OSIRIS 2030: Strategy for future plasma-based acceleration modeling

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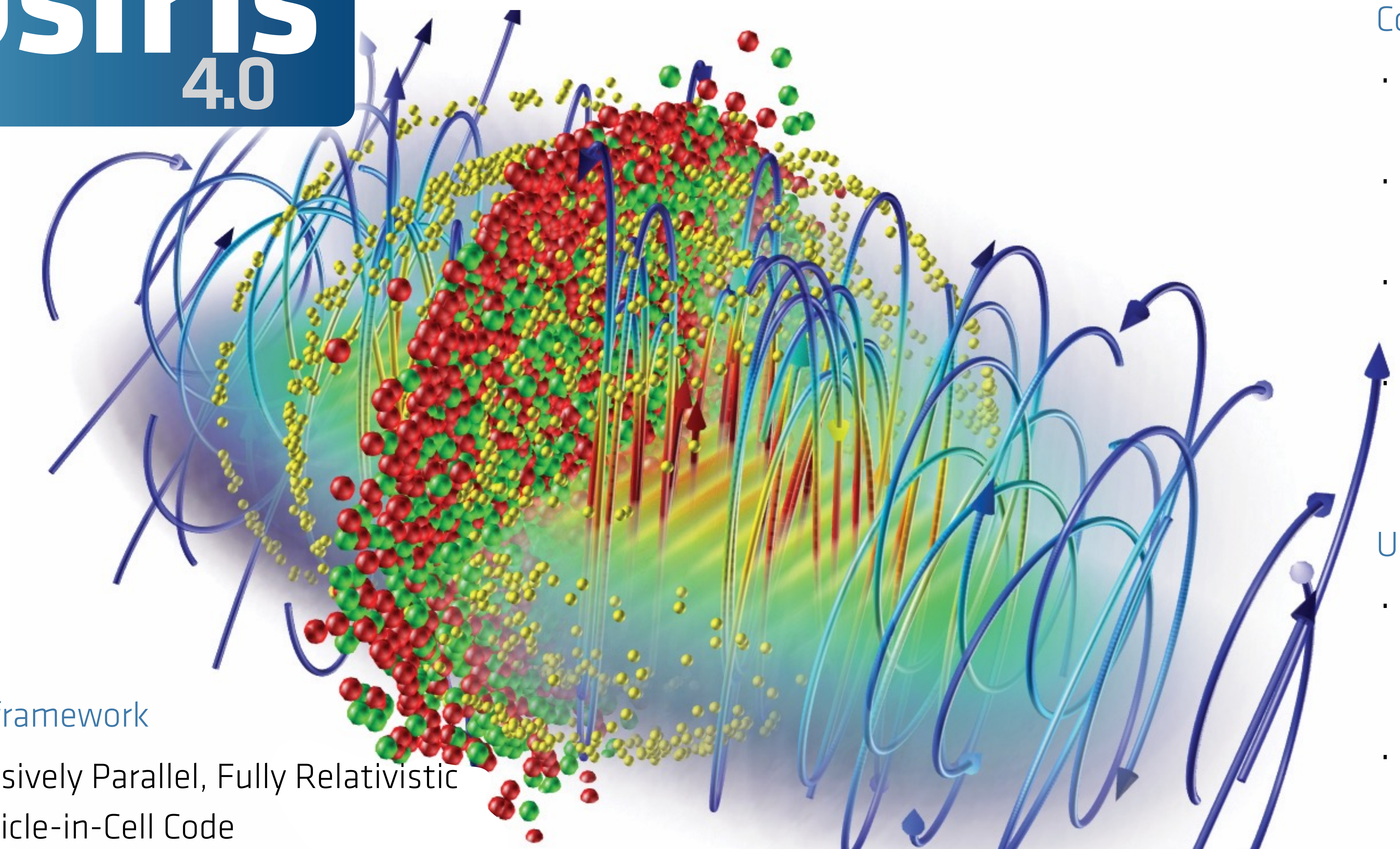
OSIRIS 4.0

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

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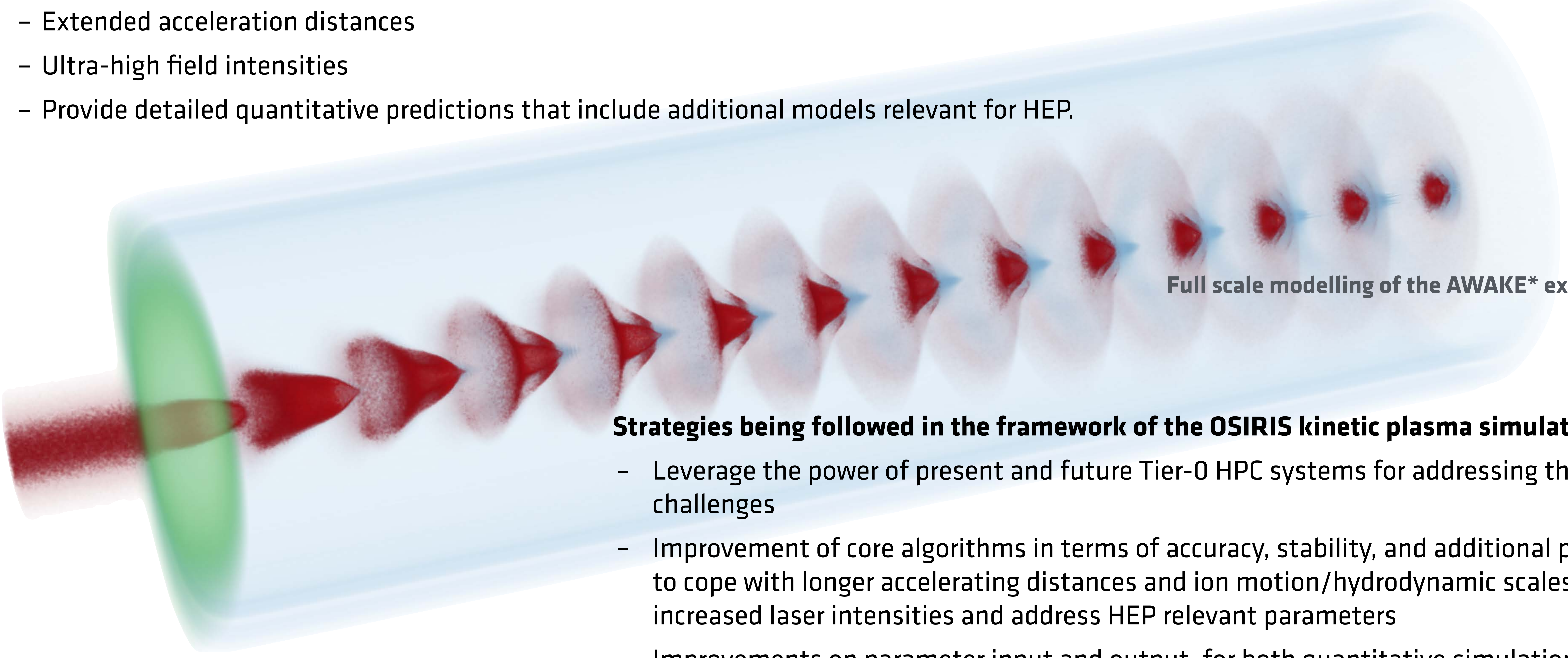
Challenges & Opportunities leading up to 2030

Over the next 10 years simulation tools for plasma based accelerators will need to address additional challenges and opportunities:

- Extended acceleration distances
- Ultra-high field intensities
- Provide detailed quantitative predictions that include additional models relevant for HEP.



Full scale modelling of the AWAKE* experiment

Strategies being followed in the framework of the OSIRIS kinetic plasma simulation code

- Leverage the power of present and future Tier-0 HPC systems for addressing these challenges
- Improvement of core algorithms in terms of accuracy, stability, and additional physics to cope with longer accelerating distances and ion motion/hydrodynamic scales, and increased laser intensities and address HEP relevant parameters
- Improvements on parameter input and output, for both quantitative simulations with one-to-one comparison with experimental setups and use in integrated modeling toolchains

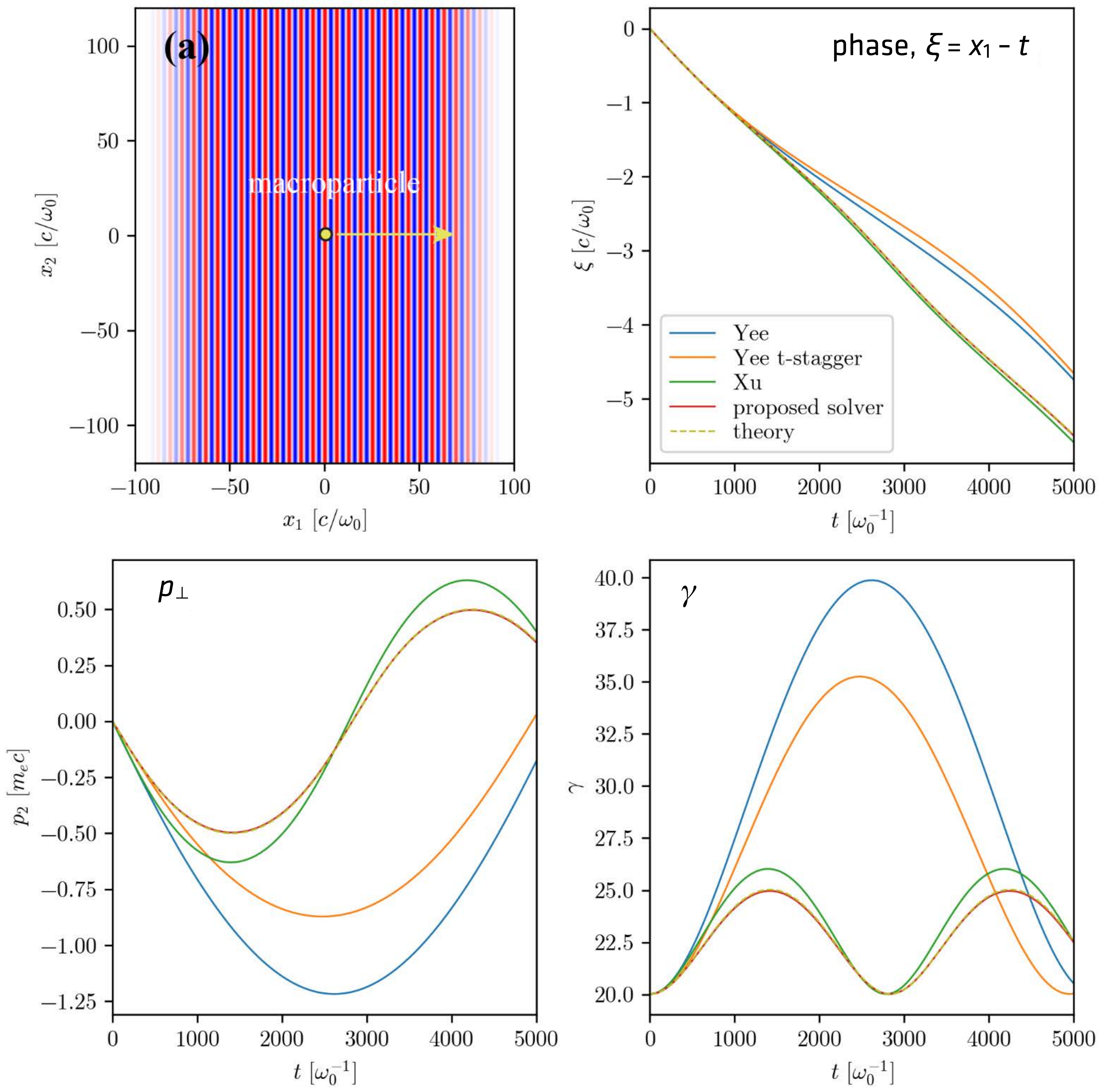
* E. Adli et al, **Nature** 561, 363-368 (2018)

A new field solver for accurate modeling of relativistic particle-laser interactions

- **Numerical errors can arise when particles with relativistic energies interact with intense EM fields that have phase velocities near the speed of light**
  - Dispersion errors in the phase velocity of the wave
  - Staggering in time between the electric and magnetic fields and between particle velocity and position
  - errors in the time derivative in the momentum advance.

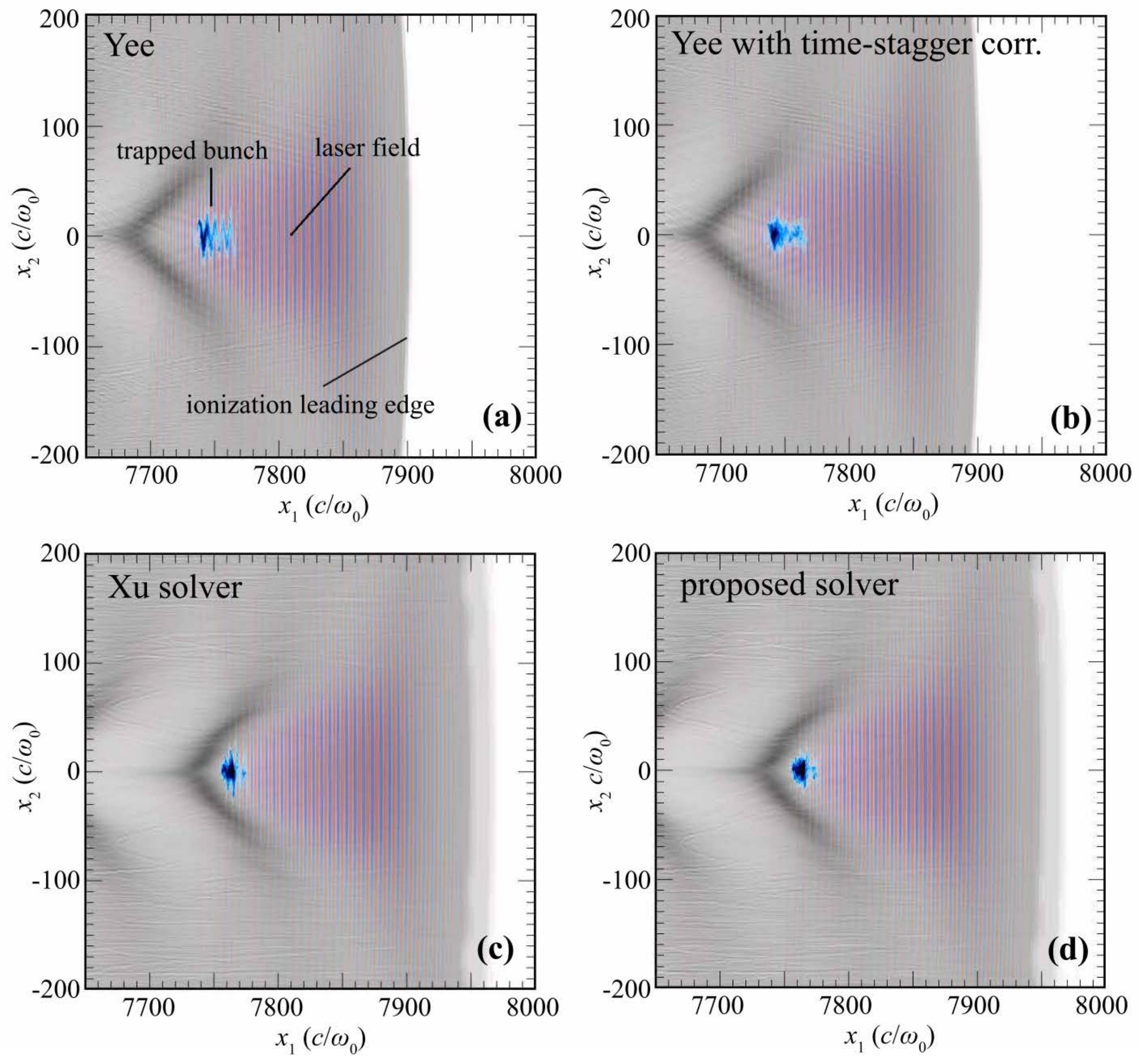
- **New field solvers with different k-space operators in Faraday's and Ampere's law**
  - Dispersion errors and magnetic field time-staggering errors in the particle pusher can be simultaneously removed for electromagnetic waves moving primarily in a specific direction

Single particle trajectory
γ_0 = 20, a_0 = 0.5



Higuera-Cary pusher is used in all the simulations

2D LWFA Simulation
Ionization injection



Boris pusher was used for all cases. The ionization injected bunch (blue) interacts with the driver laser pulse

Li. F., et. al., CPC **258**, 107580 (2021)

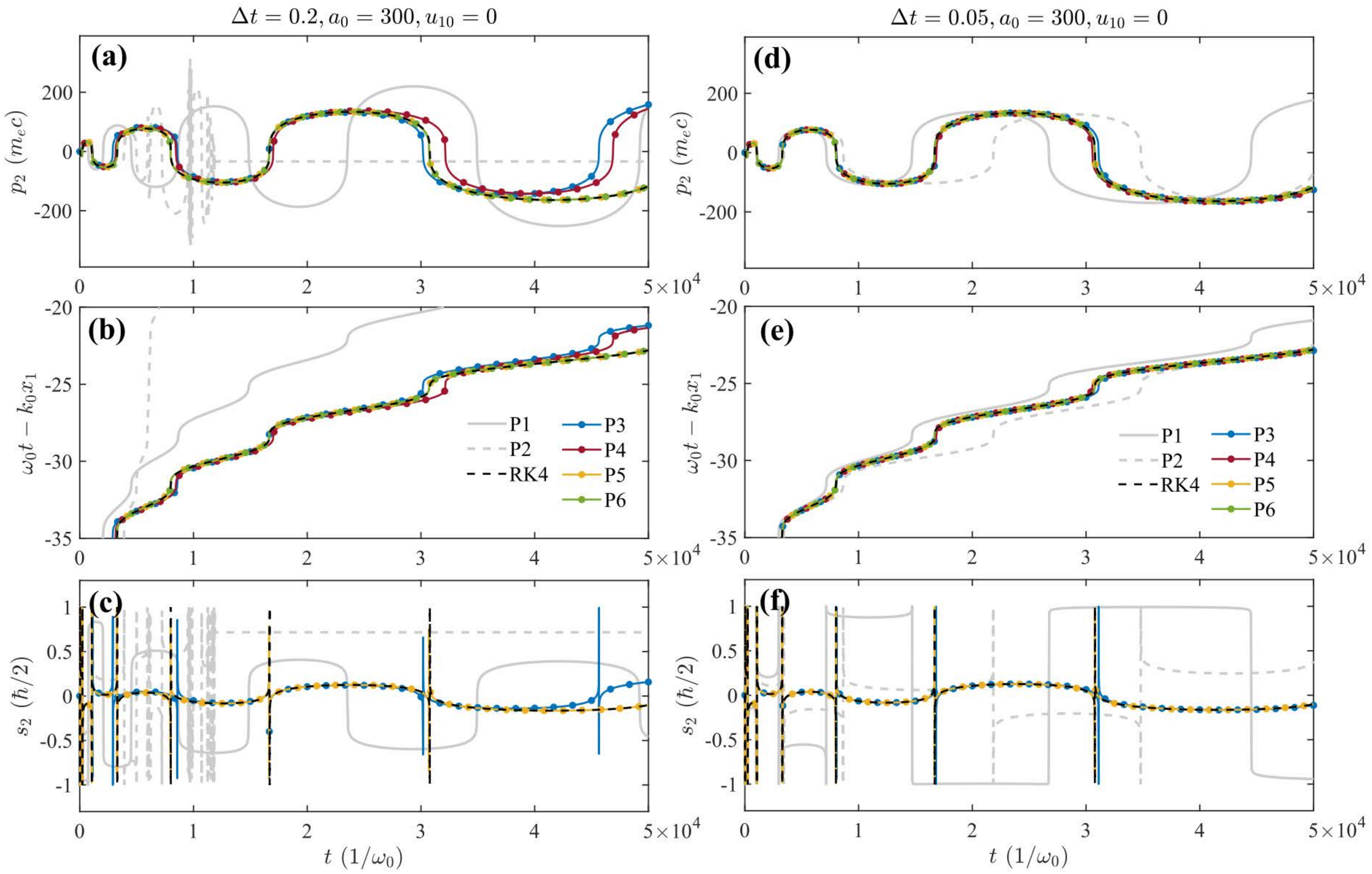
Accurately simulating nine-dimensional phase space of relativistic particles in strong fields

- **With multi-PW laser systems coming online laser intensity will soon exceed 10^{23} W/cm^2**
  - New physics coming into play, such as plasma-based acceleration in strong-field regime
  - Regular pushers based on the splitting method fail to achieve high-fidelity simulation in strong fields

- **High demand for an accurate, radiation-reaction-incorporated and 9D (including spin) particle pusher**
  - New pusher based on analytical solutions to:
  - Equation of motion with only Lorentz force
  - Landay-Lifshitz equation (semi classical radiation reaction model)
  - Bargmann-Michel-Telegdi equation for spin

Li. F., et. al., CPC **438**, 110367 (2021)

Single particle motion in an ultra-intense laser field (a0 = 300)



P1 = Boris (p) + Leapfrog (x) + Vieira (s) + split (RR)
P2 = Higuera-Cary (p) + Leapfrog (x) + Vieira (s) + split (RR)
P3 = Analytic (p) + Leapfrog (x) + Vieira (s) + split (RR)
P4 = Analytic (p, RR) + Leapfrog (x) + Vieira (s)
P5 = Analytic (p, x, s) + split (RR)
P6 = Analytic (p, x, RR, s)

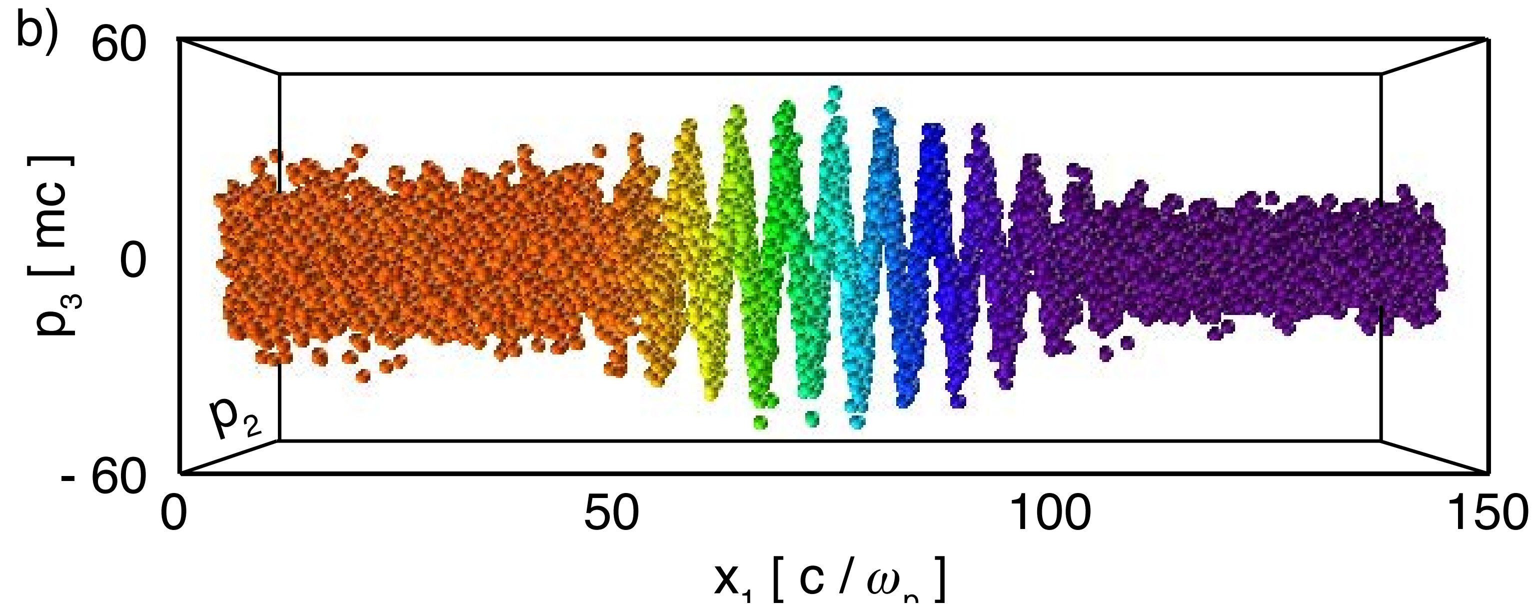
Modelling ultra-high intensity processes

What developments are necessary?

Adding classical radiation reaction

- Modelling electron beam slowdown in scattering configurations
- Modeling other configurations where only a fraction of electrons may be subject to RR but where this can alter qualitative behaviour

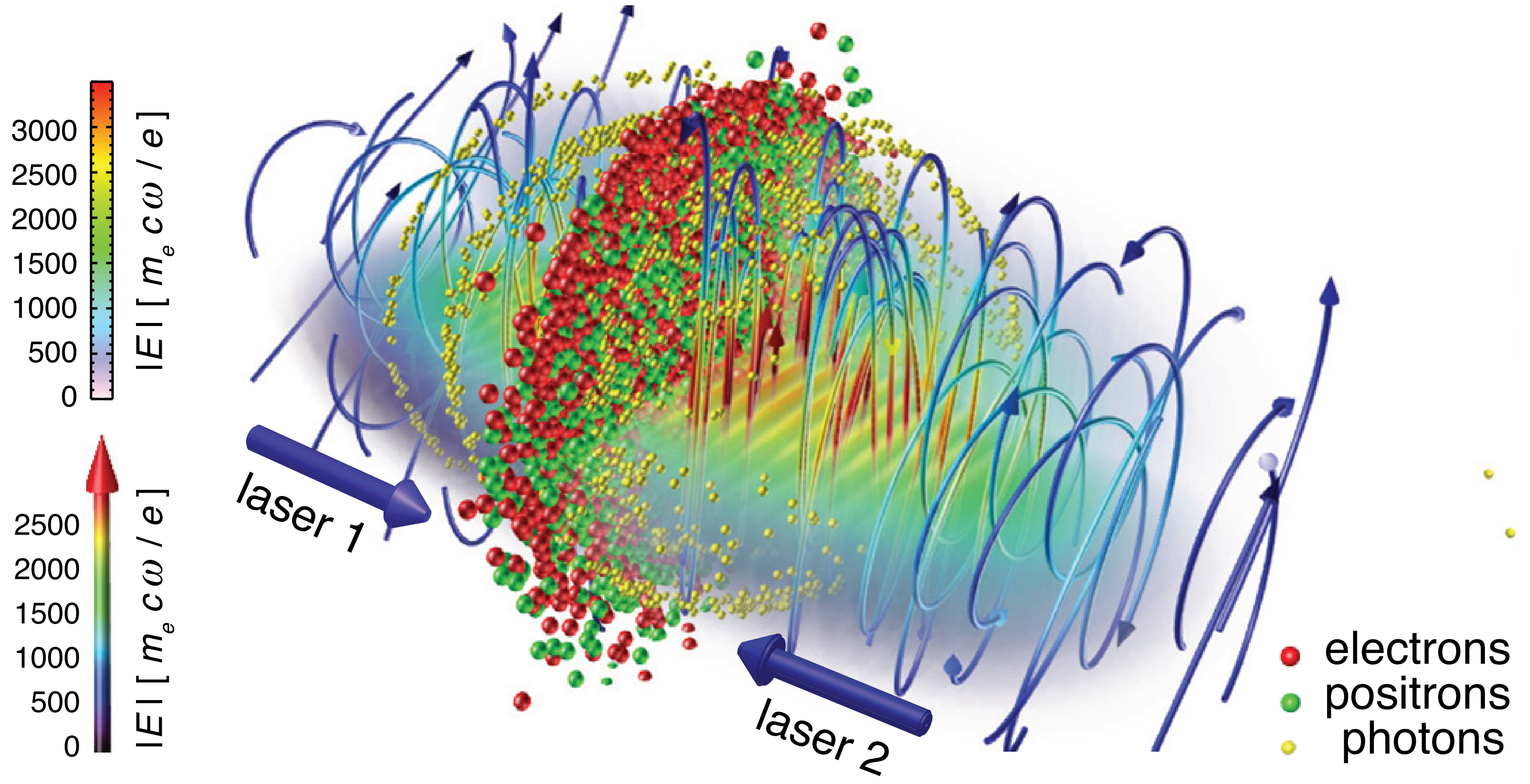
M. Vranic et al., PRL (2014); M. Vranic et al., CPC (2016); M. Vranic et al, PPCF (2018)



Adding quantum processes

- Modelling the onset of QED, RR from quantum perspective
- Modelling e+e- pair production
- QED cascades, nonlinear regimes where many particles are created and collective plasma dynamics can alter the background fields

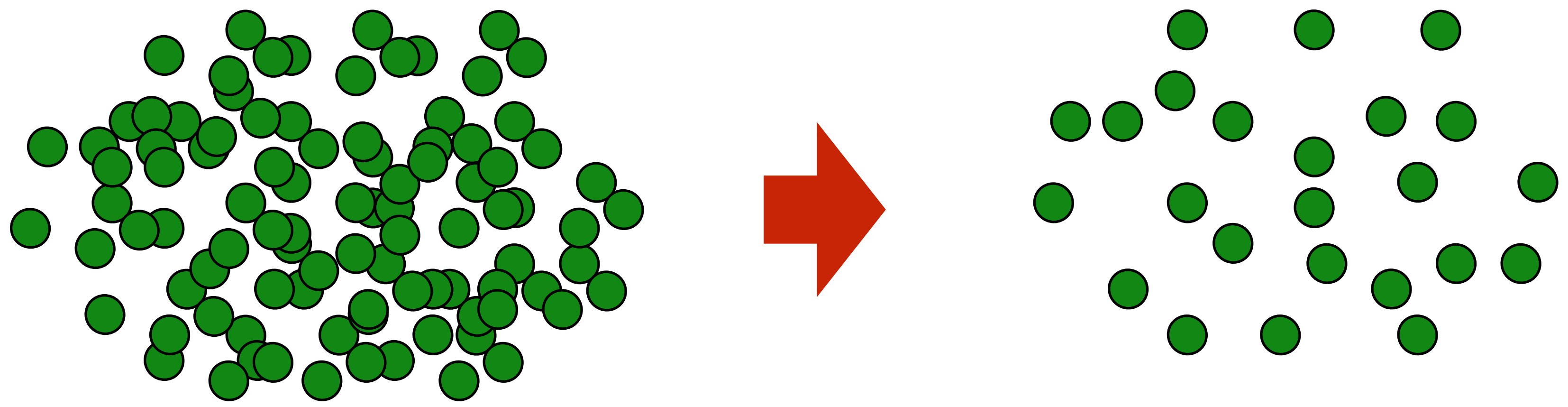
M. Vranic et al, NJP (2016); T. Grismayer et al, POP (2016); T. Grismayer et al, PRE (2017); J. L. Martins et al, PPCF (2016); M. Vranic et al, PPCF (2017); M. Vranic et al, SciRep (2018);



Adding performance improvements (particle merging, advanced load balancing schemes)

- Essential for all the projects with strong QED effects

M. Vranic et al., CPC (2015)

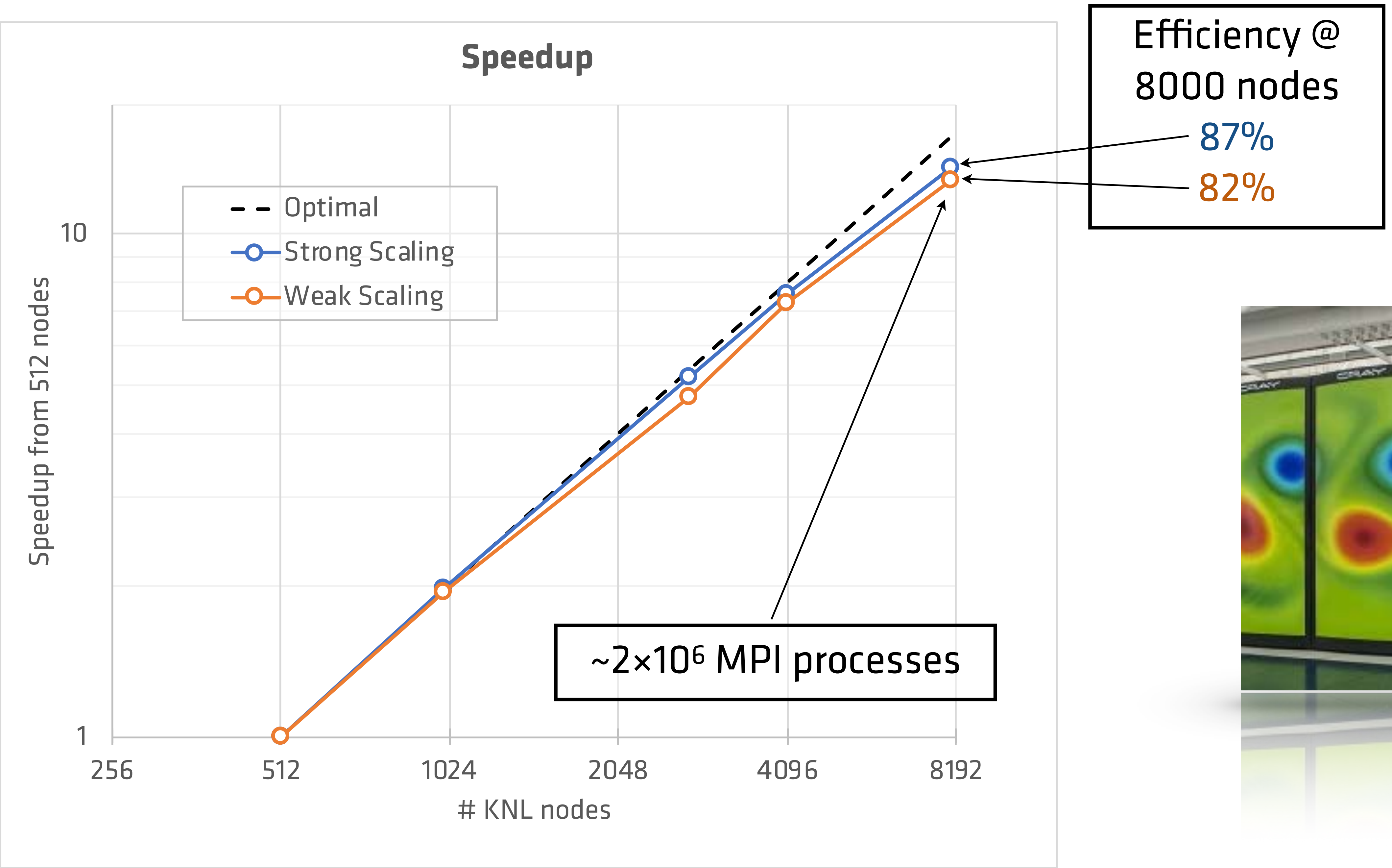


Exascale Strategy for the OSIRIS Framework

- **Exascale strategy for OSIRIS follows 3 concurrent lanes focusing on optimal performance**
  - Dealing with very large scale parallelism
  - Optimizing for current and near future hardware
  - Exploring new programming models and architectures

- **Current version can be readily deployed on most of the top systems**
  - Excellent parallel scalability through advanced dynamic load balance algorithm
  - HIgh performance on CPU systems through explicit use of SIMD (vector) units
  - High performance on GPGPU systems using CUDA

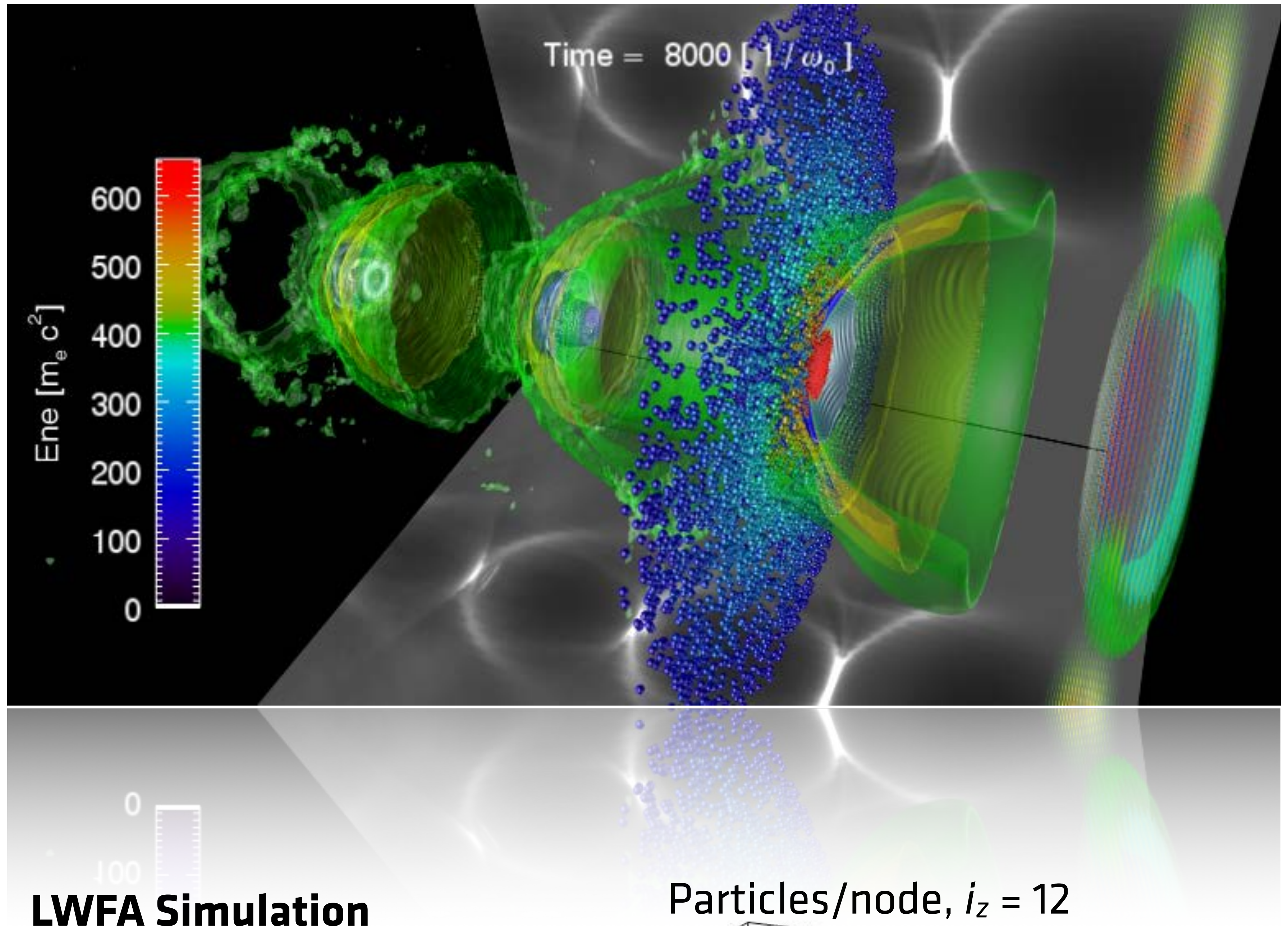
- **Future versions to add support for new hardware and programming models**
  - Unified code base for SIMD units, ARM SVE support under development
  - Use of OmpSs-2 / OpenACC paves the way for non CUDA GPGPU use and other accelerator boards (FPGA, etc.)



XEON PHI inside

NVIDIA CUDA

Improved load balance in extreme scenarios



LWFA Simulation

Parallel Partition

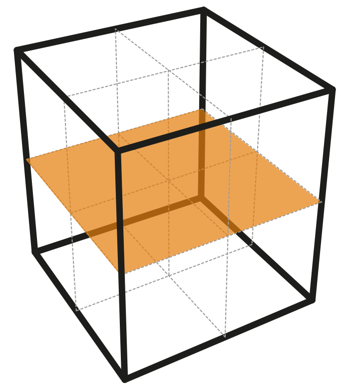
- 94×24×24 = 55k cores

Load Imbalance (max/avg load)

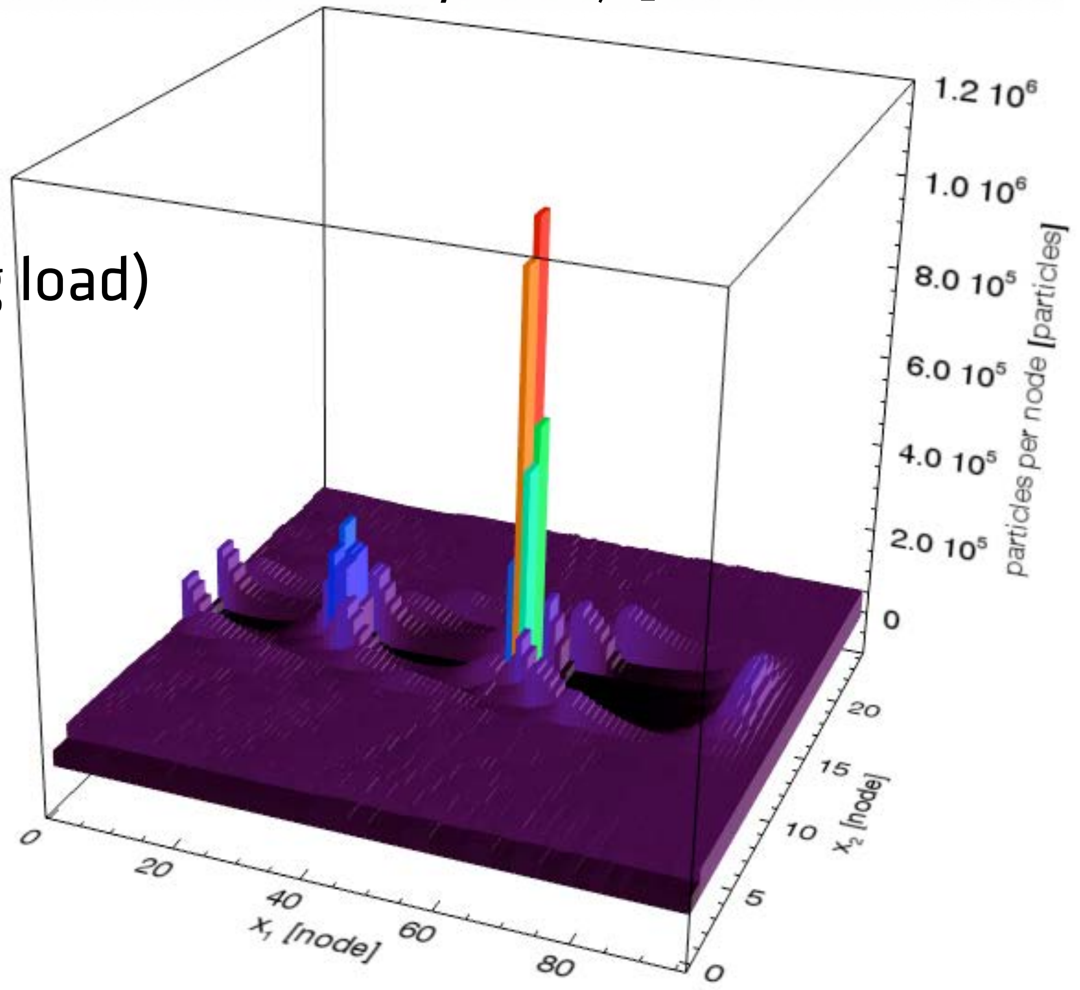
- 9.04×

Average Performance

- ~12% peak



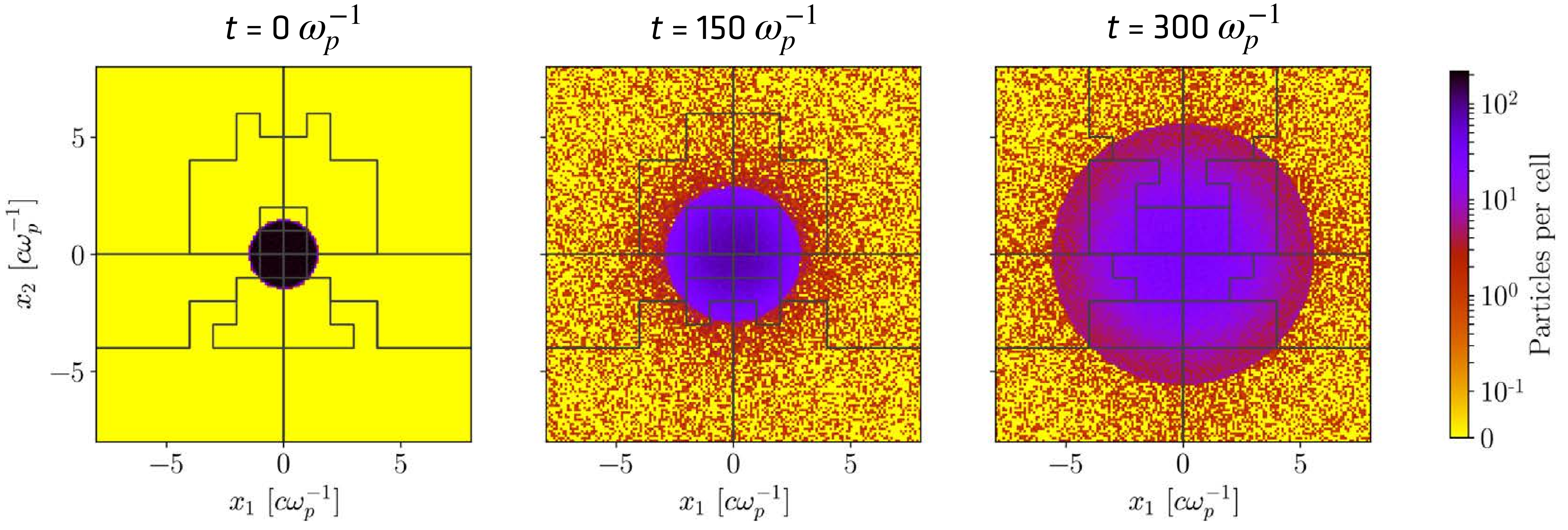
Particles/node, i_z = 12



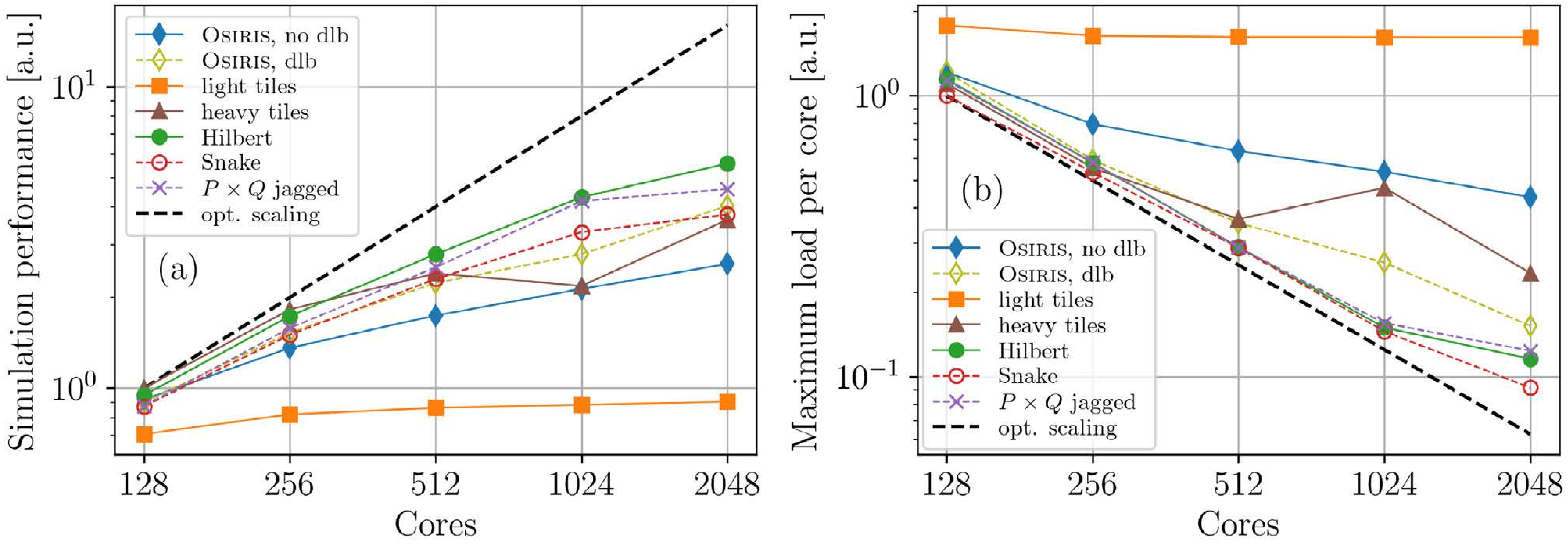
R A Fonseca et al., PPCF **55** 124011 (2013)

Ambipolar diffusion scenario

2D evolution with 16 cores



3D Strong scaling performance / load



K. G. Miller, et. al., CPC **259**, 107633 (2021)

Panel questions

- 1.4) What is the role of your work here?
  - OSIRIS has supported many of the key developments in laser and beam plasma acceleration for the past 20 years. It has served as an invaluable tool for exploring new concepts and ideas, and to guide an interpret experimental work, and is uniquely positioned to continue to do so for the next 10 years.

- 2.1) What are the important milestones for the next 10 years to get there from today?
  - Inclusion of additional physics packages relevant to HEP, improved accuracy for very long propagation distances and extreme field intensities, advanced reduced models (including AI/ML) for parameter scans, continued support for new Tier-0 computing platforms.

- 2.2) What additional support is needed to achieve these?
  - Access to Tier-0 computing resources through dedicated access programs (current access mainly through PRACE or national programs)

- 2.4) Is the R&D work for each of those deliverables already funded and, if not, what additional resources / support would be needed?
  - Work currently being funded by EU either through ERC or national grants, specific grants funding development in this context is required.

Overview

- **OSIRIS has been supporting plasma based acceleration science and technology for the past 2 decades**
  - Stability, accuracy and performance
  - Extended set of input parameters and diagnostics
  - Well documented, easy to use, large user community

- **Improved accuracy and extended physics models**
  - Improved EM field solvers
  - Advanced particle pushers for accurate particle motion in high fields, including spin
  - Addition of relevant QED processes

- **Ongoing work**
  - Improvements on parameter input and output, integration in modeling toolchains
  - Development of fast reduced models based on Artificial Intelligence / Machine Learning
  - Evolution to open-source model