Beyond the Standard Model Interactions of Solar Neutrinos in Low-Threshold Dark Matter detectors

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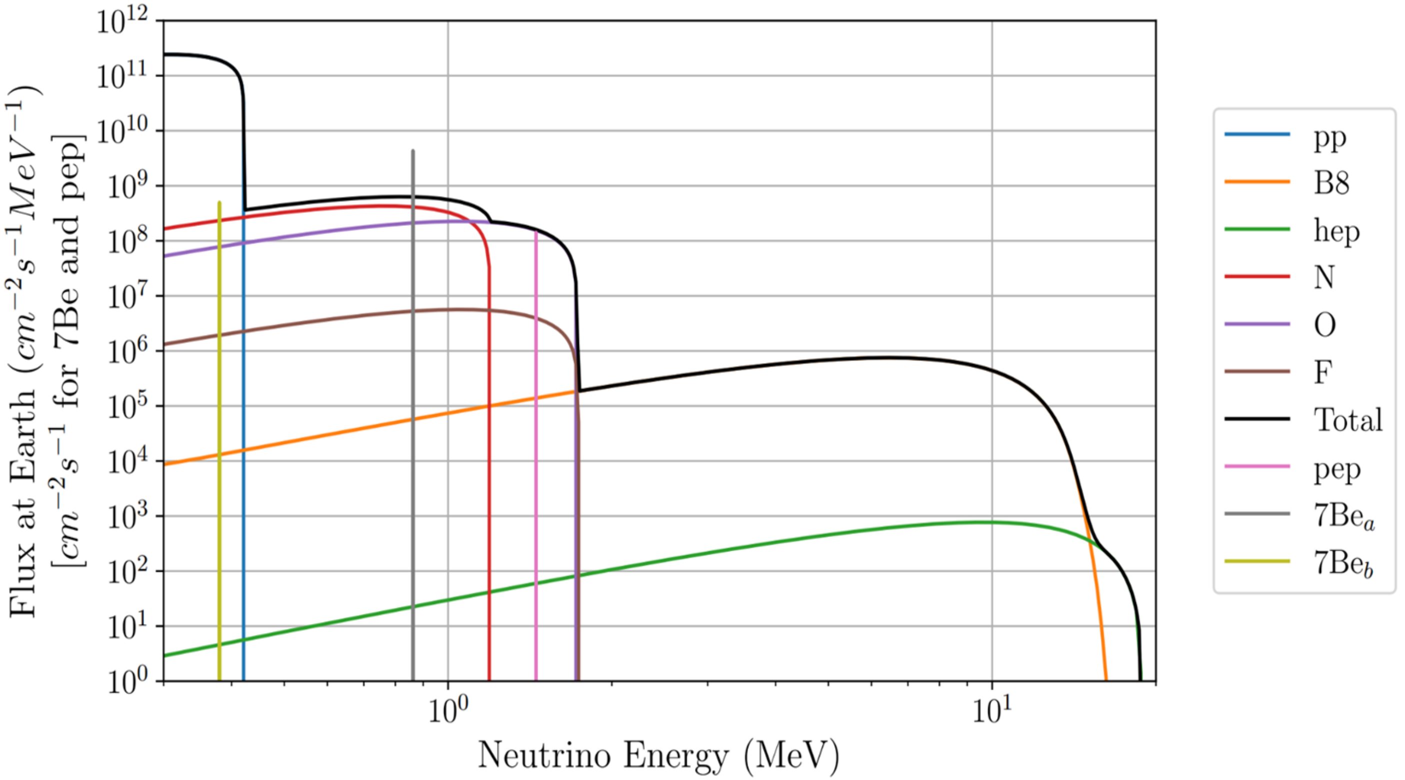
The Solar Neutrino Flux

Two main production chains: *pp* and CNO

Solar neutrinos travel far enough to oscillate → all flavors are present

Recoils of a given energy require a minimum neutrino energy



$$\frac{dR}{dE_R} = N_T \int_{E_\nu^{min}} \frac{d\sigma}{dE_R}\frac{dN_\nu}{dE_\nu} dE_\nu \qquad E_\nu^{min} = \sqrt{\frac{m_T E_R}{2}}$$

Neutrino flavors and oscillations

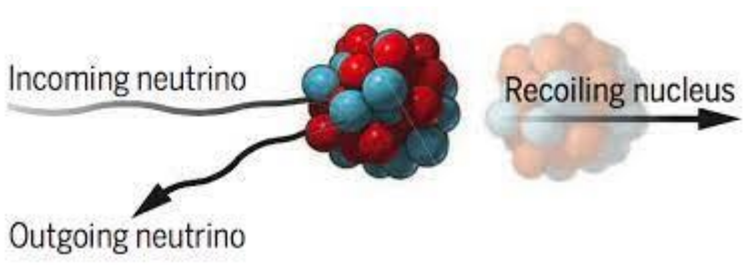
Cross-sections can vary with neutrino flavor

- Reactor detectors only see electron neutrinos; DM detectors see all flavors
  - μ or τ neutrinos can produce a signal in DM detectors without effecting reactor detectors
- Only electron neutrinos interact via charged current
- μ and τ neutrinos only interact via neutral current

Two flavor approximation:

$$P(\nu_e \to \nu_\mu) = \sin^2(2\theta_{12}) \sin^2(\pi L / L_{osc})$$

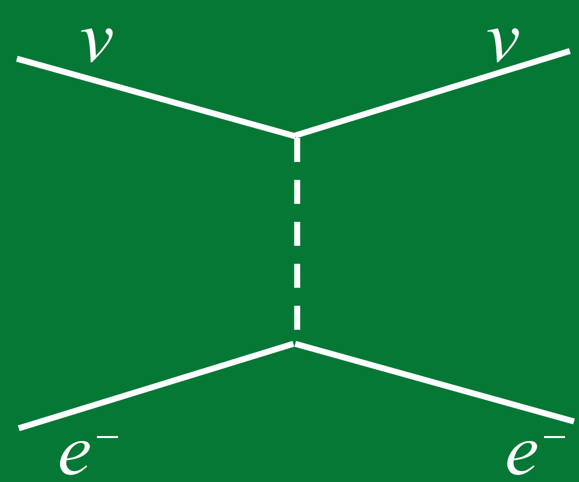
For monochromatic neutrino channels we must keep this energy dependence



Neutrino Interactions

CEνNS: Low energy effective couplings

ν — e scattering



Neutrino Interactions: The Standard Model

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

$$\frac{d\sigma}{dE_e} = \frac{G_F^2 m_e}{2\pi E_\nu^2} \left[4s_w^2(2E_\nu^2 + E_e^2 - E_e(2E_\nu + m_e)) \pm 2s_w^2(E_e m_e - 2E_\nu^2) + E_\nu^2\right]$$

CEvNS:

Weak neutral current

No S-channel process

Weak nuclear hypercharge:

$$Q_v = N - Z(1 - 4s_w^2)$$

Electron scattering:

At low energies, the SM cross-section is approximately constant

Charged current allowed for electron neutrinos, but not μ or τ

The ± distinguishes electron neutrinos (−) from other flavors (+)

BSM — The neutrino magnetic moment

$$\mathcal{L} \supset \mu_\nu \bar{\nu} \sigma^{\alpha\beta} \partial_\beta A_\alpha \nu$$

SM — An anomalous magnetic moment from W exchange → $\mu_v \sim 10^{-19} \mu_b$

BSM — New particles and interactions can increase μ_v

$$\frac{d\sigma_\mu}{dE_R} = \mu_\nu^2 \alpha Z^2 F^2(E_R) \left(\frac{1}{E_R} - \frac{1}{E_\nu} \right)$$

Scales as 1/E for low energy recoils

Electron recoils are the same up to the nuclear charge and form factor

BSM — Light Mediators:

Vector

Scalar

Axial Vector

Pseudoscalar

Light Mediator Couplings and Interactions

Mediator	Couplings	$\mathcal{O}_i(\bar{f}, f)$
Scalar (S)	$g_{\nu S}, g_{eS}, g_{qS}$	$\phi \bar{f} f$
Pseudoscalar (P)	$g_{\nu P}, g_{eP}, g_{qP}$	$-i\gamma^5 \phi \bar{f} f$
Vector (V)	$g_{\nu V}, g_{eV}, g_{qV}$	$Z'_\mu \bar{f} \gamma^\mu f$
Axial Vector (A)	$g_{\nu A}, g_{eA}, g_{qA}$	$-Z'_\mu \bar{f} \gamma^\mu \gamma^5 f$

NSIs versus Light Mediators (Propagators)

Conventional NSIs:

- Low energy EFT
- Integrate out the propagator → four-point vertex

$$\epsilon = \frac{g_\nu g_{SM}}{M_i^2 G_F}$$

- No momentum dependence

Light Mediators:

- Retain propagator
- Important when mediator mass is small

Vector Mediators

$$\mathcal{L} \supset g_{\nu V}\bar{\nu}_L\gamma^\mu\nu_L Z'_\mu + g_{fV} Z'_\mu \bar{f}\gamma^\mu f$$

$$\left.\frac{d\sigma_e}{dE_R}\right|_V = \frac{\sqrt{2}G_F m_e g_v g_{\nu V} g_{eV}}{\pi(2E_R m_e + m_V^2)} + \frac{m_e g_{\nu V}^2 g_{eV}^2}{2\pi(2E_R m_e + m_V^2)^2}$$

$$\left.\frac{d\sigma_N}{dE_R}\right|_V = -\frac{F^2(E_R)G_F m_N Q_v Q'_v(2E_\nu^2 - E_R m_N)}{2\sqrt{2}\pi E_\nu^2(2E_R m_N + m_V^2)} + \frac{F^2(E_R) m_N Q'^2_v(2E_\nu^2 - E_R m_N)}{4\pi E_\nu^2(2E_R m_N + m_V^2)^2}$$

- *Q'* is the BSM couplings times the number of quarks in a nucleus (the nuclear charge in the new U(1))
- Low Energies: Interference terms scale as $1/E_R$ while pure terms scale with $1/E_R^2$
- Really Low Energies: mediator mass dominates and the rate plateaus

Scalar Mediators

$$\mathcal{L} \supset g_{\nu S} \phi \bar{\nu}_R \nu_L + h.c. + g_{fS} \phi \bar{f} f$$

$$\left.\frac{d\sigma_N}{dE_R}\right|_S = \frac{F^2(E_R) Q'^2_s E_R m_N^2}{4\pi E_\nu^2 (2 E_R m_N + m_S^2)^2}$$

- 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

Axial Vector Mediators

$$\mathcal{L} \supset g_{\nu A} \bar{\nu}_L \gamma^\mu \nu_L Z'_\mu - g_{f A} Z'_\mu \bar{f} \gamma^\mu \gamma^5 f$$

- Interference term is positive
- Coupled to nuclear spin
  - Cannot be detected in argon or helium detectors (suppressed in silicon)
- Same low energy dependence as vector mediators

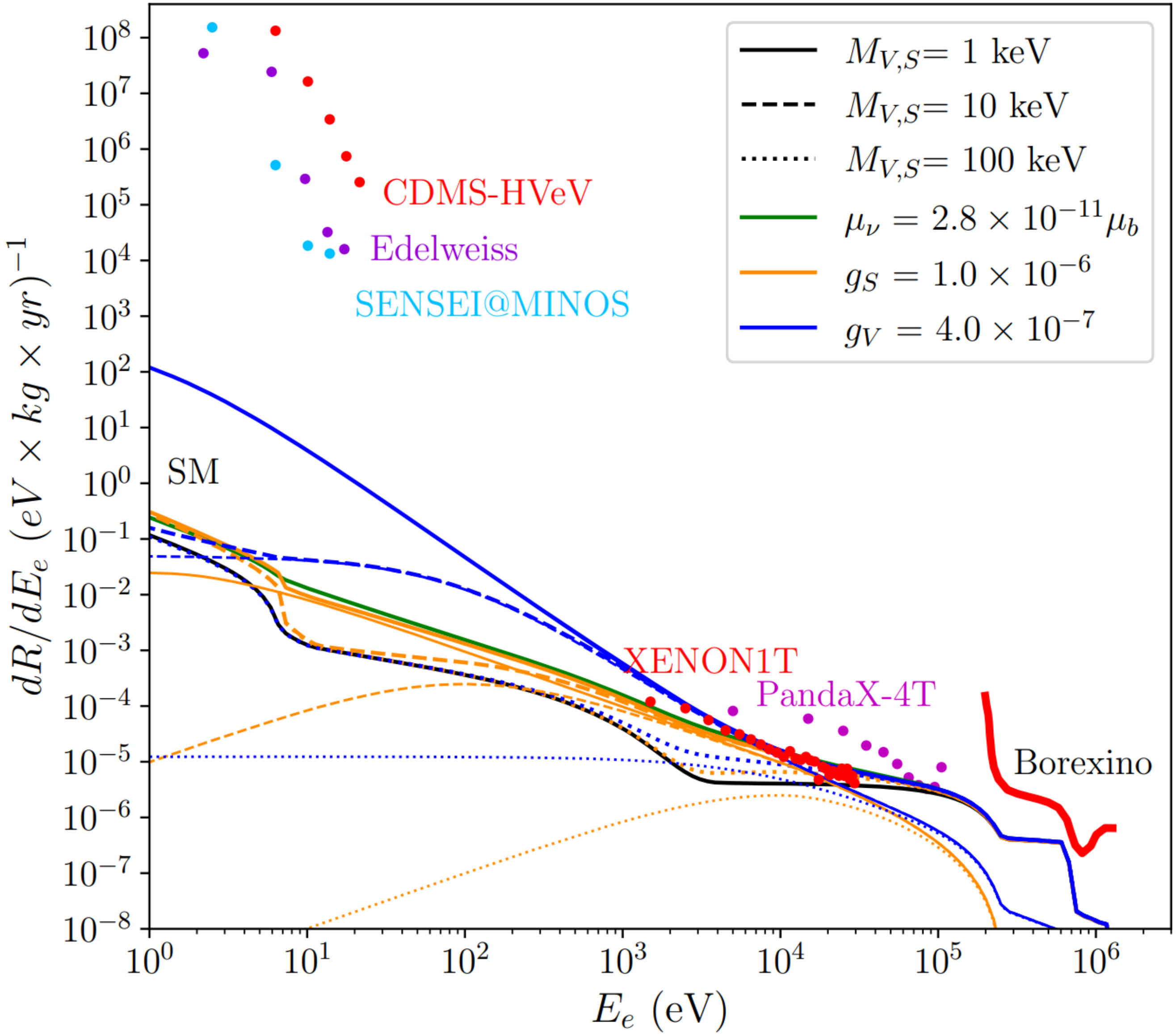
Pseudoscalar Mediators

$$\mathcal{L} \supset g_{\nu P} \phi \bar{\nu}_R \nu_L + h.c. - i g_{f P} \gamma^5 \phi \bar{f} f$$

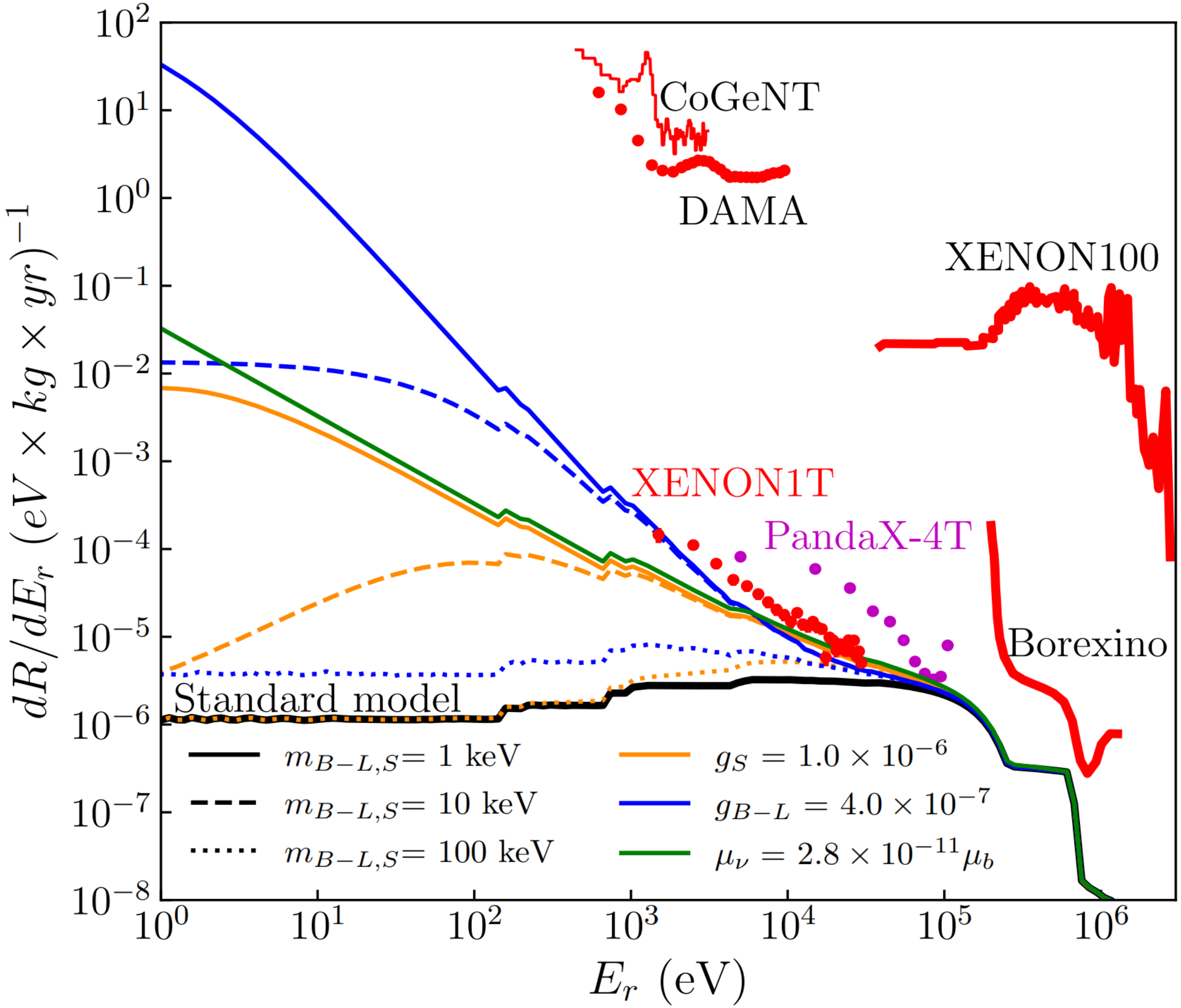
$$\left.\frac{d\sigma_e}{dE_R}\right|_P = \frac{g_{\nu P}^2 g_{eP}^2 E_R^2 m_e}{8\pi E_\nu^2 (2E_R m_e + m_P^2)^2}$$

- No interference term
- No nuclear coupling
- No low energy enhancement

Differential recoil rates



Considering electron binding energy



Signals in Dark Matter Detectors

Yield Functions — beyond the Lindhard model

Semiconductors — Si, Ge, GaAs

Liquid Noble Elements — Xe, Ar

Converting recoils to signals

Neutrino scattering produces ionization energy

Semiconductors count electrons

Noble Liquid detectors see scintillation

Reconstruct “photoelectrons”

Nuclear recoils must be converted to an equivalent electron recoil

→ Lindhard model

Low energy modifications to Lindhard

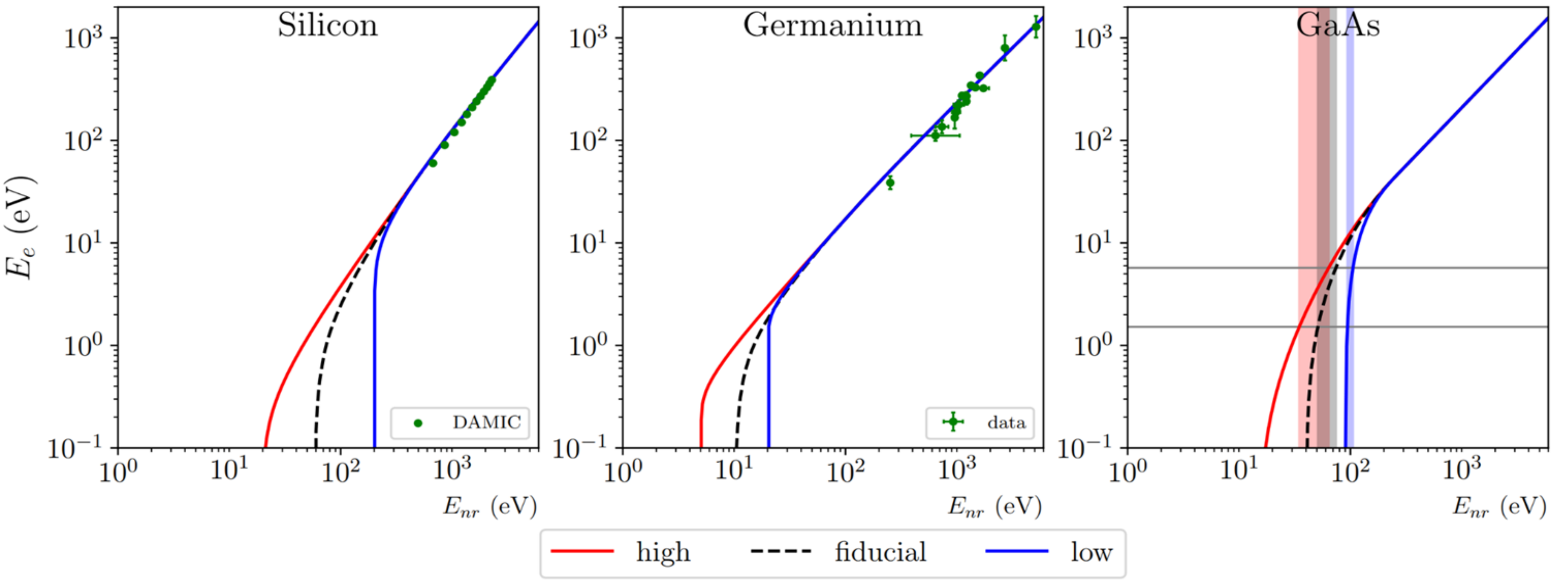
Lindhard:

- Neglects binding energy
- Assumes electron energy is much smaller than the recoiling ion,
- Assumes nuclear kinetic energy is small

Modifications include binding energy and an electronic stopping power which includes the Coulomb repulsion[1]

1. Y. Sarkis, A. Aguilar-Arevalo, and J. C. D'Olivo, "A Study of the Ionization Efficiency for Nuclear Recoils in Pure Crystals," Phys. At. Nucl. 84 no. 4, (2021)

Semiconductors

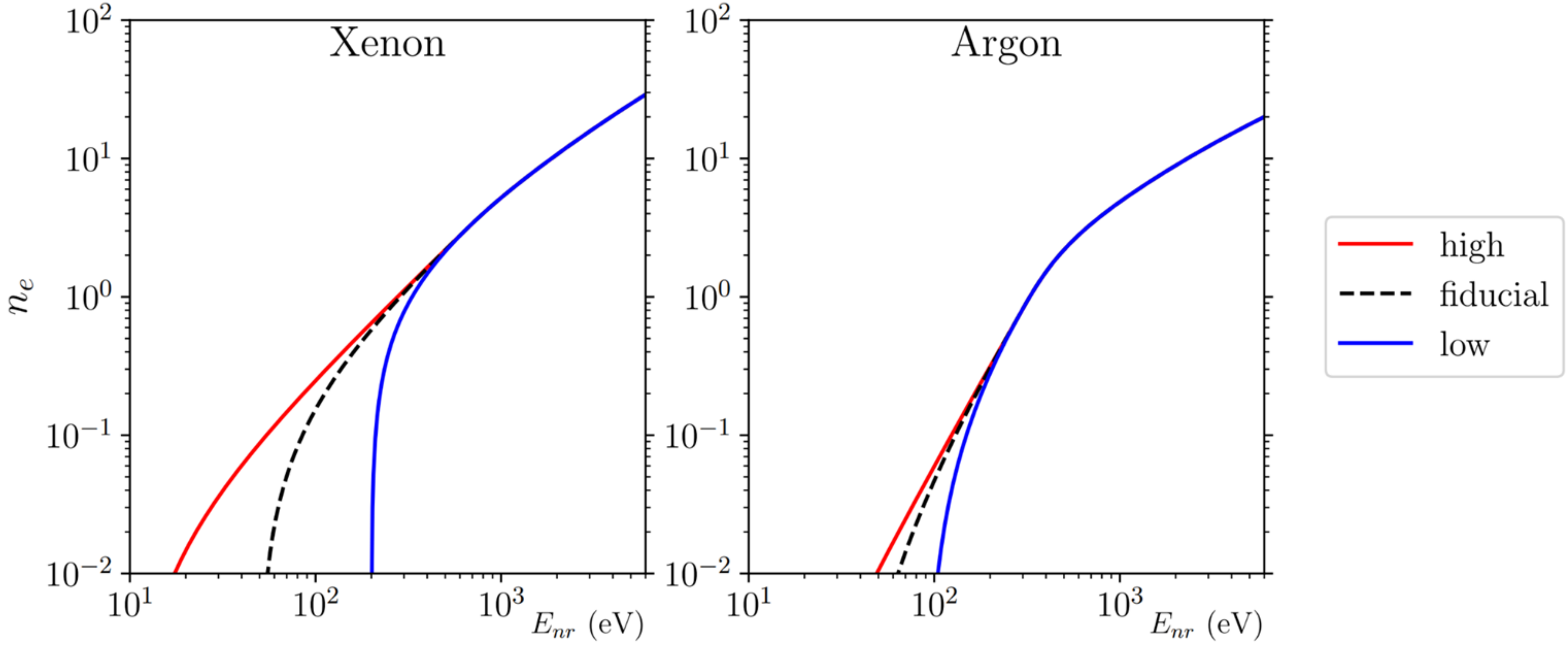


Silicon is matched to DAMIC data at high energies

Germanium matches data from multiple sources

GaAs is matched to the Lindhard model

Liquid Noble Elements — NEST simulations



Both are connected to the low energy cut-off with a power-law function

Observable Event Rates

Incorporating the neutrino flux, cross-sections, and yield functions to predict the number of events in dark matter detectors

Event binning in semiconductors

Bins starting from the bandgap with steps ε (average energy per electron-hole pair)

Electron recoils:

- Integrate the differential recoil rate through each bin

Nuclear recoils:

- Weight the differential nuclear recoils by dE_R/dE_e
- Adjust bin boundaries

Event binning in LNG detectors

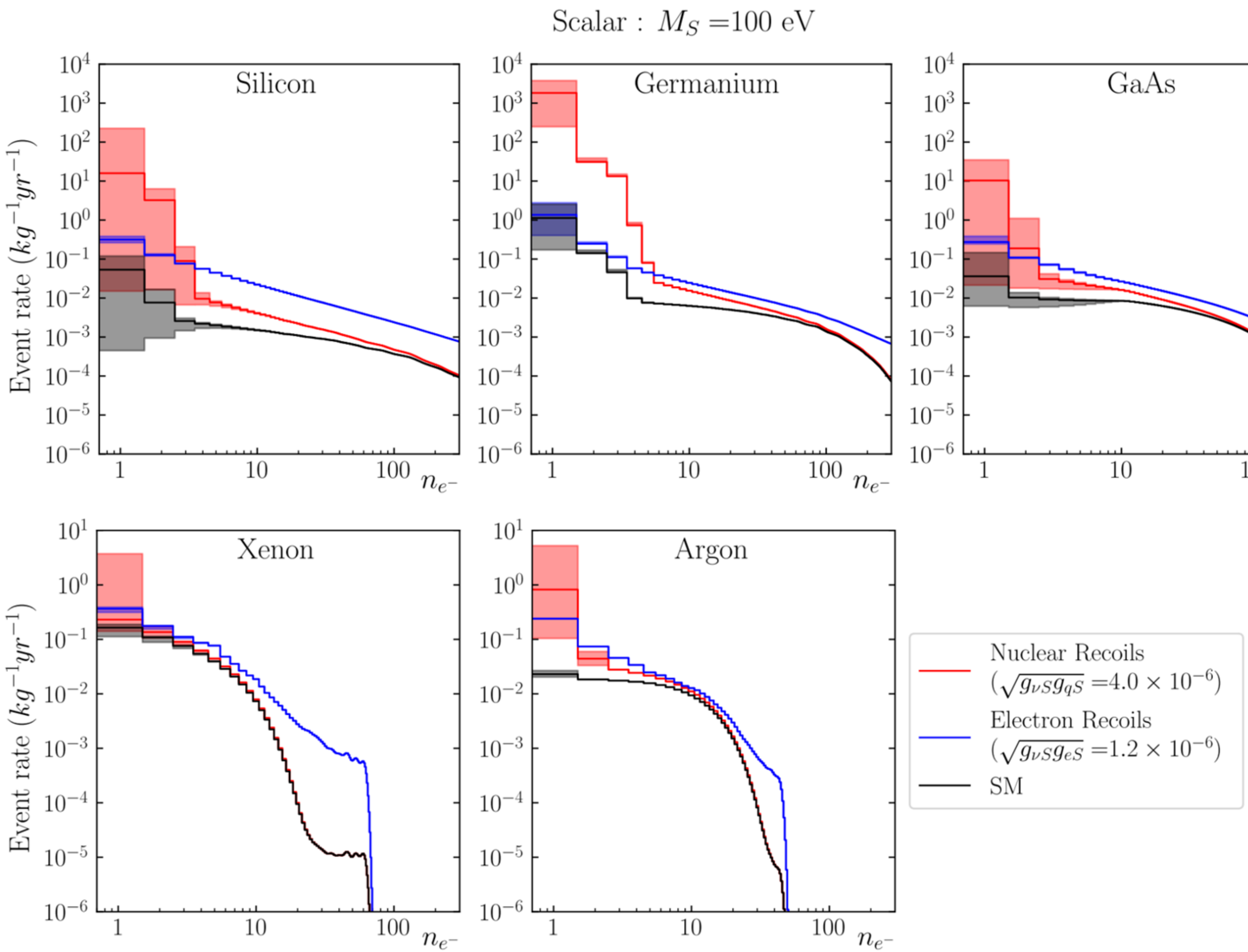
Consider S2-only data (electron recoils):

- Detectable photons from the initial recoil and de-excitation of electrons

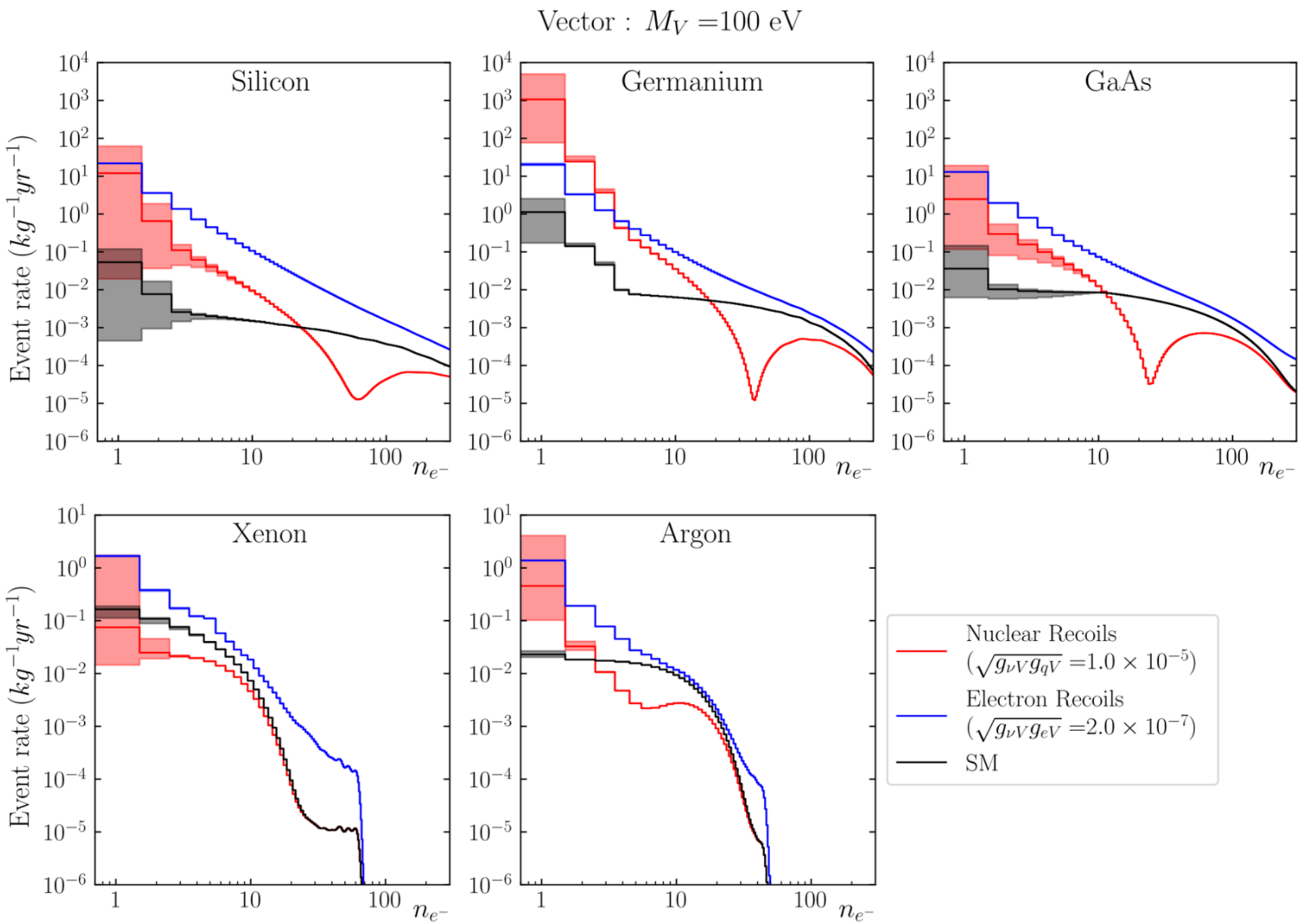
Nuclear recoils:

- Assume a Poisson distribution about the n_e predicted by NEST
- Weight the recoil spectrum by its likelihood to be in a particular bin
- Integrate over all possible recoil energies

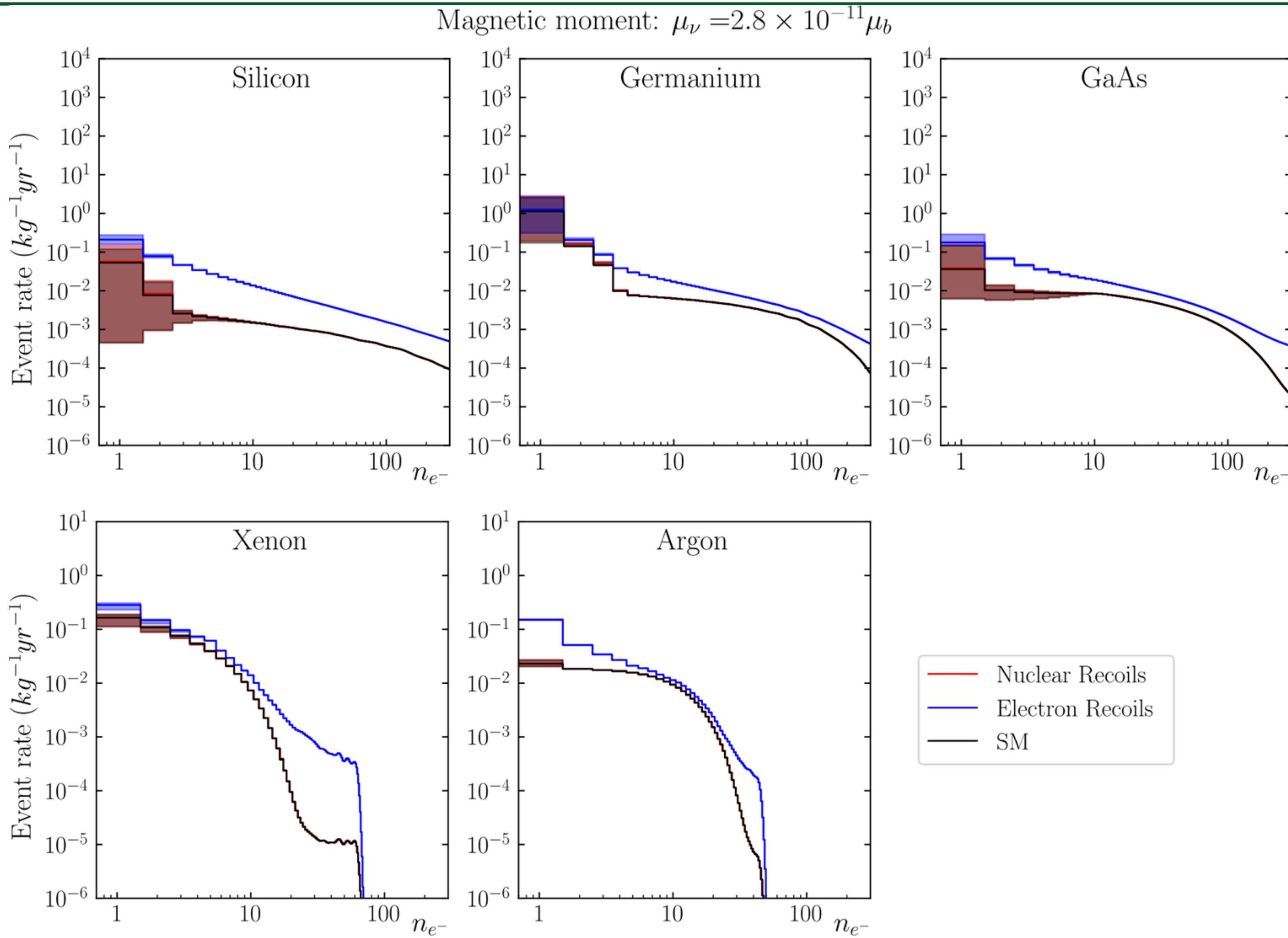
Scalar event rates



Vector event rates



Magnetic moment event rates



Statistics and Projected Sensitivities

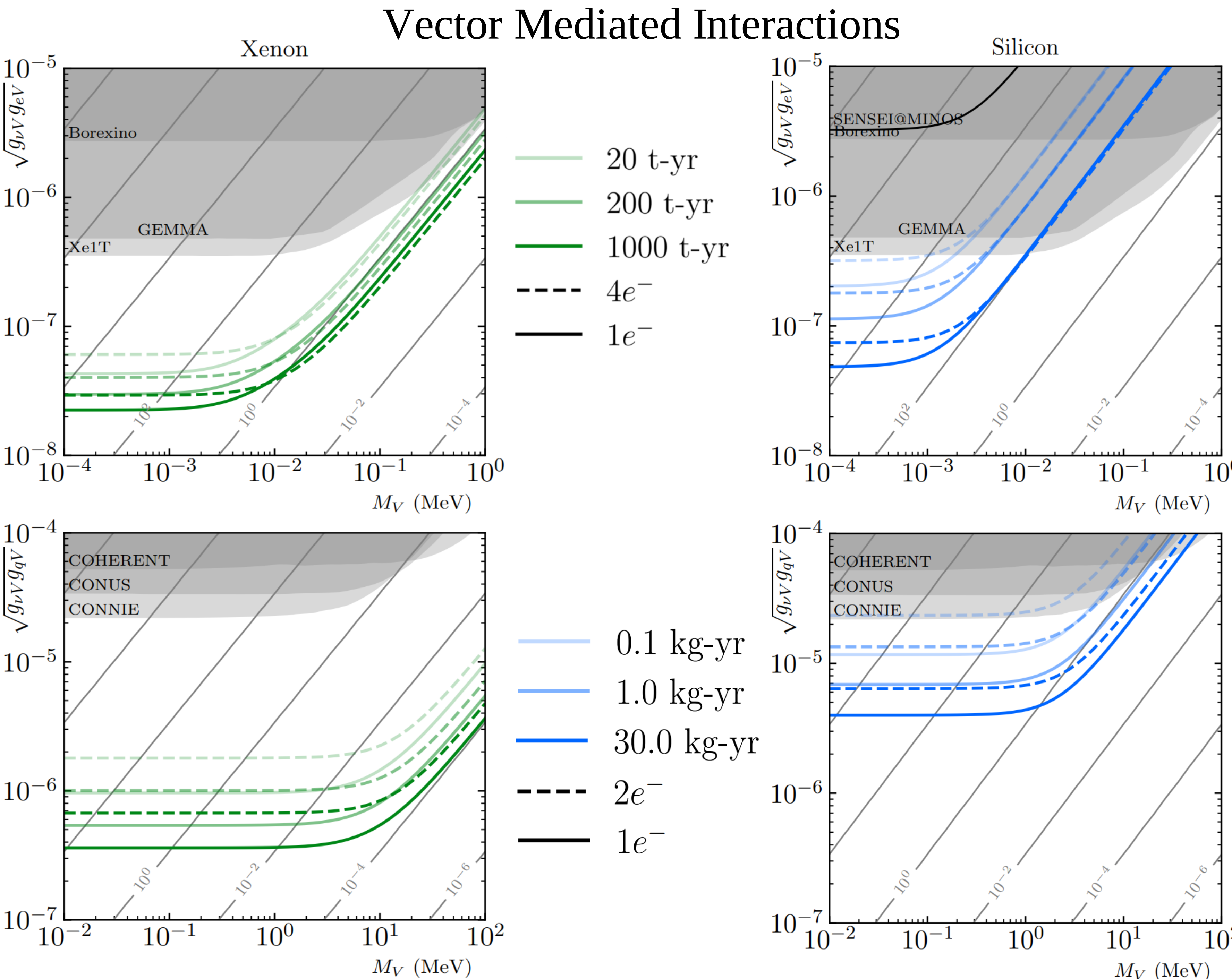
The simple approach — light mediators

Semiconductors:

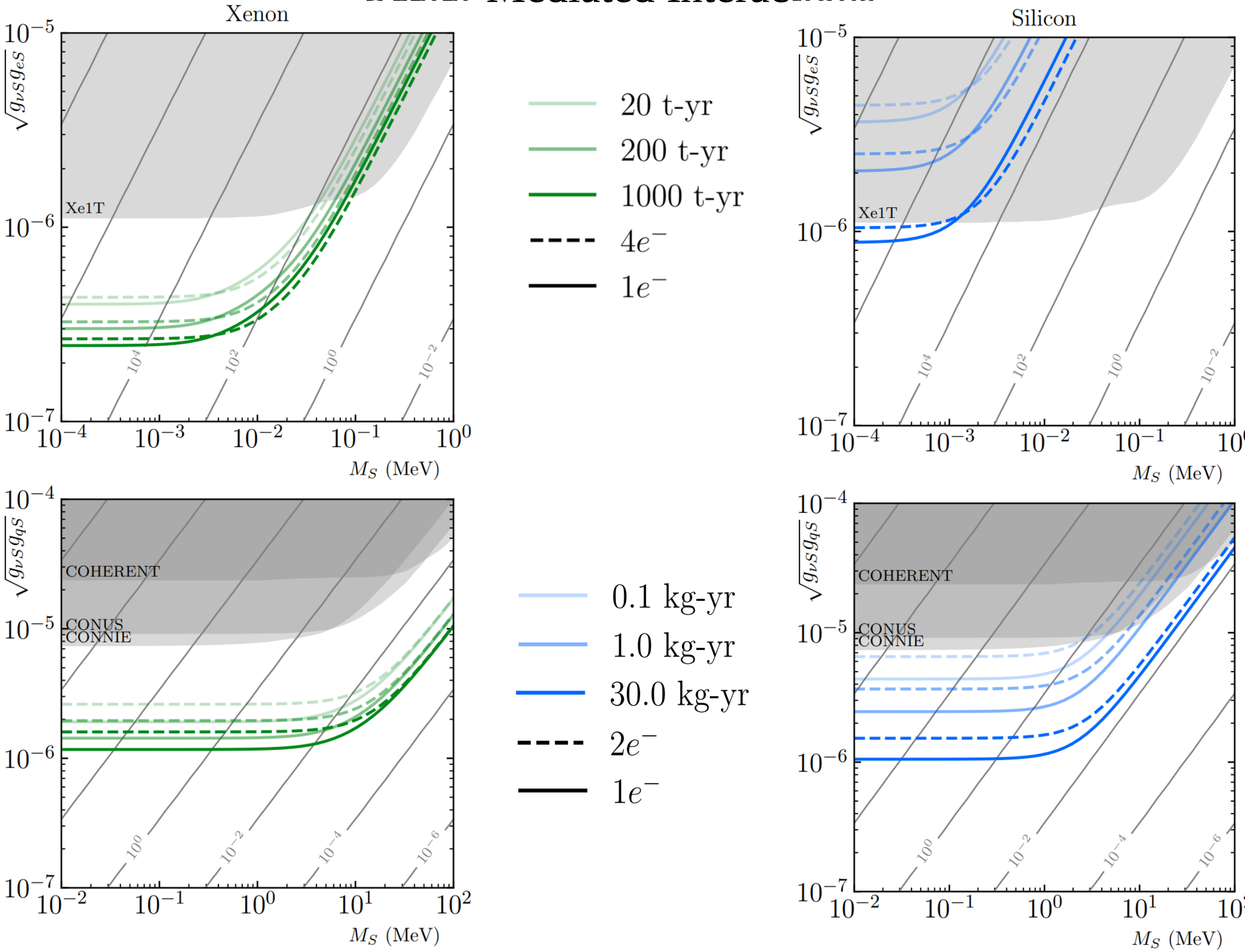
- Signal dominated by 1 and 2e- charge bins
- Find parameters which saturate the 2σ limit assuming only background

Noble Elements:

- Smaller low-energy amplification → make use of all charge bins
- Sum deviations from SM
- Consider two possible thresholds: 4e- and 1e-
- Saturate the 2σ limit assuming only background


Vector Mediated Interactions
Xenon
Silicon
Borexino
GEMMA
Xe1T
SENSEI@MINOS
COHERENT
CONUS
CONNIE
20 t-yr
200 t-yr
1000 t-yr
$4e^-$
$1e^-$
0.1 kg-yr
1.0 kg-yr
30.0 kg-yr
$2e^-$
$1e^-$
$\sqrt{g_{\nu V} g_{eV}}$
$\sqrt{g_{\nu V} g_{qV}}$
M_V (MeV)

Scalar Mediated Interactions



A more rigorous approach — log-likelihood tests

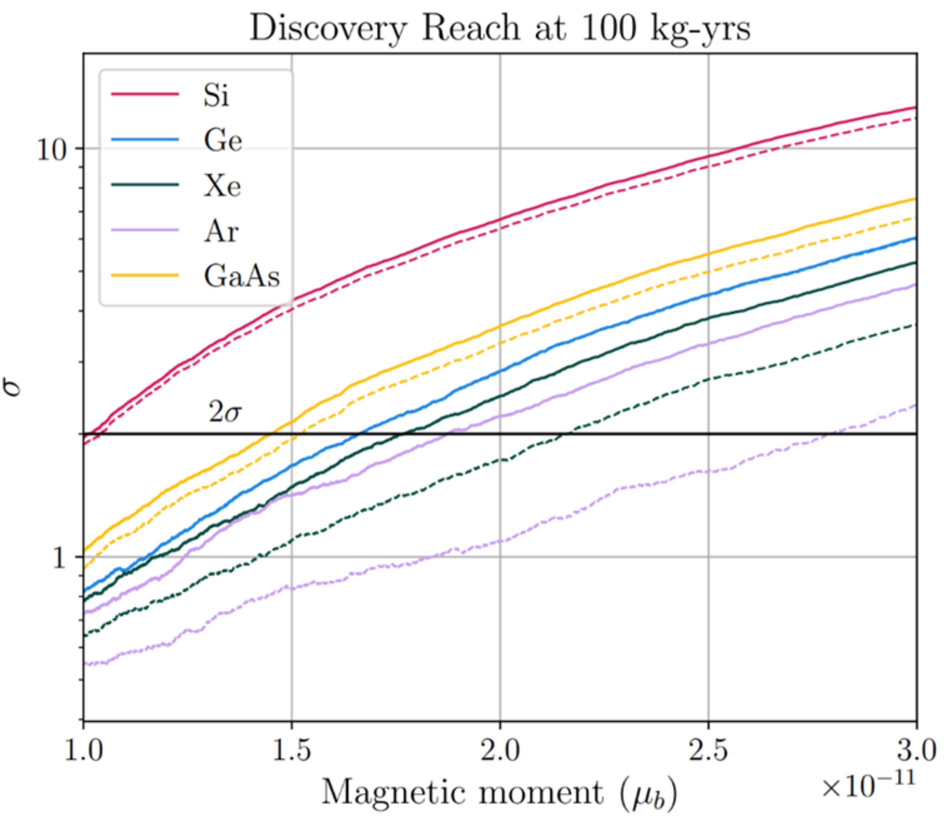
Likelihood based on:

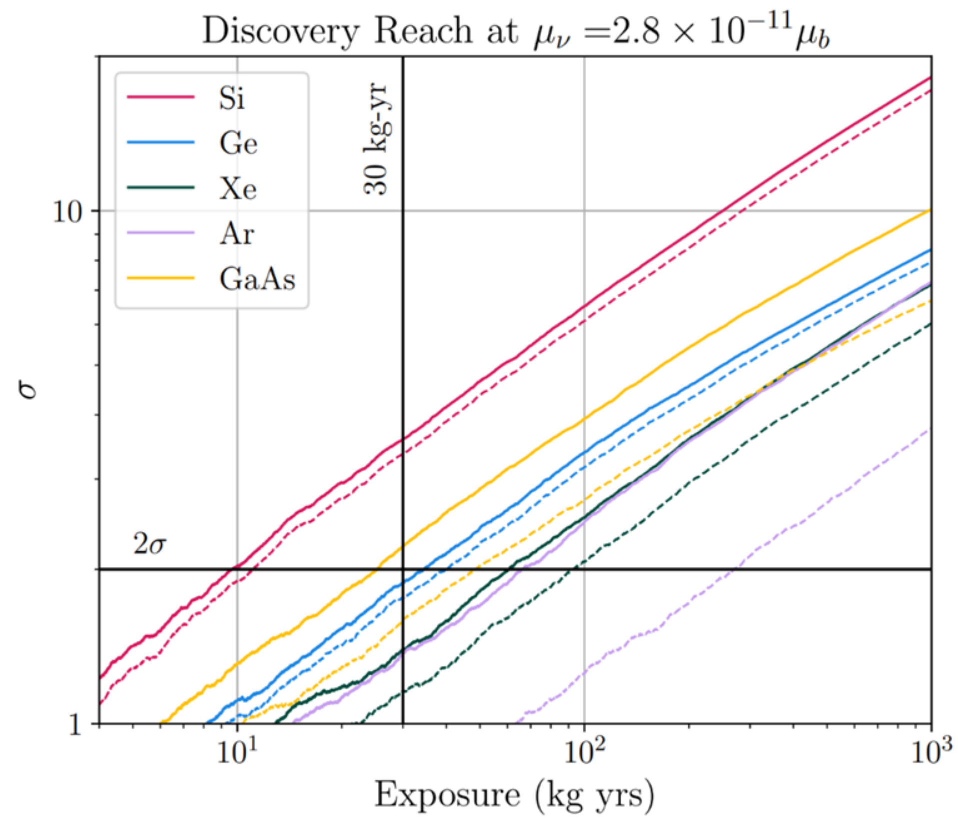
- Uncertainty of the solar flux
- Distribution of the rates (at each charge)
- Total number of events

Find the maximum of the likelihood function with and without the BSM effects

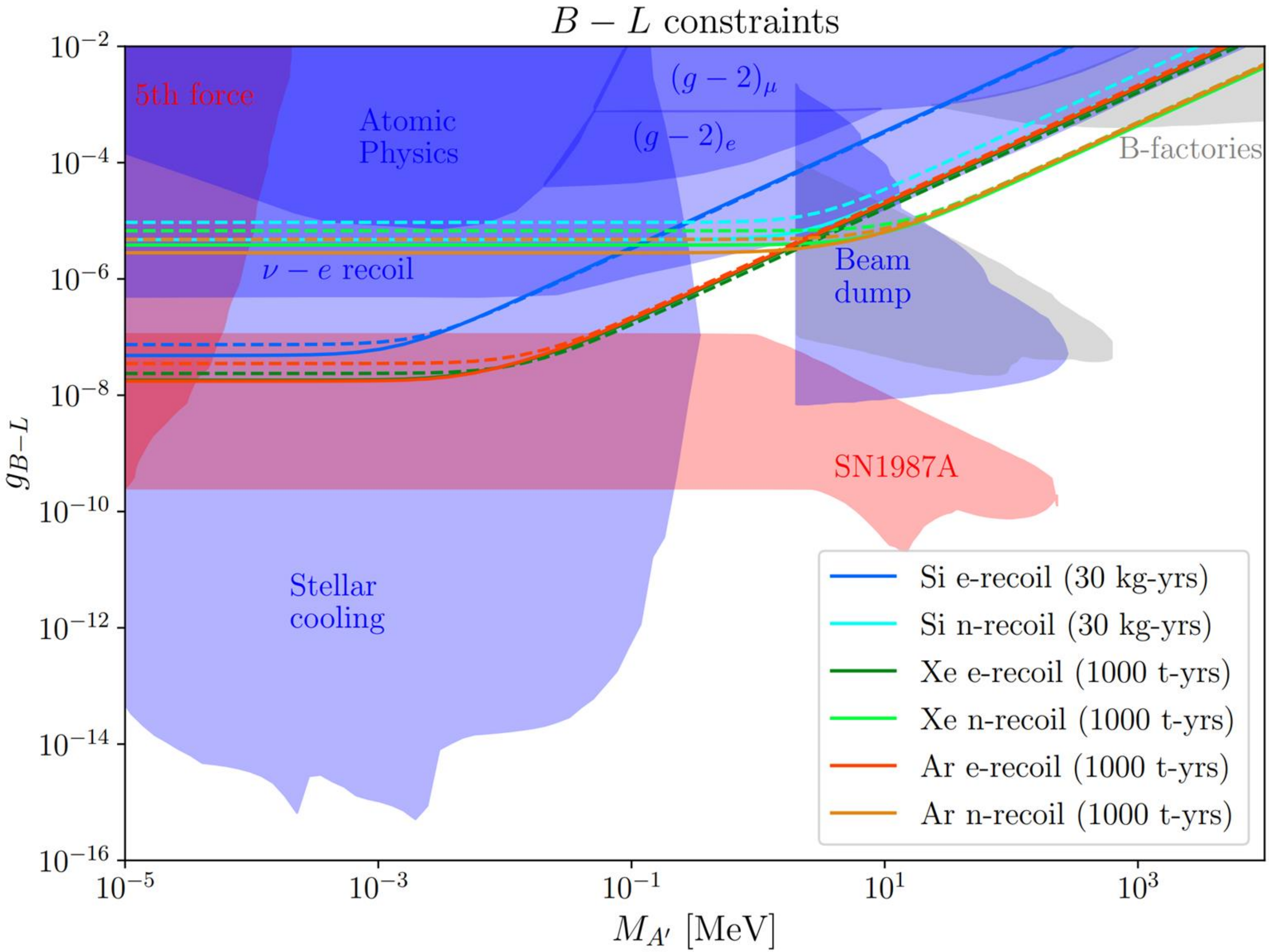
$$\lambda = \frac{\mathcal{L}_{max}(\mu_\nu = 0, \vec{\phi})}{\mathcal{L}_{max}(\mu_\nu \neq 0, \vec{\phi})} \qquad \sigma = \sqrt{-2\log(\lambda)}$$

Magnetic Moment



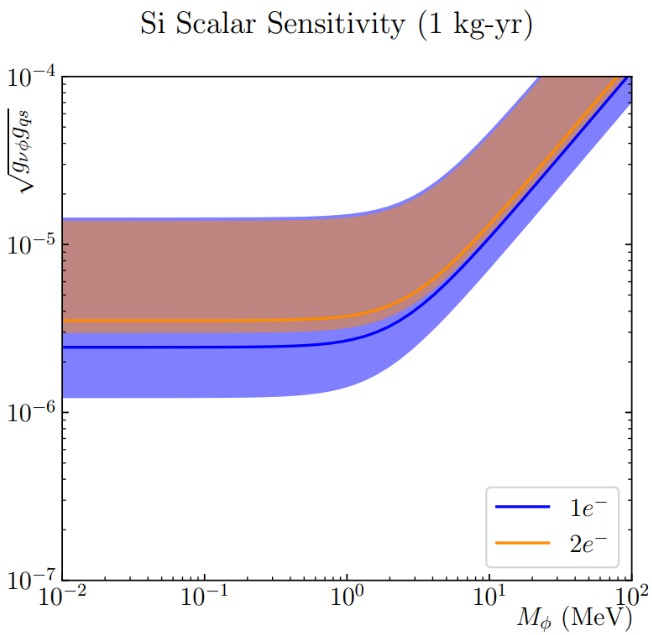


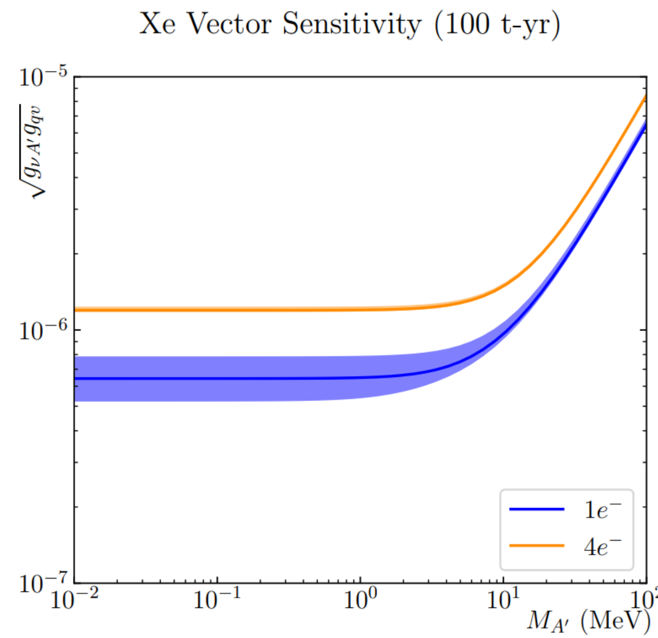
Gauged B - L

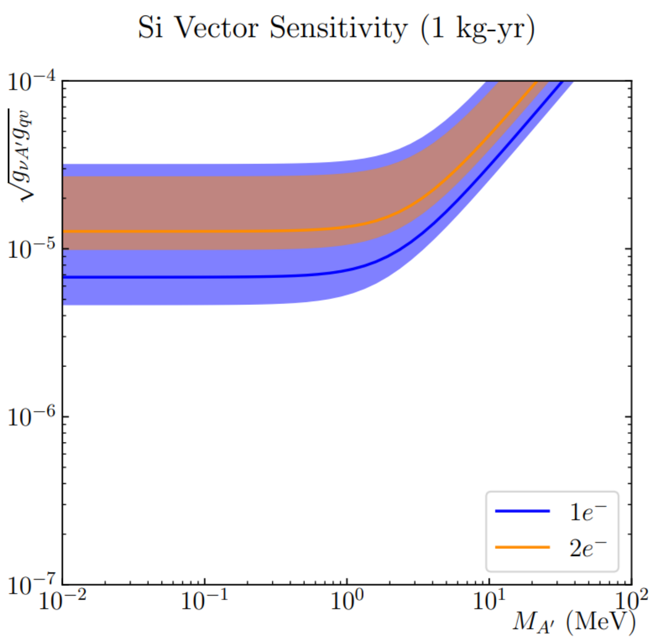


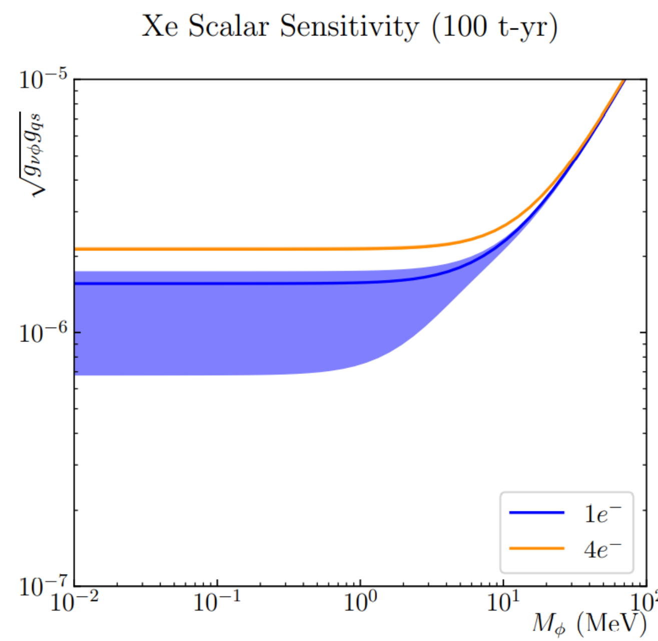
$B - L$ constraints
5th force
Atomic Physics
$(g-2)_\mu$
$(g-2)_e$
B-factories
$\nu - e$ recoil
Beam dump
SN1987A
Stellar cooling
Si e-recoil (30 kg-yrs)
Si n-recoil (30 kg-yrs)
Xe e-recoil (1000 t-yrs)
Xe n-recoil (1000 t-yrs)
Ar e-recoil (1000 t-yrs)
Ar n-recoil (1000 t-yrs)
g_{B-L}
$M_{A'}$ [MeV]

Uncertainties from yield functions









Summary

- Low threshold DM detectors can match or exceed neutrino specific detectors in searches for BSM neutrino interactions
- Yield functions dominate the uncertainties at low energies and thresholds
- Improving thresholds provides a greater improvement to the sensitivity than increasing exposures
- Neutrino interactions can constrain broader BSM physics