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

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based on work w/

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TH Motivation

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

  Generally expected to be light

  $$m_a \simeq 6\ \mu eV \left(\frac{10^{12}\ GeV}{f_a} \right)$$ [e.g. Villadoro et al., 2016]

- Interactions w/ matter amenable of rigorous EFT description

  → within Chiral Perturbation Theory

ChPT description

MANIFESTING THE INVISIBLE AXION AT LOW ENERGIES ☆

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We discuss the low energy properties of the invisible axion in an effective field theory language. We study the most general model in which the strong *CP* problem is solved by a Peccei–Quinn symmetry spontaneously broken at a large scale. We distinguish carefully between the model dependent derivative couplings of the axion associated with physics at the large scale, and the model independent nonderivative couplings that derive from the QCD anomaly. The derivative couplings may include flavor changing effects. The effects that produce a nonzero $\bar{\theta}$ and a long range force between baryons are included in the model independent nonderivative couplings.

– couplings to matter are inherently model-dependent

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

no hat

$$k_{L,R} = \begin{pmatrix} k_{11} & 0 & 0 \\ 0 & k_{22} & k_{23} \\ 0 & k_{32} & k_{33} \end{pmatrix}_{L,R}$$

No fundamental reason why k_{ij} w/ i or $j = 3$ should be negligible

Astro probes

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

QCD-axion's couplings to lab-produced matter generally $\underline{\underline{\underline{\text{tiny}}}}$

— Dense and hot enough objects may radiate axions and thereby cool down faster than expected from established mechanisms

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

SNe and axions

- The ν burst associated to SN 1987 A strongly constrains exotic sources of cooling

$\longrightarrow$ Raffelt bound $\quad Q_a \lesssim Q_\nu \quad$ [See Raffelt's Phys. Rept.]

(power radiated in axions) / volume

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

- calculable within assumptions
  - p_i^*, E_i^*, m_i^* $\longleftarrow$ in-medium effects
  - distr. functions not obvious away from ideal-gas assumption

SNe and axions

– The ν burst associated to SN 1987 A strongly constrains exotic sources of cooling

→ Raffelt bound $\quad Q_a \lesssim Q_\nu \quad$ [See Raffelt's Phys. Rept.]

estimated from $L_\nu / M_{SN\,core}$ w/

- $L_\nu \approx 3 \cdot 10^{52}$ erg/sec
- $M_{SN\,core} \sim 1 M_\odot$

$$\left[L_\nu \sim \frac{1}{2} \cdot \underbrace{\begin{pmatrix}\text{Newtonian}\\ \text{binding energy}\end{pmatrix}}_{\simeq\, 3\cdot 10^{53}\ \text{erg}} \frac{1}{\Delta t} \right]$$

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

Axions from SNe : $N_1 N_2 \to N_3 N_4 a$

Most reliable bound obtained from nucleon axionstrahlung

$N_1 N_2 \to N_3 N_4 a$ [see discussion in Caputo - Raffelt, 2024]

- "Reliable" requires taking into account many effects

$m_\pi \neq 0$ & ρ exchange & in-medium m_N & N multiple scatterings [Carenza, Fischer et al., 2019]

- Parametrisation must also comply with copious data on NN' scattering [Ericson, Mathiot, 1989]

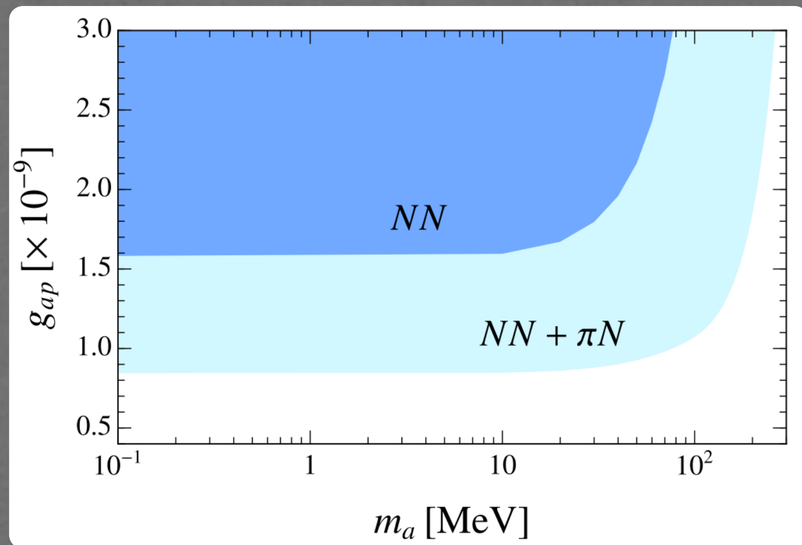
Axions from SNe : $\pi N_1 \to N_2 a$

Recent literature suggests that Compton-like $\pi N_1 \to N_2 a$ processes may even dominate axion emission

[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

[Lella et al., 2022]

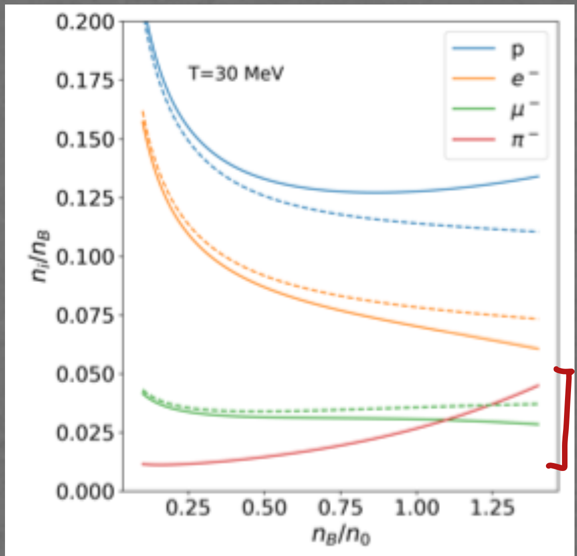


$\pi N_1 \to N_2 a$: underlying argument [Fore-Reddy, 2019]

- n-rich, dense stellar matter $\Rightarrow$ high n_{e^-}
  $\Rightarrow$ sources other like-charged particles $\Rightarrow$ π^- interesting as it interacts strongly

- for high T (5-50 MeV), low ρ ($\lesssim 3 \times 10^{14}$ g/cm³)
  $\Rightarrow$ population of thermal π

- Use virial expansion to calculate thermodyn. properties of interacting gases, if fugacities small : $z_i = \exp \beta(\mu_i - m_i) \ll 1$



$n_{\pi^-} \sim 10^{-2}$, large enough to enhance $\pi N_1 \to N_2 a$ [Carenza et al., 2020]

— $Q_a(\pi N_1 \to N_2\, a)$ critically depends on the actual n_{π^-} value which is difficult to pin down with high confidence

[see discussion in Caputo–Raffelt]

A further layer of complexity

is the possible role

of beyond-1^{st}-generation matter

What we do in short

- We consider the full meson & baryon octets
- And calculate all $B_i\, M \to B_f\, a$ (134 procs) & $B_i \to B_f\, a$ (9 procs) contributions to Q_a

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

positive definite

$\Longrightarrow$ Even if $Y_{B_i, B_f, M} \lesssim 10^{-2}$, the large number of processes yields a relevant constraint

Main findings in short

— The Raffelt bound on

$$\sum_{i,f,M} Q_a(B_i\, M \to B_f\, a) + \sum_{i,f} Q_a(B_i \to B_f\, a)$$

introduces :

- new correlations between flavor-diagonal axial couplings $(k_A)_{11,\,22,\,33}$

- a new bound on the off-diagonal, flavor-violating counterpart $(k_A)_{23}$

$\boxed{\text{This bound} \sim 10^{-1} \div 10^{-2} \text{ for } f_a = 10^9 \text{ GeV}}$

(Axions from SNe : still many TODOs (luckily !))

Subject in rapid development

- More hydrodynamical modeling required, e.g.
  - axion transport, like neutrinos
  - possible departures from spherical sym
  - axion-emitting SN volume often modeled as an object w/ one T everywhere. Can one do better?

  will be back on these points

- ...

Setup

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

Ideally :

- local values of these pars. obtainable [Bruenn, 1985]

  by solving the EoS

  (E-mom & n_B & n_e , coupled to ν transport)

- axions should enter here

  (especially if they provide $O(1)$ corrections to ν-induced cooling)

[Fischer et al., 2021; Mori et al., 2022-2023; Betranhandy + O'Connor, 2022]

Our approach

- 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
  - $n_B = \{1, 1.5\}\, n_{sat}$ $\quad \left(n_{sat} = 1.6 \cdot 10^{38} / \mathrm{cm}^3 \right)$
  - 2 EoS ("DD2Y" vs "SFHoY") w/ somewhat different strange-matter densities

[M. Fortin et al., 2017 ; M. Marques et al., 2017]

Modeling of fundamental axion – matter couplings

[Georgi – Kaplan – Randall, 1986]

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

$$\& \quad \gamma^\mu_{R,L} = \gamma^\mu P_{R,L}$$

$\mu \gtrsim \Lambda_{QCD}$

from QCD to

ChPT + 1 axion

$\mu \lesssim \Lambda_{QCD}$

$$\mathcal{L}_{aUB} = \frac{\partial_\mu a}{f_a} \sum_{b=1}^{8} \left(x^b_L\, J^{b\mu}_L + x^b_R\, J^{b\mu}_R \right)$$

octet-meson field

octet-baryon field

$$\text{w/} \quad x^b_{L,R}(a) \equiv \mathrm{Tr}\left(\hat{k}_{L,R}(a)\, \lambda^b\right)$$

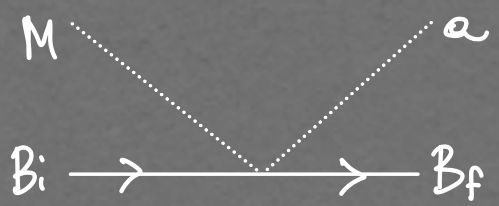
projections of the k couplings along the octet dirs.

- $$\mathcal{L}_{aUB} = \frac{\partial_\mu a}{f_a} \sum_{b=1}^{8} \left(X_L^b \, J_L^{b\mu} + X_R^b \, J_R^{b\mu} \right)$$

Noether currents of the global $SU(3)_L \times SU(3)_R$ chiral sym. applied to the ChPT + 1 axion Lagrangian

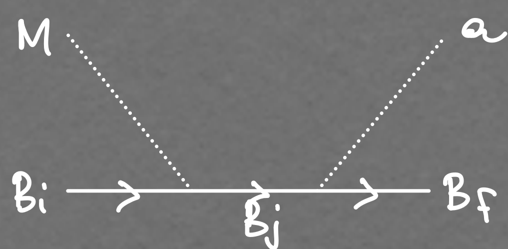
$$J_{L,R}^{b\mu} = J_{L,R}^{b\mu}(U, B)$$

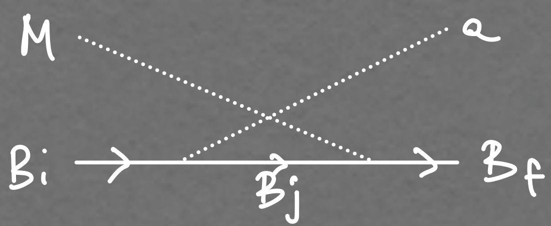
• $J^{b\mu}_{L,R} = J^{b\mu}_{L,R}(U, B)$ yield the following interactions



fully local vertex

[first included (for nucleons) in Choi et al. 2021]

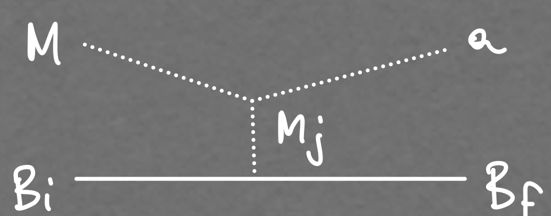




axion-strahlung

from the full baryon octet

[considered (for nucleons) in Chang-Choi, 93 & ensuing literature]



axion-strahlung

from the meson octet

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

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

real by hermiticity

one complex number

- $(k_V)_{ii}$ unobservable aside from weak-interaction contribs (which are suppressed by $\sim G_F f_\pi^2 \sim 10^{-7}$) [Bauer et al., 2021]

- $|(k_V)_{23}|$: Q_2 bound less stringent than $\Gamma(K \to \pi a)$

- $\arg\,(k_{V,A})_{23}$: Q_2 bound not constraining

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

- $(k_A)_{ii}$ bounds

$(k_A)_{11,22}$ bounded from data on isolated-NS cooling [Buschmann et al., 2021]

$(k_A)_{33}$ genuinely bounded by SNe.

Since $Q_a \propto$ (well-defined linear combi's of $(k_A)_{ii=11,22,33}$ $)^2$ we find that Q_a "transfers" the $(k_A)_{11,22}$ NS bounds to $(k_A)_{33}$

- $(\kappa_A)_{23}$ bounds from K physics ("K bounds")

[Martin-Camalich et al., 2020]

$(\kappa_{V,A})_{23}$ both constrained by

$K \to \pi a$ → constrains $|(\kappa_V)_{23}|$ only

&

$K^0 - \bar{K}^0$ mixing → constrains jointly $(\kappa_V)_{23}$ & $(\kappa_A)_{23}$

(both in abs & arg)

- We take (abs & arg)'s randomly, and filter them with K bounds before subjecting them to Q_a

∘ ($K - \bar{K}$ mixing means :)

$= \Delta m_K \equiv m_{K_L} - m_{K_S}$

$= \epsilon_K \equiv$

"indirect" CP violation (as opposed to "direct" i.e. in K decays)

i.e. mixing-induced

follows from K_L, K_S <u>not</u> being CP eigenstates

- We find that Q_a is more constraining on $|(K_A)_{23}|$ than K bounds, for the QCD axion already (i.e. for $f_a \sim 10^9$ GeV & $m_a \ll \min(m_{B_i}, m_{B_f}, m_M)$)

$\Rightarrow$ Useful to test Q_a's constraining power on $(k_A)_{ij}$ against different (motivated) approaches to modeling these couplings.

Approaches to modeling the κ couplings

- S_{ag} : "agnostic scenario"

No TH assumption whatsoever on any of the κ_{ij}.

Constrain them from data only (NSs , K bounds, Q_a)

- S_{fl} : minimal QCD-axion solution to flavour problem

[Ema et al. & Calibbi et al., 2016]

Bottom line result:

$$|(\kappa_A)_{ii}| \leq O(1) \quad ; \quad |(\kappa_A)_{23}| \leq 0.2 \cdot O(1)$$

Cabibbo angle

S_{fe}: more details

- Start with the axion – fermion Lagr. in the form

$$\mathcal{L}_{aff} \supset \lambda^f_{ij}\, a\, \bar{f}_{R_j} f_{L_i} + h.c. \qquad (f = u, d)$$

- Solution to the flavor problem achieved by a complex Φ spont. breaking $U(1)_{PQ}$ at very high scale, yielding

$$\langle \Phi \rangle = \frac{V_\Phi}{\sqrt{2}} = \sqrt{2}\, N f_a \qquad \left(w/\ N = \sum_i \left(2[q]_i + [u]_i + [d]_i\right)/2 \right)$$

$$\Longrightarrow \left(\lambda^{u,d}\right)_{ij} = i\left([q]_i + [u,d]_j\right) \frac{v}{V_\Phi} \left(y^{u,d}\right)_{ij}$$

- Match the $\lambda^{u,d}$ couplings to our $K_{L,R}$ ones paying attention that

  — K couplings are derivative ; λ couplings are not

  — ij indices count generations for $\lambda^{u,d}$ couplings and light quarks for K couplings

$\Downarrow$

$$\lambda^{u,d} \propto \frac{QNs}{N} \cdot \frac{m^{u,d}}{f_a} \cdot (V_{CKM}) \quad \xleftrightarrow{\text{matching}} \quad K \cdot \frac{m_q}{f_a}$$

sum of all quark q.n.'s

cancel in the matching

$$\Rightarrow (K)_{ii} = \frac{\text{subset of quark QNs under } U(1)_{PQ}}{\text{sum total of quark QNs under } U(1)_{PQ}} \leq O(1)$$

$$\underbrace{(K)_{23}}_{\text{down - strange}} = \text{similar ratio} \cdot \underbrace{(V_{CKM})_{12}}_{\text{Cabibbo angle}} \leq 0.2 \cdot O(1)$$

1^{st} - 2^{nd} gen

- A third plausible scenario: KSVZ / DFSZ + MFV

  - KSVZ or DFSZ models allow to fix $(k_A)_{11,22,33}$ at $\mu \sim 1$ GeV as

$$(k_A)_{11,22,33} \sim \begin{matrix} \mathcal{O}(10^{-2}) & (\text{KSVZ}) \\ \mathcal{O}(10^{-1}) & (\text{DFSZ}) \end{matrix}$$

[see Choi et al., 2021]

  - The minimal, radiatively induced, flavor violation yields

- $$(k_L)_{23} \sim \frac{(V_{CKM})^*_{31}\,(V_{CKM})_{32}}{16\pi^2} \times \text{logs}\,(\text{ratio of UV scales})$$
  $$\sim 10^{-6}$$

- $(k_R)_{23}$ not generated by def

⇒ The Q_2 constraint is trivially fulfilled within such scenario

⇒ In the numerical study, it is sufficient to restrict to S_{ag} & S_{fe}

Our conclusions hold irrespective of this choice

Results

But first a qualification.

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

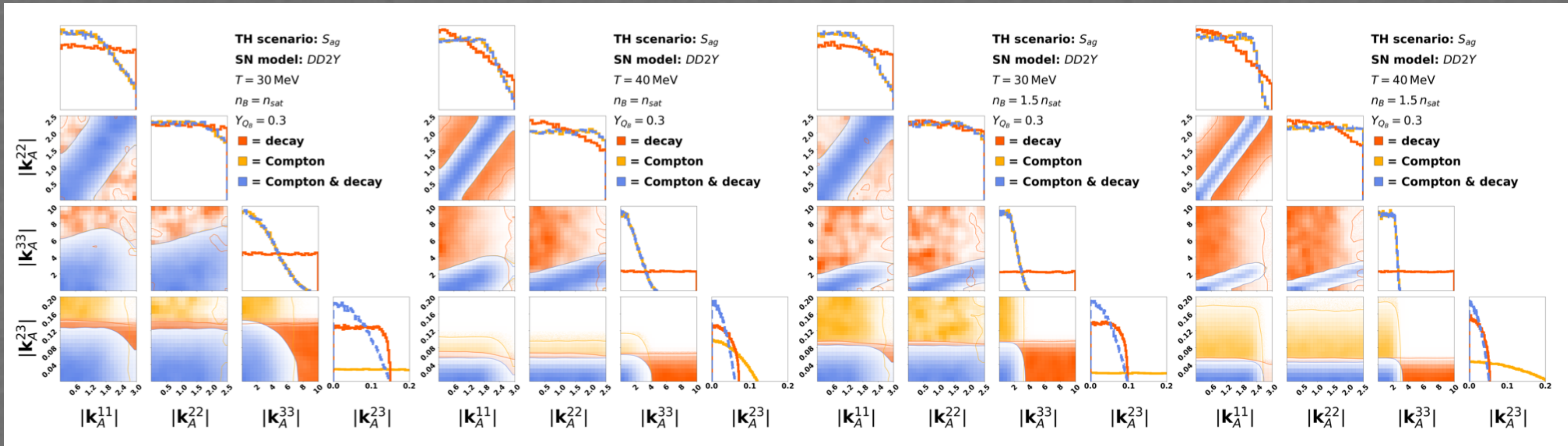
w/ vacuum E_i & m_i means treating the involved particles as ideal gases

– In-medium effects may be estimated at mean-field

[Martinez-Pinedo et al., 2012; Roberts et al., 2012; Reddy et al., 1998; Oertel et al., 2020]

mean-field interaction potential:
determined from the EoS, i.e. the underlying nucl. int's

$m_j \to m_j^*$; $\mu_j \to \mu_j^* = \mu_j - U_j$; $E_j \to E_j^*$



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

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

– $(k_A)_{33}$ bound dominated by Compton

(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

- Both findings (a) & (b) (diag. correlations & off-diag bound) sharper as n_B increases or as Y_{Q_B} decreases } hyperon phase-space increases

TABLE II: Q_a bounds on $|(\boldsymbol{k}_A)_{23,33}|$ according to the theory scenario (in parentheses) and the SN model. Bounds assume $f_a = 10^9$ GeV. The larger (smaller) value quoted in each table entry refers to DD2Y (SFHoY).

$\boldsymbol{k}$ coupling (scenario)	$n_B = n_{\rm sat}$ 30 MeV	$n_B = n_{\rm sat}$ 40 MeV	$n_B = 1.5\,n_{\rm sat}$ 30 MeV	$n_B = 1.5\,n_{\rm sat}$ 40 MeV
$\lvert(\boldsymbol{k}_A)_{23}\rvert$ ($\mathsf{S}_{\rm ag,f1}$)	$\overset{0.35}{0.15}$	$\overset{0.12}{0.061}$	$\overset{0.38}{0.097}$	$\overset{0.14}{0.052}$
$\lvert(\boldsymbol{k}_A)_{33}\rvert$ ($\mathsf{S}_{\rm ag}$)	$\overset{8.8}{8.9}$	$\overset{4.4}{4.8}$	$\overset{5.9}{3.9}$	$\overset{3.1}{2.9}$

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

- Noteworthy that DD2Y (with which we reproduce Carenza et al. in their setup) leads to tighter bounds than SFHoY.

Outlook

- SNe (and other compact astro objects) powerful probes of fundamental & solidly motivated BSM, such as QCD axions.

- 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.