# Self-Interacting Neutrinos

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CAP Congress,
Ottawa

June 22, 2025

Based on 2510.15023 and 2606.02704 with
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# Outline

Overview of known aspects of Neutrino Self-Interactions ($\nu$SI)

$\nu$SI and cosmological observables

Neutrinophilic scalar and existing constraints on the model

Radiative corrections to the EW couplings and NC and CC interactions

Pathways for testing the model using data from various experiments

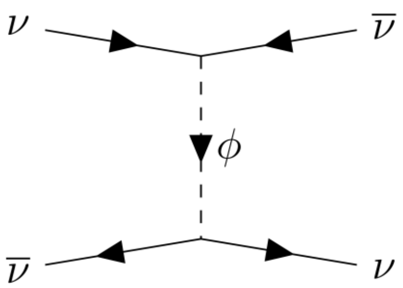
# Motivations

*What if neutrinos have sizable self-interactions?*

Neutrino Self-Interactions: A White Paper [2203.01955]

BSM: Neutrinos are elusive experimental targets

Their self-interactions are far less constrained than charged-fermion interactions



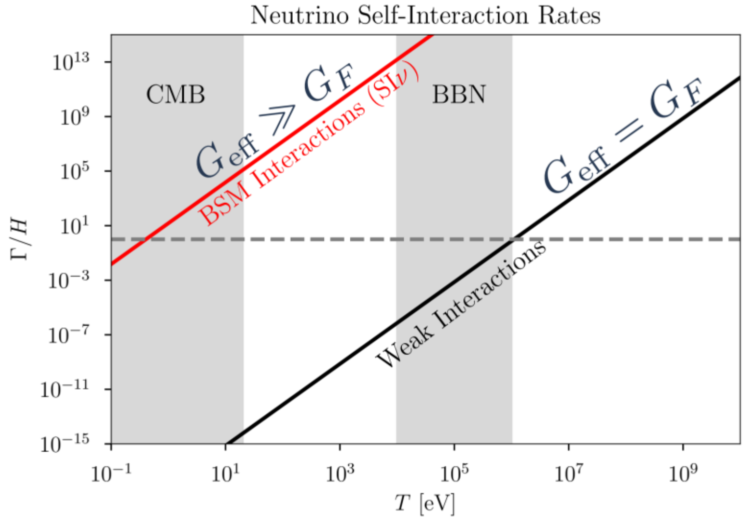

$$G_{\text{eff}} \equiv \frac{g_\phi^2}{m_\phi^2} = (10\,\text{MeV})^{-2}\left(\frac{g_\phi}{10^{-1}}\right)^2\left(\frac{\text{MeV}}{m_\phi}\right)^2$$

Neutrino mass generation: Models with a symmetry breaking mechanism in the neutrino sector (e.g. light pseudoscalar majoron) [Chikashige et al '81]

Can relax anomalies: e.g. Hubble tension

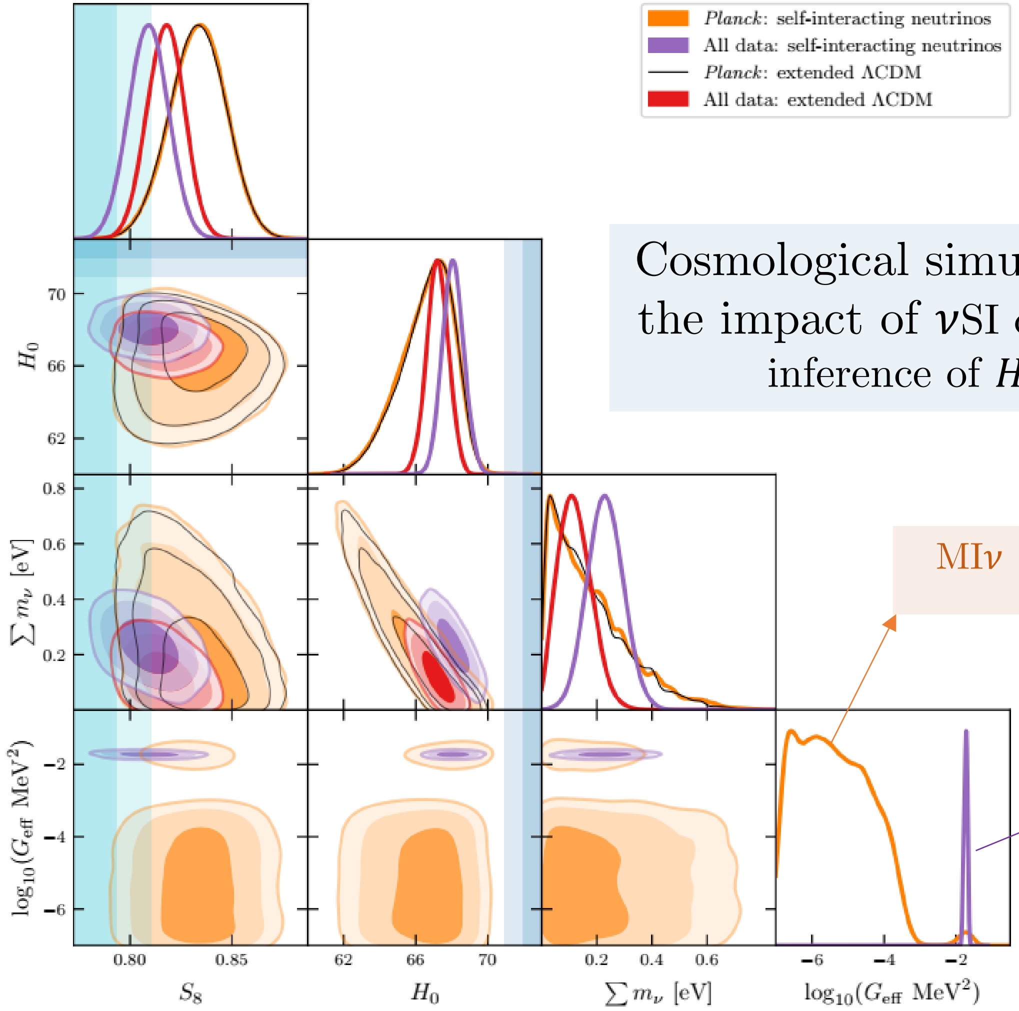
# Cosmology

With larger Geff, neutrinos may remain strongly self-coupled until late times e.g. the CMB formation!




Analyses of the CMB power spectrum & large-scale structure suggest a preference for strong $\nu$SI in the early universe. Kreisch et al [1902.00534]

$$G_{\rm eff} = \begin{cases} \left(4.7^{+0.4}_{-0.6}\text{MeV}\right)^{-2} & (\text{SI}\nu) \\ \left(89^{+171}_{-61}\text{MeV}\right)^{-2} & (\text{MI}\nu) \end{cases}$$




Cosmological simulations: the impact of $\nu$SI on CMB inference of $H_0$

MI$\nu$

SI$\nu$

He, An, Ivanov, Gluscevic [2309.03956]

# Sterile $\nu$ Dark Matter

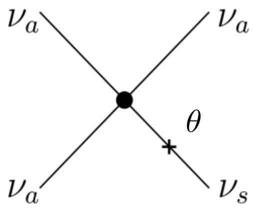
Produced warm DM through early universe oscillation mechanism.

Dodelson, Widrow [9303287, PRL]

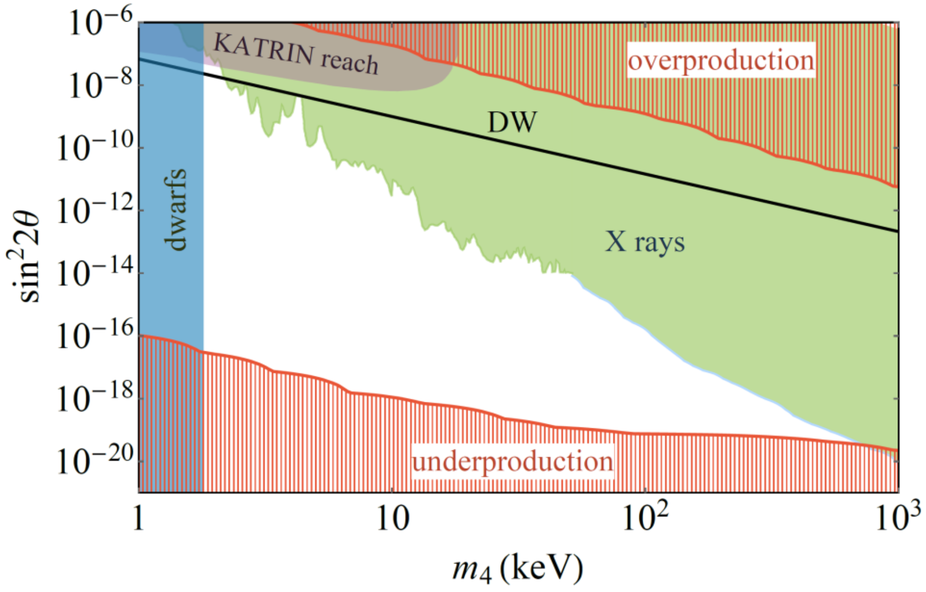
$$\nu_4 = \cos\theta\nu_s + \sin\theta\nu_a$$

active-sterile mixing in vacuum

$$P_{\nu_a \to \nu_s} = \sin^2 2\theta_{\text{eff}}$$




de Gouvêa, Sen, Tangarife, Zhang [1910.04901]



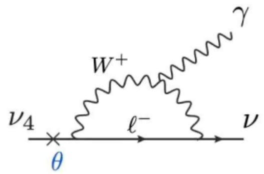

Sterile $\nu$DM production rate enhanced by number of collisions

$$\Omega_4 \sim \int \left(\frac{\Gamma}{H}\right) \sin^2\theta_{\text{eff}}$$

Larger $\Gamma \gg \Gamma_{\text{weak}}$ via neutrino self-interactions!

Save otherwise ruled out by X-rays and small-scale structure formation.

Decay: X-ray signal



# Neutrinophilic Mediator

Simplified model of light neutrinophilic scalar coupling to neutrinos

e.g., the Weinberg operator

$$\mathscr{L} \supset \frac{(L_\alpha H)\,(L_\beta H)\,\phi}{\Lambda_{\alpha\beta}^2} \longrightarrow \frac{\lambda_{\alpha\beta}}{2}\nu_\alpha \nu_\beta \phi \qquad \left(\lambda_{\alpha\beta} \equiv \frac{v^2}{\Lambda_{\alpha\beta}^2}\right)$$

Neutrino Self-Interactions White Paper [2203.01955]

- Singlet under the SM gauge symmetry
- Complex scalar carries two units of lepton number
- Neutrinophilic to avoid generating large coupling to charged leptons (constrained)
- Not introduced to explain neutrino mass and assumed to have no VEV (unlike a Majoron).

# Constraints

The new scalar, depending on its mass, can be produced in neutrino-related processes

$\mathfrak{m}^{\pm} \to \ell_{\alpha}^{\pm} \nu_{\beta} \phi$

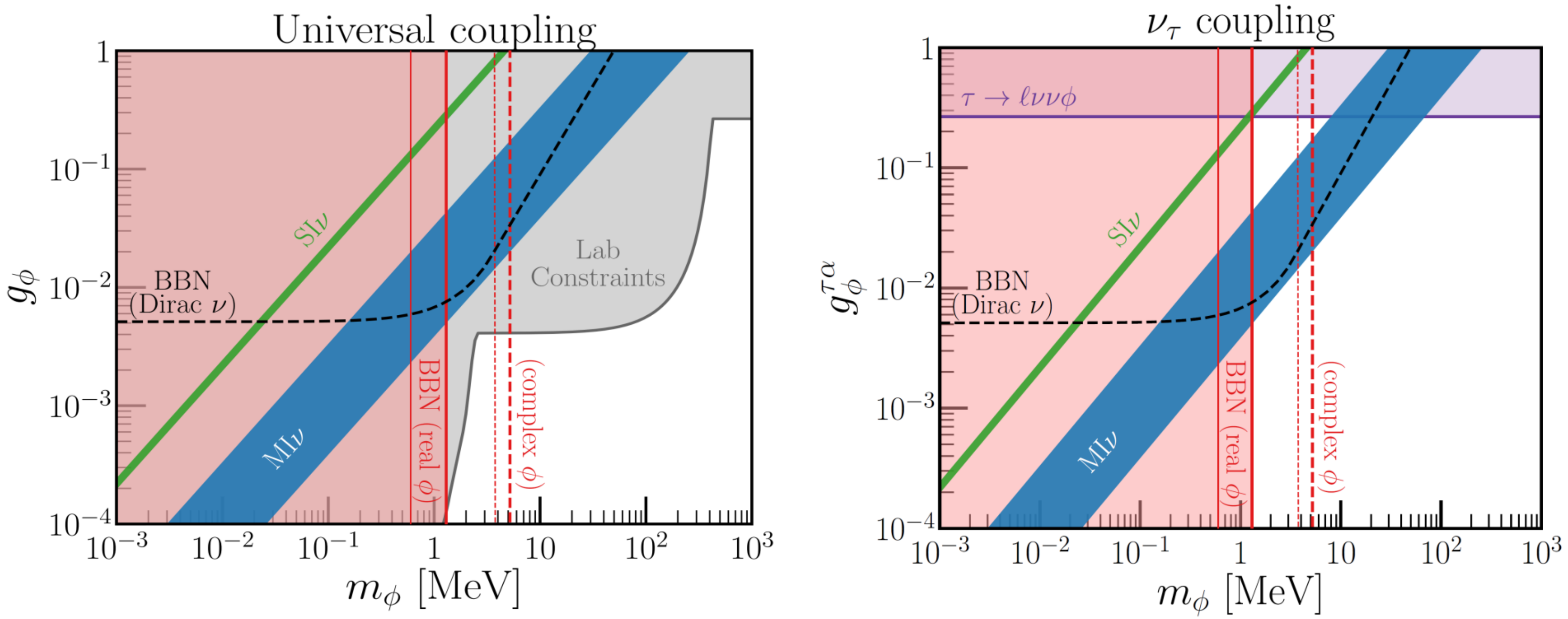
$Z \to \nu_{\alpha} \nu_{\beta} \phi$

$h \to \nu_{\alpha} \nu_{\beta} \phi$

$\phi\beta\beta$

Nuclear electron capture decay

SI$\nu$ and MI$\nu$ with flavour-universal coupling are tightly constrained!



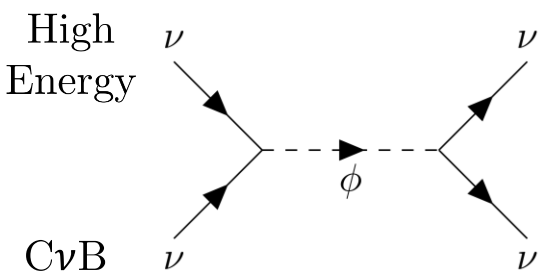

Blinov, Kelly, Krnjaic, McDermott [1905.02727]

Dev, Kim, Sathyan, et al. [2407.12738]
de Lima, McKeen, Ng, Tuckler [2601.06248]

# Absorption of Astrophysical $\nu$

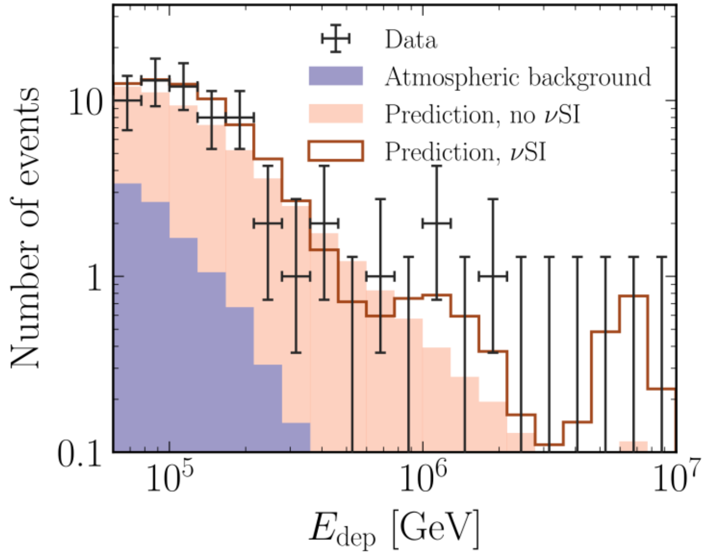
Resonant absorption of the UHE cosmogenic neutrino and one from the C$\nu$B.

e.g. see Ng, Beacom [1404.2288]



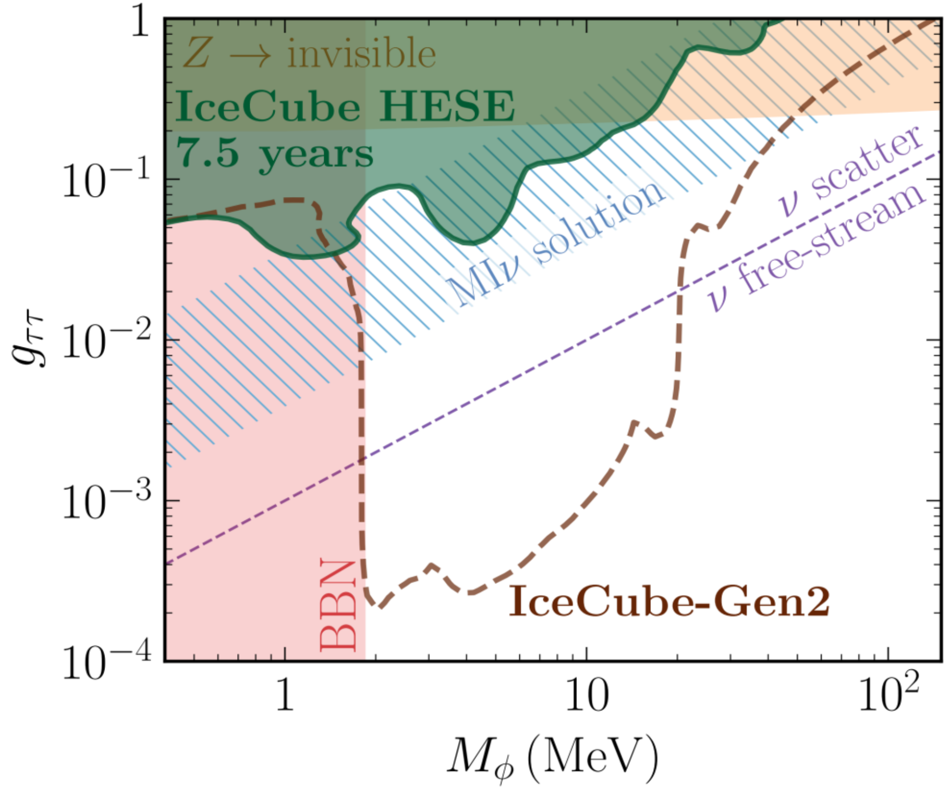

$$m_\phi^2 \sim s = 2 m_\nu E_\nu$$

Dips and bumps signature in the cosmic neutrino spectrum




$$\frac{d\Phi_{\rm astro.}}{dE_\nu} \propto \left(\frac{E_\nu}{100\ \rm TeV}\right)^{-\gamma}$$

$\nu_\tau$ coupling




Esteban, Pandey, Brdar, Beacom [2107.13568]

# UV Completion

$SU(2)_L$-triplet scalar boson $T$ with hypercharge -2

Neutrino Self-Interactions White Paper [2203.01955]

$$\mathcal{L} = \sum_{\alpha,\beta=e,\mu,\tau} \frac{y_{\alpha\beta}}{2} \bar{L}_\alpha T i\sigma_2 L^c_\beta + y' H^T i\sigma_2 T H \phi^* + \text{h.c.}$$

The neutral component of the triplet, $T_0$, only couples to neutrinos, $m_{\hat{T}^0} \simeq M$

Effective Yukawa coupling through the $\phi$-$T^0$ mass mixing, $\sin\theta \simeq \frac{|y'|v^2}{2M^2}$

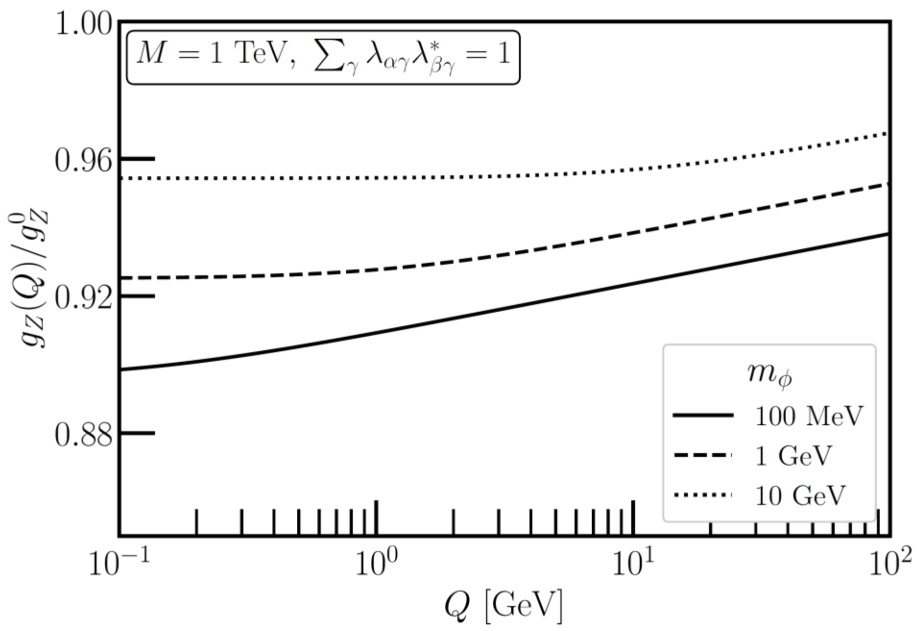
Serve as a small expansion parameter in the large-M limit: $\lambda_{\alpha\beta} = y_{\alpha\beta} \sin\theta$

The origin of neutrino masses would require further model building (type-II seesaw model).

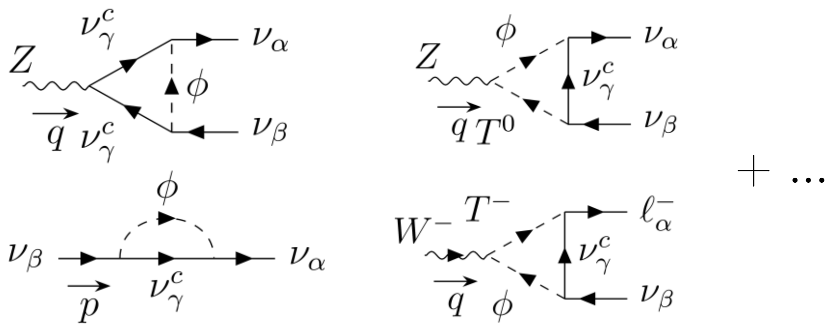
# Radiative Corrections the EW Couplings

Scalar mediators modify neutrino couplings at loop level; logarithmically enhanced!

Renormalized gauge couplings in the heavy triplet limit while keeping $\phi$ light that mediates $\nu$SI $\quad M^2 \gg m_\phi^2, Q^2$




SF, Kelly, Zhang [2510.15023]



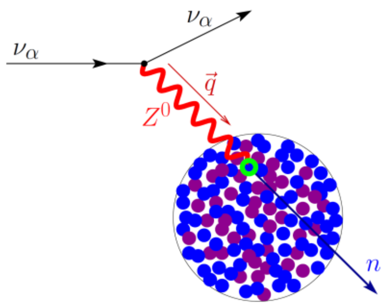

$$\frac{(g_Z)_{\alpha\beta}}{g_Z^0} = \delta_{\alpha\beta} - \frac{\lambda_{\alpha\gamma}\lambda^*_{\beta\gamma}}{32\pi^2} \times \begin{cases} \ln \frac{M^2}{Q^2} + \ln \frac{M^2}{m_\phi^2} - \frac{7}{2}\,, & Q \gg m_\phi \\ 2\ln \frac{M^2}{m_\phi^2} - 4\,, & Q \ll m_\phi \end{cases}$$

$$\frac{(\delta g_W)_{\alpha\beta}}{g_W^0} = -\frac{\lambda_{\alpha\gamma}\lambda^*_{\beta\gamma}}{64\pi^2}\left(\ln \frac{M^2}{m_\phi^2} - 2\right)$$

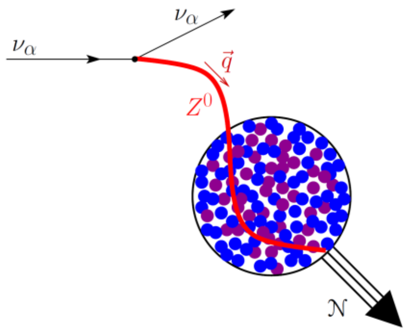
Focus on flavour-diagonal couplings for this talk.

# $\nu$-N Scattering Observables

Distinct probes for neutrino-nucleus interactions, depending on the relative size of the nuclear radius and the Compton wavelength of the mediating gauge boson




Inelastic incoherent ($\nu$DIS)
$\lambda_{Z^0} \ll 2R$




Elastic coherent (CE$\nu$NS)
$\lambda_{Z^0} \gtrsim 2R$

$$R^- \equiv \frac{\sigma_{\nu_\mu N \to \nu_\mu X} - \sigma_{\bar{\nu}_\mu N \to \bar{\nu}_\mu X}}{\sigma_{\nu_\mu N \to \mu^- X} - \sigma_{\bar{\nu}_\mu N \to \mu^+ X}} \simeq \frac{1}{2} - \sin^2\theta_W(Q)$$

$$\sigma_{\nu N \to \nu N} \propto G_F^2 Q_W^2$$

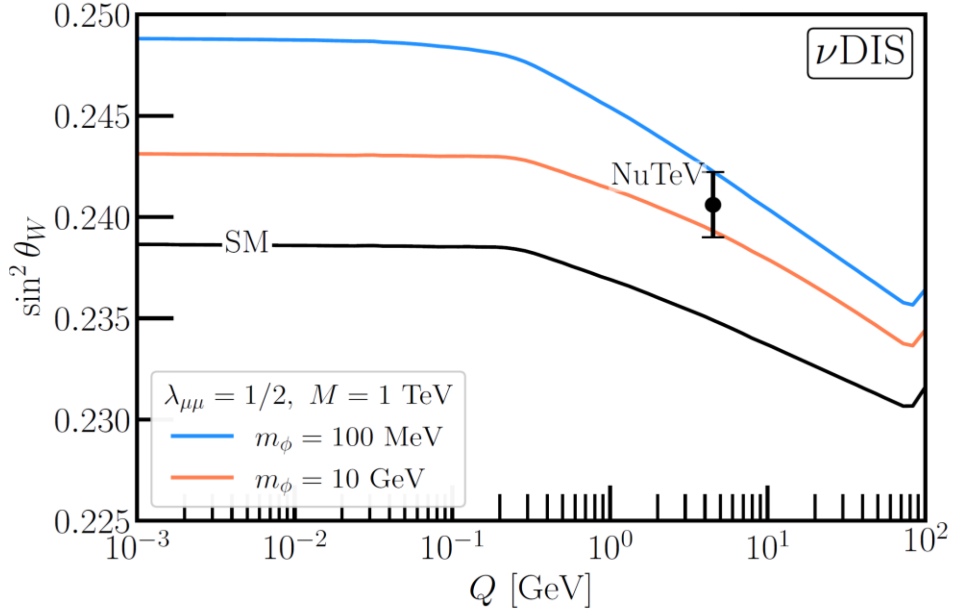
$$Q_W = N - Z(1 - 4\sin^2\theta_W(Q))$$

Scalar $\phi$ can modify neutrino scattering and shift inferred measurements of $\sin^2\theta_W$, providing a sensitive probe of EW theory.

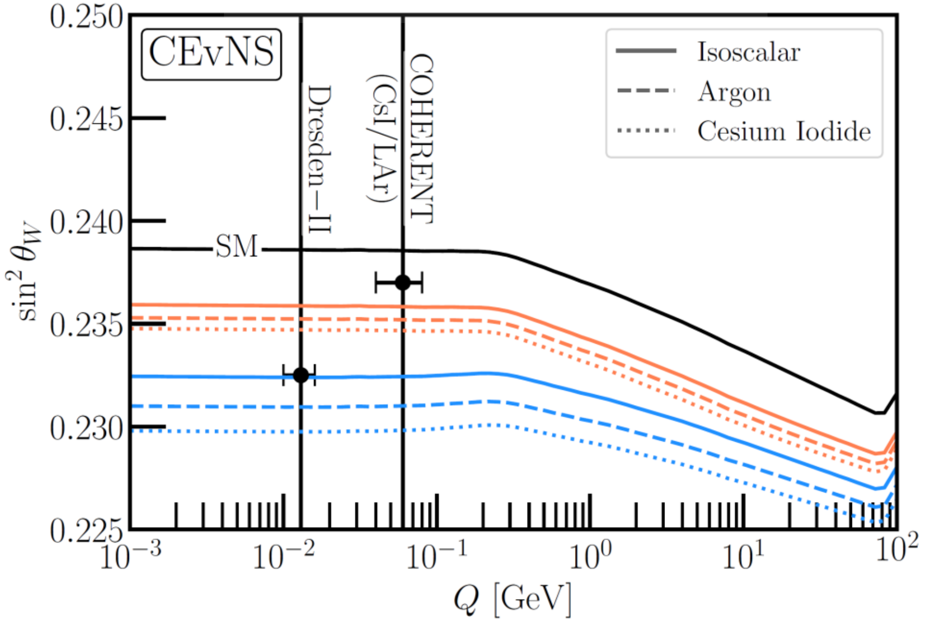
# Weak Mixing Angle

Running behavior in presence of $\nu$SI

*Larger* than expected




*Smaller* than expected



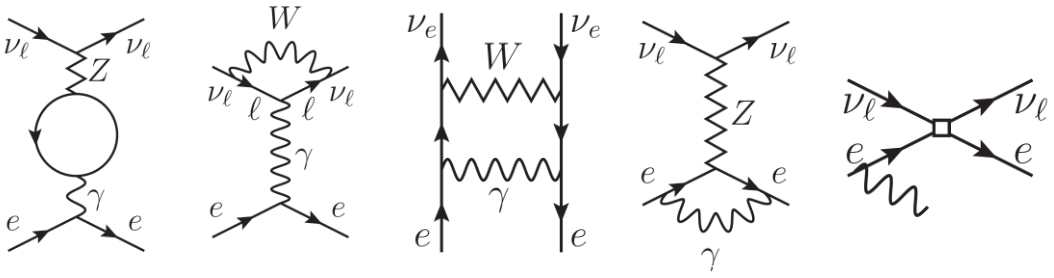

SF, Kelly, Zhang [2510.15023]

Different probes can break the degeneracy between the scale dependence and $\nu$SI induced radiative corrections

NuTeV anomaly: interpreted as evidence for self-interactions

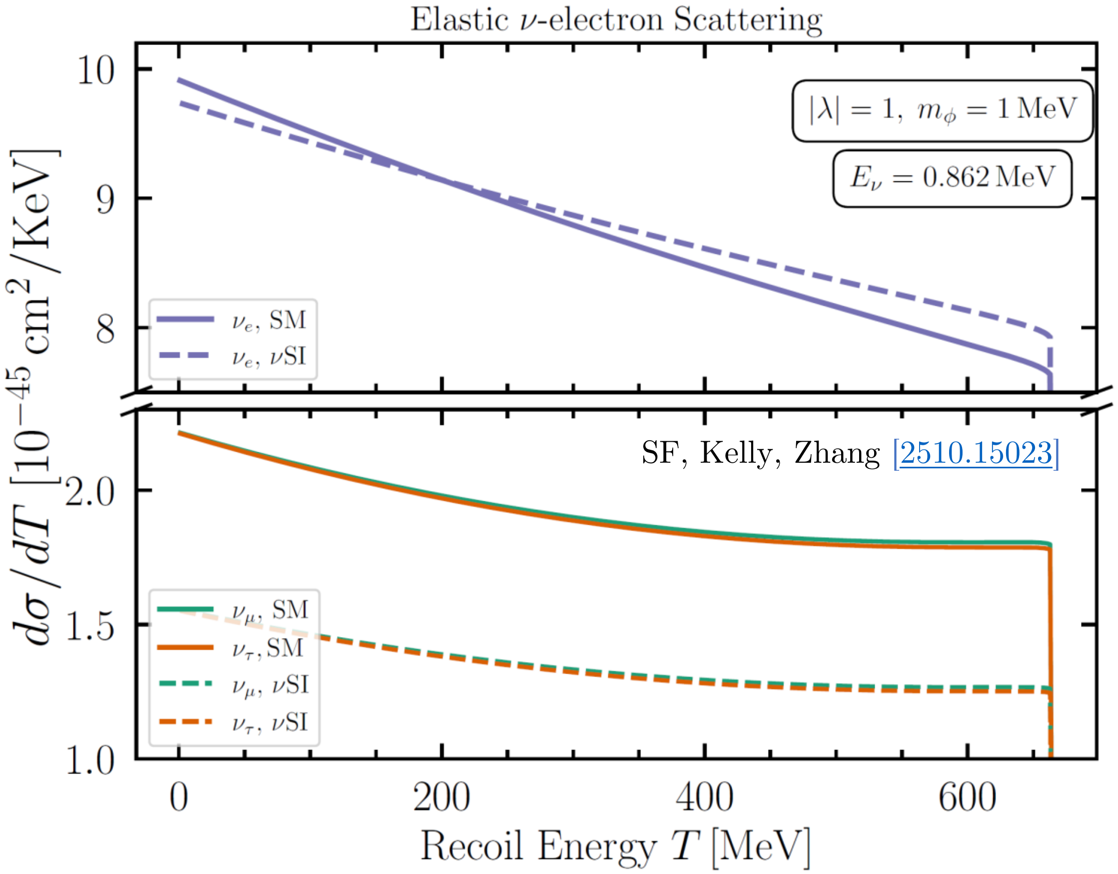
# $\nu$-$e$ Elastic Scattering

Contributions from charged and neutral current




SM radiative corrections to $\nu$-$e$ elastic scattering

$$\frac{d\sigma_{\nu_\alpha e}}{dT}(E_\nu, T) = \frac{2G_F^2 m_e}{\pi}\left[(g_L^\alpha)^2 + (g_R^\alpha)^2\left(1 - \frac{T}{E_\nu}\right)^2 - (g_L^\alpha)(g_R^\alpha)\frac{m_e T}{E_\nu^2}\right]$$

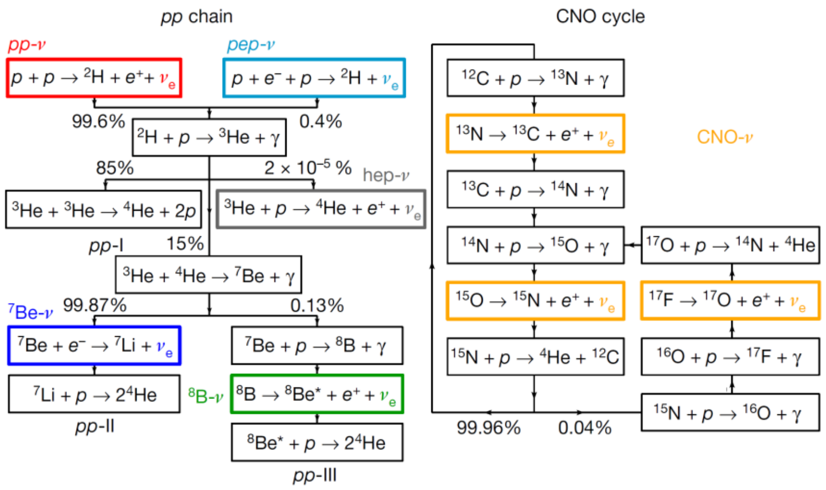


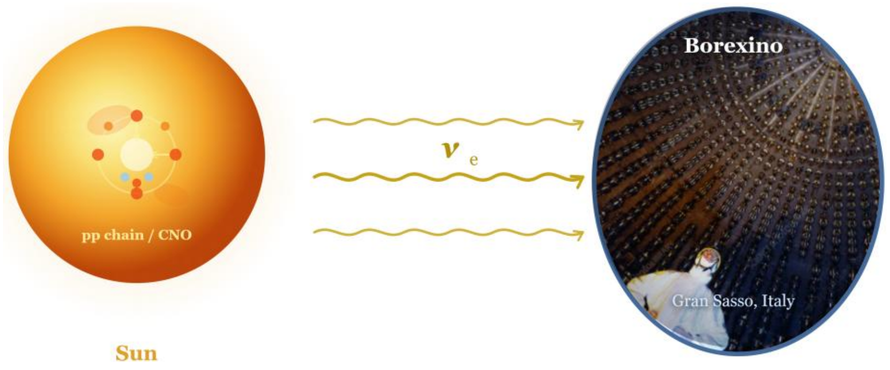

- New physics:

$$g_L^\alpha = \frac{g_Z}{g_Z^0}\left(\sin^2\theta_W - \frac{1}{2}\right) + \frac{g_W}{g_W^0}\delta_{\alpha e}, \quad g_R^\alpha = \frac{g_Z}{g_Z^0}\sin^2\theta_W$$

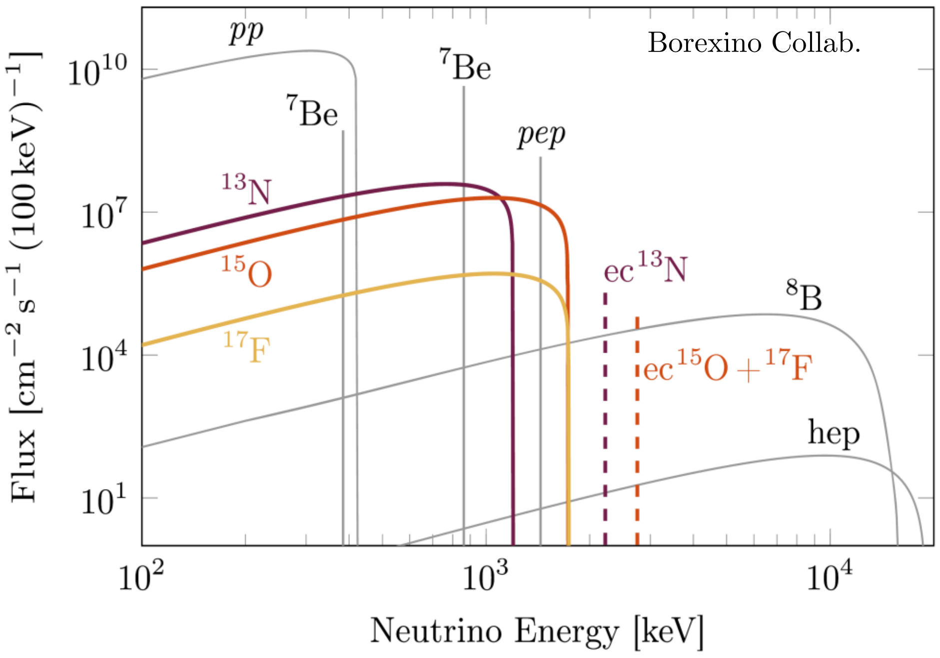
# Solar Neutrino Flux

Solar-neutrino scattering on electrons in Borexino; Directly measured neutrinos below $E_\nu < 10$ MeV



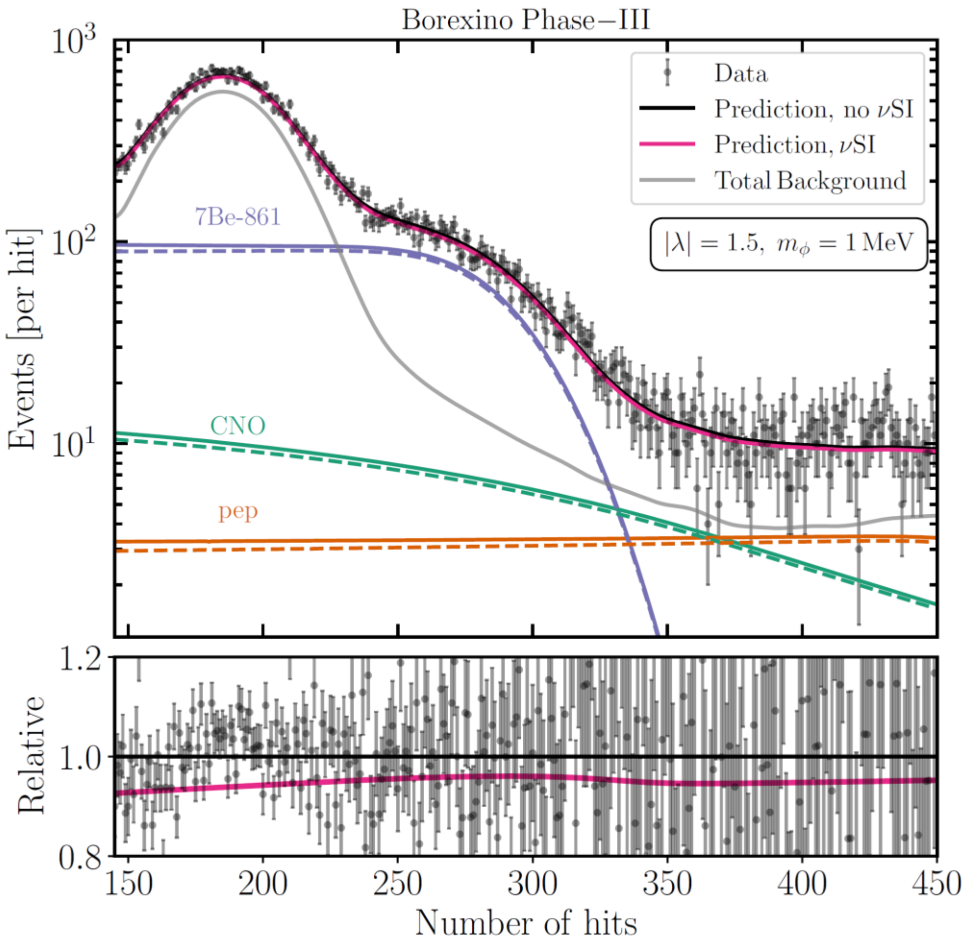

Solar neutrino spectra predicted by the Standard Solar Model

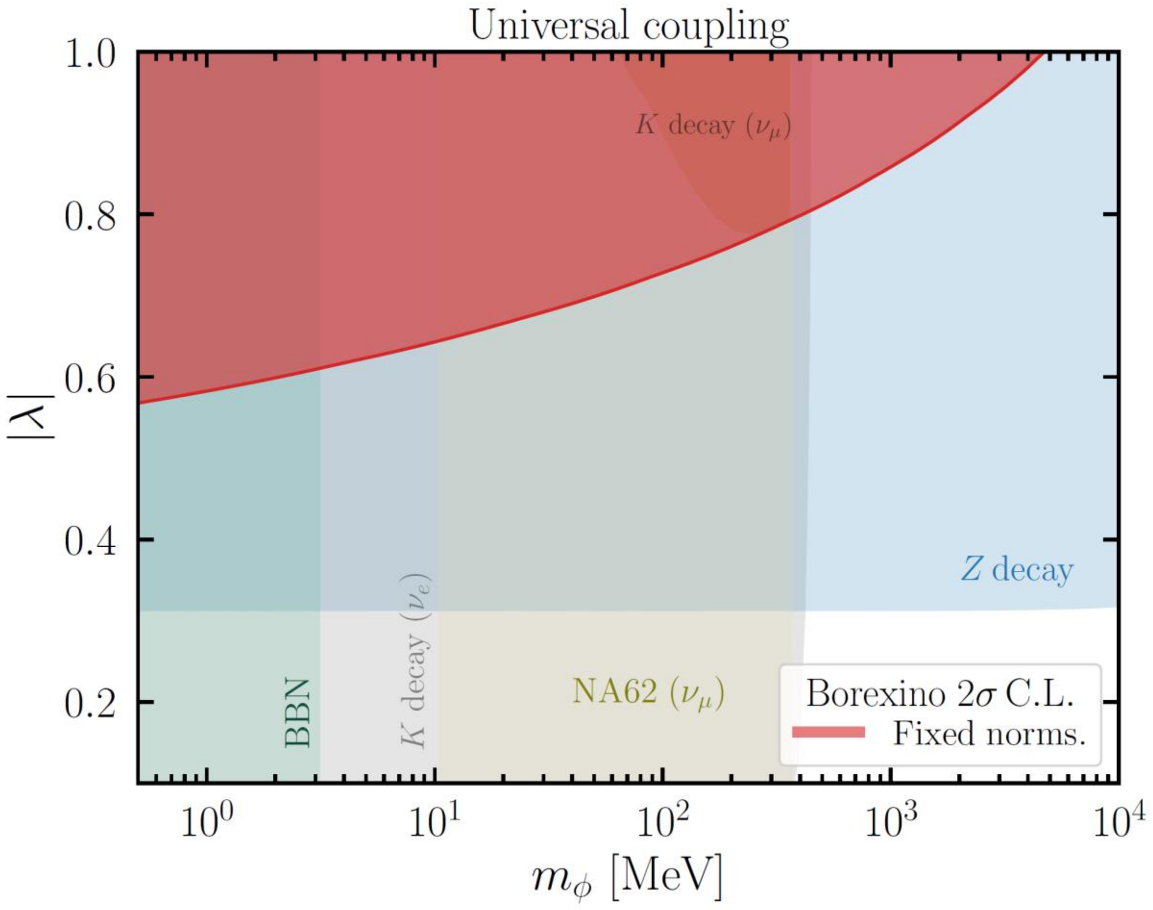


# Constraint from Solar Neutrinos

- Event spectrum of neutrino-electron elastic scattering

SF, Kelly, Zhang [2510.15023]



# Connection to Non-Standard Interactions

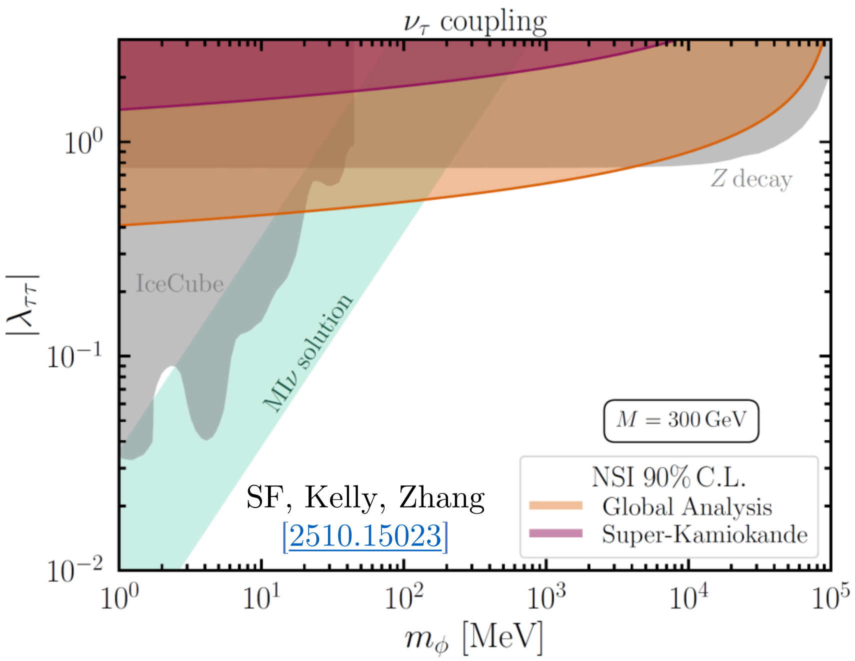
Experiments probing non-standard interactions (NSI) between neutrinos and matter

- Neutrino-matter interaction potential parametrization:

$$V_{\alpha\beta} = \sqrt{2} G_F n_e \begin{pmatrix} 1+\epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon_{\mu e} & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon_{\tau e} & \epsilon_{\tau\mu} & \epsilon_{\tau\tau} \end{pmatrix}$$

$$V_{\tau\tau} \simeq \frac{(\delta g_Z)_{\tau\tau} g_Z^0}{M_Z^2} \left( g_V^e n_e + g_V^u n_u + g_V^d n_d \right)$$

$$\epsilon_{\tau\tau} = -\frac{(\delta g_Z)_{\tau\tau}}{2 g_Z^0}$$

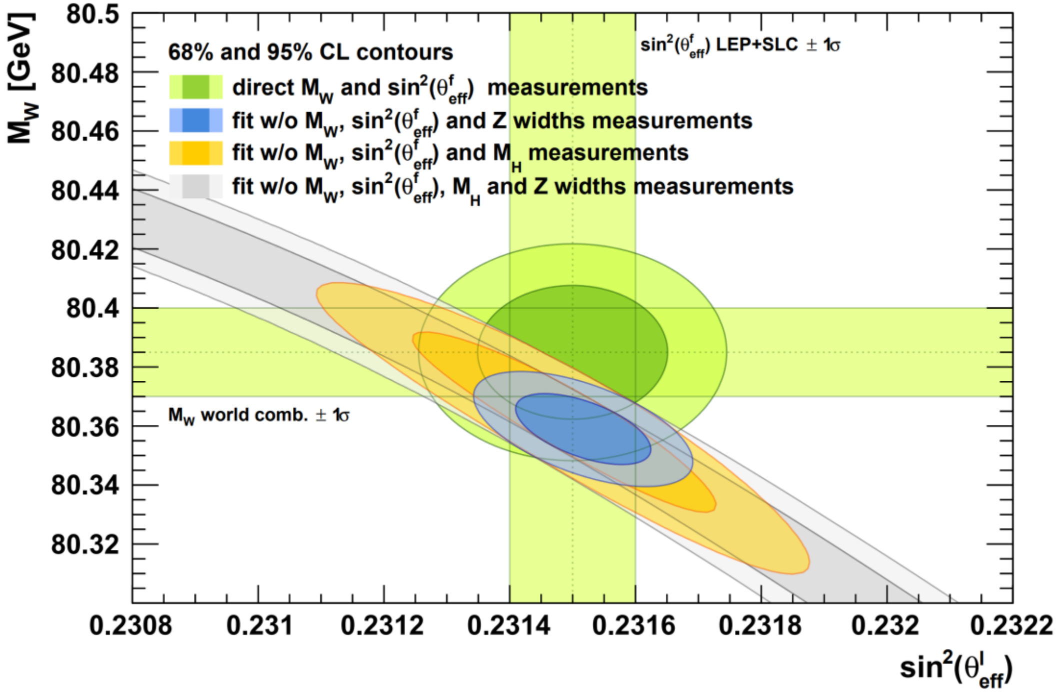



| | |
|---|---|
| Super-Kamiokande | $\lvert\epsilon_{\mu\mu} - \epsilon_{\tau\tau}\rvert < 0.049 \times 3$ |
| global fit to neutrino oscillation measurements | $-0.0215 < \epsilon_{\tau\tau} - \epsilon_{\mu\mu} < 0.0122$ |

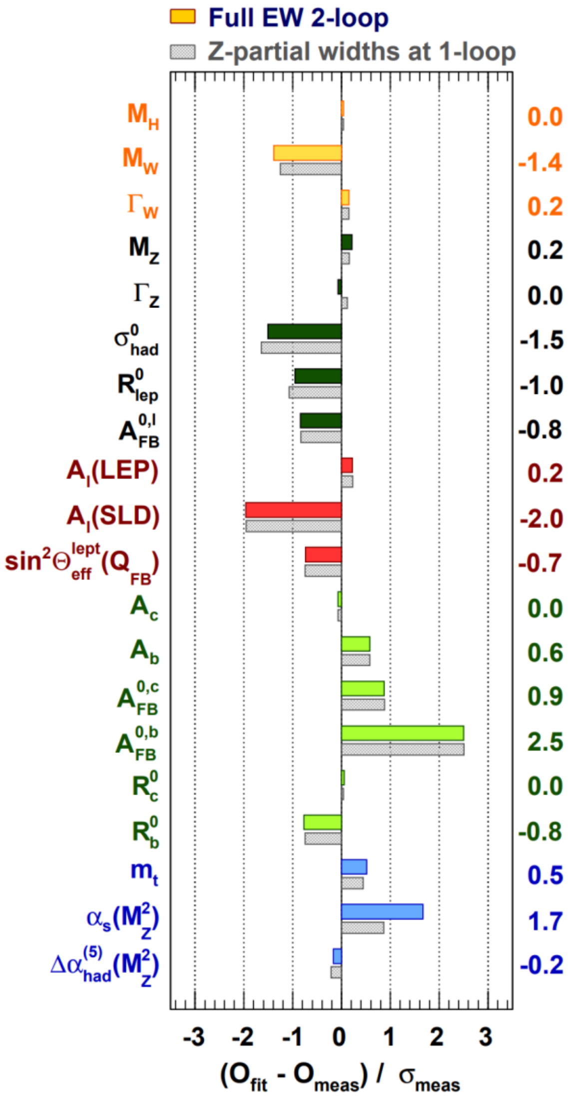
# Global fits of SM

Global electroweak fits combine precision measurements from LEP, LHC with multi-loop SM predictions,

Provide stringent tests of the SM and new physics




Gfitter [1407.3792]



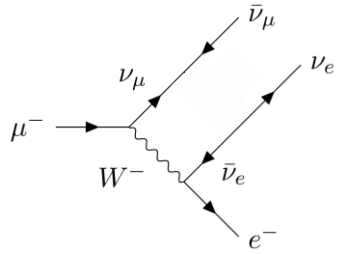
# Precision EW and $\nu$SI

The extracted Fermi constant from muon lifetime depends on the strength of $\nu$SI

New constraint comes from the new physics contribution:

$$G_F = \frac{G_\mu}{1 + \Delta r^{\mathrm{SI}\nu}} \qquad \Delta r^{\mathrm{SI}\nu} \equiv \frac{(\delta g_W)_{ee} + (\delta g_W)_{\mu\mu}}{g_W^0} < 0$$

$$\sin^2\theta_W \cos^2\theta_W = \frac{\pi\alpha}{\sqrt{2} G_\mu m_Z^2 \,(1 - \Delta r^{\mathrm{SM}} - \Delta r^{\mathrm{SI}\nu})}$$



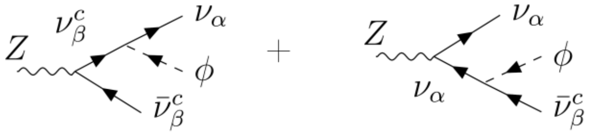

$G_\mu \equiv 1.16637 \times 10^{-5}\ \mathrm{GeV}^{-2}$

Many observables are modified:

**Z-boson**

$$\Gamma_Z = \Gamma_Z^{\mathrm{SM}}(\Delta r^{\mathrm{SI}\nu}) + \delta\Gamma_{Z\to\nu\bar{\nu}} + (\Gamma_{Z\to\nu\nu\phi^*} + \Gamma_{Z\to\bar{\nu}\bar{\nu}\phi})$$

$$A_f = \frac{2 g_{V,f} g_{A,f}}{g_{V,f}^2 + g_{A,f}^2}$$




$\sin^2\theta_{\mathrm{eff}}^\ell$

& more ...

**W-boson**

$$\Gamma_{W^-} = \Gamma_{W^-}^{\mathrm{SM}}(\Delta r^{\mathrm{SI}\nu}) + \delta\Gamma_{W^-\to\ell\bar{\nu}} + \Gamma_{W^-\to\ell\nu\phi^*}$$

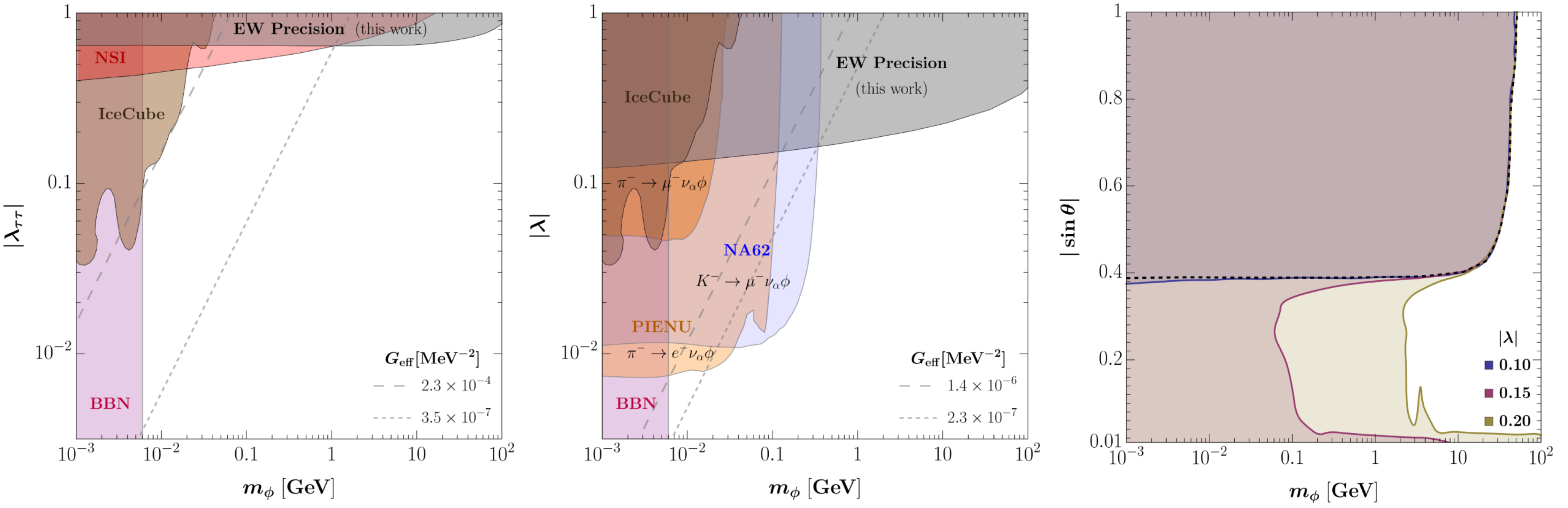
$$m_W \equiv m_Z \cos\theta_W$$

# Precision EW Constraints

Perform a global fit to EW observables using Gfitter

SF, Mupo, Vatsyayan, Zhang [2606.02704]

Constraints on the UV-complete model



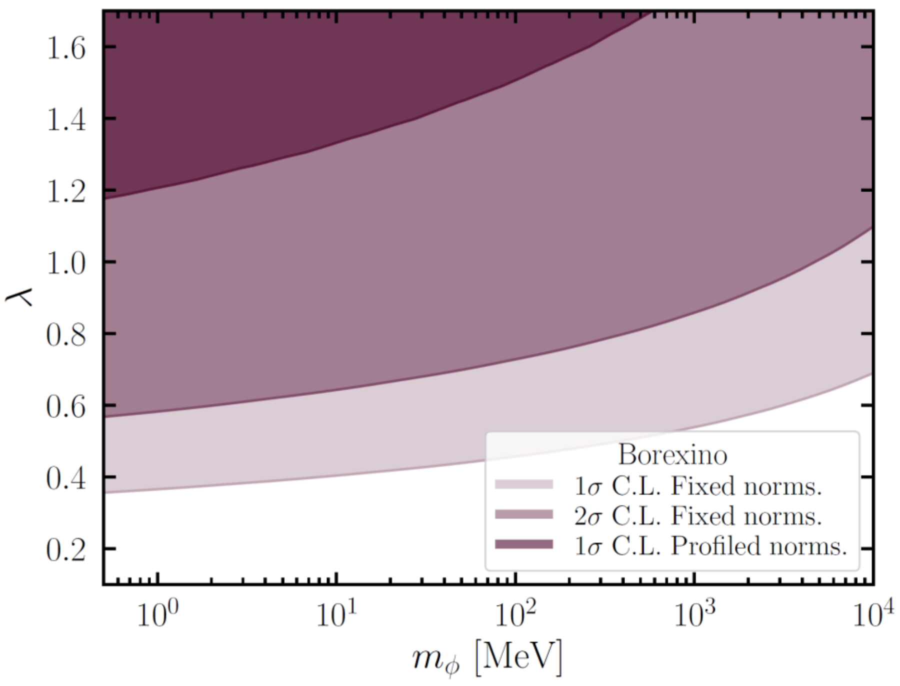
# Summary

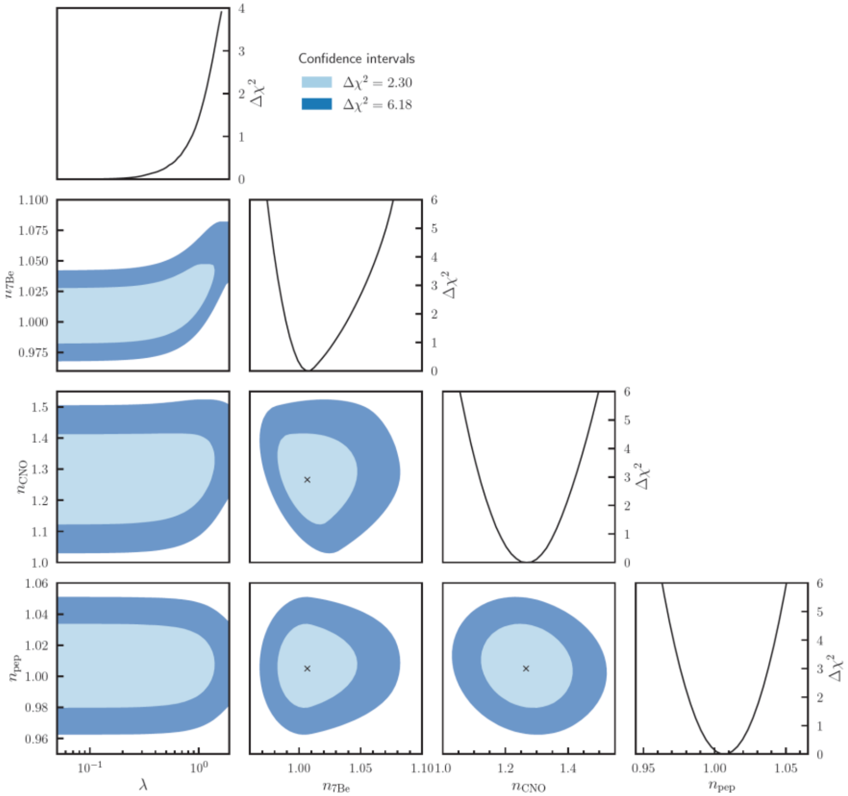
- Sizable neutrino self-interactions can address the tension in Hubble parameter measurements.
- Neutrino self-interactions mediated by a light neutrinophilic scalar has already been tightly constrained by complementary terrestrial, astrophysical, and cosmological probes.
- Neutrino scattering observables ($\nu$DIS, CE$\nu$NS, and solar neutrinos) provide a powerful and direct way to test $\nu$SI through modified cross sections and running electroweak couplings.
- Precision electroweak observables provide additional sensitivity to neutrino and gauge couplings.

Thank you!

# Constraint from Solar Neutrinos

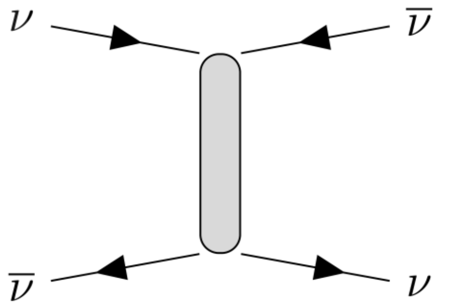
Borexino Phase III analysis of the neutrino self-interaction universal coupling for a fixed mediator mass ($m_\phi = 10$ MeV), allowing the 7Be, pep, and CNO solar neutrino flux normalizations to vary with Gaussian priors around their Standard Solar Model (SSM) predictions



# Continuum Mediation

Neutrino self interaction through the exchange of a mediator with a <u>continuous spectral density function</u>

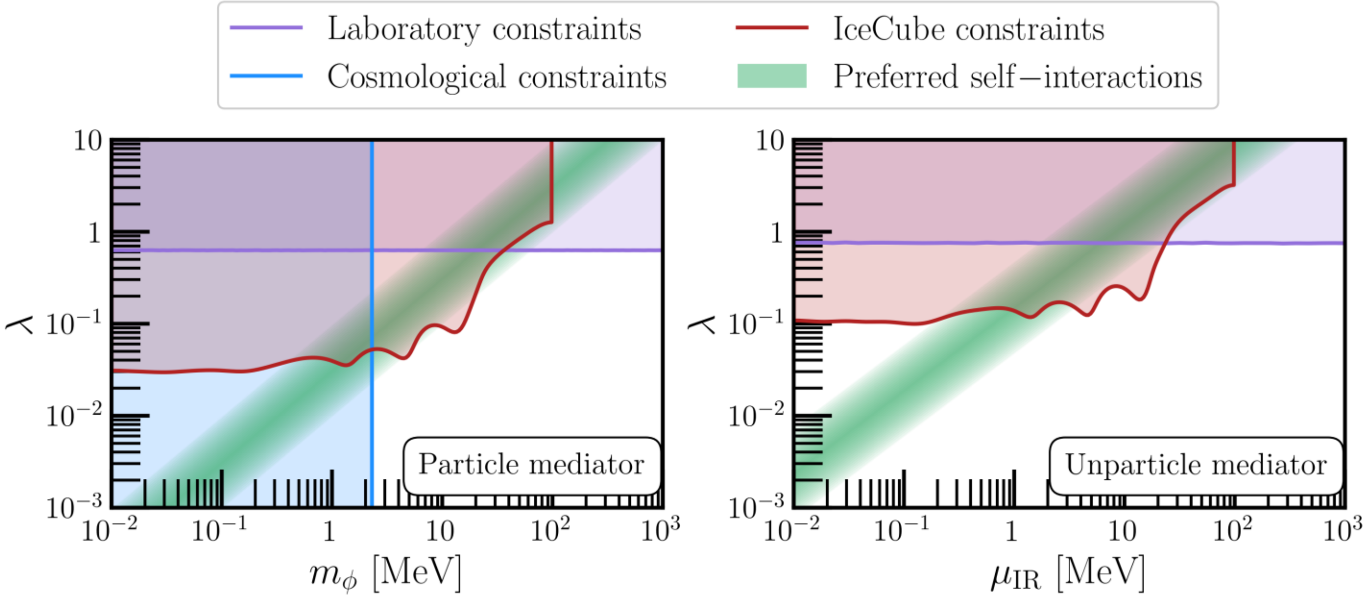



$$\mathcal{L}_{\rm int} = \frac{\lambda}{2\Lambda^{d_u-1}}\, \overline{\nu_\tau^c} P_L \nu_\tau \mathcal{U} + \text{h.c.}$$

Unparticle (conformal theory) is a low energy realization of a theory which has an IR fixed point   Georgi [0703260]

$$iD_F^{\mathcal{U}}(p^2) = \langle 0|\mathcal{O}_{\mathcal{U}}(p)\mathcal{O}_{\mathcal{U}}(-p)|0\rangle = \int_0^\infty \frac{d\mu^2}{2\pi}\frac{i\rho(\mu^2)}{p^2-\mu^2+i\epsilon}$$

$$G_{\rm eff.} = \frac{|B_{d_u}\lambda^2|}{\mu_{\rm IR}^2}\left(\frac{\mu_{\rm IR}}{\Lambda}\right)^{2d_u-2}$$




SF, Kelly, Rai, Zhang [2501.02049]