LA³NET Workshop, April 28 – 30, 2014, HZDR, Dresden

Radiative Particle-in-Cell simulations on laser-plasma interactions

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OLCF Oak Ridge Leadership Computing Facility

ZIH Center for Information Services & High Performance Computing

NVIDIA CUDA™ Center of Excellence

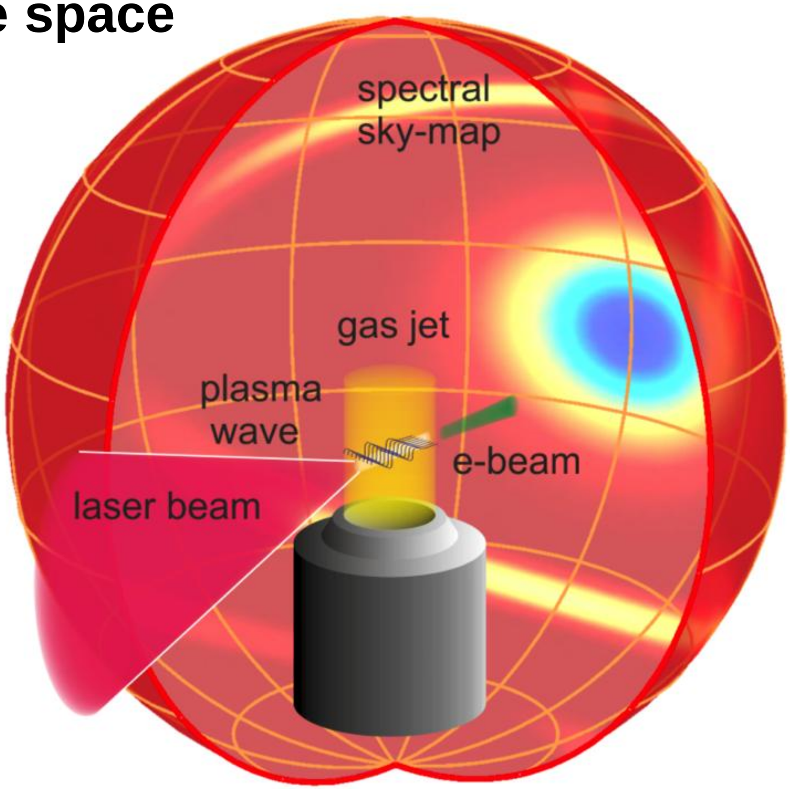
Partner von DRESDEN concept exzellenz-dresden.de

HZDR Helmholtz Zentrum Dresden Rossendorf

Simulating the radiation from Laser Plasma Interactions

shedding new light into the dynamics of laser-accelerated electrons

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



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

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Simulating the radiation from Laser Plasma Interactions

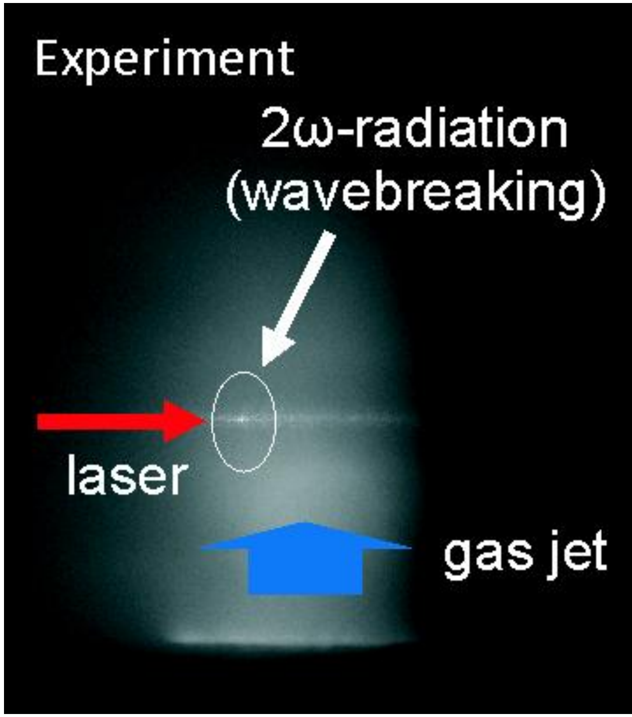
shedding new light into the dynamics of laser-accelerated electrons

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



Could this give quantitative data of electron injection?

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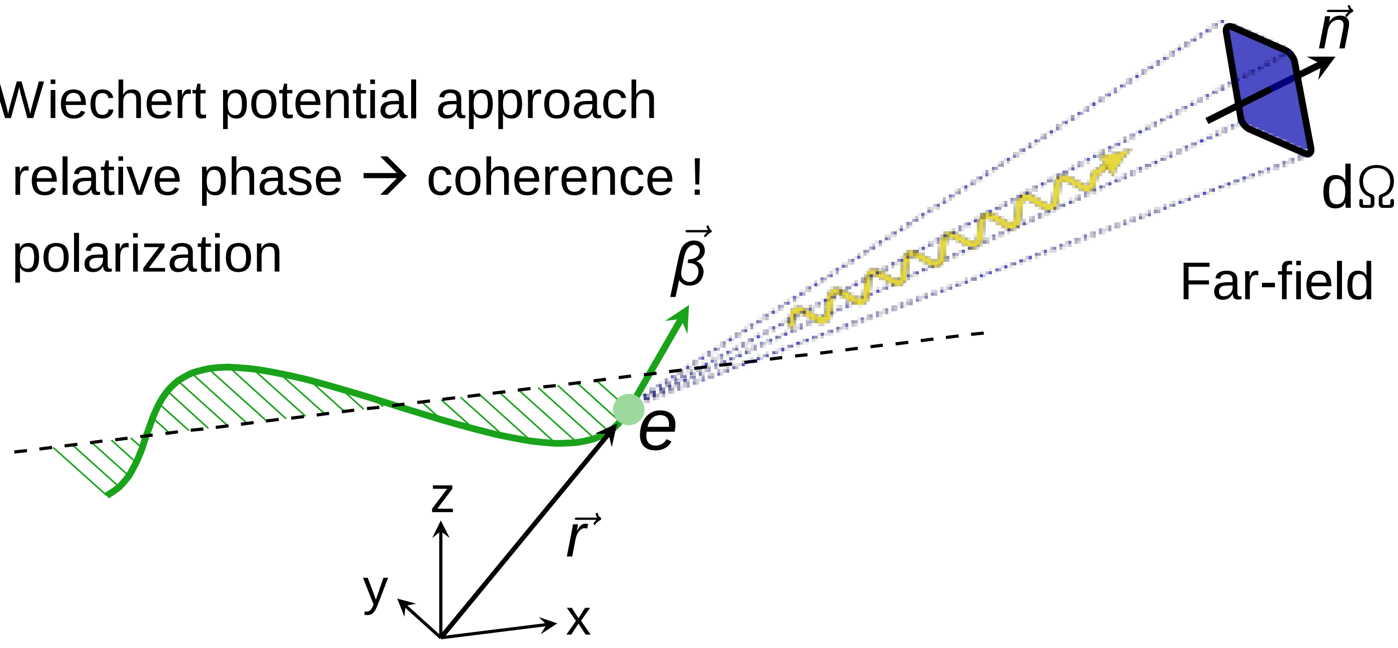
Classical radiation – accelerated electrons emit radiation.

- Liénard-Wiechert potential approach
- Includes relative phase → coherence !
- Includes polarization



$$\frac{\mathrm{d}^2 I_N}{\mathrm{d}\Omega \mathrm{d}\omega} \sim \left| \sum_{i=0}^{N} \int \frac{\vec{n} \times \left[\left(\vec{n} - \vec{\beta}_i \right) \times \dot{\vec{\beta}}_i \right]}{\left(1 - \vec{\beta}_i \cdot \vec{n} \right)^2} \cdot e^{i\omega \left(t - \frac{\vec{n}\vec{R}_i}{c} \right)} \mathrm{d}t \right|^2$$

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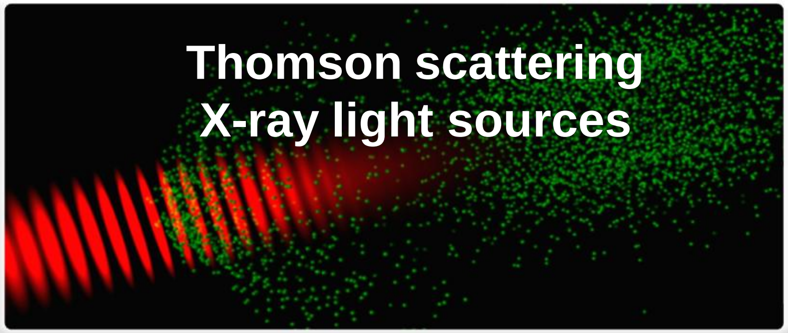
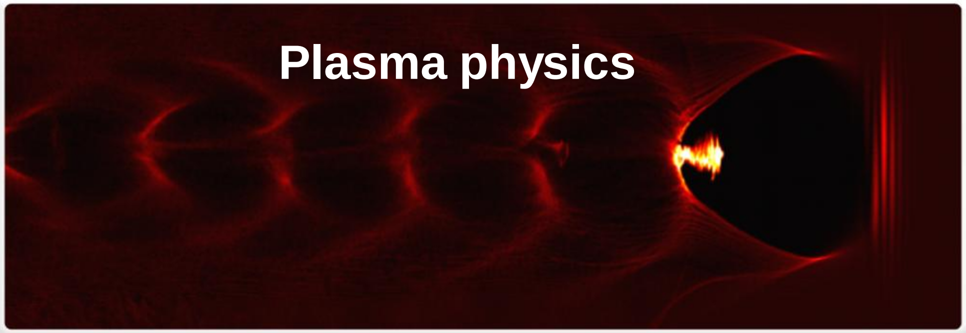
So what is the challenge in radiation from plasmas?





- Several **10^3 - 10^5** simulated electrons
- Several **GB** of electron trajectories

→ Post-processing possible.

- **10^8 - 10^{10}** (macro) particles in a plasma
- Several **100 TB** to **PB** of electron trajectories

→ **Processing must happen online during PIC.**

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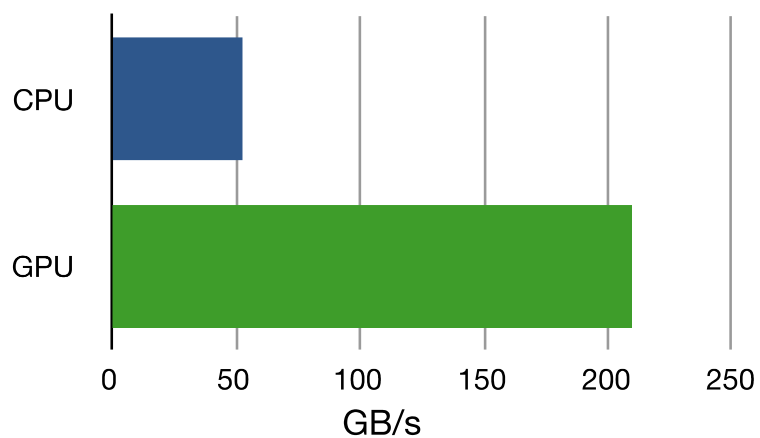
Solution - Use graphic cards (GPUs) to parallelize calculations

$$\frac{d^2 I_N}{d\Omega d\omega} \sim \left| \sum_{i=0}^{N} \int \frac{\vec{n} \times \left[\left(\vec{n} - \vec{\beta}_i \right) \times \dot{\vec{\beta}}_i \right]}{\left(1 - \vec{\beta}_i \cdot \vec{n} \right)^2} \cdot e^{i\omega \left(t - \frac{\vec{n} \vec{R}_i}{c} \right)} \mathrm{d}t \right|^2$$

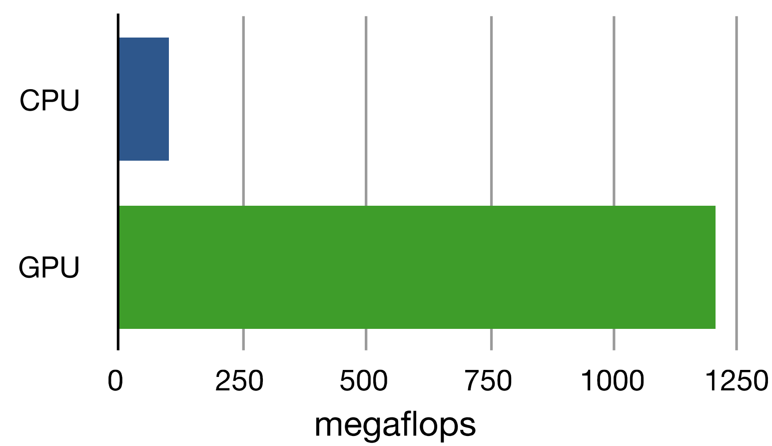
Bandwidth

Floating Point Performance

theoretical memory bandwidth



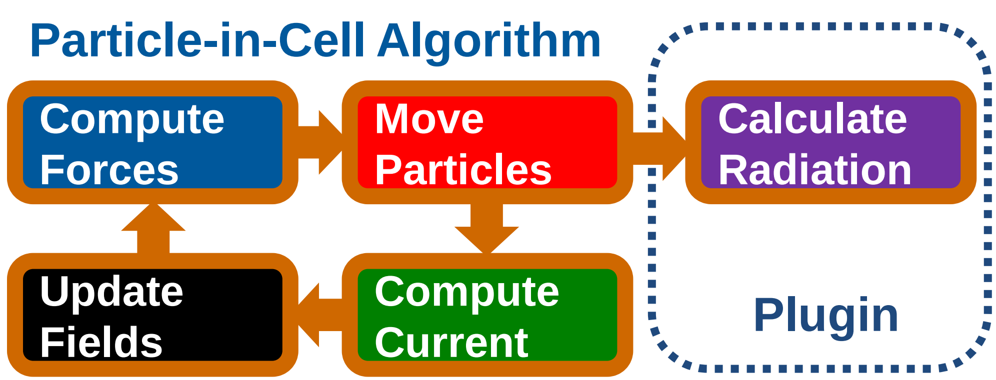
double-precision floating point performance



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

PIConGPU picongpu.hzdr.de

Radiation code implemented as a plugin for PIConGPU



Free Software
Free as in Freedom

Available for download.
It‘s open source!

- Relativistic 3D3V Yee-Lattice
- Boris & Vay Pusher
- Villasenor-Buneman, Esirkepov and Lehe Maxwell solver
- Particle Shapes NGP / CIC / TSC / PCS
- HDF5, Live Visualization

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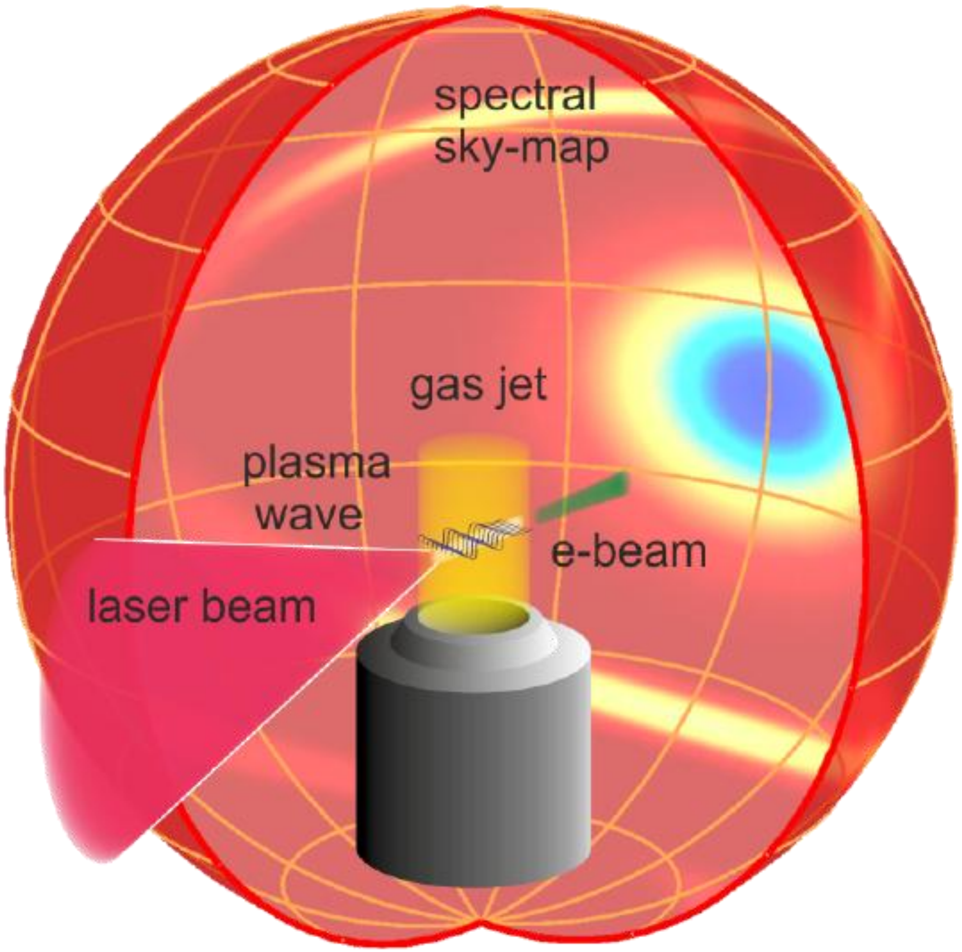
PIConGPU plugin fully integrates classical radiation emission

- Calculates online the spectra of all particles in a 3D-PIC simulation.
- Discrete Fourier Transform enables logarithmically-scaled wavelengths from IR to X-ray.
- Arbitrary number of directions and wavelengths can be computed.

  → spectral sky-maps

- Coherence and polarization of radiation is fully supported!



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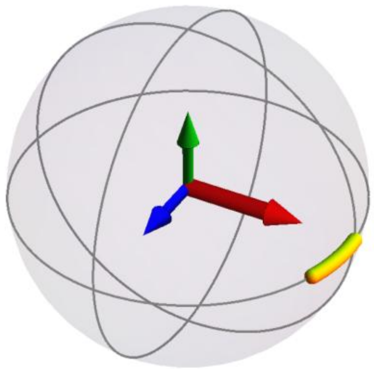
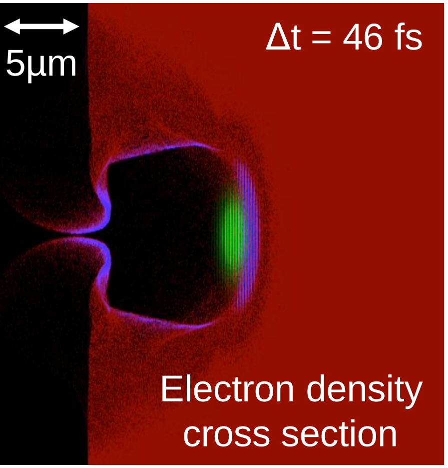
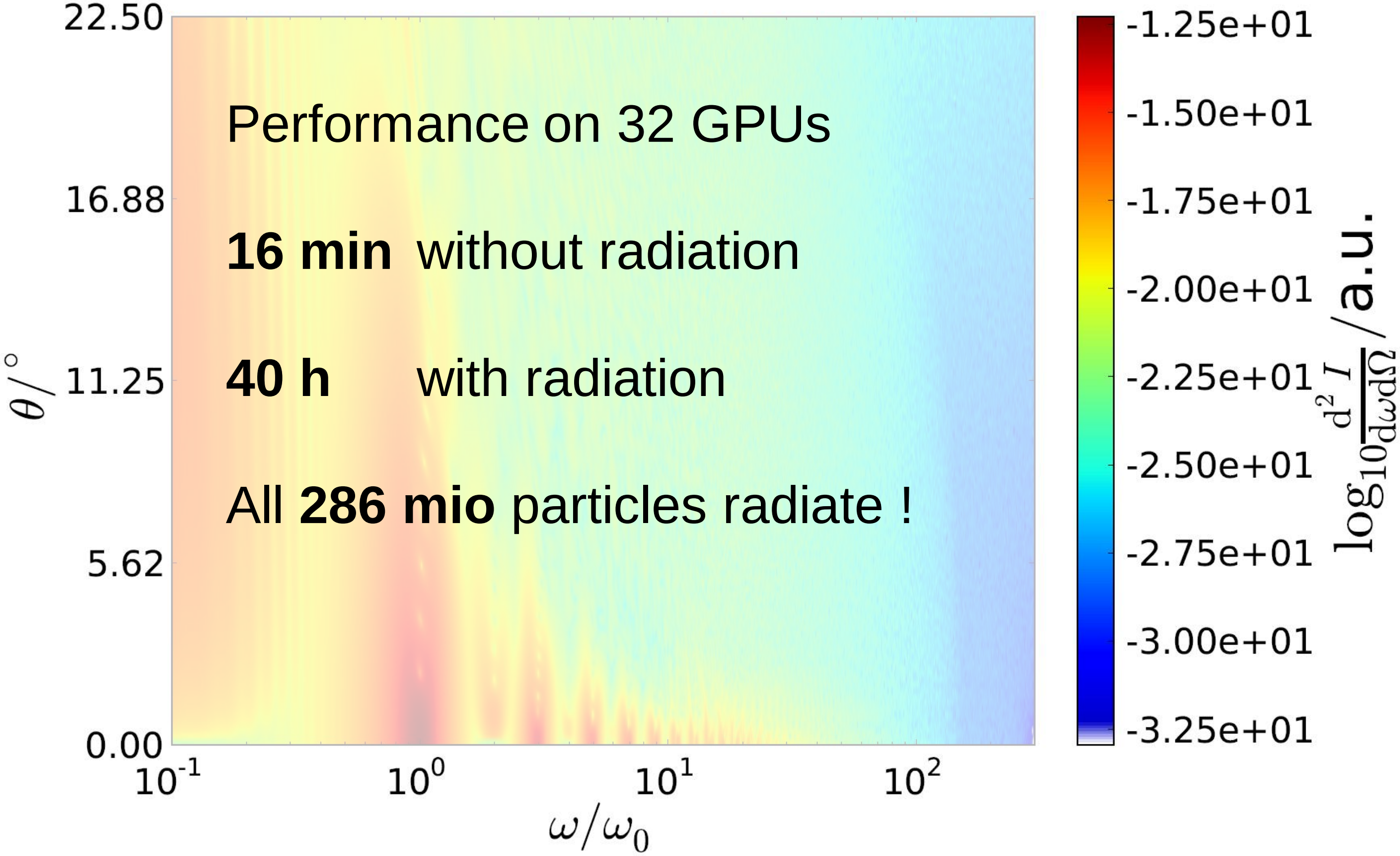
Exploring radiation from Laser-Wakefield acceleration





128 spectra à 2048 frequencies



Performance on 32 GPUs

16 min without radiation

40 h with radiation

All **286 mio** particles radiate !

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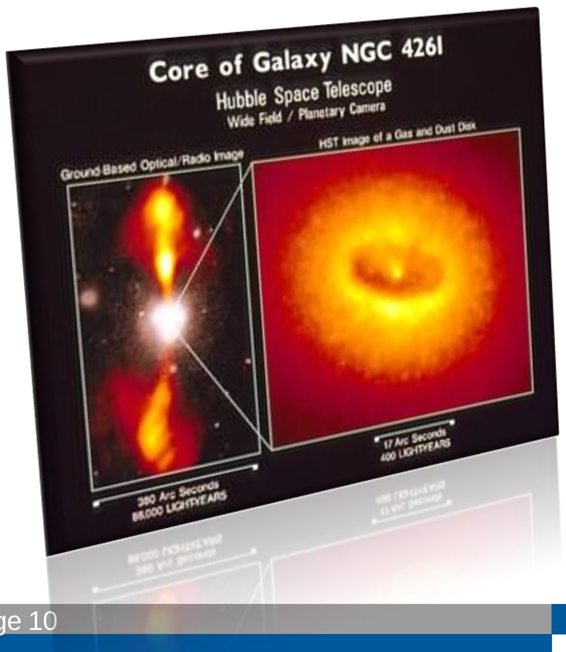
Scaling up to petaflop performance

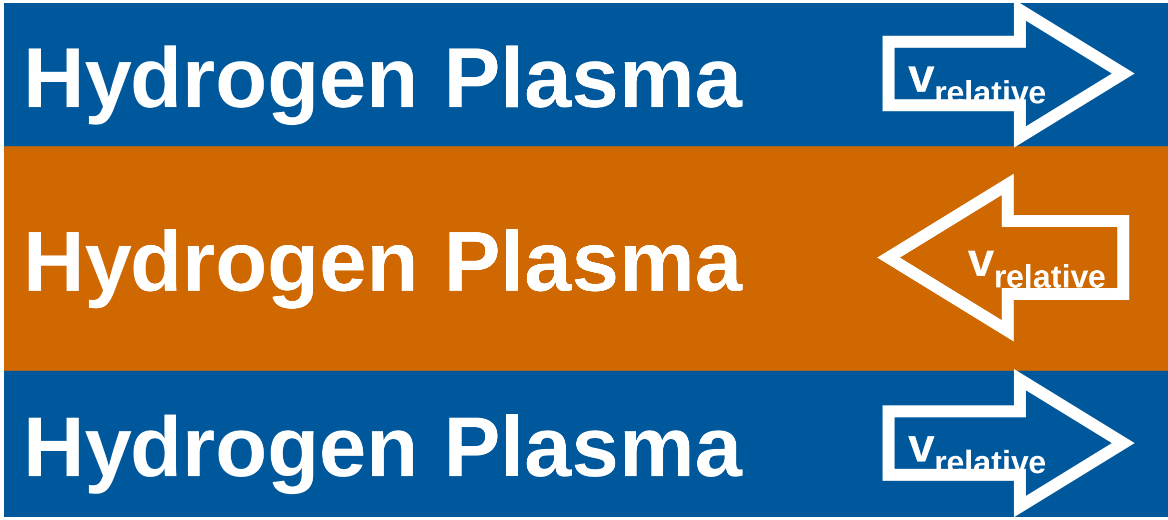
Radiation emitted by the Kelvin-Helmholtz instability

2nd largest supercomputer on earth

TITAN Cluster at
Oak Ridge National Laboratory

Important in astrophysical jets





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Scaling up to petaflop performance

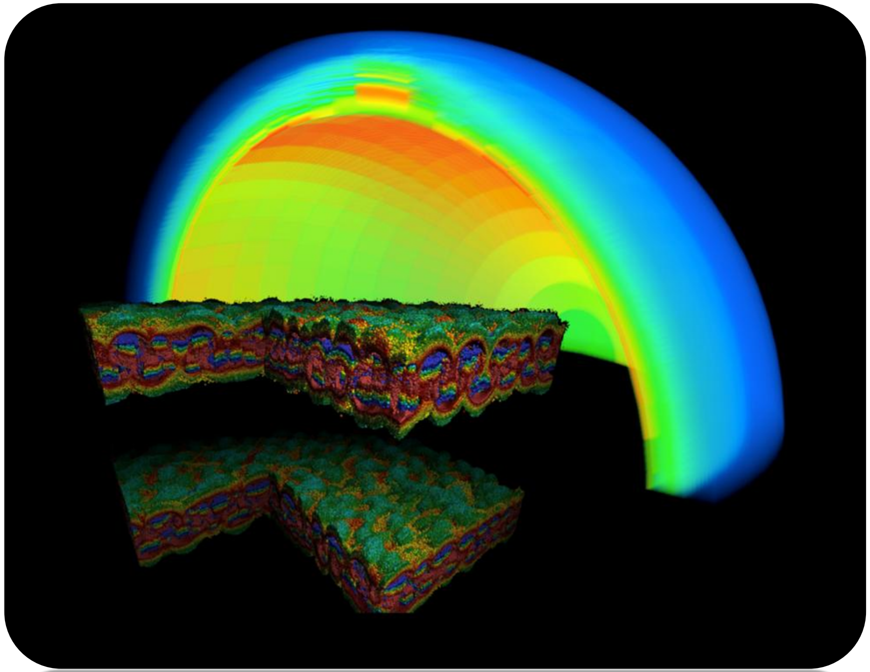
Radiation emitted by the Kelvin-Helmholtz instability

Peak performance

7.2 PFLOP/s

(performance at double precision)

on 18,432 GPUs



Grid 8000 x 768 x 768 cells

Particles 2 e^- and 2 p^+ per cell
$37.7 \cdot 10^9$ electrons

Radiation 481 directions
512 frequencies

18432 GPUs
(near all GPUs on TITAN)

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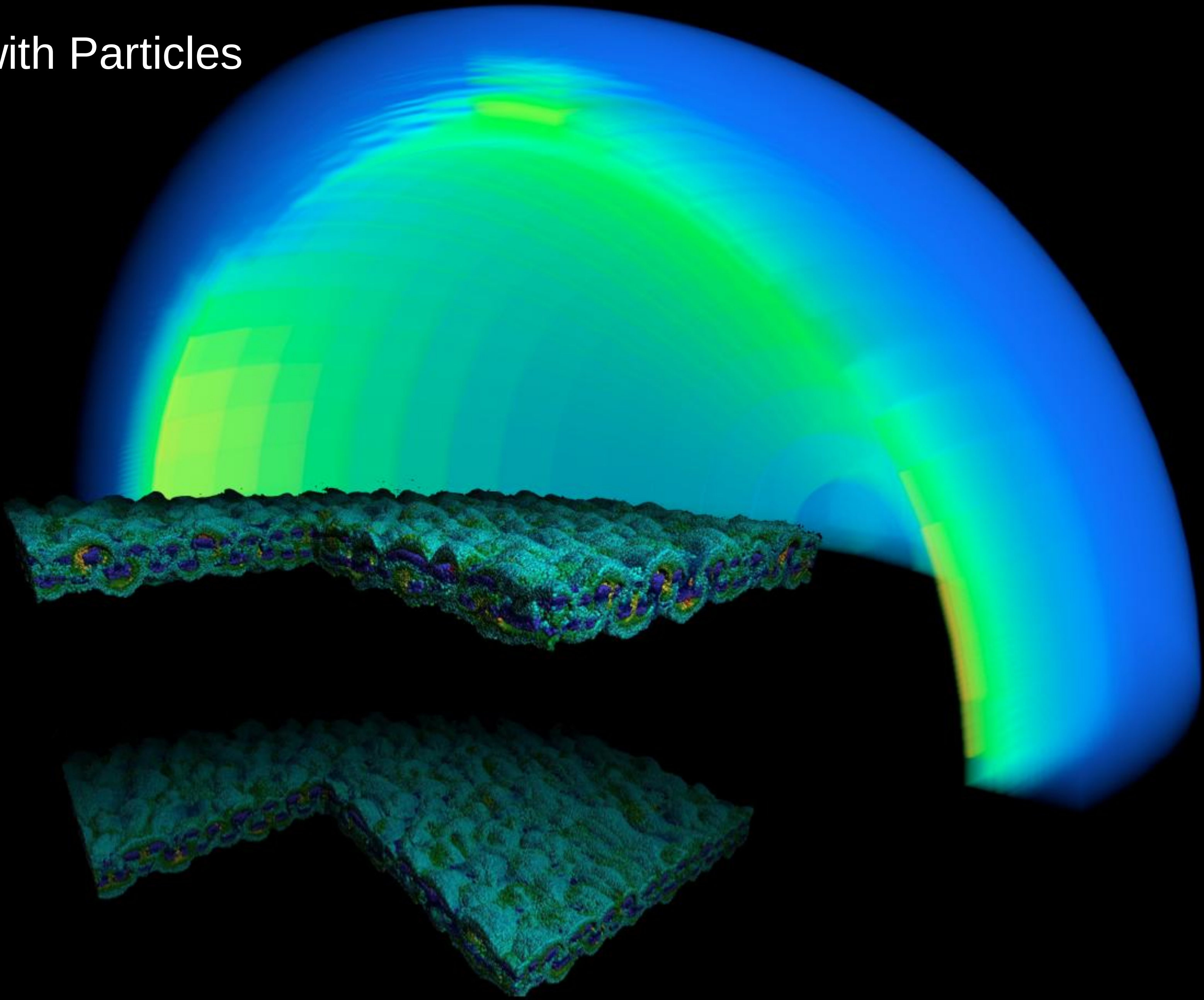
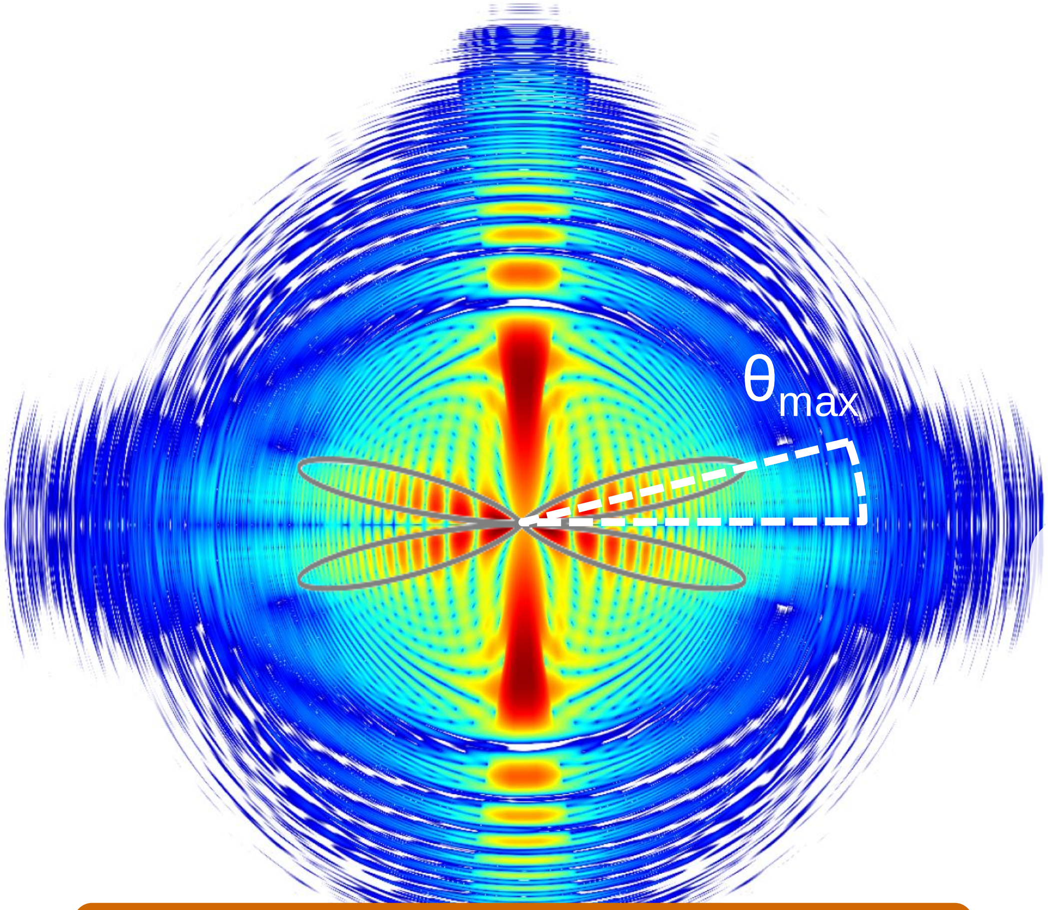
Skymap with Particles



What do we see in this huge amount of data?



$$\theta_{\max} = \cos^{-1}\left[\frac{1}{3\beta}\left(\sqrt{1+15\beta^2}-1\right)\right]$$

After 500 time steps

- K-plane along a great circle
- Logarithmic-scale (0.014 –14 ω_{pe})
- Lots of structure in spectrum

- Boost pattern of synchrotron radiation in direction of the plasma flow
- Angle between coils gives information on relativistic velocity

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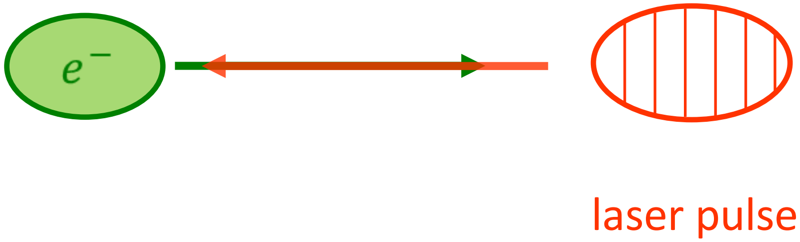
Apart from investigating the dynamics of big roaring plasmas…

All these GPU-driven techniques are great for designing light sources !

Traveling-**W**ave **T**homson-**S**cattering (TWTS)

Using pulse-front tilted petawatt lasers in side scattering geometries for arbitrarily long interaction distances



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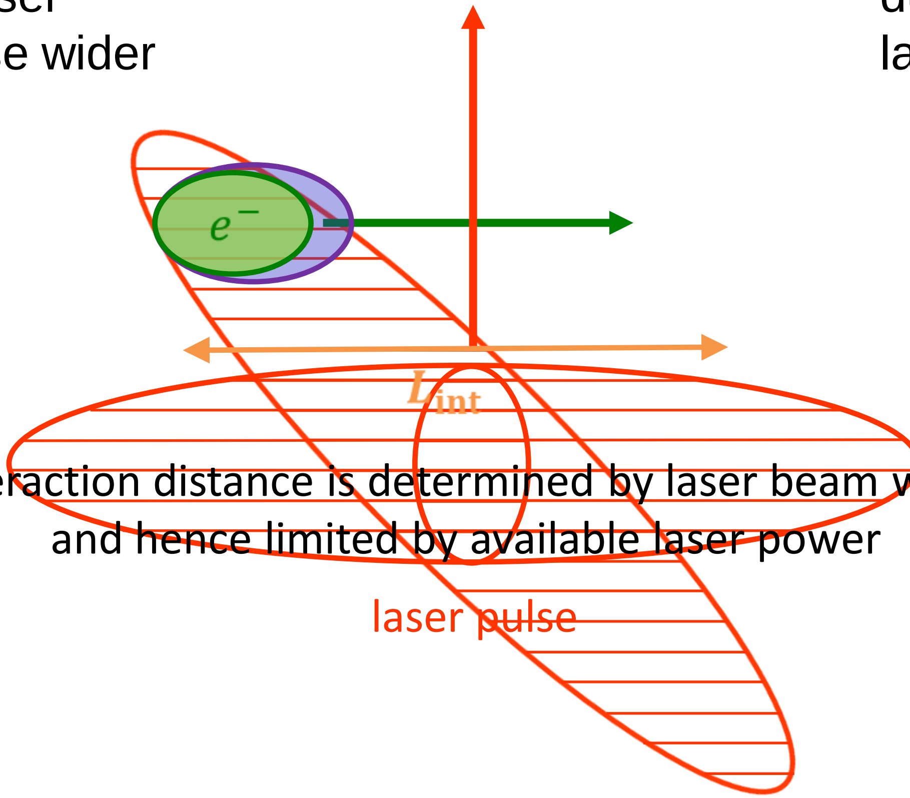
Traveling-**W**ave **T**homson-**S**cattering (TWTS)

Using pulse-front tilted petawatt lasers in side scattering geometries for arbitrarily long interaction distances

1) Reduce the local intensity of a high power laser by making the pulse wider

2) Increase interaction duration by tilting the laser pulse front



Interaction distance is determined by laser beam width and hence limited by available laser power

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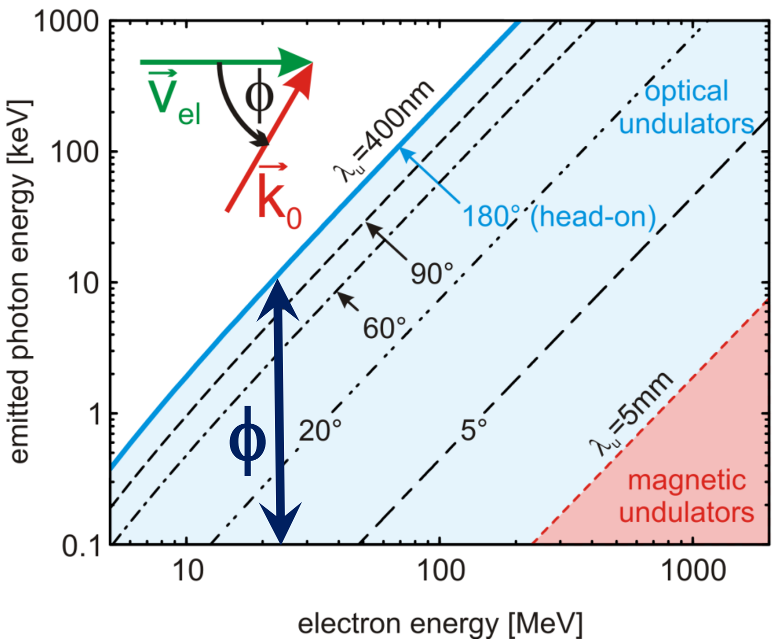
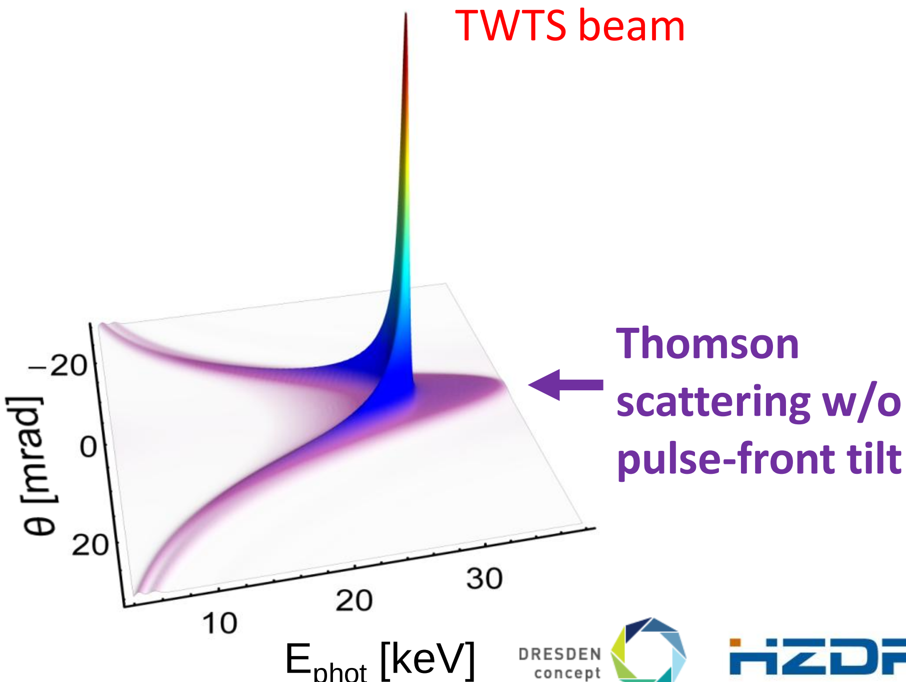
TWTS gives control over scattered photon energy and bandwidth



Vary the scattered photon energy over orders of magnitude by changing the interaction angle

$$\omega_{sc} = \frac{2\gamma^2(1-\cos\phi)\omega_{laser}}{(1+a^2/2)}$$



By increasing the laser pulse width, the spectral photon density concentrates in a single peak

$$\frac{\Delta\omega_{sc}}{\omega_{sc}} \propto \frac{1}{N_{osc}} = \frac{\lambda_0}{w_{Laser}\tan(\phi/2)}$$

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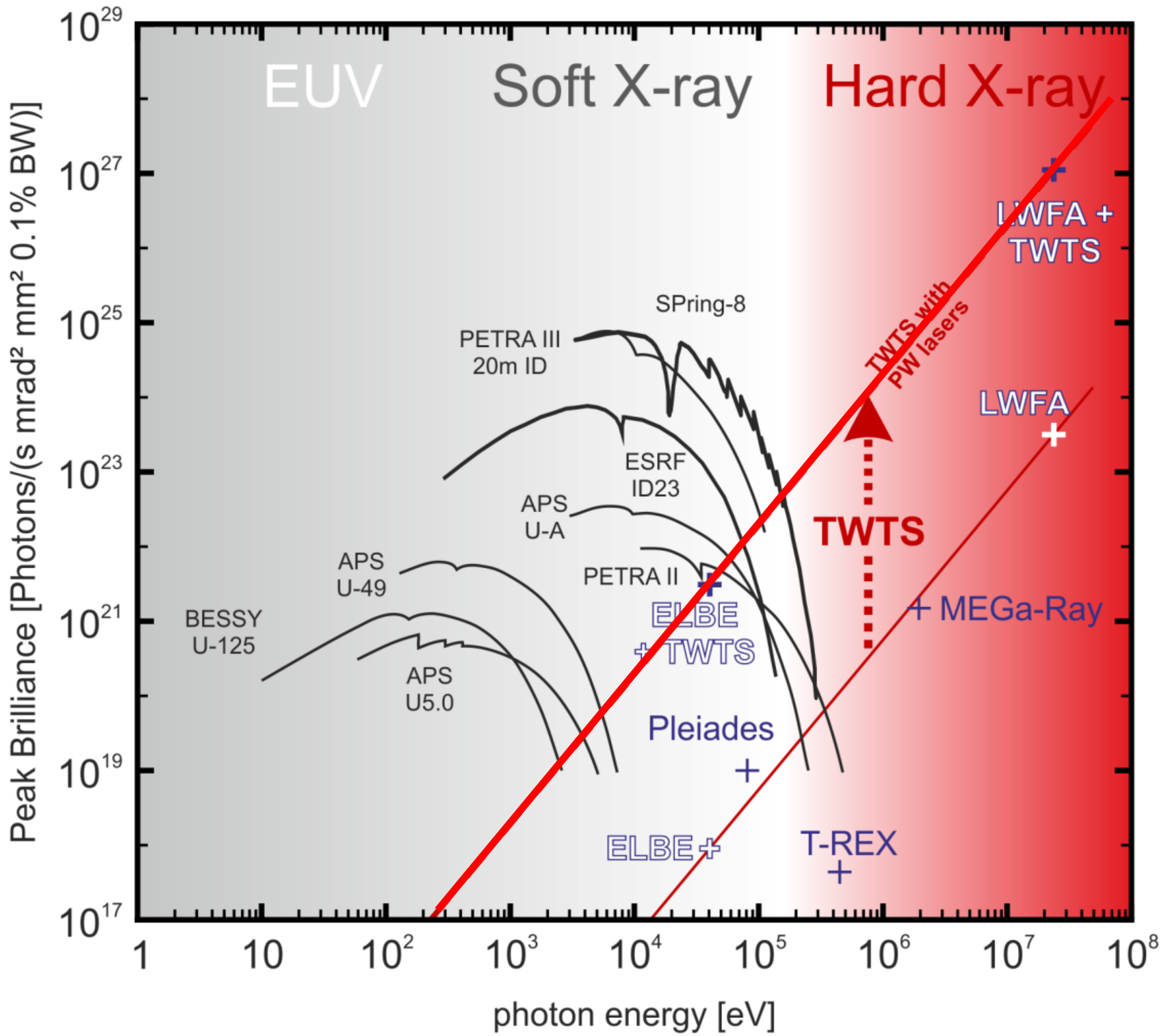
Brilliances of TWTS sources are comparable to 4th gen. synchrotrons



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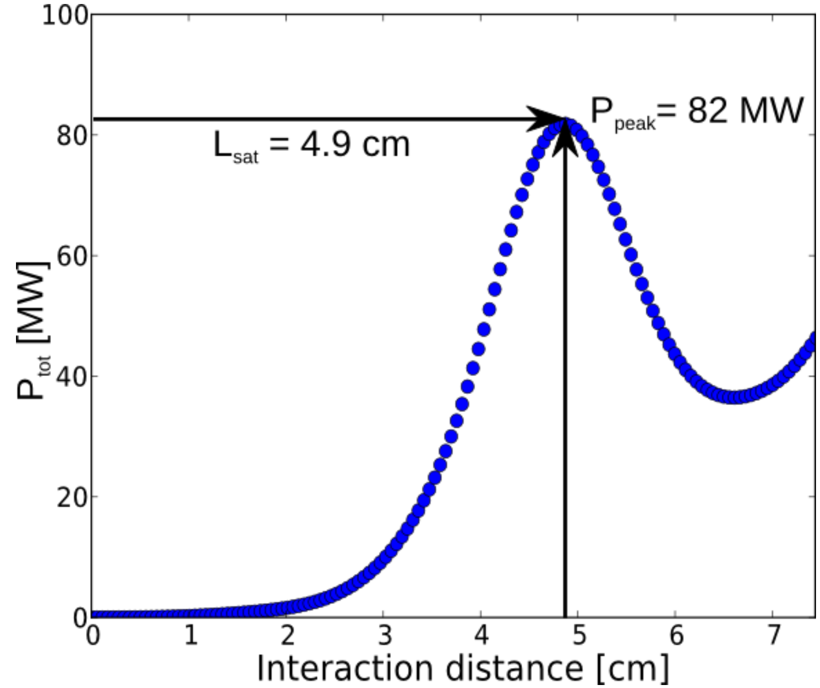
TWTS properties enable compact free-electron laser

Parameter	TWTS
scattered wavelength [nm]	6.0
electron energy [MeV]	40
bunch charge [nC]	1
peak current [kA]	2.5
norm. emittance (mm mrad)	0.6
rel. energy spread (slice)	0.1%
undulator parameter (a_0 or K)	0.5
laser power [TW]	530
interaction angle [deg]	10
saturation length [cm]	4.9
peak power [MW]	82

We have a complete analytical model for TWTS-FEL.



Compact free electron laser with ELBE-like electrons!

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Upcoming talks

„*Single-shot fs electron bunch diagnostics*“

14:40, Today
Omid Zarini

„*Laser-Thomson backscattering source at HZDR*“

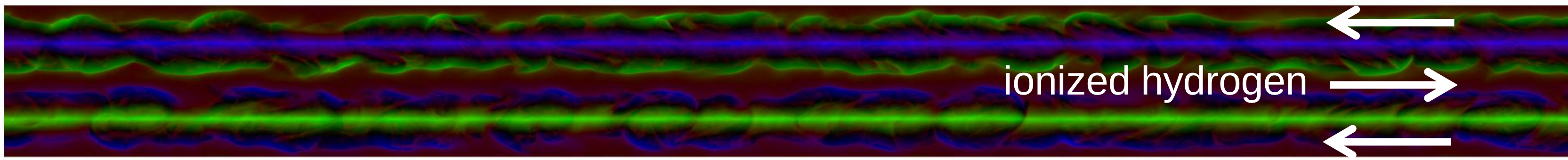
11:30, Tomorrow
Axel Jochmann

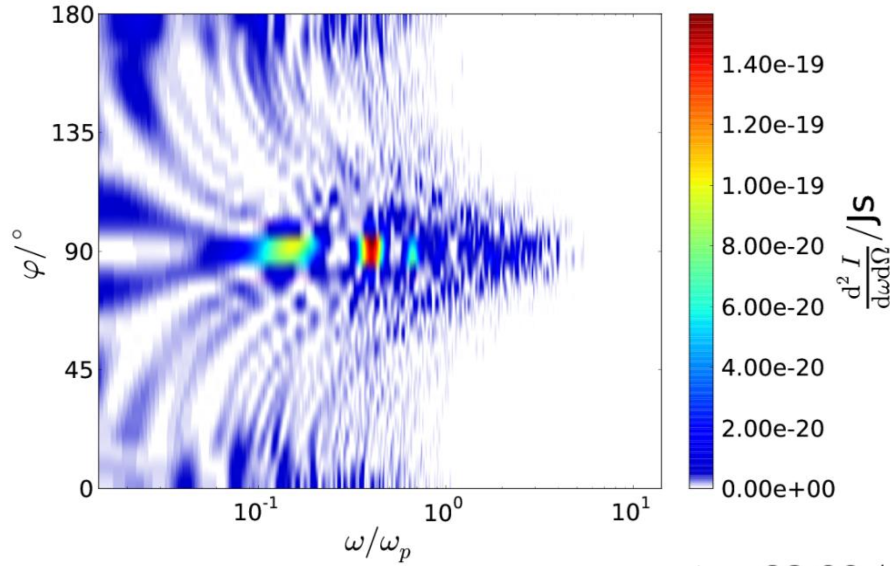
Summary

- Radiative particle-in-cell simulations allow to calculate the emitted radiation of laser plasma interactions **from all particles in a simulation**.
- Our GPU-only simulation code PIConGPU makes it possible to explore plasma radiation from **IR to X-ray wavelengths** across **„sky maps“** including **coherence effects**.
- **Example 1** Laser-wakefield accelerator
- **Example 2** Largest KHI-PIC simulation ever performed

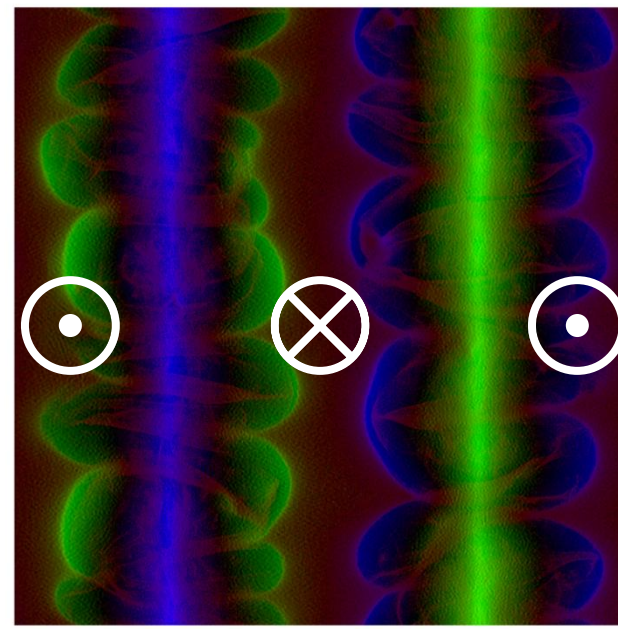
  7.2 PFLOPS double precision
  1.4 PFLOPS single precision

Time-resolved spectra can be correlated to particle dynamics.





t = 62,00 / ω_p



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