Light scalars beyond the SM:
collider searches and astrophysical constraints

Yongchao Zhang

Southeast University, Nanjing, China

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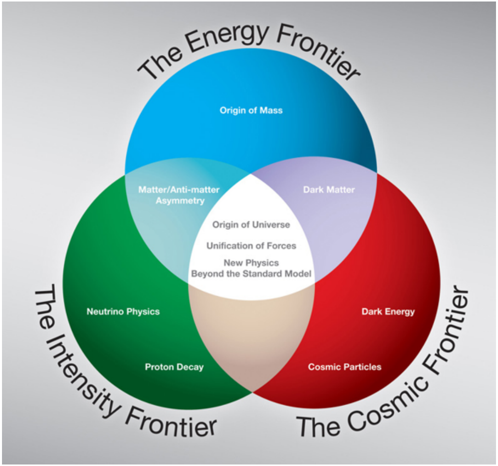
Frontiers of particle physics & cosmology



High-Energy frontier
High-Intensity frontier
Cosmic frontier

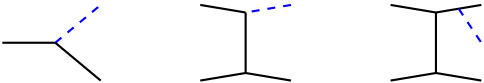
Interdisciplinary:

- particle physics
- nuclear physics
- astronomy
- astrophysics & cosmology
- engineering & industry
- applications
- economy
- ...

Productions of S from SM particles

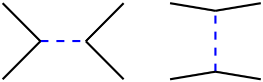
- Production from SM particle decays, scatterings, or bremsstrahlung processes

$$x \to S + y\,, \quad x + y \to x/z + S\,, \quad x + y \to x + y + S$$



- Playing the role of mediator [s- or t/u-channel]

$$x + y \to S^{(*)} \to x + y$$



See the talks of Kanazawa, Bandyopadhyay, Gabrielli & Cacciapaglia for axion/ALP (and other) searches.

Flavor signals of S

- Quark flavor violating signals
  Belanger, Ghosh, Godbole, Guchait & Sengupta '14; Herrero-Garcia, Nebot, Rajec, White & Williams '20; Altmannshofer & Zupan '22...
  - $S \to ds, sb, db, uc$
  - $t \to uS, cS$
  - $K - \bar{K}$, $B_{d,s} - \bar{B}_{d,s}$, $D - \bar{D}$ mixing
  - $B \to X_s\gamma$, $B \to K^{(*)}\gamma$
    ($K \to \pi\gamma$ forbidden by Lorentz invariance)

- Charged lepton flavor violating signals
  Hou & Wong '96; Herrero-Garcia, Rius, Santamaria '16; Dev, Mohapatra & YCZ '18; Li & Schmidt '19; Arganda, Marcano, Mileo, Morales & Szynkman '19; YCZ '22...
  - $S \to \ell_\alpha \ell_\beta$
  - $\ell_\beta \to \ell_\alpha \gamma$
  - $\ell_\delta \to \ell_\alpha \ell_\beta \ell_\gamma$
  - electron & muon $g-2$

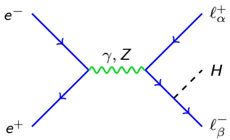
Production of H at lepton colliders

- Model-independent effective LFV couplings of H

$$\mathcal{L}_Y = h_{\alpha\beta}\bar{\ell}_{\alpha,L} H \ell_{\beta,R} + \text{H.c.}.$$

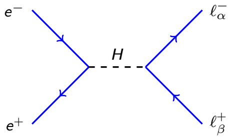
- on-shell production

$$e^+e^- \to \ell_\alpha^\pm \ell_\beta^\mp + H$$



- Off-shell production (at resonance when $m_H \simeq \sqrt{s}$)

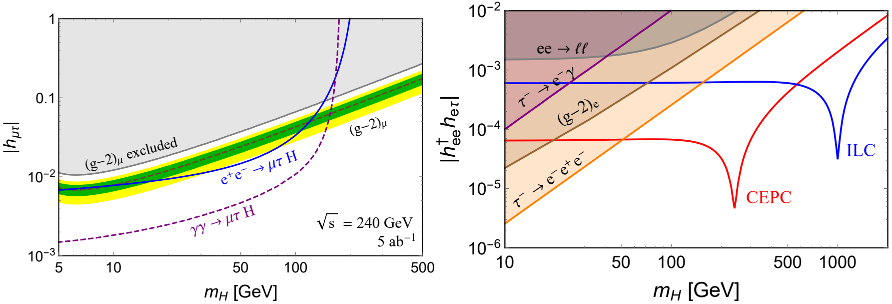
$$e^+e^- \to \ell_\alpha^\pm \ell_\beta^\mp$$



See the talks of Robens, Heinemeyer, W. Su & Klamka for more channels.

Prospects of H at high-energy e^+e^- colliders

Dev, Mohapatra & YCZ '18 PRL; '18 PRD



- $\gamma\gamma$ channel: laser photon collision.
- Assuming the dominant decay mode $H \to \mu^\pm \tau^\mp$ (left panel).
- The muon $g - 2$ discrepancy can be directly tested at future lepton colliders via the LFV signals of H.

Couplings of ϕ with neutrinos

- Effective couplings of ϕ with ν's $[L(\phi) = -2]$:
  Berryman, de Gouvea, Kelly & Zhang '18; Kelly & Zhang '19; de Gouvea, Dev, Dutta, Ghosh, Han & YCZ '19; Dev, Dutta, Ghosh, Han, Qin & YCZ '21

$$\frac{1}{\Lambda^2}(LH)(LH)\phi \Longrightarrow \mathcal{L} = \frac{1}{2}\lambda_{\alpha\beta}\phi\,\nu_\alpha\nu_\beta$$

- Signals @ LHC

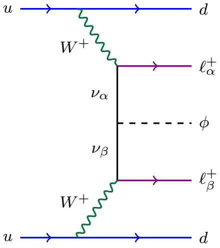
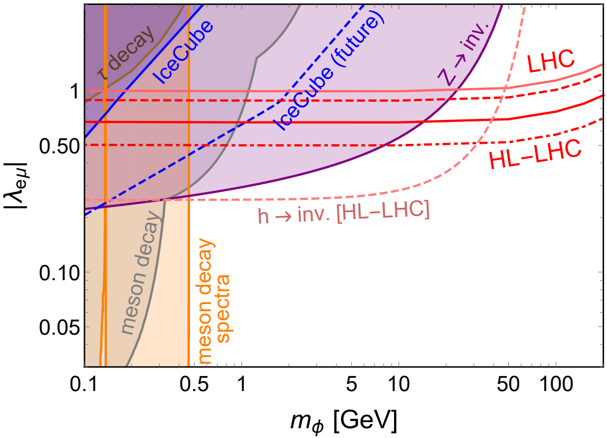


Figure: $uu \to dd + \ell_\alpha^+\ell_\beta^+ + \phi$

Prospects @ (HL-)LHC

de Gouvêa, Dev, Dutta, Ghosh, Han & YCZ '19

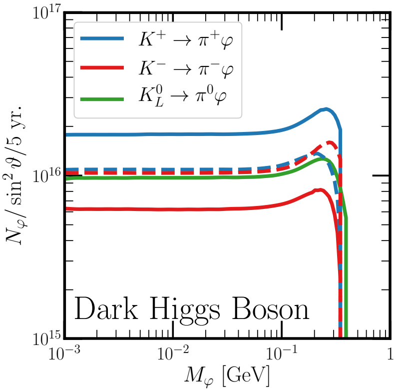


Similar prospects for $\lambda_{ee,\,\mu\mu}$.

See the talks of Kanazawa, Lagouri, Bethani, Richard, Xie & S. Su for more searches @ LHC.

S production @ DUNE

Berryman, de Gouvêa, Fox, Kayser, Kelly & Raaf '20 [JHEP]; Batell, Pospelov & Ritz '11 [PRD]



$$\Gamma(K^\pm \to \pi^\pm S) \simeq \frac{m_{K^\pm}\,|y_{sd}|^2 \sin^2\vartheta}{64\pi} \times \frac{m_{K^\pm}^2}{m_S^2}\lambda(m_{K^\pm}, m_{\pi^\pm}, m_S)\,,$$

$$\Gamma(K_L \to \pi^0 S) \simeq \frac{m_{K_L}\,(\mathrm{Re}\, y_{sd})^2 \sin^2\vartheta}{64\pi} \times \frac{m_{K^0}^2}{m_S^2}\lambda(m_{K_L}, m_{\pi^0}, m_S)\,,$$

$$y_{sd} = \frac{3\sqrt{2}G_F m_t^2 V_{ts}^* V_{td}}{16\pi^2}\,\frac{m_S}{\sqrt{2}v_{\mathrm{EW}}}$$

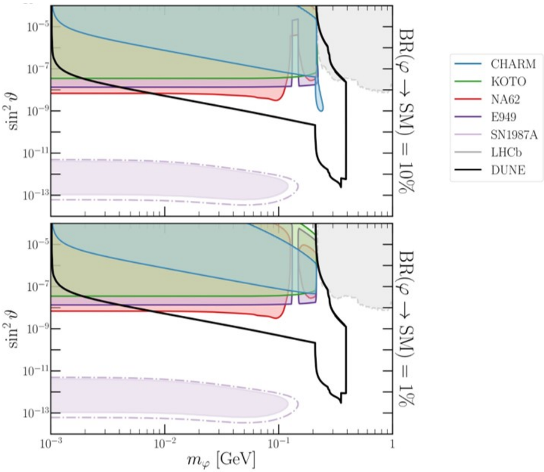
see the talks of Sakaki, Schäfer & Ueda for other LLP searches.

$pp \to ppS$ process contribution is comparatively small. [Batell, Berger & Ismail '19 [PRD]]

S prospects @ DUNE in $U(1)_{B-L}$ model

Dev, Dutta, Kelly, Mohapatra & YCZ '21;

see Berryman, de Gouvêa, Fox, Kayser, Kelly & Raaf '19 for prospects without Z'



Exposure of 1.47×10^{22} POT

In the $U(1)_{B-L}$ model

- mixing with SM h: $S \to e^+e^-,\ \mu^+\mu^-,\ \pi\pi,\ \ldots$
- gauge coupling with Z': $S \to Z'Z'$

Effects of $S \to Z'Z'$:

- Modifying BR($S \to$ vis.);
- Shortening its lifetime.

S in the stars

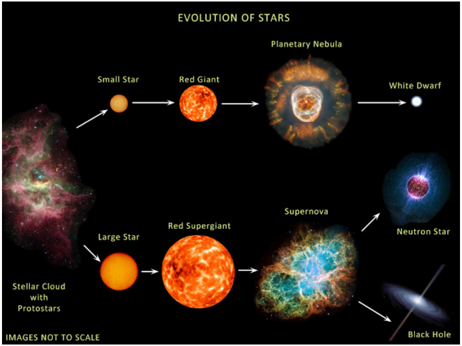


Figure: Basic stellar evolution

- High stellar density (in the core);
- Unique environment to produce copiously S;
- Raffelt criterion: the energy loss due to S can not exceed that 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...

Production of S in supernova core

Dev, Mohapatra & YCZ '20 JCAP

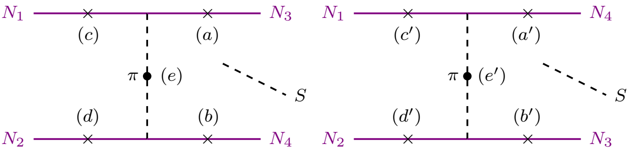


Figure: $N + N \to N + N + S$

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

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

$$y_{hNN} \sim 10^{-3},$$

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

Supernova luminosity limits

Dev, Mohapatra & YCZ '20 JCAP

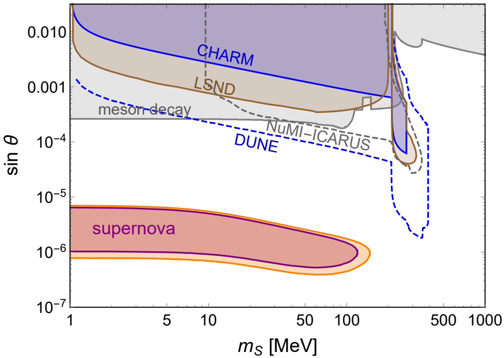
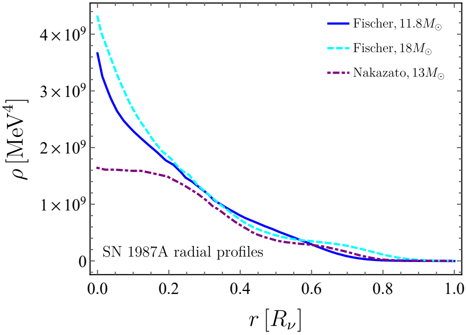


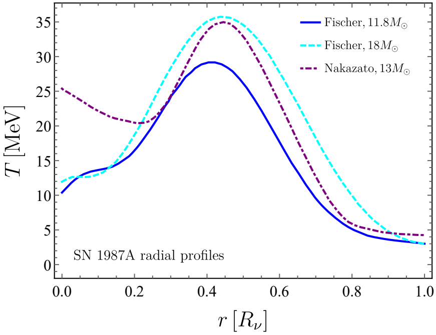
Figure: $T = 30$ MeV, $n_B = 1.2 \times 10^{38}\ \mathrm{cm}^{-3}$, $R_c = 10$ km

- Purple (orange) regions: luminosity limit of $5\,(3) \times 10^{53}$ erg/sec;
- The supernova limits can be improved at IceCube-DeepCore, Hype-Kamiokande, JUNO & DUNE.

Supernova profiles

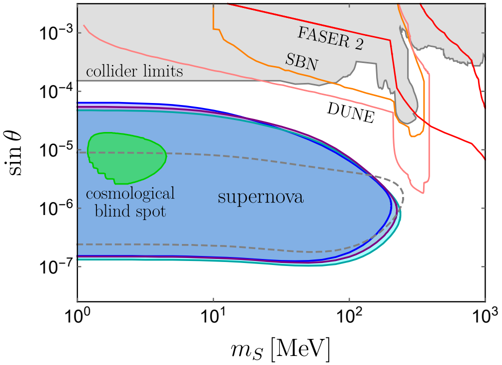
Fischer, Chakraborty, Giannotti, Mirizzi, Payez & Ringwald '16;
Nakazato, Sumiyoshi, Suzuki, Totani, Umeda & Yamada '12; Chang, Essig & McDermott '16





Updated supernova limits

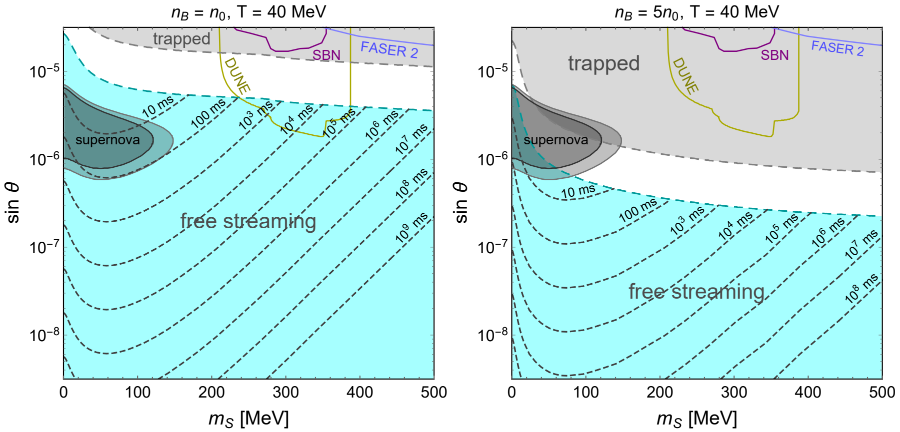
Balaji, Dev, Silk & YCZ '22



- Luminosity limit of 3×10^{52} erg/sec;
  - Including dependence on supernova profiles;
  - Including geometry for decay and absorption of S in the star;
  - Including dependence on $\lambda(r; E_S)$;
- Excluding the cosmological "blind spot". Ibe, Kobayashi, Nakayama & Shirai '21

Cooling of neutron stars due to S

Dev, Fortin, Harris, Sinha & YCZ '21



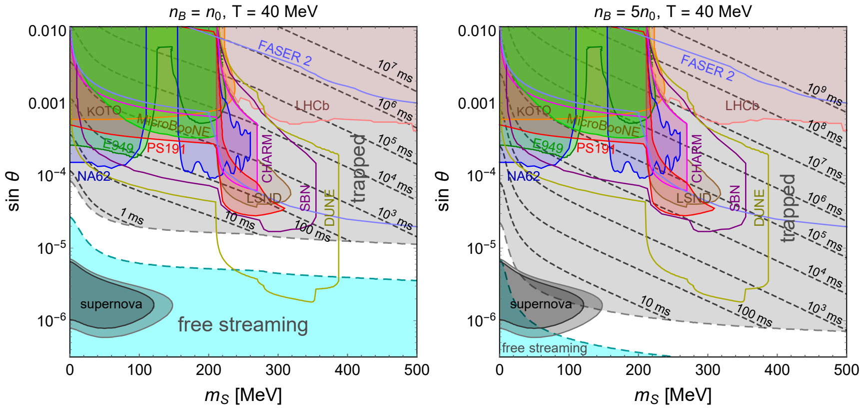
Including nuclear EoS.

Can be compared to lifetime of NS merger remnants.

Baiotti & Rezzolla '16; Lucca & Sagunski '20

Equilibration time scale

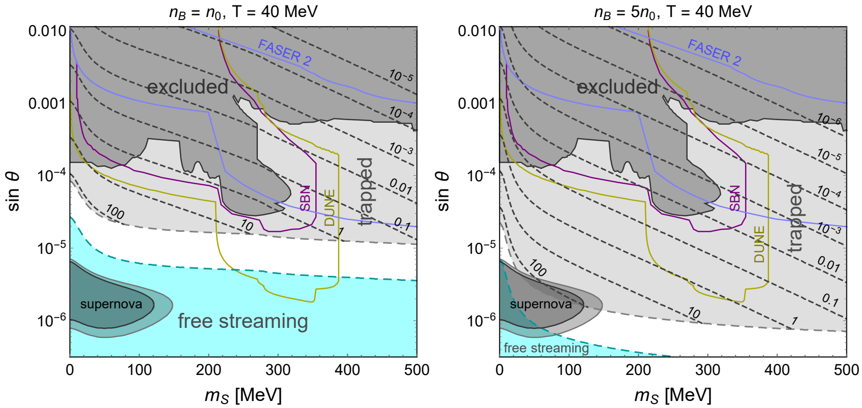
Dev, Fortin, Harris, Sinha & YCZ '21



Trapped in the stars, S thermalizes quickly with matter.

Comparison with κ_ν

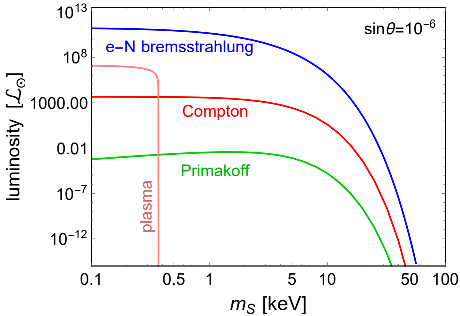
Dev, Fortin, Harris, Sinha & YCZ '21



High thermal conductivity due to BSM light scalar!

Production channels in the Sun

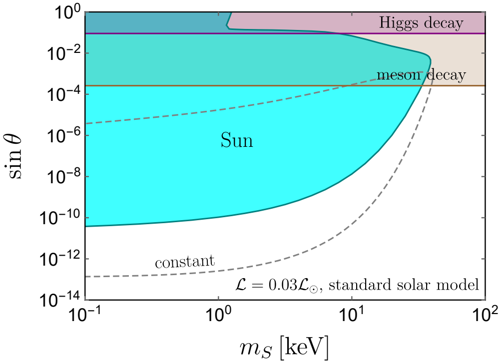
Dev, Mohapatra & YCZ '21 JCAP



- $e - N$ 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.
  Hardy & Lasenby '17 JHEP

Solar limits on S

Dev, Mohapatra & YCZ '21 [JCAP]; Balaji, Dev, Silk & YCZ '22



- Including dependence on solar profiles;
- Including geometry for decay and absorption of S in the Sun;
- Including dependence on $\lambda(r; E_S)$.

More stellar limits on S

Dev, Mohapatra & YCZ '21 [JCAP]; Balaji, Dev, Silk & YCZ '22

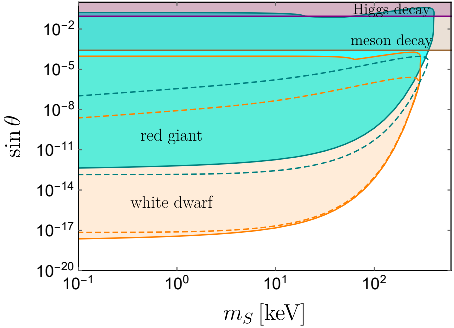


Figure: Including only geometry and dependence on $\lambda(E_S)$.

Star	Core composition	T [keV]	n_e [cm^{-3}]	R [cm]	$\mathcal{L}/\mathcal{L}_\odot$
RGs	^{4}He	10	3×10^{27}	6×10^8	2.8
WDs	50% ^{12}C 50% ^{16}O	6	10^{30}	10^9	10^{-5}

Conclusion

- Depending on the couplings with SM particles, light scalar S can be searched in a large variety of flavor signals, e.g. LFV signals.
- With couplings to neutrinos, light scalars can induce same-sign dilepton signals at the (HL-)LHC and future 100 TeV colliders.
- If sufficiently light, S can be searched in some of the high-intensity experiments, e.g. DUNE, depending on the underlying theories.

- SN1987A data exclude the mixing of S with SM Higgs at $1.0 \times 10^{-7} \lesssim \sin\theta \lesssim 5.0 \times 10^{-5}$ for scalar mass up to 238 MeV.
- The Sun, white dwarfs and red giants can exclude scalar mixing down to the order of 10^{-18}.
- NS mergers can also provide complementary limits on S, depending largely on NS parameters and observations.

Thank you very much!

backup slides

Benchmark points of S decay BRs

Dev, Dutta, Kelly, Mohapatra & YCZ '21

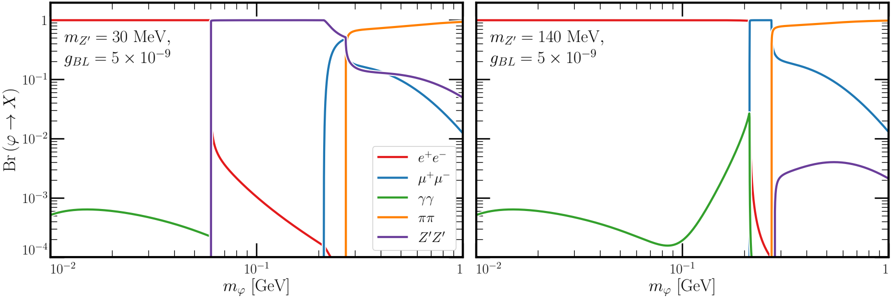


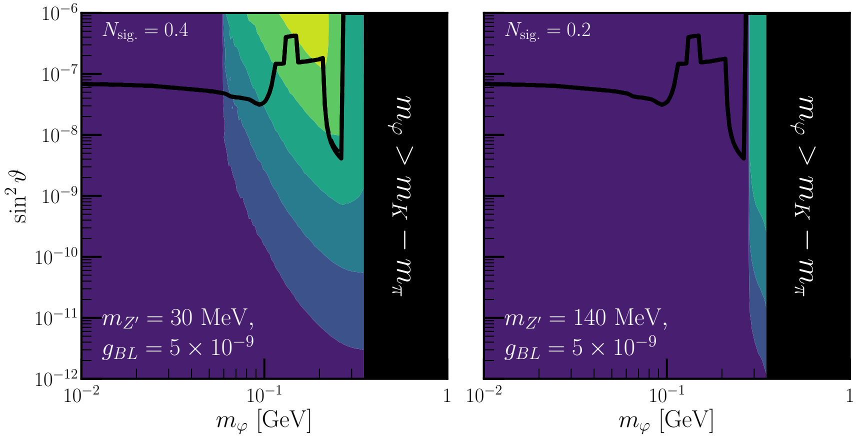
Figure: Decay BRs of S with $\sin\vartheta = 10^{-4}$.

scalar mixing : $S \to e^+e^-,\ \mu^+\mu^-,\ \gamma\gamma,\ \pi\pi$

gauge coupling : $S \to Z'Z'$

Numbers of Z' @ DUNE in presence of S

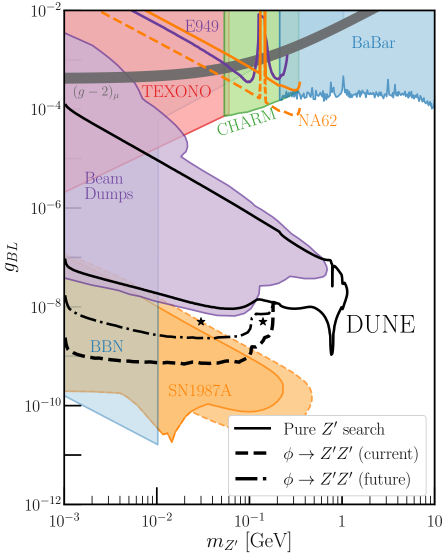
Dev, Dutta, Kelly, Mohapatra & YCZ '21



- Much more Z' can be produced from $S \to Z'Z'$.
- Color change: a factor of 10.

Improved Z' prospects @ DUNE

Dev, Dutta, Kelly, Mohapatra & YCZ '21



Lab limits from [Bauer, Foldenauer & Jaeckel '18 [JHEP]]

BBN & SN1987A limits from [Knapen, Lin & Zurek '17 [PRD]; Croon, Elor, Leane & McDermott '21 [JHEP]]

Assuming zero backgrounds & 10 signal events [Berryman, de Gouvêa, Fox, Kayser, Kelly & Raaf '20 JHEP]

Improving the pure Z' case by up to **a factor of 45**.

- dashed line: current S limits;
- dot-dashed line: future S limits

Cancellation at the leading order

Dev, Mohapatra & YCZ '20 JCAP

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

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

- 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 SNN diagrams are suppressed by the ratio $(m_S/E_S)^4$ 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 '22].
  - Very different from the axion/ALP and dark photon cases. [Chang, Essig & McDermott '17 JHEP; '18 JHEP]

Comparison of different contributions

Dev, Mohapatra & YCZ '20 JCAP

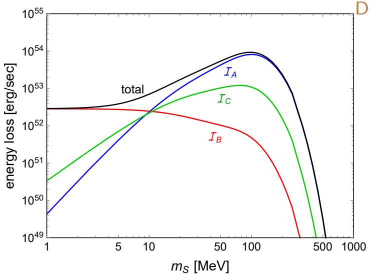


Figure: $T = 30$ MeV, $n_B = 1.2 \times 10^{38}\ \mathrm{cm}^{-3}$, $\sin\theta = 10^{-6}$

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

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

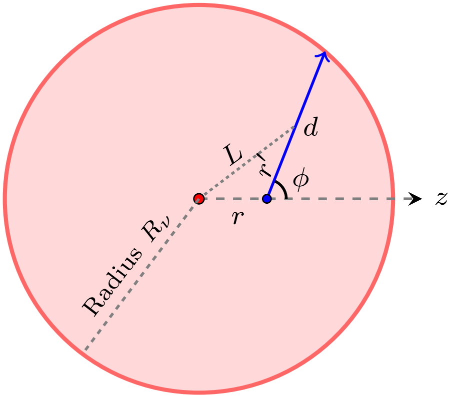
- $\mathcal{I}_B$: $S\pi\pi$ diagrams:

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

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

Geometry of S in the stars

Caputo, Raffelt & Vitagliano '22; Balaji, Dev, Silk & YCZ '22



Important for decay & absorption of S