Spatio-temporal development of QED cascade in extremely intense laser-matter interaction

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Ultra Intense Laser Technology and Intense Field Physics
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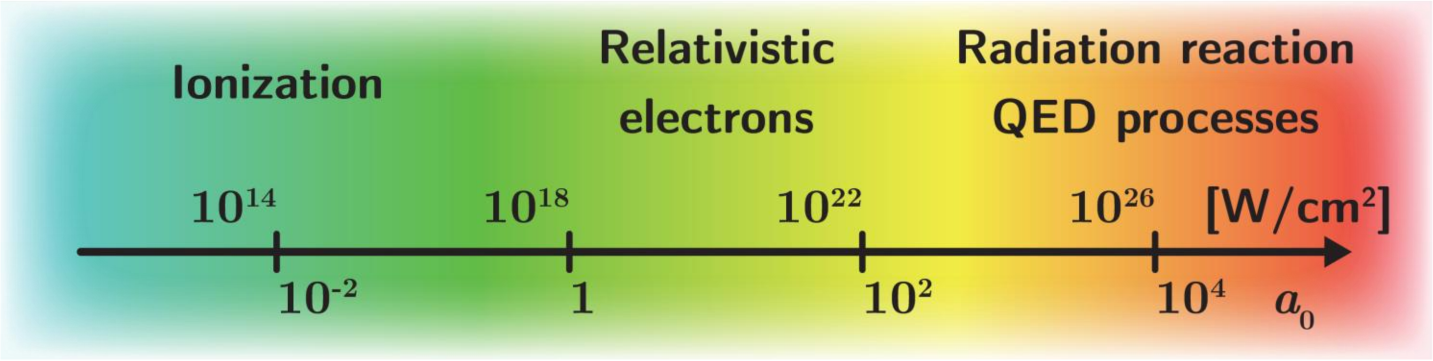
Strong fields

$$a_0 = \frac{qE_M}{mc\omega_L}$$ – dimensionless field amplitude



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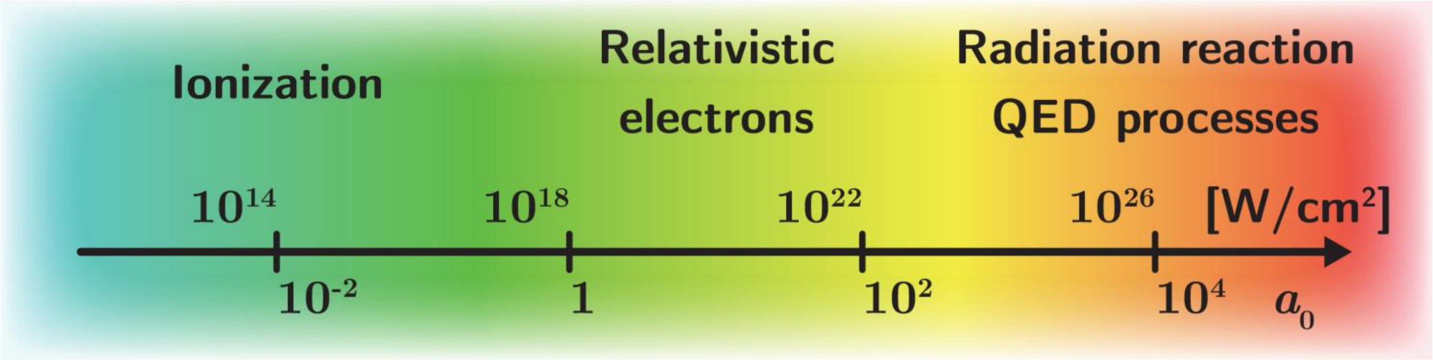


$$\chi_{e,p,ph} = \frac{\sqrt{(\varepsilon\mathbf{E}/c + \mathbf{p}\times\mathbf{B})^2 - (\mathbf{p}\cdot\mathbf{E})^2}}{m_e c E_s}$$

$$E_s = \frac{{m_e}^2 c^3}{\hbar e} \approx 1.32\cdot 10^{18}\ \mathrm{V/m}$$

($a_0 \sim 10^6$ for $\lambda = 1\ \mu$m)

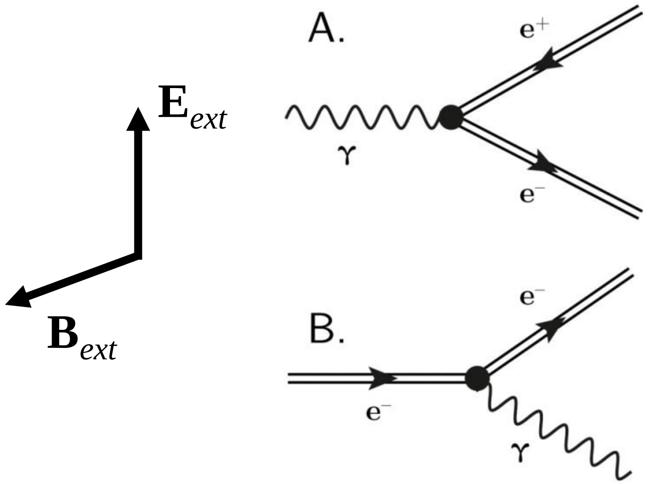
$\chi \geq 1$ – probable QED processes:

A. Photon decay into $e^- e^+$ pair

$$\gamma + n\hbar\omega \rightarrow e^+ + e^-$$

B. Nonlinear Compton scattering

$$e^{+(-)} + n\hbar\omega \rightarrow e^{+(-)} + \gamma$$



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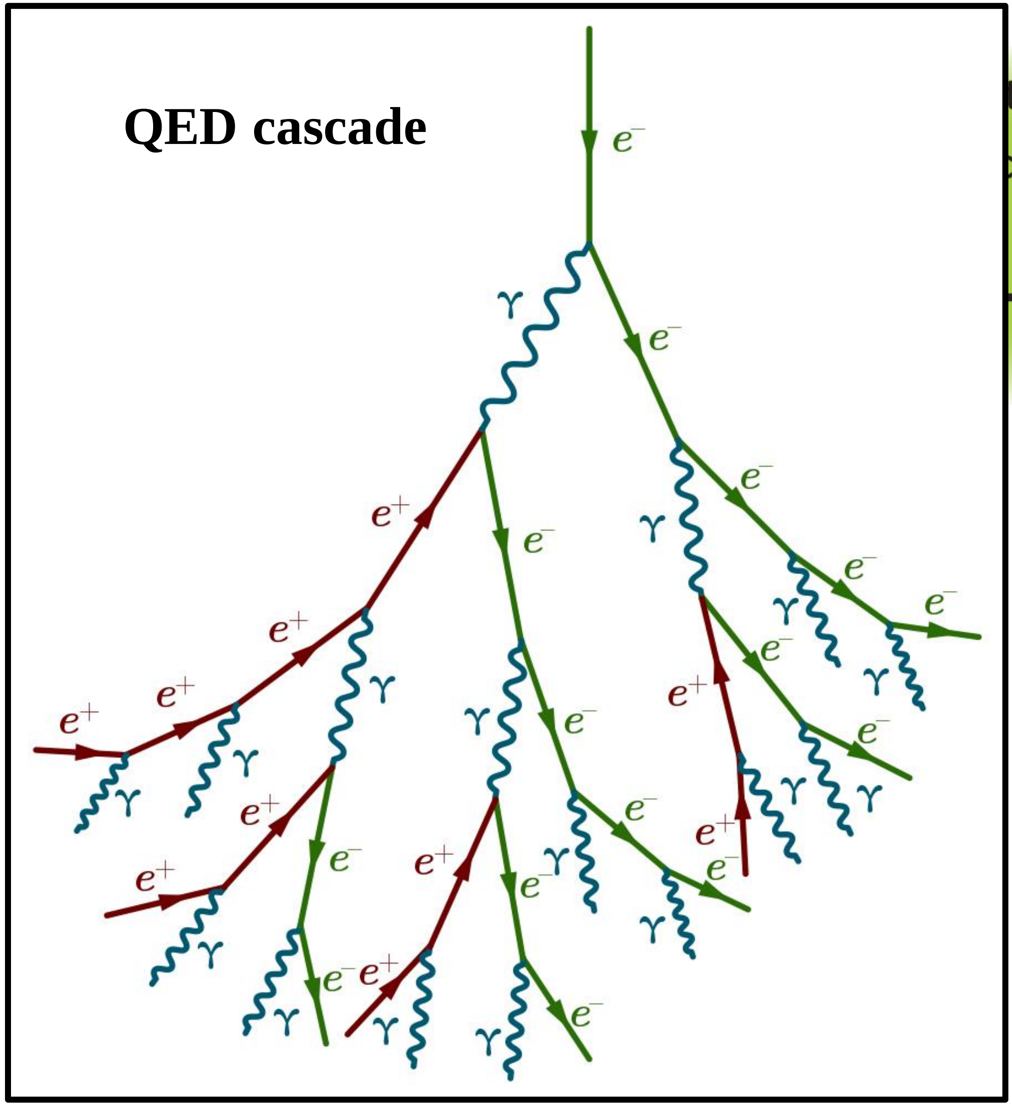

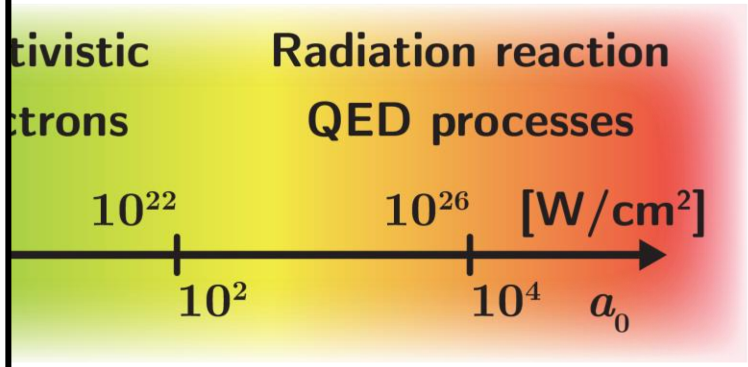

$$E_s = \frac{m_e{}^2 c^3}{\hbar e} \approx 1.32 \cdot 10^{18}\ \text{V/m}$$

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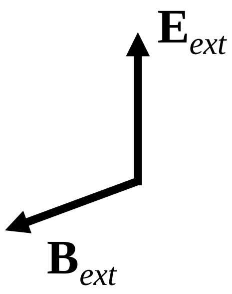

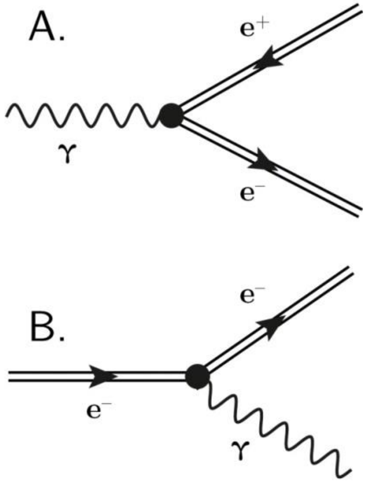

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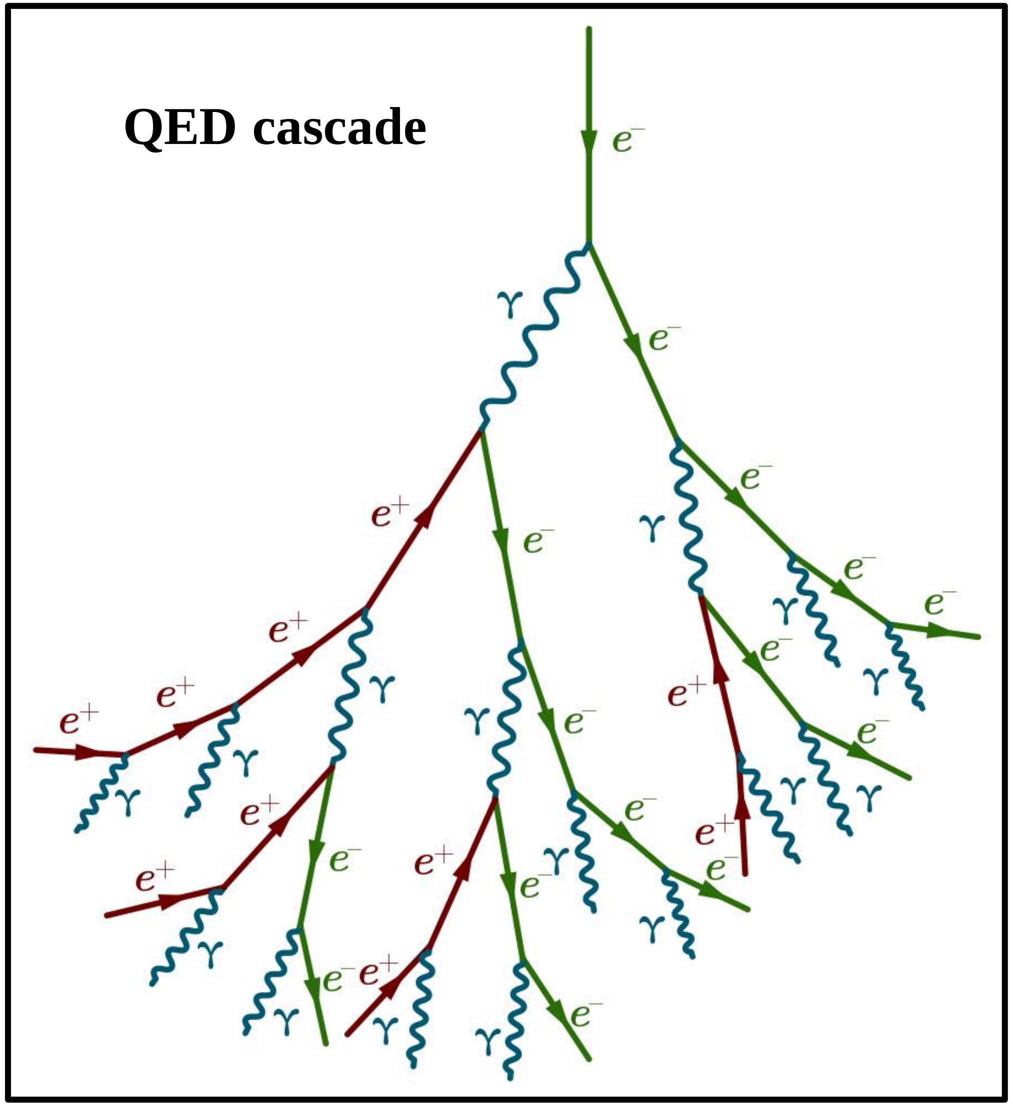
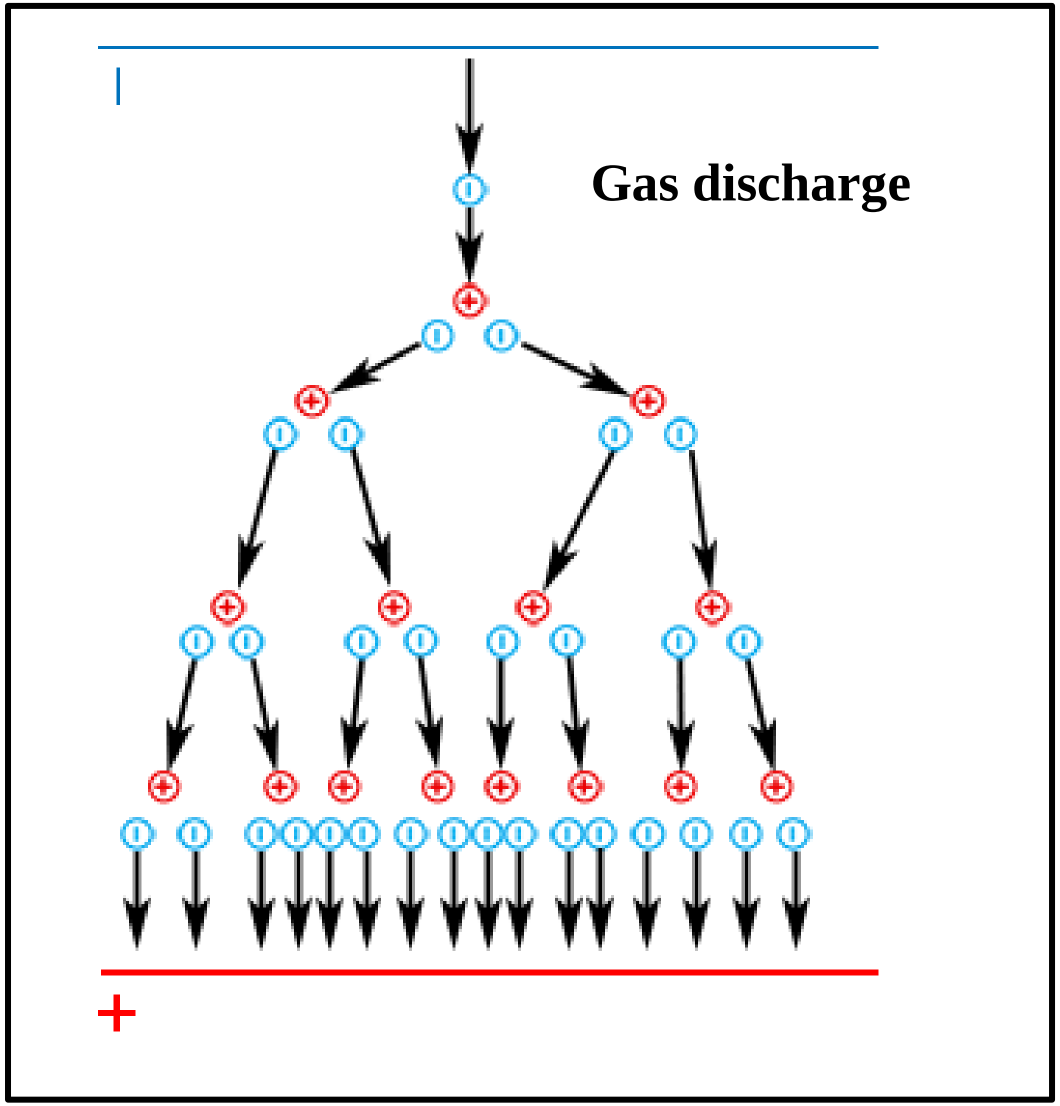


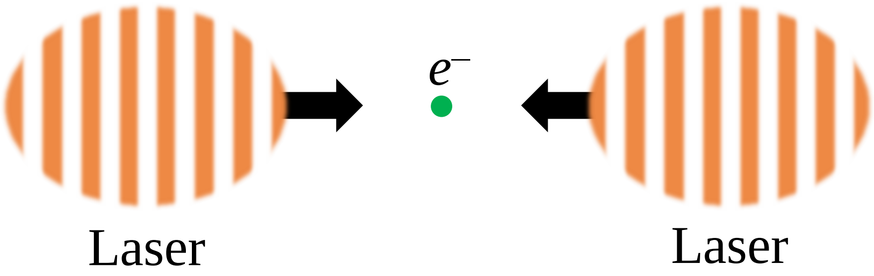


QED cascades

A(Avalanche)-type

Particles gain χ in EM field

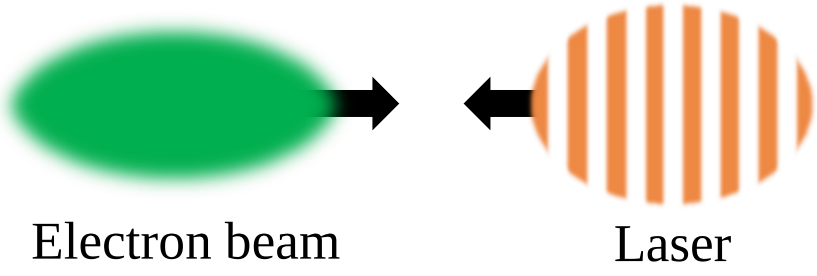
Impossible in the plane wave



S(Shower)-type

Seed particles have large χ, and χ is not gained in EM field

Possible in the plane wave



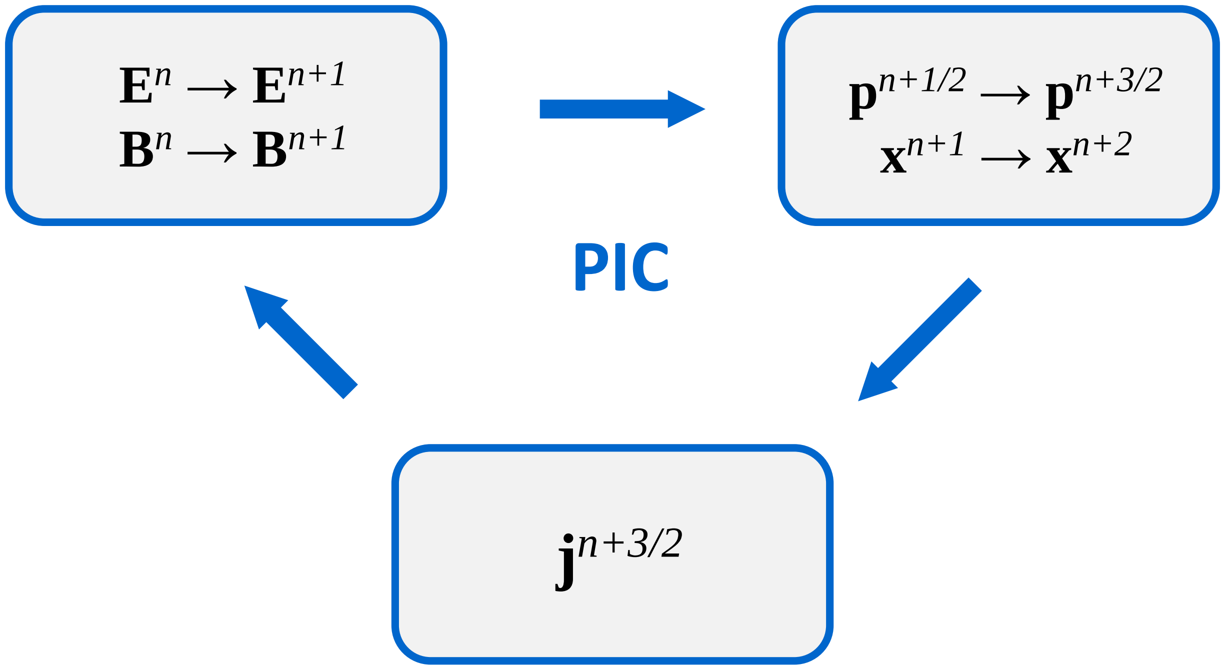
$$\boldsymbol{E} = \boldsymbol{E}_0 e^{-i\omega t + i\boldsymbol{kr}}$$

$$\boldsymbol{B} = \left[\boldsymbol{E}_0 \times \frac{\boldsymbol{k}}{k}\right] e^{-i\omega t + i\boldsymbol{kr}}$$

$$\chi_{e,p,ph} = \frac{\sqrt{(\varepsilon \mathbf{E}/c + \mathbf{p} \times \mathbf{B})^2 - (\mathbf{p} \cdot \mathbf{E})^2}}{m_e c E_s}$$

$$\partial_t \chi_e = 0$$

3D PIC code QUILL



E.N. Nerush *et al.*, Phys. Rev. Lett. **106**, 035001 (2011).

Strong fields

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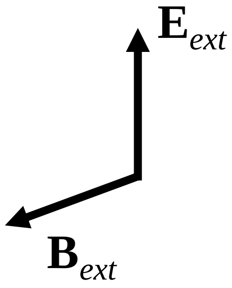
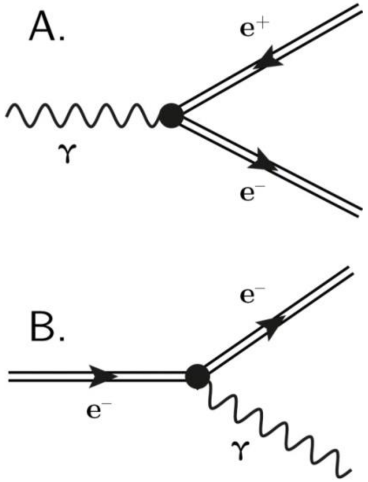




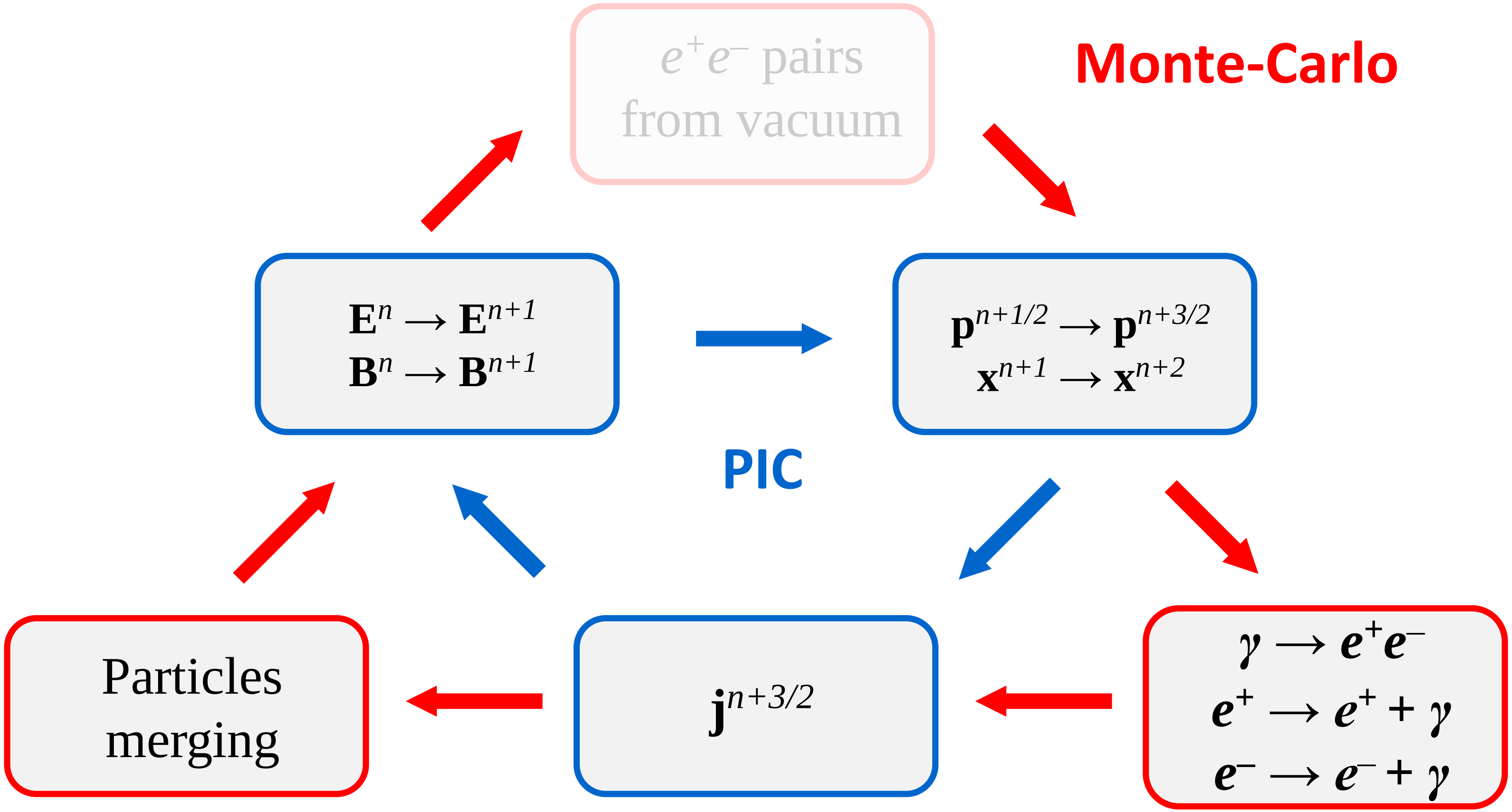
Radiation formation length $l_f \sim mc^2/F_\perp \sim \lambda_{Las}/a_0$

Mean free path $l_W \sim c/W_{rad} \approx \frac{\gamma}{\alpha}\lambda_C \chi^{-2/3}$ (for $\chi \gg 1$)

$$l_f \ll l_W$$

$$l_f \ll \lambda_{Las}$$

3D PIC-MC code QUILL



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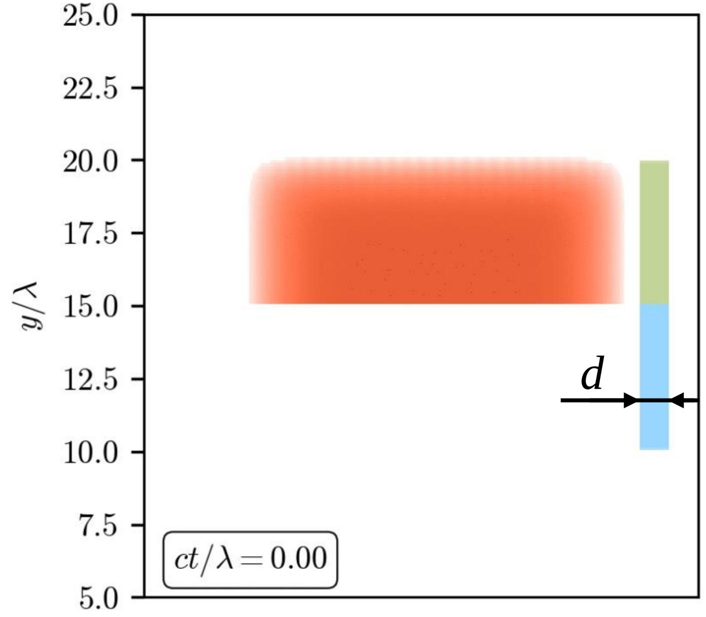
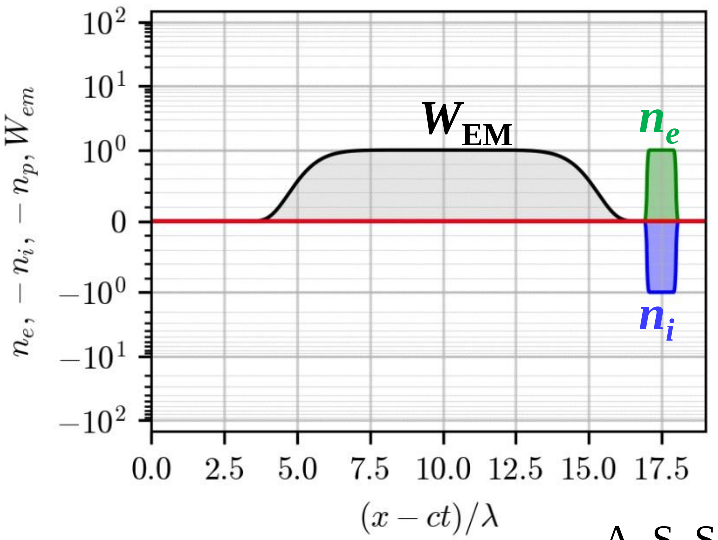
Extremely strong plane wave interaction with the solid target (QED PIC)





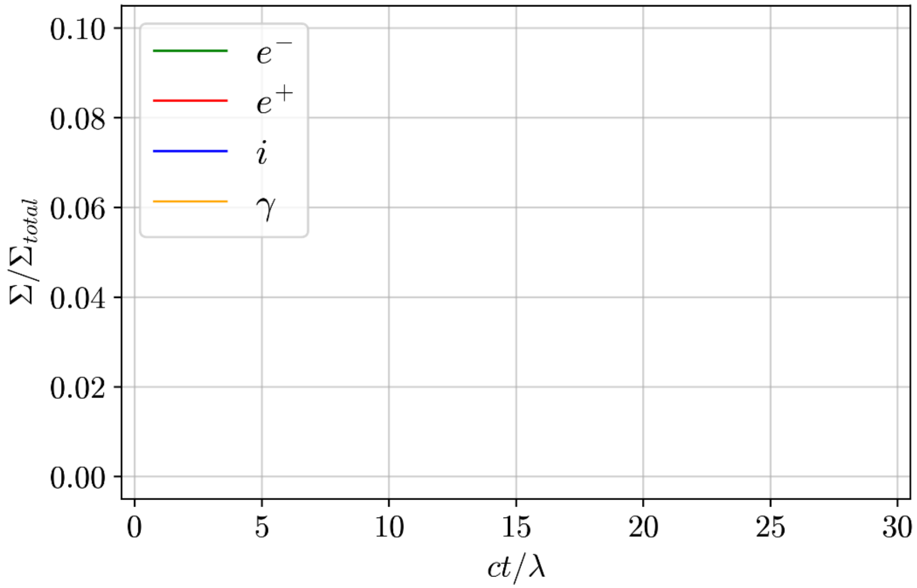
Initial conditions

$a_0 = 2500$

$\lambda = 1$ μm

$d = 1$ μm

$n_e = 5.9 \cdot 10^{23}$ cm$^{-3} \approx 530\ n_{cr}$



A. S. Samsonov, E. N. Nerush, and I. Yu. Kostyukov, *Sci. Rep.* **9**, 11133 (2019)

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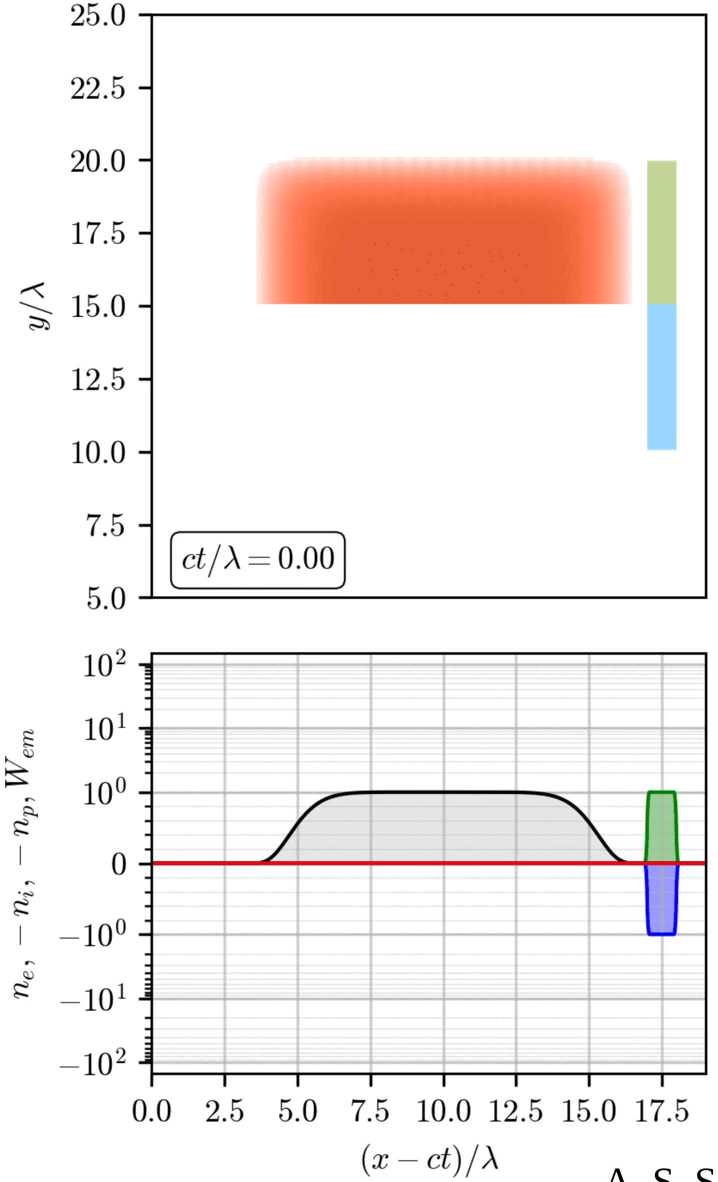

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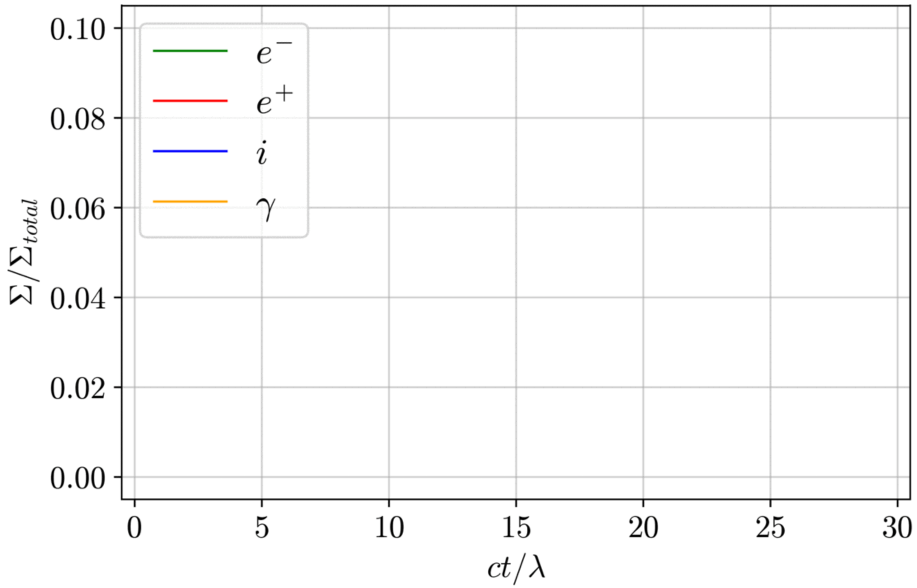

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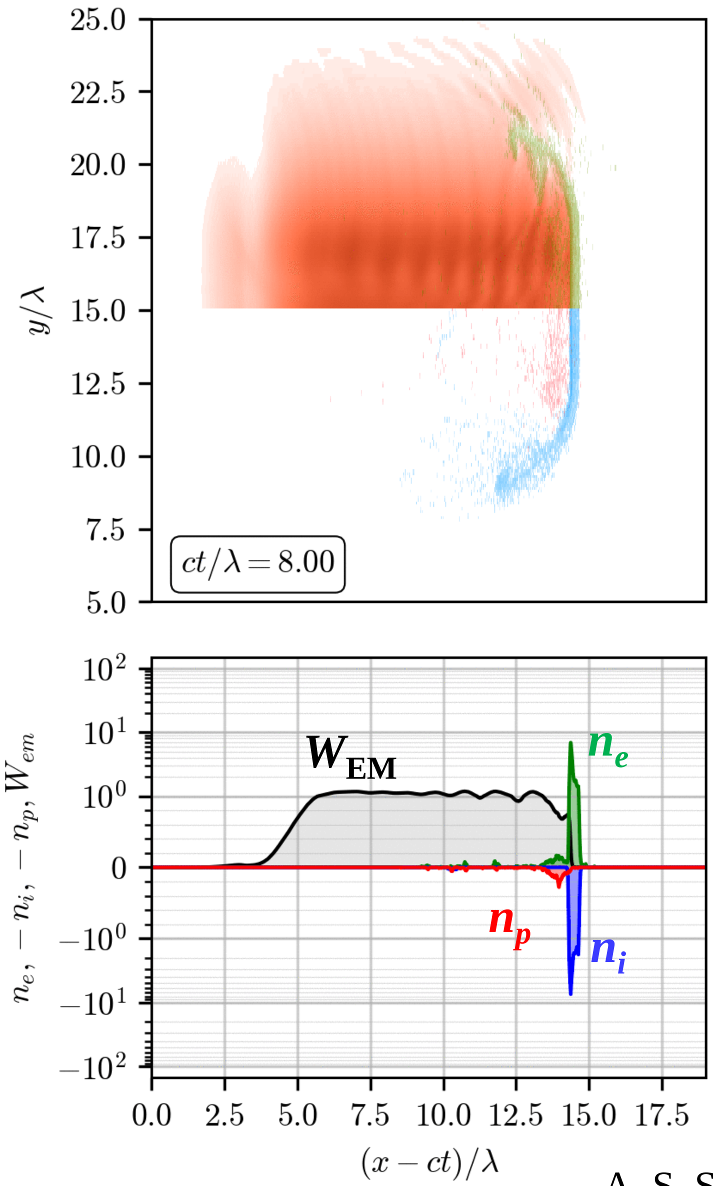

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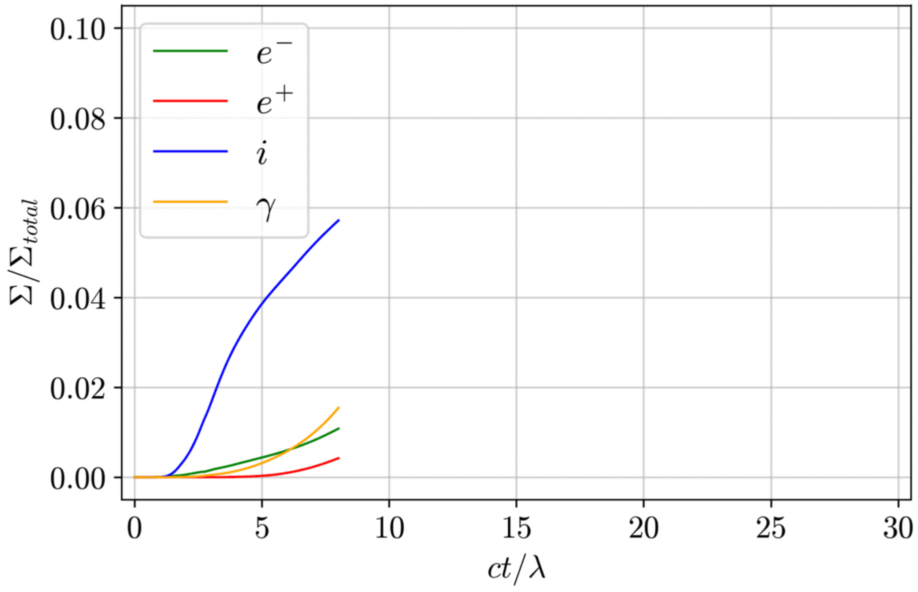

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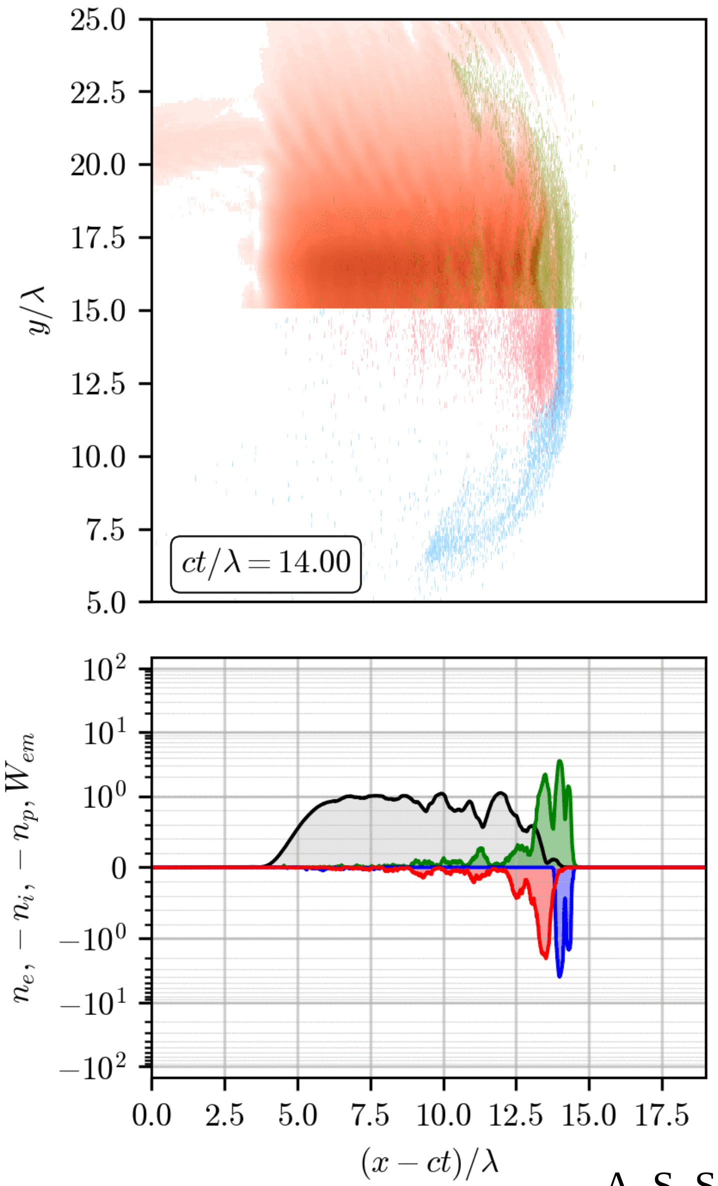

Initial conditions

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$d = 1\ \mu m$

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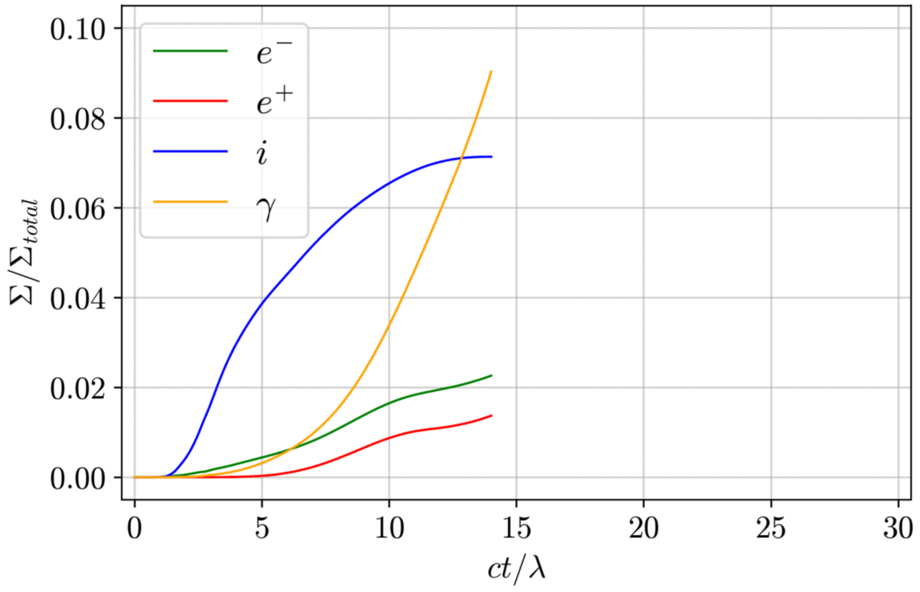

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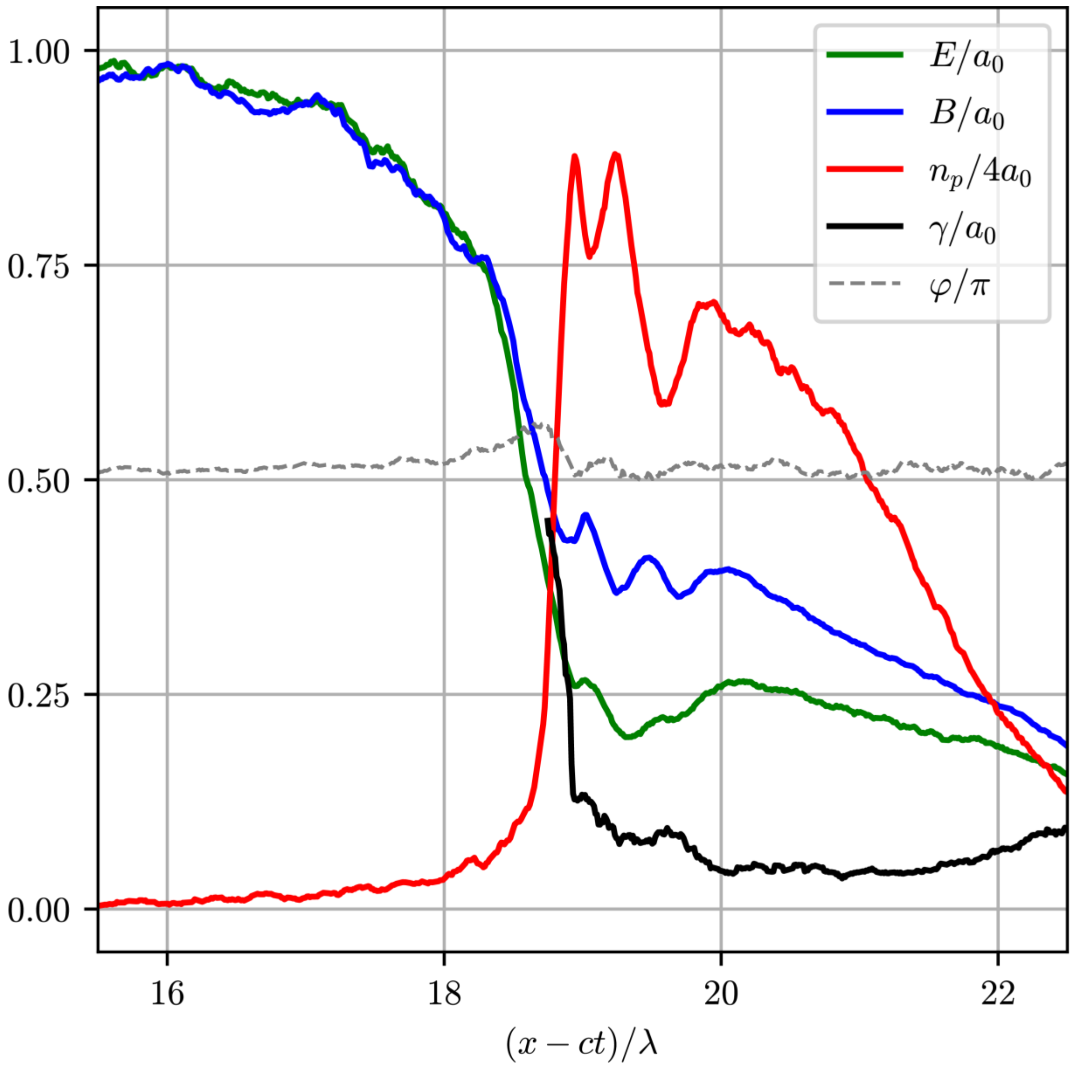
Cascade mechanism



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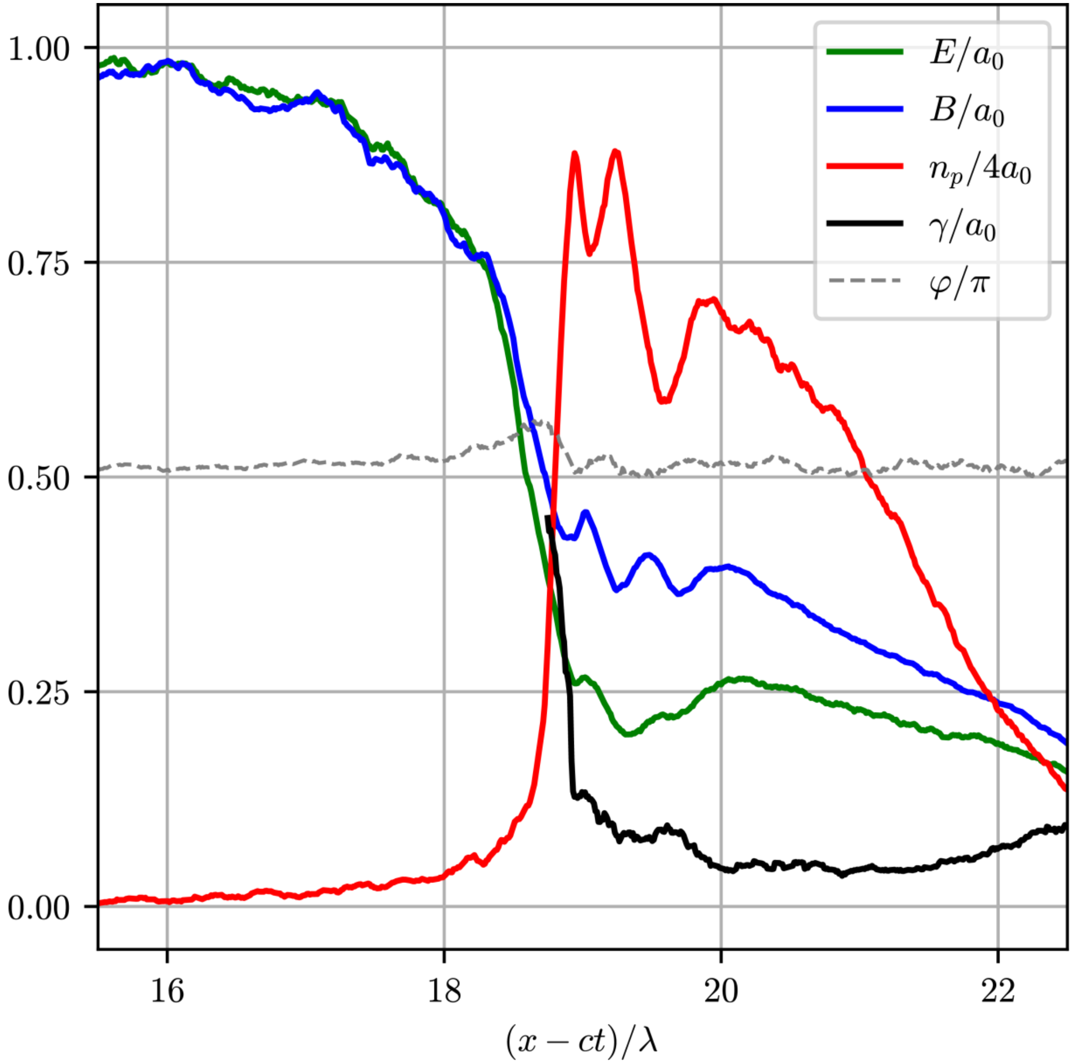
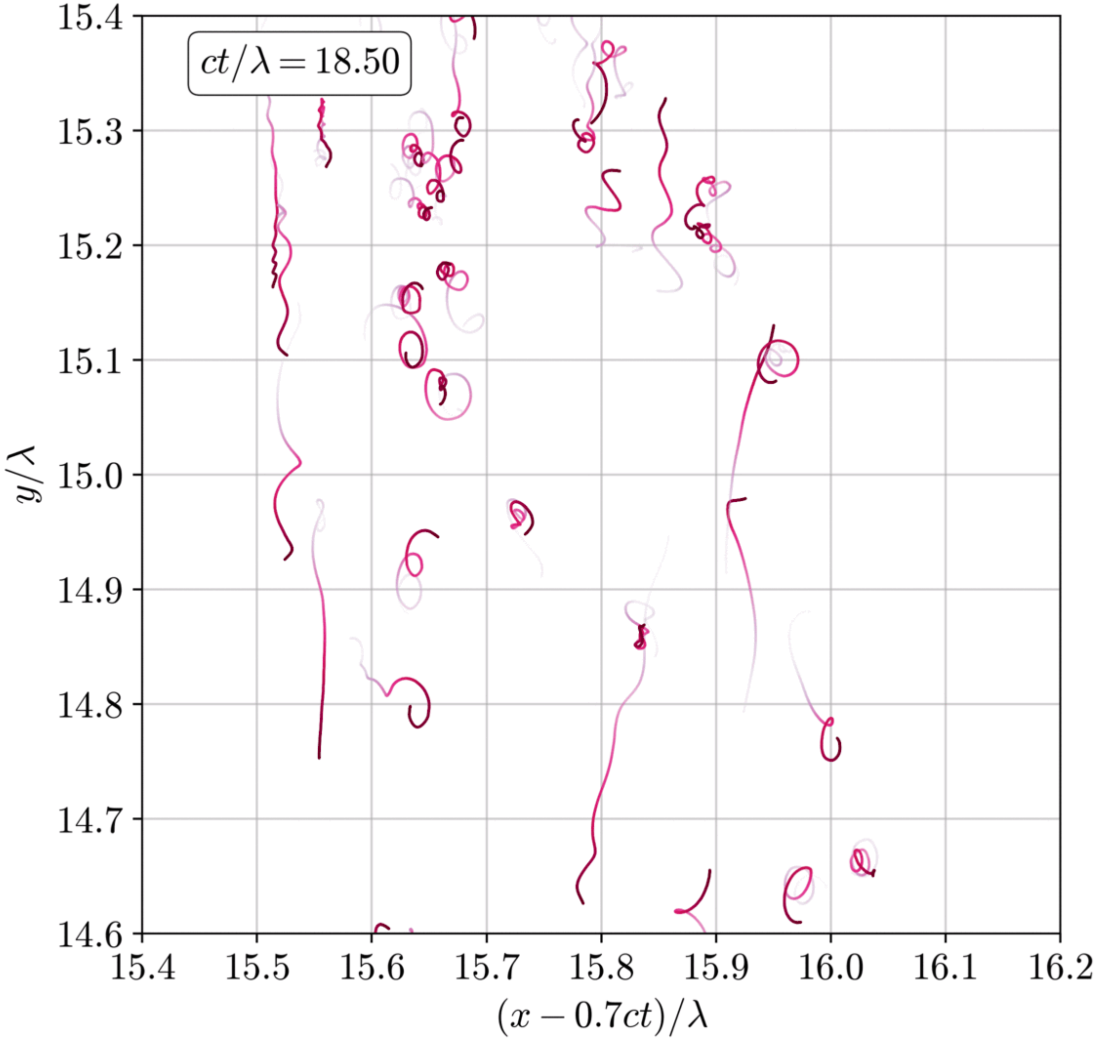
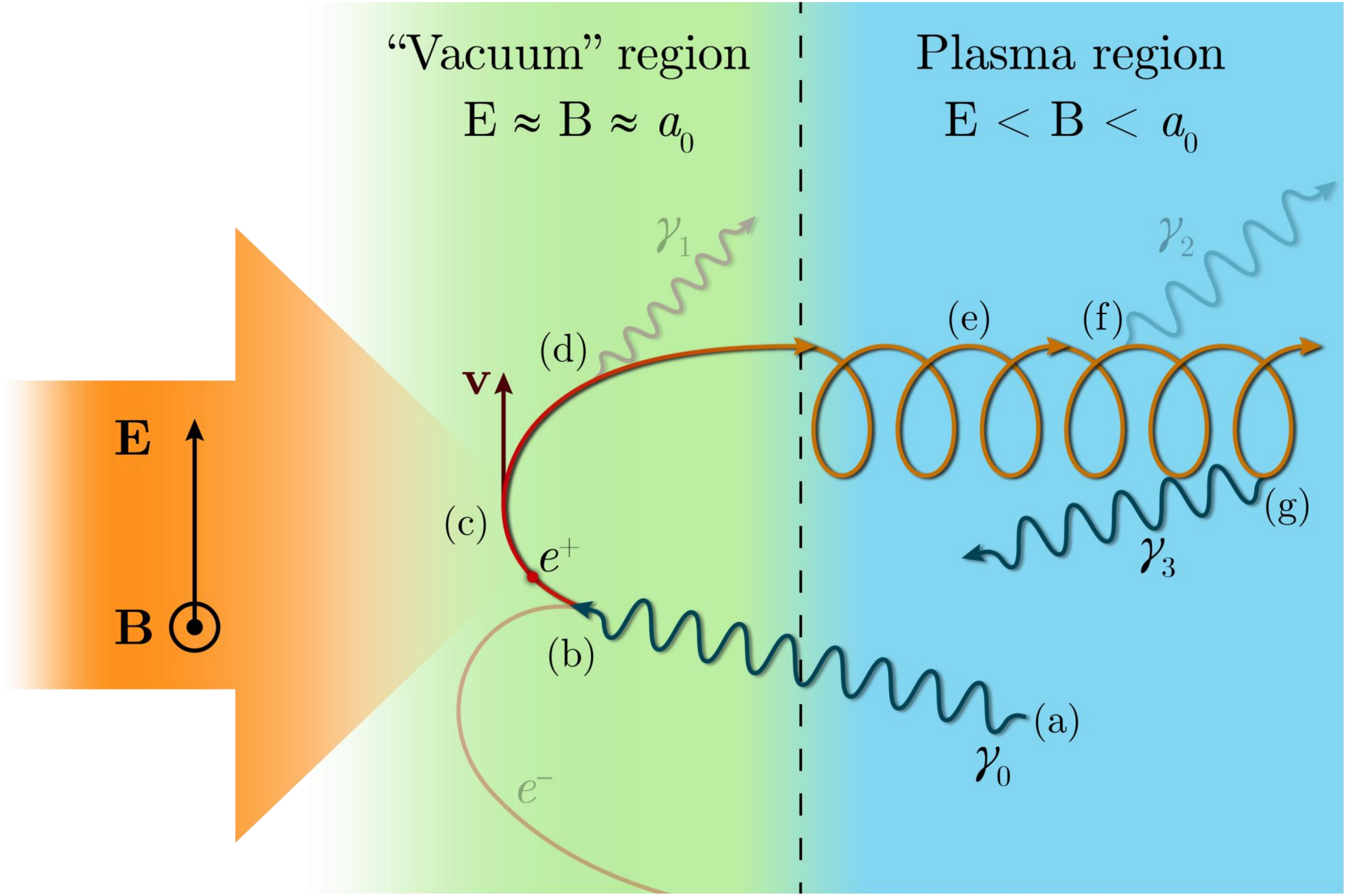




Cascade model



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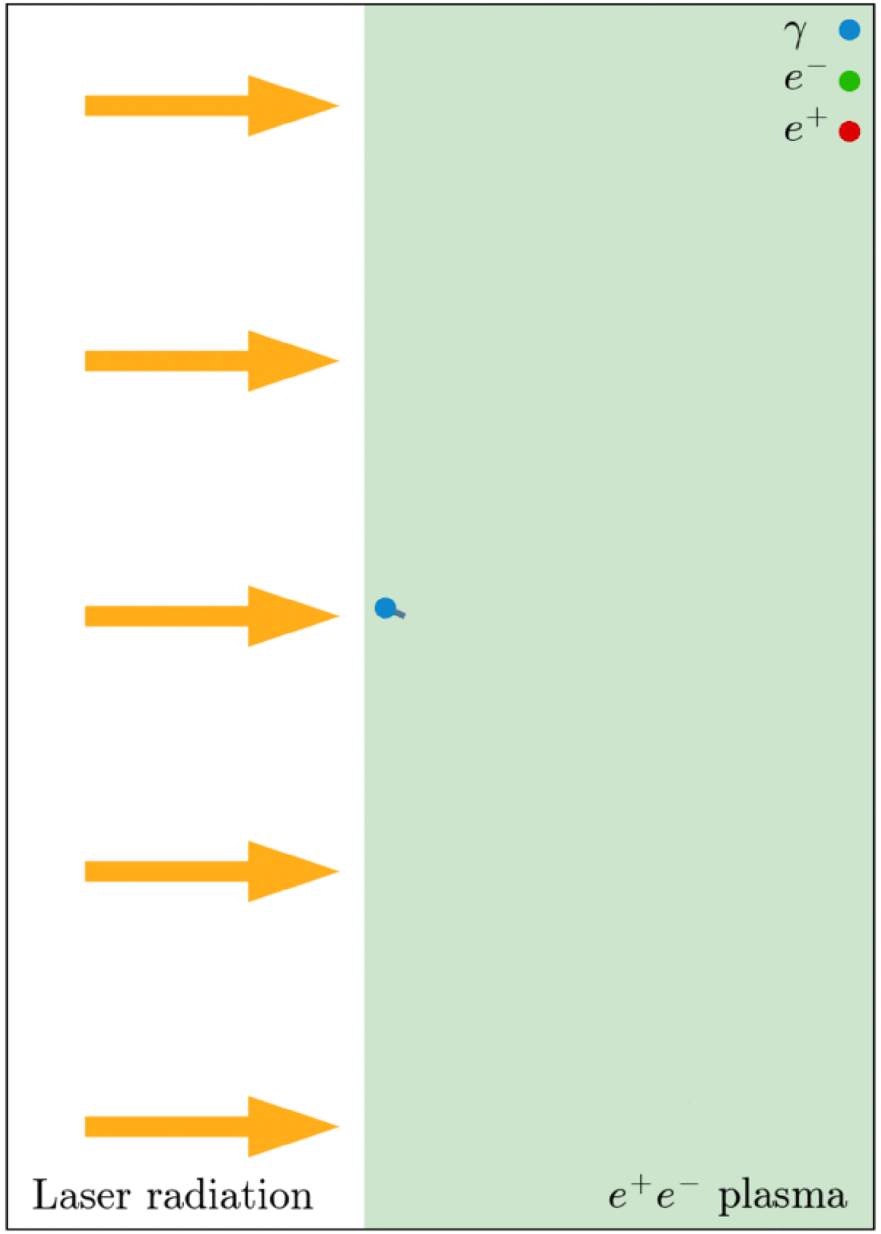


Cascade model

Kinetic equations

$$\frac{\partial f_{e^\pm}}{\partial t} + \mathbf{v}\nabla f_{e^\pm} \pm (\mathbf{E} + [\mathbf{v} \times \mathbf{B}])\frac{\partial f_{e^\pm}}{\partial \mathbf{p}} = \int f_\gamma(\mathbf{p}')w_{pair}(\mathbf{p}',\mathbf{p})d\mathbf{p}' + \int f_{e^\pm}(\mathbf{p}')w_{rad}(\mathbf{p}',\mathbf{p})d\mathbf{p}' - \int f_{e^\pm}(\mathbf{p})w_{rad}(\mathbf{p},\mathbf{p}')d\mathbf{p}' \qquad (1, 2)$$

$$\frac{\partial f_\gamma}{\partial t} + \mathbf{v}\nabla f_\gamma = -\int f_\gamma(\mathbf{p})w_{pair}(\mathbf{p},\mathbf{p}')d\mathbf{p}' + \int f_{e^\pm}(\mathbf{p}')w_{rad}(\mathbf{p}',\mathbf{p}'-\mathbf{p})d\mathbf{p}' \qquad (3)$$

Maxwell's equations

$$\nabla \times \mathbf{E} = -\frac{1}{c}\frac{\partial \mathbf{B}}{\partial t}$$
$$\nabla \times \mathbf{B} = \frac{1}{c}\frac{\partial \mathbf{E}}{\partial t} + \frac{4\pi|e|}{c}\int \mathbf{v}(f_{e^+}(\mathbf{p}) - f_{e^-}(\mathbf{p}))d\mathbf{p} \qquad (4)$$

General simplifications

1D: $\mathbf{r} \rightarrow x$ 2V: $\mathbf{p} \rightarrow \left(p = |\mathbf{p}|, \theta = \cos^{-1}\left(\frac{\mathbf{p}}{p}, \mathbf{x}_0\right)\right)$

Monoenergetic distribution functions:

$$f \propto \frac{\delta(p - \bar{p})}{p^2}$$

Hydrodynamics:

$$\int A \cdot (1,2,3) d\mathbf{p}$$

→ Continuity eq.
→ Euler eq.
→ Energy transfer eq.

$$n(x,t) = \int f(\mathbf{p}) d\mathbf{p}$$

Plasma quasi-neutrality: $n_{e^+} = n_{e^-} = n_p$

Hydrodynamics equations

$$\frac{\partial}{\partial t} n_p + \frac{\partial}{\partial x}(v_x n_p) = S[n, pp],$$

$$\frac{\partial}{\partial t}(\gamma n_p) + \frac{\partial}{\partial x}(v_x \gamma n_p) = S[\gamma, pp] + (S[\gamma, acc] - S[\gamma, rad_d])\psi_{vac} - S[\gamma, rad_c]\psi_{pl},$$

$$\frac{\partial}{\partial t} n_\gamma + \frac{\partial}{\partial x}(v_\gamma n_\gamma) = -S[n, pp] + 2S[n, rad_c]\psi_{pl},$$

$$\frac{\partial}{\partial t}(v_\gamma n_\gamma) + \frac{\partial}{\partial x}(v_\gamma^2 n_\gamma) = -S[v, pp] + 2S[v, rad_c]\psi_{pl},$$

$$\frac{\partial}{\partial t}(\epsilon n_\gamma) + \frac{\partial}{\partial x}(v_\gamma \epsilon n_\gamma) = -S[\gamma, pp] + 2S[\gamma, rad_c]\psi_{pl},$$

$$\frac{\partial}{\partial t}\left(\frac{E^2 + B^2}{2}\right) + \frac{\partial}{\partial x}[\mathbf{E} \times \mathbf{B}]_x = -2S[\gamma, acc]\psi_{vac} \equiv \mathbf{jE},$$

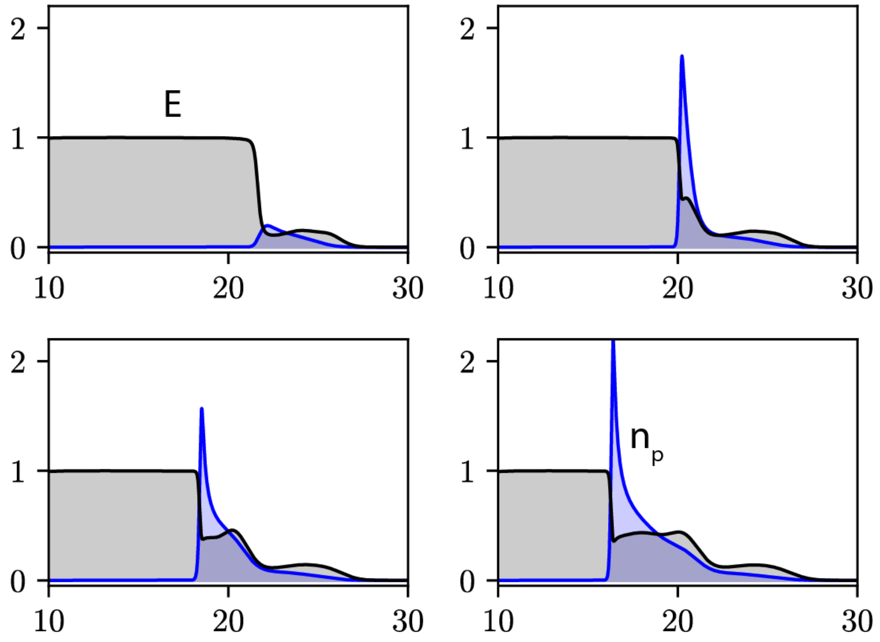
A. S. Samsonov, I. Yu. Kostyukov, E. N. Nerush *arXiv:2010.14116*

Similarity with gas discharge

$$\frac{\partial}{\partial t} n_p + \frac{\partial}{\partial x}(v_x n_p) = W_{pair} n_\gamma,$$

$$\frac{\partial}{\partial t} n_\gamma + \frac{\partial}{\partial x}(v_\gamma n_\gamma) = -W_{pair} n_\gamma + 2W_{rad} n_p,$$

$$\frac{\partial}{\partial t}\left(\frac{E^2 + E^2/v_x^2}{2}\right) + \frac{\partial}{\partial x}\left(\frac{E^2}{v_x}\right) = -2E^{2/3} n_\gamma G_{rad},$$

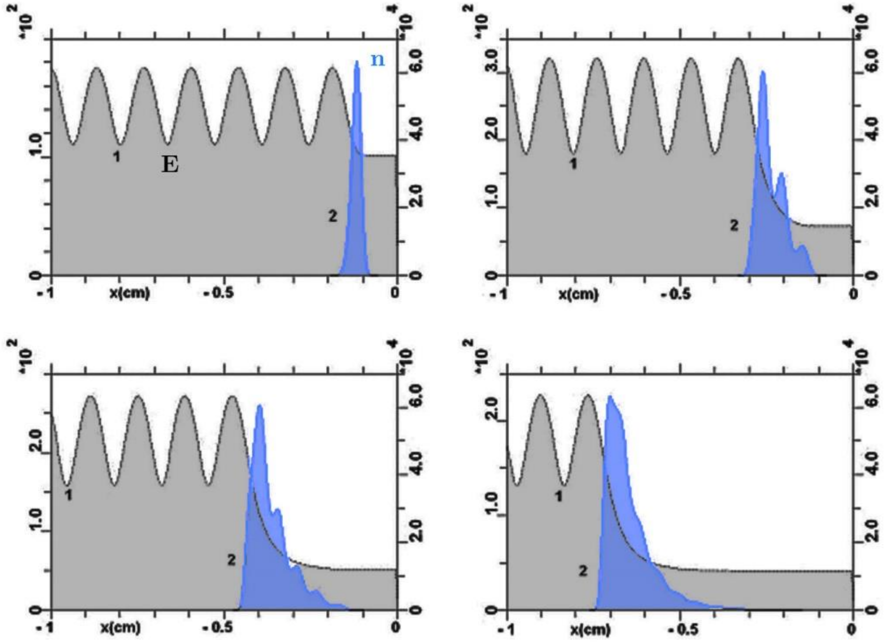


A. S. Samsonov, I. Yu. Kostyukov, E. N. Nerush *arXiv:2010.14116*

$$\frac{\partial n}{\partial t} = \frac{\partial^2 n}{\partial x^2} - \alpha n^2 + \mu\left(|E|^\beta - 1\right)n$$

$$\frac{\partial E}{\partial t} + \frac{\partial E}{\partial x} = -\varepsilon E$$

$$\varepsilon = 1 - n - i\delta n$$



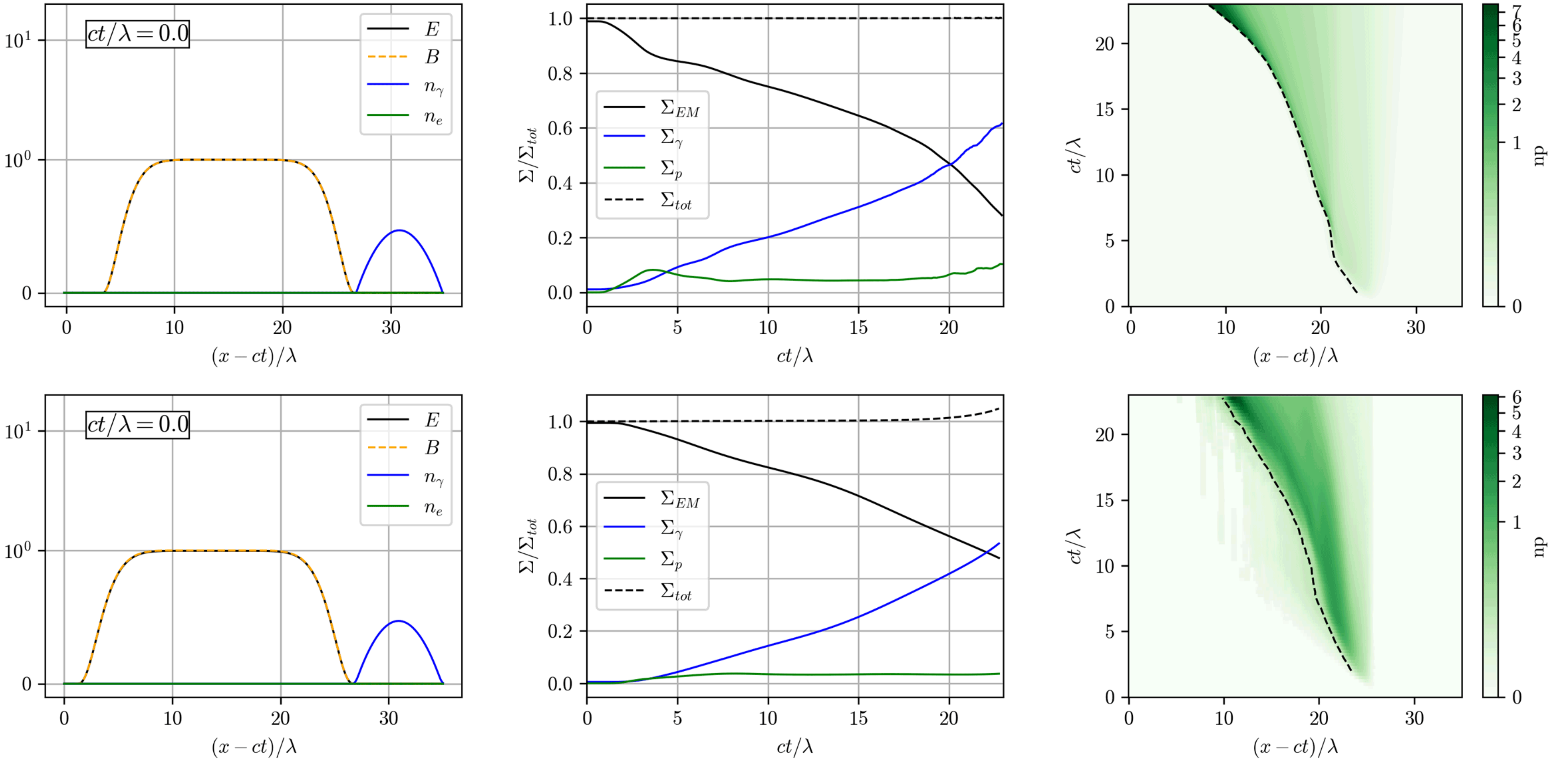
Microwave gas discharge

V. Semenov et al. *Phys. Plasmas* **22**, 092308 (2015)

Results

$a_0 = 2500$

A. S. Samsonov, I. Yu. Kostyukov, E. N. Nerush *arXiv:2010.14116*



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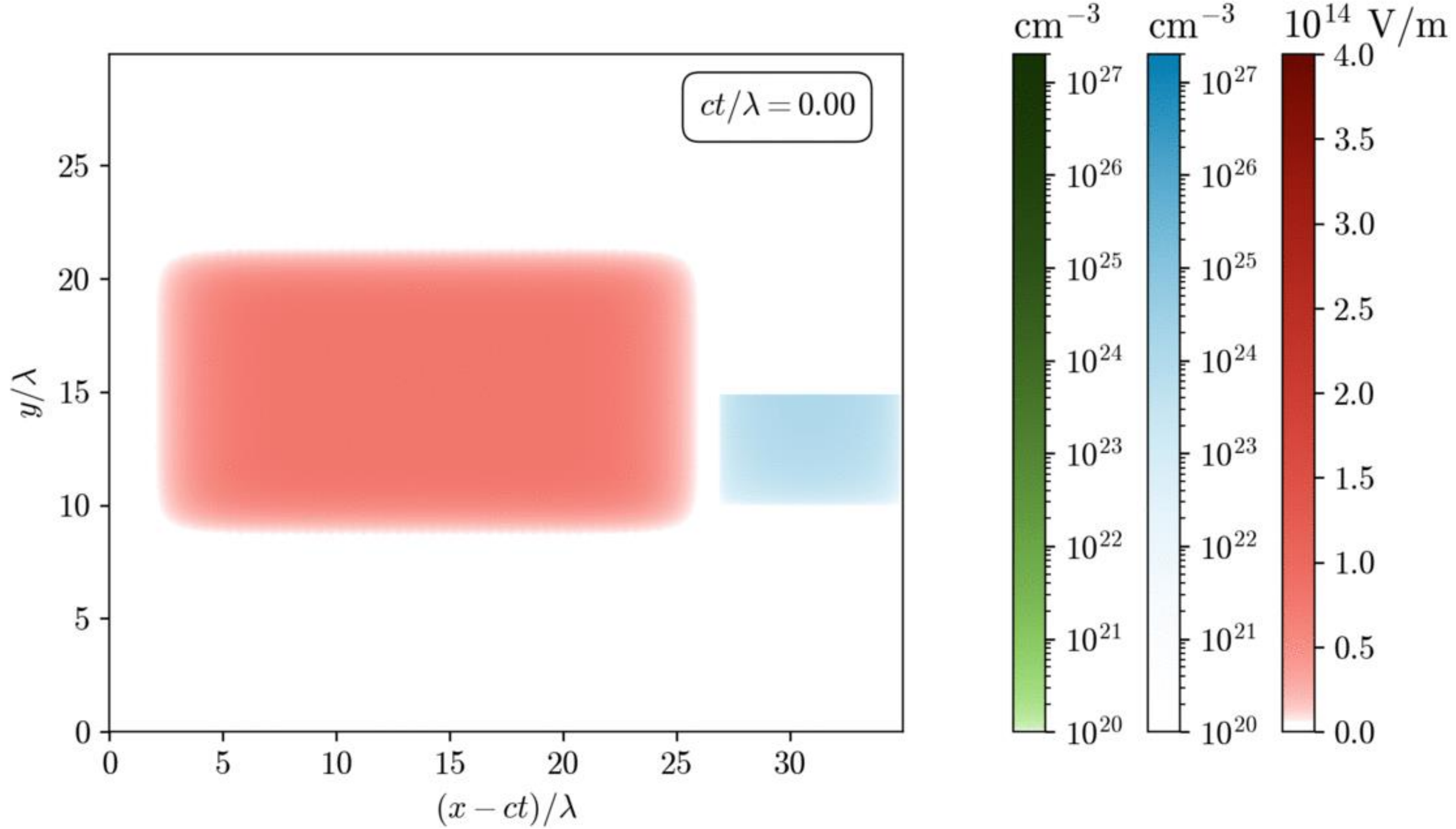

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Results

$a_0 = 1500$

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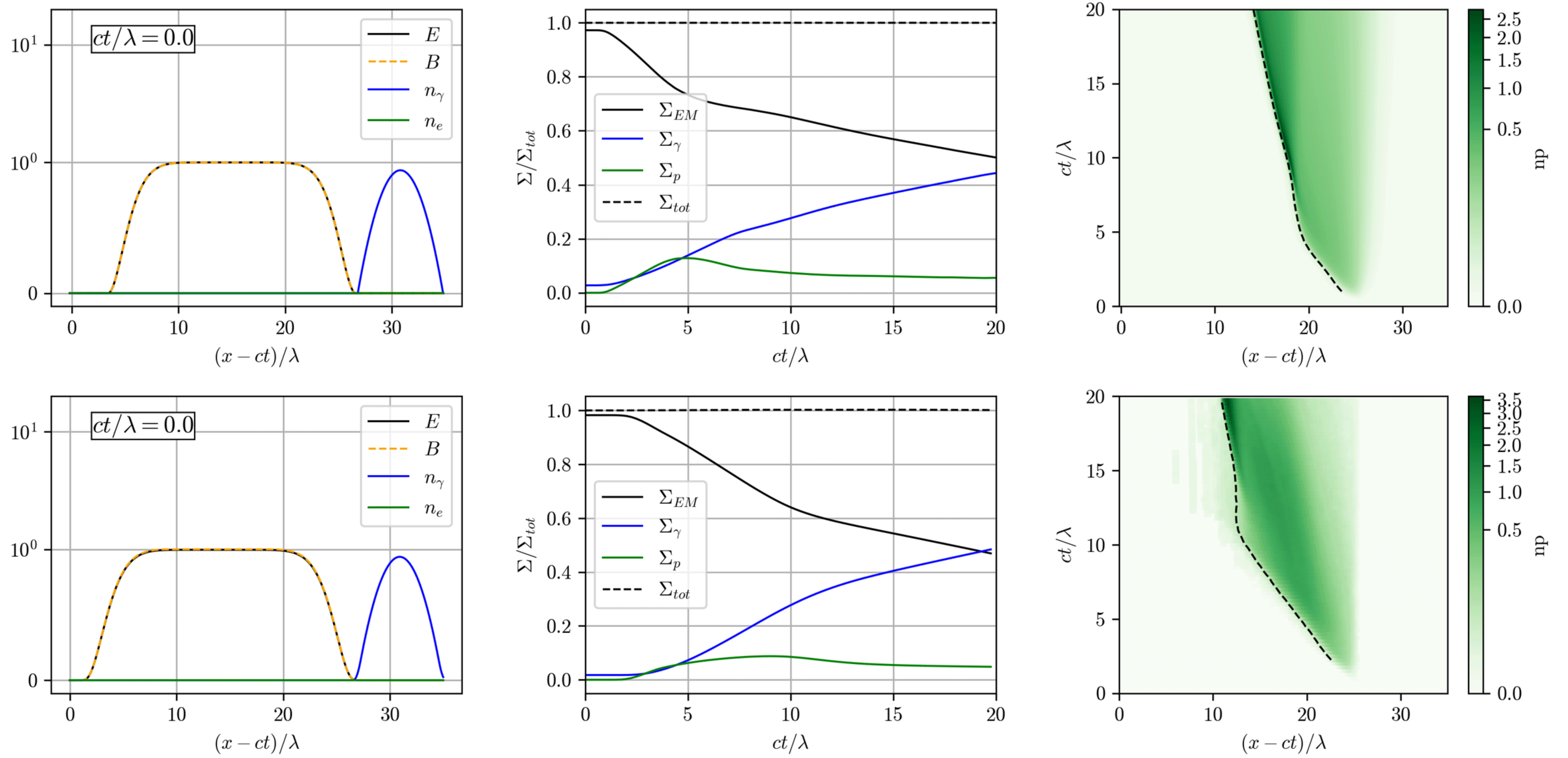

Results

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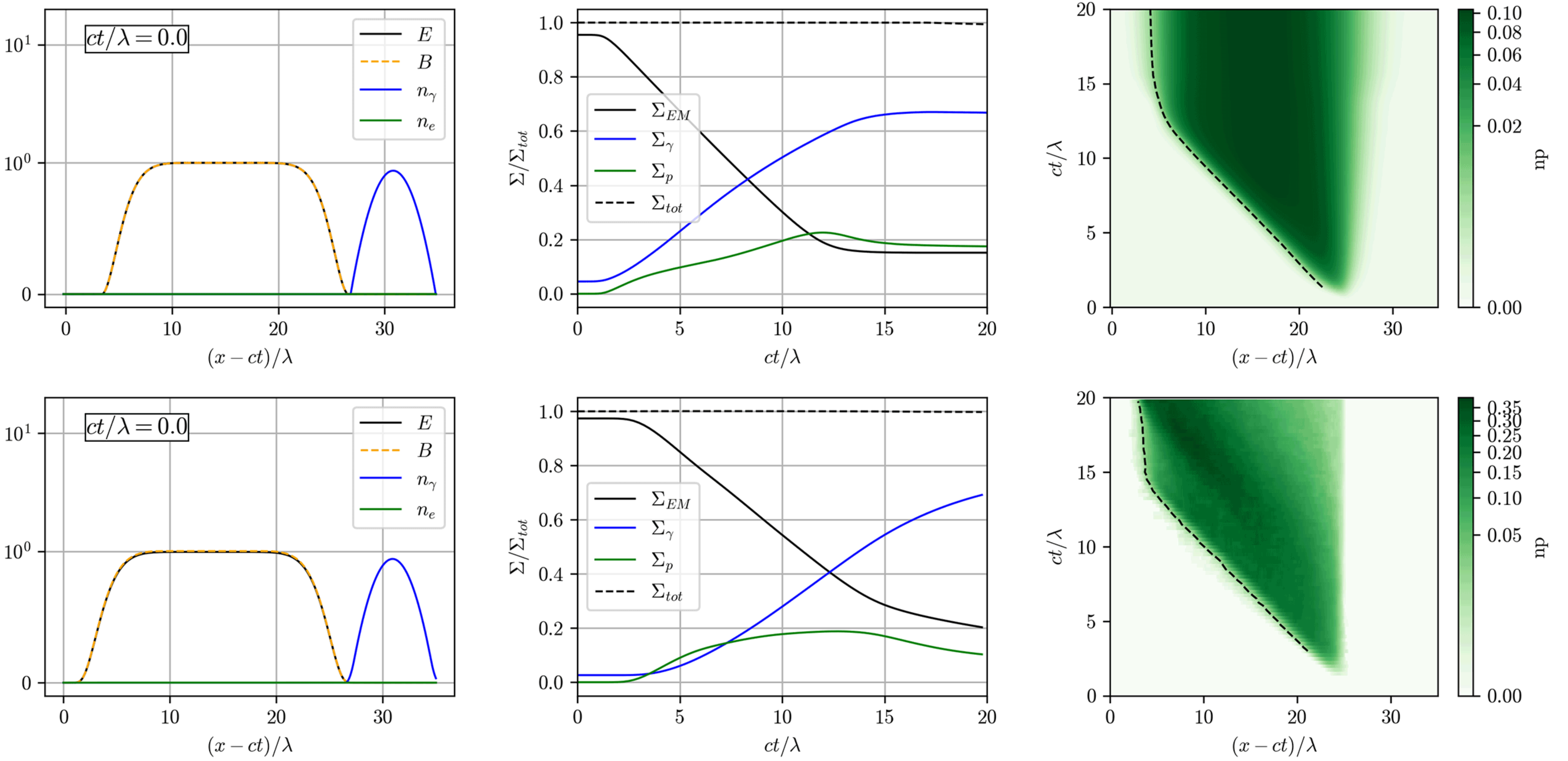
A. S. Samsonov, I. Yu. Kostyukov, E. N. Nerush *arXiv:2010.14116*



Summary

- For large enough laser intensities ($a_0 > 1500$) most of the laser energy is converted into of e^+e^- plasma cushion produced as a result of QED cascading. The cushion plasma efficiently absorbs the laser energy and decouples the radiation from the moving foil thereby interrupting the ion acceleration.
- The hydrodynamical model is proposed which is relatively simple hence incredibly fast: calculating a solution requires minutes compared to tens of hours using 3D QED-PIC
- The model coincides well with the results of full 3D QED-PIC simulations thus we argue that our understanding of the process is correct

The Research was carried out within the framework of the EU project CREMLINplus, grant agreement 871072.

Thank you for attention!