Revisiting extremely high energy QED bremsstrahlung in matter

Large modifications to the LPM effect

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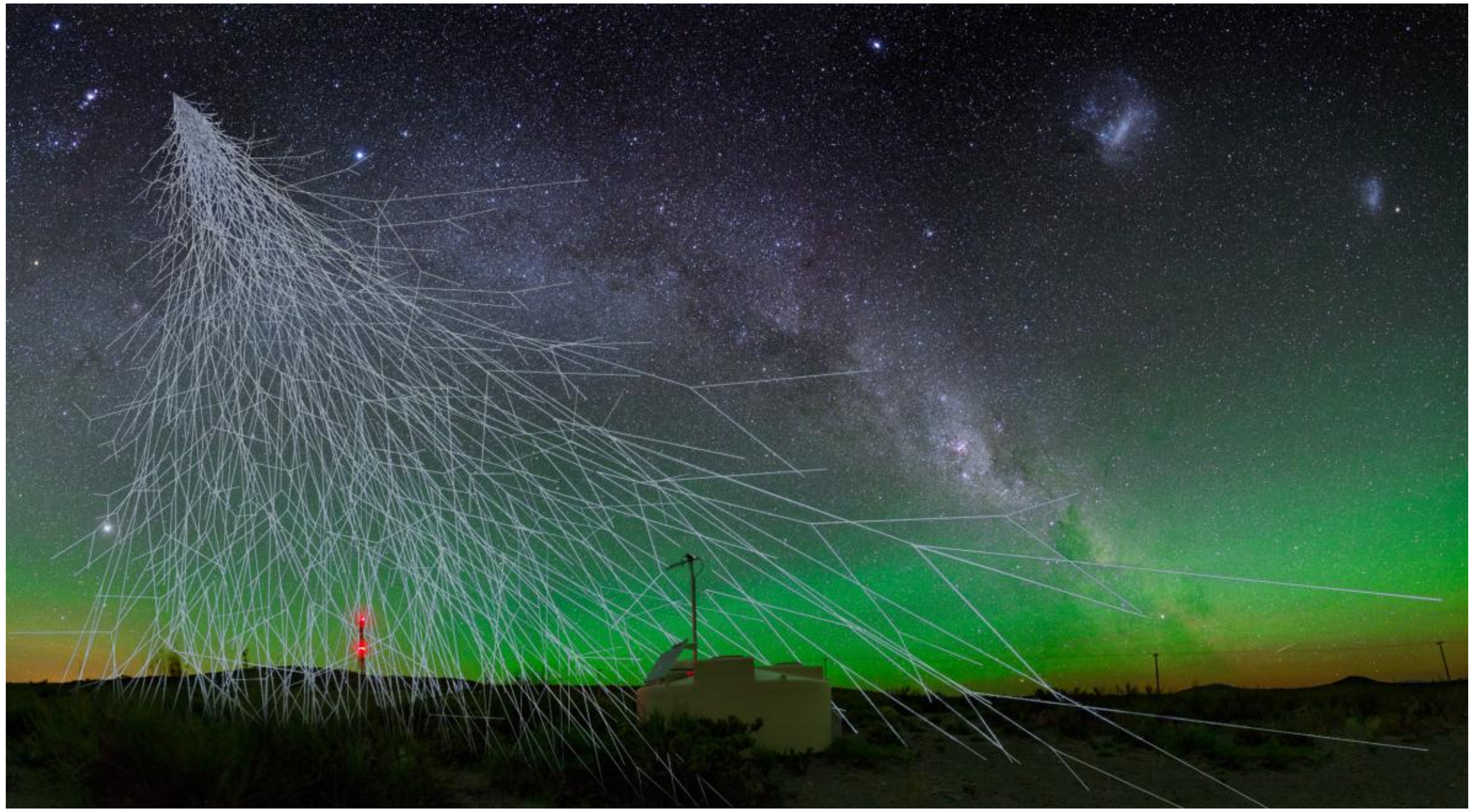
Work based on the papers below:

- *JHEP* 03 (2026) 015
- arXiv: 2604.18685, 2605.03002

May 12, 2026

Why study (extremely) high energy bremsstrahlung?



Artist's rendering of a cosmic-ray air shower with a water-Cherenkov detector of the Pierre Auger Observatory in western Argentina. Credit: A. Chantelauze, S. Staffi, L. Bret. [https://www.eurekalert.org/multimedia/896709]

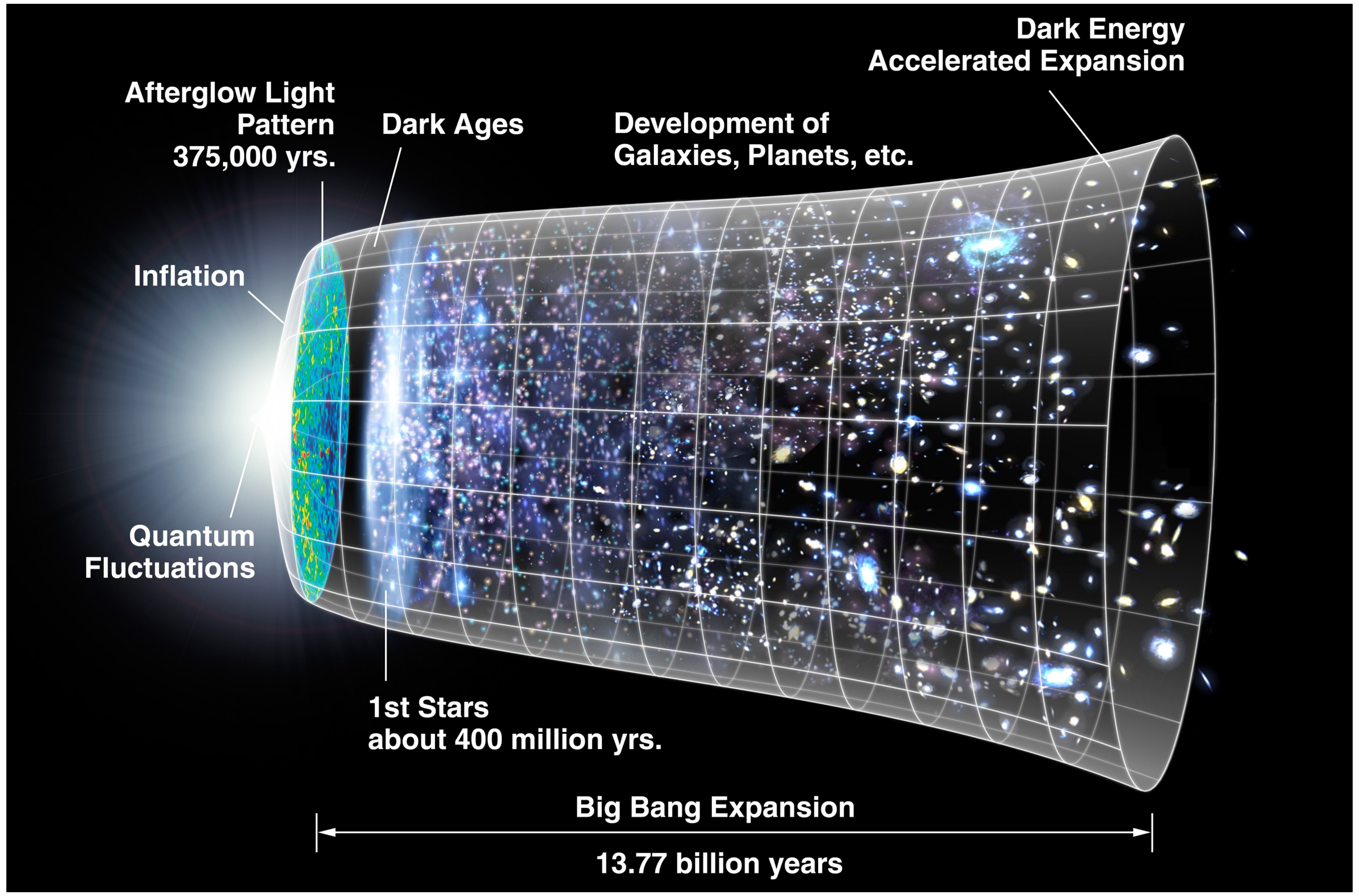
UHECRs

- Where do they come from?
- How are they made?
- What are they made of?
- Particle physics beyond collider energies?

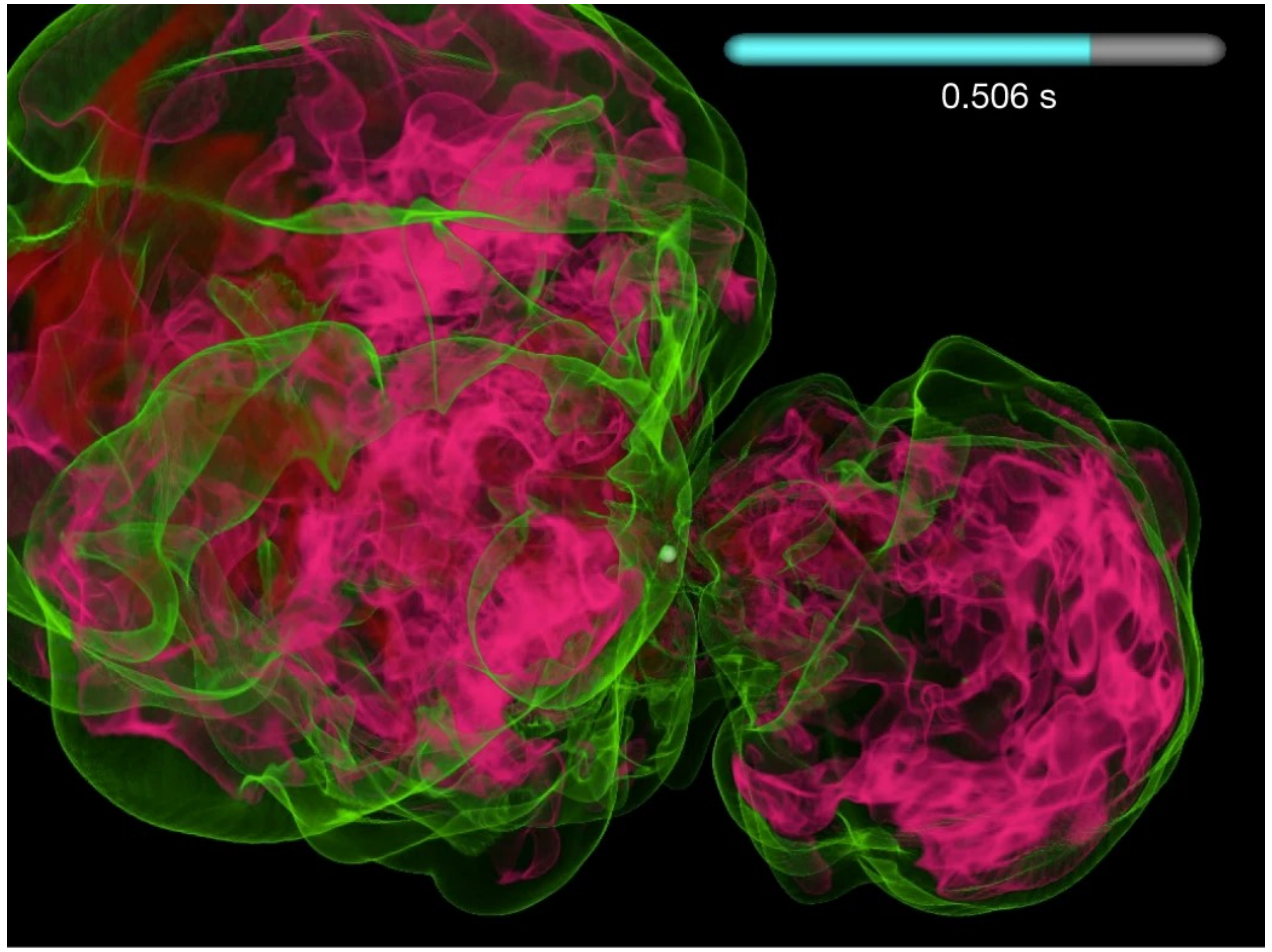
Extensive Air Showers: The primary cosmic ray particle properties are inferred from measuring the properties of the air shower and comparing it to simulations.

Why study (extremely) high energy bremsstrahlung?

Other (extremely) dense environments



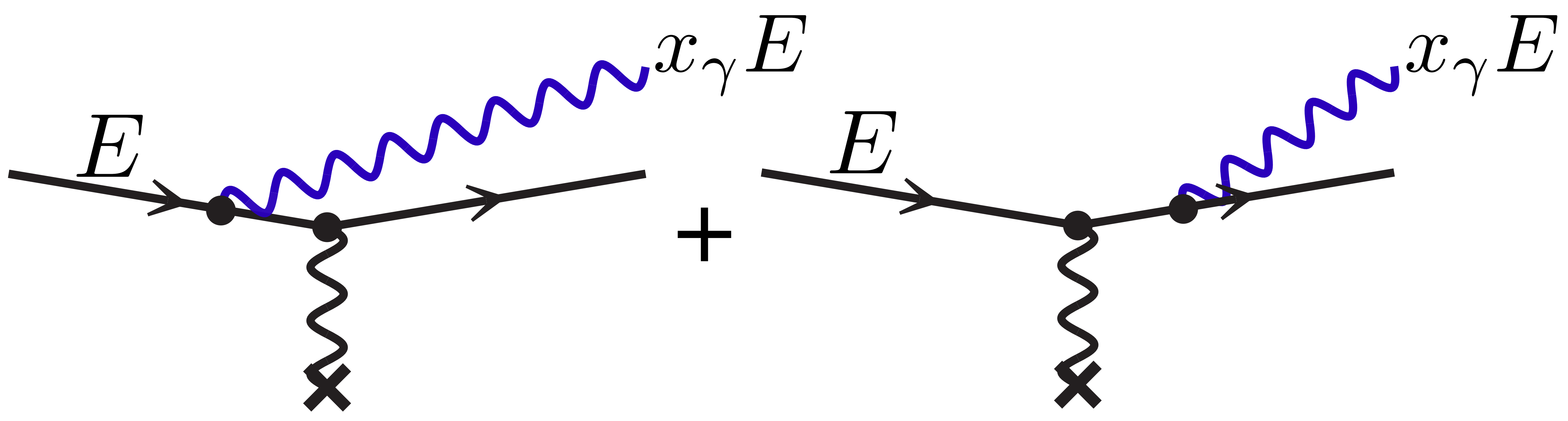
Credit: NASA / WMAP Science Team. https://science.nasa.gov/mission/wmap/wmap-overview/

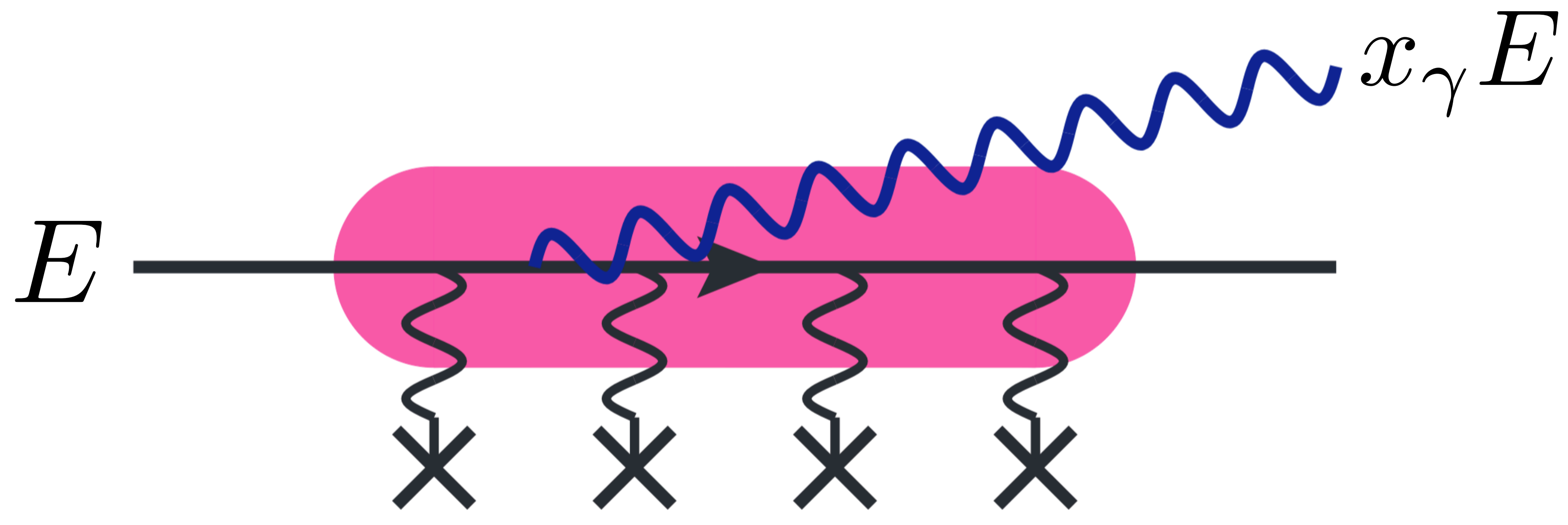


Supernova explosion simulation. Burrows, A., Vartanyan, D. Core-collapse supernova explosion theory. *Nature* **589**, 29–39 (2021). https://doi.org/10.1038/s41586-020-03059-w

What is the LPM effect?

Bethe-Heitler vs Landau-Pomeranchuk-Migdal





Bethe-Heitler

Scatterings between different atomic nuclei are quantum-mechanically independent

LPM

Destructive interference between different elastic scatterings leads to huge **suppression** of the bremsstrahlung rate

$$\left[\frac{d\Gamma}{dx_\gamma}\right]_{\rm BH} \gg \left[\frac{d\Gamma}{dx_\gamma}\right]_{\rm LPM}$$

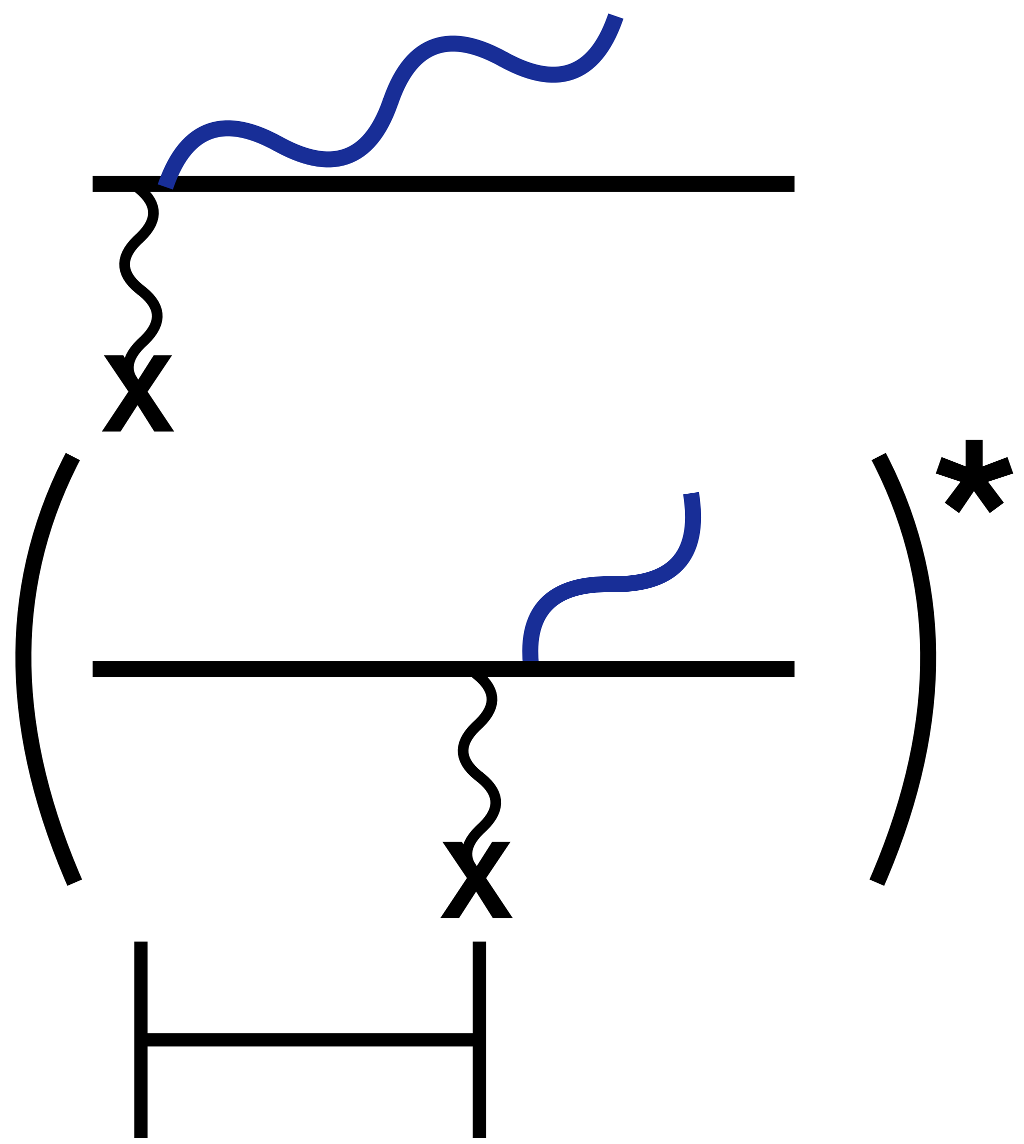
Understanding the LPM effect intuitively

Two main questions

1. When does the LPM effect matter?
   - When particles are extremely **collinear**.
2. Why does it lead to suppression?
   - This is a consequence of **Lorentz invariance**.

Understanding the LPM effect intuitively

Collinearity means more coherence

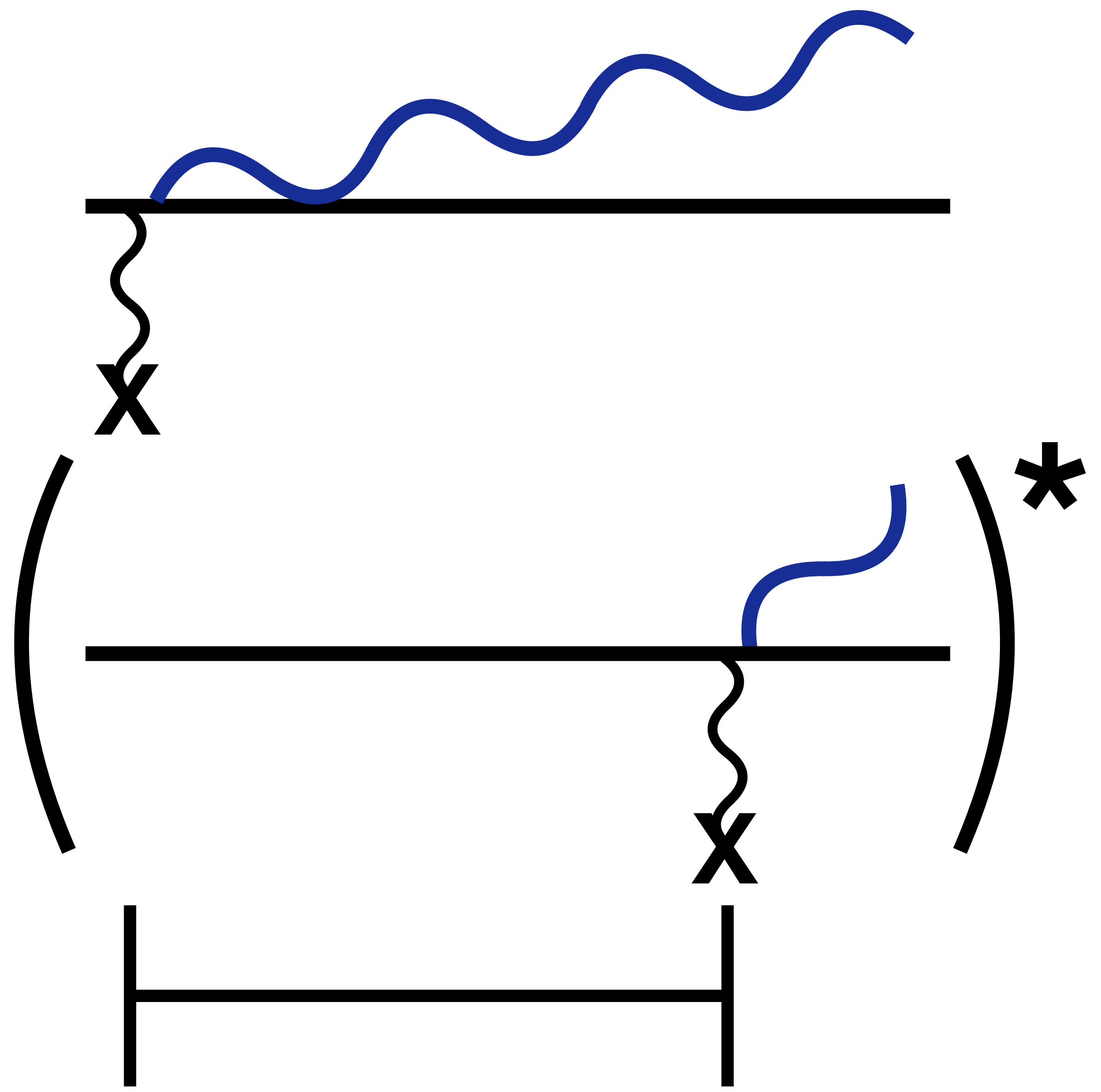


$$t_{\text{form}} \ll \tau_{\text{mean-free}}$$

Bethe-Heitler
regime

Understanding the LPM effect intuitively

Collinearity means more coherence



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Bethe-Heitler
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Understanding the LPM effect intuitively

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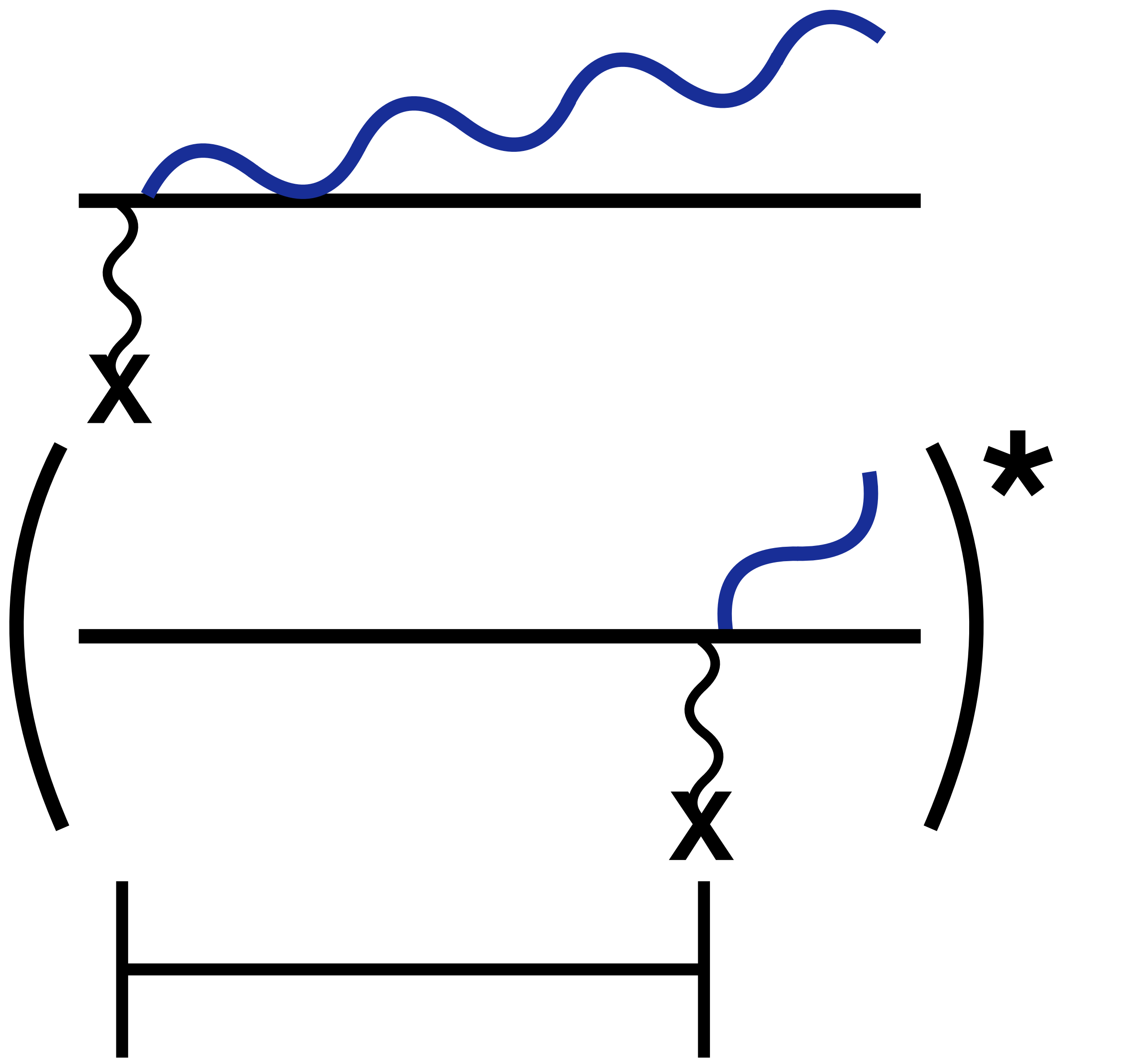

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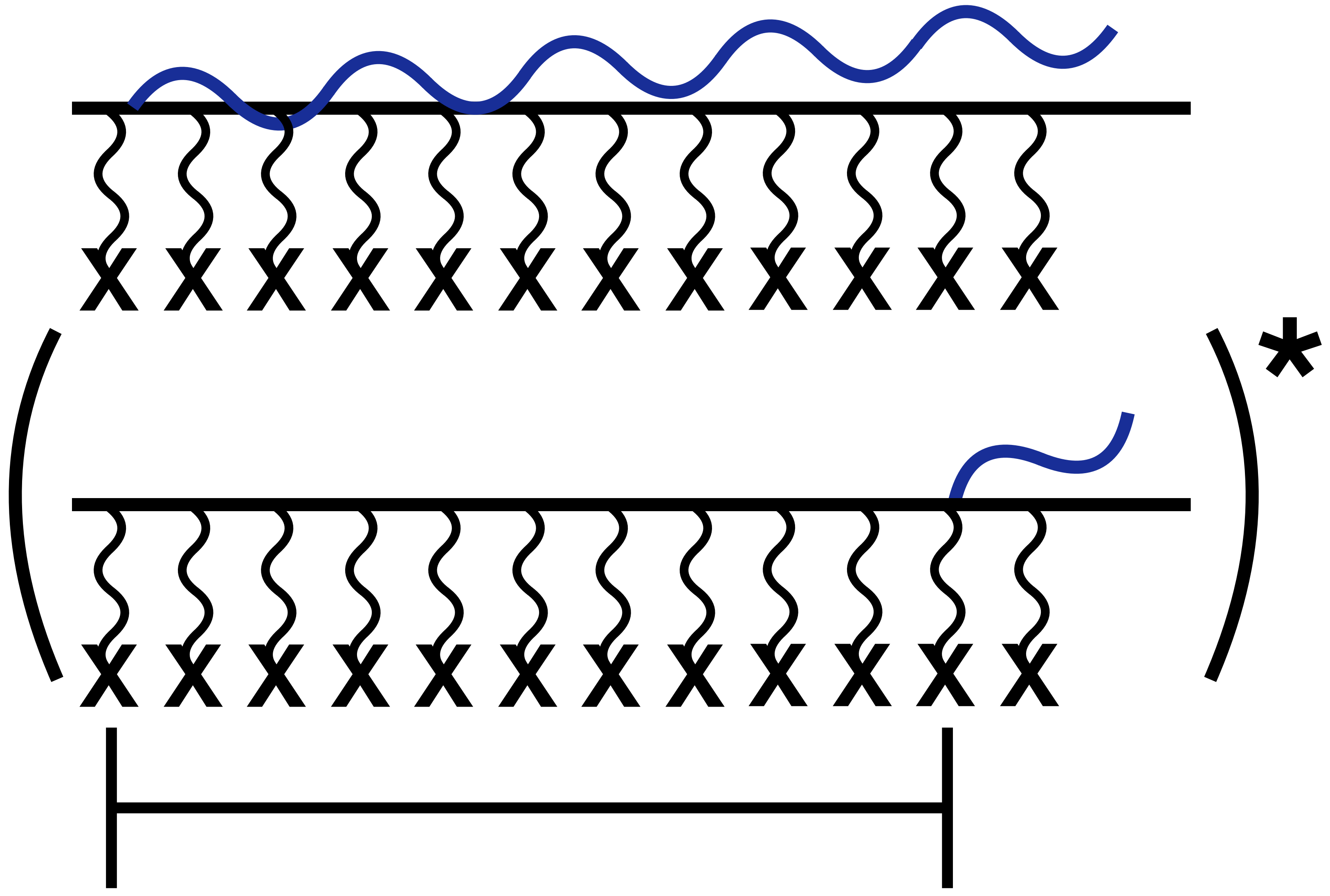
Bethe-Heitler
regime



$$t_{\text{form}} \gg \tau_{\text{mean-free}}$$

LPM
regime

More collinear

$\Downarrow$

Longer time for $e\gamma$ to separate

$\Downarrow$

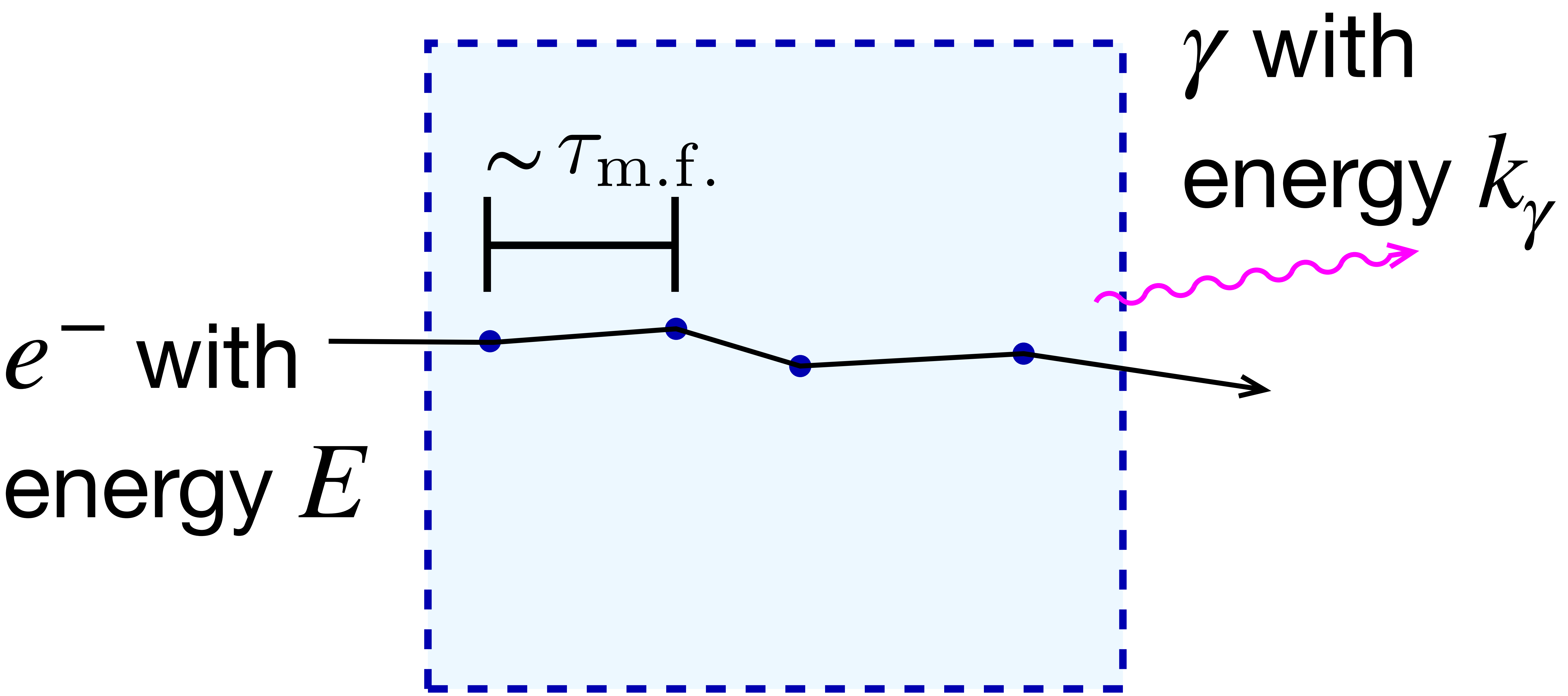
More coherence

$\Downarrow$

Need to take into account multiple scatterings

Understanding the LPM effect intuitively

Lorentz Invariance implies suppression

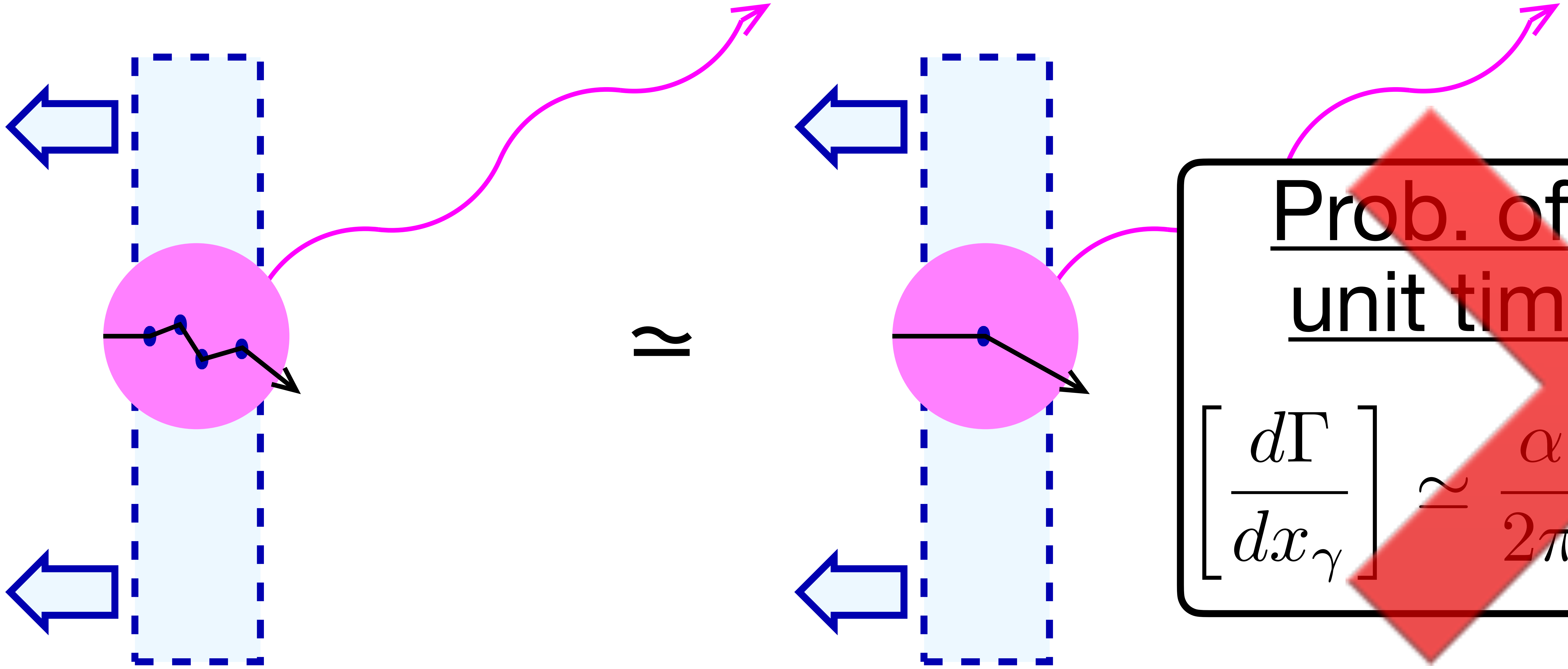


Prob. of brem. per unit time (naively)

$$\left[\frac{d\Gamma}{dx_\gamma}\right] \simeq \frac{\alpha}{2\pi} P_{e\to\gamma}(x_\gamma)\tau_{\mathrm{m.f.}}^{-1}$$

Understanding the LPM effect intuitively

Lorentz Invariance implies suppression



Prob. of brem. per unit time (naively)

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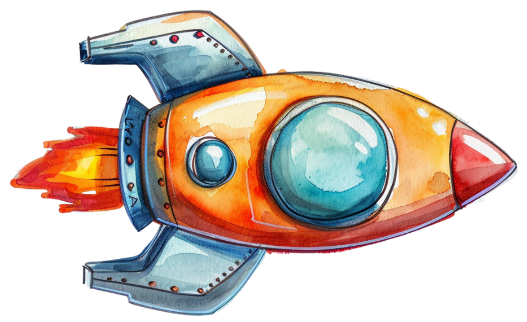
Extreme boost



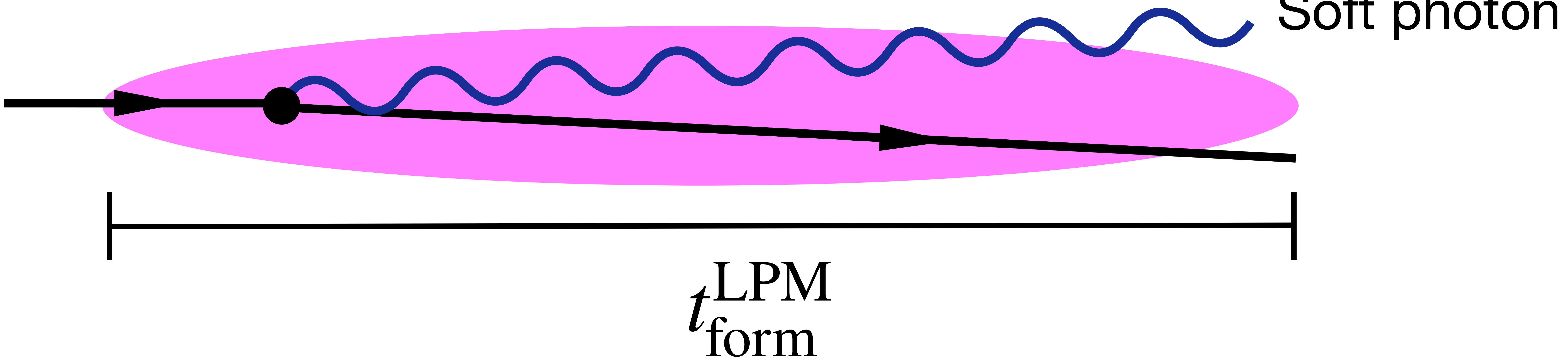
0.9999999999... c

suppression factor $\simeq \left(\frac{\tau_{\text{m.f.}}}{t_{\text{form}}}\right)$

$\left(\text{Number of unresolved scatterings}\right)^{-1}$

Large modifications to the LPM effect

Due to overlapping (soft) pair production



Large modifications to the LPM effect

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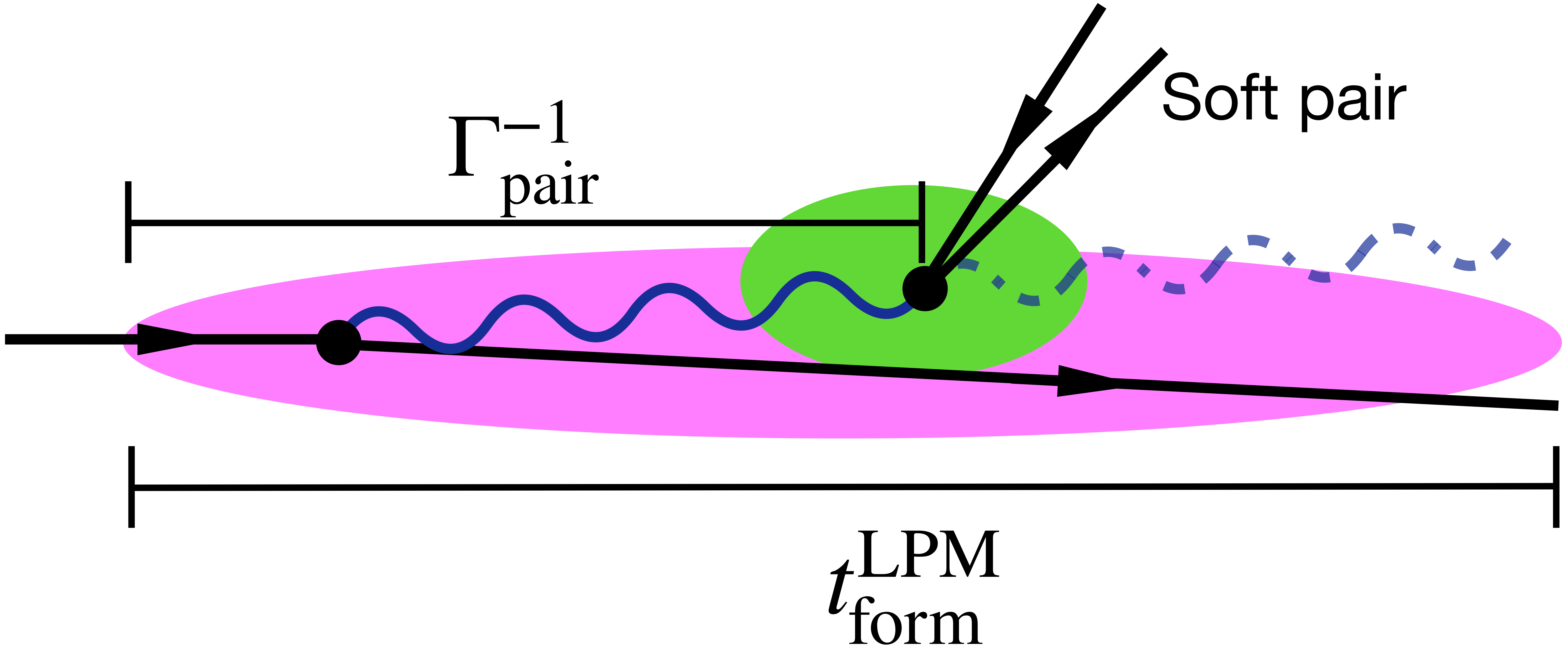


Soft pair is deflected more easily, disrupting collinearity

$$t_{\mathrm{form}}^{\mathrm{eff}} \simeq \Gamma_{\mathrm{pair}}^{-1}$$

Pair production cuts off LPM suppression

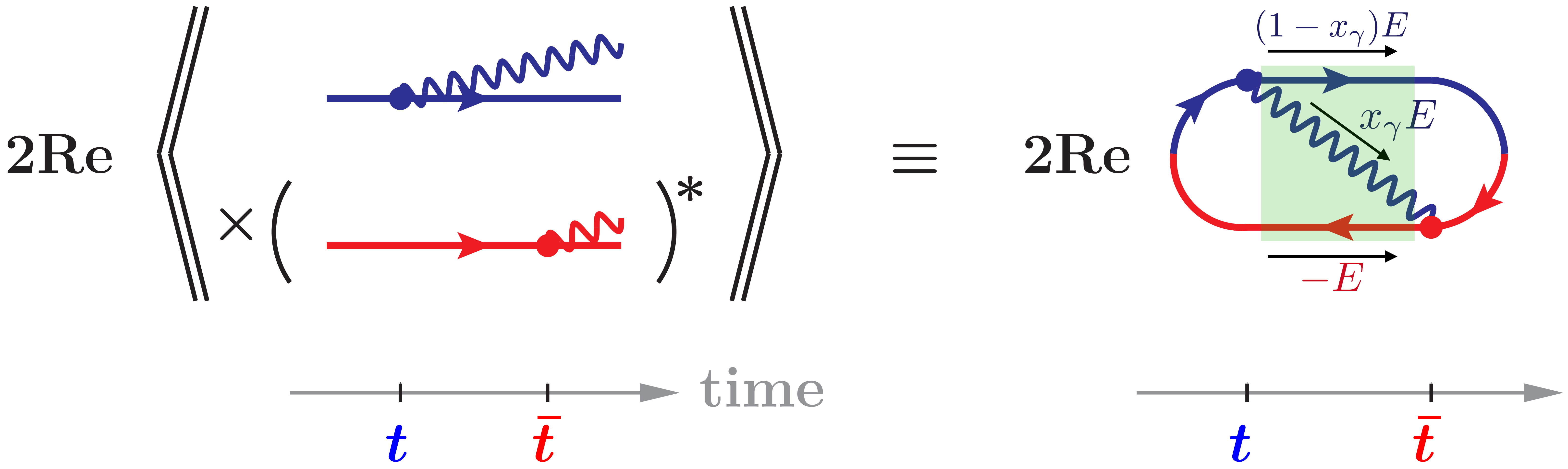
Calculation

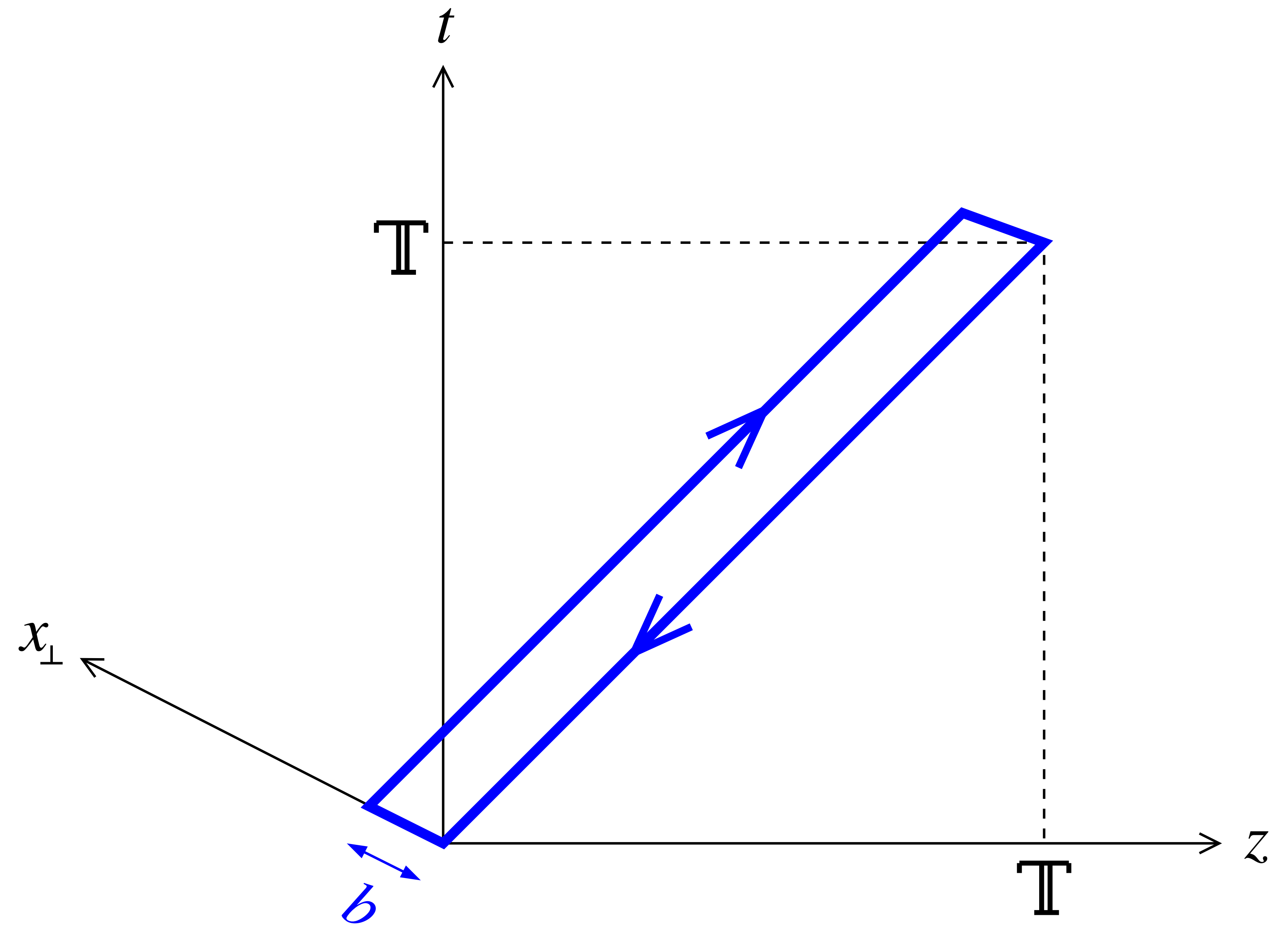
What assumptions do we make?

1. Very large, static, and homogeneous medium
2. Very many scatterings occurring within formation time
   - Transverse momentum diffusion $\langle \Delta p_{\perp}^{2} \rangle = \hat{q}\Delta t$

Calculation

Formalism





Blue and red dots: high-energy, collinear splitting matrix elements.

2D Schrödinger-like equation for 3 particles

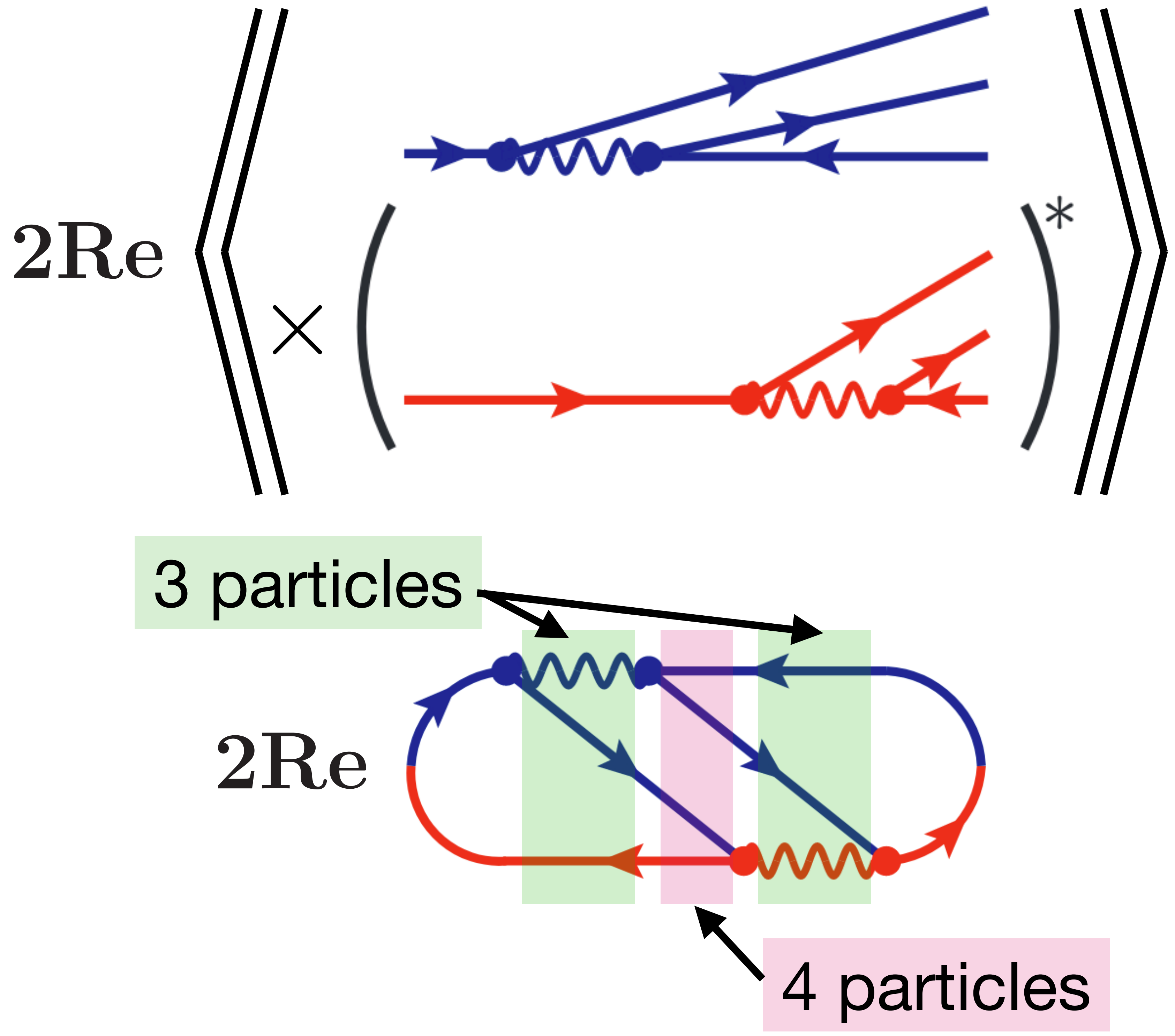
$$i\partial_t \Psi = \mathcal{H}\Psi$$

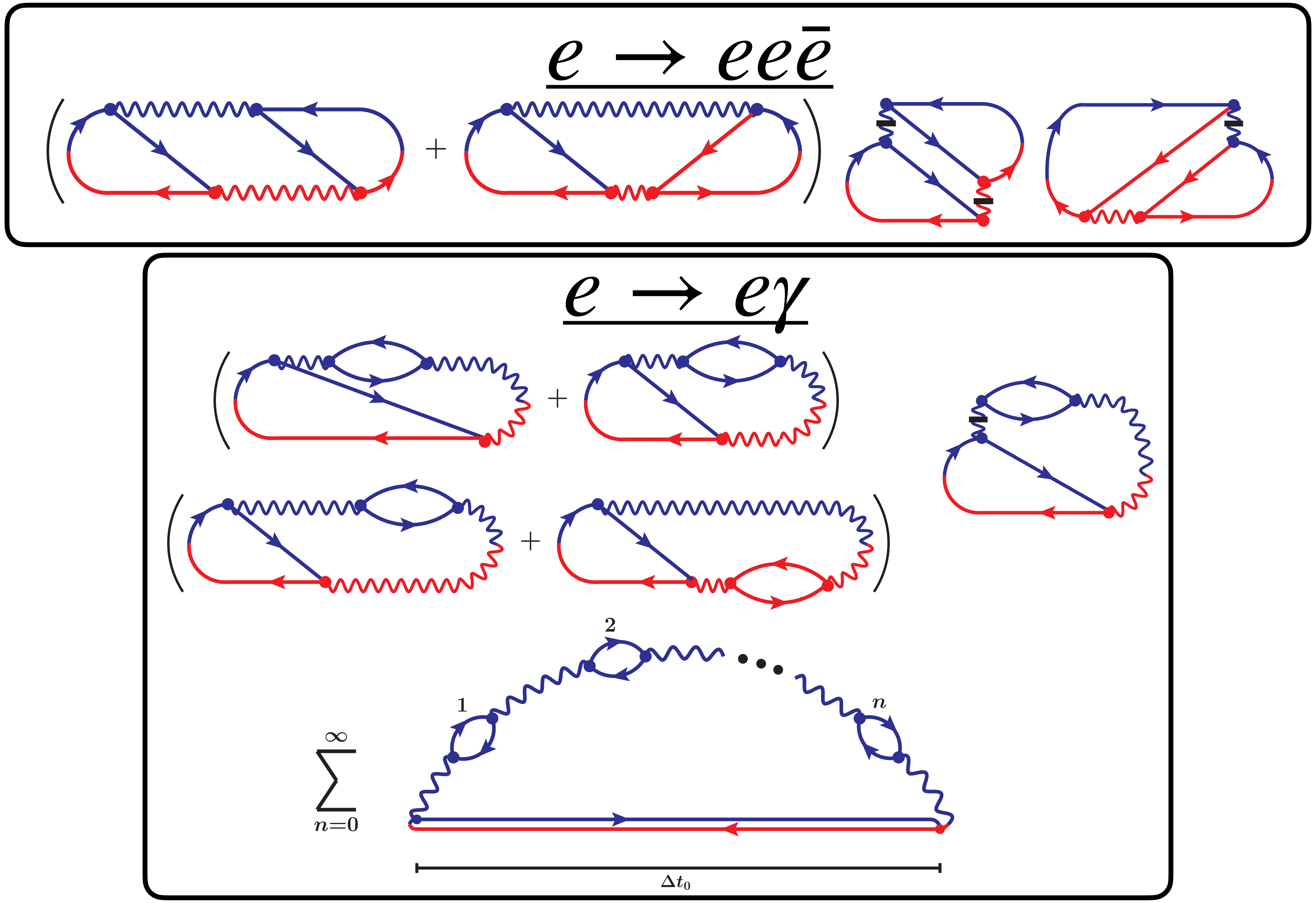
Complex effective potential accounts for medium effects

$$V_{ij} \simeq -\tfrac{i}{4}\hat{q}|\mathbf{b}_i - \mathbf{b}_j|^2$$

Calculation

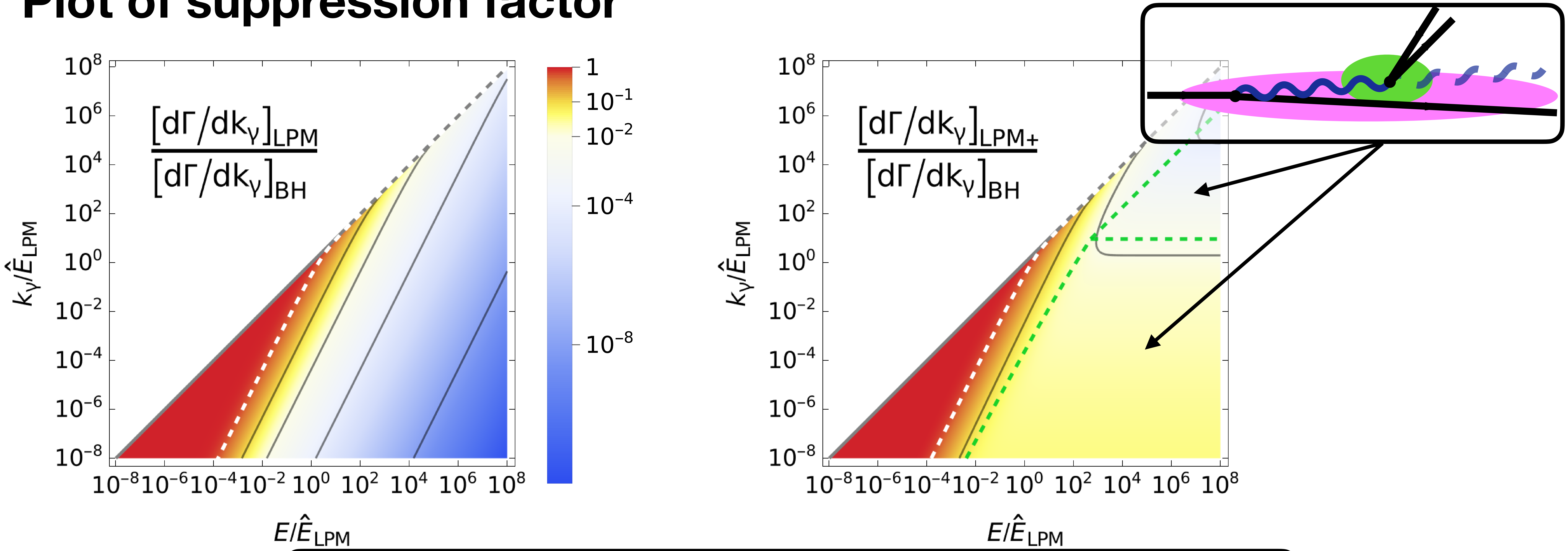
Diagrams we had to consider





Results

Plot of suppression factor

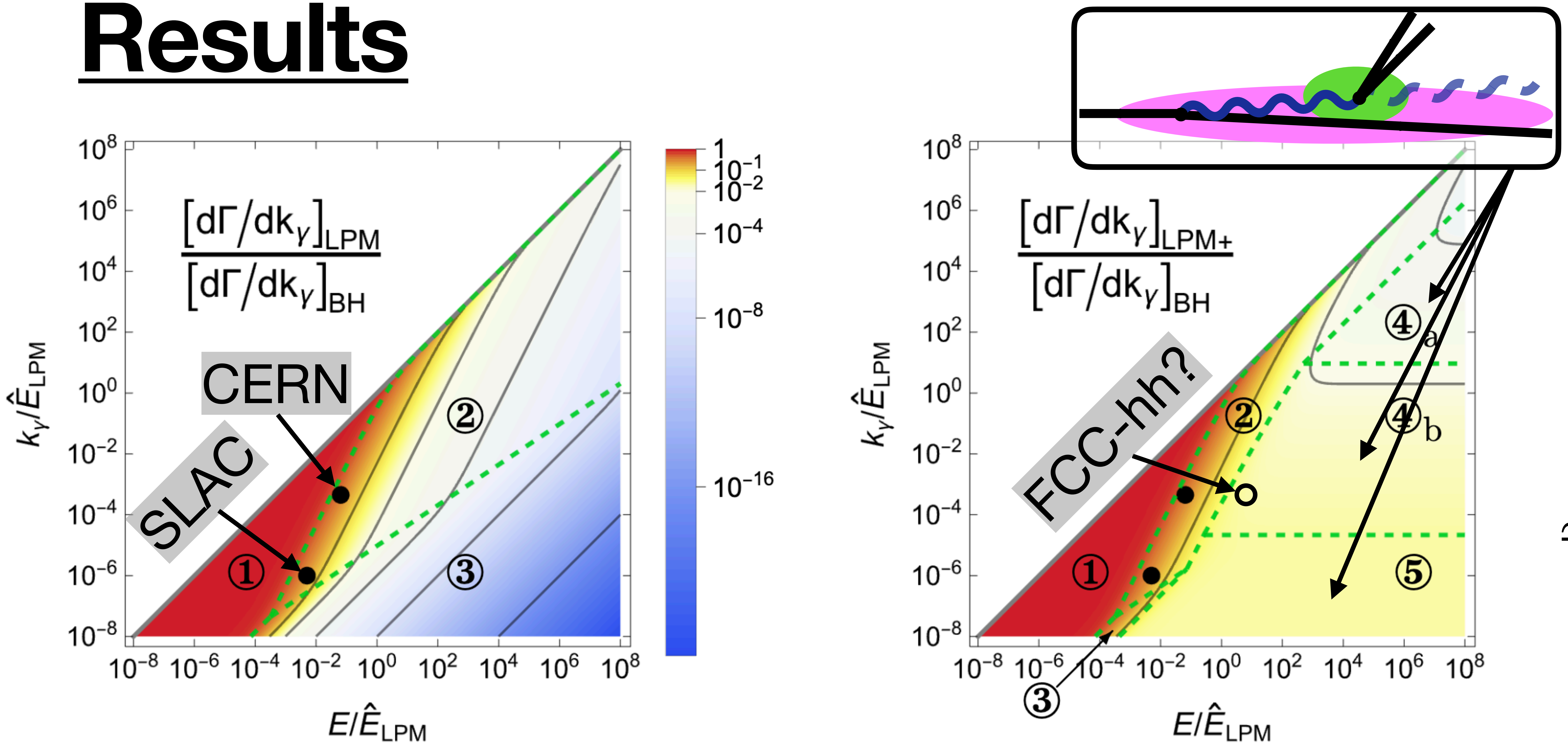


Pair production cuts off LPM suppression

Summary and Outlook

- For large enough formation times, pair-production has to be taken into account, which leads to huge modifications to the LPM effect
- Potential experiments to verify this behavior
    1. Inclusion of this effect to air shower simulations and comparing with observations
    2. Electron beam incident on thin dense foil, a la SLAC (Anthony et. al, 1995) and CERN (Hansen et. al, 2003), but undetectable at current collider energy scales.
- Experiments above need further calculations to include (among others) finite-medium effects

Results



Region 2

$$\simeq \frac{\alpha}{2\pi} P_{e\to\gamma}(x_\gamma) \sqrt{\frac{k_\gamma \hat{q}}{(E-k_\gamma)E}}$$

Regions 4 and 5

$$\simeq \frac{\alpha}{2\pi} P_{e\to\gamma}(x_\gamma) \Gamma_{\text{pair}} \ln(\cdots)$$

Pair production cuts off further LPM suppression.

For region 4a, Γ_{pair} is LPM suppressed.

For regions 4b and 5, Γ_{pair} is unsuppressed.

In regions 3 and 5, the medium-induced photon mass is not ignorable.

SLAC expt. (1995): P. L. Anthony et al. PRL 75, 1949-1952
CERN expt. (2003): H. D. Hansen et al. PRL 91, 014801