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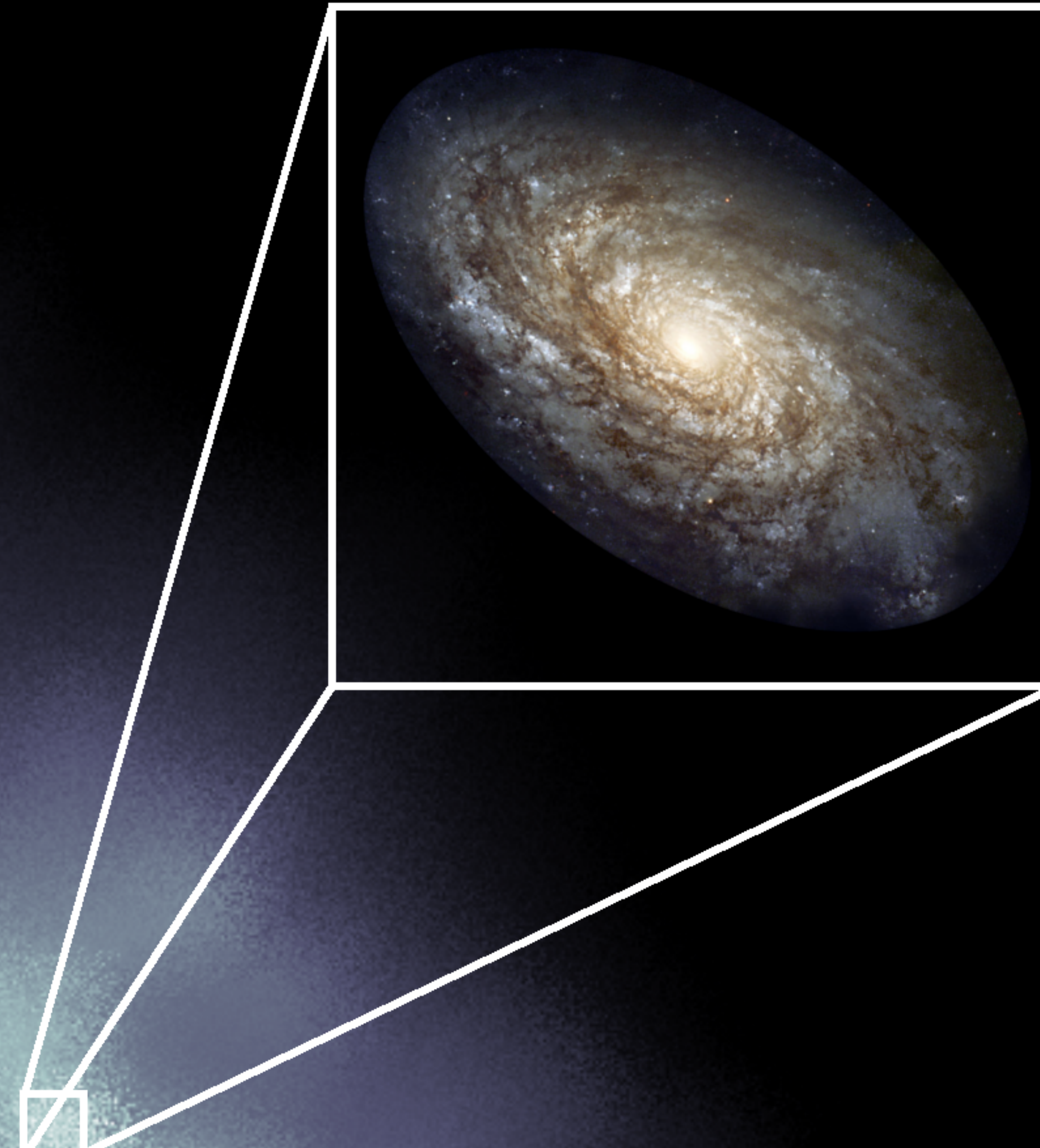

Direct detection of light dark matter

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Image credits: Cosmological Physics and Advanced Computing Group, Argonne National Laboratory

Outline

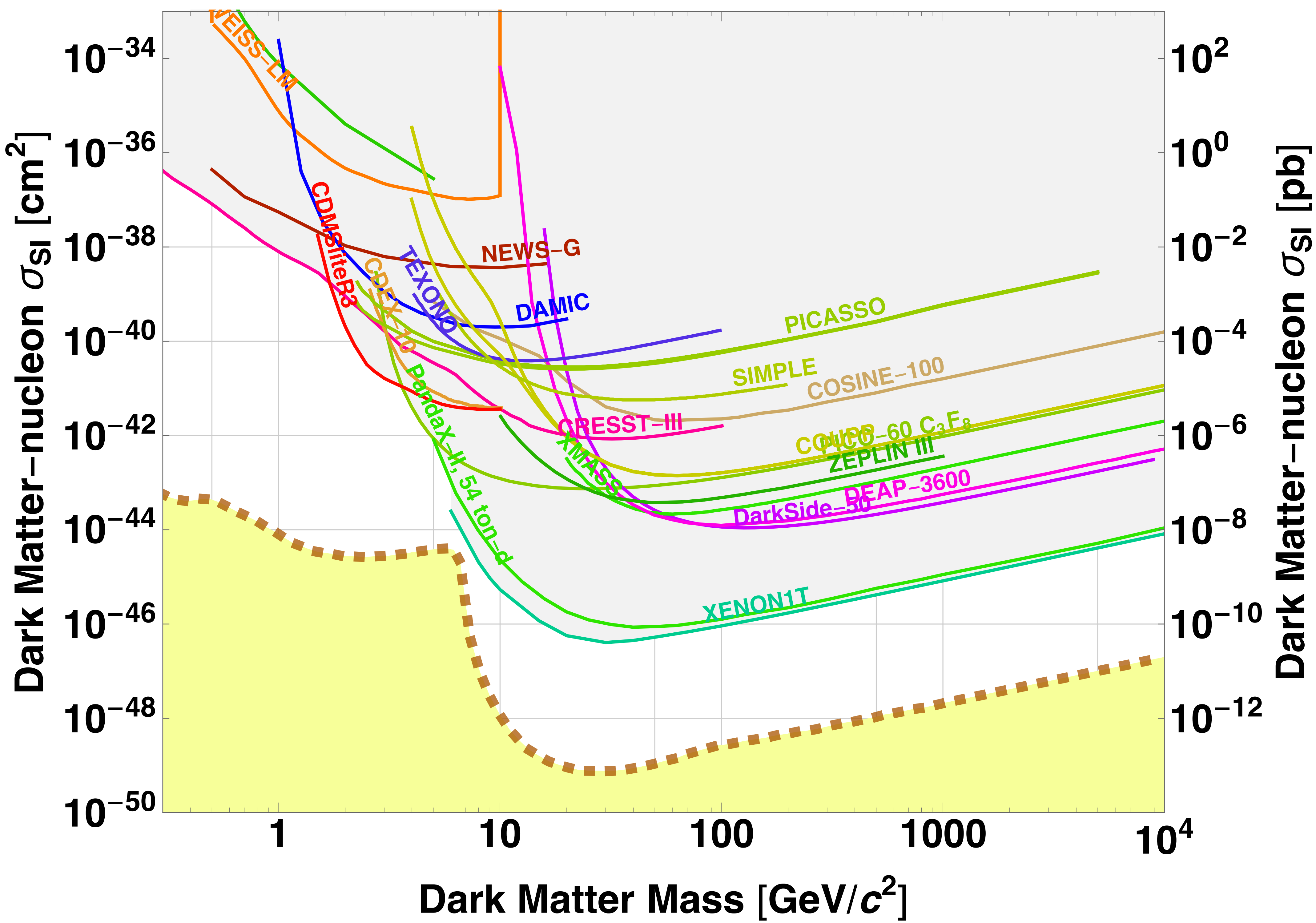
1. **Introduction**
2. **Results**
3. **Conclusions**

Based on `ArXiv:1903.08654` (to appear in PRD)

In collaboration with
Nader Mirabolfathi (Univ. Texas A & M)
Kai Nordlund and Matti Heikinheimo (Univ. of Helsinki)

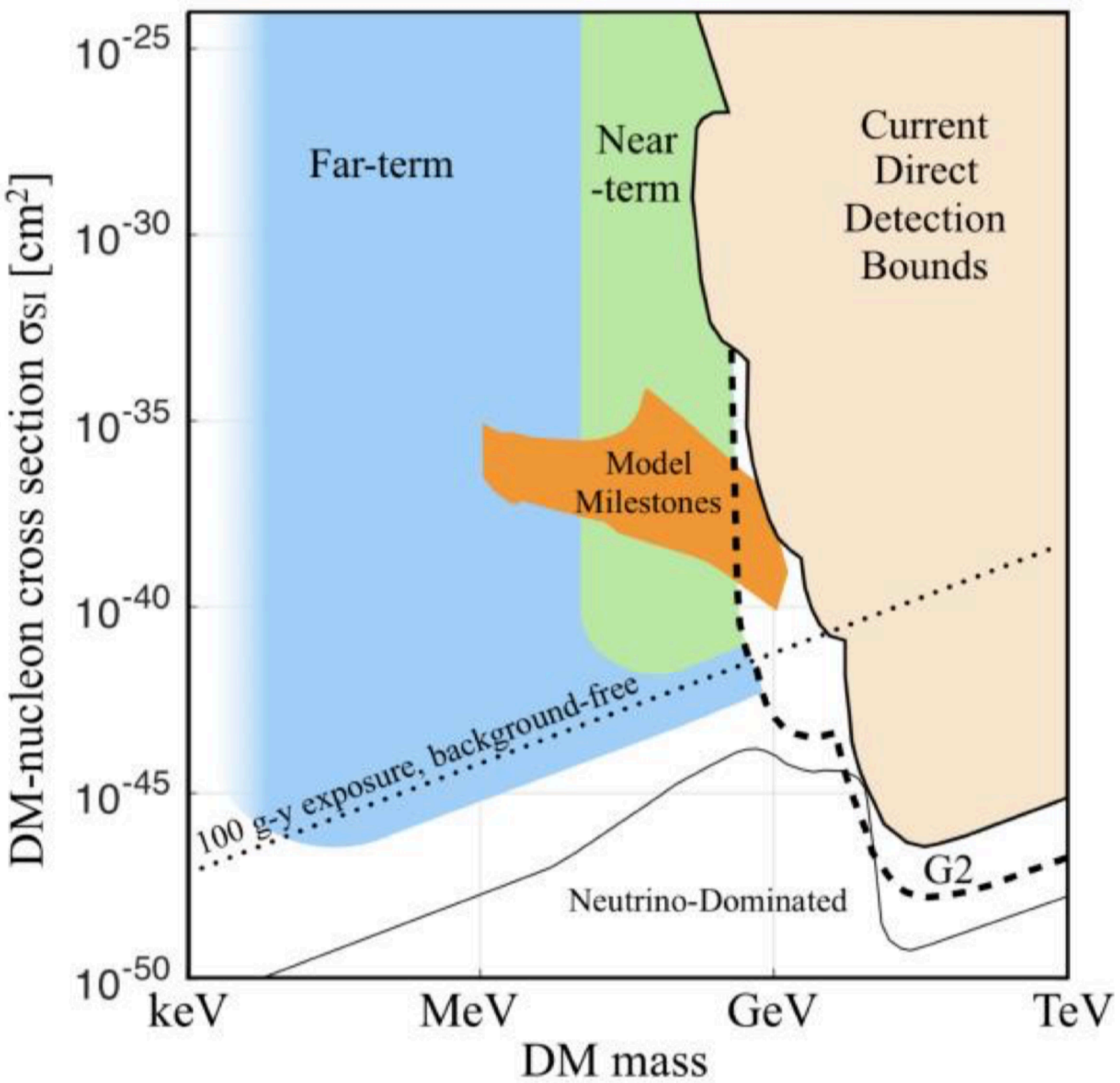
1. Introduction

The present



NEWS-G
DAMIC
TEXONO
CDMSliteR3
CDEX-10
PandaX-II, 54 ton-d
PICASSO
SIMPLE
COSINE-100
CRESST-III
XMASS
COUPP
PICO-60 C_3F_8
ZEPLIN III
DEAP-3600
DarkSide-50
XENON1T
Dark Matter–nucleon σ_{SI} [cm^2]
Dark Matter–nucleon σ_{SI} [pb]
Dark Matter Mass [GeV/c^2]

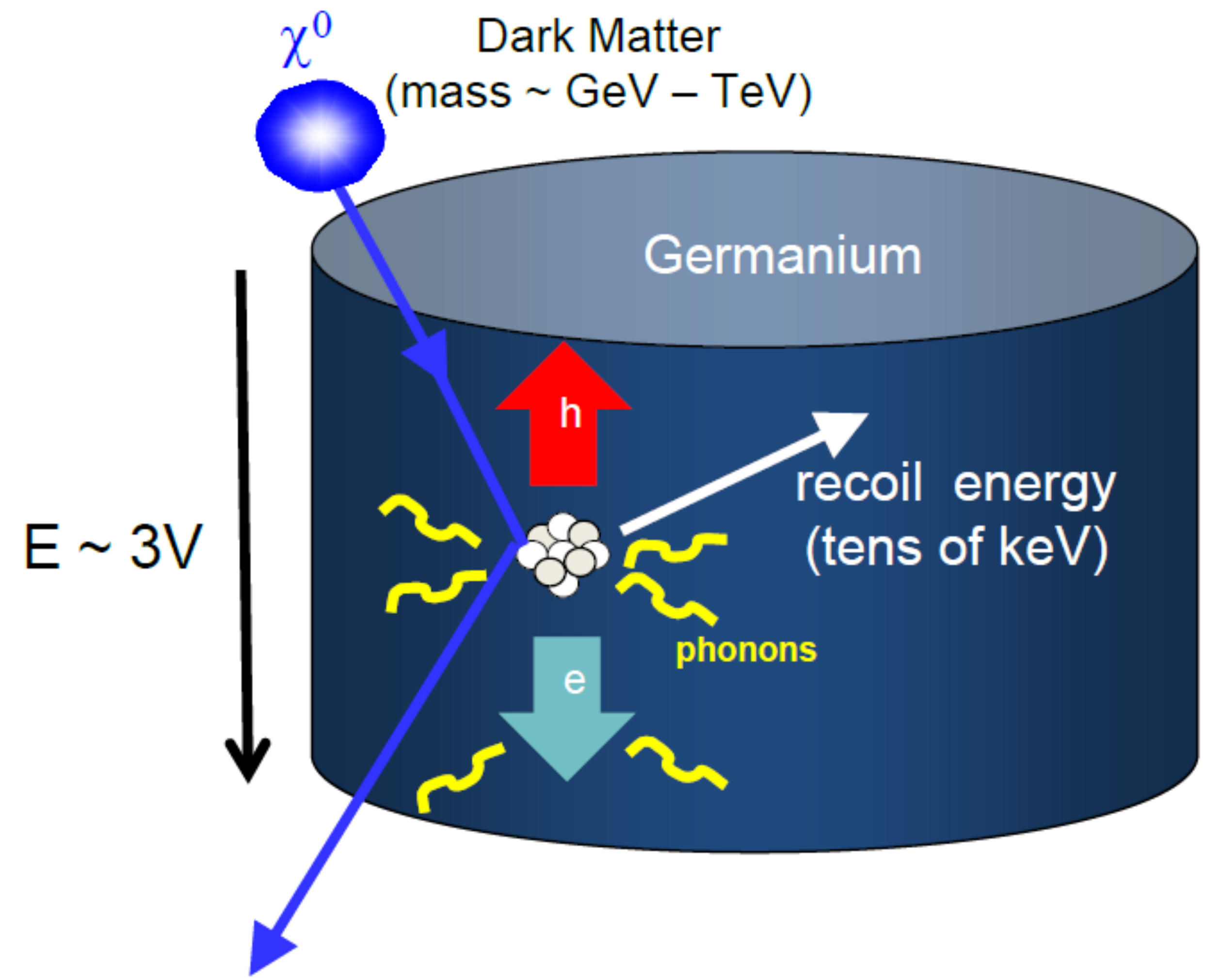
The future



Several new technologies/ detector concepts under active R&D, see

https://science.energy.gov/~/media/hep/pdf/Reports/Dark_Matter_New_Initiatives_rpt.pdf

CDMS experiment:



Smaller DM masses, smaller recoils
Higher sensitivity needed.
Means: single electron resolution.

Development beyond G2, e.g. by Nader Mirabolfathi's group (Texas A&M)

Scattering in a solid: Radiation damage

Extensively studied for beams of ordinary matter.

A key quantity: threshold displacement energy T_d

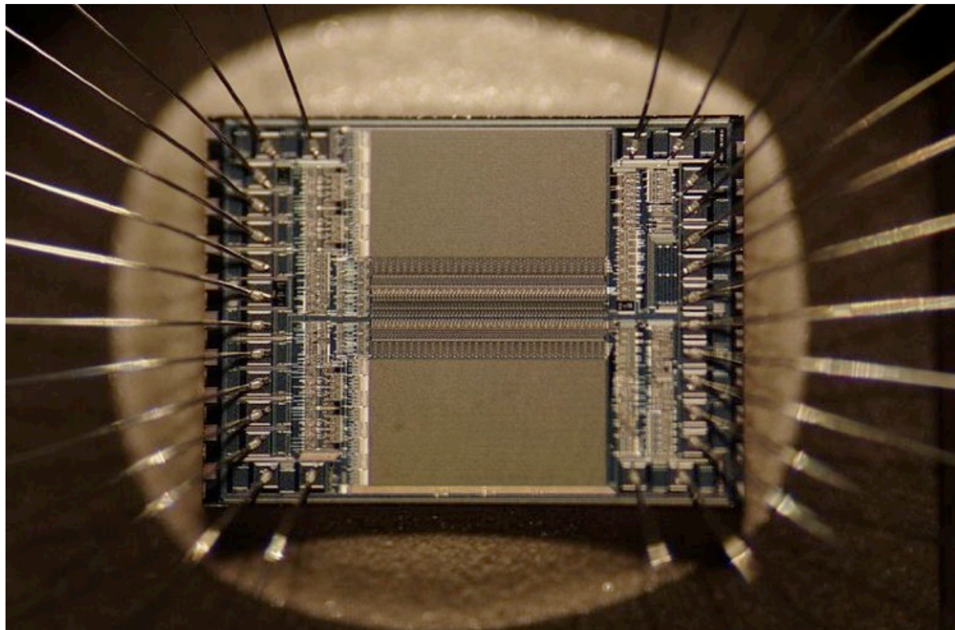
<u>Simple idea</u>:
Minimum energy needed to displace an atom in a crystal.

Typical values for metals and semiconductors: $T_d \sim 20\ldots50\ \mathrm{eV}$

Important in estimating damage production

Kinchin-Pease: $$N_{\mathrm{Frenckel}} \sim \frac{T}{2T_d}$$

e.g. in Si chip manufacturing.



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Consider DM scattering on nucleus:

$m_{\text{DM}} = 1\ \text{GeV}$

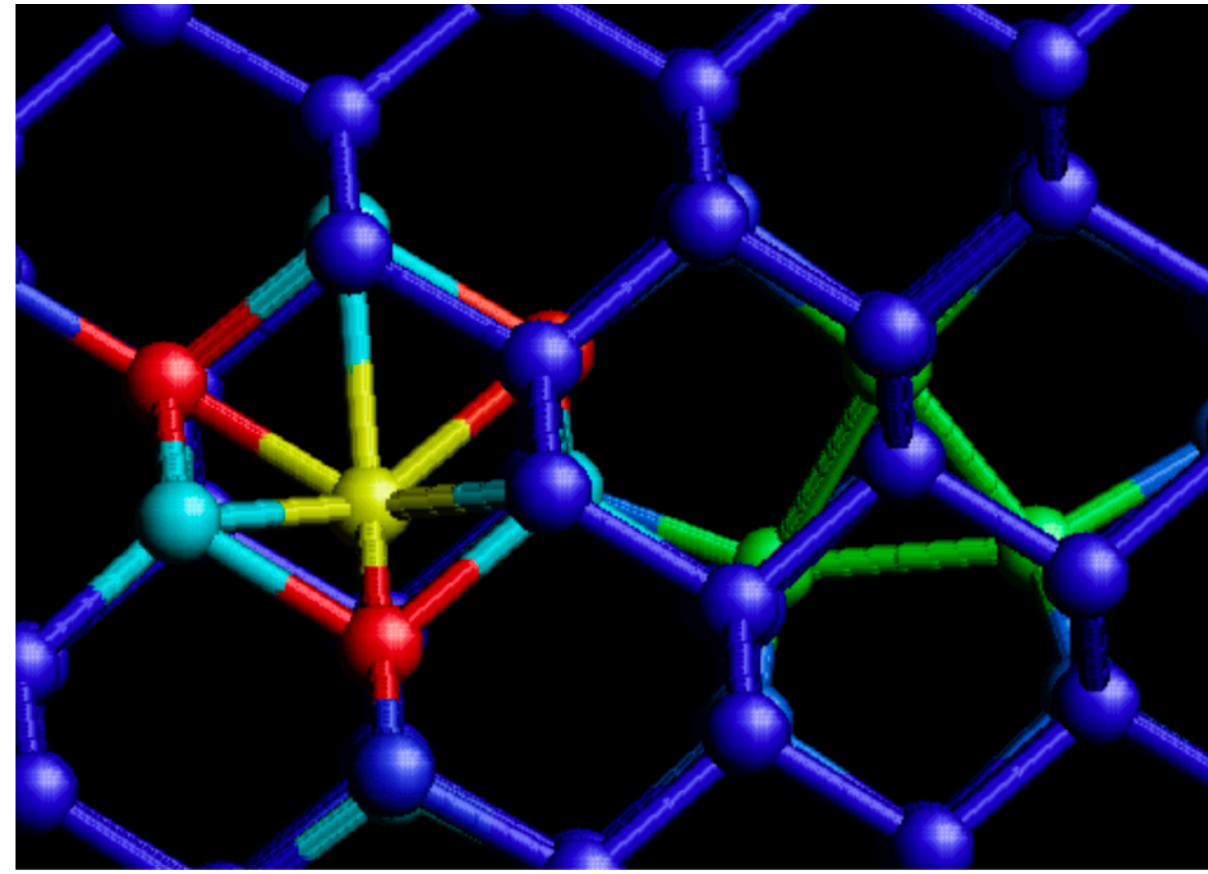
$v_{\text{DM}} = 220\ \text{km/s}$

$$\Rightarrow \qquad E_{\text{DM}} = 269\ \text{eV}$$

Energy transfer to Silicon $M = 28\,\text{u}$ in head on collision:

$$T = \frac{4 M m_{\text{DM}}}{(M + m_{\text{DM}})^2} E_{\text{DM}} = 38\ \text{eV}$$

Obviously, the threshold must depend on crystal direction



Experimentally verified
in electron irradiation experiments
(since ‘70s)

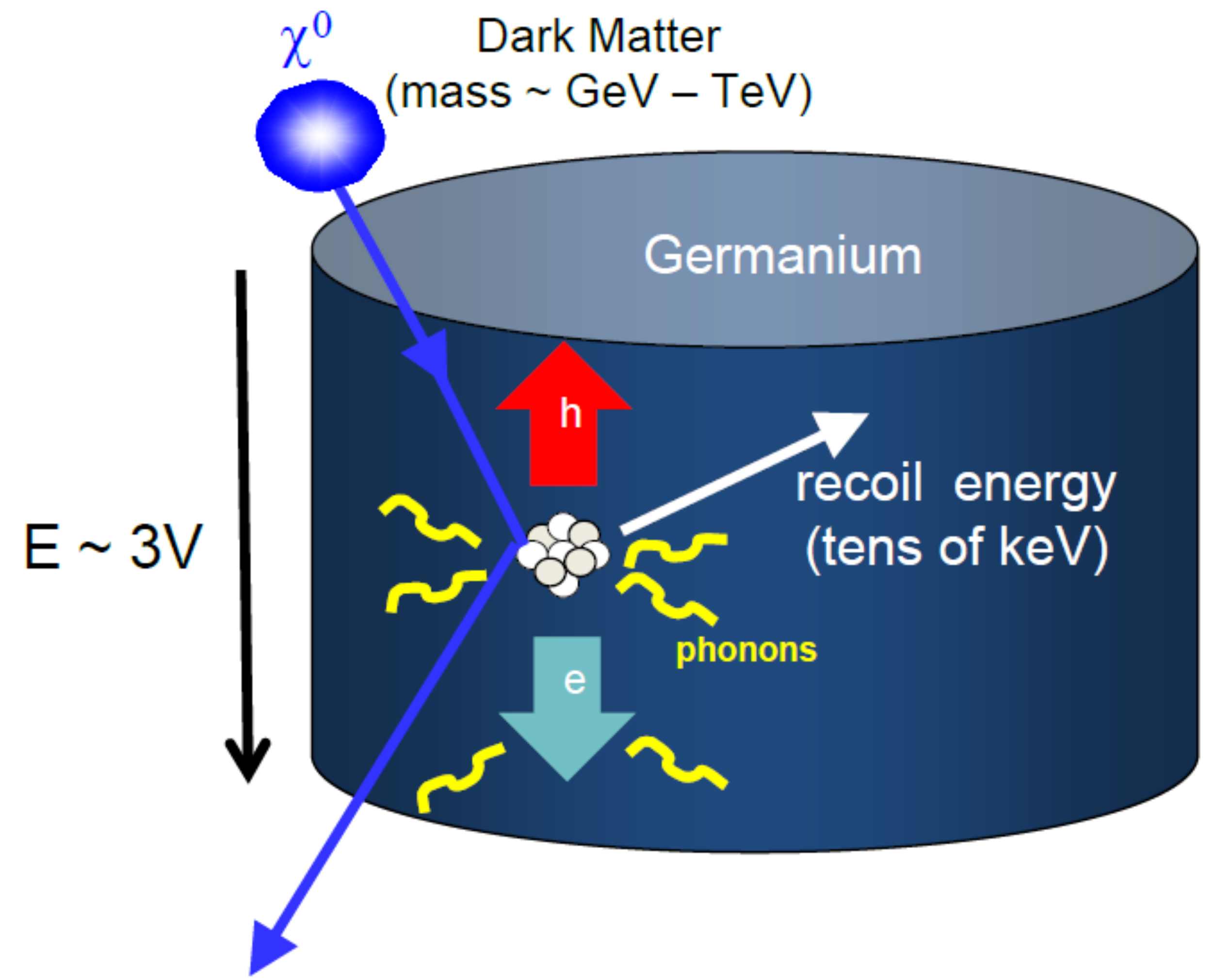
Computable by molecular dynamics simulations.

Molecular Dynamics
= simulation of atomic motion by solving Newton’s equation.

Forces from quantum or classical modelling:

Quantum: density functional theory
Classical: analytic interatomic potentials

CDMS experiment:

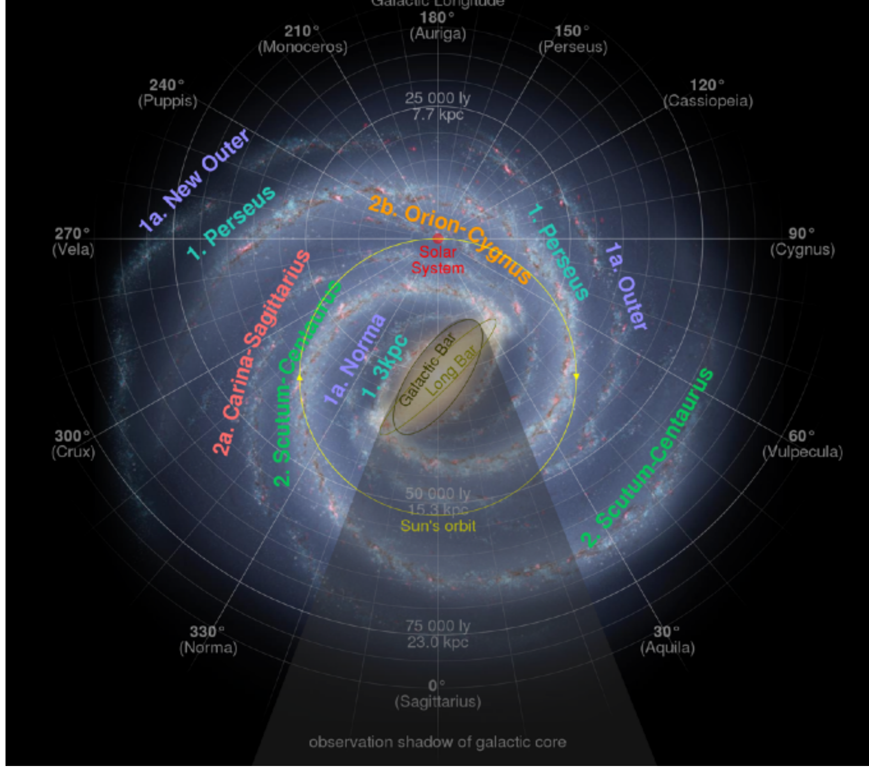


Recoiling nucleus forms a lattice defect.

Facilitates e-h creation.

Directional sensitivity due to $T_d(\theta, \phi)$

Constant level of recoils as the Sun moves in the galaxy

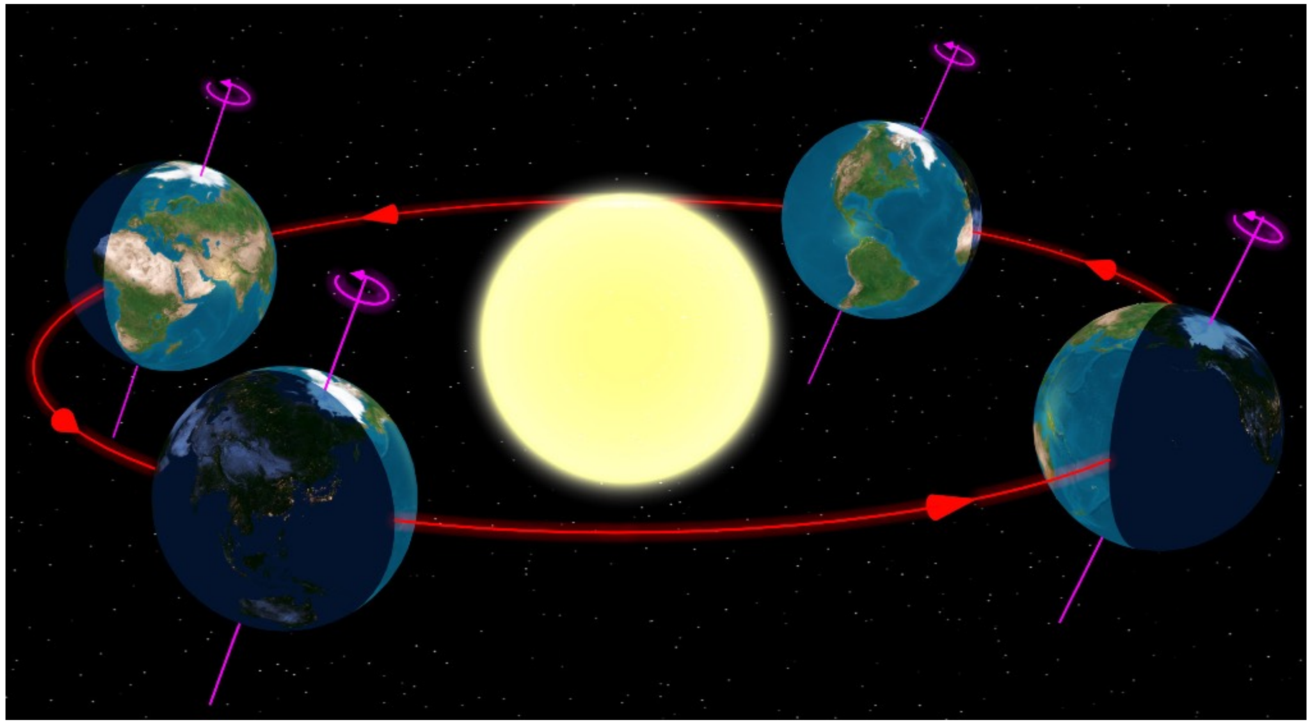


<u>Simple idea:</u>
Detector moves with respect to the dark matter background.
Depending on this, the energy transfer can be above or below threshold.

Additional effects from relative movement:

Annual modulation:
motion of Earth around Sun.

Daily modulation:
rotation of Earth.



Will distinguish the DM signal from BG

2. Detailed analysis

The event rate

$$v_{\min} = \sqrt{\frac{m_N E}{2\mu^2}}$$

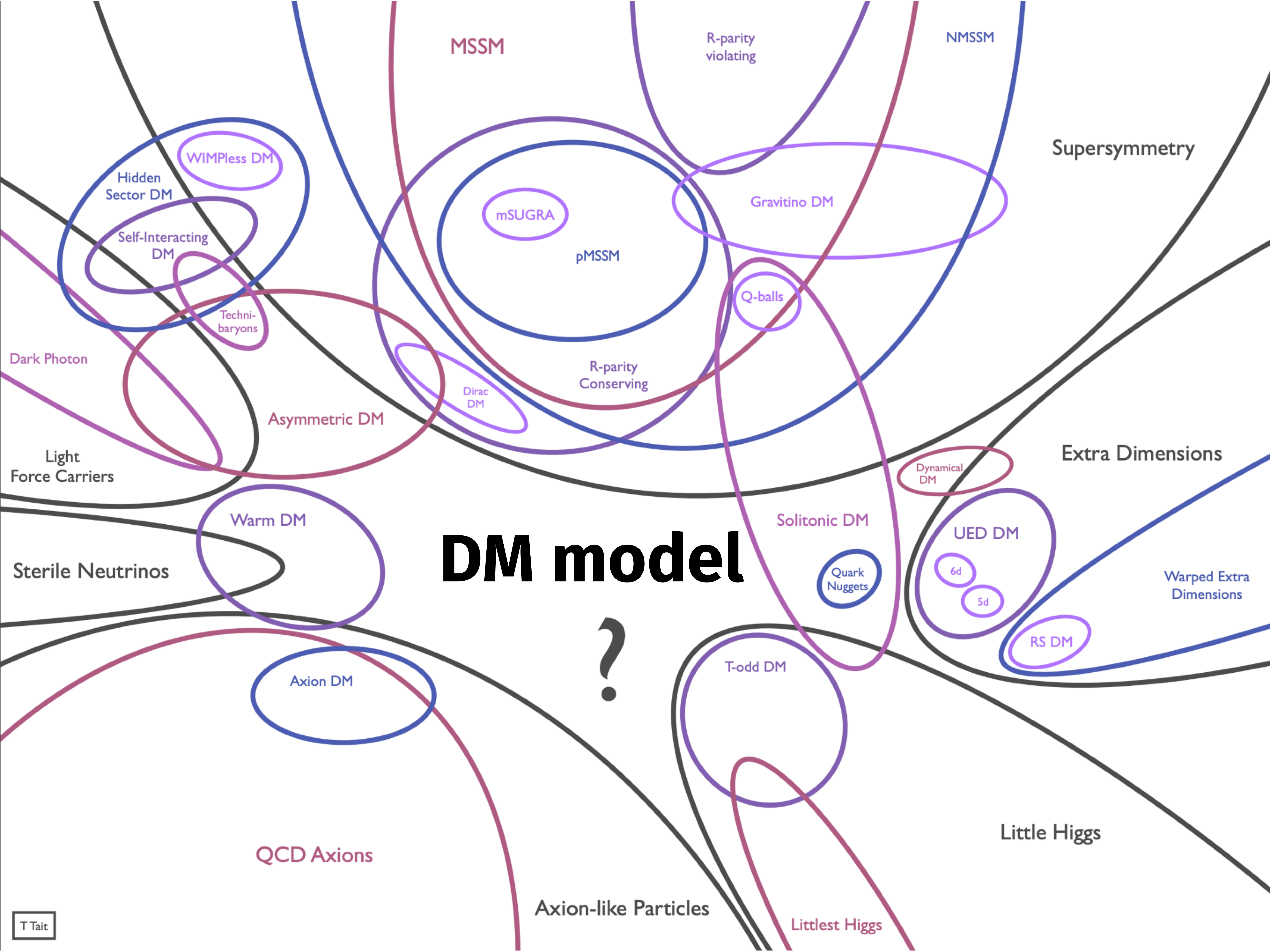
Kinematics

$$\frac{dR}{dE d\Omega_q} \sim \int d^3 v \underbrace{|\mathscr{M}|^2}_{\text{DM model}} \underbrace{f_{\text{SHM}}(v)}_{\text{Standard Halo Model}} \overbrace{\delta(\mathbf{v} \cdot \hat{\mathbf{q}} - v_{\min})}$$

DM model

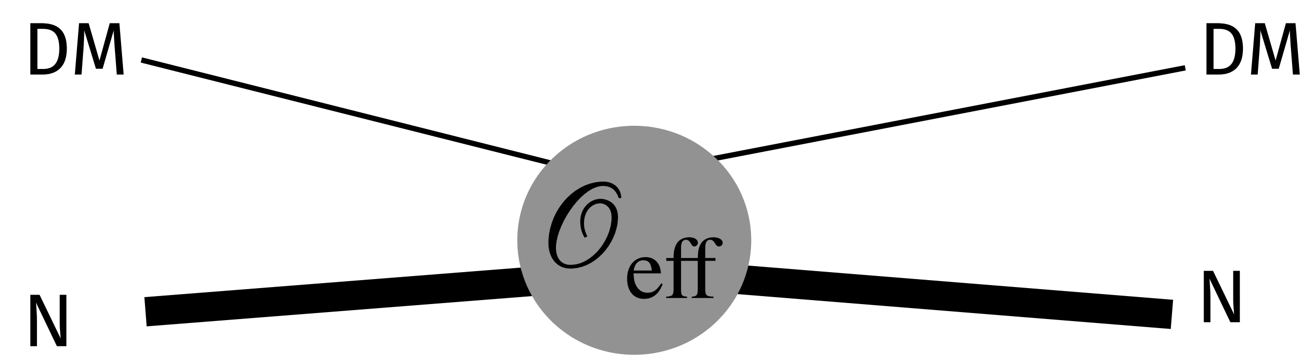
Standard Halo Model

$$f_{\text{SHM}}(v) = \frac{1}{\mathcal{N}} \frac{1}{(2\pi\sigma_v^2)^{3/2}} \exp(-v^2/(2\sigma_v^2))\Theta(v_e - v)$$


MSSM
R-parity violating
NMSSM
Supersymmetry
WIMPless DM
Hidden Sector DM
Self-Interacting DM
Techni-baryons
mSUGRA
pMSSM
Gravitino DM
Q-balls
R-parity Conserving
Dirac DM
Dark Photon
Asymmetric DM
Light Force Carriers
Extra Dimensions
Dynamical DM
Warm DM
Solitonic DM
UED DM
DM model
Sterile Neutrinos
Quark Nuggets
6d
5d
Warped Extra Dimensions
?
RS DM
Axion DM
T-odd DM
Little Higgs
QCD Axions
Axion-like Particles
Littlest Higgs
T Tait

DM effective theory

At low energy most models look like



Modest number of general eff. operators

Fitzpatrick, Haxton, Katz, Lubbers, Xu, JCAP (2013)
Anand, Fitzpatrick, Haxton, PRC (2014)

Eff. operators can depend only on

$$\mathbf{q}, \quad \mathbf{v}^{\perp}, \quad \mathbf{S}_{\text{DM}}, \quad \mathbf{S}_{\text{n}}$$

$$\mathbf{v}^{\perp} = \mathbf{v}_{\text{rel}} + \frac{\mathbf{q}}{2\mu_{\text{DM},n}}$$

$$\Rightarrow |\mathscr{M}|^2 = a_1 1 + a_2 q^2 + a_3 q^4 + b_1 v_{\perp}^2 + \ldots$$

$$\mathcal{O}_1 = 1$$
$$\mathcal{O}_2 = (v^{\perp})^2$$
$$\mathcal{O}_3 = i\mathbf{S}_n \cdot (\frac{\mathbf{q}}{m_n} \times \mathbf{v}^{\perp})$$
$$\mathcal{O}_4 = \mathbf{S}_{\mathrm{DM}} \cdot \mathbf{S}_n$$
$$\mathcal{O}_5 = i\mathbf{S}_{\mathrm{DM}} \cdot (\frac{\mathbf{q}}{m_n} \times \mathbf{v}^{\perp})$$
$$\mathcal{O}_6 = (\mathbf{S}_{\mathrm{DM}} \cdot \mathbf{q})(\mathbf{S}_n \cdot \mathbf{q})$$
$$\mathcal{O}_7 = \mathbf{S}_n \cdot \mathbf{v}^{\perp}$$
$$\mathcal{O}_8 = \mathbf{S}_{\mathrm{DM}} \cdot \mathbf{v}^{\perp}$$
$$\mathcal{O}_9 = i\mathbf{S}_{\mathrm{DM}} \cdot (\mathbf{S}_n \times \mathbf{q})$$
$$\mathcal{O}_{10} = \mathbf{S}_n \cdot \mathbf{q}$$
$$\mathcal{O}_{11} = \mathbf{S}_{\mathrm{DM}} \cdot \mathbf{q}$$
$$\mathcal{O}_{12} = i\mathbf{S}_{\mathrm{DM}} \cdot (\mathbf{S}_n \times \mathbf{v}^{\perp})$$
$$\mathcal{O}_{13} = i(\mathbf{S}_{\mathrm{DM}} \cdot \mathbf{v}^{\perp})(\mathbf{S}_n \cdot \frac{\mathbf{q}}{m_n})$$
$$\mathcal{O}_{14} = i(\mathbf{S}_{\mathrm{DM}} \cdot \frac{\mathbf{q}}{m_n})(\mathbf{S}_n \cdot \mathbf{v}^{\perp})$$
$$\mathcal{O}_{15} = -(\mathbf{S}_{\mathrm{DM}} \cdot \frac{\mathbf{q}}{m_n})((\mathbf{S}_n \times \mathbf{v}^{\perp}) \cdot \frac{\mathbf{q}}{m_n})$$
$$\mathcal{O}_1^{LR} = \frac{\mathcal{O}_1}{q^2}$$

e.g. usual SI and SD:

$$\mathcal{O}_{\mathrm{SI}} = \mathcal{O}_1$$

$$\mathcal{O}_{\mathrm{SD}} = \mathcal{O}_4$$

but more general behaviors possible:

$$|\mathcal{M}|^2 \propto \begin{cases} 1 & : \mathcal{O}_1, \mathcal{O}_4\,, \\ v_\perp^2 & : \mathcal{O}_7, \mathcal{O}_8\,, \\ q^2 & : \mathcal{O}_9, \mathcal{O}_{10}, \mathcal{O}_{11}, \mathcal{O}_{12} \\ v_\perp^2 q^2 & : \mathcal{O}_5, \mathcal{O}_{13}, \mathcal{O}_{14}\,, \\ q^4 & : \mathcal{O}_3, \mathcal{O}_6\,, \\ q^4(q^2 + v_\perp^2) & : \mathcal{O}_{15}\,, \\ q^{-4} & : \mathcal{O}_1^{LR}\,. \end{cases}$$

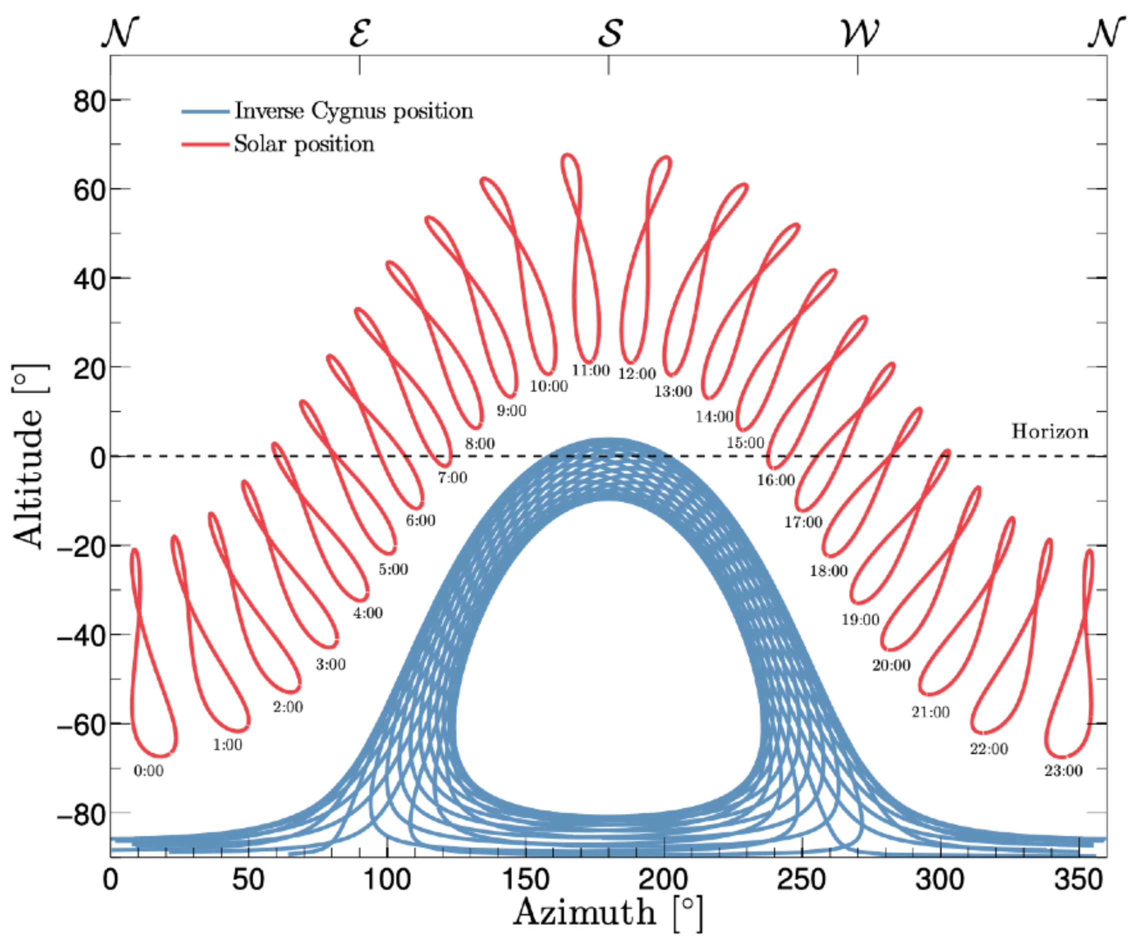
We consider: $|\mathcal{M}|^2 = a_1 1 + a_2 q^2 + a_3 q^4 + b_1 v_\perp^2 + \ldots$

Two integrals over velocity distribution

The Radon transform: $$\hat{f}(v_{\min}, \hat{\mathbf{q}}) = \int \delta(\mathbf{v} \cdot \hat{\mathbf{q}} - v_{\min}) f(v) d^3 v$$

The transverse Radon transform: $$\hat{f}_T(v_{\min}, \hat{\mathbf{q}}) = \int \delta(\mathbf{v} \cdot \hat{\mathbf{q}} - v_{\min}) (v^{\perp})^2 f(v) d^3 v$$

From galactic rest frame to the lab-frame: $\mathbf{v} \rightarrow \mathbf{v} - \mathbf{V(t)}$

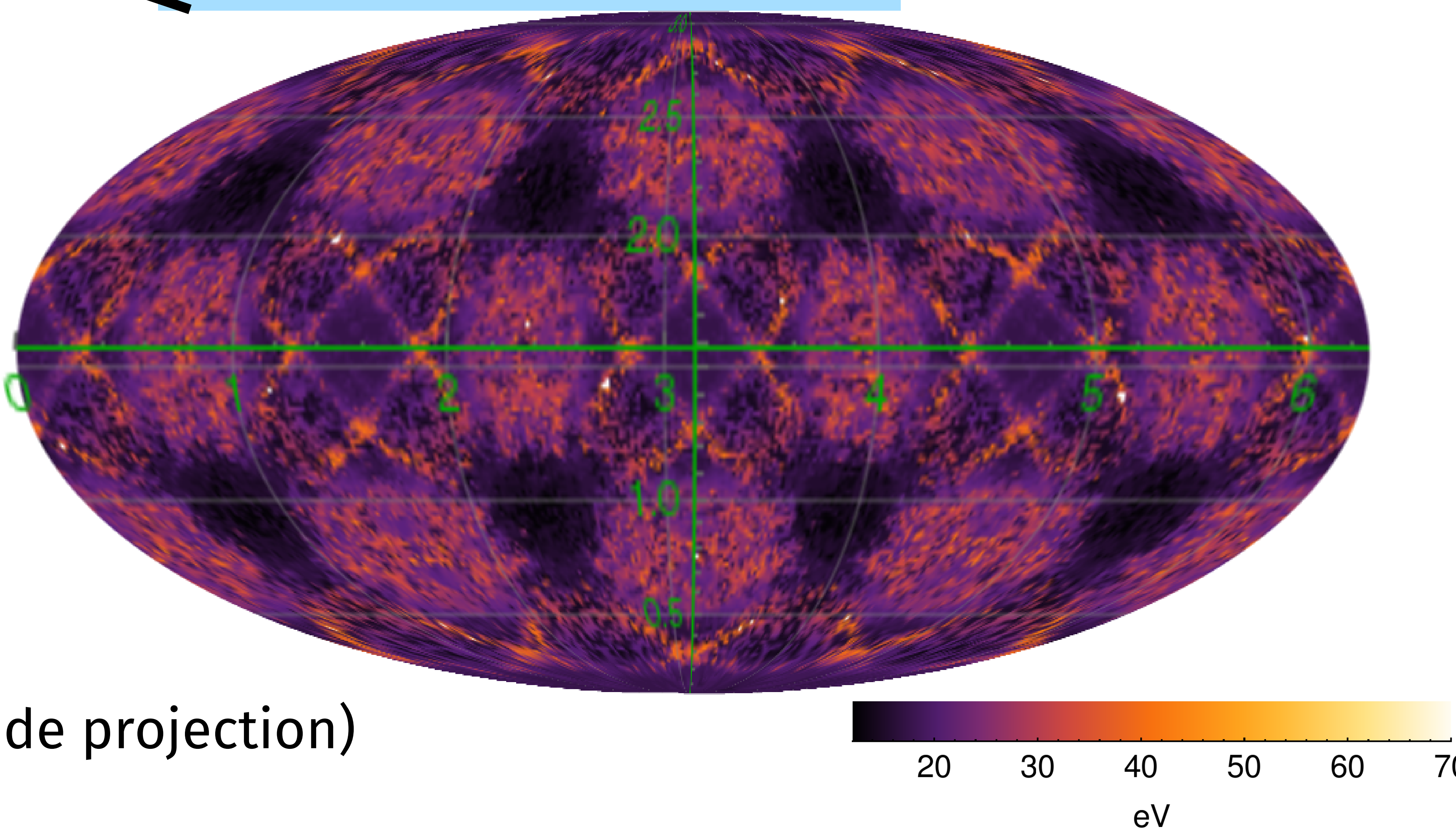


C.A.J. O'Hare *et al.*
1505.08061

$$|\mathscr{M}|^2 = a_1 1 + a_2 q^2 + a_3 q^4 + b_1 v_\perp^2 + \ldots$$

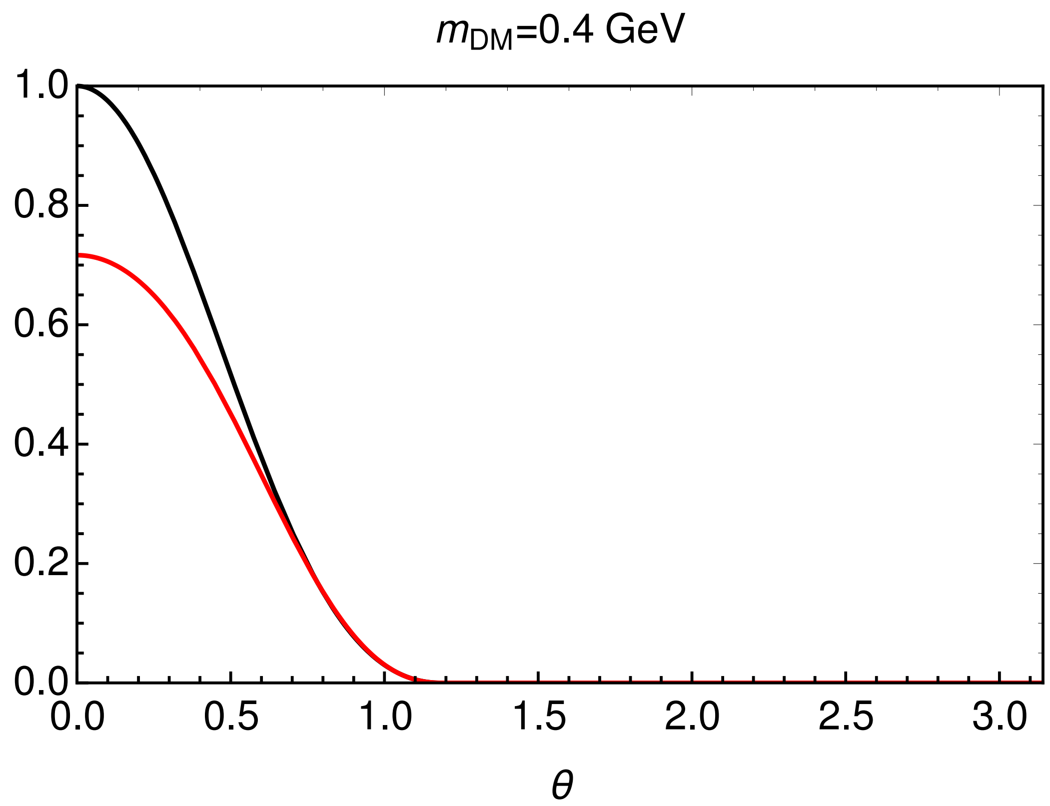
$$\frac{dR}{d\Omega_q} \sim \int_{E_{\min}(\theta,\phi)}^{E_{\max}\approx\infty} \left[(a_1 + a_2 q^2 + \ldots)\hat{f}(v_{\min}, \hat{\mathbf{q}}) + (b_1 + \ldots)\hat{f}_T(v_{\min}, \hat{\mathbf{q}}) \right]$$

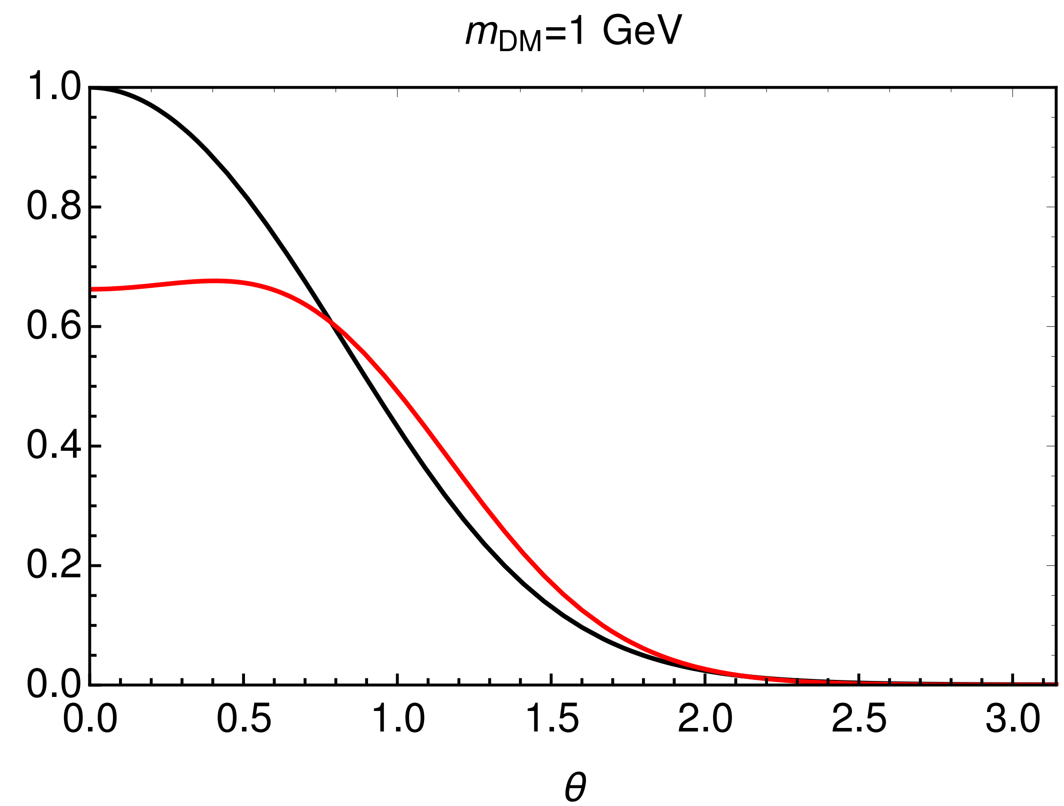
Threshold energies for Ge



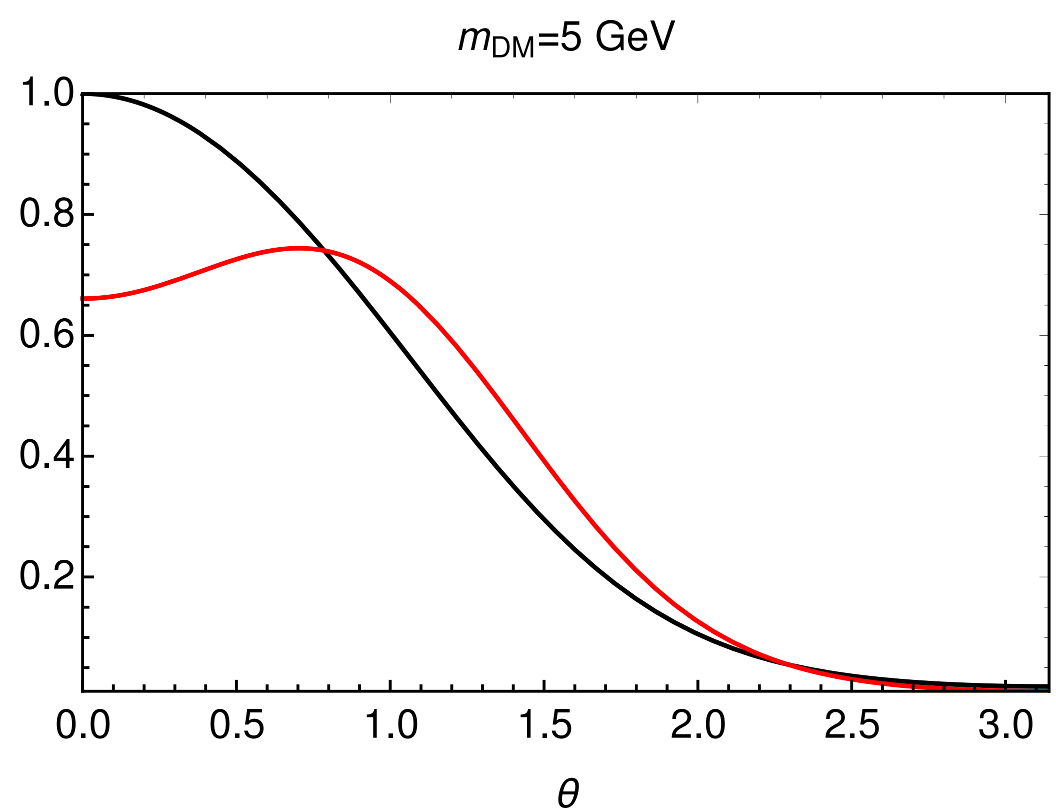
(Mölleweide projection)

Radon vs. transverse Radon trafo:





$$E = 20\,\mathrm{eV}$$

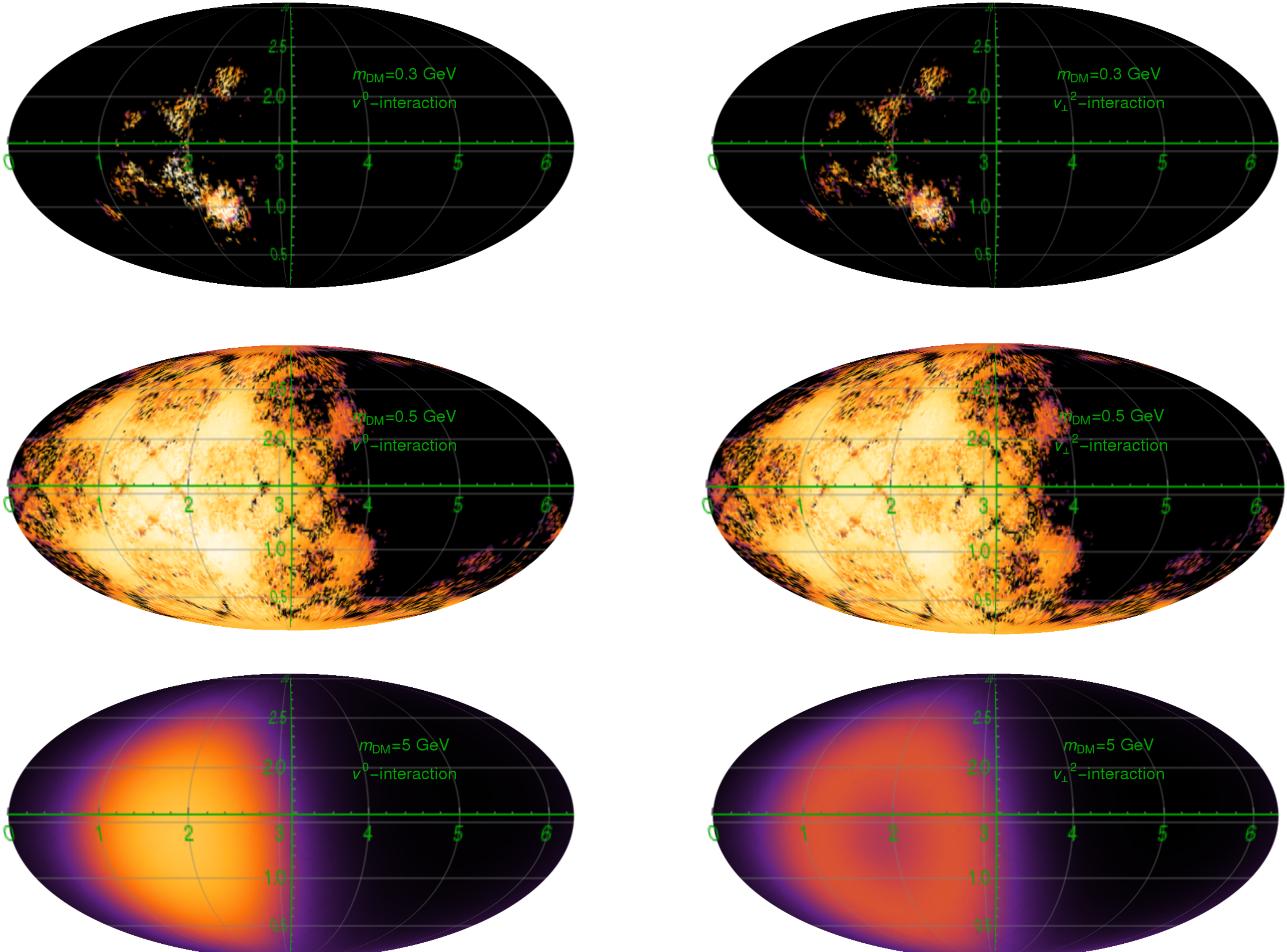


$|\mathscr{M}|^2 \sim v^0$ $|\mathscr{M}|^2 \sim v_\perp^2$

$m_{\mathrm{DM}} = 0.3$ GeV

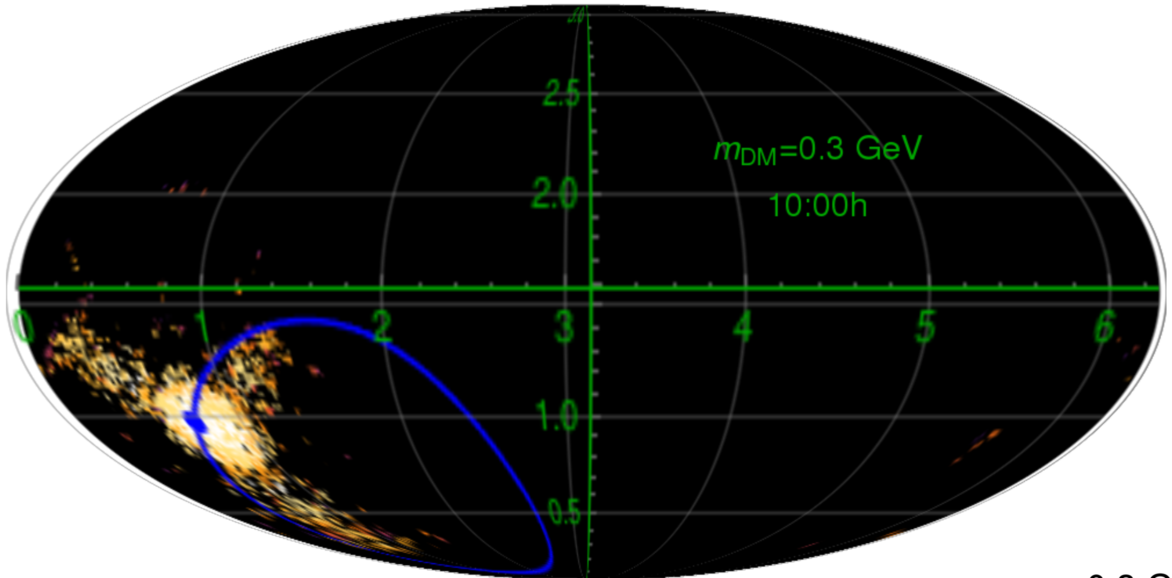
$m_{\mathrm{DM}} = 0.5$ GeV

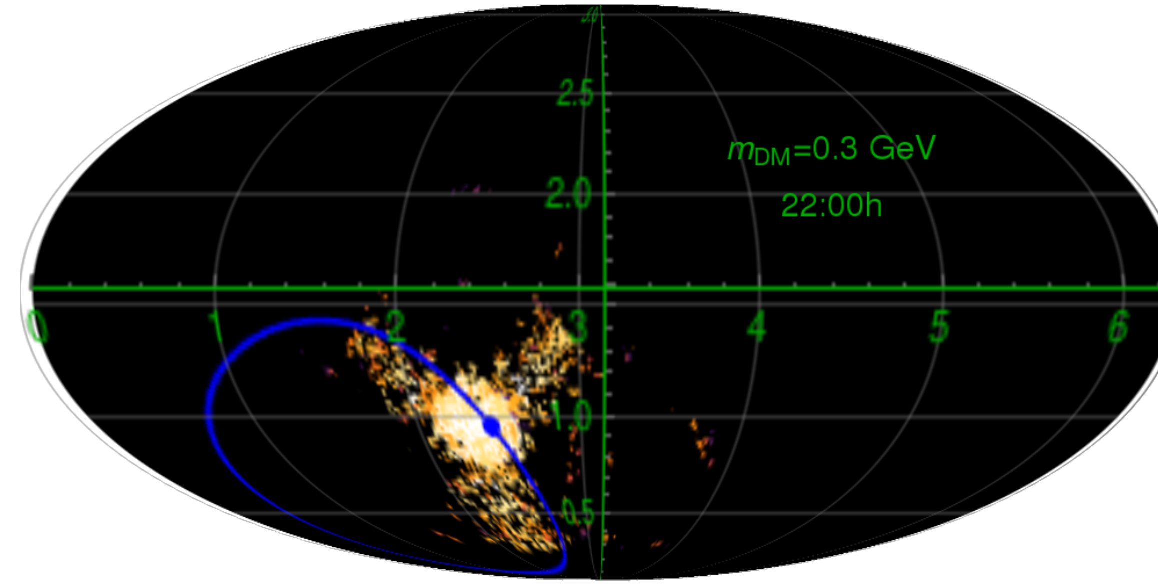
$m_{\mathrm{DM}} = 5$ GeV



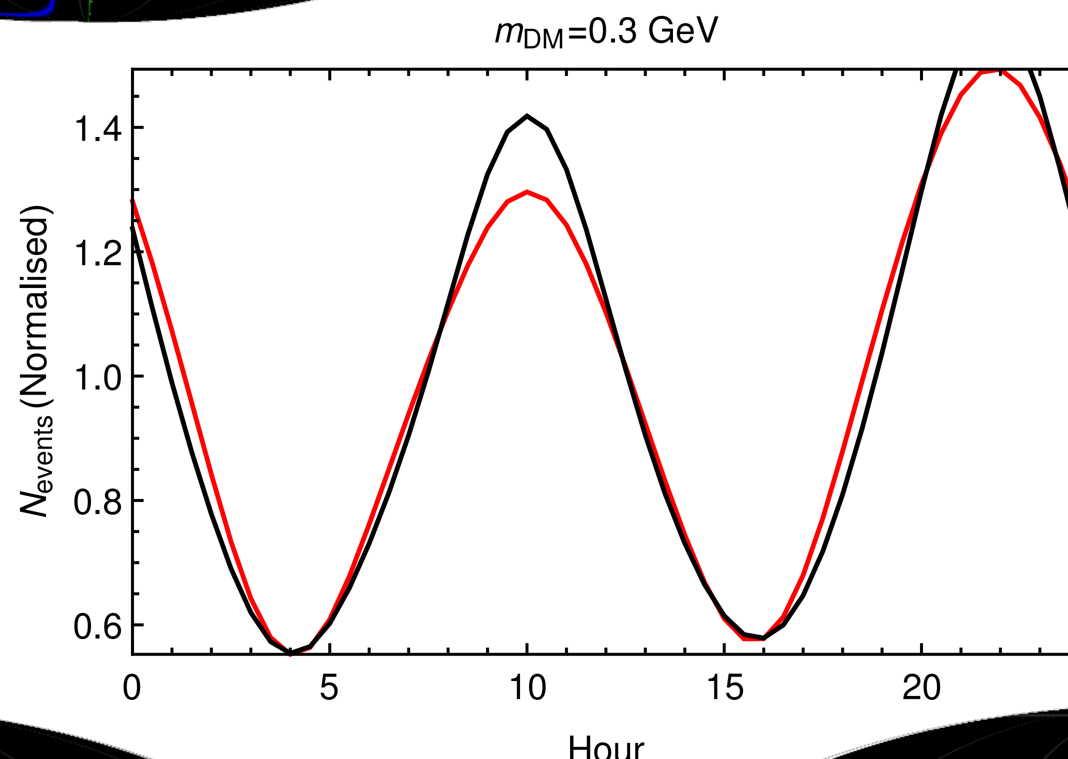
@SNOLAB, 6.9. at 18:00

The daily modulation



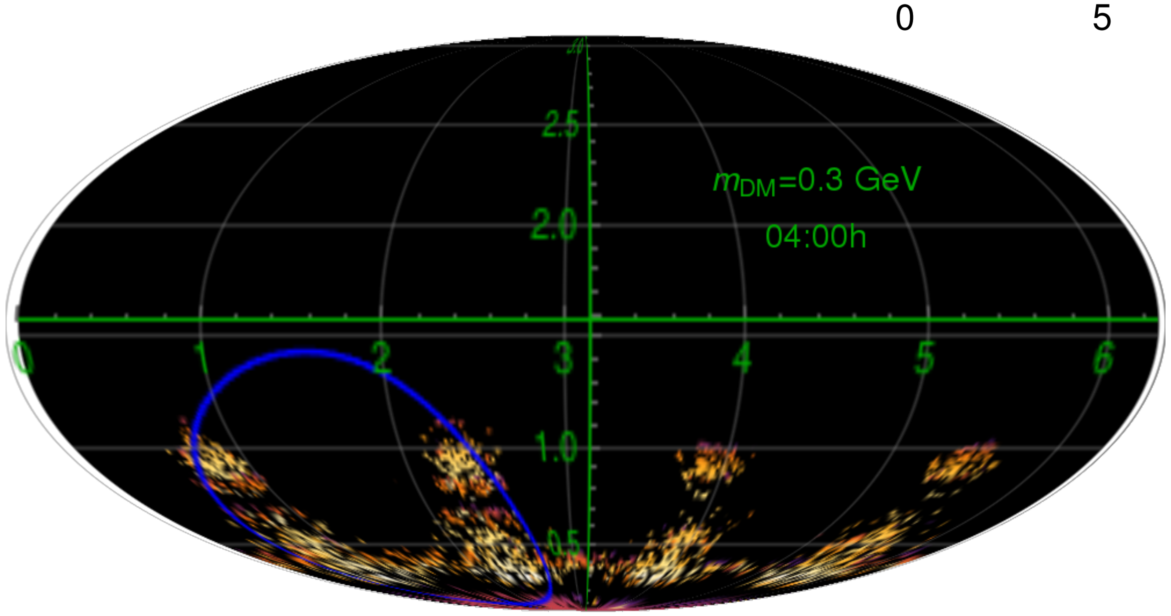


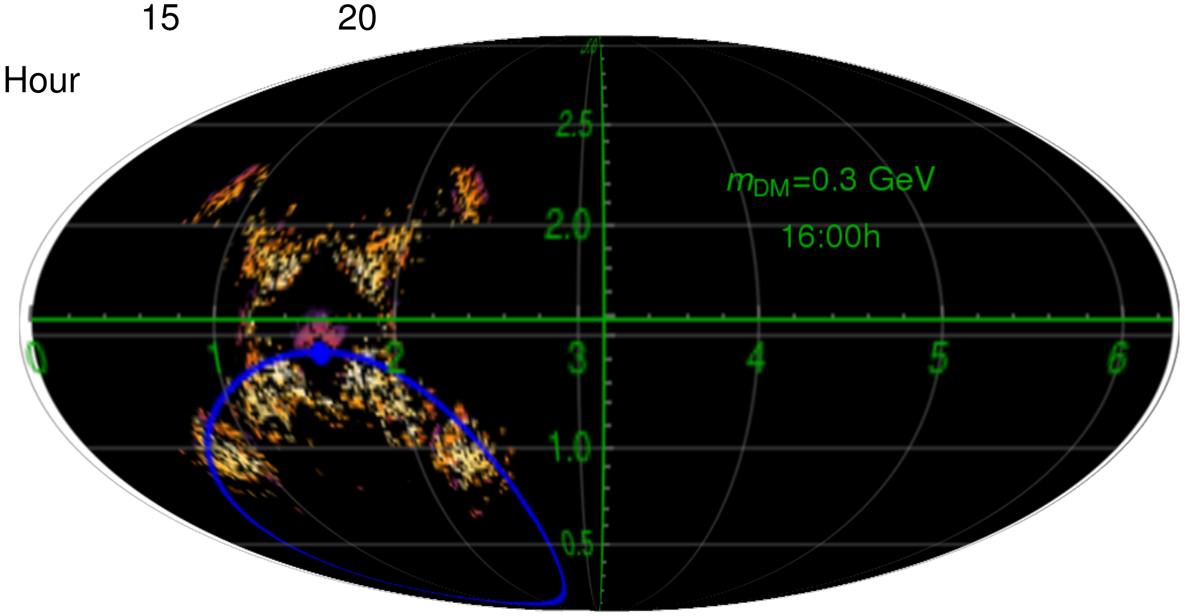
Total rate:



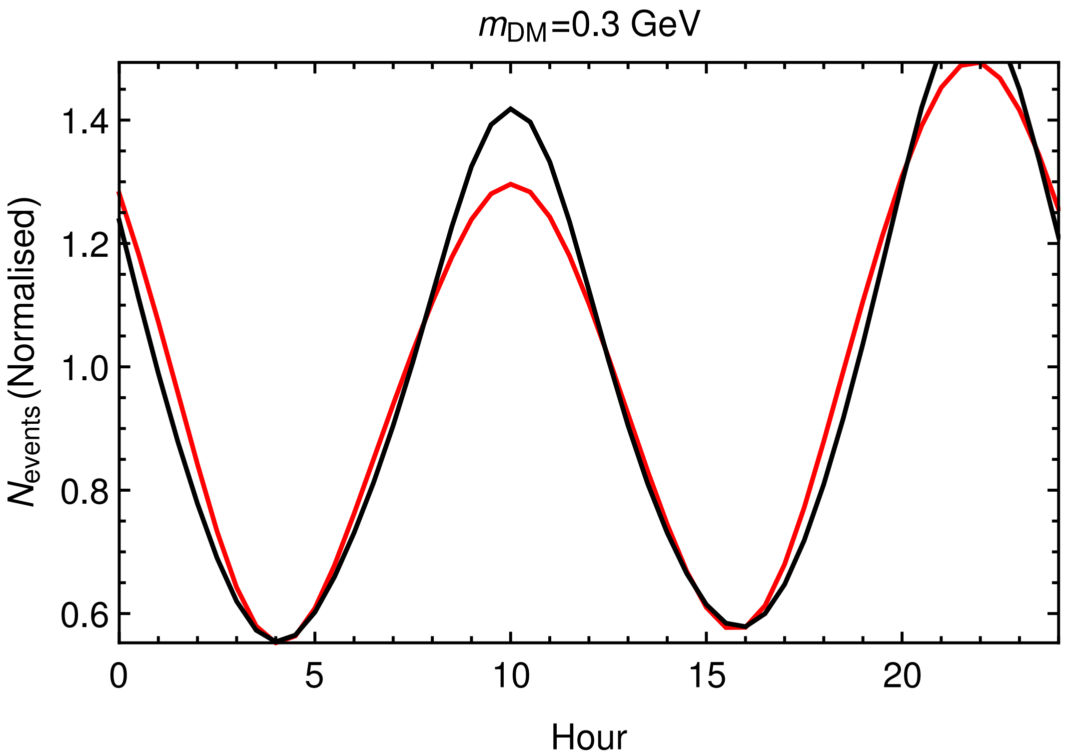
BLACK: $|\mathscr{M}|^2 \sim v^0$

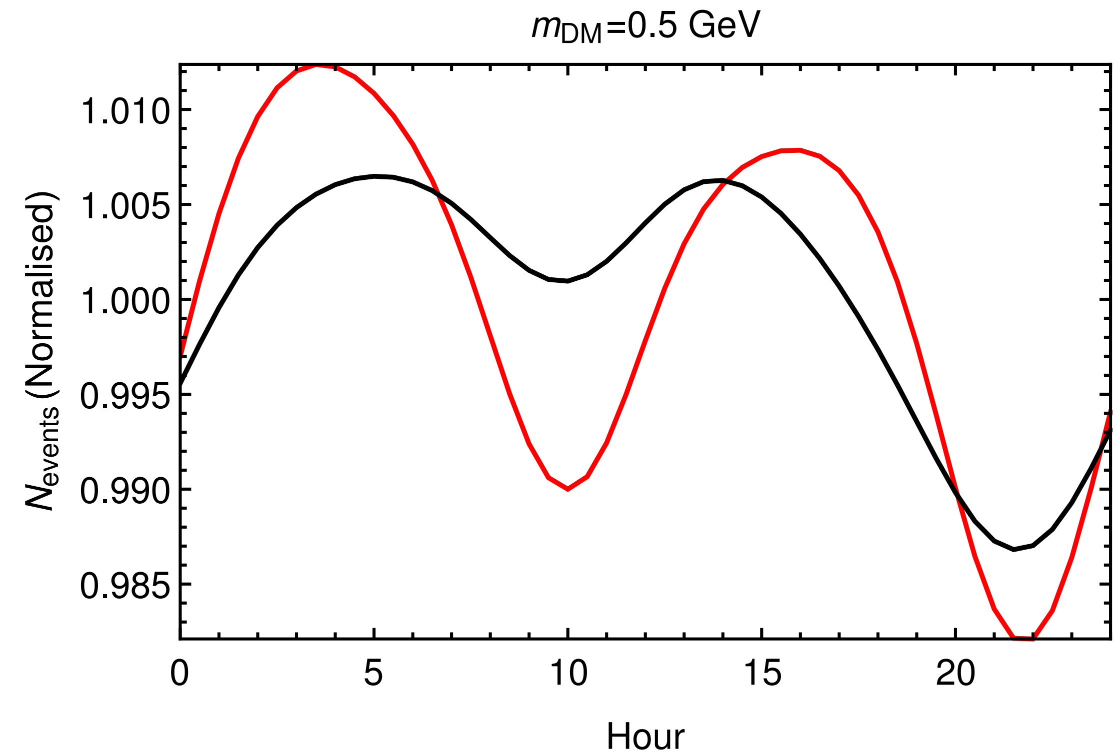
RED: $|\mathscr{M}|^2 \sim v^2$

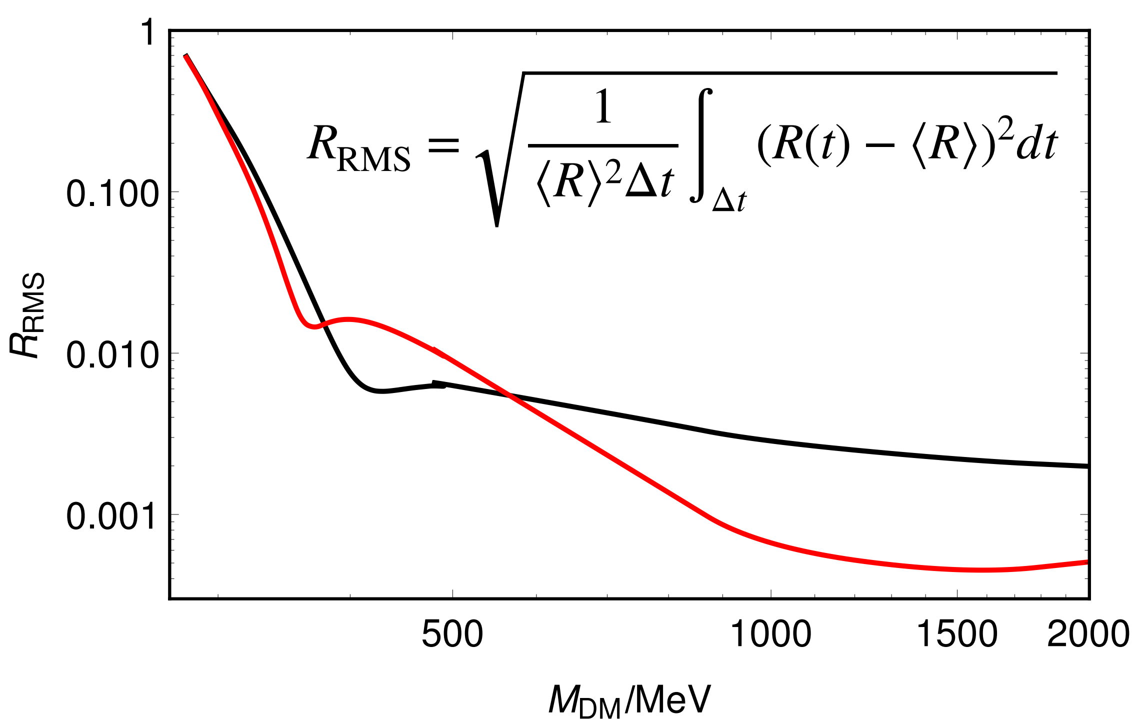




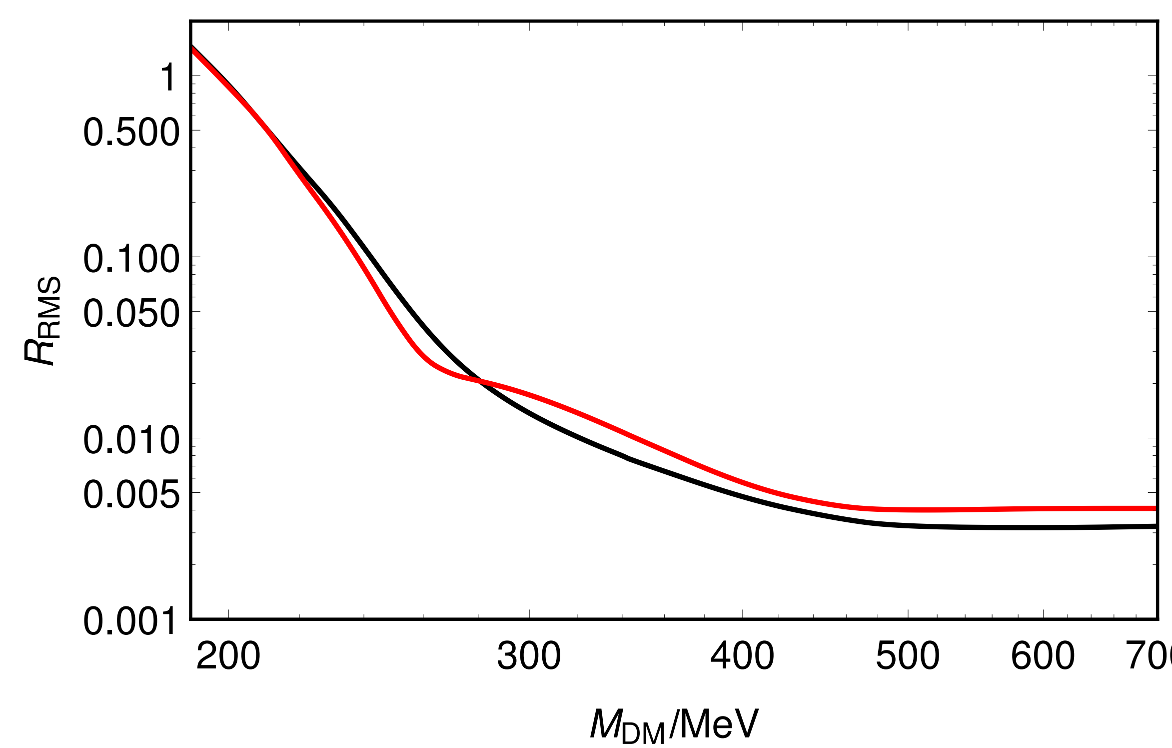
Material dependent mass range of applicability







Germanium: $m_{DM} \leq 450$ MeV

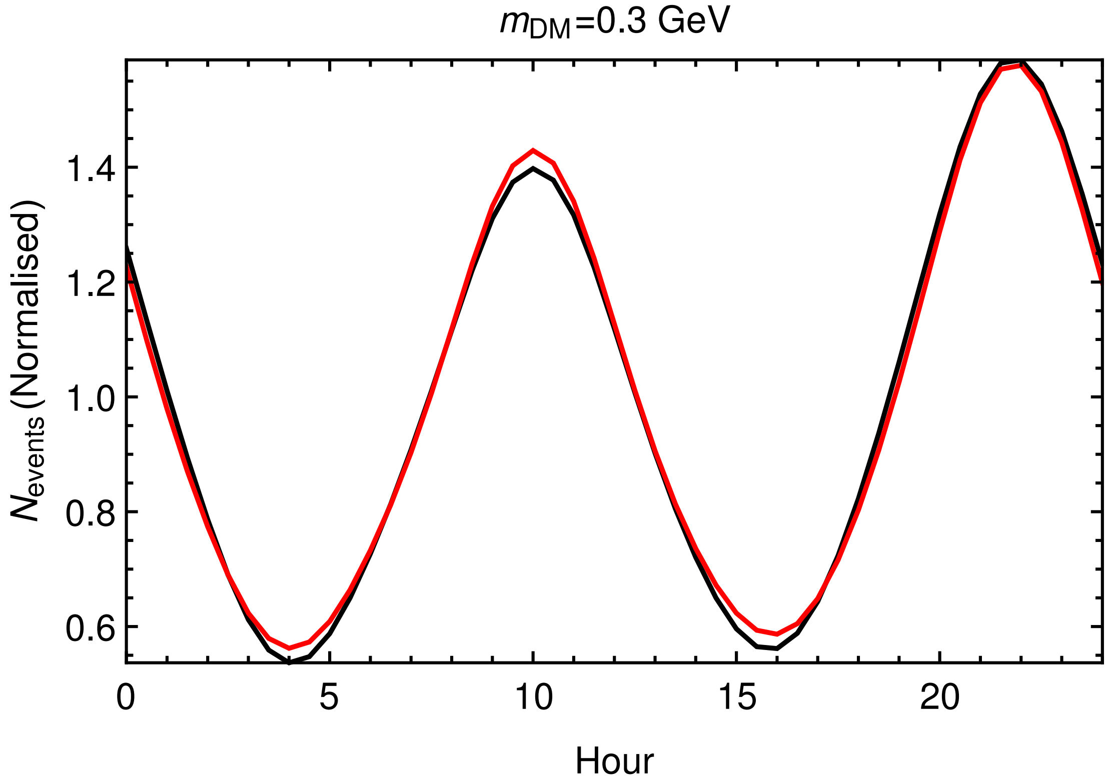


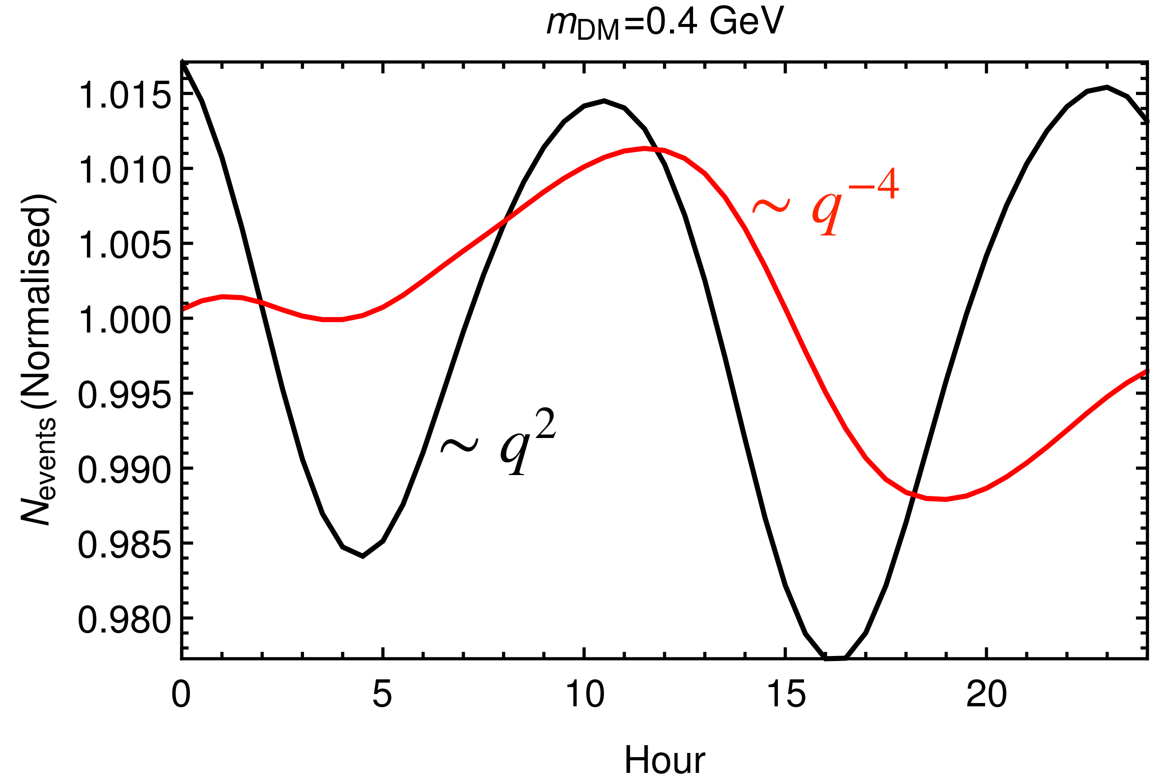
Silicon: $m_{DM} \leq 350$ MeV

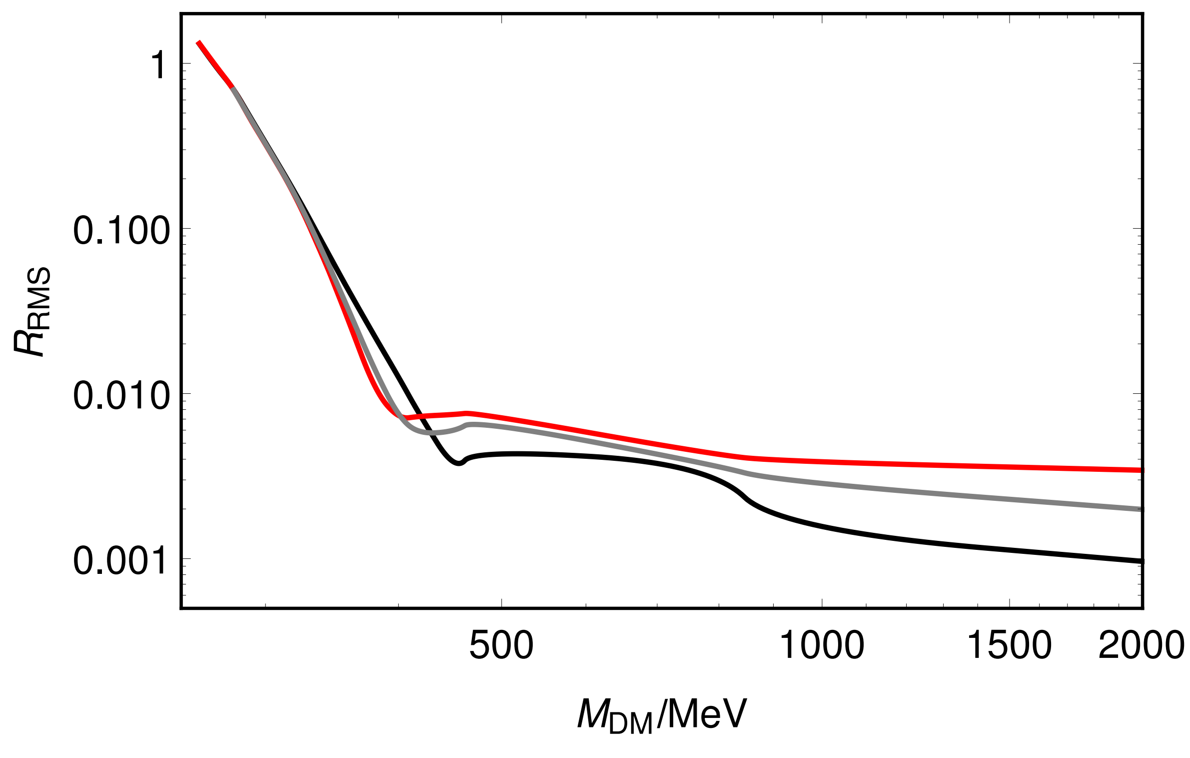
Energy dependent interactions:

$$|\mathcal{M}|^2 = a_1 1 + a_2 q^2 + a q^{-4} + \ldots$$

Similar story:







3. Concluding remarks

Advantages and limitations

Advantages:

1. Modulation signals efficient in discriminating the origin of the signal.
2. The approach naturally works in the light dark matter regime.

Limitations:

1. Modulation only in a limited range in the light dark matter regime:

   Lower E: no damage, no signal
   Higher E: continuous signal, no benefit from threshold

Conclusion and outlook

Dark matter direct detection aiming to sub-GeV masses

Input for detector design by combining state-of-the-art computational materials physics and dark matter theory:

- Light dark matter provides a daily modulation signal in a semiconductor detector.
- Interactions with different velocity/energy dependence can lead to differences in the signal

Further work on neutrino background and dark matter velocity distributions in progress.