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GRAN SASSO
SCIENCE INSTITUTE

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SCHOOL OF ADVANCED STUDIES
Scuola Universitaria Superiore

Multimessenger emission from core-collapse supernovae

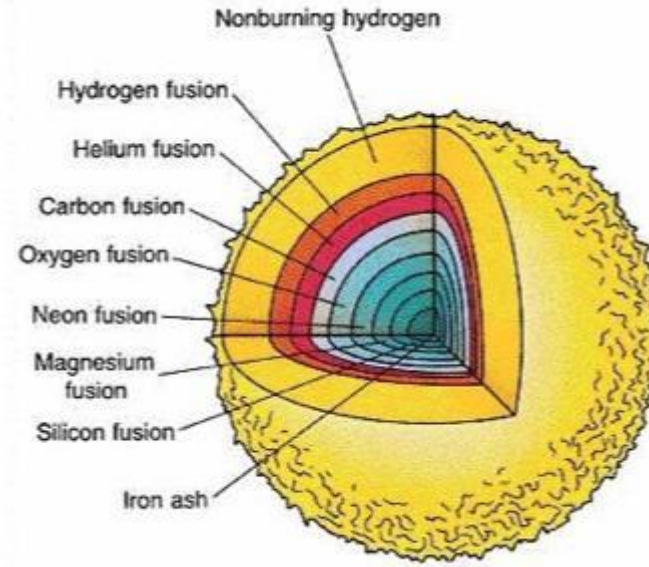
Matteo Ballelli

Supervisors: Giulia Pagliaroli, Marco Drago

Ballelli, Pompa, Ternes, Drago and Pagliaroli, 2026
<https://arxiv.org/abs/2610.12101>



Core-collapse Supernovae



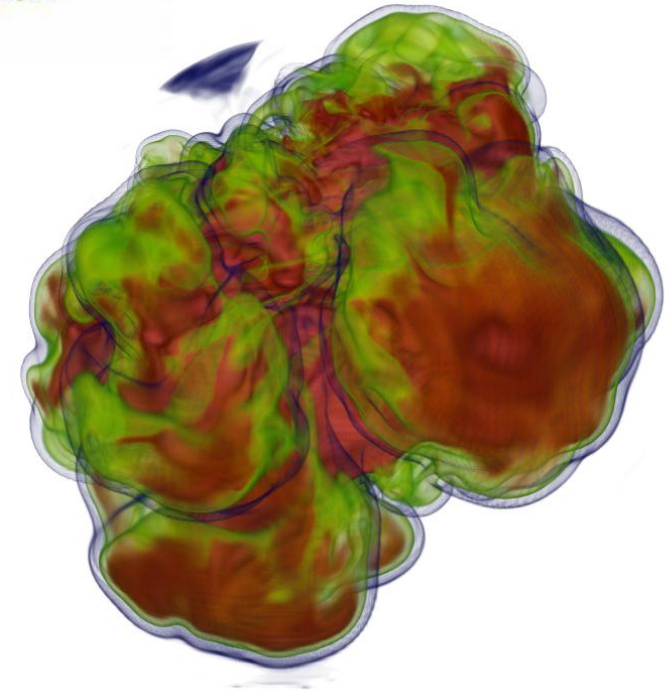
$$\epsilon_{NS}^b = \frac{3}{5} \cdot \frac{GM^2}{R} = (1-5) \cdot 10^{53} \text{ erg}$$

$$\epsilon_\nu \sim 99\% \cdot \epsilon^b$$

$$\epsilon_{\text{kin}} \sim 1\% \cdot \epsilon^b$$

$$\epsilon_\gamma \sim 0.01\% \cdot \epsilon^b$$

$$\epsilon_{GW} \sim 0.0001\% \cdot \epsilon^b$$

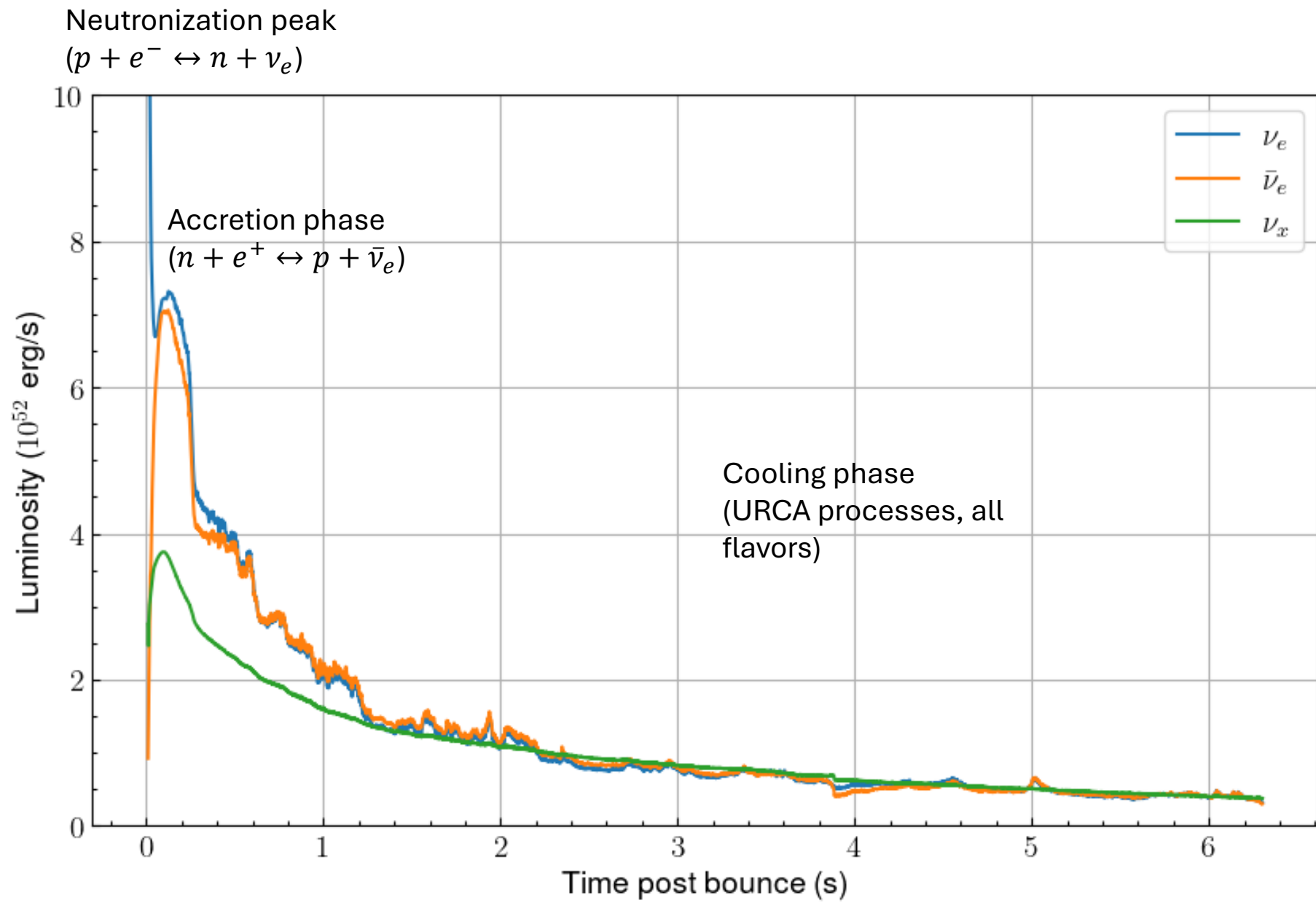


Outline

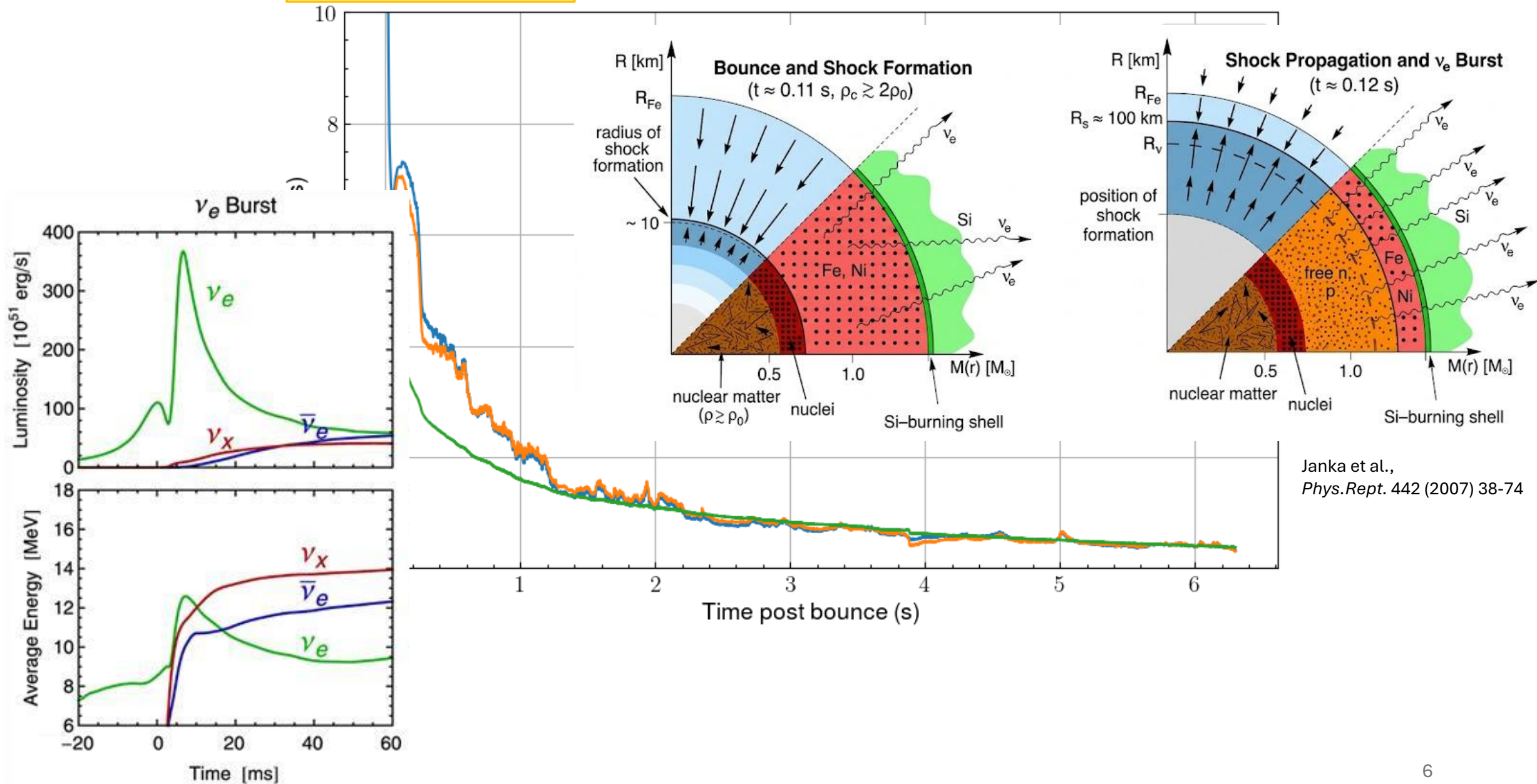
- 'Traditional' model
- Improved Modelization
- Simulation fit
- Data analysis of simulated data

Outline

- 'Traditional' model (*Pagliaroli et al., Astropart.Phys,31 (2009) 163-176*)
- Improved Modelization
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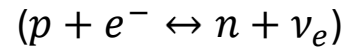


Neutronization peak
 $(p + e^- \leftrightarrow n + \nu_e)$

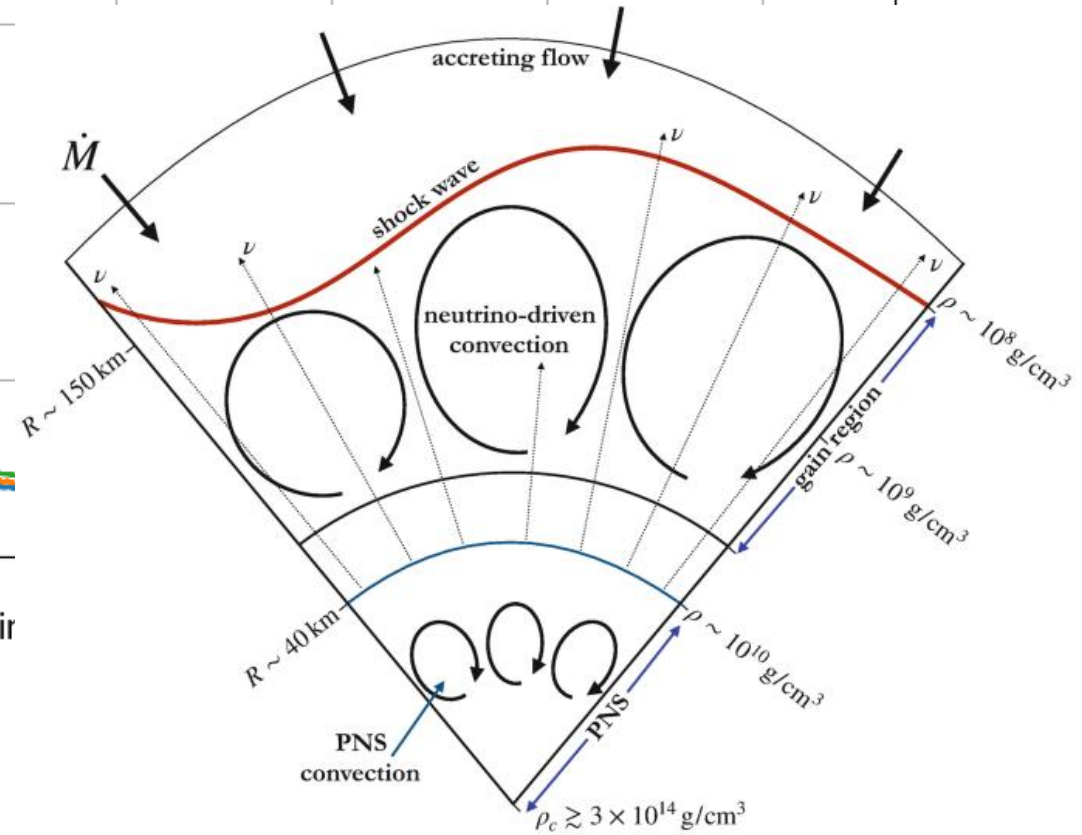
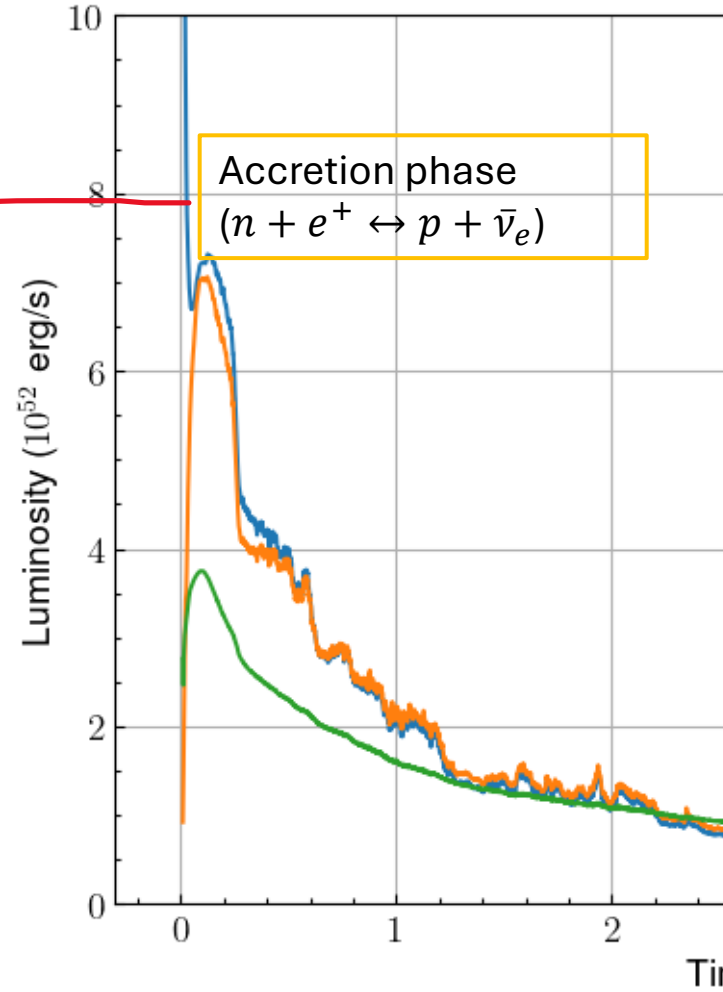


Janka et al.,
Phys.Rept. 442 (2007) 38-74

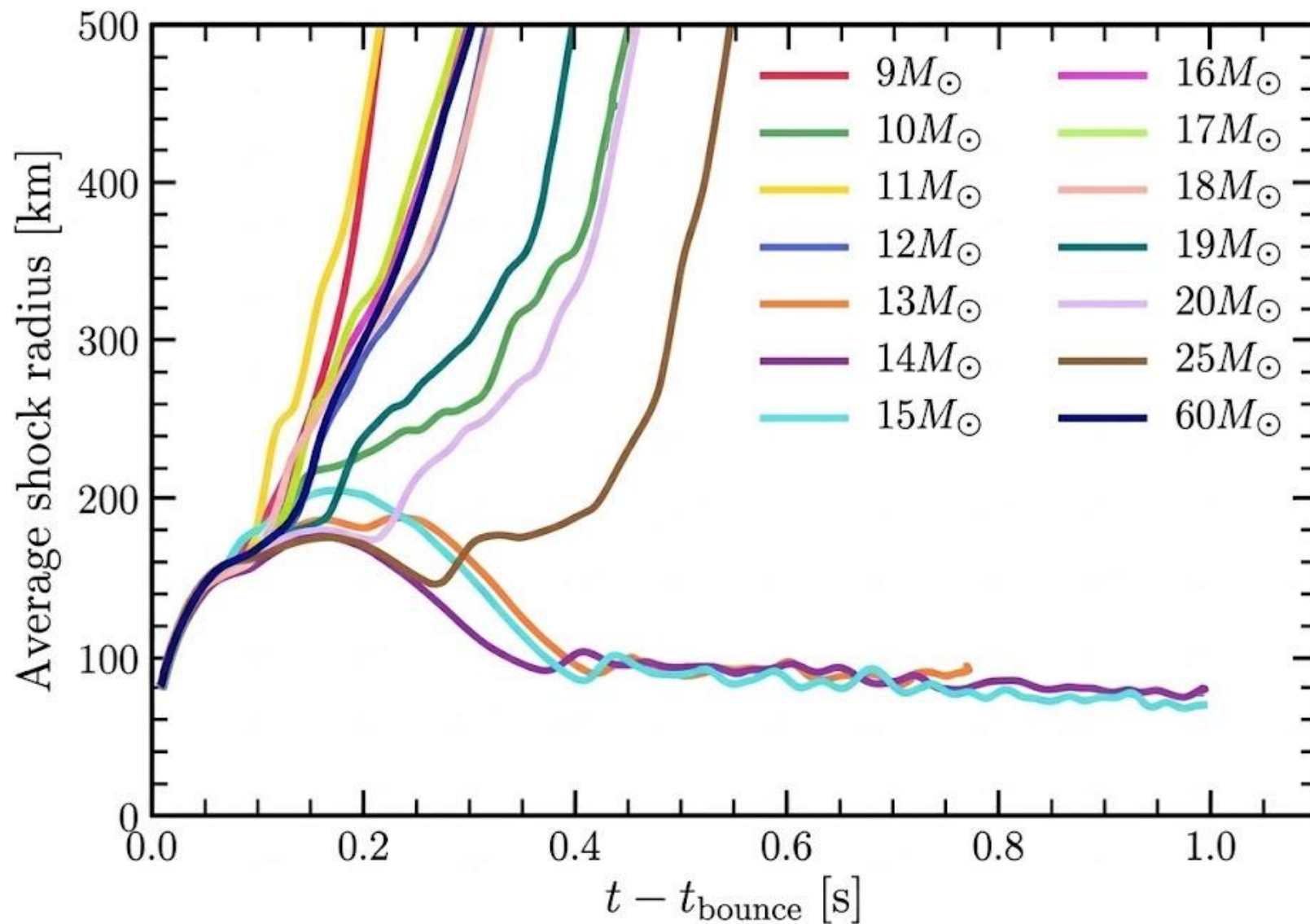
Neutronization peak



Only ν_e , $\bar{\nu}_e$ are emitted!



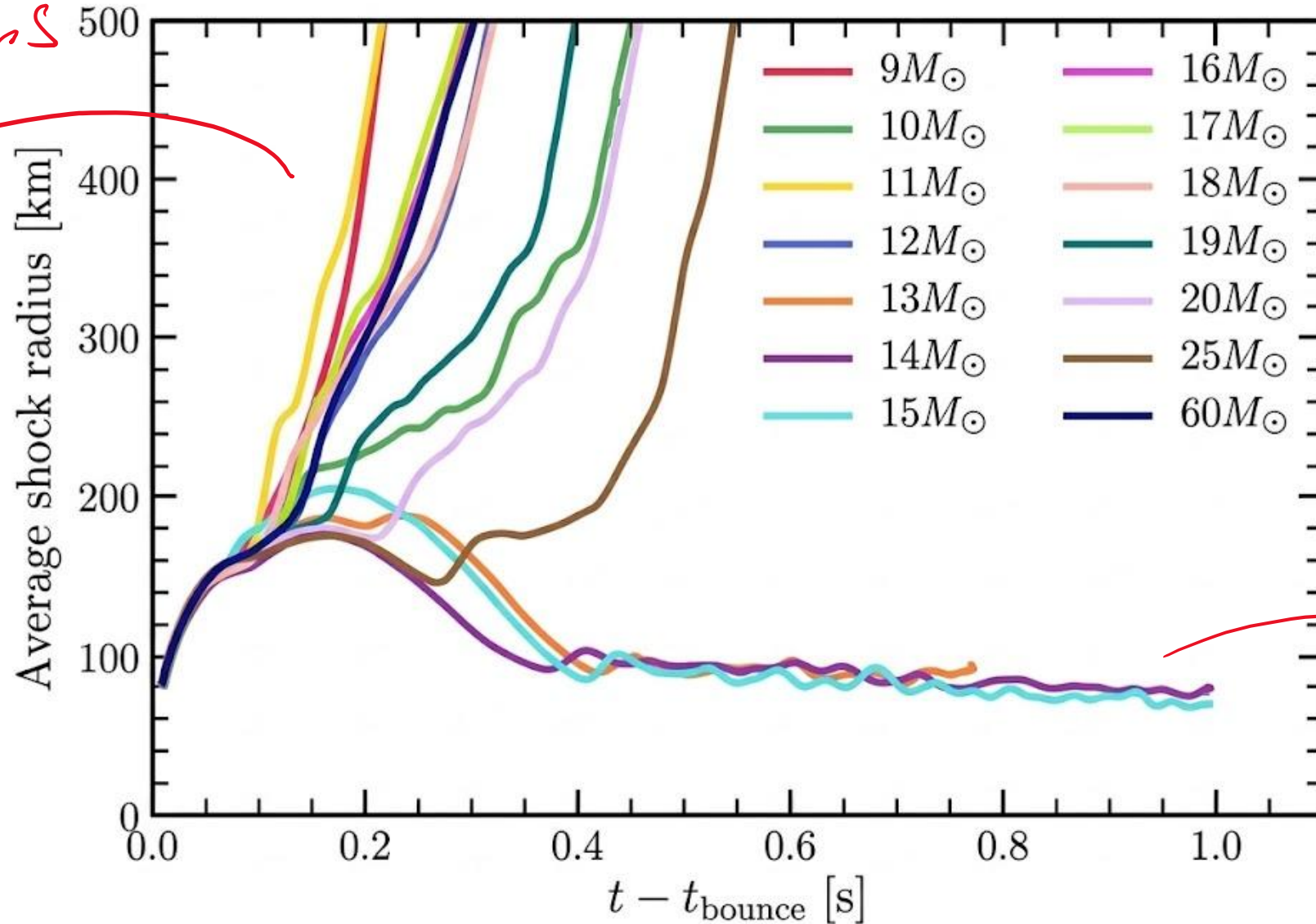
Failed vs successful explosions



Burrows et al., *MNRAS* 491
(2020) 2, 2715-2735

Failed vs successful explosions

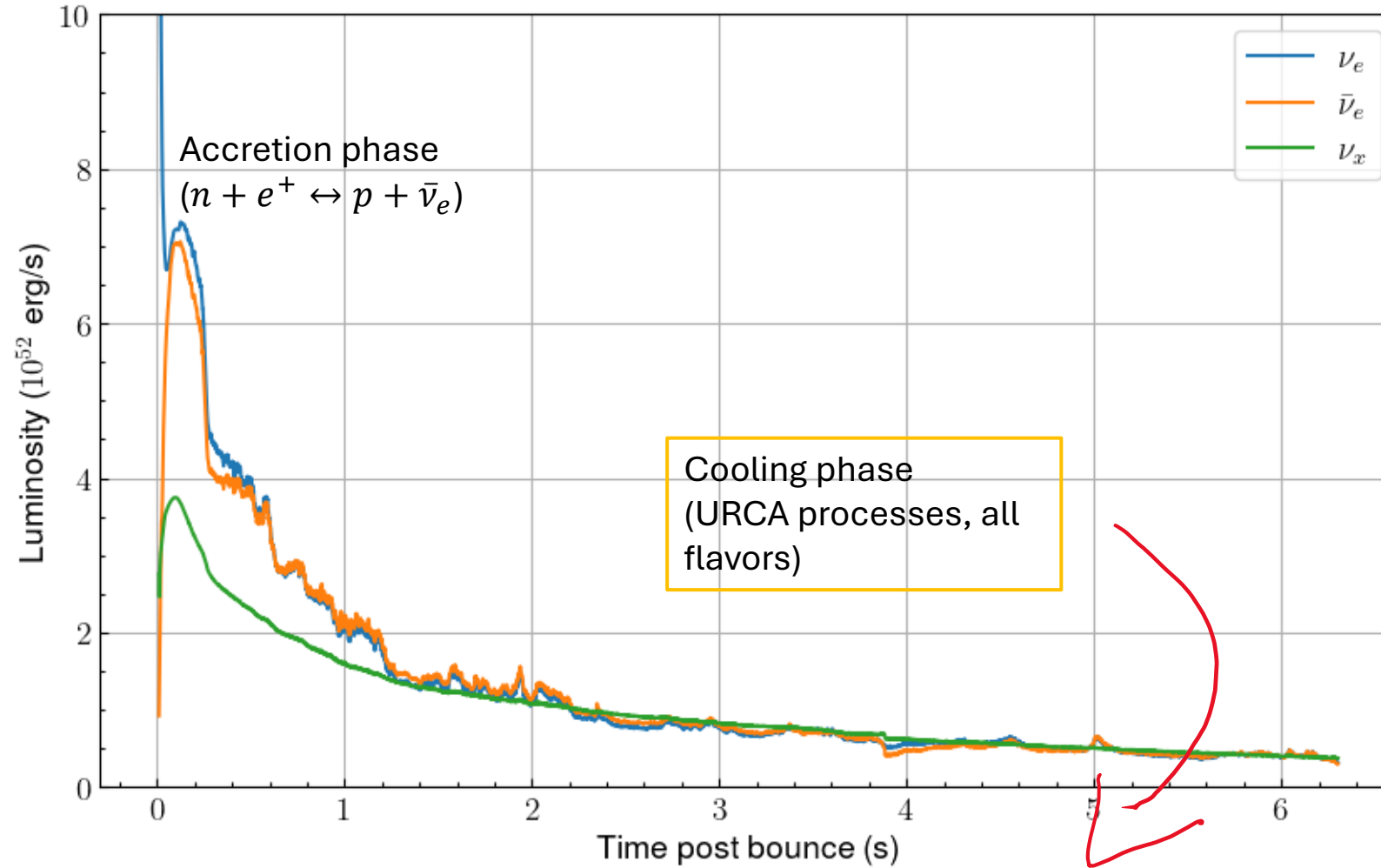
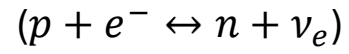
Explosions



Burrows et al., *MNRAS* 491
(2020) 2, 2715-2735

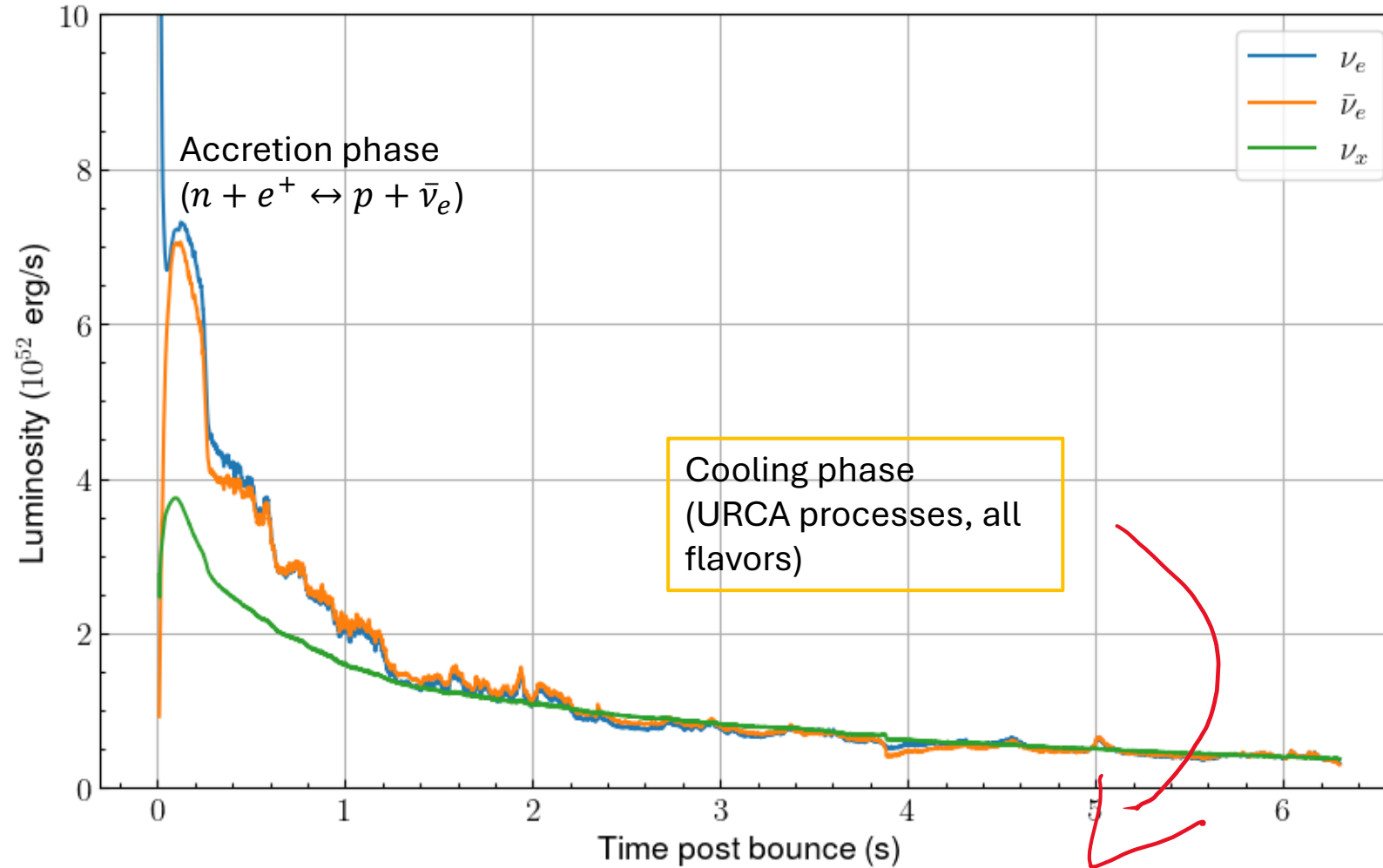
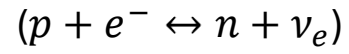
Failed
SNe

Neutronization peak



$$\Phi_c^0(E_\nu, t^{em}) \propto R_{PNS}^2 \frac{E_\nu^2}{1 + e^{\left(\frac{E_\nu}{T_c(t^{em}_{10})}\right)}}$$

Neutronization peak



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

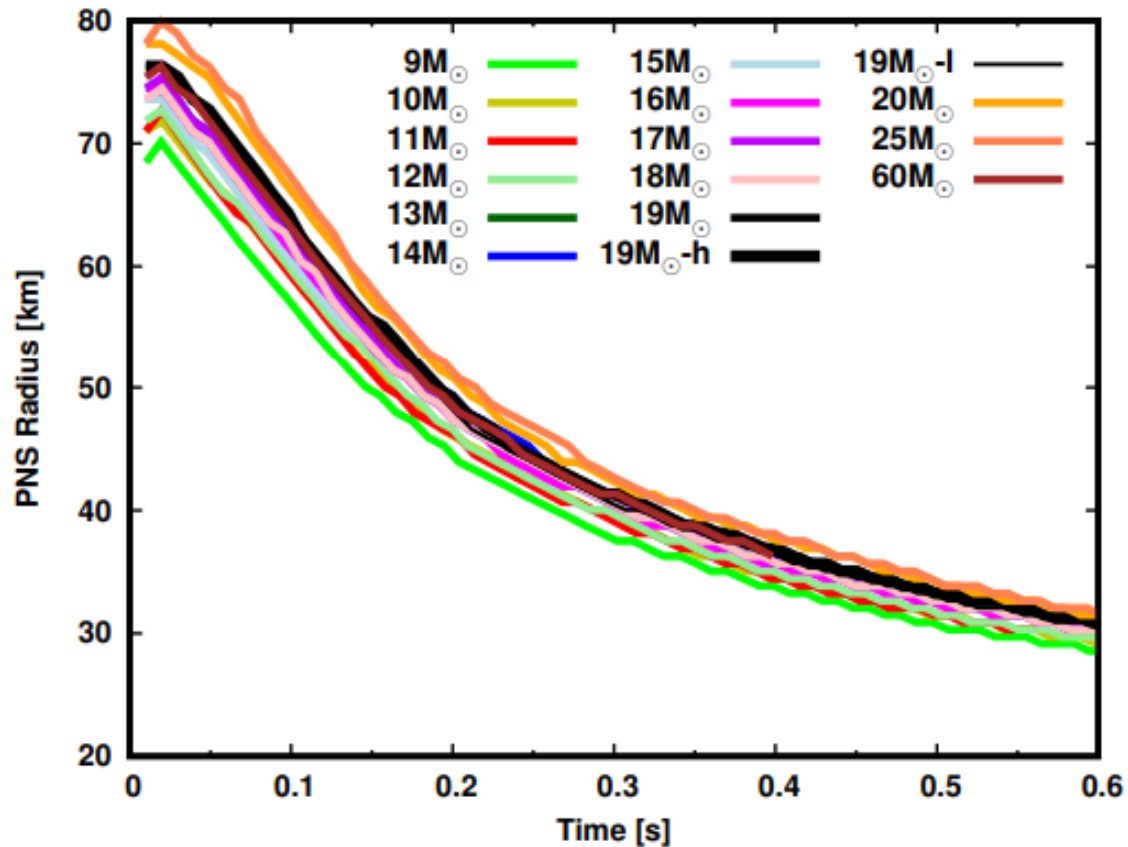
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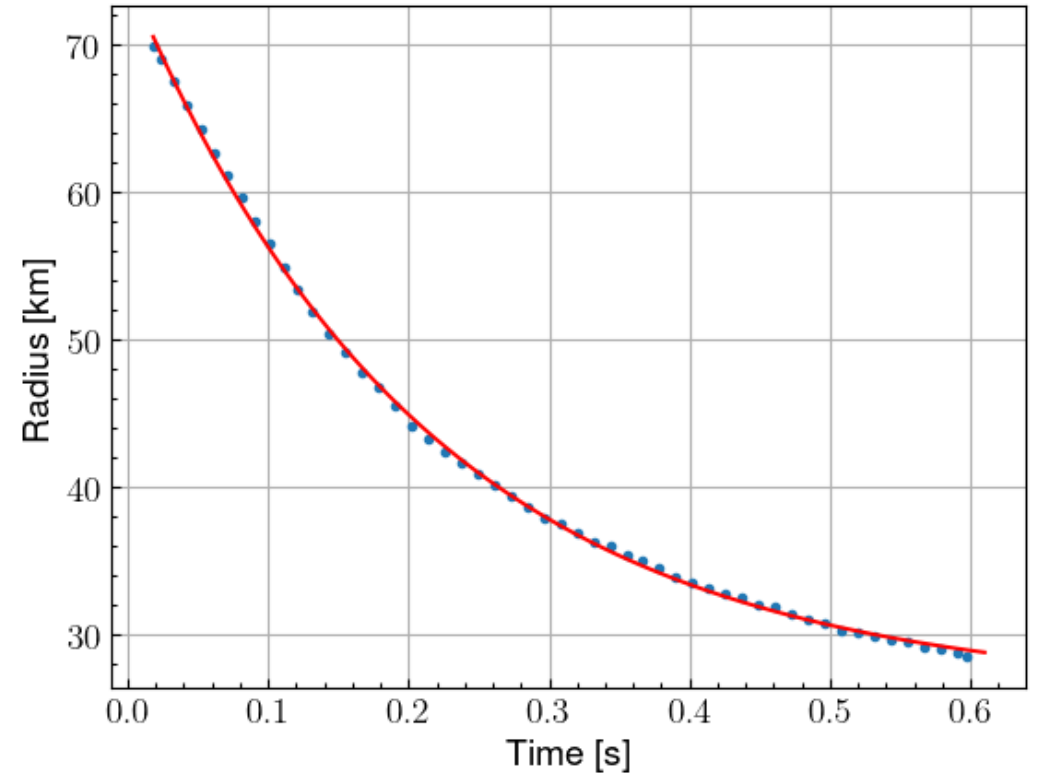
Radius modeling

$$R_c(t) = R_f [1 + \delta R \exp(-t/\tau_{T_r})]$$

$$\delta R = R_f / (R_f - R_0)$$



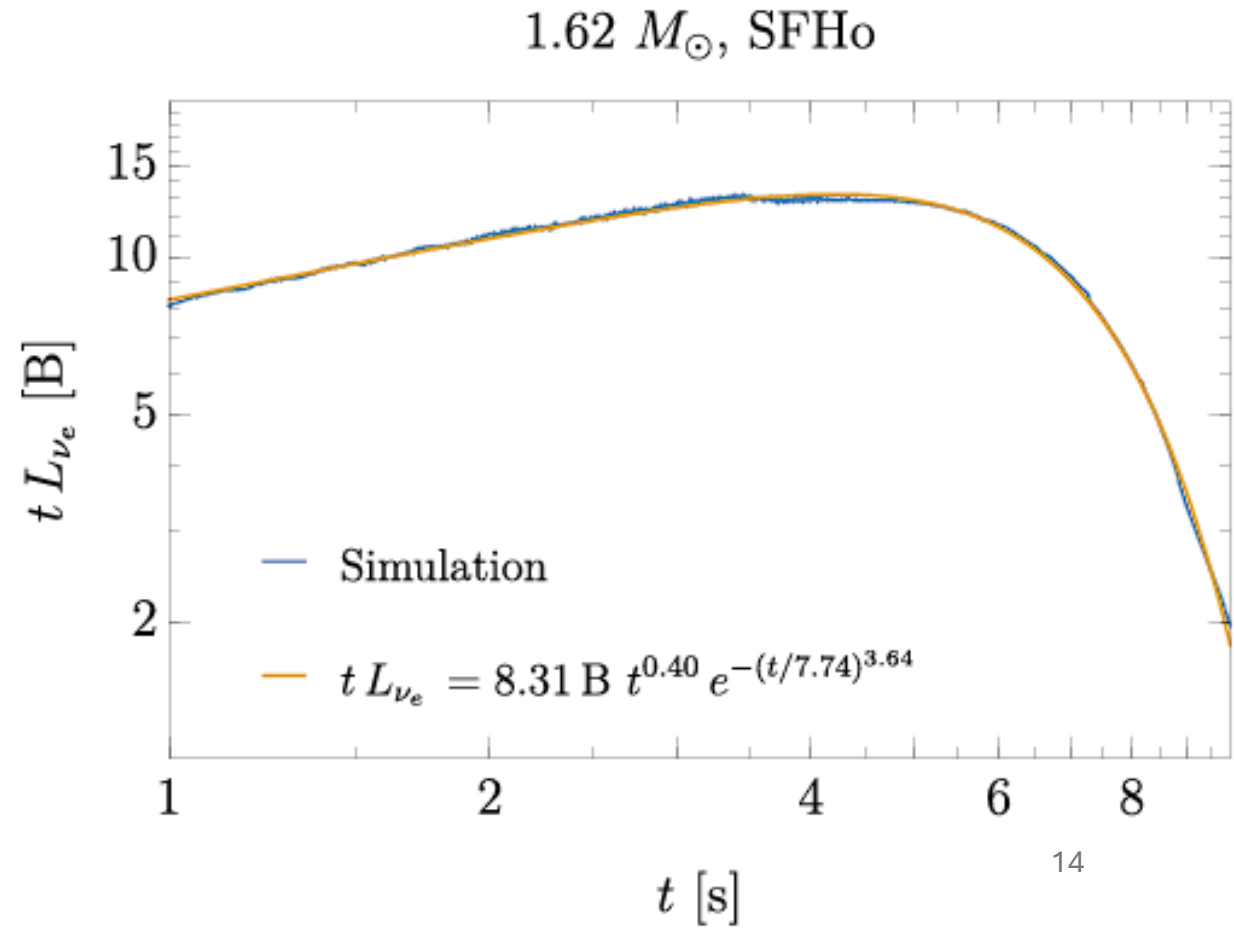
Nakagura et al., MNRAS 492 (2020) 4, 5764-5779



PNS convection

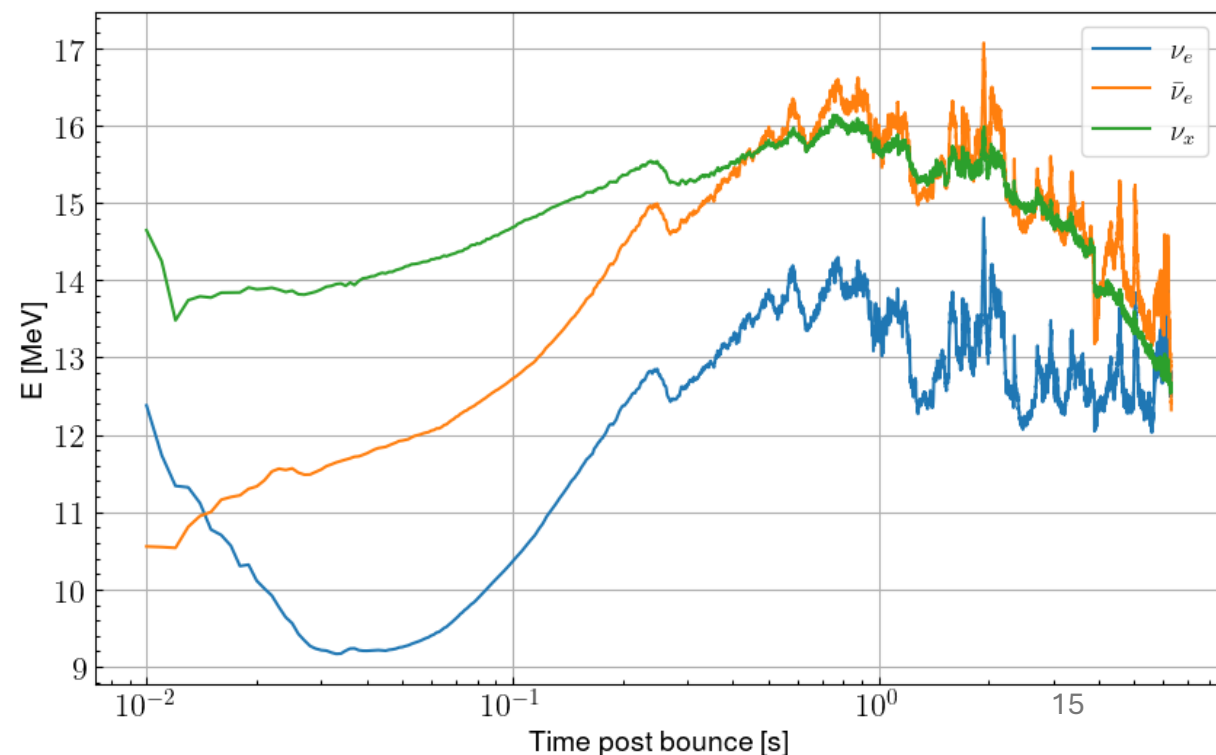
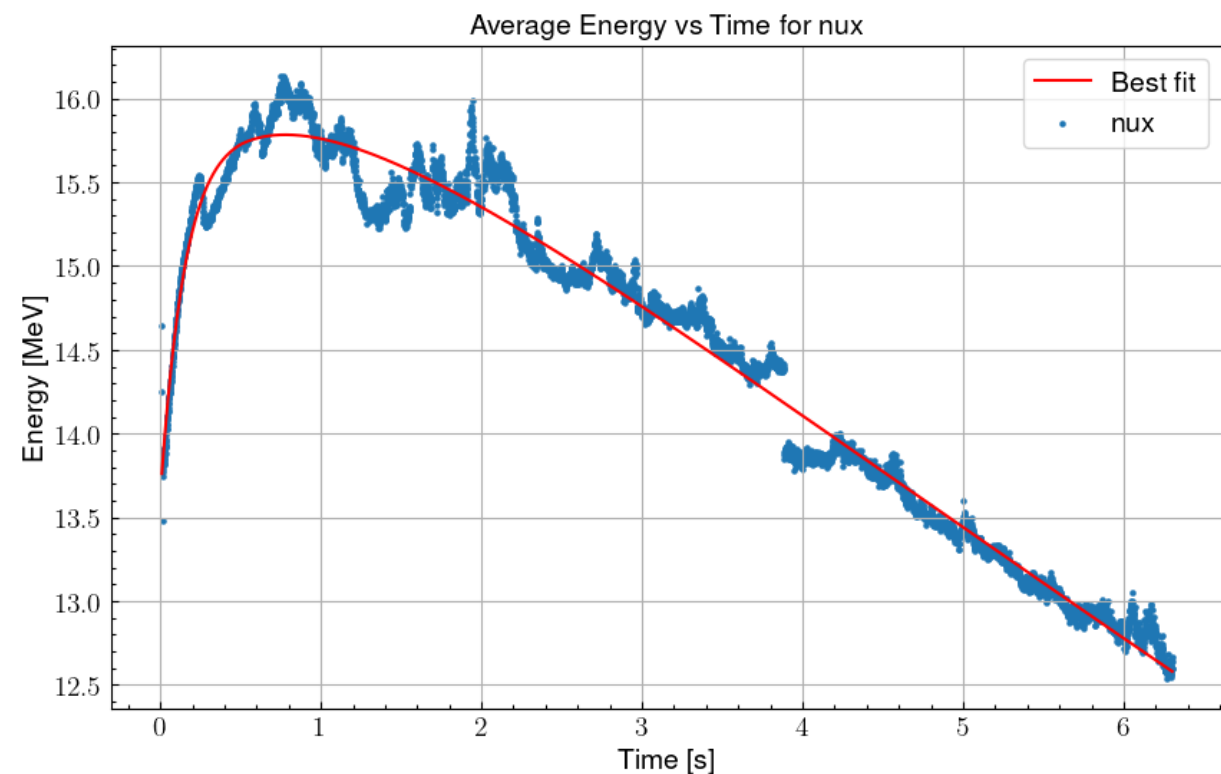
*Lucente et al.,
PRD 110 (2024) 6, 6*

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



Temperature evolution

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



Complete PNS cooling model

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

Old model (<i>Pagliaroli et al.</i> , <i>Astropart.Phys.</i> 31 (2009) 163-176)	Constant R_c (1 param)	$T_c(t)$ as a simple exponential decay (2 params)	—
This work <i>arXiv: 2610.12101</i>	$R_c(t)$ tracking PNS evolution (3 params)	$T_c(t)$ includes convection and rising (6 params)	Extra rising term (1 param)

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

Complete PNS cooling model

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

Old model (<i>Pag al., Astropart.Phys.</i> : 163-176)	Flux at the source!			—
This work <i>arXiv: 2610.12101</i>	PNS evolution (3 params)	and rising (6 params)	ction	Extra rising term (1 param)

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

Accretion phase

Old model	This work - <i>arxiv: 2610.12101</i>
Parametric T_a growing as t^2 (1 param)	Simulation based T_a growing exponentially (2 params)
Dependence on M_a, τ_a (2 params)	Same structure (2 params)

$$T_a(t) = \begin{cases} T_{a,0} + \delta T_{a,0}(1 - \exp(-t/\tau_{ta})), & \text{if } t < \tau_a \\ T_c(t) & \text{if } \tau_a < t \end{cases}$$

Outline

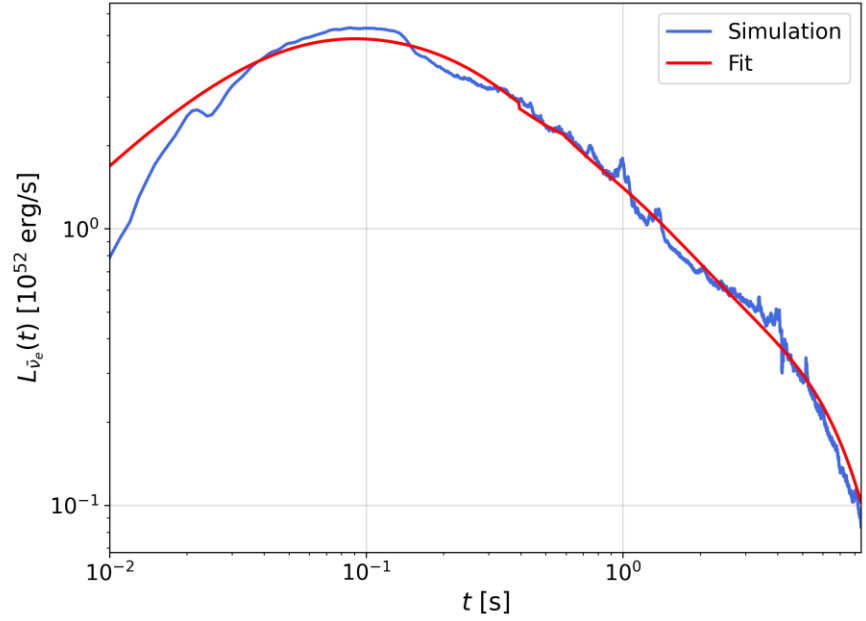
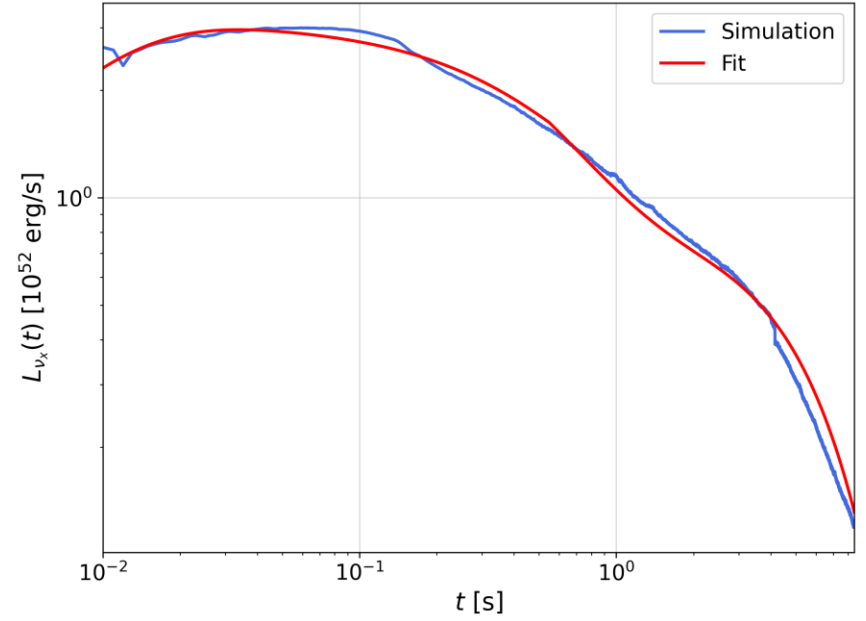
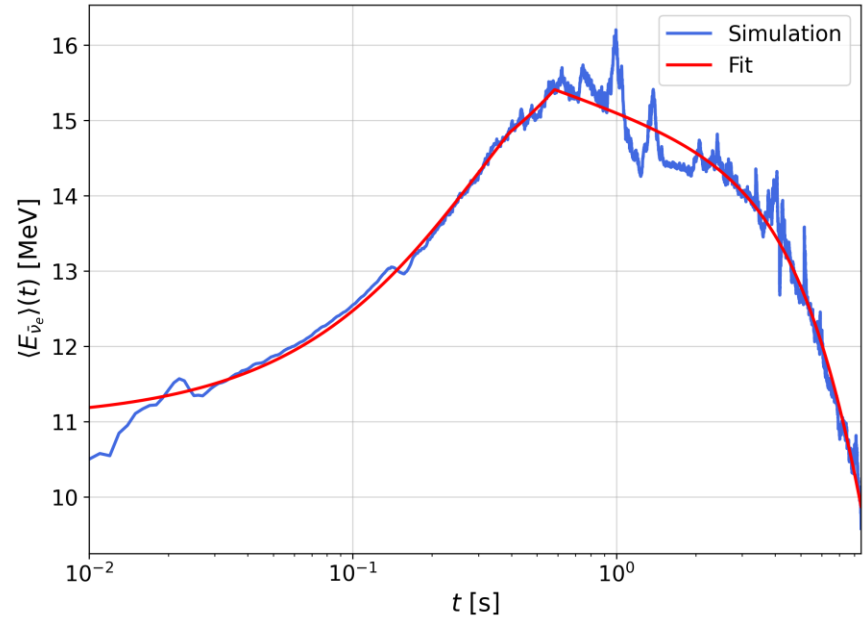
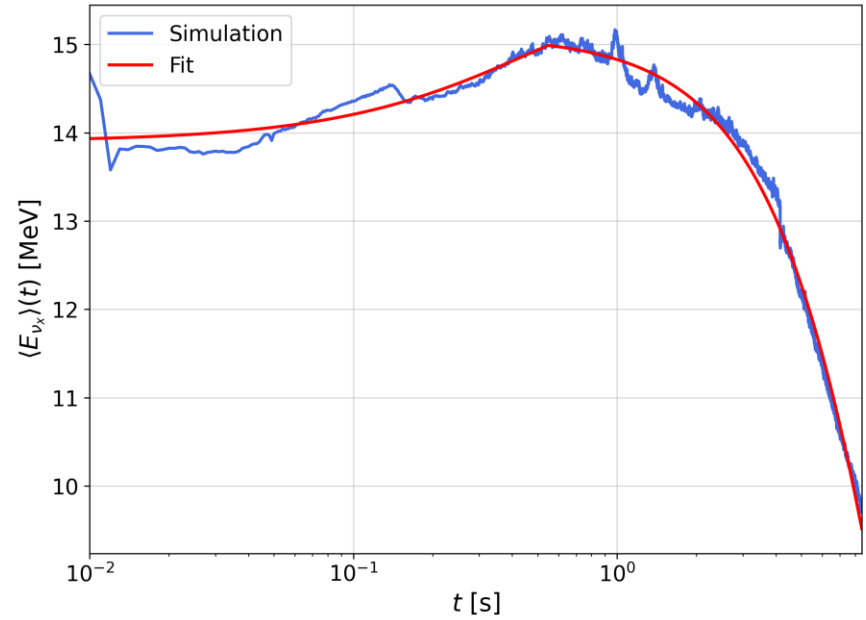
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Full simulation
testing

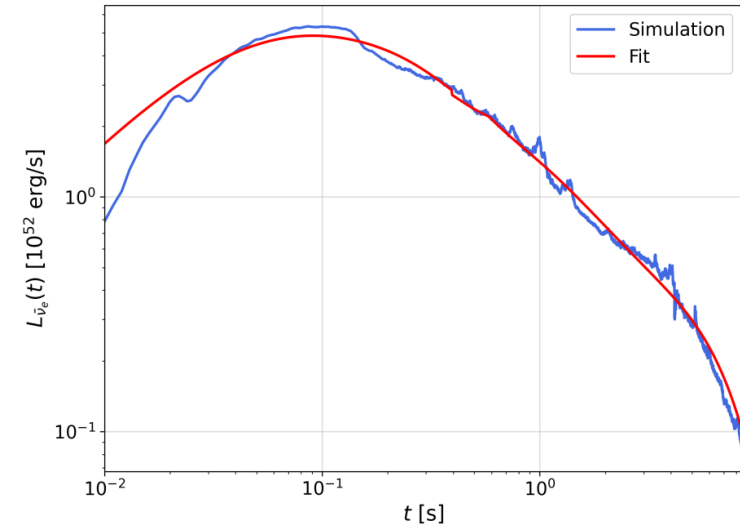
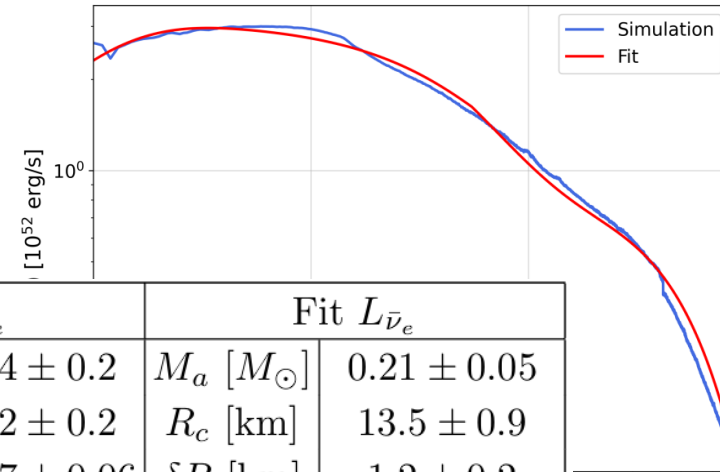
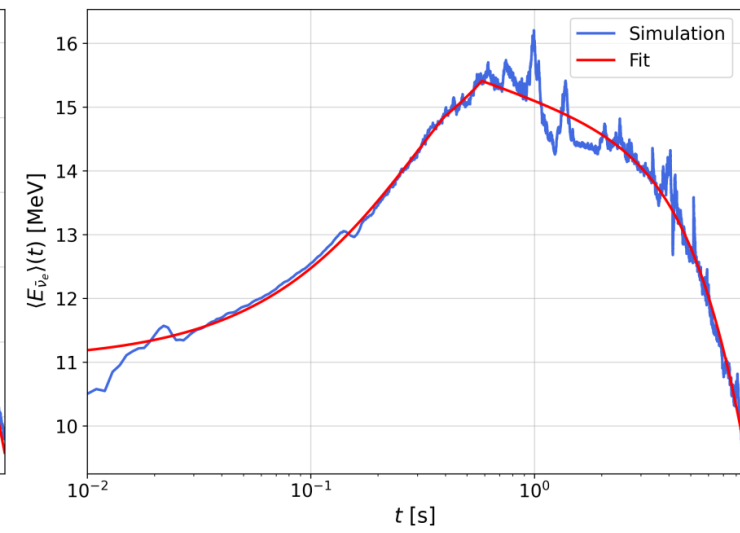
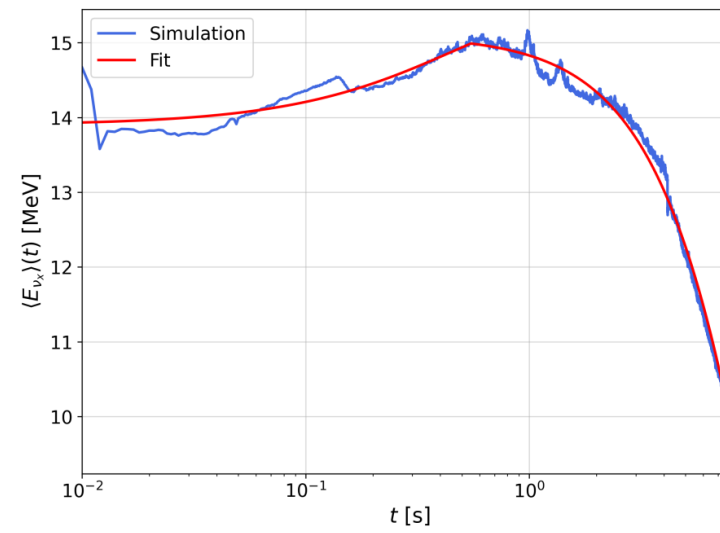
Fit energy parameters



Use them to fit
luminosities



Full simulation testing



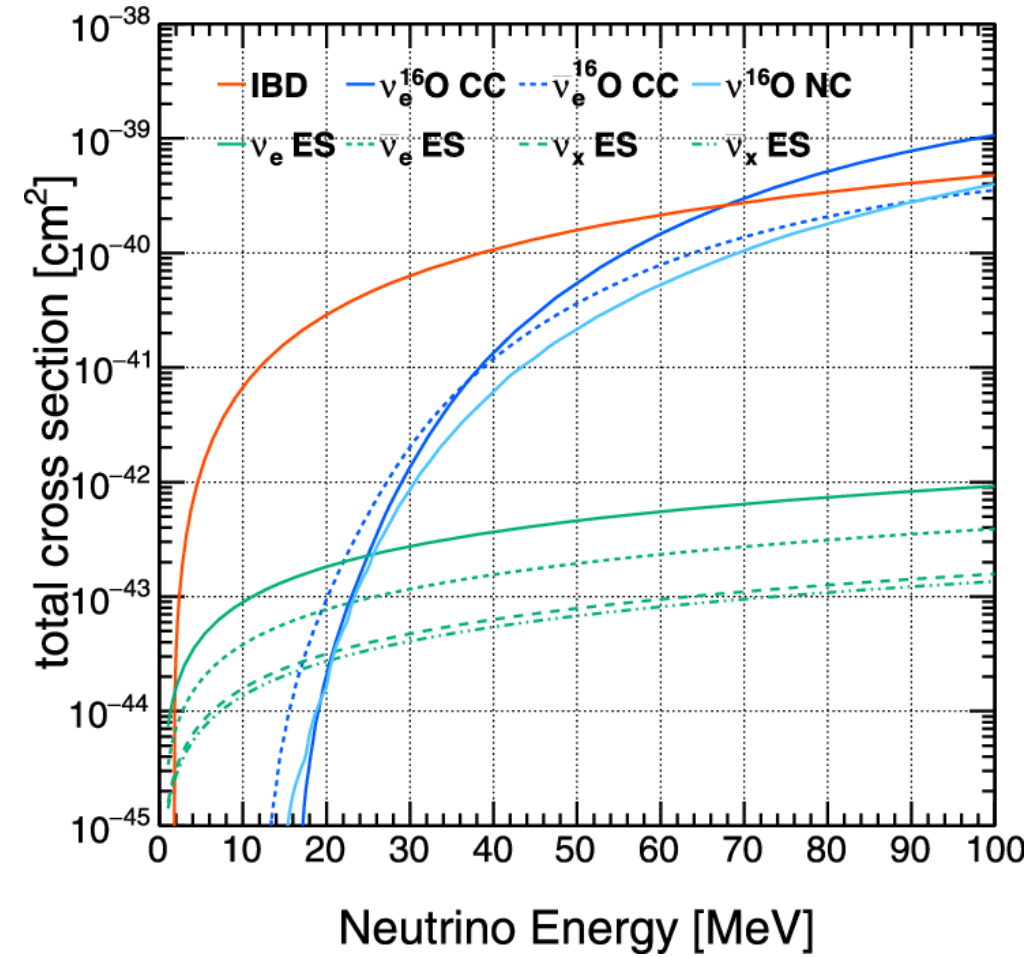
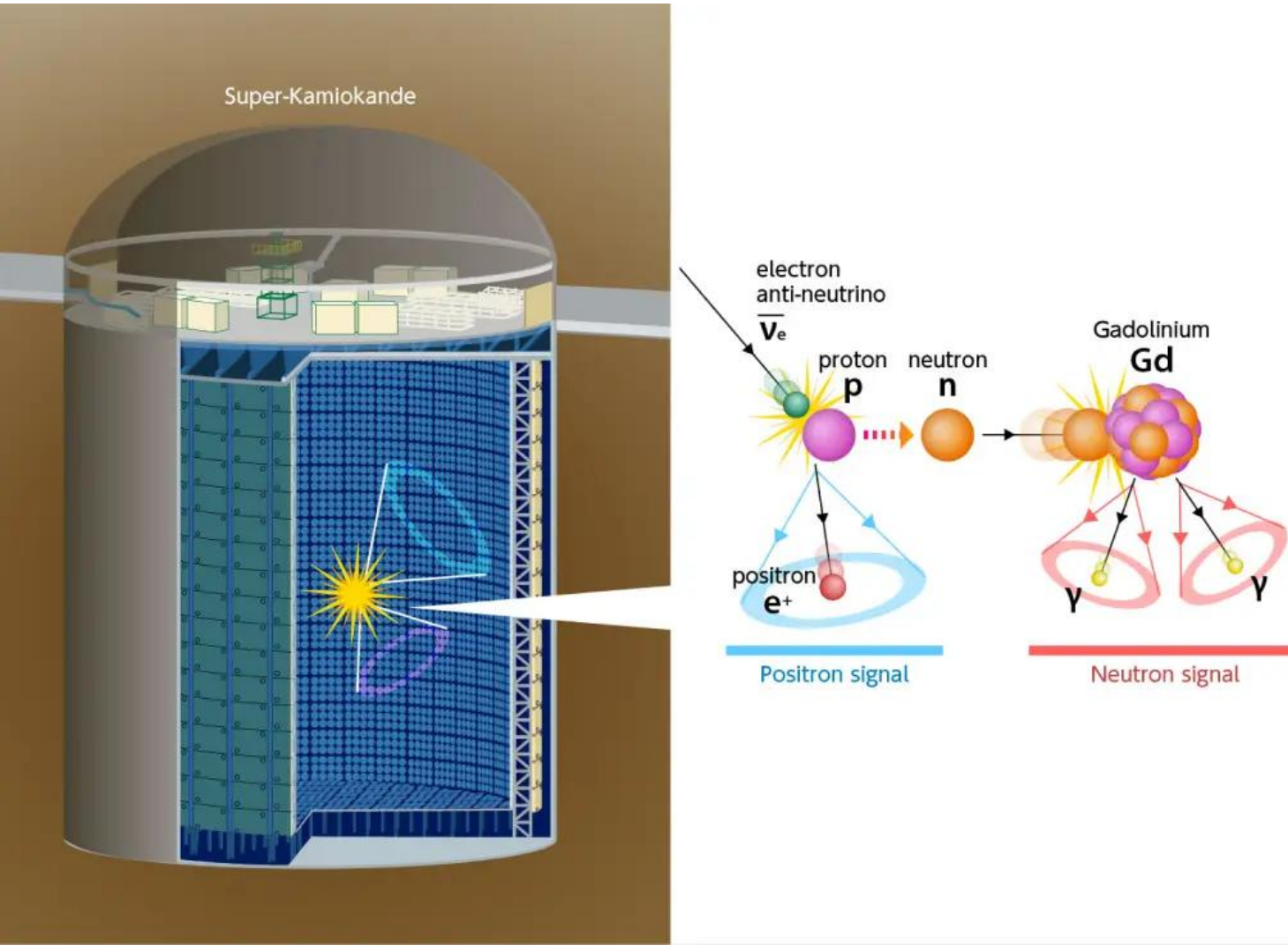
Fit E_{ν_x}		Fit L_{ν_x}		Fit $E_{\bar{\nu}_e}$		Fit $L_{\bar{\nu}_e}$	
T_0 [MeV]	4.36 ± 0.05	R_c [km]	17.4 ± 0.3	T_0 [MeV]	4.4 ± 0.2	M_a [$M_\odot$]	0.21 ± 0.05
δT [MeV]	0.7 ± 0.2	δR [km]	1.30 ± 0.02	δT_a [MeV]	1.2 ± 0.2	R_c [km]	13.5 ± 0.9
τ_{Tc} [s]	0.3 ± 0.1	τ_R [s]	0.48 ± 0.04	τ_{Ta} [s]	0.27 ± 0.06	δR [km]	1.2 ± 0.2
τ_c [s]	15 ± 3	τ_r [s]	0.008 ± 0.001	τ_a [s]	0.6 ± 0.1	τ_R [s]	2.0 ± 0.8
$\bar{t}$ [s]	0.9 ± 0.3			δT_0 [MeV]	1.2 ± 0.7	τ_r [s]	0.031 ± 0.003
α	0.04 ± 0.04			τ_{Tc} [s]	0.6 ± 0.7		
n_c	3 ± 2			τ_c [s]	40 ± 30		
				$\bar{t}$ [s]	1.0 ± 0.4		
				α	0.08 ± 0.05		
				n_c	3 ± 2		

Mean BF values $\pm$ standard deviation for the fits of 17, 18, 19, 20, 24, and 25 $M_\odot$ progenitors

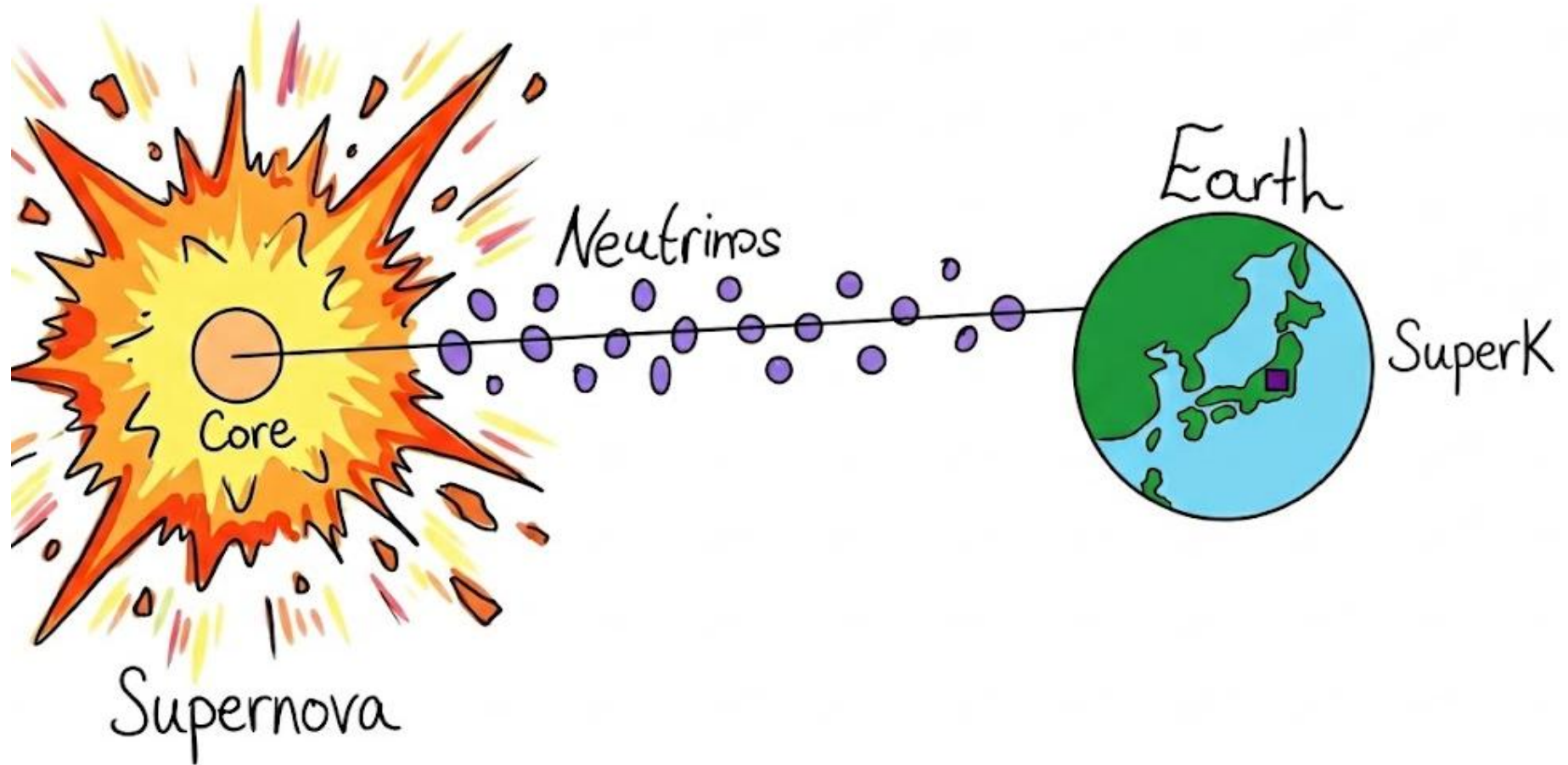
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Detection channel



Neutrino oscillations



MSW
oscillations

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



Inverted ordering:

$$\Phi_{\bar{\nu}_e} \simeq \Phi_{\nu_x}^0 = \Phi_c$$

MSW
oscillations

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



Inverted ordering:

$$\Phi_{\bar{\nu}_e} \simeq \Phi_{\nu_x}^0 = \Phi_c$$

In NO accretion is visible:



Normal ordering:

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

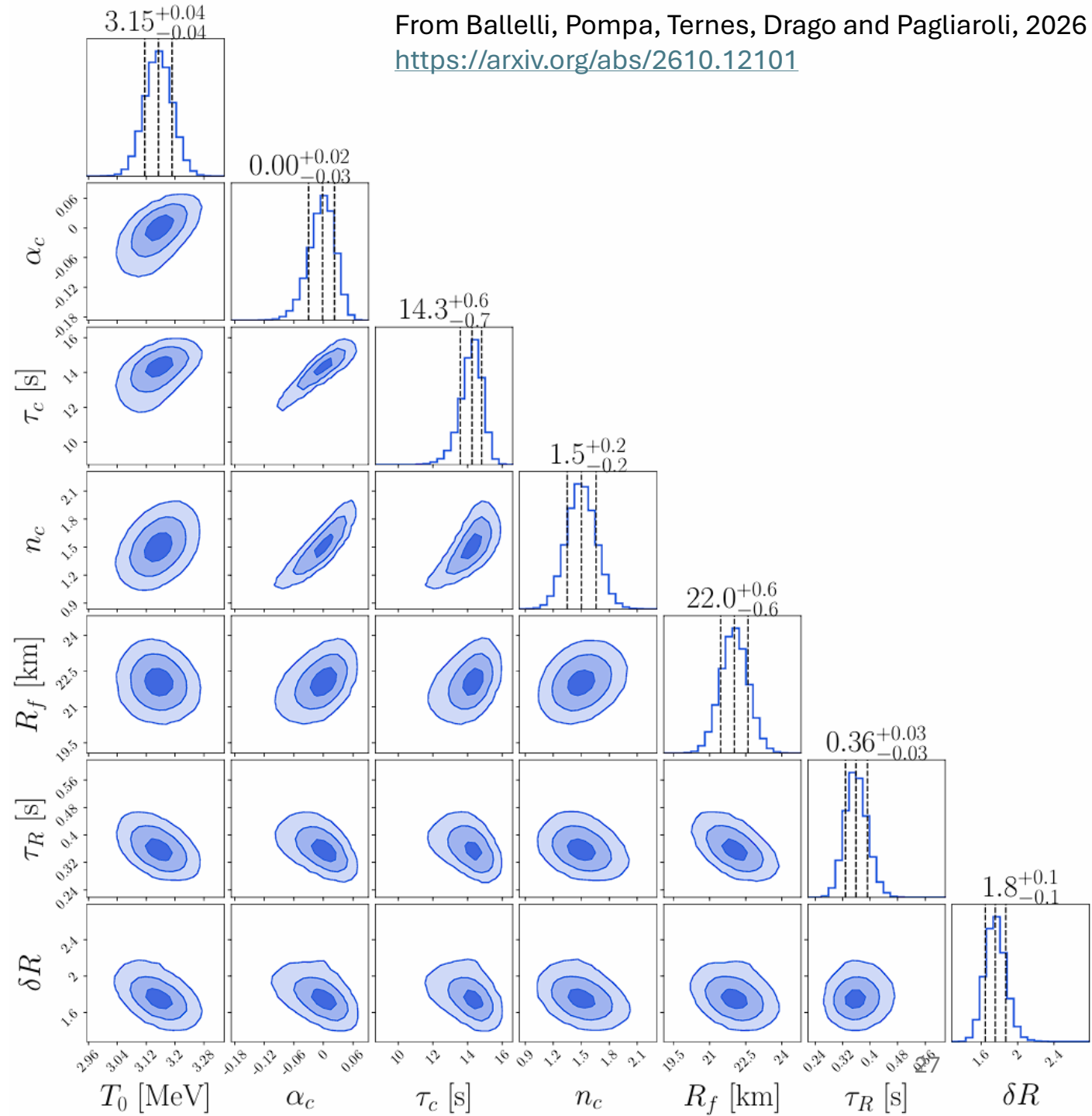
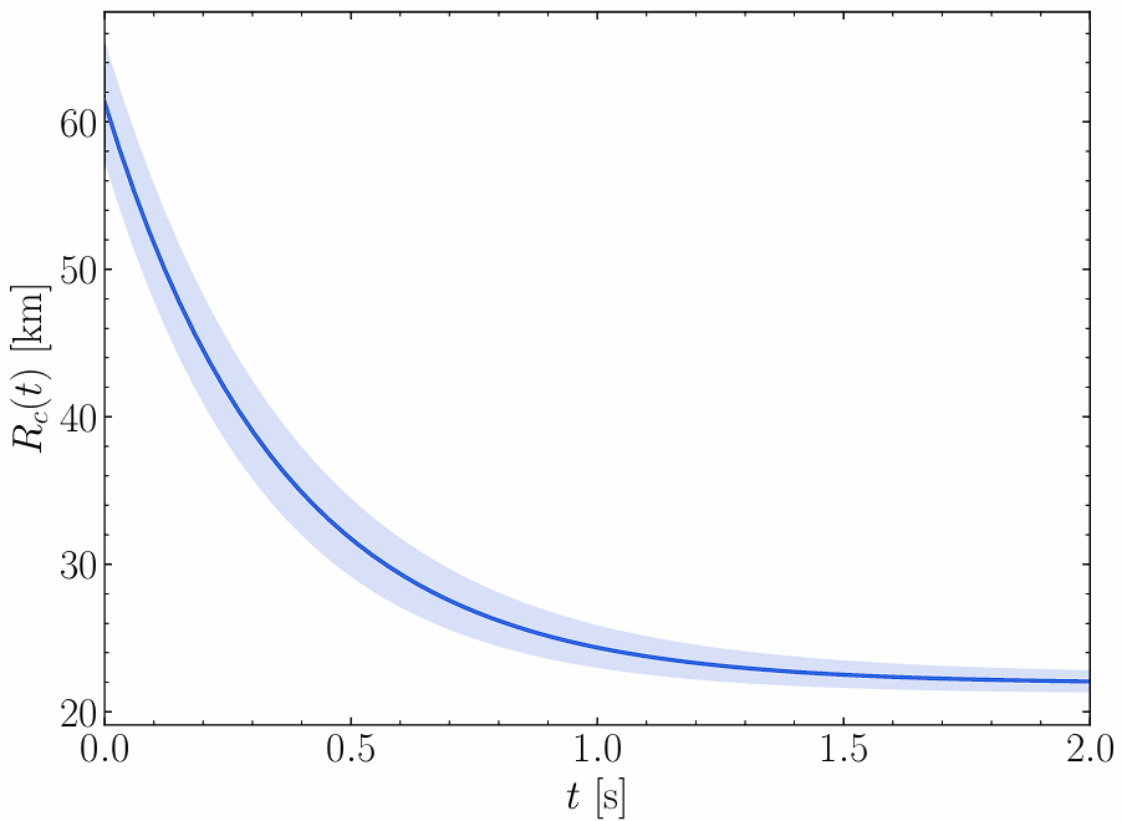
where: $P \simeq 0.7$

$$\Phi_{\bar{\nu}_e}^0 = F(M_a, T_a, \tau_a) + \Phi_c^0$$

Inverted ordering results

$\delta T, \bar{t}, \tau_{T_c}$ fixed

Radius evolution

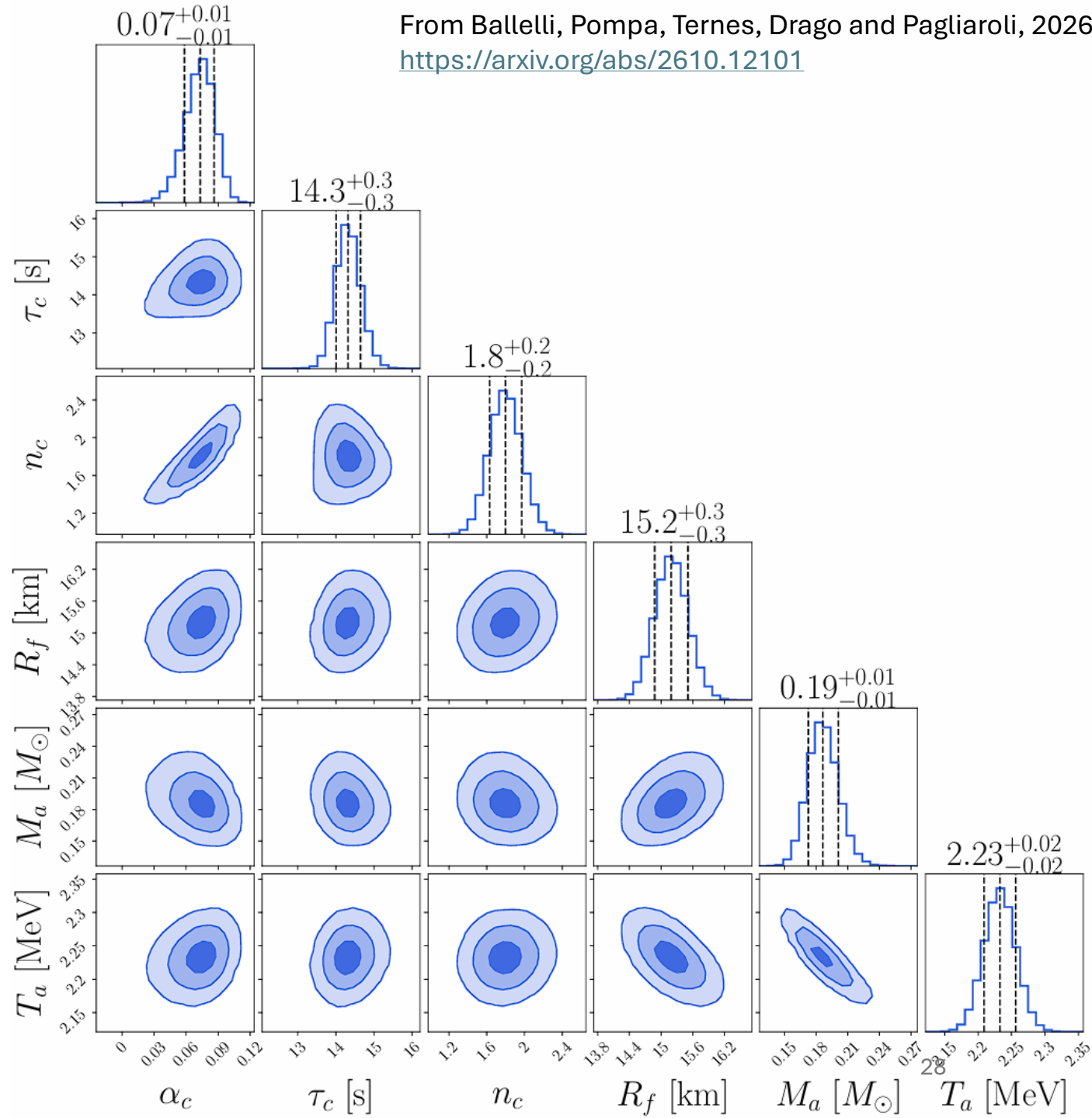


Normal ordering results

$\delta T_a, \tau_a, \tau_{T_a}$ fixed

- Accretion emission ‘covers’ radius shrinking!

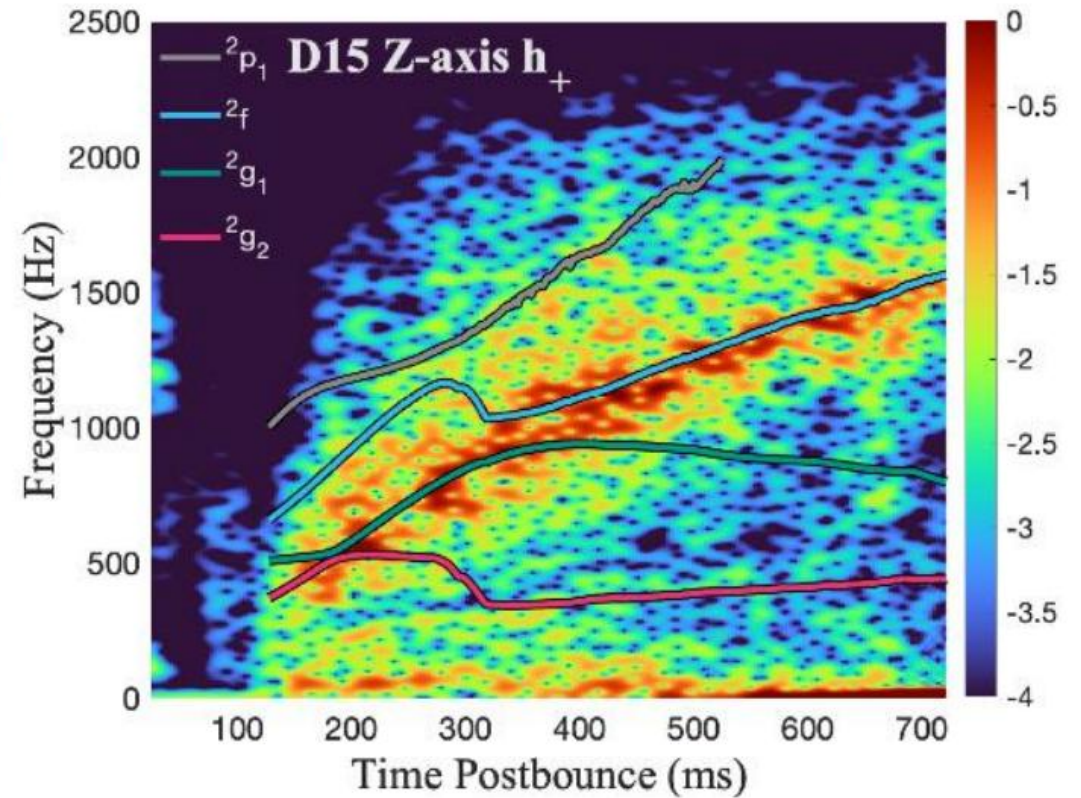
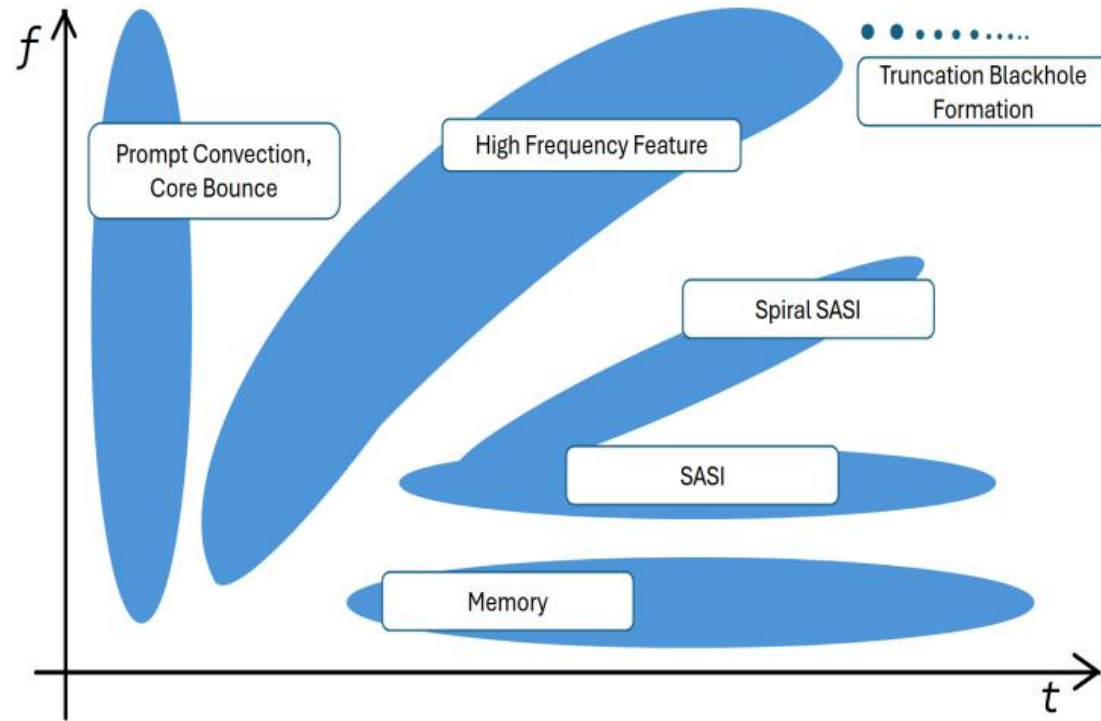
From Ballelli, Pompa, Ternes, Drago and Pagliaroli, 2026
<https://arxiv.org/abs/2610.12101>



Outline

- ‘Traditional’ model
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- Data analysis of simulated data
- Multimessenger prospects with GW

GW emission from CCSNe



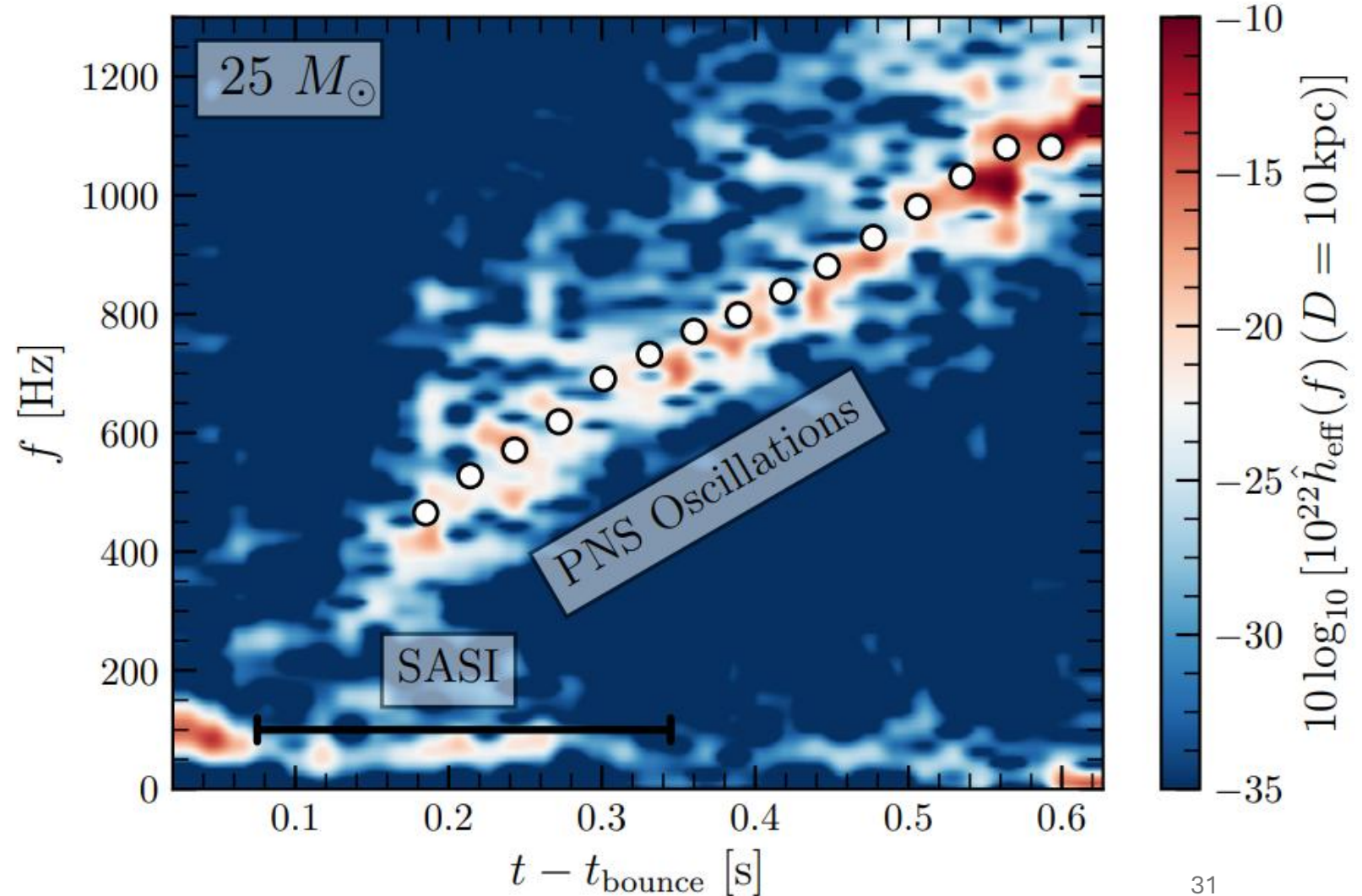
[Murphy et al. Phys. Rev. D \(2025\) arXiv:2503.06406](#)

GW high frequency feature

Abdikamalov et al., 2020

<https://arxiv.org/abs/2010.04356>

$$f(t) \sim F(M_{PNS}/R_{PNS}^n)$$



Conclusions

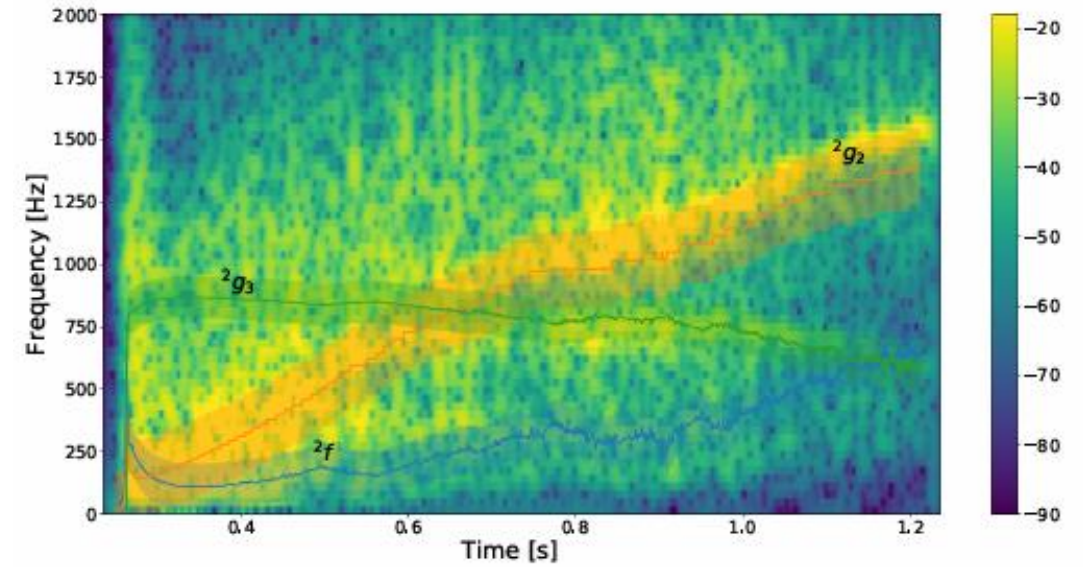
- New model for neutrino emission from Supernova, tested on simulated datasets
- Neutrino data can help constraining relevant PNS and accretion phase parameters!
- GW + neutrino analysis can be complementary in unveiling the PNS evolution in the first moments after the core bounce

Other activities

- Investigation on the possible association between a muon burst detected by the Yangbajing muon telescope (*F. Nozzoli, Astropart. Phys. 176, 103201 (2026)*) and KM3-230213A
 - Built a flux explaining both results in overshooting the events predicted in other detectors (e.g. LVD)
- Building a microquasar population and performing statistical studies on it evaluating the contribution of these sources to the galactic cosmic ray knee
- Ligo-Virgo-Kagra Collaboration-related activities:
 - High frequency unmodeled all sky search with cWB
 - Waveform reconstruction of detected CBC events with cWB
- Conferences/talks:
 - TeVPa 2026 (31 August – 5 September 2026)
 - SAIIT (4-8 May, 2026)
 - Virgo week at EGO-Virgo in Pisa, Italy (2-5 February 2026)
 - LVK Meeting in Pisa (9-13 March 2026)
- (remote) attendance to the weekly LVK Burst/Supernova group telecons
- Outreach events

PNS asteroseismology

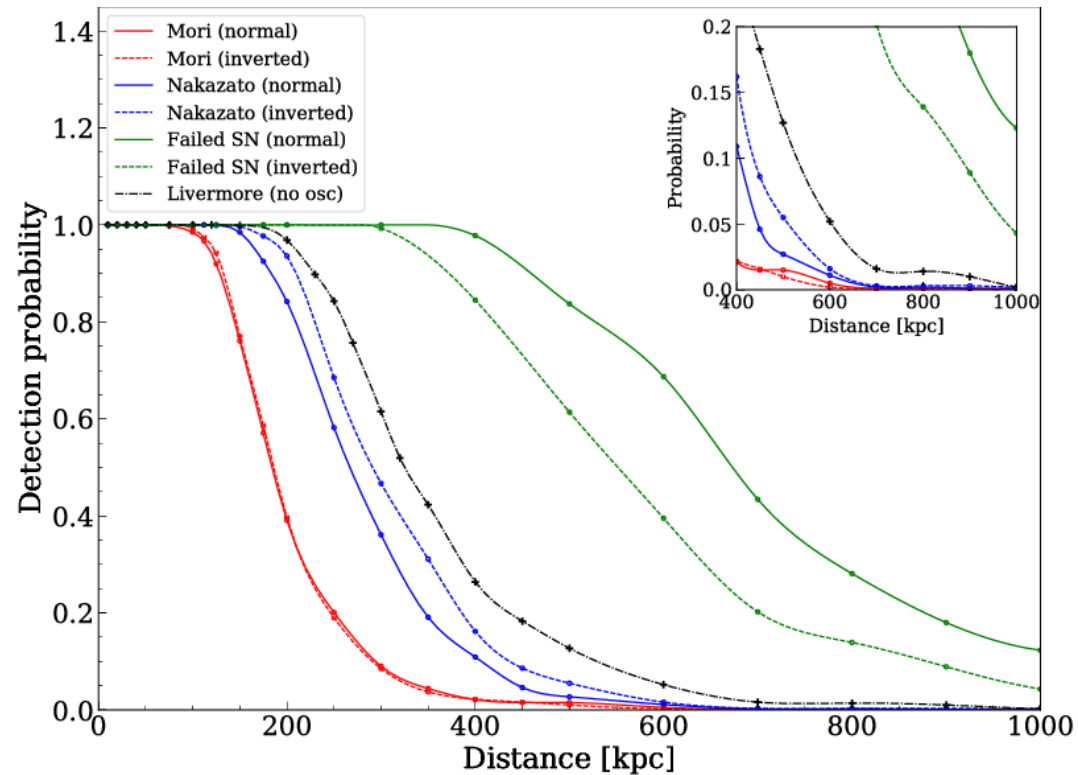
g-modes related to PNS
mass and radius



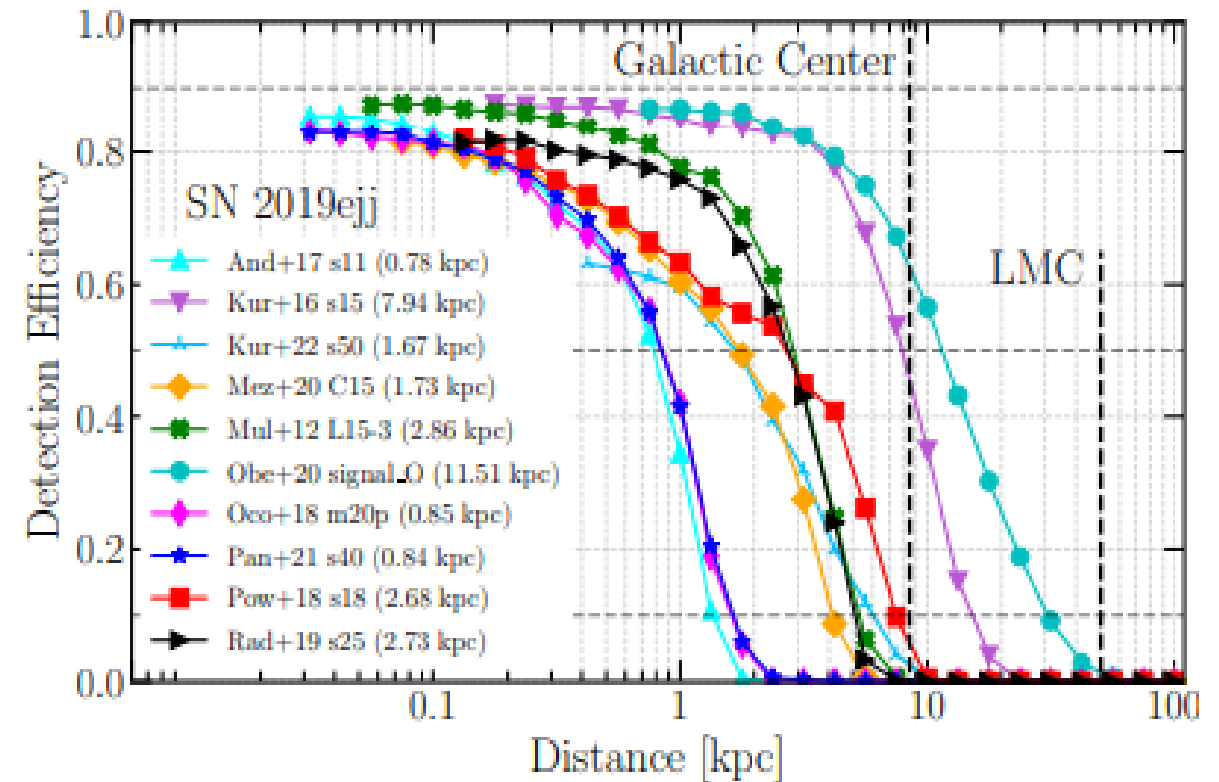
Torres-Forné et al., Phys. Rev. Lett. **127**, 239901 (2021)

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

Detection horizons



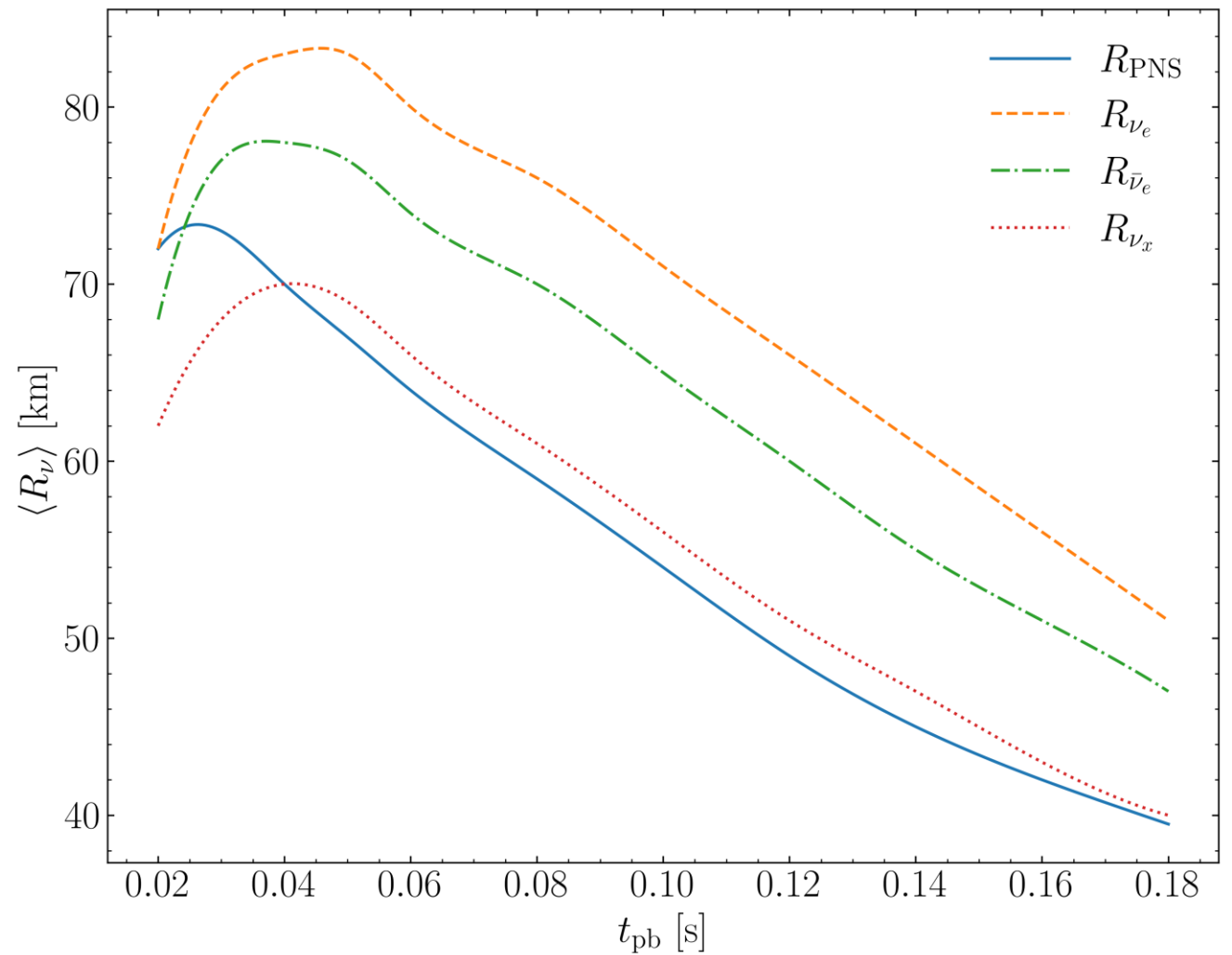
Mori et al., *Astrophys.J.* 938 (2022) 1, 35



Szczepanczyk et al, *Phys. Rev. D* 110, 042007 (2024)

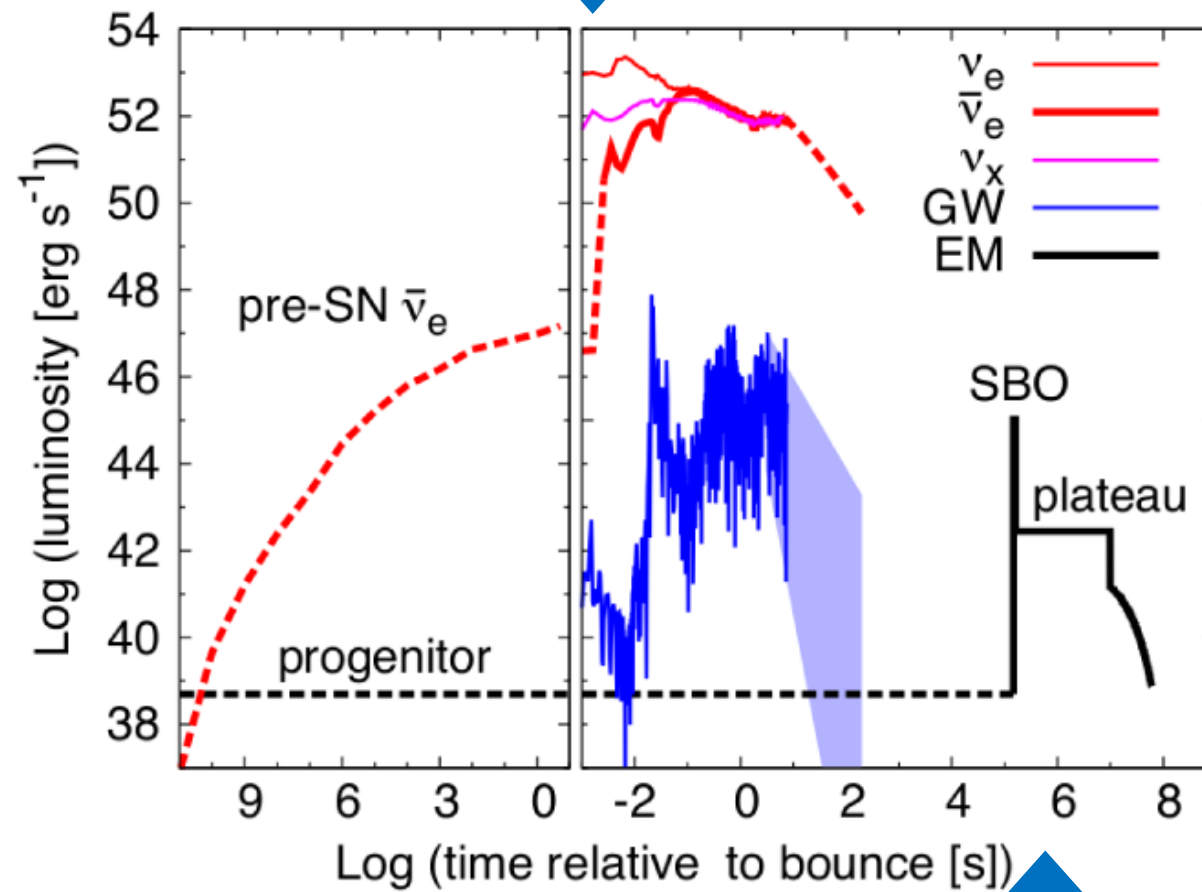
Not easy/universal
relation at early times

$R_\nu \sim R_{PNS}$ at late times



Adapted from Christian D. Ott *et al* 2013 *ApJ* **768** 115

GW and ν s are emitted
at the bounce



while photons
are late!

Accretion details

$$N_n(t) = \frac{Y_n}{m_n} M_a \left(\frac{T_a}{T_a(t)} \right)^6 \frac{\exp[-(t/\tau_a)^2]}{1 + t/(0.5 \text{ s})},$$


$$\Phi_a(t, E_\nu) = [1 - \exp(-t/\tau_r)] N_n(t) \sigma_{e+n}(E_\nu) g_{e+}(E_{e+}, T_a(t))$$

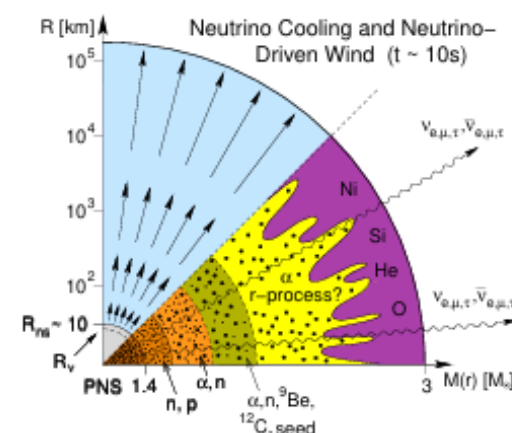
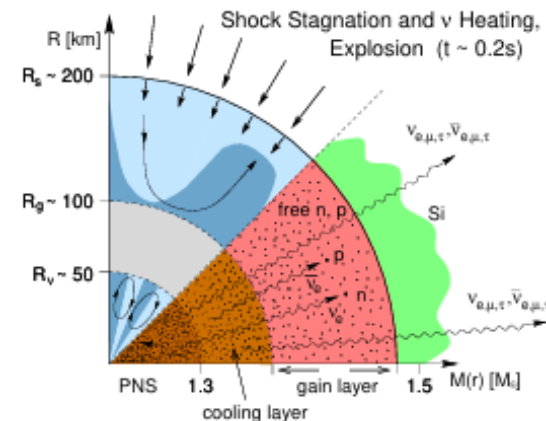
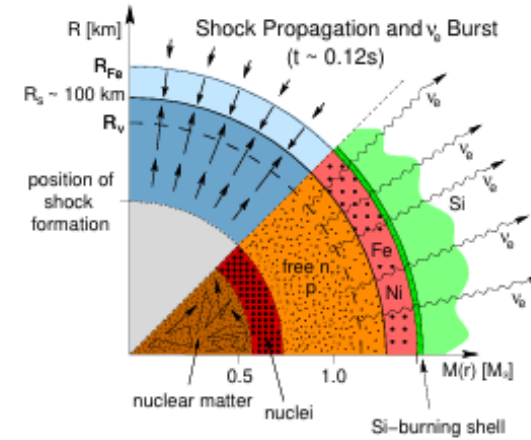
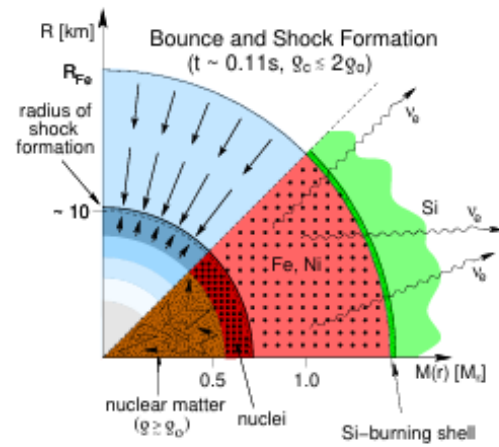
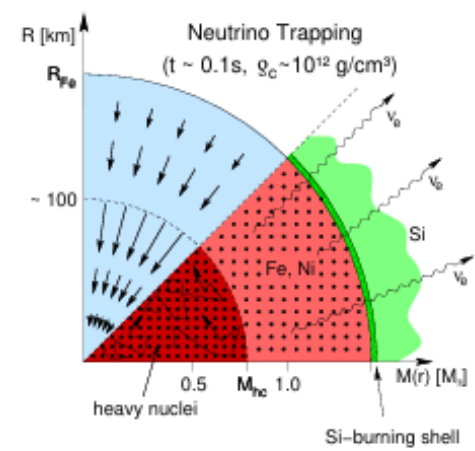
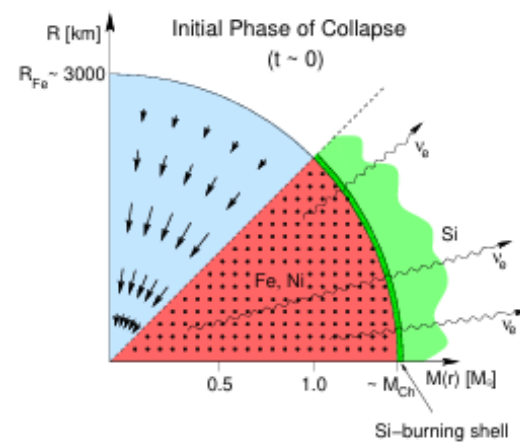

$$g_{e+}(E_{e+}, T_a(t)) = \frac{8\pi c}{(hc)^3} \frac{E_{e+}^2}{1 + \exp(E_{e+}/T_a(t))}$$

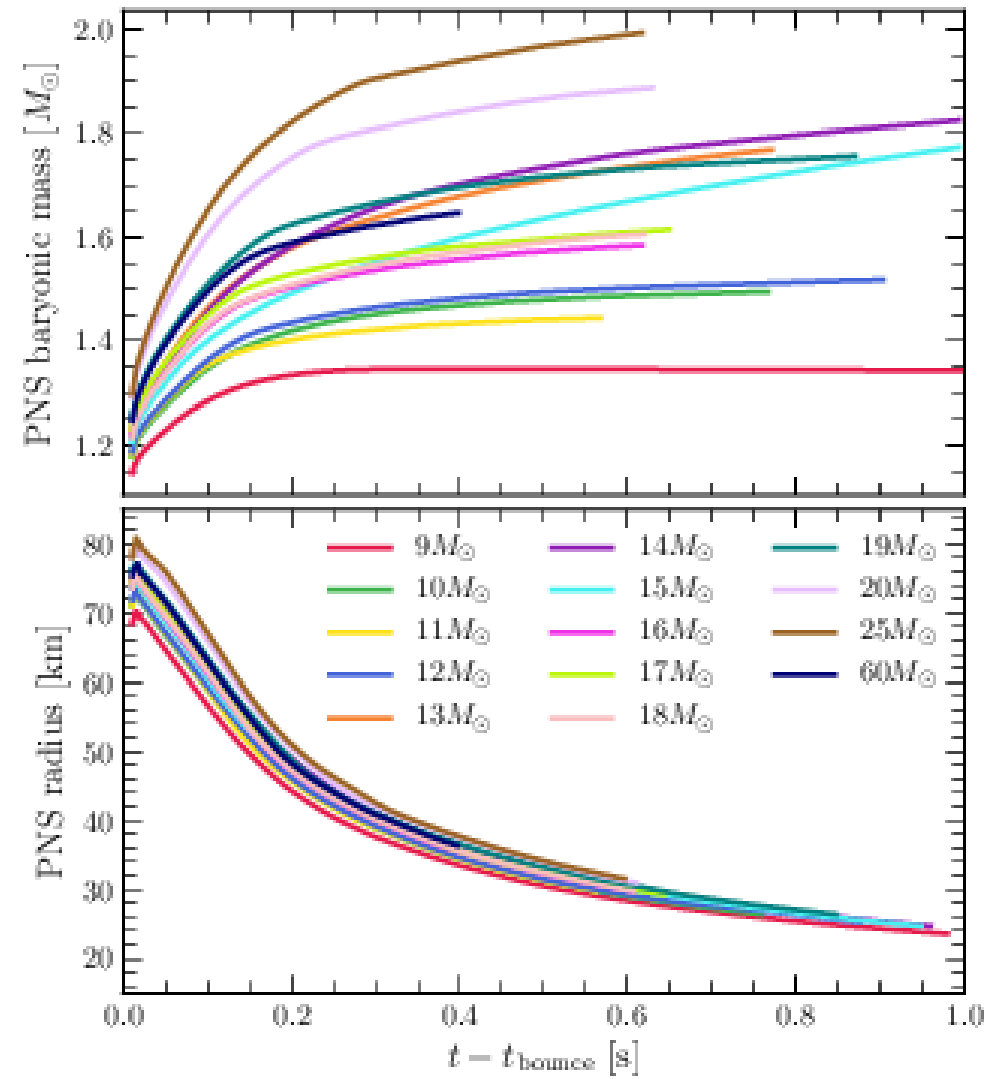
Rate & Likelihood equations

$$R(t, E_{e+}) = N_p \sigma_{IBD}(E_\nu) \Phi_{\bar{\nu}_e}(t, E_\nu) \eta(E_{e+})$$

$$\mathcal{L} = \exp \left[- \int R(t) dt \right] \prod_{i=1}^{N_d} \left[\int R(t'_i, E_{e+}) G(E_{e+}, E_i) dE_{e+} \right]$$

$$G(E_{e+}, E_i) = \frac{1}{\sqrt{2\pi}\delta E_i} \exp \left(- \frac{(E_{e+} - E_i)^2}{2\delta E_i^2} \right) ,$$





Vartanyan 2019

