An updated proto-neutron star neutrino emission model

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Core-Collapse Supernovae: multimessenger emission

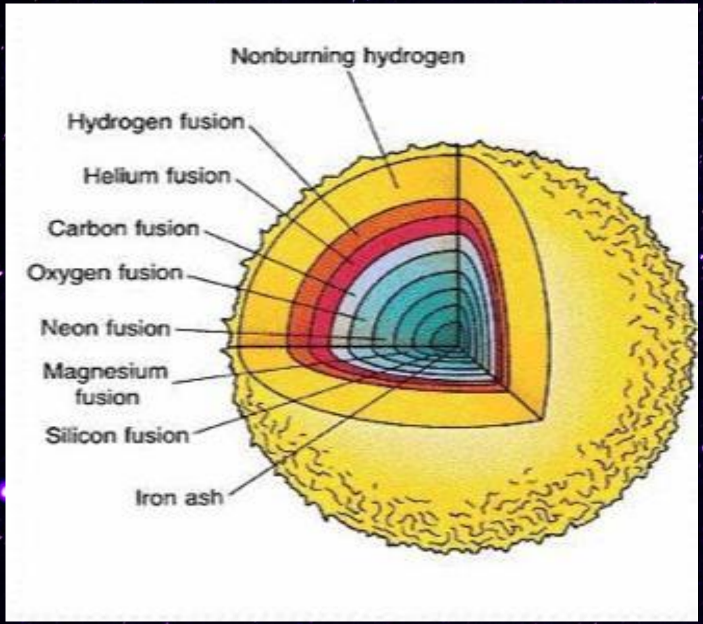
$$\varepsilon^b_{NS} = \frac{3}{5} \cdot \frac{GM^2}{R} = (1\text{–}5) \cdot 10^{53}\,\mathrm{erg}$$

$$\varepsilon_\nu \sim 99\% \cdot \varepsilon^b$$

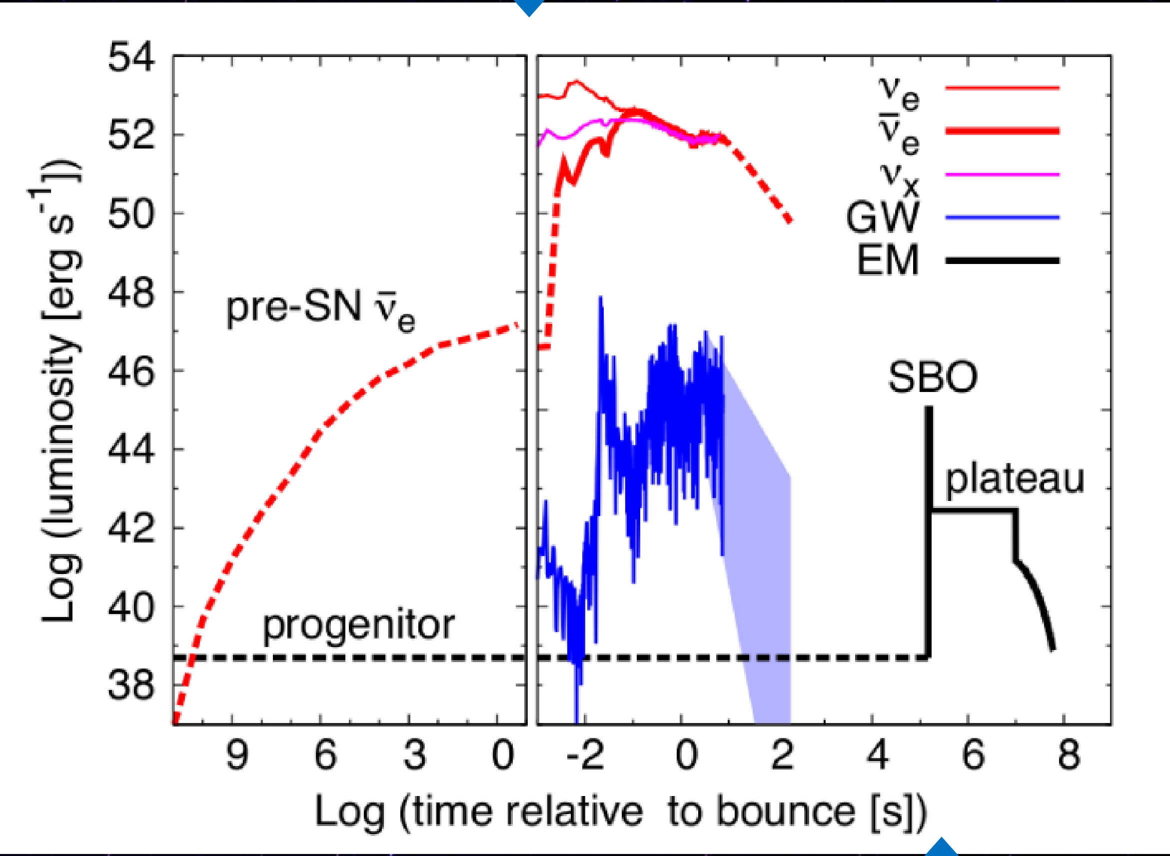
$$\varepsilon_{\rm kin} \sim 1\% \cdot \varepsilon^b$$

$$\varepsilon_\gamma \sim 0.01\% \cdot \varepsilon^b$$

$$\varepsilon_{GW} \sim 0.0001\% \cdot \varepsilon^b$$



GW and νs are emitted at the bounce...



... while photons are late!

Neutrino emission

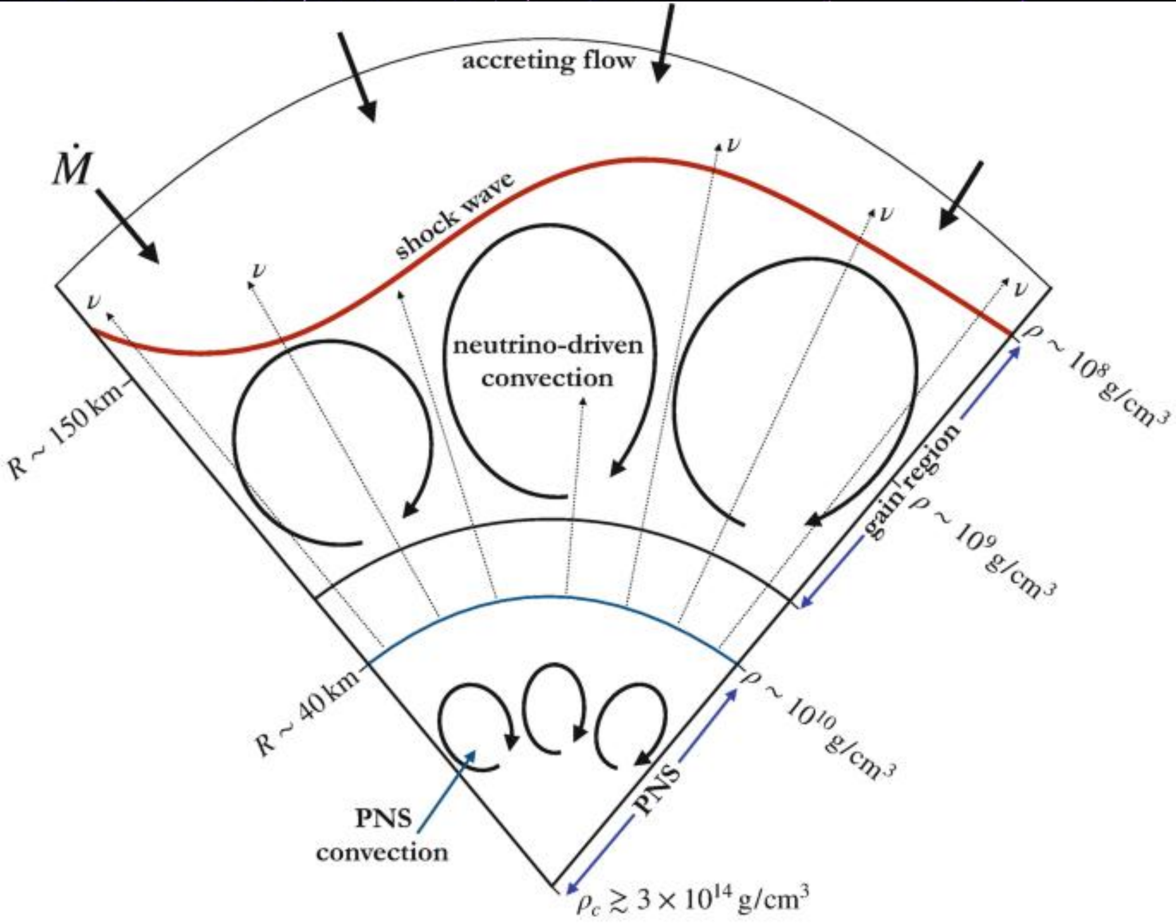
Neutrino emission can be summarized according to our current understanding into (*Pagliaroli et al., Astropart.Phys. 31 (2009) 163-176*):

- **Neutronization peak**

- **Accretion phase** ($t < 1s$): $\nu_e, \bar{\nu}_e$
  produced by (*neutrino-driven explosion*):

$$n + e^+ \leftrightarrow p + \bar{\nu}_e$$

$$p + e^- \leftrightarrow n + \nu_e$$



Neutrino emission

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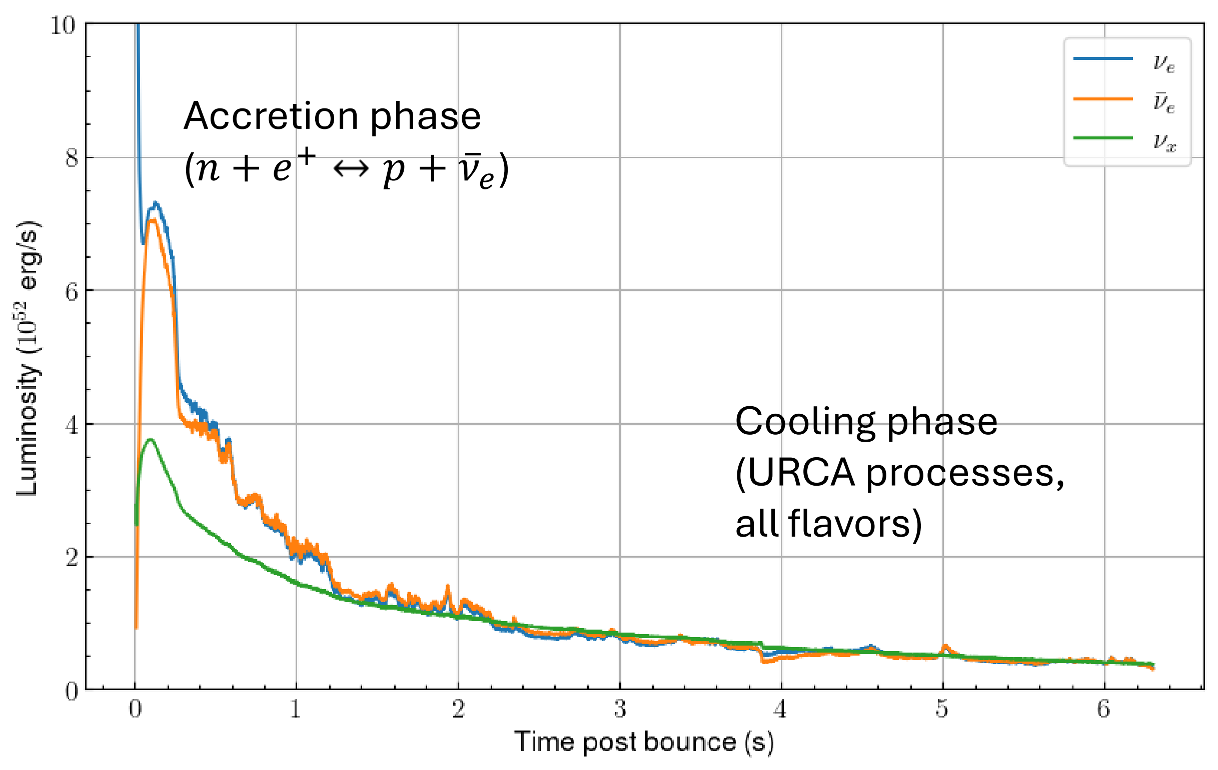
- **Neutronization peak**
- **Accretion phase**
- **Cooling phase**: long-lasting, carries 80-90% of total energy through neutrinos of all flavors:

$$\Phi_c^0(E_\nu, t^{em}) \propto \boxed{R_{PNS}^2} \frac{E_\nu^2}{1+e^{\left(\frac{E_\nu}{T_c(t^{em})}\right)}}$$

Neutronization peak
$(\mathrm{p} + e^- \rightarrow n + \nu_e)$



Simulation from Choi et al., *Phys.Rev.D* 111 (2025) 12, 123038

Refining the model — convection

- Novel approach for the luminosity of the cooling phase proposed in *Lucente et al., Phys.Rev.D 110 (2024) 6, 6.*
- PNS **convection** included through ($t > 1s$):

$$L_{\nu_x}(t) = C t^{-\alpha} e^{-(t/\tau)^n}$$

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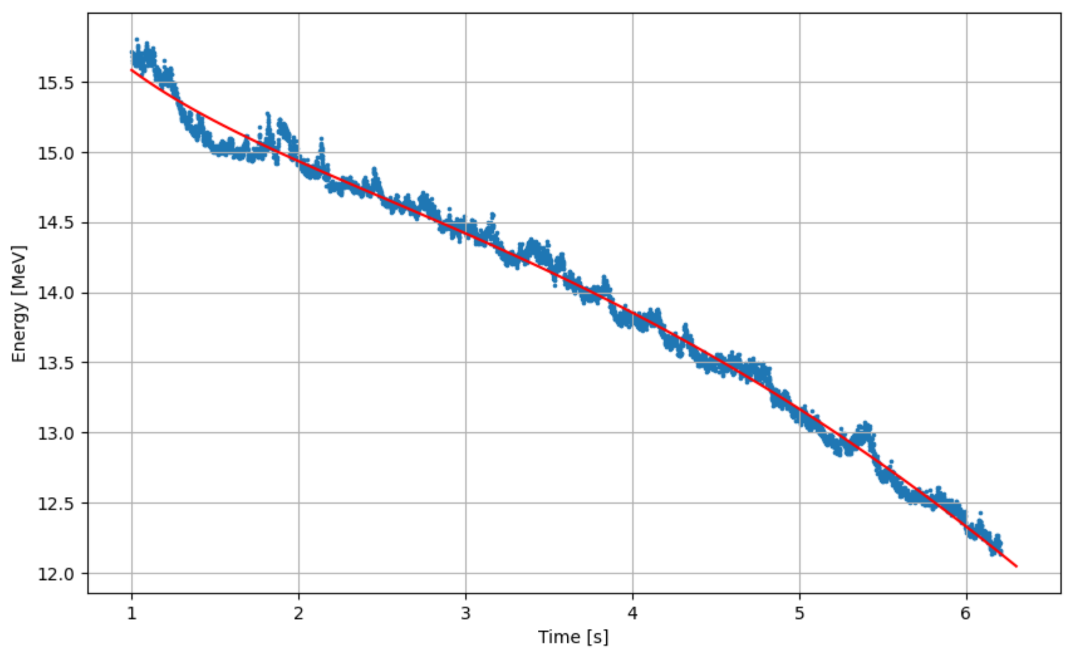
- PNS **convection** included through ($t > 1s$):

$$L_{\nu_x}(t) = C t^{-\alpha} e^{-(t/\tau)^n}$$

In our model:

$$T_c(t) = T_0 t^{-\alpha_c} e^{-(t/\tau_c)^{n_c}}$$

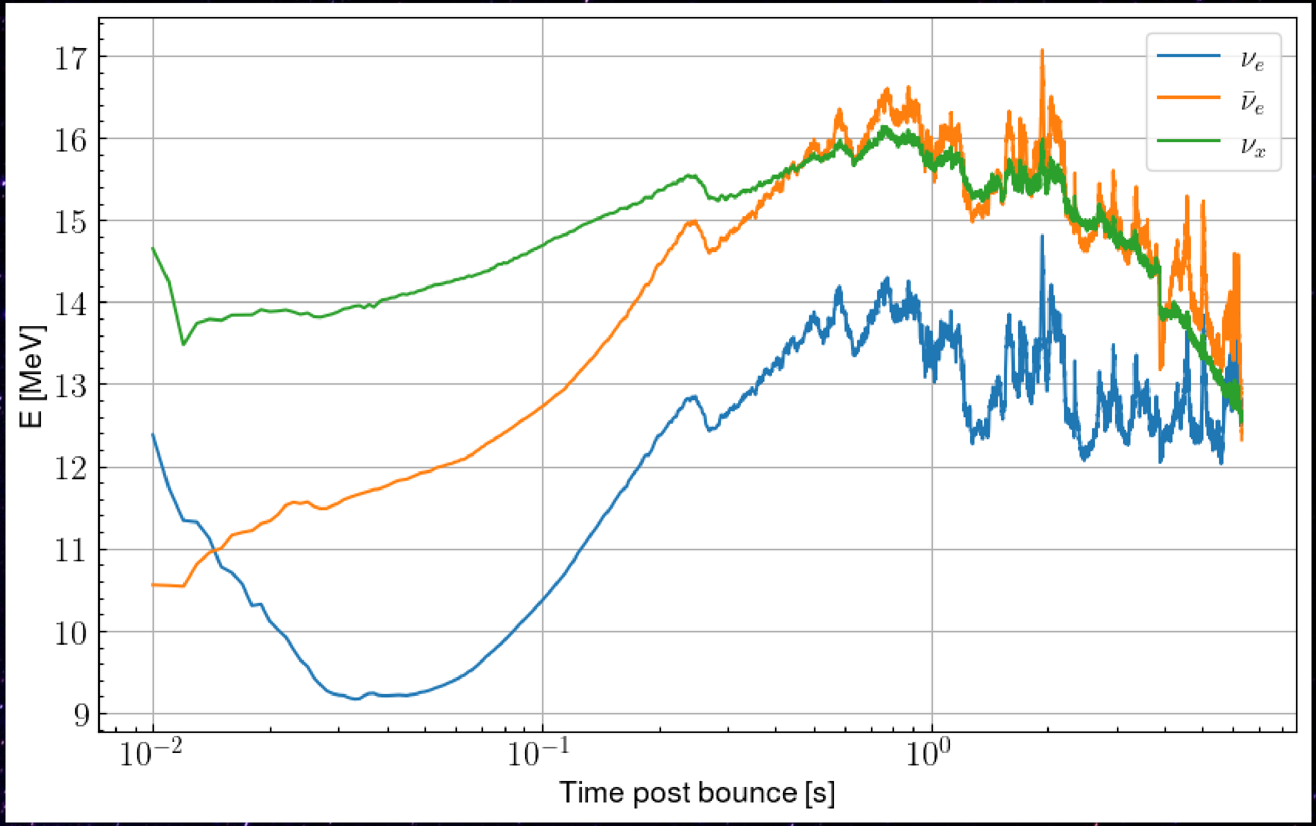
Average Energy ∝ Temperature



Refining the model – temperature evolution

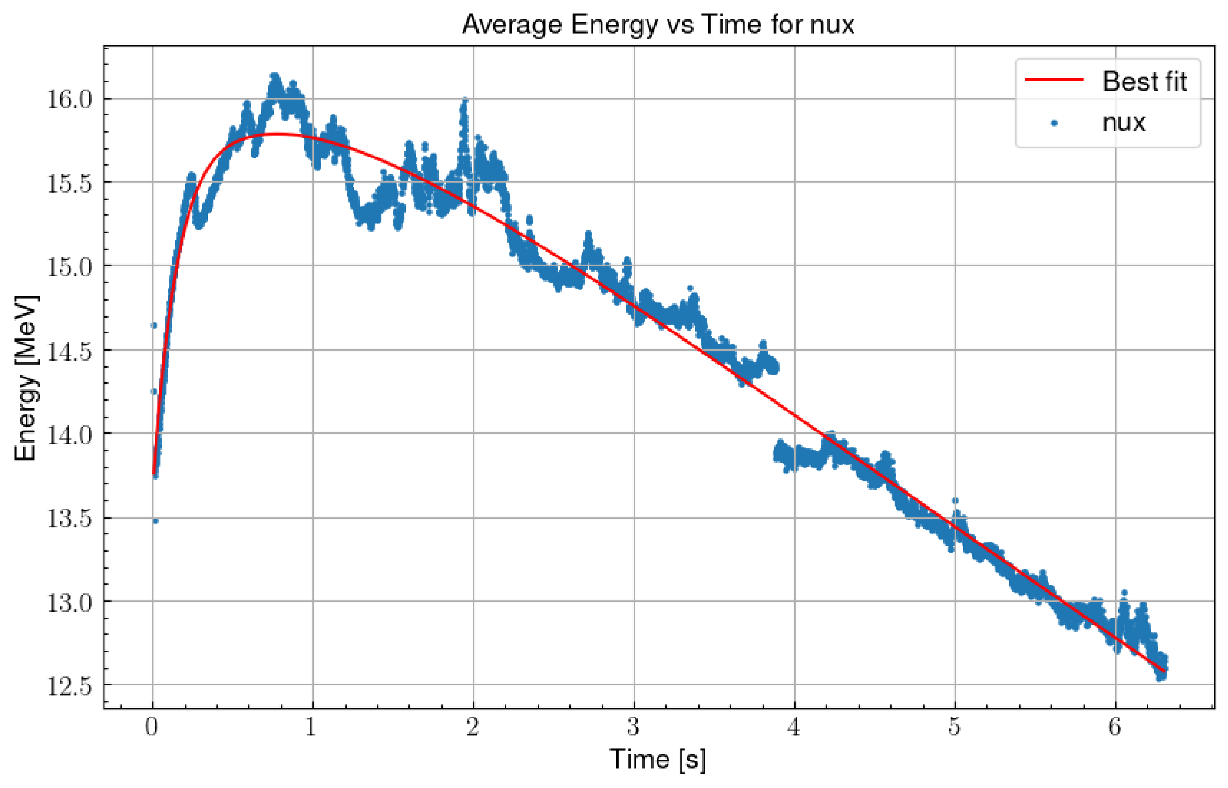
Simulation from Choi et al., *Phys.Rev.D* 111 (2025) 12, 123038

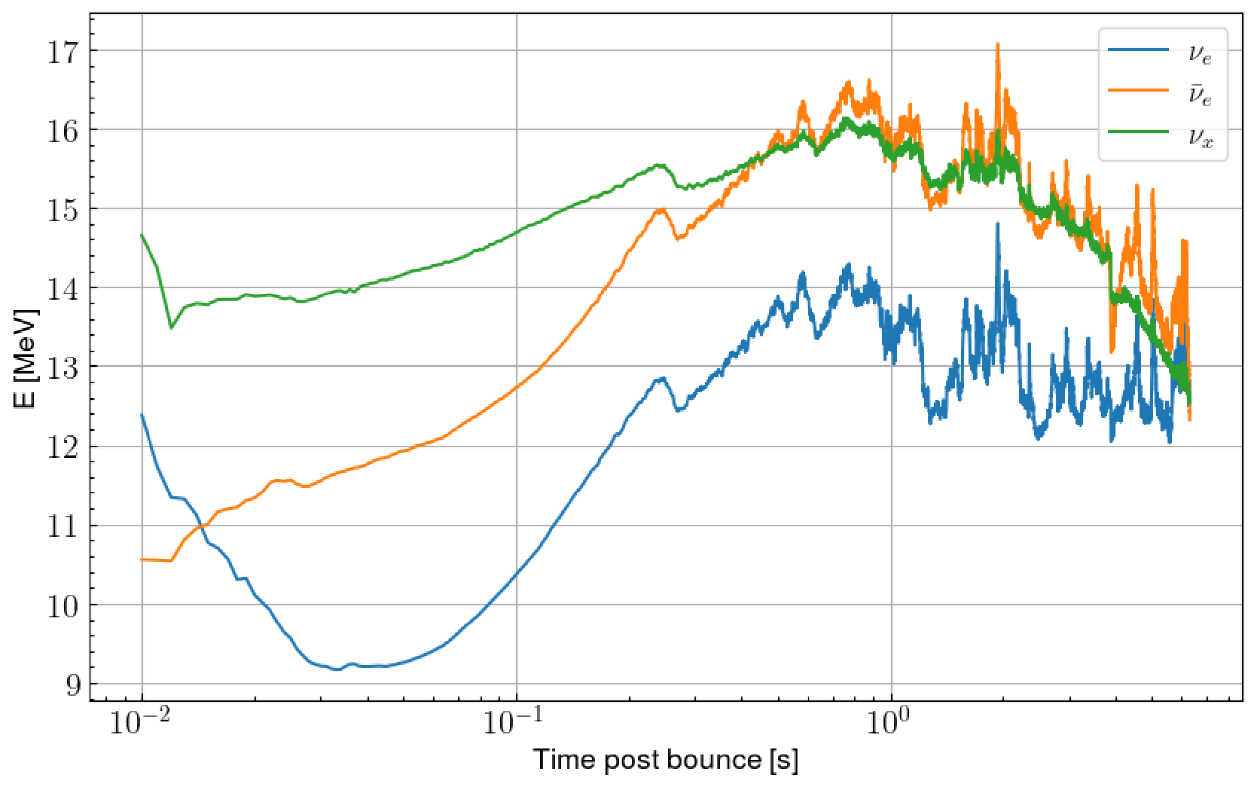
PNS temperature rises before exponential cooling



$$T_c(t) = \begin{cases} T_0 + \delta T(1 - \exp(-t/\tau_t)), & \text{if } t < \bar{t} \lesssim 1\text{s} \\ T_1\, t^{-\alpha_c} \exp(-(t/\tau_c)^{n_c}), & \text{if } t > \bar{t} \end{cases}$$

$$T_c(t) = \begin{cases} T_0 + \delta T(1 - \exp(-t/\tau_t)), & \text{if } t < \bar{t} \leq 1\text{s} \\ T_1\, t^{-\alpha_c} \exp(-(t/\tau_c)^{n_c}), & \text{if } t > \bar{t} \end{cases}$$



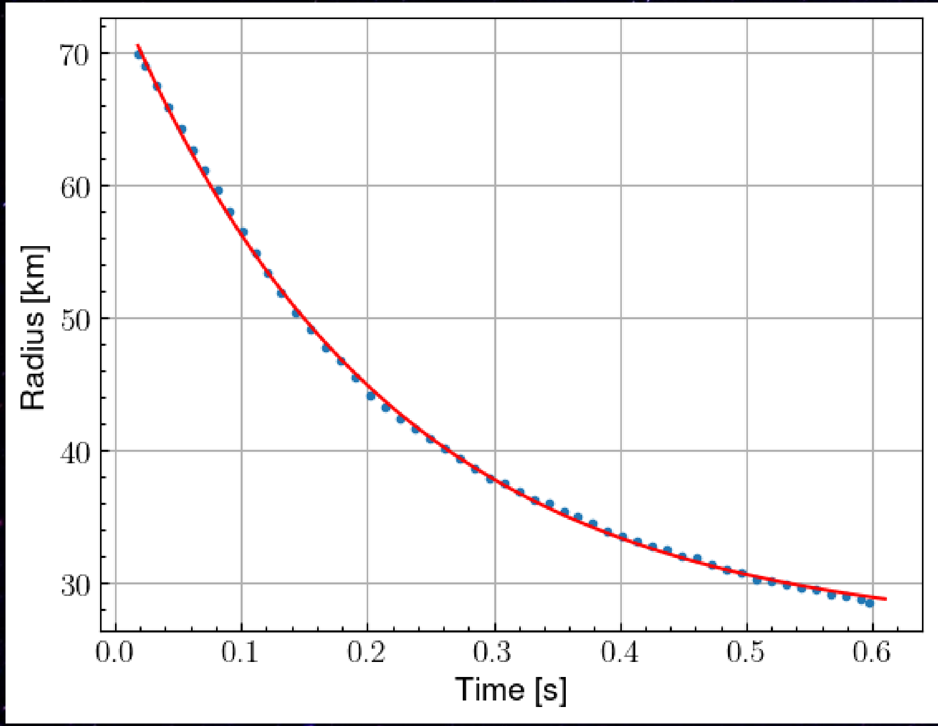


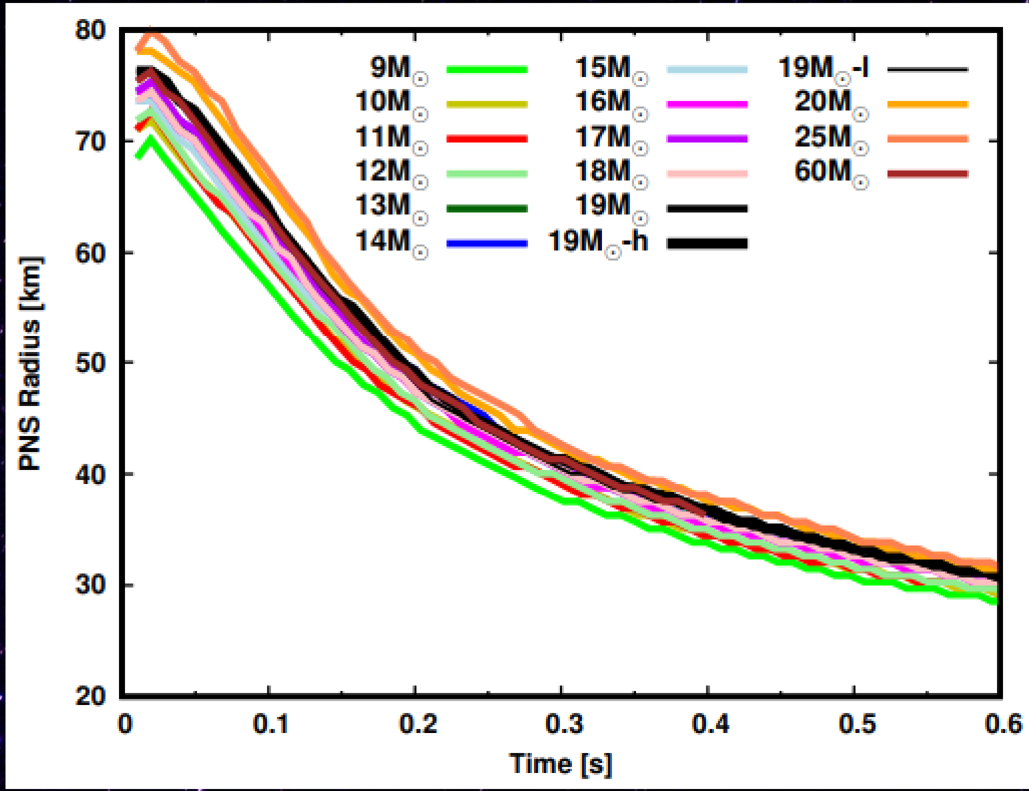
Simulation from Choi et al., *Phys.Rev.D* 111 (2025) 12, 123038

Refining the model — radius evolution

PNS radius shrinks drastically in the first second:

$$R_c(t) = R_f \cdot (1 + \delta R \exp(-t/\tau_R))$$





Nakagura et al., *MNRAS* 492 (2020) 4, 5764-5779

Note: $$\delta R \equiv \frac{R_i - R_f}{R_f}$$

Updated cooling model

Radius model

$$\Phi_c^0(E_\nu, t) \propto R_c(t)^2 \, E_\nu^2 \left[1 + \exp\left(\frac{E_\nu}{T_c(t)}\right)\right]^{-1}$$

Temperature model

Total of 10 astrophysical free parameters

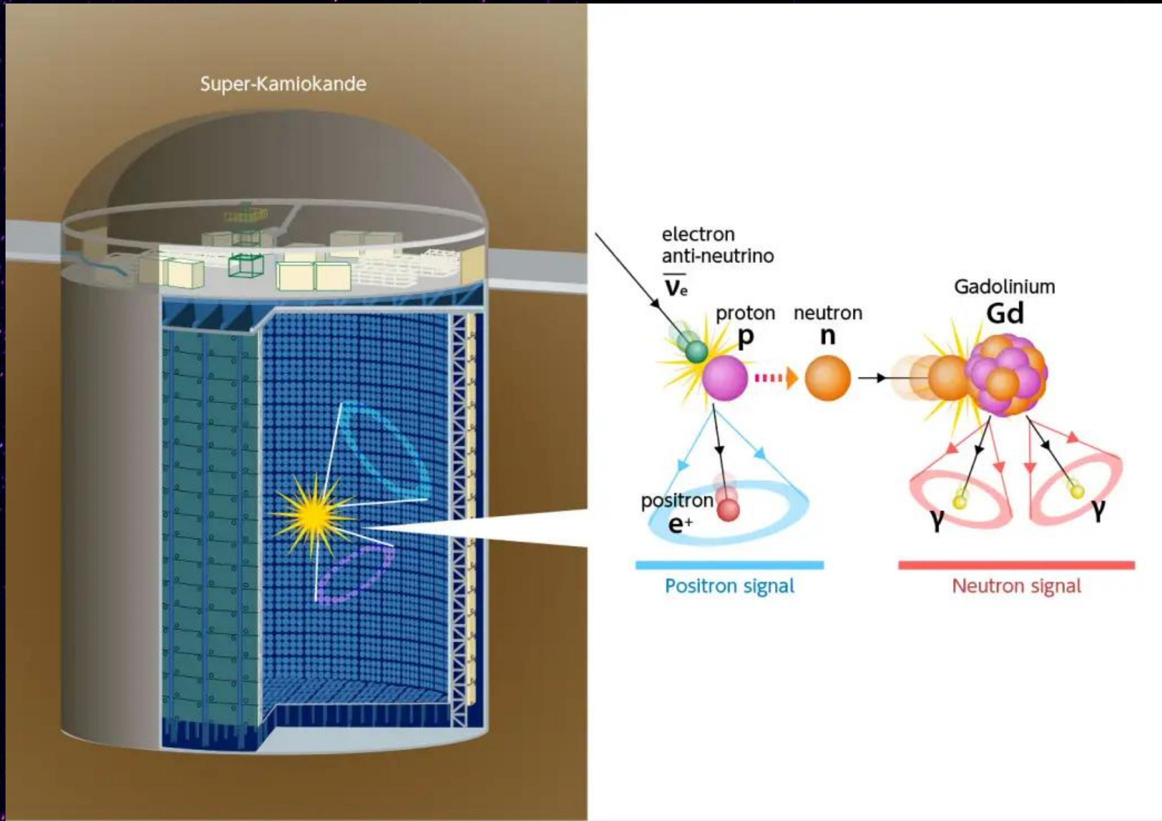
... at the source!

Survival probability for $\bar{\nu}_e$ depends on neutrino mass hierarchy

Inverted ordering:

$$\Phi_{\bar{\nu}_e} \simeq \Phi^0_{\nu_x}$$

For the detection we consider:
Super-Kamiokande inverse beta decay channel
SN at 10kpc



Results for IO on simulated data

$$T_0 = 4.37 - 4.47 MeV$$

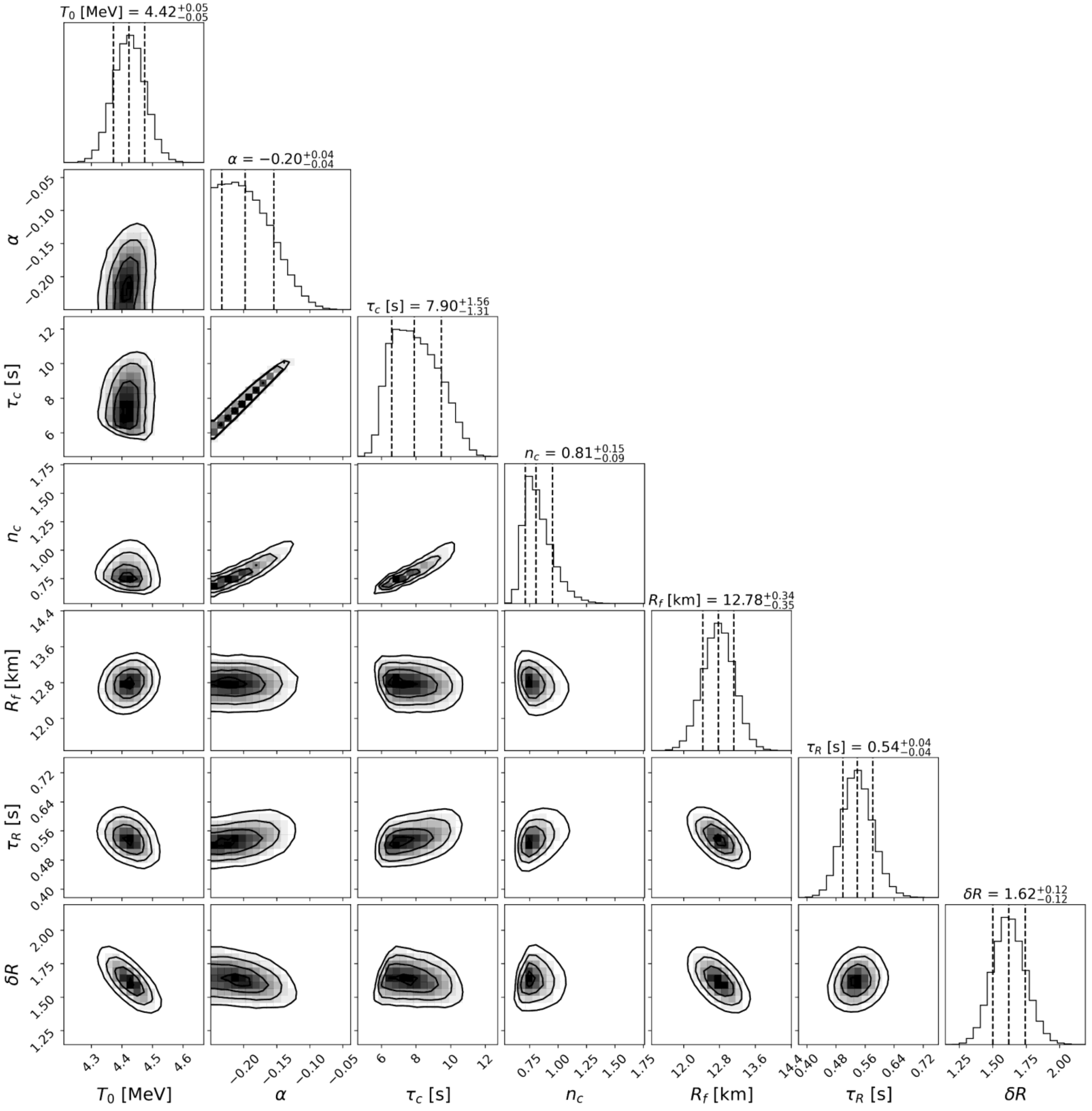
$$R_f = 12.4 - 13.1\ km$$

$$\tau_R = 0.50 - 0.58\ s$$

$$\delta R = 1.5 - 1.7\ km$$

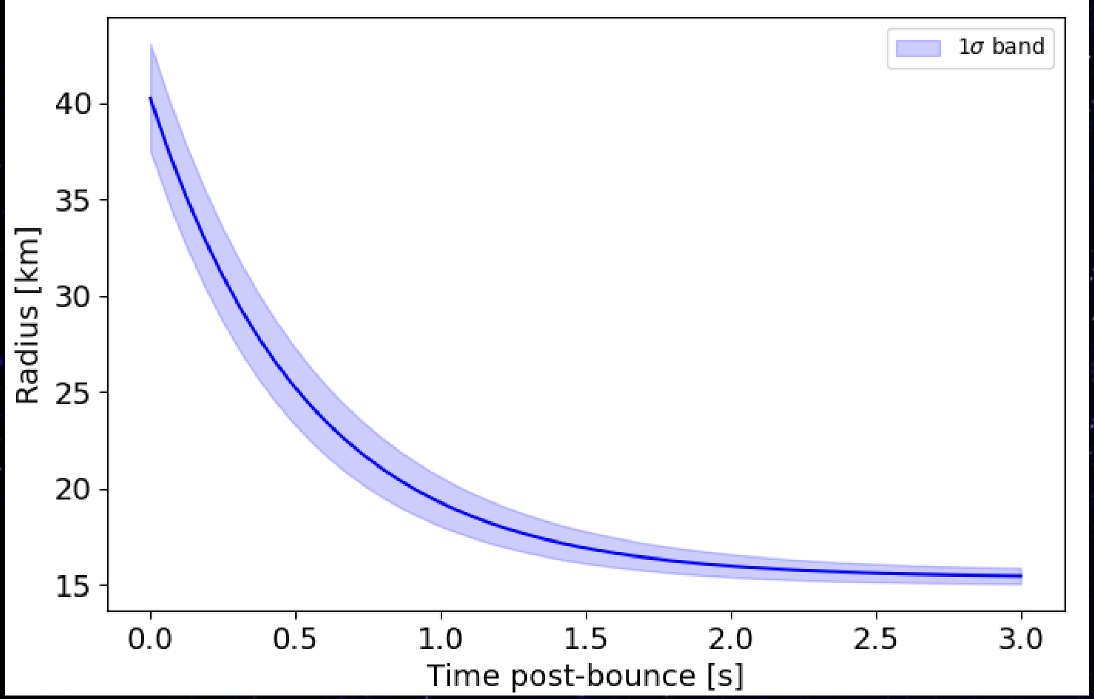
Fixed params:
$\delta T = 0.49\ MeV,\ \tau_{tc} = 0.49\ s,\ \bar{t} = 0.55s$

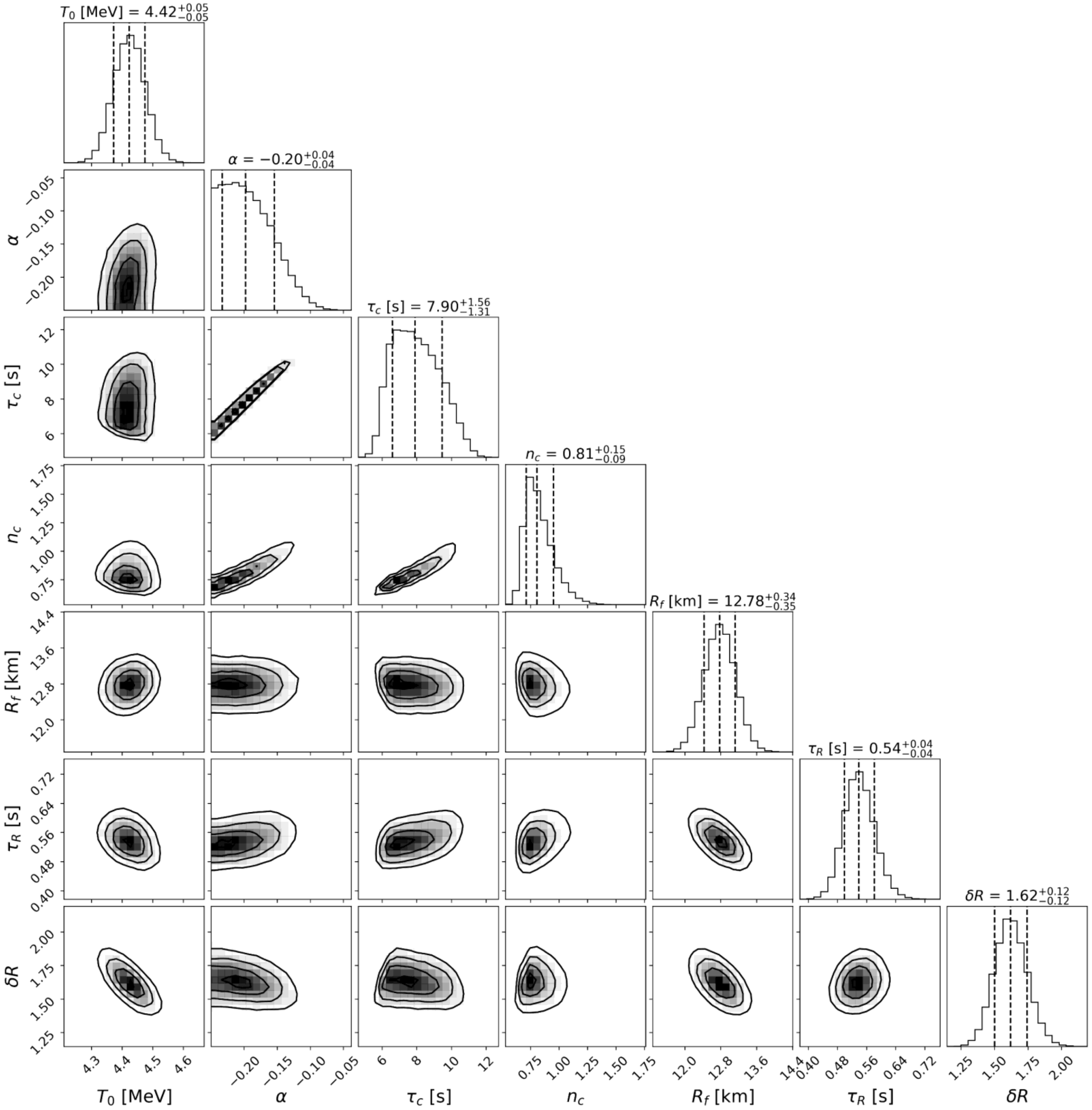
Data extracted from a $18M_{\odot}$ progenitor model



Results for IO on simulated data

$R_c(t)$ evolution:





Survival probability for $\bar{\nu}_e$ depends on neutrino mass hierarchy

Inverted ordering:

$$\Phi_{\bar{\nu}_e} \simeq \Phi^0_{\nu_x}$$

Normal ordering:

$$\Phi_{\bar{\nu}_e} \simeq +P\Phi^0_{\bar{\nu}_e} + (1-P)\Phi^0_{\nu_x}$$

where: $P \simeq 0.7$

In NO accretion is visible: $\Phi^0_{\bar{\nu}_e} = F(M_a, T_a, \tau_a) + \Phi^0_c$

Results for NO on simulated data

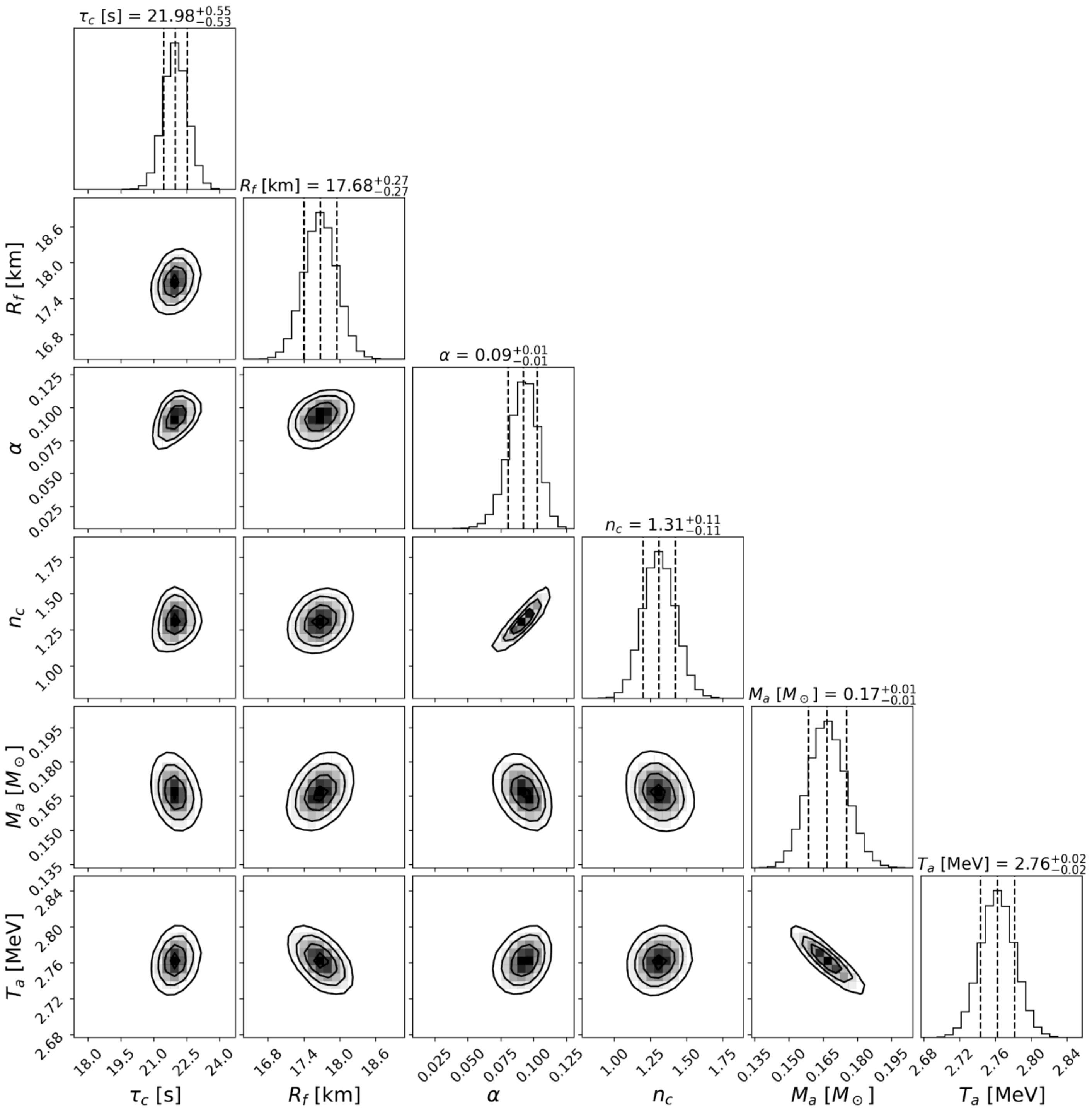
$$M_a = 0.16 - 0.18\ M_\odot$$

$$T_a = 2.74 - 2.78\ MeV$$

$$R_f = 17.4 - 18.0\ km$$

Fixed params:
$\delta T = 1.02\ MeV, \tau_{ta} = 0.28\ s, \tau_a = 0.58s$

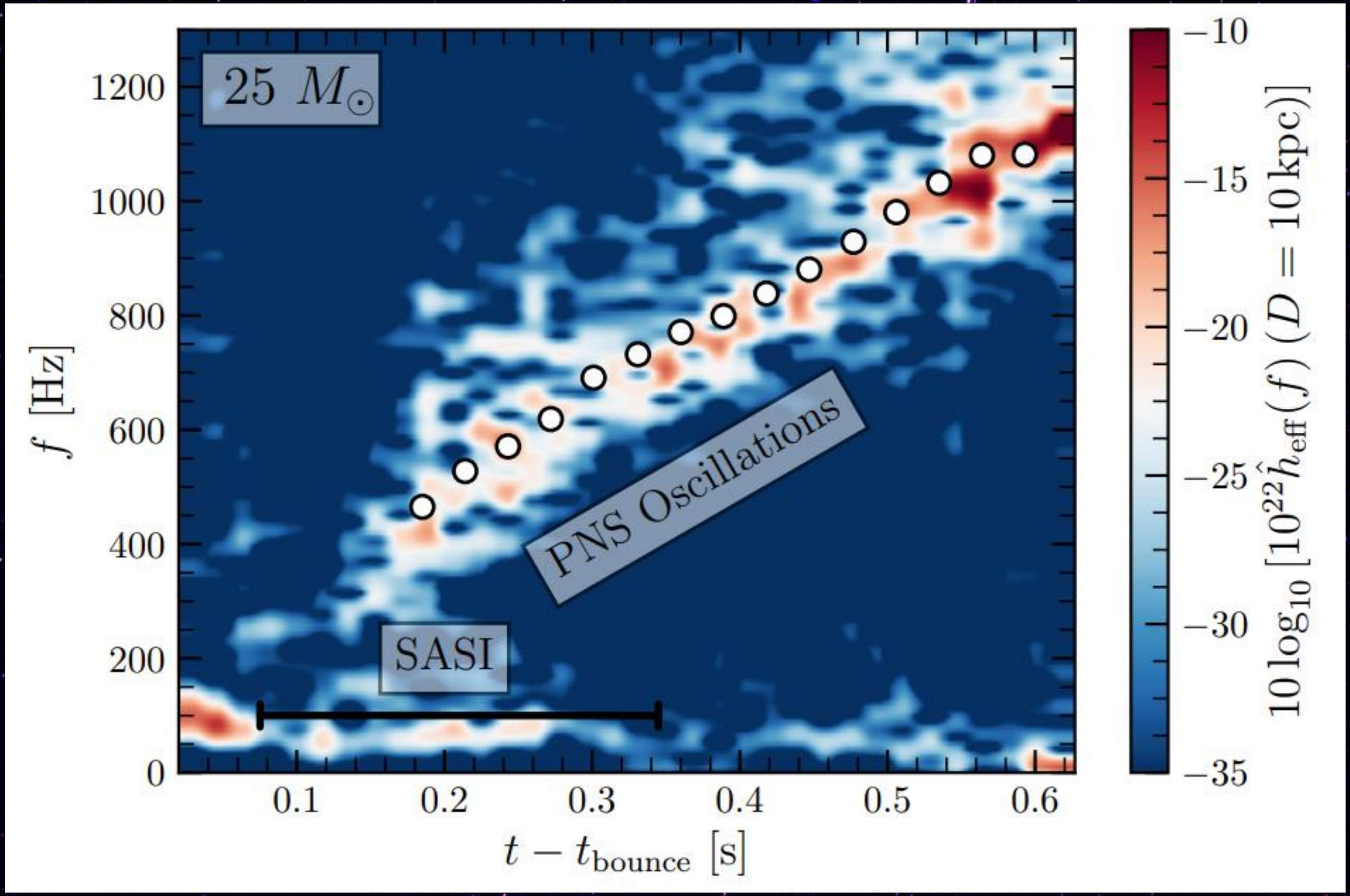
Radius evolution is hidden by the accretion flux



Multimessenger application: neutrino and GW emission

PNS oscillations frequencies are $\sim f(M_{PNS}/R_{PNS}^n)$

R_{PNS} is provided by ν counterpart!



Abdikamalov, Pagliaroli, and Radice, arXiv:2010.04356

Summary and future perspectives

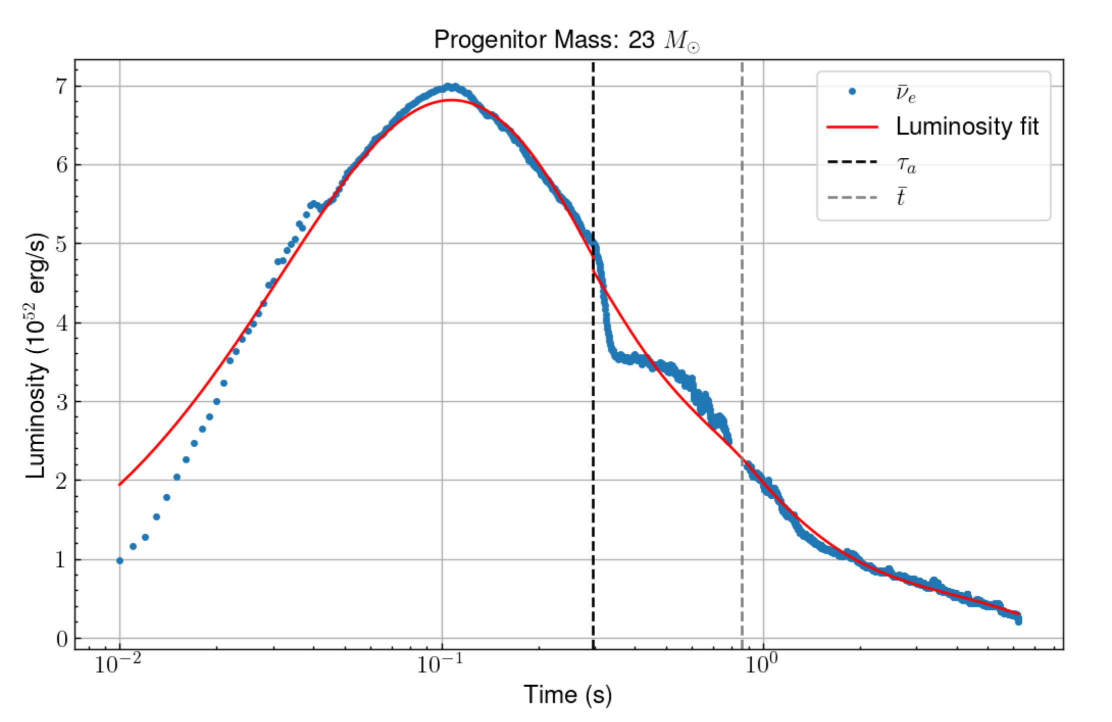
- New model for neutrino emission from Supernova, tested on simulated datasets
- Neutrino data can help constraining relevant PNS and accretion phase parameters!
- GW + neutrino analysis can be complementary in unveiling the PNS evolution in the first moments after the core bounce

Thank you for your attention

Extra slides

Accretion Temperature

$$T(t) = \begin{cases} T_a + \delta T_a(1 - \exp(-t/\tau_{ta})), & \text{if } t < \tau_a \\ T_0 + \delta T_c(1 - \exp(-t/\tau_{tc})), & \text{if } \tau_a < t < \bar{t} \\ T_1\, t^{-\alpha_c} \exp(-(t/\tau_c)^{n_c}), & \text{if } t > \bar{t} \end{cases}$$



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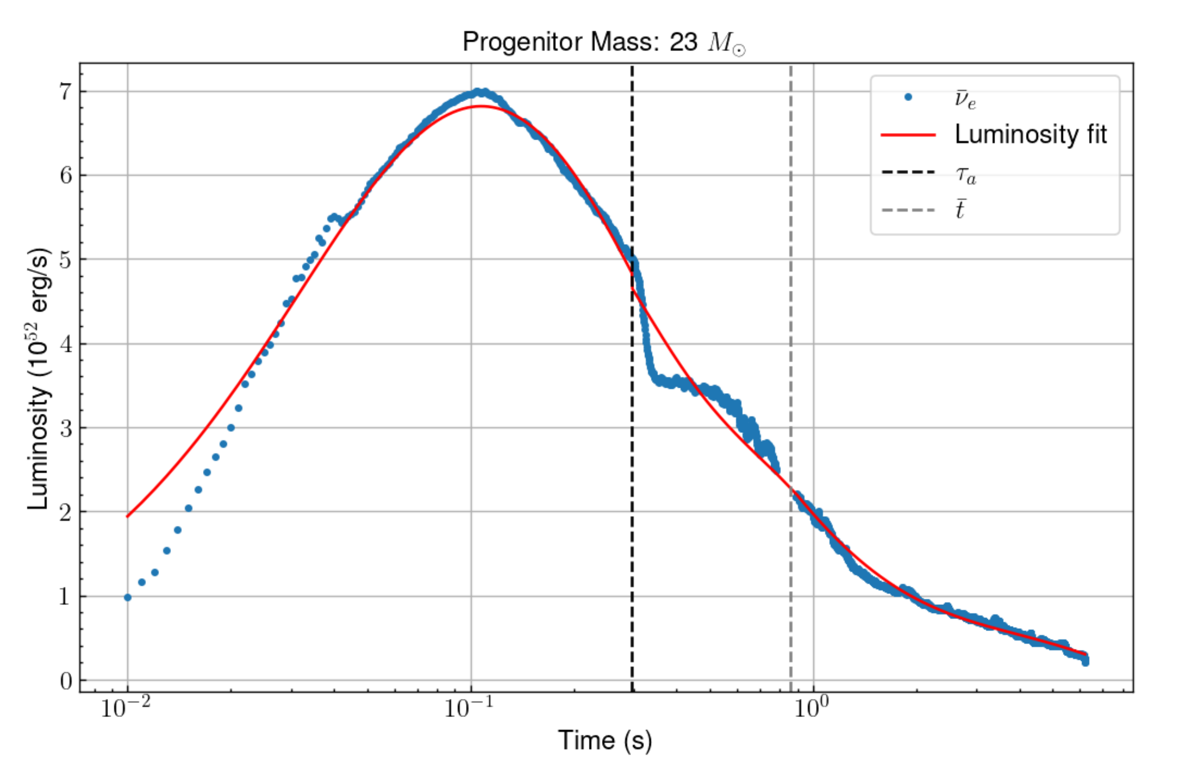
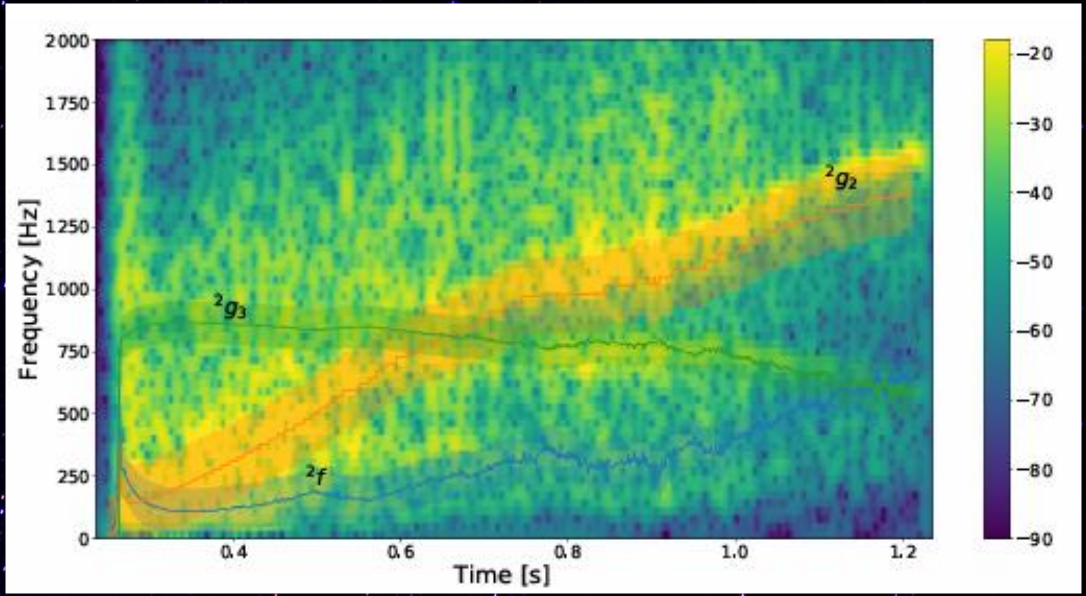


How to include GW in the analysis?



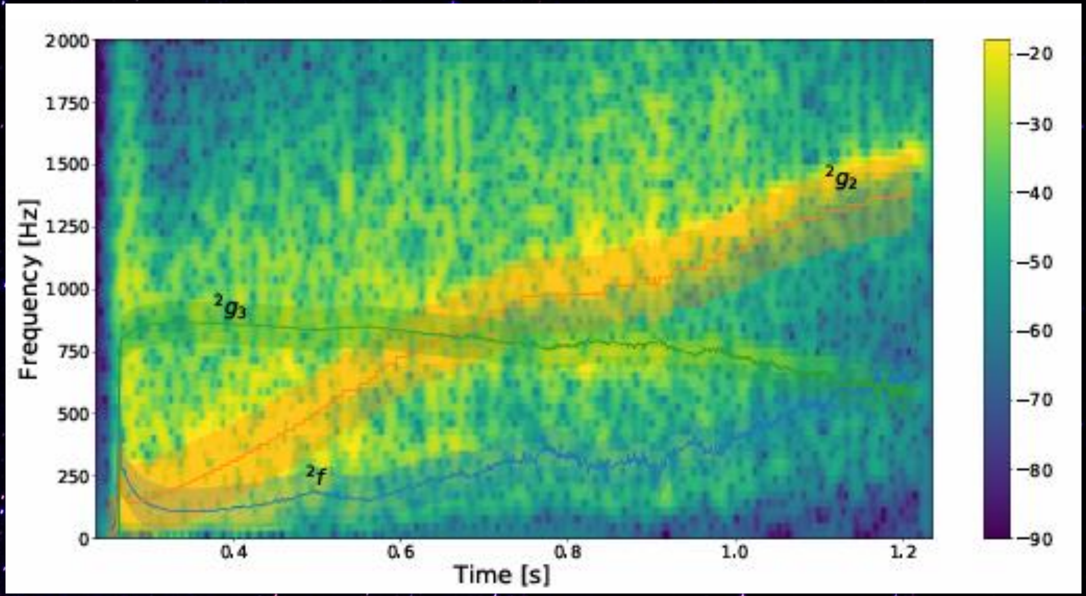
Torres-Forné et al., Phys. Rev. Lett. **127**, 239901 (2021)

g-modes related to PNS mass and radius

mode	x	a	$b/10^5$	$c/10^6$	$d/10^9$	R^2	σ
^2f	$\sqrt{M_{\rm shock}/R^3_{\rm shock}}$	-	1.410 ± 0.004	-4.23 ± 0.06	-	0.966	45
$^2p_1$	$\sqrt{M_{\rm shock}/R^3_{\rm shock}}$	-	2.205 ± 0.007	4.63 ± 0.09	-	0.991	61
$^2p_2$	$\sqrt{M_{\rm shock}/R^3_{\rm shock}}$	-	4.02 ± 0.02	7.4 ± 0.3	-	0.983	123
$^2p_3$	$\sqrt{M_{\rm shock}/R^3_{\rm shock}}$	-	6.21 ± 0.03	-1.9 ± 0.6	-	0.979	142
$^2g_1$	$M_{\rm pns}/R^2_{\rm pns}$	-	8.67 ± 0.03	-51.9 ± 0.5	-	0.958	205
$^2g_2$	$M_{\rm pns}/R^2_{\rm pns}$	-	5.88 ± 0.03	-86.2 ± 1.0	4.67 ± 0.08	0.956	85
$^2g_3$	$\sqrt{M_{\rm shock}/R^3_{\rm shock}}\ \ p_C/\rho_C^{2.5}$	905 ± 3	-79.9 ± 1.7	-11000 ± 2000	-	0.925	41

PNS Asteroseismology

- Universal relations
- Mode association (f/g ?)
- Mass evolution?
- …



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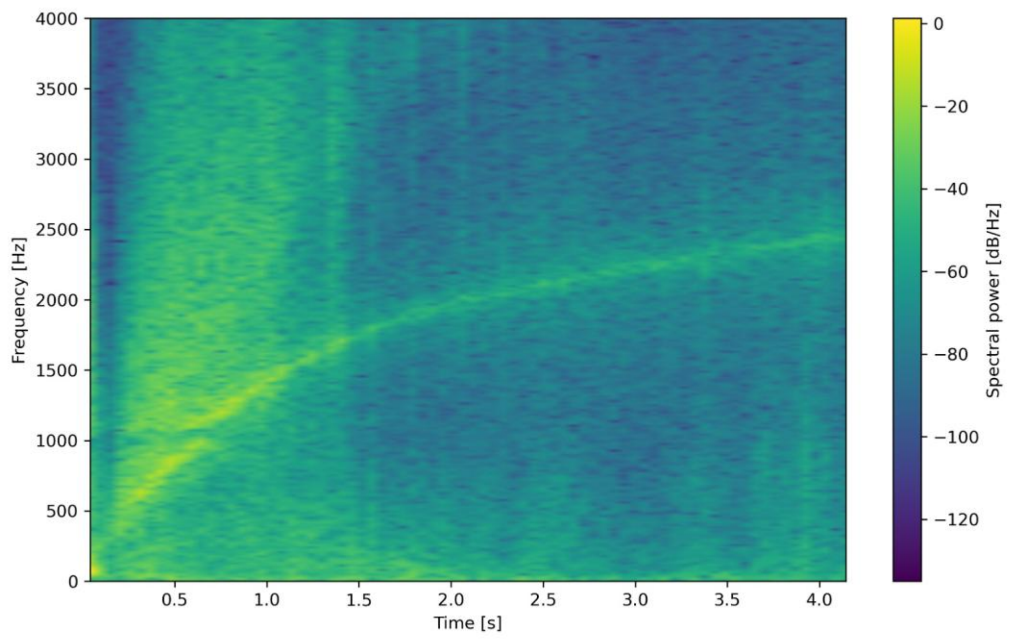

Spectrogram from a 18 $M_{\odot}$ progenitor