Axion emission from beyond-1st-generation matter in core-collapse SNe

— Diego Guadagnoli, LAPTh Annecy —

based on work w/

Maël Caron-Piton (LAPTh), Micaela Oertel (Meudon), Hyeonseok Seong (DESY), Ludovica Vittorio (LAPTh)

TH Motivation

- the (QCD) axion is one of the best motivated BSM particles

Generally expected to be light

$$m_a \simeq 6\ \mathrm{meV} \left(\frac{10^9\ \mathrm{GeV}}{f_a} \right)$$

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  = The axion couples to matter derivatively

$$\mathcal{L}_{a,\,\mathrm{hadrons}} = \frac{\partial_\mu a}{f_a} \cdot \left(x_L^b\, J_L^{\mu b}(U, B) + x_R^b\, J_R^{\mu b}(U, B) \right)$$

fields of octet mesons and baryons

Astro probes

— the coupling $\propto \frac{\partial_f}{f_a}$ $\longrightarrow$ coupling strength goes as $\frac{\text{external momenta}}{f_a\ (\leftarrow \text{large})}$

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$\longrightarrow$ SNe (in the core-collapse picture) stand out as QCD-axion probes

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$$Q_a = \int \left[\begin{array}{c}\text{elem. of}\\ \text{phase space}\end{array}\right] \times E_a \times \left| \begin{array}{c}\text{matr. elem.}\\ \text{of axion-producing}\\ \text{process}\end{array} \right|^2 \times \left[\begin{array}{c}\text{ext. states'}\\ \text{distr. functions}\end{array}\right]$$

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— calculable within assumptions

- distr. functions not obvious away from ideal-gas assumption
- p_i^*, E_i^*, m_i^* ← in-medium effects

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difficult to go beyond a crude estimate

$$Q_\nu \sim 1.5 \cdot 10^{19} \frac{\text{erg}}{\text{sec} \cdot \text{gr}} \cdot \rho \qquad \text{w/} \quad \rho = \rho_{core} \sim 3 \div 8 \cdot 10^{14} \frac{\text{gr}}{\text{cm}^3}$$

Axions from SNe : processes

- Most established bound obtained from nucleon axionstrahlung

$N_1 N_2 \to N_3 N_4 a$ [Ericson, Mathiot, 1989; Carenza et al., 2019; Caputo, Raffelt, 2024]

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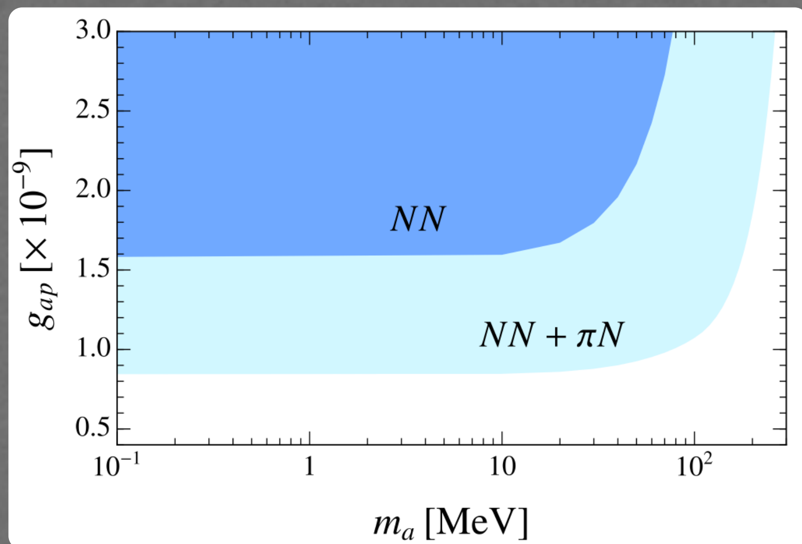
[Lella et al., 2022]

[Carenza et al., 2020]

ρ		$\bar{g}_{aN}$	m_a	f_a
		$(\times 10^{-9})$	(meV)	$(\times 10^8$ GeV)
ρ_0	only NN	0.81	21.02	2.71
	$\pi N + NN$	0.46	11.99	4.75
$\rho_0/2$	only NN	0.93	24.11	2.36
	$\pi N + NN$	0.42	10.96	5.20



A further layer of complexity

is the possible role

of beyond-1^{st}-generation matter

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contributions to Q_2

What we do in short

- We consider the full meson & baryon octets
- And calculate all $B_i\, M \to B_f\, a$ ("Compton") & $B_i \to B_f\, a$ ("decay") contributions to Q_a

- $$Q_a = \int E_a (2\pi)^4 \delta^4(p) |\mathcal{M}|^2 F_i F_M (1-F_f) \prod_k \frac{d^3\vec{p}_k}{(2\pi)^3 2E_k}$$

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$\Rightarrow$ Even if B_i, B_f, M fractions "small", the large number of processes yields a relevant constraint

▨ Modeling of fundamental axion – matter couplings

[Georgi – Kaplan – Randall, 1986]

$$\mathcal{L}_{aqq} \equiv \frac{\partial_\mu a}{f_a}\left(\bar{q}\,\gamma^\mu_L\, k_L\, q + \bar{q}\,\gamma^\mu_R\, k_R\, q\right) \qquad w/ \quad q = \begin{pmatrix} u \\ d \\ s \end{pmatrix}$$

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From QCD to ChPT + 1 axion

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U: octet-meson field

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w/ $x^b_{L,R} \equiv$ projections of the k couplings along the octet dirs.

$\Rightarrow$ The axion-hadron dynamics is also parameterized in terms of the fundamental k-couplings ($\equiv$ axion-quark couplings)

- Ten k-coupling d.o.f. to start with

$(k_{V,A})_{11,\,22,\,33,\,23\,\&\,32}$ w/ $k_{V,A} \equiv k_R \pm k_L$

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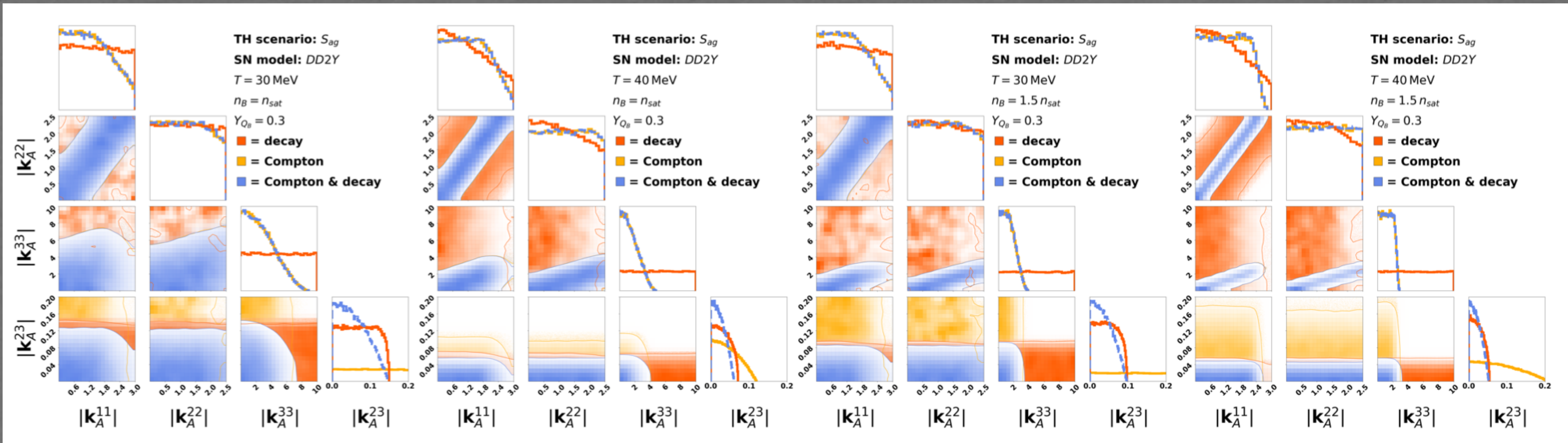
$\Longrightarrow$ $\boxed{Q_2 \text{ chiefly constrains } (k_A)_{11,\,22,\,33} \;\&\; |(k_A)_{23}|}$


TH scenario: S_{ag}
SN model: $DD2Y$
$T = 30\,\mathrm{MeV}$
$n_B = n_{sat}$
$Y_{Q_B} = 0.3$
= decay
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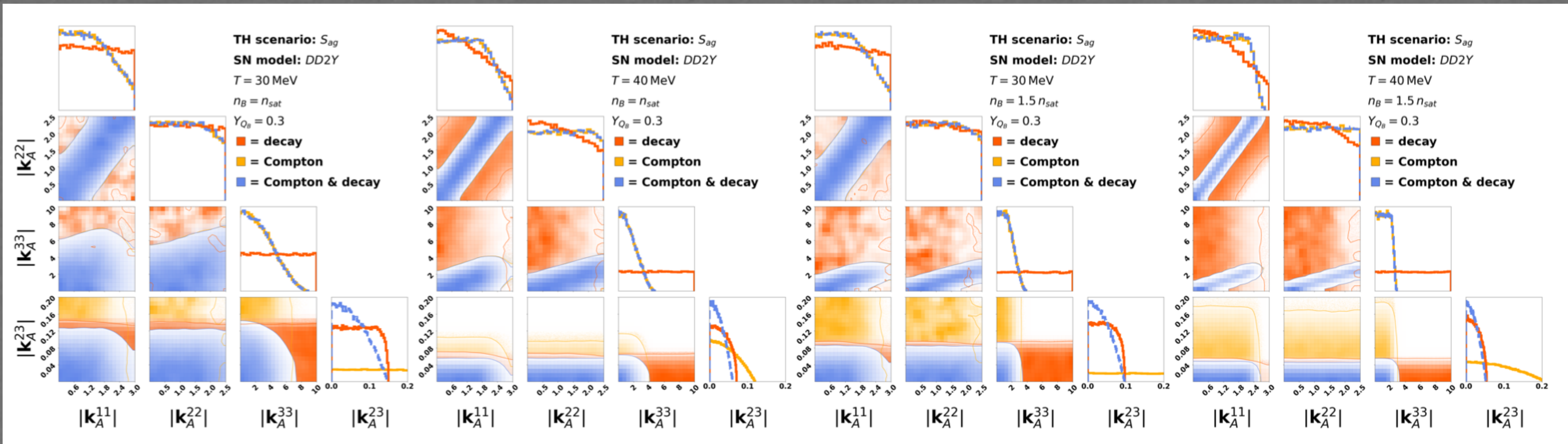
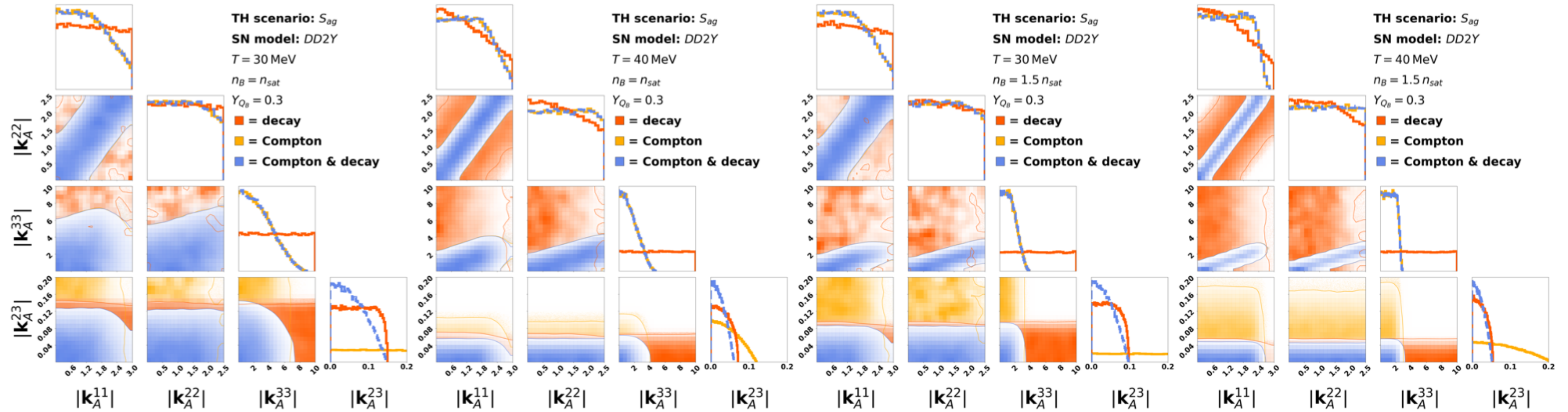


(a) $(k_A)_{ii} \longleftrightarrow (k_A)_{jj}$ correlations

(b) A direct constraint on $|(k_A)_{23}|$, of $\mathcal{O}(10^{-1} - 10^{-2})$



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– that become sharper (i.e. bounds tighter) for larger T

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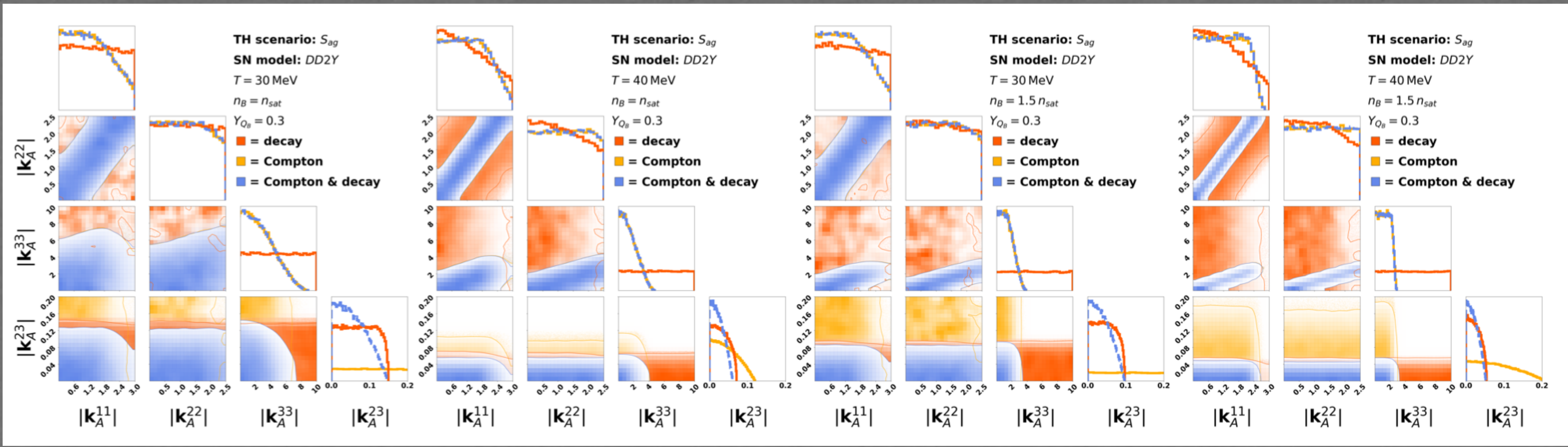

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(b) A direct constraint on $|(k_A)_{23}|$, of $O(10^{-1} - 10^{-2})$

- dominated by decay, although Compton increases in importance as T increases

Two alternative EoS models with different strange-matter densities

TABLE I. Q_a bounds on $|(\boldsymbol{k}_A)_{23,33}|$, assuming $f_a = 10^9$ GeV. The larger boldfaced vs smaller value quoted in each table entry refers to the EOS model being considered, DD2Y [57] vs SFHoY [58] (see text for details on these models).

$\boldsymbol{k}$ coupling	$n_B = n_{sat}$ 30 MeV	$n_B = n_{sat}$ 40 MeV	$n_B = 1.5n_{sat}$ 30 MeV	$n_B = 1.5n_{sat}$ 40 MeV
$\lvert(\boldsymbol{k}_A)_{23}\rvert$	0.35 **0.15**	0.12 **0.061**	0.38 **0.097**	0.14 **0.052**
$\lvert(\boldsymbol{k}_A)_{33}\rvert$	8.8 **8.9**	4.4 **4.8**	5.9 **3.9**	3.1 **2.9**

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$\mathcal{O}(10^{-2})$ bound

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- They probe not only interactions w/ ordinary matter, but also beyond-1st-generation ones.

- Improved understanding of the sources crucial to go beyond $O(1)$ answers.

SPARES

Robustness of conclusions

Our conclusions must be proved robust at least w.r.t. the modeling of

- the axion-emitting SN volume
- the axion-hadron interactions

SN-core modeling

- State of matter defined by 3 thermodyn. pars. : T, n_B, Y_e
  - one can determine all abundances

- We estimate Q_a a posteriori, surveying its variation as thermodynamics is changed within reasonable ranges
  - $T = \{30, 40\}$ MeV
    - "standard" choice in literature & provides more "conservative" bound
    - quantifies the effect of T variation in a reasonable, yet large enough range

- Two n_B values ; two EoS with somewhat different strange-matter densities