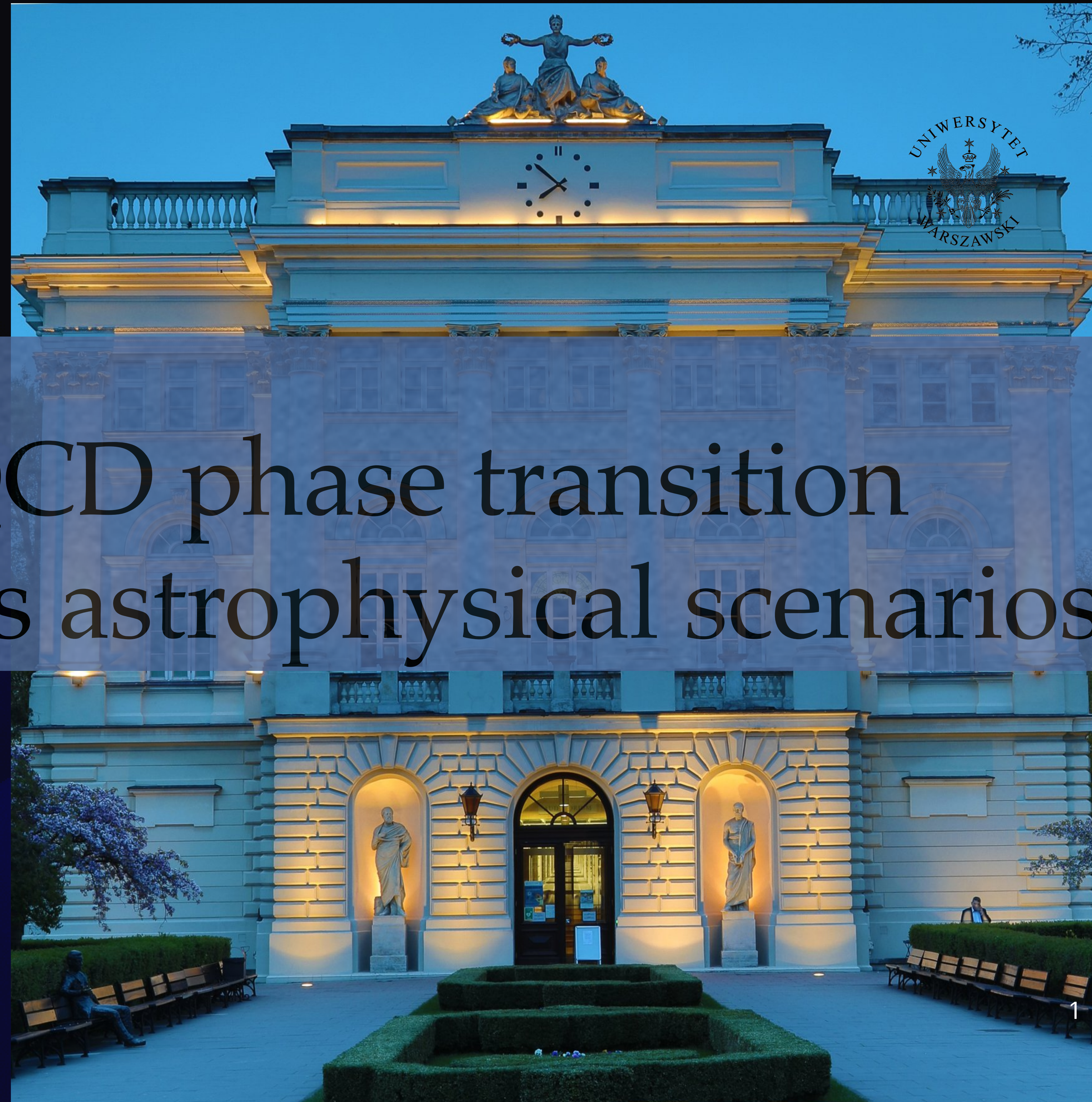
Uniwersytet Wrocławski

Narodowe Centrum Nauki

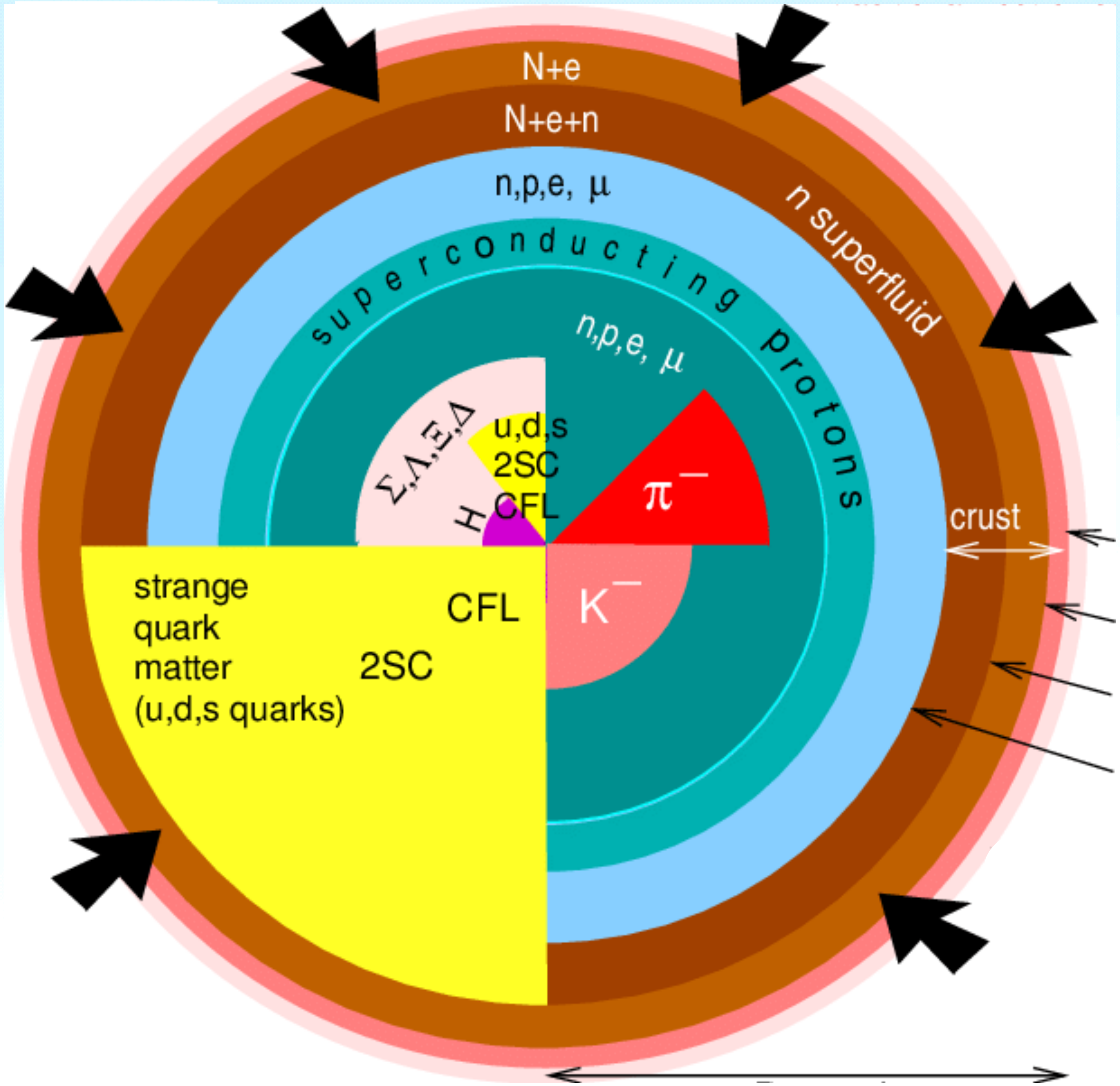
Probing the QCD phase transition within various astrophysical scenarios



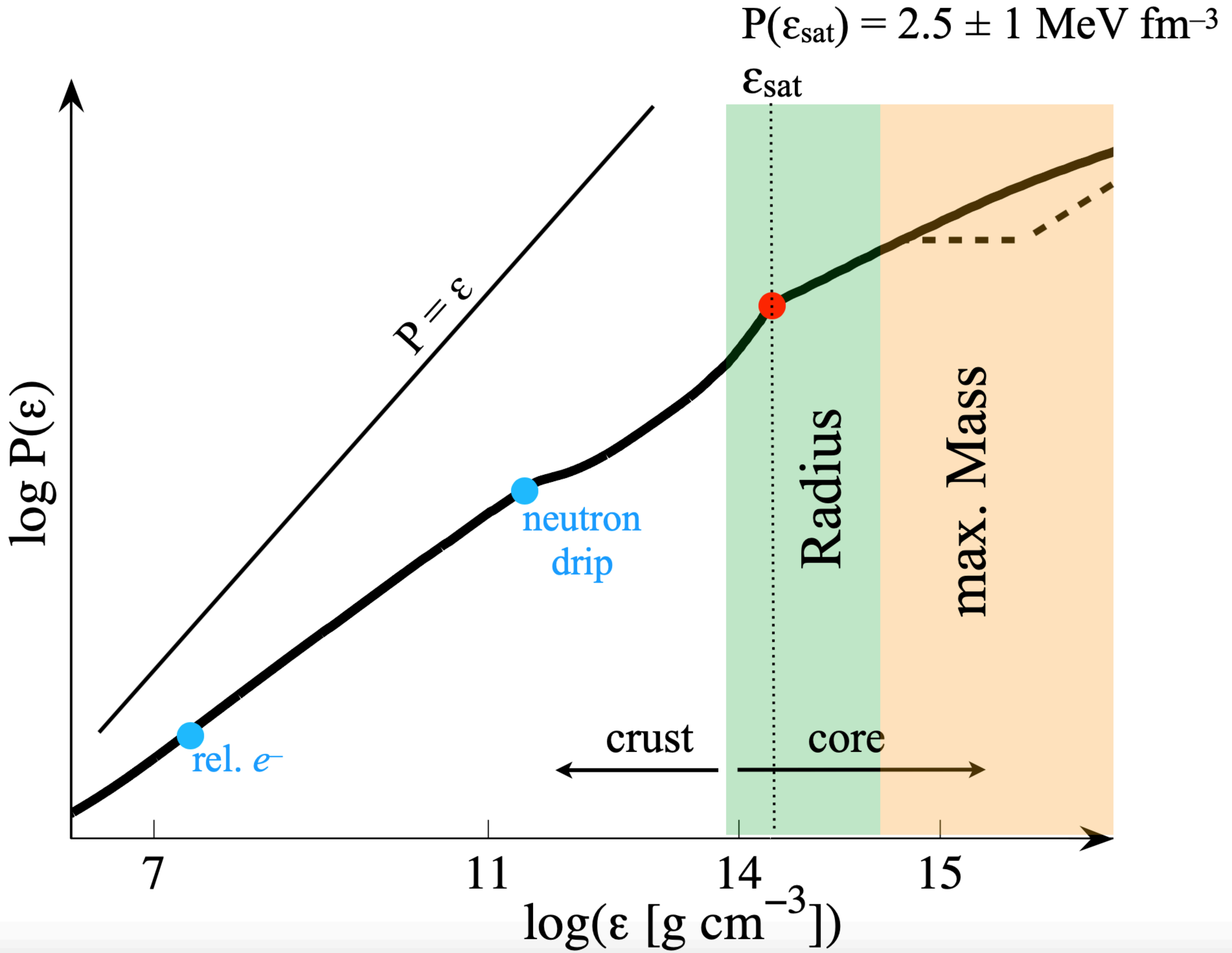
Noshad Khosravi Largani

Brainstorming workshop

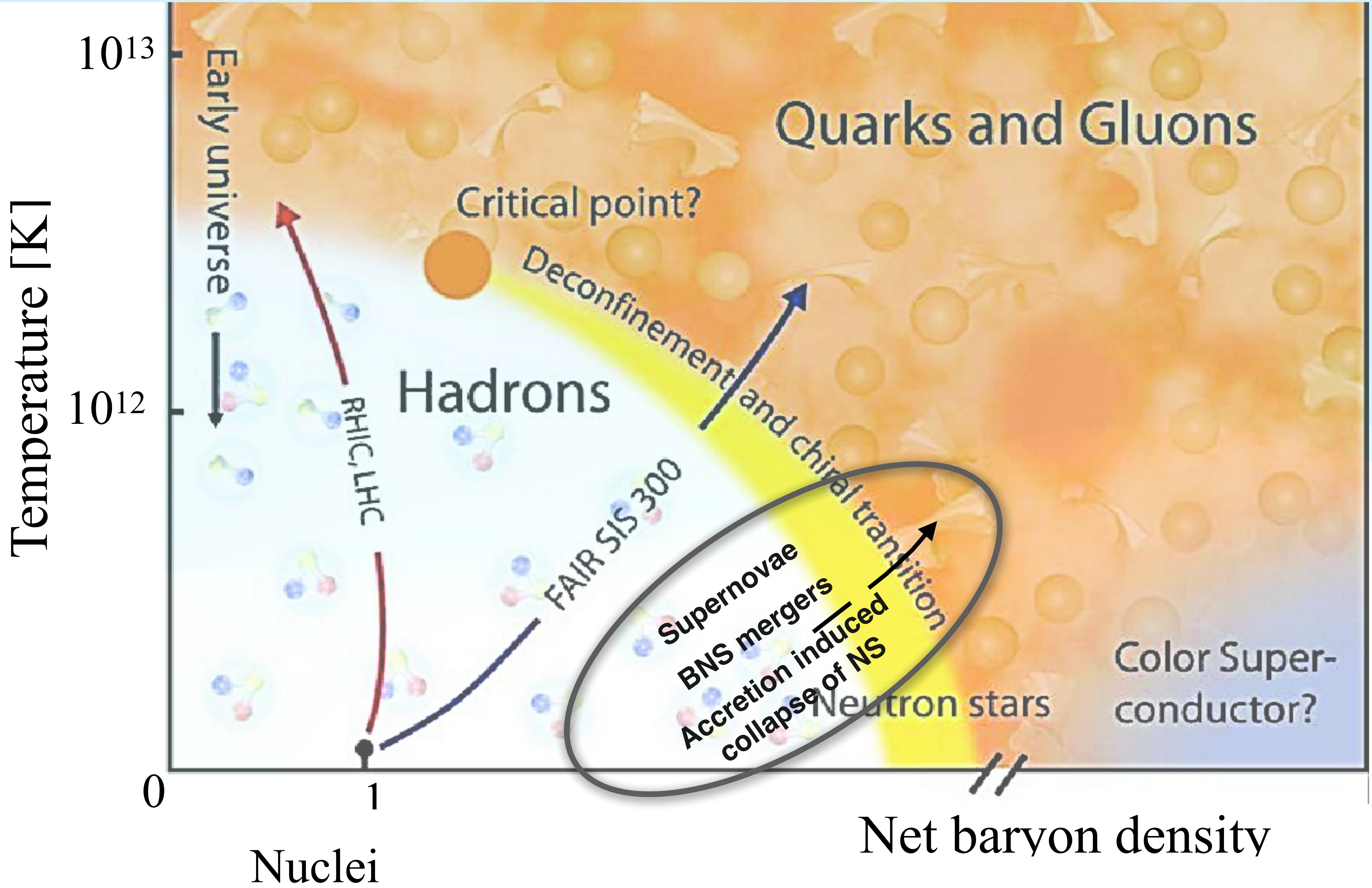
University of Warsaw, August 2024



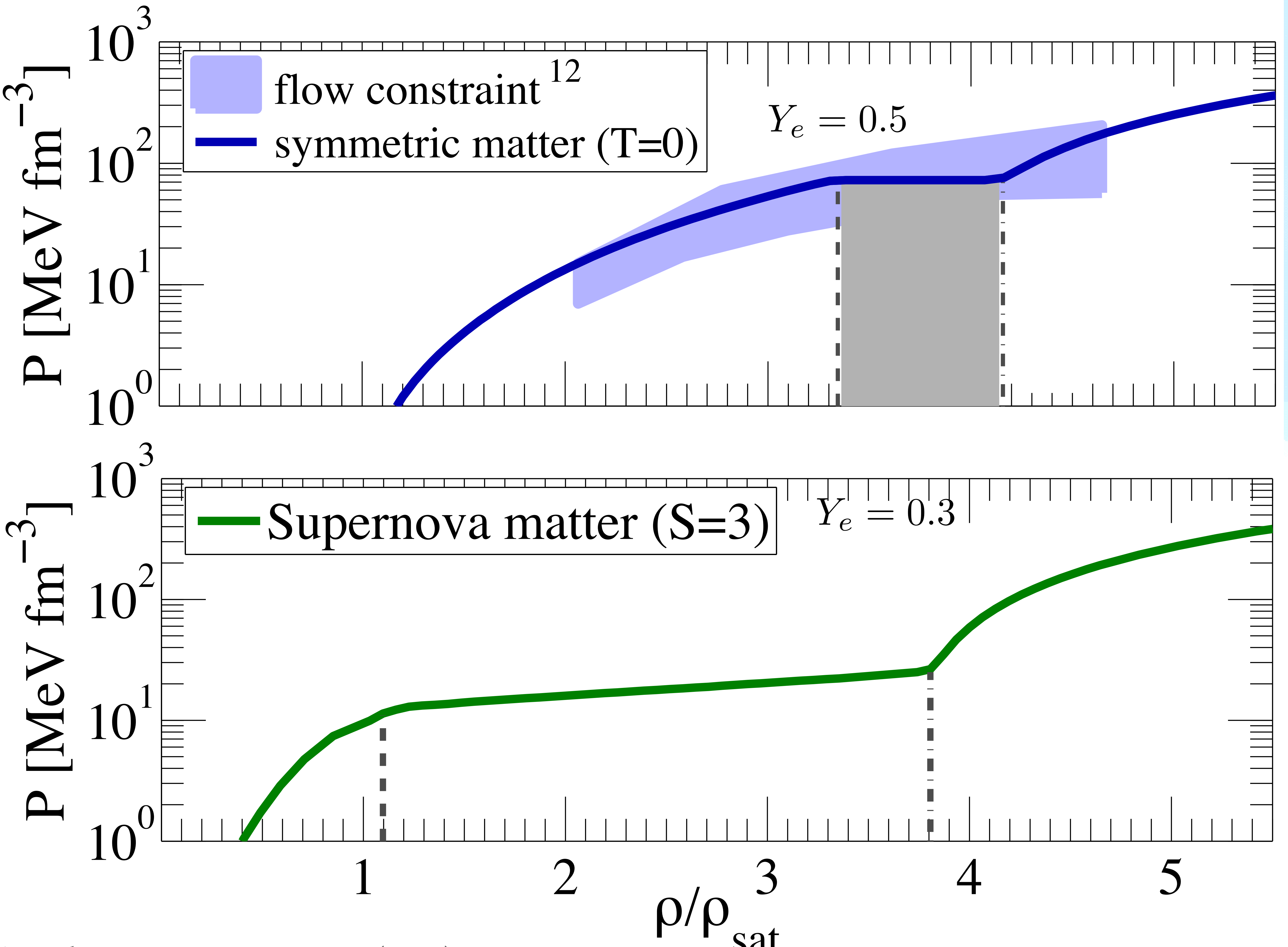
Weber, F. & Negreiros, Rodrigo & Rosenfield, Philip. (2007)



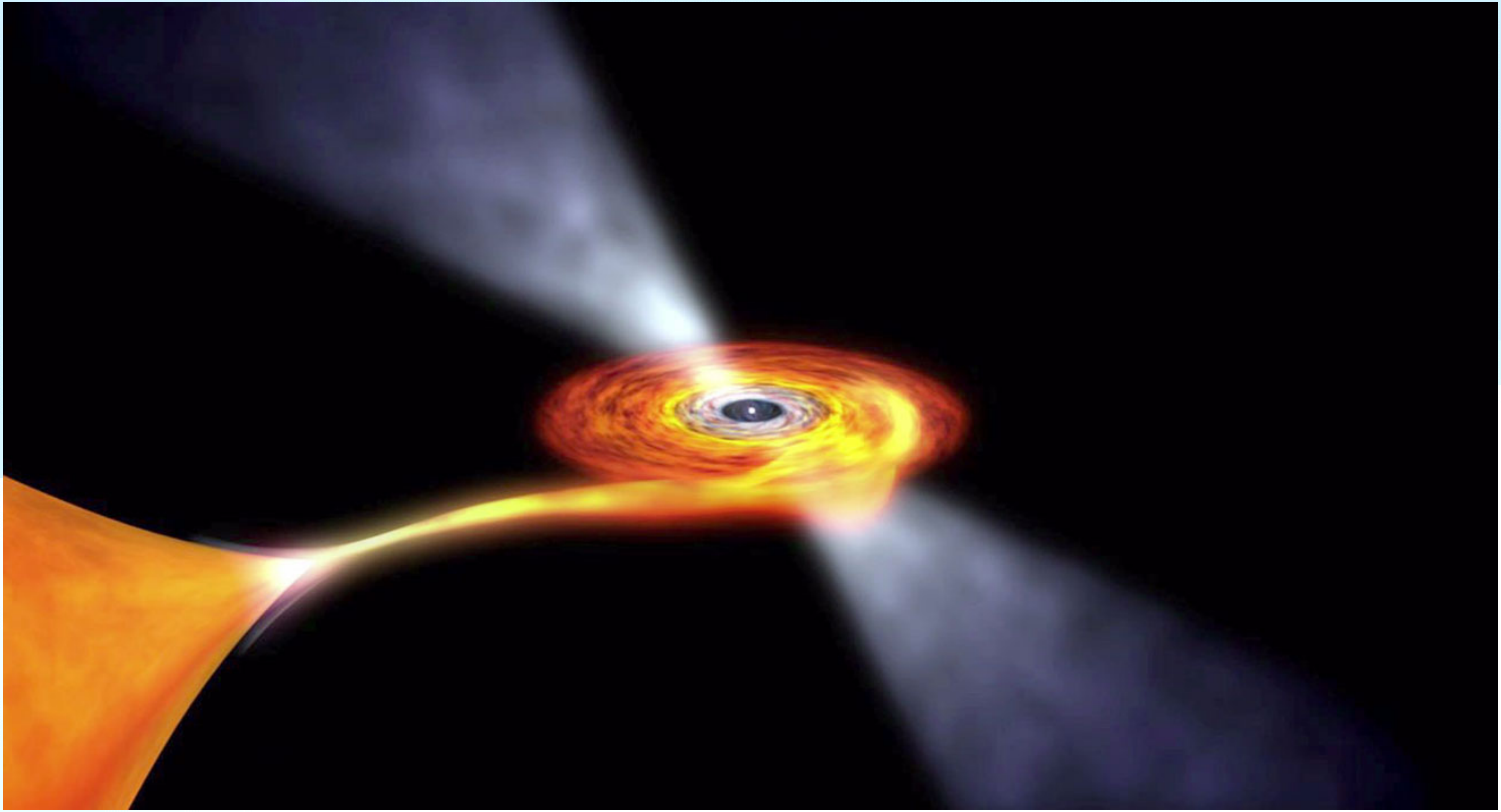
P(εsat) = 2.5 ± 1 MeV fm⁻³
εsat
P = ε
log P(ε)
neutron
drip
rel. e⁻
crust
core
Radius
max. Mass
7
11
14
15
log(ε [g cm⁻³])



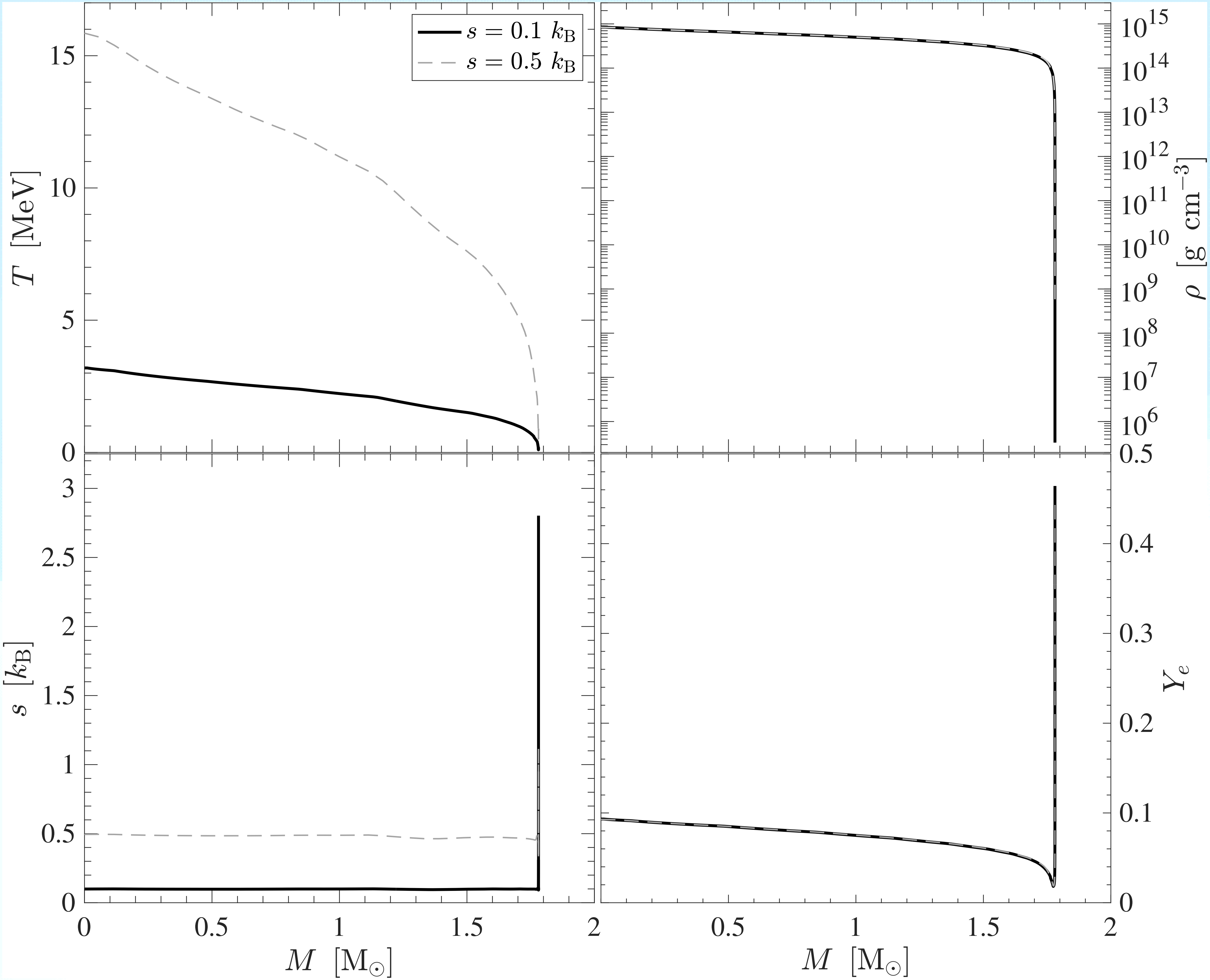
10^{13}
10^{12}
Temperature [K]
Early universe
Quarks and Gluons
Critical point?
Deconfinement and chiral transition
Hadrons
RHIC, LHC
FAIR SIS 300
Supernovae
BNS mergers
Accretion induced
collapse of NS
Neutron stars
Color Super-
conductor?
0
1
Nuclei
Net baryon density



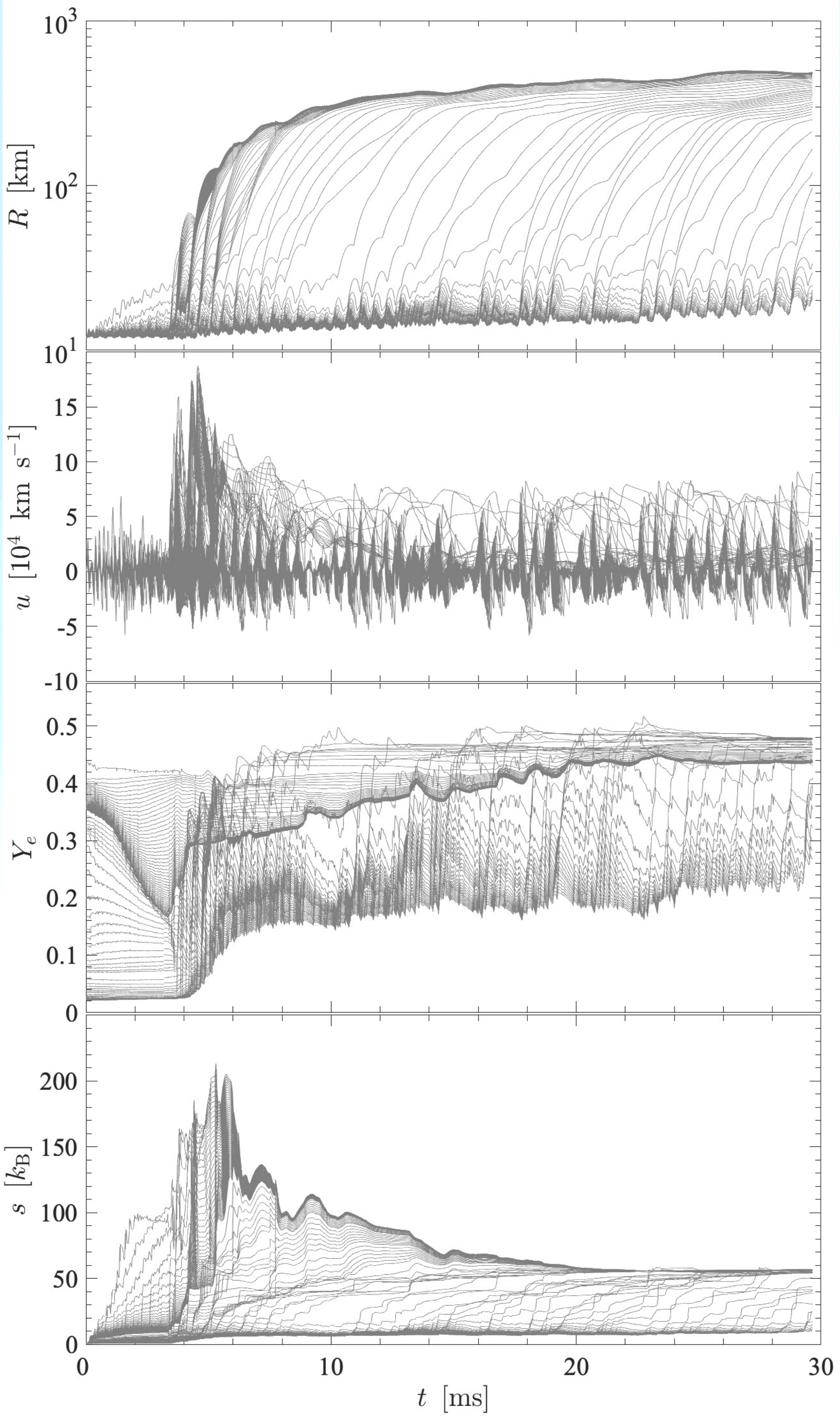
Bastian, Phys. Rev. D, 103, 023001 (2021)



Credit: NASA

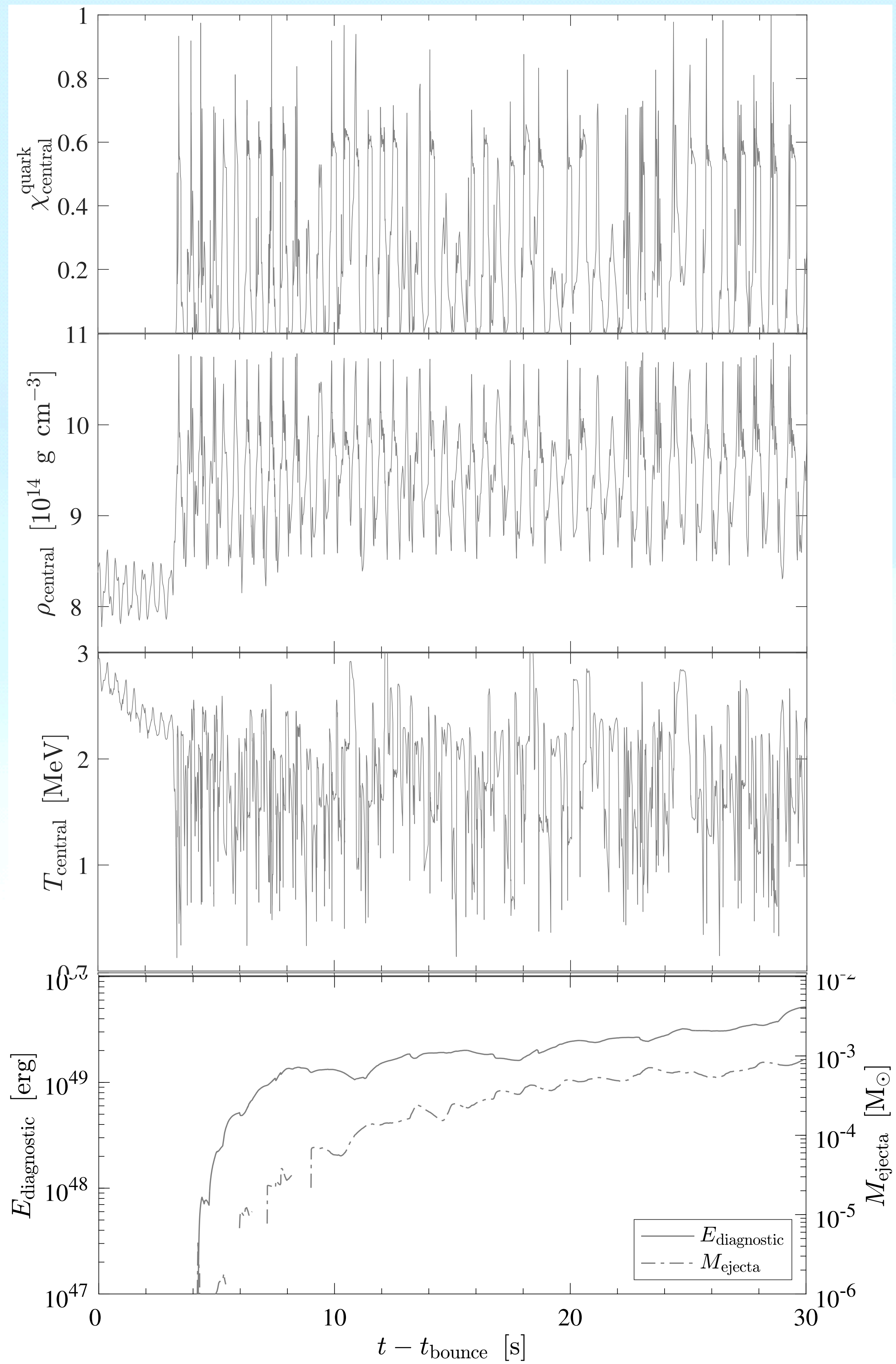


Khosravi Largani et al., A&A 687, A245 (2024)



Khosravi Largani et al., A&A 687, A245 (2024)

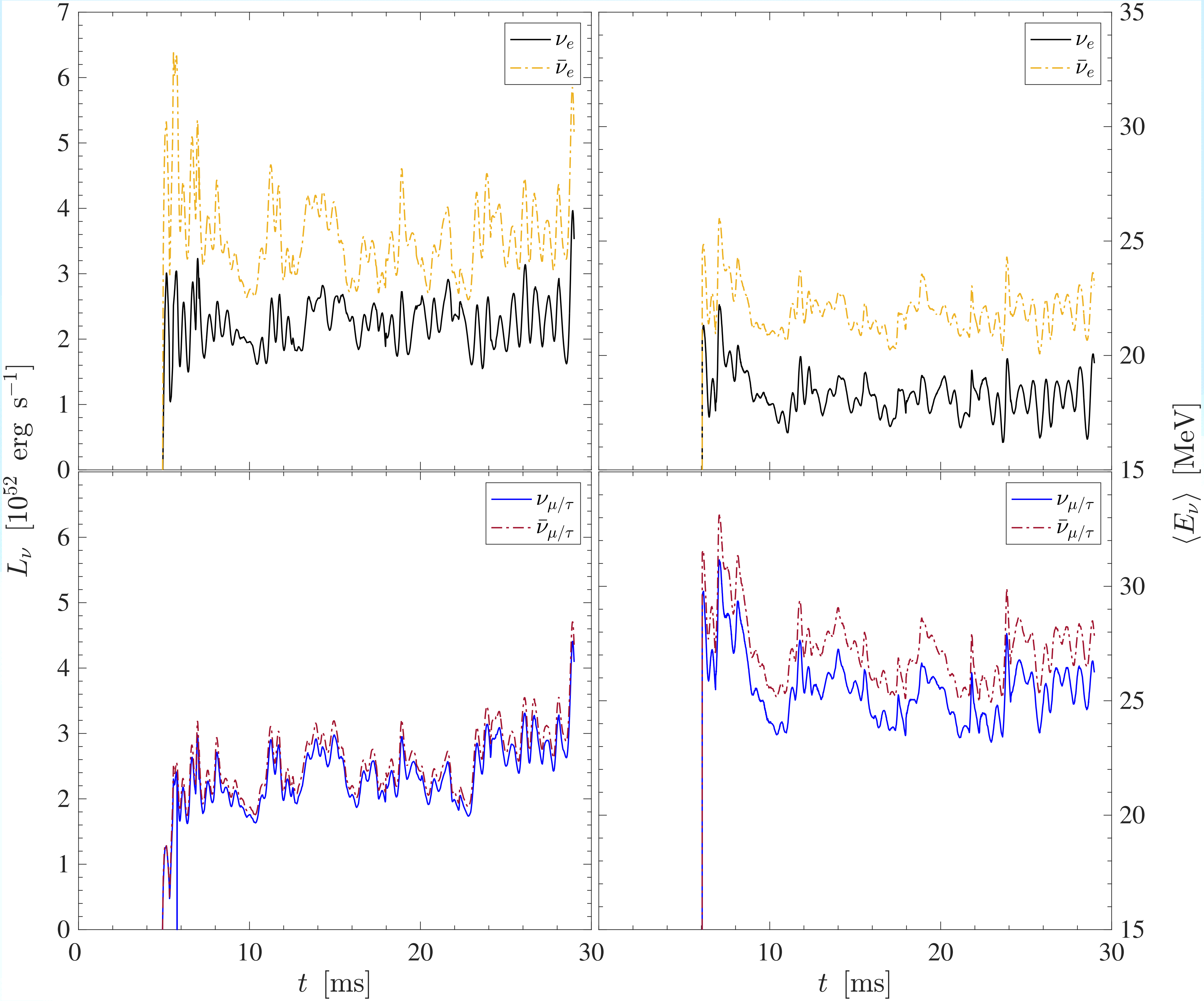
$M_{\rm NS} = 1.55\ M_\odot$



Khosravi Largani et al., A&A 687, A245 (2024)

	Weak process
1	$e^- + p \rightleftarrows n + \nu_e$
2	$e^+ + n \rightleftarrows p + \bar{\nu}_e$
3	$n \rightleftarrows p + e^- + \bar{\nu}_e$
4	$\nu_e + (A, Z-1) \rightleftarrows (A, Z) + e^-$
5	$\nu + N \rightleftarrows \nu' + N$
6	$\nu + (A, Z) \rightleftarrows \nu' + (A, Z)$
7	$\nu + e^{\pm} \rightleftarrows \nu' + e^{\pm}$
8	$e^- + e^+ \rightleftarrows \nu + \bar{\nu}$
9	$N + N \rightleftarrows \nu + \bar{\nu} + N + N$
10	$\nu_e + \bar{\nu}_e \rightleftarrows \nu_{\mu/\tau} + \bar{\nu}_{\mu/\tau}$

$\nu = \{\nu_e, \bar{\nu}_e, \nu_{\mu/\tau}, \bar{\nu}_{\mu/\tau}\}$ and $N = \{n, p\}$



Khosravi Largani et al., A&A 687, A245 (2024)

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

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

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

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

g-modes:

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

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

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

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

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

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

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

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

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

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

Types of fluid modes (non-radial oscillations of non-rotating stars)

p-modes

- Pressure modes ($l \geq 0$)
- Restoring force = pressure
- Standing sound waves
- Lamb frequency (L):

$$L^2 \approx c_s^2 \frac{l(l+1)}{r^2}$$

- Mode frequency

$$f \propto c_s \propto \sqrt{\bar{\rho}} \propto \sqrt{M / R^3}$$

f-mode

- Fundamental mode ($l \geq 2$)
- Node-less mode (simple case)
- Lowest-order p-mode?

$$L^2 \approx c_s^2 \frac{l(l+1)}{r^2}$$

- Mode frequency

$$f \propto c_s \propto \sqrt{\bar{\rho}} \propto \sqrt{M / R^3}$$

g-modes

- Gravity modes ($l \geq 1$)
- Restoring force = buoyancy
- Brunt-Väisälä frequency (N)

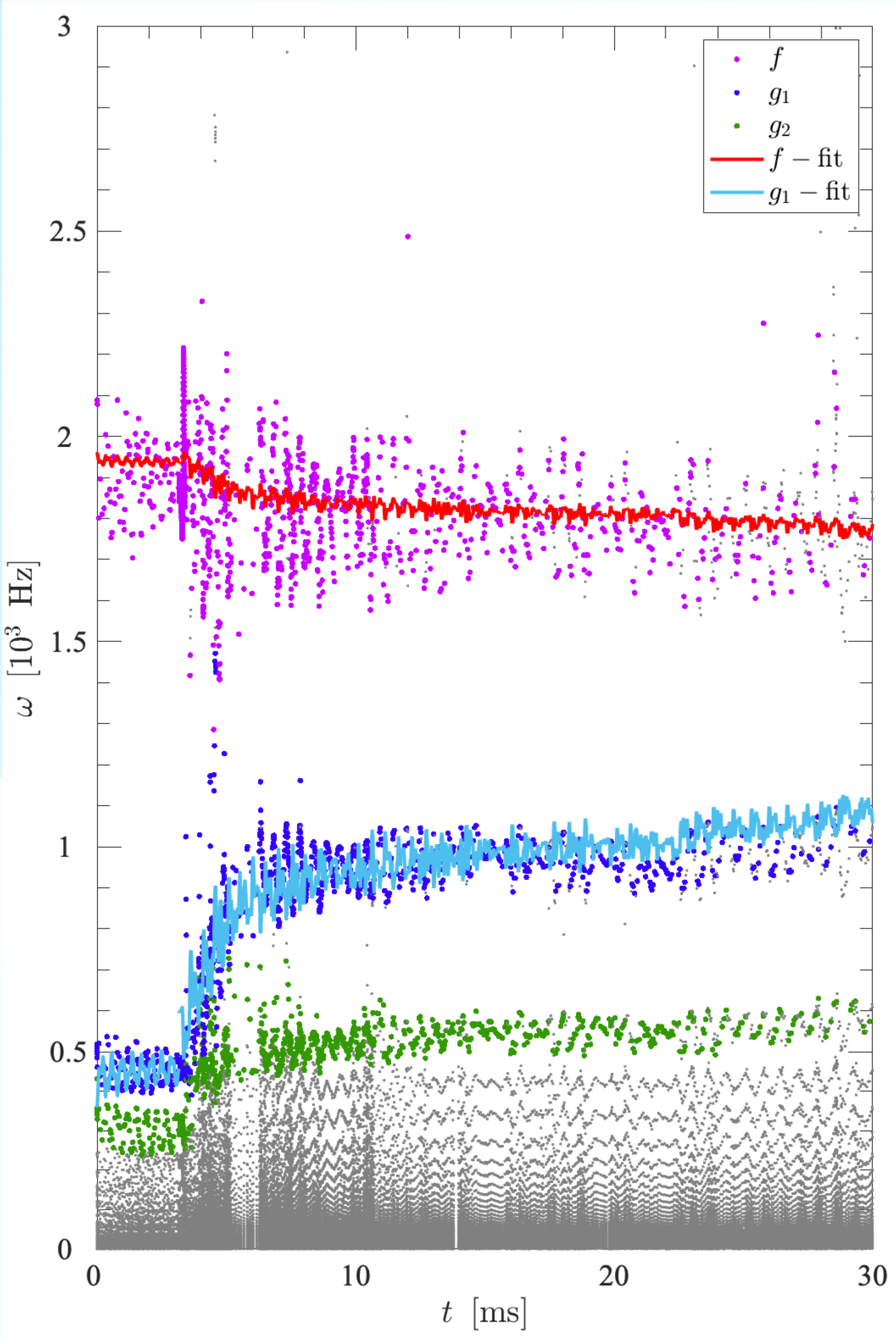
$$N^2 \approx \frac{\partial \Phi}{\partial r} \frac{1}{\rho} \left(\frac{1}{c_s^2} \frac{\partial P}{\partial r} - \frac{\partial \rho}{\partial r} \right)$$

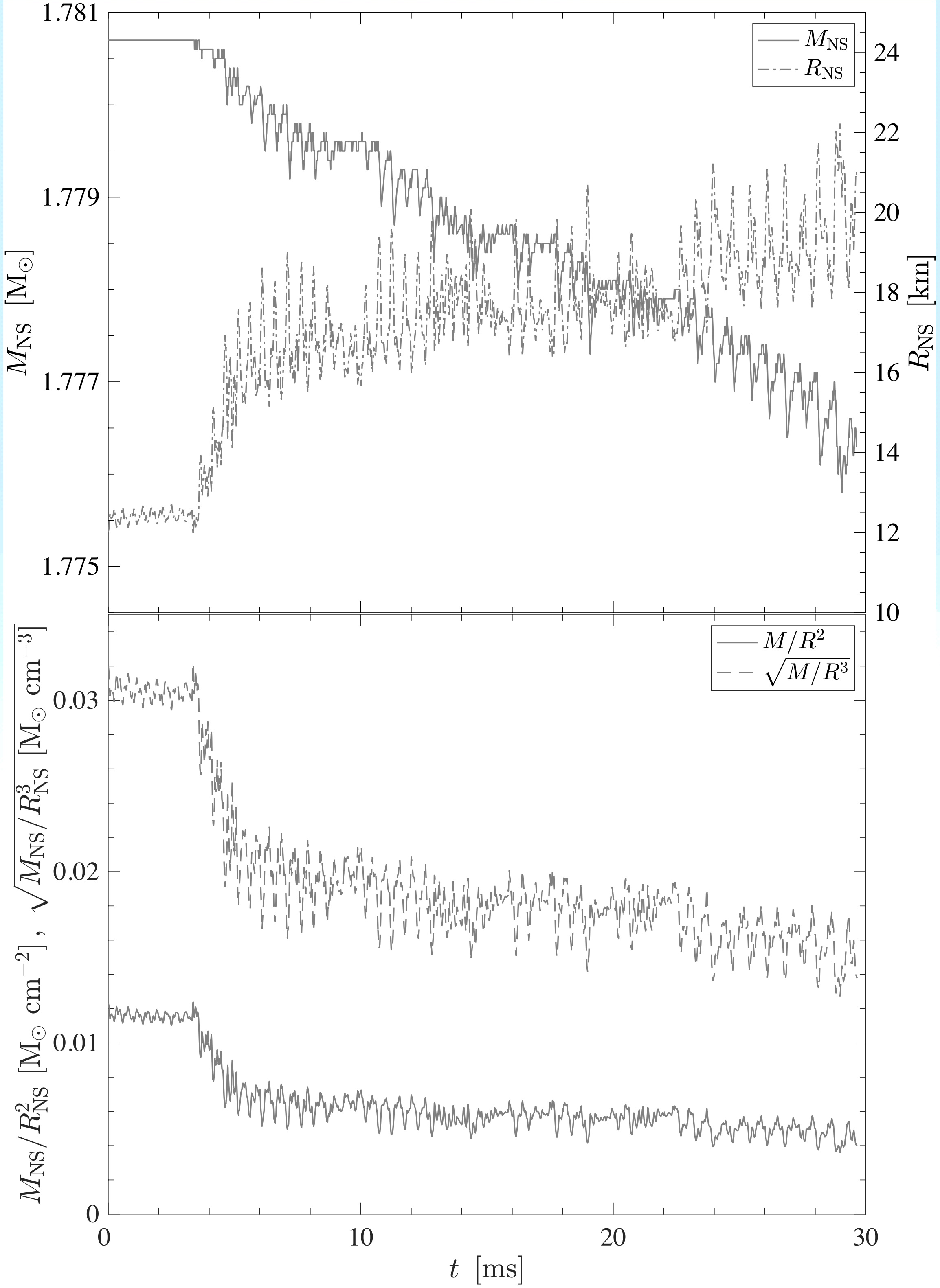
- Mode frequency

$$f \propto \frac{M}{R^2} \times \sqrt{\frac{(\Gamma - 1) m_n}{\Gamma k_b T}}$$

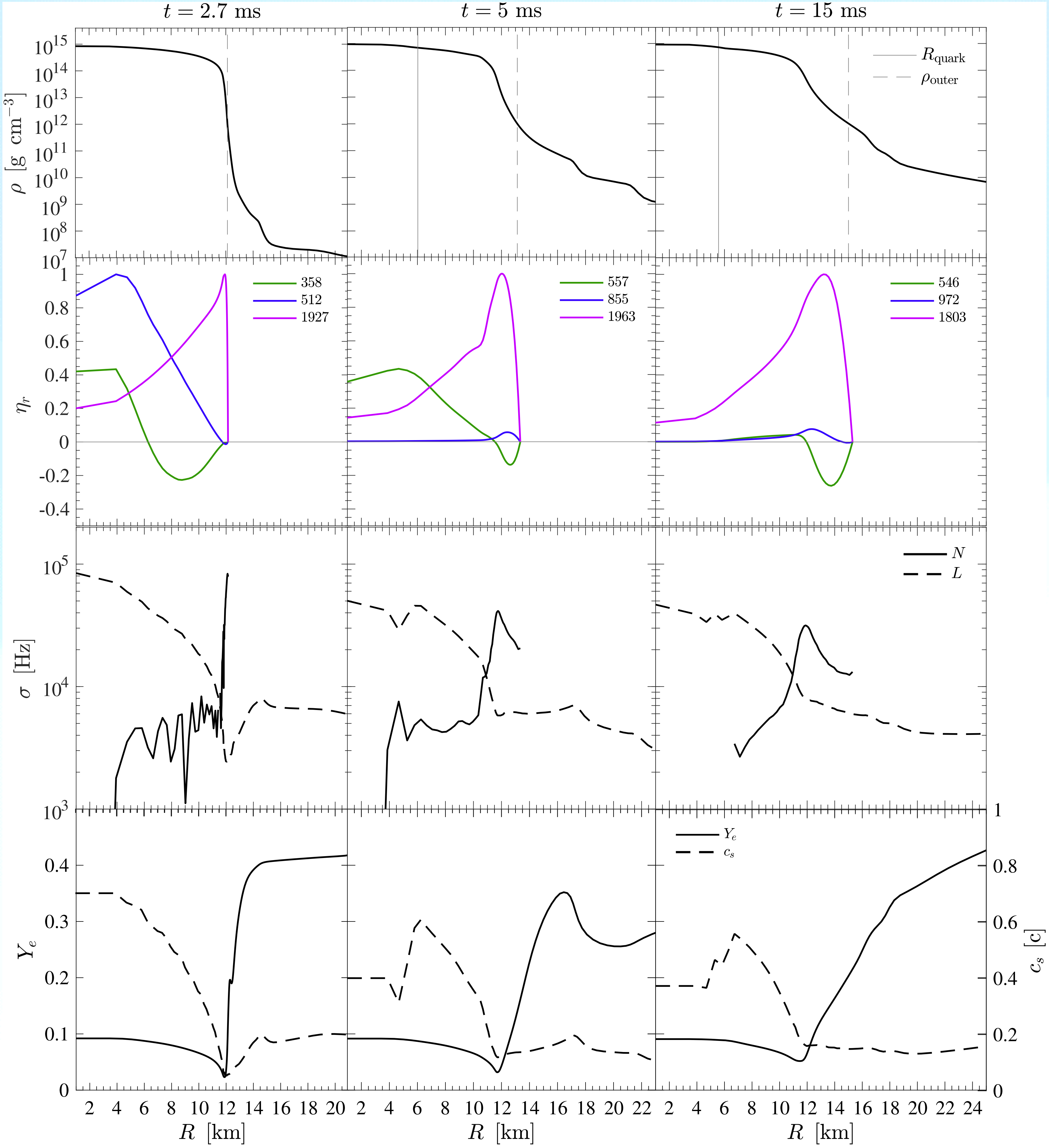
Courtesy: P. Cerda Duran

$M_{NS} = 1.55\ M_\odot$

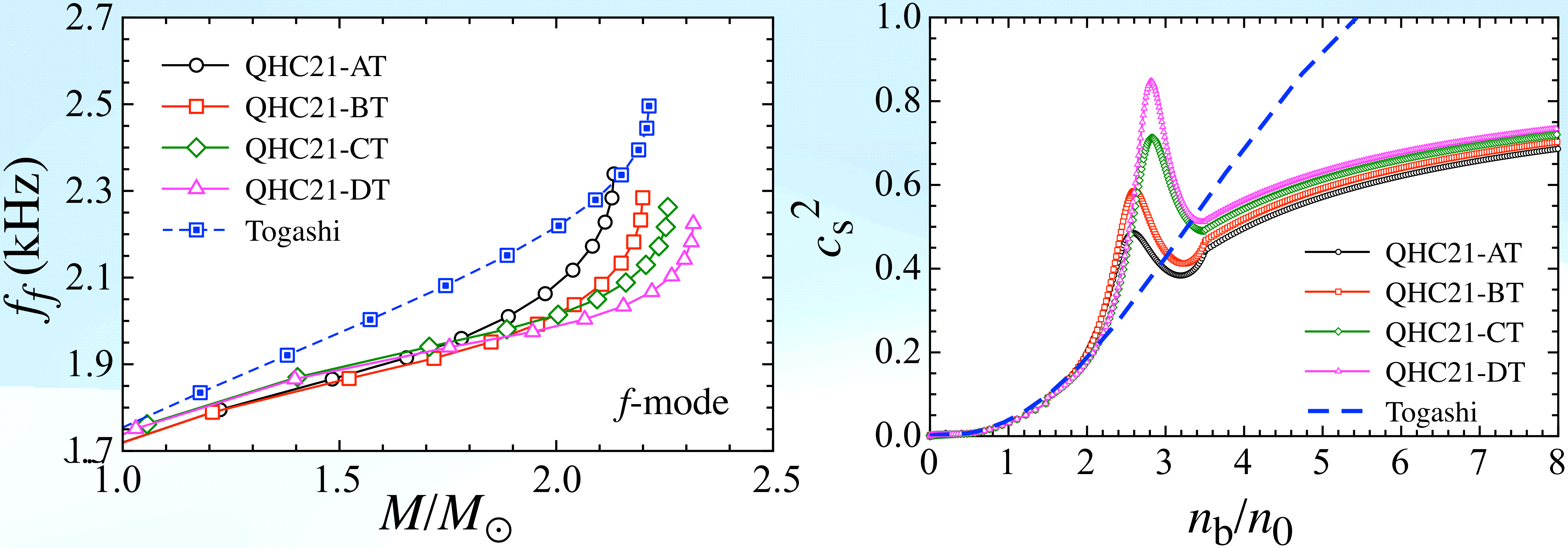




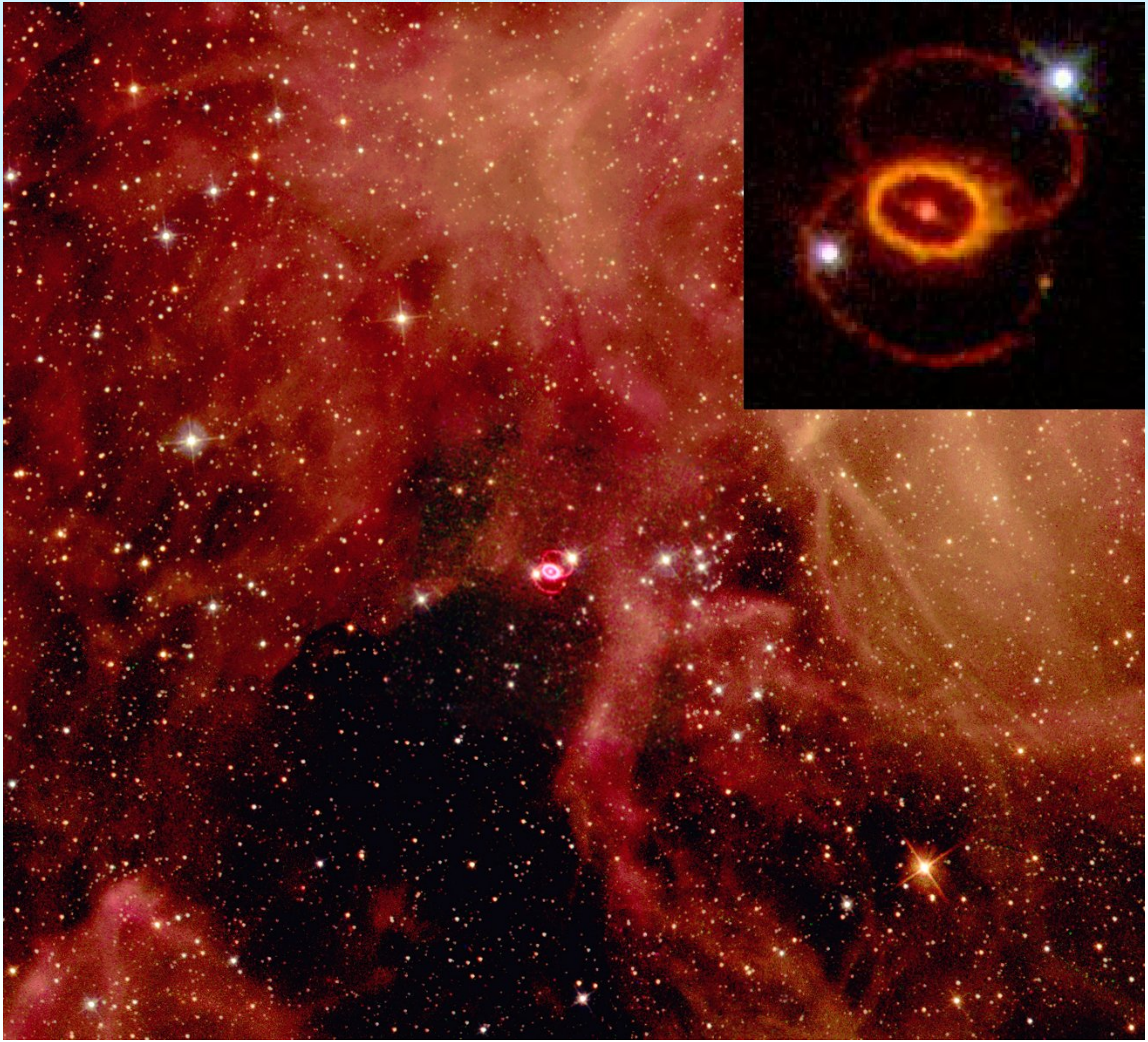
Khosravi Largani et al., A&A 687, A245 (2024)



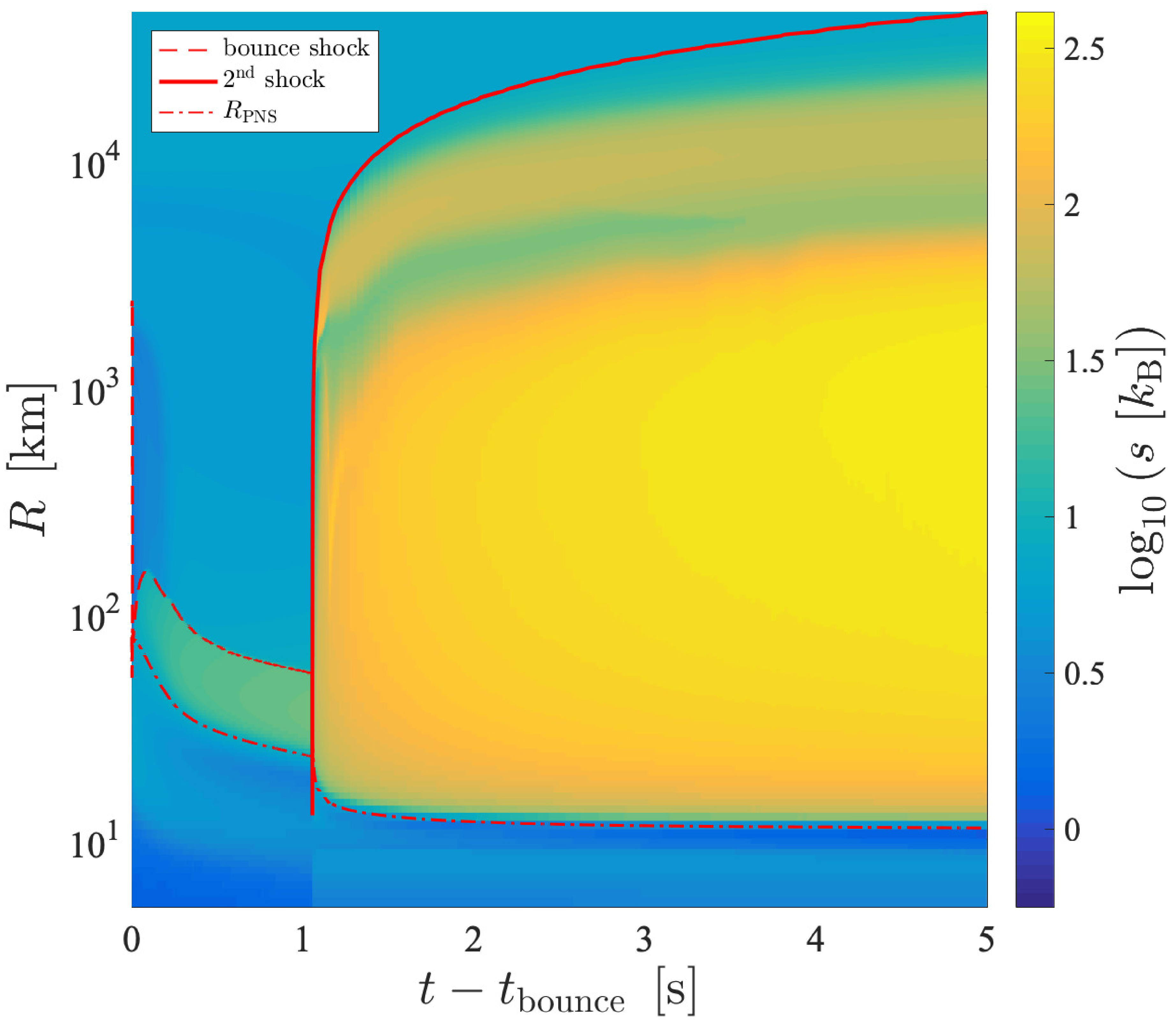
t = 2.7 ms
t = 5 ms
t = 15 ms
ρ [g cm^-3]
R_quark
ρ_outer
η_r
358
512
1927
557
855
1963
546
972
1803
σ [Hz]
N
L
Y_e
c_s
c_s [c]
R [km]
R [km]
R [km]



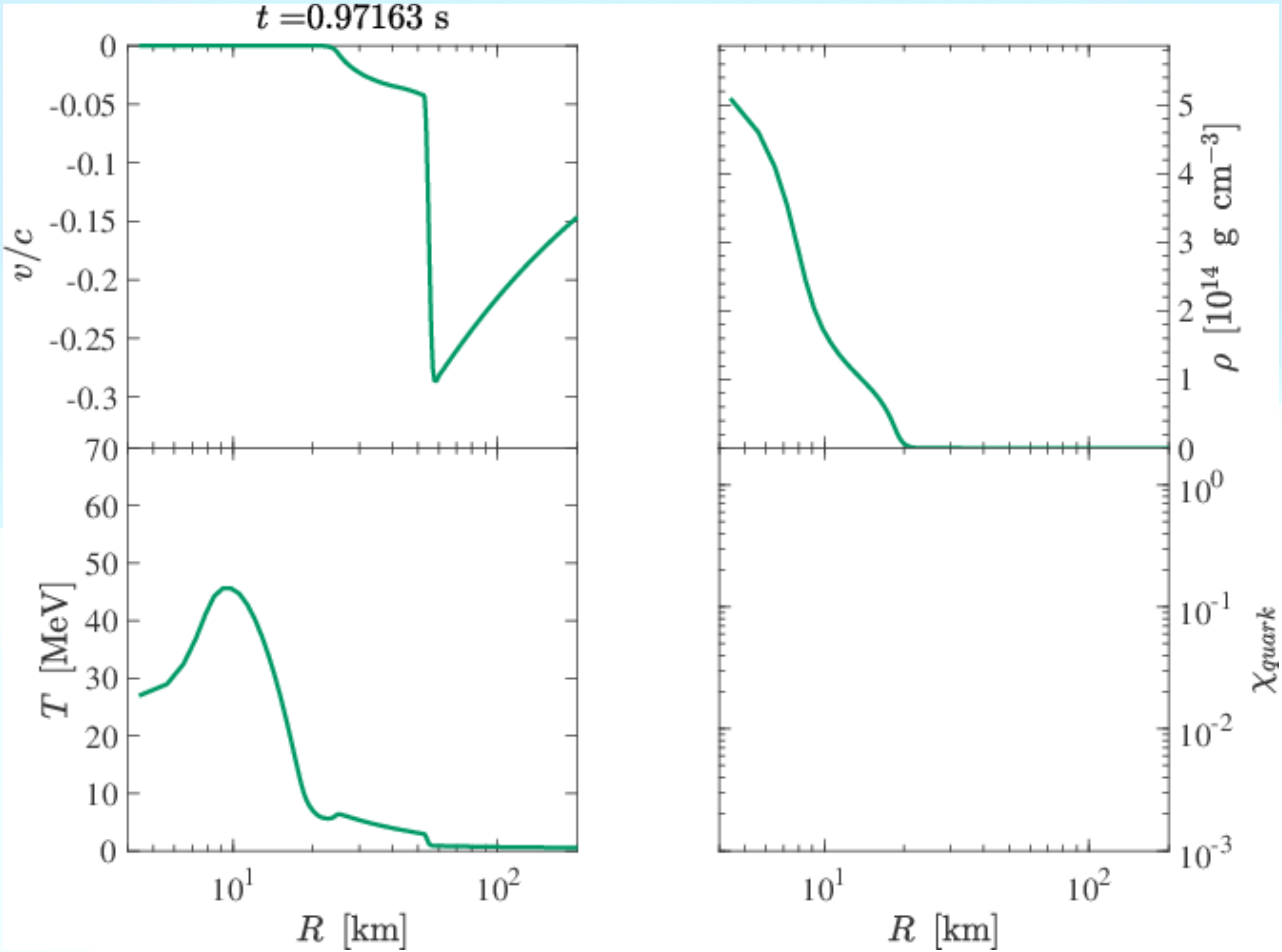
Sotani et al. Phys.Rev. D, 108, 063004 (2023)



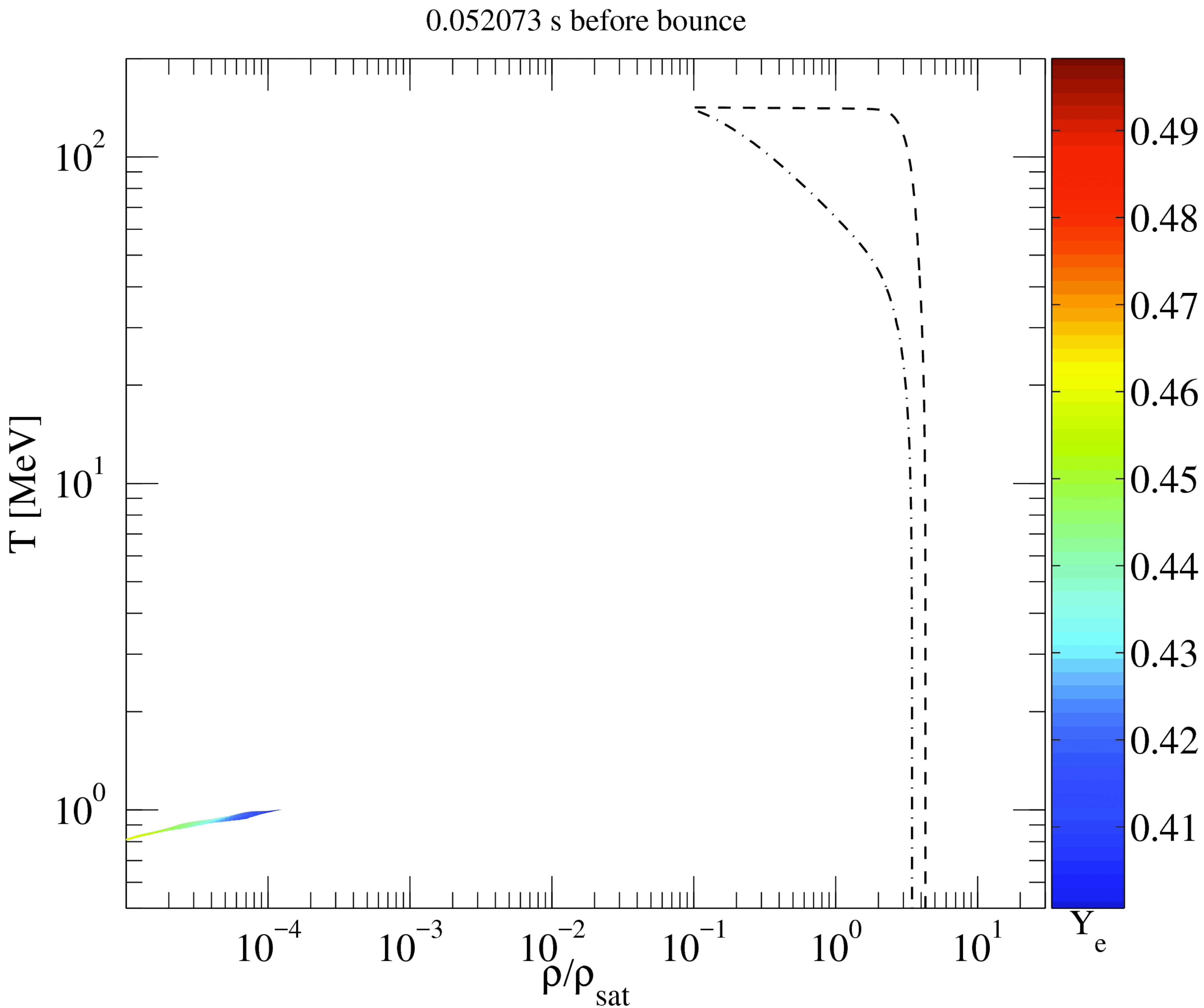
Credit: NASA images from Hubble telescope

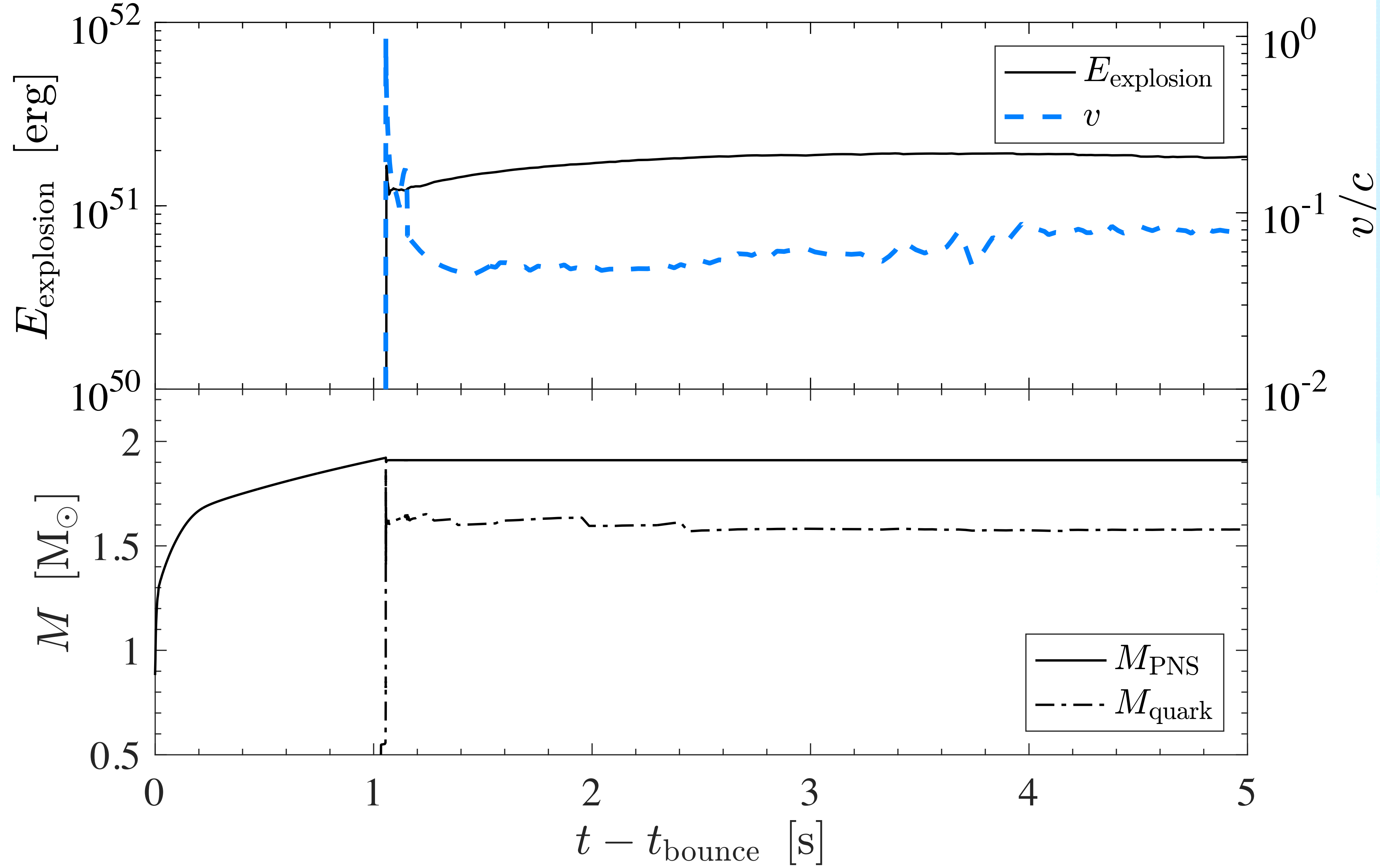


Khosravi Largani et al., ApJ 946, 143 (2024)



t =0.97163 s
v/c
0
-0.05
-0.1
-0.15
-0.2
-0.25
-0.3
ρ [10^14 g cm^-3]
5
4
3
2
1
0
T [MeV]
70
60
50
40
30
20
10
0
10^1
10^2
R [km]
χ_quark
10^0
10^-1
10^-2
10^-3
10^1
10^2
R [km]


0.052073 s before bounce
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

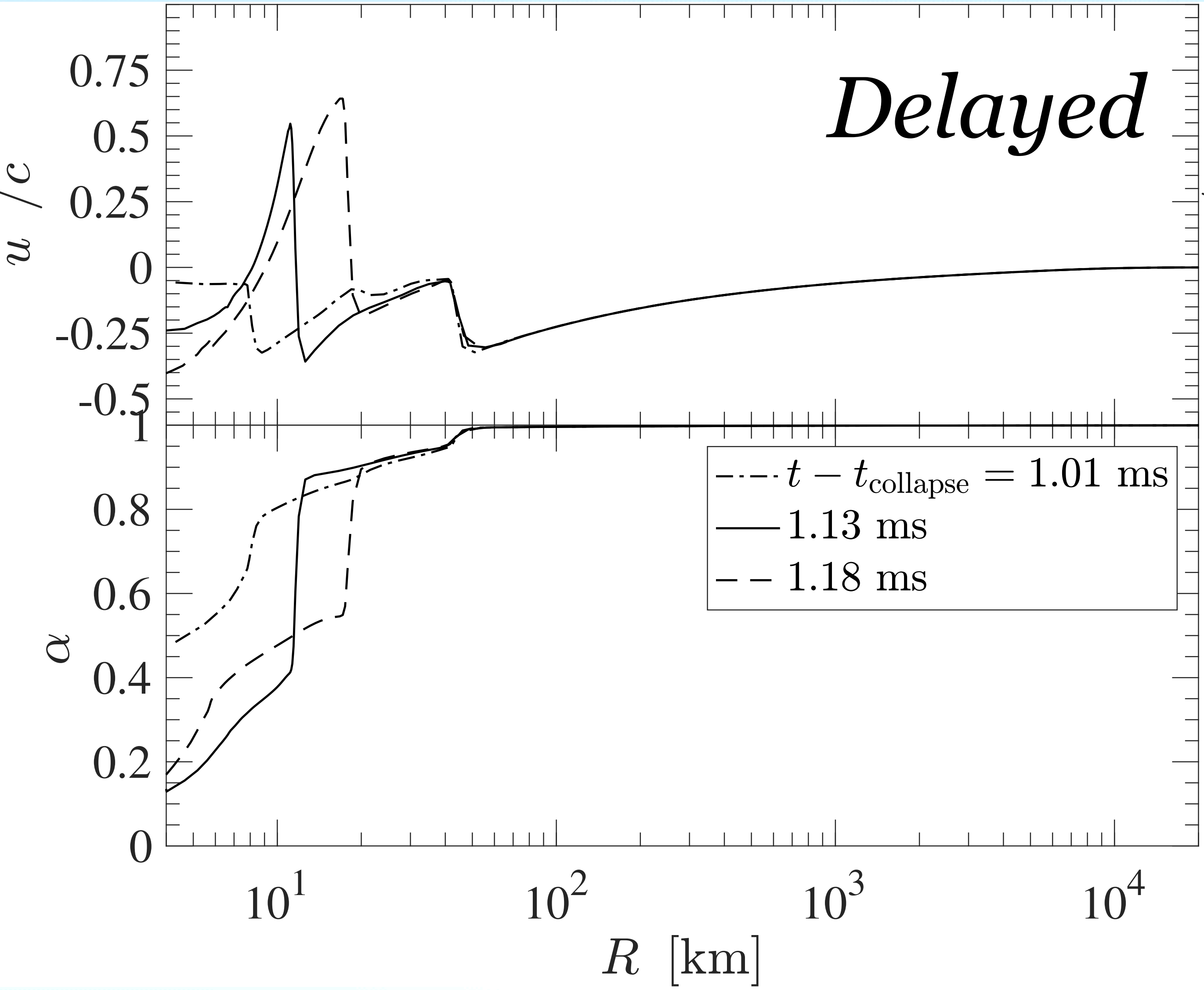


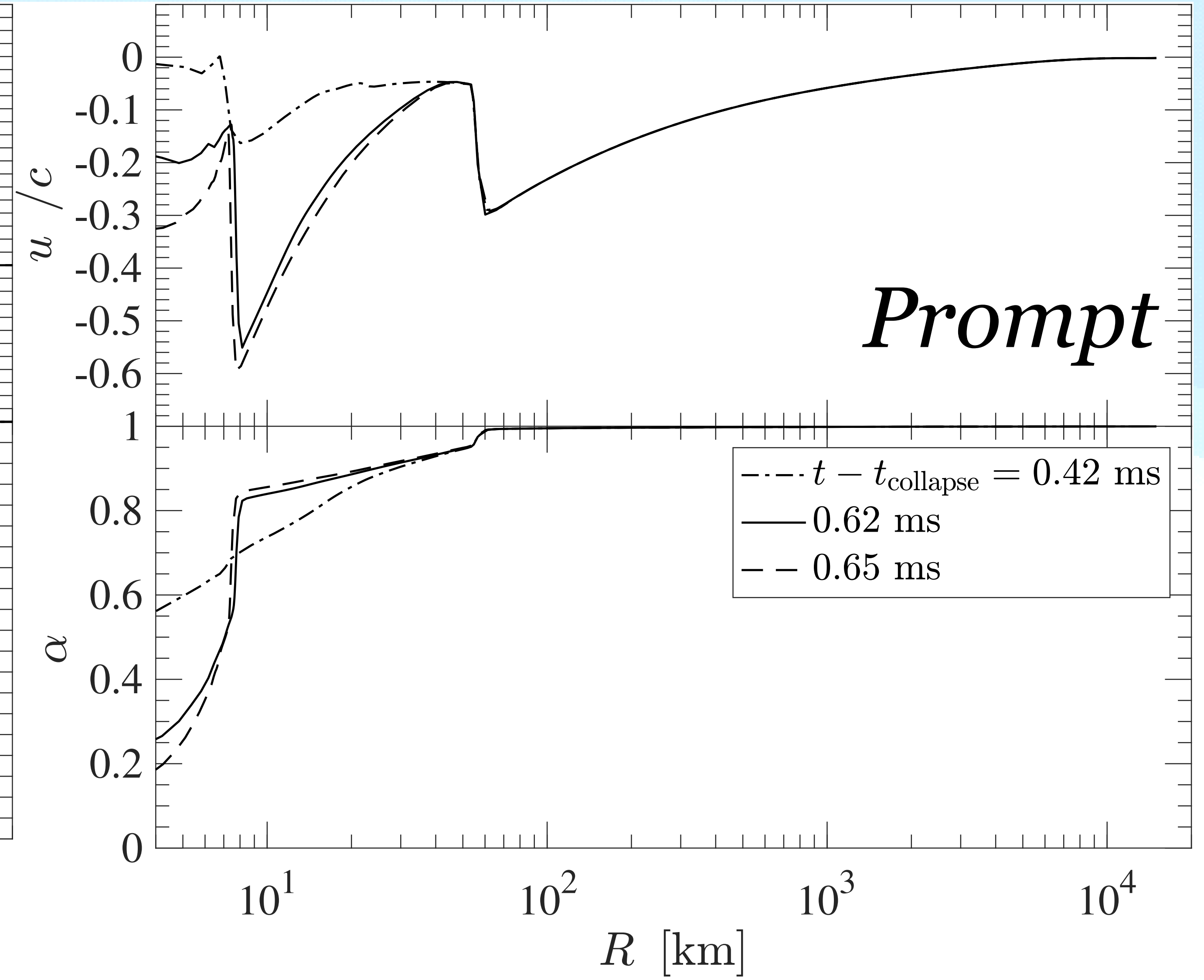
$$E_{\rm expl} = 3 \times 10^{51}\ {\rm erg}$$

$$M_{\rm NS} \simeq 2\ M_\odot$$

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

Black-hole formation: **Two distinct scenarios**

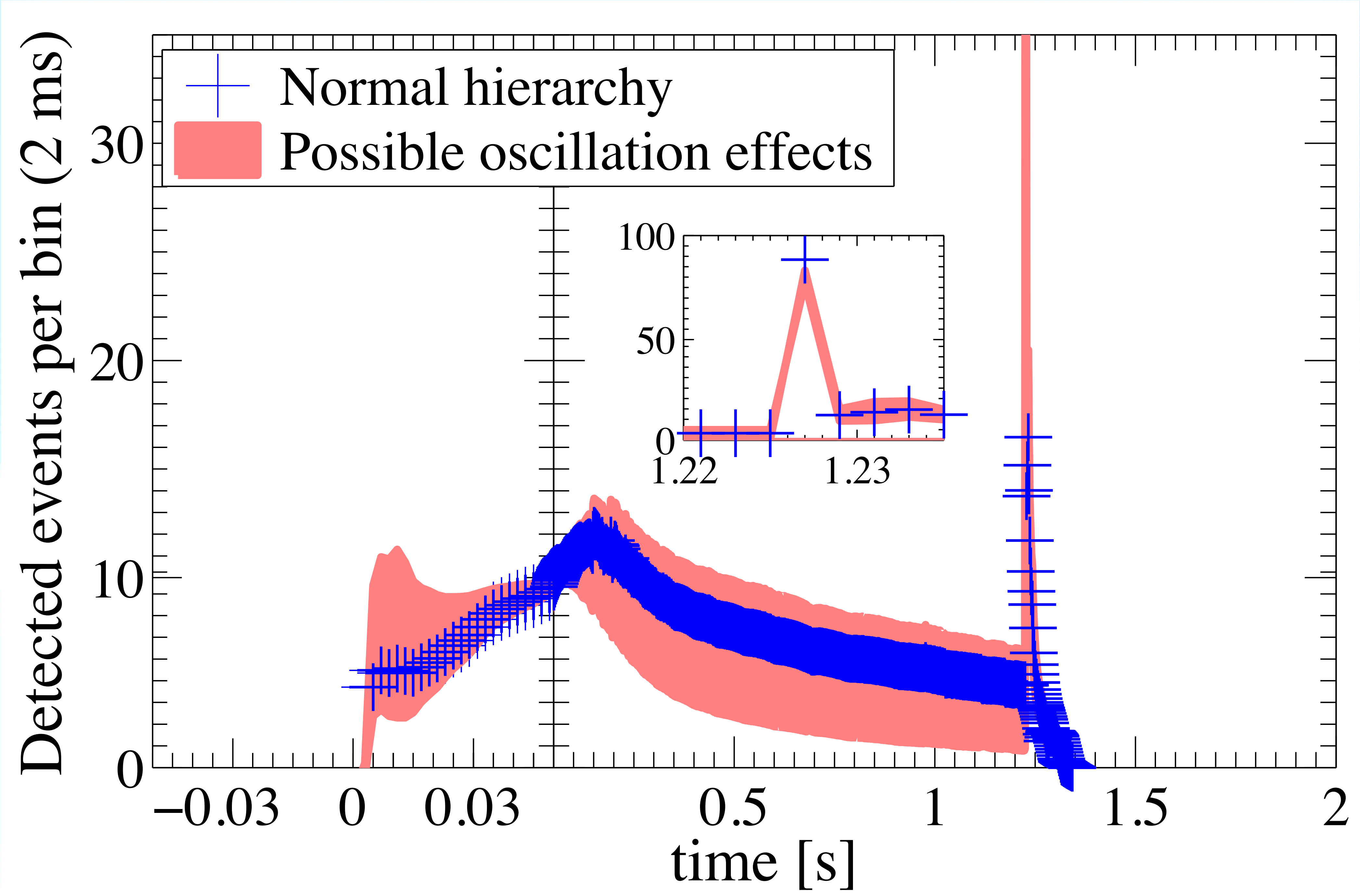




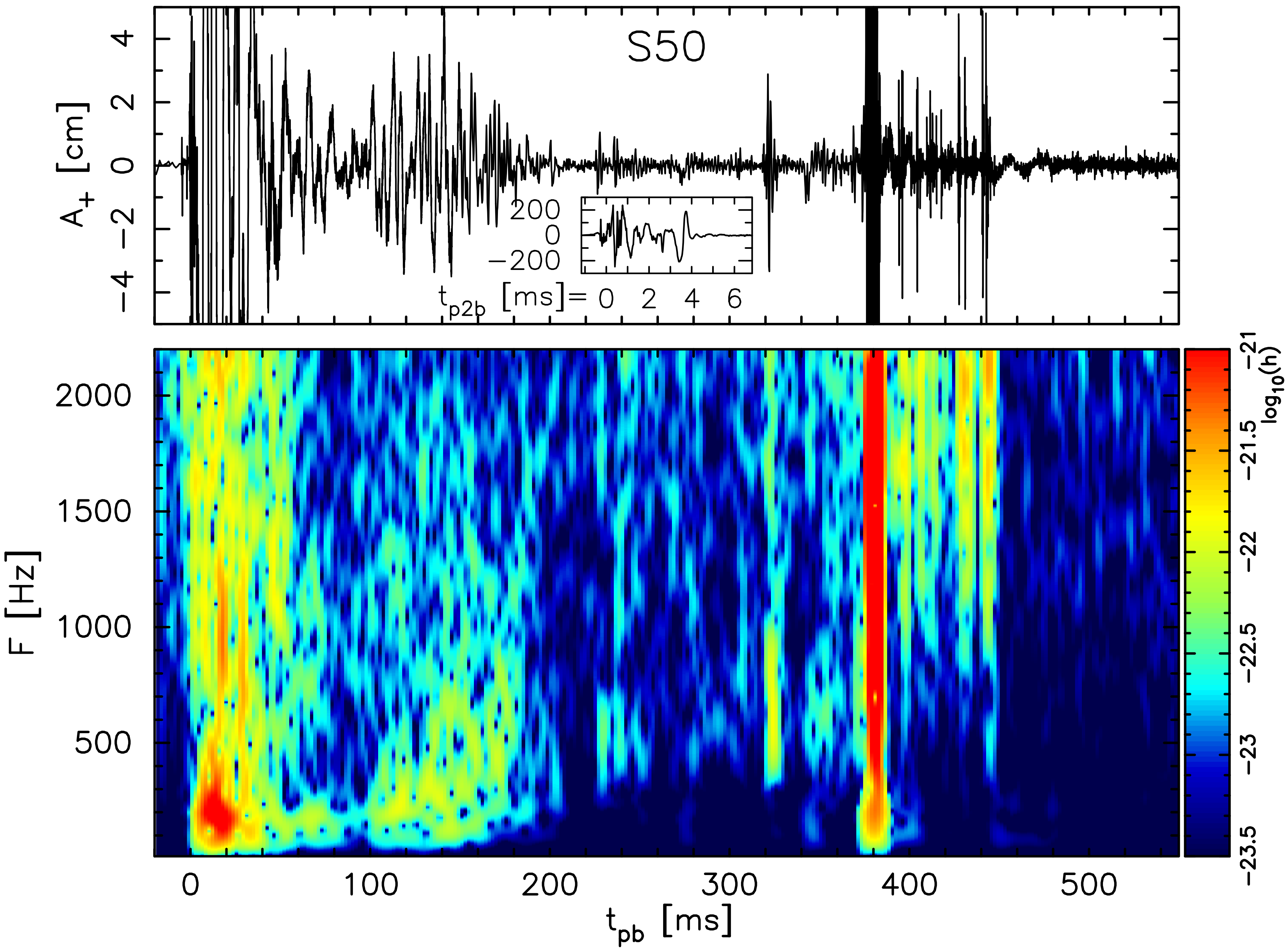
Jakobus et al., MNRAS, 516, 2554 (2022)

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

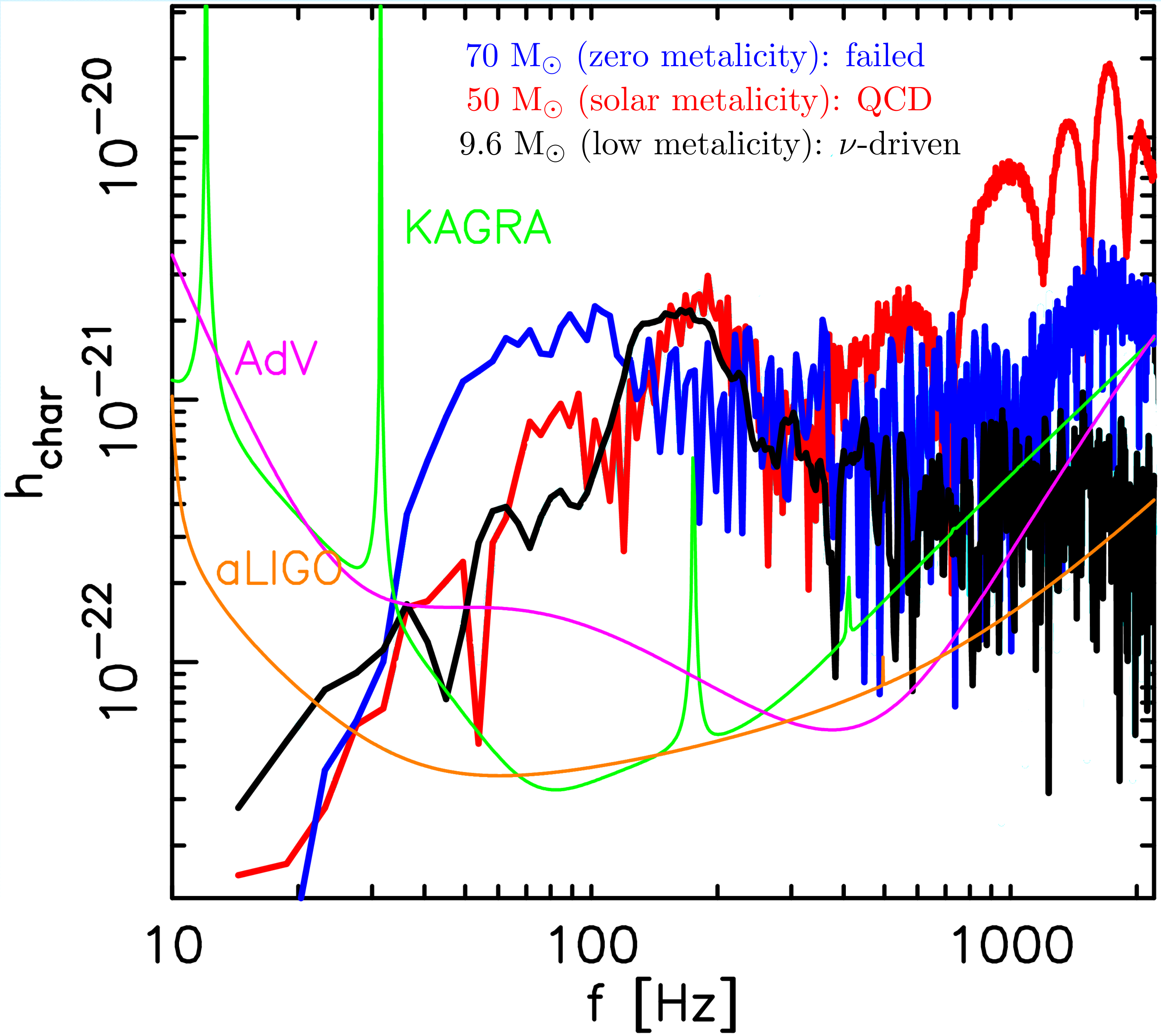
ν – signal @ Super-Kamiokande (d ~ 10 kpc)



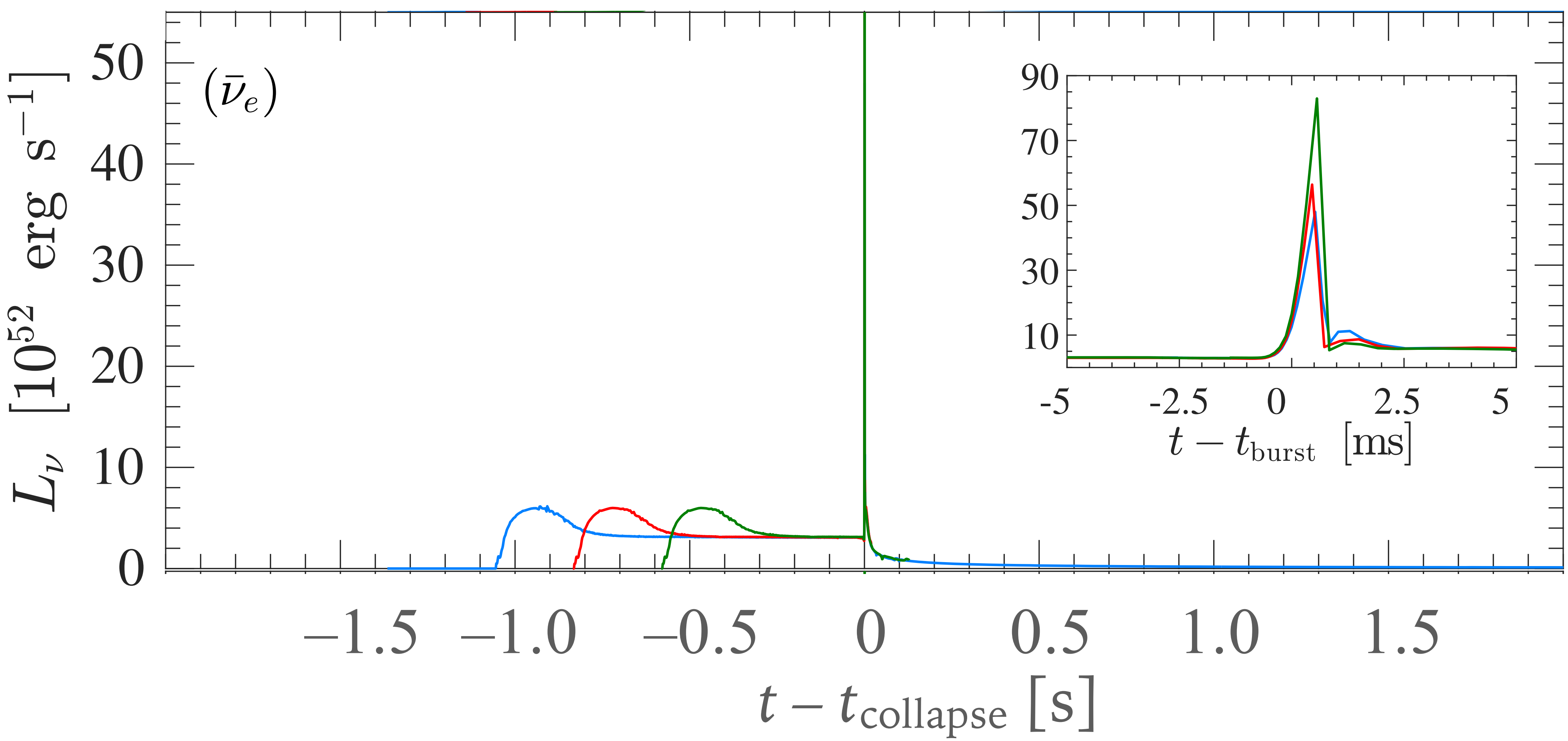
Fischer et al., Nature Astron. **2**, 980 (2018)



Kuroda et al., ApJ 924, 38 (2022)



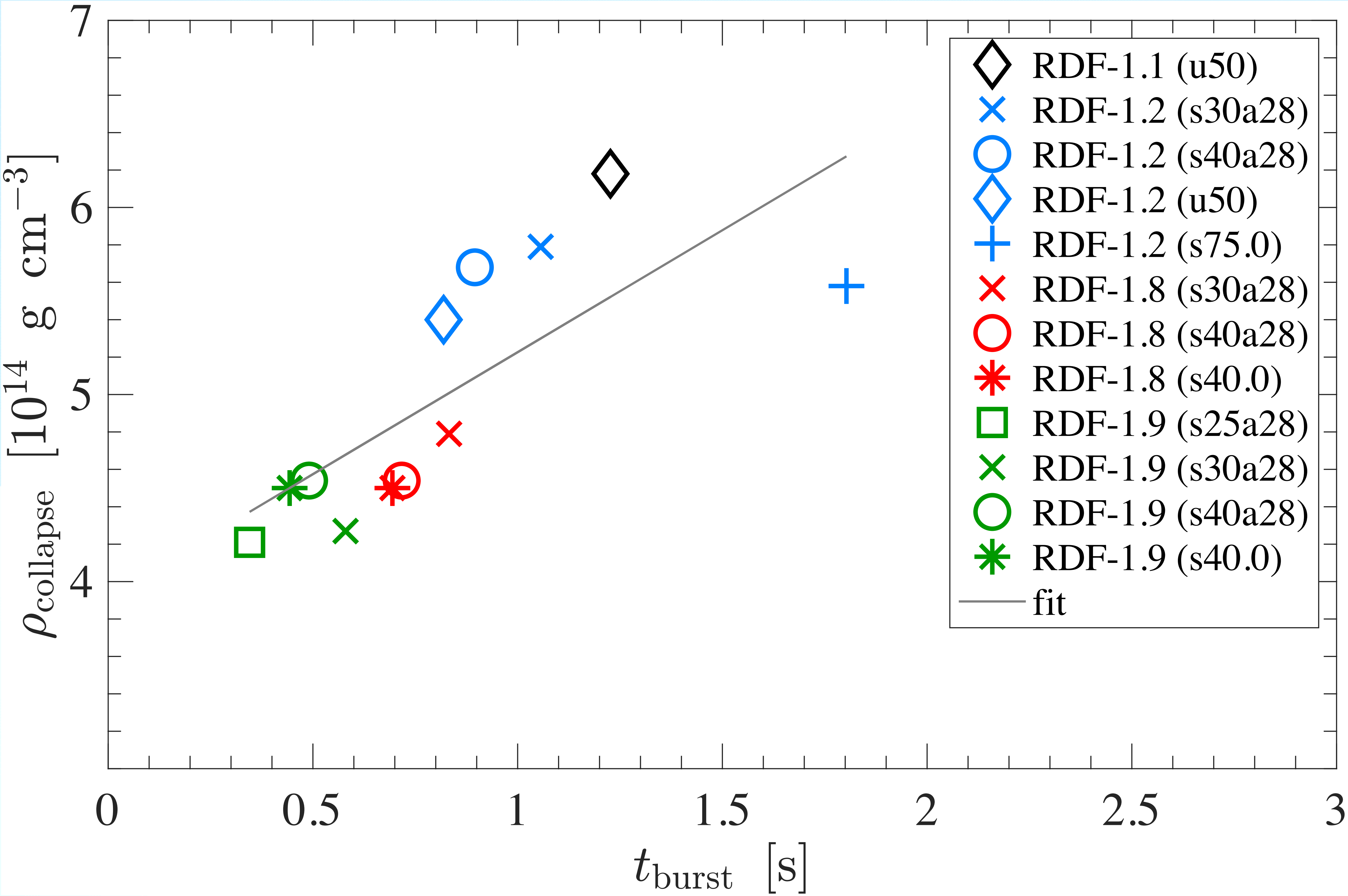
Kuroda et al., ApJ 924, 38 (2022)



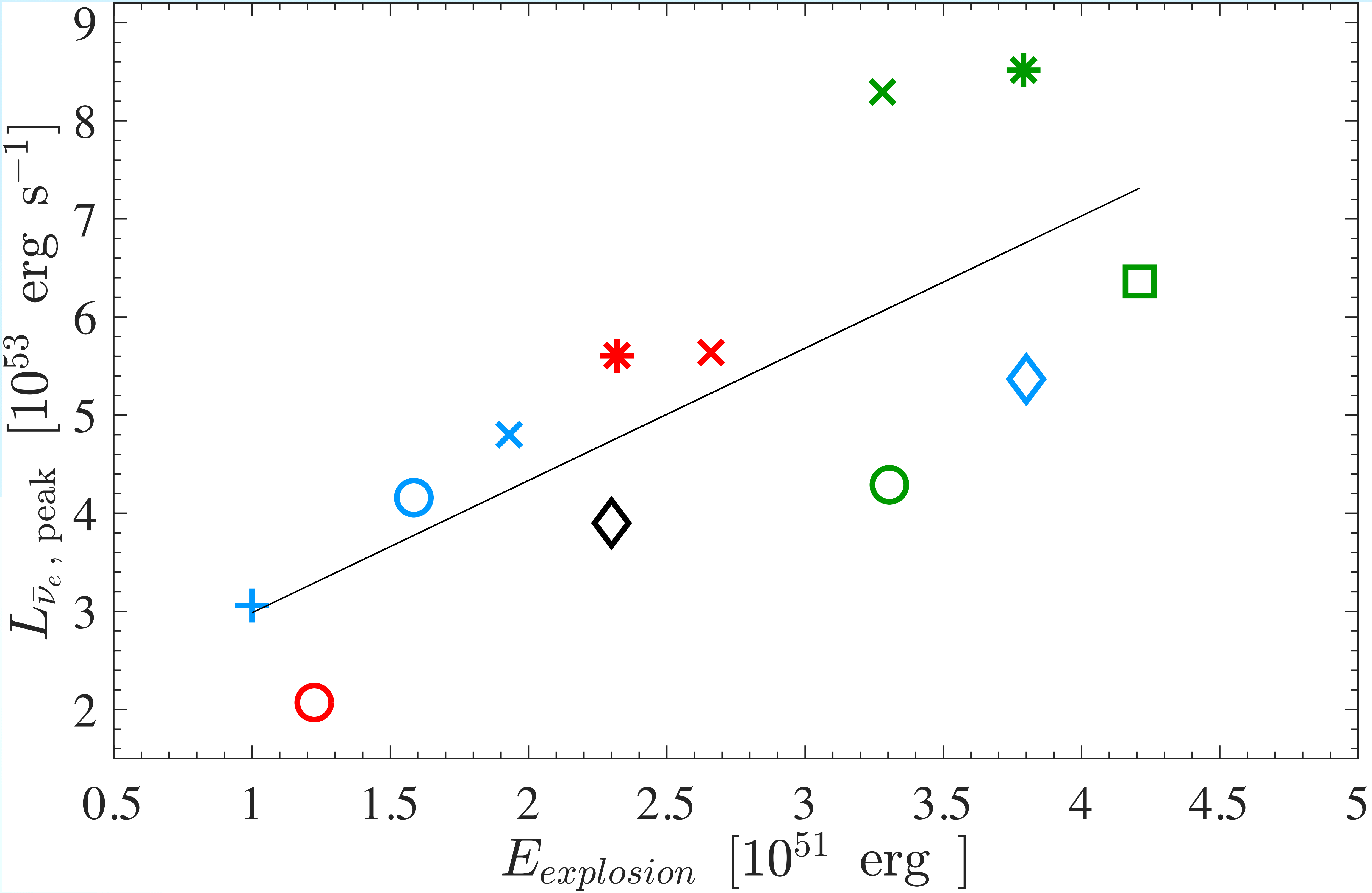
Khosravi Largani et al., ApJ 946, 143 (2024)

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]
s25a28	1.9	0.345	6.36	38.59	4.21
s30a28	1.2	1.056	4.80	56.21	1.93
s30a28	1.8	0.833	5.64	42.21	2.66
s30a28	1.9	0.580	8.30	43.49	3.28
s40a28	1.2	0.895	4.15	38.60	1.59
s40a28	1.8	0.717	2.06	35.77	1.23
s40a28	1.9	0.491	4.28	39.94	3.31
s40.0	1.8	0.694	5.61	43.03	2.32
s40.0	1.9	0.443	8.52	48.69	3.79
u50	1.1	1.227	3.90	26.55	2.3
u50	1.2	0.819	5.37	36.19	3.8
s75.0	1.2	1.803	3.06	34.35	1.0

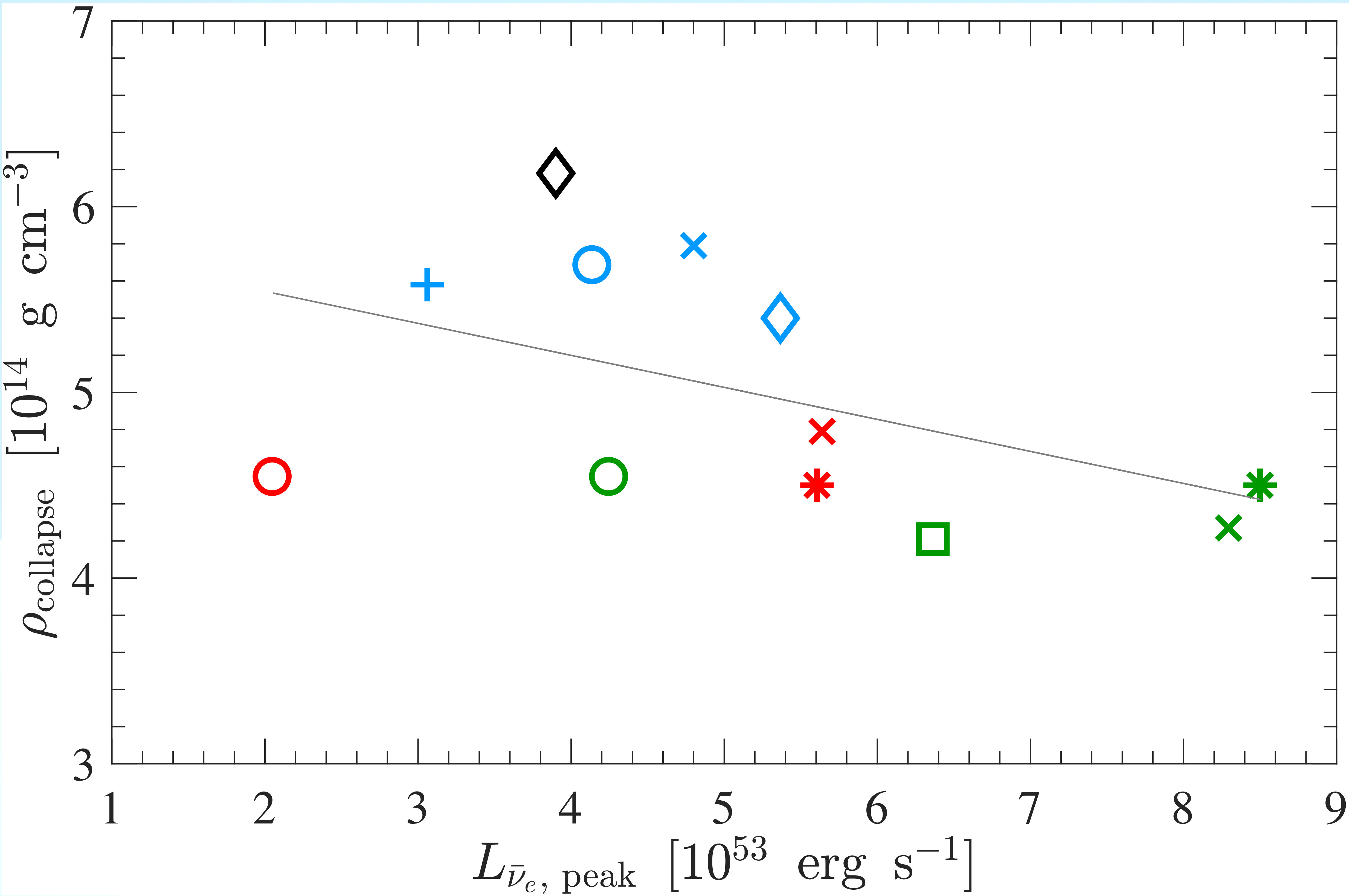
Khosravi Largani et al., ApJ 946, 143 (2024)



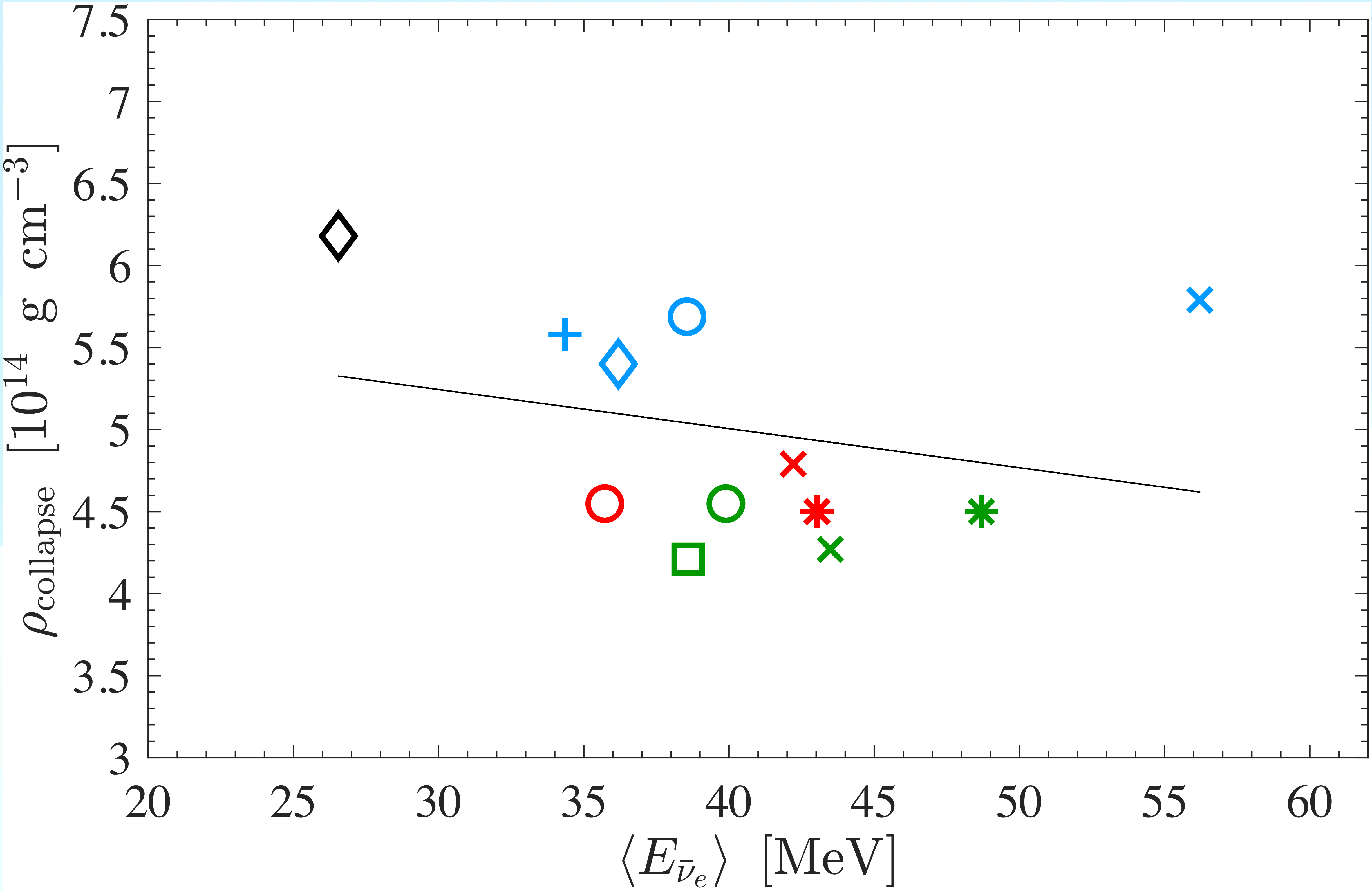
Khosravi Largani et al., ApJ 946, 143 (2024)



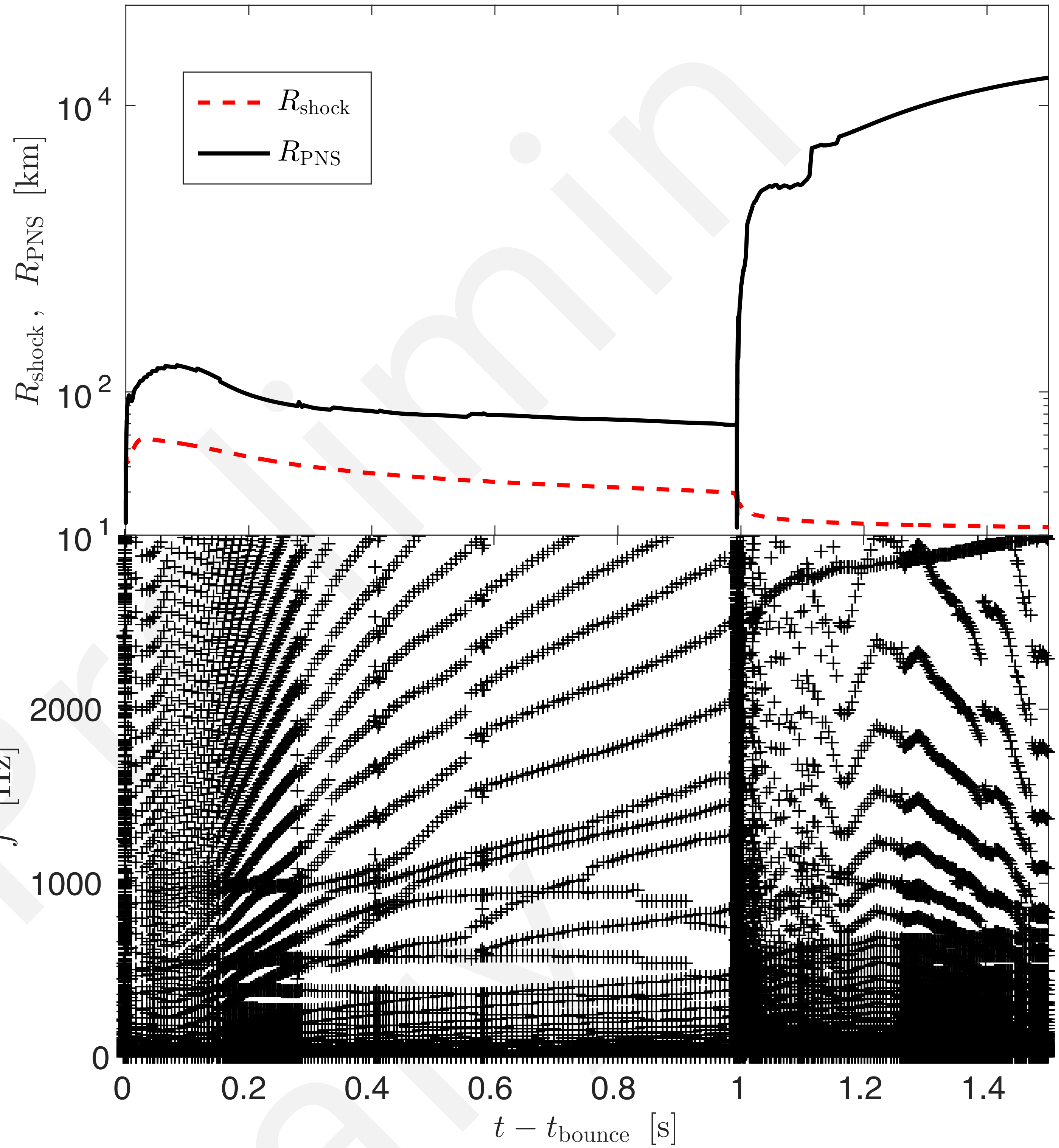
Khosravi Largani et al., ApJ 946, 143 (2024)



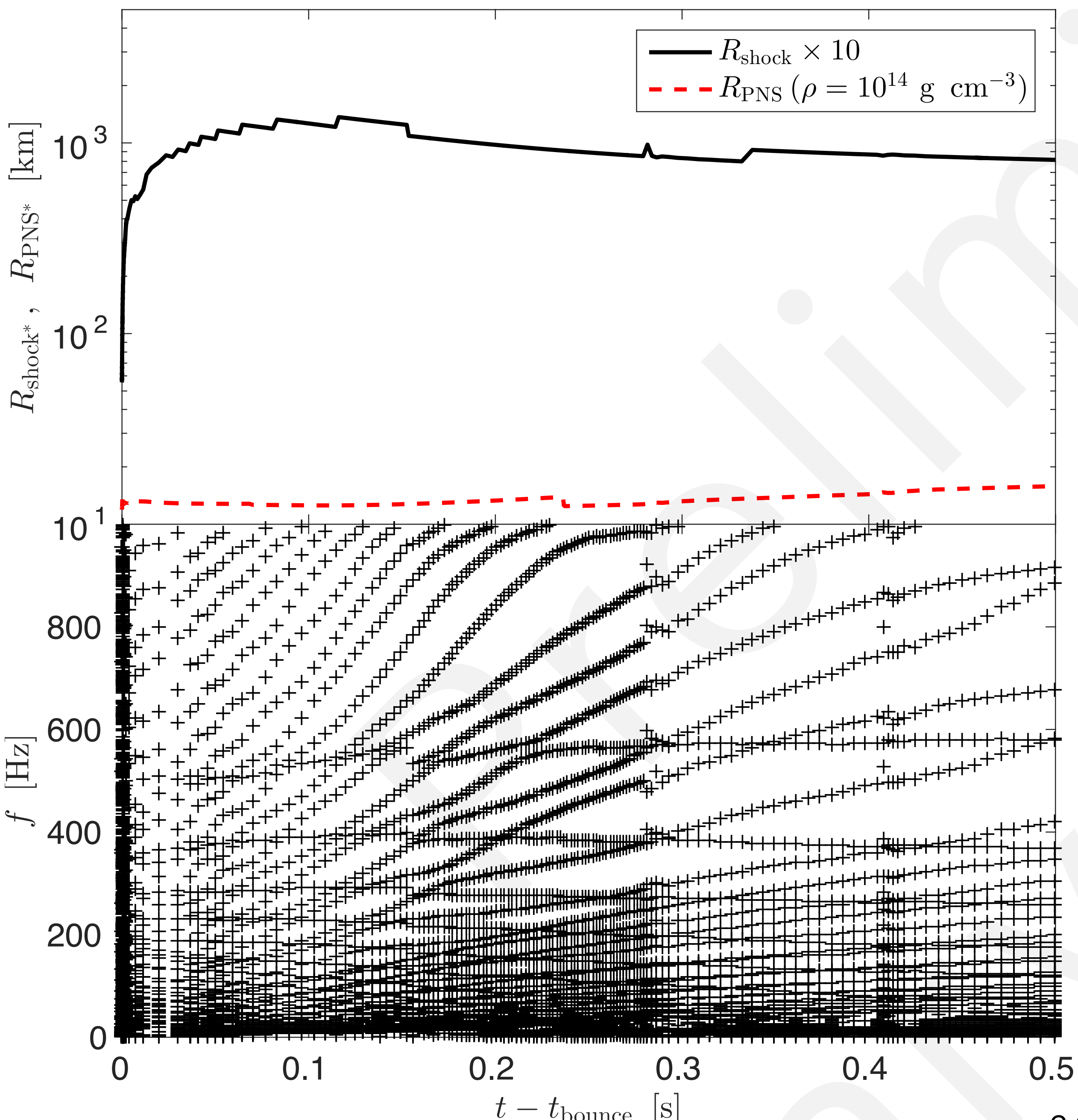
Khosravi Largani et al., ApJ 946, 143 (2024)

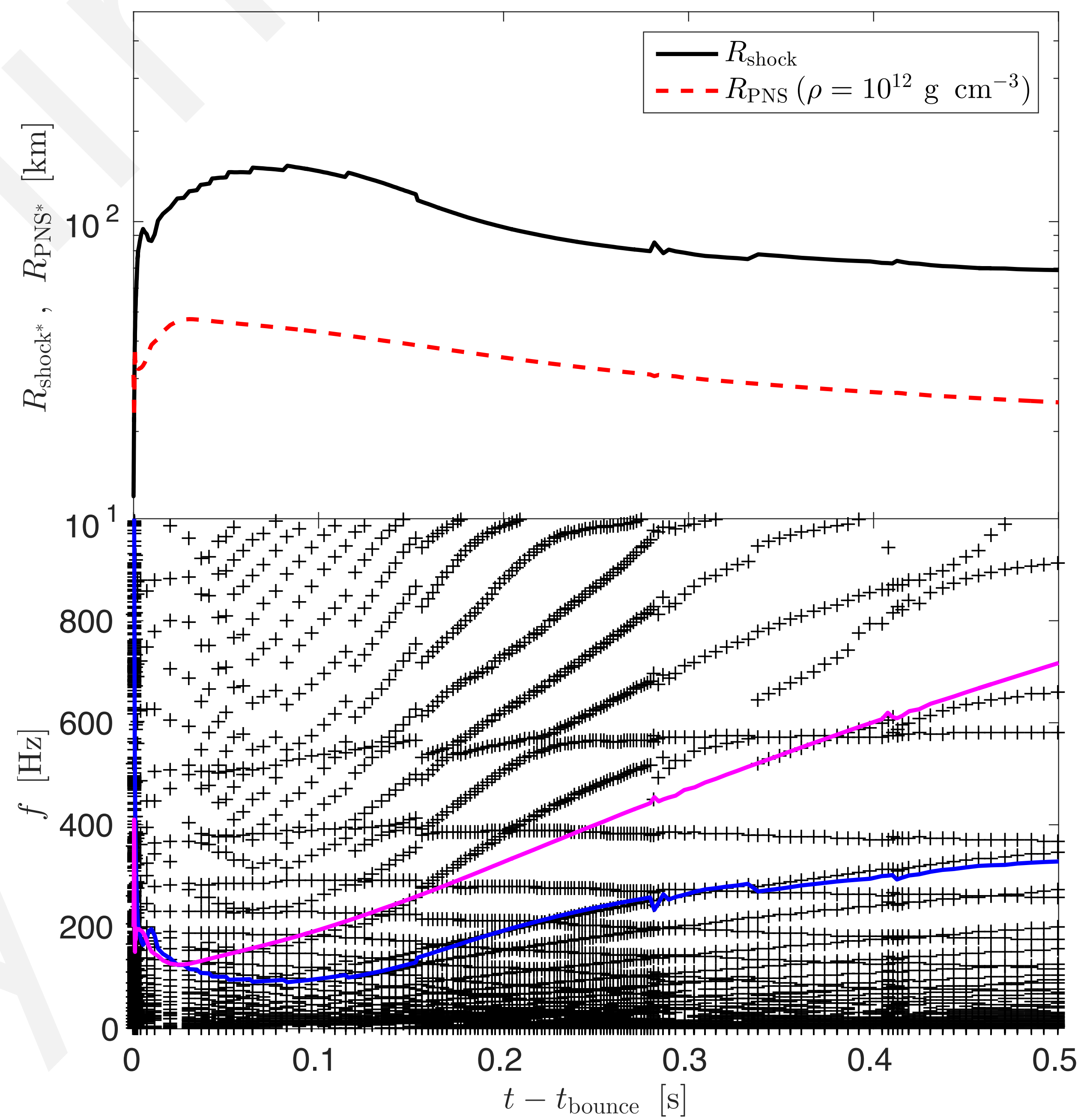


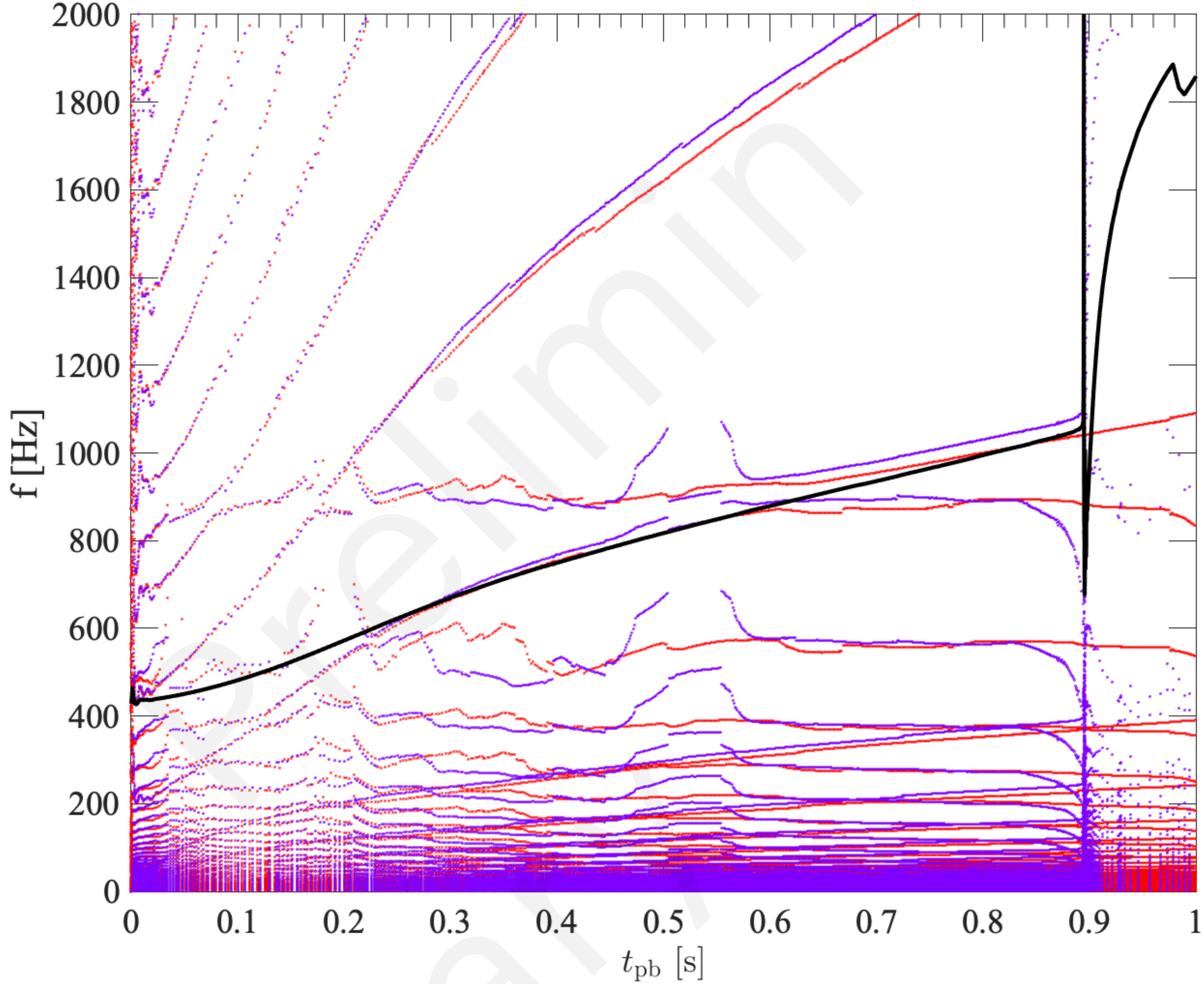
Khosravi Largani et al., ApJ 946, 143 (2024)

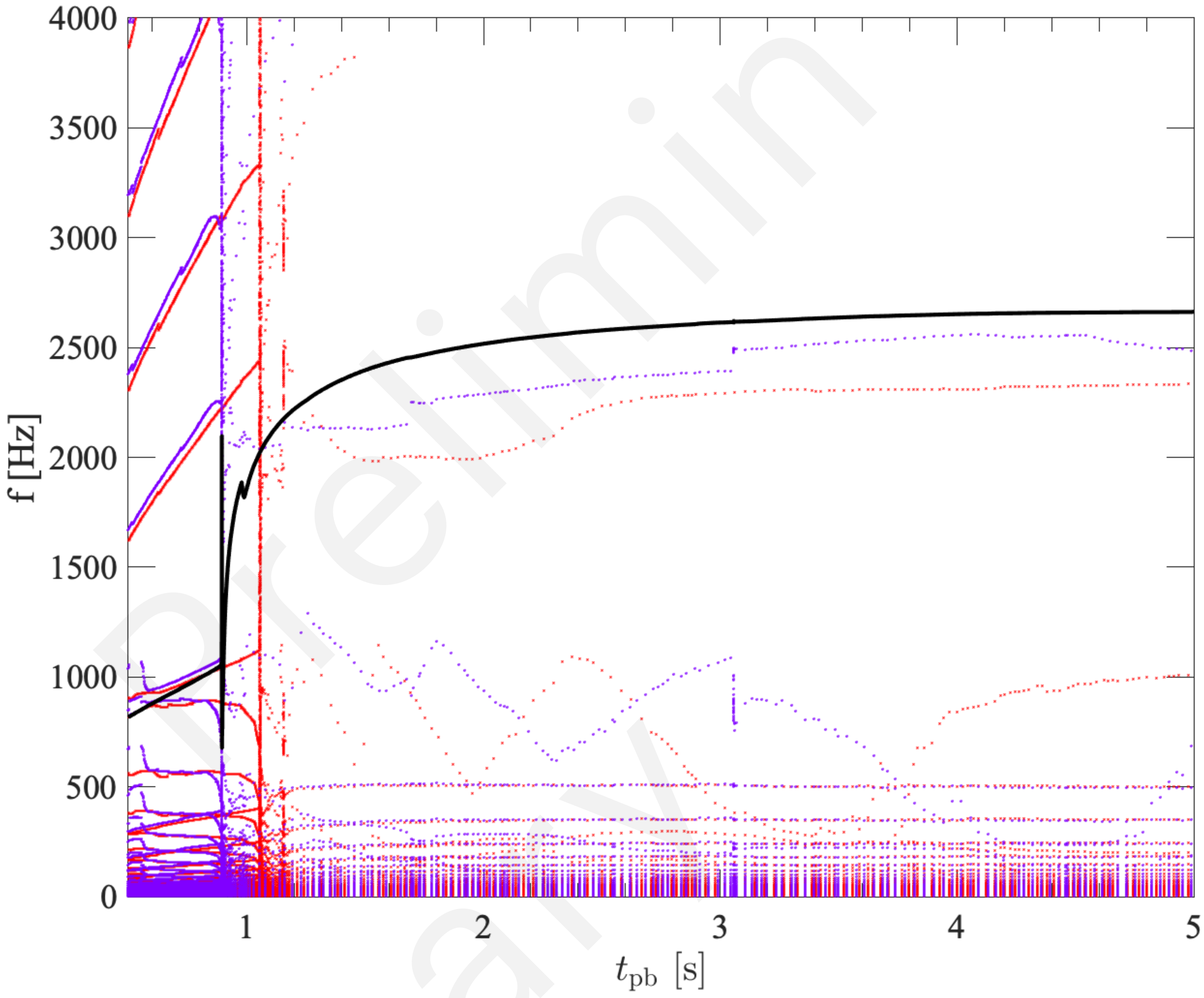


$R_{\rm shock}$
$R_{\rm PNS}$
$R_{\rm shock}\,,\;\;R_{\rm PNS}$ [km]
10^4
10^2
10^1
f [Hz]
2000
1000
0
0.2
0.4
0.6
0.8
1
1.2
1.4
$t - t_{\rm bounce}$ [s]


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


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


2000
1800
1600
1400
1200
1000
800
600
400
200
0
f [Hz]
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
t_{pb} [s]



4000
3500
3000
2500
2000
1500
1000
500
0
f [Hz]
1
2
3
4
5
$t_{\rm pb}$ [s]

Thank you