Superradiance and temporal coherence in the non-linear blowout regime

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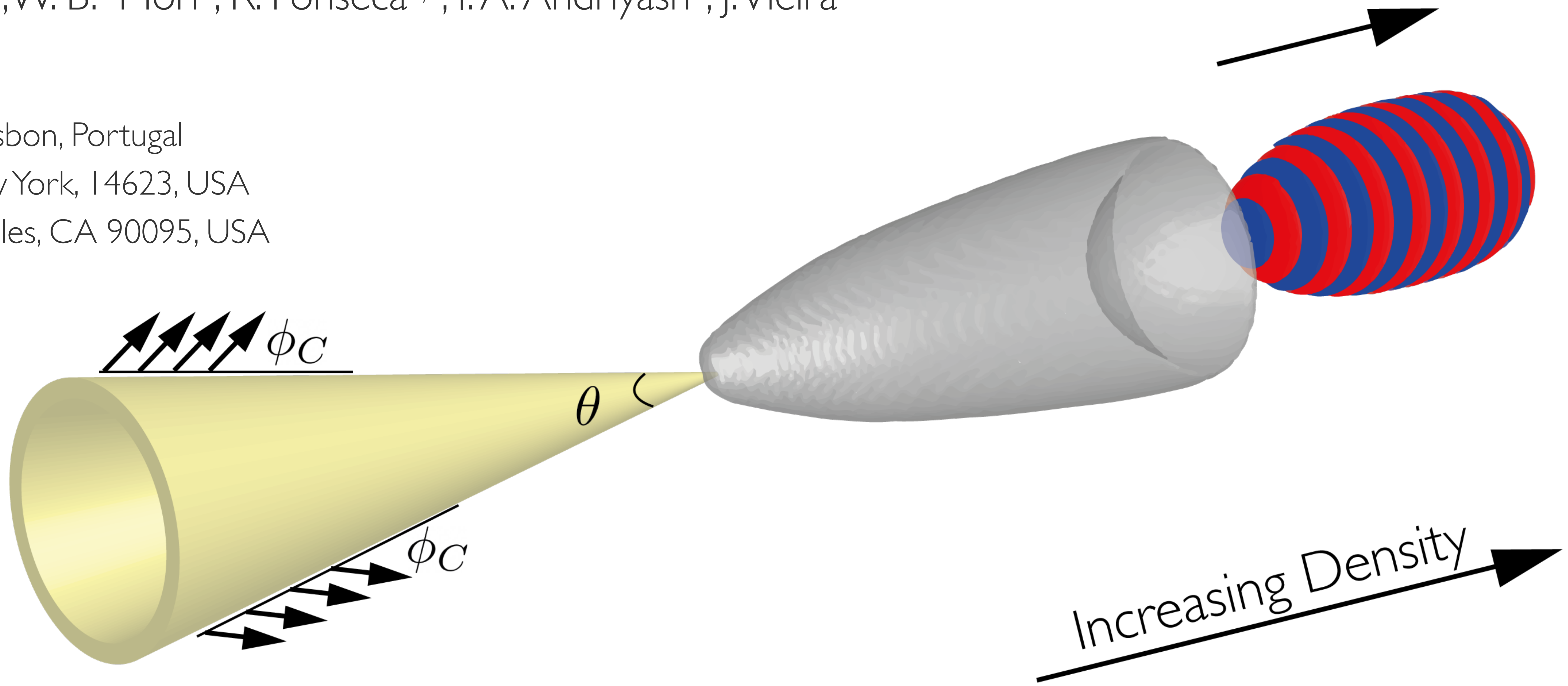

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ipfn INSTITUTO DE PLASMAS E FUSÃO NUCLEAR

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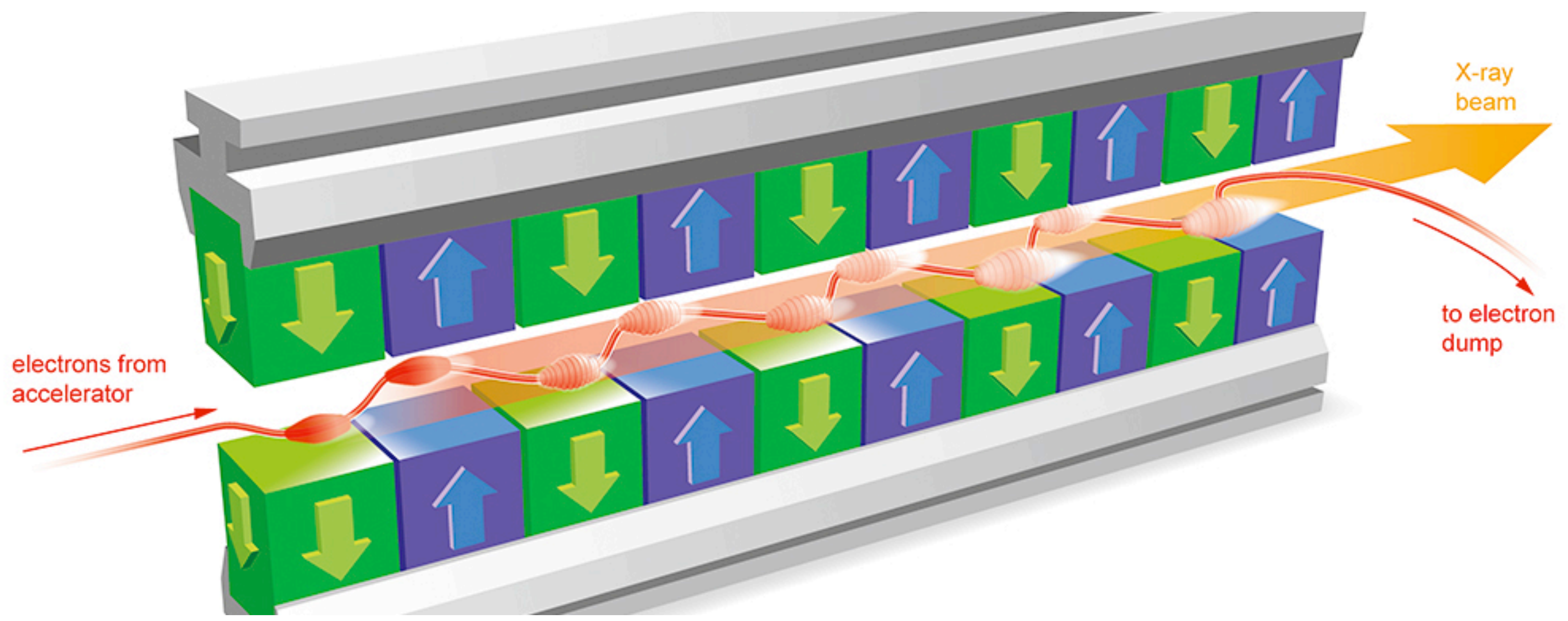
Collective motions allow for exotic trajectories

Radiation by single particle motion

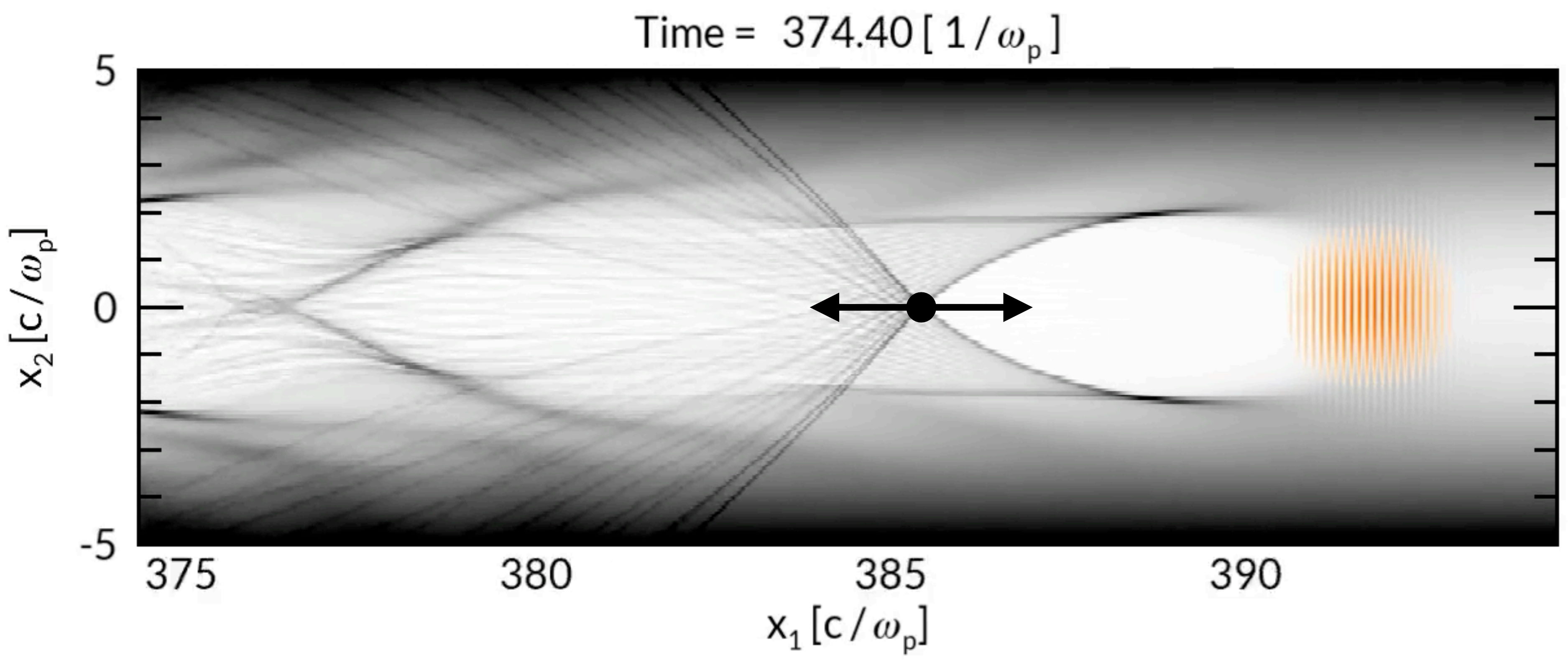


Usual radiation mechanisms are based in single particle motion.

The trajectories of single particles are constrained:

- they cannot travel faster than light
- they require arbitrarily large fields to undergo exotic trajectories

Radiation by collective motion



We study the radiation coming from collective charge motion.

Collective motions are relatively unconstrained:

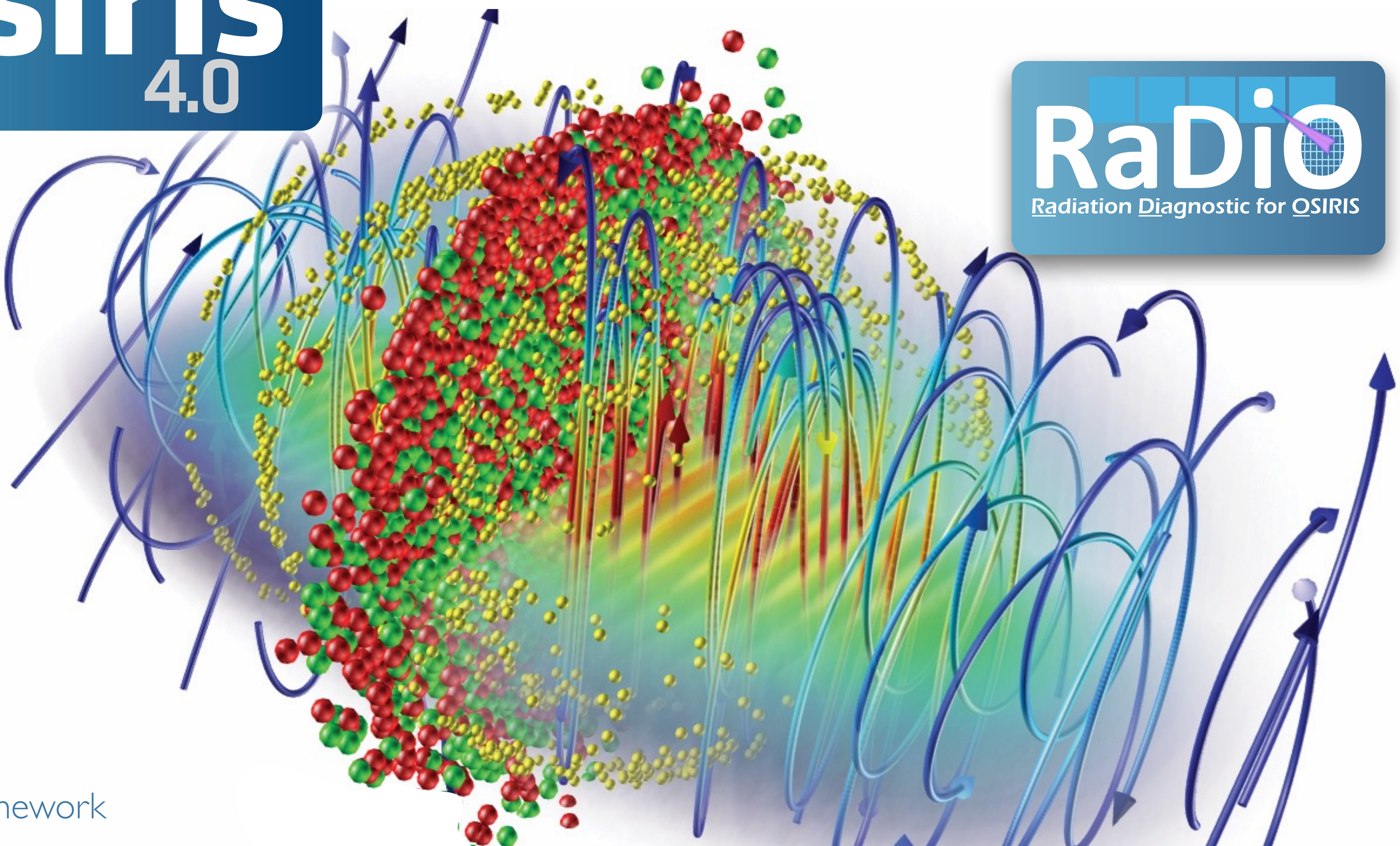
- they can travel faster than light
- large accelerations do not require large fields

Plasmas are exceptional as a medium because they can support very large fields and currents (which generate radiation)

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

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**

RaDiO – Radiation Diagnostic for OSIRIS

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**

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Trajectory of a collective motion determines the radiation spectrum

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

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

Coherence is determined by the excitation trajectory

Assuming that fields and currents evolve with time only via $\mathbf{r_c}(t)$ [e.g. $\mathbf{j}(\mathbf{r}, t) = \mathbf{j}(\mathbf{r} - \mathbf{r_c}(t))$] we can simplify the expression by using $\xi = \mathbf{r} - \mathbf{r_c}(t)$ and $t = t$:

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

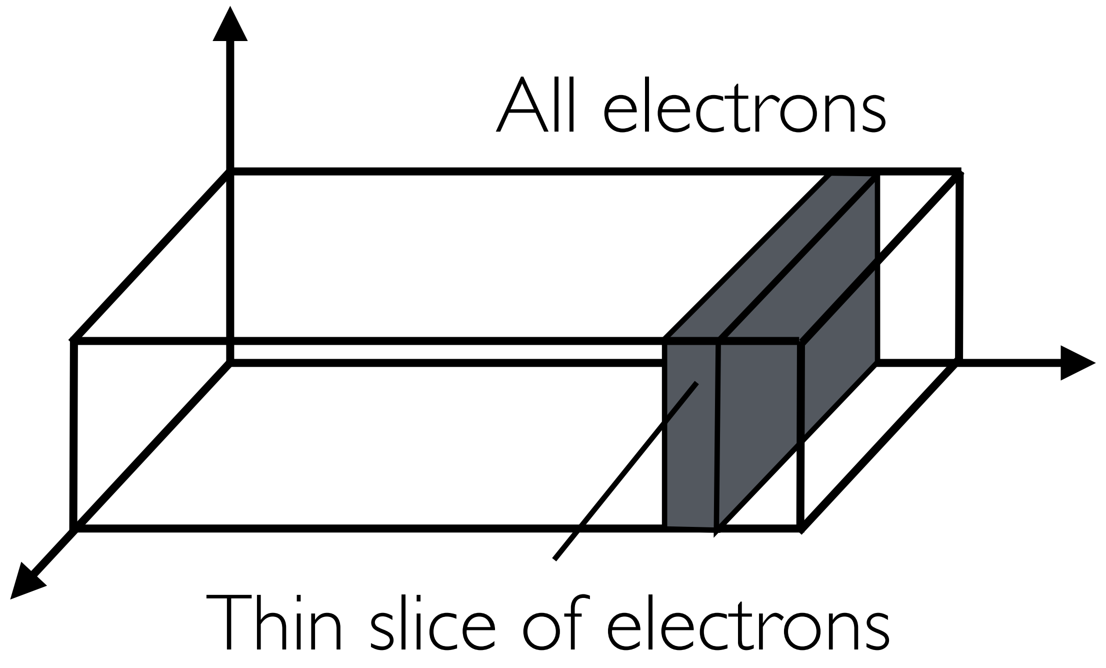
Contribution of the excitation trajectory (first factor)

Internal spectrum of the excitation (second factor)

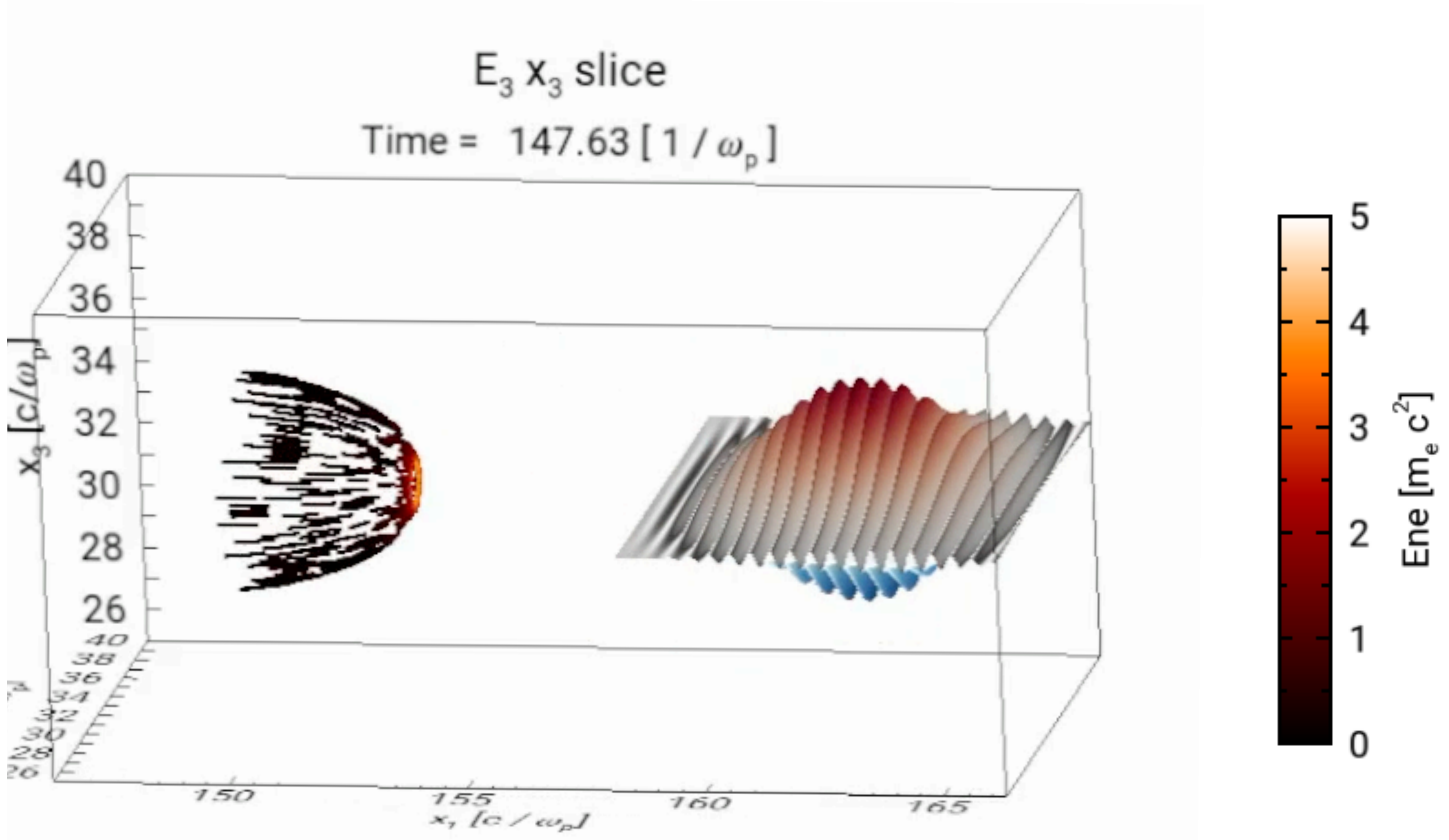
Temporal coherence features from collective excitation are fully determined by the trajectory, as if it were a real particle

Radiation from a nonlinear plasma wave

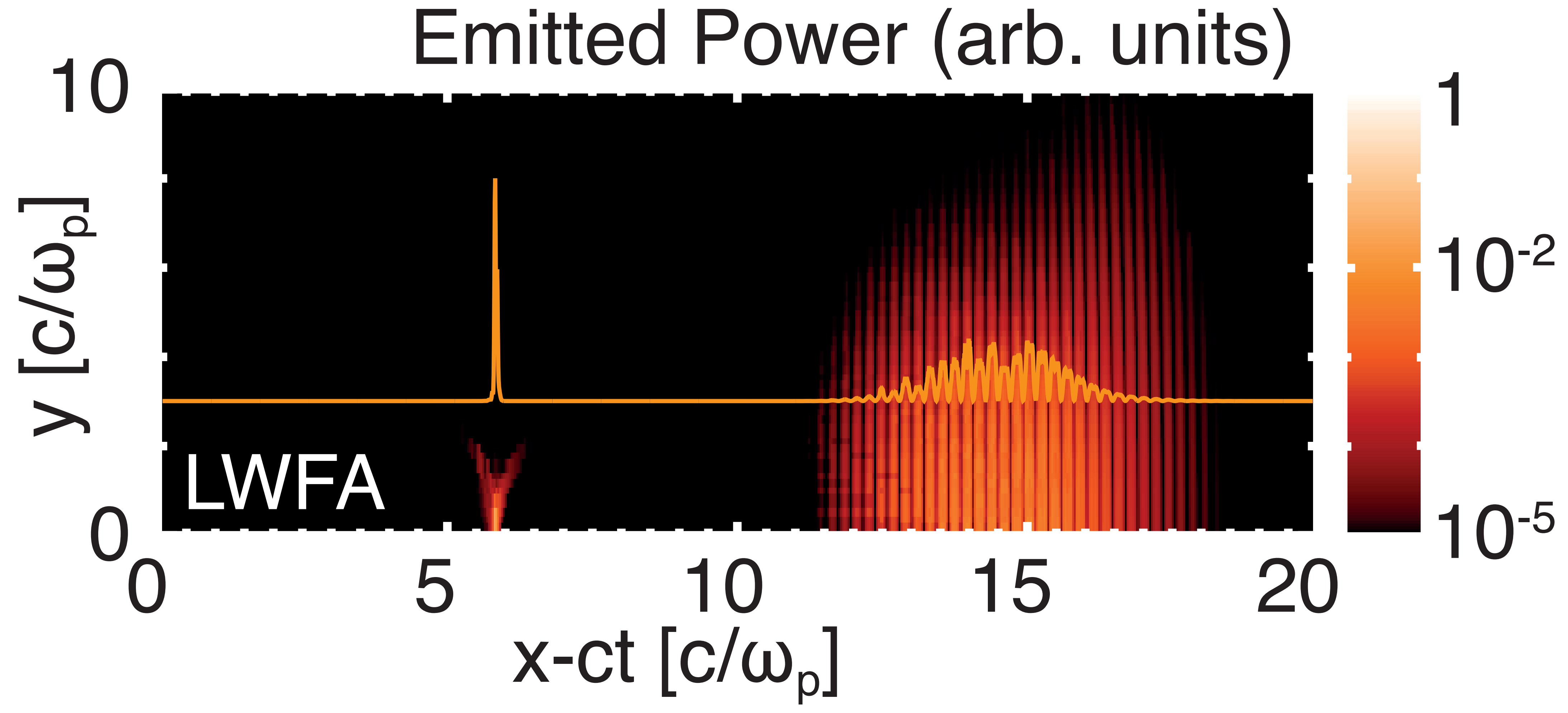
How to calculate the internal spectrum?

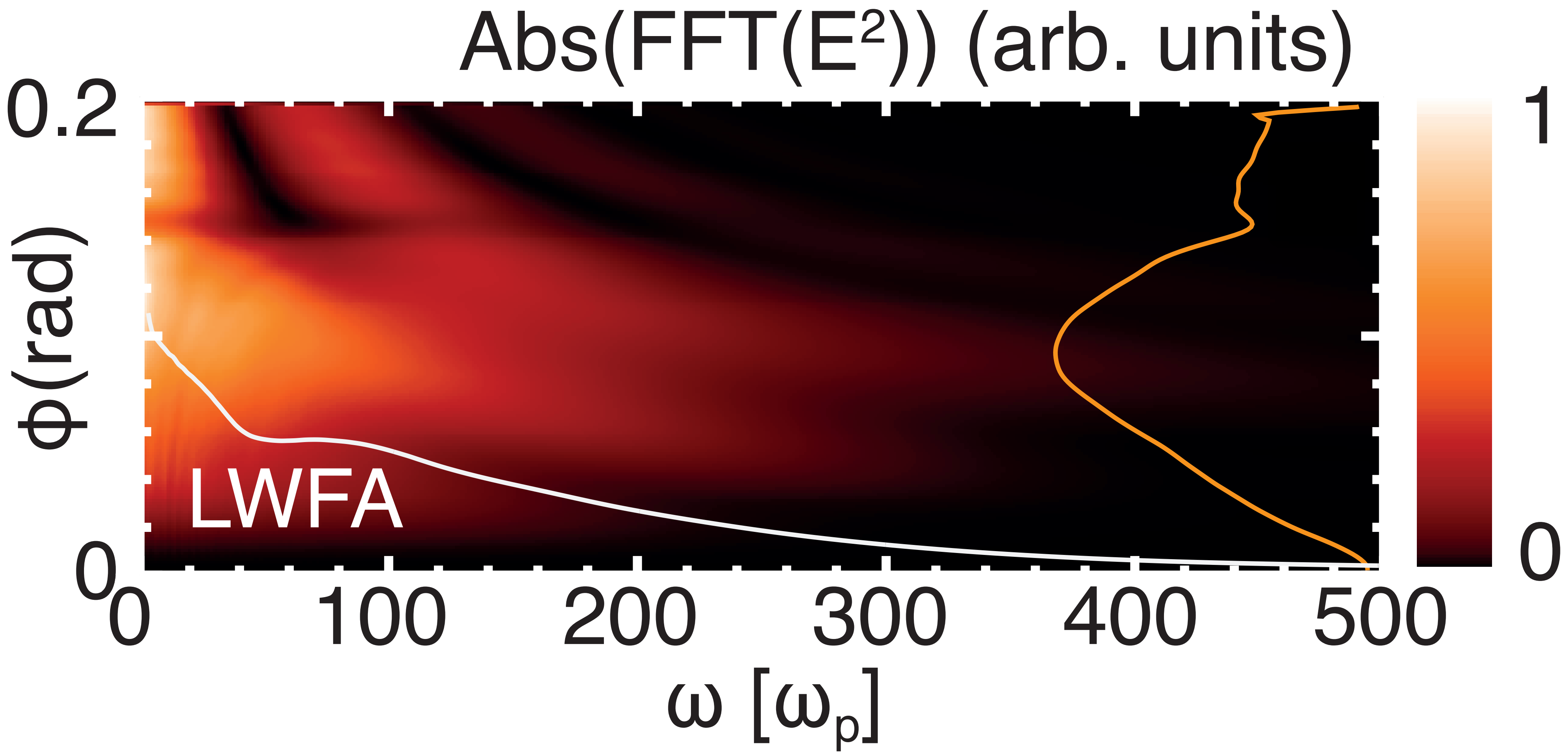


The radiation of a thin slice of electrons (in the case of a 1D trajectory) is the internal radiation of the excitation



Back of the bubble is responsible for most radiation





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

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Contribution of the excitation trajectory

Internal spectrum of the excitation

Temporal coherence features from collective excitation fully determined by the trajectory, as if it were a real particle

Contribution from a superluminal excitation

Superluminal excitation is superradiant

$$\mathbf{r_c}(t) = (vt, 0, 0)$$

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

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

This is a collective Cherenkov-like effect!

An engineered ramp provides the ideal case

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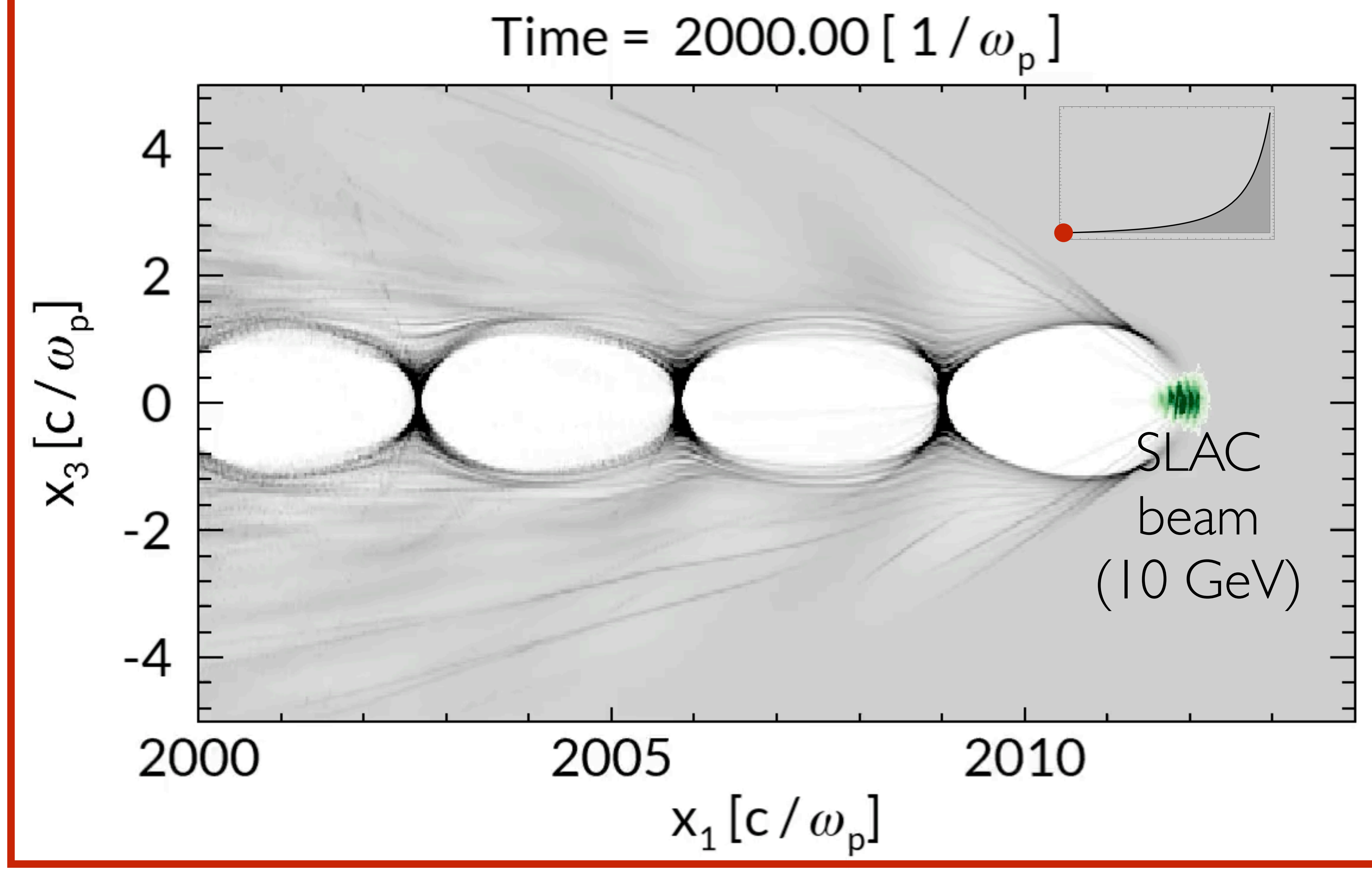
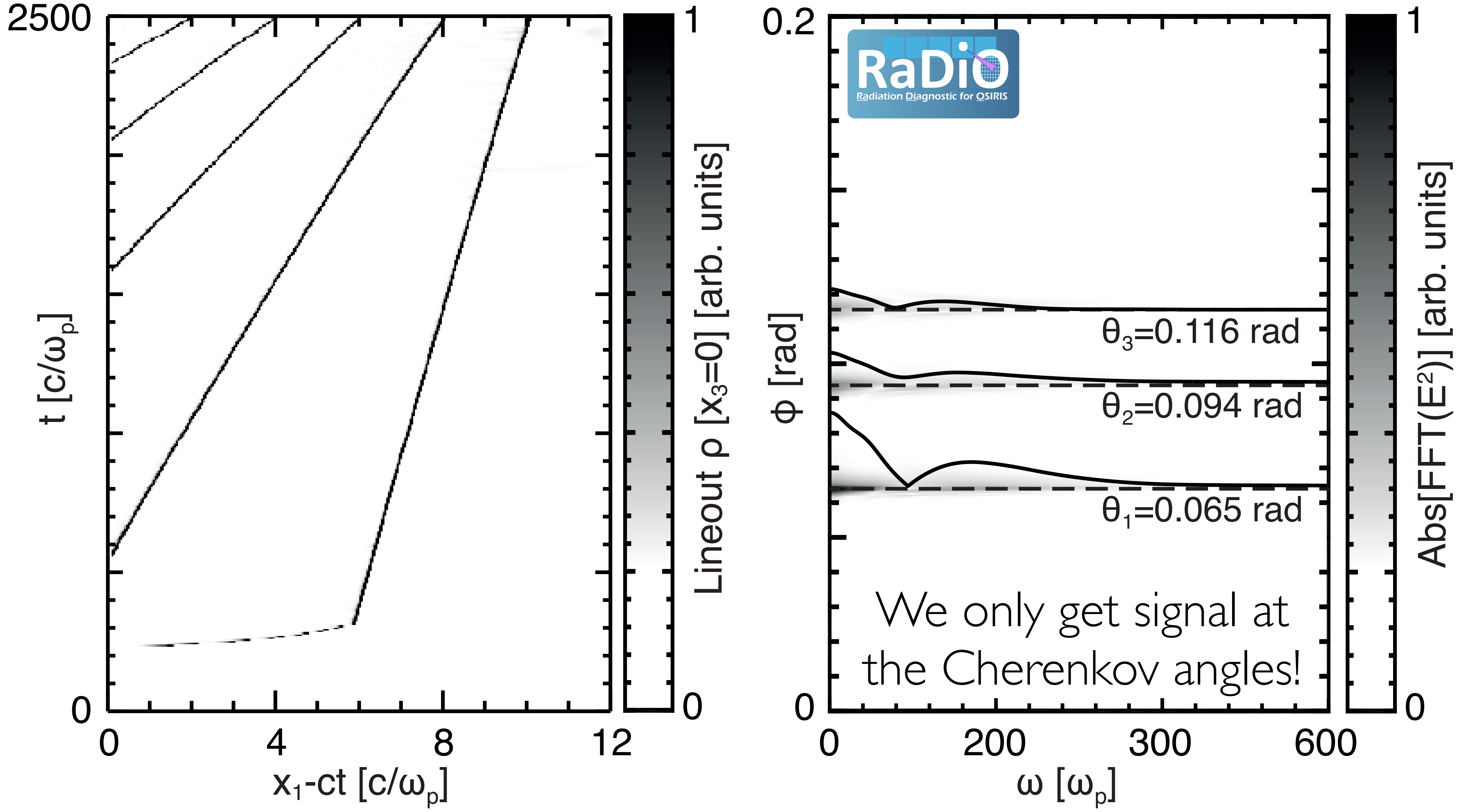
Goal trajectory ($x = x_0 + vt$)

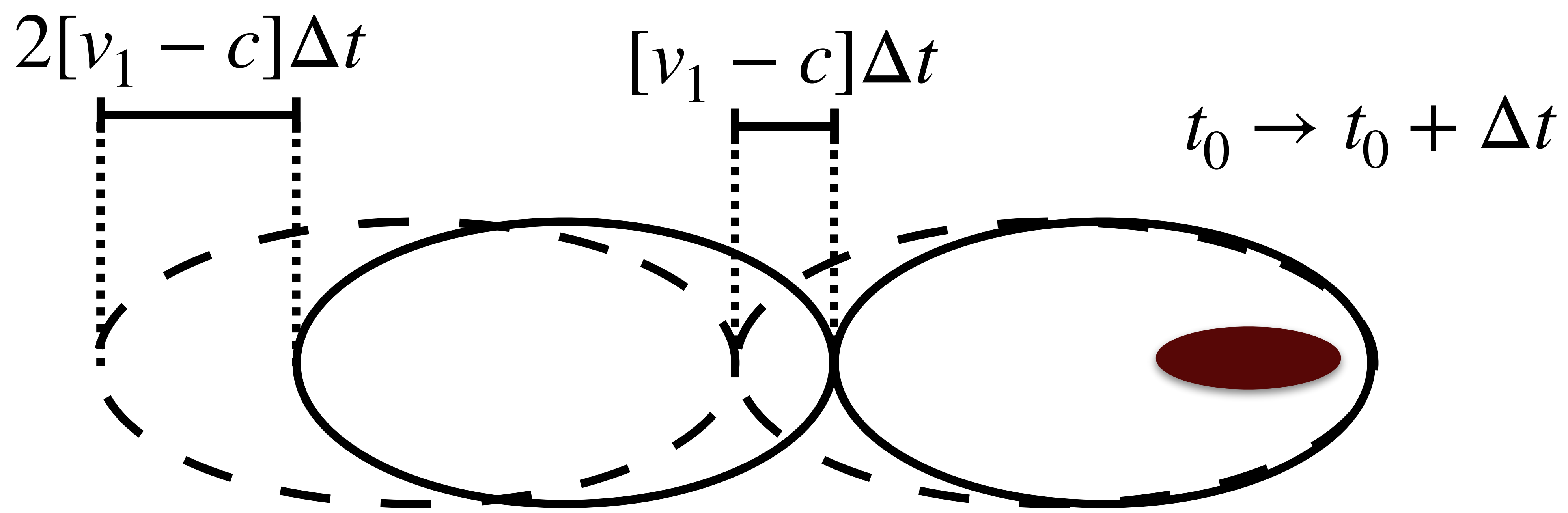
Engineered ramp (constant speed)

$$n(x) = n_0 \frac{4r_{b0}^2}{\left[2r_{b0} - \left(\frac{v}{c} - 1\right)x\right]^2}, v = 1.002c$$



We get a signal for each back of the bubble



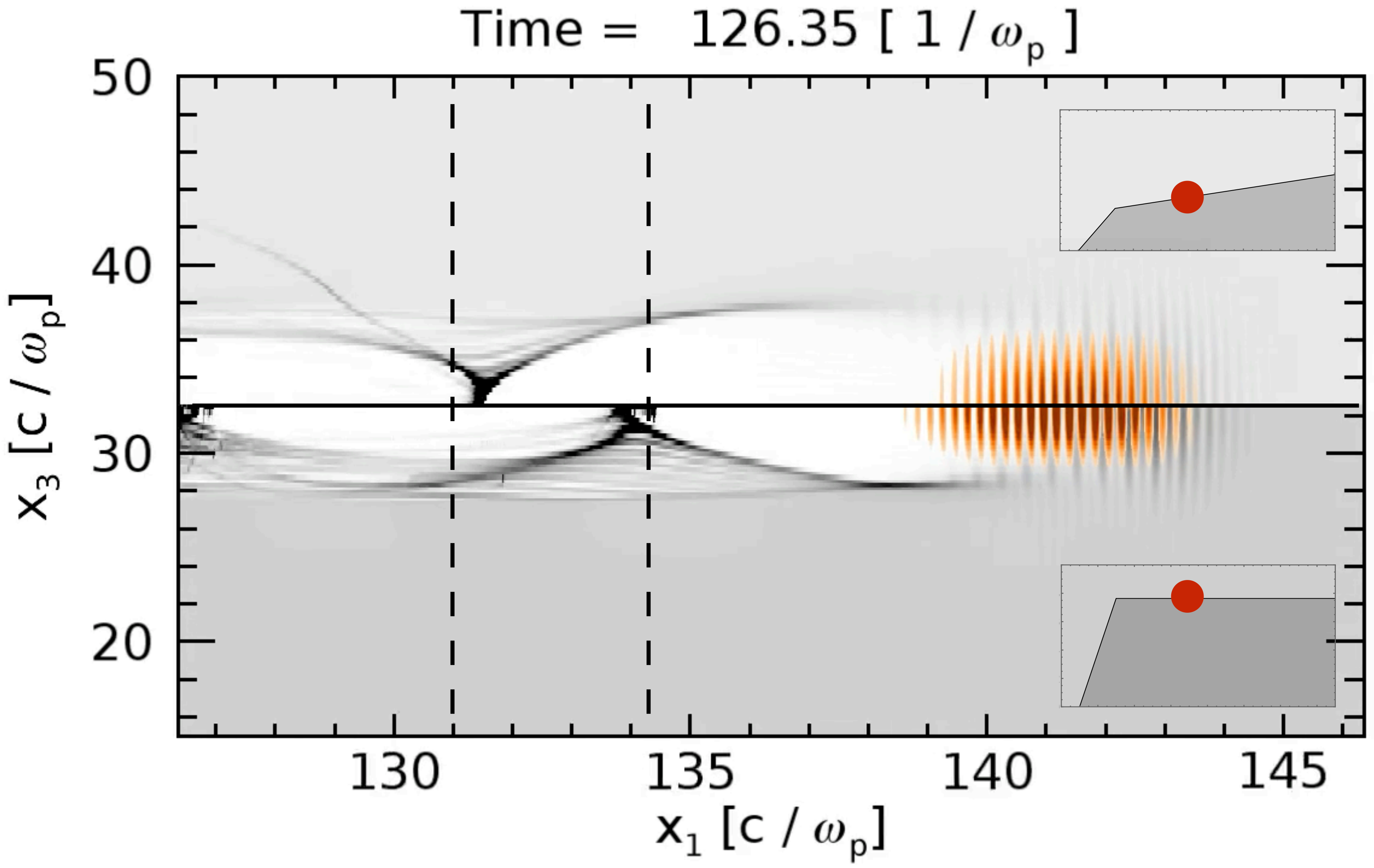


A linear ramp also ensures superradiant emission

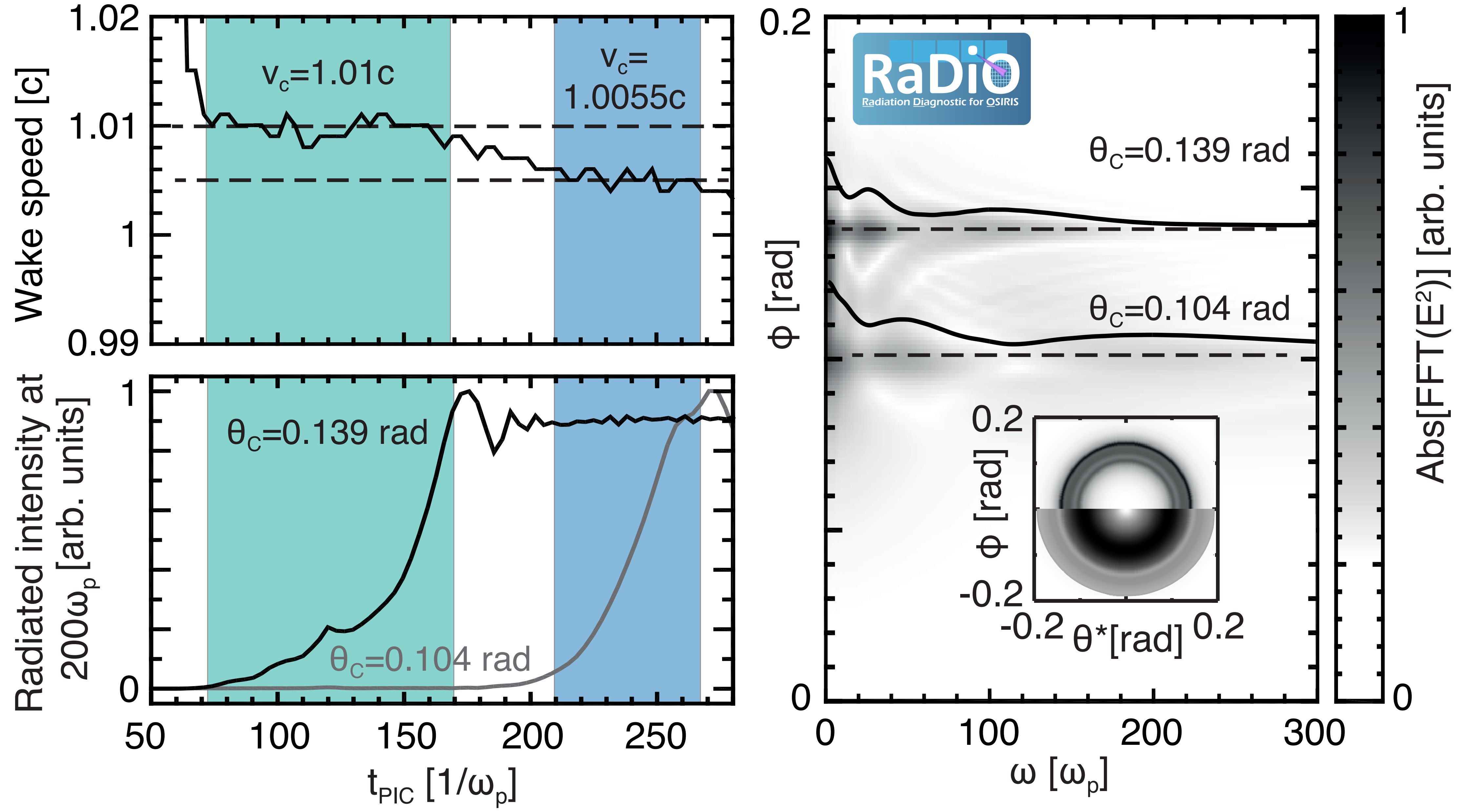
Goal trajectory ($x \approx x_0 + vt, v > c$)

For small values of x we can Taylor expand the engineered ramp to get a linear plasma ramp

$$n(x) = n_0 \left(1 + 2\left(\frac{v}{c} - 1\right)\frac{x}{r_{b0}}\right)$$



Spectrum is broadband at the Cherenkov angle

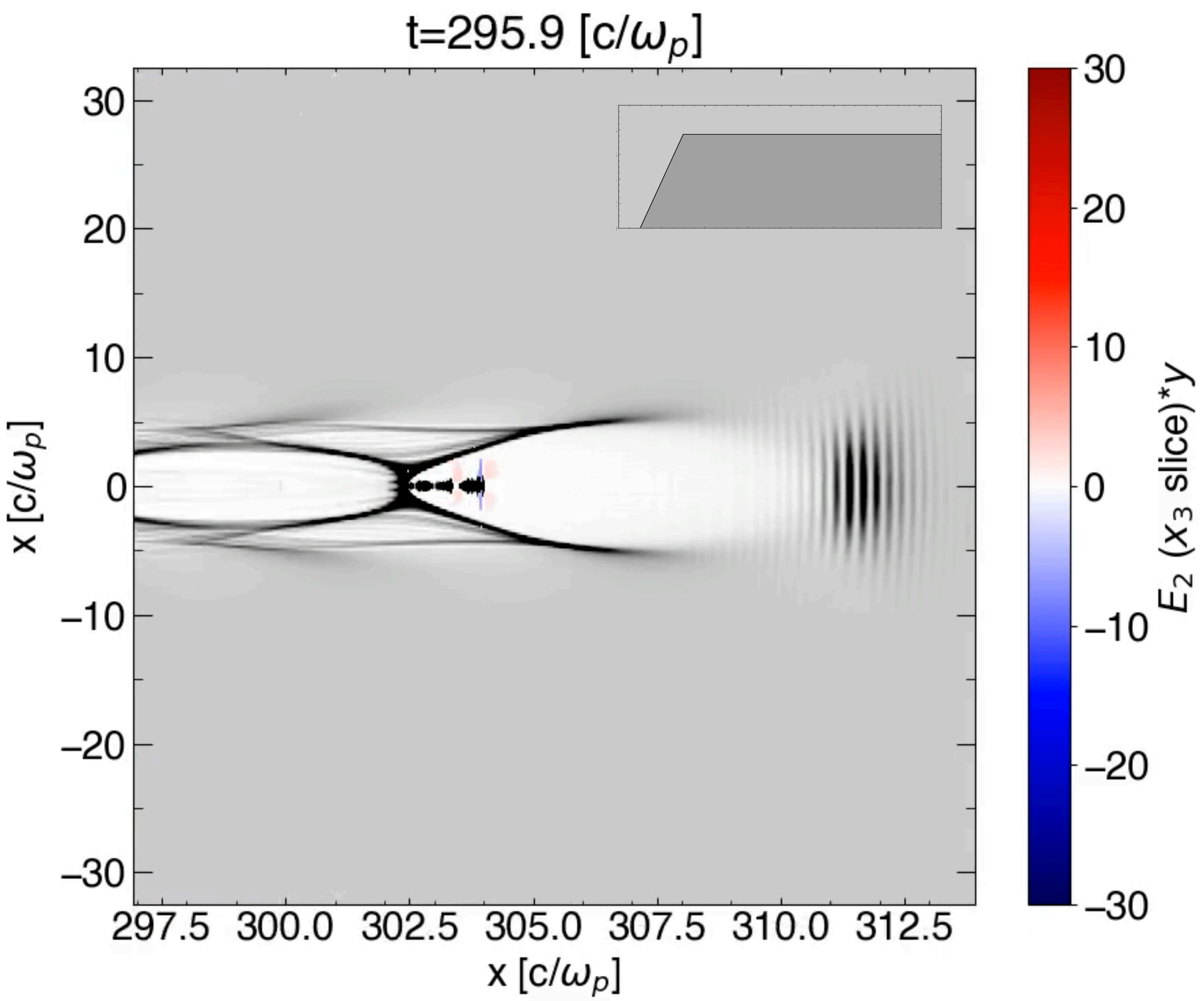


We get a **quadratic growth** (superradiant) at the corresponding Cherenkov angle of the speed of the back of the bubble

Cherenkov emission in the linear regime using a narrow plasma column was explored by W. Sollfrey et al, Physical Review 139, 1A (1965), S. Kalmykov et al, PPCF 63 045024 (2021) and A. Pukhov et al, PRL 127, 175001 (2021)

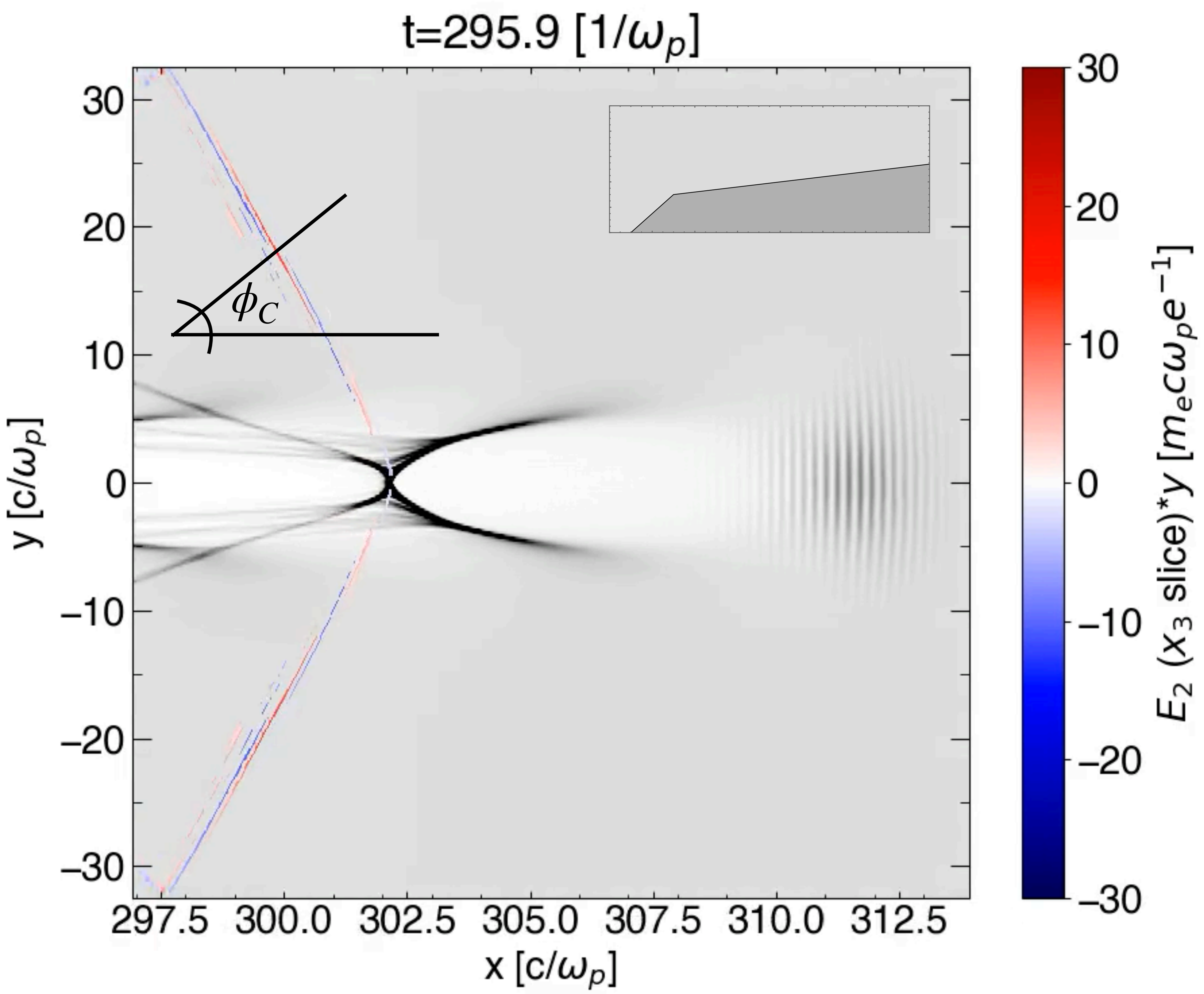
Very similar internal spectra lead to dramatically different emission

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

Narrow bandwidth emission (2D)

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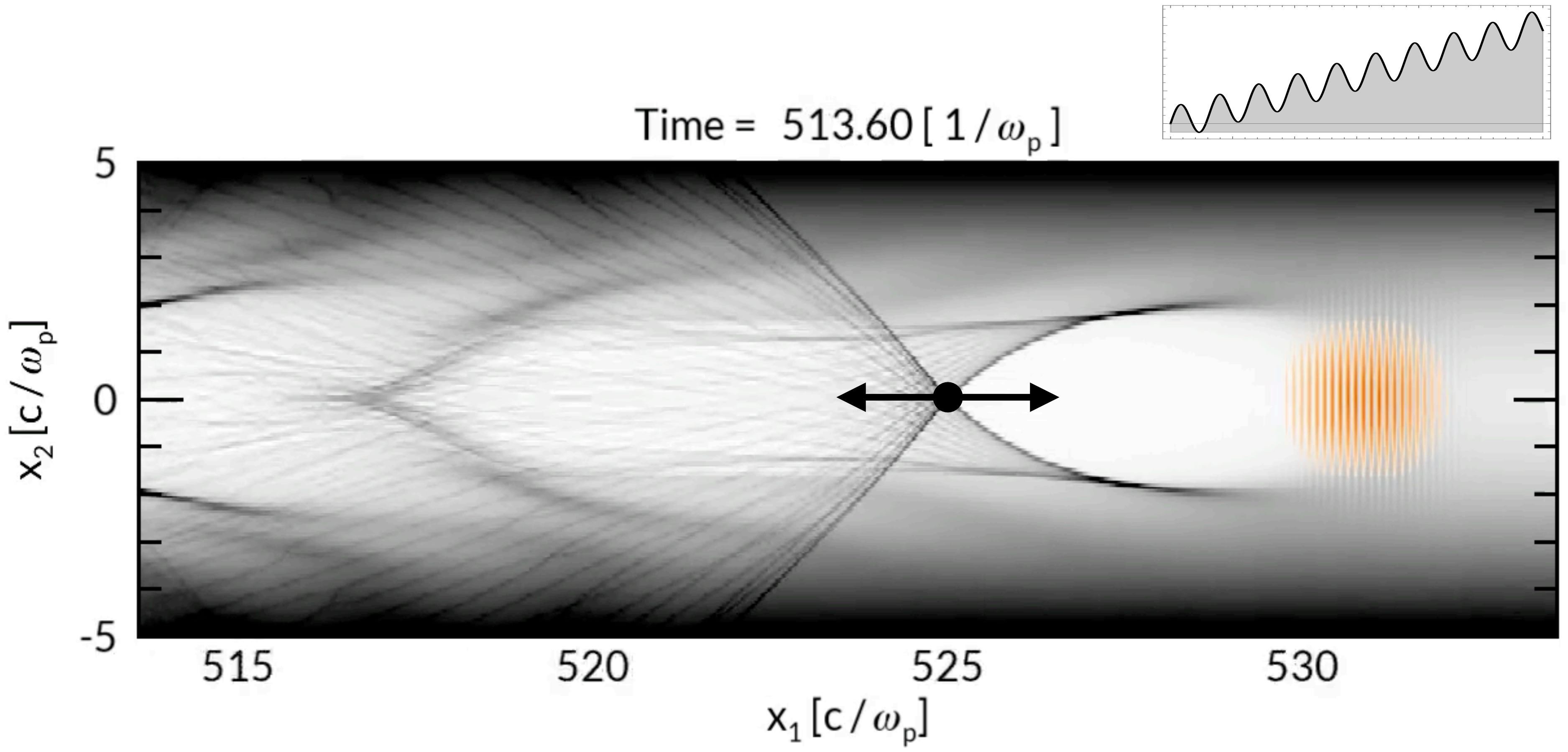
Goal trajectory ($x_0 \approx vt + A\sin\omega_m t$)

Plasma channel

We add a sinusoidal modulation in the plasma density such as $\sin\omega_m x$

This forces the radius of the bubble to change with time and creates a longitudinal oscillation (wavelength ~60 plasma skin depths)



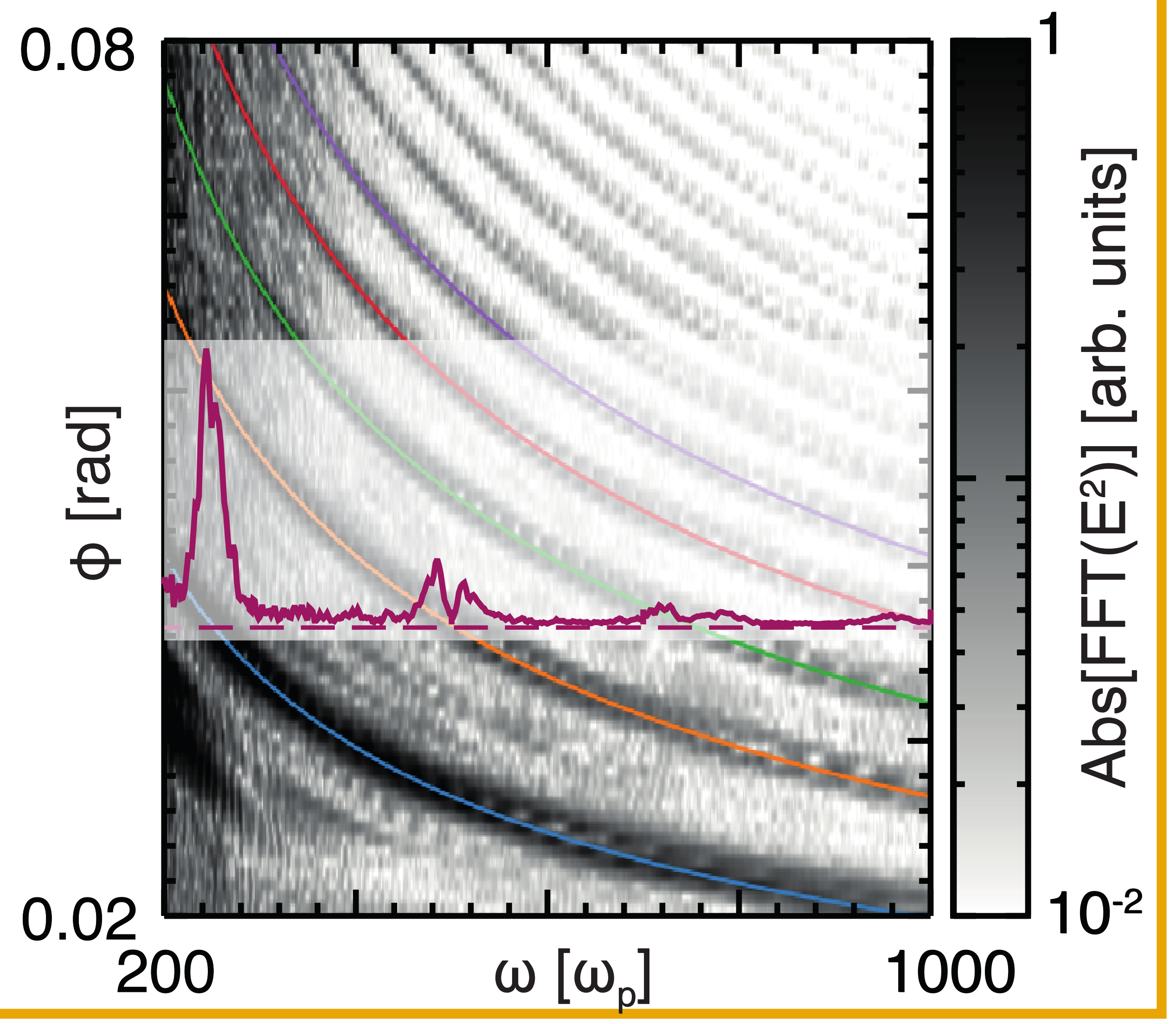
Spectrum is narrow and depends on angle

Theory predicts harmonics of the double doppler shifted oscillation frequency (for average excitation speeds close to c)

$$I(\omega,\Omega) \propto T^2 \left\{ \sum_n J_n\left(\frac{r_b\omega}{c}\cos(\theta)\right) \text{sinc}\left[\frac{\omega T}{2}\left(\omega - \frac{n\omega_b}{1-\bar{v}\cos(\phi)}\right)\right]\right\}^2$$

$$\omega \propto n\omega_b\gamma^2$$

Results agree with theory: smaller angles yield larger frequencies



*B. Malaca *et al*, 2022 (in prep.)

Conclusions

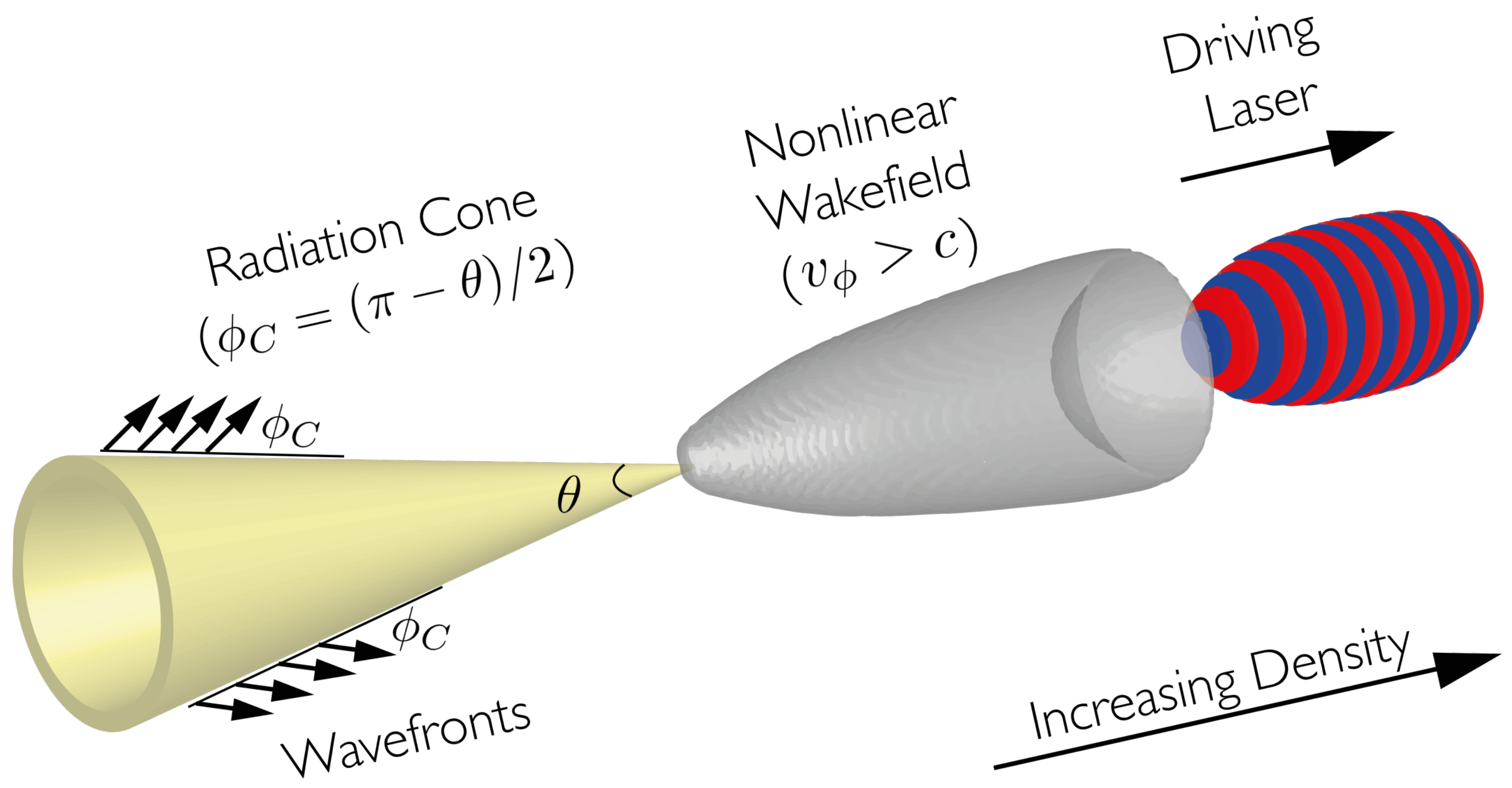
Trajectory of the excitation defines the spectrum

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

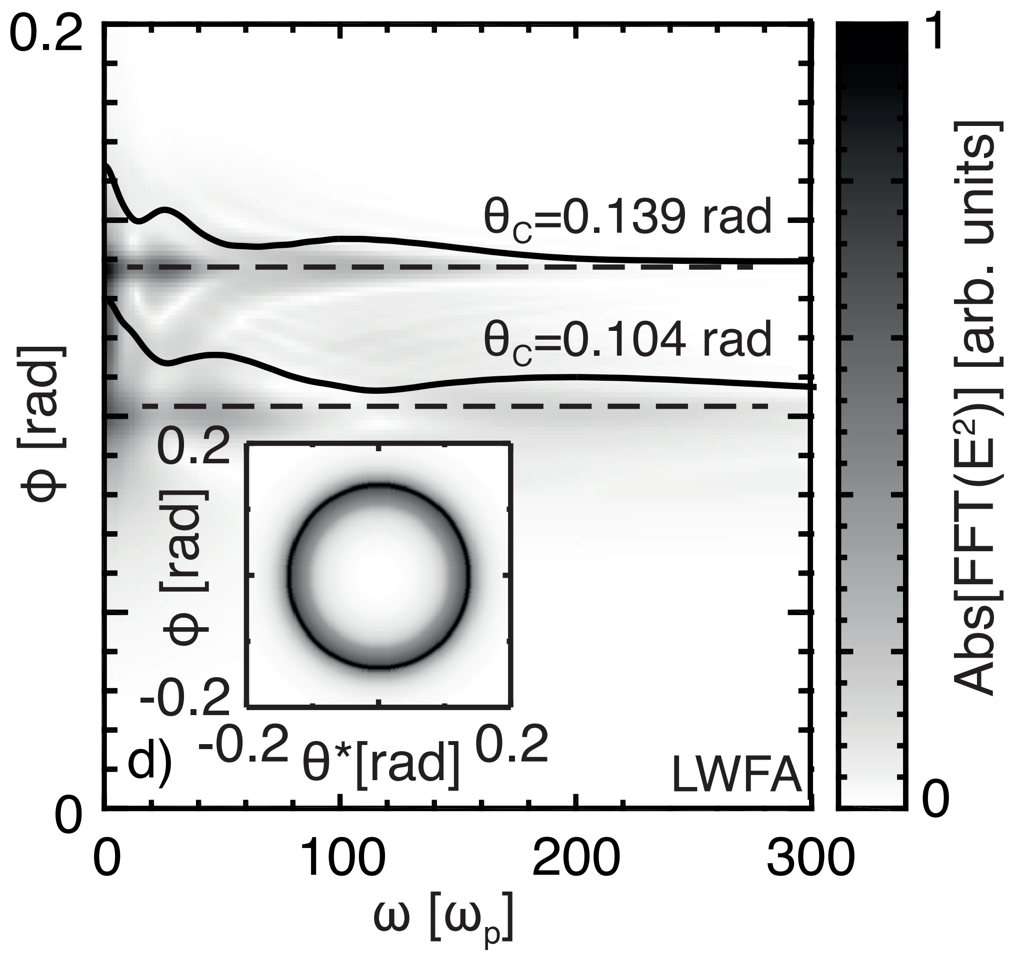
Contribution of the excitation trajectory

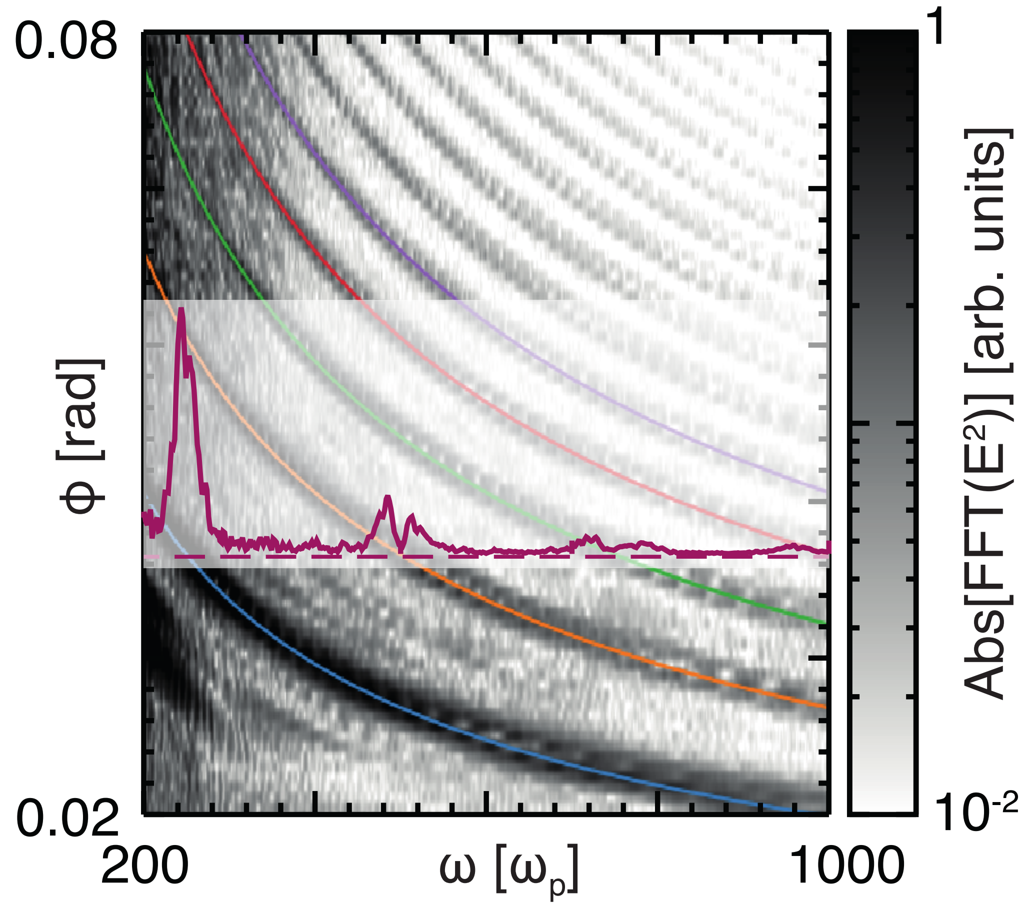
Spectrum of the excitation

A superluminal wakefield is superradiant



Broadband or narrowband emission





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*B. Malaca *et al*, 2022 (in prep.)