Coherent radiation from nonlinear plasma wakefields in the blowout regime

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EuPRAXIA EuroHPC Joint Undertaking

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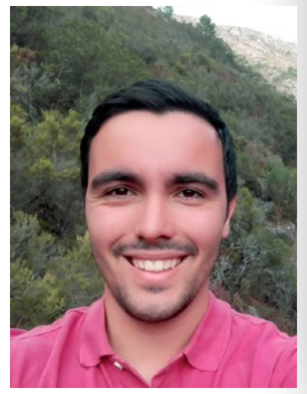
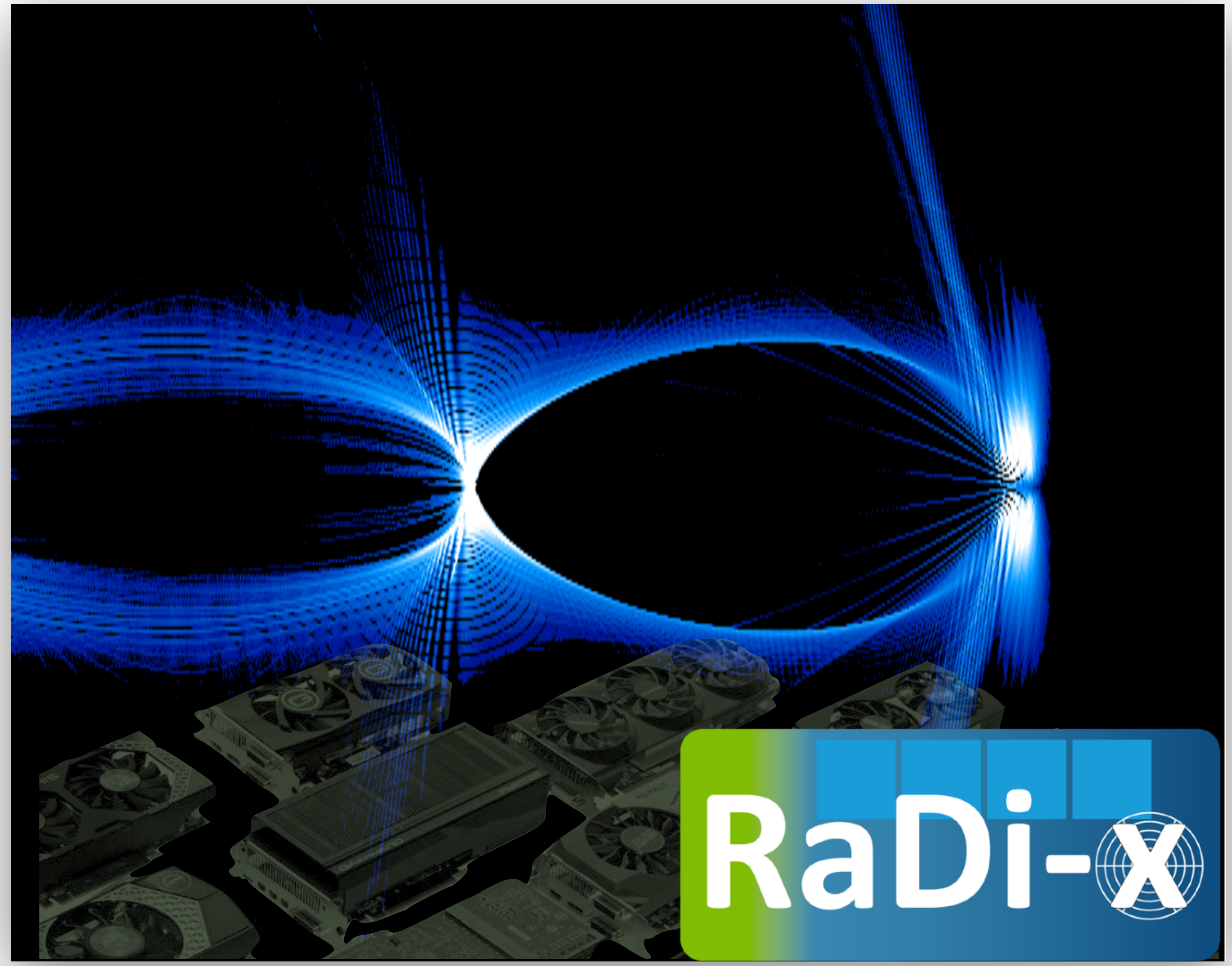
golp ipfn INSTITUTO DE PLASMAS E FUSÃO NUCLEAR TÉCNICO LISBOA

M. Pardal



B. Malaca



Accelerated with NVIDIA.

Why do we need light sources?

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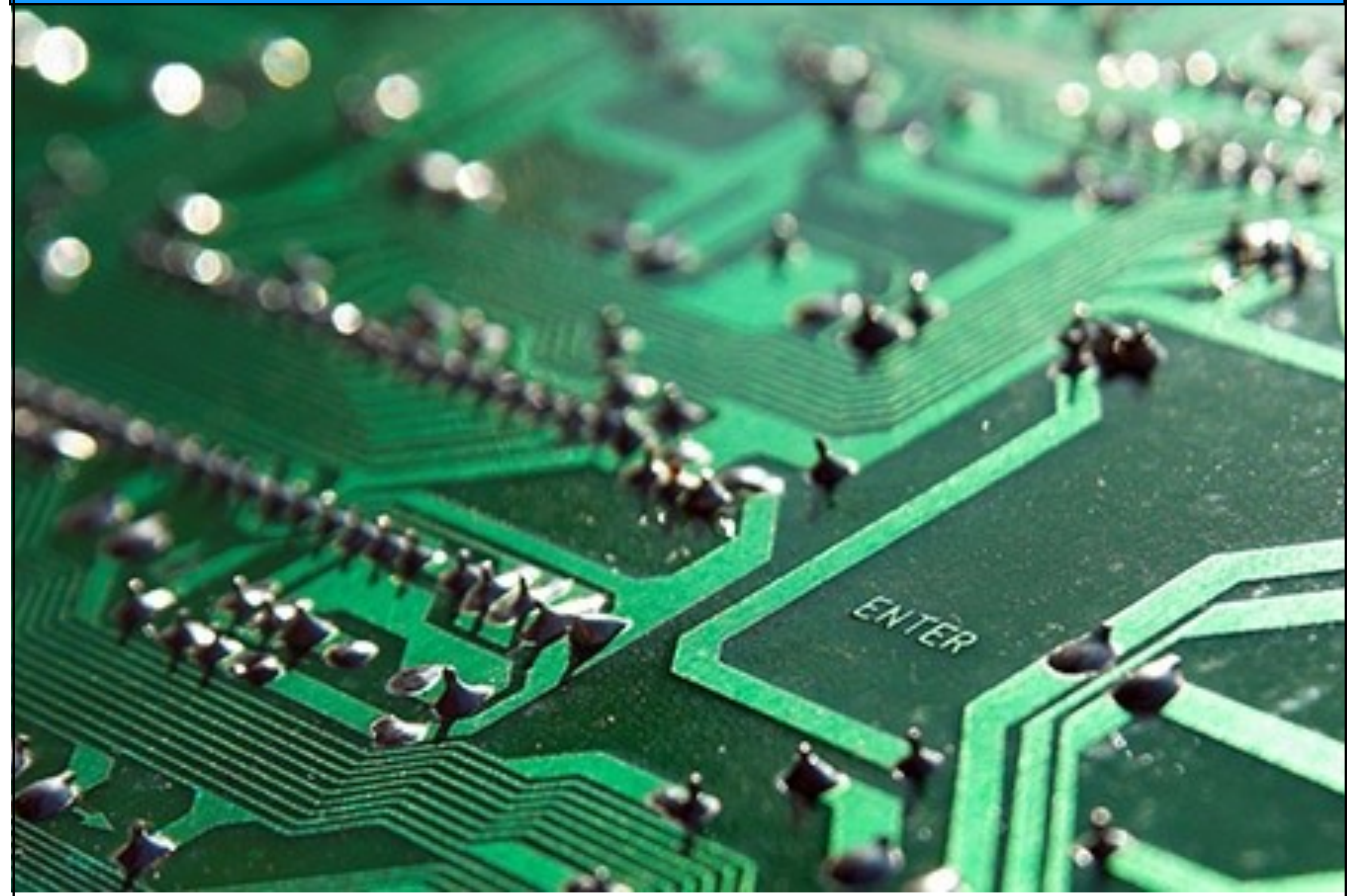
Harnessing sun's light

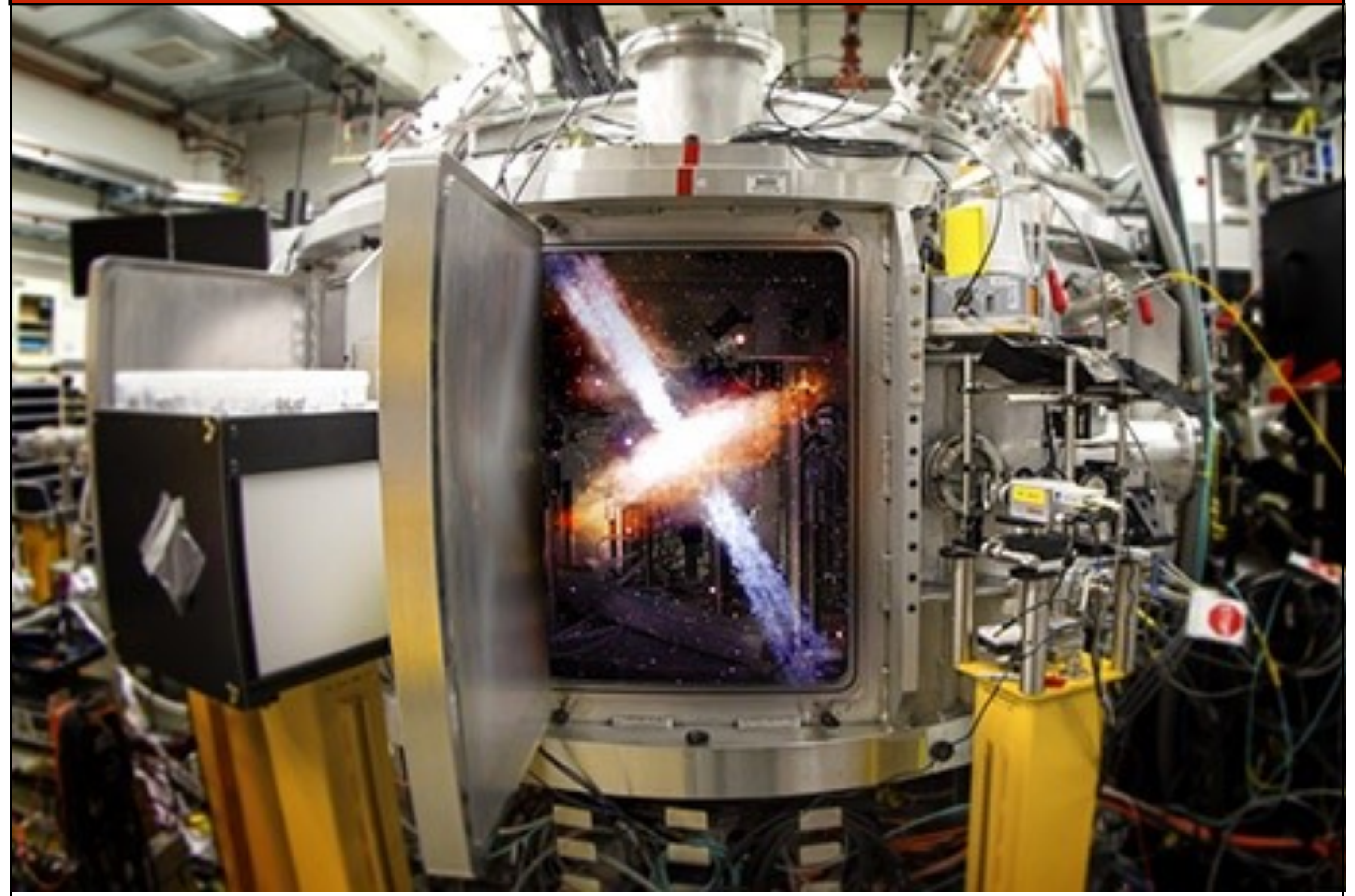
- Understand photo-synthesis
- Control chemical reactions

Future electronics



- Control magnetism and electronics
- Ultra-fast computers

New materials and fusion

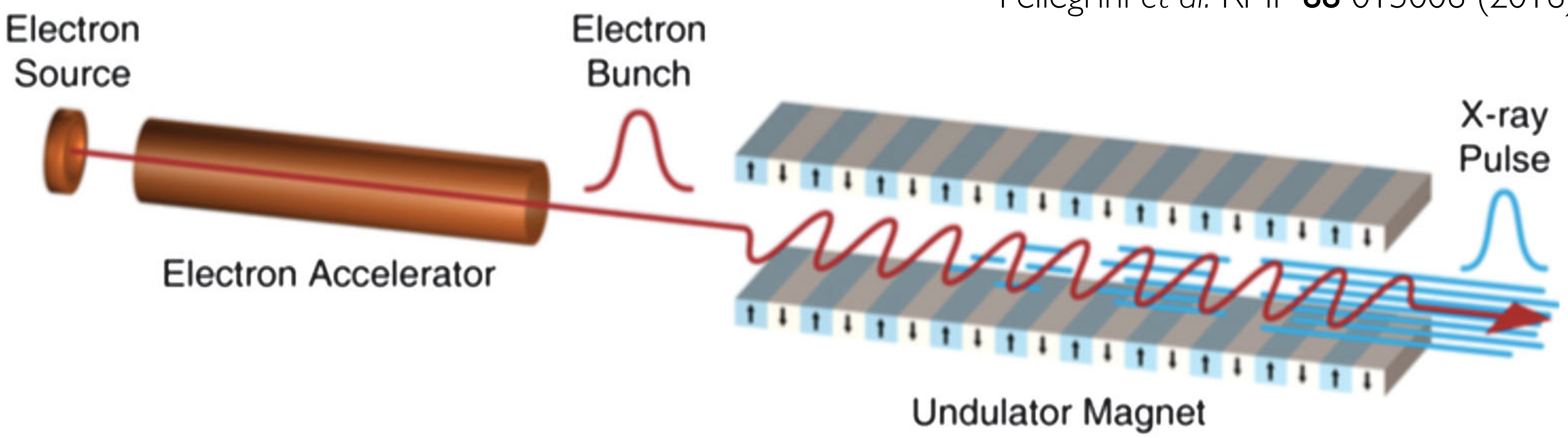


- Matter under extreme conditions
- Explore interior of stars

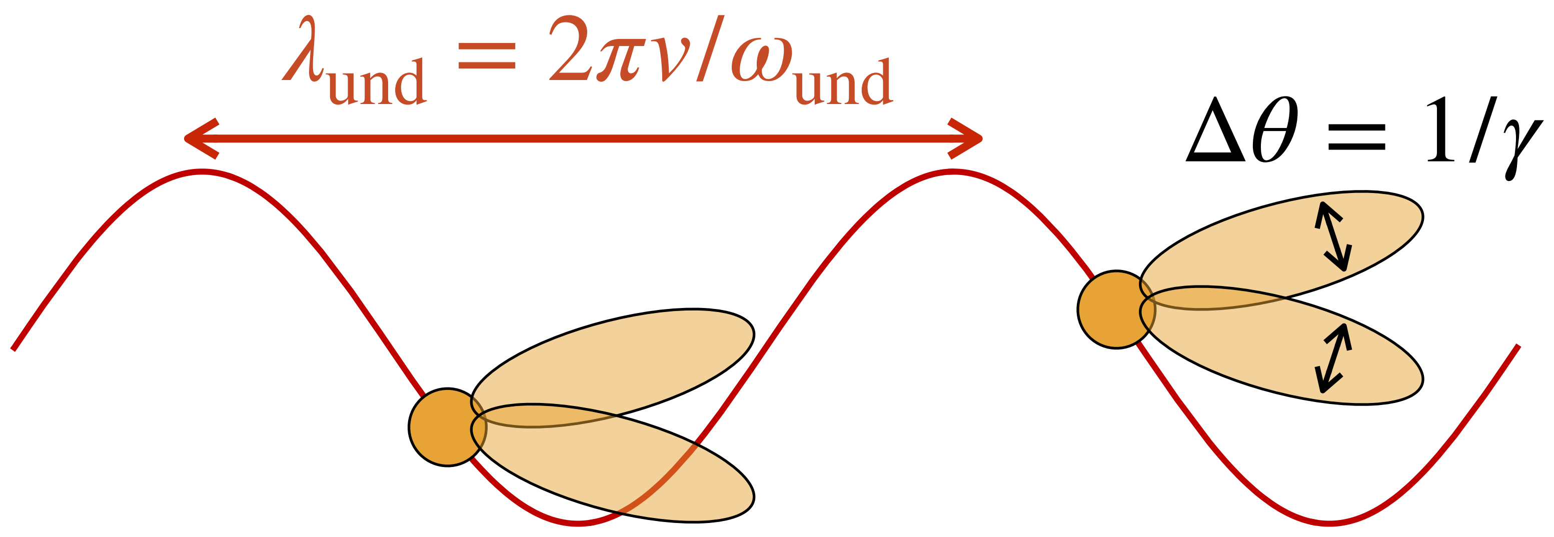
Adapted from https://lcls.slac.stanford.edu/overview

(superradiant) Free electron lasers are the brightest x-ray sources

Pellegrini *et al.* RMP **88** 015006 (2016).

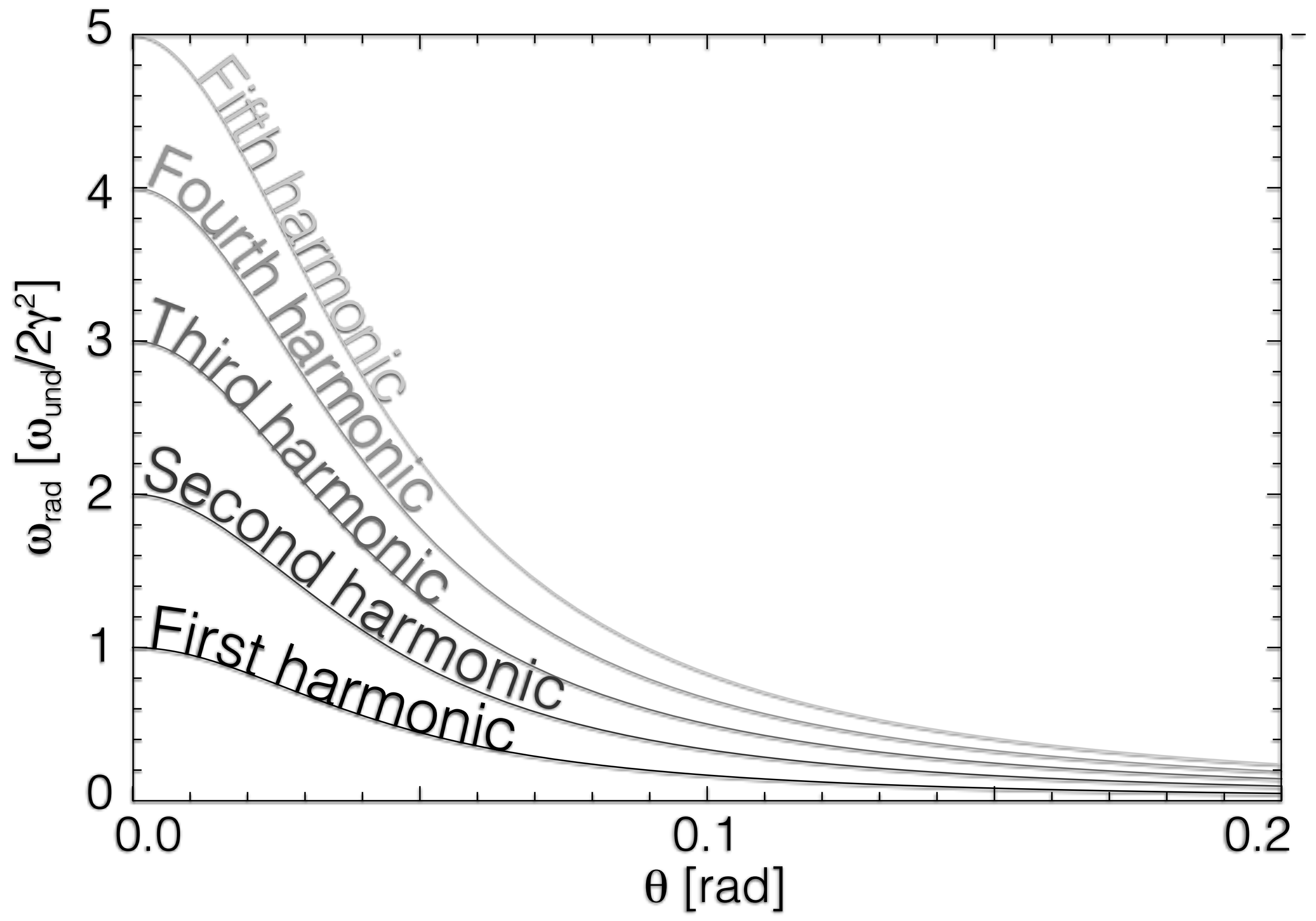


Basics



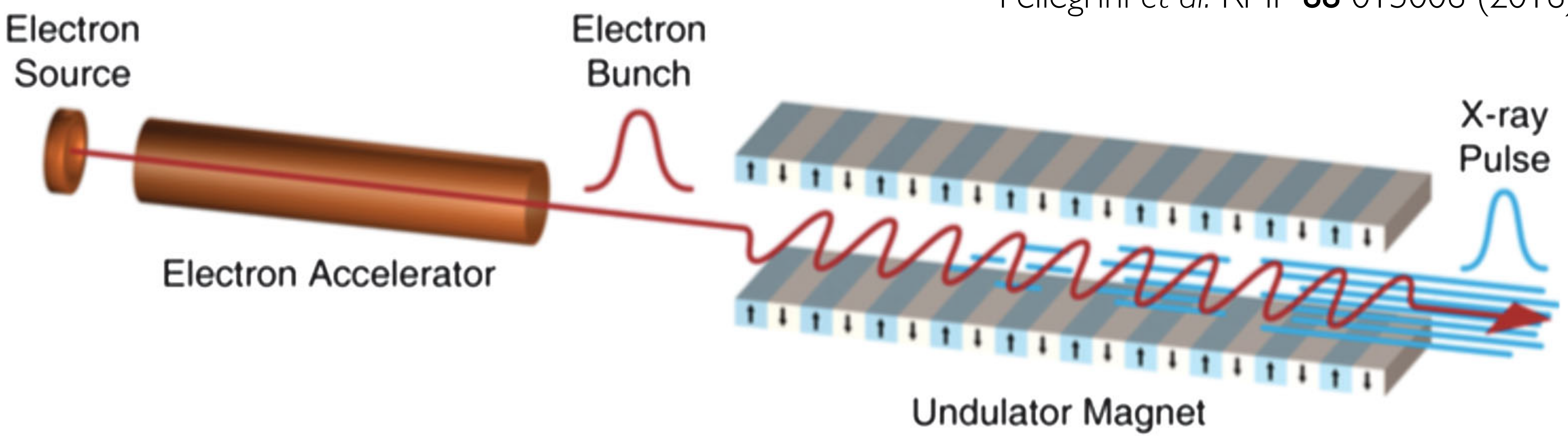
$$\omega_{\text{rad}} = \frac{n\omega_{\text{und}}}{1 - v/c\cos\theta} \xrightarrow[\theta=0]{} \omega_{\text{rad}} = 2n\gamma^2\omega_{\text{und}}$$

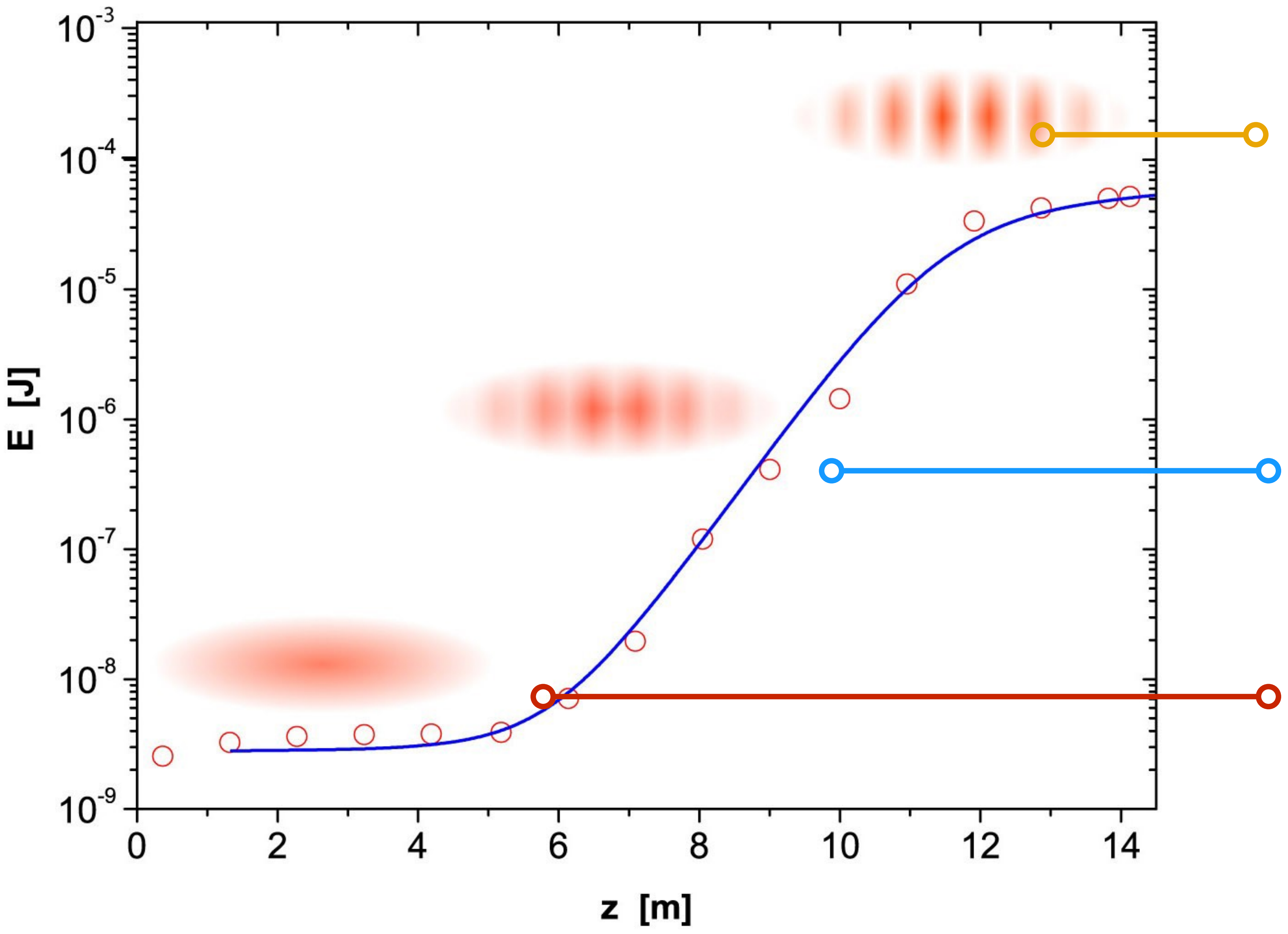
Undulator harmonic spectrum



Superradiance: what is it and how it works?

Pellegrini *et al.* RMP **88** 015006 (2016).



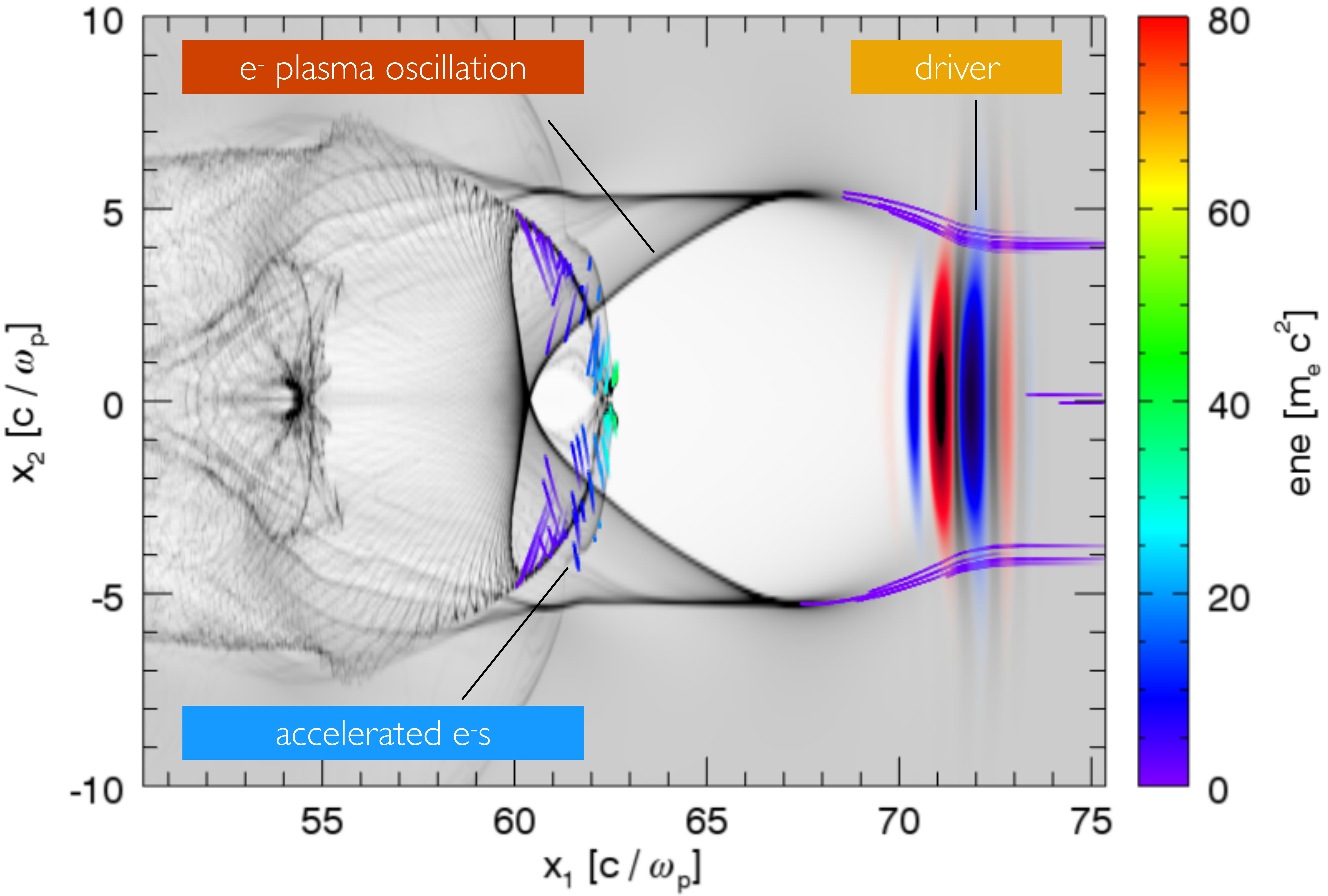


Electrons in each micro bunch radiate in phase — **coherent** $I \propto N^2$

Start micro-bunching at radiation wavelength

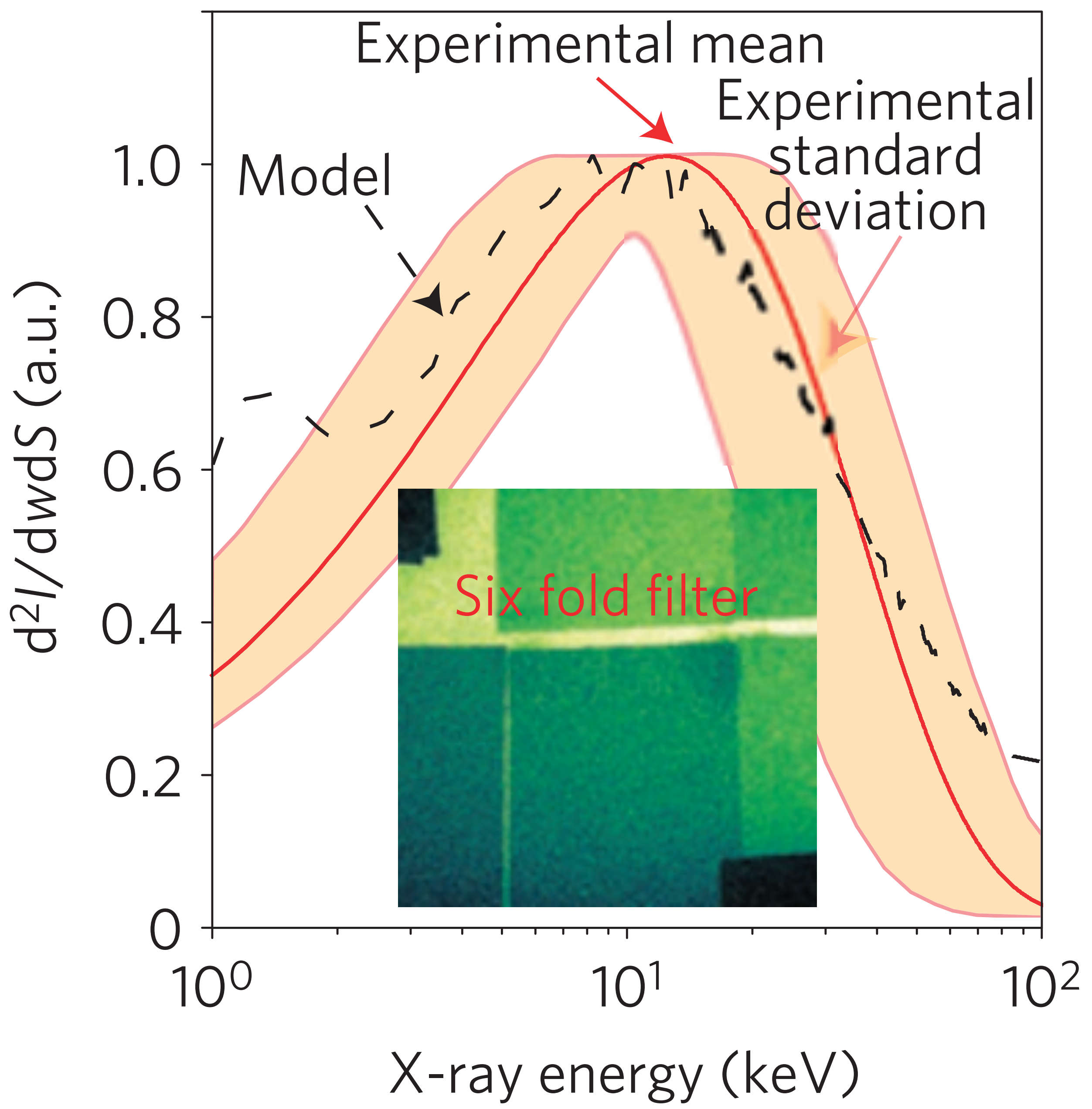
N electrons radiate out of phase — **incoherent** $I \propto N$

What is a plasma accelerator?



Betatron radiation

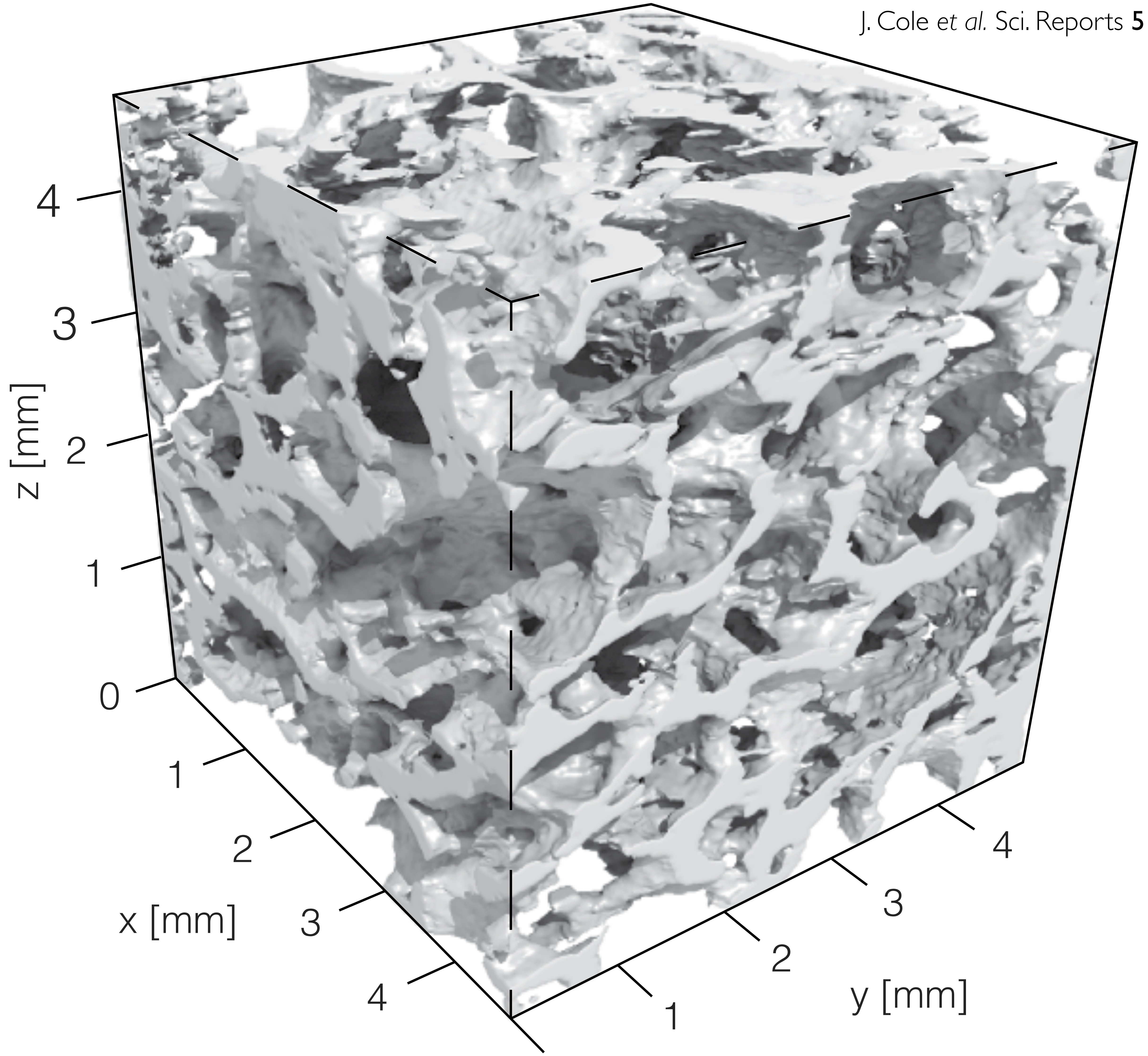
Spectrum



S. Kneip *et al.* Nat. Physics **6** 980 (2010).

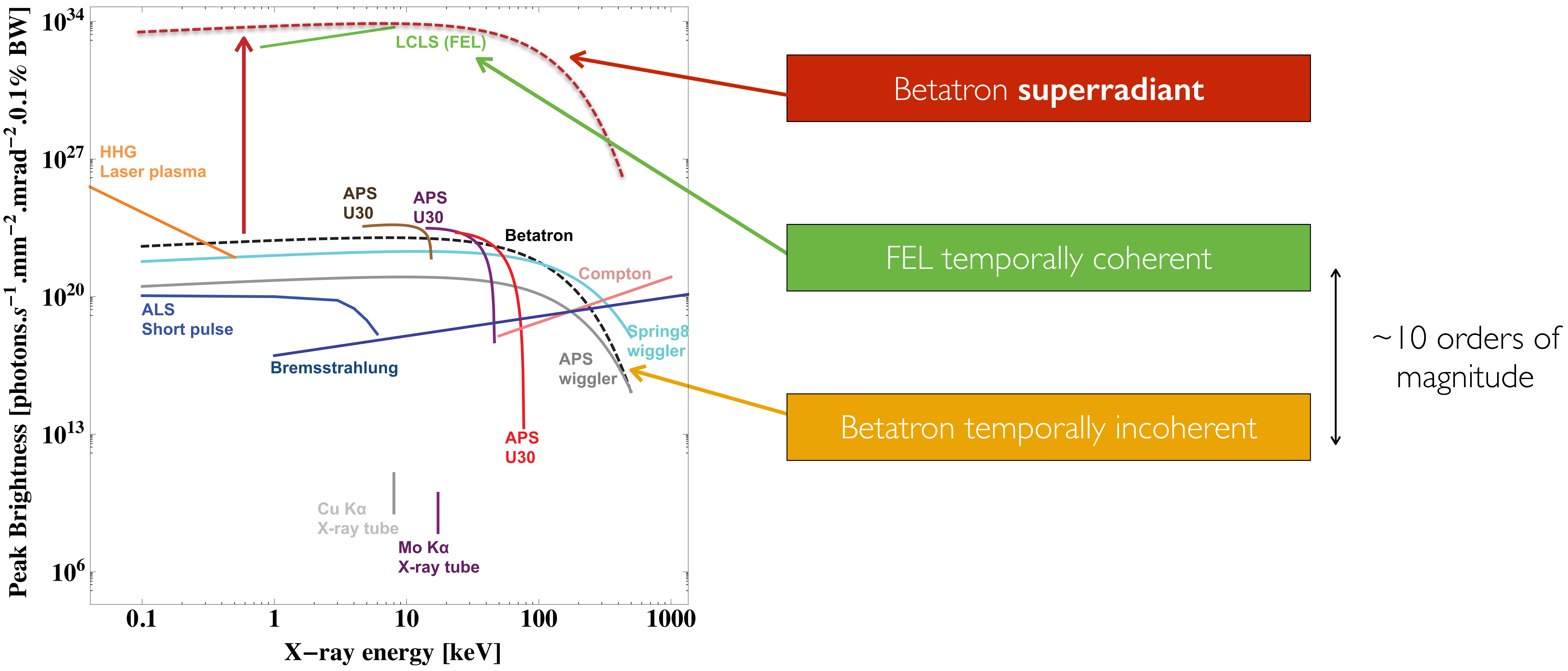
Tomographic reconstruction of a bone sample

J. Cole *et al.* Sci. Reports **5** 132244 (2015).



Temporal coherence in plasma based light sources

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



Temporal coherence in plasma based light sources

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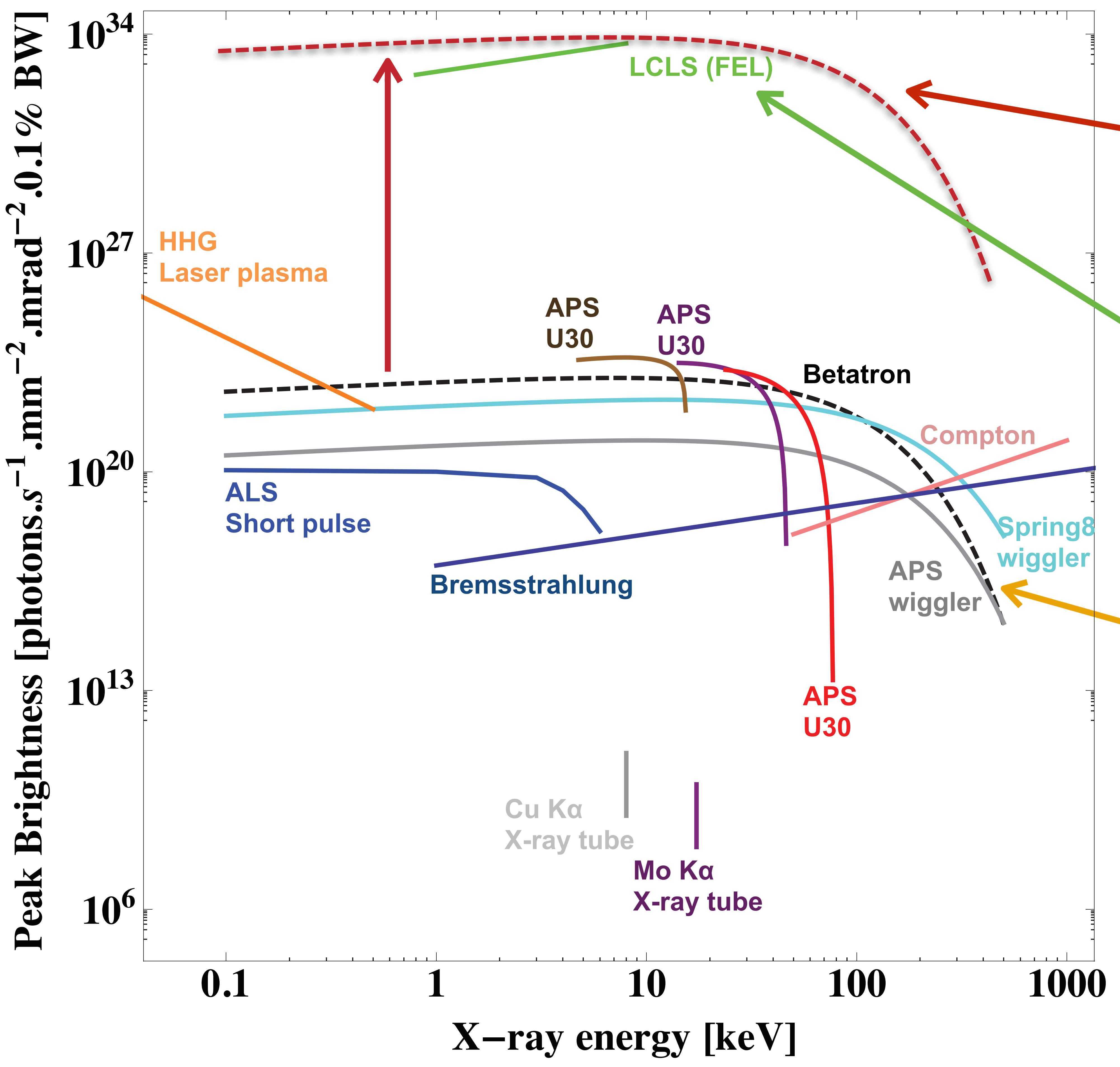


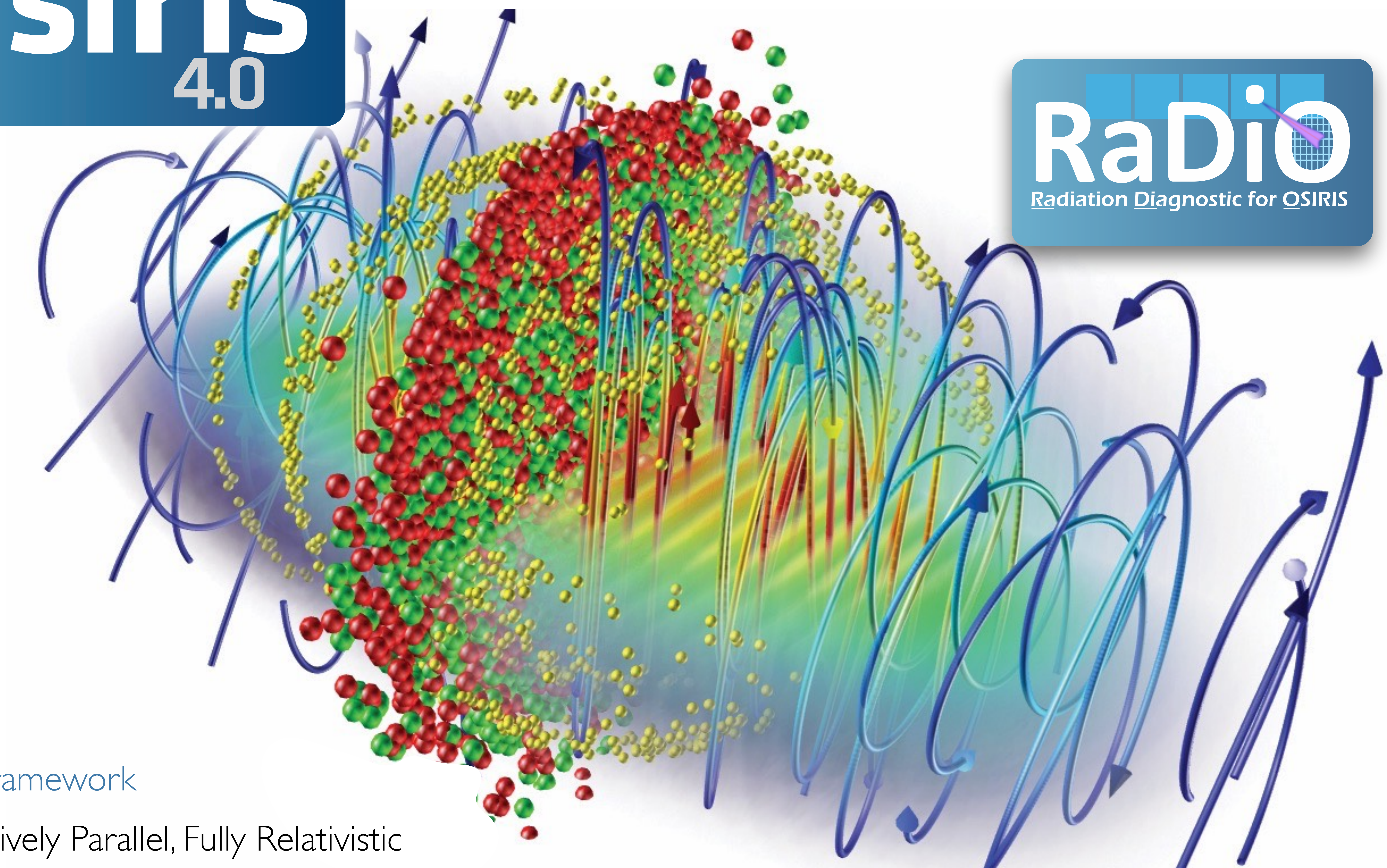
Can we make plasma accelerator based light sources **superradiant** and **temporally coherent?**

FEL temporally coherent

Betatron temporally incoherent

~10 orders of magnitude

OSIRIS open source available



Open-source 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
- Find out more at:

https://osiris-code.github.io/
epp.tecnico.ulisboa.pt/osiris

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**

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

Contents

Contents

RaDiO's algorithm*

PIC Codes and Líenard-Wiechert Fields

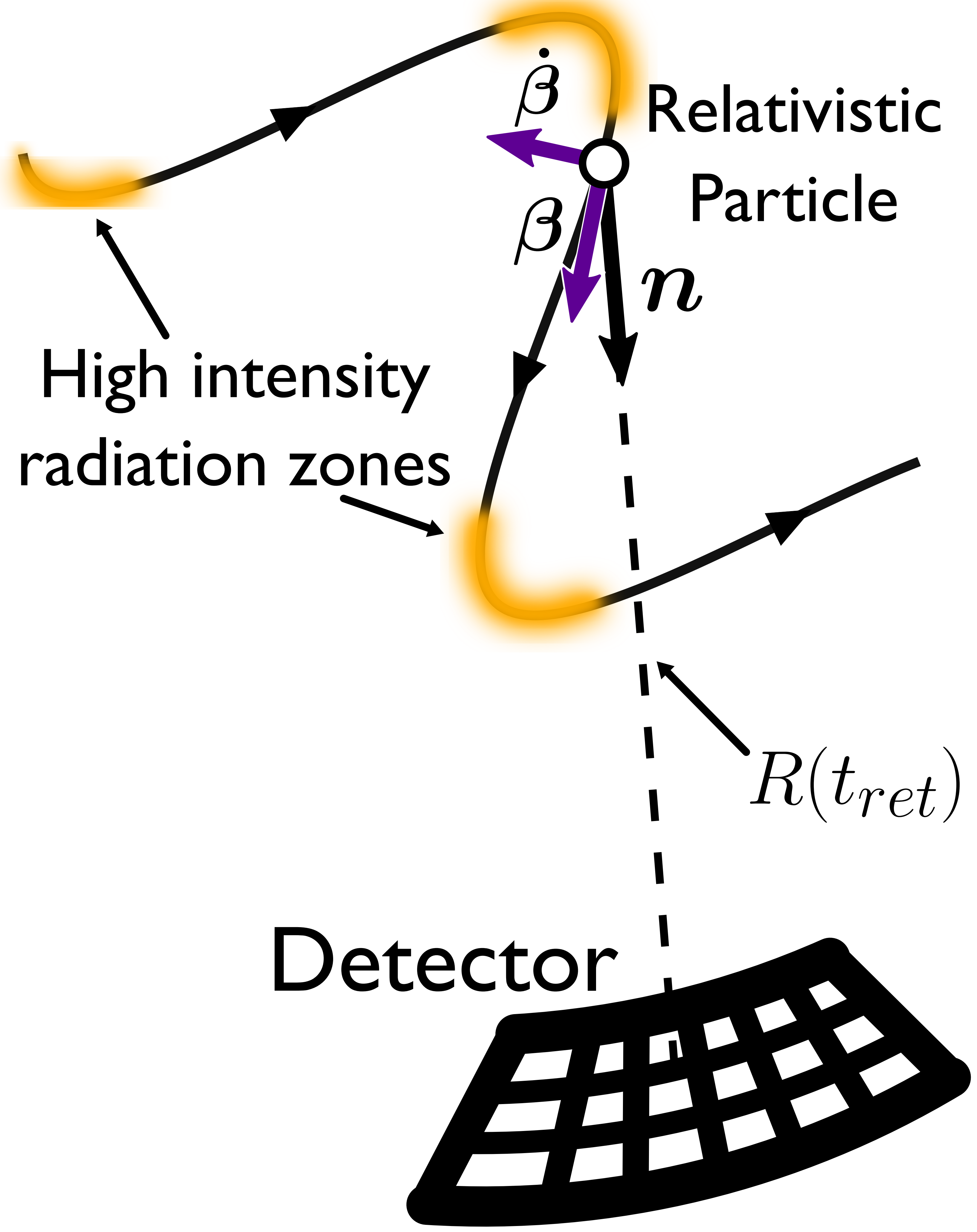
Particles exist in a **grid** which intermediates **EM interactions.**

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

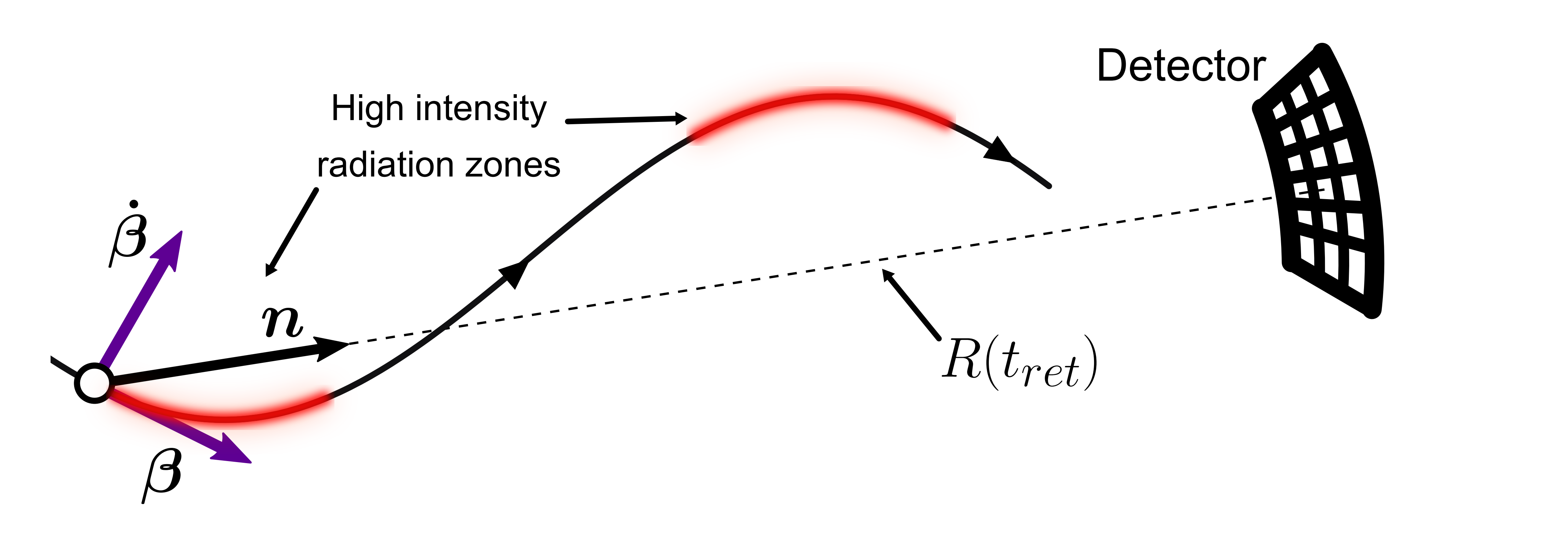
$$\mathbf{E}(\mathbf{x}, t_{det}) = \frac{q_e}{c}\left[\frac{\mathbf{n}\times[(\mathbf{n}-\boldsymbol{\beta})\times\dot{\boldsymbol{\beta}})]}{(1-\boldsymbol{\beta}\cdot\mathbf{n})^3 R}\right]_{\text{ret}}$$



*M. Pardal, et al, Computer Physics Communications, 285, 108634 (2022)

RaDiO's algorithm*

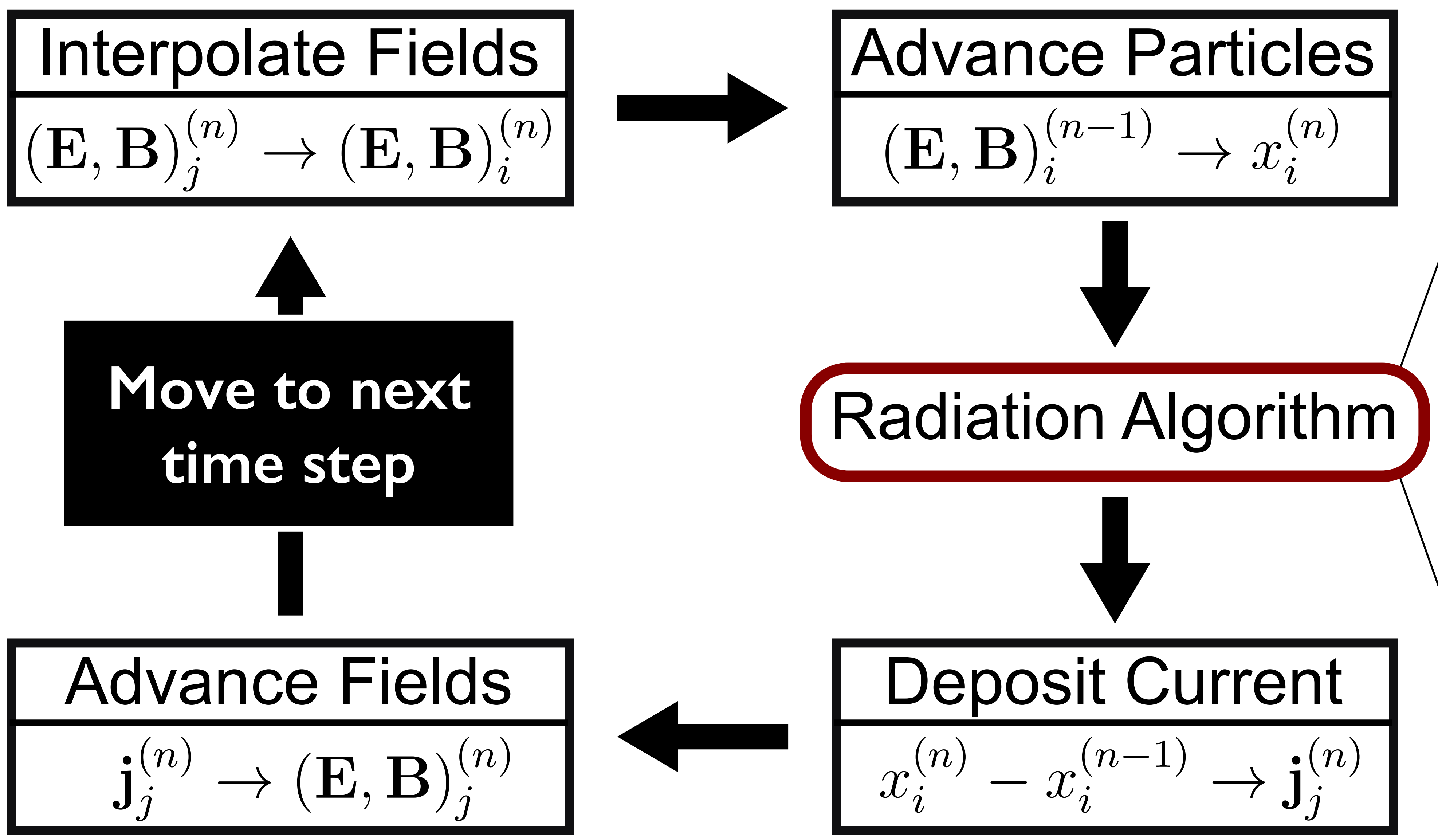
Spatiotemtporal, Run-Time Algotithm



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

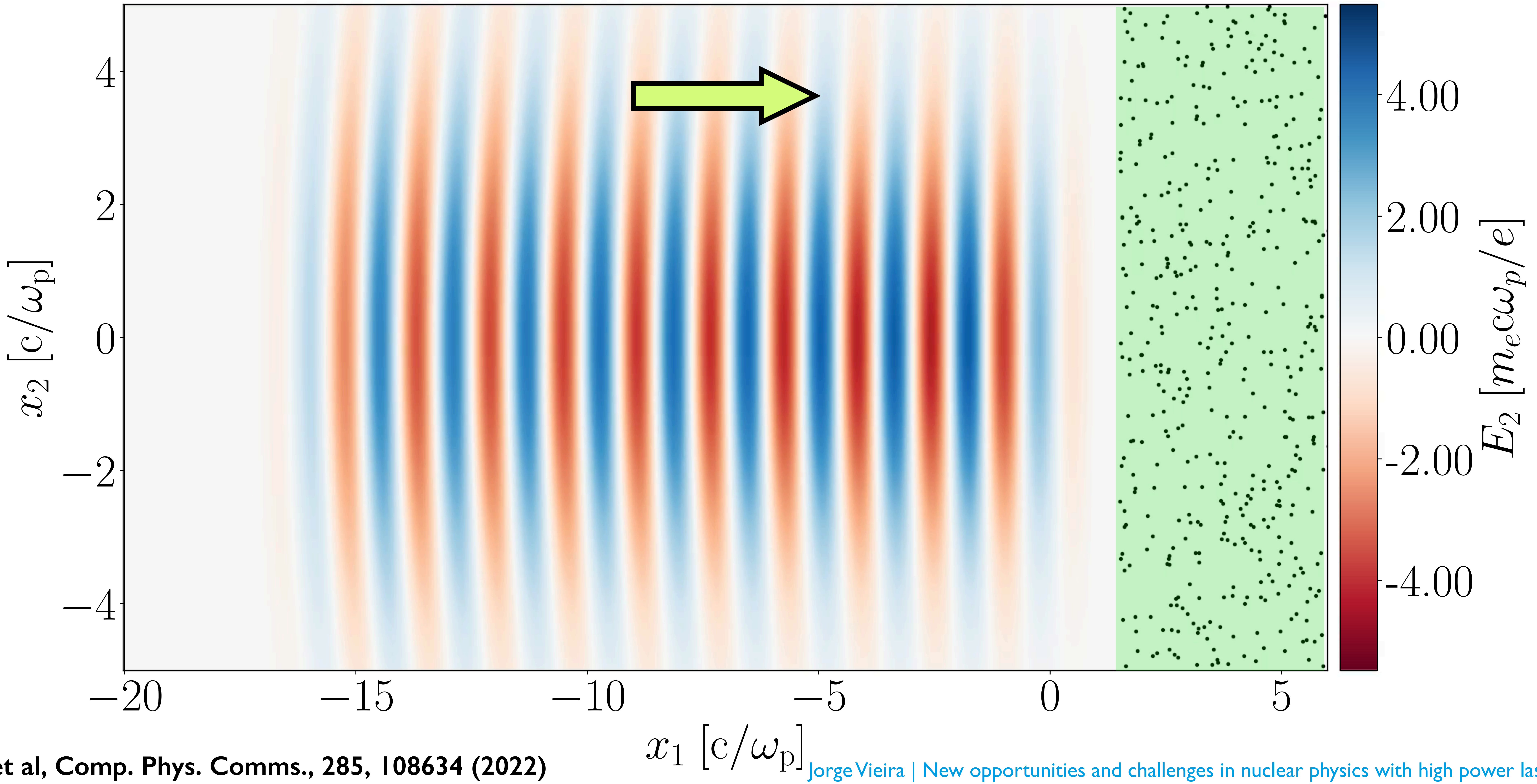


procedure RADIATIONCALCULATOR
  for all *particle* **in** simulation **do**
    $\beta \leftarrow \text{velocity}(particle) = \mathbf{p}/\sqrt{|\mathbf{p}|^2+1}$
    $\dot{\beta} \leftarrow \text{acceleration}(particle) = (\beta - \beta_{prev})/dt$
    for all *cell* **in** detector **do**
      $R \leftarrow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

*M. Pardal, et al, Computer Physics Communications, 285, 108634 (2022)

RaDiO Results

HHG Radiation from a Plasma Mirror

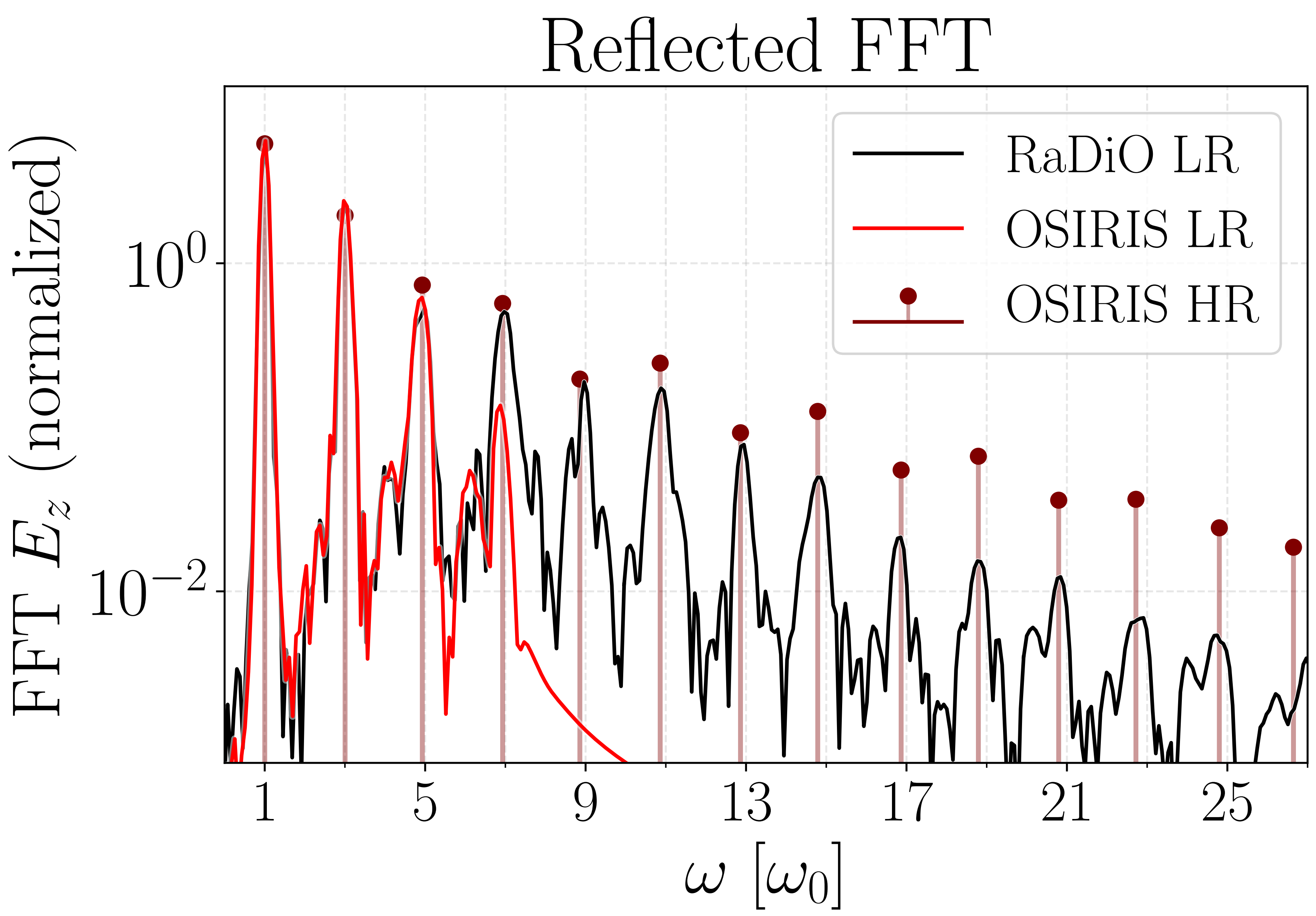


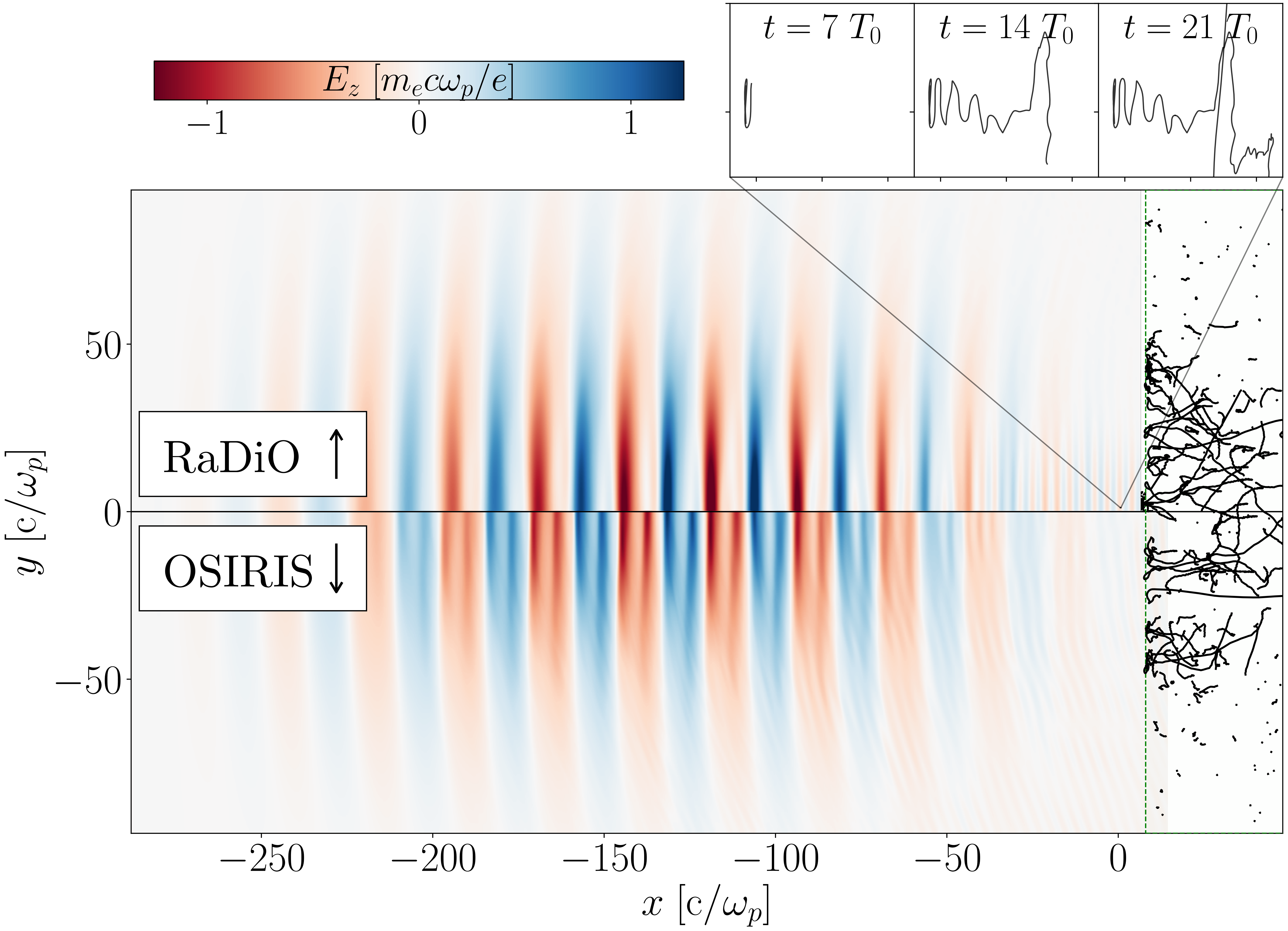
*M. Pardal, et al, Comp. Phys. Comms., 285, 108634 (2022)

RaDiO Results*

HHG Radiation from a Plasma Mirror

- **Radiation** from $> 10^6$ plasma **particles**;
- Time resolution $> 5\times$ **PIC resolution**;
- Much **more harmonics** in the spectrum;





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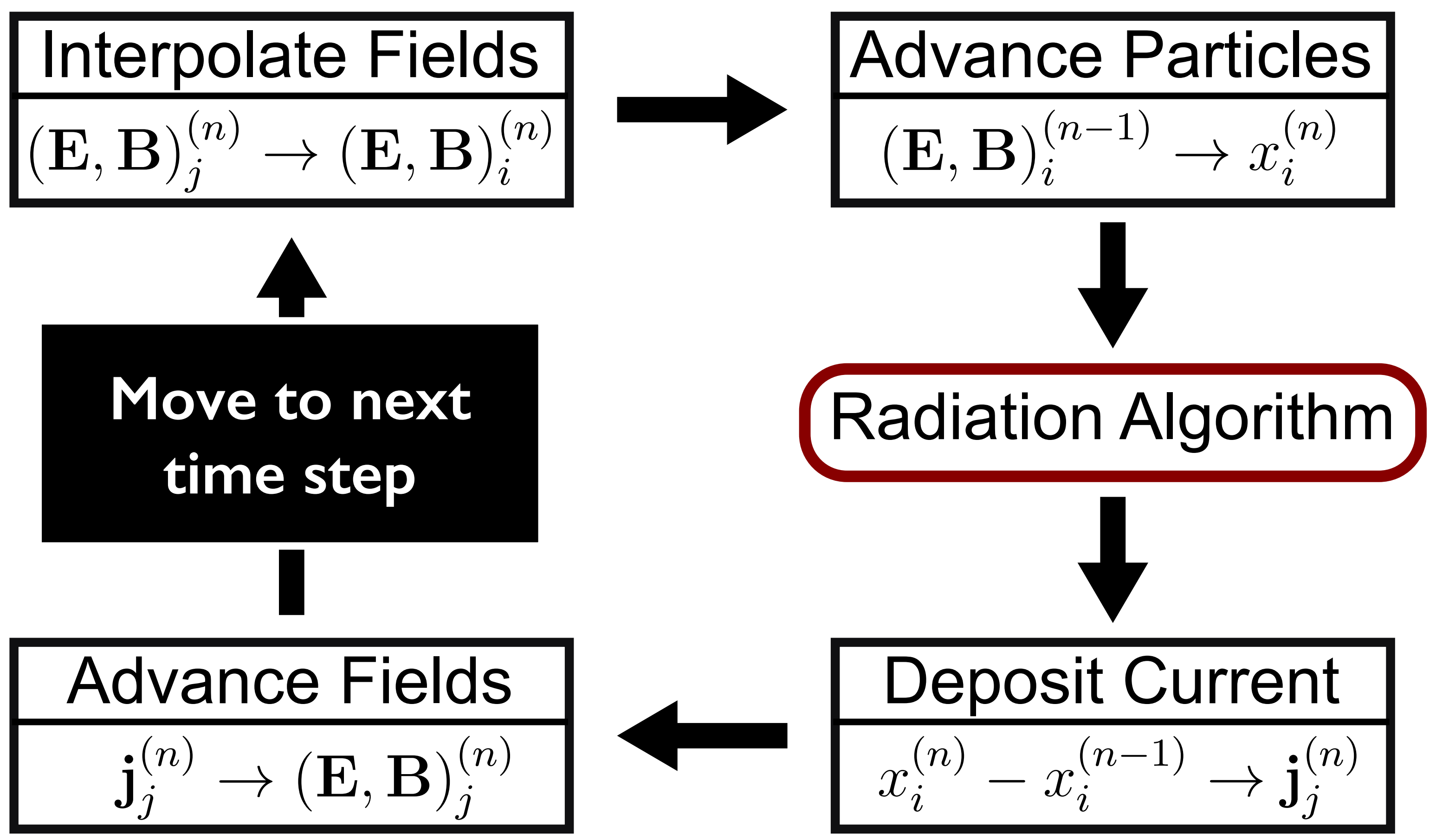
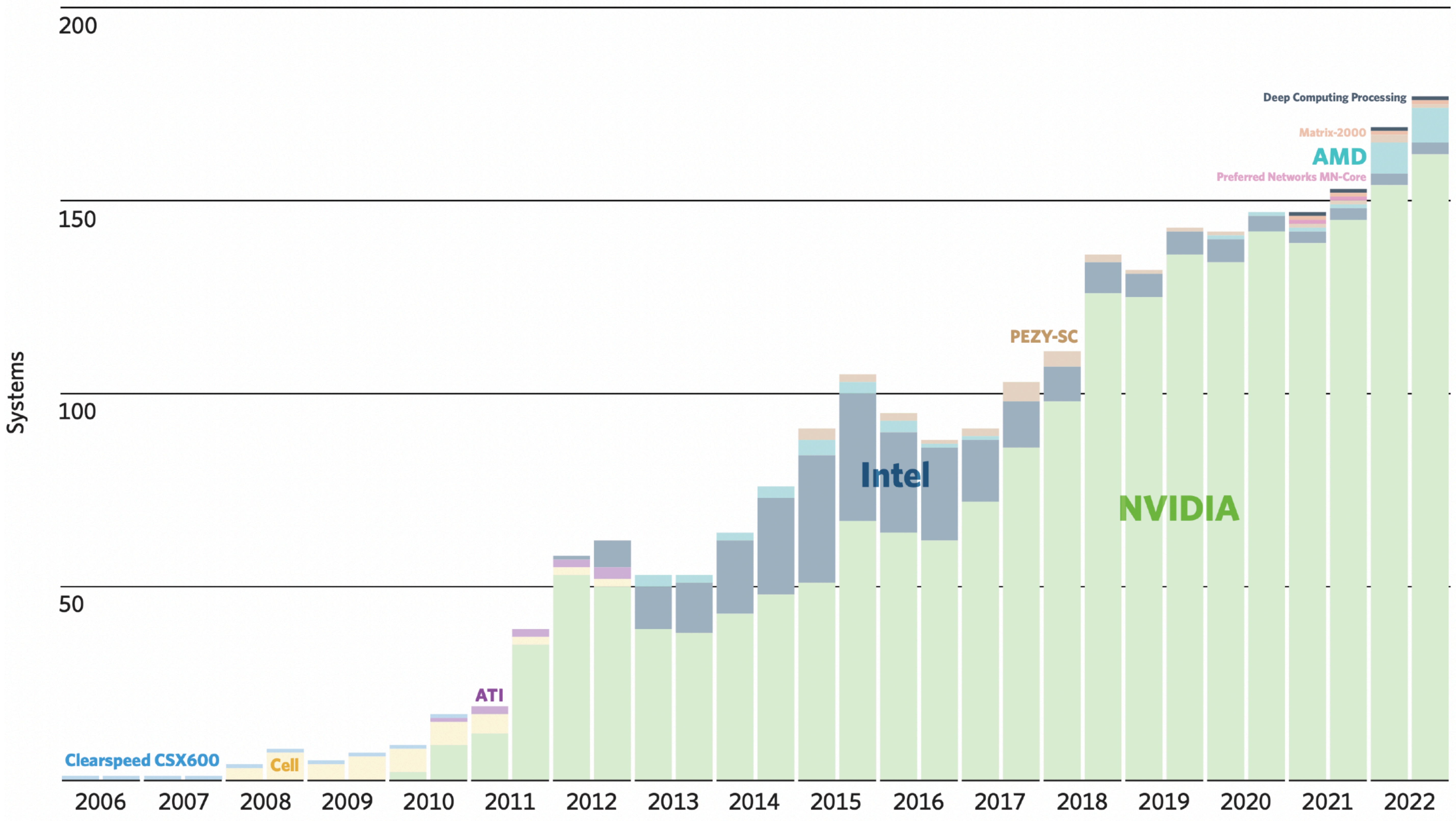
RaDiO's Algorithm for CUDA

Resource Allocation



- ✓ The **PIC Loop** is performed in the **CPU**
- ✓ The **radiation calculations** are **offloaded to the GPU**

ACCELERATORS/CO-PROCESSORS



* Top 500 November 2022 Poster

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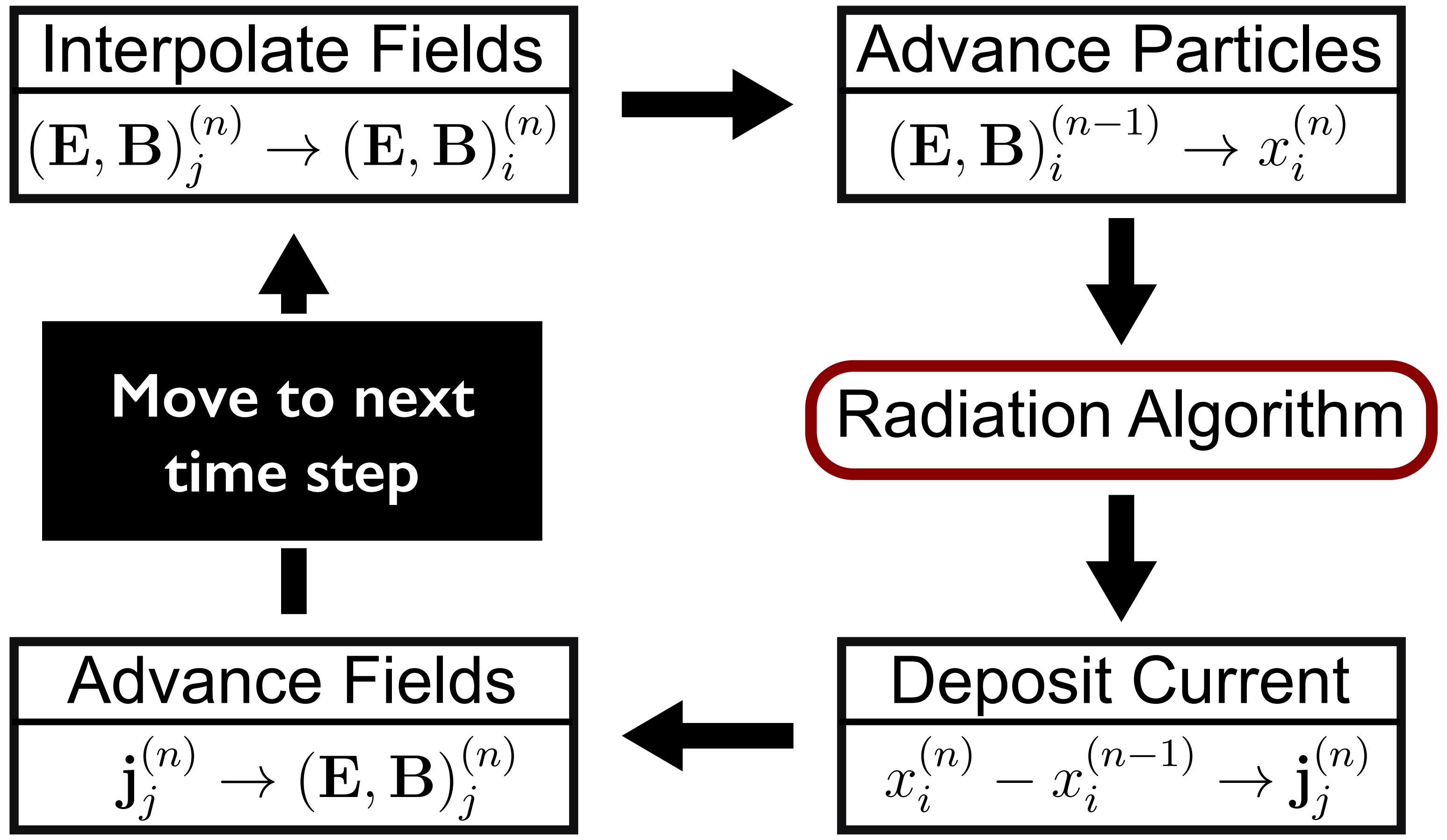

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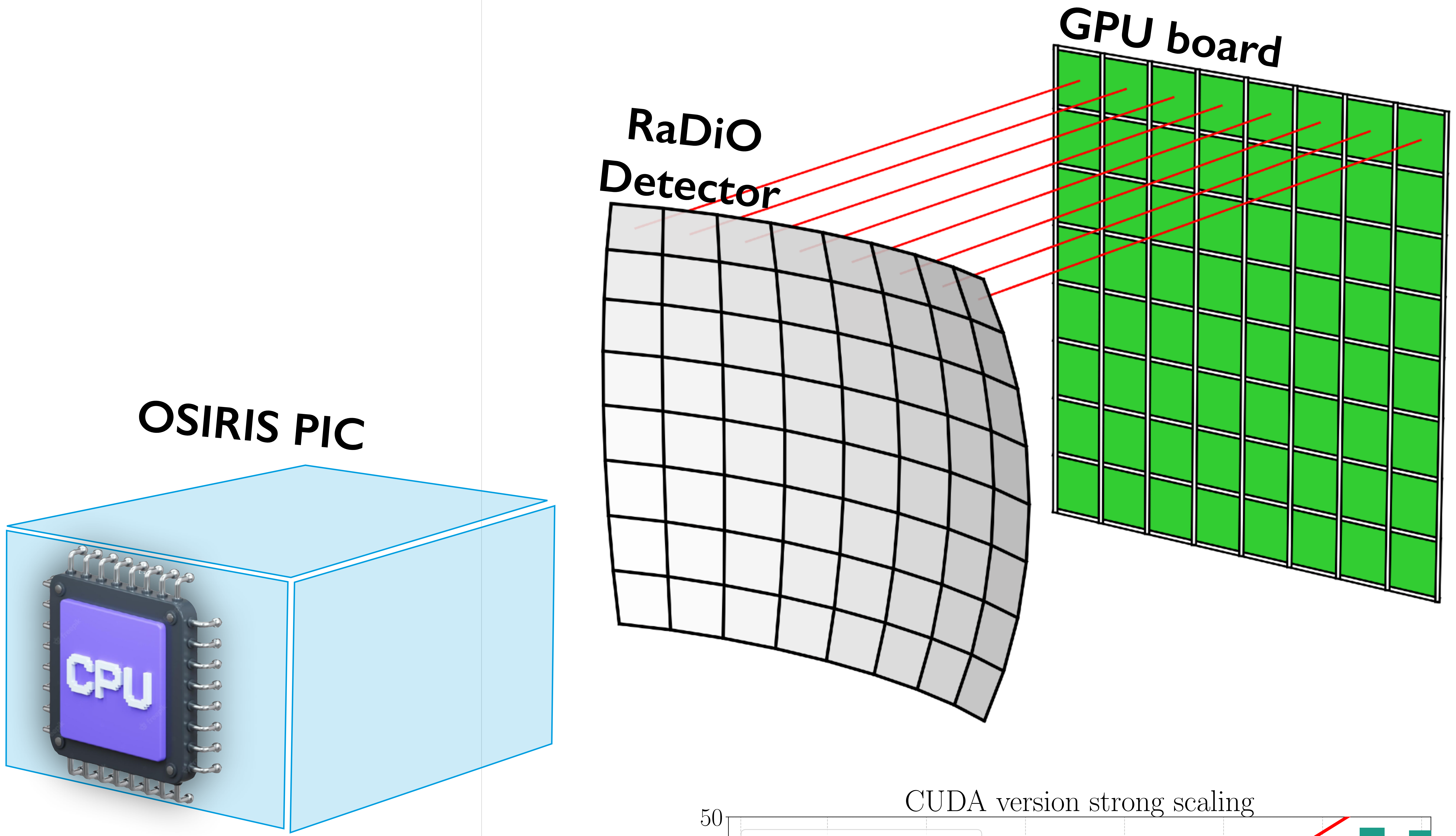
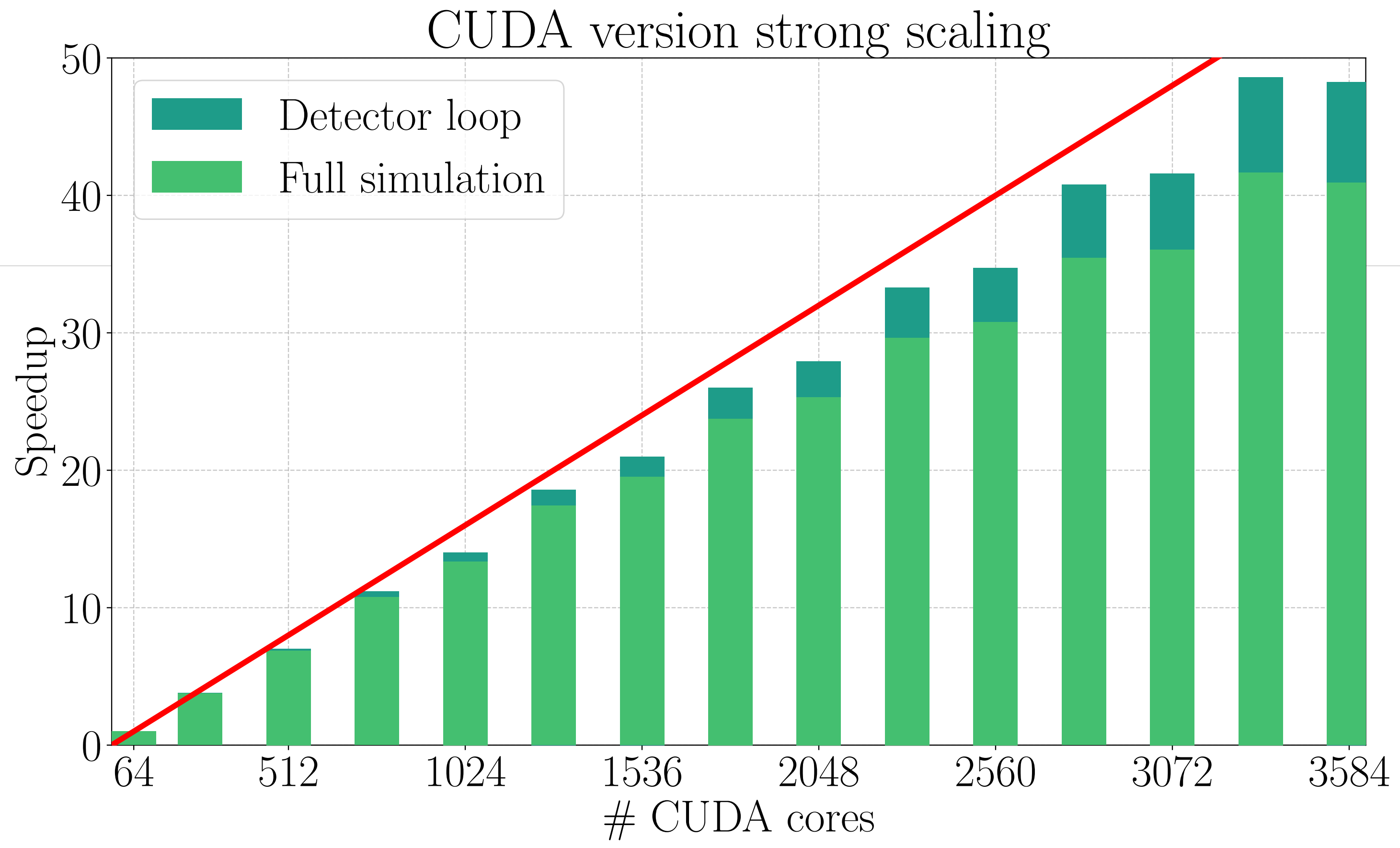


500x faster than serial



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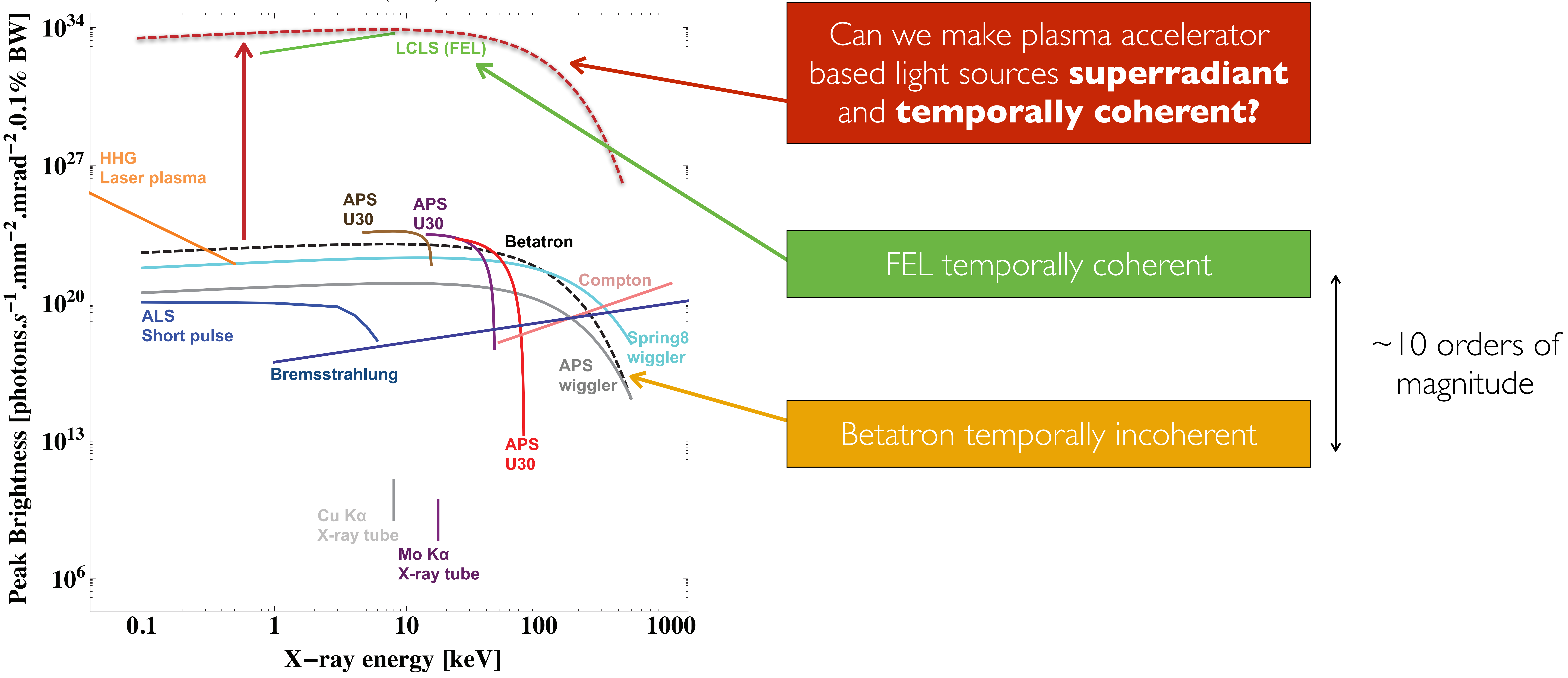
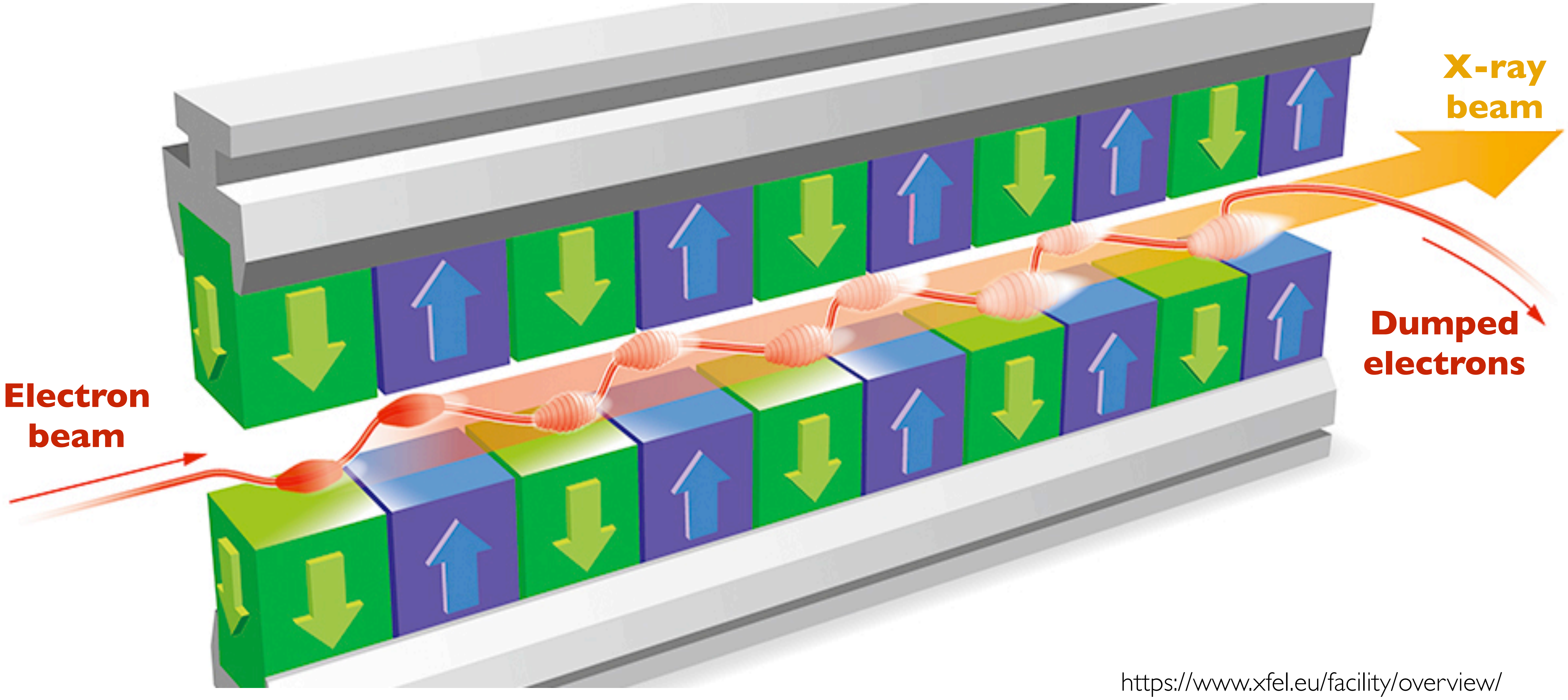


Contents

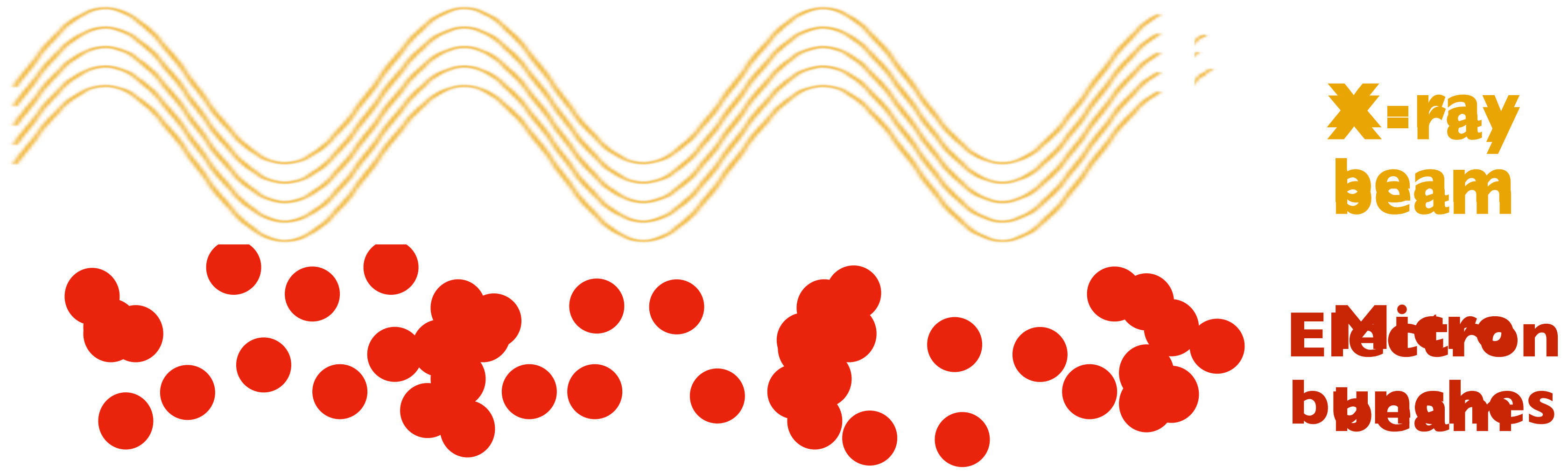
Collective effects are critical to advanced light sources

Collective motions explain the high brightness in an free electron laser (FEL)

FEL setup



https://www.xfel.eu/facility/overview/



In the FEL every microbunch emits like a single finite-sized particle

The collective trajectory and single particle trajectory are the same

But there are other light-emitting systems where these trajectories are **completely decoupled**

B. Malaca *et al.*

Collective effects: that's what plasma physics is all about!

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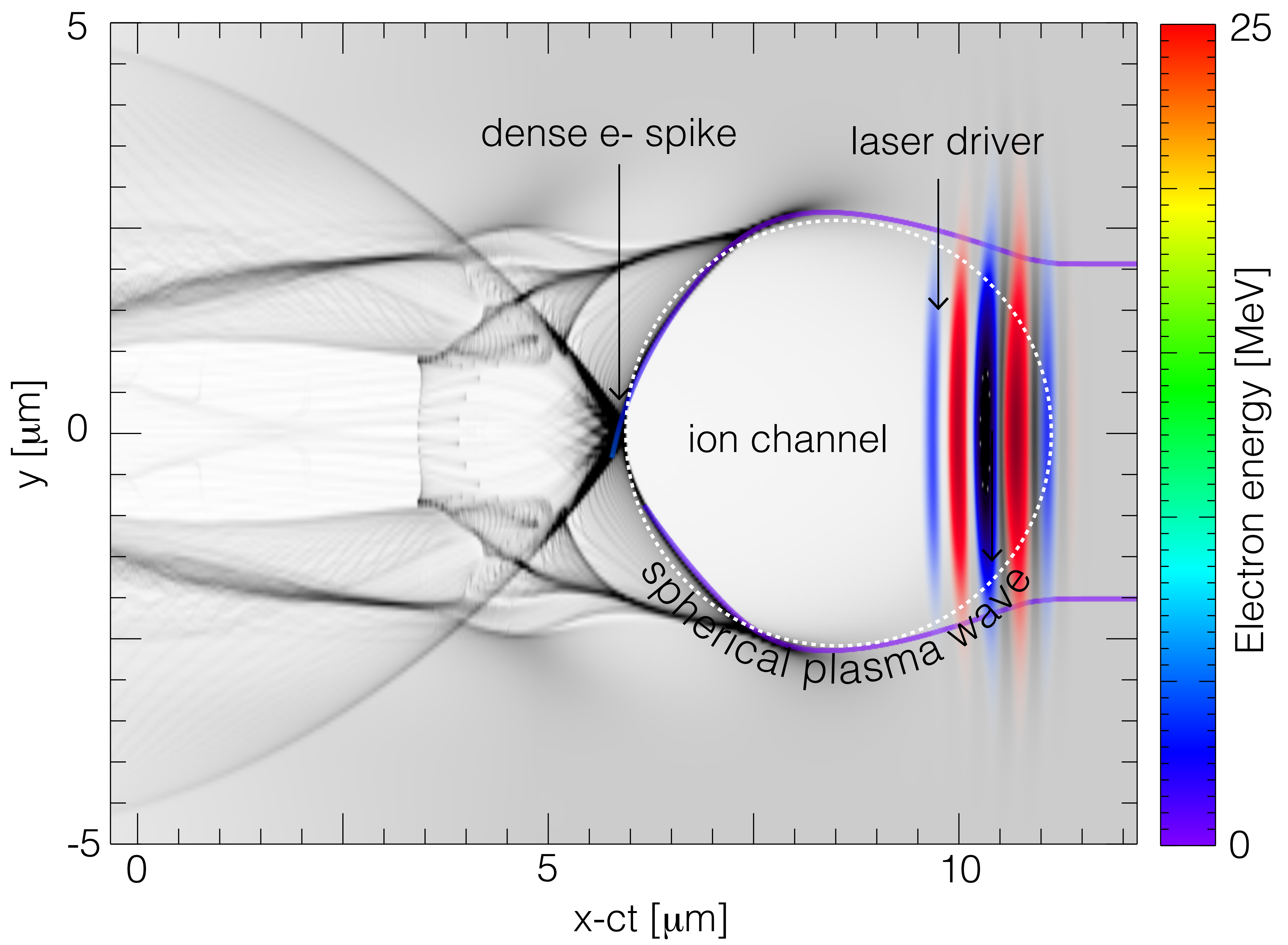
Nonlinear plasma wakefields



Single e- and wake trajectories are decoupled

- Wakefield moves **forward in x** at the driver velocity
- Plasma electrons travel **sideways** and **forward/ backward** and **radiate!**

B. Malaca *et al. Nature Photonics 18, 39–45 (2024)*

Collective effects: that's what plasma physics is all about!

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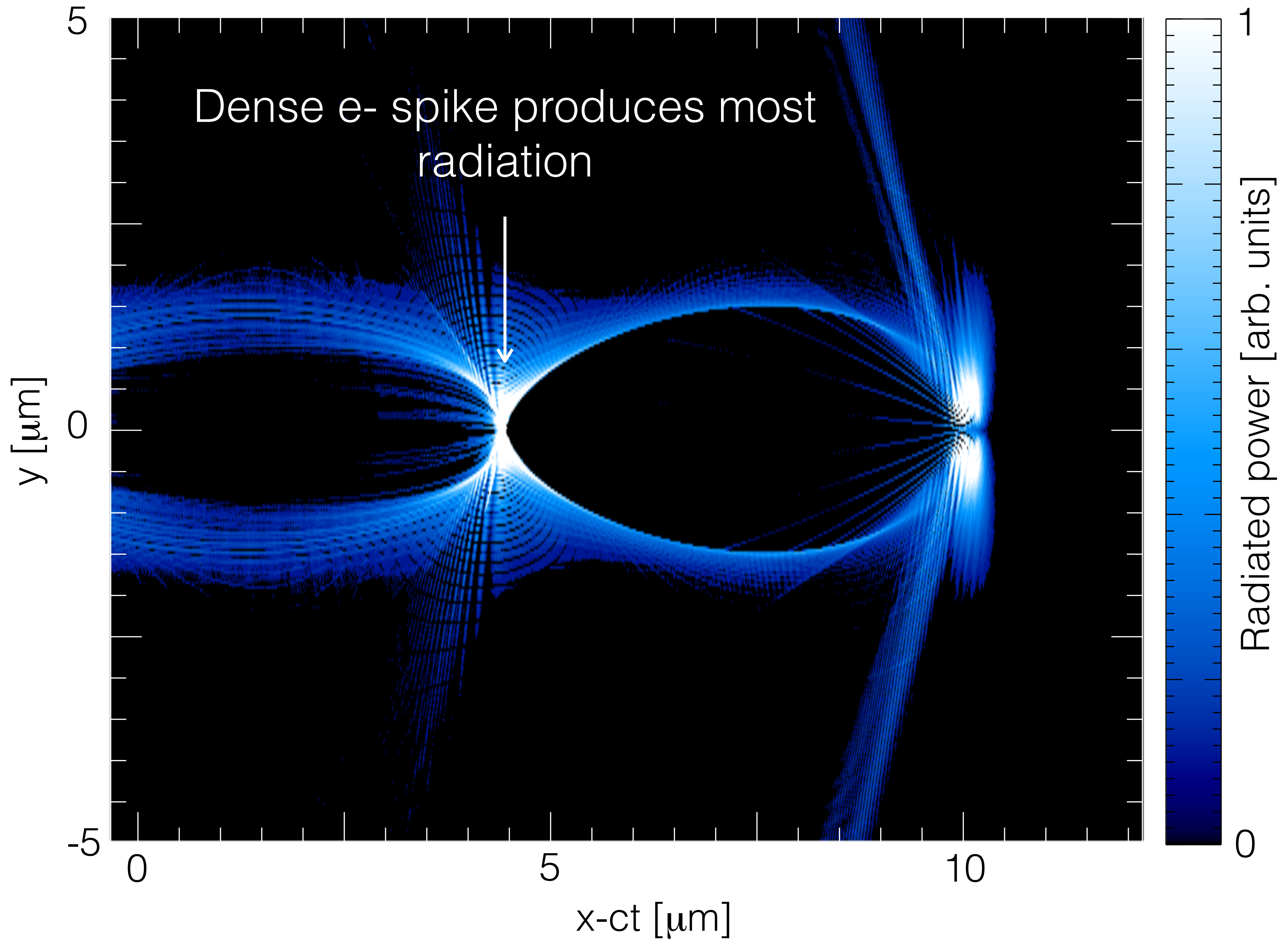
Nonlinear plasma wakefields radiate



Single e- and wake trajectories are decoupled

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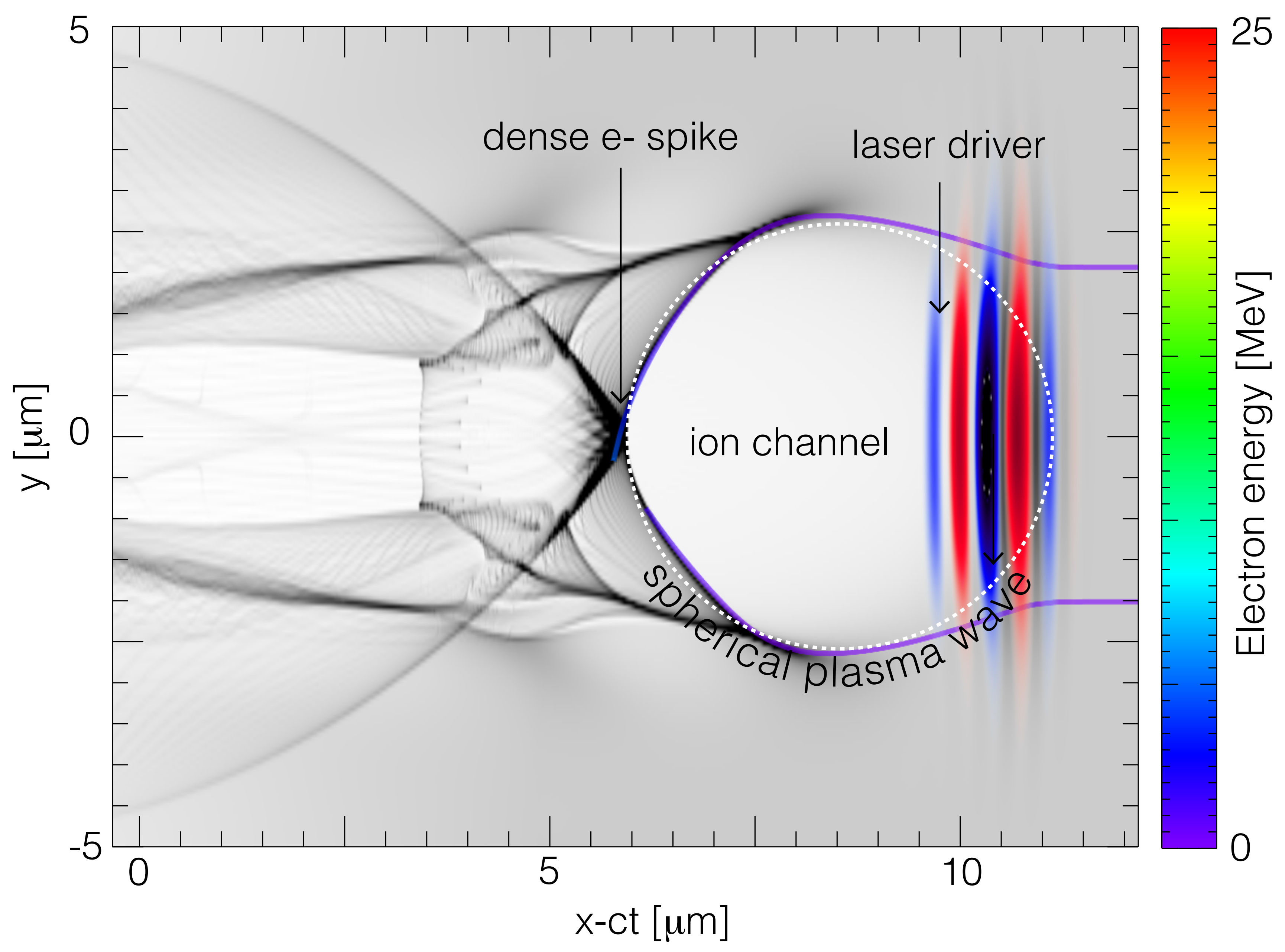
What are the new radiation phenomena emerging from collective effects?

B. Malaca *et al. Nature Photonics 18, 39–45 (2024)*

Radiation from collective modes

$$\frac{d^2 I}{d\omega d\Omega} = \frac{\omega^2}{4\pi^2 c^3} \left| \int \mathrm{d}\mathbf{r}\mathrm{d}t \; \mathbf{n} \times \{\mathbf{n} \times \mathbf{j}[\mathbf{r} - \mathbf{r}_c(t)]\} e^{i\omega[t - \mathbf{n}\cdot\mathbf{r}/c]} \right|^2$$

Laser driven plasma waves $\mathbf{r}_c = \mathbf{v}_g t$

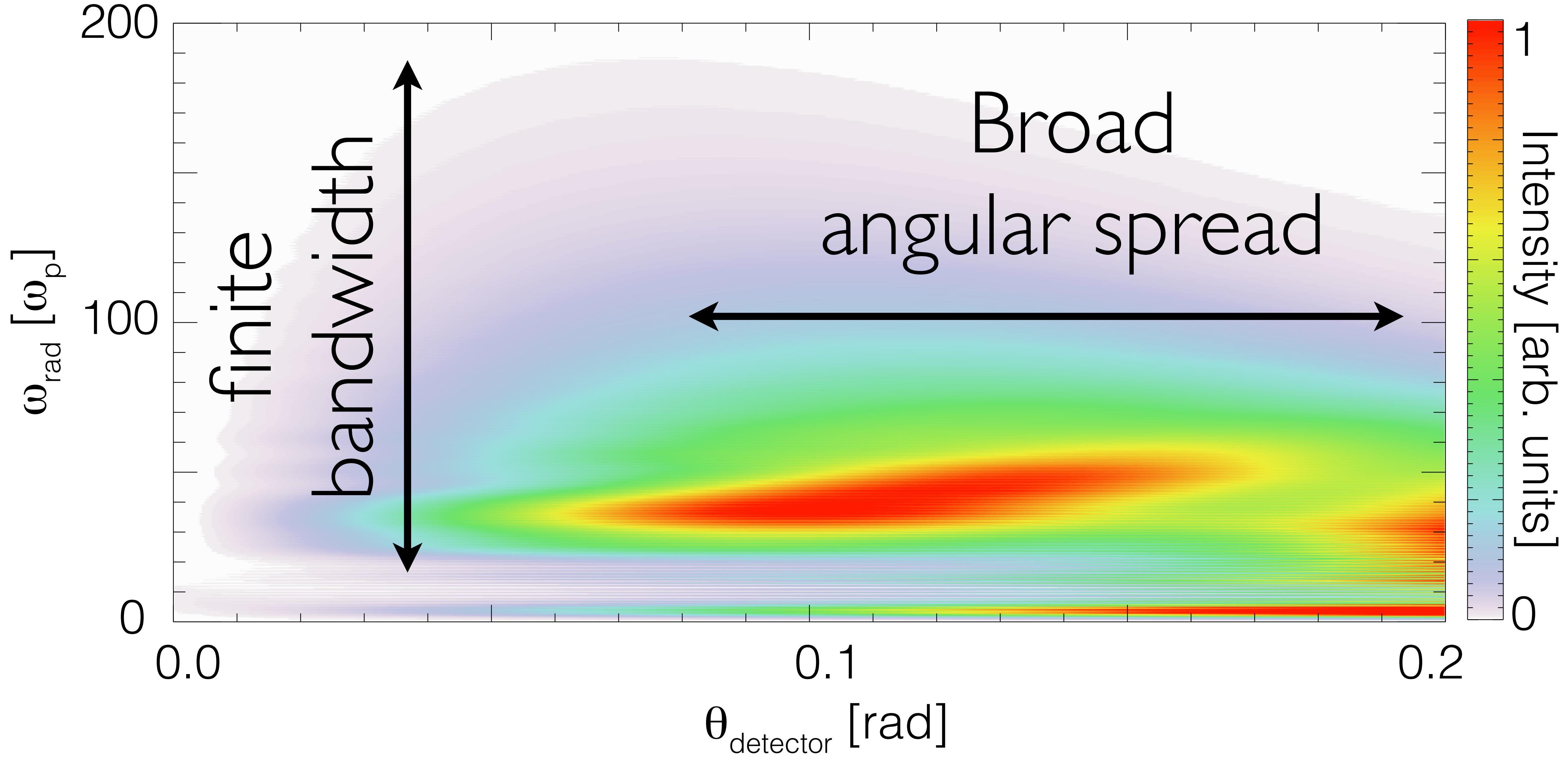


B. Malaca et al.

Radiation from collective modes

$$\frac{d^2I}{d\omega d\Omega} = \frac{\omega^2}{4\pi^2c^3}\left|\int dt\ \mathcal{S} e^{i\omega[t-\mathbf{n}\cdot\mathbf{r}_c(t)/c]}\right|^2$$

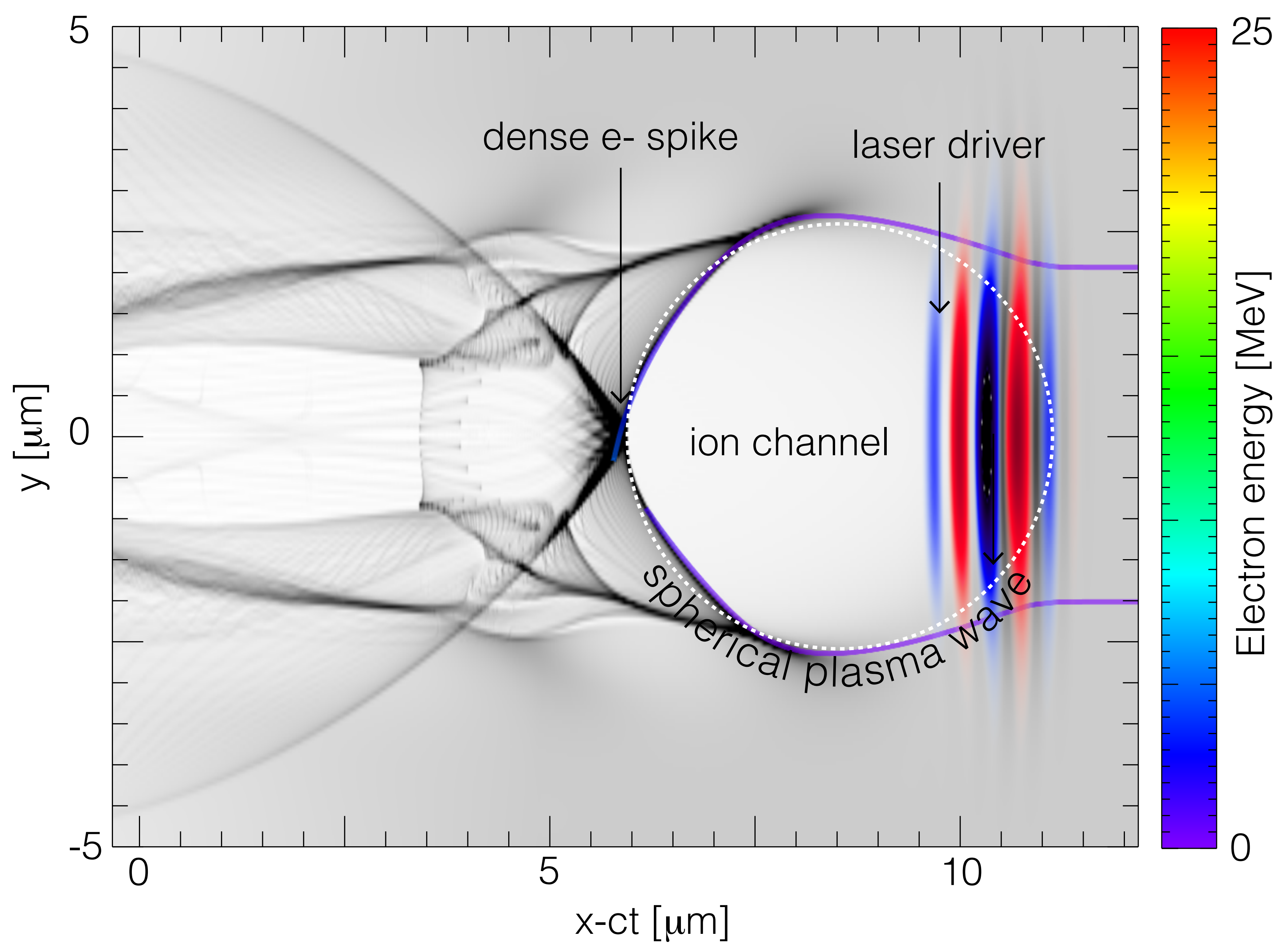
Shape factor



$$\mathcal{S} = \int d\boldsymbol{\xi}\ \mathbf{n}\times[\mathbf{n}\times\mathbf{j}(\boldsymbol{\xi})]e^{-i\omega\mathbf{n}\cdot\boldsymbol{\xi}/c} \qquad \boldsymbol{\xi} = \mathbf{r} - \mathbf{r}_c(t)$$

RaDiO Radiation Diagnostic for OSIRIS

Laser driven plasma waves $\mathbf{r}_c = \mathbf{v}_g t$



B. Malaca et al.

Can quasiparticles radiate as a finite-sized single-particle?

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Collective motion (quasiparticle)

$$\frac{d^2I}{d\omega d\Omega} = \frac{\omega^2}{4\pi^2c^3}\left|\int \mathrm{d}t\ \mathcal{S} e^{i\omega[t-\mathbf{n}\cdot\mathbf{r}_c(t)/c]}\right|^2$$

$$\mathcal{S} = \int \mathrm{d}\boldsymbol{\xi}\ \mathbf{n}\times[\mathbf{n}\times\mathbf{j}(\boldsymbol{\xi})]e^{-i\omega\mathbf{n}\cdot\boldsymbol{\xi}/c}$$

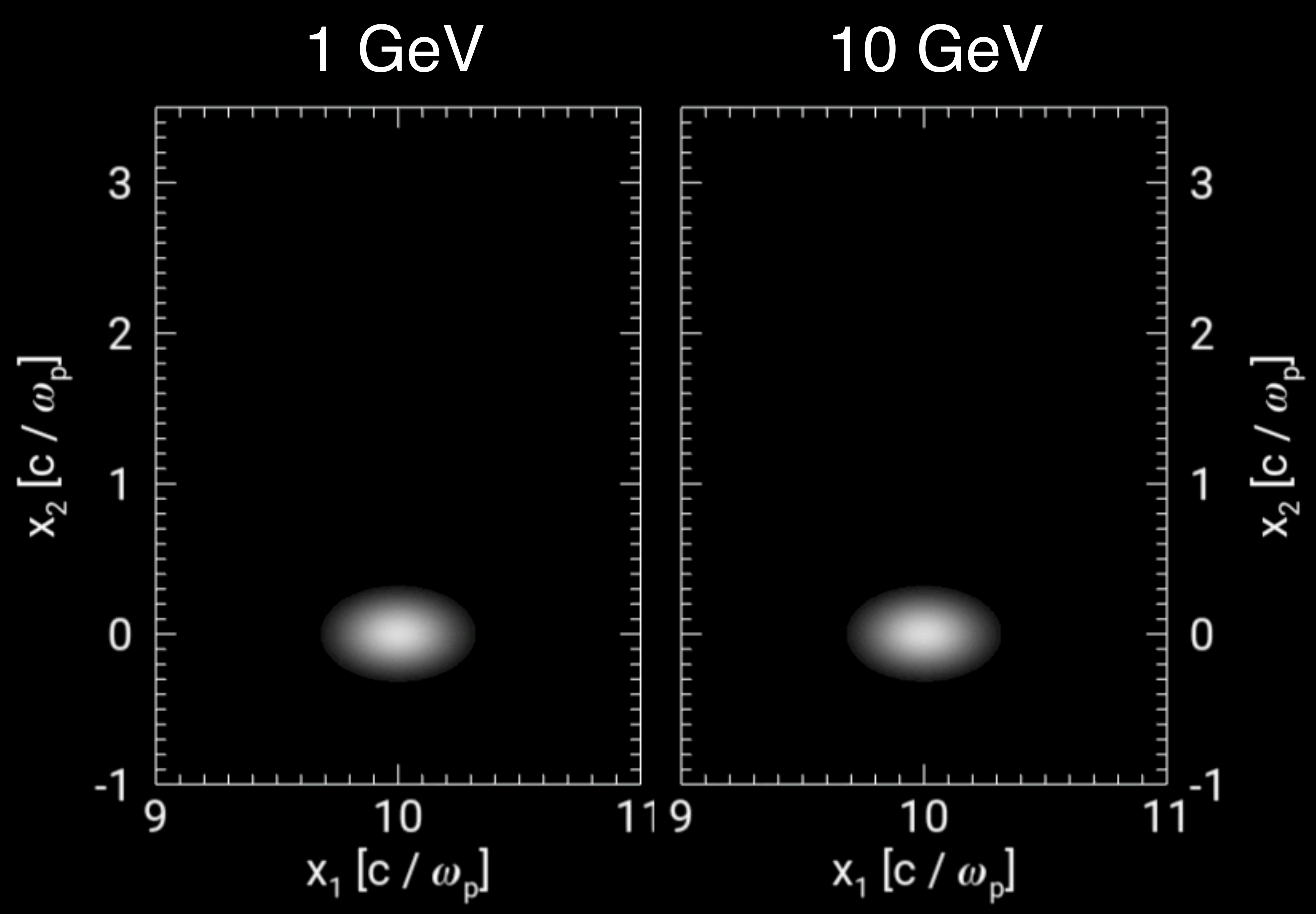
Single electron

$$\frac{d^2I}{d\omega d\Omega} = \frac{\omega^2}{4\pi^2c^3}\left|\int \mathrm{d}t\ \mathbf{n}\times(\mathbf{n}\times\mathbf{v})\ e^{i\omega[t-\mathbf{n}\cdot\mathbf{r}_c(t)/c]}\right|^2$$

B. Malaca et al.

Can quasiparticles radiate as a finite-sized single-particle?

Relativistic electron bunch in external B



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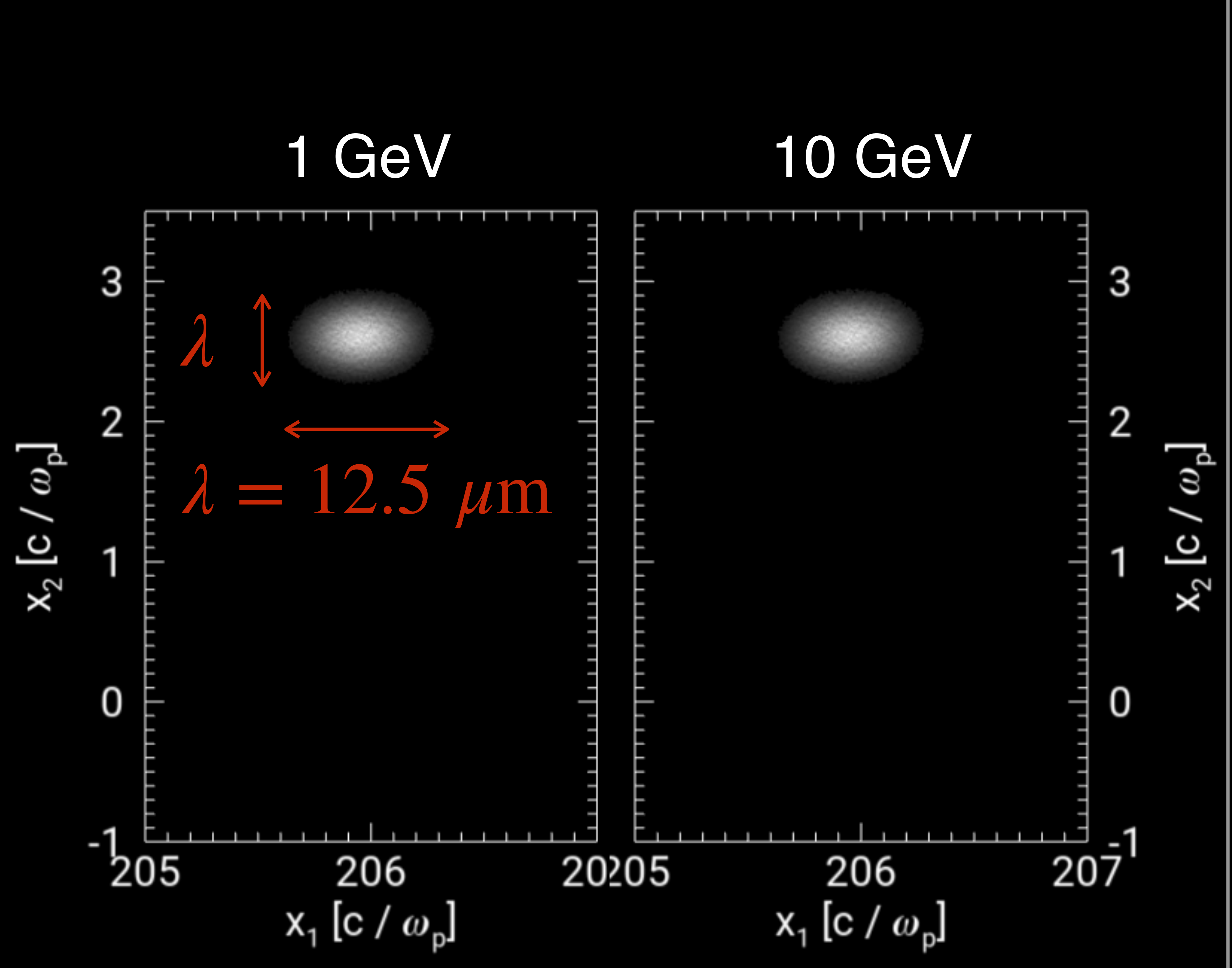

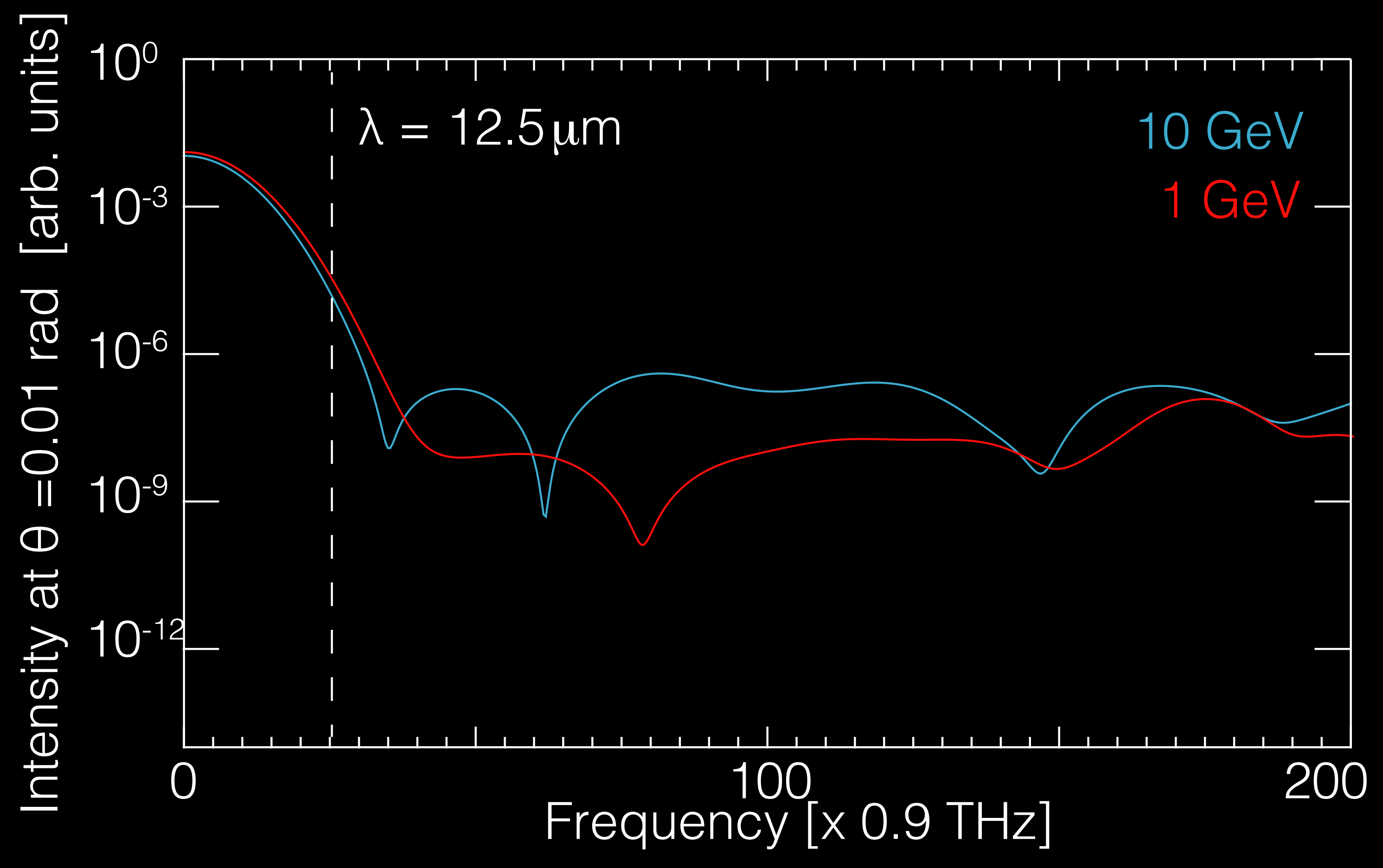

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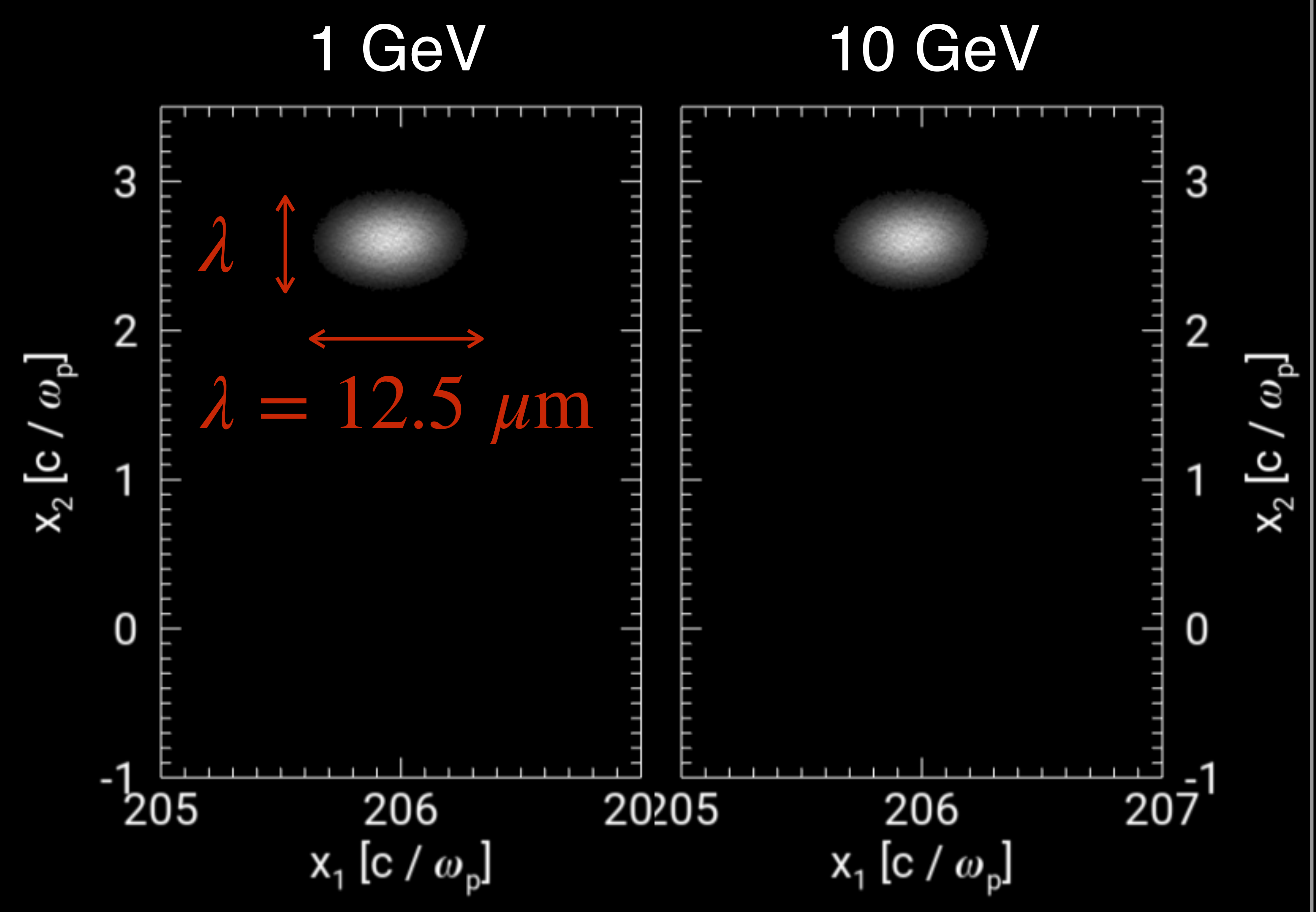

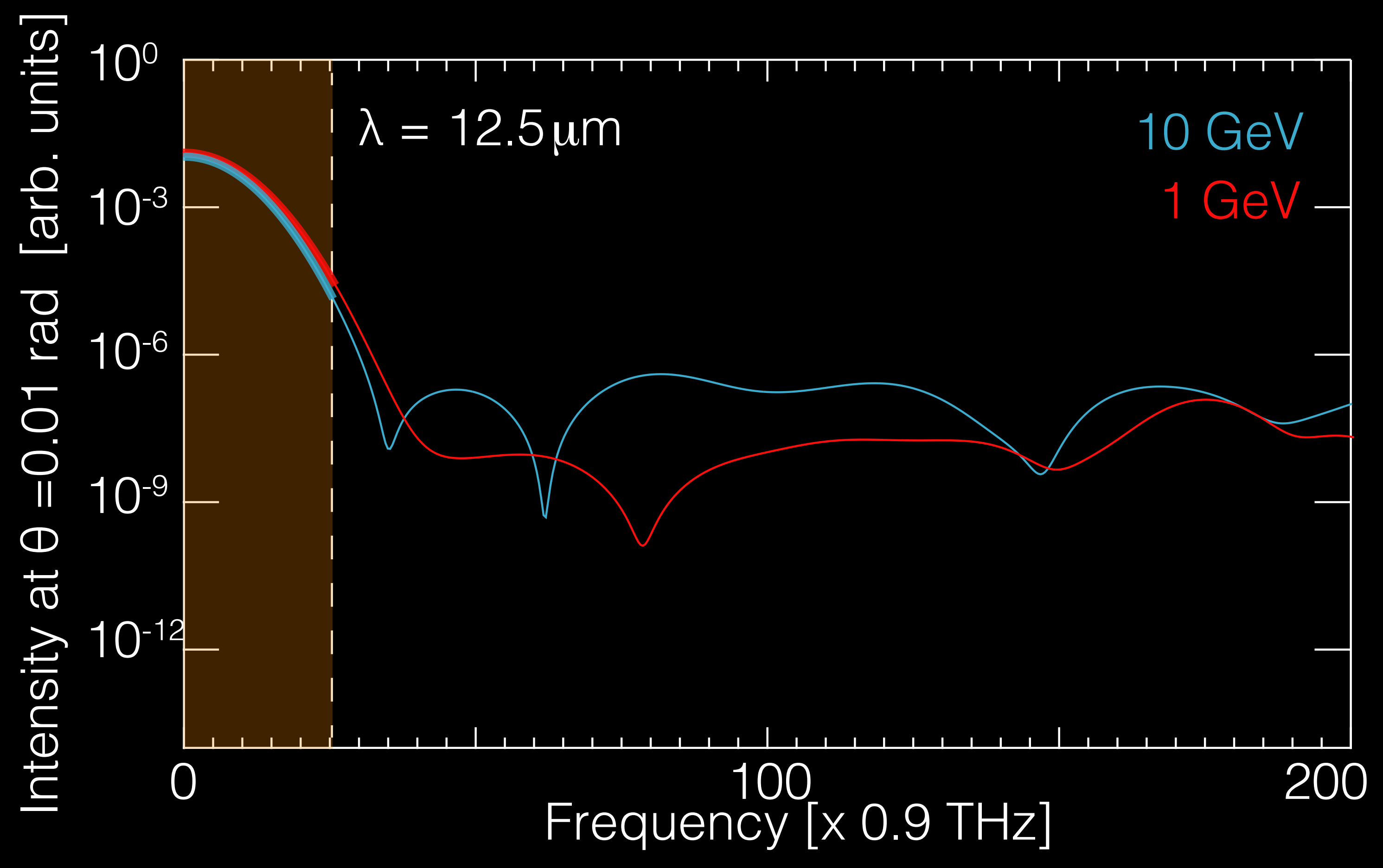

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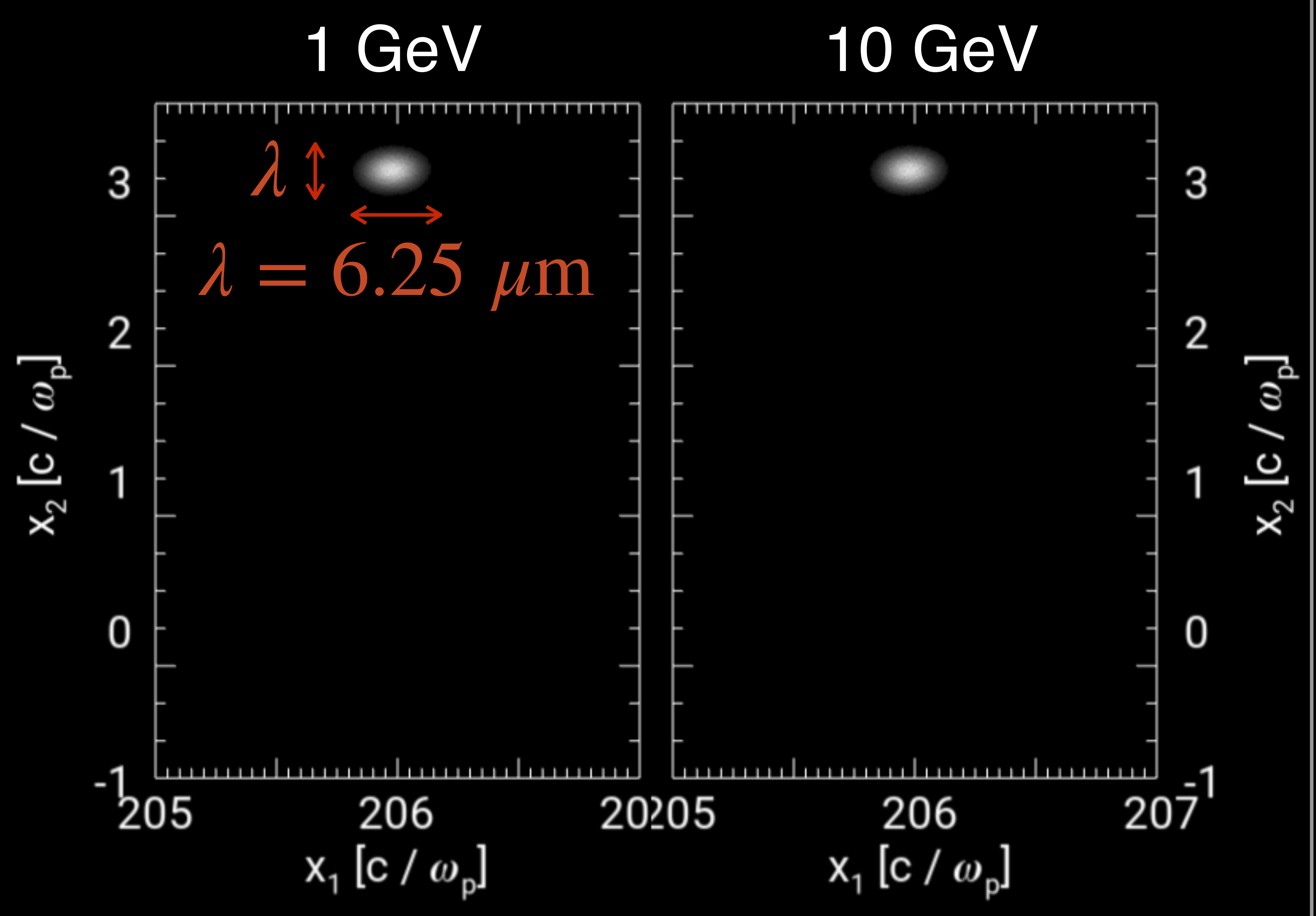
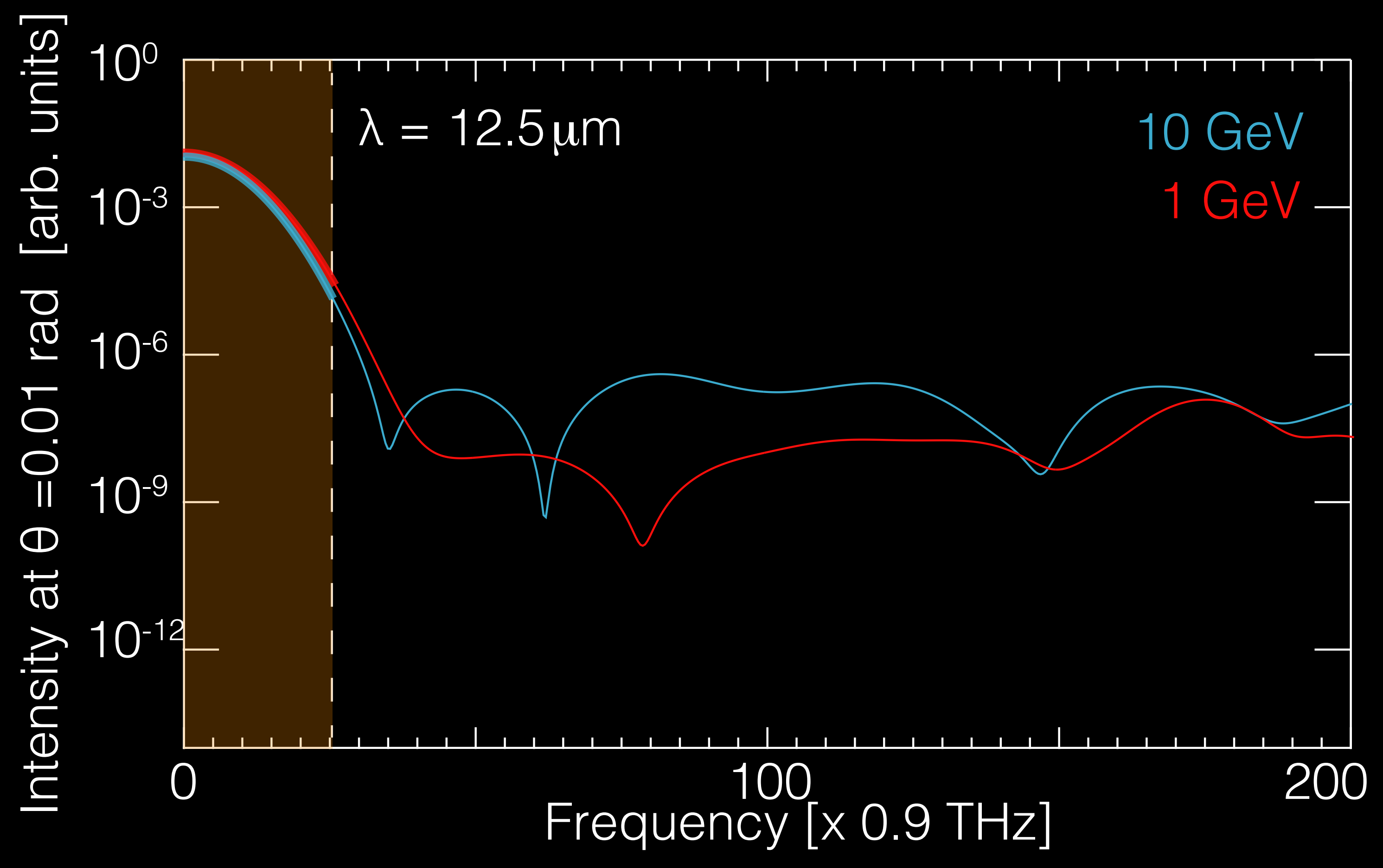
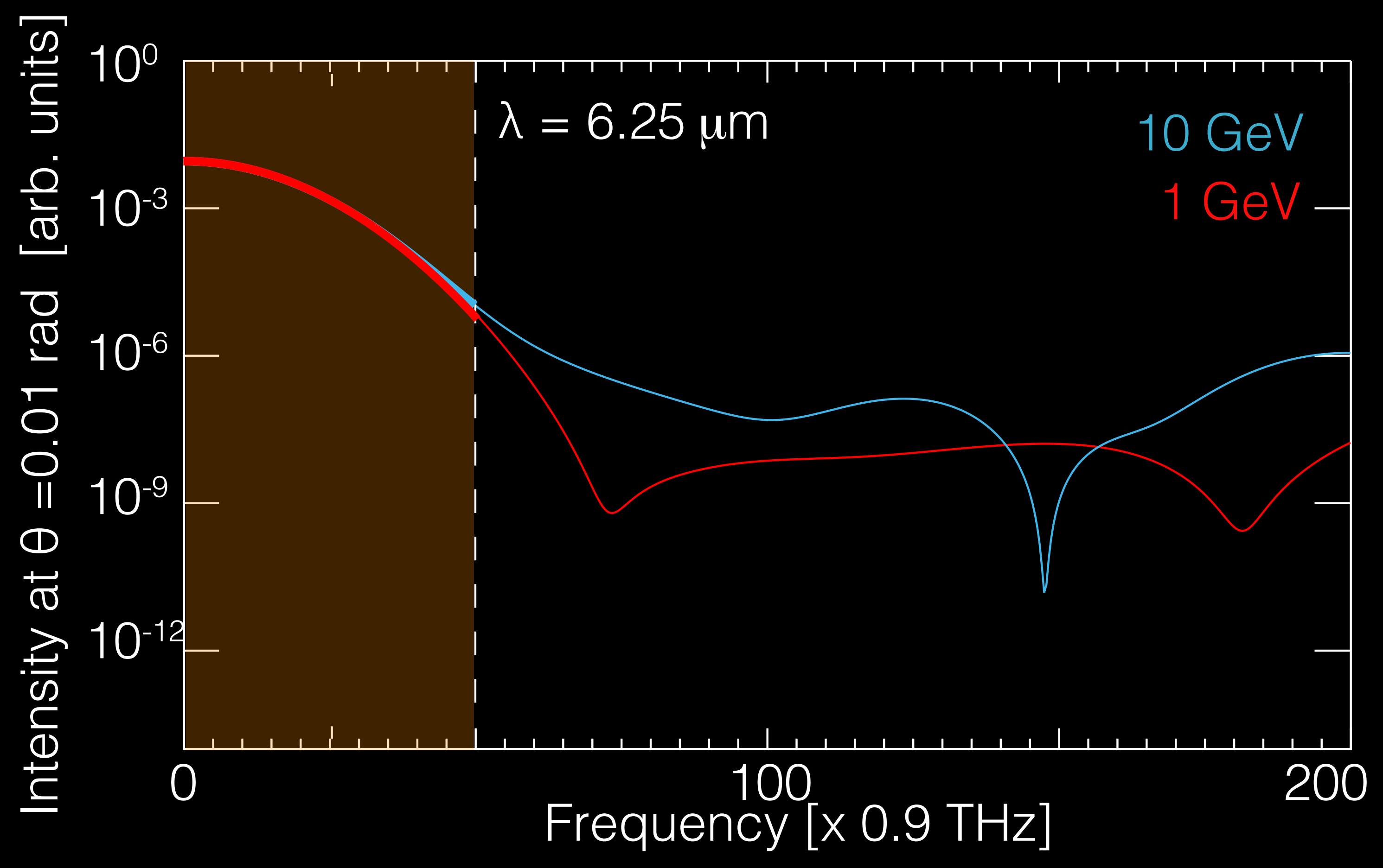
Can quasiparticles radiate as a finite-sized single-particle?

A quasiparticle radiates like a a finite-sized **single** particle
for radiation wavelengths **longer** than its size, **regardless** of microscopic e- trajectories

Relativistic electron bunch in external B







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Can quasiparticles radiate as a finite-sized single-particle?

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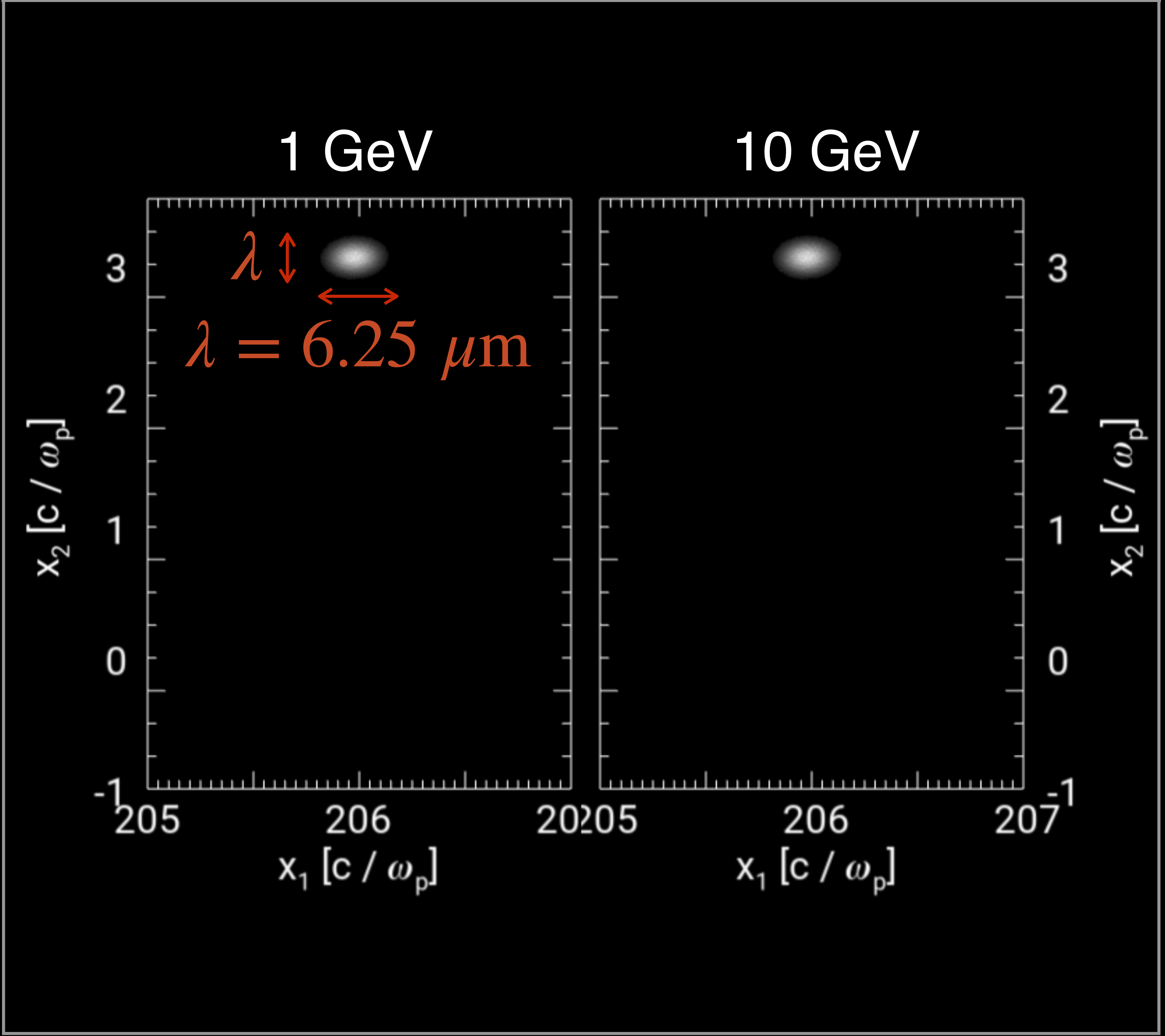
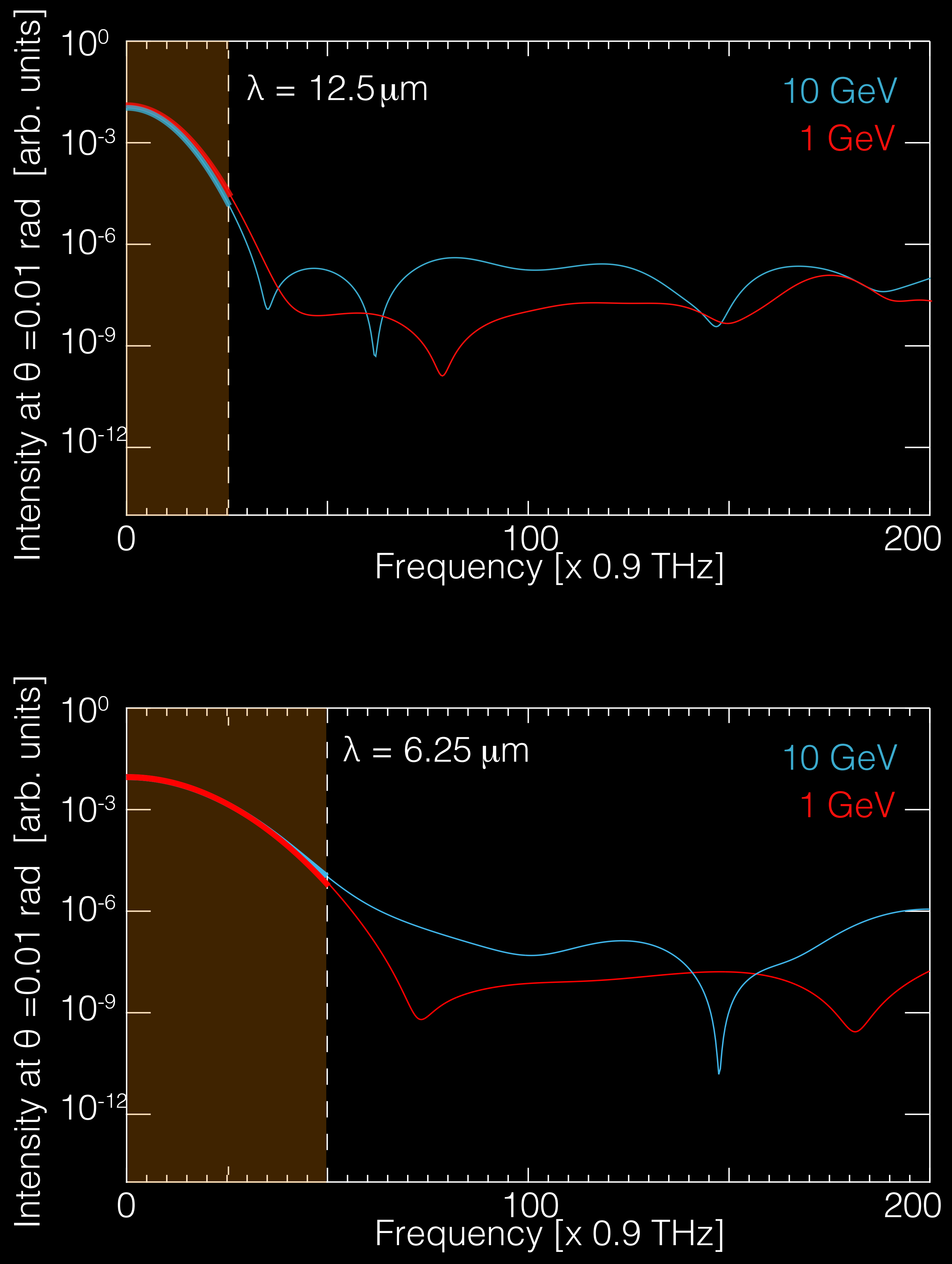
Controlling the quasiparticle trajectory will allow us to **obtain superradiance and temporal coherence in new conditions**

Relativistic electron bunch in external B

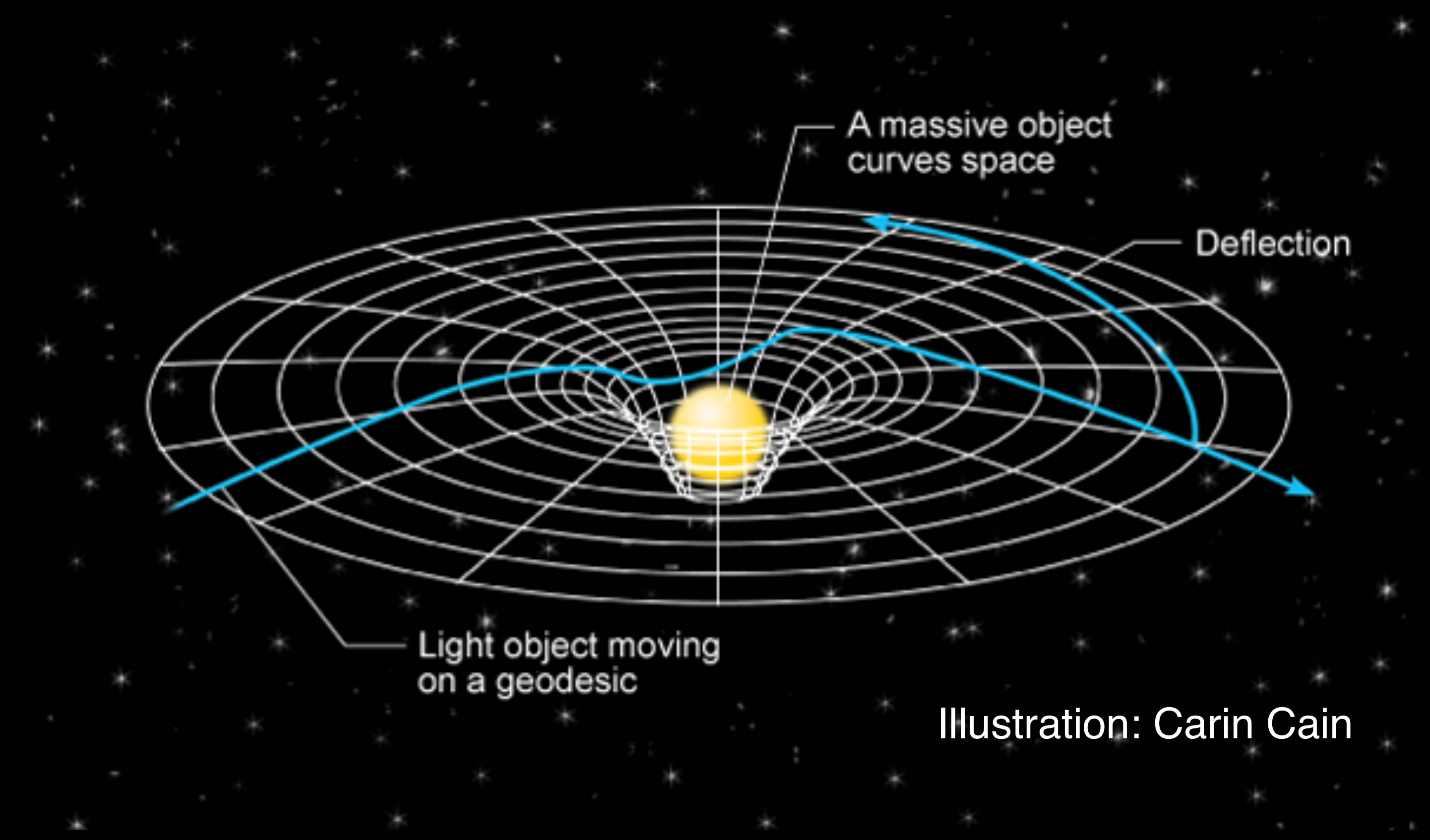


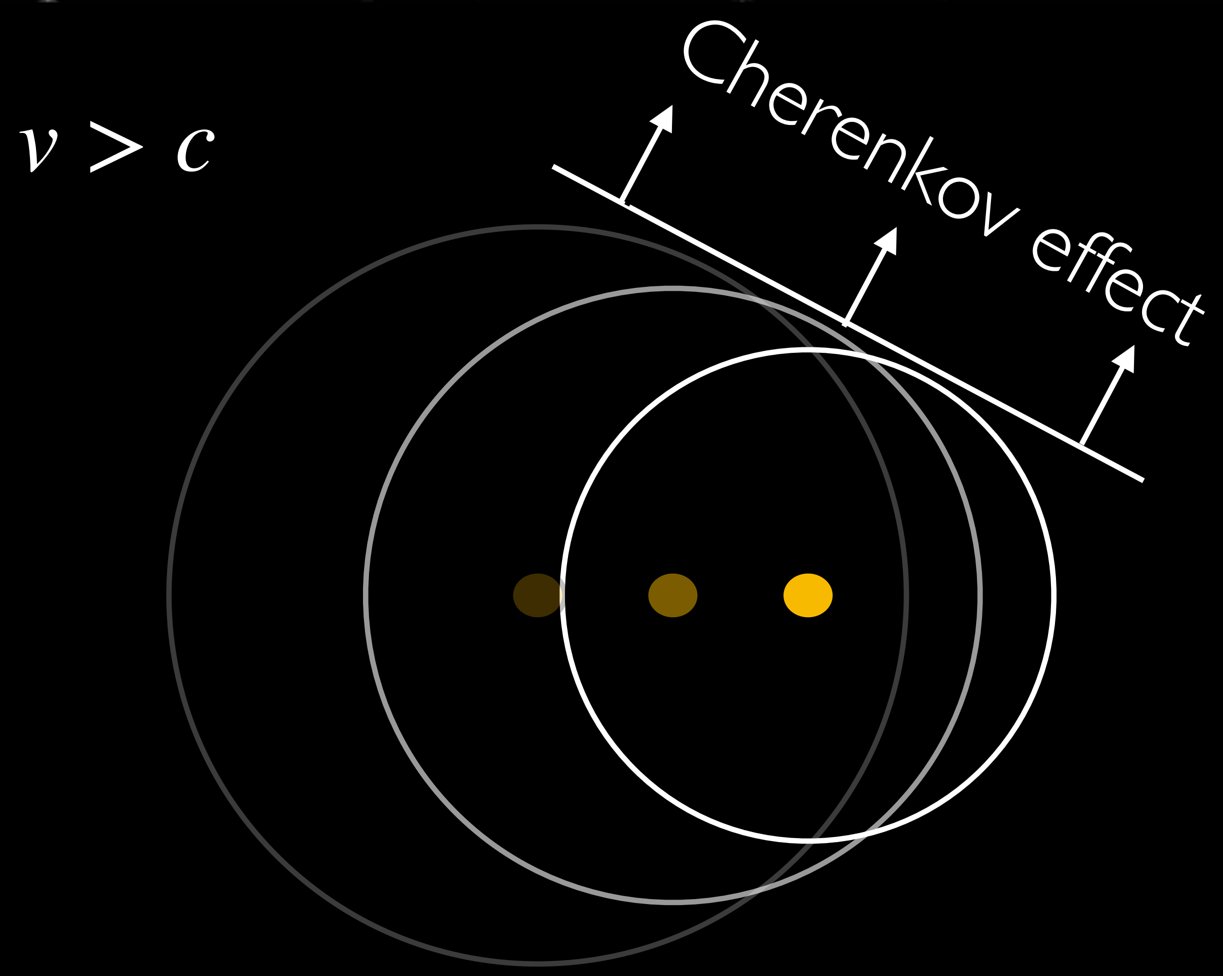


B. Malaca et al.

Can quasiparticles radiate as a finite-sized single-particle?

Unlike single particles, quasiparticles can be subject to **arbitrary accelerations** and travel at **any velocity**





Collective motion (quasiparticle)

$$\frac{d^2 I}{d\omega d\Omega} = \frac{\omega^2}{4\pi^2 c^3}\left|\int \mathrm{d}t\ \mathcal{S} e^{i\omega[t - \mathbf{n}\cdot\mathbf{r}_c(t)/c]}\right|^2$$

$$\mathcal{S} = \int \mathrm{d}\boldsymbol{\xi}\ \mathbf{n}\times[\mathbf{n}\times\mathbf{j}(\boldsymbol{\xi})]e^{-i\omega\mathbf{n}\cdot\boldsymbol{\xi}/c}$$

Single electron

$$\frac{d^2 I}{d\omega d\Omega} = \frac{\omega^2}{4\pi^2 c^3}\left|\int \mathrm{d}t\ \mathbf{n}\times(\mathbf{n}\times\mathbf{v})\ e^{i\omega[t - \mathbf{n}\cdot\mathbf{r}_c(t)/c]}\right|^2$$

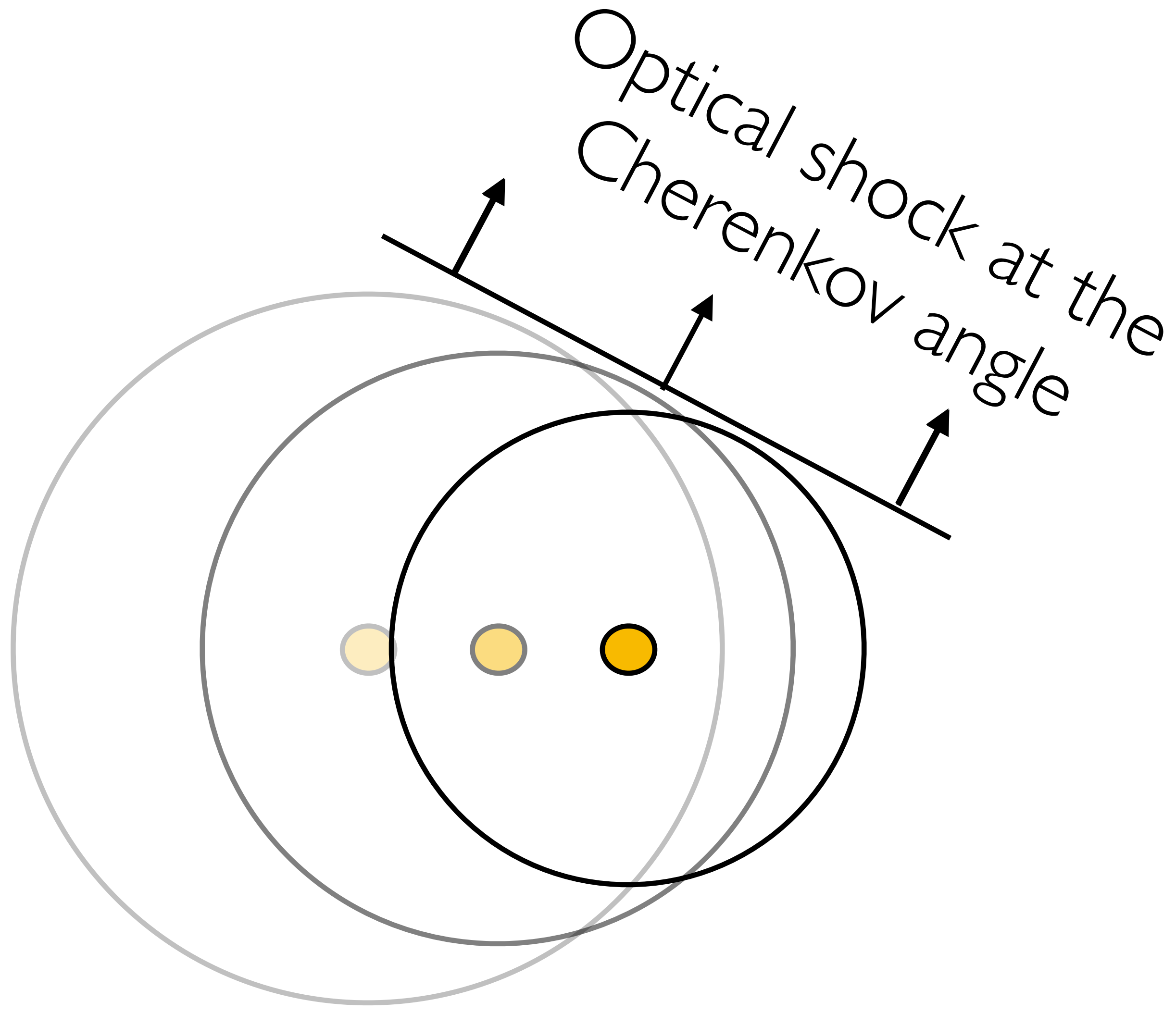
Quasiparticles suggest new forms of radiation

B. Malaca et al.

Contents

Cherenkov radiation

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

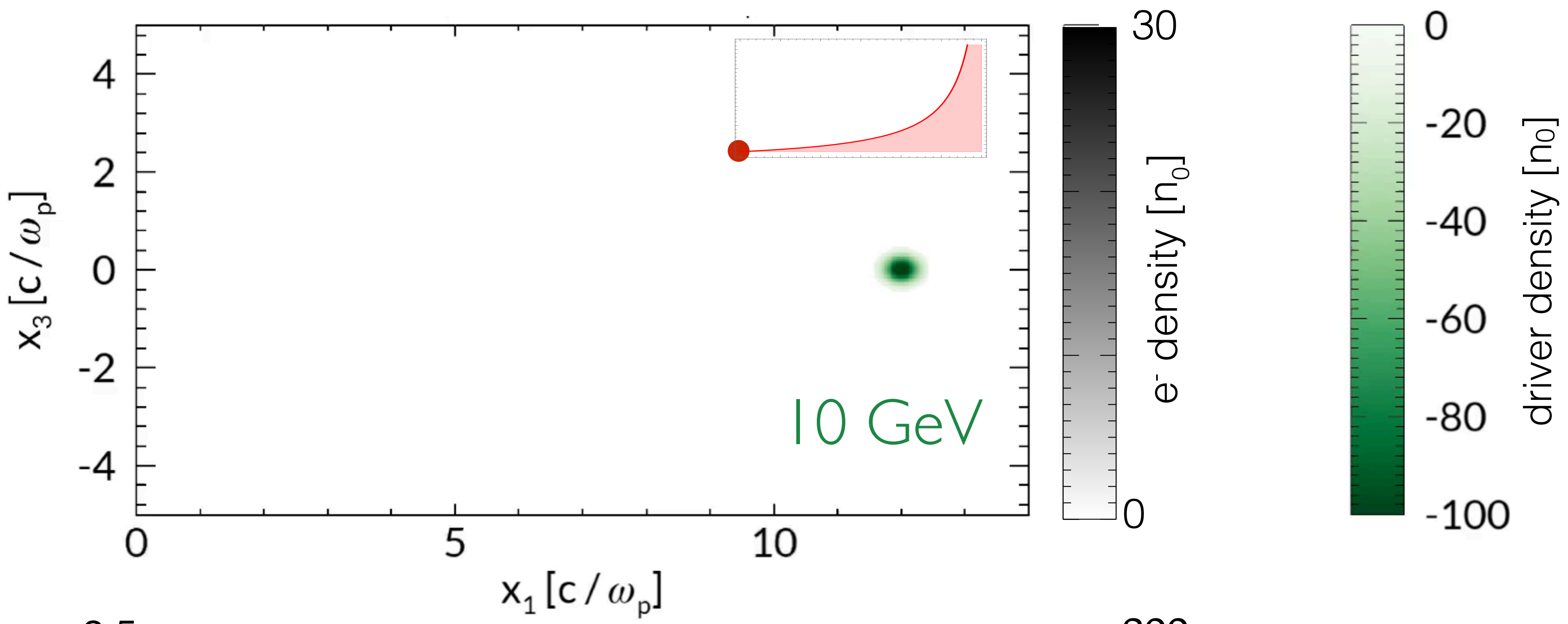


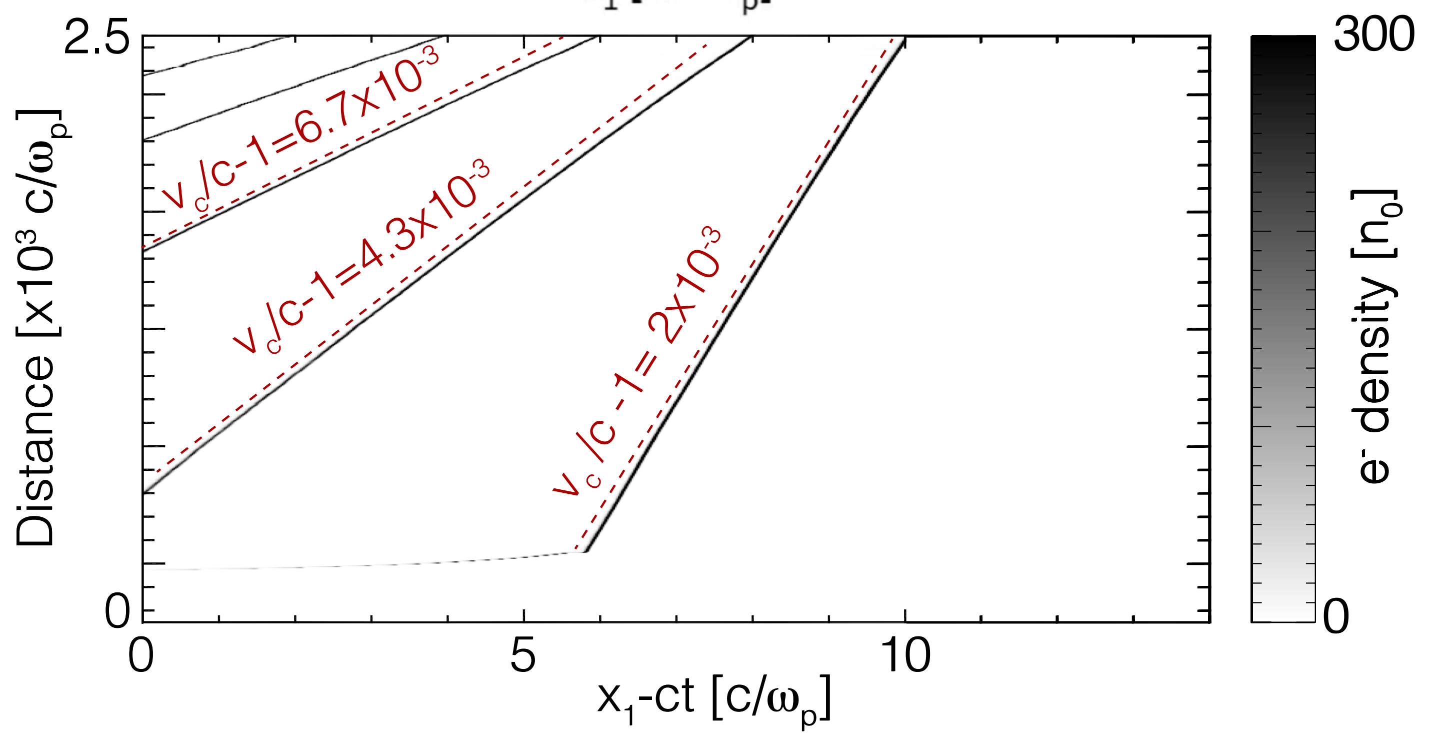
This requires $v_p > c$, which is usually impossible :(
But if we use quasiparticles…

Quasiparticle velocity control with density ramps

Engineered ramp (constant speed)

$$\frac{n(x)}{n_0} = \frac{\lambda_{p0}^2}{\left[\lambda_{p0} - (v/c - 1)\,x\right]^2}$$



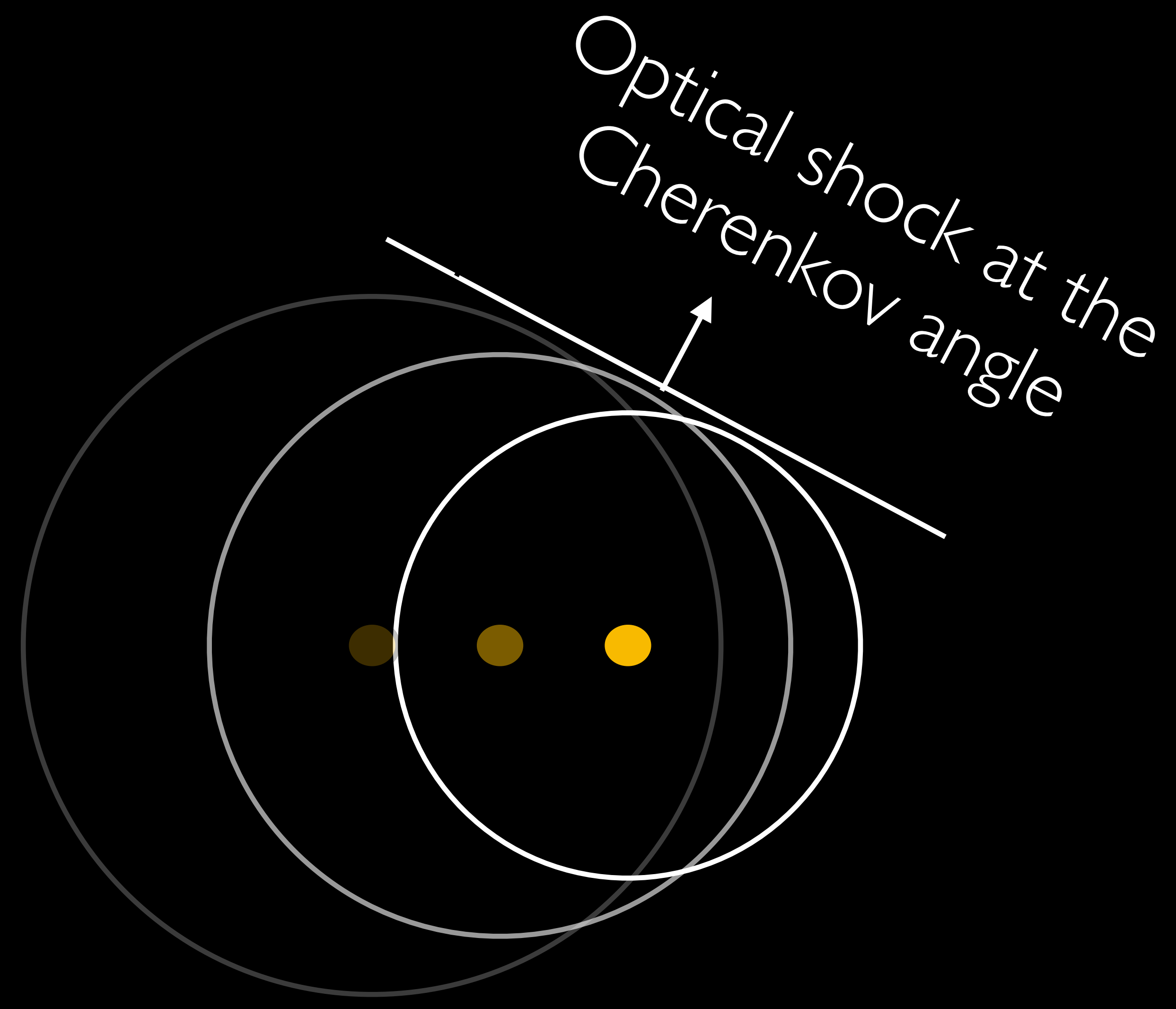


B. Malaca et al.

Quasiparticle Cherenkov superradiance

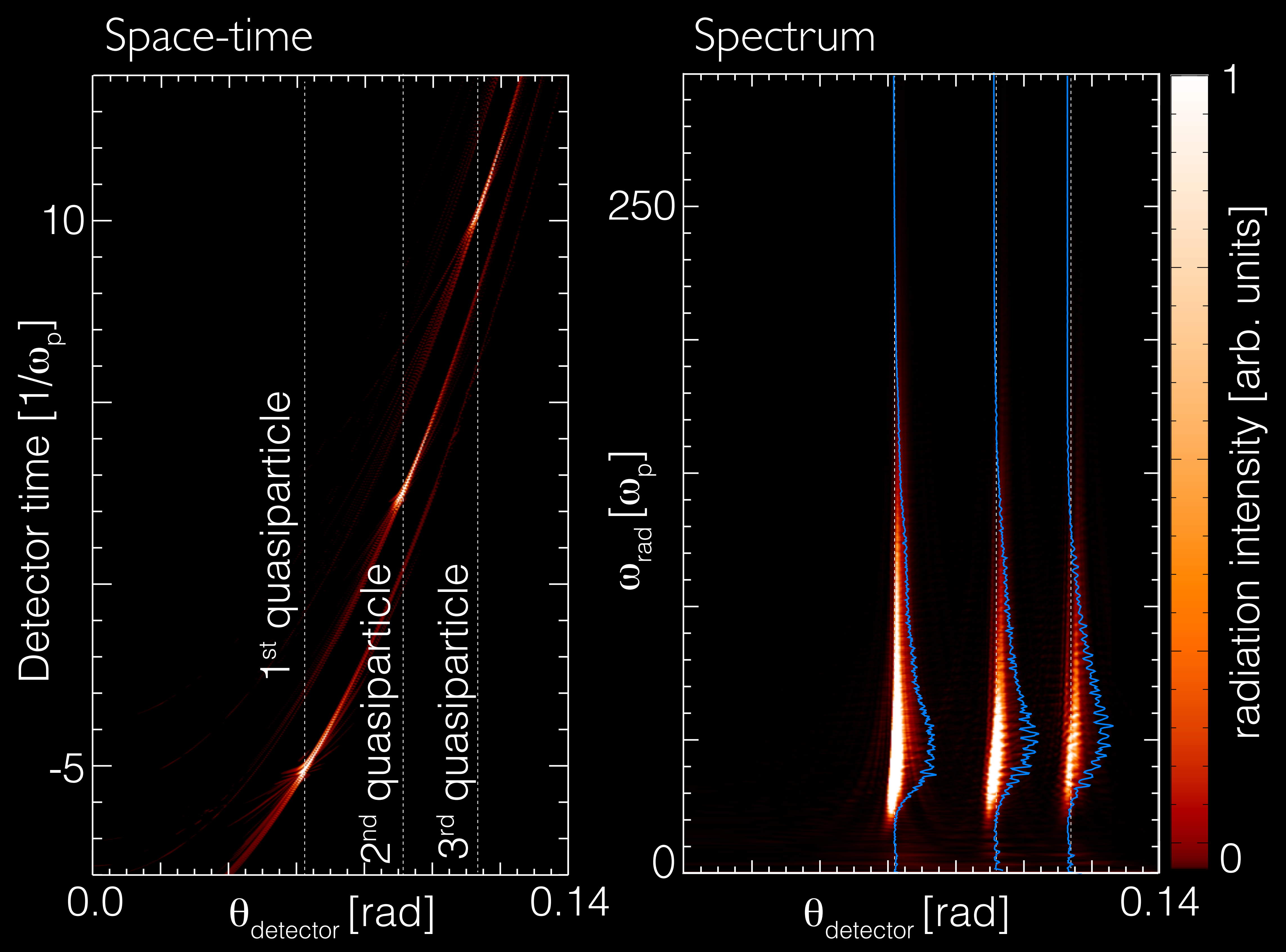
TÉCNICO LISBOA

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 quasiparticles…

Spatiotemporal and spectral radiation features



RaDiO Radiation Diagnostic for OSIRIS

B. Malaca et al.

Quasiparticle Cherenkov superradiance

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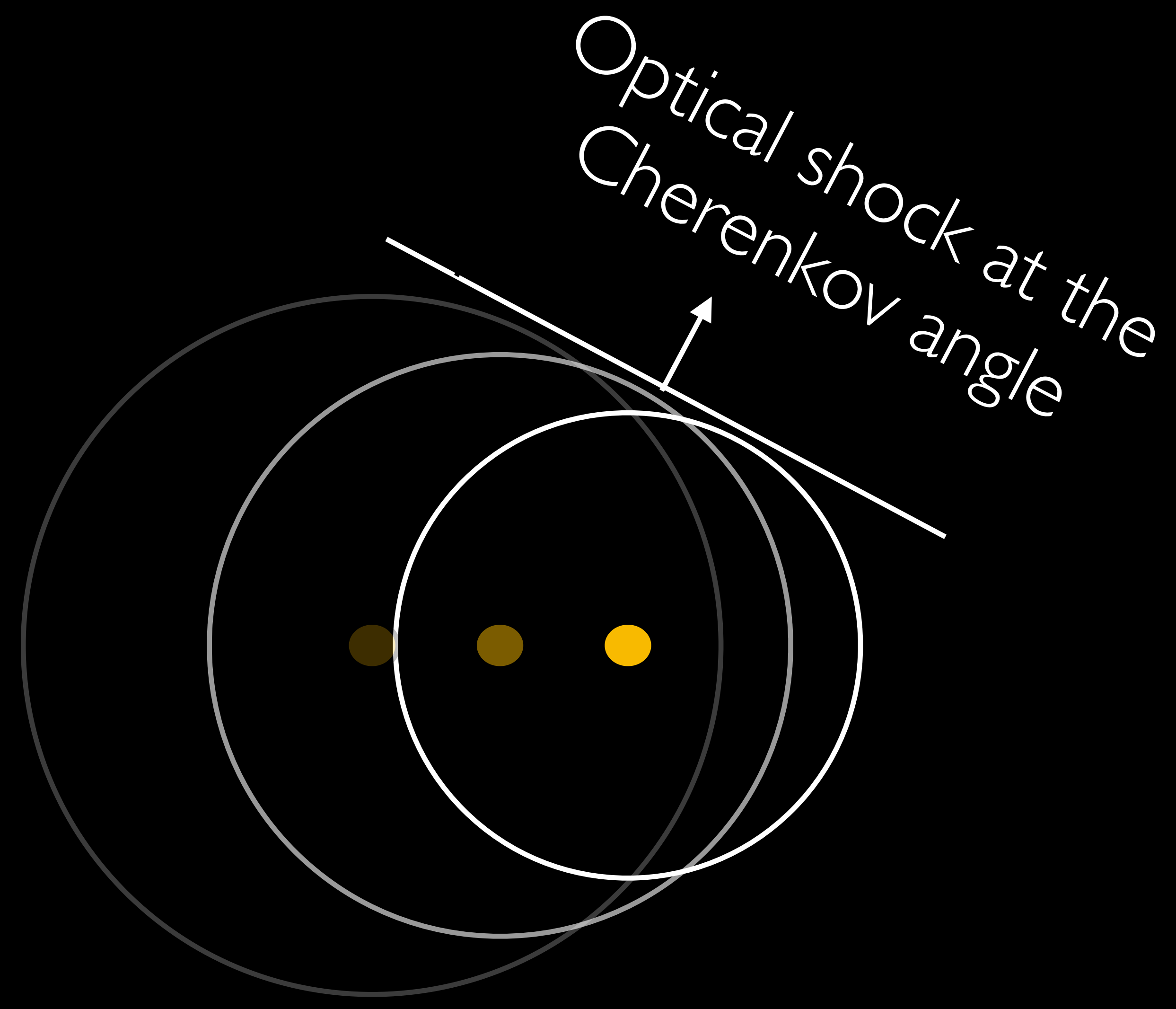

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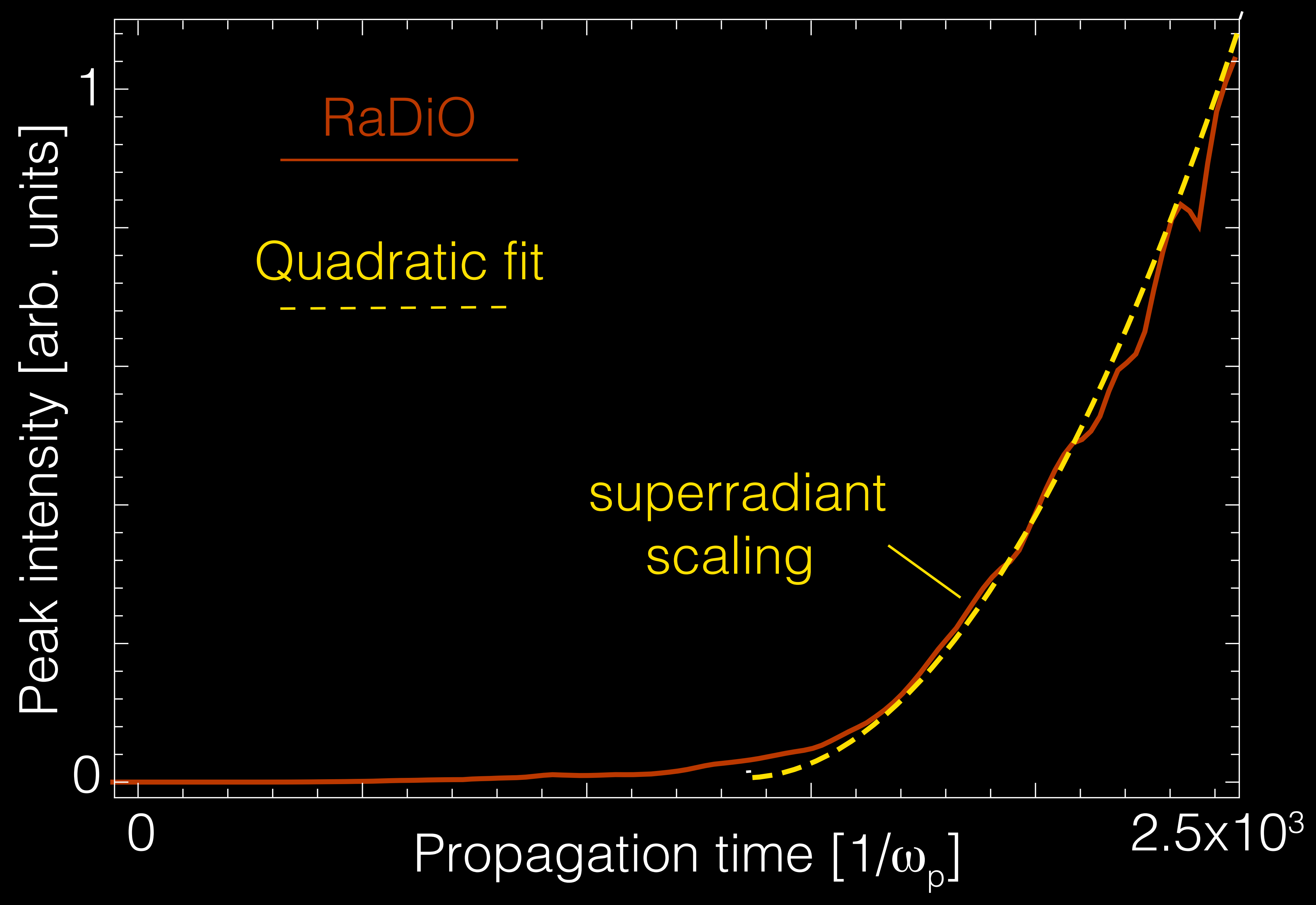
Quadratic peak intensity growth at Cherenkov angle



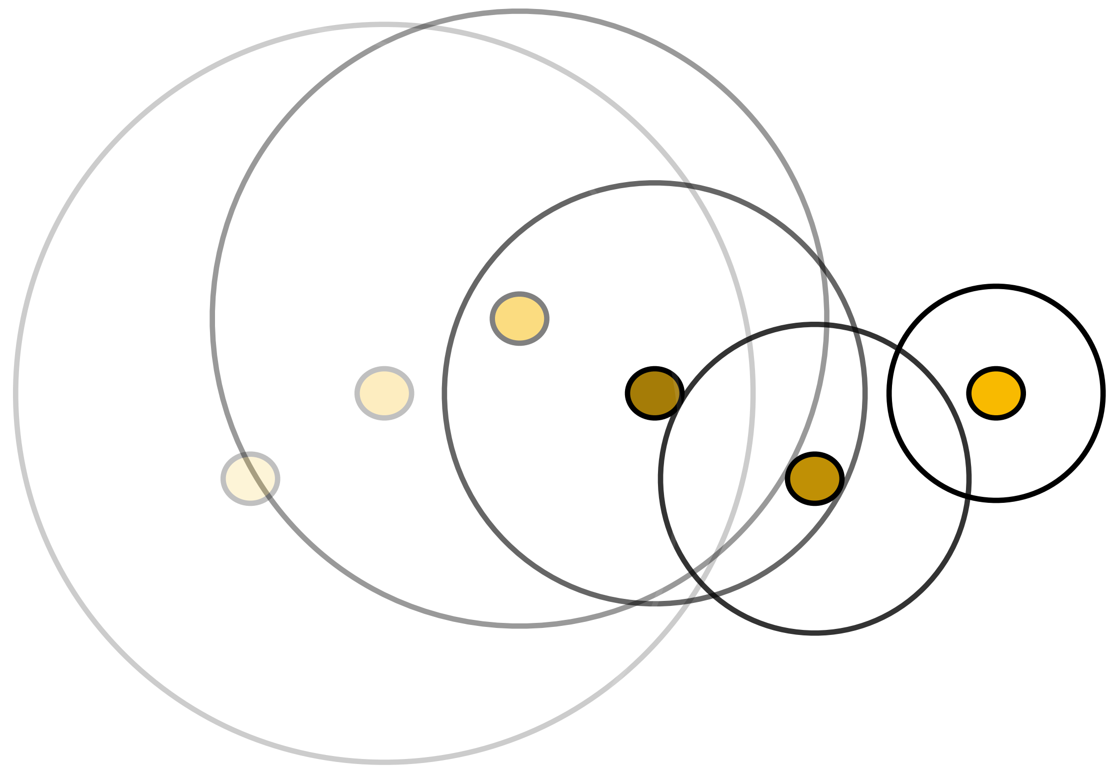
- Same in **LWFA**
- more **realistic** density profiles (e.g. linear ramp)

RaDiO Radiation Diagnostic for OSIRIS

B. Malaca et al.

Quasiparticle undulator radiation

Coherent, **narrowband** radiation



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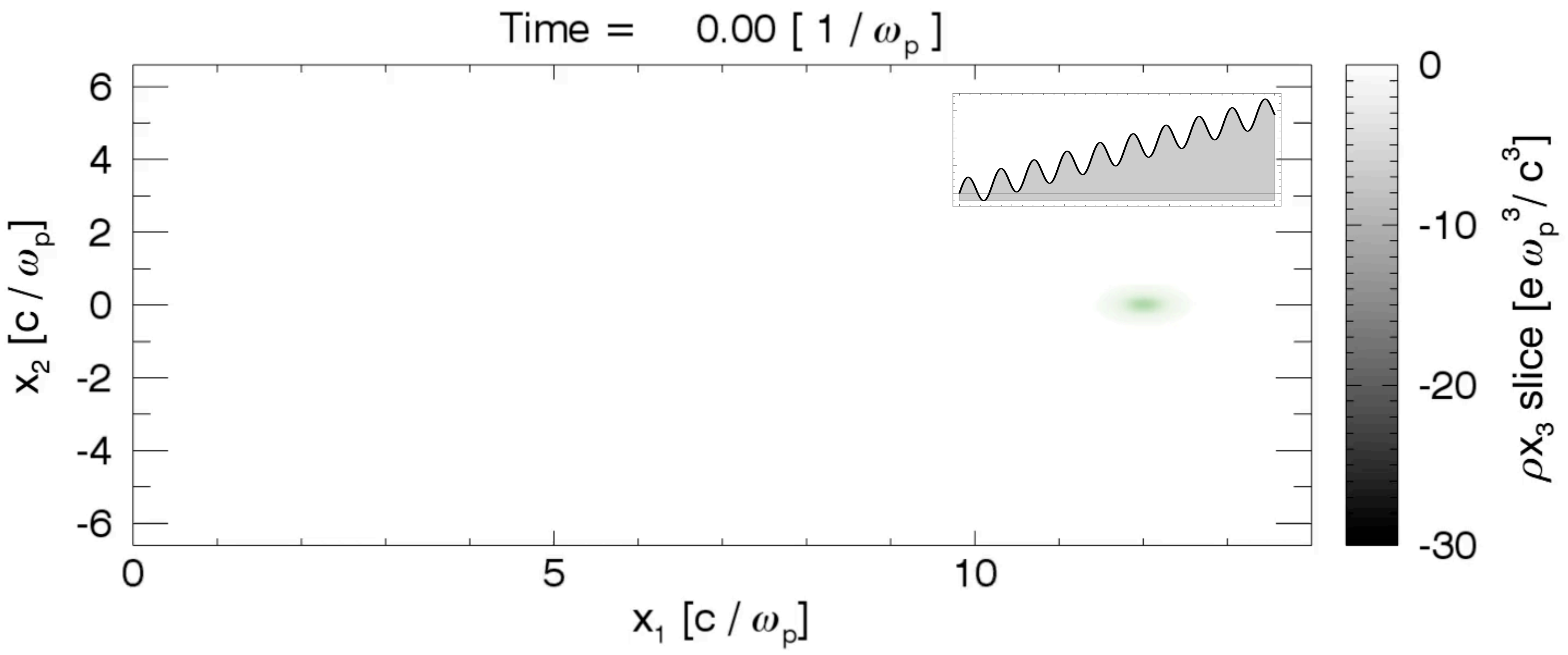
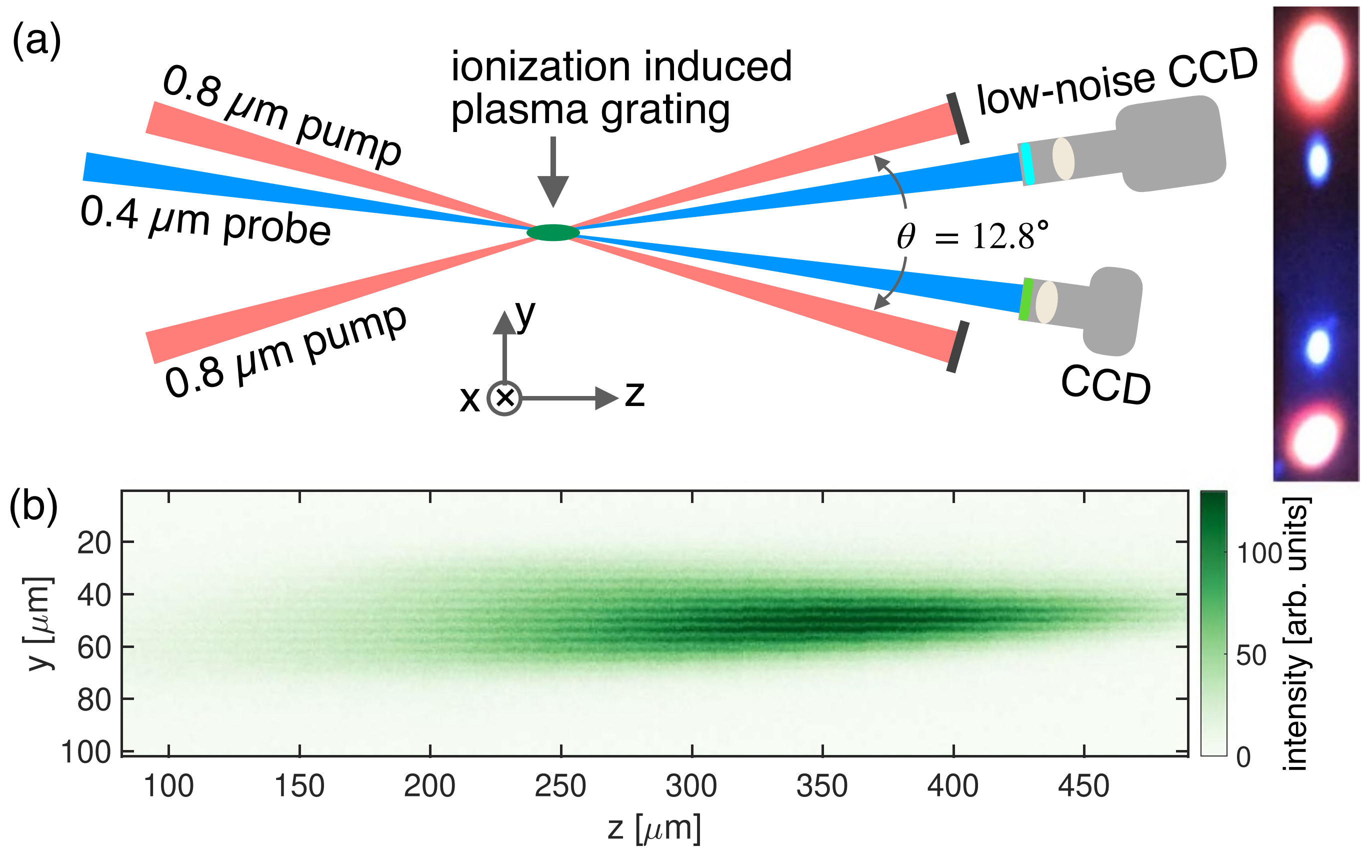


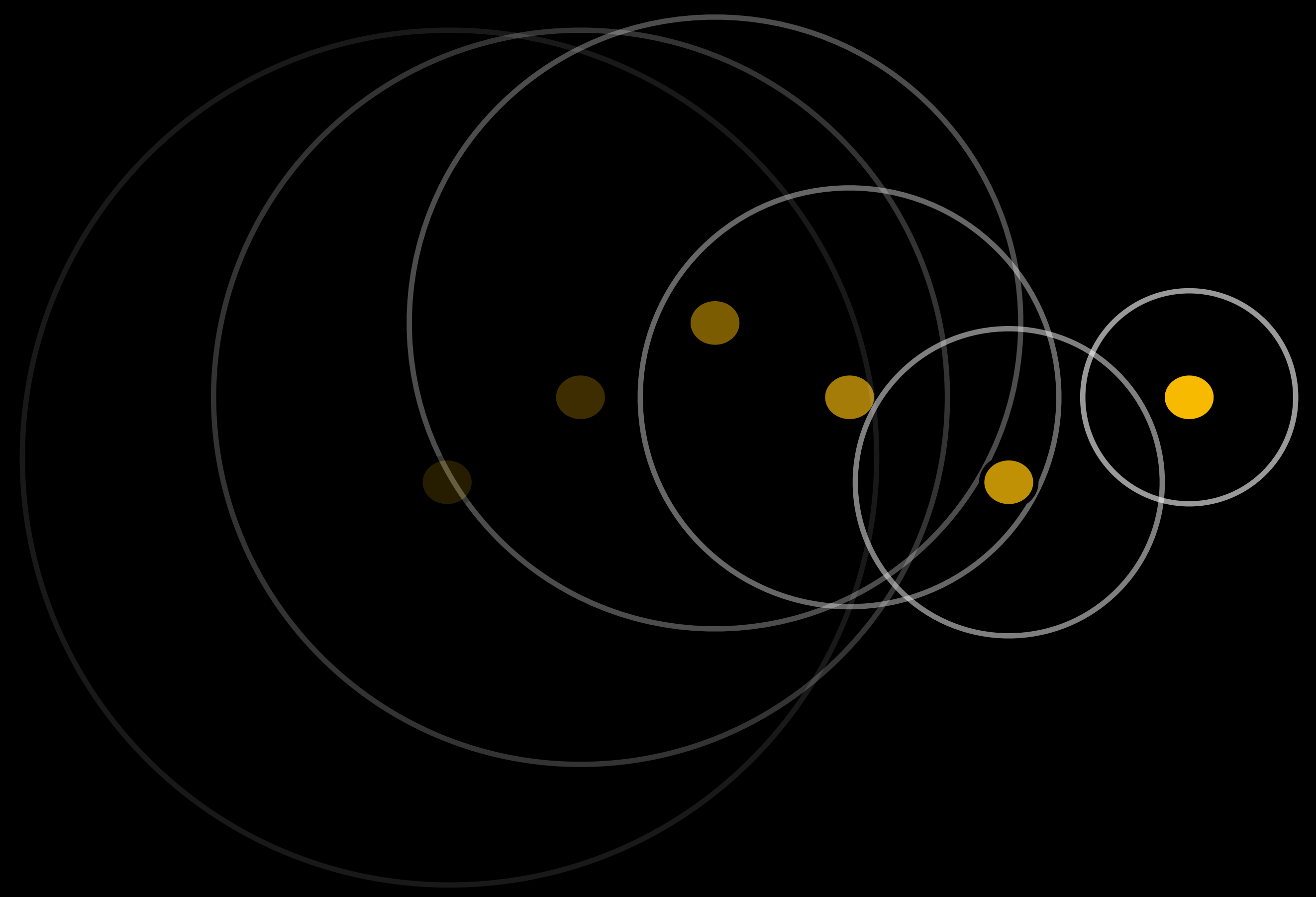


C. Zhang *et al.*, PPCF **63** 095011 (2021)

B. Malaca et al.

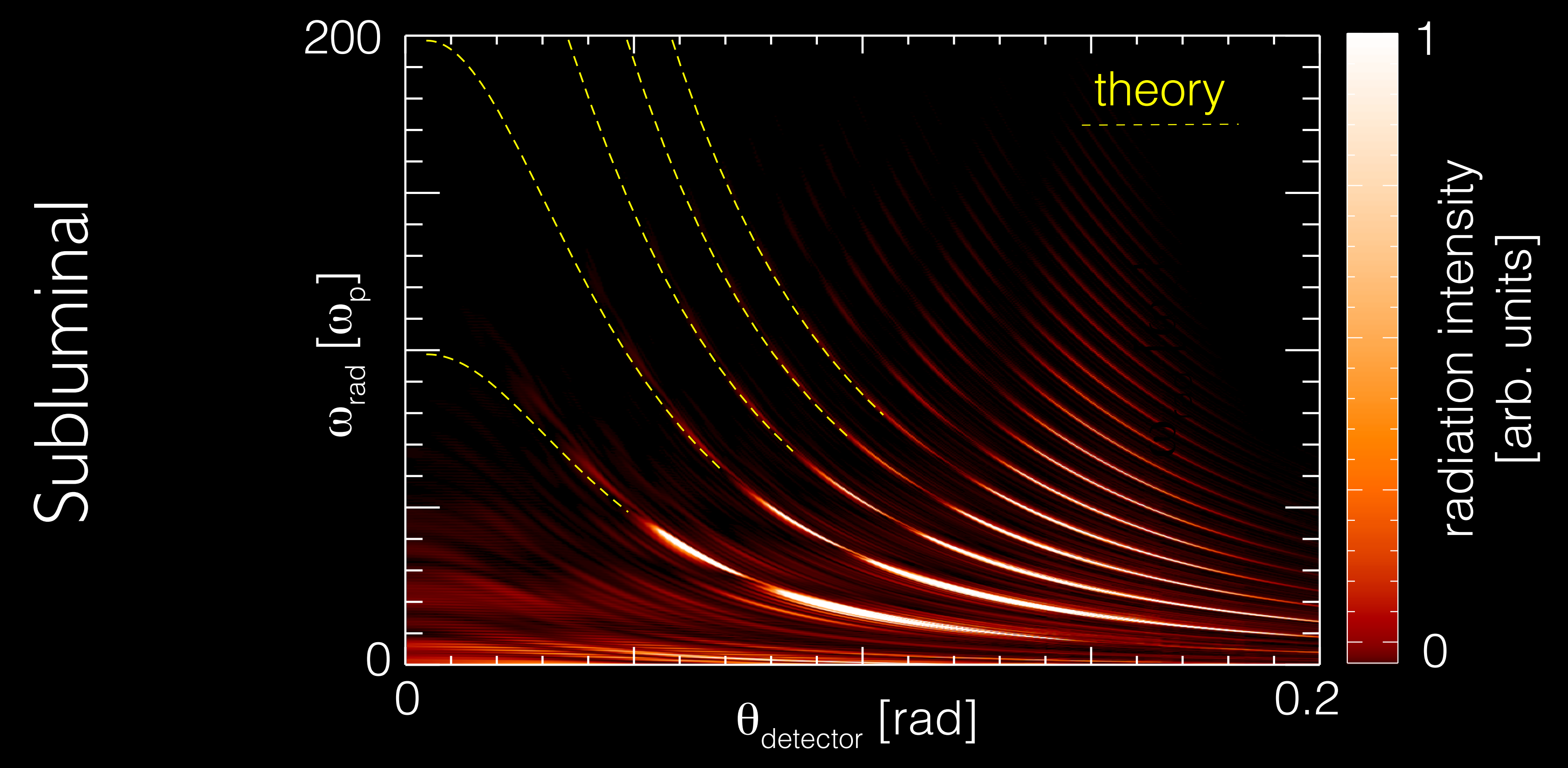
Undulator radiation

Coherent, **narrowband** radiation



Undulator radiation with $v_p > c$ is usually impossible :(
But if we use quasiparticles…

Quasiparticle undulator radiation



RaDiO
Radiation Diagnostic for OSIRIS

B. Malaca et al.

Undulator radiation

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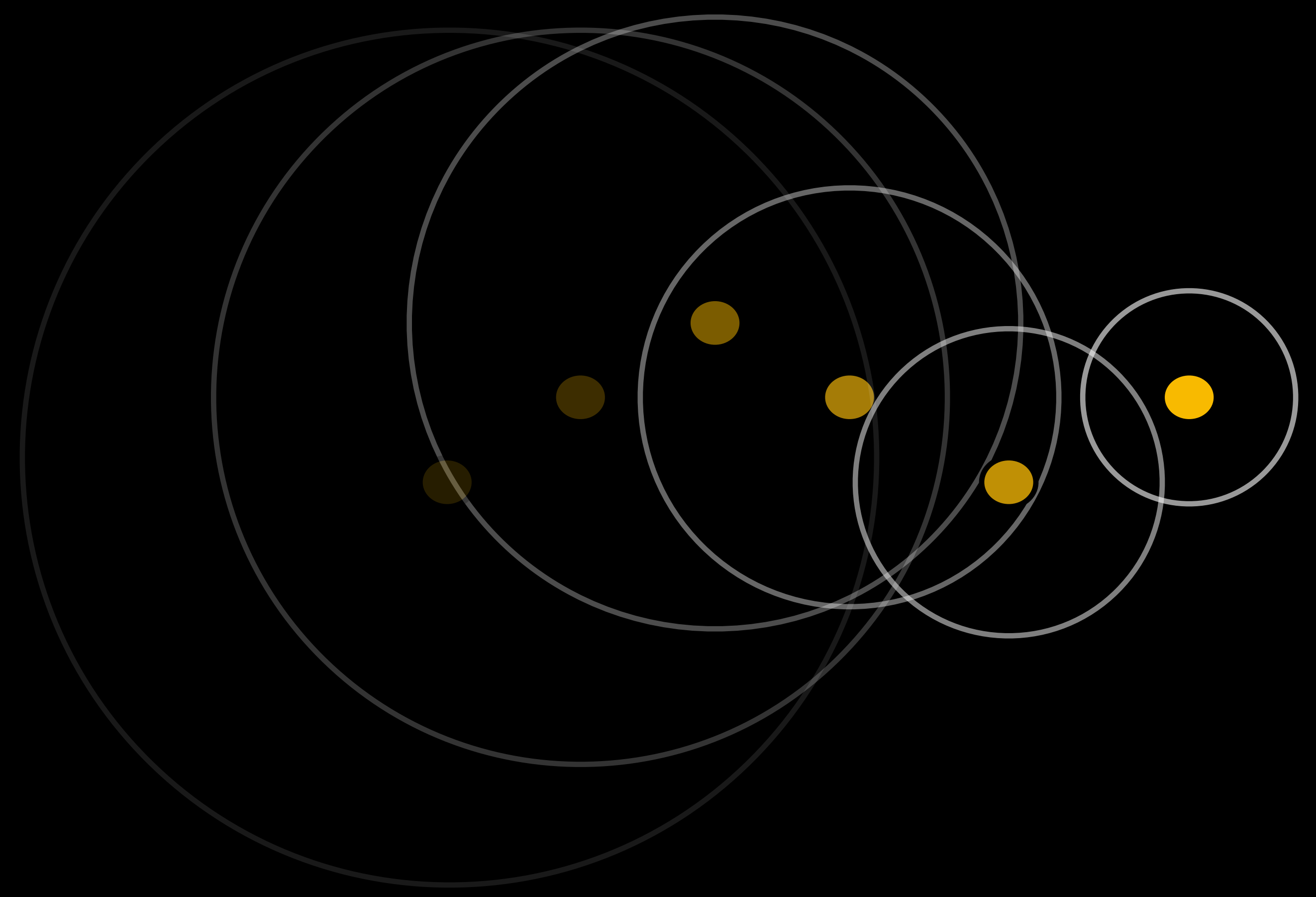

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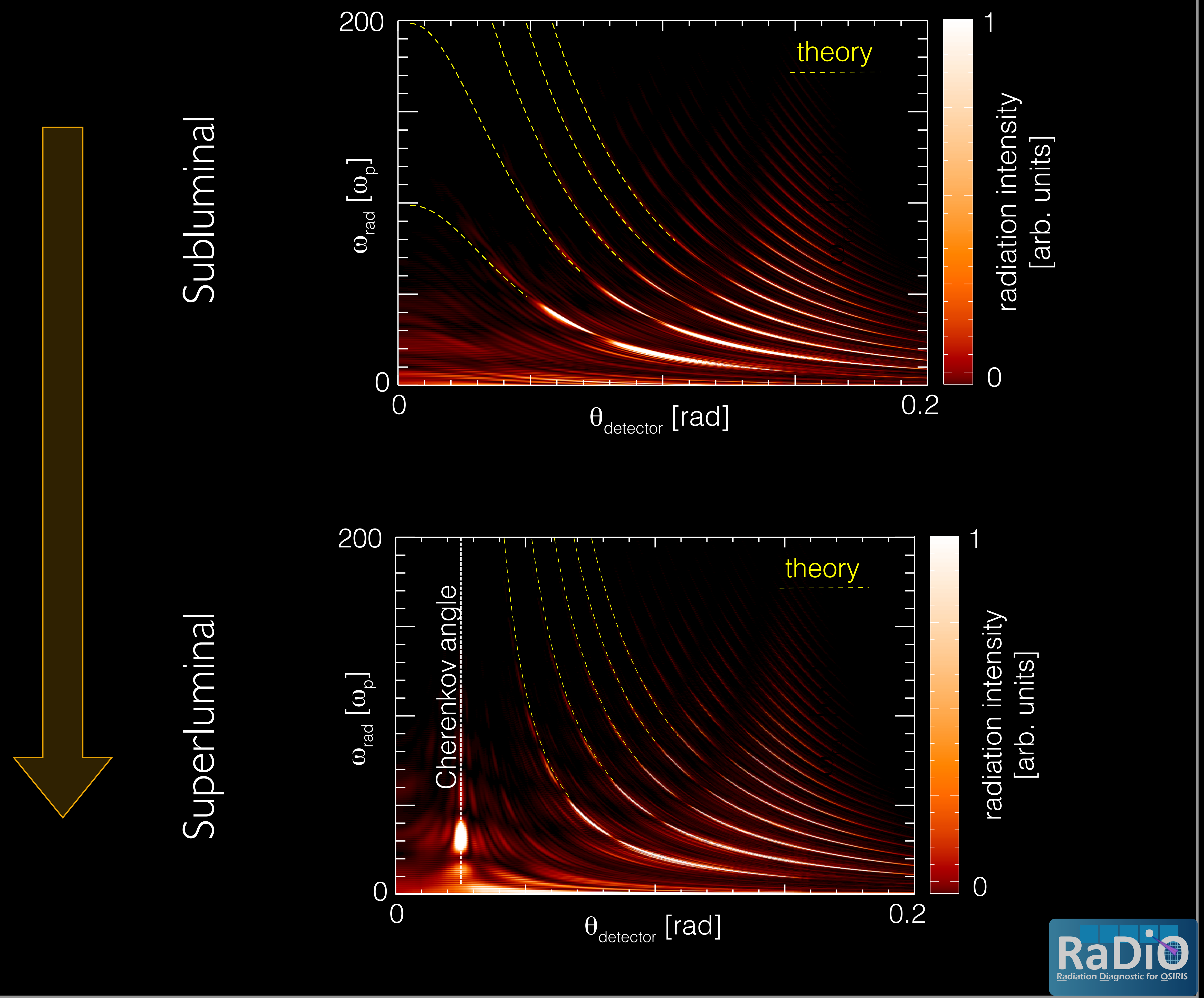

B. Malaca et al.

Undulator radiation

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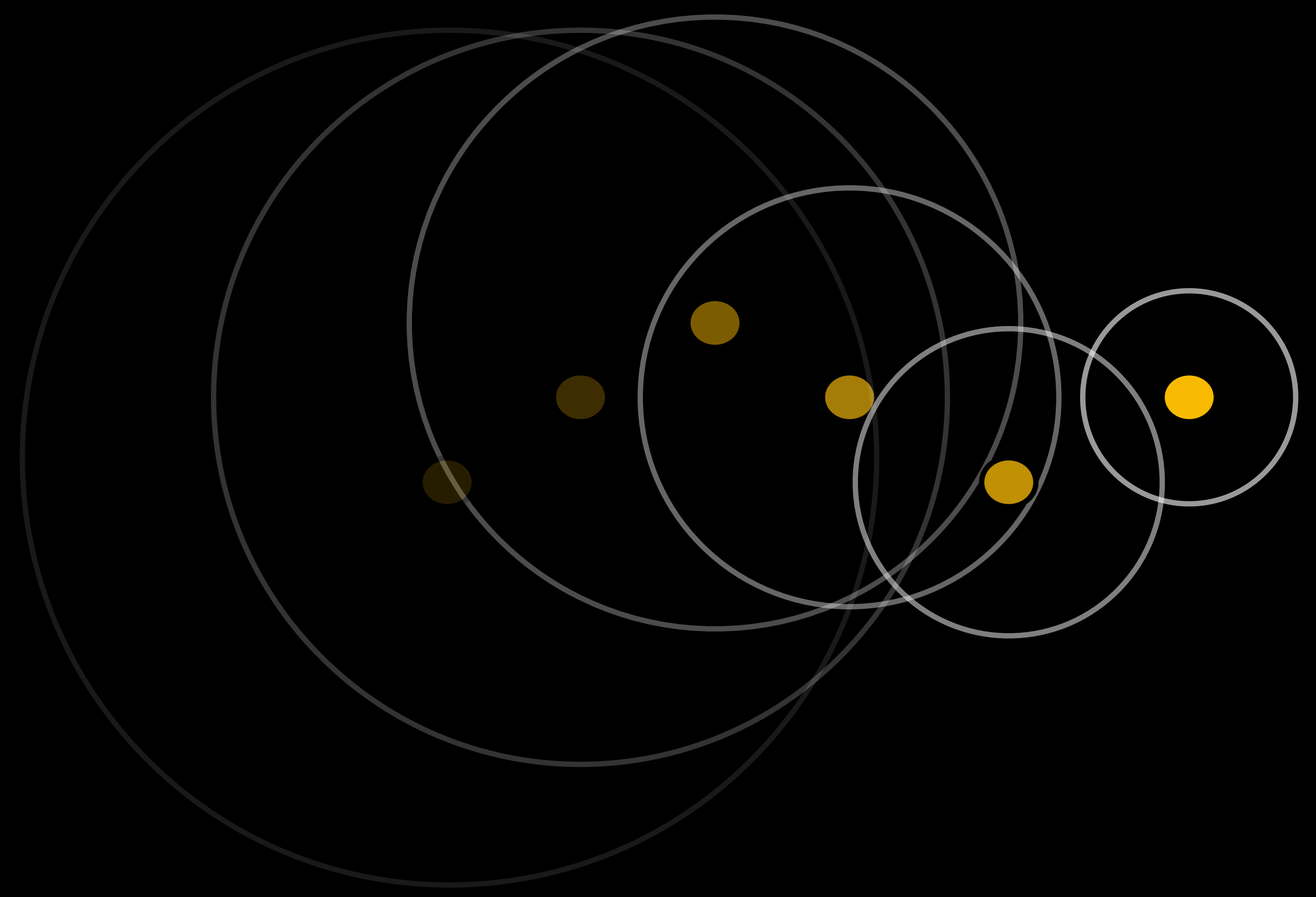

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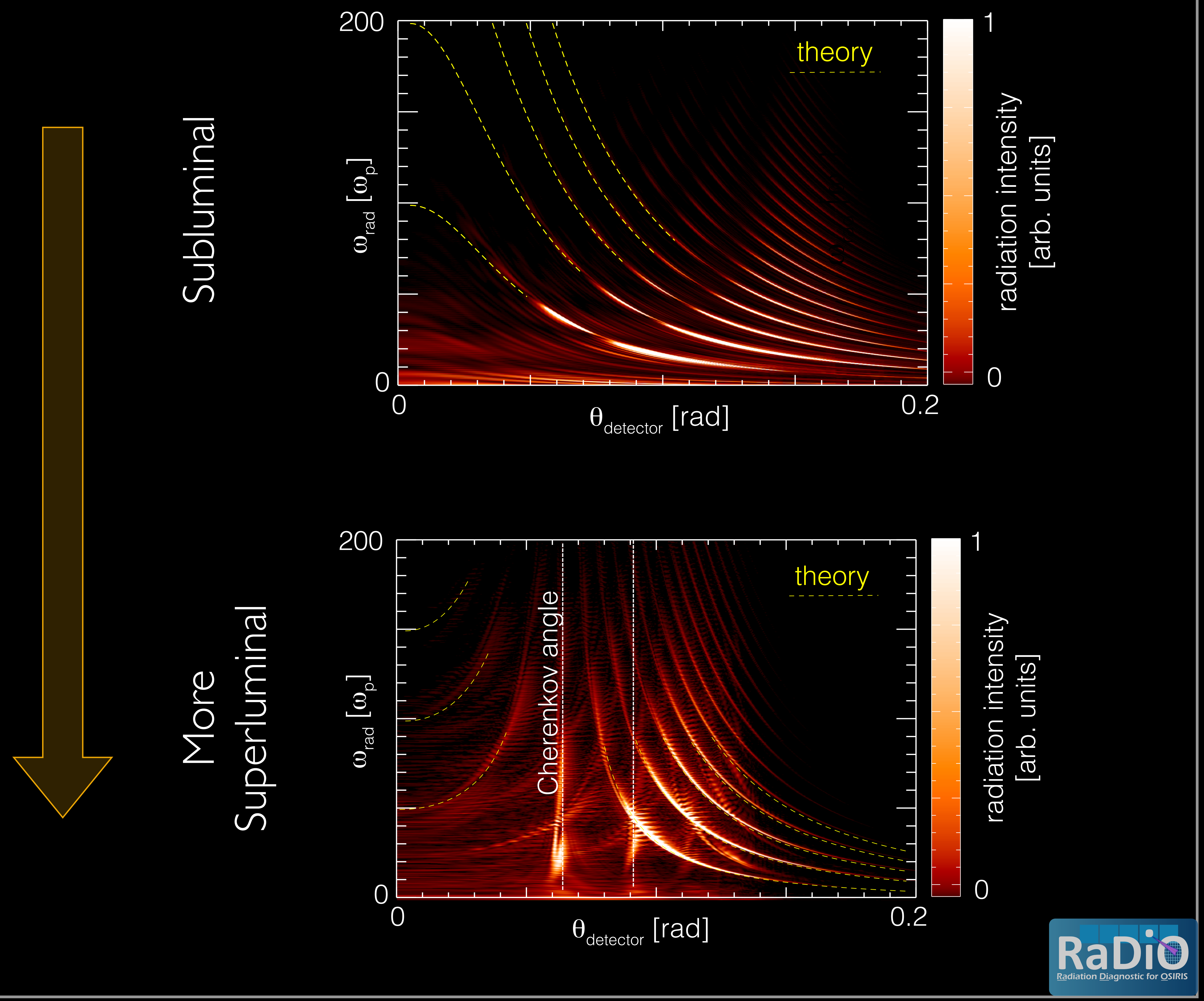
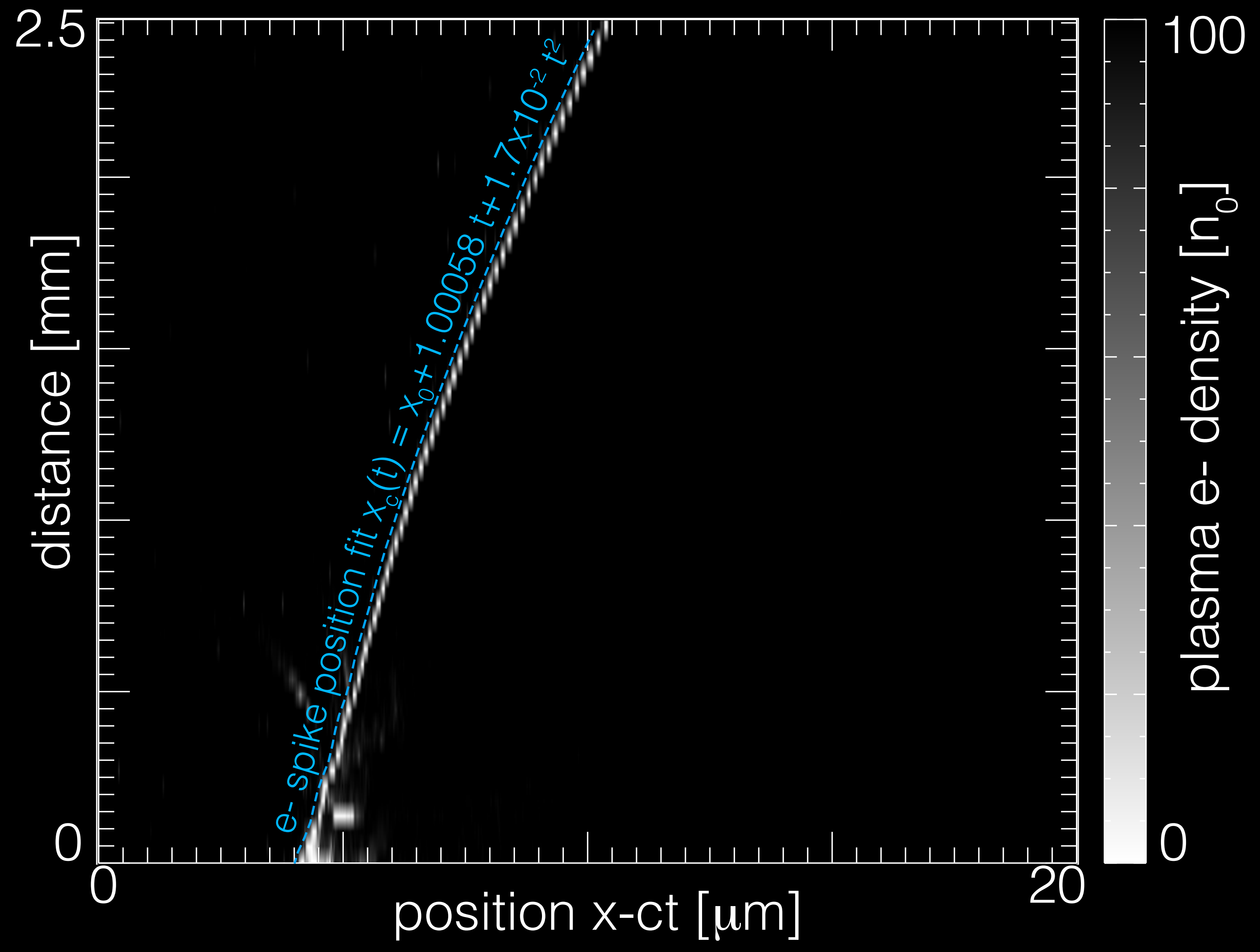


B. Malaca et al.

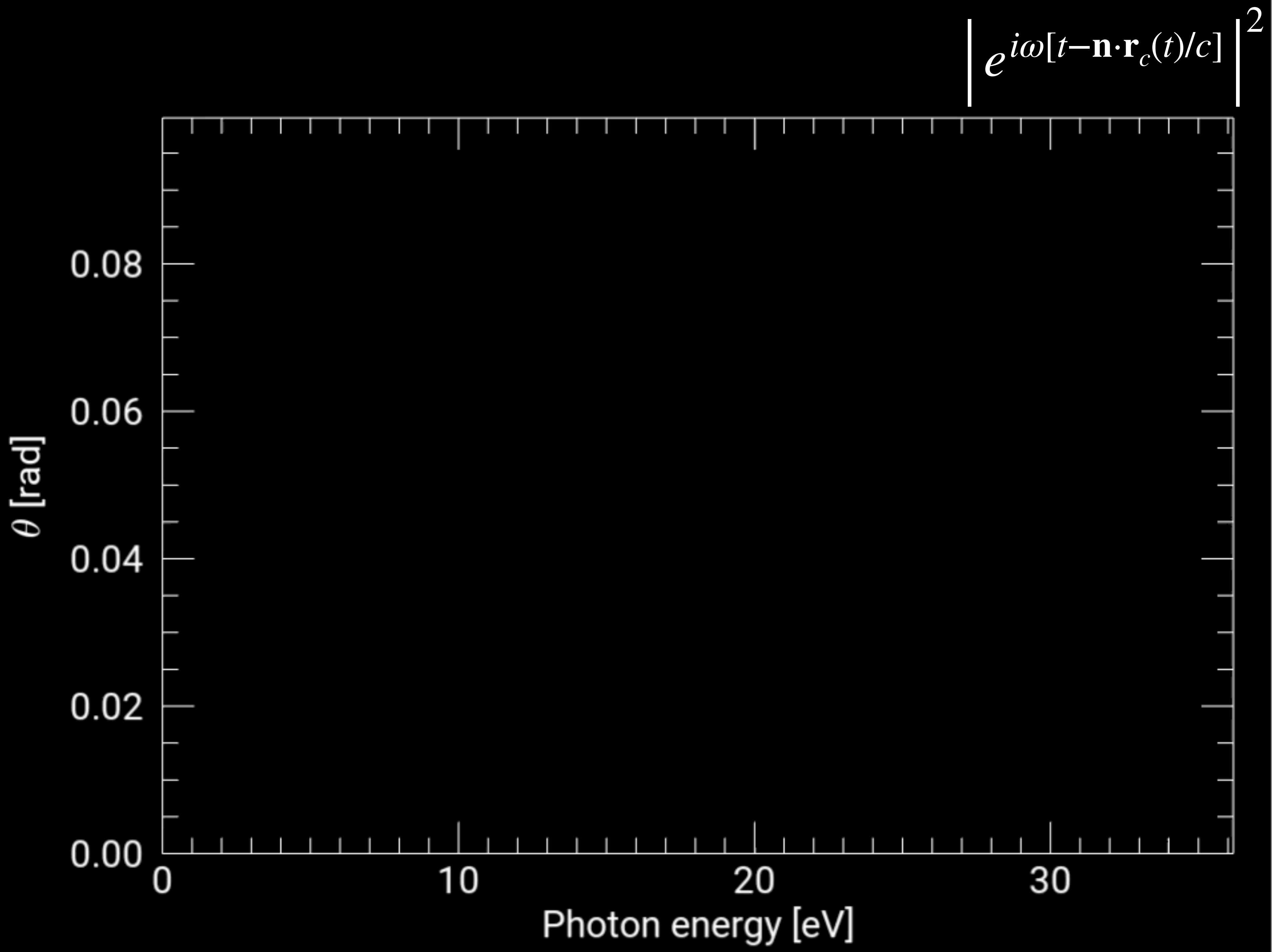
Peak brightness: practical limits

$$B\ [\mathrm{ph/s/mm^2/0.1\,\%\,BW/mrad^2}] \simeq \frac{\alpha(c[\mathrm{cm/s}])}{4\pi^2\times 10^{11}}\left(\frac{\omega}{\omega_p}\right)^2\left(\frac{c}{\omega_p}\right)^3 (n_{\mathrm{qp}}[\mathrm{cm^{-3}}])^2\left(T[\omega_p^{-1}]\right)^2\left(\sigma_\perp[c/\omega_p]\right)^2\left(\sigma_\parallel[c/\omega_p]\right)\sin^2\theta$$

Quasiparticles can accelerate



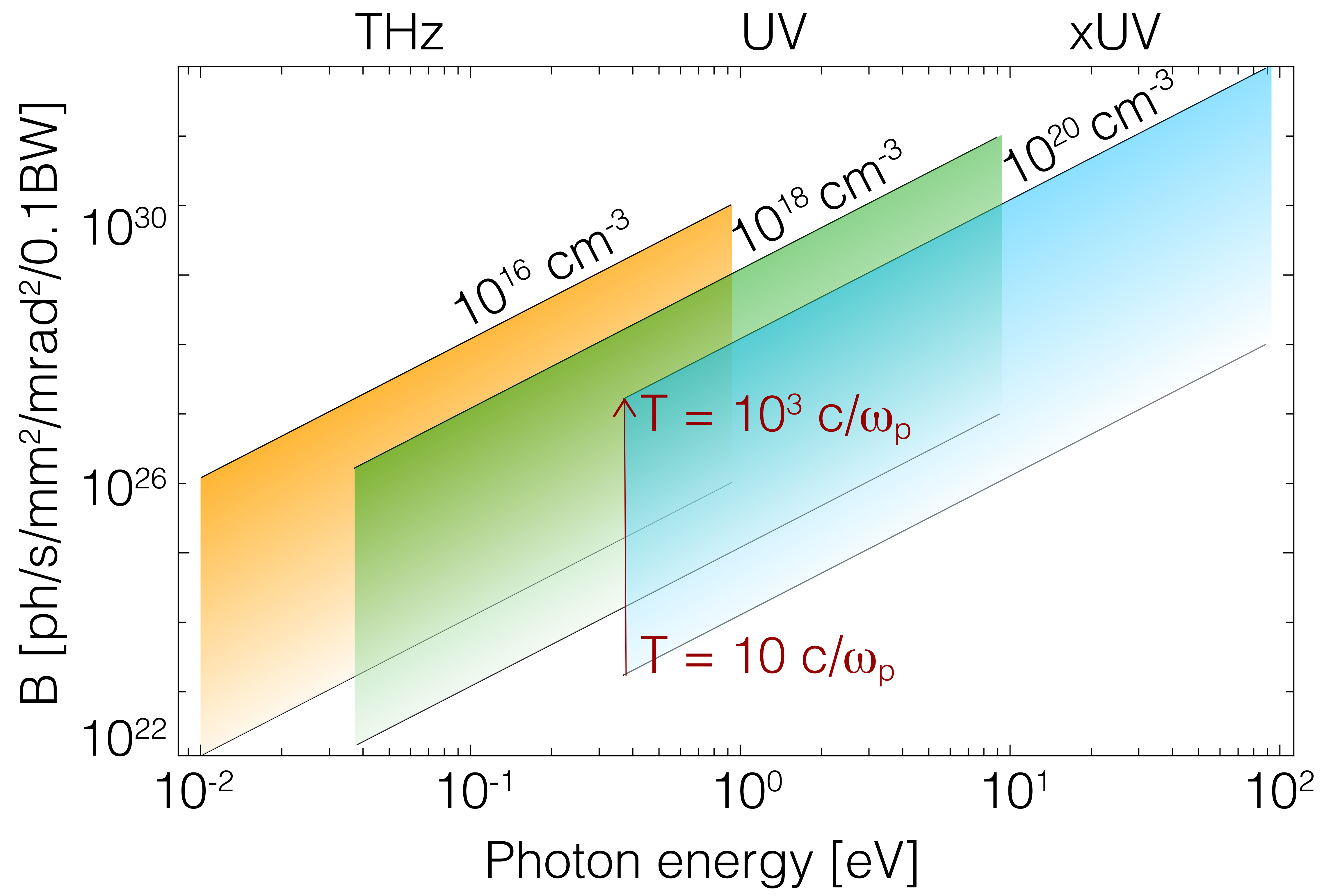
Cherenkov angle spread limits brightness



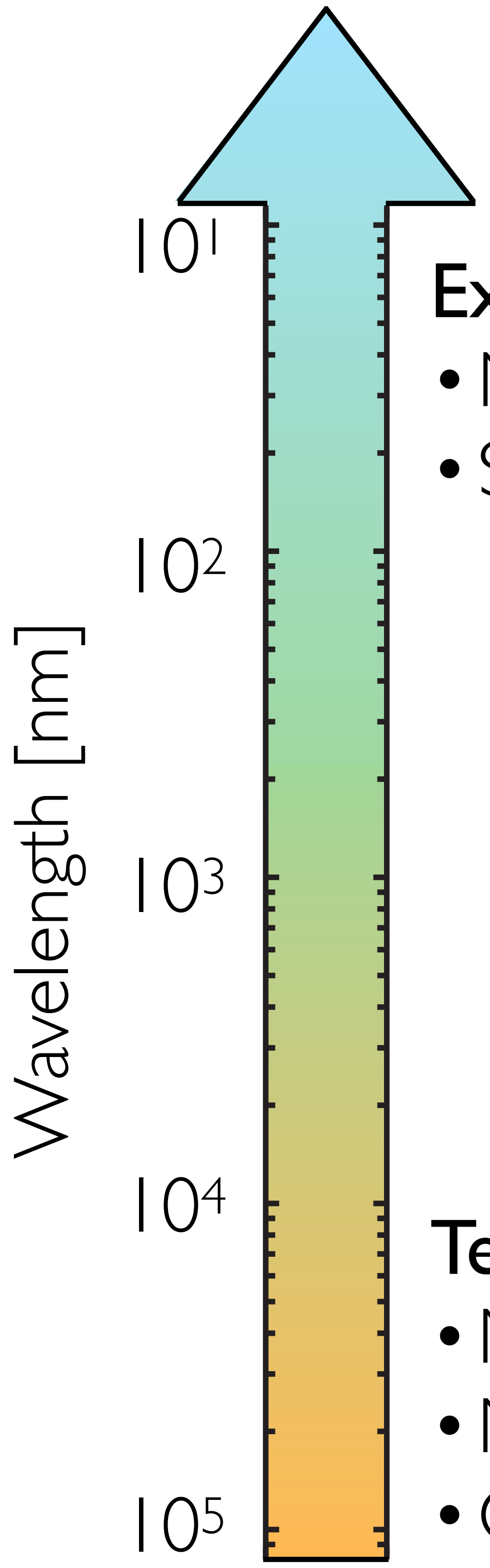
B. Malaca et al.

Tuneable and bright superradiant source of radiation

Frequency range control spans nearly 10 octaves



B. Malaca *et al*, submitted (2023); arXiv:2301.11082v1



Extreme UltraViolet (XUV)
- Nanolitography
- Spectroscopy

TeraHertz (THz)
- Medical imaging
- Manufactoring
- Quality control

B. Malaca et al.

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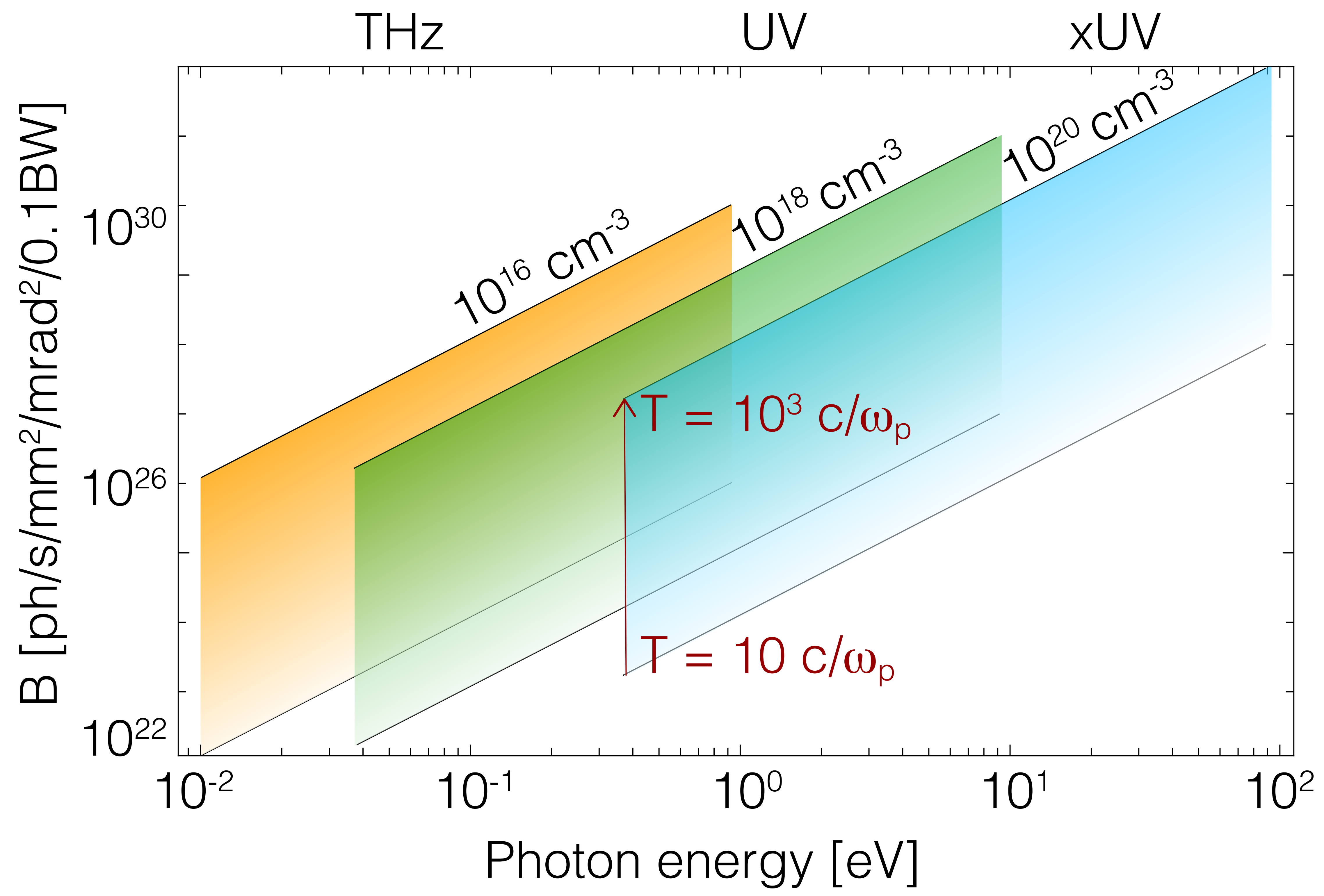

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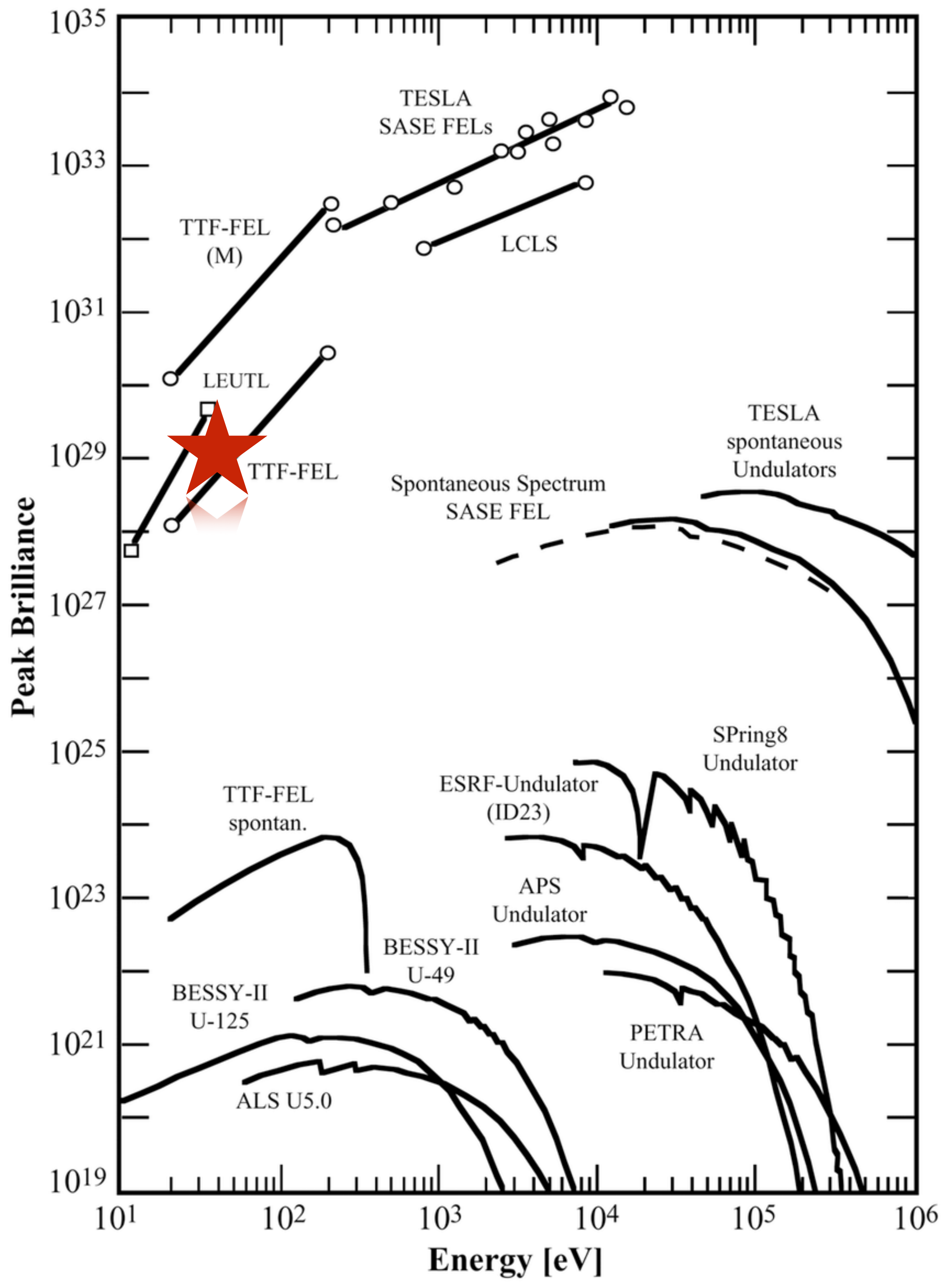

P. O'Shea, H.P. Freund, Science **292** 1853 (2001)

B. Malaca et al.

Contents

Conclusions

Miguel Pardal

Bernardo Malaca

M. Pardal, et al, Computer Physics Communications, 285, 108634 (2022)

New tool and algorithm for radiation calculations in PIC codes

Suitable to analyse large number of simulation particles

B. Malaca et al. Nature Photonics 18, 39–45 (2024)

Radiation from quasiparticles

Brings previously unexplored temporally coherent and superradiant emission mechanisms

Temporal coherence and superradiance in plasma accelerators

Tuneable source from THz to XUV/soft x-rays

Many other examples

Thank you!