

# 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

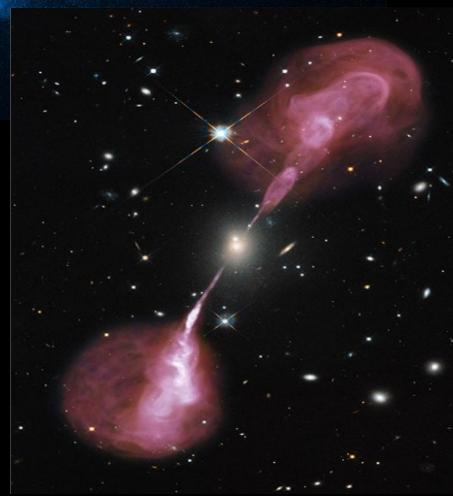
Relativistic  
magnetospheres



Pulsar Wind Nebulae



Jets



Gamma-ray bursts  
Fast radio bursts



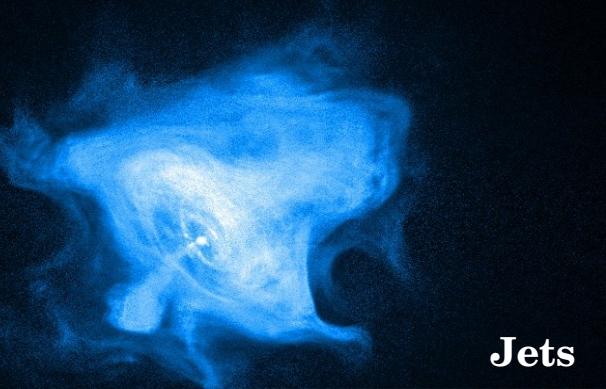
# Astrophysical environments

Collisionless, relativistic, magnetized environments

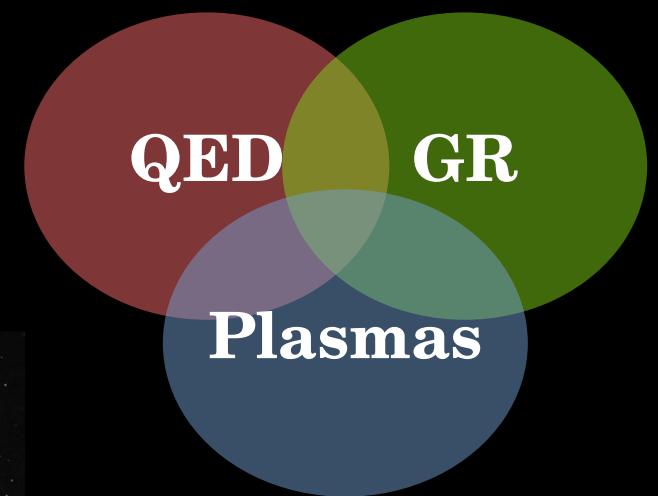
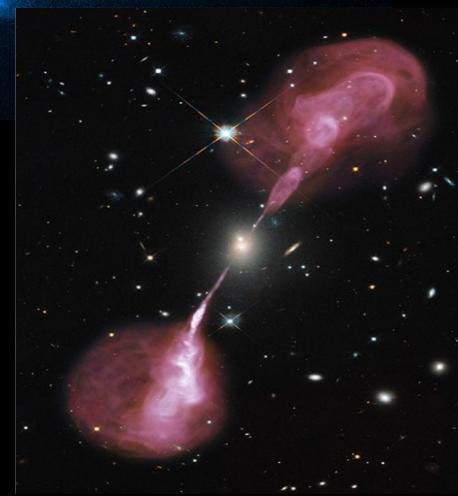
Relativistic  
magnetospheres



Pulsar Wind Nebulae



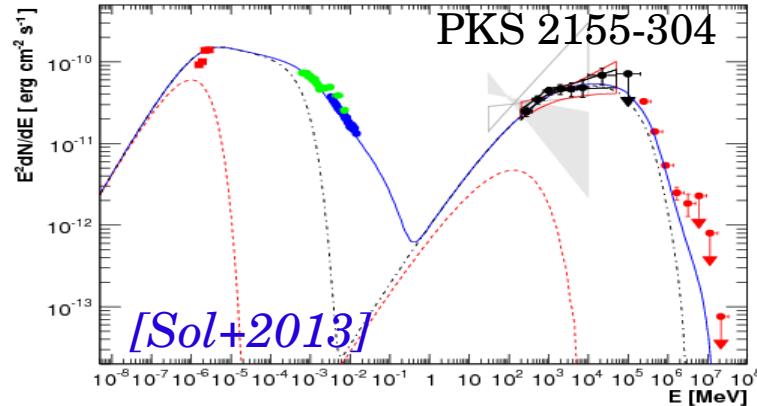
Gamma-ray bursts  
Fast radio bursts



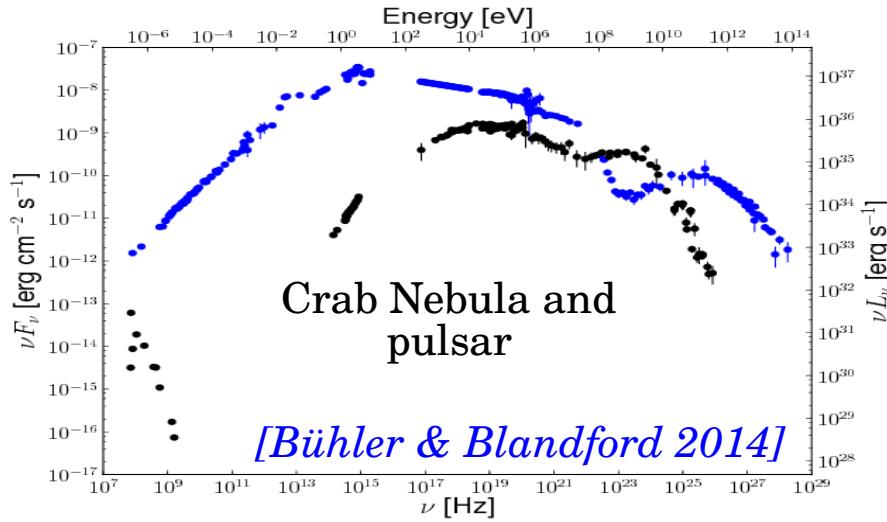
Untractable analytically  
=> simulations!

# How are particles accelerated in these astrophysical environments?

## Blazars



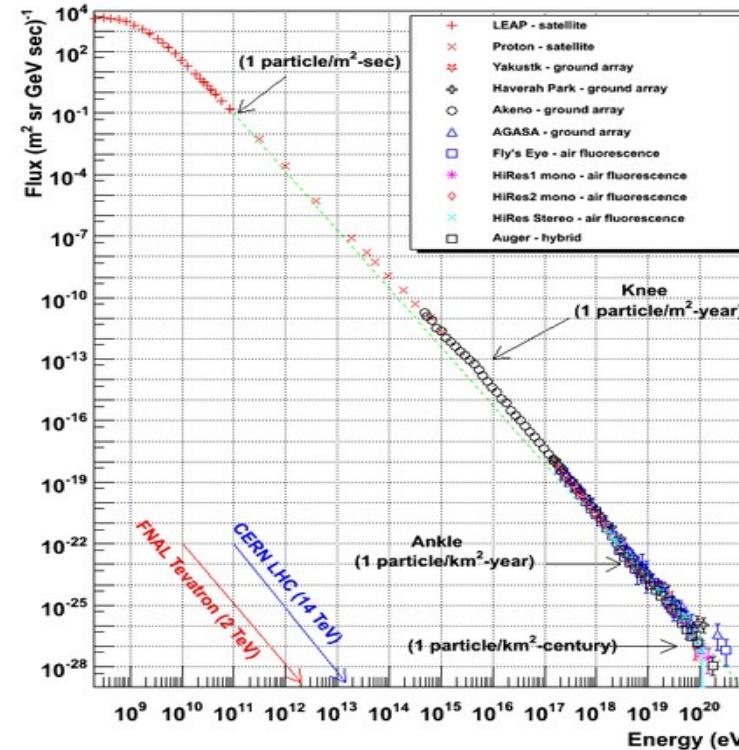
## Pulsars & Pulsar Wind Nebulae



## Challenge:

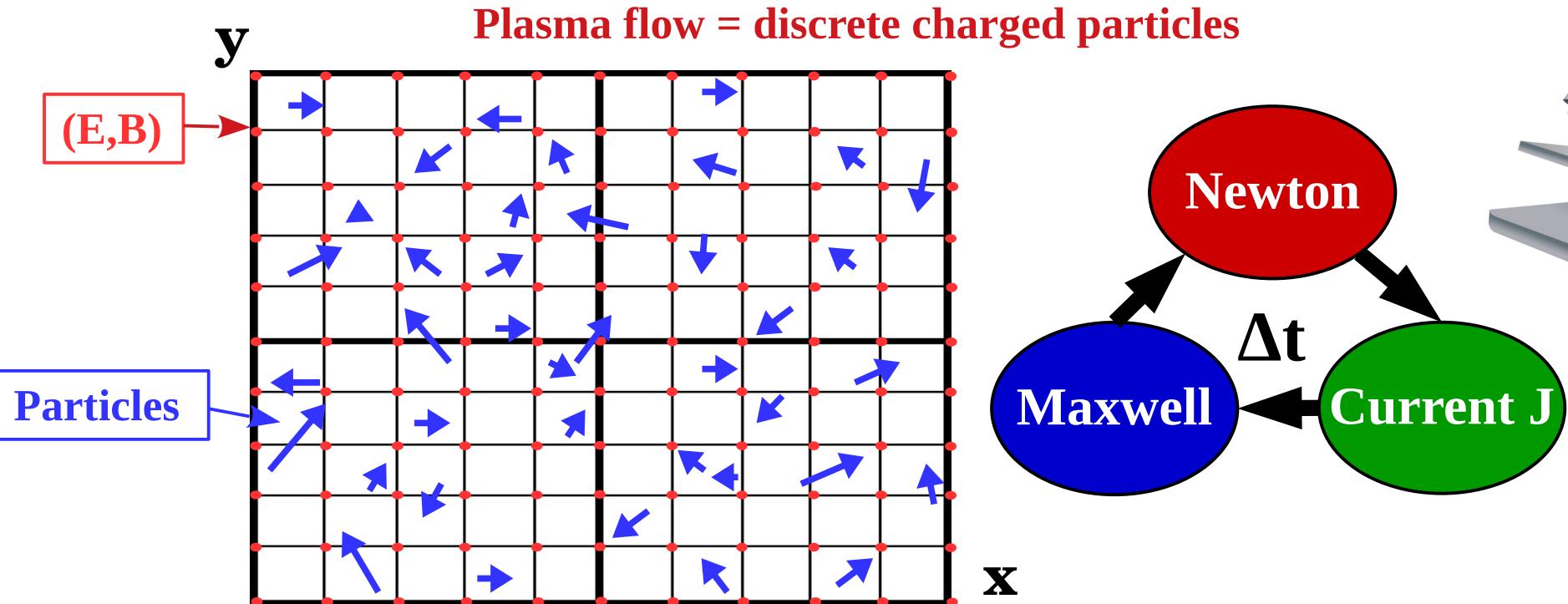
Particle acceleration at microscopic scales << system size

Cosmic Ray Spectra of Various Experiments

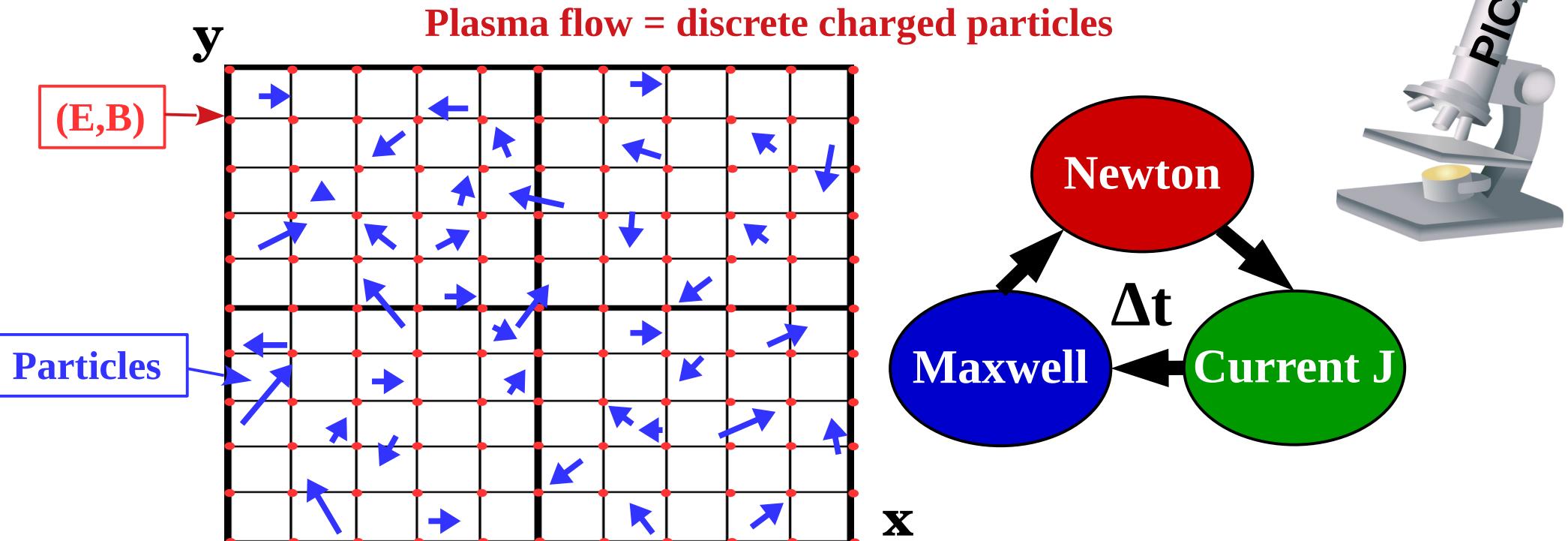


[\[http://www.physics.utah.edu/~whanlon/spectrum.html\]](http://www.physics.utah.edu/~whanlon/spectrum.html)

# The spirit of the particle-in-cell approach

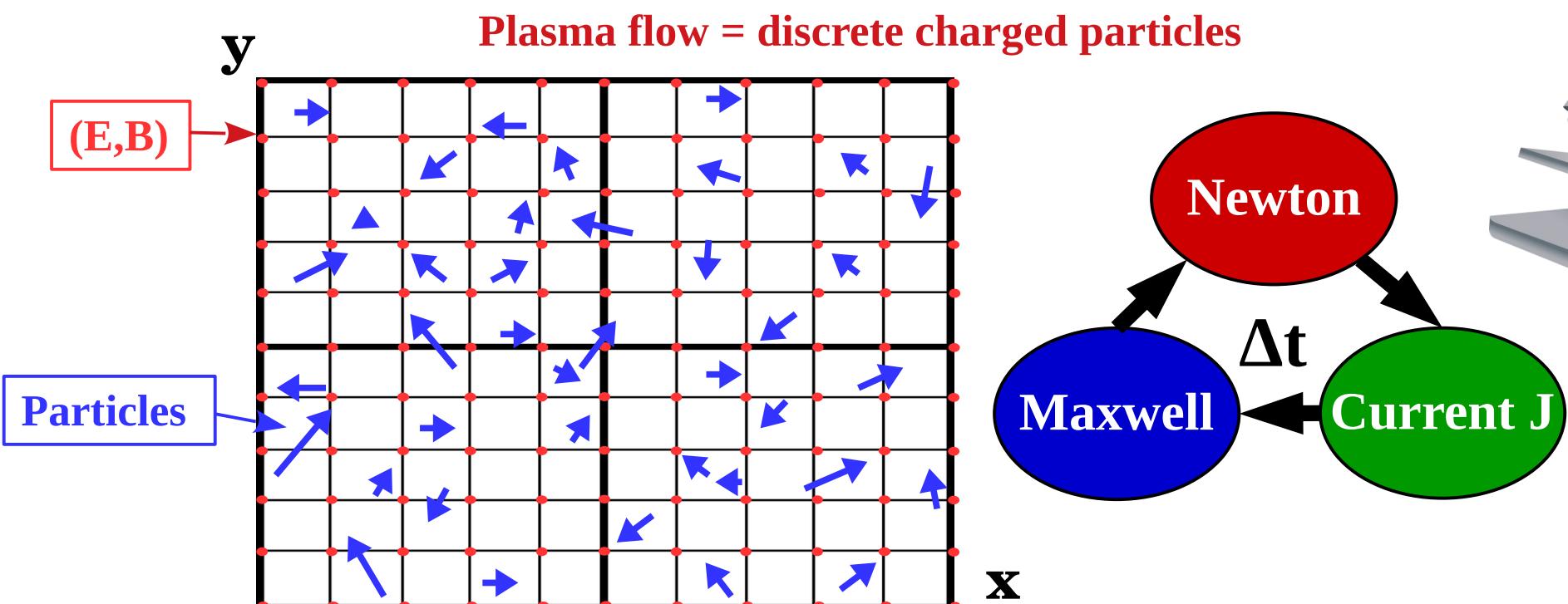


# The spirit of the particle-in-cell approach



- ✓ Ab-initio modeling of plasmas, capture  $\mu$ -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



- ✓ Ab-initio modeling of plasmas, capture  $\mu$ -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 first principles  
Numerical observatory => PIC simulations has become a real discovery tool!

# 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).

The Zeltron code

Home

Features

Download

Quickstart

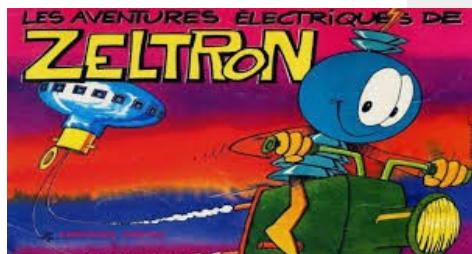
User guide

Gallery

Publications

Developers

Contact



## The Zeltron code project

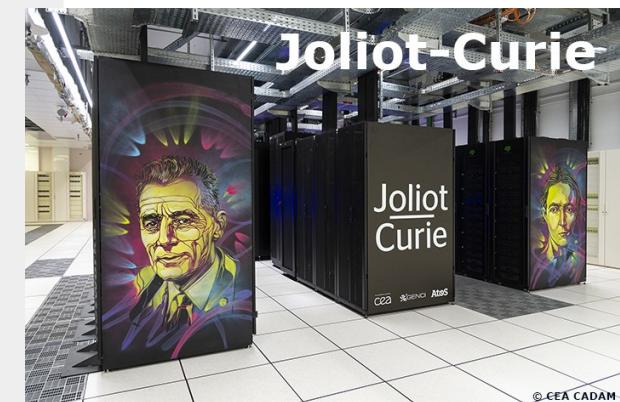
Zeltron is an explicit 3D relativistic electromagnetic [Particle-In-Cell code](#), ideally suited for modeling particle acceleration in astrophysical plasmas. The code is efficiently parallelized with the [Message Passing Interface](#), and can be run on a laptop computer or on multiple cores on current supercomputers.

The Zeltron code is freely available here, and runs on linux and OS X operating systems.

[Learn more ➔](#)

[Download ⓘ](#)

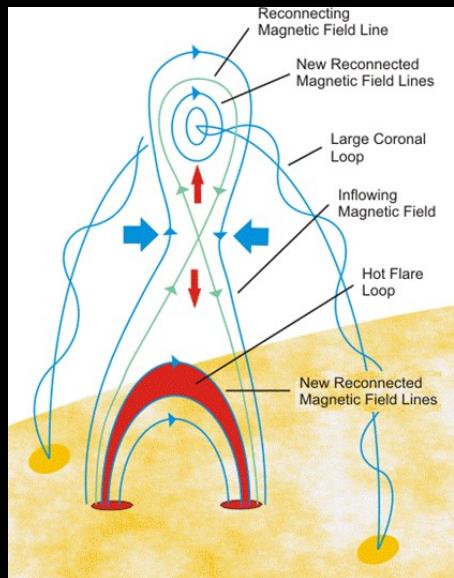
Parallel computing  
( $10^2$ - $10^5$  processors)



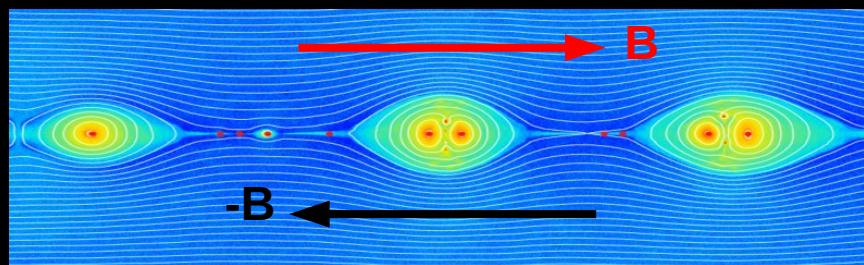
# Acceleration processes

## Magnetic reconnection

Magnetic energy => Particles

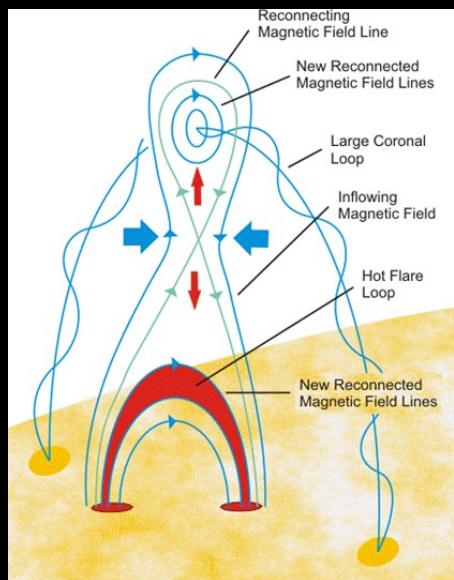


Produce hard power-laws  $dN/d\gamma \sim \gamma^{-1.5-1.2}$

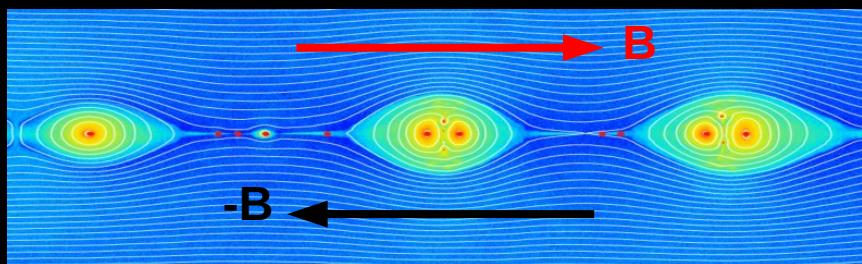


# Acceleration processes

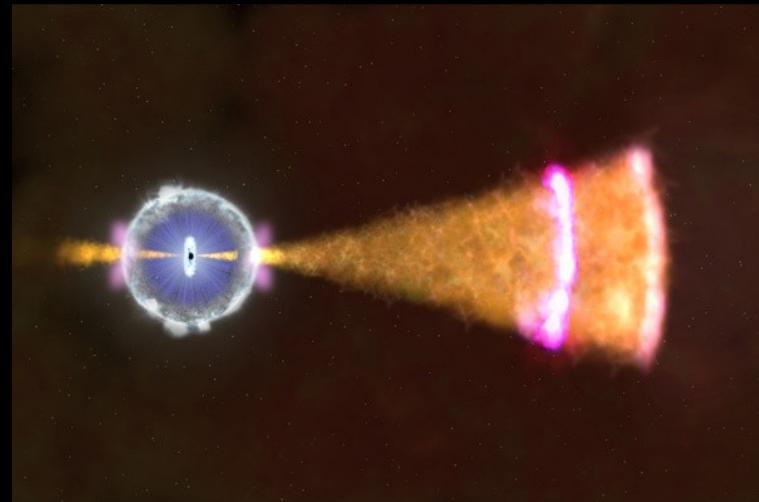
**Magnetic reconnection**  
Magnetic energy => Particles



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



**Collisionless shocks**  
Flow kinetic energy => Particles

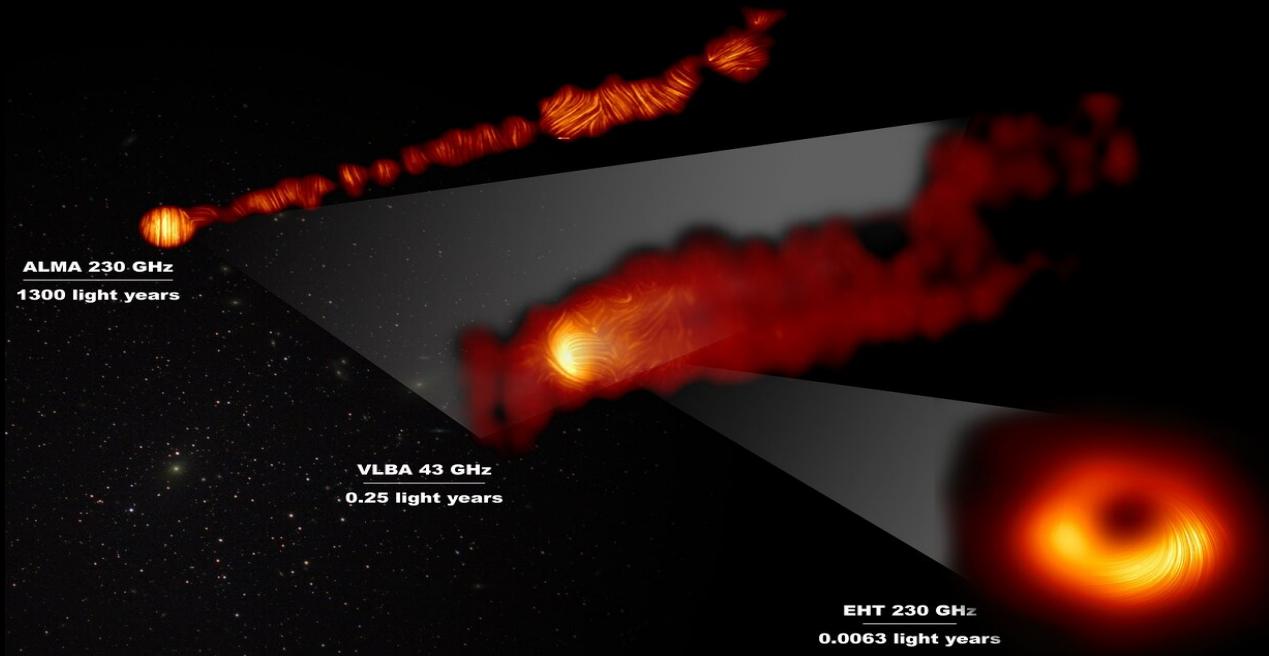


Produce steep power-laws  $dN/d\gamma \sim \gamma^{-2.5}$

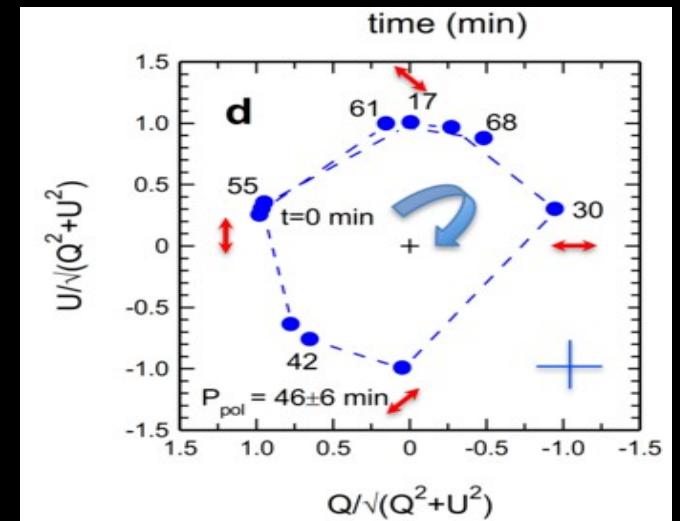


# Supermassive black-hole horizon-scale

EHT collaboration (M87\*, SgrA\*) **observations**



Gravity collaboration (SgrA\*)

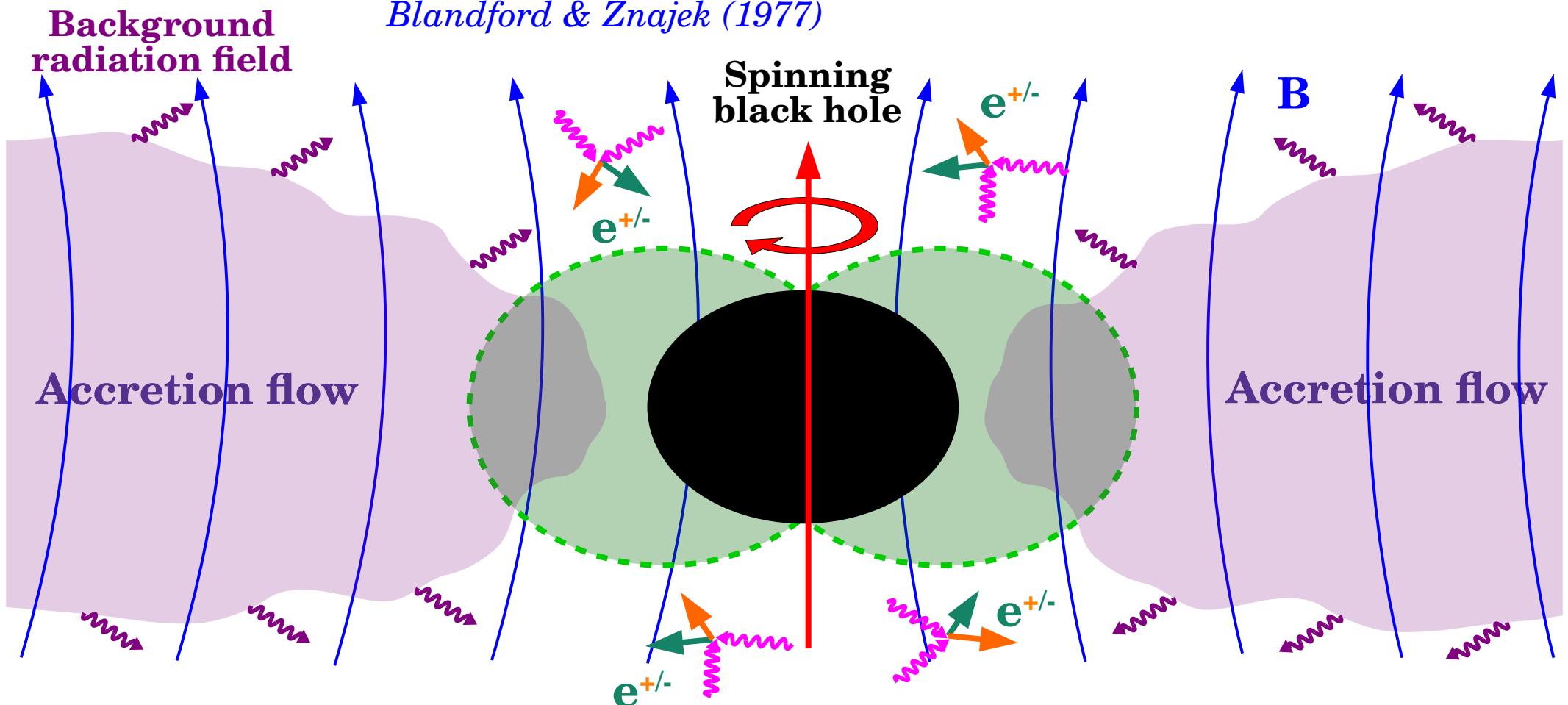


Non-thermal synchrotron radiation => particle acceleration  
Polarized emission => Large-scale magnetic field

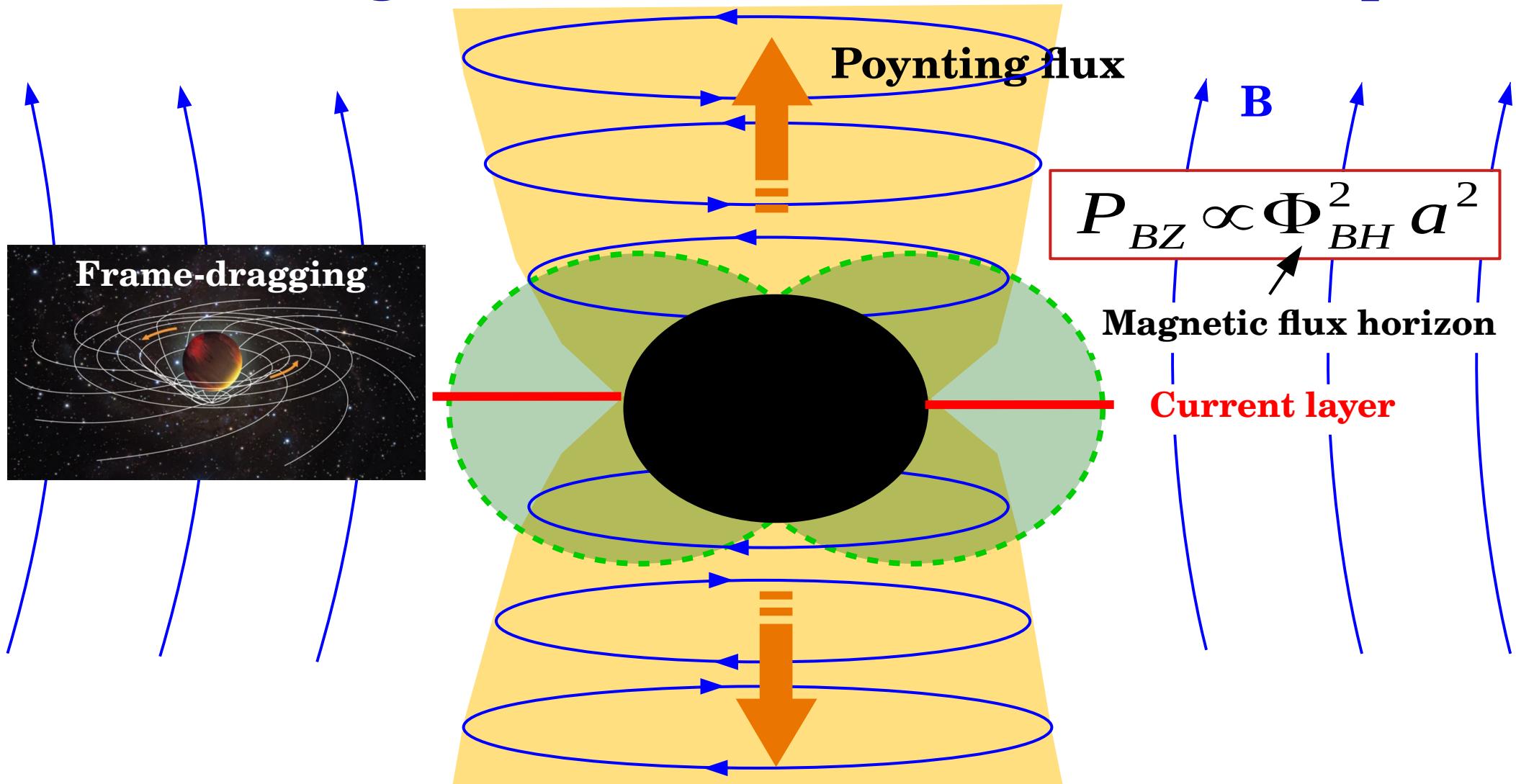
A magnetospheric origin?

# Black-hole electrodynamics

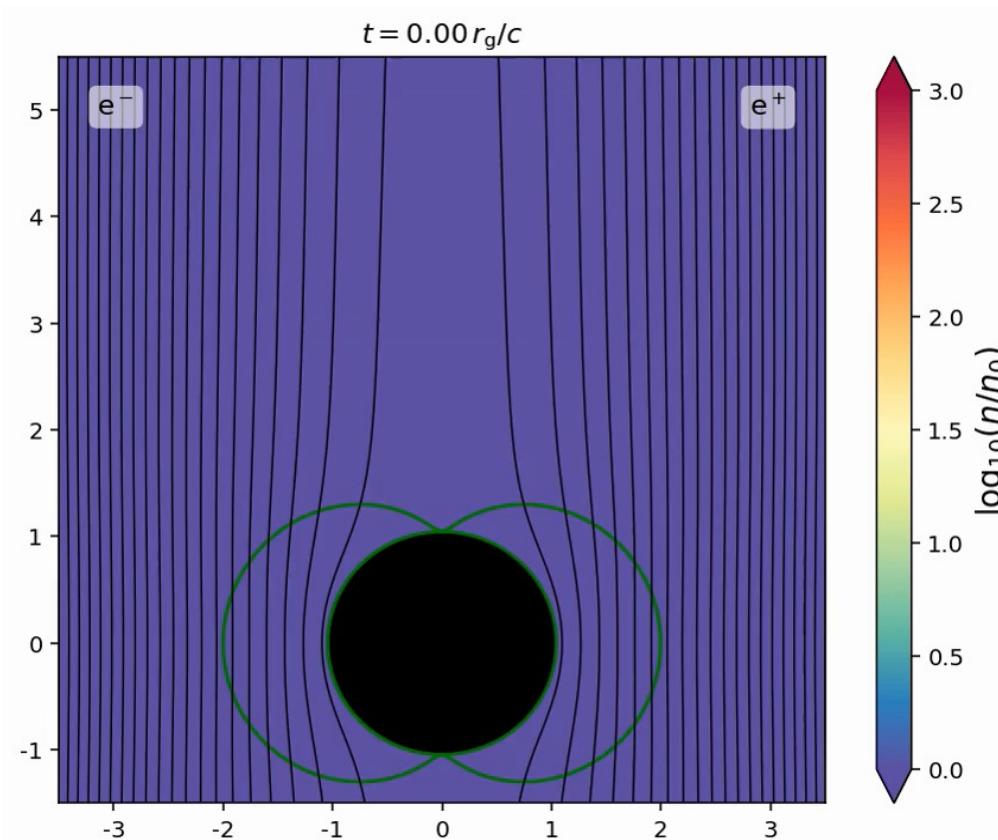
*Blandford & Znajek (1977)*



# Electromagnetic extraction of the black hole spin

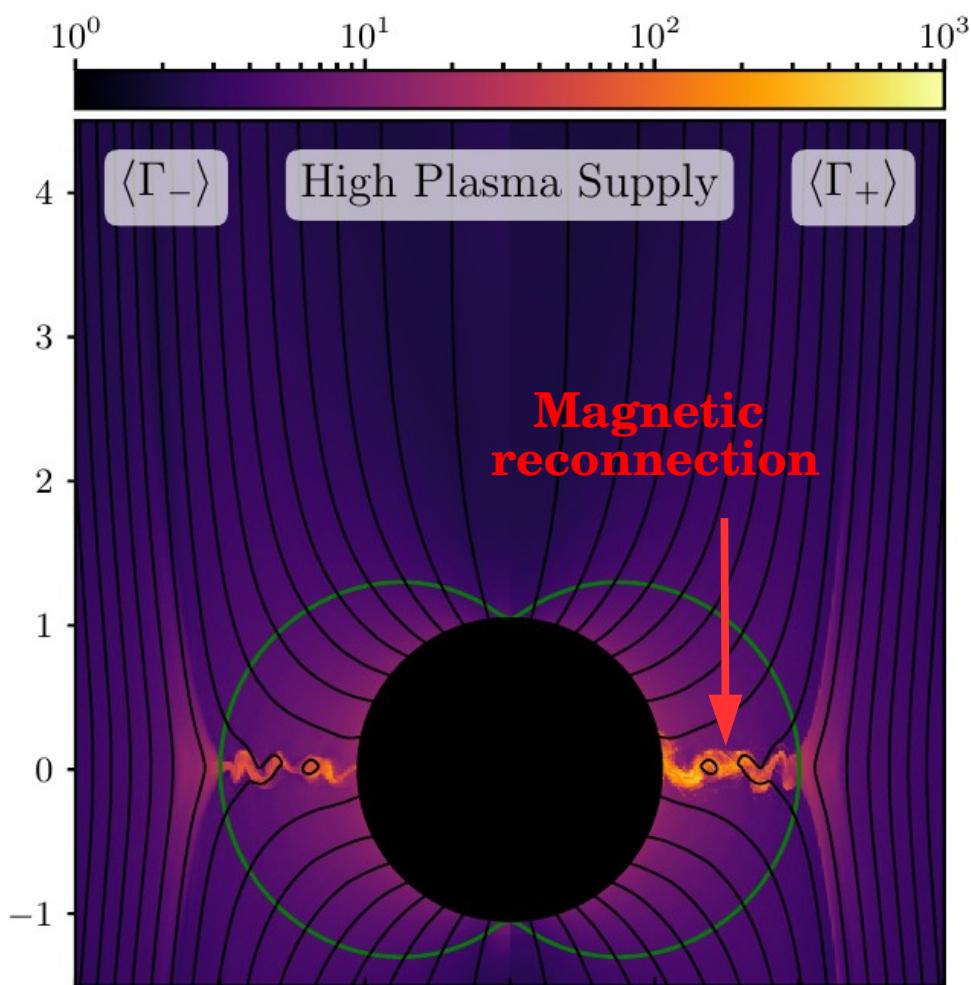


# Plasma evolution (2D axisymmetric model)

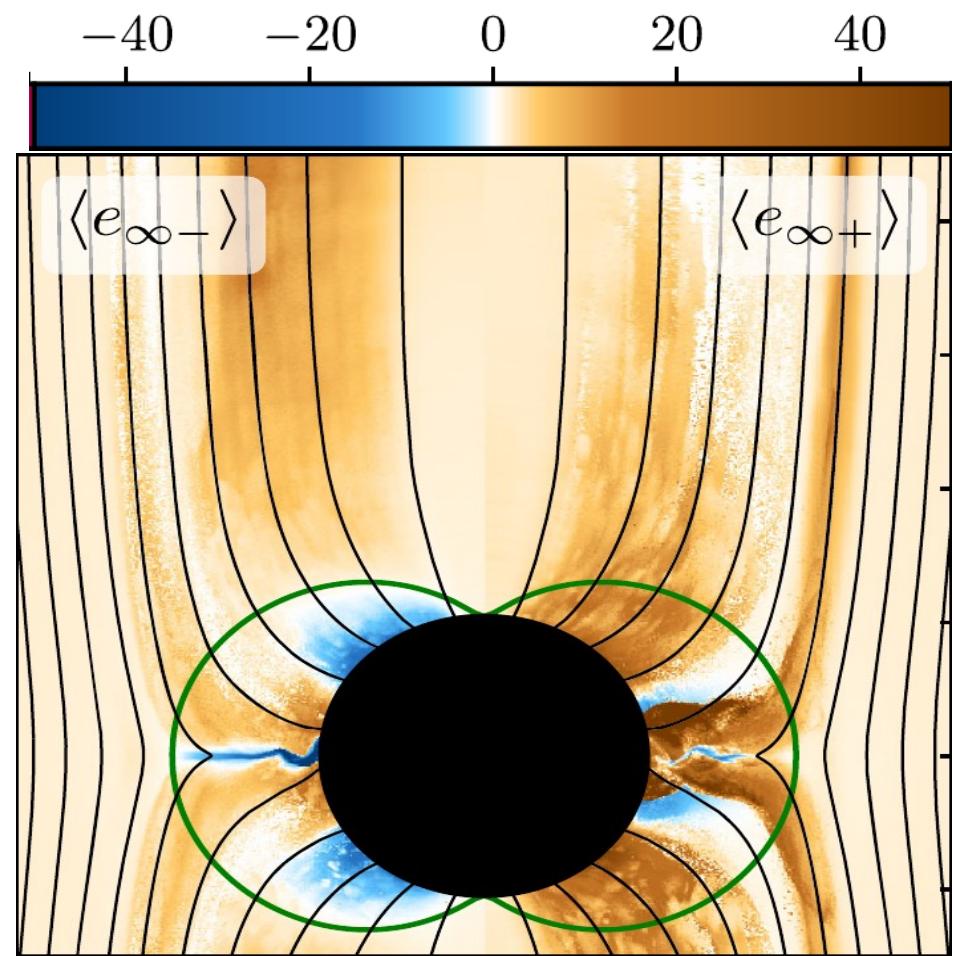


*Parfrey, Philippov & Cerutti (2019)*

## Particle acceleration



## Penrose particles

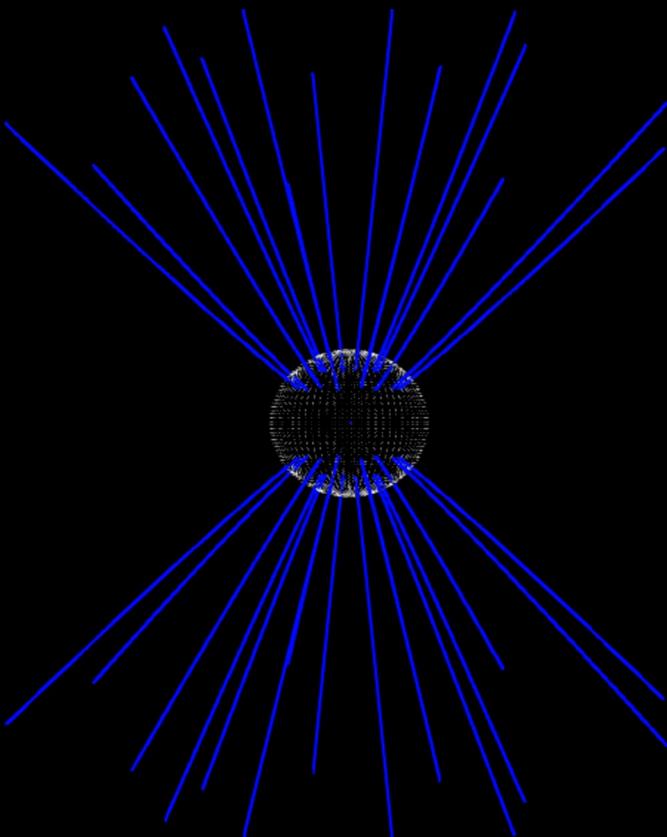


*Parfrey, Philippov & Cerutti (2019)*

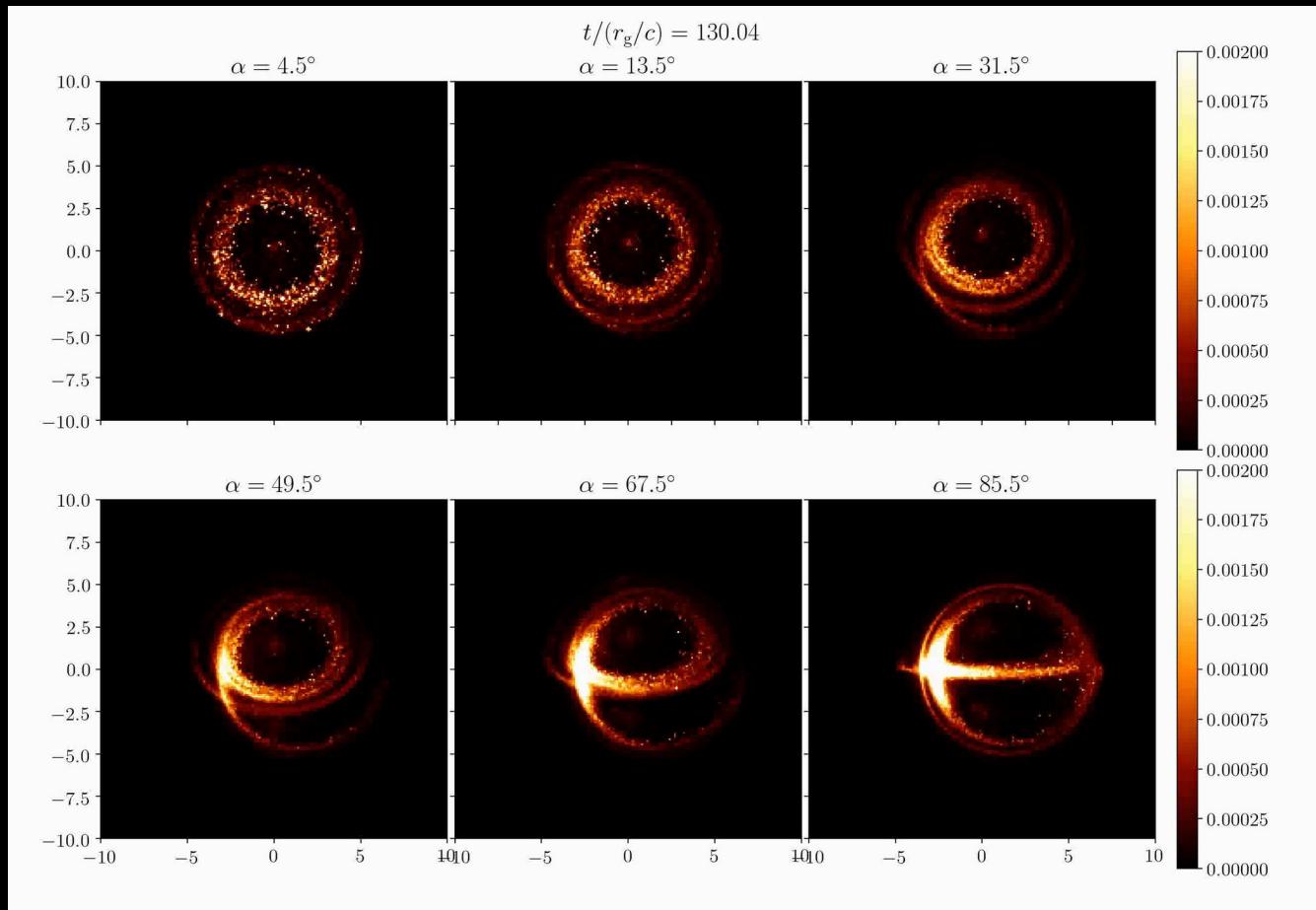
# 3D magnetospheric simulation

*Crinquand, Cerutti, Dubus et al. (2022)*

# **Extension to full 3D**



# Synthetic synchrotron images



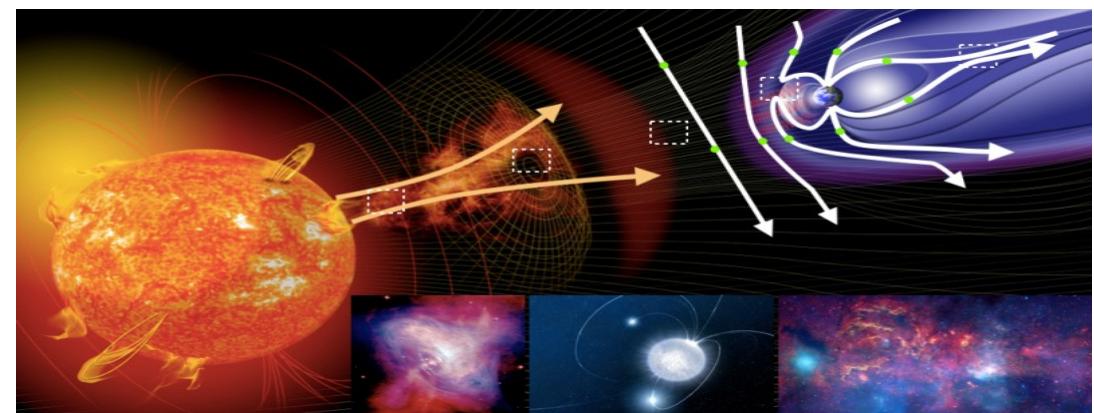
*Crinquand, Cerutti, Dubus et al. (2022)*

# 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

Guillaume  
Dubus

Jonathan  
Ferreira

Geoffroy  
Lesur

Didier  
Fraix-  
Brunet

Maïca  
Clavel



6 chercheurs CNRS  
2 professeurs UGA  
10 doctorants  
4 postdoctorants

## Thématiques:

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

@ Bruno Maillard



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