RaDiO: an efficient radiation processing tool for PIC simulations

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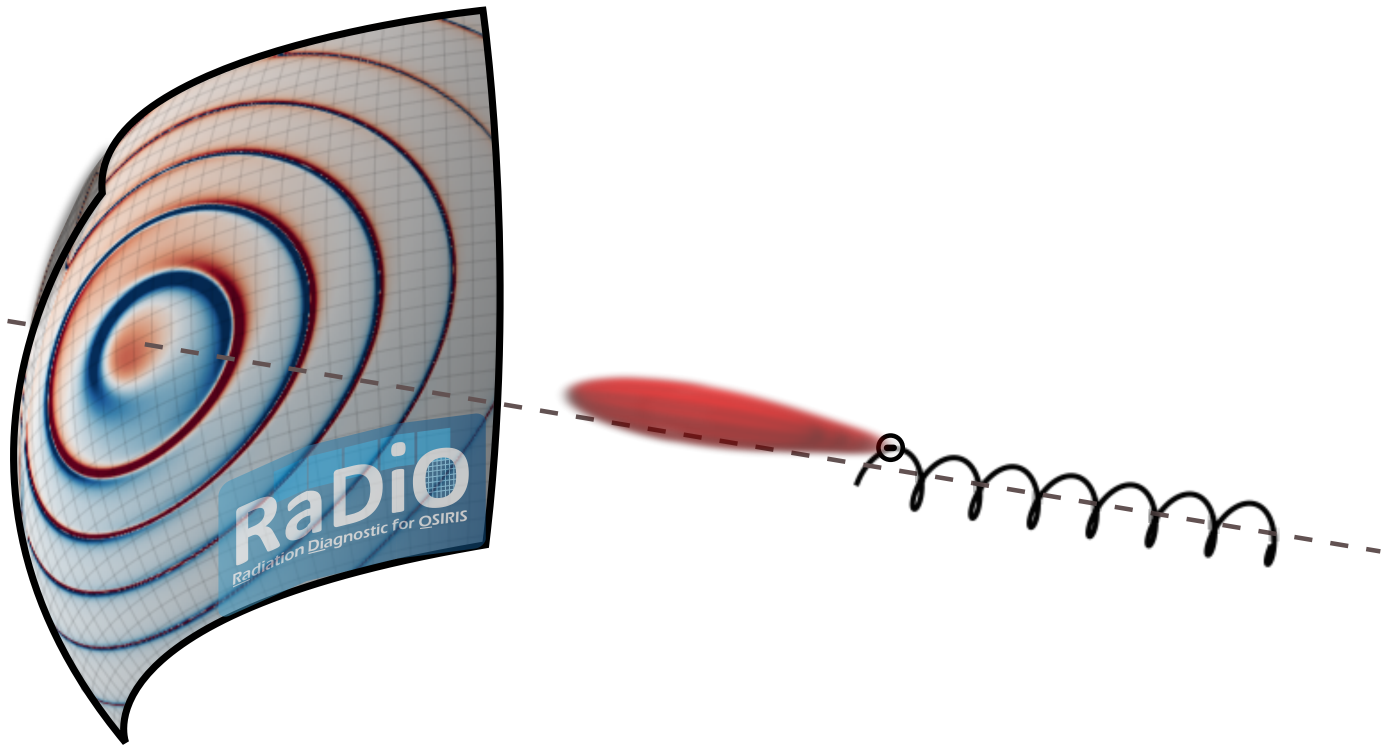

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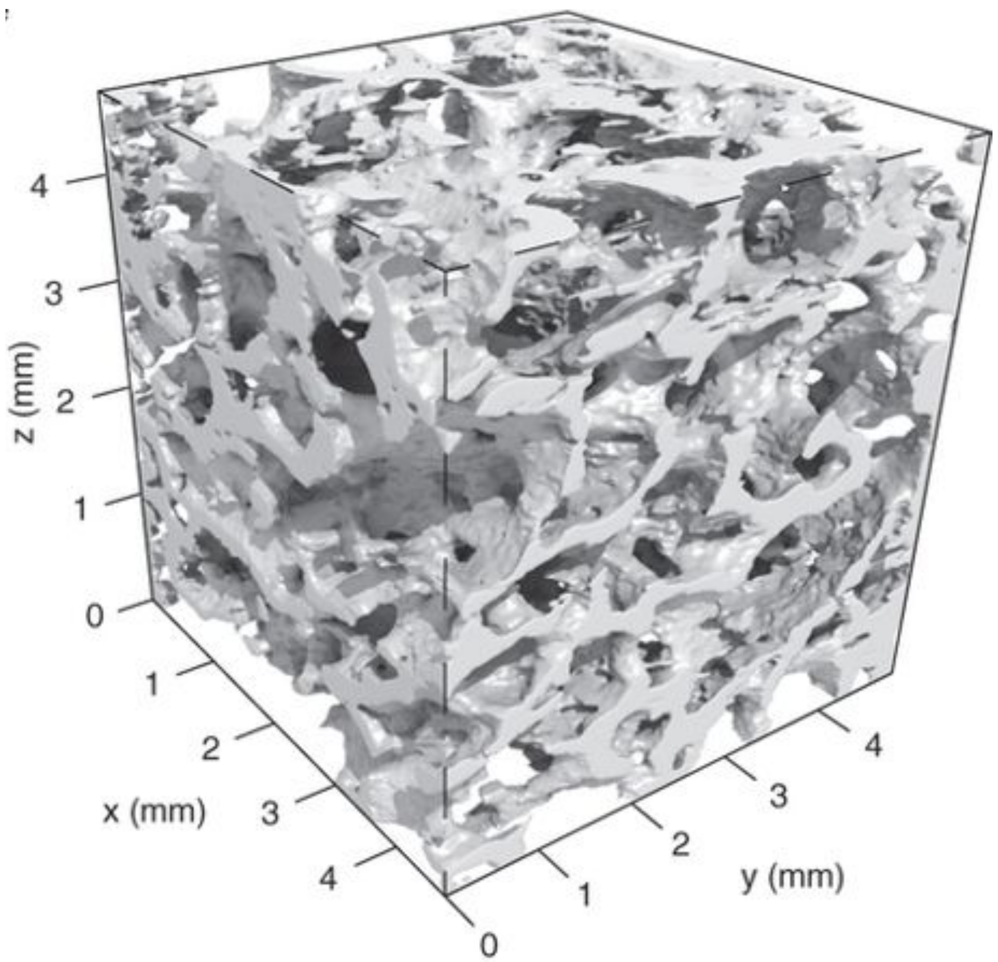
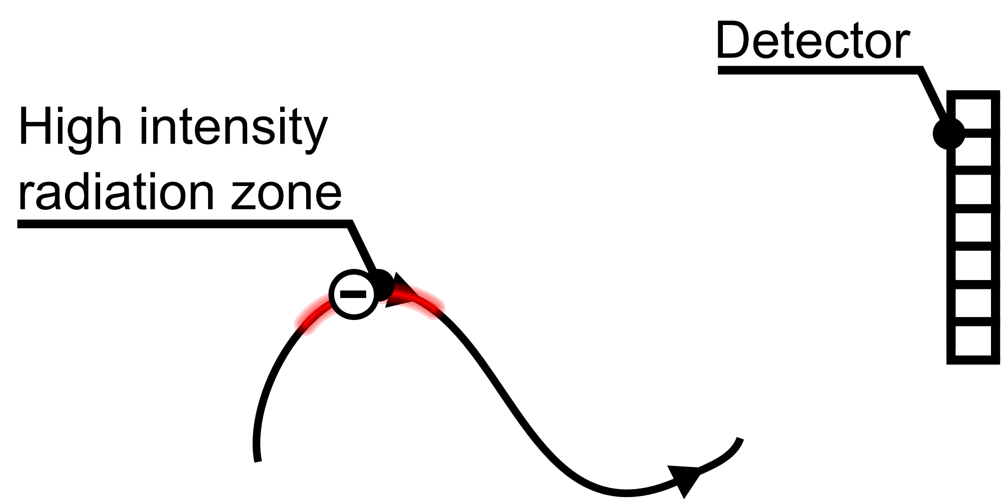
Why we care about radiation emission



"A bright μm-sized source of *hard* synchrotron x-rays […] based on the **betatron oscillations of laser wakefield accelerated electrons** has been developed. The potential of this source for **medical imaging** was demonstrated by performing micro-computed tomography of a human […] bone sample" *



Extreme plasma conditions in radiation sources or astrophysical scenarios may be very difficult to model or observe

Theory ⟷ **Simulation** ⟷ **Experiment**

* J. M. Cole *et al.*, Scientific Reports, **5**, 13244 (2015)

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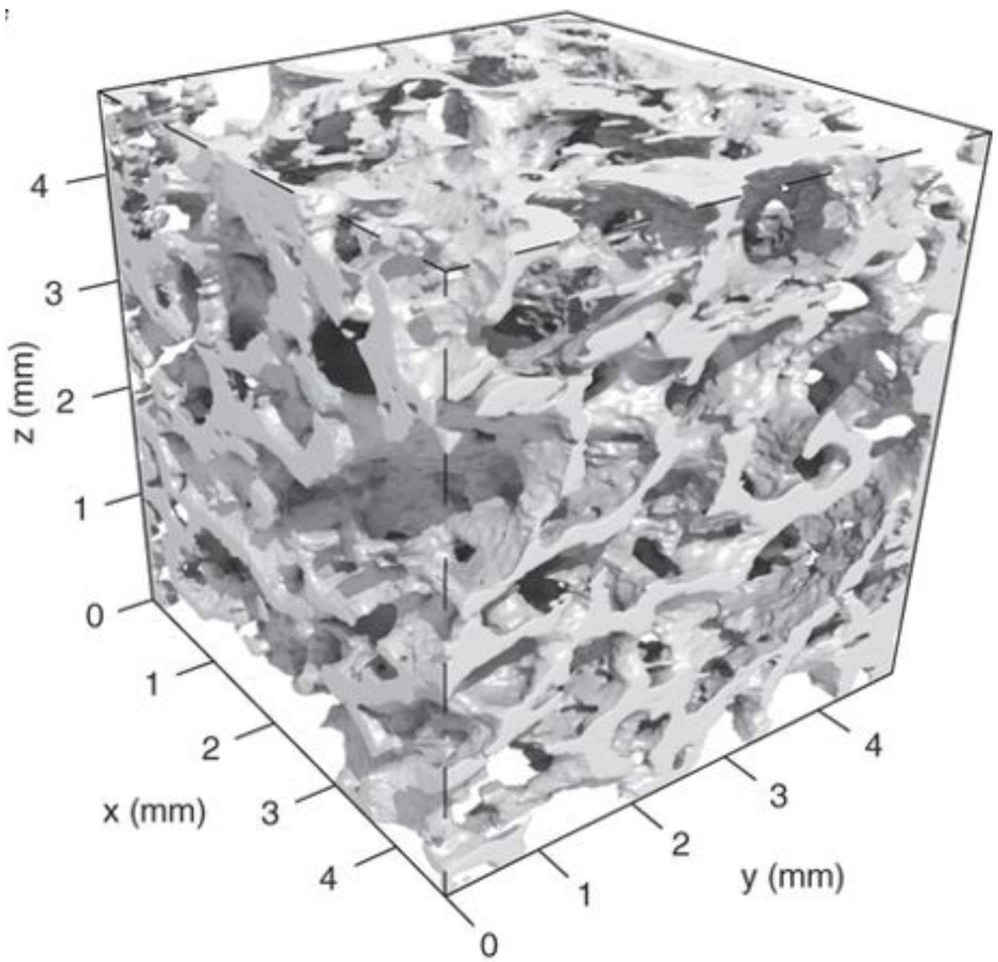

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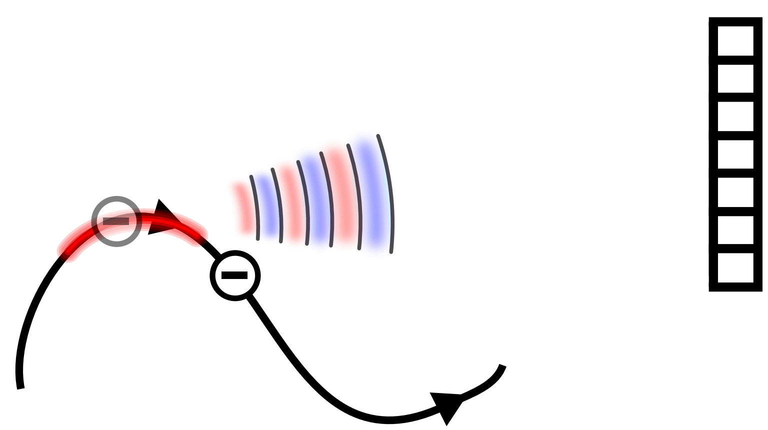

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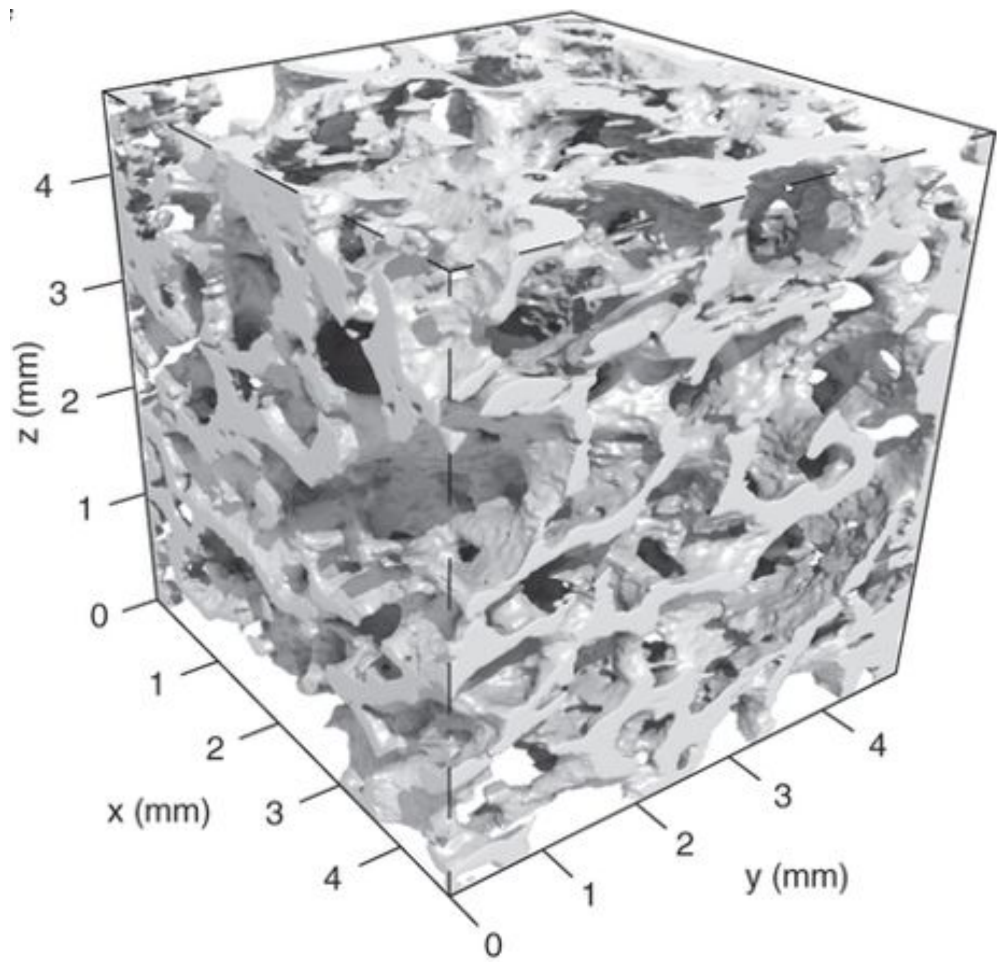

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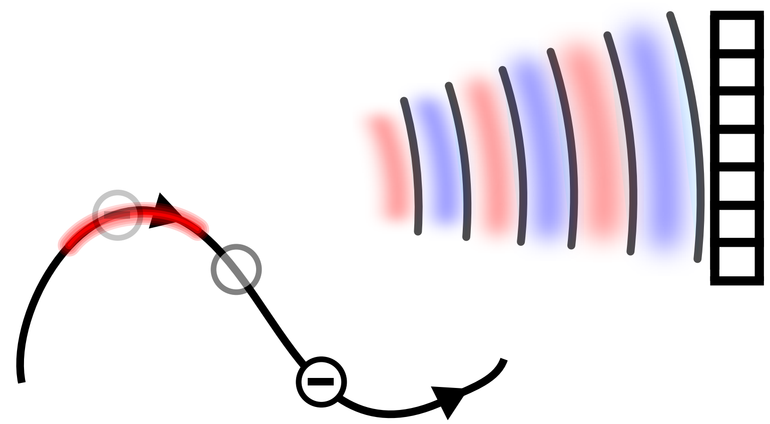

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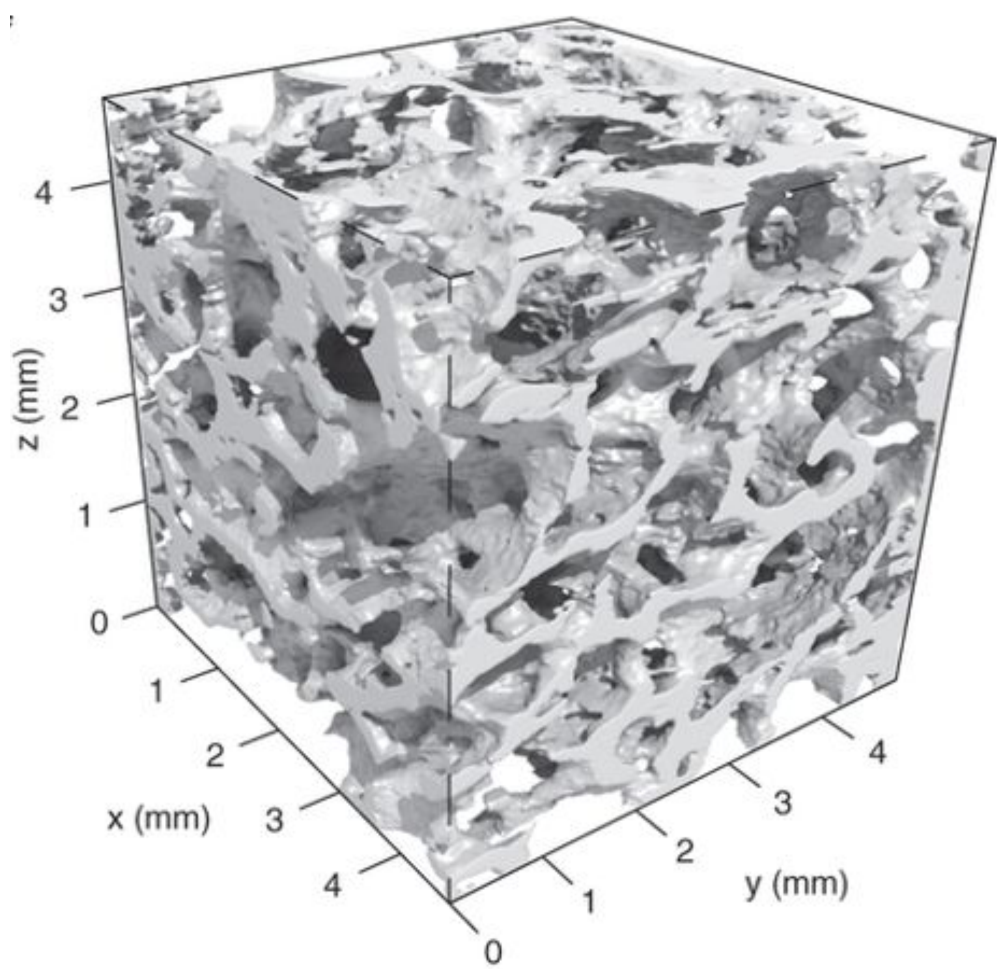

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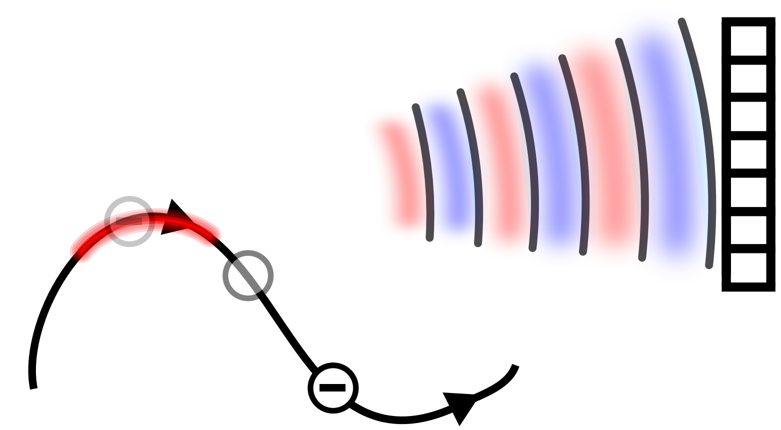

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Osiris 4.0

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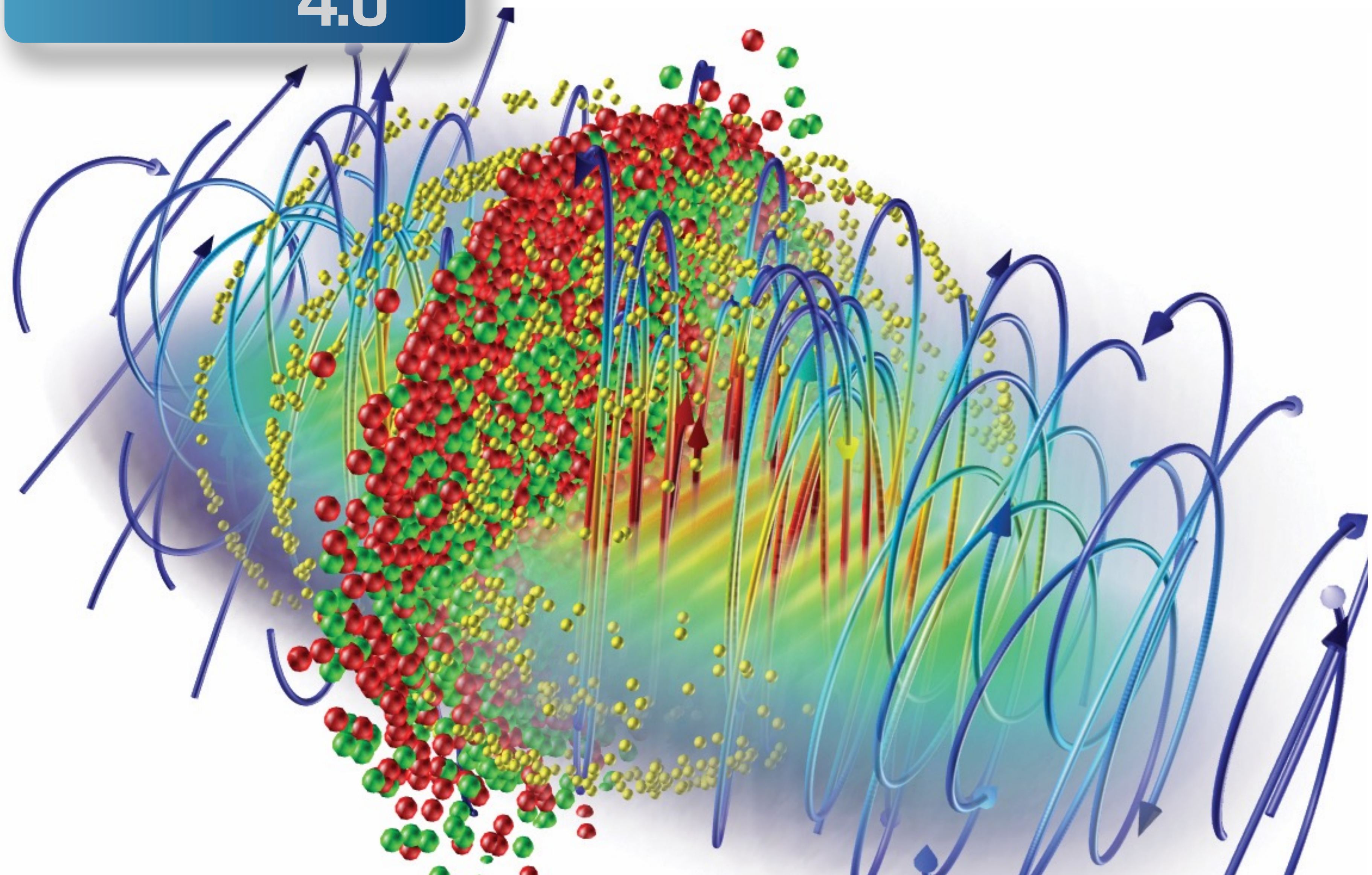
Osiris 4.0

Committed to open science



OSIRIS framework

- Massively Parallel, Fully Relativistic Particle-in-Cell Code
- Parallel scalability to 2 M cores
- Explicit SSE / AVX / QPX / Xeon Phi / CUDA support
- Extended simulation/physics models

visXD

Open-access model

- 40+ research groups worldwide are using OSIRIS
- 300+ publications in leading scientific journals
- Large developer and user community
- Detailed documentation and sample inputs files available

Using OSIRIS 4.0

- The code can be used freely by research institutions after signing an MoU
- Find out more at:

http://epp.tecnico.ulisboa.pt/osiris

UCLA TÉCNICO LISBOA

Ricardo Fonseca: ricardo.fonseca@tecnico.ulisboa.pt

Contents

PIC Limitations

Resolution is a bottleneck of the PIC method

PIC codes*

Particles exist in a grid

The grid cells intermediate EM interactions

No of operations: $N_p + N_g$

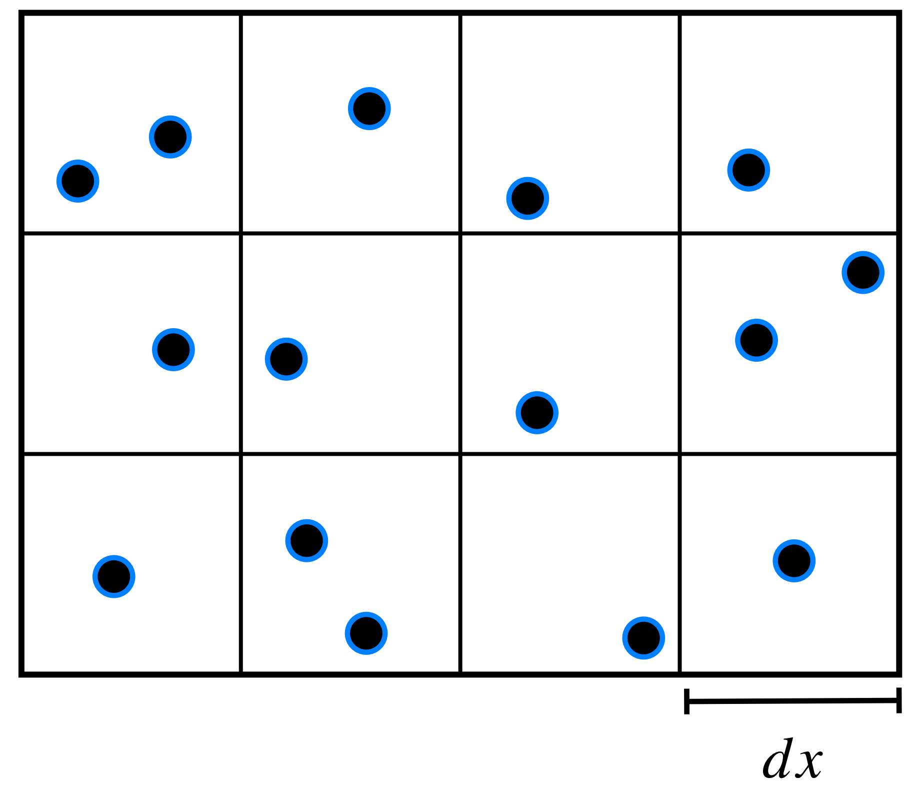
Radiation Resolution

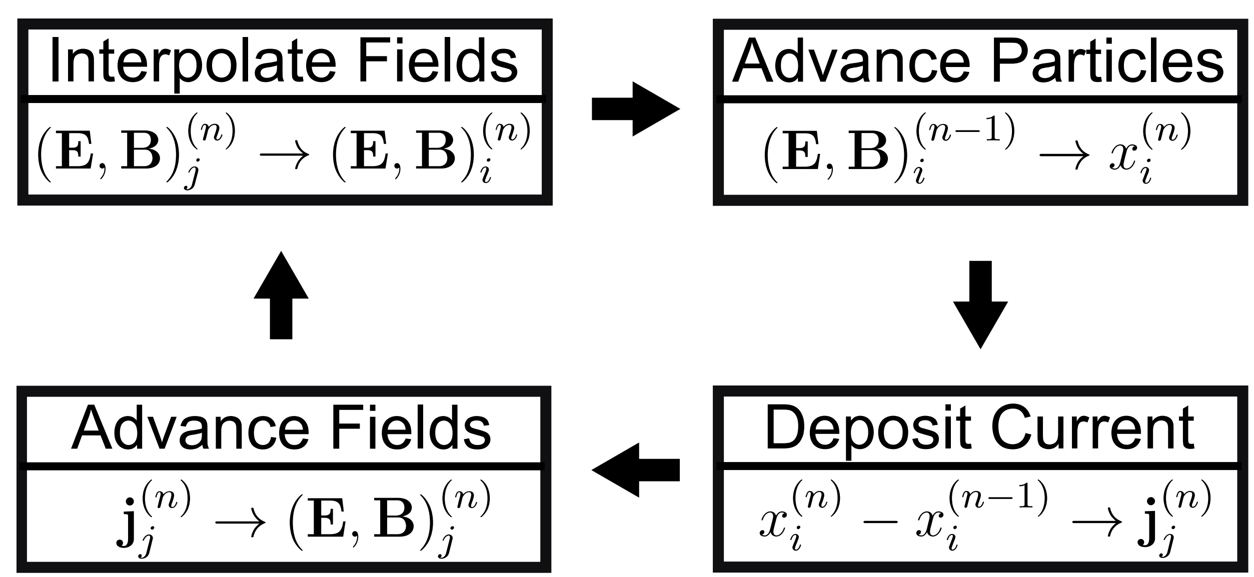
The PIC grid resolves the particle's motion

$\lambda > dx$

Relativistic particles ($\gamma \geq 100$) emit short wavelengths

Resolving such wavelengths would require γ^2 more cells





* J. M. Dawson, Rev. Mod. Phys., 55,403–447 (1983)
** J. D. Jackson, *Classical Electrodynamics* Wiley, 3rd edition (1999).

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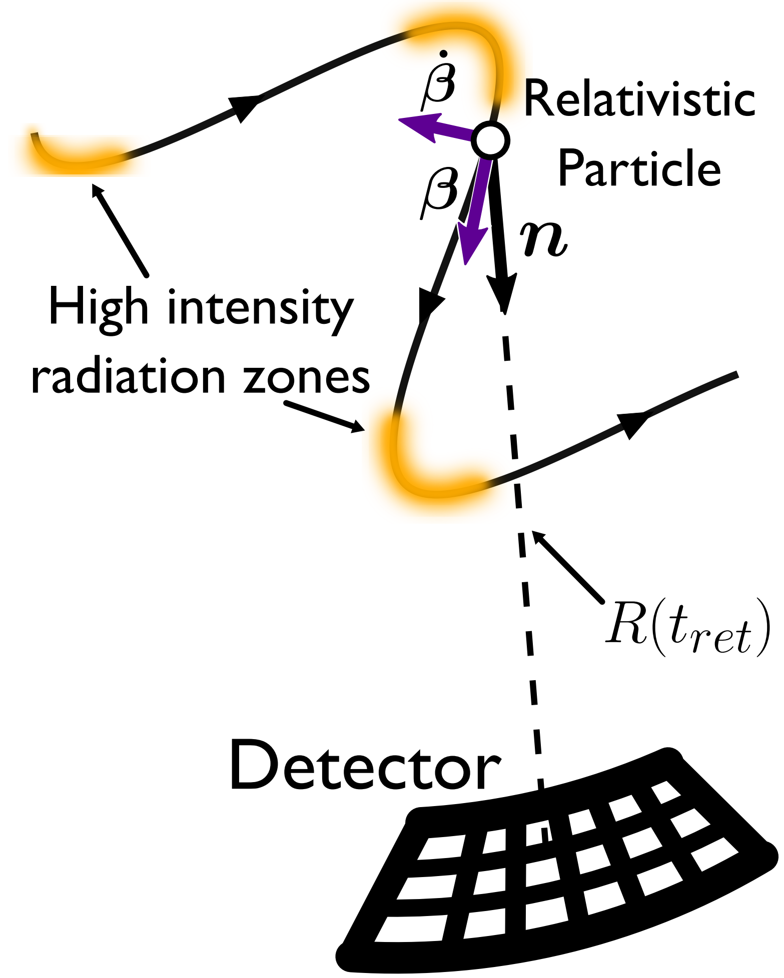
Liénard-Wiechert Potentials**

Using the information from the PIC simulations

$$\mathbf{E}(\mathbf{x}, t_{det}) = \frac{q_e}{c}\left[\frac{\mathbf{n}\times[(\mathbf{n}-\boldsymbol{\beta})\times\dot{\boldsymbol{\beta}})]}{(1-\boldsymbol{\beta}\cdot\mathbf{n})^3 R}\right]_{\text{ret}}, \qquad \mathbf{B}(\mathbf{x}, t_{det}) = [\mathbf{n}\times\mathbf{E}]_{\text{ret}}$$



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What can we do about it?

Develop a spatiotemporal diagnostic under the OSIRIS framework

BUILT-IN Coherence effects

Post-processing tool*

✓ Only deals with radiation

↓

Ideal for parameter scans

Run-time diagnostic**

✓ No need to store trajectories

↓

Large number of radiative particles

* J. L. Martins *et al.*, Proc. SPIE 7359 (2009)

** R. Pausch *et al.*, Nuclear Instruments and methods in Physics research **A 740**, 250-256 (2014)

Goals

Introducing RaDiO: The Radiation Diagnostic for OSIRIS

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Radiation Diagnostic for OSIRIS

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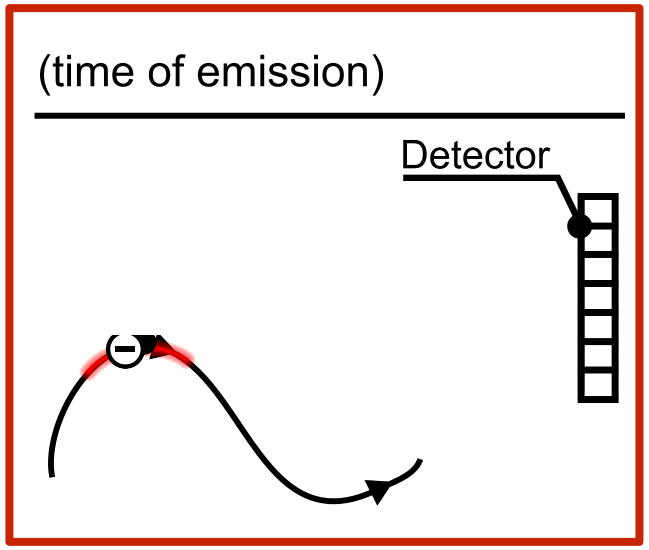
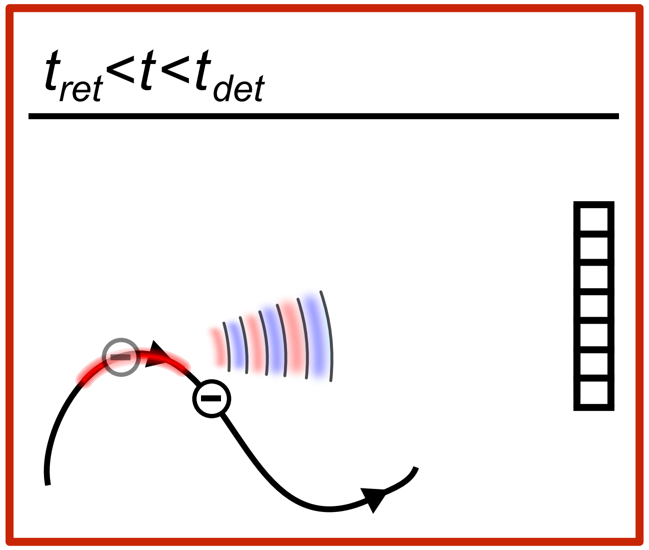
Spatiotemporal expression

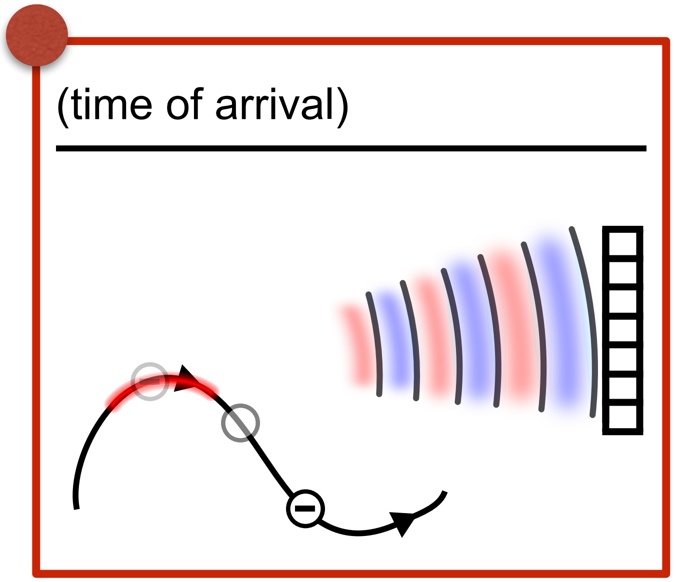
Our approach

Spatiotemporal version of the Liénard-Wiechert Potentials

$$\mathbf{E}(\mathbf{x}, t_{det}) = \frac{q_e}{c}\left[\frac{\mathbf{n}\times[(\mathbf{n}-\boldsymbol{\beta})\times\dot{\boldsymbol{\beta}})]}{(1-\boldsymbol{\beta}\cdot\mathbf{n})^3 R}\right]_{\text{ret}}, \qquad \mathbf{B}(\mathbf{x}, t_{det}) = [\mathbf{n}\times\mathbf{E}]_{\text{ret}}$$







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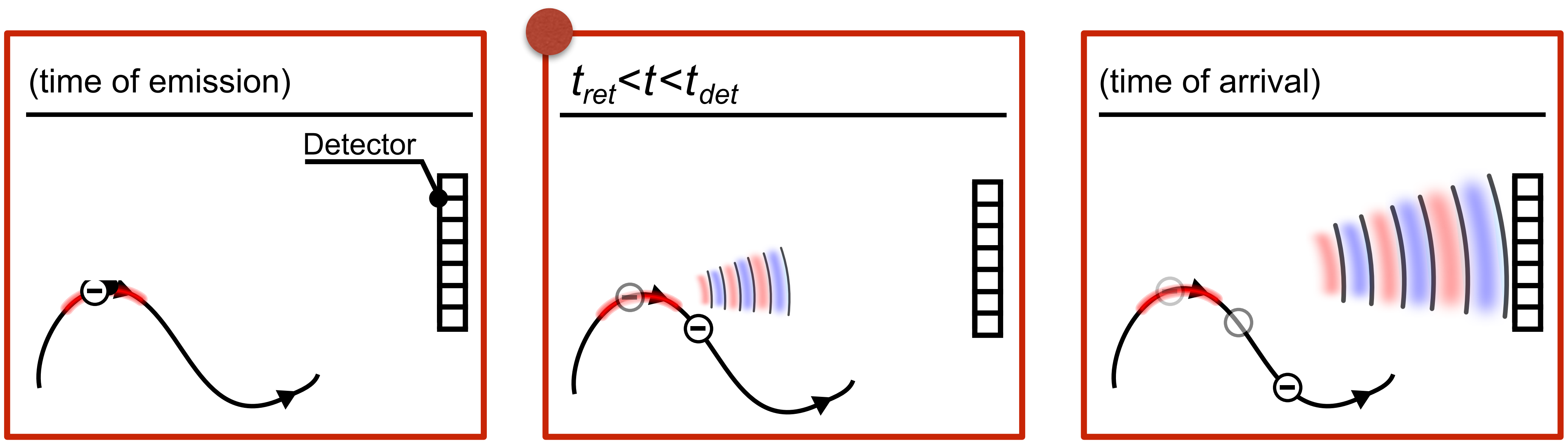

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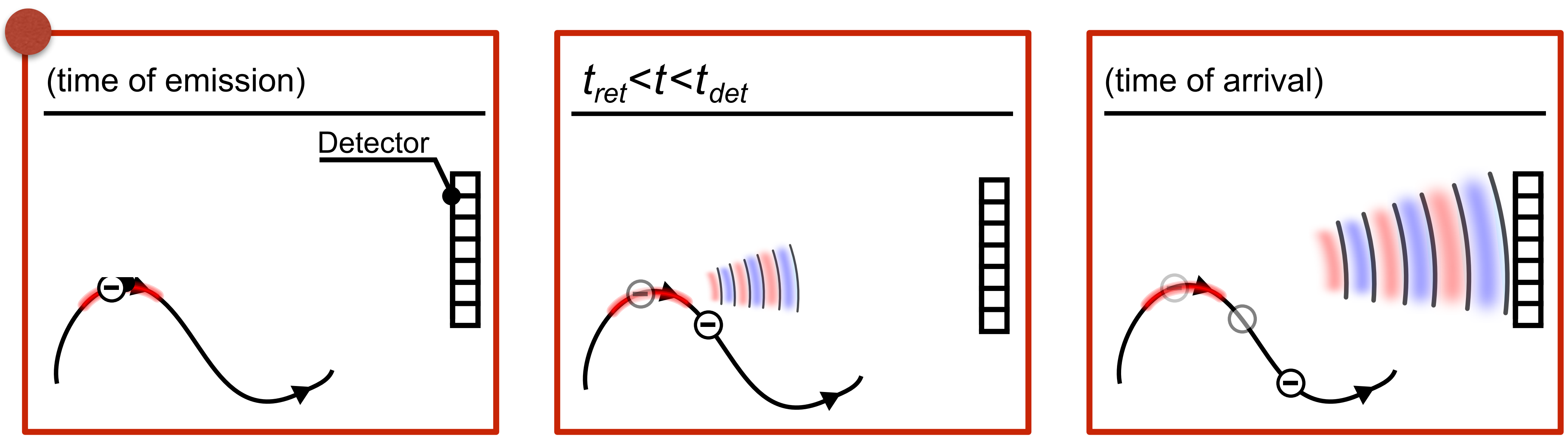

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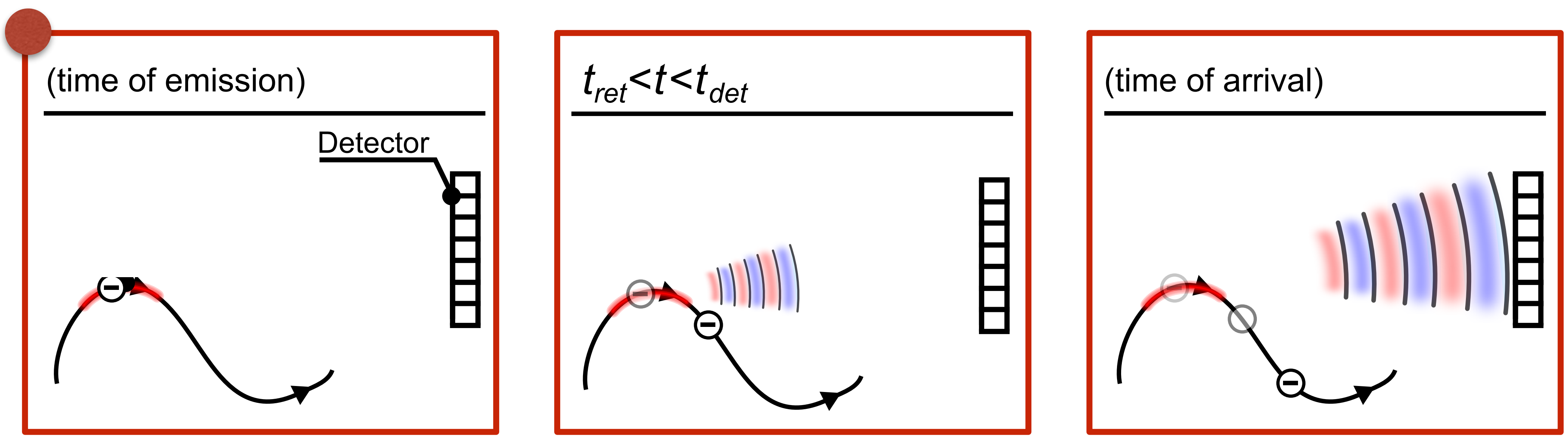

For each t_{ret} **find the corresponding** t_{det}

Deposition Scheme

Interpolation of the radiation

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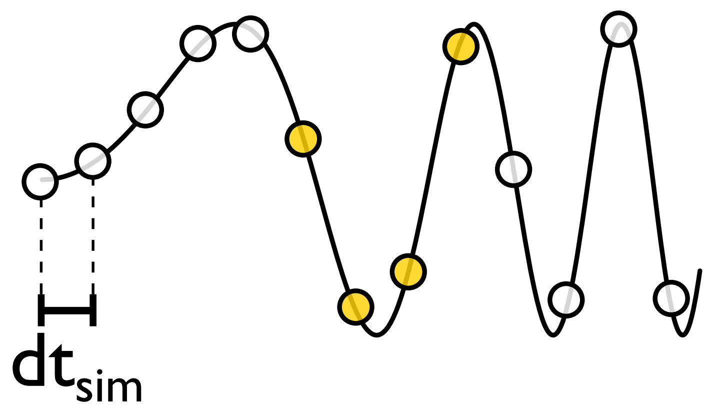
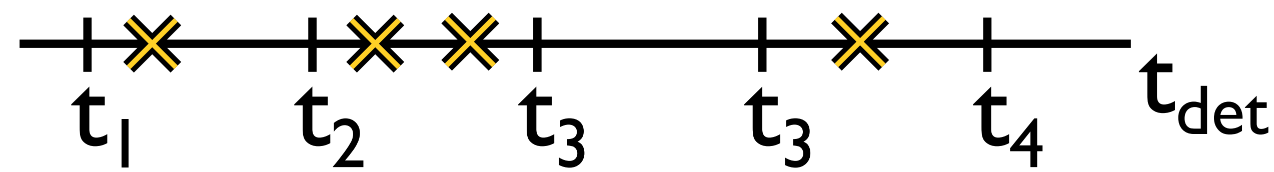
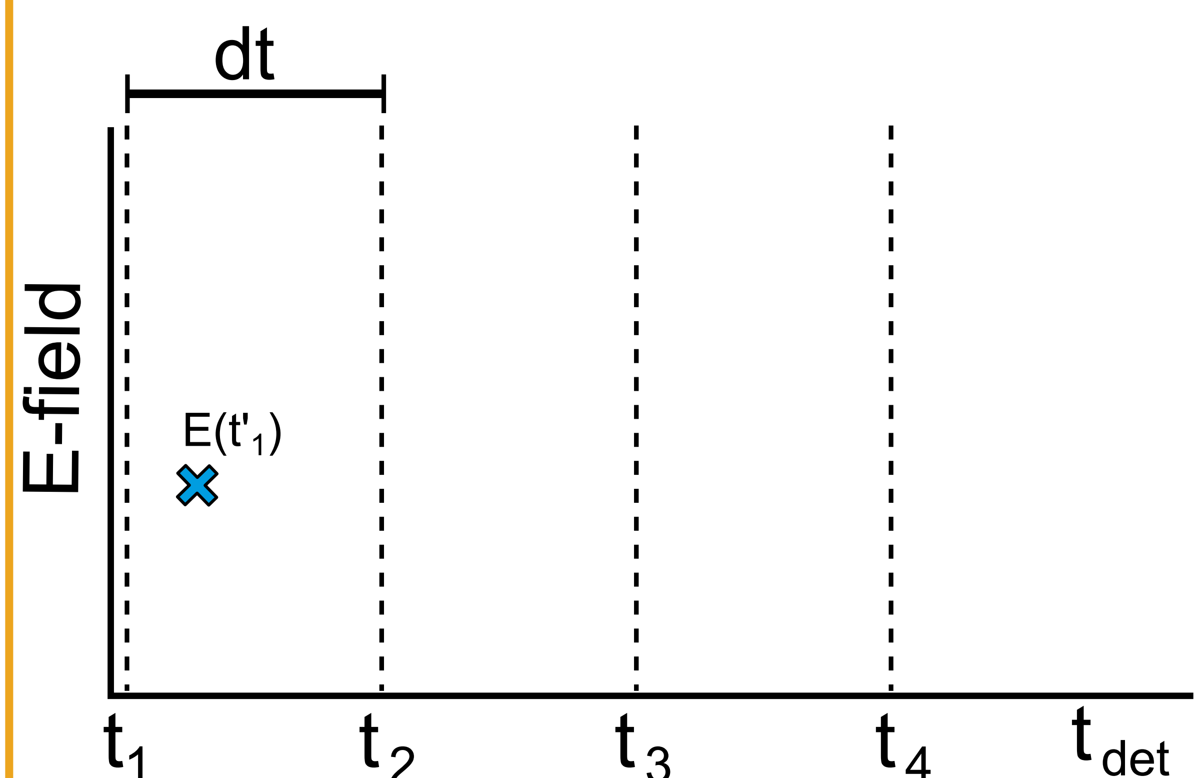
Radiation deposition at the detector



$$t_{det} = t_{ret} + R(t_{ret})/c$$



Radiation is a continuous process



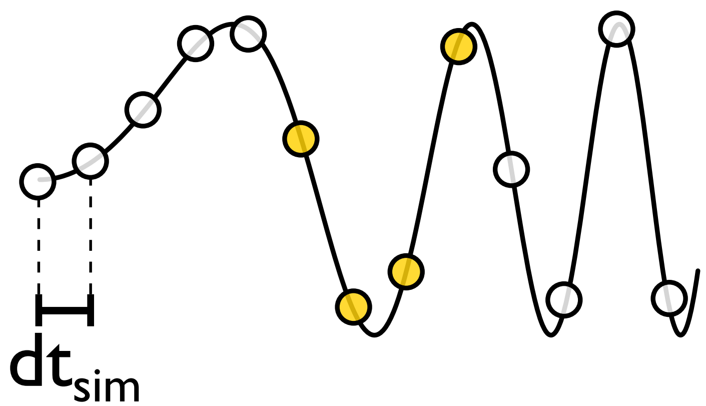
Smooth deposition

Deposits the radiation of the previous time step

Deposition Scheme

Interpolation of the radiation

Radiation deposition at the detector



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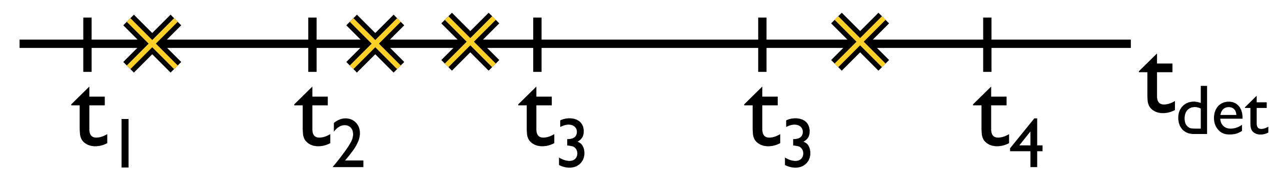

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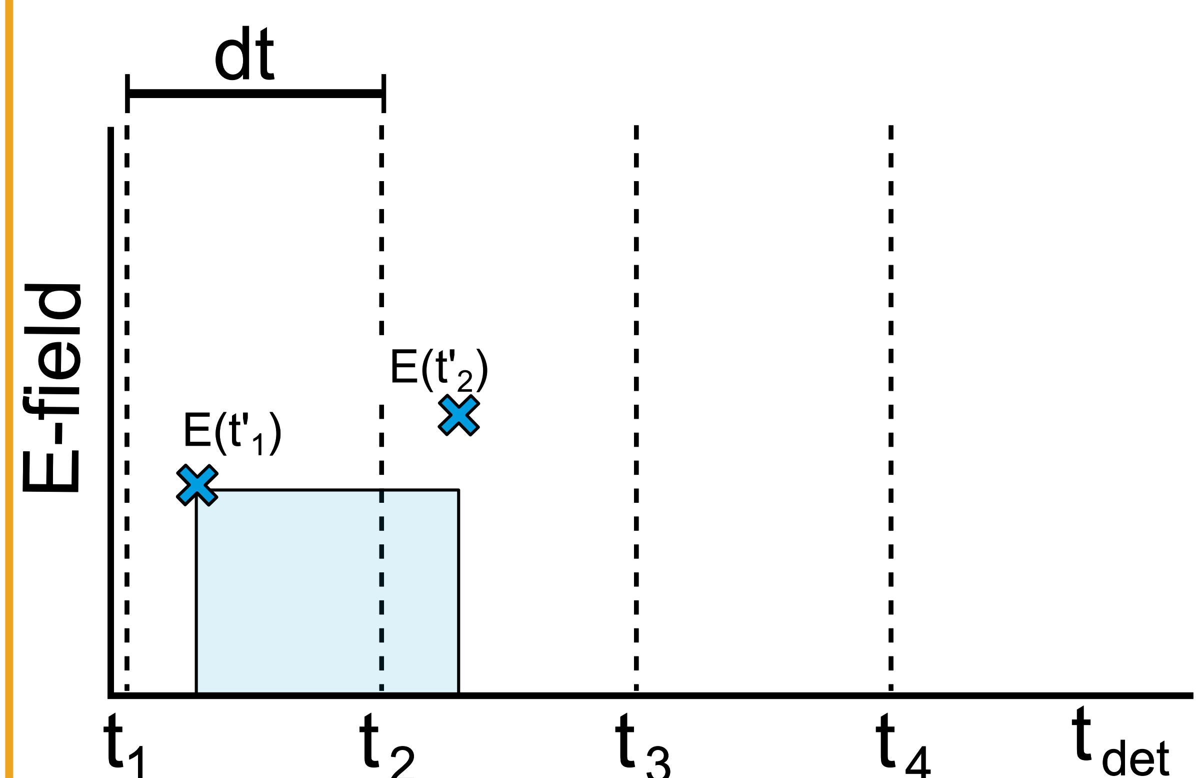

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$$dtE(t_1) = E(t_1')(t_2 - t_1')$$

Deposition Scheme

Interpolation of the radiation

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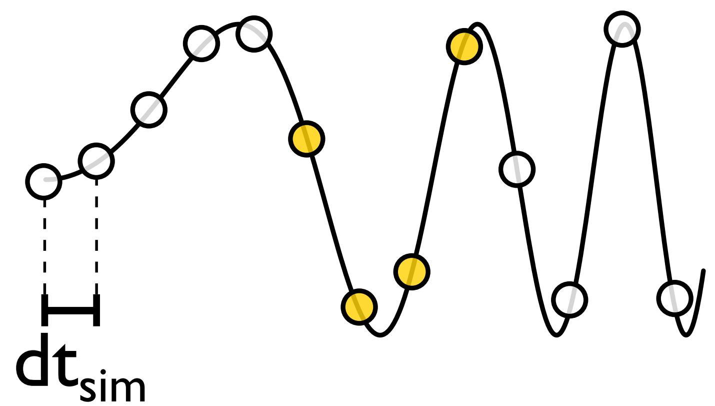

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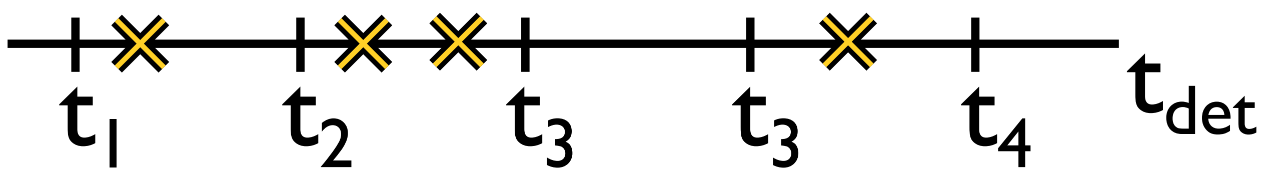

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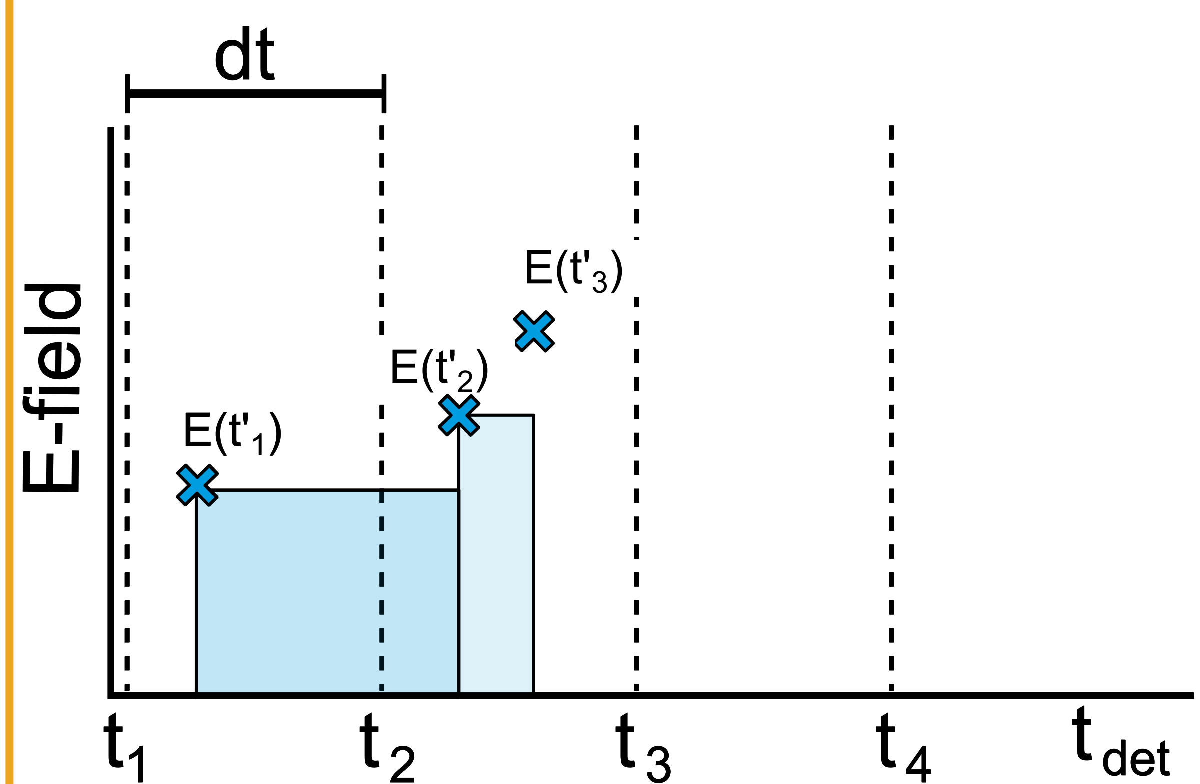

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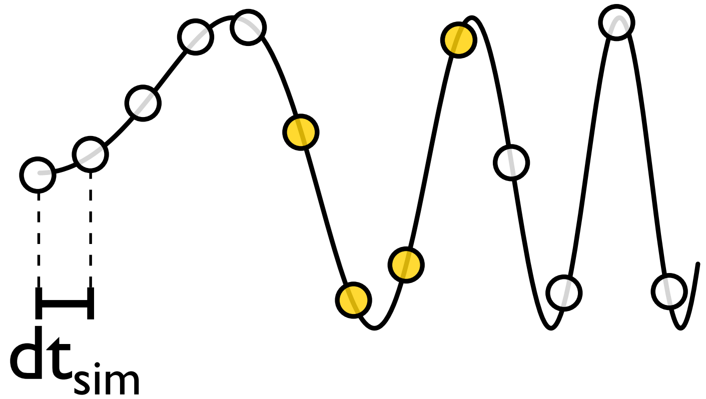
$$dtE(t_1) = E(t_1')(t_2 - t_1')$$

$$dtE(t_2) = E(t_1')(t_2' - t_2) +$$

Deposition Scheme

Interpolation of the radiation

Radiation deposition at the detector



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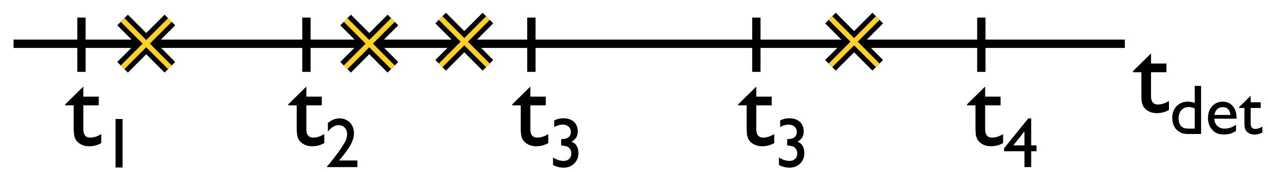

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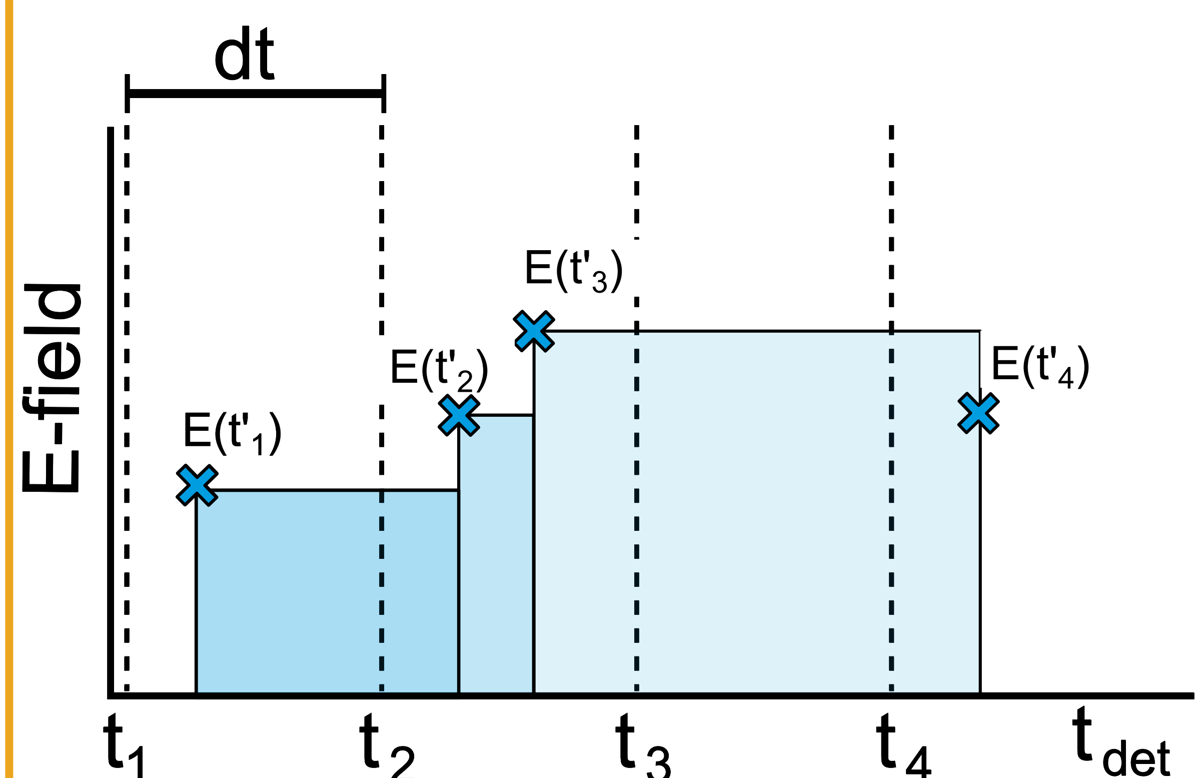


Smooth deposition

Deposits the radiation of the previous time step

$$dtE(t_1) = E(t'_1)(t_2 - t'_1)$$

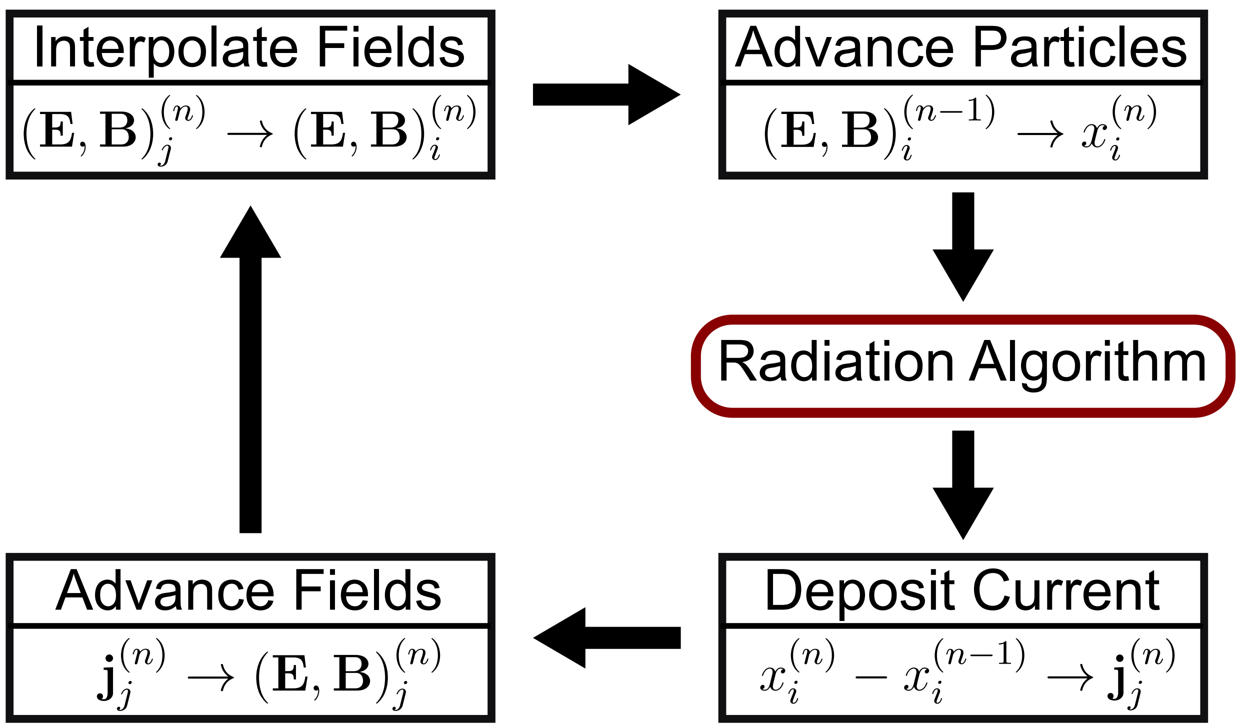
$$dtE(t_2) = E(t'_1)(t'_2 - t_2) + E(t'_2)(t'_3 - t'_2) + E(t'_3)(t_3 - t'_3)$$

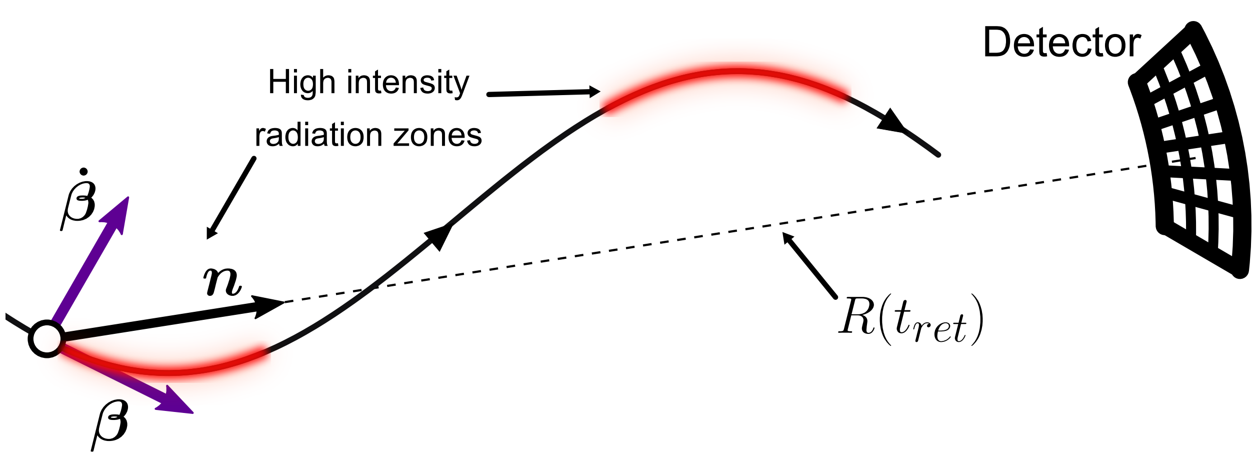
$$dtE(t_3) = E(t'_3)(t_4 - t_3)$$

Radiation algorithm

How to capture radiation efficiently

Radiation algorithm for both versions





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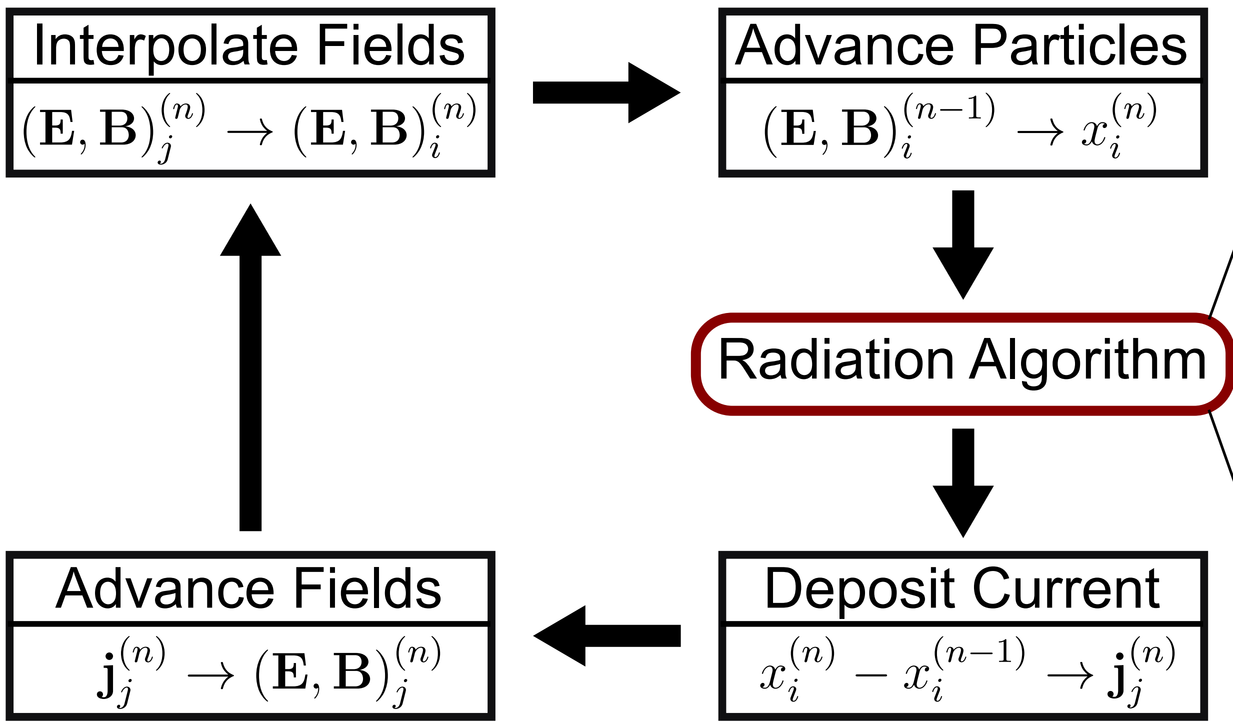
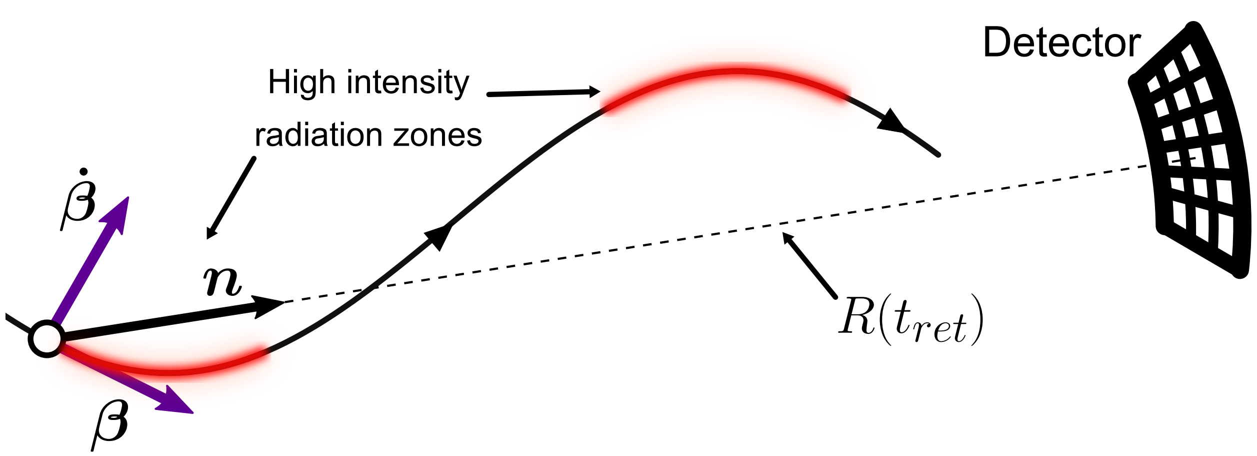


procedure RadiationCalculator
  for all $particle$ **in** simulation **do**
    for all $cell$ **in** detector **do**
      $\mathbf{n} \leftarrow$ direction$(particle, cell)$
      $\beta \leftarrow$ velocity$(particle)$
      $\dot{\beta} \leftarrow$ acceleration$(particle)$
      $R \leftarrow$ distance$(particle, cell)$
      $t_{\text{det}} \leftarrow R/c + t$
      if $t_{\text{det}}min < t_{\text{det}} < t_{\text{det}}max$ **then**
        $E(cell, t_{arrive}) \leftarrow \mathbf{E}(\mathbf{n}, \beta, \dot{\beta})$



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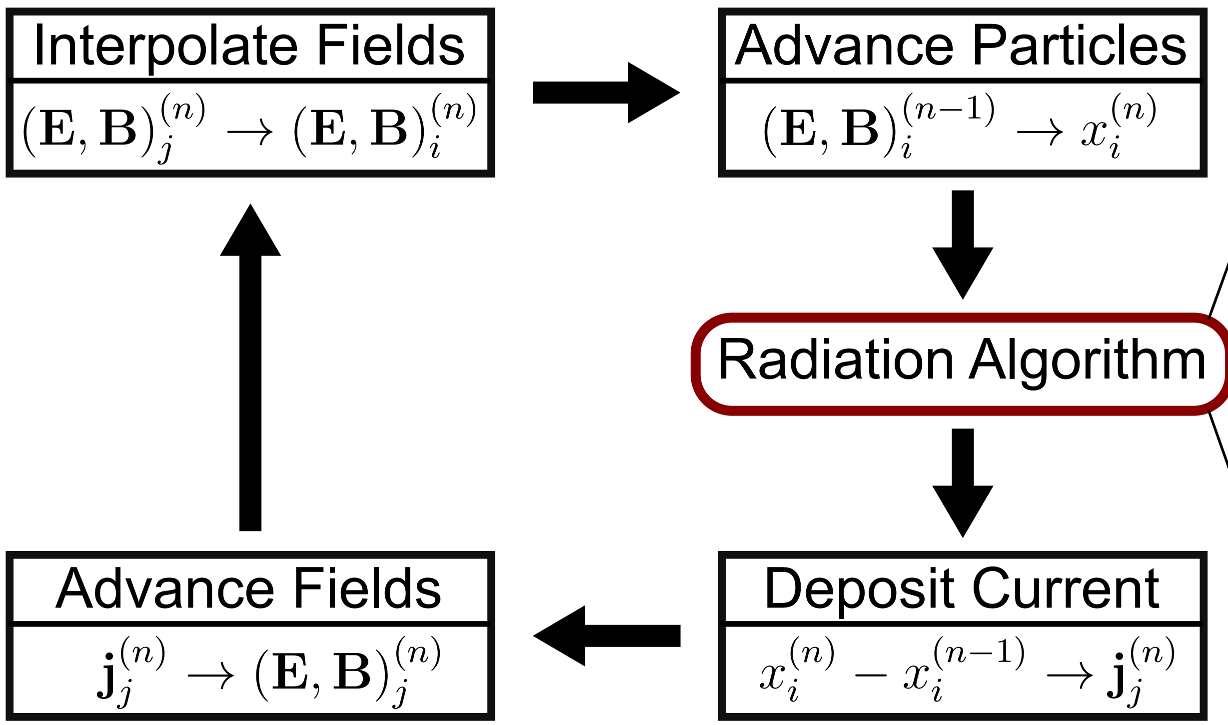

procedure RADIATIONCALCULATOR
  for all $particle$ **in** simulation **do**
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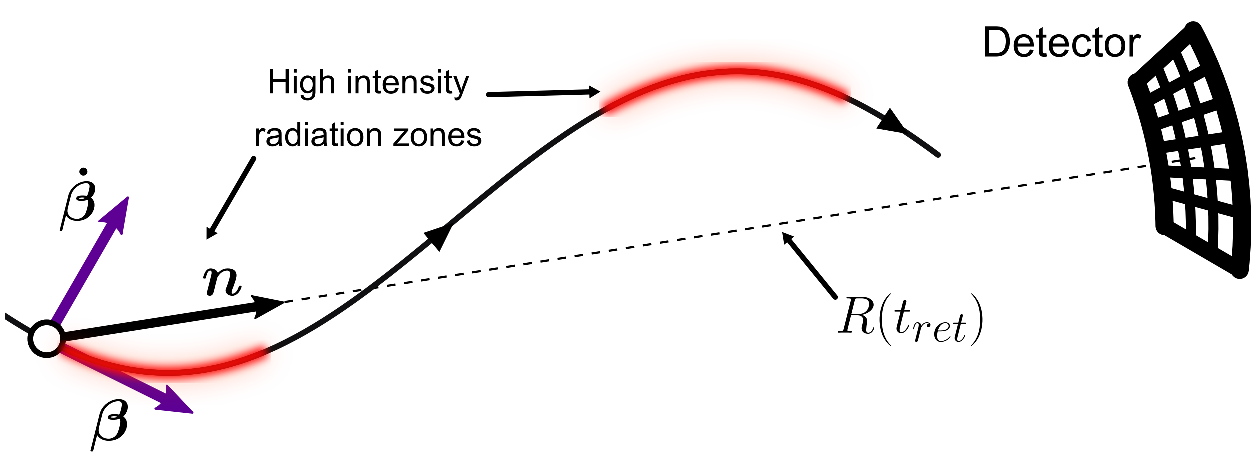


Only spatial cells

Increasing the temporal resolution does not affect the computational load

Contents

Tackling the problem
How to obtain the spatiotemporal profile of radiation in PIC

Benchmarking and coherence
To make sure our results are reliable

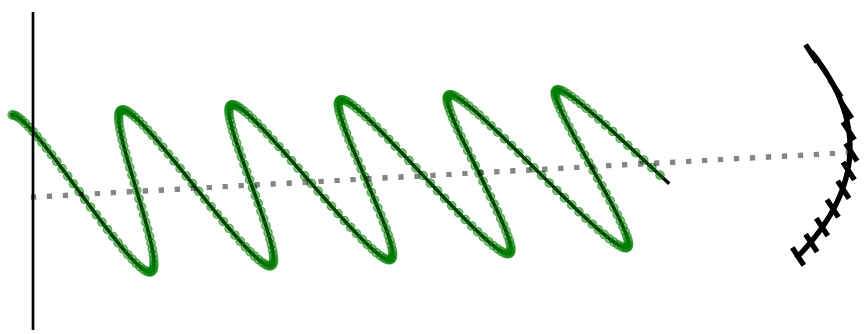
RaDiO simulations of real scenarios
Can we see radiation emitted in realistic scenarios?

Conclusions & Future work

Sinusoidal trajectory in a plane

A synchrotron favourite

Trajectory & Detector



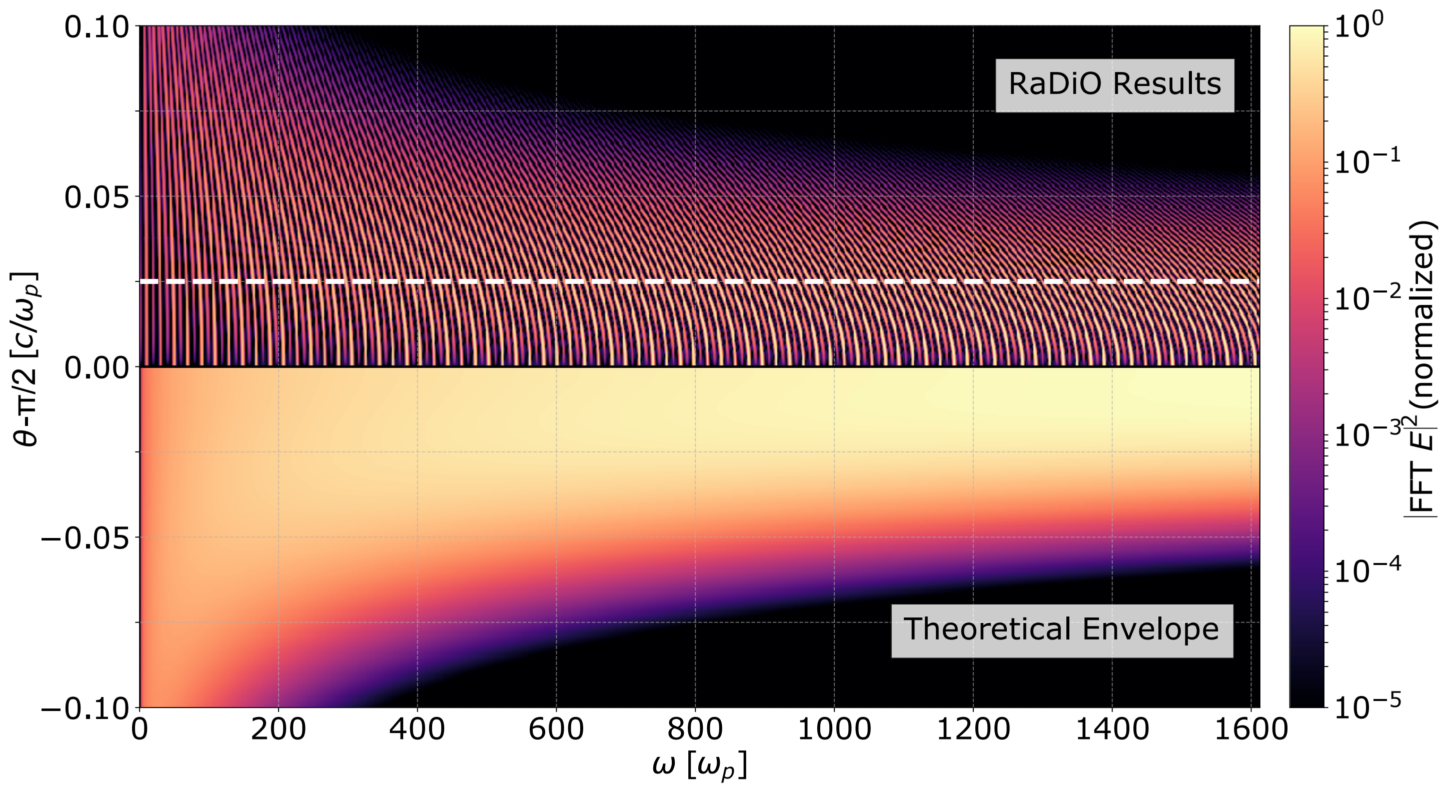
Trajectory

Amplitude: $2\, c/\omega_p$
Lorenz Factor, $\gamma_{||}$: 50
Frequency: $0.1\omega_p$

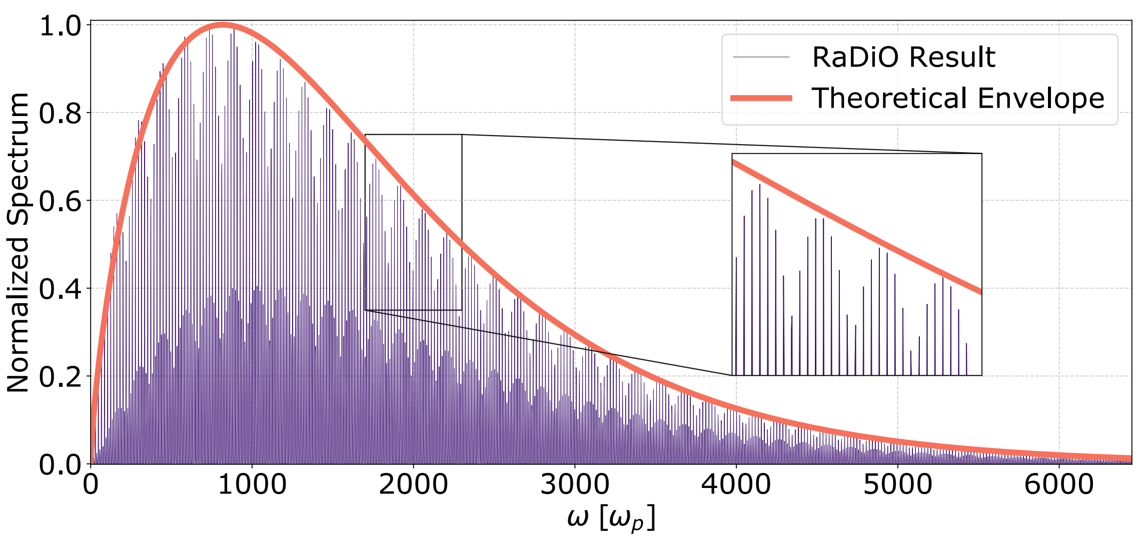
Detector

Aperture: 0.1 rad
Radius: $10^5\, c/\omega_p$
Spatial cells: 512
Time resolution: $2.98 \times 10^{-5}\, \omega_p^{-1}$

Benchmark- spectral domain*



$$|\mathsf{FFT}\{\mathbf{E(t)}\}|^2 \propto \frac{d^2 I}{d\omega d\Omega}$$

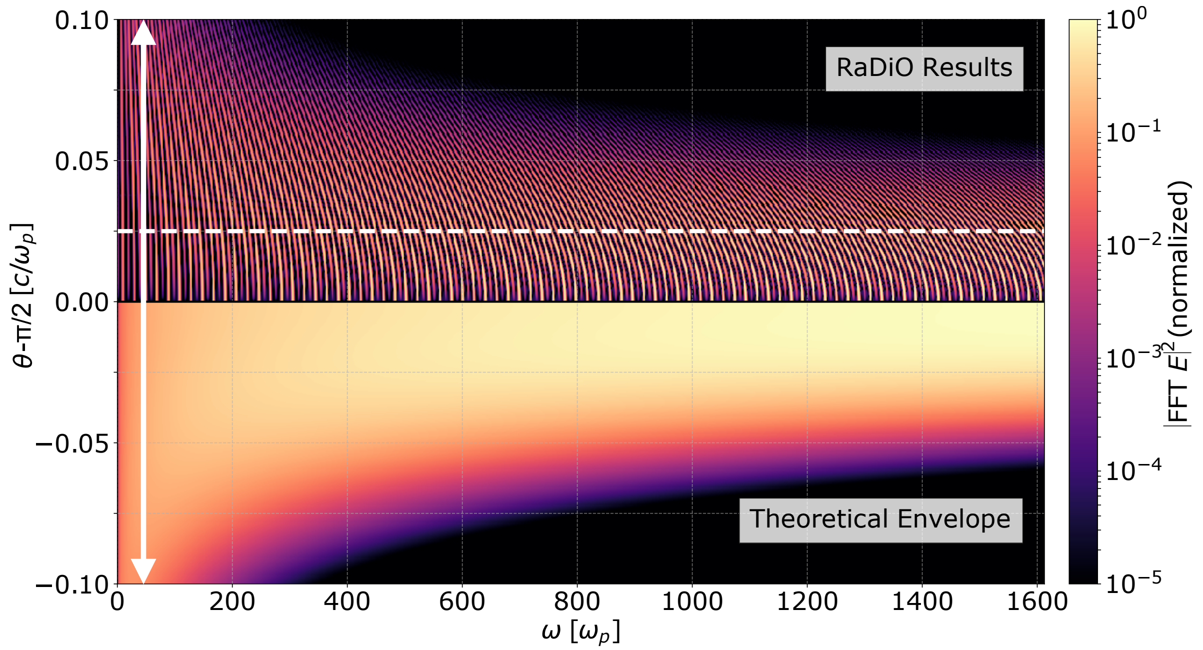


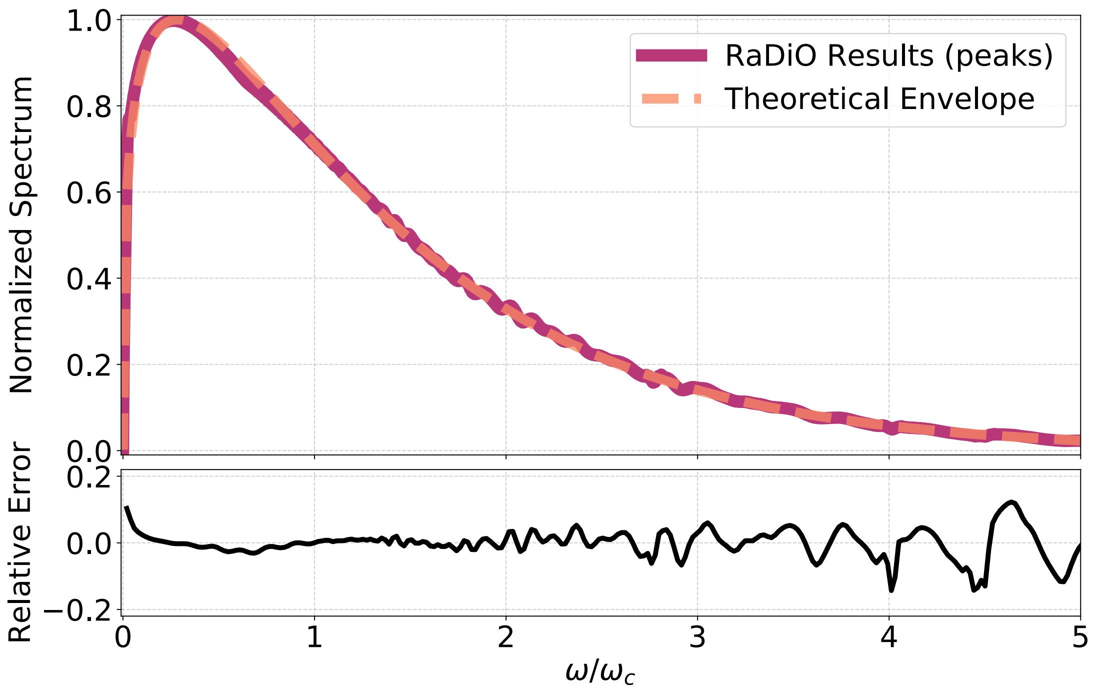
* E. Esarey *et al.*, Phys. Rev. E 65, 6505 (2002)

Sinusoidal trajectory in a plane

Integral comparison & JRad

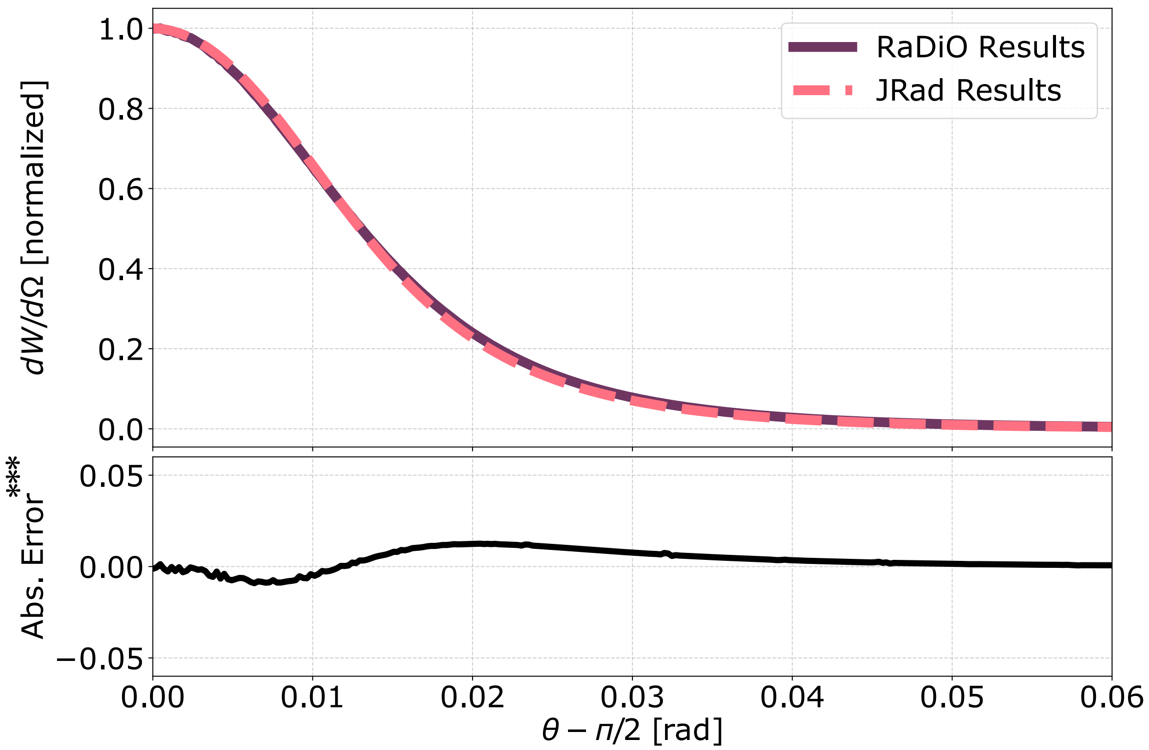
Integrated spectra





Angle integrated spectrum*: $\frac{dI}{d\omega}$

Frequency integrated spectrum:** $\frac{dI}{d\Omega}$



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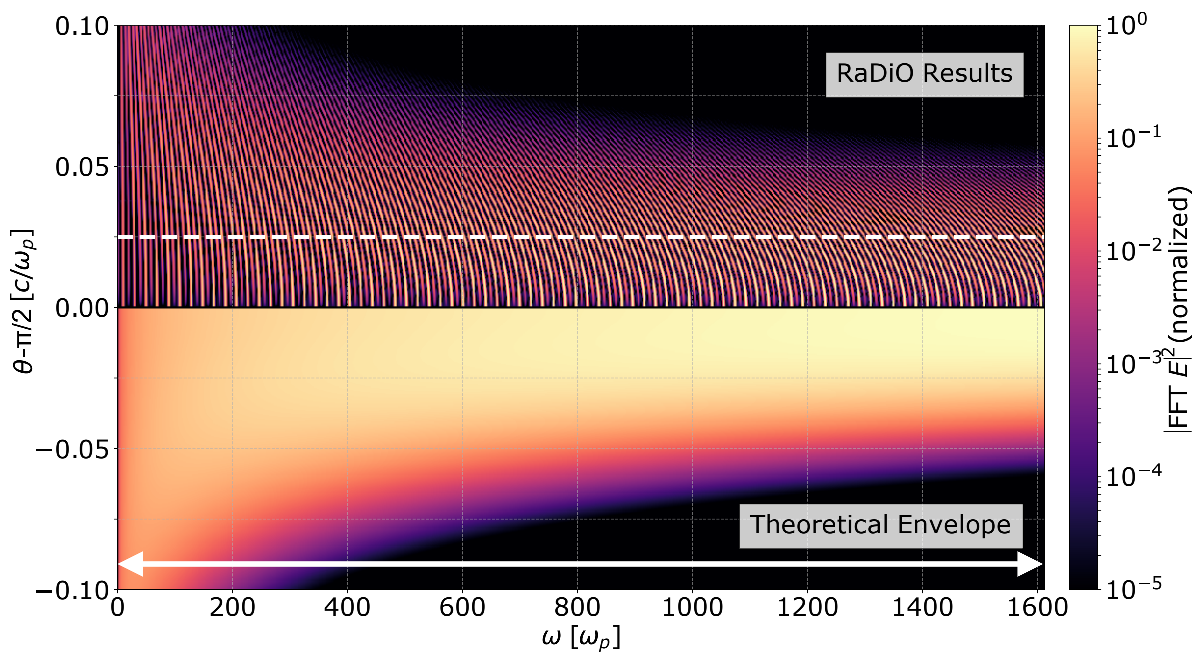
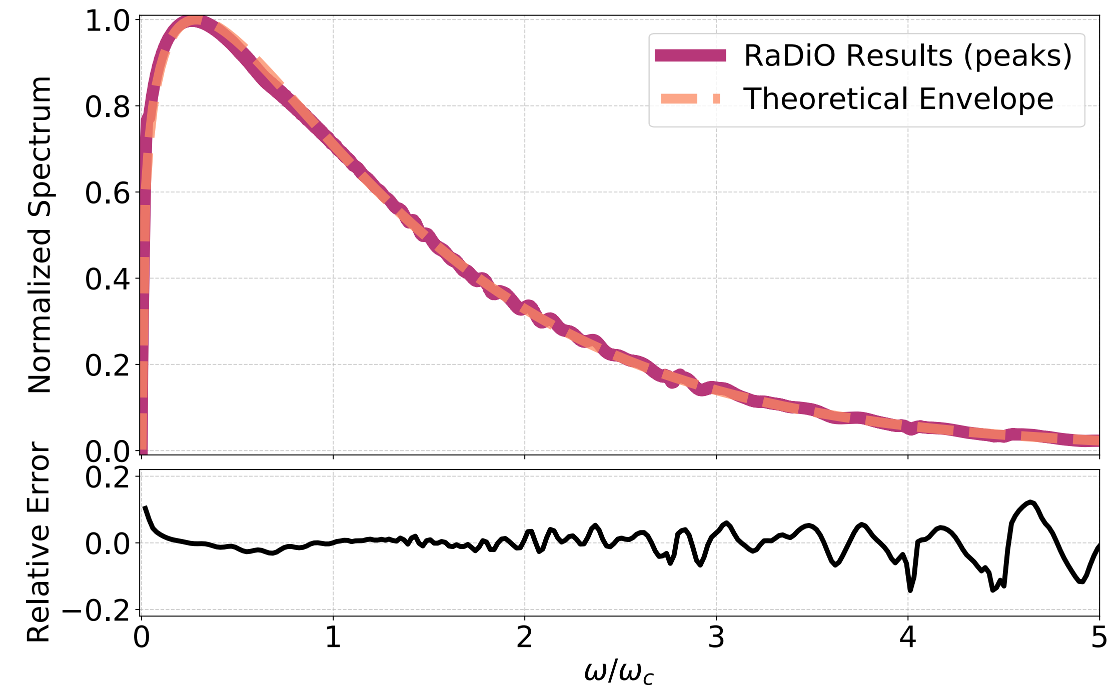
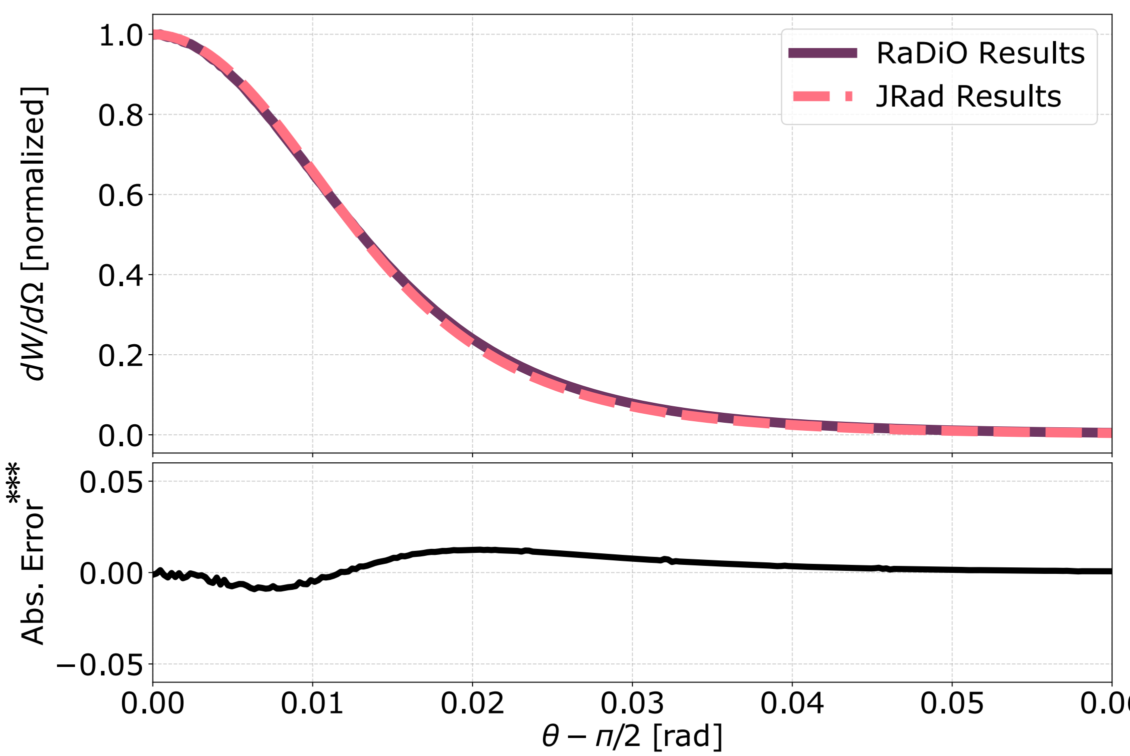




Angle integrated spectrum*: $\frac{dI}{d\omega}$

Frequency integrated spectrum:** $\frac{dI}{d\Omega}$



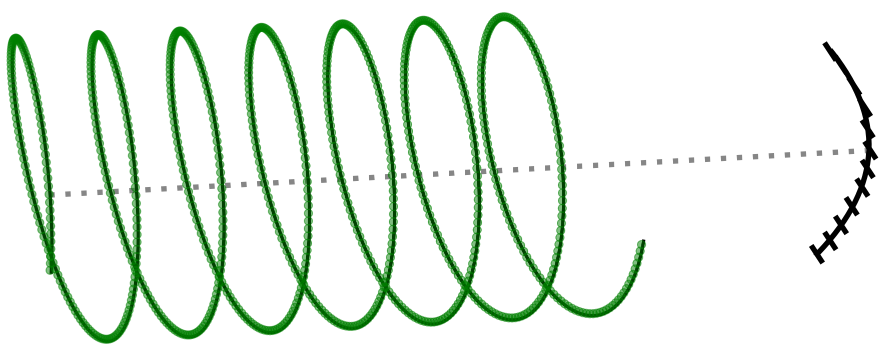
* E. Esarey *et al.*, Phys. Rev. E 65, 6505 (2002) *** As defined in Wolfram MathWorld

** J. L. Martins *et al.*, Proc. SPIE 7359 (2009)

3D helical trajectory

A promising alternative

Trajectory & Detector



Trajectory

Amplitude: $0.02\, c/\omega_p$

Lorenz Factor, $\gamma_{\|}$: 100

Frequency: $1\, \omega_p$

Detector

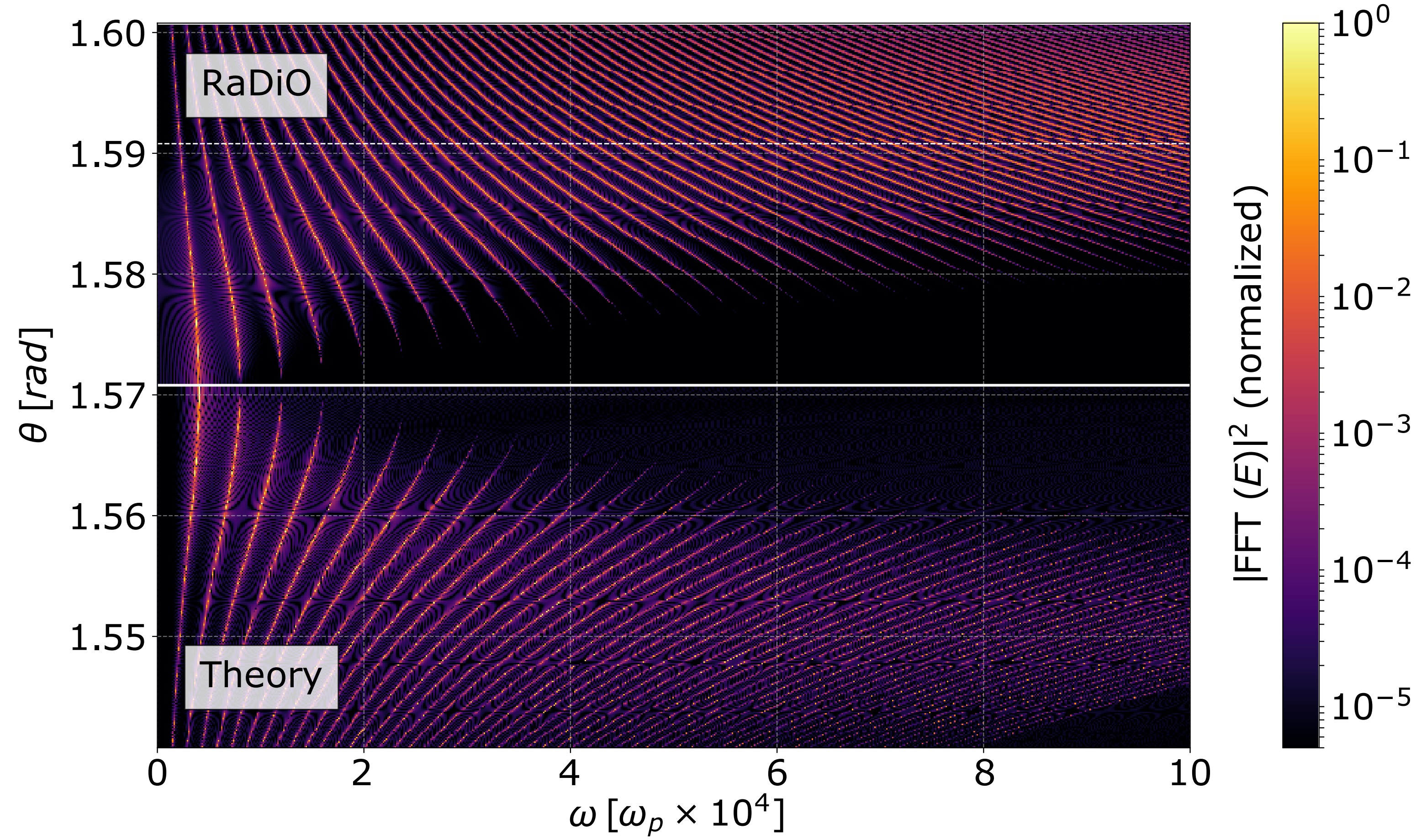
Aperture: 0.03 rad

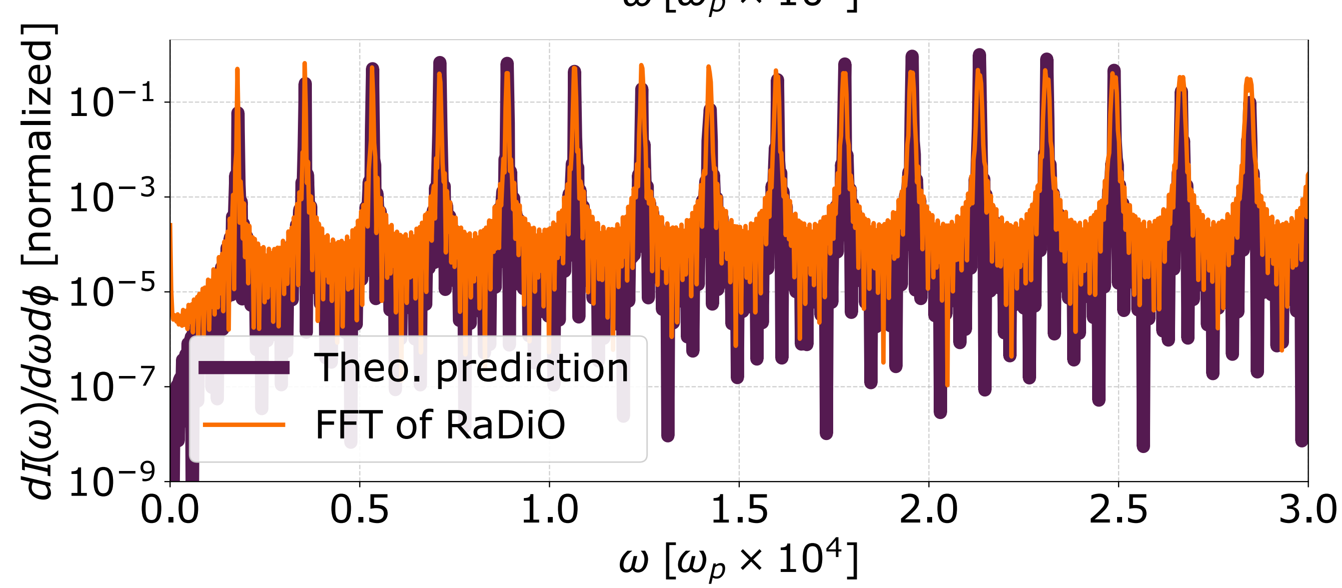
Radius: $10^5\, c/\omega_p$

Spatial cells: 512

Time resolution: $1.33 \times 10^{-5}\, \omega_p^{-1}$

Benchmark- spectral domain





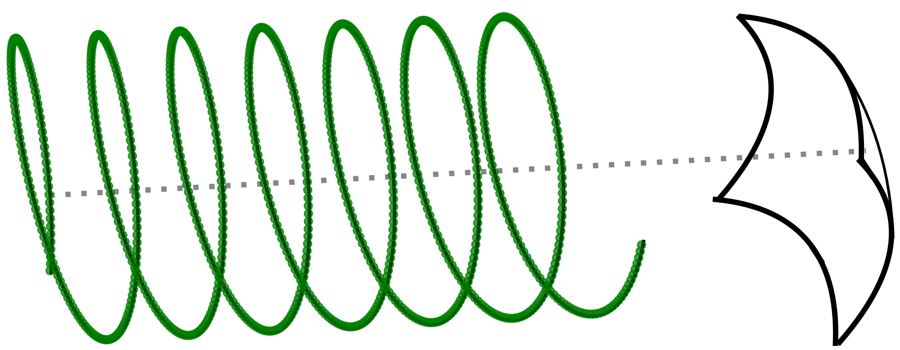
* B. M. Kincaid, Journal of Applied Physics. 48(7), 2684 (1977)

3D helical trajectory

A sneak peek at the spatiotemporal structure

TÉCNICO LISBOA

Trajectory & Detector



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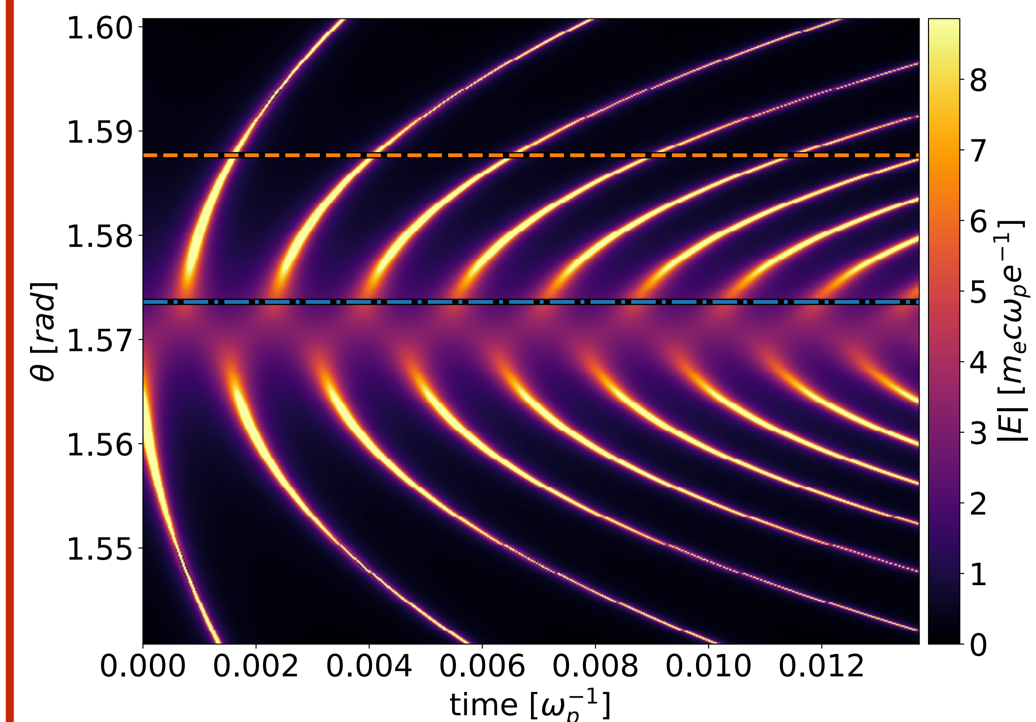
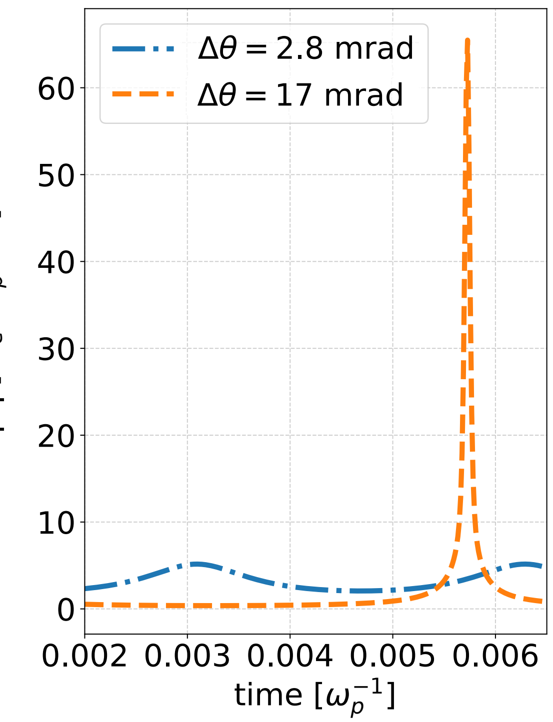
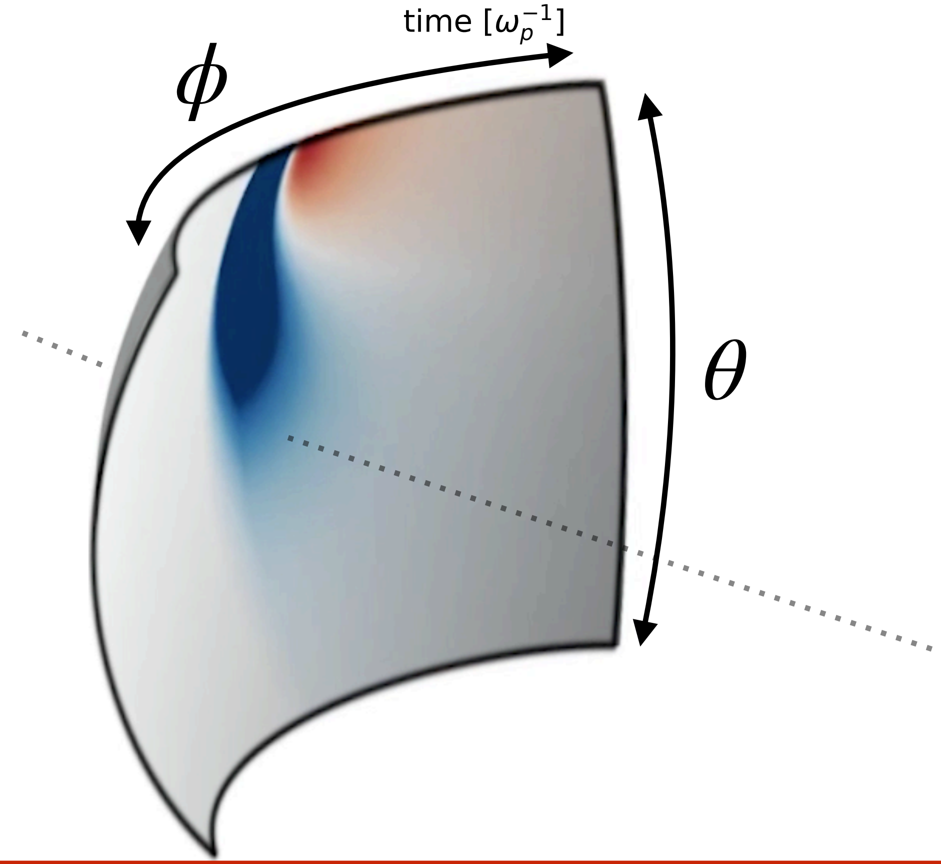
Spatiotemporal profile







$t_{det} = 0.0000\omega_p^{-1}$

Temporal offset:

$$t = t_{sim} - R/c$$

3D helical trajectory

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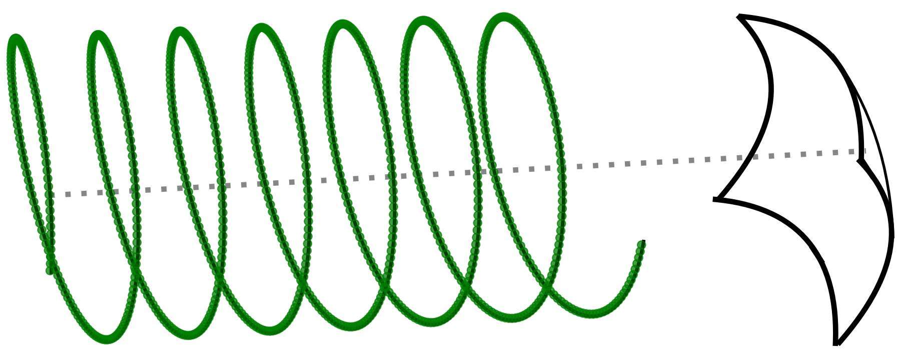
Trajectory & Detector



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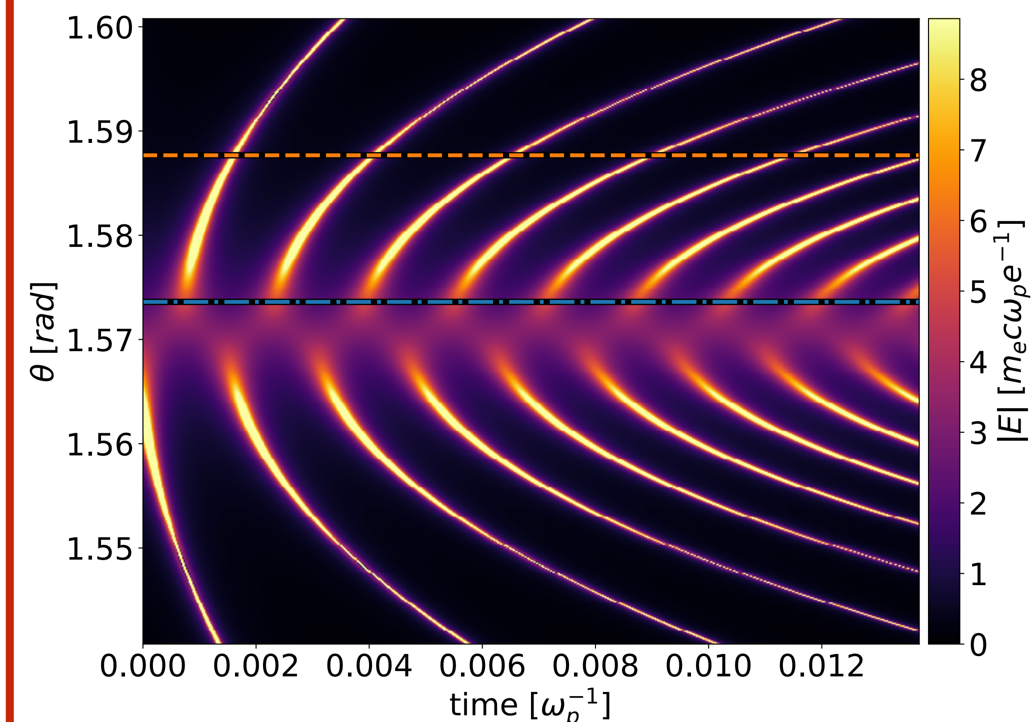

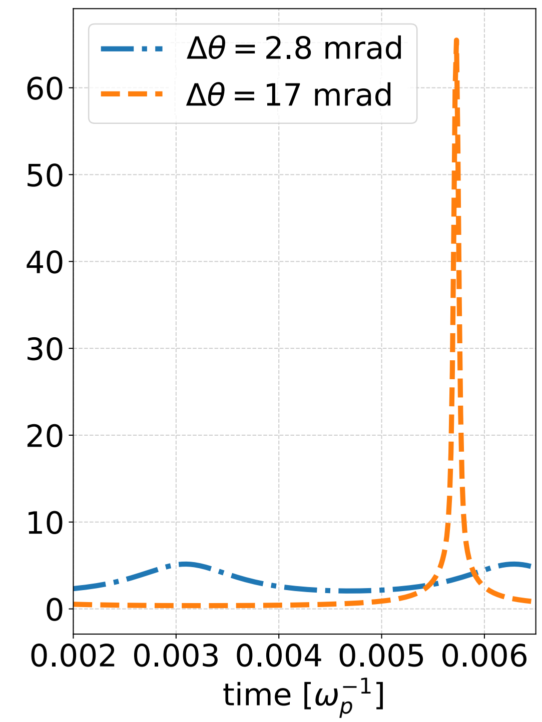

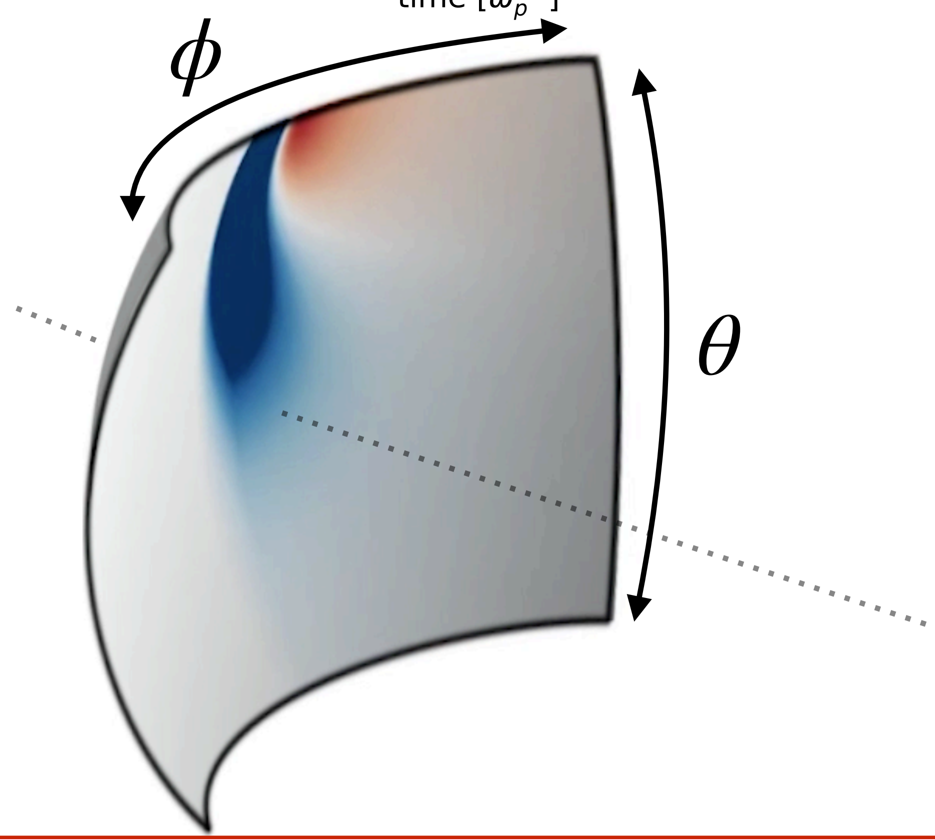

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Spatiotemporally coherent radiation

Why we care about coherence

Plasma coherent sources

Sources of coherent radiation are in high demand.

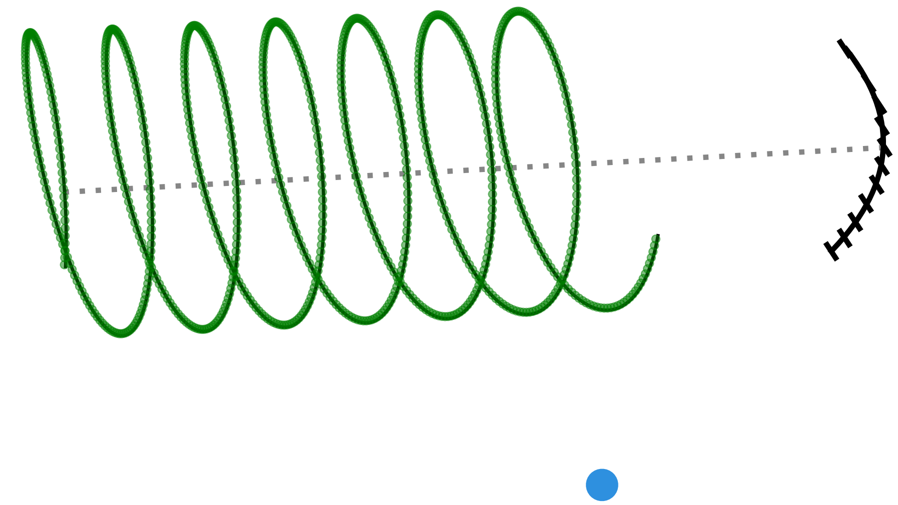
Plasma based radiation processes are being investigated as promising alternative

Betatron in WFA* **HHG****

$$\mathbf{E}(\mathbf{x}, t_{det}) = \frac{q_e}{c}\left[\frac{\mathbf{n}\times[(\mathbf{n}-\boldsymbol{\beta})\times\dot{\boldsymbol{\beta}})]}{(1-\boldsymbol{\beta}\cdot\mathbf{n})^3 R}\right]_{\mathrm{ret}}$$

$$\sum_i E_i$$

Spatiotemporal profile



* S. Kneip *et al.*, Nature Physics, **6,** 980-983 (2010)
** G. Gariepy Phys. Rev. Lett. **113**, 153901 (2014)

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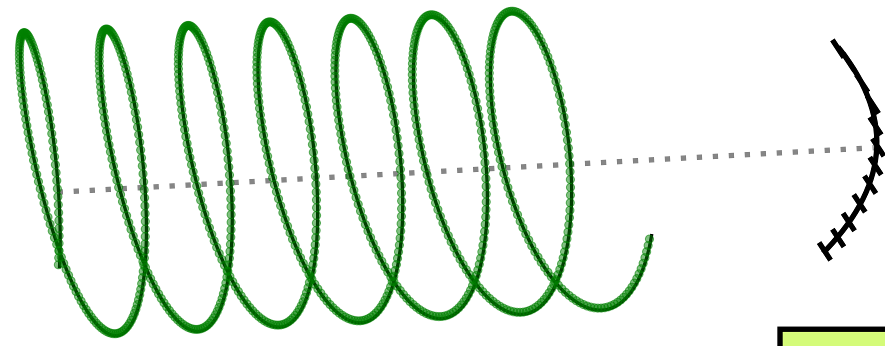

65 particles

* S. Kneip *et al.*, Nature Physics, **6,** 980-983 (2010)
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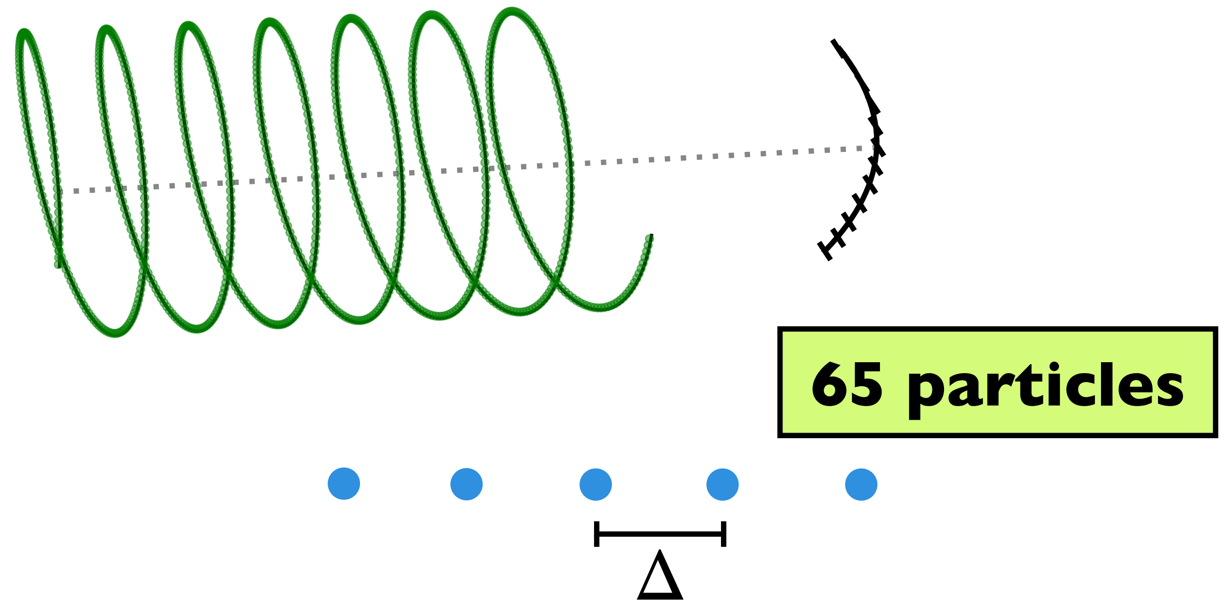

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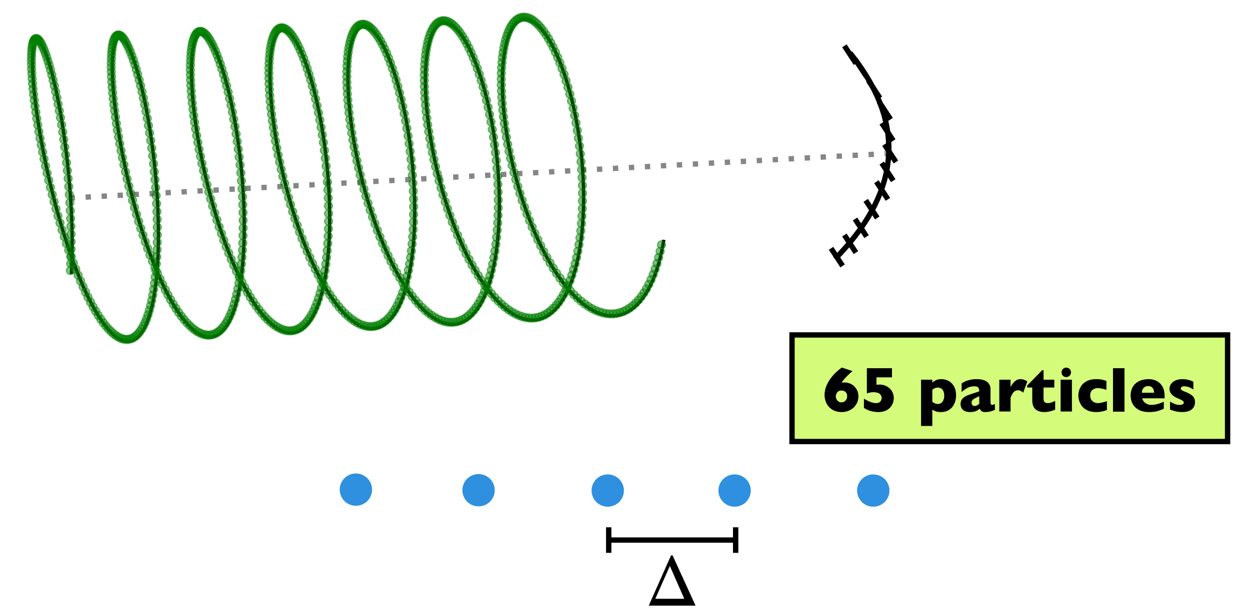

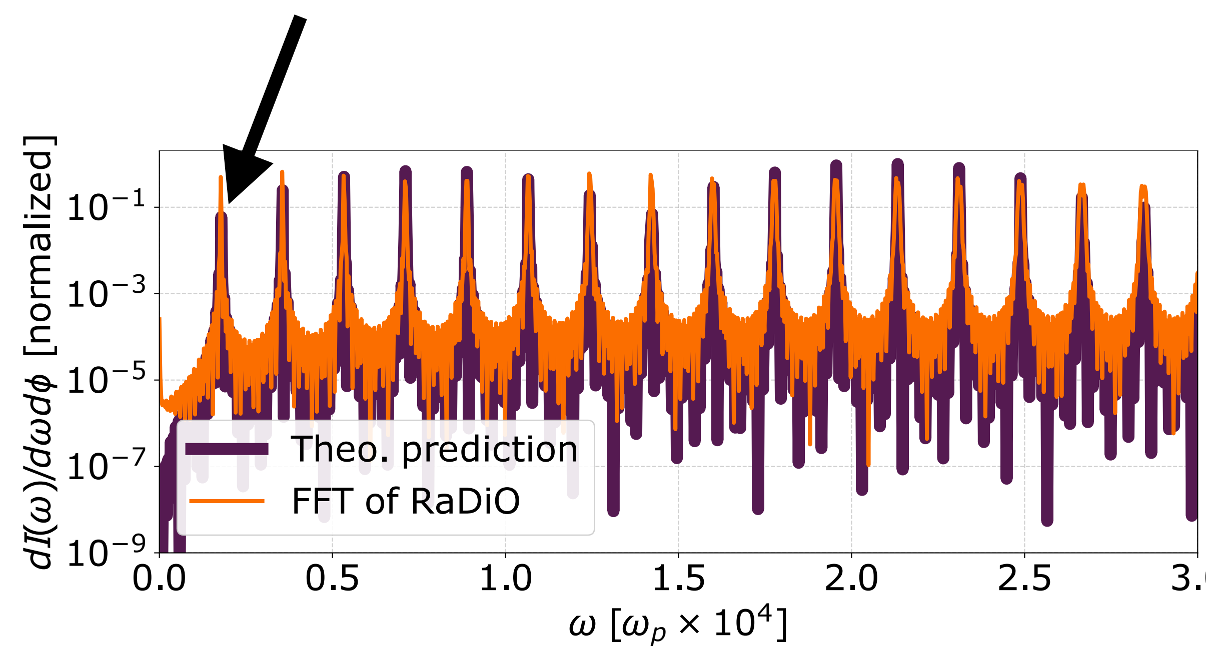

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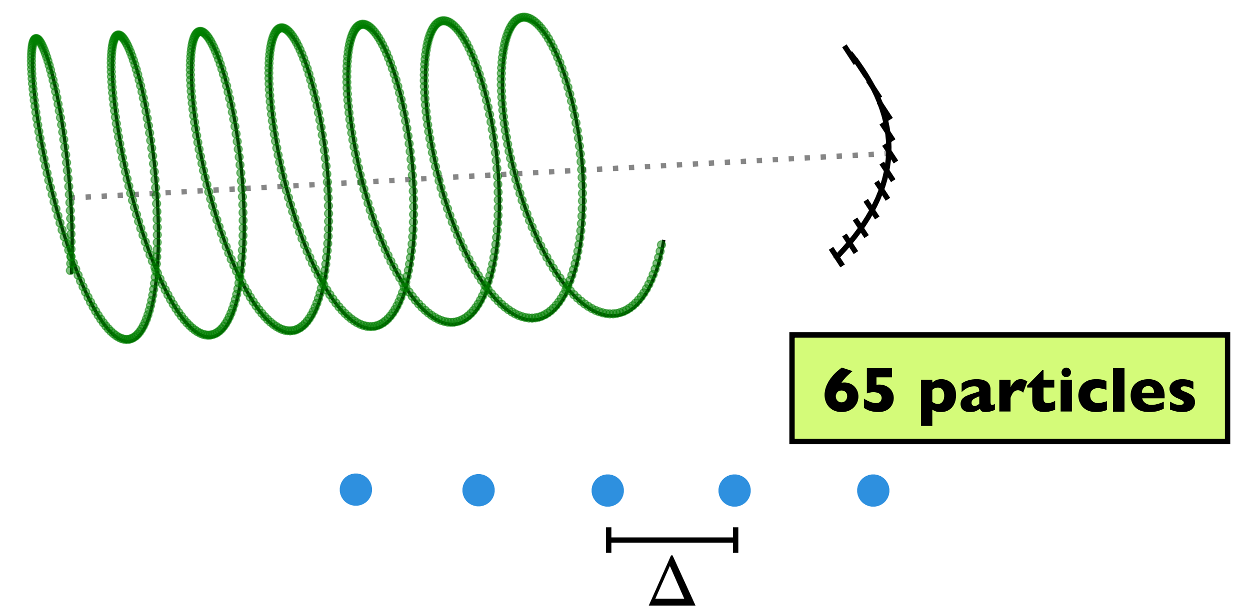

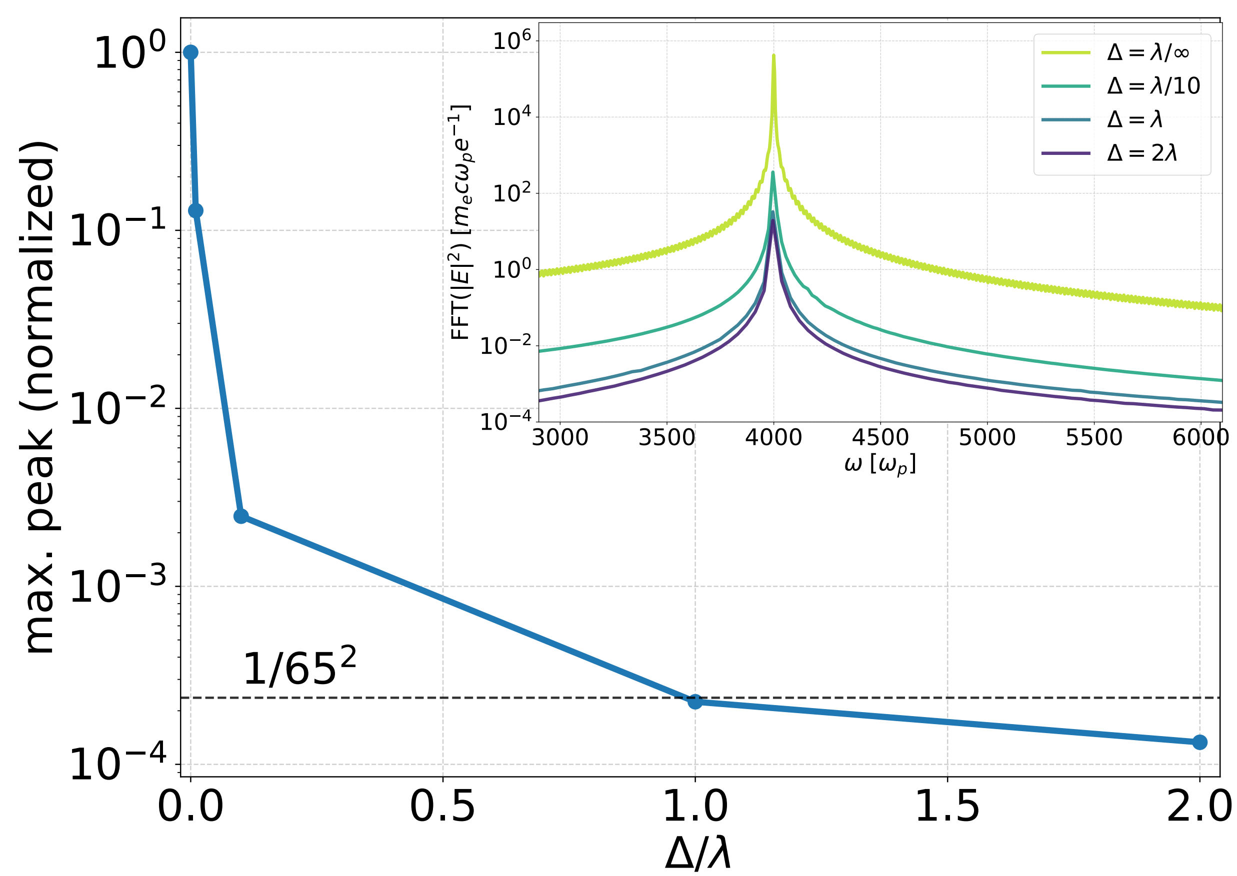

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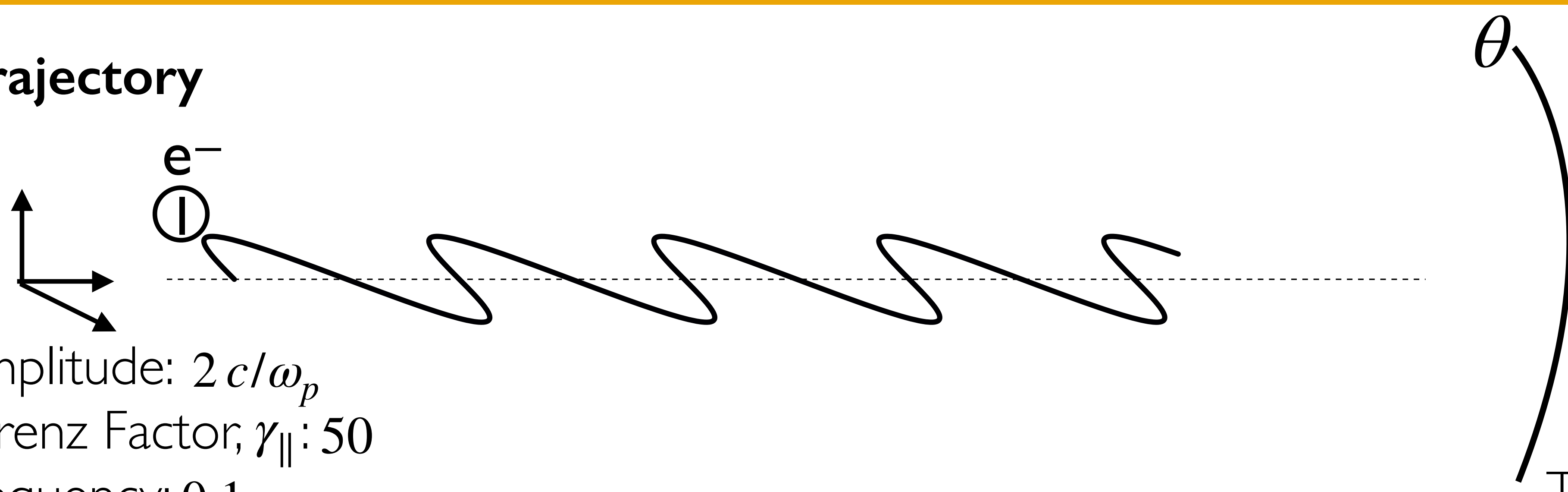
Coherence tests

A feature of the spatiotemporal profile

Trajectory & Detector

Trajectory



Amplitude: $2\,c/\omega_p$
Lorenz Factor, $\gamma_{||}$: 50
Frequency: $0.1\,\omega_p$

Detector

Aperture: 0.1 rad
Radius: $10^5\,c/\omega_p$
Spatial cells: 512
Time resolution: $3 \times 10^{-5}\,\omega_p^{-1}$

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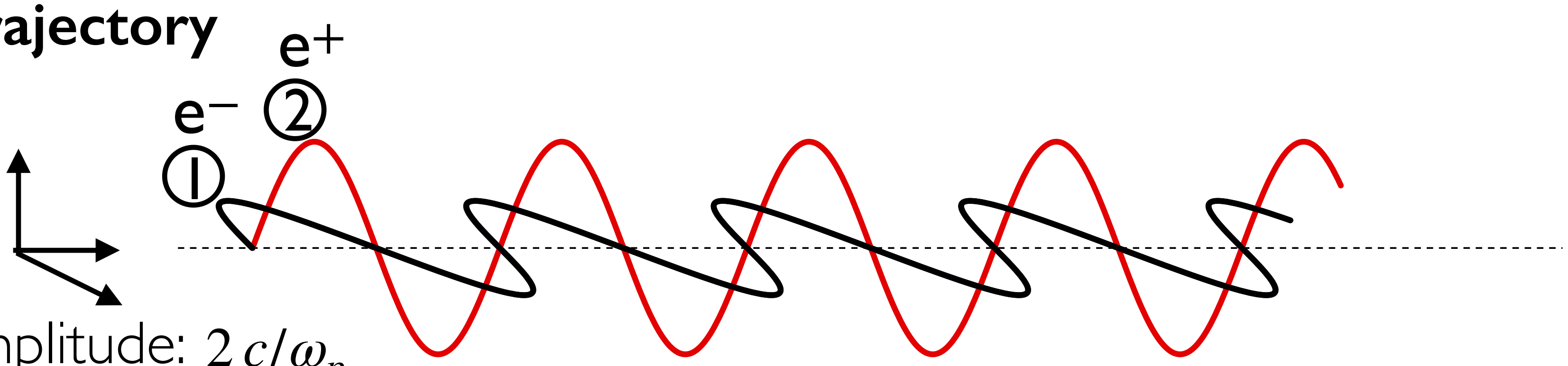

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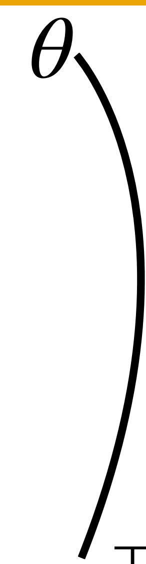

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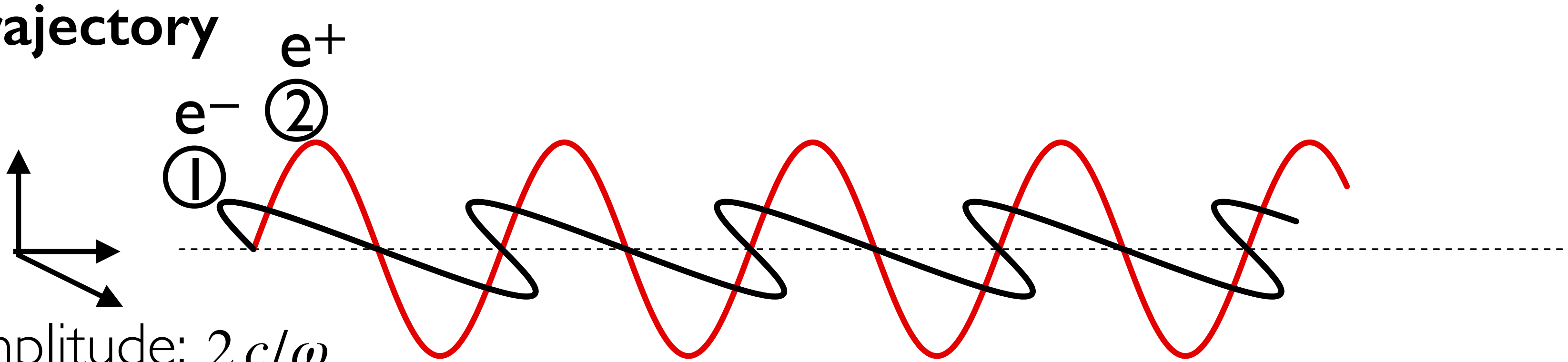

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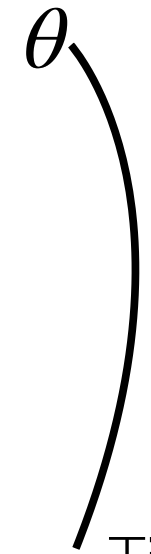
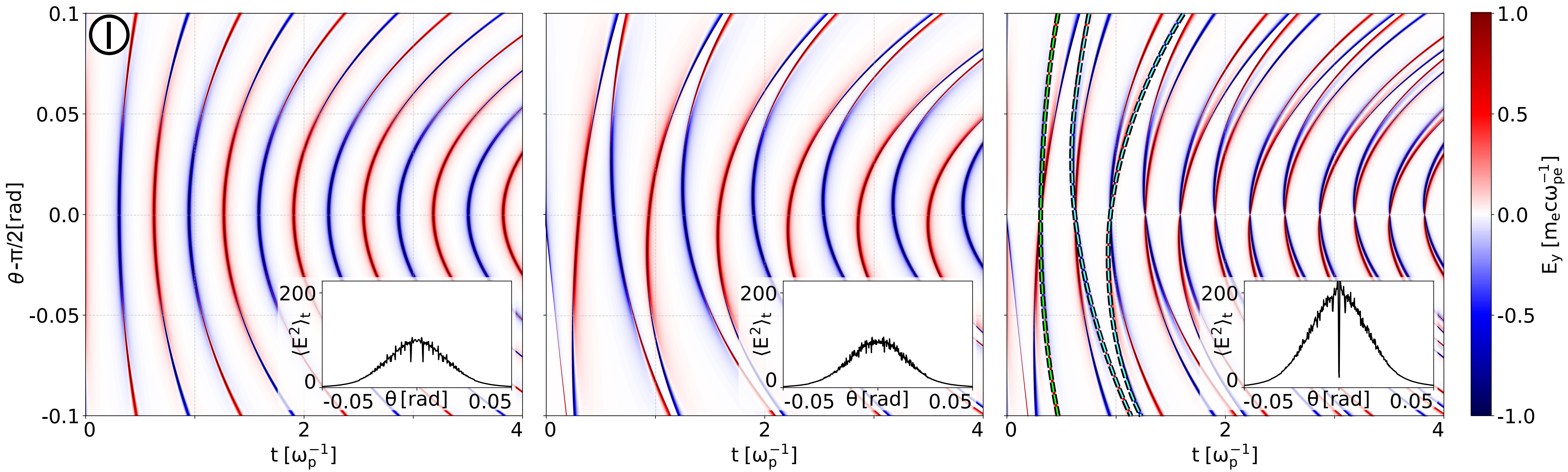


Detector

Aperture: 0.1 **rad**
Radius: $10^5\, c/\omega_p$
Spatial cells: 512
Time resolution: $3 \times 10^{-5}\, \omega_p^{-1}$

Results

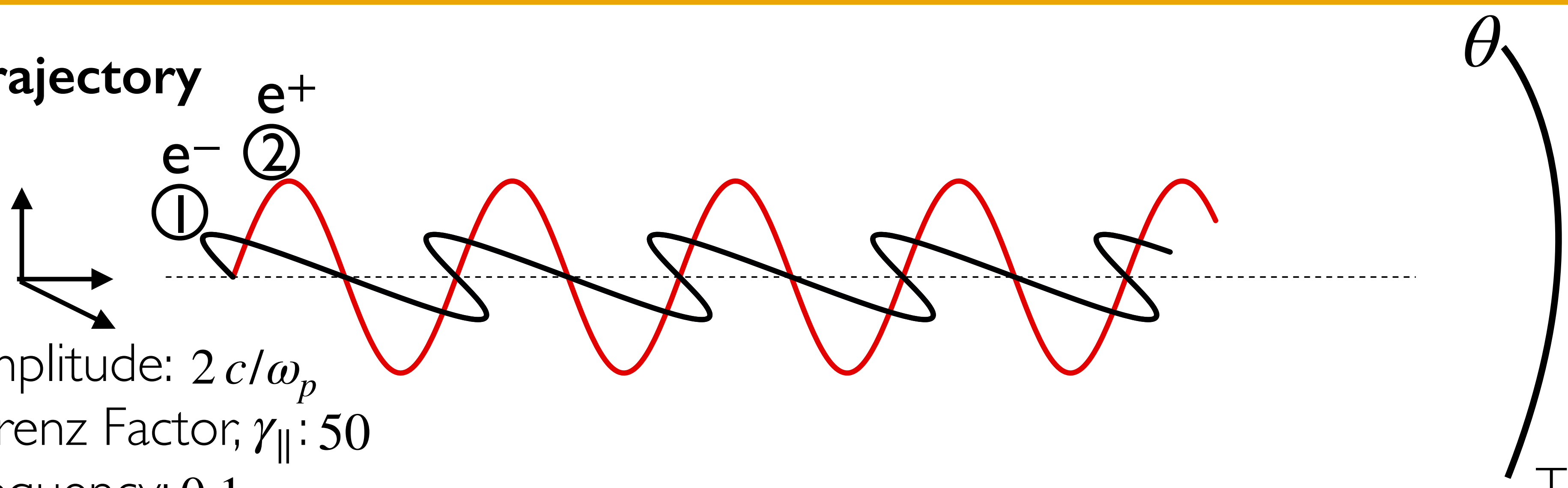


Coherence tests

A feature of the spatiotemporal profile

Trajectory & Detector

Trajectory



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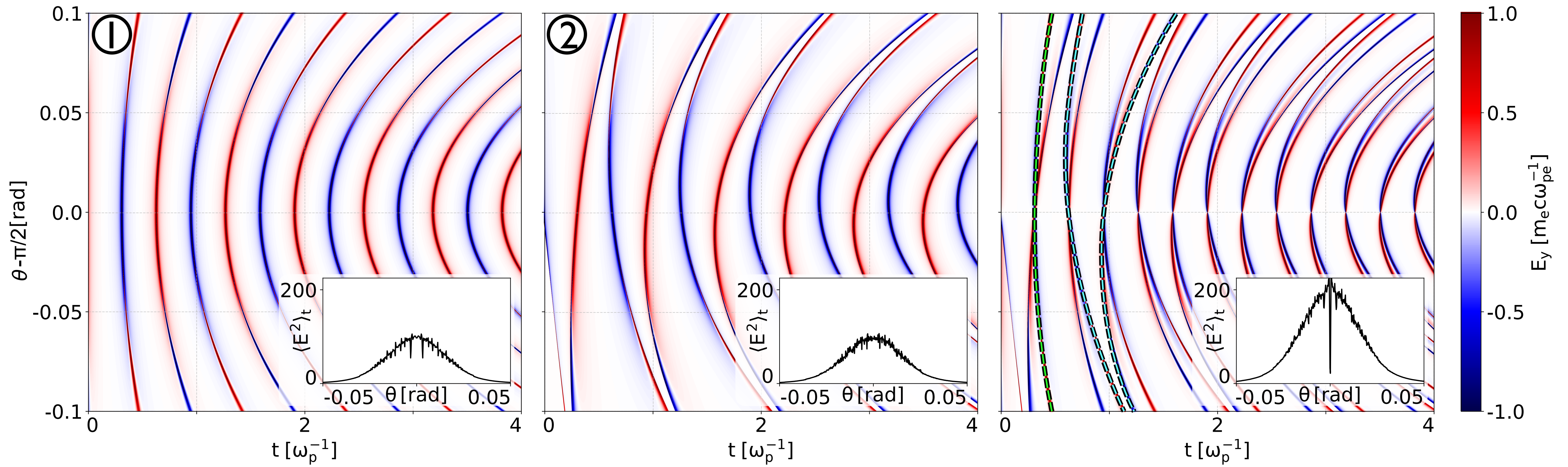

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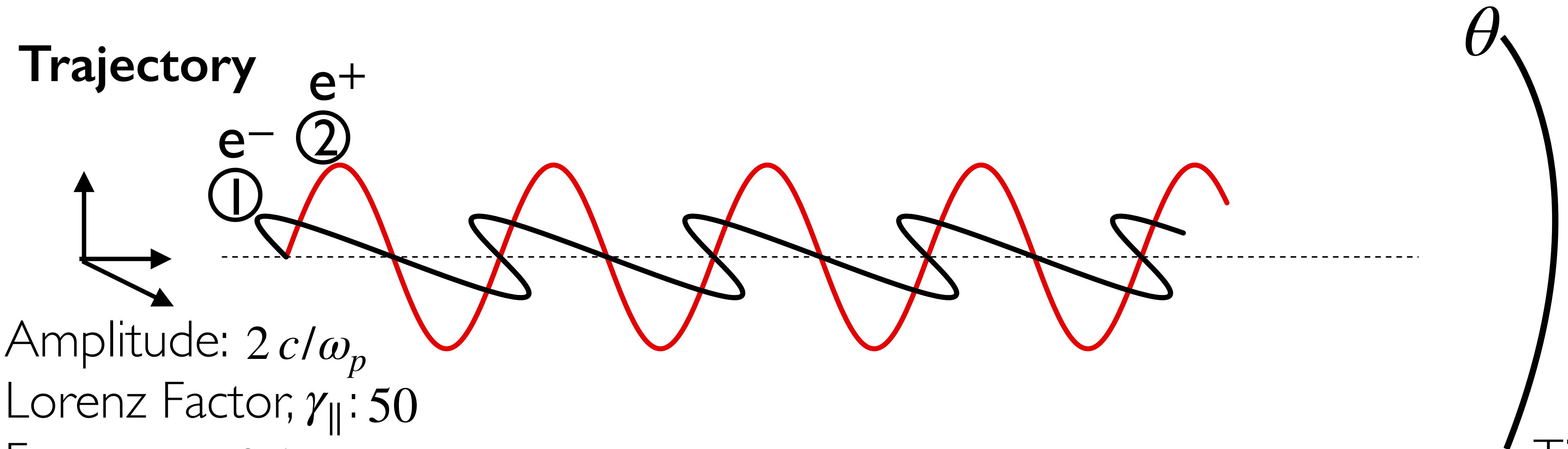

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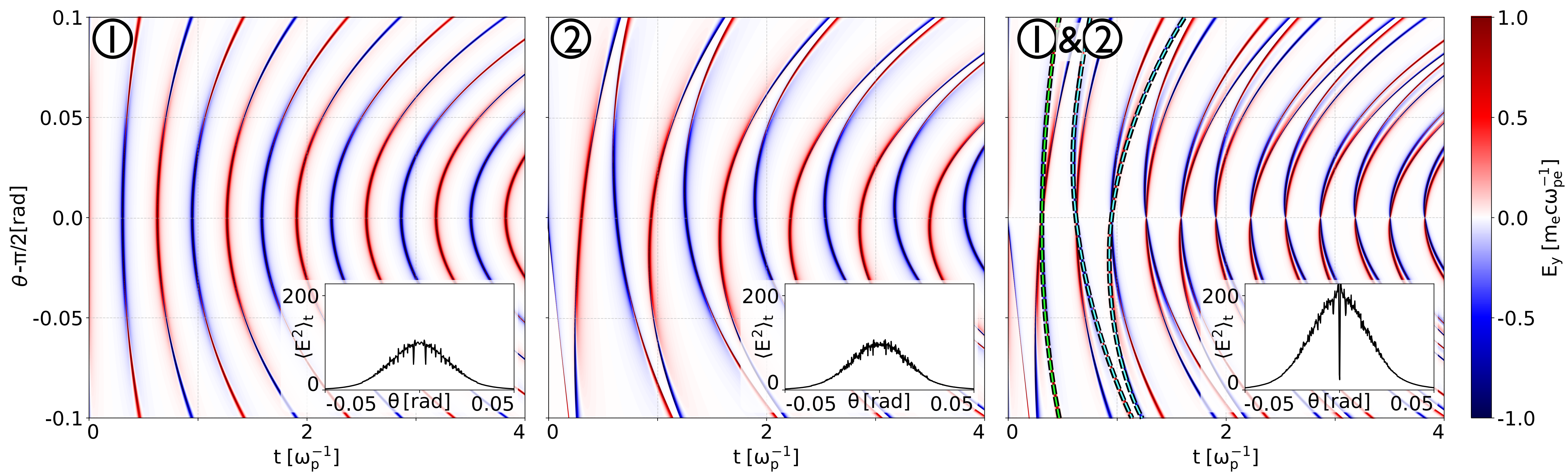


Contents

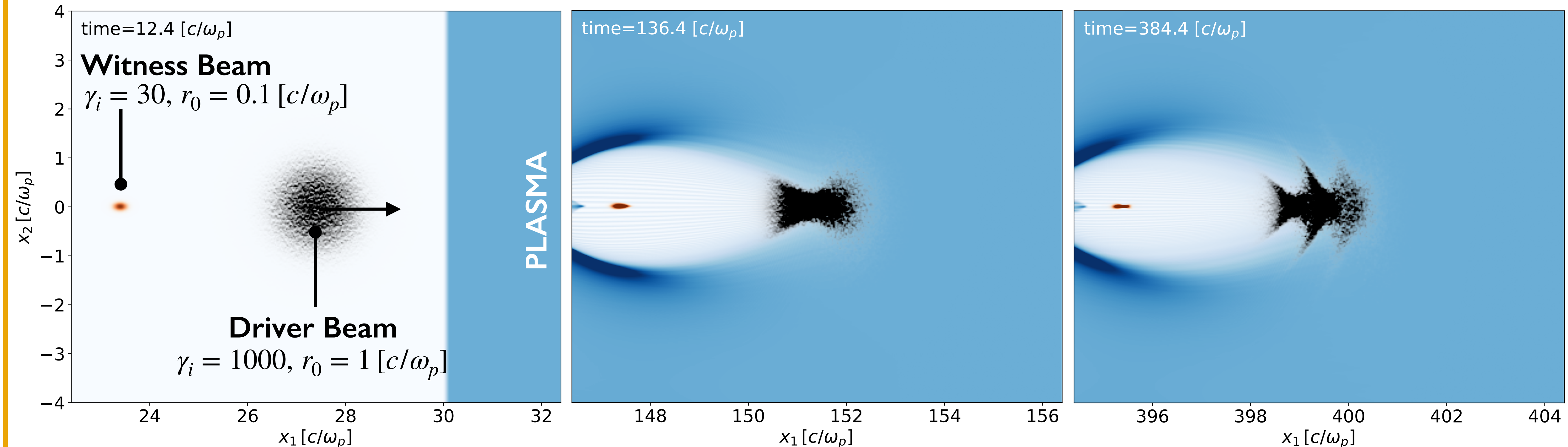
TÉCNICO LISBOA

Plasma Wakefield Acceleration

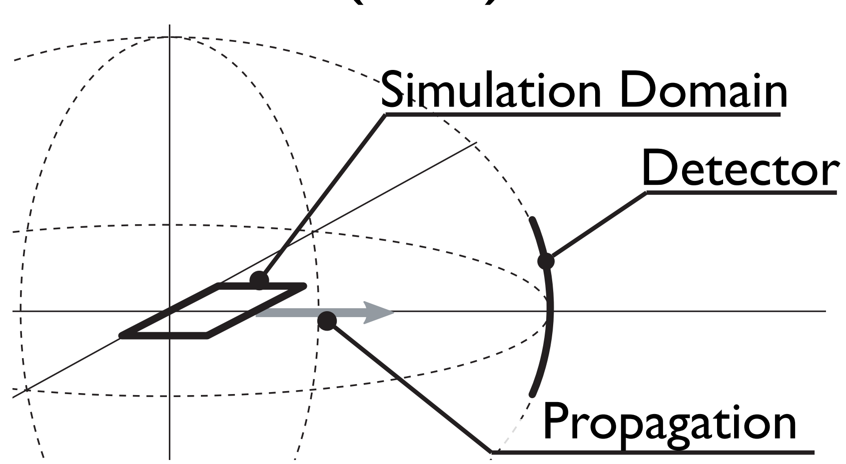
RaDiO simulations of real scenarios

Radiation emitted by the witness beam

2D simulation @ ISTcluster



Spherical detector (slice)



Aperture: 0.05 rad

Radius: $10^5\ c/\omega_p$

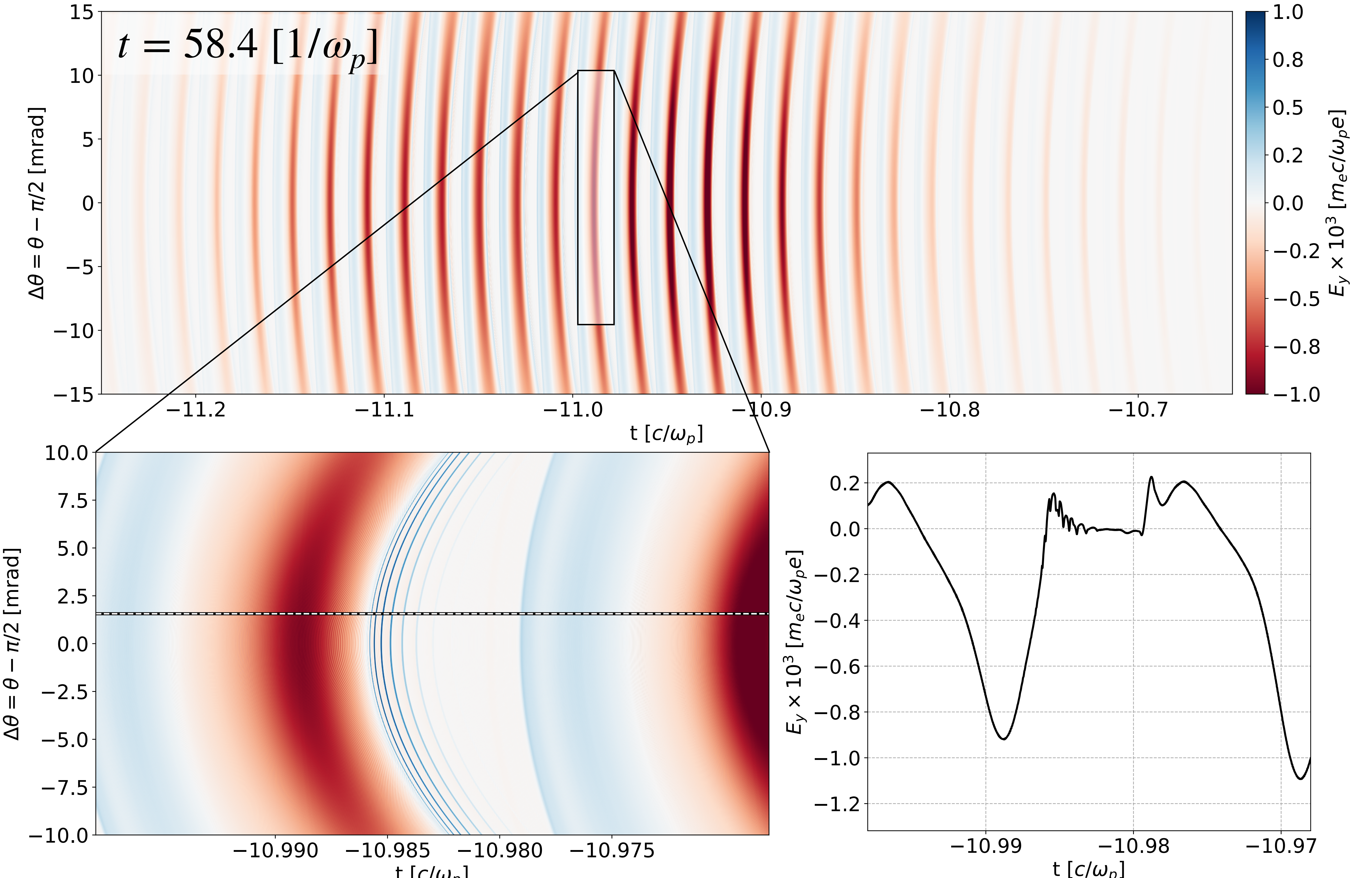
Spatial cells: 1024

Temporal cells: 130672

Radiative Particles: 800000

Spatiotemporal structure of the full beam

Radiation emitted by all the particles in the witness beam (At the beginning)



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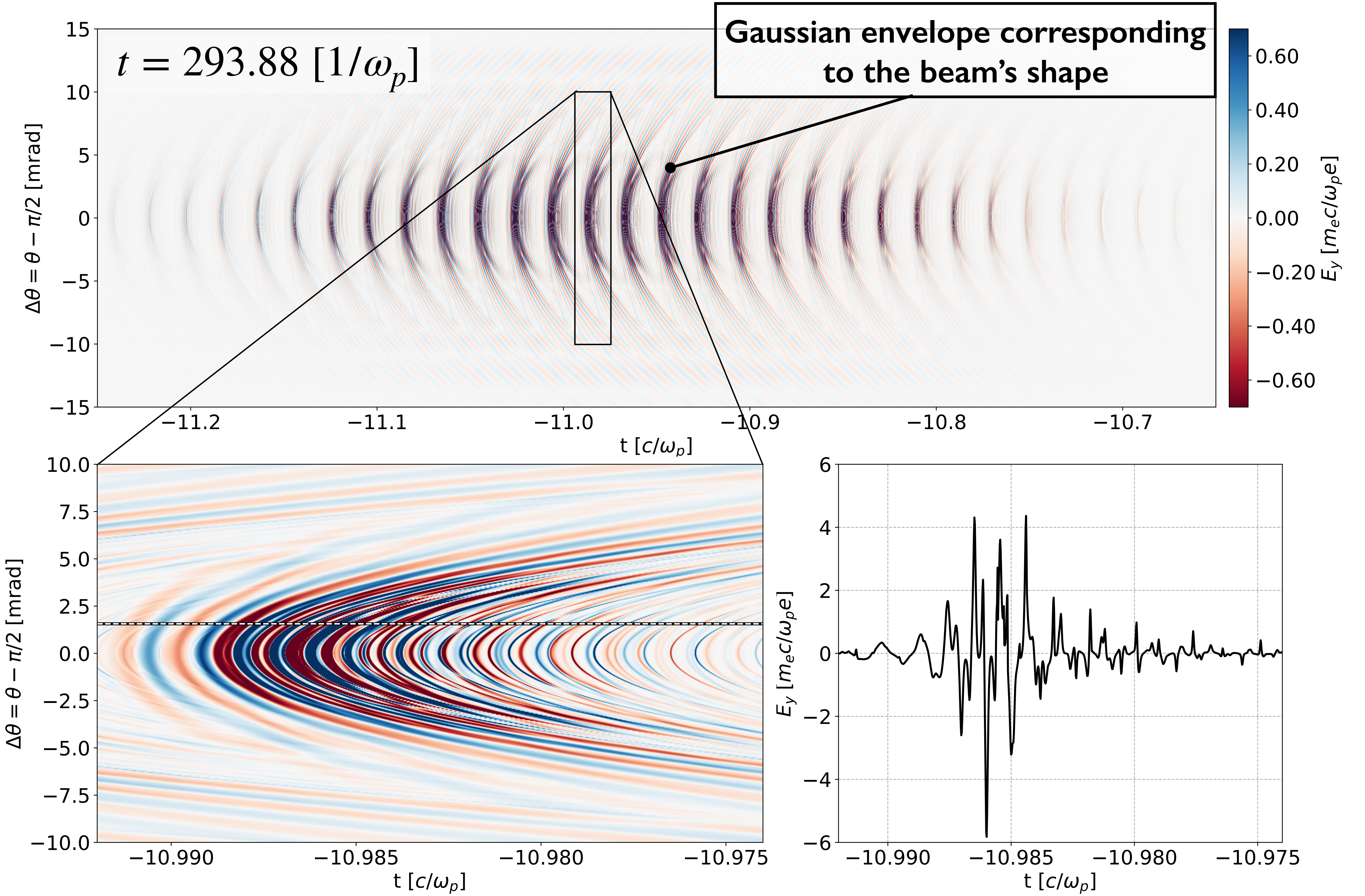
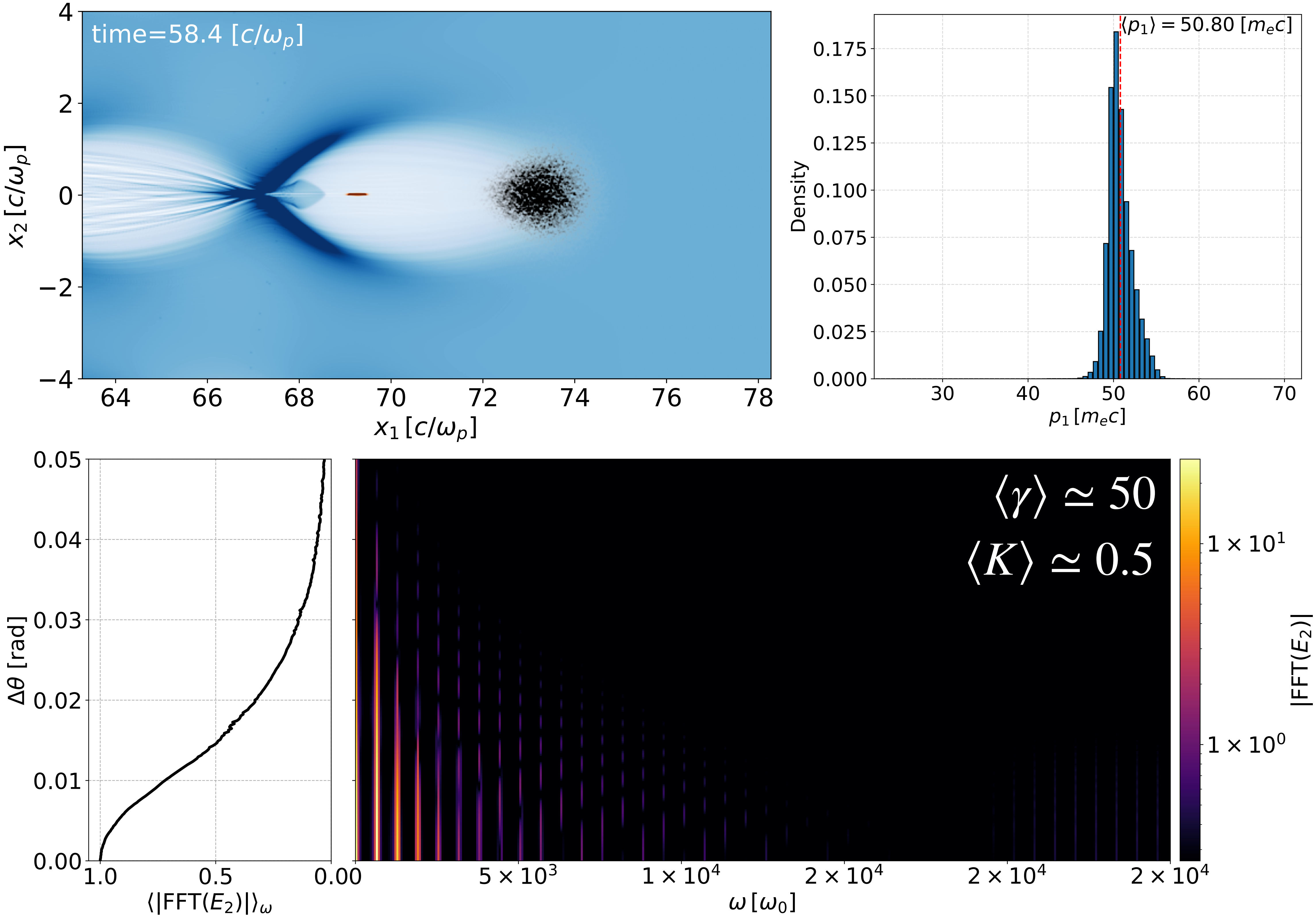


What about the radiation spectrum?

The frequency domain is only one FFT away



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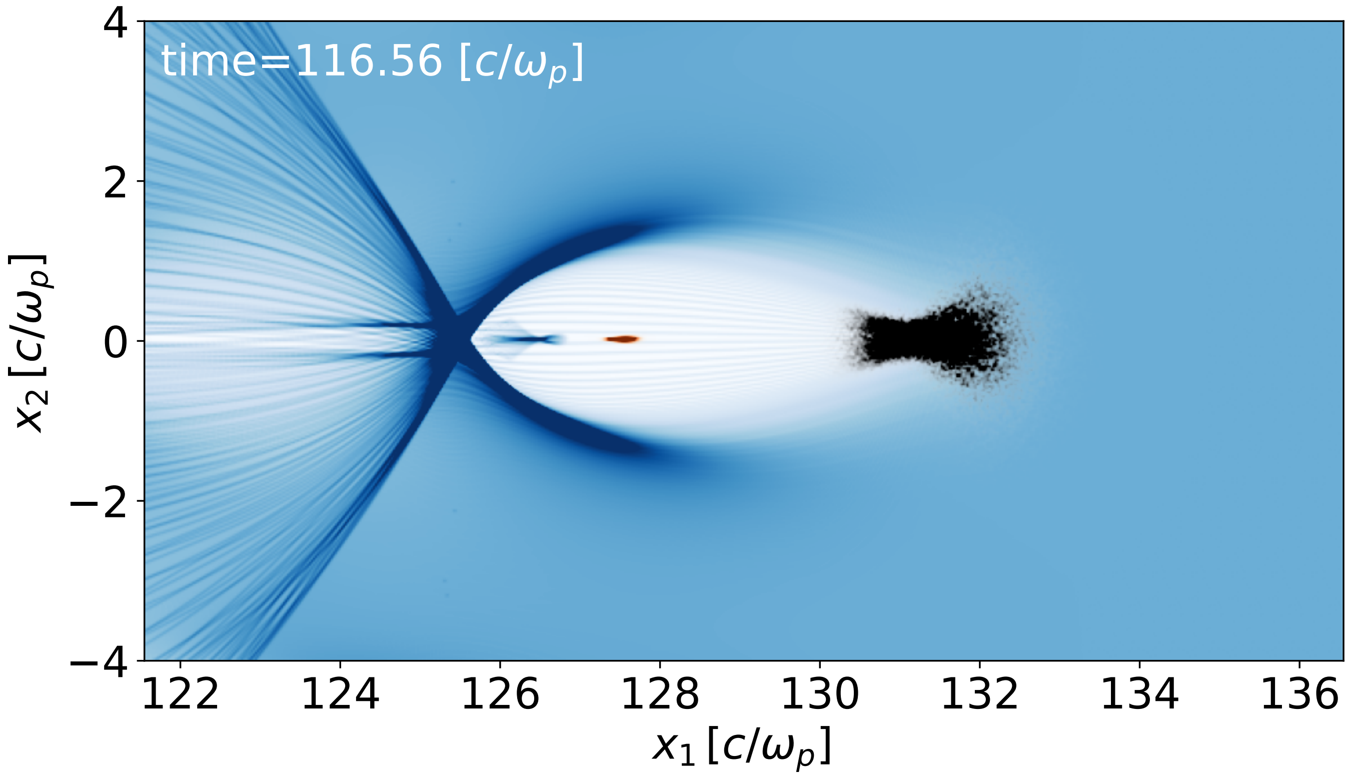

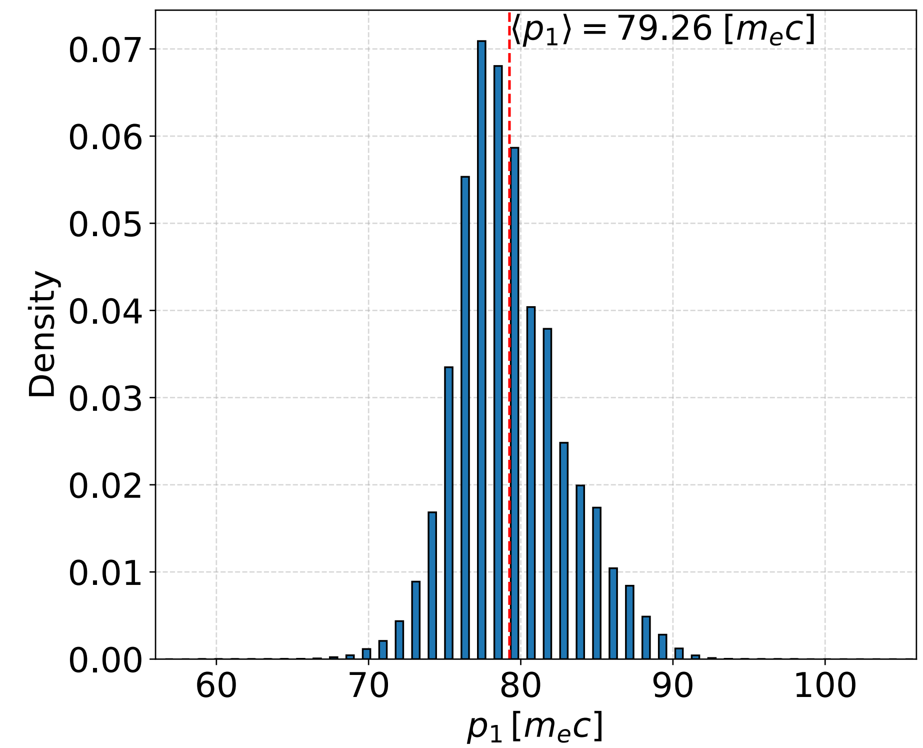

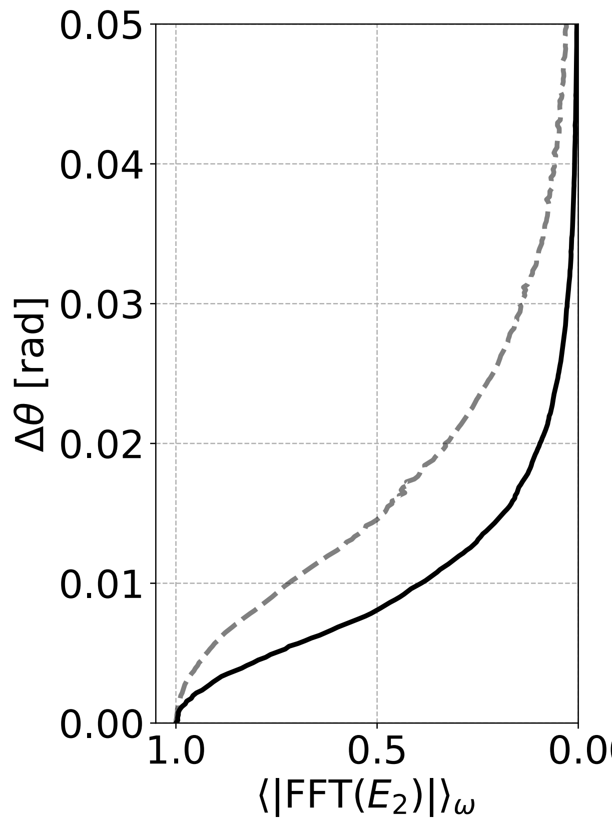

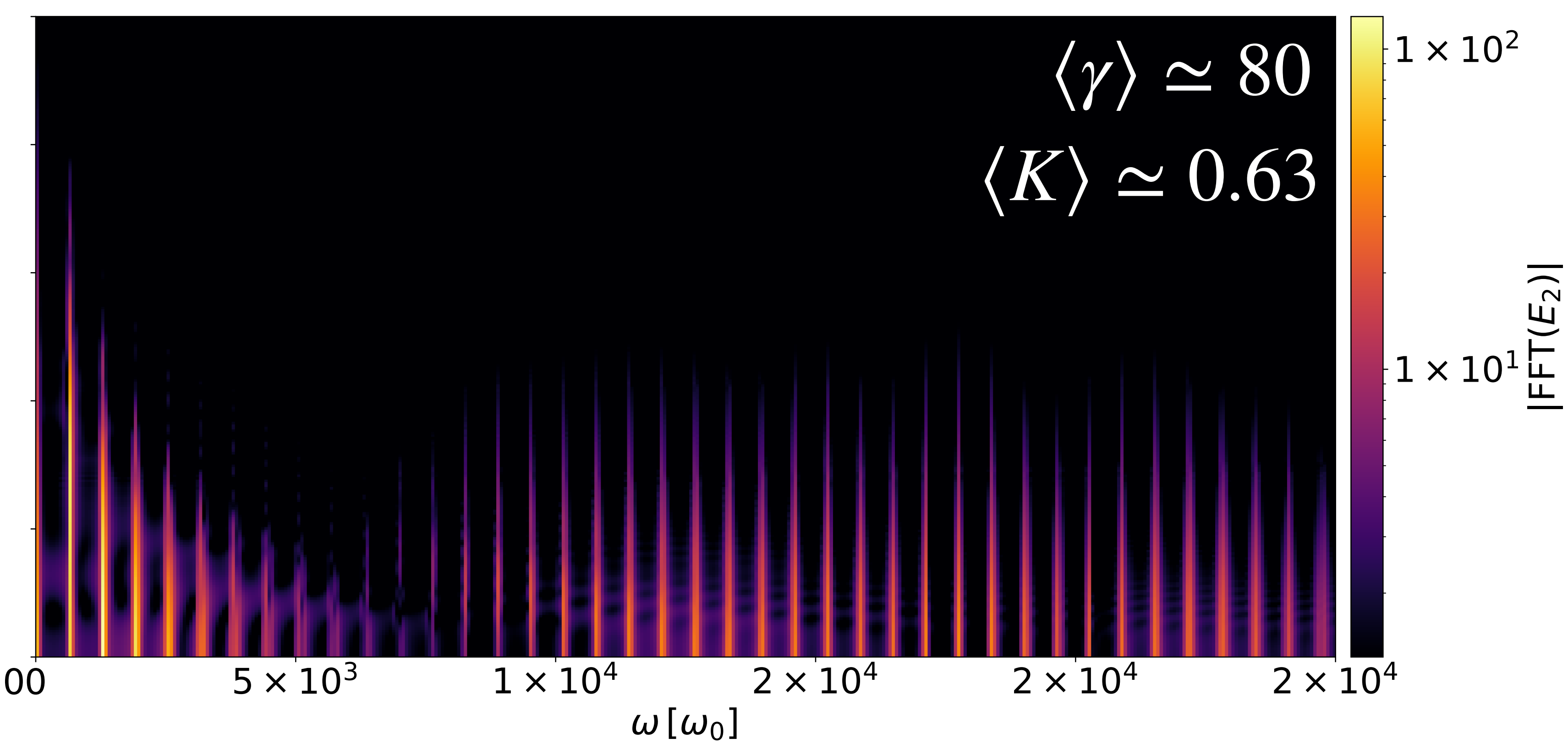

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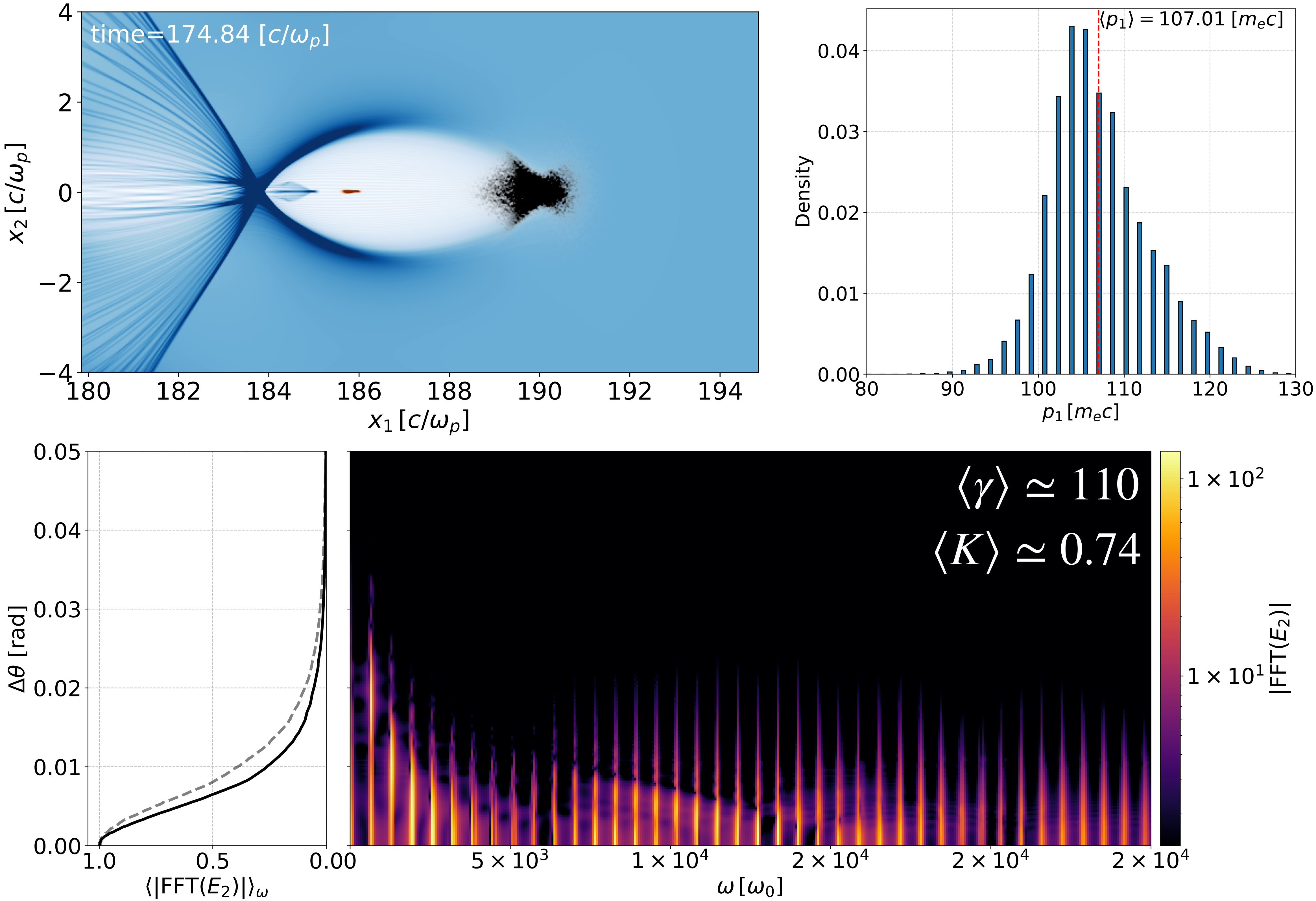

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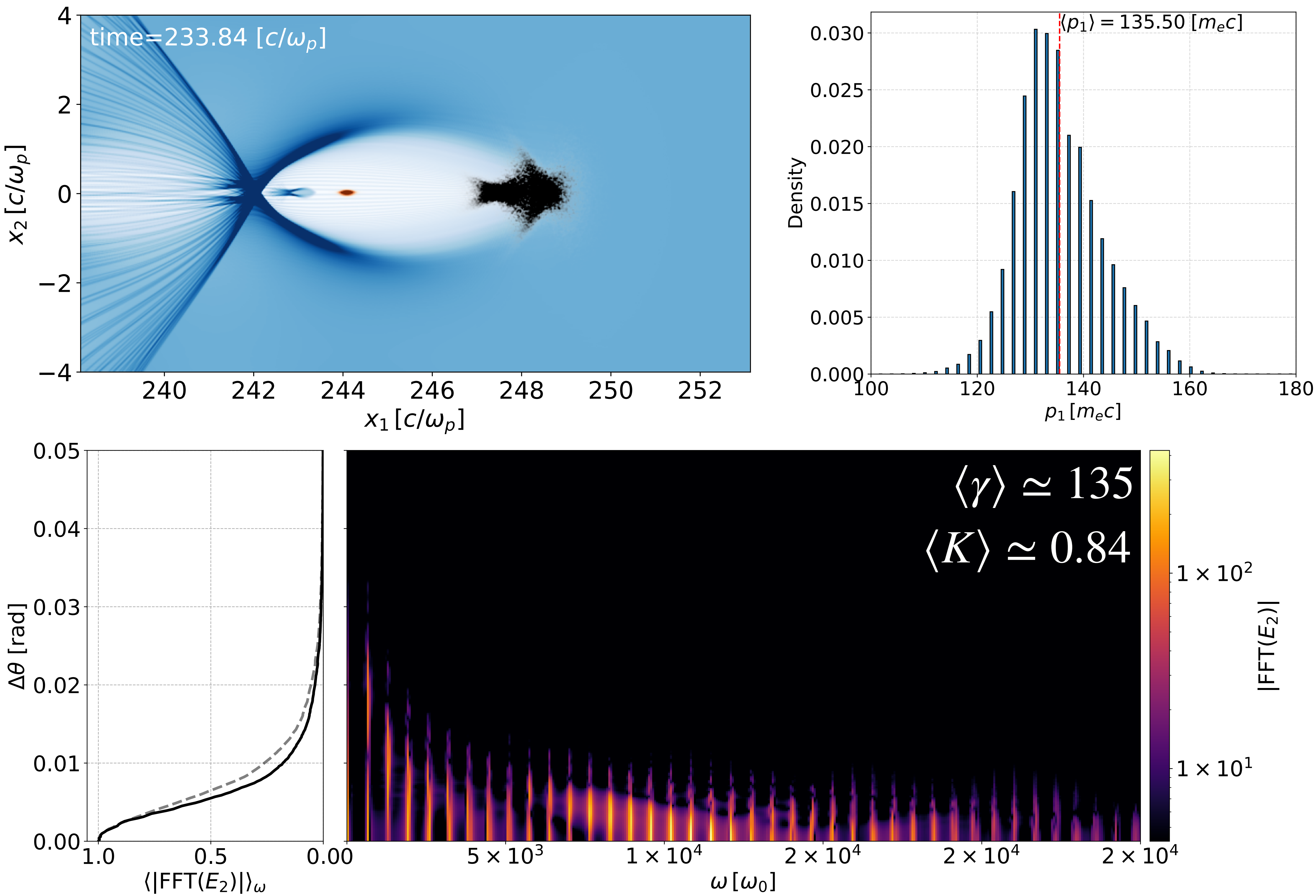

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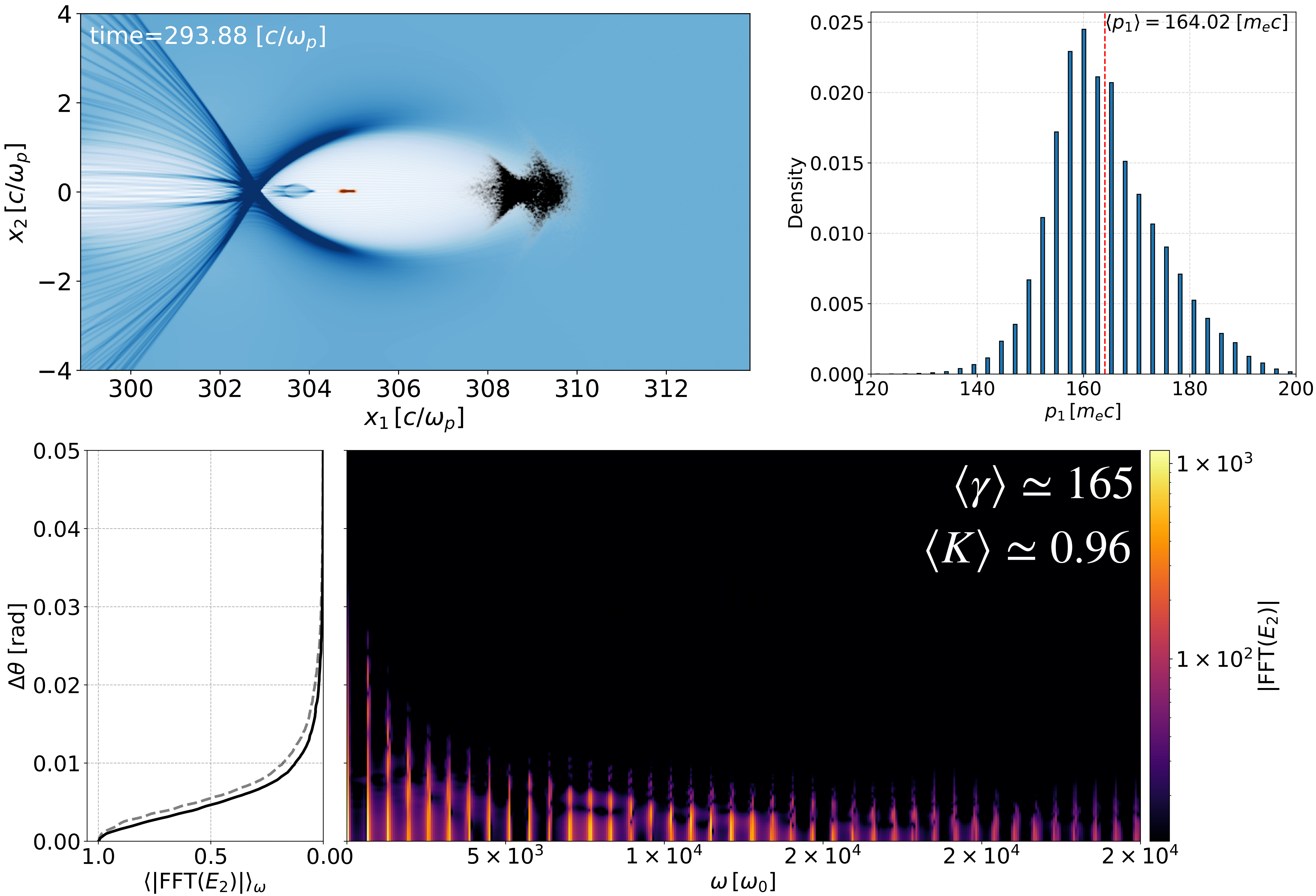

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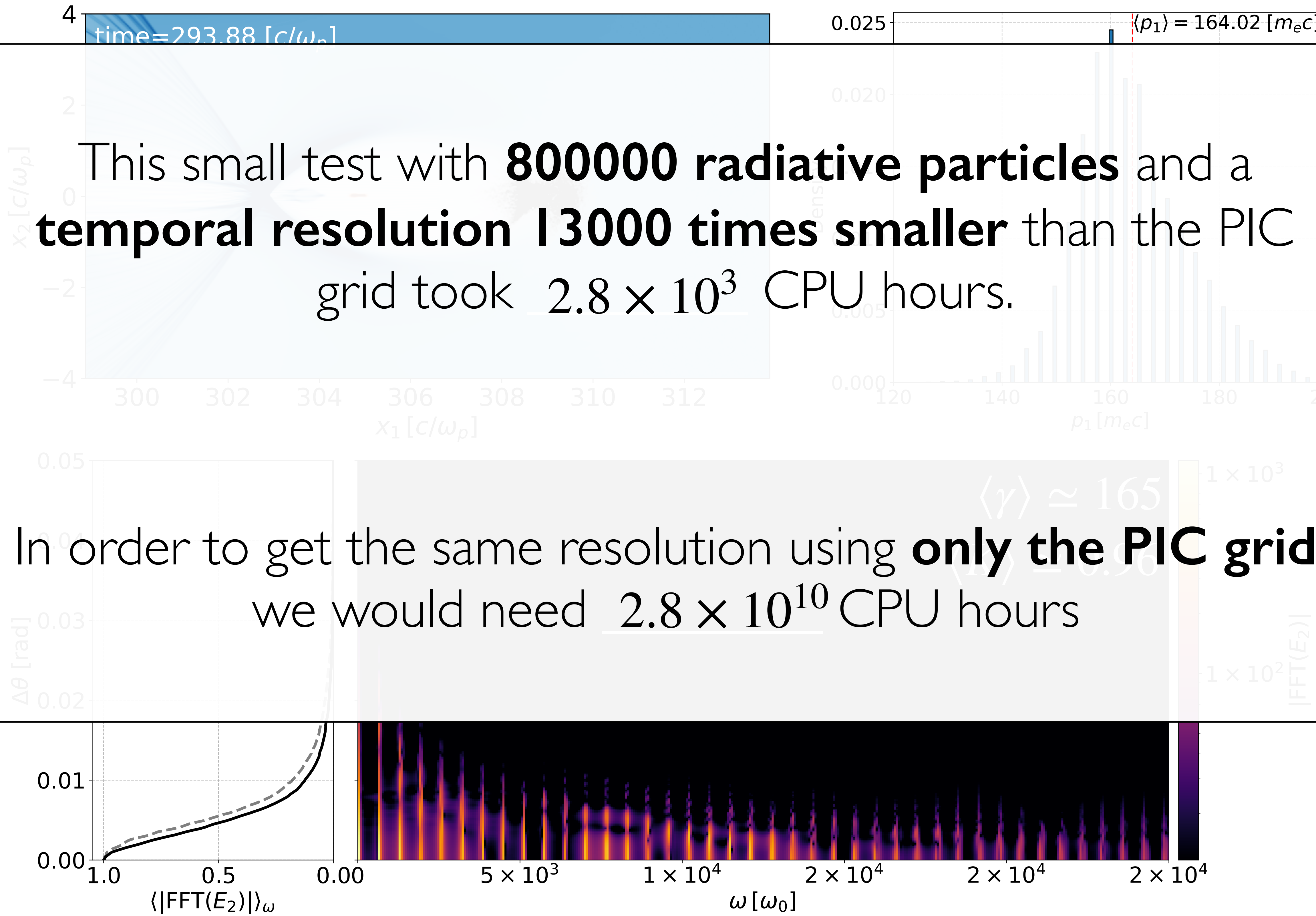

This small test with **800000 radiative particles** and a **temporal resolution 13000 times smaller** than the PIC grid took 2.8×10^3 CPU hours.

In order to get the same resolution using **only the PIC grid** we would need 2.8×10^{10} CPU hours

Contents

TÉCNICO LISBOA

Conclusions & Future Work

TÉCNICO LISBOA

RaDiO is already available

Included in the OSIRIS code.

A detailed guide is also provided

Reliable Results

Benchmarked against theoretical predictions and well-established codes;

Built-in coherence effects

A quick look at the unexplored

Spatiotemporal simulations of the radiation emitted by a full witness beam in PWFA;

Possibly leading to new diagnostic methods;

There are always improvements to be made

New features, such as alternative deposition schemes, or particle selection schemes.

There are a lot of scenarios where radiation may play a major role.