Lighting up the inner workings of LWFA

How radiative particle-in-cell simulations can shed new light onto the dynamics of laser-accelerated electrons

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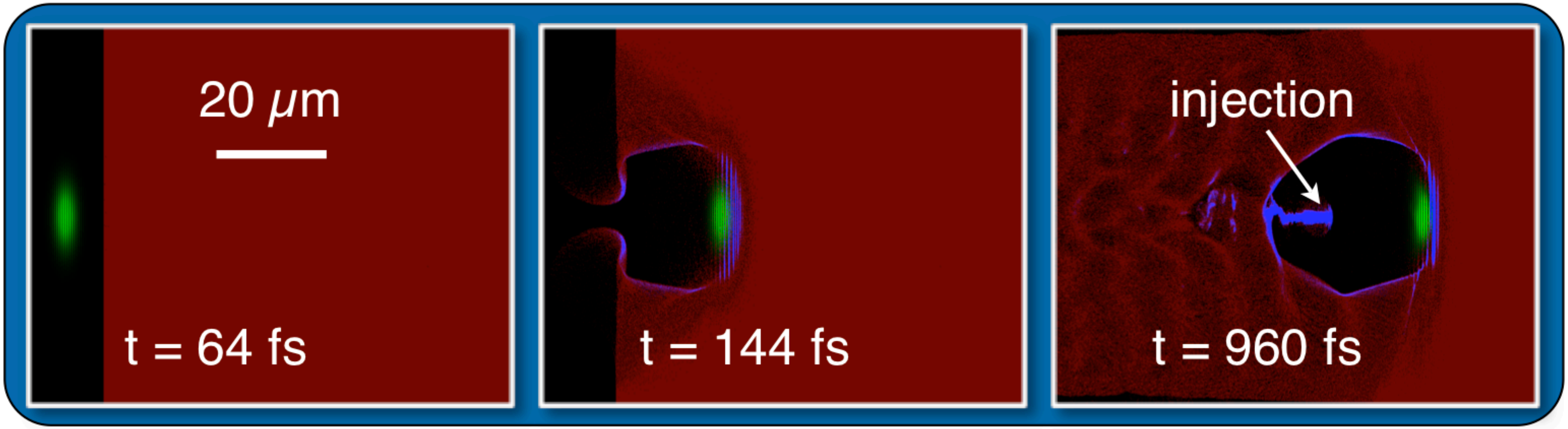
Particle-in-Cell simulations

predicting particle dynamics in LWFA



Problem: How does one experimentally diagnose LWFA?

need to resolve **fs – nm** electron dynamics

or

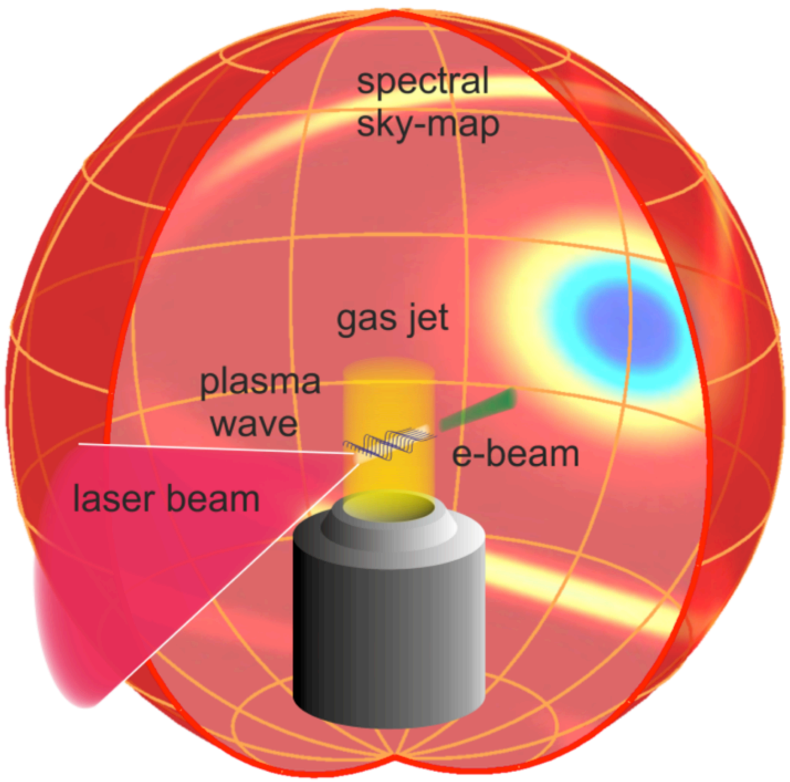
use **spectral** information

Simulating the radiation from Laser Wakefield Acceleration

shedding new light into the dynamics of laser-accelerated electrons

- Radiation spectra give insight into the **momentum distribution**
- Spectra are **accessible in experiments**

- **Quantitatively** predict spectral intensities
- Link them to specific regions in **phase space**
- Input to new **diagnostic** methods



Simulating the radiation from Laser Wakefield Acceleration

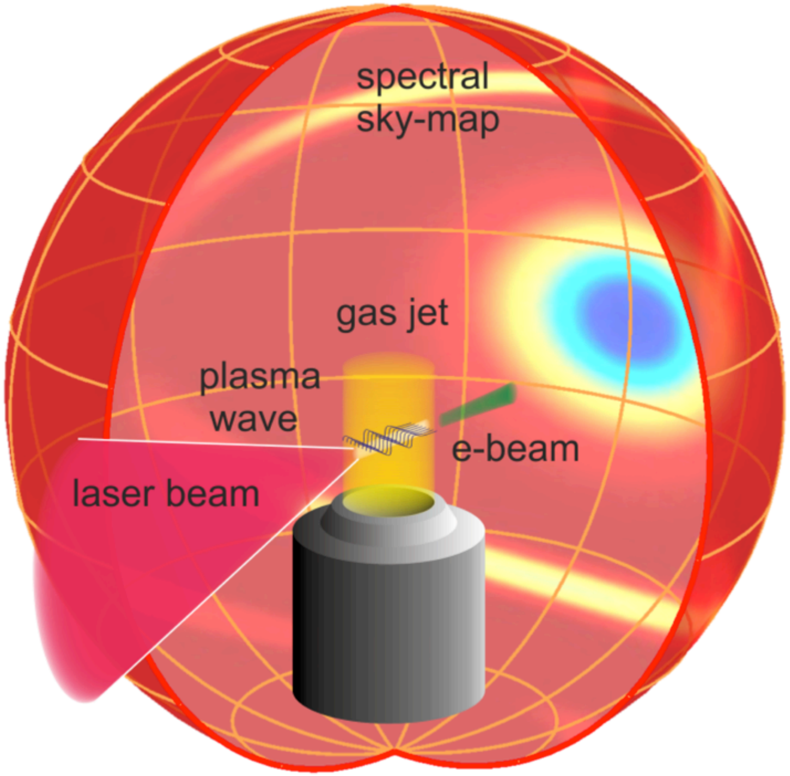
shedding new light into the dynamics of laser-accelerated electrons

This allows to study

- e^- dynamics during the formation of the Wakefield
- Injection of the e^- into the Wakefield
- Coherent motion of the e^- during acceleration (betatron oscillation)

Simulating

- All macro-particles
- Spectrum: IR - X-ray
- Multiple observation directions



Computational challenges

Combining the radiation code with a PIC code to speed up the simulation.

Computing the radiation spectra is computationally expensive.

- Particle trajectories of all particles (~ 100 TB data)
- Computing spectra in hundreds of directions for all particles

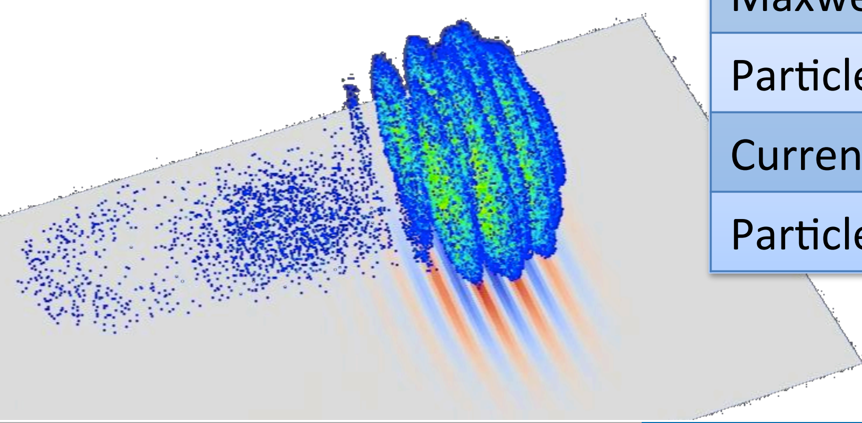
Solution: combining the radiation code with PIConGPU

- Direct data access (with 200 GB/s)
- Utilizing the performance of multiple GPUs

Prerequisite: PIConGPU
speeding up simulations by using GPUs

What is PIConGPU?

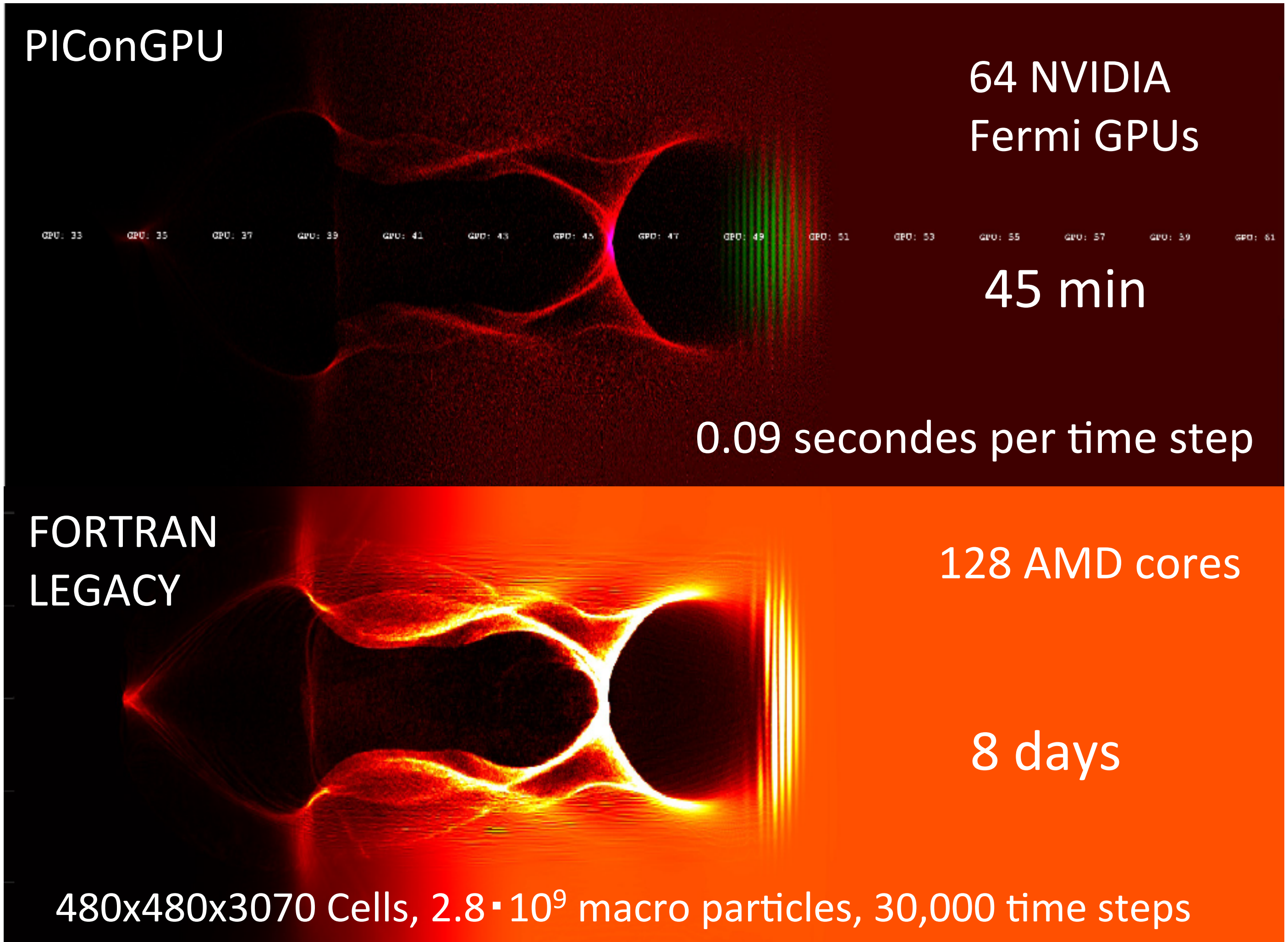
- A fully relativistic, 3D3V Particle-in-Cell simulation
- Extensively tested
- Will be published under GPL license soon



Algorithm	Options
Maxwell-Solver	Yee, Directional Splitting
Particle-Pusher	Boris, Vay
Current Deposition	Villasenor-Buneman, Esirkepov
Particle Shapes	NGP, CIC, TSC, PQS

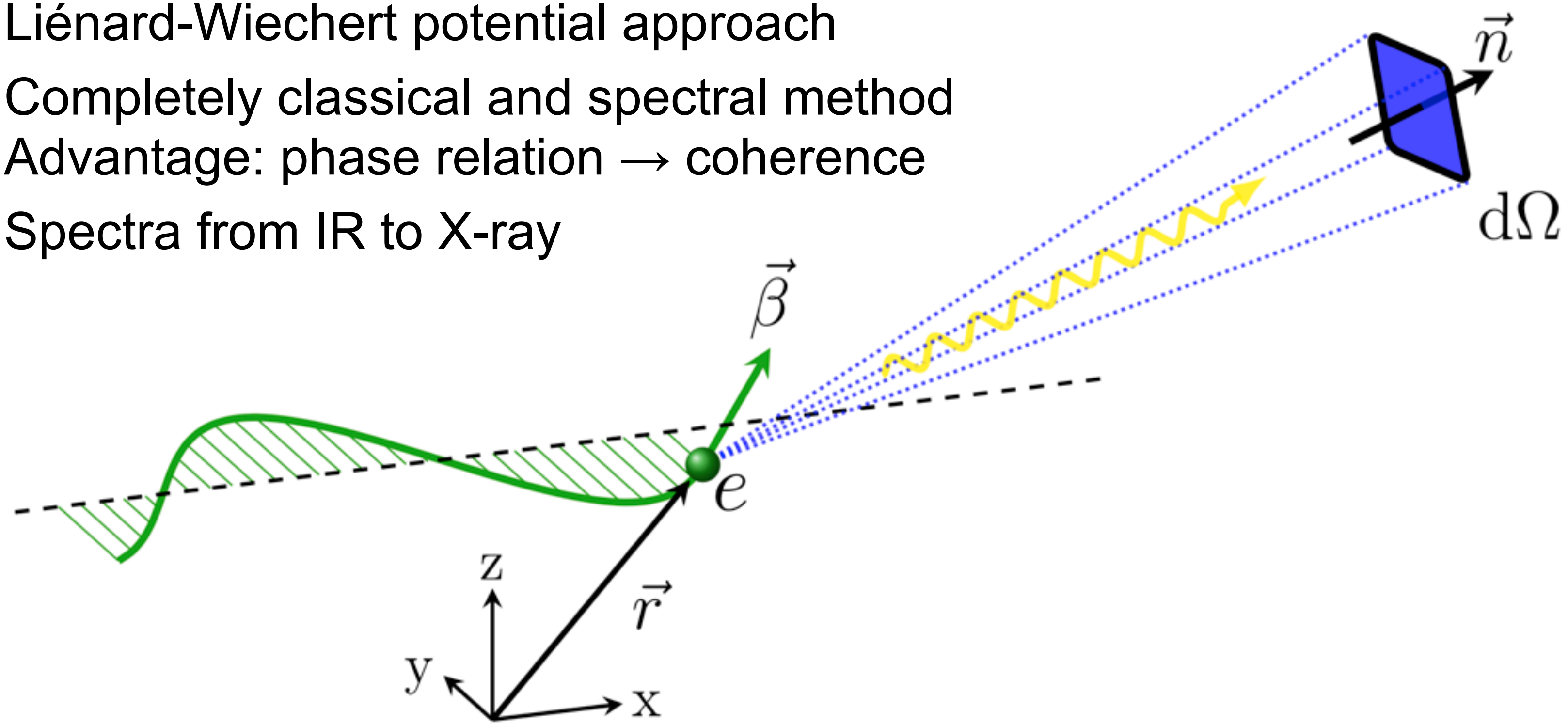
Prerequisite: PIConGPU

watching the PIC simulation live



The radiation of a single electron

- Liénard-Wiechert potential approach
- Completely classical and spectral method
  Advantage: phase relation → coherence
- Spectra from IR to X-ray

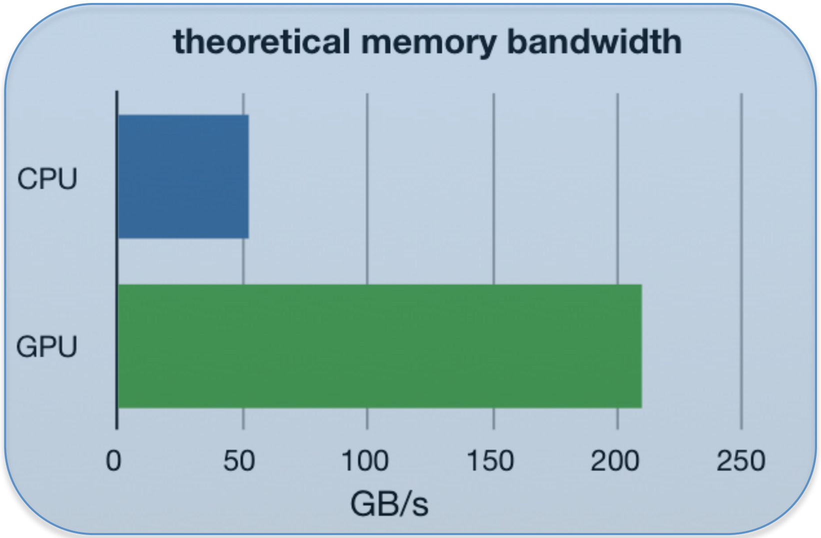


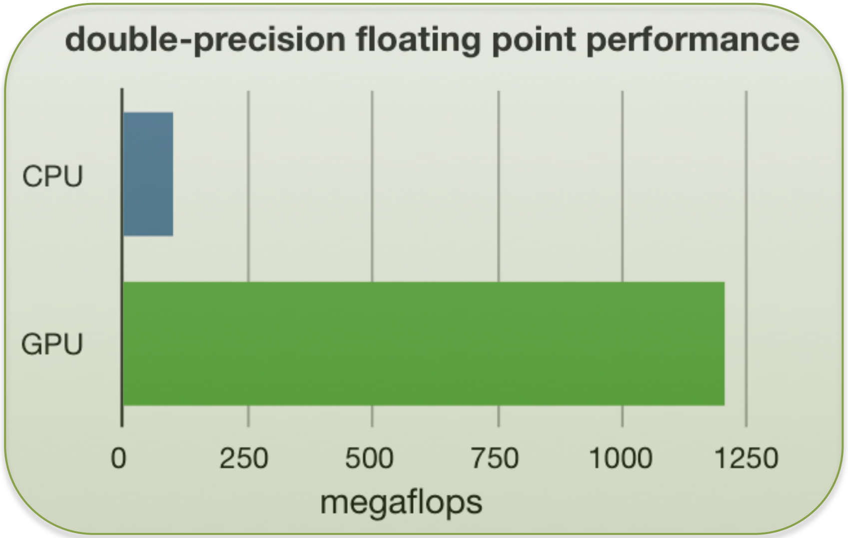
$$\frac{d^2 I_1}{d\Omega d\omega} = \frac{q^2}{16 \cdot \pi^3 \cdot \varepsilon_0 \cdot c} \cdot \left| \int \frac{\vec{n} \times \left[\left(\vec{n} - \vec{\beta} \right) \times \dot{\vec{\beta}} \right]}{\left(1 - \vec{\beta} \cdot \vec{n} \right)^2} \cdot e^{i\omega \left(t - \frac{\vec{n}\vec{r}}{c} \right)} \, dt \right|^2$$

DRESDEN concept HZDR

Computing the spectra of all particles in the simulation

$$\frac{d^2 I_N}{d\Omega d\omega} \sim \left| \sum_{k=1}^{N} \int \frac{\vec{n} \times \left[\left(\vec{n} - \vec{\beta}_k \right) \times \dot{\vec{\beta}}_k \right]}{\left(1 - \vec{\beta}_k \cdot \vec{n}\right)^2} \cdot e^{i\omega\left(t - \frac{\vec{n}\vec{r}_k}{c}\right)} dt \right|^2$$

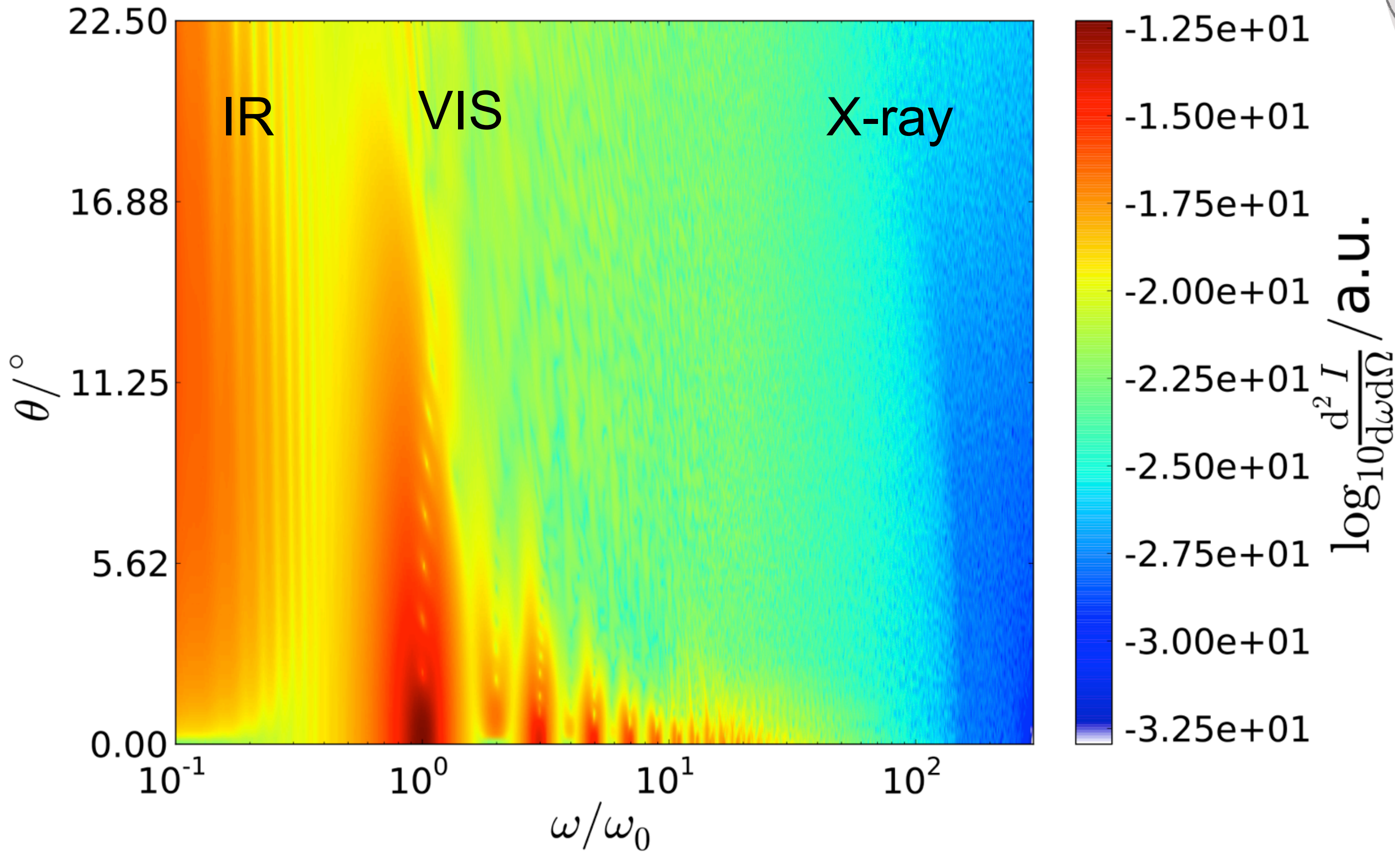


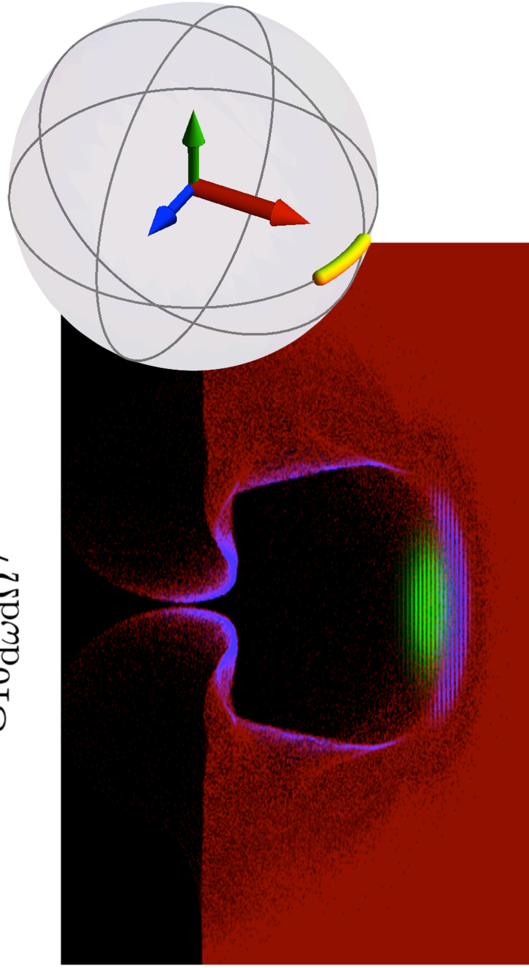


- CPU Xeon - 10 cores (20 hyper threads)
- GPU Tesla K20 - 13 streaming multiprocessor

Considering coherent and incoherent collective effects by computing the spectra of all particles in the simulation

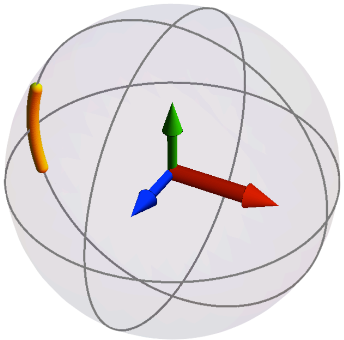
- Quantitative predictions
- Coherent and incoherent collective effects





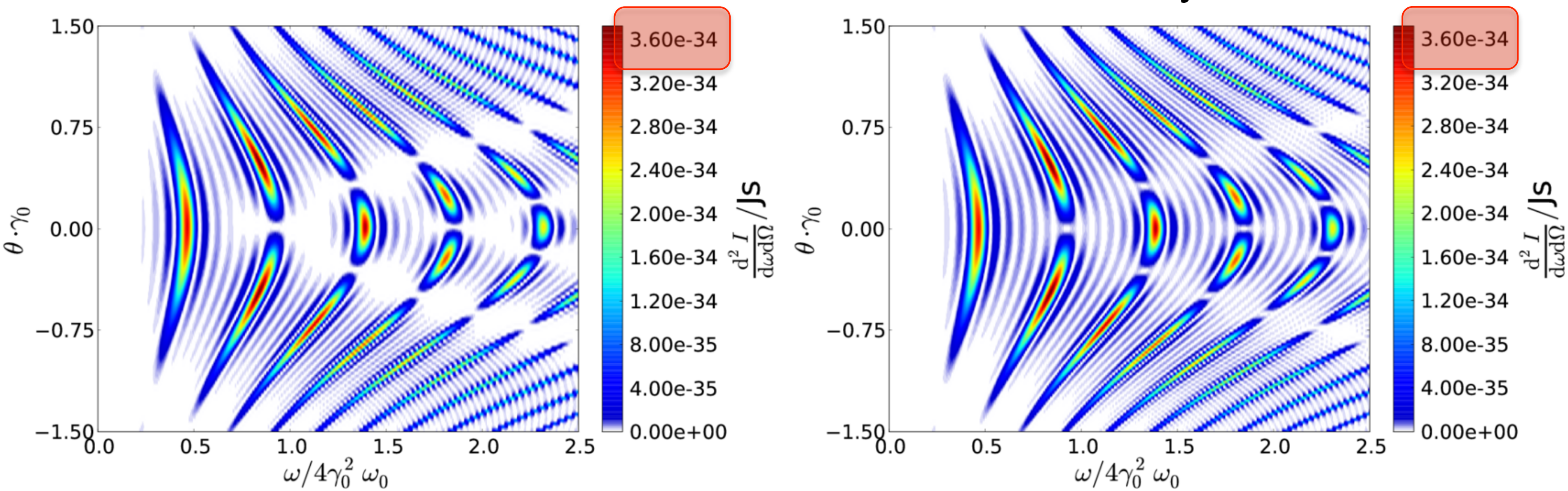
What have we done so far with this code?

verifying the algorithm with **single** particle tests



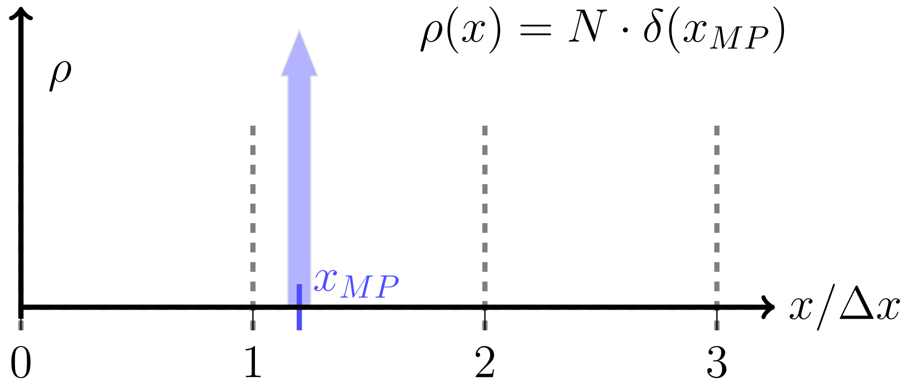
Non-linear Thomson Scattering

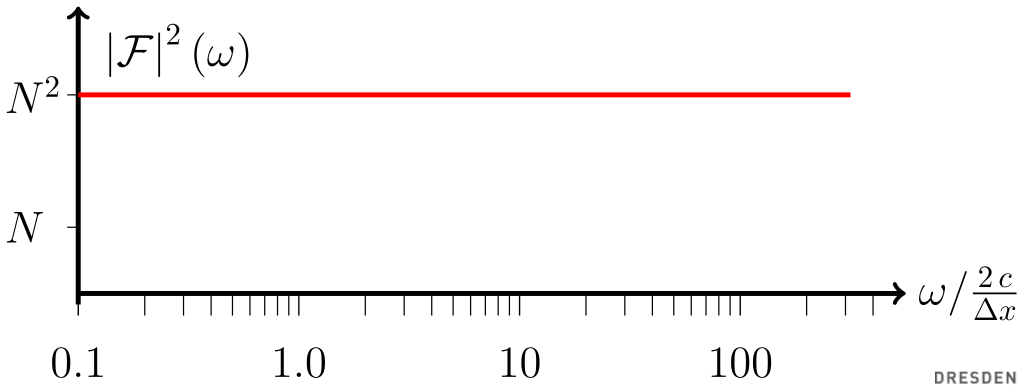
Simulation | Theory



Taking into account the shape of the macro-particle

$$\frac{\mathrm{d}^2 I_N}{\mathrm{d}\Omega \mathrm{d}\omega} \sim \left| \sum_{k=1}^{N} \int \frac{\vec{n} \times \left[\left(\vec{n} - \vec{\beta}_k \right) \times \dot{\vec{\beta}}_k \right]}{\left(1 - \vec{\beta}_k \cdot \vec{n} \right)^2} \cdot e^{\mathrm{i}\omega \left(t - \frac{\vec{n}\vec{r}_k}{c} \right)} \cdot \mathcal{F}_k(\omega) \, \mathrm{d}t \right|^2$$





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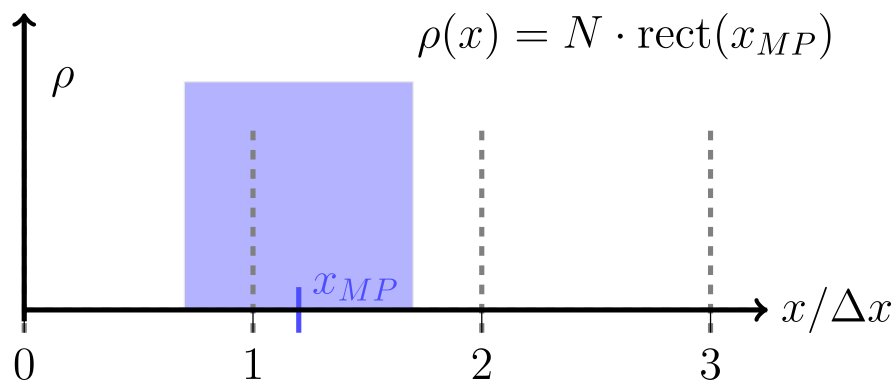

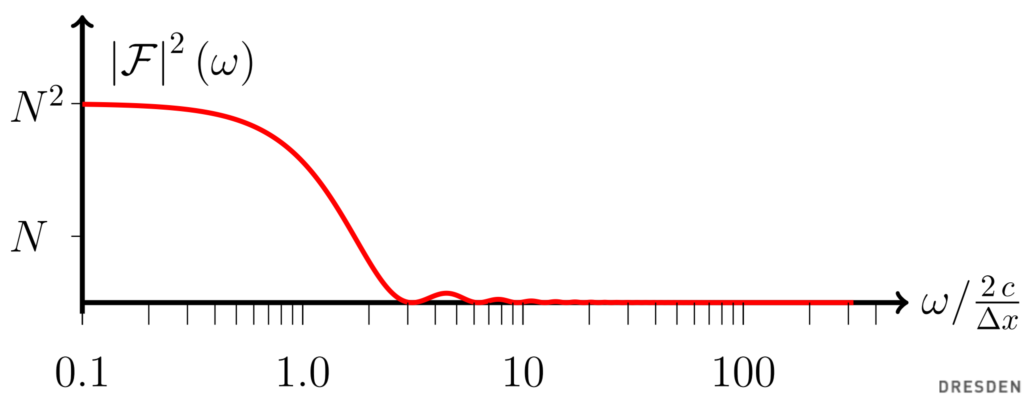

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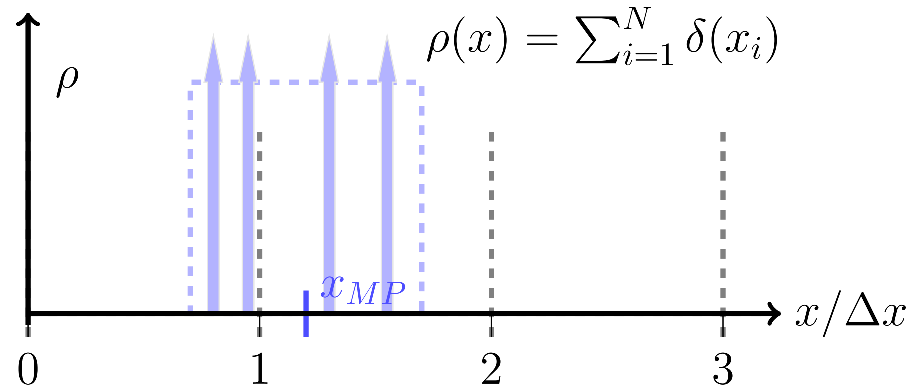
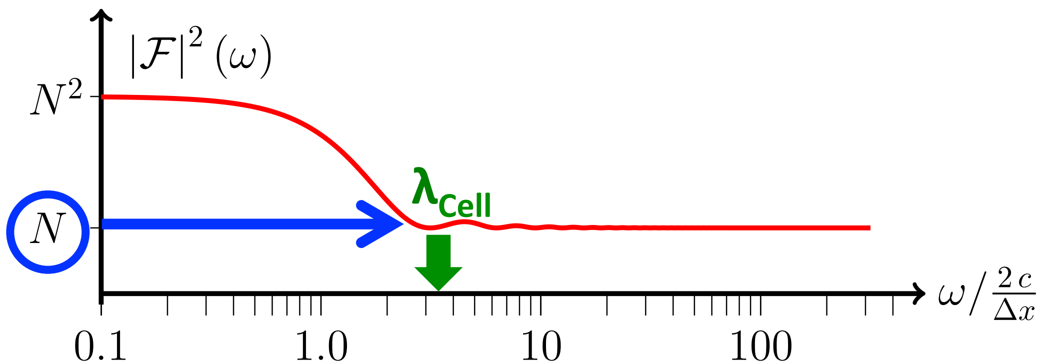
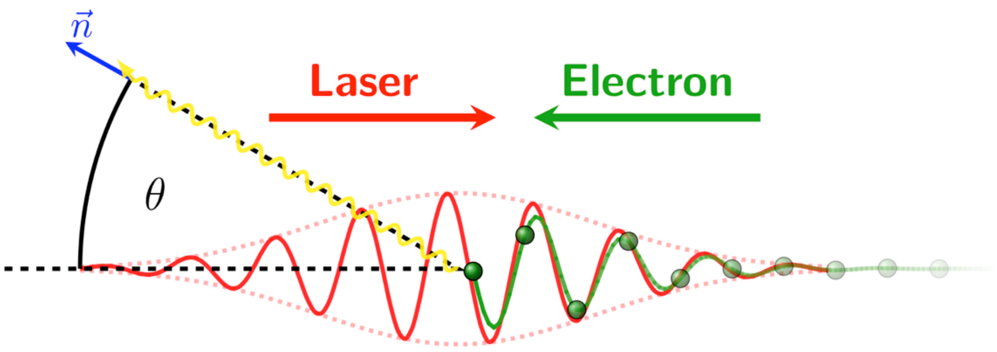
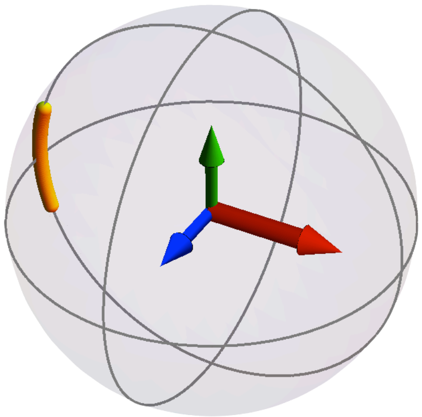


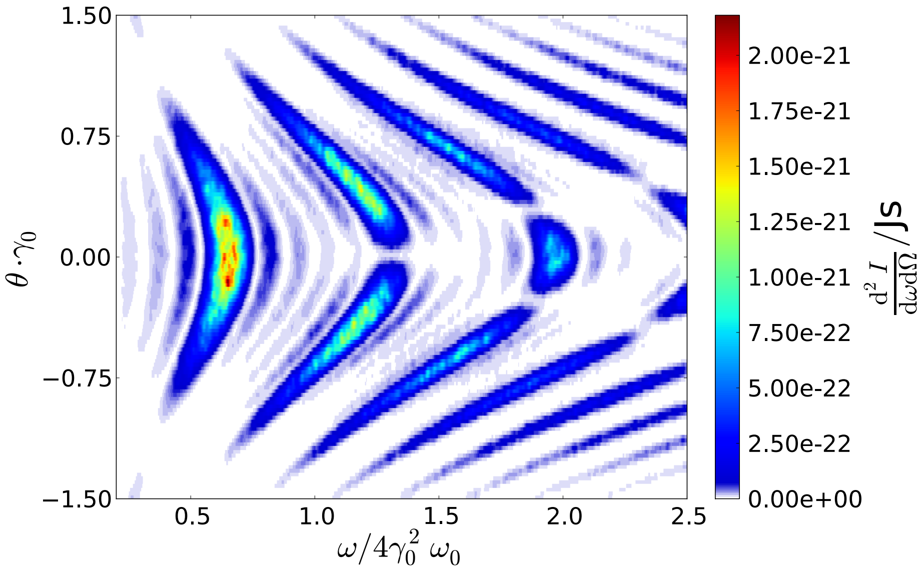


Taking into account the shape of the macro-particle

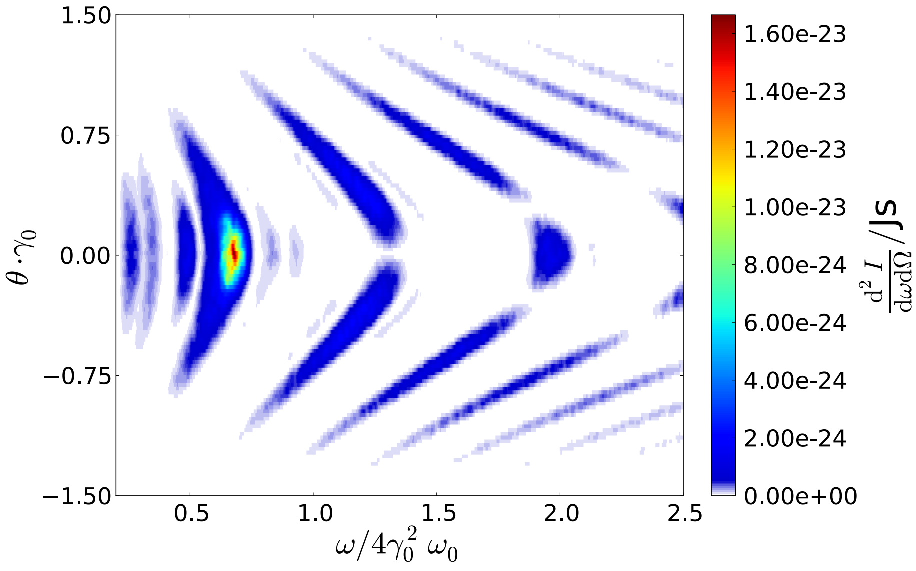




without form factor

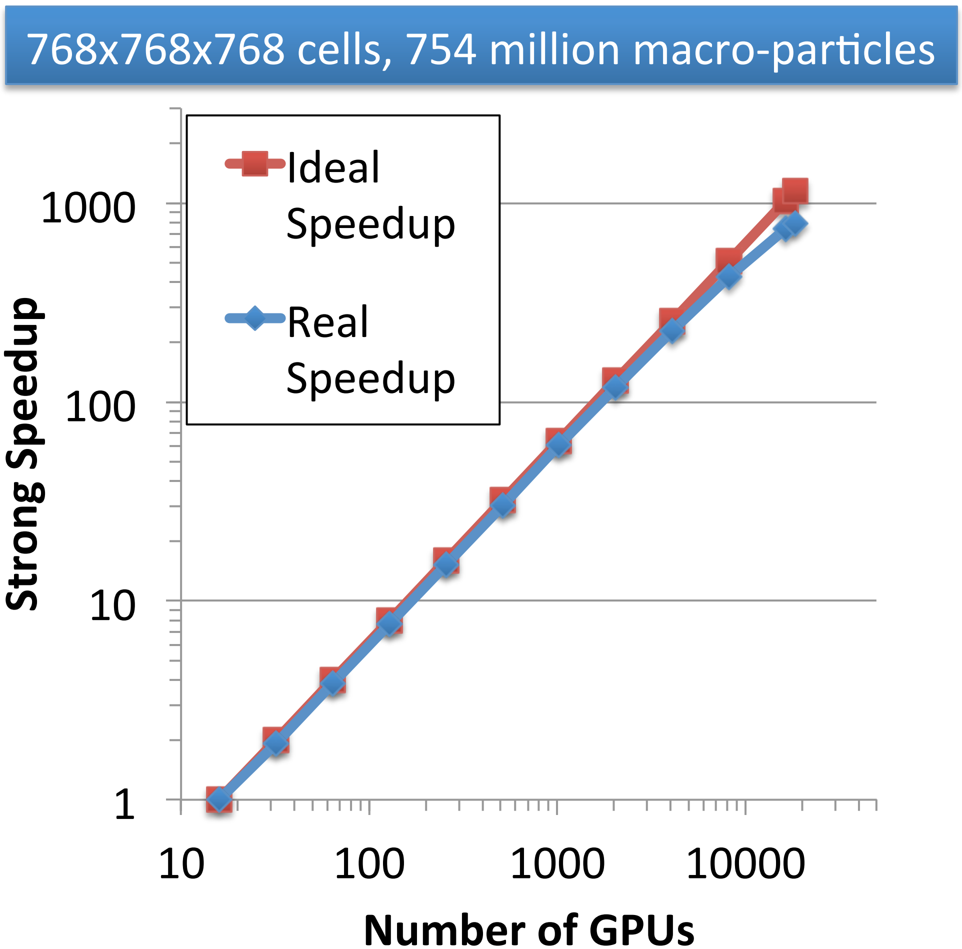


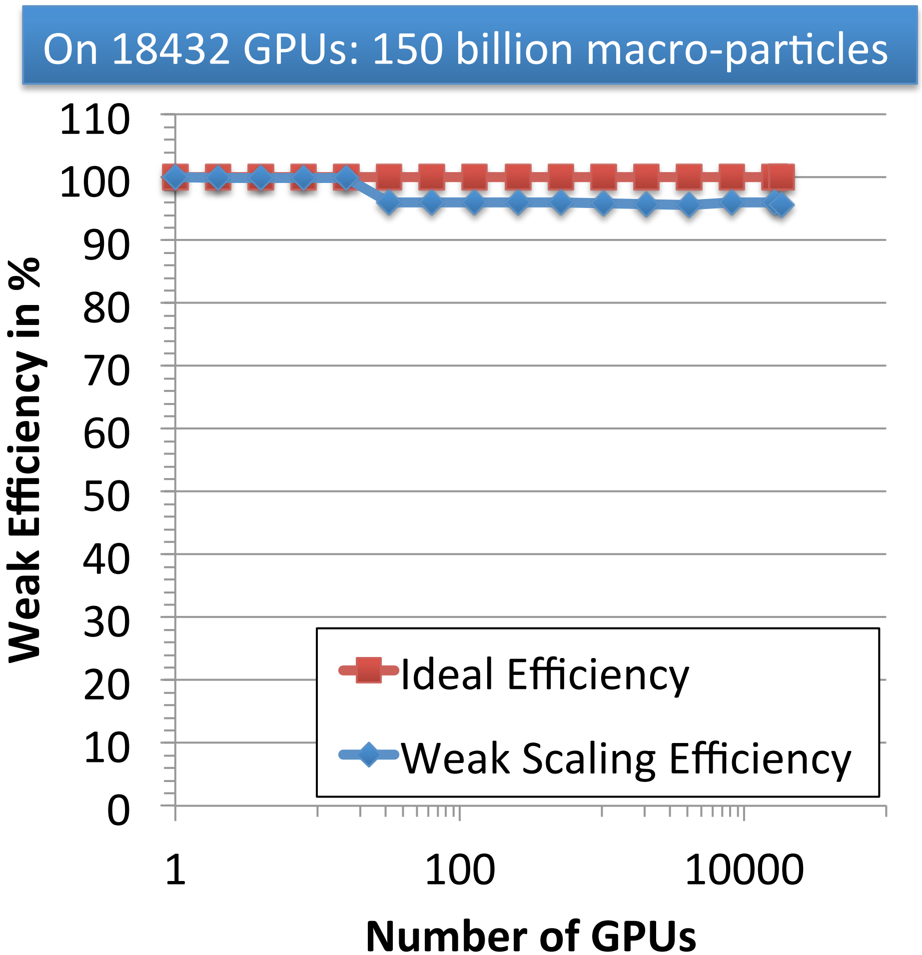
with form factor



Prerequisite: PIConGPU

Scaling test using the world's biggest supercomputer TITAN



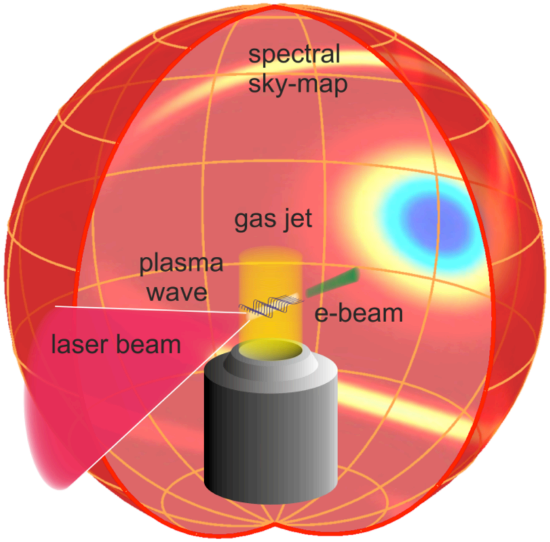


7.176 PFLOP/s double precision performance

Outlook: a large scale LWFA simulation

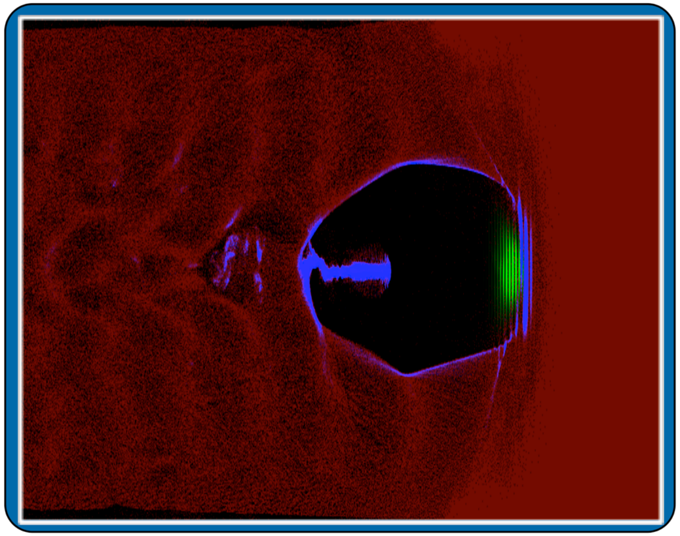
Resources

- TITAN (GPU cluster)
- largest supercomputer on Earth
- 18,688 GPUs



Physics scenario

- Bubble regime
- Self injection
- Betatron oscillation
- Spectra from IR to X-ray
- Entire LWFA



Summary

- Electromagnetic spectra are of interest for LWFA since fs-nm electron dynamic is hard to observe directly.
- Simulating radiation from full plasma is computational expensive but possible.
- Spectral signatures of coherent and incoherent collective effects contain information on the electron dynamics during LWFA.

Code exists now!

Machines exist today!