Hunting Nonstandard Neutrino Interactions in Dark Matter Experiments

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with Tien-Tien Yu

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Outline

- Dark Matter experiments and neutrino scattering
- Light Mediators:
  - Vectors
  - U(1) gauge theories
- Heavy Mediators:
  - Scalars
  - Leptoquarks

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Liquid Noble Element Experiments

Looking for recoiling (nuclei) from collisions with dark matter particles

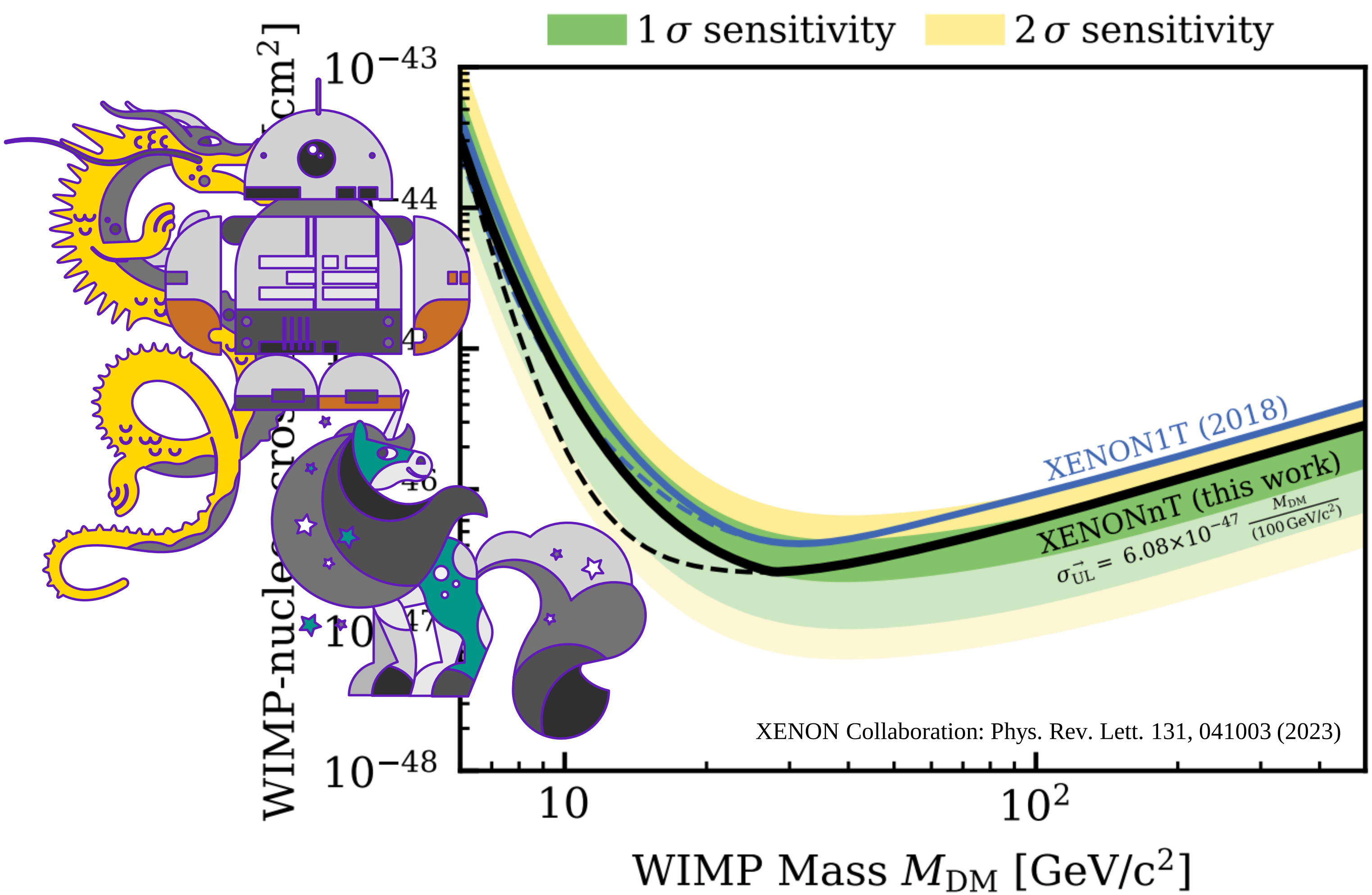
Thresholds of ~keV

Liquid noble element experiments:

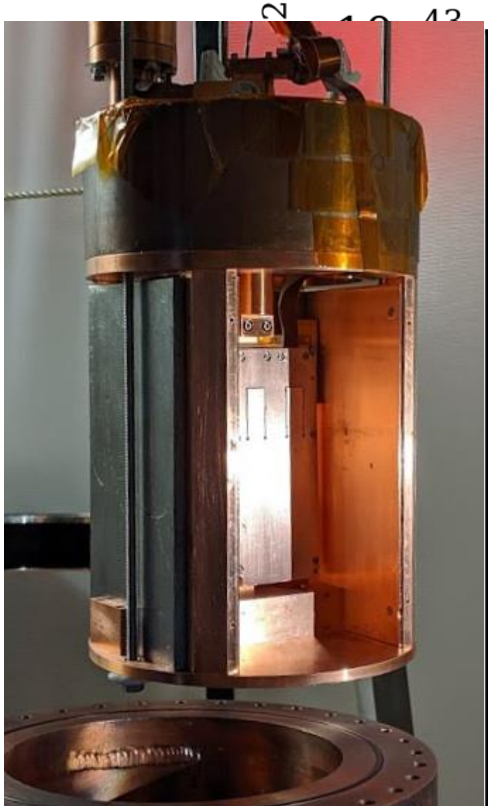
- XENONnT ~1.5 t-yrs (so far)
- LZ ~0.9 t-yrs (so far)

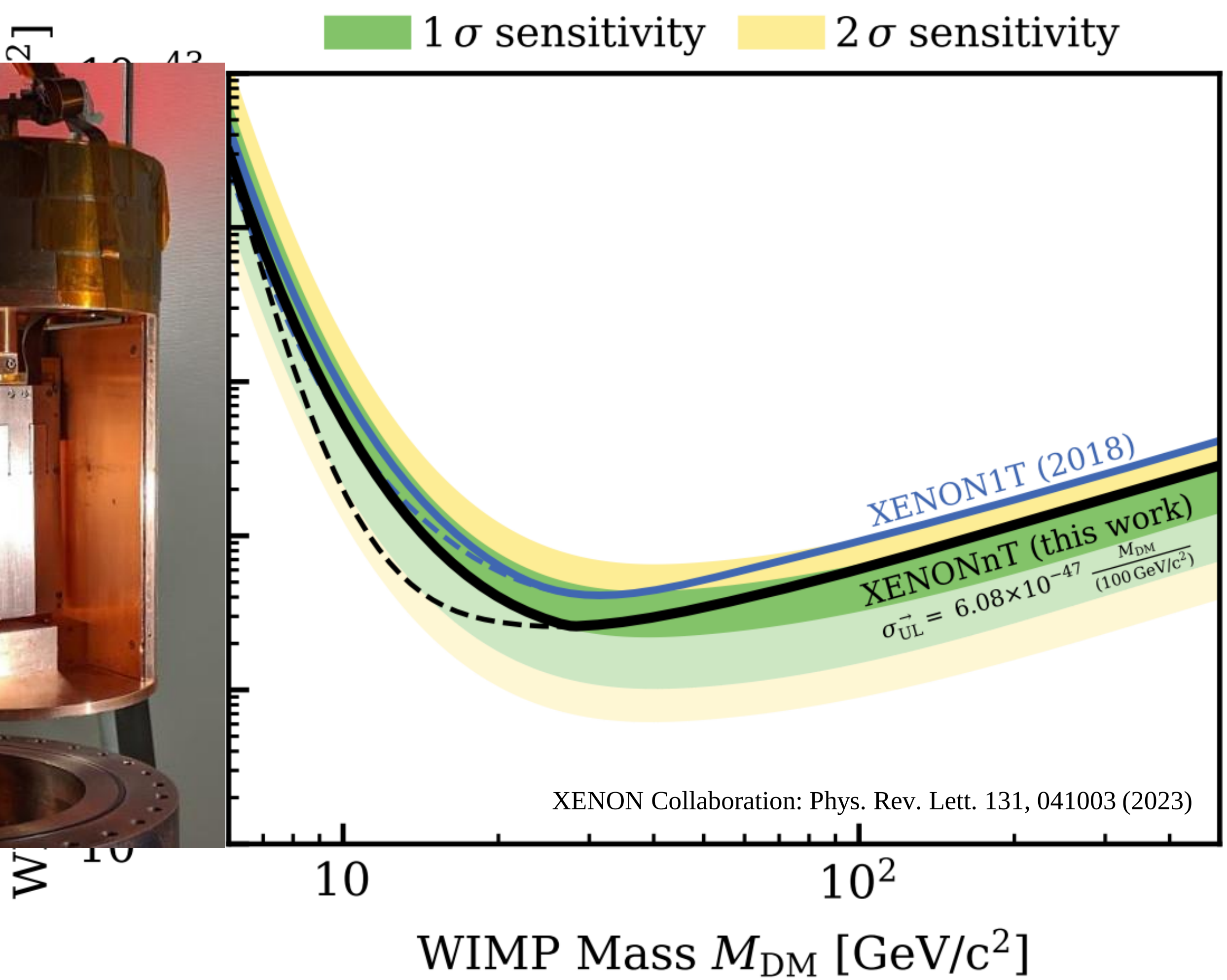
- DarkSide-20k ~50 t-yrs (planned)
- DARWIN ~200 t-yrs (planned)
- Argo ~360 t-yrs (planned)

Liquid Noble Element Experiments



Liquid Noble Element Experiments





XENON Collaboration: Phys. Rev. Lett. 131, 041003 (2023)

Semiconductor Experiments

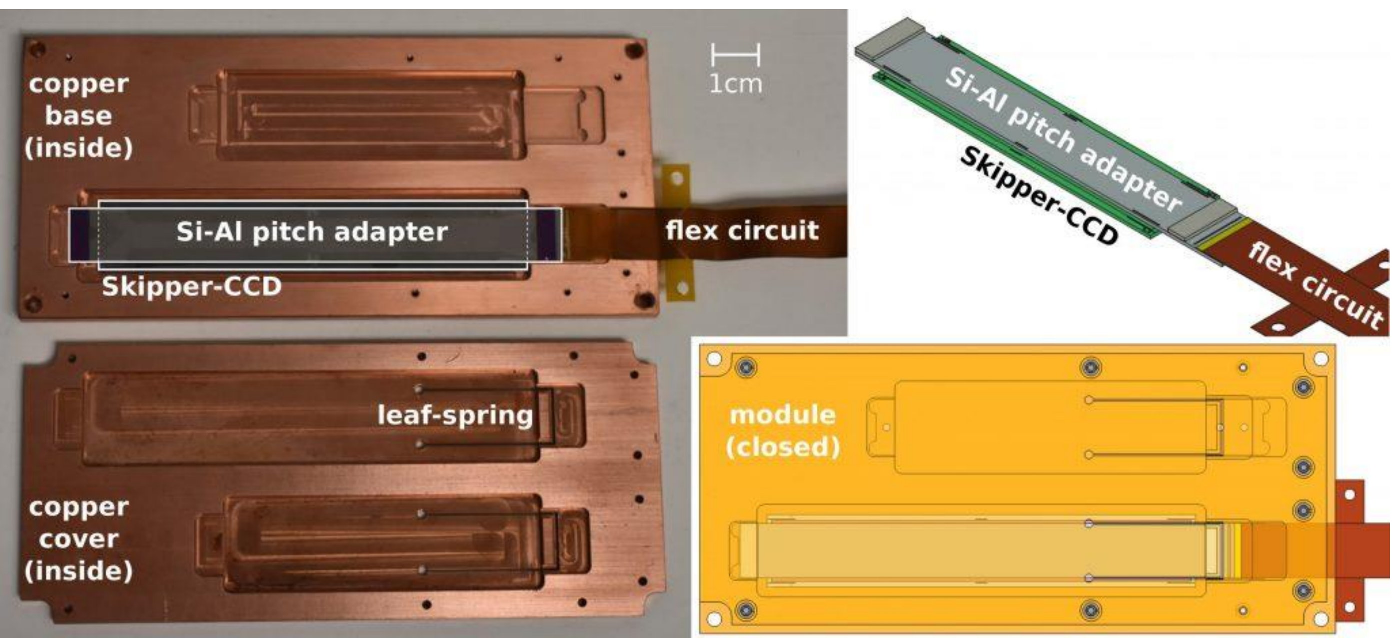
Pushing to lower masses:

- Smaller experiments
- Thresholds of ~eV
- Emphasis on electron recoils

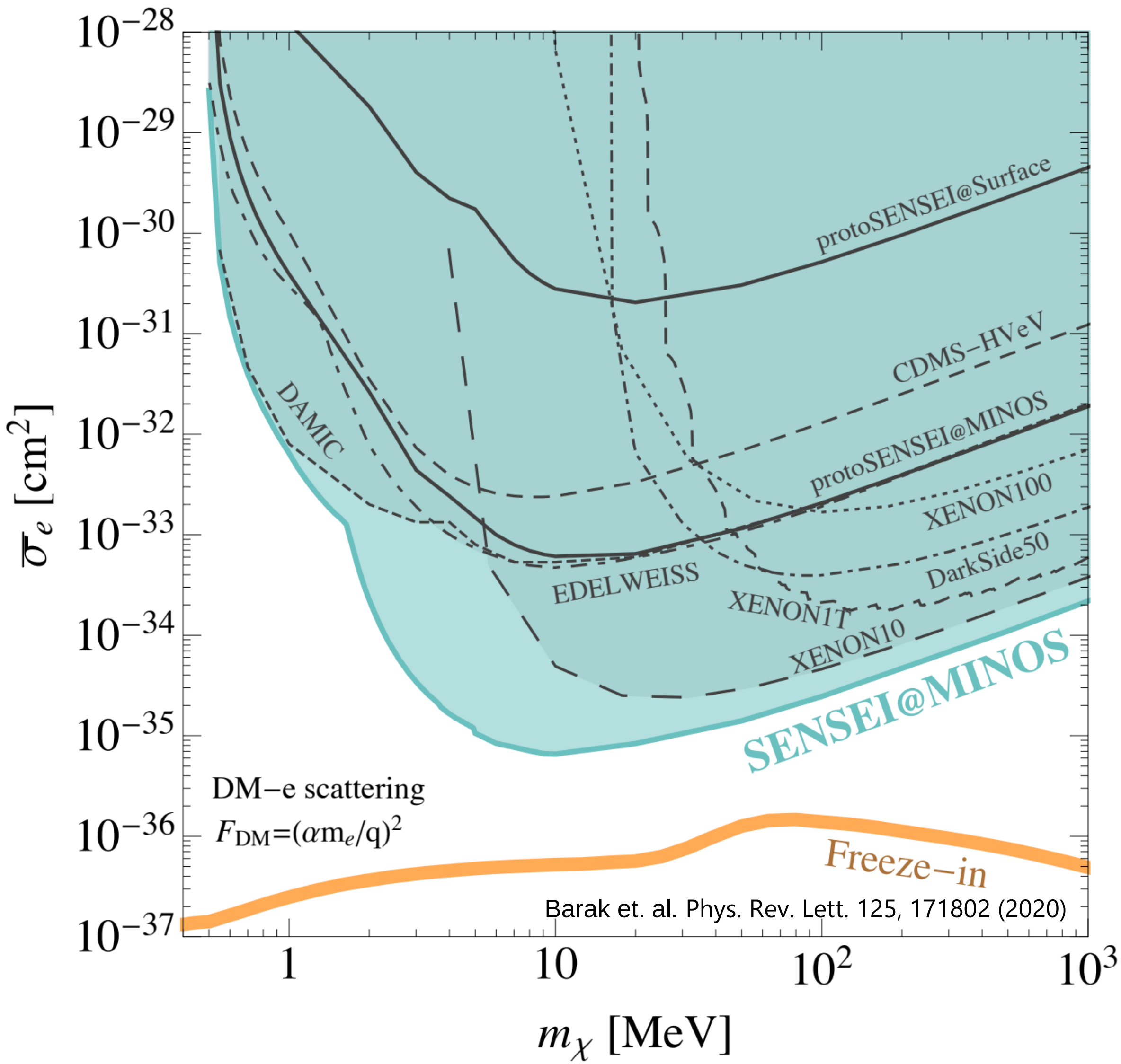
Experiments:

- Edelweiss
- CDMS
- Sensei ~9 g-days (so far)

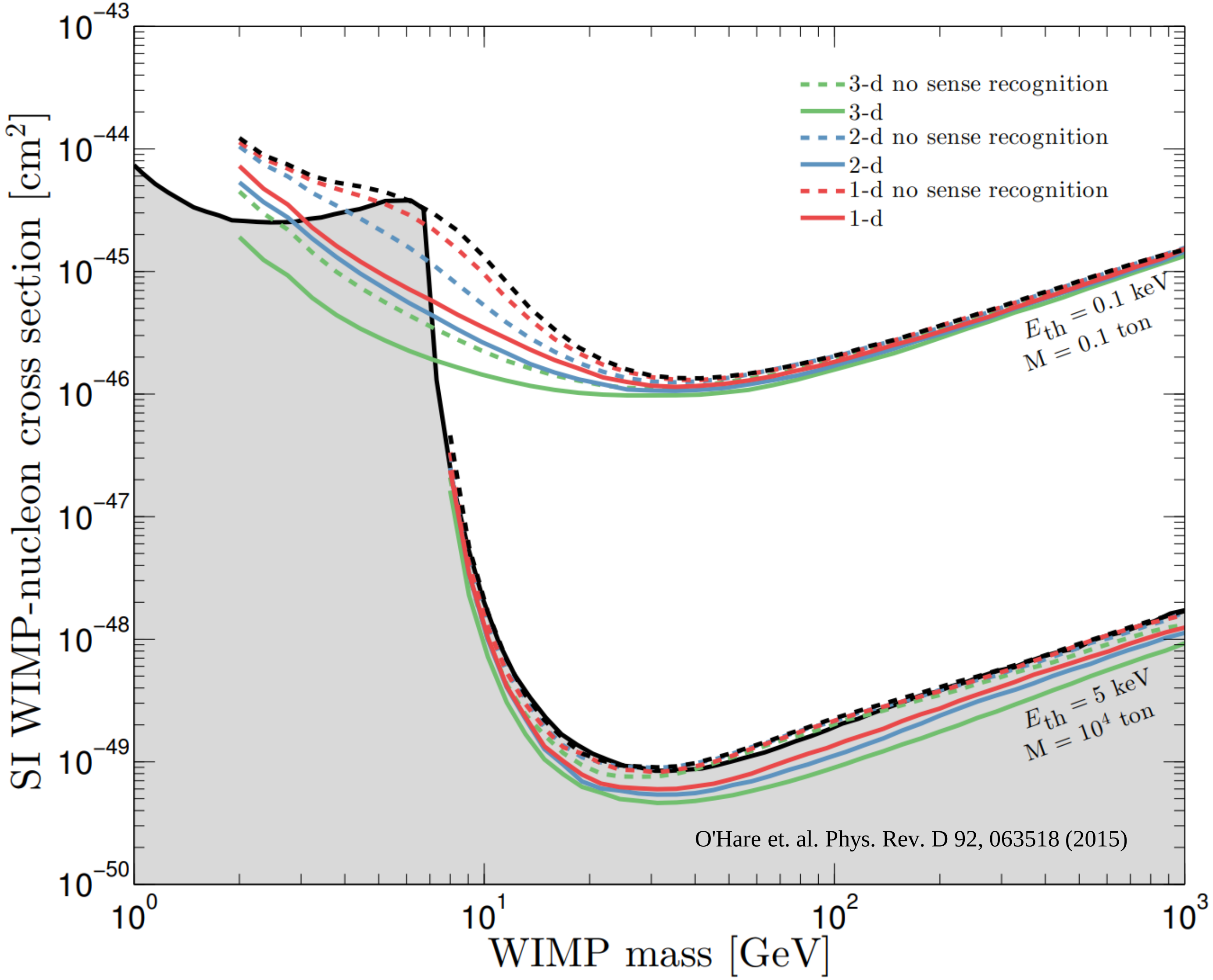
- Sensei ~100 g-yrs (planned)
- Oscura ~30 kg-yrs (planned)



Semiconductor Experiments



The Neutrino Floor



Neutrino Scattering

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

$$E_{min} = \sqrt{\frac{m_T E_R}{2}}$$

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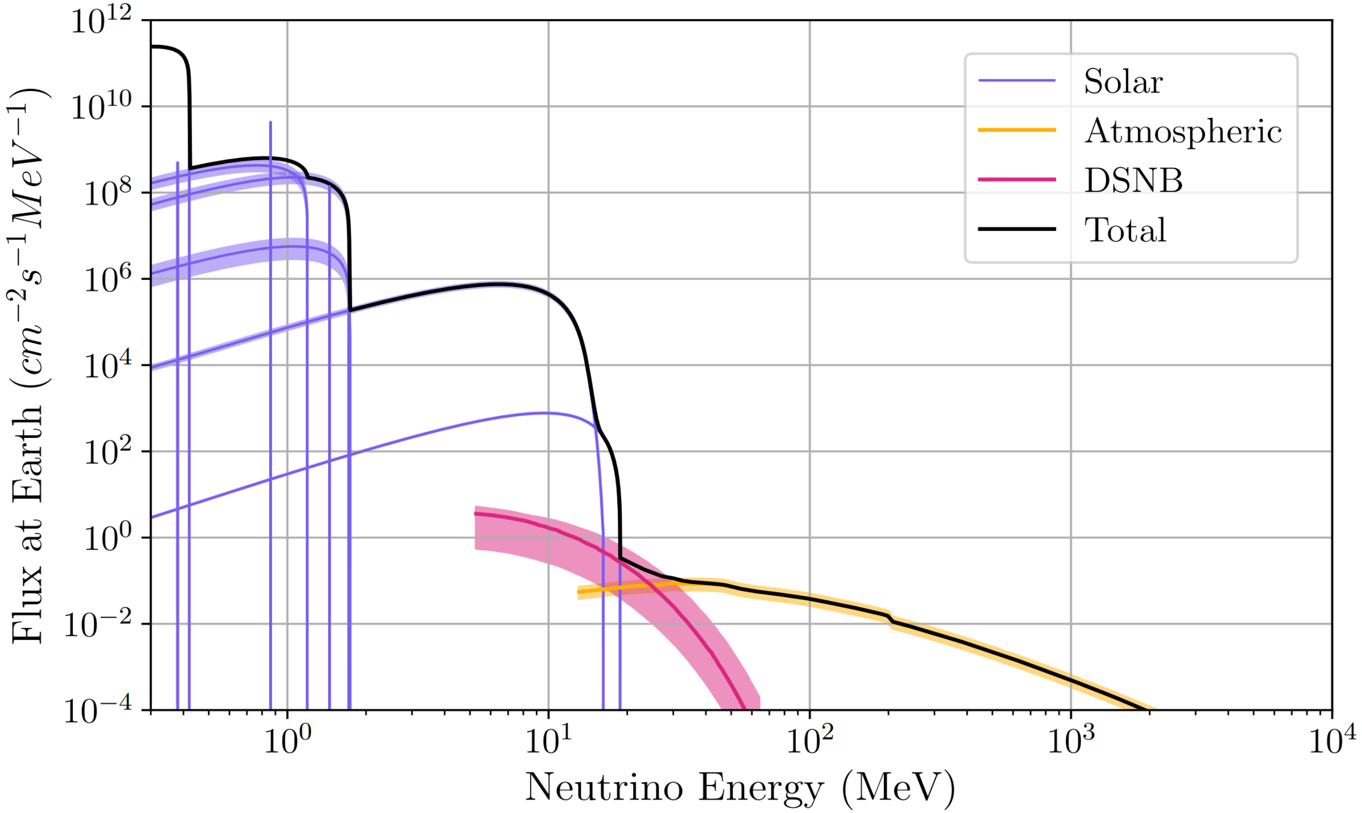
The Neutrino Flux

Solar:
Nuclear processes, two main production chains: *pp* and CNO

Diffuse Supernova Neutrino Background (DSNB):
Theoretical prediction of neutrinos from the cosmic history of supernovae

Atmospheric:
Produced in the decays of pions from cosmic rays

- Contains ν and $\bar{\nu}$
- Produced with μ and e flavors



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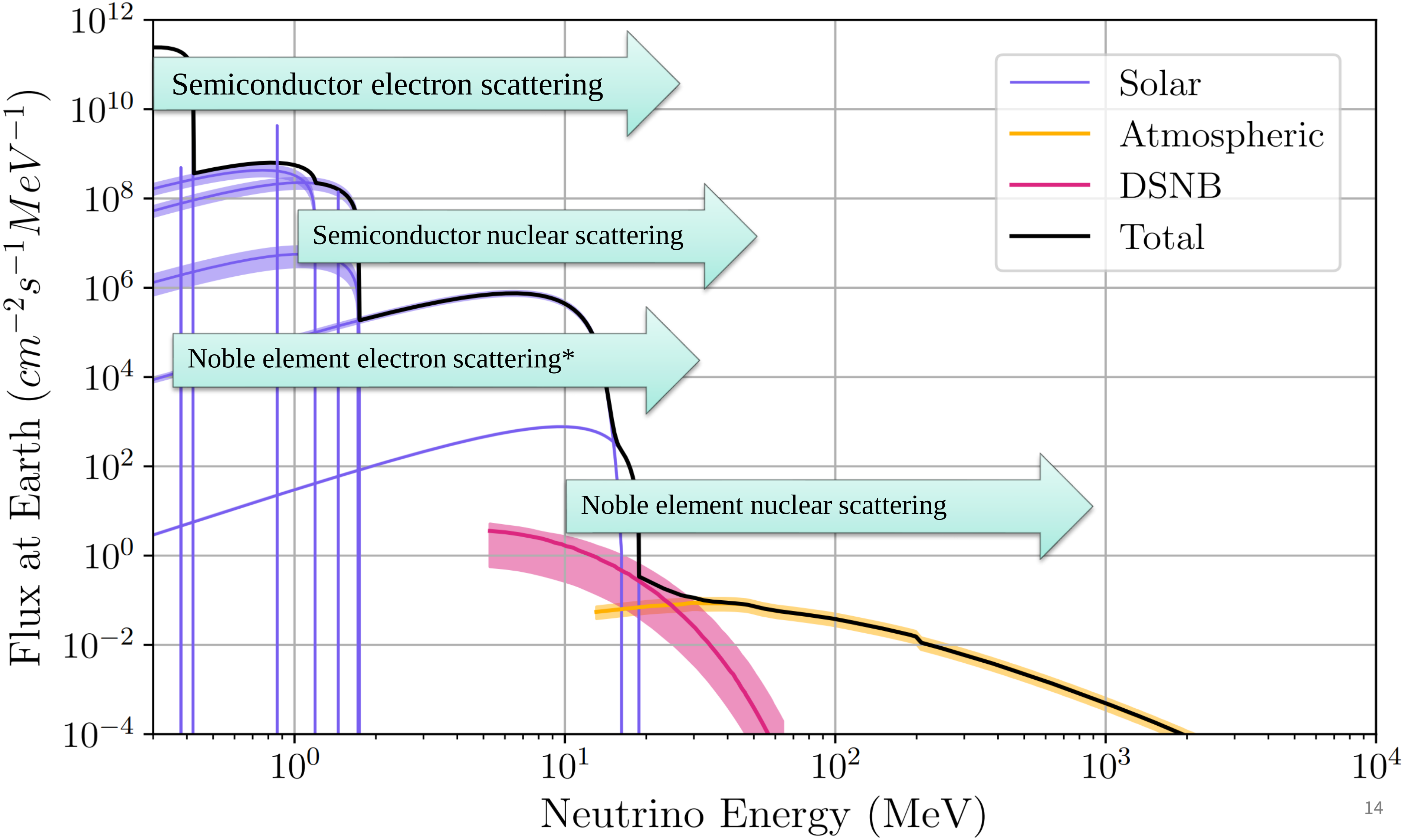
The Neutrino Flux



Neutrino Scattering

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

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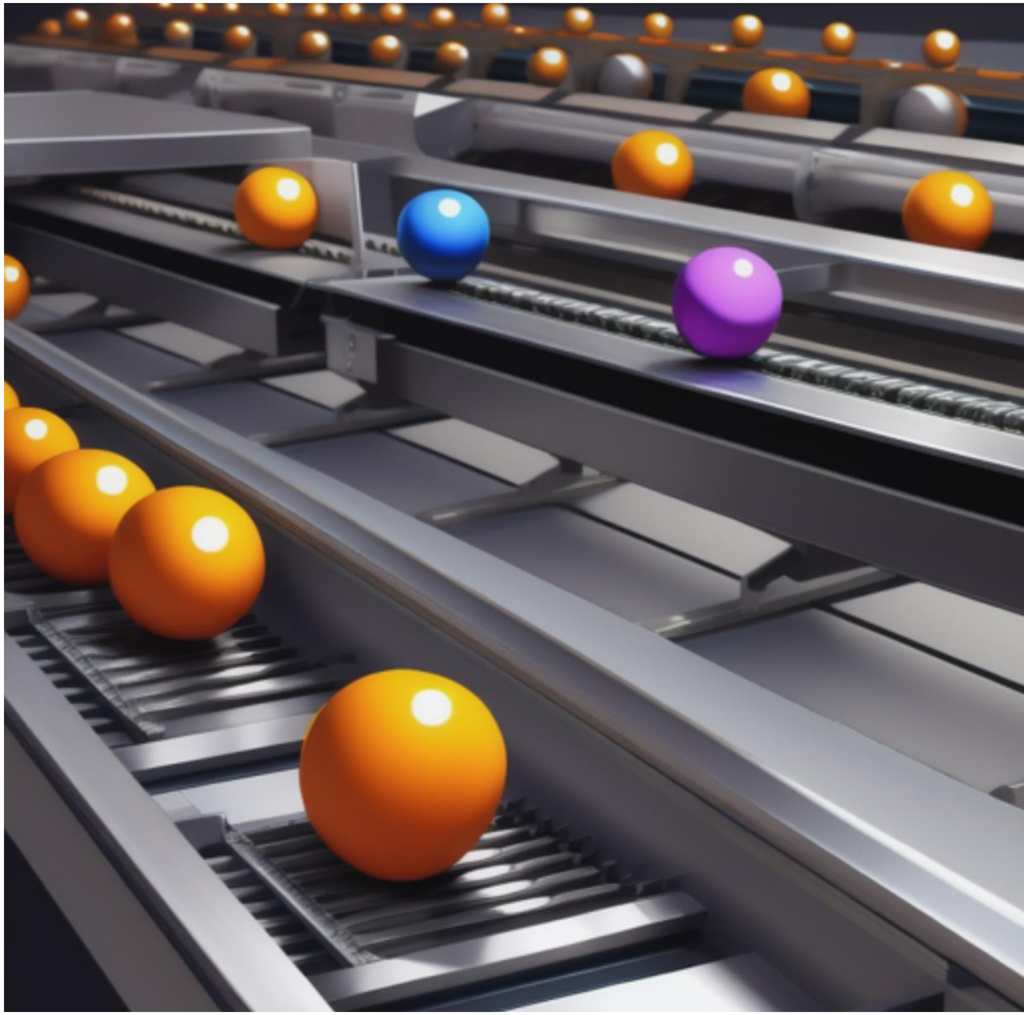
Neutrino Scattering

$$\frac{dR}{dE_R} = N_T \sum_{\ell} \int_{E_{min}}^{\infty} \frac{d\sigma_\ell}{dE_R} \frac{dN_{\nu_\ell}}{dE_{\nu_\ell}} dE_\nu$$

$$E_{min} = \sqrt{\frac{m_T E_R}{2}}$$

Neutrino Flavors and Oscillations (Round 1)

- Long baseline → All flavors
- Reactor neutrino experiments are generally only sensitive to electron neutrinos
- Scattering rates differ for neutrino flavors
  - Only electron neutrinos interact via charged current
  - Certain BSM models such as gauged $L_\mu - L_\tau$ don't affect electron neutrinos



Neutrino Scattering

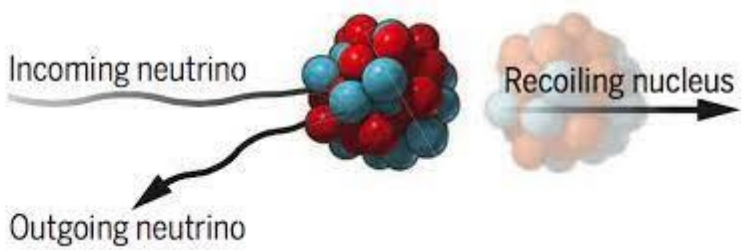
$$\frac{dR}{dE_R} = N_T \int_{E_{min}}^{\infty} \boldsymbol{\frac{d\sigma}{dE_R}} \frac{dN_\nu}{dE_\nu} dE_\nu$$

$$E_{min} = \sqrt{\frac{m_T E_R}{2}}$$

Neutrino Interactions

Coherent Elastic Neutrino Nuclear Scattering (CEνNS)

- Low energy effective couplings



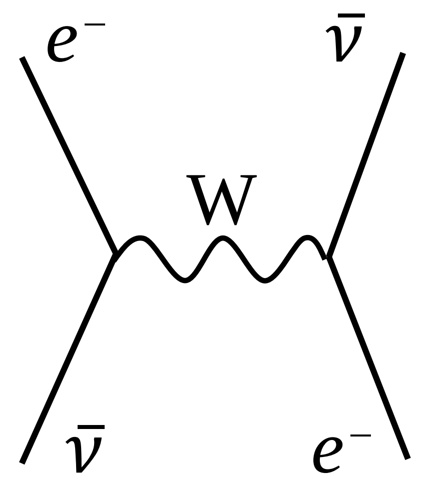
$$\frac{d\sigma}{dE_R} \sim Q^2 m_N \qquad\qquad Q \sim N - Z \times (1 - 4s_w)$$

- Energy independent for $E_R < E_\nu^2/m_N$

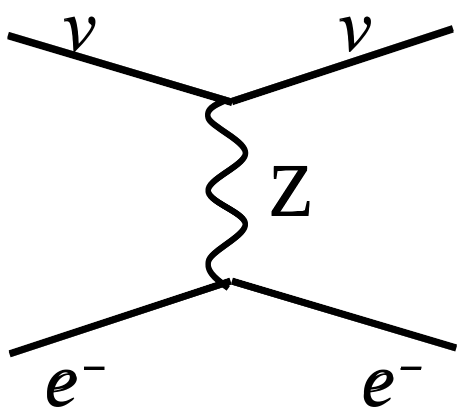
Neutrino Interactions

ν — e scattering:

- Charged Current



- Neutral Current



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- **Light Mediators:**
  - **Vectors**
  - U(1) gauge theories
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  - Scalars
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Beyond the Standard Model — Light Mediators

Mediator	Couplings	Lorentz Structure	Cross-Section Scaling
Scalar (S)	$g_{\nu S}, g_{eS}, g_{qS}$	$\phi \bar{f} f$	$1/E_R$
Pseudoscalar (P)	$g_{\nu P}, g_{eP}, g_{qP}$	$i\gamma^5 \phi \bar{f} f$	const.
Vector (V)	$g_{\nu V}, g_{eV}, g_{qV}$	$Z'_\mu \bar{f} \gamma^\mu f$	$1/E_R^2$
Axial Vector (A)	$g_{\nu A}, g_{eA}, g_{qA}$	$Z'_\mu \bar{f} \gamma^\mu \gamma^5 f$	$1/E_R^2$

Even assuming flavor diagonal couplings... That's a lot of parameters

Flavor Universal Interactions:

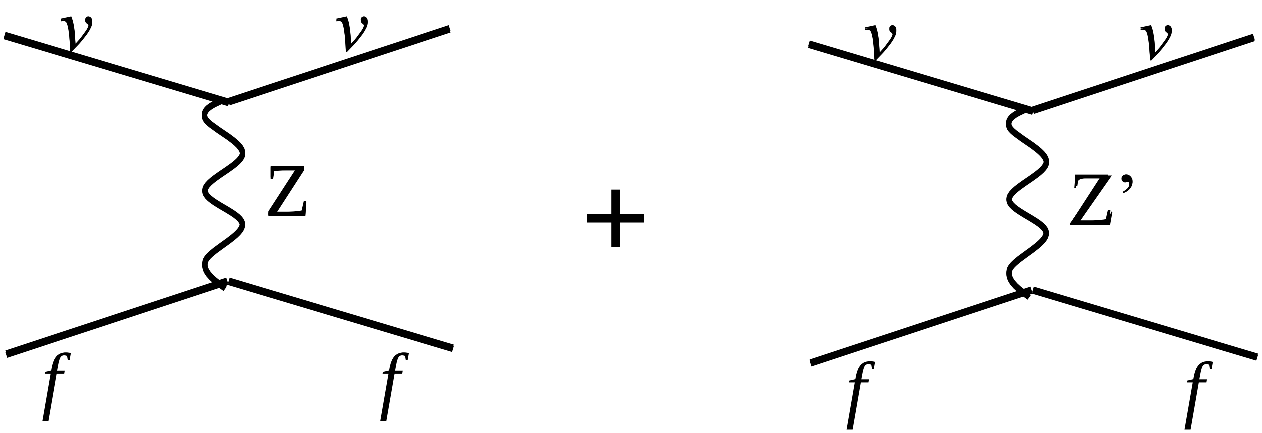
- Couplings to all neutrinos and quarks are identical

Minimal NSI:

- Couplings to only one flavor of neutrino and quark

Low threshold detectors → Most interested in vector mediators

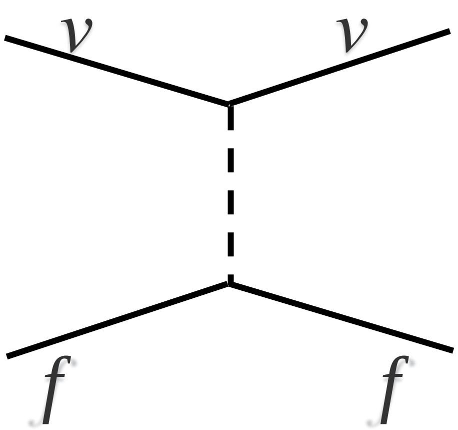
Vector Mediators



$$\sim \cancel{\frac{g^2}{p_Z^2 - m_Z^2}} \quad \frac{1}{m_Z^2} \qquad\qquad \sim \cancel{\frac{g^2}{p_{Z'}^2 - m_{Z'}^2}} \quad \frac{1}{E_R\, m_f}$$

- $M_{Z'} \ll M_Z \rightarrow$ momentum dependence is only relevant for Z'
  - NSI contribution scales as $1/E_R^2$
  - Cross term scales as $1/E_R$
- BSM nuclear coupling $\sim g^2 N_q$

Scalar Mediators



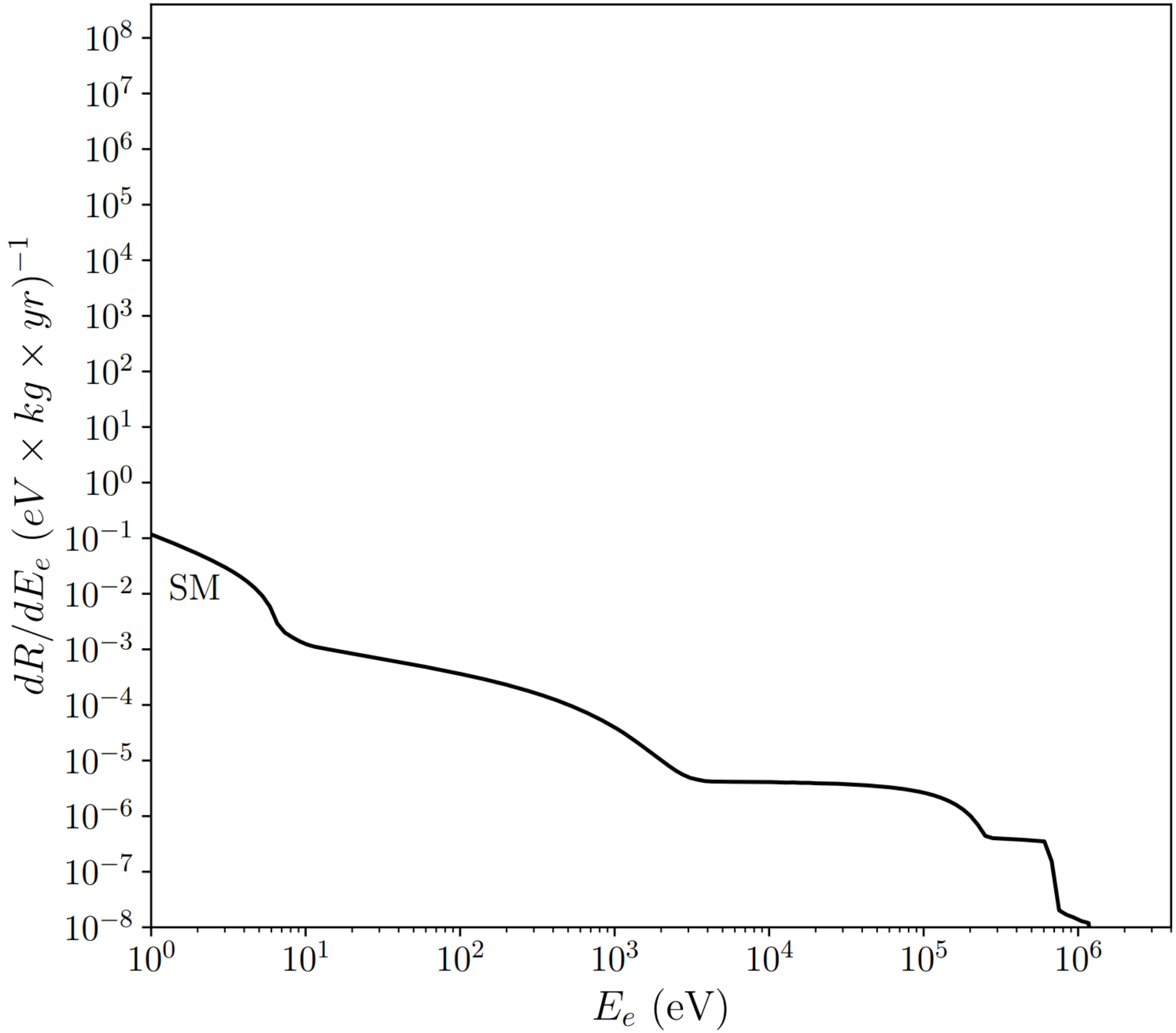
$$\sim \frac{E_R}{\left(E_R m_f + m_S^2\right)^2}$$

- No interference term
- Nuclear coupling is determined numerically and summed over quark content to give *Q'* ~ 14A + 1.1Z
- Low Energy: cross-section scales as $1/E_R$ until the propagator momentum becomes smaller than its mass

Differential recoil rates

Low Energy

- Solar neutrinos dominate

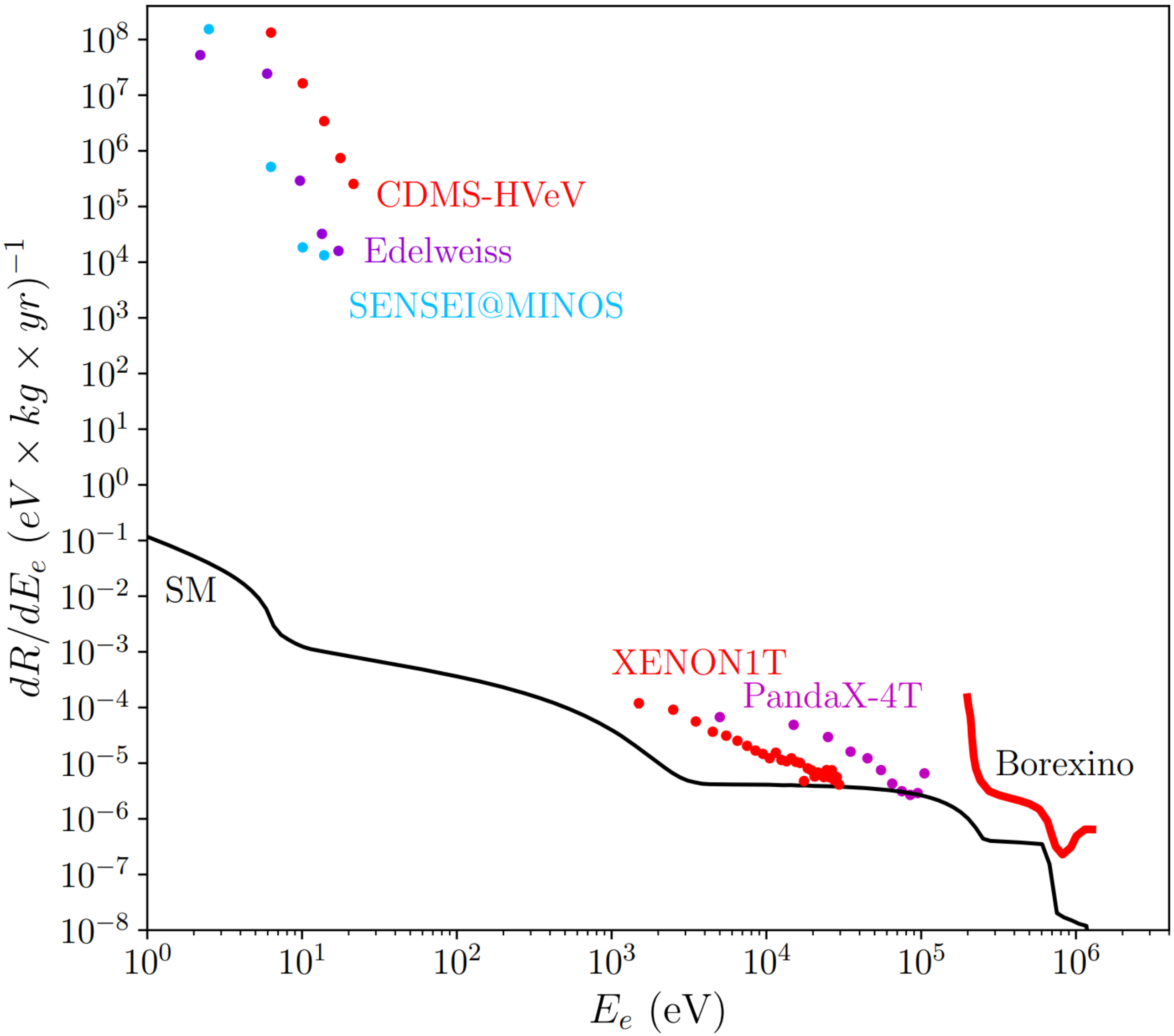


Differential recoil rates

Low Energy

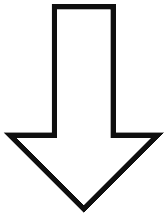
- Solar neutrinos dominate

Weaker constraints below ~ keV



Differential recoil rates

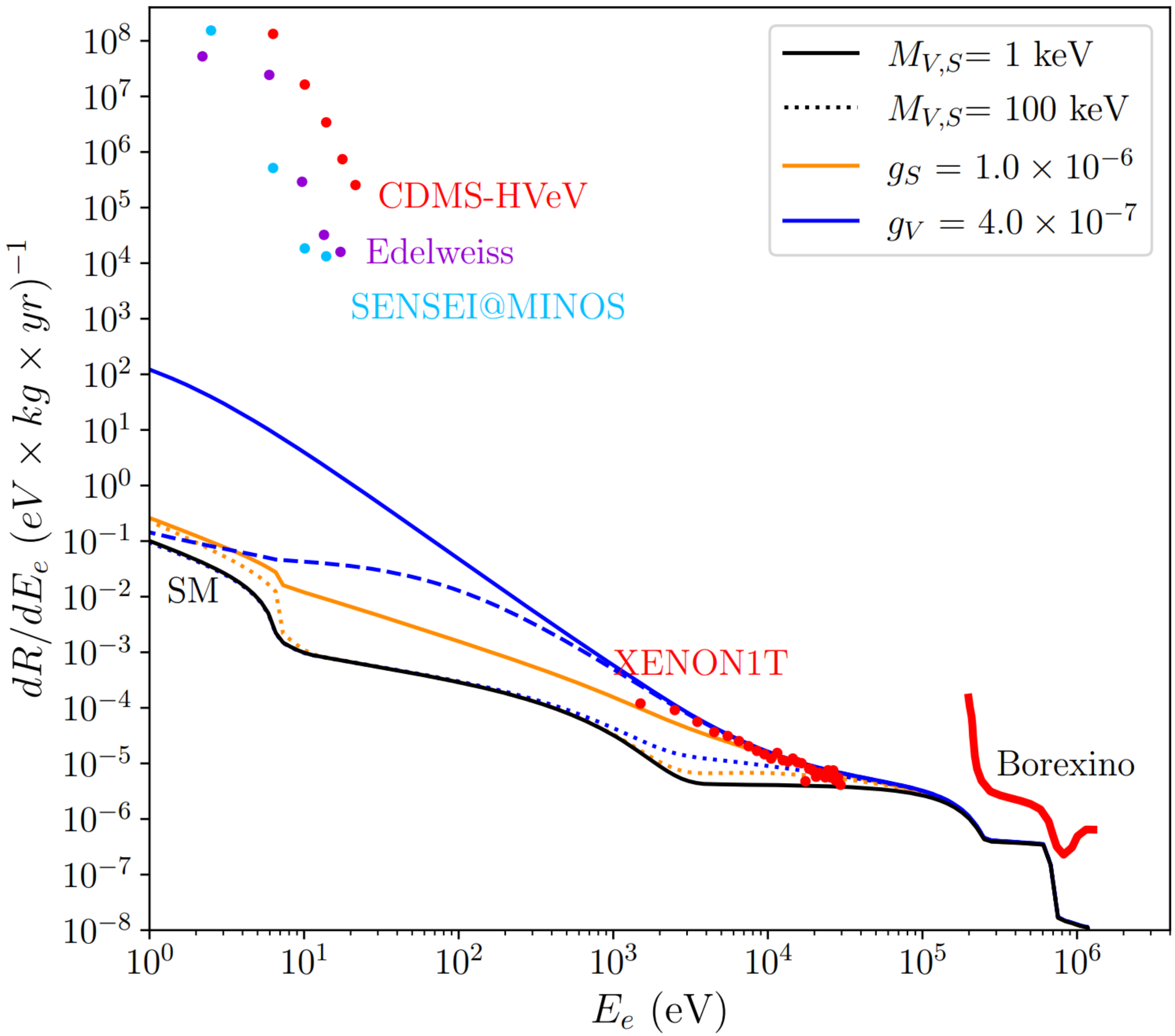
Low Energy



- Solar neutrinos dominate

Weaker constraints below ~ keV

Light vectors are most visible



Signals in Dark Matter Experiments

Large liquid noble element detectors

NEST simulation

Low threshold semiconductor detectors

Energy bins → electron counts

Semiconductor signals

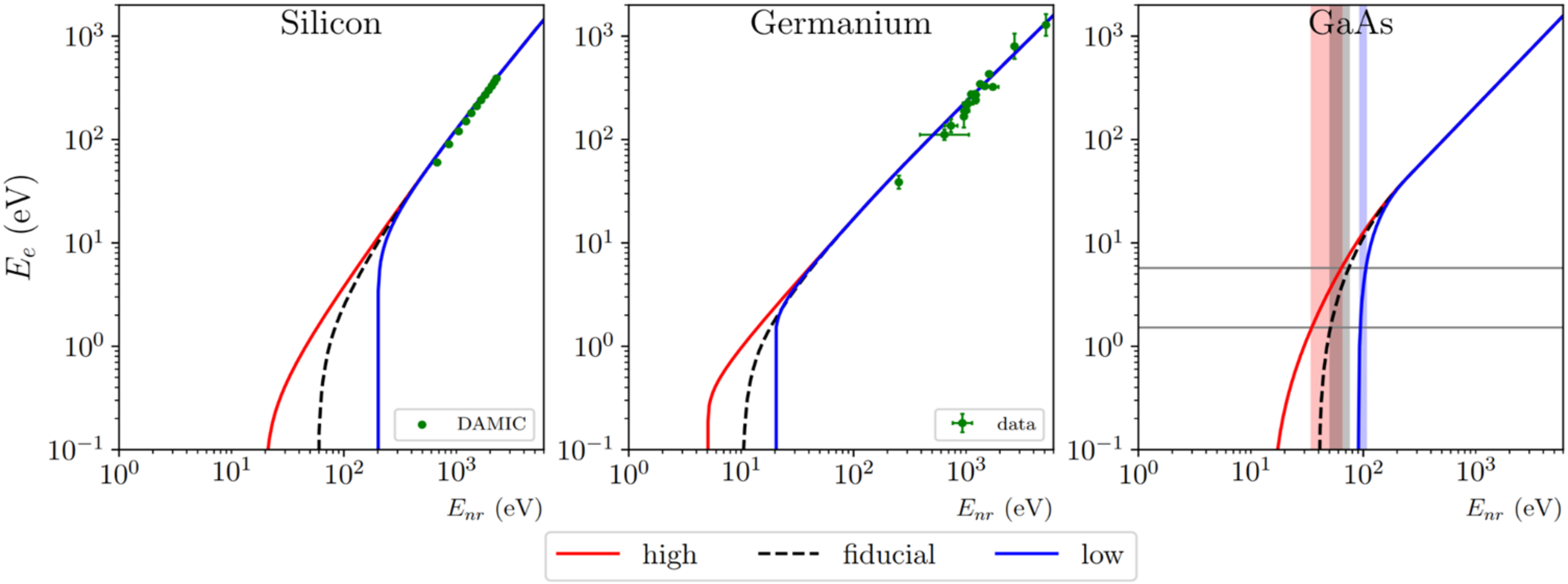
Electron recoils:

- Simple linear model of energy bands

Nuclear recoils:

- Higher recoil energy for the same number of electrons
- Yield Function—Lindhard Model
    - Doesn’t match data at low energies
    - Neglects binding energy

Low energy modifications to the Lindhard Model



Energies on the y-axis correspond to the number of electrons excited to the conduction band

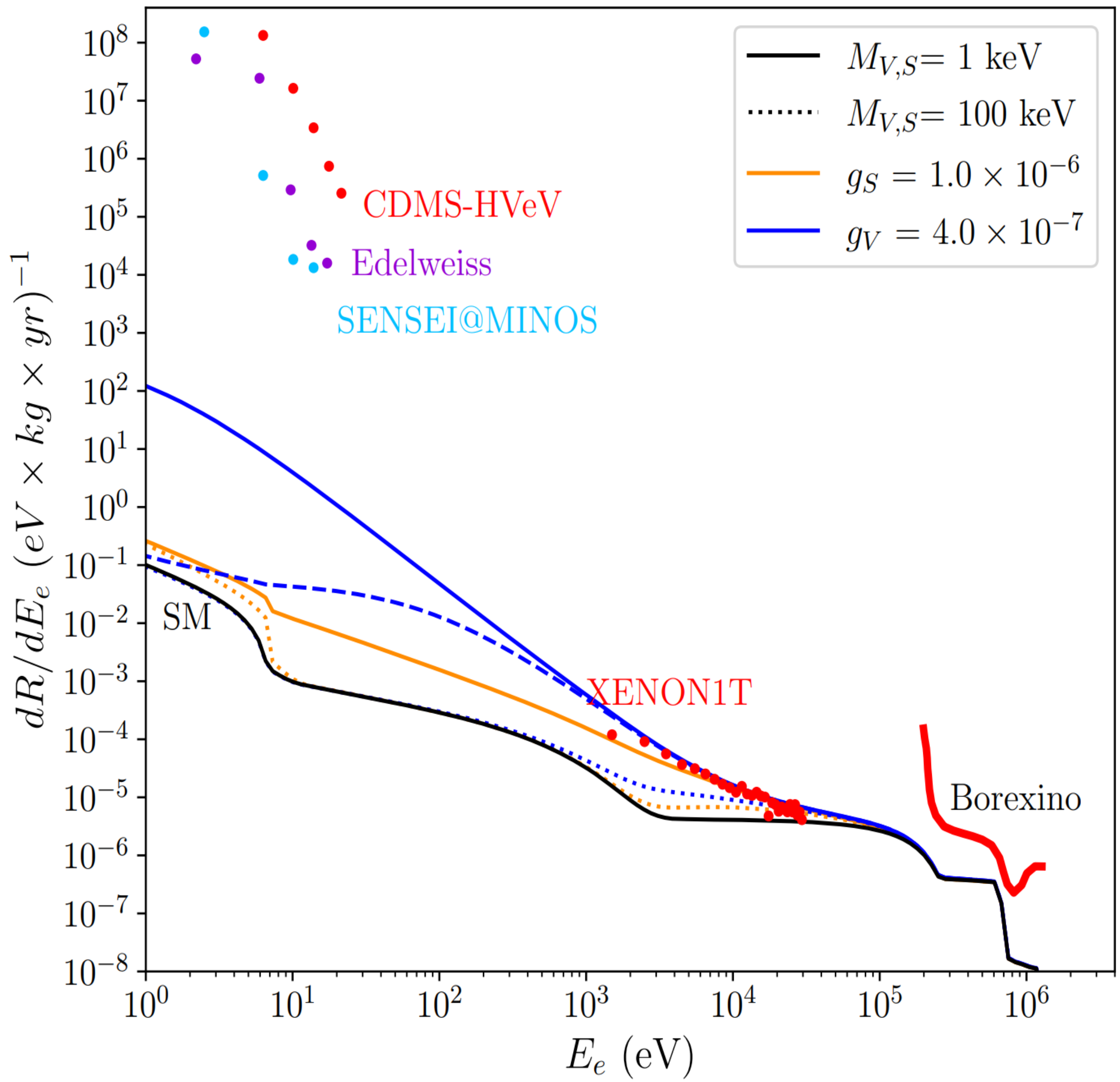
Observable Event Rates

Electron Recoils:

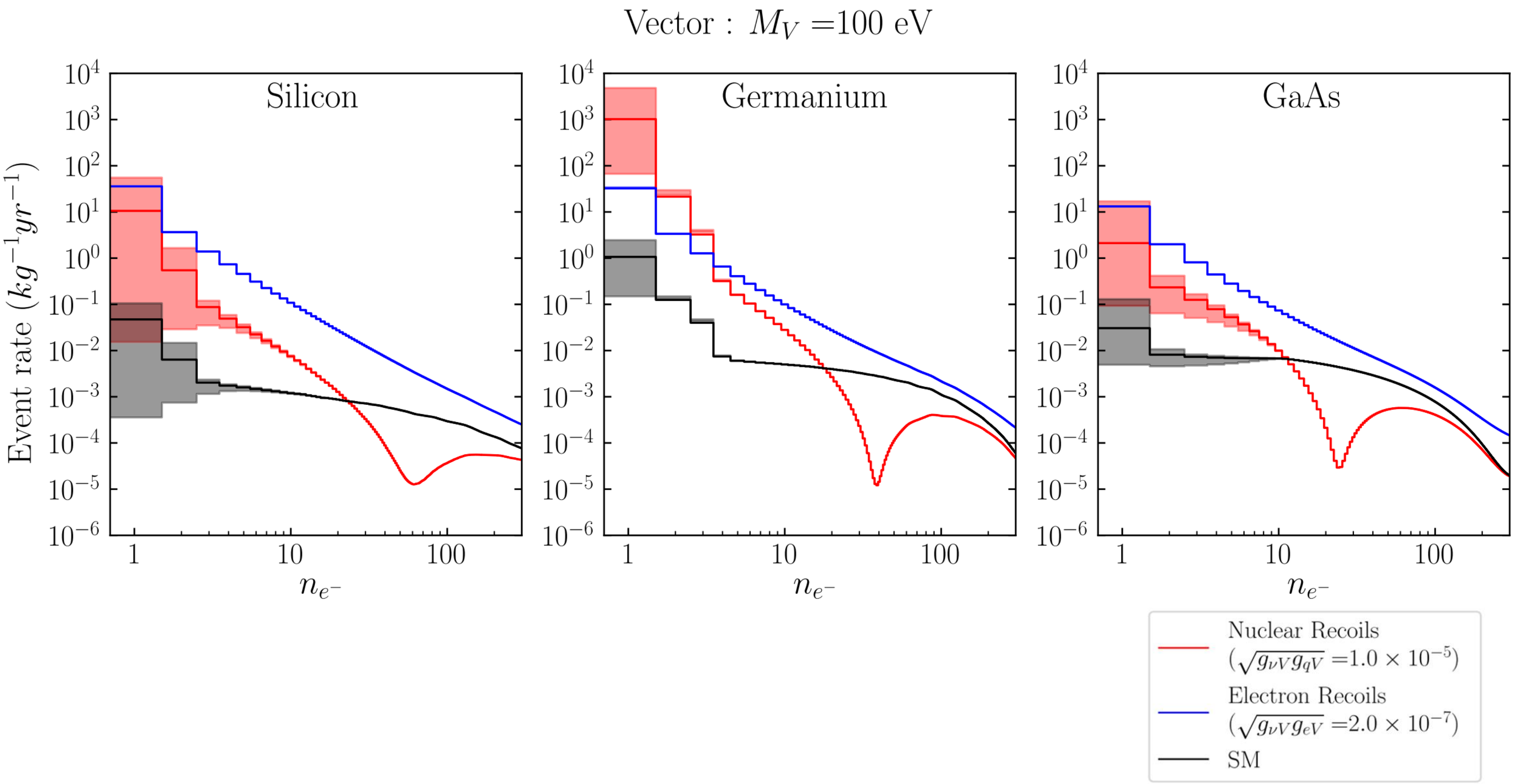
- Integrate the differential rate over the range of energies corresponding to each electron bin

Nuclear Recoils:

- Convert electron bins to nuclear recoil energies and integrate
- Weight by the derivative of the yield function

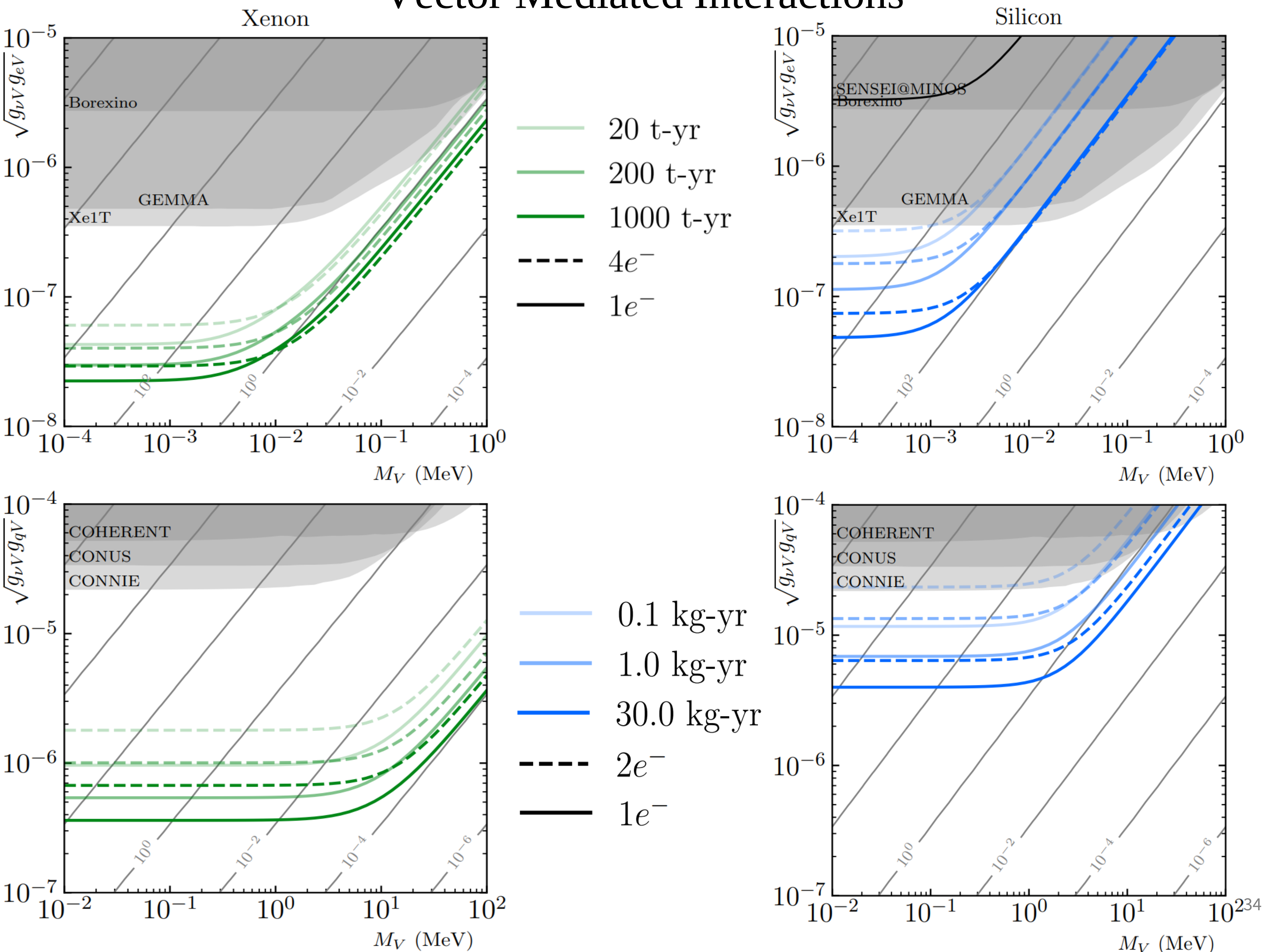


Vector event rates



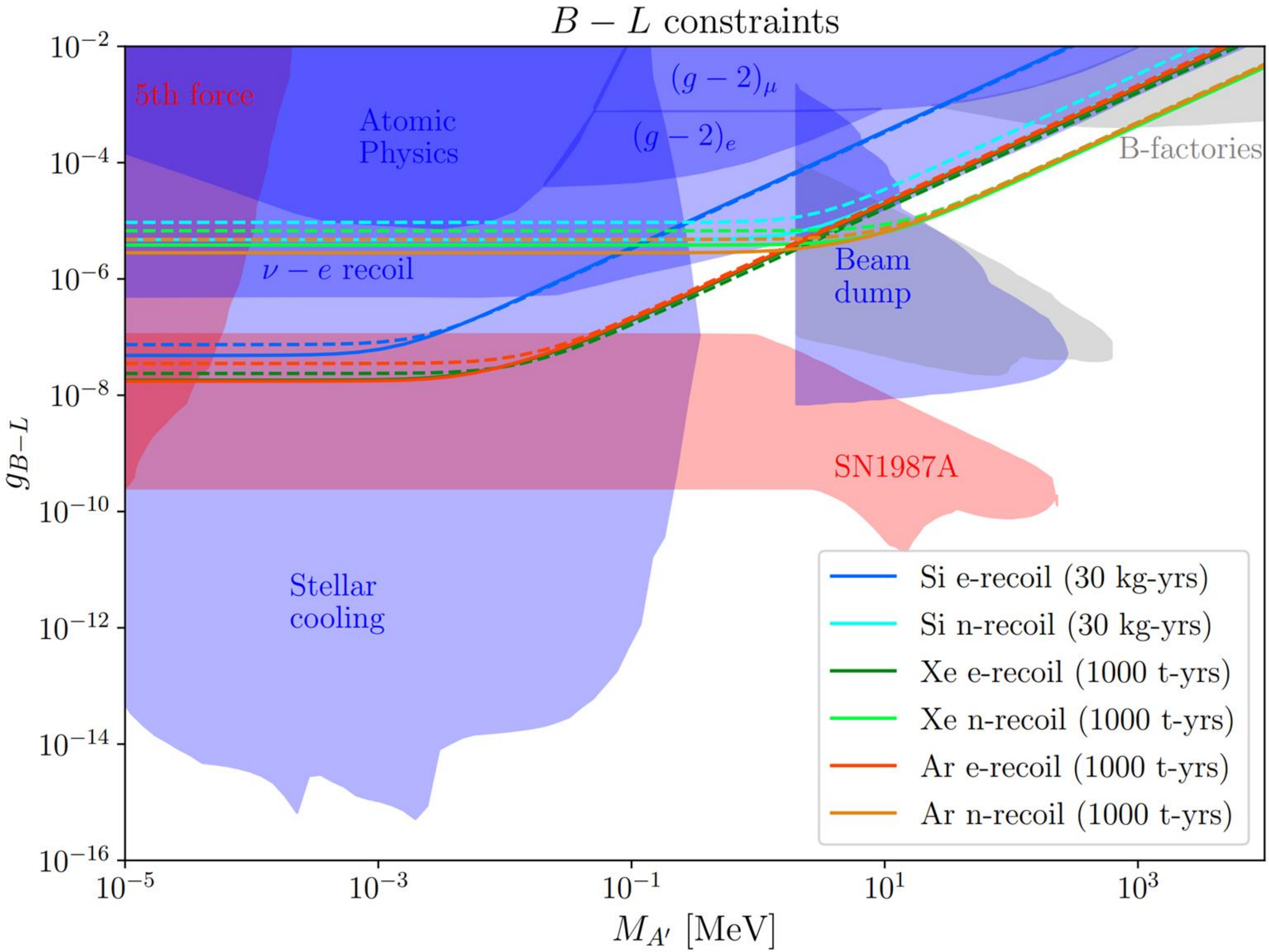
Projected Sensitivities

Vector Mediated Interactions



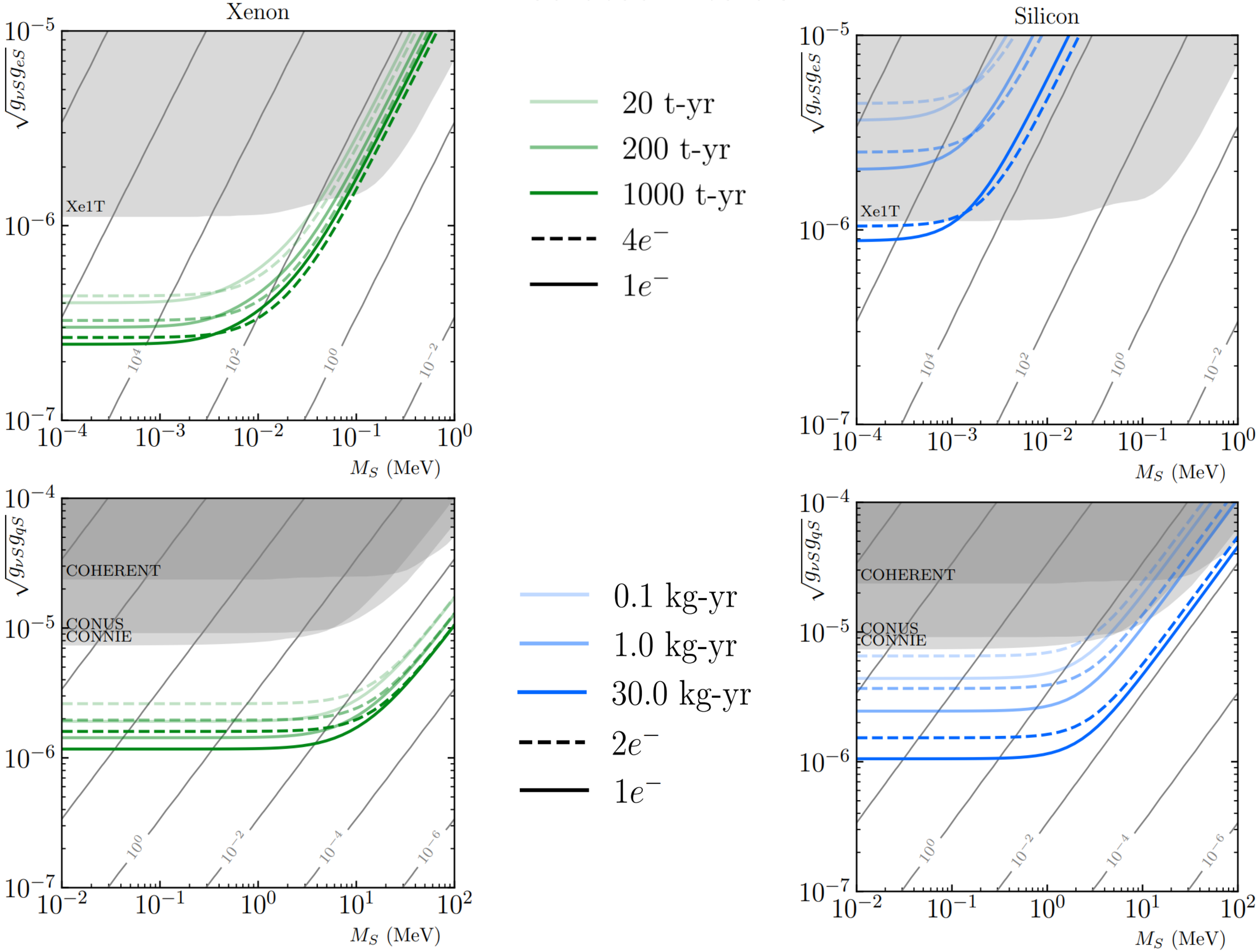
Mapping to U(1) B - L

Gauged B - L



$B - L$ constraints
5th force
Atomic Physics
$(g-2)_\mu$
$(g-2)_e$
B-factories
$\nu - e$ recoil
Beam dump
SN1987A
Stellar cooling
Si e-recoil (30 kg-yrs)
Si n-recoil (30 kg-yrs)
Xe e-recoil (1000 t-yrs)
Xe n-recoil (1000 t-yrs)
Ar e-recoil (1000 t-yrs)
Ar n-recoil (1000 t-yrs)
g_{B-L}
$M_{A'}$ [MeV]
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-12}
10^{-14}
10^{-16}
10^{-5}
10^{-3}
10^{-1}
10^{1}
10^{3}

Scalar Mediated Interactions



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- **Heavy Mediators:**
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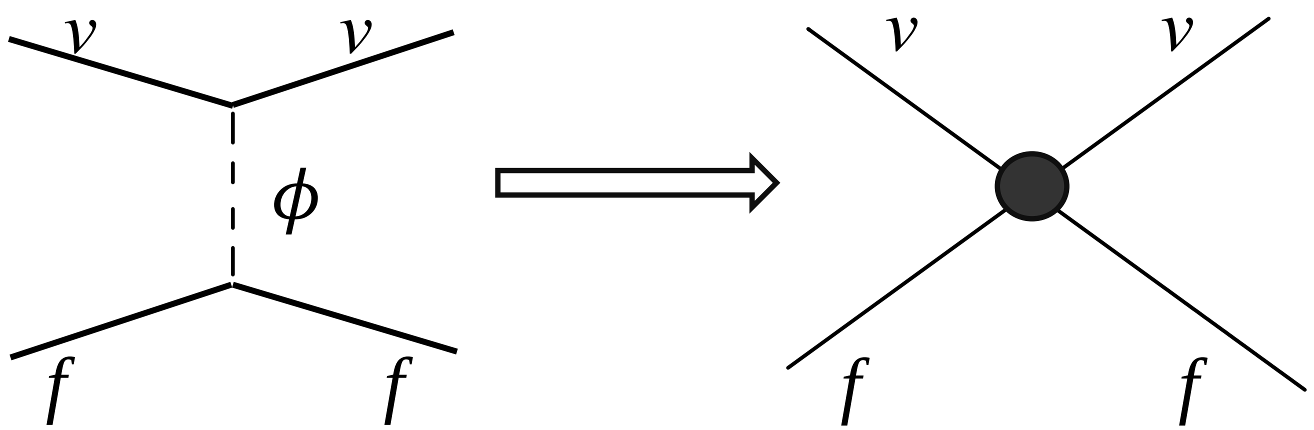
Heavy Scalars

- $M_S \gg E_R \rightarrow$ Integrate out the scalar (conventional NSI)

- Minimal → Only one flavor of neutrino scatters off one species of fermion
  - ❖ Need to be more careful about neutrino oscillations

- Consider higher energy recoils
  - ❖ Liquid noble elements and energy binning
  - ❖ Include other neutrino sources

Integrating out the mediator



- With $m_S \gtrsim 1$ TeV and $E_R \lesssim 1$ MeV we can integrate out the field ϕ

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

Scalar NSI

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

- Standard Scalar NSI parameterization
- Lepton Flavor Violation (LFV) constraints → Only consider one lepton coupling at a time
- ϵ^S_{qe} is well constrained → look at $\epsilon^S_{q\mu}$ and $\epsilon^S_{q\tau}$ instead
  - Looking at specific neutrinos → treat oscillations more carefully

Neutrino Oscillations (Round 2)

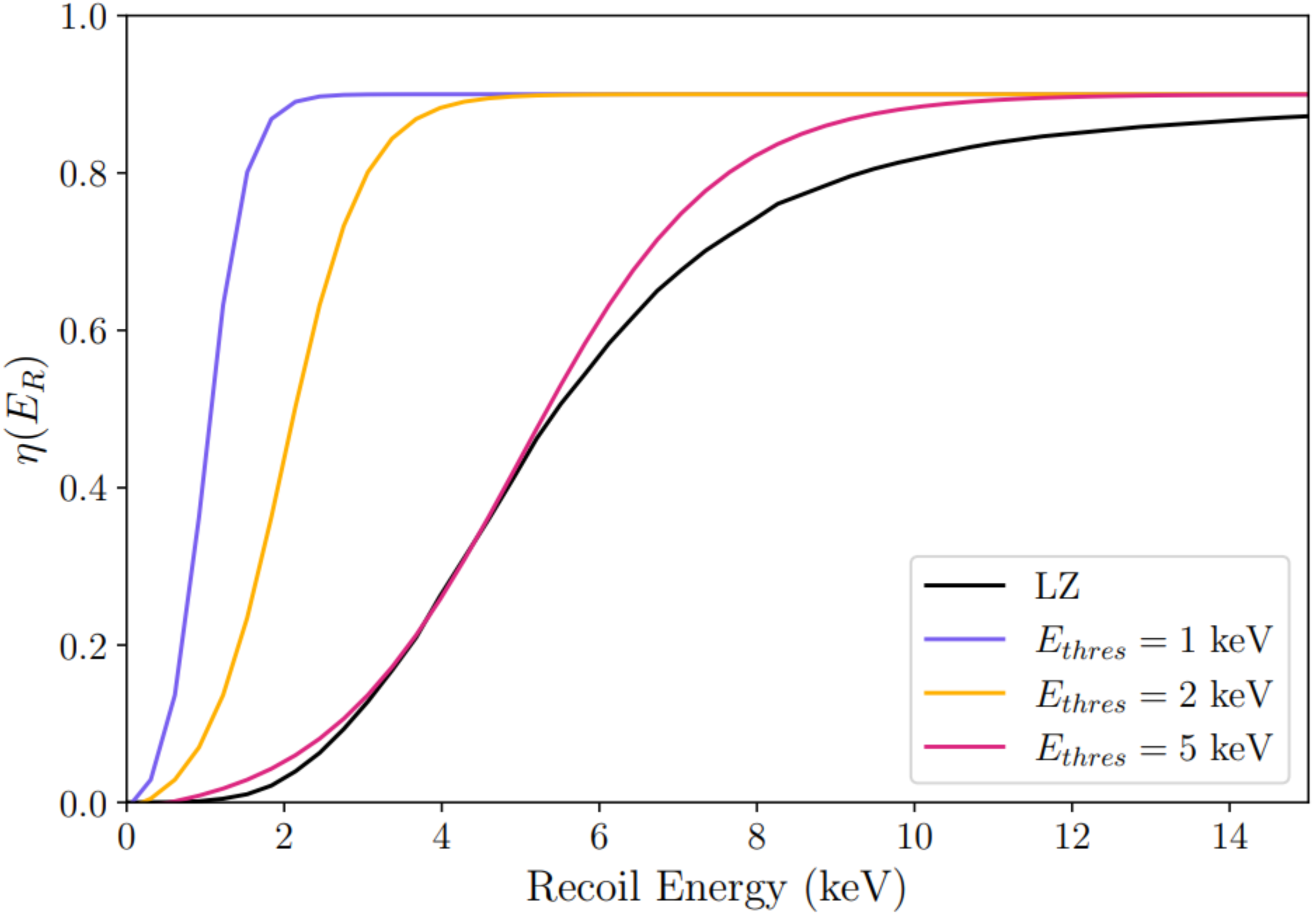
- Propagation of neutrinos through Earth → matter effects
- NSI → corrections to matter effect

$$\mathcal{H}_{\mathrm{sNSI,matter}} = E_\nu + \frac{M_{eff} M_{eff}^\dagger}{2E_\nu} + V_{\mathrm{SI}}$$

- Some simplifying assumptions:
  - Production of atmospheric neutrinos is spherically symmetric
  - Constant Earth density

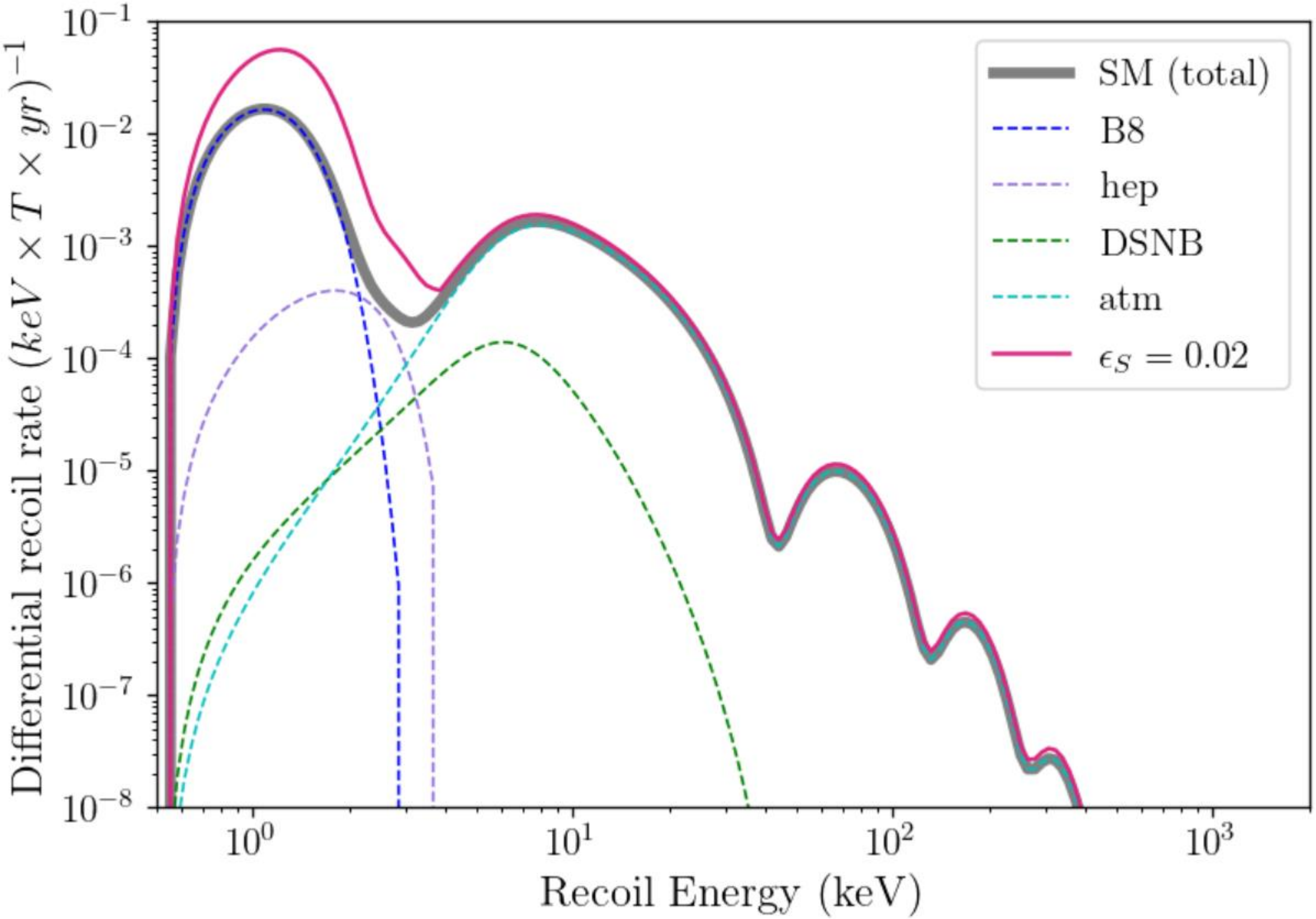
- Small scalar NSIs do not appreciably modify neutrino oscillations

Noble element detector efficiency

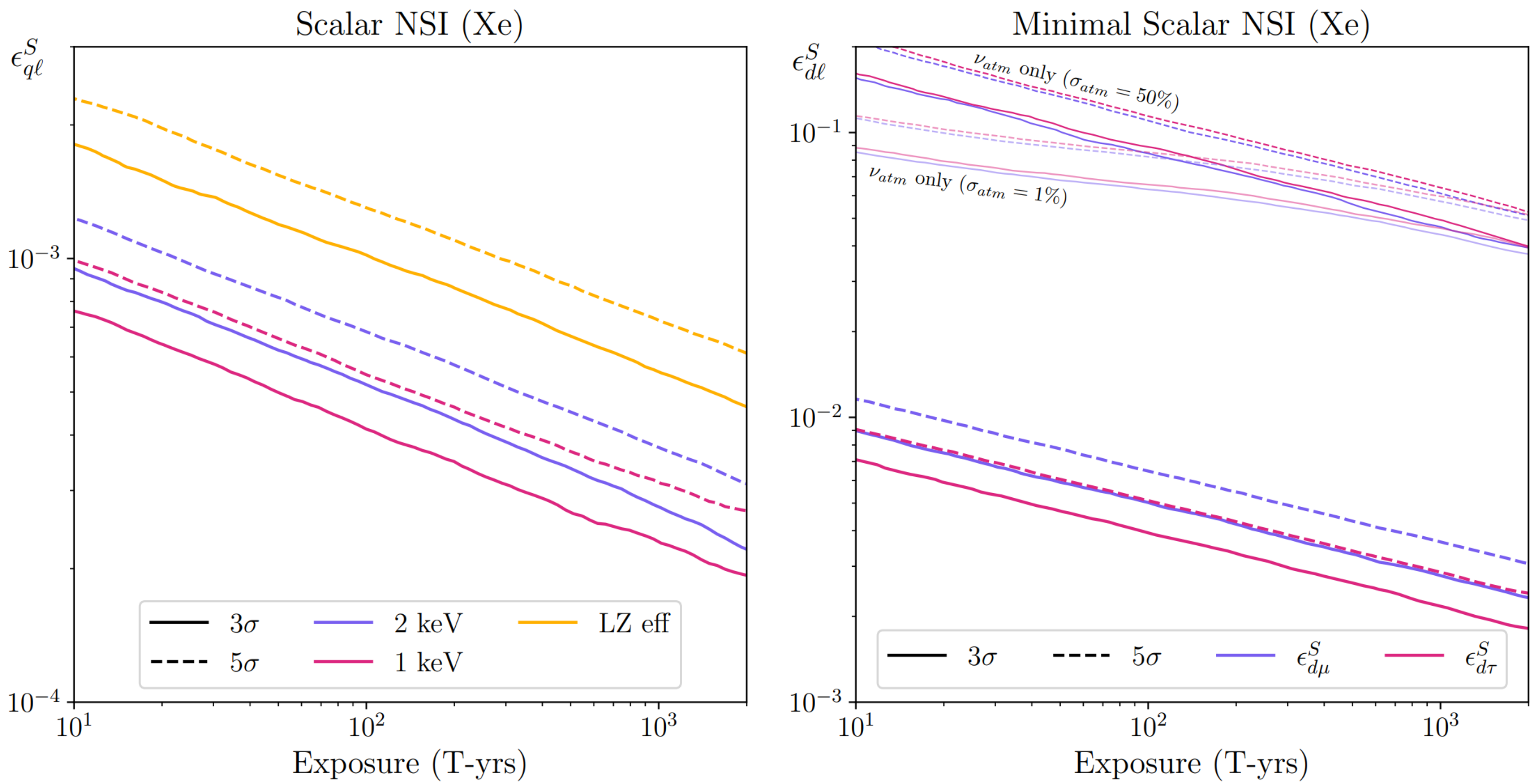


Use efficiency function to enforce threshold and
Use 2 keV as a goal of future experiments

CEvNS with a heavy scalar



Projected Discovery Reach



- DSNB has no significant effect
- A directional detector seeing only atmospheric neutrinos can place subdominant constraints

Mapping NSI to Leptoquarks

- Leptoquarks motivated by
  - GUT models
  - Flavor anomalies
  - $(g-2)_\mu$
  - Neutrino masses

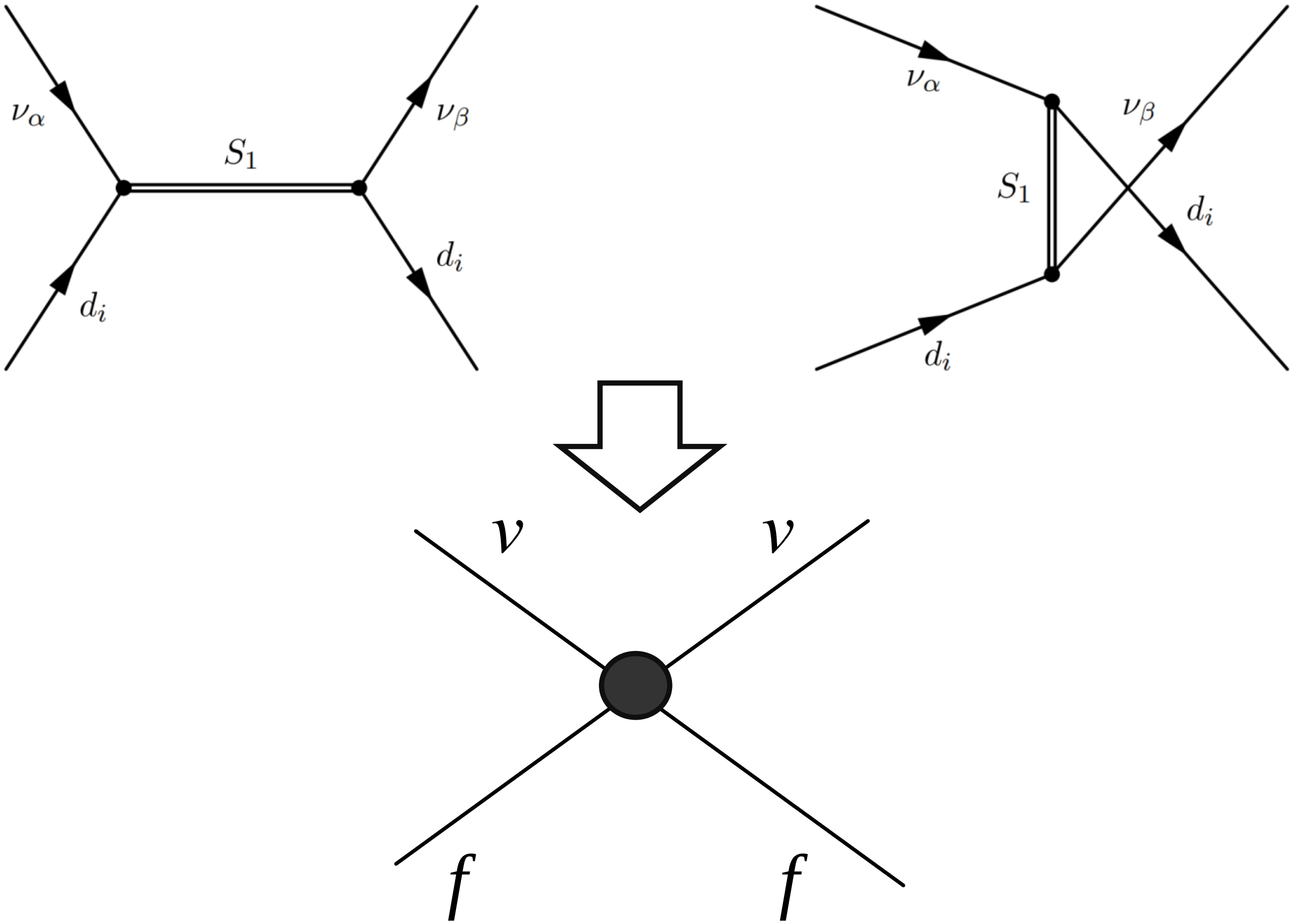
- Carry baryon and lepton number

- S_1 couples to $SU(2)_{\mathrm{L}}$ doublet → Same coupling for neutrinos and charged leptons
  - Don't need to produce τ-leptons to measure $\lambda_{q\tau}$

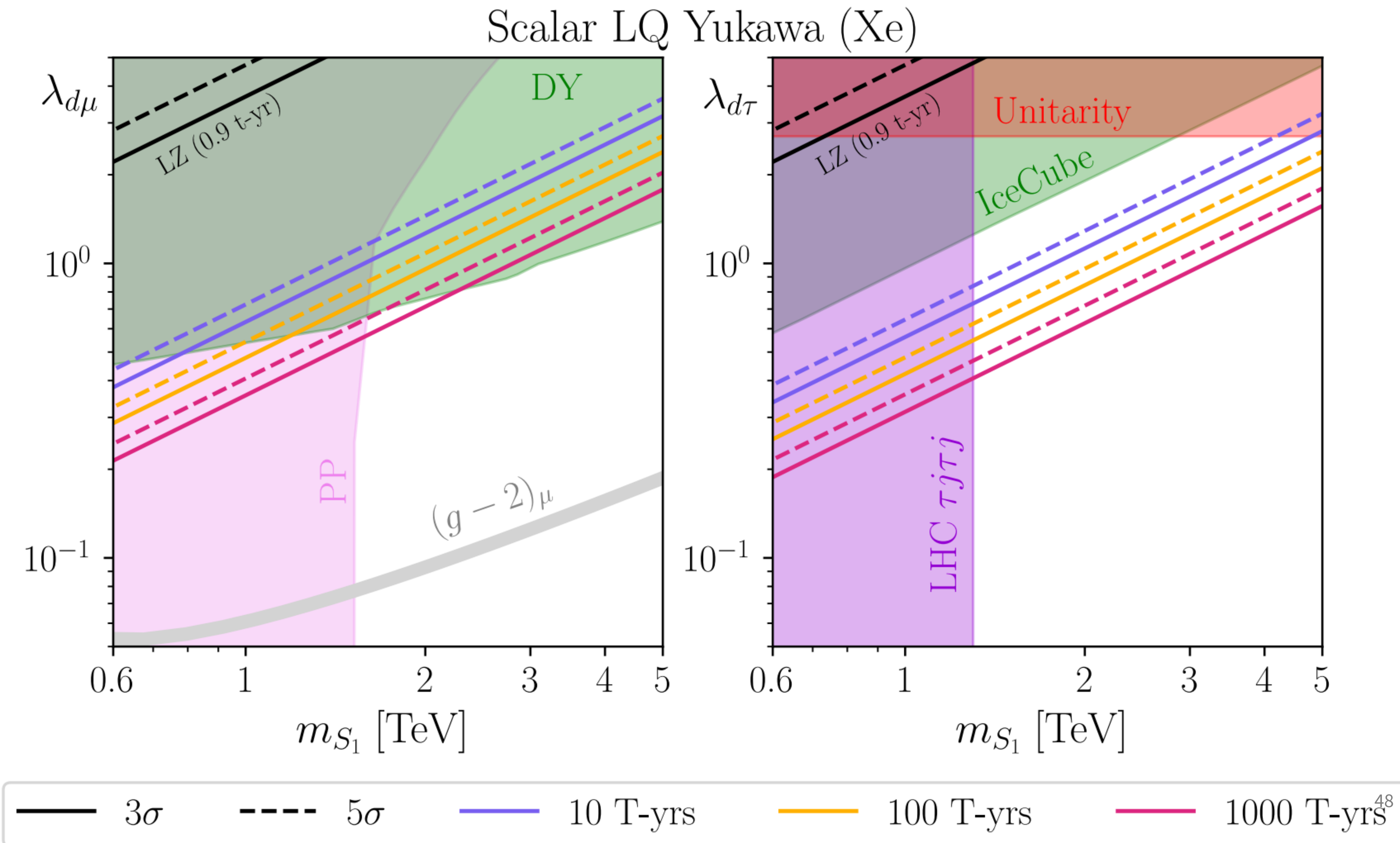
- Integrate out the LQ → Conventional scalar NSI

Mapping NSI to Leptoquarks

- NSI scattering now proceeds via s and u-channel diagrams (rather than the t-channel considered previously)



Constraints on LQ Yukawas



Summary

- Low threshold DM experiments are well optimized for BSM neutrino interactions mediated by a light vector
  - Can match or exceed neutrino specific detectors in searches for BSM neutrino interactions
  - Yield functions dominate the uncertainties at low energies and thresholds
- Dark Matter experiments can place constraints on heavy scalar Leptoquarks beyond the reach of colliders