Coherence and superradiance from a plasma-based quasiparticle accelerator

B. Malaca[1],

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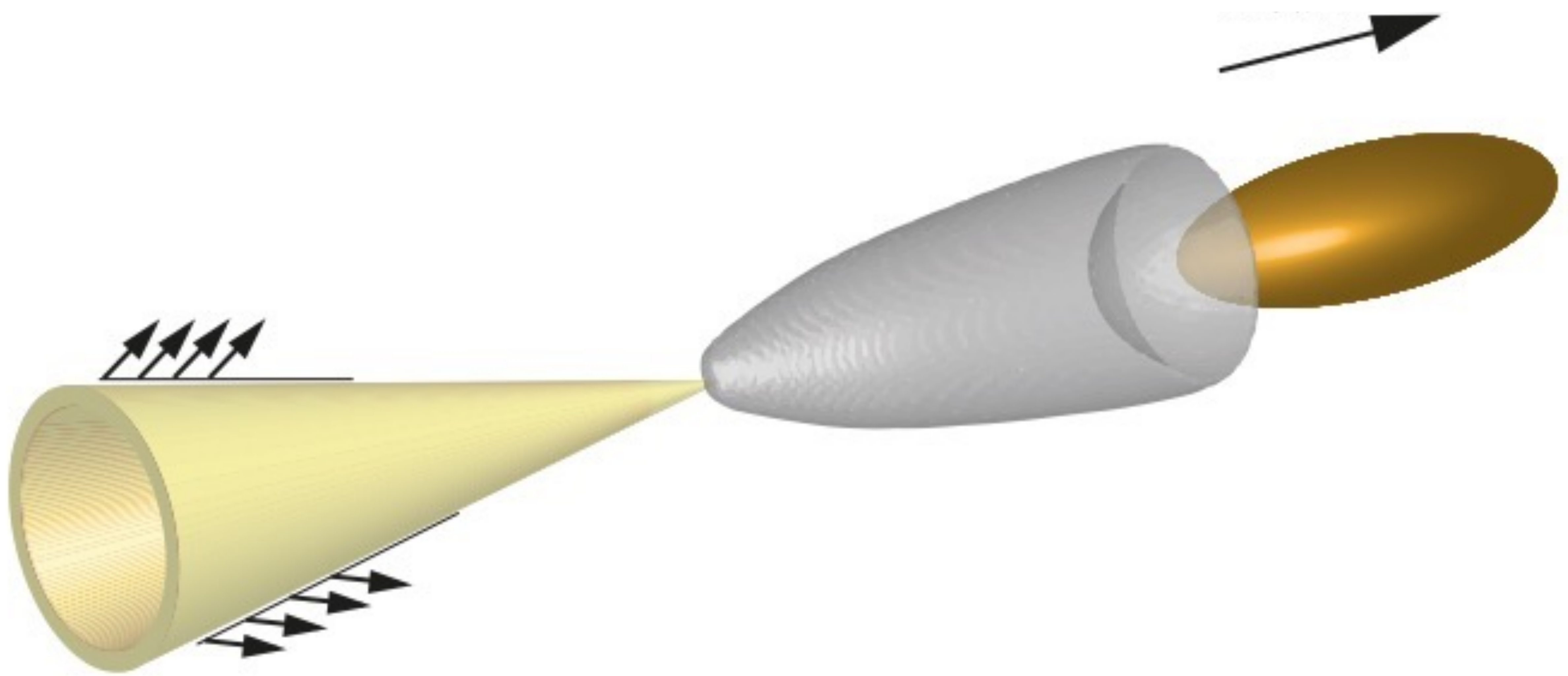

B. Malaca et al, 2023 (accepted, *Nature Photonics*), arxiv 2301.11082

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ipfn INSTITUTO DE PLASMAS E FUSÃO NUCLEAR

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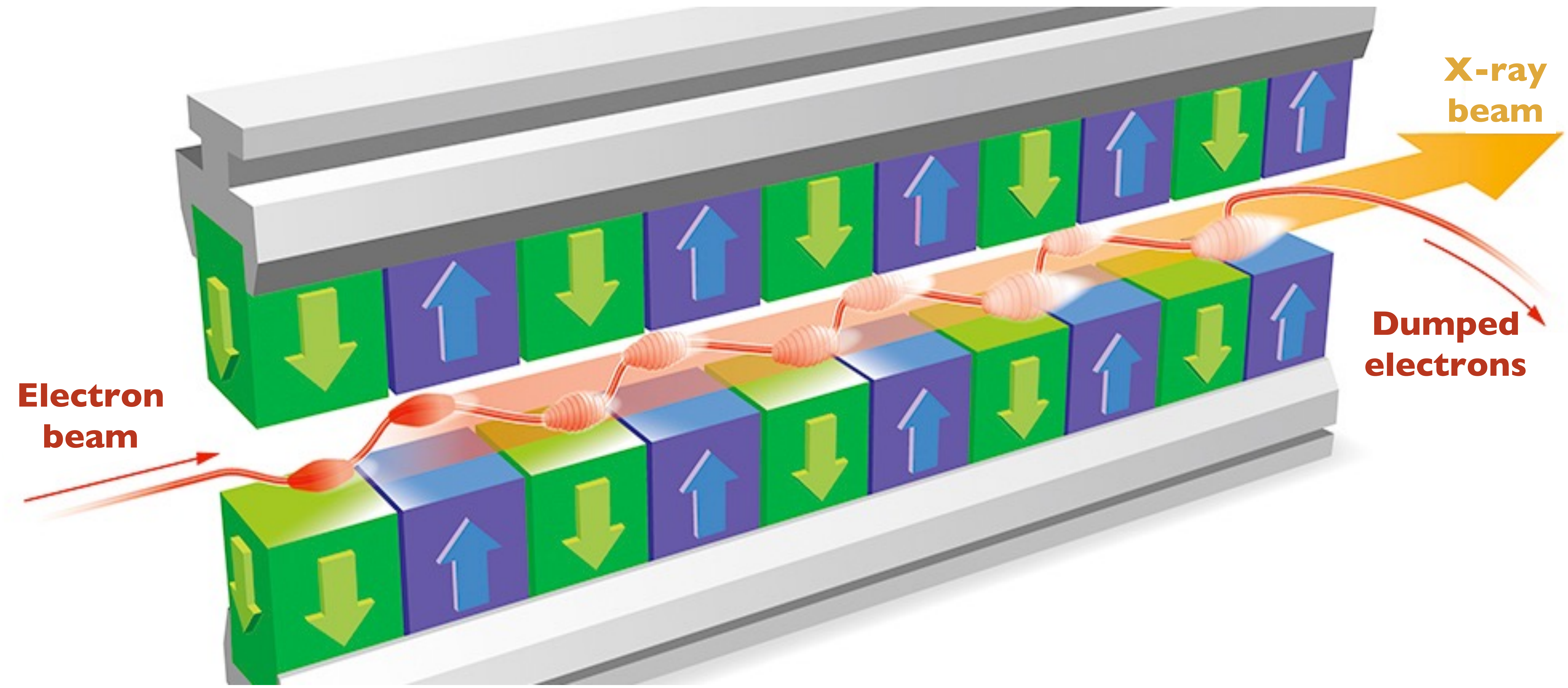
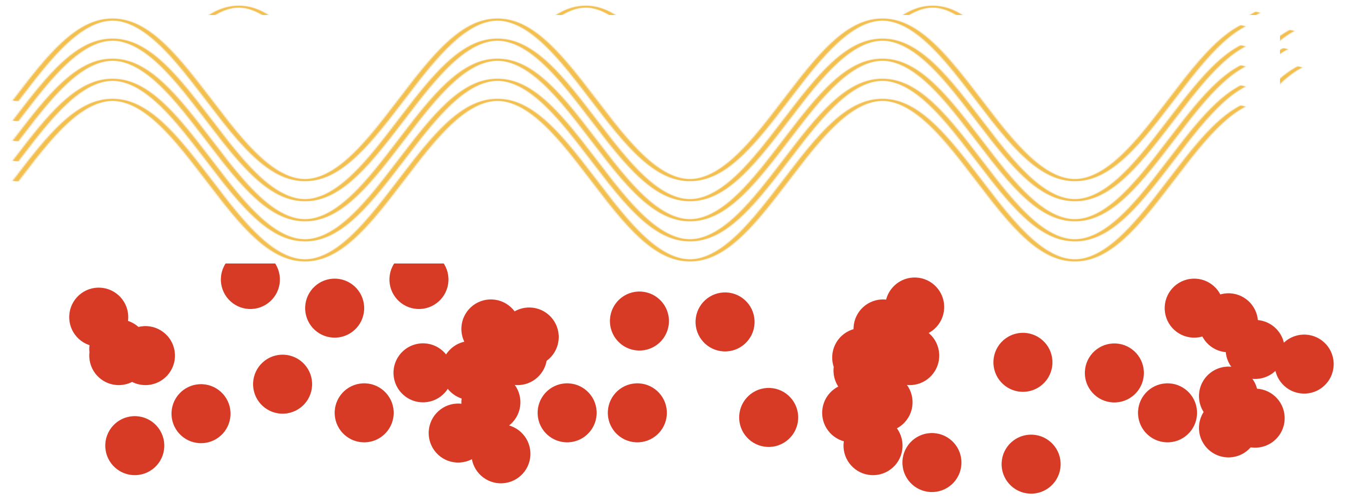
Contents

Collective motion is critical to advanced light sources

Collective motion enables amplification in an free electron laser (FEL)

FEL setup





In an FEL every microbunch emits like a single particle

The collective trajectory and single particle trajectory are nearly identical

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

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

Decoupling collective and single particle trajectories

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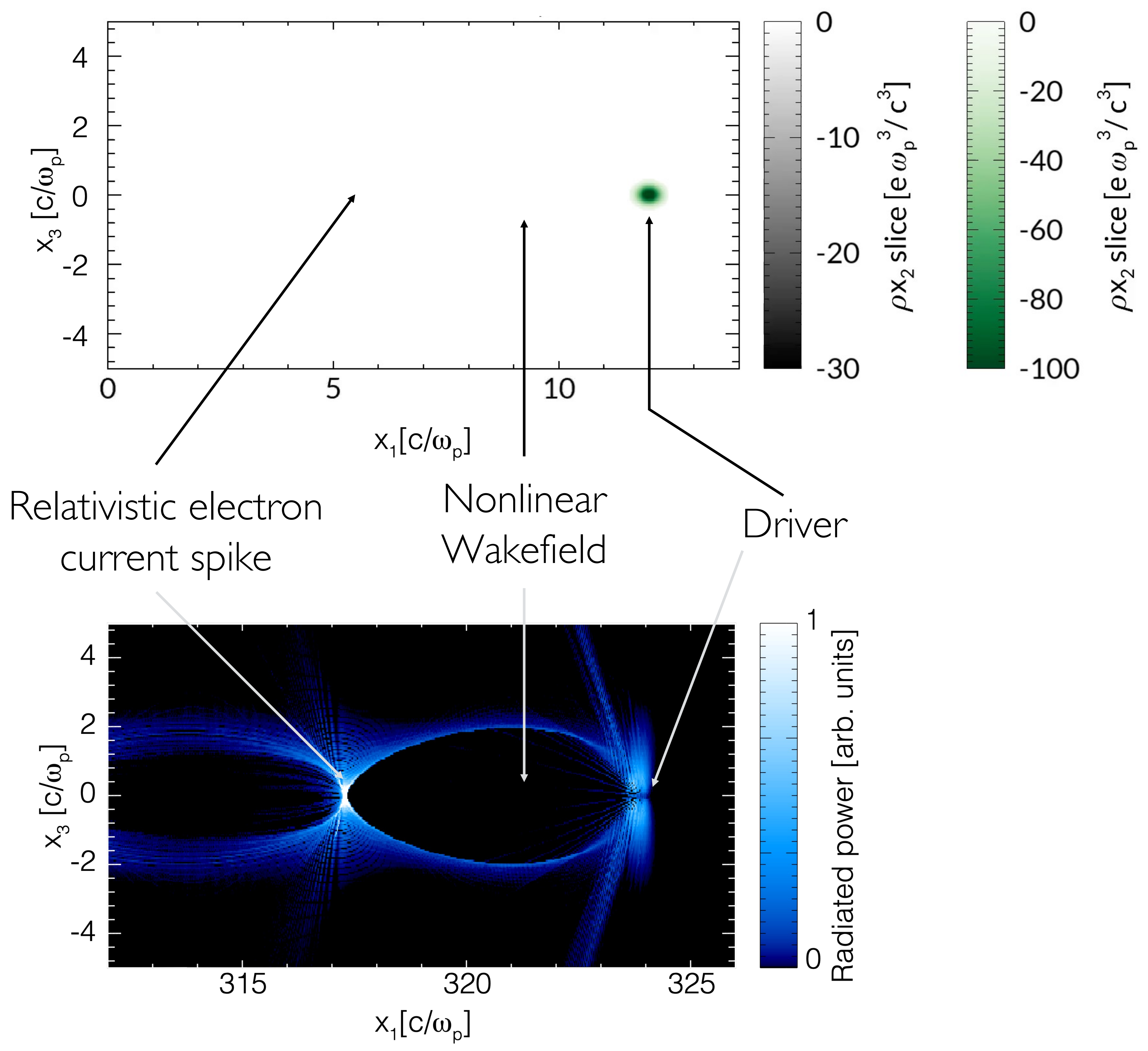
Plasma accelerators exhibit decoupled trajectories



Electron current spike trajectory

The electron current spike travels at a superluminal speed

Electron trajectory

Every electron travels at subluminal speeds in the wakefield

Decoupled trajectories lead to new regimes of superradiance and temporal coherence

Contents

The collective trajectory determines the radiation spectrum

Emission from a collective feature*

Radiated intensity per frequency per solid angle according to a current density $\mathbf{j}[\mathbf{r}, t]$

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

The expression can be simplified!

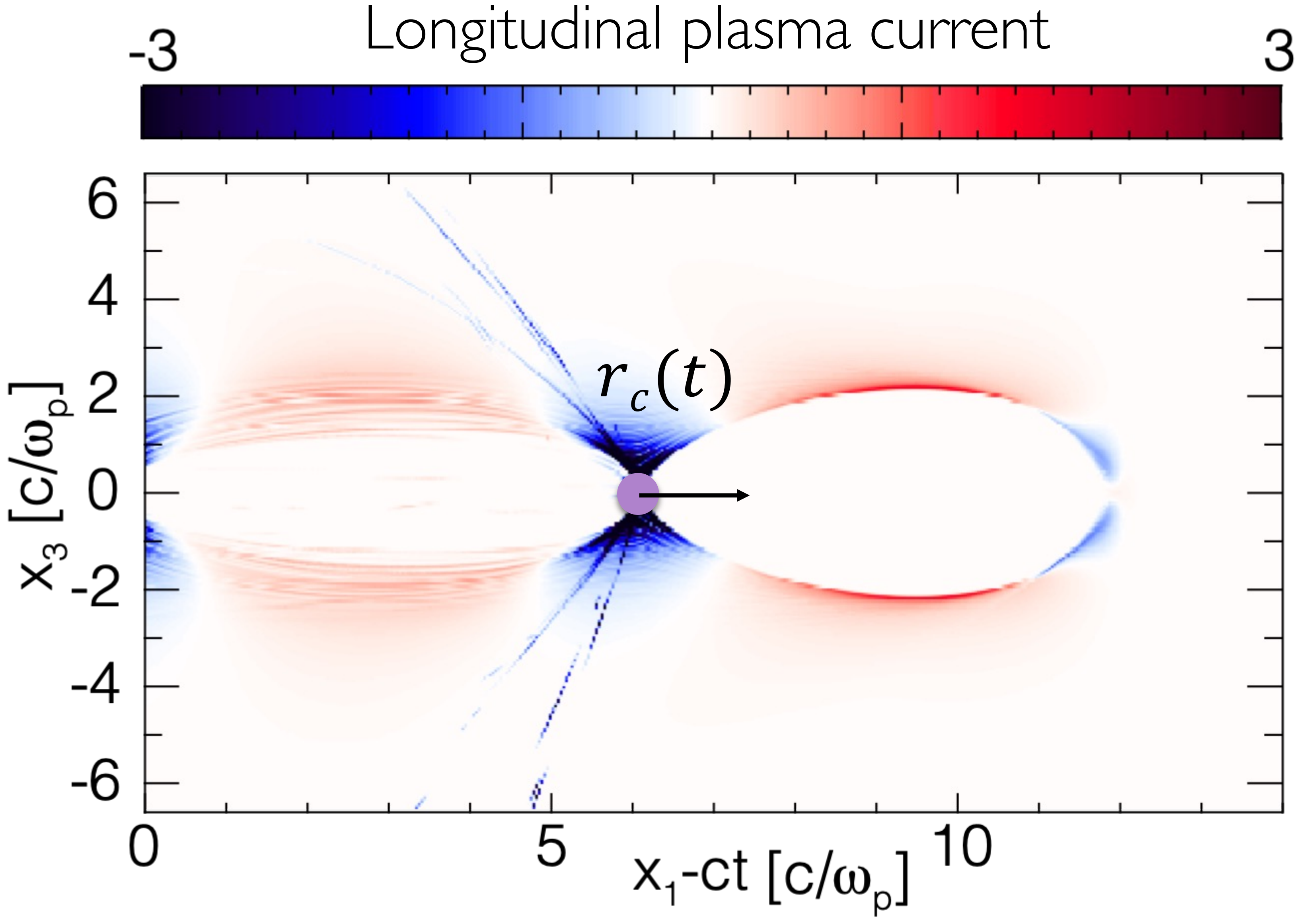
Radiated intensity per frequency per solid angle according to a current density $\mathbf{j}[\mathbf{r}, t] = \mathbf{j}[\mathbf{r} - \mathbf{r_c}(t), t] = \mathbf{j}[\boldsymbol{\xi}, t]$

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

$\mathcal{S}(\omega, \Omega)$ is the shape factor of the collective object

The collective trajectory: the driver of superradiance

$\omega^2 \mathcal{S}(\omega, \Omega)$ for the plasma wave



$\mathbf{r_c}(t)$ determines all of the temporal coherence properties

*J. D. Jackson, *Classical Electrodynamics*, 3rd edition

Quasiparticle trajectory determines the radiation spectrum

Emission from a quasiparticle

Radiated intensity per frequency per solid angle according to a current density $\mathbf{j}[\mathbf{r},t]$

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

The expression can be simplified!

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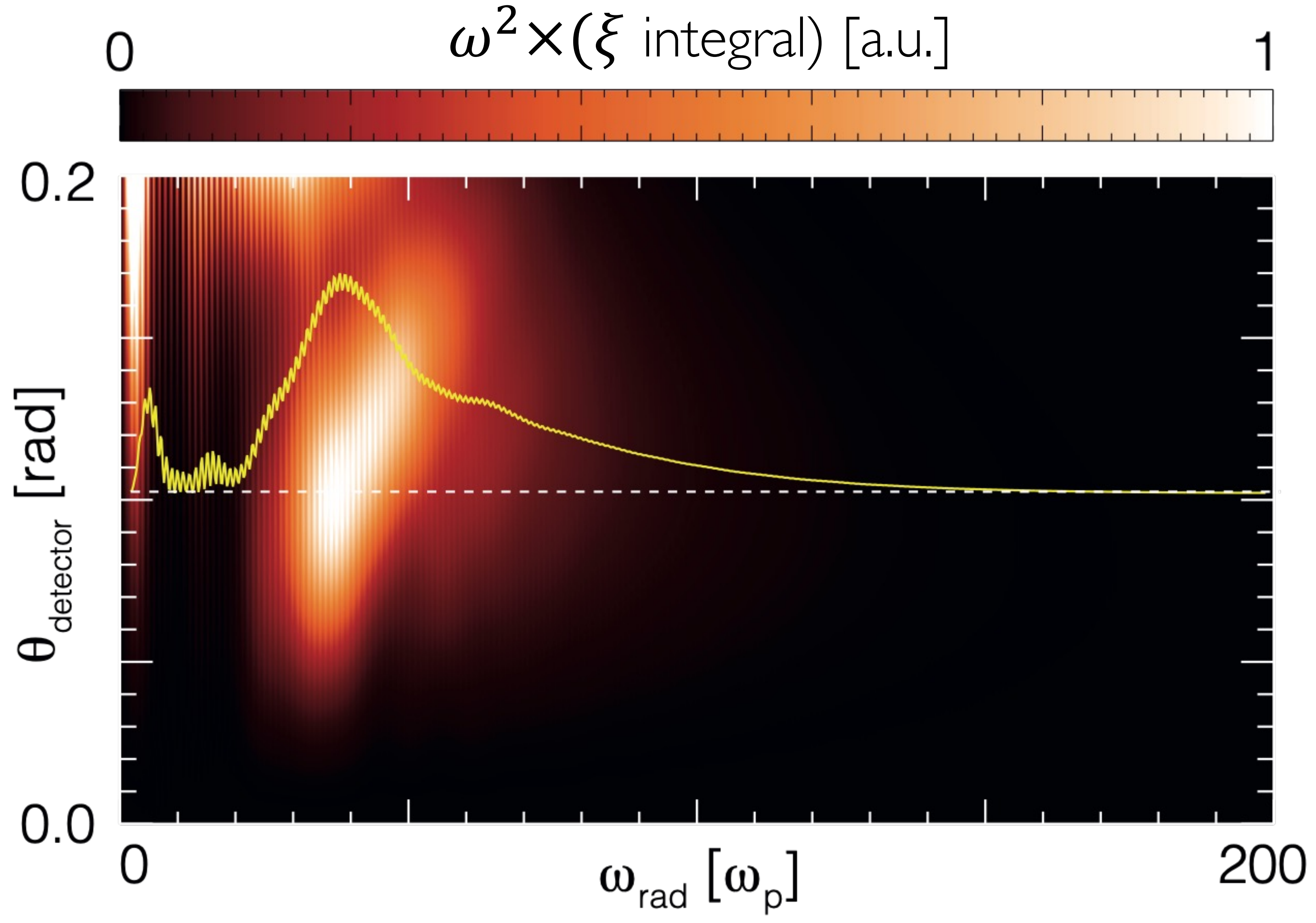
$\mathcal{S}(\omega,\Omega)$ is the shape factor of the quasiparticle

The quasiparticle: the driver of superradiance

$\omega^2\mathcal{S}(\omega,\Omega)$ for the plasma wave



$\mathbf{r_c}(t)$ determines all of the temporal coherence properties

*J. D. Jackson, *Classical Electrodynamics*, 3rd edition

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

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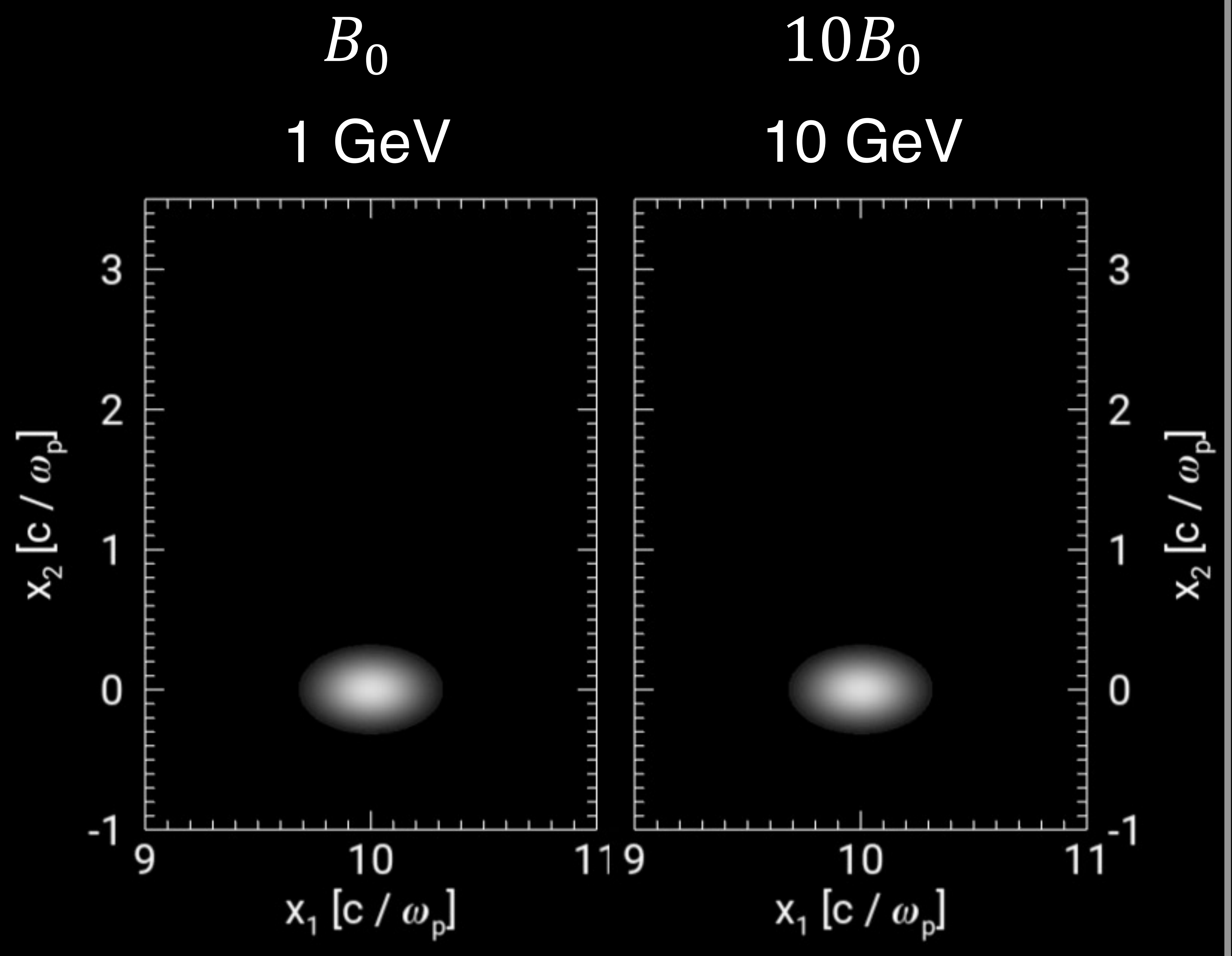
Relativistic electron bunch in external B



Collective motion (quasiparticle)

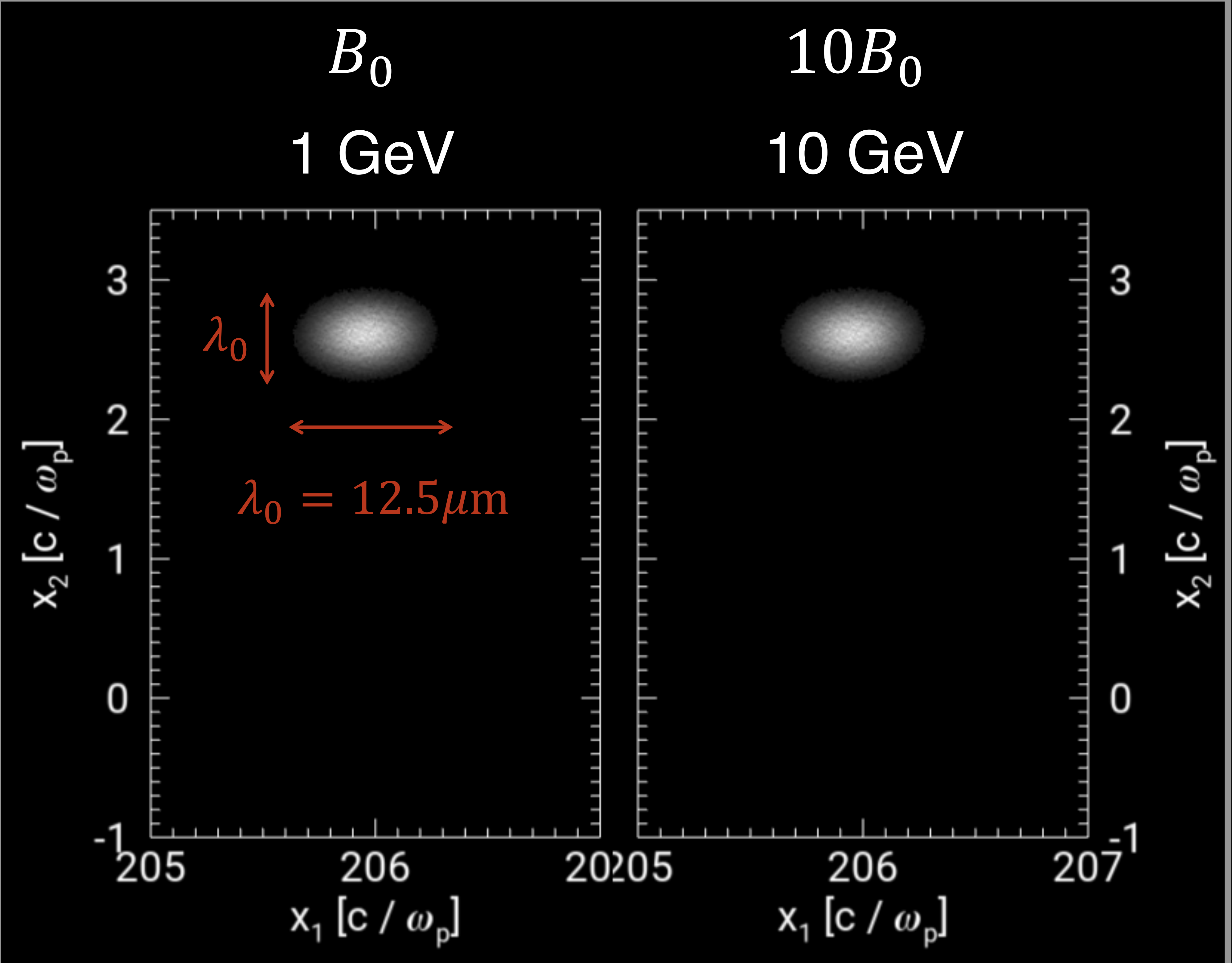
$$\frac{d^2I}{d\omega d\Omega} = \frac{\omega^2}{4\pi^2c^3}\left|\int dt\,\mathcal{S}e^{i\omega[t-\mathbf{n}\cdot\mathbf{r}_c(t)/c]}\right|^2$$

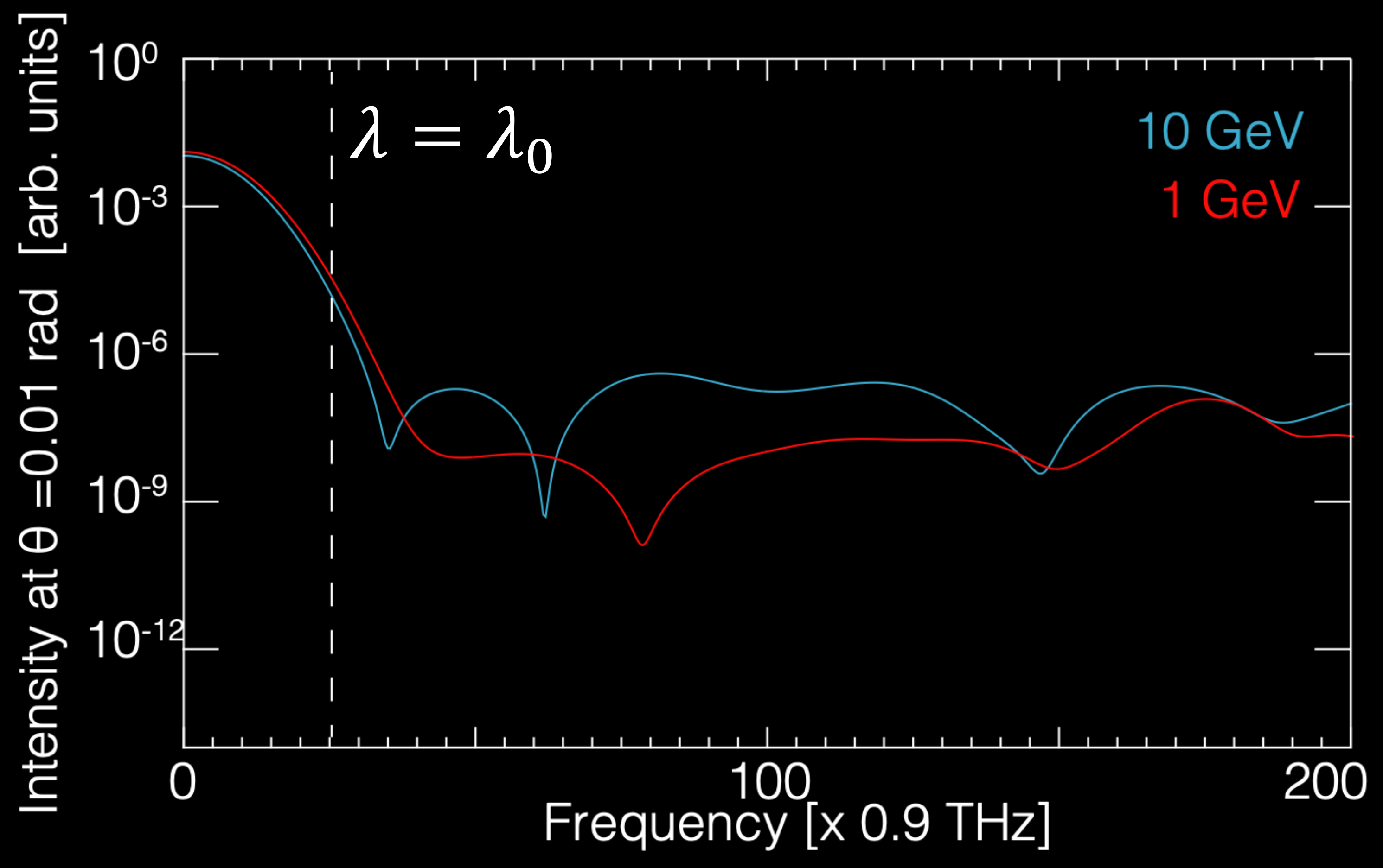
Single electron

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

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

Relativistic electron bunch in external B





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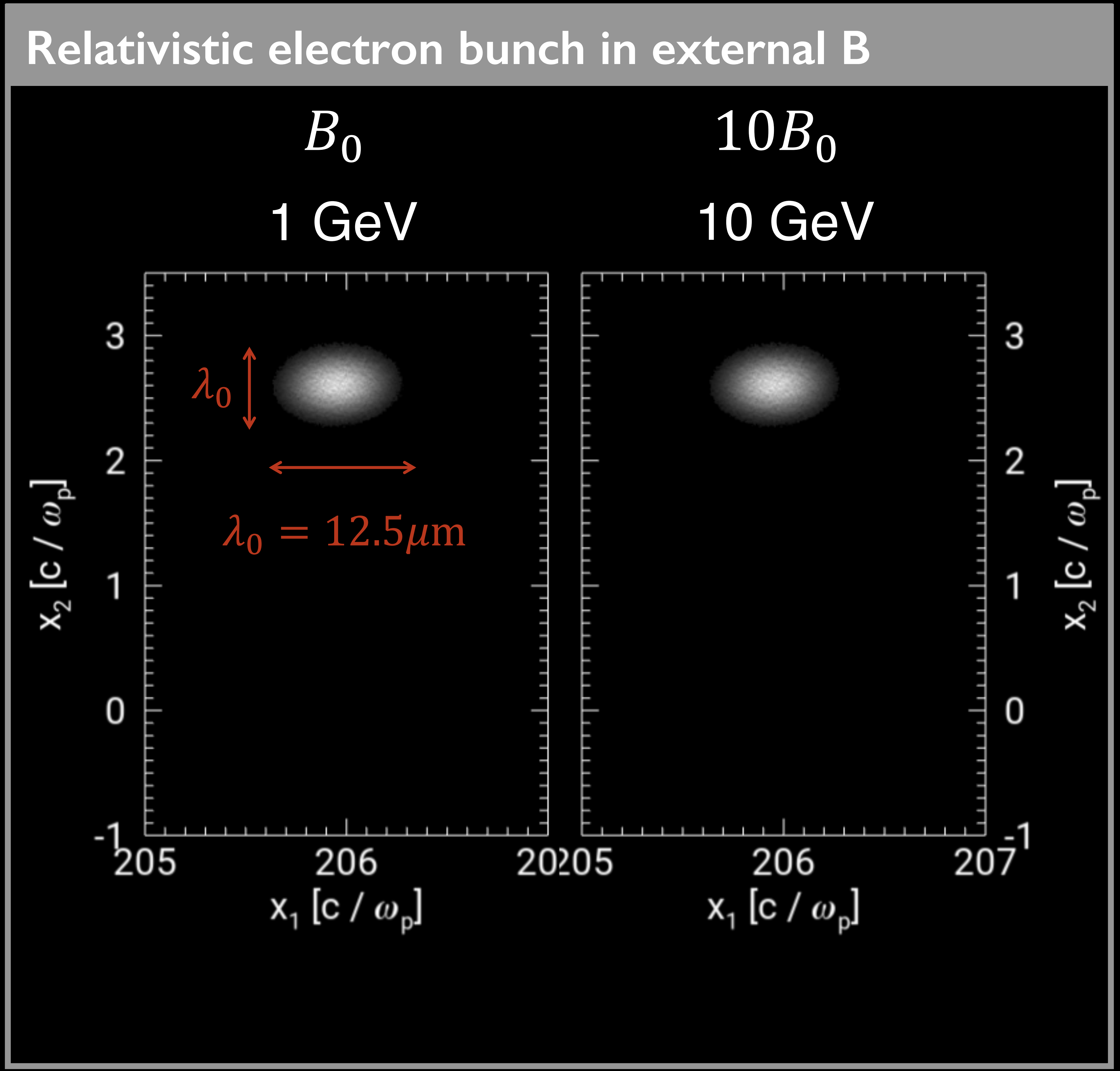

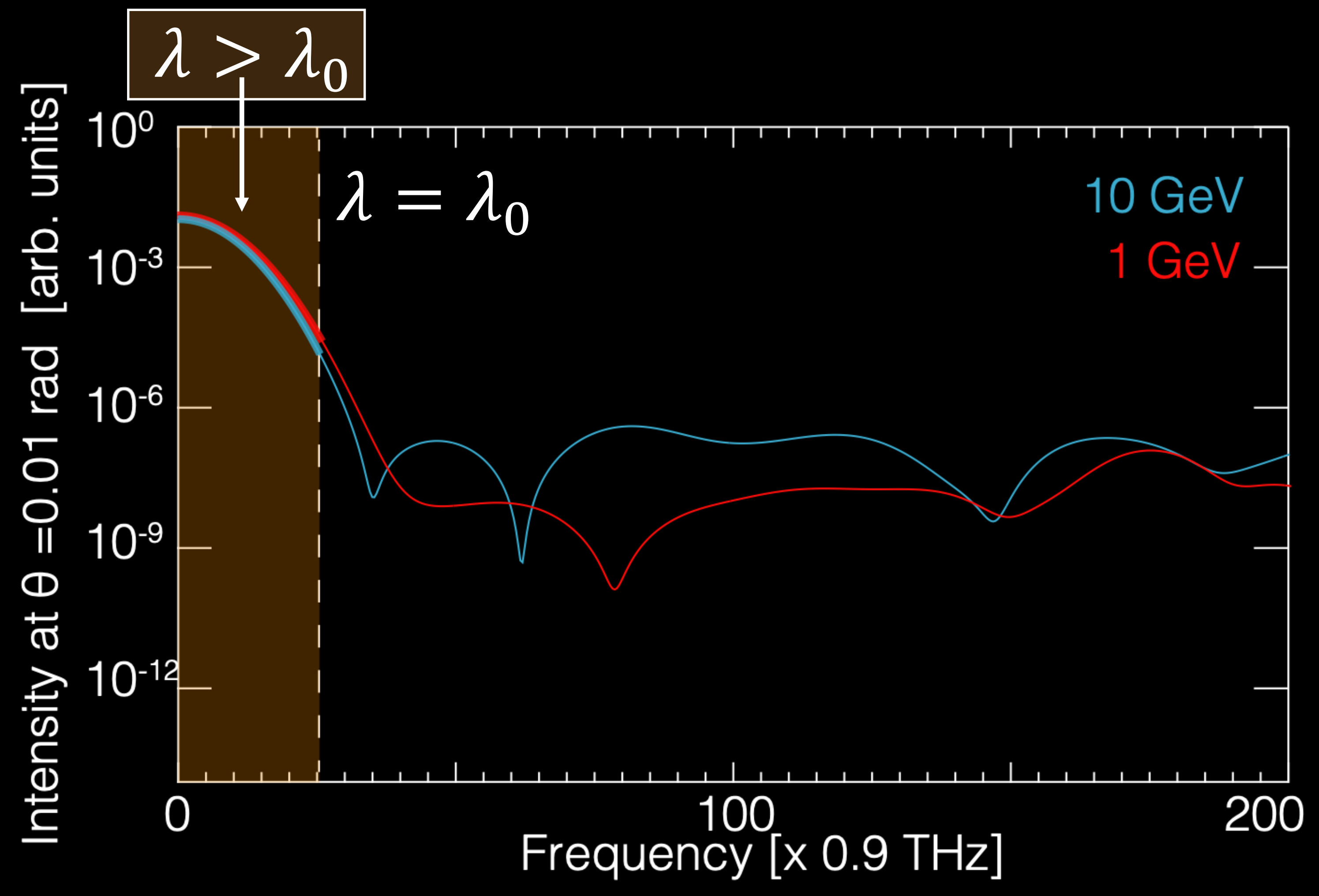

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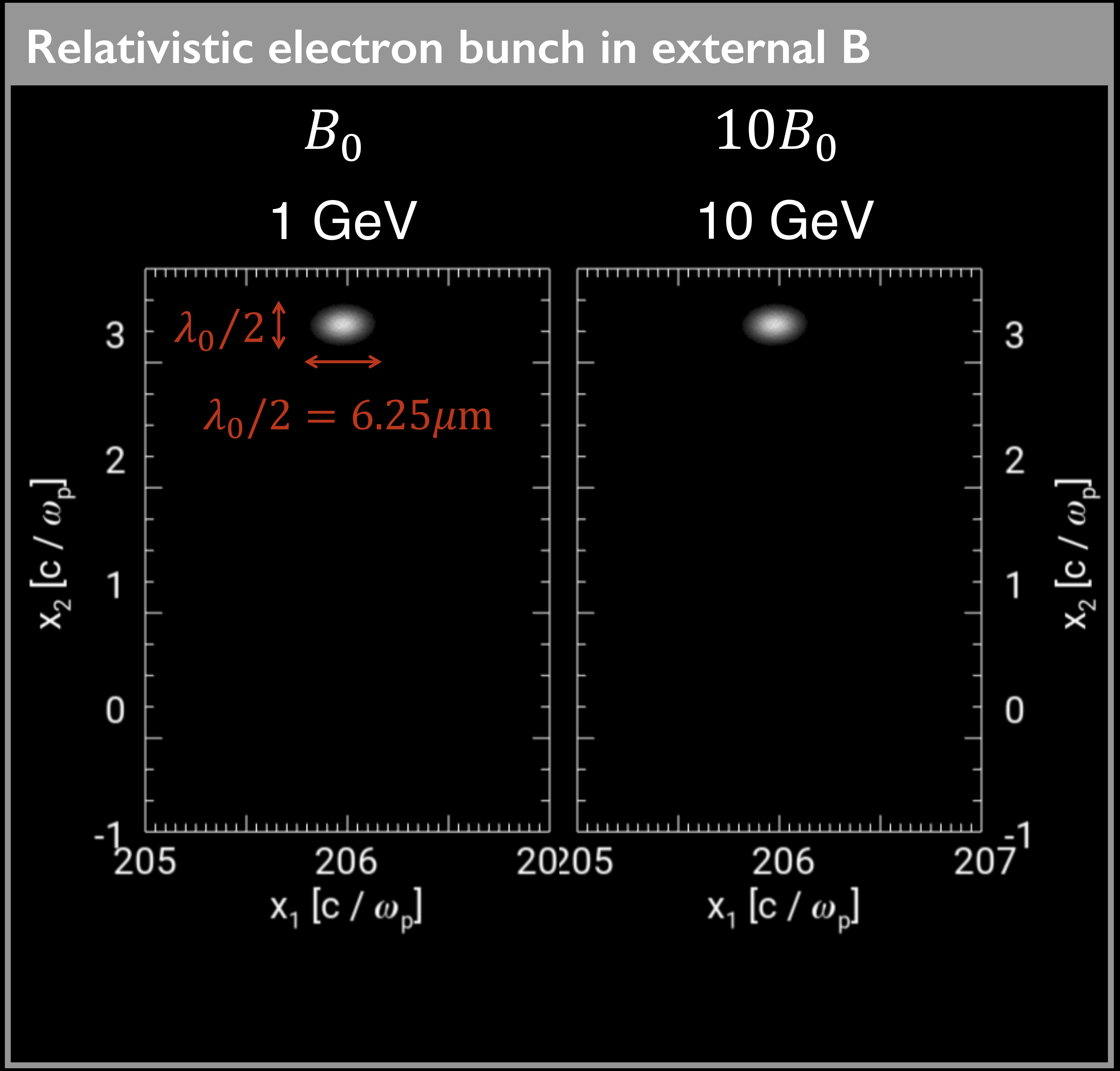
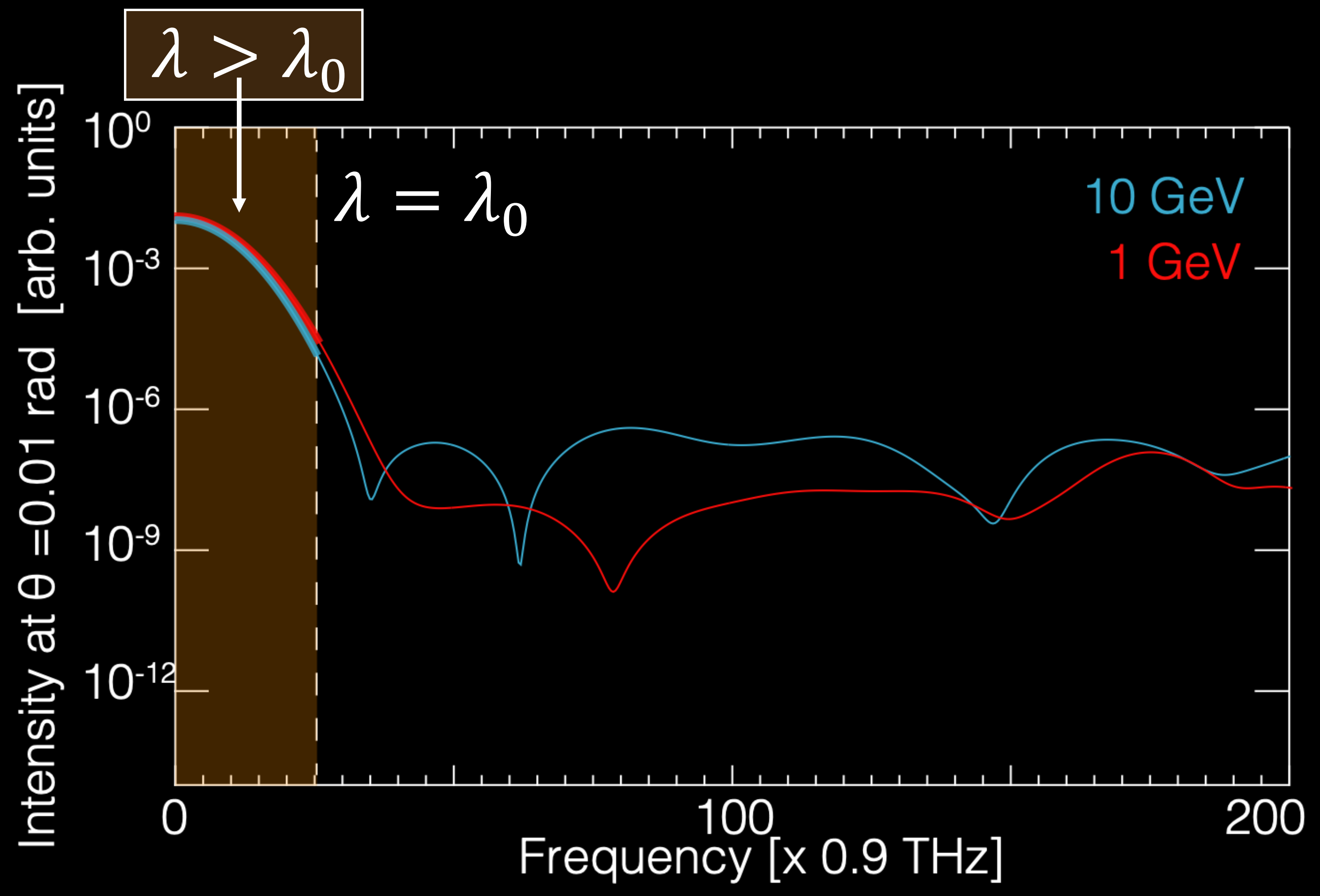
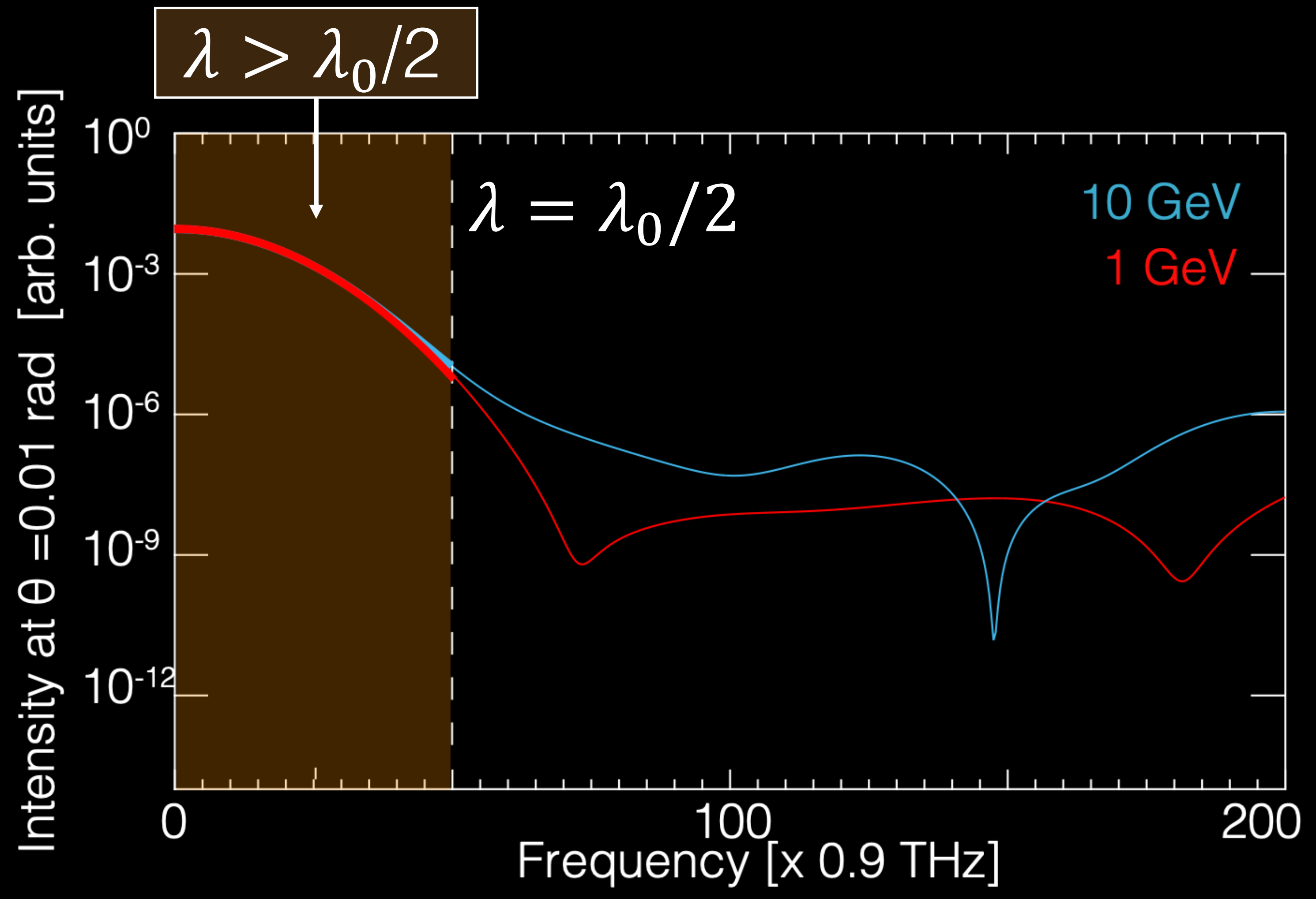


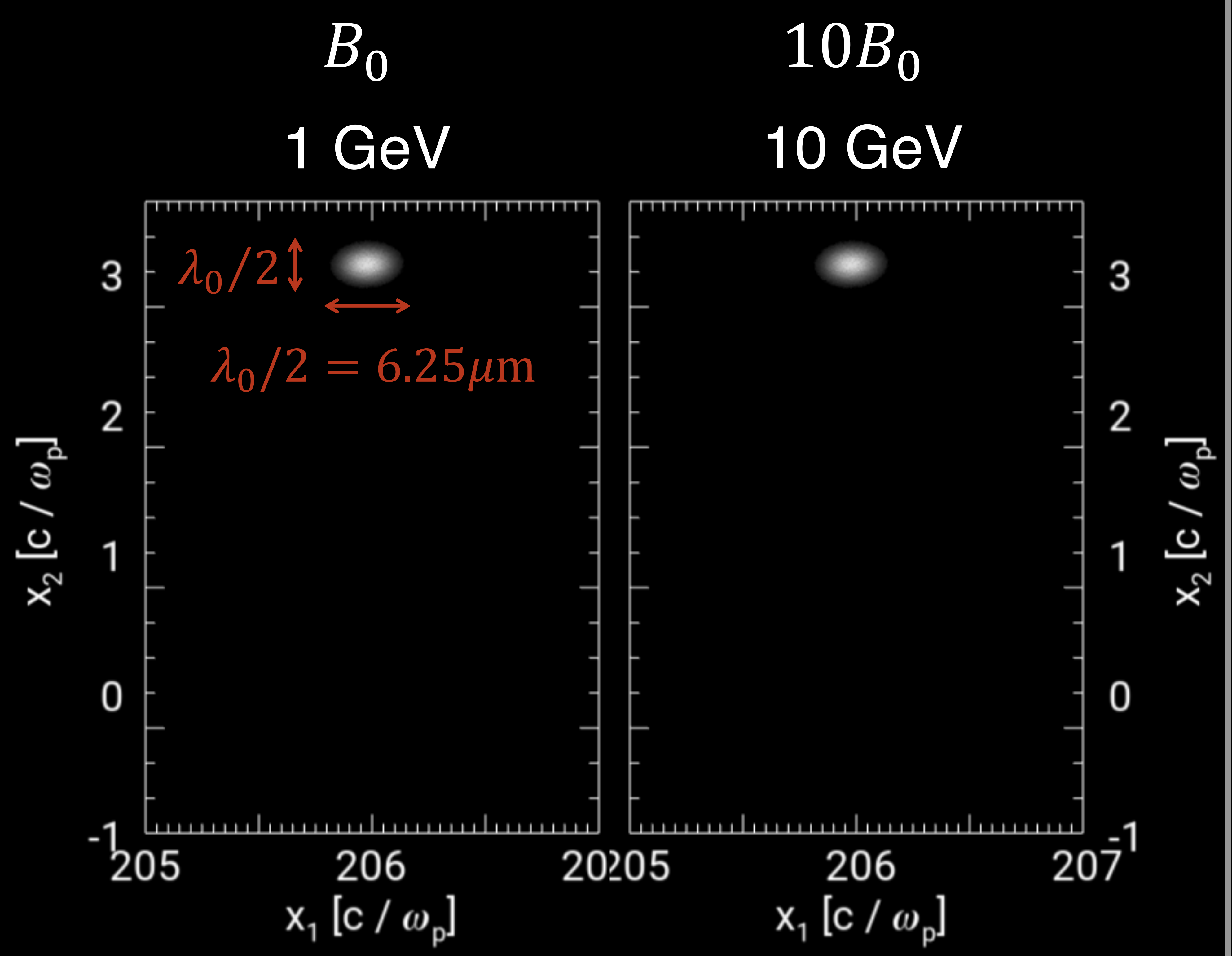


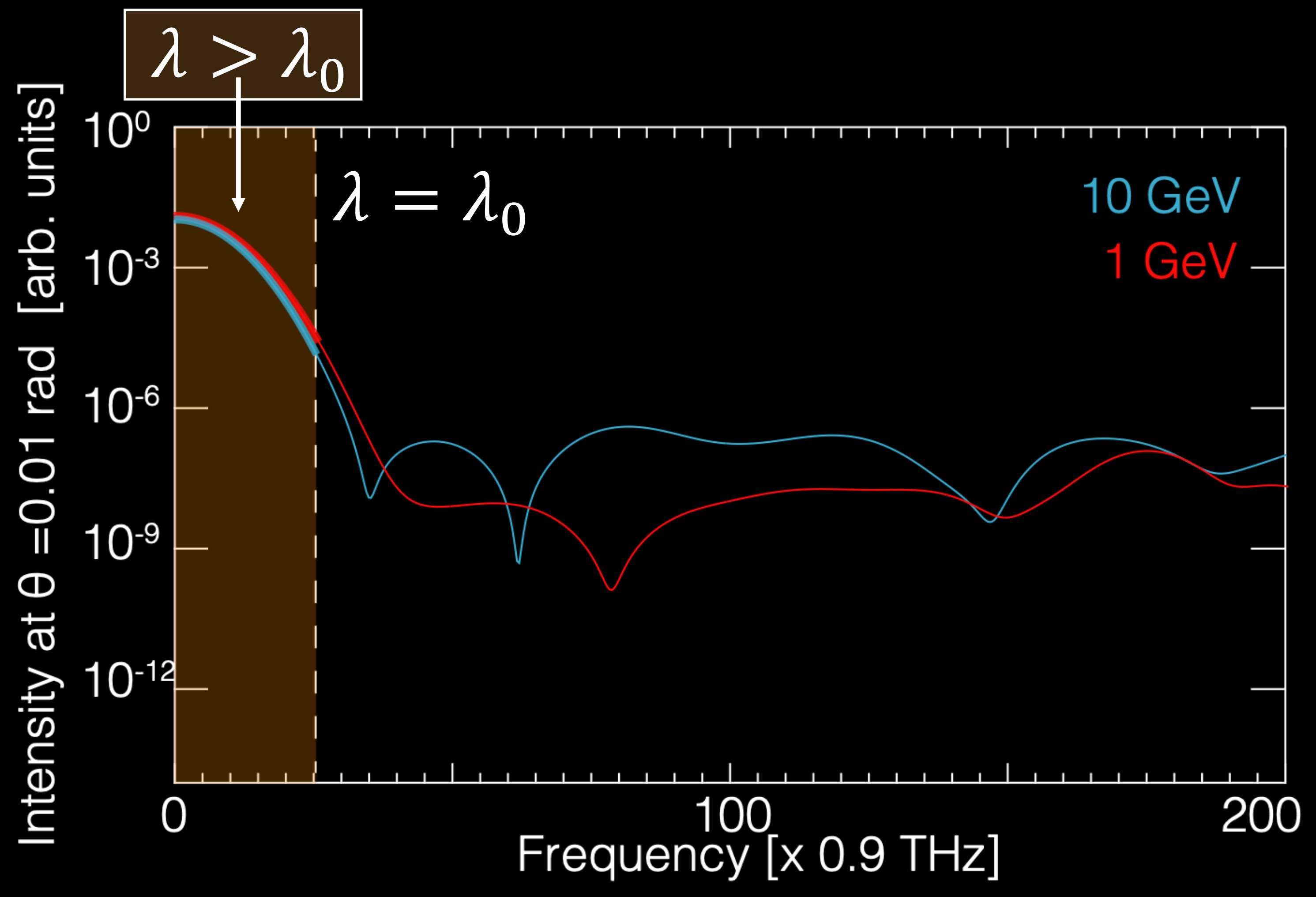


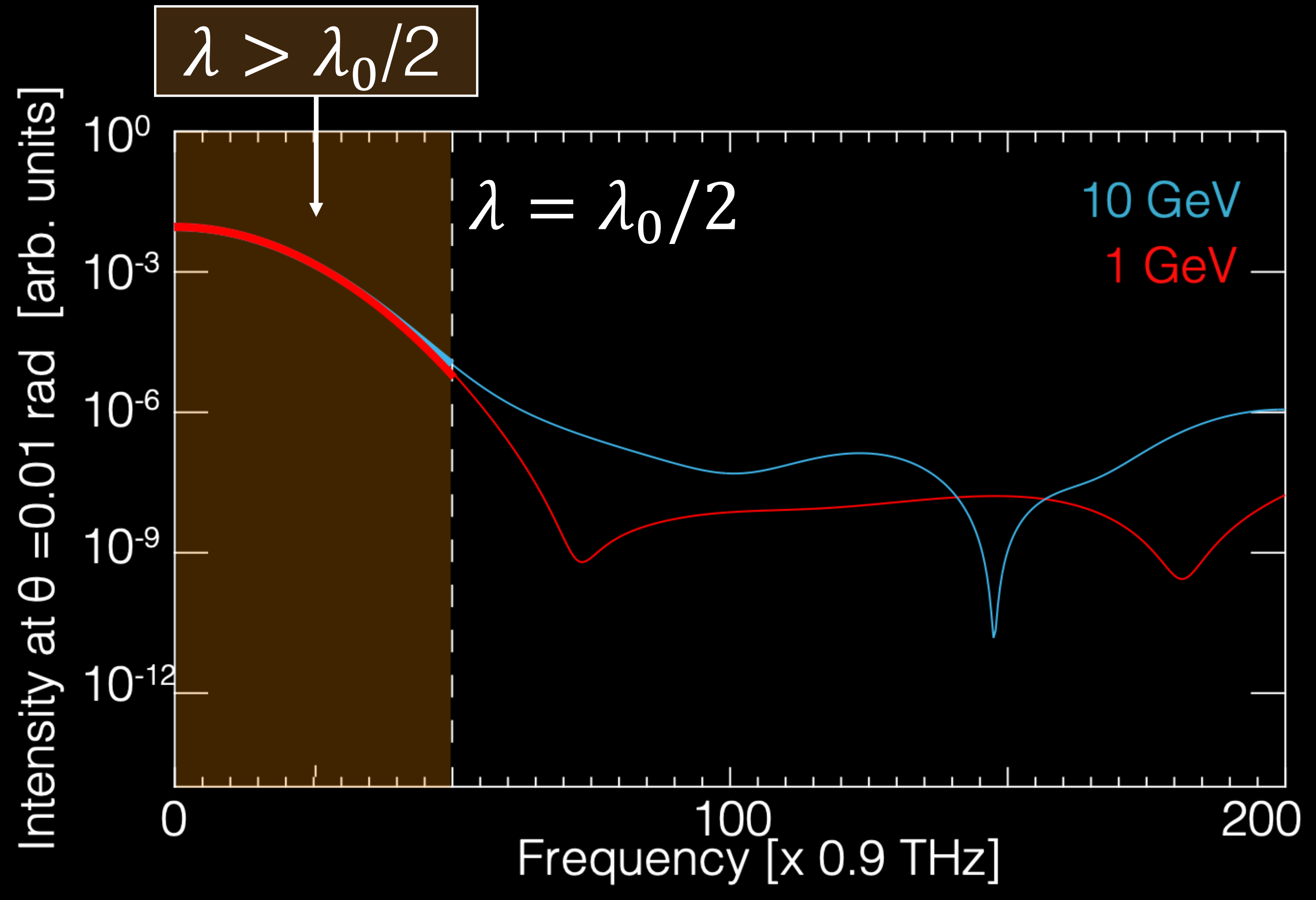
Can quasiparticles radiate as a finite-sized single-particle?

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

Relativistic electron bunch in external B







Contents

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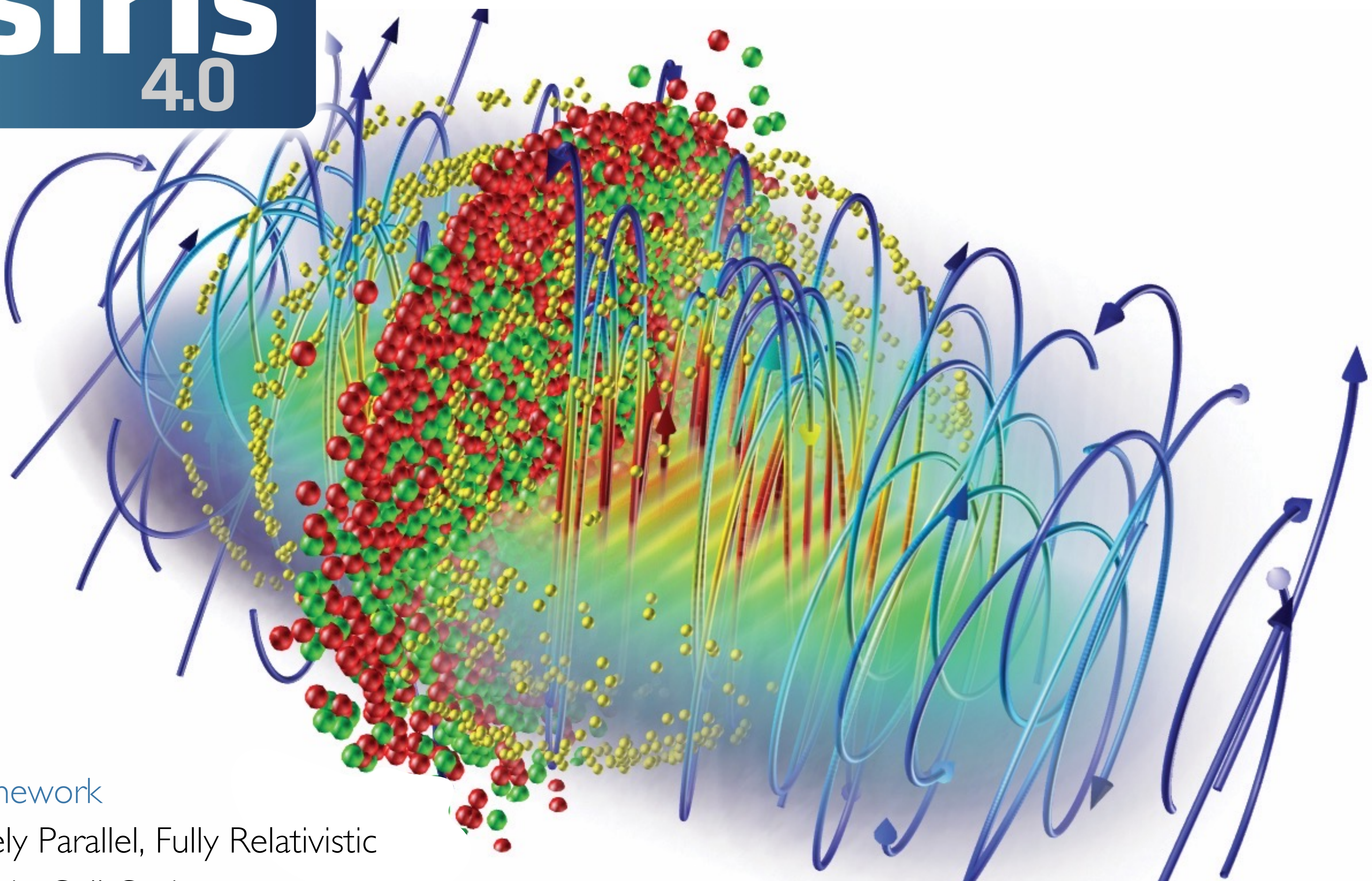
OSIRIS open source available



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/

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

The quasiparticle trajectory can be controlled using a density ramp

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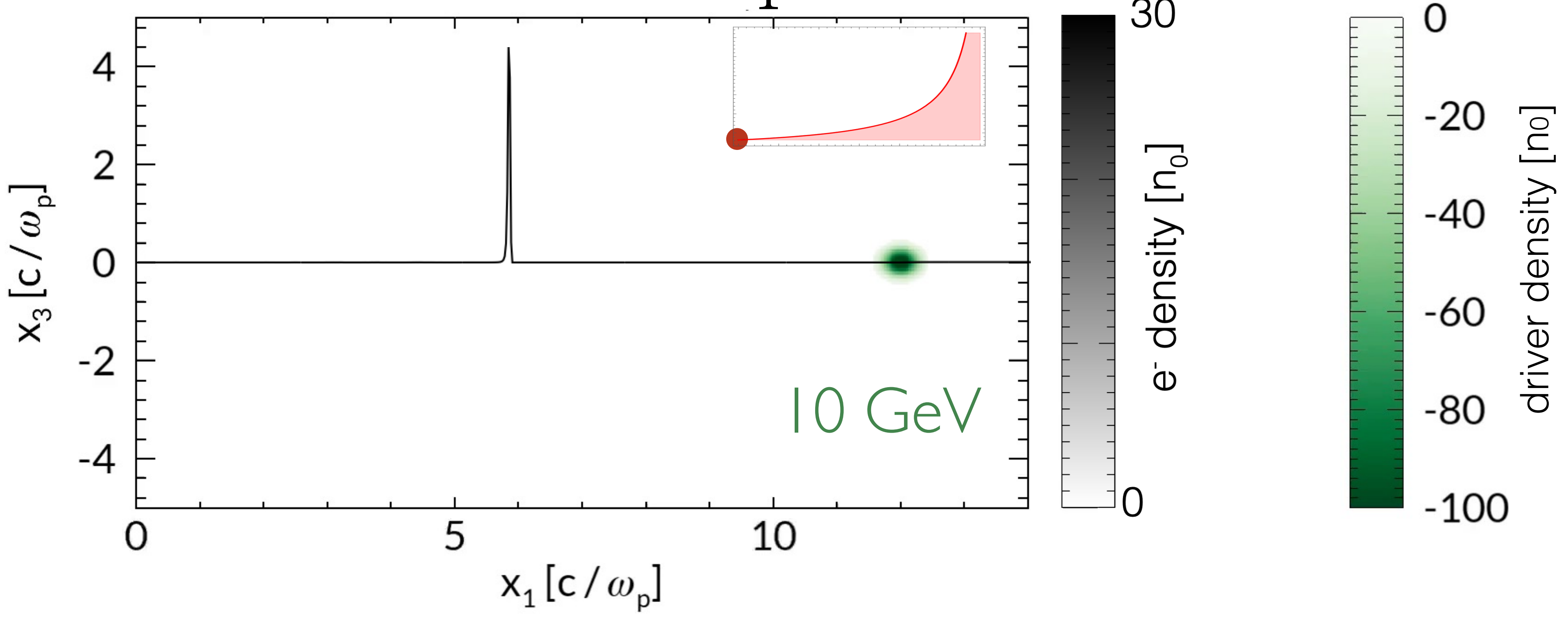
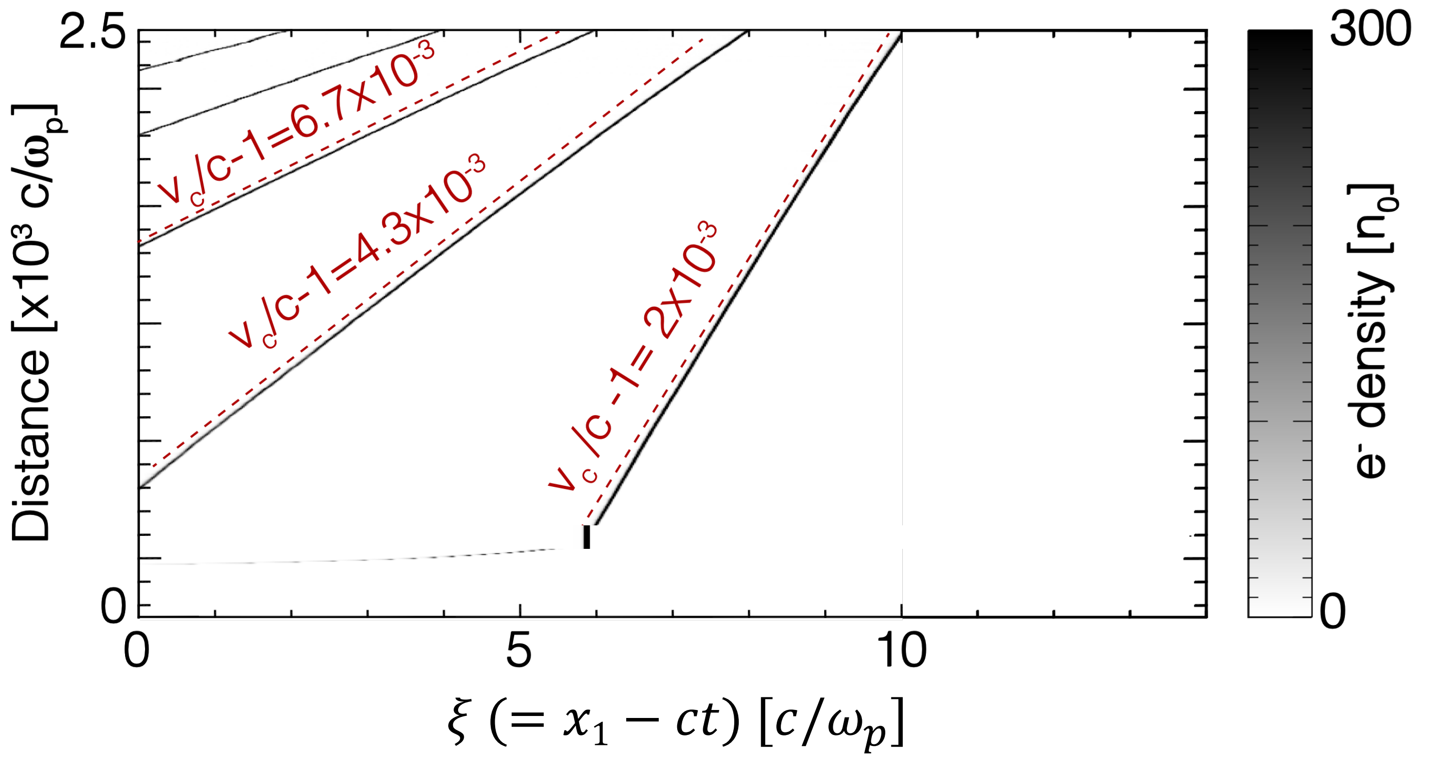
A superluminal quasiparticle

For a constant speed*: $n(x) = n_0 \dfrac{\lambda_{p0}^2}{\left[\lambda_{p0} - \left(\frac{v_1}{c} - 1\right) x\right]^2}$

$v_1 = 1.002c$





Each successive quasiparticle travels faster!

$(\beta_n - 1) \approx n(\beta_1 - 1)$

$\mathbf{r}_{\mathbf{c},n}(t) = v_n t \mathbf{e}_\parallel$

$$\left| \int_{-T/2}^{T/2} dt \, \exp[i\omega(t - \mathbf{n} \cdot \mathbf{r}_{\mathbf{c},n}(t)/c)] \right|^2 = T^2 \mathrm{sinc}^2 \left[\frac{\omega T}{2} \left(1 - \frac{v_n \cos\theta}{c} \right) \right]$$

Coherent emission when $\cos\theta = \dfrac{c}{v_n}$

This is an example of a Cherenkov emission at multiple angles using collective dynamics!

*X. L. Xu and W.B. Mori, PRAB **20**, 111303 (2017)

We get radiation data at runtime using RaDiO*

PIC Codes and Líenard-Wiechert Fields

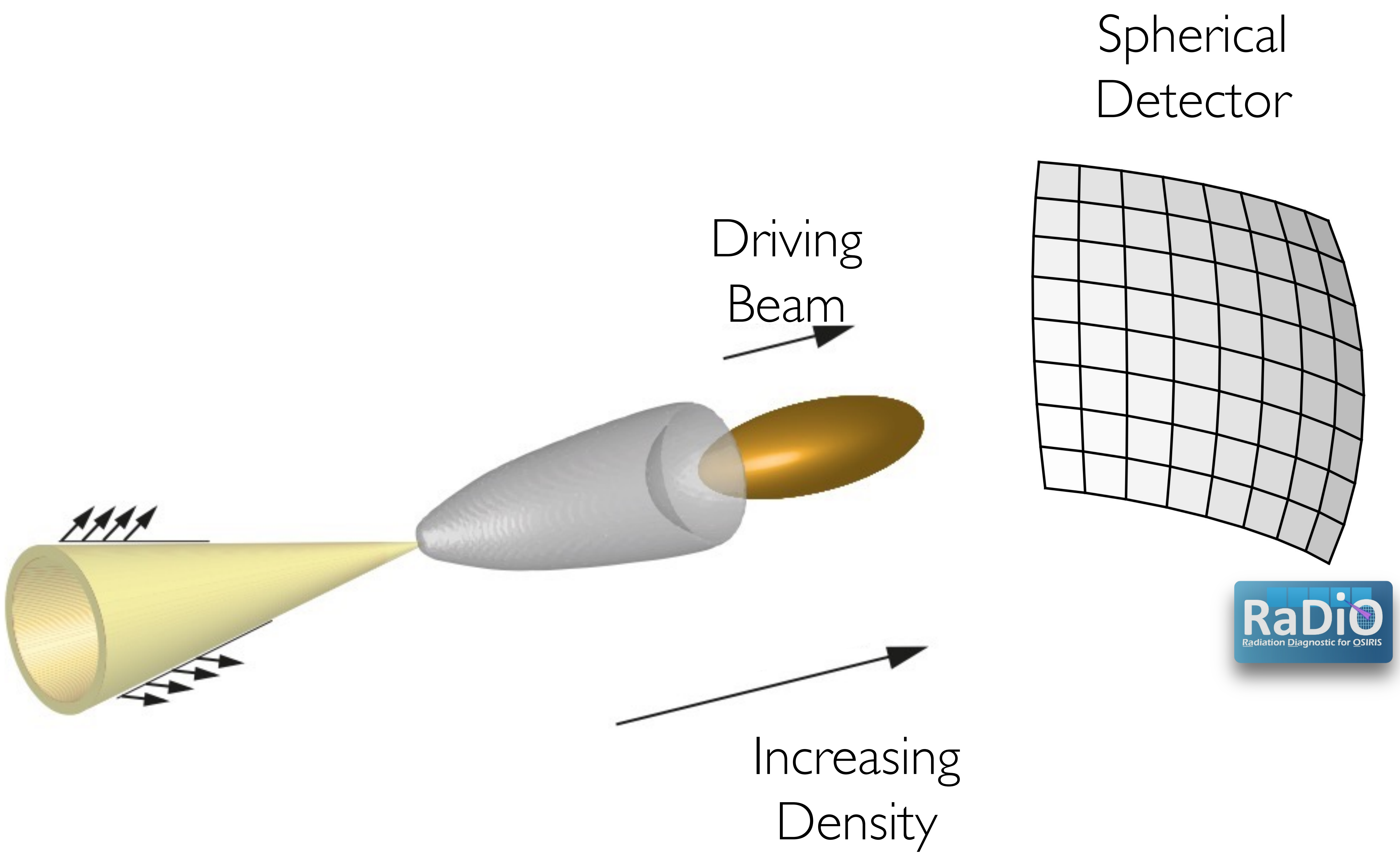
Particles exist in a **grid** which intermediates **EM interactions.**

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

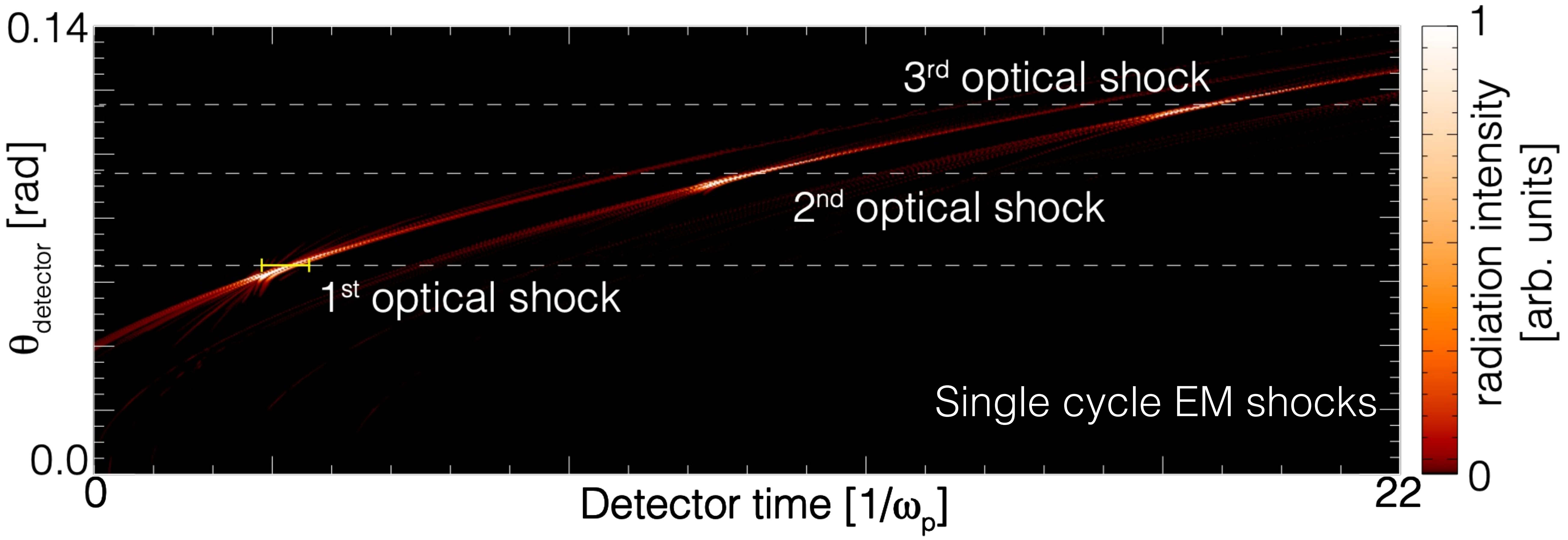
$$\mathbf{E}(\mathbf{x}, t_{det}) = \frac{q_e}{c}\left[\frac{\mathbf{n} \times [(\mathbf{n} - \boldsymbol{\beta}) \times \dot{\boldsymbol{\beta}})]}{(1 - \boldsymbol{\beta} \cdot \mathbf{n})^3 R}\right]_{\text{ret}}$$



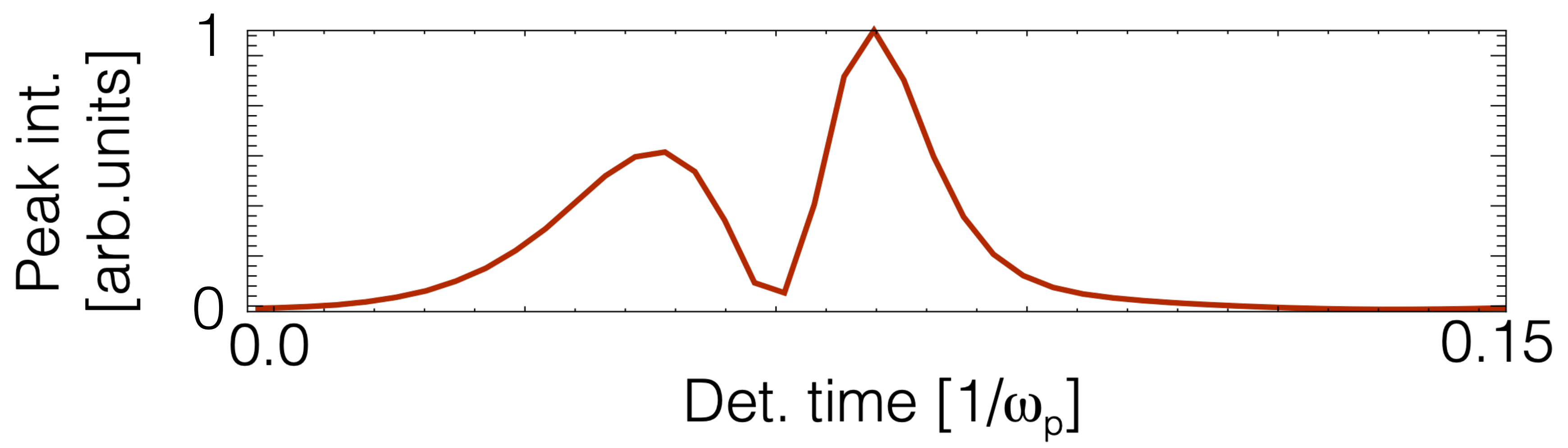
*M. Pardal, *et al*, Computer Physics Communications, 285, (2022)

The quasiparticle theory agrees with simulations

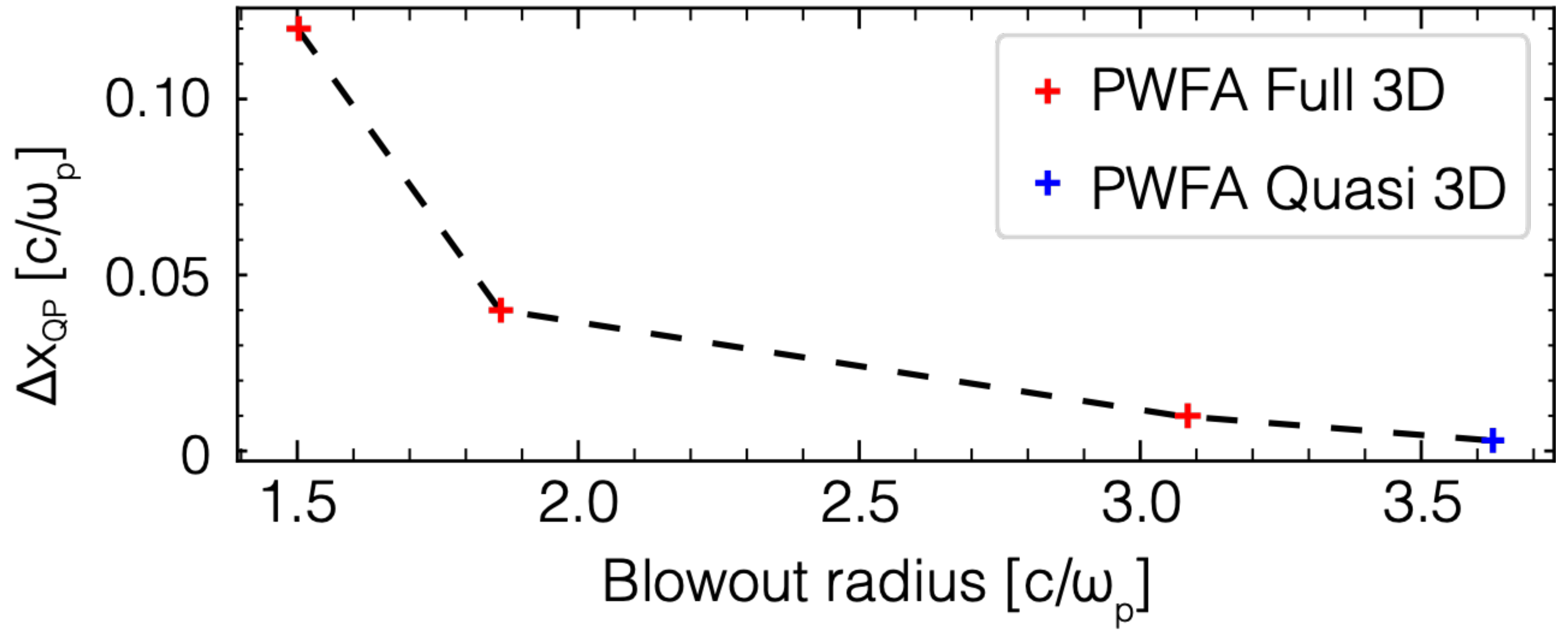
A detector in the far field collects the radiation from the quasiparticles



Each quasiparticle emits a single-cycle super radiant optical shock



The single-cycle shocks are emitted at the predicted angle



As the intensity of the driver grows, the quasiparticle shrinks and the expected bandwidth increases

At 10^{18} cm^{-3}:
77eV (cold plasma)
50eV (20 eV plasma*)

*S. Diederichs et al, PoP **30**, 073104 (2023)

The quasiparticle theory agrees with simulations

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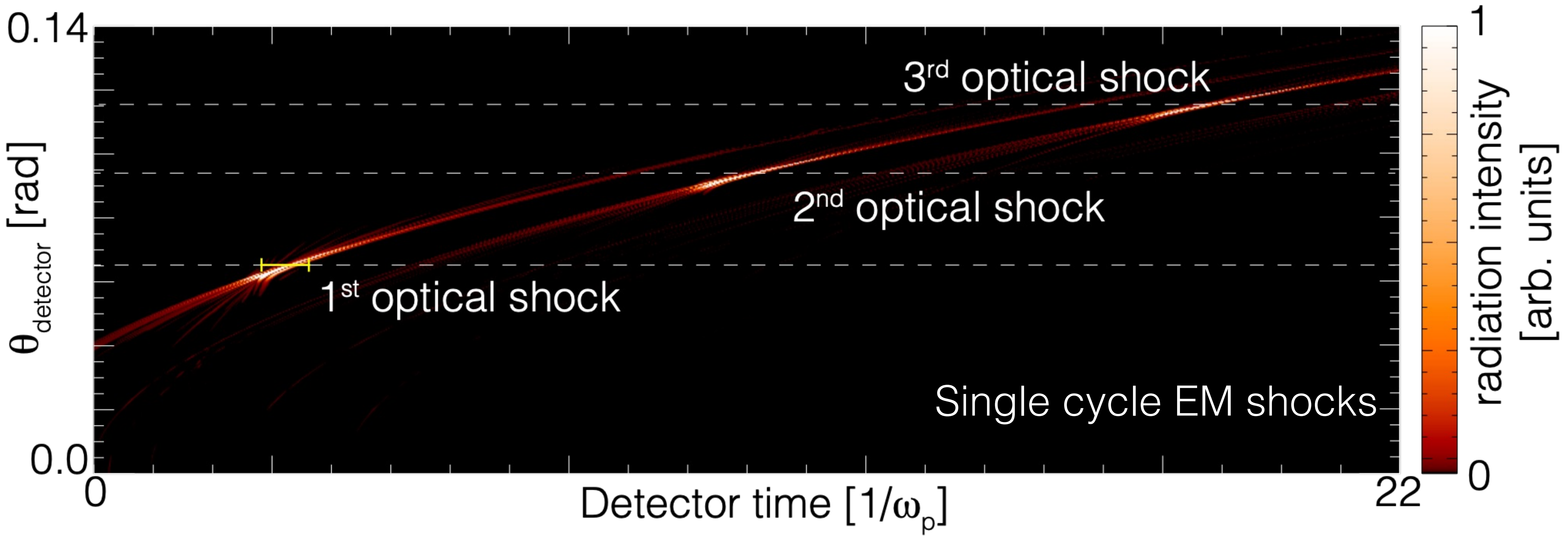
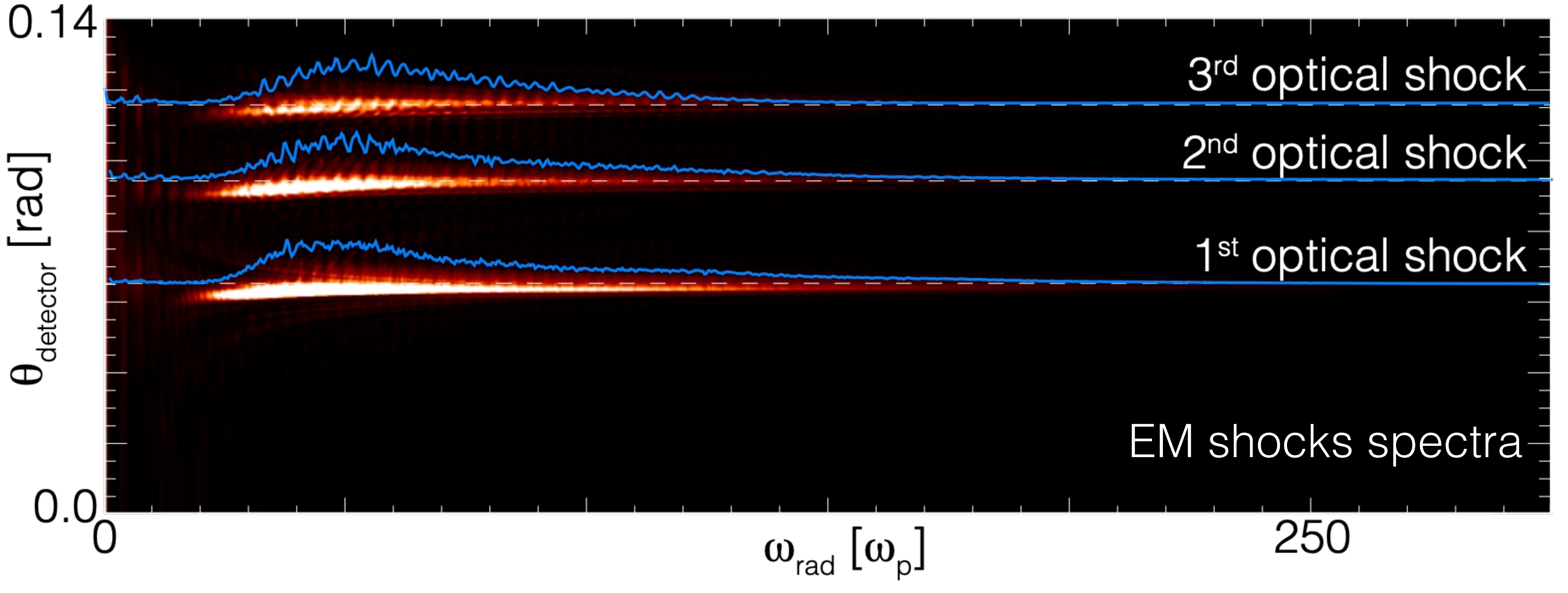
A detector in the far field collects the radiation from the quasiparticles





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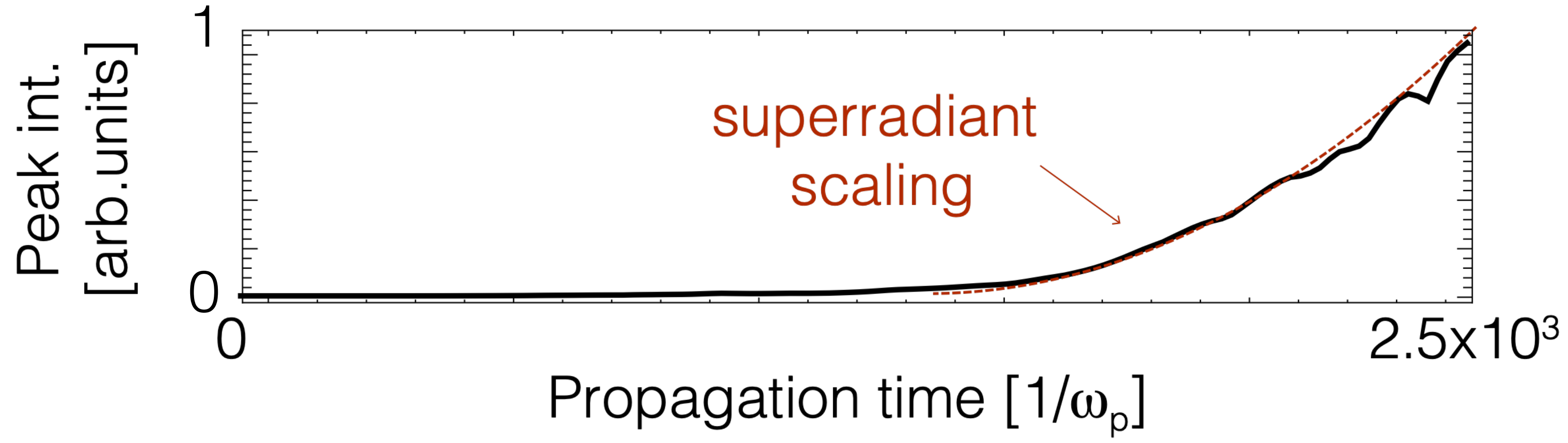
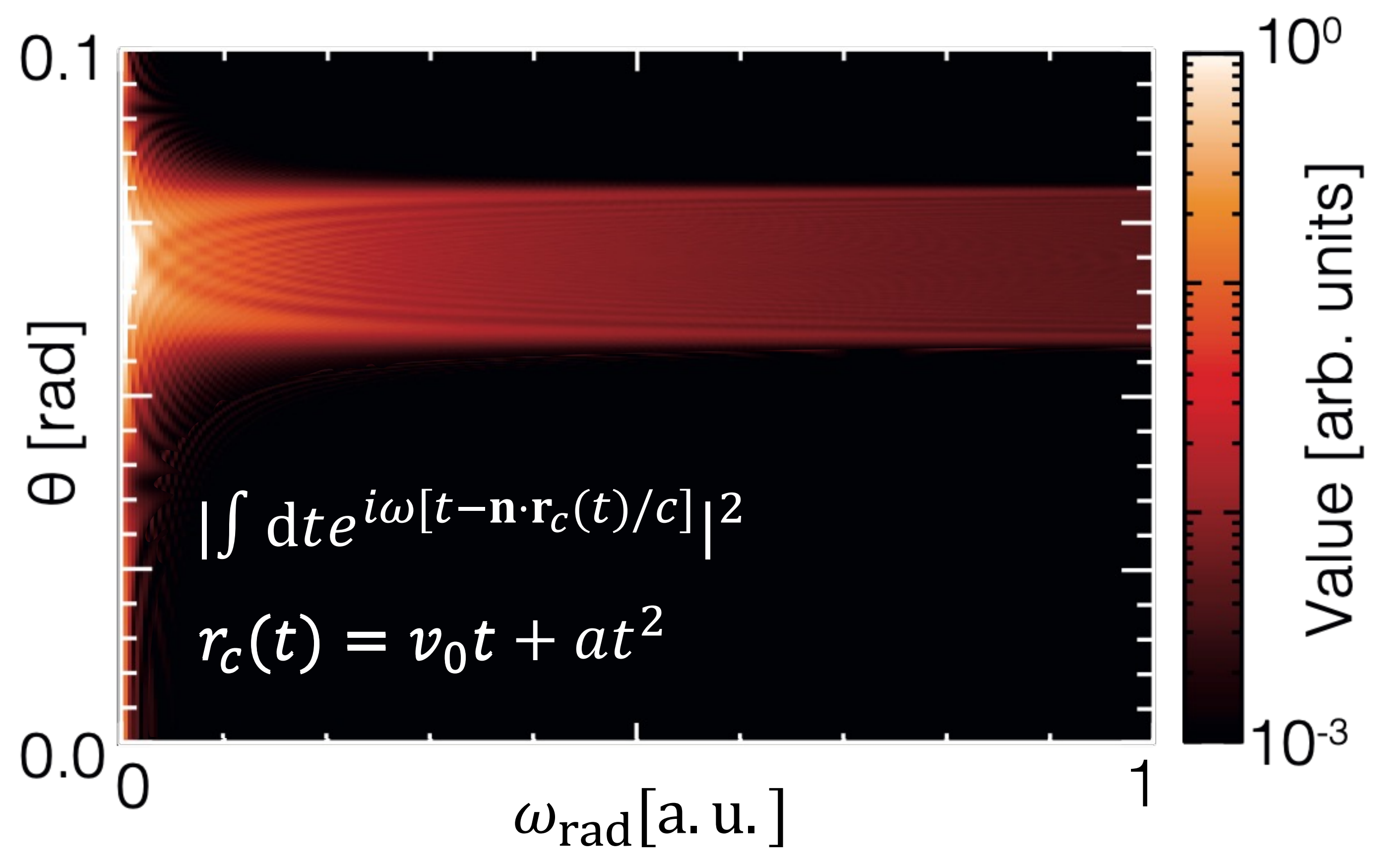


The intensity exhibits **quadratic growth** indicating **superradiance** (**$N \propto T$**)

How about if we have acceleration?



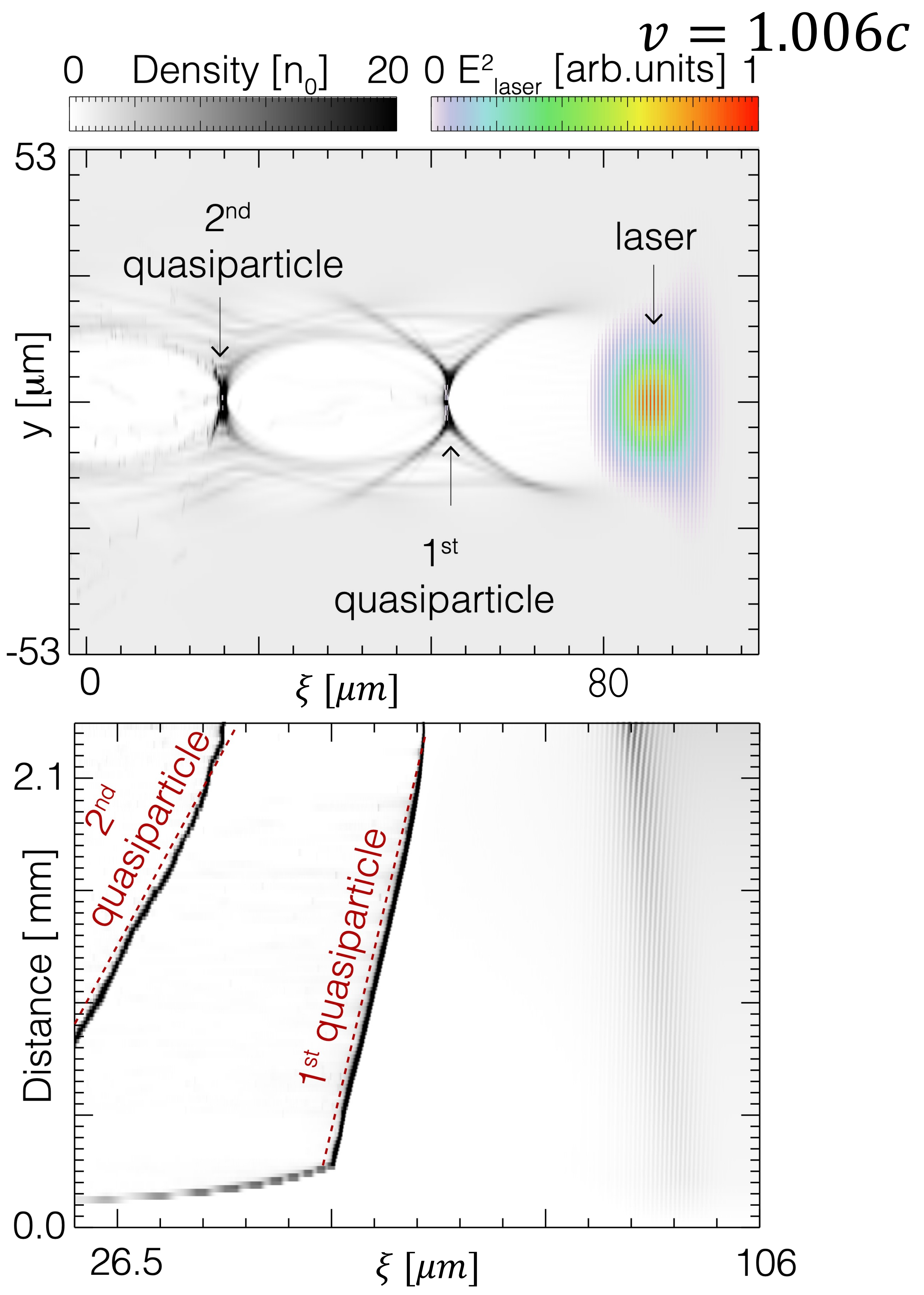
Quadratic growth at $\theta_0 = \mathrm{acos}(c/v_0)$ stops at

$$T_m = \frac{2\pi c}{\omega_{rad}|\Delta v|}$$

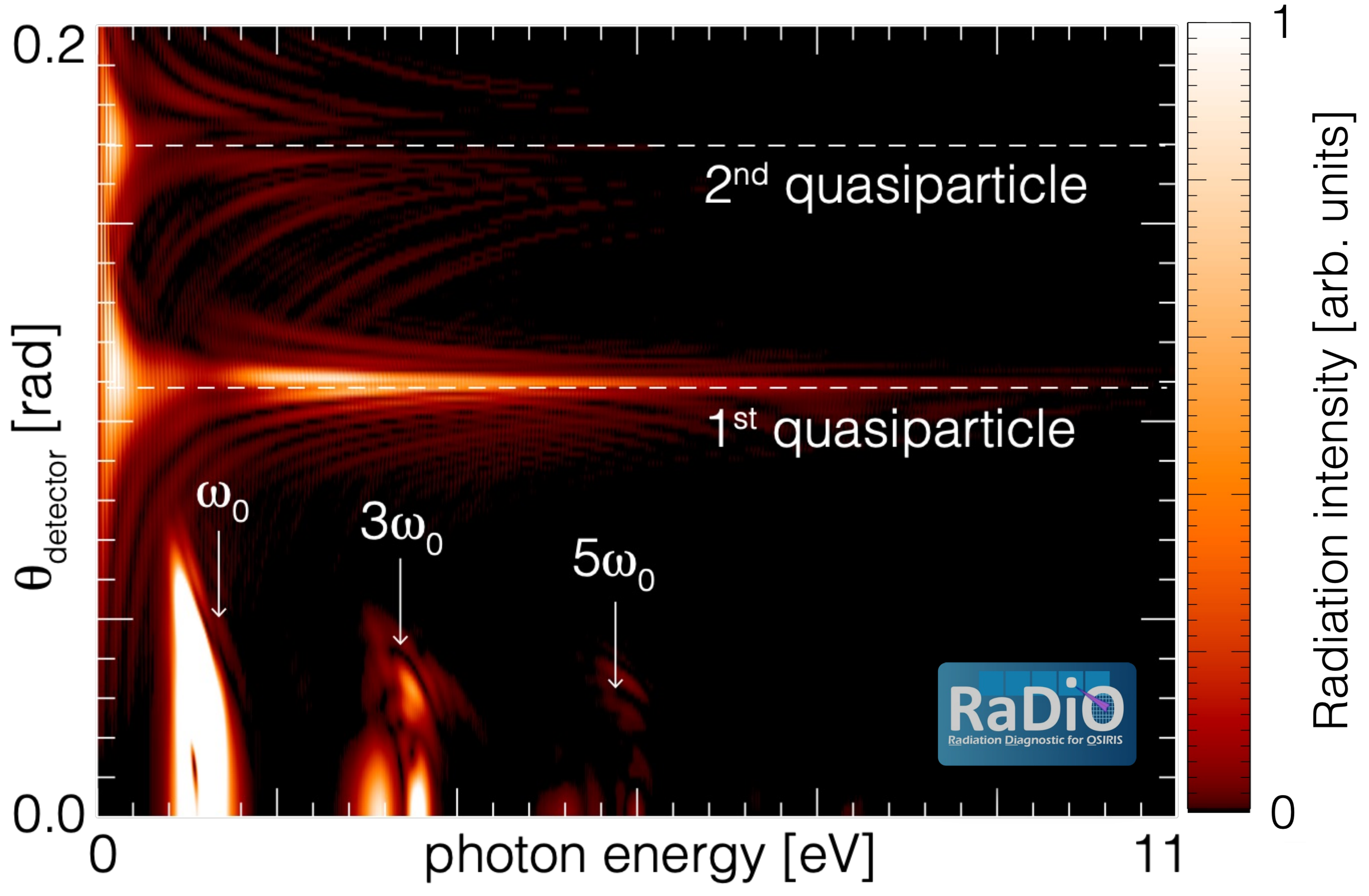
$$\Delta v = |v - v_0|$$

An LWFA quasiparticle is possible

Goal trajectory ($\mathbf{r_c}(t) = x_0 + vt\mathbf{e_x}$)



Radiation from the quasiparticle can be measured



- The radiated power above $3\omega_0$ is 4 times higher in the quasiparticle than in the direct laser interaction
- The quasiparticle emission would be measurable in laboratory conditions

Contents

Narrow bandwidth emission

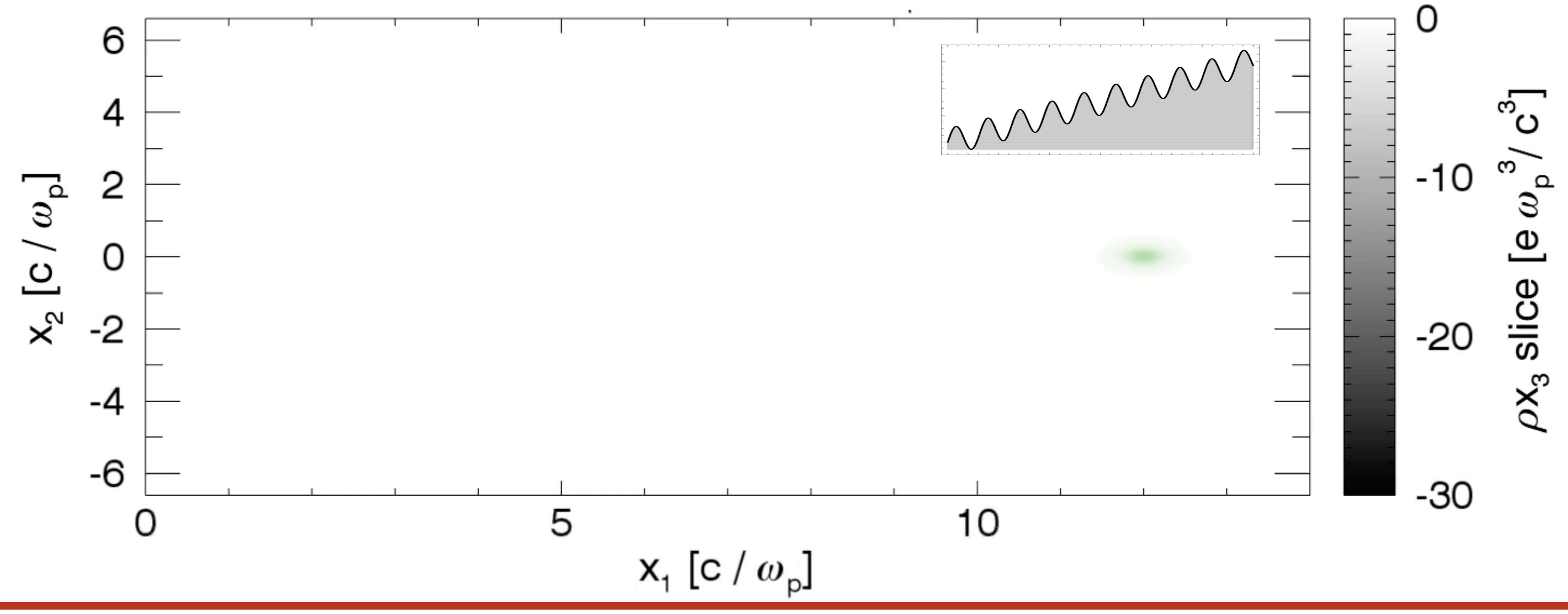
Quasiparticle undulator radiation ($\mathbf{r_c}(t) \approx vt + A\sin\omega_b t\mathbf{e_x}$)

$$I(\omega,\Omega) \propto T^2 \sum_{n=-\infty}^{\infty} J_n^2\left[\frac{A\omega}{c}\cos(\theta)\right]\times$$

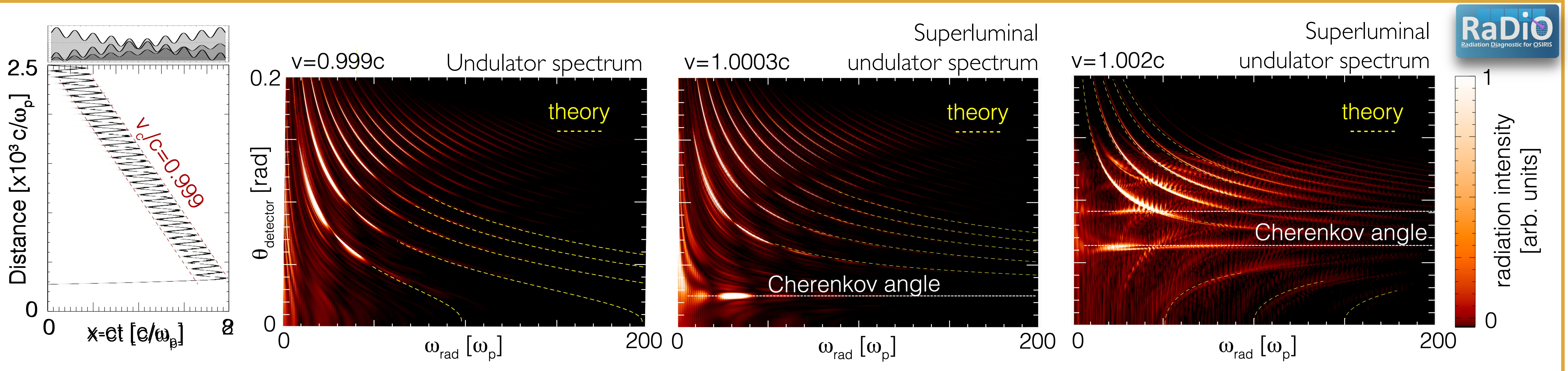
$$\times\mathrm{sinc}^2\left[\frac{T}{2}\left(\omega - \frac{n\omega_b}{1-\frac{v_c}{c}\cos(\theta)}\right)\right]$$

Sinusoidal density modulation such as $\sin\omega_b x$

(wavelength ~60 plasma skin depths)



Harmonic behaviour agrees with theory



Narrow bandwidth temporally coherent emission

Quasiparticle undulator radiation ($\mathbf{r_c}(t) \approx vt + A\sin\omega_b t\,\mathbf{e_x}$)

$$I(\omega,\Omega) \propto T^2 \sum_{n=-\infty}^{\infty} J_n^2\left[\frac{A\omega}{c}\cos(\theta)\right] \times$$

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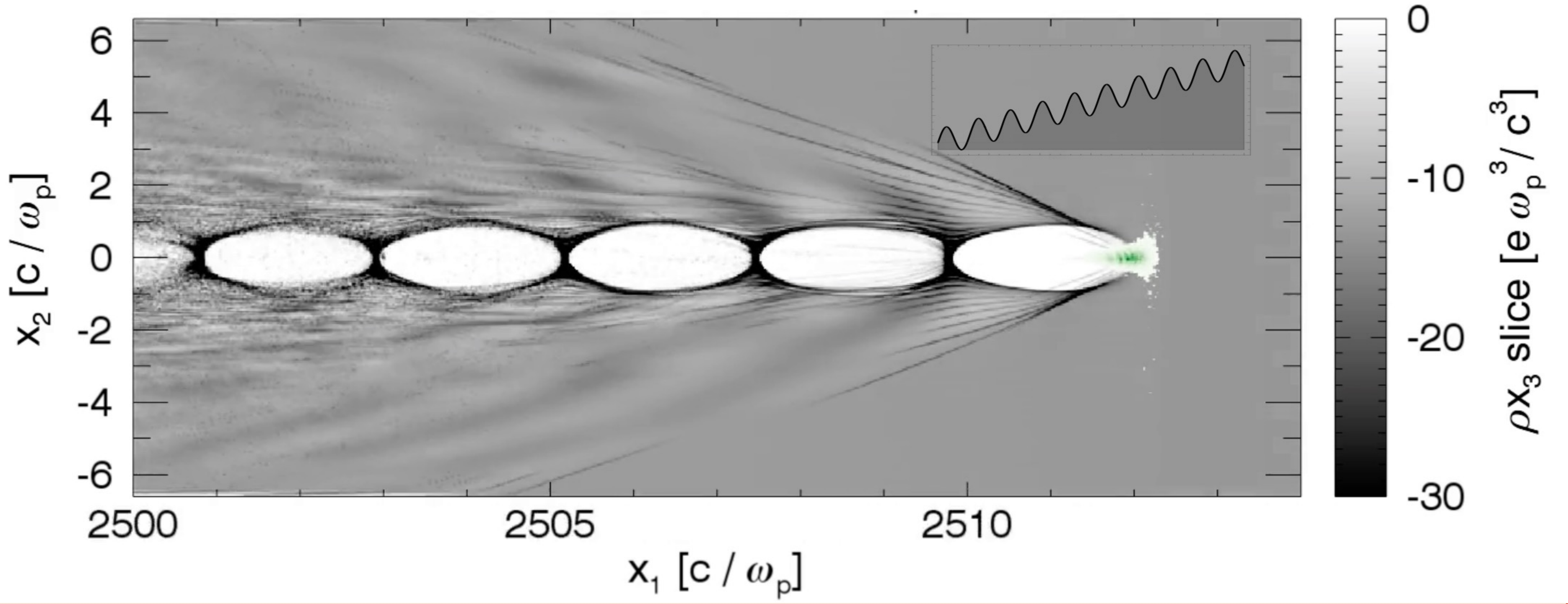
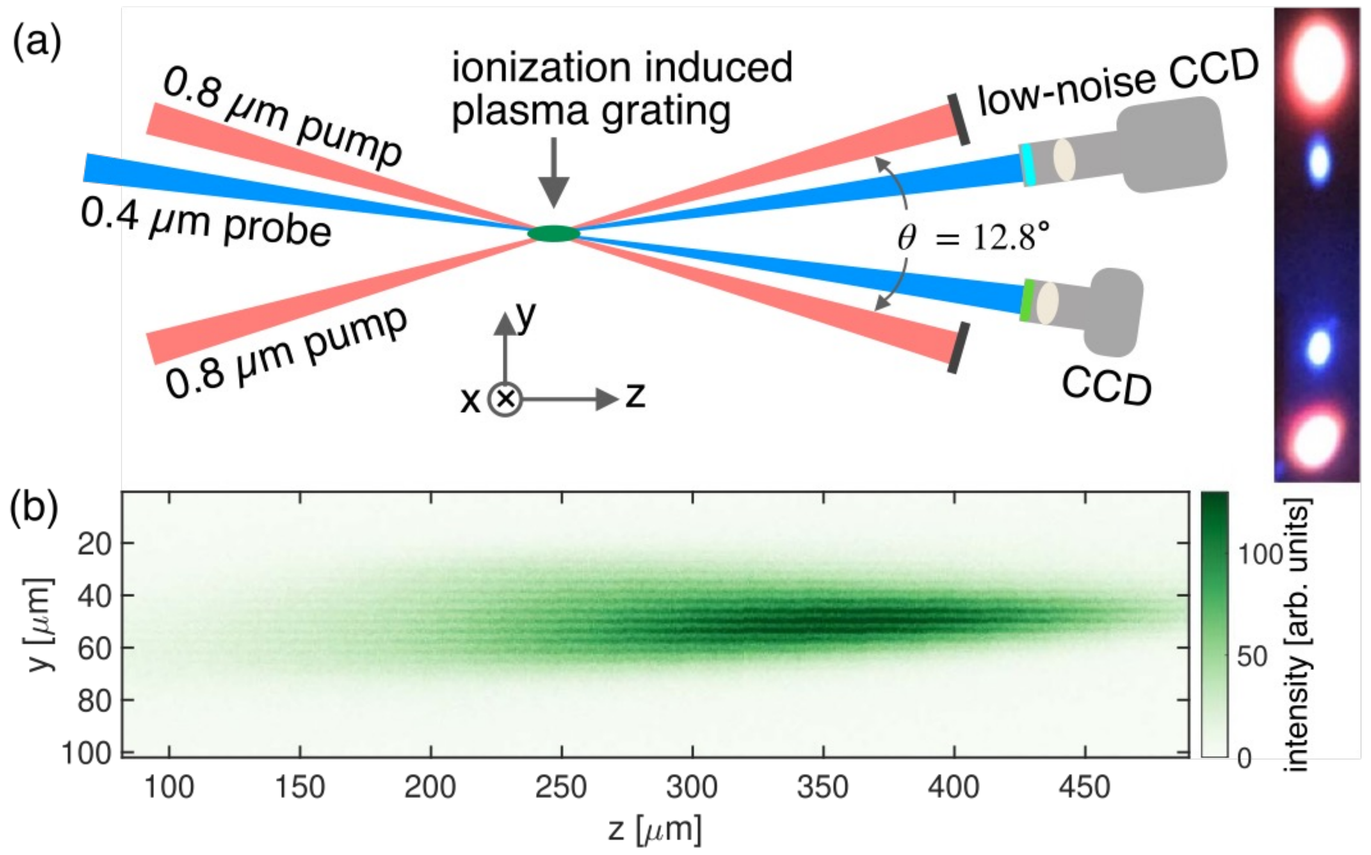
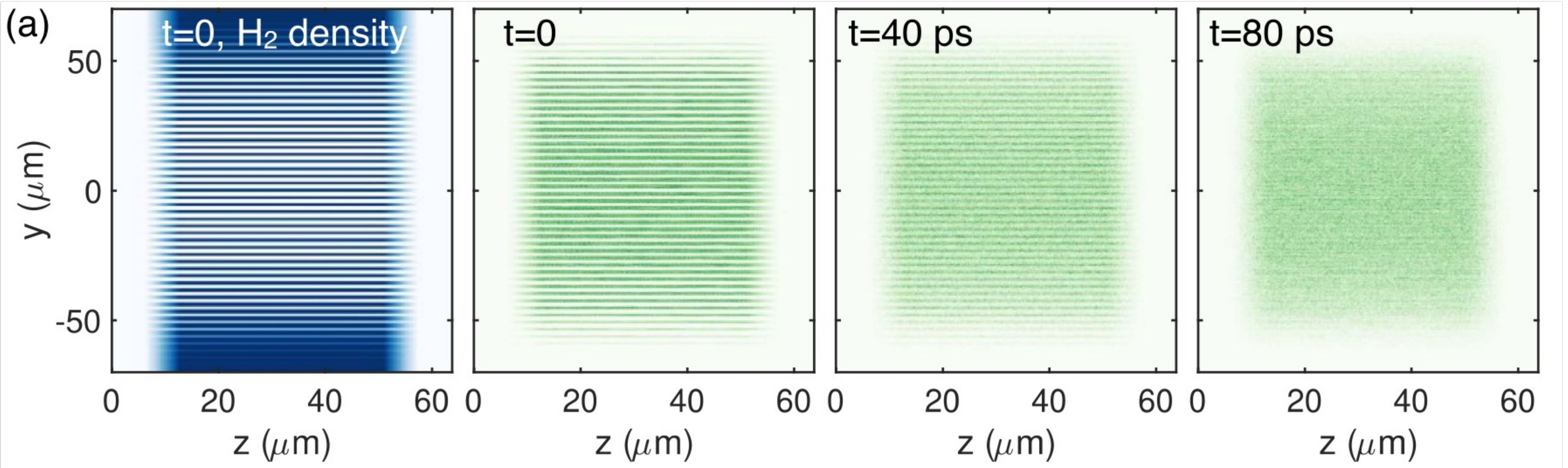


Experimental demonstration of ionisation induced plasma density gratings

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

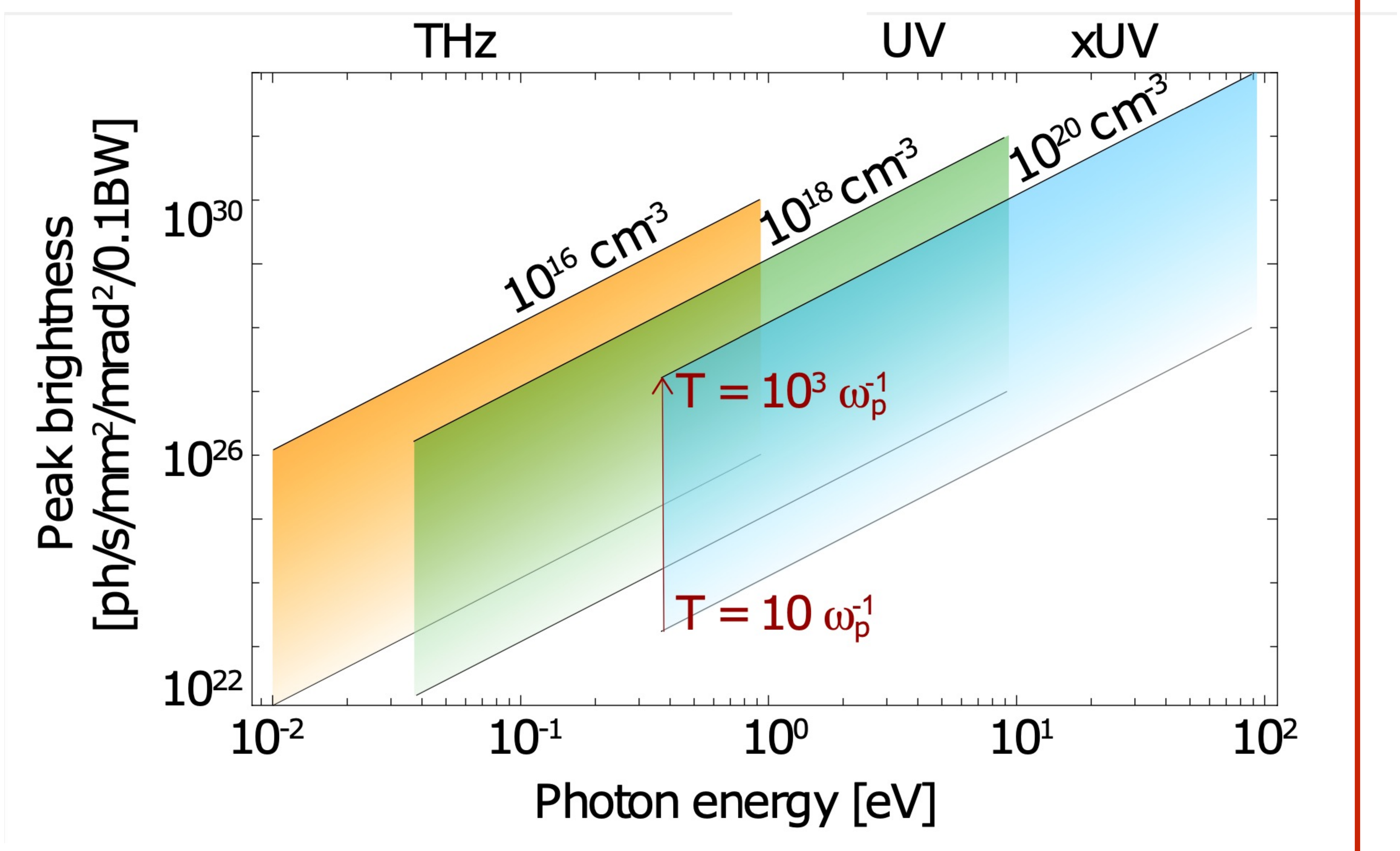


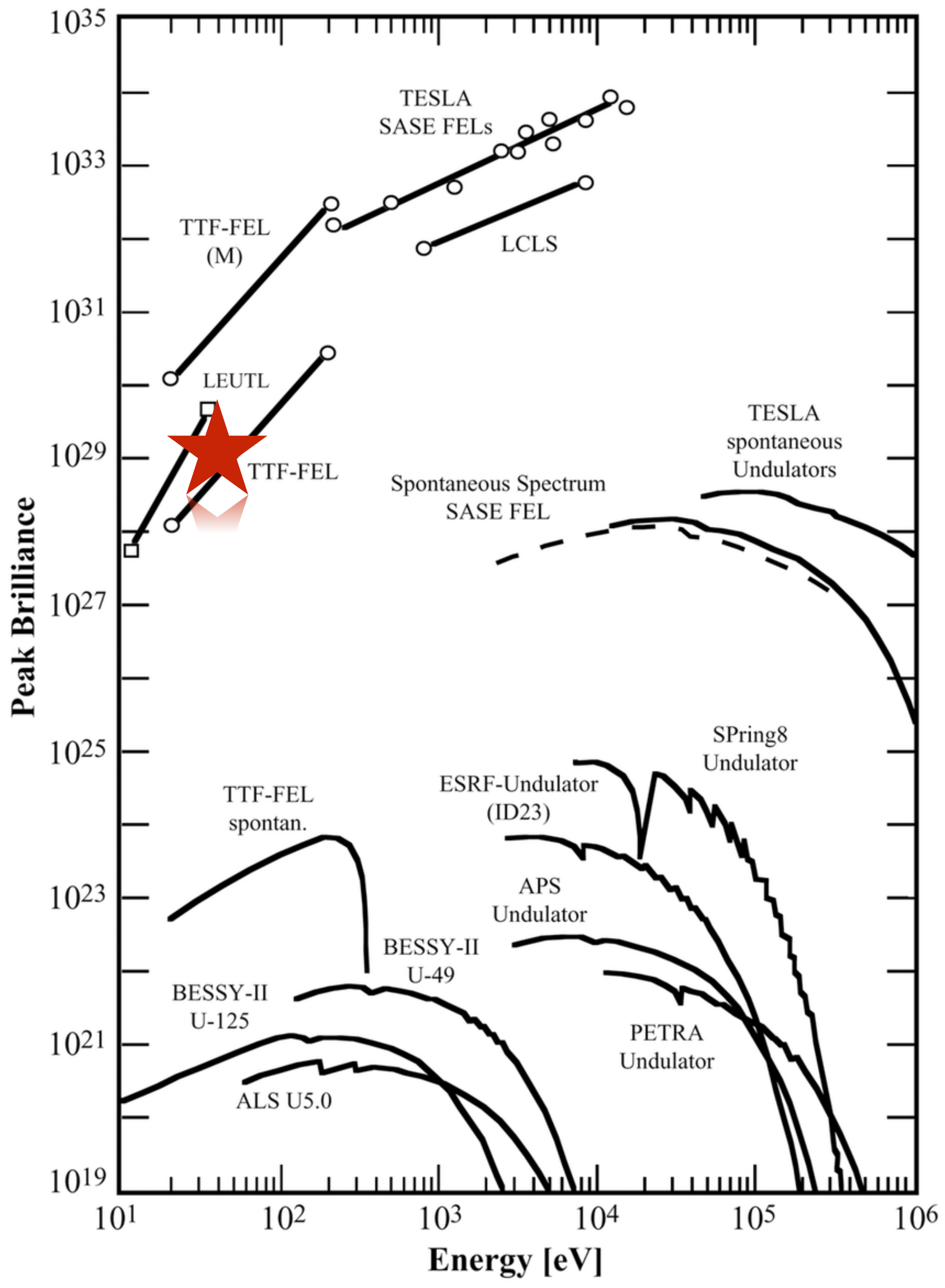


Contents

Quasiparticles are a tuneable and bright source of radiation

Frequency range spans nearly 4 decades





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

Contents

Conclusions

Thank you for listening. Questions?

B. Malaca et al, 2023 (accepted, *Nature Photonics*), arxiv 2301.11082

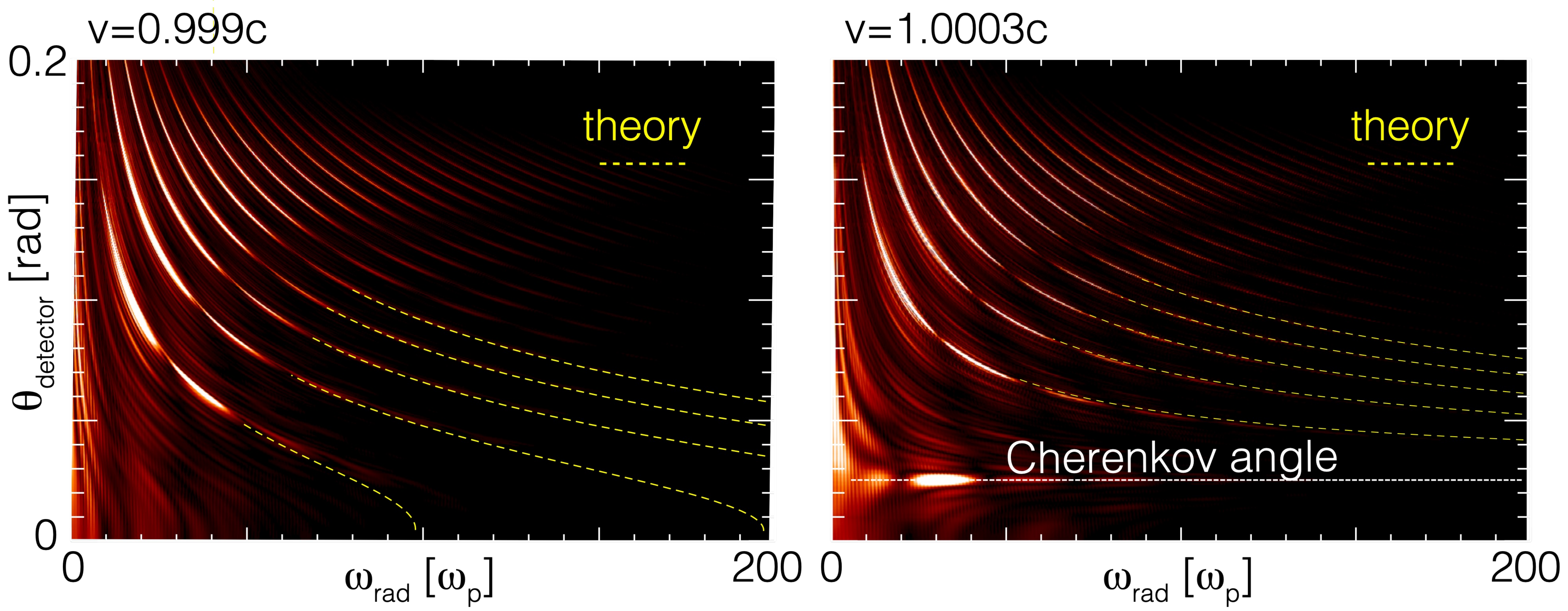
Trajectory of the QP defines the spectrum

$$\frac{d^2 I}{d\omega d\Omega} = \left| \int dt \exp[i\omega(t - \mathbf{n}\cdot\mathbf{r_c}(t)/c)] \right|^2 \times \mathcal{S}(\omega,\Omega)$$

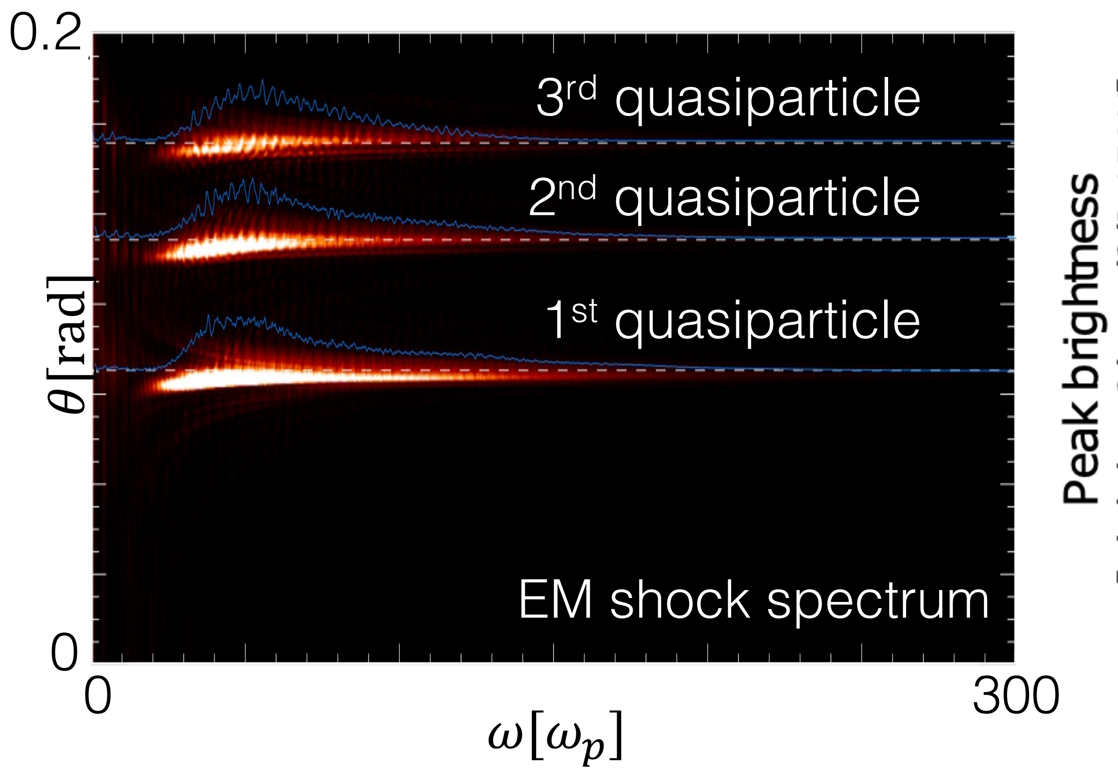
Contribution of the quasiparticle trajectory

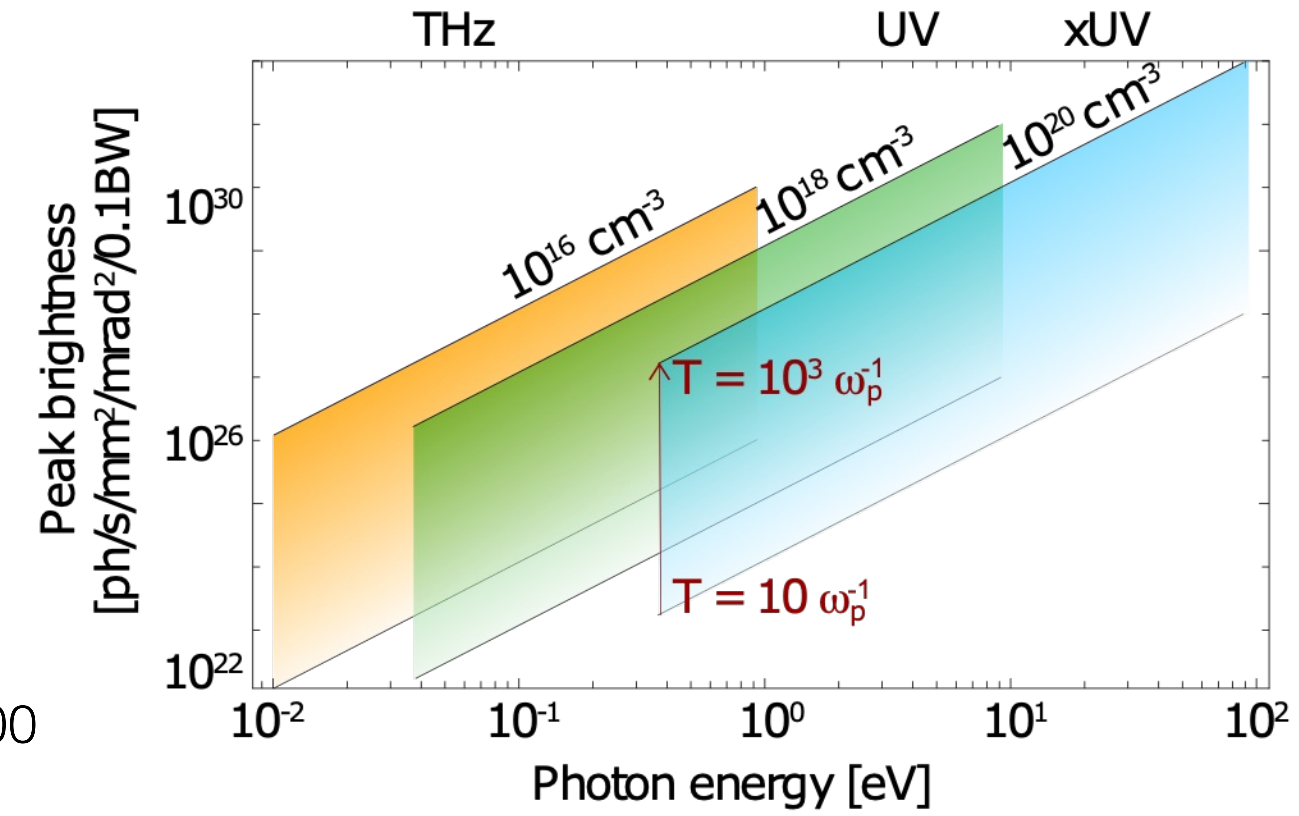
QP shape factor

Scheme allows for narrowband spectra



Very bright radiation production





Acknowledgements

LUMI

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Centro Nacional de Supercomputación

Laserlab Europe

PRACE

EuPRAXIA
Design Study Project

FCT scholarship PD/BD/150409/2019

Backup slides

RaDiO's algorithm*

M. Pardal *et al.*

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

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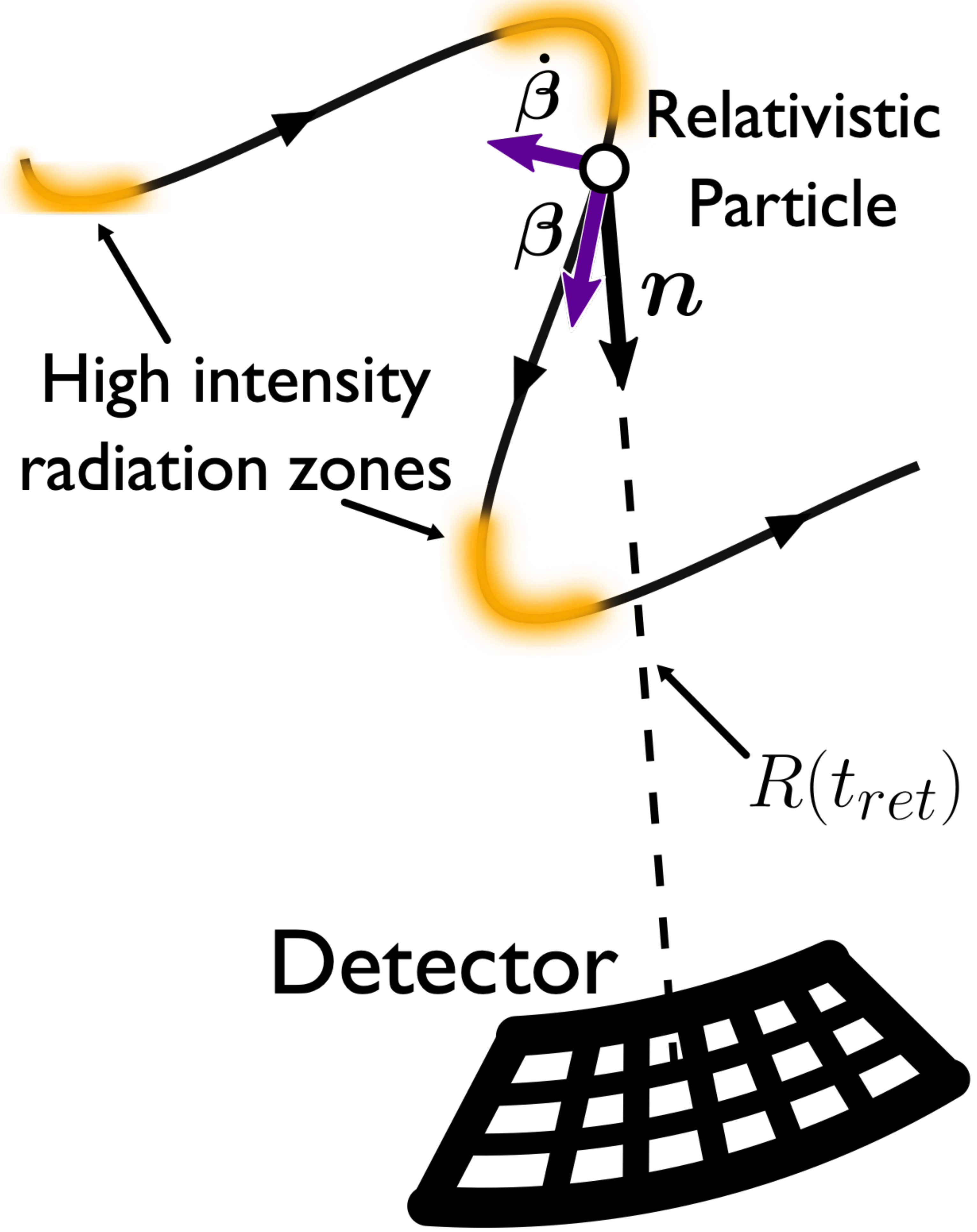
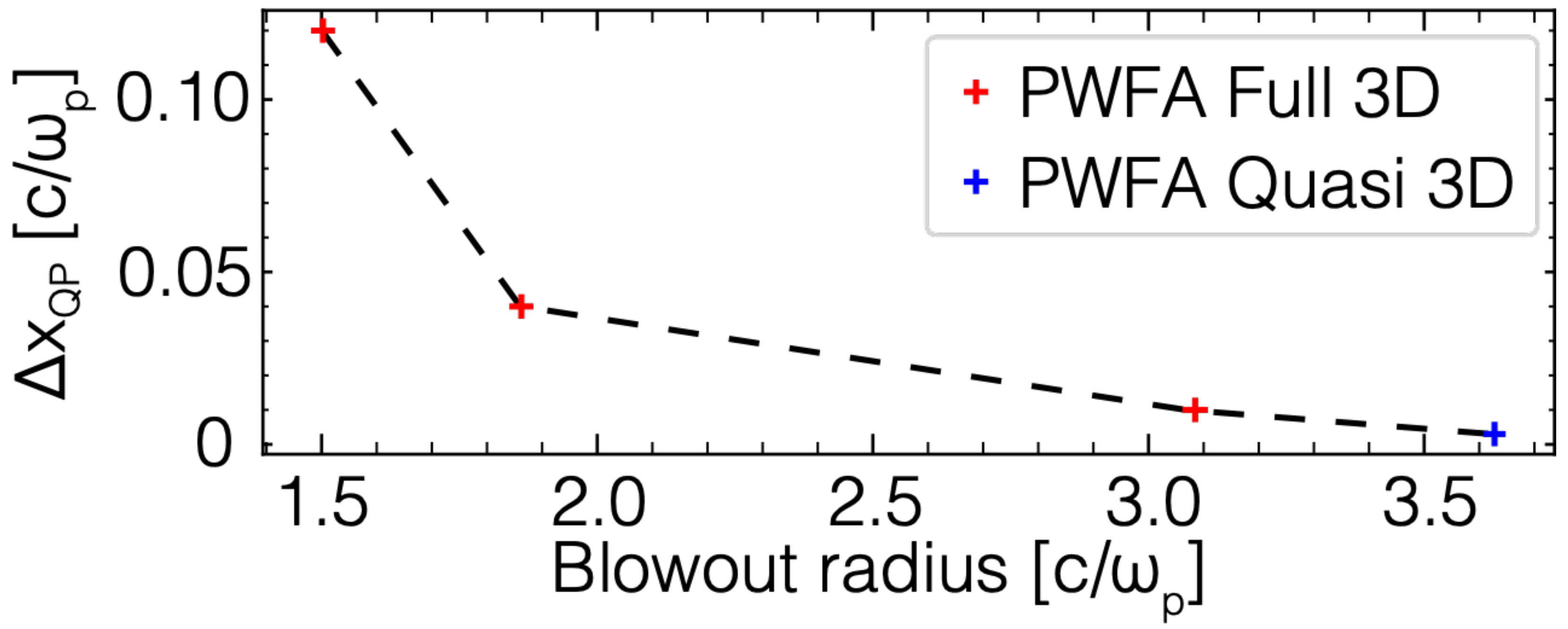


*M. Pardal, *et al*, Computer Physics Communications, 285, (2022)

Practical limits may prevent brighter radiation at high frequencies

The size of the quasiparticle

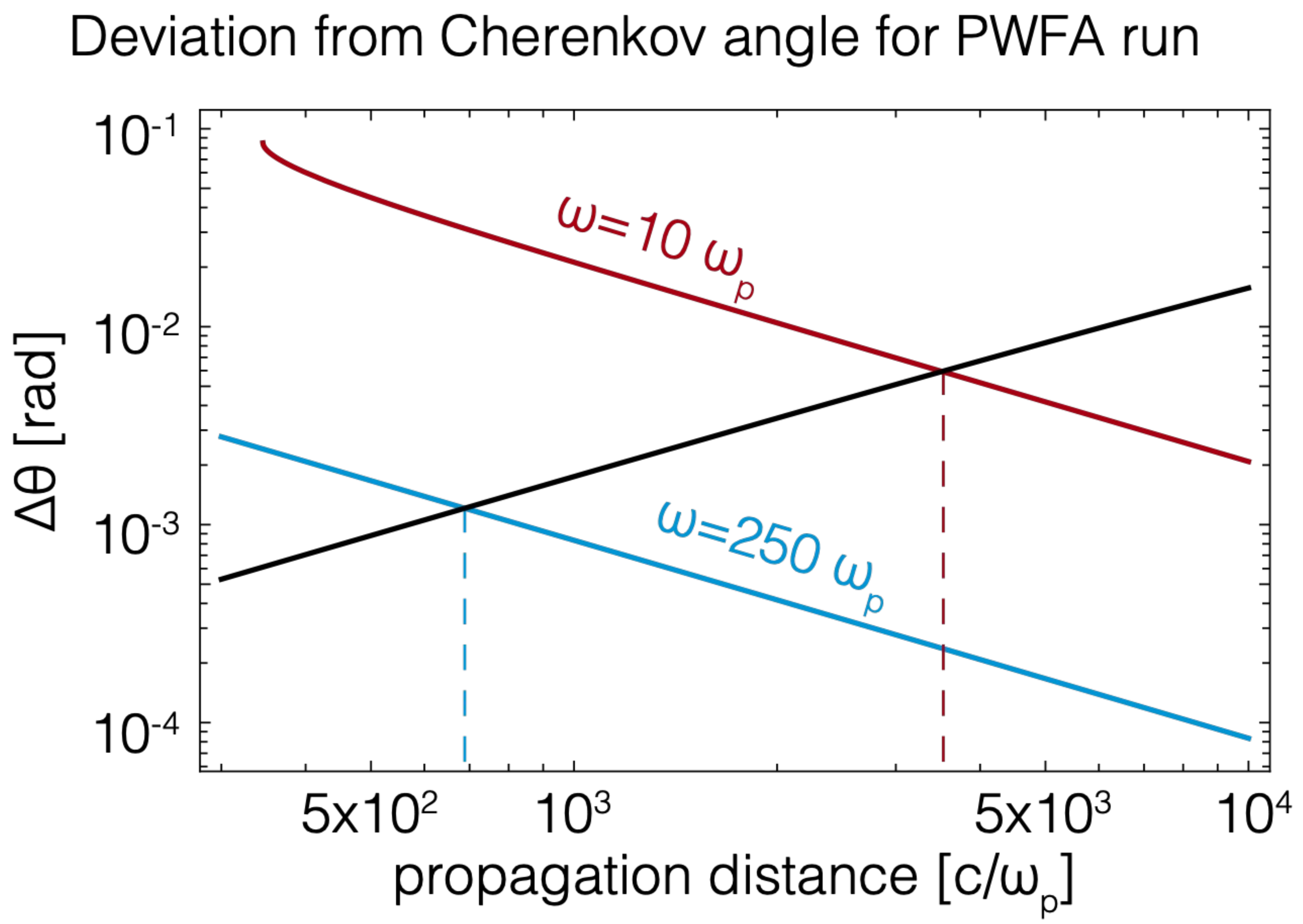


More intense drivers lead to larger blowout radii

The evidence suggests the size of the quasiparticle decreases with the blowout radius (can we create quasiparticles with 1 nm length?)

At the same plasma frequency, a more intense driver will lead to larger frequencies.

Variance in the speed



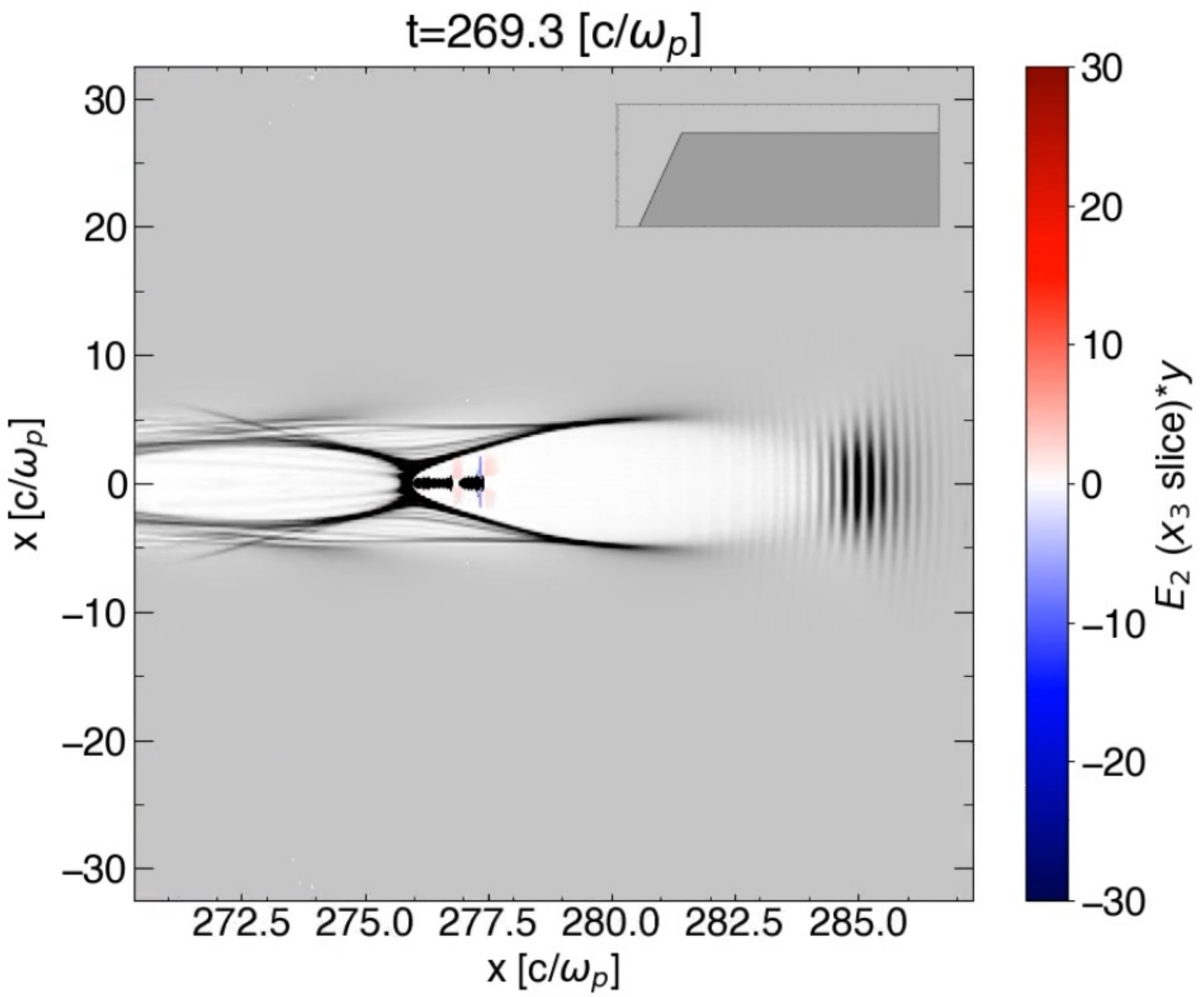
If the speed changes with time, the time over which the growth is quadratic is limited (can we design a more stable trajectory?):

$$T_m \sim \frac{2\pi c}{\omega|\Delta v|}$$

All things equal, a more stable speed leads to larger brightnesses, and this effect acts on larger frequencies the most.

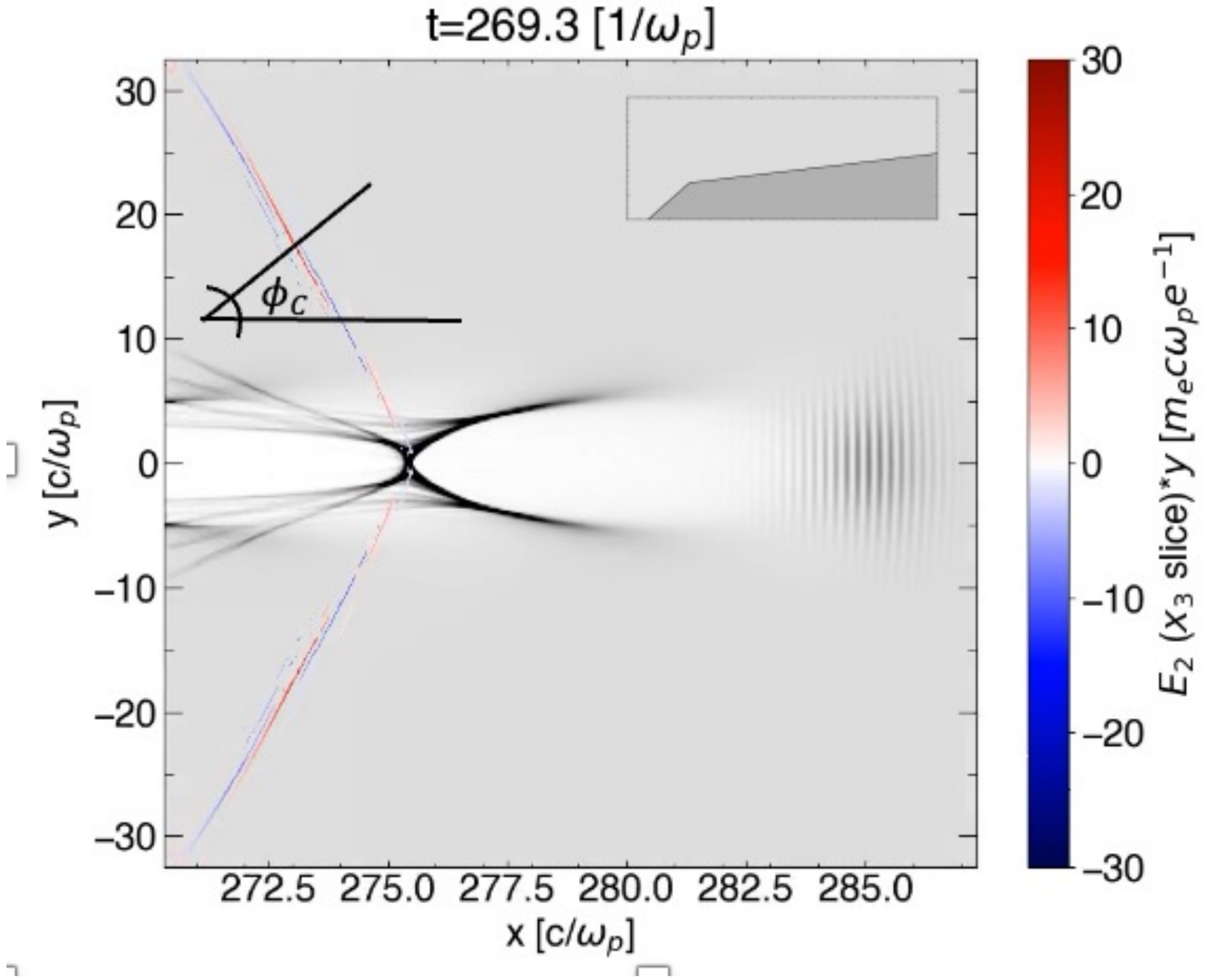
Very similar internal spectra lead to dramatically different emission

Control run (flat profile)



No electric field builds coherently at the back of the wakefield

Run with plasma ramp

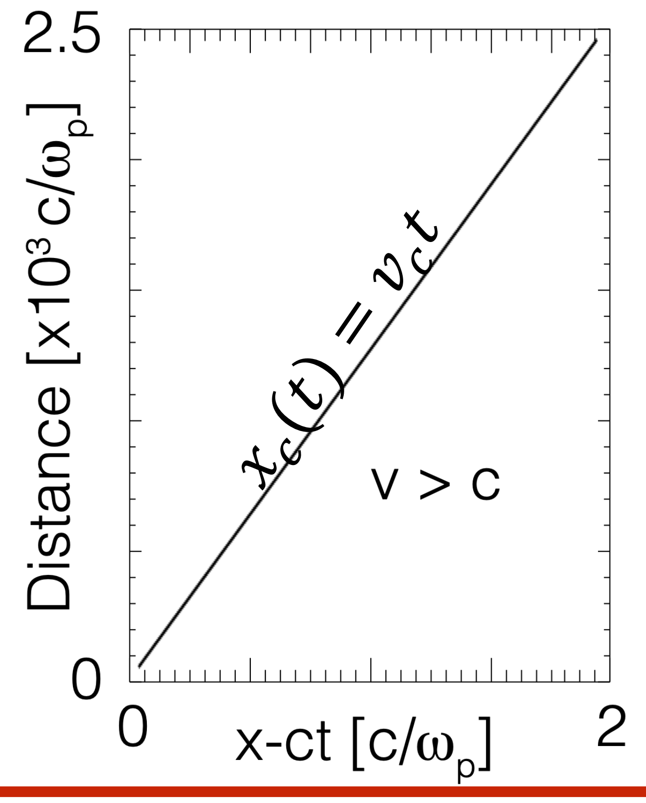


Coherent radiation emanates from the back of the wakefield at the angles predicted

Contribution from different quasiparticles

Superluminal quasiparticle is superradiant and broadband

1. Superluminal quasiparticle



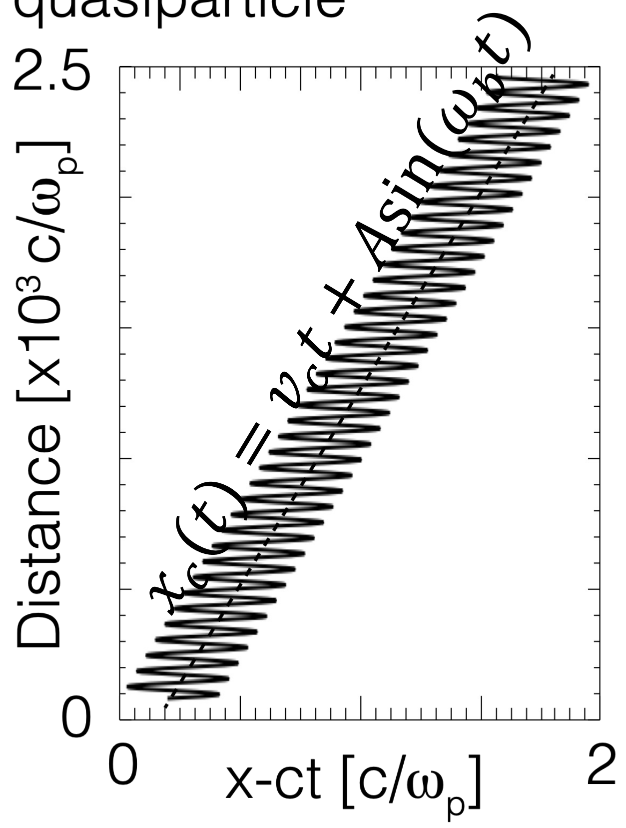
$$\left|\int_{-T/2}^{T/2} dt \exp[i\omega(t - \mathbf{n}\cdot\mathbf{r_c}(t)/c)]\right|^2 \propto T^2 sinc^2\left[\frac{\omega T}{2}\left(1 - \frac{v_c \cos\theta}{c}\right)\right]$$

This scales quadratically with the interaction time if $c/v = \cos\theta$

This is a collective Cherenkov-like effect!

Undulating quasiparticle spectrum becomes narrowband

2. Undulating quasiparticle



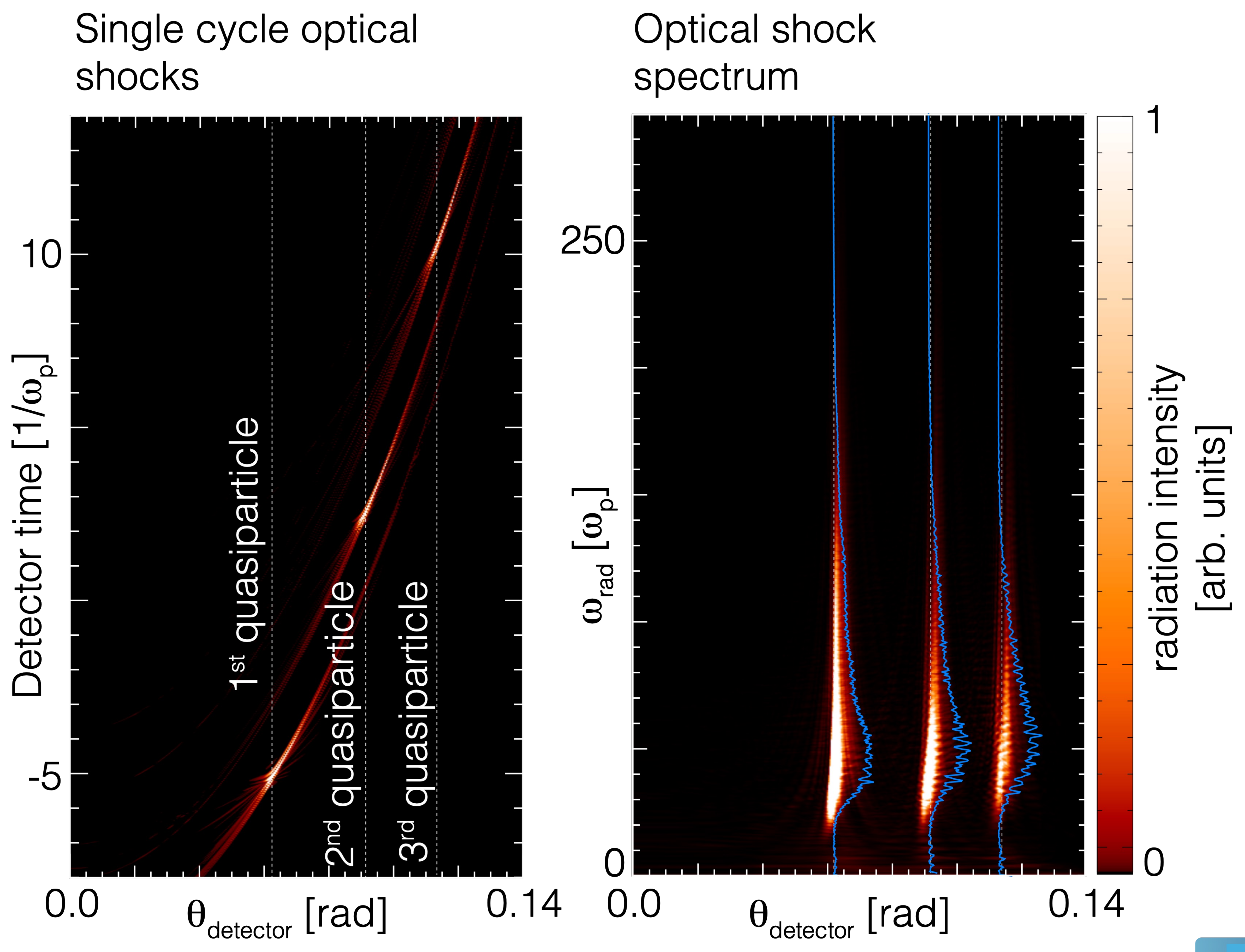
$$\left|\int_{-T/2}^{T/2} dt \exp[i\omega(t - \mathbf{n}\cdot\mathbf{r_c}(t)/c)]\right|^2 \propto$$

$$\propto T^2 \left|\sum_n J_n\left(\frac{A\omega}{c}\cos(\theta)\right) \times sinc\left[\frac{T}{2}\left(\omega - \frac{n\omega_b}{1 - \overline{v}\cos(\theta)}\right)\right]\right|^2$$

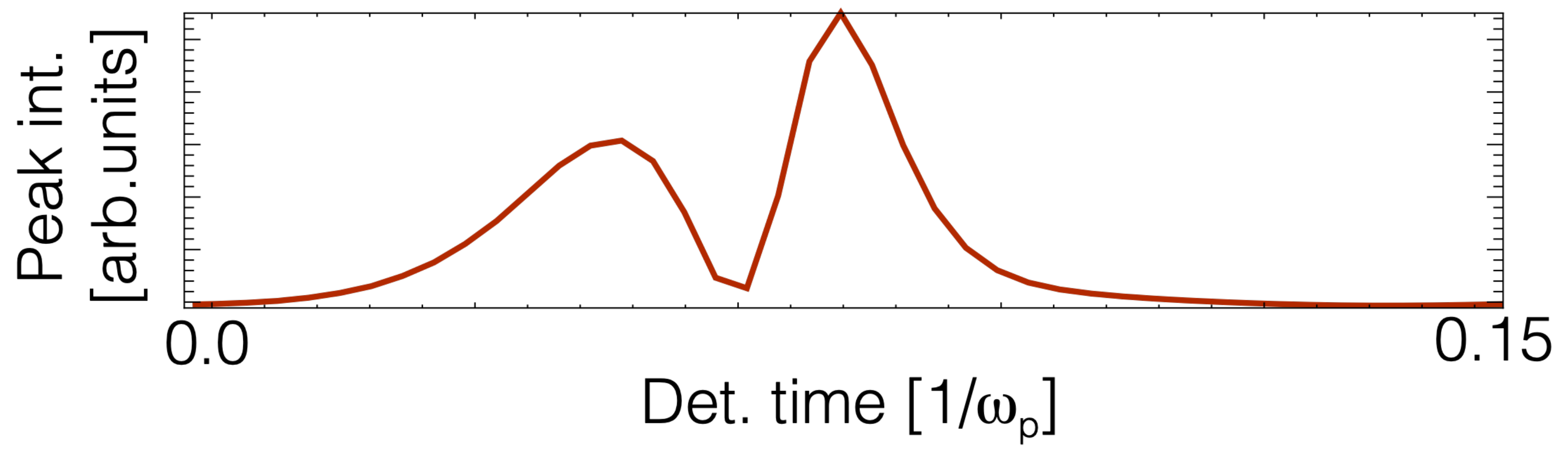
Harmonic like behaviour!

The quasiparticle theory agrees with simulations

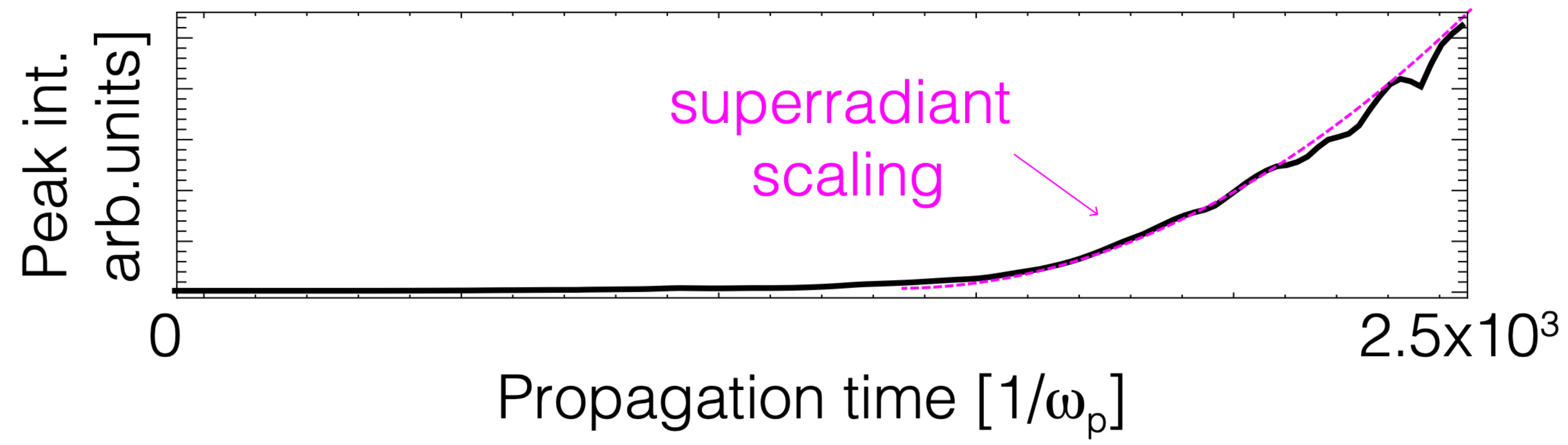
A detector in the far field collects the radiation from the quasiparticles



Each quasiparticle emits a single-cycle super radiant optical shock



The single-cycle shocks are emitted at the predicted angle

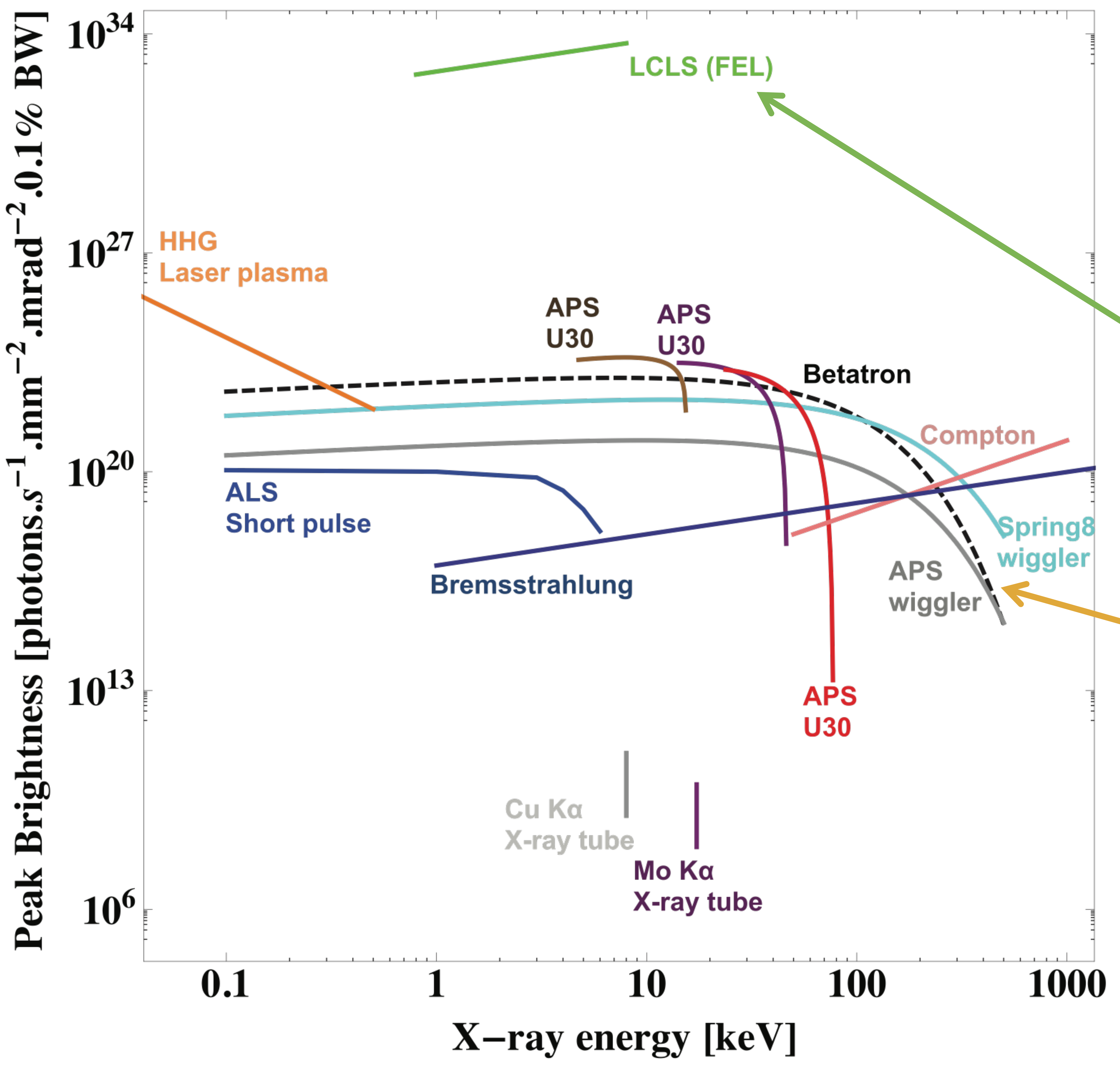


The intensity exhibits **quadratic growth** indicating **superradiance**

This also works with a laser driver and with less ideal density profiles

Quasiparticles bridge the gap between plasma accelerators and FELs

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



FEL temporally coherent

Betatron temporally incoherent

~10 orders of magnitude