

General method of atomic ionisation for scattering and absorption for *SM* and *BSM* physics

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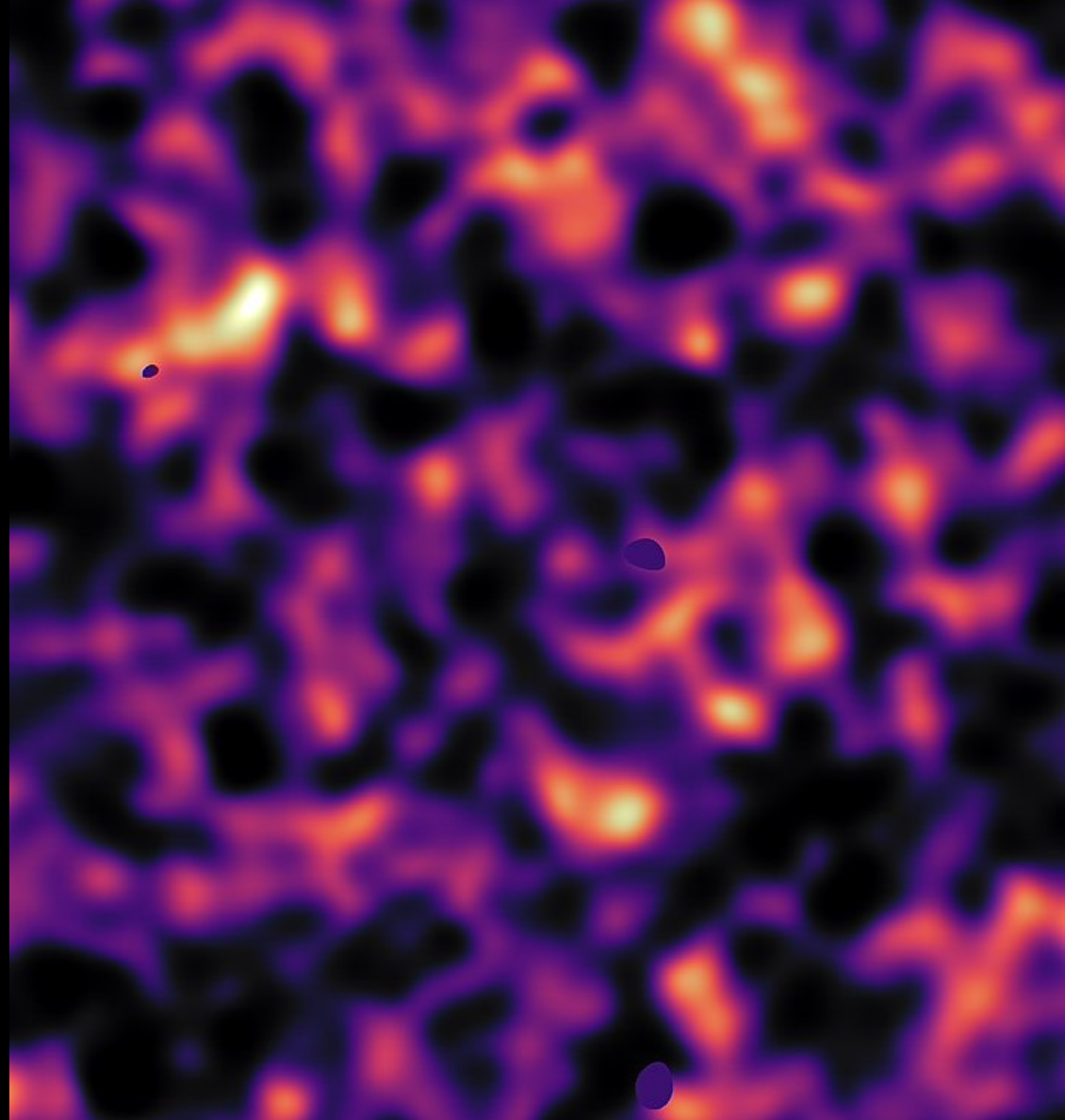
XIX International Conference on
Interconnections between
Particle Physics and Cosmology



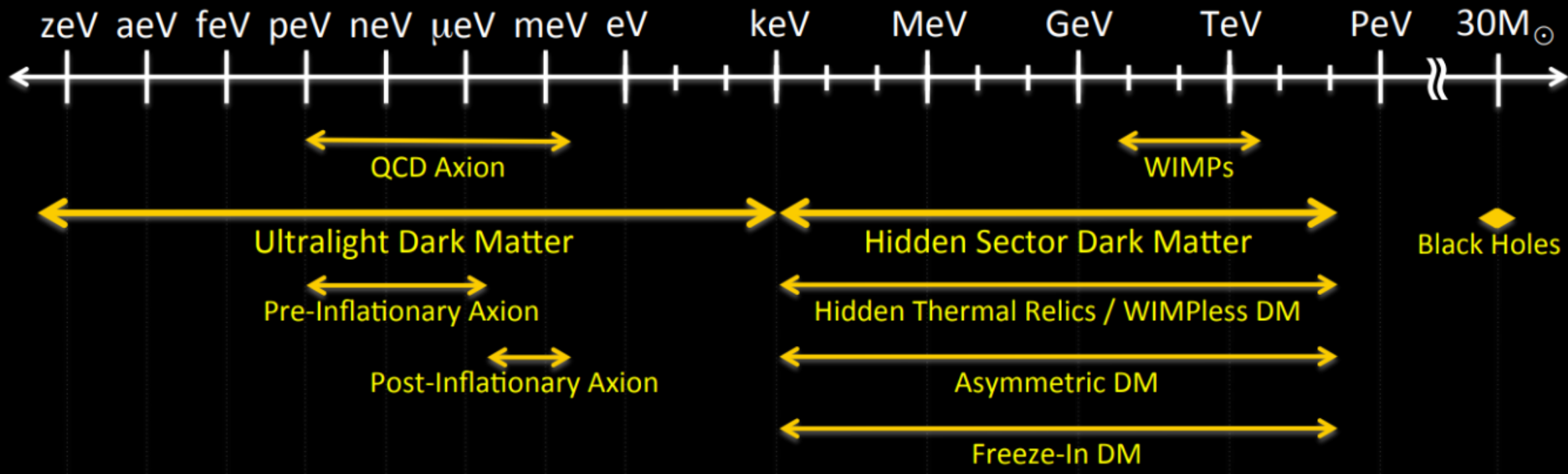
Physics Beyond the Standard Model

Dark Matter

- Many cosmological and astrophysical measures all pointing towards 85% of the matter in our Universe is dark matter
- Cannot be explained by the Standard Model of Particle Physics
- So far only detected through only its gravitational effects on visible matter

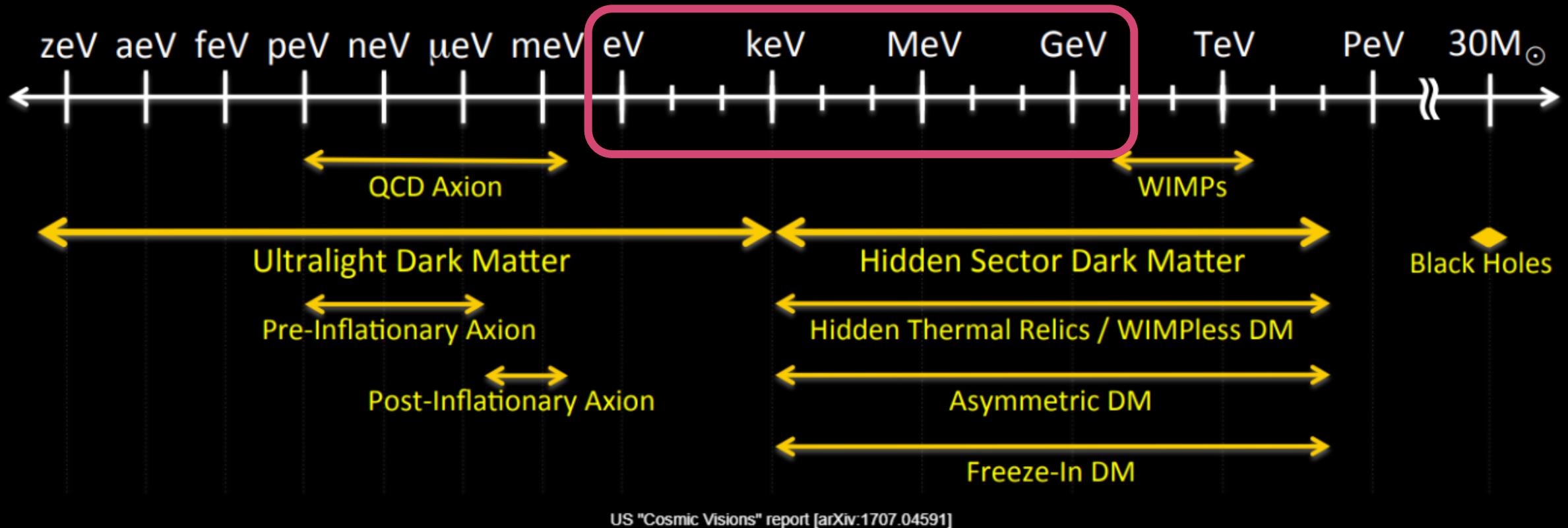


Map of dark matter using gravitational lensing from Kilo-Degree survey, an example of indirect detection of dark matter. Kilo-Degree Survey Collaboration/H. Hildebrandt & B. Giblin/ESO



US "Cosmic Visions" report [arXiv:1707.04591]

Possible mass ranges 90 orders of magnitude
50 orders of magnitude for particle DM



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Direct Detection Experiments

Liquid noble gas time projection chambers

- Target material: Liquid xenon (or argon)
- Detects interactions via the emission of light (scintillation) and electrons (ionisation)
- Experiments: XENON, LUX, PandaX

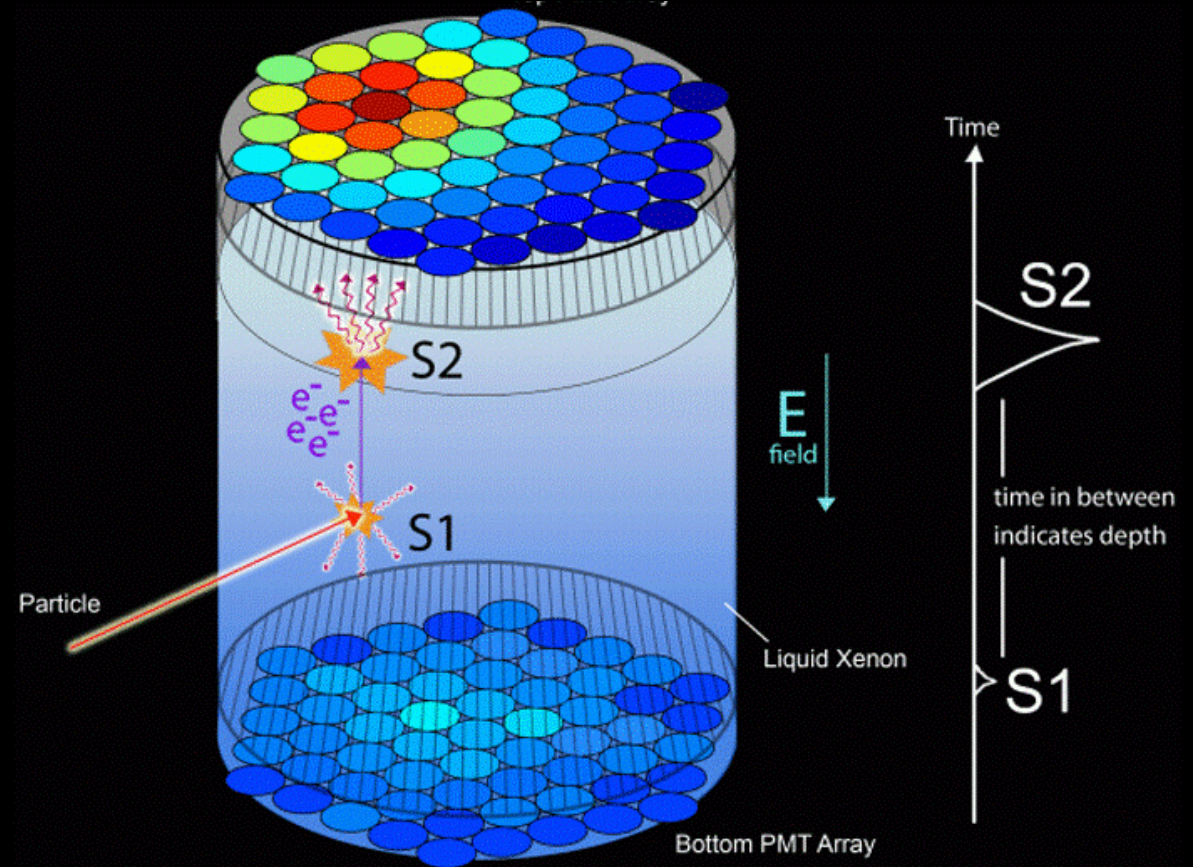


Figure: LUX Experiment

Direct Detection Experiments

Neutrino floor

- Largest detectors are beginning to detect solar neutrinos
- As larger detectors are built, these neutrinos will become an unavoidable background
- Dark matter and neutrinos look the same in liquid noble gas TPCs

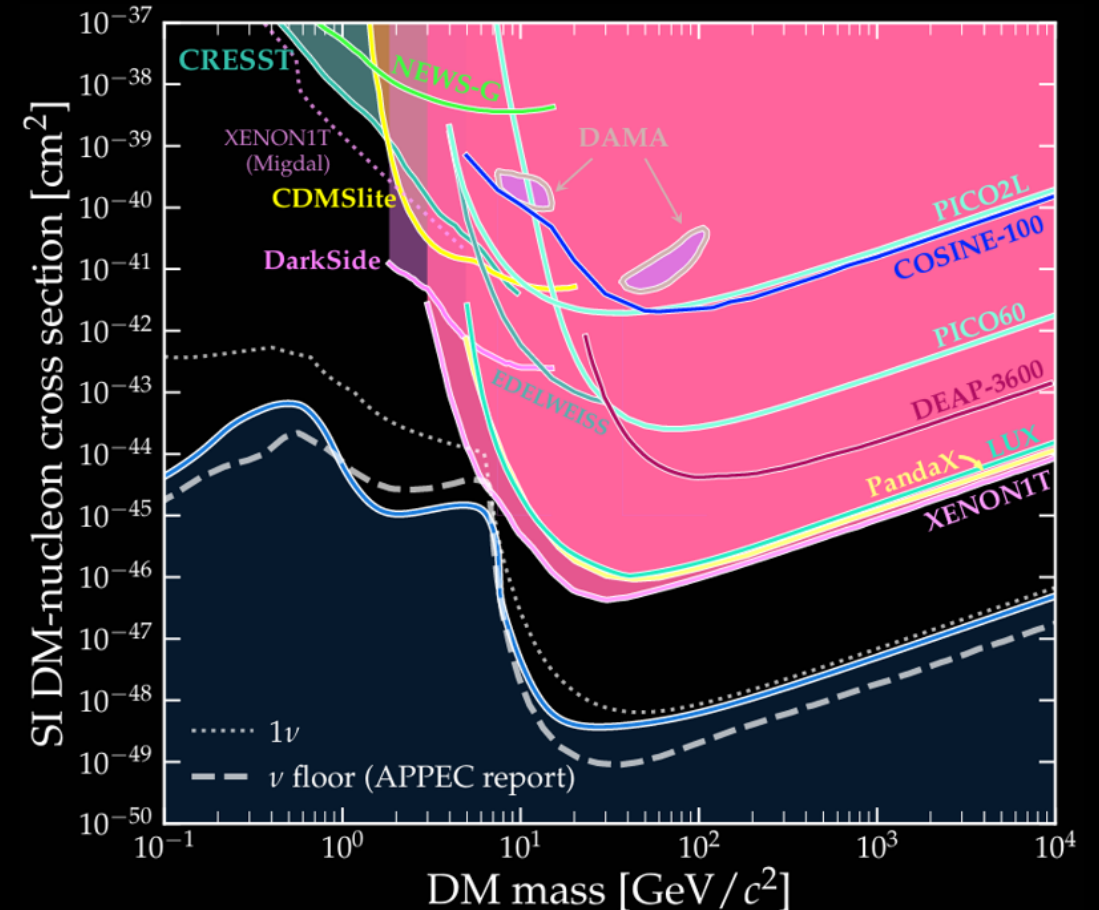


Figure: Ciaran A. J. O'Hare, Phys. Rev. Lett. 127, 251802 (2021)

Direct Detection Experiments

Tests of SM/BSM physics

- Neutrino-electron scattering in dark matter direct detectors can be used as tests of SM and BSM physics
- E.g.
 - Weak mixing angle (Maity & Bøehm, Phys. Rev. D 112, 053001 (2025))
 - Neutrino magnetic moment (Aprile et al., Phys. Rev. Lett. 129, 161805 (2022))
 - Non-Standard Neutrino Interactions (Amaral et al., JHEP 07 (2023) 071)

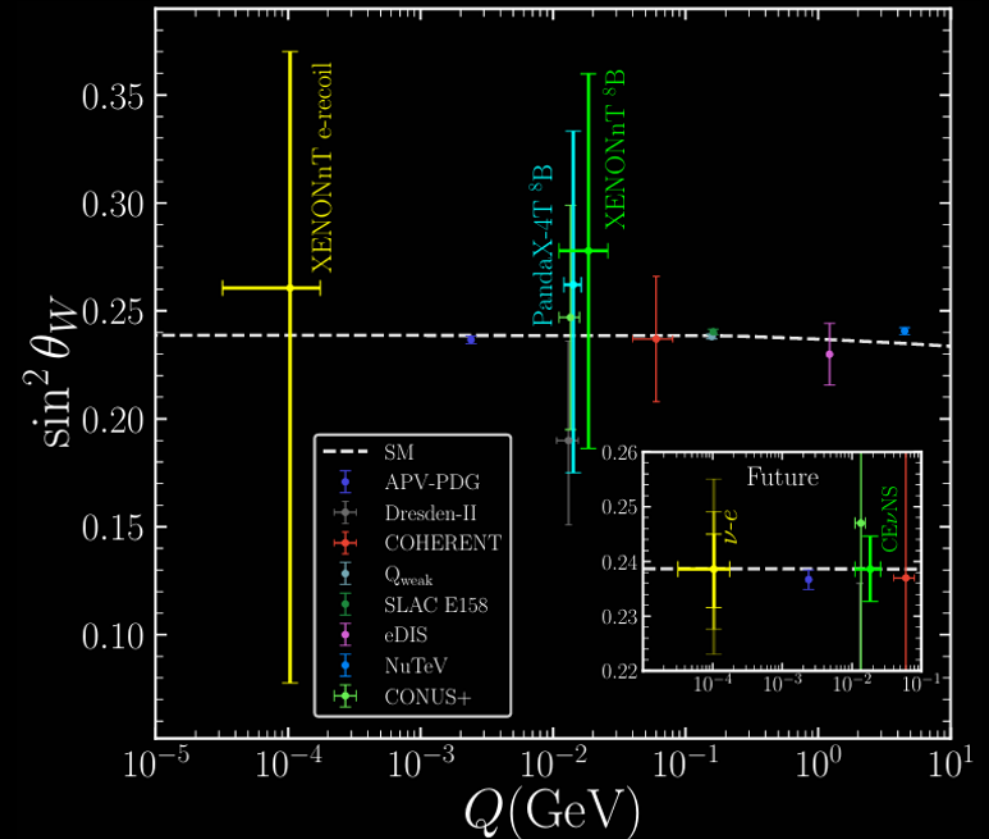


Figure: First constraint on the weak mixing angle using direct detection experiments. Maity & Bøehm, Phys. Rev. D 112, 053001 (2025)

Modelling ionisation signals

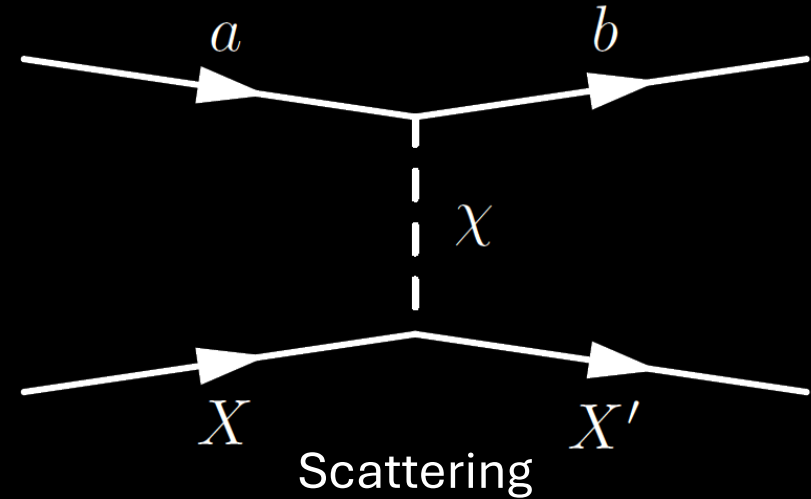
Using atomic physics

Modelling ionisation signals

Using atomic physics

Mass drops below nuclear mass:

- No nuclear recoils. Instead: electron recoils + ionisation
- See: A.R. Caddell, V.V. Flambaum, B.M. Roberts, Phys. Rev. D 108, 083030 (2023)



Modelling ionisation signals

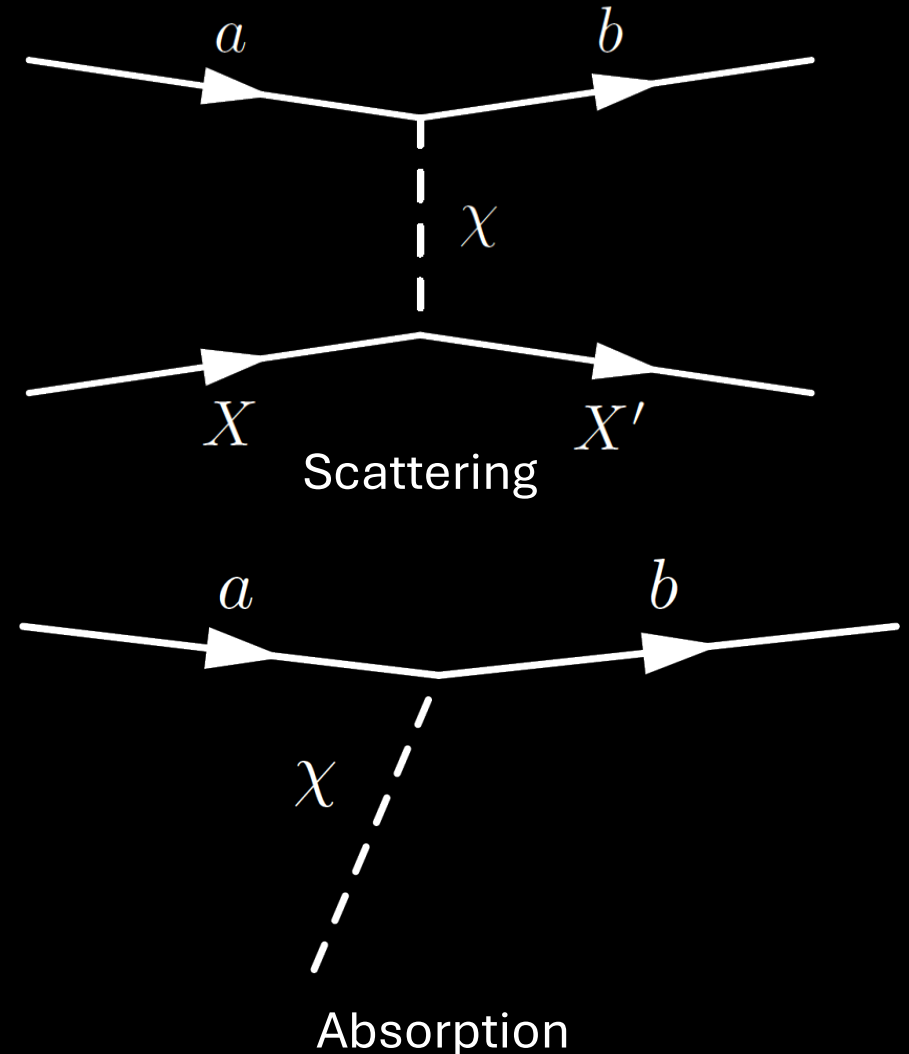
Using atomic physics

Mass drops below nuclear mass:

- No nuclear recoils. Instead: electron recoils + ionisation
- See: A.R. Caddell, V.V. Flambaum, B.M. Roberts, Phys. Rev. D 108, 083030 (2023)

Mass drops below electron mass:

- No electron recoils, instead: absorption
- Used to probe lower mass ranges



Modelling ionisation signals

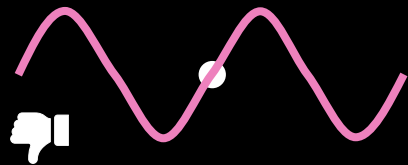
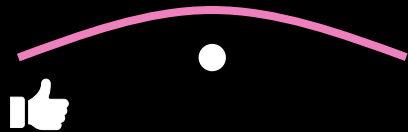
Usual Approximations Do Not Work!

Modelling ionisation signals

Usual Approximations Do Not Work!

Electric-dipole
approximation

$$e^{i\vec{q}\cdot\vec{r}} \approx 1$$

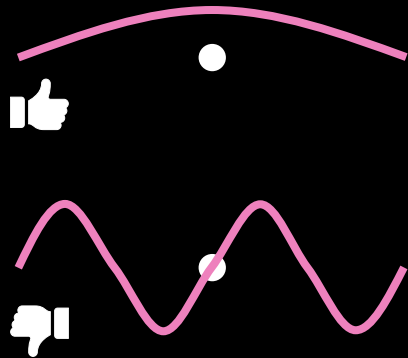


Modelling ionisation signals

Usual Approximations Do Not Work!

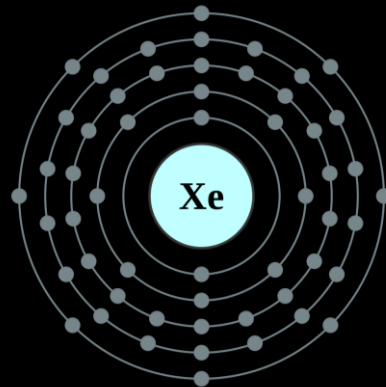
Electric-dipole
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Non-relativistic limit

$$\chi \approx \frac{\vec{\sigma} \cdot \vec{p}}{2mc} \phi$$

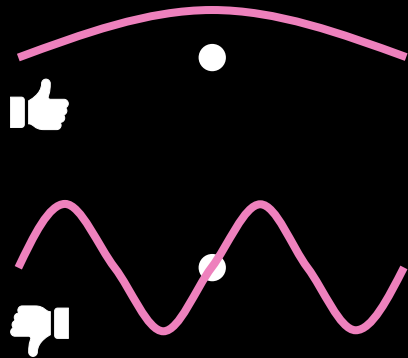


Modelling ionisation signals

Usual Approximations Do Not Work!

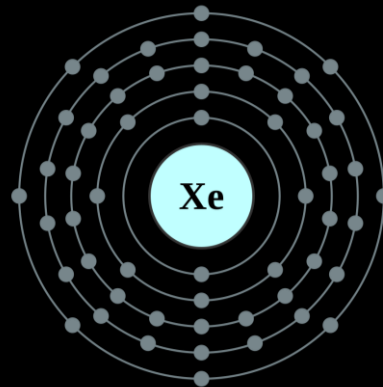
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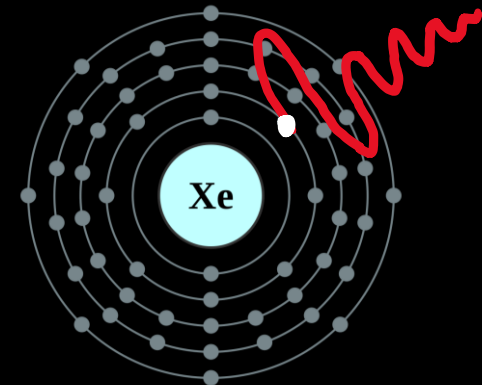
Non-relativistic limit

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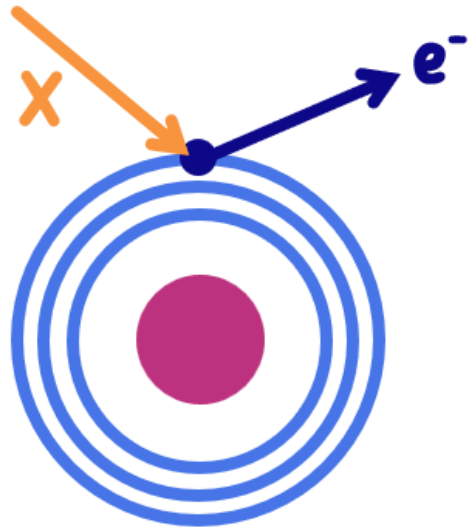
Plane-wave
approximation

$$|f\rangle \sim e^{i\vec{q}\cdot\vec{r}}$$

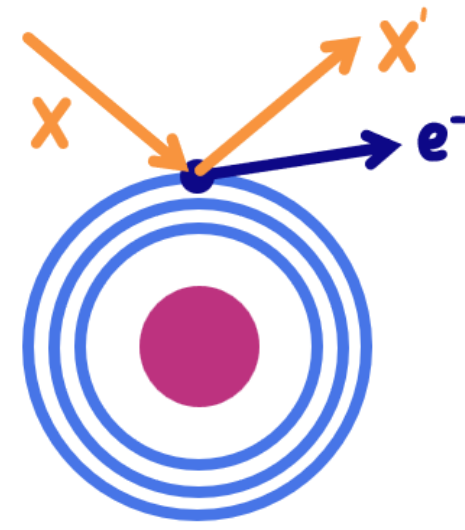


General method of ionisation

For scattering and absorption



Absorption



Scattering

General method of ionisation

For scattering and absorption

$$d\sigma \sim F^2 |w_\mu J^\mu|^2$$

General method of ionisation

For scattering and absorption

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Particle Physics



General method of ionisation

For scattering and absorption

$$d\sigma \sim F^2 |w_\mu J^\mu|^2$$

Particle Physics

Scattering/absorbing
particle current

General method of ionisation

For scattering and absorption

$$d\sigma \sim F^2 |w_\mu J^\mu|^2$$

Particle Physics

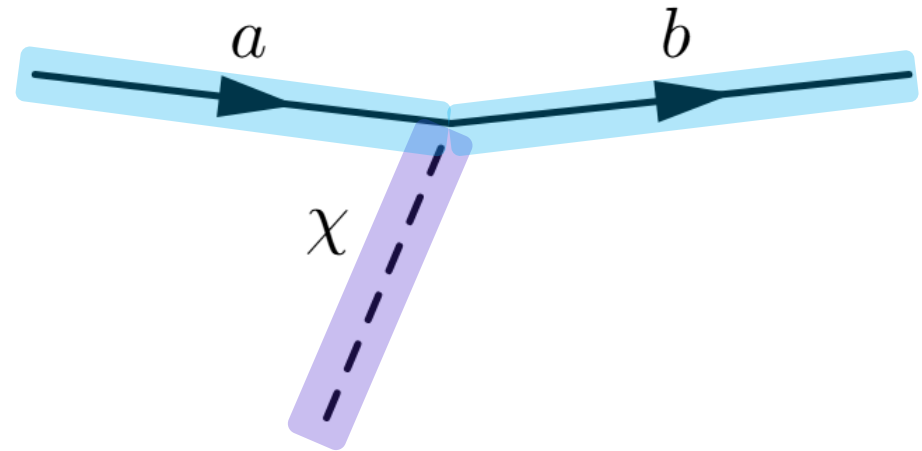
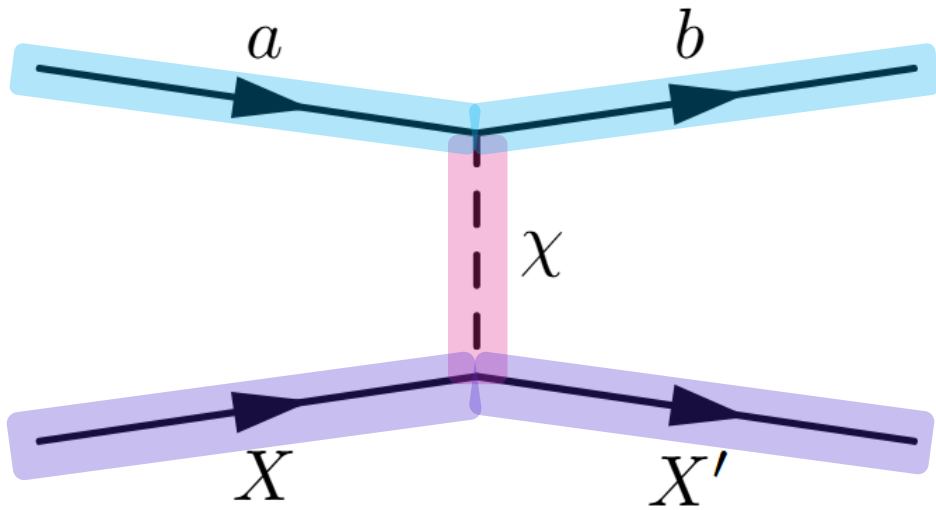
Scattering/absorbing
particle current

Atomic current

General method of ionisation

For scattering and absorption

$$d\sigma \sim F^2 |w_\mu J^\mu|^2$$



General method of ionisation

For scattering and absorption

For a **vector** interaction, we want to calculate the matrix element:

$$\bar{\psi} e^{i\mathbf{q}\cdot\mathbf{r}} \gamma^\mu \psi$$

General method of ionisation

For scattering and absorption

For a vector interaction, we want to calculate the matrix elements:

$$\bar{\psi} e^{i\mathbf{q}\cdot\mathbf{r}} \gamma^0 \psi$$

Temporal

$$\bar{\psi} e^{i\mathbf{q}\cdot\mathbf{r}} \vec{\gamma} \psi$$

Spatial

General method of ionisation

For scattering and absorption

For an **axial** interaction, we want to calculate the matrix elements:

$$\bar{\psi} e^{iqr} \gamma^0 \gamma^5 \psi$$

Axial Temporal

$$\bar{\psi} e^{iqr} \vec{\gamma} \gamma^5 \psi$$

Axial Spatial

General method of ionisation

For scattering and absorption

For a scalar interaction, we want to calculate the matrix elements:

$$\bar{\psi} e^{i\mathbf{q}\cdot\mathbf{r}} \psi$$

General method of ionisation

For scattering and absorption

For a **pseudoscalar** interaction, we want to calculate the matrix elements:

$$\bar{\psi} e^{iqr} \gamma^5 \psi$$

General method of ionisation

For scattering and absorption

We can write decompose our spatial terms into 3 components:

$$|\boldsymbol{w}_{\perp}|^2$$

Transverse (Electric + Magnetic)

$$|\hat{\boldsymbol{q}} \cdot \boldsymbol{w}|^2$$

Longitudinal

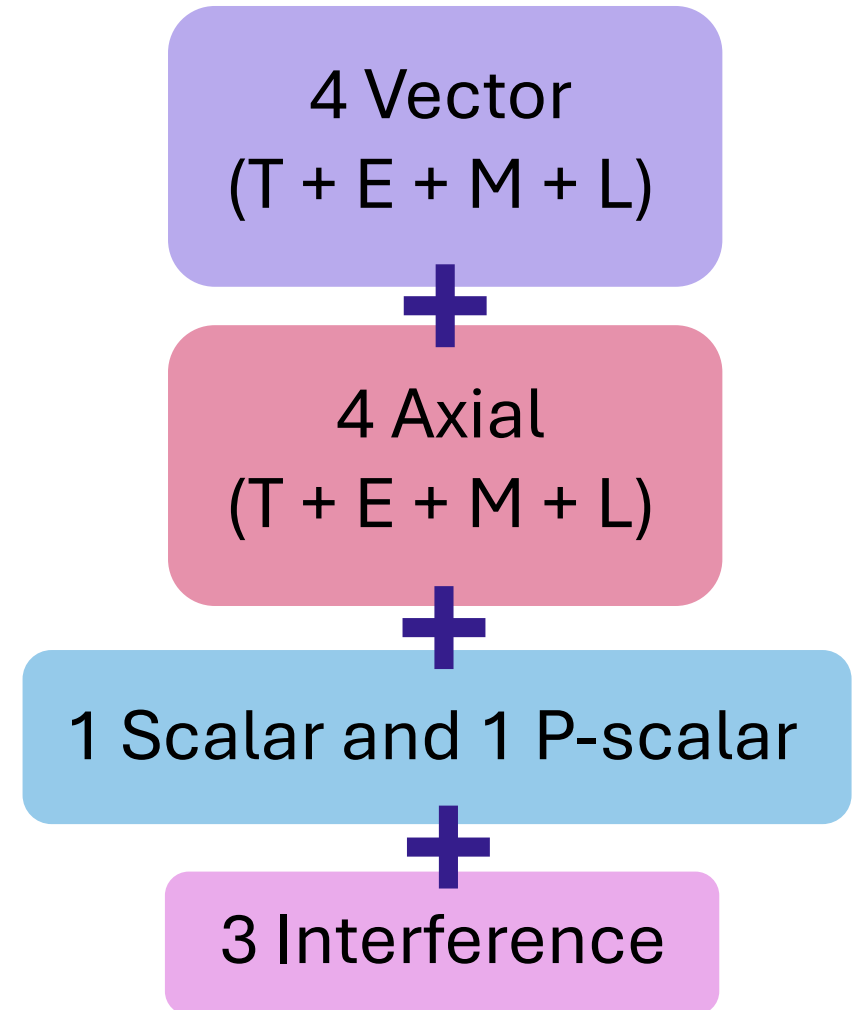
This is **completely general** for the vector $\boldsymbol{w}$

General method of ionisation

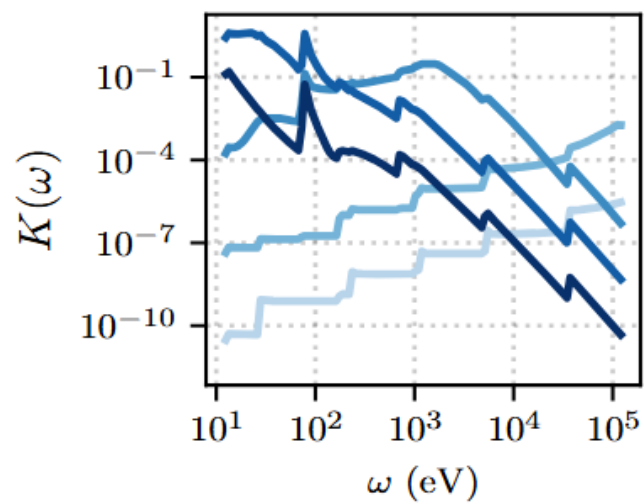
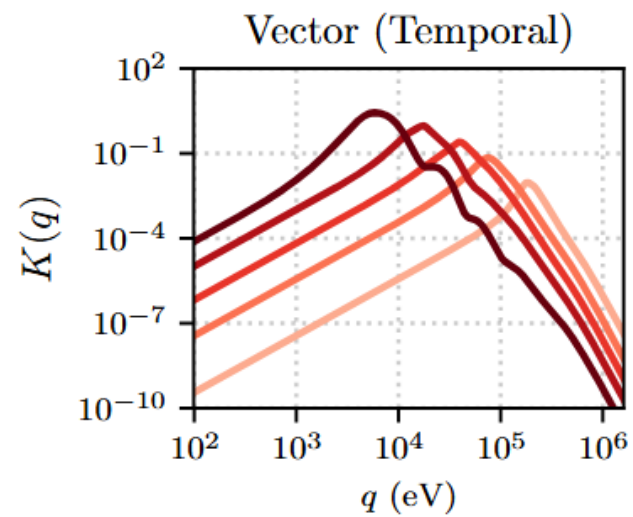
For scattering and absorption

We only need to calculate **13 components** of the atomic current to calculate any process.

Includes interference terms for axial-vector interactions.

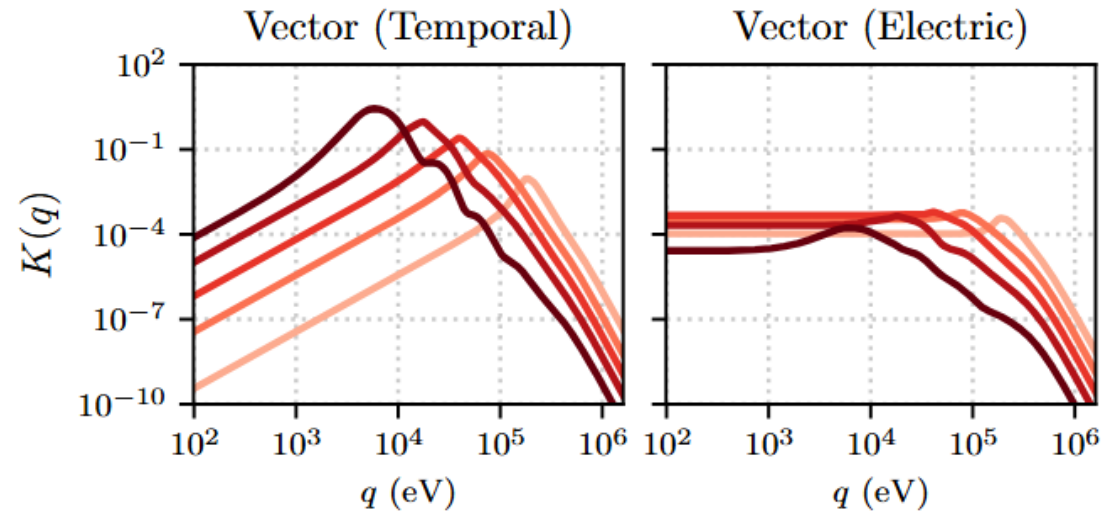


$$J^\mu(q, \omega)$$

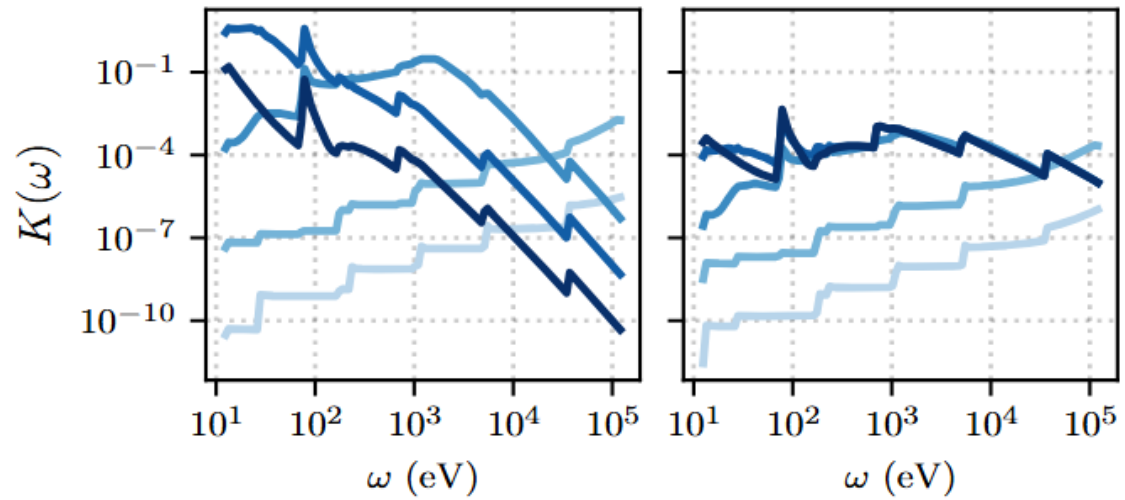


Preliminary

$$J^\mu(q, \omega)$$

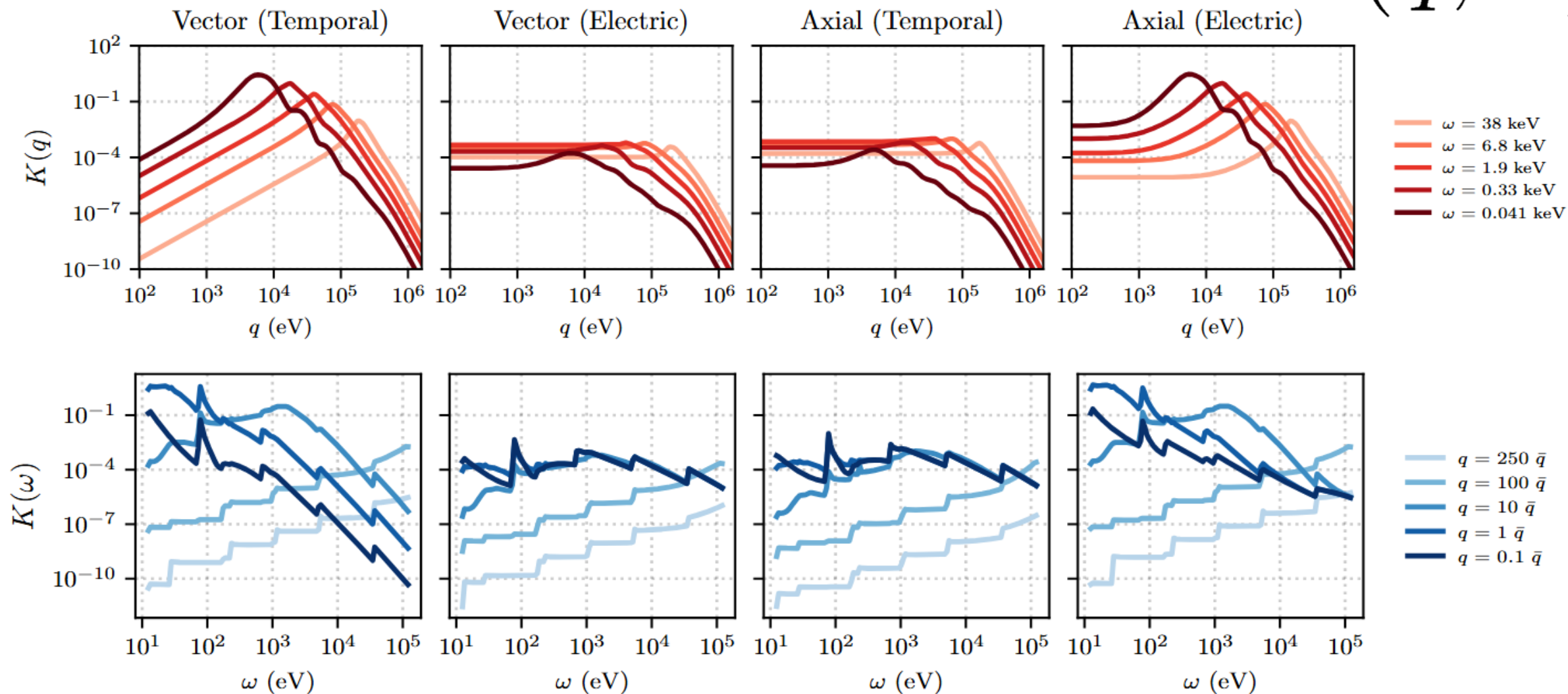


+ Magnetic and Longitudinal



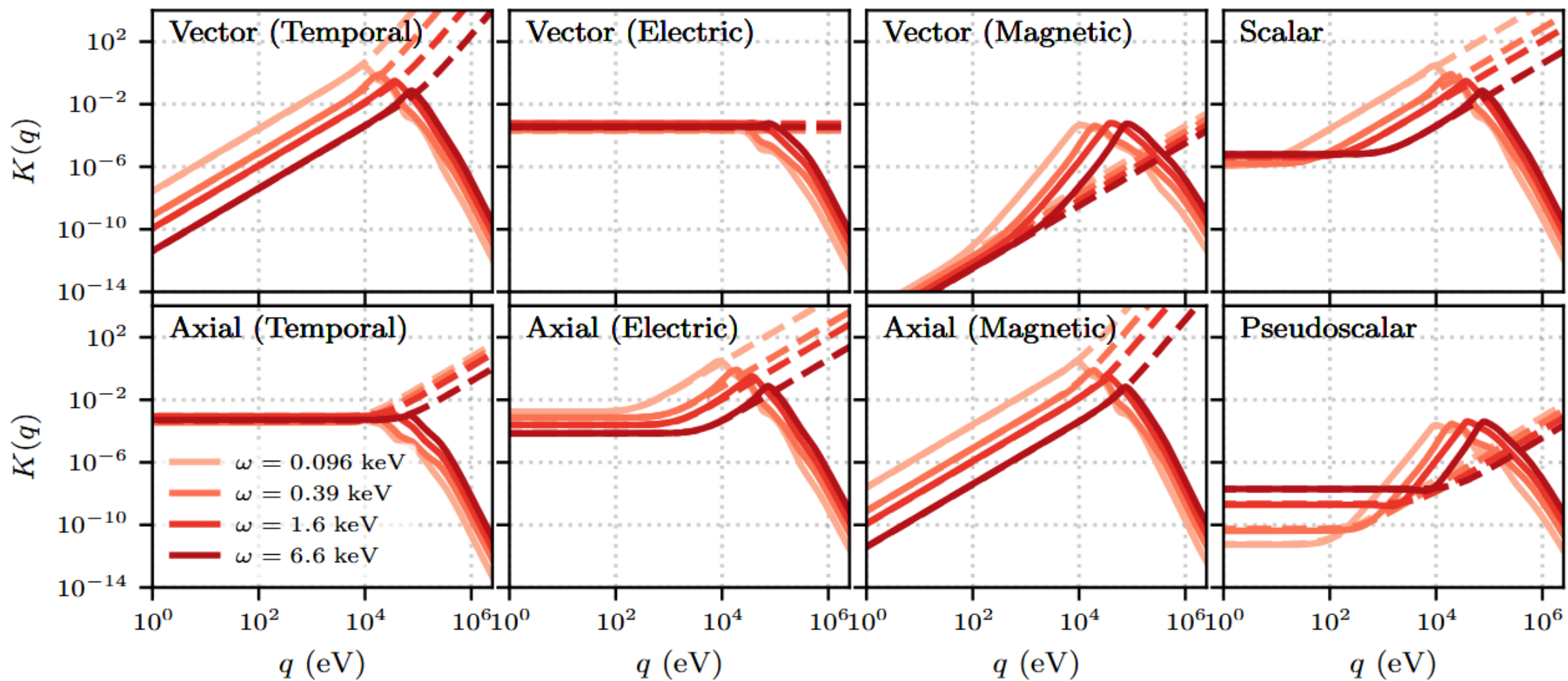
Preliminary

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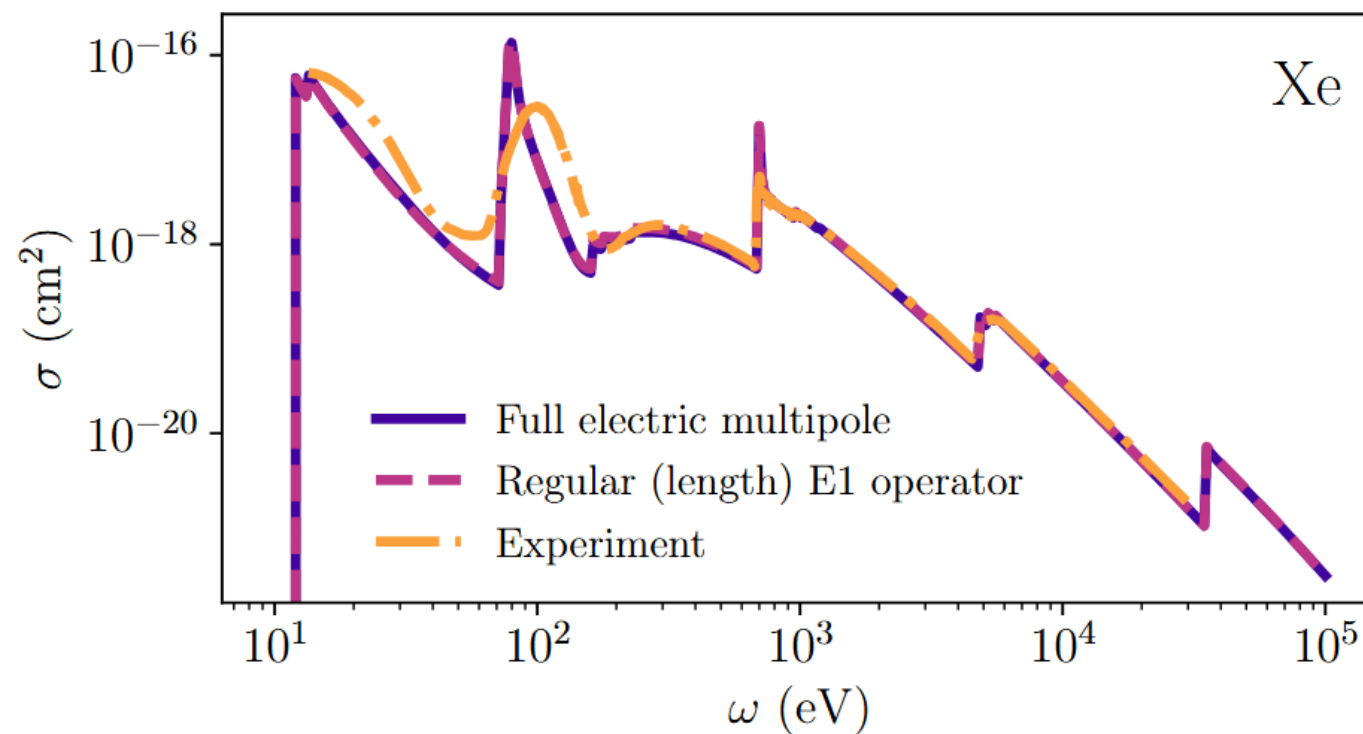
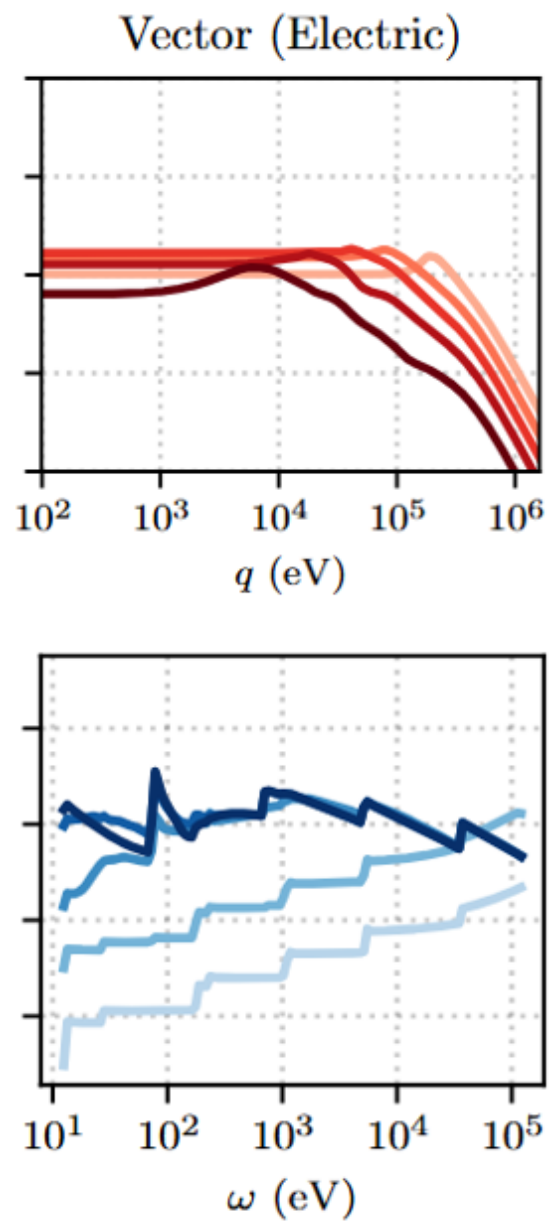


Preliminary

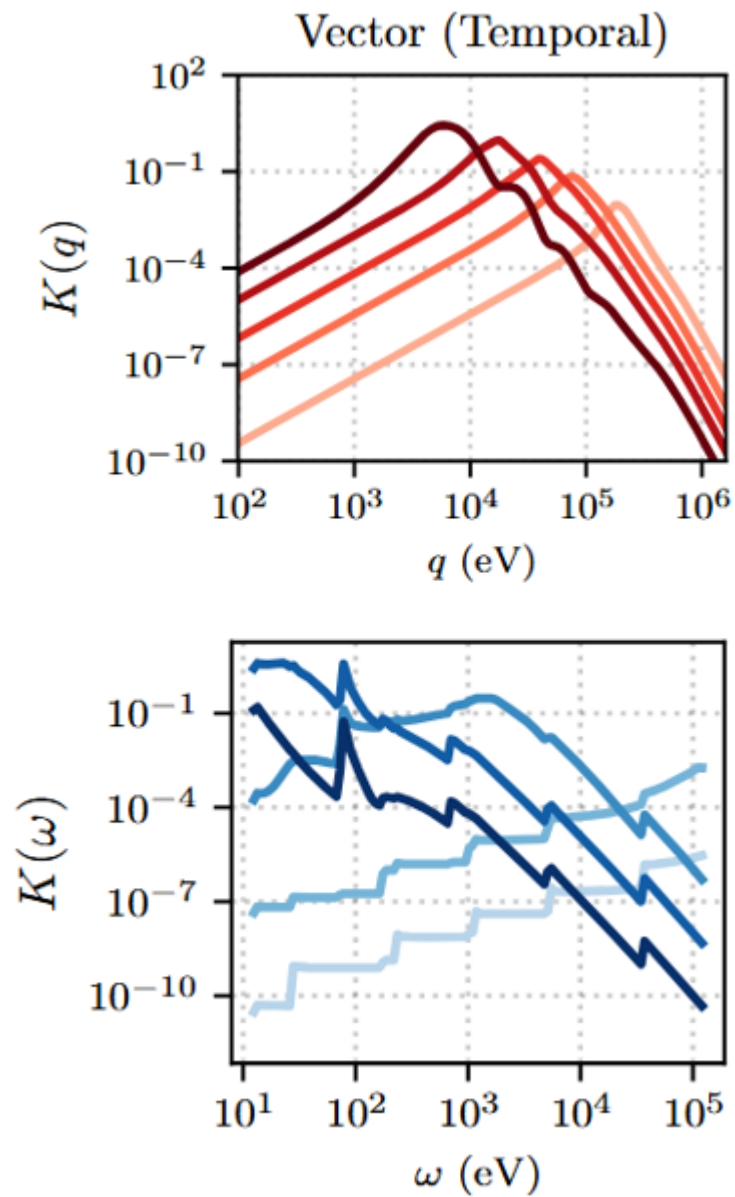
Low Momentum Transfer (Dipole) Limit



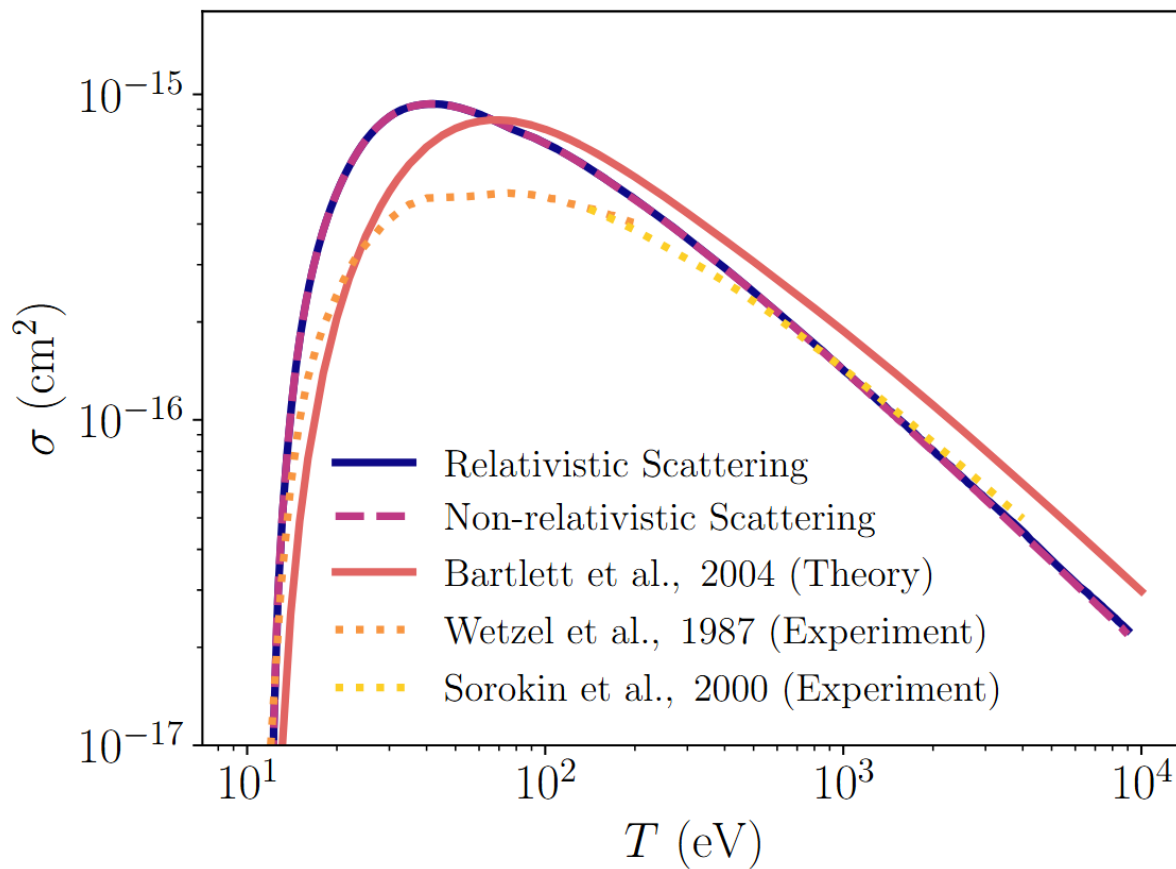
Photoionisation



Preliminary

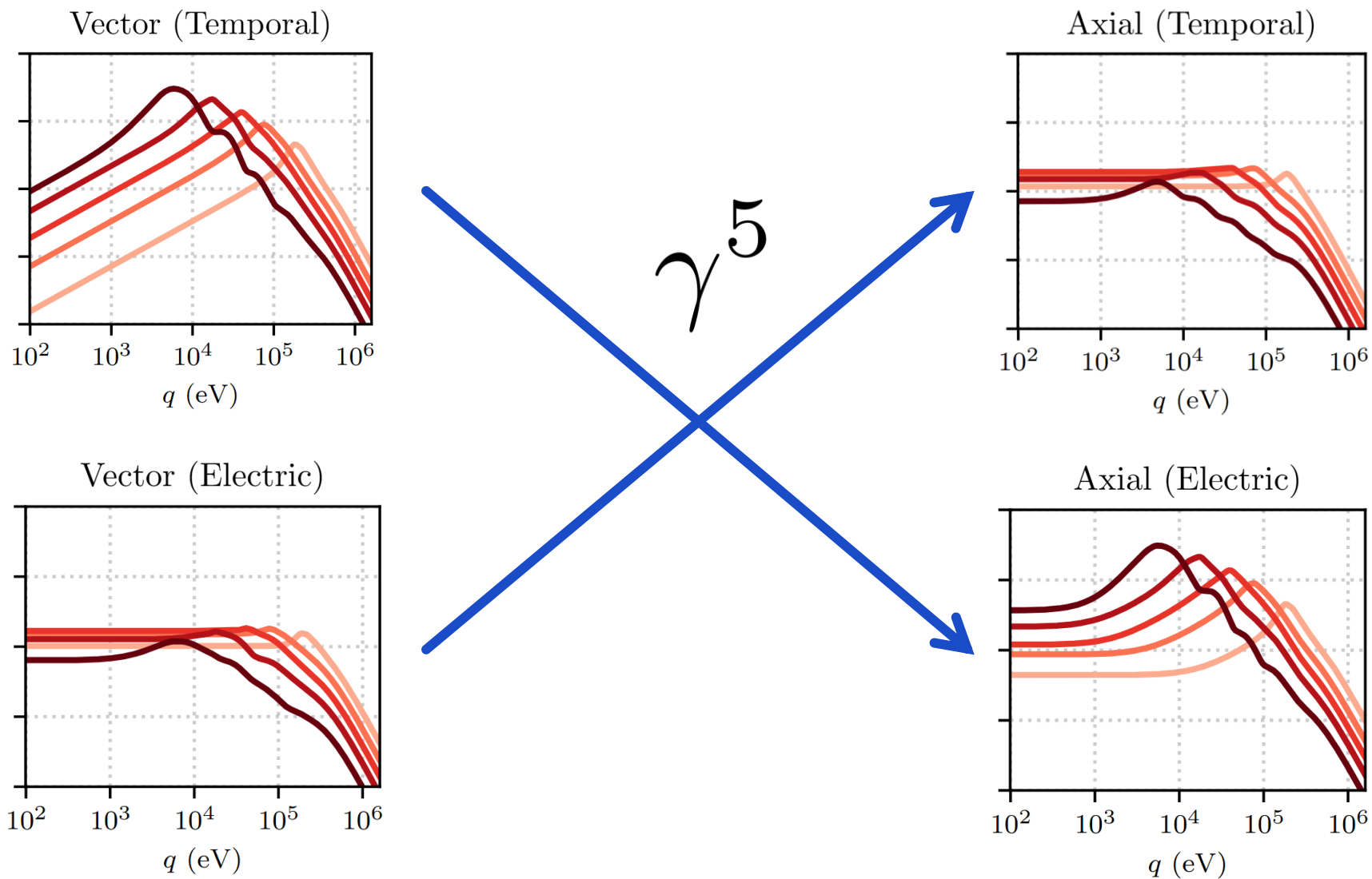


Electron-Impact Ionisation



Preliminary

Checking Axial Parts



General method of ionisation

Summary

This method can be applied to a range of interactions including:

- Standard Model Interactions
- Low-mass DM $\sim$ eV – GeV
- Neutrino-electron scattering (paper in preparation in collaboration with Andrew Cheek and Yevgeny Stadnik)

Completely general; relativistic

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