Radiation Diagnostic for OSIRIS: Applications in coherent betatron emission

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FCT Fundação para a Ciência e a Tecnologia

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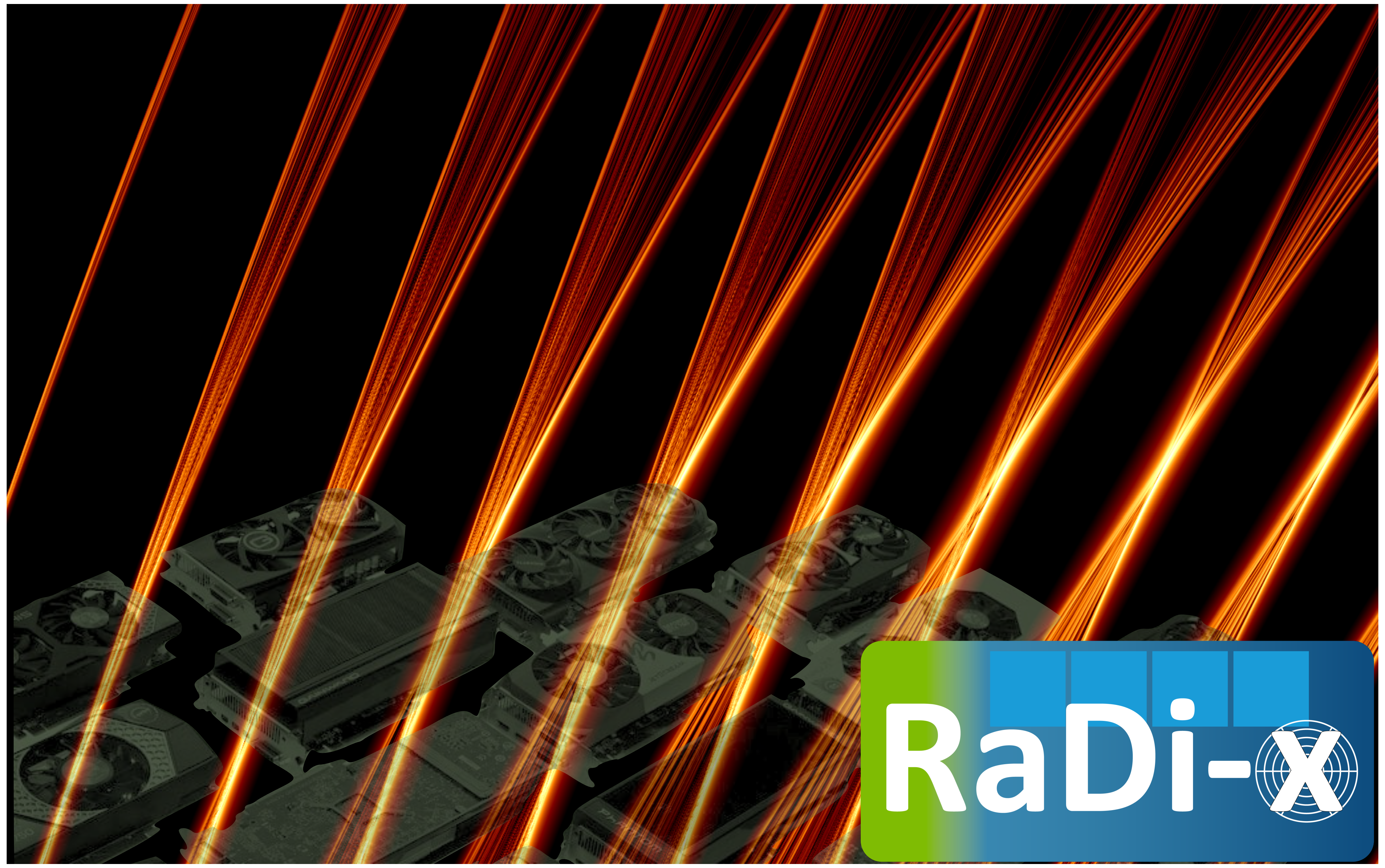
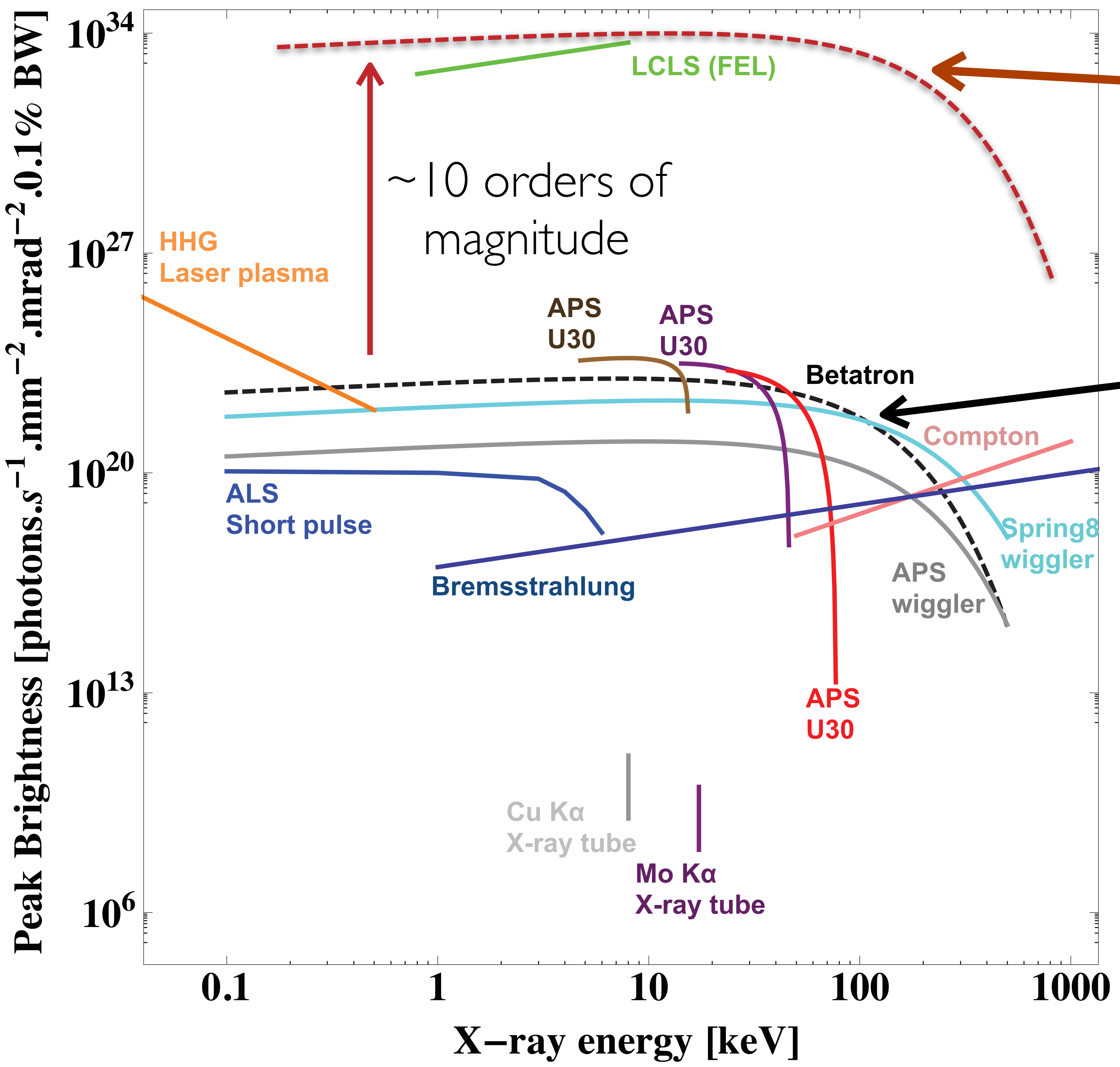


Accelerated with NVIDIA

Temporal coherence in plasma-based light sources

F. Albert et al., PPCF **58** 103001 (2016)

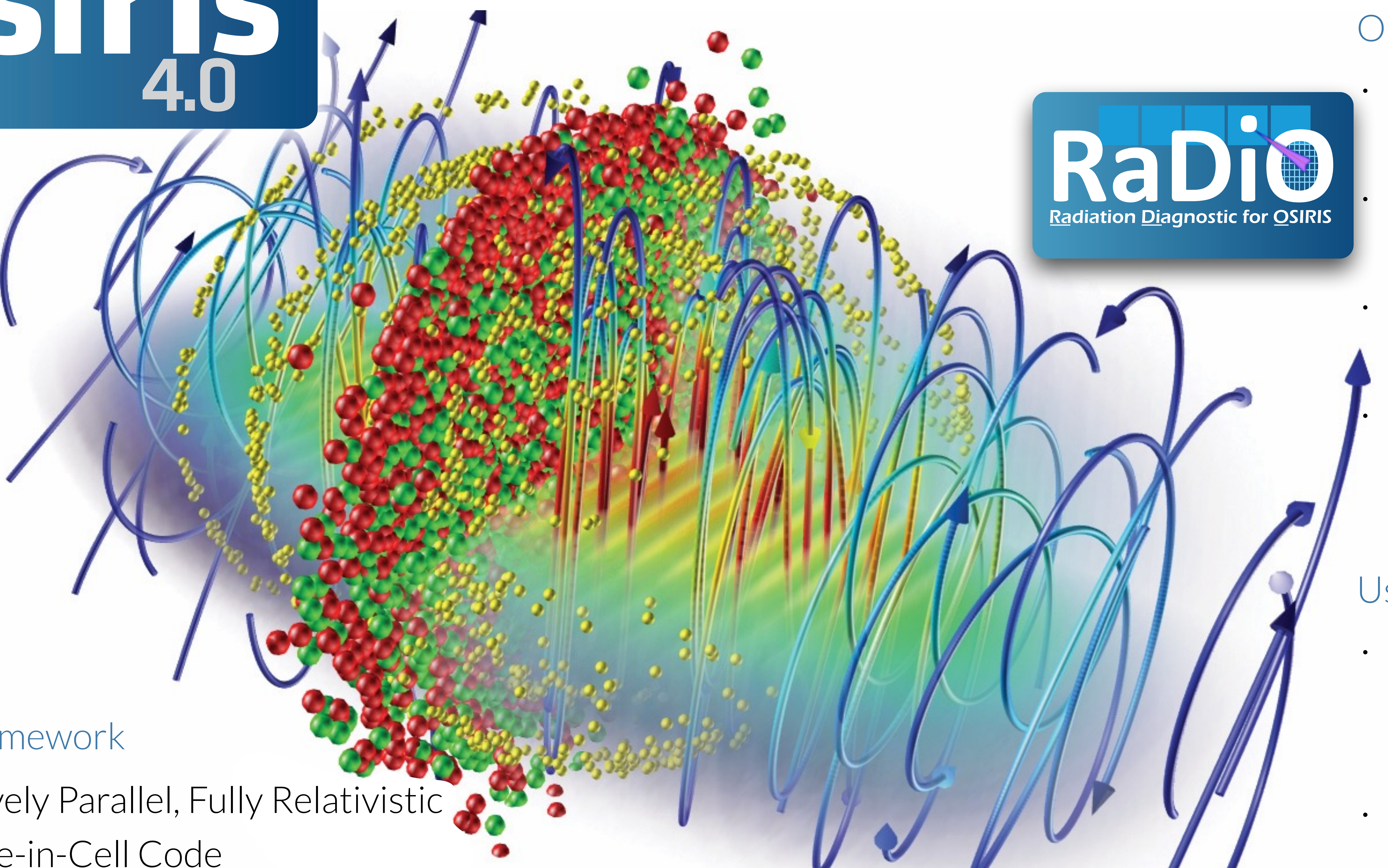


Temporally **coherent** Betatron

Temporally incoherent Betatron

OSIRIS 4.0

Open source version coming soon



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 physics/simulation models

RaDiO
Radiation Diagnostic for OSIRIS

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

RaDiO's Algorithm

PIC Codes and Líenard-Wiechert Fields

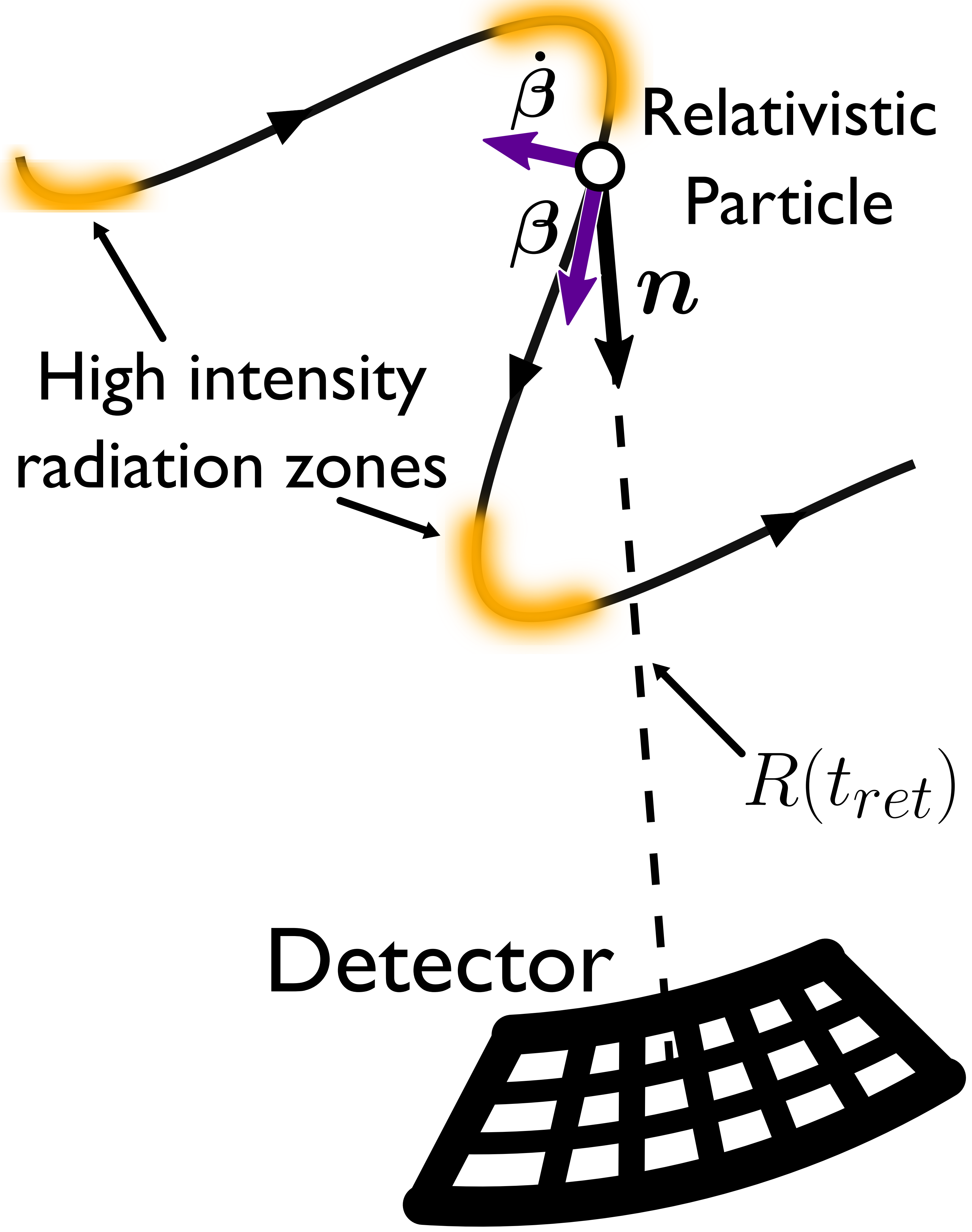
Particles exist in a **grid** which intermediates **EM interactions.**

The PIC grid resolves the particle's motion, **but** relativistic particles ($\gamma > 100$) **emit short wavelengths**

Resolving such wavelengths in the PIC grid would require $\sim \gamma^2$ **more cells**

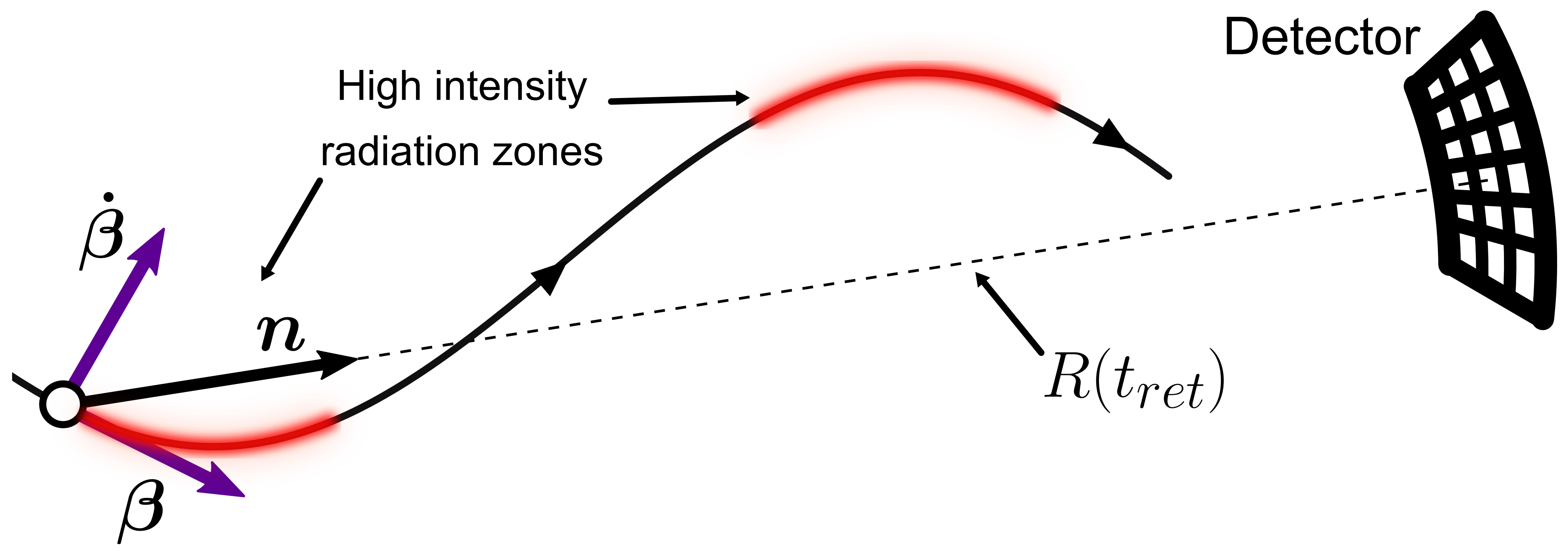
The Liénard-Wiechert Potentials **allow us** to capture radiation **without increasing** the PIC resolution

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



RaDiO's Algorithm

Liénard-Wiechert Expression



Only spatial cells

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

Increasing the temporal resolution does not affect the computational load

Interpolate Fields
$(\mathbf{E},\mathbf{B})_j^{(n)} \rightarrow (\mathbf{E},\mathbf{B})_i^{(n)}$

Advance Particles
$(\mathbf{E},\mathbf{B})_i^{(n-1)} \rightarrow x_i^{(n)}$

Radiation Algorithm

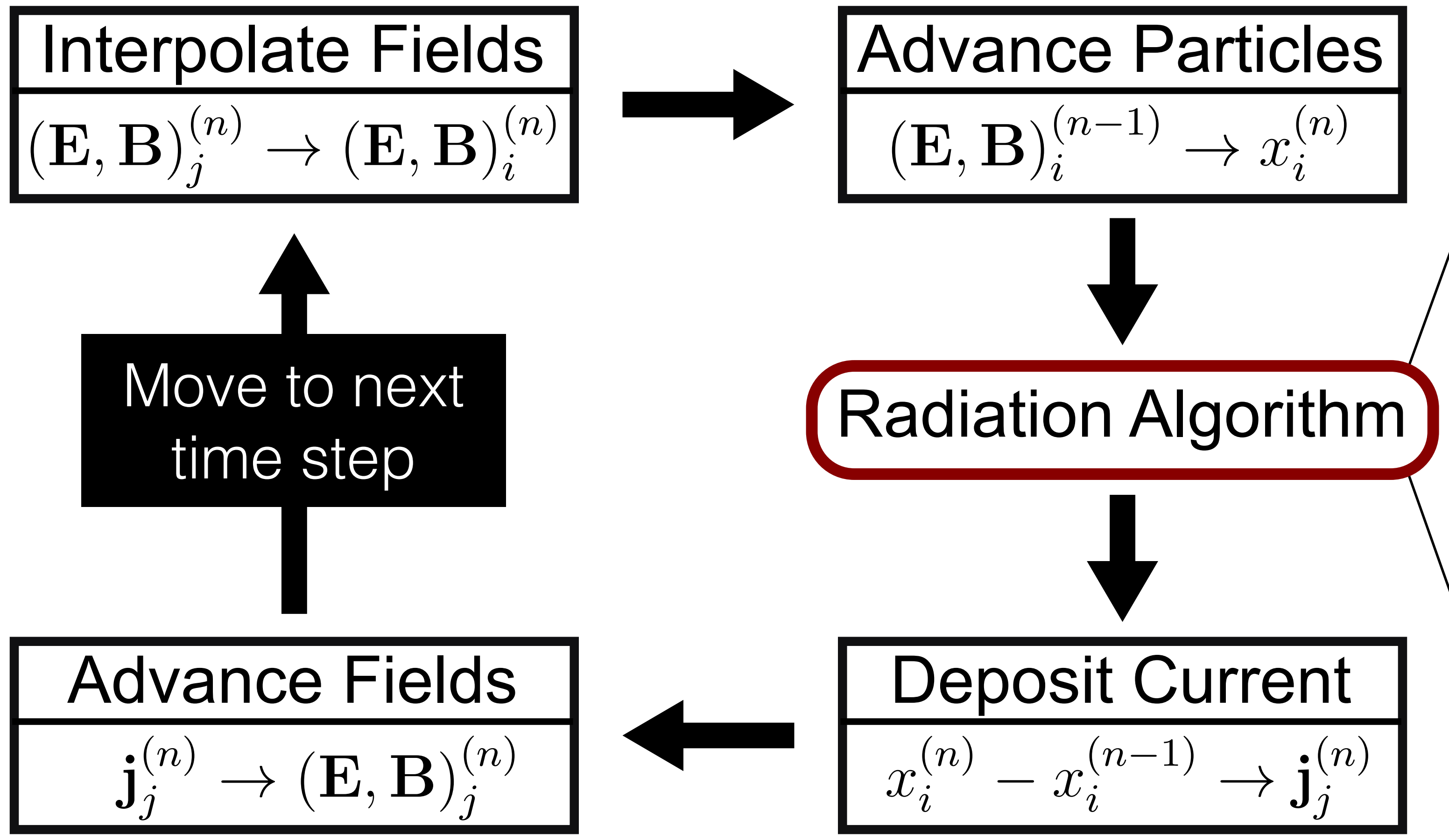
Deposit Current
$x_i^{(n)} - x_i^{(n-1)} \rightarrow \mathbf{j}_j^{(n)}$

Advance Fields
$\mathbf{j}_j^{(n)} \rightarrow (\mathbf{E},\mathbf{B})_j^{(n)}$

Move to next time step

procedure RadiationCalculator
  for all *particle* in simulation **do**
    $\beta \leftarrow \text{velocity}(particle) = \mathbf{p}/\sqrt{|\mathbf{p}|^2+1}$
    $\dot{\beta} \leftarrow \text{acceleration}(particle) = (\beta - \beta_{prev})/dt$
    for all *cell* in detector **do**
      $R \leftarrow \text{distance}(particle, cell) = |\mathbf{x_{part}} - \mathbf{x_{cell}}|$
      $\mathbf{n} \leftarrow \text{direction}(particle, cell) = (\mathbf{x_{part}} - \mathbf{x_{cell}})/R$
      $t_{det} \leftarrow R/c + t$
      $t_{det,prev} \leftarrow R_{prev}/c + t - dt$
      if $t_{\text{det}}min < t_{\text{det}} < t_{\text{det}}max$ **then**
        $\text{RadiationInterpolator}(\mathbf{E}(\mathbf{n}, \beta, \dot{\beta}), t_{\text{det}}, t_{\text{det,prev}})$

RaDiO's Algorithm for CUDA



procedure RADIATIONCALCULATOR
  for all *particle* **in** simulation **do**
    $\beta \leftarrow \text{velocity}(particle) = \mathbf{p}/\sqrt{|\mathbf{p}|^2+1}$
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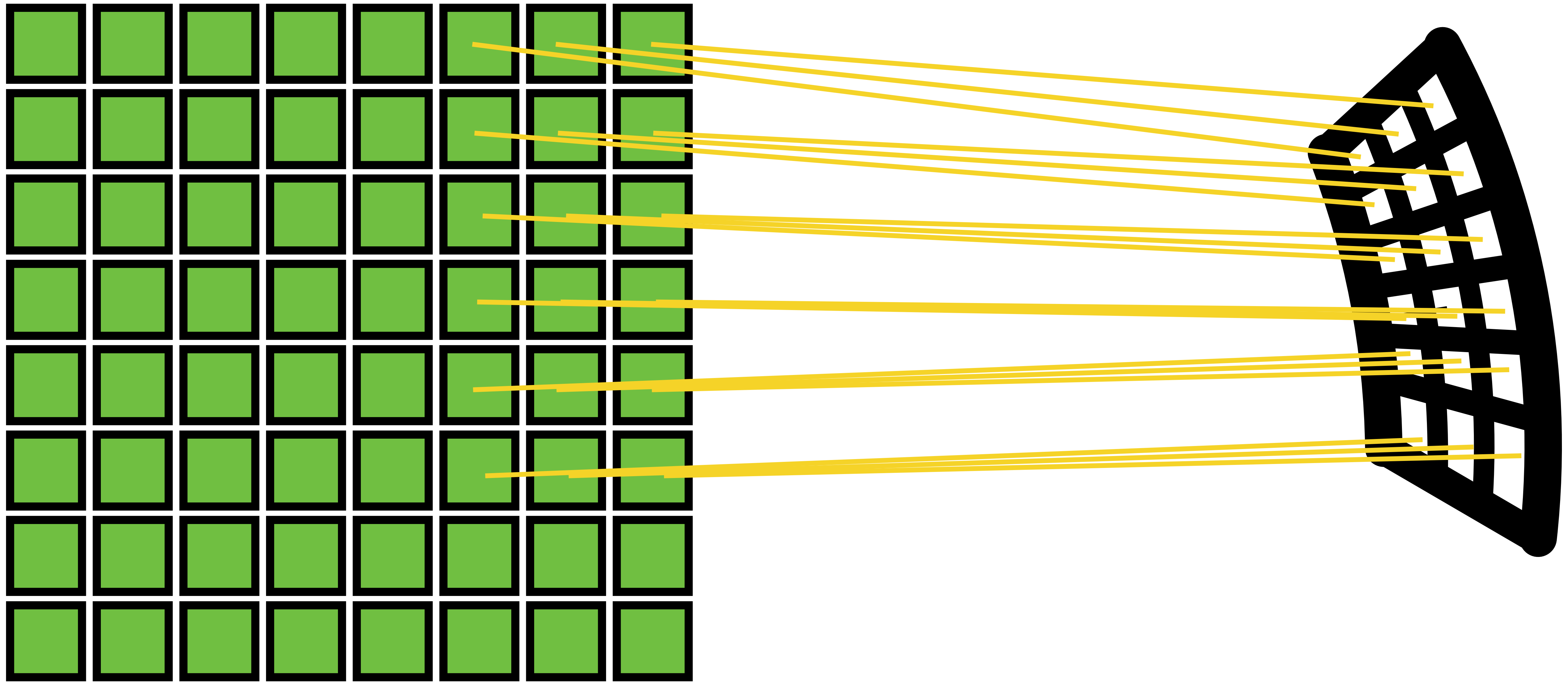
      if $t_{\text{det}}min < t_{\text{det}} < t_{\text{det}}max$ **then**
        RADIATIONINTERPOLATOR$(\mathbf{E}(\mathbf{n},\beta,\dot{\beta}), t_{\text{det}}, t_{\text{det,prev}})$

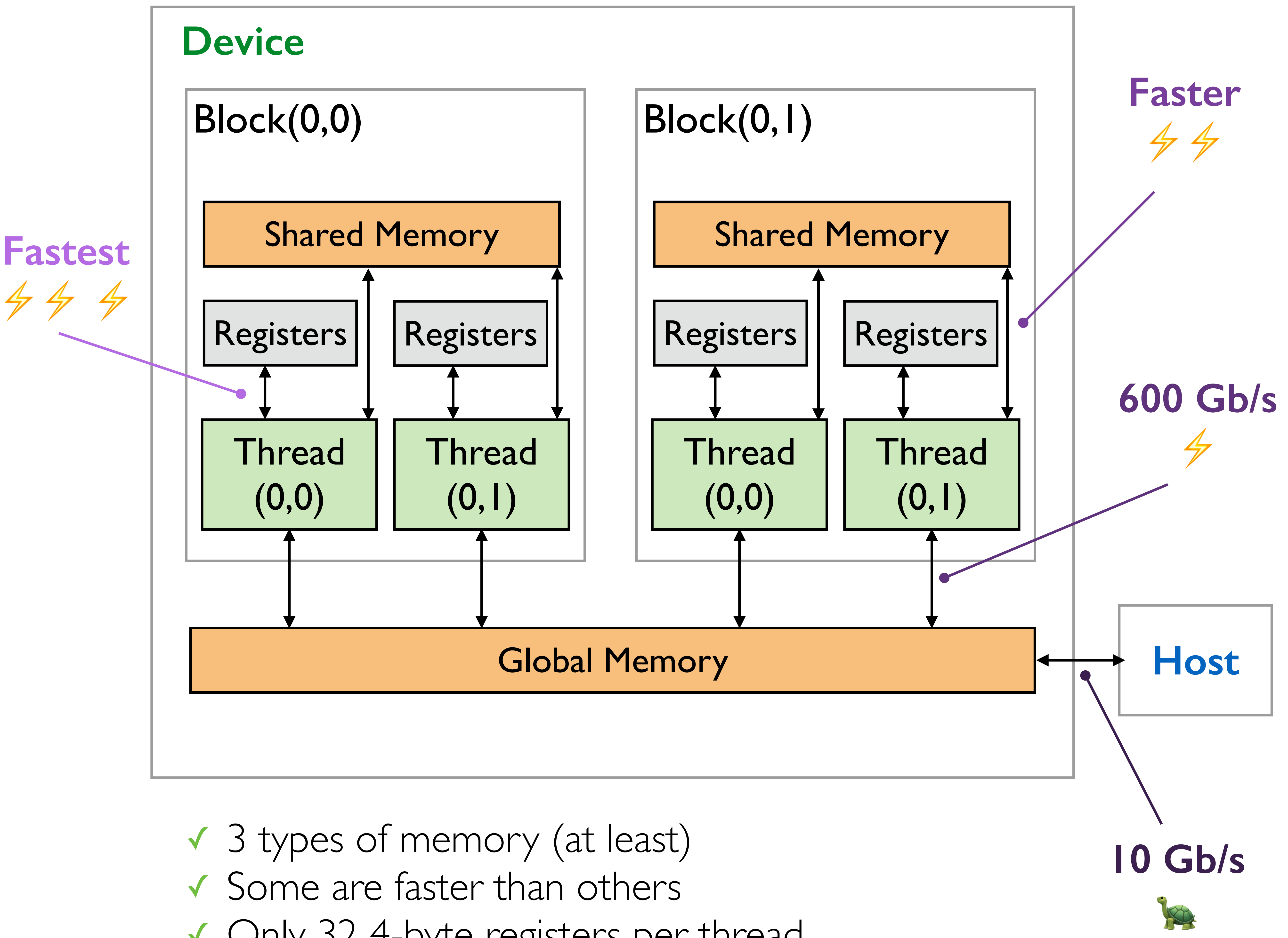
GPU board



- ✓ Assign **each CUDA core** (thread) to a **cell** in the detector;
- ✓ Sometimes (most times) there are **more cells than cores**;
- ✓ In this case we either do a **smaller loop for each core** or launch **more threads than cores**;

Kernel designs

CUDA Memory Hierarchy



- ✓ 3 types of memory (at least)
- ✓ Some are faster than others
- ✓ Only 32 4-byte registers per thread

Algorithm 4 Radiation calculation CUDA Shared Memory

for all *particle* **in** track **do**
  procedure RADIATIONCALCULATOR KERNEL (TRACK)
    for all chunk **in** track **do**
      Shared memory ← chunk of track
      for all timestep **in** chunk **do**
        $R \leftarrow \text{distance}(particle, cell) = |\mathbf{x_{part}} - \mathbf{x_{cell}}|$
        $\mathbf{n} \leftarrow \text{direction}(particle, cell) = (\mathbf{x_{part}} - \mathbf{x_{cell}})/R$
        $t_{det} \leftarrow R/c + t$
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        if $t_{\text{det}}min < t_{\text{det}} < t_{\text{det}}max$ **then**
          $\text{RADIATIONINTERPOLATOR}(\mathbf{E}(\mathbf{n}, \beta, \dot{\beta}), t_{\text{det}}, t_{\text{det,prev}})$

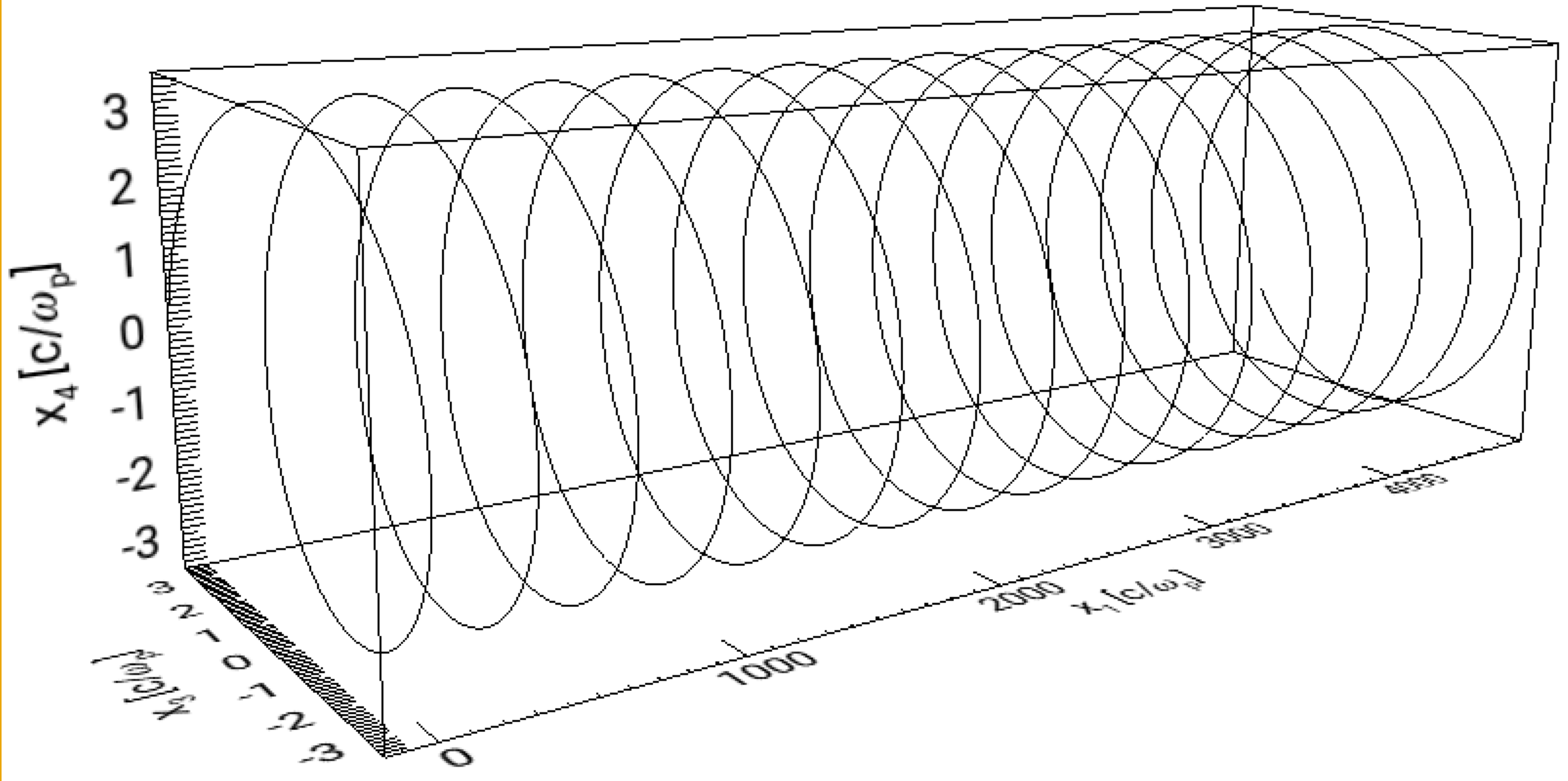
```
: Compiling entry function '_Z20calc_comp_cuda5_E2E31
: Function properties for _Z20calc_comp_cuda5_E2E312
ack frame, 0 bytes spill stores, 0 bytes spill loads
: Used 40 registers, 11520 bytes smem, 672 bytes cmem
```

Up to 78% Occupancy of the GPU :)

Strong Scaling Analysis

Test Conditions

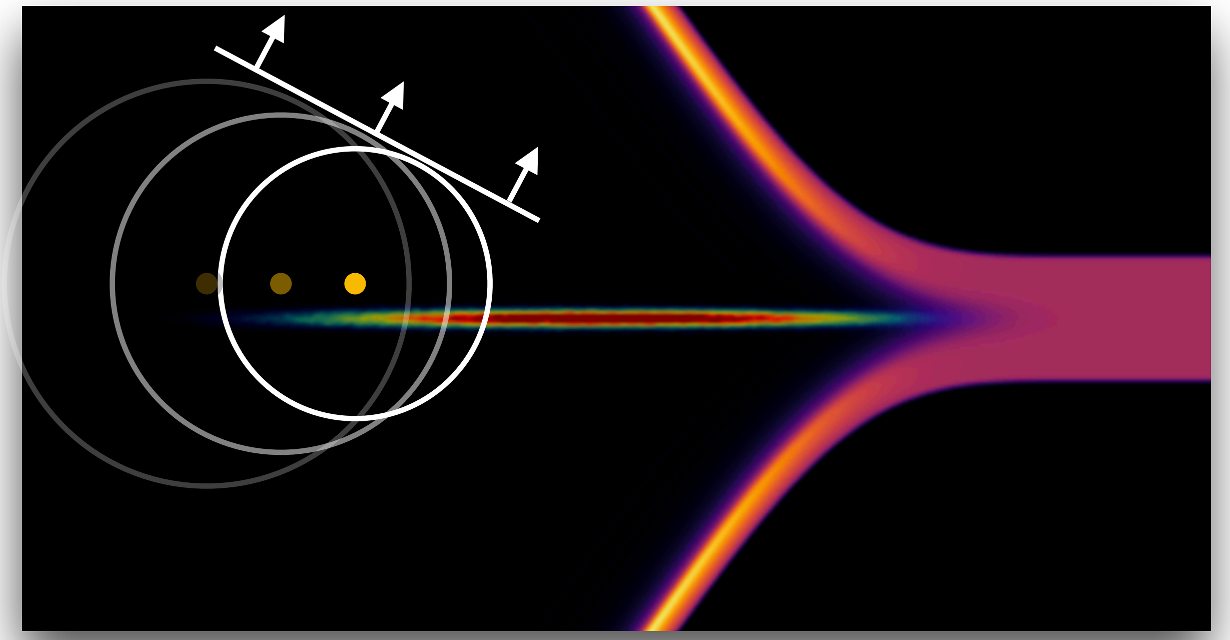
Single Electron track

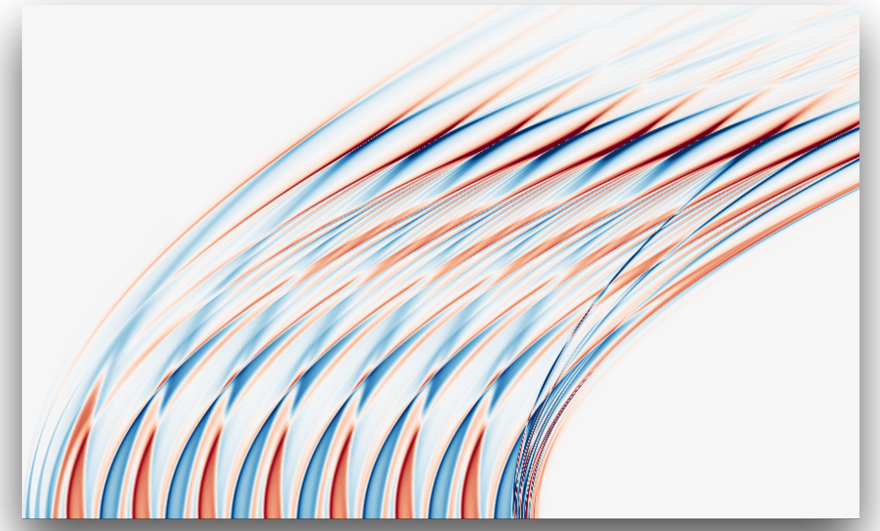


Spherical Detector

Aperture: 0.1 rad
Radius: 10^5 c/ω_p
Time resolution: 0.08 1/ω_p
Nr of Cells: 262144

Contents





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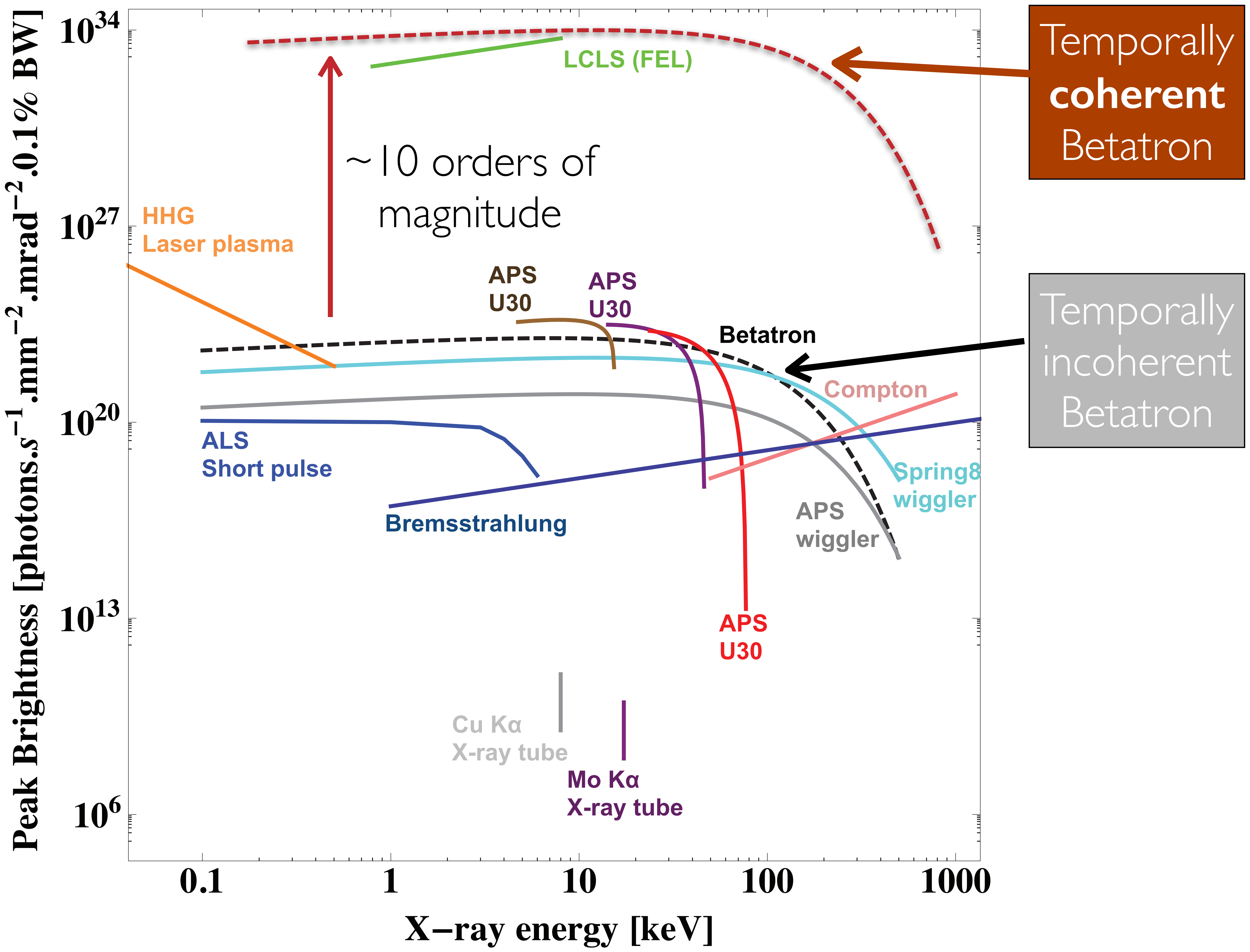
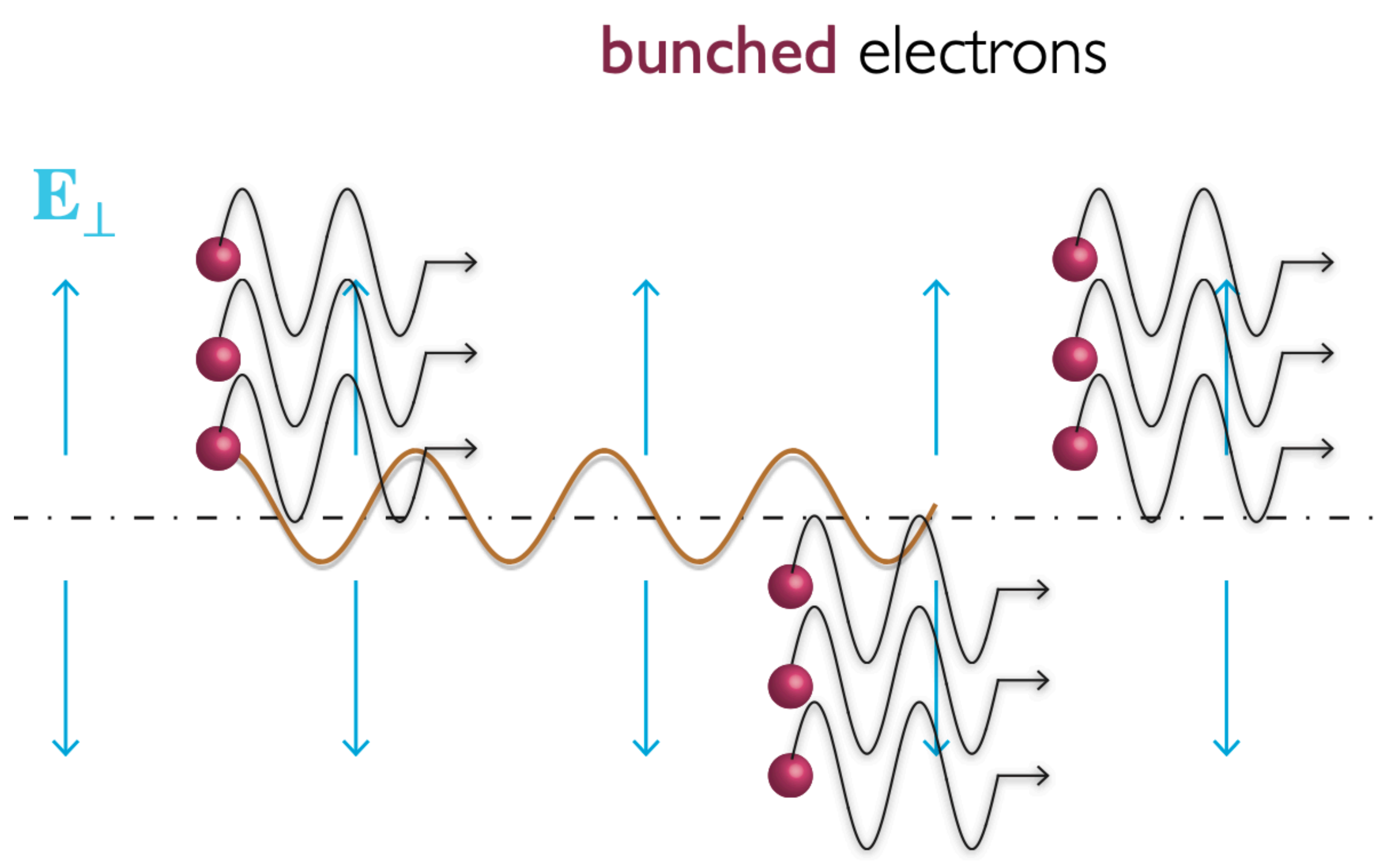


Ion Channel Laser*,**



coherent photon emission $I \propto N^2$

- Avoid **microbunching**
- Best for **broadband emission**
- **Isolated** photon bursts
- **Off-axis** emission $(K \gg 1)$

ength

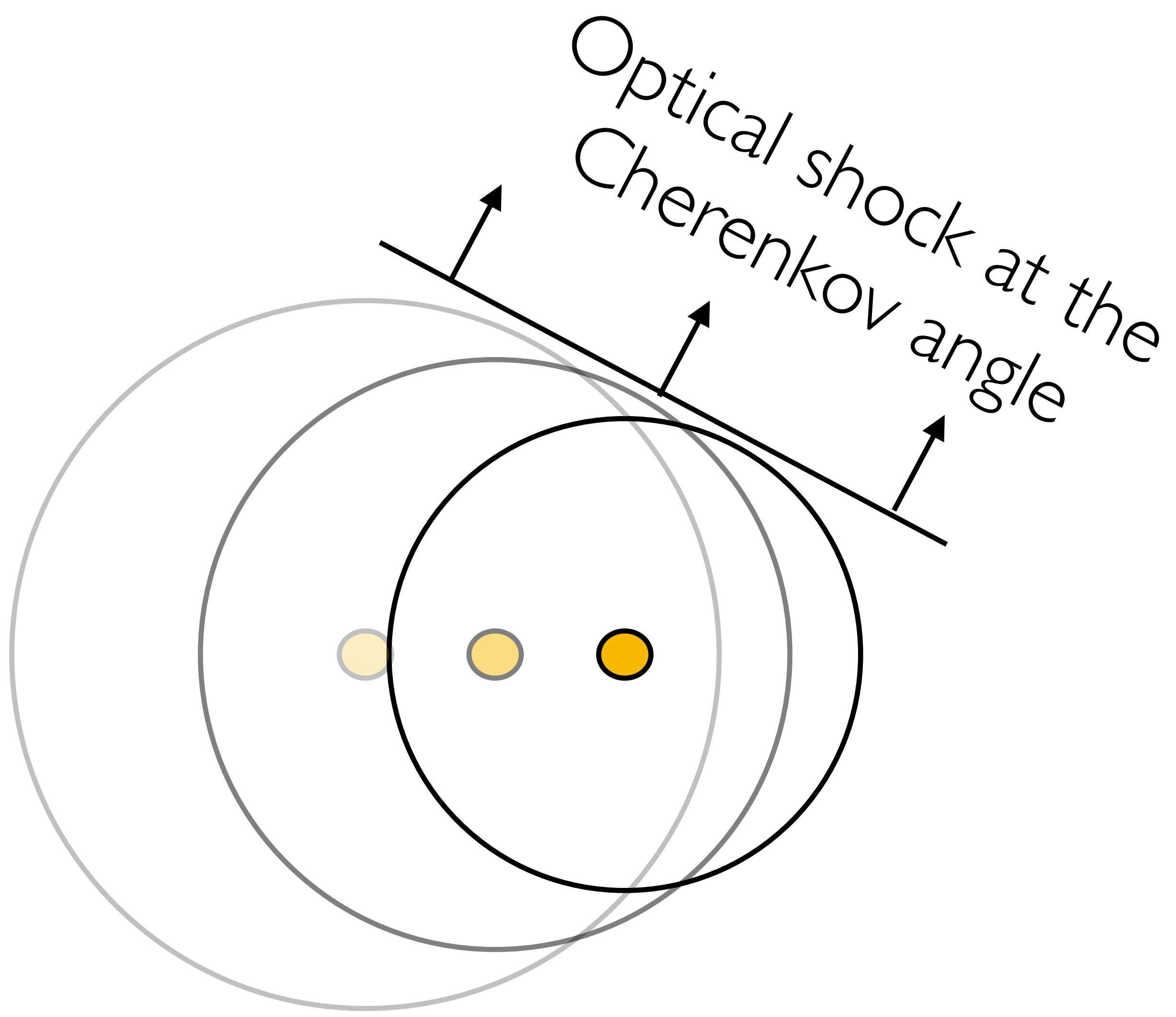
on

* D. Whittum, A. Sessler, J. Dawson PRL 64**,** 2511 (1990).
** X. Davoine *et al.*, JPP 84 905840304 (2018)

Generalized Superradiance*

Generalized superwhat?: Physical picture

This scheme allows for **broadband, single-cycle, off-axis** photon bursts, relying on **optical shocks** of **superluminal sources** of radiation.



This requires $v_p > c$, which is usually impossible :(
But if we use a particle beam…

* J. Vieira, M. Pardal, J.T. Mendonça, R.A. Fonseca, Nature Physics 17, 99–104 (2021).

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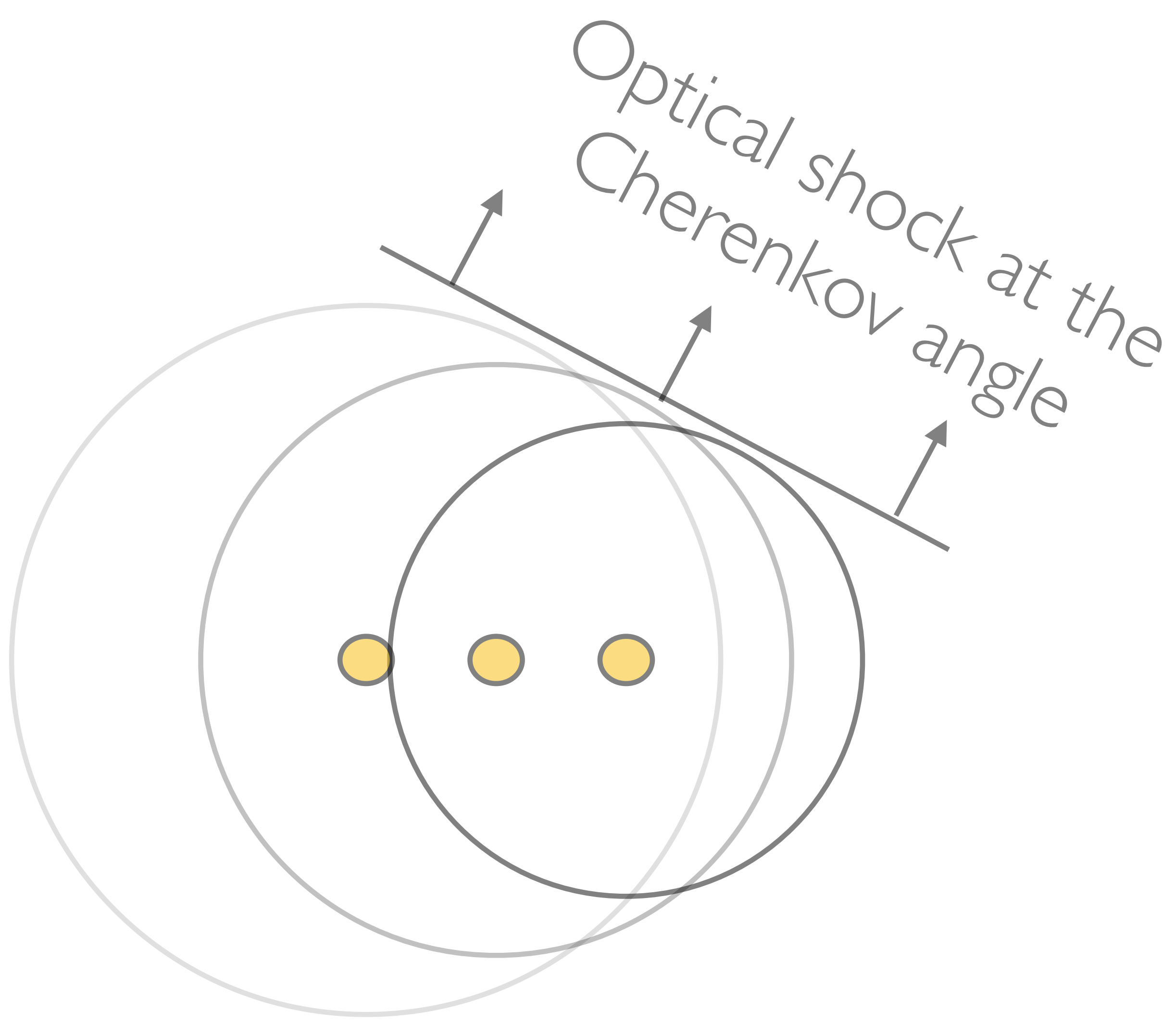

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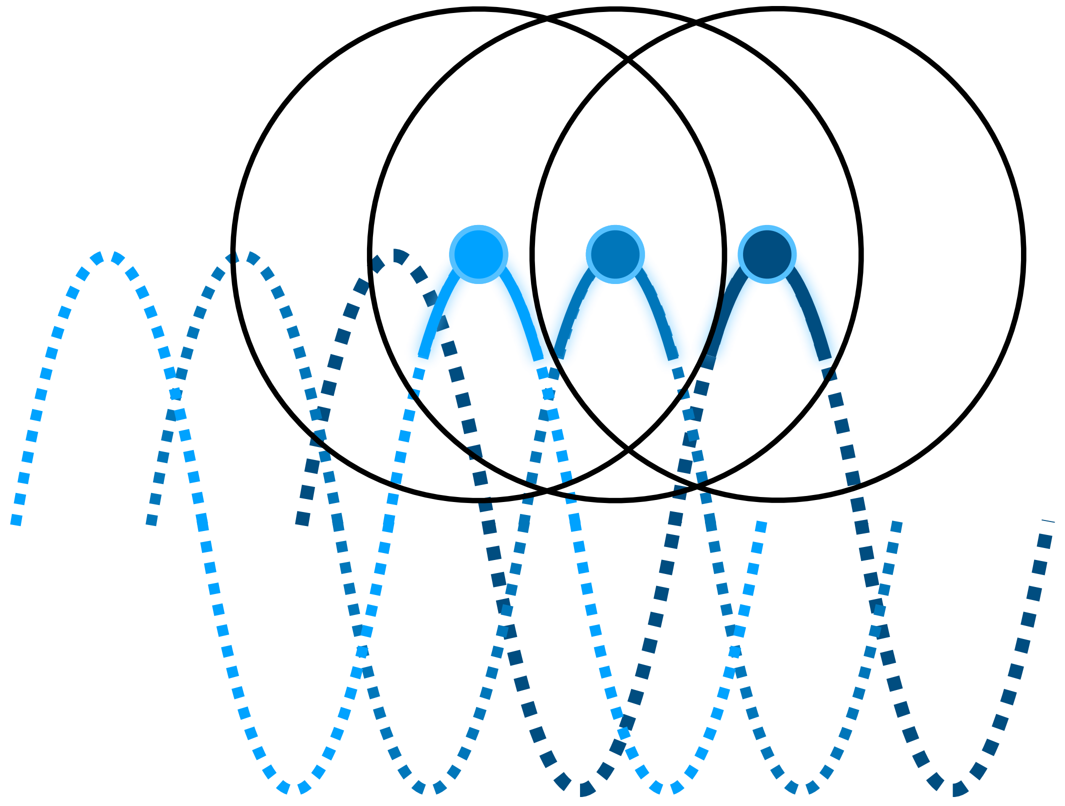
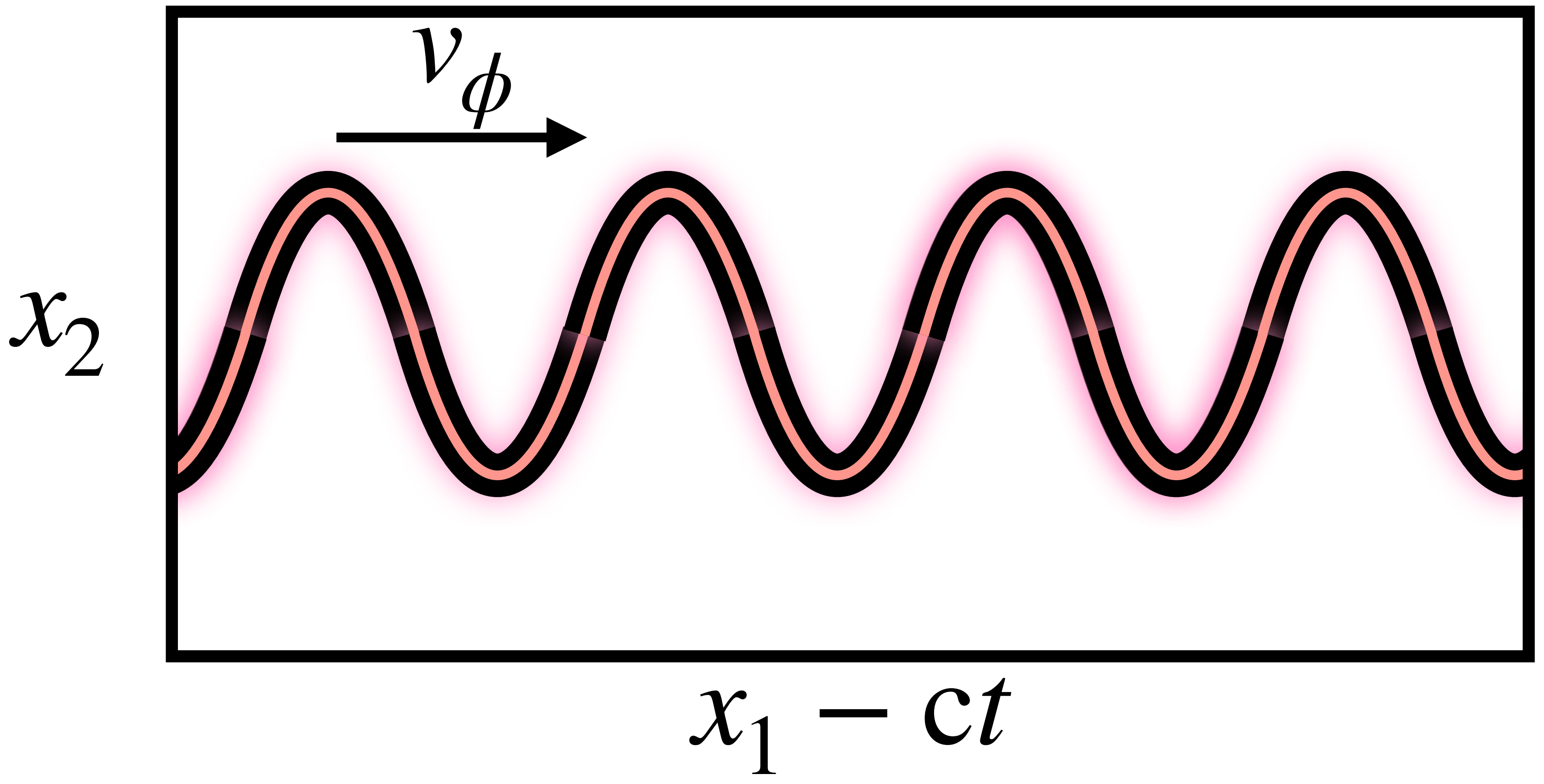


Consecutive particles radiate as a single superluminal particle! :)

Requirement: $v_\varphi > c$

* J. Vieira, M. Pardal, J.T. Mendonça, R.A. Fonseca, Nature Physics 17, 99–104 (2021).

Formalism



Trajectory of each particle

$$x_{1,p}(t, t_{0p}) = v_0(t - t_{0p})$$

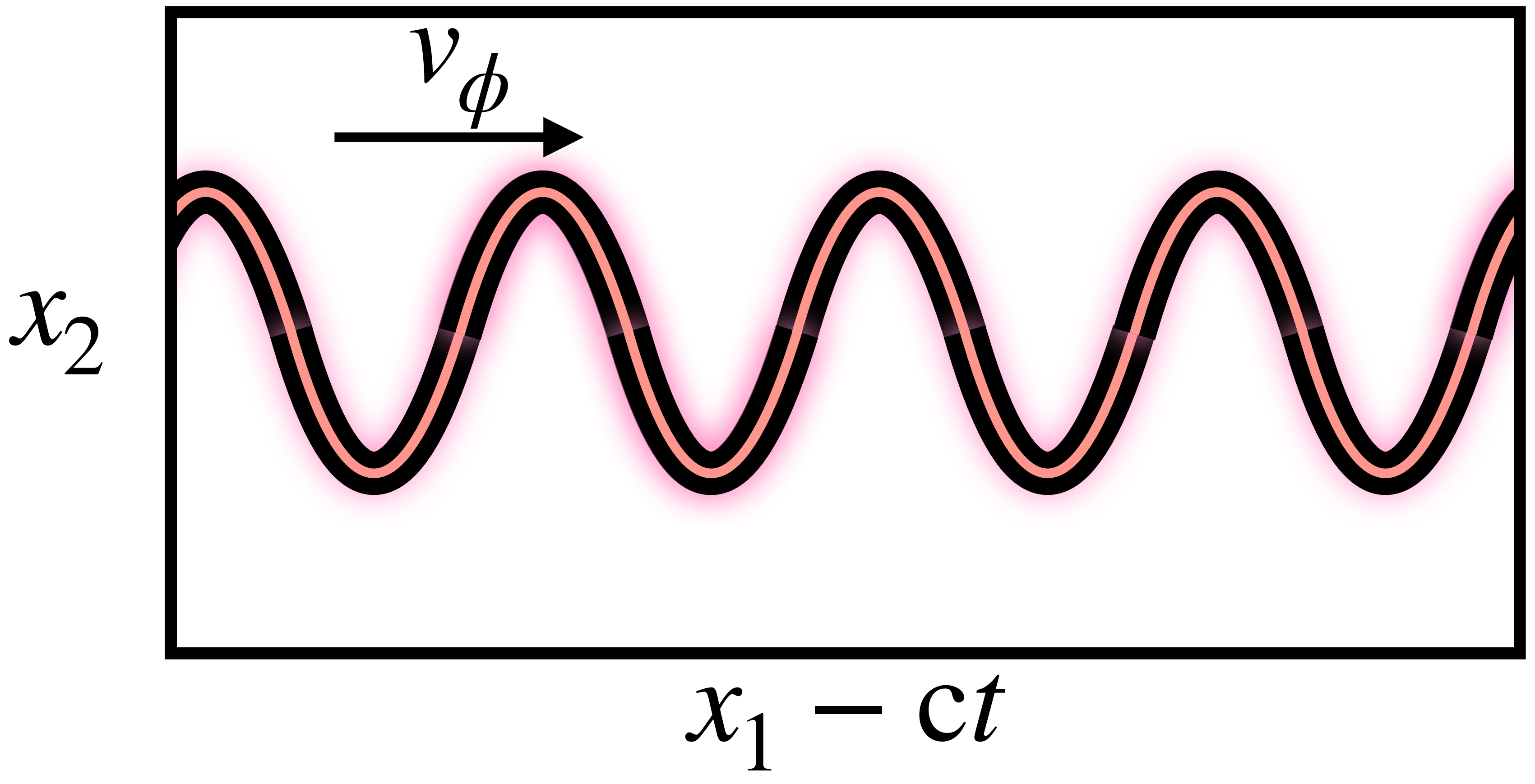
$$x_{2,p}(t, t_{0p}) = r_\beta \sin\left[\omega_\beta(t - t_{0p}) + \omega_m t_{0p}\right]$$

$$v_\phi = \frac{v_0}{1 - \omega_\beta/\omega_m}$$ "phase-like" velocity

$$\boxed{(v_0 \simeq c) \wedge (\omega_m > \omega_\beta) \Rightarrow v_\phi > c}$$

(may be superluminal)

Formalism



Trajectory of each particle

$$
\left.\begin{aligned}
x_{1,p}(t, t_{0p}) &= v_0(t - t_{0p}) \\
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\end{aligned}\right\} \quad v_\phi = \frac{v_0}{1 - \omega_\beta/\omega_m}
$$

"phase-like" velocity

$$\boxed{(v_0 \simeq c) \wedge (\omega_m > \omega_\beta) \Rightarrow v_\phi > c}$$

(may be superluminal)

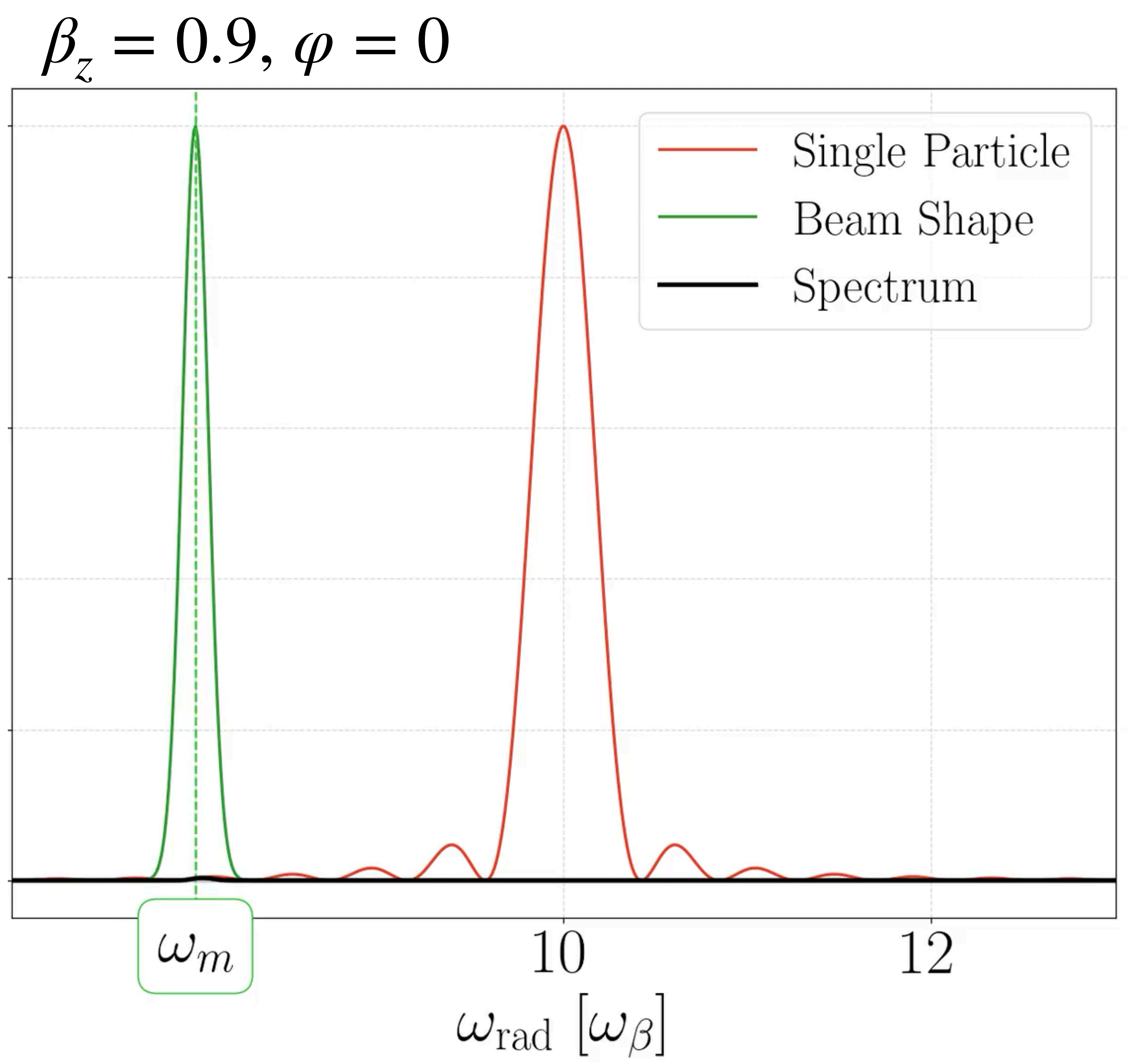
From Liénard-Wiechert Potentials

Single Particle Contribution — Beam Contribution

$$\frac{d^2 I}{d\omega_{\text{rad}} d\Omega} \propto \sum_n \boxed{F(n, \omega_{\text{rad}}, \varphi)\,\text{sinc}^2\left[\frac{\omega_{\text{rad}}\left(1 - \beta_z \cos\varphi\right) - n\omega_\beta}{2c\beta_z} L\right]}\;\boxed{\exp\left[-\sigma_t^2\left(\omega_{\text{rad}} - n\omega_m\right)^2\right]}$$

$$n\omega_\beta/(1 - \cos(\varphi)\beta_z) = \omega_{\text{rad}} = n\omega_m$$

(betatron radiation frequency) (particle beam modulation frequncy)



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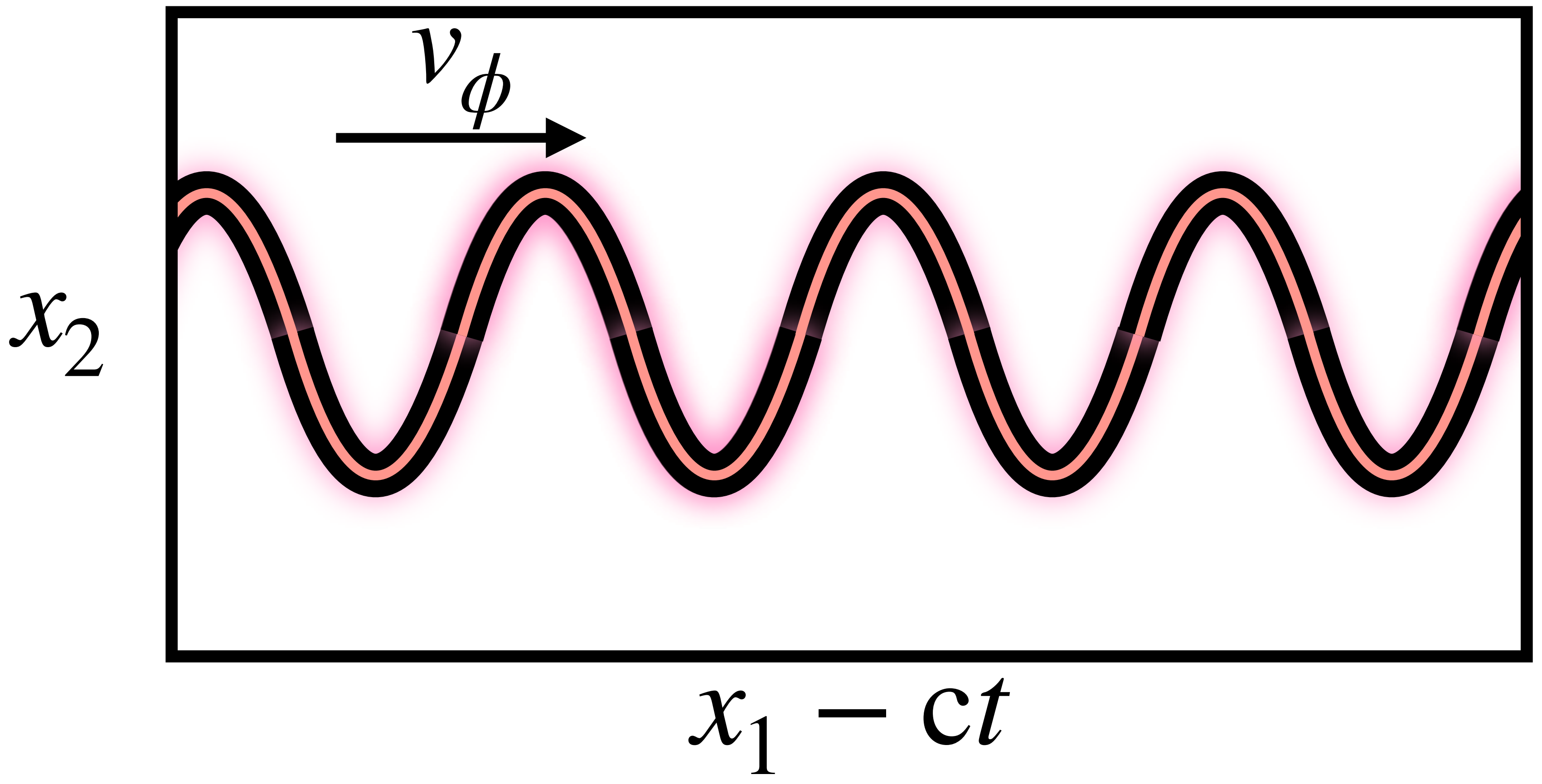

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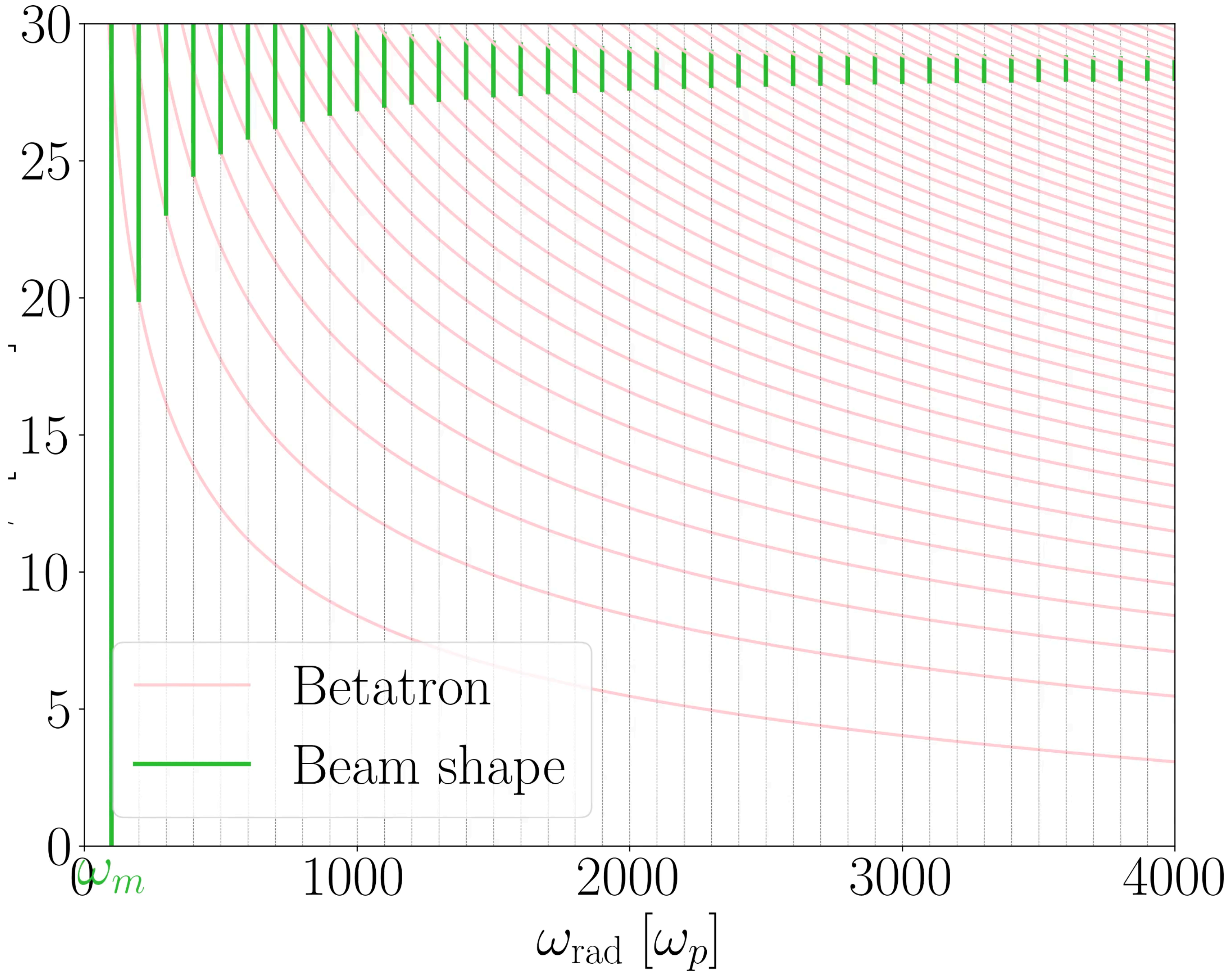
(betatron radiation frequency) (particle beam modulation frequncy)

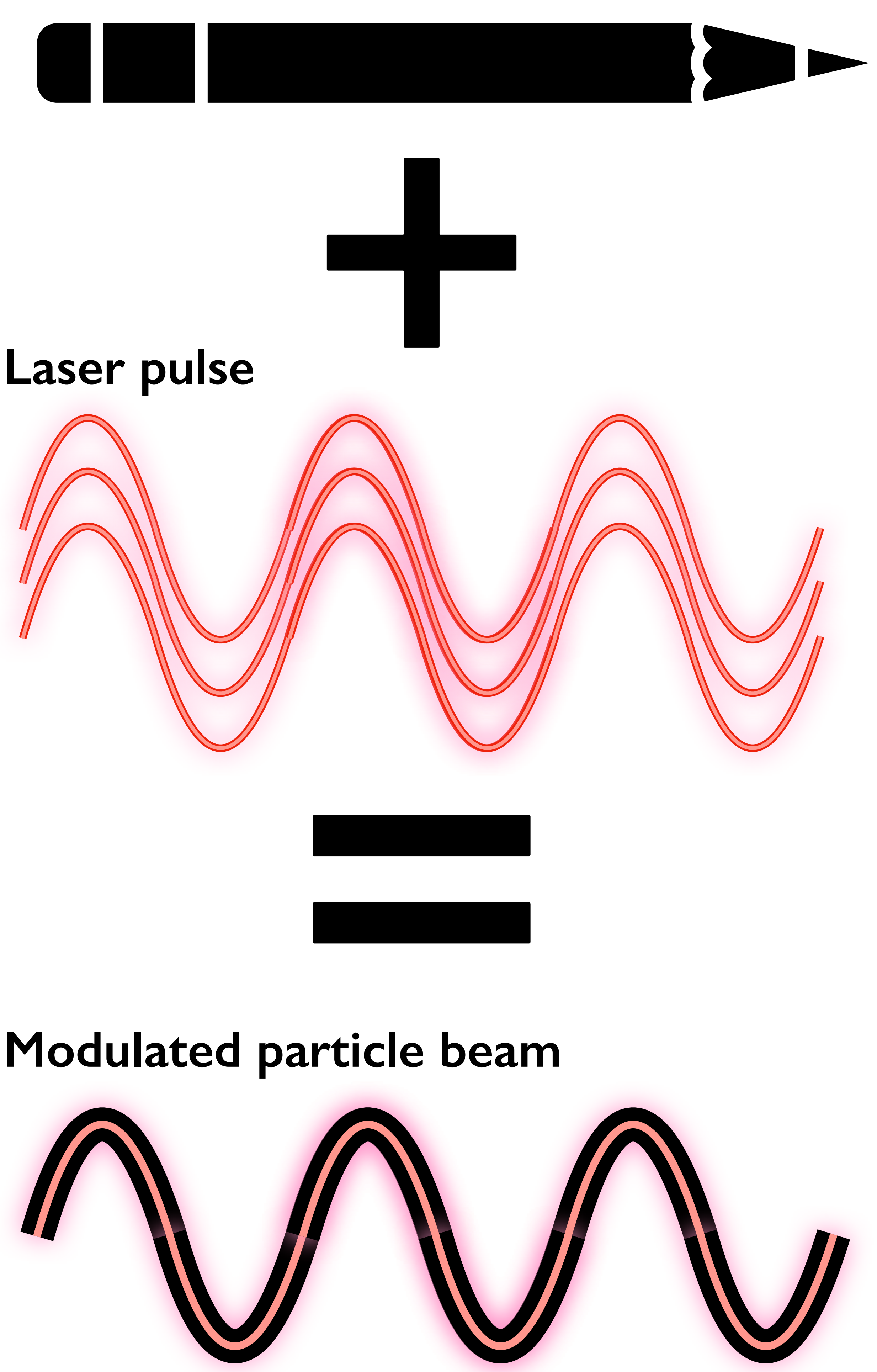
$\gamma = 300$



Contents

Accelerated with NVIDIA

Modulating a particle beam



We can modulate a **pencil-like** particle beam in a betatron field by using a strong enough $(a_0 \sim 1)$ **laser pulse.**

Resonance can be obtained if the **laser frequency** $\omega_L \; (= \omega_m)$ **matches** the **betatron frequency** ω_β in the **particles' frame**.

Constraints on the laser properties

- $v_\varphi > c$ **(for superradiance)**
- **Stability during a long interaction time**
- **Resonance matching conditions:**

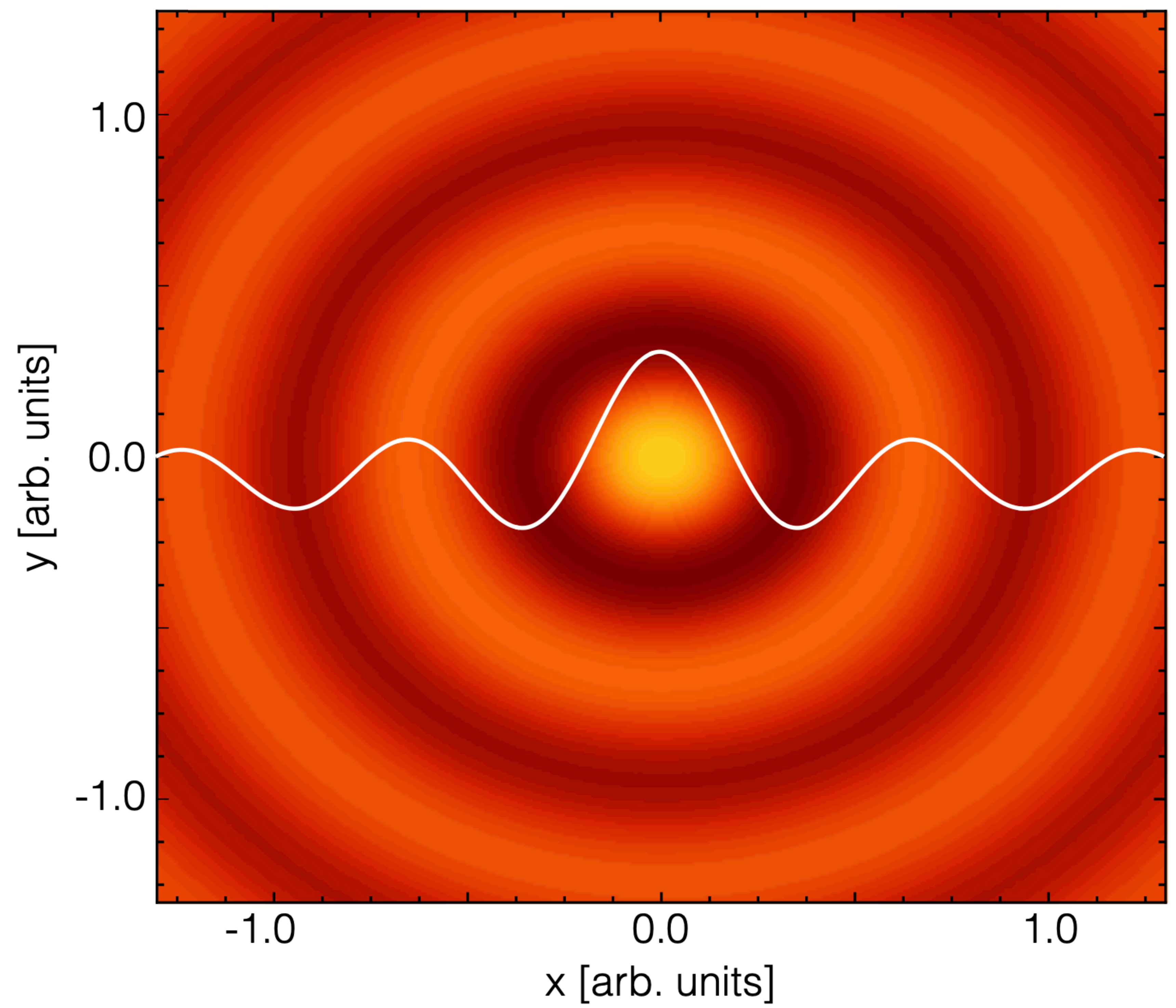
$$\frac{k_L}{k_p} = \frac{\sqrt{2\gamma^3}}{1 - 2\gamma^2(\sec(\varphi) - 1)} \qquad \frac{\omega_L}{\omega_p} = \frac{\sec(\varphi)\sqrt{2\gamma^3}}{1 - 2\gamma^2(\sec(\varphi) - 1)}$$

The Bessel Beam is our friend

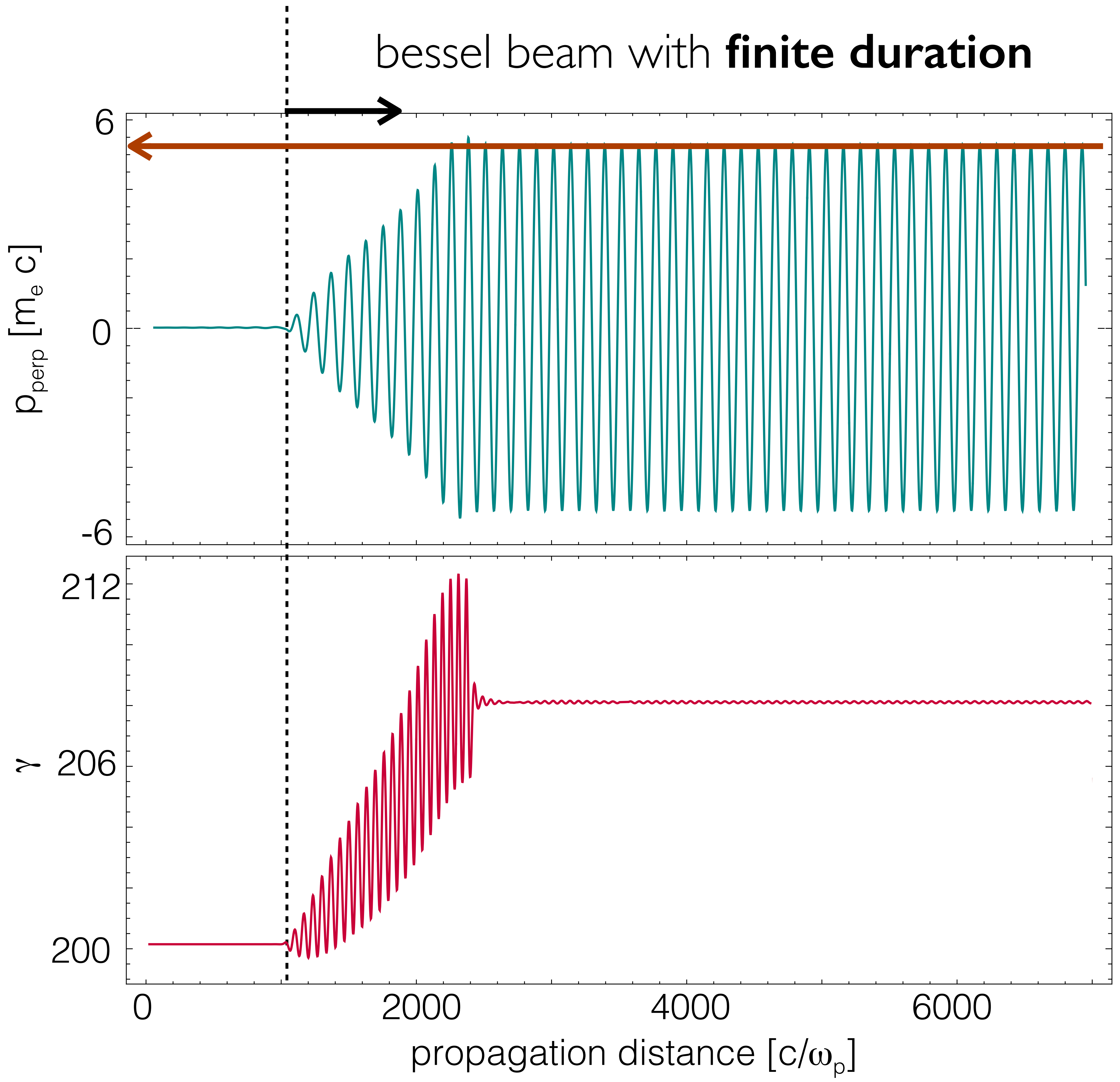
Features of a Bessel Beam

✅ $v_\varphi > c$ ✅ **Flat wavefronts** ✅ **Non-diffracting**

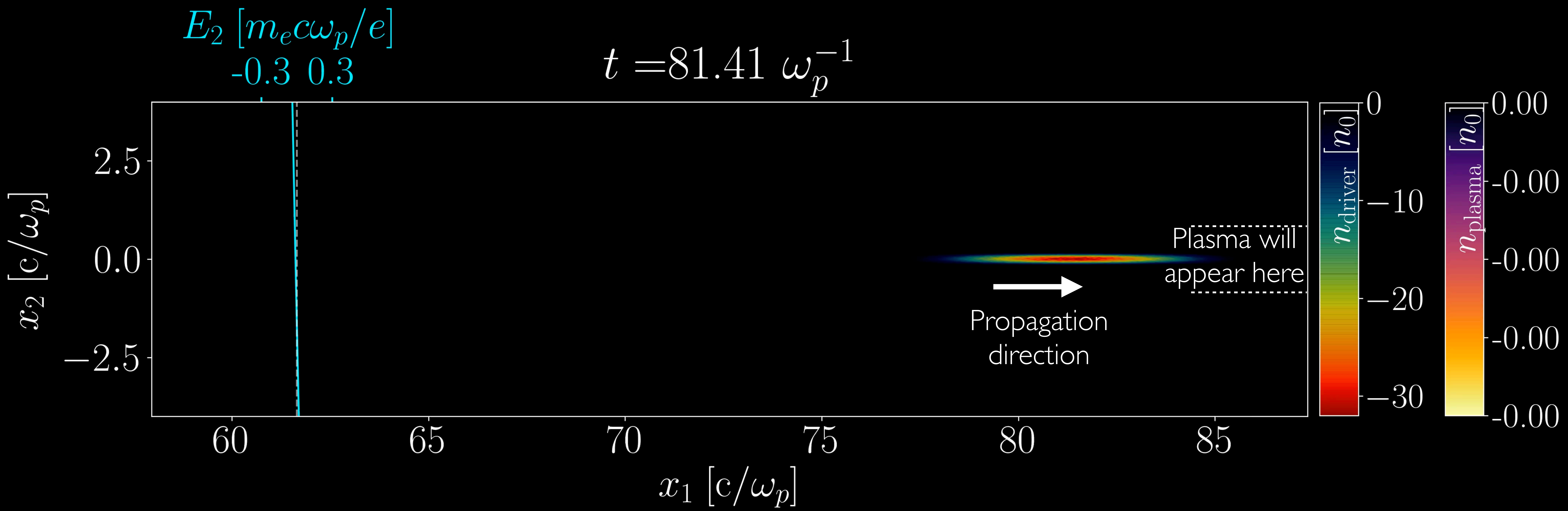
$$E_\perp = E_0 \exp(i[k_L x - \omega_L t + n\theta]) J_n(k_r r)$$

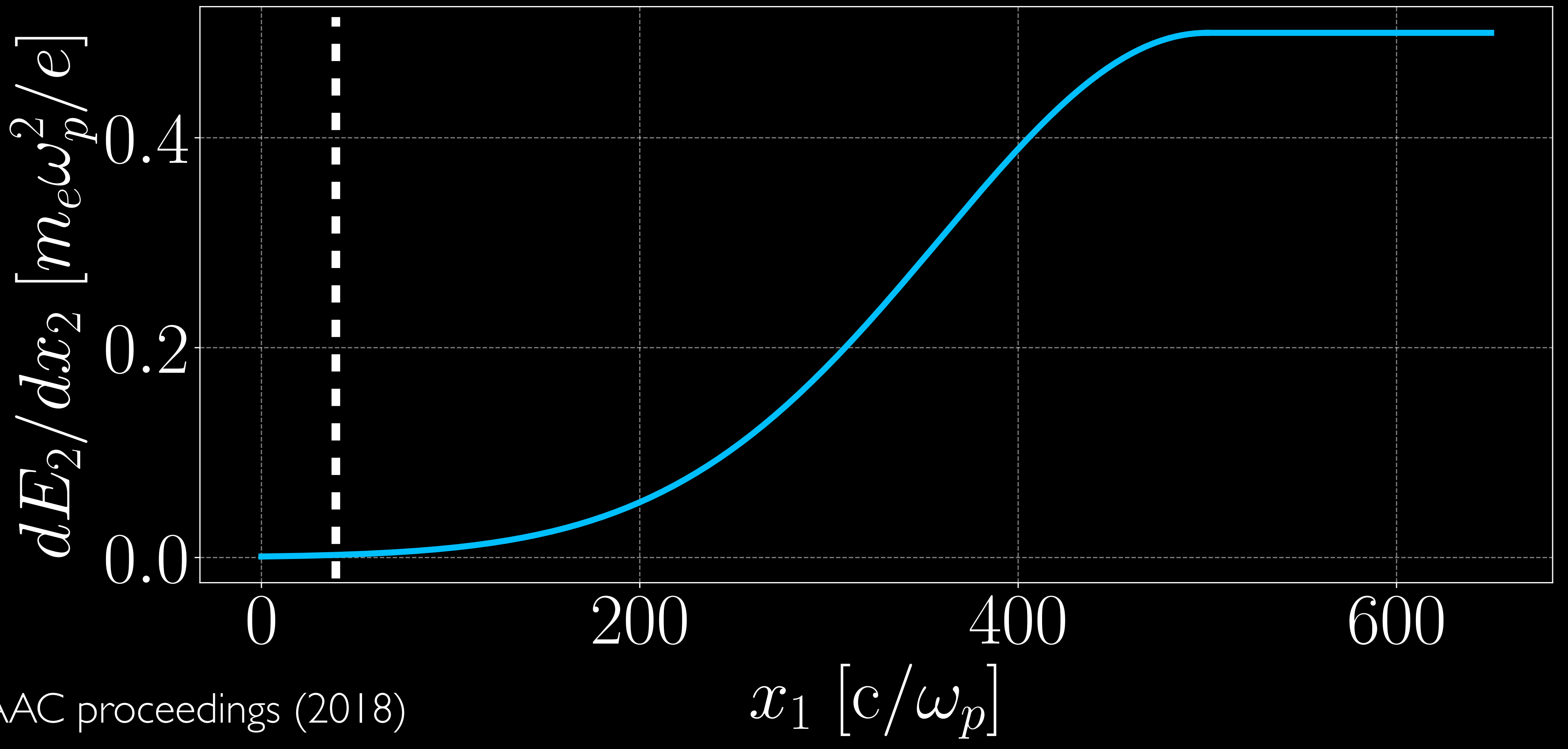


Dynamics of a single particle $(\gamma = 200)$



Wakeless regime* - 2D simulation





- 10 GeV electron beam
- Plasma density grows smoothly (Gaussian ramp)
- Plasma column width ≪ bubble radius
- Leaves an ion channel behind

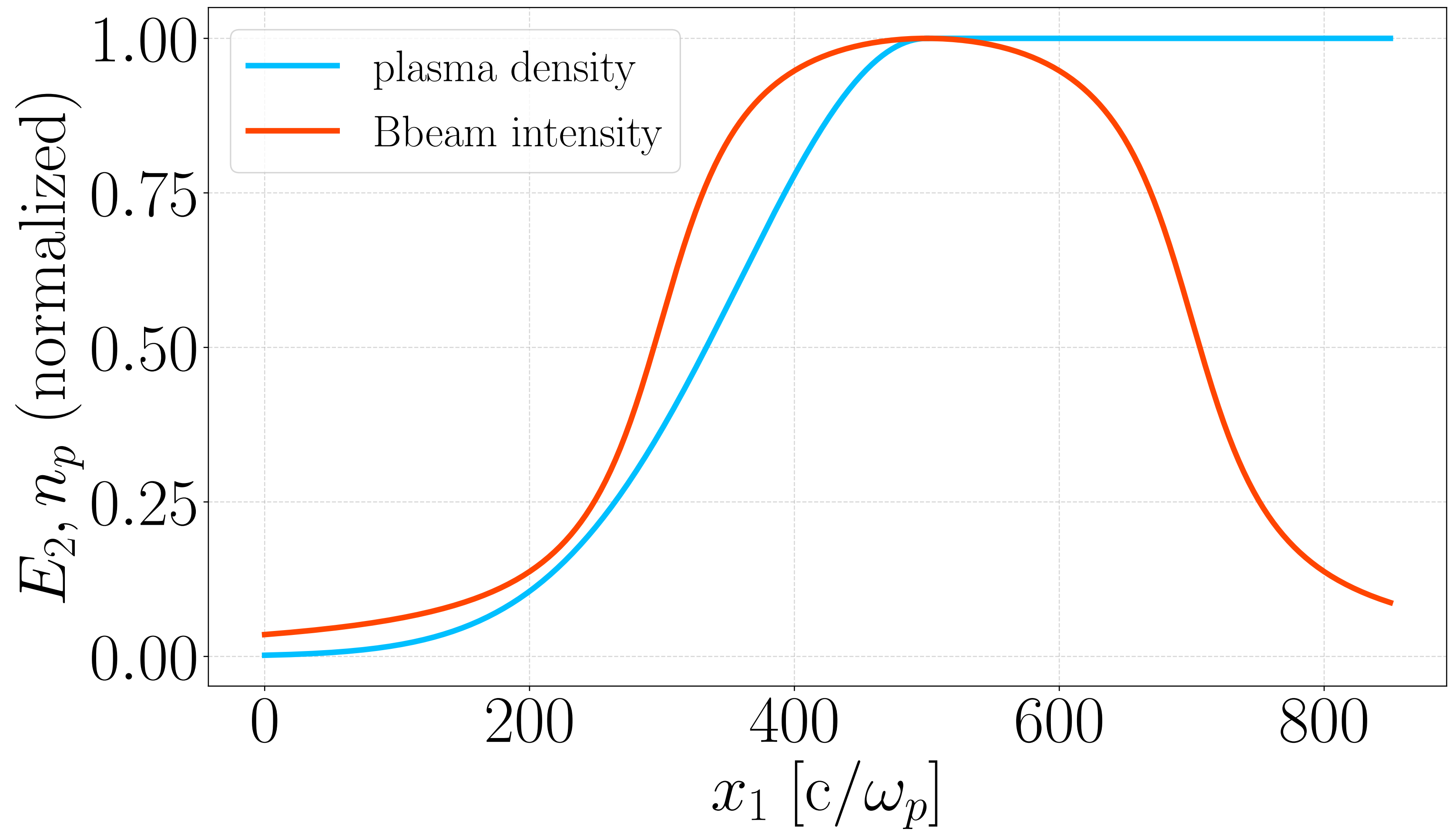
* M. Litos ***et al.*** AAC proceedings (2018)

Particle beam modulation

Simulation parameters

Bessel Beam:

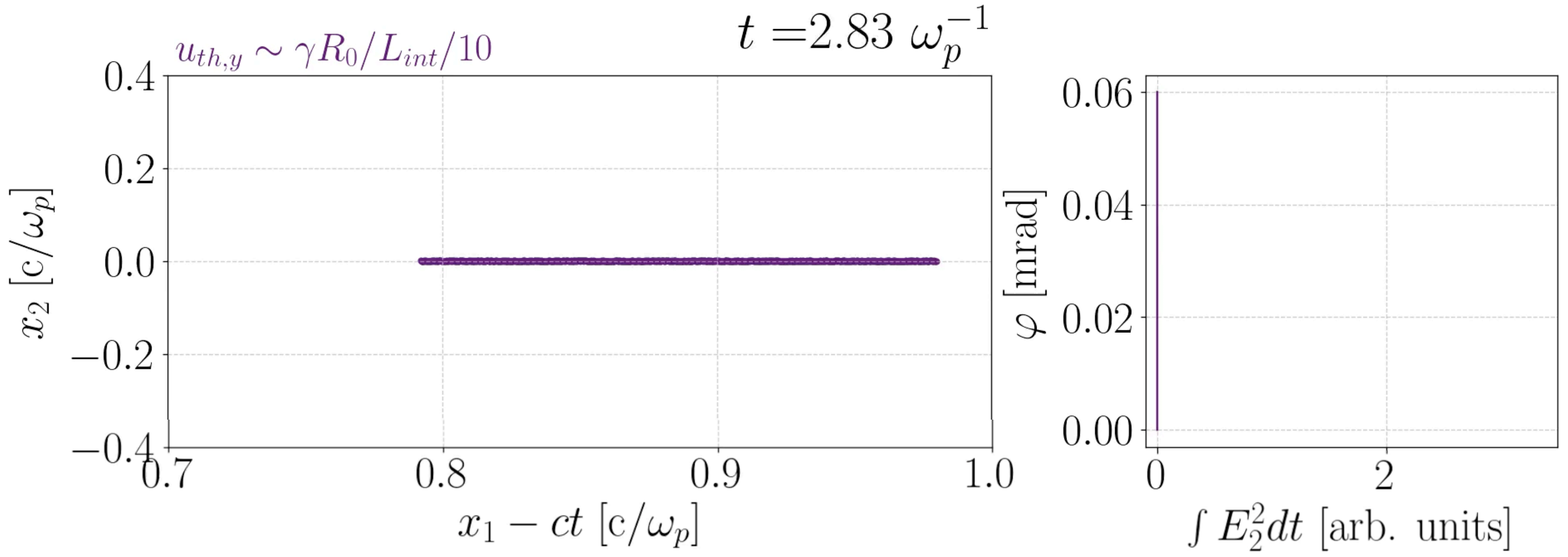
- $a_0 = 0.85$, $v_\varphi = 1.00035\ c$
- $\omega_L = 182\ \omega_p$
- Smooth intensity ramp (similar to plasma)
- Interaction Length $\sim 500\ c/\omega_p$

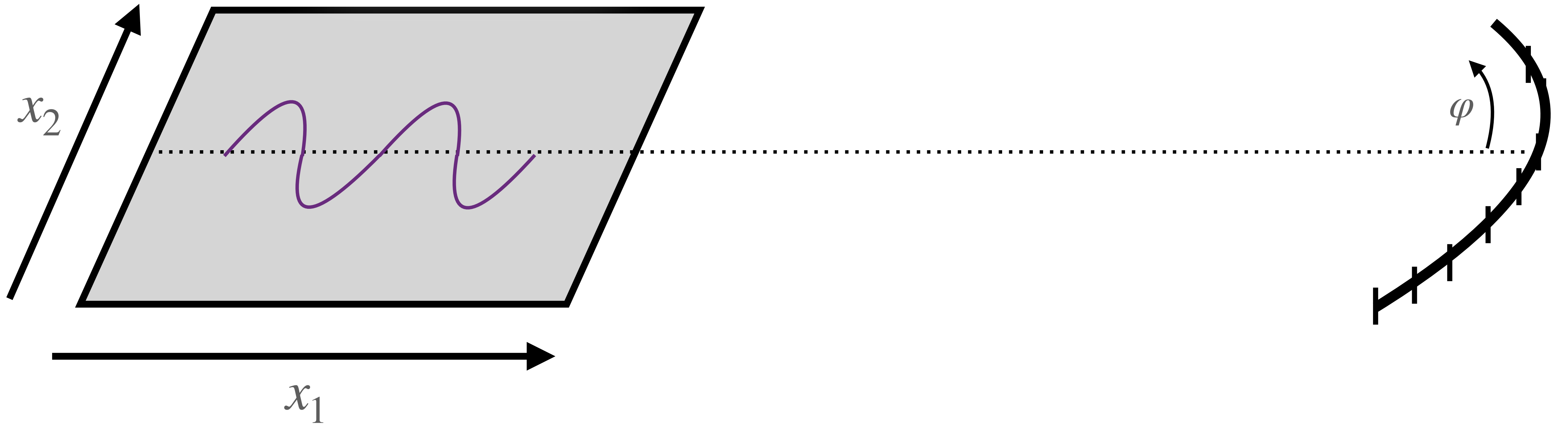


Particle Beam:

- $\gamma = 300$, $u_{th} = 0.018$
- $l = 0.2\ c/\omega_p \sim 5\ \lambda_B$

$$(u_{th}/\gamma)L_{int} \ll R_0\ ;\quad u_{th} \sim 0.018$$



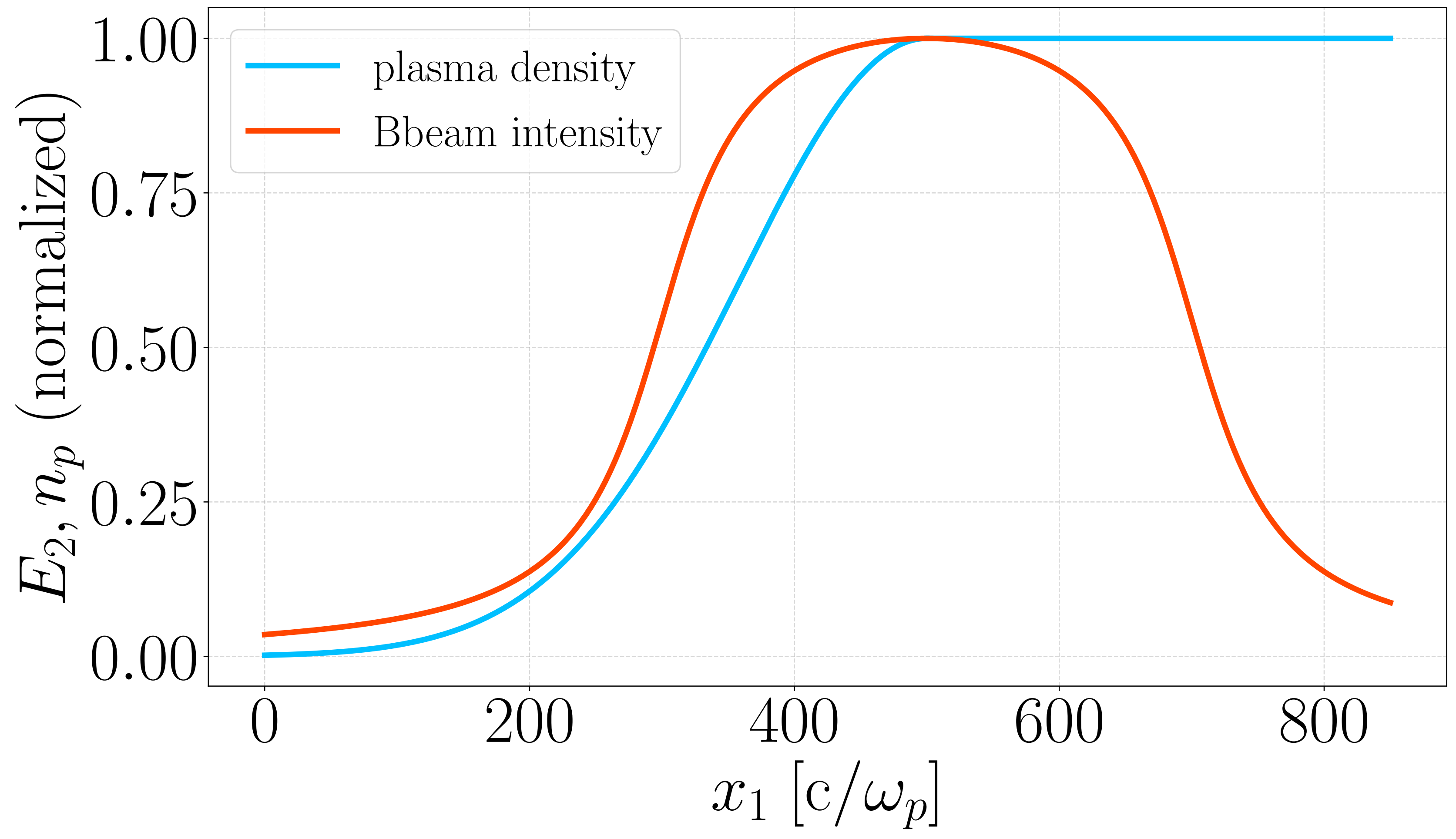


Particle beam modulation: thermal analysis

Simulation parameters

Bessel Beam:

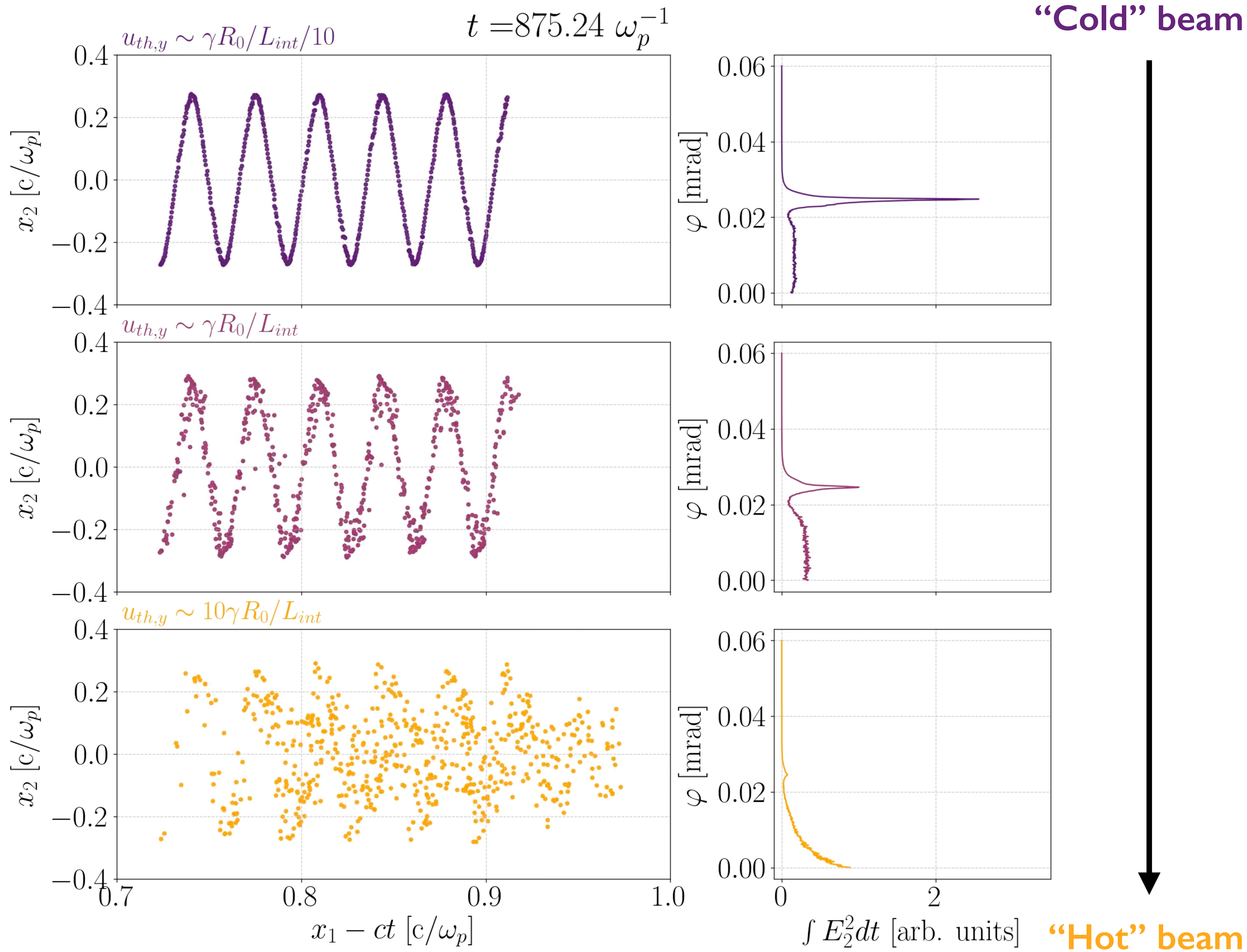
- $a_0 = 0.85$, $v_\varphi = 1.00035\ c$
- $\omega_L = 182\,\omega_p$
- Smooth intensity ramp (similar to plasma)
- Interaction Length $\sim 500\ c/\omega_p$



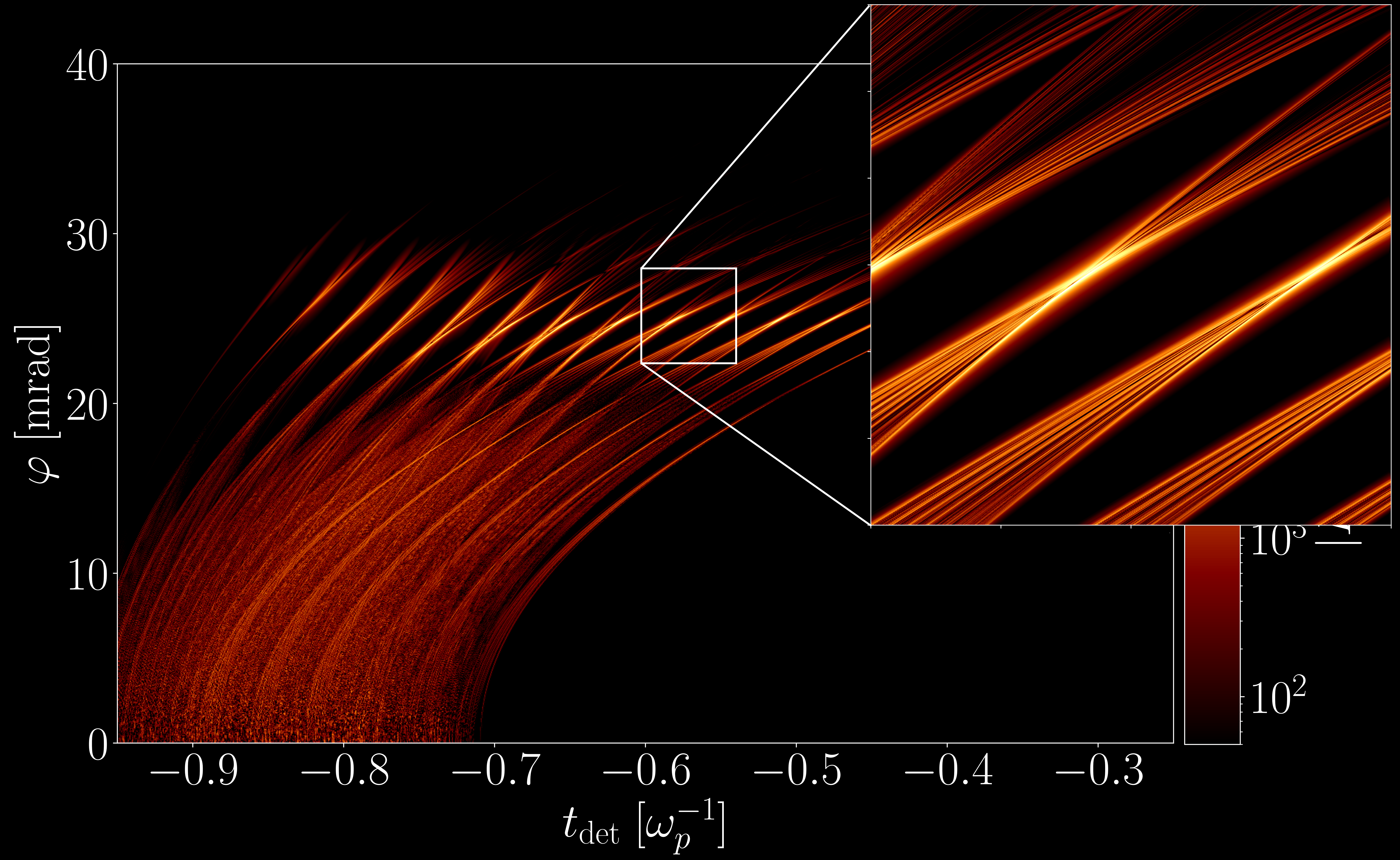
Particle Beam:

- $\gamma = 300$, $u_{th} = 0$
- $l = 0.2\,c/\omega_p \sim 5\,\lambda_B$

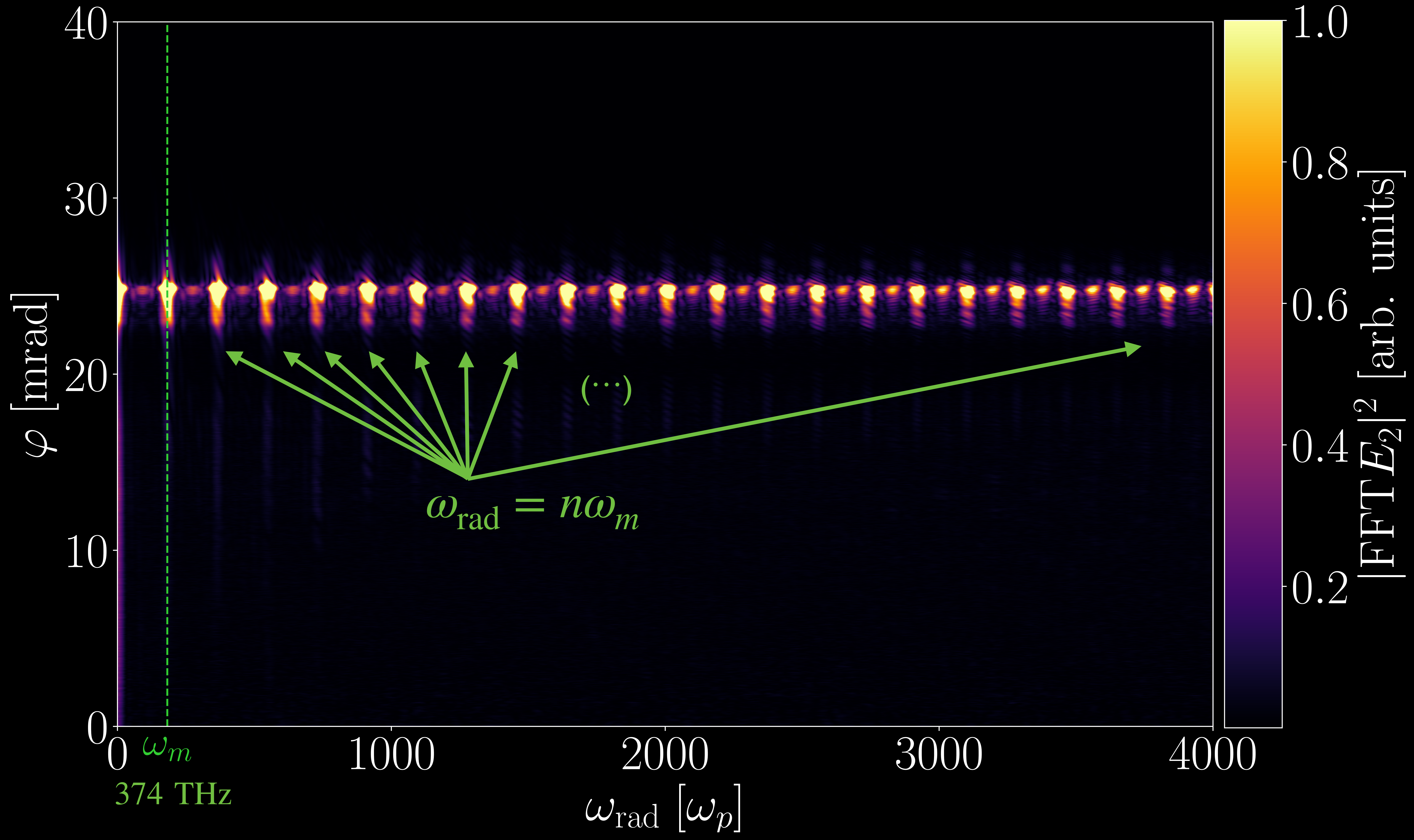
$$(u_{th}/\gamma)L_{int} \ll R_0\ ;\quad u_{th} \sim 0.018$$



Spatiotemporal Radiation Profile

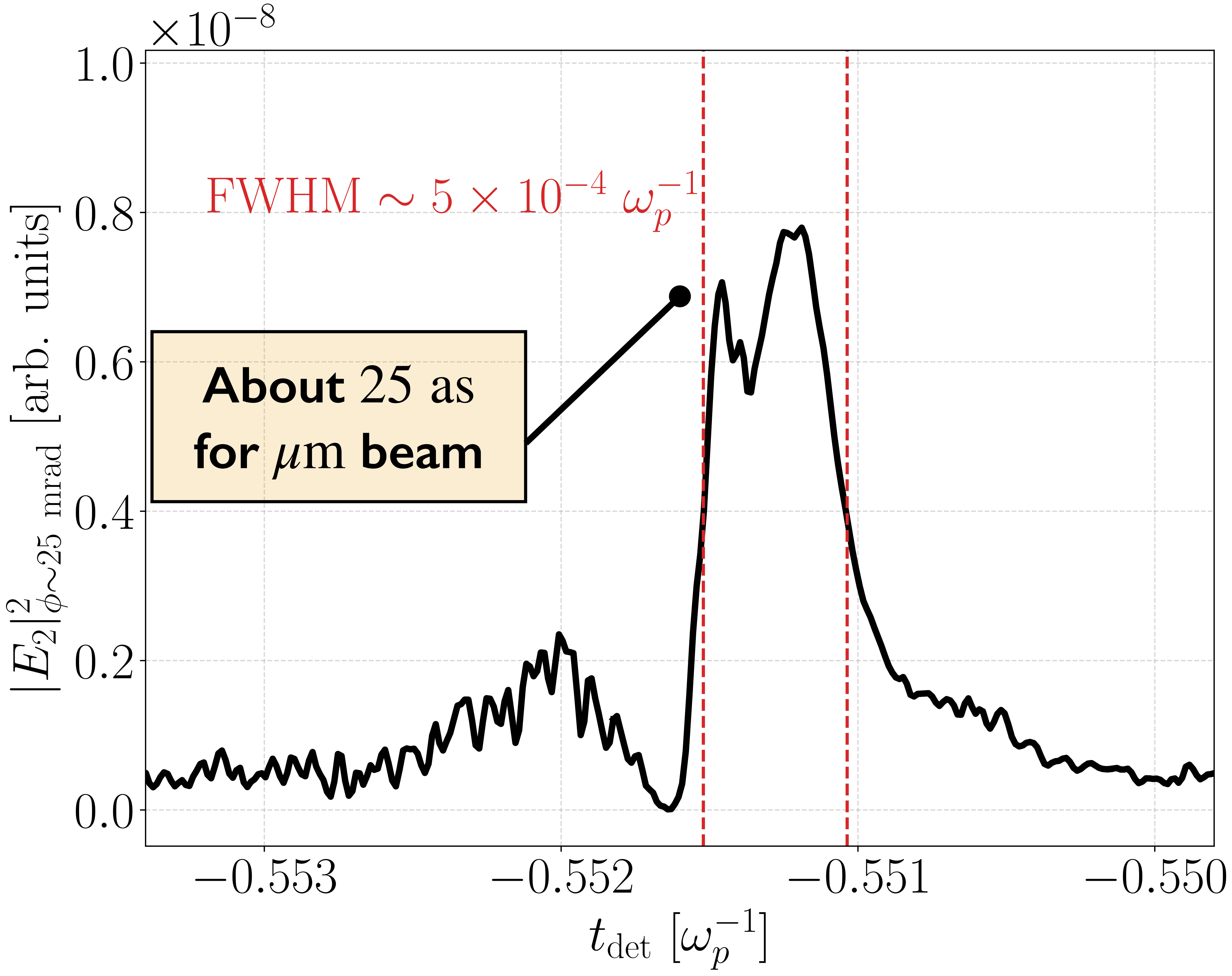


Spectral Radiation Profile

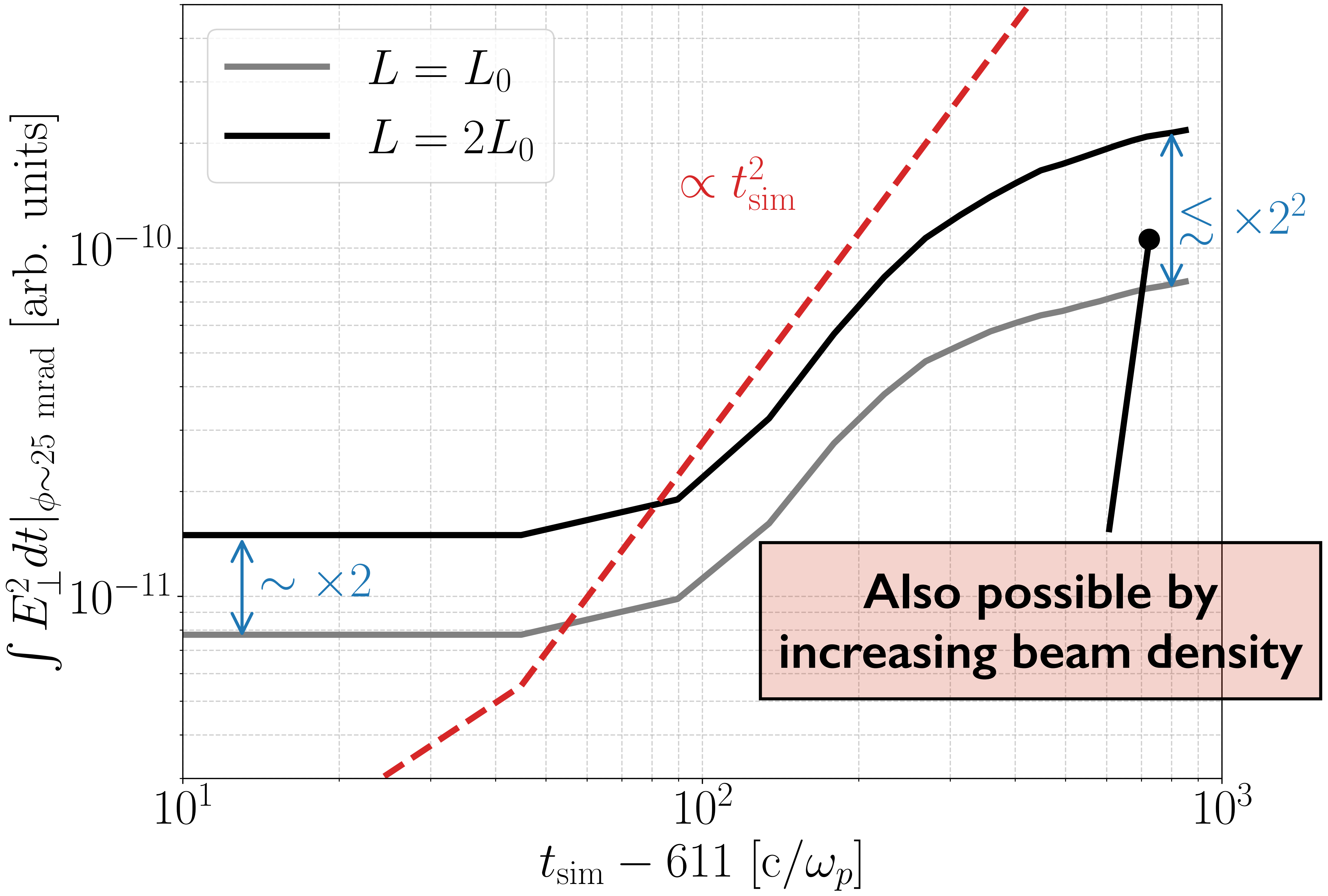


Superradiance

Short, attosecond photon burst



Quadratic intensity growth



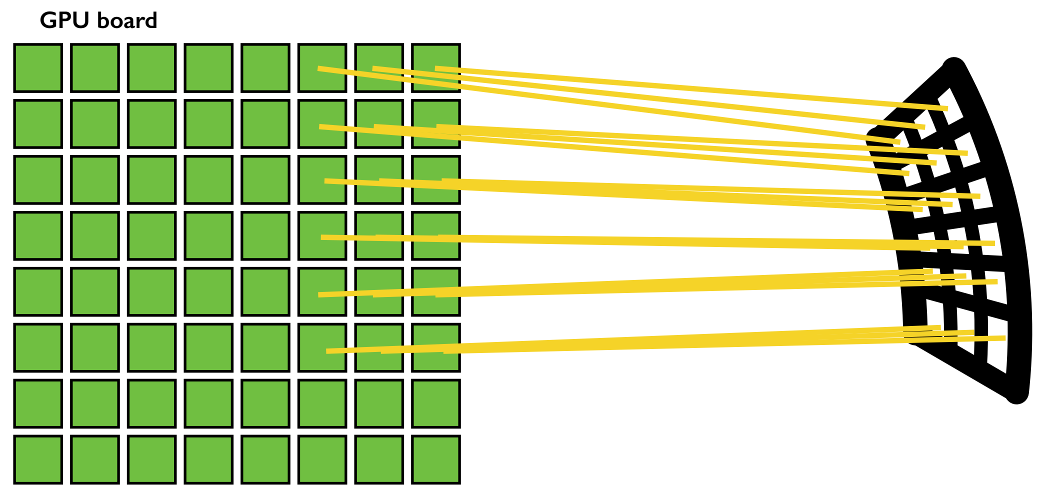
Conclusions and Future Work

Thank You!

TÉCNICO LISBOA

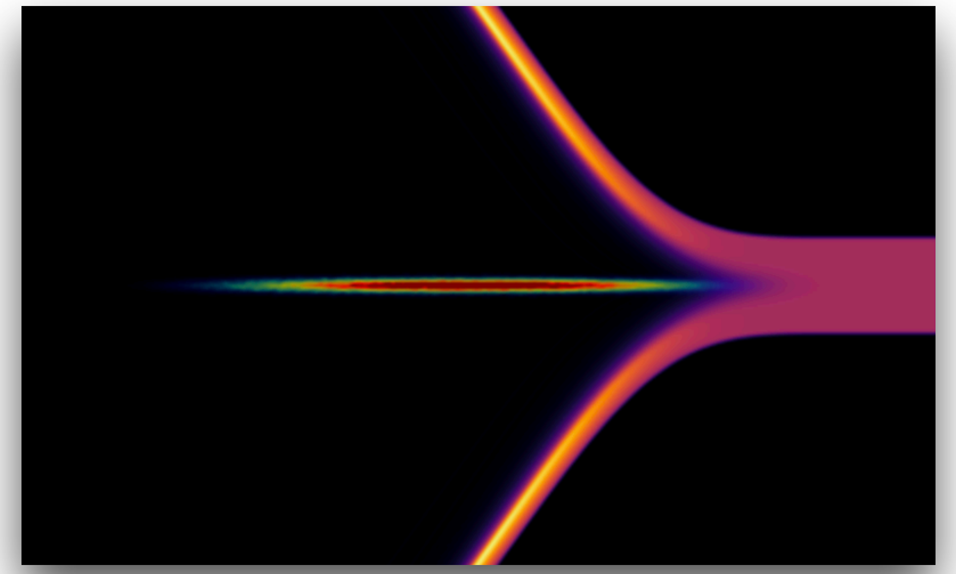
The GPU implementation of RaDi-x scales well

- Each detector cell is fully independent from the others;
- Both strong and weak scaling show good results;
- The GPU can do the radiation workload as the CPU take care of the rest;



We can modulate particle beams in the wakeless regime

- The wakeless regime provides a pure ion channel
- The bessel beam induces a modulation in the particle beam with superluminal phase velocity.



Betatron superradiance is possible

- Betatron particle beams modulated with superluminal phase velocities produce off-axis optical shocks.
- Intensity grows quadratically with number of particles and propagation distance.