Universal relations in astrophysics

Wigner institute seminar, Budapest

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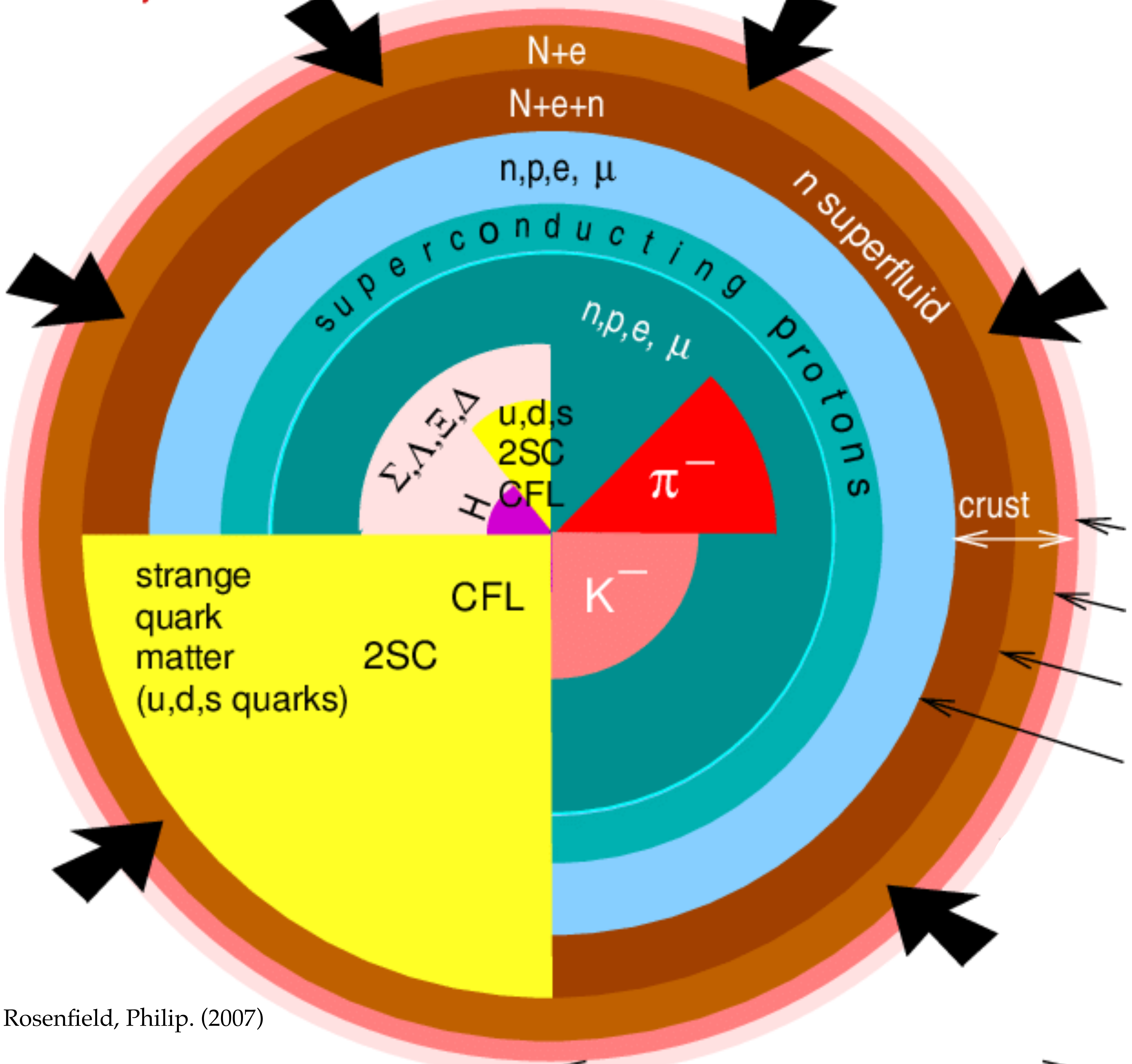
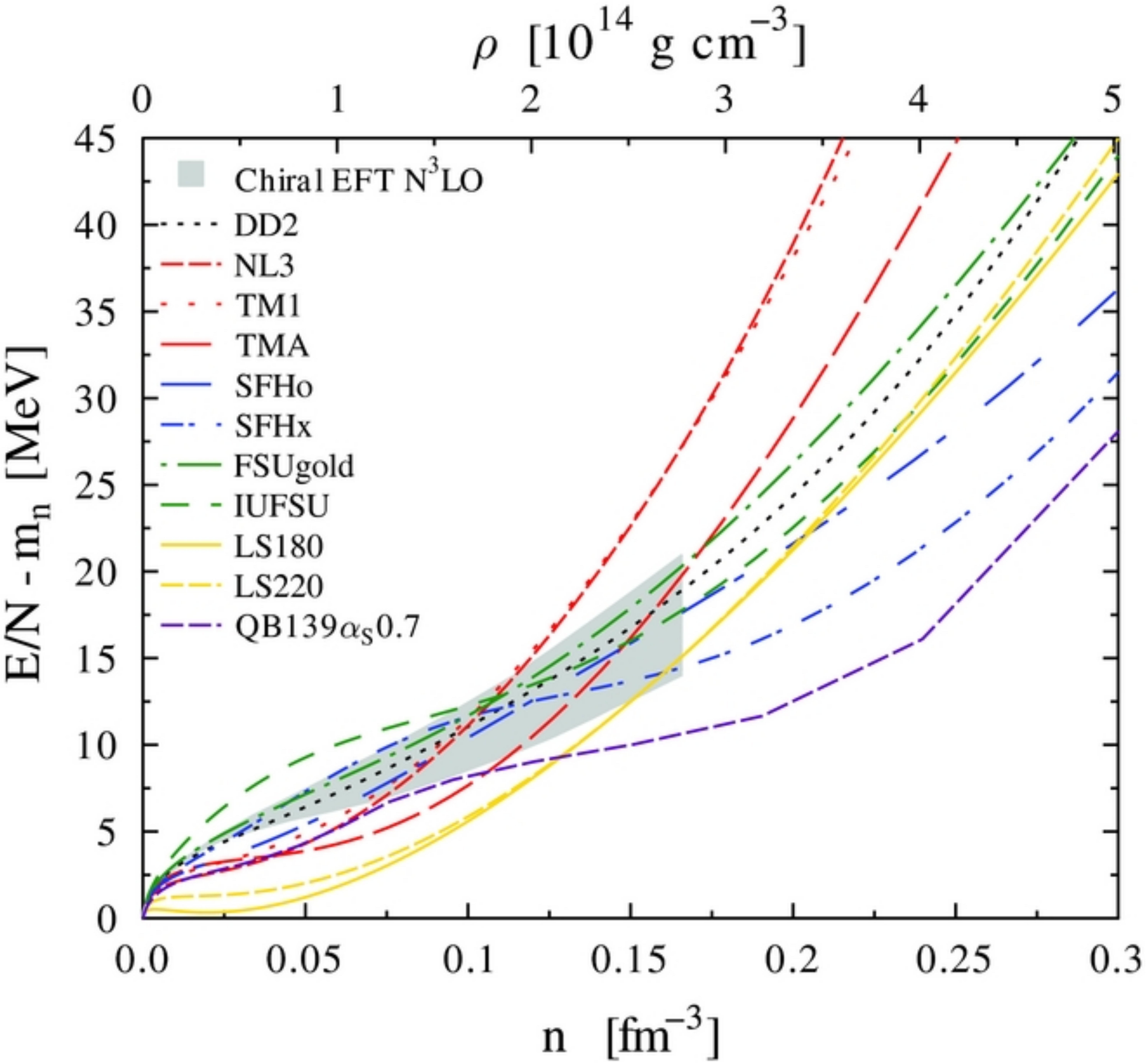
University of Wroclaw
17 June 2022

1. Rapidly Rotating Neutron Stars

arXiv: 2112.10439v1

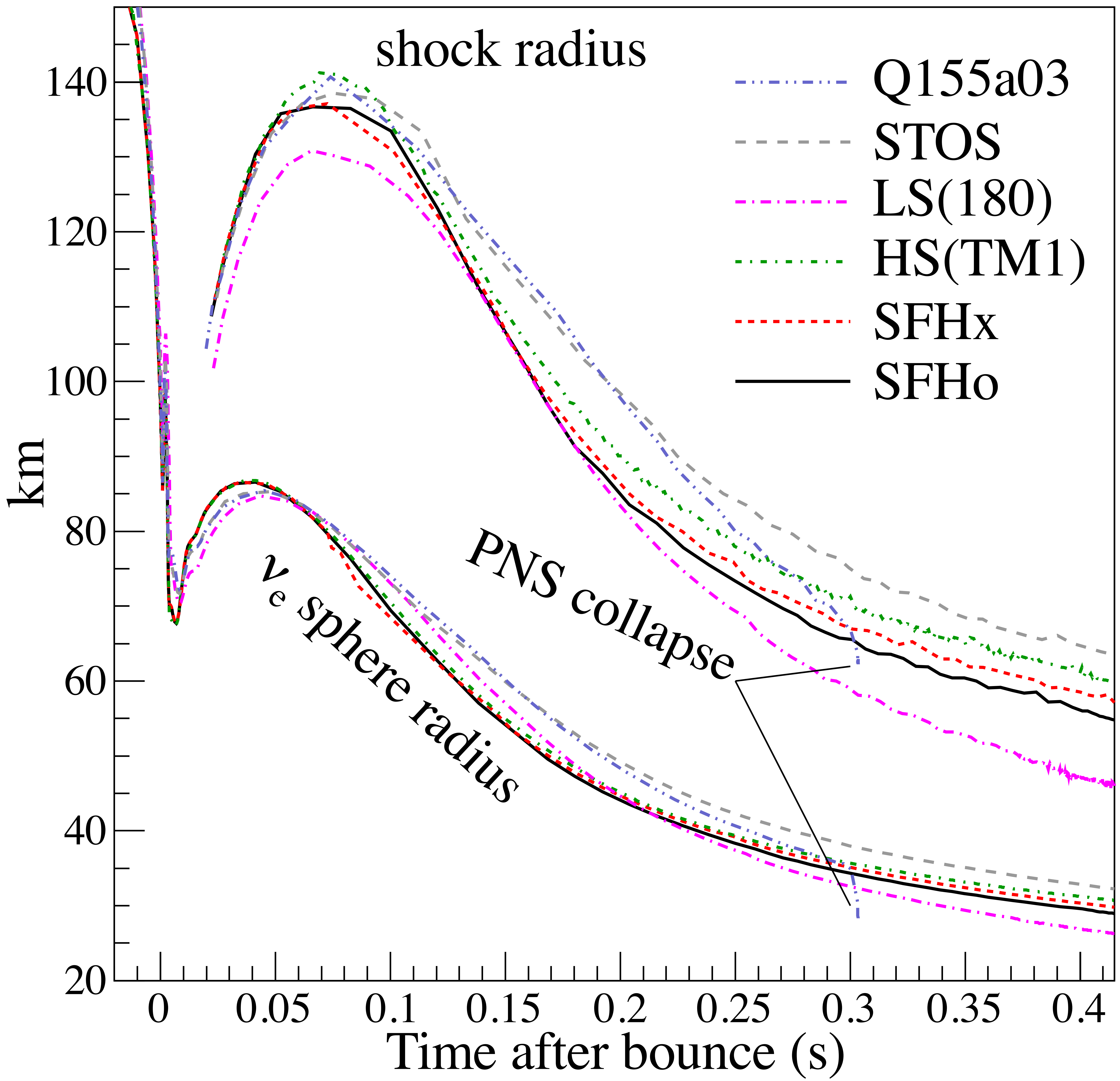


Weber, F. & Negreiros, Rodrigo & Rosenfield, Philip. (2007)

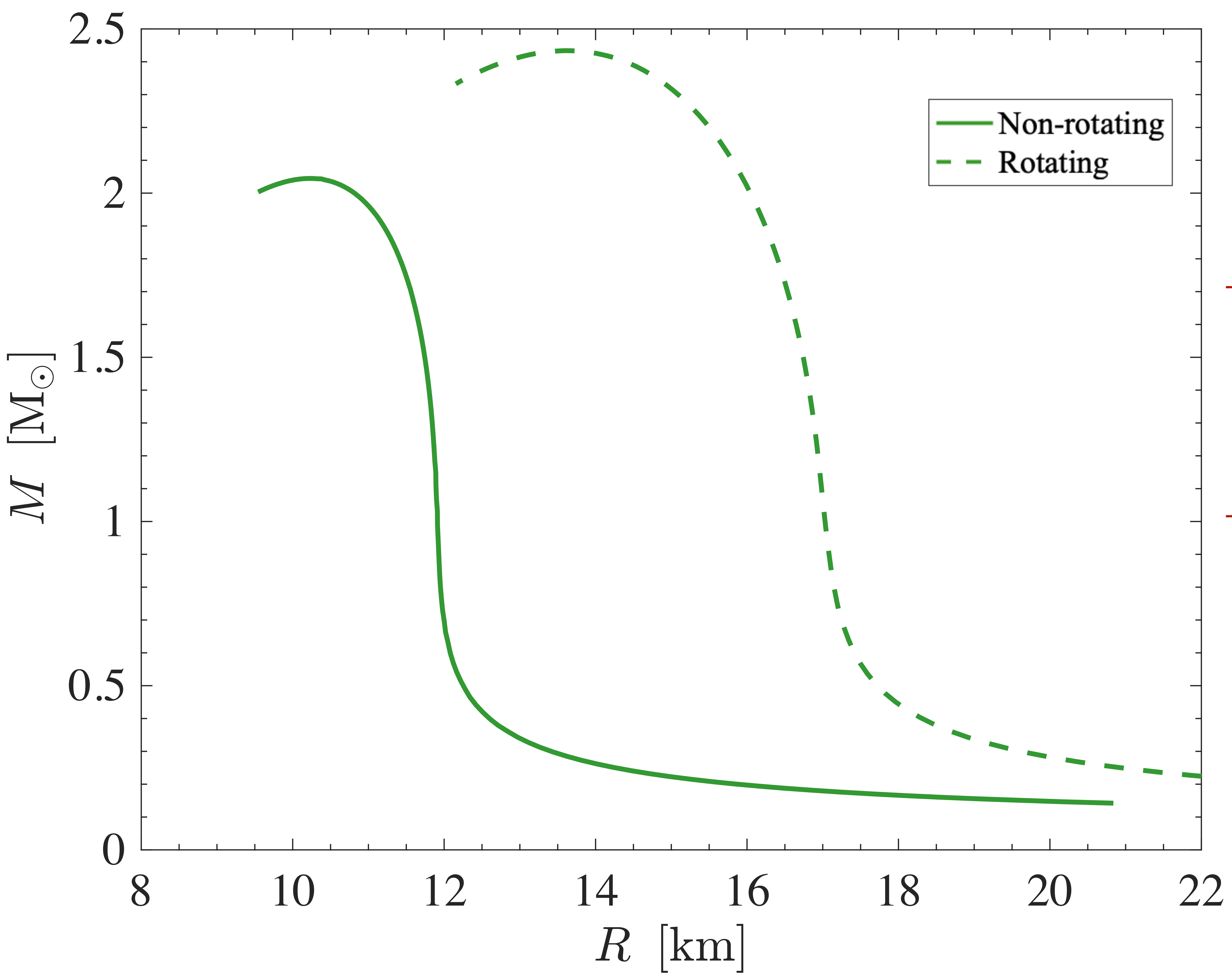


Neutron matter energy per particle

PASA, 34, e067 (2017)



ApJ, 774, 17 (2013)



$$\frac{dp}{dr} = -\frac{(\epsilon + p/c^2)G(m + 4\pi r^3 p/c^2)}{r^2(1 - 2Gm/rc^2)}$$

$$\frac{dm}{dr} = 4\pi r^2 \epsilon$$

$$x_p = x_e$$

$$\mu_n - \mu_p = \mu_e = \mu_\mu$$

$$p(\epsilon)$$

$$ds^2 = -e^{\gamma+\rho}dt^2 + e^{2\alpha}\left(dr^2 + r^2 d\theta^2\right) + e^{\gamma-\rho}\, r^2 \sin^2\theta\, (d\phi - \omega dt)^2$$

$$u^\mu = \frac{e^{-(\gamma+\rho)}}{\Gamma}(1, 0, 0, \Omega)$$

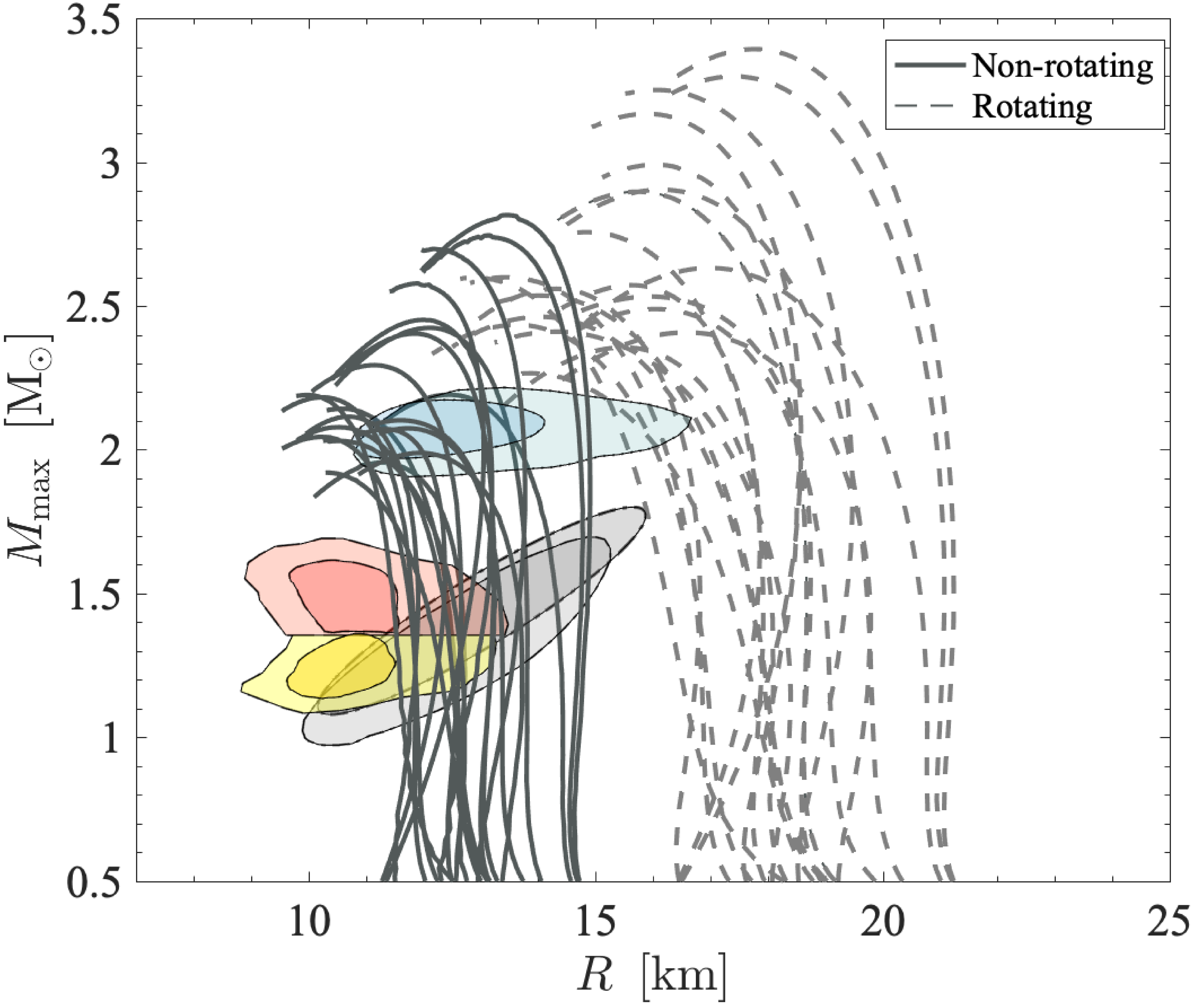
$$\Gamma = \sqrt{1 - \mathrm{v}^2}$$

$$\mathrm{v} = (\Omega - \omega)\, r \sin\theta\, e^{-\rho}$$

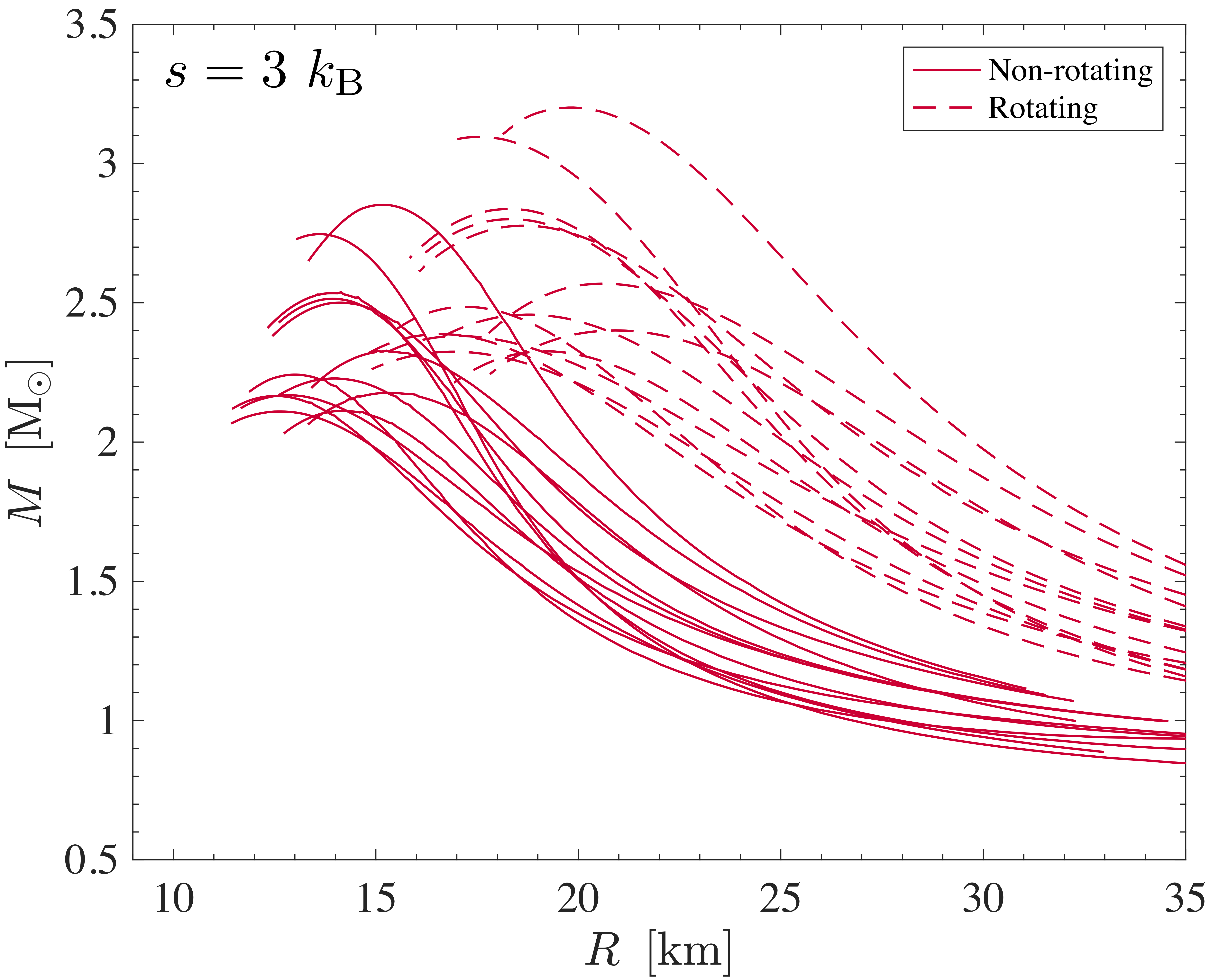
Cook G. B. Et al.(1994), Astrophys. J.

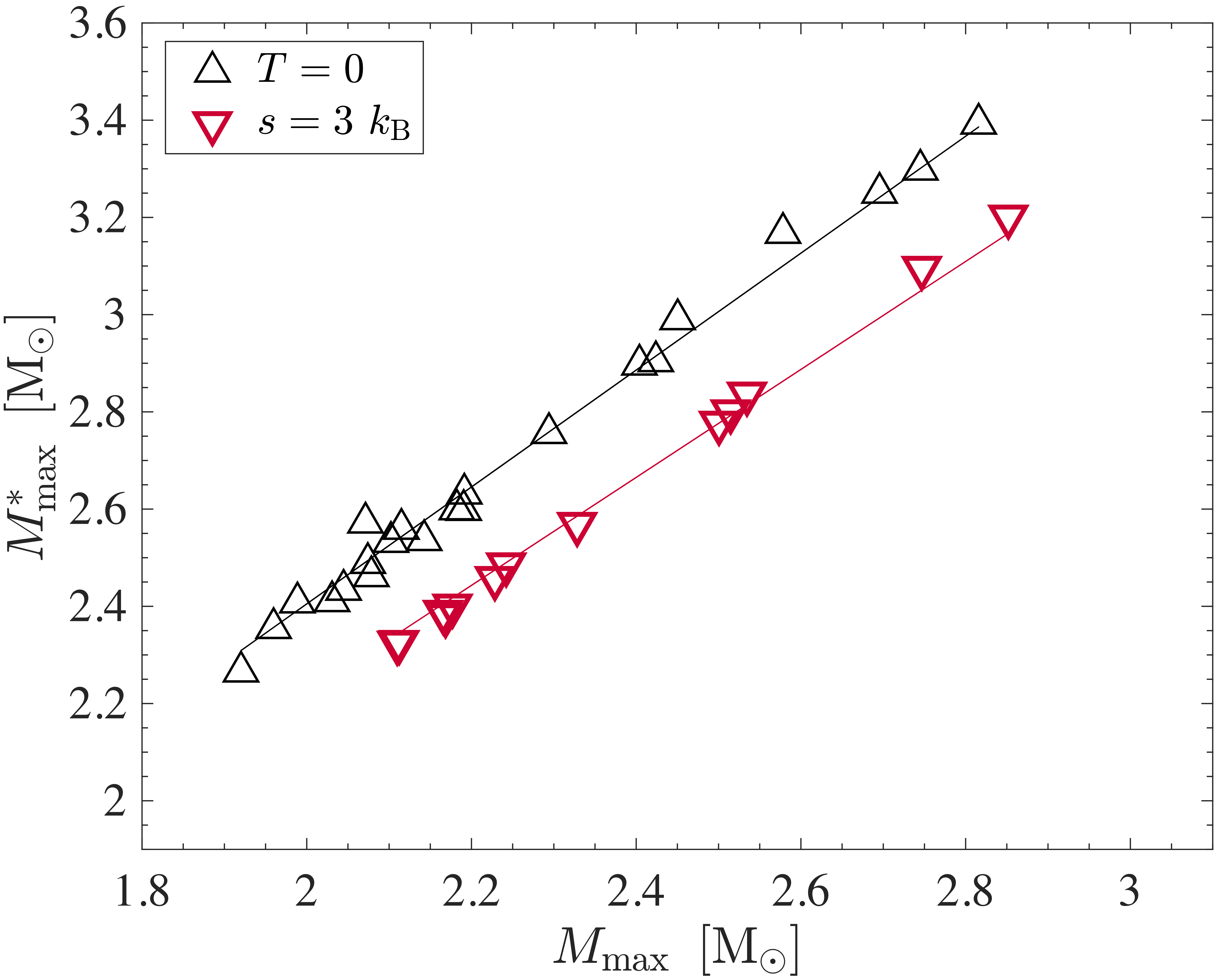
Numerical tool : RNS

Stergioulas et al. (1995), Astrophys. J.

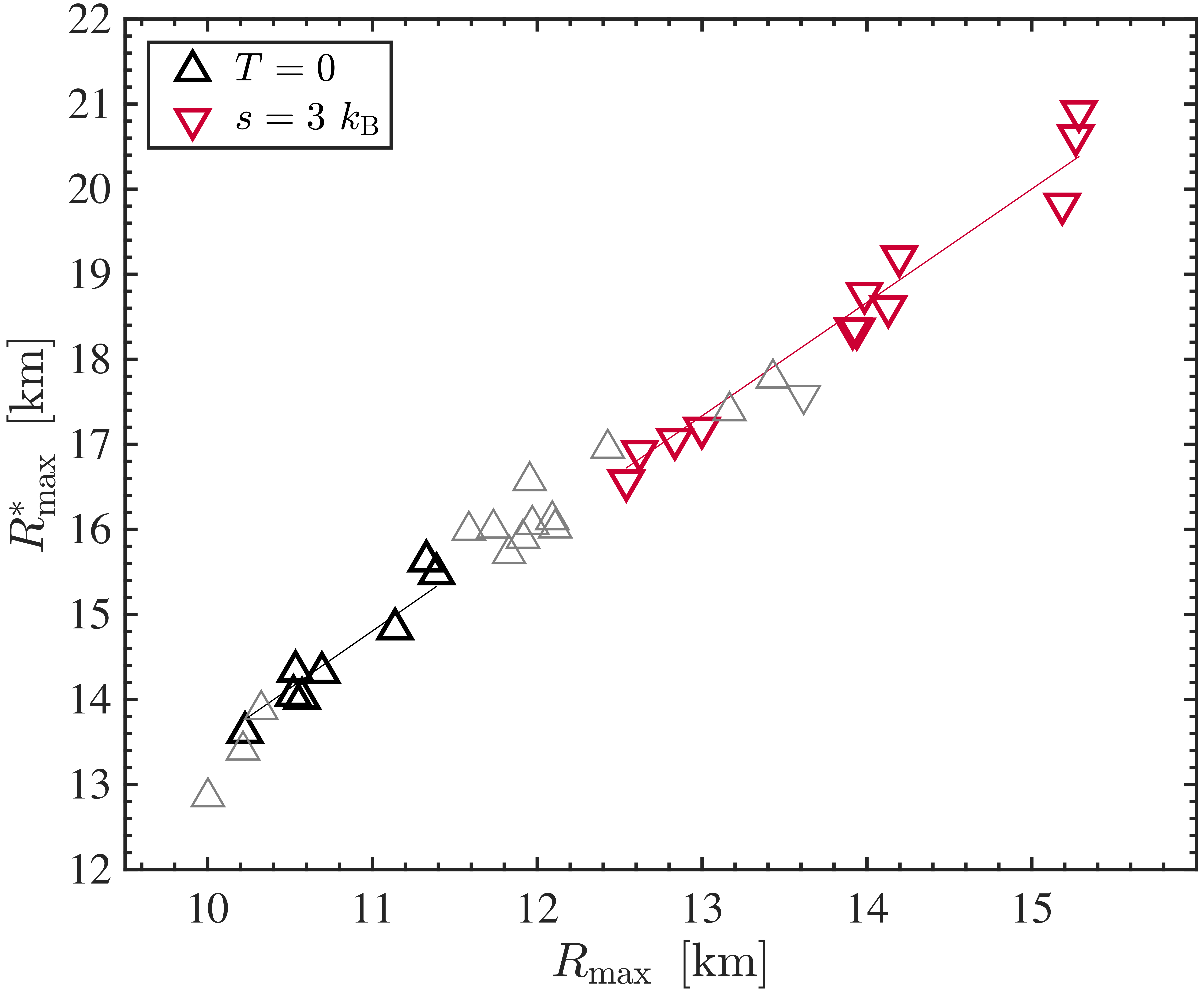


Non-rotating
Rotating
$M_{\max}$ $[\mathrm{M}_\odot]$
R [km]
3.5
3
2.5
2
1.5
1
0.5
10
15
20
25


$s = 3\ k_B$
Non-rotating
Rotating
$M\ [M_\odot]$
$R\ [km]$
3.5
3
2.5
2
1.5
1
0.5
10
15
20
25
30
35



$T = 0$
$s = 3\ k_\mathrm{B}$
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
2.8
3



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

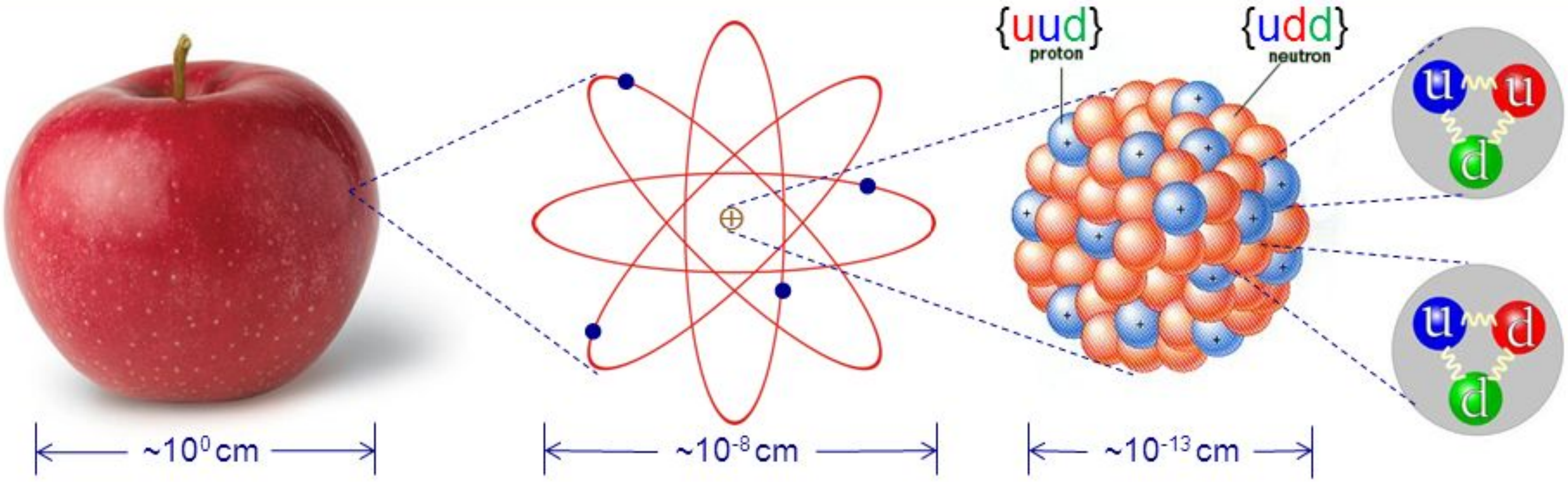
$$T = 0$$

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

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

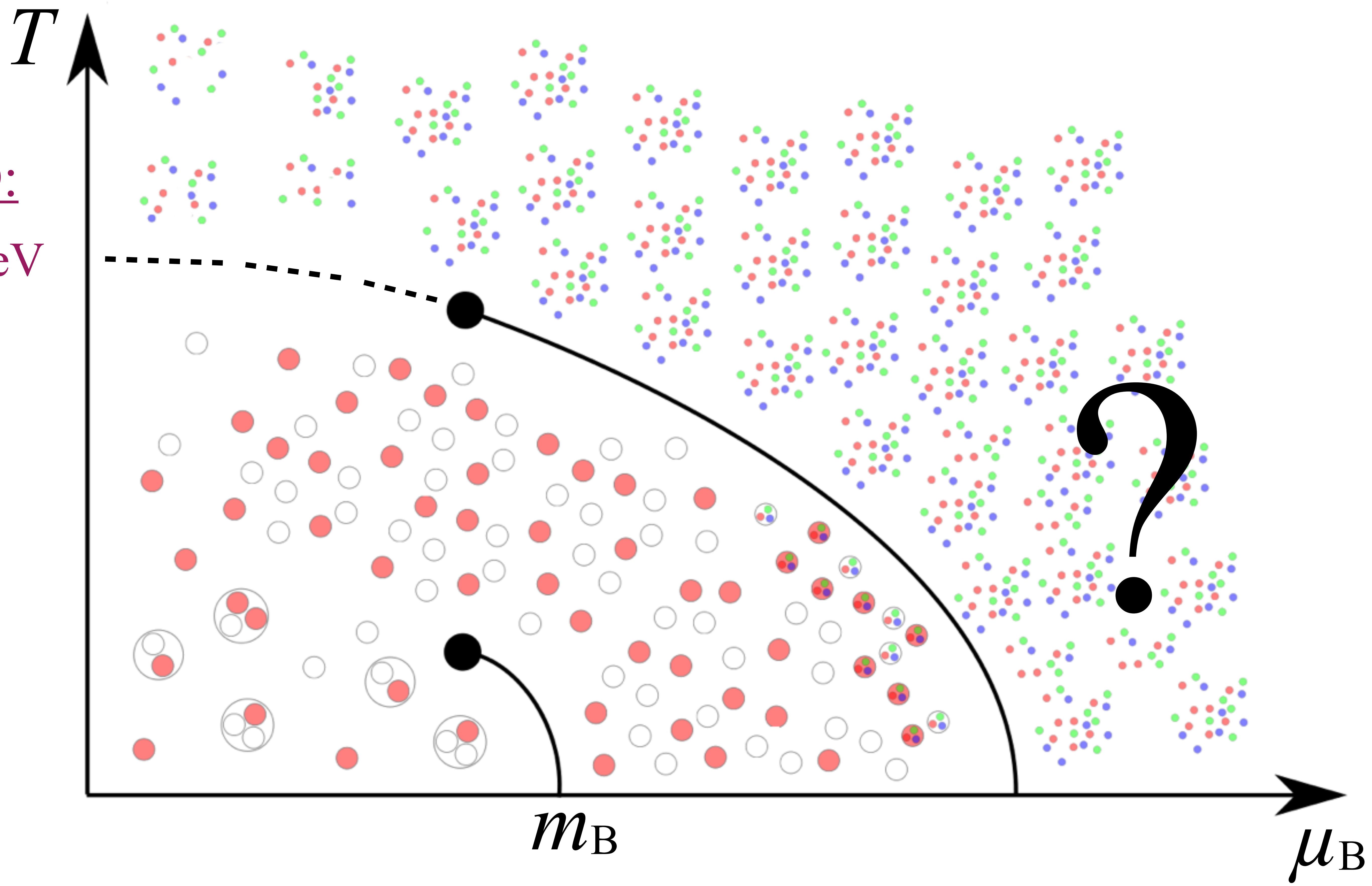
$$\frac{M^*_{\max}}{M_{\max}} = 1.109 \pm 0.0055 \qquad \frac{R^*_{\max}}{R_{\max}} = 1.334 \pm 0.0125$$ (Hadronic)

PRD 103, 055811 (2021)



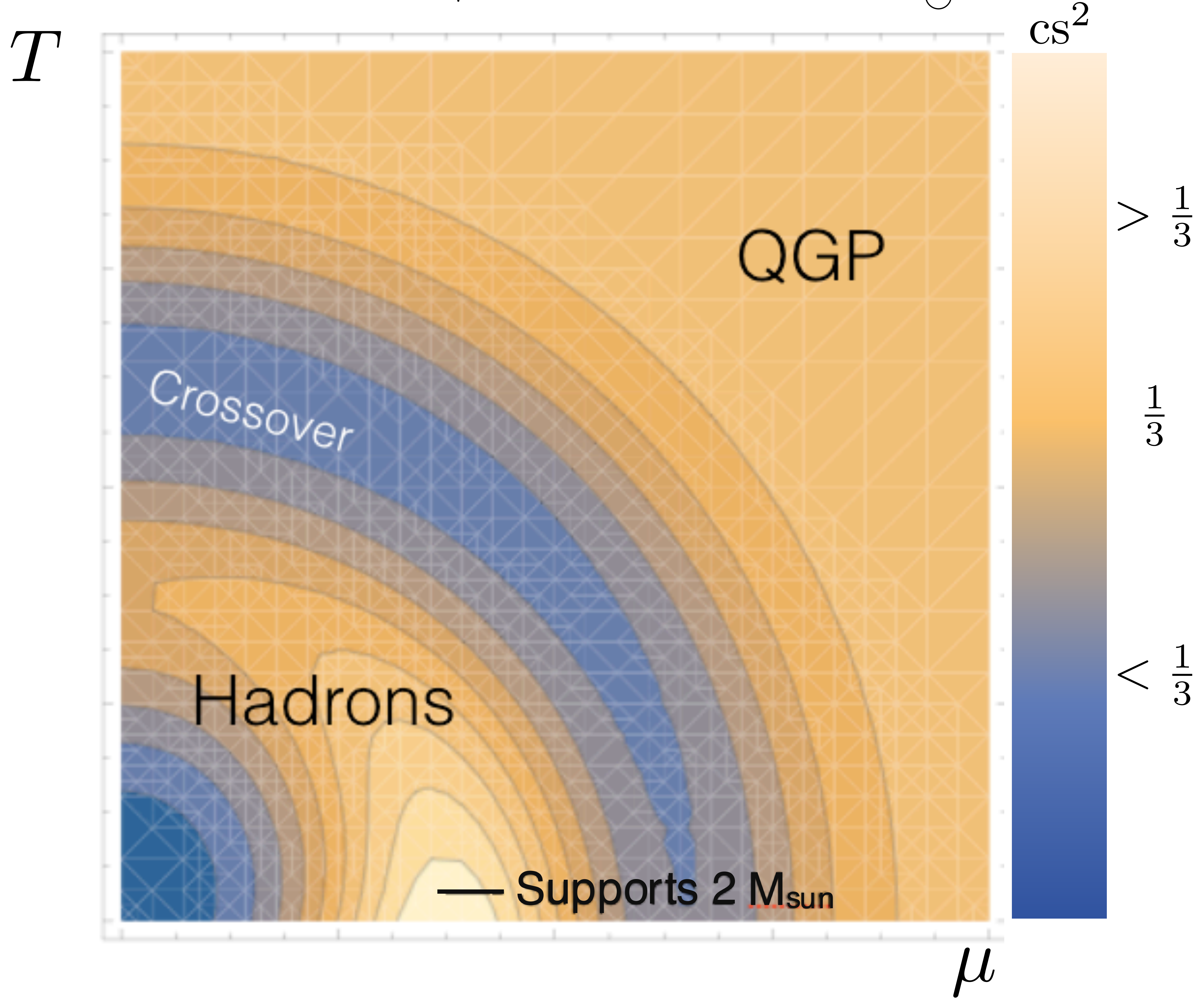
Lattice QCD:

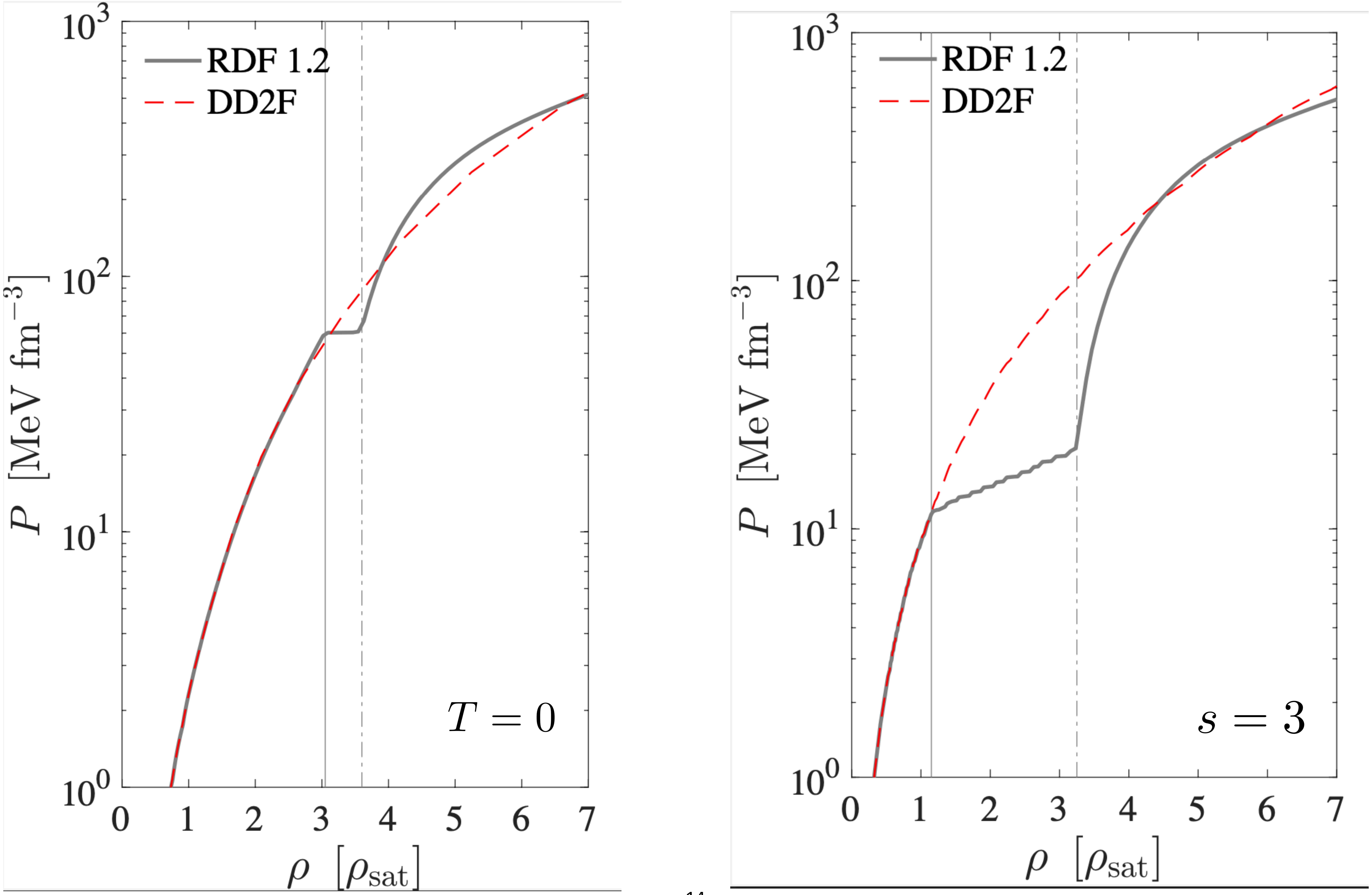
$T_{\text{pseud.}} \sim 150$ MeV
($\mu_B \sim 0$)



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

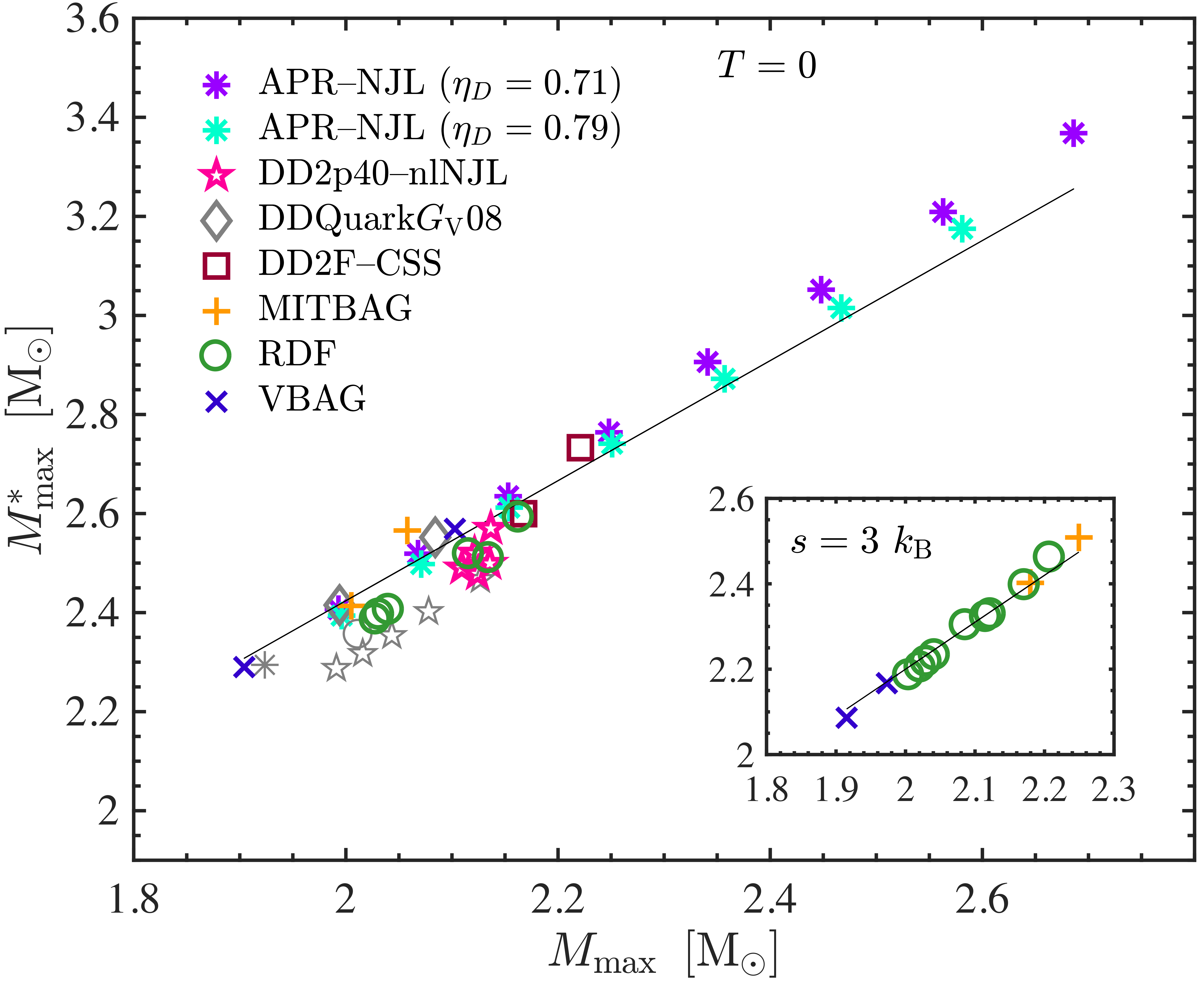
PSR J0348+0432: $2.01 \pm 0.04\ M_\odot$



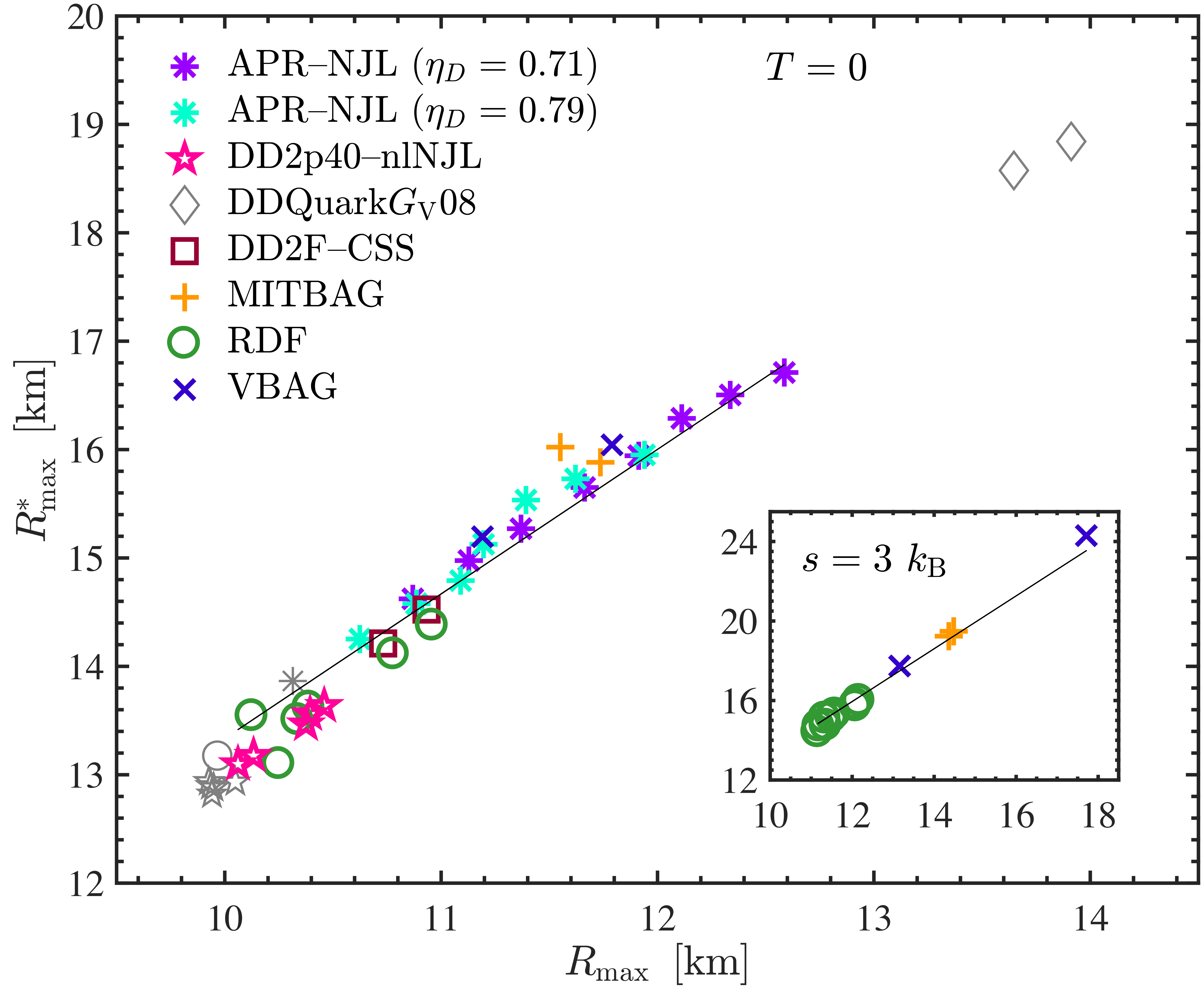


RDF 1.2
DD2F
$T = 0$
P [MeV fm^{-3}]
ρ [$\rho_{\rm sat}$]
RDF 1.2
DD2F
$s = 3$
P [MeV fm^{-3}]
ρ [$\rho_{\rm sat}$]

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 (ηD = 0.71)
APR–NJL (ηD = 0.79)
DD2p40–nlNJL
DDQuarkGV08
DD2F–CSS
MITBAG
RDF
VBAG
s = 3 kB
M*max [M⊙]
Mmax [M⊙]



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]

$$T = 0$$

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

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

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

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

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

2. Core Collapse Supernovae

Supernova explosions of massive stars triggered by the QCD phase transition

PRL **102,** 081101 (2009) PHYSICAL REVIEW LETTERS week ending 27 FEBRUARY 2009

Signals of the QCD Phase Transition in Core-Collapse Supernovae

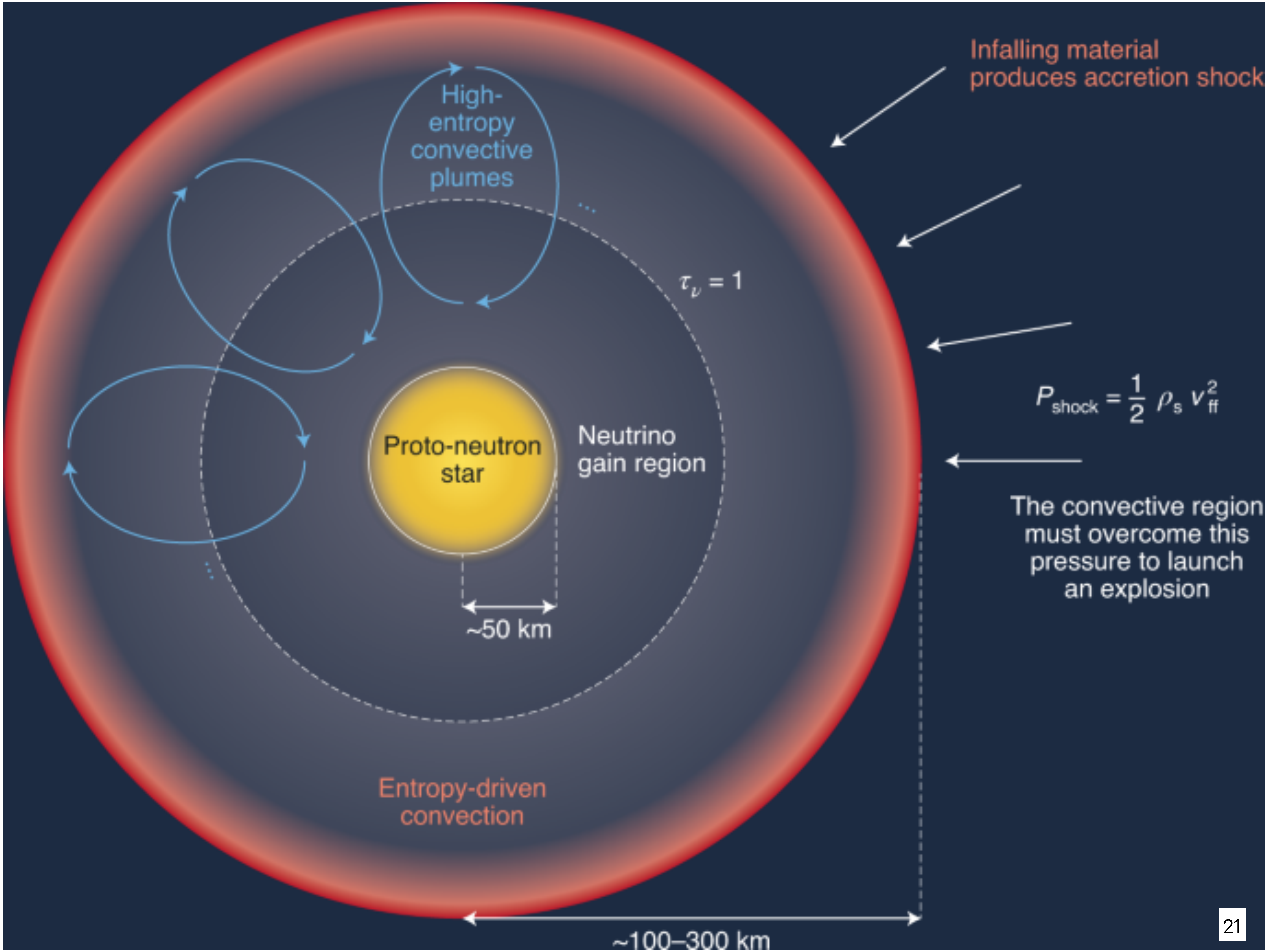
I. Sagert,[1] T. Fischer,[3] M. Hempel,[1] G. Pagliara,[2] J. Schaffner-Bielich,[2] A. Mezzacappa,[4] F.-K. Thielemann,[3] and M. Liebendörfer[3]

[1]*Institut für Theoretische Physik, Goethe-Universität, Max-von-Laue-Str. 1, 60438 Frankfurt am Main, Germany*
[2]*Institut für Theoretische Physik, Ruprecht-Karls-Universität, Philosophenweg 16, 69120 Heidelberg, Germany*
[3]*Department of Physics, University of Basel, Klingelbergstr. 82, 4056 Basel, Switzerland*
[4]*Physics Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831, USA*

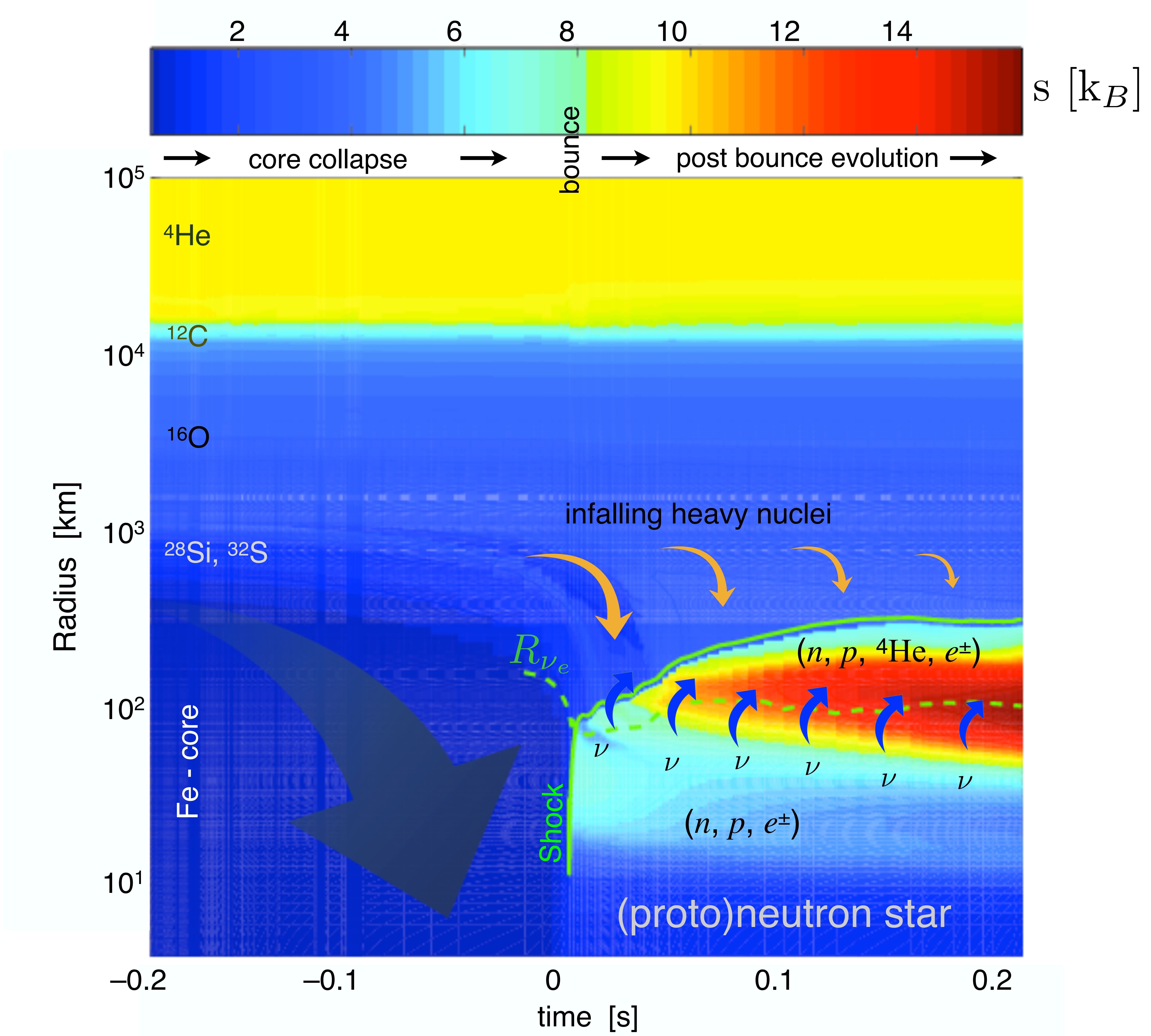
(Received 12 August 2008; published 26 February 2009)

We explore the implications of the QCD phase transition during the postbounce evolution of core-collapse supernovae. Using the MIT bag model for the description of quark matter, we model phase transitions that occur during the early postbounce evolution. This stage of the evolution can be simulated with general relativistic three-flavor Boltzmann neutrino transport. The phase transition produces a second shock wave that triggers a delayed supernova explosion. If such a phase transition happens in a future galactic supernova, its existence and properties should become observable as a second peak in the neutrino signal that is accompanied by significant changes in the energy of the emitted neutrinos. This second neutrino burst is dominated by the emission of antineutrinos because the electron degeneracy is reduced when the second shock passes through the previously neutronized matter.

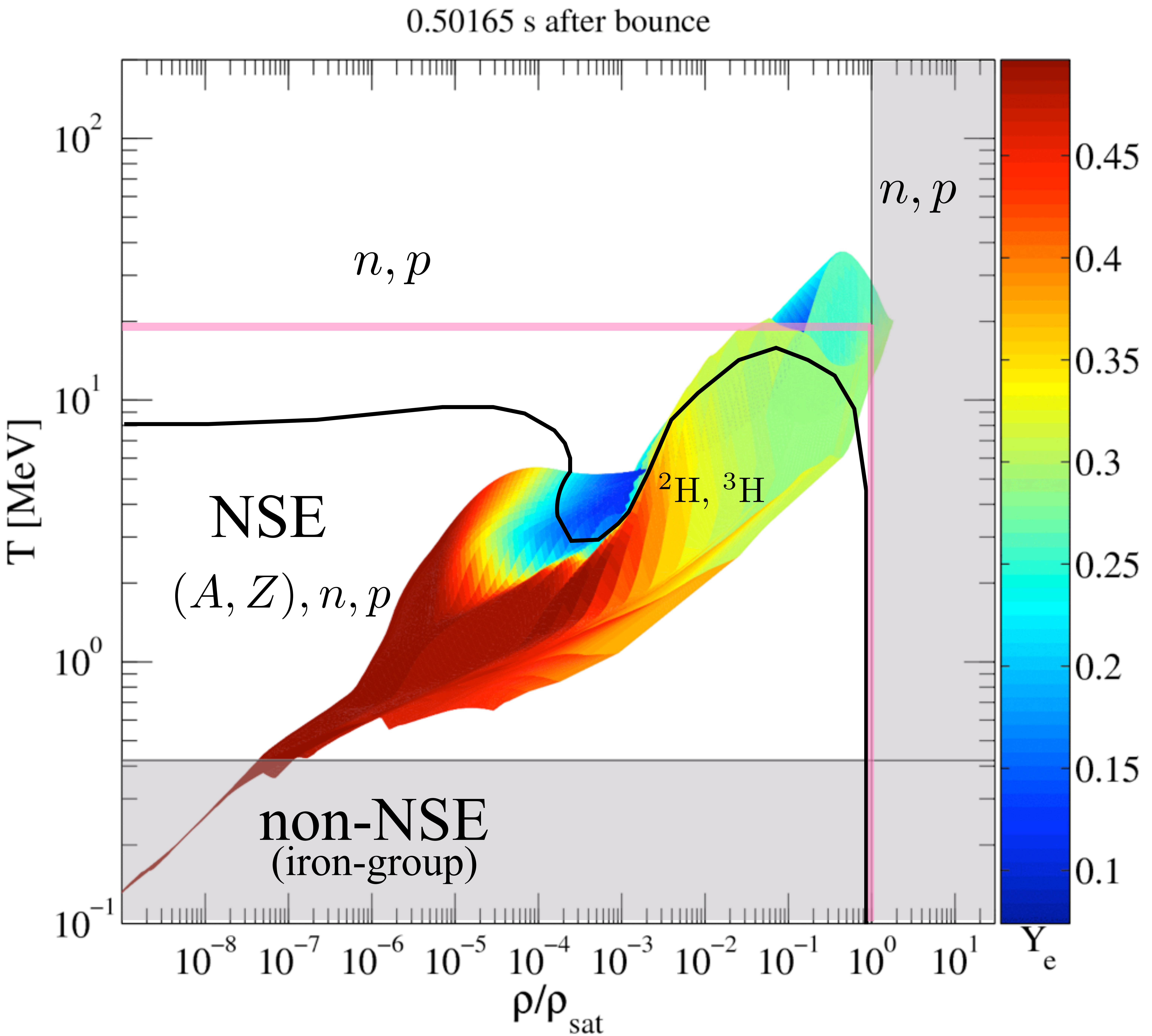
DOI: 10.1103/PhysRevLett.102.081101 PACS numbers: 26.50.+x, 21.65.Qr, 26.60.−c, 95.85.Ry



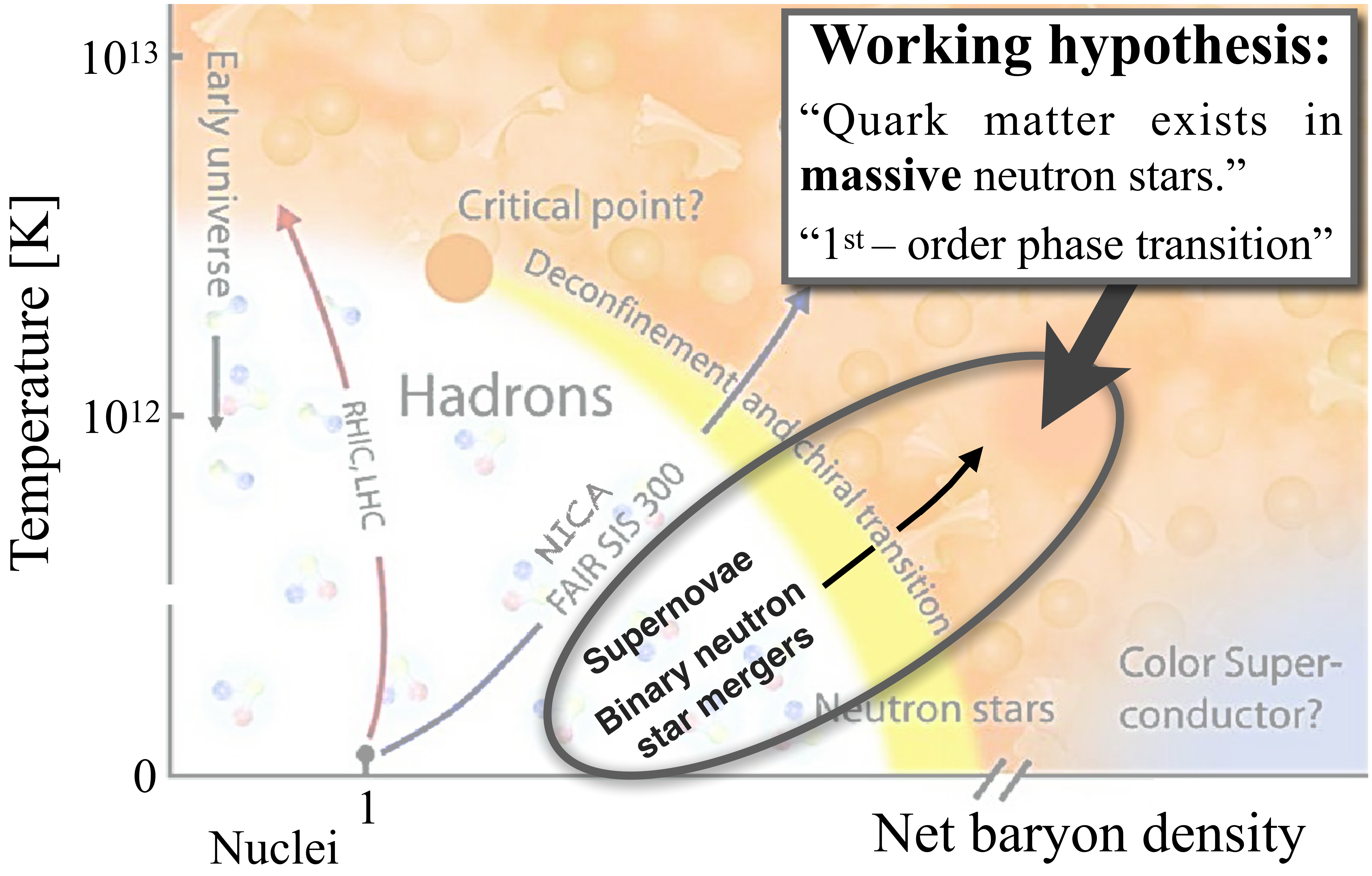
Young, P. *Nat Astron* **5,** 434–435 (2021)



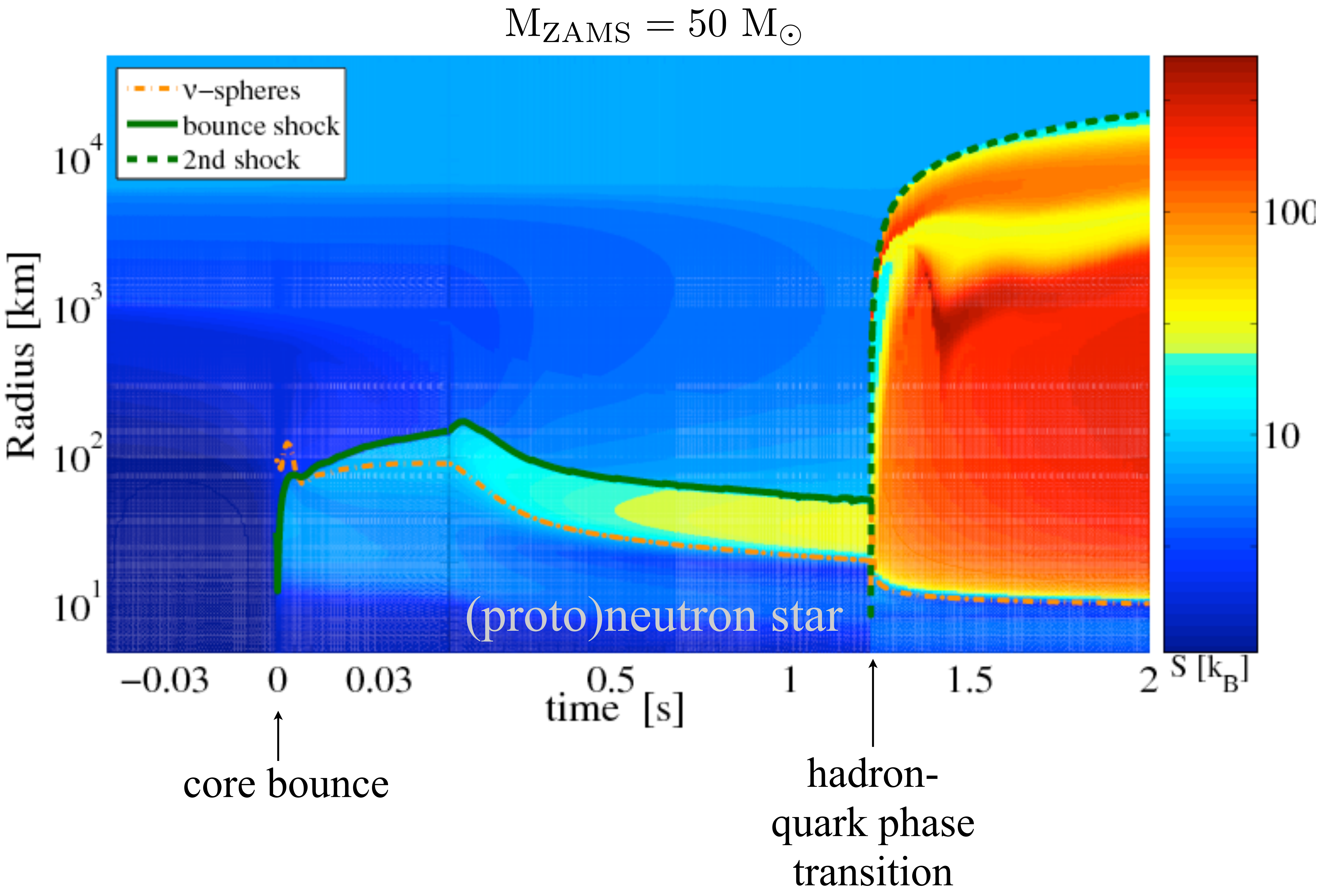
2 4 6 8 10 12 14
s [k_B]
core collapse
bounce
post bounce evolution
4He
12C
16O
28Si, 32S
Fe - core
infalling heavy nuclei
R_νe
(n, p, 4He, e±)
ν
(n, p, e±)
Shock
(proto)neutron star
Radius [km]
10^5
10^4
10^3
10^2
10^1
–0.2 –0.1 0 0.1 0.2
time [s]



0.50165 s after bounce
n, p
n, p
NSE
$(A, Z), n, p$
^{2}H, ^{3}H
non-NSE
(iron-group)
T [MeV]
ρ/ρ_{sat}
Y_e
10^{-1}
10^{0}
10^{1}
10^{2}
10^{-8} 10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 10^{0} 10^{1}
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1

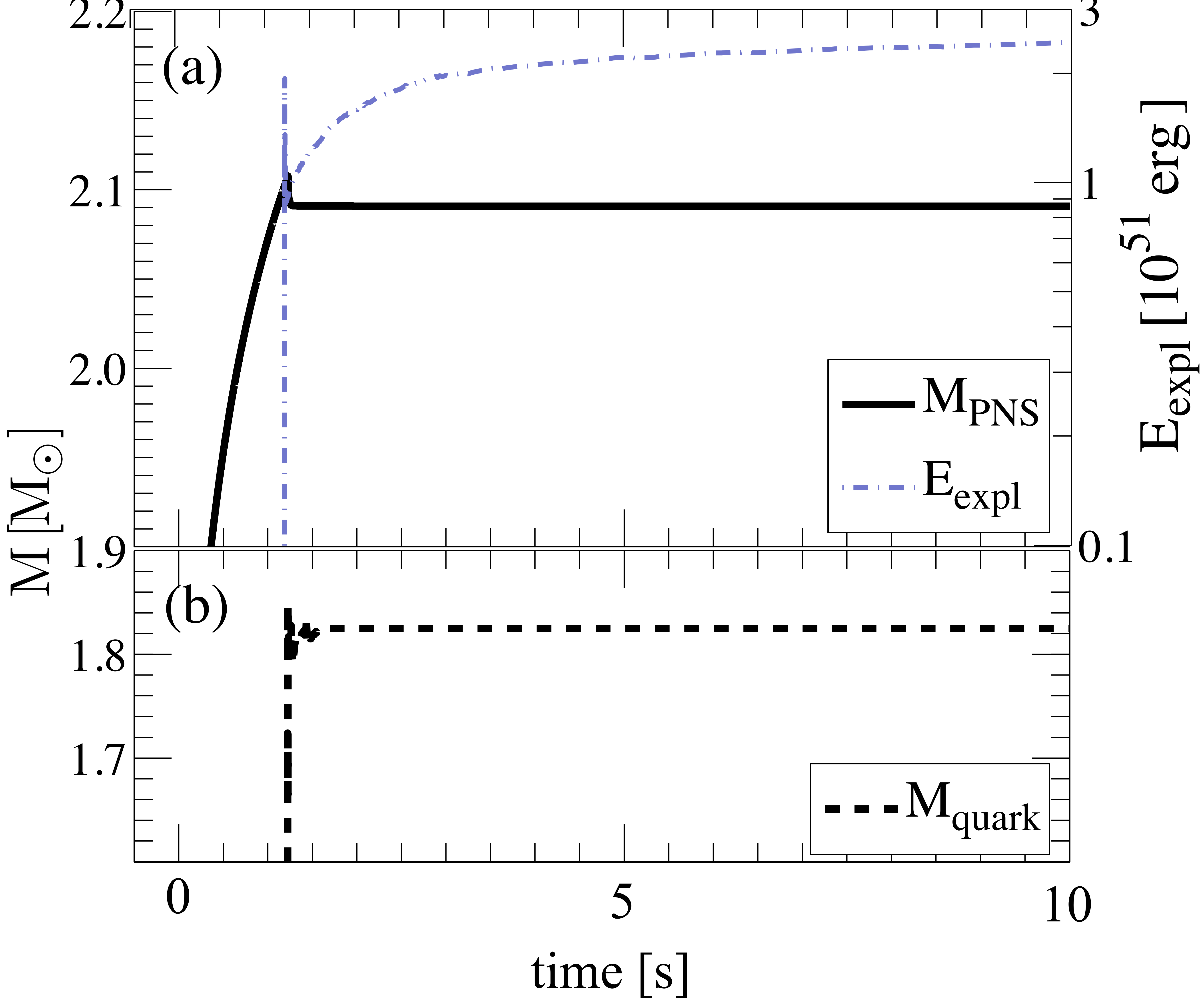


Working hypothesis:
"Quark matter exists in massive neutron stars."
"1st – order phase transition"
Temperature [K]
10^13
10^12
0
Early universe
RHIC, LHC
Critical point?
Hadrons
Deconfinement and chiral transition
NICA
FAIR SIS 300
Supernovae
Binary neutron star mergers
Neutron stars
Color Super-conductor?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

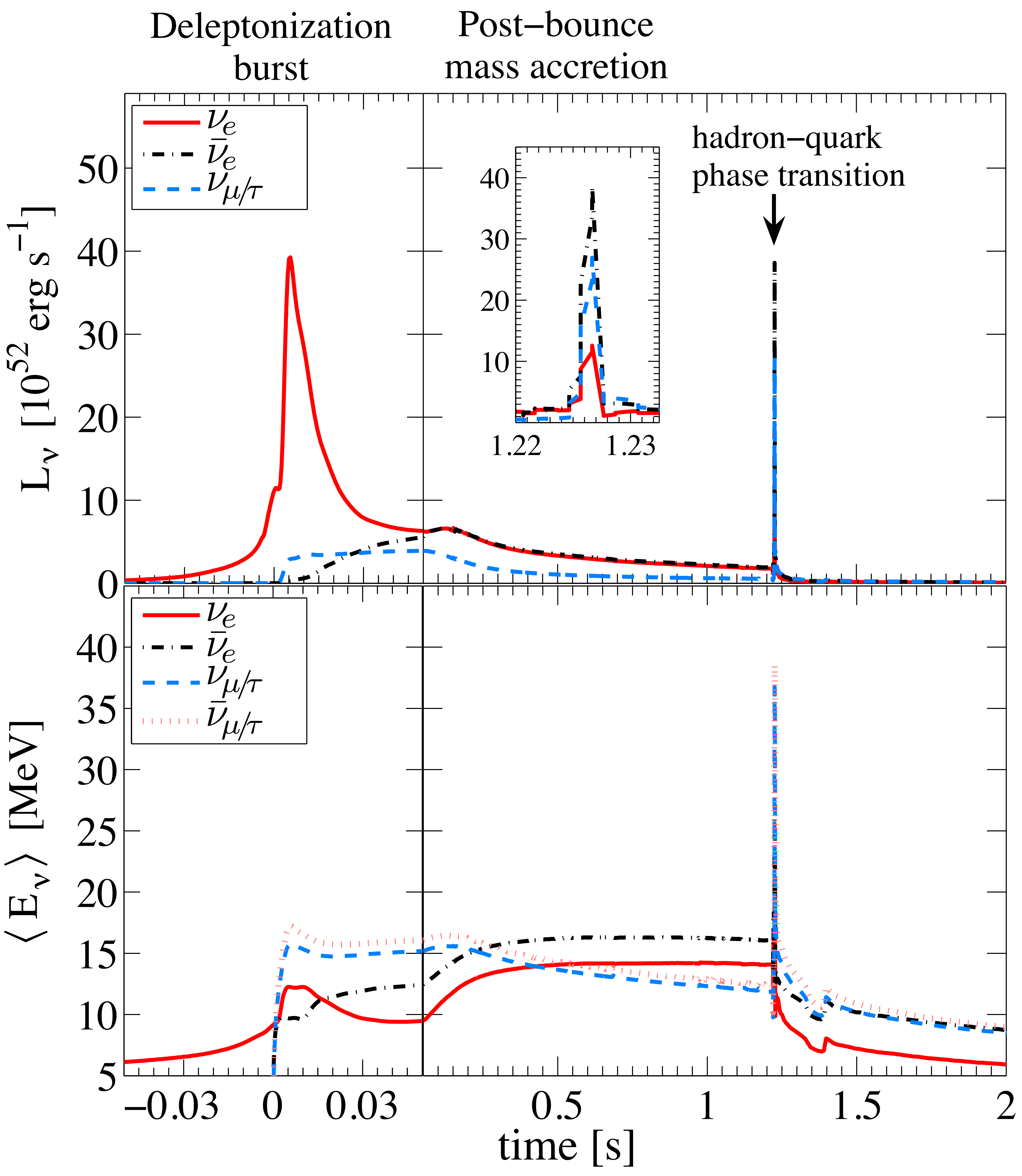


Nature Astron. **2**, 980 (2018)

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

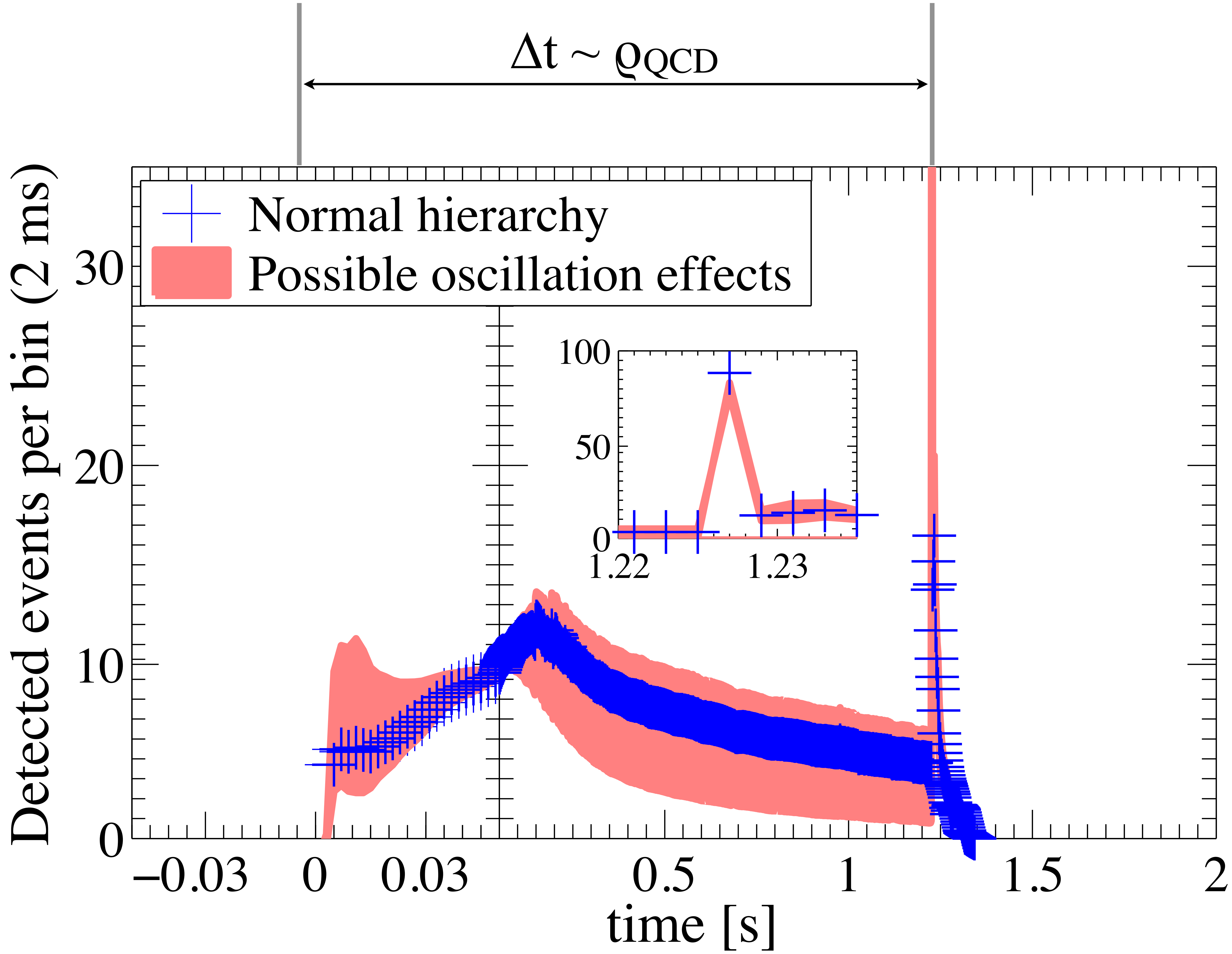


Nature Astron. **2**, 980 (2018)

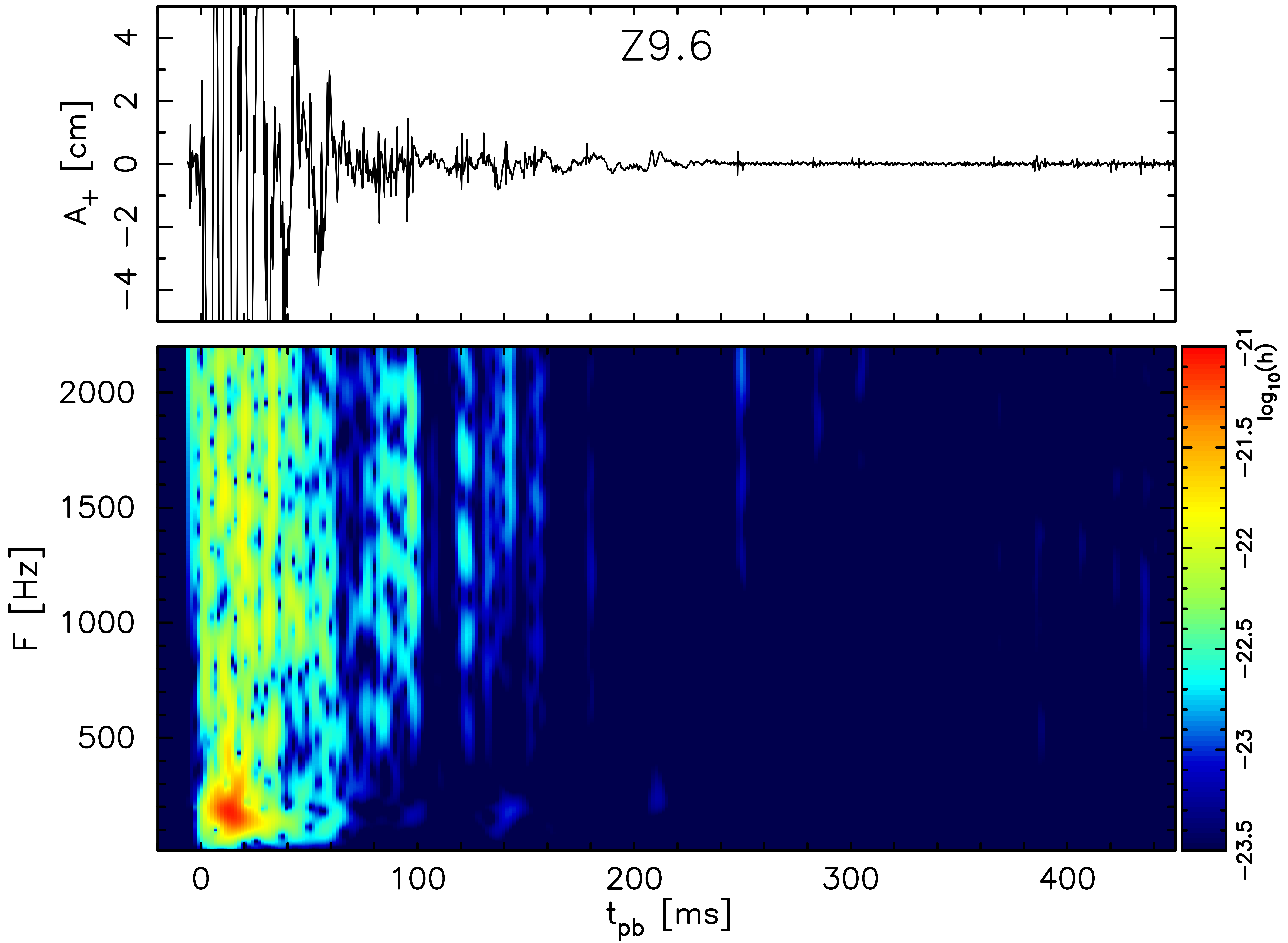


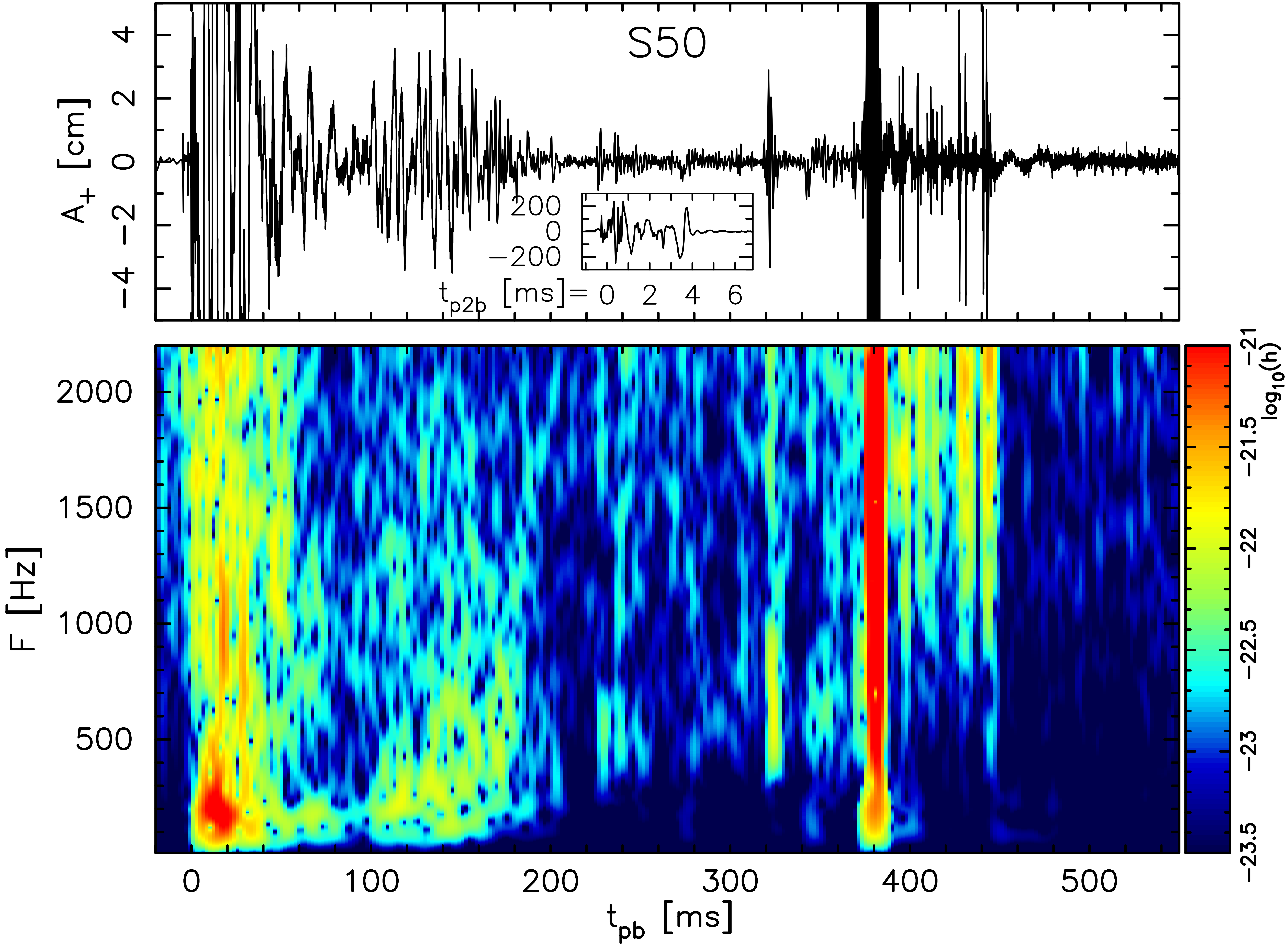
Nature Astron. **2**, 980 (2018)

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

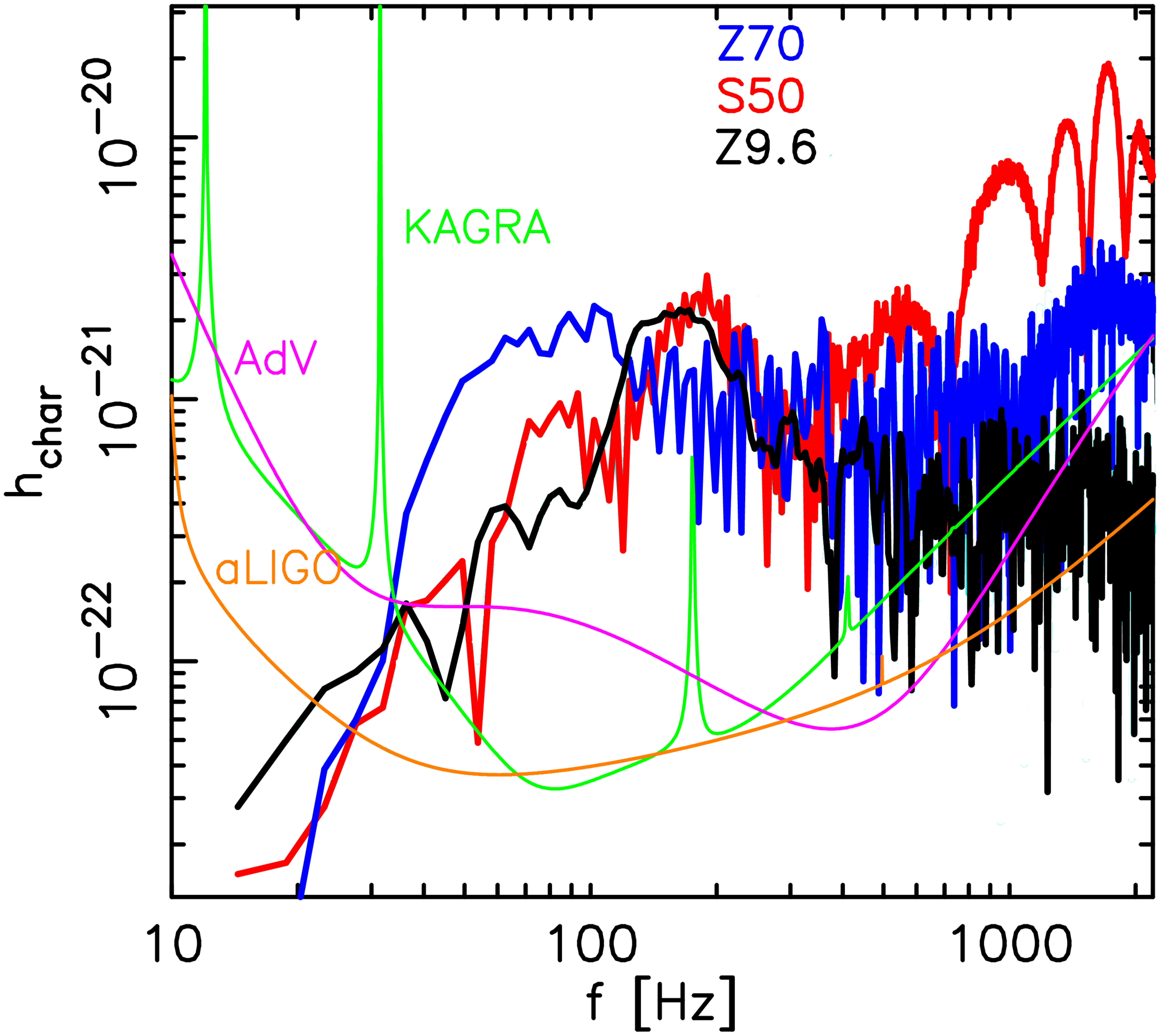


Nature Astron. **2**, 980 (2018)


Z9.6
A+ [cm]
F [Hz]
t_pb [ms]
log10(h)



ApJ 924, 38 (2021)



ApJ 924, 38 (2021)

Numerical tool for mode analysis : GREAT

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

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

$$\rho \to \rho + \delta\rho$$

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

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

g-modes

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

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

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

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

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

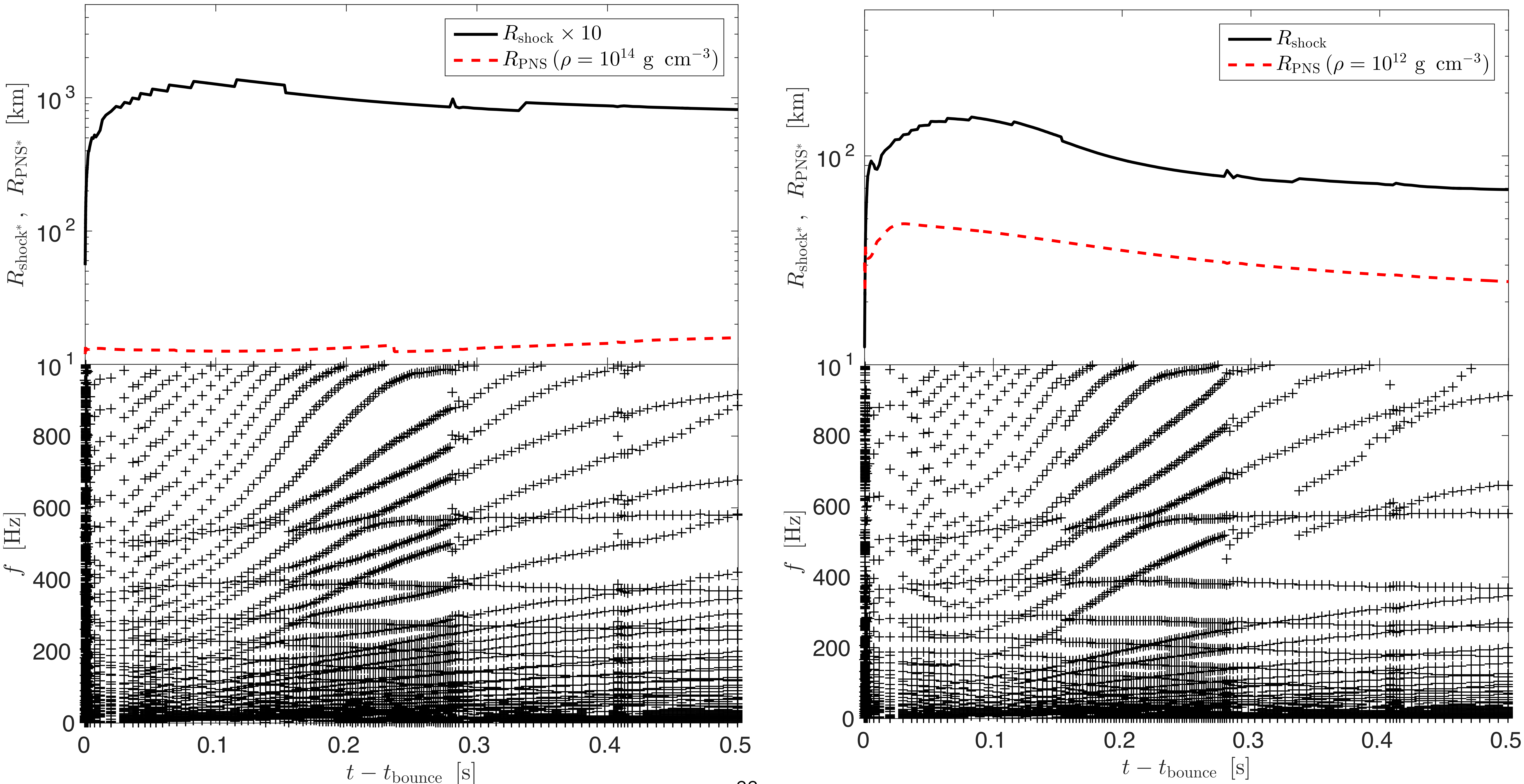
$$\xi^r = \eta_r\, Y_{lm} e^{-i\sigma t},$$

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

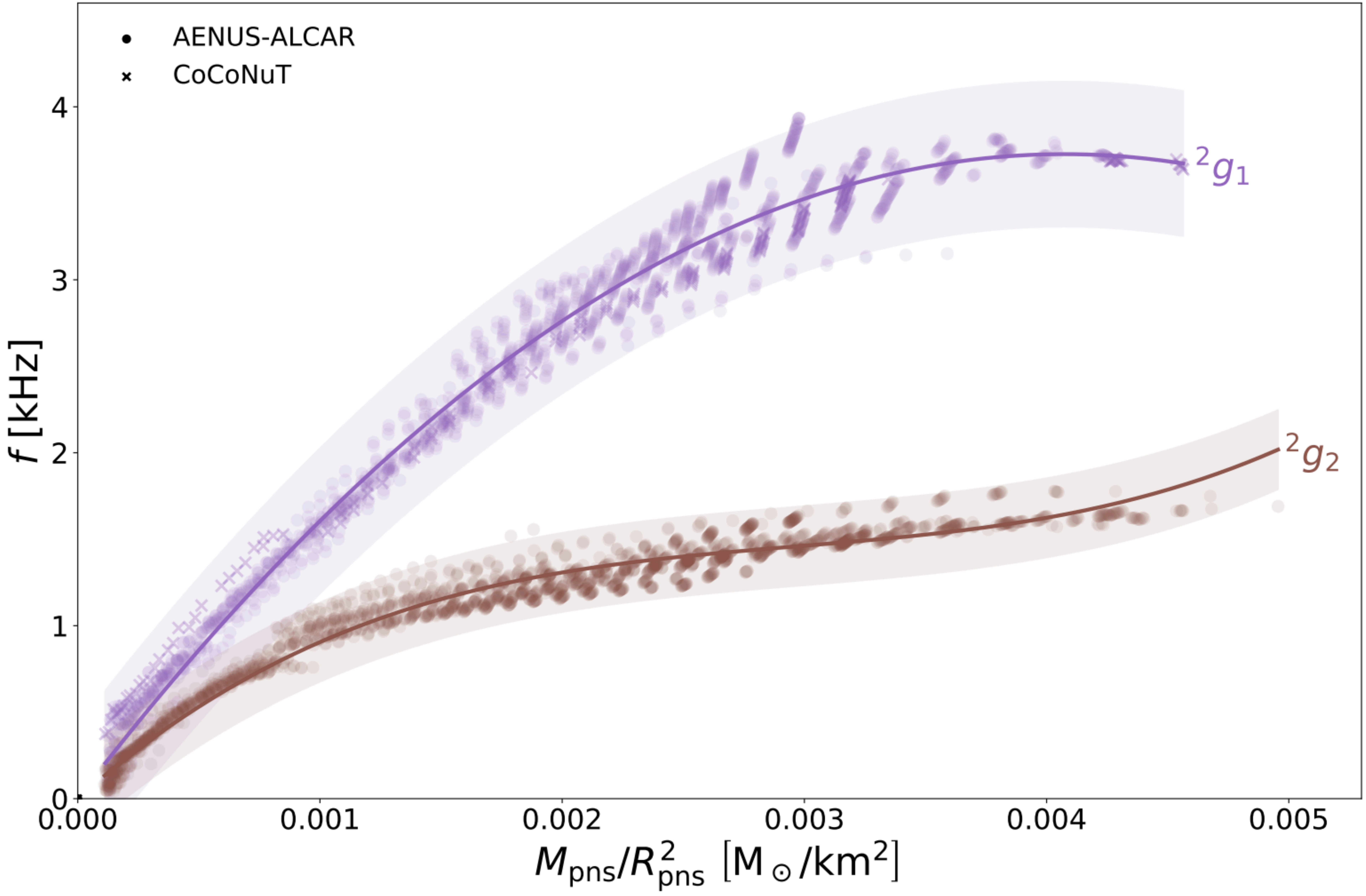
$$\xi^\varphi = \eta_\perp\, \frac{1}{r^2 \sin^2\theta}\partial_\varphi Y_{lm} e^{-i\sigma t}$$

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

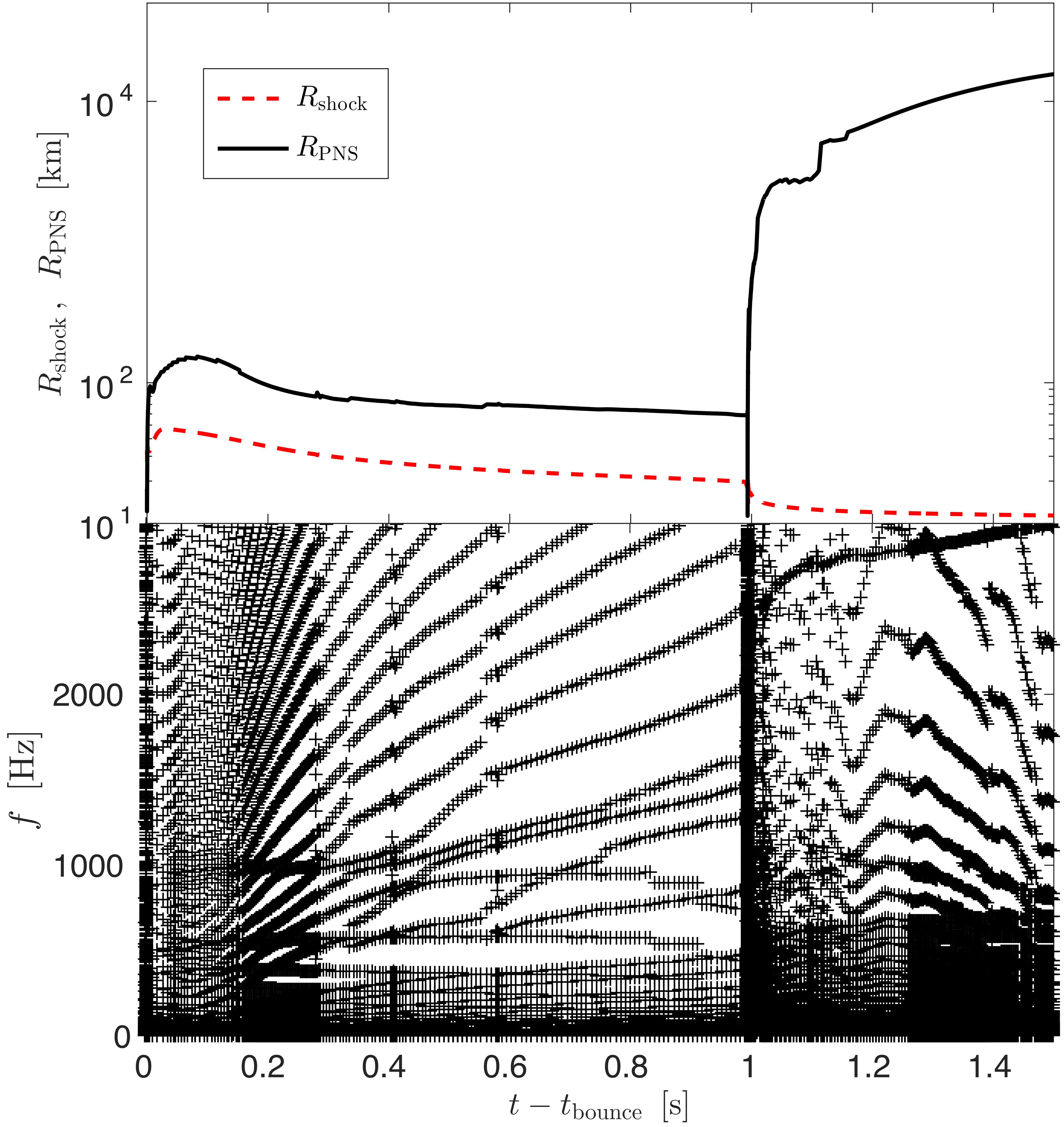
Torres-Forne et al. (2018), Mon. Not. Roy. Astron. Soc.



$R_{\rm shock} \times 10$
$R_{\rm PNS}$ ($\rho = 10^{14}$ g cm^{-3})
$R_{\rm shock^*}$, $R_{\rm PNS^*}$ [km]
f [Hz]
$t - t_{\rm bounce}$ [s]
$R_{\rm shock}$
$R_{\rm PNS}$ ($\rho = 10^{12}$ g cm^{-3})



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



Model: s15.0
Woosley et al. (2002),Rev. Mod. Phys.

EoS : DD2
Typel S. et al., 2010, Phys. Rev. C


köszönöm
TERIMA KASIH
GRACIAS
MERCI
K SALAMAT
OBRIGADO
GRAZIE
THANK YOU
متشكرم
DZIĘKUJĘ
감사합니다
DANKIE
TƏŞƏKKÜR
DĚKUJI
СПАСИБО
DANKE
FALEMNDERIT
DANK U
ありがとう
MULȚUMESC
TACK
ÞAKKA ÞÉR