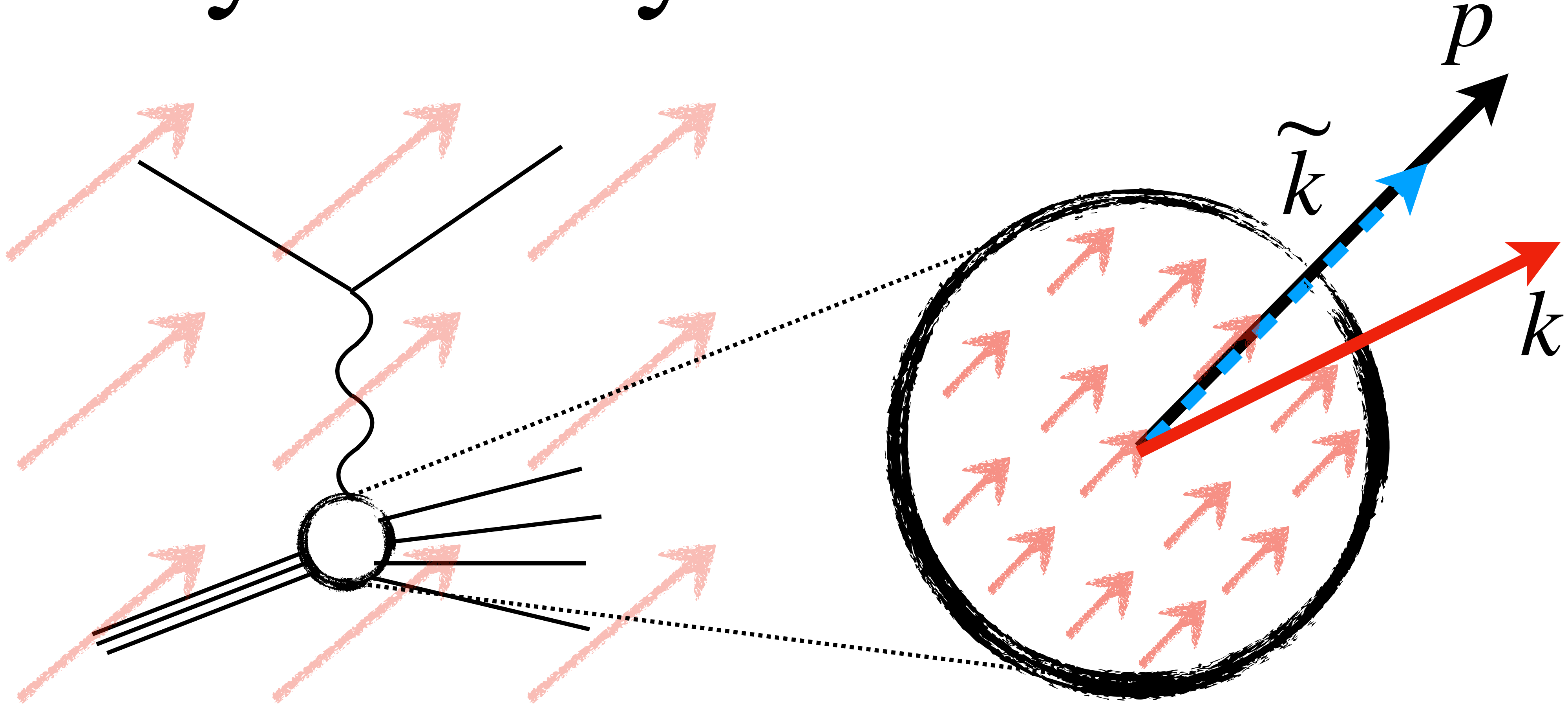
Testing Lorentz and CPT symmetry at the EIC



Based on: arXiv:1911.04002; PRD **98**, 115018 (2018); PLB **769**, 272 (2017)

Nathan Sherrill, Enrico Lunghi
Indiana University

1st EIC Yellow Report Workshop
Temple University

http://www.indiana.edu/~iucss/

What is Lorentz violation?

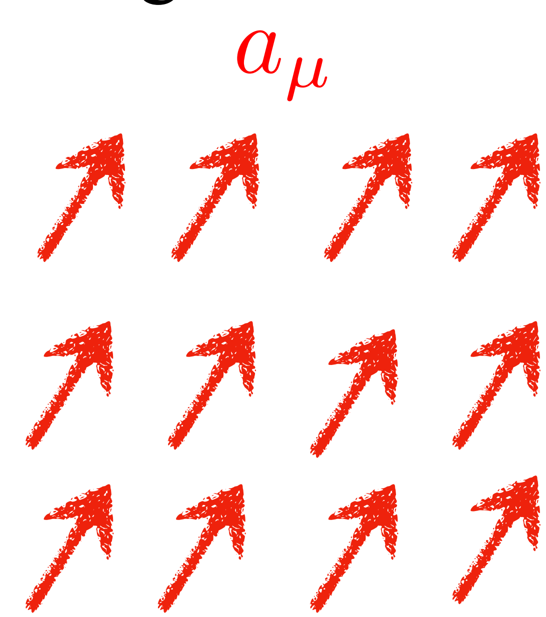
Lorentz invariance: Experimental results do not depend on the orientation of the laboratory/system or its velocity through space

Consider operators

$$\mathcal{O}^{\mu\nu\cdots} \supset \bar{\psi}\gamma^\mu\psi, \quad \bar{\psi}\gamma^\mu iD^\nu\psi, \quad \cdots \qquad \mathcal{L}_{\rm LI} \not\supset \mathcal{O}^{\mu\nu}$$

Make coordinate scalars by contracting with objects possessing Lorentz indices!

E.g. $\mathcal{L}_a \supset -a_\mu\bar{\psi}\gamma^\mu\psi, \quad [a_\mu] = [\mathrm{GeV}]$



a_μ is a fixed background vector field filling the vacuum

Generic terms: $$\mathcal{L}_{\rm LV} = \sum_i k_{i\,\mu\nu\ldots}\mathcal{O}_i^{\mu\nu\cdots}$$

= EFT test framework = Standard-Model Extension (SME)

$\Longrightarrow$ D. Colladay, V. A. Kostelecký, PRD 55, 6760 (1997); PRD 58, 1166002 (1998)

What is Lorentz violation?

What effects are induced by $\mathcal{L}_a$?

An observer Lorentz transformation is a coordinate transformation

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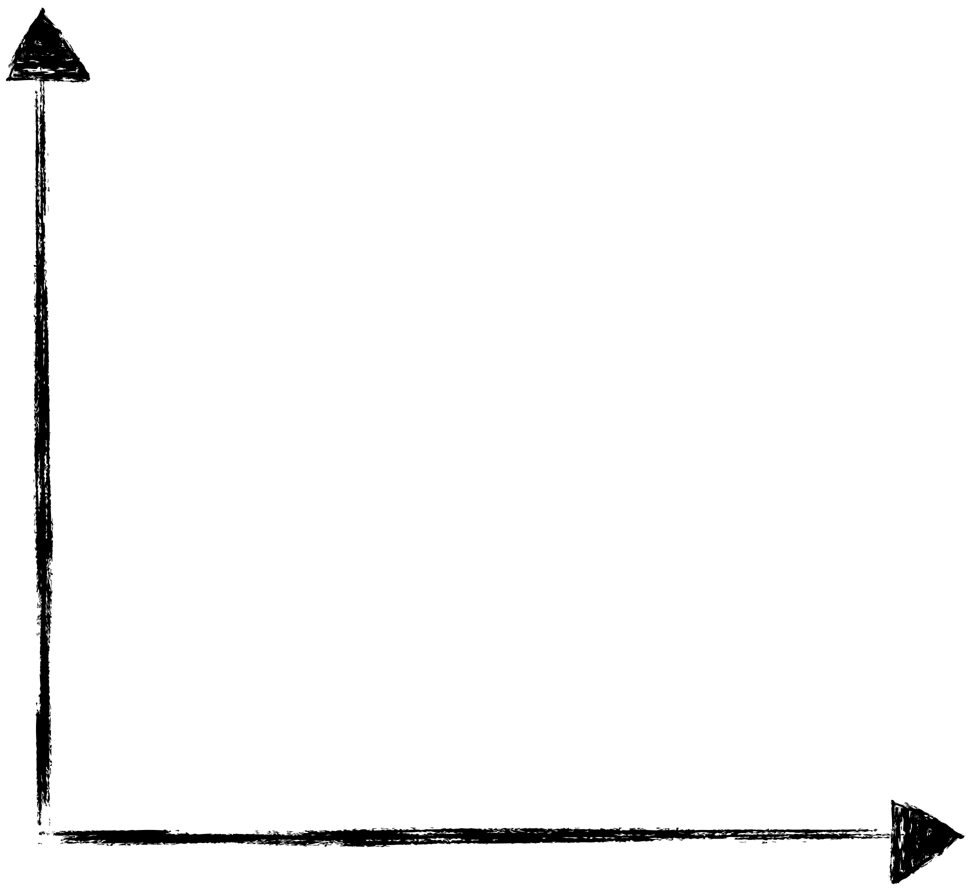

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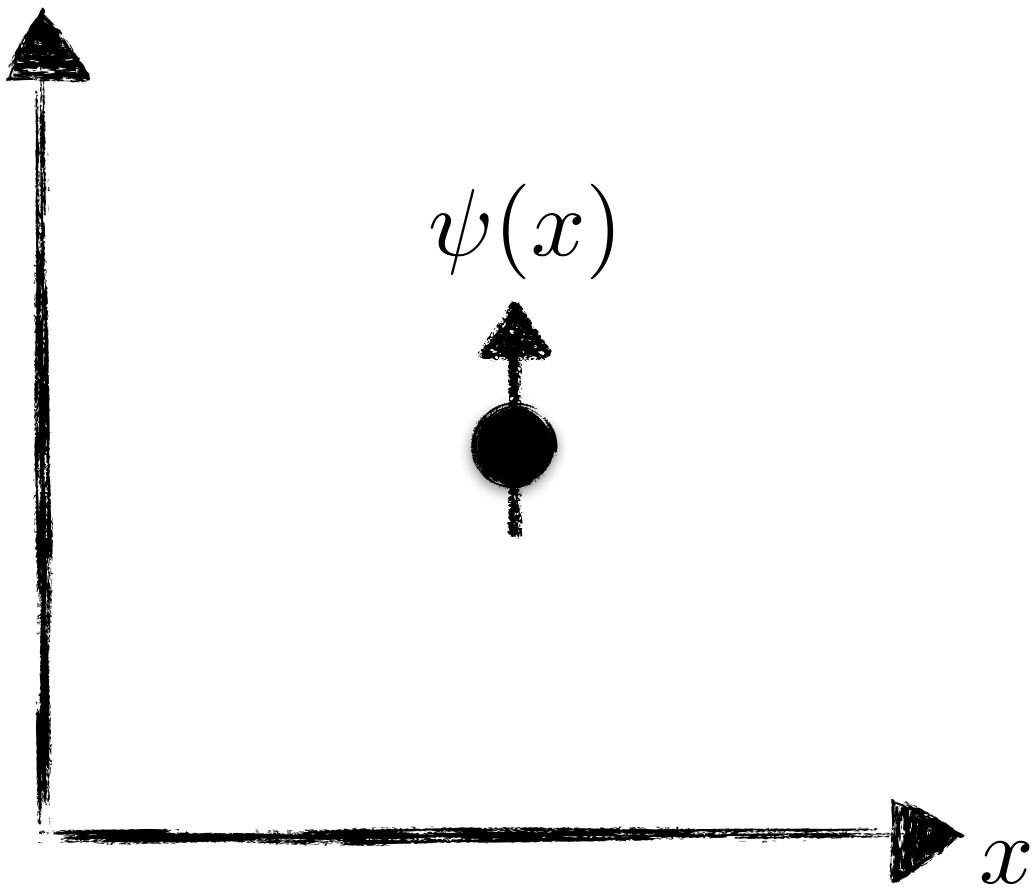

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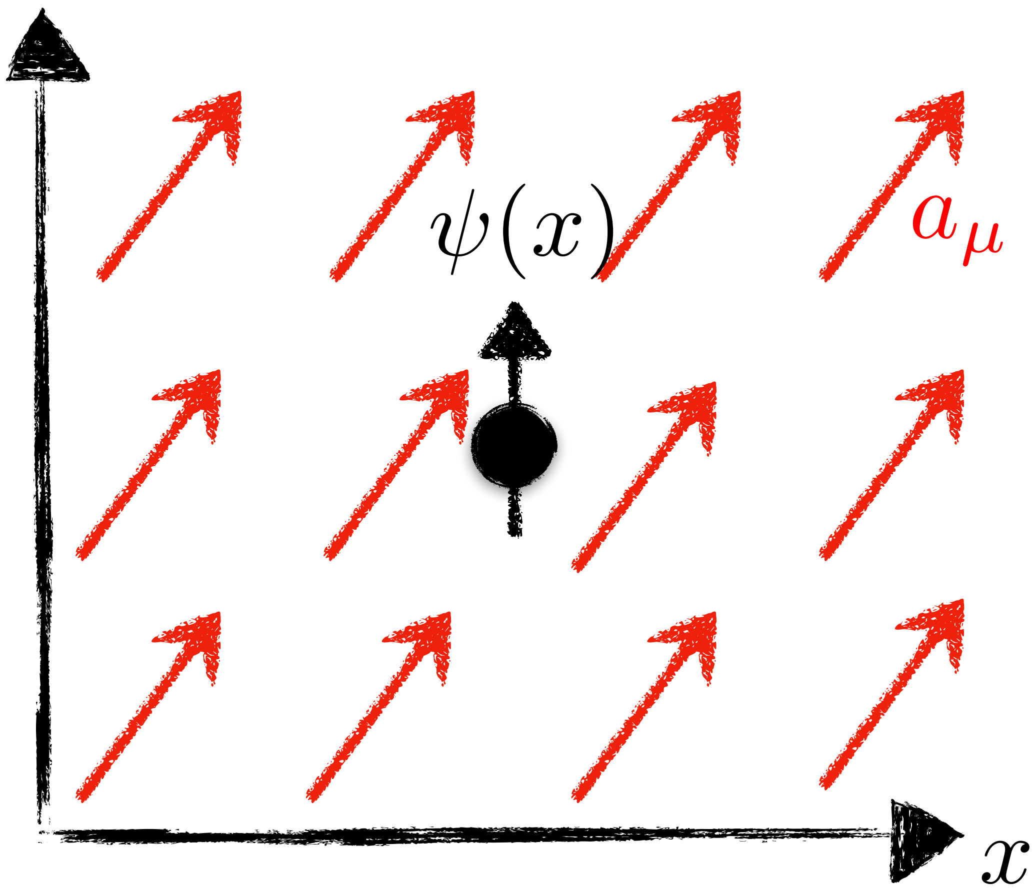

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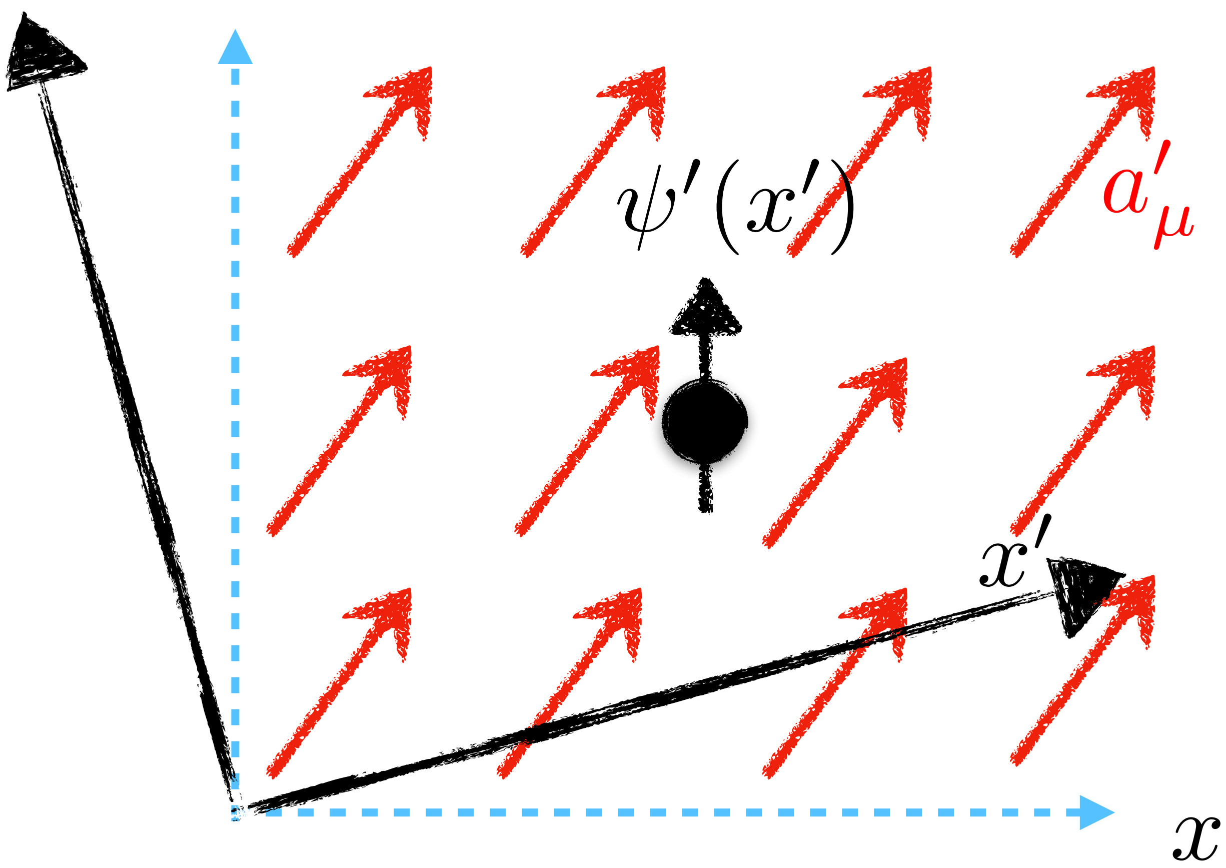

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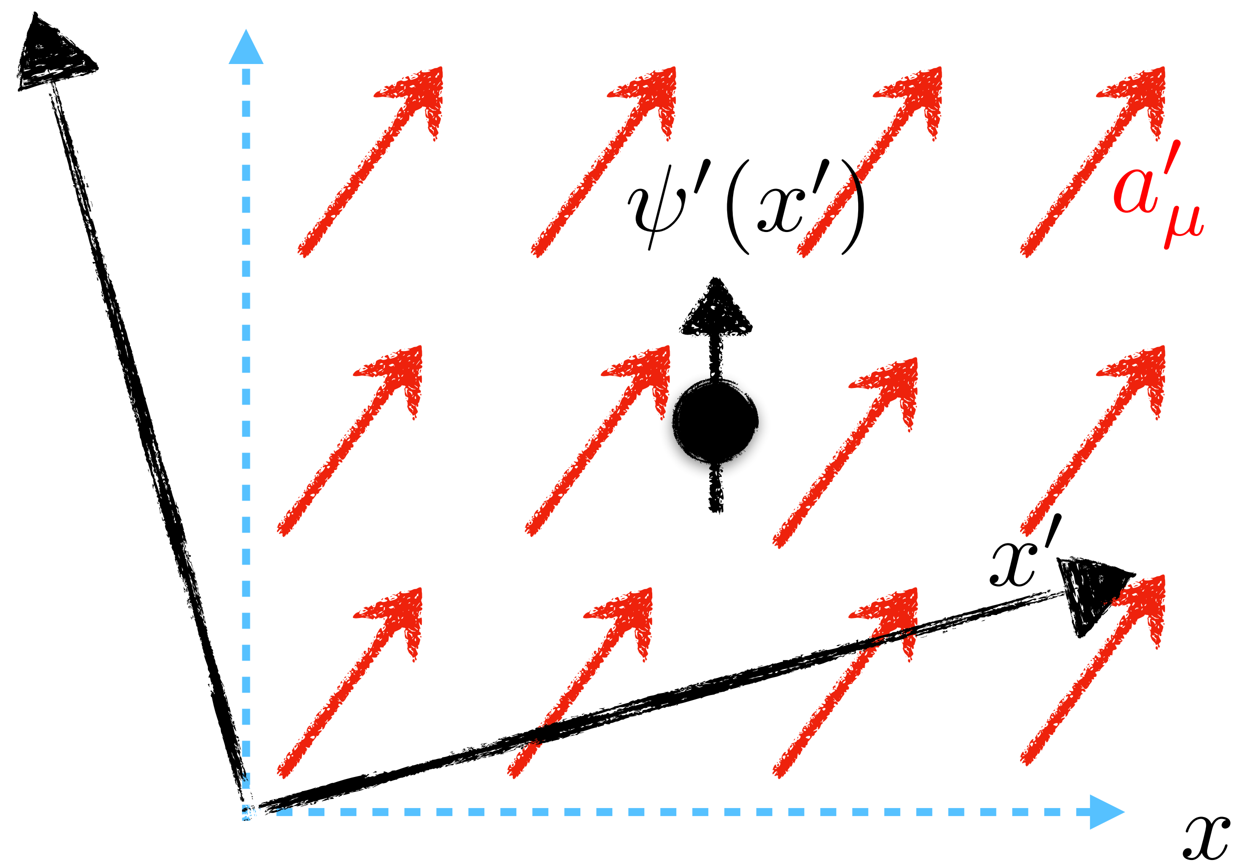

$$a^\mu \to \Lambda^\mu{}_\nu a^\nu$$

$$\psi(x) \to \psi'(x') = S\psi(x)$$

$$-a_\mu \bar{\psi}\gamma^\mu\psi \to -a_\mu \bar{\psi}\gamma^\mu\psi$$

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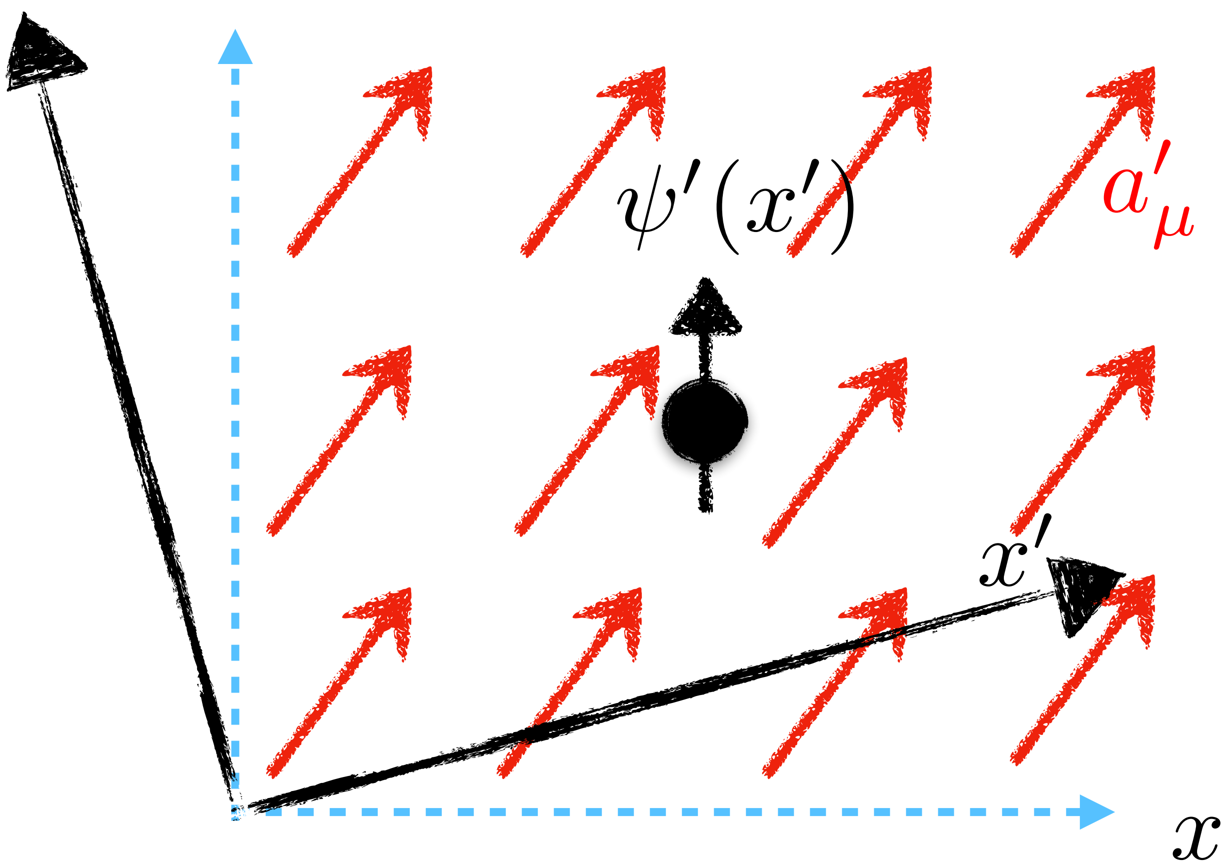

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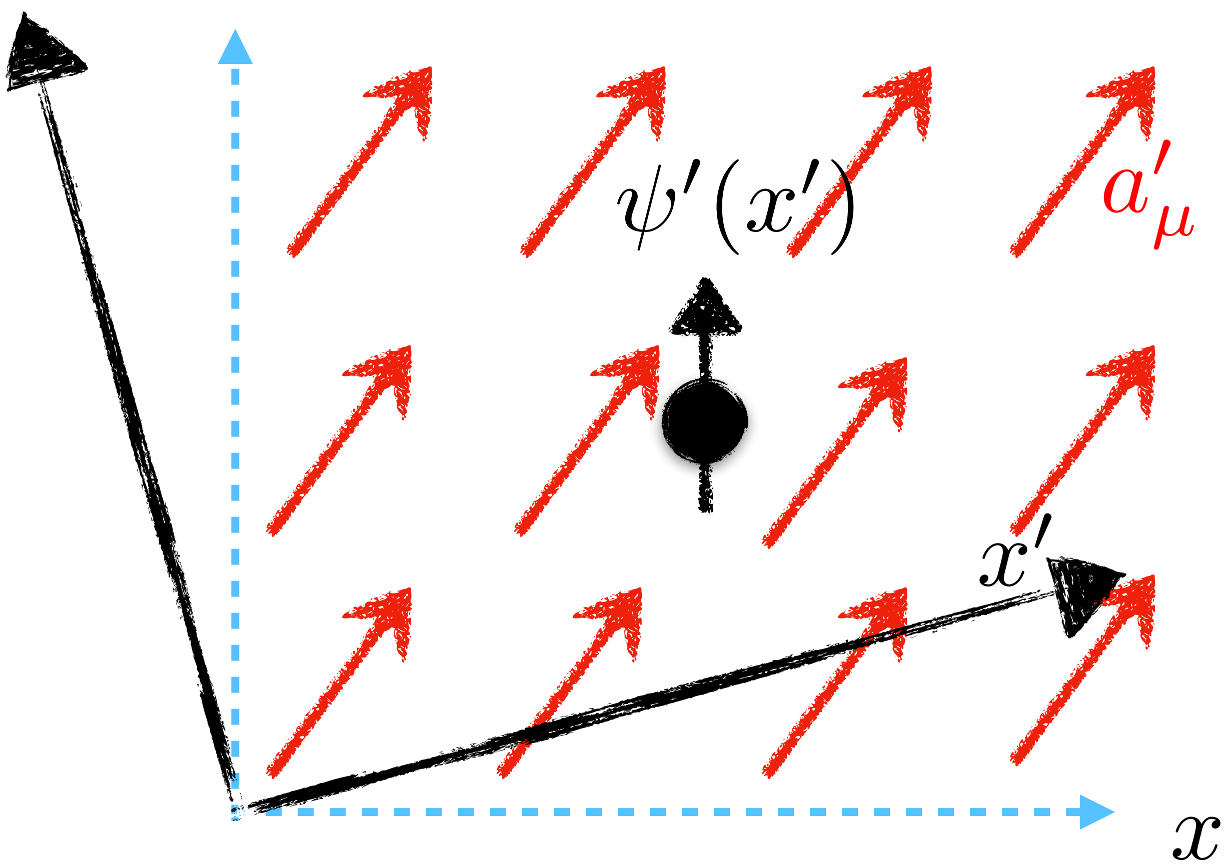

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Under an observer transformation the background a_μ transforms like an ordinary four vector

$\Rightarrow$ No change in the physics!

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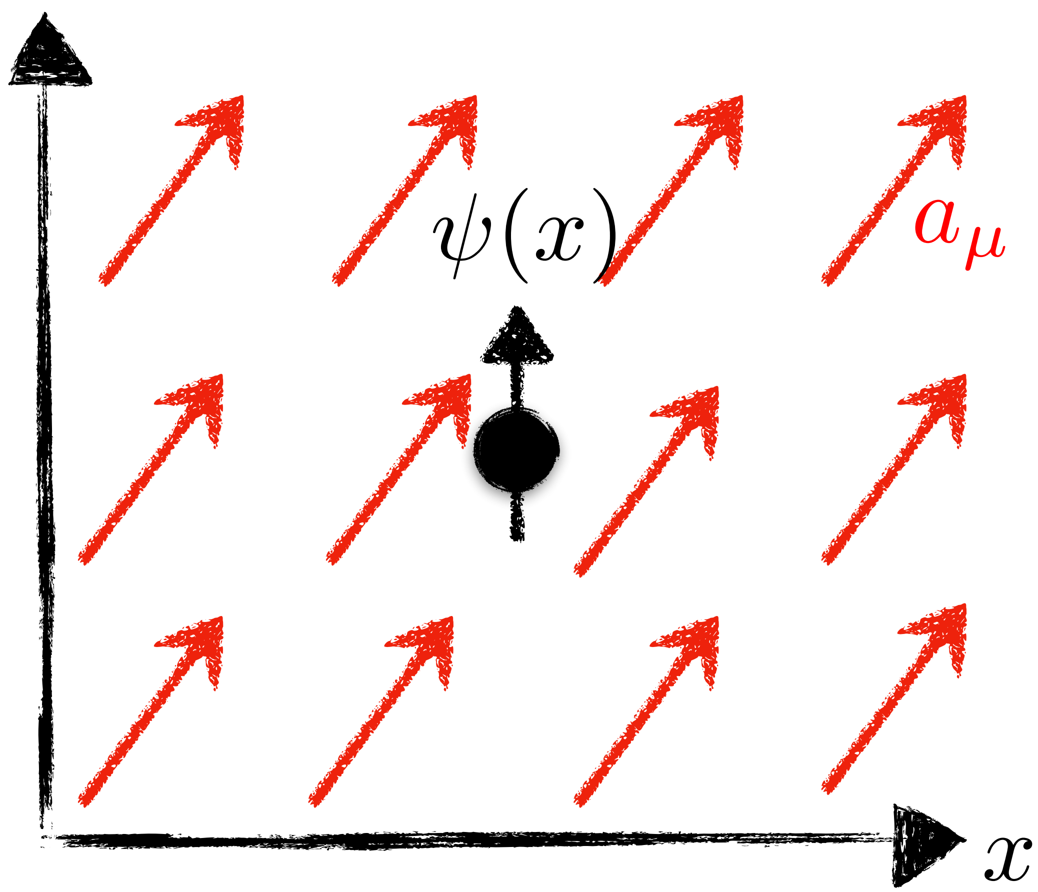

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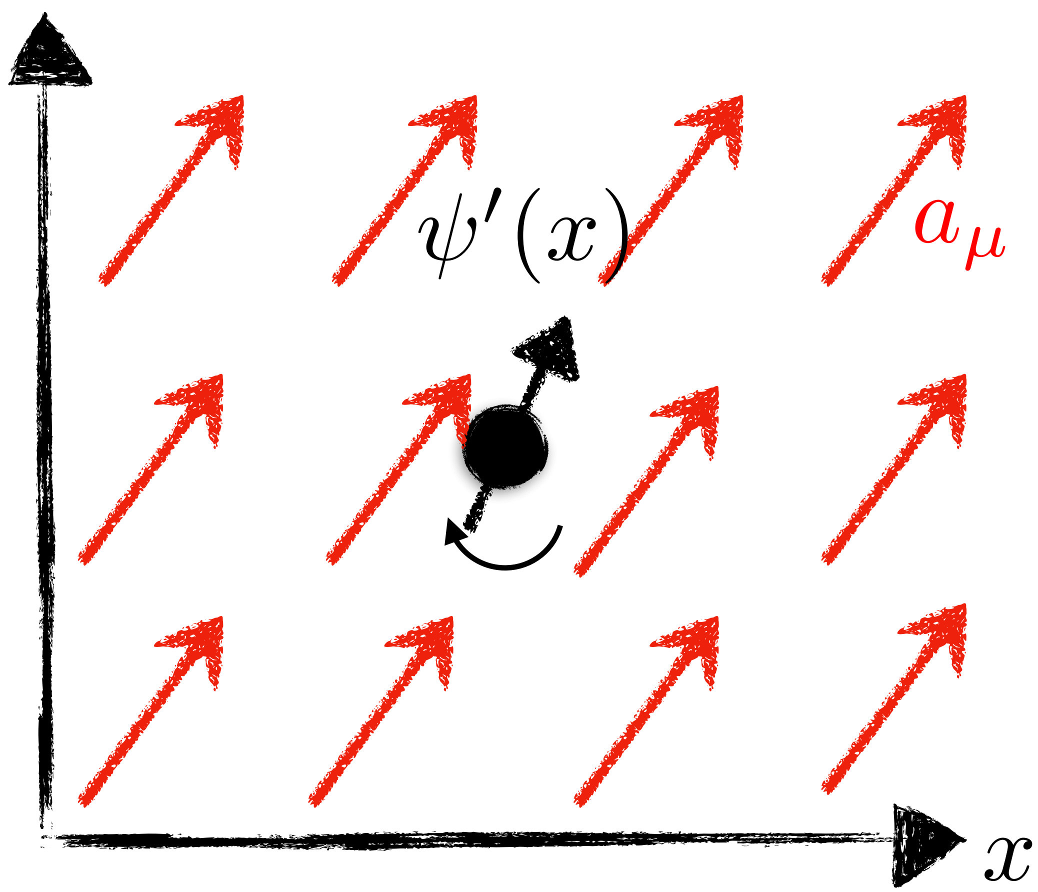

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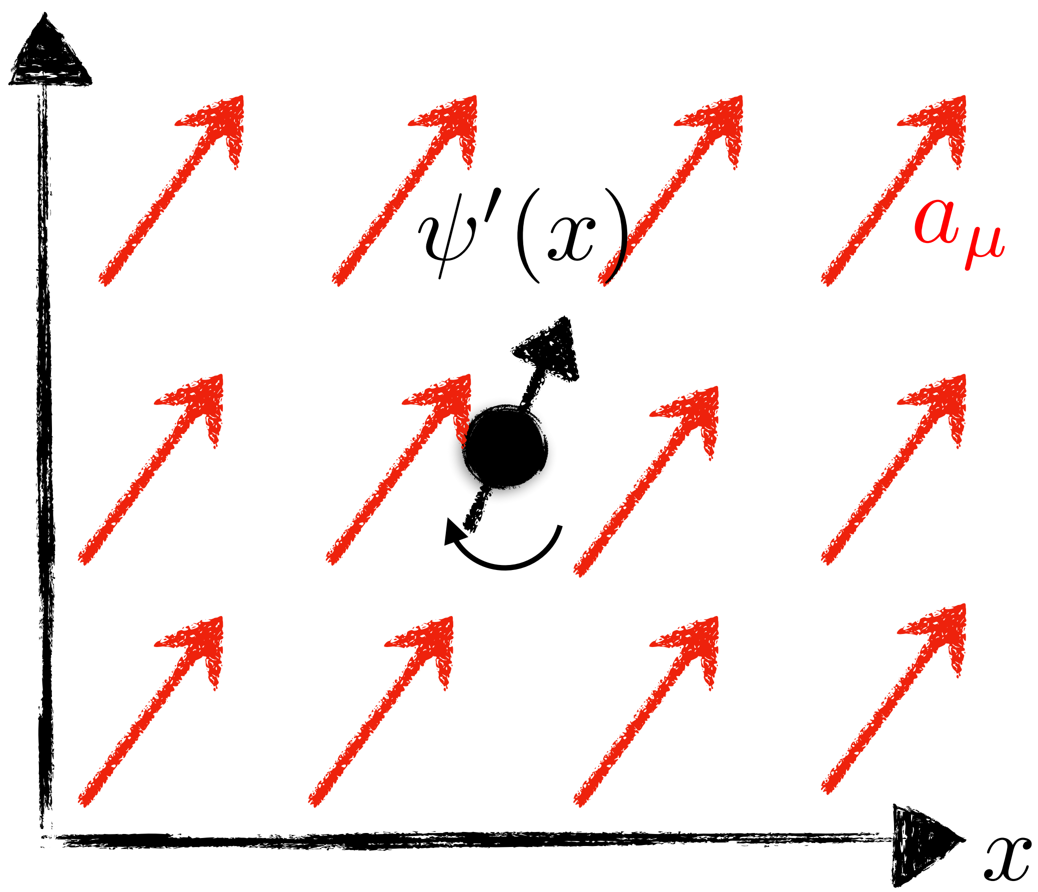

$$a_\mu \rightarrow a_\mu$$

$$\psi(x) \rightarrow \psi'(x) = S\psi(\Lambda^{-1}x)$$

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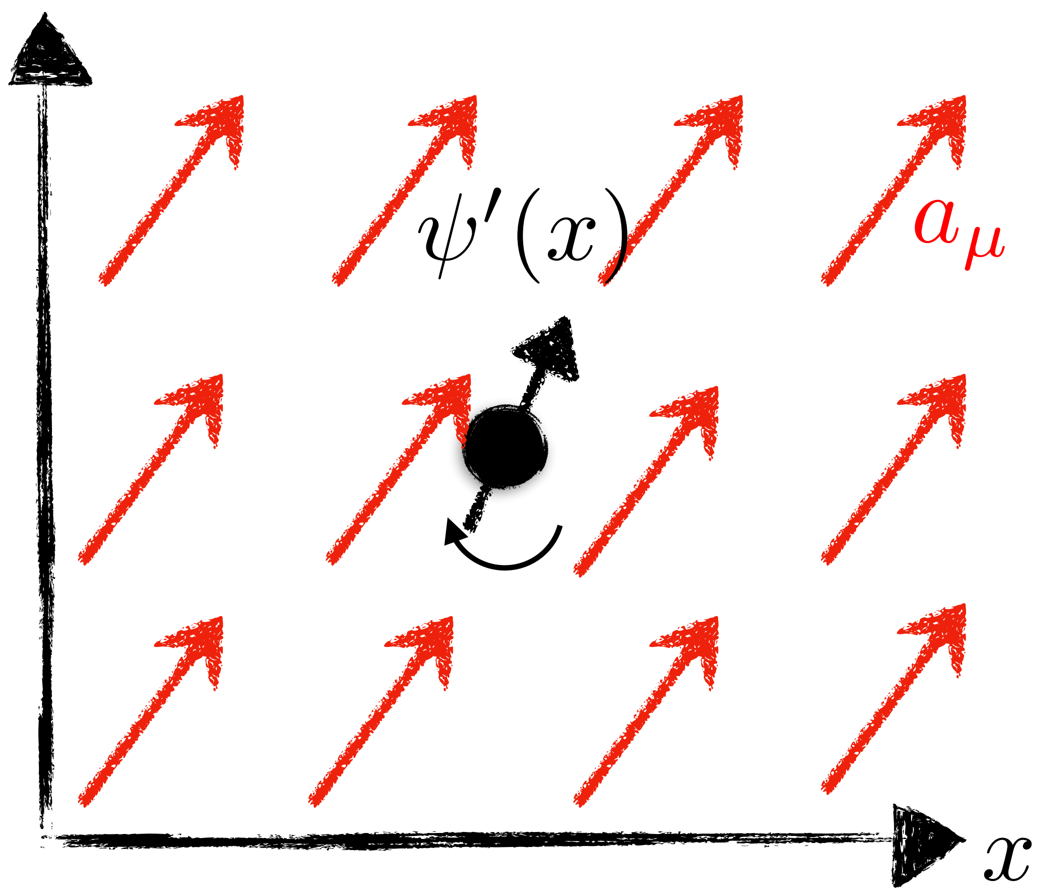

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Net physical effect

$$-a_\mu \bar{\psi}\gamma^\mu\psi \to -\left(\Lambda^{-1}\right)_{\mu\nu} a^\nu \bar{\psi}\gamma^\mu\psi$$

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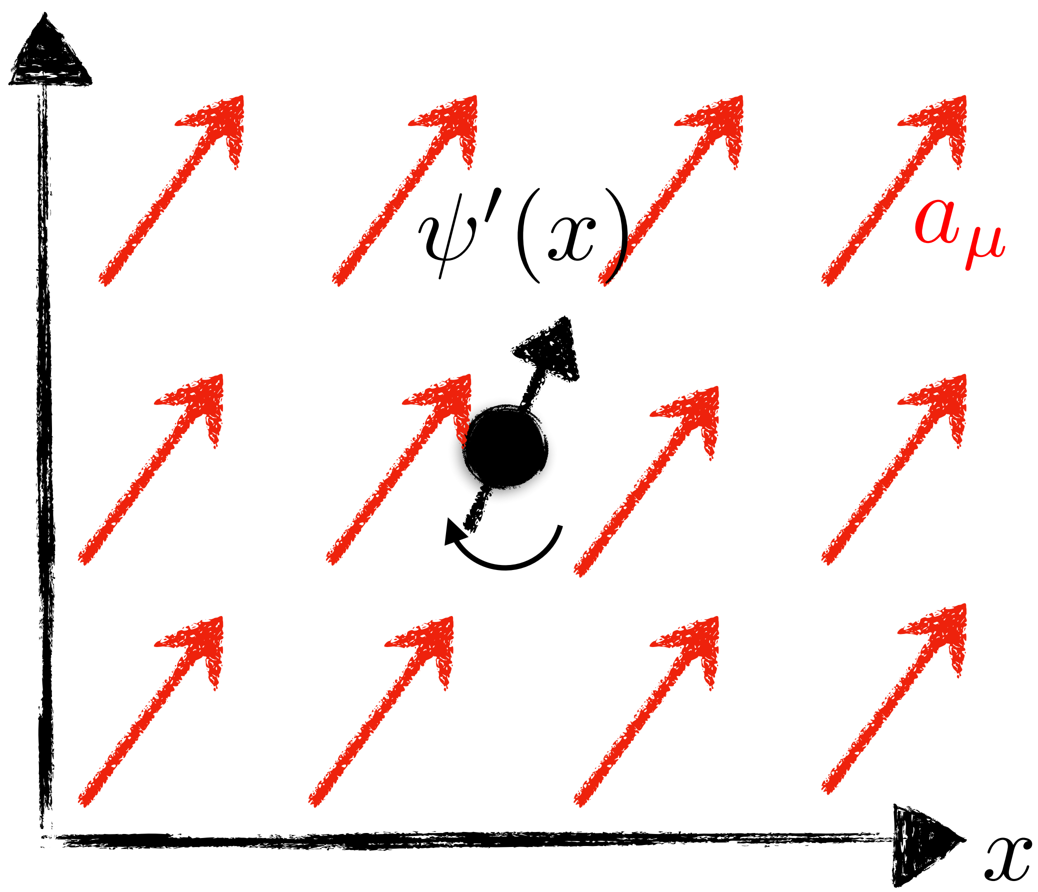

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Unlike observer transformations, particle transformations produce in general physical effects because the background is unaffected

Consequence: the rotated system obeys a different physical law than the original system with rotated coordinates

$\Rightarrow$ Lorentz violation!

[This setup is very reminiscent of spontaneous symmetry breaking]

Quark-sector Lorentz-violating effects

Quarks modified by Lorentz- and CPT-violating operators

$$\mathcal{L}_\psi = \frac{1}{2}\bar{\psi}(\gamma^\mu i D_\mu + \widehat{\mathcal{Q}})\psi + \text{h.c.}$$

Modified kinetic terms

$$\begin{aligned}\frac{1}{2}\bar{\psi}\widehat{\mathcal{Q}}\psi \supset & -\left(a^{(3)}\right)^{\mu}_{AB}\bar{\psi}_A\gamma_\mu\psi_B - \left(b^{(3)}\right)^{\mu}_{AB}\bar{\psi}_A\gamma_5\gamma_\mu\psi_B + \cdots \\ & + \left(c^{(4)}\right)^{\mu\nu}_{AB}\bar{\psi}_A\gamma_\mu iD_\nu\psi_B + \left(d^{(4)}\right)^{\mu\nu}_{AB}\bar{\psi}_A\gamma_5\gamma_\mu iD_\nu\psi_B \cdots \\ & - \left(a^{(5)}\right)^{\mu\alpha\beta}_{AB}\bar{\psi}_A\gamma_\mu iD_{(\alpha}iD_{\beta)}\psi_B + \cdots\end{aligned}$$

We consider the following (spin-independent, flavor-diagonal) effects

$$\begin{aligned}\mathcal{L} = \sum_{f=u,d} & \frac{1}{2}\bar{\psi}_f\gamma^\mu iD_\mu\psi_f + \frac{1}{2}(c_f^{(4)})^{\mu\nu}\bar{\psi}_f\gamma_\mu iD_\nu\psi_f \\ & - (a_f^{(5)})^{\mu\alpha\beta}\bar{\psi}_f\gamma_\mu iD_{(\alpha}iD_{\beta)}\psi_f + \text{h.c.}\end{aligned}$$

Deep inelastic scattering

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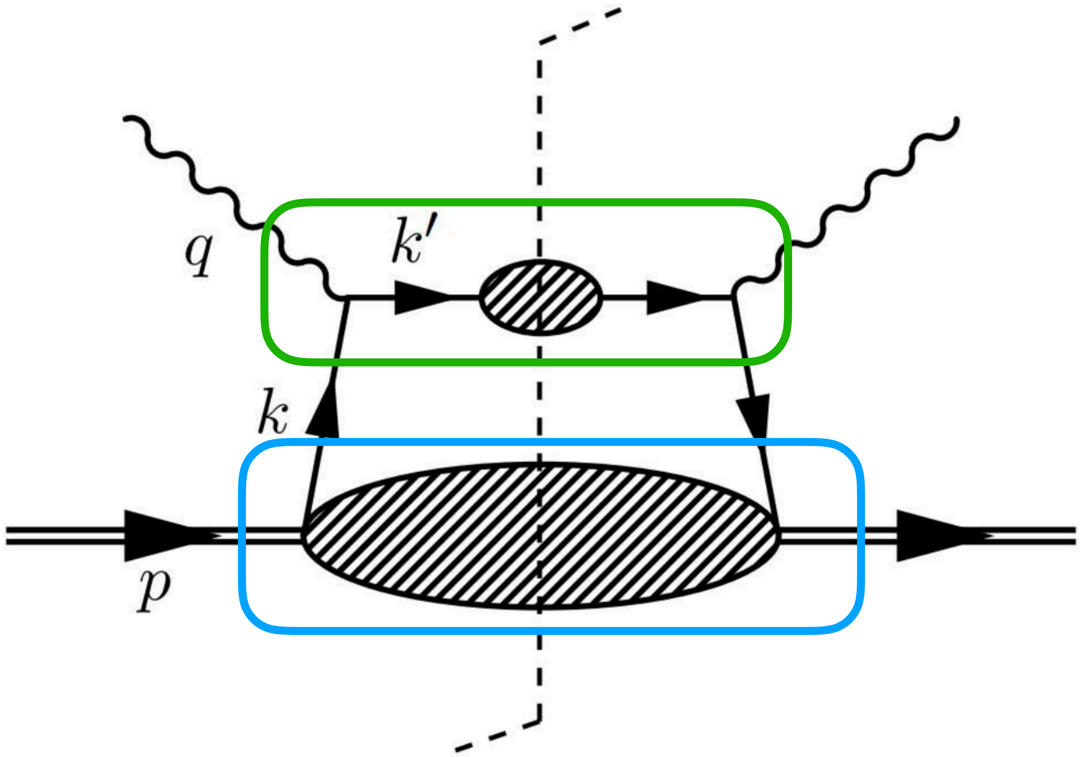
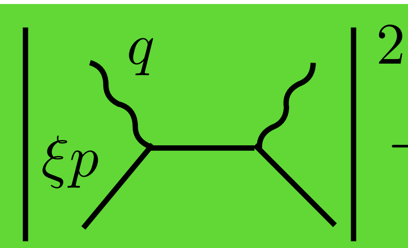


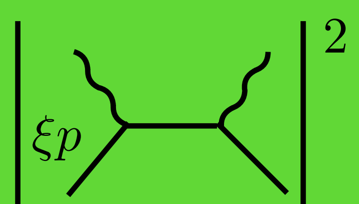
$$\sigma \simeq \int d\xi \, \sigma_{\text{parton}}(\xi) \, f(\xi)$$

$\sim$ 

$+ \cdots$

$\sim \langle \text{hadron} | \Gamma^{+} | \text{hadron} \rangle$

Example: $\mathcal{L}_c \supset \frac{1}{2} c_f^{\mu\nu} \bar{\psi}_f i \gamma_\mu \overset{\leftrightarrow}{\partial}_\nu \psi_f$



$$\sim \quad \text{Tr}\left[(\gamma^\mu + c_f^{\alpha\mu} \gamma_\alpha) \frac{1}{(\xi p^\alpha + q^\alpha + c_f^{\alpha\beta} q_\beta)\gamma_\alpha + i\epsilon} (\gamma^\nu + c_f^{\alpha\nu} \gamma_\alpha) \gamma_\beta \xi p^\beta \right]$$

$\langle \text{hadron} | \Gamma^{+} | \text{hadron} \rangle$

$$\sim \quad f_f(\xi, \cdots) = \int \frac{d\lambda}{2\pi} e^{-i\xi p \cdot n \lambda} \langle p | \bar{\psi}(\lambda \widetilde{n}_f) \frac{\gamma_\mu n^\mu}{2} \psi(0) | p \rangle$$

$\widetilde{n}_f \to n^\mu + c_f^{\mu\alpha} n_\alpha$

Estimating sensitivities at colliders

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Differential cross sections enable extraction of (estimated) bounds using pseudo data for the EIC. Technique relies on coefficient combinations that exhibit sidereal time dependence

$\sim$ **23 hrs 56 mins**

$$\sigma(T_\oplus) \sim \sigma_{\rm SM}\left(1 + c_0 + c_1 \cos(\omega_\oplus T_\oplus) + c_2 \cos(2\omega_\oplus T_\oplus) + \cdots\right)$$

$c_f^{\mu\nu}$ 6 observable, sidereal-time dep. Lorentz-violating coeff. combos per flavor, up to 2nd sidereal harmonics

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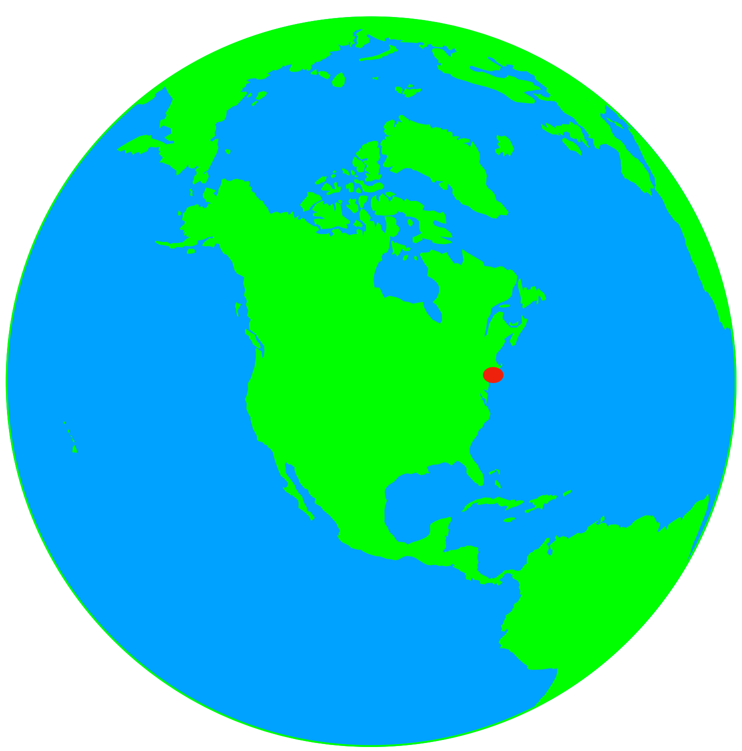

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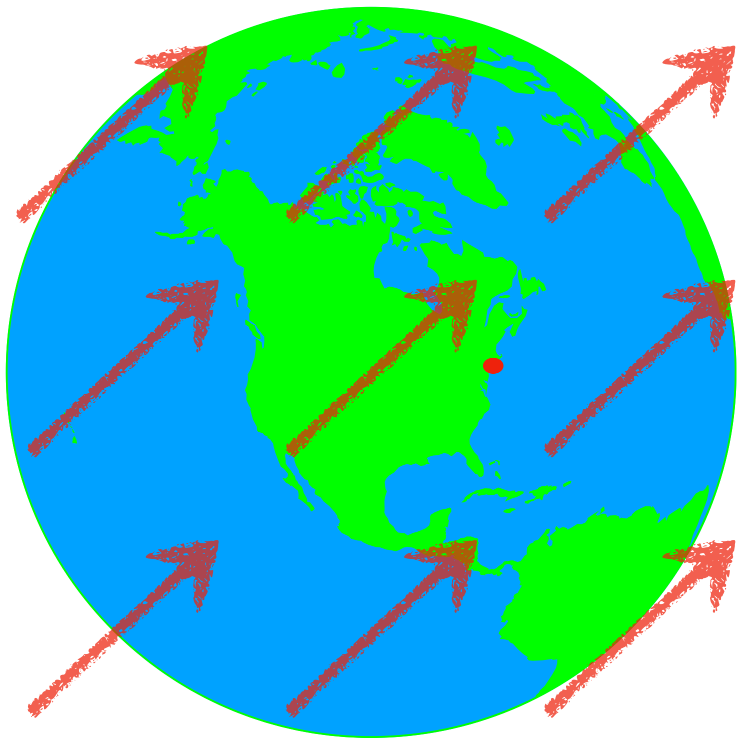

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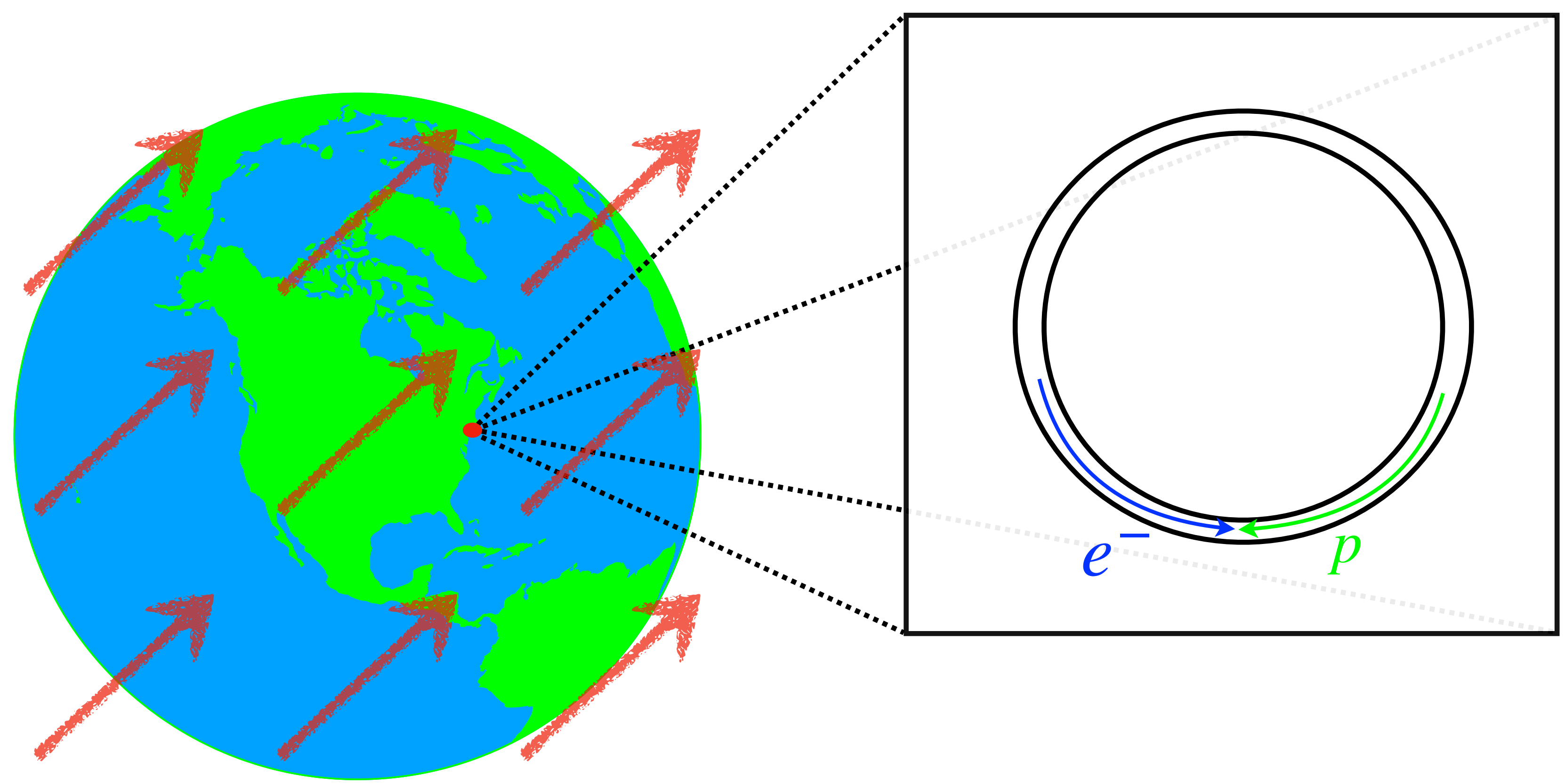

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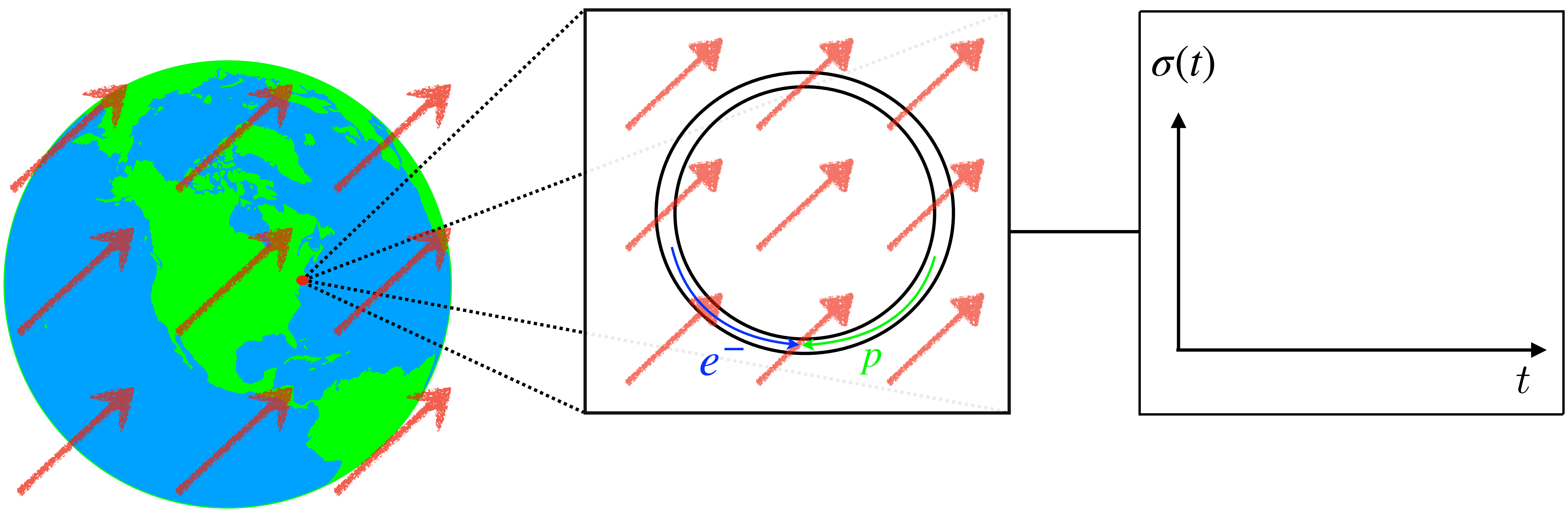

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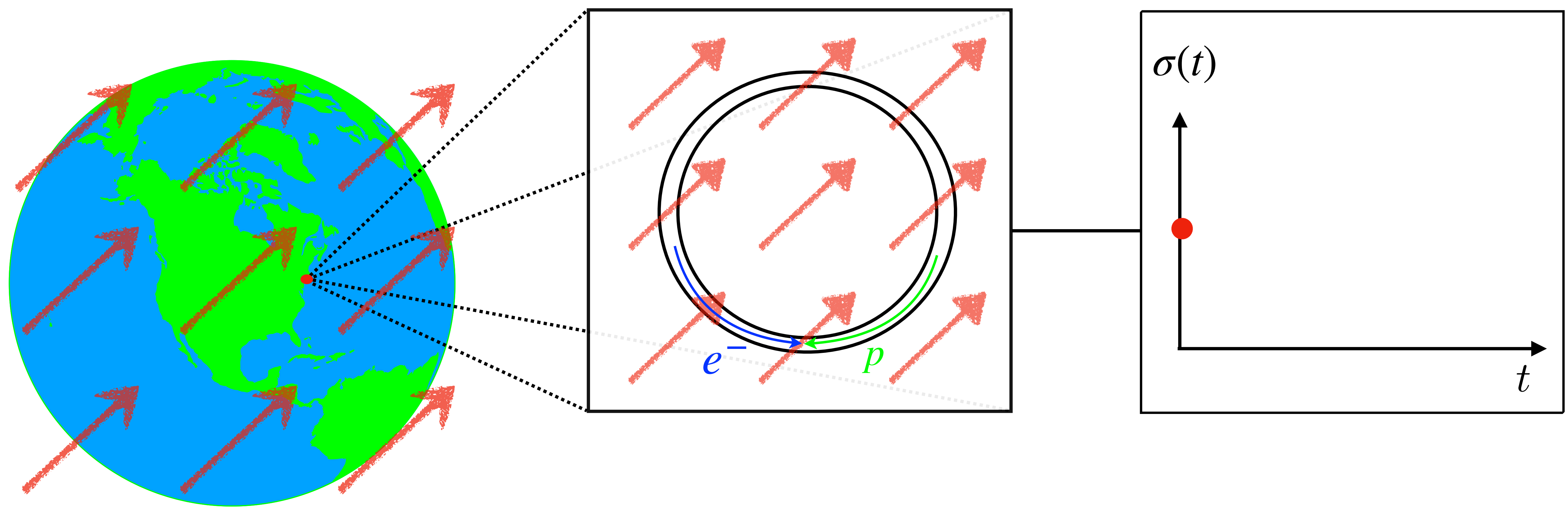

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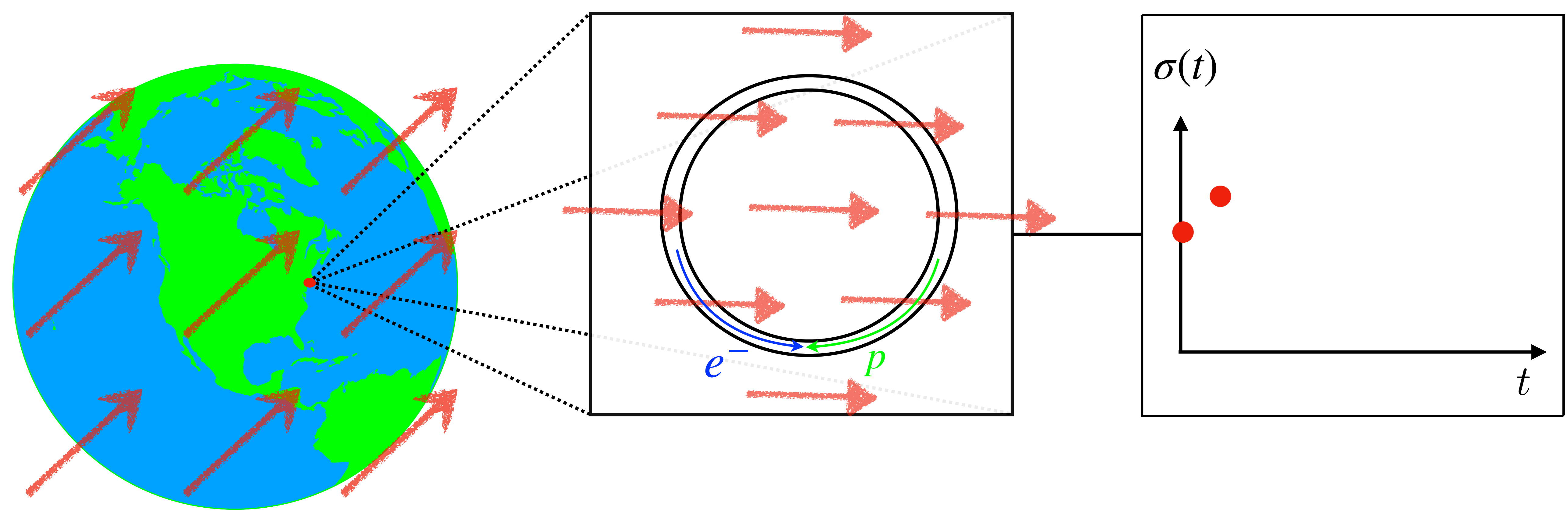

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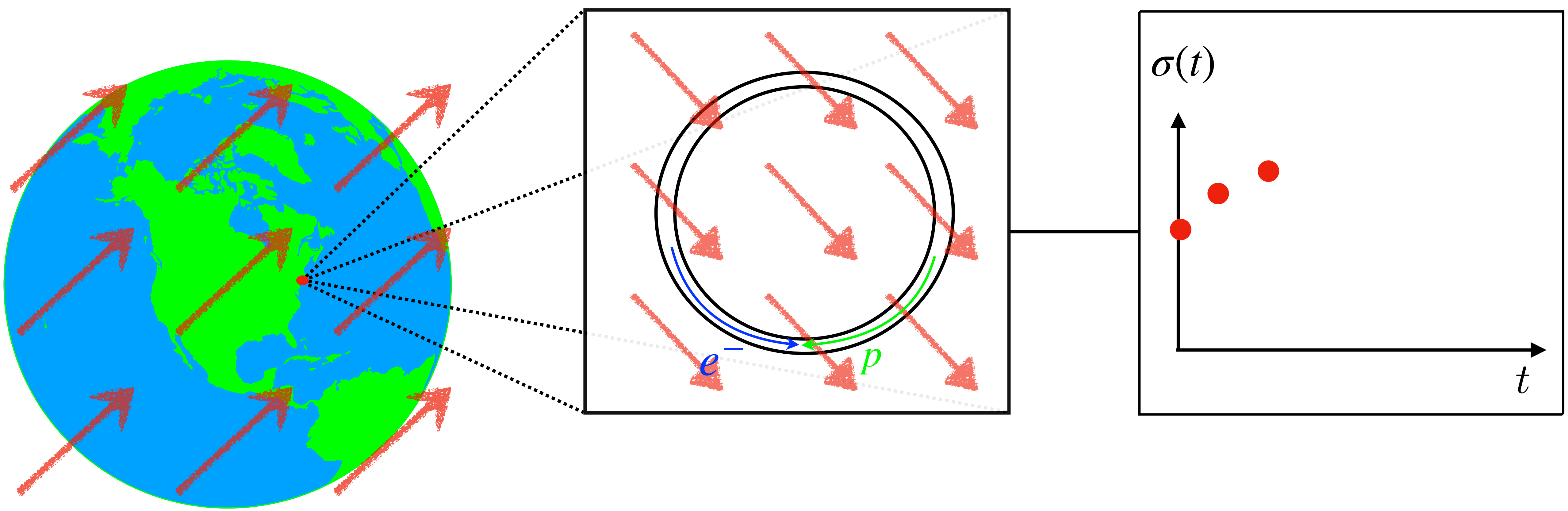

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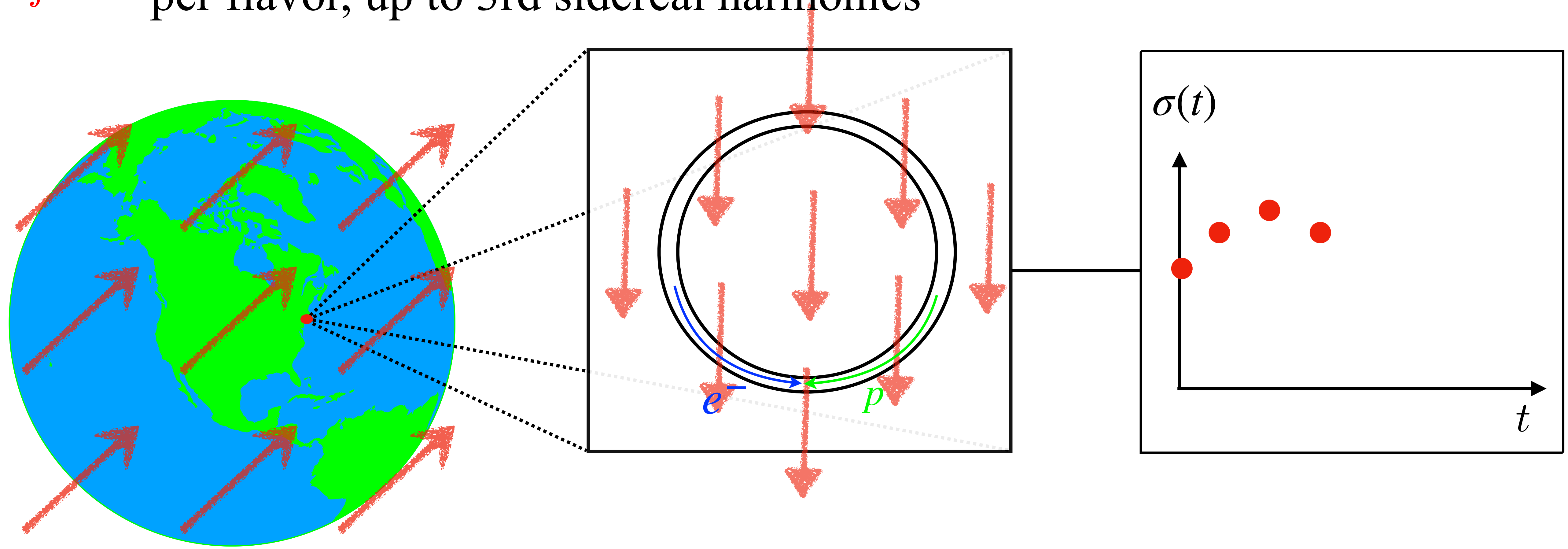

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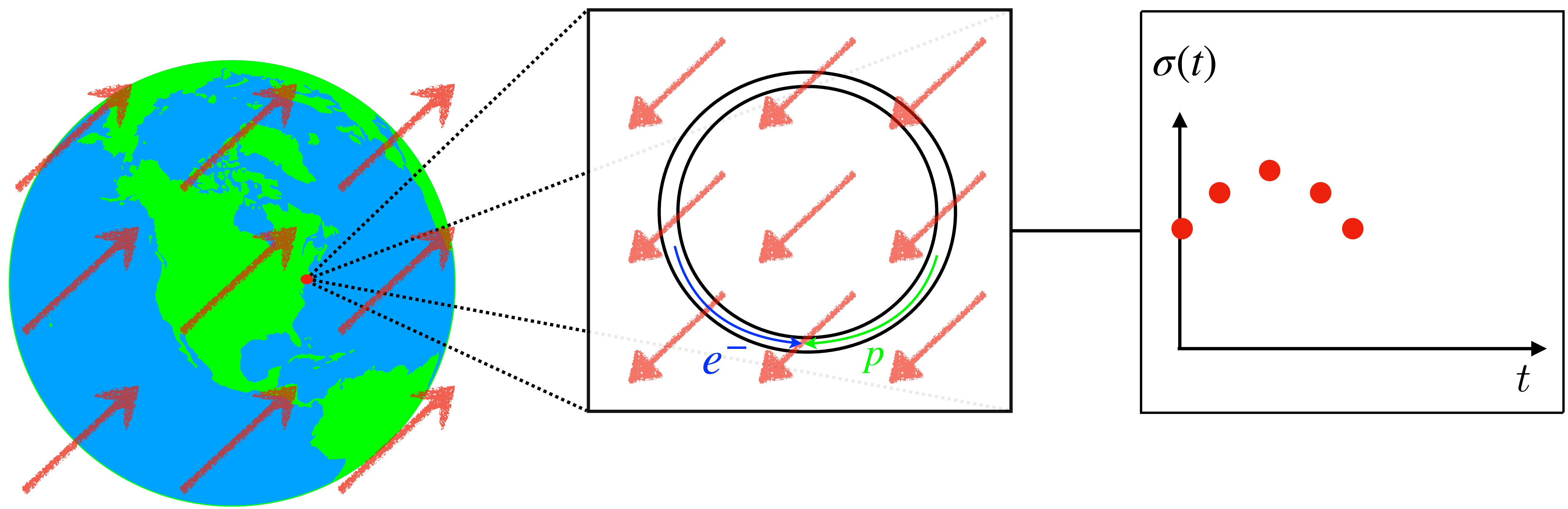

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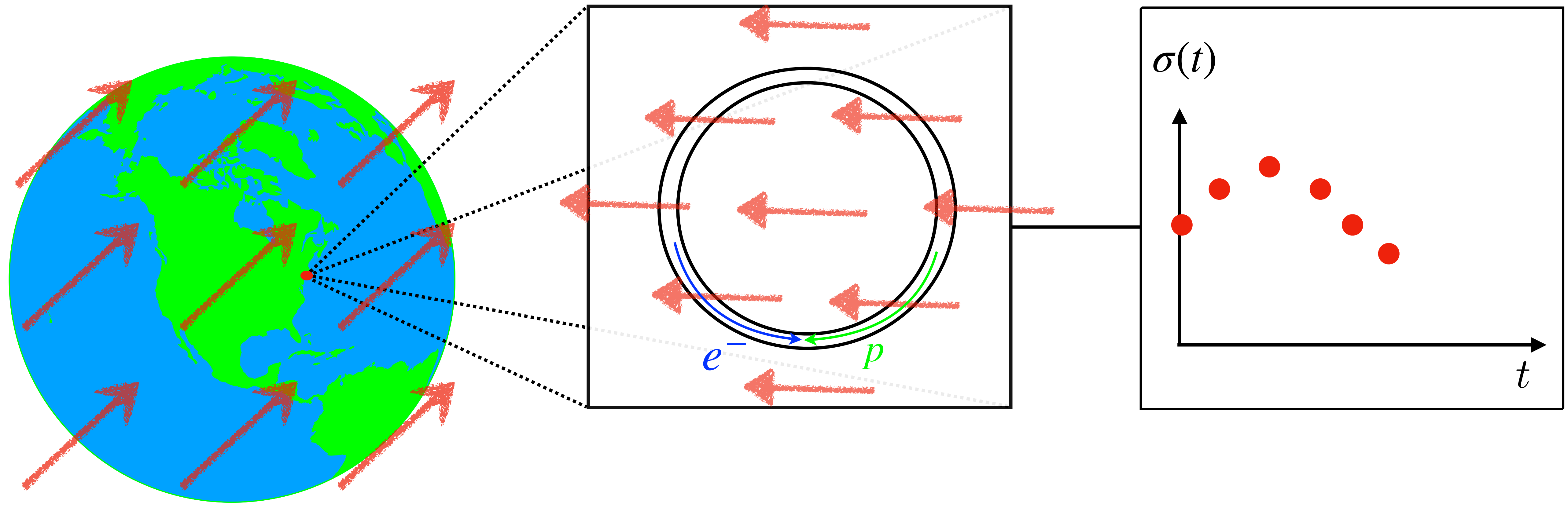

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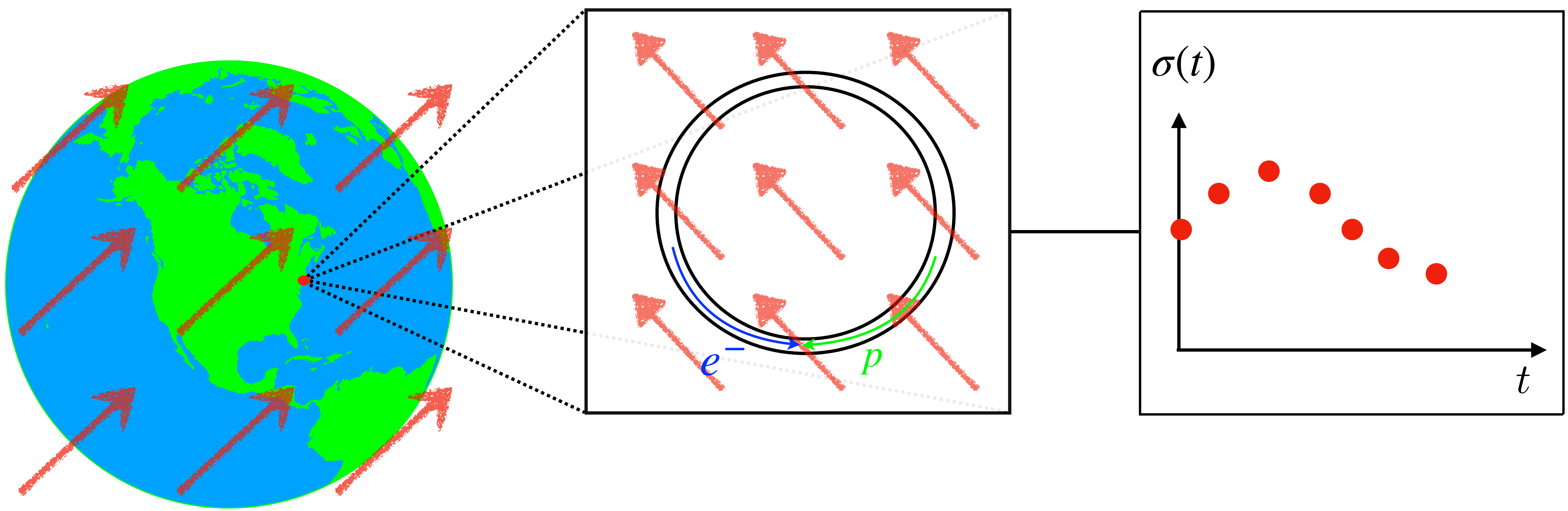

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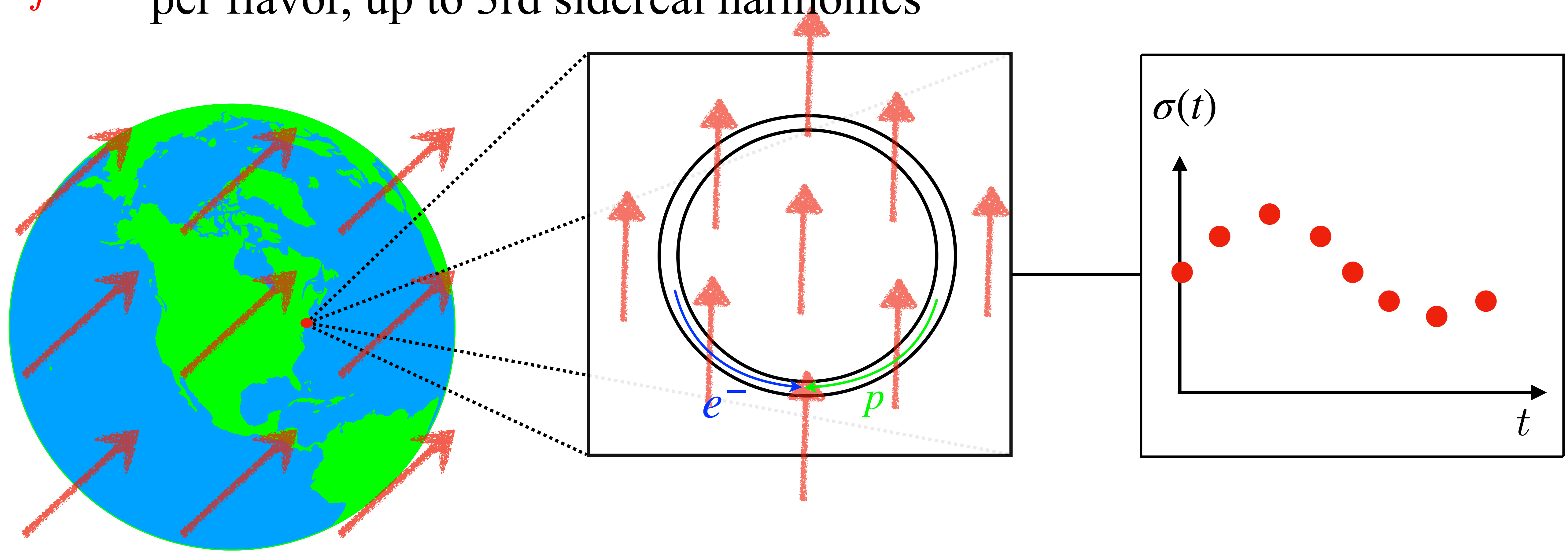

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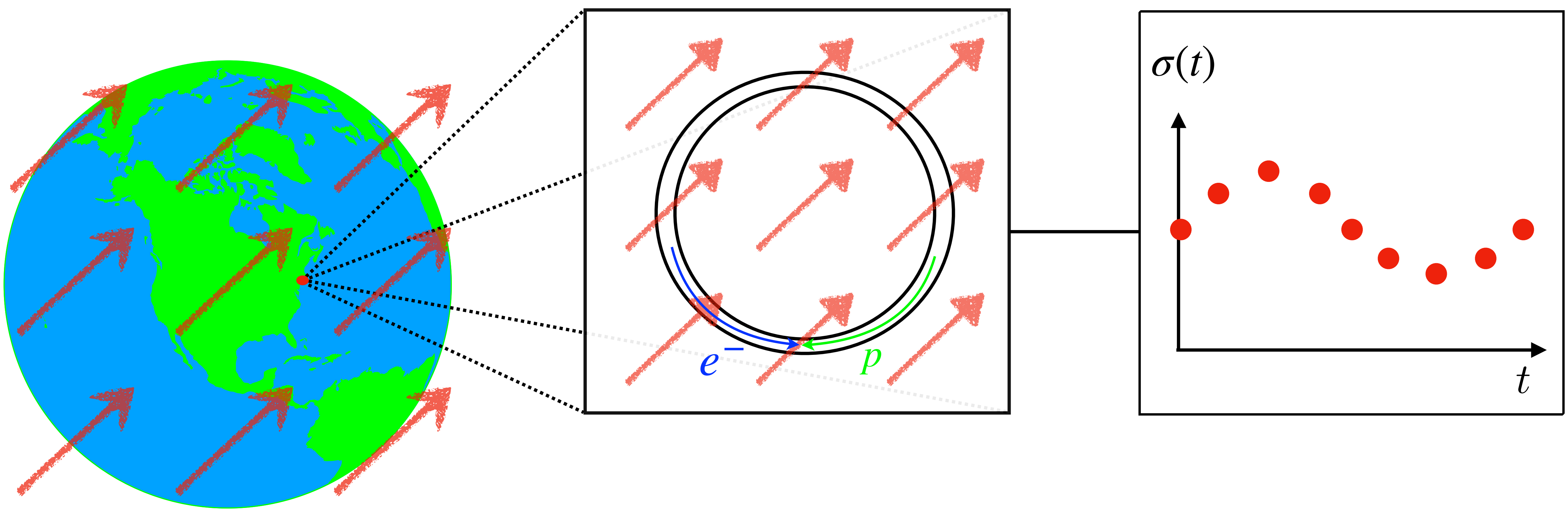
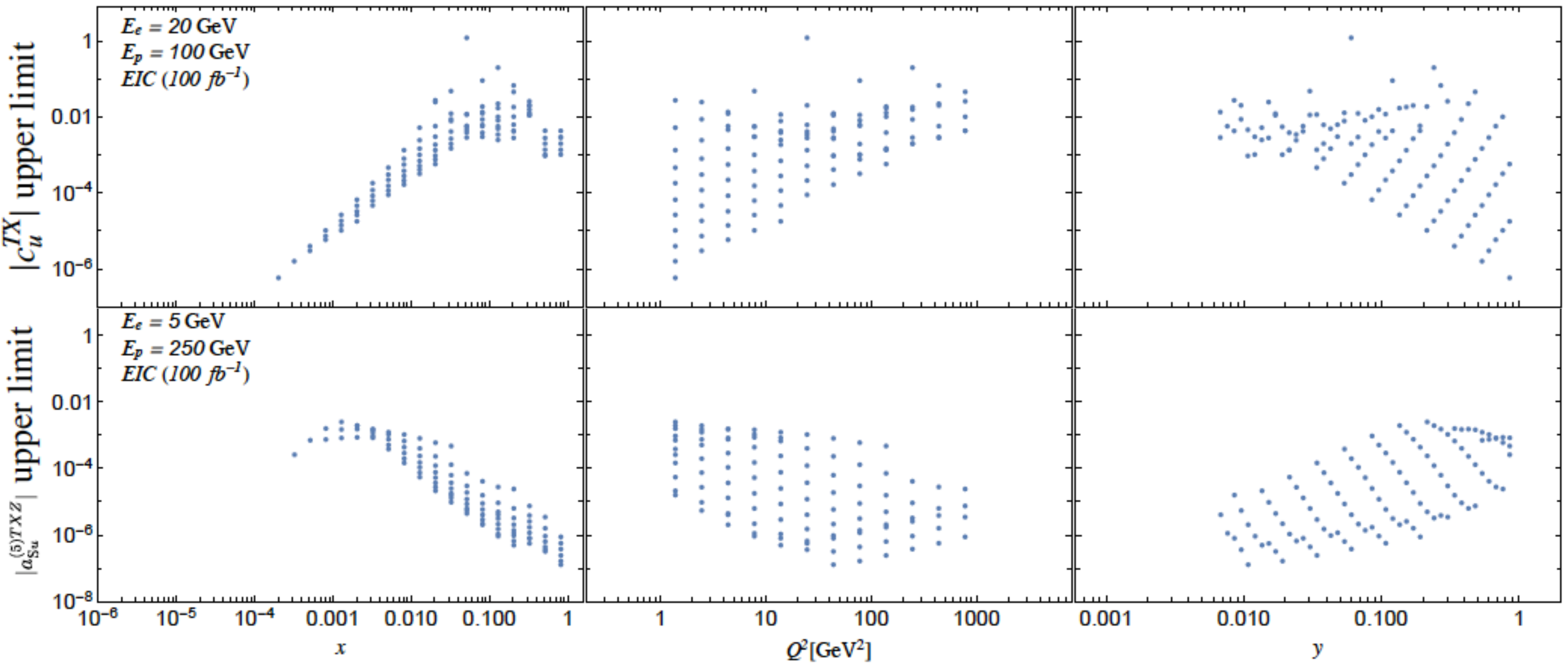


Estimating sensitivities at colliders



Some remarks:

- Regions of sensitivity at low/high x, low-moderate Q, and higher CM energies
- **Expected bounds ~ 1-2 orders of magnitude more stringent than with HERA data**, primarily due to reduced statistical uncertainties
- Need to quantify primary sources of (time dependent) systematic errors (e.g., luminosity)