QCD Phase transition in Core Collapse Supernovae

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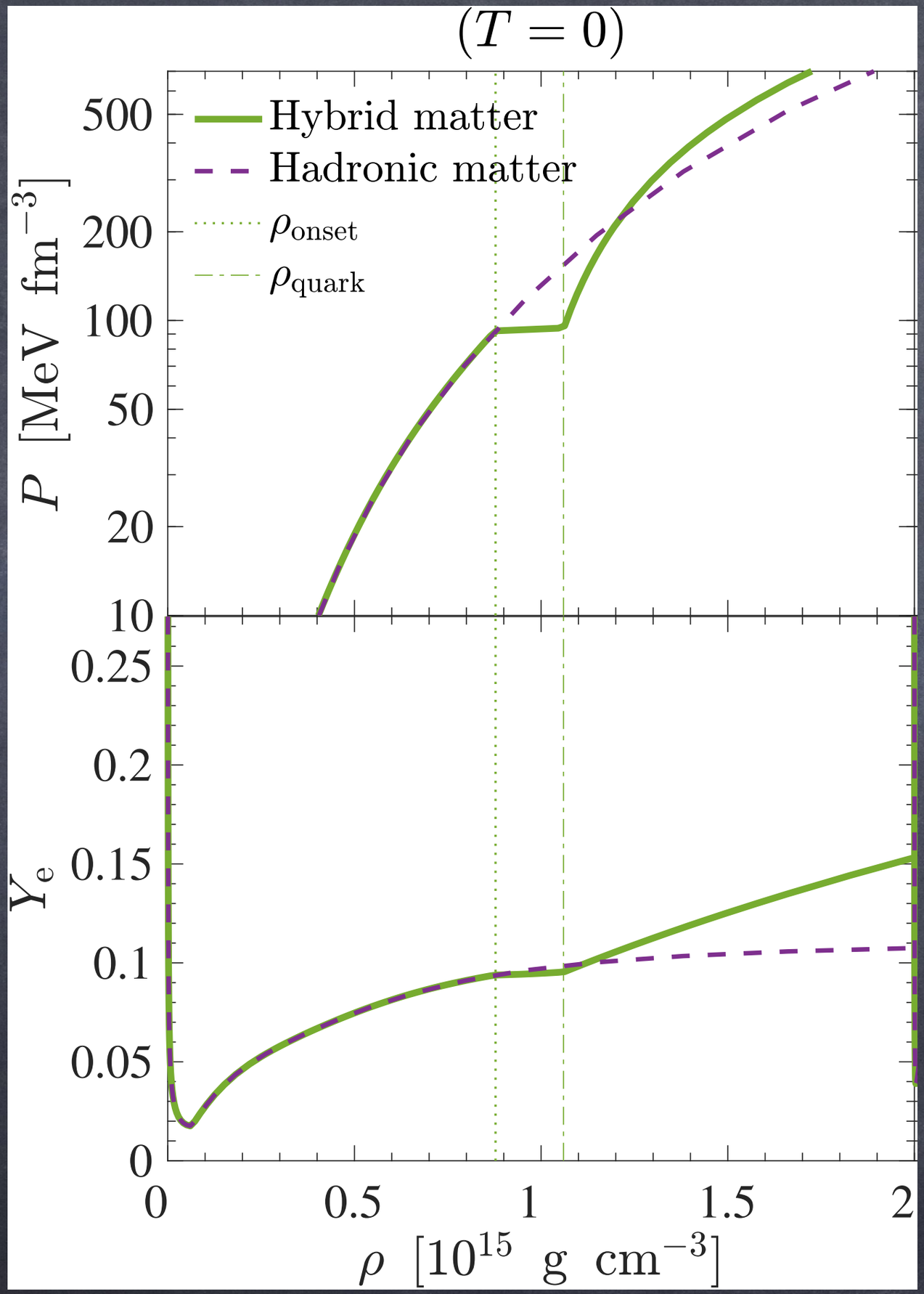
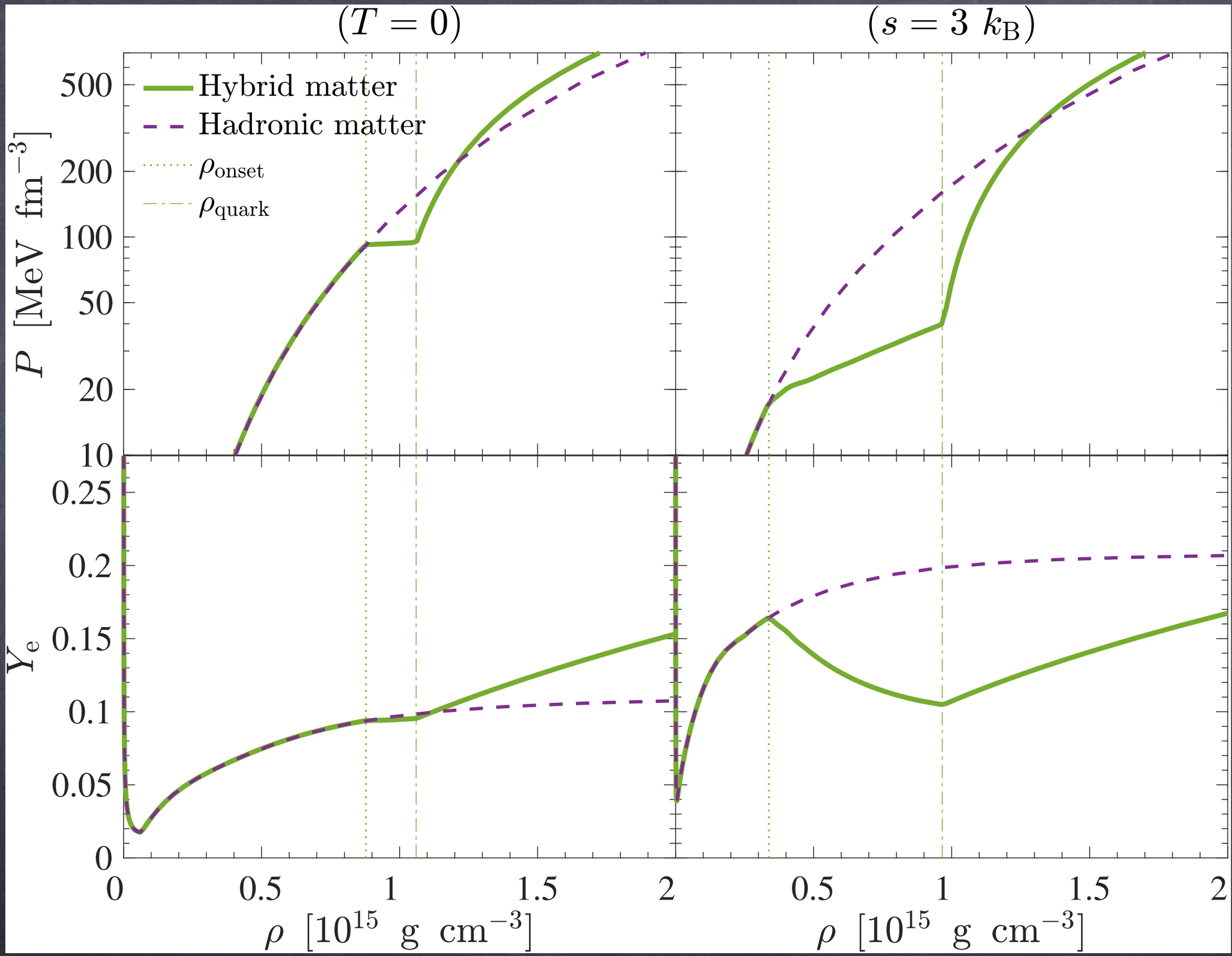
thematic school GWsNS 2026 1 July 2026, Roscoff



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



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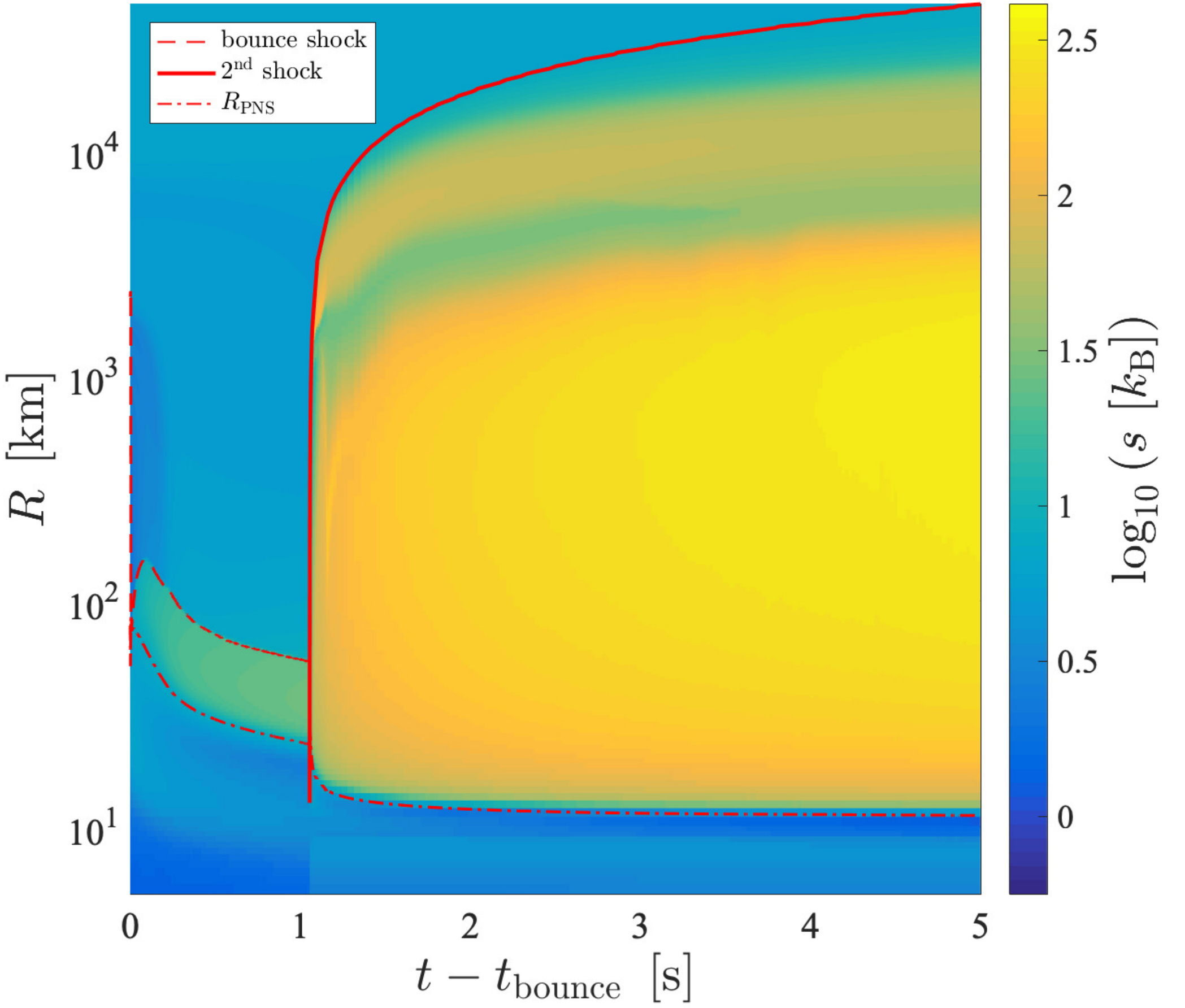
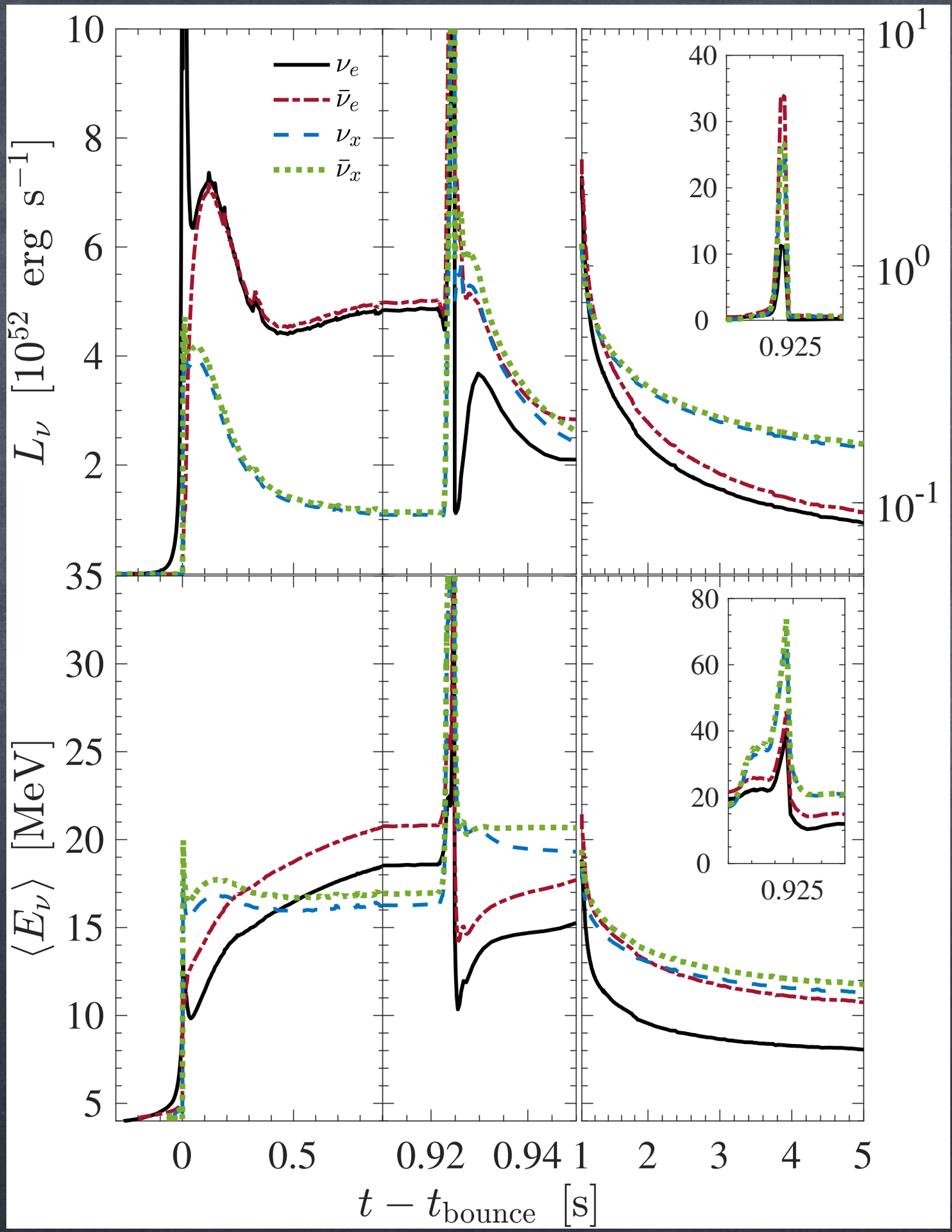
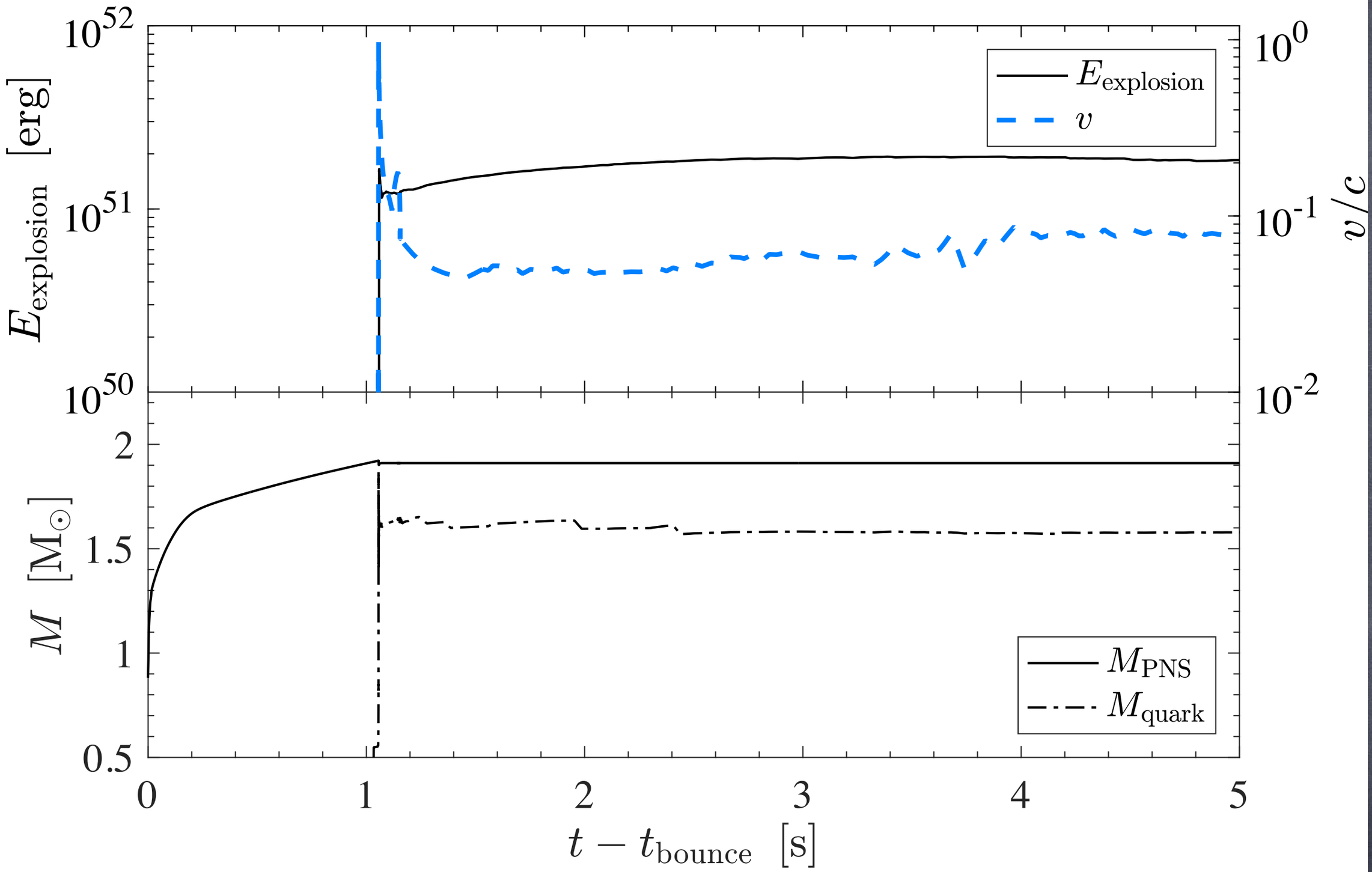


Khostravi Largani et al., Astrophys. J, 946, 143


ν_e
$\bar{\nu}_e$
ν_x
$\bar{\nu}_x$
L_ν [10^{52} erg s^{-1}]
$\langle E_\nu \rangle$ [MeV]
$t - t_{\rm bounce}$ [s]
0.925
0.925

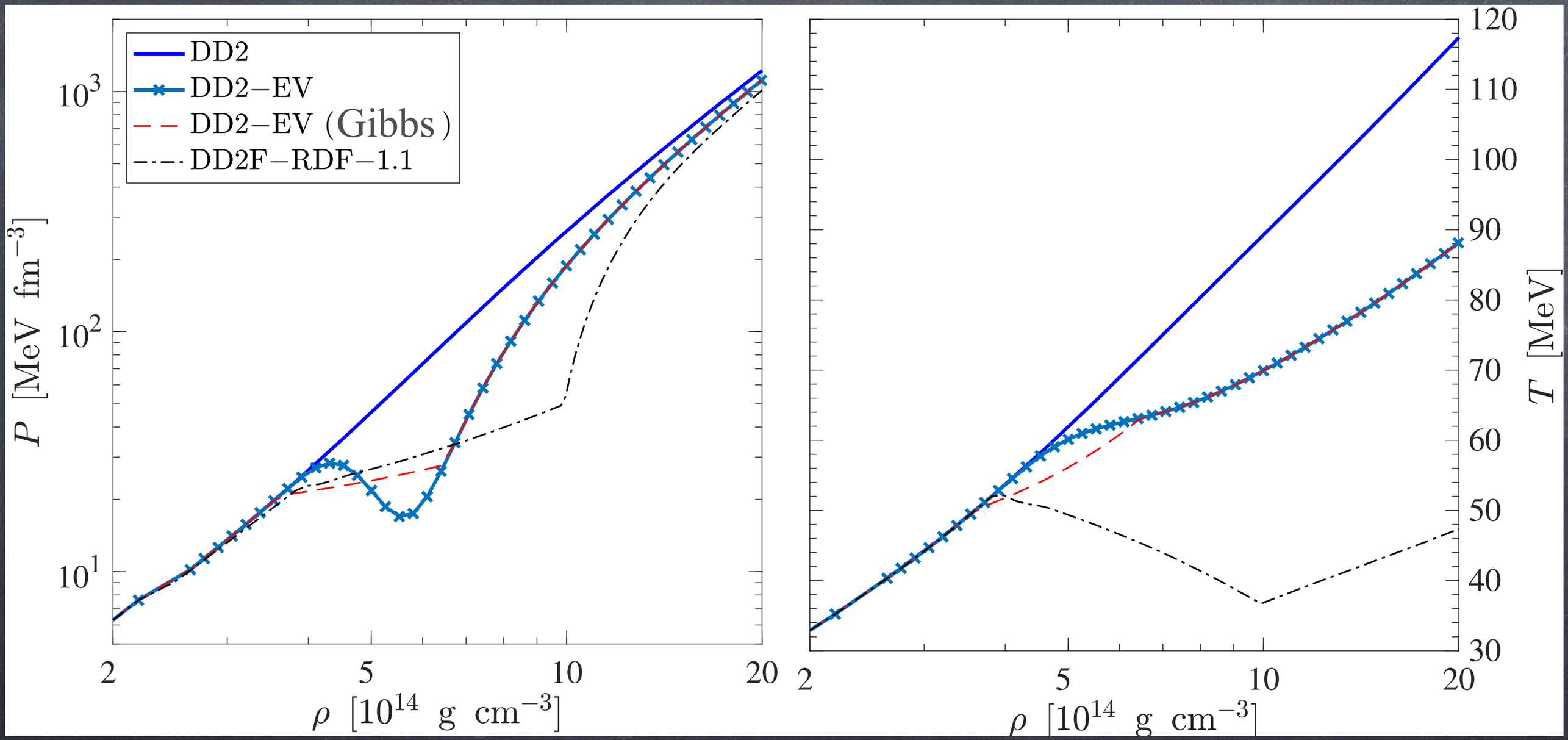
Khosravi Largani et al., Astrophys. J. 946, 143



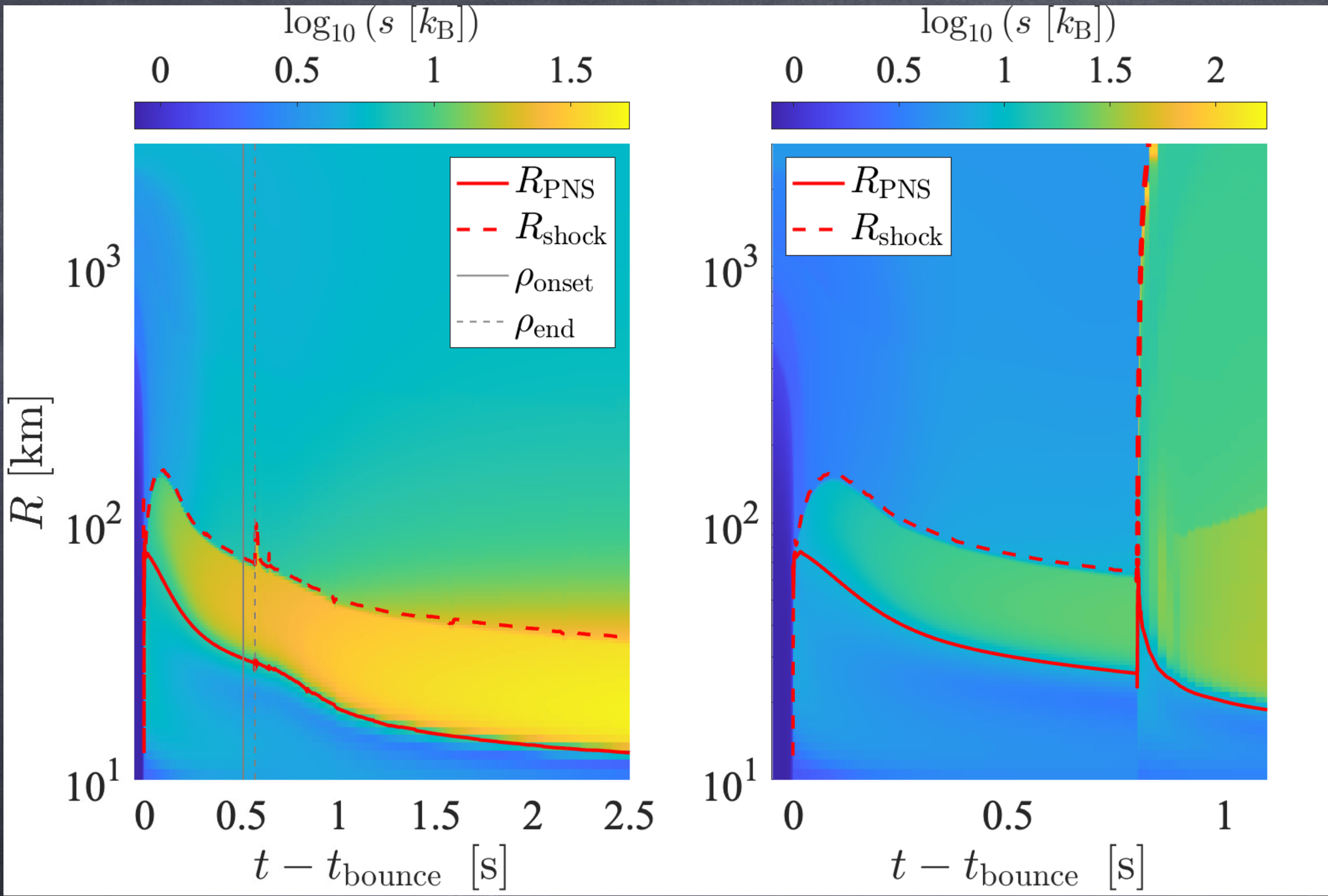
$$\mathrm{E_{expl}} = 3 \times 10^{51}\ \mathrm{erg}$$
$$\mathrm{M_{NS}} \simeq 2\ \mathrm{M_\odot}$$

$$g_N \longrightarrow g_{\rm eff}(T, n_{\rm B}) = g_N \, \Phi_N(T, n_{\rm B})$$

Typel, Blaschke 2018, Universe 4 32



Kumar et. Al., CQG (In prep.)



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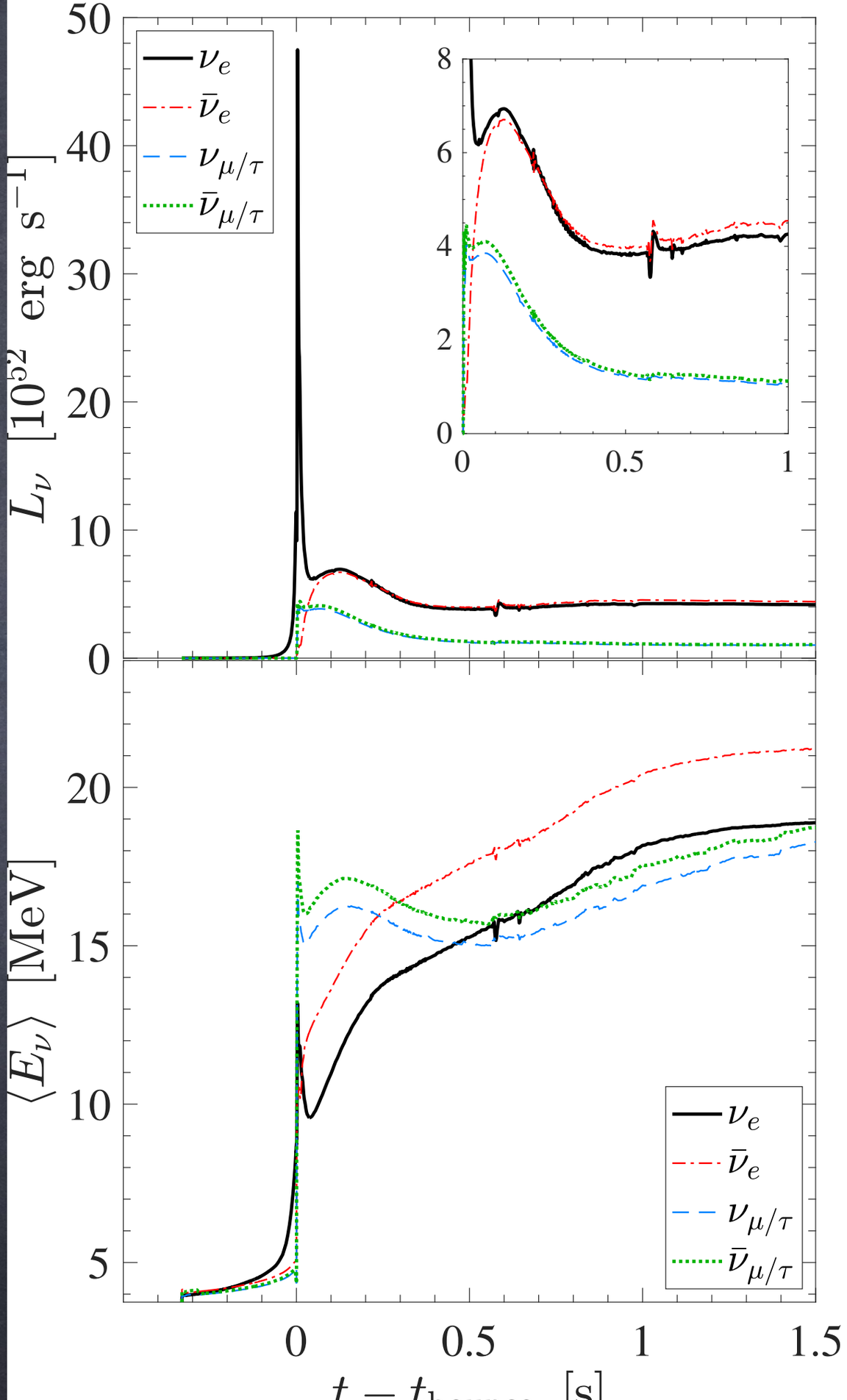
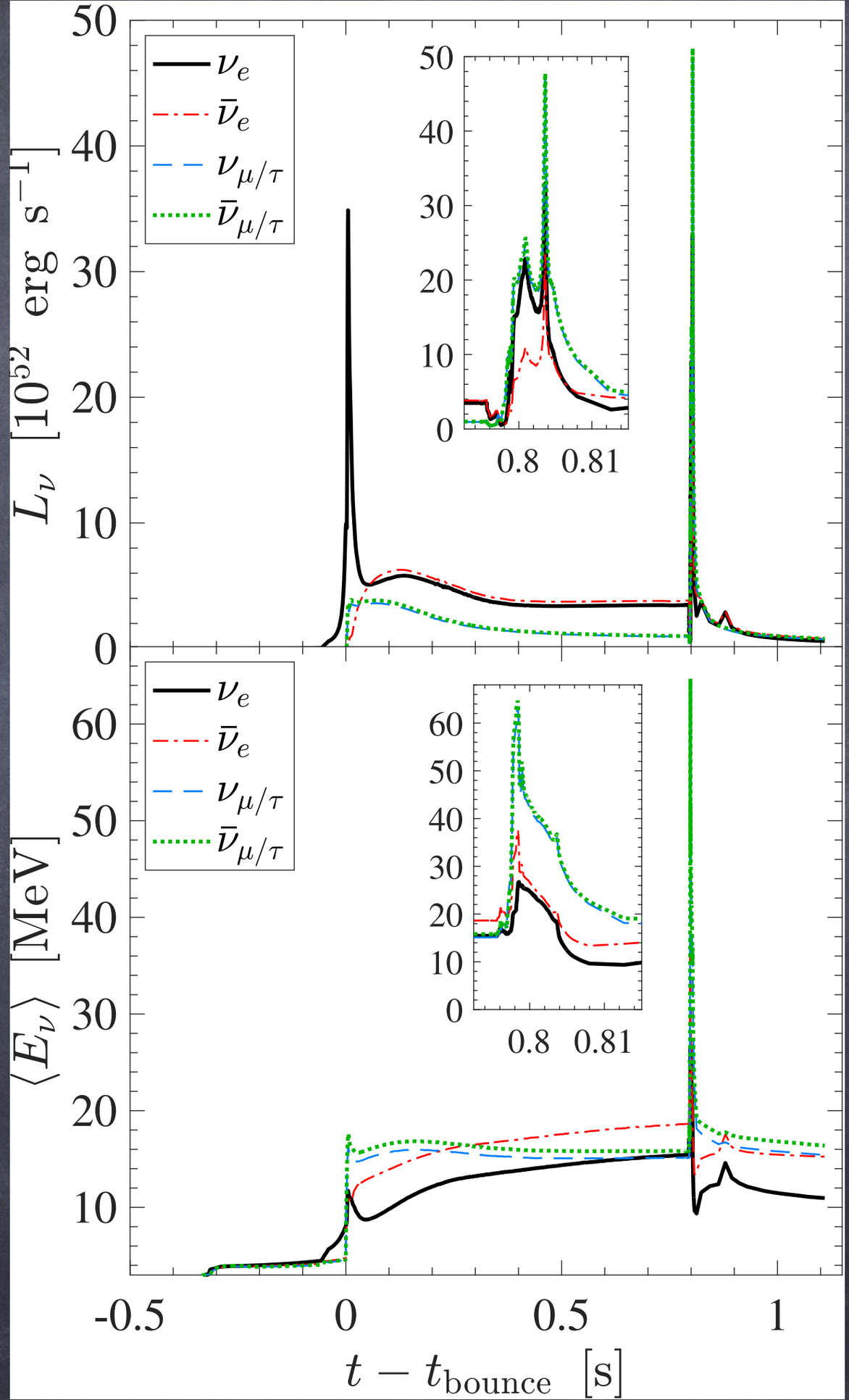




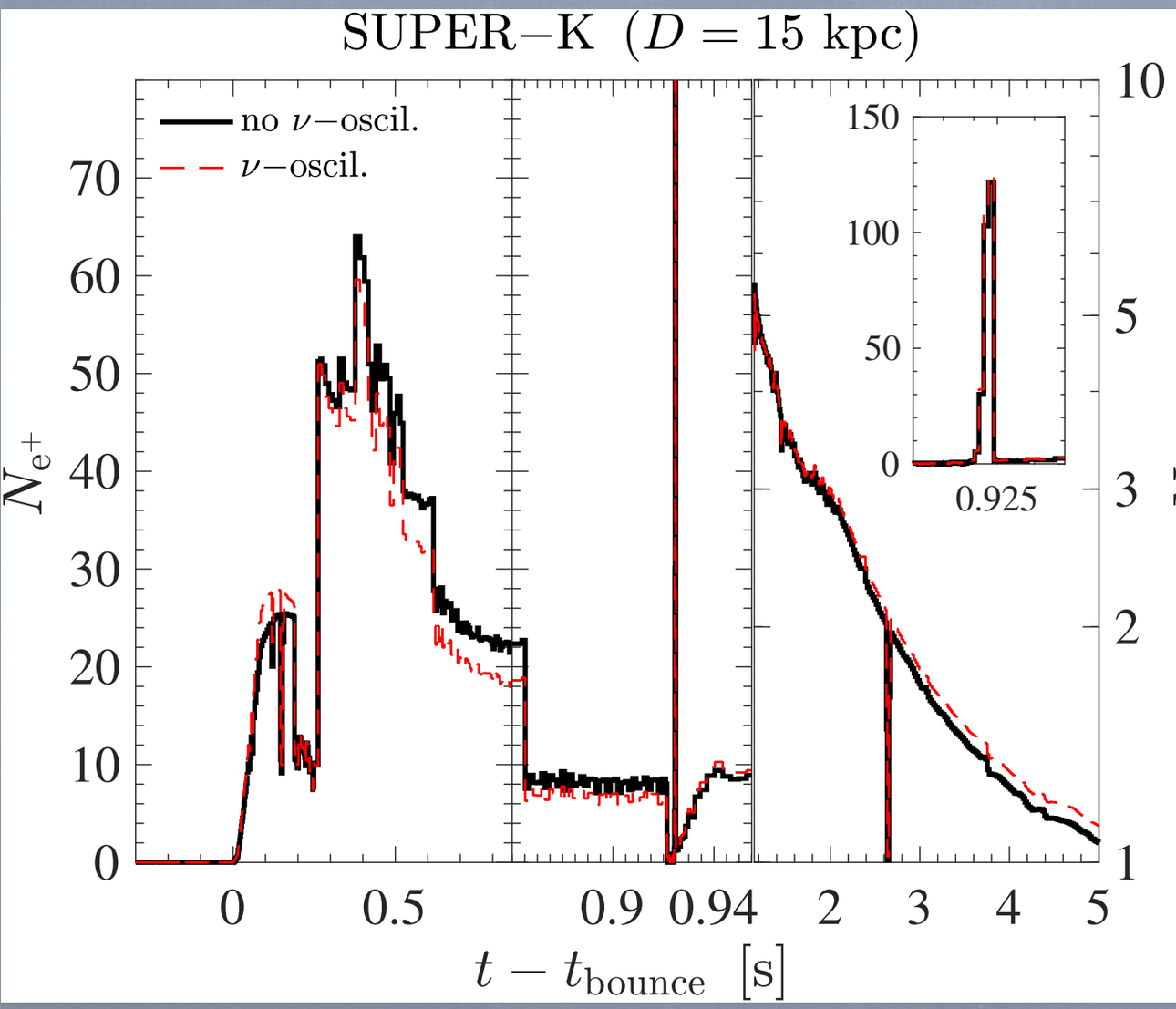
GW modes and more in preparation

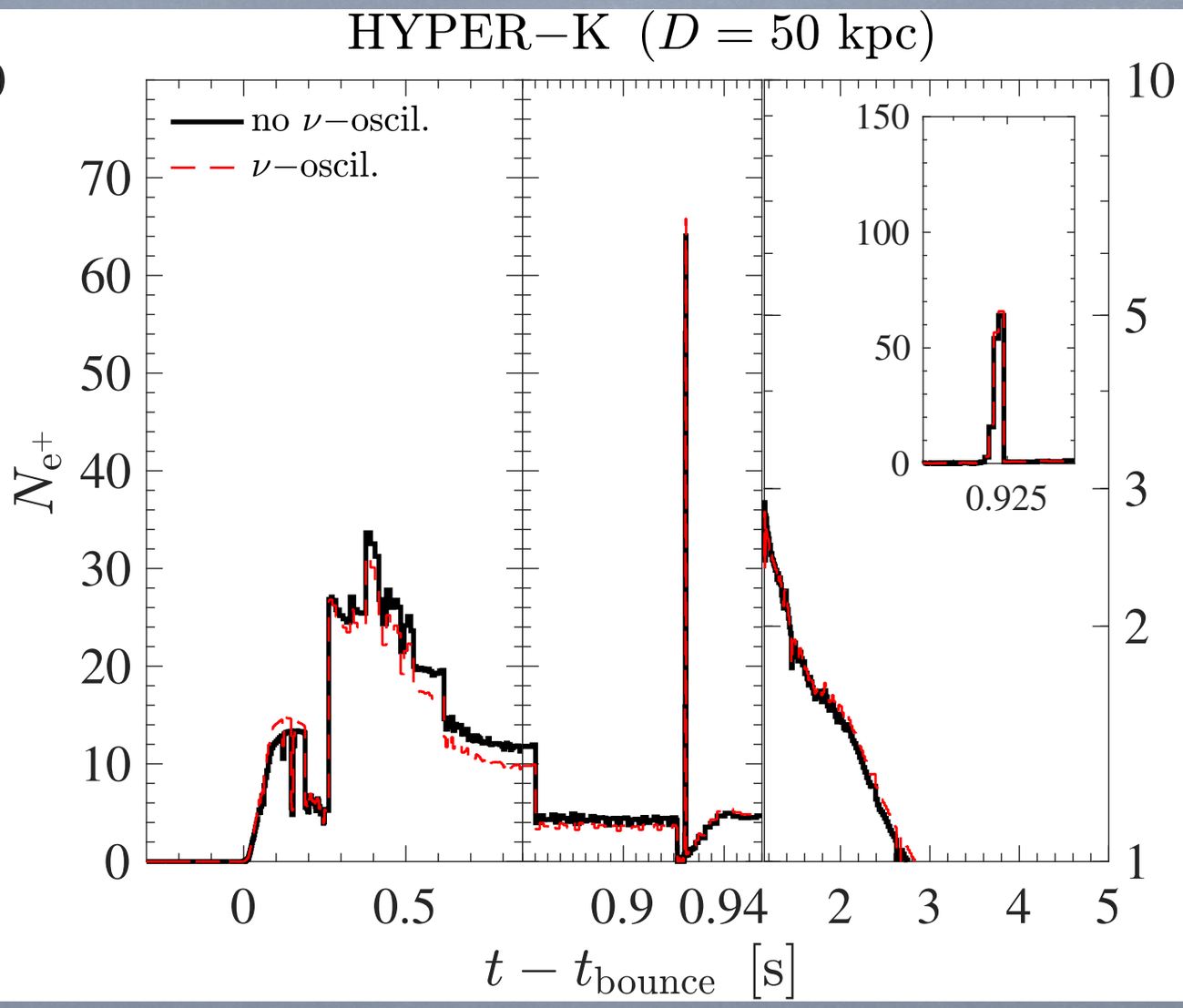
Stay Tuned!

Backup slides

$$\text{inverse } \beta-\text{decay}: \qquad \bar{\nu}_e + \mathrm{p} \longrightarrow \mathrm{e}^+ + \mathrm{n} \quad (Q = m_\mathrm{n} - m_\mathrm{p} = 1.2935 \text{ MeV})$$

$$N_{\mathrm{e}^+} \simeq N_\mathrm{p}\, N_{\bar{\nu}_e}\, \frac{\lambda_{\bar{\nu}_e \mathrm{p}}}{4\pi D^2}$$





General relativistic neutrino radiation hydrodynamics

- **The general framework**

$$ds^2 = -\alpha^2 dt^2 + \left(\frac{r'}{\Gamma}\right)^2 da^2 + r^2(d\theta^2 + \sin^2\theta d\phi^2)$$

The co-moving reference frame:

$(t,\, a)$ (system time, baryon mass)

$(\theta,\, \phi)$ (2-sphere of radius $r(t,a)$)

$\nabla_\nu T^{\mu\nu} = 0$ matter microphysics

$$\begin{aligned}
T^{tt} &= \rho(1+e &+ J)\\
T^{ta} = T^{at} &= &\rho H\\
T^{aa} &= p &+ \rho K\\
T^{\theta\theta} = T^{\phi\phi} &= p &+ \tfrac{1}{2}\rho(J-K)
\end{aligned}$$

The metric functions:

$G_{\mu\nu} = R_{\mu\nu} - \frac{R}{2} g_{\mu\nu} = 8\kappa T_{\mu\nu}$ (Einstein equation)

$\alpha(t,a)$ (lapse function) $\Gamma(t,a) = \sqrt{1 - 2m/r + u^2}$

$u = \frac{\partial r}{\alpha \partial t}$ (matter velocity)

$m(t,a)$ (gravitational mass)

- **Microphysics; the neutrino moments**

$F_\nu\,(t, \vec{x}, \vec{v}) \longrightarrow F_\nu(t, a, \mu = \cos\theta, E)$

(Specific neutrino distribution functions)

$$\begin{aligned}
J &= \frac{2\pi}{(h\,c)^3}\int_{-1}^{+1} d\mu \int_0^\infty E^3 dE\, F_\nu(t,a,\mu,E)\\
H &= \frac{2\pi}{(h\,c)^3}\int_{-1}^{+1} \mu d\mu \int_0^\infty E^3 dE\, F_\nu(t,a,\mu,E)\\
K &= \frac{2\pi}{(h\,c)^3}\int_{-1}^{+1} \mu^2 d\mu \int_0^\infty E^3 dE\, F_\nu(t,a,\mu,E)
\end{aligned}$$

Liebendörfer et al., Phys. Rev. D, 63, 10, 103004 (2001)

Liebendörfer et al., Astrophs. J. Suppl, 150, 263 (2004)

Boltzmann neutrino transport

$$
\begin{aligned}
\frac{\partial F}{\alpha \partial t}(\mu, E) &= \frac{\mu}{\alpha}\frac{\partial}{\partial a}\left(4\pi r^2 \alpha \rho F\right) \\
&+ \Gamma\left(\frac{1}{r} - \frac{1}{\alpha}\frac{\partial \alpha}{\partial r}\right)\frac{\partial}{\partial \mu}\left[\left(1-\mu^2\right)F\right] \\
&+ \left(\frac{\partial \ln \rho}{\alpha \partial t} + \frac{3u}{r}\right)\frac{\partial}{\partial \mu}\left[\mu\left(1-\mu^2\right)F\right] \\
&- \mu\Gamma\frac{1}{\alpha}\frac{\partial \alpha}{\partial r}\frac{1}{E^2}\frac{\partial}{\partial E}\left(E^3 F\right) \\
&+ \left[\mu^2\left(\frac{\partial \ln \rho}{\alpha \partial t} + \frac{3u}{r}\right) - \frac{u}{r}\right]\frac{1}{E^2}\frac{\partial}{\partial E}\left(E^3 F\right) \\
&+ j(E)\left(\frac{1}{\rho} - F(\mu, E)\right) - \chi(E) F(\mu, E) \\
&+ \frac{1}{c}\frac{E^2}{h^3 c^3}\int d\mu' R_{IS}(\mu', \mu, E) F(\mu', E) - \frac{1}{c}\frac{E^2 F(\mu, E)}{h^3 c^3}\int d\mu' R_{IS}(\mu, \mu', E) \\
&+ \frac{1}{c}\frac{1}{h^3 c^3}\left(\frac{1}{\rho} - F(\mu, E)\right)\int dE' E'^2 d\mu' R^{in}_{\mathrm{NES}}(\mu, \mu', E, E') F(\mu', E') \\
&- \frac{1}{c}\frac{1}{h^3 c^3} F(\mu, E)\int dE' E'^2 d\mu' R^{out}_{\mathrm{NES}}(\mu, \mu', E, E')\left(\frac{1}{\rho} - F(\mu', E')\right)
\end{aligned}
$$

Weak processes:

(a) Electronic charged current reactions

$e^- + p \rightleftharpoons n + \nu_e$ Fischer et al., Astrophys. J, 894, 1, 9 (2020)

$e^+ + n \rightleftharpoons p + \overline{\nu}_e$

$e^- + \langle A, Z\rangle \rightleftharpoons \langle A, Z-1\rangle + \nu_e$

(b) Neutral current reactions

$\nu + N \rightleftharpoons \nu' + N$ (elastic scattering)

$e^- + e^+ \rightleftharpoons \nu + \overline{\nu}$

$N + N \rightleftharpoons N + N + \nu + \overline{\nu}$

$\nu_e + \overline{\nu}_e \rightleftharpoons \nu_{\mu/\tau} + \overline{\nu}_{\mu/\tau}$ Buras et al. (2003)

$\nu + e^{-/+} \rightleftharpoons \nu' + e^{-/+}$ Fischer et al., Astron. Astrophys., 499, 1, 1 (2009)

Evolution of the proton-to-baryon ratio

$$\frac{\partial Y_e}{\partial t} = -\frac{2\pi m_B c}{(h\,c)^3}\int_{-1}^{+1} d\mu \int_0^{\infty} E^2 dE\left(j\left(\frac{1}{\rho} - F\right) - \chi F\right)$$

Mezzacappa, Bruenn, Astrophys. J, 405, 669(1993)

Mezzacappa, Bruenn, Astrophys. J, 405, 637(1993)

Mezzacappa, Bruenn, Astrophys. J, 410, 740(1993)

Liebendörfer et al., Astrophys. J. Suppl., 150, 1, 263 (2004)