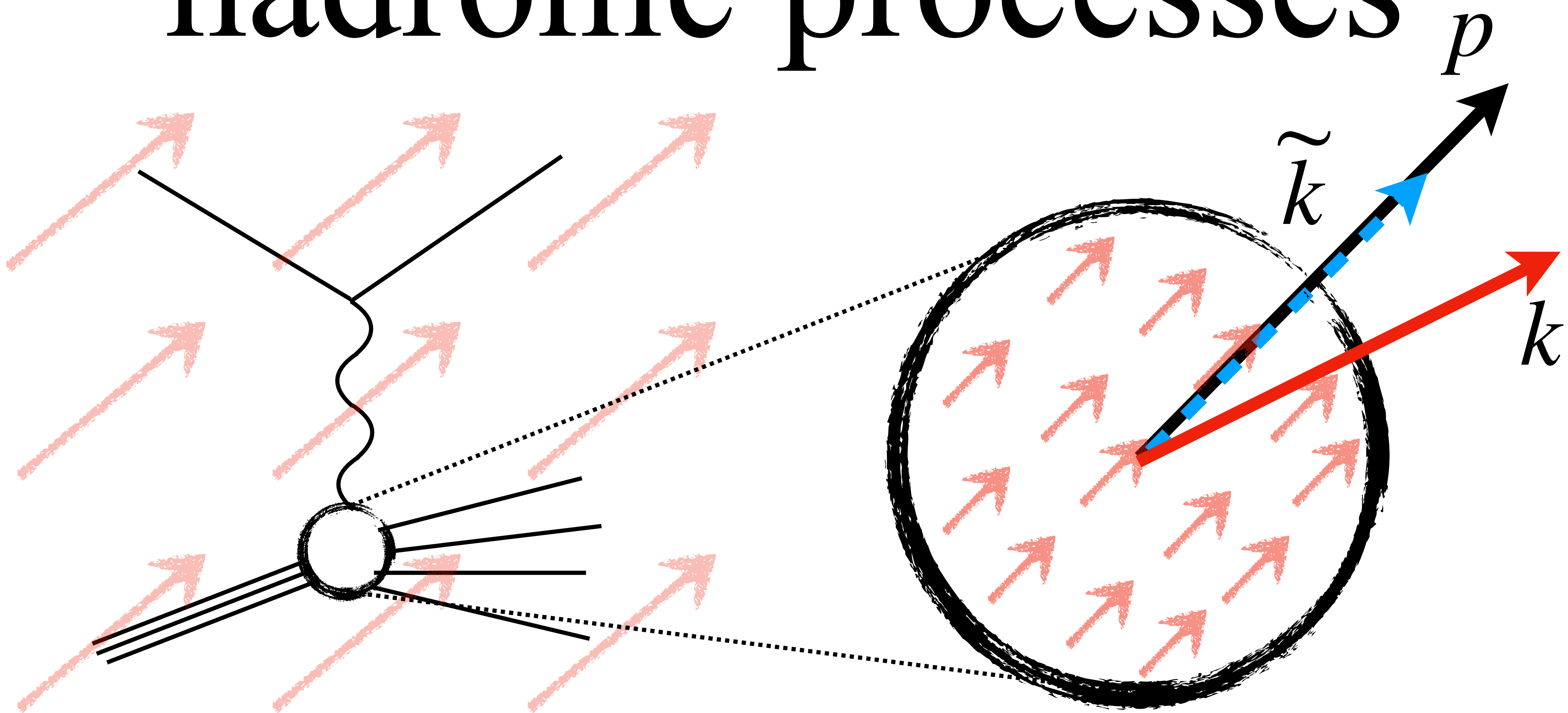
Lorentz-violating effects in hadronic processes



Nathan Sherrill
Indiana University

HC2NP
Tenerife, 23-28 September 2019

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

*Talk based on: V. A. Kostelecký, E. Lunghi, N. S., A. R. Vieira — to appear

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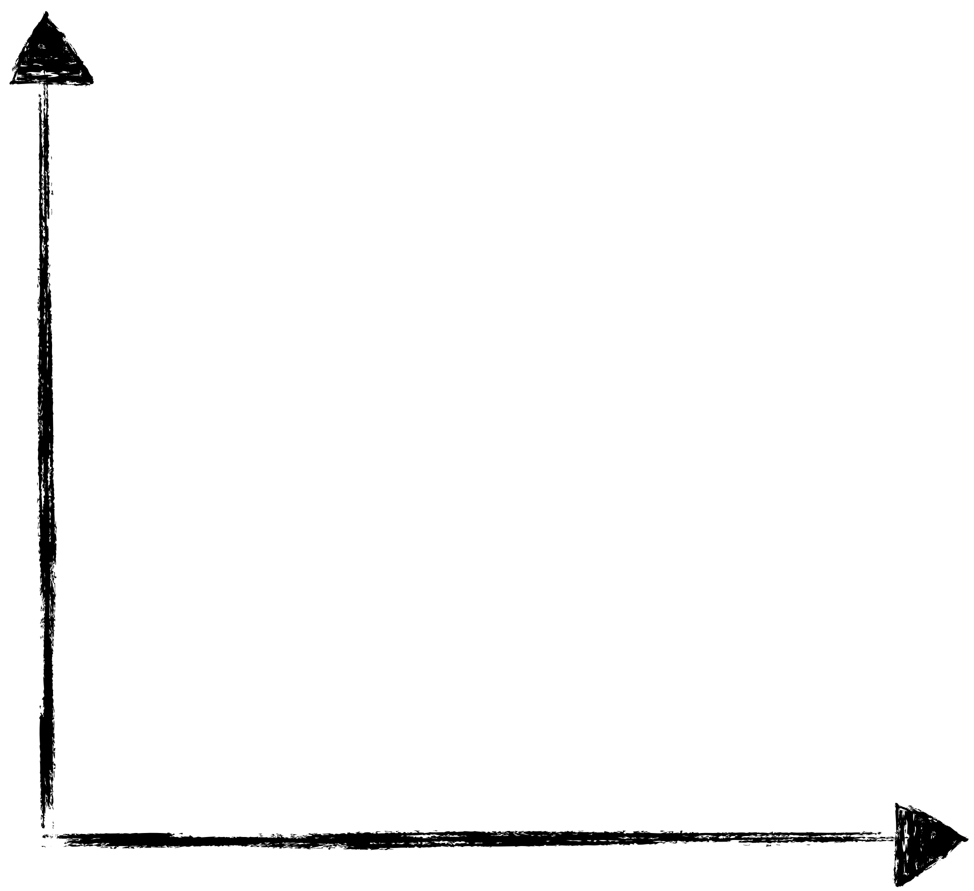

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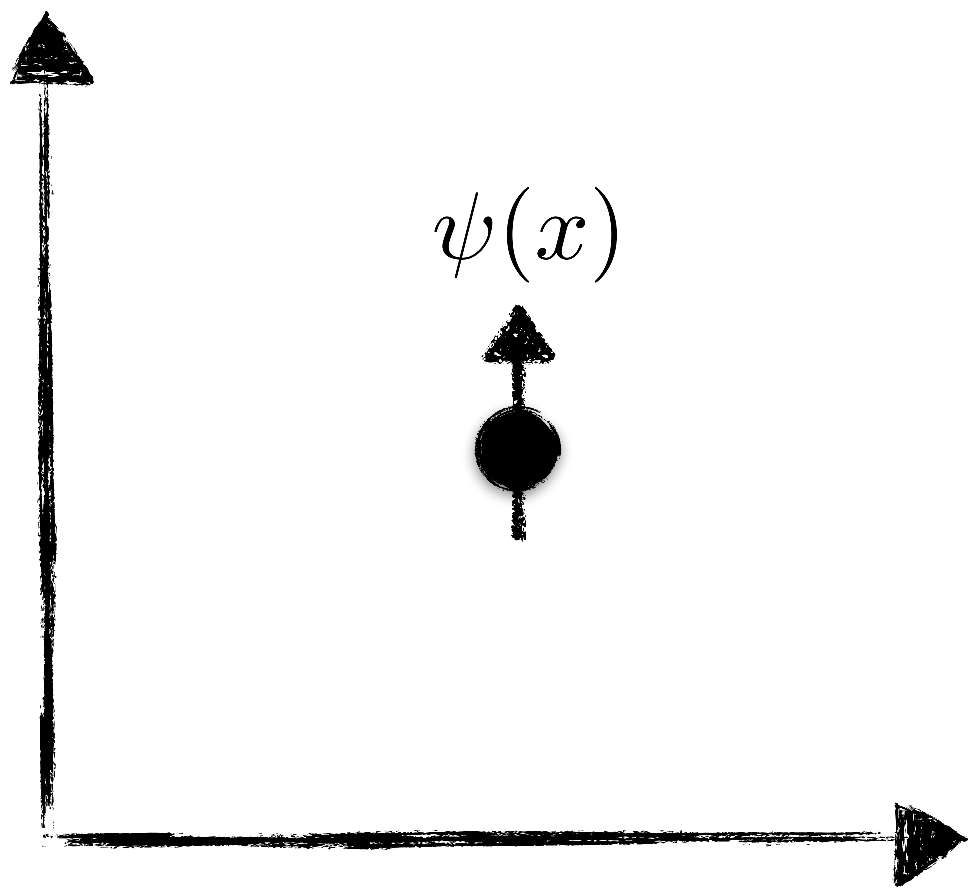

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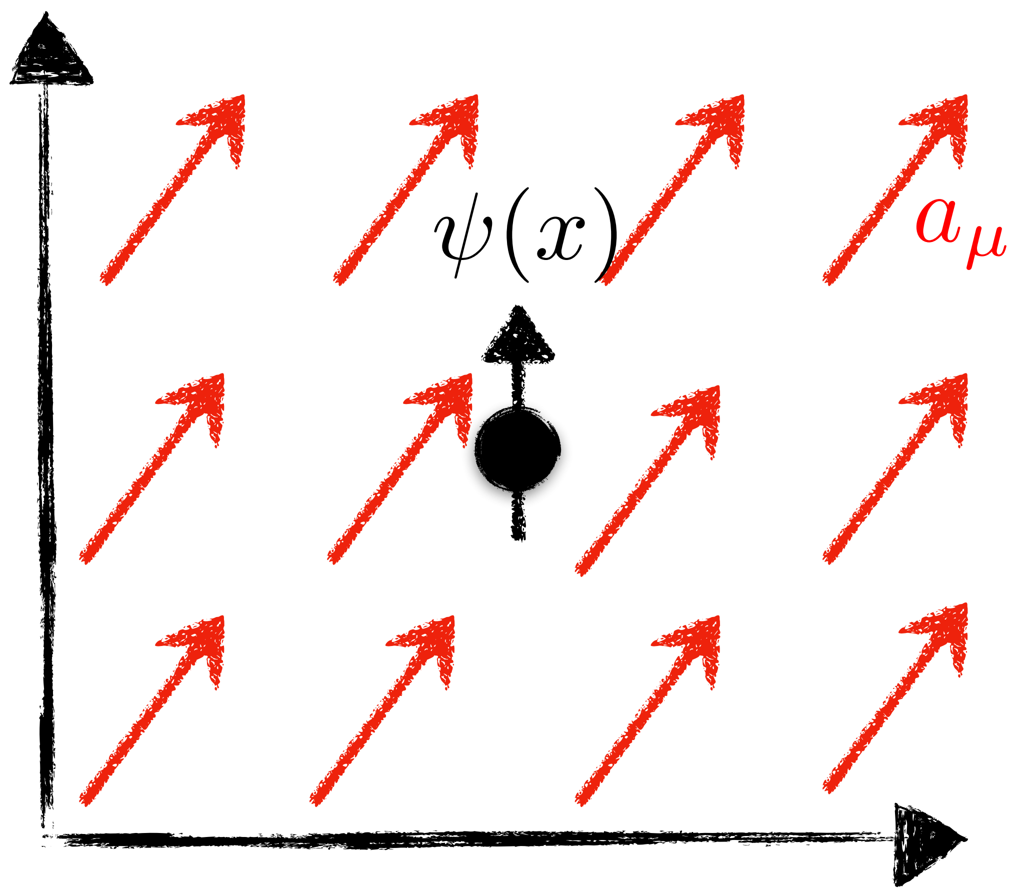

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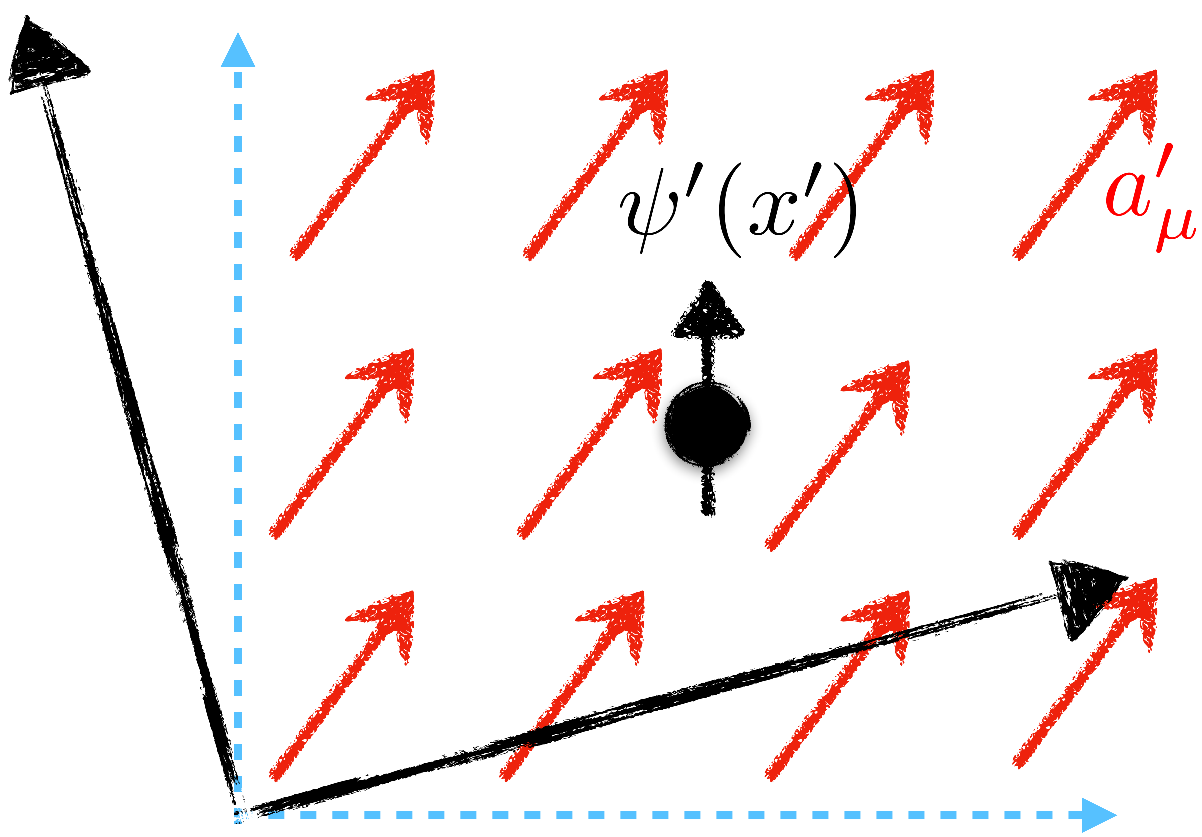

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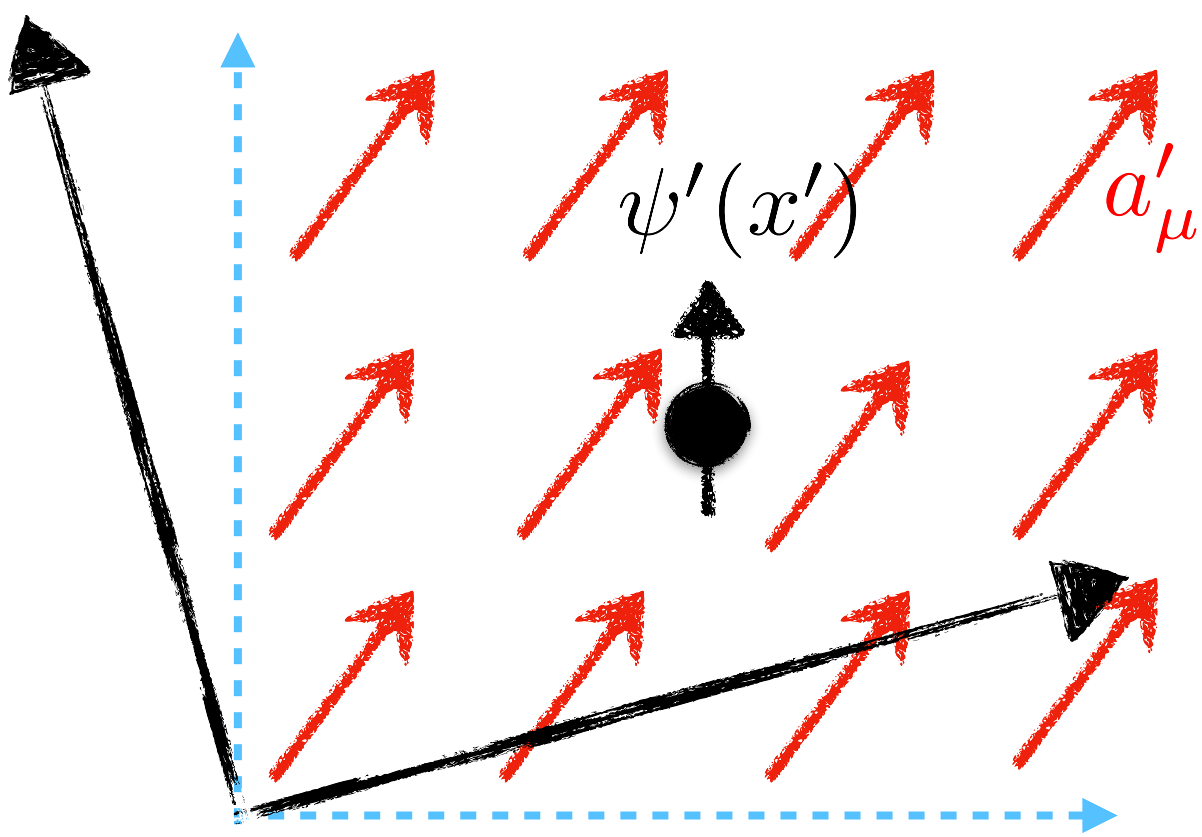

$$a^\mu \to \Lambda^\mu{}_\nu a^\nu$$

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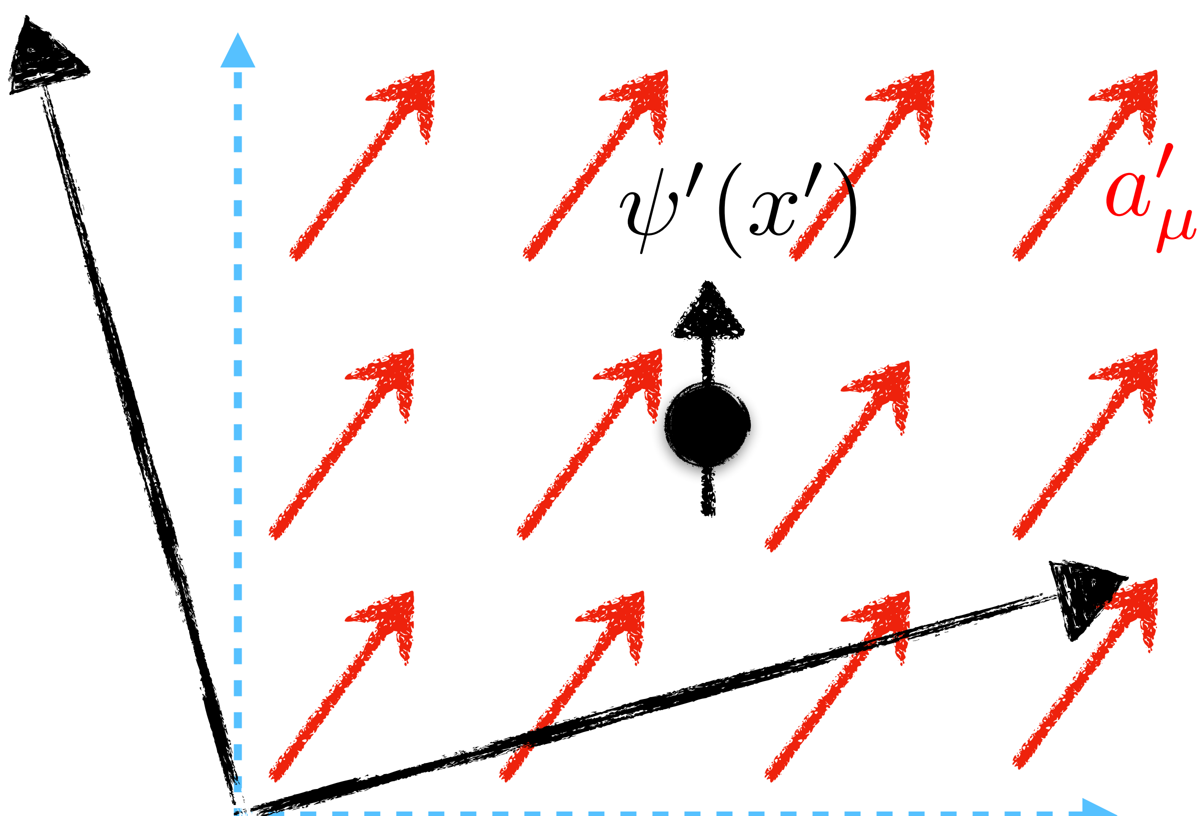

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No change in the physics; the presence of the background cannot be seen by performing observer transformations

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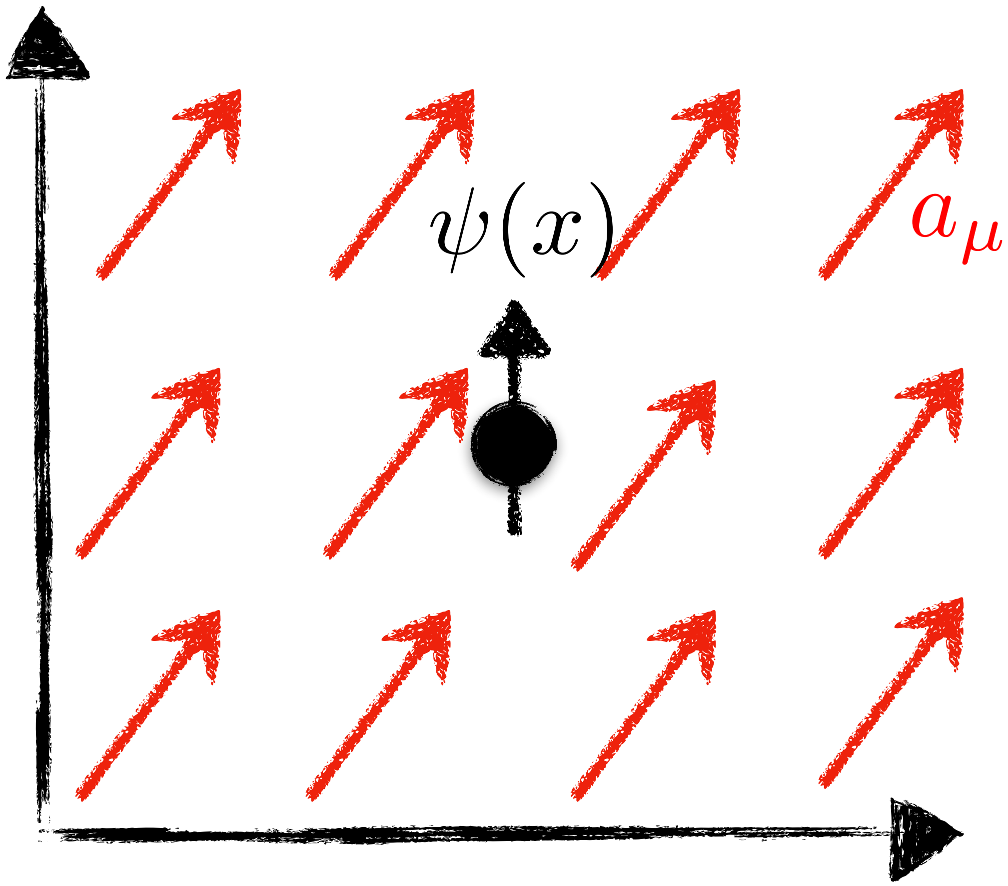

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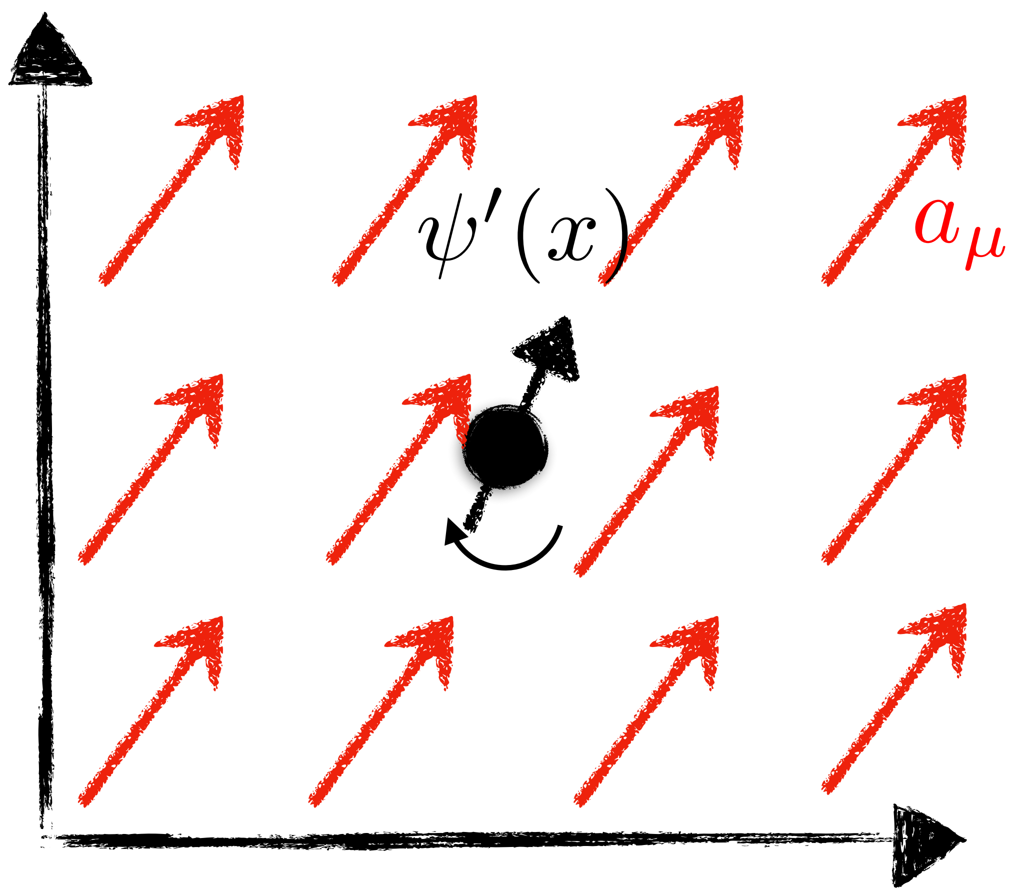

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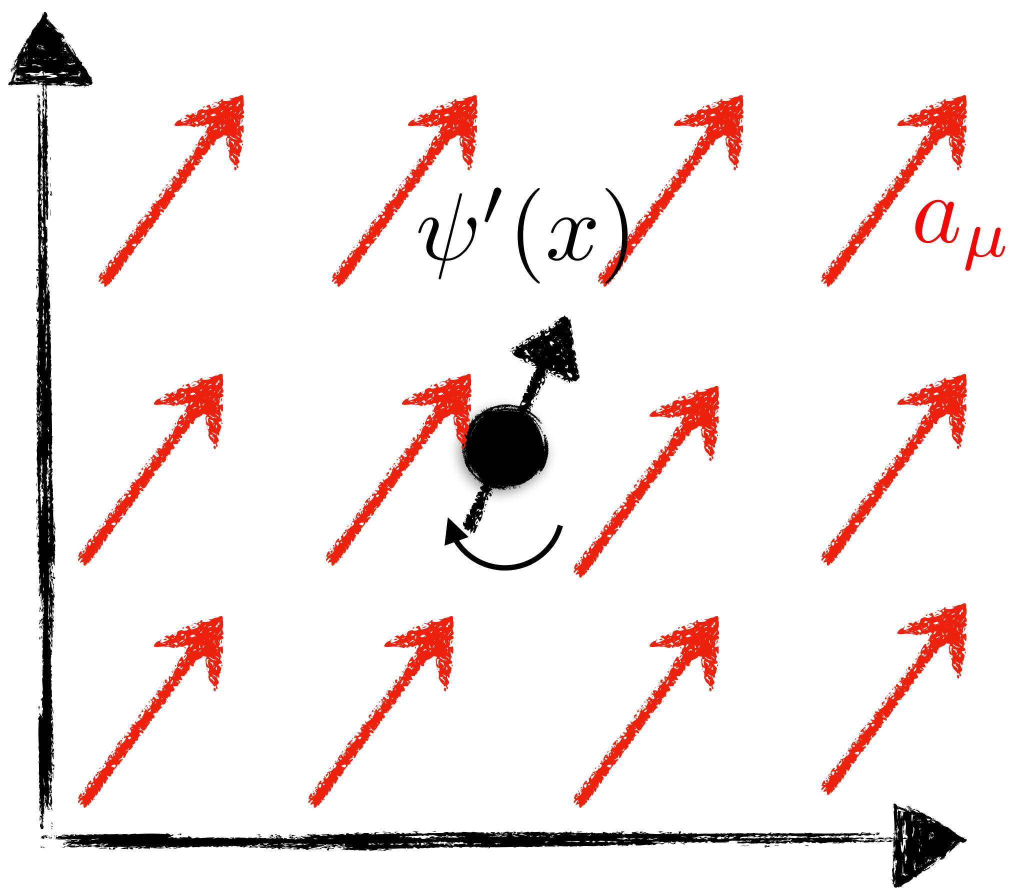

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Net physical effect

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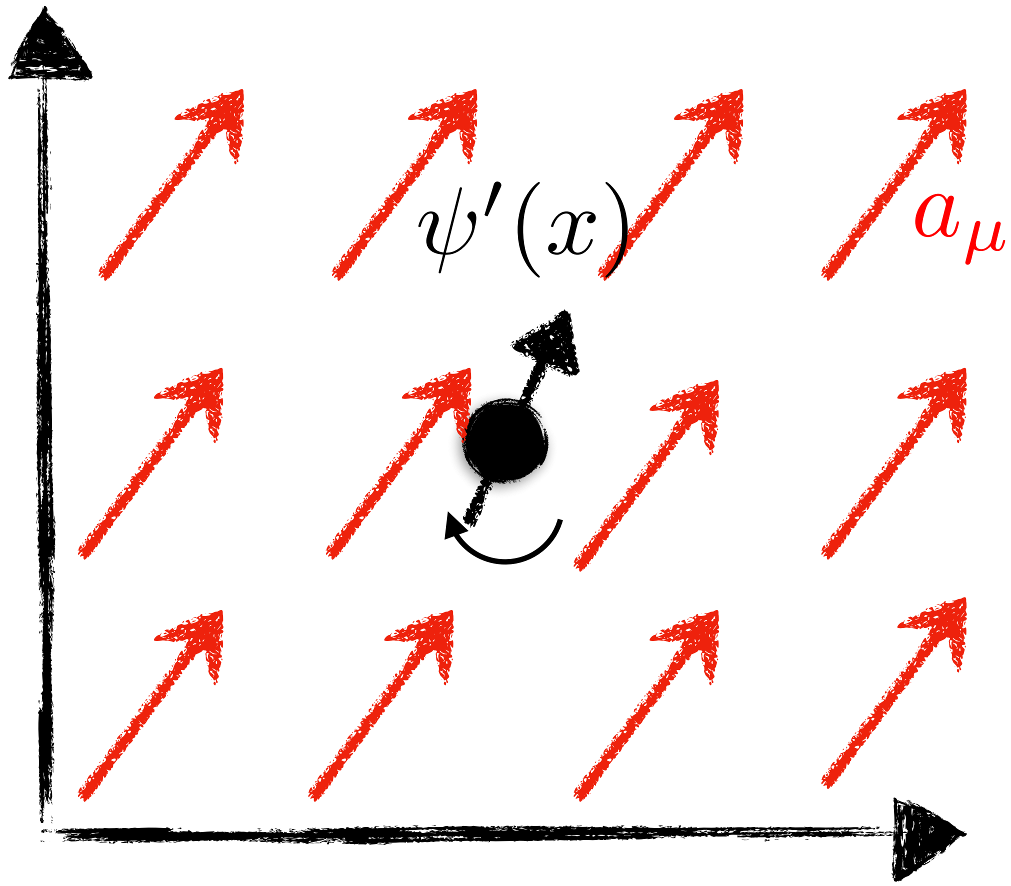

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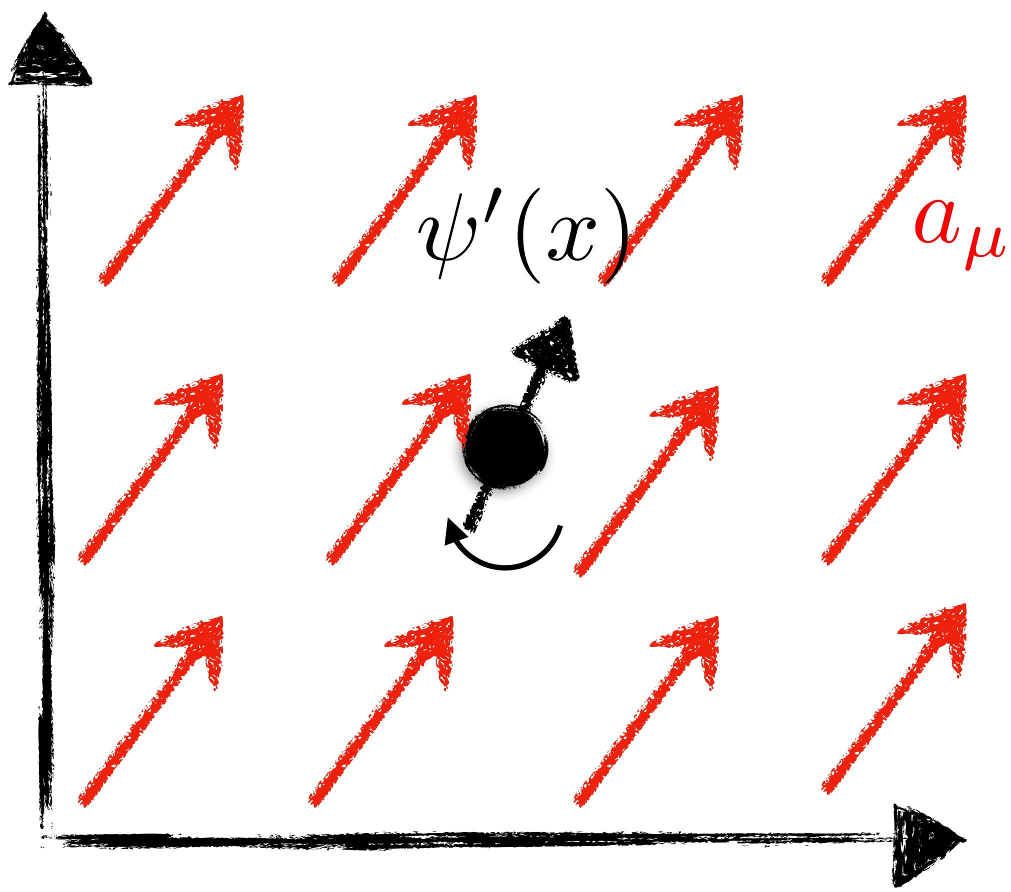

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Rotated system obeys different physical law than rotated coordinates $\Rightarrow$ Lorentz violation!

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*See, e.g., V. A. Kostelecký, S. Samuel, Phys. Rev. D39, 683 (1989); S. Carroll, J. Harvey, V. A. Kostelecký, C. Lane, T. Okamoto Phys. Rev. Lett. 87 141601 (2001)

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Contains all possible terms that break Lorentz and CPT symmetry* consistent with the particle/field content of GR and the SM

CPTV $\Rightarrow$ LV in realistic EFT*

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- "Coefficients for Lorentz violation"
- Observer Lorentz tensors
- Necessarily small (perturbative)
- <u>Experimentally accessible</u>!

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Data Tables for Lorentz and CPT Violation

V. Alan Kostelecký[a] and Neil Russell[b]
[a] *Physics Department, Indiana University, Bloomington, IN 47405*
[b] *Physics Department, Northern Michigan University, Marquette, MI 49855*

January 2019 update of *Reviews of Modern Physics* **83**, 11 (2011) [arXiv:0801.0287]*

This work tabulates measured and derived values of coefficients for Lorentz and CPT violation in the Standard-Model Extension. Summary tables are extracted listing maximal attained sensitivities in the matter, photon, neutrino, and gravity sectors. Tables presenting definitions and properties are also compiled.

⋮

Table D17. Nonminimal photon sector, $d = 5$

Combination	Result	System	Ref.
$\lvert \sum_{jm} Y_{jm}(110.47°, 71.34°) k^{(5)}_{(V)jm} \rvert$	$< 1 \times 10^{-23}$ GeV^{-1}	Spectropolarimetry	[163]
$\lvert \sum_{jm} Y_{jm}(330.68°, 42.28°) k^{(5)}_{(V)jm} \rvert$	$< 3 \times 10^{-23}$ GeV^{-1}	"	[163]
$\lvert k^{(5)}_{(V)00} \rvert$	$< 5 \times 10^{-23}$ GeV^{-1}	"	[163]
$\lvert k^{(5)}_{(V)00} \rvert$	$< 5.0 \times 10^{-26}$ GeV^{-1}	Astrophysical birefringence	[167]
$\lvert k^{(5)}_{(V)10} \rvert$	$< 6.5 \times 10^{-26}$ GeV^{-1}	"	[167]

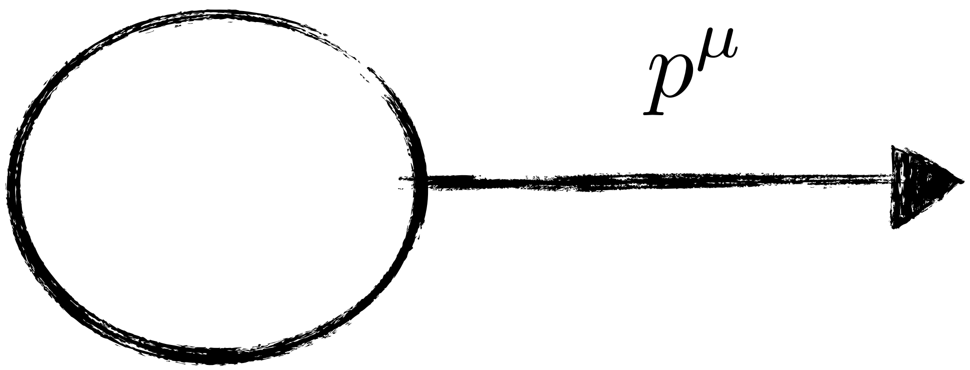
⋮

100s of bounds for nearly every major subfield of physics*

<u>Much of the QCD sector is yet to be explored!</u>

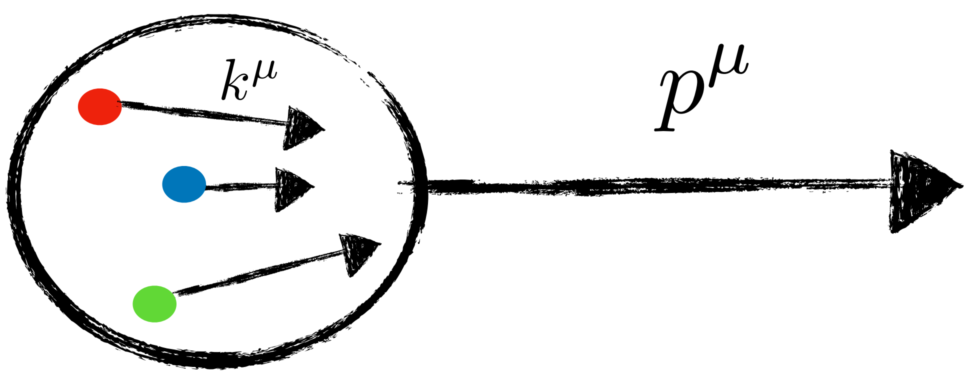
Quick overview of high-energy hadrons

Consider a high-energy hadron



$$p^\mu = \left(p^+, \frac{M^2}{2p^+}, 0_\perp\right), \quad p^+ \gg M$$

Partons have momenta that scale like p^μ



$$k^\mu \sim \left(p^+, \frac{M^2}{2p^+}, M\right)$$

Fraction of plus momentum is boost invariant, leading to familiar parameterization for high-energy, massless, on-shell partons within hadrons

$$\xi \equiv k^+/p^+$$

$$k^\mu = \xi p^\mu$$

Covariant expression; can be used in any frame

Quark-sector Lorentz-violating effects

Massless quarks modified by Lorentz-violating effects

$$\mathcal{L} \supset \tfrac{1}{2}\bar{\psi}\left[\gamma^\mu iD_\mu\right]\psi + \text{h.c.} + \mathcal{L}^{(d)}_{\psi D}$$

$$\begin{aligned}\mathcal{L}^{(d)}_{\psi D} \supset & -(a^{(3)})^\mu\bar{\psi}\gamma_\mu\psi + (c^{(4)})^{\mu\nu}\bar{\psi}\gamma_\mu iD_\nu\psi + \cdots \\ & -(a^{(5)})^{\mu\alpha\beta}\bar{\psi}\gamma_\mu iD_{(\alpha}iD_{\beta)}\psi + \cdots \\ & +(c^{(6)})^{\mu\alpha\beta\gamma}\bar{\psi}\gamma_\mu iD_{(\alpha}iD_\beta iD_{\gamma)}\psi + \cdots \\ & + \cdots\end{aligned}$$

Modified Dirac equation, dispersion relation

$$\gamma_\mu\widetilde{k}^\mu\psi = 0,$$

$$\widetilde{k}^2 = k^2 + \mathcal{O}(\text{coefficients}) = 0$$

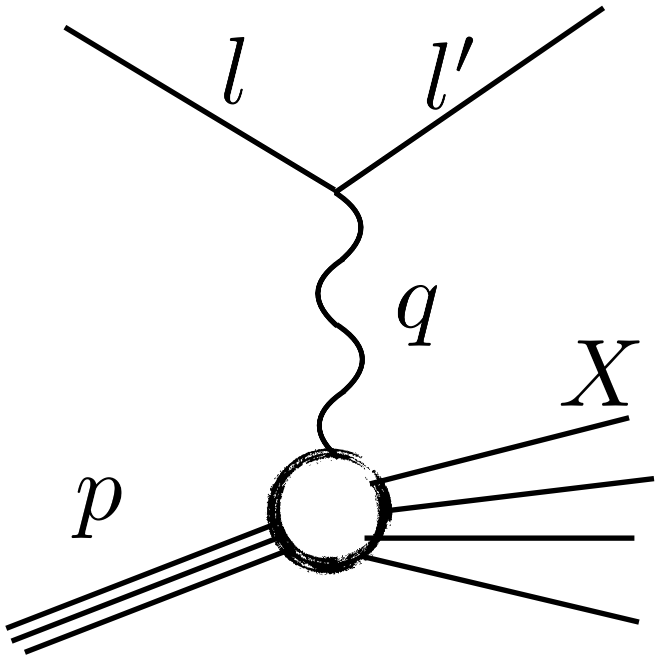
Bottom line: implies $k^\mu = \xi p^\mu$ is no longer consistent

Instead, for a covariant definition to be retained $\widetilde{k}^\mu = \xi p^\mu$

Factorization

Want to understand effects in lepton-hadron and hadron-hadron collisions

E.g., deep inelastic scattering (DIS)



$$T_{\mu\nu} = i\int d^4w e^{iq\cdot w}\langle p, s|\mathrm{T} j^\dagger_\mu(w) j_\nu(0)|p, s\rangle_c$$

$$\sigma \propto L_{\mu\nu}\mathrm{Im}T^{\mu\nu}$$

$$\sigma \sim \int d\xi \sigma_{\mathrm{parton}}(\xi) f(\xi) + \text{small corrections}$$

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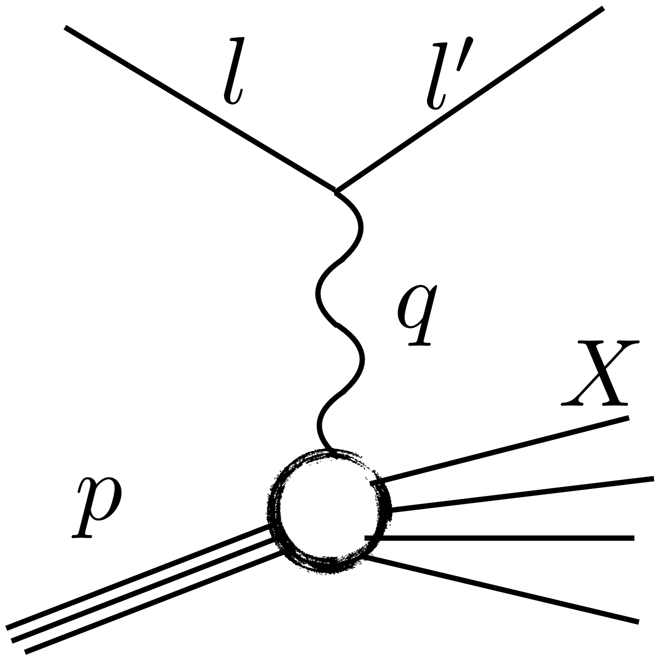

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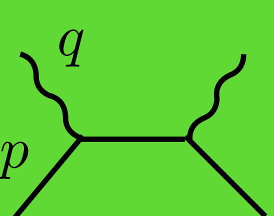
$\sim \left| \right.$  $\left. \right|^2 + \cdots$

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

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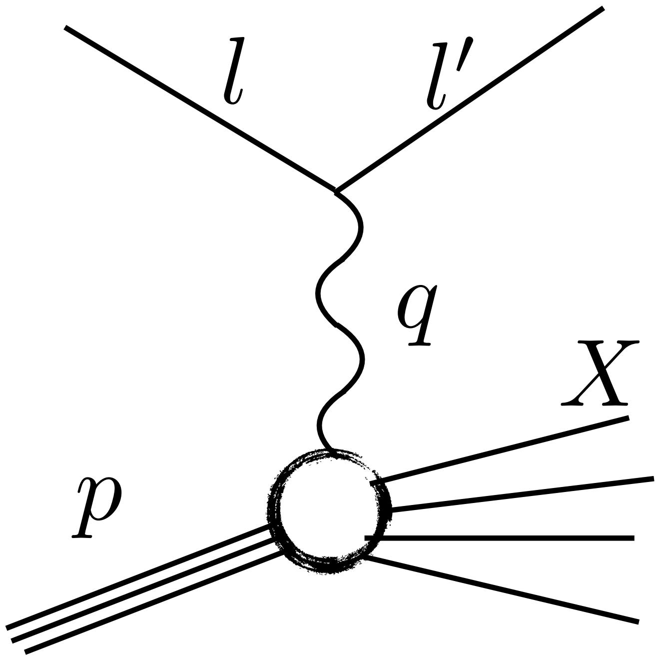

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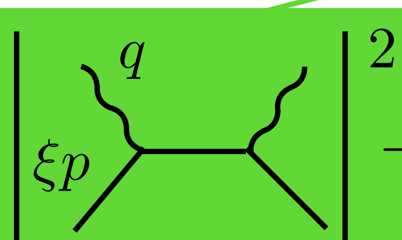
$\sim$ 

$+ \cdots$

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Similar conclusions reached for the Drell-Yan process

What happens when Lorentz violation is present?

Factorization

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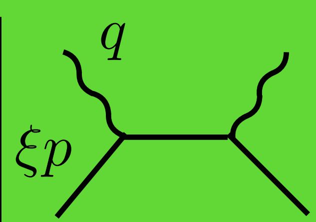
$\sim \Big|$ 

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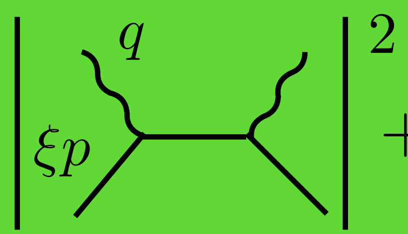
$\sim$ 

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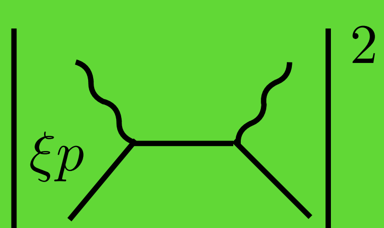
Factorization at the parton-level occurs in a modified Breit frame $\vec{p} + \widetilde{\vec{q}} = \vec{0}$

E.g. $\mathcal{L}_c \supset \frac{1}{2} c_f^{\mu\nu} \bar{\psi}_f(x) i\gamma_\mu \overleftrightarrow{\partial}_\nu \psi_f(x)$



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

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

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

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

PDFs

PDFs still satisfy reparameterization invariance and are consistent with the operator product expansion (OPE)

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Test this for DIS and DY using minimal and nonminimal spin-independent coefficients for Lorentz violation*

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*V. A. Kostelecký, E. Lunghi, and A. R. Vieira, Phys. Lett. B **769**, 272 (2017); V. A. Kostelecký and Z. Li, Phys. Rev. D **99**, 056016 (2019)

$$\#\ \ physical\ \ \text{comps.}\ \ (c_{Sf}^{(4)})^{\mu\nu} = 16 - 6 - 1 = 9$$

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Matching to OPE gives the potential *nonperturbative* dependence on Lorentz violation in the considered model

$$f_f(\xi, \cdots) = f_f(\xi, (c_{Sf}^{(4)})^{pp}, (a_{Sf}^{(5)})^{ppp}/\Lambda^2)$$

Estimating sensitivities at colliders

Using data from HERA, the LHC, and the future electron-ion collider (EIC) we obtain estimates on the sensitivity to the coefficients of interest

Rely on coefficient combinations that exhibit sidereal-time dependence

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

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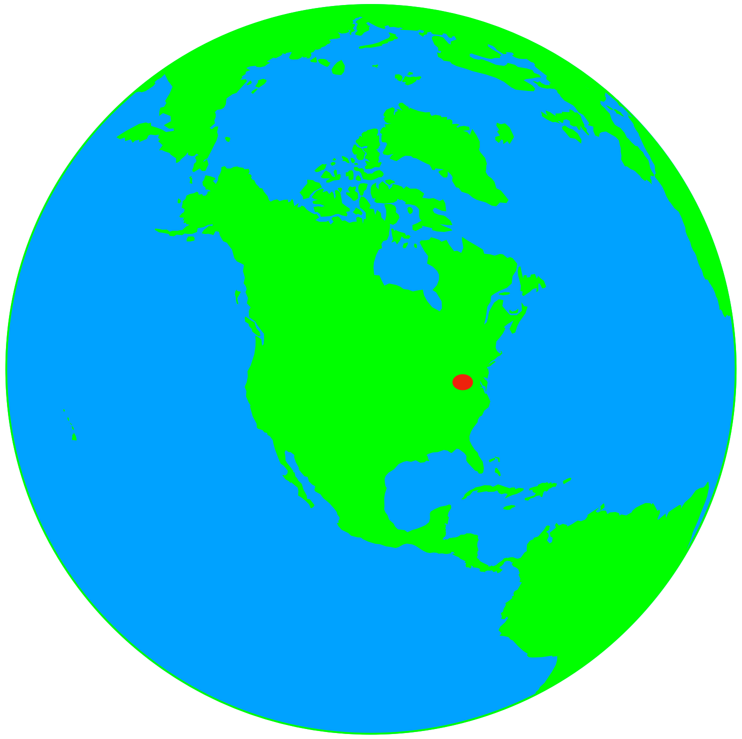

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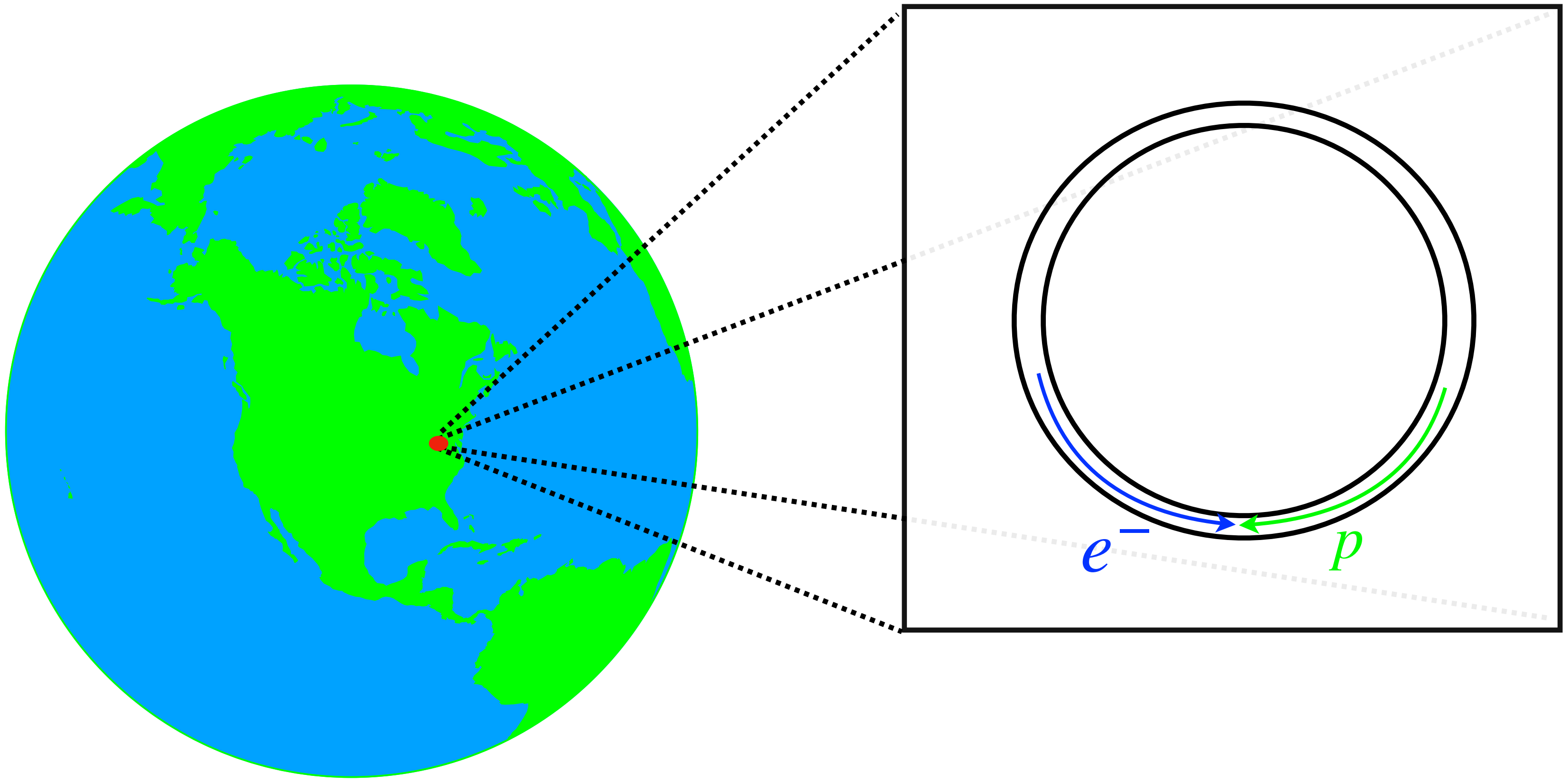

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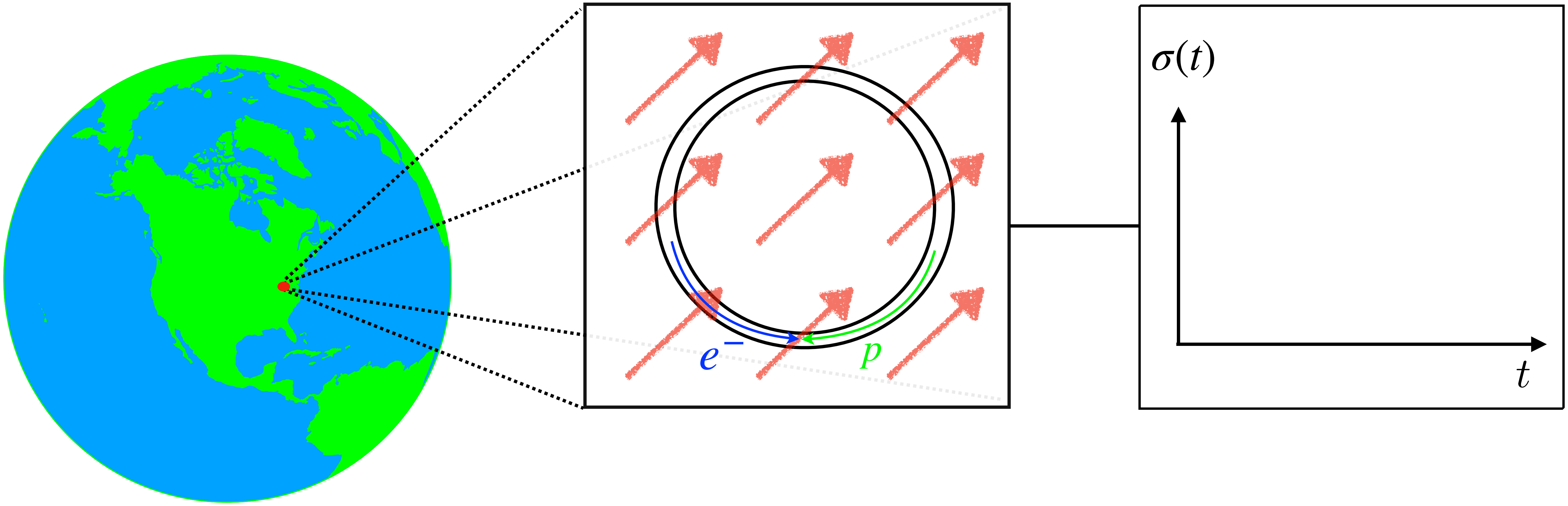

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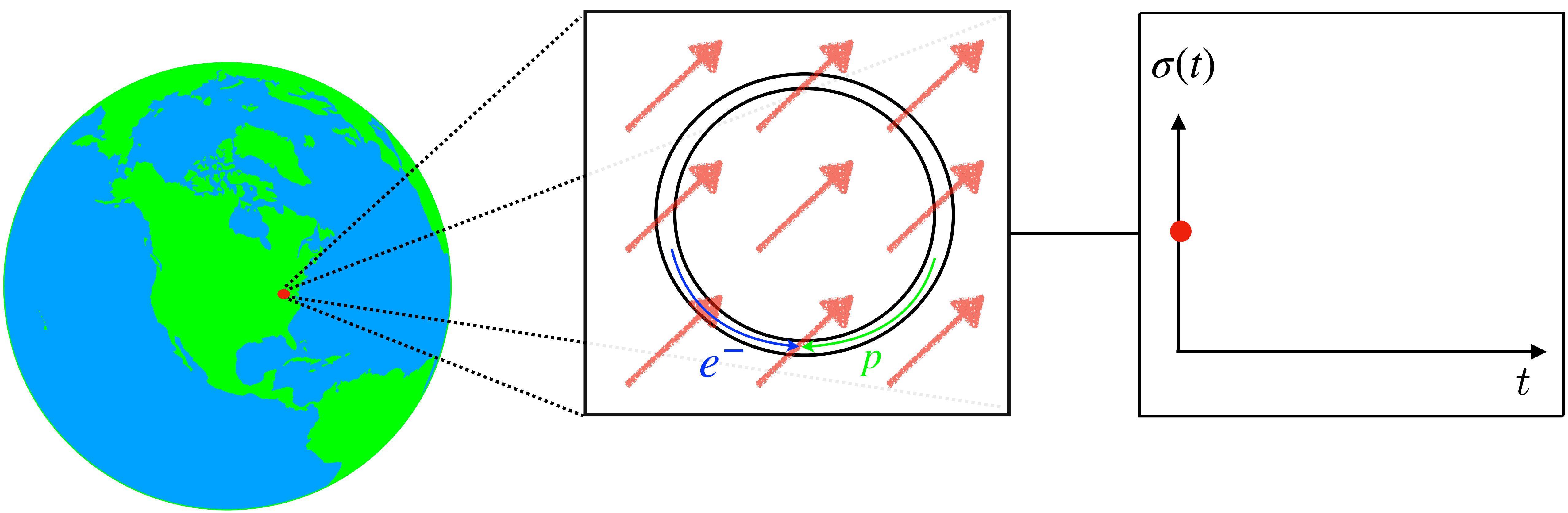

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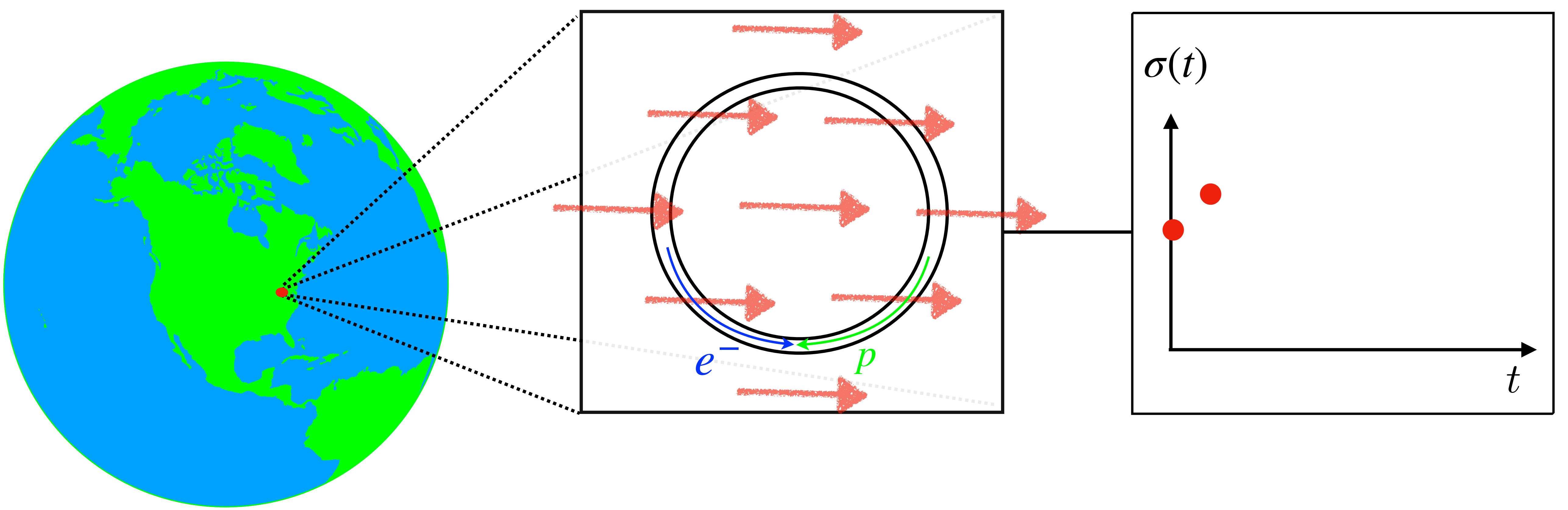

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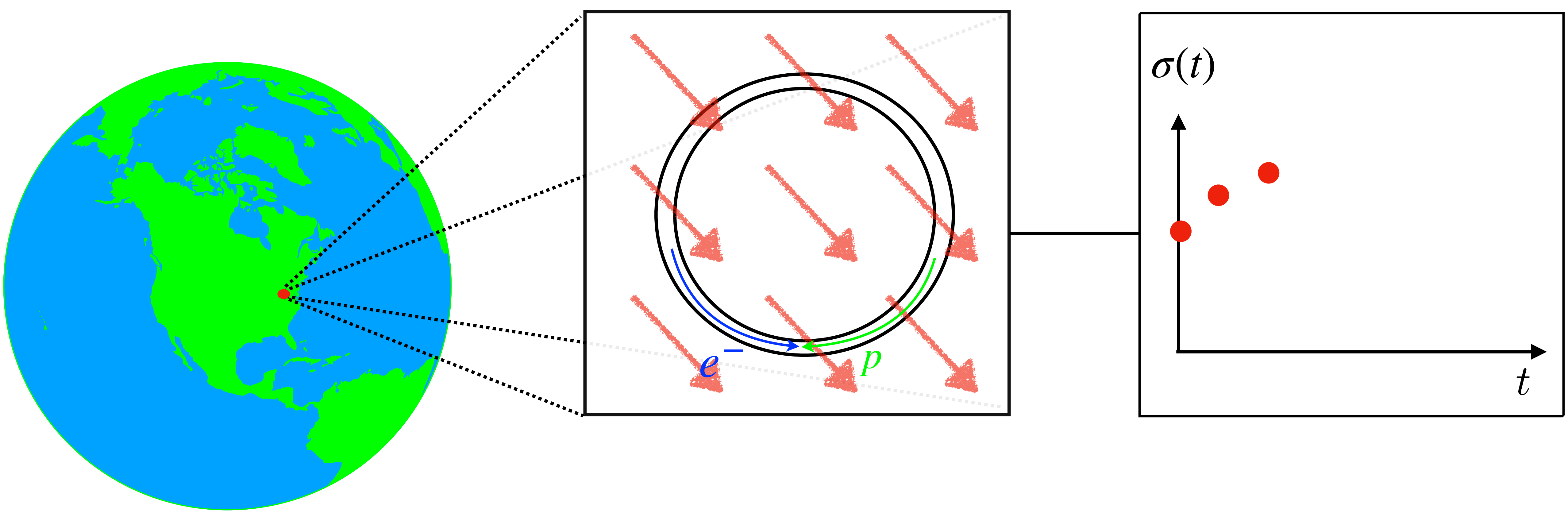

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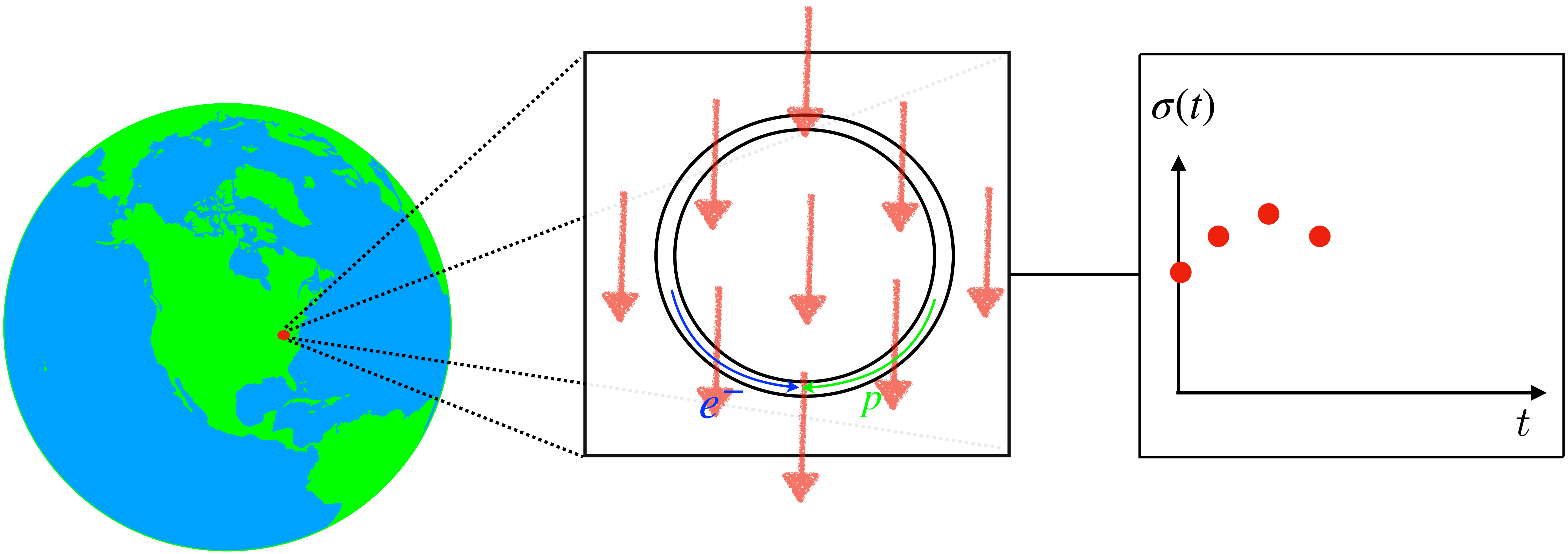

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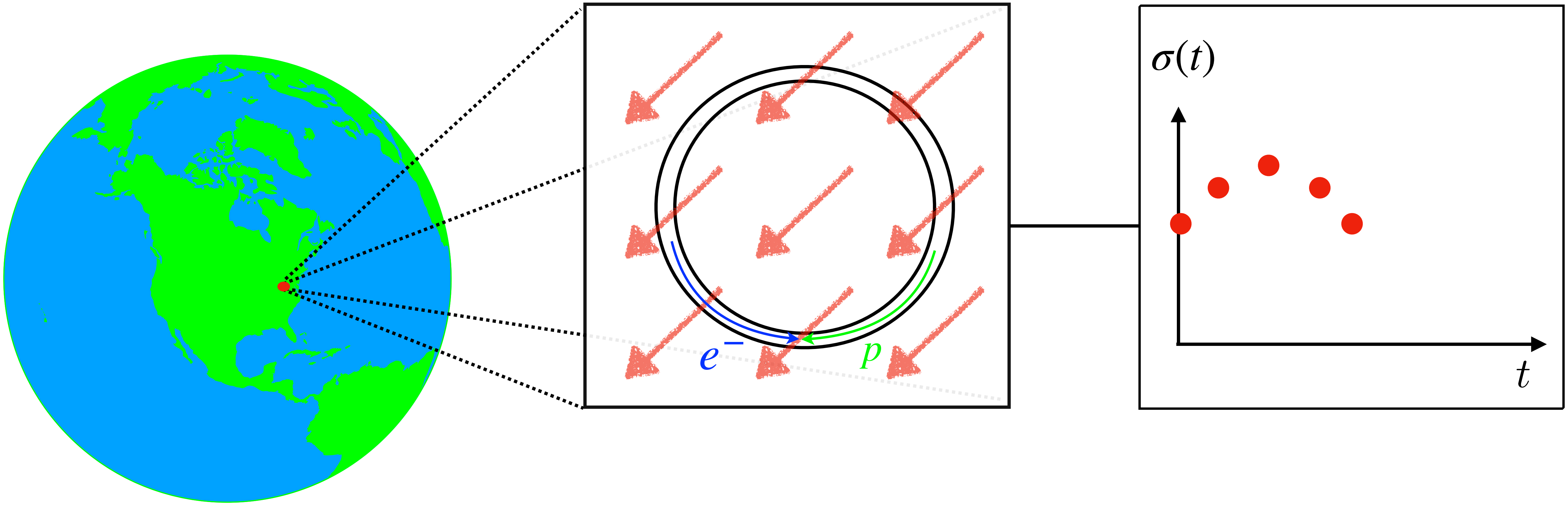

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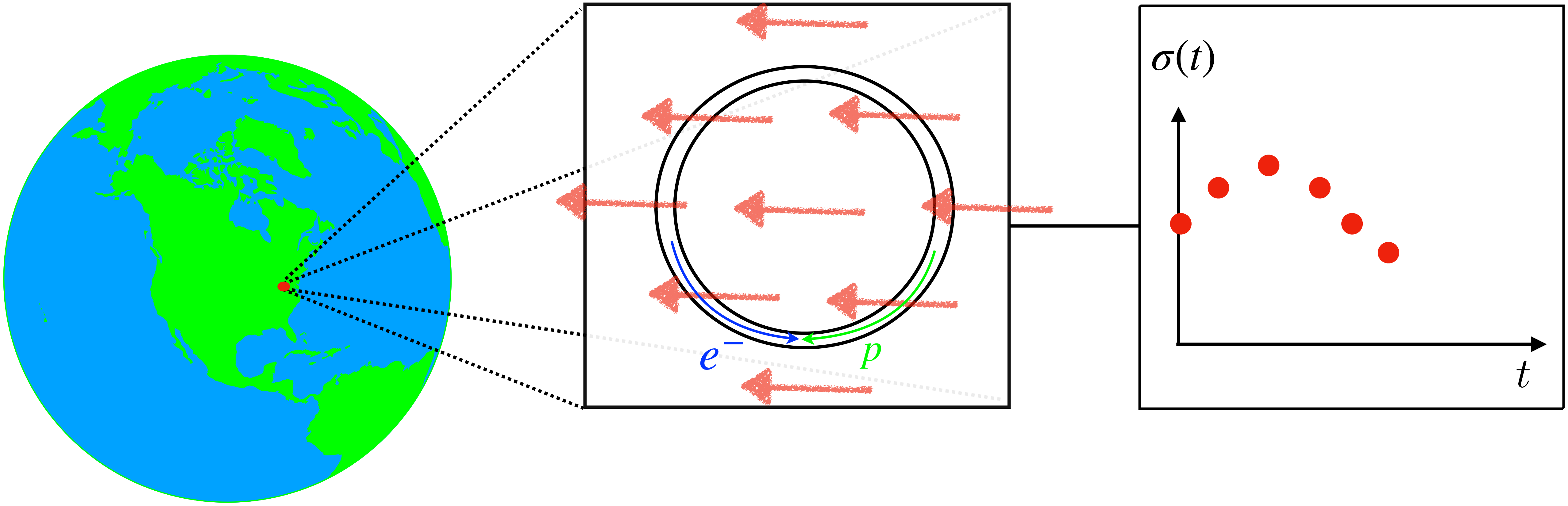

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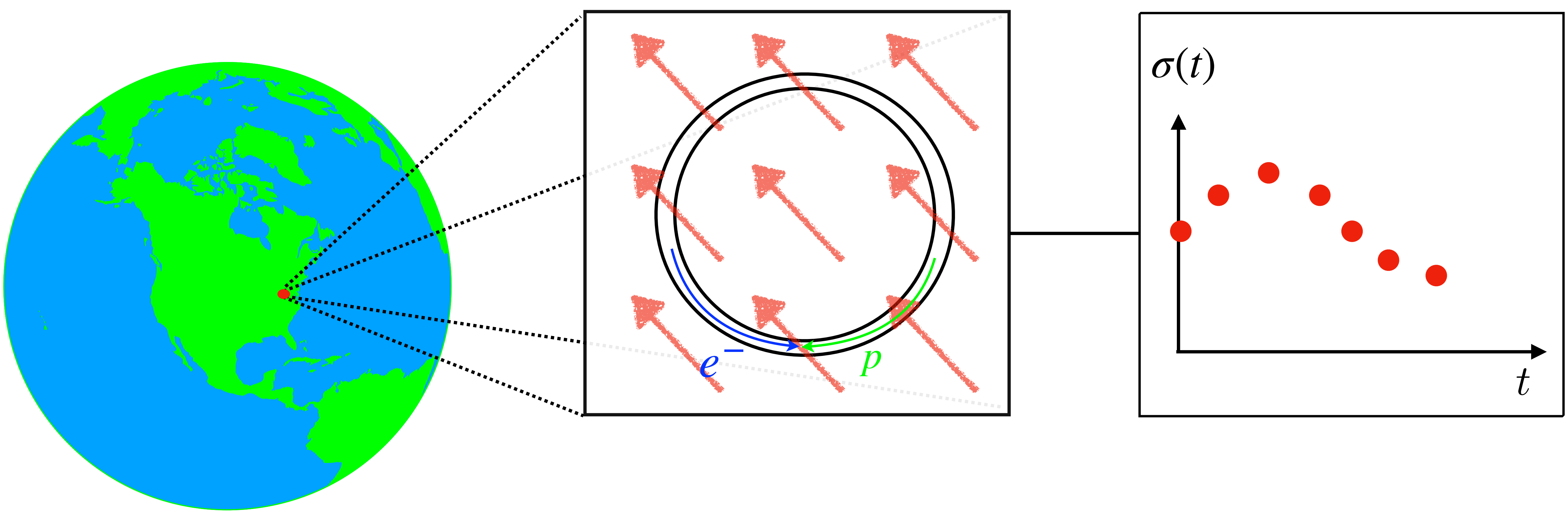

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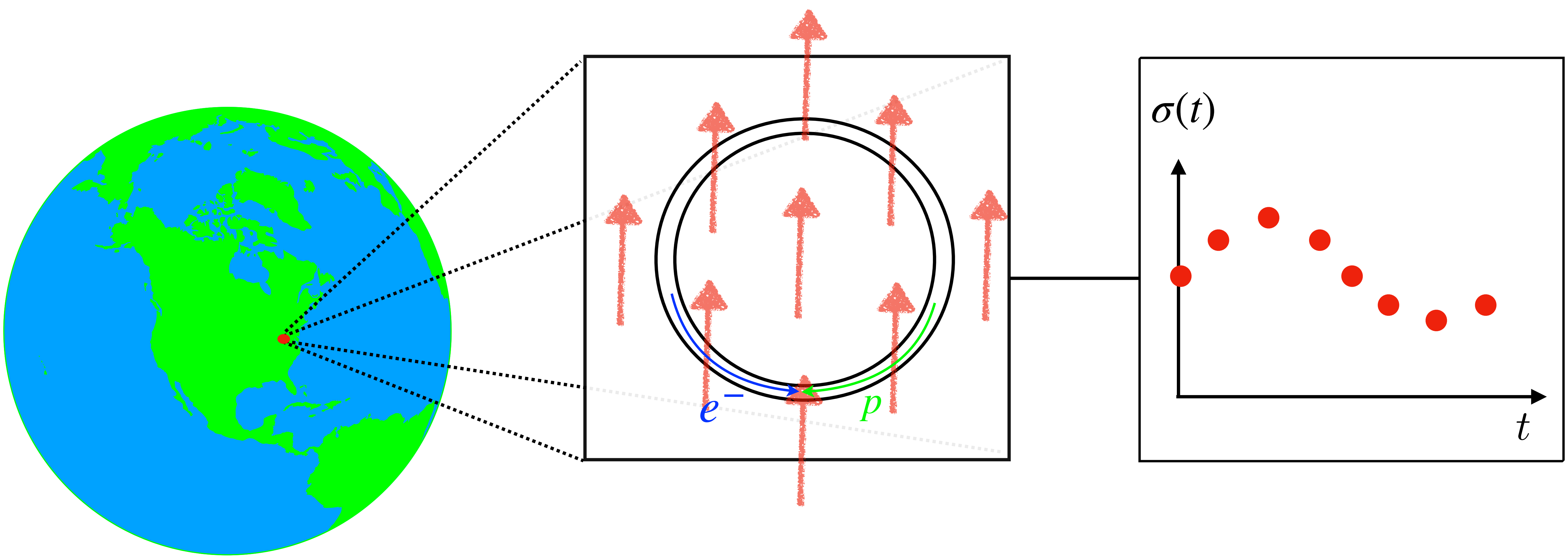

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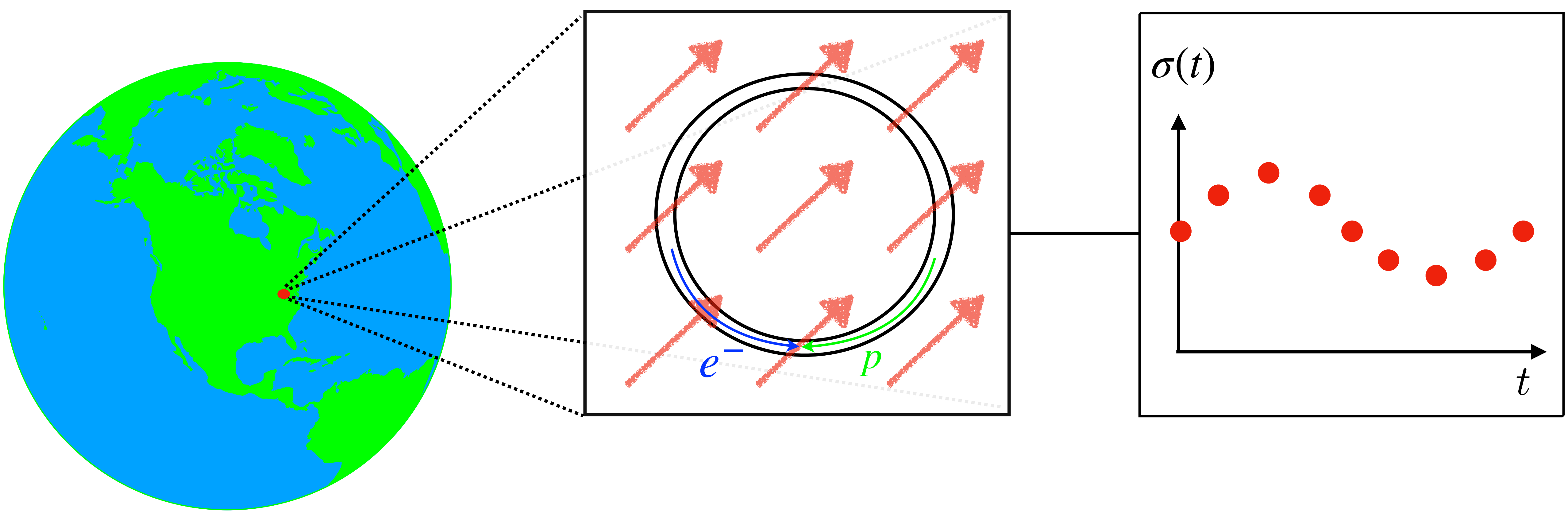

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	EIC	**LHC**
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$\lvert (c_{Su}^{(4)})^{XY} \rvert$	0.26	2.7
$\lvert (c_{Su}^{(4)})^{XZ} \rvert$	0.23	7.3
$(c_{Su}^{(4)})^{YZ} \rvert$	0.23	7.1
$\lvert (a_{Su}^{(5)})^{TXX} - (a_{Su}^{(5)})^{TYY} \rvert$	0.15	0.022
$\lvert (a_{Su}^{(5)})^{TXY} \rvert$	0.12	0.0039
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Results suggest improved sensitivity to nonminimal coefficients through the Drell-Yan process at the LHC and minimal coefficients through DIS at the EIC*

*E. Lunghi and N. S., Phys. Rev. D **98**, 115018 (2018)

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- We developed a framework for studying quark-sector Lorentz violation in hadronic processes using the SME
- Show factorization at the parton level for DIS and the Drell-Yan process
- Consistency checks: Approach is consistent with the OPE and Ward identities
- Lorentz- and CPT-violating effects on PDFs deduced
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Thank you!