Probing BSM physics with Solar and Atmospheric Neutrinos in Dark Matter Experiments

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Phenomenology 2023 Symposium — Pittsburg, PA

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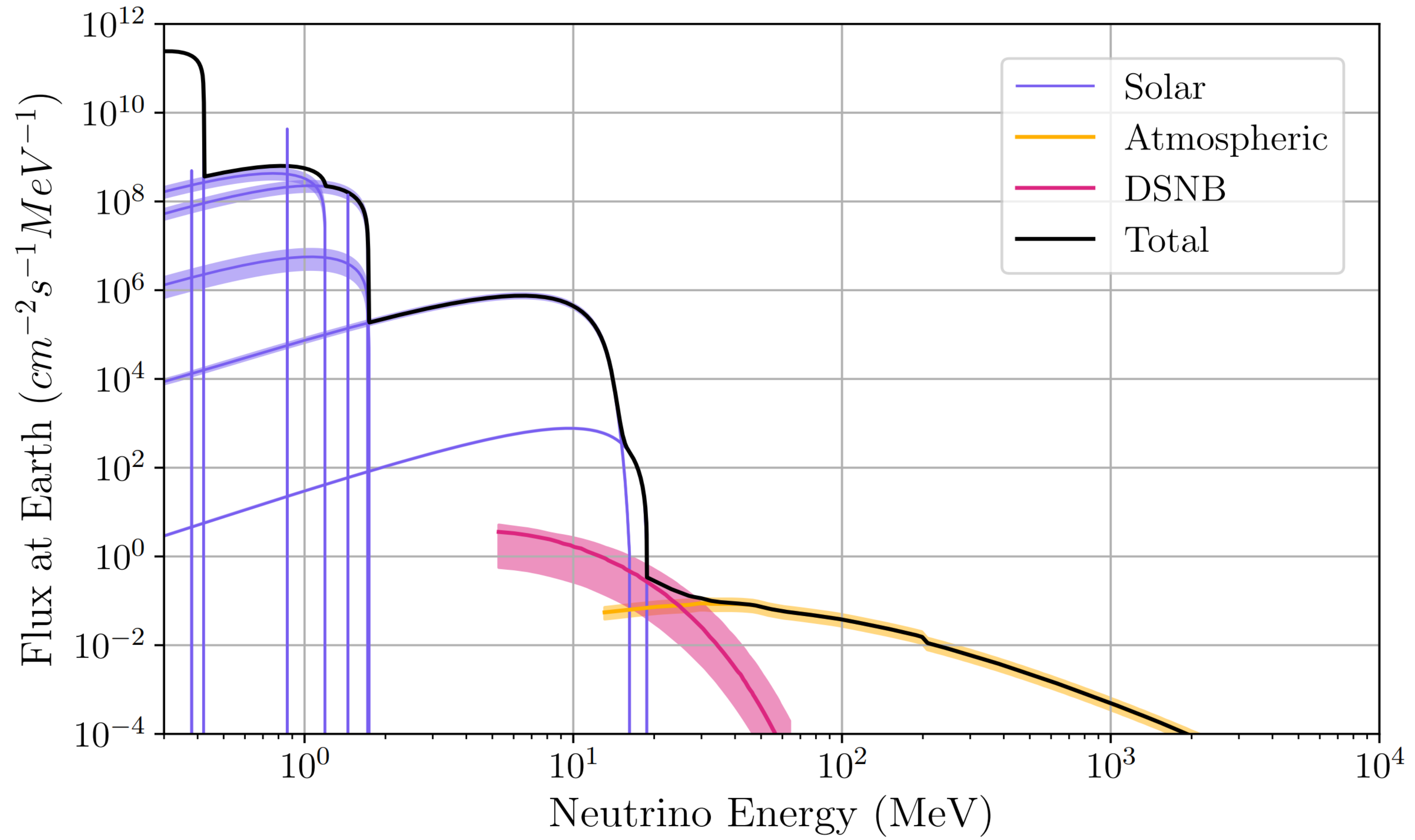
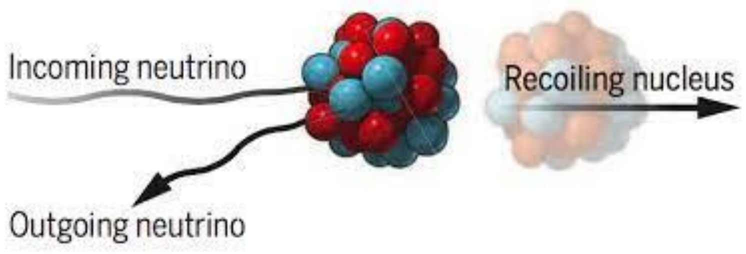
Based on work with Tien-Tien Yu and Volodymyr Takhistov

The Neutrino Flux



Neutrino Scattering

Coherent Scattering:



Differential recoil rate:

$$\frac{dR}{dE_R} = N_T \int_{E_\nu^{min}} \frac{d\sigma}{dE_R} \frac{dN_\nu}{dE_\nu} dE_\nu$$

A little kinematics:

$$E_\nu^{min} = \frac{1}{2}\left(E_R + \sqrt{E_R^2 + 2E_R m_N}\right)$$

SM cross-section:

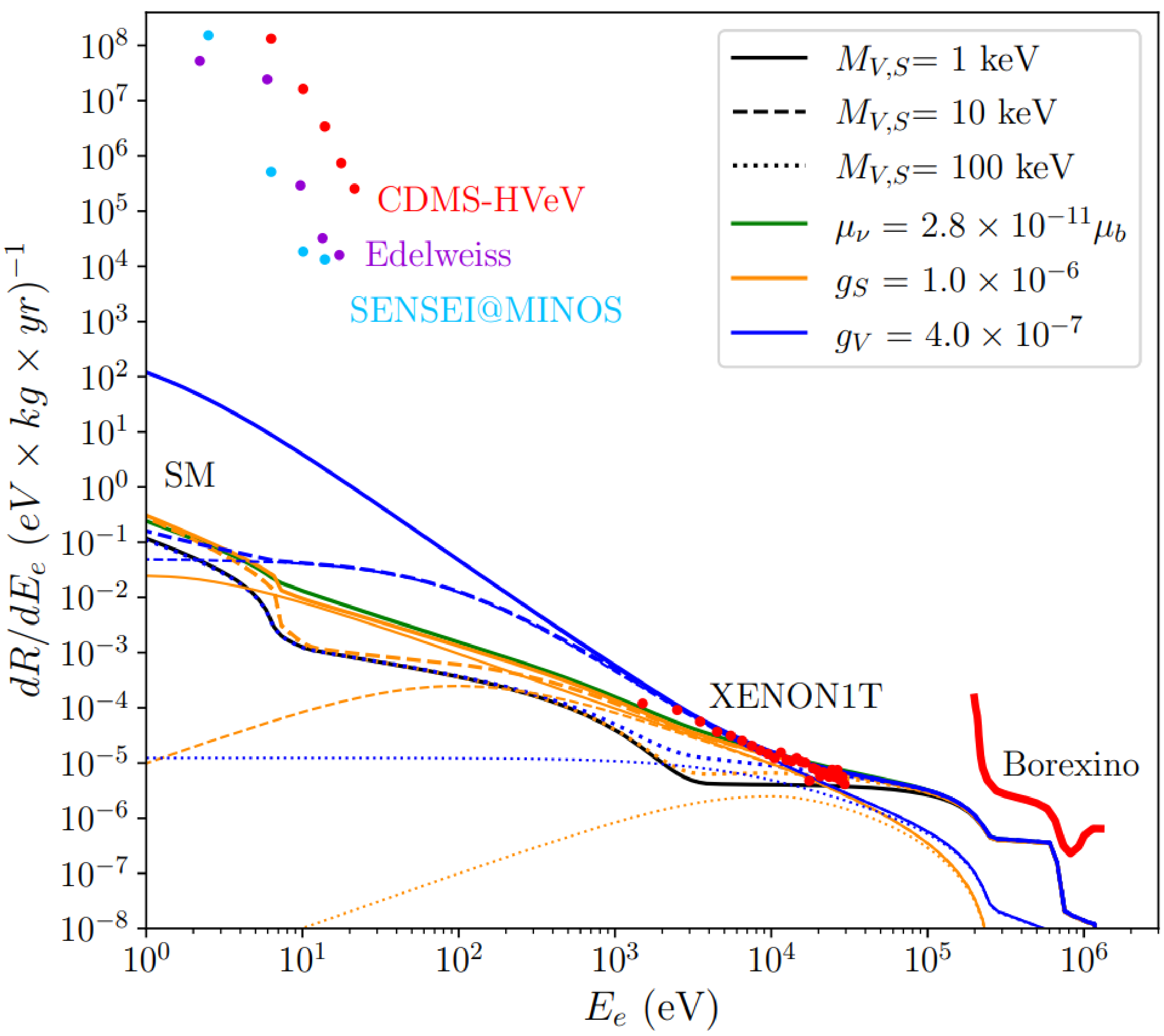
$$\frac{d\sigma}{dE_N} = \frac{G_F^2}{4\pi} Q_v^2 m_N \left(1 - \frac{m_N E_N}{2E_\nu^2}\right) F^2(E_N)$$

Recoil Energy

Scattering events produce a spectrum of recoils

Light vector mediators are most visible at low energy

Looking at higher energy has advantages for scalar interactions



Scalar NSI

- Two dimension 4 operators

$$\mathcal{L} \supset \phi\left(g_{\nu S}\bar{\nu}_R\nu_L + g_{qS}\bar{q}q\right)$$

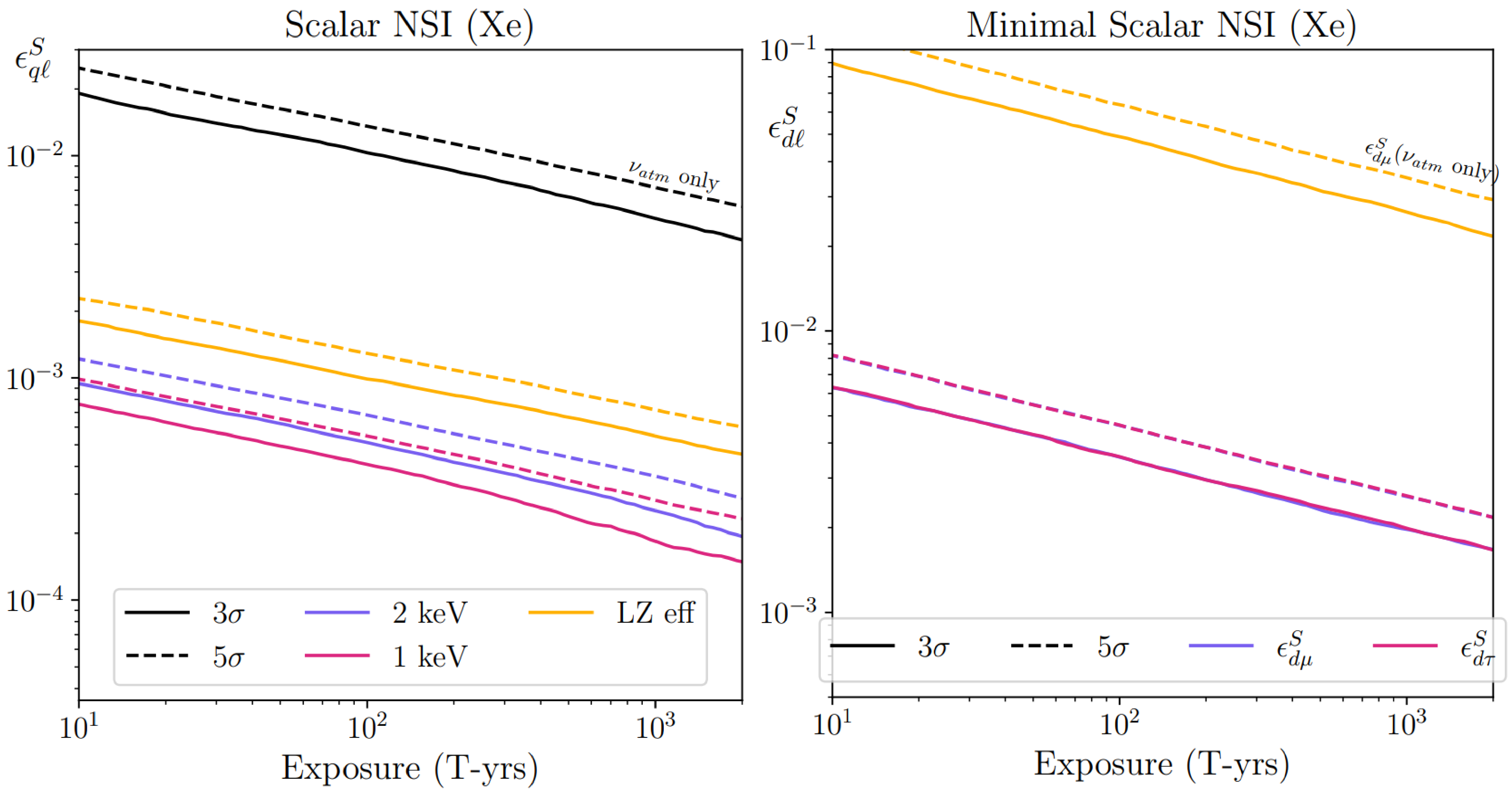
- Dimension 6 operator

$$\mathcal{L} \supset G_F \sum_{q,\ell} \epsilon^S_{q\ell}\bar{\nu}_\ell\nu_\ell\bar{q}q \qquad \epsilon^S_{q\ell} = \frac{g_{\nu_\ell S}g_{qS}}{M_S^2 G_F}$$

- High mass cross section

$$\left.\frac{d\sigma_N}{dE_R}\right|_S = \frac{F^2(E_R)q_s^2 E_R m_N^2}{4\pi E_\nu^2(2E_R m_N + m_S^2)^2} \Longrightarrow \frac{G_F^2\epsilon_{q\ell}^2 q_S^2 E_R m_N^2}{4\pi E_\nu^2}$$

$$q_S \approx 14.7A - 3.3Z$$



Scalar NSI (Xe)
$\epsilon^S_{q\ell}$
ν_{atm} only
3σ
5σ
2 keV
1 keV
LZ eff
Exposure (T-yrs)
Minimal Scalar NSI (Xe)
$\epsilon^S_{d\ell}$
$\epsilon^S_{d\mu}(\nu_{atm}$ only)
3σ
5σ
$\epsilon^S_{d\mu}$
$\epsilon^S_{d\tau}$
Exposure (T-yrs)

UV Motivation: Leptoquarks

- GUT models (unification of quarks and leptons)
- Possible solutions to:
  - Neutrino masses
  - $(g-2)_\mu$
  - Flavor anomalies
- LHC constraints currently dominant (from pair production and Drell-Yan)

A Two Leptoquark Model

- Based on the Zee Model of neutrino mass generation
- $S_1 = (\bar{3}, 1\,, 1/3\,)$

$$\mathcal{L}_{S_1} \supset \lambda_L^{i\ell} S_1 \bar{Q}_i^c \epsilon L_\ell + \lambda_R^{i\ell} S_1^* \bar{u}_R^i \bar{\ell}_R + \tilde{\lambda}_R^{i\ell} S_1^* \bar{d}_R^i \bar{\nu}_R^\ell + h.c. - \frac{1}{2} m_{S_1}^2 S_1^2$$

- $\tilde{R}_2 = (\bar{3}, 2, 1/6)$

$$\mathcal{L}_{\tilde{R}_2} \supset \lambda^{i\ell} \bar{d}_R^i \tilde{R}_2 \epsilon L_\ell + \tilde{\lambda}^{i\ell} \bar{Q}_i^c \tilde{R}_2^\dagger \bar{\nu}_R^\ell + h.c. - \frac{1}{2} m_{\tilde{R}_2}^2 \tilde{R}_2^2$$

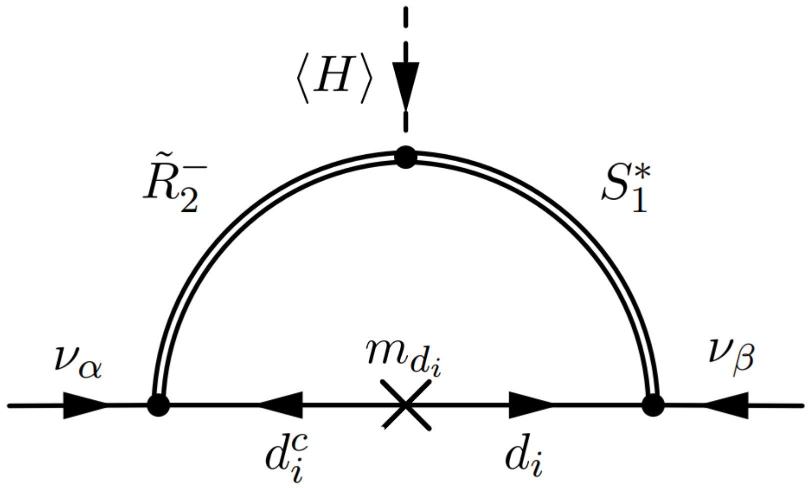
Neutrino Masses

- Expanding SU(2) doublets, dropping unnecessary terms, adding a higgs coupling

$$\mathcal{L} \supset \lambda^{i\ell}\left(\nu_\ell \bar{d}_i R^- - \ell \bar{d}_i R^+\right) + \lambda_L^{i\ell}\left(\nu_\ell d_i - \ell \bar{u}_i^c\right) S_1 - \mu R^- H^0 S_1^* + h.c.$$

- R^- and S_1^* mix via Higgs → $m_{1,2}$ in the new basis mixed by angle θ

$$M_\nu = \frac{3\sin(2\theta)}{32\pi^2}\log\left(\frac{m_1^2}{m_2^2}\right)\left(\lambda M_d \lambda_L^T + \lambda_L M_d \lambda^T\right)$$



Babu et. al. JHEP 2003, 006 (2020)

Leptoquarks in the IR

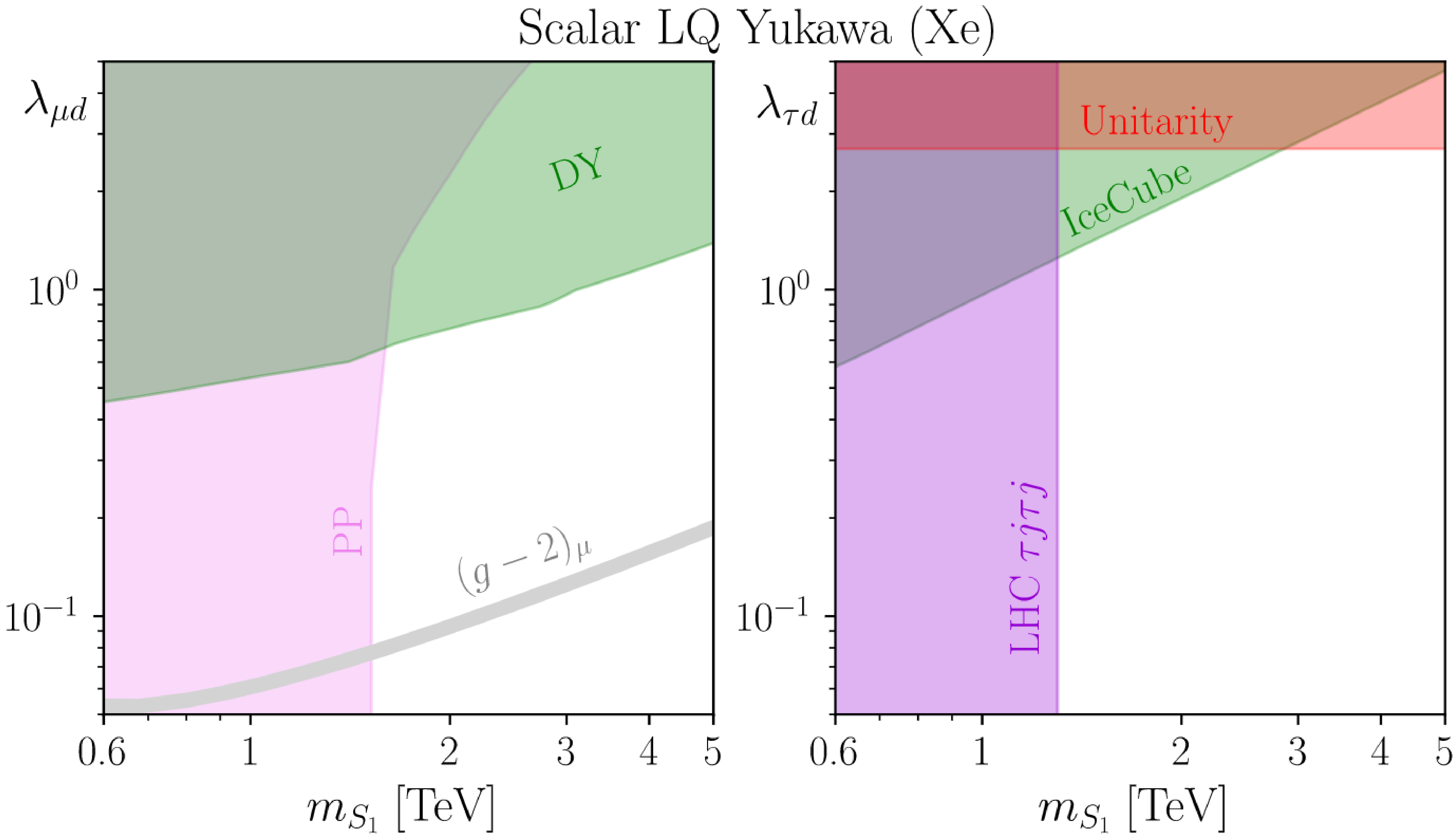
- Integrate out the LQ

$$\mathcal{L} \supset \frac{\lambda^L_{d\ell}\lambda^R_{d\ell}}{2m^2_{S_1}}(\bar{d}^c_L \nu_{L\ell})(\bar{d}^c_R \nu_{R\ell}) \Longrightarrow \quad \epsilon^{S_1}_{d\ell} = \lambda^2_{d\ell}/4G_F m^2_{S_1}$$

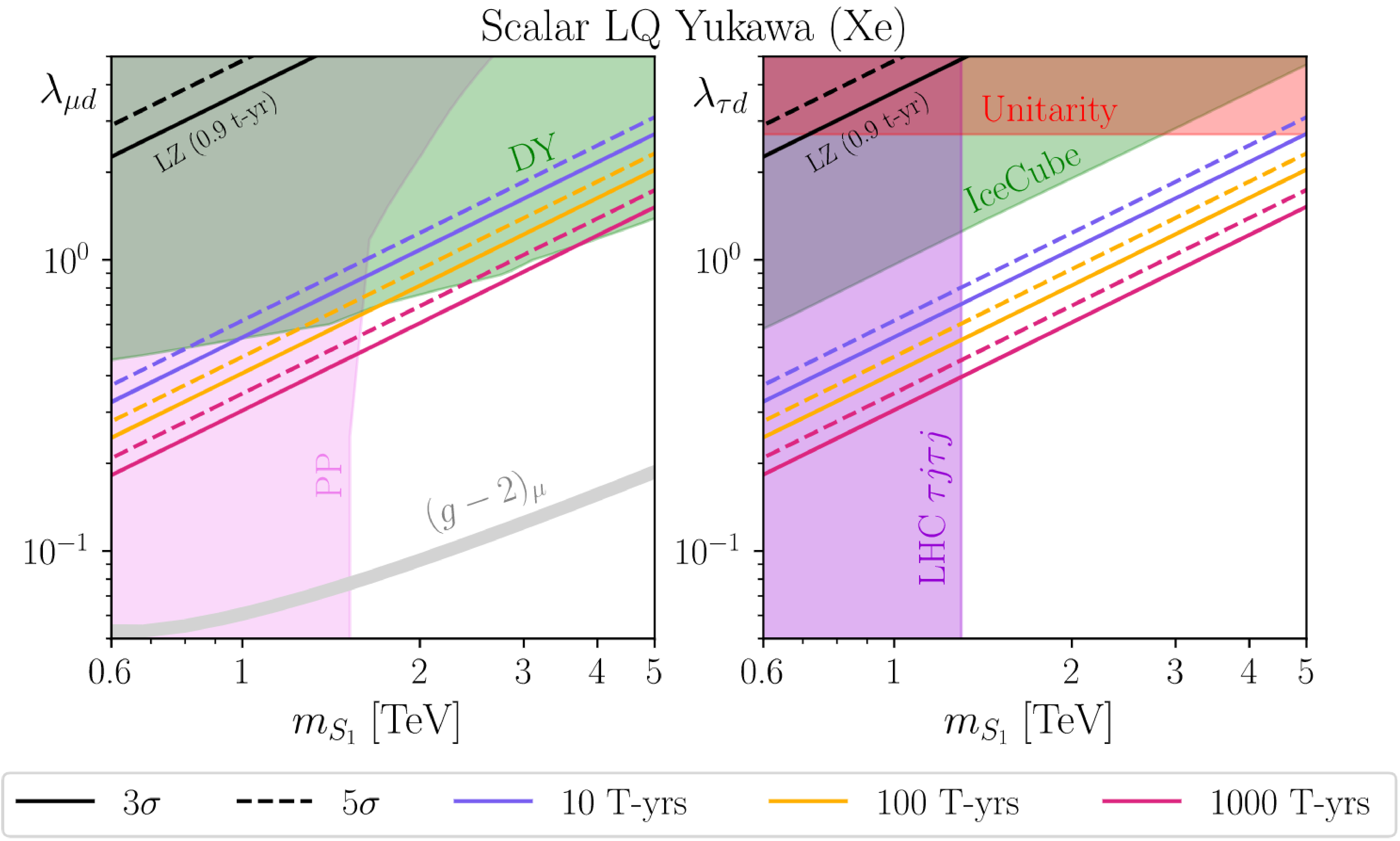
- New effective nuclear charge:

$$q_s = \frac{1}{m_d}(Zm_p f^p_d + Nm_n f^n_d) \approx 3.74A - 0.75Z$$

- Careful which neutrinos we use



Scalar LQ Yukawa (Xe)
$\lambda_{\mu d}$
DY
PP
$(g-2)_\mu$
10^0
10^{-1}
0.6
1
2
3
4
5
m_{S_1} [TeV]
$\lambda_{\tau d}$
Unitarity
IceCube
LHC $\tau j \tau j$
10^0
10^{-1}
0.6
1
2
3
4
5
m_{S_1} [TeV]



Scalar LQ Yukawa (Xe)
$\lambda_{\mu d}$
LZ (0.9 t-yr)
DY
PP
$(g-2)_\mu$
10^0
10^{-1}
0.6
1
2
3
4
5
m_{S_1} [TeV]
$\lambda_{\tau d}$
Unitarity
IceCube
LHC $\tau j \tau j$
3σ
5σ
10 T-yrs
100 T-yrs
1000 T-yrs

Summary

- Non-Standard Neutrino interactions can produce measurable signals in Dark Matter experiments
- Such interaction can be mediated by heavy Leptoquarks
  - Future DM experiments can improve constraints on certain Leptoquarks
- Removing backgrounds and lowering thresholds is critical to realize these constraints

Thank You