International Center for
Quantum-field Measurement Systems for
Studies of the Universe and Particles
WPI research center at KEK

Direct Dark Matter Detection with Liquid Gas Experiments

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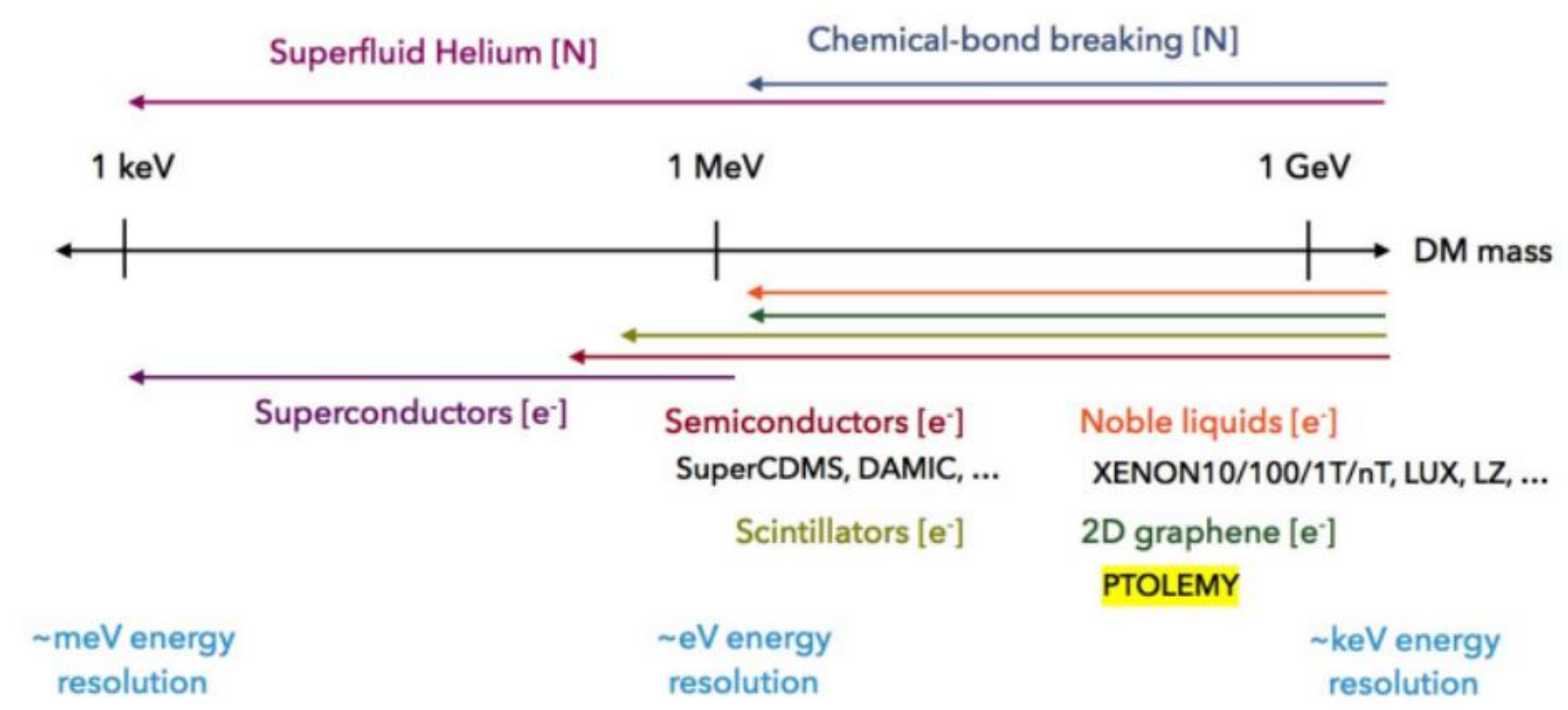
Direct Detection

Direct dark matter (DM) detection attempts to measure the energy deposited within a detector by collisions of DM particles from the dark halo of our Galaxy passing through the detector.

DM-nuclei scattering detectors (E_{thres}~keV) are used to detect DM heavier than ~GeV (WIMP), whereas DM-electron scattering detectors (E_{thres}~eV) are used to detect sub-GeV DM (Light DM, or LDM).

Dark Sector Workshop, 1608.08632



DM-Nucleus Scattering Overview

The differential rate for target nuclide T,

$$\frac{dR_T}{dE_R} = N_T \int_{v>v_{\min}} \frac{d\sigma_T}{dE_R} \times \frac{\rho}{m} f(\vec{v},t)\, d^3v$$

Example: DM-nuclei spin-independent interaction,

$$\frac{d\sigma_T}{dE_R} = \frac{\sigma_T(E_R)\, M_T}{2\mu_T^2 v}$$

$$\frac{dR_T}{dE_R} = N_T \frac{\sigma_T(E_R)}{2m\mu_T^2}\rho\eta(v_{min})\ , \quad \eta(v_{\min}) \equiv \int_{v>v_{\min}} d^3v\, \frac{f(\vec{v})}{v} = \int_{v_{\min}}^{\infty} dv\, \frac{F(v)}{v}\ .$$

Halo Dependent (HD) Analysis: Assume a local dark halo model, i.e., $\eta(v_{\min})$. Plots are made in (m, σ_{ref}) parameter space.

Halo Independent (HI) Analysis: The halo model is not assumed but is to be found using the observed rate. All the dependence on the halo is in $\eta(v_{\min})$, common to all experiments, . Plots are made in the $(v_{\min},\ \tilde{\eta})$ plane[1].

Complications: experiments do not directly observe the recoil energy; instead, they observe a proxy E' for E_R with E' dependent energy resolutions/efficiencies.

The observed rate is $$\frac{dR}{dE'} = \varepsilon(E') \int_0^\infty dE_R \sum_T G_T(E_R, E')\, \frac{dR_T}{dE_R}$$

$\varepsilon(E')$: counting efficiency; $G_T(E_R, E')$: energy resolution.

Formulation for general nuclear form factor, interaction type and energy resolution[2]

$$\frac{dR}{dE'} = \int_0^{v_{\max}} dv_{\min}\ \frac{d\mathcal{R}}{dE'}(v_{\min}, E')\ \tilde{\eta}(v_{\min})\ , \quad \tilde{\eta}(v_{\min}) = \frac{\rho\sigma_{\rm ref}}{m}\eta(v_{\min})$$

$d\mathcal{R}/dE'$: DM, particle model, and detector dependent response function.
It acts as a "**window function**" in $v_{\min}$. We can get information about $\tilde{\eta}(v_{\min})$, only for the $v_{\min}$ range in which it is significantly different from 0.

Convex geometry tells us that for d data points[3],

$$F(v) = \sum_{n=1}^{d} F(v_n)\delta(v - v_n)$$

$\tilde{\eta}$ can be parameterized by v_n and $F(v_n)$.

New DM-Electron Scattering Analysis

Motivation: Extending the halo-independent analysis to DM-electron scattering and showing the limited speed range in which particular detectors can only provide information on the DM velocity distribution, which is needed for a more detailed inference of the DM distribution.

Due to their kinematic difference, the DM-Nuclei scattering cross section only depends on v, but DM-electron scattering depends on both v (DM velocity) and q (momentum transfer).

DM-Nucleus scattering: the target nuclei are free, the recoil energy $E_R = q^2/2m_N$.
DM-electron scattering: the target electrons are bounded and have an unknown initial momentum, the electron energy $E_e = \vec{q}\cdot\vec{v} - q^2/2m_\chi$. $E_e = E_R$ + binding energy.

DM-electron scattering rate:

$$\frac{dR}{dE_R} = \frac{1}{2\mu_{\chi e}^2}\frac{1}{E_R}\sum_{i,f}{}' \int_{q_{\min}}^{q_{\max}} dq\, q\ \tilde{\eta}(v_{\min}(q, E_R + E_{{\rm B}i}))\ |F_{\rm DM}(q)|^2 |f^{i,f}(q, E_R)|^2.$$

DM form factor: $F_{DM}(q)$=1 or $F_{DM}(q) = 1/q^2$;
electron form factor: $f^{i,f}(q, E_R)$, overlap of the initial and final electron wavefunctions.

Change of variable, from $(q,\ E_R)$ to $(v_{\min},\ E_R)$ (two branches, $q_\pm(v_{\min},\ E_R)$), the response function

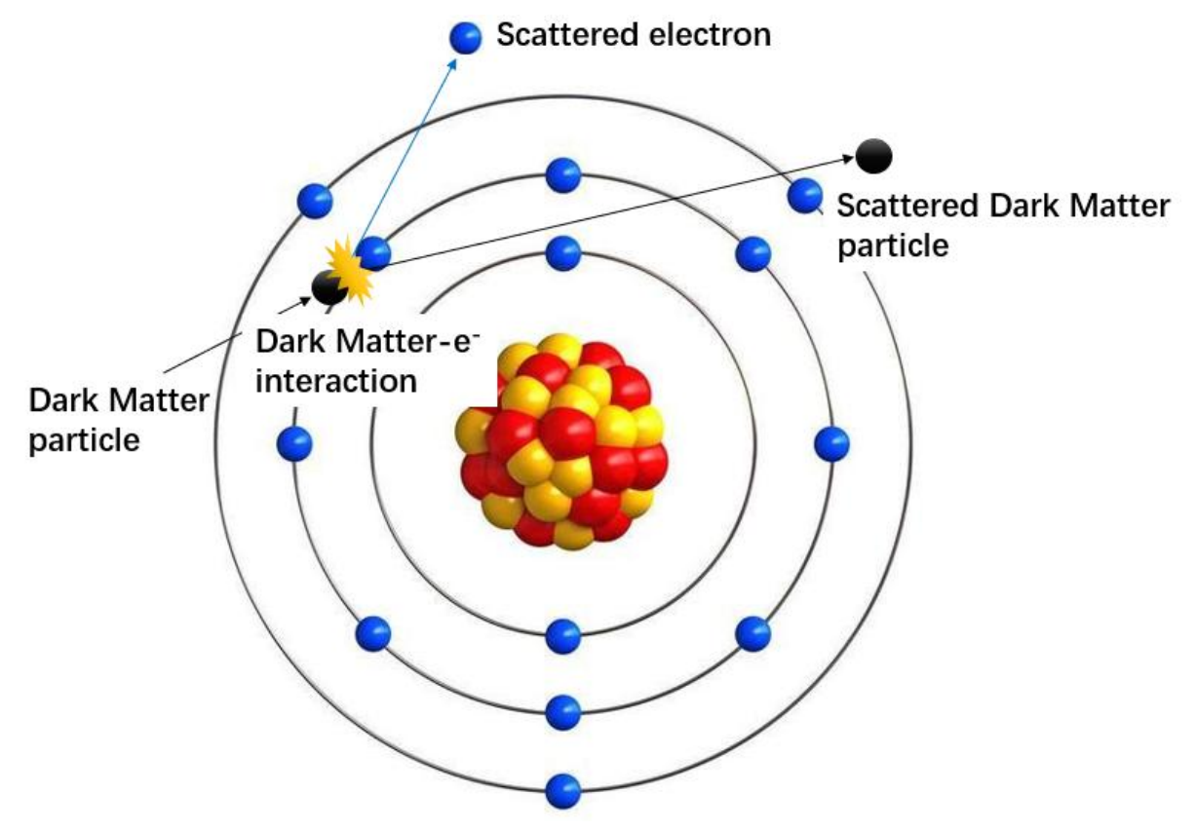
$$\frac{d\mathcal{R}_\pm}{dE'}(v_{\min}, E') = \sum_\pm \frac{\epsilon(E')}{2\mu_{\chi e}^2}\sum_{i,f}{}' \int_0^{E_{\max}} \frac{dE_R}{E_R} G(E', E_R) J_\pm(v_{\min}, E_R + E_{{\rm B}i})\ q_\pm(v_{\min}, E_R + E_{{\rm B}i})$$
$$|F_{\rm DM}(q_\pm(v_{\min}, E_R + E_{{\rm B}i}))|^2 |f^{i,f}(q_\pm(v_{\min}, E_R + E_{{\rm B}i}), E_R)|^2\ .$$

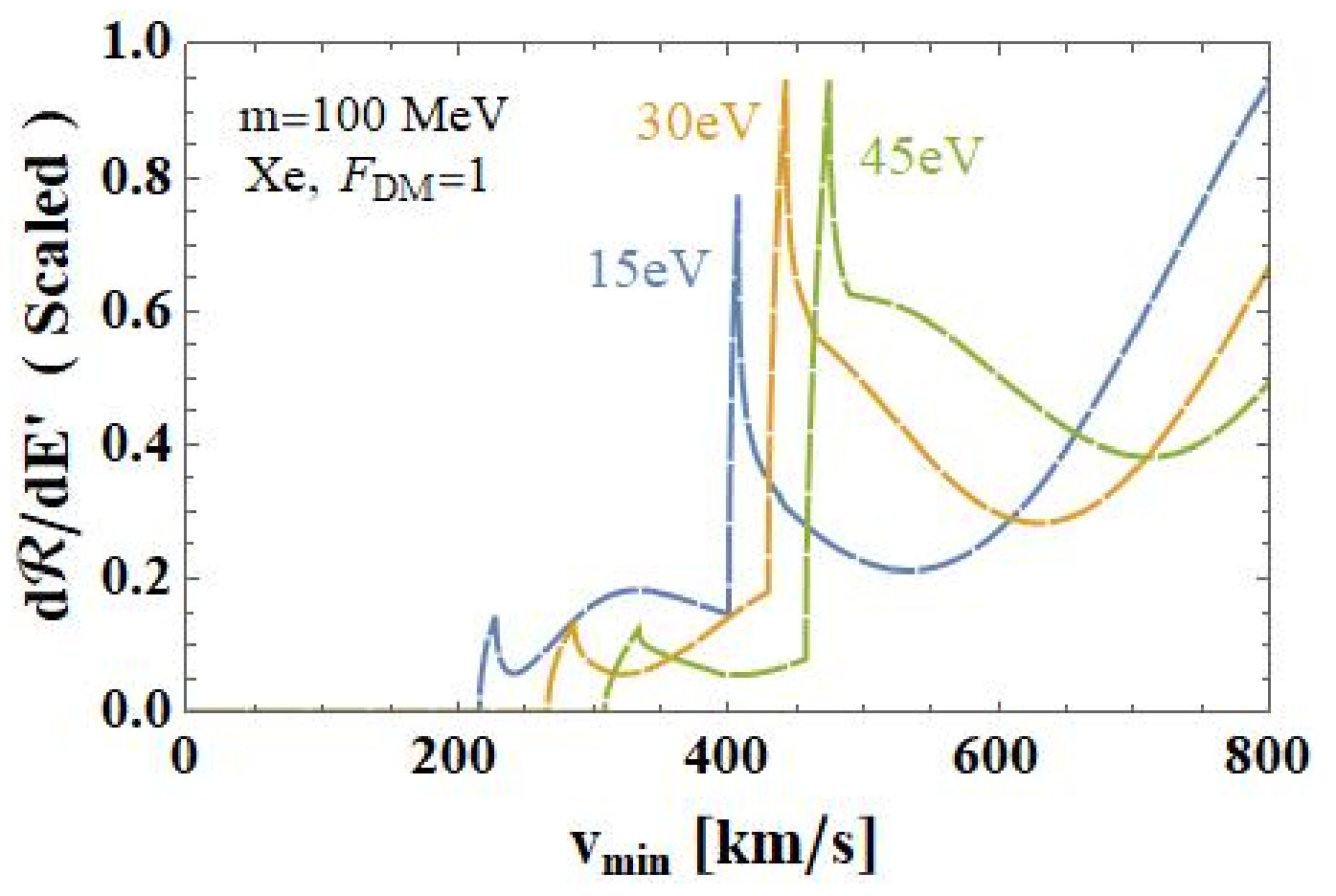
In free atoms, electrons are excited from an orbital to a free state, $E_e = E_R + E_{Bnl}$.
Differential rate[4]:

$$\frac{dR_{\rm ion}}{dE_R} = \sum_{nl} \frac{1}{8\mu_{\chi e}^2}\frac{1}{E_R}\int_{q_{\min}}^{q_{\max}} dq\, q\, \tilde{\eta}(v_{\min}(q, E_R{+}E_{Bnl}))\ |F_{\rm DM}(q)|^2\ |f_{\rm ion}^{nl}(q, E_R)|^2\ ,$$

Response function:

$$\frac{d\mathcal{R}_{\rm ion}}{dE'}(v_{\min}, E') = \sum_\pm \frac{\epsilon(E')}{8\mu_{\chi e}^2}\sum_{nl}\int \frac{dE_R}{E_R}\, G_{\rm ion}(E', E_R) J_\pm(v_{\min}, E_R + E_{{\rm B}nl}) q_\pm(v_{\min}, E_R + E_{{\rm B}nl})$$
$$\times |F_{\rm DM}(q_\pm(v_{\min}, E_R + E_{{\rm B}nl}))|^2 |f_{\rm ion}^{nl}(q_\pm(v_{\min}, E_R + E_{{\rm B}nl}), E_R)|^2$$





Loop Order Correction in Ar and Xe

Motivation: Understanding how much of a disadvantage argon-based detectors have with respect to those that are xenon-based to detect pseudoscalar-mediated interactions.

Pseudoscalar coupling:

$$\mathcal{L}_{\rm S-PS} = g_\chi\, \phi\, \bar{\chi}\, \chi + g_{\rm SM} \sum_f \frac{m_f}{v} \phi\, \bar{f}\, i\gamma_5\, f$$

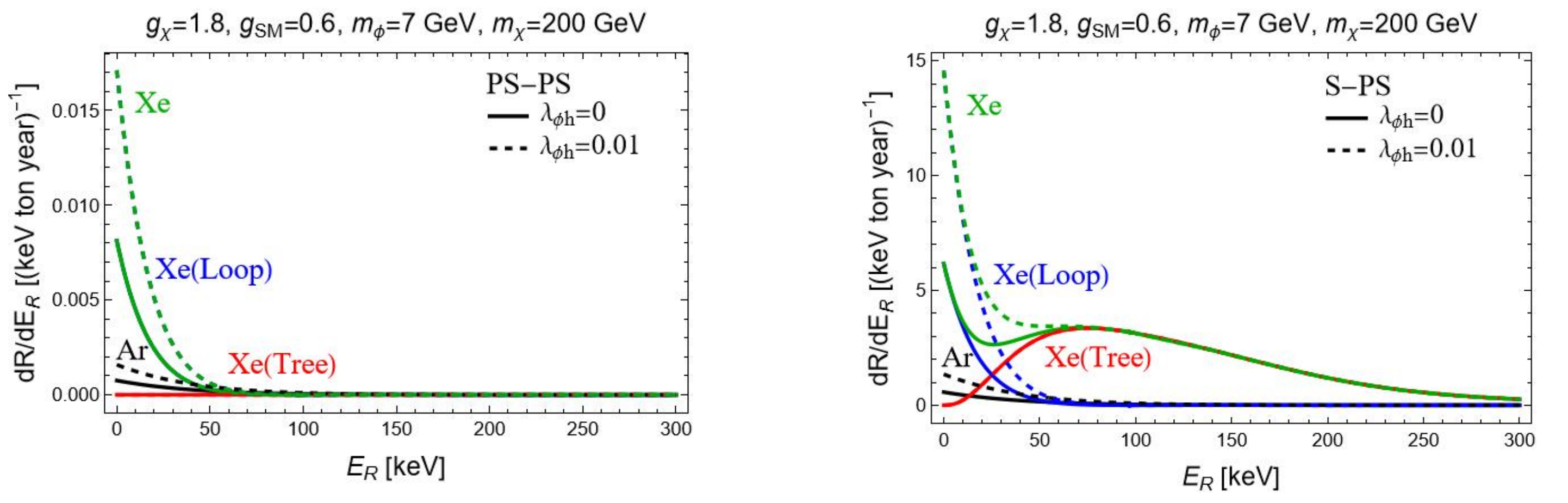
$$\mathcal{L}_{\rm PS-PS} = g_\chi\, \phi\, \bar{\chi}\, i\gamma_5\, \chi + g_{\rm SM} \sum_f \frac{m_f}{v} \phi\, \bar{f}\, i\gamma_5\, f$$

with Higgs coupling

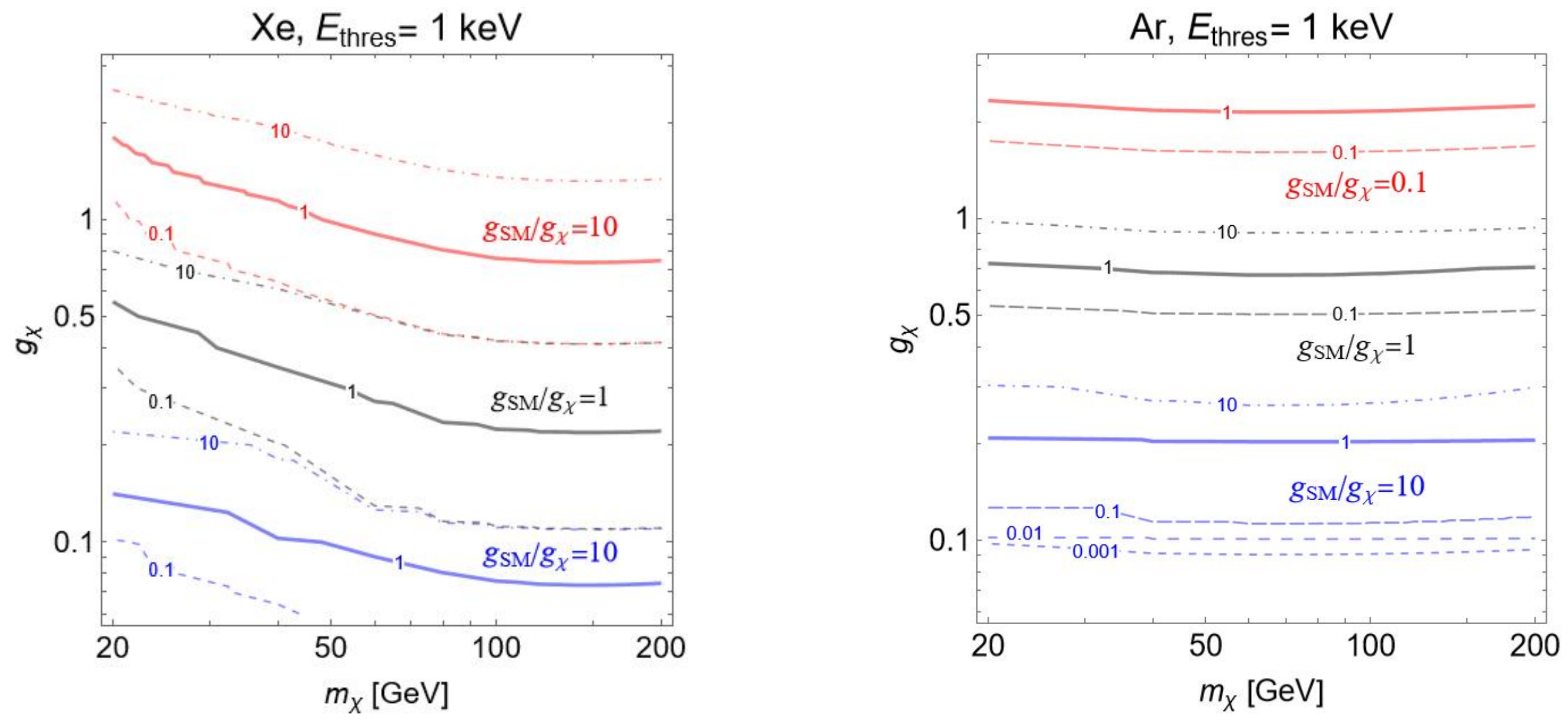
$$\mathcal{L}_{\rm int}^{\rm Higgs} = \frac{1}{2}\lambda_{\phi h} v h \phi^2$$

DM-nuclei interaction detectablility:
  Ar: zero nuclear spin, only has loop-level contributions.
  Xe: nonzero nuclear spin, has both tree-level and loop-level contribution.

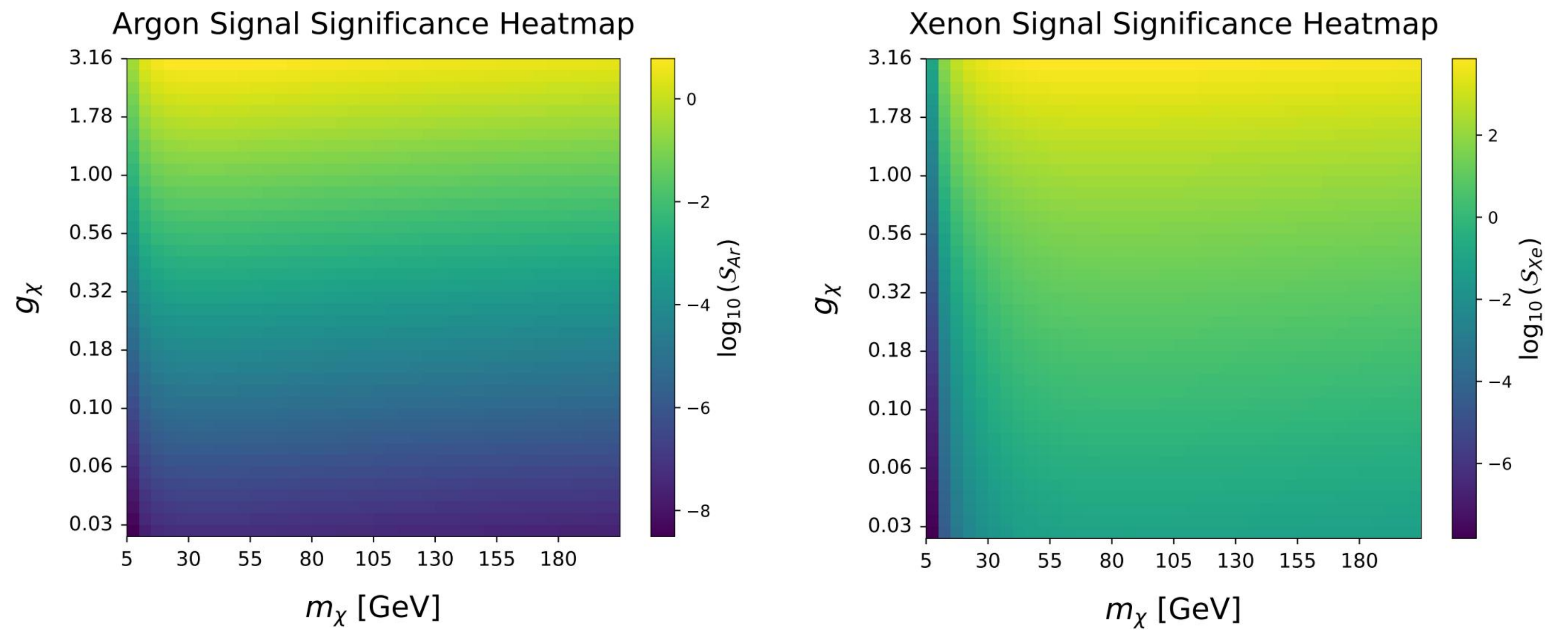
Differential rate:



Lines of equal energy-integrated event rate:



Signal significance: heat map for the proposed DS-LM argon experiment (left) and the LZ xenon experiment (right)[5,6].



Conclusion

- Response function acts as a window through which direct detection data can give information on the local dark halo. Different materials can be sensitive to different DM speed ranges.
- In general for large DM masses and small DM couplings, Ar-based DS-LM experiment requires larger exposure to reach a sensitivity similar to that of the Xe-based LZ experiment, except for a small region of parameter space (m_χ~GeV, g_χ~1−3) in which the Ar-based experiment is favored and can reach a sensitivity which is ~10 times better than the Xe-based experiment.

Reference

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[3] Gelmini et al, JCAP 12 (2017) 039 [1707.07019]
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