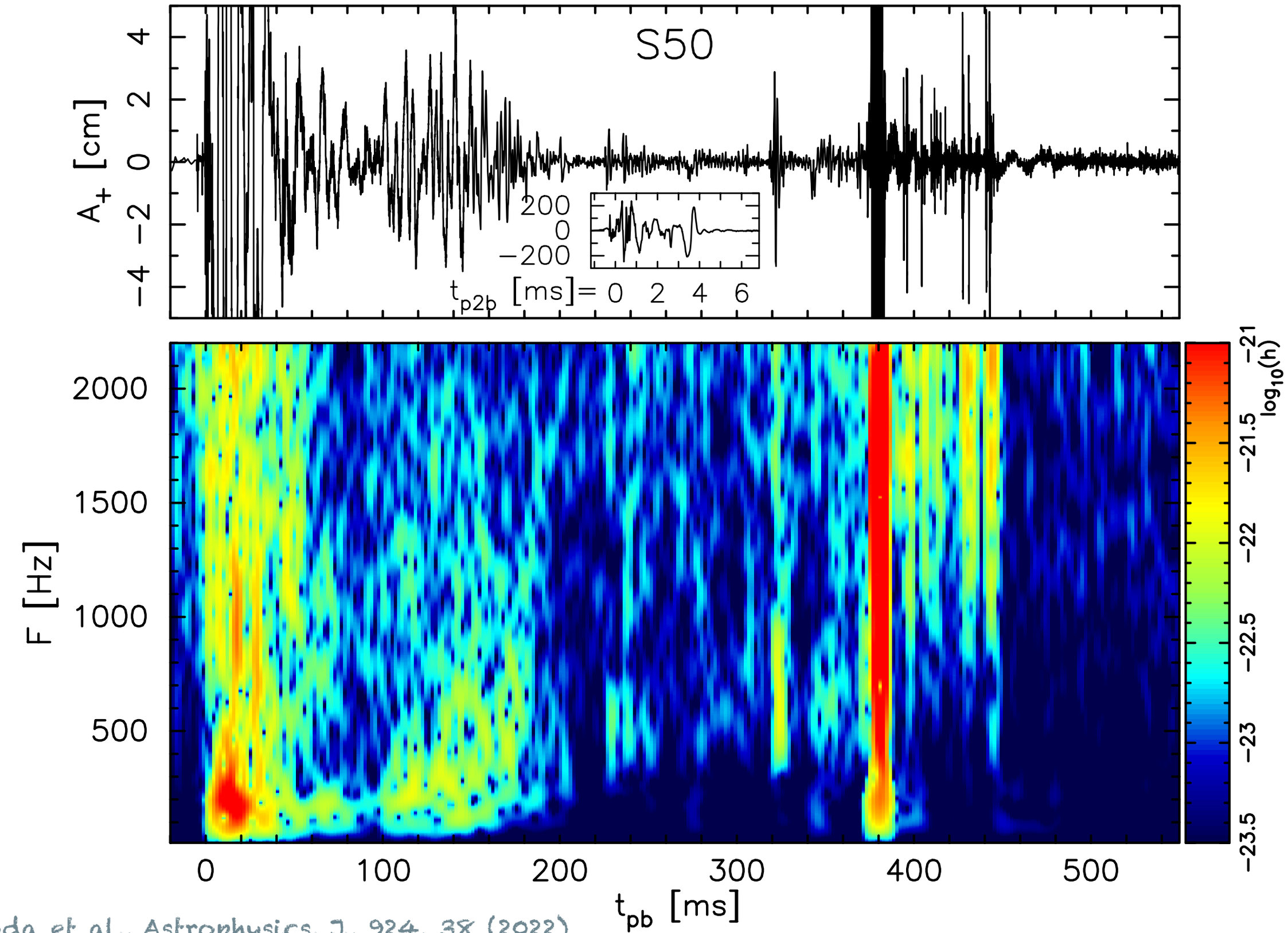
Kuroda et al., Astrophysics. J., 924, 38 (2022)



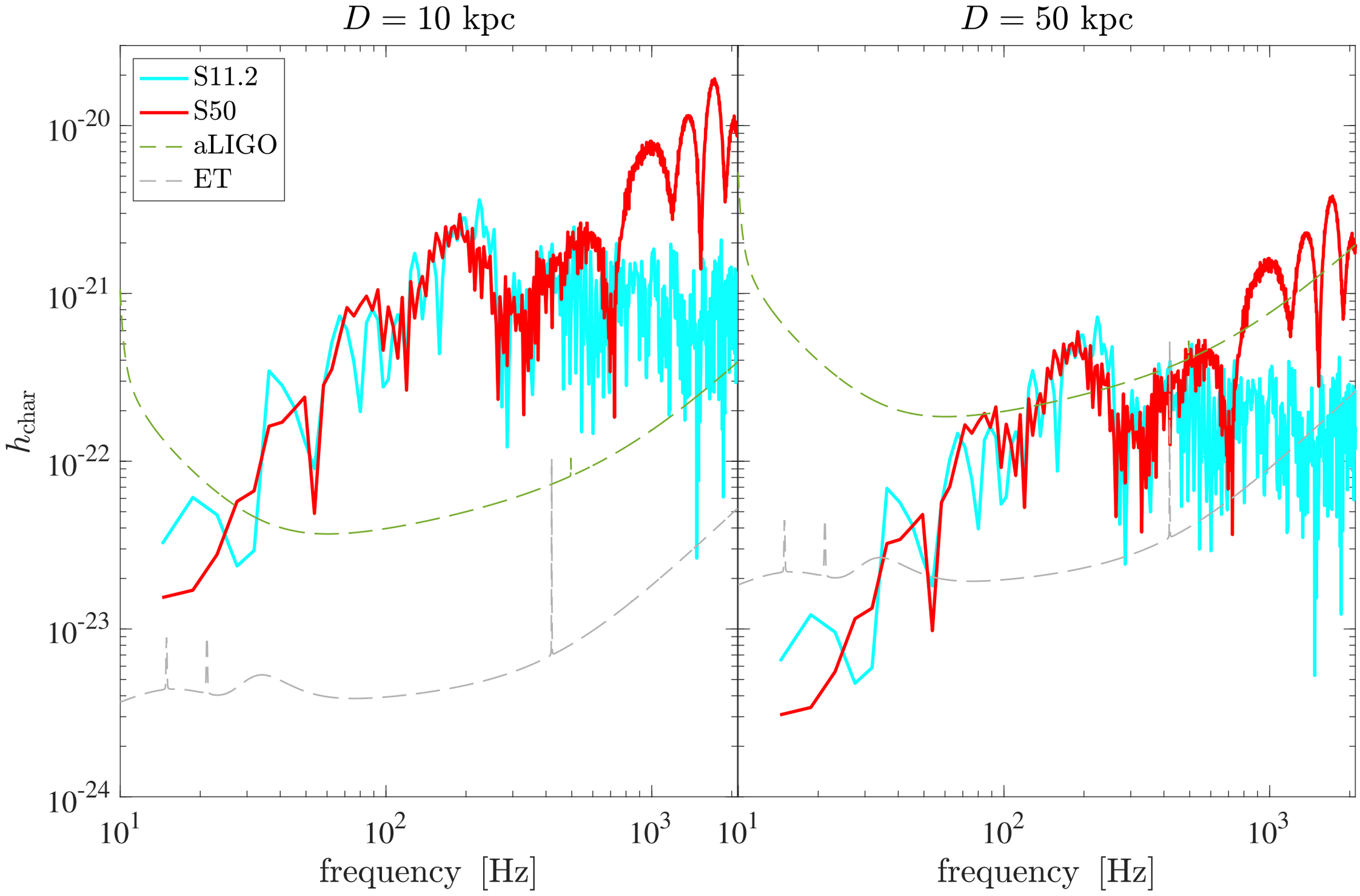
Kuroda et al., Astrophysical J., 924, 38 (2022)



Kuroda et al., Astrophysical J., 924, 38 (2022)

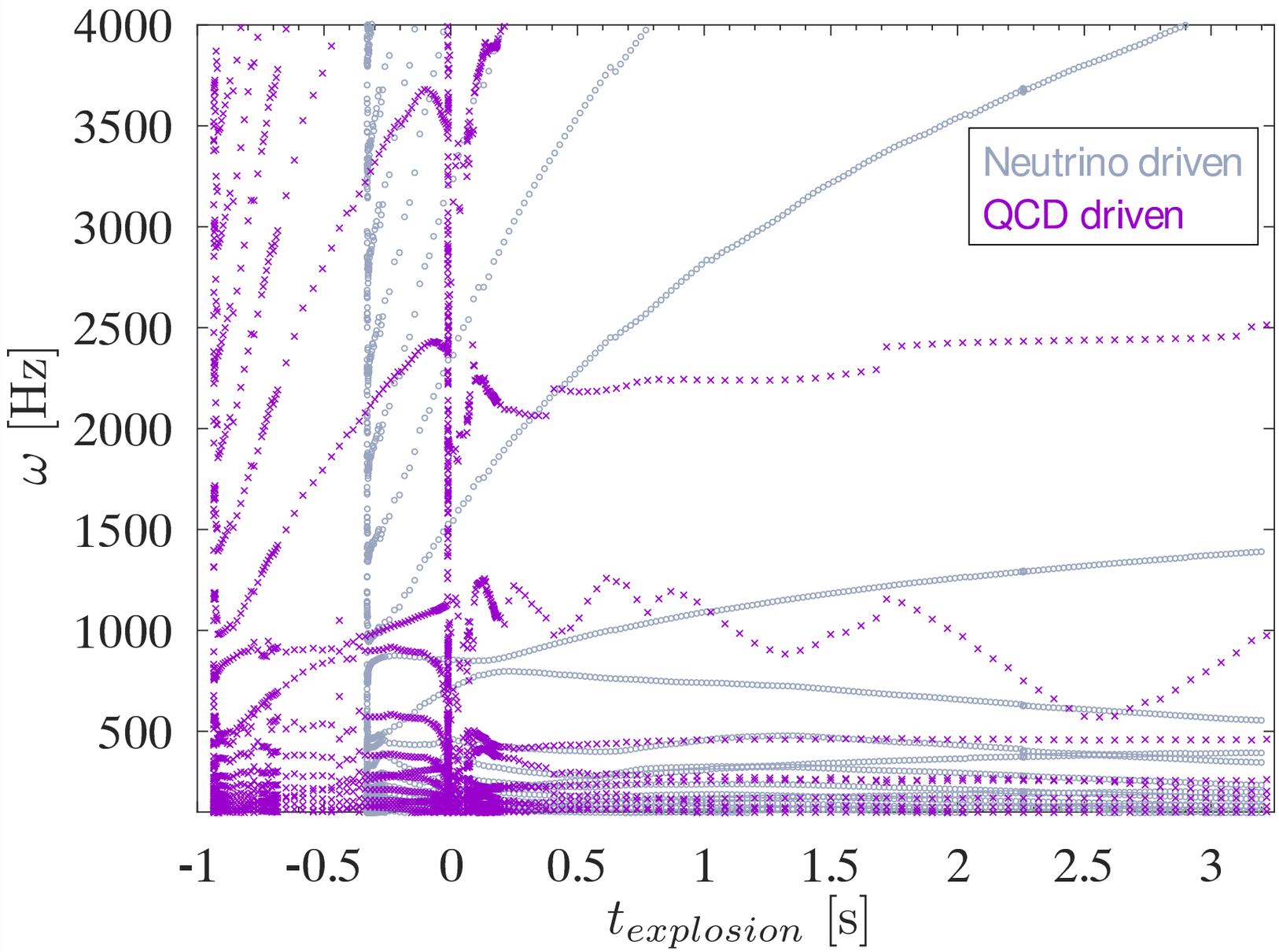


Kuroda et al., Astrophysics. J., 924, 38 (2022)
Zha et al., Phys. Rev. L., 125, 051102 (2020)



The Science of the Einstein Telescope, Adrian Abac et al, JCAP03(2026)081

Mode Analysis



$$\Delta\rho = \delta\rho + \xi^i \partial_i \rho$$

$$\delta P = \delta\hat{P}\, Y_{lm} \mathrm{e}^{-\mathrm{i}\sigma t},$$

$$\xi^r = \eta_r\, Y_{lm} \mathrm{e}^{-\mathrm{i}\sigma t},$$

$$\xi^\theta = \eta_\perp \frac{1}{r^2} \partial_\theta Y_{lm} \mathrm{e}^{-\mathrm{i}\sigma t},$$

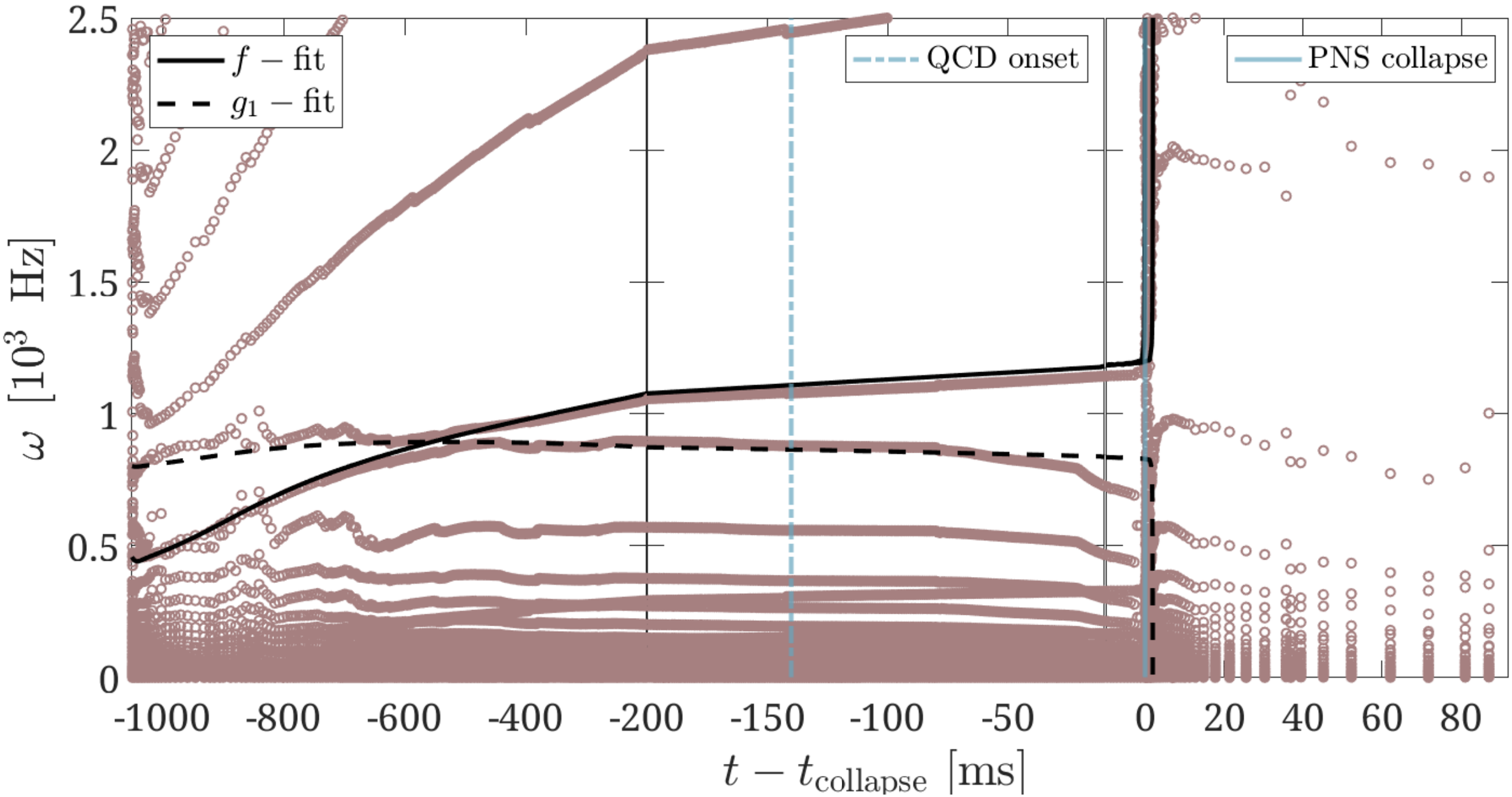
$$\xi^\varphi = \eta_\perp \frac{1}{r^2 \sin^2\theta} \partial_\varphi Y_{lm} \mathrm{e}^{-\mathrm{i}\sigma t}$$

Torres-Forne et al. (2019), Mon. Not. Roy. Astron. Soc.
Torres-Forne et al. (2018), Mon. Not. Roy. Astron. Soc.

f $\quad x = \sqrt{M_{\rm PNS}/R^3_{\rm PNS}}$

g_1 $\quad x = M_{\rm PNS}/R^2_{\rm PNS}$

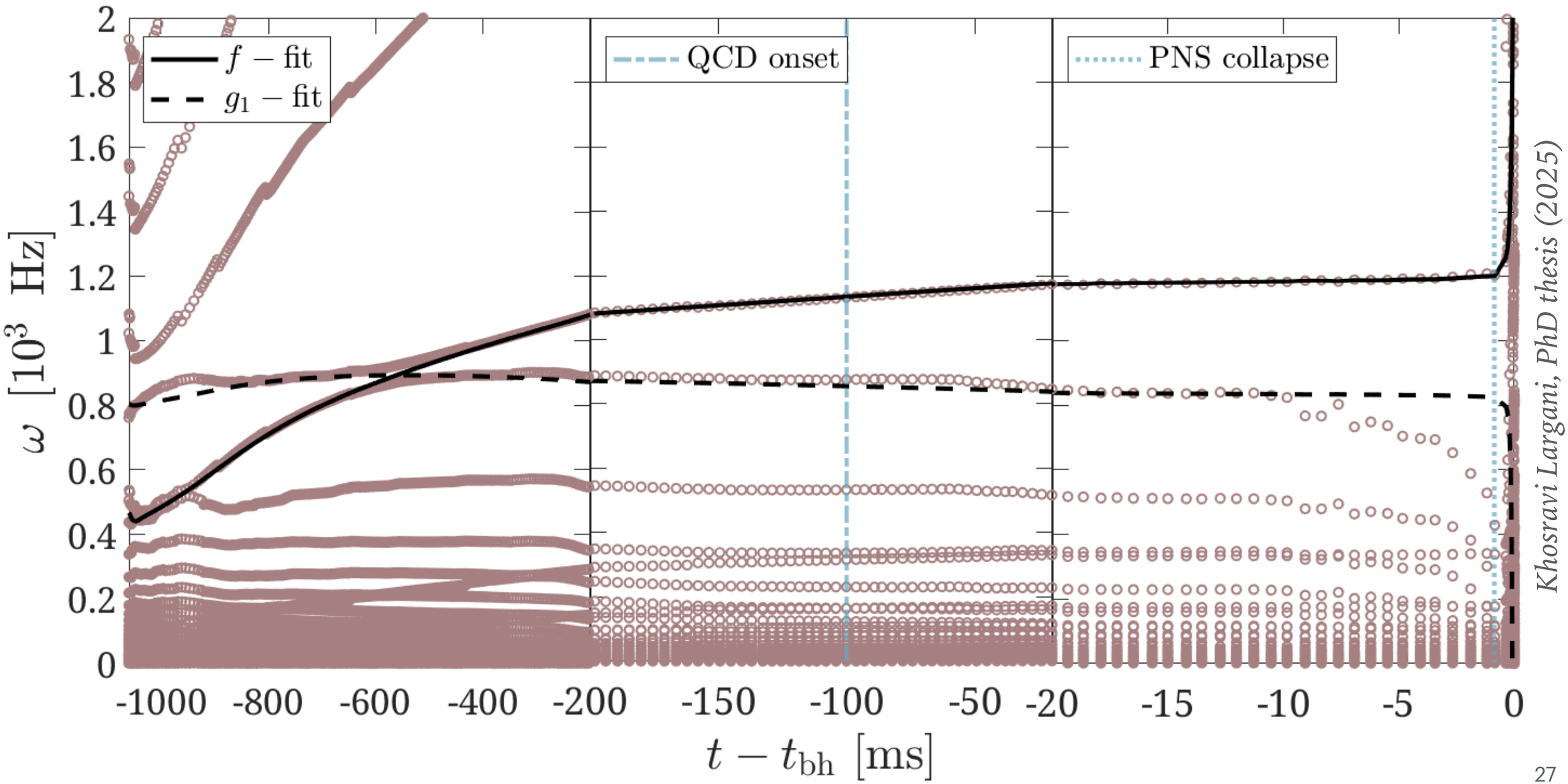
$$\omega_{\rm fit}(x) = a_0 + a_1\,x + a_2\,x^2 + a_3\,x^3$$



$$f \qquad x = \sqrt{M_{\rm PNS}/R^3_{\rm PNS}}$$

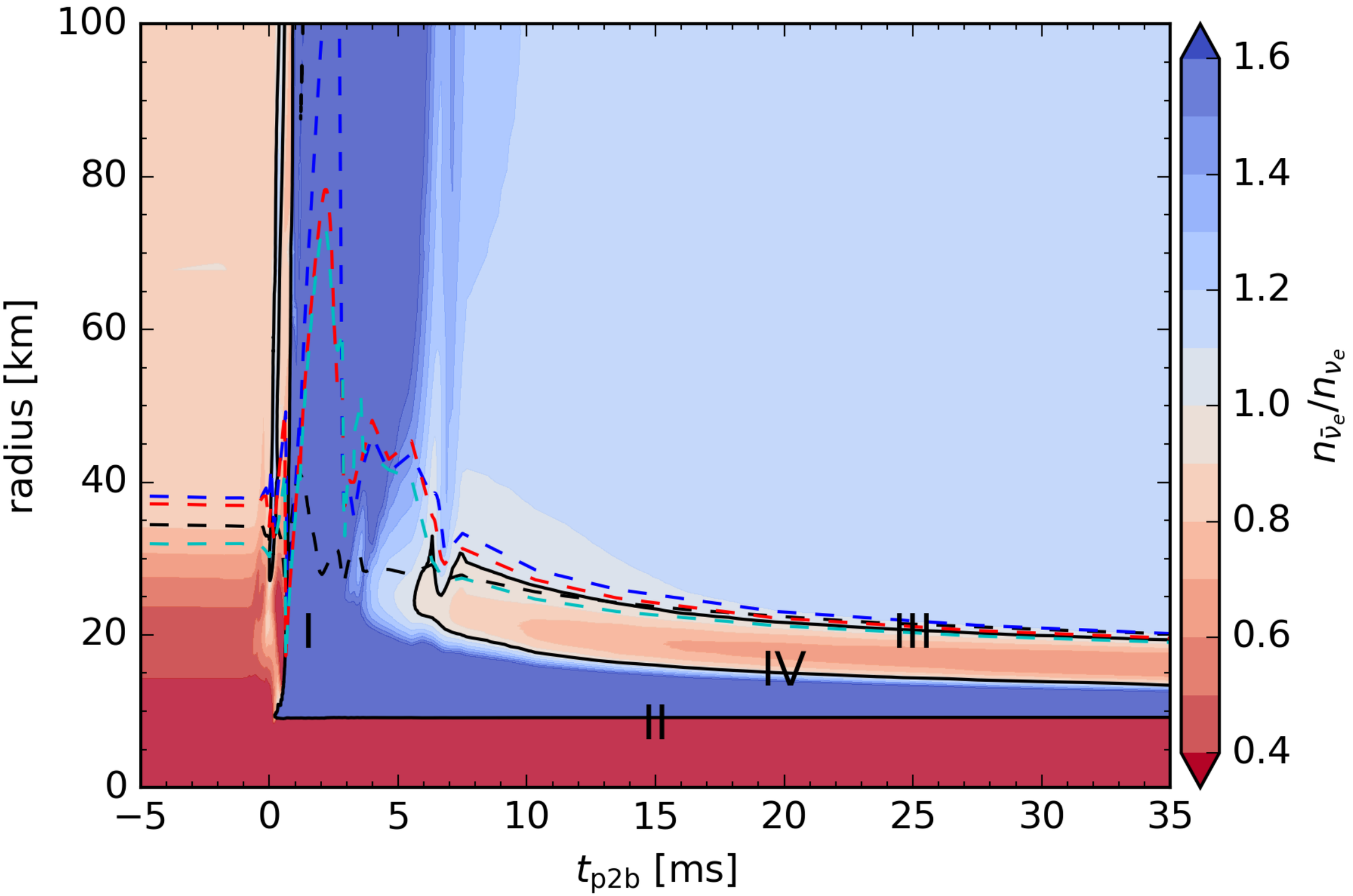
$$g_1 \qquad x = M_{\rm PNS}/R^2_{\rm PNS}$$

$$\omega_{\rm fit}(x) = a_0 + a_1\,x + a_2\,x^2 + a_3\,x^3$$

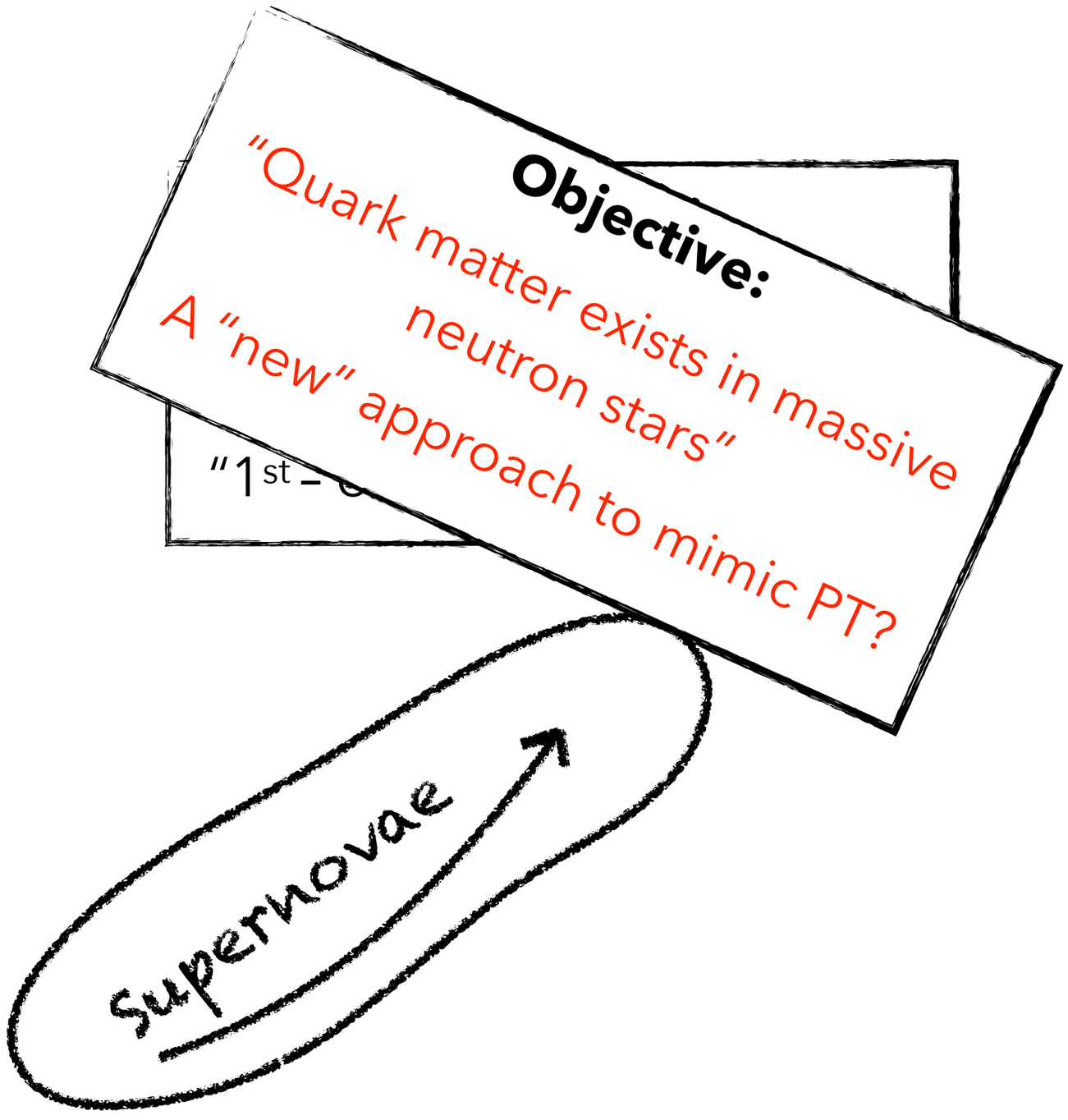


Khosravi Largani, PhD thesis (2025)

Fast flavor conversions in QCD driven CCSN



Xiong et al., PRD 112, 063024 (2025)



Redrawn and adapted from GSI Helmholtz Centre, Darmstadt



Redrawn and adapted from GSI Helmholtz Centre, Darmstadt


t_{pb} = 0.0 s
0.5 s
1.0 s
$\log_{10}(\rho\ [\mathrm{g\ cm^{-3}}])$
10 11 12 13 14
CCSN simulations
• Core collapse
• PNS evolution
• QCD phase transition?
• ν & GW signatures
kofola
original
CCSN
Supernovae
Neutron Stars
Neutrinos in Astrophysics
Gravitational Waves

Thank you!