Supernova limits on a light CP-even scalar and implications for the KOTO anomaly

Yongchao Zhang

Washington University in St. Louis
yongchao.zhang@physics.wustl.edu

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based on
P. S. B. Dev, R. N. Mohapatra & YCZ, PRD**101**, 075014 [1911.12334]
P. S. B. Dev, R. N. Mohapatra & YCZ, 2005.00490

Supernova limits on light particles

- Supernovae provide a unique environment to produce copiously light hypothetical particles:
  - axion/ALP [Iwamoto '84; Pantziris & Kang '86; Turner '88; Raffelt & Seckel, '88; Mayle, Wilson, Ellis, Olive, Schramm & Steigman '88; Brinkmann & Turner '88; Burrows, Turner & Brinkmann '89; more recent papers...]
  - dark photon [Bjorken, Essig, Schuster, & Toro '09; Dent, Ferrer & Krauss '12; Kazanas, Mohapatra, Nussinov, Teplitz & YCZ '14; ...]
  - sterile neutrino [Kainulainen, Maalampi & Peltoniemi '91; Kuflik, McDermott & Zurek '12...]
  - compact extra dimensions [Hanhart, Phillips, Reddy & Savage '00; Hanhart, Pons, Phillips & Reddy '01...]
  - CP-even scalar [Ishizuka & Yoshimura '90; Diener & Burgess '13; Krnjaic '15; Lee '18; Arndt & Fox (saxion) '02]
- Raffelt criterion: the energy loss due to these exotic particles can not exceed that from neutrino emission [Raffelt criterion '96].

Supernova limits on light CP-even scalar S

- Very limited supernova limits in the literature on light CP-even scalar (compared to axion/ALP & dark photon)

- Motivations:
  - natural DM candidate [Silveira & Zee '85; McDonald '94; Burgess, Pospelov & ter Veldhuis '00; Cline, Kainulainen, Scott & Weniger '13]
  - dark force mediator [Pospelov, Ritz & Voloshin '07; Kainulainen, Tuominen & Vaskonen '15; Bell, Busoni Sanderson '16; Knapen, Lin & Zurek '17; Matsumoto, Tsai & Tseng '18; Batell, Freitas, Ismail & Mckeen '18]
  - baryogenesis [Espinosa & Quiros '93; Profumo, Ramsey-Musolf & Shaughnessy '07; Espinosa, Konstandin & Riva '11; Croon, Howard, Ipek & Tait '19]
  - KOTO anomaly in $K_L \to \pi^0 \nu \bar{\nu}$ [Kitahara, Okui, Perez, Soreq & Tobioka '19 PRL; Egana-Ugrinovic, Homiller, and Meade '19; Dev, Mohapatra & YCZ '19 PRD; Liu, McGinnis, Wagner & Wang '20; Cline, Puel & Toma, '20]

Production of S in supernova core

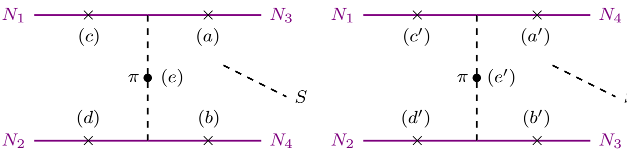


Figure: $N + N + S \to N + N$

- The couplings of S to SM particles are all from mixing with the SM Higgs.
- Two contributions: SNN coupling + $S\pi\pi$ coupling

$$\mathcal{L} \;=\; \sin\theta S \left[y_{hNN} \overline{N} N + A_\pi (\pi^0\pi^0 + \pi^+\pi^-) \right] \,,$$

$$y_{hNN} \sim 10^{-3} \,, \quad \mathcal{A}_\pi \;=\; \frac{2}{9 v_{\rm EW}} \left(m_S^2 + \frac{11}{2} m_\pi^2 \right) \sim 10^{-3} m_\pi \,,$$

- Neglecting the contributions from Se^+e^- and $S\gamma\gamma$ couplings, which are both very small.

Emission rate of S

Energy emission rate per unit volume in the supernova core:

$$Q = \int \mathrm{d}\Pi_5 \mathcal{S} \sum_{\rm spins} |\mathcal{M}|^2 (2\pi)^4 \delta^4 (p_1 + p_2 - p_3 - p_4 - k_S) E_S f_1 f_2 P_{\rm decay} P_{\rm abs} \,,$$

- $\mathrm{d}\Pi_5$: 5-body phase space
- $\mathcal{S}$: symmetry factor for (non-)identical particles
- $f(\mathbf{p})$: non-relativistic Maxwell-Boltzmann distribution
- $P_{\rm decay} = \exp\{-R_c \Gamma_S\}$: decay factor,
- $P_{\rm abs} = \exp\{-R_c/\lambda\}$: re-absorption factor due to $N + N + S \to N + N$ [λ : mean free path (MFP)]

Cancellation at the leading order

- To the LO of $m_S^2/m_N E_S$:

$$\begin{aligned} \mathcal{M}_a + \mathcal{M}_b + \mathcal{M}_c + \mathcal{M}_d &\simeq 0\,, \\ \mathcal{M}_{a'} + \mathcal{M}_{b'} + \mathcal{M}_{c'} + \mathcal{M}_{d'} &\simeq 0\,. \end{aligned}$$

- Expand to the NLO of $m_S^2/m_N E_S$:

$$\frac{1}{(p_i \pm k_S)^2 - m_N^2} \simeq \frac{1}{\pm 2 m_N E_S + m_S^2} \simeq \frac{1}{\pm 2 m_N E_S}\left[1 \mp \frac{m_S^2}{2 m_N E_S}\right]$$

- The contributions of the *SNN* diagrams to production rate will be suppressed by the ratio of $(m_S/E_S)^4$ in the limit of small m_S.

Comparison of different contributions

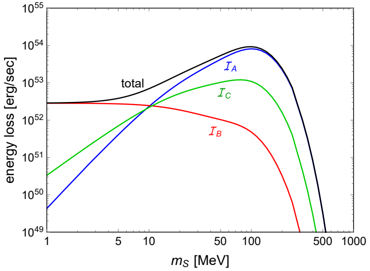


Figure: $T = 30$ MeV, $n_B = 1.2 \times 10^{38}\ \mathrm{cm}^{-3}$, $\sin\theta = 10^{-6}$

- $\mathcal{I}_A$: SNN diagrams:

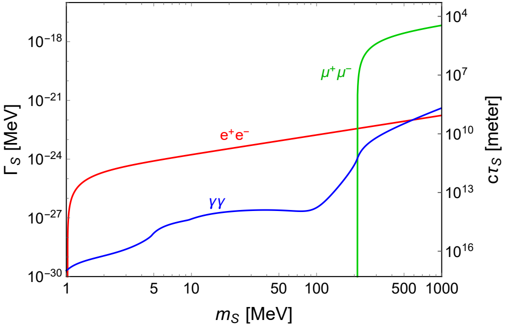
$$\propto y_{hNN}^2 \left(\frac{m_S}{E_S}\right)^4 \Longleftarrow \quad \text{cancellation}$$

- $\mathcal{I}_B$: $S\pi\pi$ diagrams:

$$\propto \left(\frac{m_N}{v_{\rm EW}}\right)^2 \left[\left(\frac{m_S}{T}\right)^2 \left(\frac{T}{m_N}\right) + \frac{11}{2}\frac{m_\pi^2}{m_N T}\right]^2$$

- $\mathcal{I}_C$: always in between $\mathcal{I}_A$ and $\mathcal{I}_B$.

Decay of S



- S decays mostly into e^+e^- or $\mu^+\mu^-$ (for $m_S \gtrsim 2m_\mu$)
- Not include $S \to \pi^+\pi^-$, $\pi^0\pi^0$ as S decays so fast for $m_S \gtrsim 2m_\pi$ that it can not escape from the core.

Re-absorption of S

- Re-absorption of S via the process

$$N + N + S \to N + N$$

- Inverse MFP [Giannotti & Nesti '05; Burrows, Ressell & Turner '90]:

$$\begin{aligned}\lambda^{-1}(E_S) &\equiv \frac{1}{2E_S}\frac{d\mathcal{N}_S(-k_S)}{d\Pi_S} \\ &= \frac{1}{2E_S}\int \mathrm{d}\Pi_4 \mathcal{S} \sum_{\text{spins}} |\mathcal{M}'|^2 (2\pi)^4 \delta^4(p_1 + p_2 - p_3 - p_4 + k_S) f_1 f_2 \,,\end{aligned}$$

- Effective energy-independent inverse MFP [Ishizuka & Yoshimura '90]:

$$\langle \lambda^{-1} \rangle \equiv \frac{\int \mathrm{d}E_S \frac{E_S^3}{e^{E_S/T}-1}\lambda^{-1}(E_S)}{\int \mathrm{d}E_S \frac{E_S^3}{e^{E_S/T}-1}} = \frac{\int \mathrm{d}x \frac{x^3}{e^x-1}\lambda^{-1}(x)}{\int \mathrm{d}x \frac{x^3}{e^x-1}} \,.$$

MFP of S

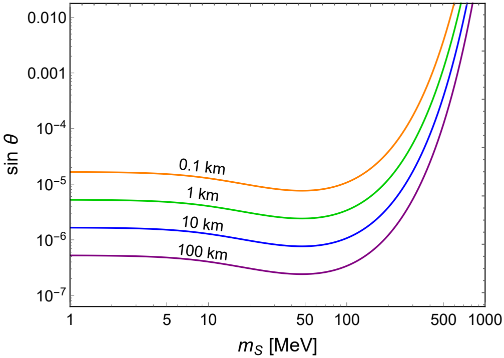


Figure: $T = 30$ MeV, $n_B = 1.2 \times 10^{38}\ \mathrm{cm}^{-3}$

Supernova luminosity limits on S

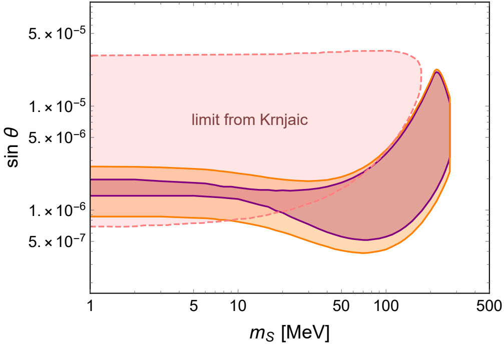
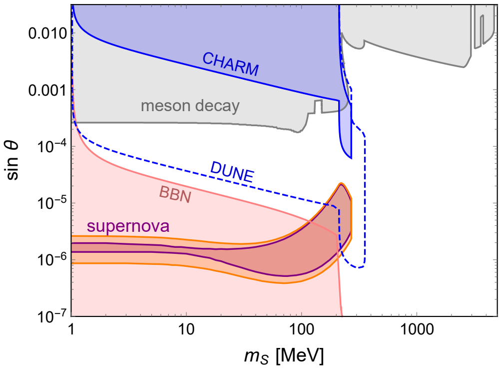


Figure: $T = 30$ MeV, $n_B = 1.2 \times 10^{38}\ \mathrm{cm}^{-3}$, $R_c = 10$ km

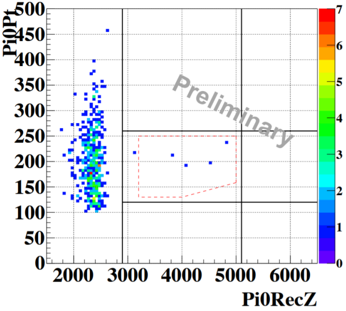
- Purple (orange) regions: luminosity limit of $5\,(3) \times 10^{53}$ erg/sec;
- Limit from Krnjaic ['15]: not consider the cancellation & the $S\pi\pi$ diagrams;
- The supernova limits can be improved at IceCube-DeepCore, Hype-K & DUNE;
- More limits from neutron star mergers [Harris, Fortin, Sinha & Alford '20]

Complementarity to other limits



- Meson decay: FCNC decays $K \to \pi + X$, $B \to K(\pi) + X$, with $X = ee,\ \mu\mu,\ \gamma\gamma$, missing energy;
- DUNE could probe the supernova excluded regions $m_S \gtrsim 100$ MeV [Berryman, de Gouvêa, Fox, Kayser, Kelly & Raaf '19; Dev, Mohapatra & YCZ '19 PRD].

"KOTO anomaly"



- The SM prediction:

$$\mathrm{BR}(K_L \to \pi^0 \nu\bar{\nu})_{\mathrm{SM}} = \left(3.4 \pm 0.6\right) \times 10^{-11}$$

- 3 "signal events" are observed at KOTO: [Kitahara, Okui, Perez, Soreq & Tobioka '19 PRL]

$$\mathrm{BR}(K_L \to \pi^0 \nu\bar{\nu})_{\mathrm{KOTO}} = 2.1^{+2.0(+4.1)}_{-1.1(-1.7)} \times 10^{-9}$$

CAUTION [Shinohara, Talk given at KAON2019]:

The 3 events are beyond the reasonable expectation. The KOTO collaboration is checking the events, detector status, and background estimations.
The KOTO collaboration did **NOT** claim the observed events as signals, or give any numbers on the branching ratio or physics results.

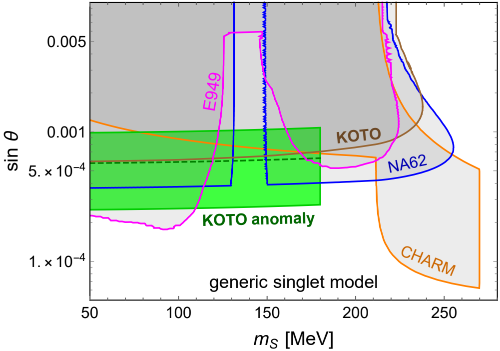
If the 3 events are a signal of BSM...

- heavy mediators (effective operators)
- long-lived light mediators or dark particles
- light mediator decaying off-axis into photons
- ....

Kitahara, Okui, Perez, Soreq & Tobioka '19 PRL; Egana-Ugrinovic, Homiller, and Meade '19; Dev, Mohapatra & YCZ '19 PRD; Fabbrichesi† & Gabrielli '19; Liu, McGinnis, Wagner & Wang '20; Cline, Puel & Toma '20; Jho, Lee, Park, Park & Tseng '20; Camalich, Pospelov, Vuong, Ziegler & Zupan '20; He, Ma, Tandean, Valencia '20; Ziegler, Zupan, Zwicky '20

[see also the talks by J. Liu, S. Homiller & B. Lehmann]

One simplest explanation: light long-lived scalar S



- Limits from (LLP = long-lived particle):

$$\texttt{E949}\,['09] : K^+ \to \pi^+ + \text{LLP}\,, \quad \texttt{NA62}\,['19] : K^+ \to \pi^+\nu\bar{\nu}\,,$$
$$\texttt{KOTO}\,['18] : K_L \to \pi^0\nu\bar{\nu}\,, \quad \texttt{CHARM}\,['85] : K \to \pi + \text{LLP}$$

- The supernova limits are roughly two orders of magnitude lower than the KOTO signal region.

Conclusion

- We have performed the first full calculation of supernova limits on the light CP-even scalar S.
- Different from the axion/ALP and dark photon cases, there is a cancellation for the production of S.
- We have taken into consideration the decay and re-absorption of S in the supernova core.
- Depending on the scalar mass up to the $2m_\pi$, the mixing angle of S with the SM Higgs is excluded in the range of 3.5×10^{-7} to 2.5×10^{-5}.
- The light scalar S is a good explanation for the "KOTO anomaly".

Thank you very much!