In collaboration with Riccardo Catena, Timon Emken, Nicola Spaldin, Marek Matas

General Dark Matter Electron Interactions in Detector Materials

With a focus on Graphene and Carbon Nanotubes, Materials of Novel Experiments

Einar Urdshals
PhD student at Chalmers Technical University, Gothenburg, Sweden

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Outline

- Dark Matter (DM) distribution in our galaxy
- Directional detection of DM
- DM induced electron ejections in graphene and carbon nanotubes
- Potential for discovering smoking gun signals from DM in graphene and carbon nanotubes based detectors.

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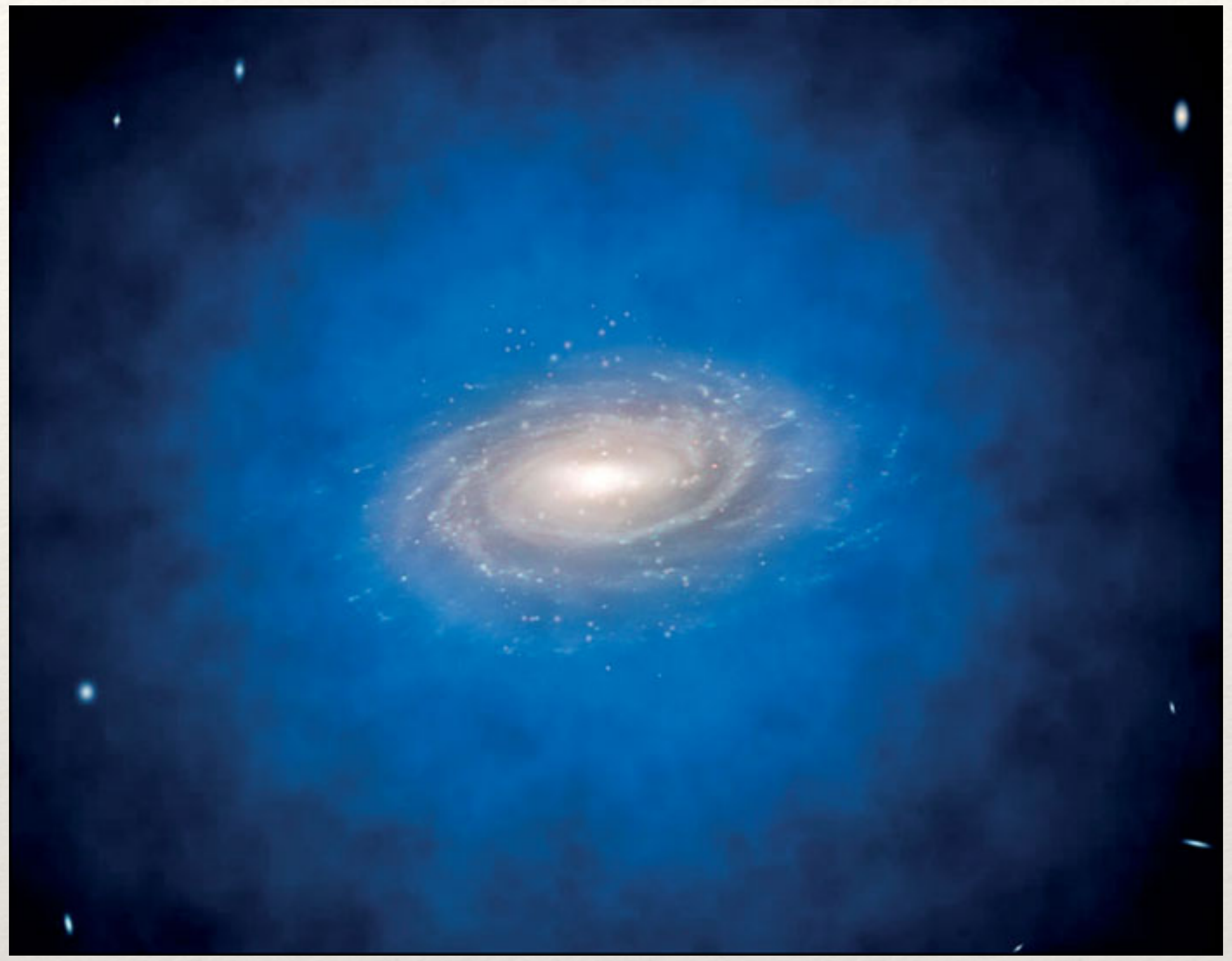
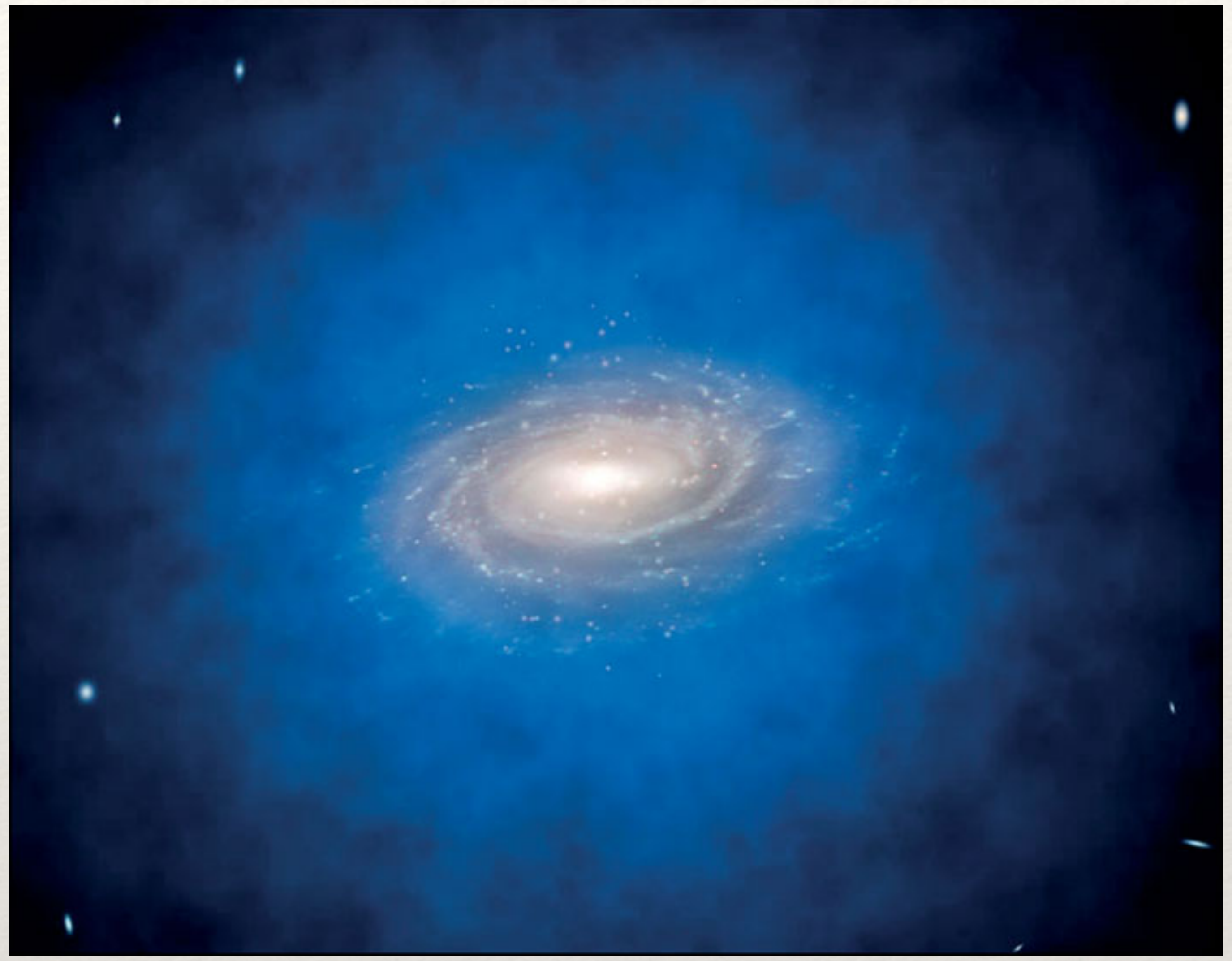
The Standard Halo Model



Credits: ESO/L Calçada

The Standard Halo Model

- DM density $\rho_\chi \approx 0.4\,\mathrm{GeV/cm^3}$



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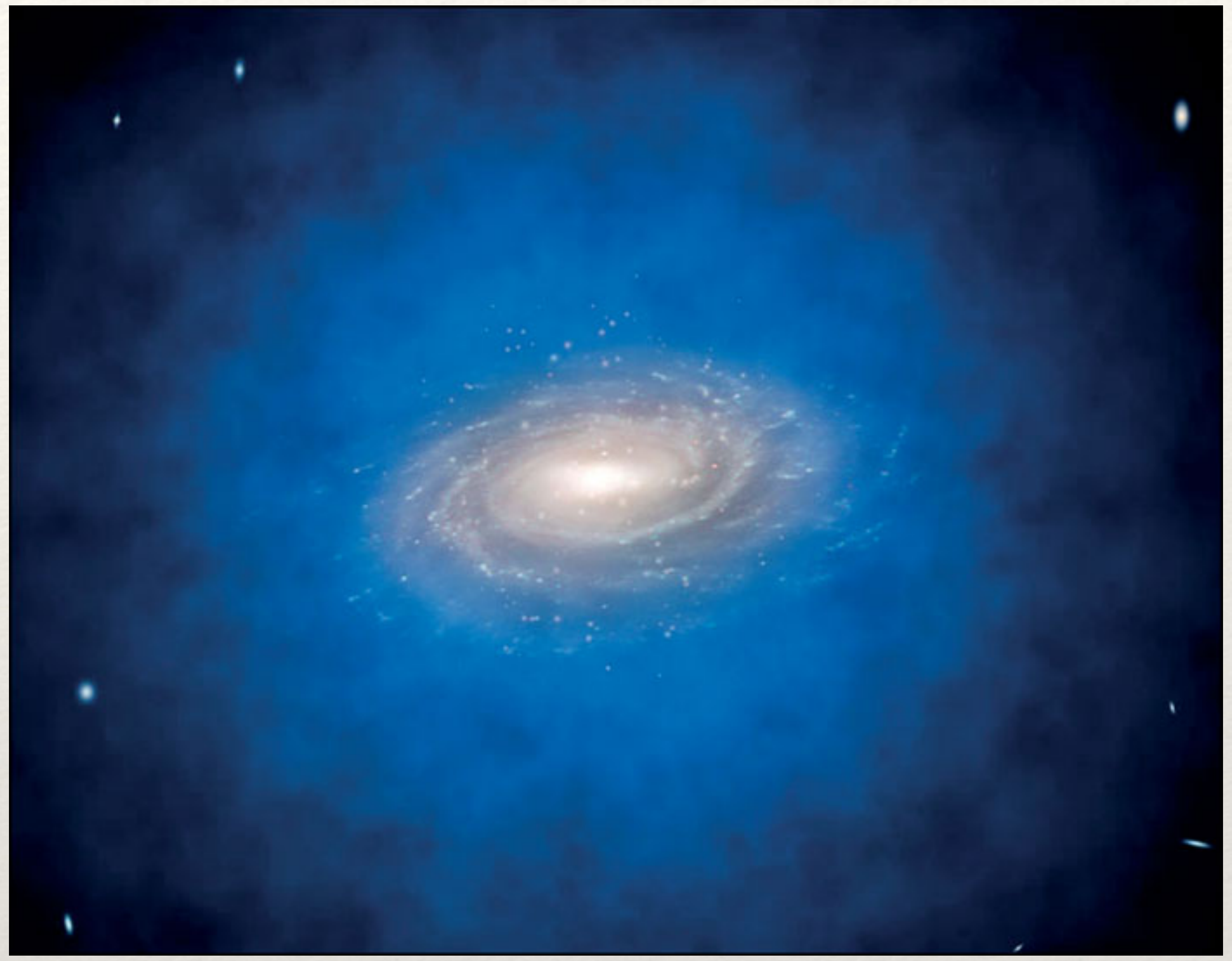
- DM density $\rho_\chi \approx 0.4\,\text{GeV/cm}^3$
- DM velocity is Boltzmann distributed, $\mathbf{v} \sim e^{\frac{-\mathbf{v}^2}{v_0^2}}$



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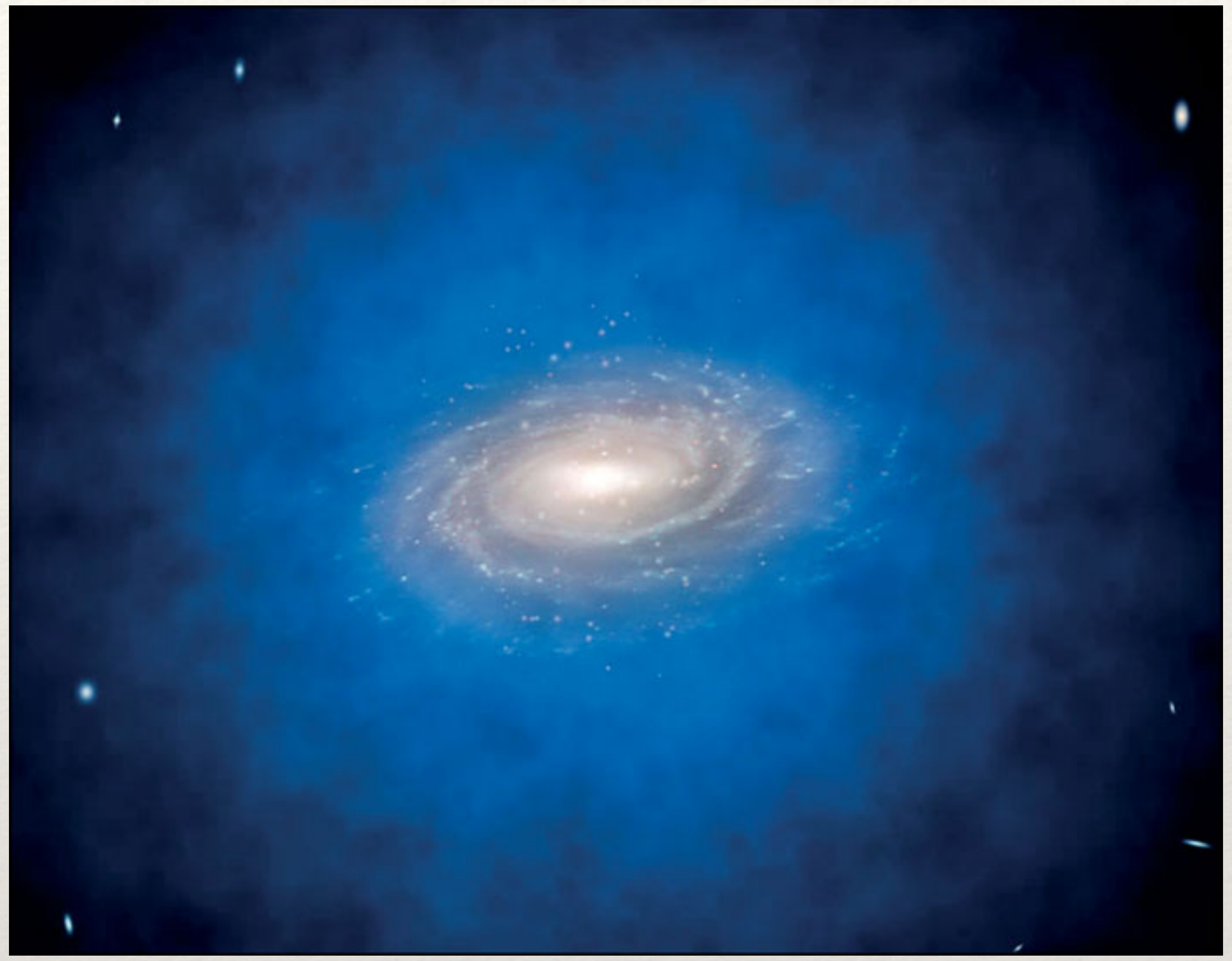
- Motion of Sun shifts the velocity by $\mathbf{v}_e$, $\mathbf{v} \sim e^{\frac{-(\mathbf{v}+\mathbf{v}_e)^2}{v_0^2}}$



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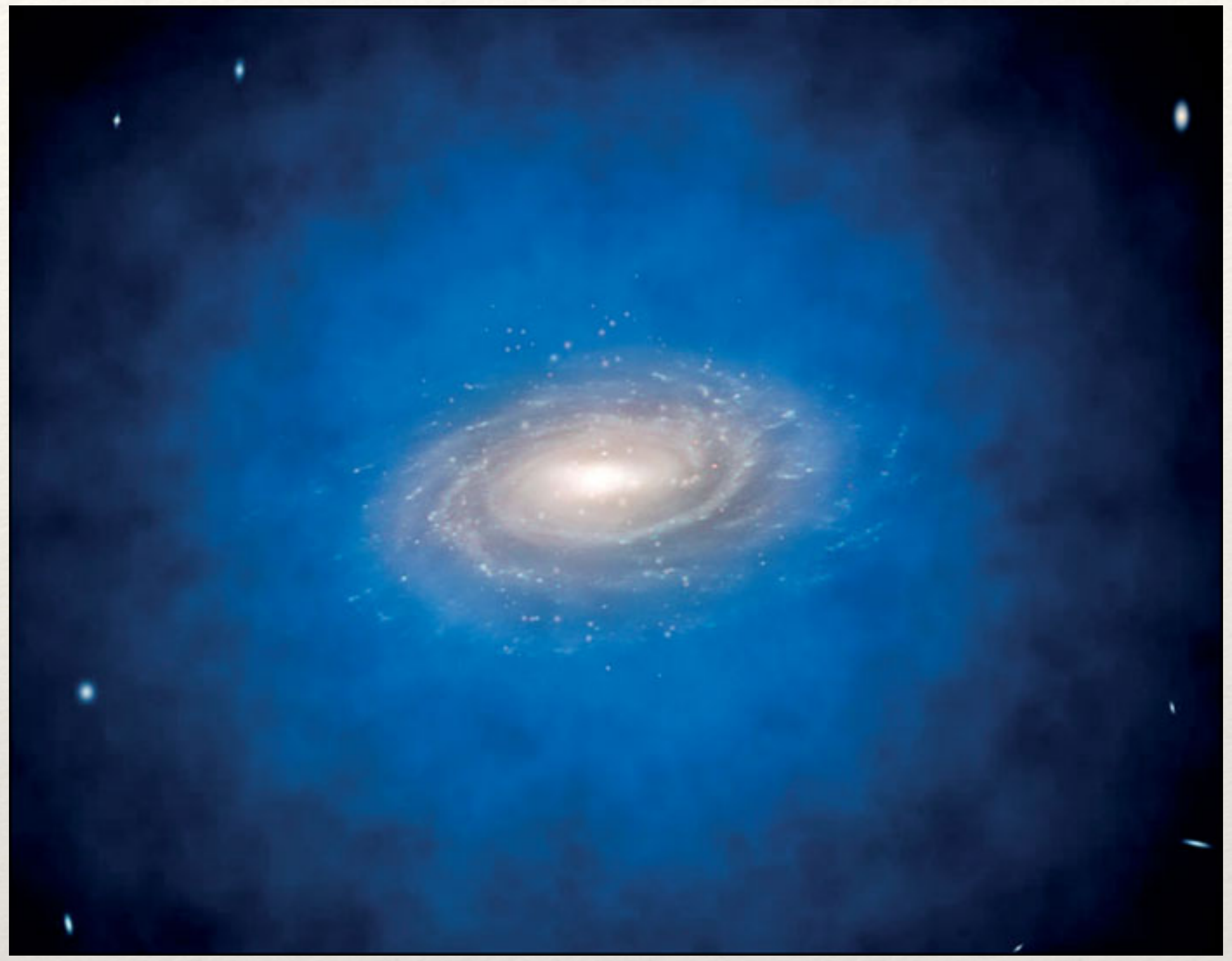
- $v_0 \approx 238\,\mathrm{km/s}$ and $v_e \approx 250\,\mathrm{km/s}$, so $v \ll c$



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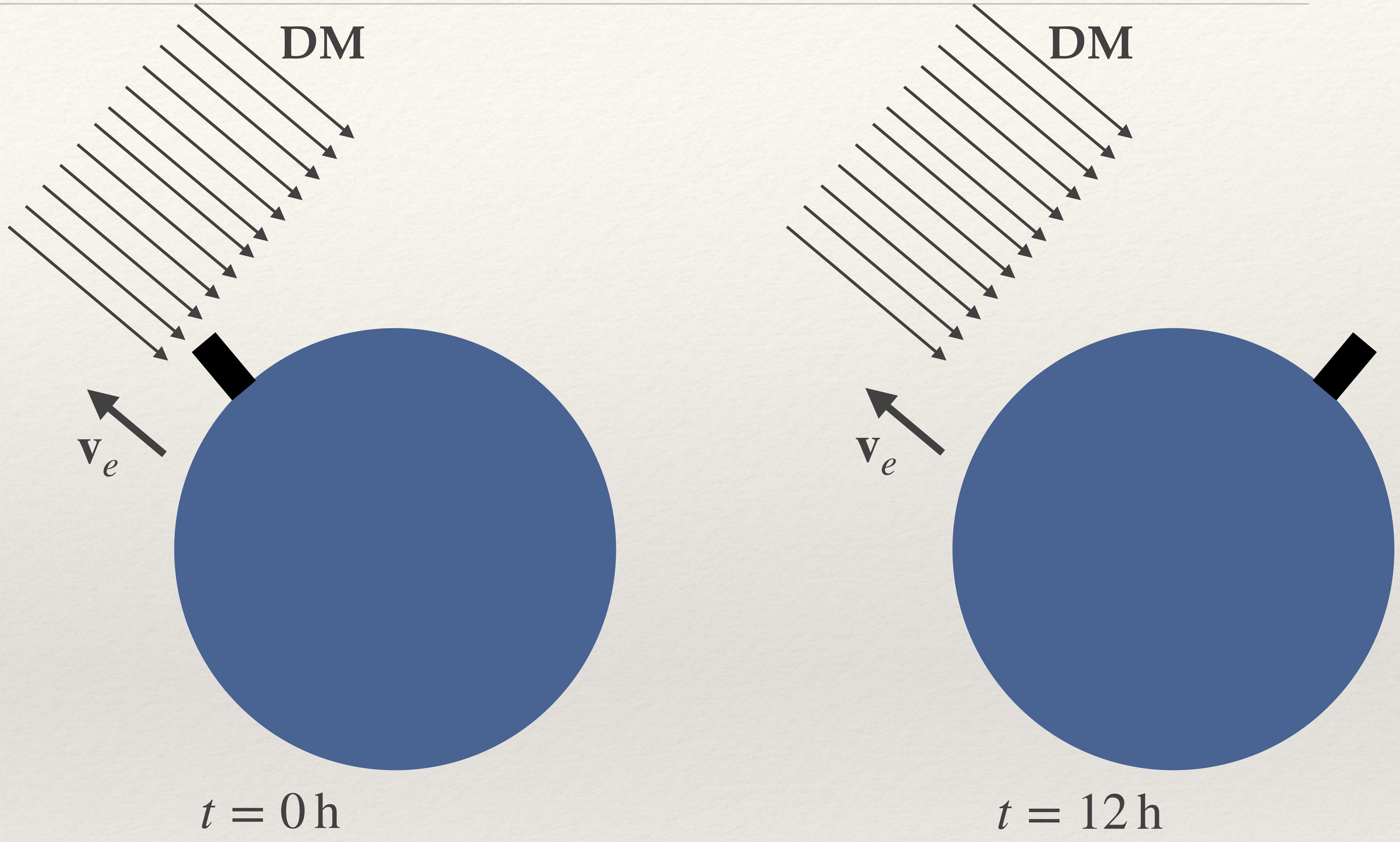
Directional Detection of DM



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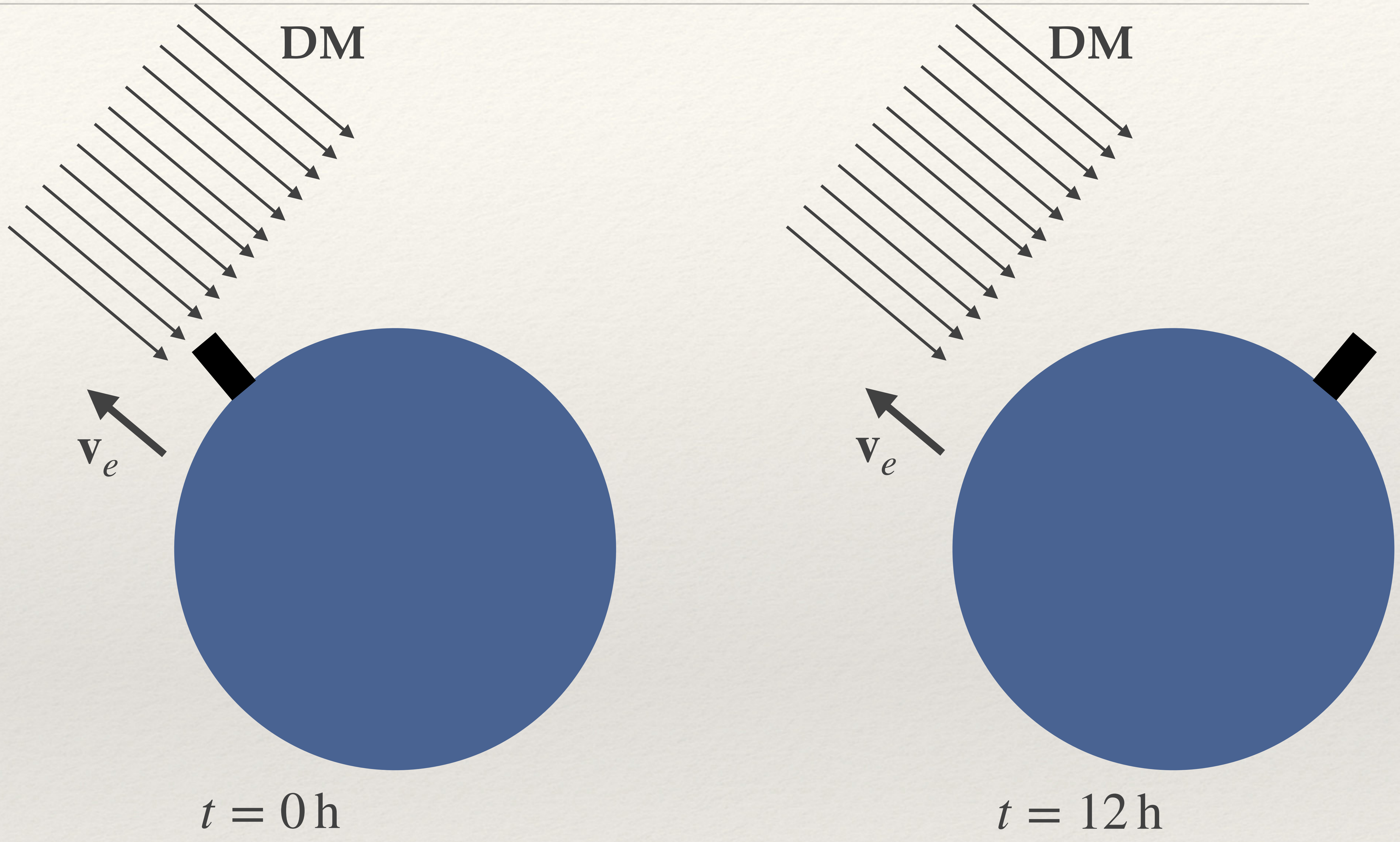
Directional Detection of DM

- Direction of DM wind changes throughout the day



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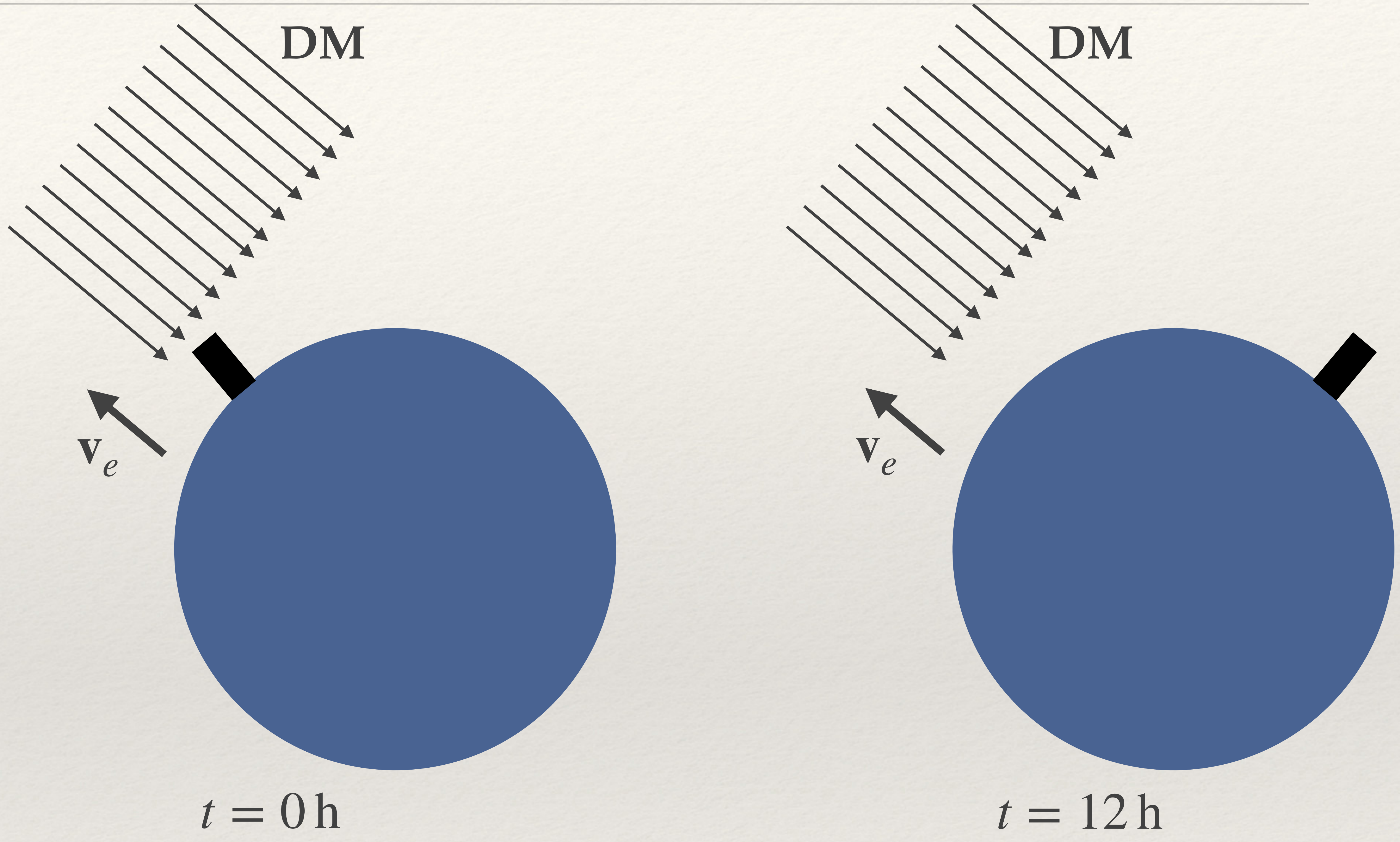
Directional Detection of DM

- Direction of DM wind changes throughout the day
- Experiments sensitive to directionality can discriminate signal from background



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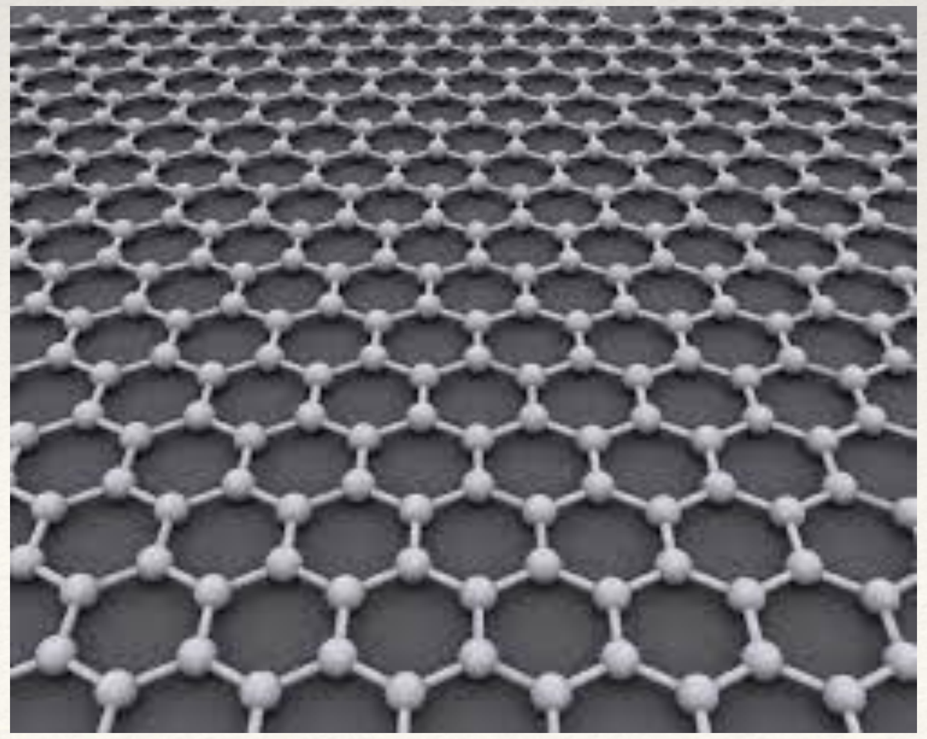
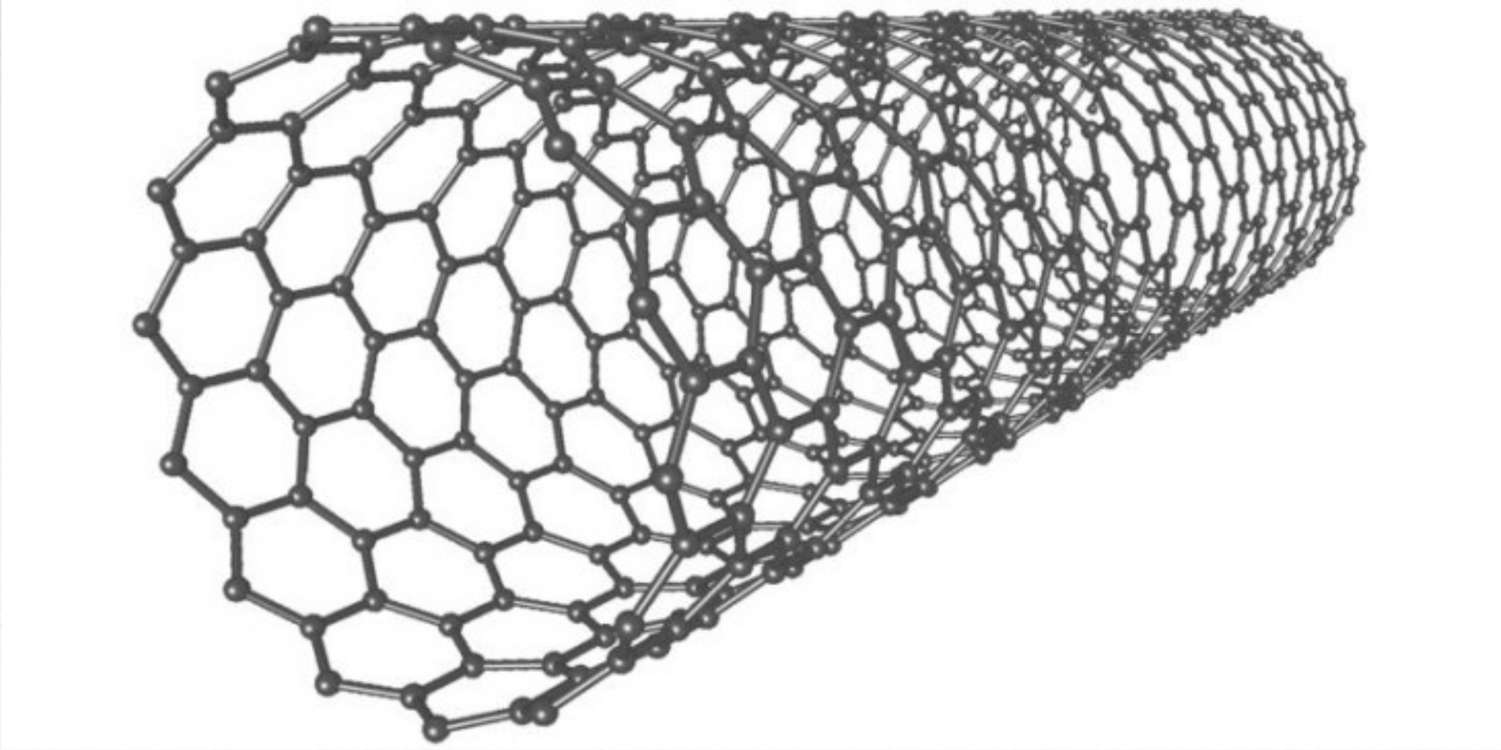
DM induced electron ejections from graphene and nanotubes





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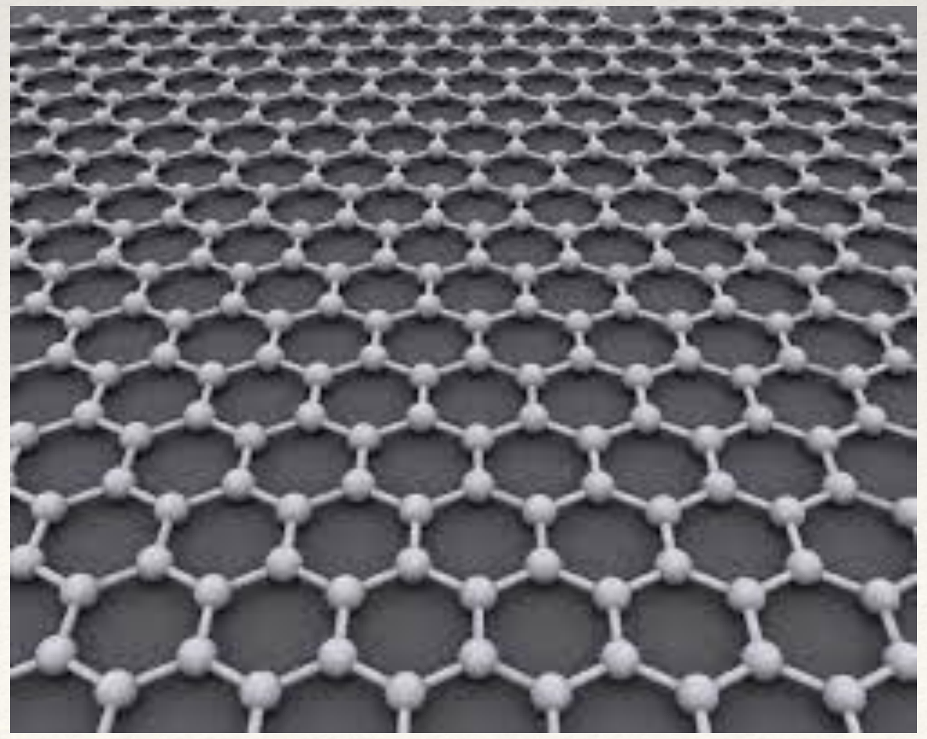
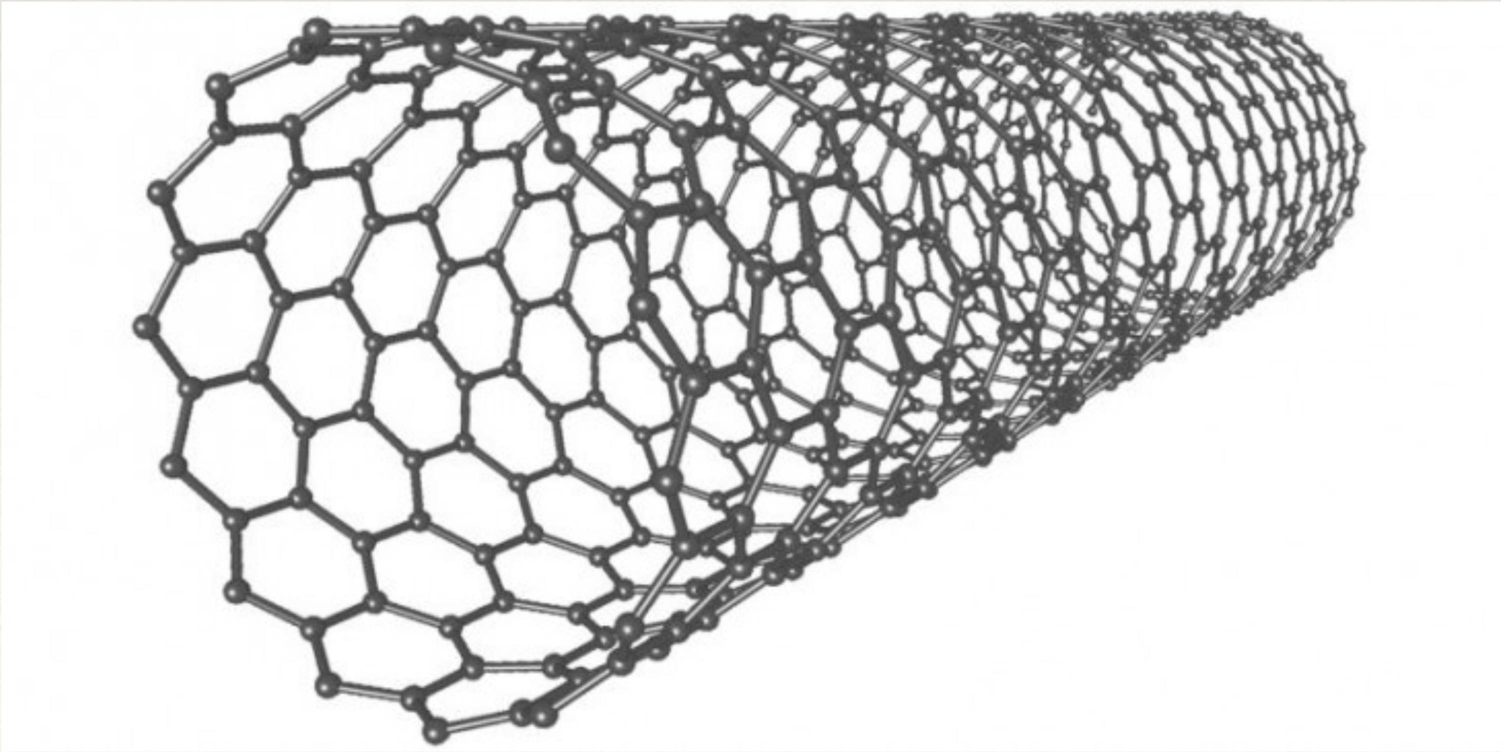
DM induced electron ejections from graphene and nanotubes

- The materials have asymmetric electron momentum distributions





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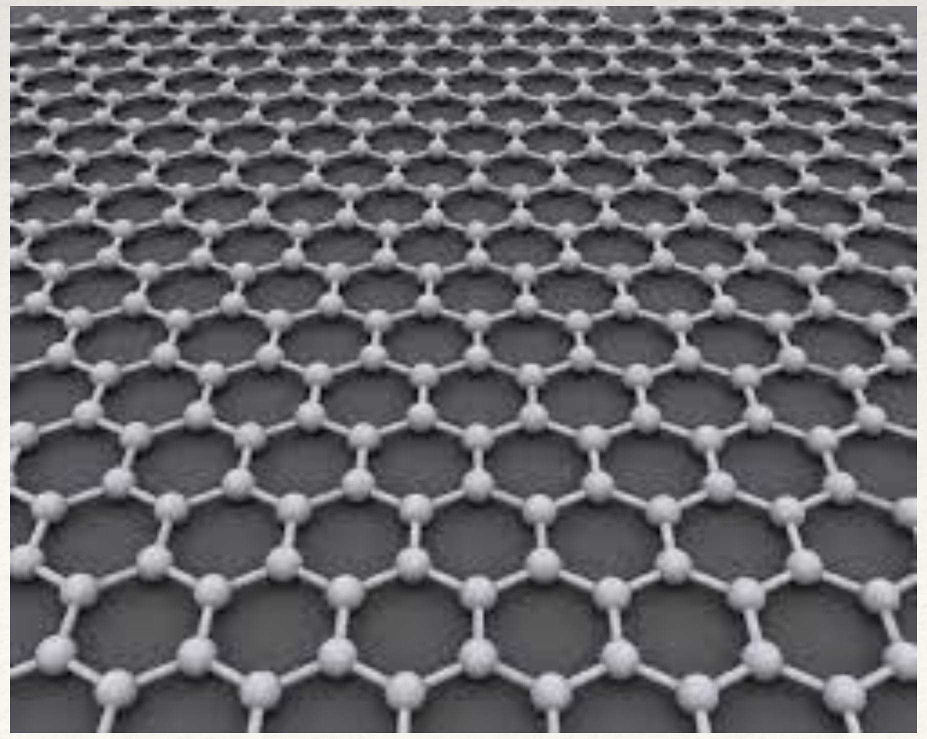
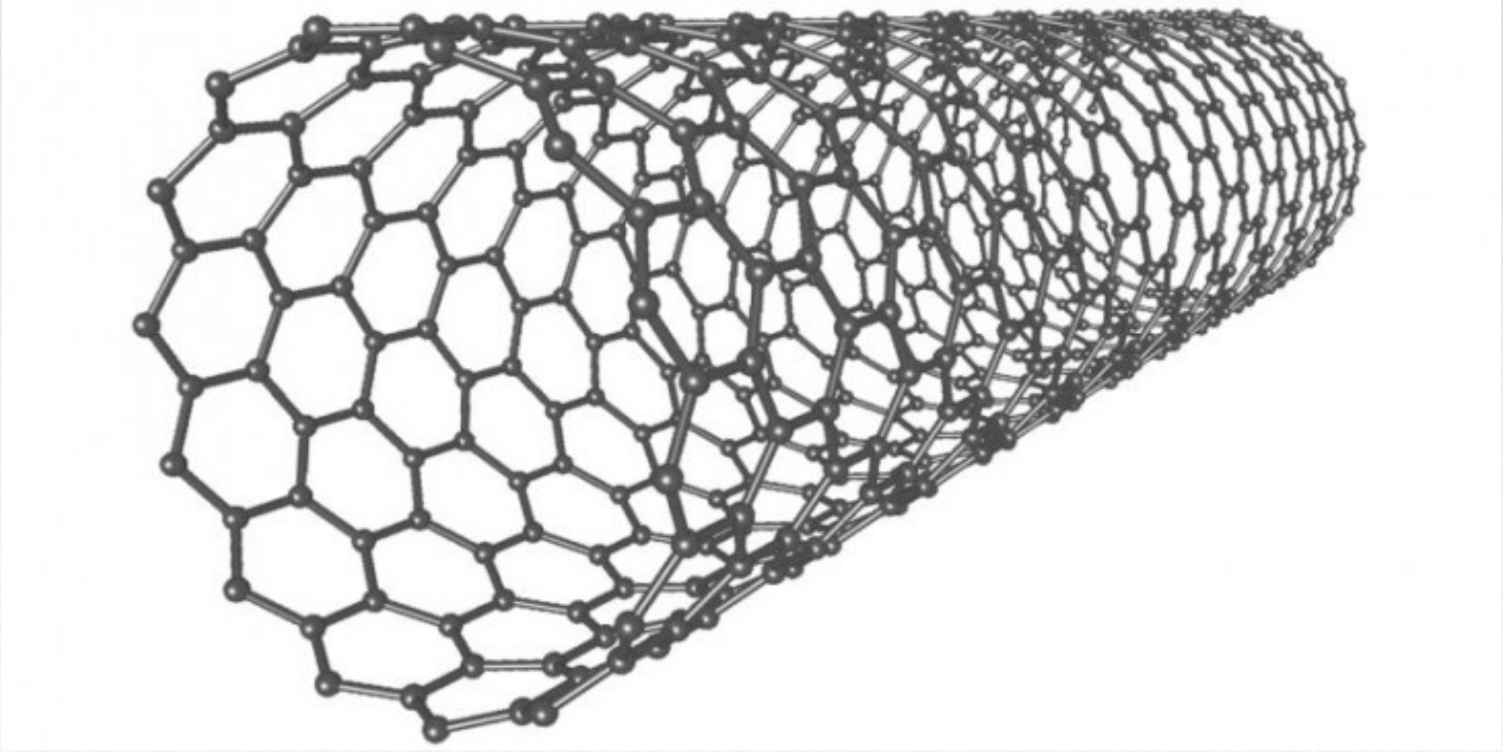
DM induced electron ejections from graphene and nanotubes

- The materials have asymmetric electron momentum distributions
- Electron scatterings are sensitive to DM masses down to a couple MeV





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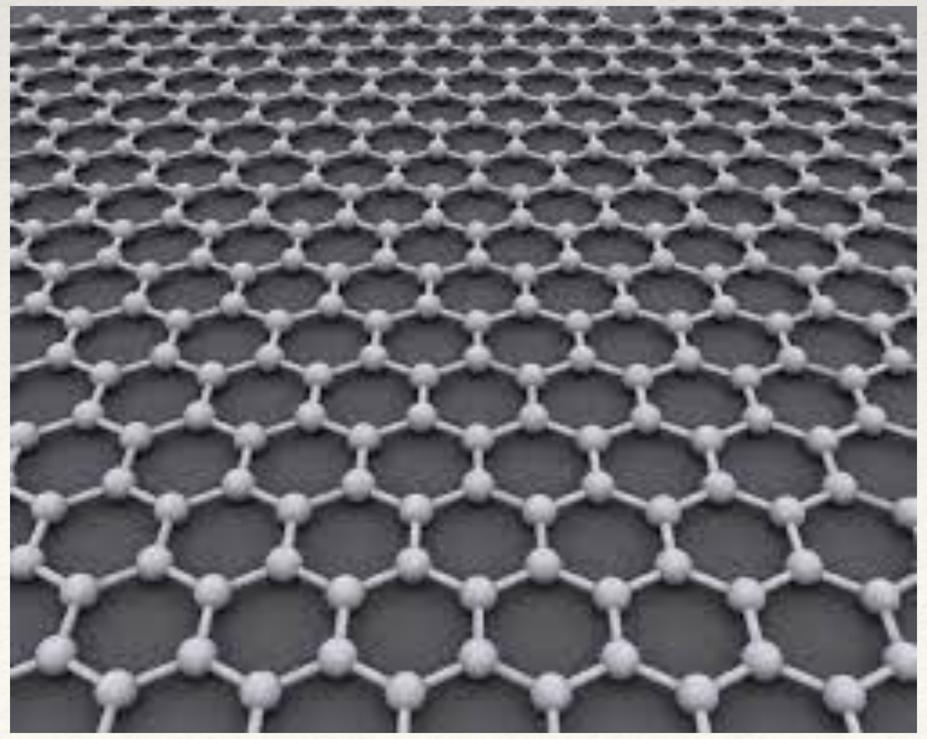
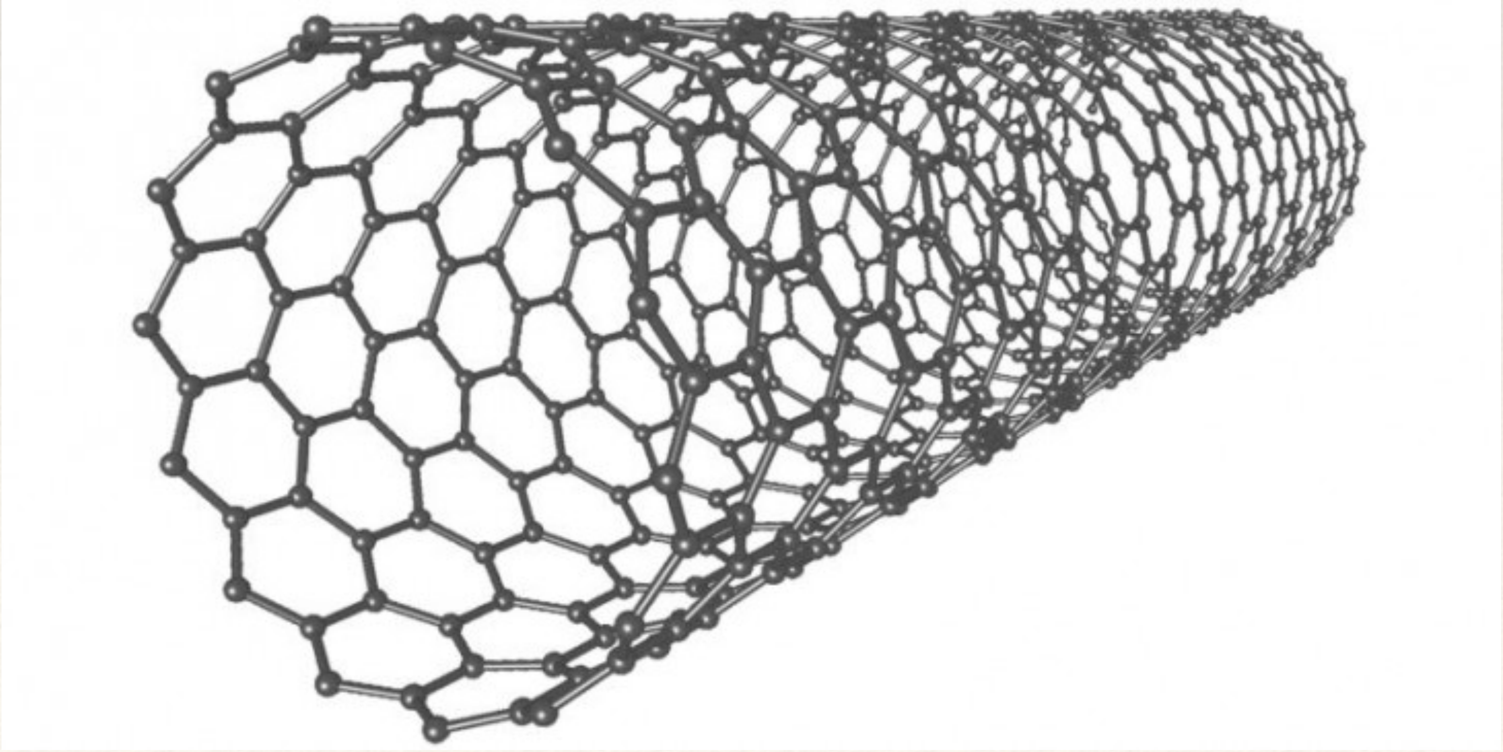
DM induced electron ejections from graphene and nanotubes

- The materials have asymmetric electron momentum distributions
- Electron scatterings are sensitive to DM masses down to a couple MeV
- Using NR-EFT to model arbitrary DM electron interactions, we find

$$\left|\mathscr{M}_{1\to 2}\right|^2 = \underbrace{R_{\text{free}}(\mathbf{k}', \mathbf{q}, \mathbf{v})}_{\text{DM particle physics}} \times \frac{1}{V} \underbrace{\left|\widetilde{\psi}_1(\mathbf{k}' - \mathbf{q})\right|^2}_{\text{target properties}}$$





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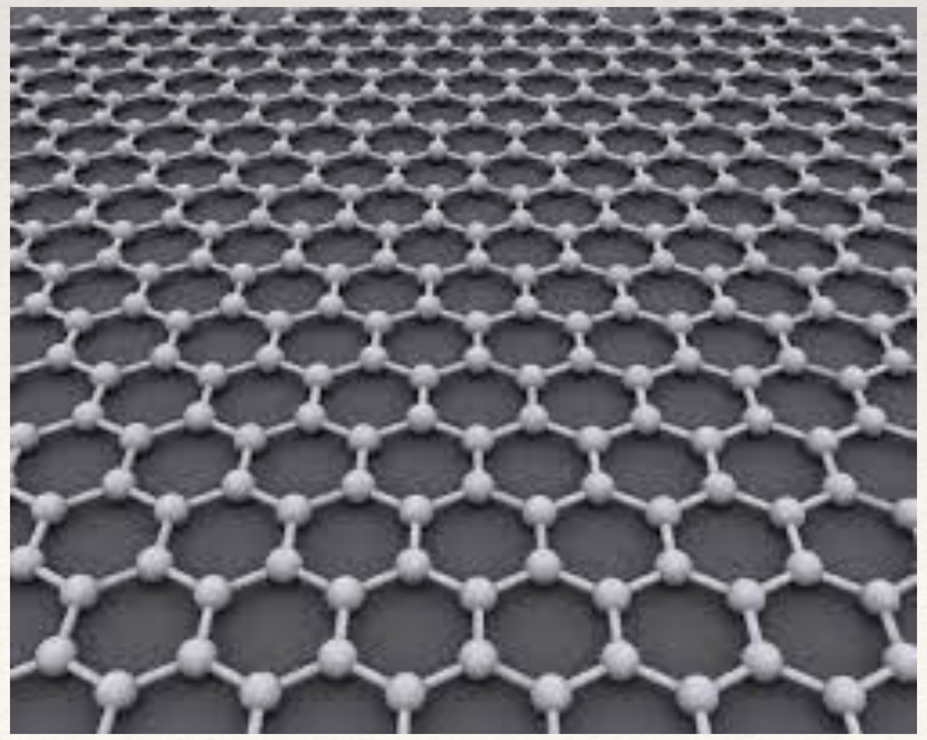

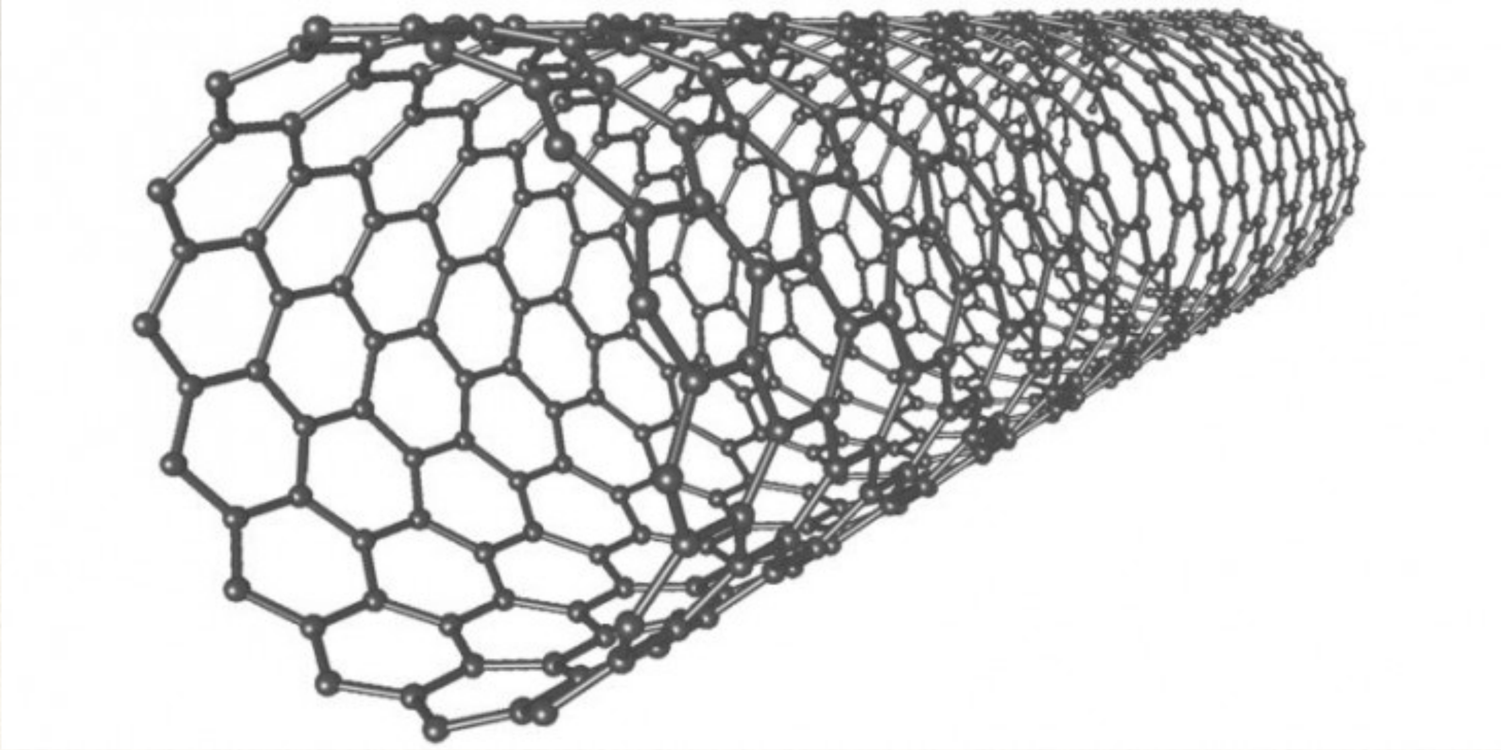

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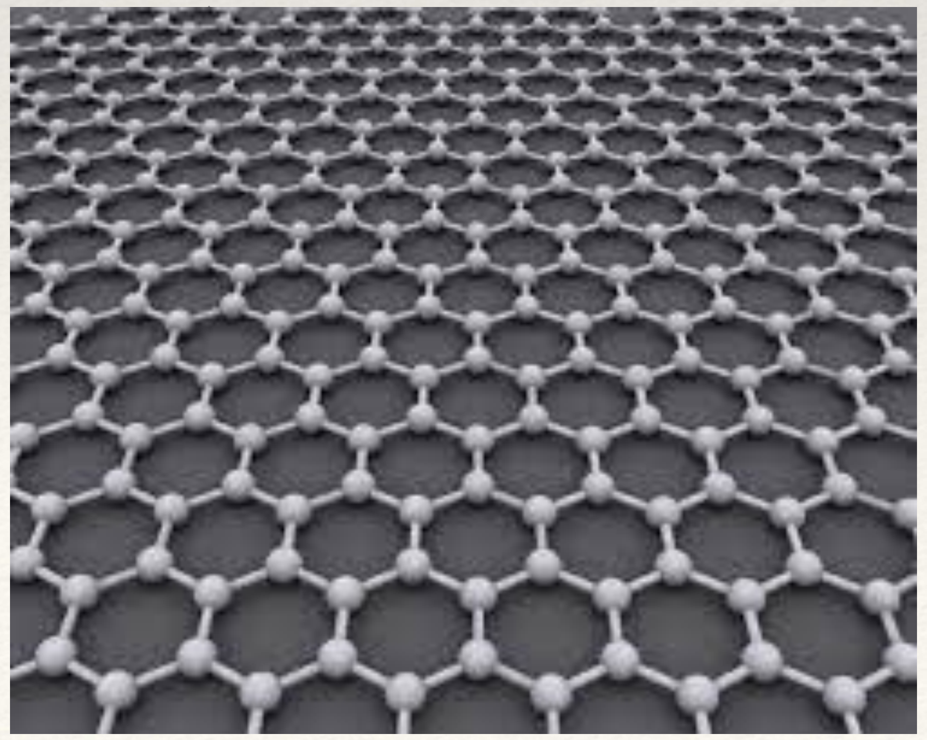
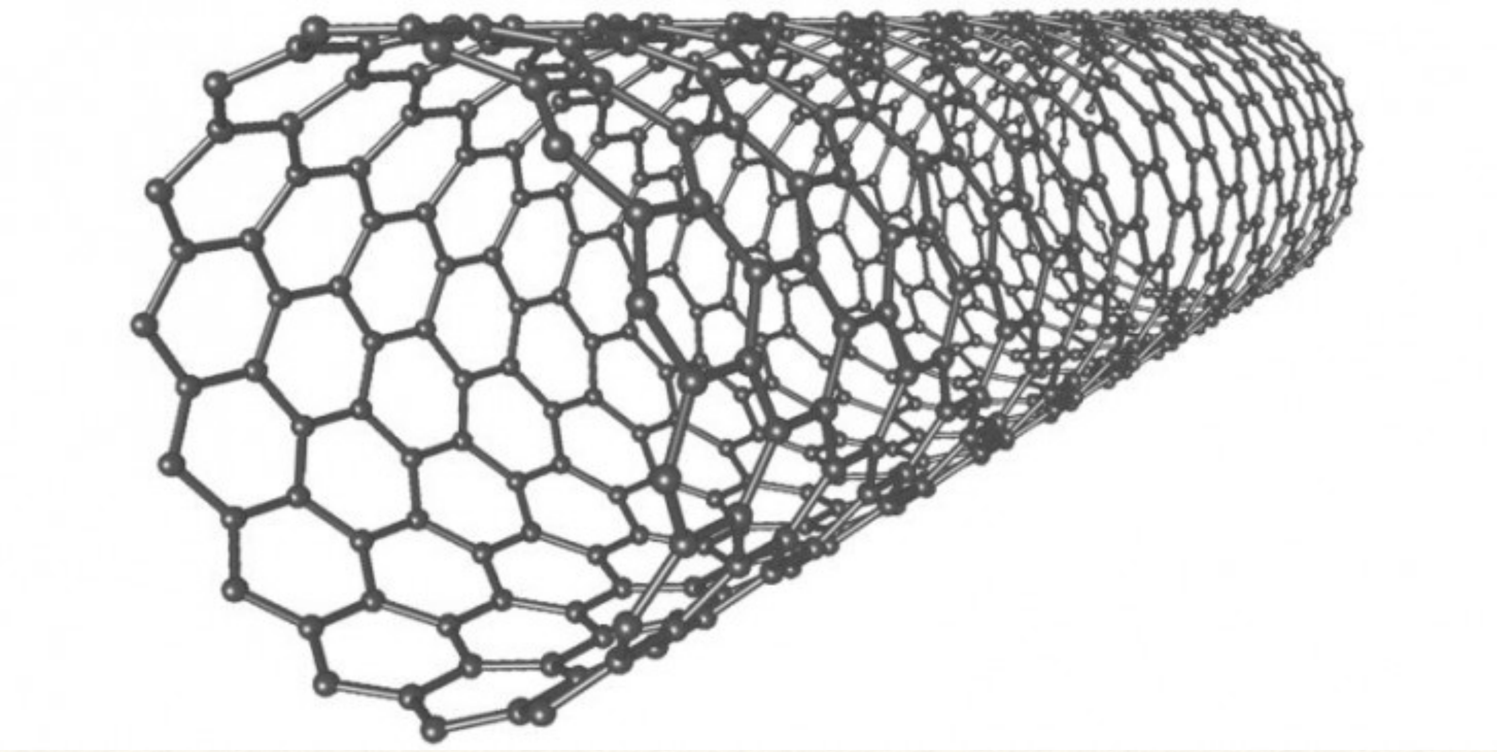
Catena, Emken, Matas, Spaldin, **EU**: Work in progress





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

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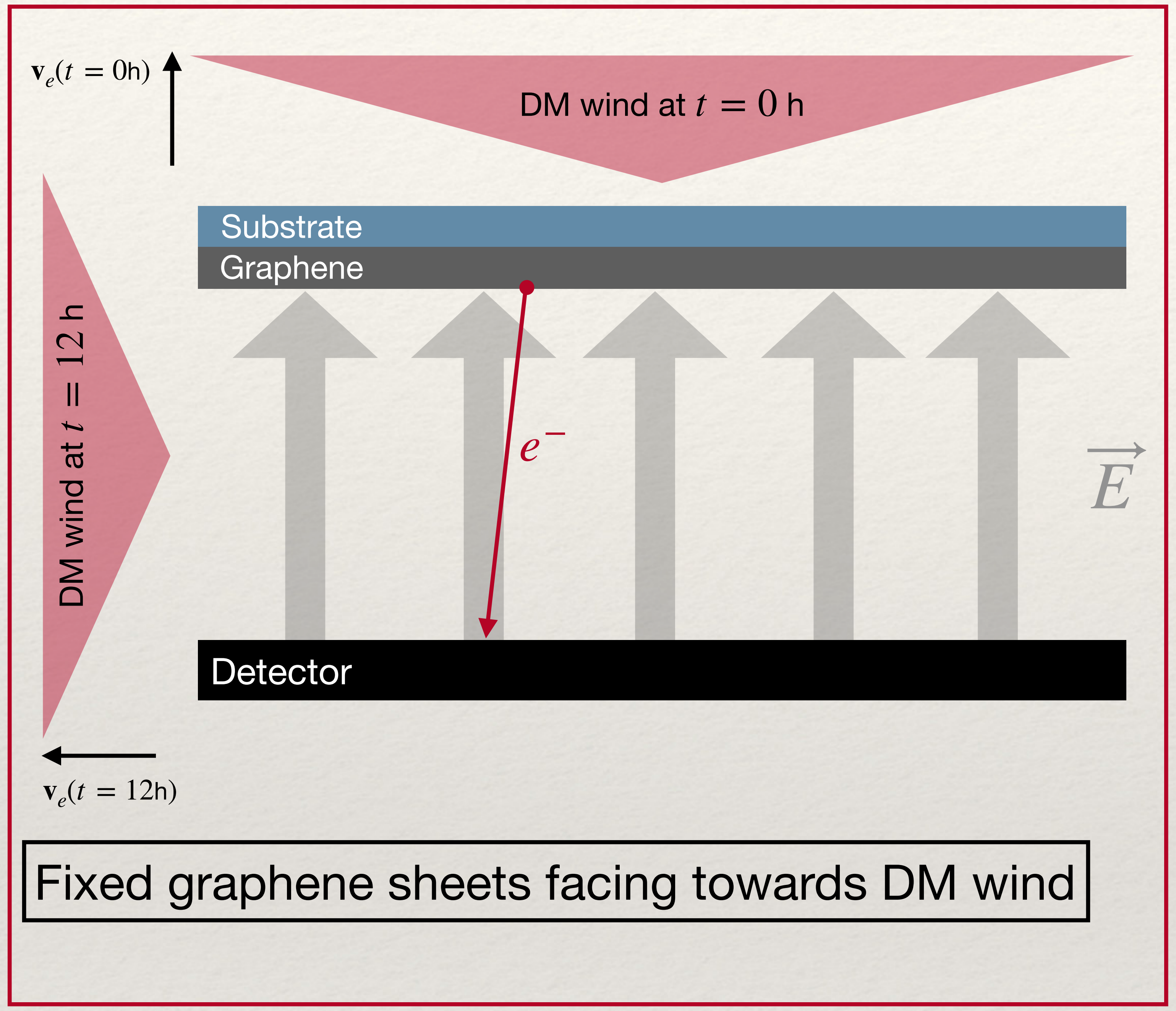
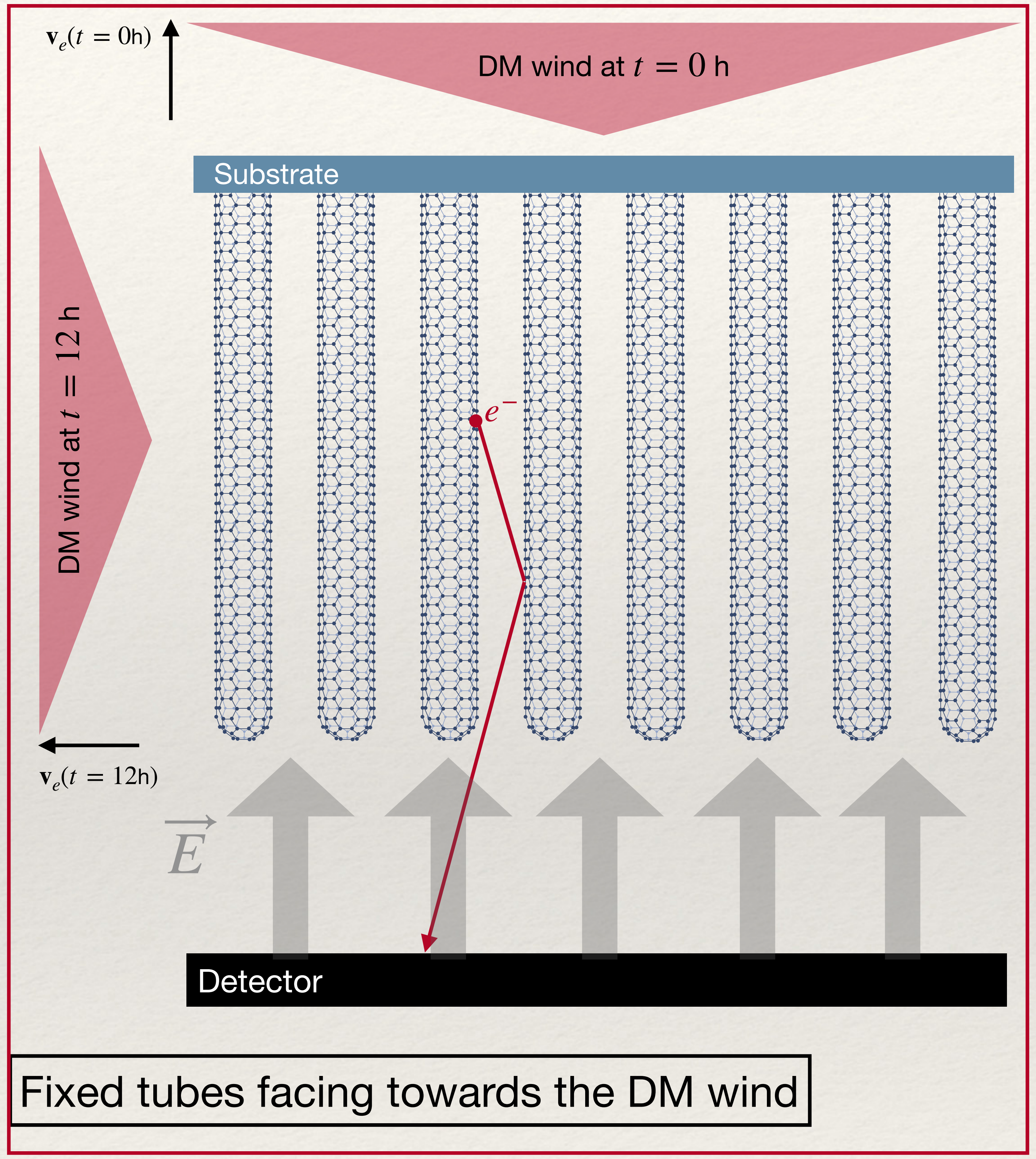
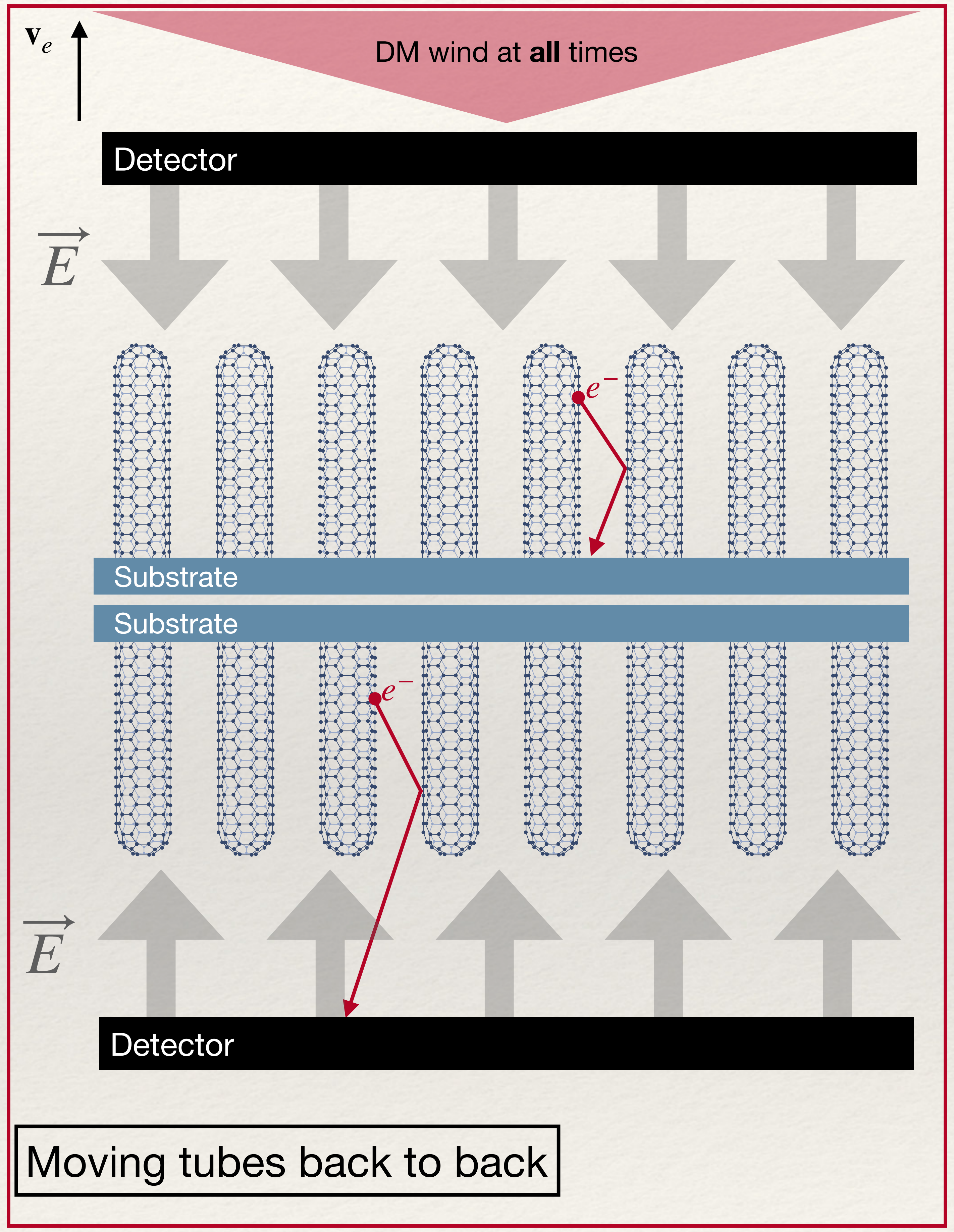
Experimental setups







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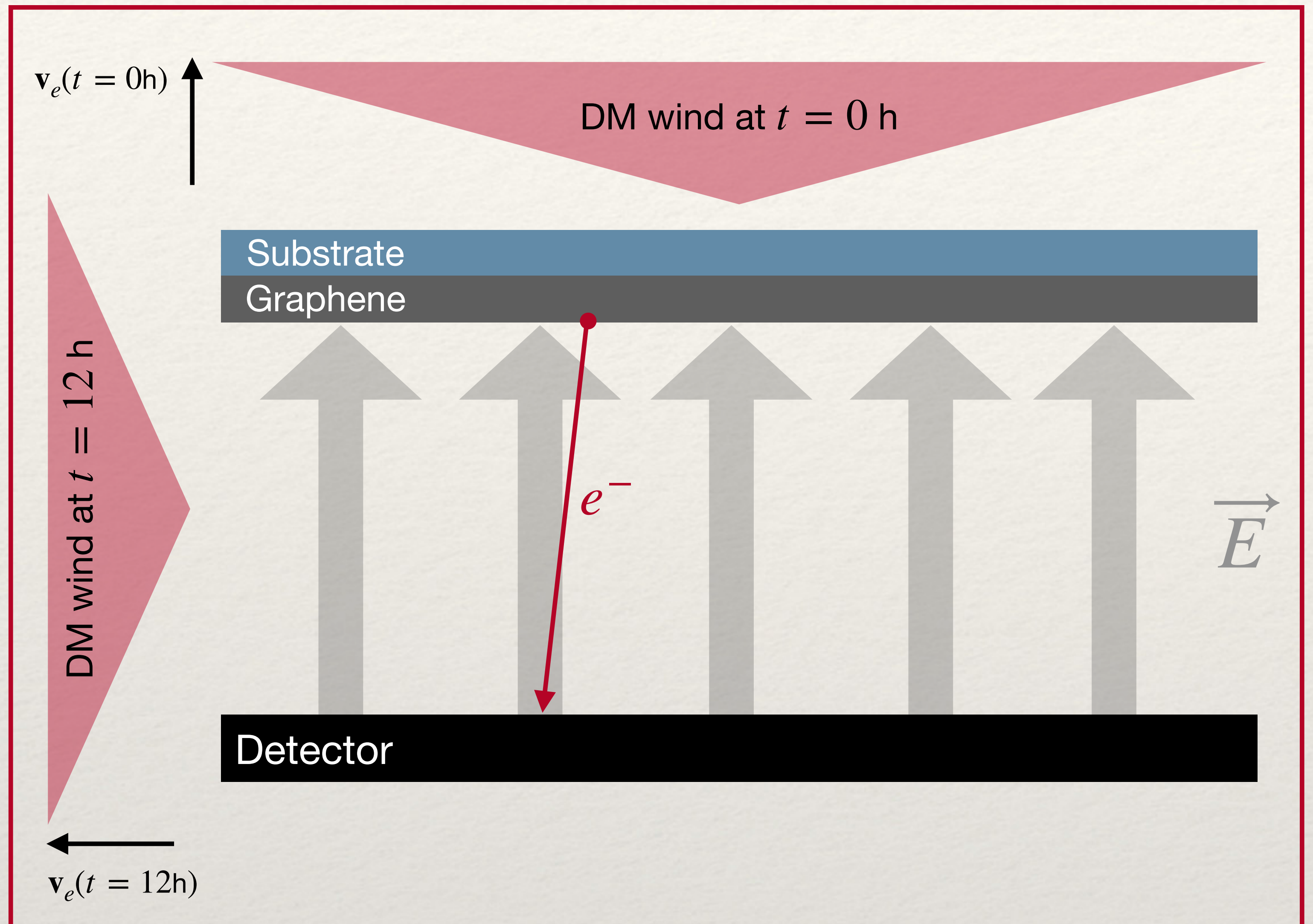
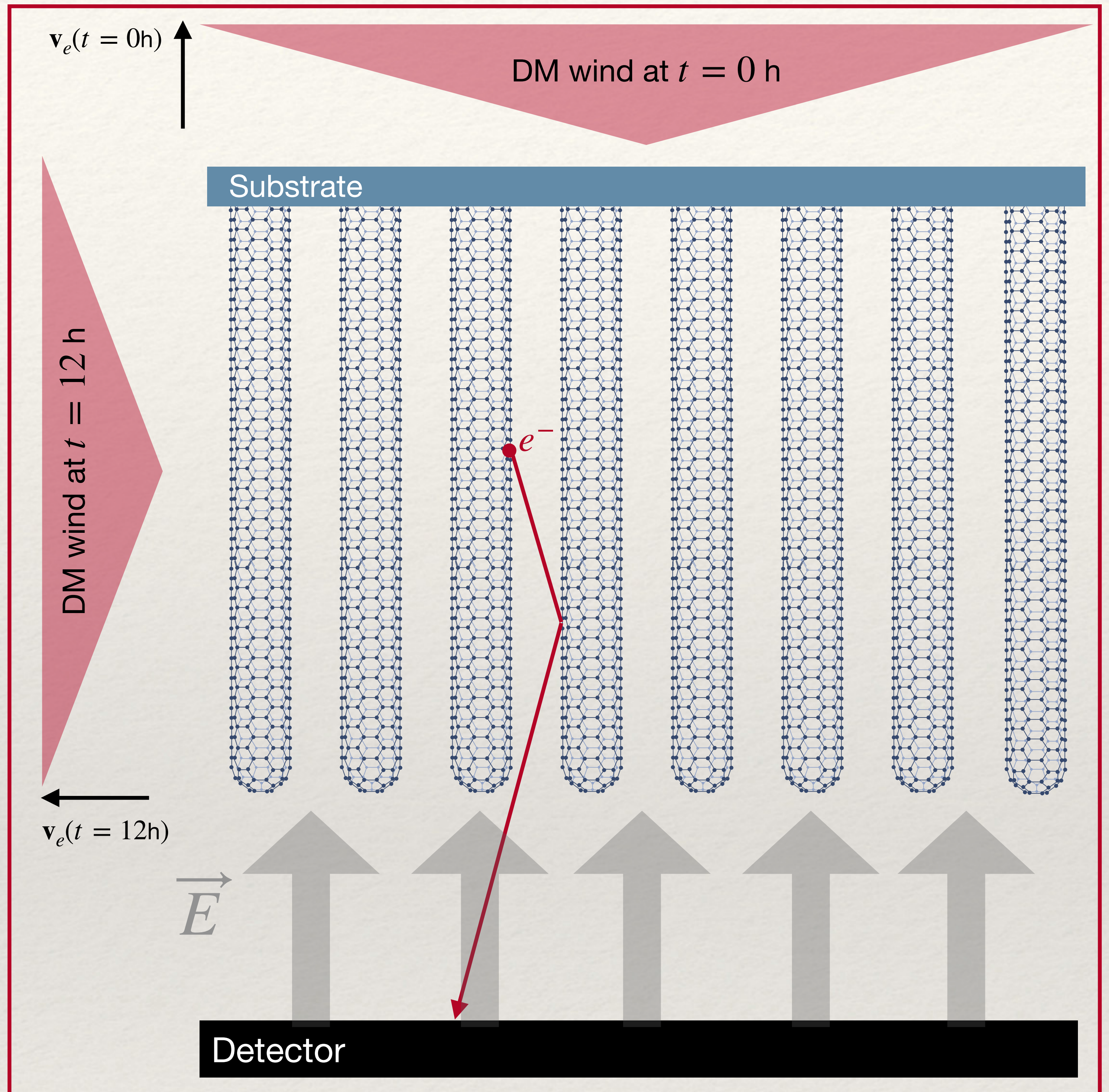
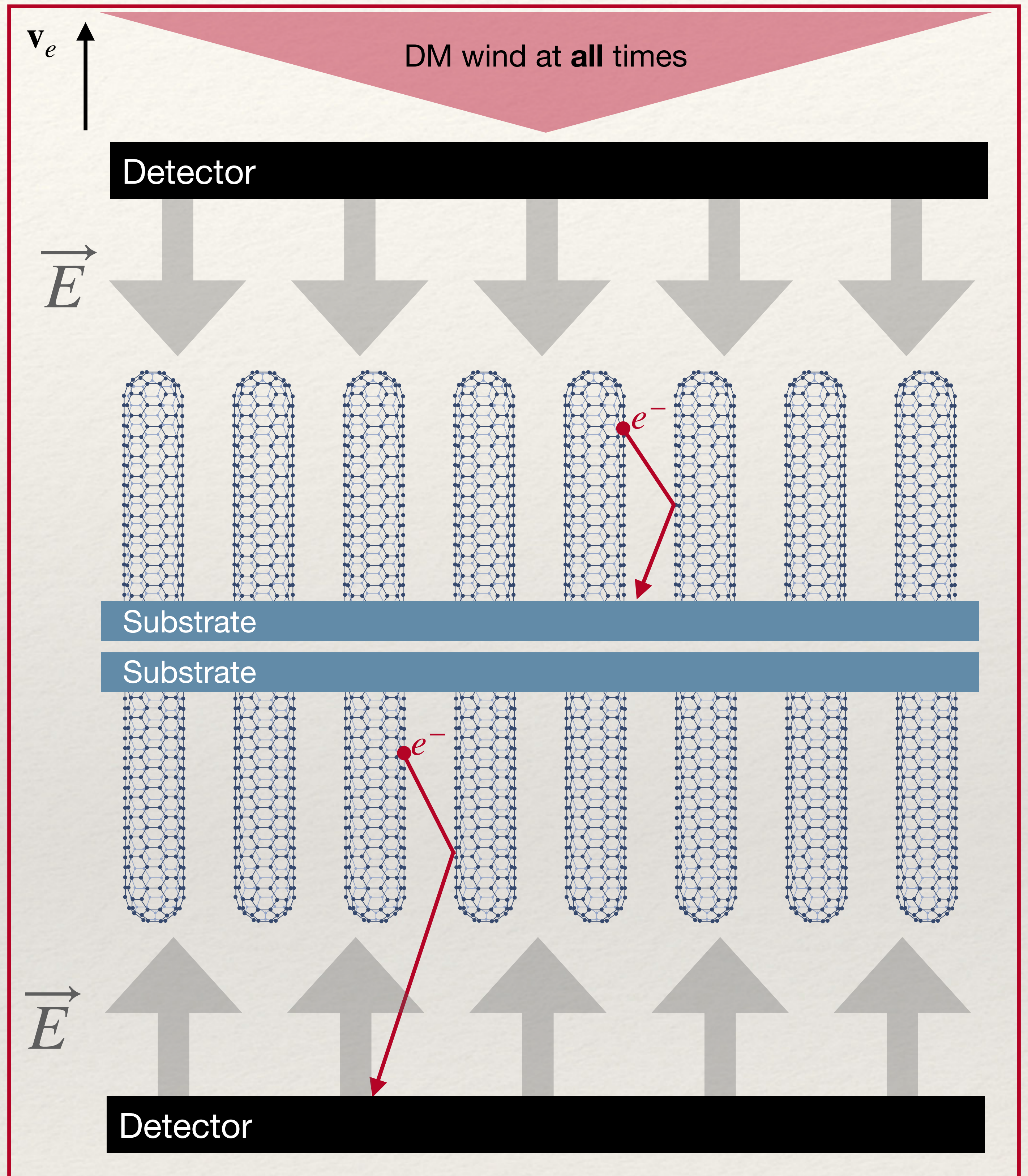


Fixed graphene sheets facing towards DM wind



Fixed tubes facing towards the DM wind



Moving tubes back to back

Setup considered by ANDROMEDA

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Expected Sensitivity at 90% Confidence level

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- Moving setups: N_{max} (N_{min}) is the number of events recorded in the twin detector expected to see the most (fewest) number of events.

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- $\chi^2 = \dfrac{\left(N_{\mathrm{max}} - N_{\mathrm{min}}\right)^2}{N_{\mathrm{max}} + N_{\mathrm{min}} + N_{\mathrm{b}}} > 2.71$ means we expect to be at least 90 % sure that N_{max} and N_{min} are not drawn from the same distribution.

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[Geilhufe, Kahlhoefer, Winkler: 1910.02091]

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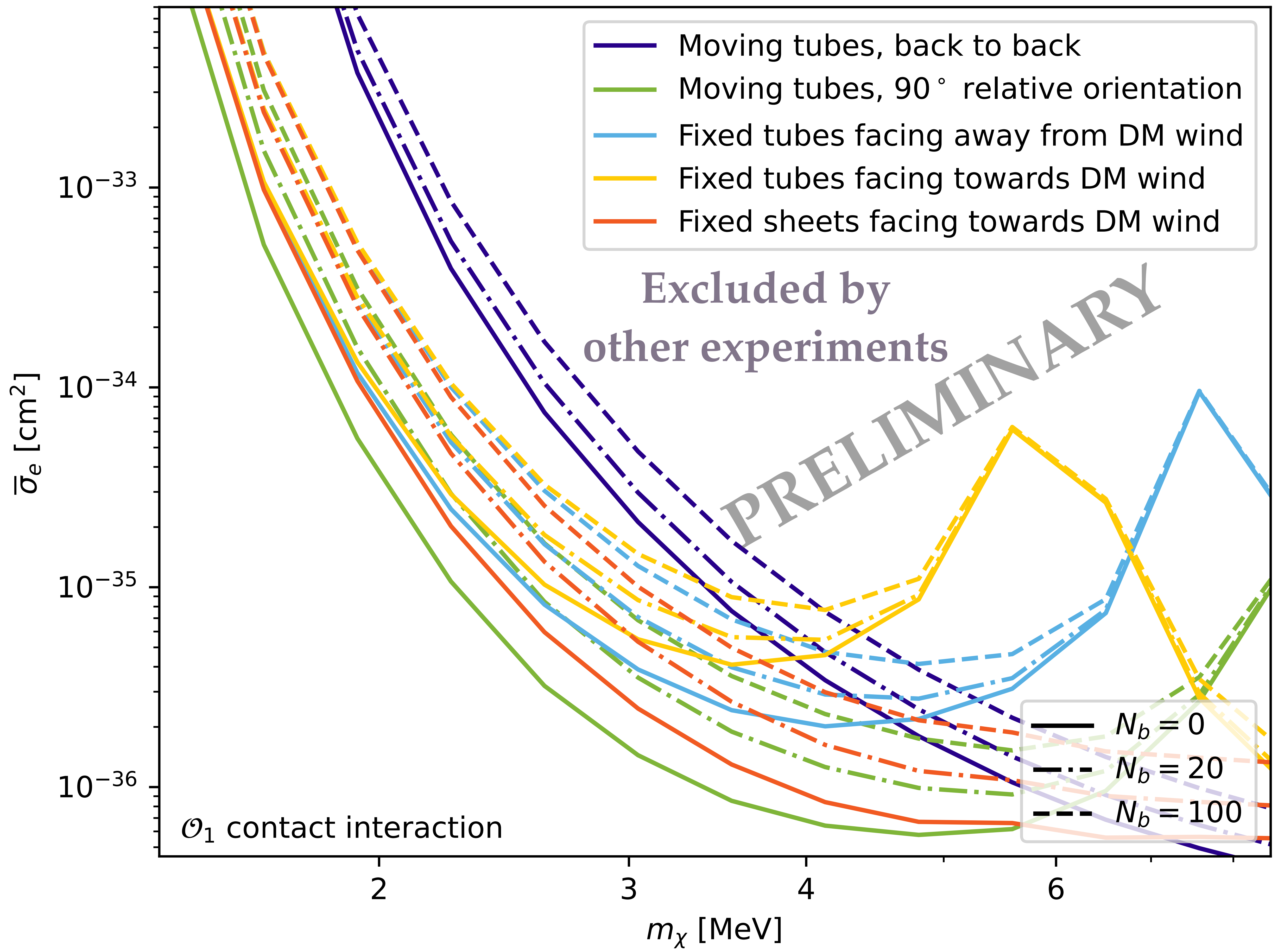
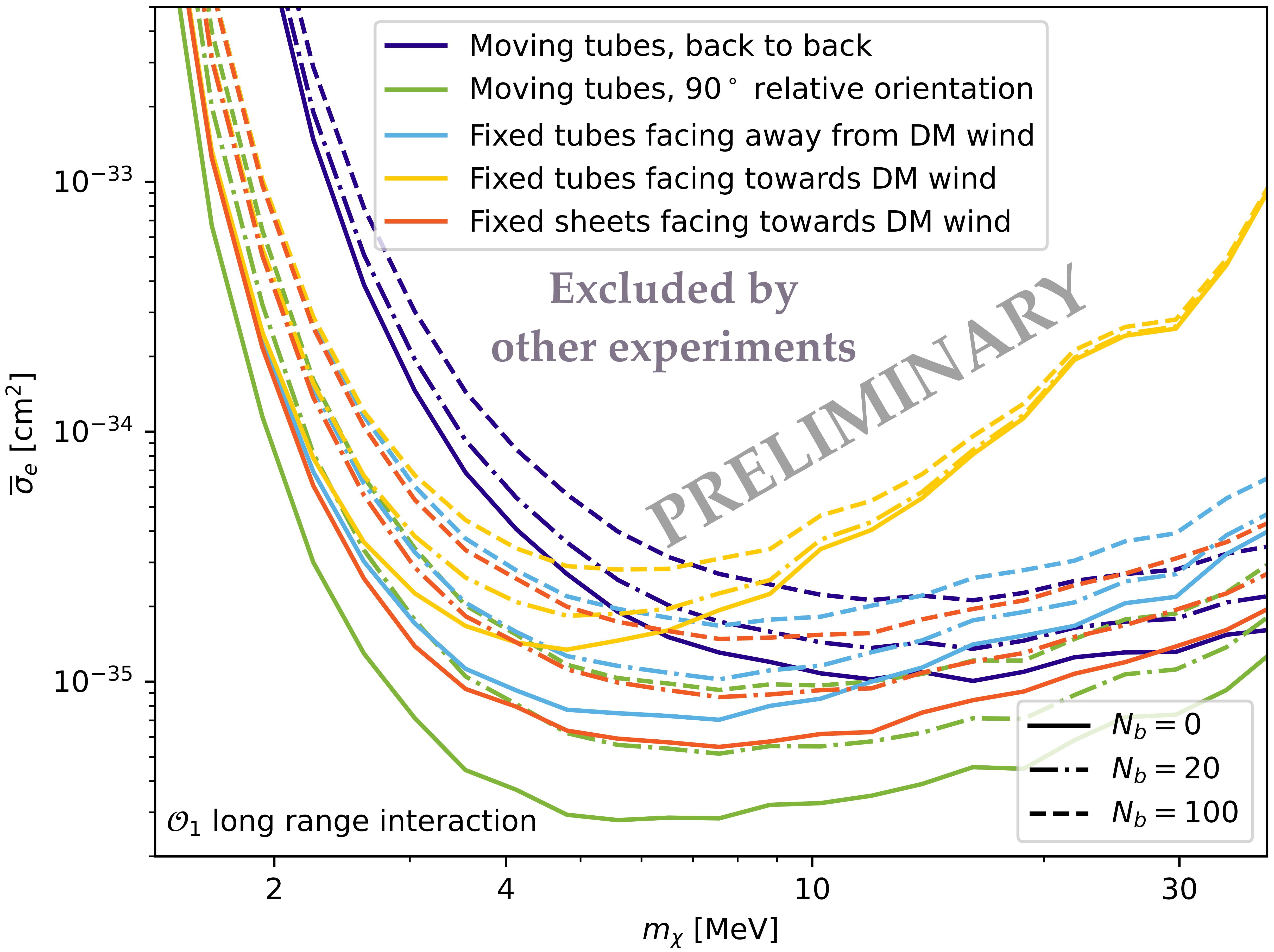
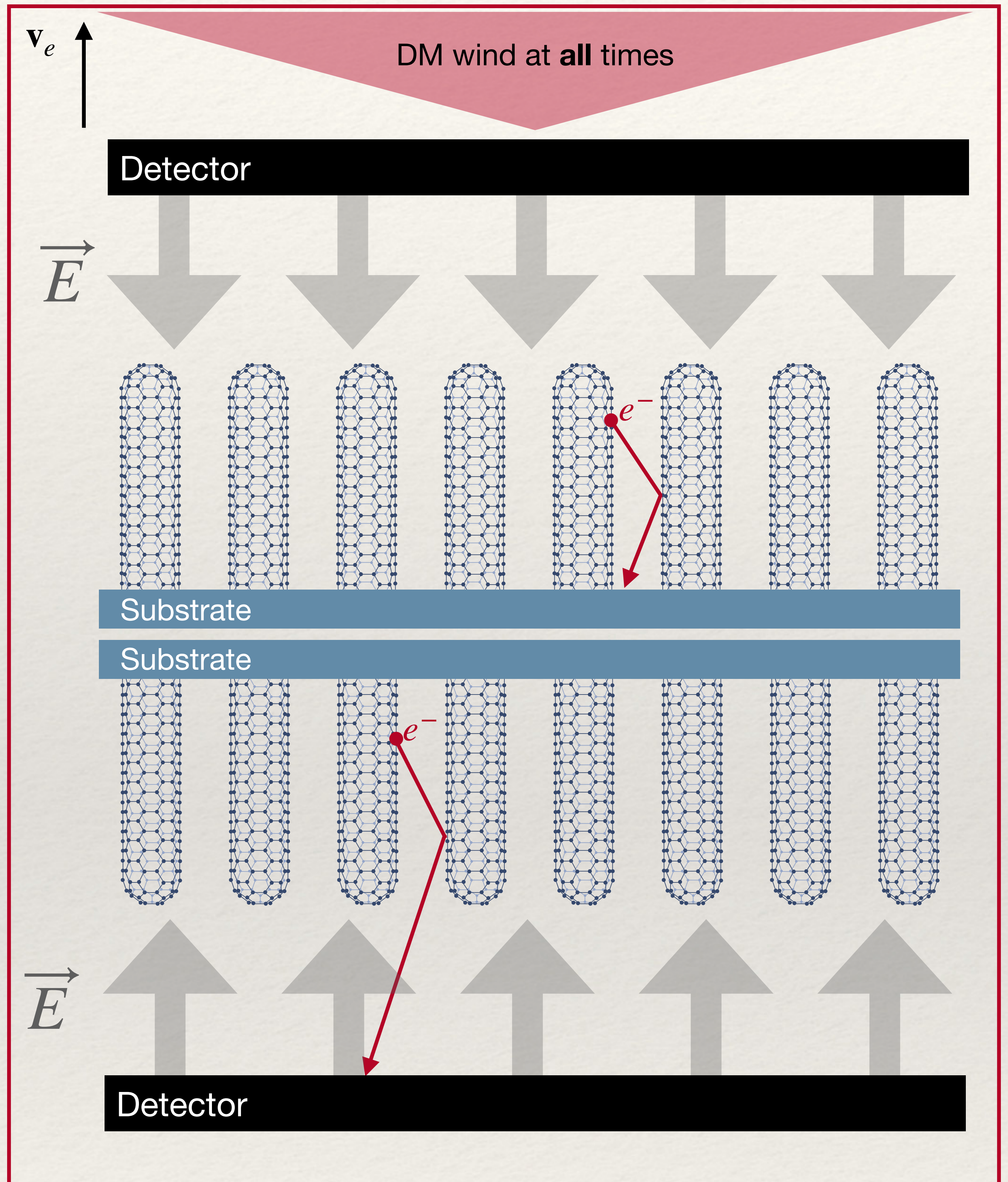


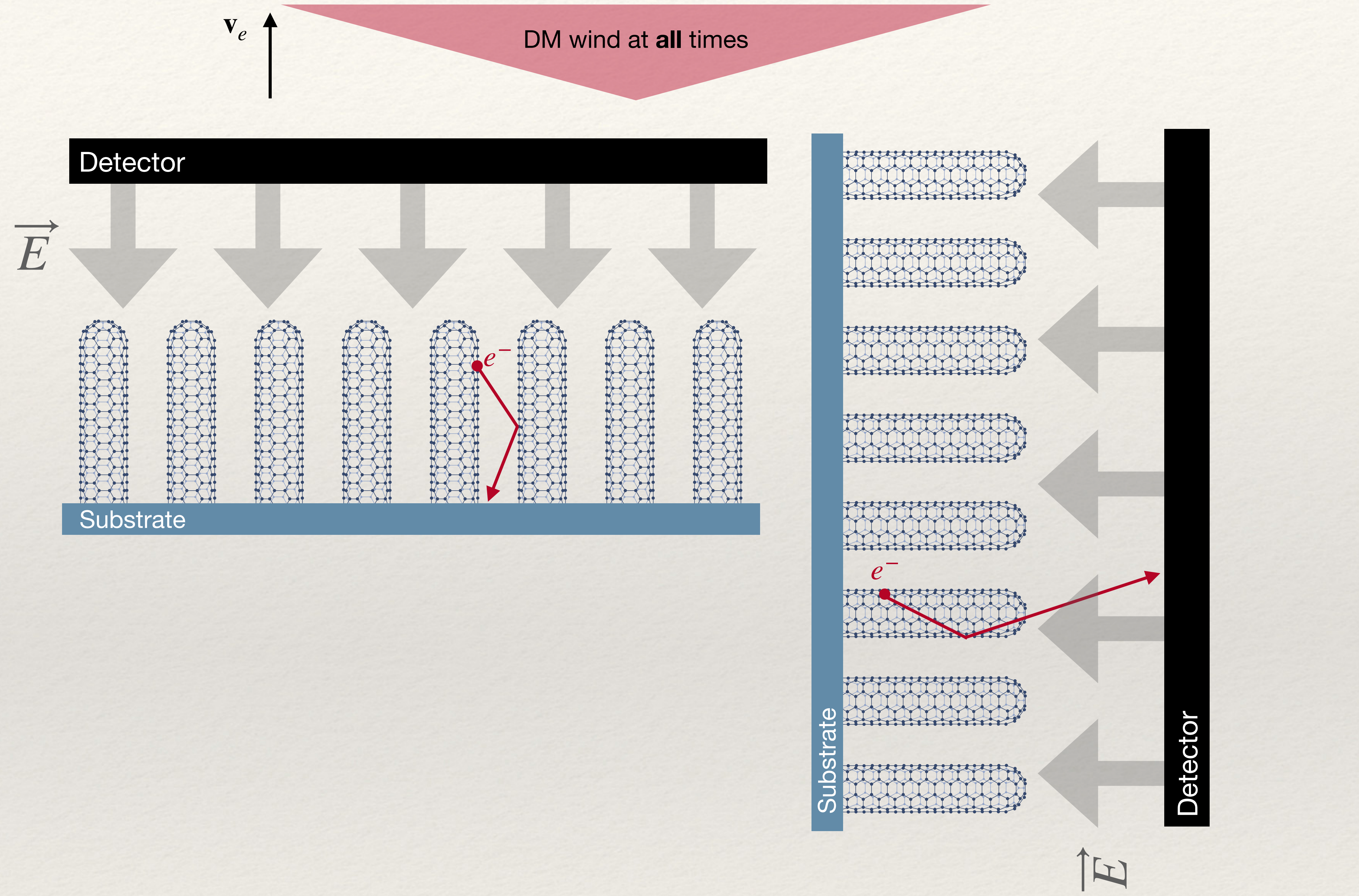


Assuming graphene/carbon nanotube exposure of 1g year

Moving experimental setups



Moving tubes back to back



Moving tubes, 90° relative orientation

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Expected Sensitivity at 90% Confidence level

Assuming graphene/carbon nanotube exposure of 1g year

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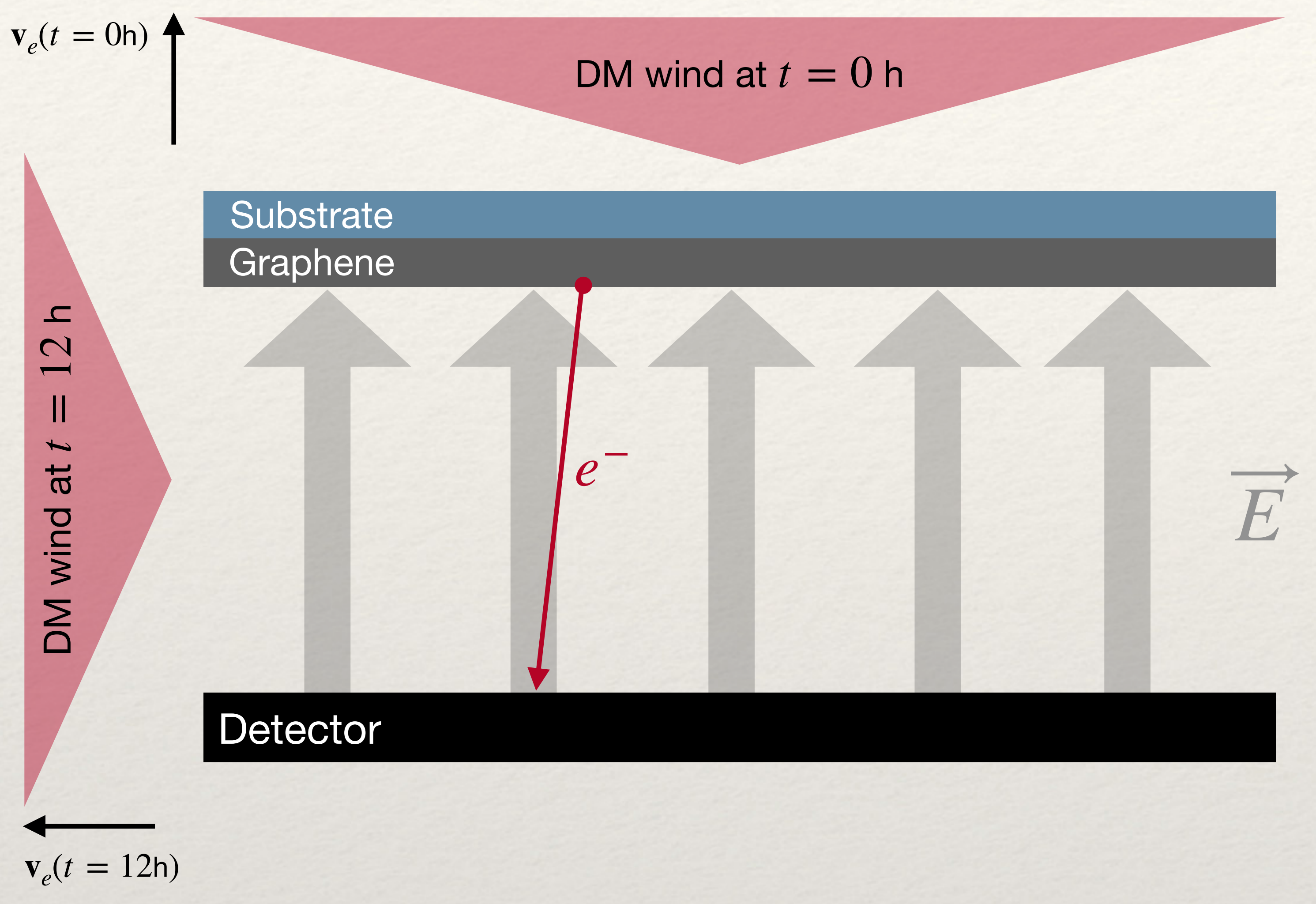
Fixed experimental setups



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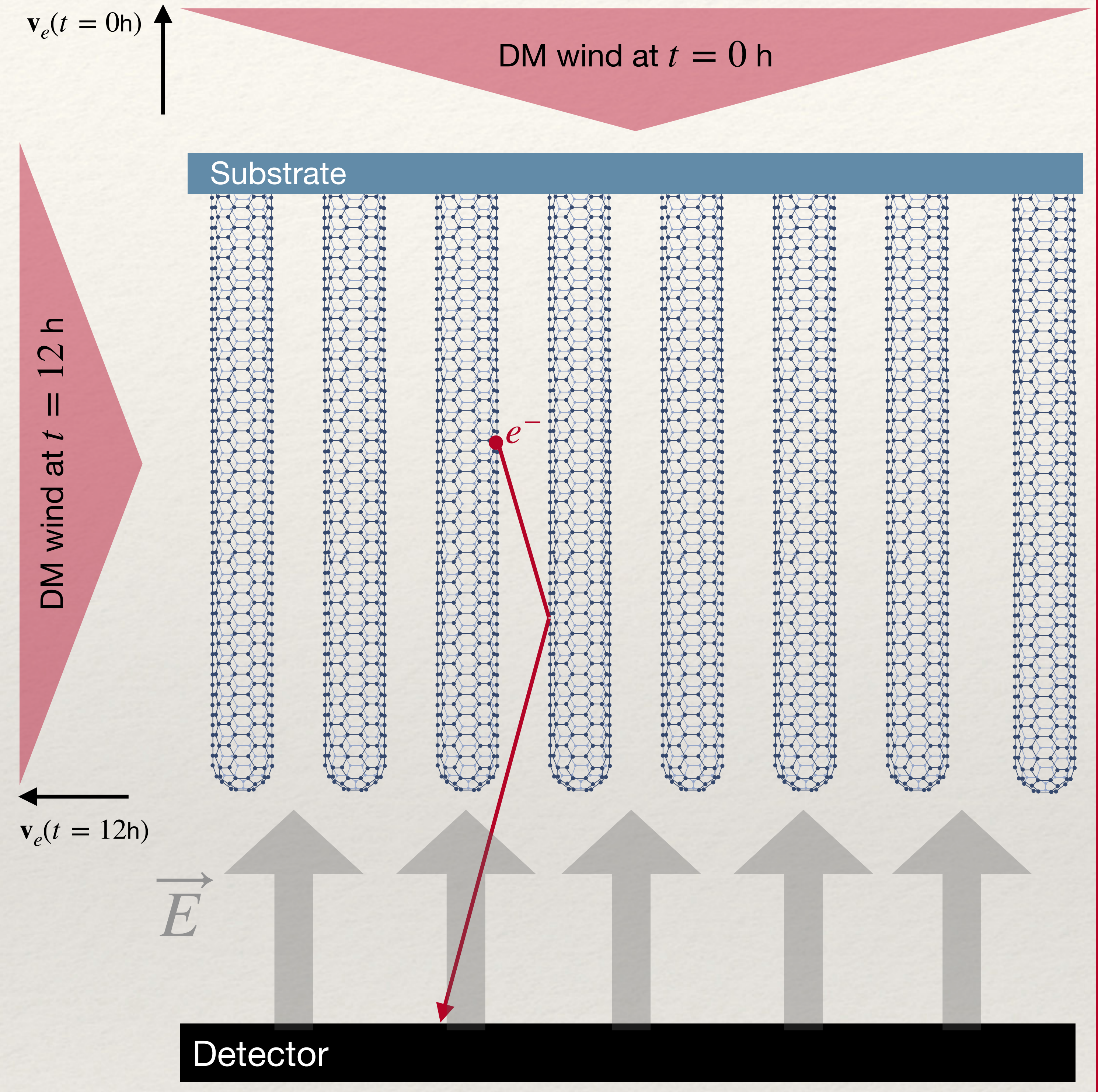

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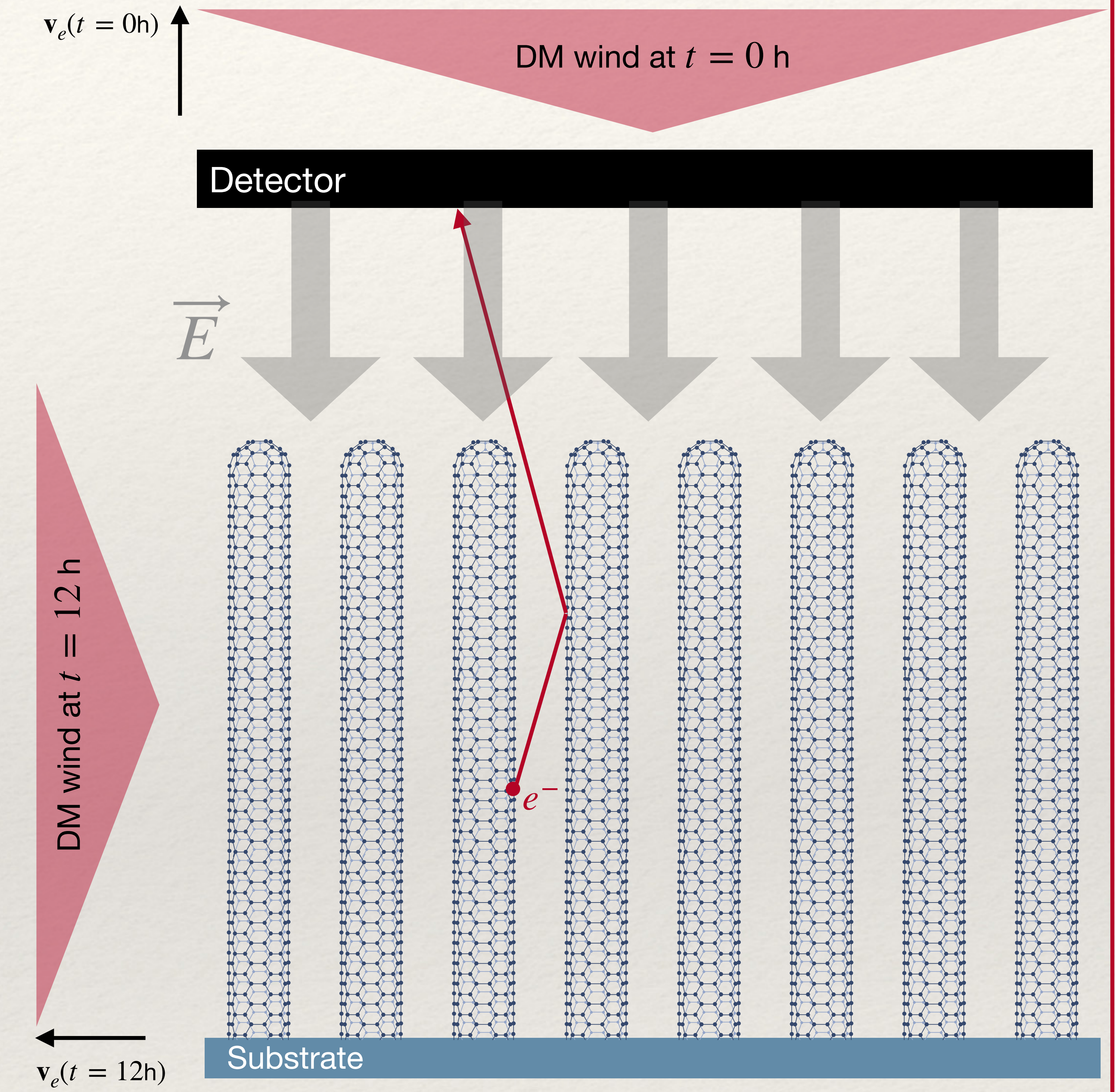

Fixed tubes facing away from DM wind

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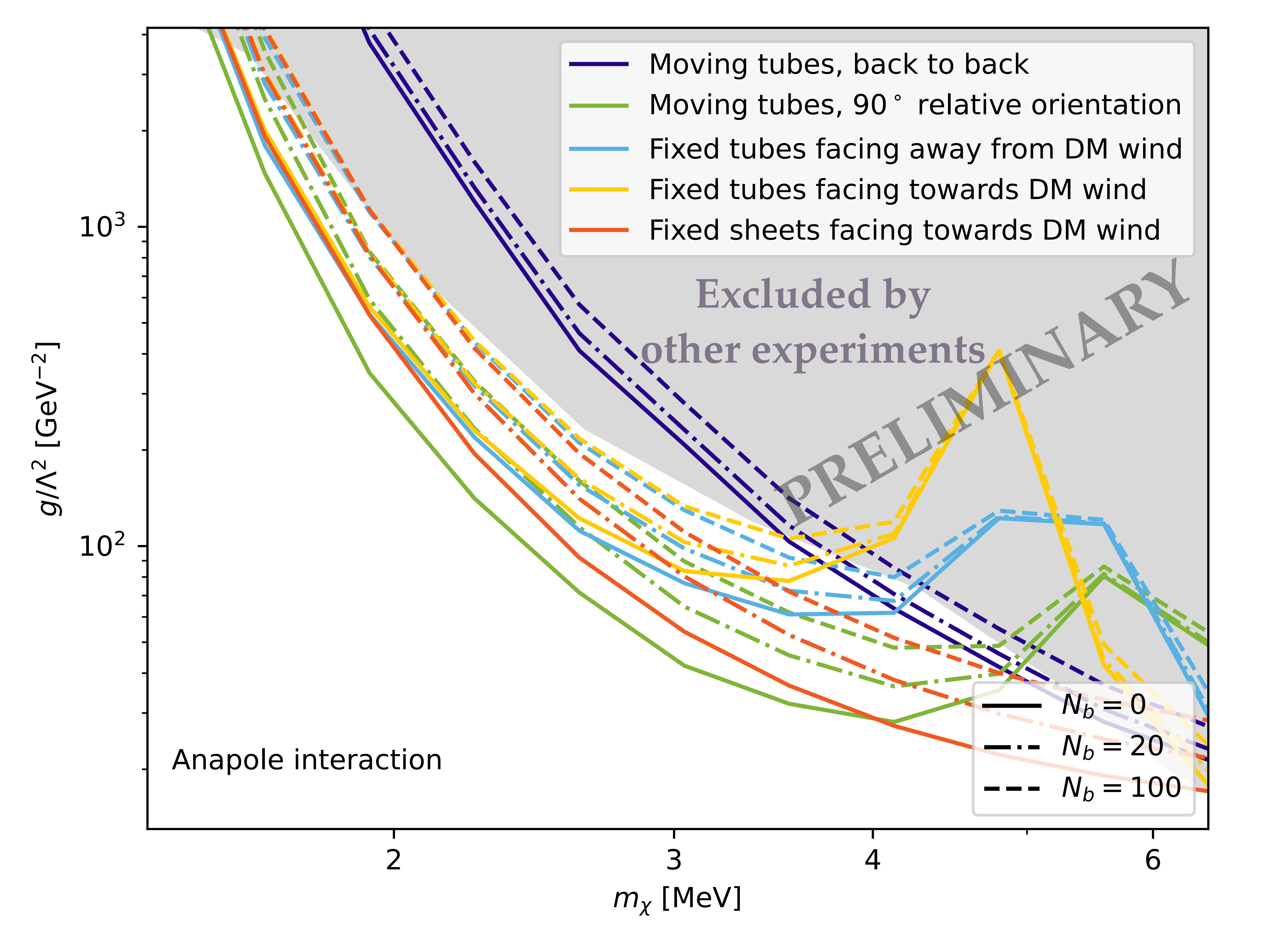

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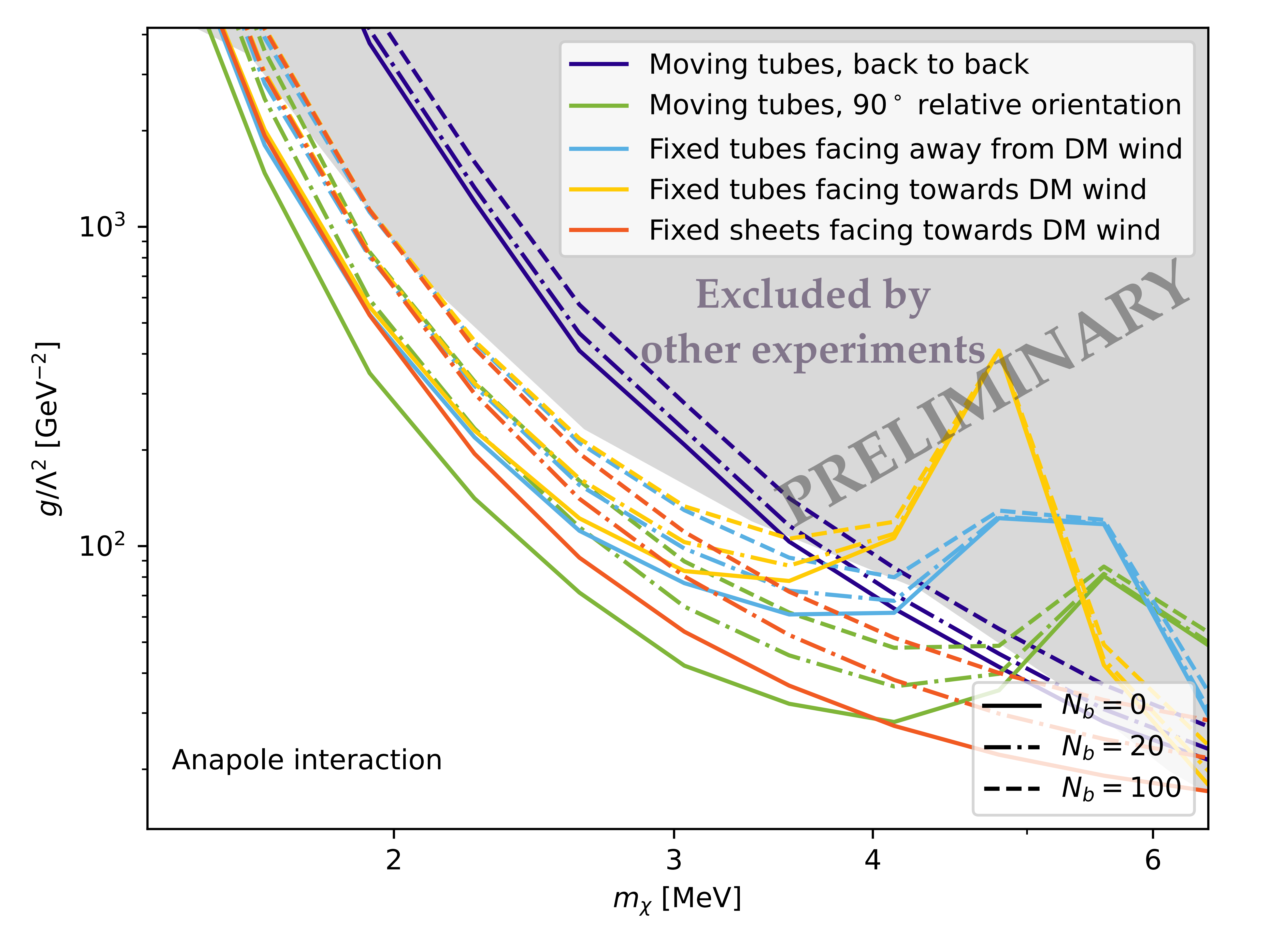

- Anapole interaction,
  $$\mathcal{L}_{\text{int}} = \frac{g}{2\Lambda^2}\bar{\chi}\gamma^\mu\gamma^5\chi\,\partial^\nu F_{\mu\nu}$$

Assuming graphene/carbon nanotube exposure of 1g year

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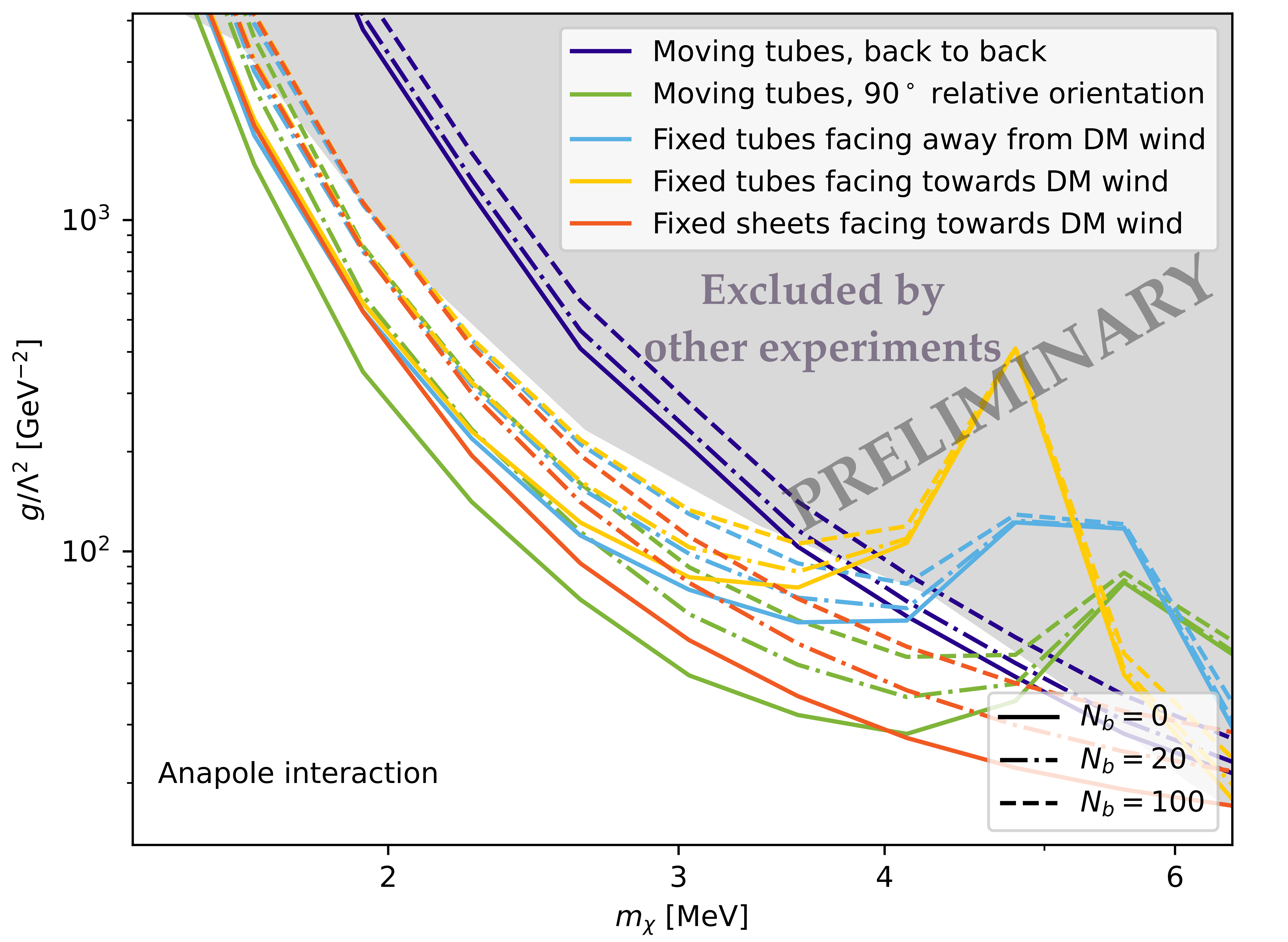

- Anapole interaction,
  $\mathscr{L}_{\rm int} = \frac{g}{2\Lambda^2}\,\bar{\chi}\gamma^\mu\gamma^5\chi\,\partial^\nu F_{\mu\nu}$
- Gives contact interactions with $\mathcal{O}_8$ and $\mathcal{O}_9$ contributing with coupling strengths $c_8 = 8em_e m_\chi \frac{g}{\Lambda^2}$ and $c_9 = -8em_e m_\chi \frac{g}{\Lambda^2}$

Assuming graphene/carbon nanotube exposure of 1g year

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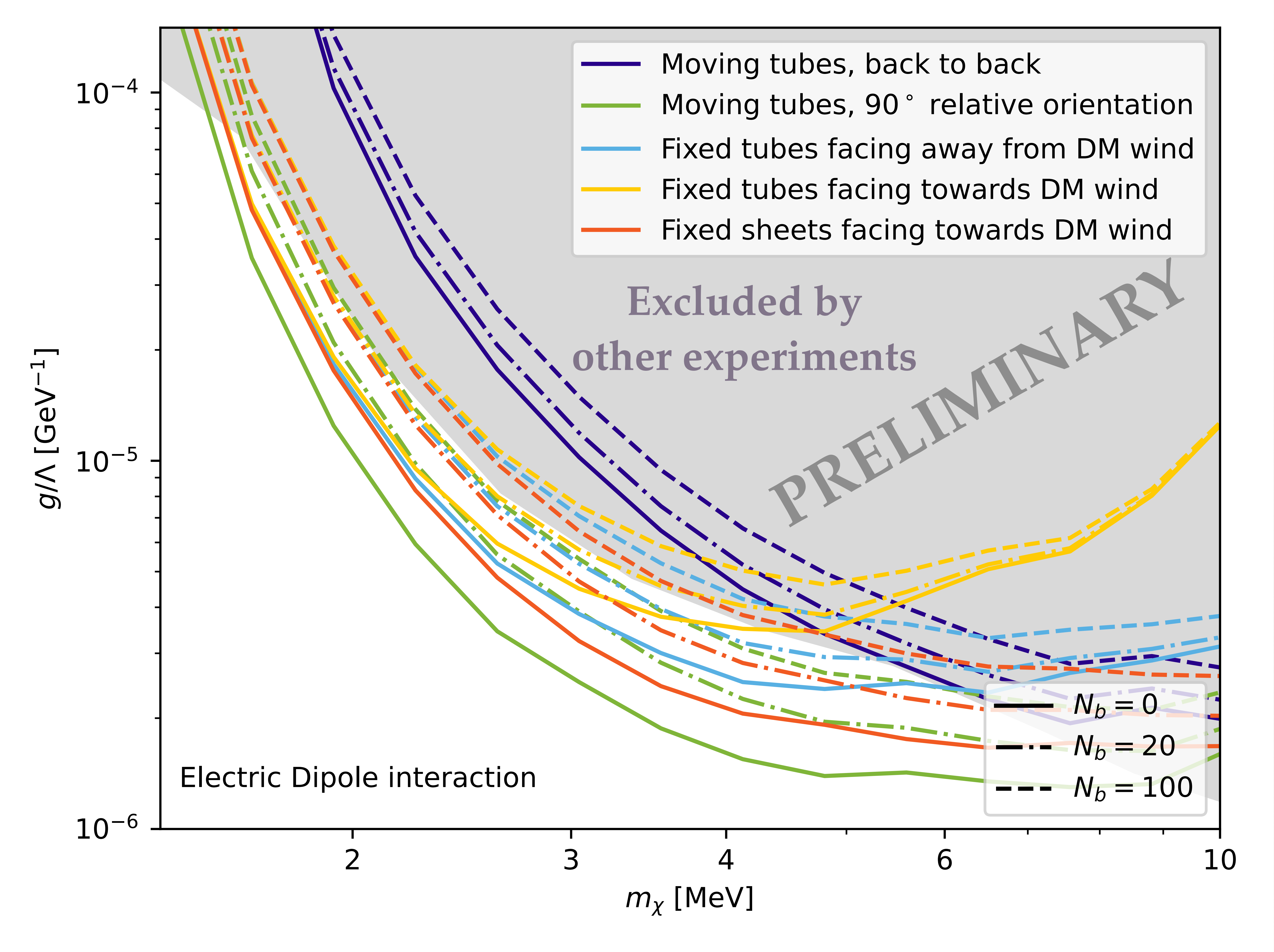

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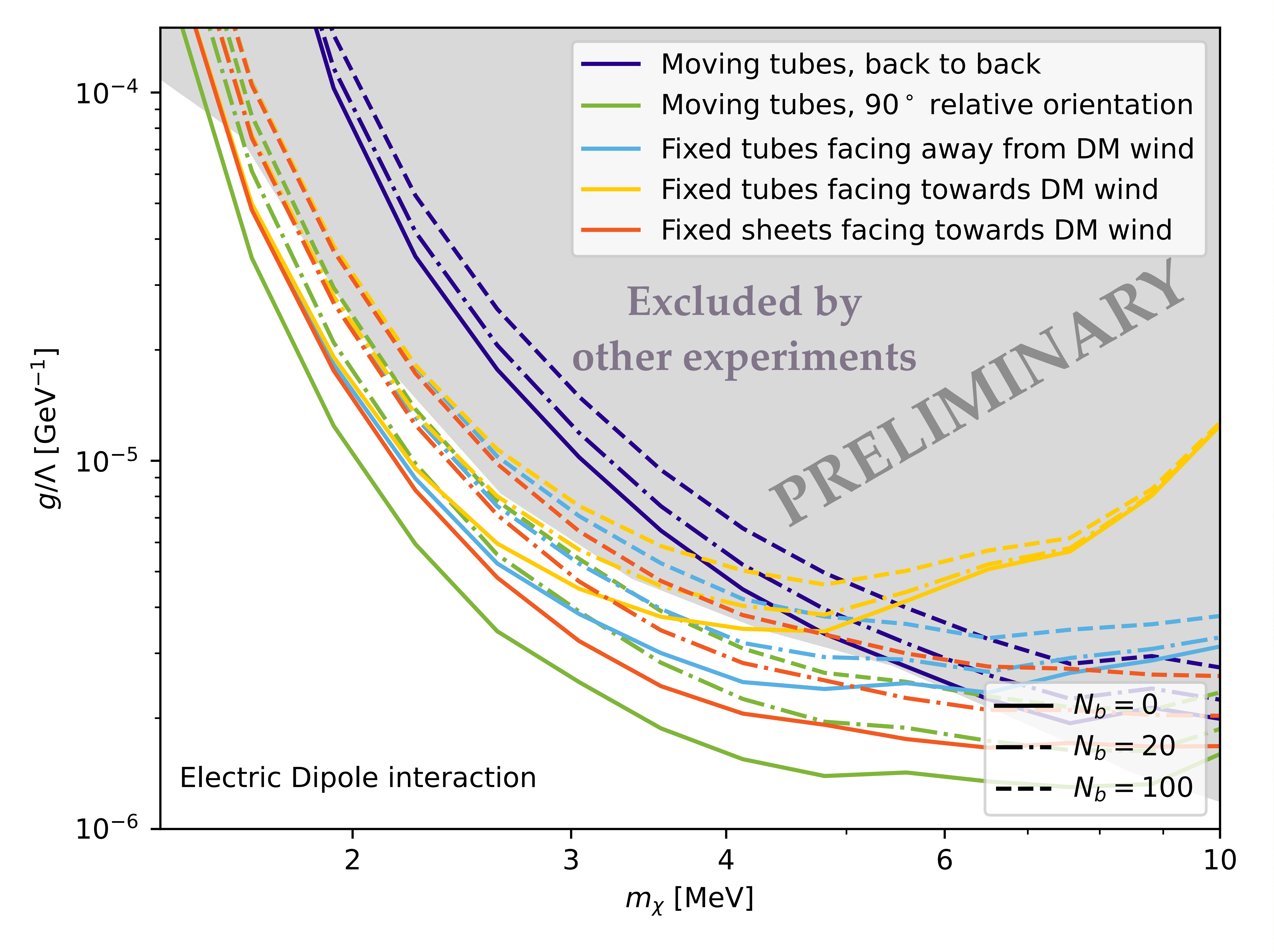

- Electric dipole interaction, $\mathscr{L}_{\text{int}} = \frac{g}{\Lambda} i\bar{\chi}\sigma^{\mu\nu}\gamma^5\chi F_{\mu\nu}$

Assuming graphene/carbon nanotube exposure of 1g year

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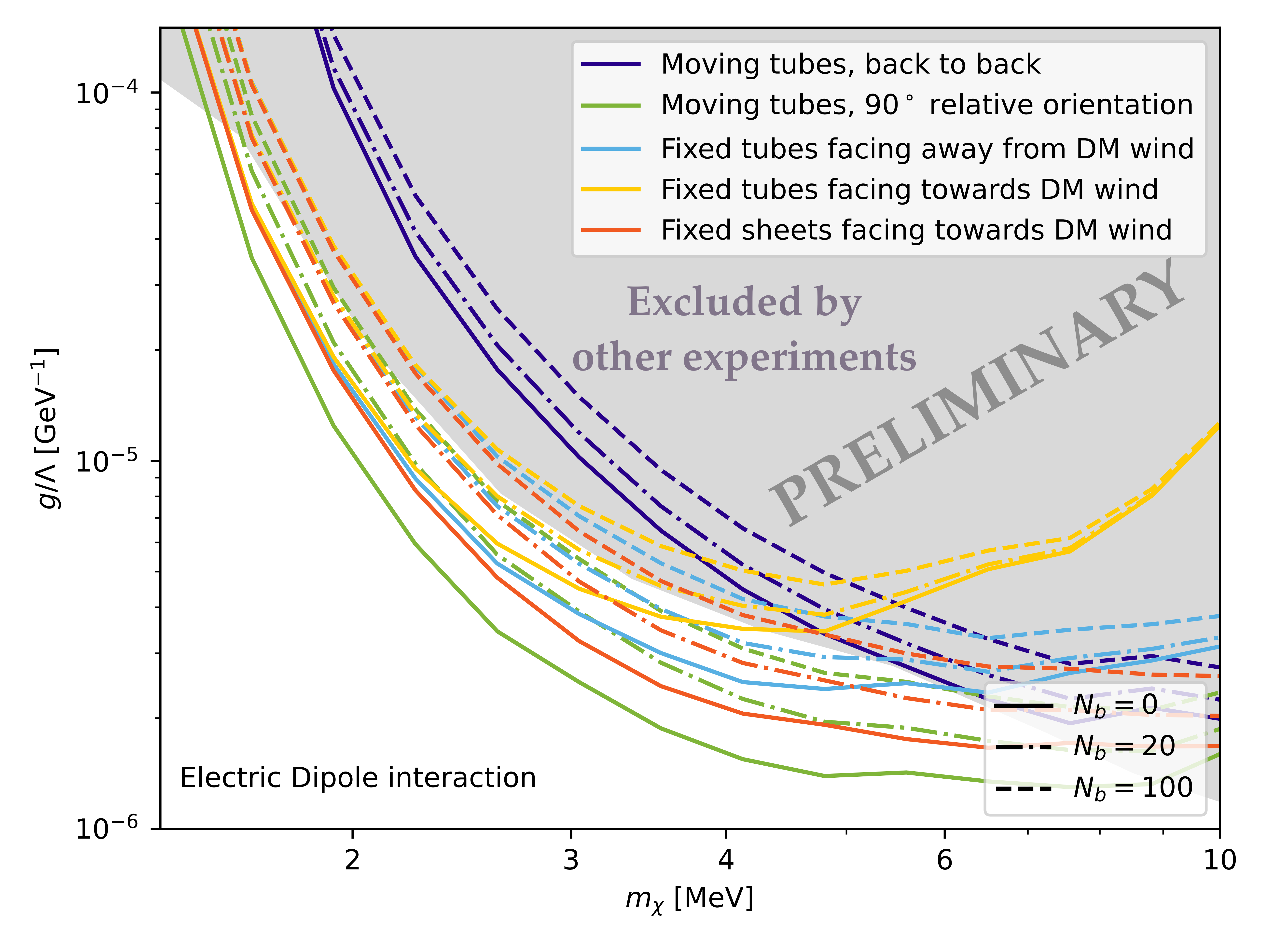

- Electric dipole interaction, $\mathscr{L}_{\text{int}} = \frac{g}{\Lambda} i\bar{\chi}\sigma^{\mu\nu}\gamma^5\chi F_{\mu\nu}$
- Gives long range interactions with $\mathcal{O}_{11}$ contributing with coupling strength $c_{11} = \frac{16em_\chi m_e^2}{q_{\text{ref}}^2}\frac{g}{\Lambda}$

Assuming graphene/carbon nanotube exposure of 1g year

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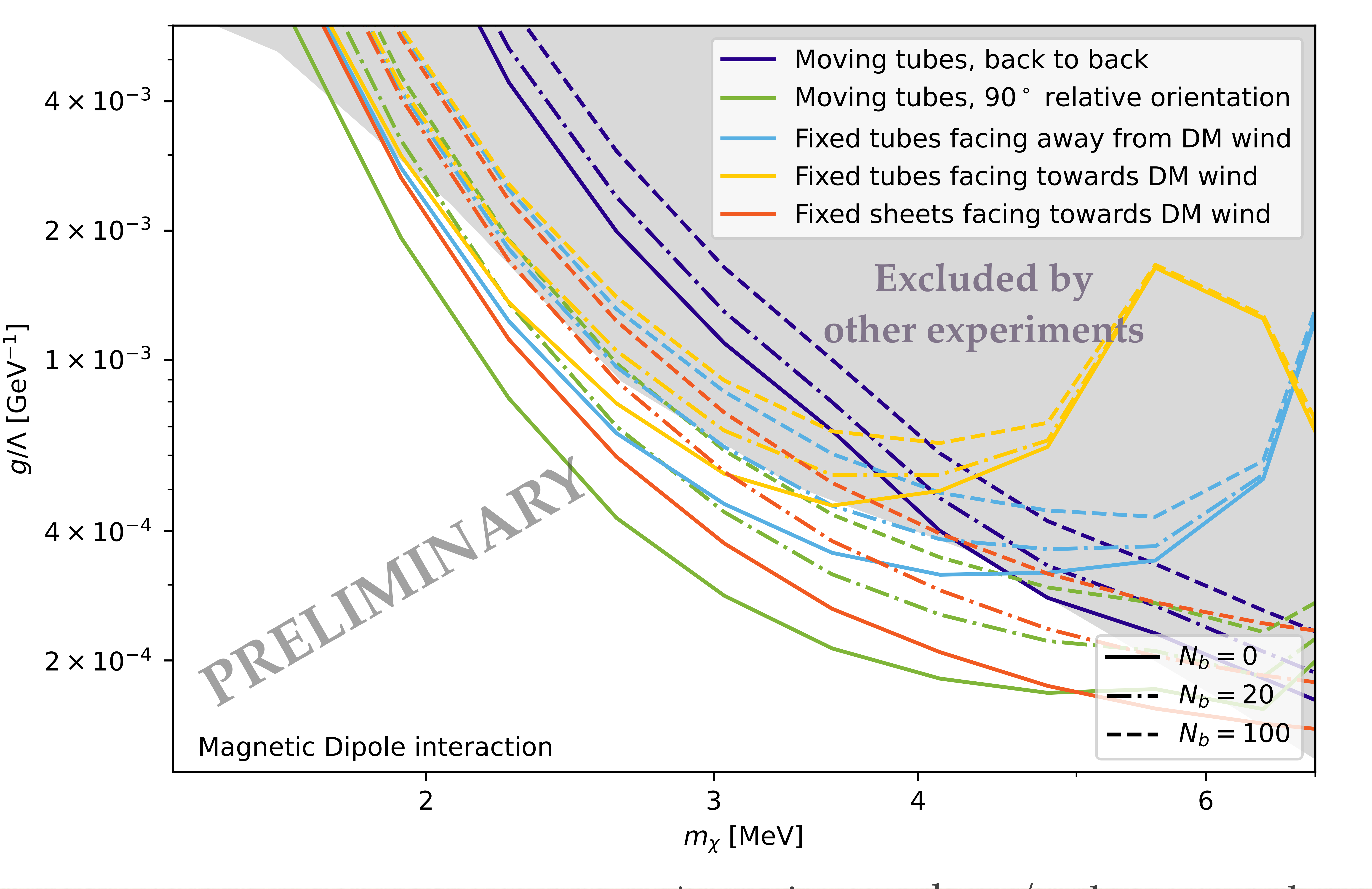

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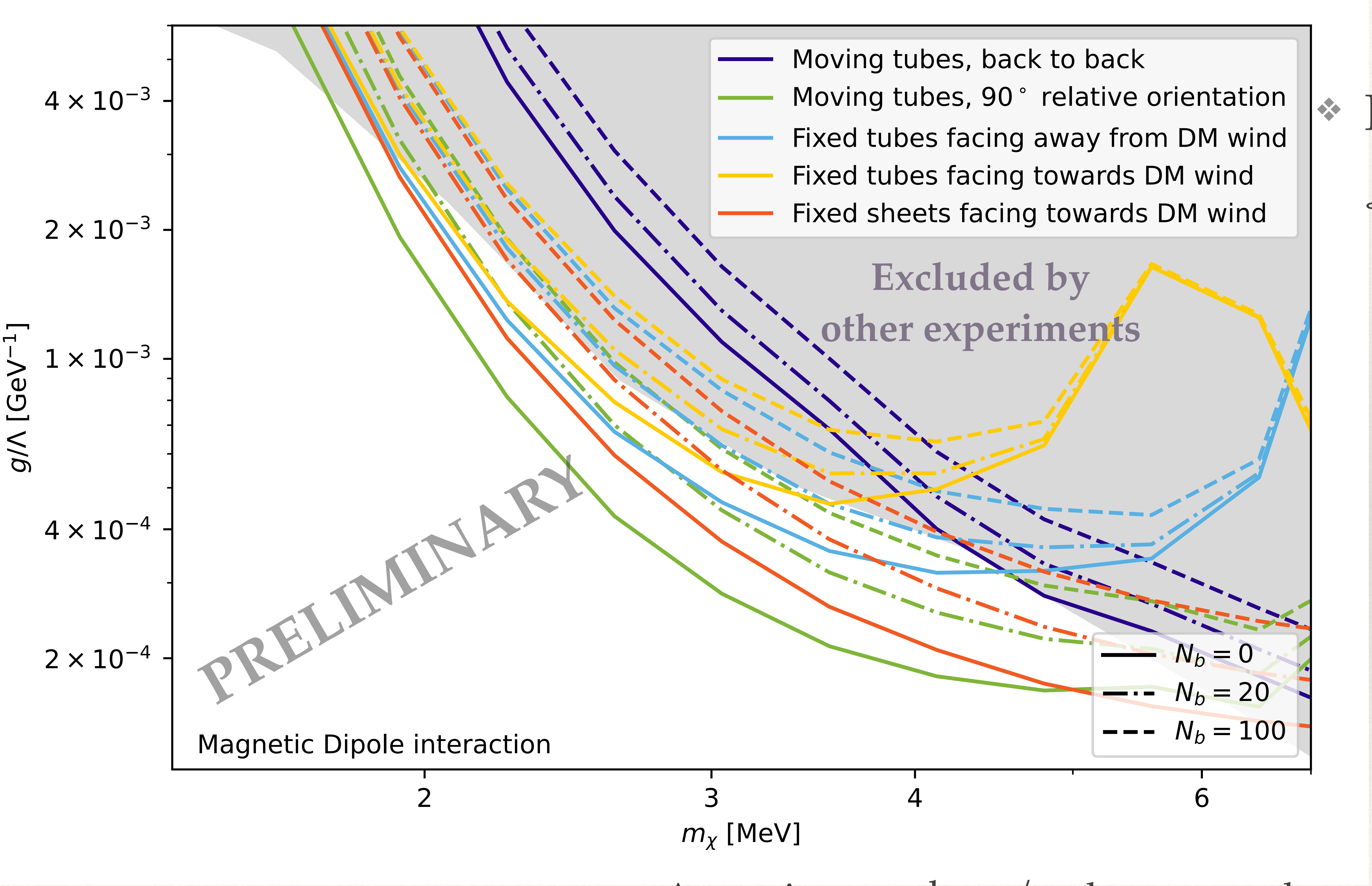

- Magnetic dipole interaction, $\mathscr{L}_{\text{int}} = \frac{g}{\Lambda} \bar{\chi}\sigma^{\mu\nu}\chi F_{\mu\nu}$

Assuming graphene/carbon nanotube exposure of 1g year

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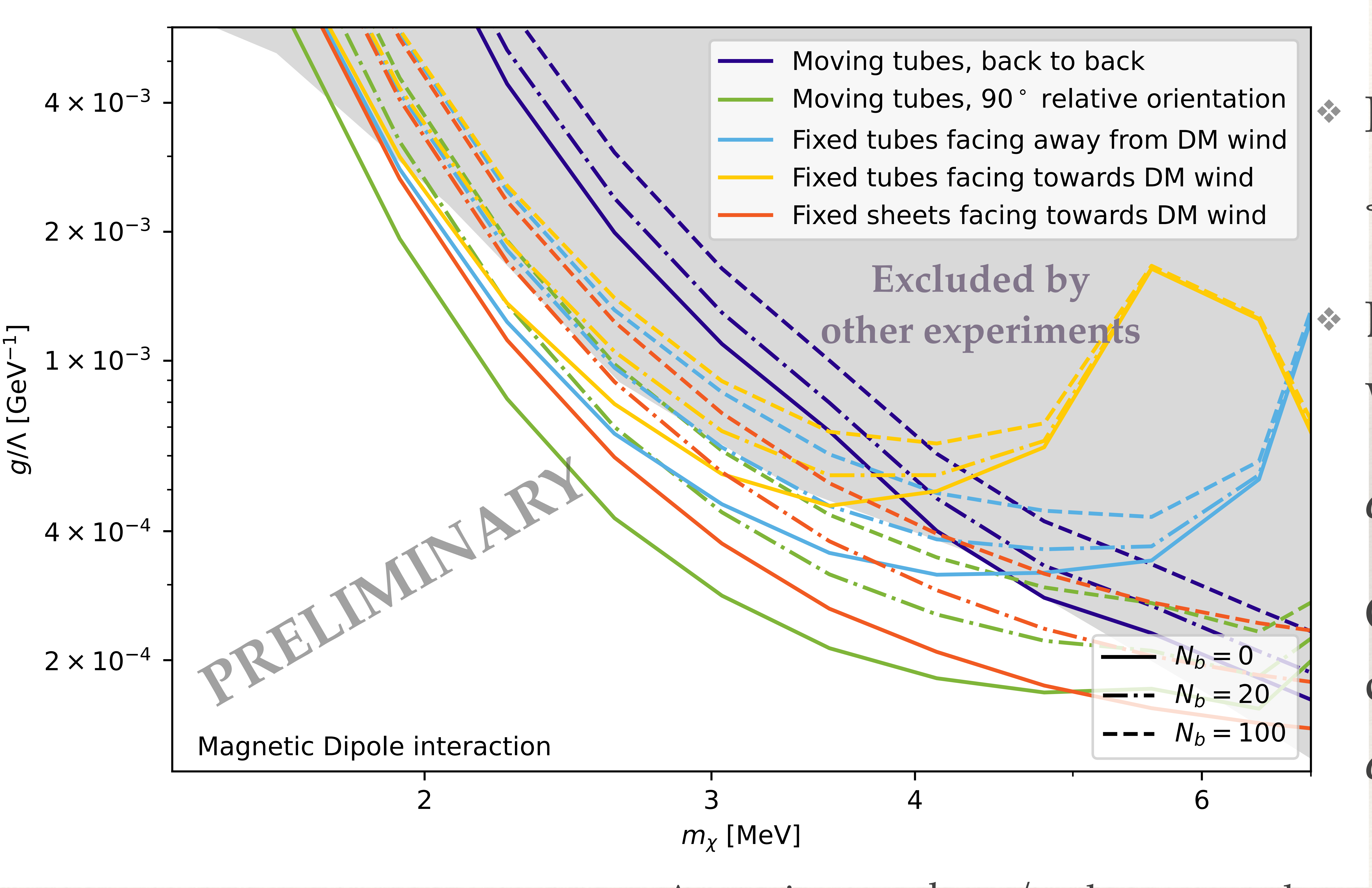

- Magnetic dipole interaction, $\mathscr{L}_{\text{int}} = \frac{g}{\Lambda} \bar{\chi}\sigma^{\mu\nu}\chi F_{\mu\nu}$
- Long range interaction with $\mathcal{O}_5$ and $\mathcal{O}_6$ with coupling strengths $c_5 = \frac{16em_e^2 m_\chi}{q_{\text{ref}}^2}\frac{g}{\Lambda}$ and $c_6 = -\frac{16em_e^2 m_\chi}{q_{\text{ref}}^2}\frac{g}{\Lambda}$

Contact interaction with $\mathcal{O}_1$ and $\mathcal{O}_4$ with coupling strengths $c_1 = 4em_e\frac{g}{\Lambda}$ and $c_4 = 16em_\chi\frac{g}{\Lambda}$

Assuming graphene/carbon nanotube exposure of 1g year

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Take Home Message

- For plane wave final state electrons, the physics of general non-relativistic dark matter electron interactions factorises into the product of a single free particle response function and the norm of the momentum space initial state electron wave-function.
- Graphene and carbon nanotubes can be used to detect a smoking gun signals from DM.
- For DM masses of a few MeV both carbon nanotube and graphene based experiments are sensitive to yet viable parameter space for a range of DM models with an exposure of 1g year.

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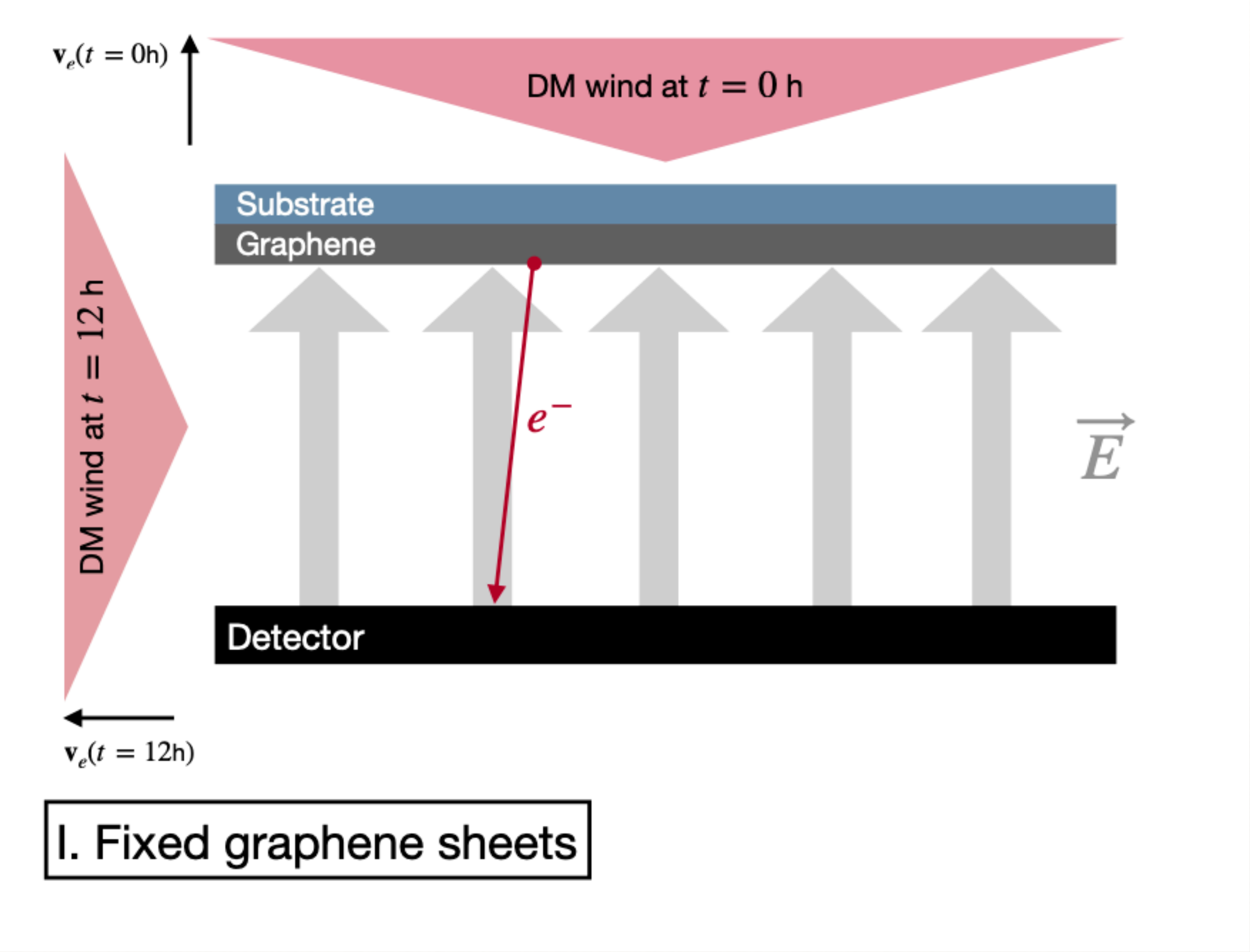
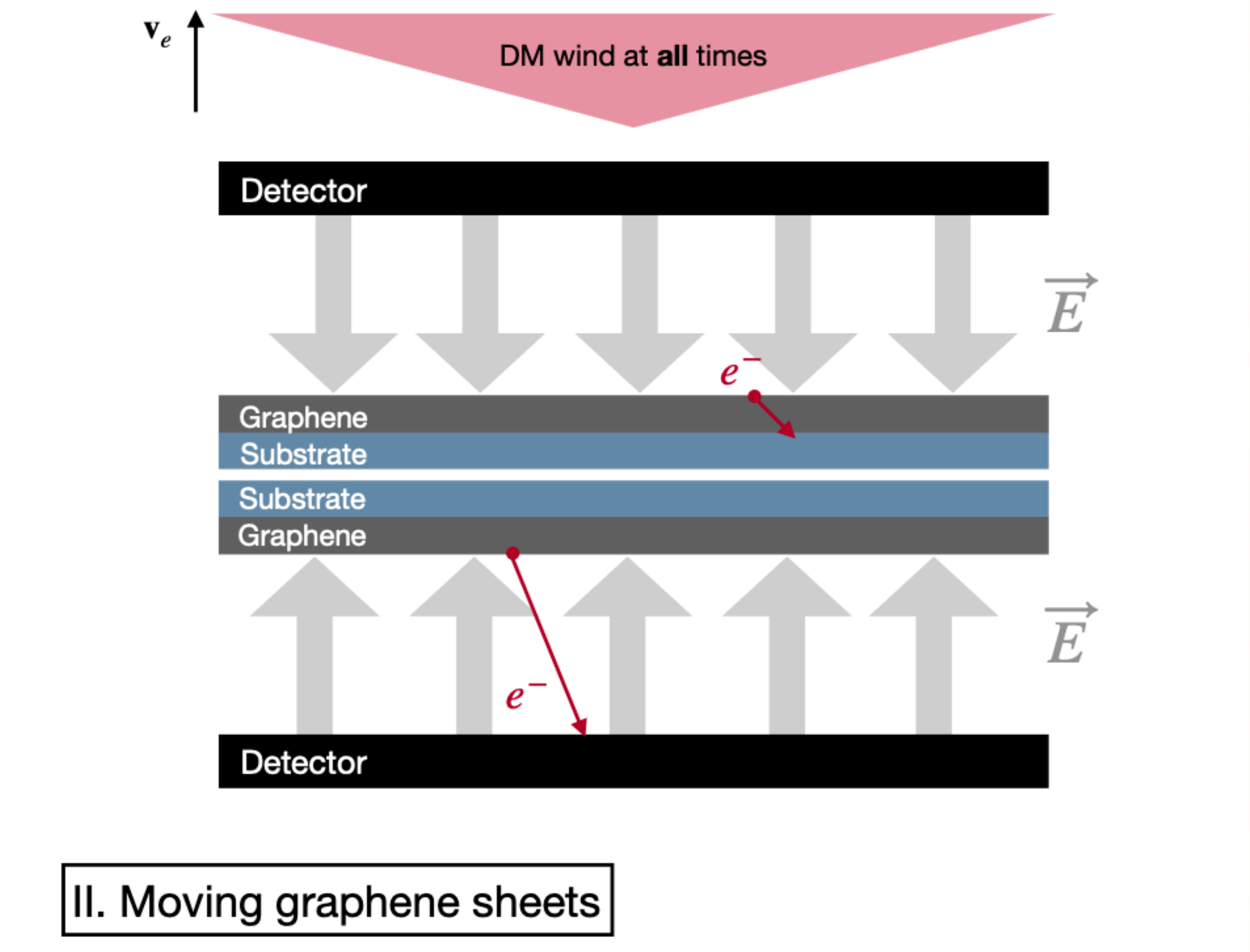
Backup slides

Experimental setups: Graphene





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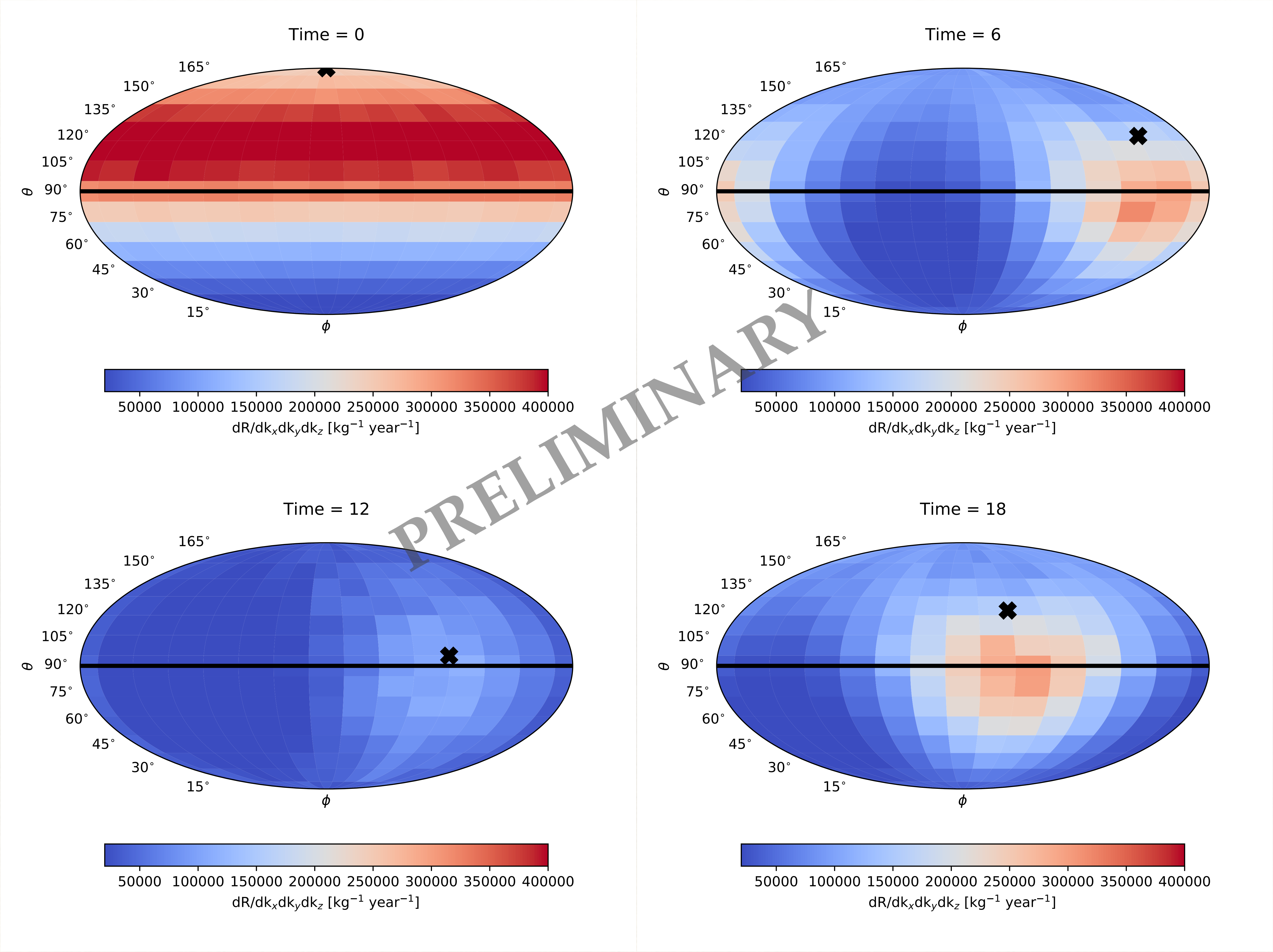
Daily Modulation in Fixed Graphene Experiments



$$\mathcal{O}_5 = i\mathbf{S}_\chi \cdot \left(\frac{\mathbf{q}}{m_e} \times \mathbf{v} \right)$$

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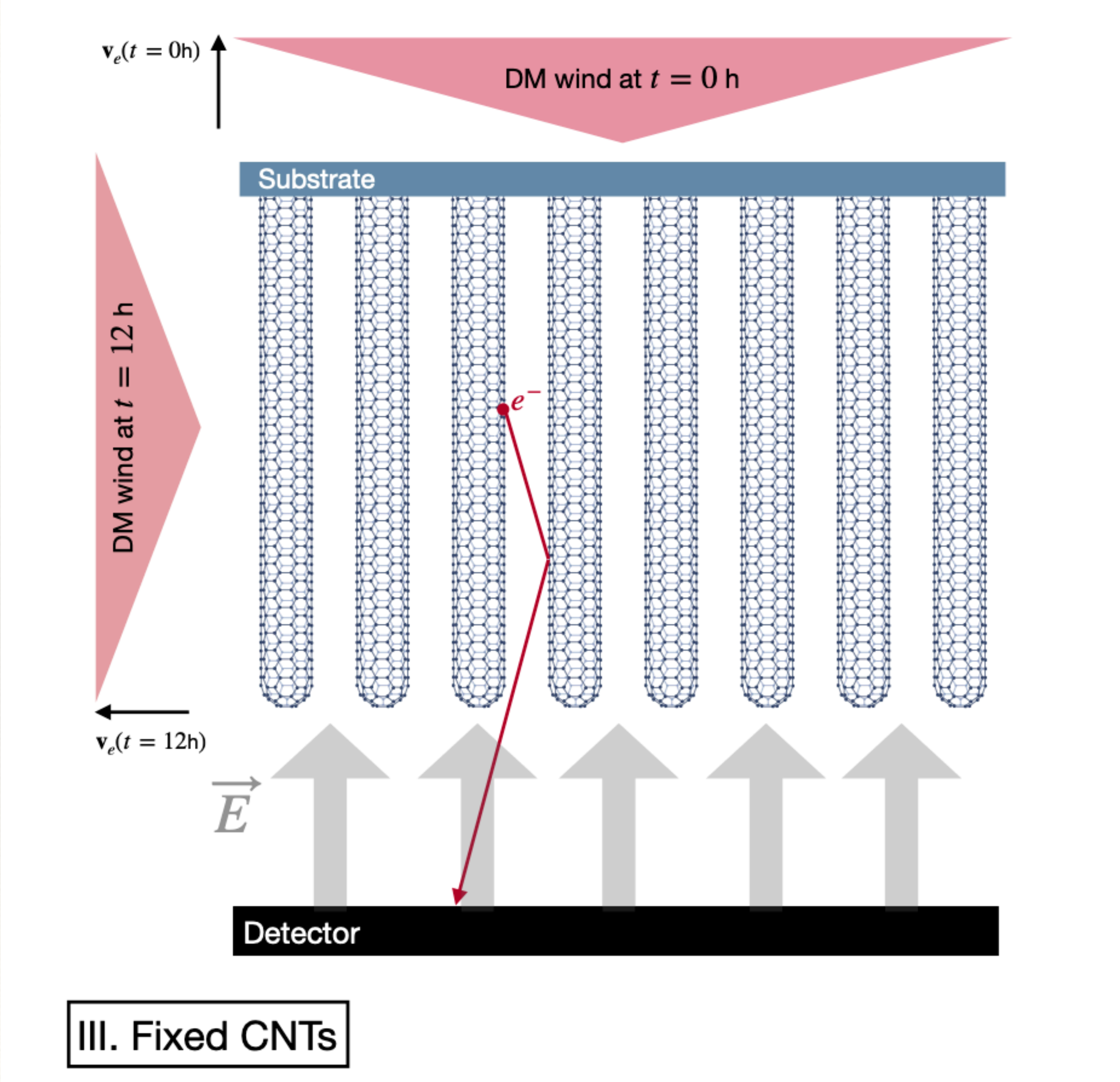
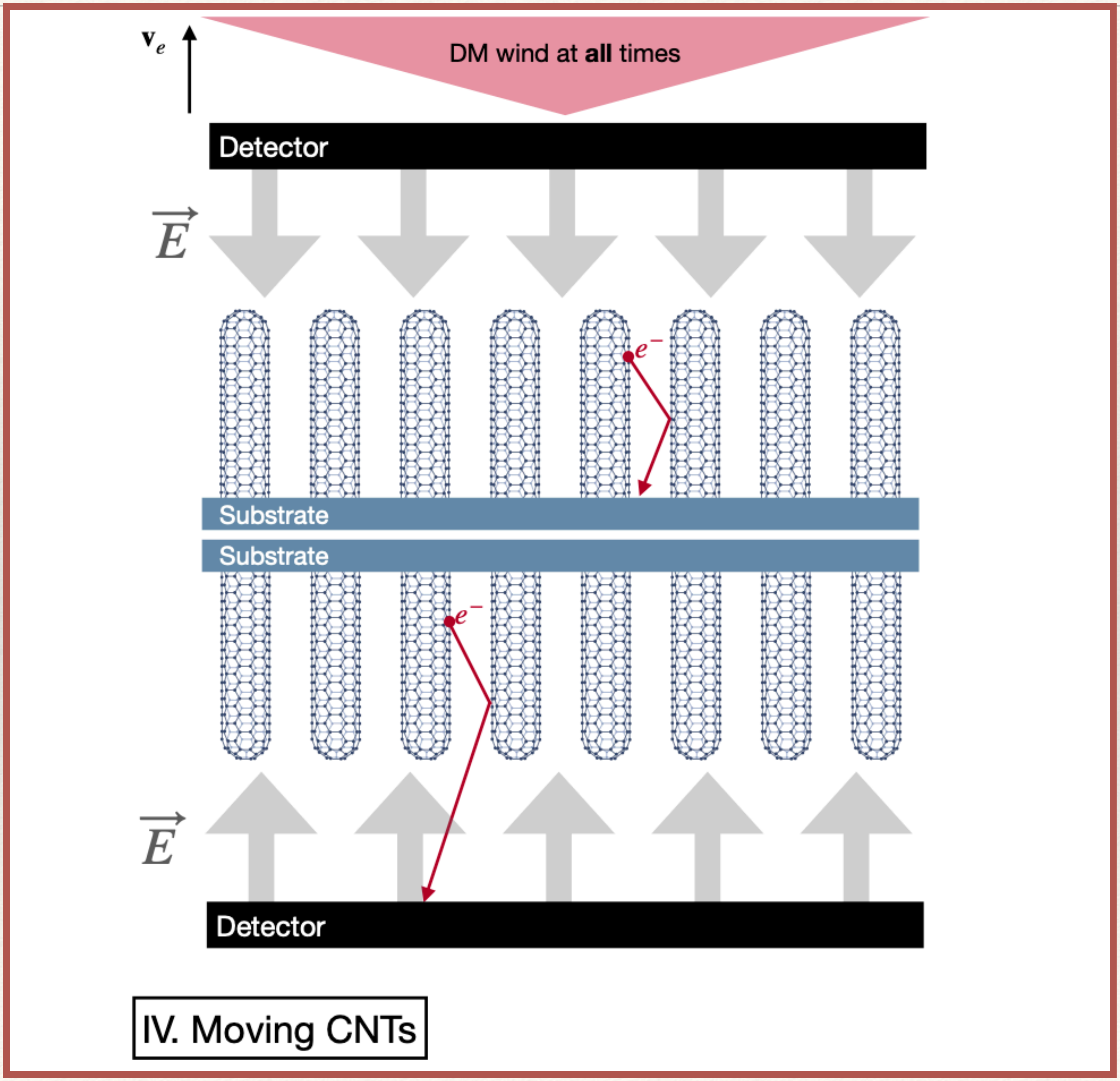
Experimental setups: Carbon Nanotubes





To be built by ANDROMEDA

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