Société Française de Physique
DIVISION ACCÉLÉRATEURS

Journées
Accélérateurs 2019

Modélisation numérique des accélérateurs à plasma pour des machines « exascale »

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CEA-Saclay

Theoretical/numerical branch of the

PHI PHYSICS AT HIGH INTENSITY

group


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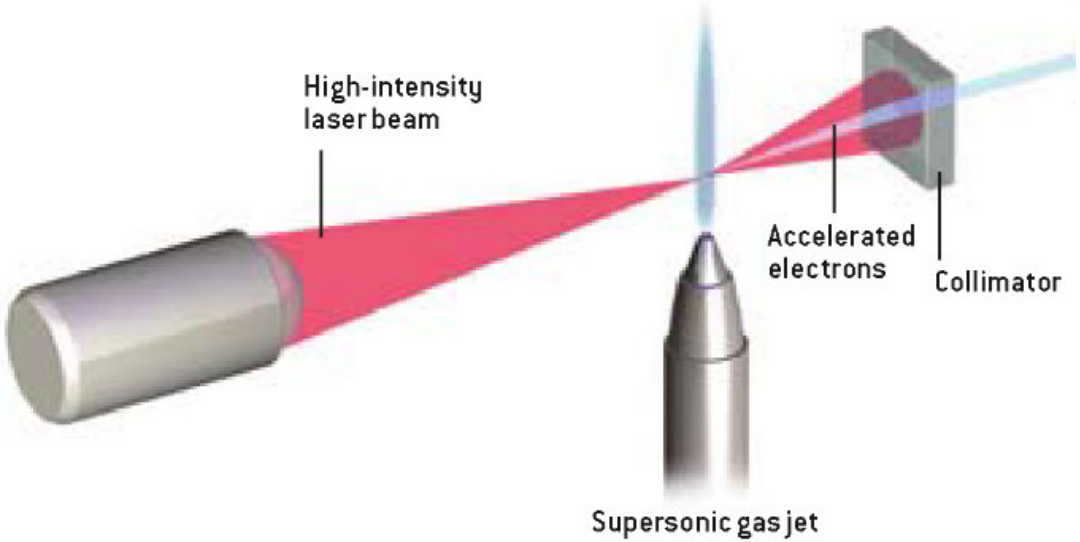
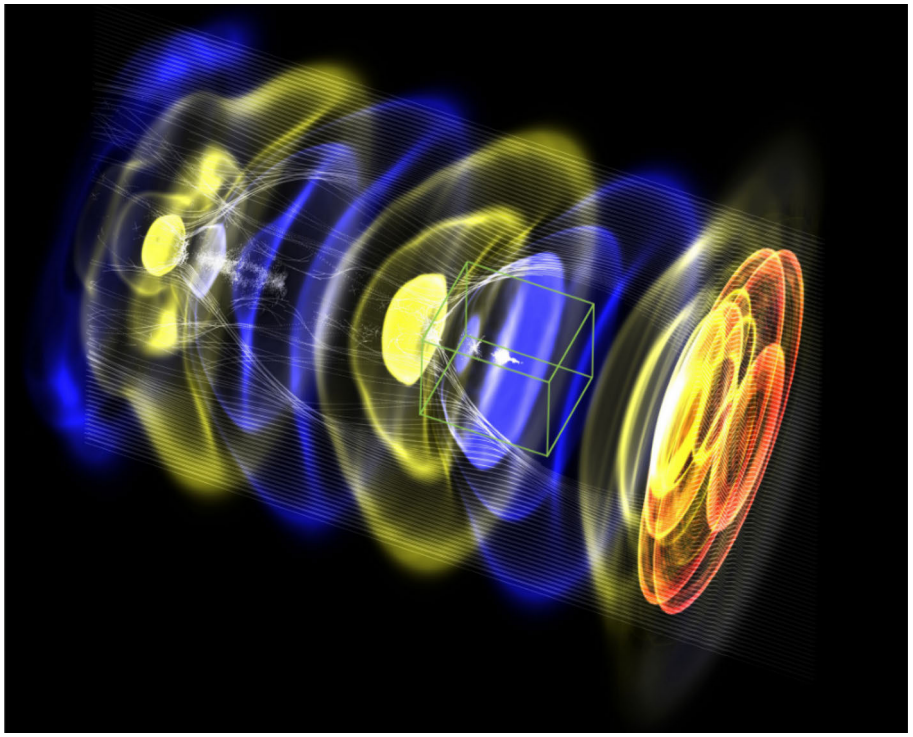
Modélisation numérique des accélérateurs à plasma pour des machines « exascale »

WarpX

Modélisation numérique des **accélérateurs à plasma** pour des machines « exascale »

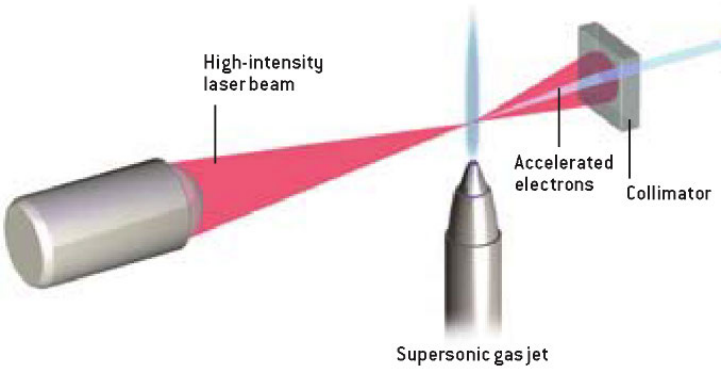


Modélisation numérique des accélérateurs à plasma pour des machines « exascale »

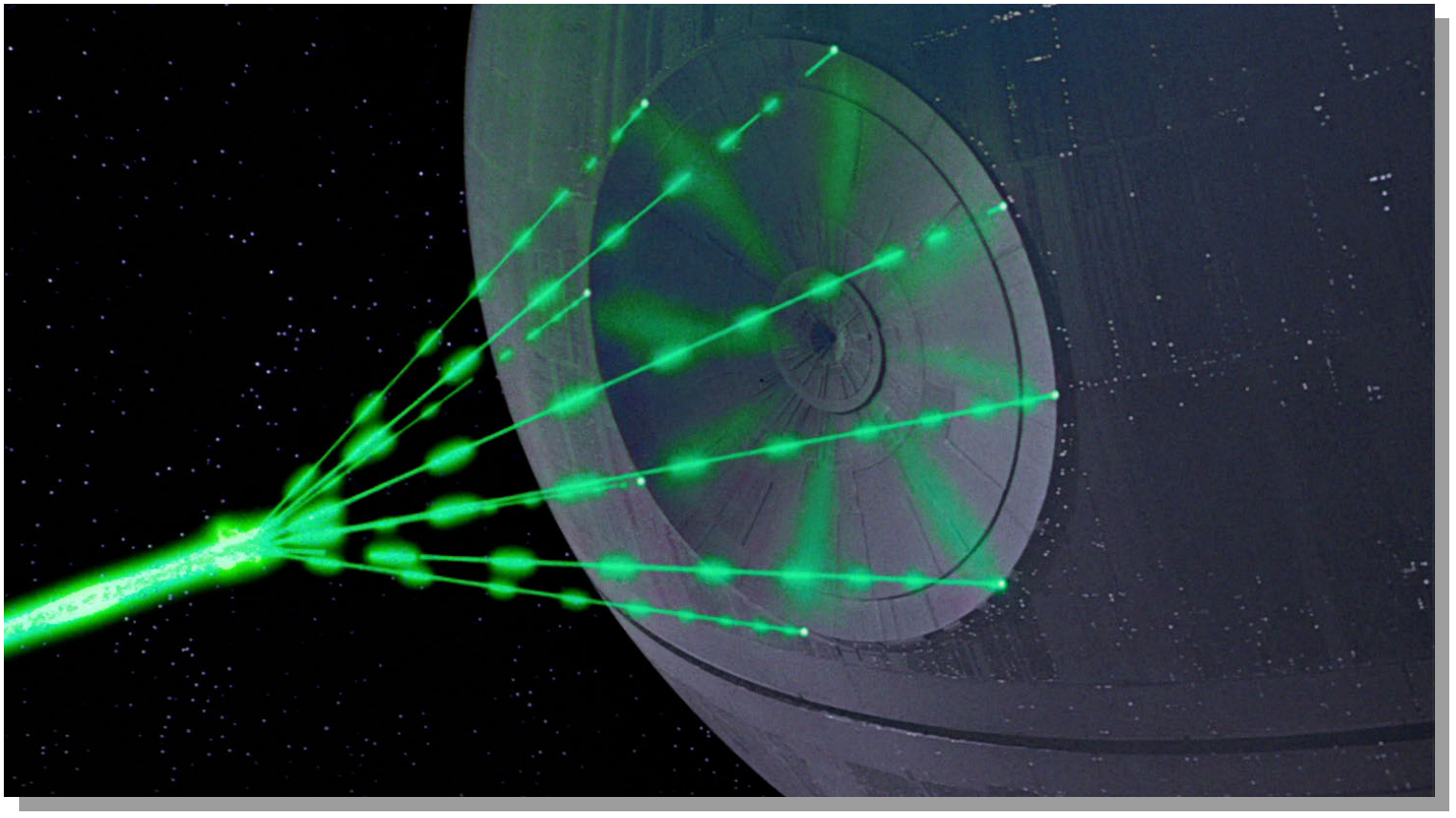


Modélisation numérique des accélérateurs à plasma pour des **machines « exascale »**

We can use **plasma-based schemes** to accelerate particles



Many plasma-based accelerators exploit **very powerful lasers**



We can use **Ti:Sapphire lasers** (from TeraWatt to PetaWatt) or **PW-class Nd-based lasers**

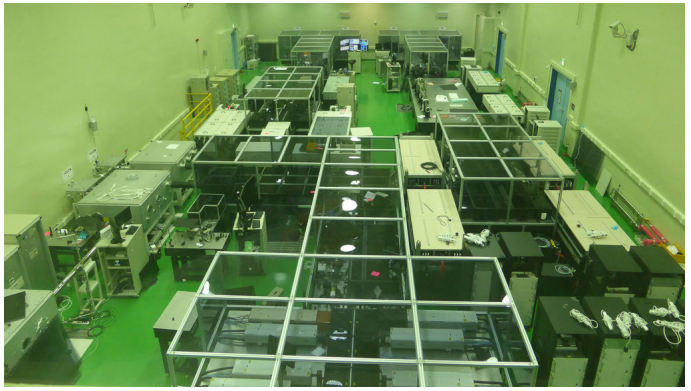
Ti:Sapphire (10s fs, λ ~ 800 nm)

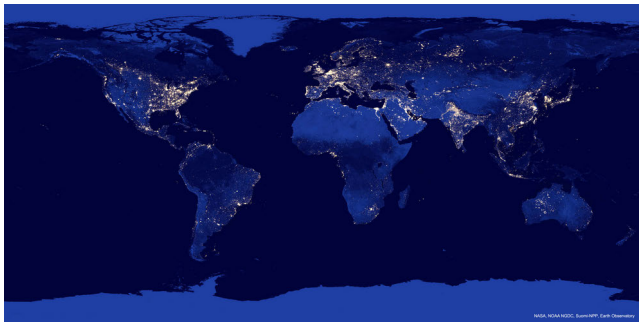
Nd-based (ps, λ ~ 1 μm)

~ 1 TW
table-top

~ 1 PW
huge
facilities

~ 1 PW
many tables

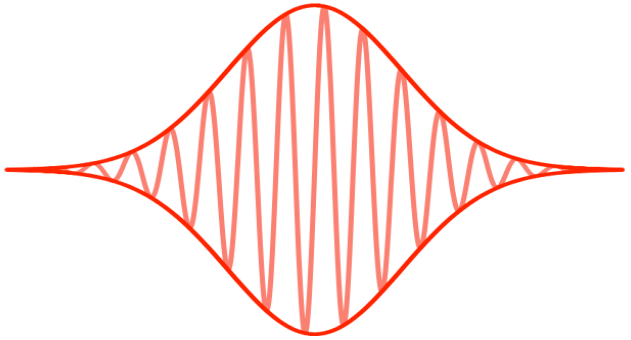




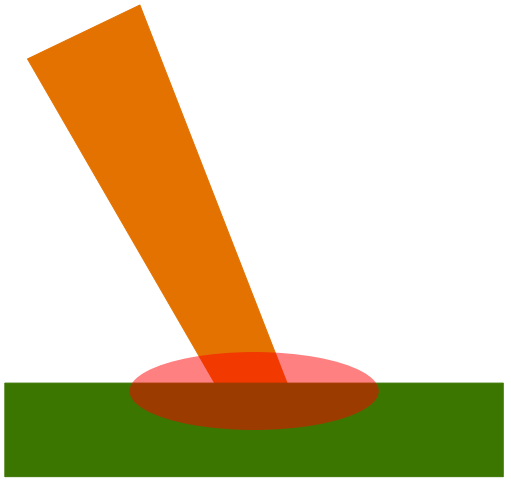
World electricity generation: **3 TW!**

These lasers are **very short** and can be **tightly Focused**, up to $I \sim 10^{22}$ W/cm^2 !

Very short
(10s fs - ps)



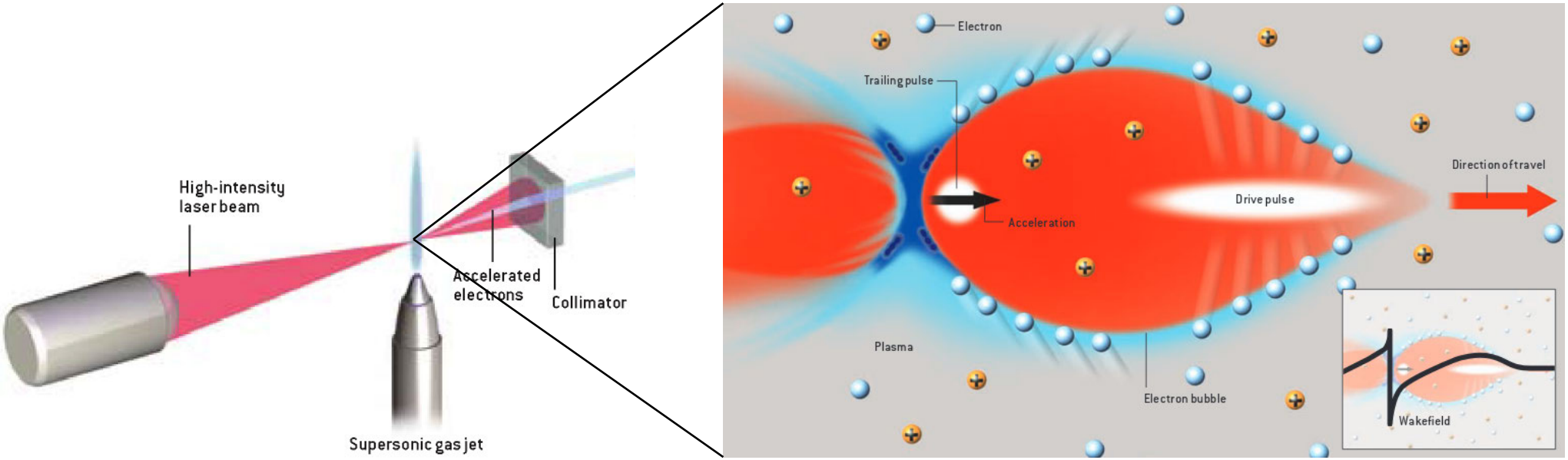
Tightly focused
(few μm)



Current record:
$I \sim 10^{22}$ W/cm^2

Any irradiated material becomes a **plasma**

Lasers interacting with low-density plasmas can accelerate few pC of electrons up to GeV energies



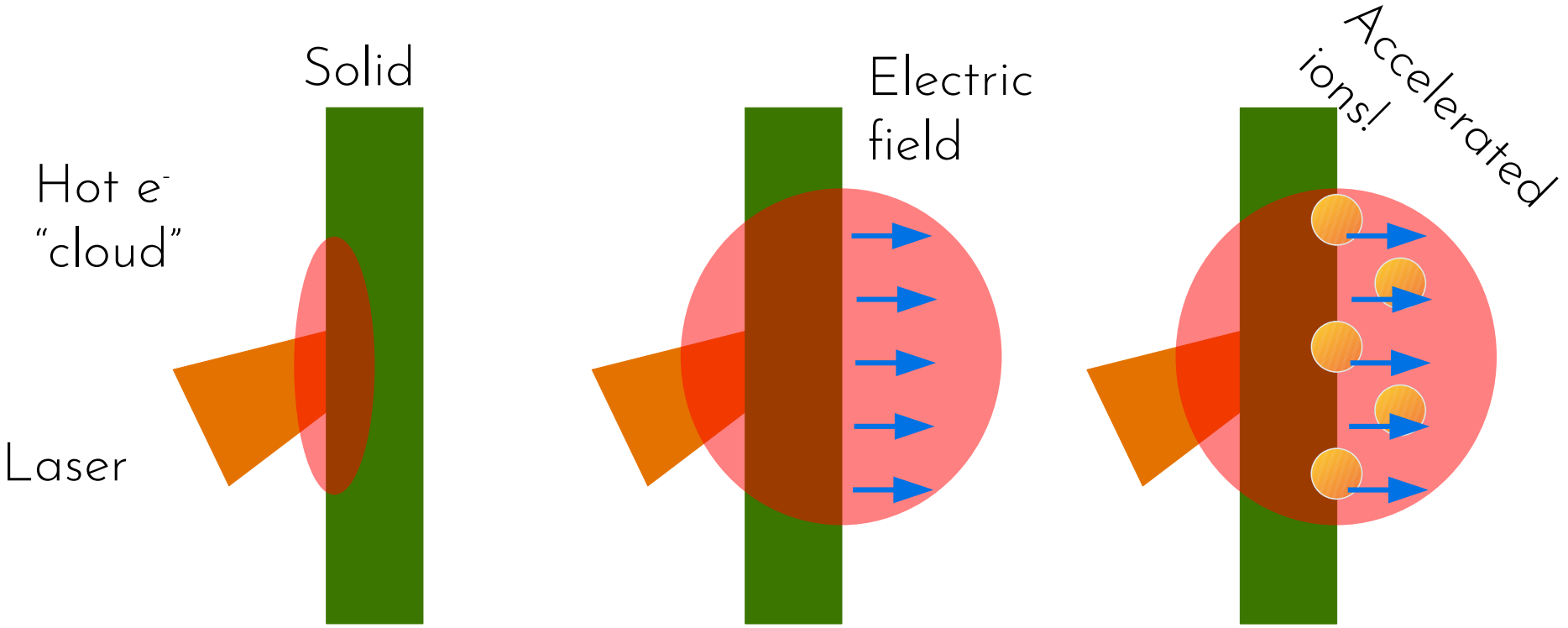
Scientific American 294, 40-47 (2006)

S.P.D. Mangles & al. Nature 431 (2004)

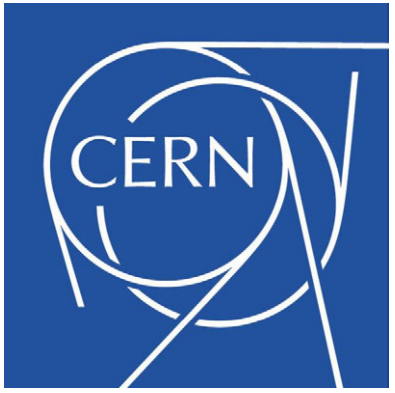
C.G.R. Geddes & al. Nature 431 (2004)

J. Faure & al. Nature 431 (2004)

Few nC of Ions can be accelerated up to ~ 100 MeV e.g. via Target Normal Sheath Acceleration

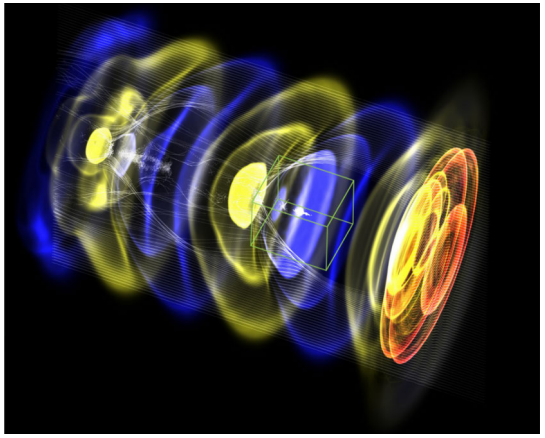


There are also non laser-based plasma accelerators



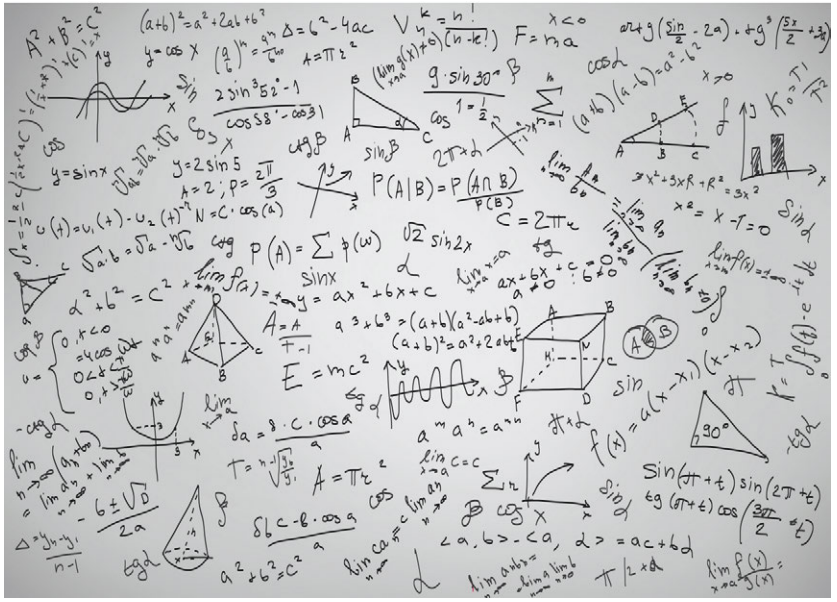
The AWAKE project at CERN exploits proton-driven wakefield acceleration to generate **several GeVs electrons**

E. Adli & al. Nature 561 (2018)

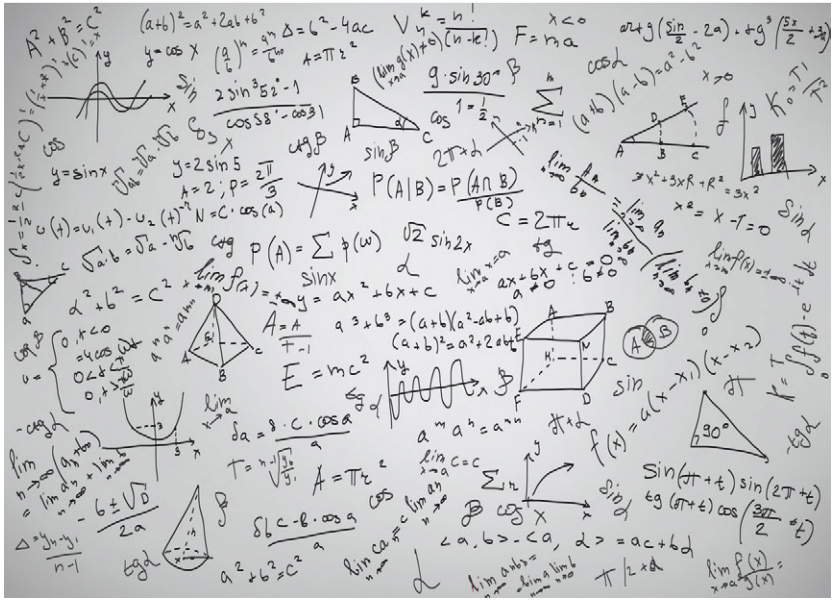


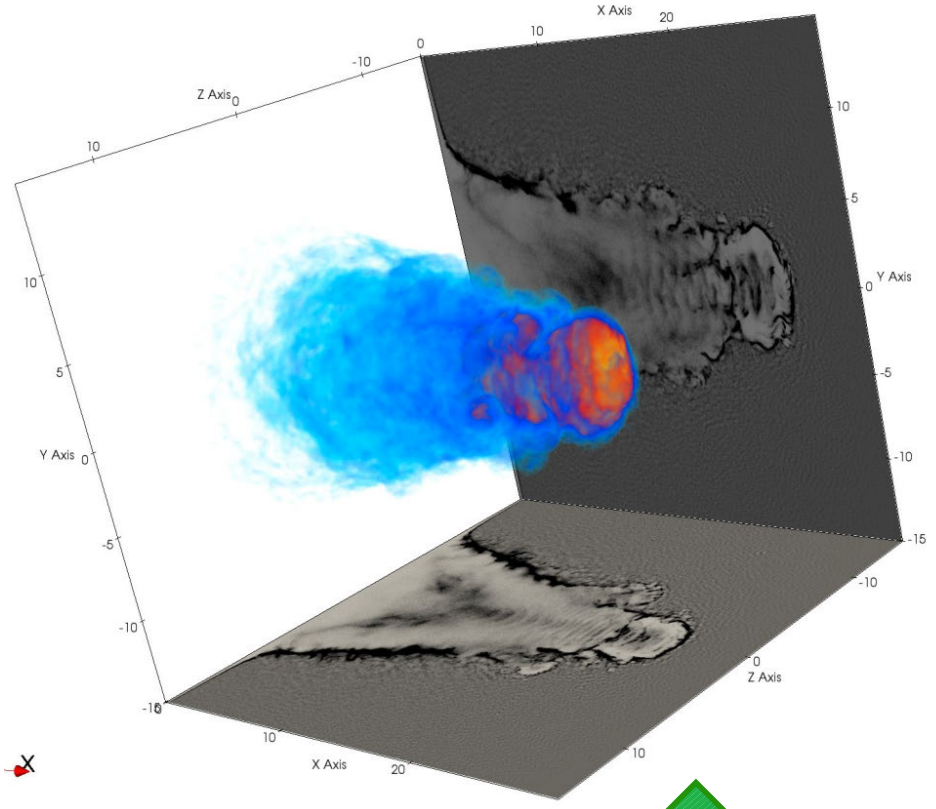
We need to **model** these accelerators

Complexity of plasma phenomena often defies an analytical description



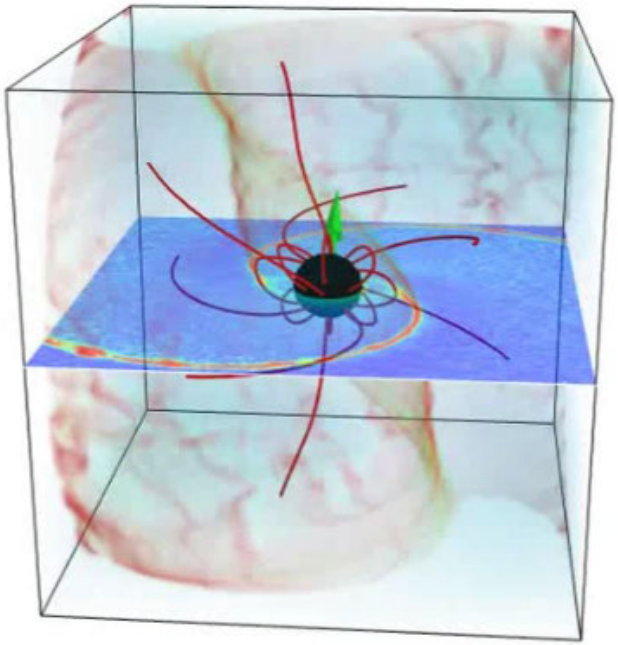
Complexity of plasma phenomena often defies an analytical description → **numerical simulations**



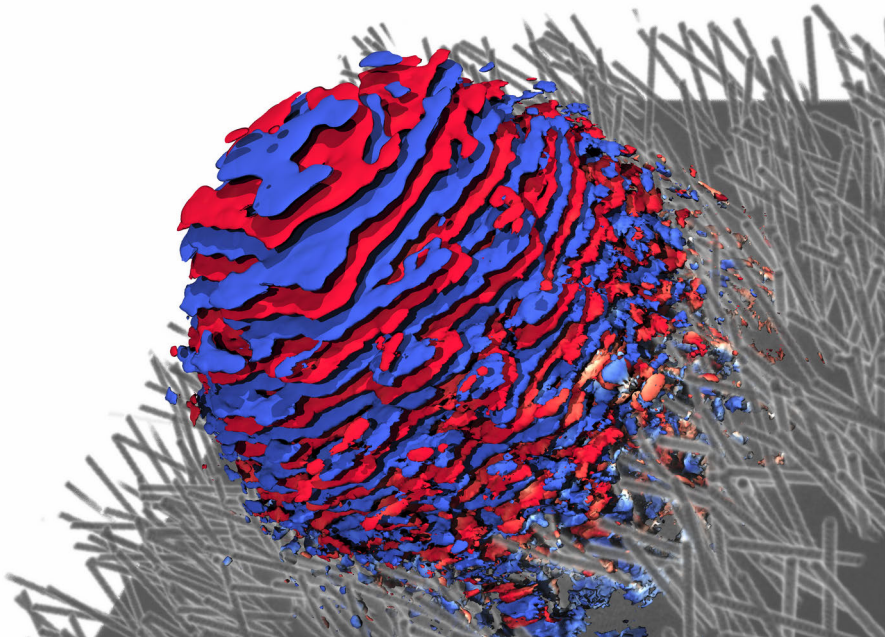


Particle-In-Cell (PIC) codes are a standard numerical tool to model kinetic plasmas

From **astrophysics** to **laser-plasma interaction**

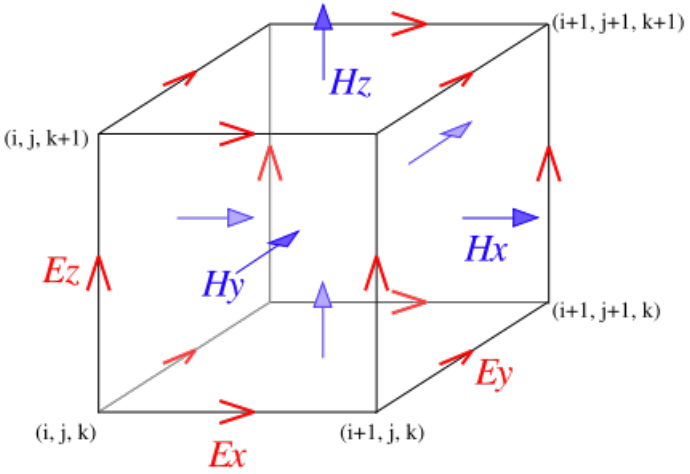


A.A. Philippov & al.
Astrophys J. Lett.
801 (2015)

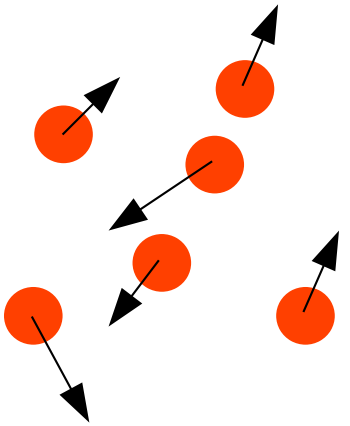


PIC codes: Maxwell equations are solved on a grid and macro-particles are used for the plasma

Maxwell solver



Particle pusher



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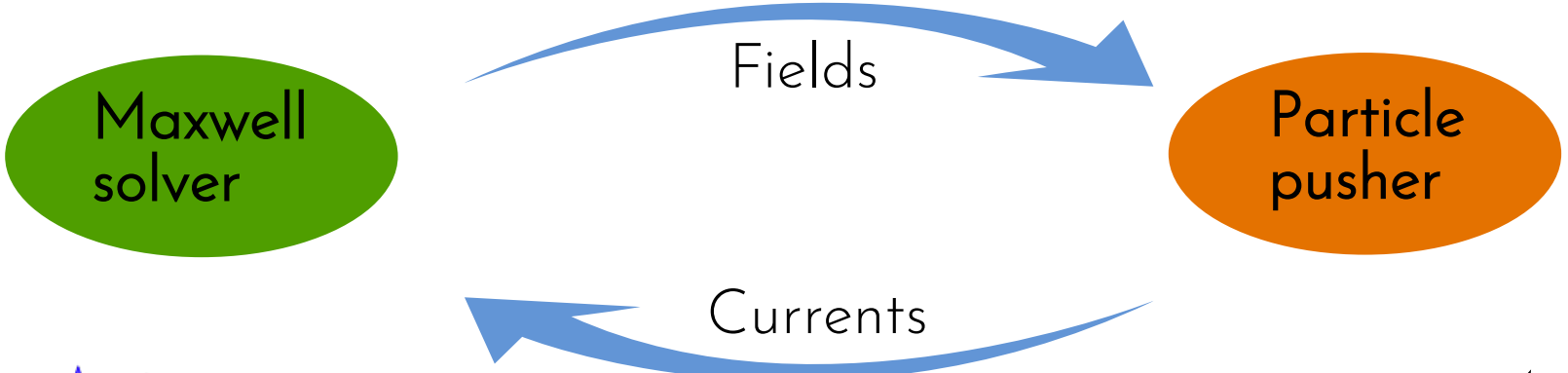
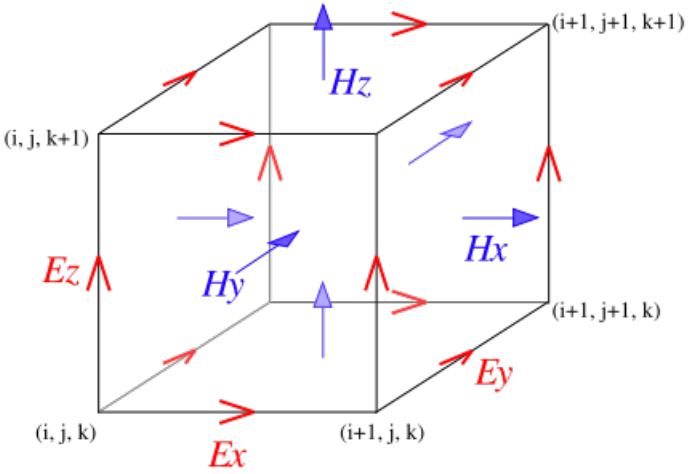
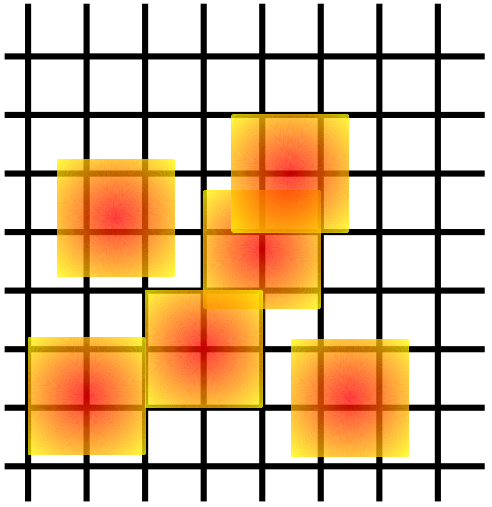
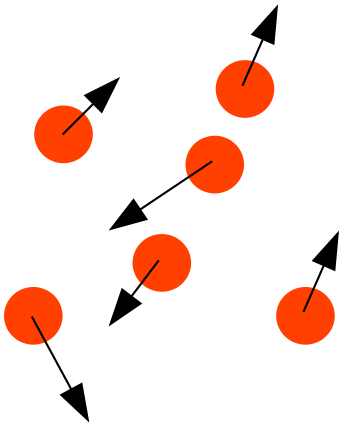




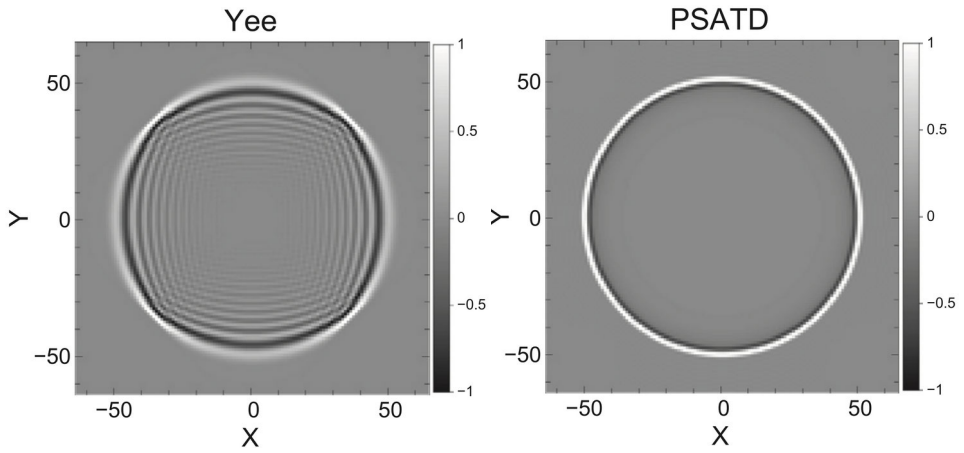
grid ⟷ particles interpolations





We need to face several challenges:

1) For some problems we need **very high accuracy**

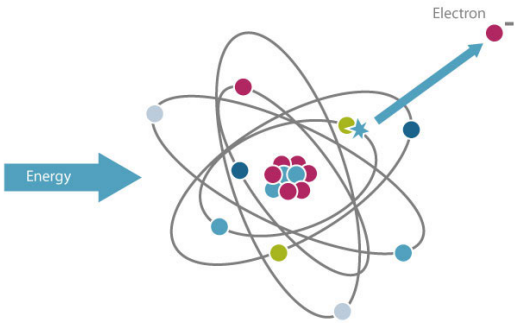


Spectral solvers can reduce numerical dispersion

H.Vincenti & al. Comput. Phys. Comm. 200 (2016)

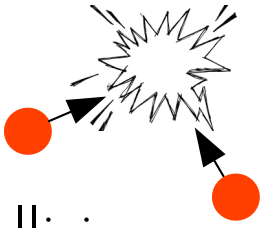
We need to face several challenges:

1) For some problems we need **very high accuracy**

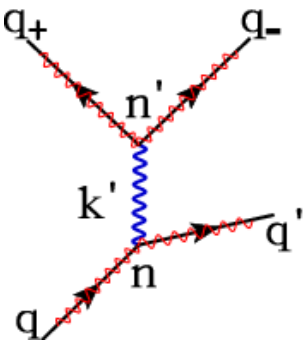


Ionization

2) For some problems we need to include **more physics**



Collisions



QED

We need to face several challenges:

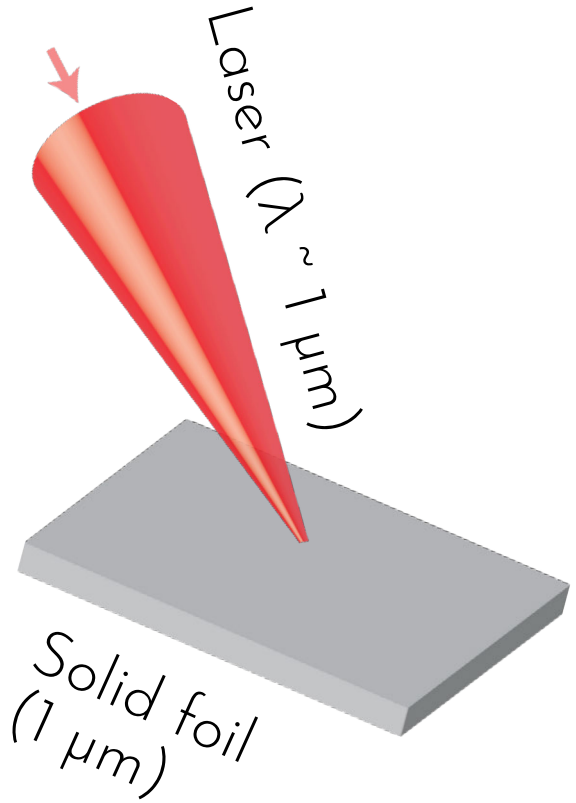
1) For some problems we need
very high accuracy

2) For some problems we need
to include **more physics**

3) Simulations can be **huge!**

Simulations can be huge

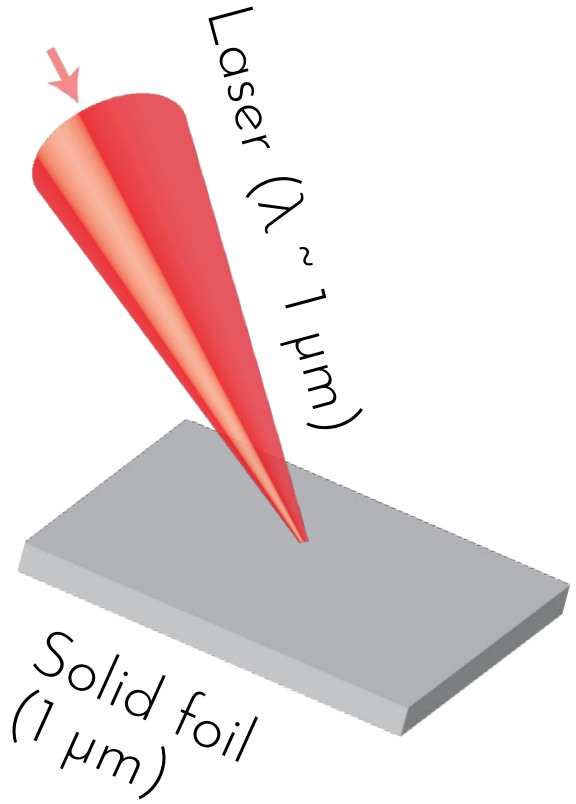
Physical problem



Timescale to
simulate: 100 fs

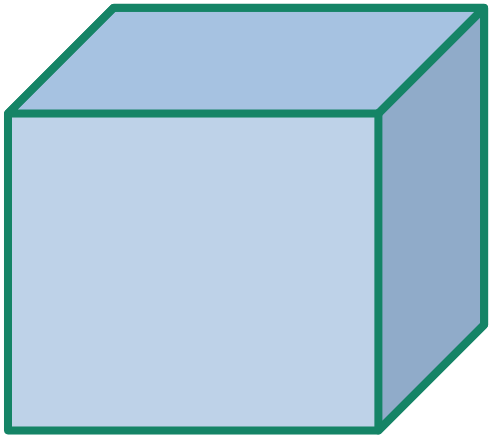
Simulations can be huge

Physical problem



Timescale to
simulate: 100 fs

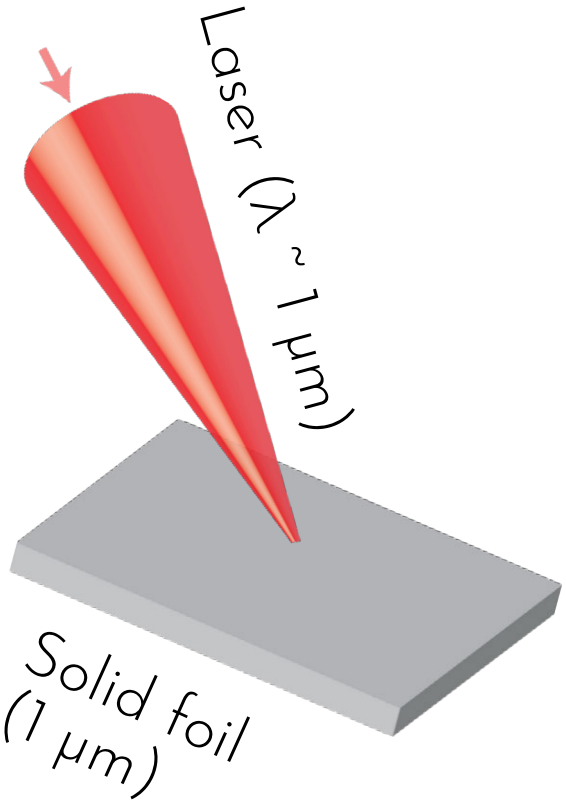
Numerical problem



30x30x30 μm^3 box
5 nm resolution
200 particles per cell

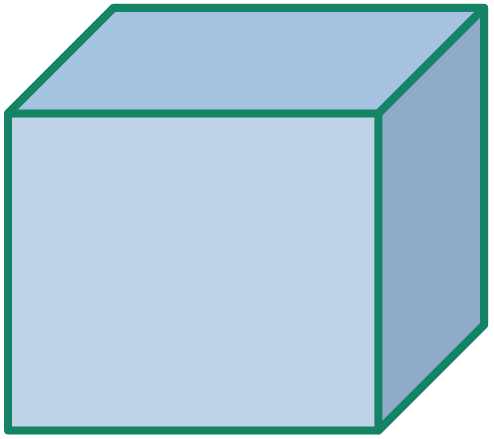
Simulations can be huge

Physical problem



Timescale to simulate: 100 fs

Numerical problem



30x30x30 μm^3 box
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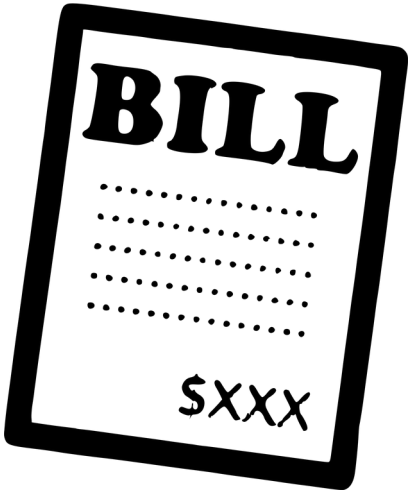
Computational cost



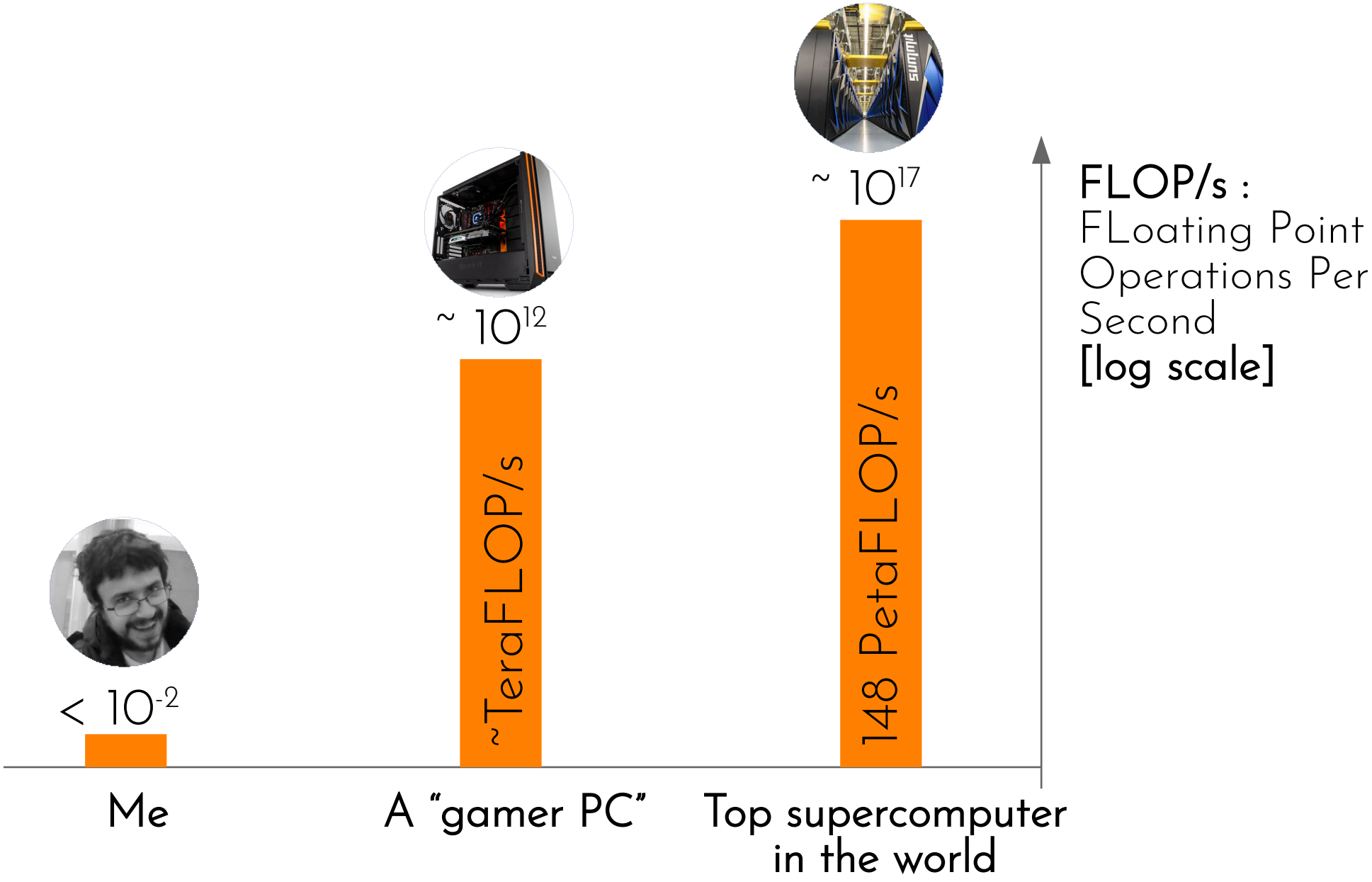
~100 Terabytes of RAM
~10.000 steps
~100 core-hours each!

~ 10.000 – 100.000 $

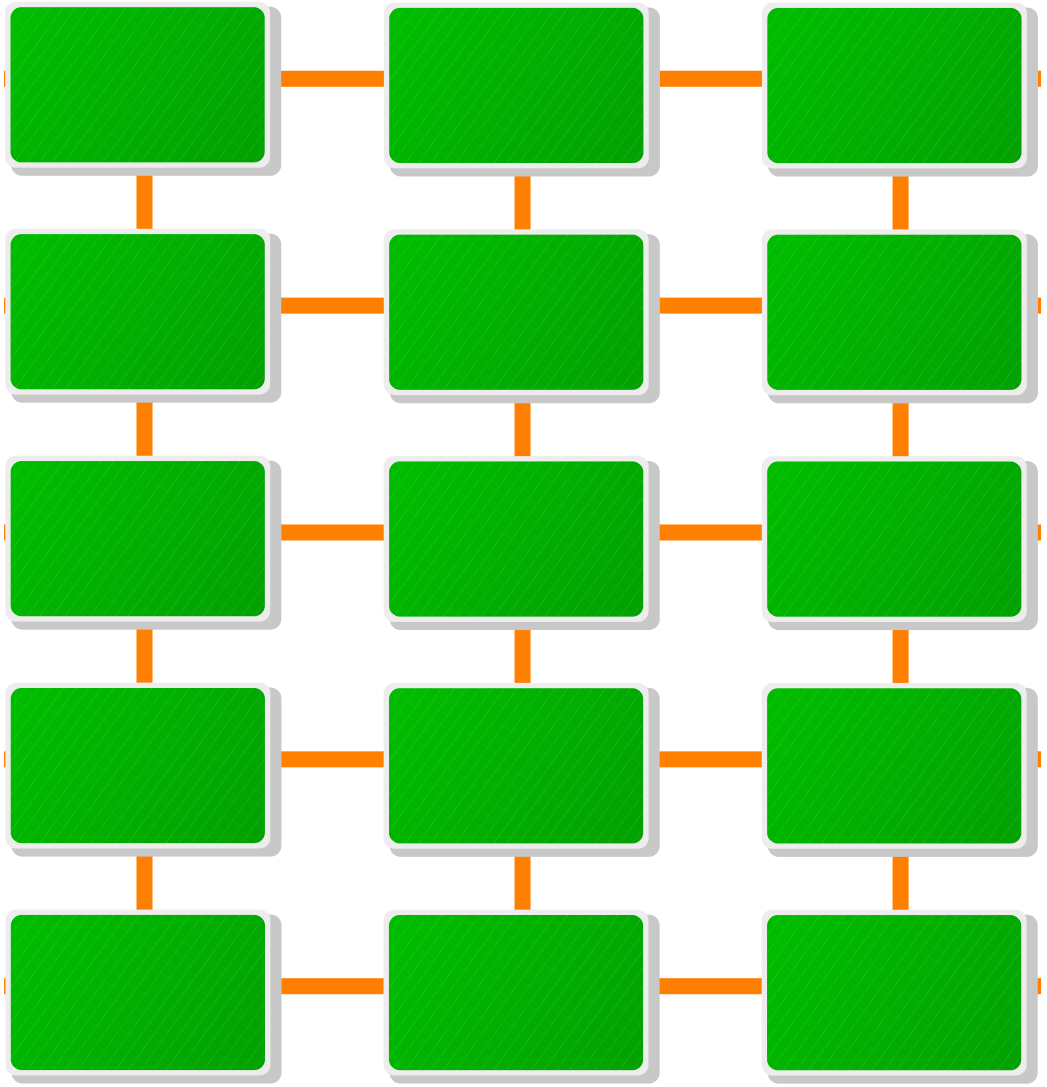
We need **supercomputers** to perform these simulations

Supercomputers are much more powerful than ordinary computers

Supercomputers are much more powerful than ordinary computers (and people)!



Supercomputers are made by many nodes (thousands) connected with a high speed network



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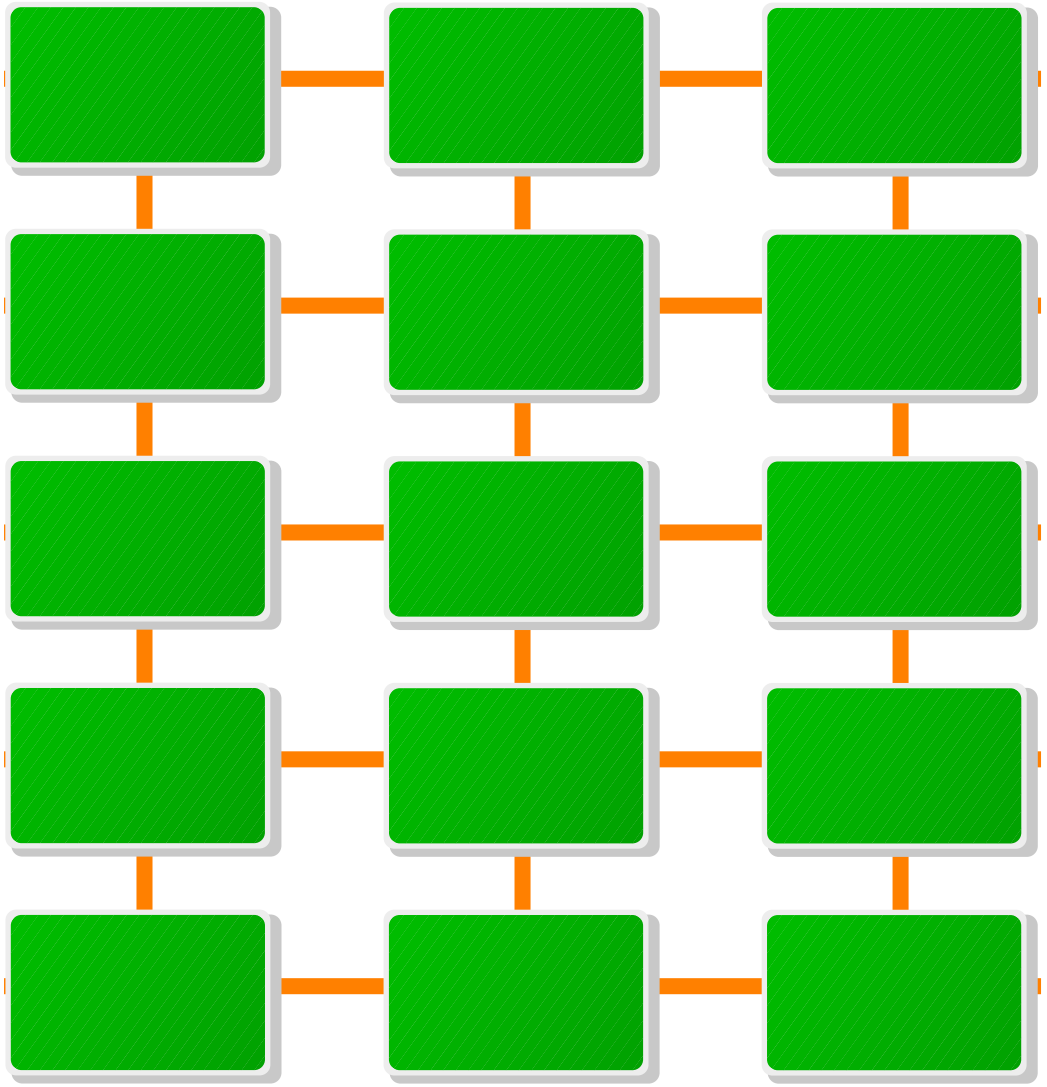
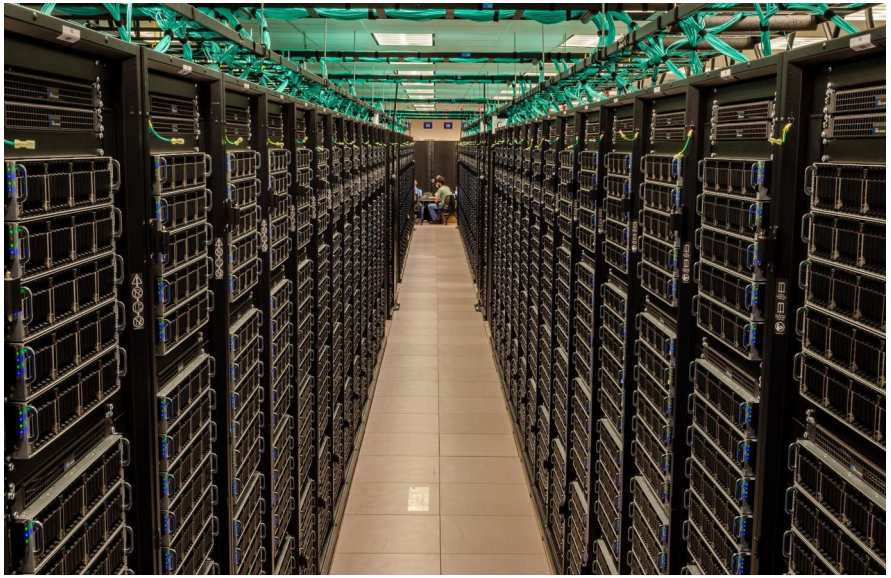
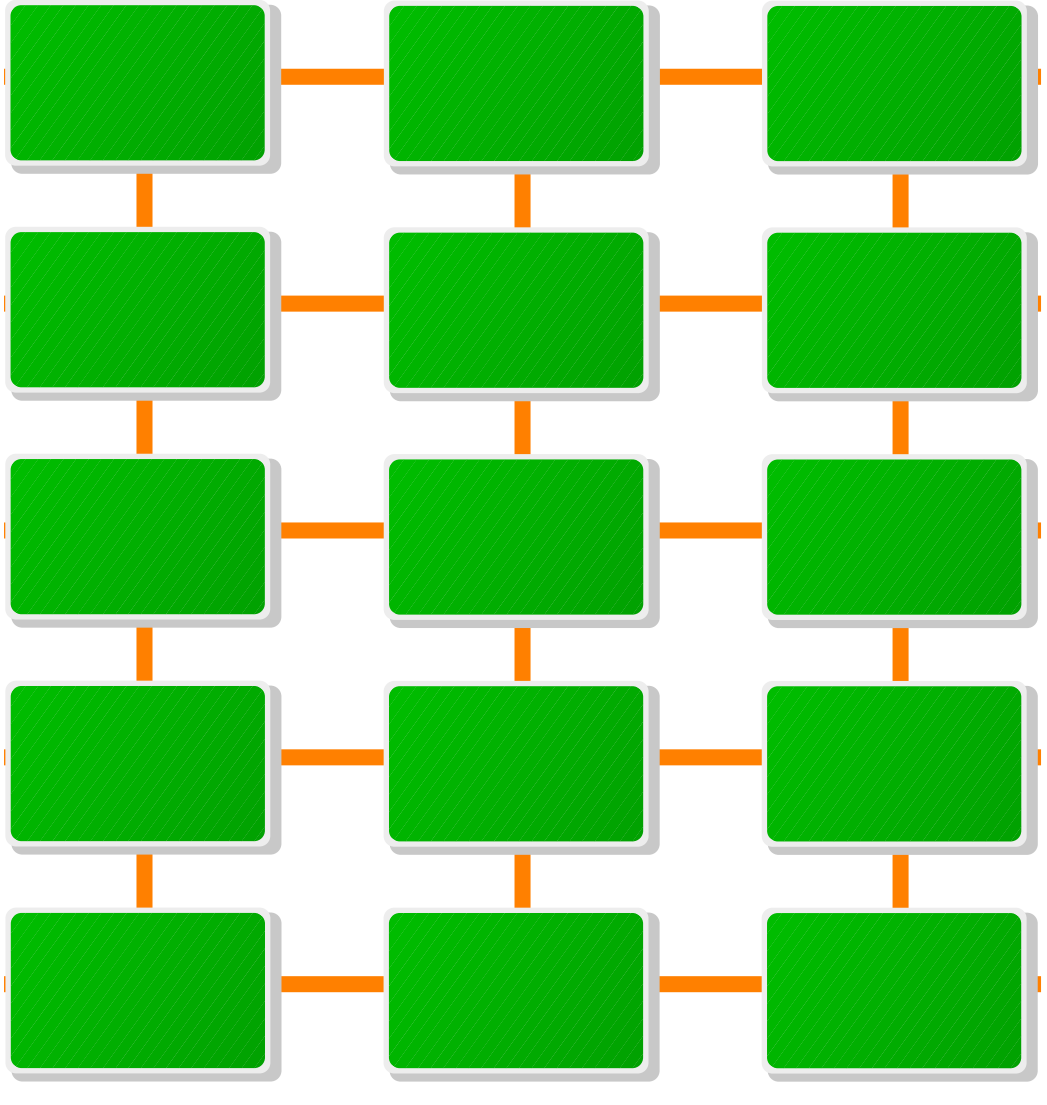
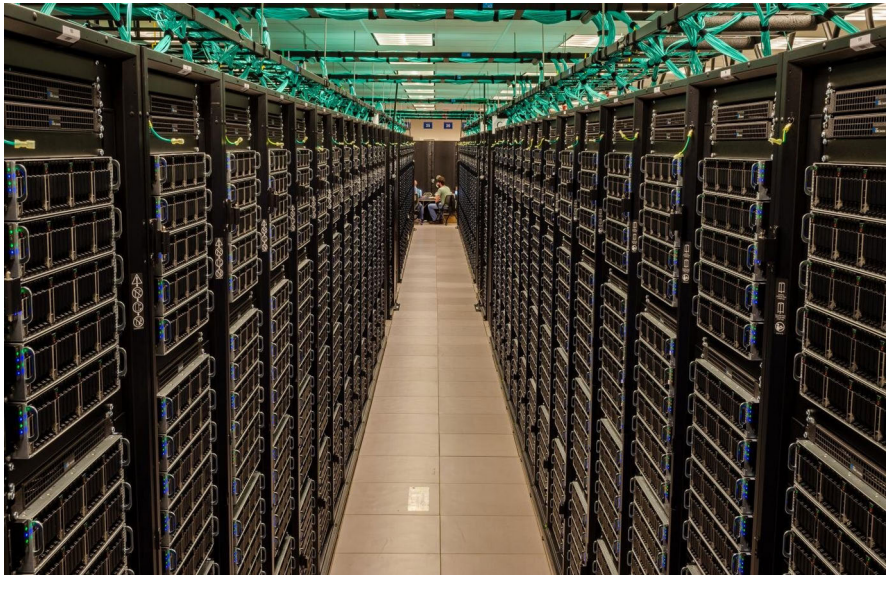




In real life they look like this

Supercomputers are made by many nodes (thousands) **connected with a high speed network**



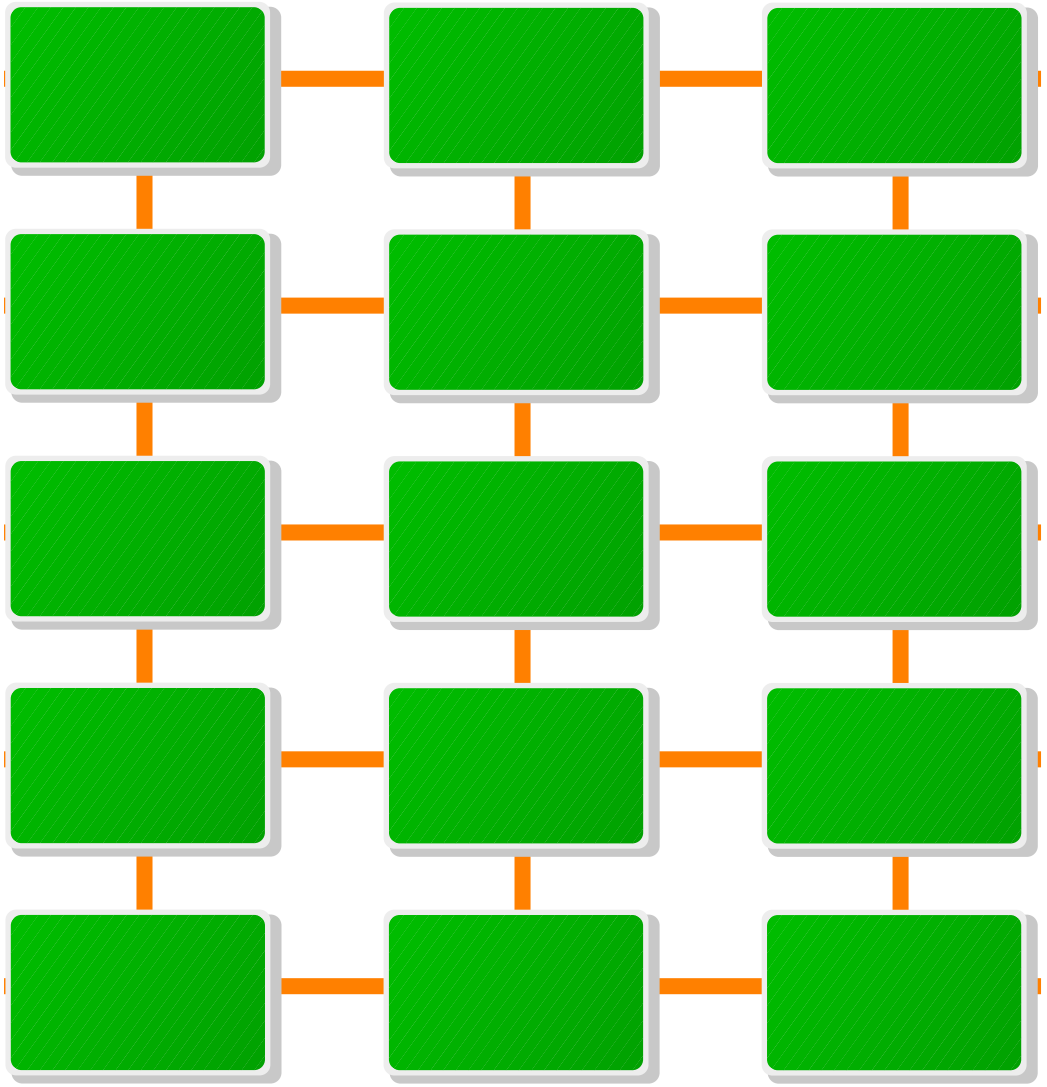


In real life they look like this

And they require several **MegaWatts** of electrical power!

Éguzon Dam
(12 MW, France)

Computation is cheap, while moving data across the system is very expensive!



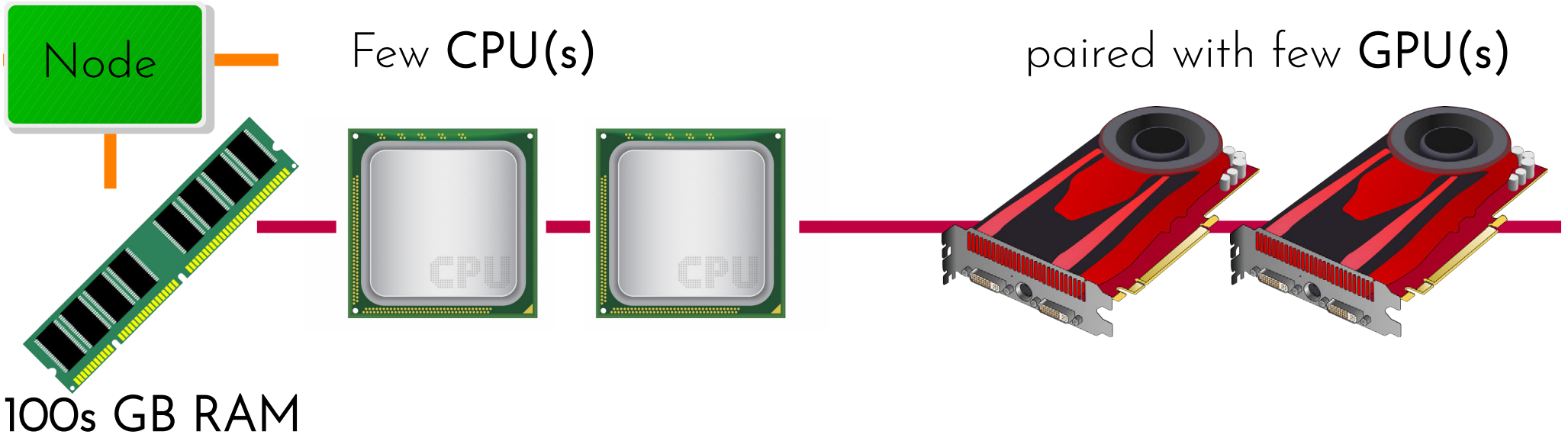
Computing is cheap
11 picoJoules for a FMA operation

Local access to data is cheap
24 picoJoules for cross-die word access

Reading from RAM is expensive
4800 picoJoules for DP DRAM read to register

Moving data across the network is expensive!
9000 picoJoules for DP word transmit across system

Modern supercomputers have many computing units per node ("fat nodes")



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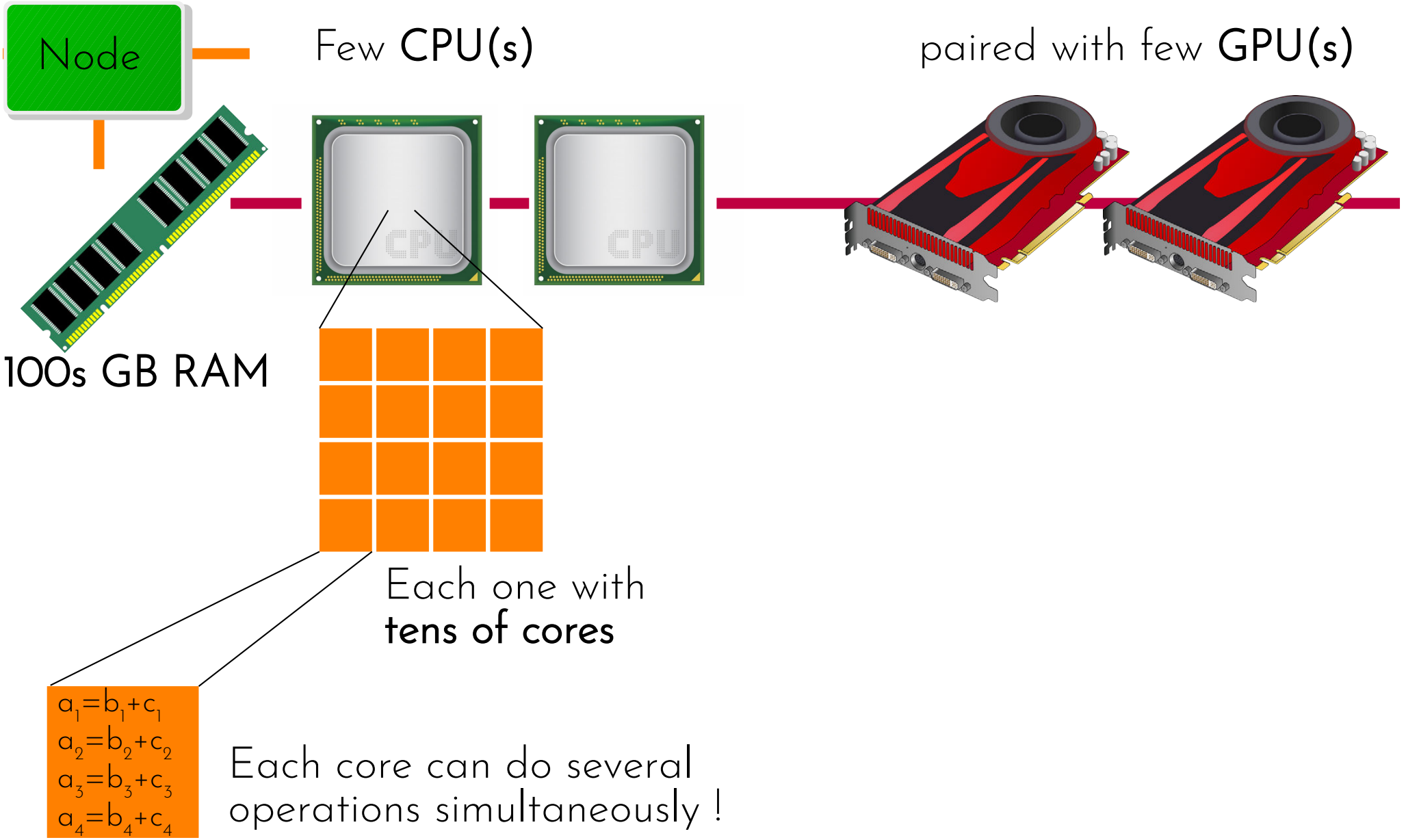

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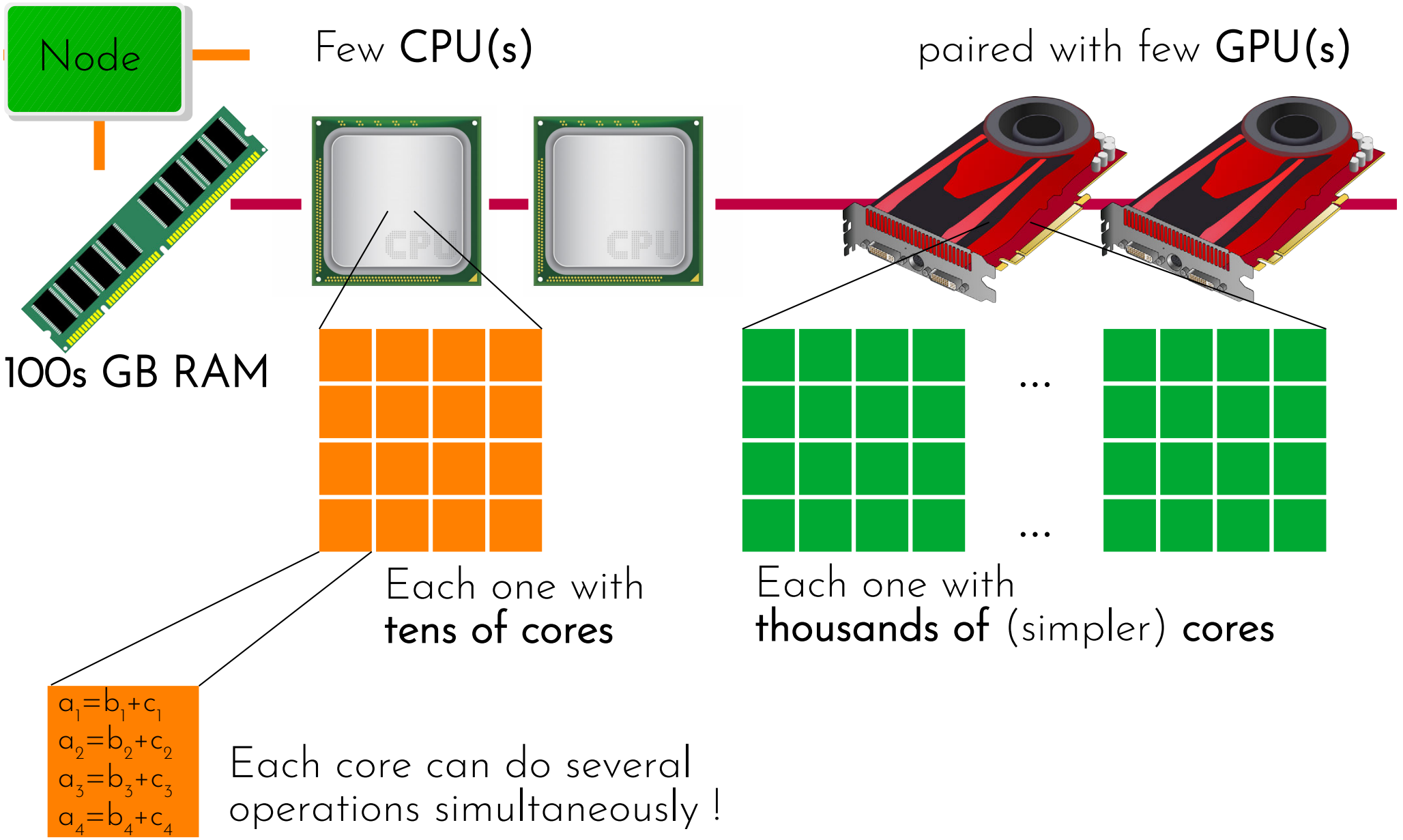
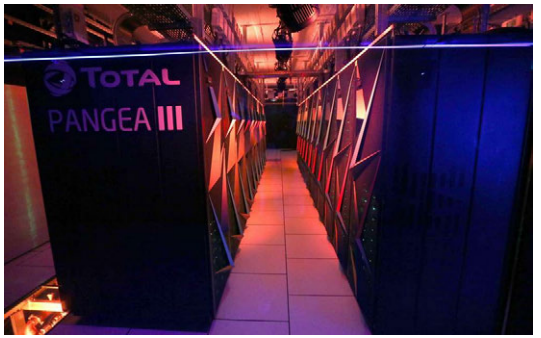


Top supercomputers have this heterogeneous architecture

1st supercomputer in **France** (11th in the world)
Pangea III (Total, FR): **17.86 PetaFLOP/s**

IBM POWER9 + NVIDIA Volta GV 100



TOTAL

1st supercomputer in **the World**
Summit (ORNL, USA): **148.6 PetaFLOP/s**

IBM POWER9 + NVIDIA Volta GV 100

OAK RIDGE
National Laboratory

TOP 500
The List.

Top supercomputers have this heterogeneous architecture

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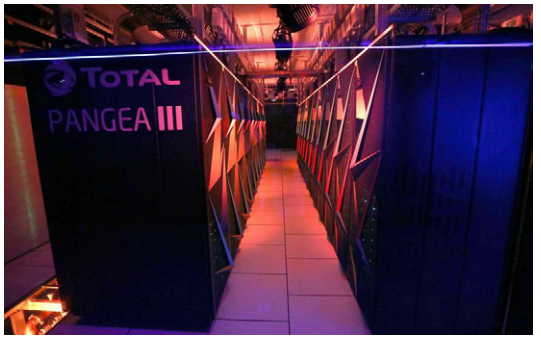

TOTAL

1st supercomputer in **the World**
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OAK RIDGE National Laboratory

1st **exascale** machine in the **World** (2021?)
Aurora (ANL, USA): ~ **1 ExaFLOP/s**

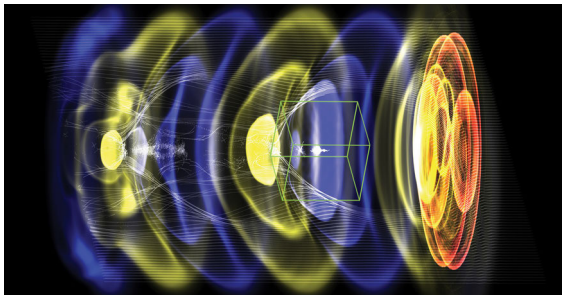
Intel CPU + Intel Xe integrated GPU

Argonne NATIONAL LABORATORY

We need **numerical codes** up to these machines

WarpX: an advanced electromagnetic Particle-In-Cell code for exascale architectures

WarpX: an advanced electromagnetic Particle-In-Cell code for exascale architectures



BERKELEY LAB

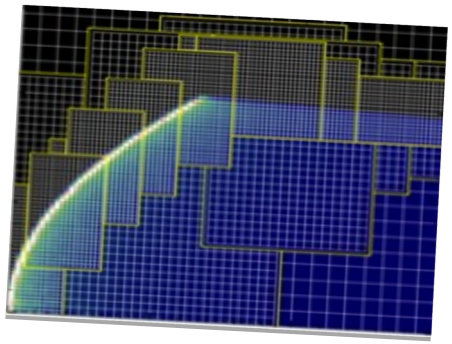
EXASCALE COMPUTING PROJECT

open source initiative Approved License®

Open-source & available on Github

- Source: **github.com/ECP-WarpX/WarpX/**
- Documentation: **ecp-warpx.github.io/**

Built on top of other open-source codes:



AMReX
Infrastructure

PICSAR
Additional physics:
QED [WIP]

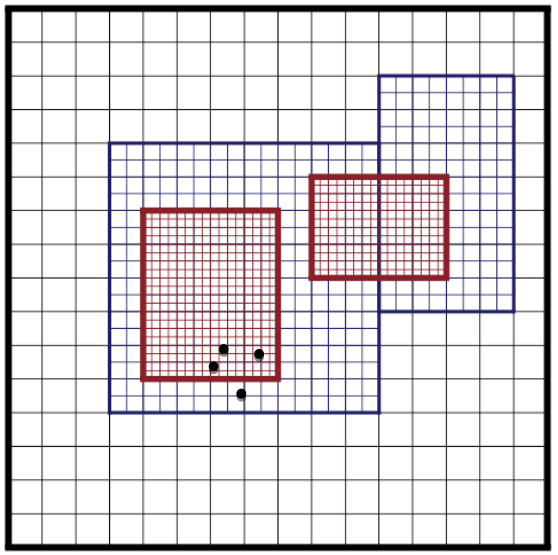
P-I-C-S-A-R
Particle-In-Cell Scalable Application Resource

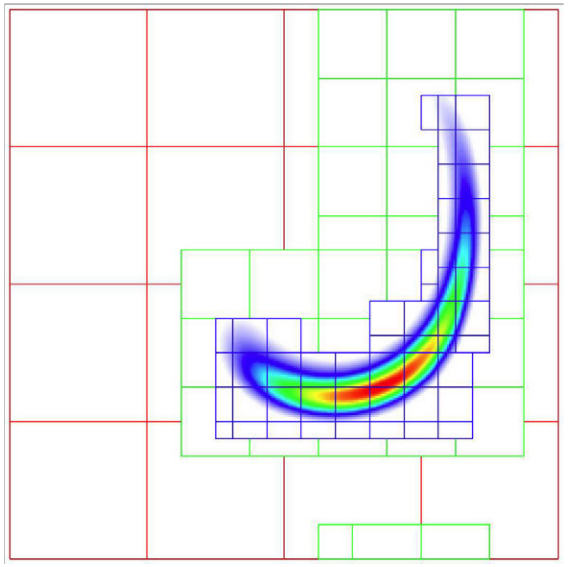
WarpX implements a unique combination of advanced algorithms

- Load balancing
- Mesh refinement
- Spectral solvers
- Boosted-frame simulations
- Axisymmetric solver

In some cases they allow for **orders of magnitude speed-ups!**

AMReX provides mesh refinement capability (most "exotic" feature in a PIC code)



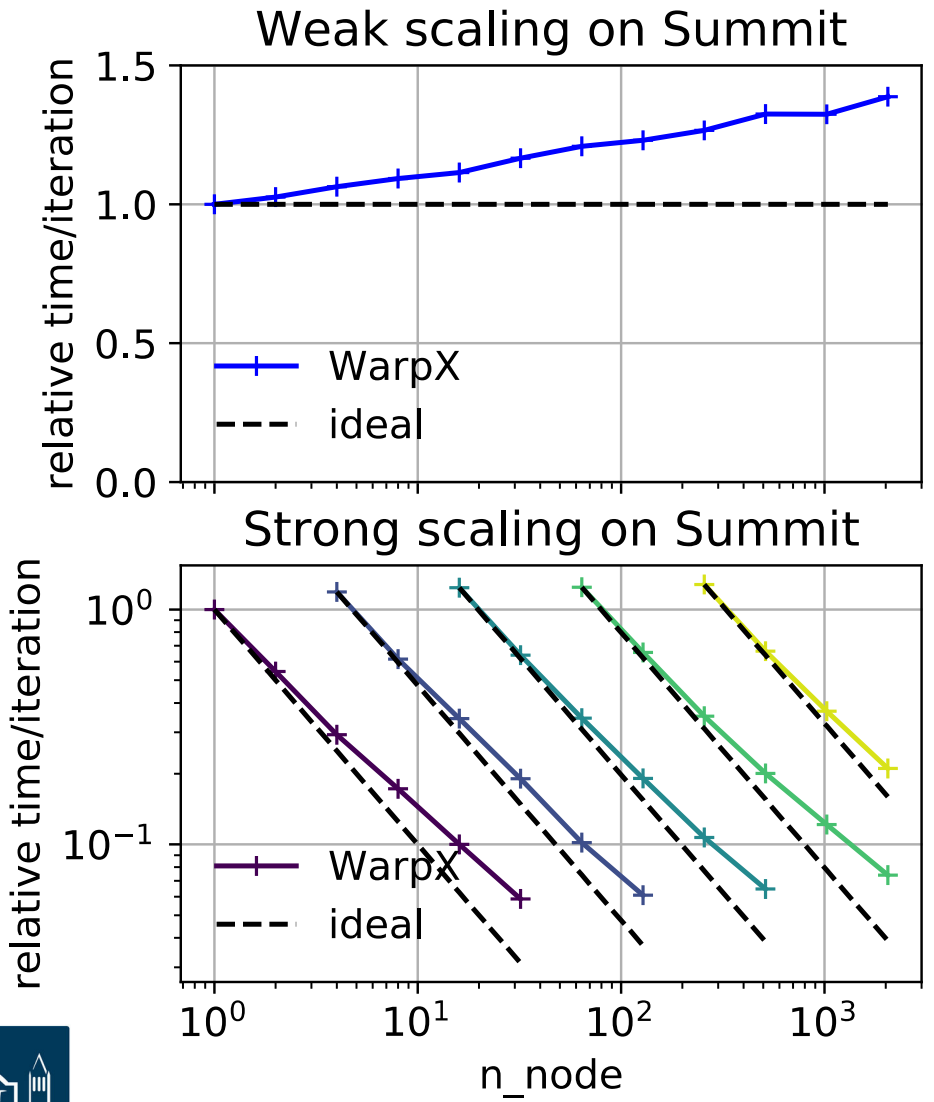


WarpX has been ported for GPUs

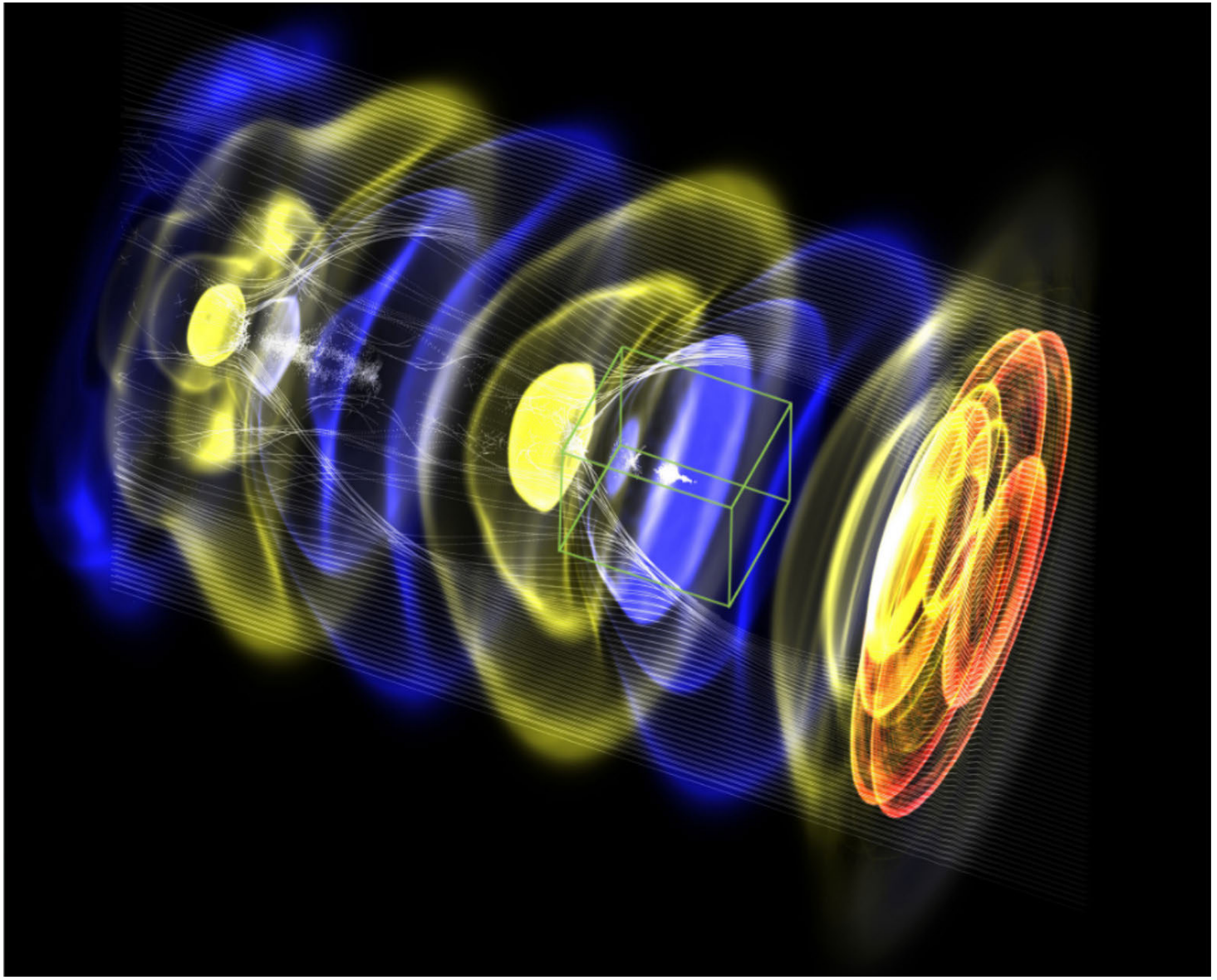
AMReX allows to write code once for multiple architectures (CPU, GPU)

```
amrex::ParallelFor(N,
[=] AMREX_GPU_DEVICE (int j, int k, int l){
    do_stuff(j,k,l,[...]);
});
```

WarpX already scales up to half of the largest supercomputer in the world!



Courtesy of M.Thévenet



Laser-driven Wakefield Acceleration

Courtesy of M.Thévenet

BERKELEY LAB

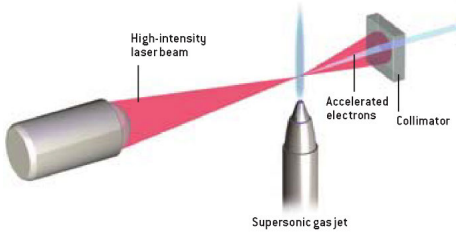
Laser-driven Wakefield Acceleration

Courtesy of

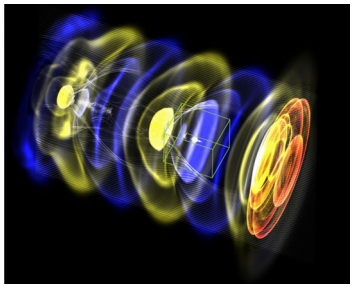
M.Thévenet

BERKELEY LAB

Conclusions



We can use **plasma-based schemes** to accelerate particles



We can use **Particle-In-Cell** codes to model these accelerators

We need **supercomputers**, but they have **complex heterogeneous architectures**

EXASCALE COMPUTING PROJECT

WarpX is a PIC code which is being developed for **upcoming supercomputers**