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Scuola Universitaria Superiore

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PNS parameters estimation with neutrino emission from supernovae

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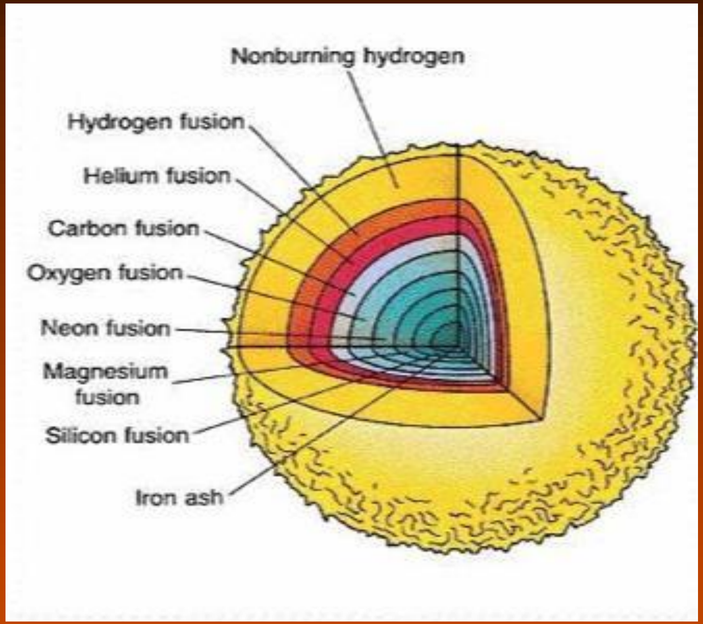
Core-Collapse Supernovae: neutrino and GW emission



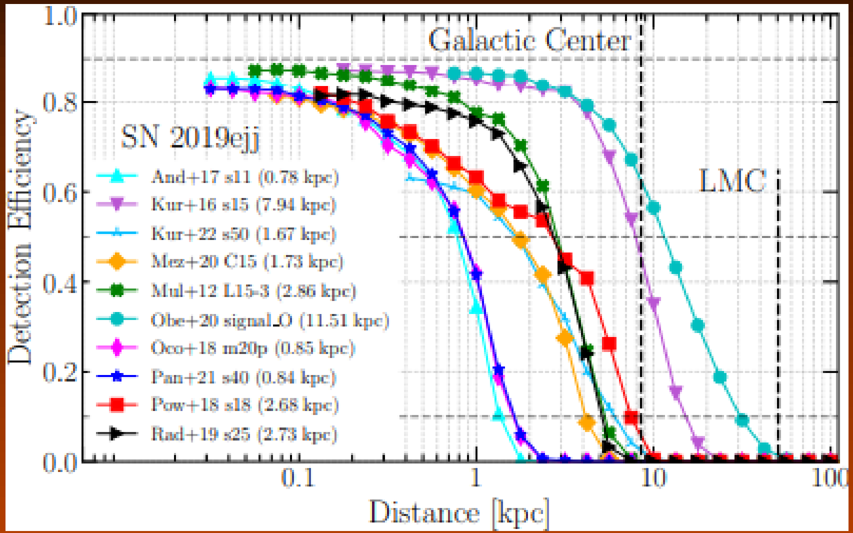
$$\varepsilon_{NS}^{b} = \frac{3}{5} \cdot \frac{GM^2}{R} = (1\text{–}5) \cdot 10^{53}\ \mathrm{erg}$$

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

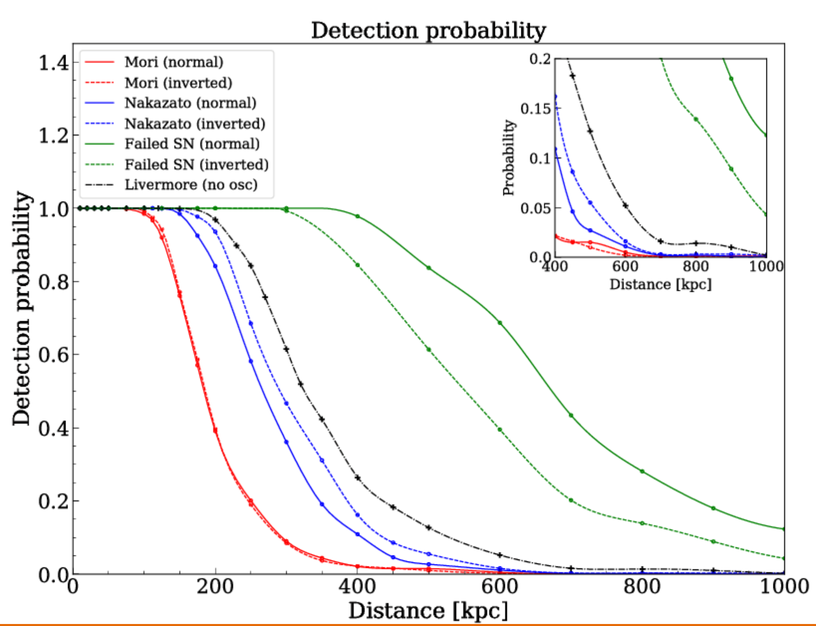
$$\varepsilon_{\mathrm{kin}} \sim 1\% \cdot \varepsilon^{b}$$

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

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



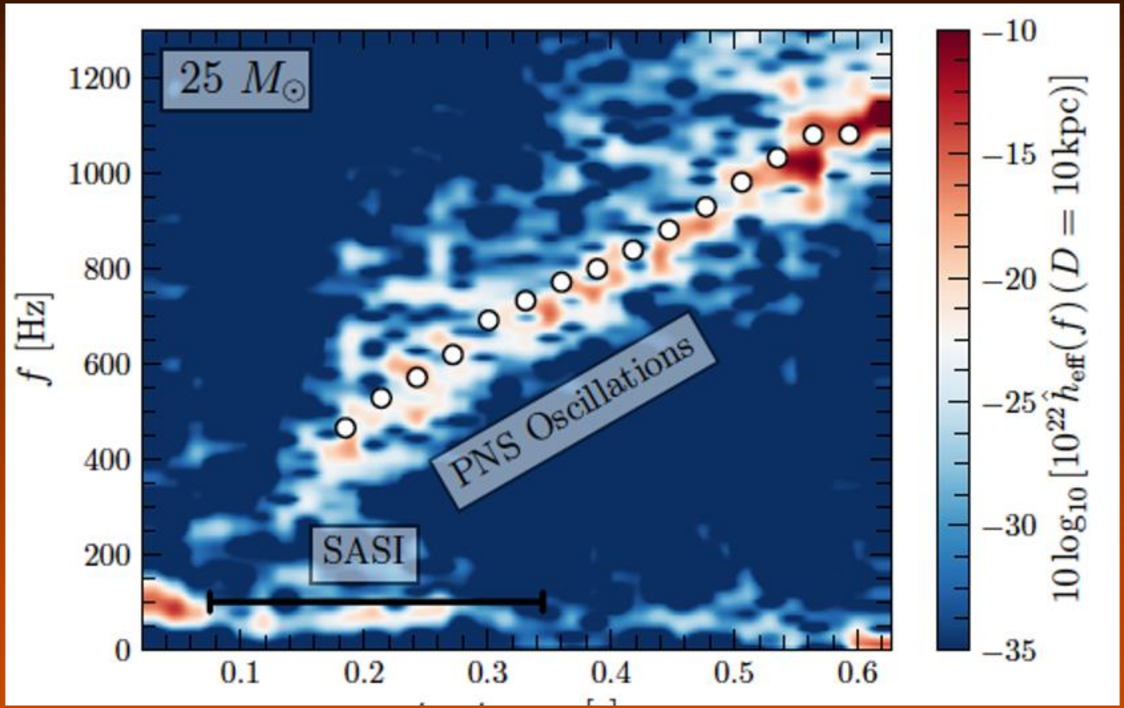
Szczepanczyk et al, Phys. Rev. D 110, 042007 (2024)



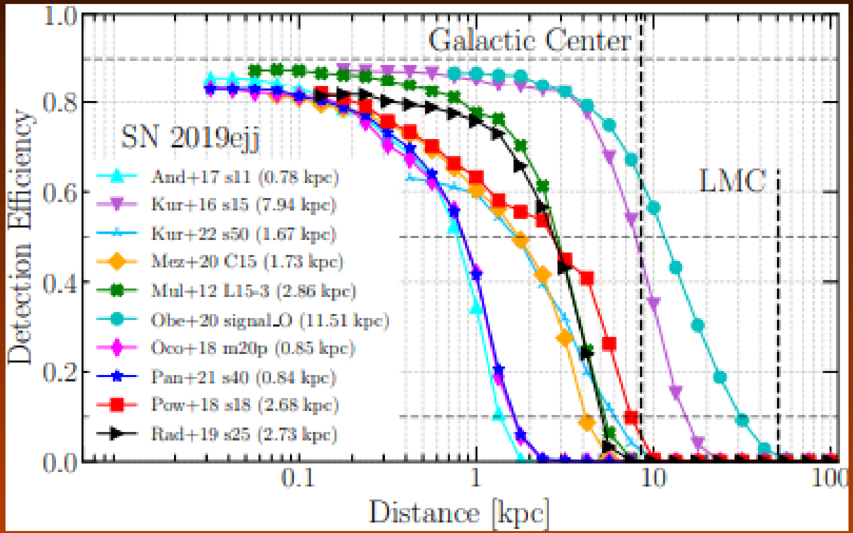
Mori et al., *Astrophys.J.* 938 (2022) 1, 35

- It is difficult to detect neutrinos from CCSN, and even more so for GWs
- Information from neutrino detection can improve GW detection sensitivity

Core-Collapse Supernovae: neutrino and GW emission



Abdikamalov, Pagliaroli, and Radice, arXiv:2010.04356



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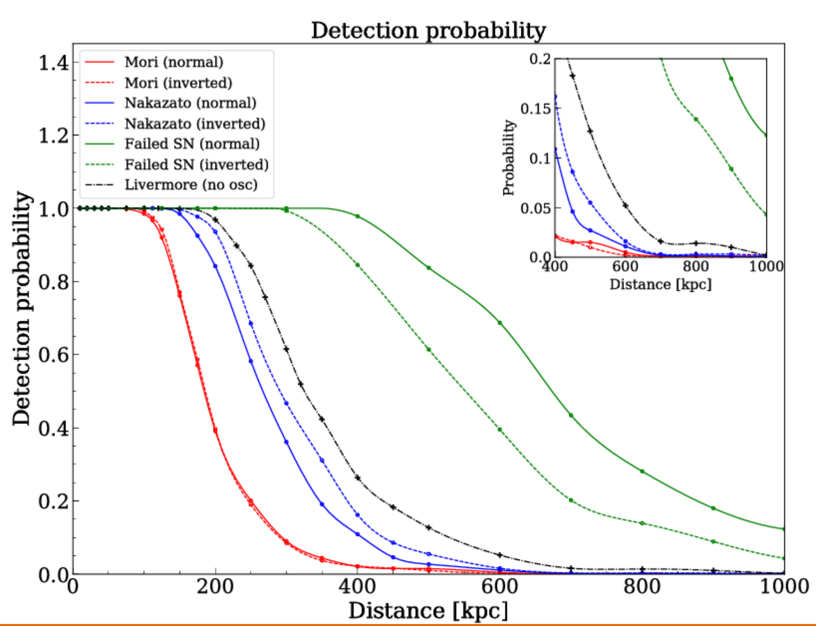


Mori et al., *Astrophys.J.* 938 (2022) 1, 35

PNS oscillations frequencies are $\sim f(M/R^n)$ ⟵ R may be provided by ν!

Core-Collapse Supernovae emission

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

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

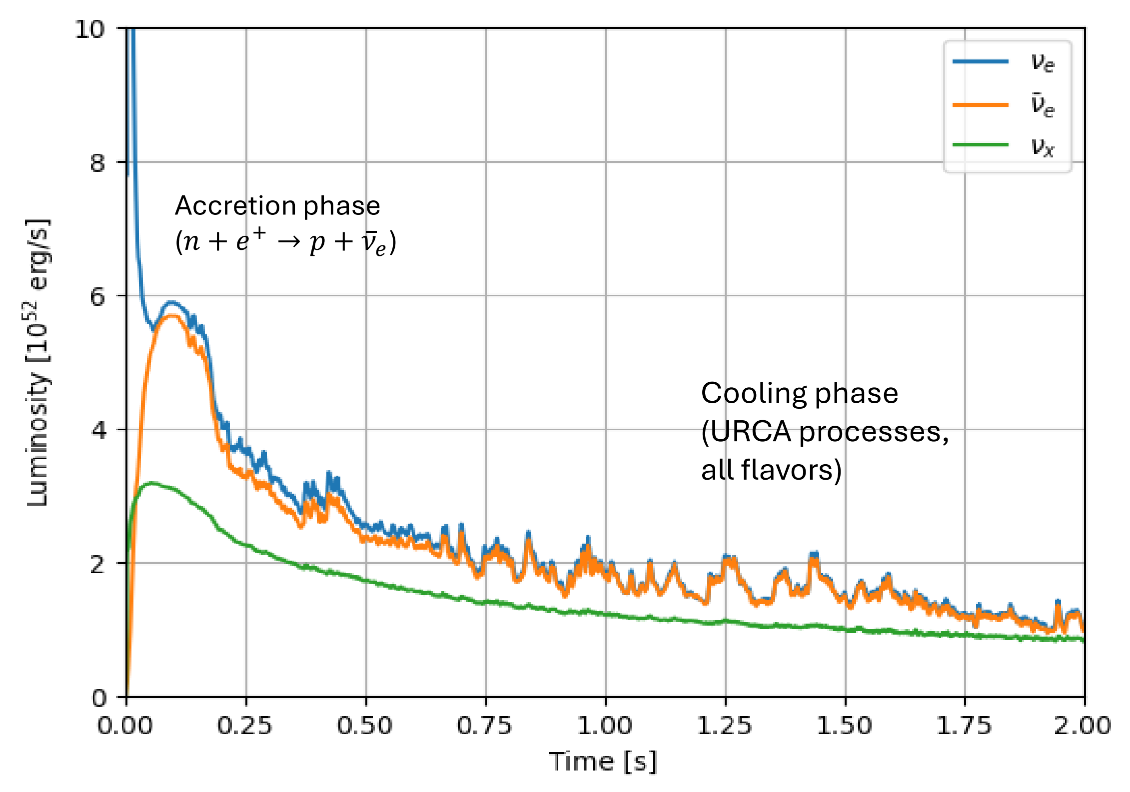
  $n + e^+ \leftrightarrow p + \bar{\nu}_e$ $\quad\quad$ $p + e^- \leftrightarrow n + \nu_e$

$$\Phi^0_A(E_\nu, t^{em}) \propto N_n(t^{em})\, \sigma_{e^+n}(E_{e^+}) \frac{E^2_{e^+}}{1+e^{\left(\frac{E_{e^+}}{T_A(t^{em})}\right)}}$$

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

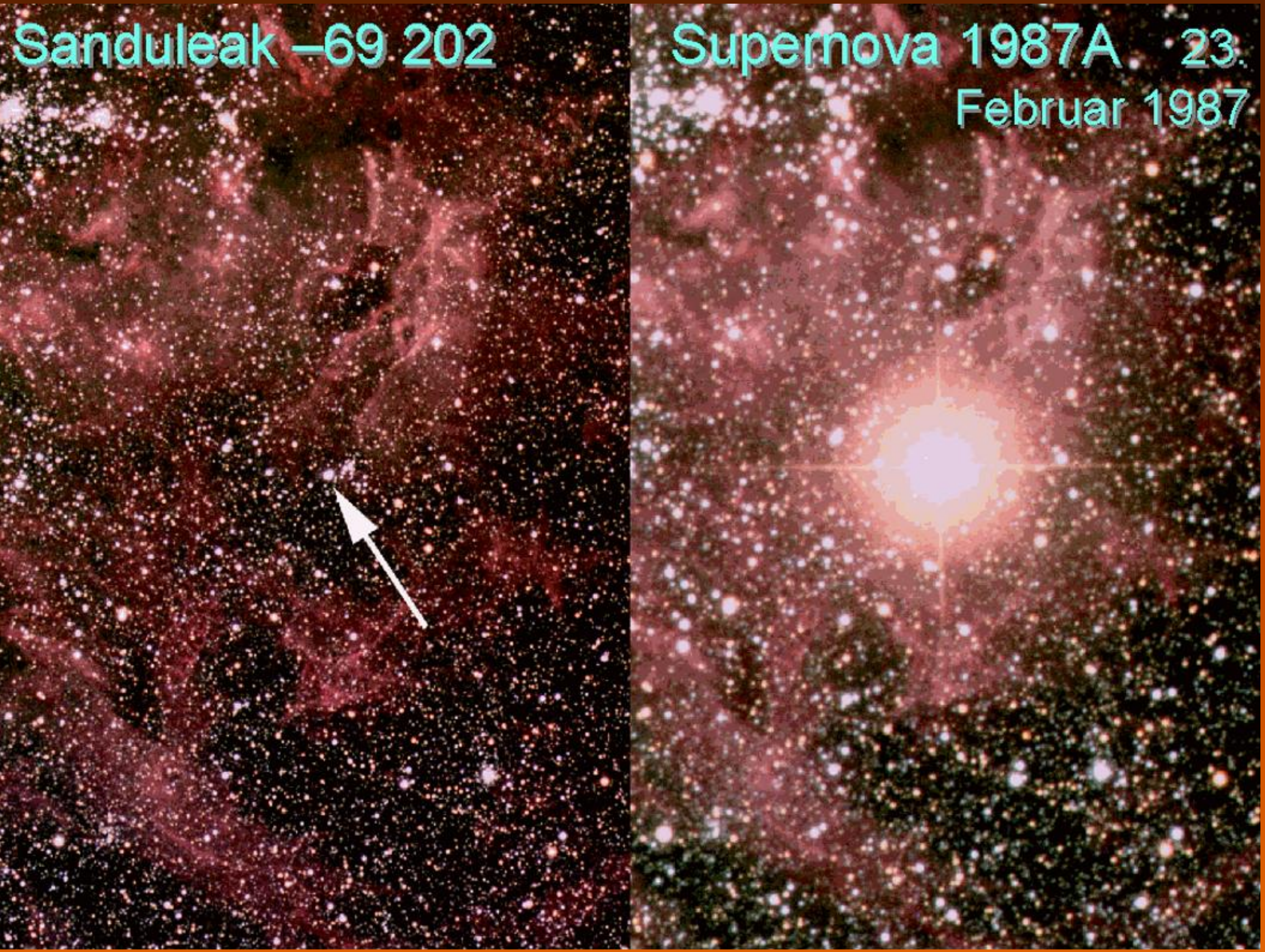
$$\Phi^0_C(E_\nu, t^{em}) \propto \boxed{R^2_{PNS}} \frac{E^2_\nu}{1+e^{\left(\frac{E_\nu}{T_C(t^{em})}\right)}}$$

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

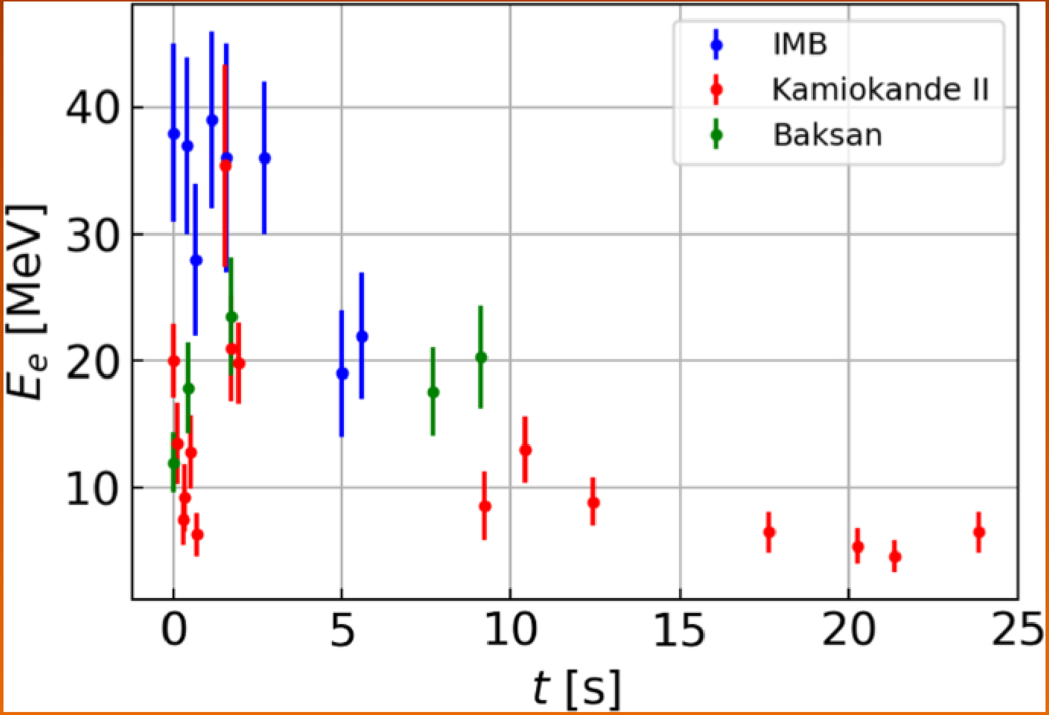


Simulation from Vartanyan, Burrows,
Mon.Not.Roy.Astron.Soc. 526 (2023) 4, 5900-5910

SN1987a



- SN neutrinos were only detected from SN1987
- Models (accretion+cooling) can be tested with real data

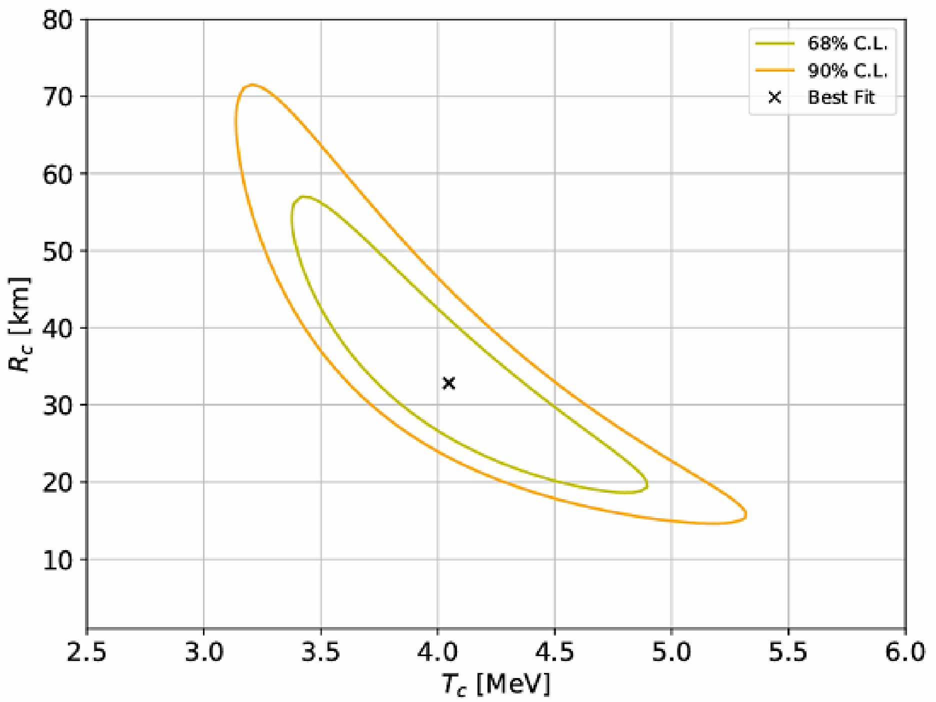


SN1987a – standard cooling model

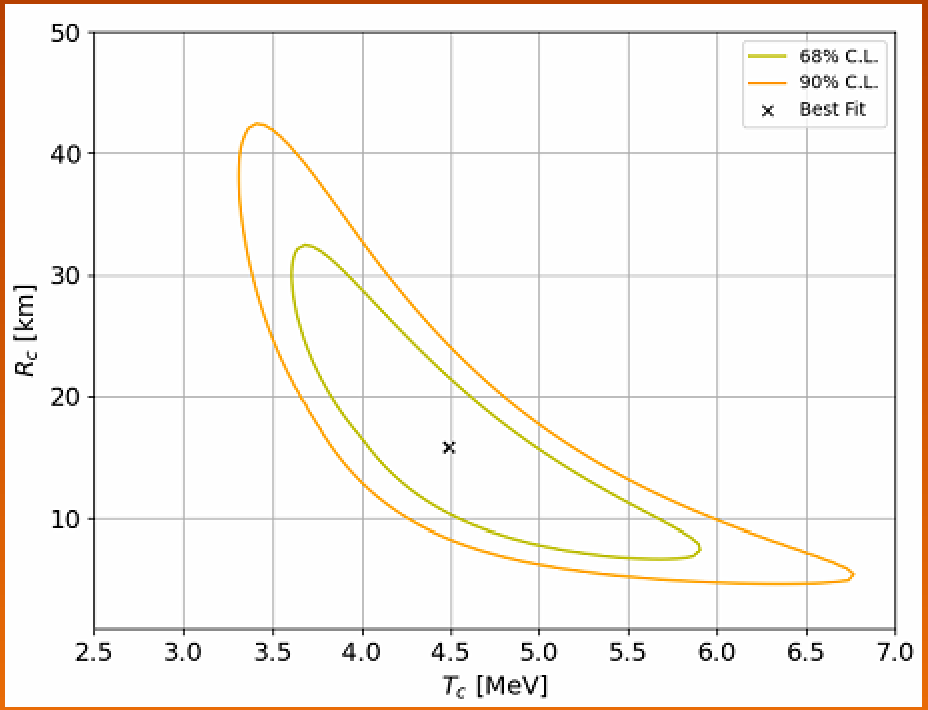
- Poissonian likelihood:

$$-2\log\mathcal{L} \propto -2\left(\sum_i^{N_{events}} \tau_d \int R(t,E)dtdE\left[B_i \log \int R(E)G(E,E_i)dE\right] - f_d \int R(t,E)dtdE\right)$$

Cooling only: $R_c = 32^{+14}_{-10}$ km, $T_c = 4.1^{+0.5}_{-0.5}$ MeV



Accretion + cooling: $R_c = 15^{+9}_{-6}$ km, $T_c = 4.5^{+0.8}_{-0.7}$ MeV



Alternative cooling model

- A step forward in the analysis can be done using a novel approach for the luminosity of the cooling phase proposed in *Lucente et al., Phys.Rev.D 110 (2024) 6, 6*.
- It considers an enhanced neutrino transport inside the PNS caused by **convection**, through ($t > 1s$):

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

➢ It may be used to distinguish EoS families:

$3 < n < 5, \quad 0 < \alpha < 1$

$0 < n < 1, \quad -1 < \alpha < 0$

Model	C_{ν_μ} [B/s]	α_{ν_μ}	τ_{ν_μ} [s]	n_{ν_μ}	$C_{\bar{\nu}_\mu}$ [B/s]	$\alpha_{\bar{\nu}_\mu}$	$\tau_{\bar{\nu}_\mu}$ [s]	$n_{\bar{\nu}_\mu}$
1.36-DD2	6.333 ± 0.008	0.421 ± 0.002	5.687 ± 0.003	4.413 ± 0.009	6.927 ± 0.008	0.479 ± 0.002	5.754 ± 0.003	4.468 ± 0.008
1.36-SFHo	7.053 ± 0.006	0.579 ± 0.001	6.945 ± 0.003	3.926 ± 0.005	7.679 ± 0.004	0.634 ± 0.001	7.067 ± 0.002	4.045 ± 0.003
1.36-SFHx	7.113 ± 0.007	0.598 ± 0.001	7.110 ± 0.003	3.873 ± 0.005	7.868 ± 0.004	0.662 ± 0.001	7.245 ± 0.002	3.964 ± 0.003
1.36-LS220	69.88 ± 8.62	-0.177 ± 0.045	0.252 ± 0.040	0.499 ± 0.012	107.4 ± 17.9	-0.301 ± 0.057	0.164 ± 0.033	0.473 ± 0.013

Lucente cooling implementation

- We thus extend the cooling model implementing the new time evolution
- It is done including the temporal shape in the temperature evolution:

$$T_c(t) = T_0 t^{-\alpha} e^{-(t/\tau_c)^n}$$

- Note there could be also some time dependence in the radius evolution

Lucente vs Cooling

The Lucente parametrization introduced inside the cooling model as a new temporal shape of the PNS temperature bring to this correlations:

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

$C \propto R_c^2 T^4$

$\tau = 4^{-1/n}\tau_c$

$n = n_c$

$\alpha = 4\alpha_c$

First Family of EOS:

$3 < n < 5, 0 < \alpha < 1$

Becomes

$3 < n_c < 5, 0 < \alpha_c < 1/4$

$\tau_c > 1.3\tau$

Second Family of EOS:

$0 < n < 1, -1 < \alpha < 0$

Becomes

$0 < n_c < 1, -1/4 < \alpha_c < 0$

$\tau_c > 4\tau$

SN1987a – alternative cooling model

First approach:

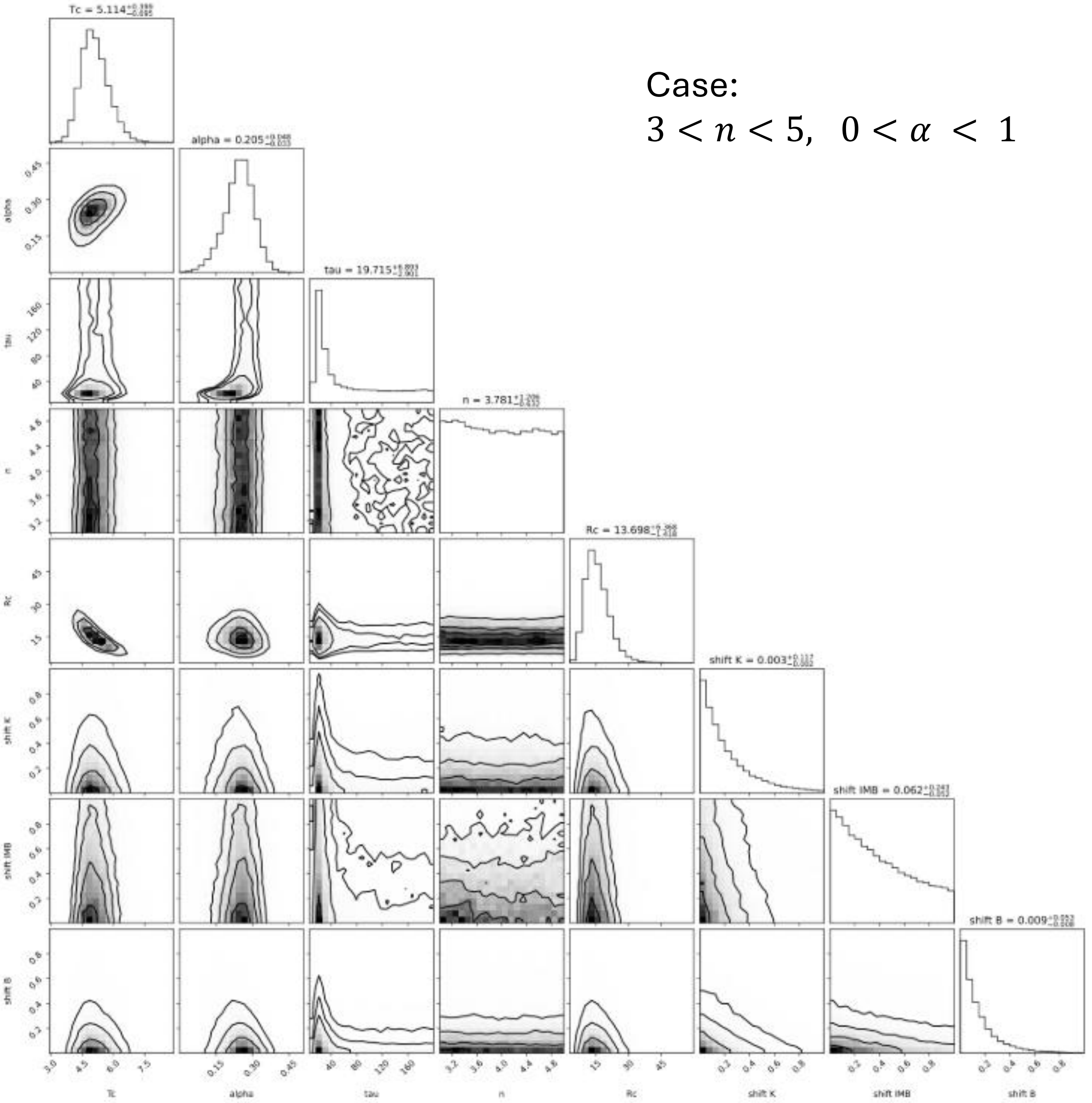
just cut the 1° second of data

Best fit values:

$T_c = 5.1^{+0.3}_{-0.1}\text{MeV}, \;\; \alpha = 0.21^{+0.05}_{-0.03}$

$\tau = 20^{+7}_{-3}\ \text{s}, \;\; R_c = 14^{+7}_{-1}\ \text{km}$

- *n* distribution is nearly flat in the range (the term $e^{-(t/\tau)^n}$ acts as a temporal cut for these values of *n*)



Case:
$3 < n < 5, \;\; 0 < \alpha < 1$

SN1987a – alternative cooling model

First approach:

just cut the 1° second of data

Best fit values:

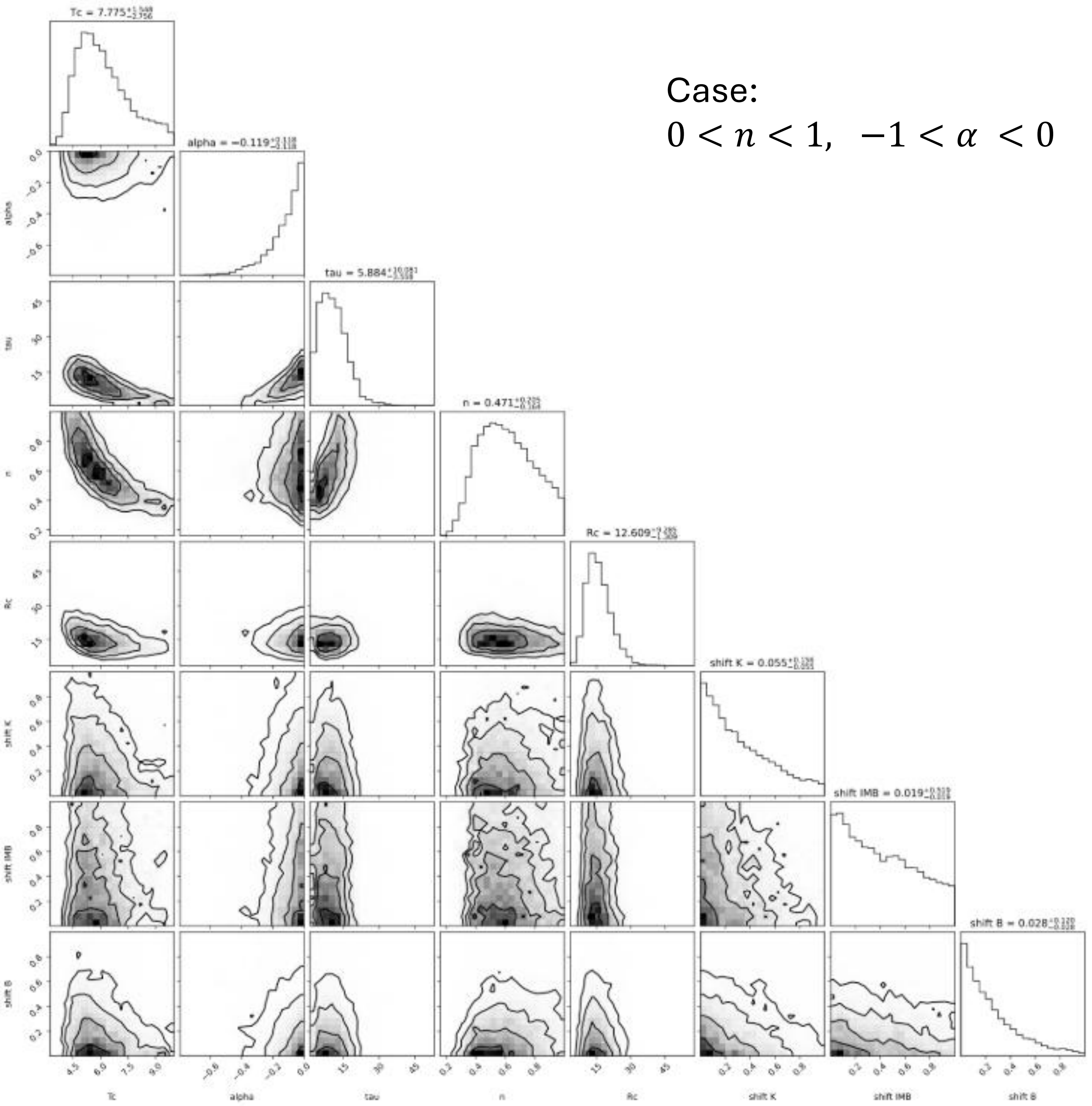
$T_c = 7.7^{+1.5}_{-2.8}$ MeV, $\alpha = -0.2^{+0.1}_{-0.1}$

$\tau = 5^{+10}_{-3}$ s, $R_c = 13^{+9}_{-1}$ km

This model is slightly disfavored (1σ level)

Case:

$0 < n < 1, \quad -1 < \alpha < 0$



Modified version (rising time)

To avoid cutting the dataset we also have to consider the emission during the 1st second

Normal ordering: add accretion flux as in the 'standard' model

$$\Phi_A^0(E_\nu, t^{em}) \propto N_n(t^{em})\, \sigma_{e^+n}(E_{e^+})\, \frac{E_{e^+}^2}{1+e^{\left(\frac{E_{e^+}}{T_A(t^{em})}\right)}}$$

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

Inverted ordering: $\bar{\nu}_\mu \to \bar{\nu}_e$, no accretion

$$L_{\nu_x}(t) = (1 - e^{-t/t_{rising}})Ct^{-\alpha}e^{-(t/\tau)^n}$$

Simulations fit with rising

Fit with the ‘rising’ modification:

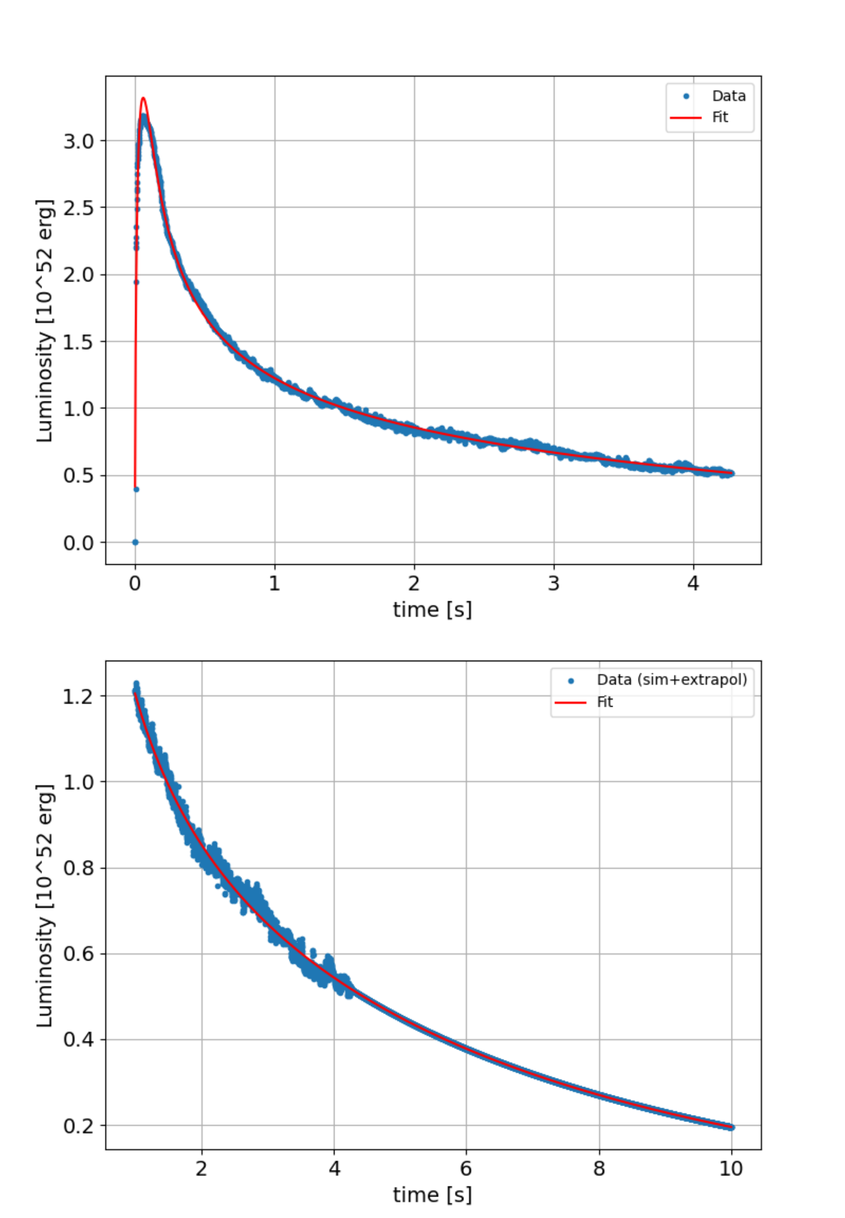
$$L_{\nu_x}(t) = (1 - e^{-t/t_{rising}})Ct^{-\alpha}e^{-(t/\tau)^n}$$

$C = 1.276 \pm 0.008$
$\tau_{rising} = 0.0389 \pm 0.0005\ s$
$\tau = 10.9 \pm 0.4\ s$
$\alpha = 0.426 \pm 0.004$
$n = 1.33 \pm 0.08$

To compare fit results with no rising model we extrapolate data up to 10 s:

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

$C = 1.280 \pm 0.003$
$\tau = 10.01 \pm 0.09\ s$
$\alpha = 0.382 \pm 0.004$
$n = 1.22 \pm 0.02$



Simulation from Vartanyan, Burrows, *Mon.Not.Roy.Astron.Soc.* 526 (2023) 4, 5900-5910

Next steps

- Extensively analyze the new cooling model adding the accretion component
- Extend the analysis to possible future detections with simulations

SN1987a:	Today (SN @ 20 kpc):
$\delta R_c = 44\%$	$\delta R_c = 7\%$
$\delta T_c = 15\%$	$\delta T_c = 2\%$

Pagliaroli et al.,
PRL103 (2009) 031102

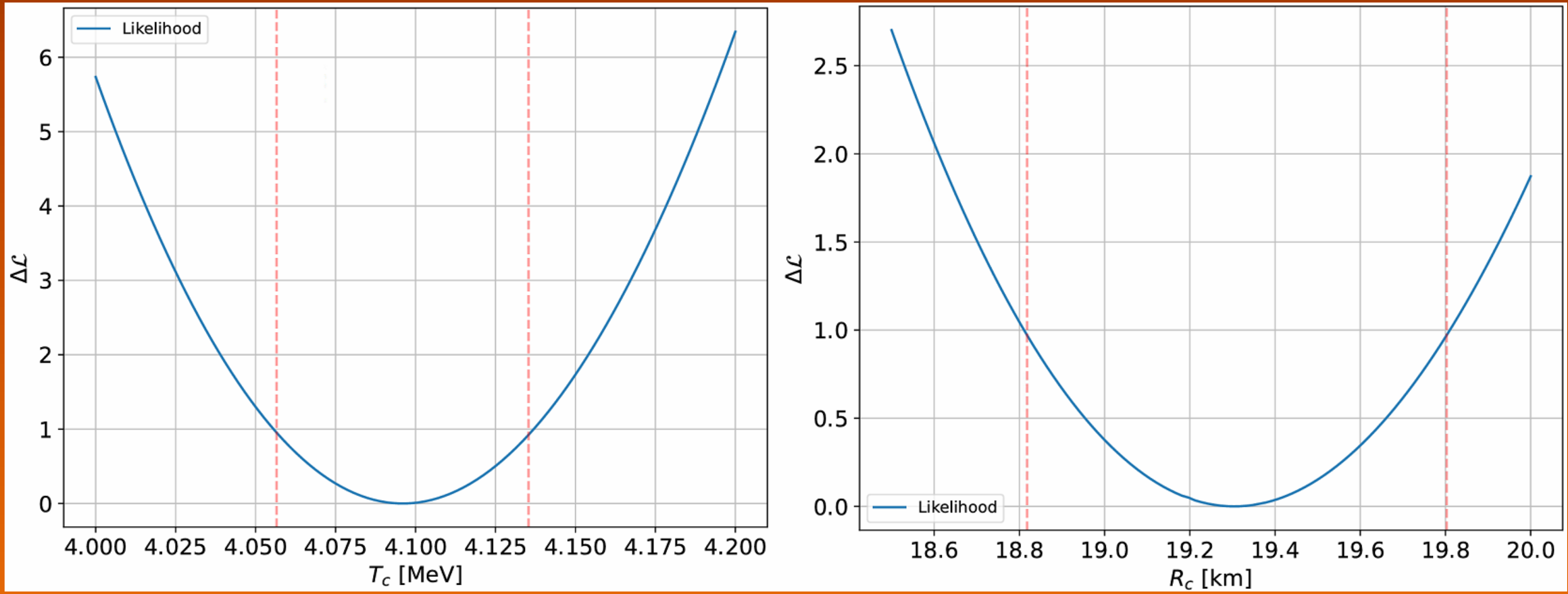
Next steps

- Extensively analyze the new cooling model adding the accretion component
- Extend the analysis to possible future detections with simulations

Example fit from simulation @ 10kpc ($\sim$ 3000 events):

$$T_c = 4.1^{+0.04}_{-0.04}\ \mathrm{MeV}$$

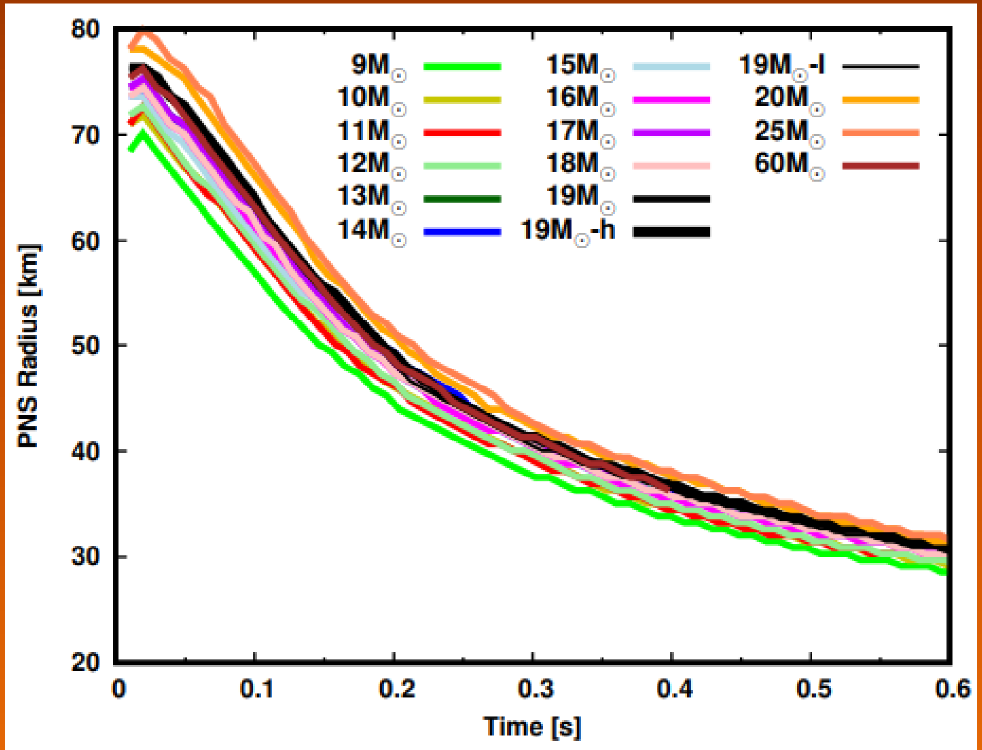
$$R_c = 19.3^{+0.5}_{-0.5}\ \mathrm{km}$$



Simulation from Nakazato *et al* 2013 *ApJS* **205** 2

Next steps

- Extensively analyze the new cooling model adding the accretion component
- Extend the analysis to possible future detections with simulations
- Extend the model to consider the temporal evolution of the PNS radius



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

Summary

- We want to refine our data analysis techniques to extract the maximum information from a future galactic SN explosion, especially focusing on PNS parameters

- This can lead to a powerful joint neutrino-GW detection, which would be able to constrain both mass and radius of the PNS

Thank you for your attention