Stellar limits on a light scalar

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based on

Dev, Mohapatra & YCZ, JCAP**05**(2021)014 [2010.01124]
Dev, Mohapatra & YCZ, JCAP**08**(2020)003 [2005.00490]
Dev, Fortin, Harris, Sinha & YCZ, 210x.abcde
Balaji, Dev & YCZ, 21yy.abcde

Multimessage universe: Light particles in the stars

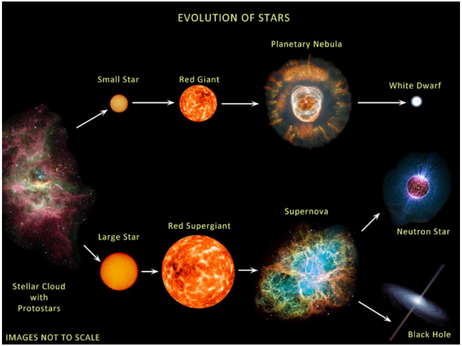


Figure: Basic stellar evolution

- High stellar density (in the core);
- Unique environment to produce copiously light (BSM) particles;
- Raffelt criterion: the energy loss due to new particles can not exceed that observed from photon/neutrino emission [Raffelt '96];
- One of the multi-messengers to probe the stars:
  complementary to detection of neutrinos/GRs/GWs in some cases...

Why light CP-even scalar?

Some hypothetical light particles:

- axion, axion-like particle (ALP);
- Majoron: couplings to neutrinos (and other fermions);
- dark photon, Z' boson;
- CP-even scalar S: dilaton, saxion (from supersymmetric theorey)...
- light sterile neutrino
- ...

Couplings of S:

- from mixing with SM Higgs ($\sin\theta$);
- leptonic scalar.

Production of S in supernova core: $T \sim \mathcal{O}(10\,\mathrm{MeV})$

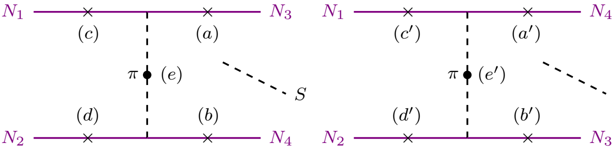


Figure: $N + N + S \to N + N$

- Two contributions: SNN coupling + $S\pi\pi$ coupling

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

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

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.
- Including all high order terms will reduce the $a^{(\prime)}$ through $d^{(\prime)}$ diagram amplitudes by a factor of $1/2$ [Dev, Fortin, Harris, Sinha & YCZ, 210x.abcde].

Comparison of different contributions

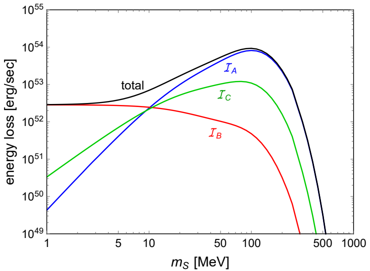


Figure: $T = 30$ MeV, $n_B = 1.2 \times 10^{38}\ \mathrm{cm}^{-3}$, $\sin\theta = 10^{-6}$

- $\mathcal{I}_A$: 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 & re-absoprtion of S

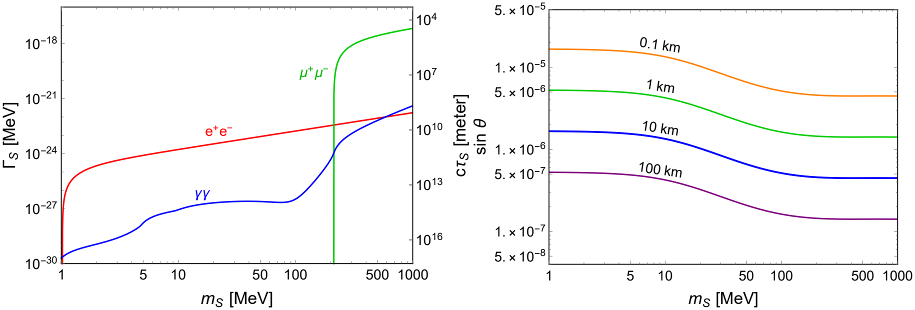


Figure: $T = 30$ MeV, $n_B = 1.2 \times 10^{38}\ \mathrm{cm}^{-3}$

- S decays mostly into e^+e^- or $\mu^+\mu^-$ (for $m_S \gtrsim 2m_\mu$)
- Re-absorption of S via the process $\Rightarrow$ MFP of S

$$N + N + S \rightarrow N + N$$

Supernova luminosity limits on S

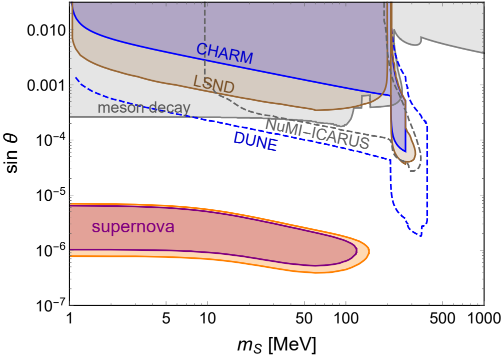
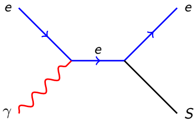


Figure: $T = 30$ MeV, $n_B = 1.2 \times 10^{38}\ \mathrm{cm}^{-3}$, $R_c = 10$ km

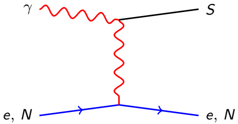
- Purple (orange) regions: luminosity limit of $5\,(3) \times 10^{53}$ erg/sec;
- Meson decay: FCNC decays $K \to \pi + X$, $B \to K(\pi) + X$, with $X = ee$, $\mu\mu$, $\gamma\gamma$, missing energy;
- The supernova limits can be improved at JUNO, DUNE, IceCube-DeepCore & Hype-Kamiokande.

Production channels of S in the $T \sim$ keV stars

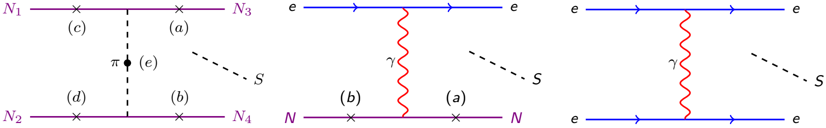
- Compton-like process



- Primakoff-like process

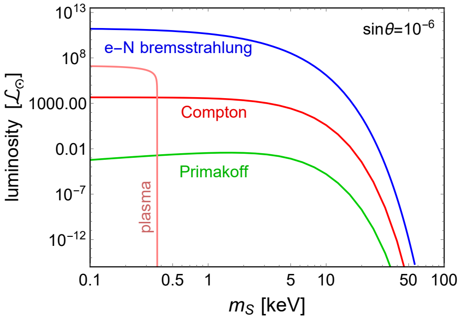


- Breamsstrahlung processes



- Plasma effect: For $m_S \lesssim w_p \simeq \sqrt{n_e e^2/m_e} < T$, S can be produced resonantly from mixing with longitudinal mode of photon [Hardy & Lasenby, JHEP 02(2017)033 [1611.05852]].

Comparison of these channels



- $e - N$ bremsstrahlung: $y_N \sim 10^{-3}$;
- Compton: $y_e \sim 10^{-6}$;
- Primakoff: suppressed by loop-level $S\gamma\gamma$ coupling;
- Plasma: $\propto y_e^2$, suppressed by small Yukawa coupling

Comparing the bremsstrahlung channels

$e - N$ brem vs. π-mediated $N - N$ brem (γ-mediated even smaller)

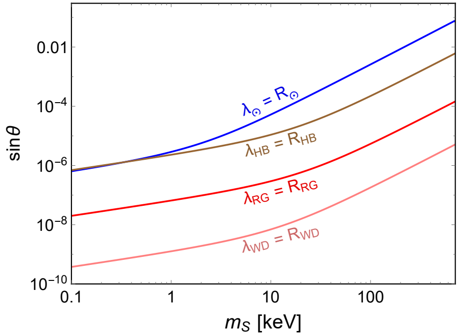
$$\frac{Q_{\rm B}^{(NN)}}{Q_{\rm B}^{(eN)}} \sim \frac{(2m_N/m_\pi)^4 A_N^4 f_{pp}^4}{e^4} \frac{m_e^2}{m_N^2} \frac{T^4}{m_\pi^4} \frac{m_S^2}{m_N^2} \ll 1\,.$$

- First factor: couplings;
- m_e^2/m_N^2: phase space;
- T^4/m_π^4: propagators;
- m_S^2/m_N^2: cancellation effect for $N - N$ brem process.

Dominant production channel: $e - N$ bremsstrahlung process!

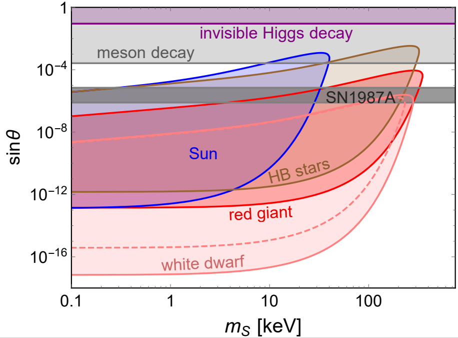
$$Q_{\rm B}^{(eN)} \simeq \left(\sum_i Z_{N_i}^2 A_{N_i}^2 n_{N_i} \right) \frac{\alpha^2 y_N^2 \sin^2\theta\, T^{1/2} n_e}{\pi^{3/2} m_e^{3/2}} \times \mathcal{O}(1) \text{ factor}$$
$$\times P_{\rm decay} P_{\rm abs}$$

MFP of S in the stars



Star	Core composition	T [keV]	n_e [cm^{-3}]	R [cm]	$\mathcal{L}/\mathcal{L}_\odot$
Sun	75% H 25% ^{4}He	1	10^{26}	7×10^{10}	0.03
red giant (RG)	^{4}He	10	3×10^{29}	6×10^{8}	2.8
white dwarf (WD)	50% ^{12}C 50% ^{16}O	6	10^{30}	10^{9}	10^{-5} to 0.03
horizontal-branch (HB) star	^{4}He	8.6	3×10^{27}	3.6×10^{9}	5

Limits on S from Sun, RGs, WDs & HB stars



Star	Luminosity limit $[\mathcal{L}_\odot]$	$\sin\theta$ range	m_S range
Sun	0.03	$1.4 \times 10^{-13} - 1.2 \times 10^{-3}$	< 40.2 keV
red giant (RG)	2.8	$1.4 \times 10^{-13} - 9.0 \times 10^{-5}$	< 350 keV
white dwarf (WD)	0.03 10^{-5}	$3.8 \times 10^{-16} - 1.7 \times 10^{-6}$ $7.0 \times 10^{-18} - 2.5 \times 10^{-6}$	< 232 keV < 282 keV
horizontal-branch (HB) star	5	$1.5 \times 10^{-12} - 3.4 \times 10^{-3}$	< 323 keV

Neutron-star merger: $T \sim \mathcal{O}(10\,\mathrm{MeV})$

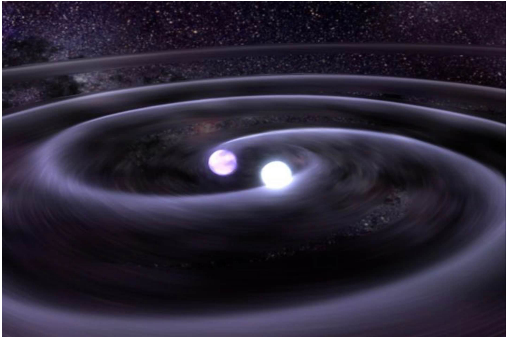
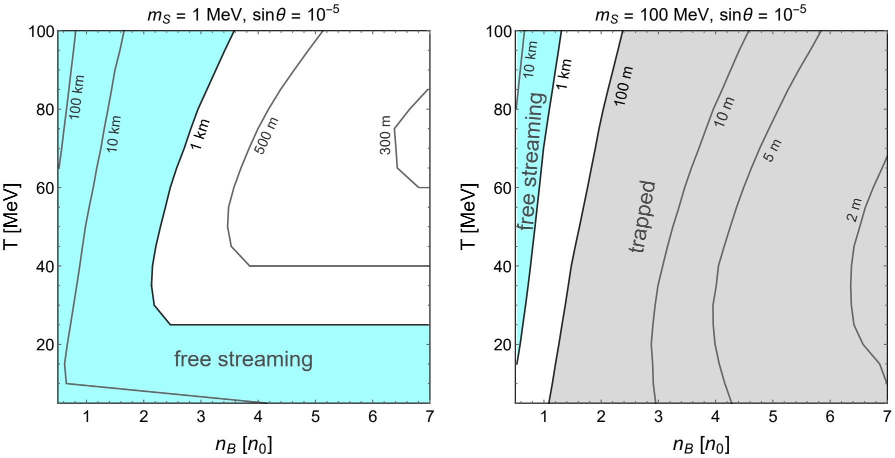


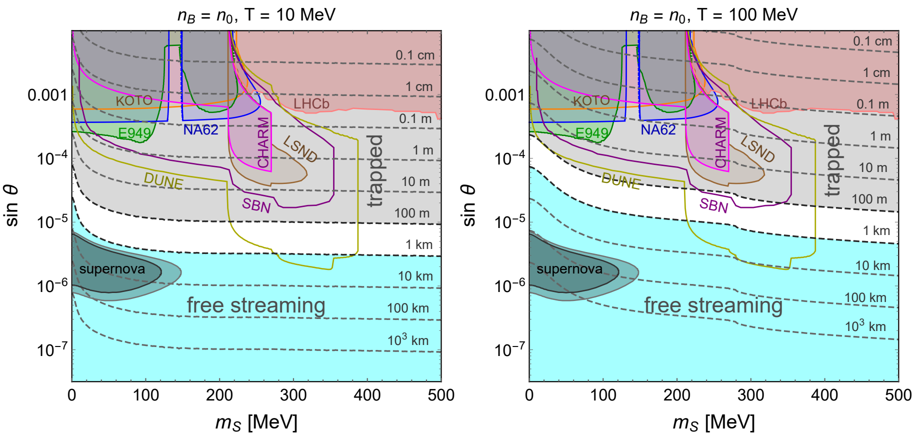
Figure: GWs from NS merger have been observed in LIGO/Virgo!

Neutron-star merger: MFP of S



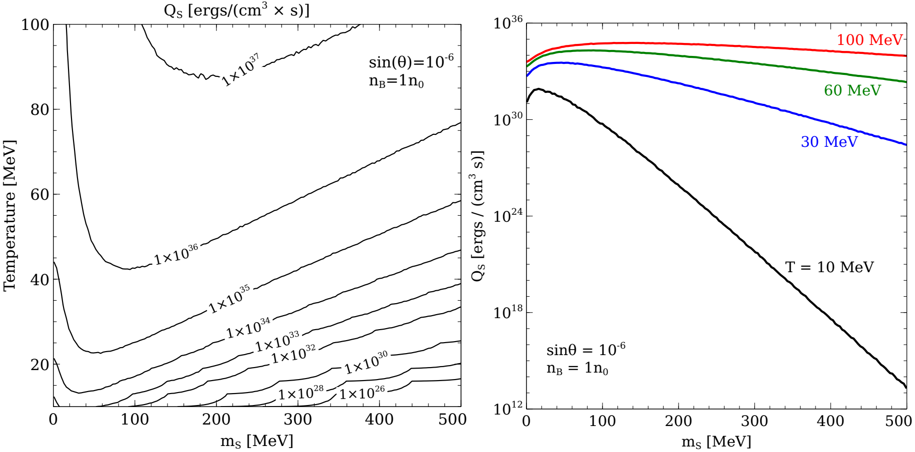
Including the nuclear EoS.

Neutron-star merger: MFP of S

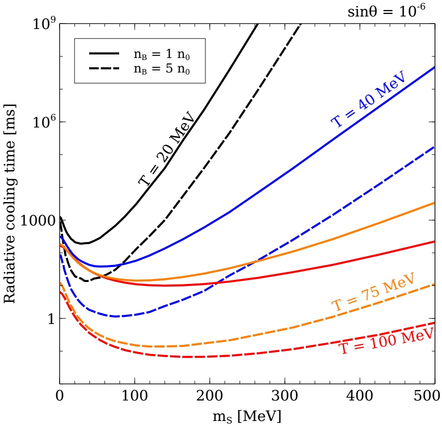


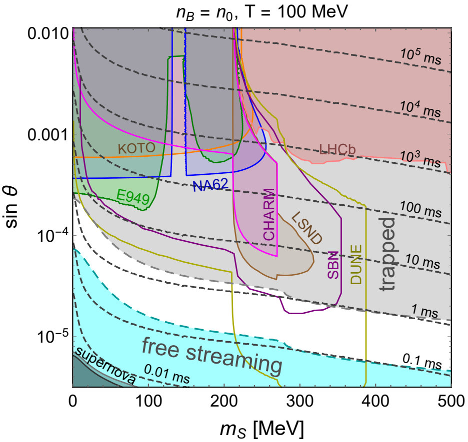
Including the nuclear EoS.

Energy emission



Cooling time





Can be compared to lifetime of NS merger remnants. [Baiotti & Rezzolla '16 Rept. Prog. Phys.; Lucca & Sagunski '20 JHEAp]

Conclusion

- Light CP-even scalars can be produced abundantly in the compact stars.
- Supernovae can exclude the parameter space of m_S up to roughly 100 MeV and mixing angle roughly 10^{-7} to 10^{-5}.
- For scalar S mixing with the SM Higgs, the $T \sim$ keV stars (Sun, red giants, white dwarf & horizontal-branch stars) can exclude a large parameter space, with m_S up to roughly 280 keV, and $\sin\theta$ down to 10^{-18}.
- Neutron star merger limits on S depend largely on stellar temperature and density (still working on it).
- These limits can be largely improved in future precision cosmological & astrophysical observations, and are largely complementary to other probes of stars such as photons & GWs.

Thank you very much!

Future prospects

Bollig, DeRocco, Graham & Janka '20 PRL; Croon, Elor, Leane & McDermott '21 JHEP

We are implementing the effects from

- supernova profiles;
- muons in supernovae and neutron stars;
- $SZ'Z'$ gauge interaction.

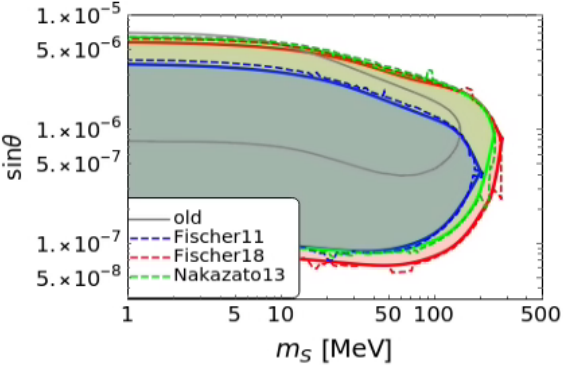


Figure: Preliminary limits on S including supernova profiles.

backup slides

Emission rate of S

Energy emission rate per unit volume in the supernova core:

[Dent, Ferrer & Krauss '12]

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

$\mathrm{d}\Pi_5$: 5-body phase space

$\mathcal{S}$: symmetry factor for (non-)identical particles

$f_{1,2}(\mathbf{p})$: non-relativistic Maxwell-Boltzmann distribution

$P_{\mathrm{decay}} = \exp\{-R_c \Gamma_S\}$: decay factor,

$P_{\mathrm{abs}} = \exp\{-R_c/\lambda\}$: re-absorption factor due to $N + N + S \to N + N$

[λ : mean free path (MFP)]

Re-absorption of S and MFP

Inverse MFP due to the process $N + N + S \to N + N$:

[Giannotti & Nesti '05; Burrows, Ressell & Turner '90]

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

$\mathcal{N}_S$:	number production rate of S per unit volume
$d\Pi_S$:	phase space of S
$\mathrm{d}\Pi_4$:	4-body phase space for N
$\mathcal{S}$:	symmetry factor for (non-)identical particles
$f_{1,2}(\mathbf{p})$:	non-relativistic Maxwell-Boltzmann distribution