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

Uniwersytet Wrocławski

Noshad Khosravi Largani

60th Karpacz Winter school

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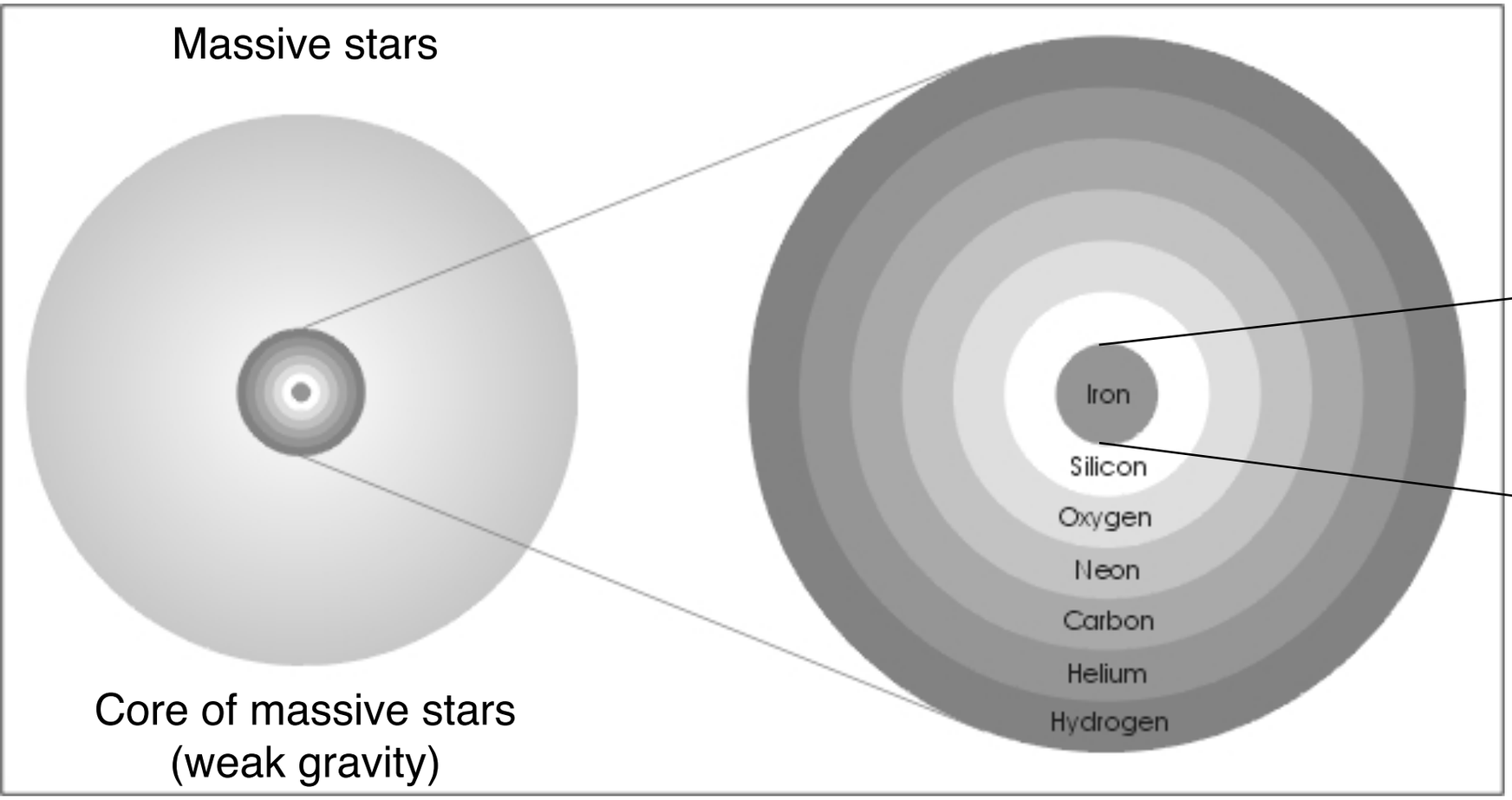
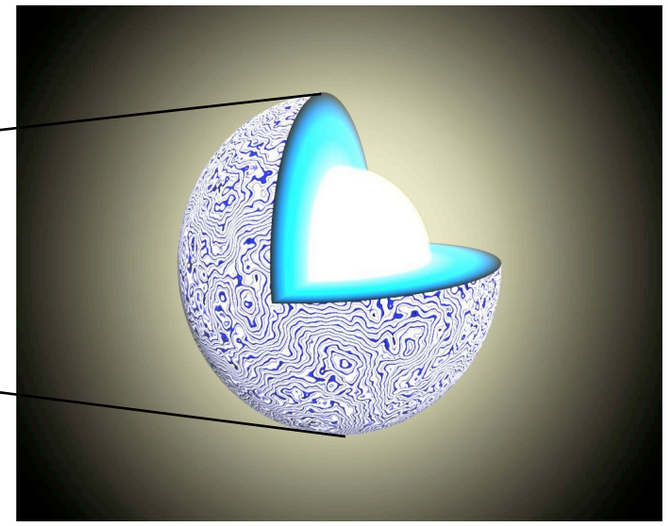
NARODOWE CENTRUM NAUKI

Global Picture



(Proto)neutron stars
(very strong gravity)



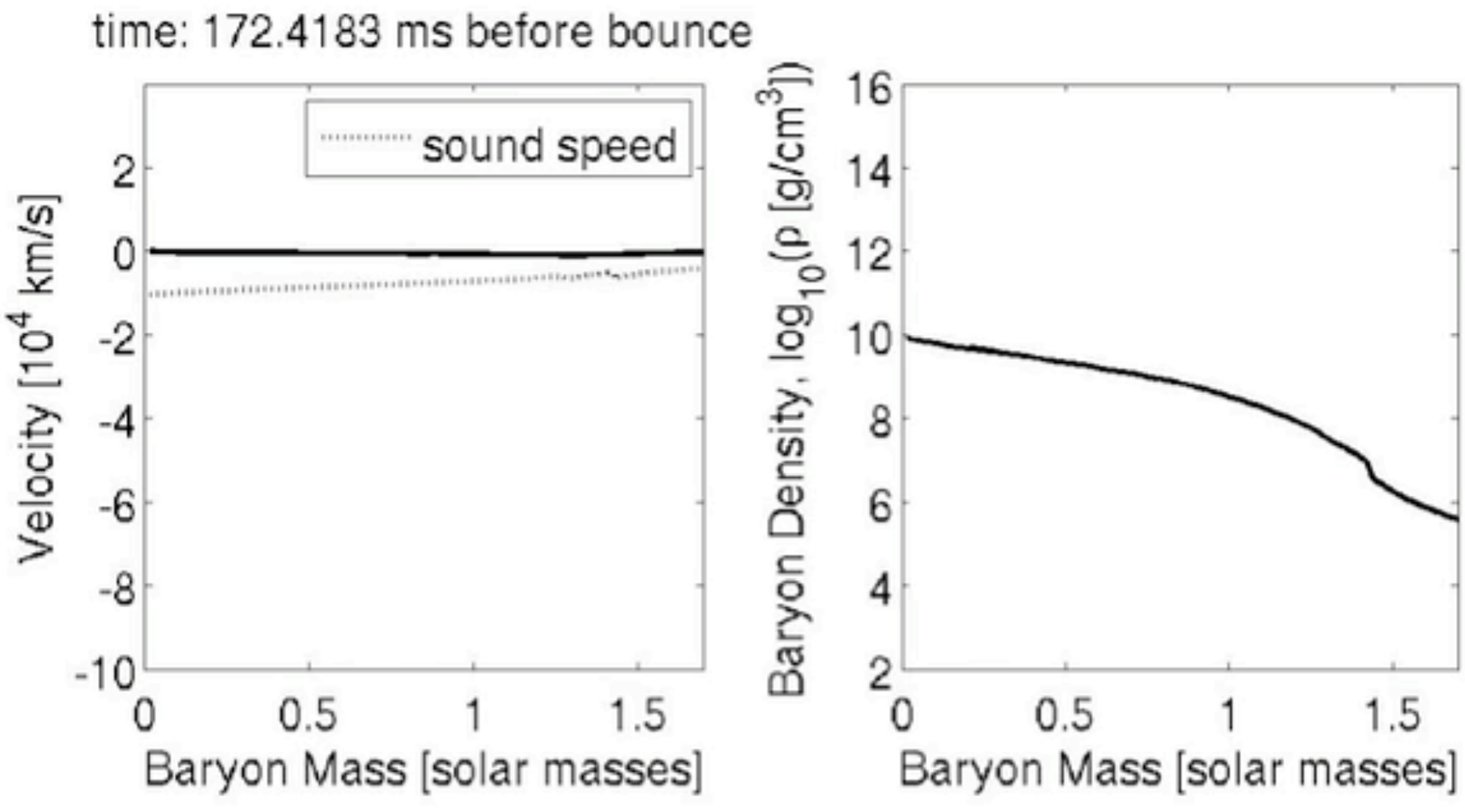
Energy released: $\triangle E_G \simeq 3 - 6 \times 10^{53}$ erg $\longrightarrow (\nu_e, \bar{\nu}_e, \nu_{\mu/\tau}, \bar{\nu}_{\mu/\tau})$

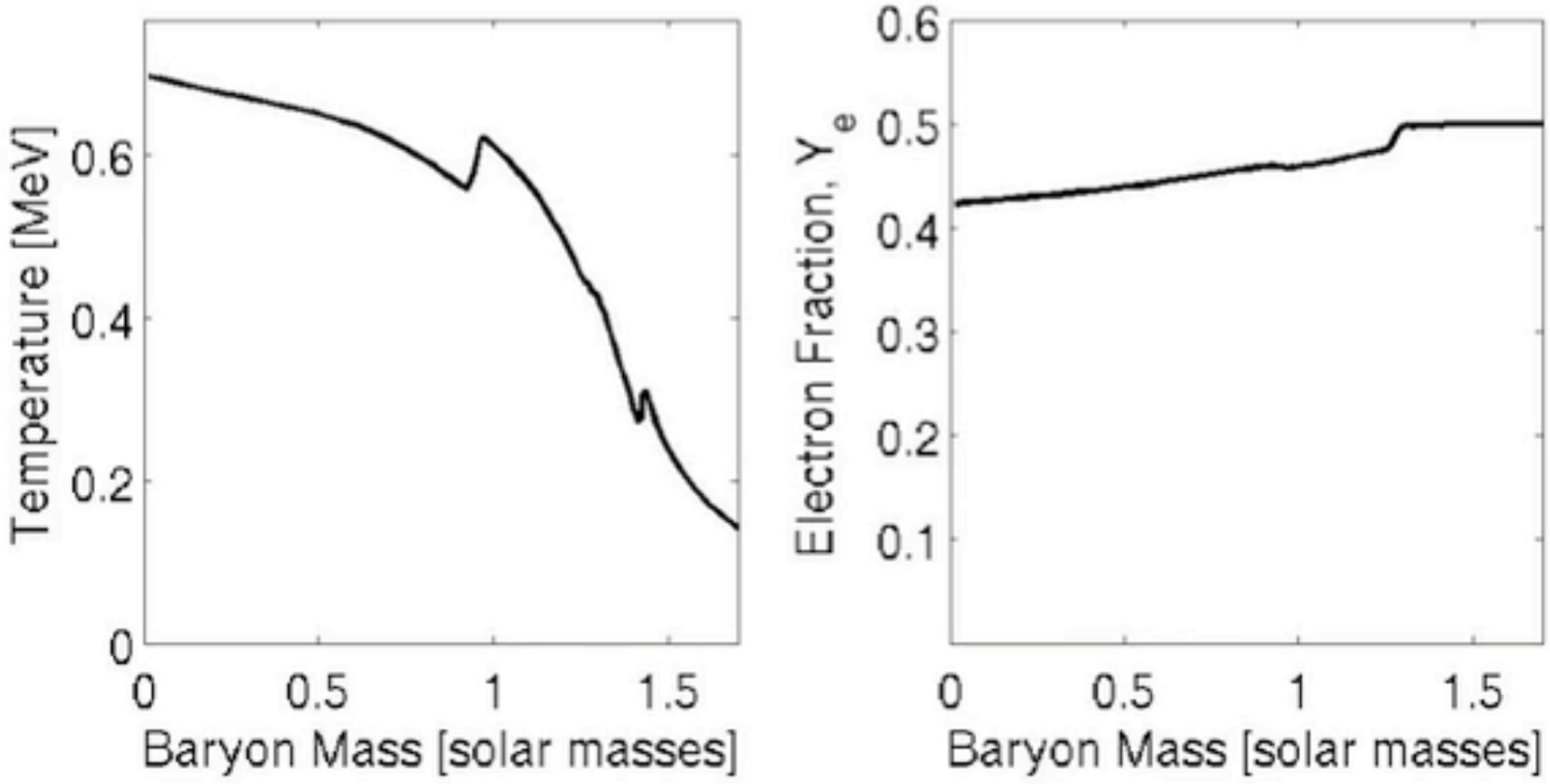
(Proto)neutron star is a hot and isospin asymmetric “heavy nucleus” with large atomic mass

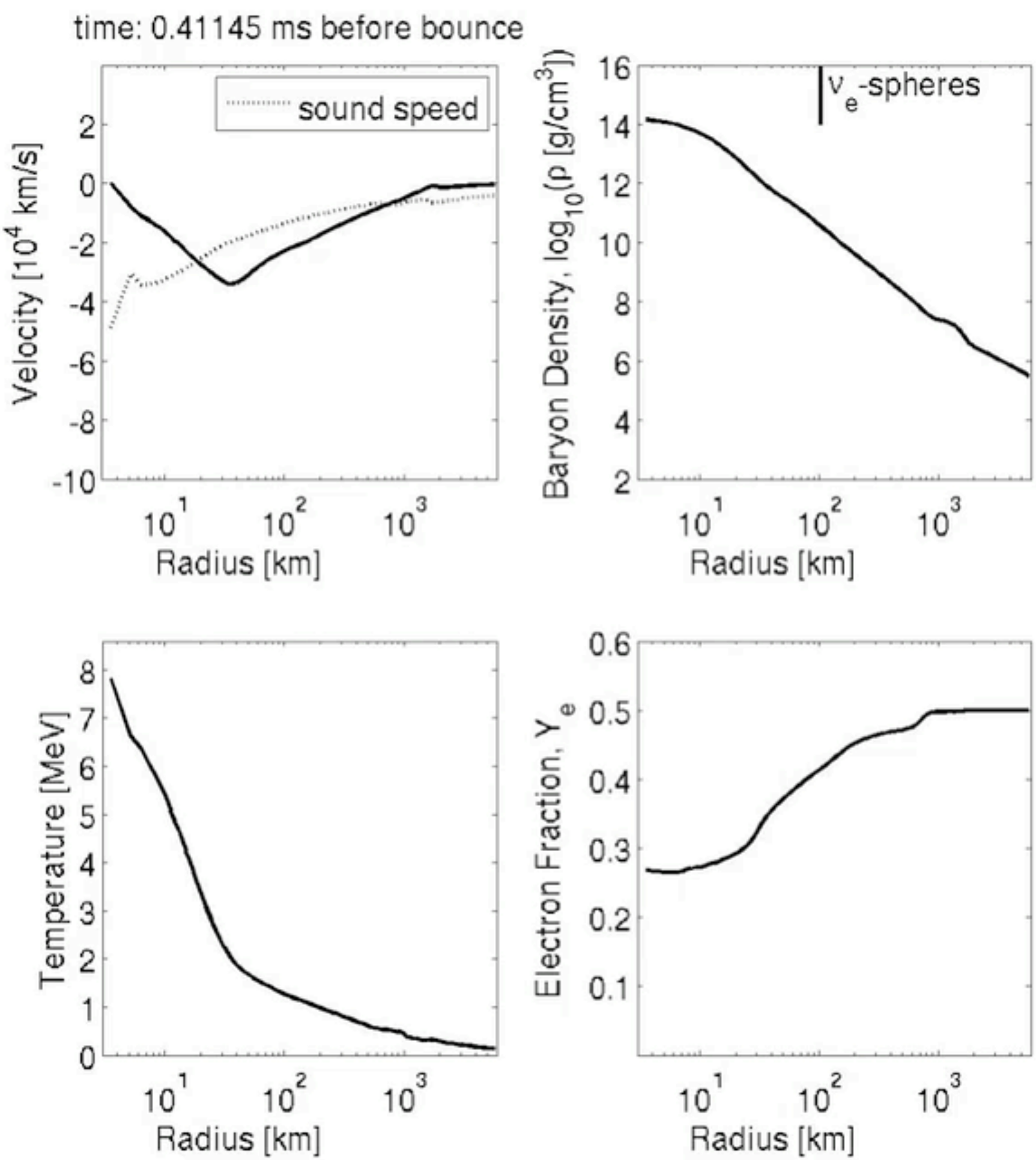
$\langle A \rangle_{\rm PNS} = 0.5 - 1.5$ M$_\odot$

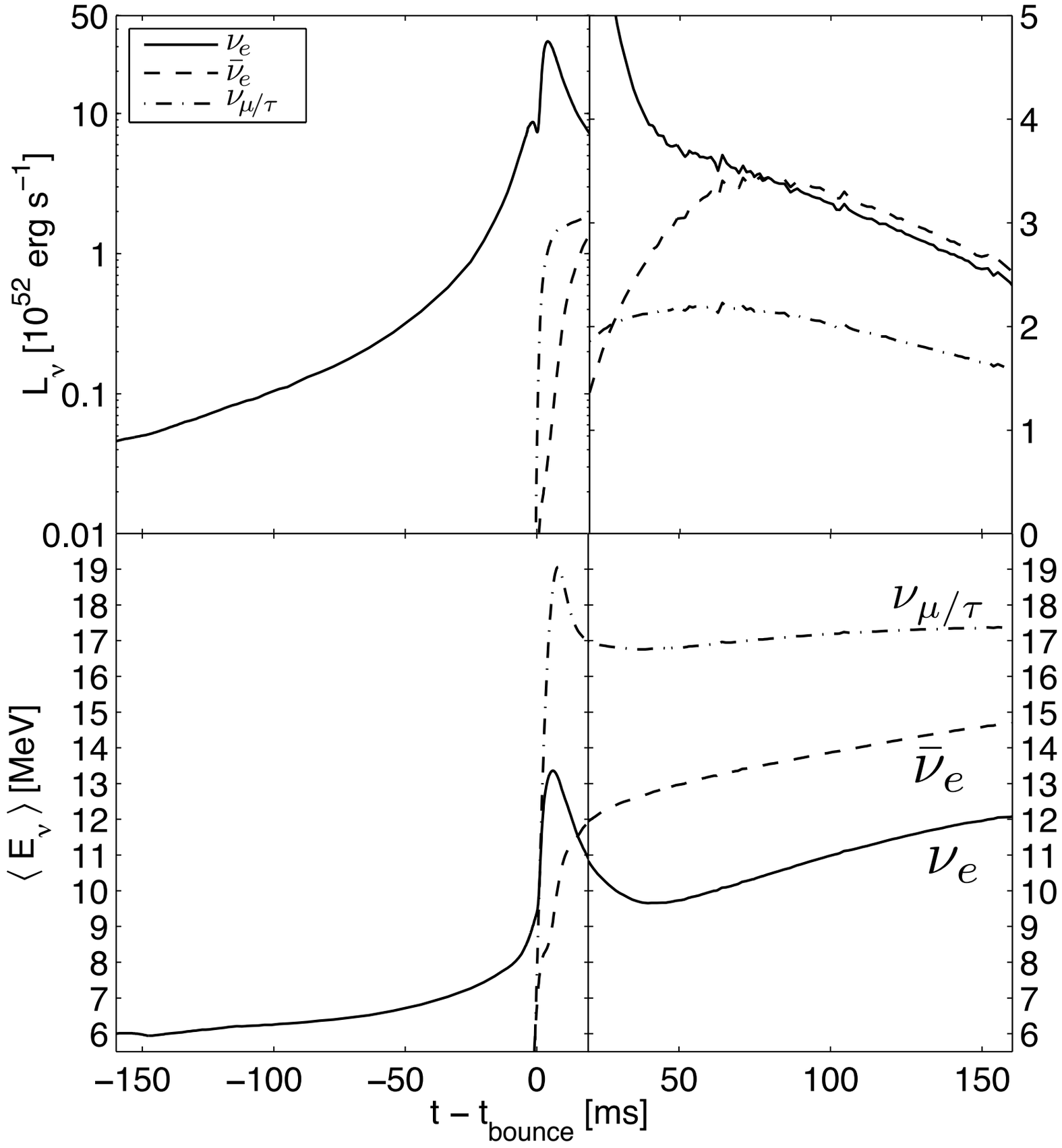
(1 M$_\odot = 1.9891 \times 10^{33}$ g)

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

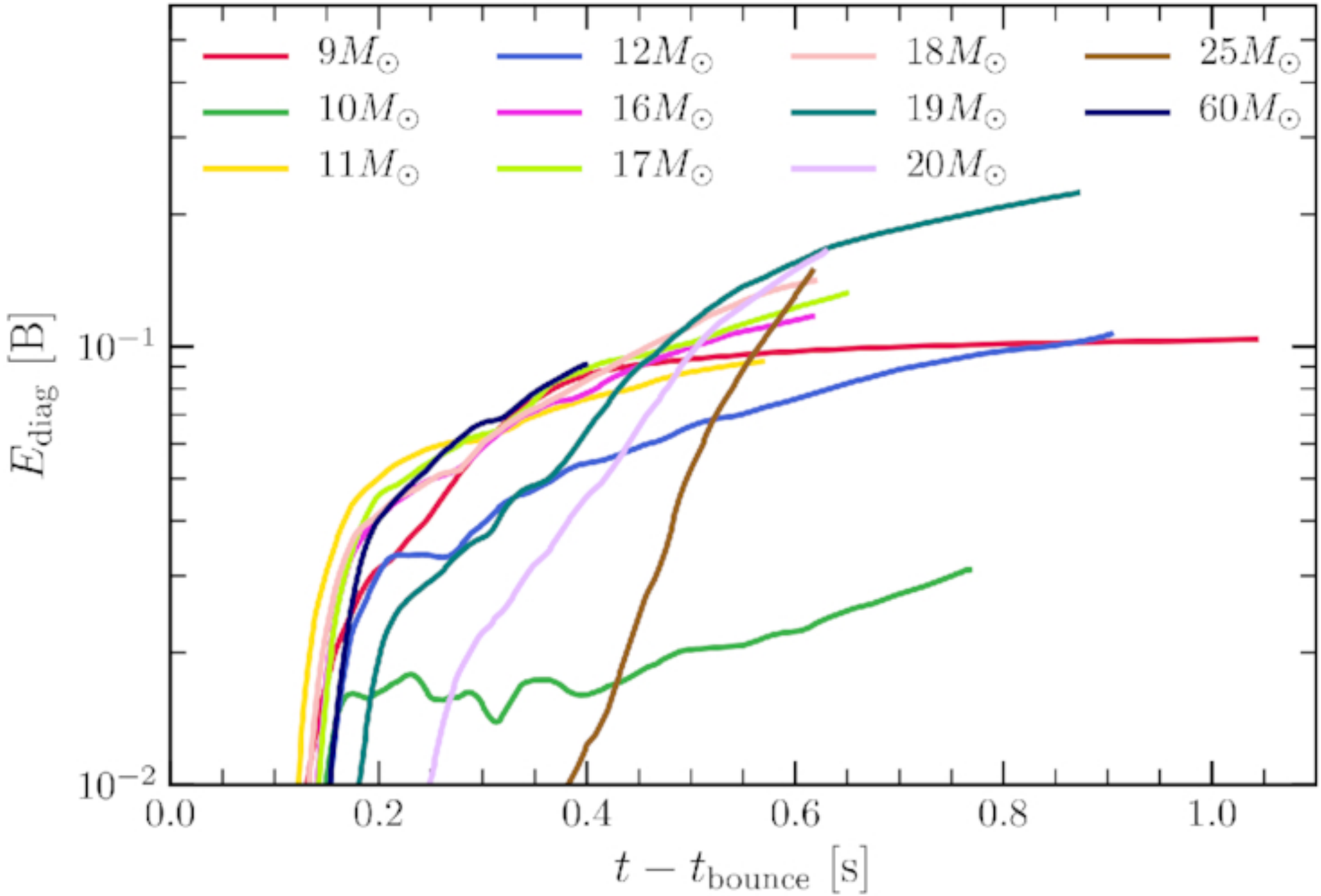
$$\nu + \langle A, Z \rangle \quad \leftrightarrows \quad \langle A, Z \rangle + \nu$$
$$\nu + N \quad \leftrightarrows \quad \nu' + N$$

inelastic scattering

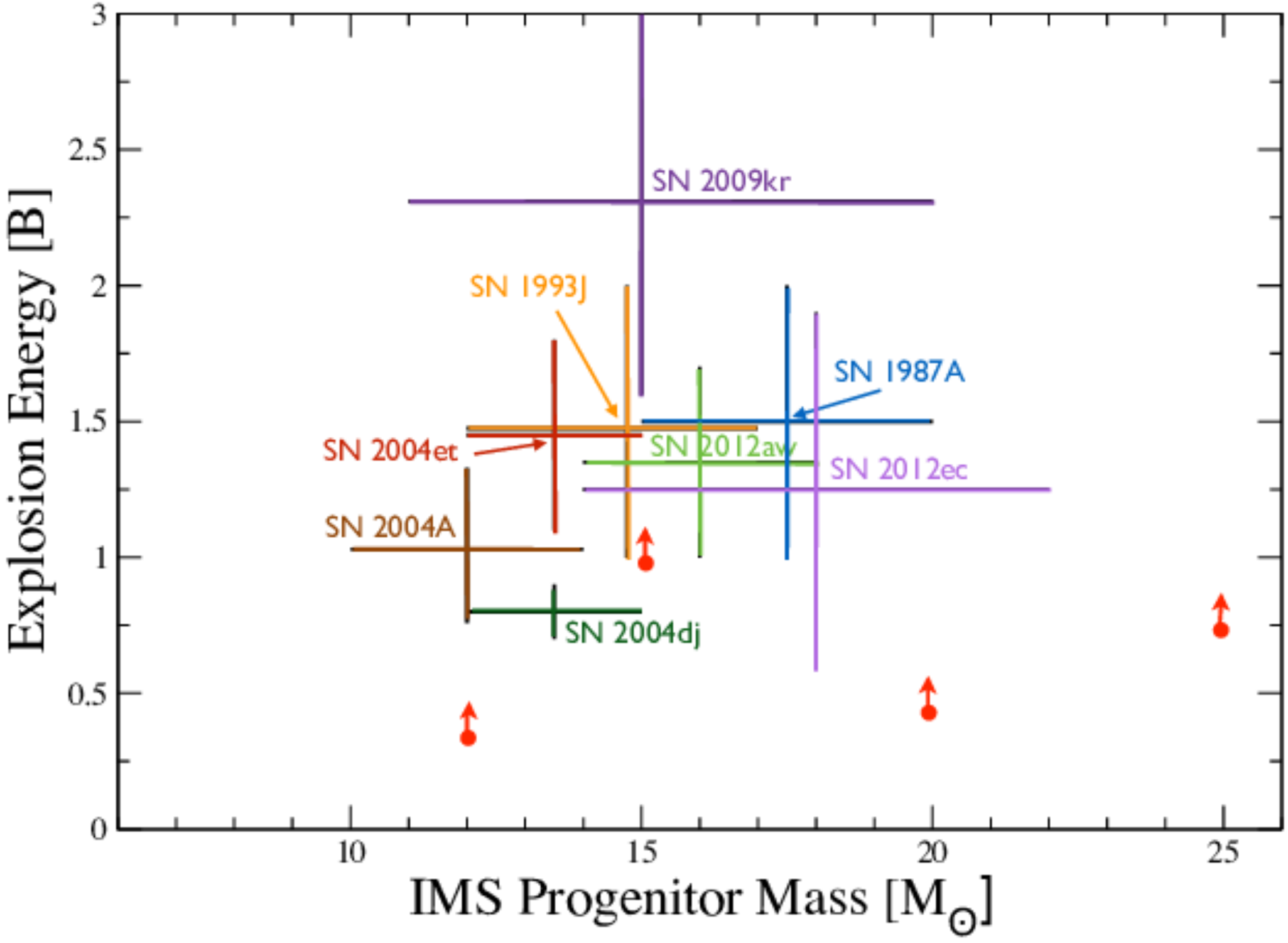
$$\nu + e^\pm \quad \leftrightarrows \quad \nu' + e^\pm$$

pair processes

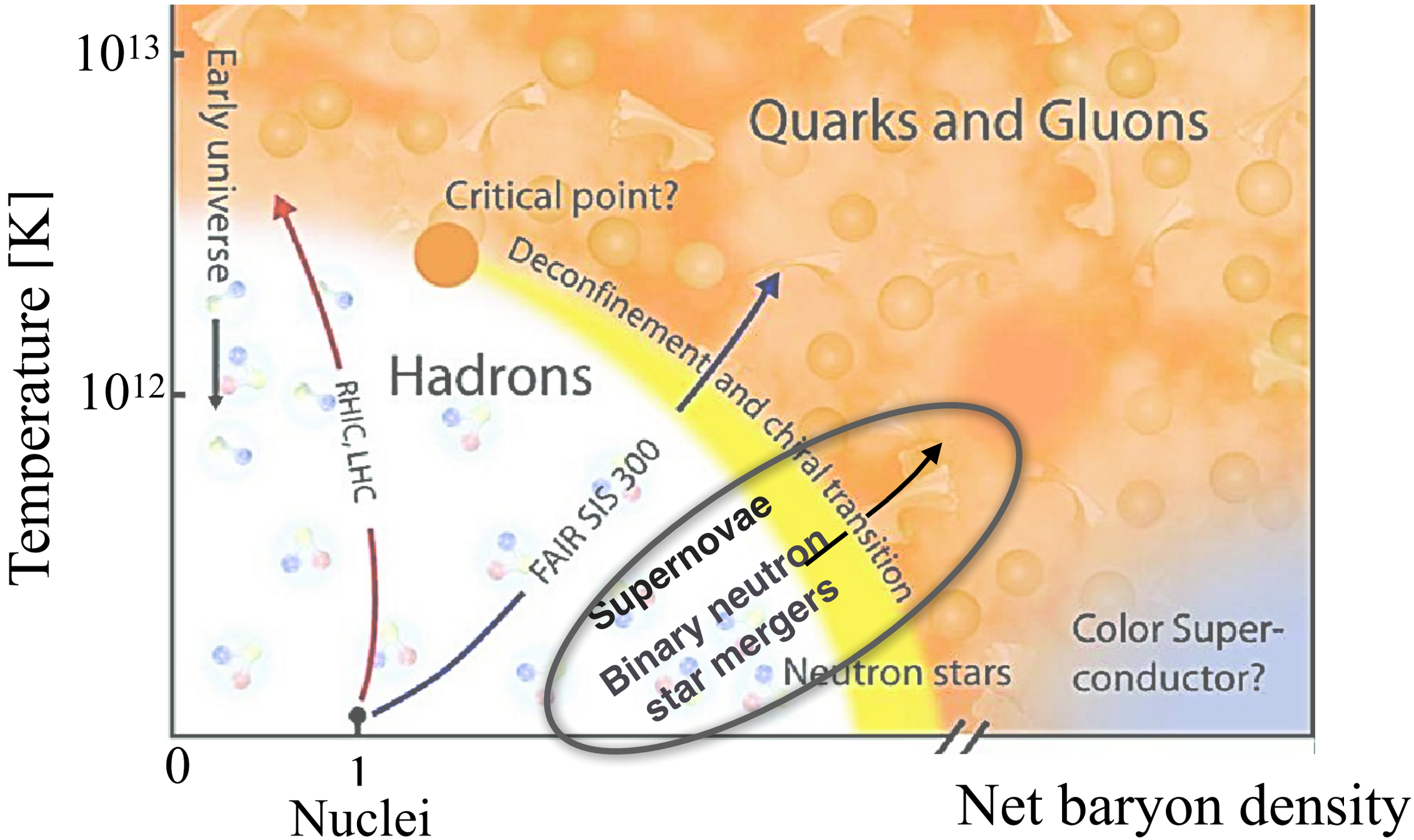
$$e^- + e^+ \quad \leftrightarrows \quad \nu + \bar{\nu}$$
$$N + N \quad \leftrightarrows \quad N + N + \nu + \bar{\nu}$$
$$\nu_e + \bar{\nu}_e \quad \leftrightarrows \quad \nu_{\mu/\tau} + \bar{\nu}_{\mu/\tau}$$



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

P [MeV fm^{-3}]

$Y_e = 0.5$

flow constraint

symmetric matter (T=0)

(a)

$Y_e = 0.3$

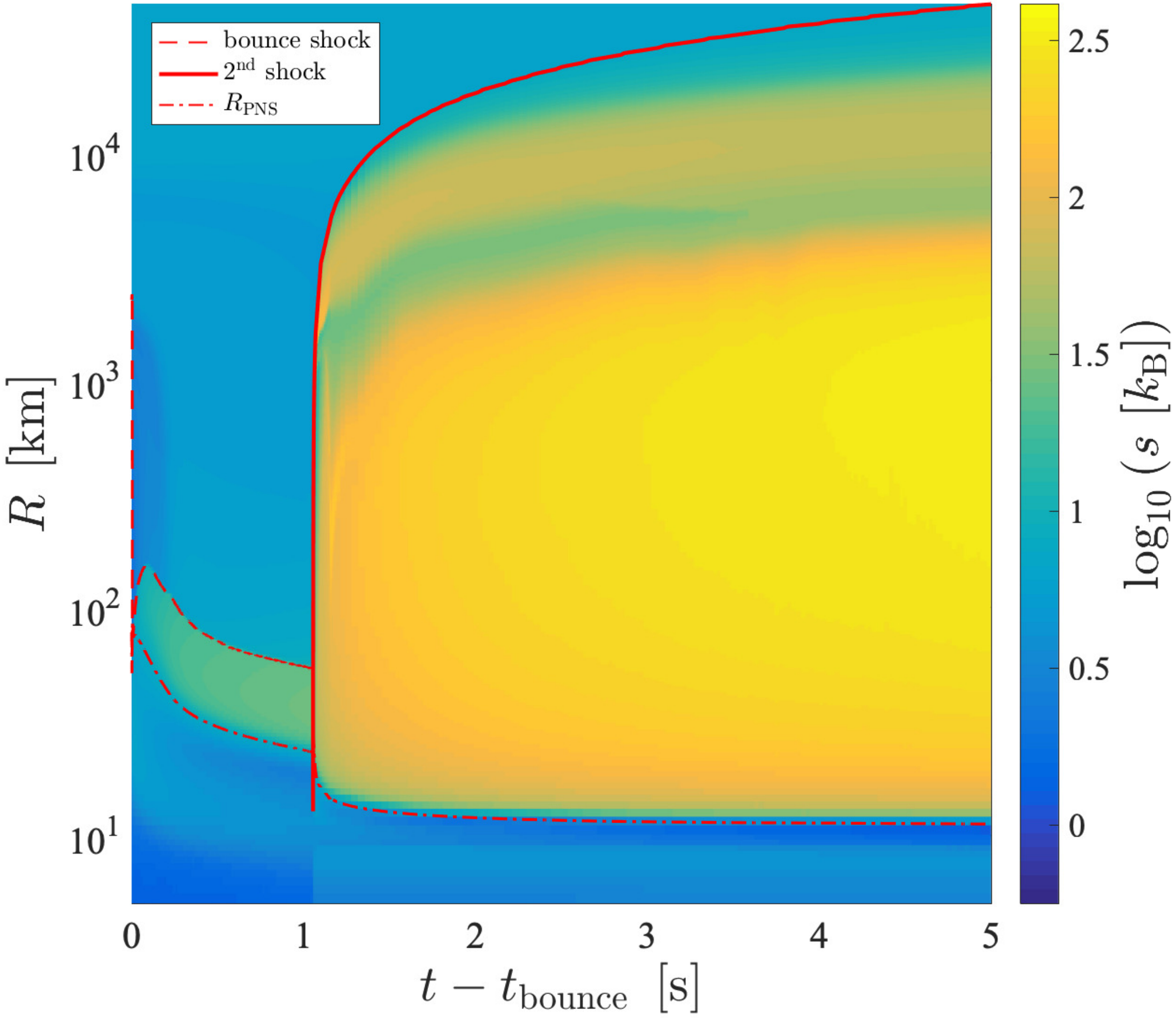
Supernova matter (S=3)

(b)

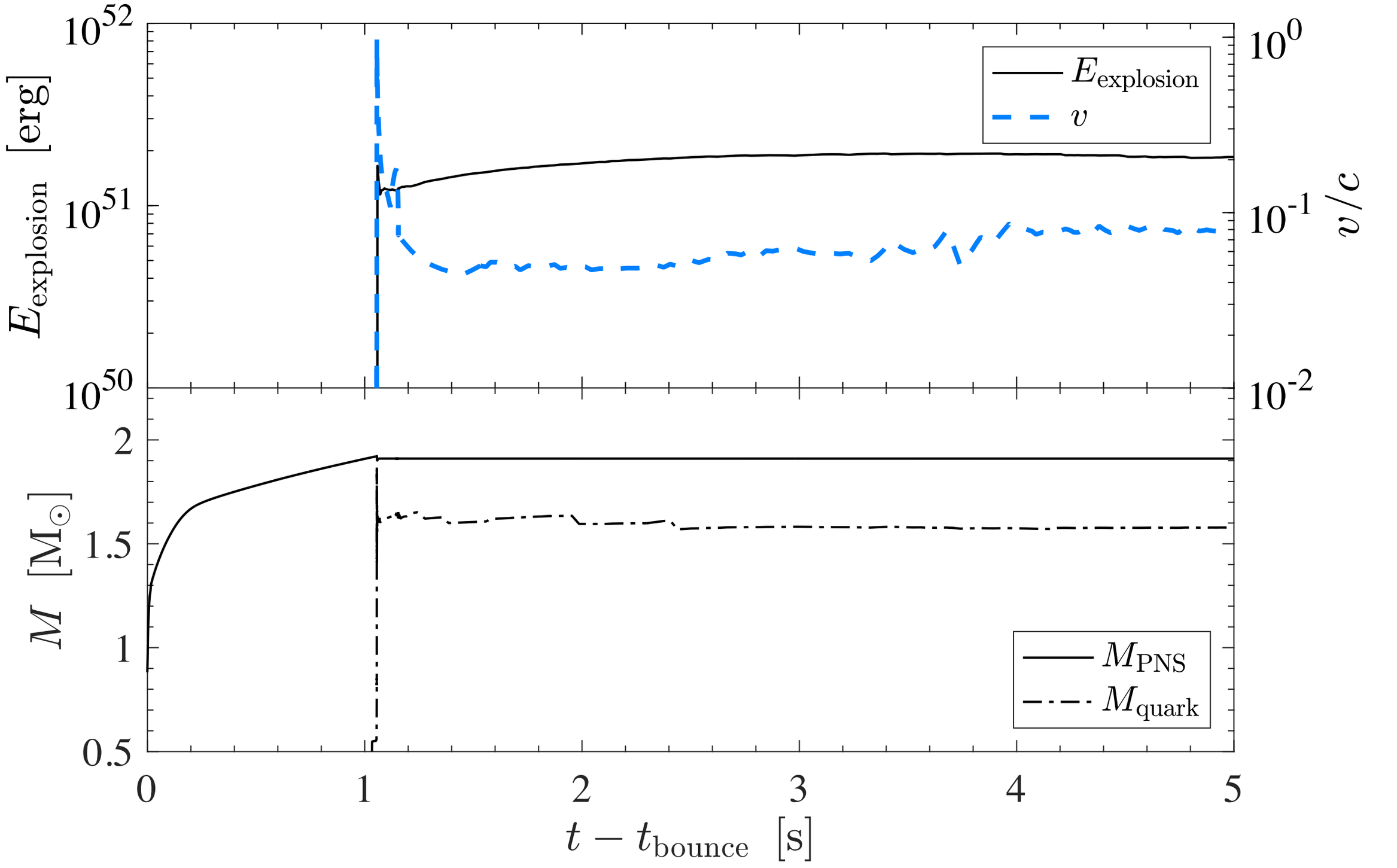
P [MeV fm^{-3}]

ρ/ρ_{sat}

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

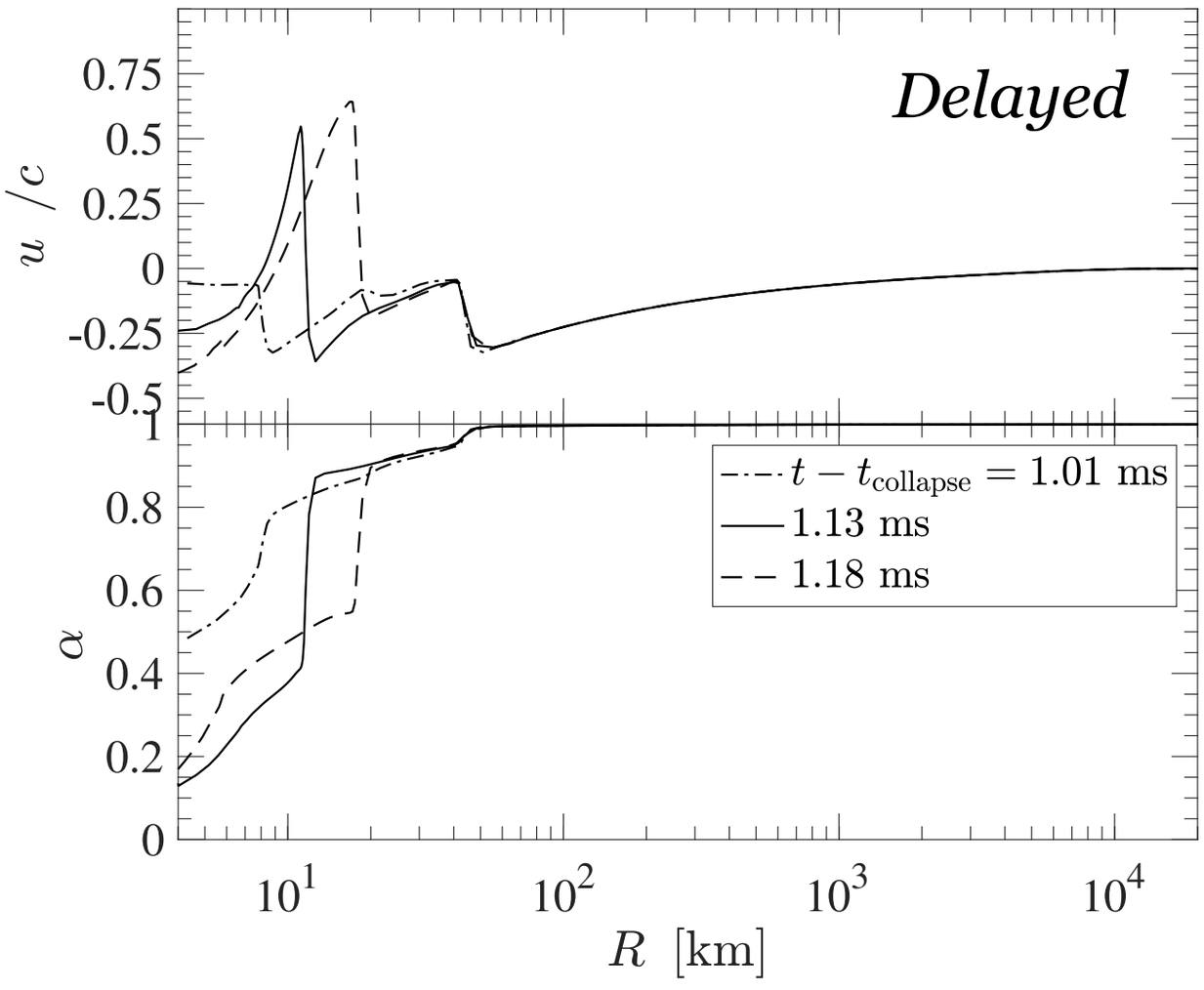


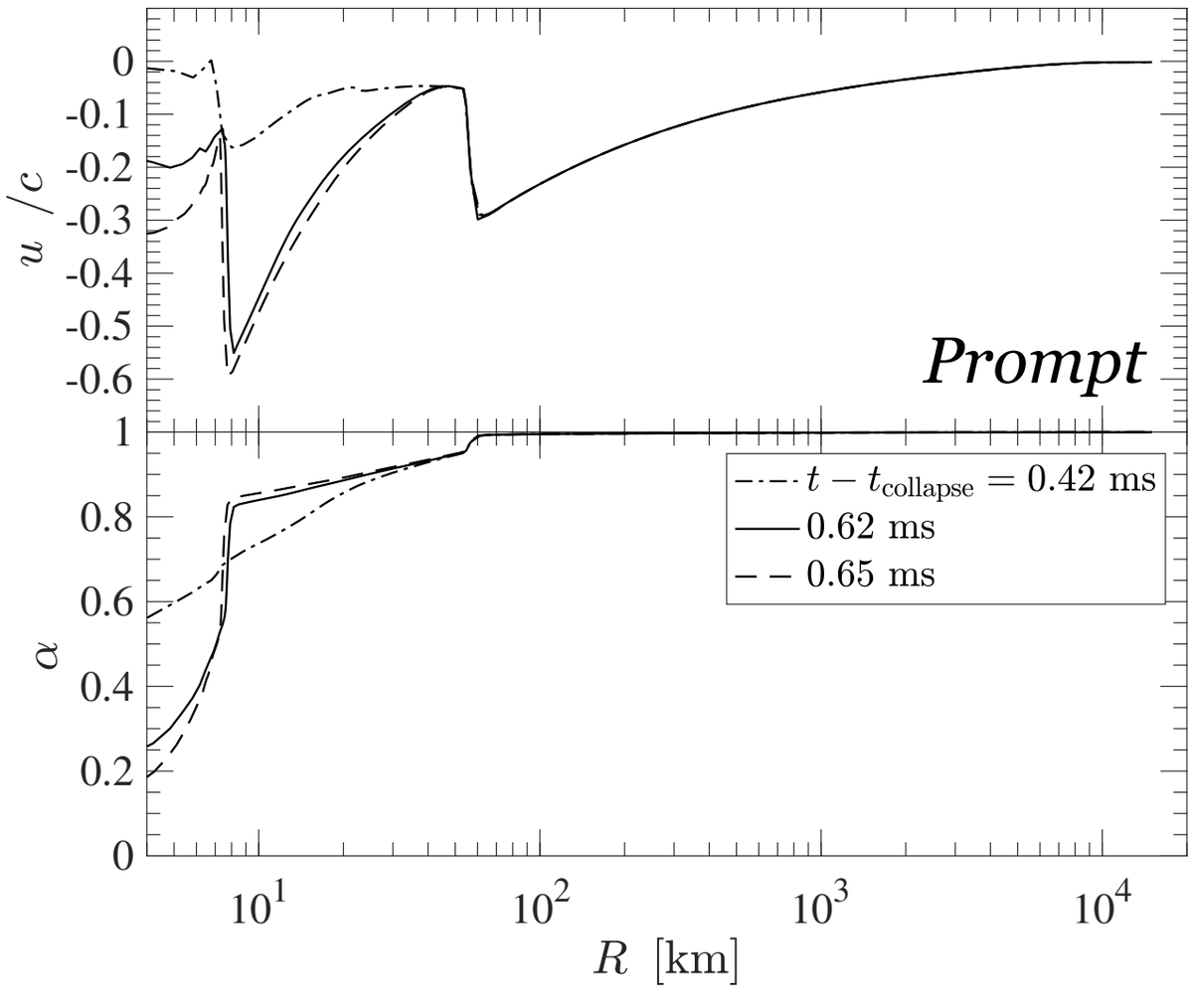
Khosravi Largani et al., ApJ 946, 143 (2024)



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

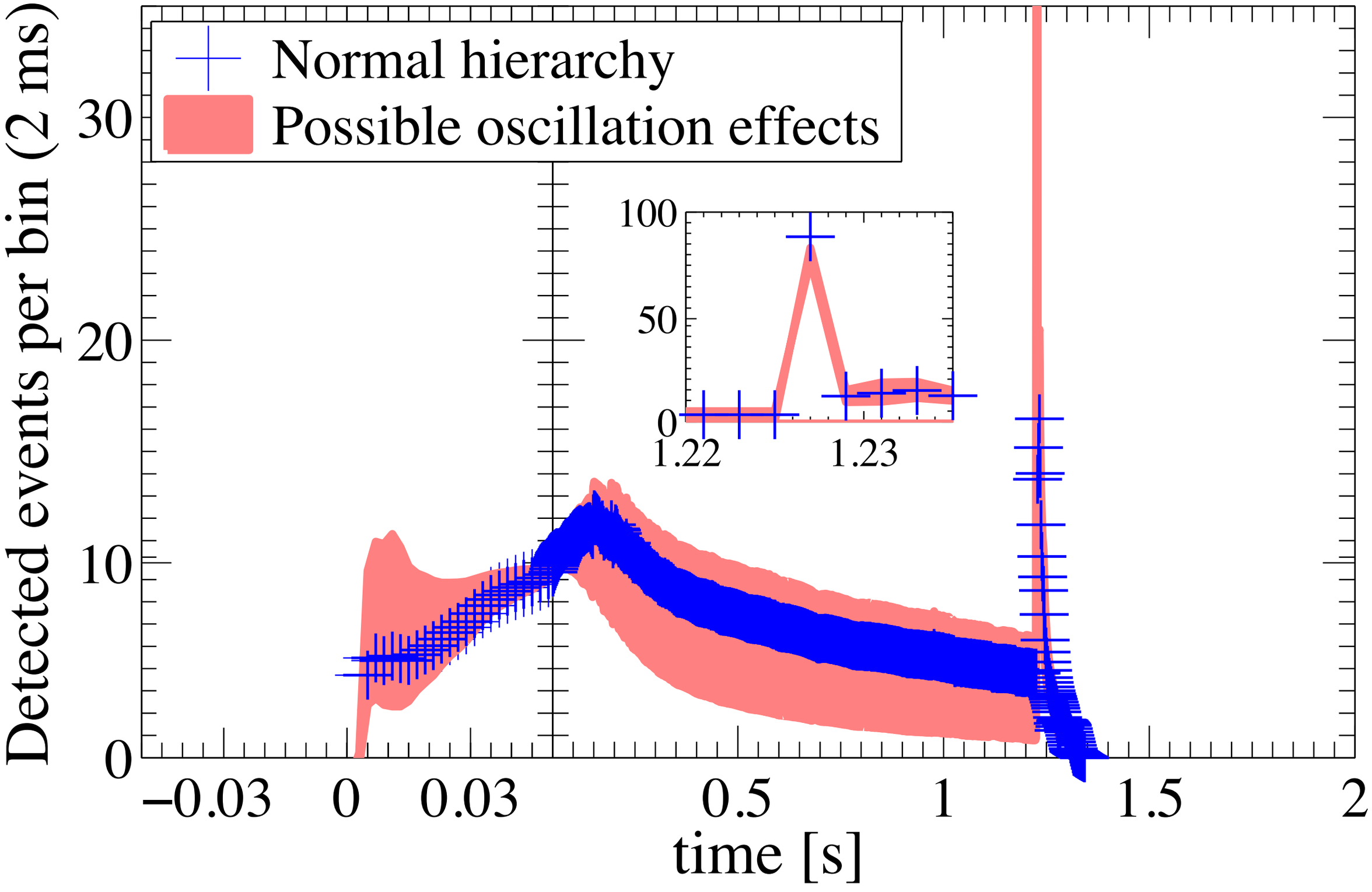
Black-hole formation: **Two distinct scenarios**





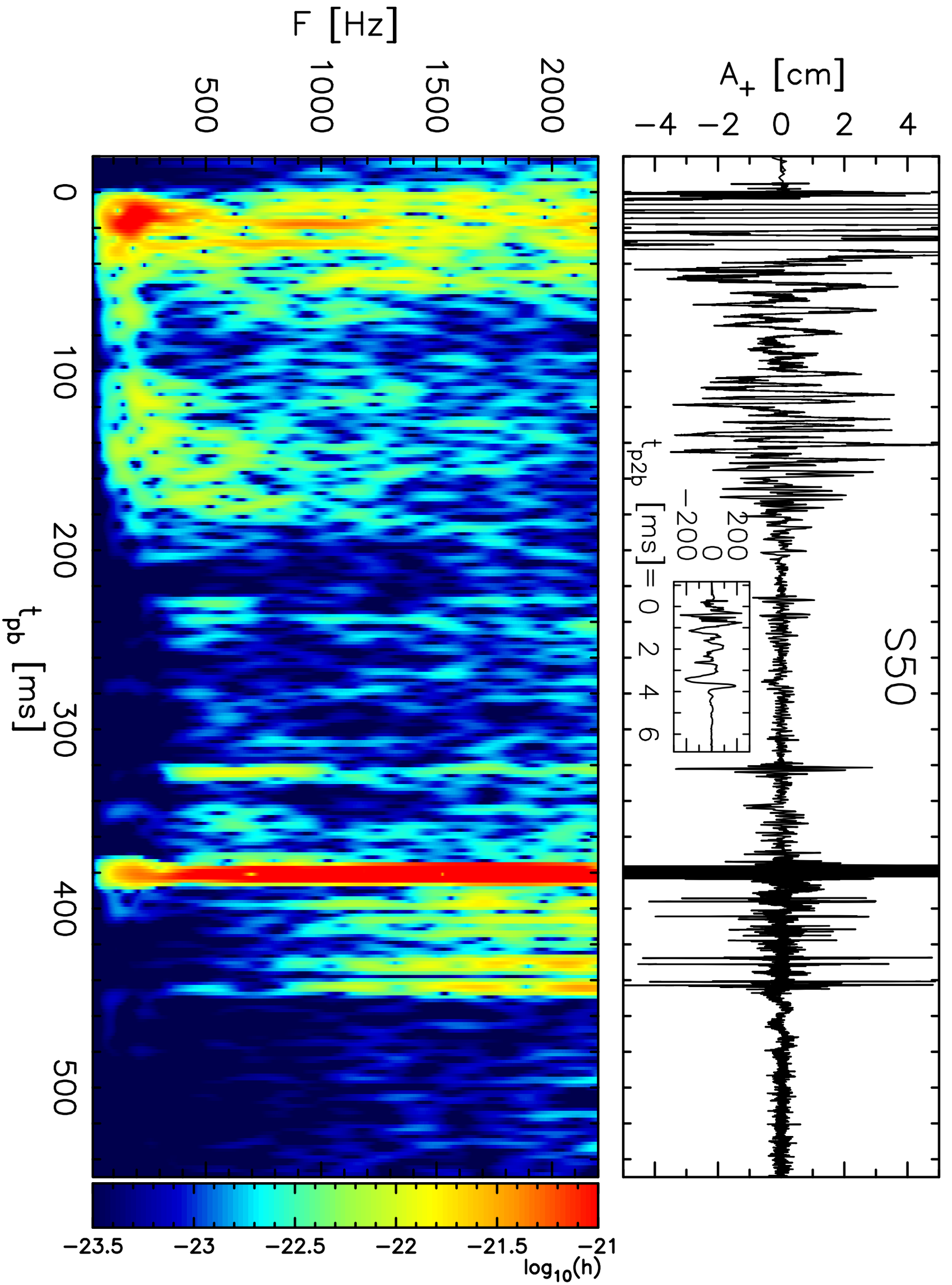
Jakobus et al., MNRAS, 516, 2554 (2022)
Khosravi Largani et al., ApJ 946, 143 (2024)

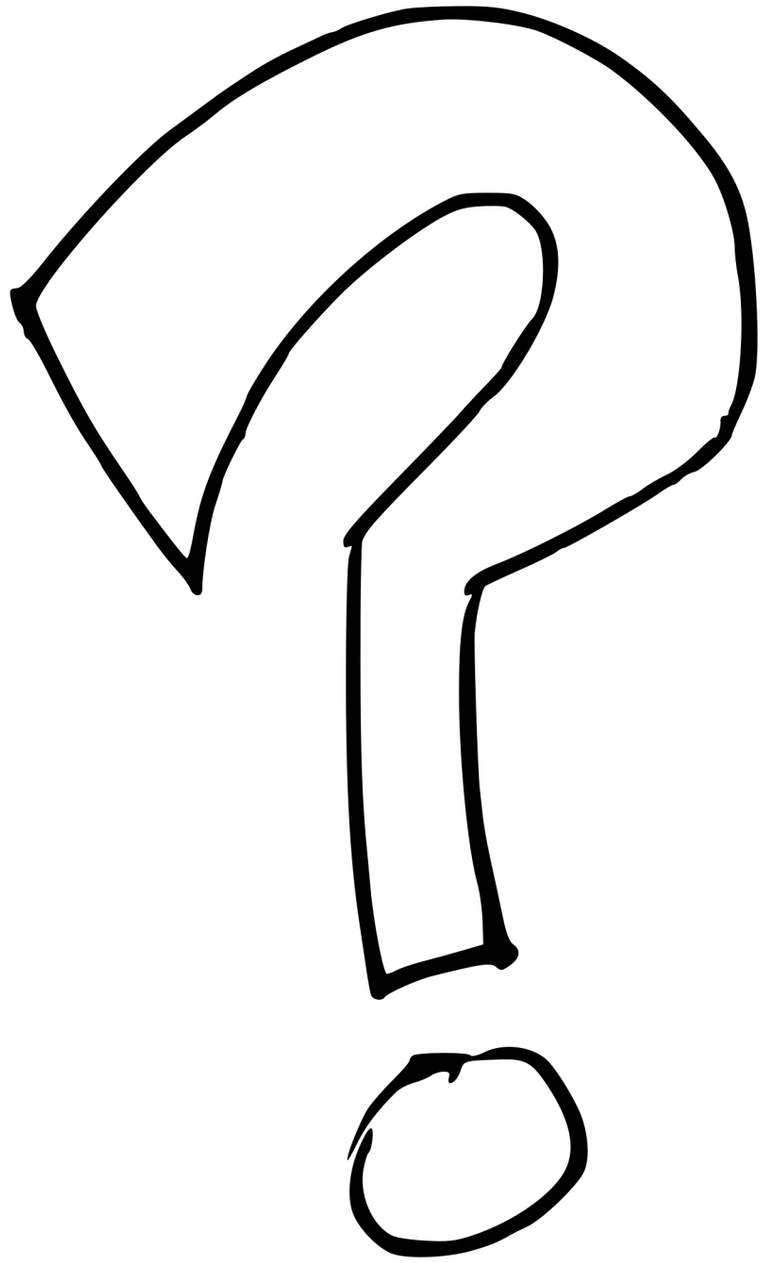
ν – signal @ Super-Kamiokande (d ~ 10 kpc)

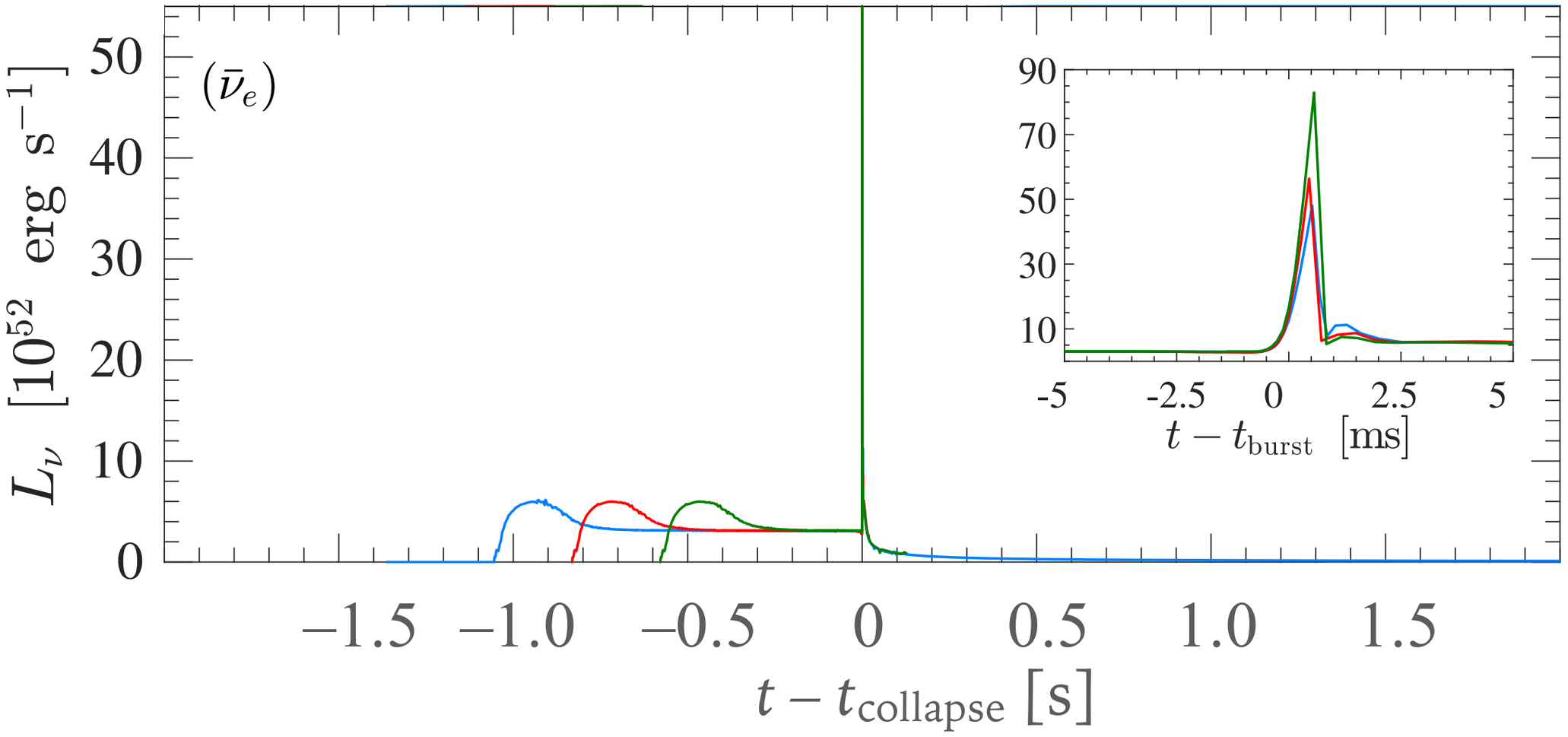


Fischer et al., Nature Astron. **2**, 980 (2018)

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

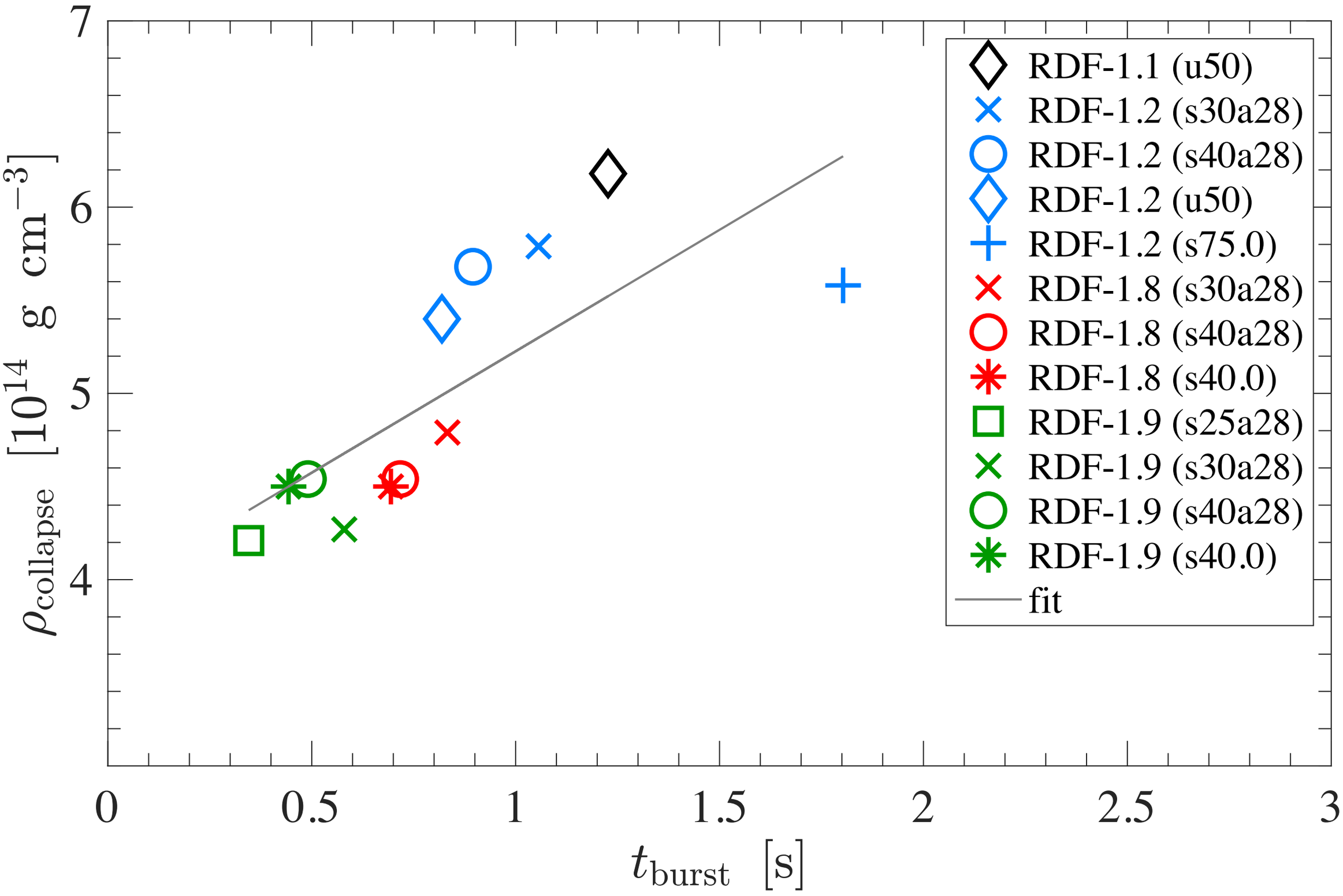






Khosravi Largani et al., ApJ 946, 143 (2024)

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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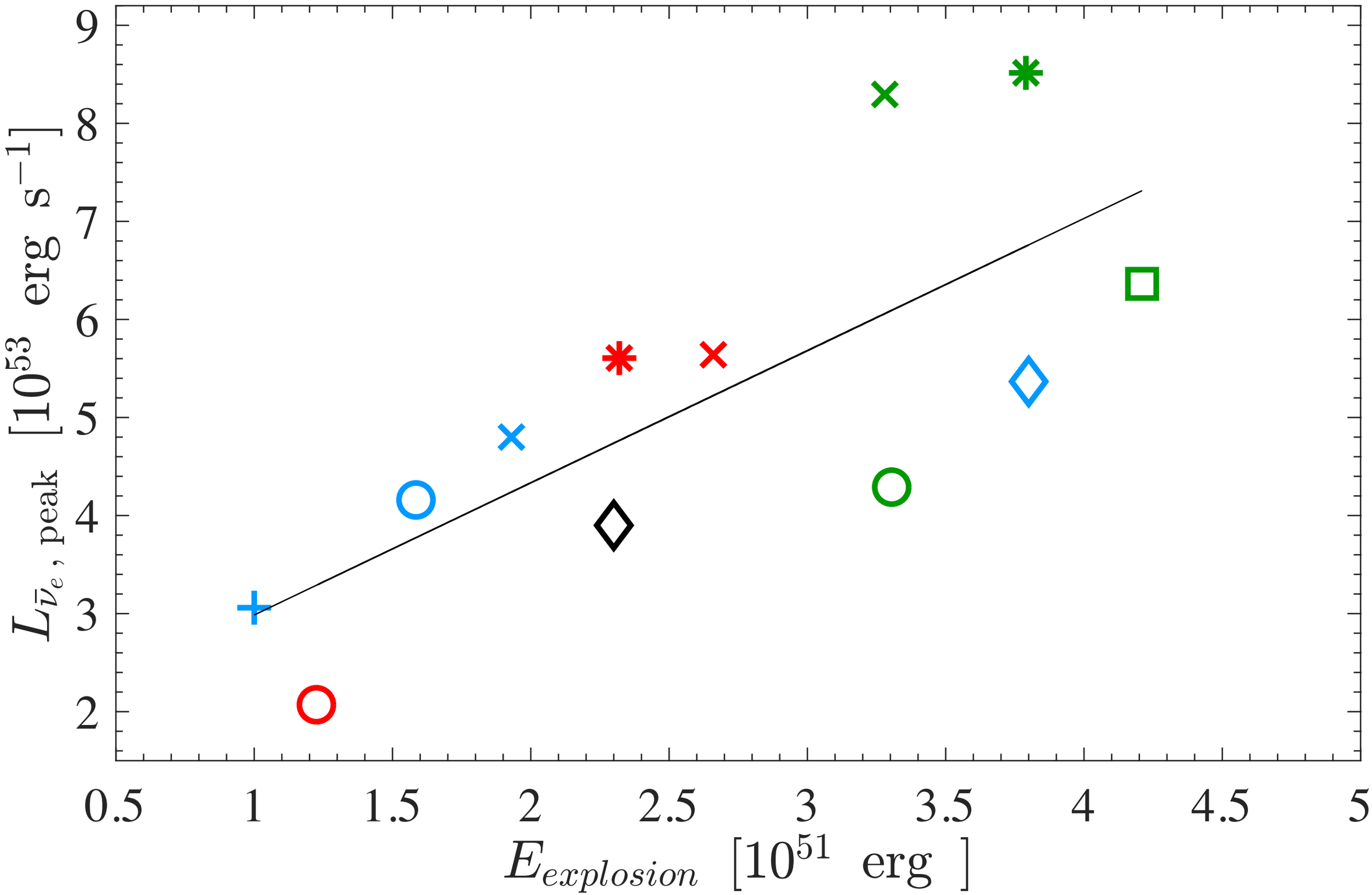

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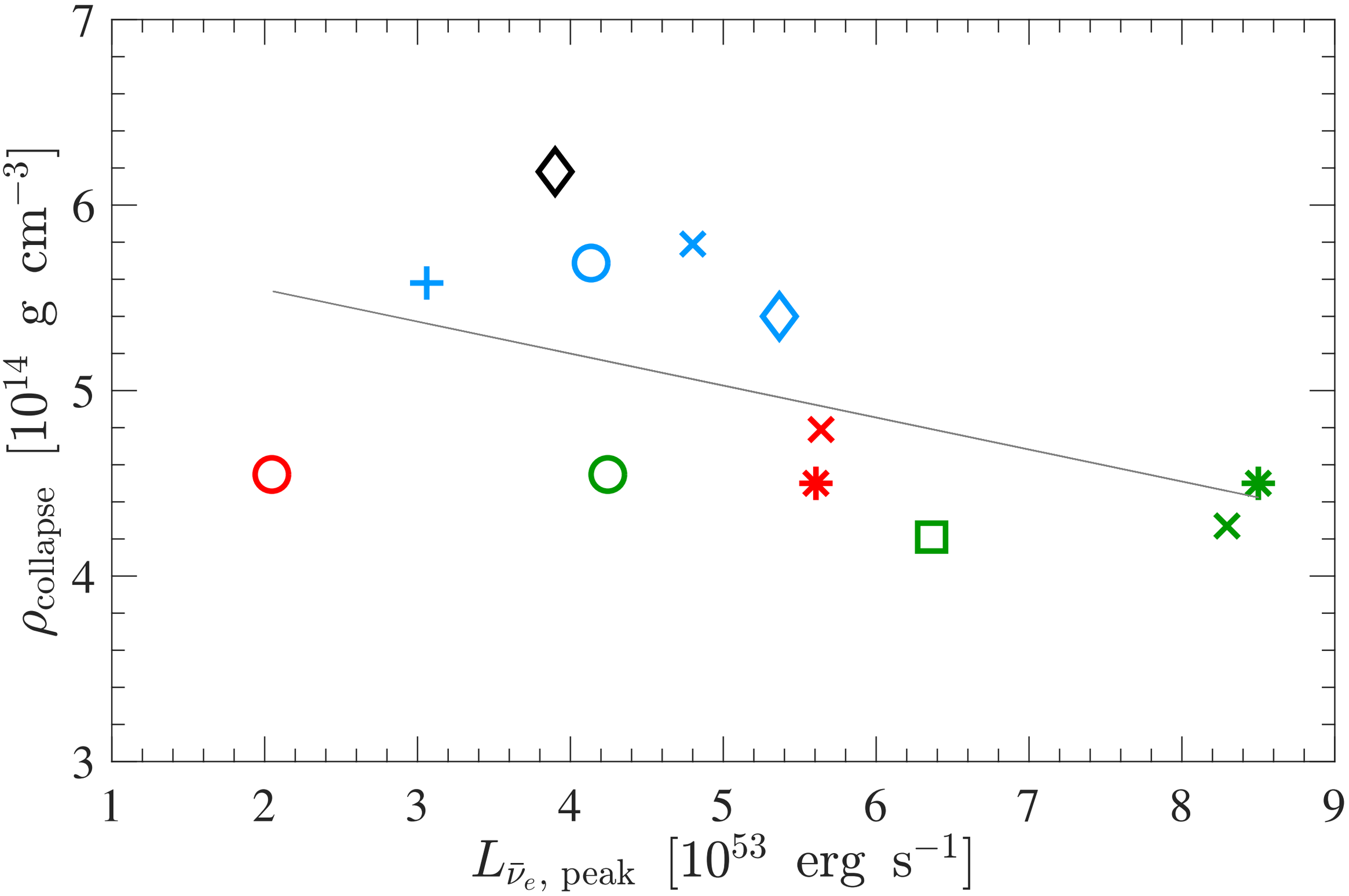

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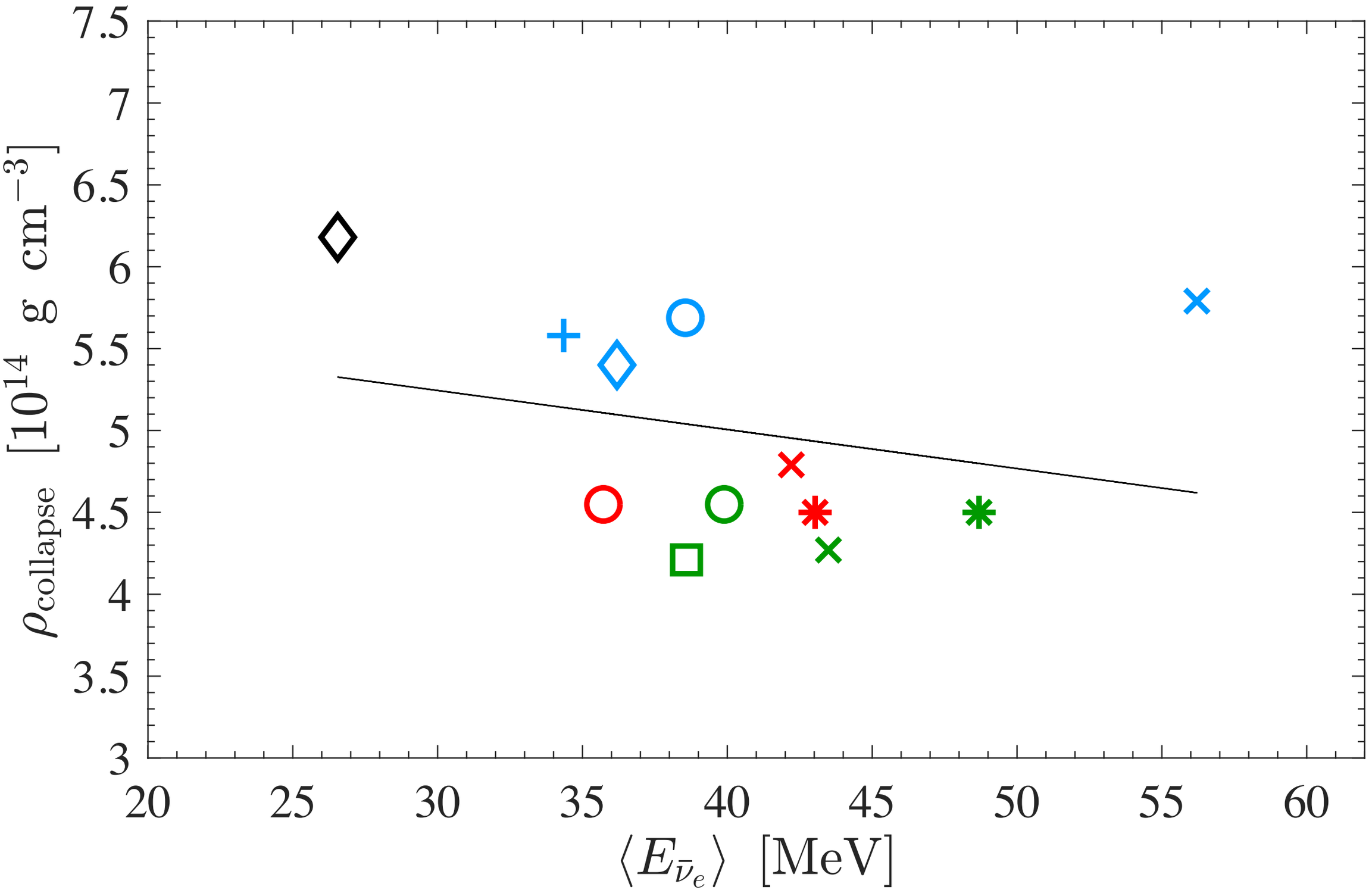

Khosravi Largani et al., ApJ 946, 143 (2024)