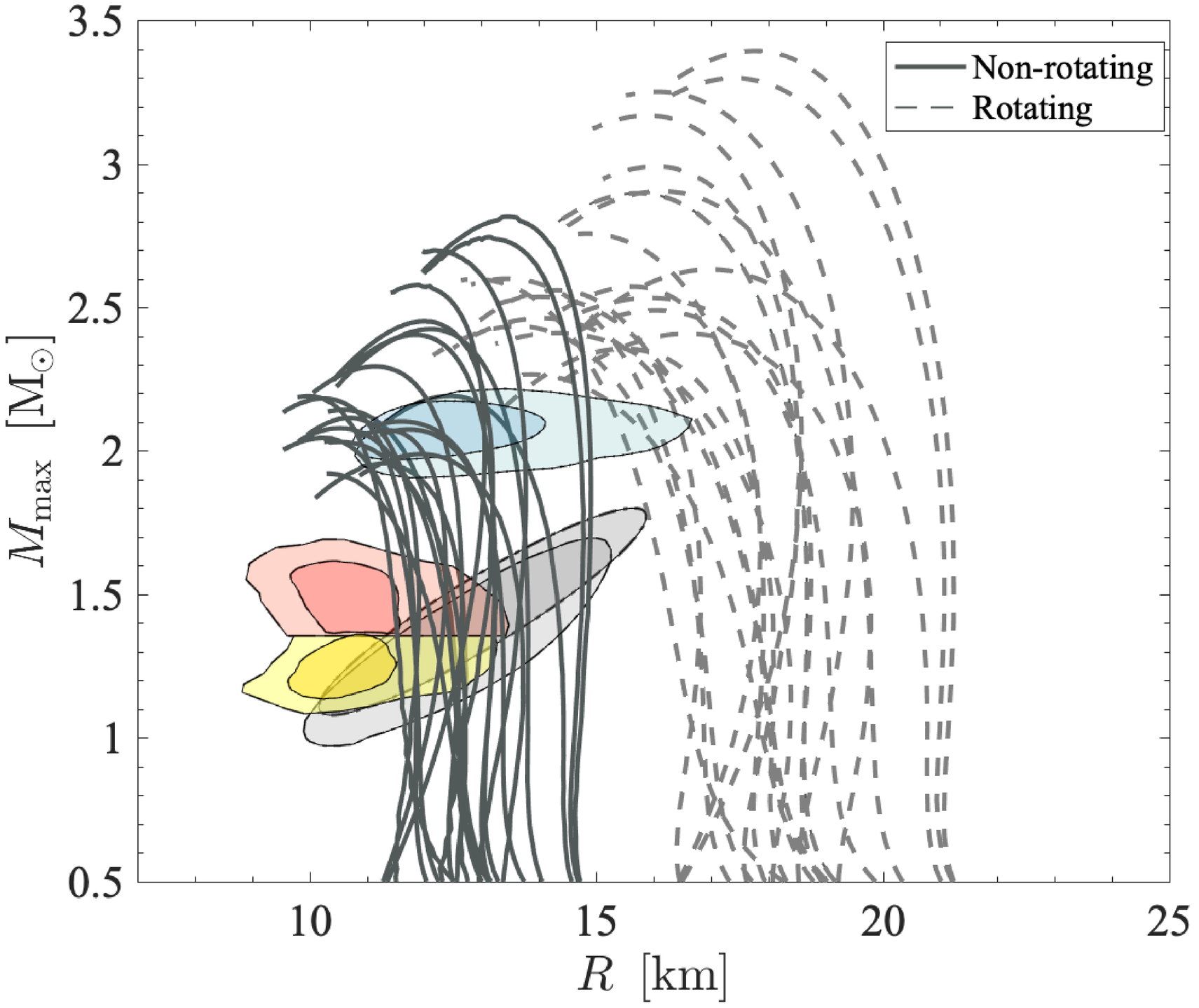
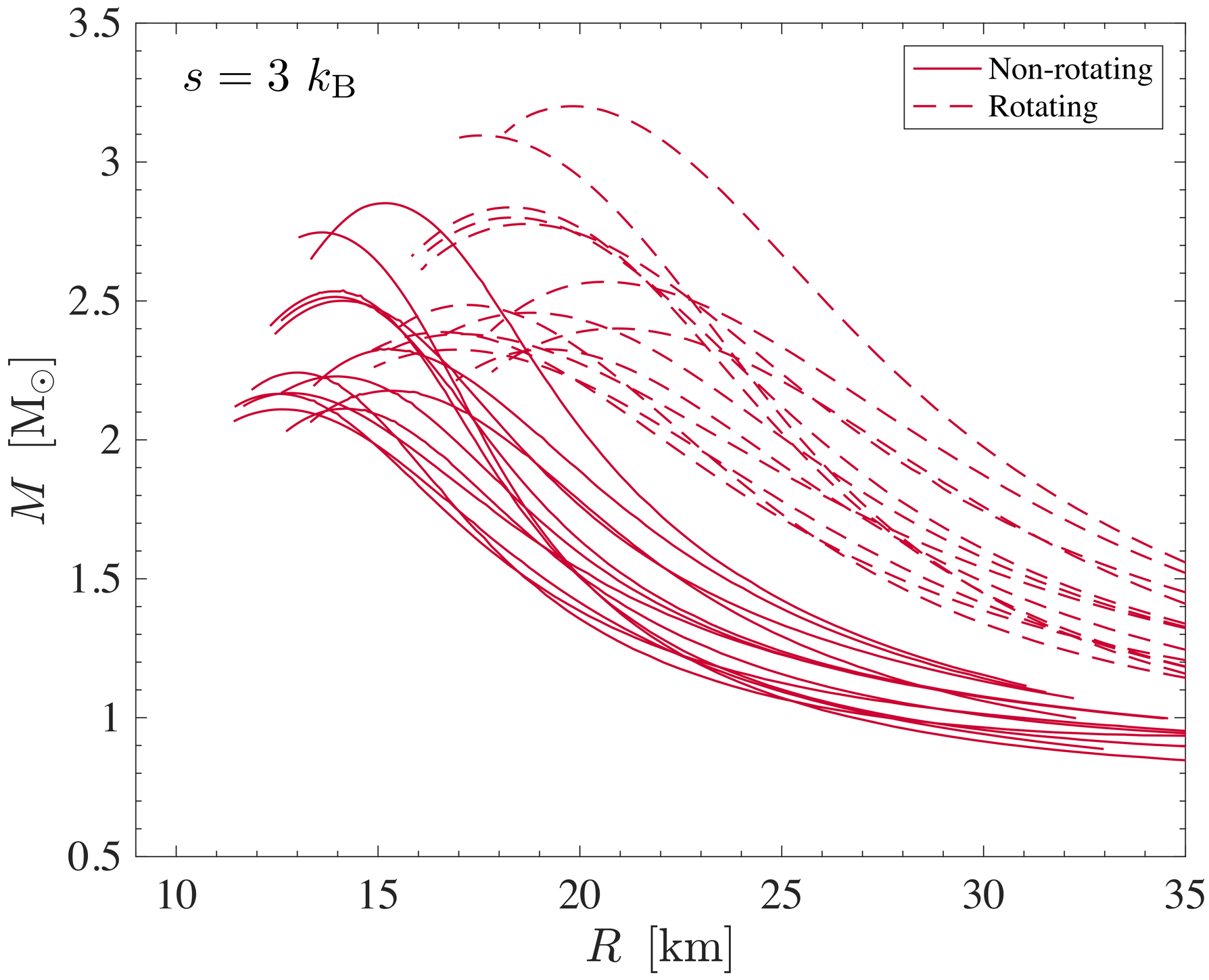
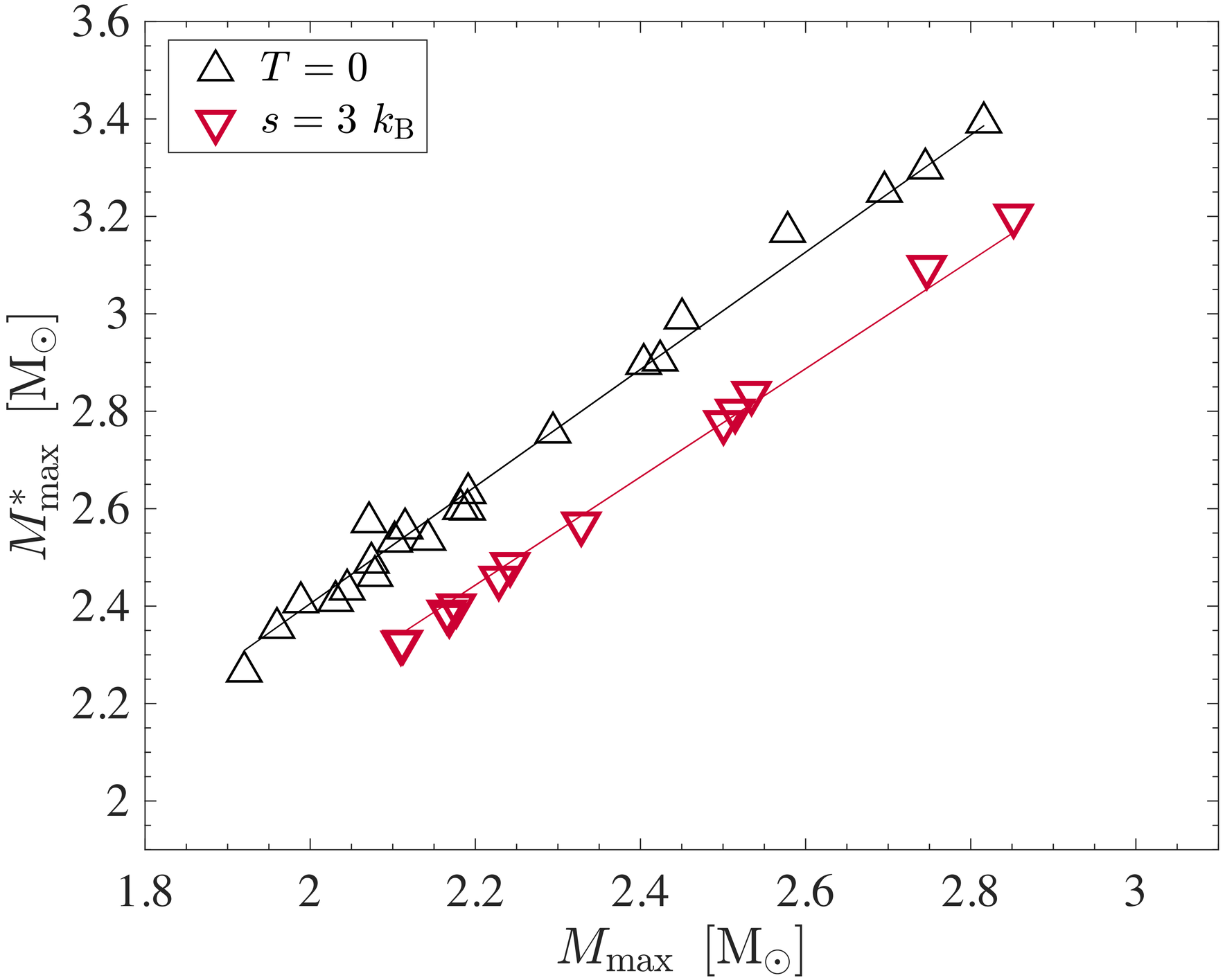
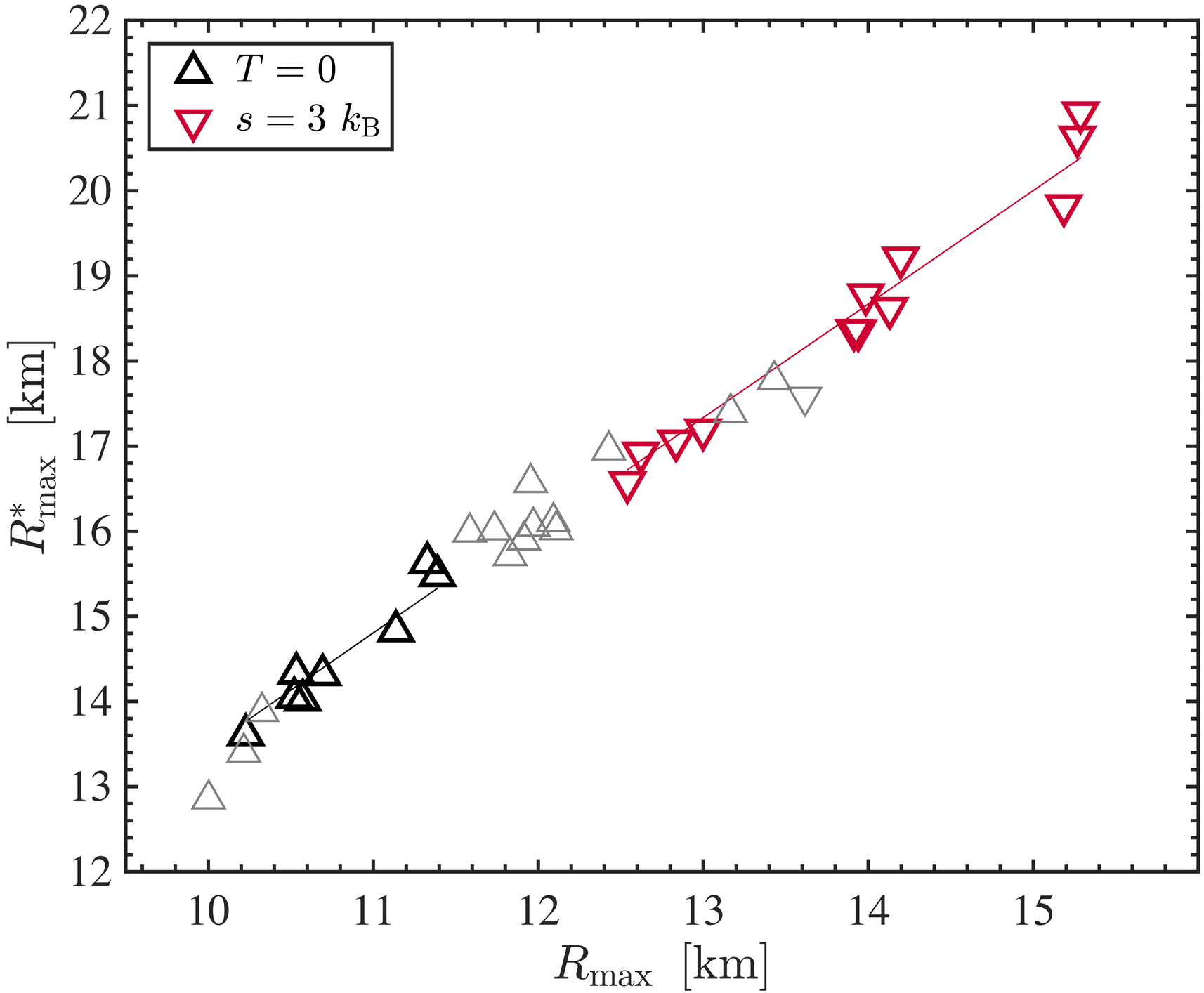
1. Rapidly Rotating Neutron Stars

N.K. Largani et al., MNRAS (2022)


Non-rotating
Rotating
3.5
3
2.5
2
1.5
1
0.5
$M_{\max}$ [$M_\odot$]
10
15
20
25
R [km]


$s = 3\ k_{\mathrm{B}}$
Non-rotating
Rotating
M [$\mathrm{M}_\odot$]
R [km]
3.5
3
2.5
2
1.5
1
0.5
10
15
20
25
30
35


$T = 0$
$s = 3\ k_{\rm B}$
$M^*_{\rm max}$ [M$_\odot$]
$M_{\rm max}$ [M$_\odot$]
3.6
3.4
3.2
3
2.8
2.6
2.4
2.2
2
1.8
2
2.2
2.4
2.6
2.8
3


$T = 0$
$s = 3\ k_{\rm B}$
$R^*_{\rm max}$ [km]
$R_{\rm max}$ [km]
22
21
20
19
18
17
16
15
14
13
12
10
11
12
13
14
15

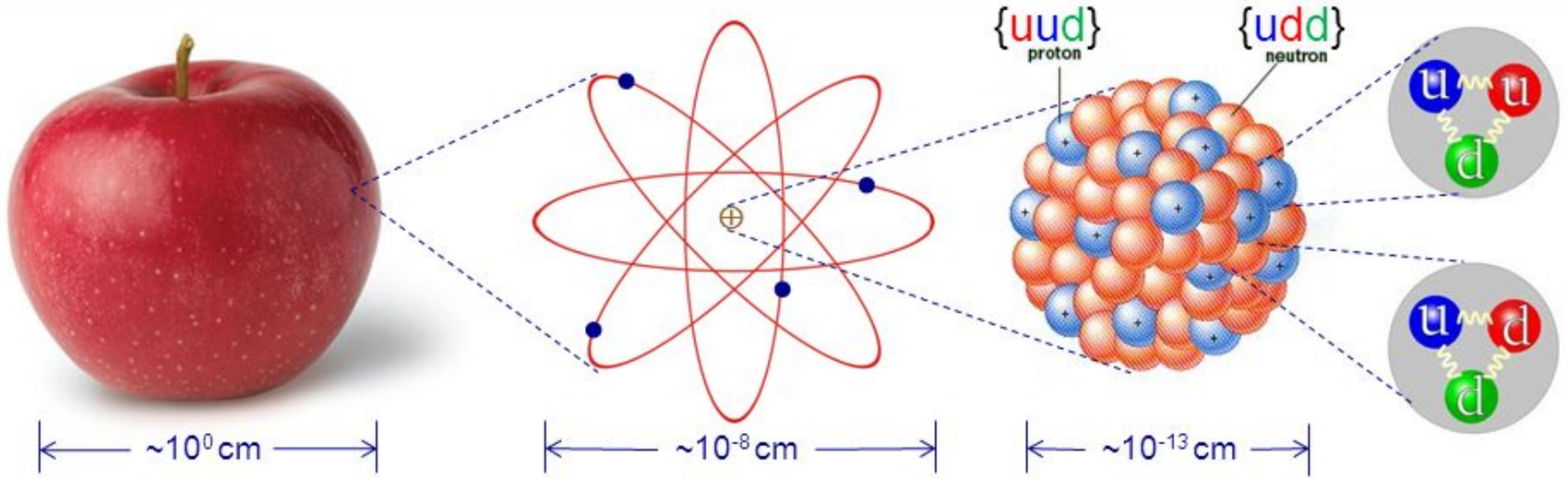
$$T = 0$$

$$\frac{M^*_{\rm max}}{M_{\rm max}} = 1.200 \pm 0.0160 \qquad \frac{R^*_{\rm max}}{R_{\rm max}} = 1.346 \pm 0.0160 \quad \text{(Hadronic)}$$

$$s = 3\ k_{\rm B}\ , Y_{\rm L} = 0.3$$

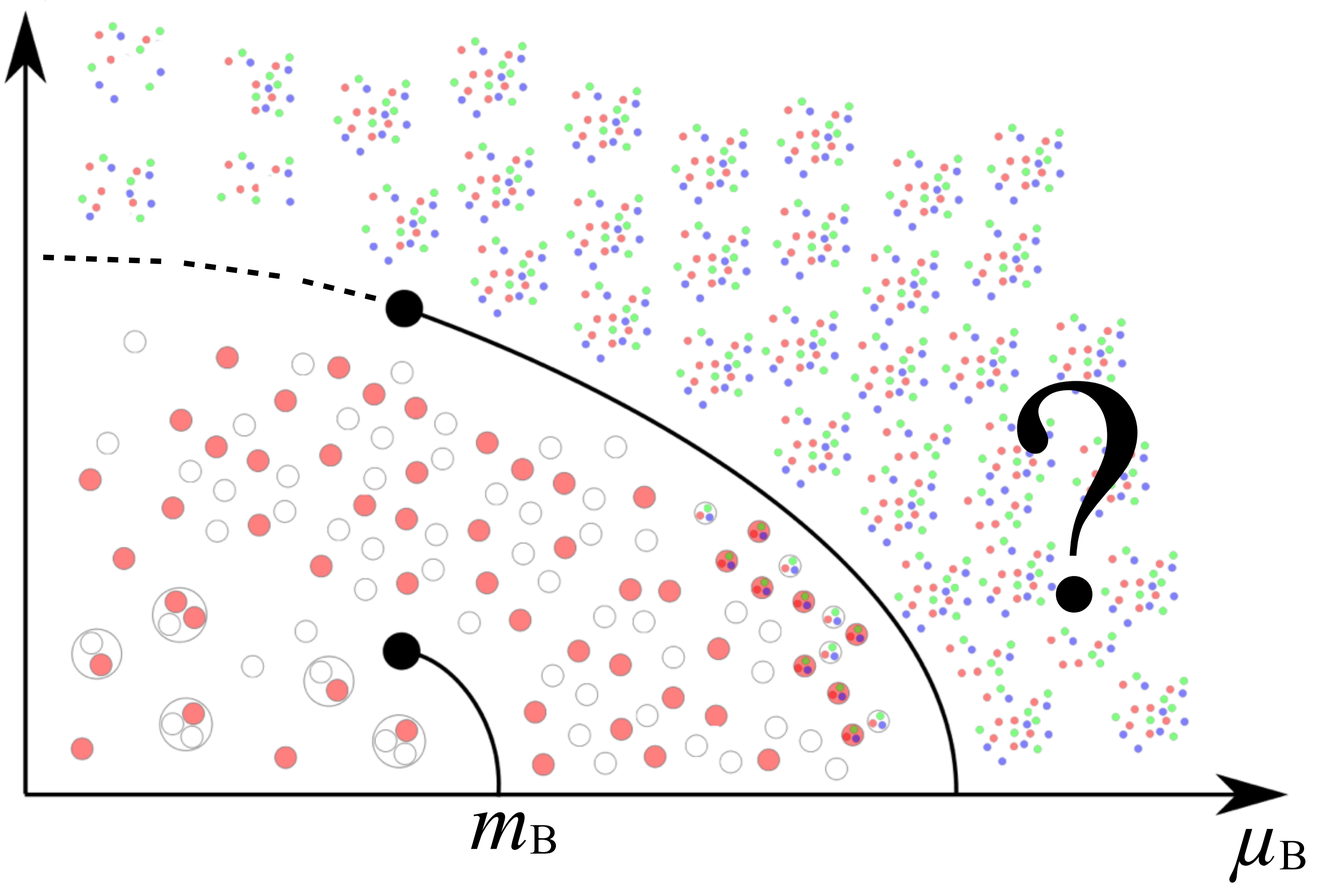
$$\frac{M^*_{\rm max}}{M_{\rm max}} = 1.109 \pm 0.0055 \qquad \frac{R^*_{\rm max}}{R_{\rm max}} = 1.334 \pm 0.0125 \quad \text{(Hadronic)}$$

Khadkikar et al., Phys. Rev. C 103, 055811 (2021)

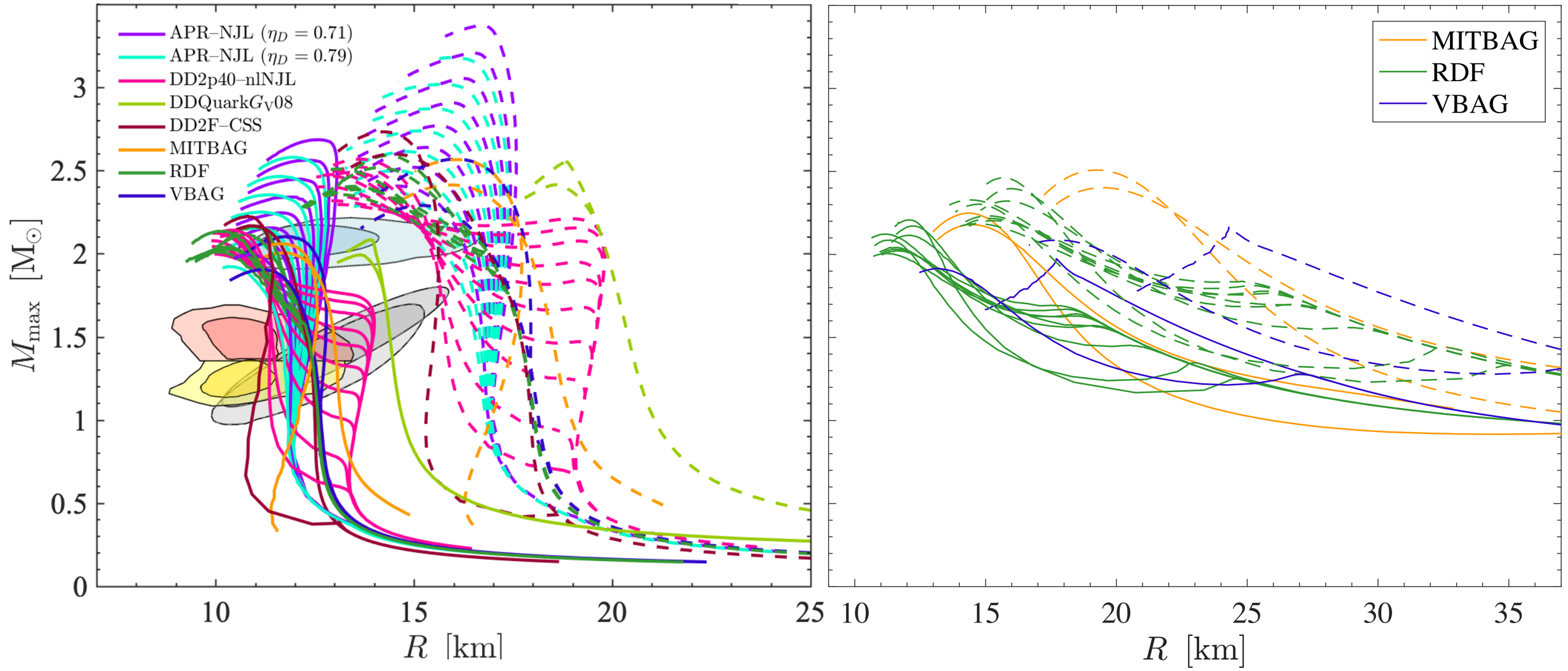


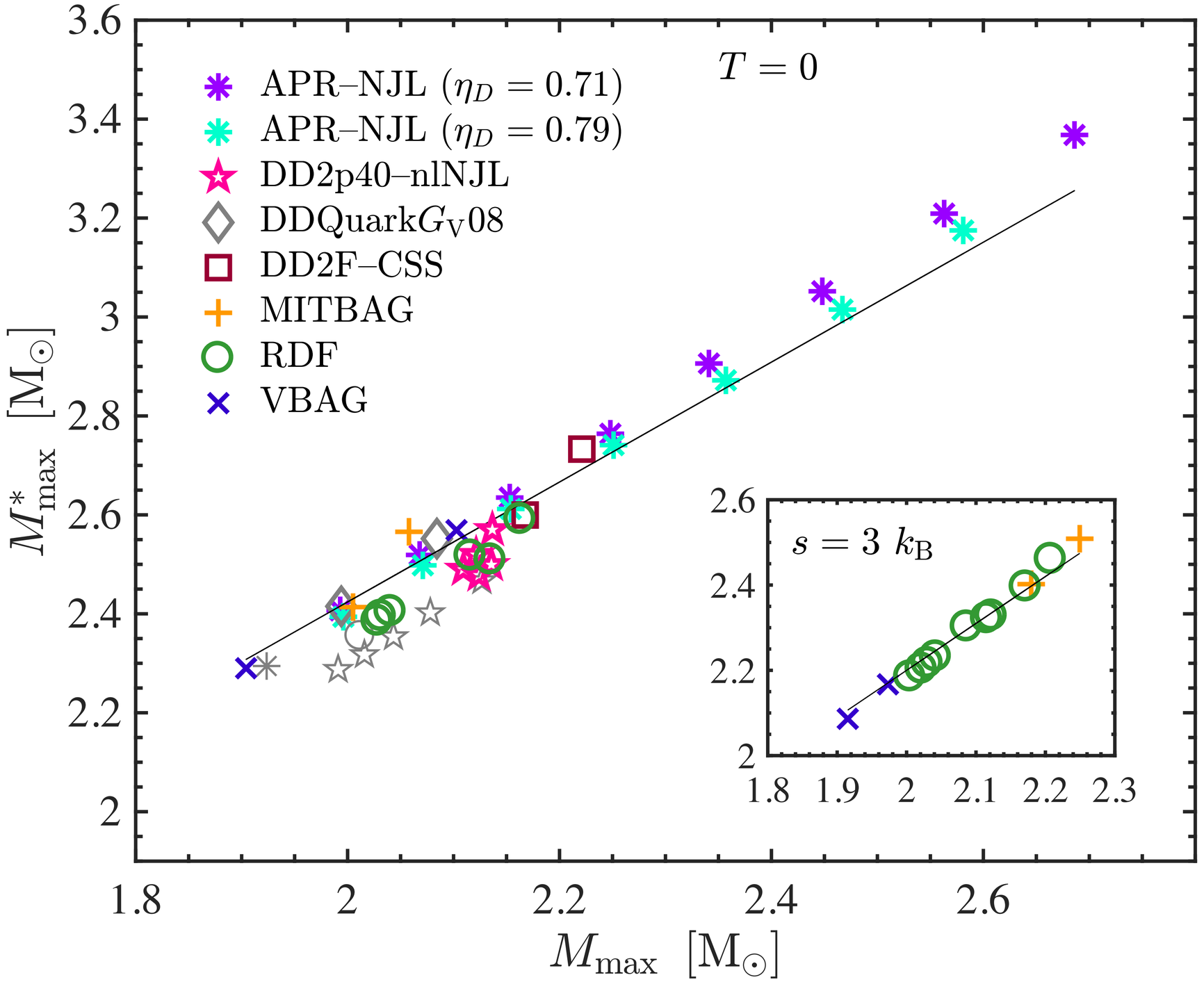
Lattice QCD:

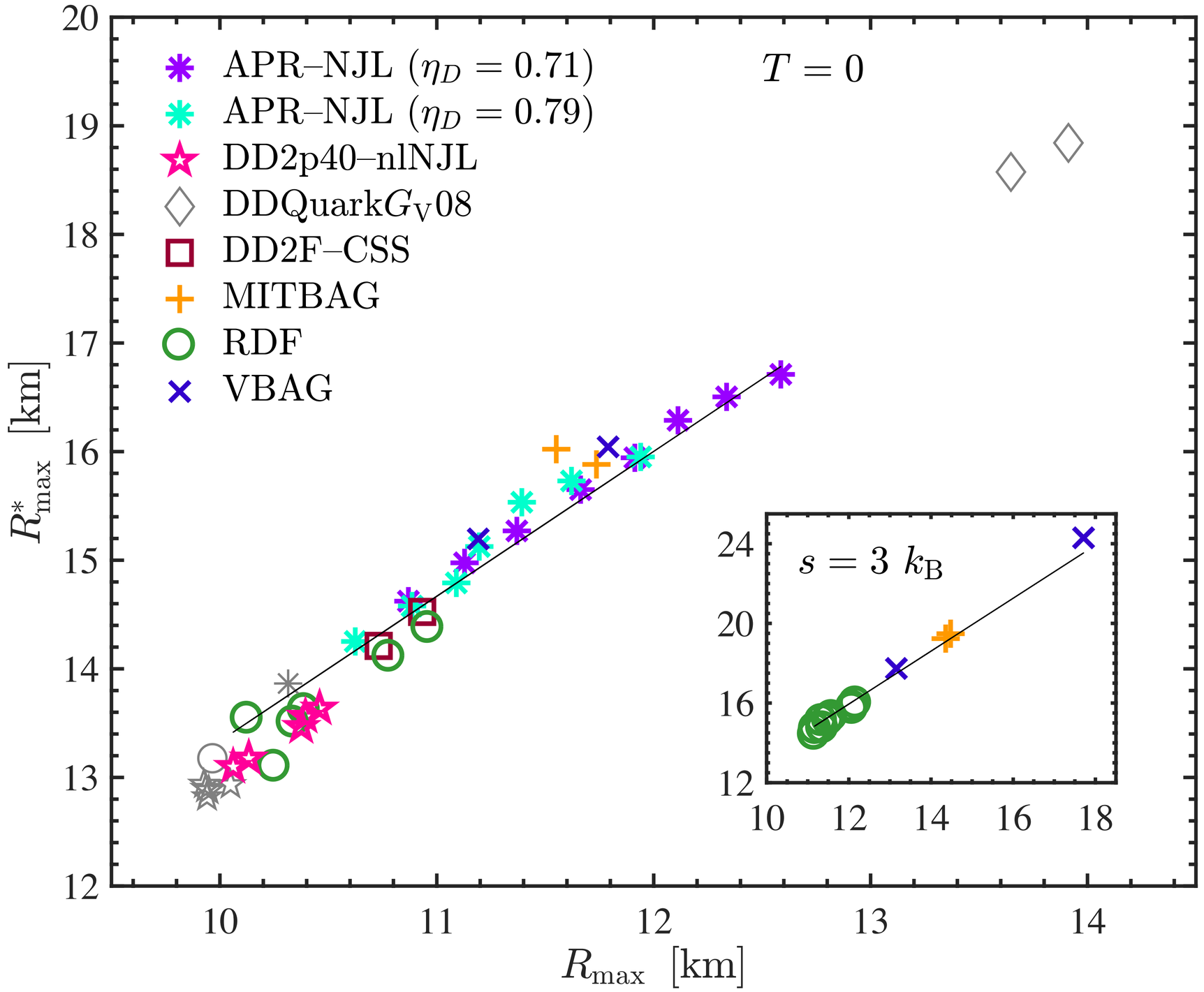
$T_{\text{pseud.}} \sim 150$ MeV
($\mu_B \sim 0$)



Borsányi et al., Phys. Lett. B 730, 99 (2014)


APR–NJL ($\eta_D = 0.71$)
APR–NJL ($\eta_D = 0.79$)
DD2p40–nlNJL
DDQuarkG_V08
DD2F–CSS
MITBAG
RDF
VBAG
M_{max} [$M_\odot$]
R [km]
MITBAG
RDF
VBAG
R [km]


$T = 0$
APR–NJL ($\eta_D = 0.71$)
APR–NJL ($\eta_D = 0.79$)
DD2p40–nlNJL
DDQuarkG_V08
DD2F–CSS
MITBAG
RDF
VBAG
$M^*_{\max}$ [M$_\odot$]
$M_{\max}$ [M$_\odot$]
3.6
3.4
3.2
3
2.8
2.6
2.4
2.2
2
1.8
2
2.2
2.4
2.6
$s = 3\ k_B$
2.6
2.4
2.2
2
1.8
1.9
2
2.1
2.2
2.3


APR–NJL ($\eta_D = 0.71$)
APR–NJL ($\eta_D = 0.79$)
DD2p40–nlNJL
DDQuark$G_{\rm V}$08
DD2F–CSS
MITBAG
RDF
VBAG
$T = 0$
$s = 3\ k_{\rm B}$
$R^*_{\rm max}$ [km]
$R_{\rm max}$ [km]
20
19
18
17
16
15
14
13
12
10
11
12
13
14
24
20
16
12
10
12
14
16
18

$$T = 0$$

$$\frac{M^*_{\max}}{M_{\max}} = 1.200 \pm 0.0160 \qquad \frac{R^*_{\max}}{R_{\max}} = 1.346 \pm 0.0160 \quad \text{(Hadronic)}$$

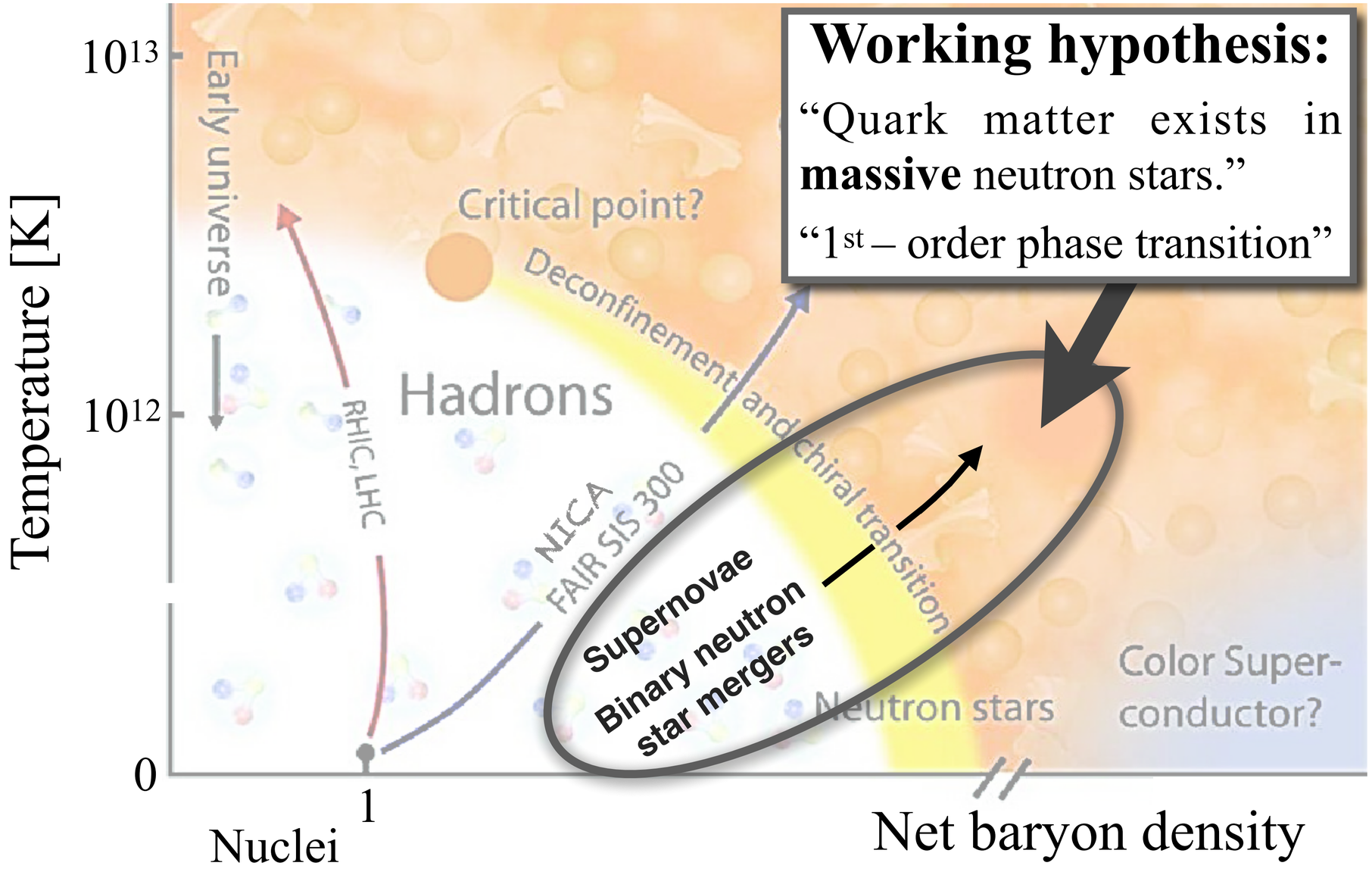
$$\frac{M^*_{\max}}{M_{\max}} = 1.212 \pm 0.0090 \qquad \frac{R^*_{\max}}{R_{\max}} = 1.334 \pm 0.0085 \quad \text{(Hybrid)}$$

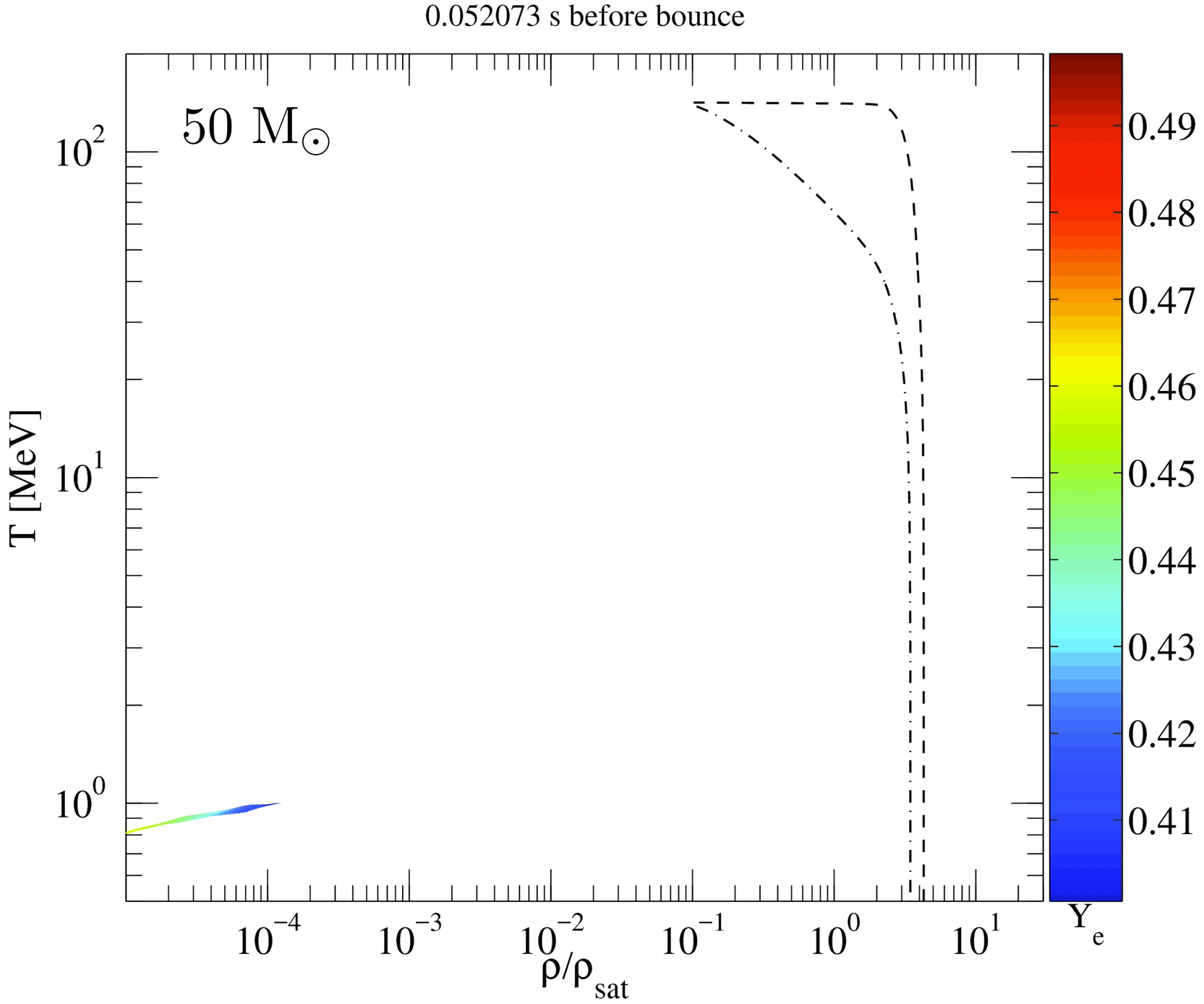
$$s = 3\ k_{\mathrm{B}}\,, Y_{\mathrm{L}} = 0.3$$

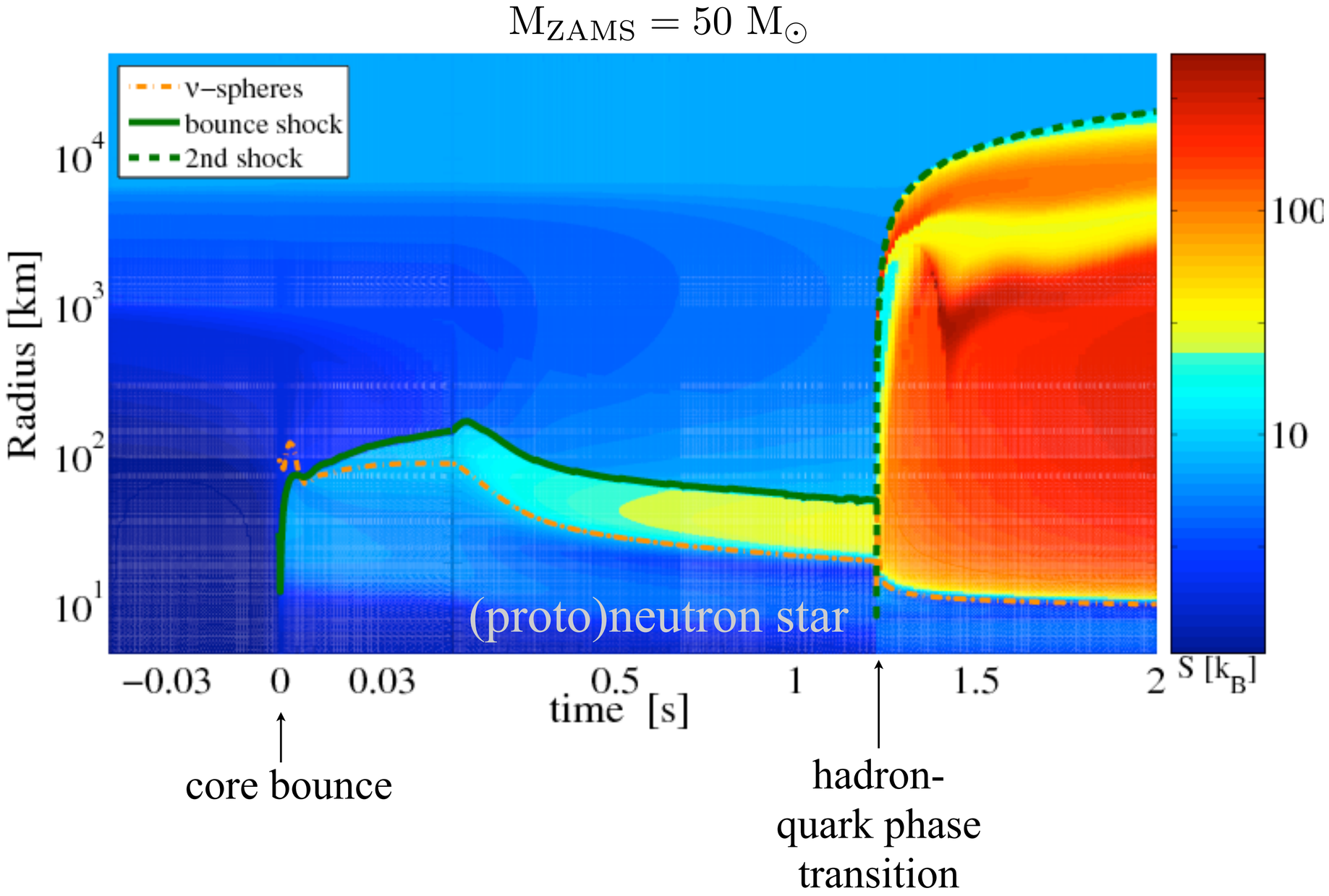
$$\frac{M^*_{\max}}{M_{\max}} = 1.109 \pm 0.0055 \qquad \frac{R^*_{\max}}{R_{\max}} = 1.334 \pm 0.0125 \quad \text{(Hadronic)}$$

$$\frac{M^*_{\max}}{M_{\max}} = 1.100 \pm 0.0055 \qquad \frac{R^*_{\max}}{R_{\max}} = 1.329 \pm 0.0160 \quad \text{(Hybrid)}$$

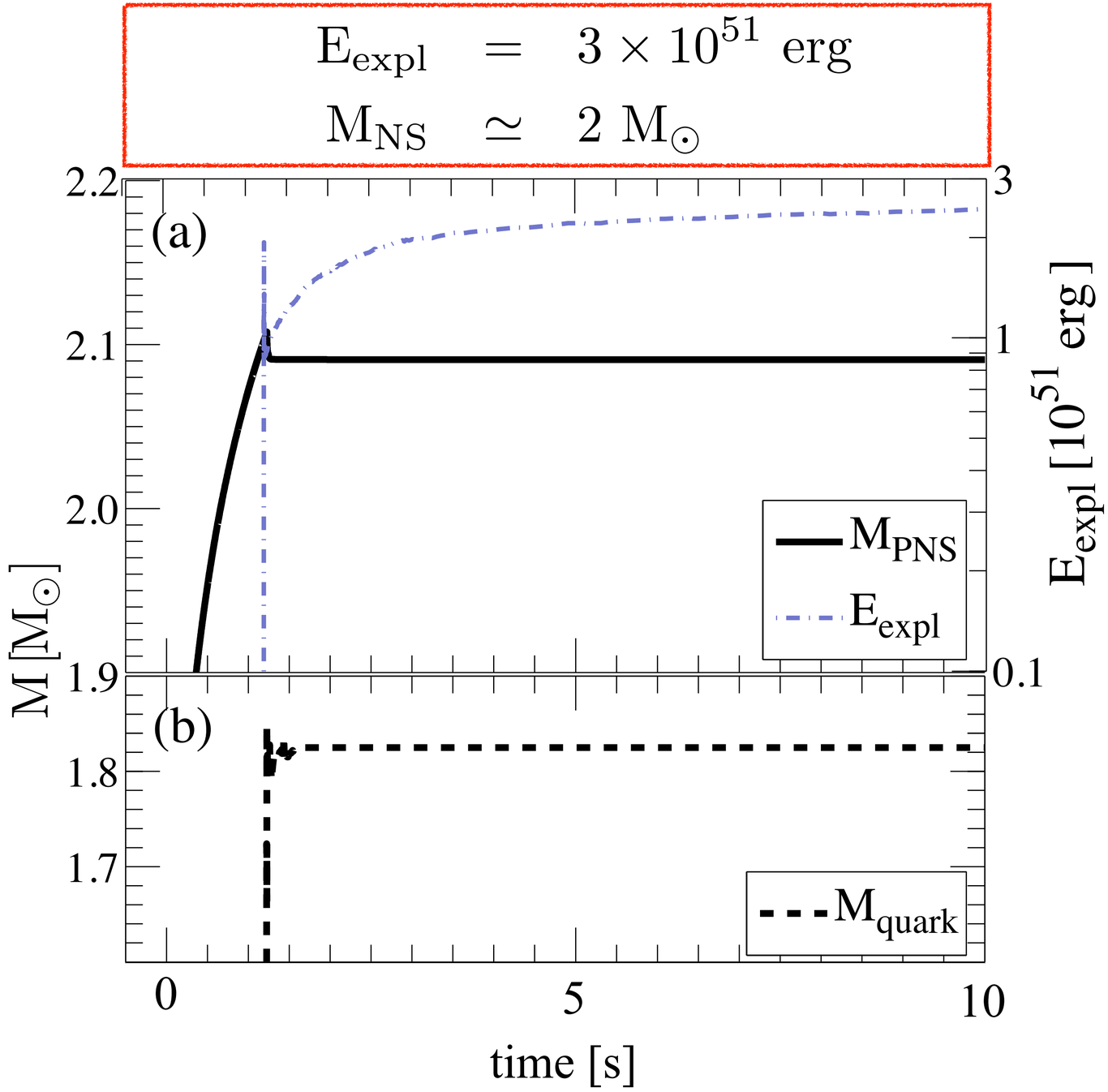
2. Core Collapse Supernovae


Working hypothesis:
"Quark matter exists in massive neutron stars."
"1st – order phase transition"
Temperature [K]
10^{13}
10^{12}
0
Early universe
RHIC, LHC
Critical point?
Deconfinement and chiral transition
Hadrons
NICA
FAIR SIS 300
Supernovae
Binary neutron star mergers
Neutron stars
Color Super-conductor?
Nuclei
1
Net baryon density

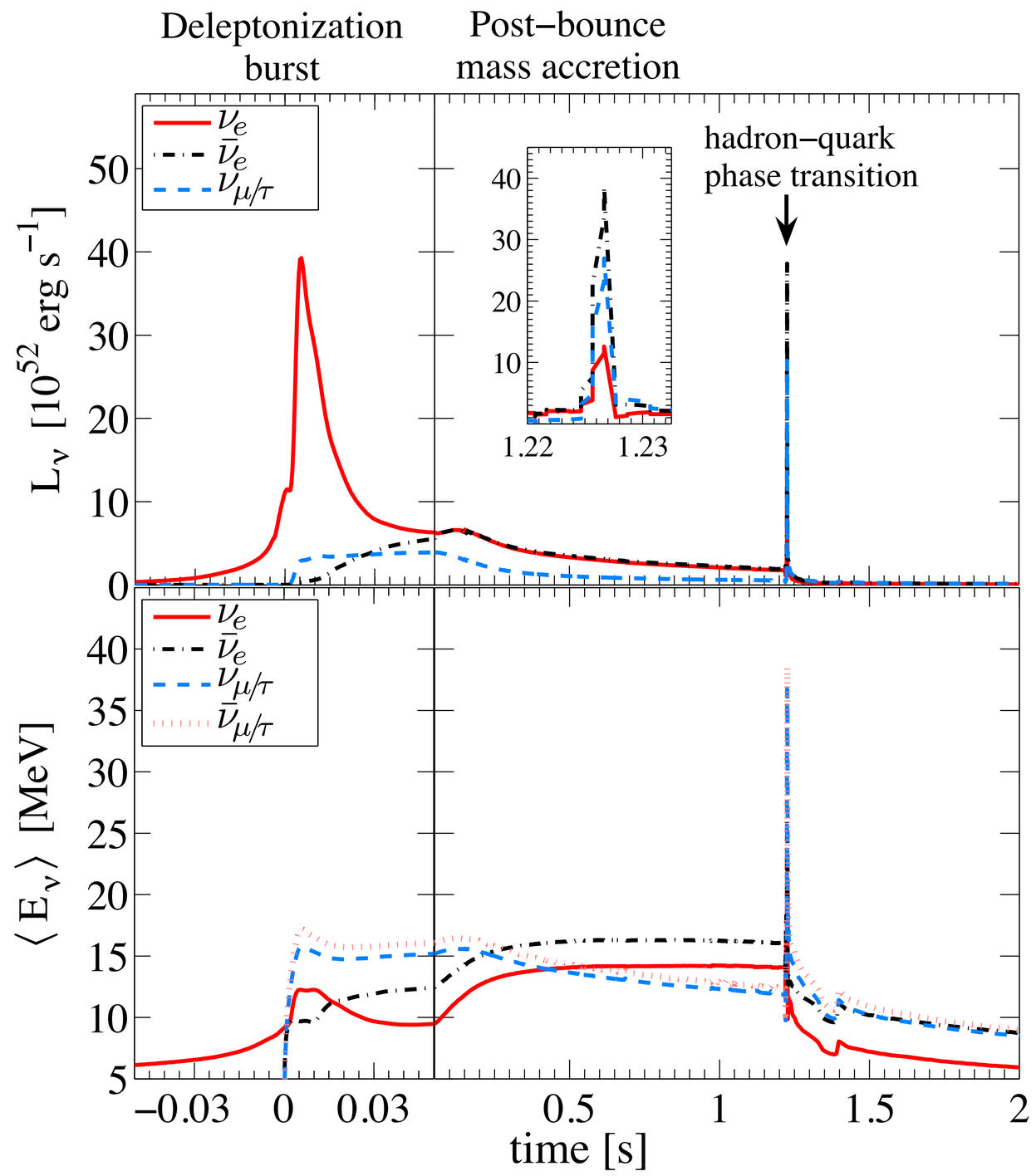

0.052073 s before bounce
50 M⊙
T [MeV]
10^2
10^1
10^0
10^−4
10^−3
10^−2
10^−1
10^0
10^1
ρ/ρ_sat
0.49
0.48
0.47
0.46
0.45
0.44
0.43
0.42
0.41
Y_e



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

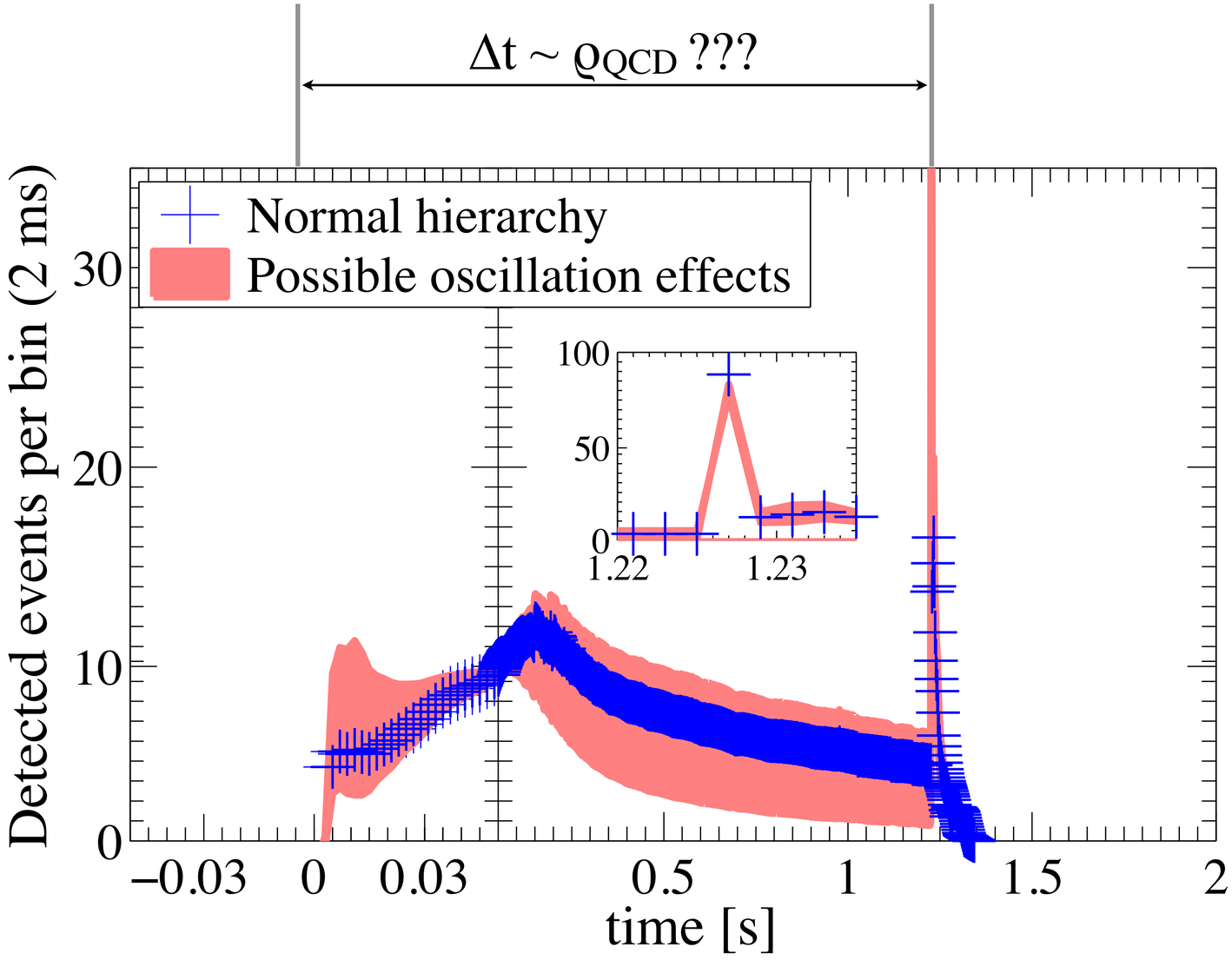


Fischer et al., Nat. Astron. 2, 980 (2018)

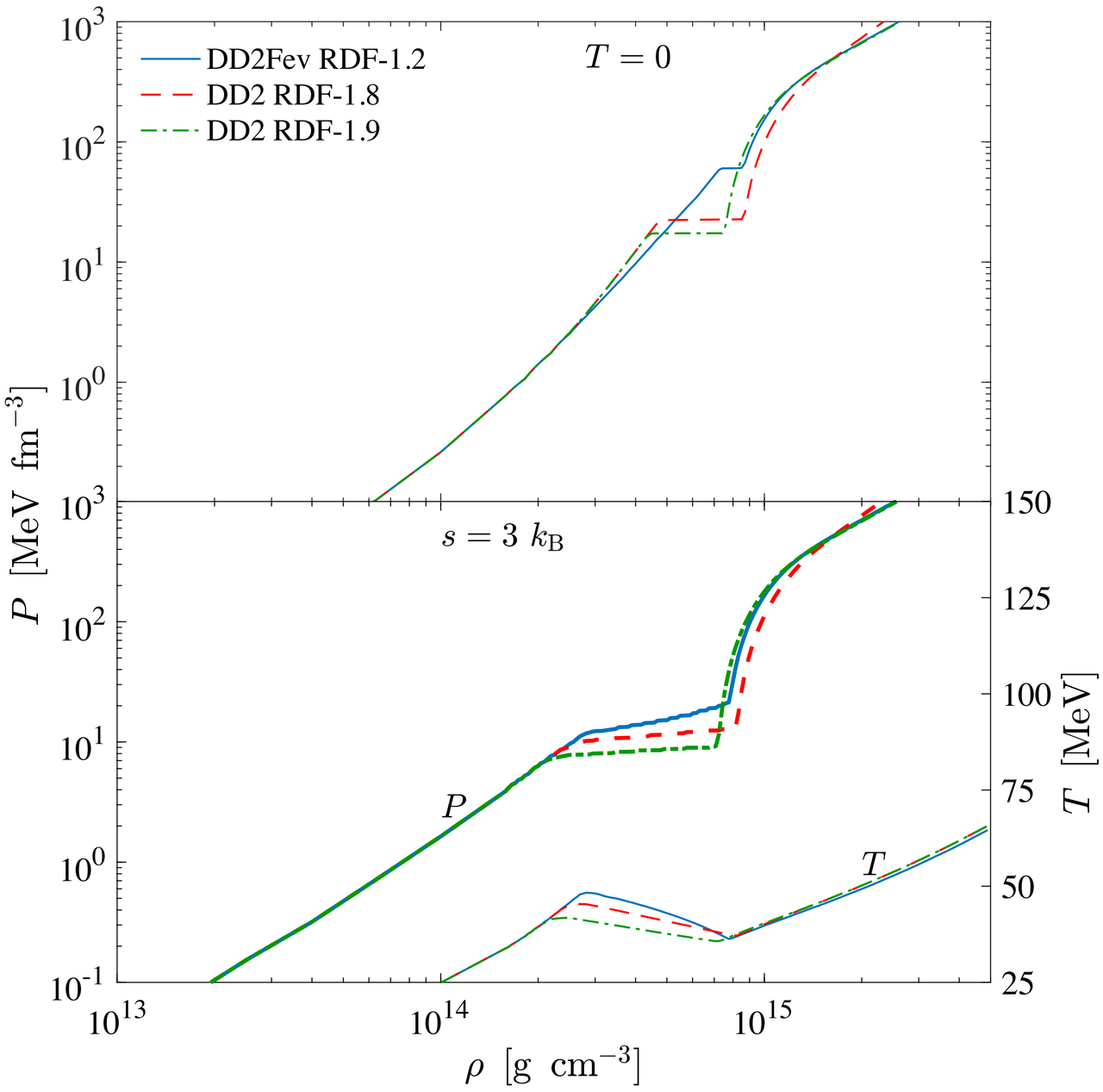


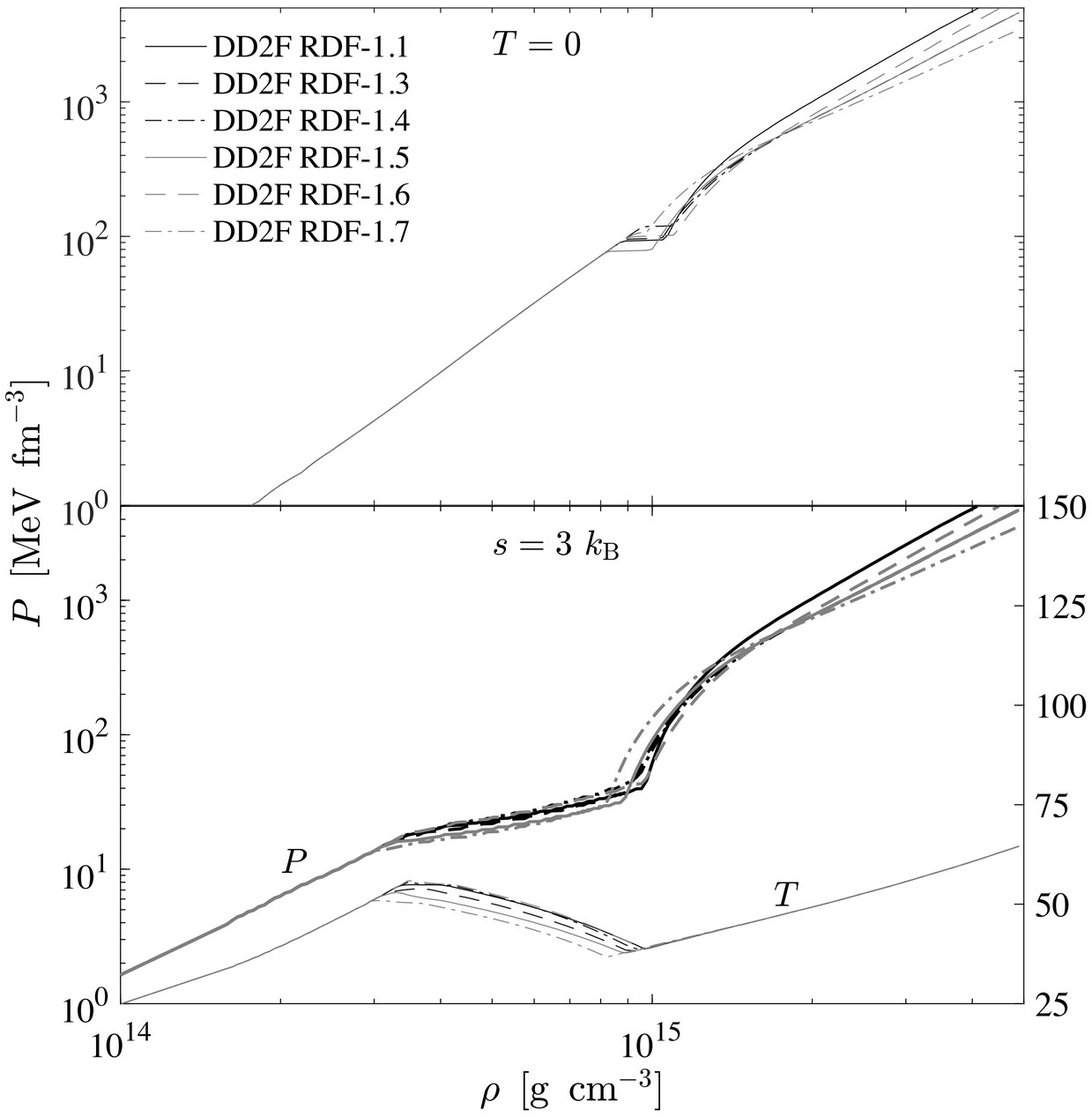
Fischer et al., Nat. Astron. 2, 980 (2018)

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

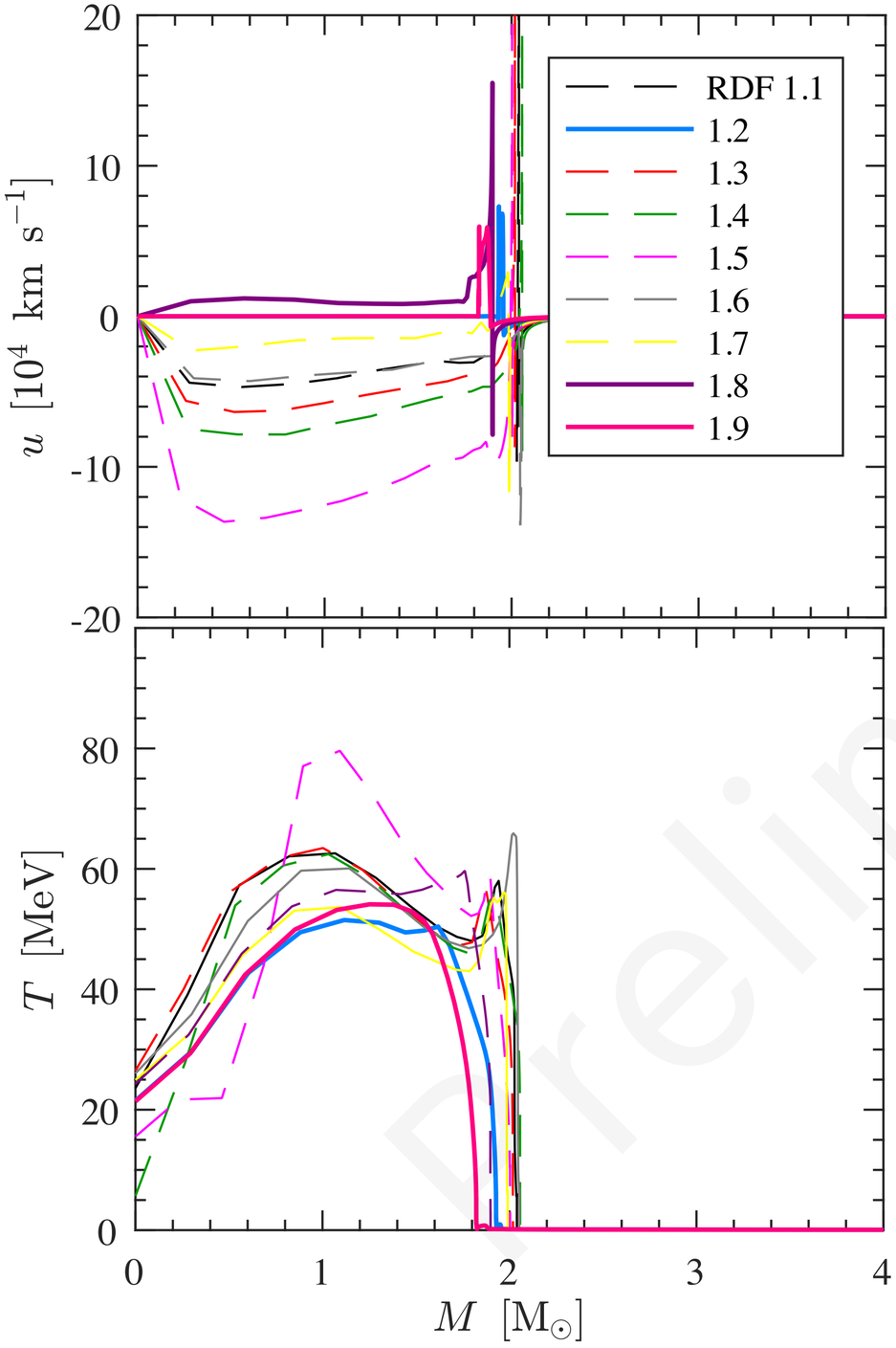


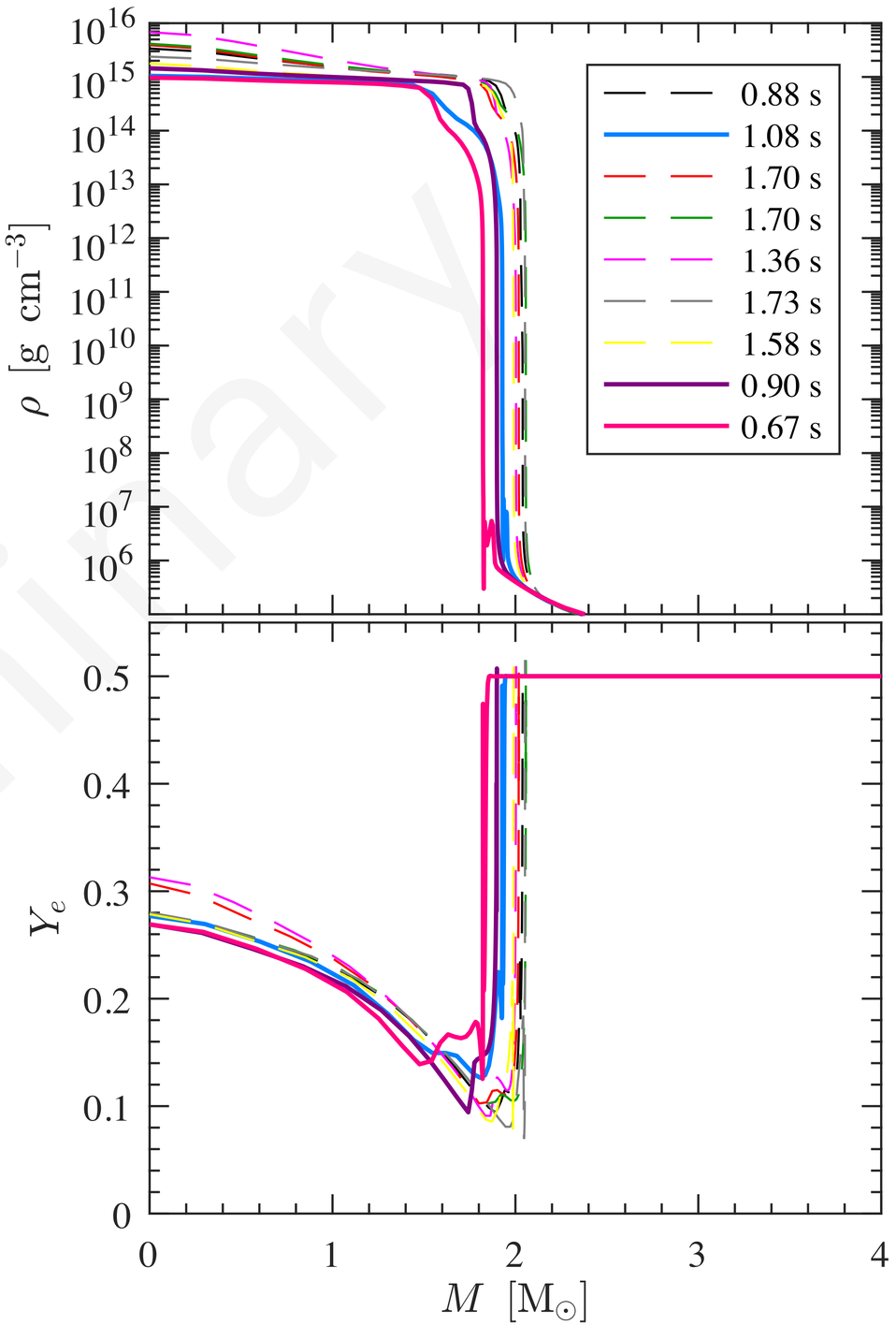
Fischer et al., Nat. Astron. 2, 980 (2018)


DD2Fev RDF-1.2
DD2 RDF-1.8
DD2 RDF-1.9
$T = 0$
$s = 3\ k_{\rm B}$
P
T
P [MeV fm^{-3}]
T [MeV]
ρ [g cm^{-3}]

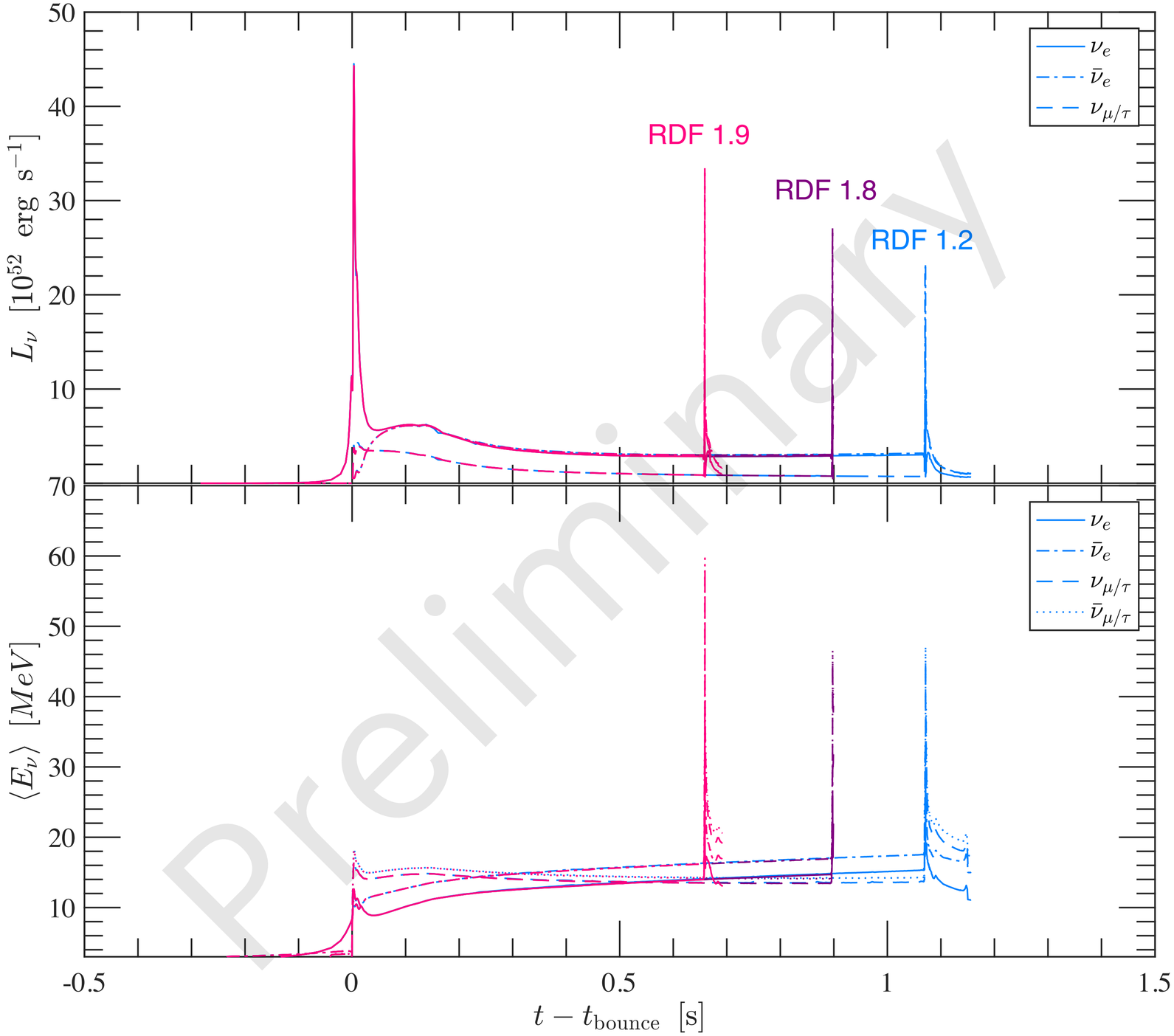

DD2F RDF-1.1
DD2F RDF-1.3
DD2F RDF-1.4
DD2F RDF-1.5
DD2F RDF-1.6
DD2F RDF-1.7
$T = 0$
$s = 3\ k_{\rm B}$
P
T
P [MeV fm^{-3}]
ρ [g cm^{-3}]

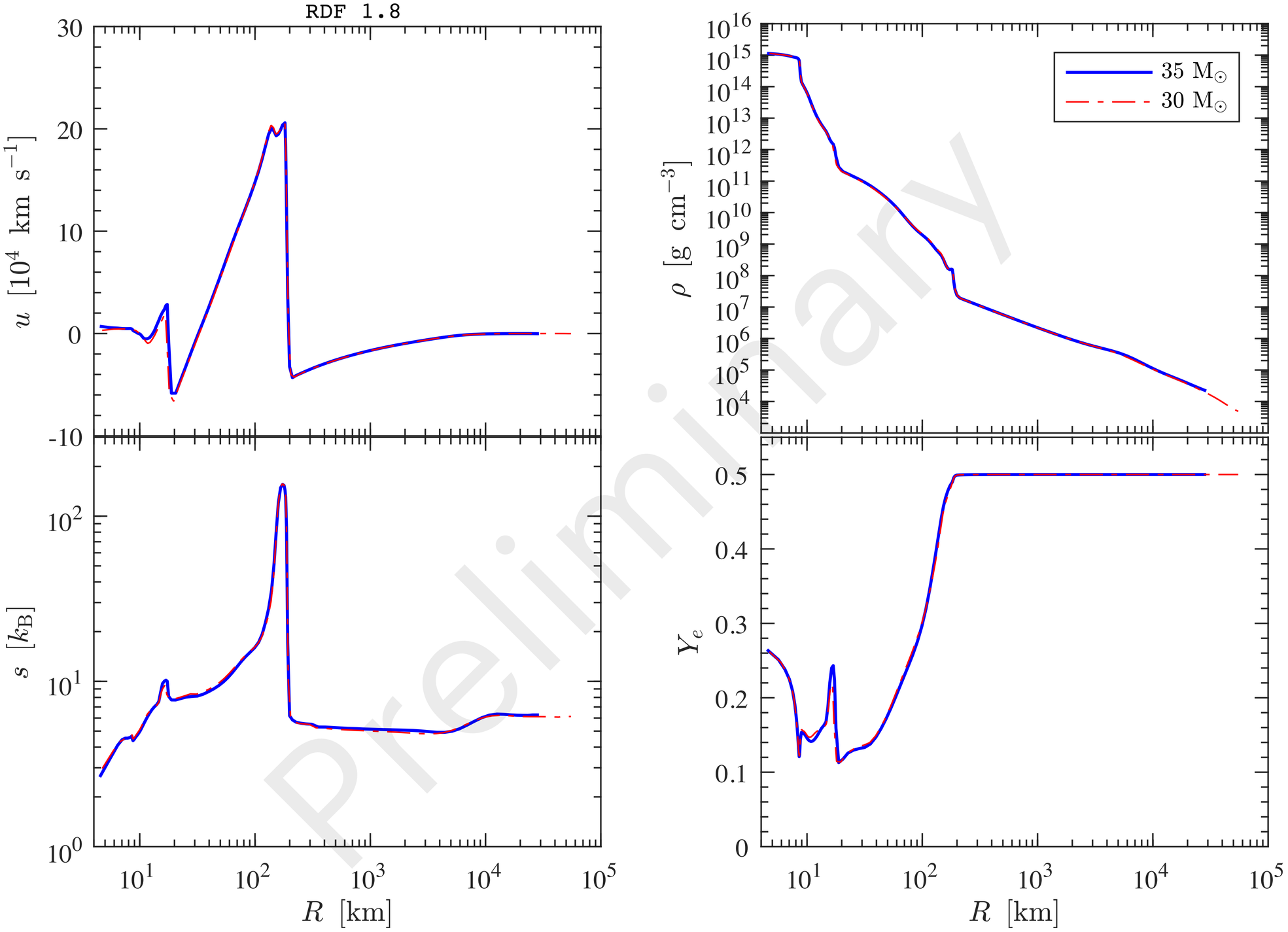
30 $M_\odot$





30 $M_\odot$


RDF 1.9
RDF 1.8
RDF 1.2
ν_e
$\bar{\nu}_e$
$\nu_{\mu/\tau}$
$\bar{\nu}_{\mu/\tau}$
L_ν [10^{52} erg s^{-1}]
$\langle E_\nu \rangle$ [MeV]
$t - t_{\rm bounce}$ [s]
Preliminary



Numerical tool for mode analysis : GREAT

$$Q_{ij} = \int \rho(r)(3r_i r_j - |\vec{r}|^2 \delta_{ij}) d^3 r$$

$$h_{ij} = \frac{2G}{c^4 r} \frac{d^2}{dt^2} Q_{ij}$$

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

$$\partial_t \xi^i = \delta v^{*i}$$

g-modes

$$\partial_r \eta_r = A\eta_r + B\eta_\perp,$$

$$\partial_r \eta_\perp = C\eta_r + D\eta_\perp.$$

$$\partial_r \eta_r + \left[\frac{2}{r} + 6\frac{\partial_r \psi}{\psi}\right] \eta_r - \frac{l(l+1)}{r^2}\eta_\perp = 0,$$

$$\partial_r \eta_\perp - \left(1 - \frac{\mathcal{N}^2}{\sigma^2}\right) \eta_r + [\partial_r \ln q - G]\, \eta_\perp = 0.$$

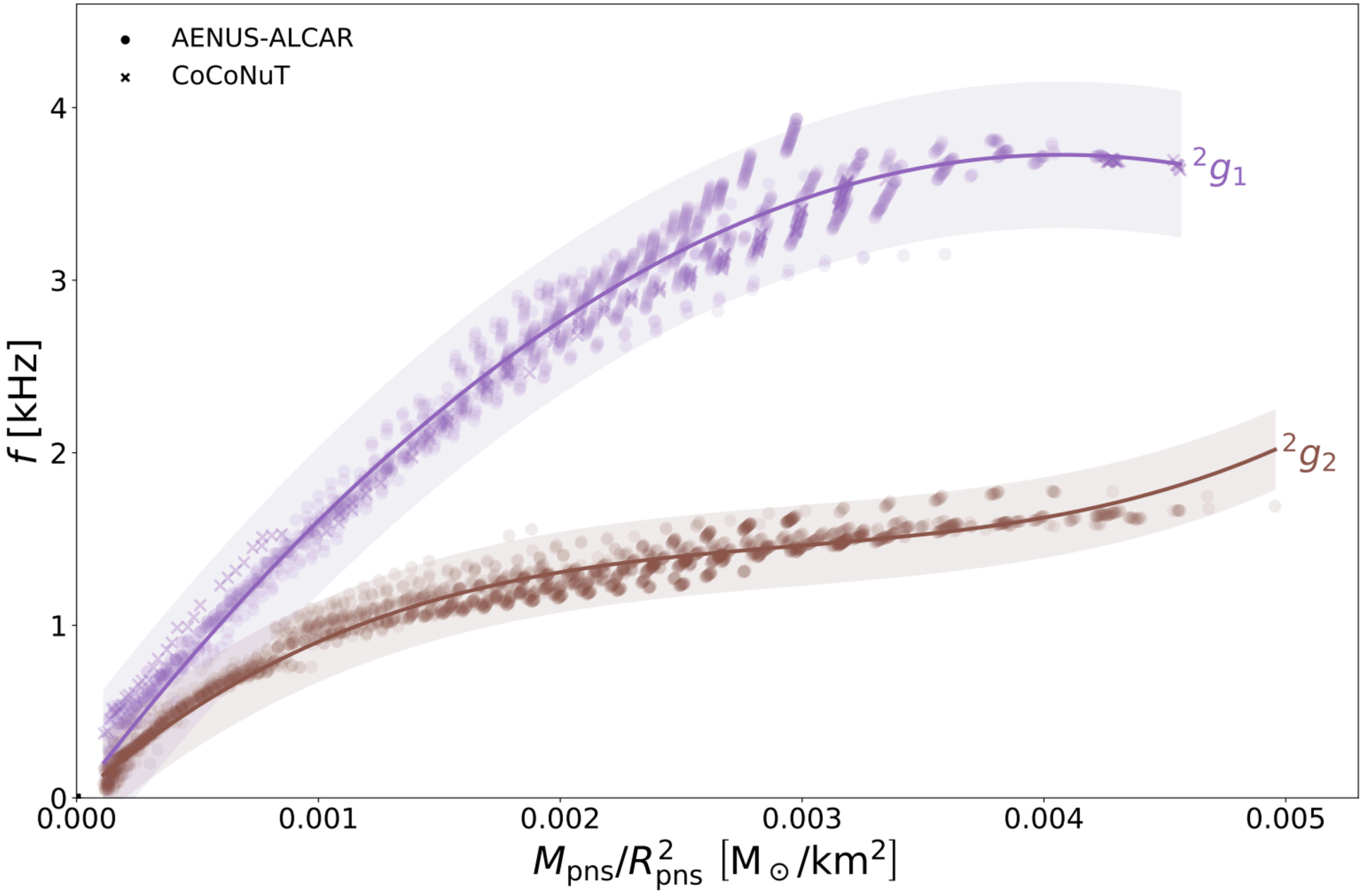
$$\delta P = \delta\hat{P}\, Y_{lm} \mathrm{e}^{-\mathrm{i}\sigma t},$$

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

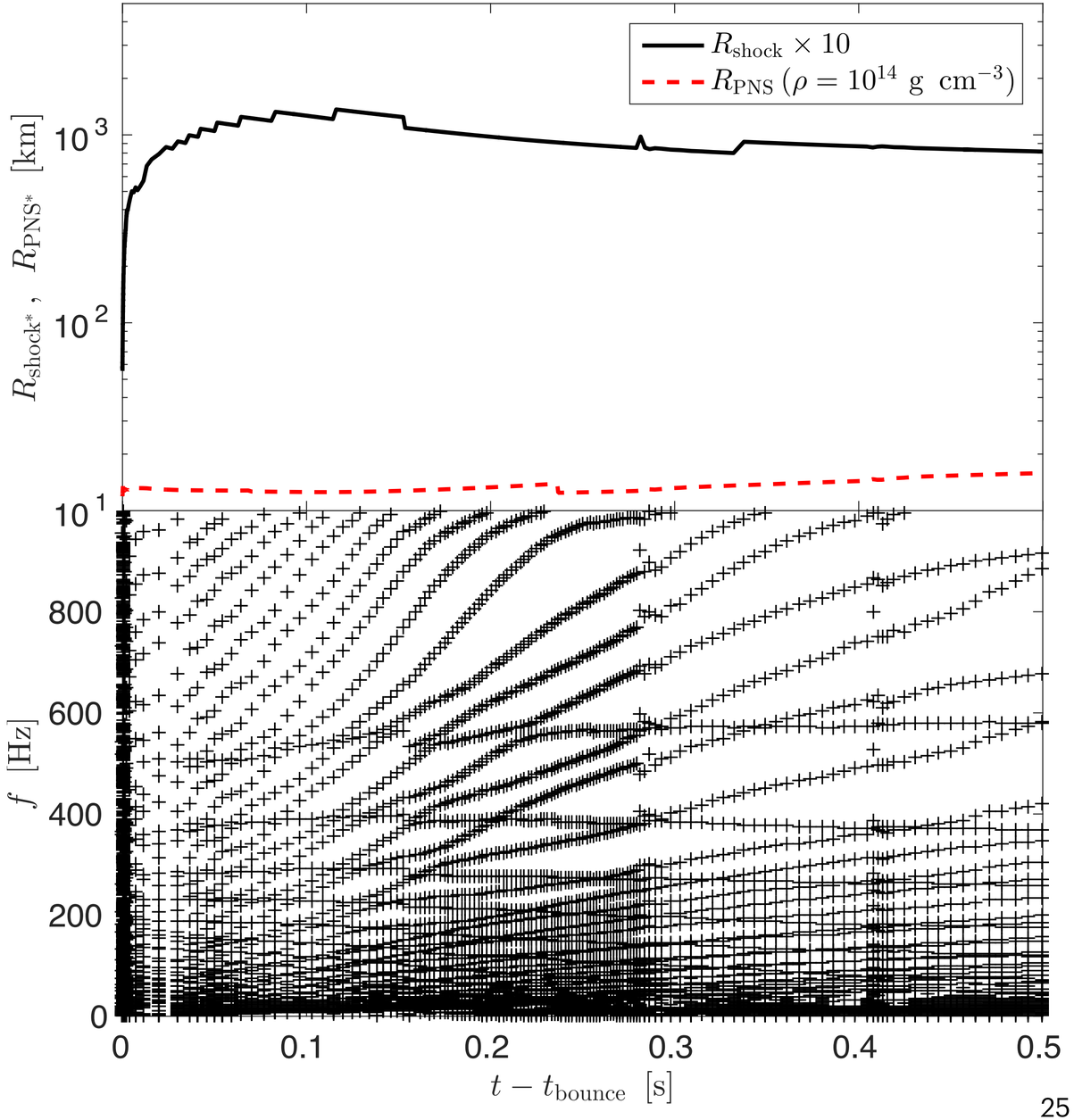
$$\xi^\theta = \eta_\perp \frac{1}{r^2} \partial_\theta Y_{lm} \mathrm{e}^{-\mathrm{i}\sigma t},$$

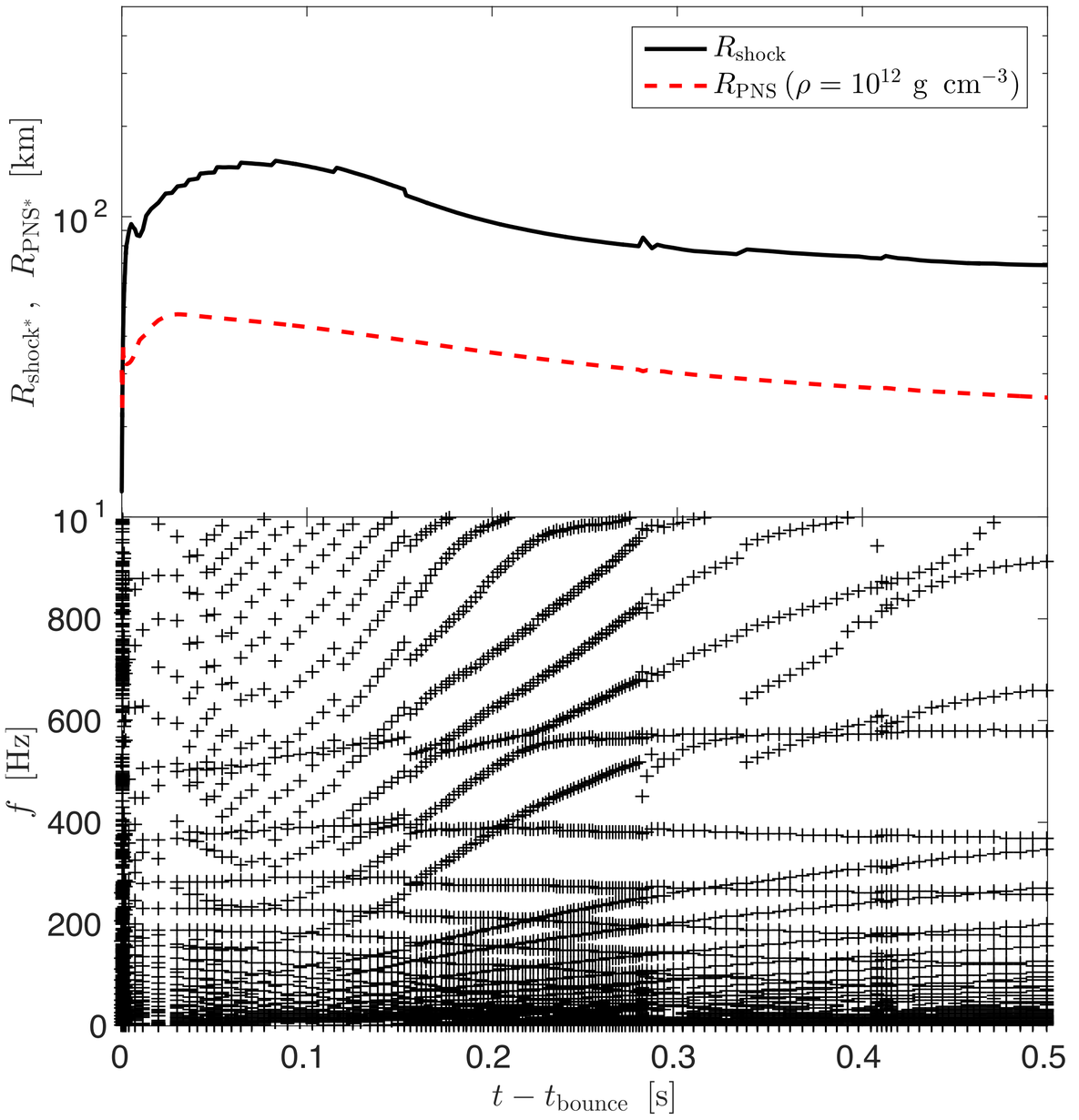
$$\xi^\varphi = \eta_\perp \frac{1}{r^2 \sin^2\theta} \partial_\varphi Y_{lm} \mathrm{e}^{-\mathrm{i}\sigma t}$$

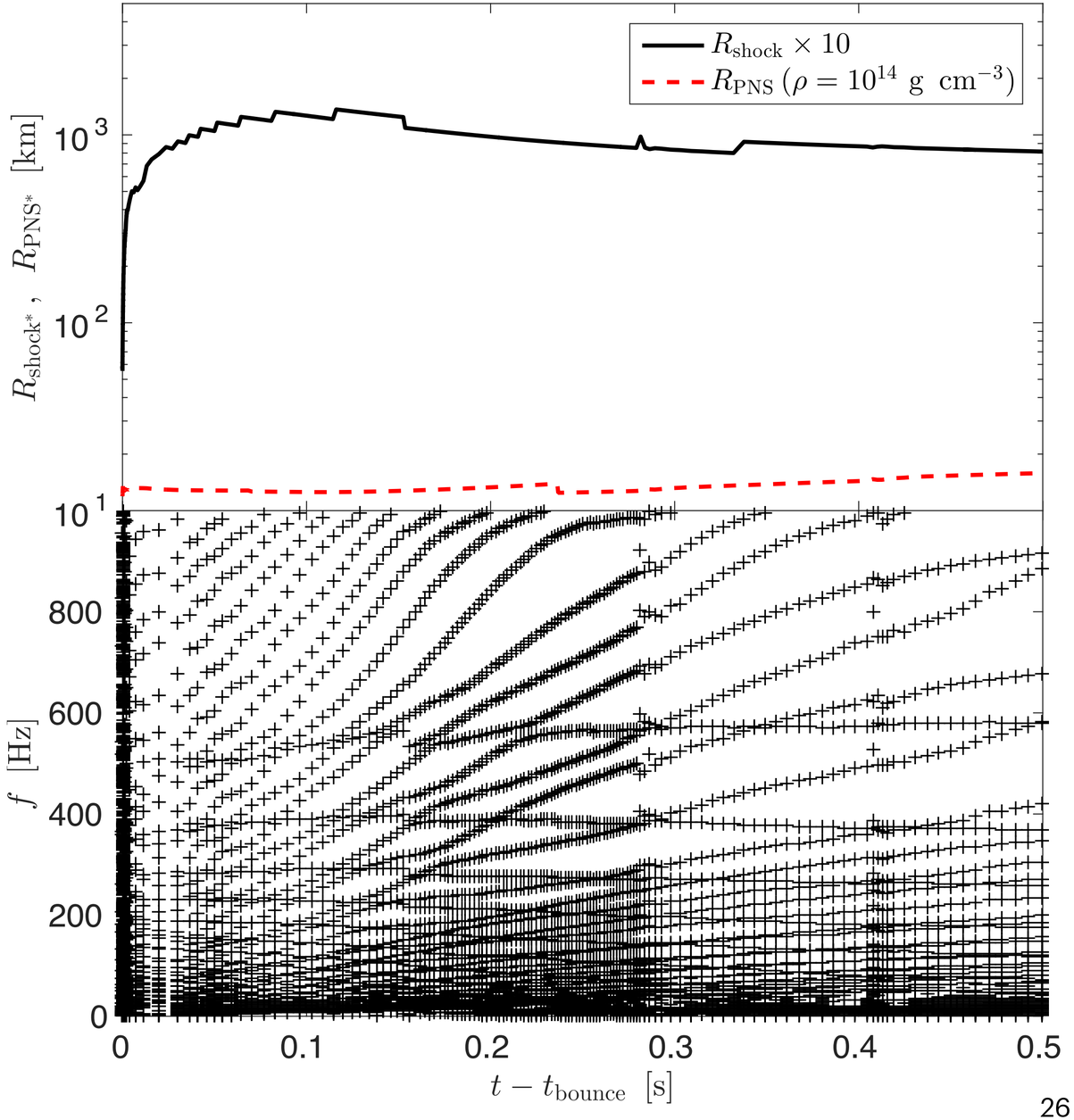
Torres-Forne et al. (2019), Mon. Not. Roy. Astron. Soc.
Torres-Forne et al. (2018), Mon. Not. Roy. Astron. Soc.

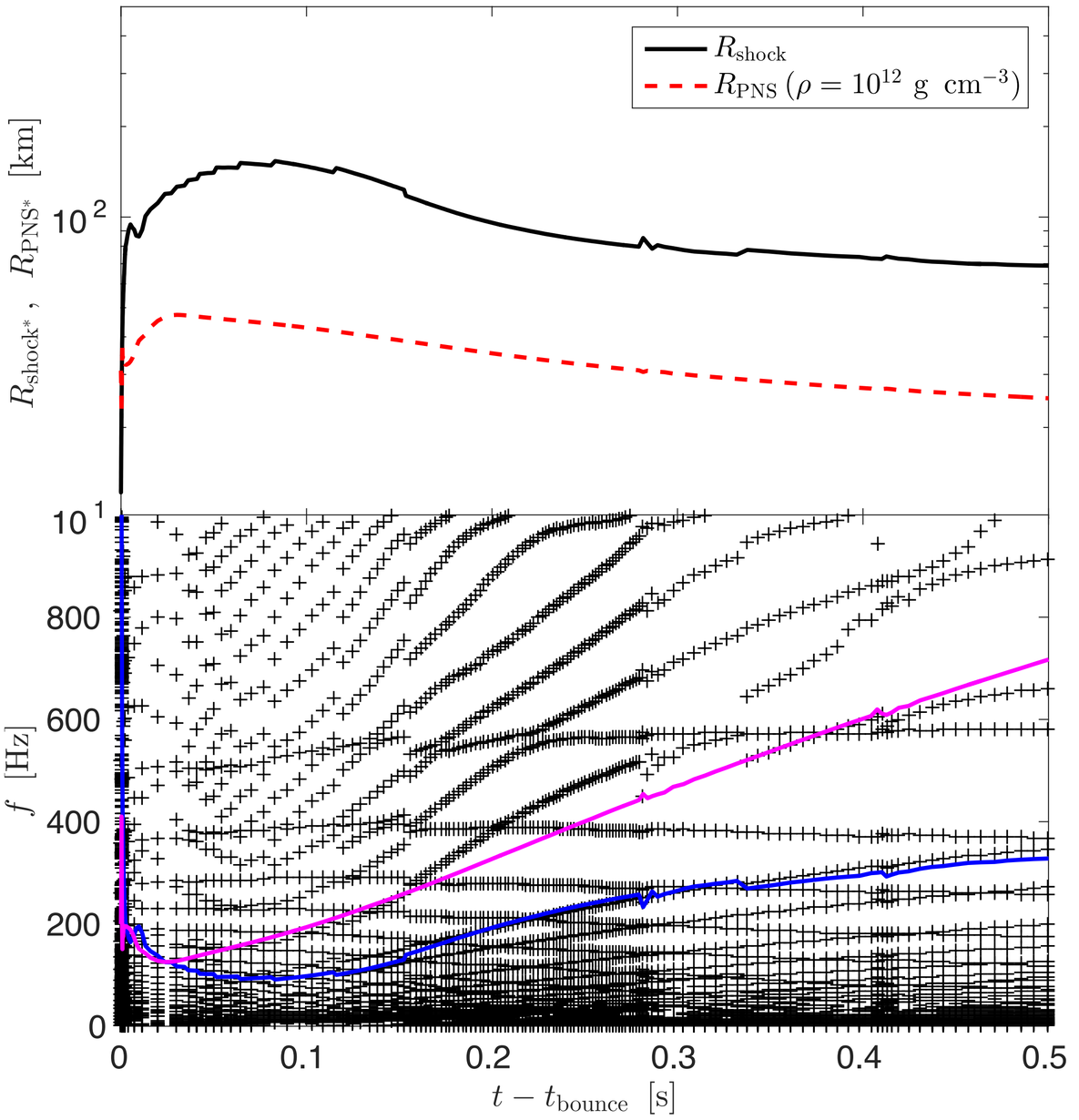


Torres Forne et al., Phys. Rev. Lett. 123, 051102 (2019)


$R_{\rm shock} \times 10$
$R_{\rm PNS}\ (\rho = 10^{14}\ {\rm g\ cm^{-3}})$
$R_{\rm shock^*}\ ,\ R_{\rm PNS^*}$ [km]
10^3
10^2
10^1
f [Hz]
0
200
400
600
800
0
0.1
0.2
0.3
0.4
0.5
$t - t_{\rm bounce}$ [s]


$R_{\rm shock}$
$R_{\rm PNS}\ (\rho = 10^{12}\ {\rm g\ cm^{-3}})$
$R_{\rm shock^*}\ ,\ R_{\rm PNS^*}$ [km]
10^2
10^1
f [Hz]
0
200
400
600
800
0
0.1
0.2
0.3
0.4
0.5
$t - t_{\rm bounce}$ [s]


$R_{\rm shock} \times 10$
$R_{\rm PNS}\ (\rho = 10^{14}\ {\rm g\ cm^{-3}})$
$R_{\rm shock^*}\ ,\ R_{\rm PNS^*}$ [km]
10^3
10^2
10^1
f [Hz]
0
200
400
600
800
0
0.1
0.2
0.3
0.4
0.5
$t - t_{\rm bounce}$ [s]


$R_{\rm shock}$
$R_{\rm PNS}\ (\rho = 10^{12}\ {\rm g\ cm^{-3}})$
$R_{\rm shock^*}\ ,\ R_{\rm PNS^*}$ [km]
10^2
10^1
f [Hz]
0
200
400
600
800
0
0.1
0.2
0.3
0.4
0.5
$t - t_{\rm bounce}$ [s]