Apollon 10PW

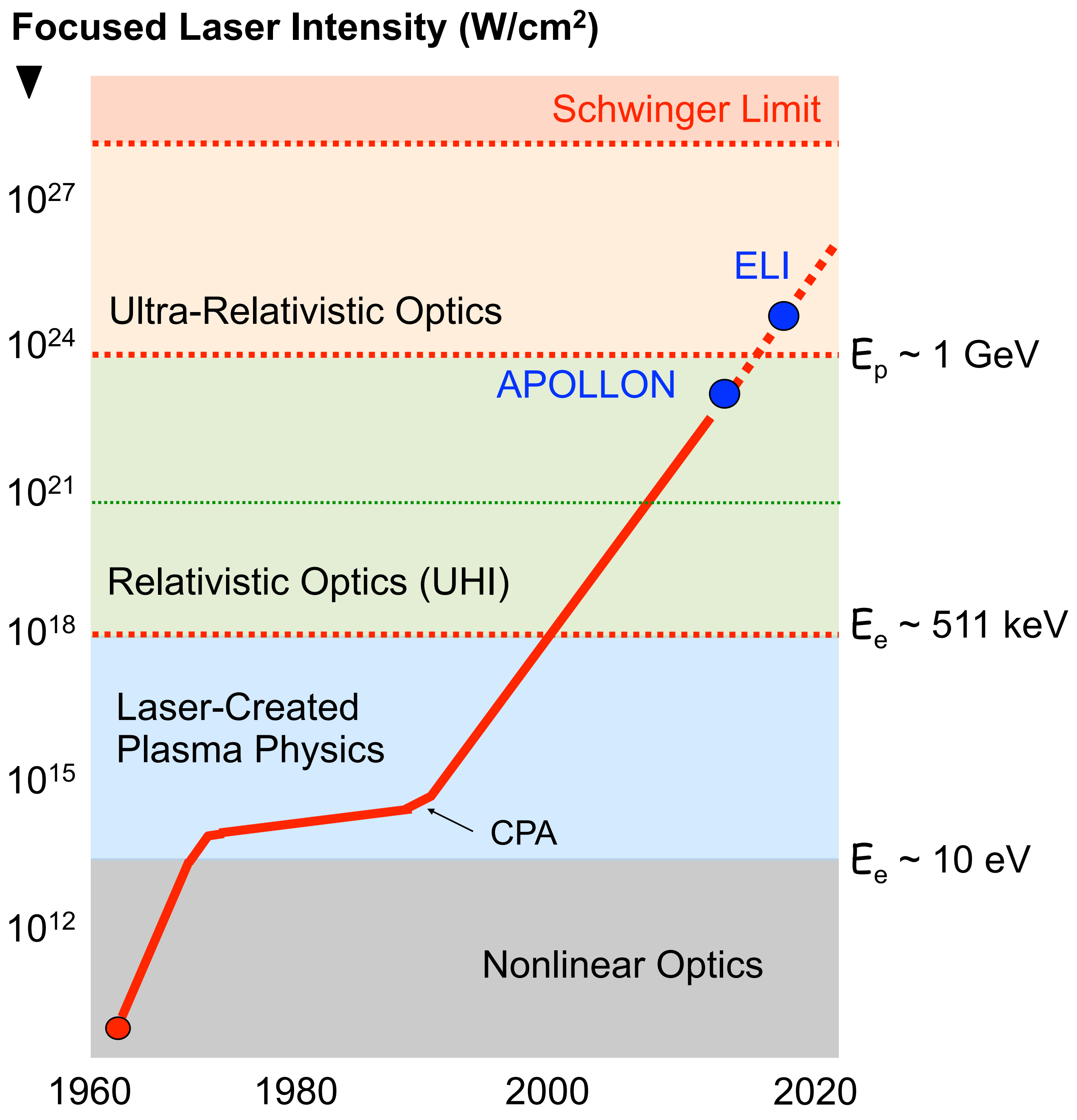
Advances, 1st Experimental Campaigns
Theory & Simulation developments

Mickael Grech
LULI, CNRS
Laboratoire d'Utilisation des Lasers Intenses

EMMI Day 2017, Darmstadt, Germany

From Ultra-High Intensity (UHI) to Extreme Light

New opportunities & challenges for laser-matter interaction



Electron-positron pair production
in the laser field (Breit-Wheeler)
in Coulomb fields (Bethe-Heitler, Trident)

High-energy photons & back-reaction
Radiation reaction

Laser-Plasma Acceleration
of electron (up to 4 GeV)
and ions (up to now below 100 MeV)

Ultra-short (as) ultra-bright X-UV sources
High-harmonic generation, betatron…

Inertial Fusion Plasma
High-energy density physics
& Warm dense Matter Studies
nanosecond kJ - MJ laser systems

Di Piazza et al., Rev. Mod. Phys. **84**, 1177 (2012)

Related Conf.: ExHILP, L'PHYS, EPS, …

From classical to quantum electrodynamics

Typical scales	**CED** m, e, c	**QED** $m, e, c, \hbar$
Energies	electron rest energy: $U_0 = mc^2 \simeq 0.511\ \mathrm{MeV}$	
Lengths	classical radius of the electron $r_e = e^2/(mc^2) \simeq 2.8 \times 10^{-15}\ \mathrm{m}$	Compton length $\lambda_C = \hbar/(mc) \simeq 3.9 \times 10^{-13}\ \mathrm{m}$
Times	$\tau_e = r_e/c \simeq 1.0 \times 10^{-23} s$	$\tau_C = \lambda_C/c \simeq 1.3 \times 10^{-21} s$
Fields	critical field of CED $E_{\mathrm{CED}} = U_0/(e r_e) \simeq 1.8 \times 10^{20}\ \mathrm{V/m}$	Schwinger field $E_{\mathrm{S}} = U_0/(e\lambda_C) \simeq 1.3 \times 10^{18}\ \mathrm{V/m}$
Intensities	$I_{\mathrm{CED}} = cE_{\mathrm{CED}}^2/4\pi \simeq 8.6 \times 10^{33} \mathrm{W/cm}^2$	$I_{\mathrm{S}} = cE_{\mathrm{S}}^2/4\pi \simeq 4.6 \times 10^{29} \mathrm{W/cm}^2$

①

Introducing the **fine-structure constant:**

$$\alpha = e^2/(\hbar c) \simeq 1/137$$

gives a relation between CED & QED scales:

$$r_e = \alpha \lambda_C \simeq \lambda_C/137 \qquad E_{\mathrm{CED}} = E_{\mathrm{S}}/\alpha \simeq 137\ E_{\mathrm{S}}$$

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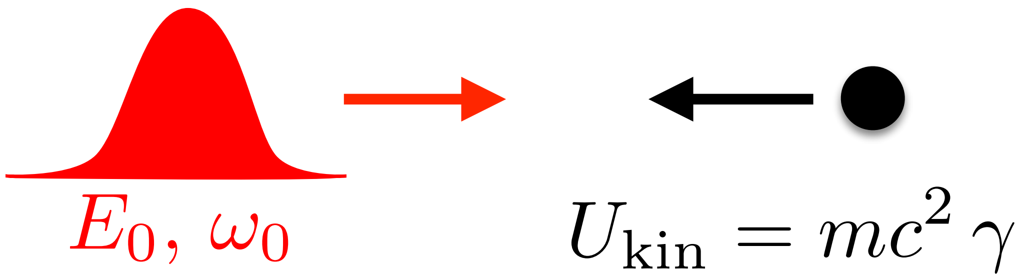
For **head-on collisions**, a **Lorentz boost** leads to an increased field in the proper-frame of the particle: ②



(i) direct e⁻/laser head-on collision

(ii) laser-solid interaction

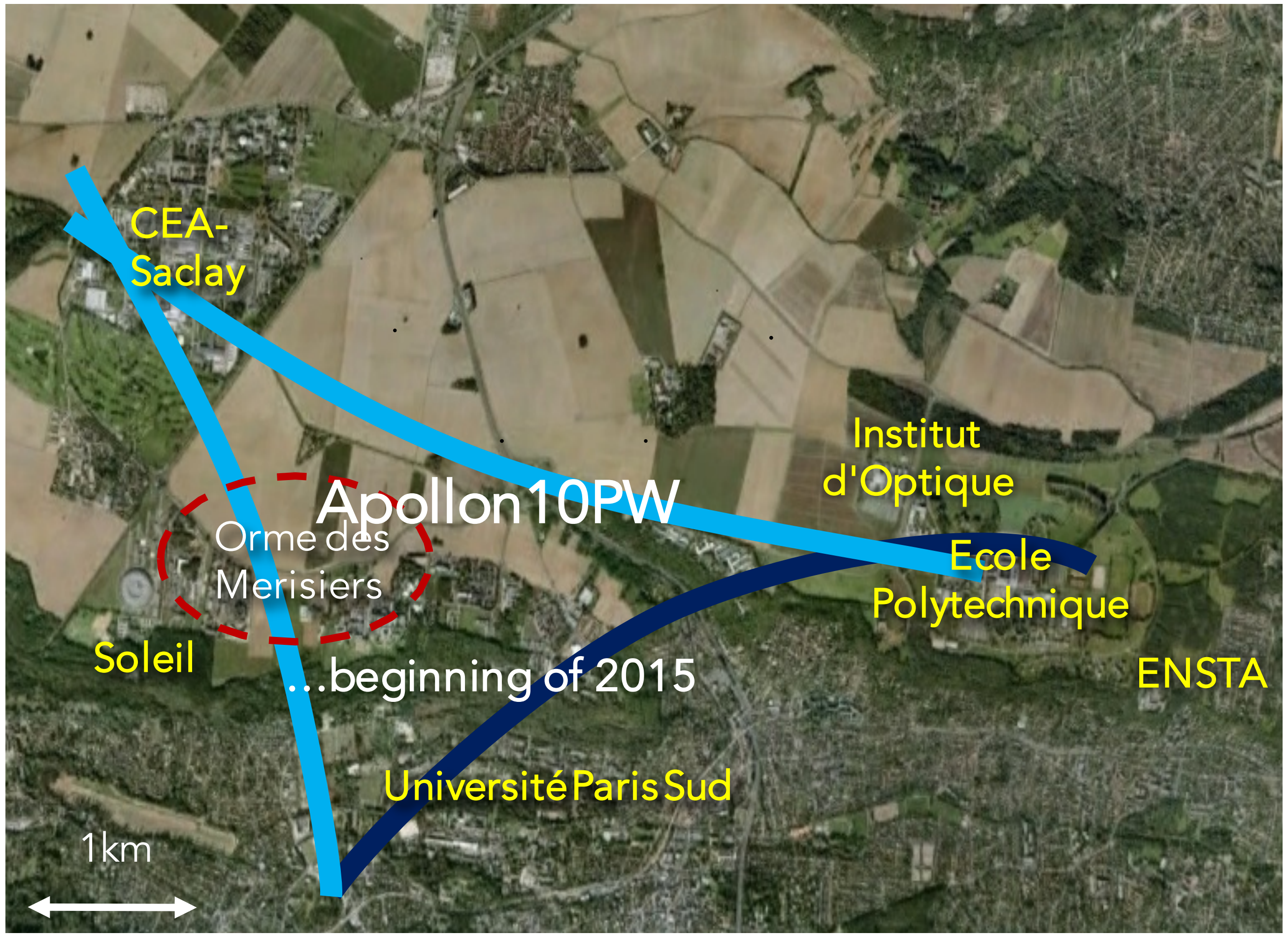
CILEX: Centre Interdisciplinaire Lumière Extrême

5 ultra-high intensity lasers:

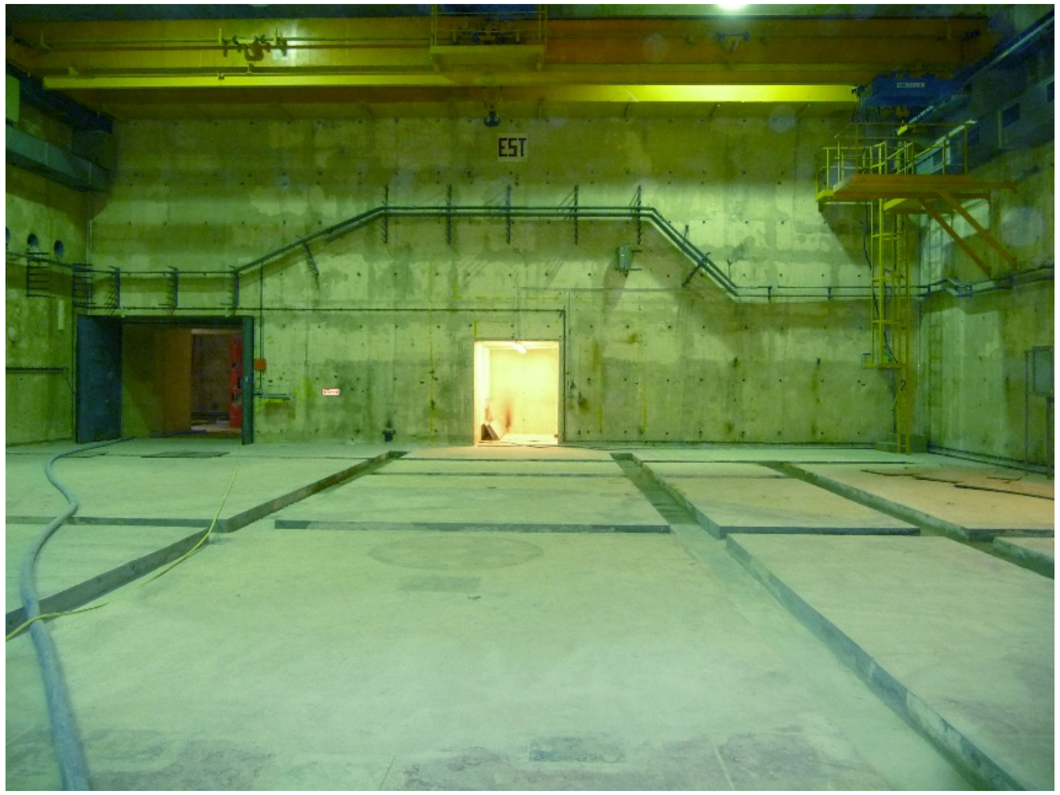
- ELFIE 100 TW (30 J, 300 fs)
- UHI 100 (2.5 J, 25 fs)
- Salle Jaune (6 J, 30 fs)
- Laserix (@10nm, 4-5 μJ, 2 ps)
- Apollon 10PW laser (150 J, 15 fs)

Studying laser-plasma interaction under extreme light conditions:

- new diagnostics & experimental expertise
- simulation capability
- theoretical understanding



Former linear accelerator facility
(1969 – 2006)



A renewed building : 5000 m², radio-protected experimental areas

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The Particle-In-Cell code SMILEI

an open-source, collaborative & multi-purpose code for plasma simulation

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Bridging relativistic laser-plasma interaction & QED

high-energy photon emission &
pair production in strong fields

F. Amiranoff, E. d'Humières, A. Di Piazza, R. Duclous, L. Gremillet, M. Lobet, F. Niel, C. Riconda and M. Grech

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The multi-PW laser Apollon: Specifications

Ultra-high power and intensity:

- delivered on target: 150 J, 15 fs, 10 PW
- intensity of ~2.5×10^{22} W/cm^2 over 5×5 µm^2

High-repetition rate:

- 1 shot/min (>300 shots/day)
- improved statistics

High-contrast ratio:

- CR $> 10^{12}$
- avoid pre-plasma formation

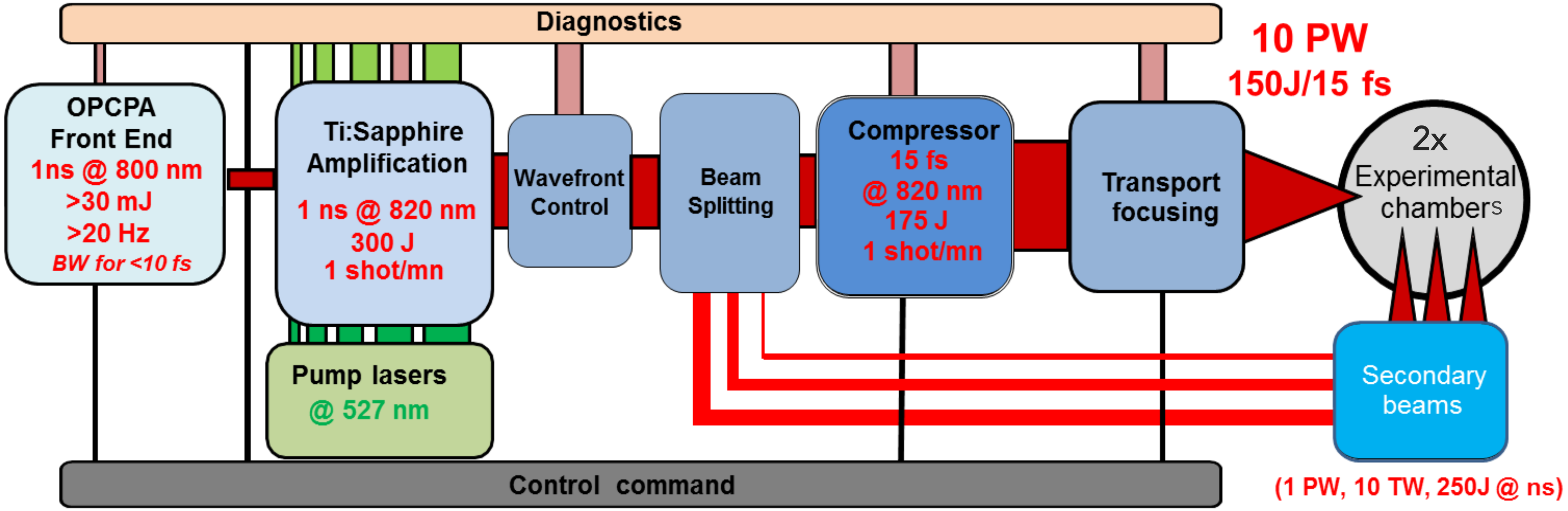
A Multiple-beam facility:

- 4 beam lines F1 [4-10 PW], F2 [1 PW], F3 [250 J (1ns)], F4 [0.2 J (<20 fs)]
- pump-probe experiments
- multi-stage laser wakefield acceleration

2 experimental rooms

- long focal (f = 8 - 32m)
- short focal (f = 1m)

The multi-PW laser Apollon: Key features



Diagnostics

OPCPA
Front End
1ns @ 800 nm
>30 mJ
>20 Hz
BW for <10 fs

Ti:Sapphire
Amplification
1 ns @ 820 nm
300 J
1 shot/mn

Pump lasers
@ 527 nm

Wavefront
Control

Beam
Splitting

Compressor
15 fs
@ 820 nm
175 J
1 shot/mn

Transport
focusing

10 PW
150J/15 fs

2x
Experimental
chambers

Secondary
beams

(1 PW, 10 TW, 250J @ ns)

Control command

Hybrid architecture: OPCPA + Ti:Sapphire Contrast + Bandwidth

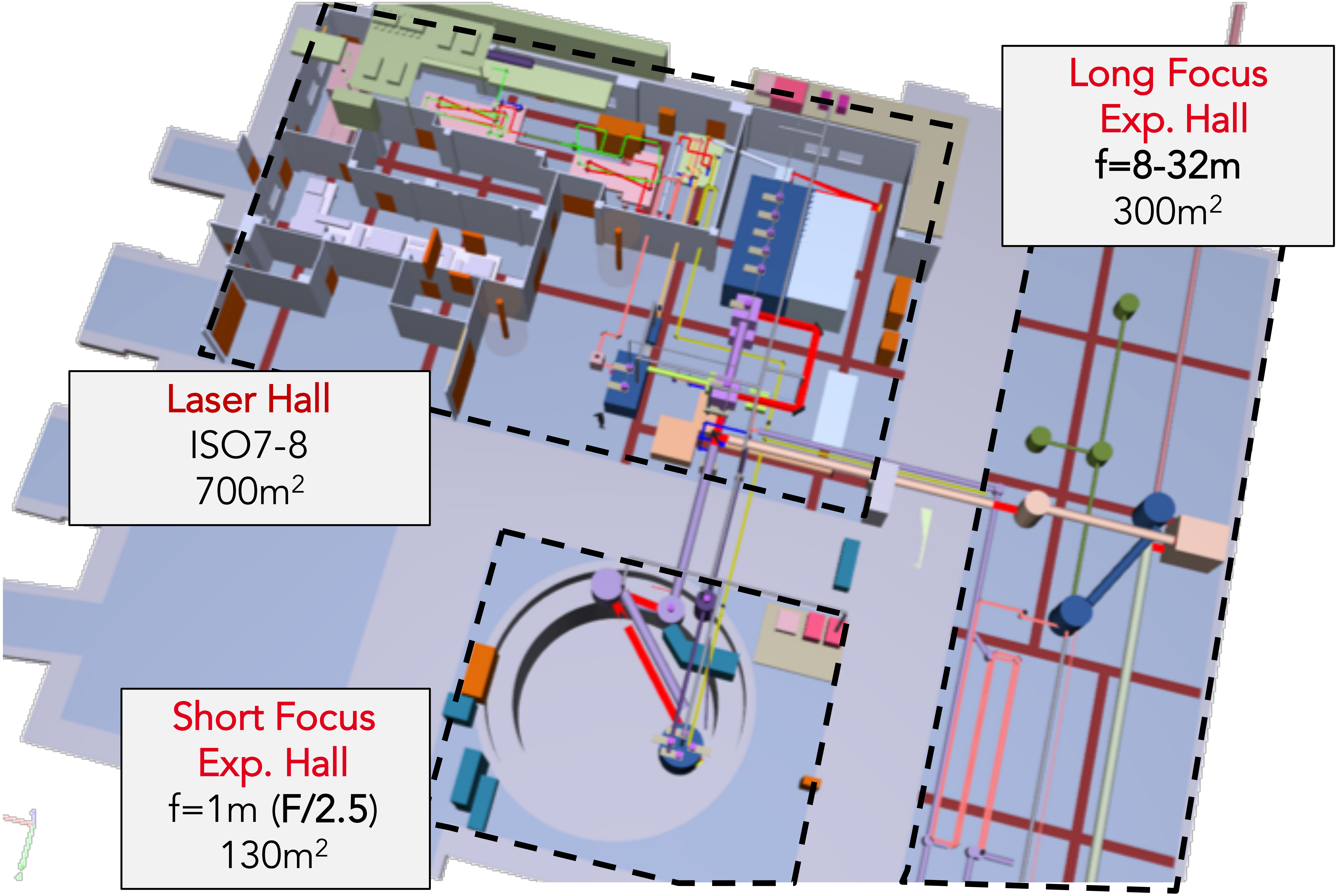
Unique Material: Φ10-175mm Ti:Sapphire crystals, meter-size gold gratings, state-of the-art optics

High energy pump sources: up to 700 J/min

Adaptive control: spatial (Deformable mirrors) and spectral phase (Dazzler)

4 beam lines/2 experimental halls

The multi-PW laser Apollon: The facility



Long Focus
Exp. Hall
f=8-32m
300m^2

Laser Hall
ISO7-8
700m^2

Short Focus
Exp. Hall
f=1m (**F/2.5**)
130m^2

Timeline & Operation of the facility

June 2016
32 J demonstrated
(before compression)

Sept. 2017
1PW (F2) commissioned

March 2018
demonstration full energy
(before compression)

December 2018
First experiments @ 1PW

Spring 2019
First multi-PW experiments
@4-5 PW

Facility open to international scientists

Independent Program Committee yearly

Beam time allocation per year

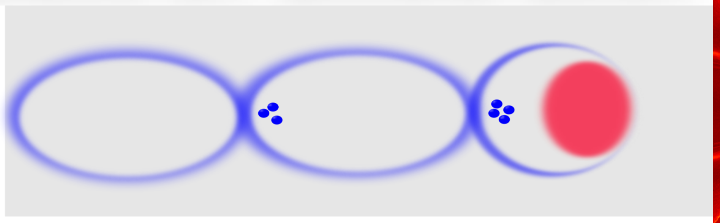
20 experimental campaigns
60 days Maintenance and configuration changes
50 days Laser development

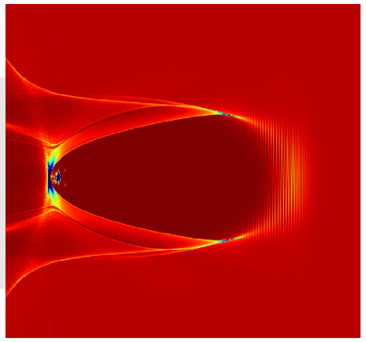
Experiments

Experimental areas will perform in alternate way
Pulse sequences delivered on demand 5 h/day
2 days for configuration (area switching)
4-week basis experiment

Physics studies at Apollon:
from new light & particle source to strong-field QED

Electron acceleration



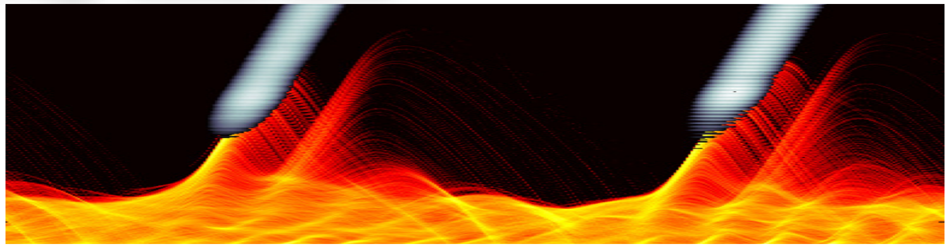


- wakefield / bubble acceleration
- multi-stage acceleration
- acceleration (up to 10s GeV) of elect. & posit.
- x-ray production (coupling to an undulator)

Ion acceleration

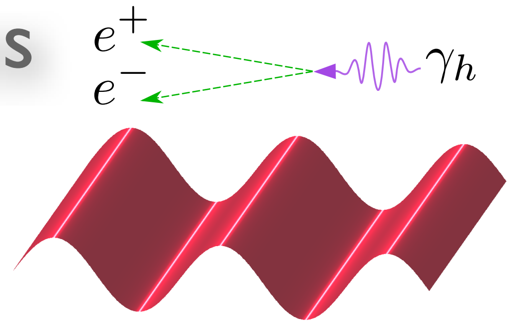
- breaking the 100 MeV limit
- advanced TNSA mechanisms
- radiation pressure acceleration
- warm dense matter, lab. relativistic astrophys.

x-ray sources



- plasma mirror & high-harmonic generation from solid targets
- x-ray laser
- betatron radiation

High-field physics



- QED effects in laser-plasma interaction
- high-energy gamma photon production and their back-reaction on the electron dynamics
- positron generation (in laser & Coulomb field)

Partners & support to the CILEX/Apollon project

loa

INSTITUT d'OPTIQUE GRADUATE SCHOOL
Laboratoire Charles Fabry

IRAMIS

cea SACLAY

Irfu
Institut de recherche sur les lois fondamentales de l'Univers

Centre de physique théorique
ÉCOLE POLYTECHNIQUE

LIDYL

SOLEIL SYNCHROTRON

ISMO

LASERIX

LAL
LABORATOIRE DE L'ACCÉLÉRATEUR LINÉAIRE

cnrs

l'X ÉCOLE POLYTECHNIQUE

cea

UPMC PARISUNIVERSITAS

INSTITUT d'OPTIQUE GRADUATE SCHOOL

UNIVERSITÉ PARIS SUD

ENSTA ParisTech

INSTITUT LASERS ET PLASMAS

INVESTISSEMENTS D'AVENIR

AGENCE NATIONALE DE LA RECHERCHE
ANR

Liberté • Égalité • Fraternité
RÉPUBLIQUE FRANÇAISE
MINISTÈRE DE L'ENSEIGNEMENT SUPÉRIEUR ET DE LA RECHERCHE

îledeFrance

Essonne
LE CONSEIL GÉNÉRAL

l'Europe s'engage en Ile-de-France
avec le FEDER

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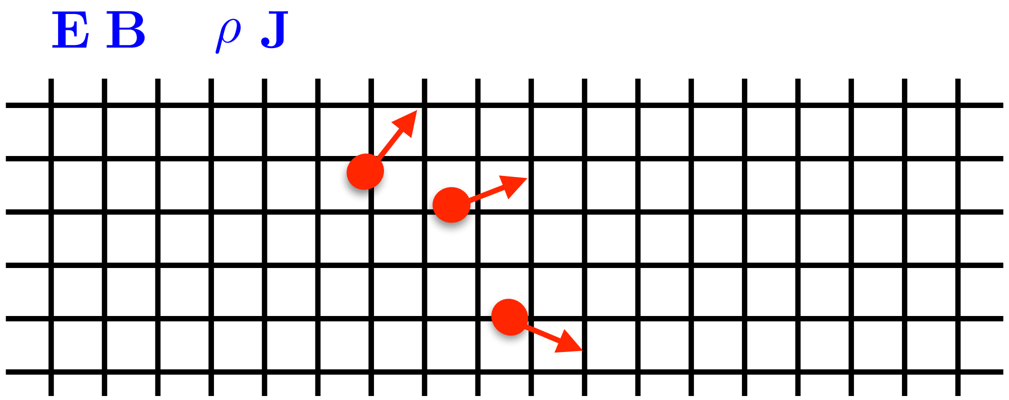
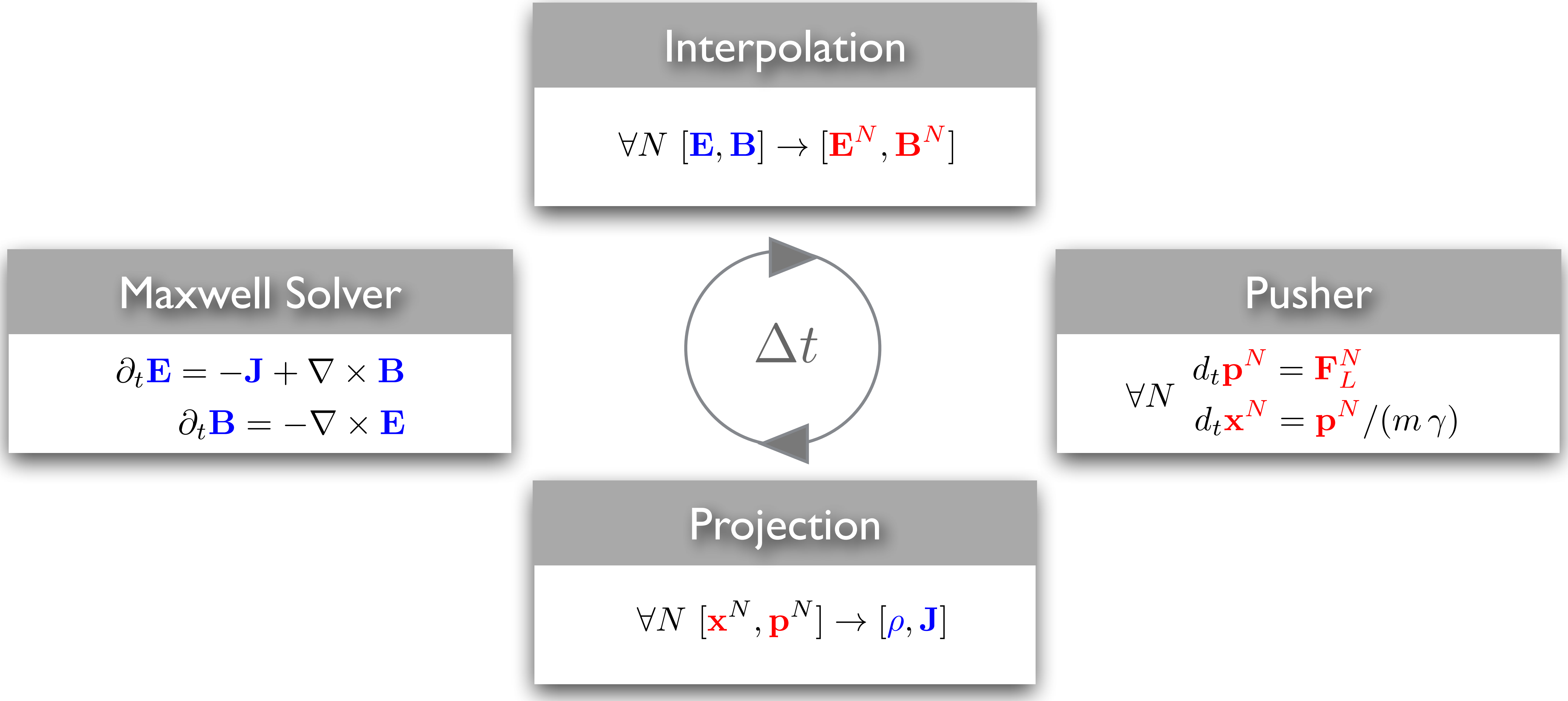
The Particle-In-Cell (PIC) method in a nutshell

Laser-plasma interaction at ultra-high intensity is supported by relativistic kinetic simulation



- Vlasov Eq. is solved using so-called macro-particles

$$f_s(t,\mathbf{x},\mathbf{p}) = \sum_N w^N\, S(\mathbf{x}-\mathbf{x}^N(t))\,\delta(\mathbf{p}-\mathbf{p}^N(t))$$



Interpolation

$$\forall N\ [\mathbf{E},\mathbf{B}] \to [\mathbf{E}^N,\mathbf{B}^N]$$

Maxwell Solver

$$\partial_t \mathbf{E} = -\mathbf{J} + \nabla\times\mathbf{B}$$
$$\partial_t \mathbf{B} = -\nabla\times\mathbf{E}$$

Δt

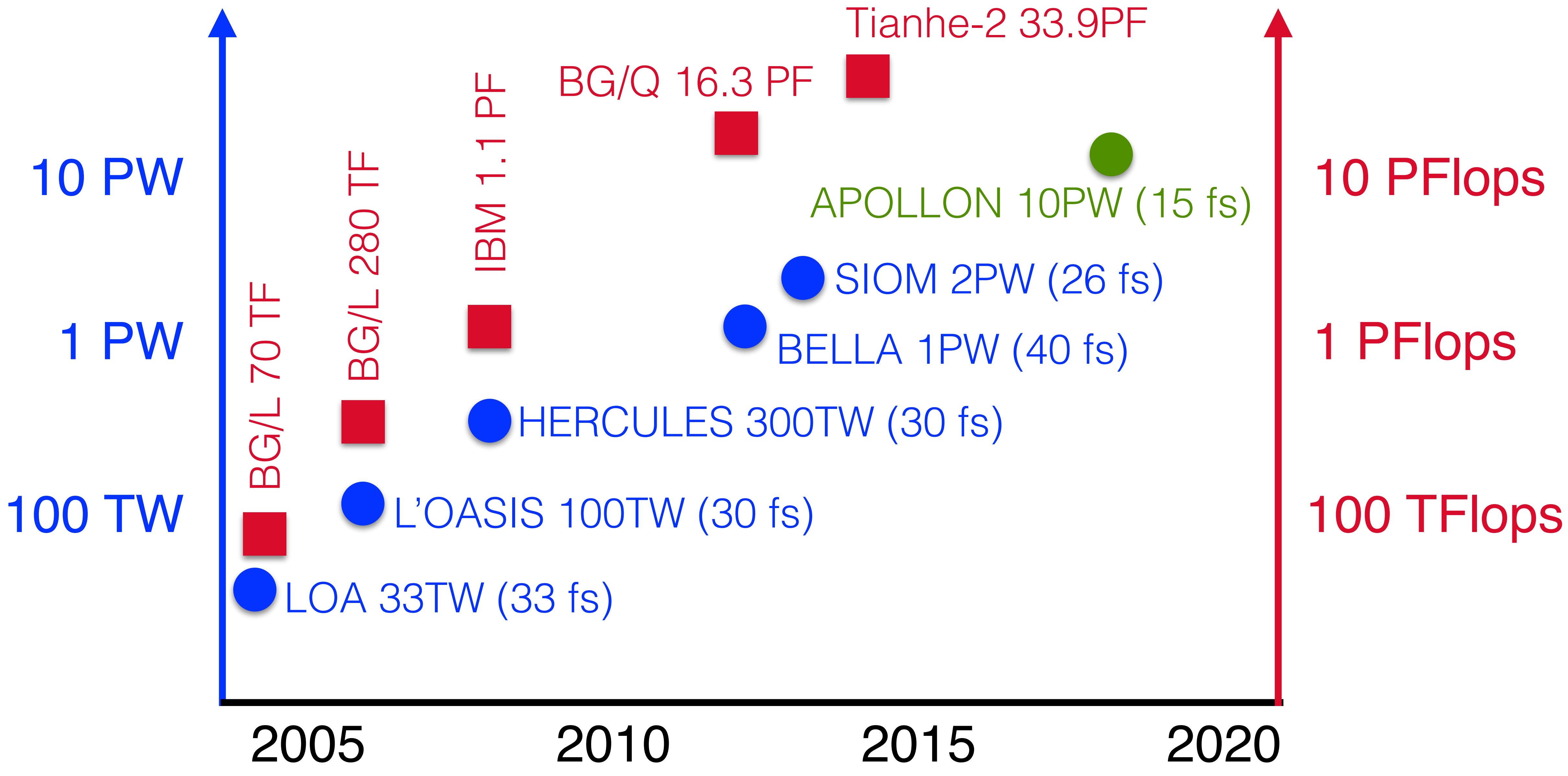
Pusher

$$\forall N\quad \begin{aligned} d_t\mathbf{p}^N &= \mathbf{F}_L^N \\ d_t\mathbf{x}^N &= \mathbf{p}^N/(m\,\gamma) \end{aligned}$$

Projection

$$\forall N\ [\mathbf{x}^N,\mathbf{p}^N] \to [\rho,\mathbf{J}]$$

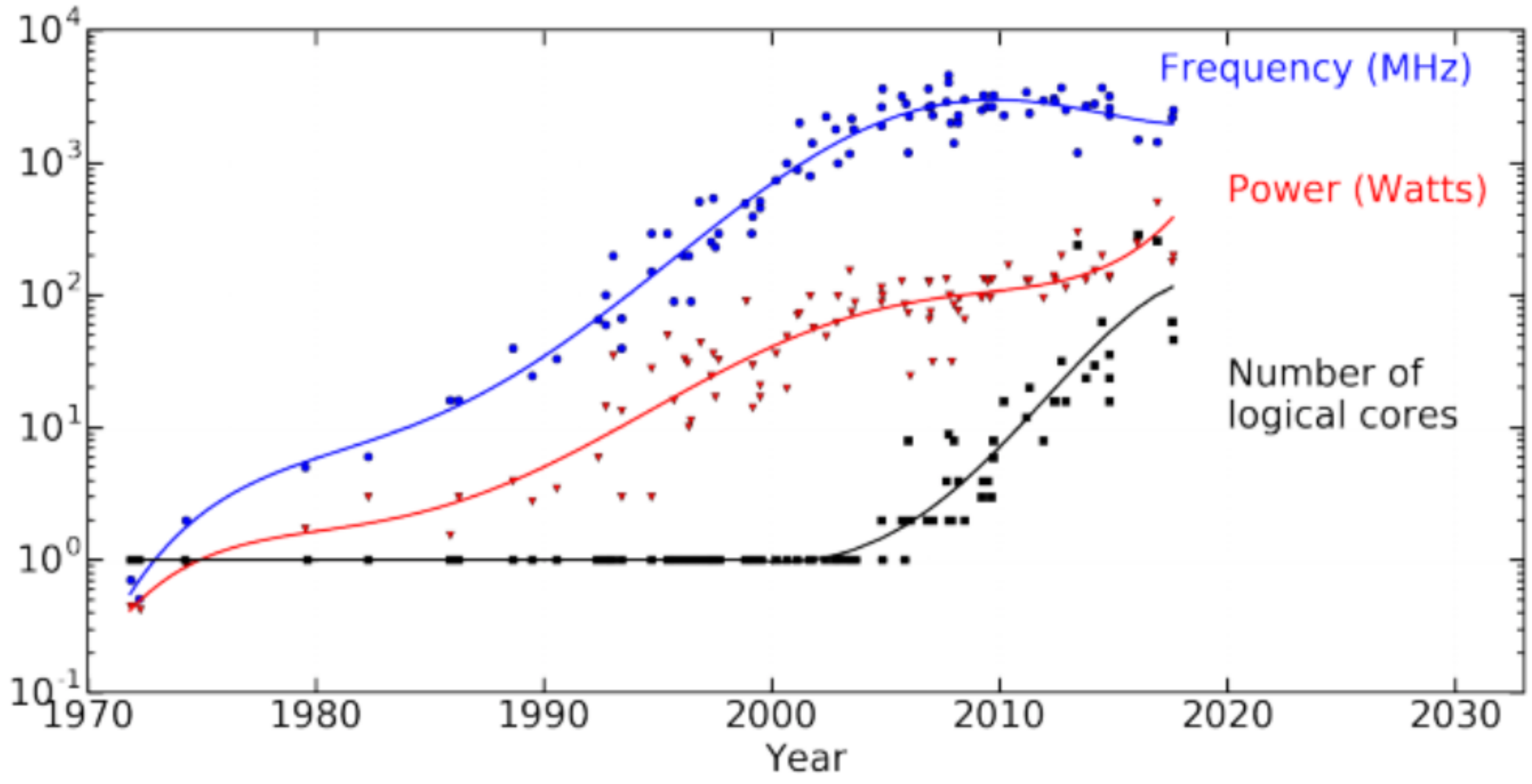
The cross-road of 2 fast-evolving technologies

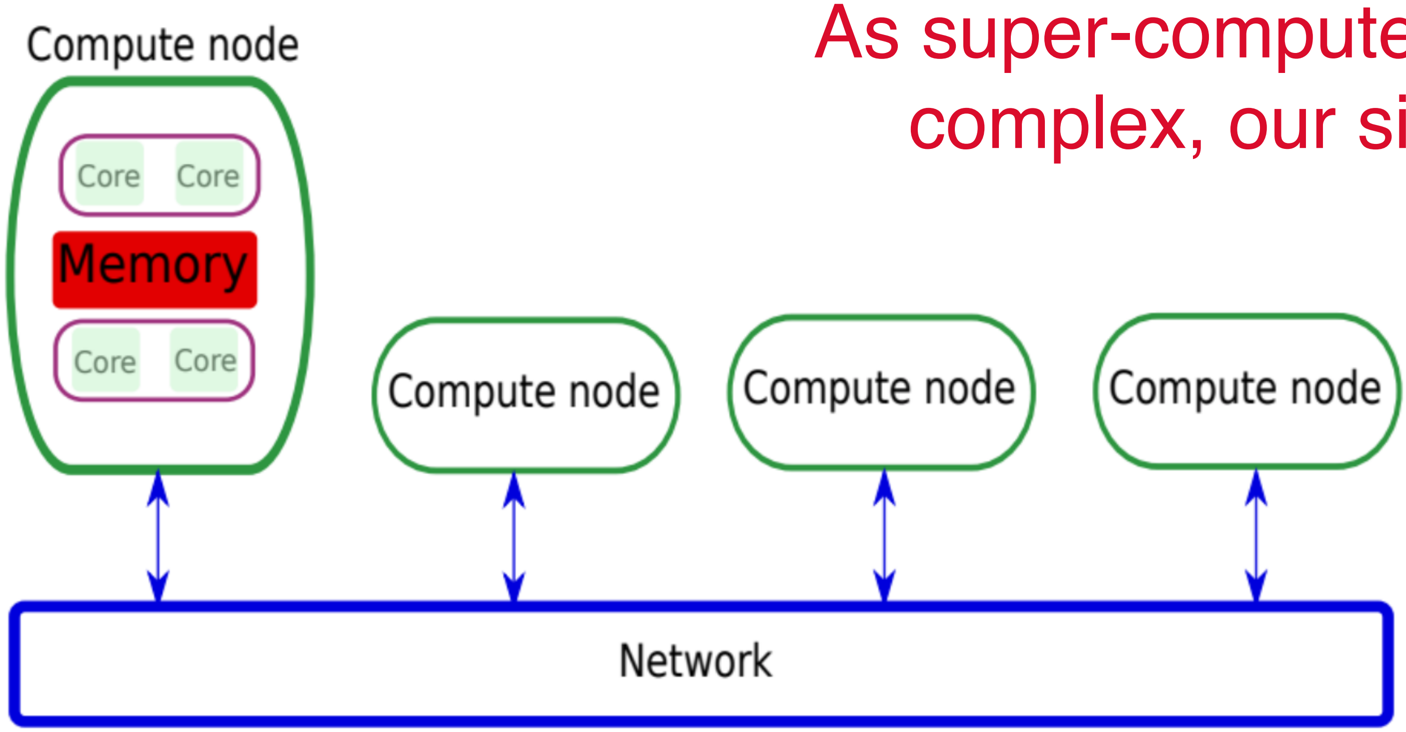


On the road to the exaFlops (by 2020):

Tianhe-2 34PFlops (17 MW) ⟶ 1 exaFlops (500 MW)

Emergence of new paradigms in High-Performance Computing (HPC)



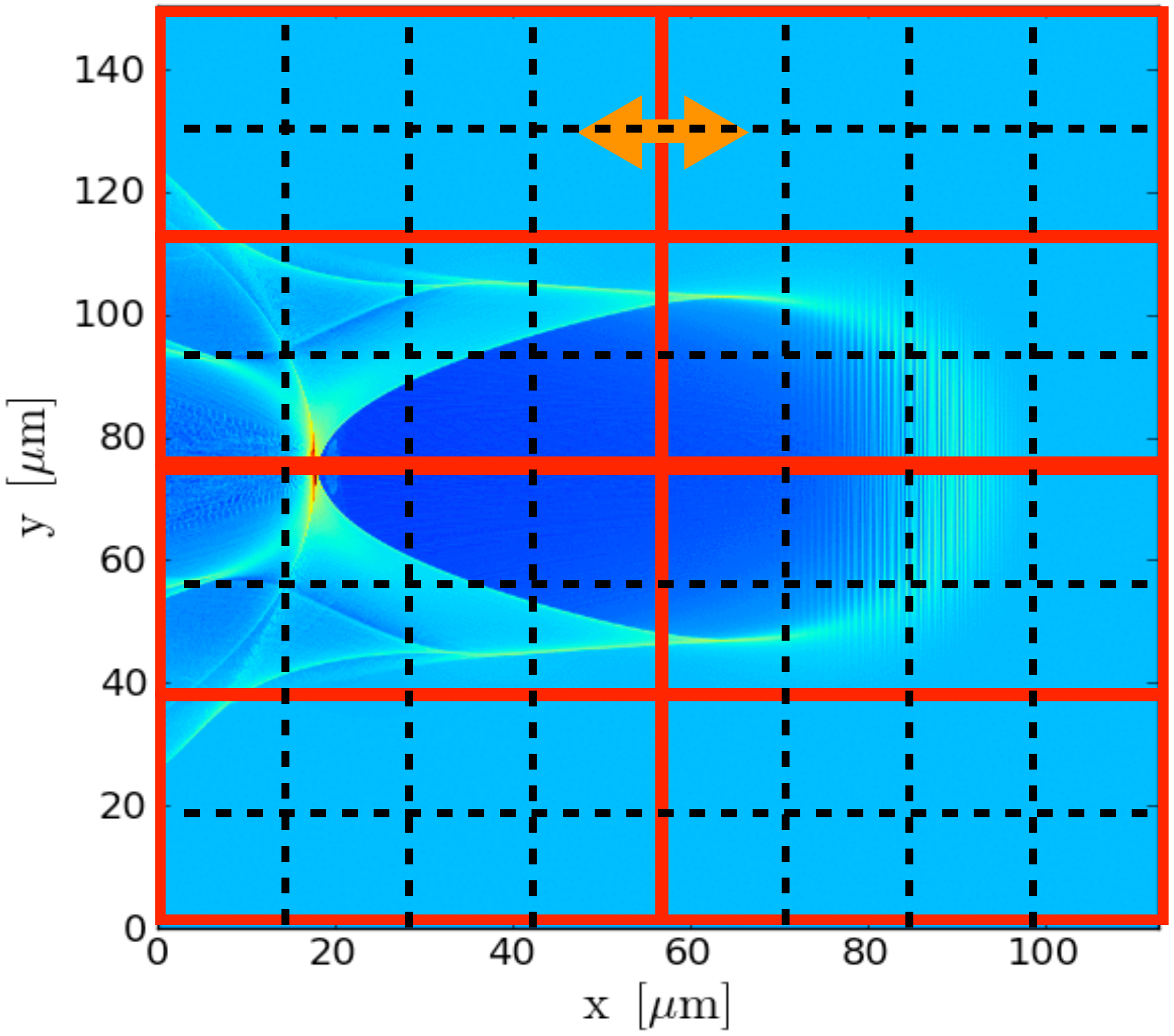


As super-computer architectures become more complex, our simulation tools need to adapt!

distributed memory
shared memory
cache issues
SIMD/vectorization
Parallel I/O management

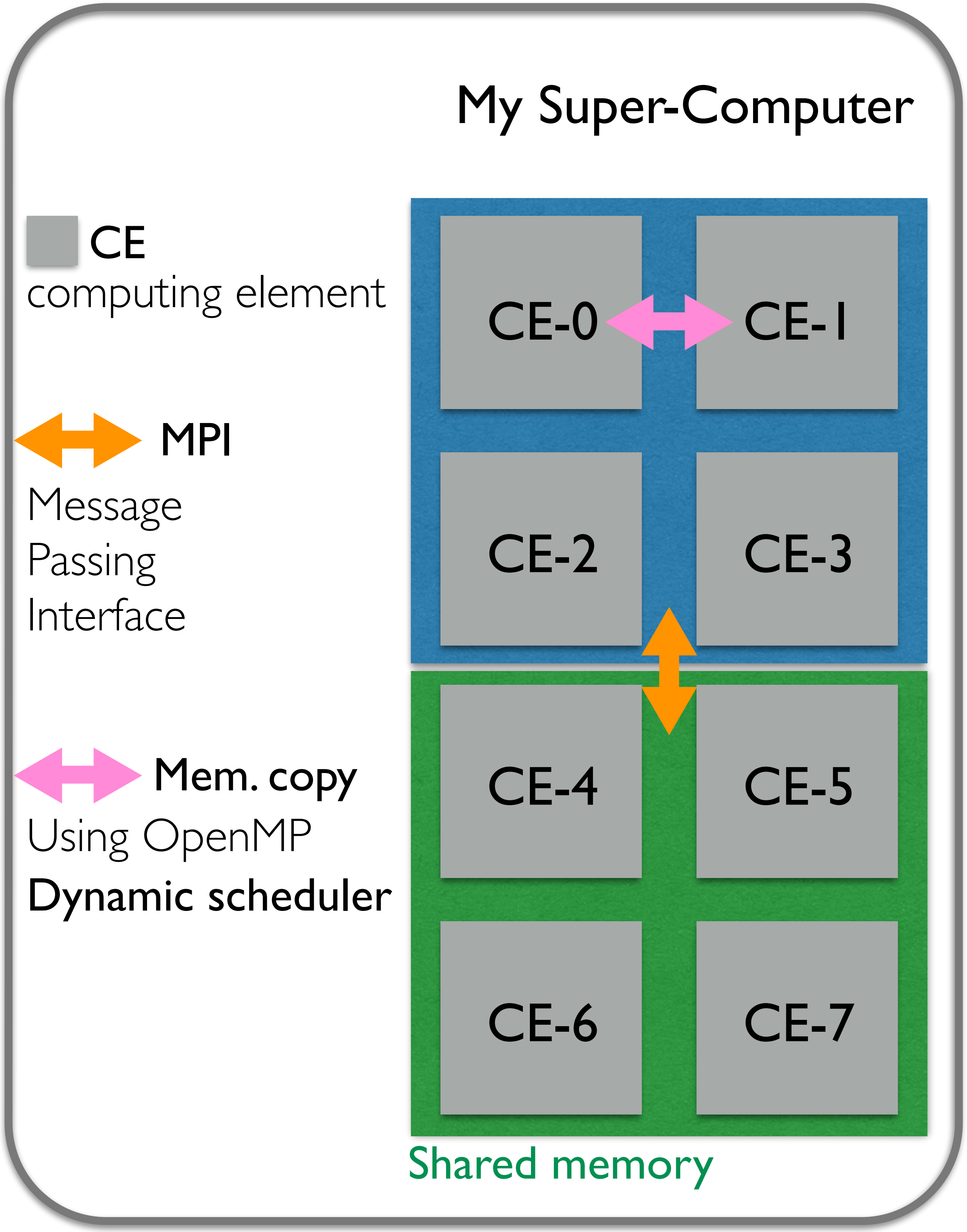
SMILEI: an open-source, collaborative, HPC-relevant PIC code for *Simulation Matter Irradiated by Light at Extreme Intensities*

Simulation of laser wakefield acceleration of electrons



Domain decomp. is not enough!!!

- workload not optimally shared
- not adapted to new architectures!



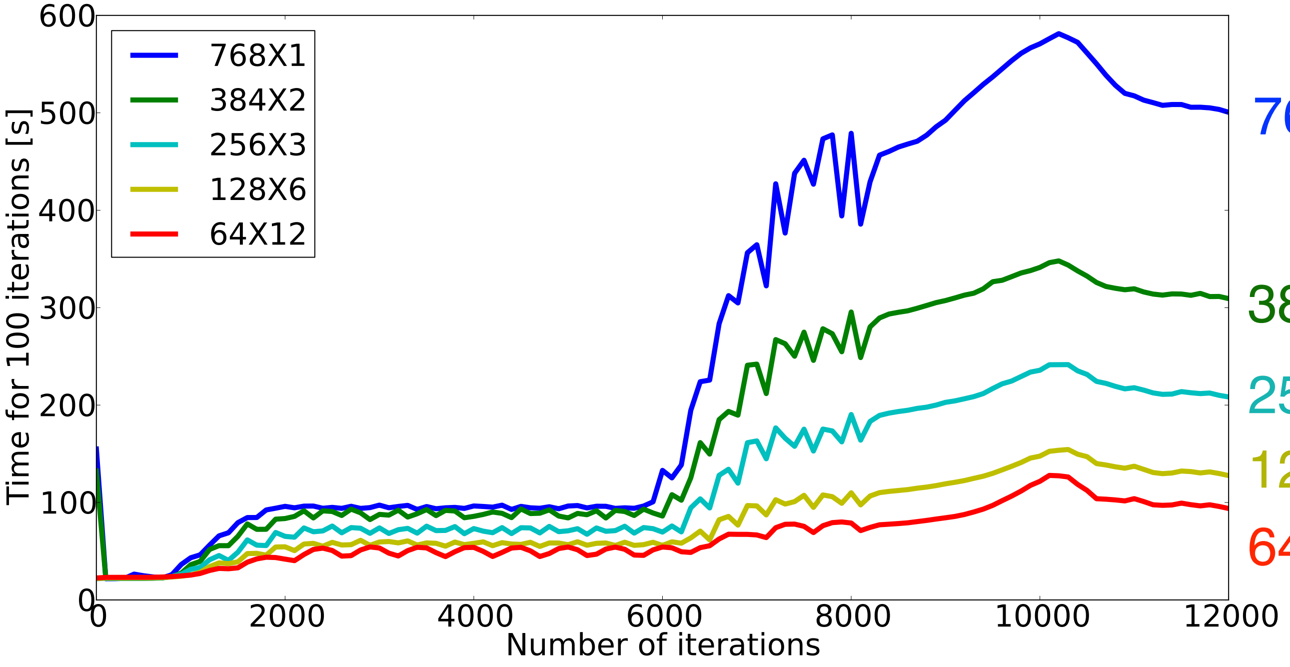
■ **CE**
computing element

⟷ **MPI**
Message
Passing
Interface

⟷ **Mem. copy**
Using OpenMP
Dynamic scheduler

SMILEI uses an hybrid MPI-OpenMP parallelisation strategy

Hybrid MPI/Open parallelization significantly reduces computation time



768 MPI x 1 OMP

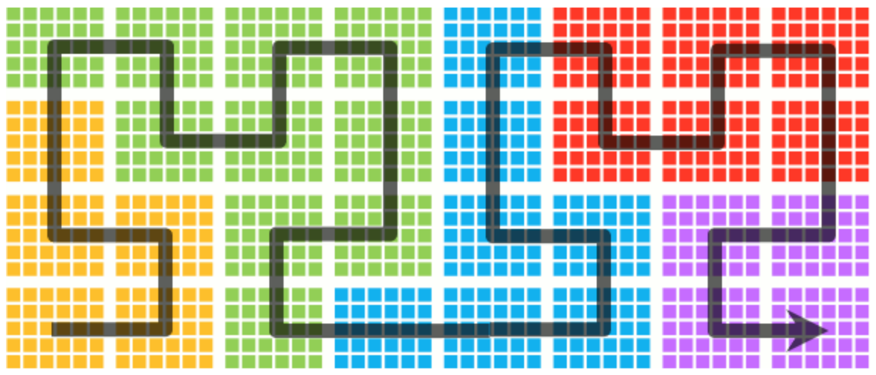
384 MPI x 2 OMP

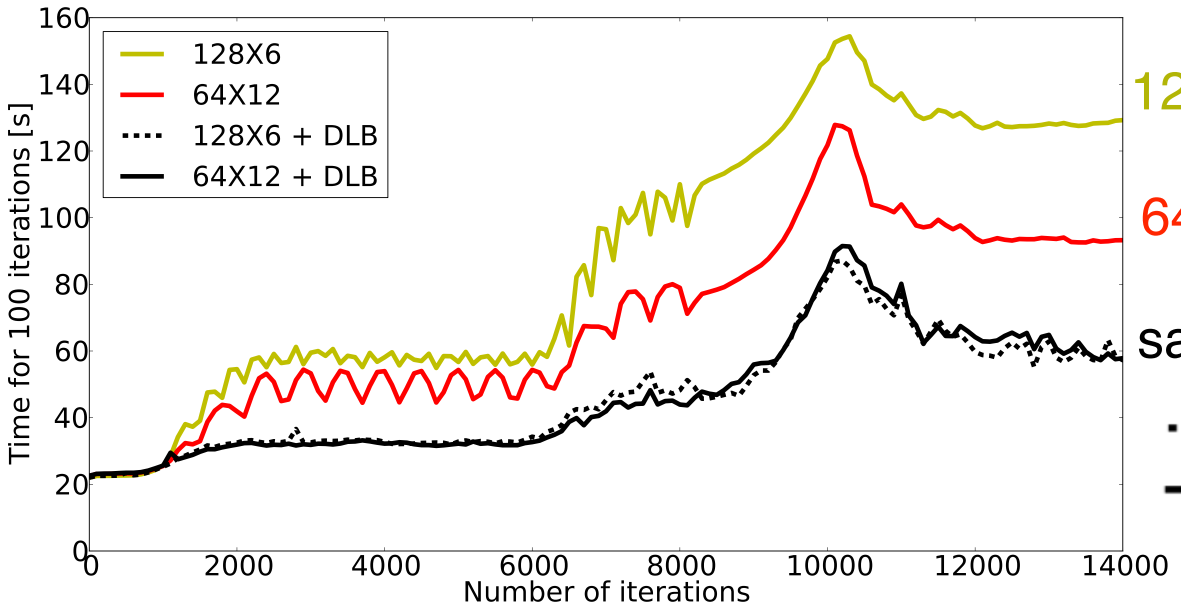
256 MPI x 3 OMP

128 MPI x 6 OMP

64 MPI x 12 OMP

Patch decomposition also allows for an ‘easy’ implementation of dynamic load balancing





128 MPI x 6 OMP

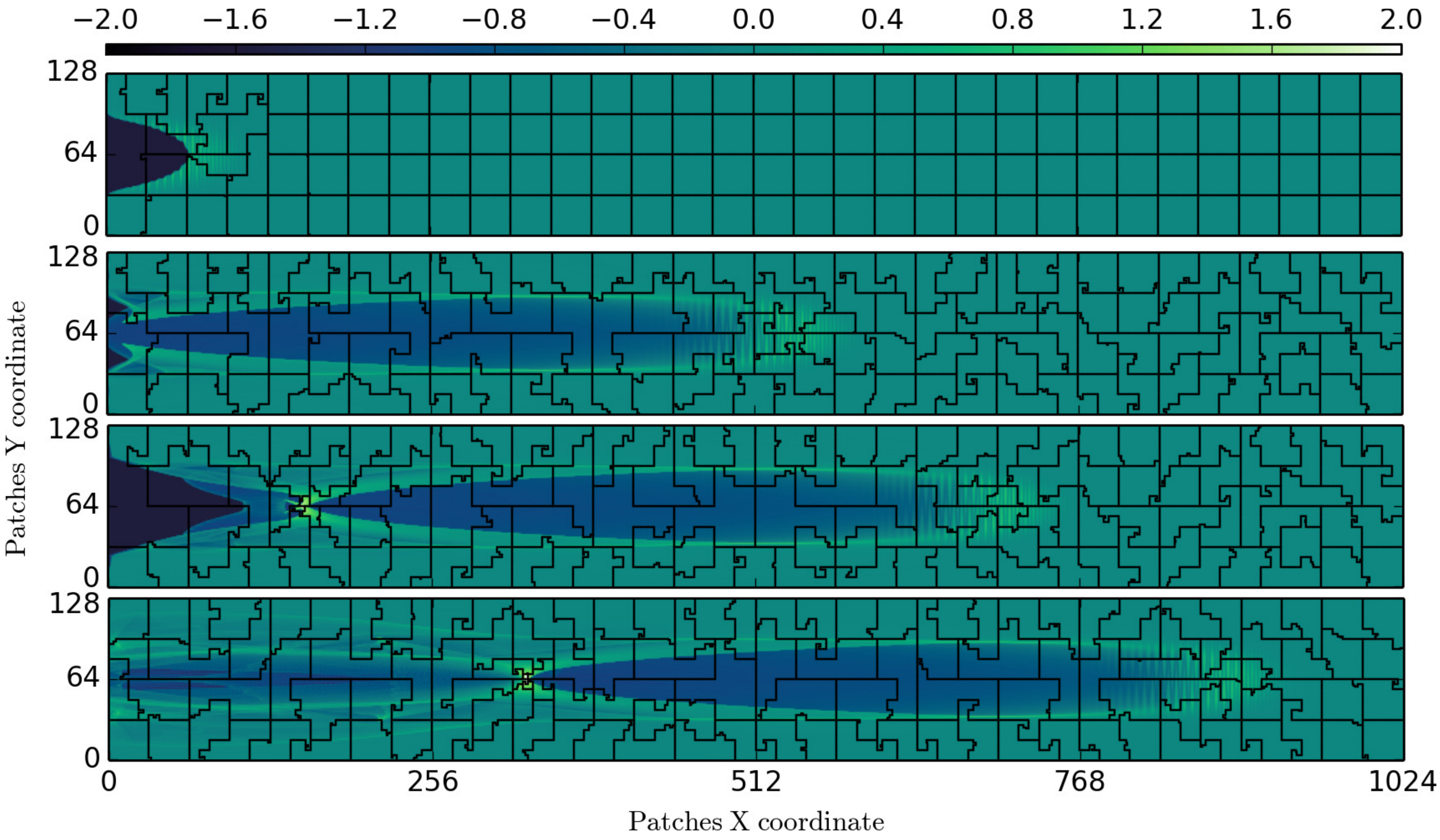
64 MPI x 12 OMP

same with DLB

128X6 + DLB

64X12 + DLB

SMILEI’s dynamic load balancing at work

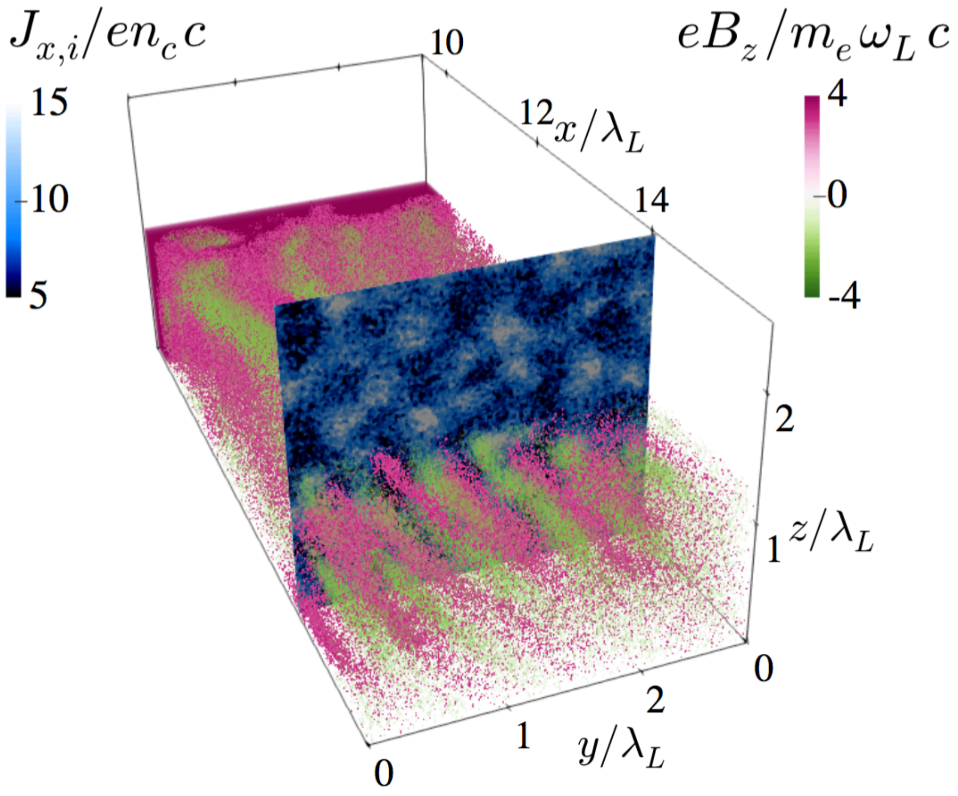


J. Derouillat et al., *Computer Phys. Comm.* **22**, 351 (2018)
www.maisondelasimulation.fr/smilei

Smilei)

Version 3.3 is now available online

[J. Dérouillat et al., Comp. Phys. Comm. (2017)]



Code, processing tools and documentation avalaible online at: www.maisondelasimulation.fr/smilei

1D, 2D, 3D Cartesian geometries

Advanced physics modules

- Charge conserving current deposition (Esirkepov)
- Advanced Maxwell solvers & filters
- Antenna & external electromagnetic fields
- Binary collisions & impact ionization
- **High-emission photon emission & back-reaction**
- **Breit-Wheeler electron-positron pair production**

User friendly

- Full (updated) doc
- Python I/O management
- Extensive (built-in) diagnostics
- Python post-processing tools

High-Performance oriented

- Hybrid MPI/OpenMP
- Dynamic Load Balancing
- HDF5 parallel I/O (OpenPMD compliant)
- Vectorization (available soon)

MAISON DE LA SIMULATION · LULI · iris · LIDYL · LPP · irap astrophysique & planétologie · PLAS@PAR Plasmas à Paris · PALM Laboratoire d'Excellence Physique : Atomes Lumière Matière

A research and teaching platform for plasma simulation, from laser-plasma interaction to astrophysics

A teaching platform:

- Plasma physics numerical hands at the Master level (UPMC)
- Training workshops (1st Nov. 2017)

7 PhD thesis in various fields:

M. Chiaramello (LULI, UPMC), *Short laser pulse amplification* (2016)
A. Grassi (LULI, UPMC), *Relativistic lab. astrophysics* (2017)
J. Dargent (LPP/IRAP), *Magnetic reconnection in astrophysics* (2017)
G. Bouchard (LIDyL, Paris-Saclay), *High-harmonic generation* (2018)
F. Niel (LULI, UPMC), *QED processes at extreme light* (2018)
H. Kallala (MdlS, Paris-Saclay), *HPC-relevant Spectral solvers* (2019)
I. Zemzemi (LLR, Paris-Saclay), *Laser wakefield acceleration* (2020)

3 Postdoctoral fellows:

A. Sgattoni (LULI, UPMC), *Solar wind astrophysics* (since 2015)
F. Massimo (LULI, UPMC), *Laser wakefield acceleration* (from 2017)
S. Marini (LULI, UPMC), *Surface plasma waves* (from 2018)

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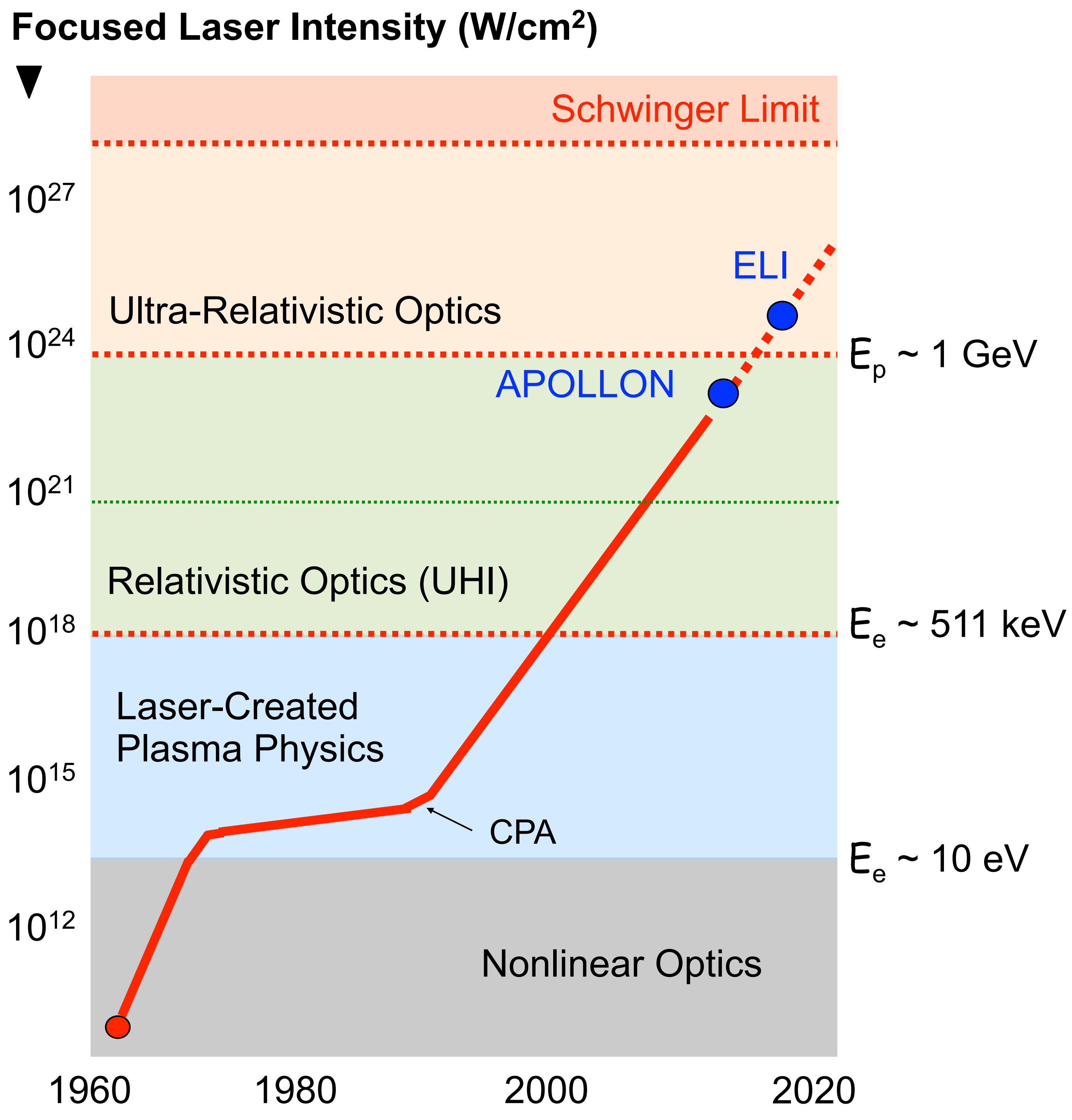
New opportunities & challenges for laser-matter interaction



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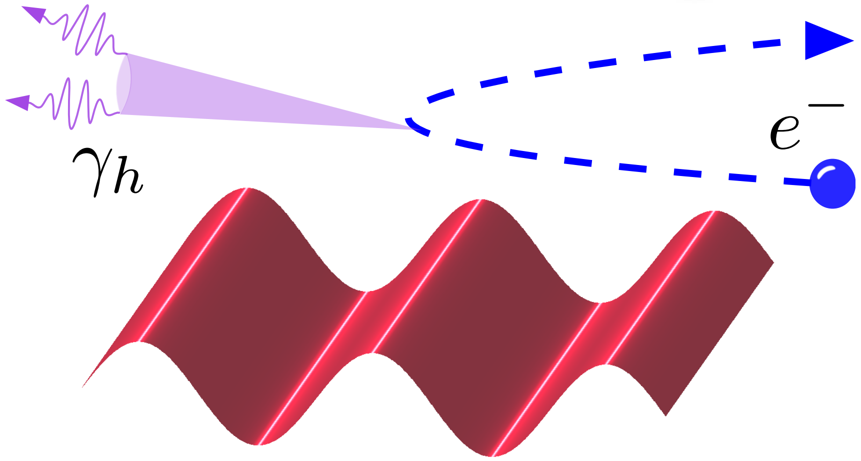
Di Piazza et al., Rev. Mod. Phys. **84**, 1177 (2012)

ExHILP, L'PHYS, EPS

QED processes in extreme light laser-plasma interaction

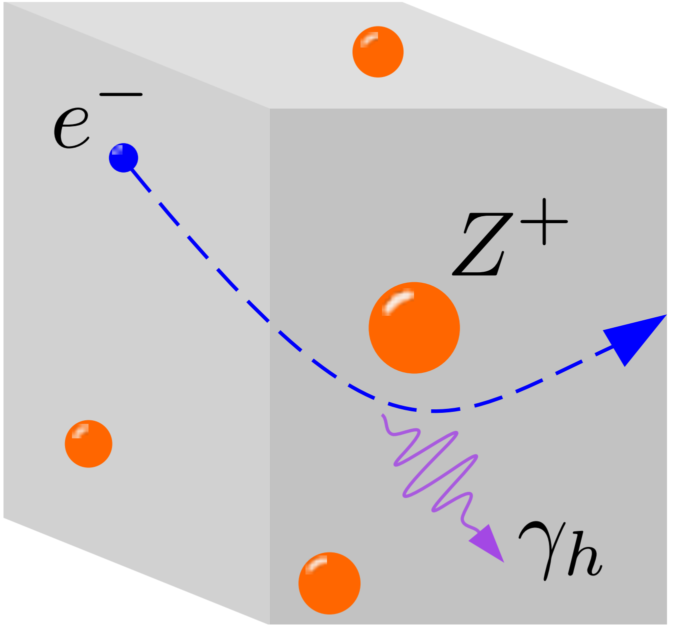
High-Energy Photon Production

Nonlinear Thomson and Compton scattering



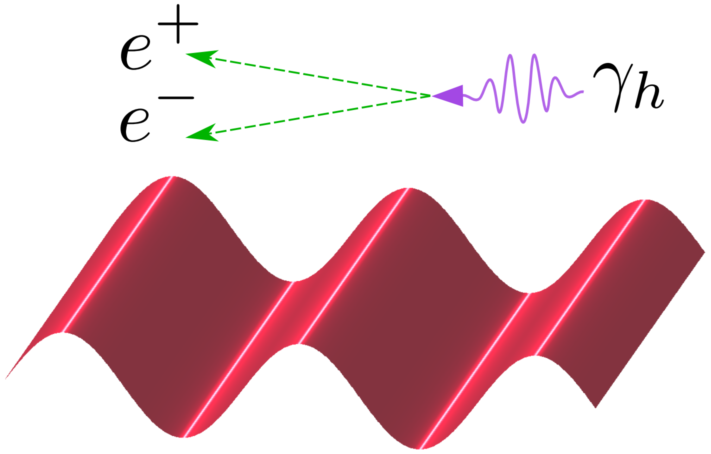
$$e^- + n\,\gamma_L \rightarrow e^- + \gamma_h$$

Bremsstrahlung



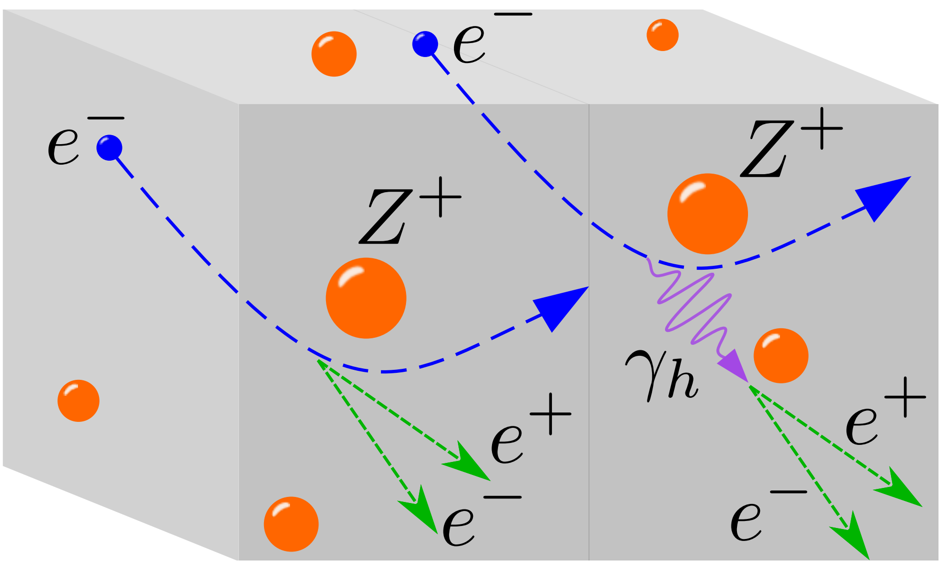
Electron-Positron Pair Production

Multi-Photon Breit-Wheeler Process

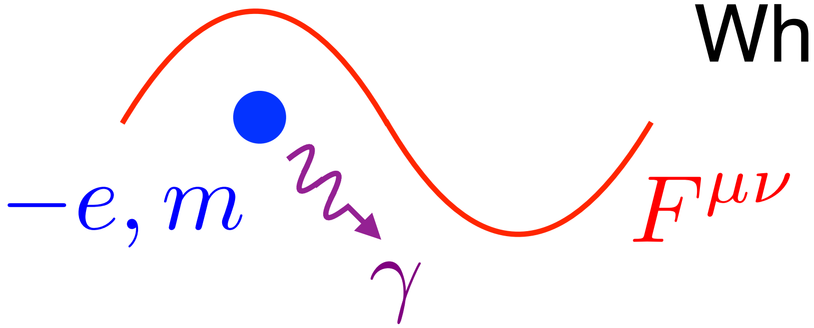


$$\gamma_h + n\,\gamma_L \rightarrow e^- + e^+$$

Pair production in strong Coulomb field



A closer look at the so-called radiation reaction problem



What is the equation of motion of a charged particle in a *given* electromagnetic field?

High-energy (γ) photon emission and its back-reaction

- in laser-matter interaction under extreme light conditions
- in relativistic astrophysics:
  e.g. γ-ray flares in the Crab nebulae

Niel et al., arXiv:1707.02618 (2017)

A closer look at the so-called radiation reaction problem

In CED, Radiation Reaction (RR) is modelled by a so-called radiation reaction force:

$$\frac{dp^\mu}{d\tau} = -\frac{e}{mc}\,F^{\mu\nu}\,p_\nu + g^\mu$$

The Landau-Lifshitz RR force:

$$g^\mu = -\frac{2}{3}\,\tau_e\,\left[\frac{e}{m^2\,c}\,\partial_\eta F^{\mu\nu}\,p_\nu\,p^\eta + \frac{e^2}{m^2\,c^2}\,F^{\mu\nu}\,F_{\eta\nu}\,p^\eta \right. \\ \left. - \frac{e^2}{m^4\,c^4}\,(F^{\nu\eta}\,p_\eta)\,(F_{\nu\alpha}\,p^\alpha)\,p^\mu\right]$$

Which for an ultra-relativistic radiating electron simplifies into a friction force:

$$mc^2\,\frac{d\gamma}{dt} = -ec\,\mathbf{u}\cdot\mathbf{E} - P_{\rm cl}$$

$$\frac{d\mathbf{p}}{dt} = -e\,(\mathbf{E} + \mathbf{u}\times\mathbf{H}) - P_{\rm cl}\,\mathbf{u}/(c\mathbf{u}^2)$$

A closer look at the so-called radiation reaction problem

In QED, one needs to account for the discrete and stochastic nature of high-energy photon emission:

$$\begin{aligned}
\frac{d}{dt} f_e &= \int_0^{+\infty} d\gamma_\gamma \, w_\chi(\gamma+\gamma_\gamma,\gamma_\gamma)\, f_e(t,\mathbf{x},\gamma+\gamma_\gamma,\mathbf{\Omega}) \\
&- f_e(t,\mathbf{x},\gamma,\mathbf{\Omega}) \int_0^{+\infty} d\gamma_\gamma w_\chi(\gamma,\gamma_\gamma)\,, \\
\frac{d}{dt} f_\gamma &= \int_1^{+\infty} d\gamma \, w_\chi(\gamma+\gamma_\gamma,\gamma_\gamma)\, f_e(t,\mathbf{x},\gamma+\gamma_\gamma,\mathbf{\Omega})
\end{aligned}$$

with the emission rate:

$$w_\chi(\gamma,\gamma_\gamma) = \left.\frac{d^2N}{dt d\gamma_\gamma}\right|_\chi (\gamma_\gamma,\gamma) = \frac{2}{3}\frac{\alpha^2}{\tau_e}\frac{\widetilde{G}(\chi,\gamma_\gamma/\gamma)}{\gamma\gamma_\gamma}$$

Linear Boltzmann description ⇔ Monte-Carlo procedure (PIC)

A closer look at the so-called radiation reaction problem

The classical limit of RR corresponds to the cumulative effect of the emission of many photons each carrying a tiny fraction of the emitting electron energy $\gamma_\gamma \ll \gamma$.

This allow us to derive a Fokker-Planck description:

$$\begin{aligned}\partial_t f_e \;&+\; \nabla\cdot[cu\mathbf{\Omega} f_e] - \frac{1}{mc^2}\partial_\gamma[ecu(\mathbf{\Omega}\cdot\mathbf{E})f_e] \\ &-\; \frac{e}{p}\nabla_{\mathbf{\Omega}}\cdot[(\mathbb{1}-\mathbf{\Omega}\otimes\mathbf{\Omega})\cdot(\mathbf{E}+u\mathbf{\Omega}\times\mathbf{H})f_e] = \mathcal{C}\,[f_e]\;,\end{aligned}$$

with the *Fokker Planck* operator:

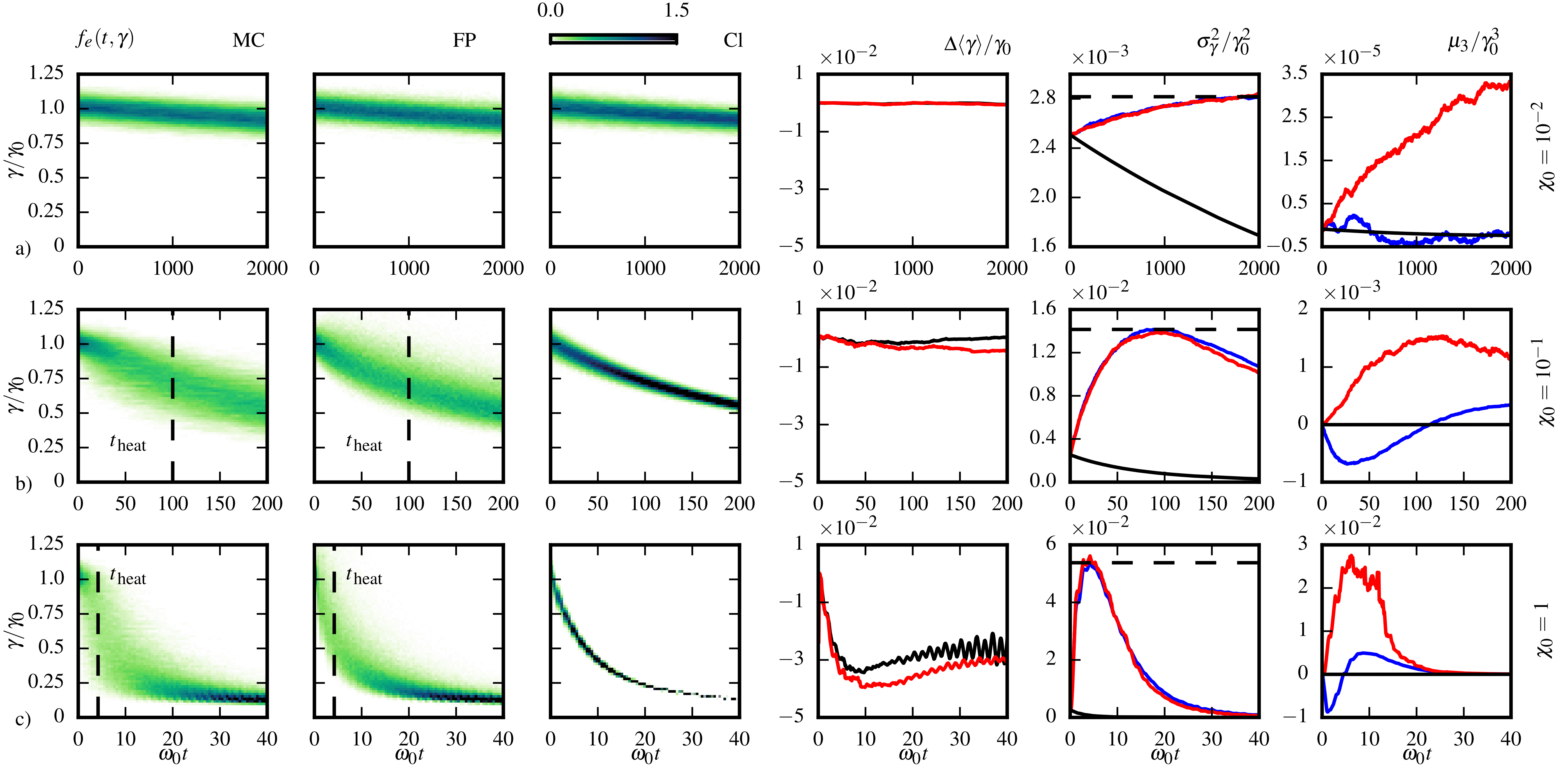
$$\mathcal{C}_{\rm FP}\,[f_e] = \partial_\gamma[S(\chi)f_e] + \frac{1}{2}\partial_\gamma^2[R(\chi,\gamma)f_e]$$

which is mathematically equivalent to the SDE:

$$d\mathbf{p} = -e(\mathbf{E}+\mathbf{u}\times\mathbf{H})dt - \underbrace{mc^2 S(\chi)}_{mc^2\,S(\chi)\,=\,P_{\rm cl}\,g(\chi)}\,\mathbf{u}/(c\mathbf{u}^2)dt + mc^2\sqrt{R(\chi,\gamma)}\,\underbrace{dW}_{\text{Wiener process}}\,\mathbf{u}/(c\mathbf{u}^2)$$

A closer look at the so-called radiation reaction problem

$$d\mathbf{p} = -e(\mathbf{E}+\mathbf{u}\times\mathbf{H})dt - \underbrace{mc^2 S(\chi)}_{mc^2\, S(\chi) \,=\, P_{\rm cl}\, g(\chi)}\,\mathbf{u}/(c\mathbf{u}^2)dt + mc^2\sqrt{R(\chi,\gamma)}\,\underbrace{dW}_{\text{Wiener process}}\,\mathbf{u}/(c\mathbf{u}^2)$$



Conclusions

The Apollon laser:

- multi-beam, multi-PW laser facility
- first experimental campaigns in 2018
- open to the scientific community at the horizon 2020

Kinetic simulation of plasmas:

- the open-source, collaborative PIC code SMILEI
- available to scientific community
- laser-plasma interaction (LPI) & astrophysics
- research & teaching platform
- High-Performance Computing (co-development with HPC experts)

Bridging relativistic LPI & Quantum Electrodynamics (QED):

- high-energy photon emission & its back-reaction
- pair production in laser & Coulomb field
- theory & simulation