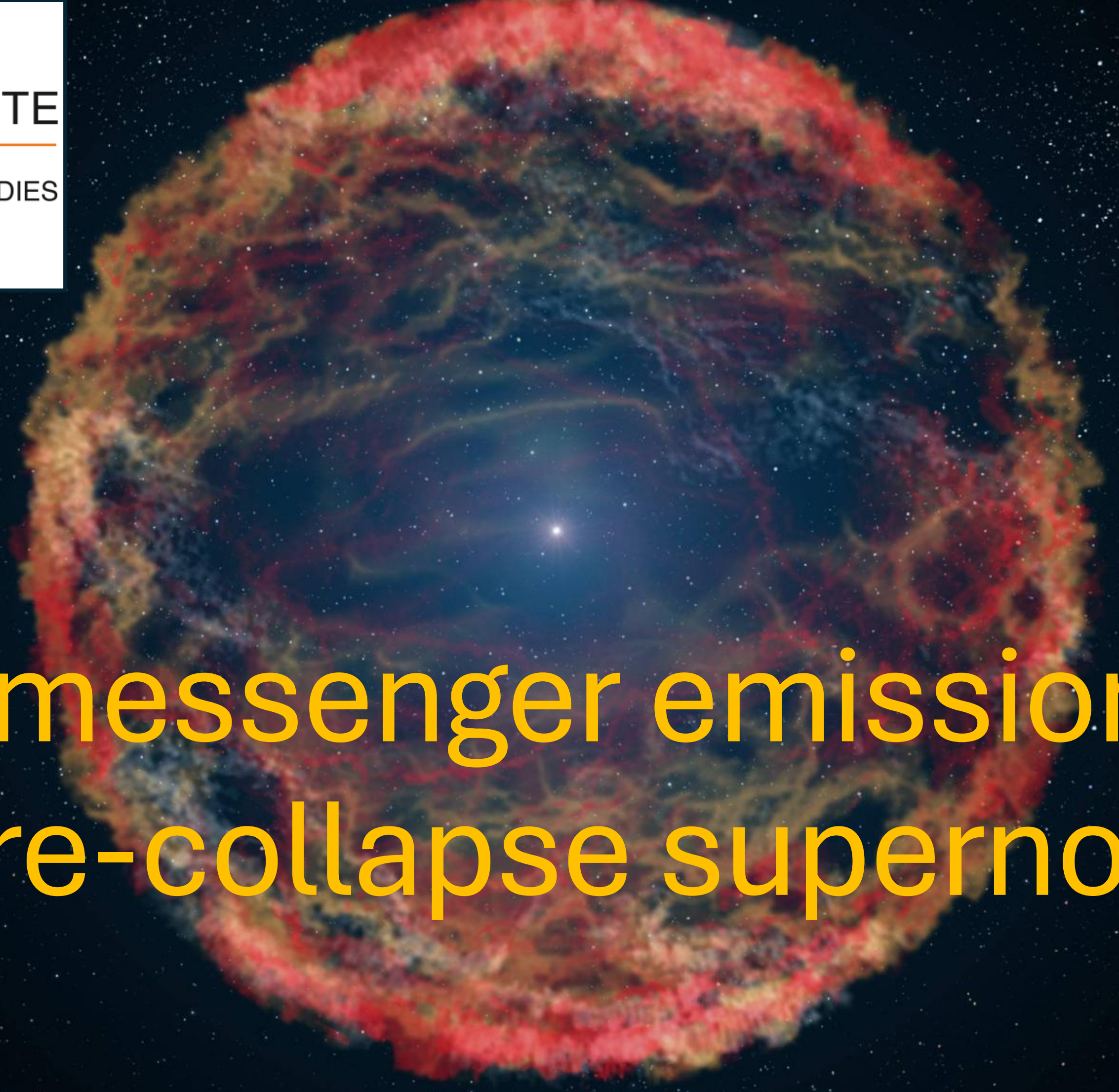
GRAN SASSO SCIENCE INSTITUTE
SCHOOL OF ADVANCED STUDIES
Scuola Universitaria Superiore

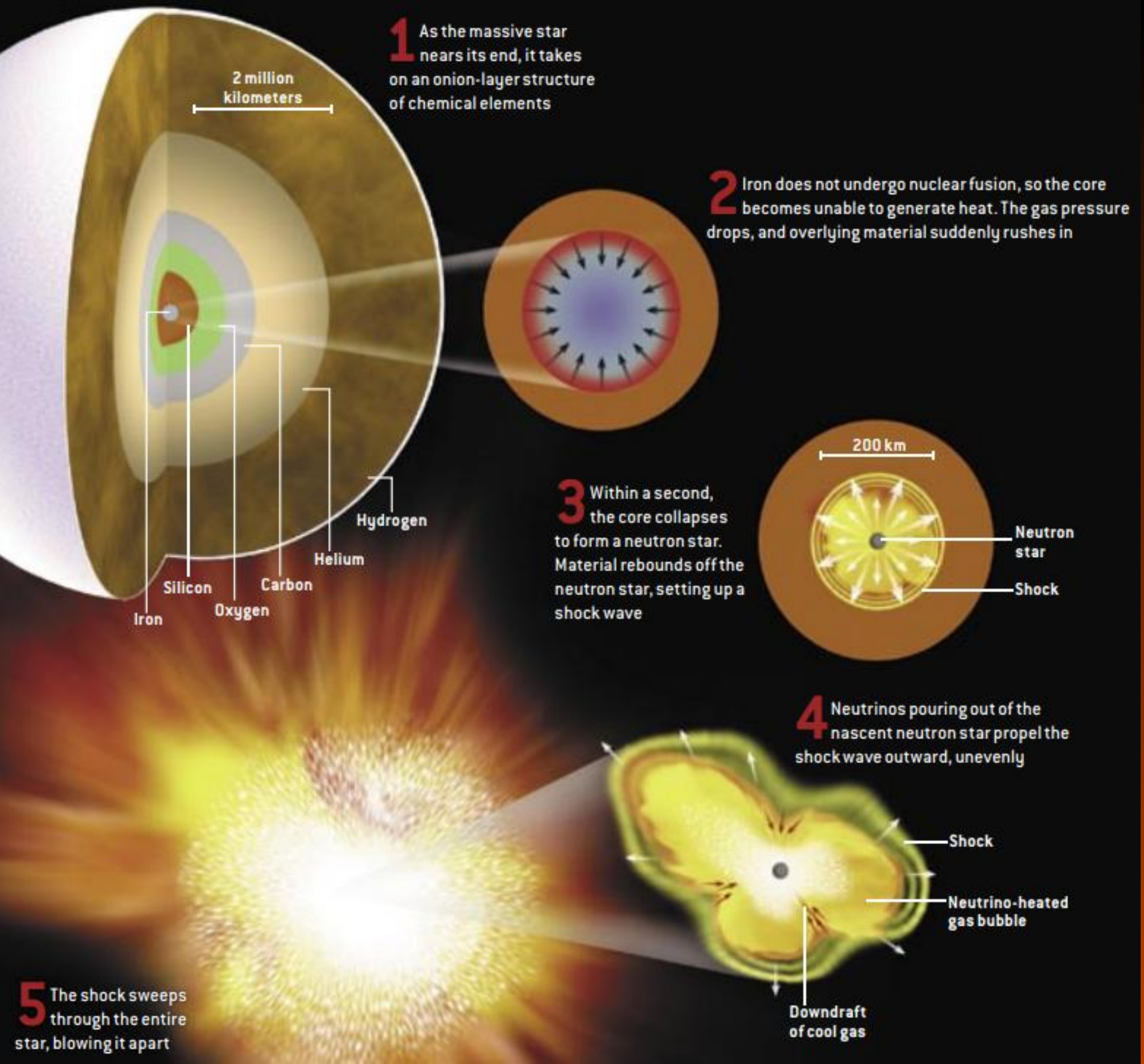
INFN
Istituto Nazionale di Fisica Nucleare

VIRGO



Multimessenger emission from core-collapse supernovae

Matteo Ballelli, Giulia Pagliaroli, Marco Drago, Christoph Ternes



What and why?

- Explosive deaths of massive stars
- Can form compact objects
- Carry information on the forming hot NS

Janka et al., Sci Am . 2006 Oct;295(4):42-9

Core-Collapse Supernovae: neutrino and GW emission

GW and νs are emitted at the bounce...

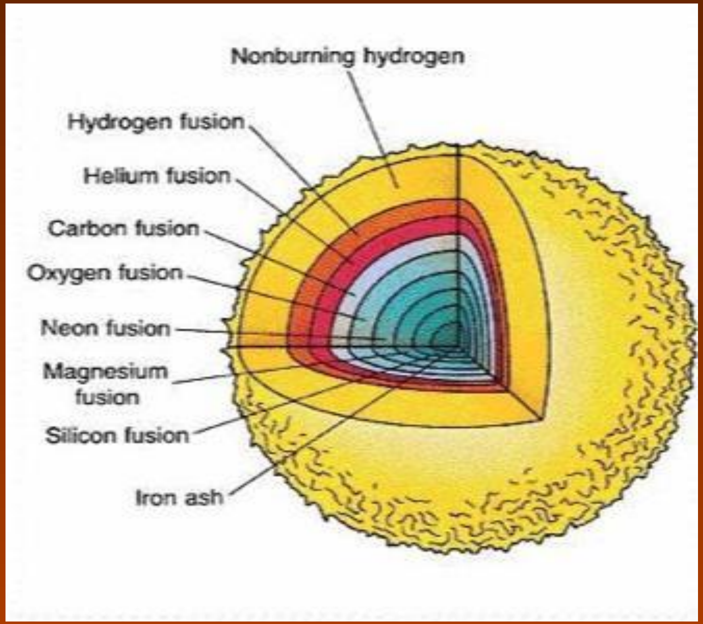
$$\varepsilon^b_{NS} = \frac{3}{5} \cdot \frac{GM^2}{R} = (1\text{–}5) \cdot 10^{53}\,\text{erg}$$

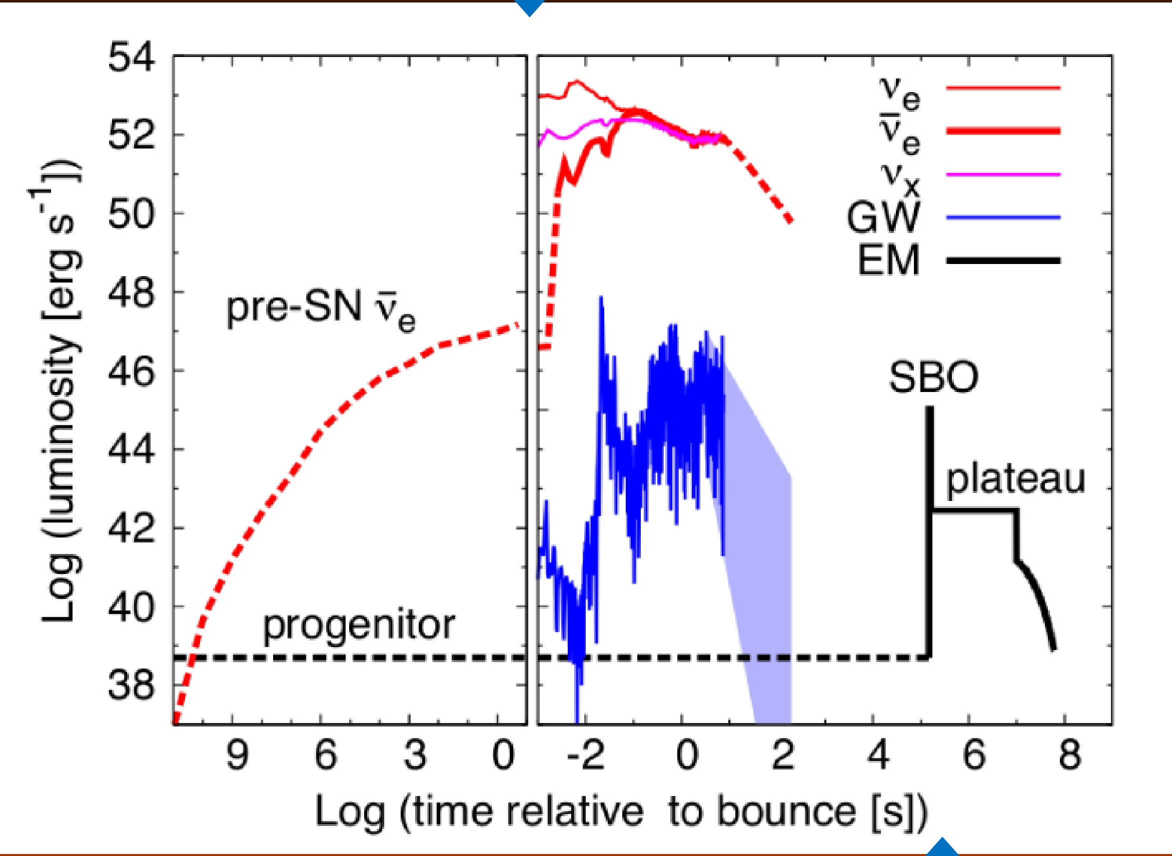
$$\varepsilon_\nu \sim 99\% \cdot \varepsilon^b$$

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

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

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

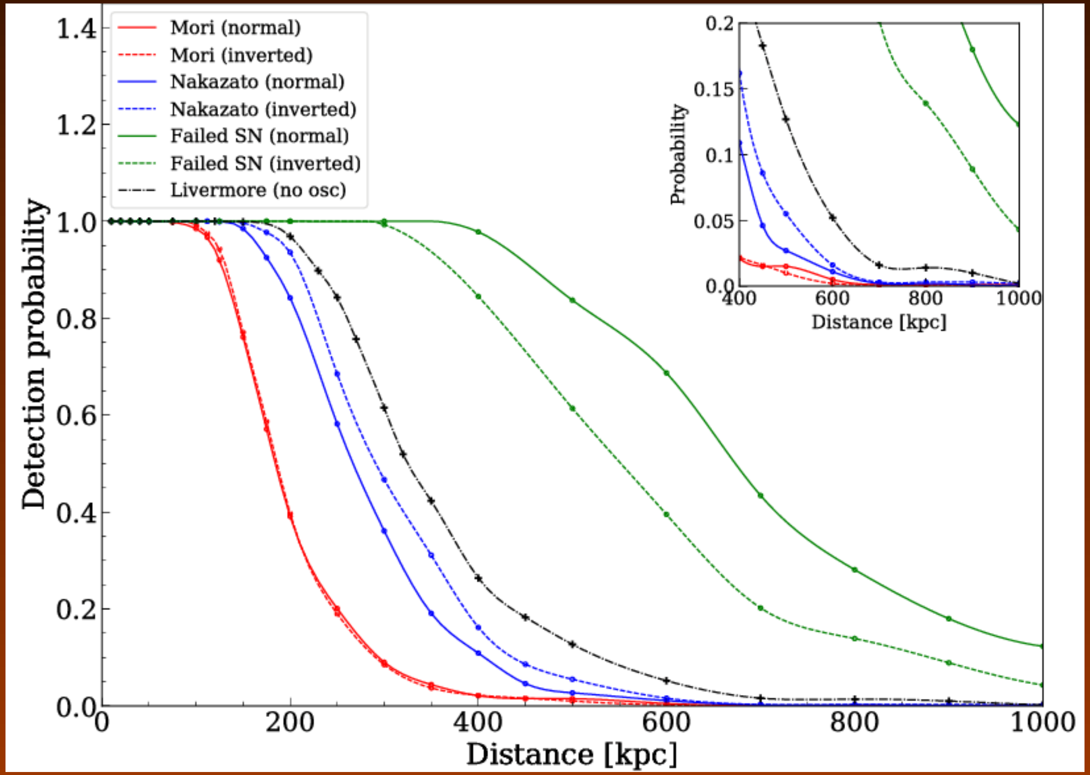




... while photons are late!

Core-Collapse Supernovae: neutrino and GW emission

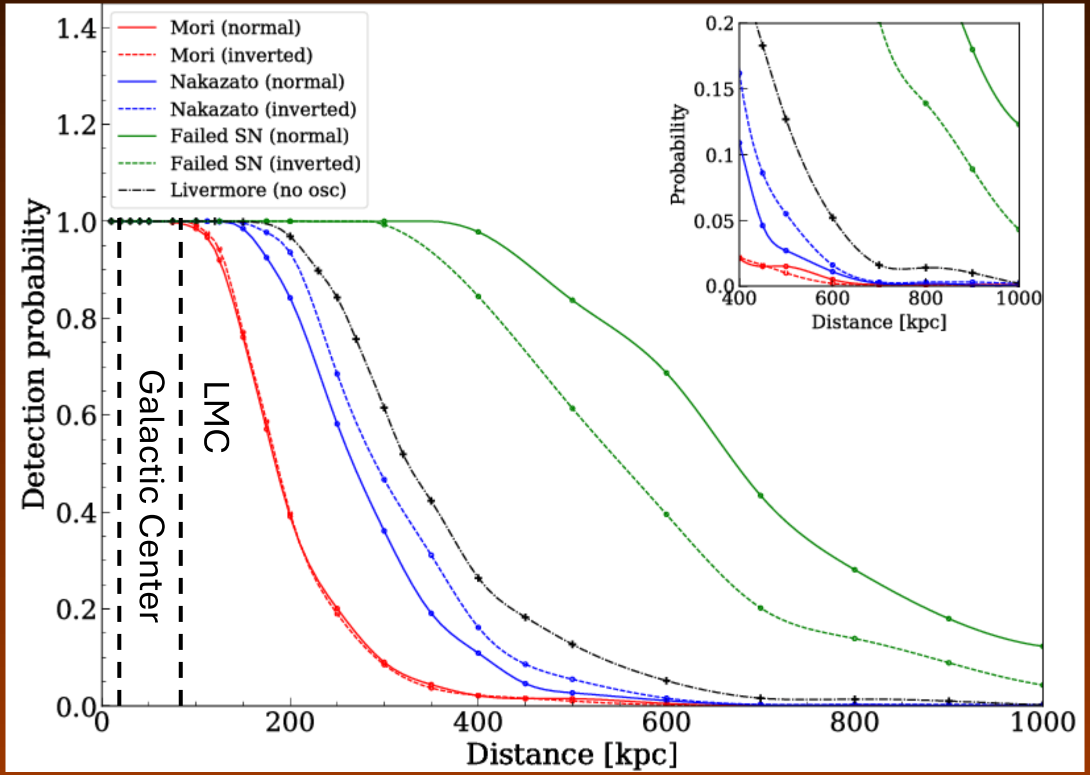
- It is difficult to detect neutrinos from CCSN…



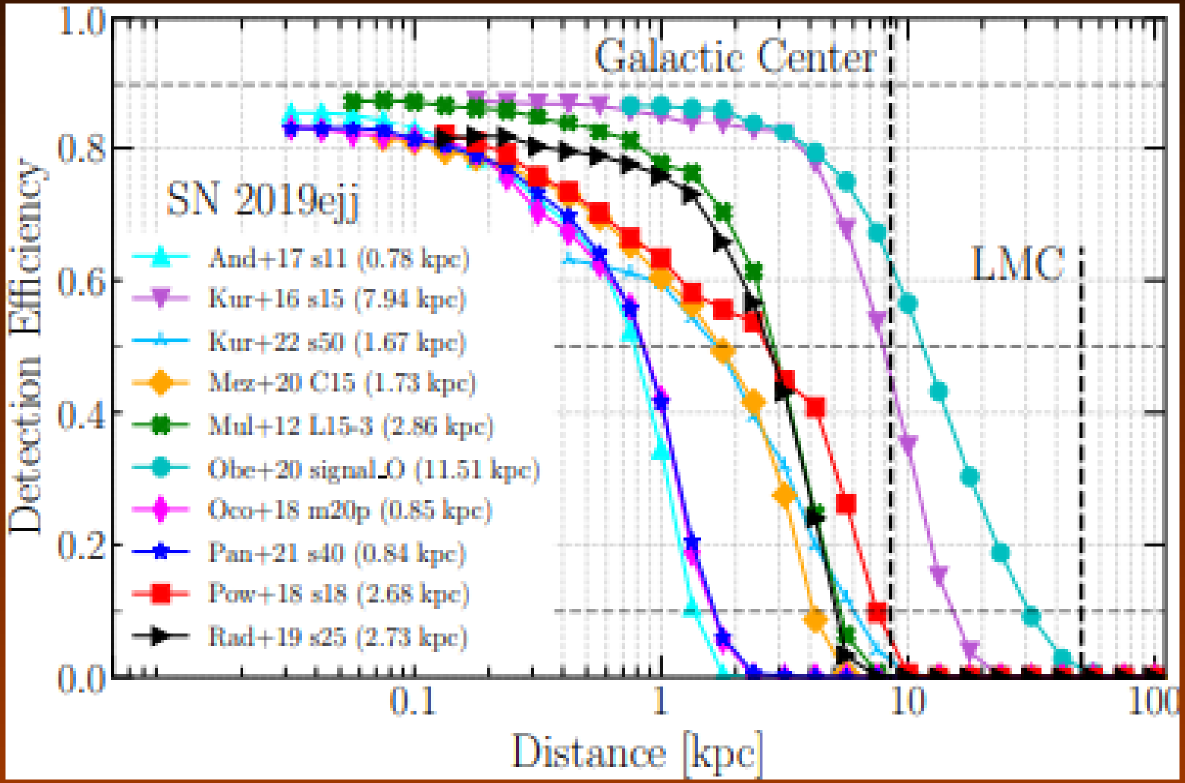
Mori et al., *Astrophys.J.* 938 (2022) 1, 35

Core-Collapse Supernovae: neutrino and GW emission

- It is difficult to detect neutrinos from CCSN… and even more so for GWs



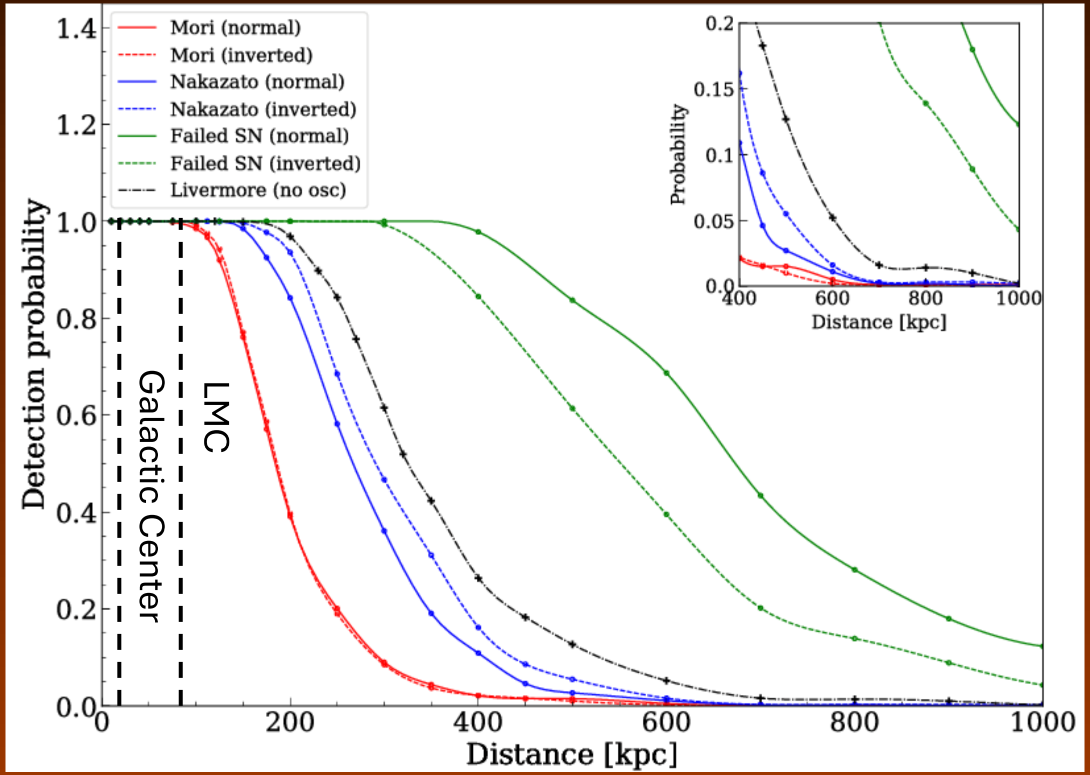
Mori et al., *Astrophys.J.* 938 (2022) 1, 35



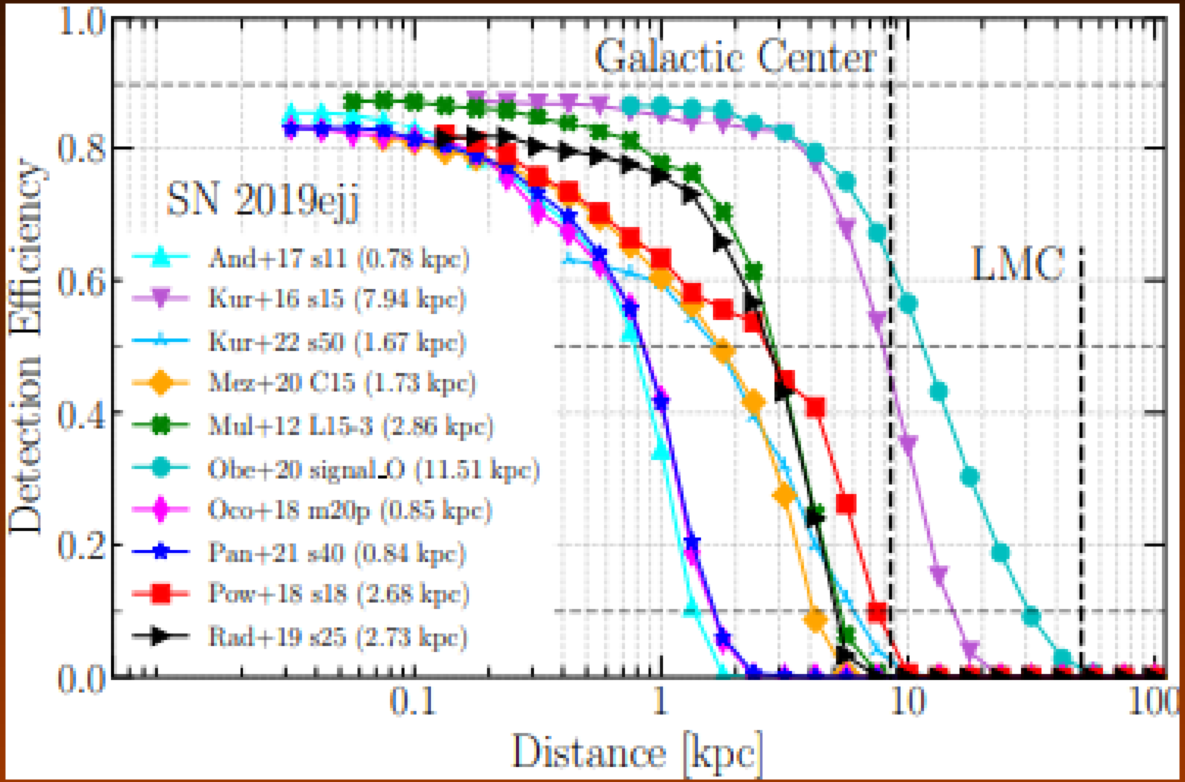
Szczepanczyk et al, Phys. Rev. D 110, 042007 (2024)

Core-Collapse Supernovae: neutrino and GW emission

- It is difficult to detect neutrinos from CCSN… and even more so for GWs



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



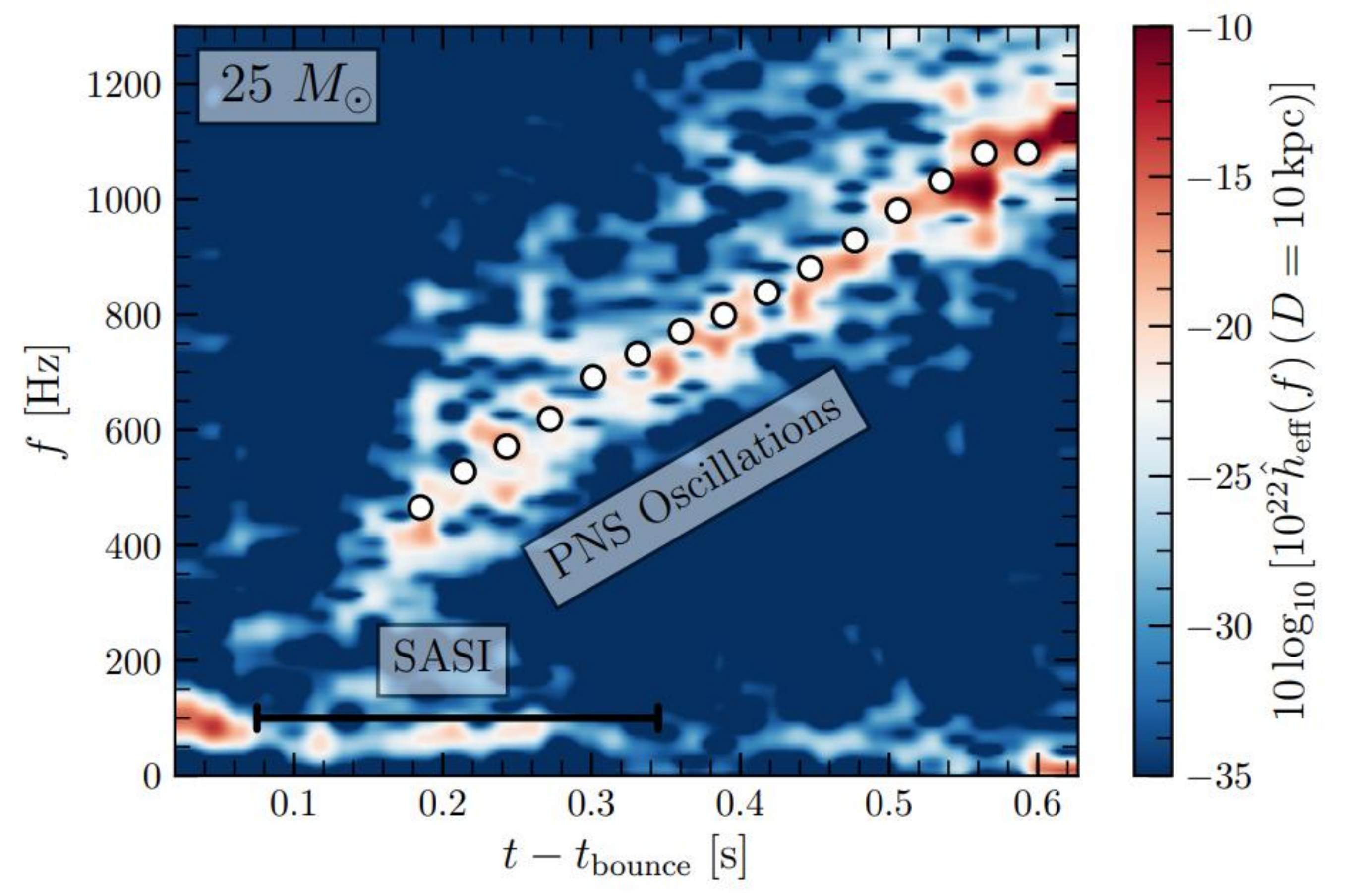
Szczepanczyk et al, Phys. Rev. D 110, 042007 (2024)

Information from neutrino detection can improve GW detection sensitivity

Core-Collapse Supernovae: neutrino and GW emission

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

R_{PNS} may be provided by ν!



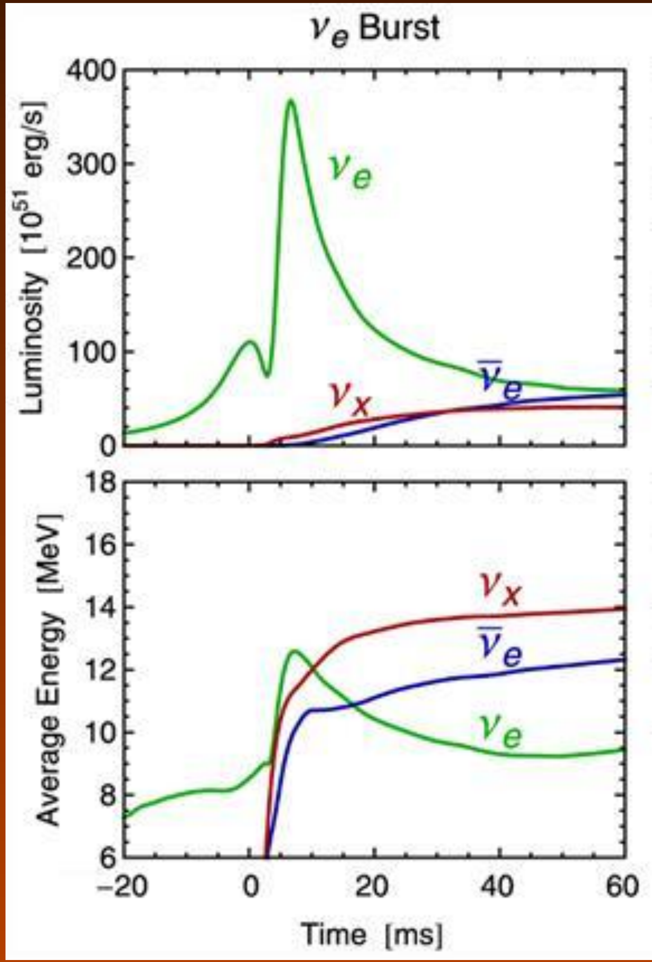
Abdikamalov, Pagliaroli, and Radice, arXiv:2010.04356

Core-Collapse Supernovae emission

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

- **Neutronization peak** $(\sim 1\text{ms})$: very high ν_e peak due to neutronization of matter during collapse

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



Core-Collapse Supernovae emission

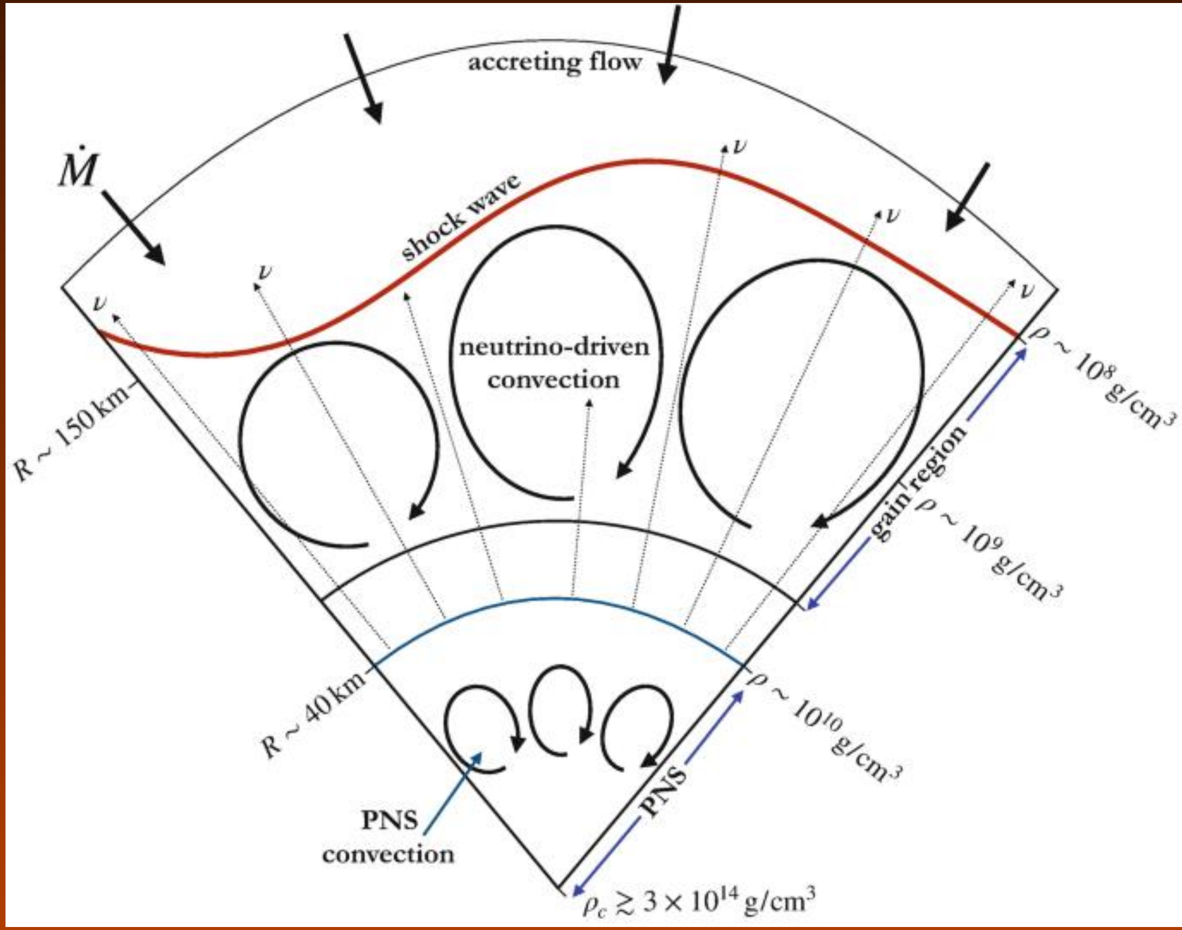
Neutrino emission can be summarized according to our current understanding into (*Pagliaroli et al., Astropart.Phys. 31 (2009) 163-176*):

- **Neutronization peak**

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

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

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



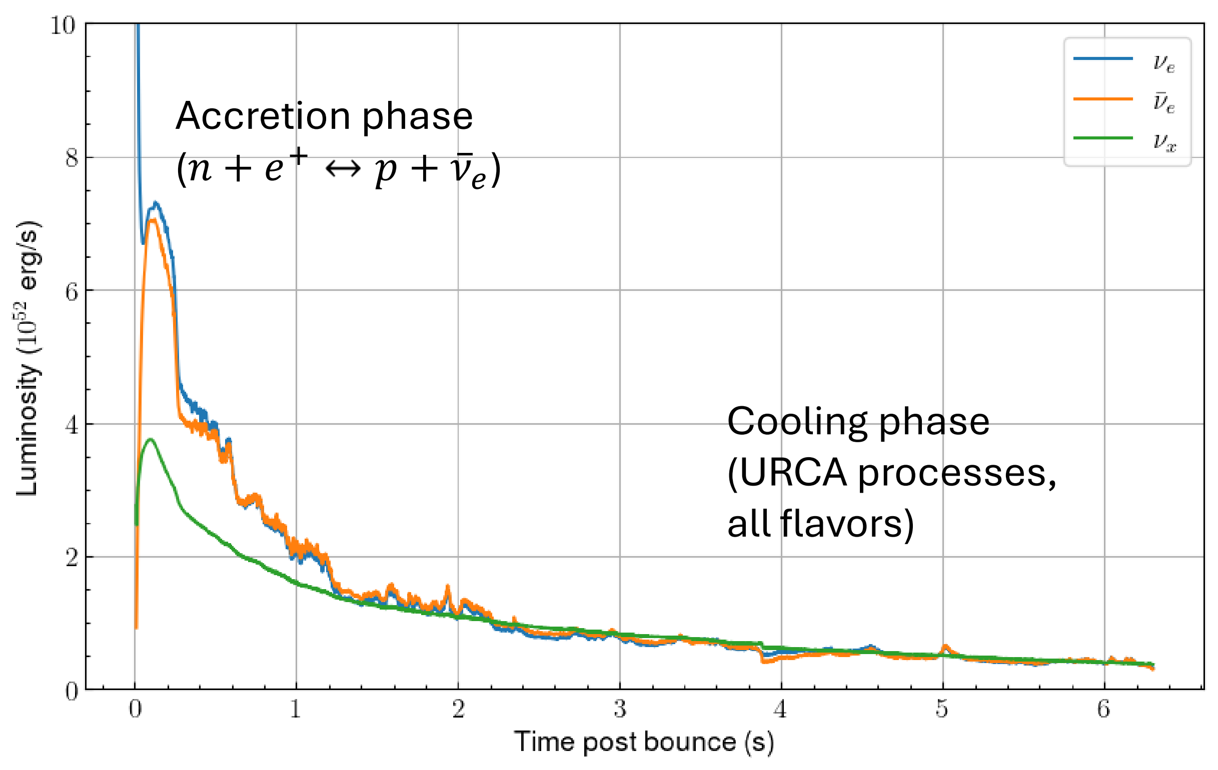
Core-Collapse Supernovae emission

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

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

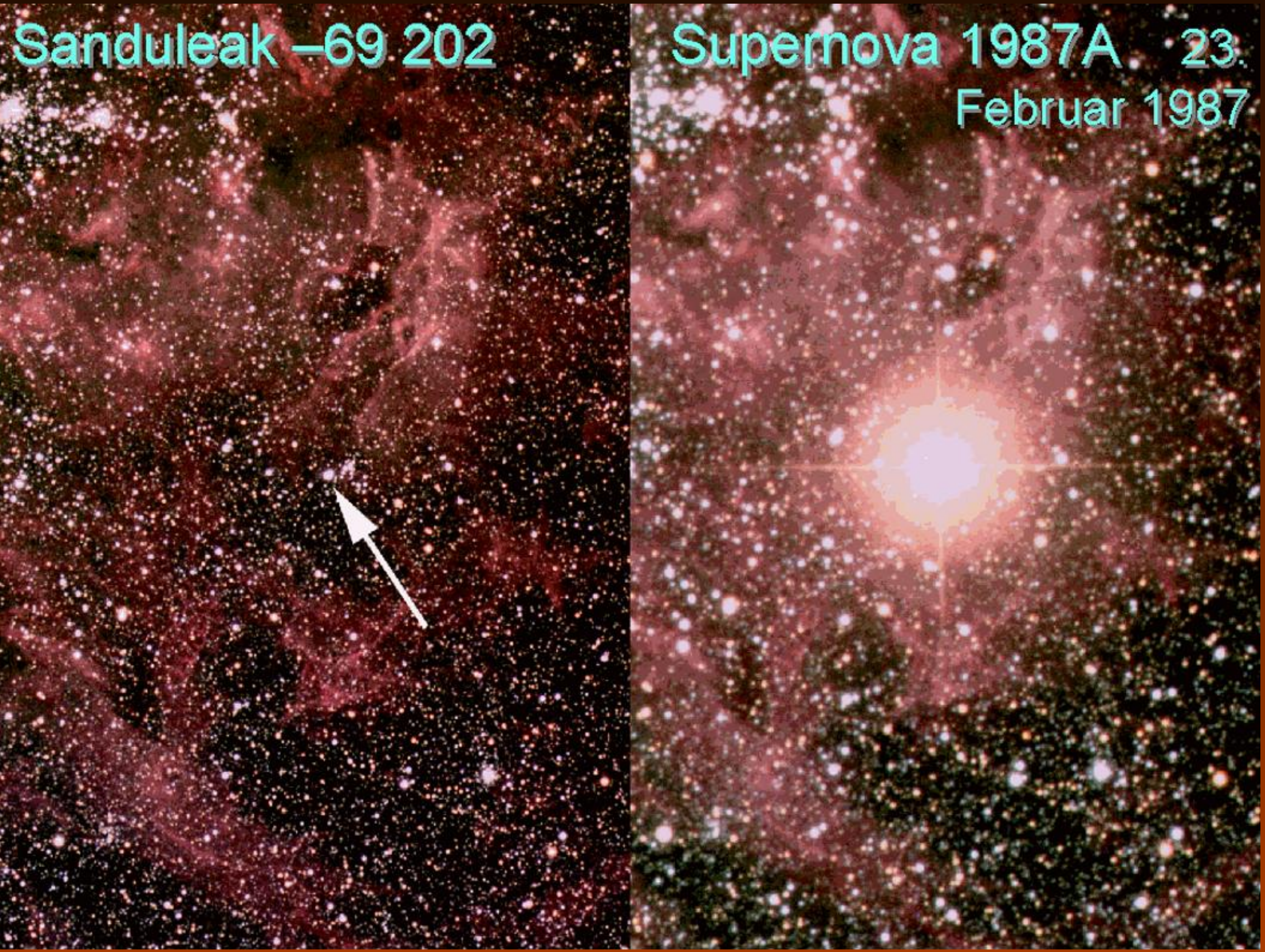
$$\Phi_c^0(E_\nu, t^{em}) \propto R_{PNS}^2 \frac{E_\nu^2}{1+e^{\left(\frac{E_\nu}{T_c(t^{em})}\right)}}$$

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

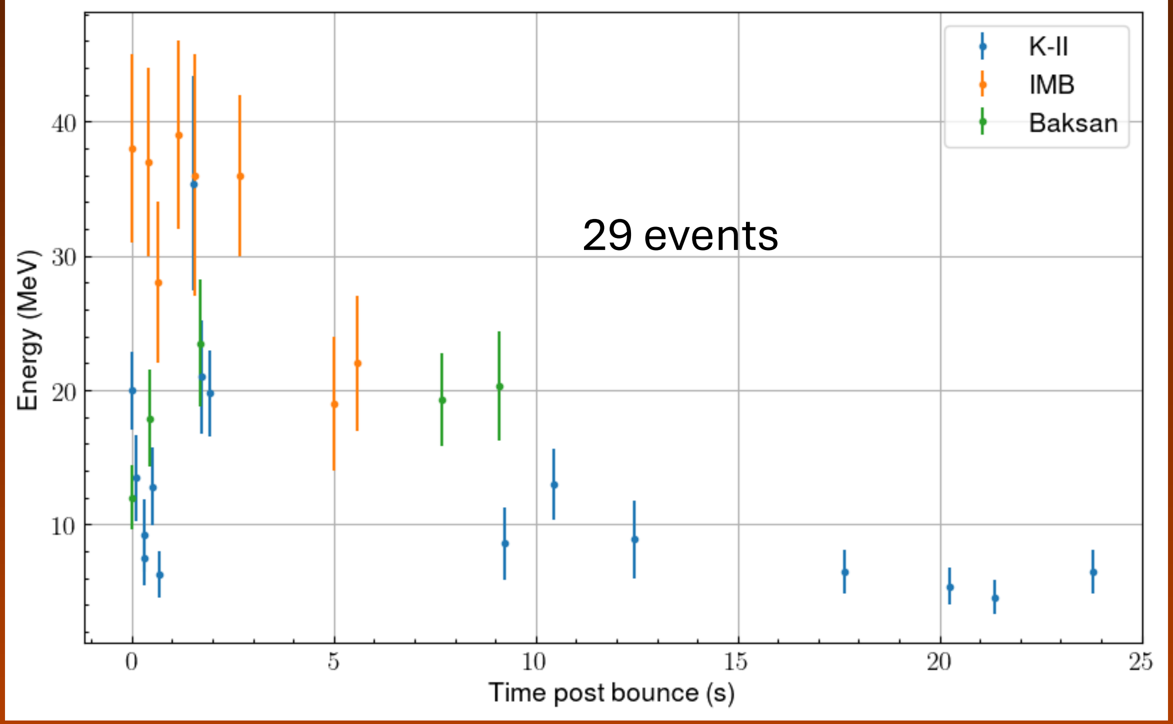


Simulation from Choi et al., *Phys.Rev.D* 111 (2025) 12, 123038

SN1987a



- SN neutrinos were only detected from SN1987 (50 kpc)
- Any model should be tested with these data



Clocks not synchronized: 3 free offset times

SN1987a – analysis framework

Neutrino emission model

↓

Flux at the source for each flavor

N astrophysical free parameters

SN1987a – analysis framework

Neutrino emission model

N free parameters

Flux at the source for each flavor

Neutrino oscillations:
assumption on mass hierarchy
(normal, inverted)

Flux at the Earth

SN1987a – analysis framework

Neutrino emission model

↓

Flux at the source for each flavor

↓

Flux at the Earth

↓

Rate of events

N free parameters

Neutrino oscillations (NO / IO)

Detection channel (IBD, …), detector characteristics (efficiency, energy resolution, …)

SN1987a – analysis framework

Neutrino emission model — N free parameters

↓

Flux at the source for each flavor

↓ Neutrino oscillations (NO / IO)

Flux at the Earth

↓ Channel, detector characteristics

Rate of events

↓ Unbinned, N+3 free parameters

Combined Likelihood

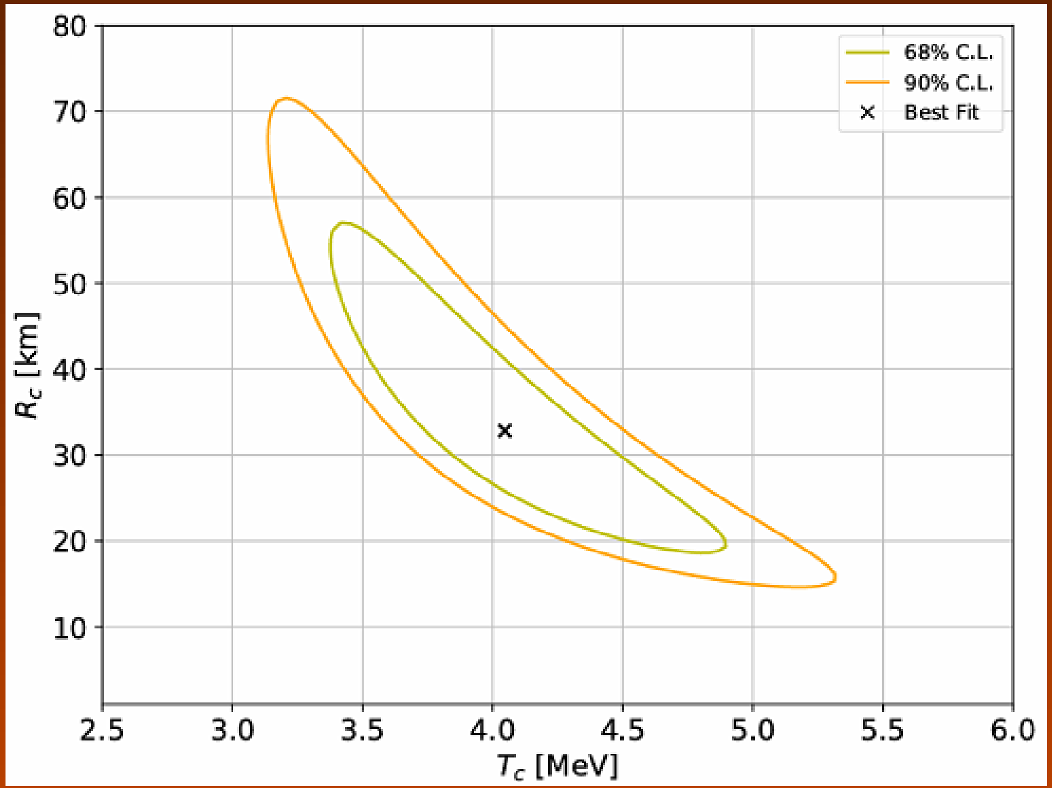
SN1987a – standard model

Free parameters:

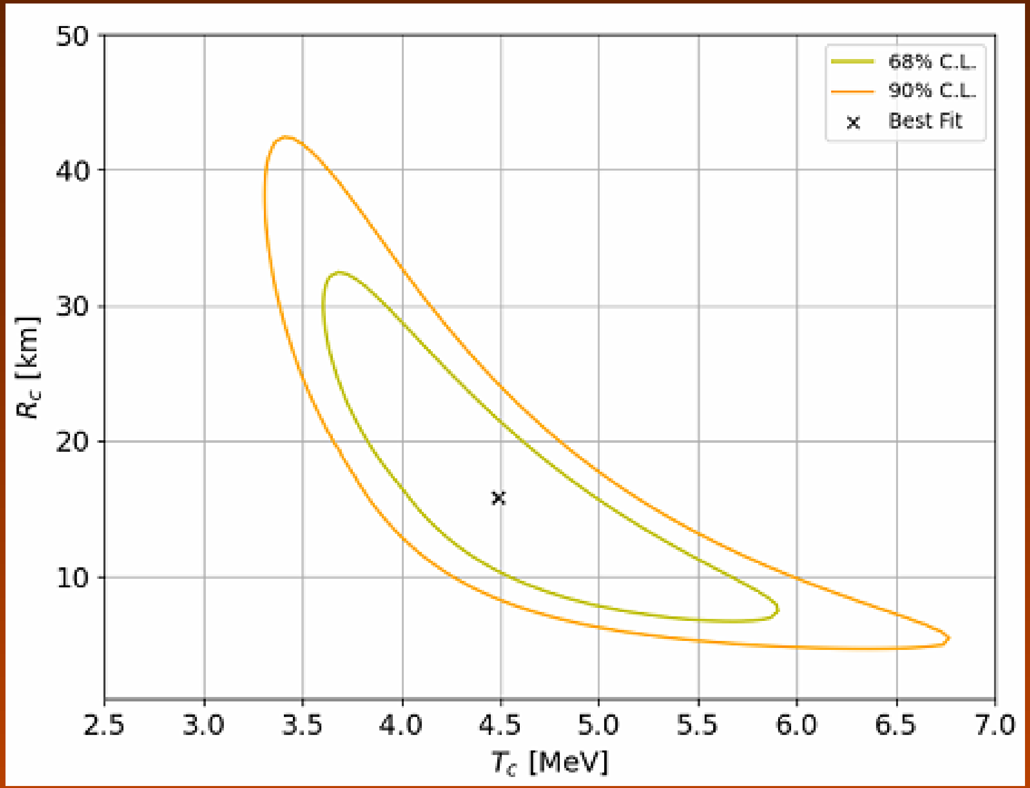
3 offset times

3 astrophysical: T_{PNS}, τ_c, R_{PNS} ✚ 6 astrophysical: cooling + T_a, τ_a, M_a

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



Refining the model (1)

- 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 ($t > 1s$):

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

➢ 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

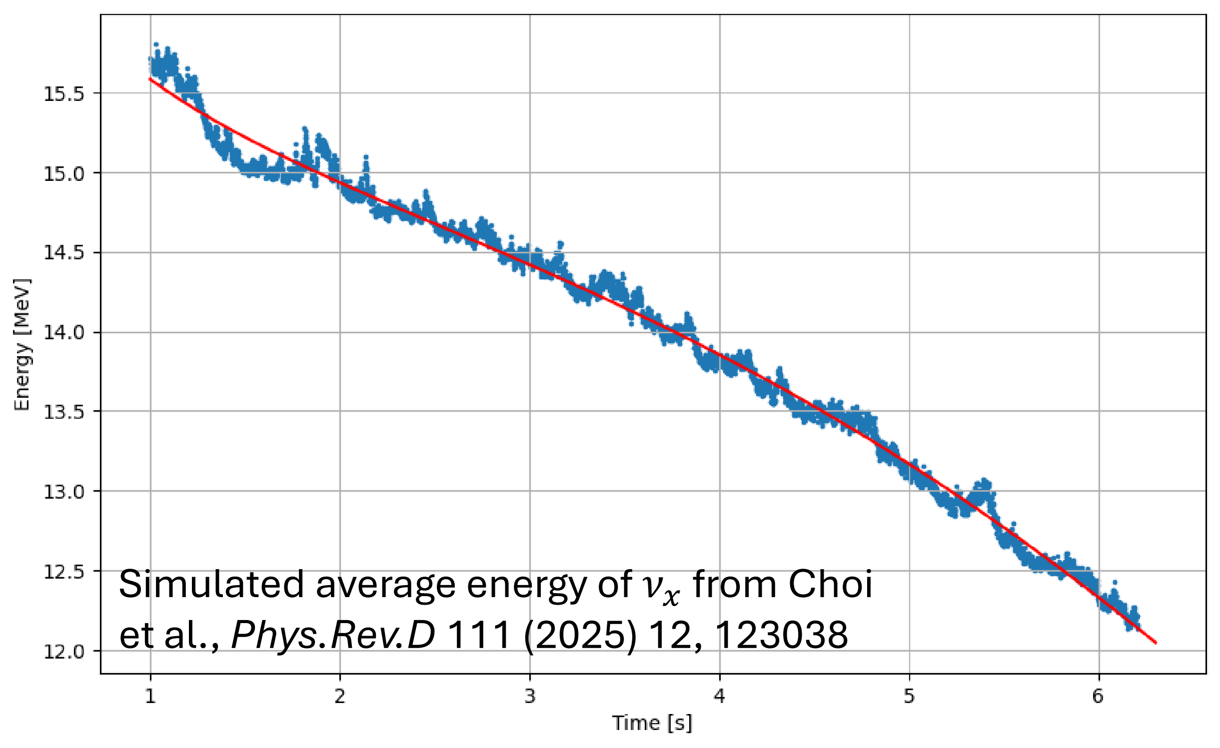
Time dependence in: radius, temperature, ...?

For $t > 1s$:

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

works!

Average Energy ∝ Temperature



Lucente cooling implementation

Time dependence in: radius, temperature, ...?

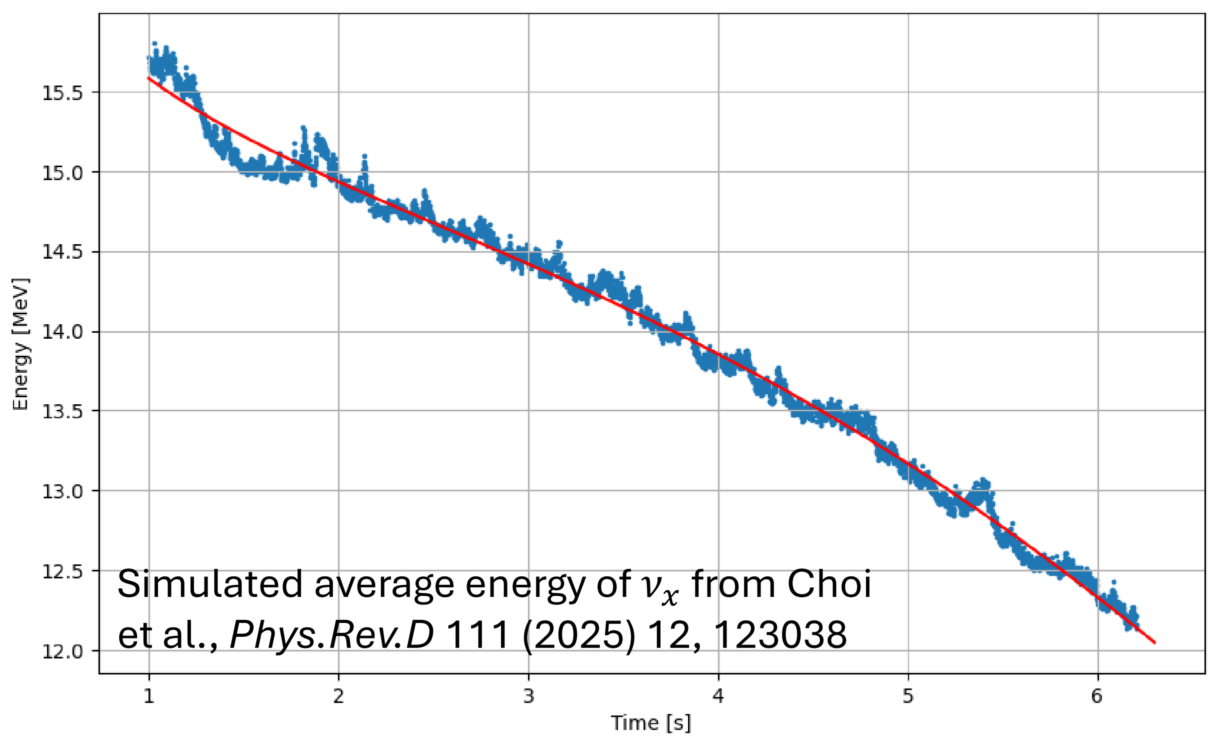
For $t > 1s$:

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

works!

We analyzed SN1987a dataset fot t>1s

Average Energy ∝ Temperature



Simulated average energy of ν_x from Choi et al., *Phys.Rev.D* 111 (2025) 12, 123038

Lucente cooling implementation

Time dependence in: radius, temperature, …?

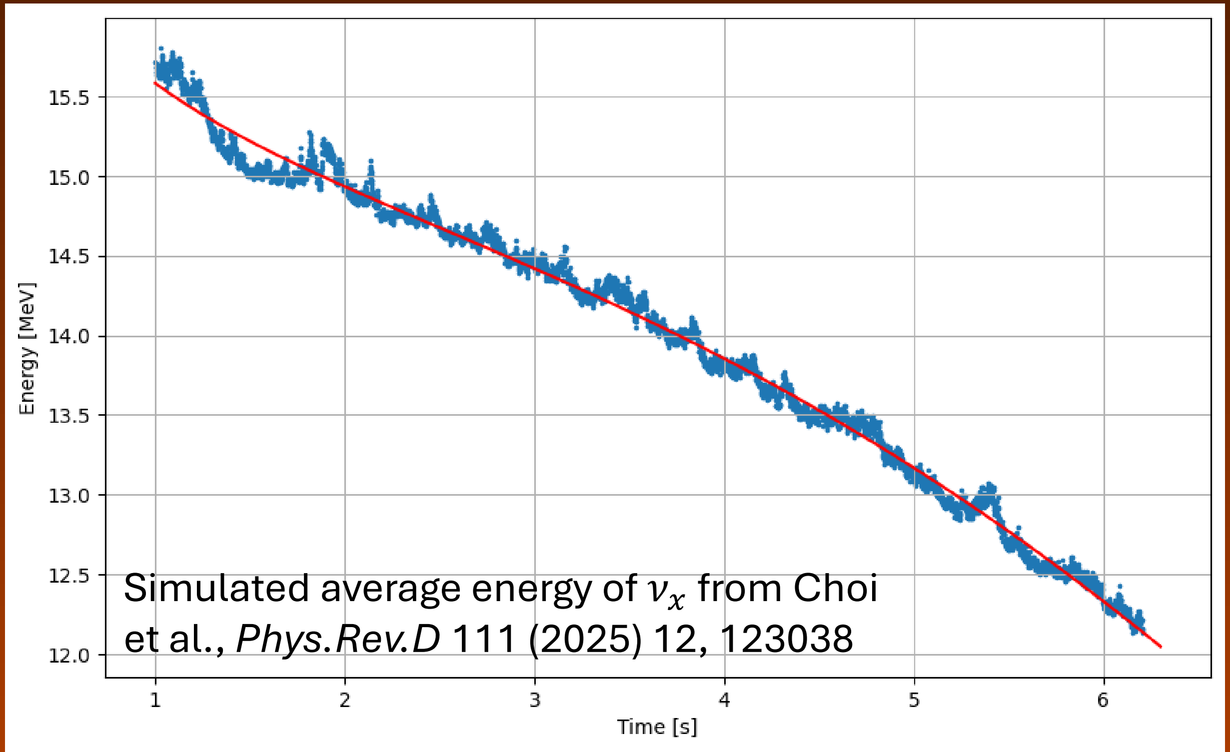
For $t > 1s$:

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

works!

Divergence at $t = 0$

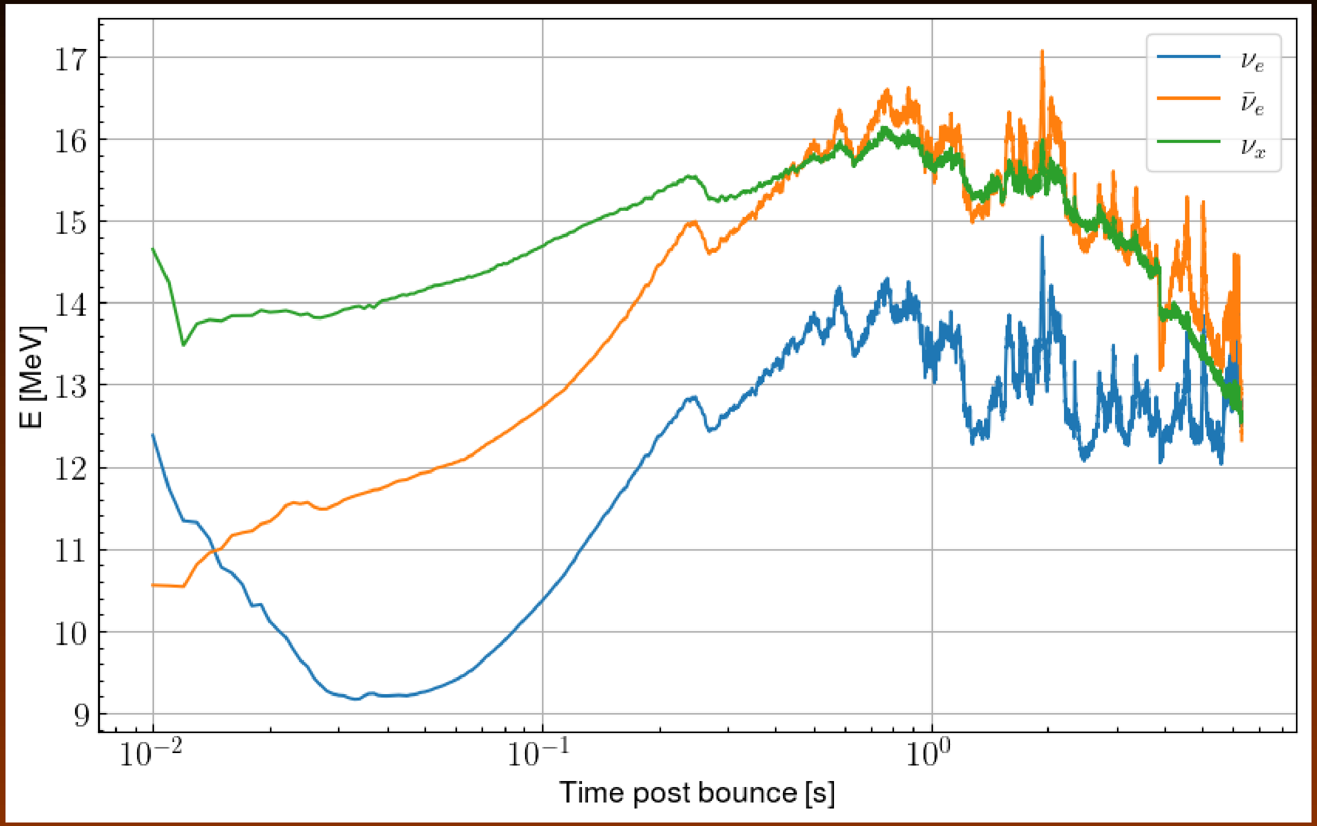
Average Energy $\propto$ Temperature



Simulated average energy of ν_x from Choi et al., *Phys.Rev.D* 111 (2025) 12, 123038

Refining the model (2)

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

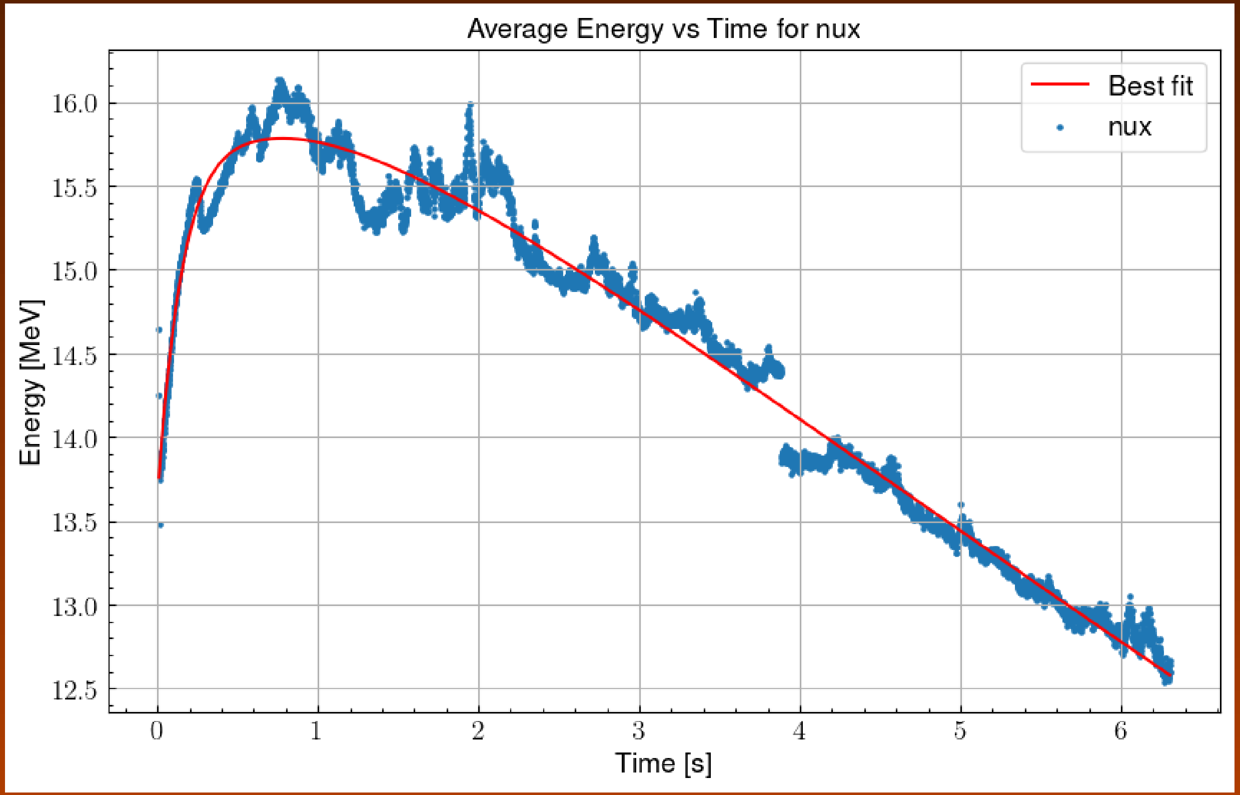


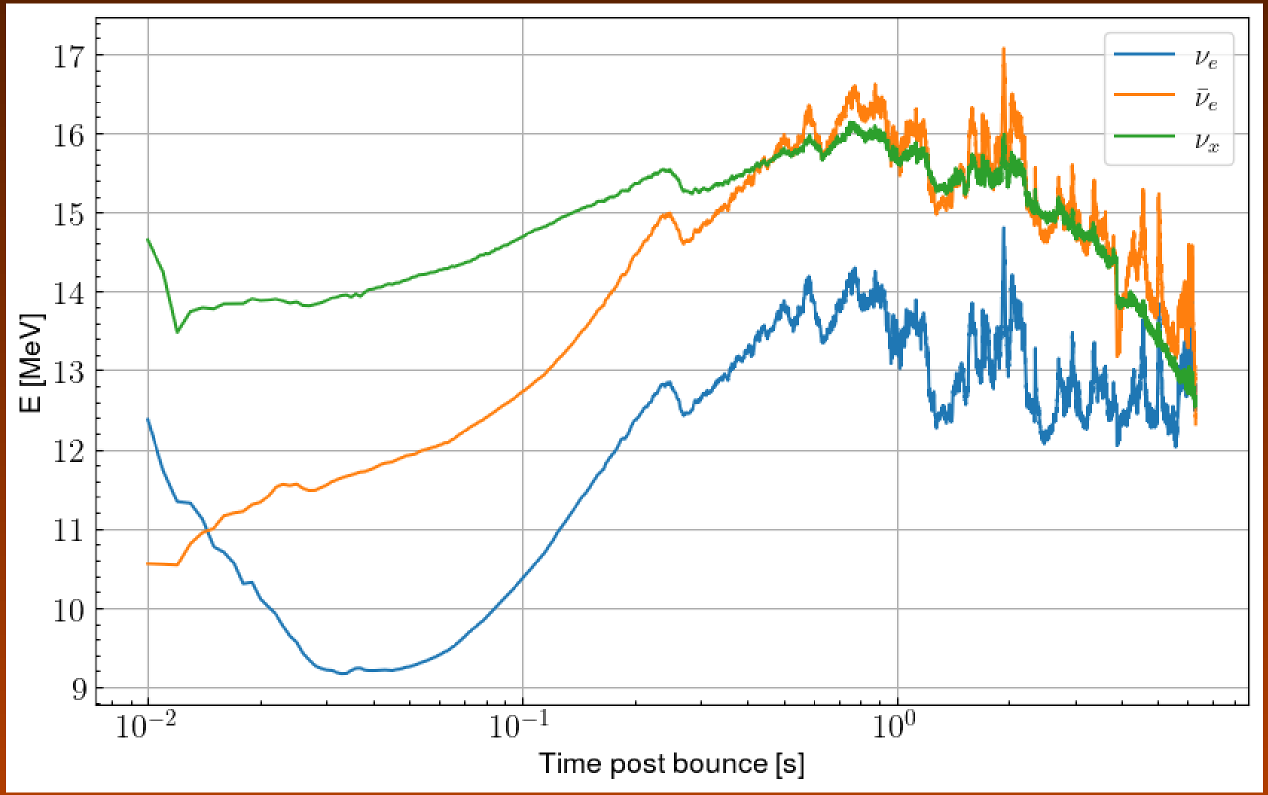
PNS temperature rises before exponential cooling

$$T_c(t) = \begin{cases} T_0 + B(1 - \exp(-t/\tau_1)), & \text{if } t < \bar{t} \leq 1\text{s} \\ C_{\bar{t}}\, t^{-\alpha_c} \exp(-(t/(\tau_c)^{n_c})), & \text{if } t > \bar{t} \end{cases}$$

Refining the model (2)

$$T_c(t) = \begin{cases} T_0 + B(1 - \exp(-t/\tau_1)), & \text{if } t < \bar{t} \leq 1\text{s} \\ C_{\bar{t}}\, t^{-\alpha_c} \exp(-(t/(\tau_c)^{n_c})), & \text{if } t > \bar{t} \end{cases}$$



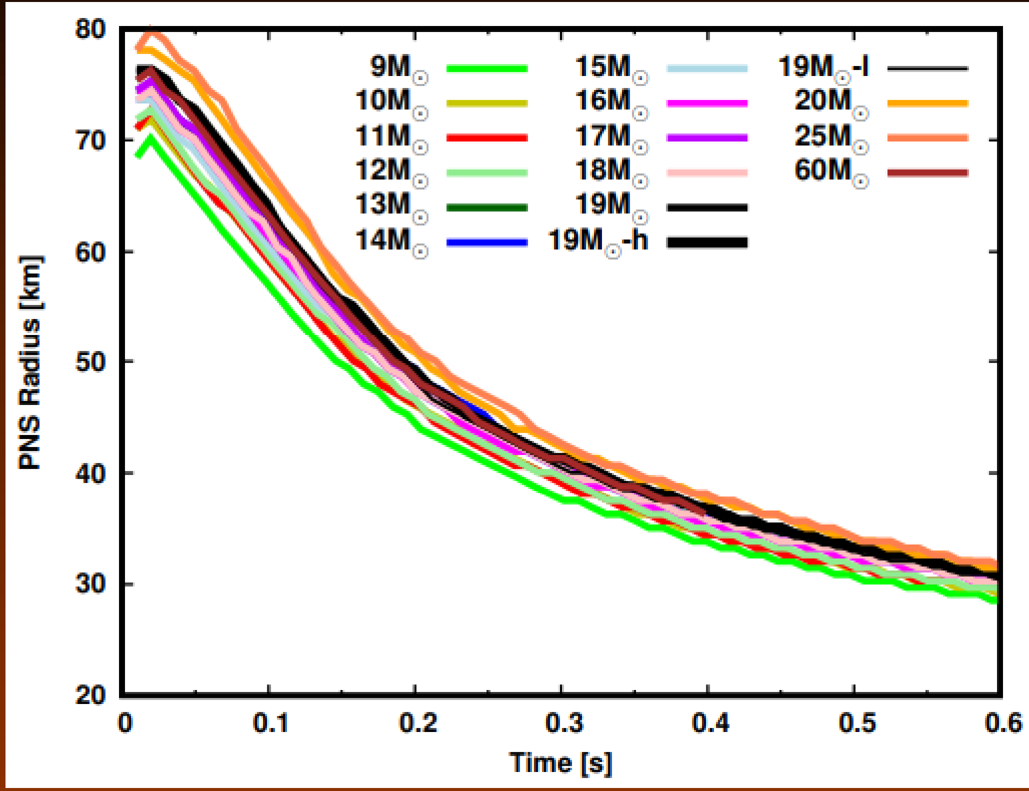


Simulation from Choi et al., *Phys.Rev.D* 111 (2025) 12, 123038

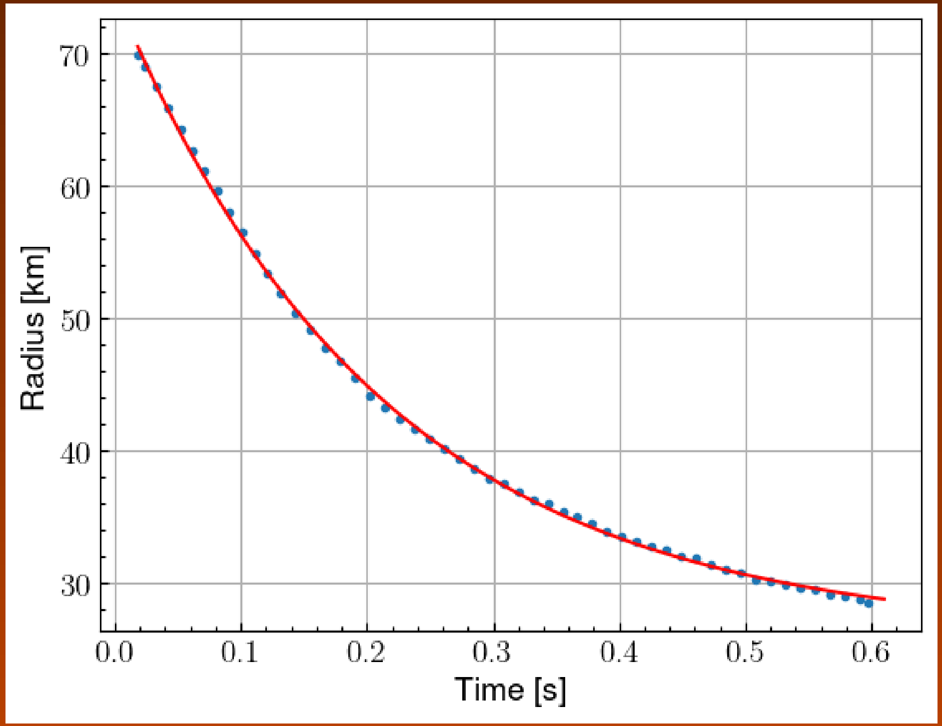
Refining the model (3)

PNS shrinks drastically in the first second:

$$R_c(t) = R_f \cdot (1 + A\exp(-t/\tau_2))$$



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



Note: $A \equiv \frac{R_i - R_f}{R_f}$

New cooling model

Radius model

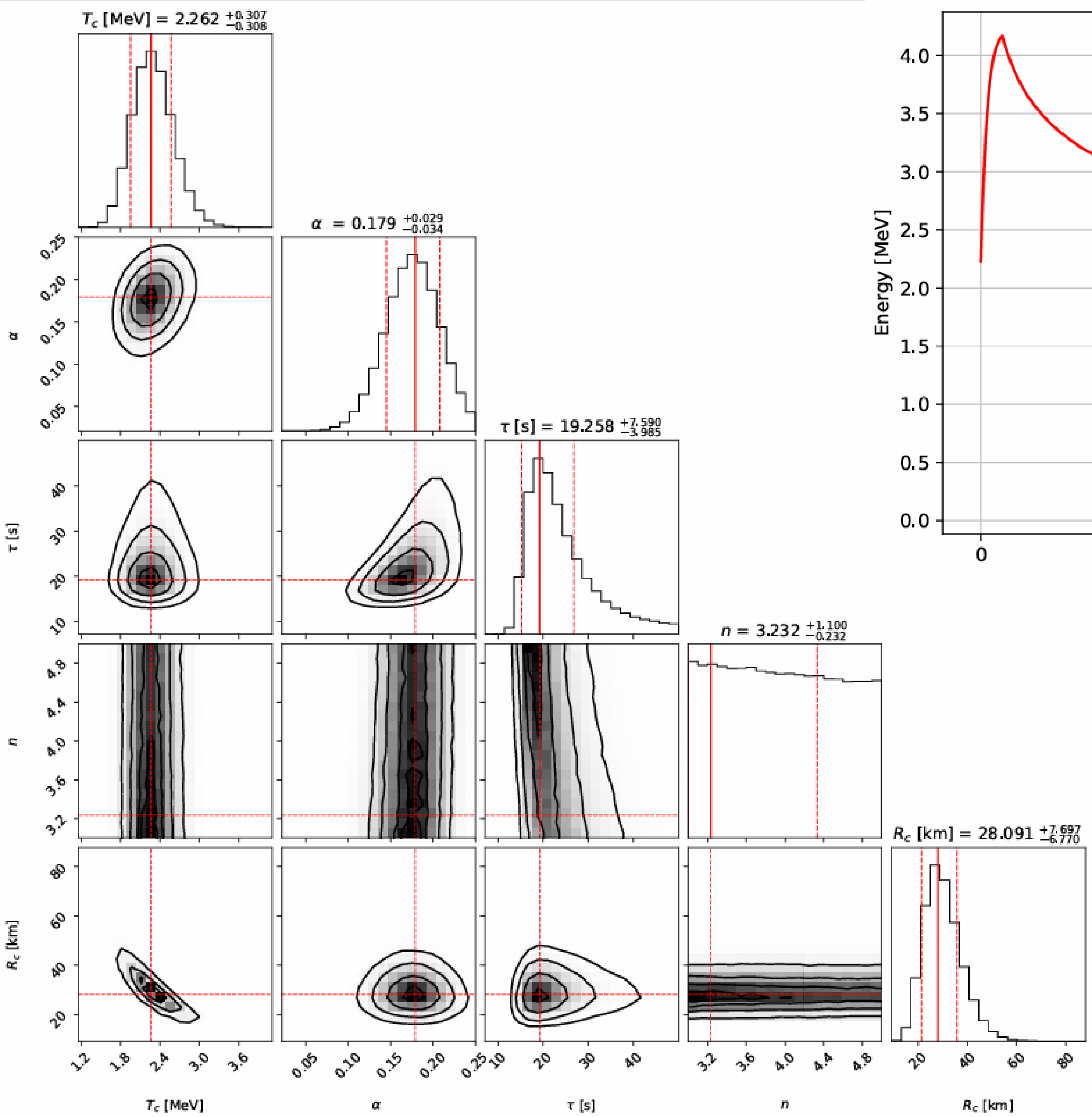
Temperature model

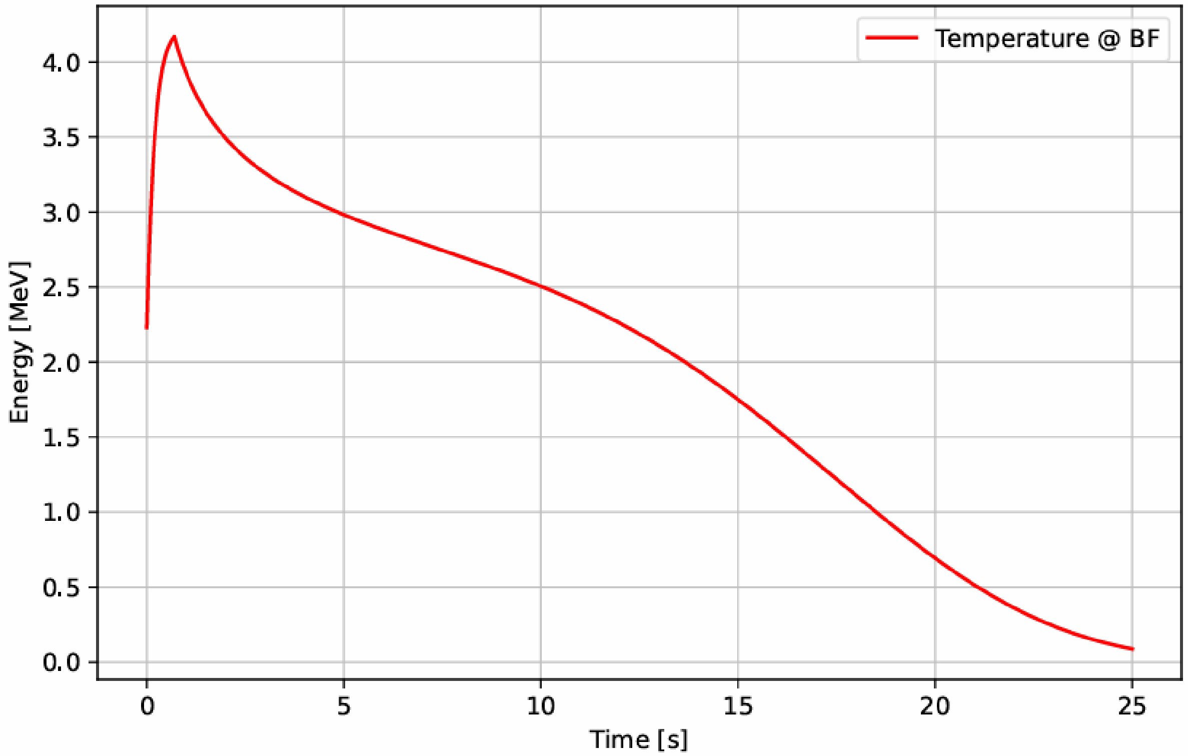
$$\Phi_c^0(E_\nu, t) \propto R_c(t)^2\, E_\nu^2 \left[1 + \exp\left(\frac{E_\nu}{T_c(t)}\right)\right]^{-1}$$

10 astrophysical free parameters → Ok for next Galactic CCSN, too many for SN1987a

For SN1987a fit: $A \equiv 1.25, B \equiv 2.25, \bar{t} = 0.7\ s, \tau_1 \equiv 0.2\ s, \tau_2 \equiv 0.5\ s$

5 astrophysical free parameters

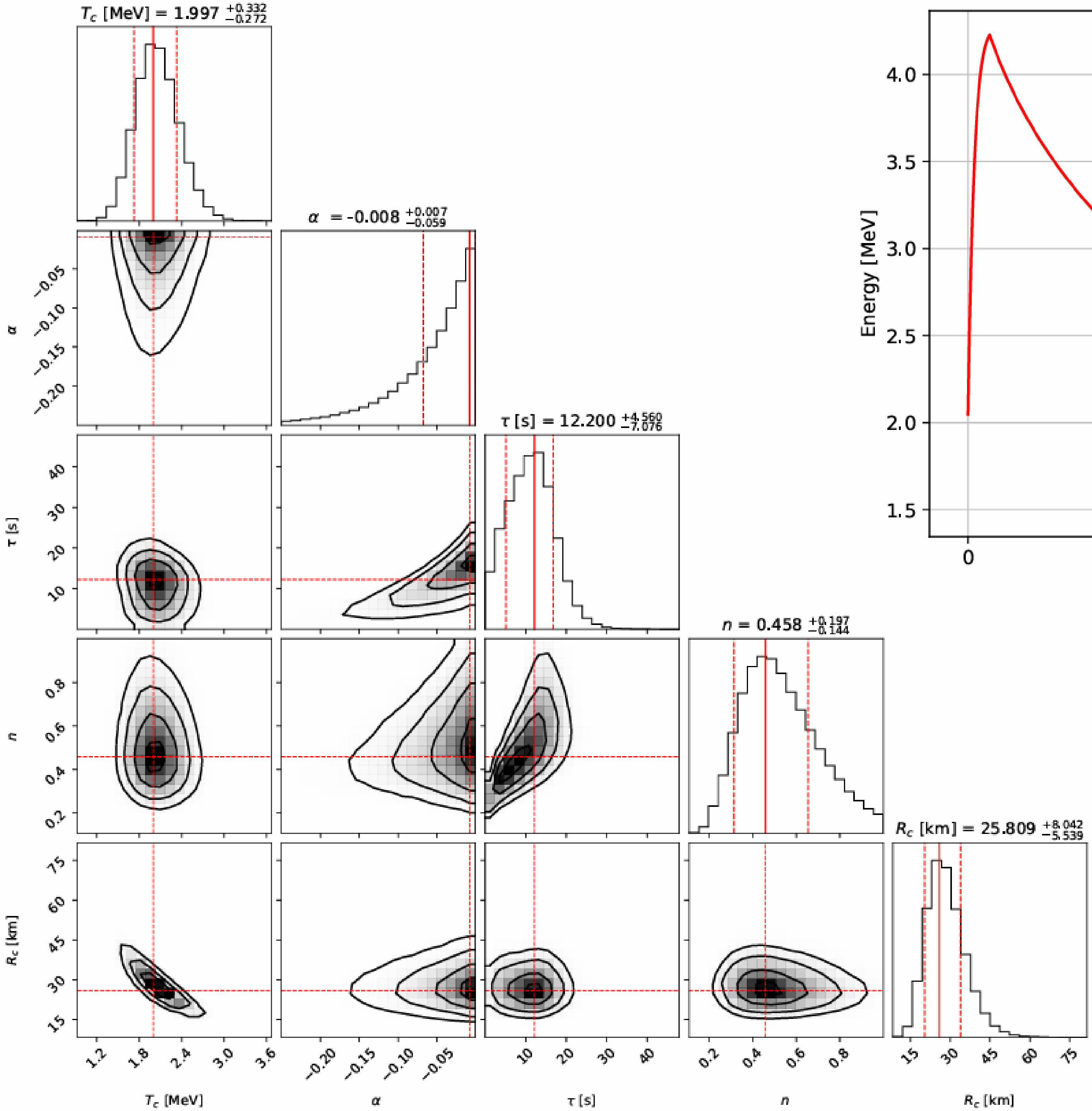


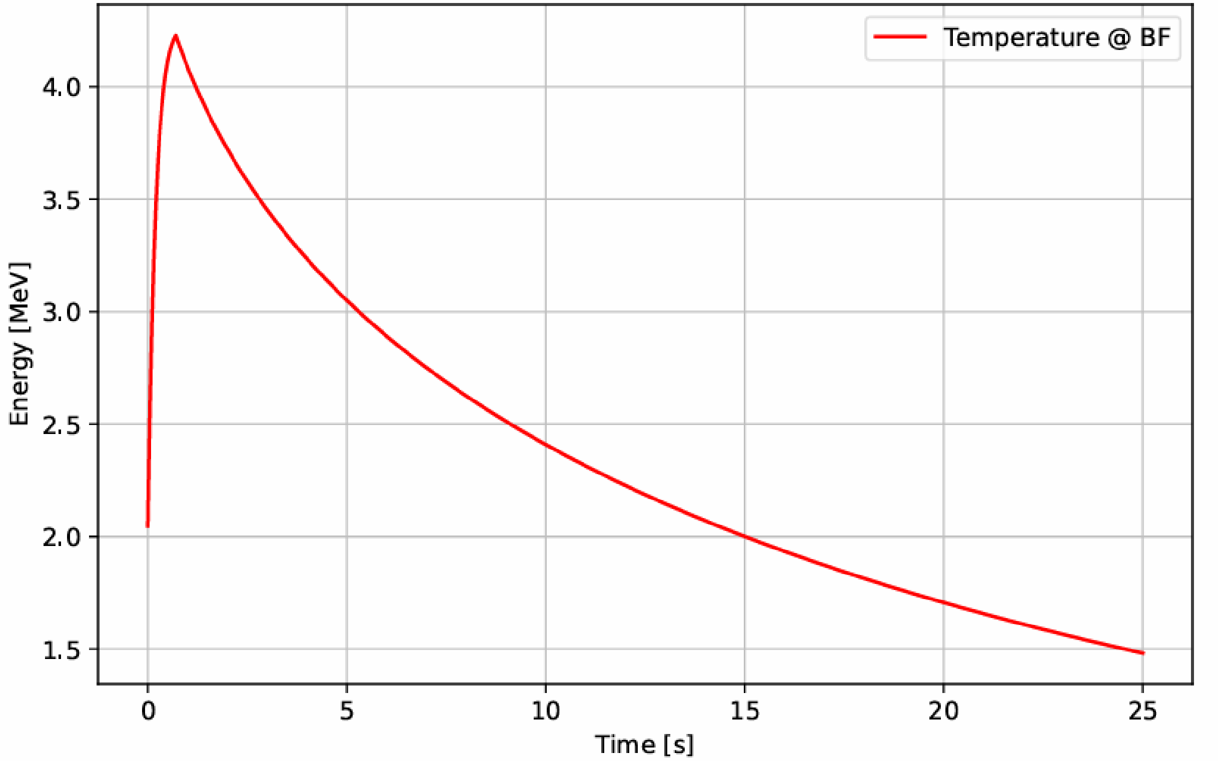


Results for EoS 'A'

$R_c = 30^{+8}_{-7}$ km

Slightly favored ($\sim 1.8\,\sigma$)





Results for EoS 'B'

$$R_c = 29^{+12}_{-9} \text{ km}$$

Next steps

Short term:

- Include Accretion phase → paper in preparation

Long term:

- Application on simulated dataset to correlate with GW signal
- Combination of the two analysis in a new GW detector pipeline

Summary

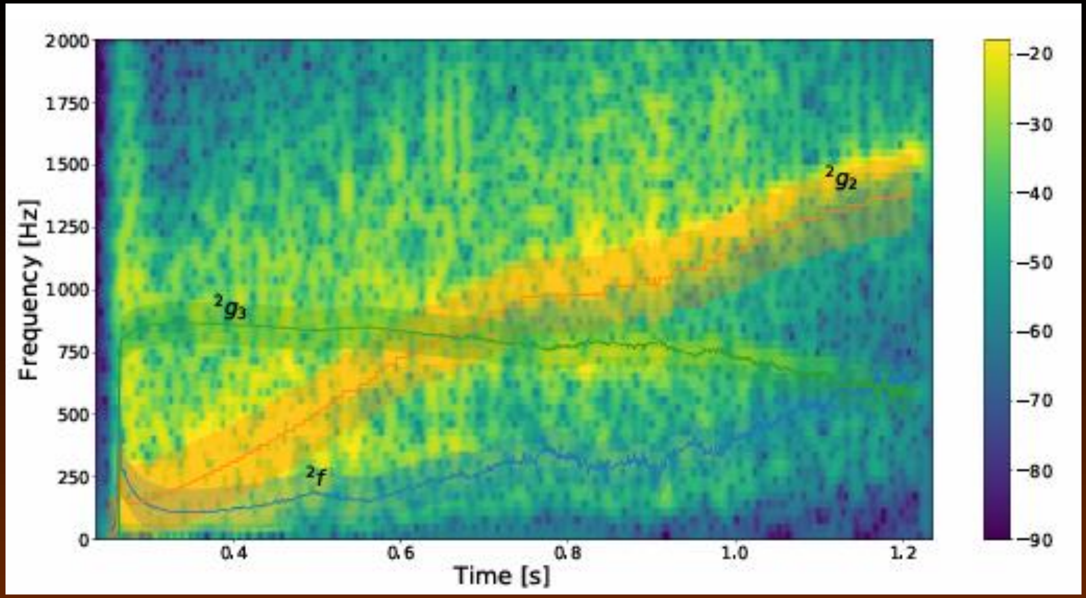
- New model for neutrino emission from Supernova, tested on SN1987a data
- Tests on simulated data and joint detection with GW soon
- We can learn a lot from the next galactic Core-Collapse Supernova!

Thank you for your attention

Other activities

- Learning cWB analysis
- MAYORANA (Multi-Aspect Young ORiented Advanced Neutrino Academy) international School in Modica, Italy (19-25 June 2025) - poster and short talk
- ISAPP School on Gravitational waves: from theory to detection, in Vienna, Austria (7-18 July 2025) - poster
- SN2025GW: First IGWN symposium on Core-collapse Supernova gravitational wave theory and detection (21-25 July 2025) – talk
- Virgo week at EGO-Virgo in Pisa, Italy (3-6 February 2025)
- (remote) attendance to the weekly LVK Burst group telecon and the biweekly Supernova subgroup telecon
- Soon: joining RRT shifts for LVK (thanks Pawan!)

How to include GW in the analysis?



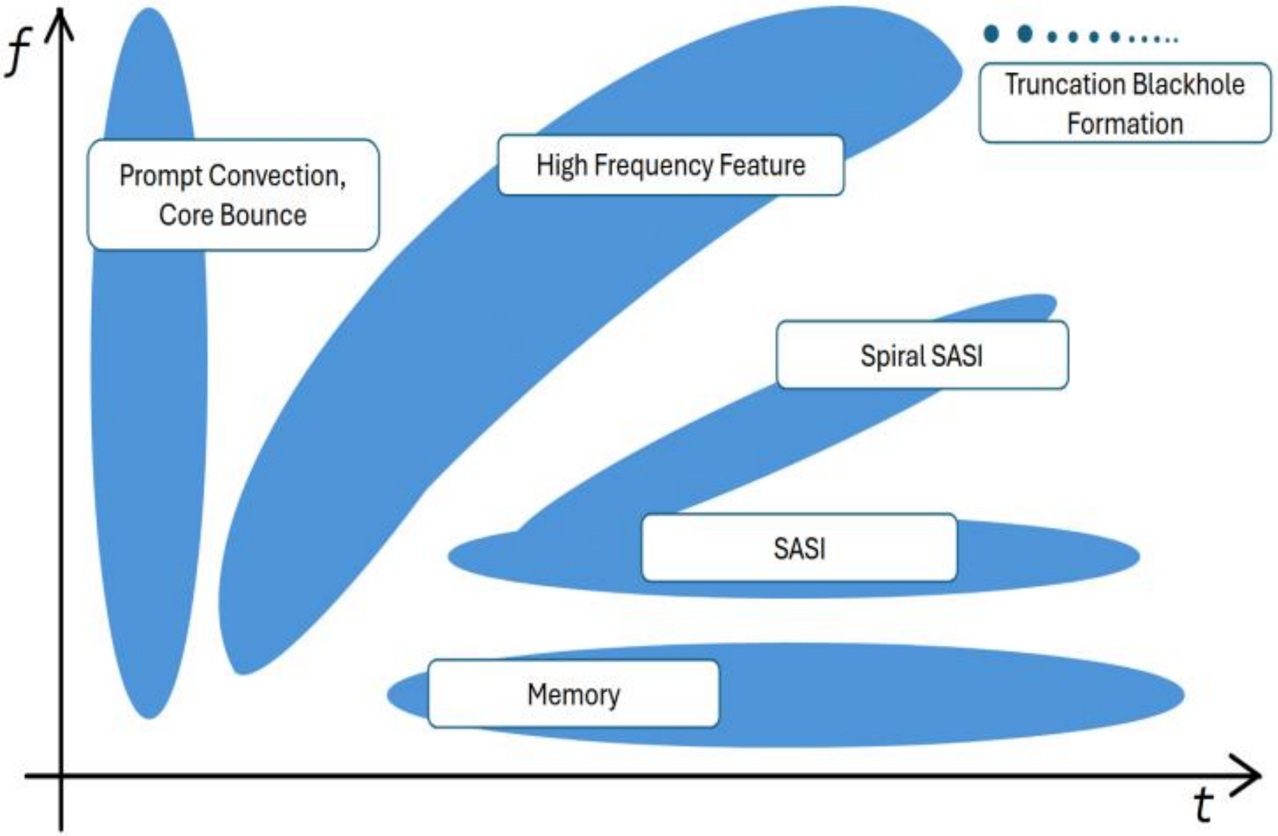
g-modes related to PNS mass and radius

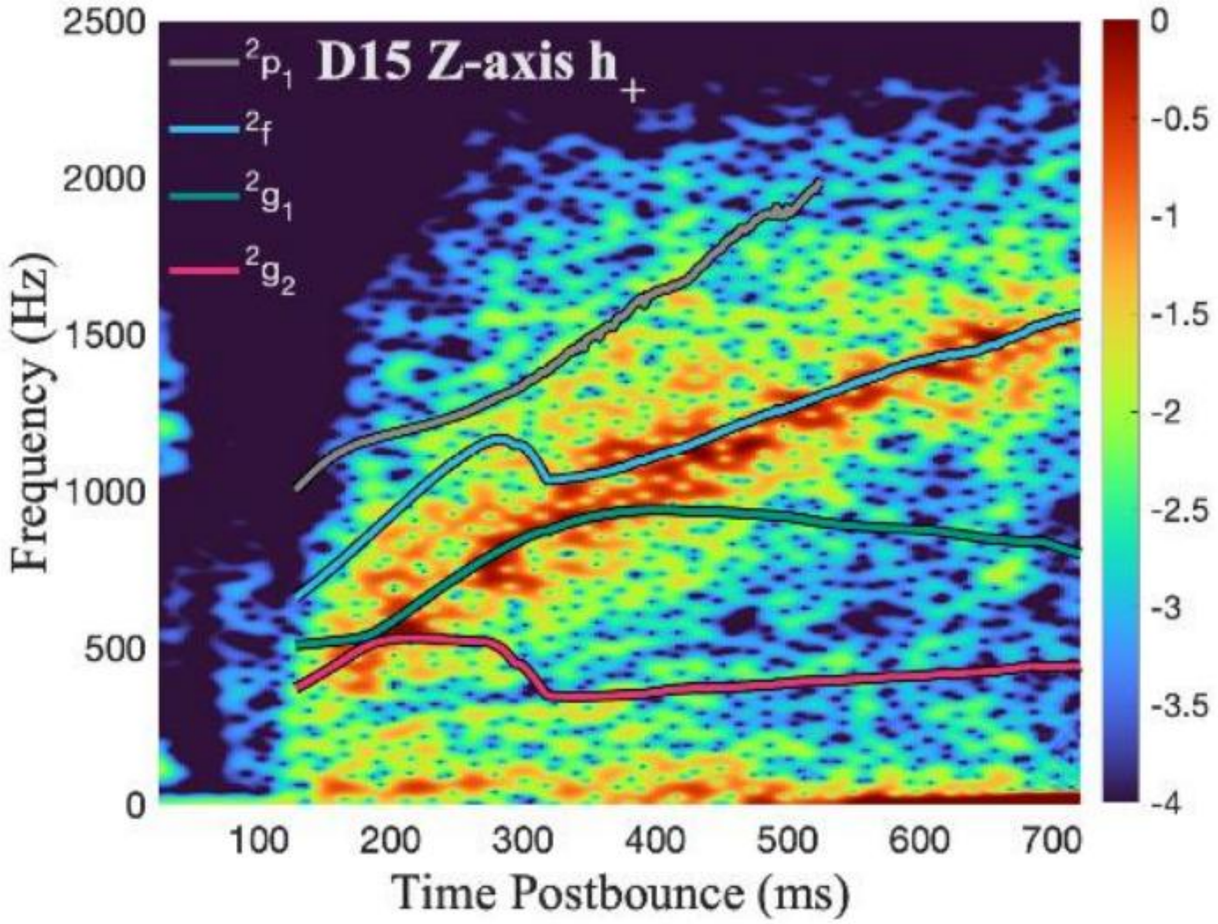
Torres-Forné et al., Phys. Rev. Lett. **127**, 239901 (2021)

mode	x	a	$b/10^5$	$c/10^6$	$d/10^9$	R^2	σ
^2f	$\sqrt{M_{\rm shock}/R^3_{\rm shock}}$	-	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

Extra

GW emission from CCSNe





Murphy et al. Phys. Rev. D (2025) arXiv:2503.06406

Extra

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

Normal ordering:

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

where: $P \simeq 0.7$

Inverted ordering:

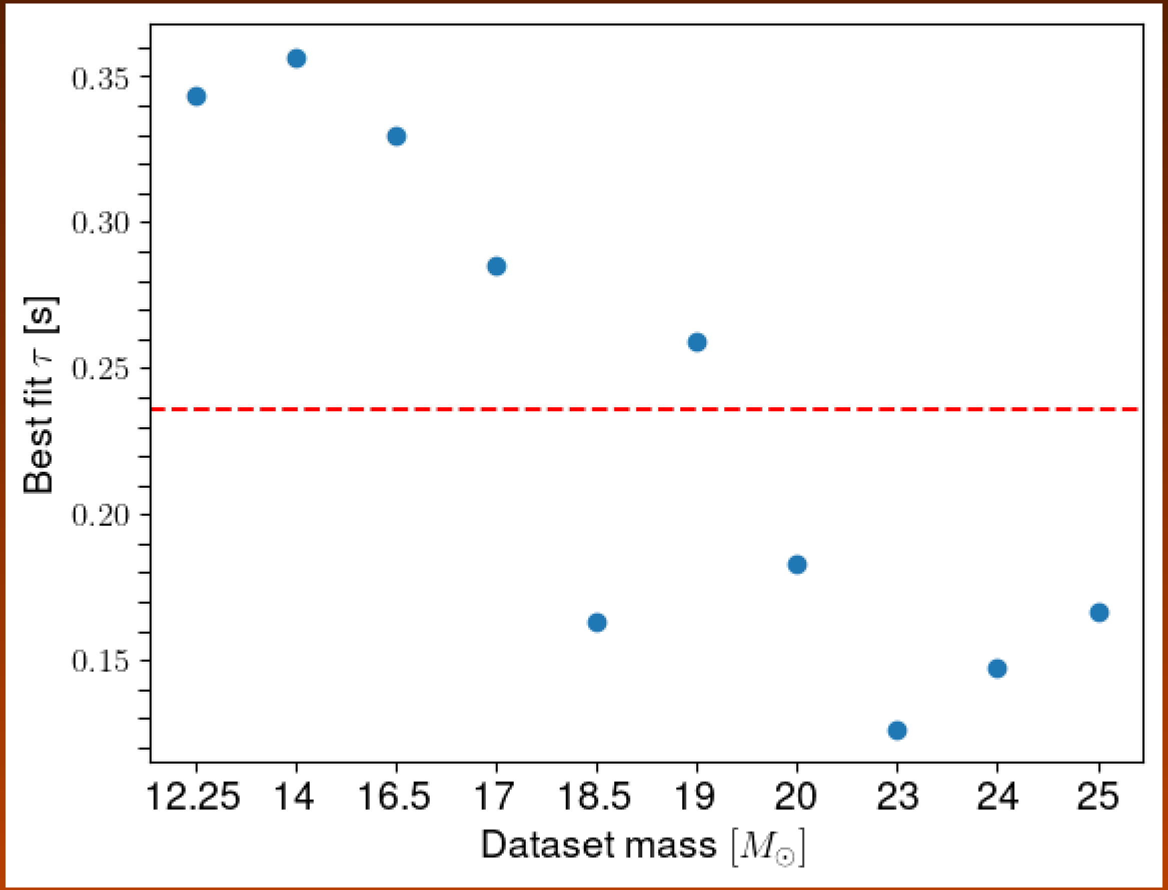
$$\Phi_{\bar{\nu}_e} \simeq \Phi^0_{\nu_x}$$

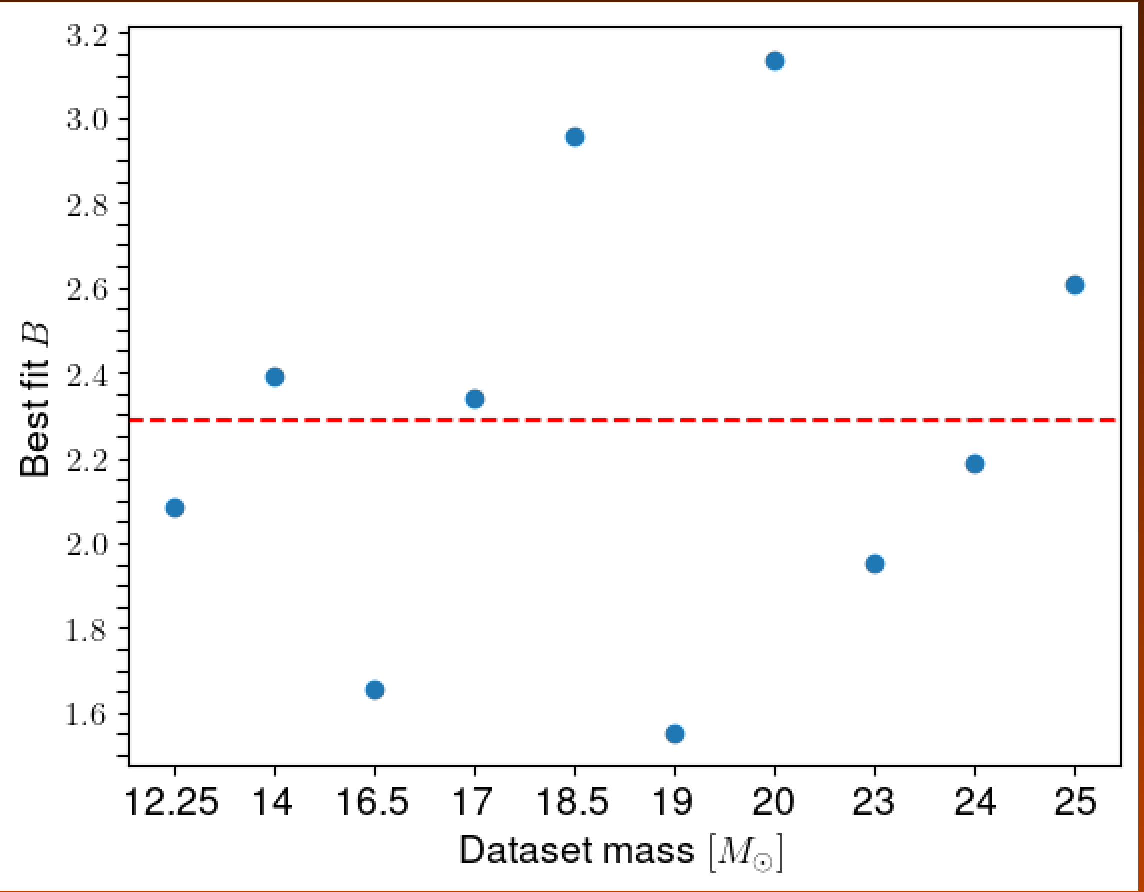
Extra

$$T_0 + B(1 - \exp(-t/\tau_1))$$

$$\tau_1 = \mathbf{0.24 \pm 0.08}\,\mathrm{s}$$

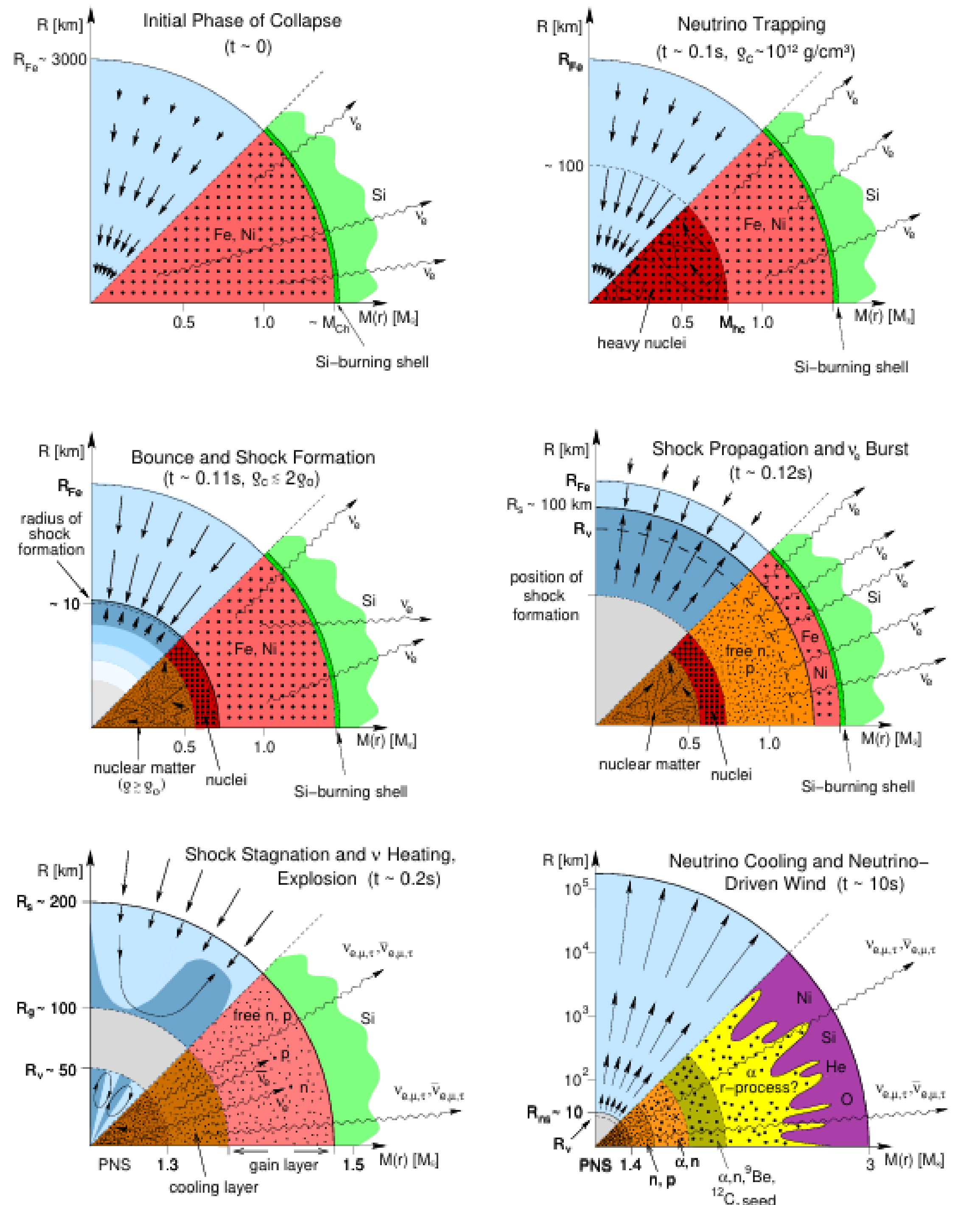
$$B = \mathbf{2.3 \pm 0.5}\,\mathrm{MeV}$$





Extra

More on emission mechanism



Density gets so high that neutrinos are trapped

Shock dissociates iron nuclei, density drops and ν_e are free

Shock stalls and need to be revived (by neutrinos from accretion?)

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

Lucente vs Cooling

The Lucente parametrization, introduced inside the cooling model as a new temporal shape of the PNS temperature, leads to these correlations:

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

$C \propto R_c^2 T^4$

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

$n = n_c$

$\alpha = 4\alpha_c$

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

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

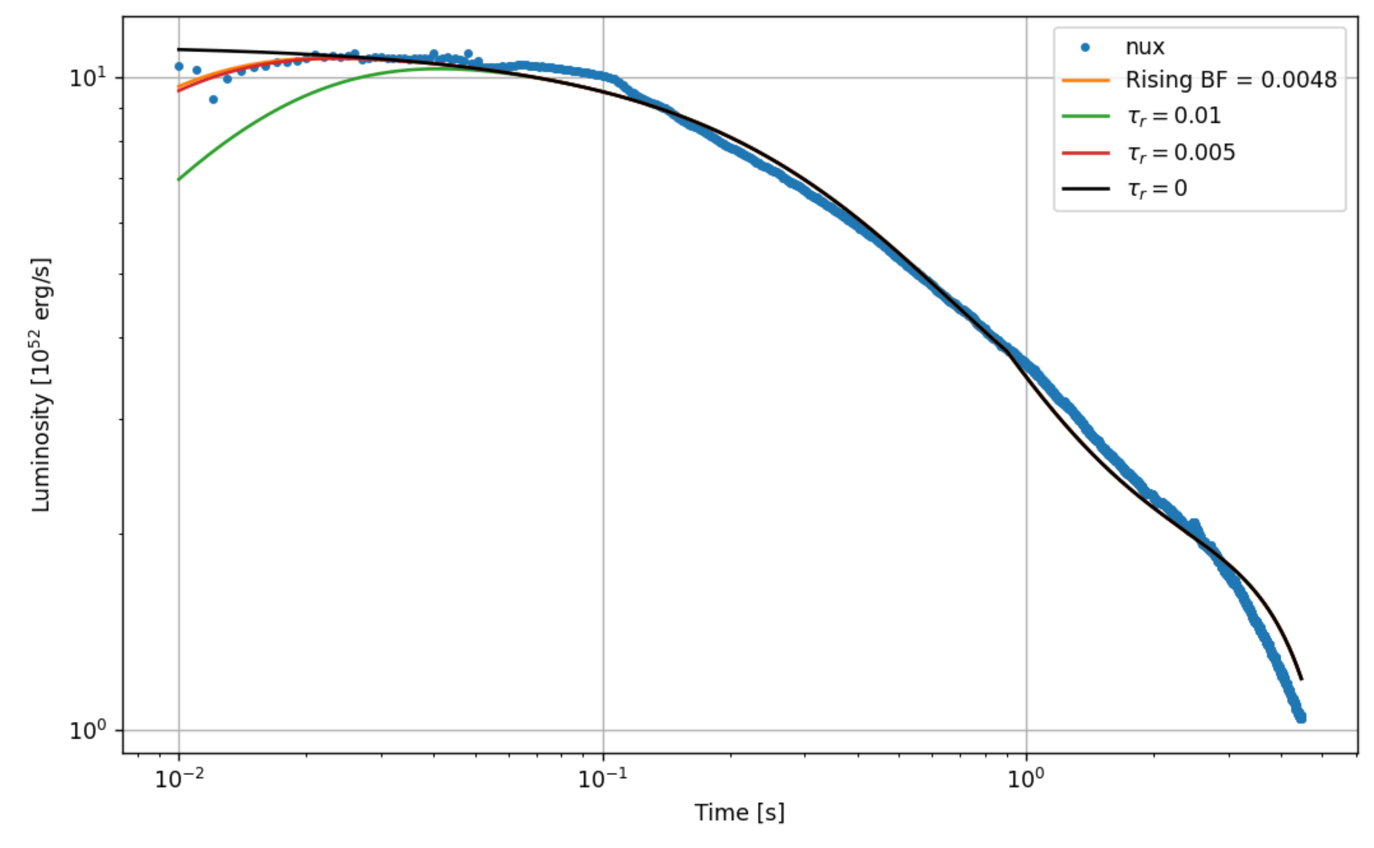
$\tau_c > 4\tau$

Refining the model – rising time

Still not enough!

$$L_\nu^{\mathrm{mod}} = L \cdot (1 - \exp(-t/\tau_r))$$

Esempio (da rifare il plot)



New cooling model

Radius model

Temperature model

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

11 astrophysical free parameters → Ok for next Galactic CCSN, too many for SN1987a

For SN1987a fit: $A \equiv 1.25, B \equiv 2.25, \bar{t} = 0.7\ \mathrm{s}, \tau_1 \equiv 0.2\ \mathrm{s}, \tau_2 \equiv 0.5\ \mathrm{s}, \tau_r = 8\,\mathrm{ms}$

→ 5 astrophysical free parameters