# *Simulations of massive star explosions driven by a first-order QCD phase transition Neutrino signal and gravitational wave mode analysis*


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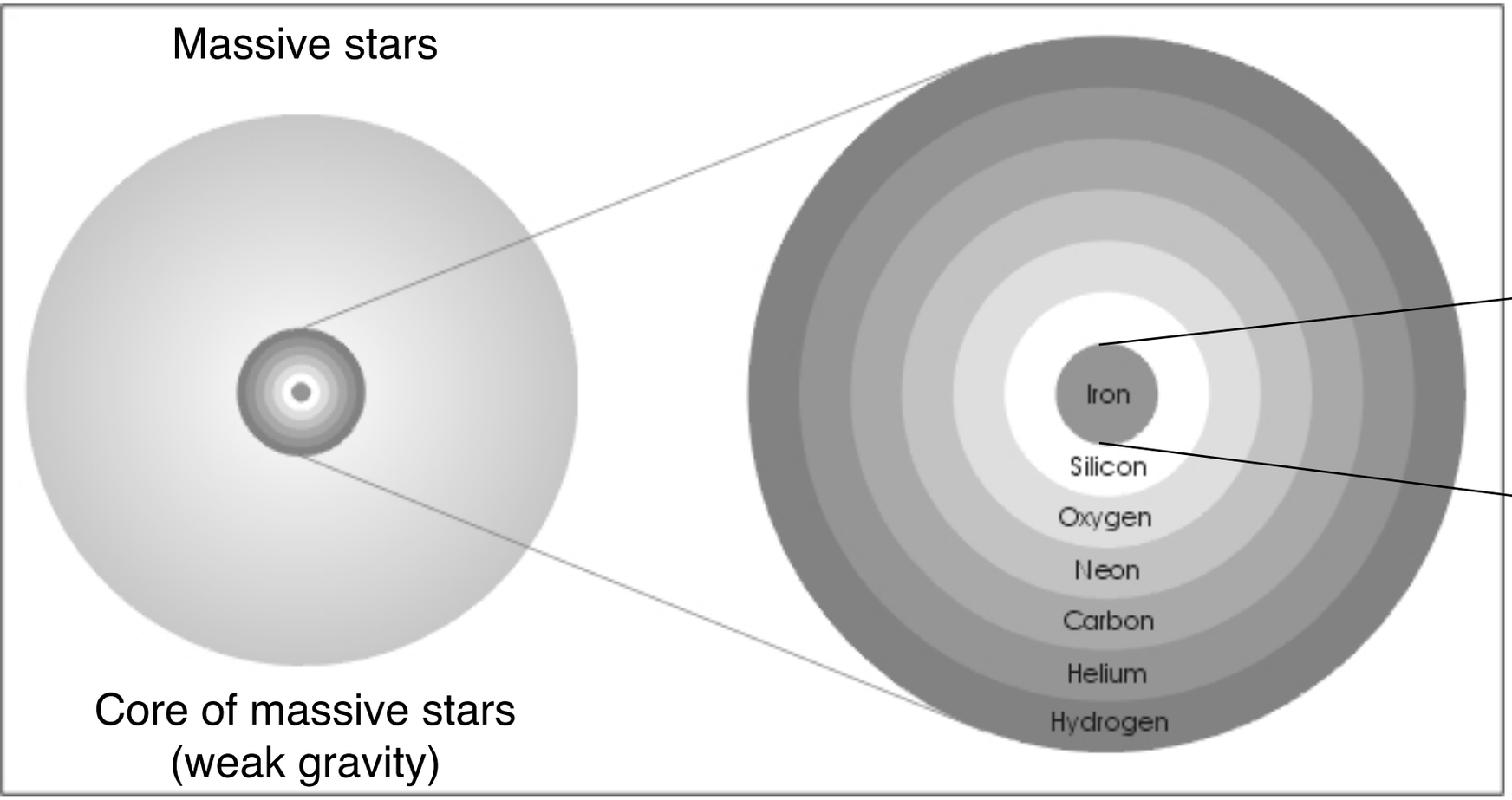
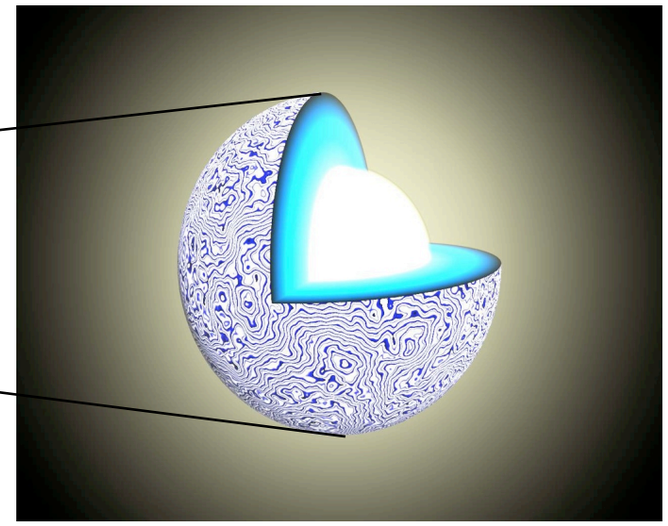
*Various Faces of QCD Symposium,*

*April 2024, Wroclaw*

# Global Picture




(Proto)neutron stars
(very strong gravity)



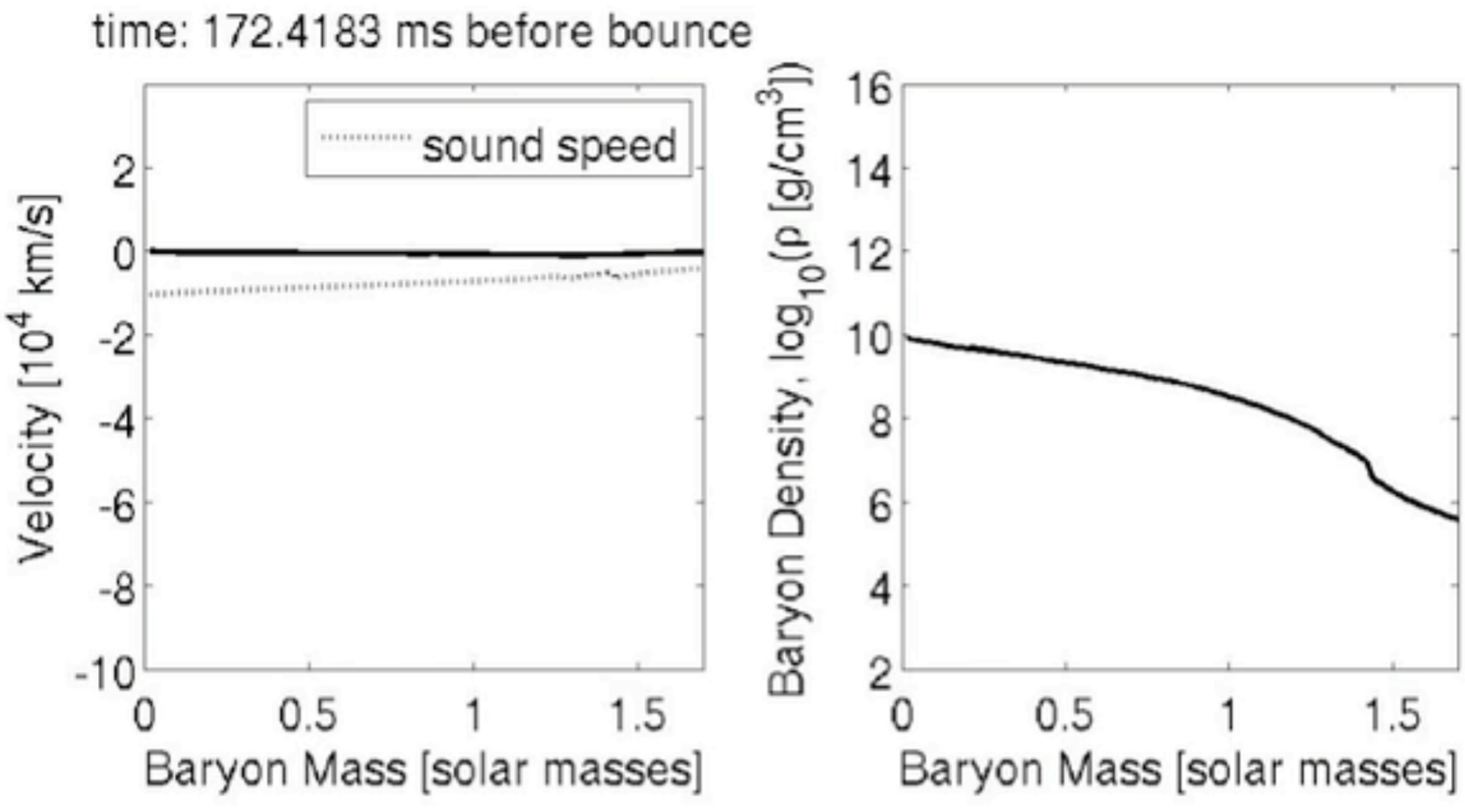
Energy released: $\triangle E_G \simeq 3 - 6 \times 10^{53}$ erg $\longrightarrow (\nu_e, \bar{\nu}_e, \nu_{\mu/\tau}, \bar{\nu}_{\mu/\tau})$

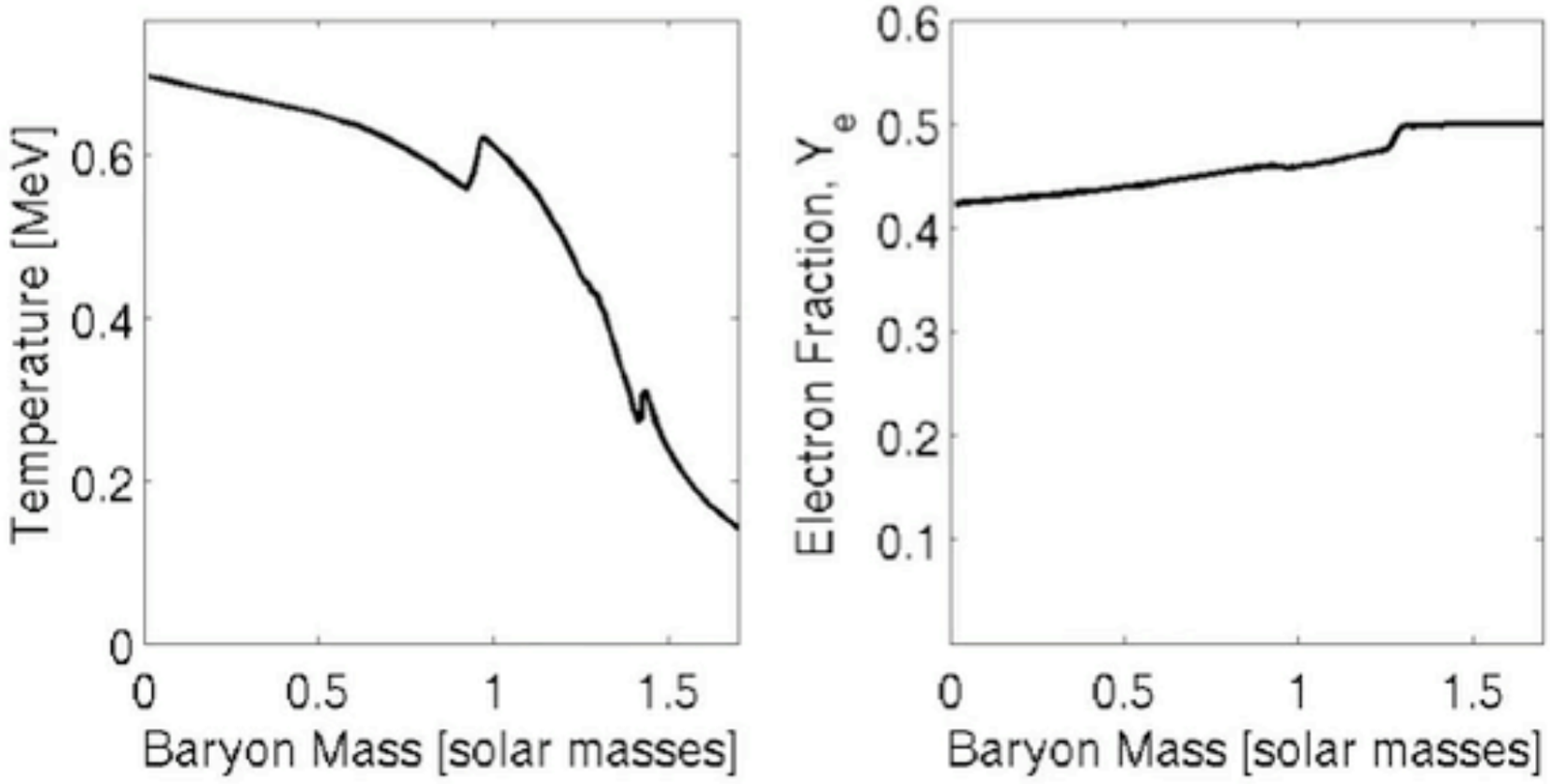
(Proto)neutron star is a hot and isospin asymmetric “heavy nucleus” with large atomic mass

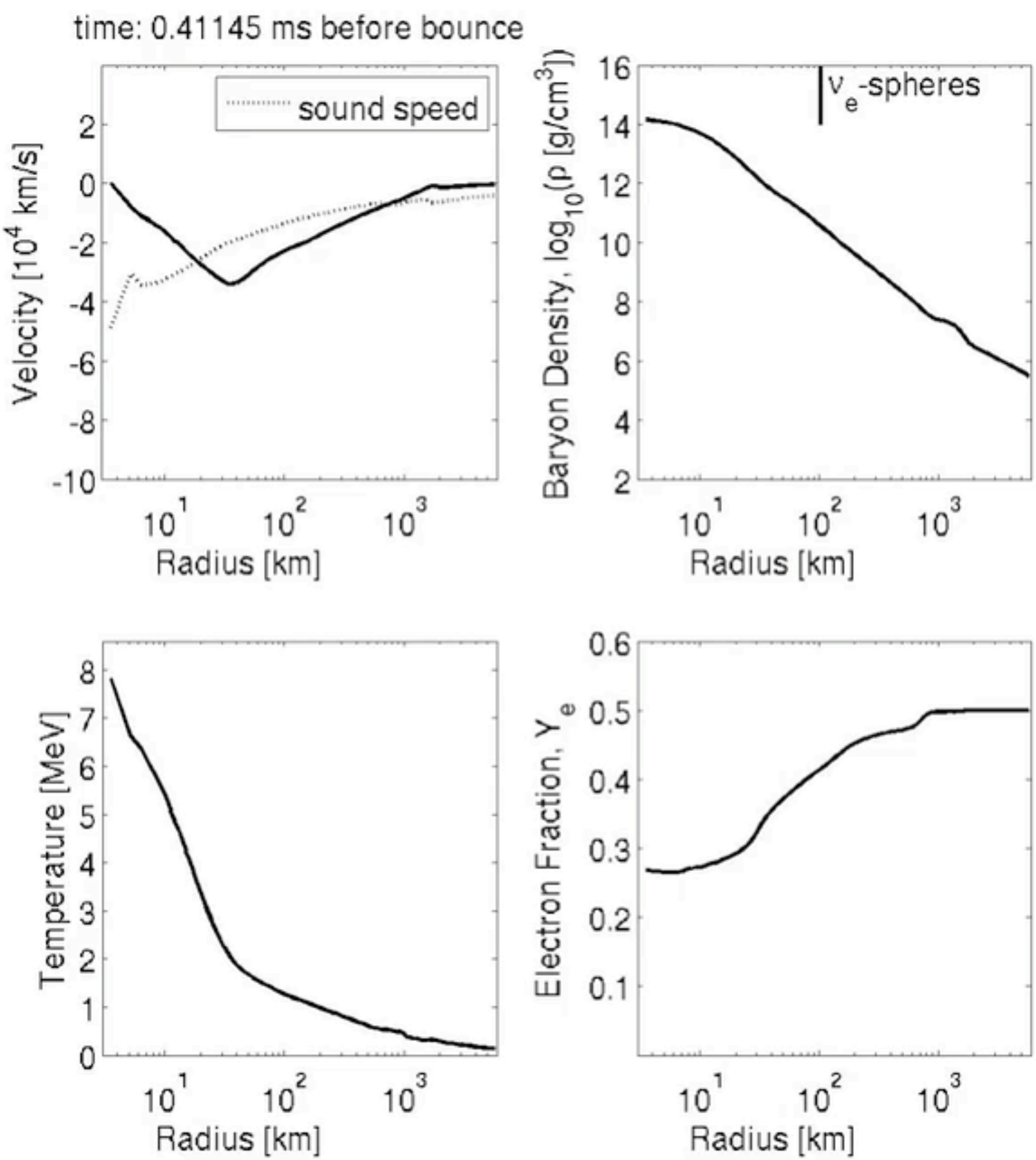
$\langle A \rangle_{\rm PNS} = 0.5 - 1.5$ M$_\odot$

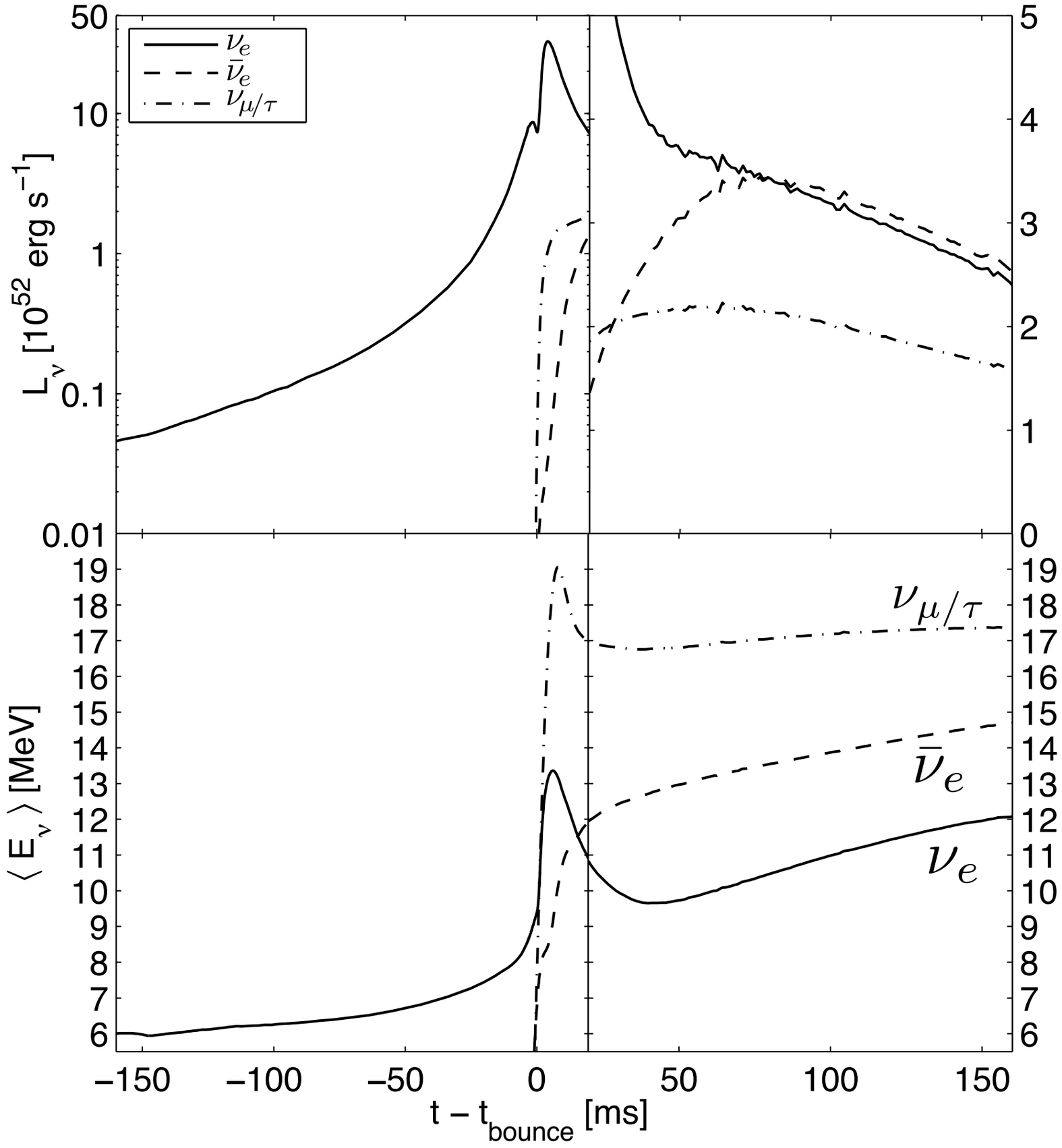
(1 M$_\odot = 1.9891 \times 10^{33}$ g)

Exception: gravity (!)


time: 172.4183 ms before bounce
sound speed
Velocity [10^4 km/s]
Baryon Mass [solar masses]
Baryon Density, log10(ρ [g/cm^3])
Baryon Mass [solar masses]


Temperature [MeV]
Baryon Mass [solar masses]
Electron Fraction, Ye
Baryon Mass [solar masses]


time: 0.41145 ms before bounce
sound speed
Velocity [10^4 km/s]
Radius [km]
ν_e-spheres
Baryon Density, log10(ρ [g/cm^3])
Radius [km]
Temperature [MeV]
Radius [km]
Electron Fraction, Y_e
Radius [km]




## charged current reactions

$$e^- + \langle A, Z \rangle \quad \leftrightarrows \quad \langle A, Z-1 \rangle + \nu_e$$
$$e^- + p \quad \leftrightarrows \quad n + \nu_e$$
$$e^+ + n \quad \leftrightarrows \quad p + \bar{\nu}_e$$

## elastic scattering

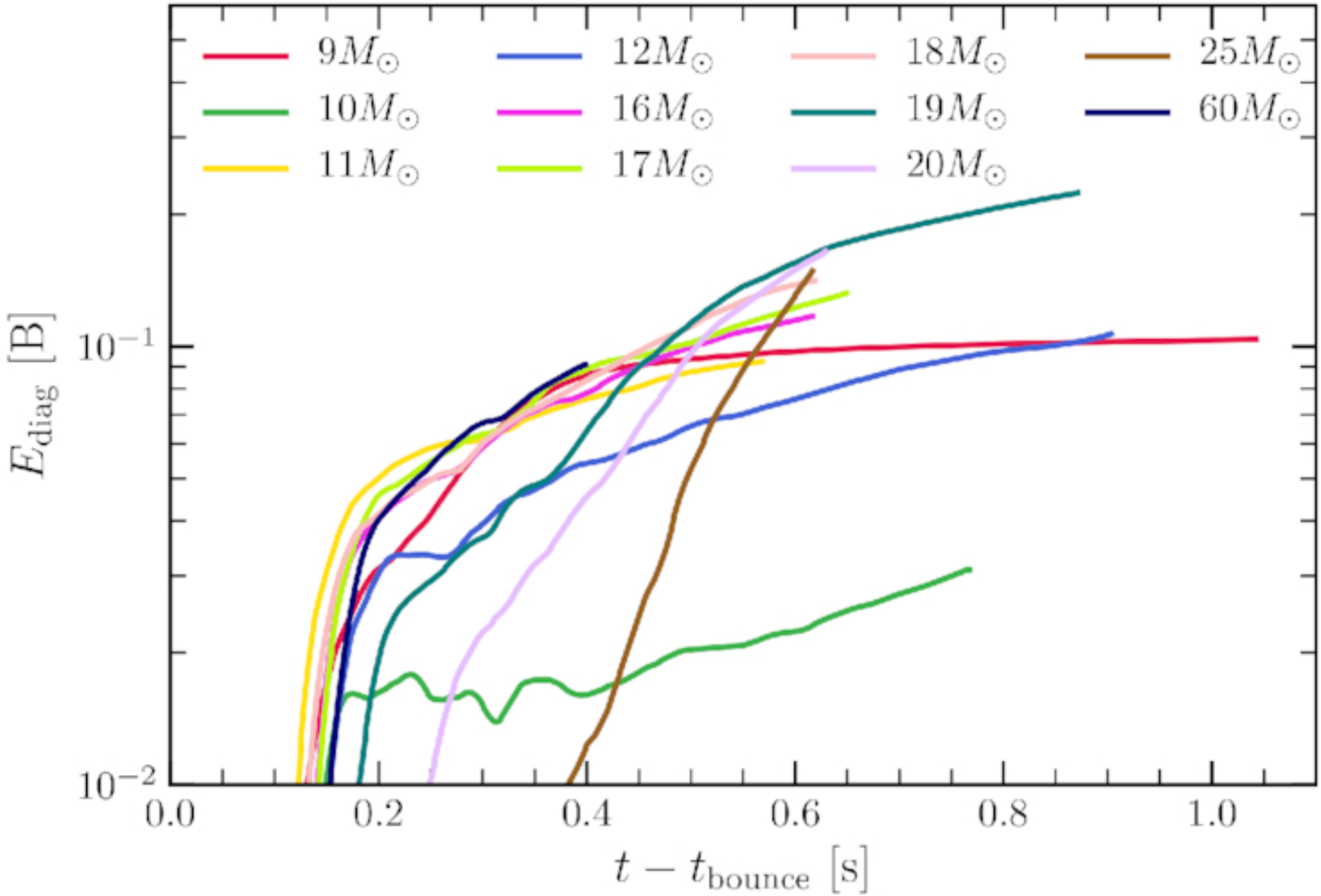
$$\nu + \langle A, Z \rangle \quad \leftrightarrows \quad \langle A, Z \rangle + \nu$$
$$\nu + N \quad \leftrightarrows \quad \nu' + N$$

## inelastic scattering

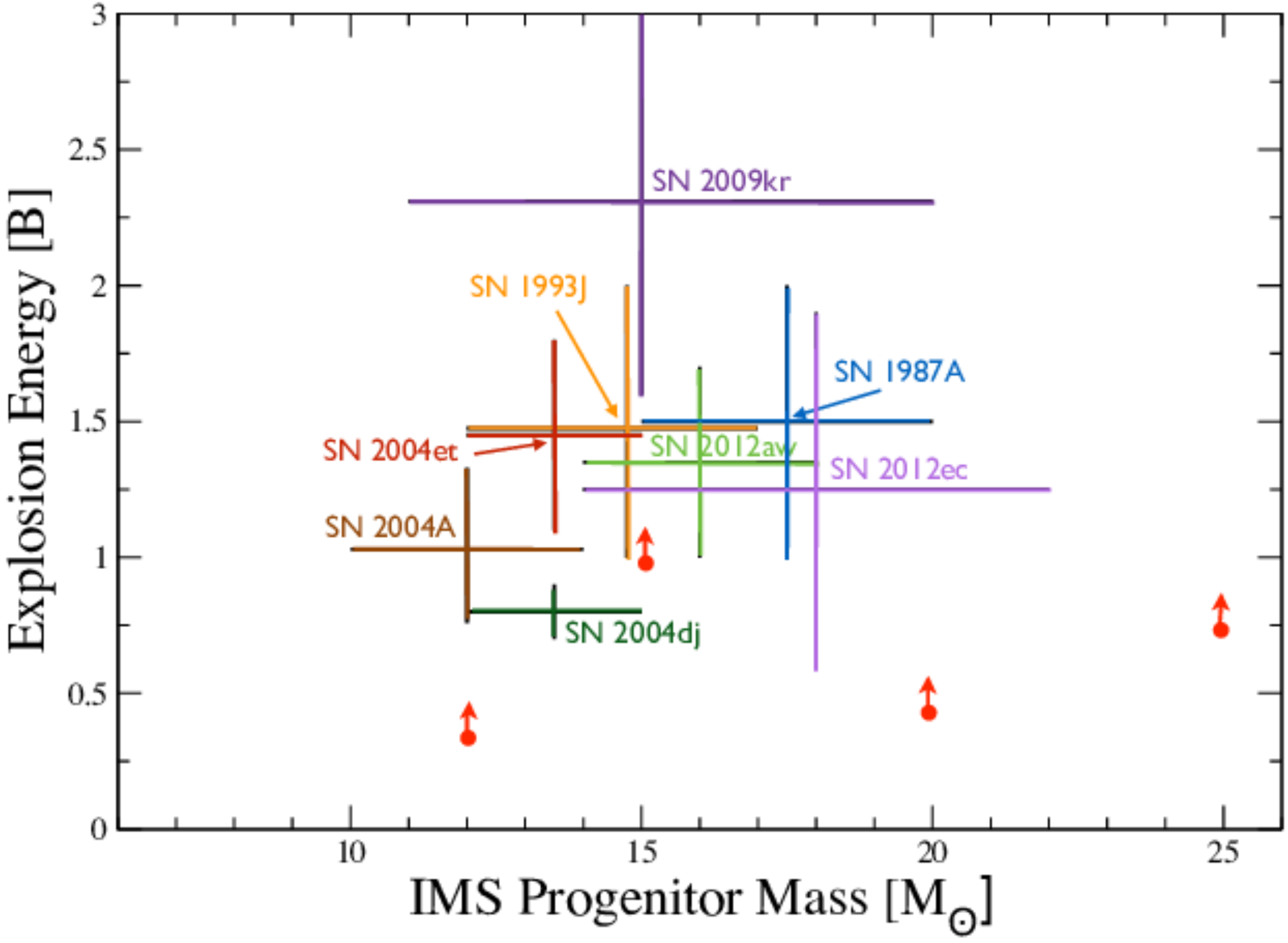
$$\nu + e^\pm \quad \leftrightarrows \quad \nu' + e^\pm$$

## pair processes

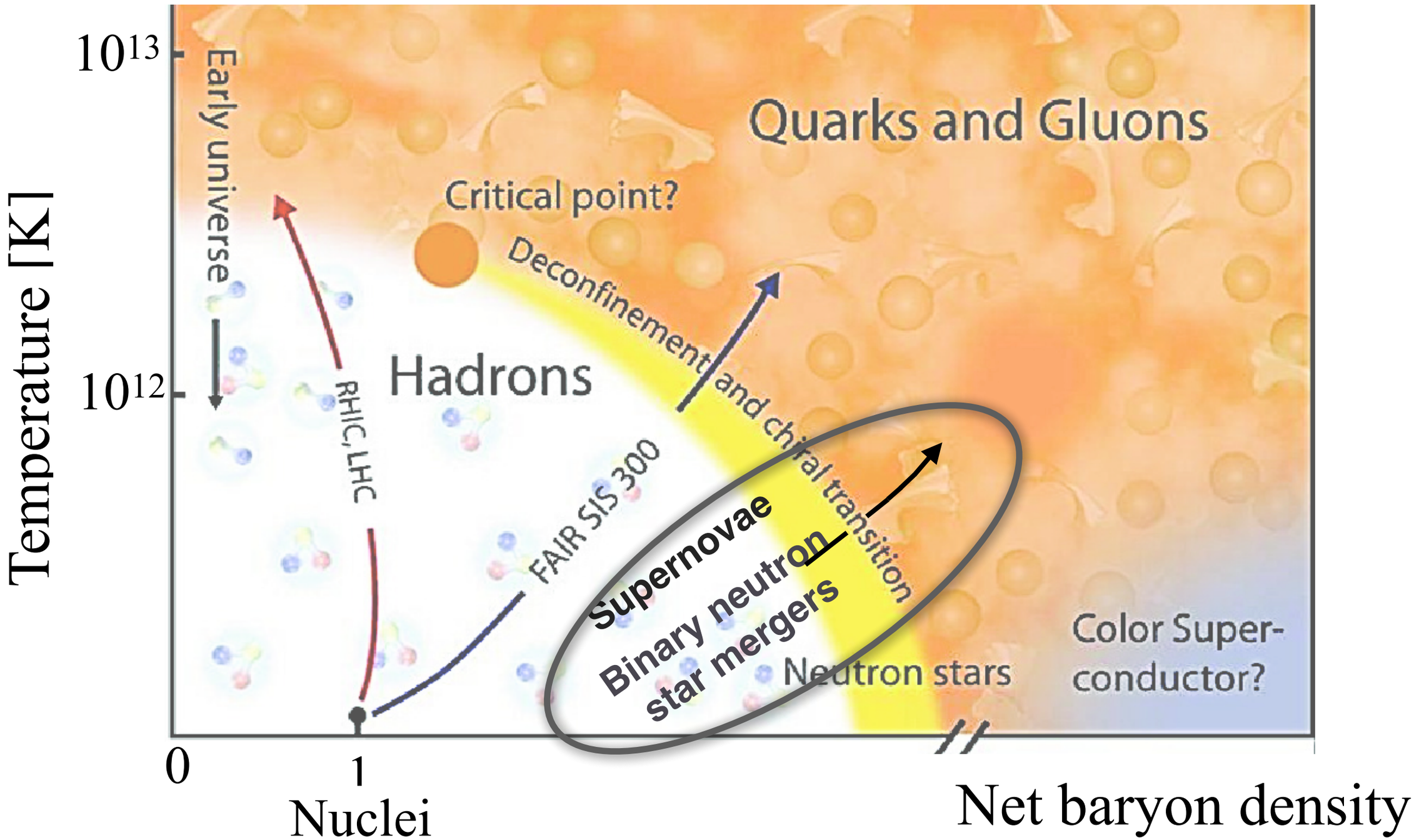
$$e^- + e^+ \quad \leftrightarrows \quad \nu + \bar{\nu}$$
$$N + N \quad \leftrightarrows \quad N + N + \nu + \bar{\nu}$$
$$\nu_e + \bar{\nu}_e \quad \leftrightarrows \quad \nu_{\mu/\tau} + \bar{\nu}_{\mu/\tau}$$

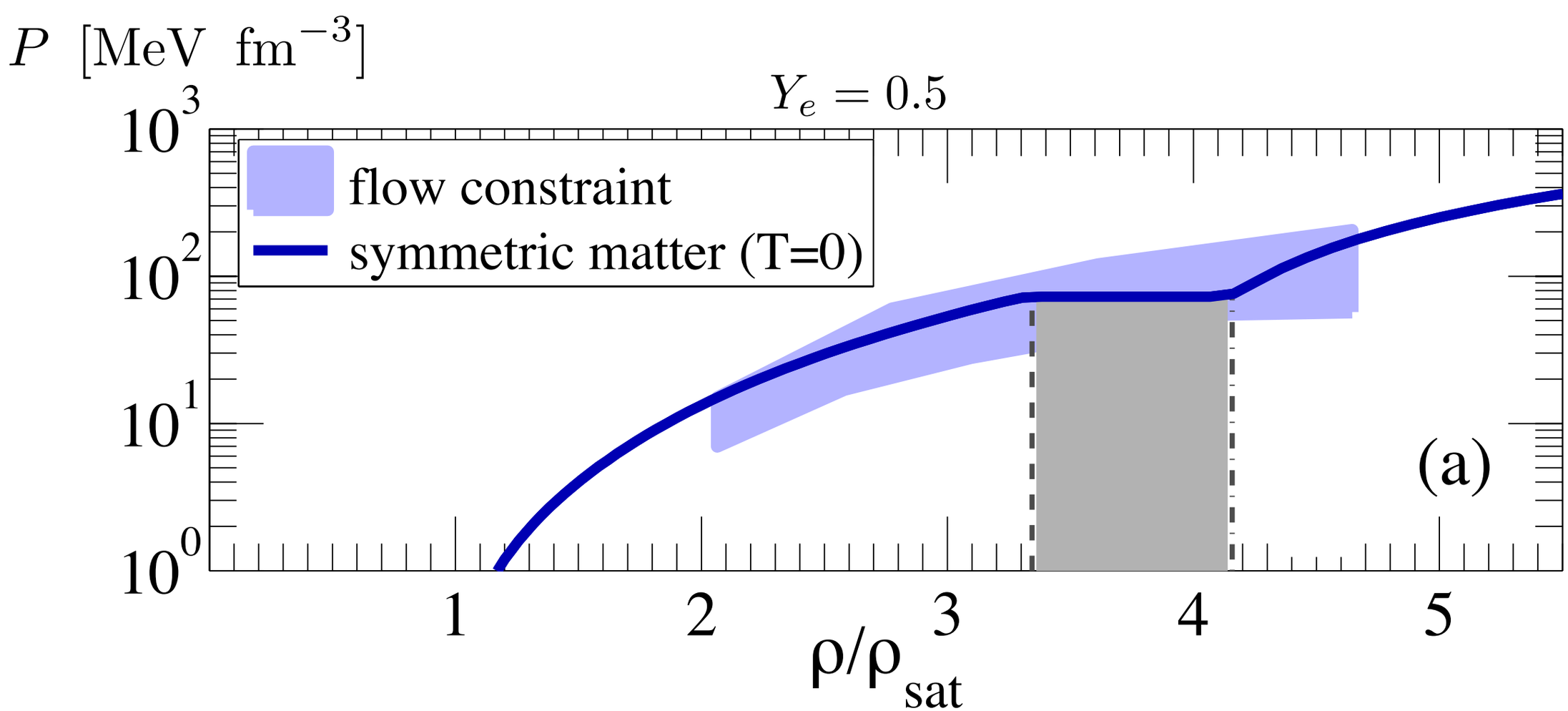



Adam Burrows et al 2020 Mon Not R Astron Soc,491,2




Mezzacappa et al. 2014 ASP vol 488,p.102


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




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

$P$ [MeV fm$^{-3}$]

$Y_e = 0.5$

flow constraint

symmetric matter (T=0)

(a)

$Y_e = 0.3$

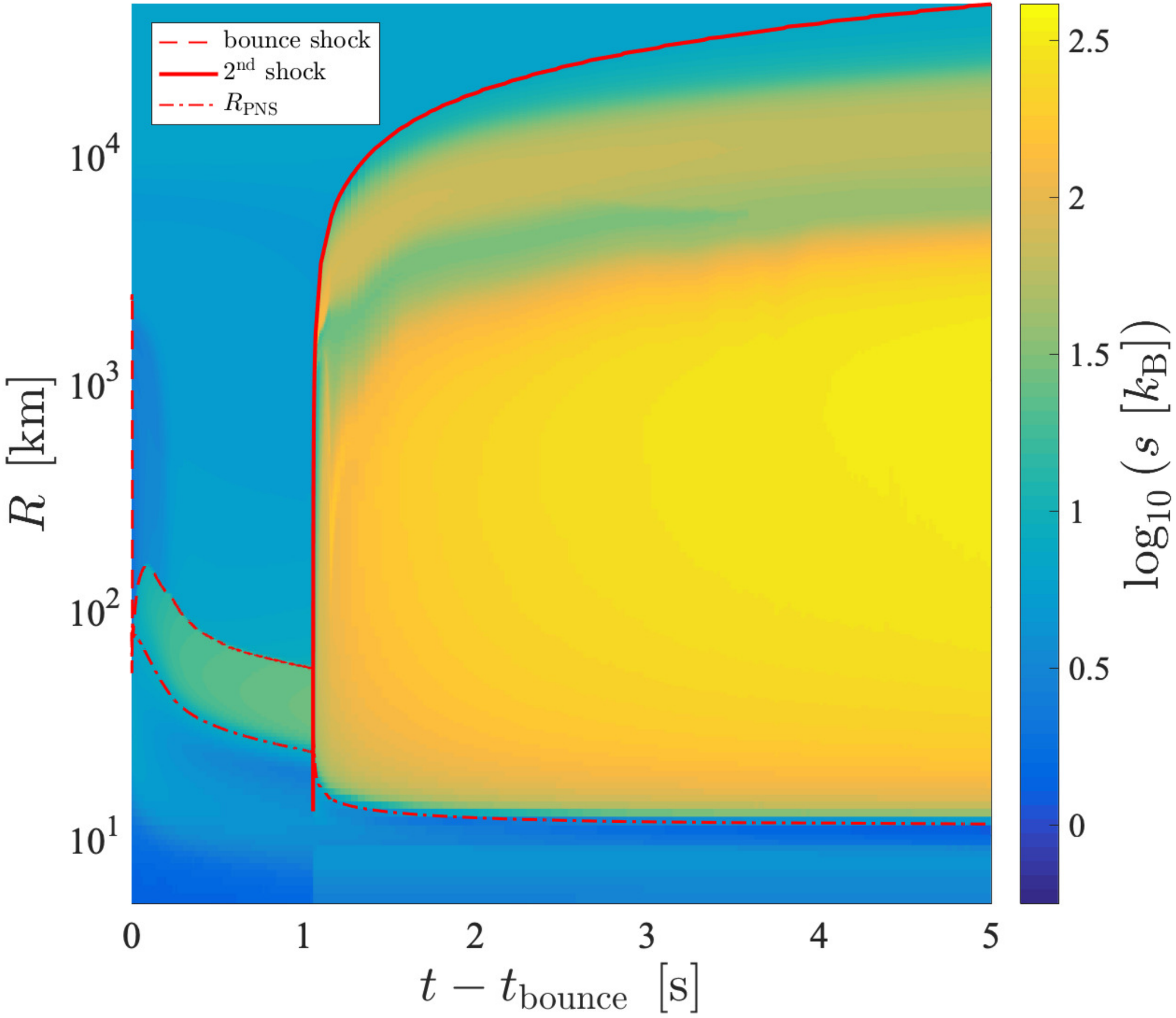
Supernova matter (S=3)

(b)

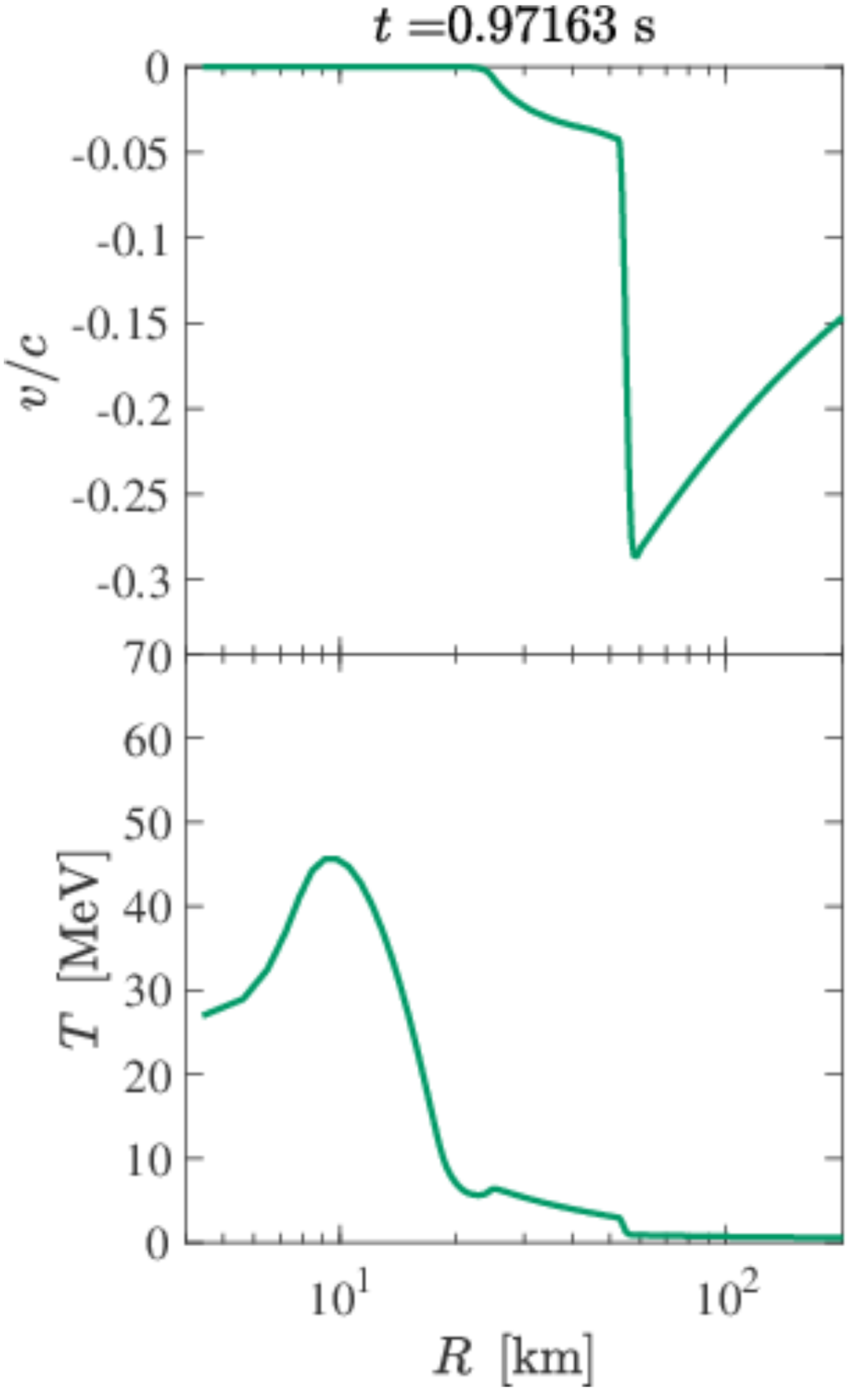
P [MeV fm$^{-3}$]

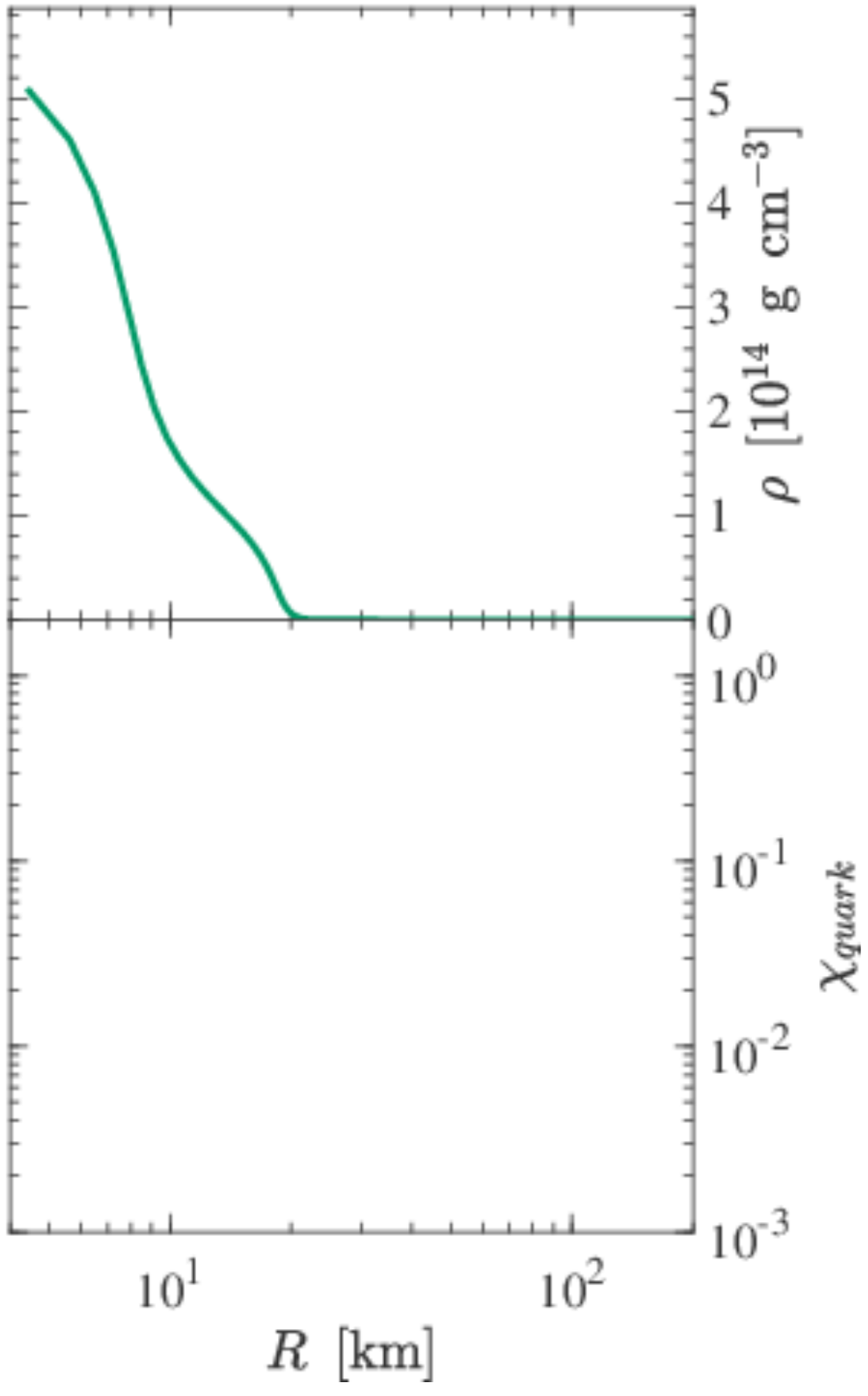
$\rho/\rho_{sat}$

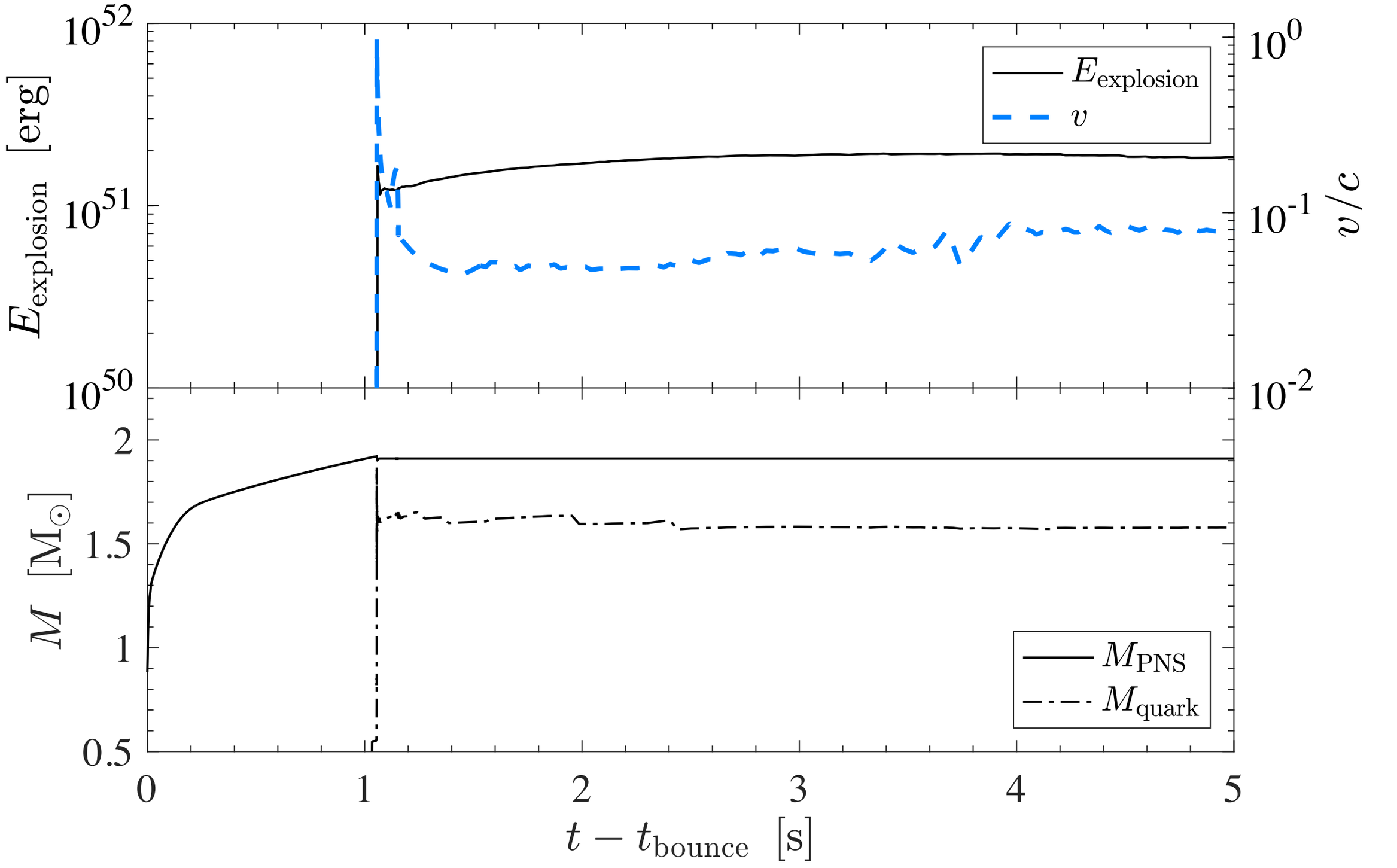
Bastian, Phys. Rev. D, 103, 023001 (2021)




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

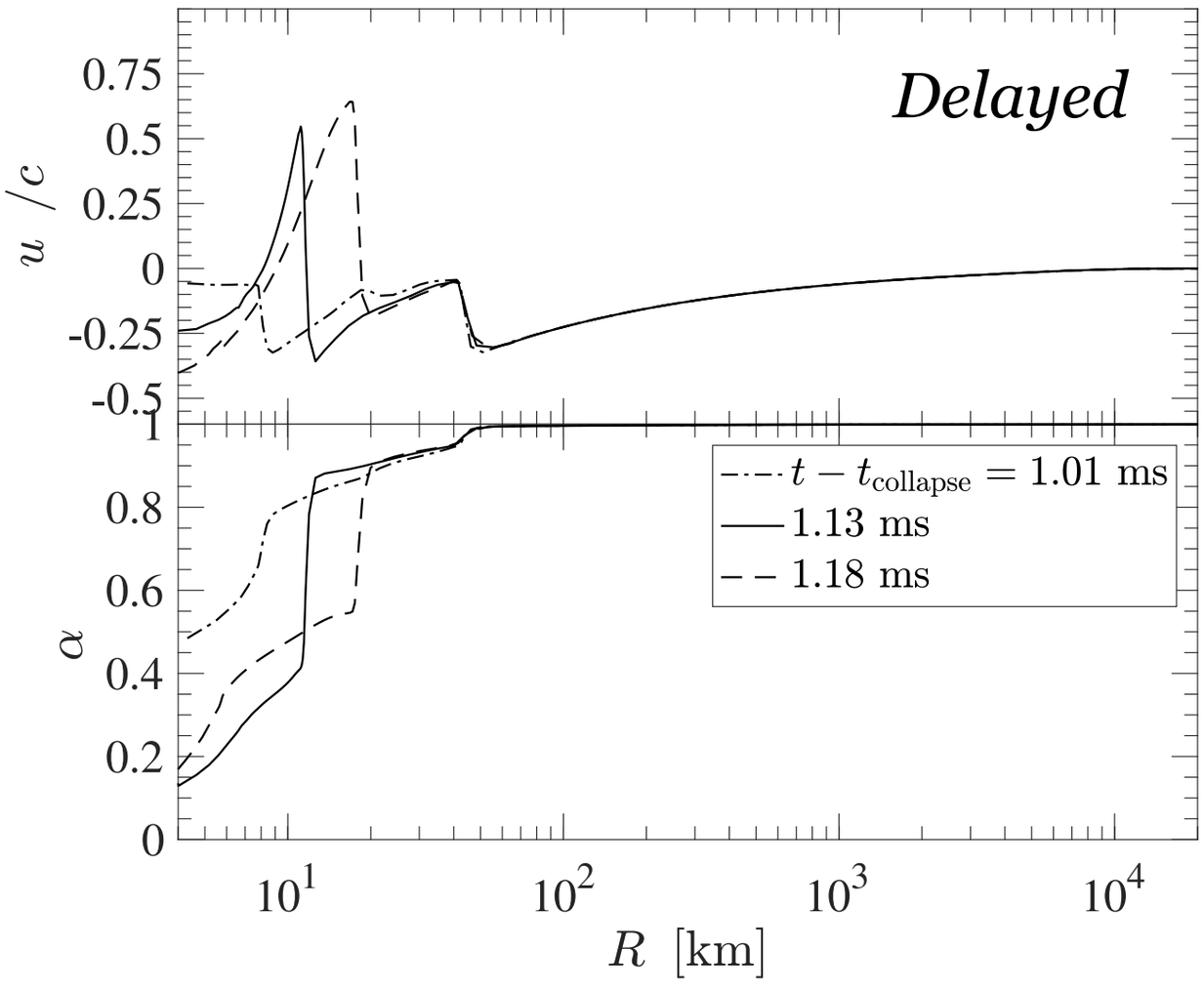

$t$ =0.97163 s
$v/c$
0
-0.05
-0.1
-0.15
-0.2
-0.25
-0.3
$T$ [MeV]
70
60
50
40
30
20
10
0
$10^1$
$10^2$
$R$ [km]

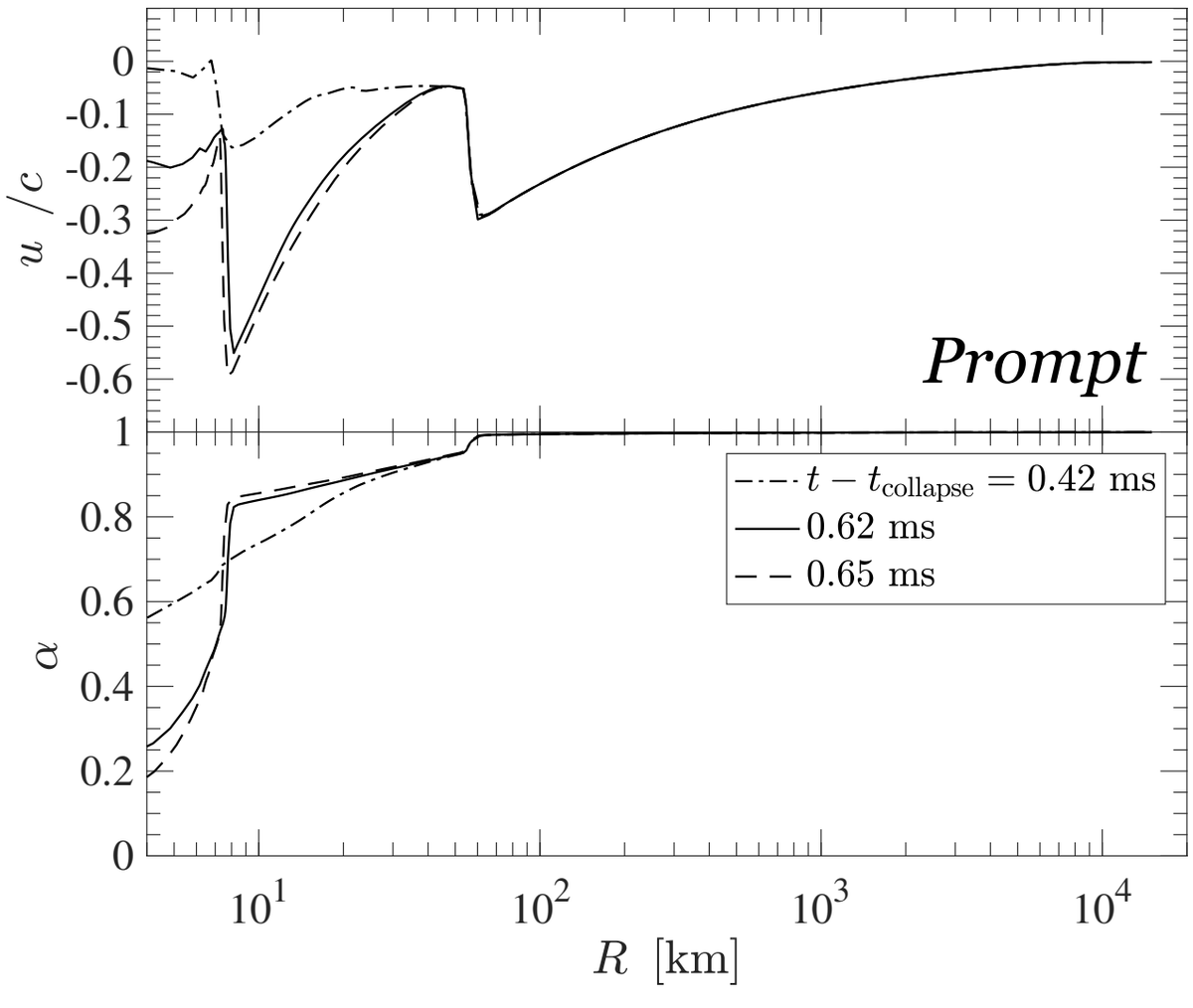

$\rho$ [$10^{14}$ g cm$^{-3}$]
5
4
3
2
1
0
$\chi_{quark}$
$10^0$
$10^{-1}$
$10^{-2}$
$10^{-3}$
$10^1$
$10^2$
$R$ [km]




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

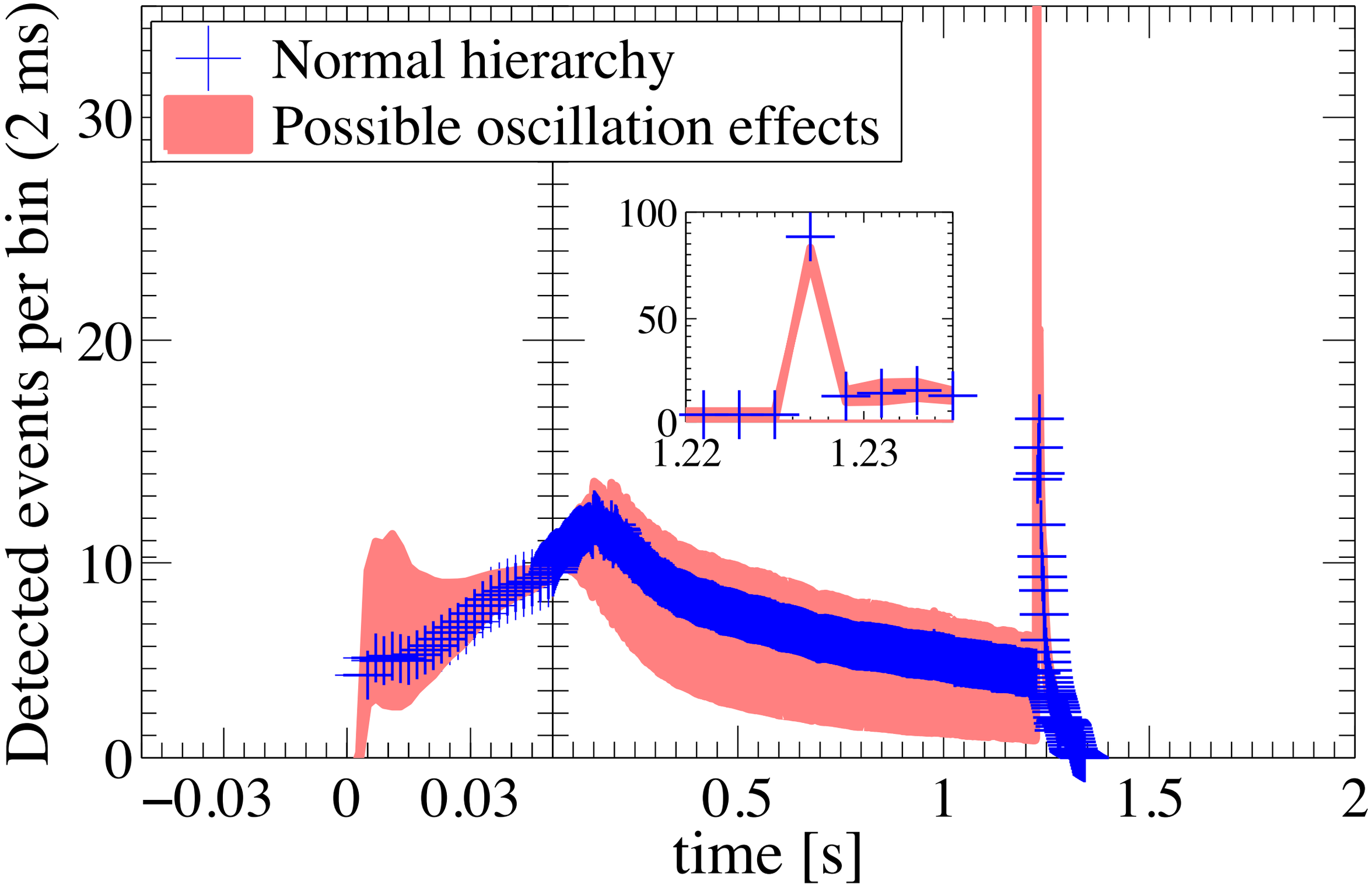
# Black-hole formation: **Two distinct scenarios**



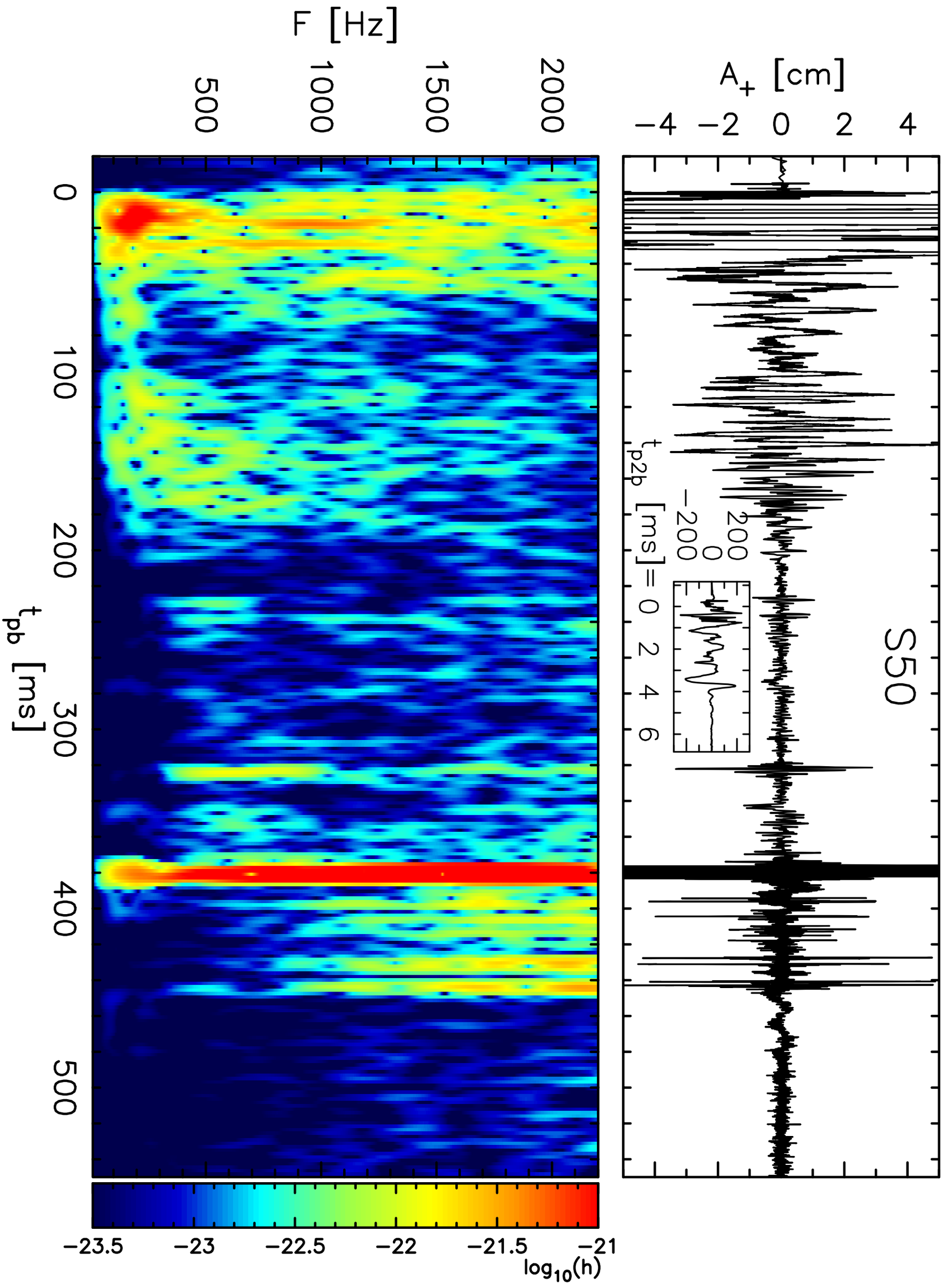

Jakobus et al., MNRAS, 516, 2554 (2022)
Khosravi Largani et al., ApJ 946, 143 (2024)

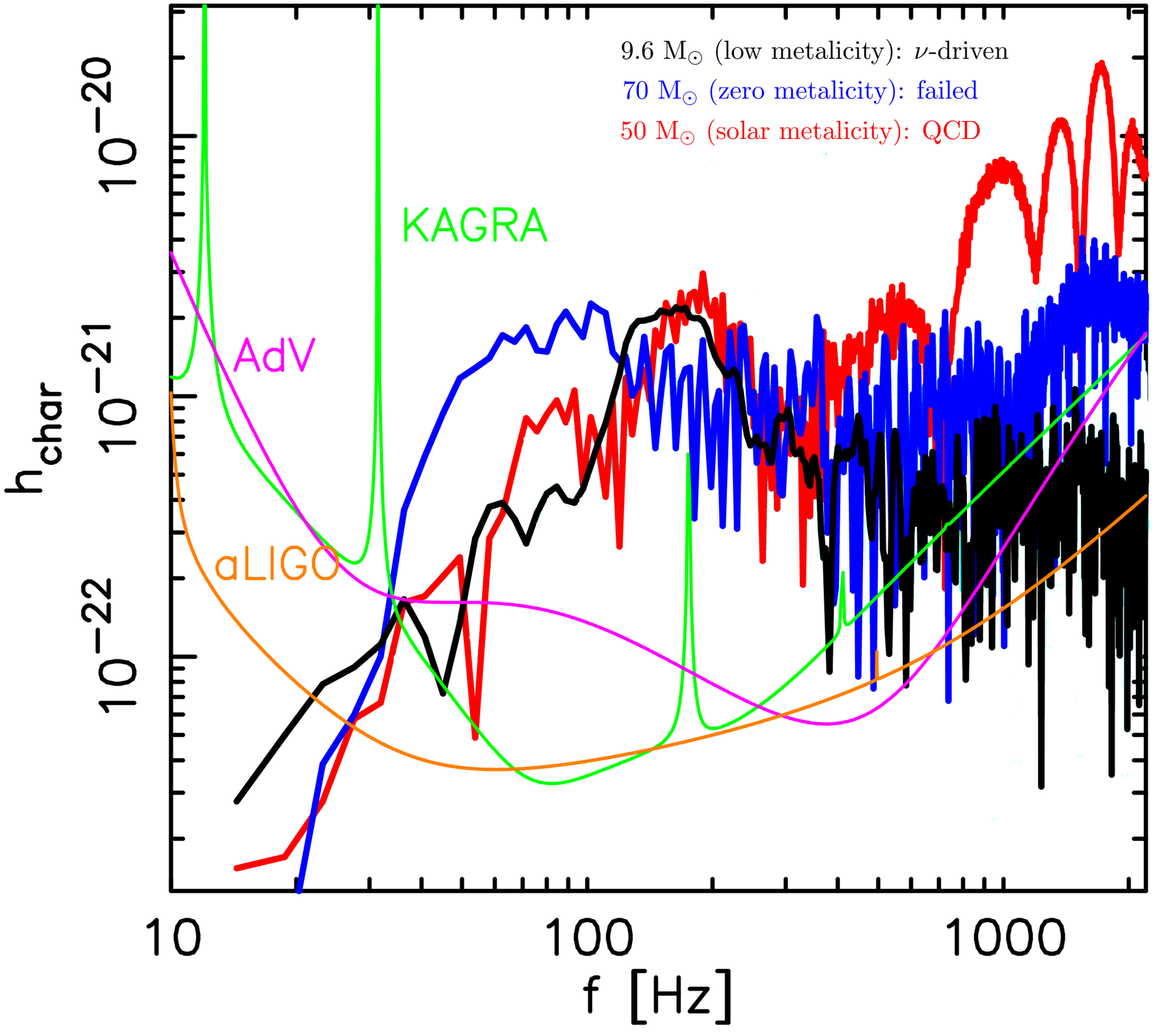
# *ν – signal @ Super-Kamiokande (d ~ 10 kpc)*



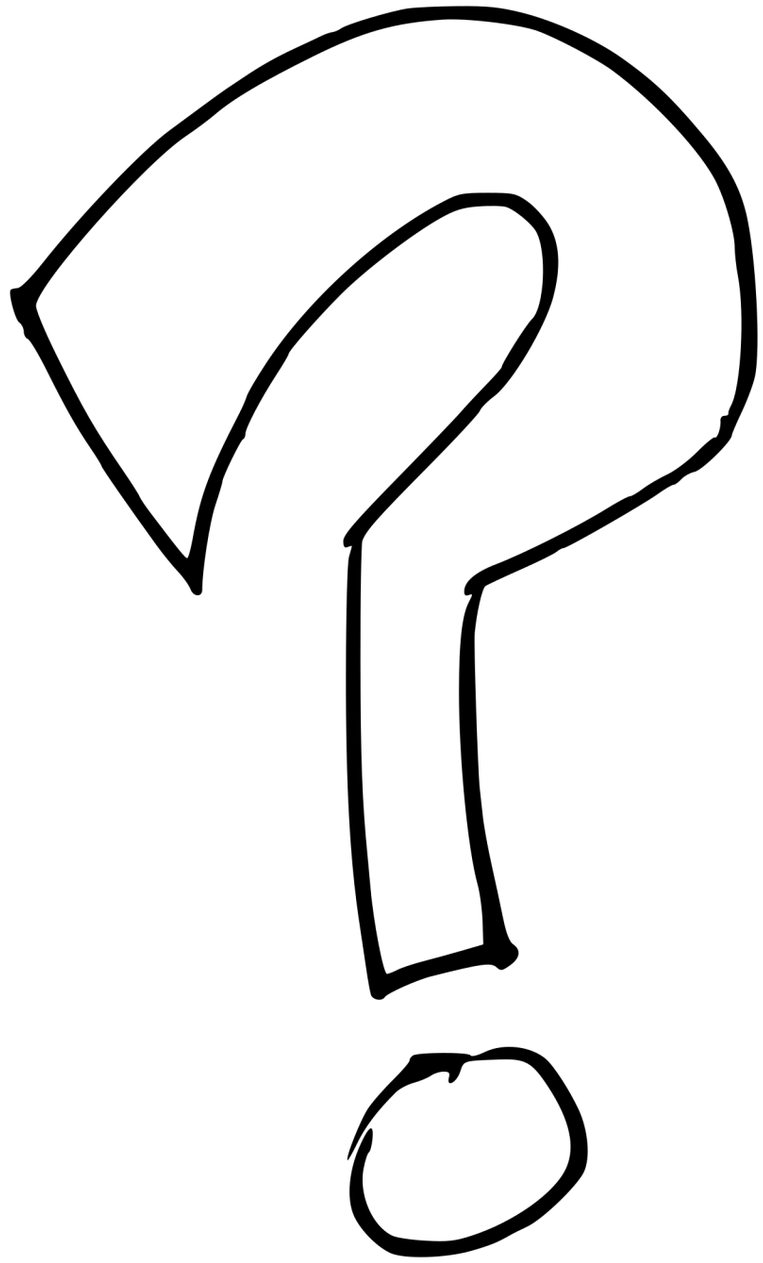

Fischer et al., Nature Astron. **2**, 980 (2018)

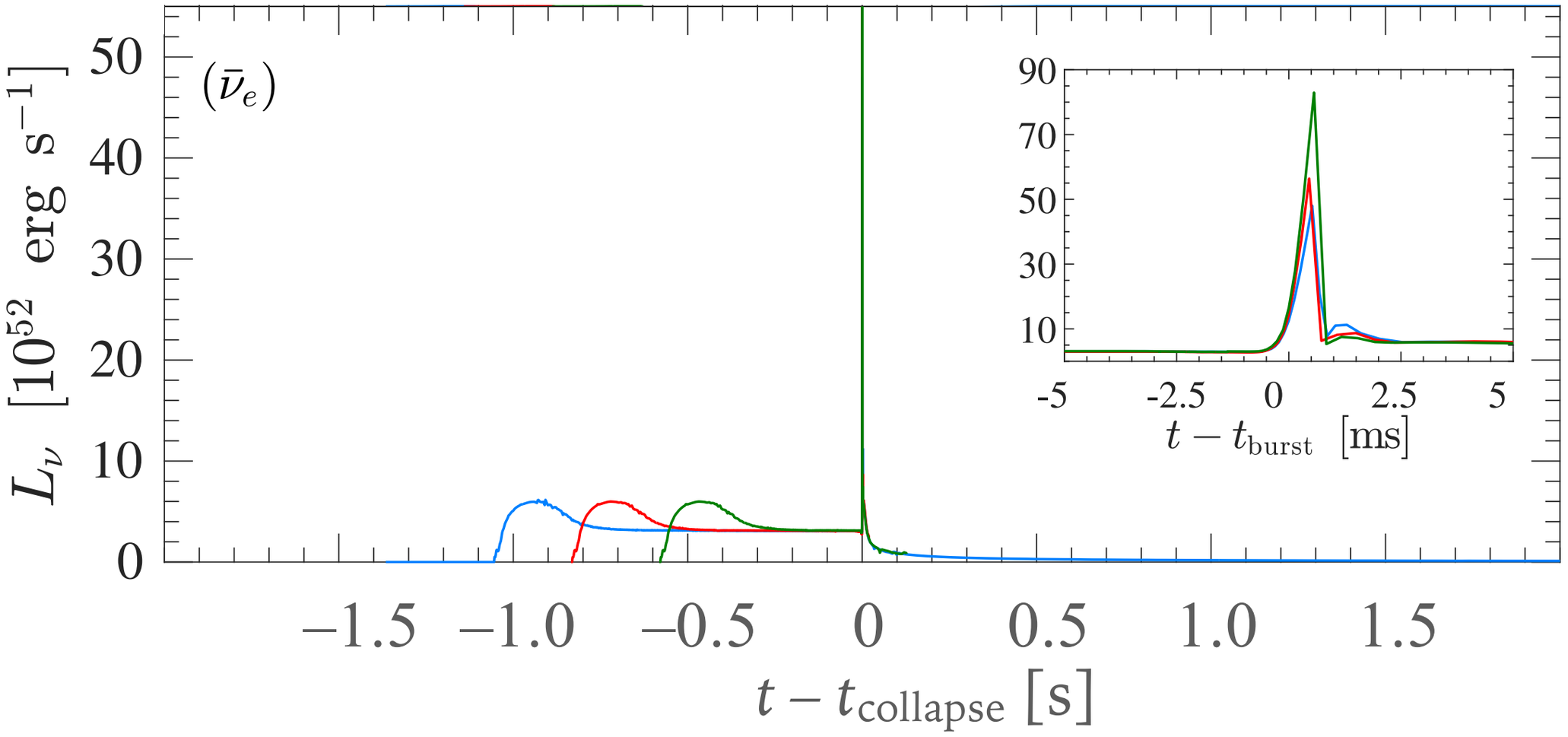
Kuroda et al., ApJ 924, 38 (2022)
Zha et al., PRL 125, 051102 ( 2020)





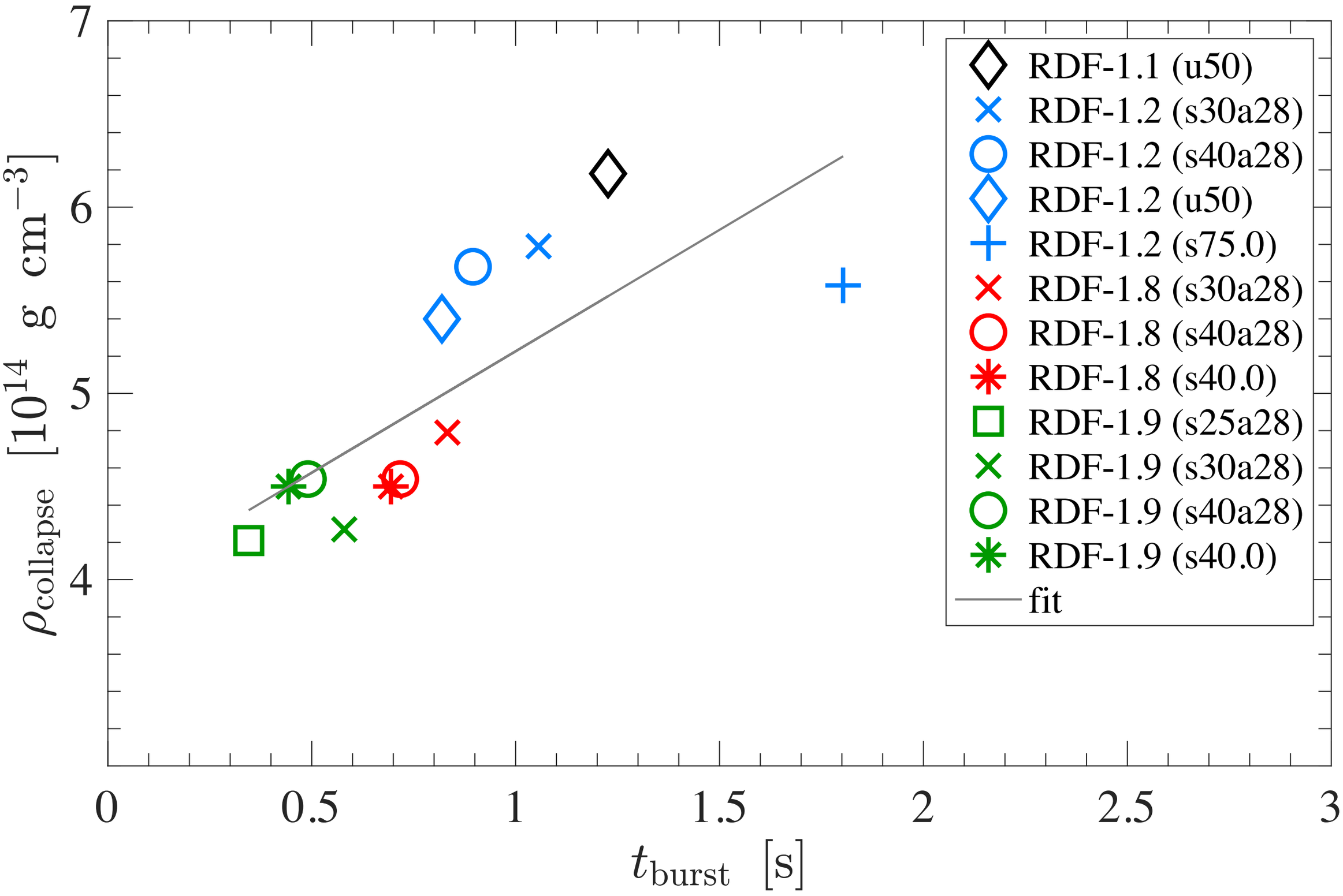

Kuroda et al., ApJ 924, 38 (2022)






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 |

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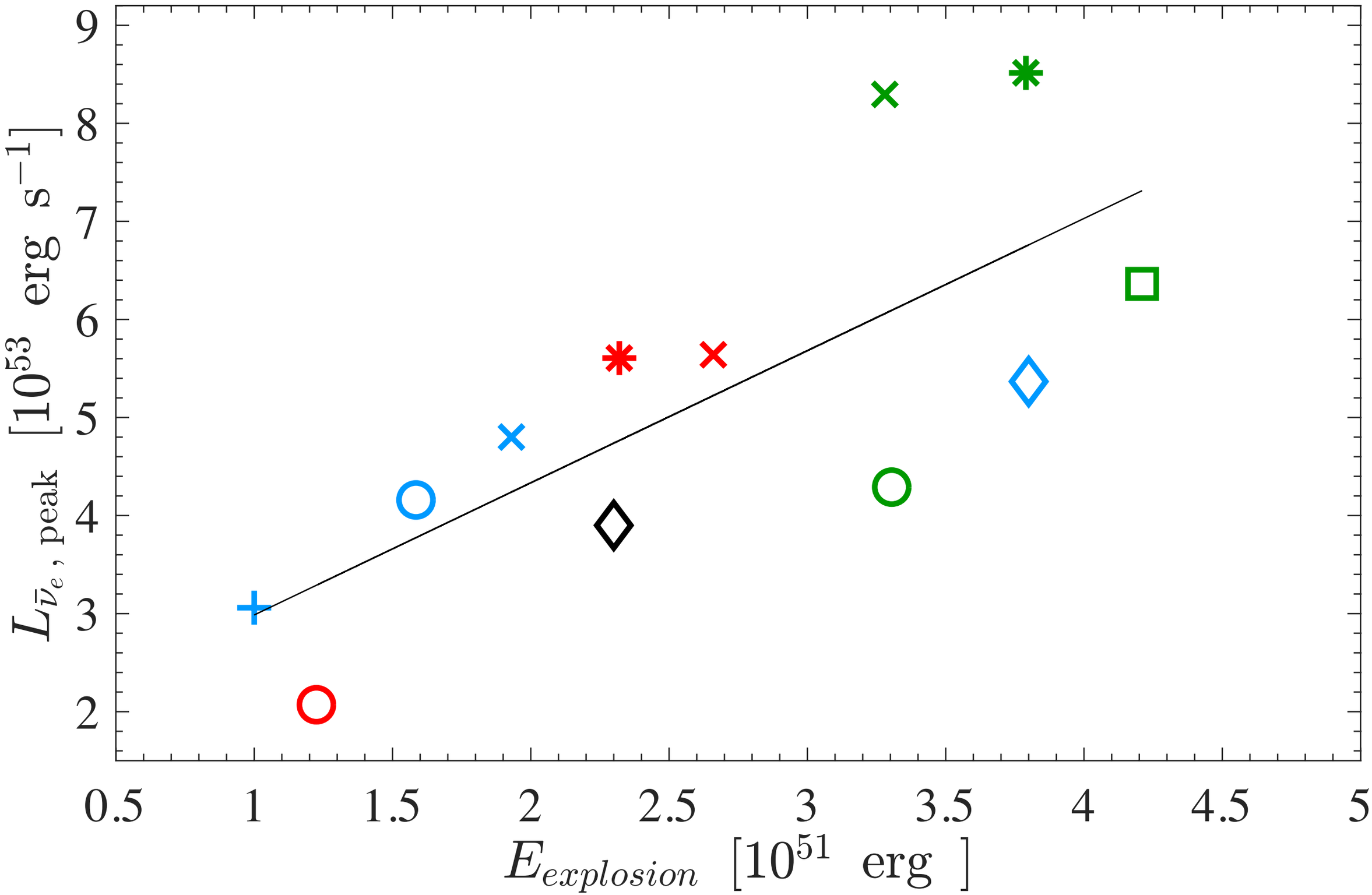
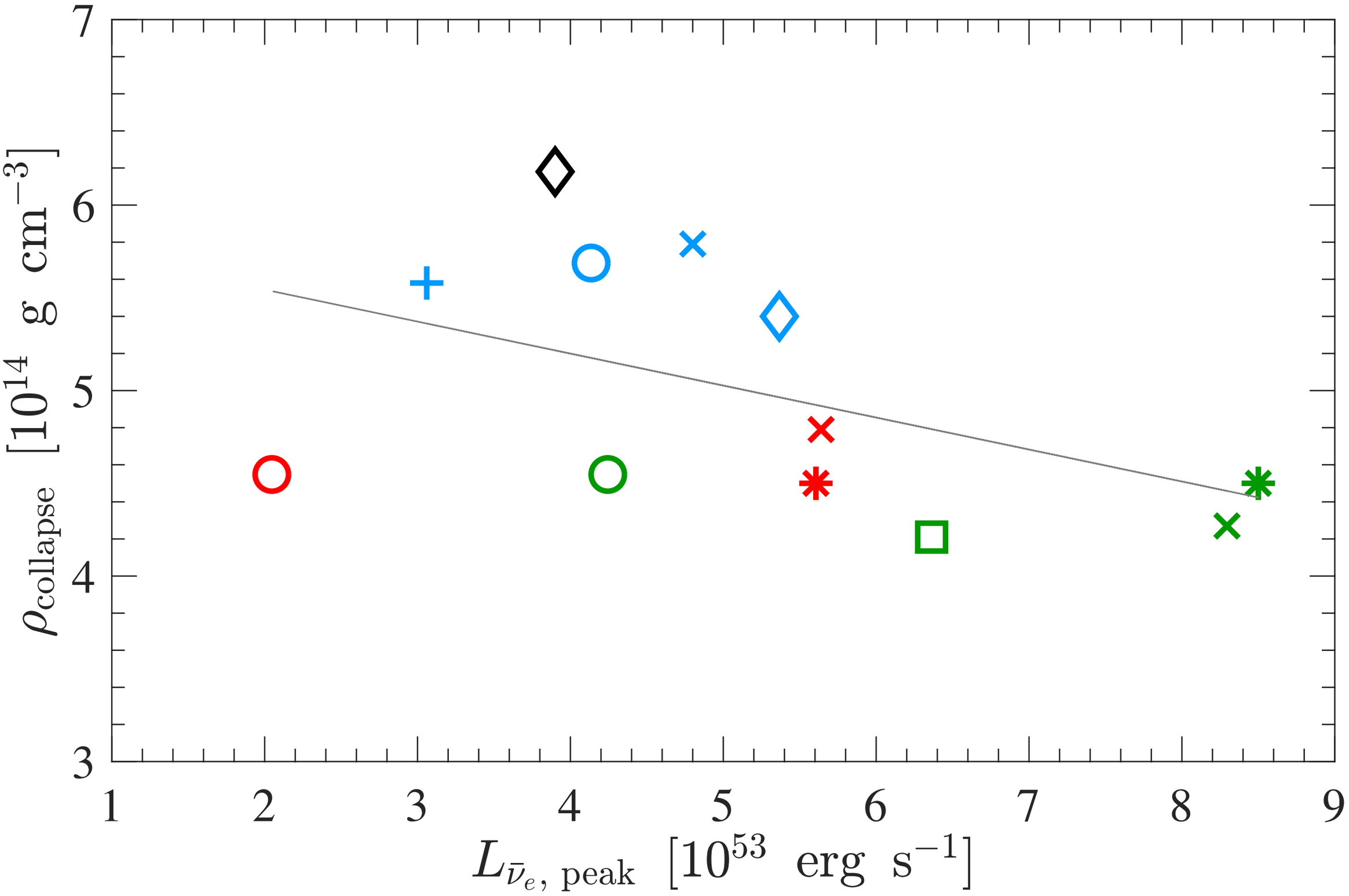



Khosravi Largani et al., ApJ 946, 143 (2024)

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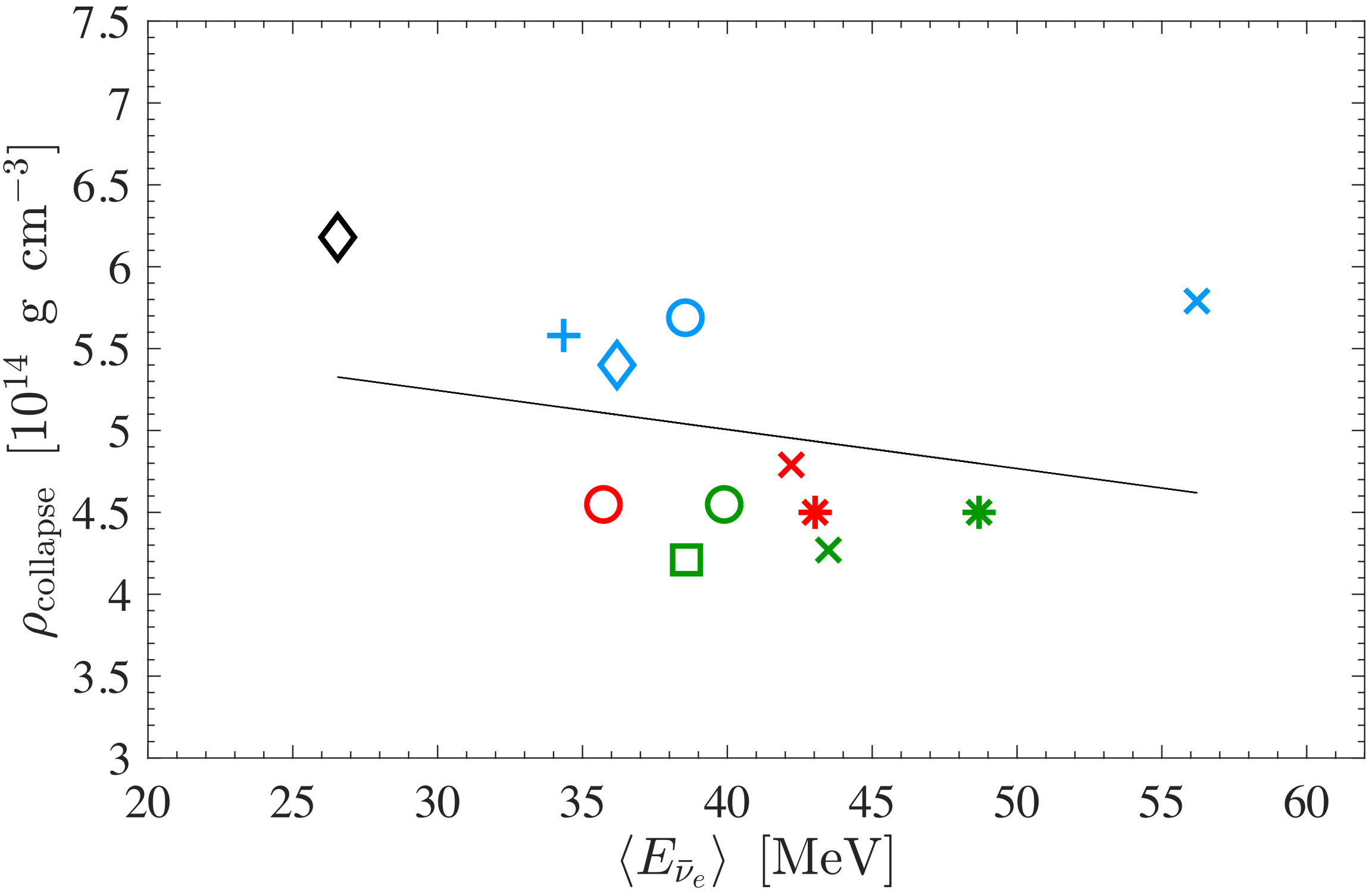


Khosravi Largani et al., ApJ 946, 143 (2024)