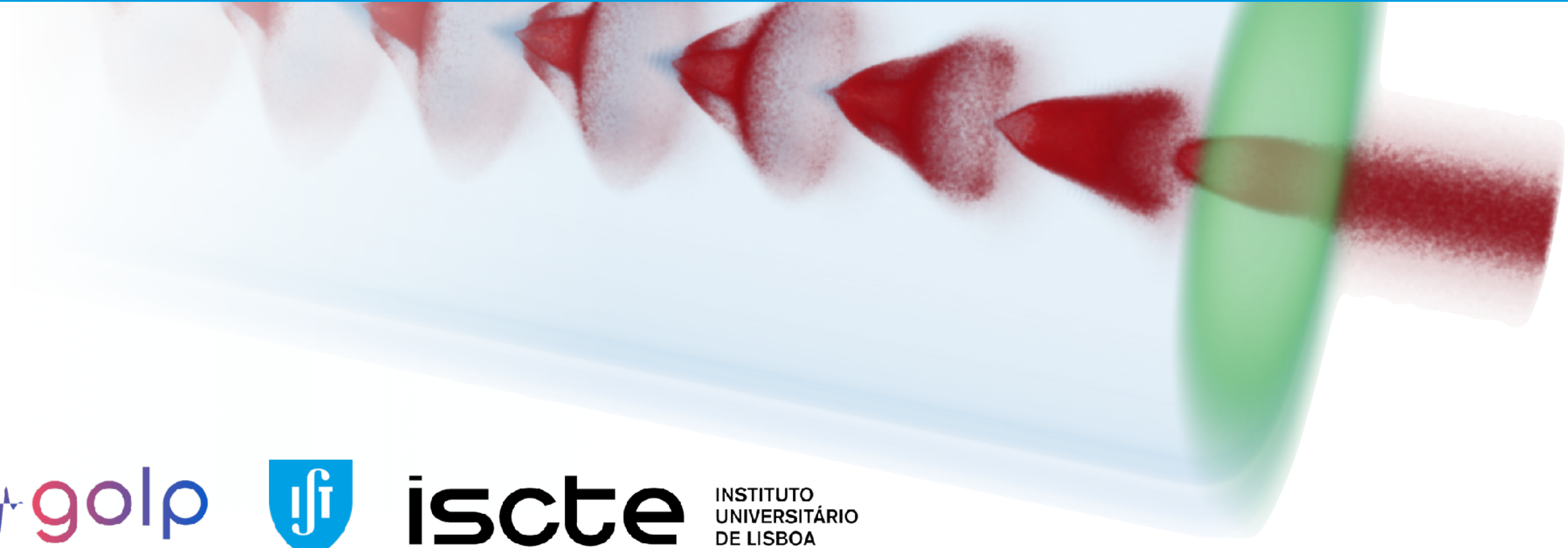
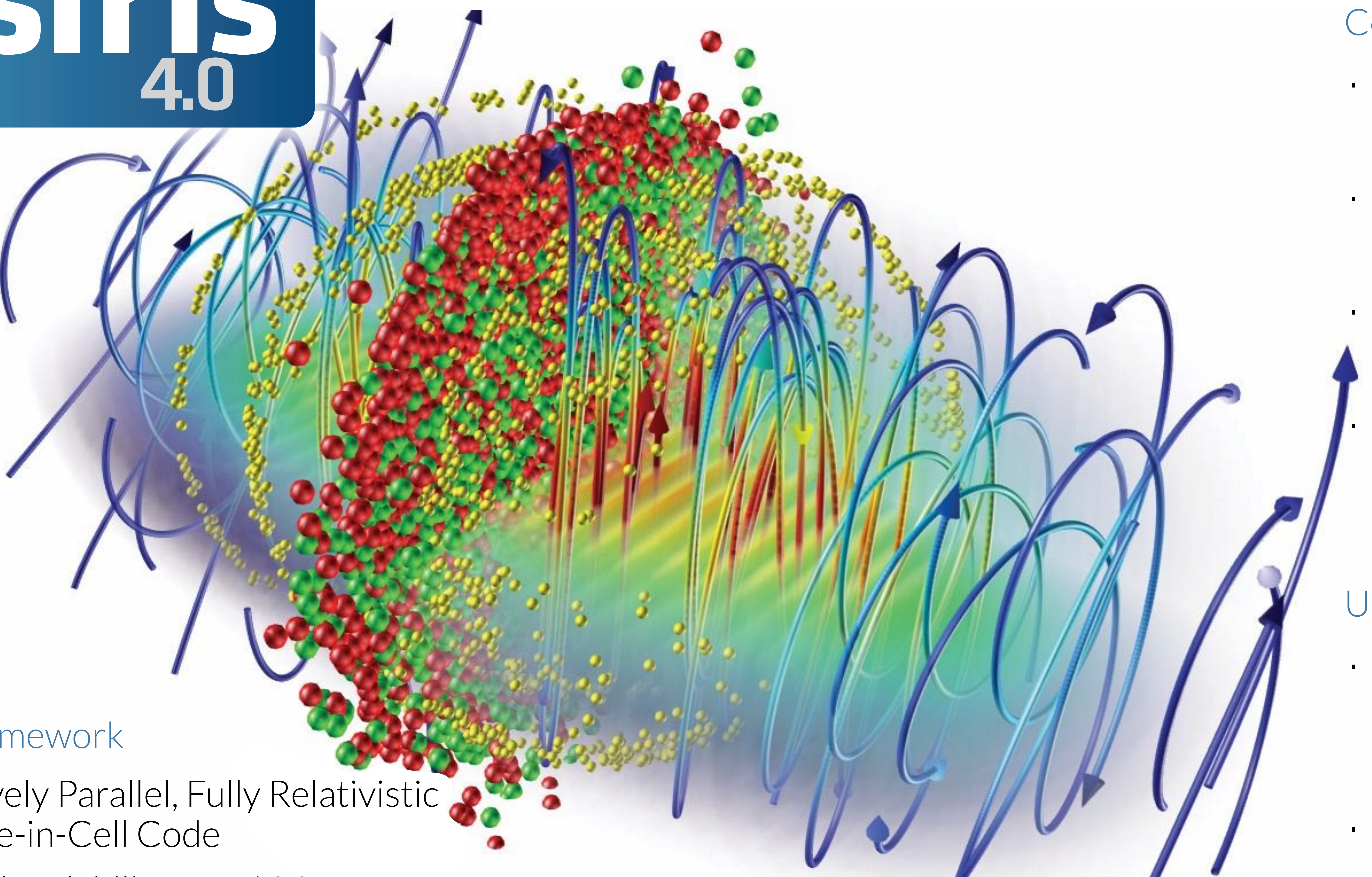
Simulation tools for plasma-based accelerators and colliders



Ricardo Fonseca | HEP European Strategy Discussion | LIP, January 20, 2025

Osiris 4.0

Committed to open science



OSIRIS framework

- Massively Parallel, Fully Relativistic Particle-in-Cell Code
- Parallel scalability to > 1 M cores
- Explicit SSE / AVX / QPX / Xeon Phi / ARM Neon / CUDA support
- **Extended physics/simulation models**

Community driven research

- 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

UCLA TÉCNICO LISBOA

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Full scale simulations on the most advanced HPC resources

TÉCNICO LISBOA

Exascale developments

- New cross-platform codebase
  - Support for next-gen HPC Exascale architectures
    - **x86 / ARM** cpus
    - **NVIDIA**, **AMD** and **Intel** gpus
    - **Intel** fpga
- Same algorithm, multiple toolkits
  - Micro-spatial domain decomposition
  - **OpenMP** + **vectorization** for cpu targets
  - **CUDA**, **ROCm** and **SYCL** for gpu/fpga targets
  - Unified top-level interface
- Current development
  - MPI implementation
  - Expected operational by Q1-2025
  - Continuous integration of OSIRIS features into new codebase

Deucalion
MACC, Portugal

Marenostrum 5
BSC, Spain

Leonardo
Cineca, Italy

Full-scale modeling of AWAKE @ CERN
- Ran on Marenostrum 4 @ BSC
- 17664 cores
- ~ 3M core×h

Simulation Parameters
- Simulation by A. Helm
- Simulation box: 75 mm × 13 mm × 13 mm
- Propagation distance; 10 m
- 678 297 600 cells
- ~ 10^{10} particles
- > 10^{6} time-steps

Reduced models enable speedup while preserving relevant physics

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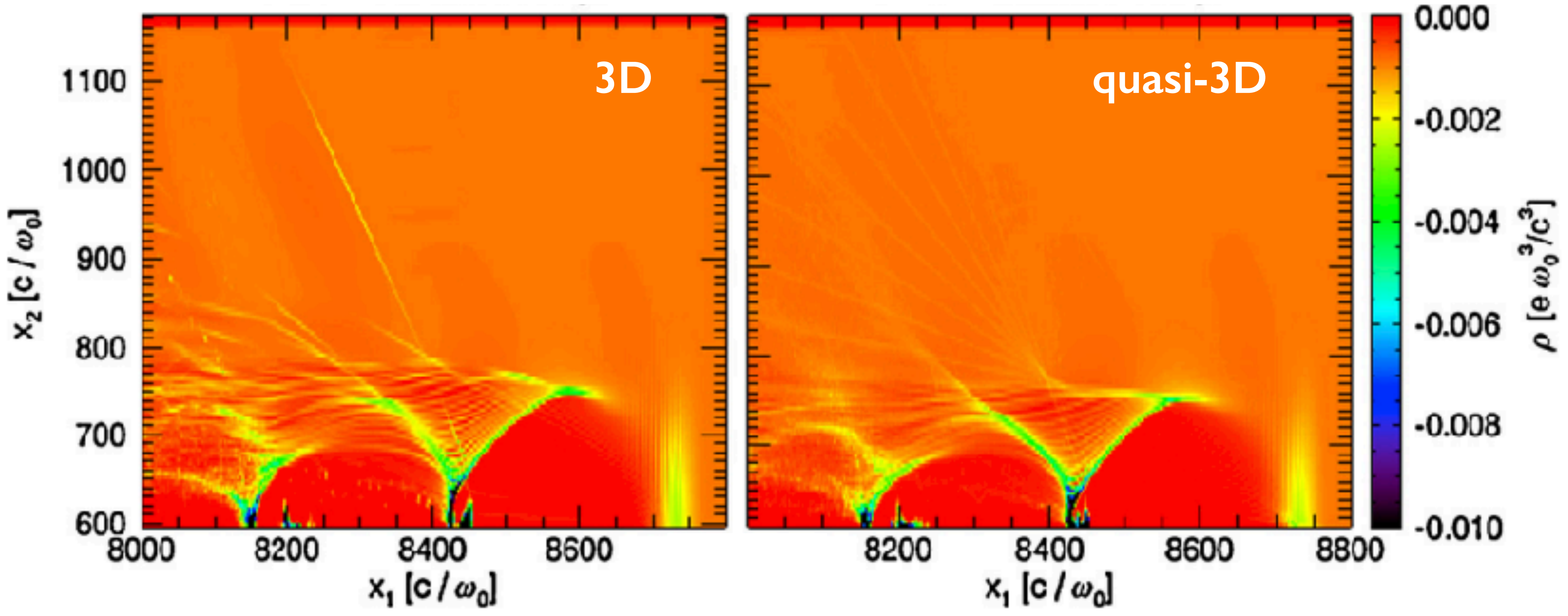
OSIRIS quasi-3D[1]

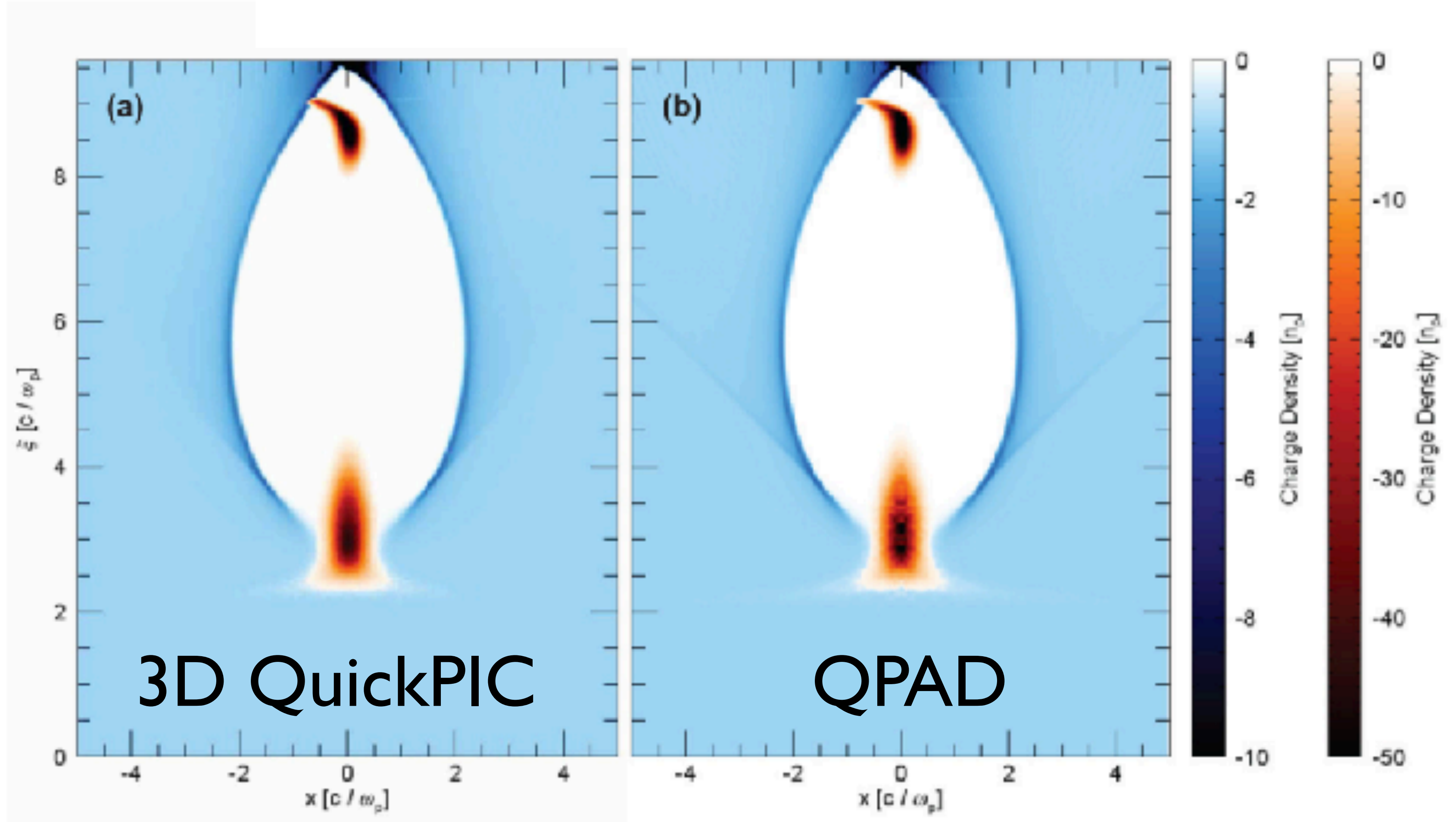
- Fields and currents are expanded in cylindrical modes



- Takes advantage of the OSIRIS framework (QED, ionization, and other relevant modules)
- Versatile: capable of simulating beam-driven or laser-driven plasma accelerators, as well as physics of beam-beam collisions.
- Approximates 3D physics at a computational cost comparable to 2D

Quasi-static codes: QuickPIC[2] and QPAD[3]

- Primarily used for beam-driven wakefield accelerators
- Provides substantial speedup compared to full PIC simulations
- Relies on the quasi-static approximation, where beam evolution is much slower than the plasma evolution
- Codes include:
  - QuickPIC: 3D quasi-static
  - QPAD: Quasi-3D geometry / quasi-static approximation



1 A. Davidson *et al.*, Journal of Computational Physics **281**, 1063 (2015) 2 W. An *et al.*, Journal of Computational Physics **250**, 165 (2013) 3 F. Li *et al.*, Computer Physics Communications **261**, 107784 (2021)

QED-PIC and its application to simulate the interaction point

QED processes coupled to PIC

Osiris 4.0

1) Classical Radiation recoil

M. Vranic *et al.*, CPC **204** (2016), J. L. Martins *et al.*, PPCF **58** (2016)

2a) Non-linear Compton and Non-linear Breit-Wheeler

T. Grismayer *et al.*, POP **23** (2016), T. Grismayer *et al.*, PRE **95** (2017)

2b) Particle merging algorithm

M. Vranic *et al.*, CPC **191** (2015)

3) Linear Compton scattering

F. Del Gaudio *et al.*, JPP **86**(5) (2020), F. Del Gaudio *et al.*, PRL **125** (2020)

4) Bremstrahlung and Bethe-Heitler

B. Martinez et al, arXiv:2406.02491 (2024)

5) Euler-Heisenberg solver (quantum vacuum polarisation)

T. Grismayer *et al.*, NJP **9** 095005 (2021)

6) Heuristic photon emission and pair production for astro setups

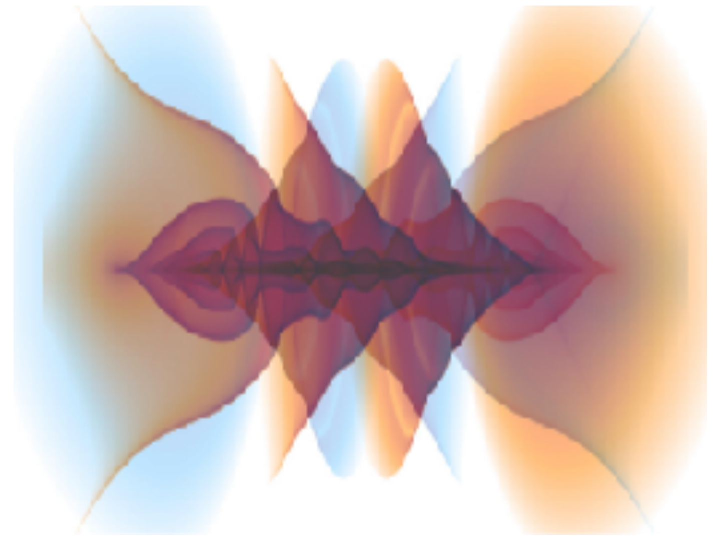
F. Cruz *et al.*, ApJL, **919** L4 (2021) and F. Cruz *et al.*, ApJ, **908** (2021)

Interaction point physics studies with OSIRIS

Disruption beam physics

Disruption in e+e- beams

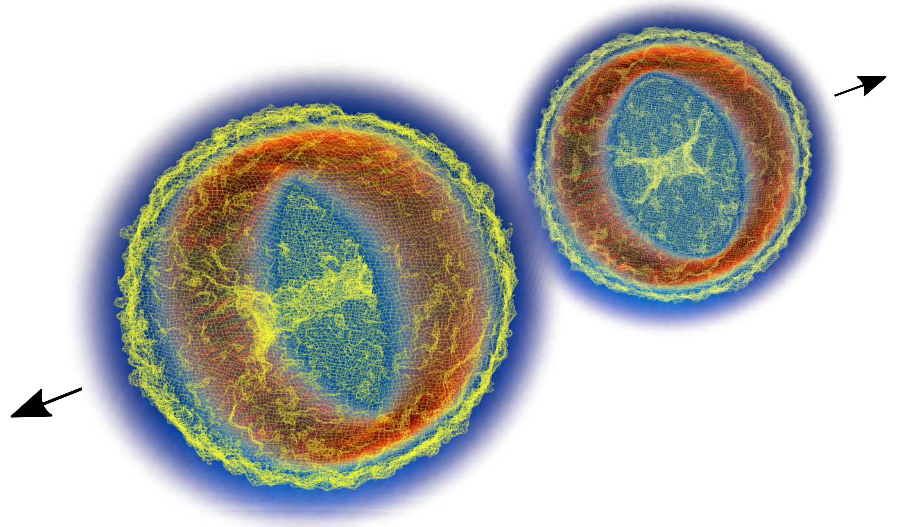
A way of increasing the luminosity



Platform to study strong field QED

Probe non-perturbarive SFQED

V. Yakimenko et al., PRL **122**, 190404 (2019)



Electron-electron collision

Regime where disruption and SFQED couple

Guinea-Pig inadequate for this regime

W. Zhang et al., arXiv:2412.09398 (2024)