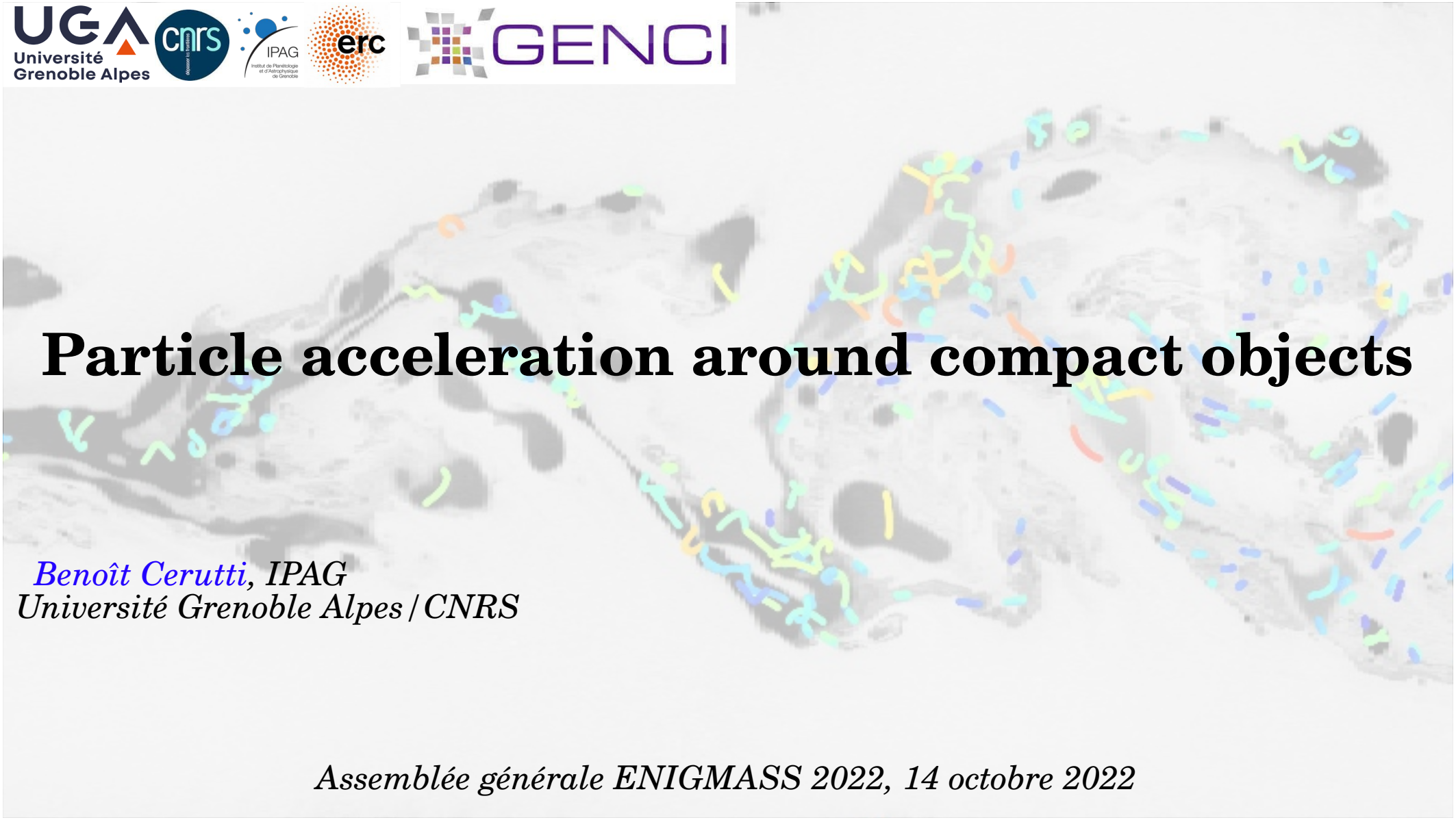


Particle acceleration around compact objects

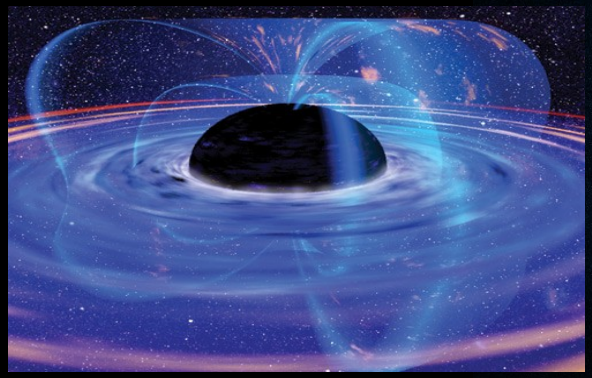
Benoît Cerutti, *IPAG*
Université Grenoble Alpes / CNRS

Assemblée générale ENIGMASS 2022, 14 octobre 2022

Astrophysical environments

Collisionless, relativistic, magnetized environments

Relativistic magnetospheres



Pulsar Wind Nebulae

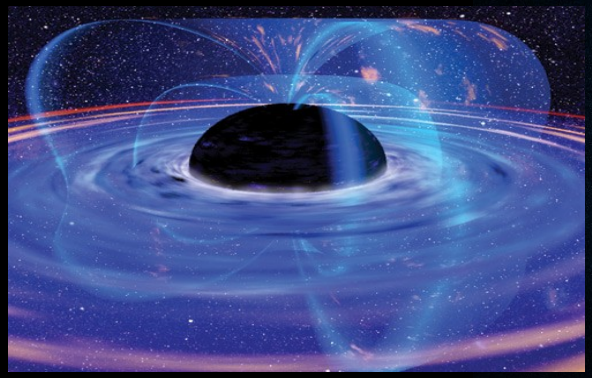
Jets

Gamma-ray bursts
Fast radio bursts

Astrophysical environments

Collisionless, relativistic, magnetized environments

Relativistic magnetospheres



Pulsar Wind Nebulae

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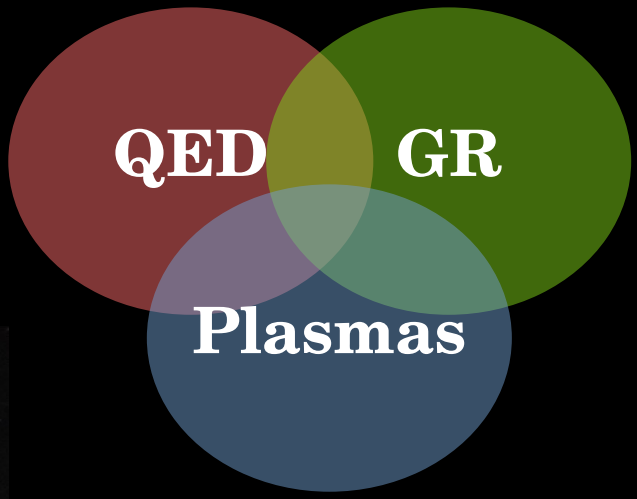
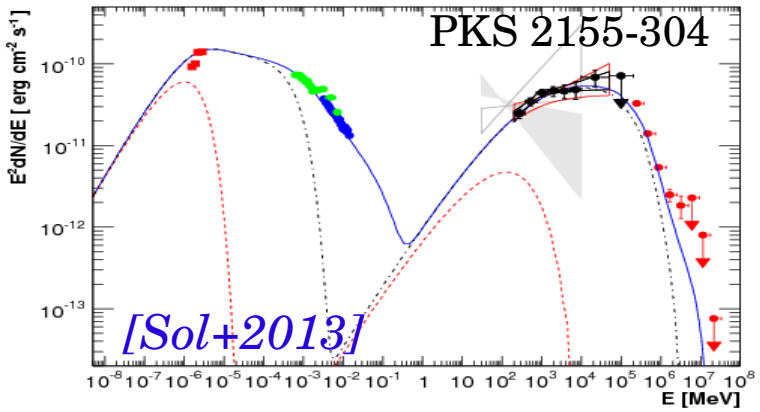


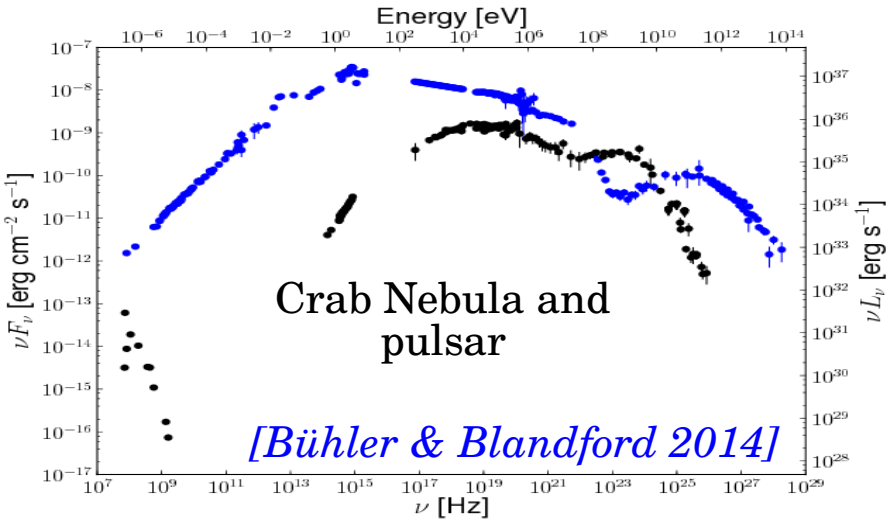
Untractable analytically
=> simulations!

How are particles accelerated in these astrophysical environments?

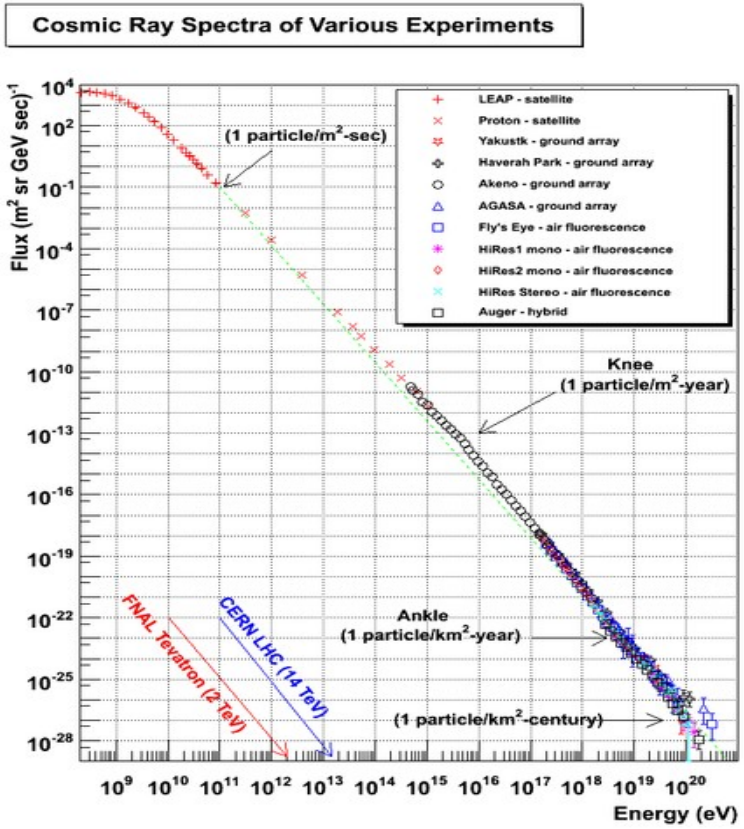
Blazars



Pulsars & Pulsar Wind Nebulae



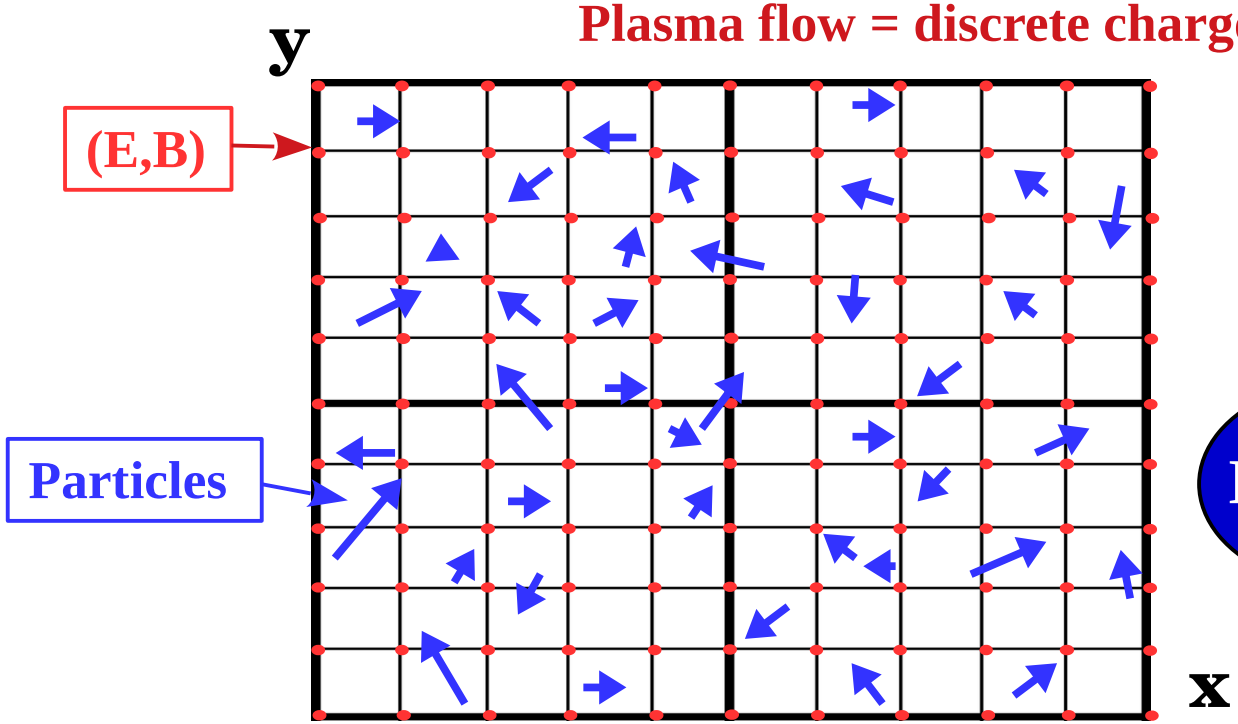
Challenge:
Particle acceleration at microscopic scales << system size

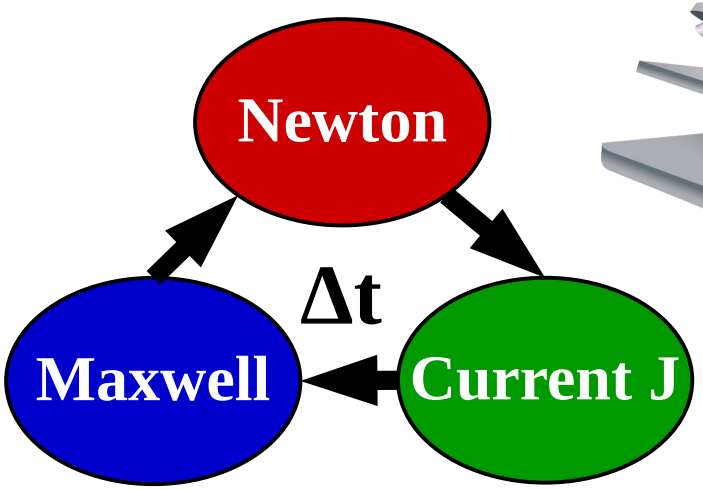


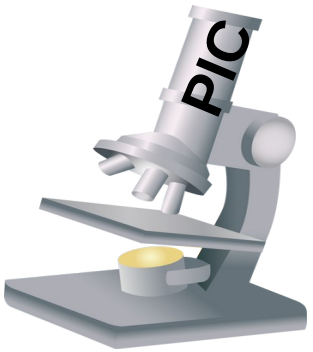
[http://www.physics.utah.edu/~whanlon/spectrum.html]

The spirit of the particle-in-cell approach

Plasma flow = discrete charged particles

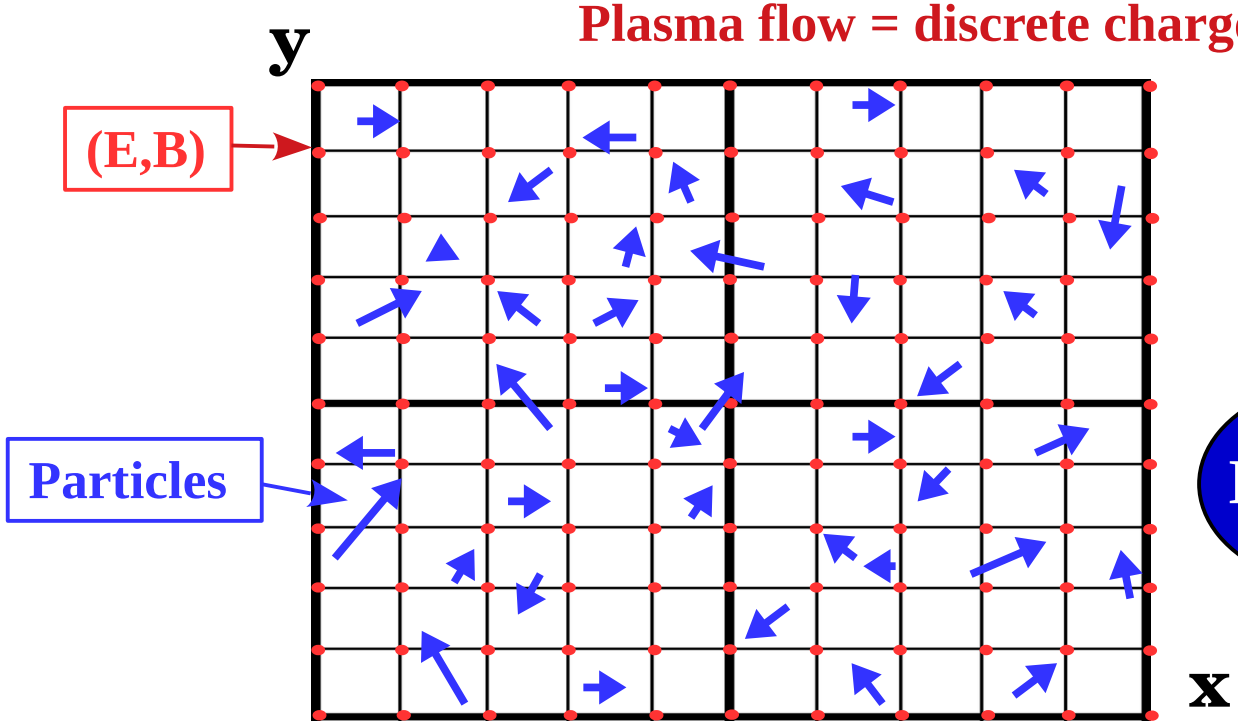


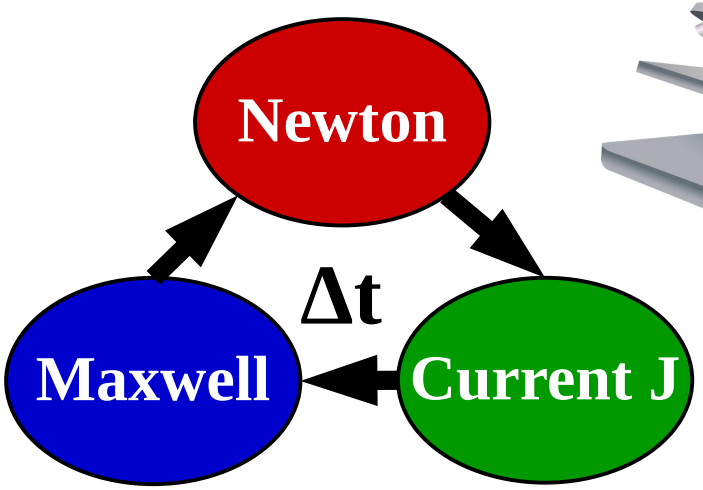


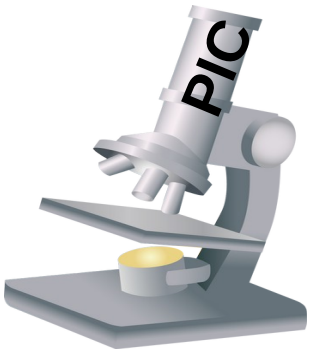


The spirit of the particle-in-cell approach

Plasma flow = discrete charged particles



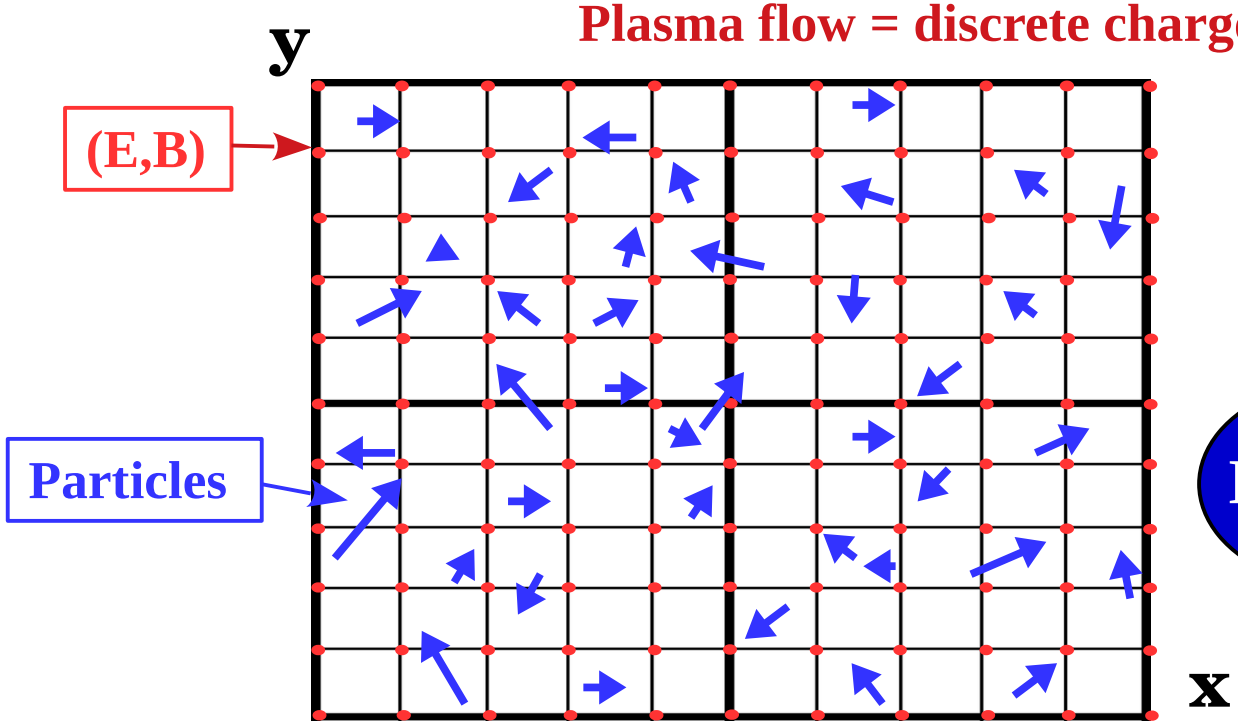


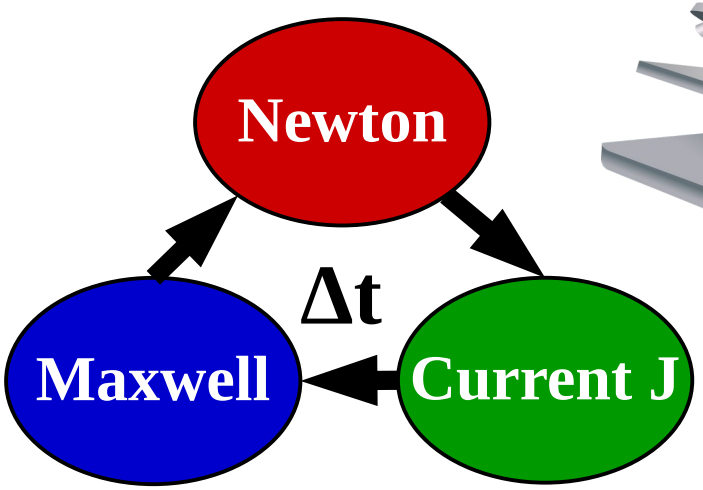


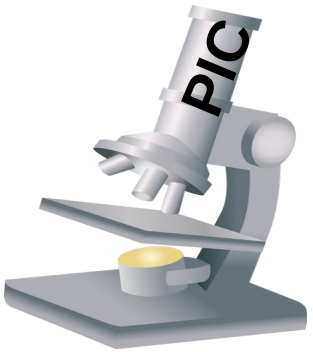
- ✔ Ab-initio modeling of plasmas, capture μ-physics
- ✔ Particle acceleration, radiation, pair creation
- ✔ Model observables
- ✖ Computationally expensive strong need of HPC
- ✖ Short-term evolution, small scale-separation

The spirit of the particle-in-cell approach

Plasma flow = discrete charged particles







- ✅ Ab-initio modeling of plasmas, capture μ-physics
- ✅ Particle acceleration, radiation, pair creation
- ✅ Model observables
- ❌ Computationally expensive strong need of HPC
- ❌ Short-term evolution, small scale-separation

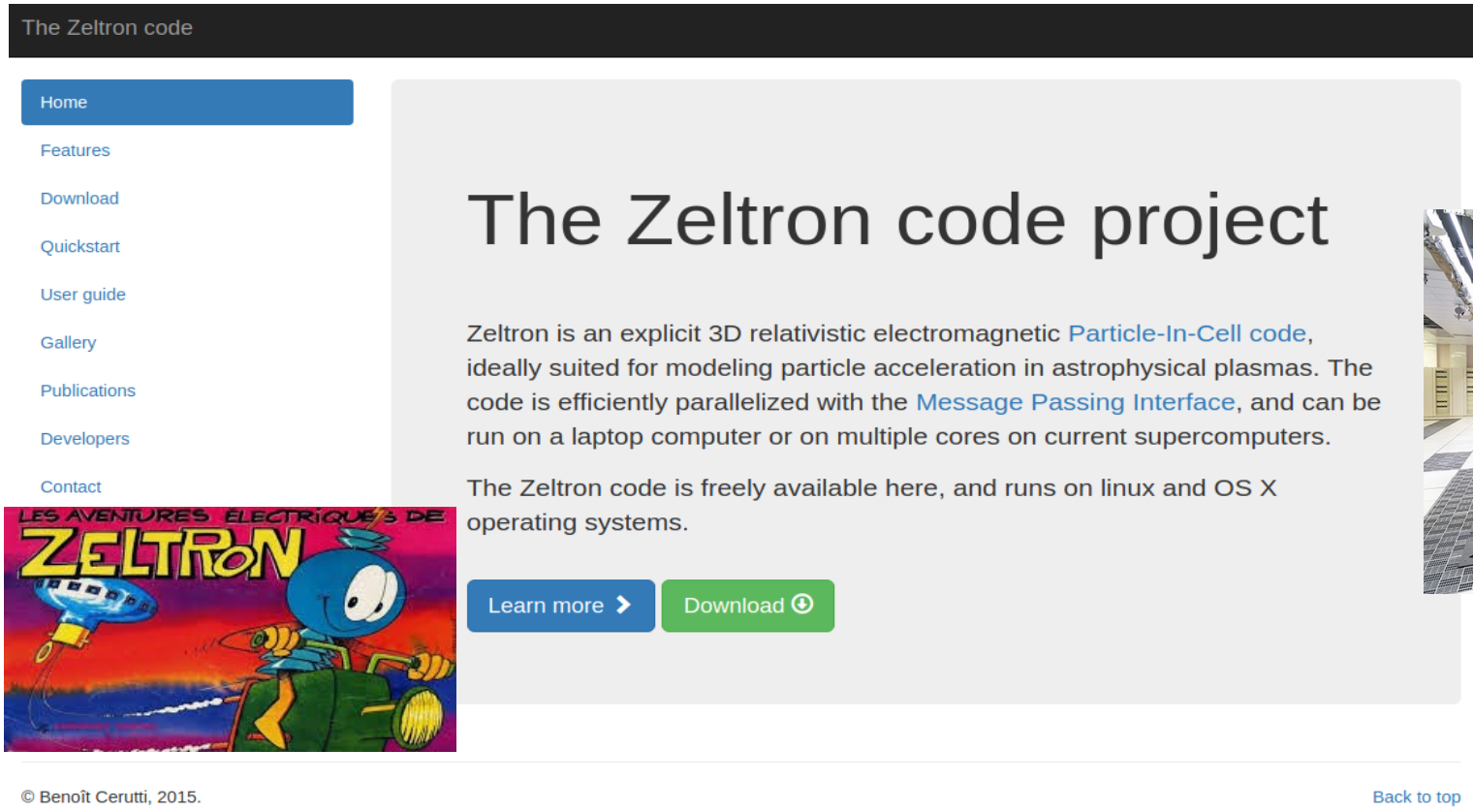
Study non-thermal particle acceleration from <u>first principles</u>

Numerical observatory => PIC simulations has become a real <u>discovery tool</u>!

The Zeltron code

URL: http://ipag.osug.fr/~ceruttbe/Zeltron

Created in 2012 and Cartesian version published in 2015.
Includes QED and General Relativistic effects since 2019 (currently private repo @ GRICAD).

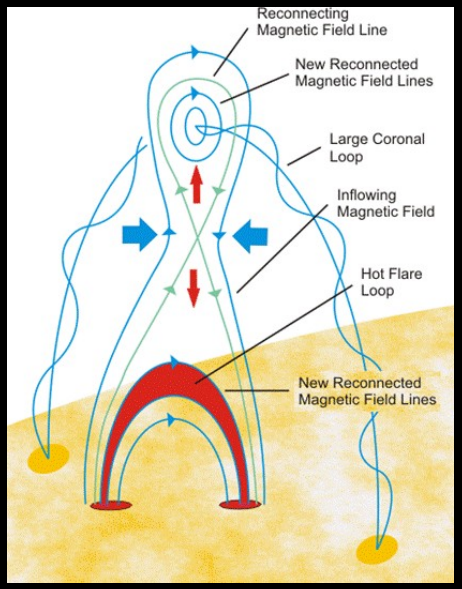


Parallel computing
(10^2-10^5 processors)

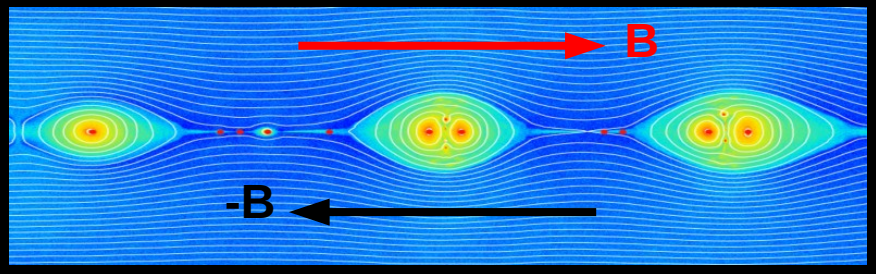
Acceleration processes

Magnetic reconnection

Magnetic energy => Particles



Produce hard power-laws $dN/d\gamma \sim \gamma^{-1.5\text{-}1.2}$



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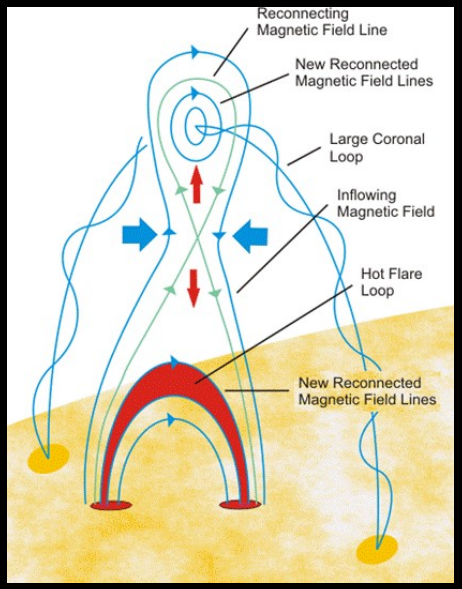

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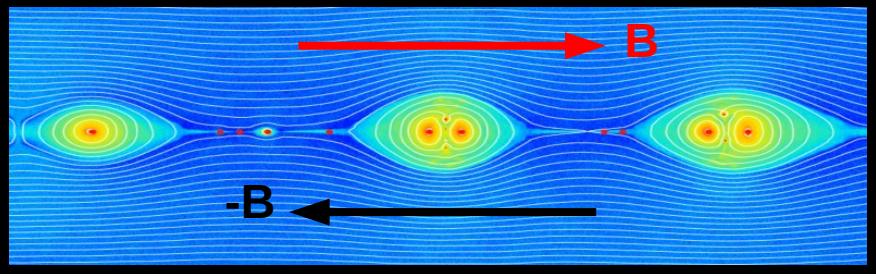
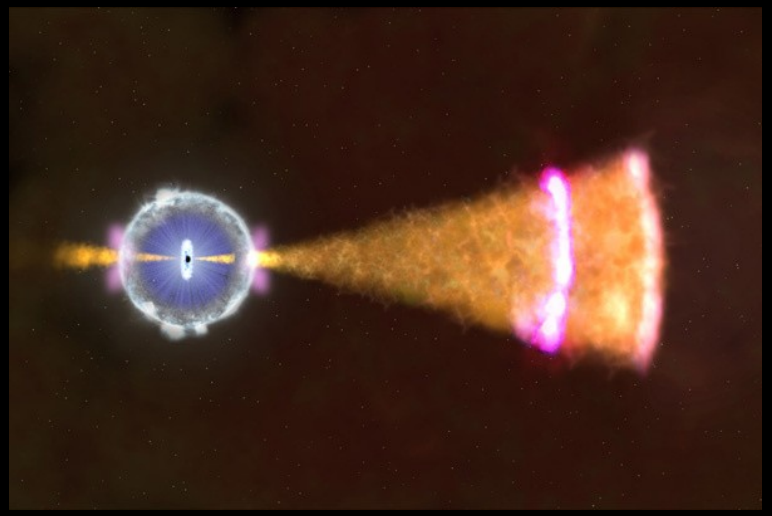
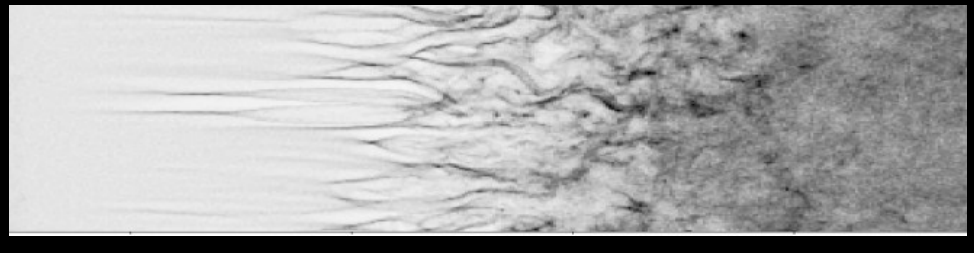


Collisionless shocks

Flow kinetic energy => Particles

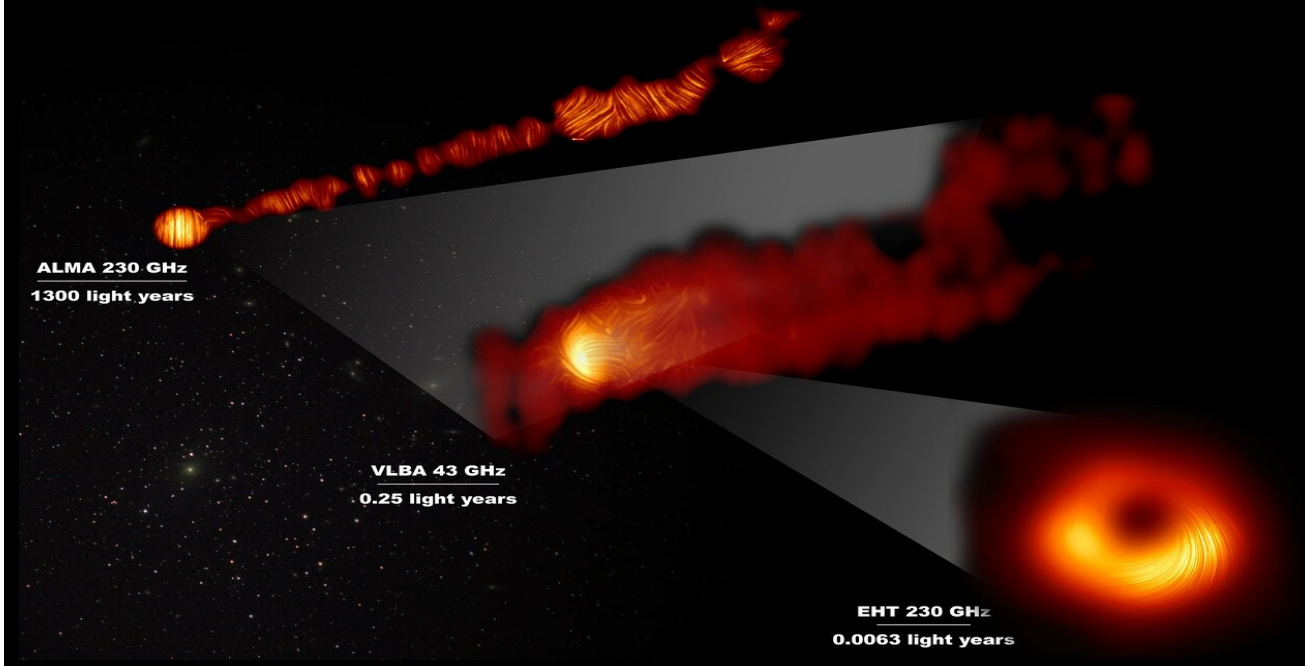


Produce steep power-laws $dN/d\gamma \sim \gamma^{-2.5}$

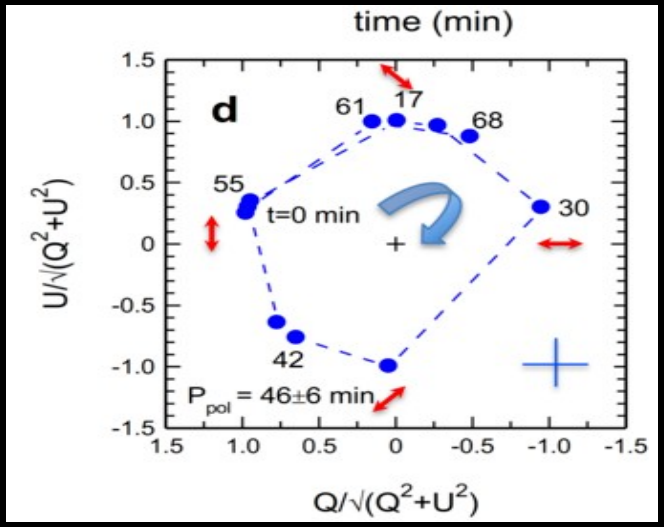


Supermassive black-hole horizon-scale observations

EHT collaboration (M87*, SgrA*)



Gravity collaboration (SgrA*)

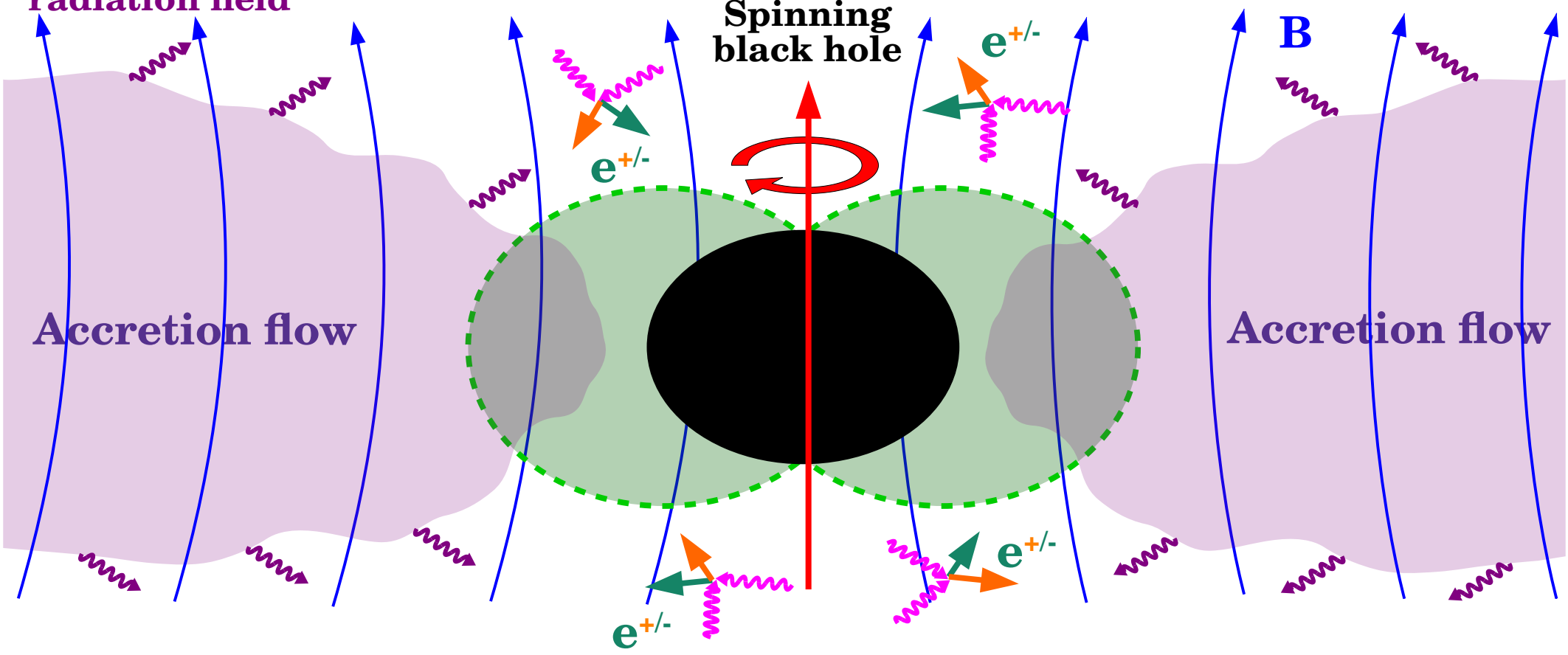


Non-thermal synchrotron radiation => **particle acceleration**
Polarized emission => **Large-scale magnetic field**

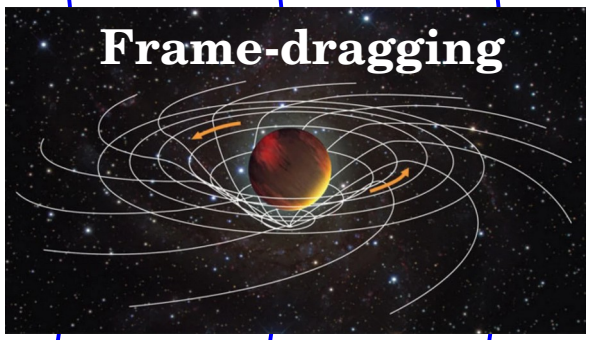
A magnetospheric origin?

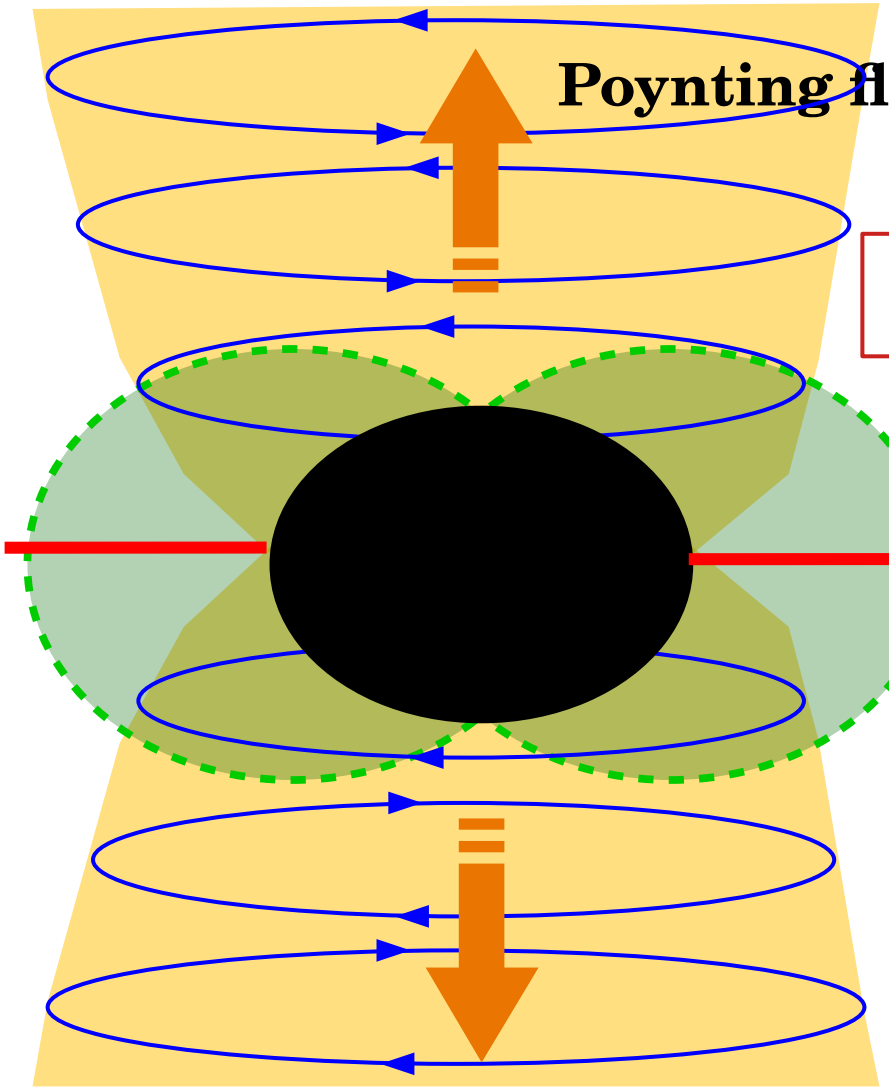
Black-hole electrodynamics

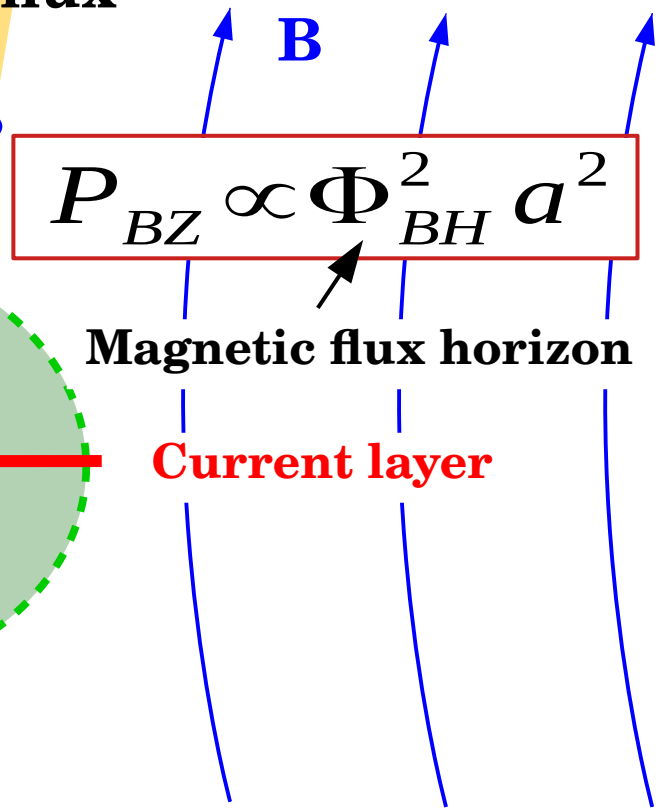
Blandford & Znajek (1977)



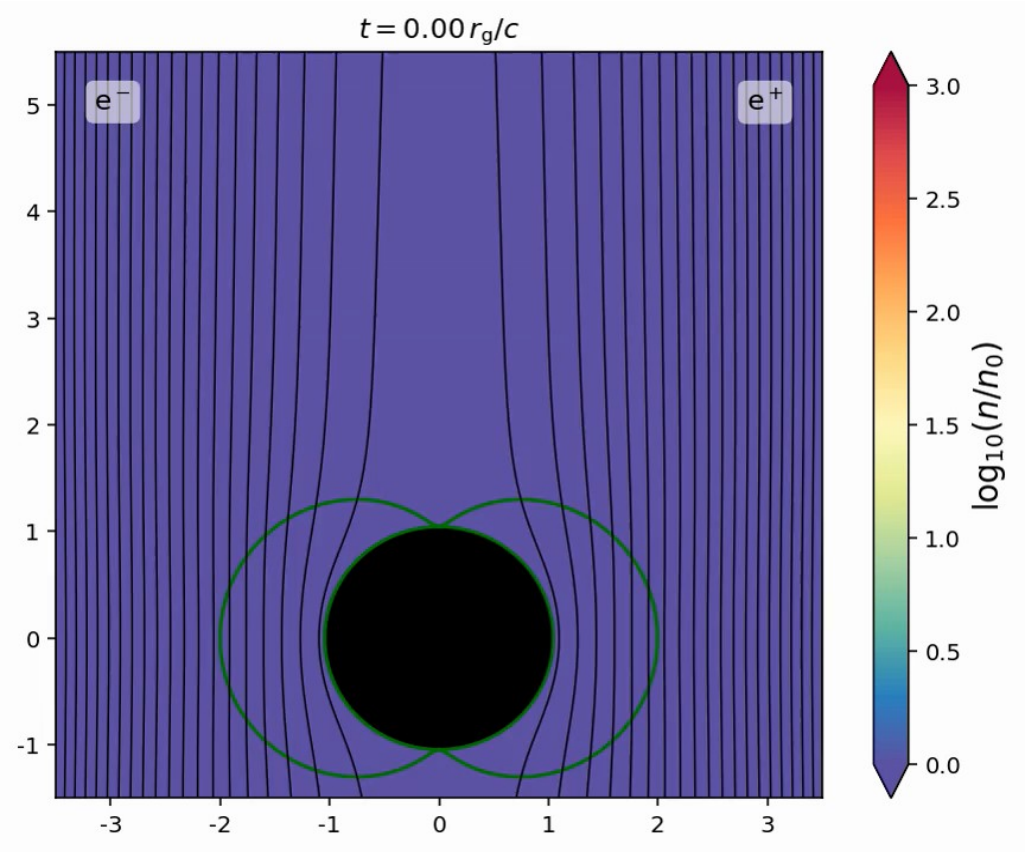
Electromagnetic extraction of the black hole spin





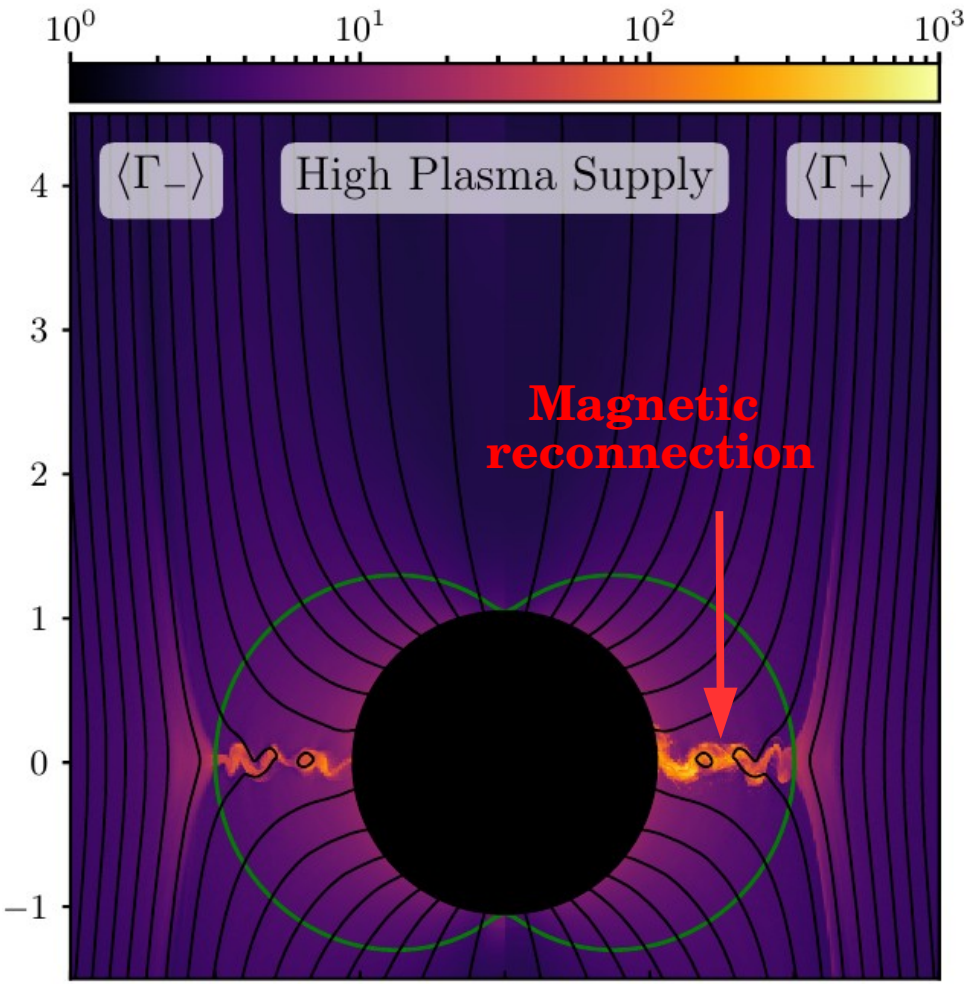


Plasma evolution (2D axisymmetric model)

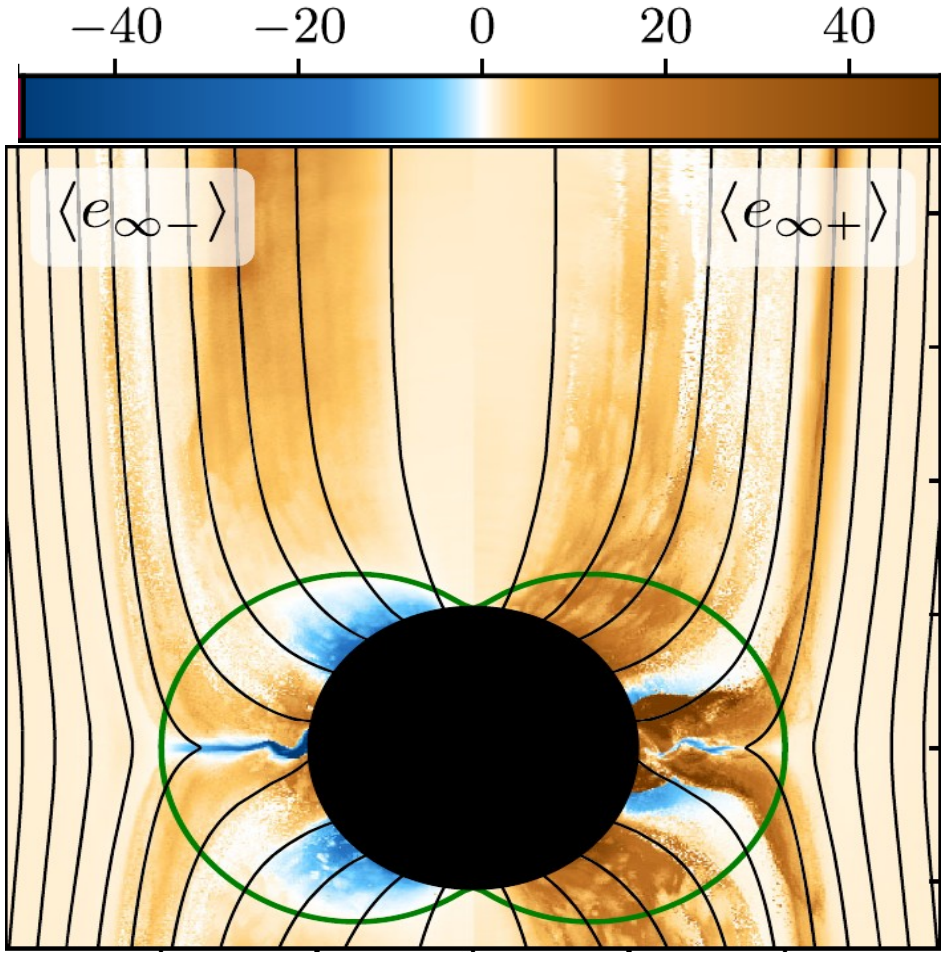


Parfrey, Philippov & Cerutti (2019)

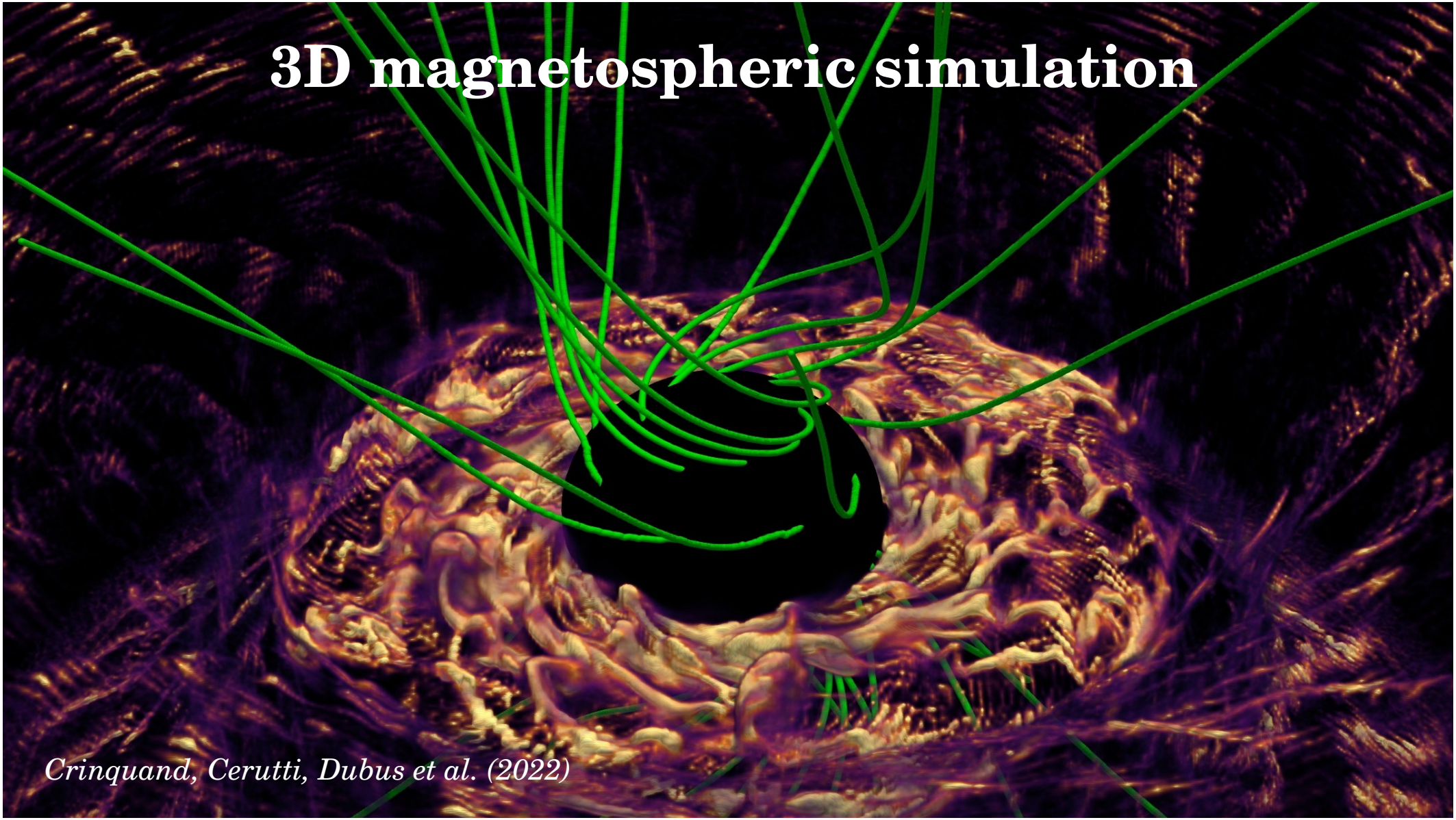
Particle acceleration



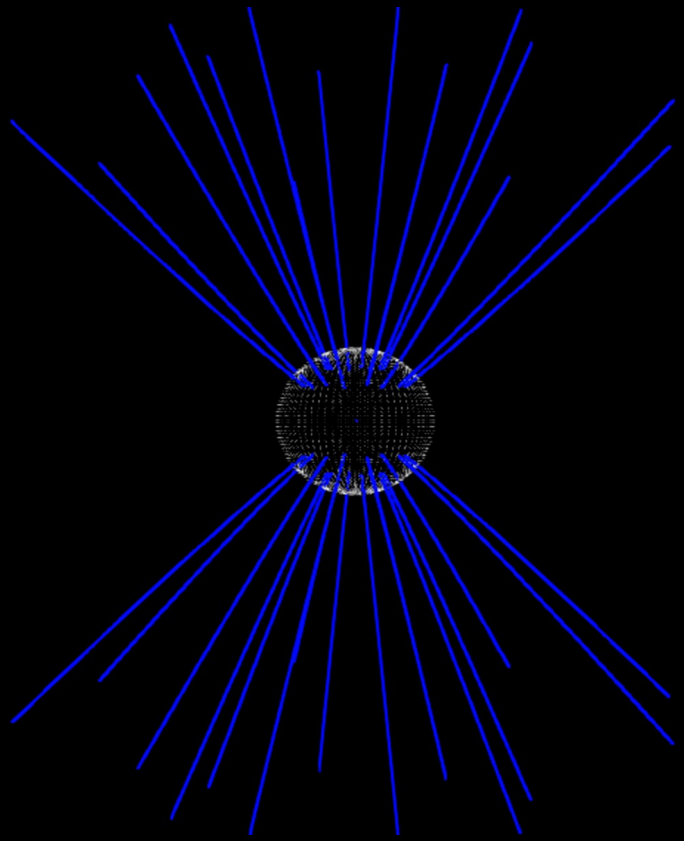
Penrose particles



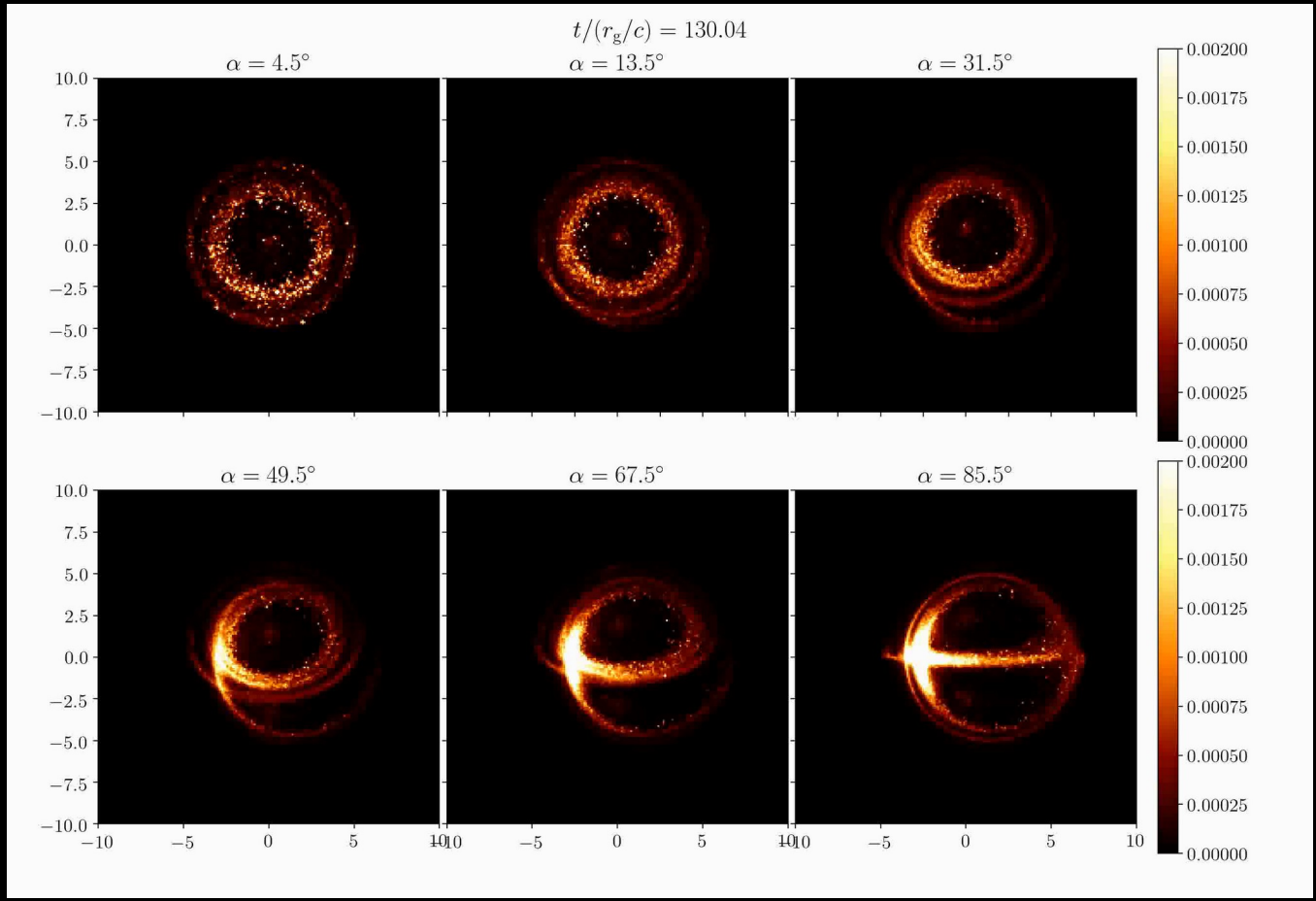
Parfrey, Philippov & Cerutti (2019)


3D magnetospheric simulation
Crinquand, Cerutti, Dubus et al. (2022)

Extension to full 3D



Synthetic synchrotron images



Crinquand, Cerutti, Dubus et al. (2022)

The multi-challenges

Multi-architecture

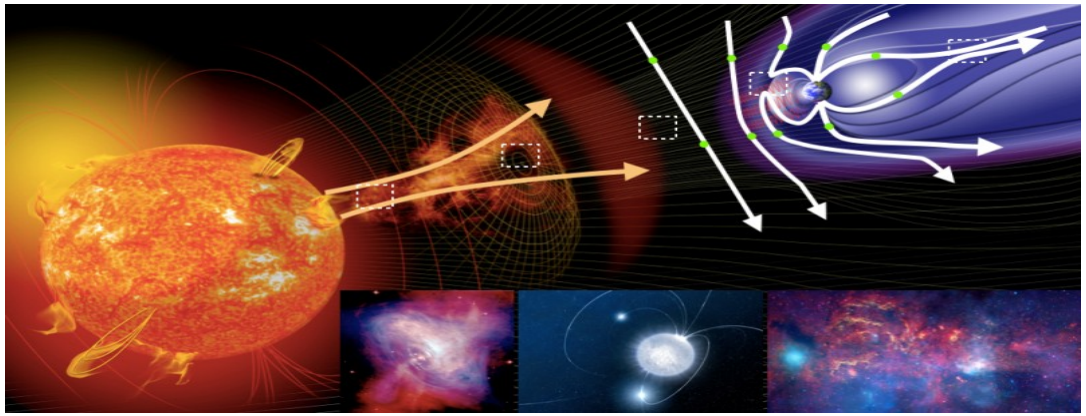
CPU, GPU, ARM
MPI, OpenMP,
Vectorization

Multi-physics

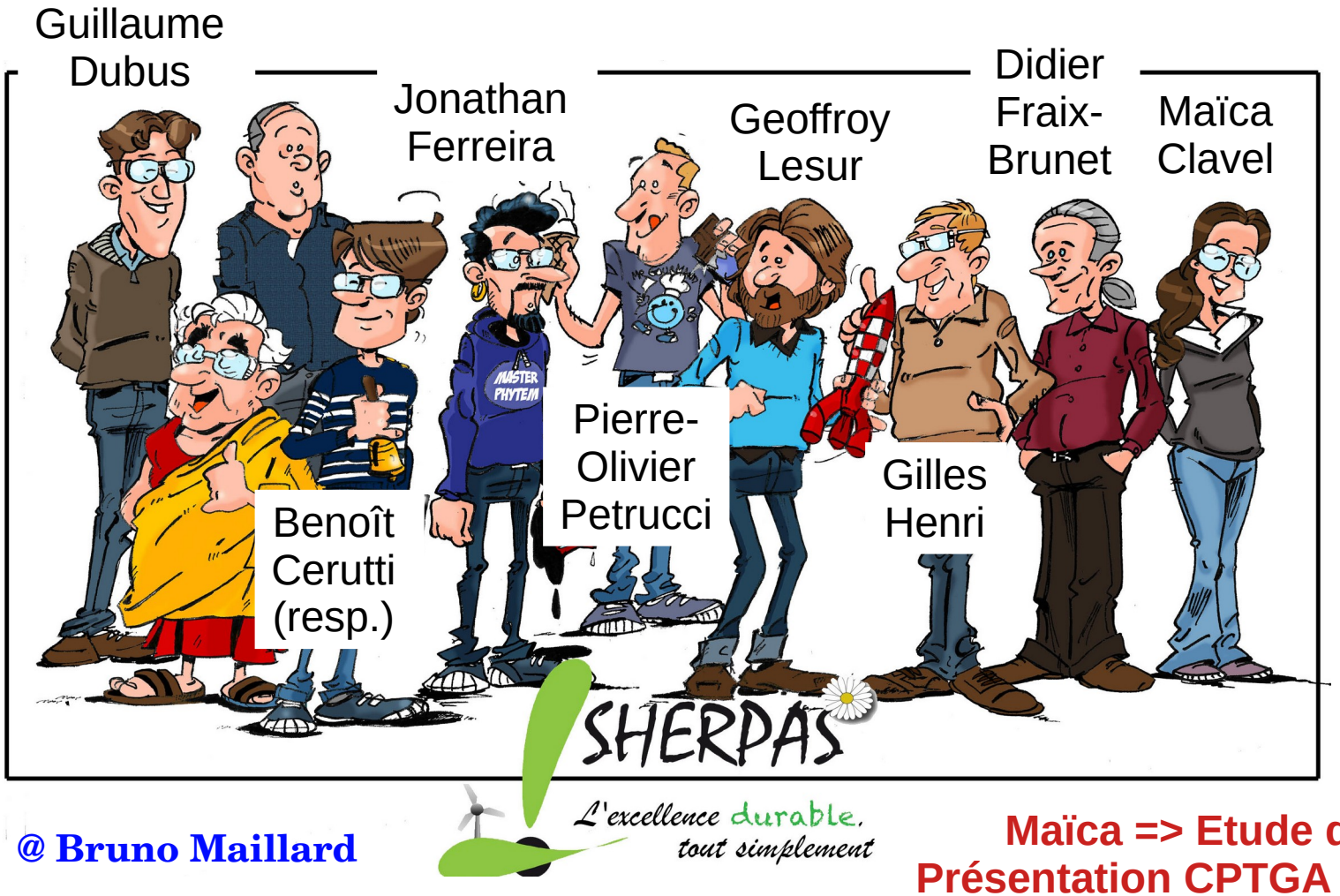
QED, GR, neutrinos

Multi-scales

Kinetic <-> global
Long integration
Hybrid codes



L'équipe SHERPAS @ IPAG



@ Bruno Maillard

6 chercheurs CNRS
2 professeurs UGA
10 doctorants
4 postdoctorants

Thématiques:

- Objets compacts
- Accrétion/éjections
- Accélération de particules
- Observation haute énergie
- Simulations HPC plasmas

Maïca => Etude du centre galactique
Présentation CPTGA mardi prochain @ LPSC