General Dark Matter Electron Interactions in Graphene

R. Catena, T. Emken, M. Matas, N. Spaldin, E. Urdshals:

2303.15497 & 2303.15509

Einar Urdshals, 14. Sep 2023

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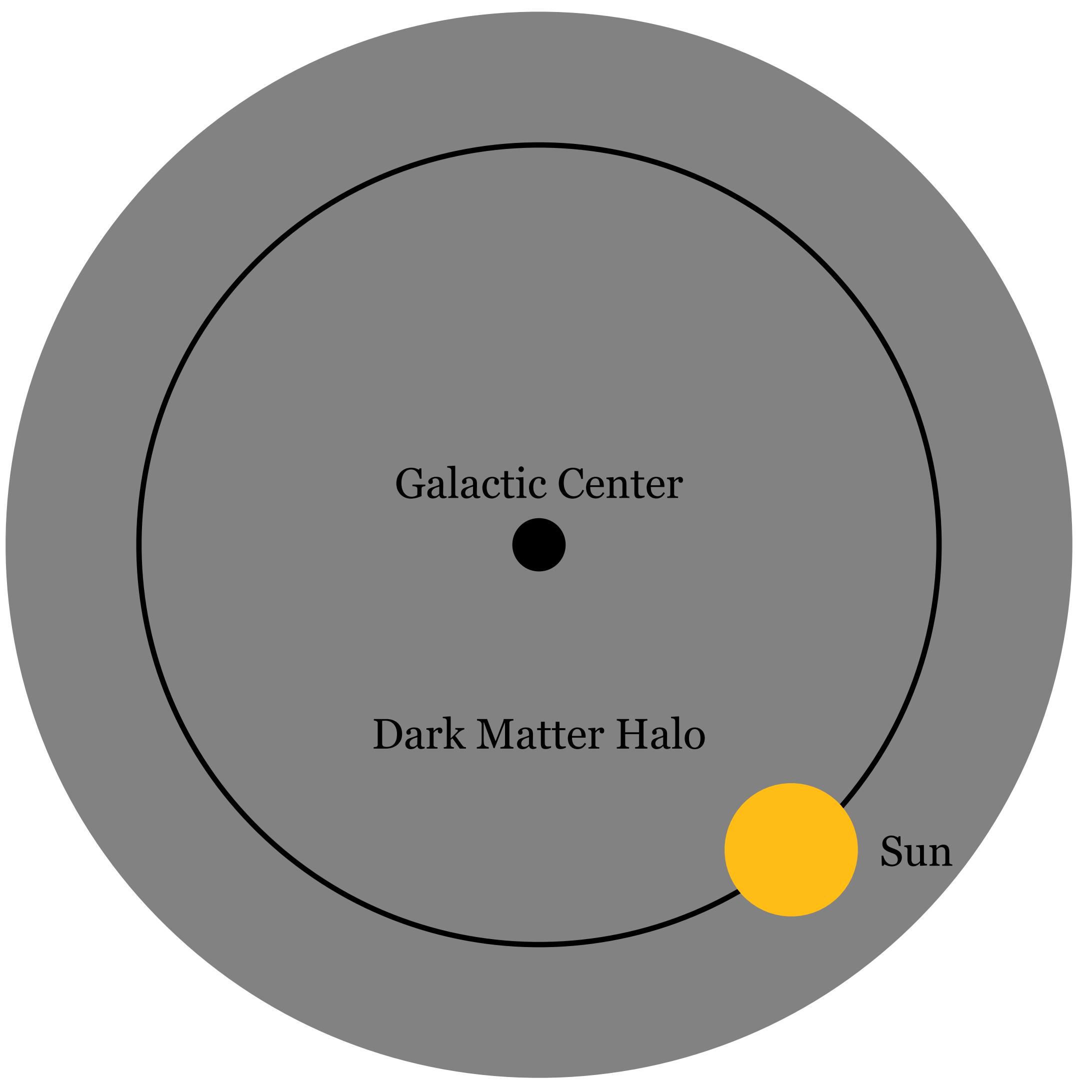
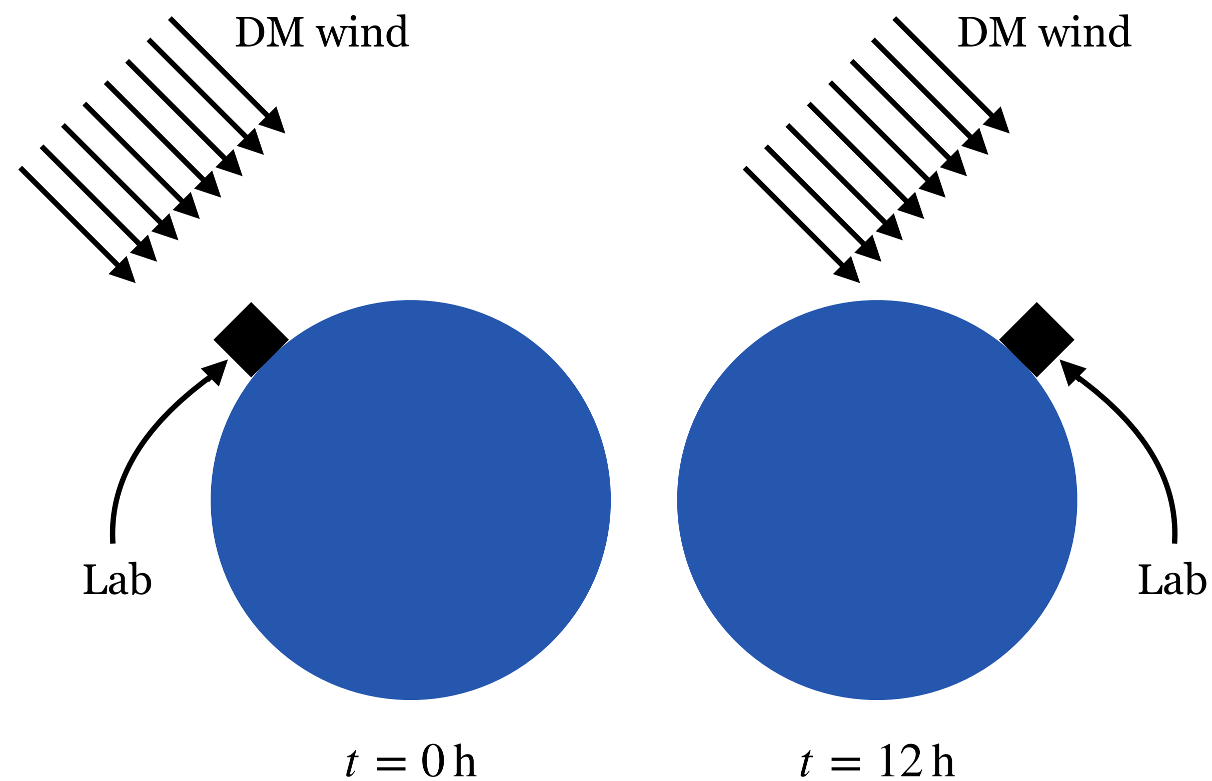
The Dark Matter Wind

Milky Way



Earth



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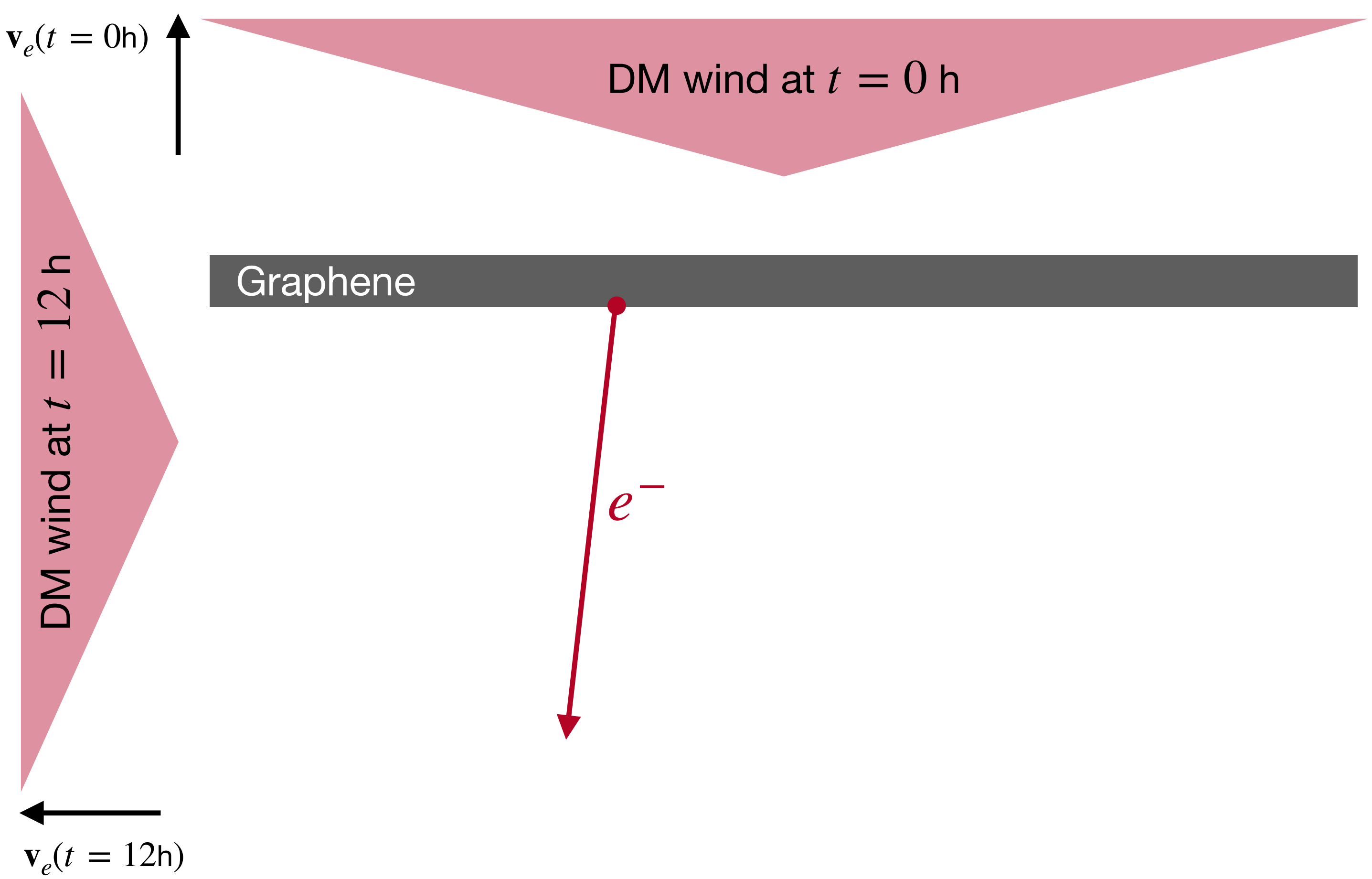
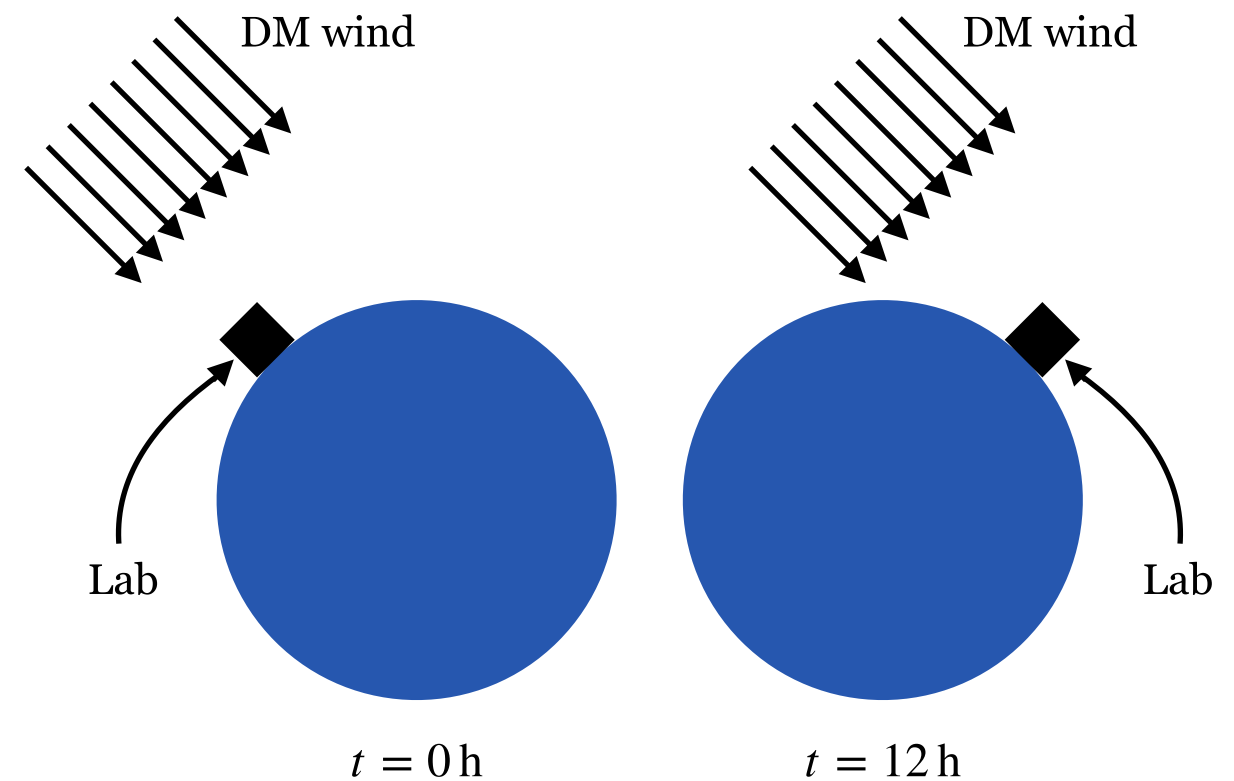
Detecting a Daily Modulation





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Motivation

- Electron recoils are sensitive to dark matter (DM) masses $\gtrsim 1\,\mathrm{MeV}$
- Need to discriminate between DM events and background
- Graphene-like targets can produce a strong daily modulation, a smoking gun signal of DM

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DM Induced Electron Ejections from Graphene

- $R \propto \int f_\chi(\mathbf{v}, t)\, R_{\text{free}}(\mathbf{v}, \mathbf{q}, \mathbf{k}') \; \left|\psi(\boldsymbol{\ell}, E_e)\right|^2$ R. Catena, T. Emken, M. Matas, N. Spaldin, **EU**: 2303.15497
- $f_\chi(\mathbf{v}, t)$ is the DM velocity distribution
- R_{free} is the free particle response function and depends on the physics of free particles
- $\left|\psi(\boldsymbol{\ell}, E_e)\right|^2$ contains all the material physics

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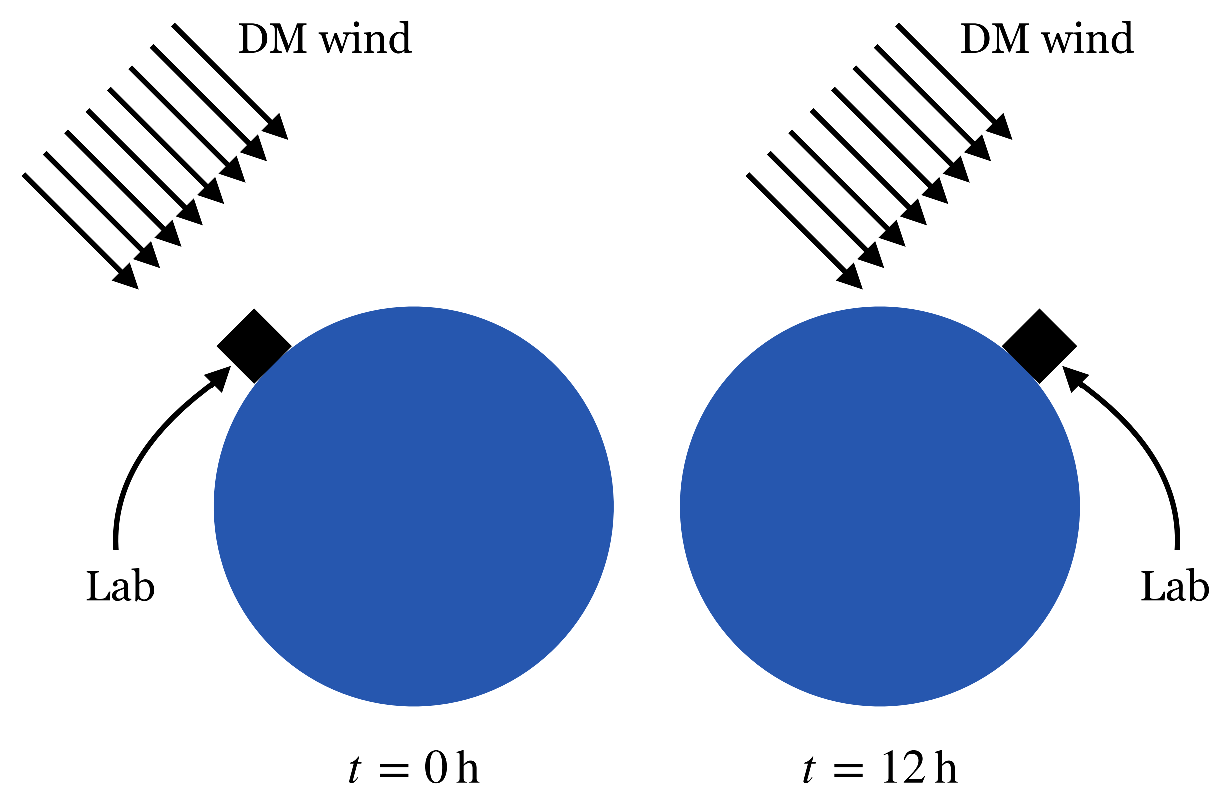
DM Velocity Distribution

- Seen from the lab on Earth the DM velocity distribution is anisotropic and time dependent
- $f_\chi(\mathbf{v}, t) \propto \exp\left[-\frac{(\mathbf{v} + \mathbf{v}_e(t))^2}{v_0^2}\right] \times \Theta\left(v_{\rm esc} - |\,\mathbf{v} + \mathbf{v}_e(t)\,|\right)$



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Free Particle Response Function

- R_{free} is built from non-relativistic effective operators, allows covering arbitrary spin 0 and 1/2 DM models.
- Depends on the physics of the free particles, i.e. the DM particle and the final state electron

$$\mathcal{O}_1 = \mathbb{1}_{\chi e}$$
$$\mathcal{O}_3 = i\mathbf{S}_e \cdot \left(\frac{\mathbf{q}}{m_e} \times \mathbf{v}_{\text{el}}^{\perp}\right)$$
$$\mathcal{O}_4 = \mathbf{S}_\chi \cdot \mathbf{S}_e$$
$$\mathcal{O}_5 = i\mathbf{S}_\chi \cdot \left(\frac{\mathbf{q}}{m_e} \times \mathbf{v}_{\text{el}}^{\perp}\right)$$
$$\mathcal{O}_6 = \left(\mathbf{S}_\chi \cdot \frac{\mathbf{q}}{m_e}\right)\left(\mathbf{S}_e \cdot \frac{\mathbf{q}}{m_e}\right)$$
$$\mathcal{O}_7 = \mathbf{S}_e \cdot \mathbf{v}_{\text{el}}^{\perp}$$
$$\mathcal{O}_8 = \mathbf{S}_\chi \cdot \mathbf{v}_{\text{el}}^{\perp}$$
$$\mathcal{O}_9 = i\mathbf{S}_\chi \cdot \left(\mathbf{S}_e \times \frac{\mathbf{q}}{m_e}\right)$$
$$\mathcal{O}_{10} = i\mathbf{S}_e \cdot \frac{\mathbf{q}}{m_e}$$
$$\mathcal{O}_{11} = i\mathbf{S}_\chi \cdot \frac{\mathbf{q}}{m_e}$$
$$\mathcal{O}_{12} = \mathbf{S}_\chi \cdot \left(\mathbf{S}_e \times \mathbf{v}_{\text{el}}^{\perp}\right)$$
$$\mathcal{O}_{13} = i\left(\mathbf{S}_\chi \cdot \mathbf{v}_{\text{el}}^{\perp}\right)\left(\mathbf{S}_e \cdot \frac{\mathbf{q}}{m_e}\right)$$
$$\mathcal{O}_{14} = i\left(\mathbf{S}_\chi \cdot \frac{\mathbf{q}}{m_e}\right)\left(\mathbf{S}_e \cdot \mathbf{v}_{\text{el}}^{\perp}\right)$$
$$\mathcal{O}_{15} = i\mathcal{O}_{11}\left[\left(\mathbf{S}_e \times \mathbf{v}_{\text{el}}^{\perp}\right) \cdot \frac{\mathbf{q}}{m_e}\right]$$

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Modelling Graphene

Tight Binding Approximation

- Approximation based on analytic atomic wave functions
- Not self consistent
- Accurate near the nucleus
- Computationally cheap
- Semi-analytic, not a black box

Density Functional Theory

- Works by finding the electron density that minimises the energy of the system
- Self consistent from first principles
- Can not treat the electron wave-function close to the nucleus
- Computationally expensive

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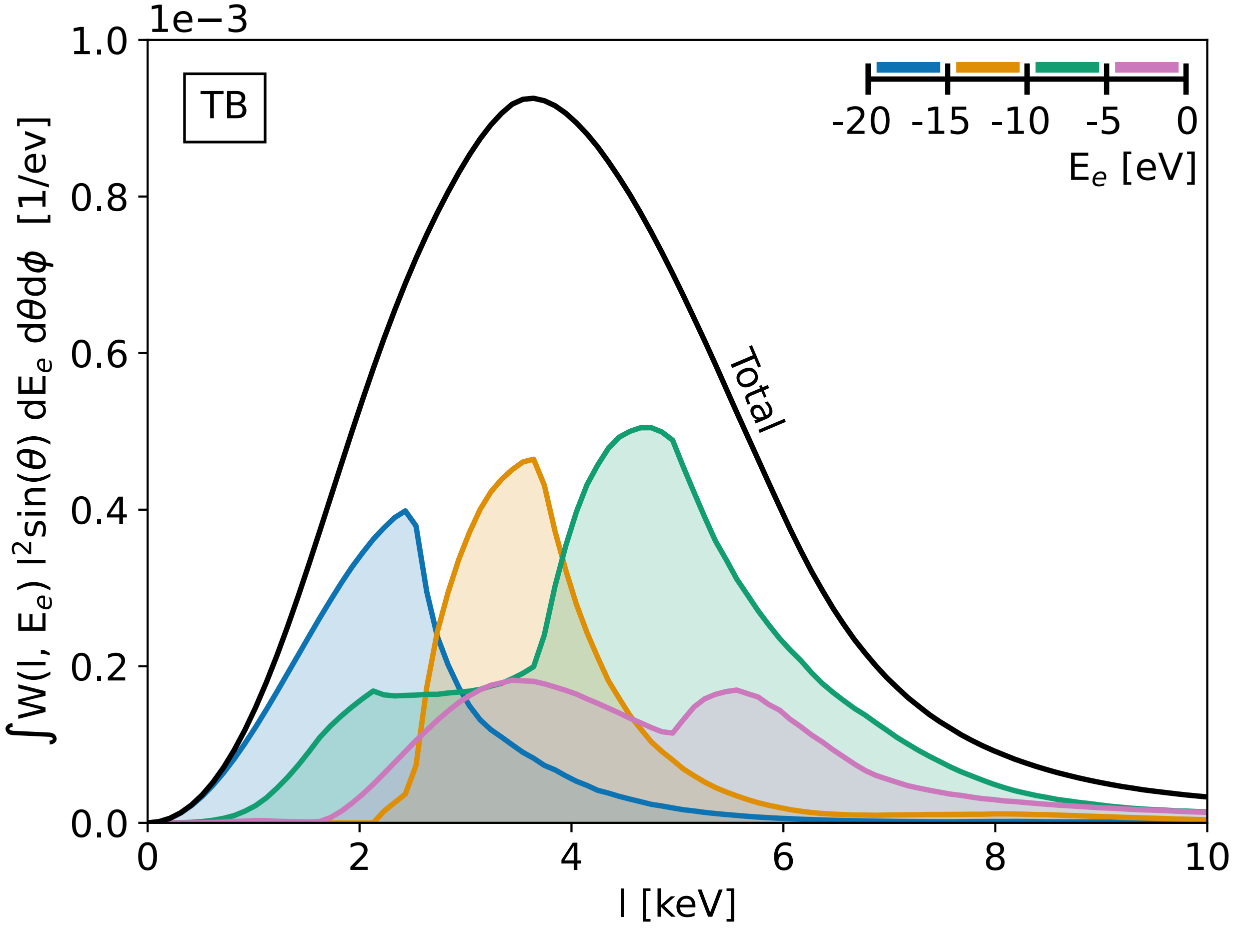
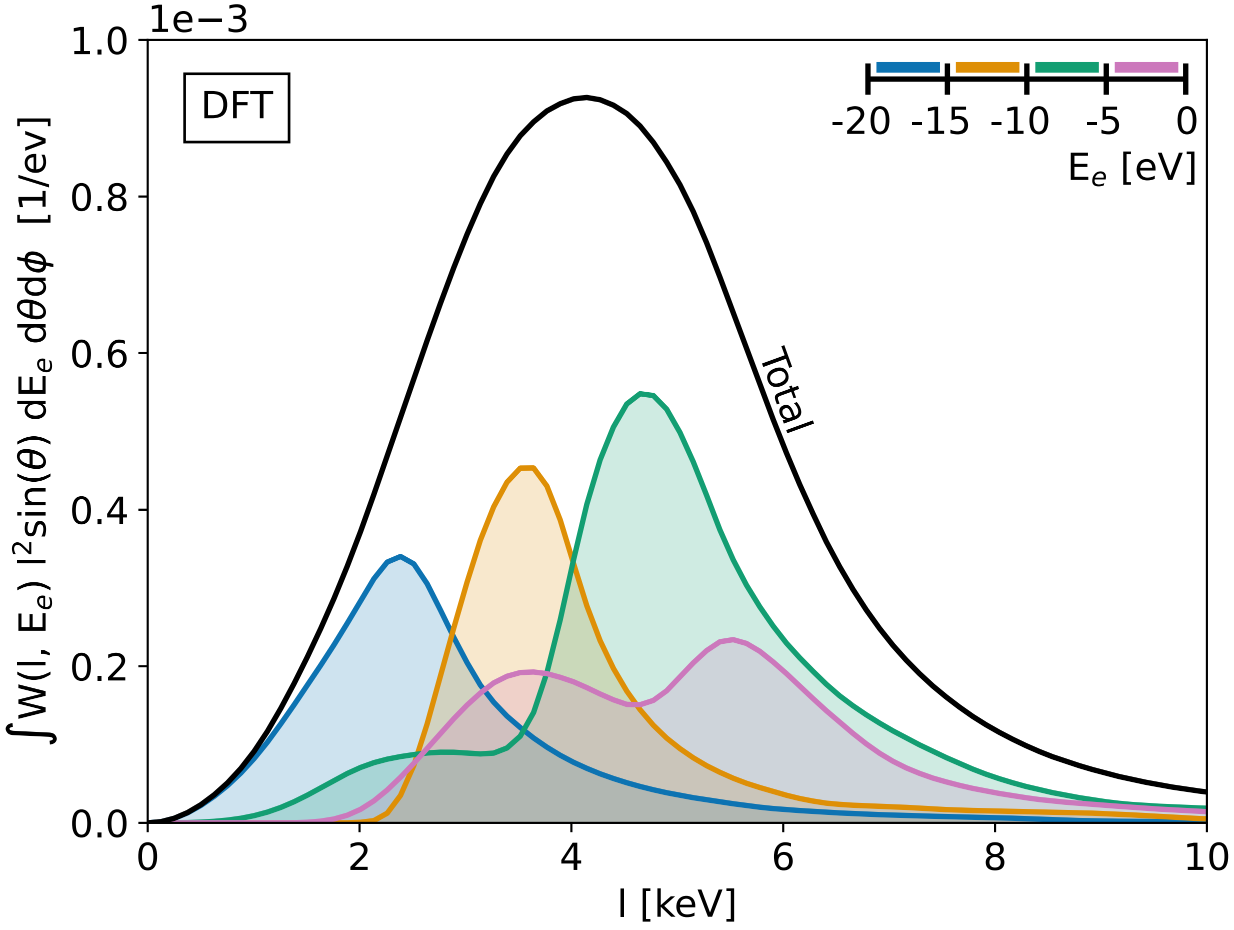
Momentum Distribution in Graphene

Tight Binding Approximation



Density Functional Theory



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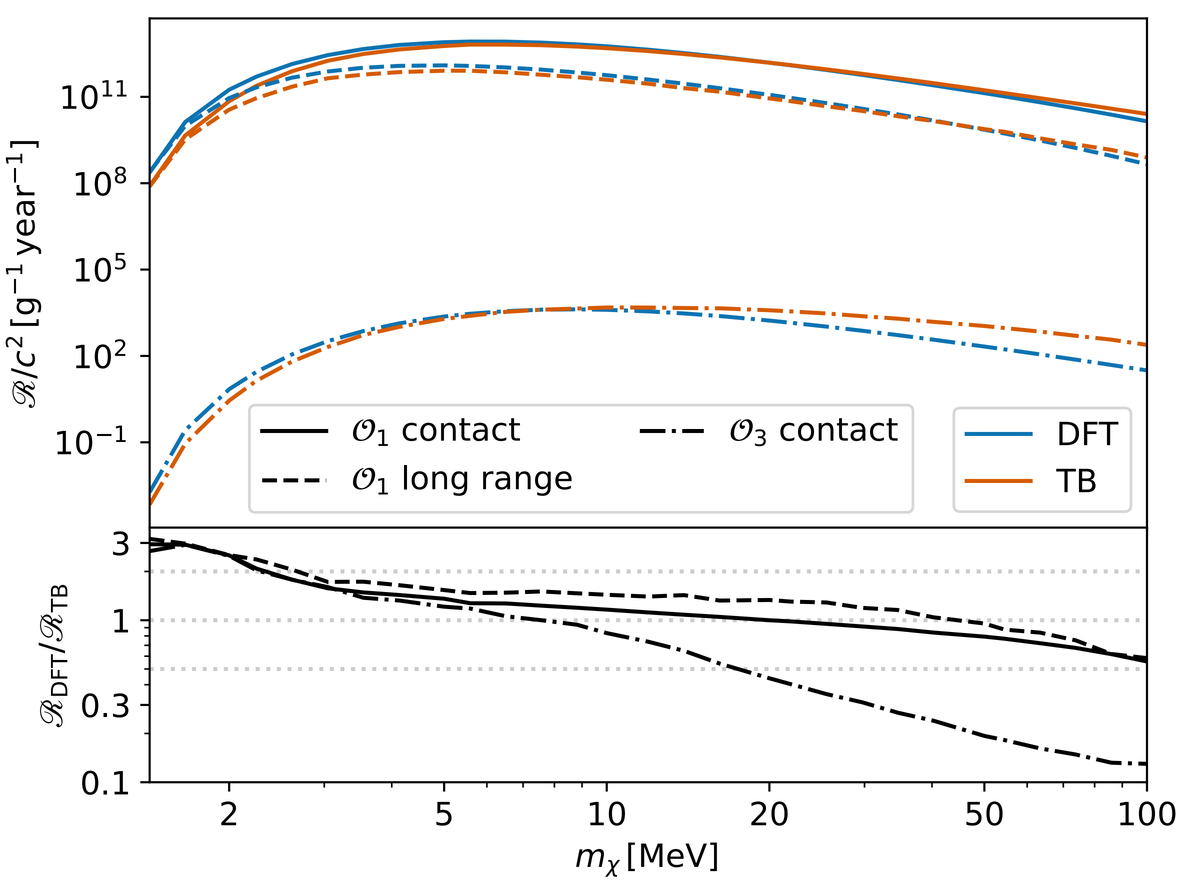
Total Rate of Ejected Electrons

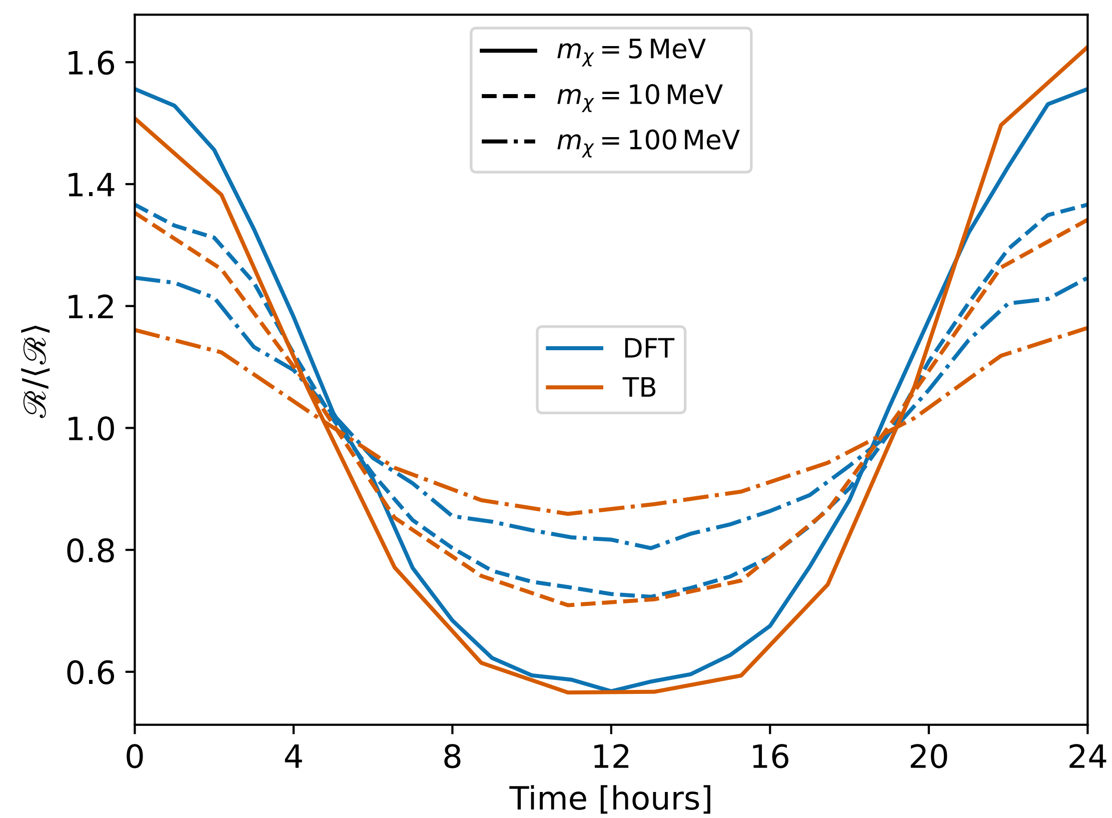
Time Averaged Rate



$\mathscr{O}_1$ contact is dark photon with heavy mediator
$\mathscr{O}_1$ long range is dark photon with light mediator
$\mathscr{O}_3 \propto \mathbf{q} \times \mathbf{v}$

Daily Modulation

$\mathscr{O}_1$ contact, dark photon with heavy mediator



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We recommend using DFT, and all rates will from now be DFT-obtained

Statistical Tests

Establishing Daily Modulation

- Divide the data set in two parts, n_+ and n_-
- No modulation $\implies E\left[n_+\right] = E\left[n_-\right]$
- Wish to reject the hypothesis that n_+ and n_- are drawn from the same distribution

Excluding Parameter Space

- Exclude DM unlikely to produce $n_+ + n_-$ or fewer events

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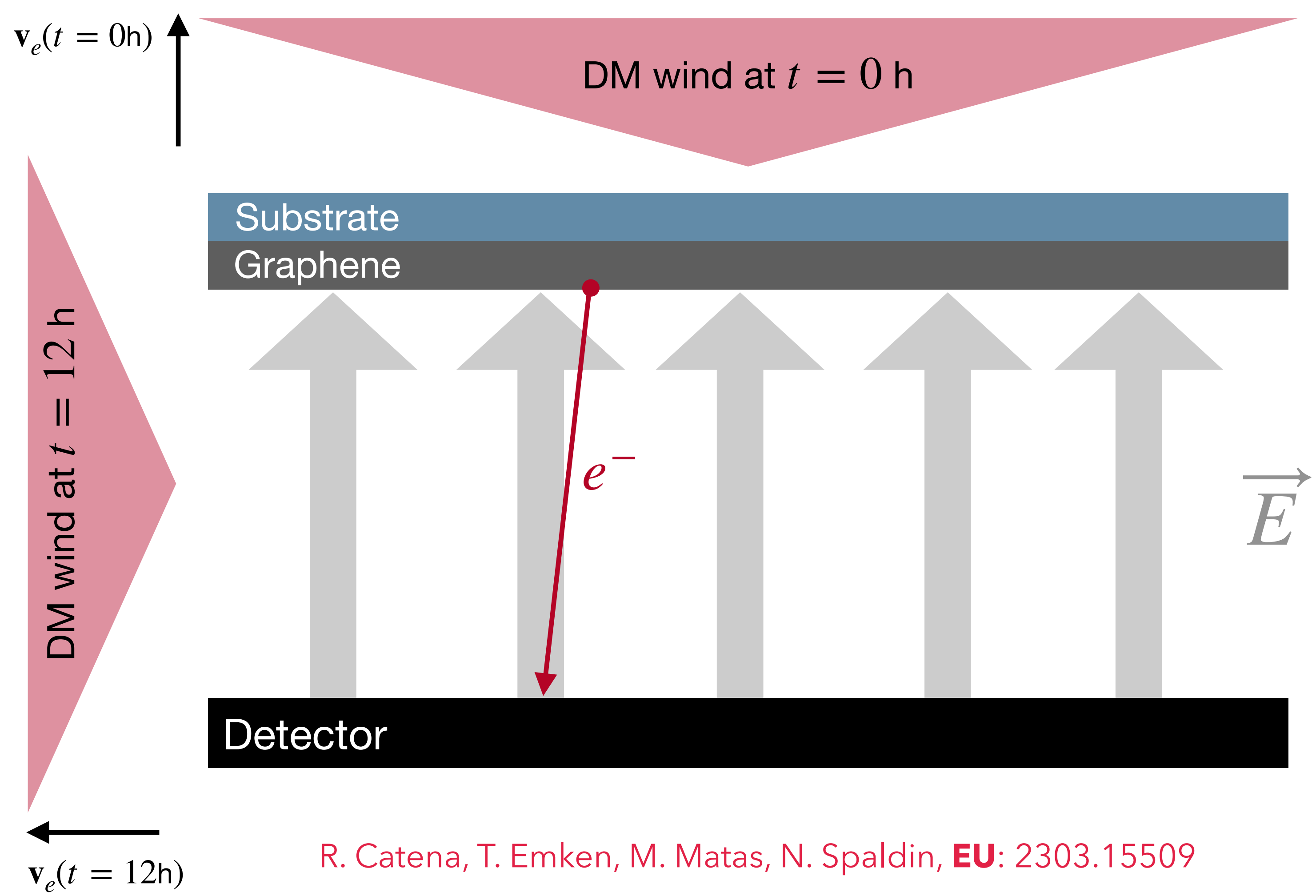
Specific Detector Setups

Detector Setups

Fixed Graphene

n_+: Number of detected events in 12 hours with most events



n_-: Number of detected events in 12 hours with least events

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Fixed graphene sheets

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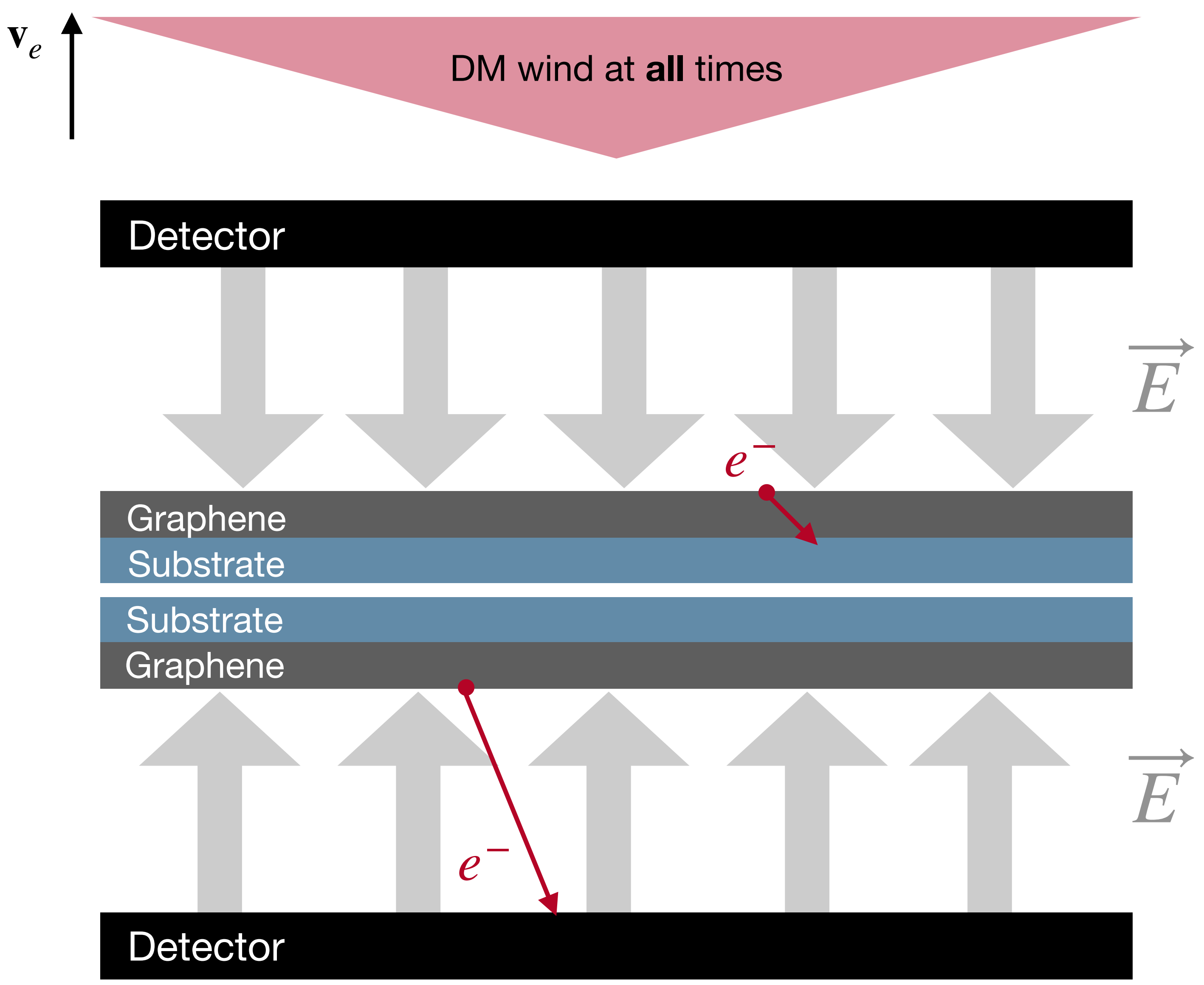
Detector Setups

Moving Graphene



n_-: Number of detected events upper detector

n_+: Number of detected events in lower detector

Moving graphene sheets

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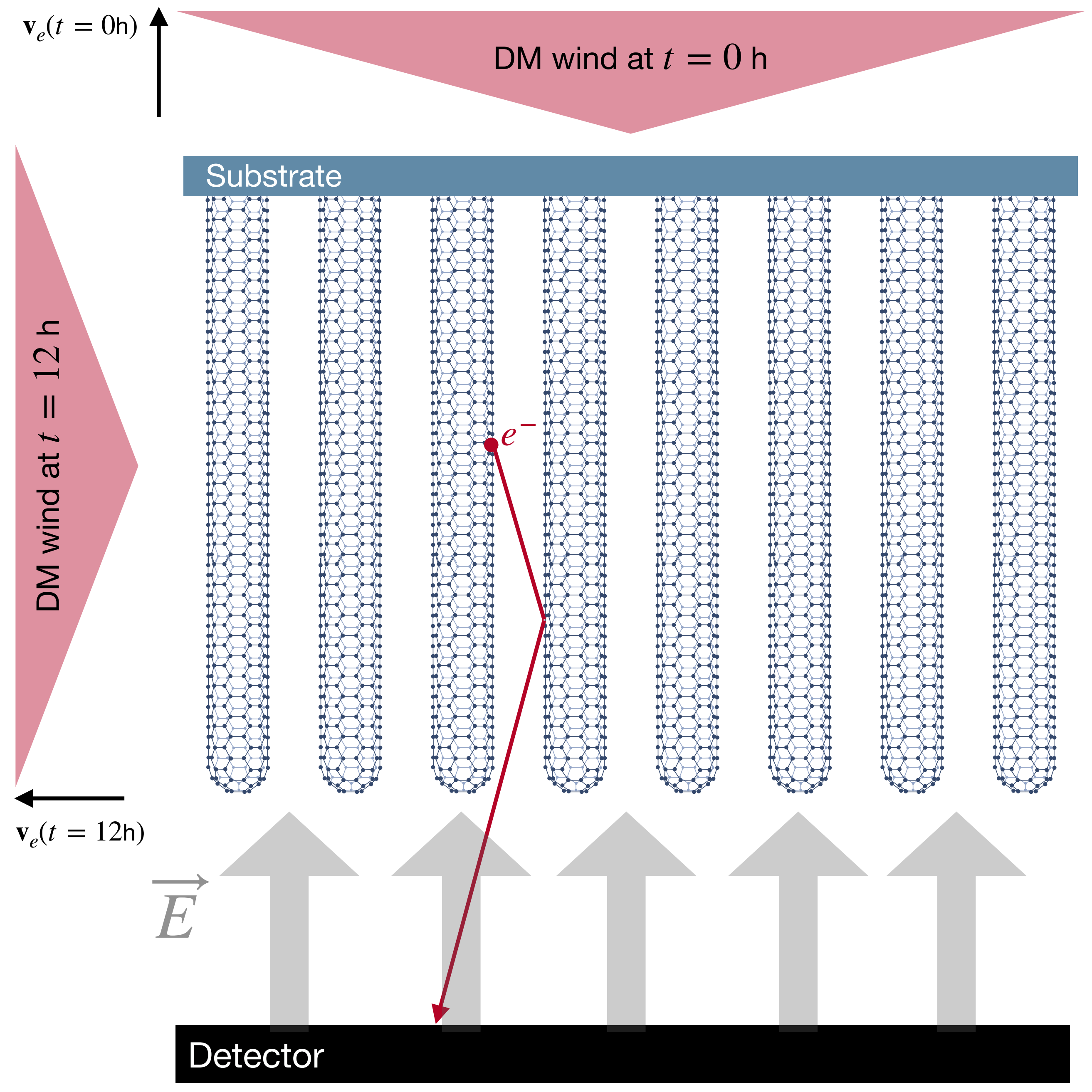
Detector Setups

Fixed Carbon NanoTubes (CNTs)

n_+: Number of detected events in 12 hours with most events

n_-: Number of detected events in 12 hours with least events



Fixed CNTs

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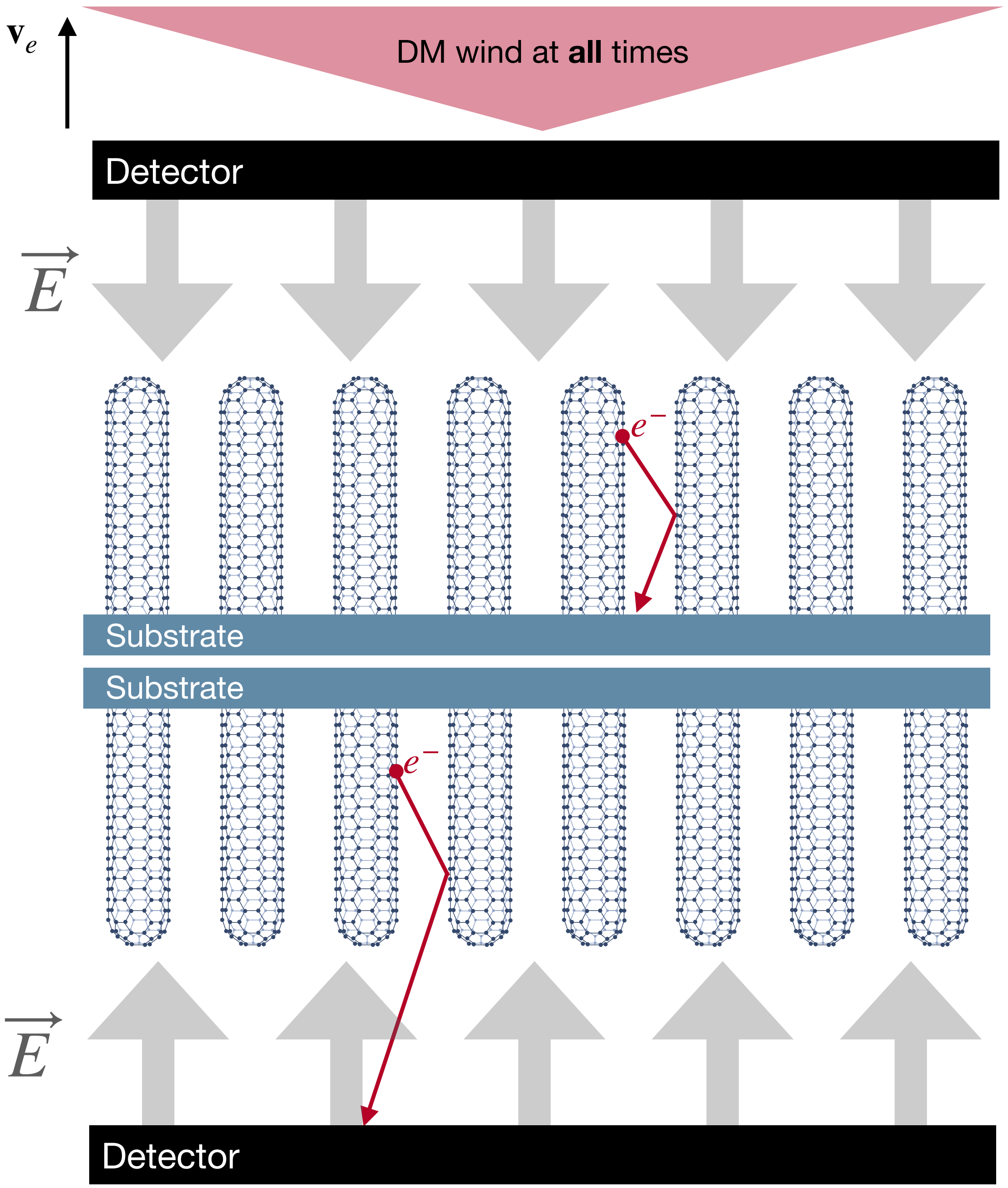
Detector Setups

Moving Carbon NanoTubes (CNTs)



n_-: Number of detected events upper detector

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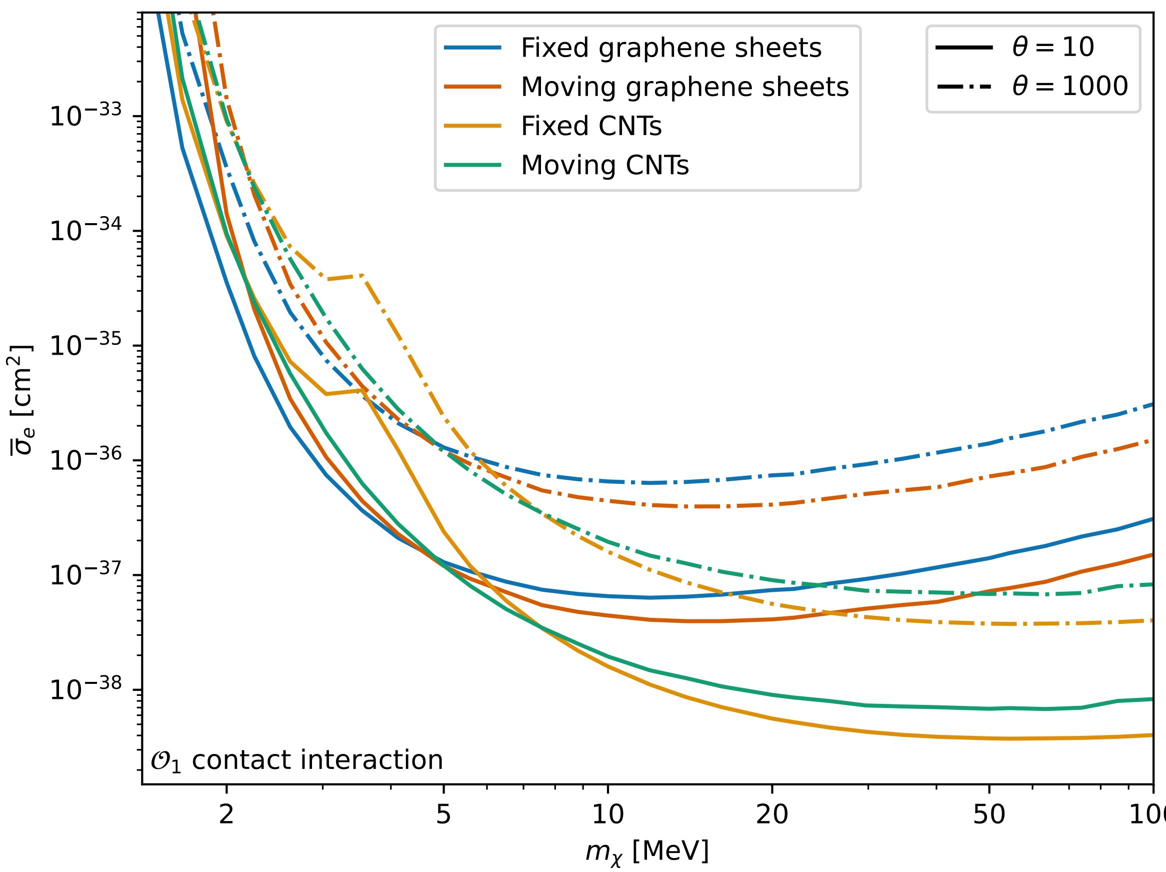
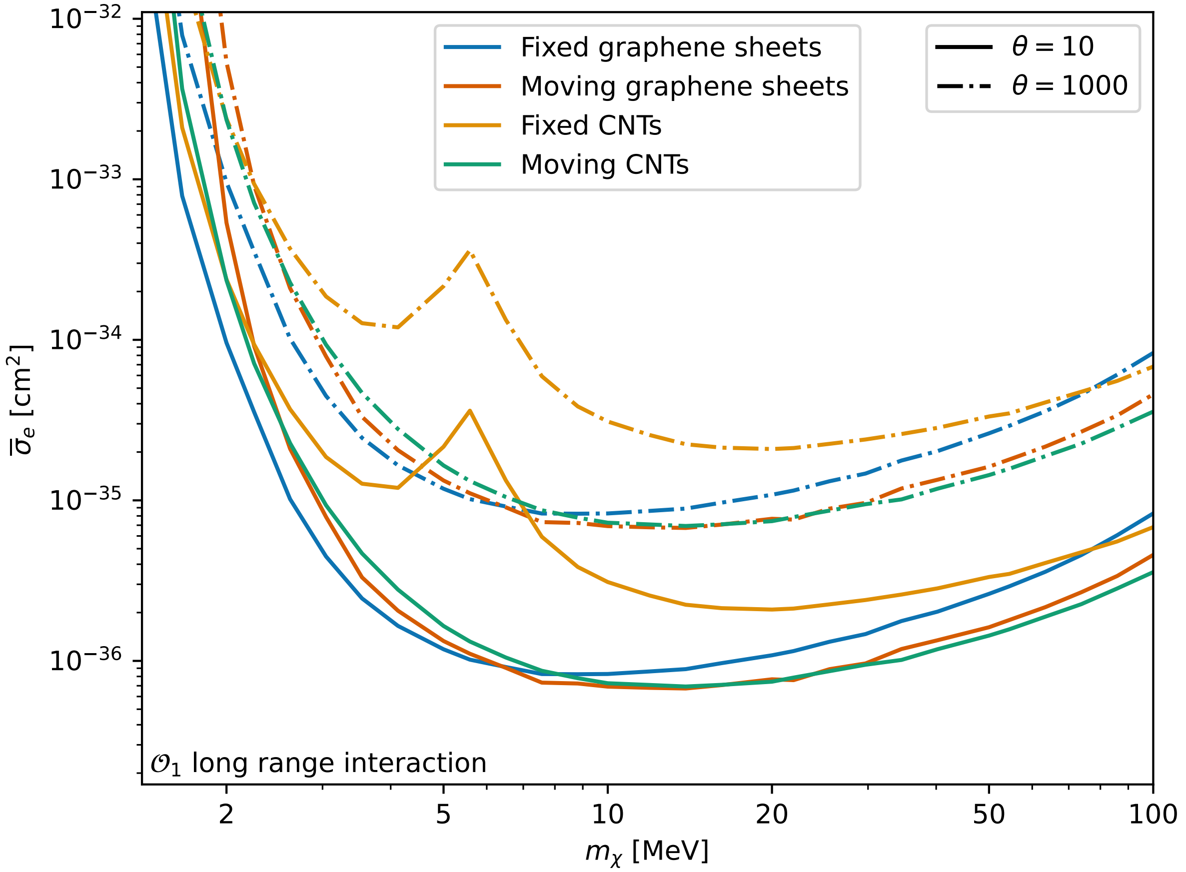
Potential for Establishing Modulation at 3σ

$\mathcal{O}_1$ Contact Interaction



$\mathcal{O}_1$ Long Range Interaction



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Corresponds to dark photon model with a heavy mediator

10 g year exposure

Corresponds to dark photon model with a light mediator

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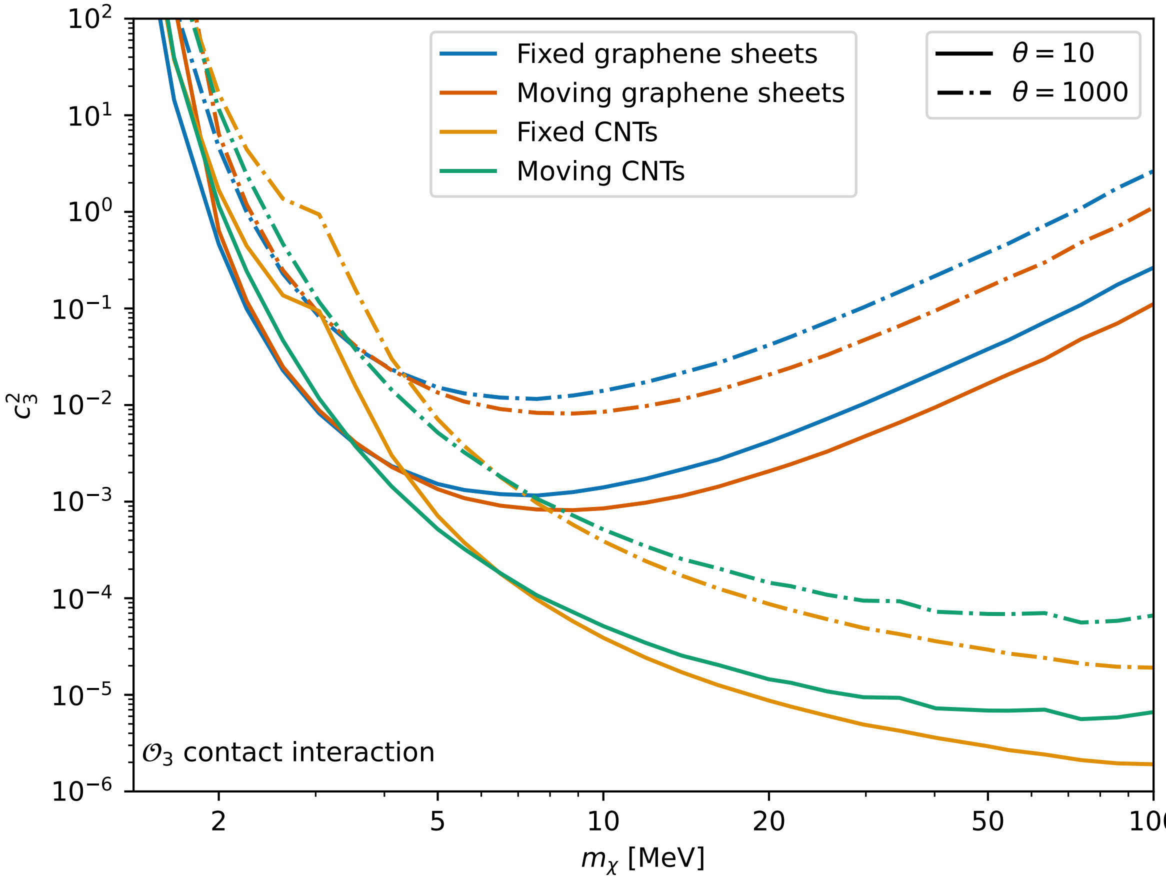
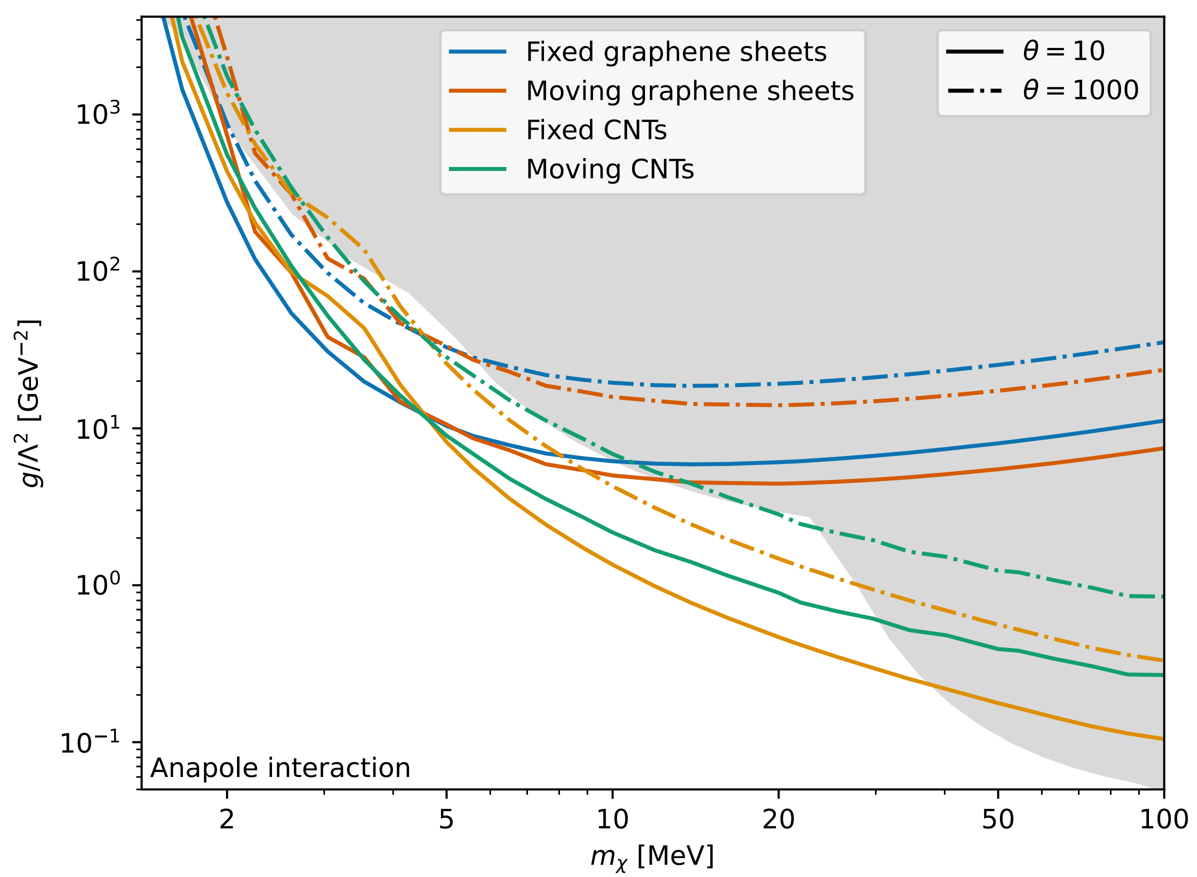
Potential for Establishing Modulation at 3σ

$\mathcal{O}_3$ Contact Interaction



Anapole Interaction



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$\mathcal{O}_3 \propto \mathbf{q} \times \mathbf{v}$

10 g year exposure

$$L_{\text{Anapole}} = \frac{g}{2\Lambda^2}\,\bar{\chi}\gamma^\mu\gamma^5\chi\,\partial^\nu F_{\mu\nu}$$

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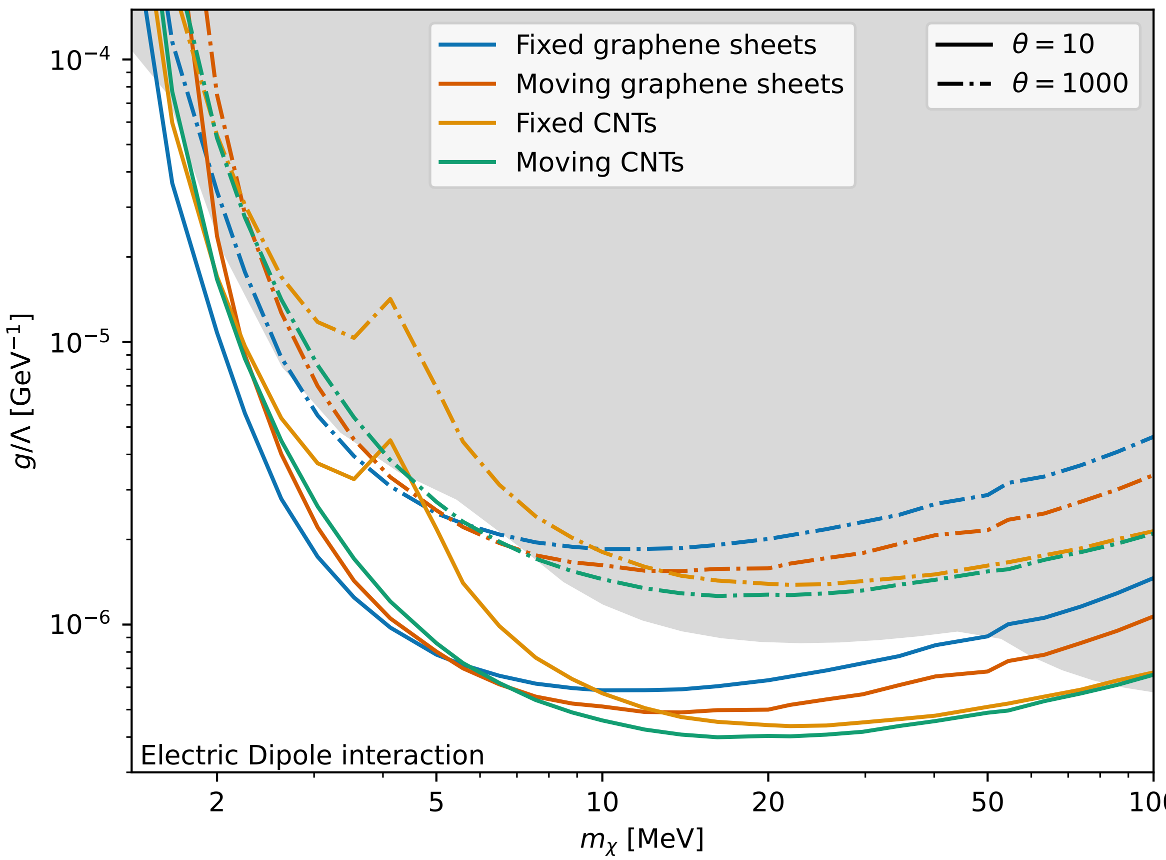
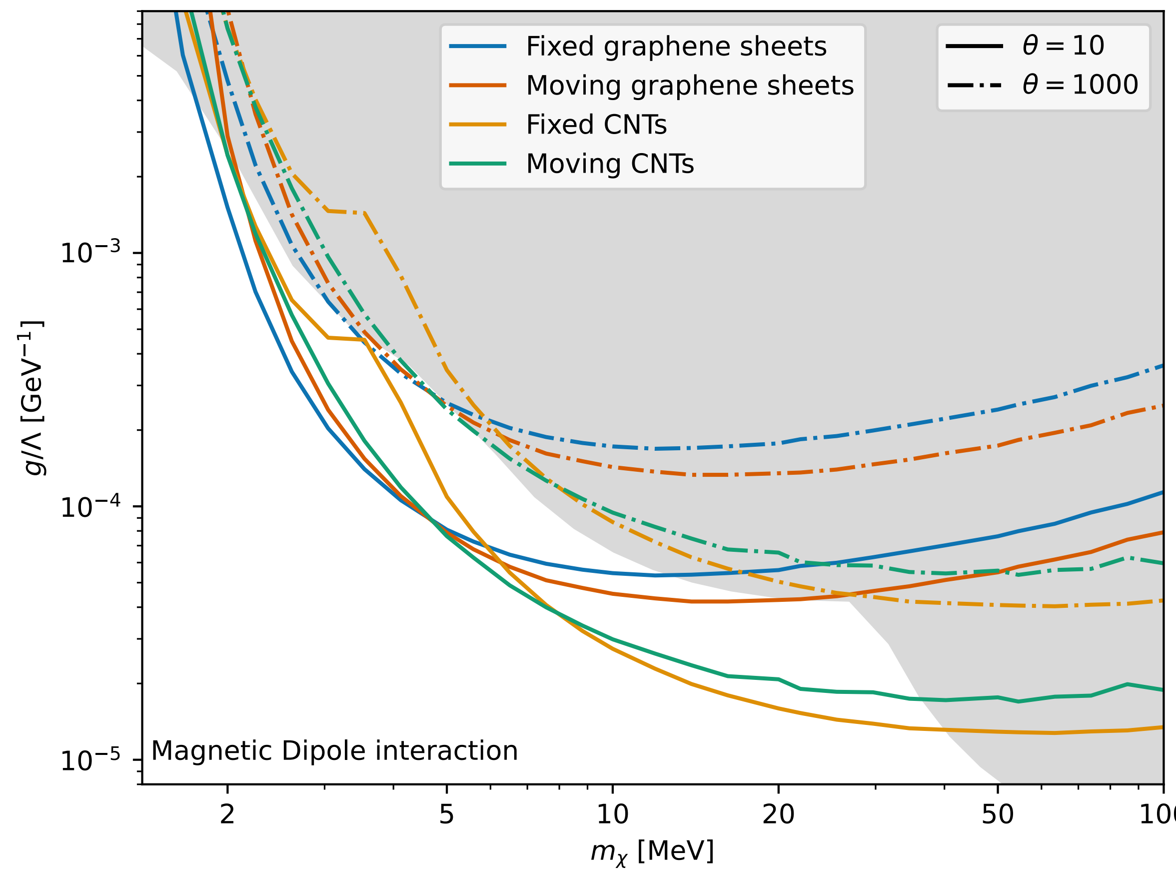
Potential for Establishing Modulation at 3σ

Electric Dipole Interaction



Magnetic Dipole Interaction



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$$L_{\text{Electric dipole}} = \frac{g}{\Lambda}\, i\bar{\chi}\sigma^{\mu\nu}\gamma^5\chi F_{\mu\nu}$$

10 g year exposure

$$L_{\text{Magnetic dipole}} = \frac{g}{\Lambda}\, \bar{\chi}\sigma^{\mu\nu}\chi F_{\mu\nu}$$

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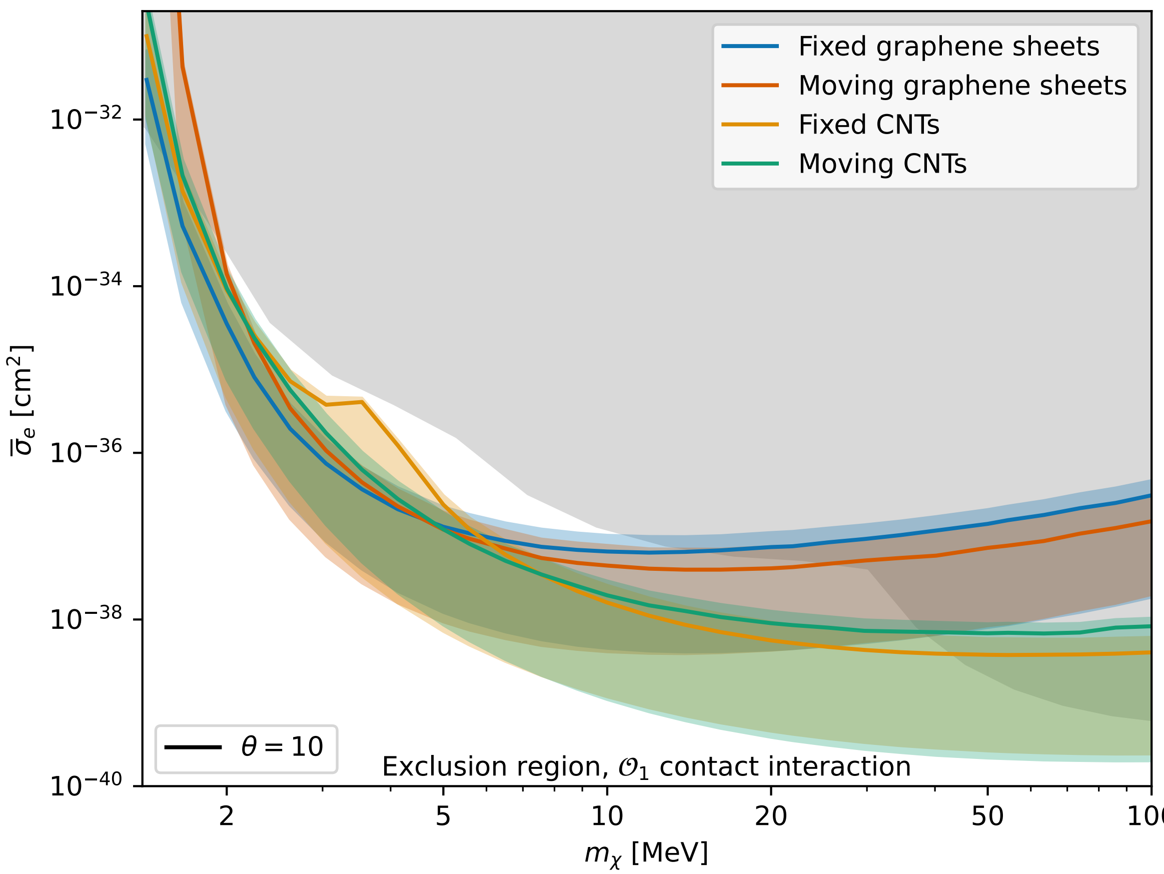
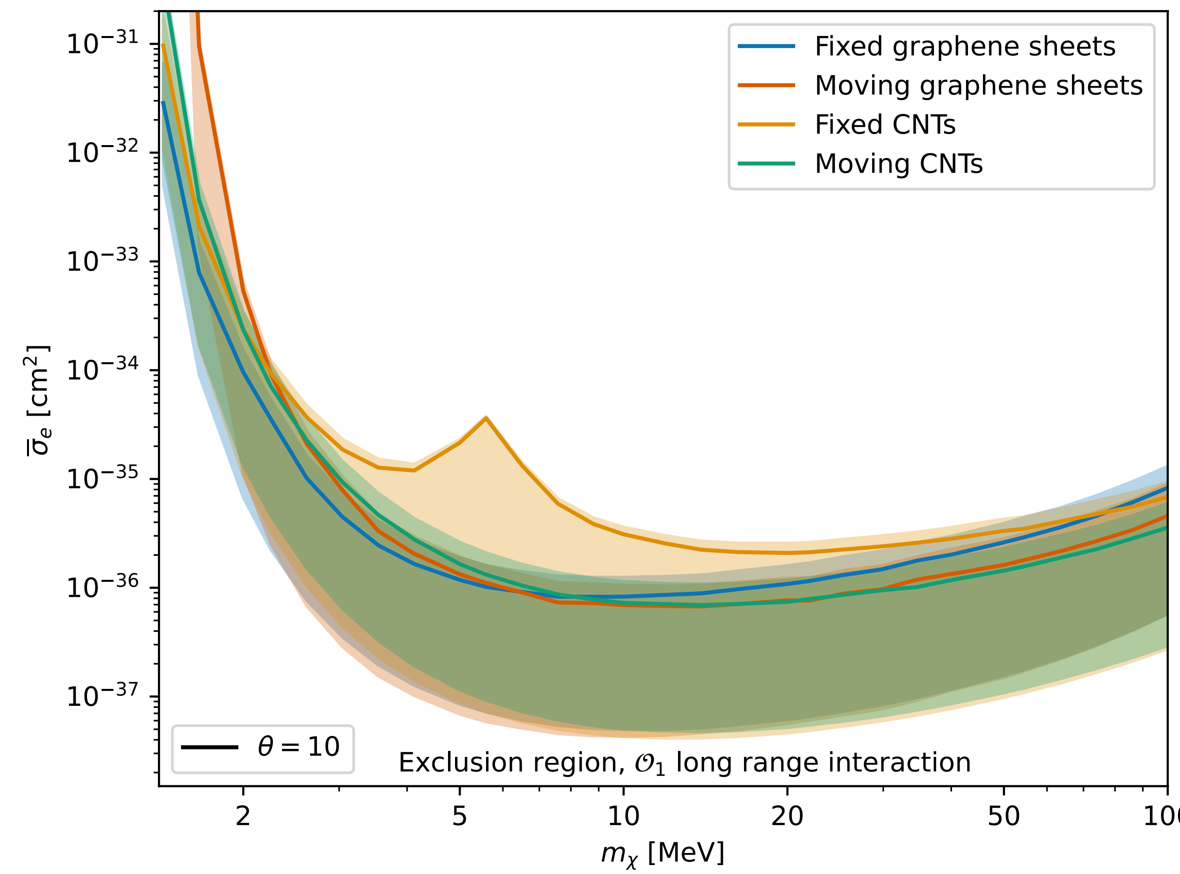
Exclusion Potential

$\mathcal{O}_1$ Contact Interaction

$\mathcal{O}_1$ Long Range Interaction





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Corresponds to dark photon model with a heavy mediator

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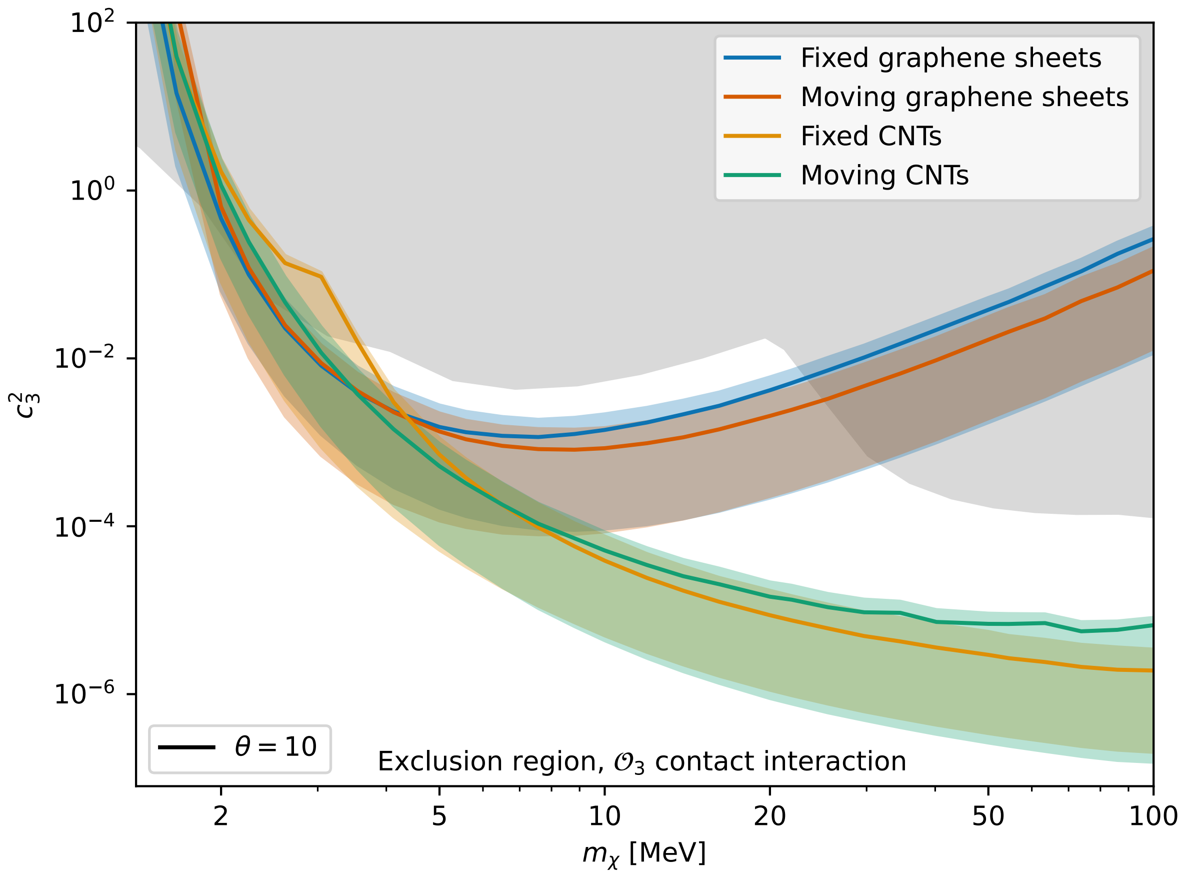
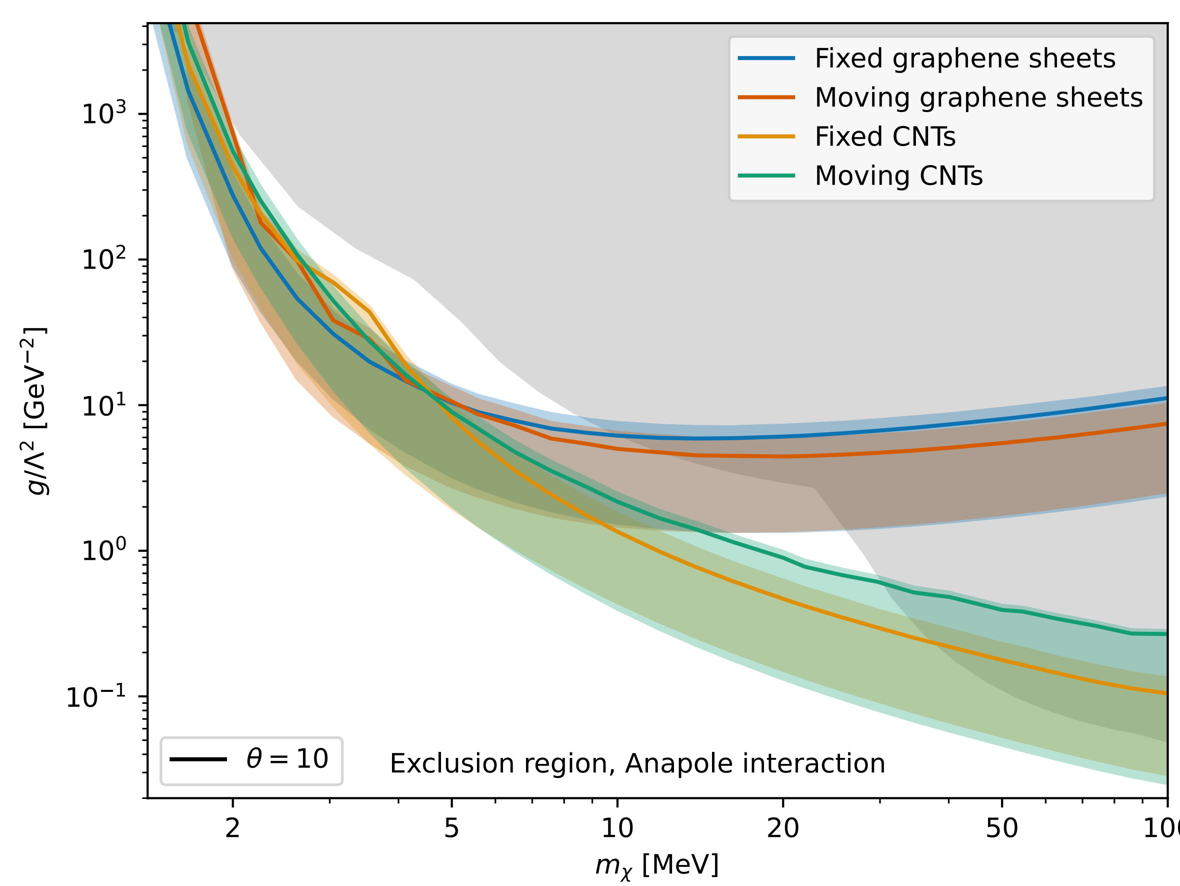
Exclusion Potential

$\mathcal{O}_3$ Contact Interaction



Anapole Interaction



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$\mathcal{O}_3 \propto \mathbf{q} \times \mathbf{v}$

10 g year exposure

$$L_{\text{Anapole}} = \frac{g}{2\Lambda^2}\,\bar{\chi}\gamma^\mu\gamma^5\chi\,\partial^\nu F_{\mu\nu}$$

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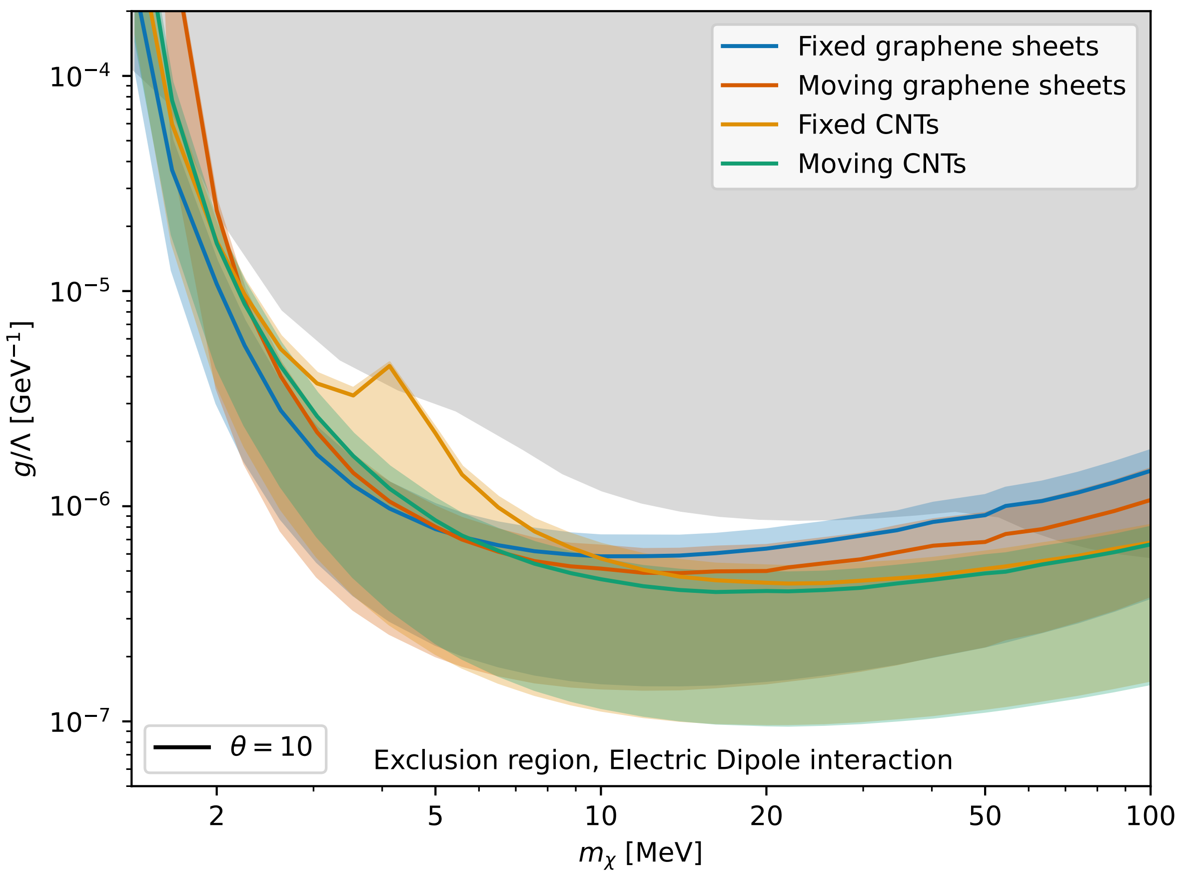
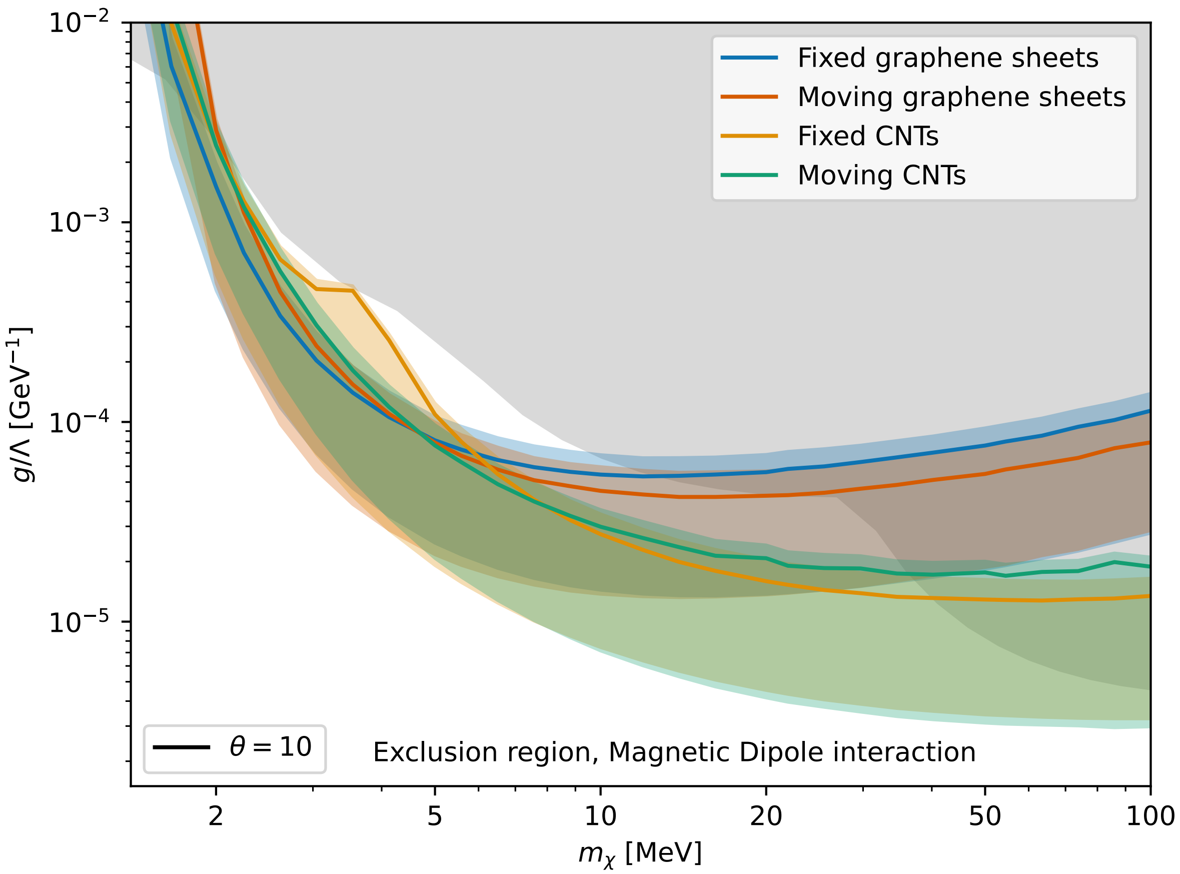
Exclusion Potential

Electric Dipole Interaction



Magnetic Dipole Interaction



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$$L_{\text{Electric dipole}} = \frac{g}{\Lambda} i\bar{\chi}\sigma^{\mu\nu}\gamma^5\chi F_{\mu\nu}$$

10 g year exposure

$$L_{\text{Magnetic dipole}} = \frac{g}{\Lambda} \bar{\chi}\sigma^{\mu\nu}\chi F_{\mu\nu}$$

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Summary

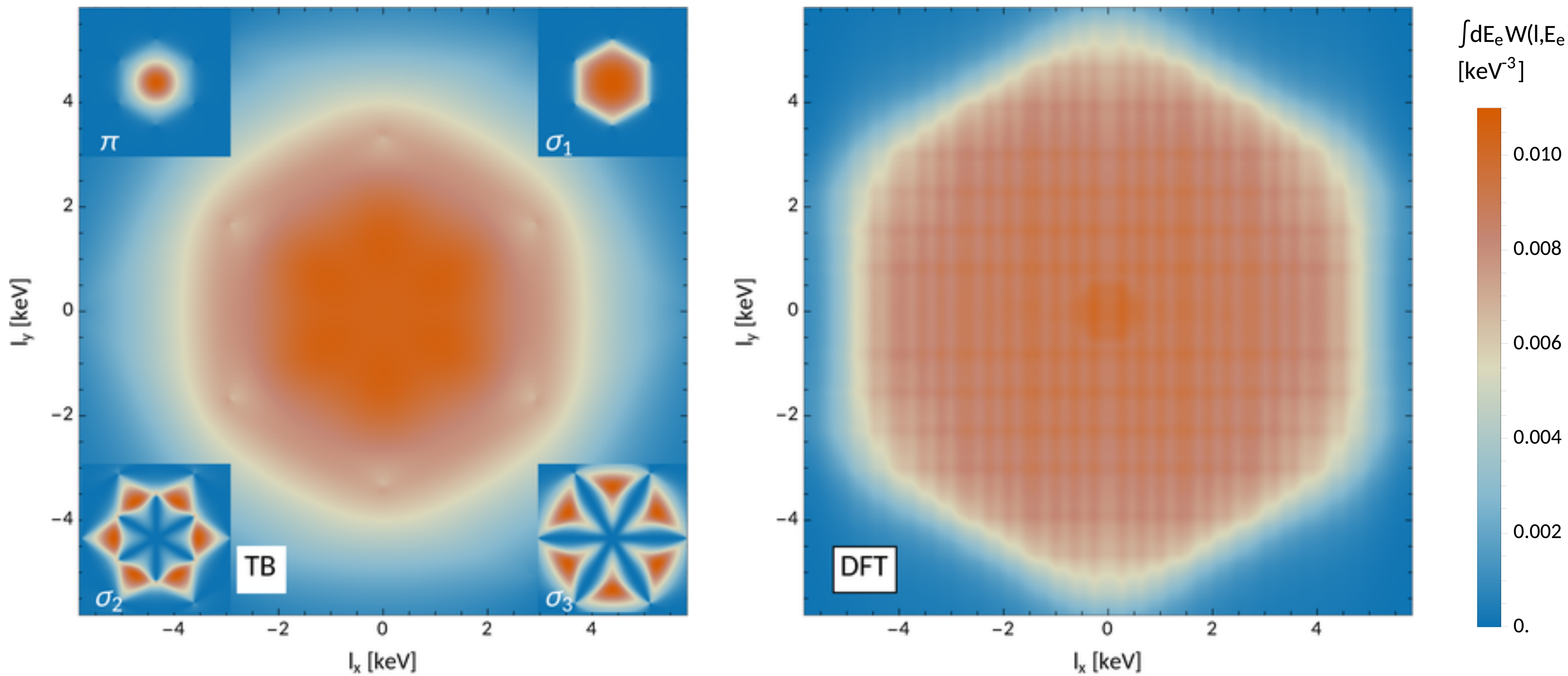
- Experiments based on graphene and CNTs are suitable to produce a smoking gun signal of DM.
- The relative performance of the experimental setups depends on the form of the DM electron interaction. Need to consider non-standard interactions.
- For more details, see our papers 2303.15497 & 2303.15509

Backup Slides

Electron Density

Tight Binding Approximation

Density Functional Theory



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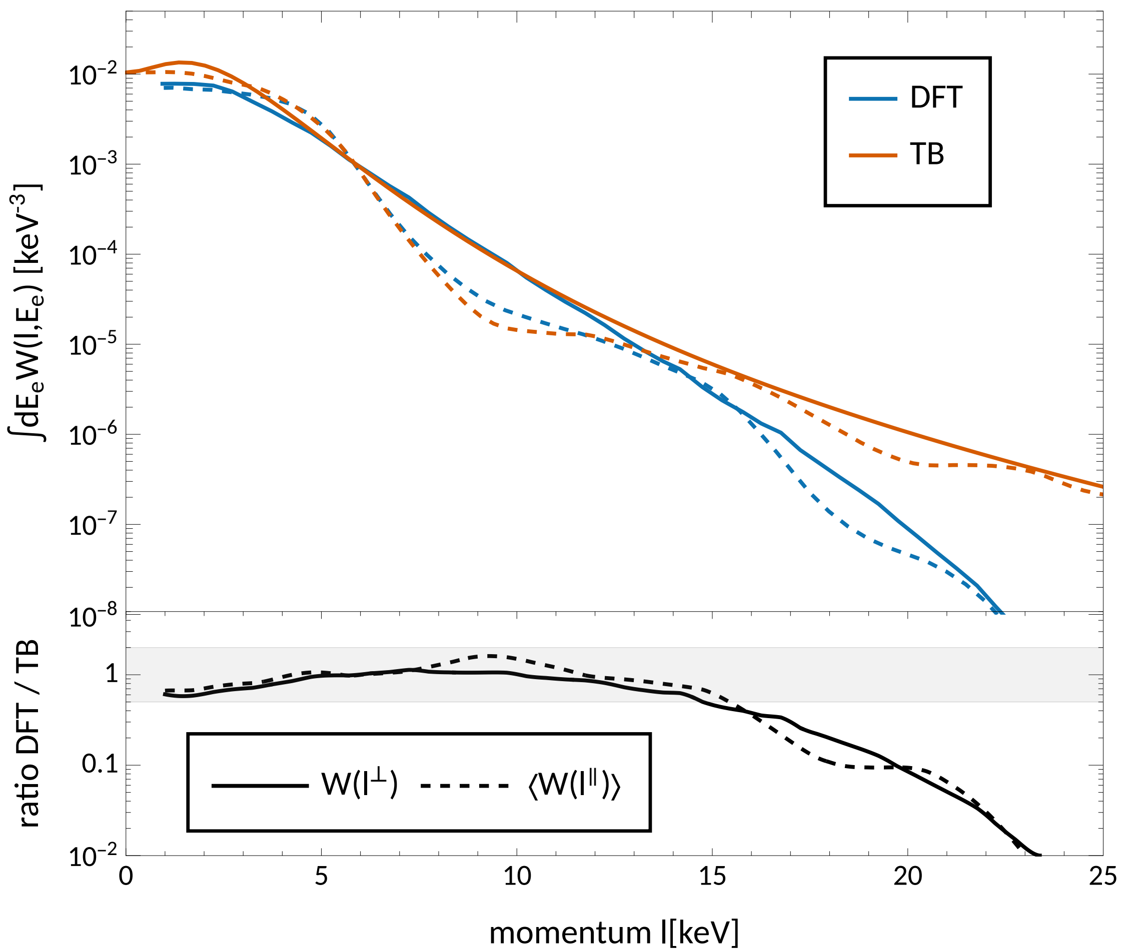
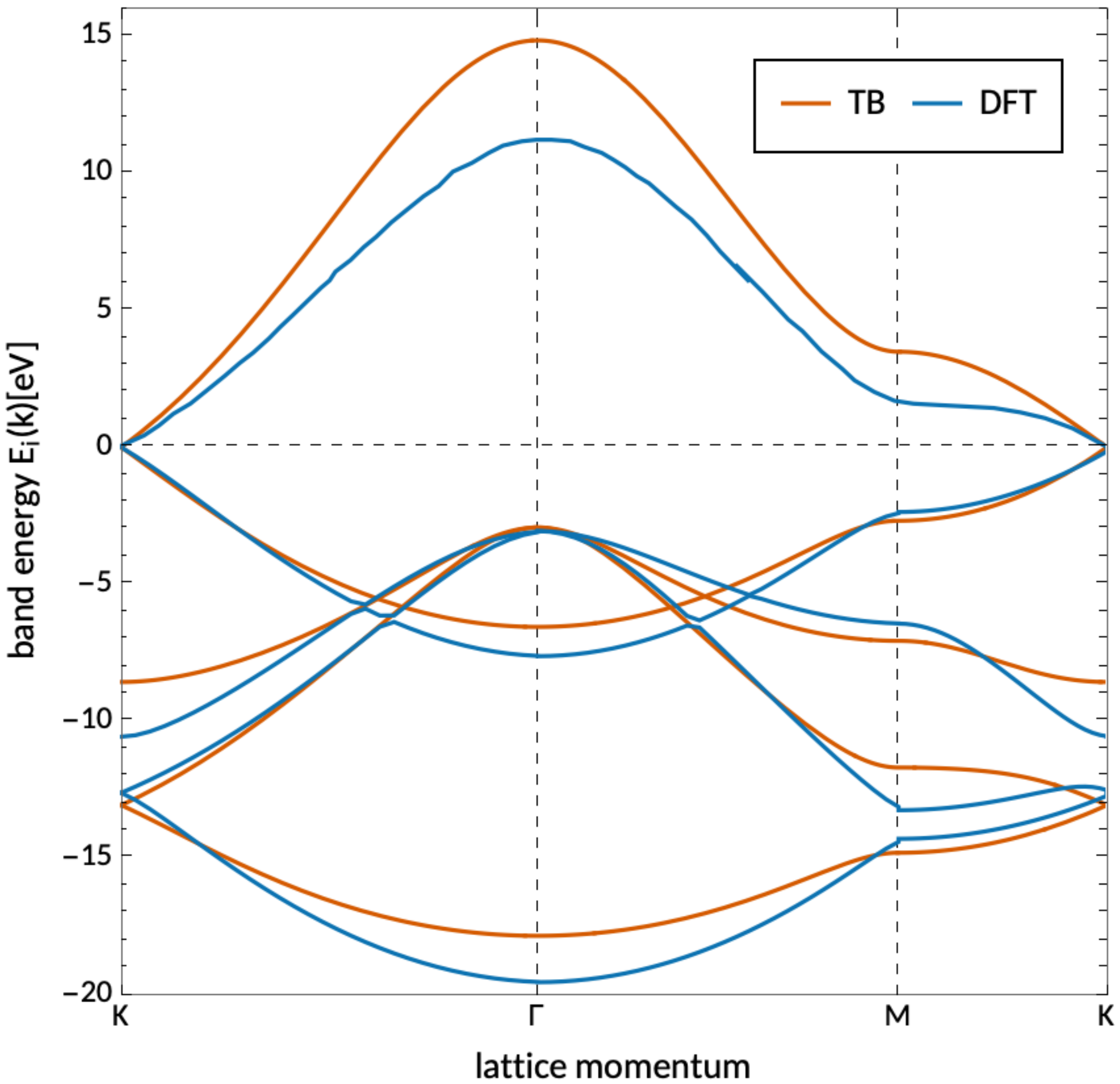
Modelling Graphene

Momentum Density



Band Structure



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Daily Modulation in Total Ejection Rates

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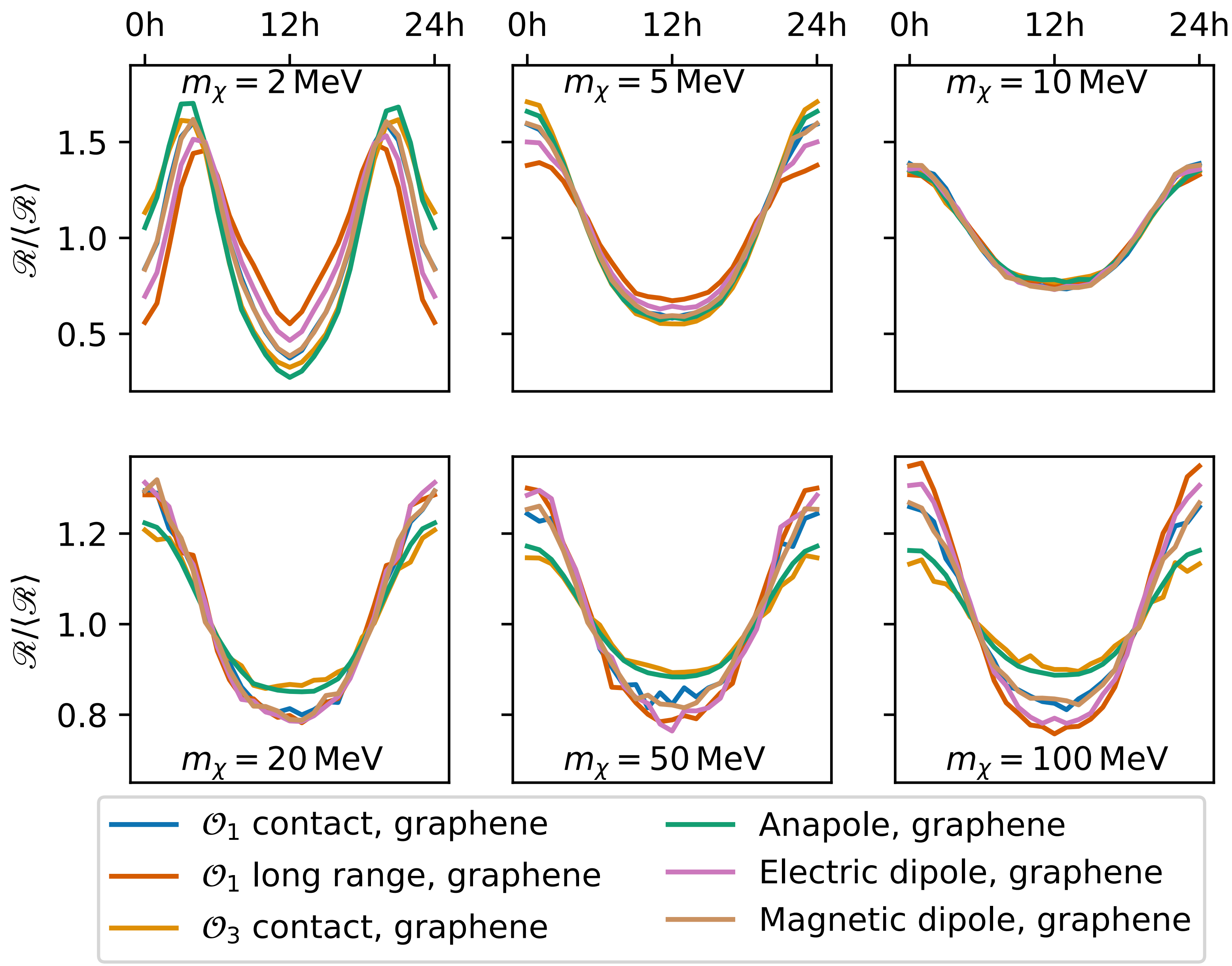
$$L_{\text{Anapole}} = \frac{g}{2\Lambda^2}\,\bar{\chi}\gamma^{\mu}\gamma^{5}\chi\,\partial^{\nu}F_{\mu\nu}$$

$$L_{\text{Electric dipole}} = \frac{g}{\Lambda}\,i\bar{\chi}\sigma^{\mu\nu}\gamma^{5}\chi\,F_{\mu\nu}$$

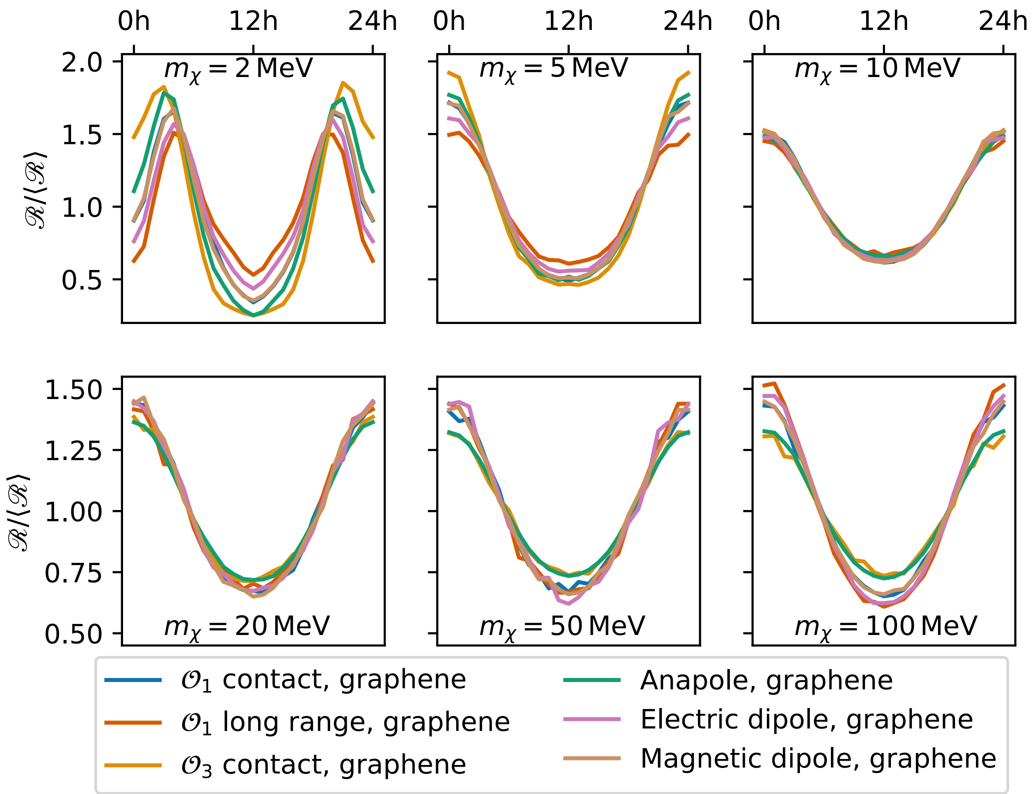
$$L_{\text{Magnetic dipole}} = \frac{g}{\Lambda}\,\bar{\chi}\sigma^{\mu\nu}\chi\,F_{\mu\nu}$$

$$\mathcal{O}_3 \propto \mathbf{q}\times\mathbf{v}$$

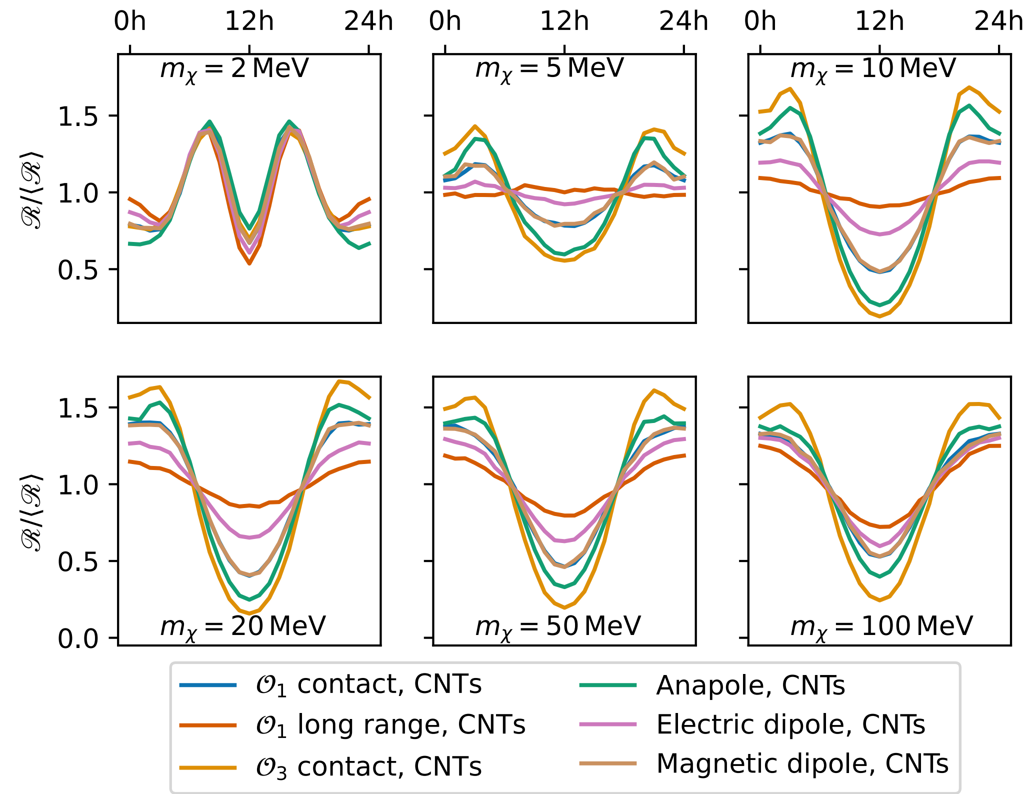


Daily Modulation in Observed Events

Fixed Graphene



Fixed CNTs



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$$L_{\text{Anapole}} = \frac{g}{2\Lambda^2}\,\bar{\chi}\gamma^\mu\gamma^5\chi\,\partial^\nu F_{\mu\nu}$$

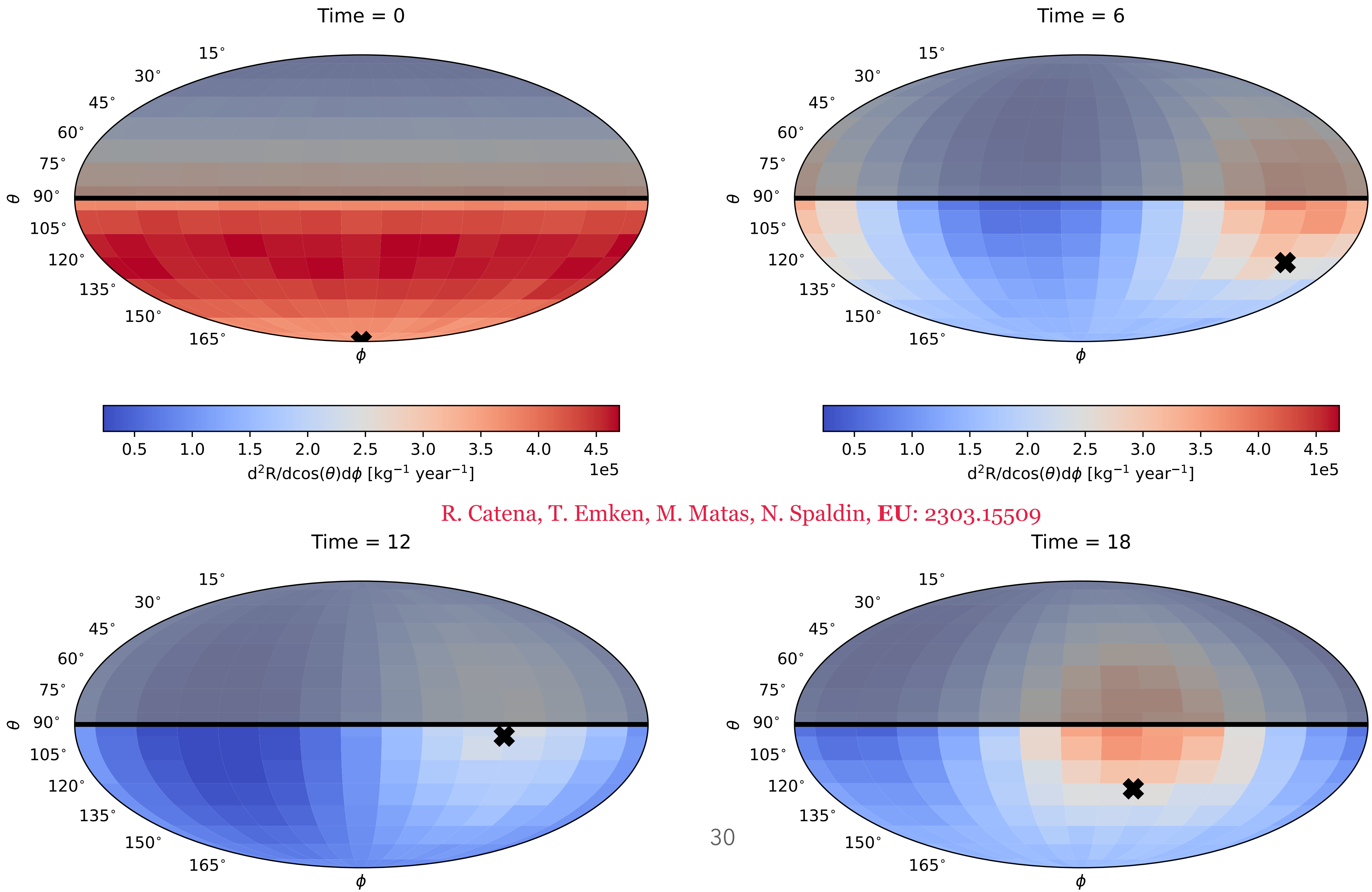
$$L_{\text{Magnetic dipole}} = \frac{g}{\Lambda}\,\bar{\chi}\sigma^{\mu\nu}\chi\,F_{\mu\nu}$$

$$L_{\text{Electric dipole}} = \frac{g}{\Lambda}\,i\bar{\chi}\sigma^{\mu\nu}\gamma^5\chi\,F_{\mu\nu}$$

$$\mathcal{O}_3 \propto \mathbf{q}\times\mathbf{v}$$

Scattering Directions Fixed Sheets

$\mathcal{O}_3 \propto \mathbf{v} \times \mathbf{q}$, contact type interaction, $m_\chi = 5\,\mathrm{MeV}$



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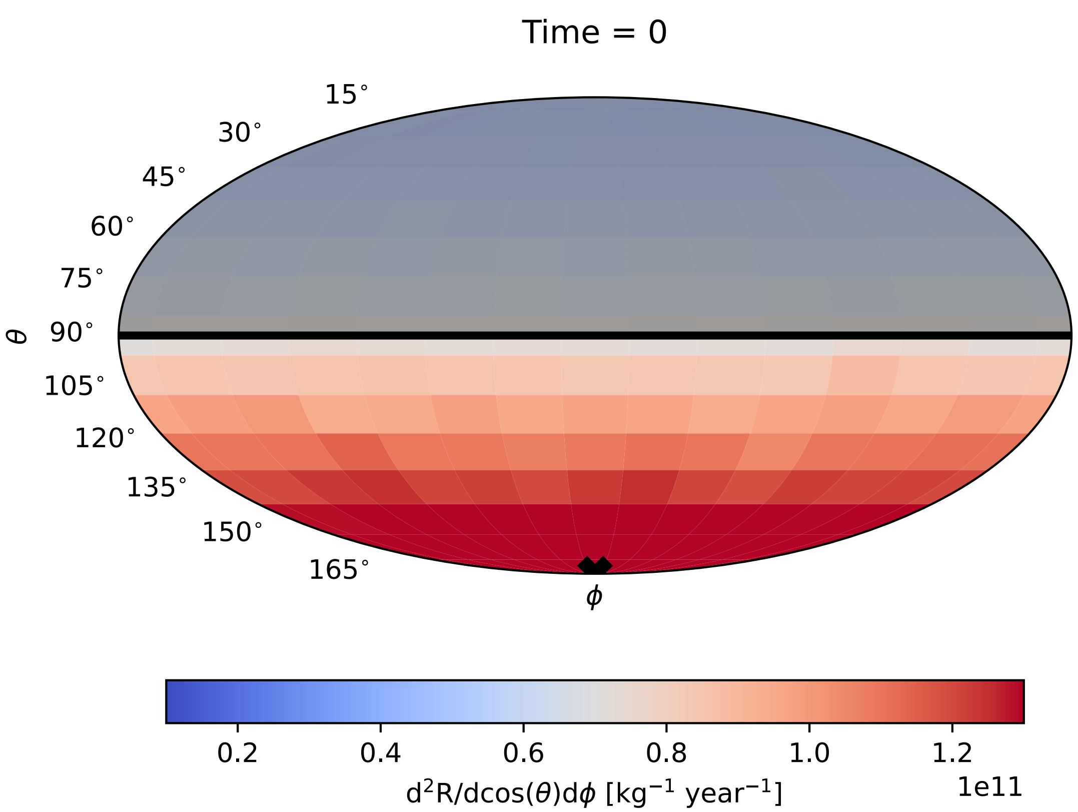
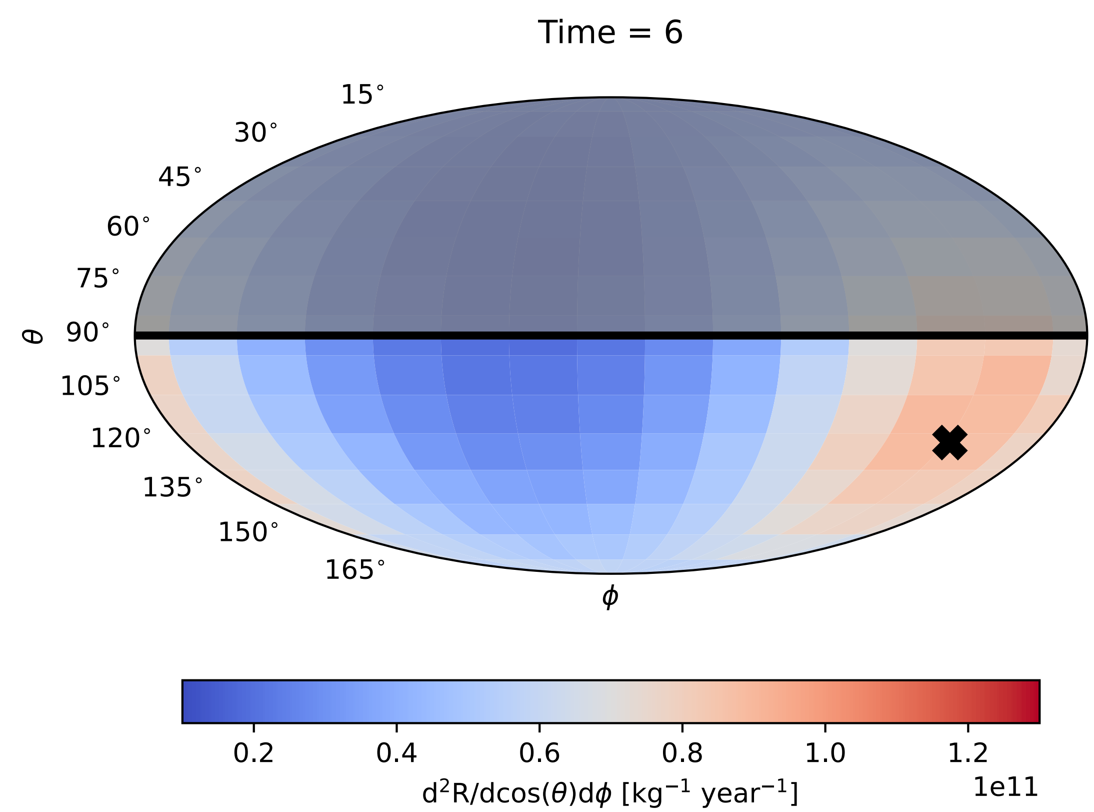
Scattering Directions Fixed Sheets

Magnetic Dipole Type Interaction, $m_\chi = 5\,\mathrm{MeV}$





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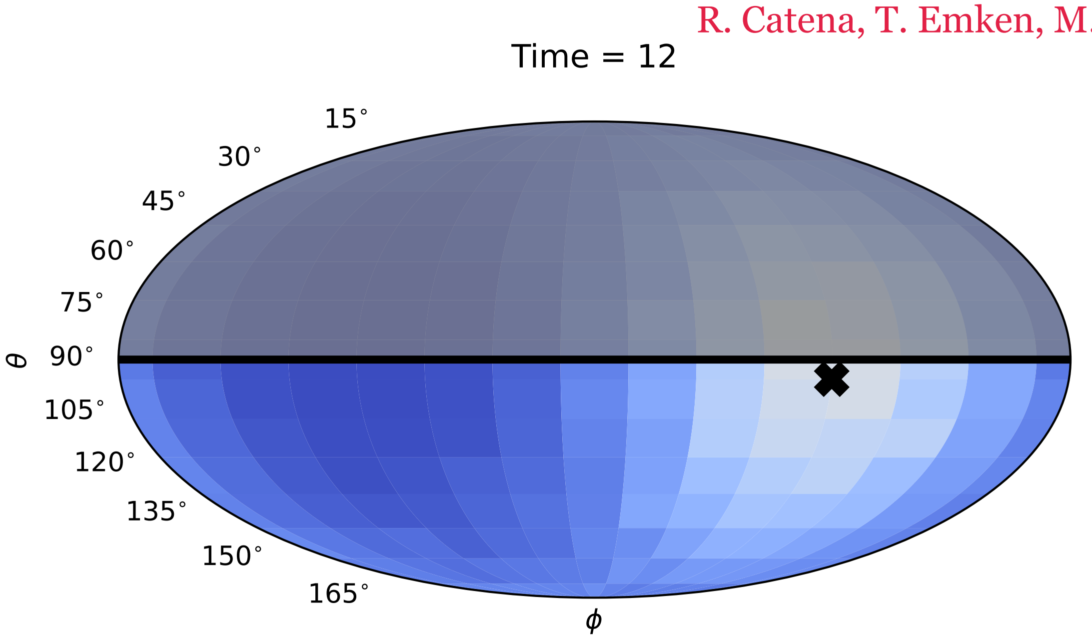
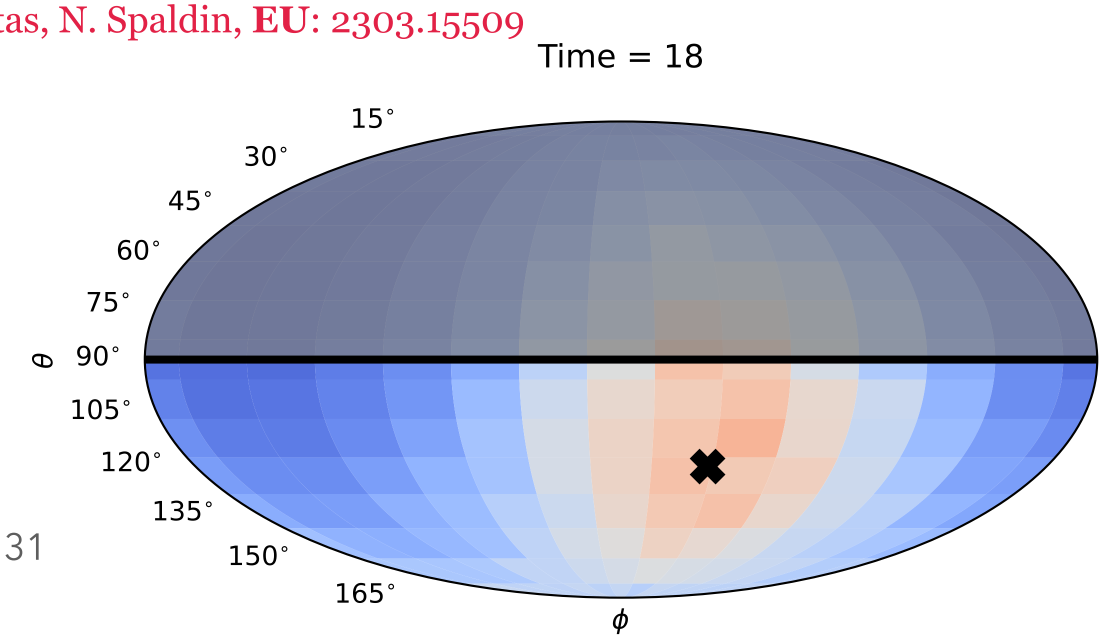
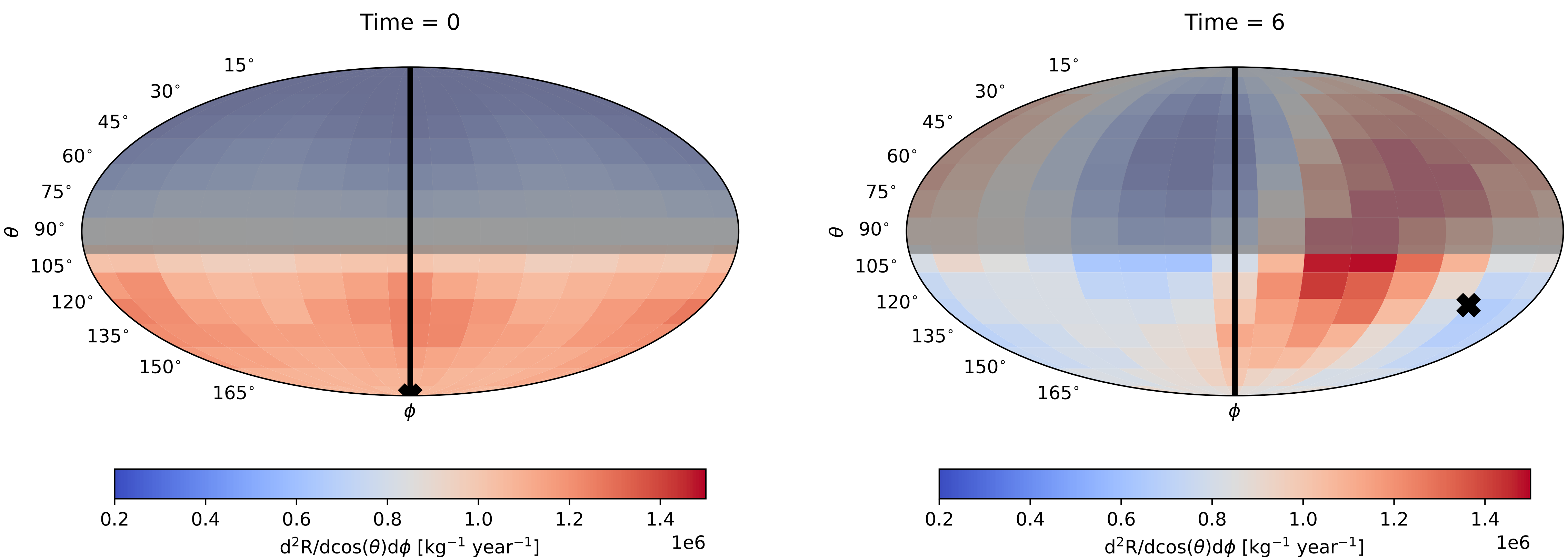




Scattering Directions Fixed CNTs

$\mathcal{O}_3 \propto \mathbf{v} \times \mathbf{q}$, contact type interaction, $m_\chi = 5\,\mathrm{MeV}$



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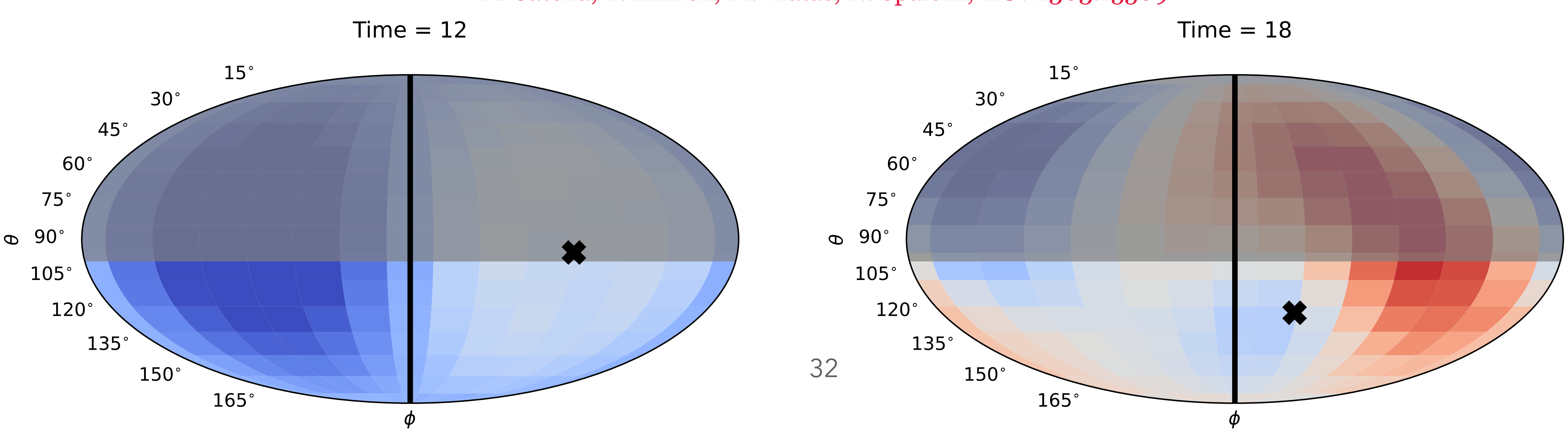
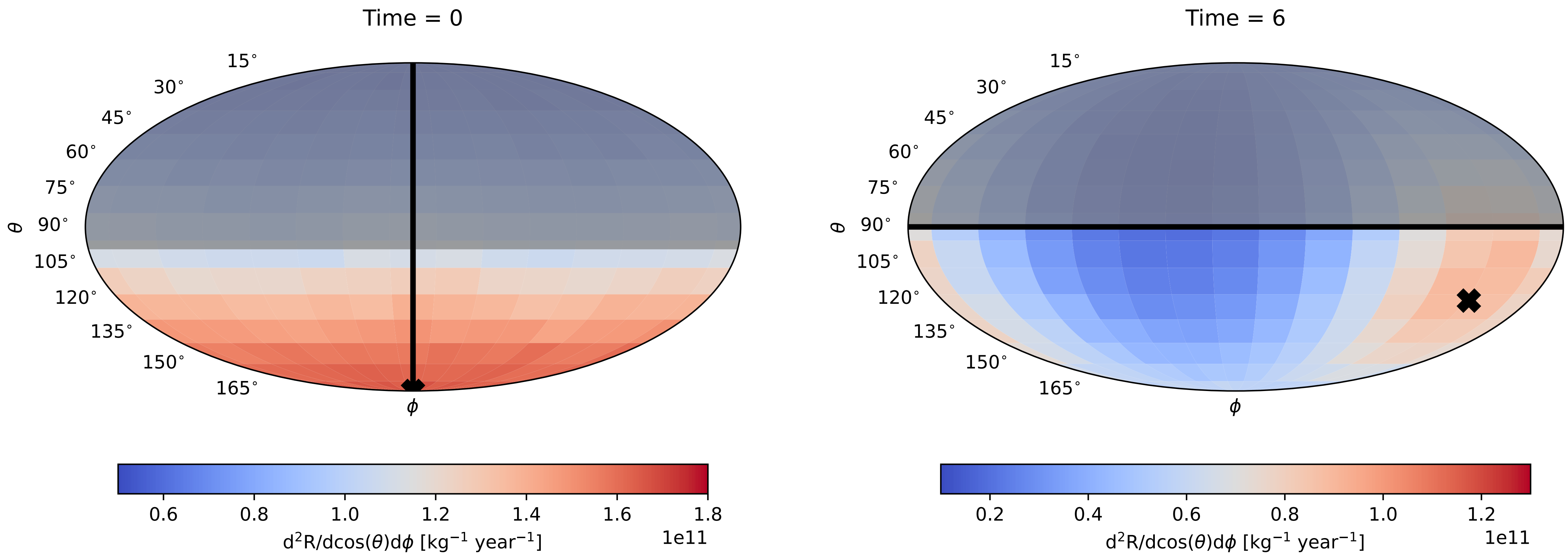


Scattering Directions Fixed CNTs

Magnetic Dipole Type Interaction, $m_\chi = 5\,\mathrm{MeV}$



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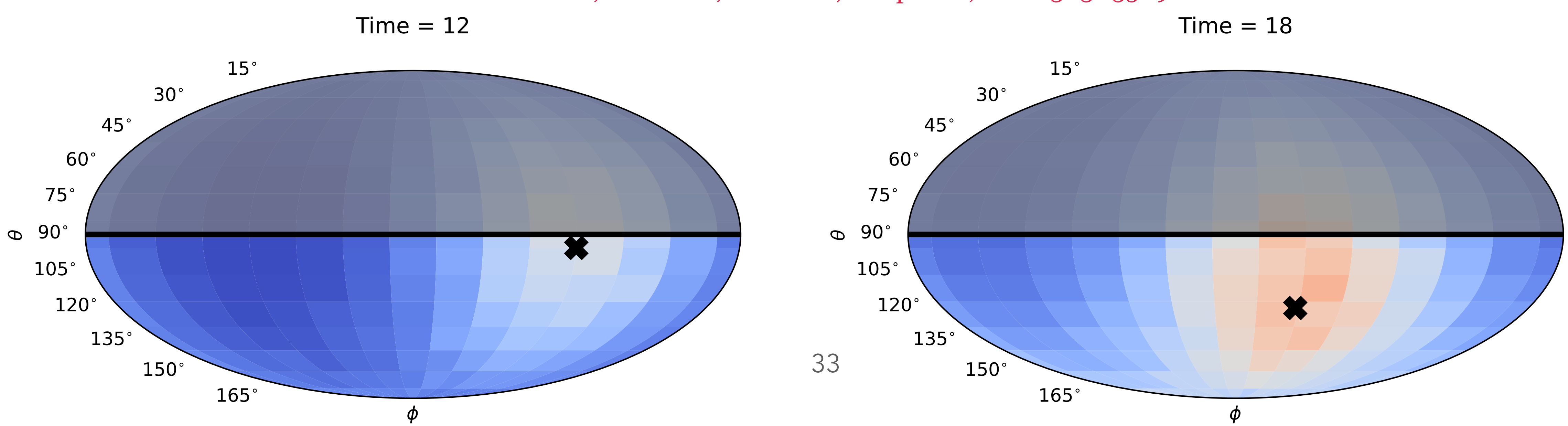
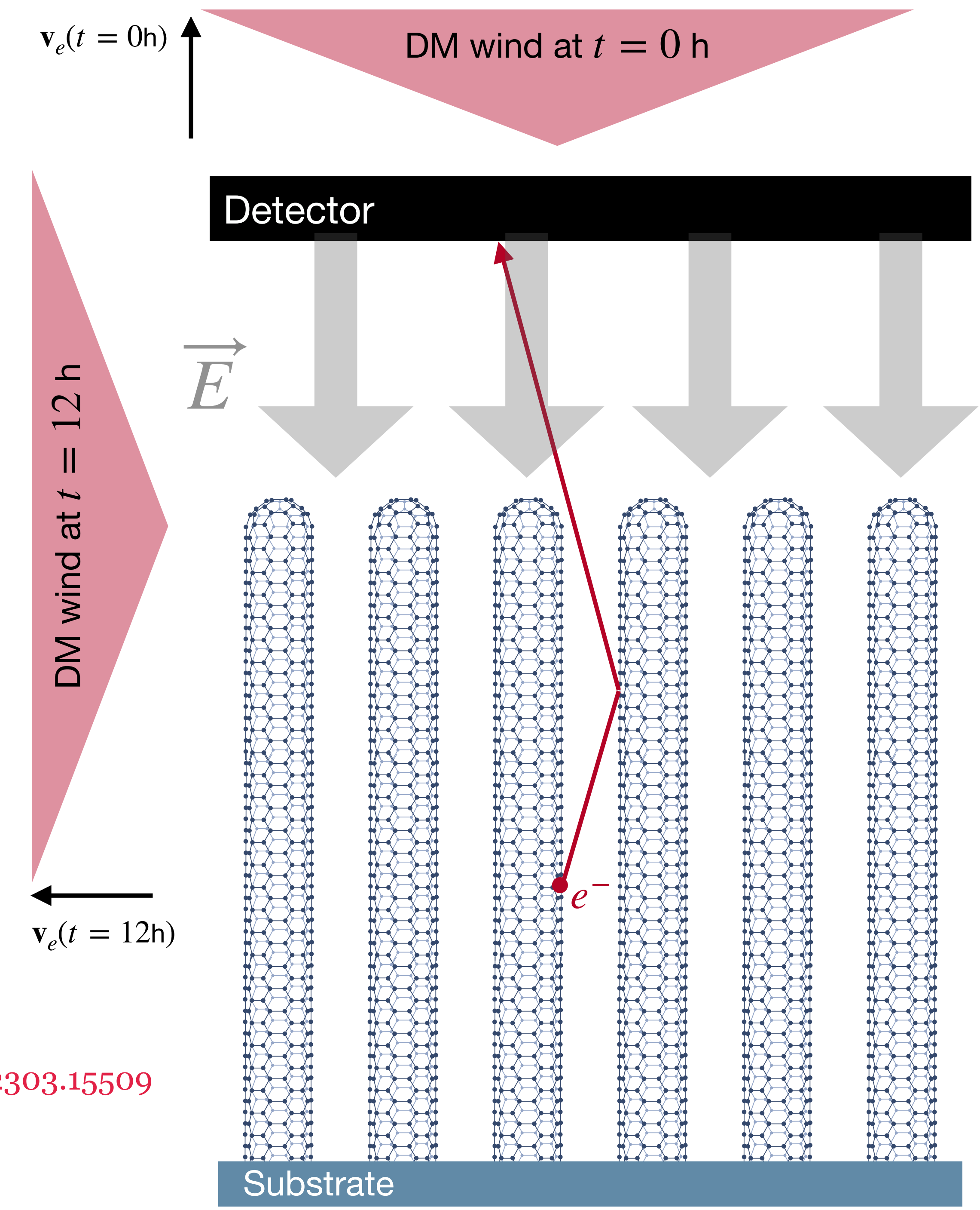


More CNT Based Setups

Fixed CNTs Facing Away From DM Wind

n_+: Number of detected events in 12 hours with most events

n_-: Number of detected events in 12 hours with least events



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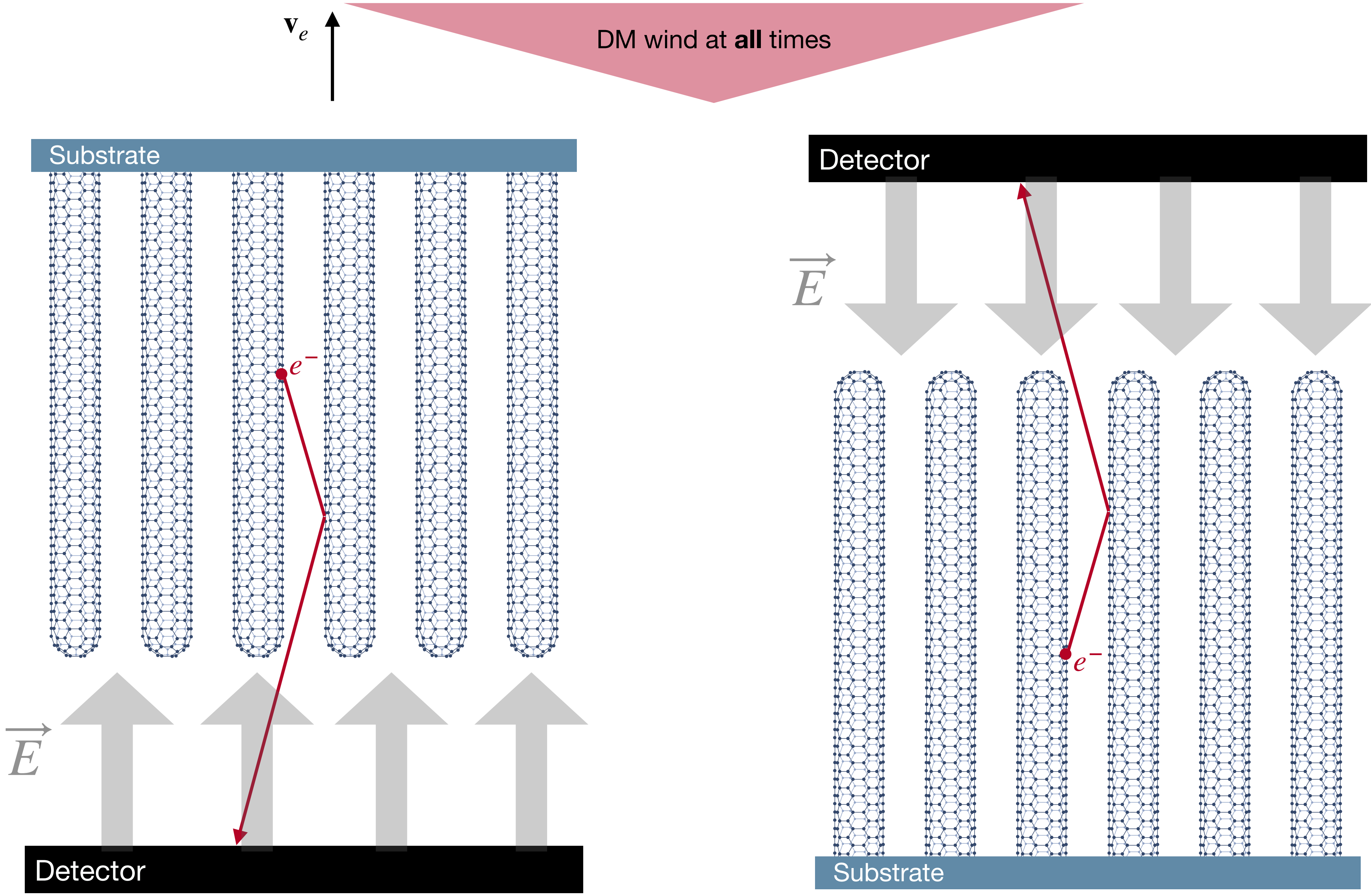
Fixed CNTs, facing away from the DM wind

More CNT Based Setups

Moving CNTs, Back to Back



n_-: Number of detected events upper detector

Moving CNTs, back to back

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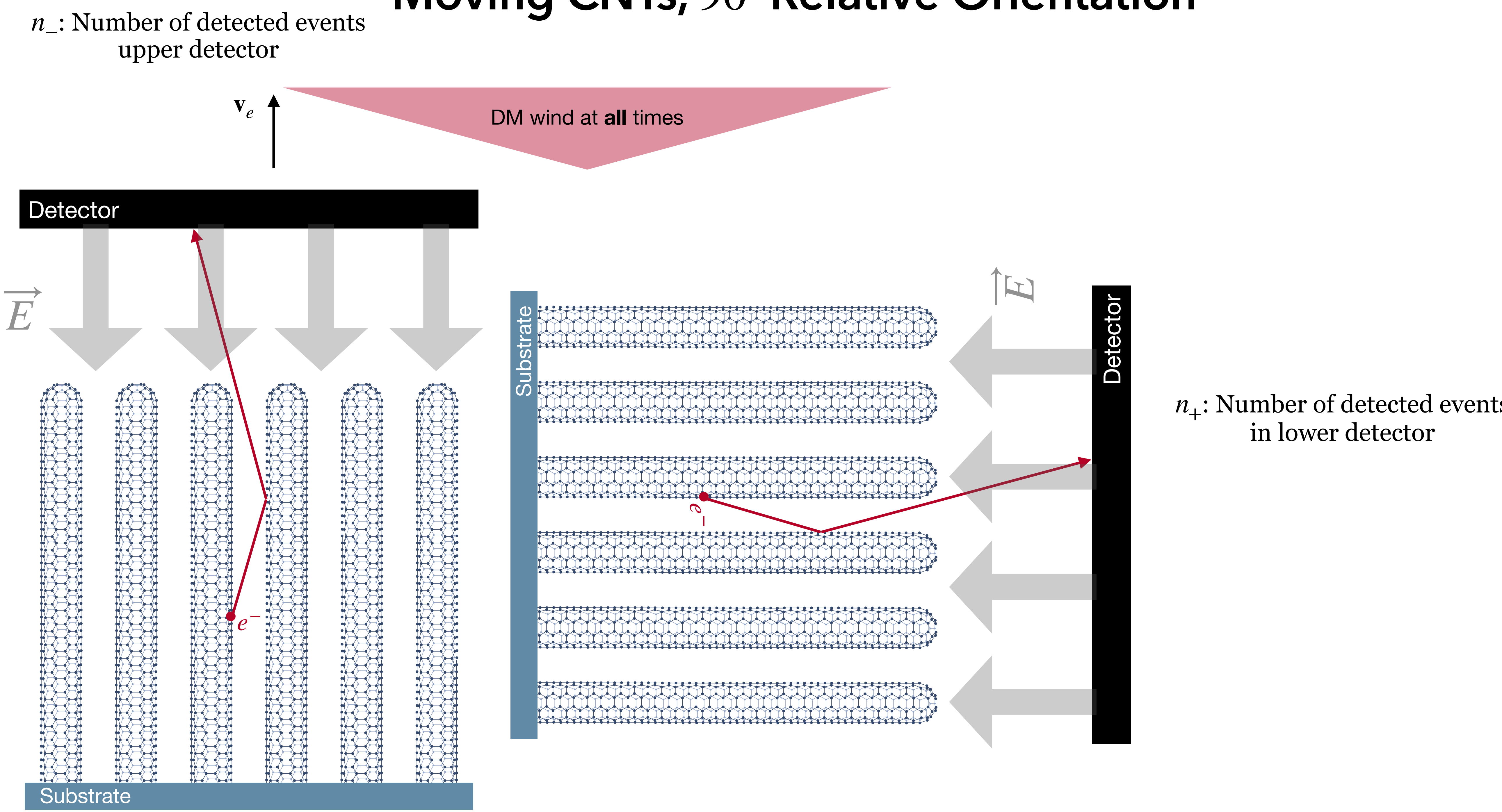
n_+: Number of detected events in lower detector

More CNT Based Setups

Moving CNTs, 90° Relative Orientation



Moving CNTs, 90° relative orientation

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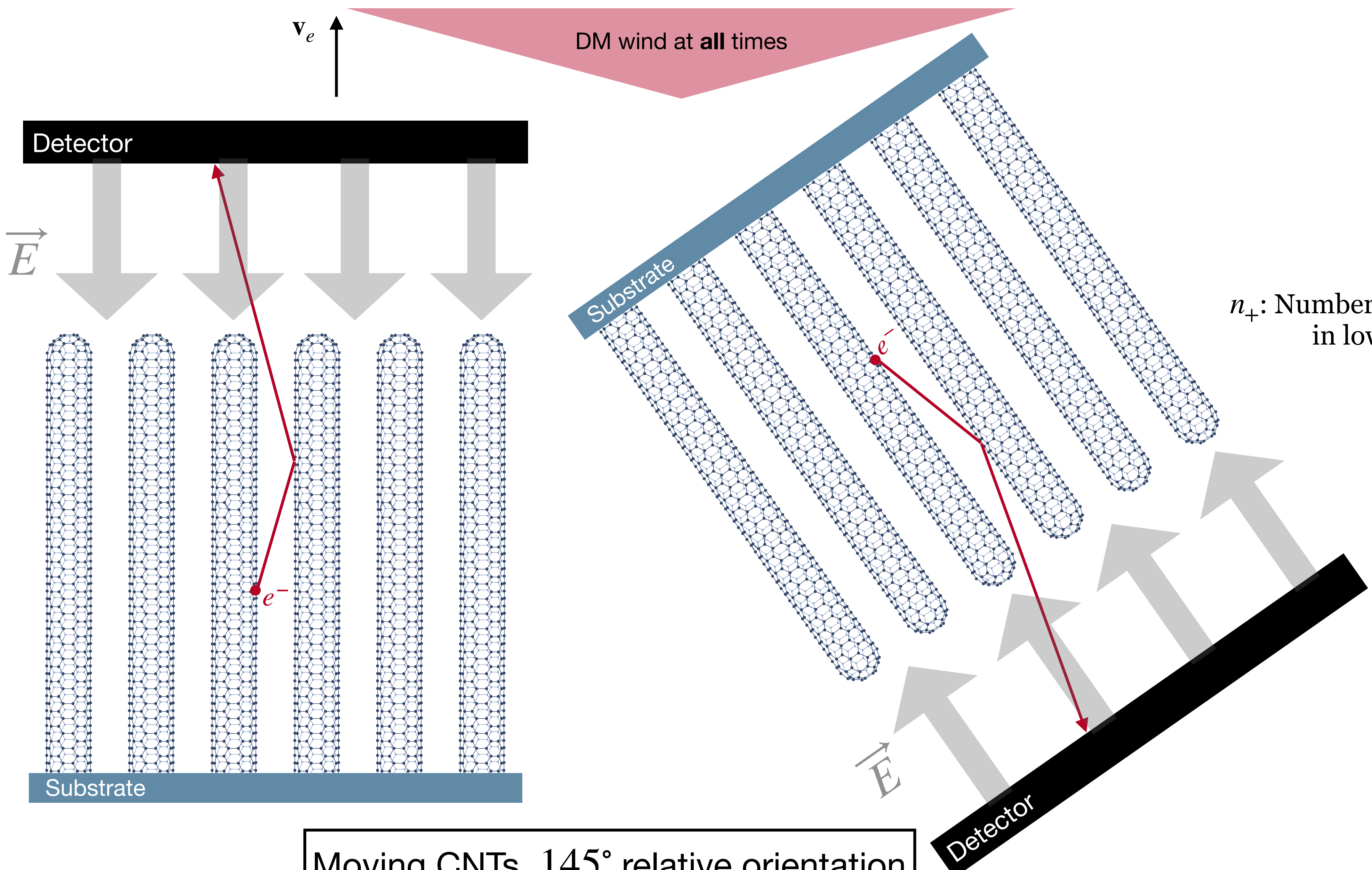
More CNT Based Setups

Moving CNTs, 145° relative orientation



n_+: Number of detected events in lower detector

Moving CNTs, 145° relative orientation

n_-: Number of detected events upper detector

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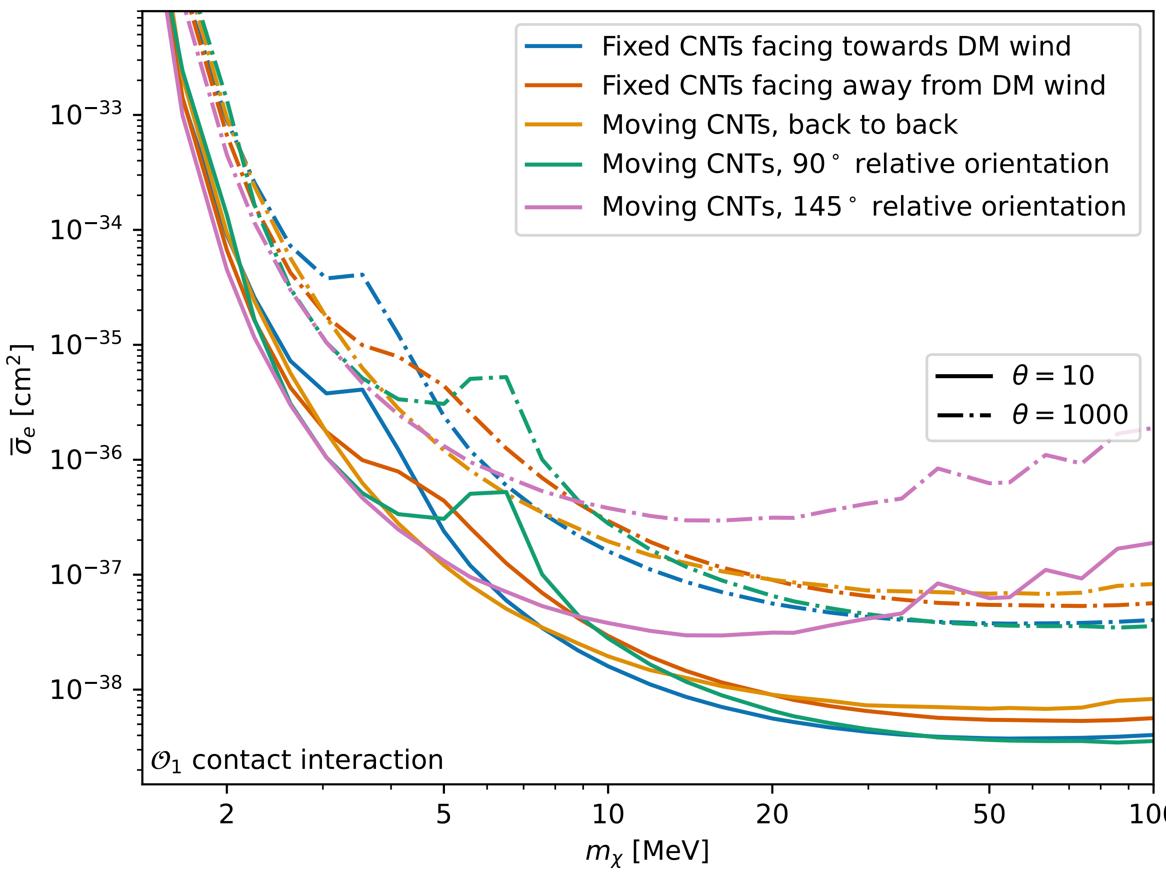
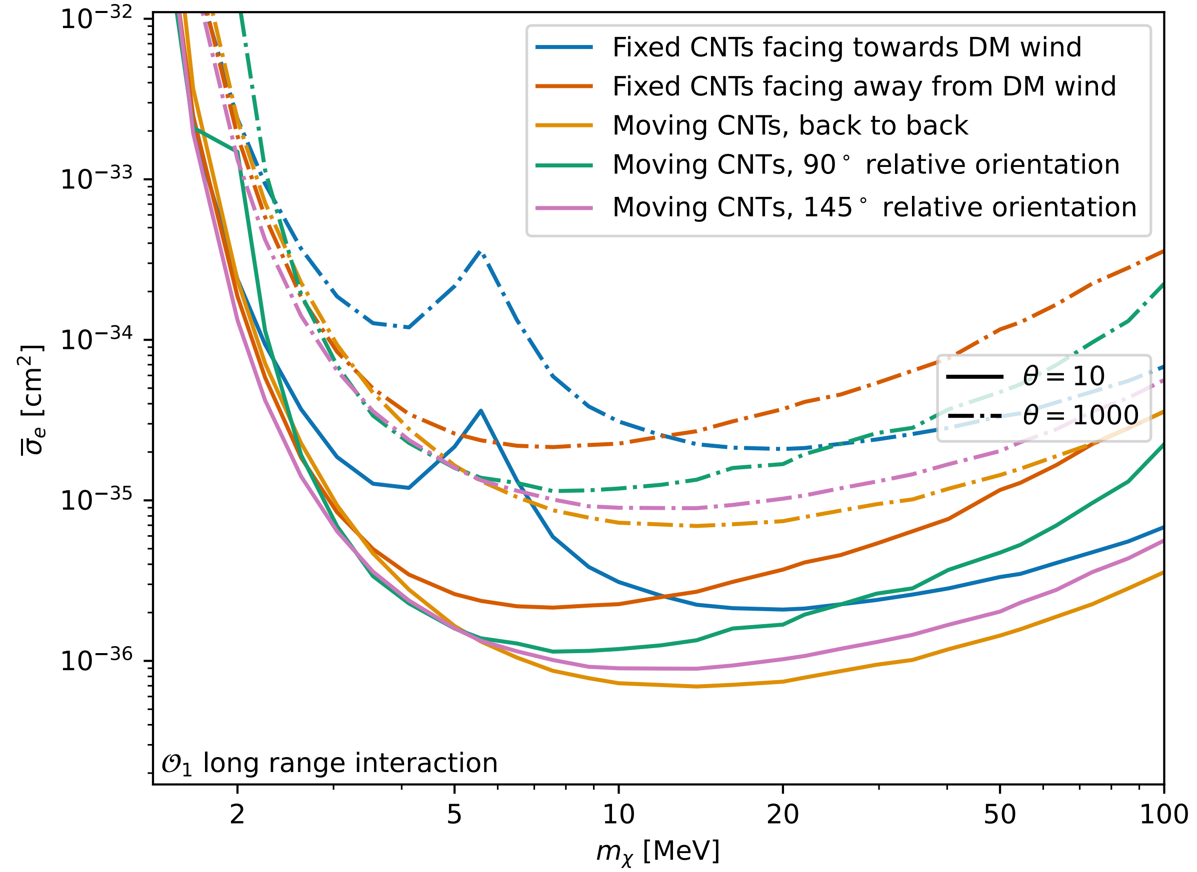
Potential for Establishing Modulation at 3σ

$\mathcal{O}_1$ Contact Interaction



$\mathcal{O}_1$ Long Range Interaction



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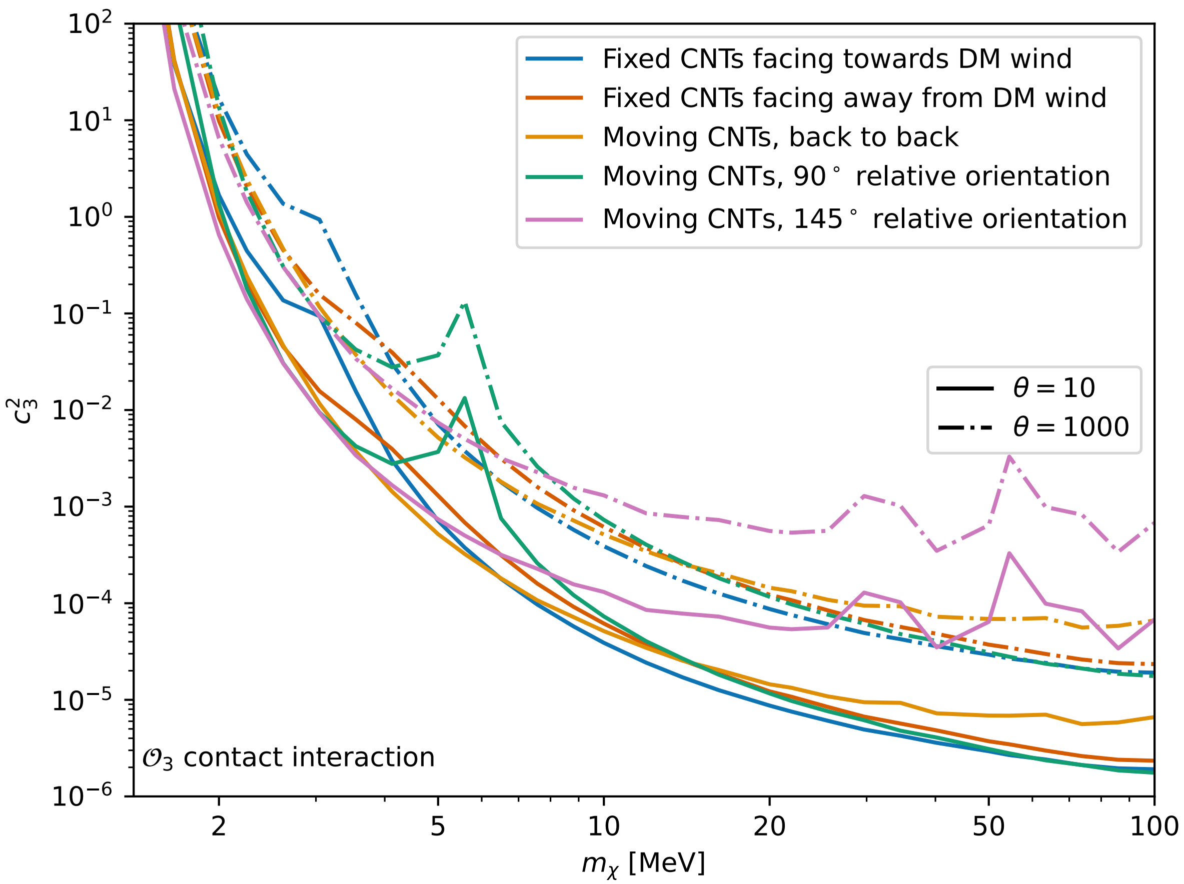
Corresponds to dark photon model with a heavy mediator

10 g year exposure

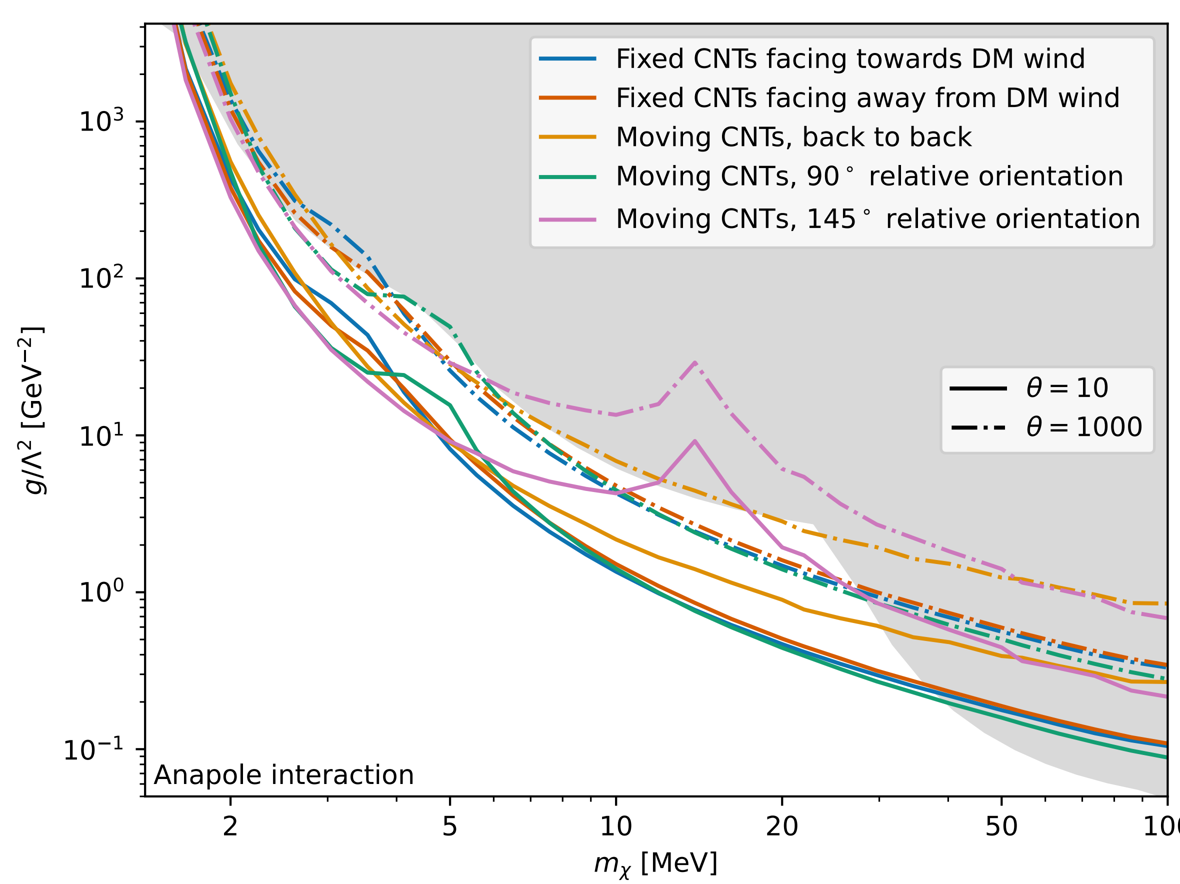
Corresponds to dark photon model with a light mediator

Potential for Establishing Modulation at 3σ

$\mathcal{O}_3$ Contact Interaction



Anapole Interaction



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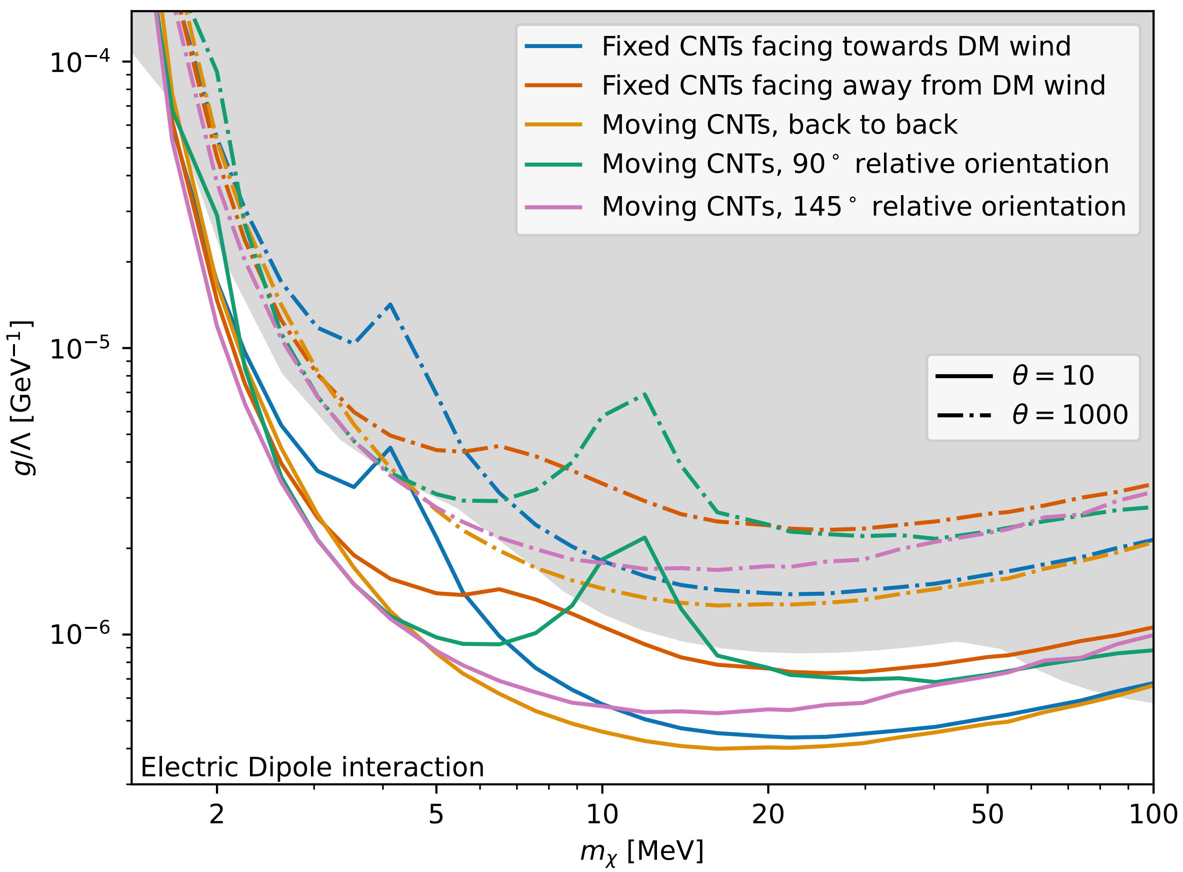
$\mathcal{O}_3 \propto \mathbf{q} \times \mathbf{v}$

10 g year exposure

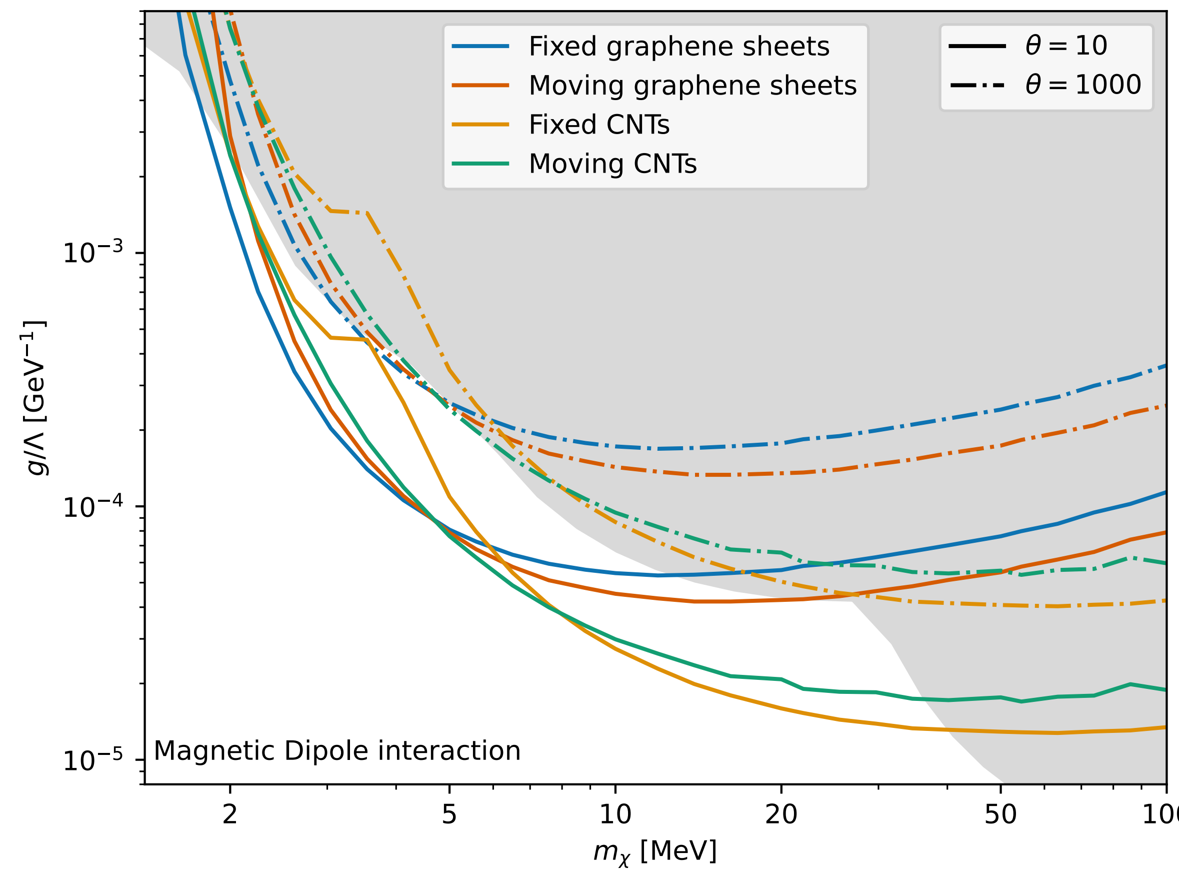
$$L_{\text{Anapole}} \in \frac{g}{2\Lambda^2}\, \bar{\chi}\gamma^\mu\gamma^5\chi\, \partial^\nu F_{\mu\nu}$$

Potential for Establishing Modulation at 3σ

Electric Dipole Interaction



Magnetic Dipole Interaction



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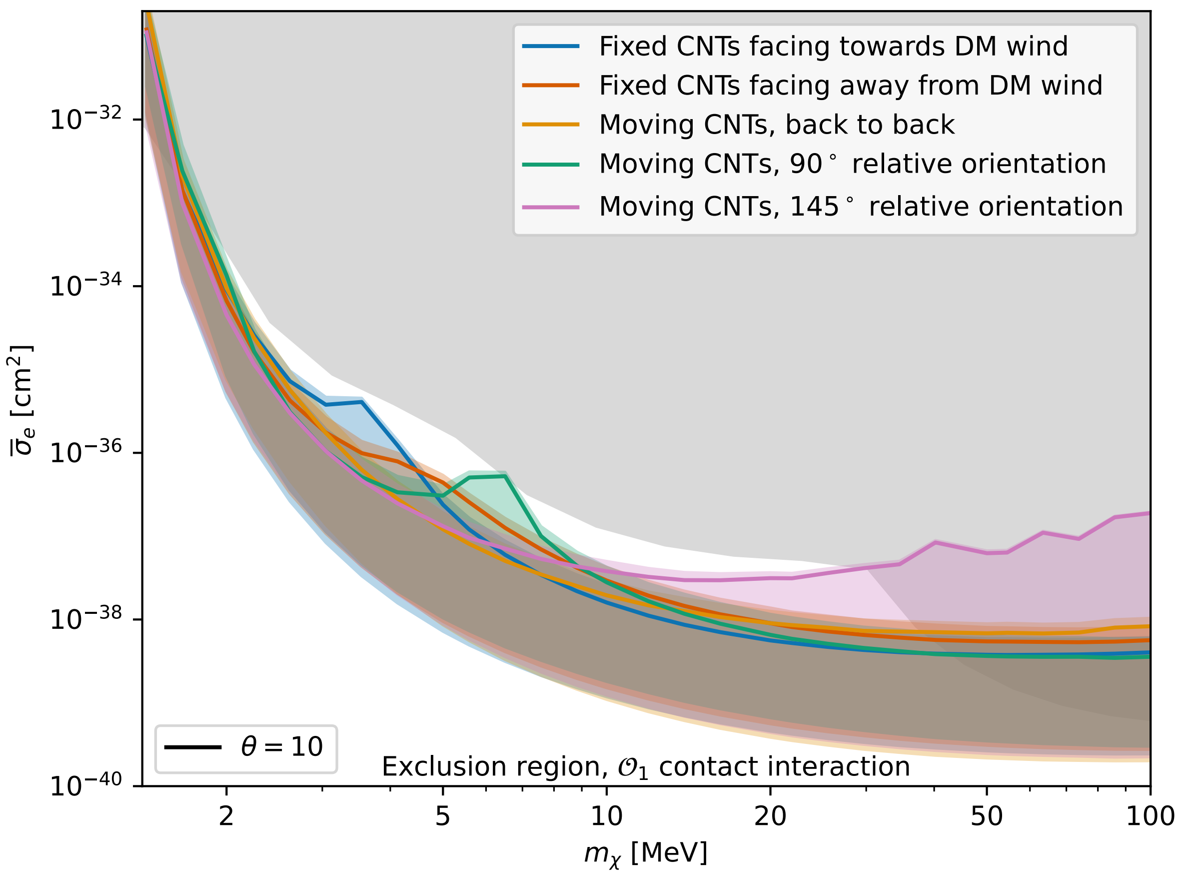
$L_{\text{Electric dipole}} \in \frac{g}{\Lambda} i\bar{\chi}\sigma^{\mu\nu}\gamma^5\chi F_{\mu\nu}$

10 g year exposure

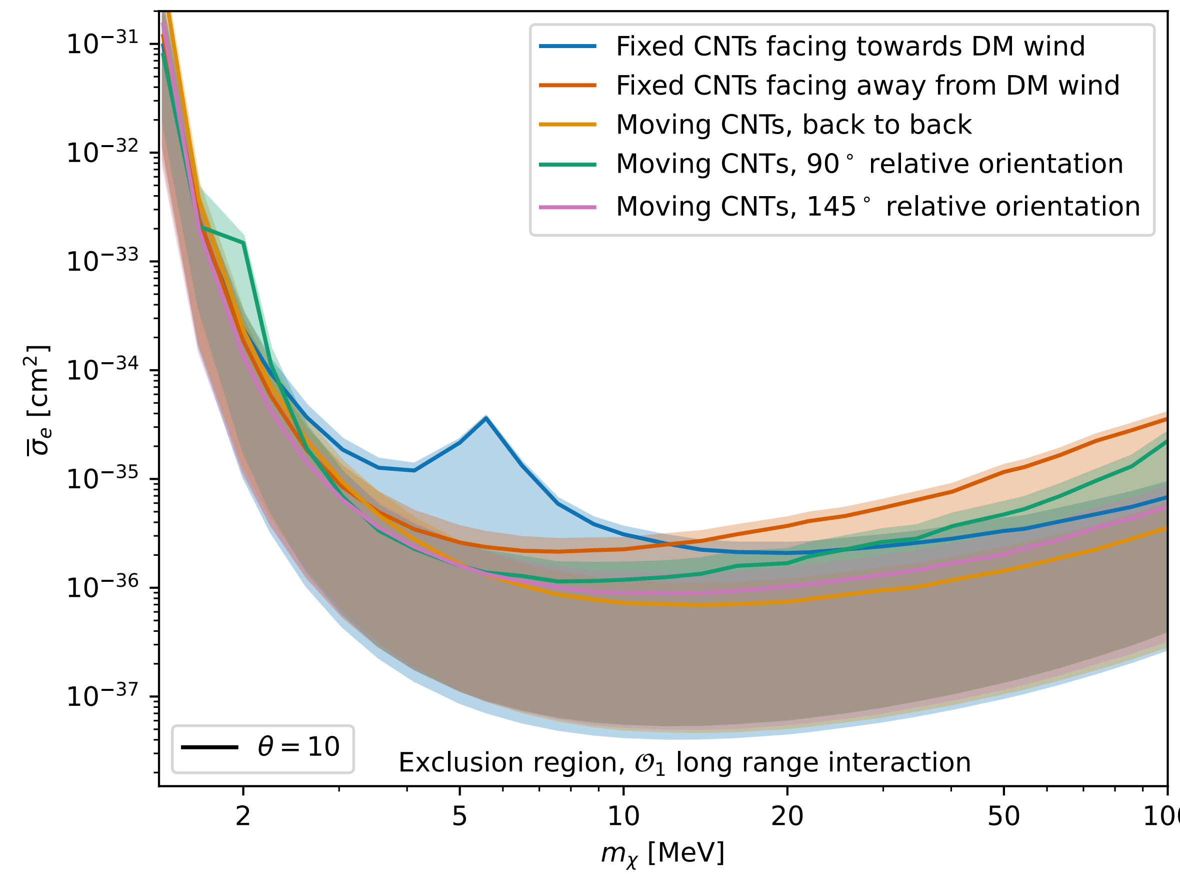
$L_{\text{Magnetic dipole}} \in \frac{g}{\Lambda} \bar{\chi}\sigma^{\mu\nu}\chi F_{\mu\nu}$

Exclusion Potential

$\mathcal{O}_1$ Contact Interaction



$\mathcal{O}_1$ Long Range Interaction



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Corresponds to dark photon model with a heavy mediator

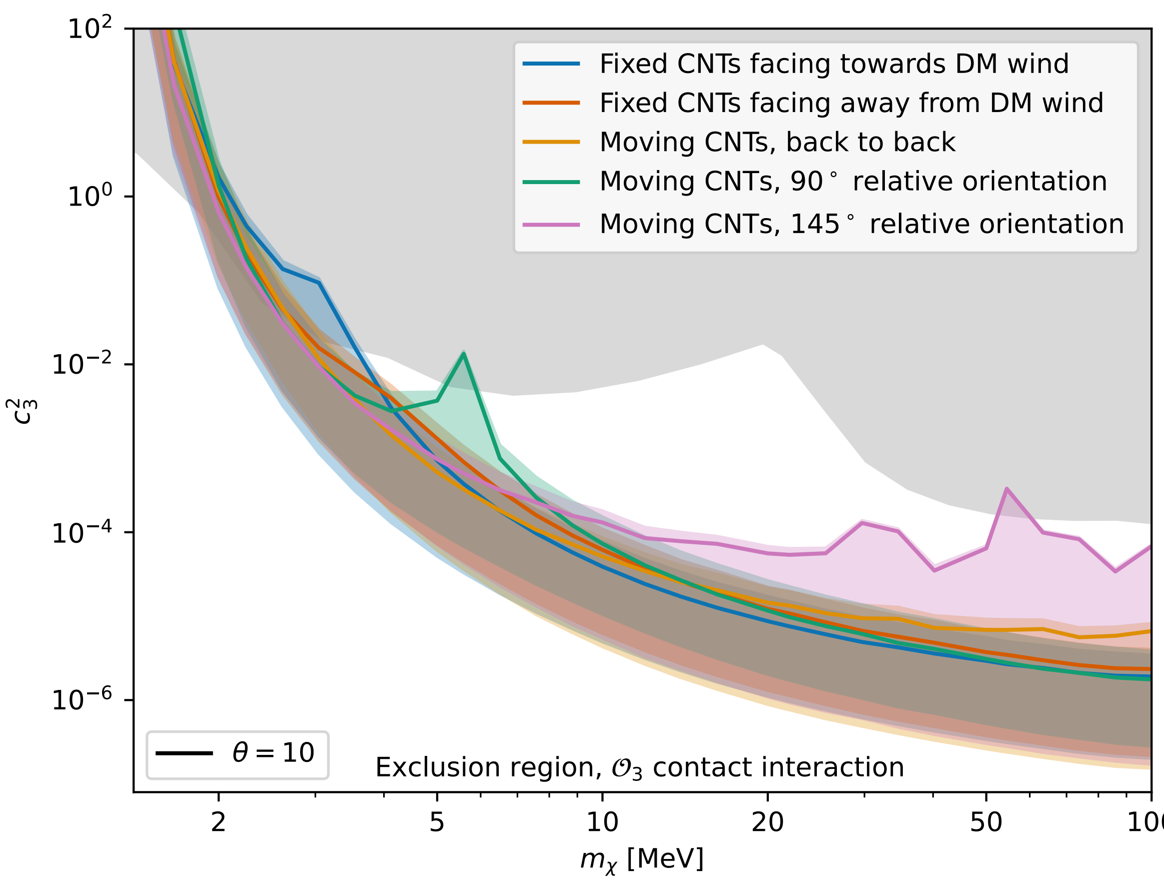
10 g year exposure

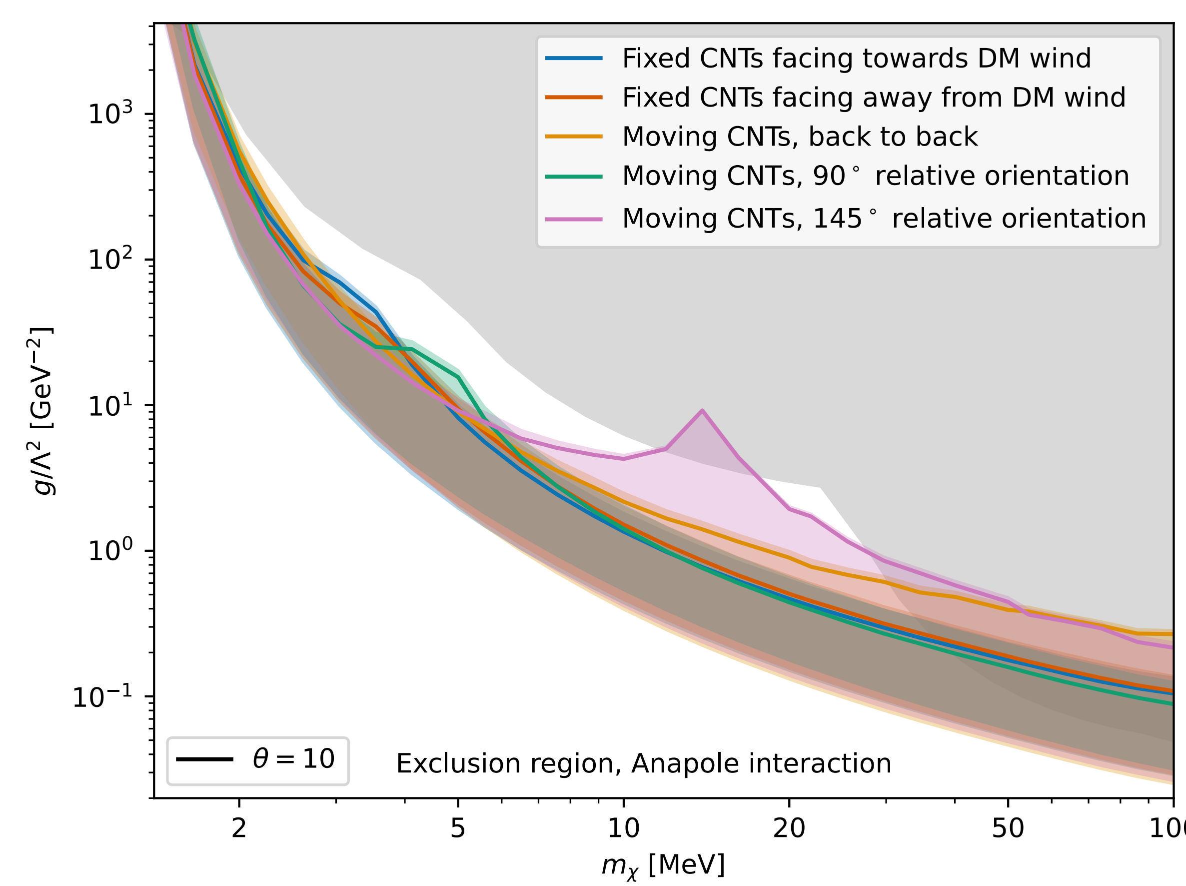
Corresponds to dark photon model with a light mediator

Exclusion Potential

$\mathcal{O}_3$ Contact Interaction

Anapole Interaction





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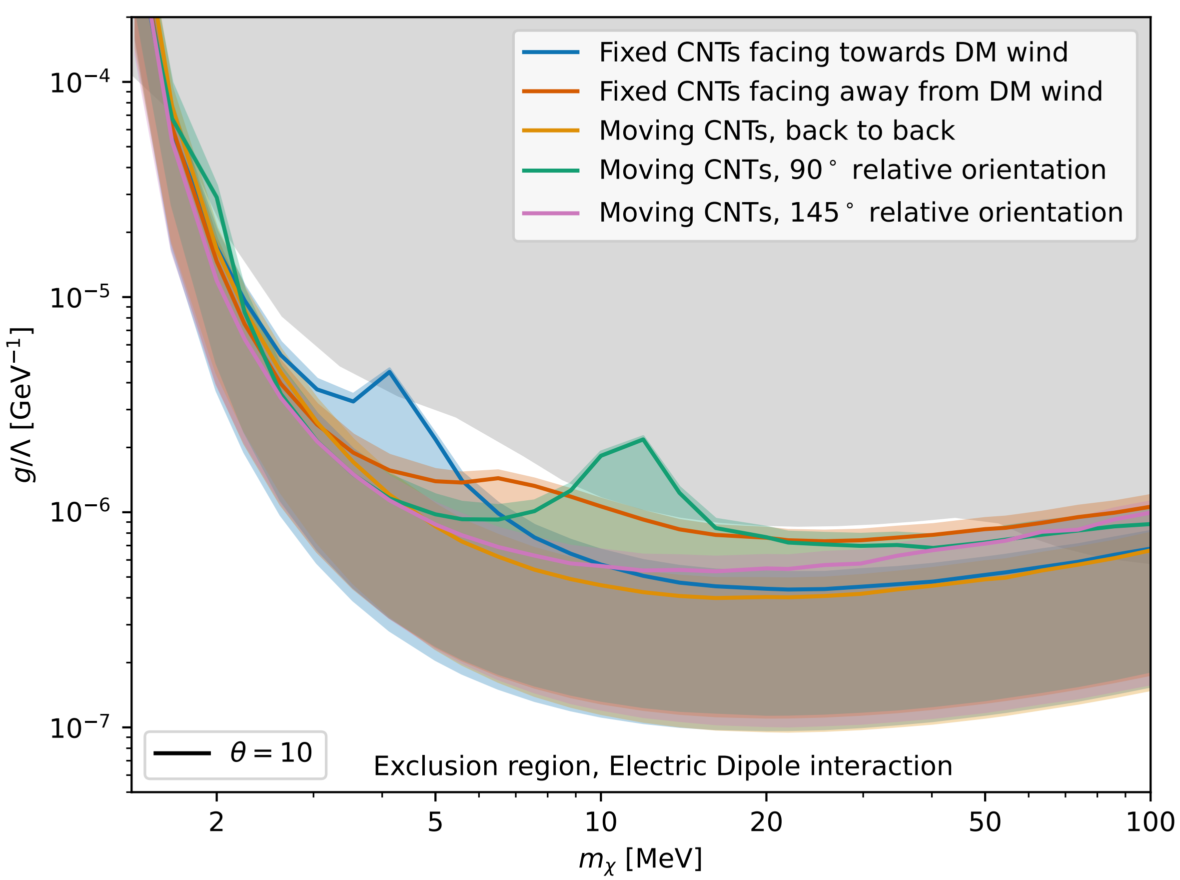
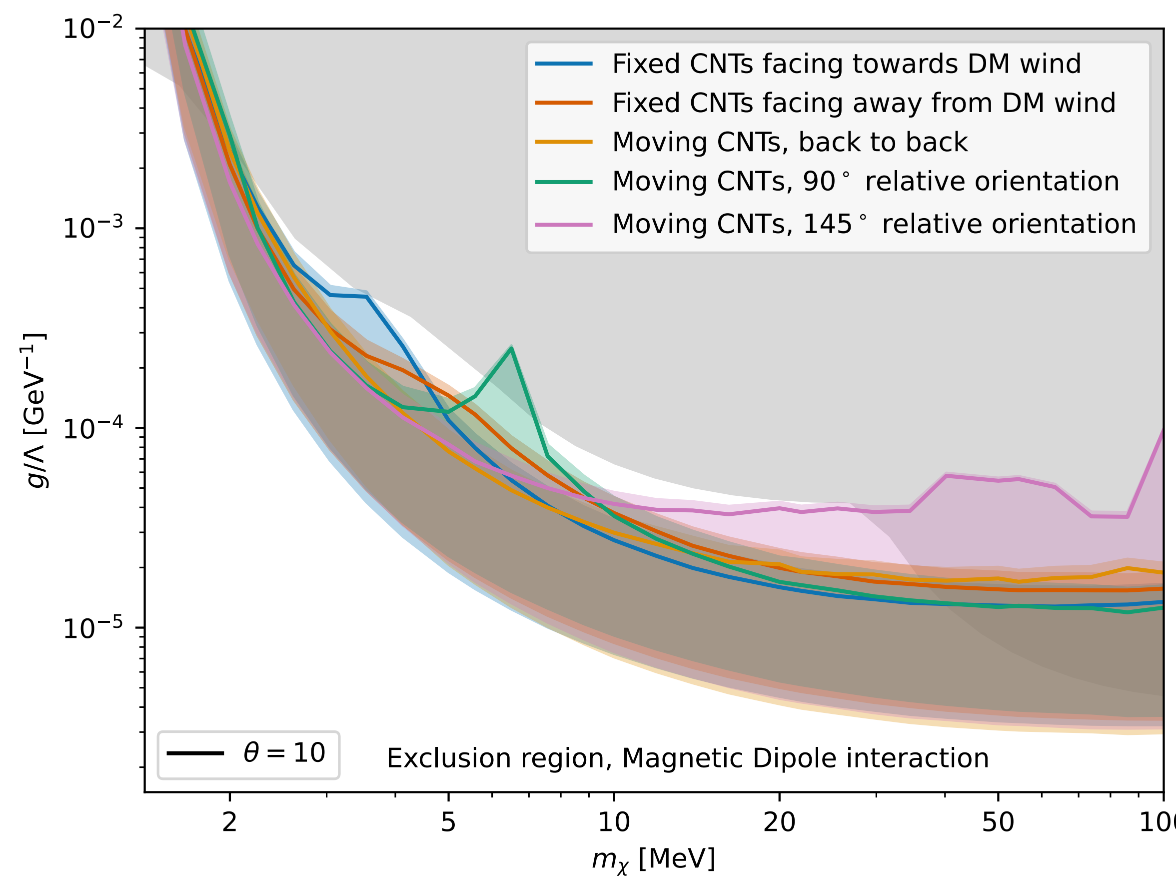
$\mathcal{O}_3 \propto \mathbf{q} \times \mathbf{v}$ 10 g year exposure $L_{\text{Anapole}} \in \frac{g}{2\Lambda^2}\bar{\chi}\gamma^\mu\gamma^5\chi\,\partial^\nu F_{\mu\nu}$

Exclusion Potential

Electric Dipole Interaction



Magnetic Dipole Interaction



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$L_{\text{Electric dipole}} \in \frac{g}{\Lambda} i\bar{\chi}\sigma^{\mu\nu}\gamma^5\chi F_{\mu\nu}$ 10 g year exposure $L_{\text{Magnetic dipole}} \in \frac{g}{\Lambda} \bar{\chi}\sigma^{\mu\nu}\chi F_{\mu\nu}$