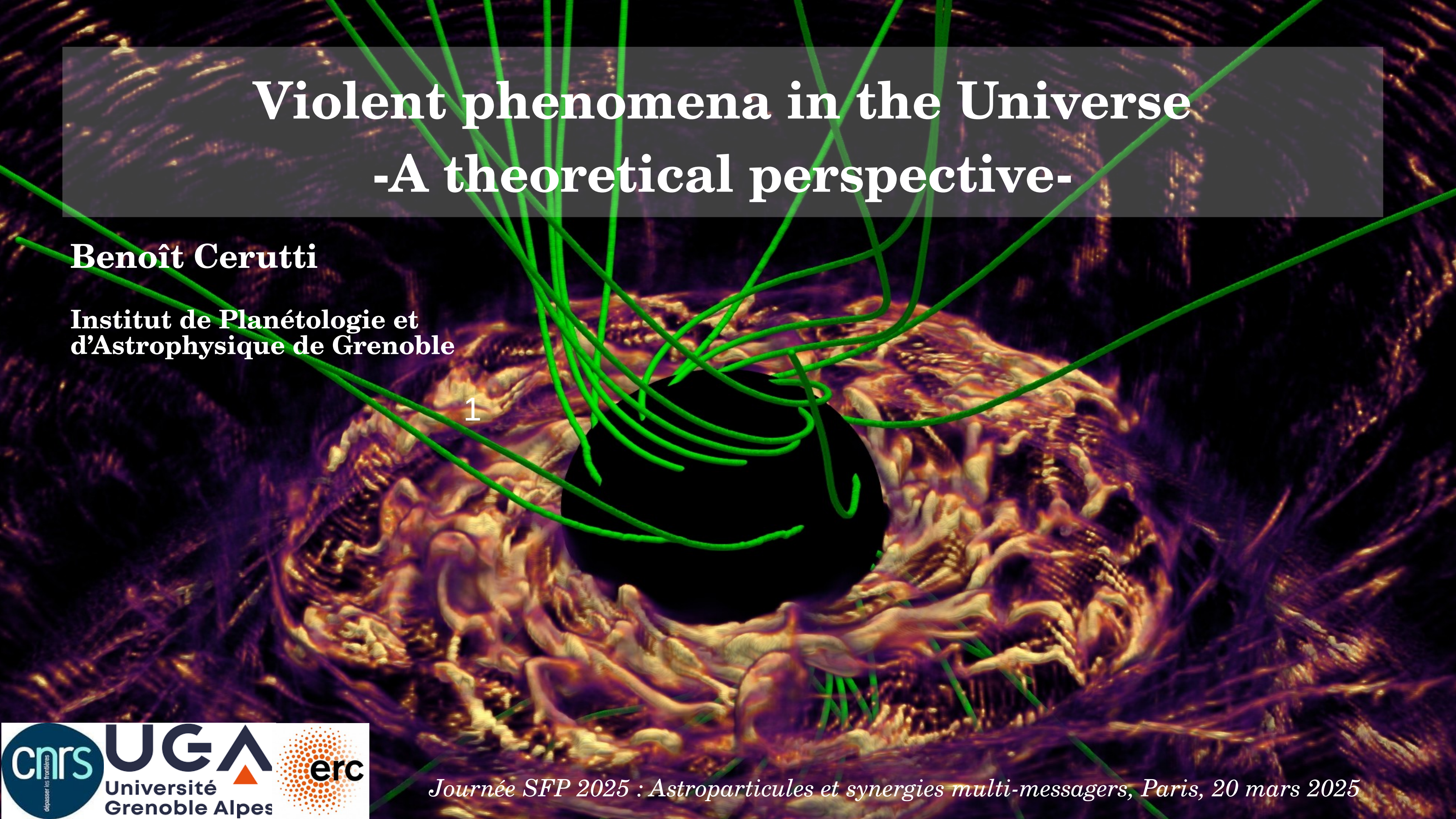


Violent phenomena in the Universe
-A theoretical perspective-

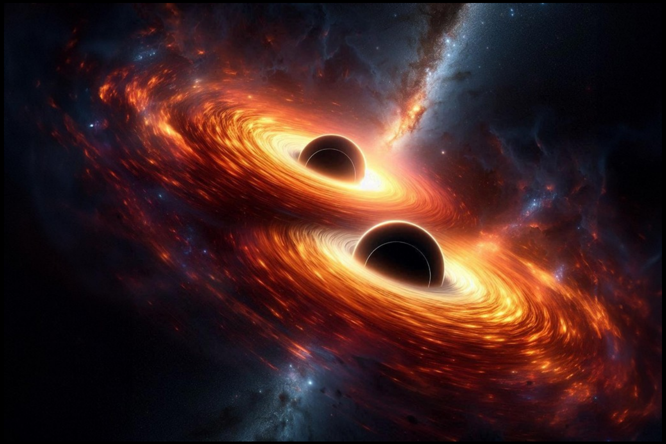
Benoît Cerutti

Institut de Planétologie et d'Astrophysique de Grenoble

Journée SFP 2025 : Astroparticules et synergies multi-messagers, Paris, 20 mars 2025

High-power transient astrophysical phenomena

Black hole mergers

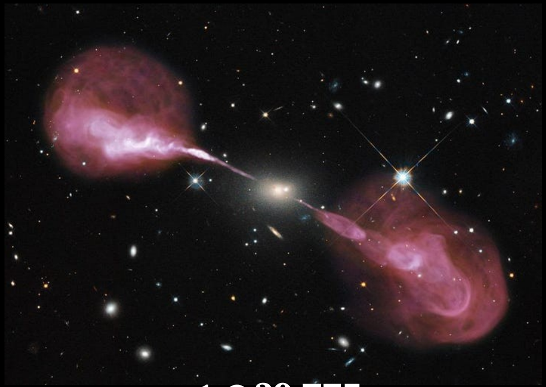


10^{49} W

Gamma-ray bursts

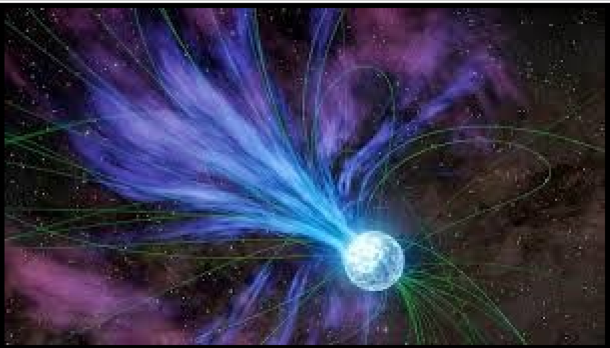
10^{45} W

Active galactic Nuclei



10^{39} W

Giant magnetar flares/FRB



10^{37} W

Tidal disruption events

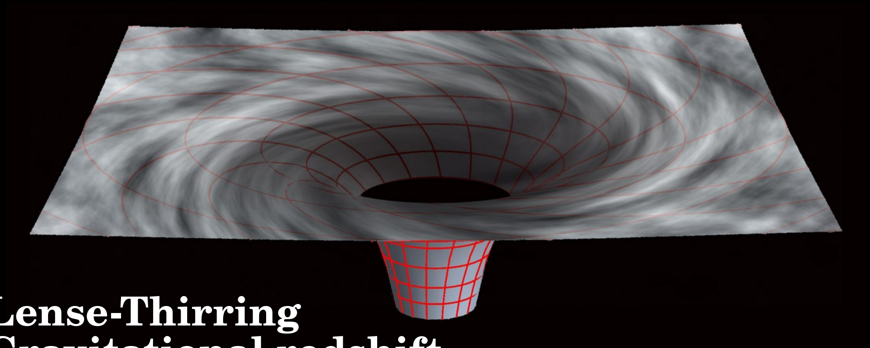
10^{38} W

Sun 10^{26} W

Milky Way 10^{37} W

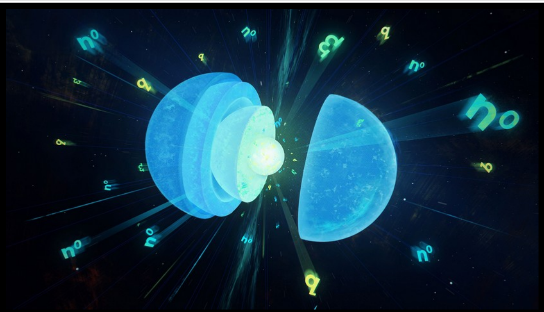
Extreme gravitational & EM fields, extreme densities

Black holes



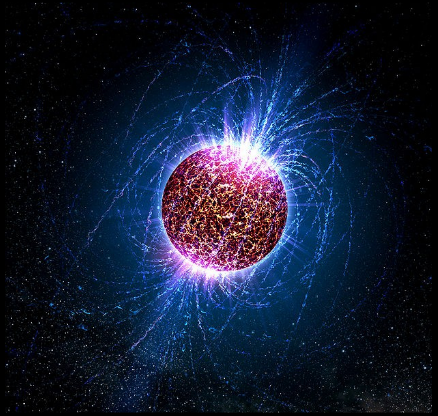
Lense-Thirring
Gravitational redshift
Lensing

Neutron star interior,
SNR/GRB engine



Super-nuclear densities
Superconductivity
Superfluidity
Neutrinos cooling/transfer

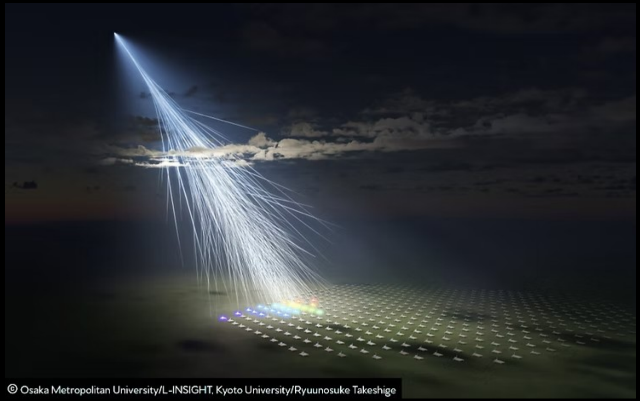
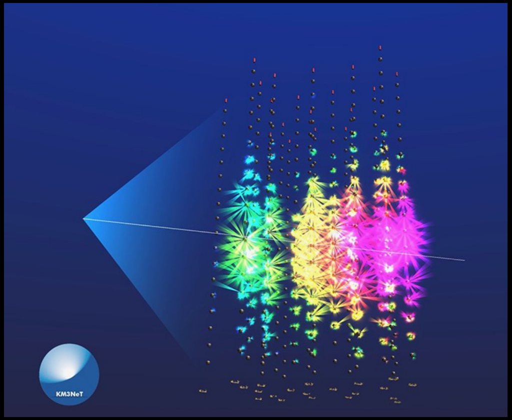
Neutron star



$B \sim 10^{8}$-10^{11} T
QED field $B_{QED}=4.4\times10^{9}$T
Extreme radiative cooling
Pair creation

Fundamental physics
Regimes unreachable on Earth

Extreme particle energies

Gamma rays	Cosmic rays	Neutrinos
		
PeV	**200 EeV**	**200 PeV**

What are the sources?
What are the acceleration mechanisms?

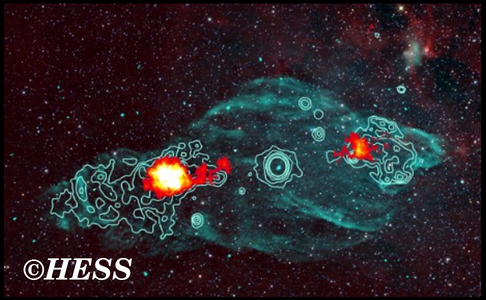
Extreme particle acceleration

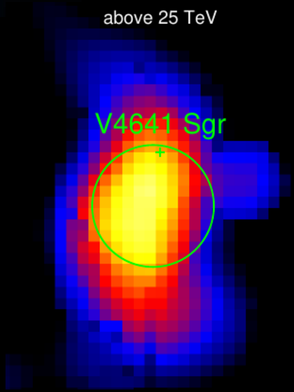
Galactic PeVatrons

Pulsar wind nebulae

PeV

Microquasars





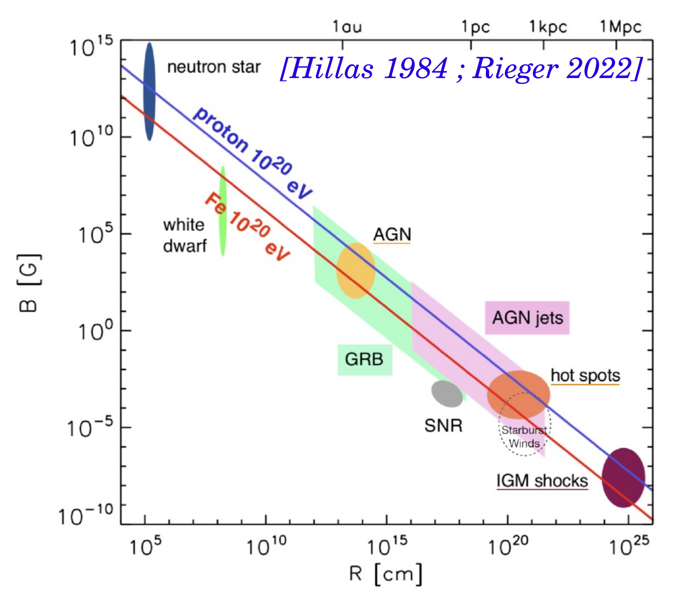
©LHAASO

100 TeV- 1 PeV

Ultra-High Energy CR

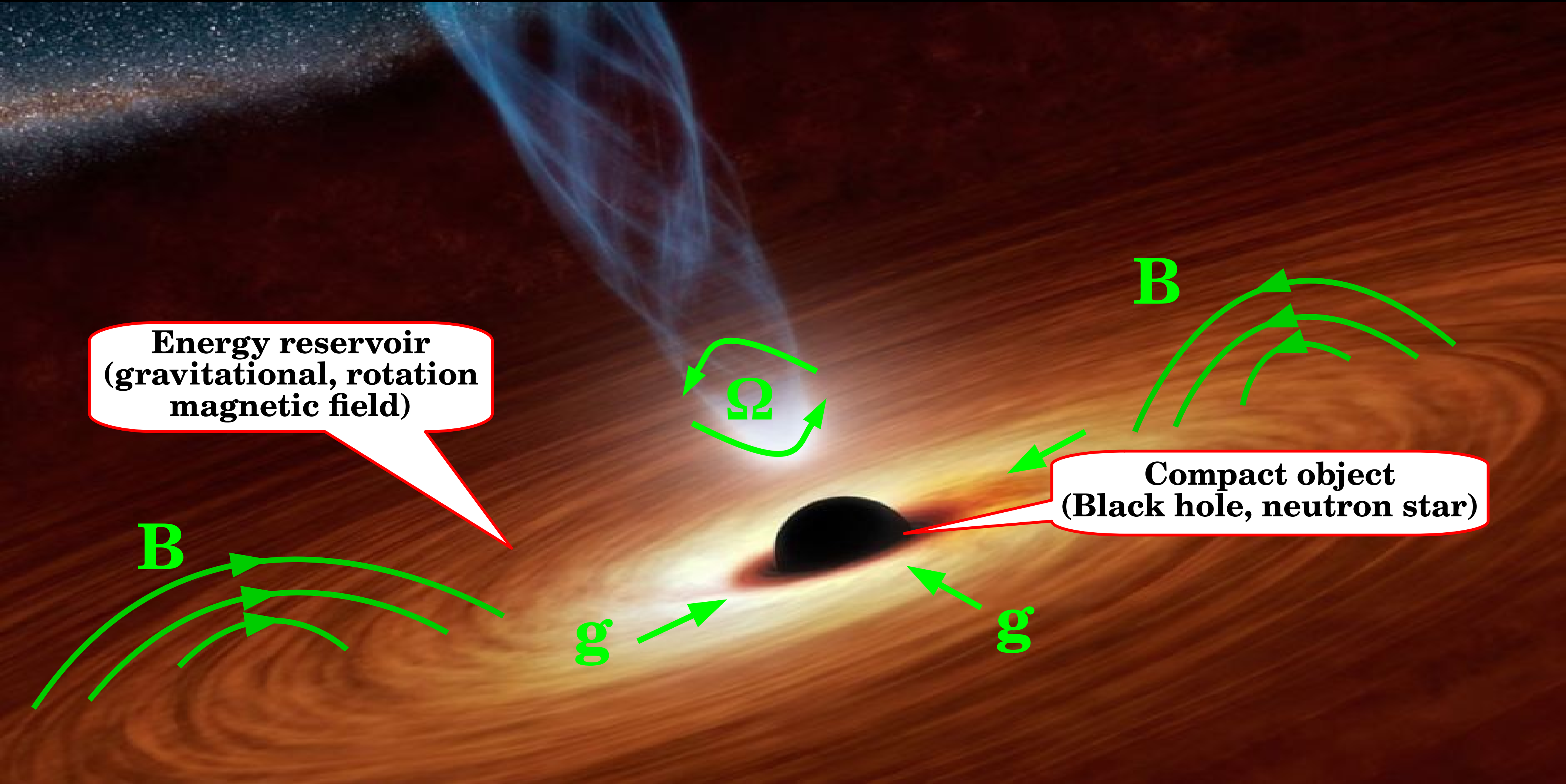
Larmor radius = source

$$E \leq 10^{20}\, Z \left(\frac{B}{10\mu\,\mathrm{G}}\right)\left(\frac{L}{10\ \mathrm{kpc}}\right)\ \mathrm{eV}$$

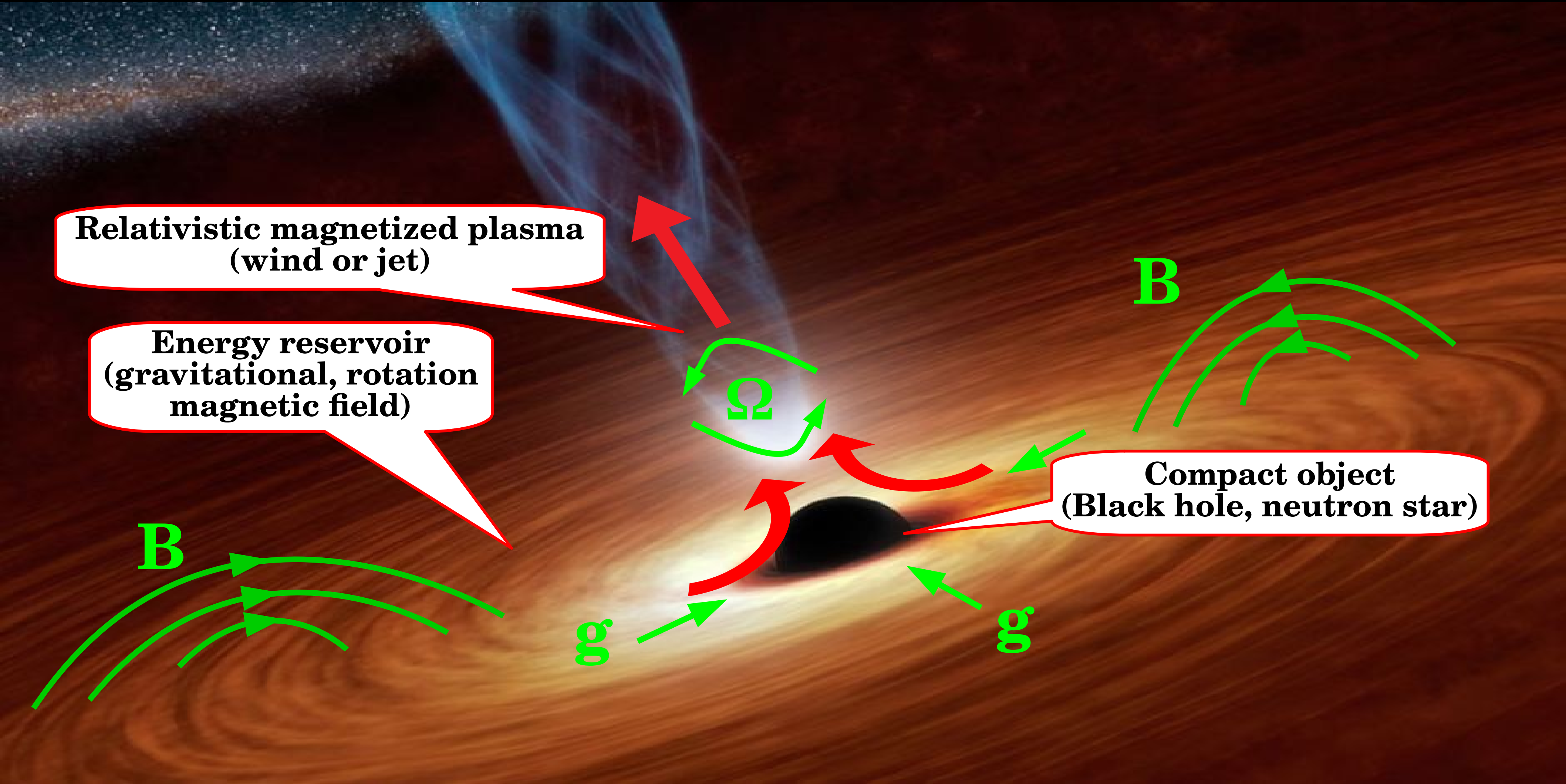


=> Particle acceleration up to the confinement limit
Major challenges for acceleration mechanisms

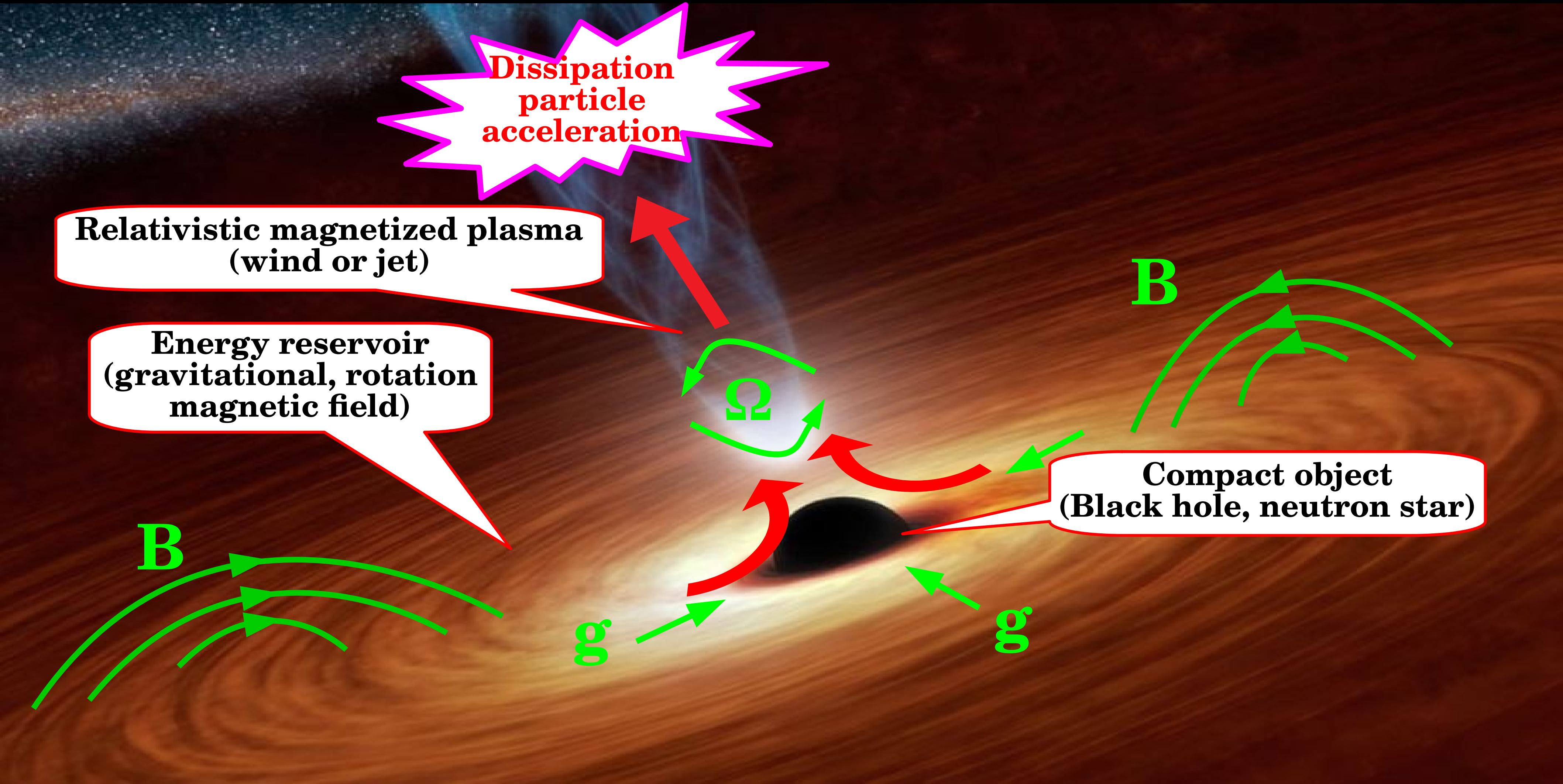
Energy channels



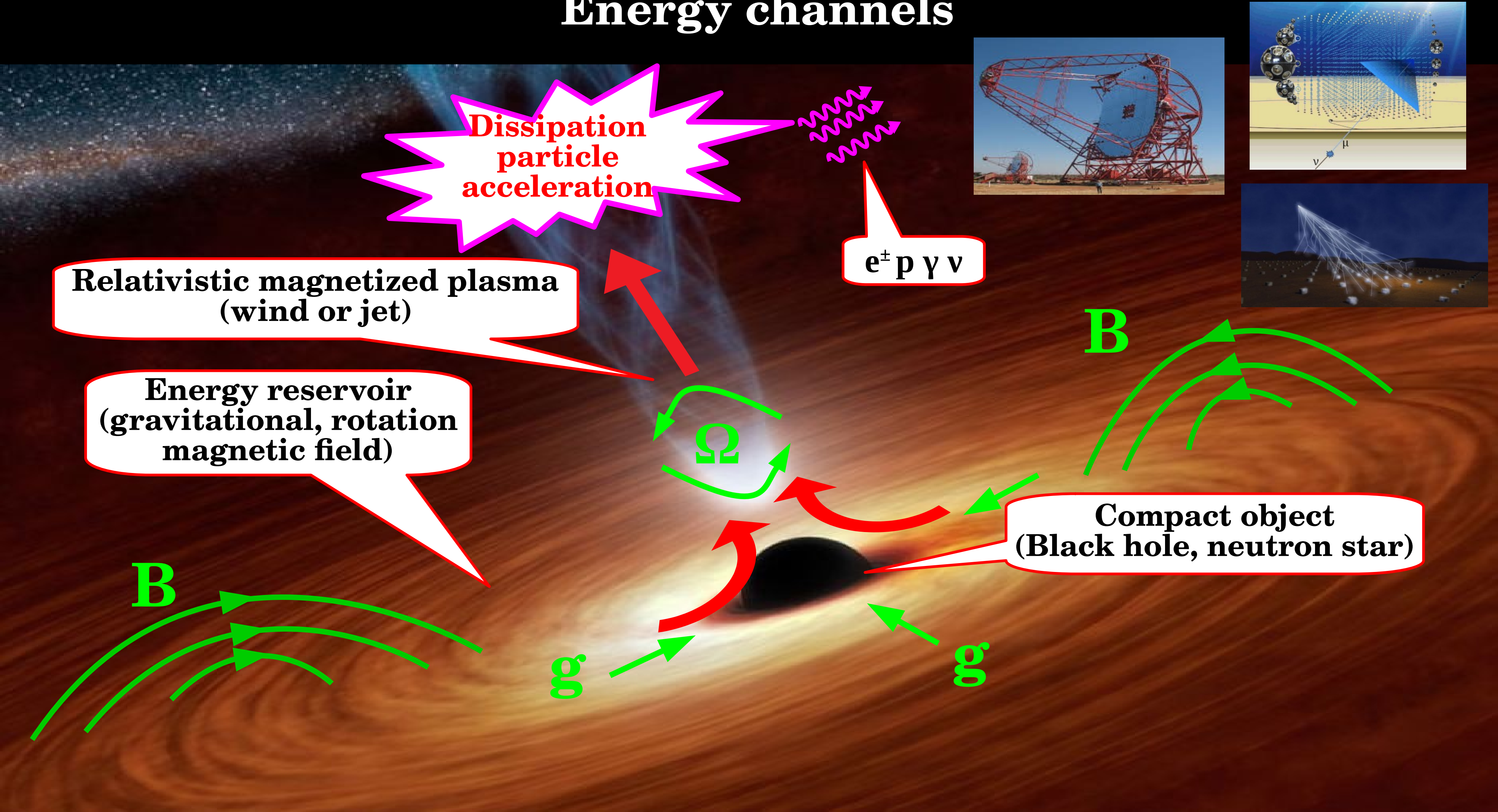
Energy channels



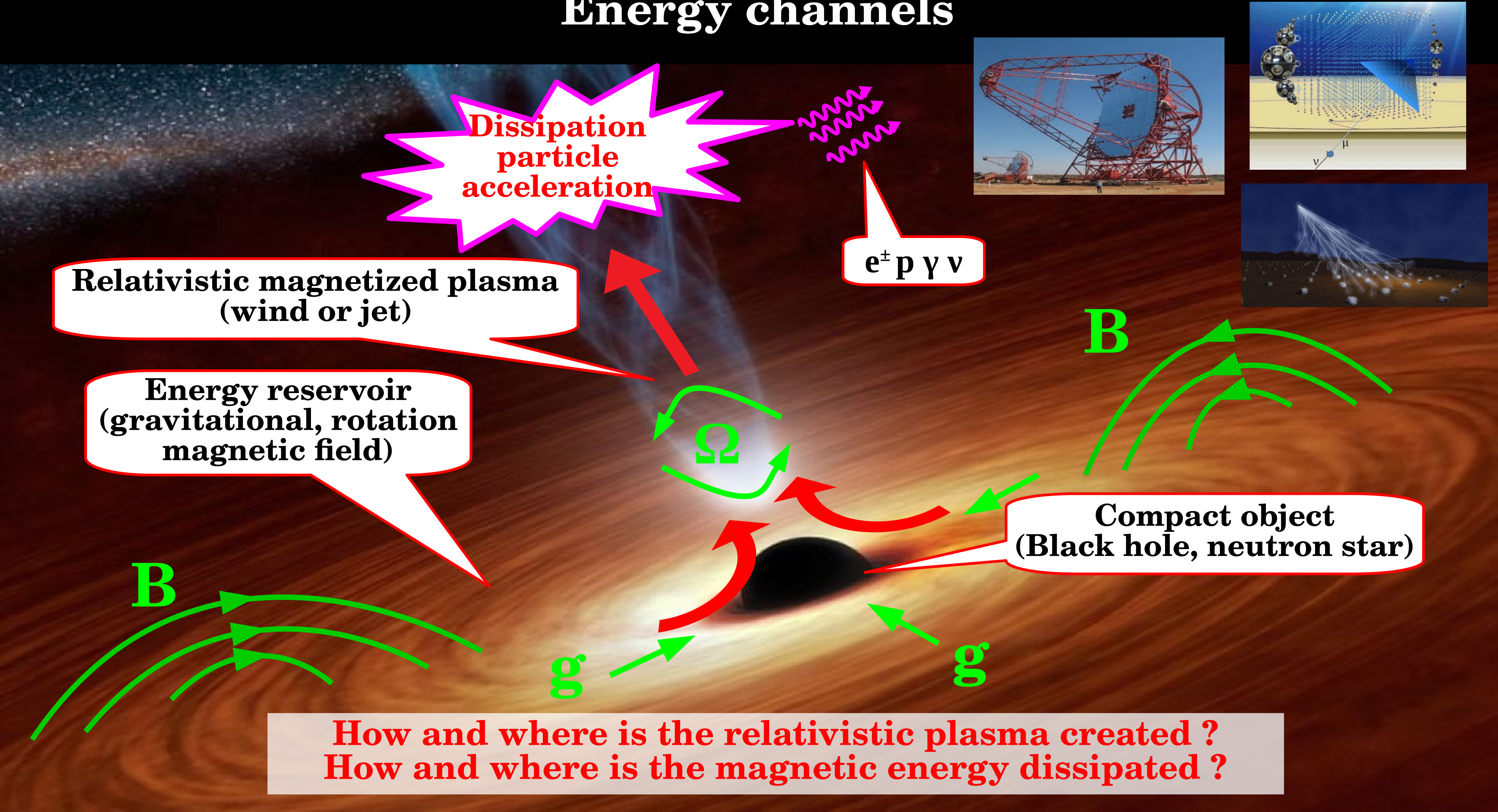
Energy channels



Energy channels



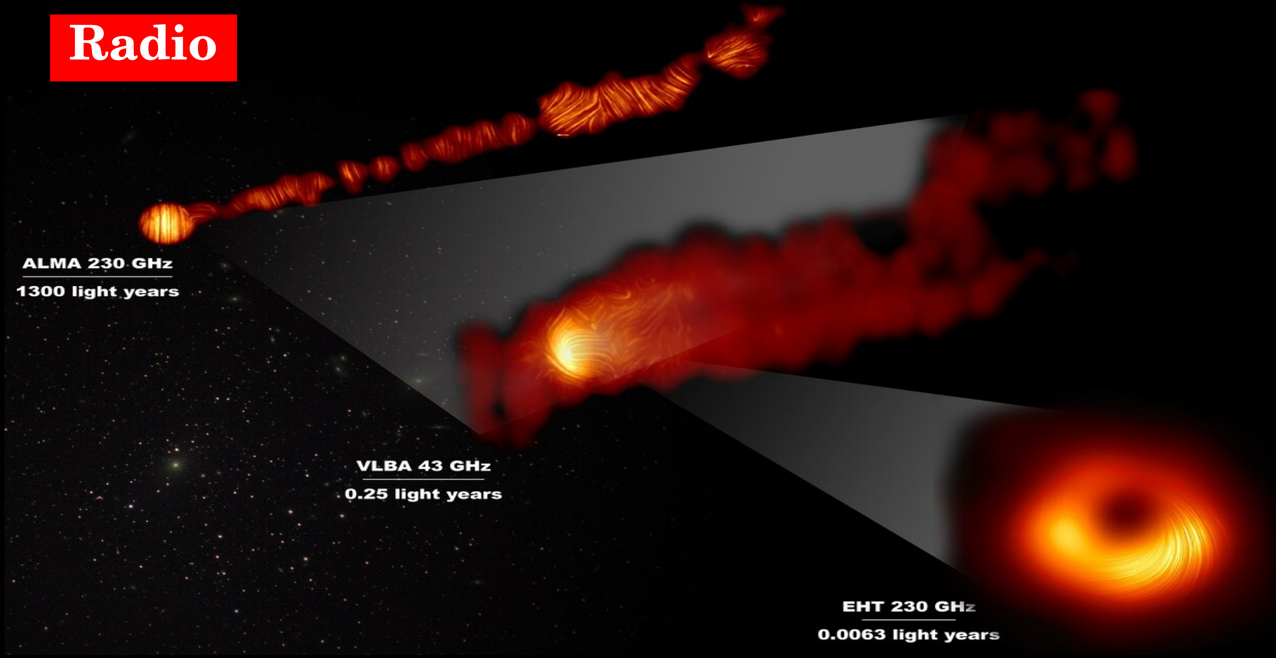
Energy channels



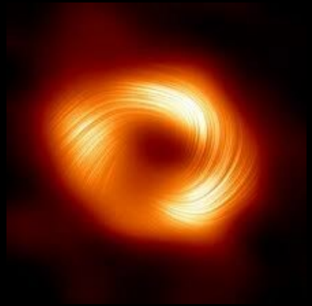
Black-hole jet engine : Horizon-scale observations

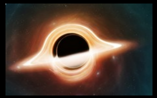
EHT collaboration (M87*)

Radio



SgrA*



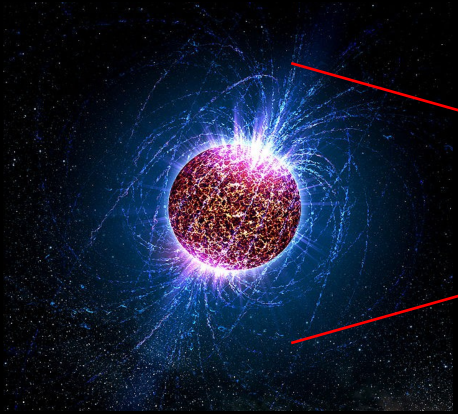


<u>Non-thermal</u> synchrotron radiation => **particle acceleration**
<u>Polarized</u> emission => **Large-scale magnetic field**

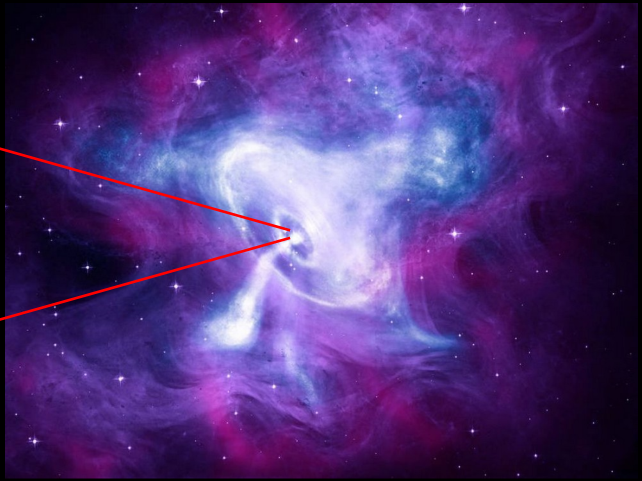
“Nearby” playground for black-hole jet physics

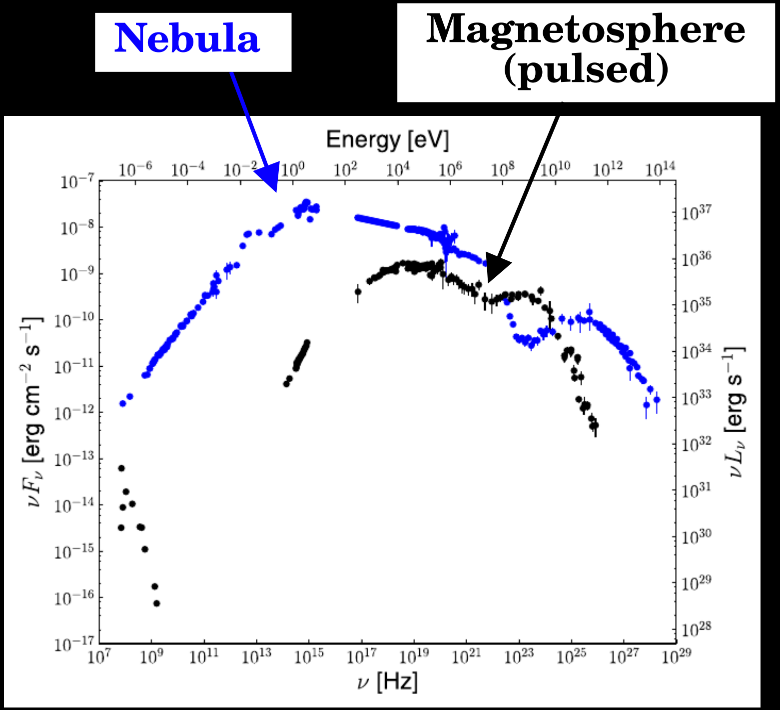
Pulsars and pulsar wind nebulae

Spinning (1ms-1s) neutron star
$B \sim 10^5 - 10^{11}$ T



Pulsar wind nebula





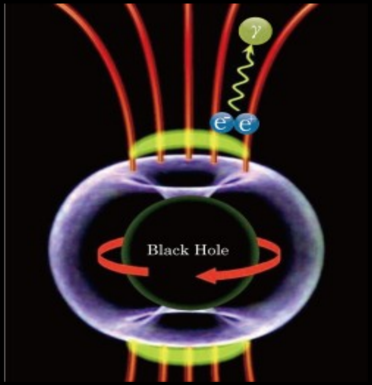
[Buehler & Blandford 2014]

Well-posed problem
Geometry known
Energetics known
Broadband observations

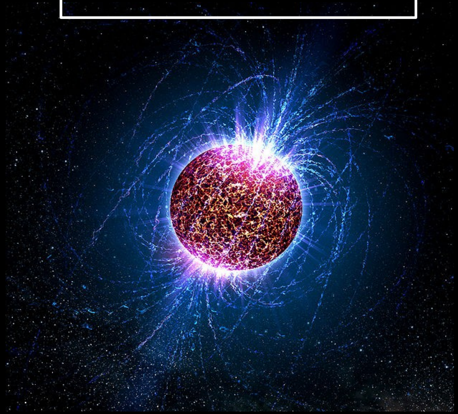
=> Fantastic nearby relativistic plasma machine

The common denominator and beating heart

Black holes



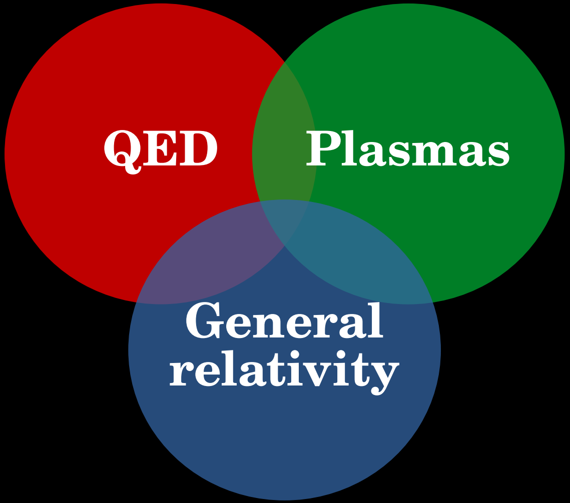
Neutron stars



Magnetosphere
=
plasma + large-scale magnetic field

Closest region accessible to observations

IN2P3 INP INSU



Relativistic in many ways :

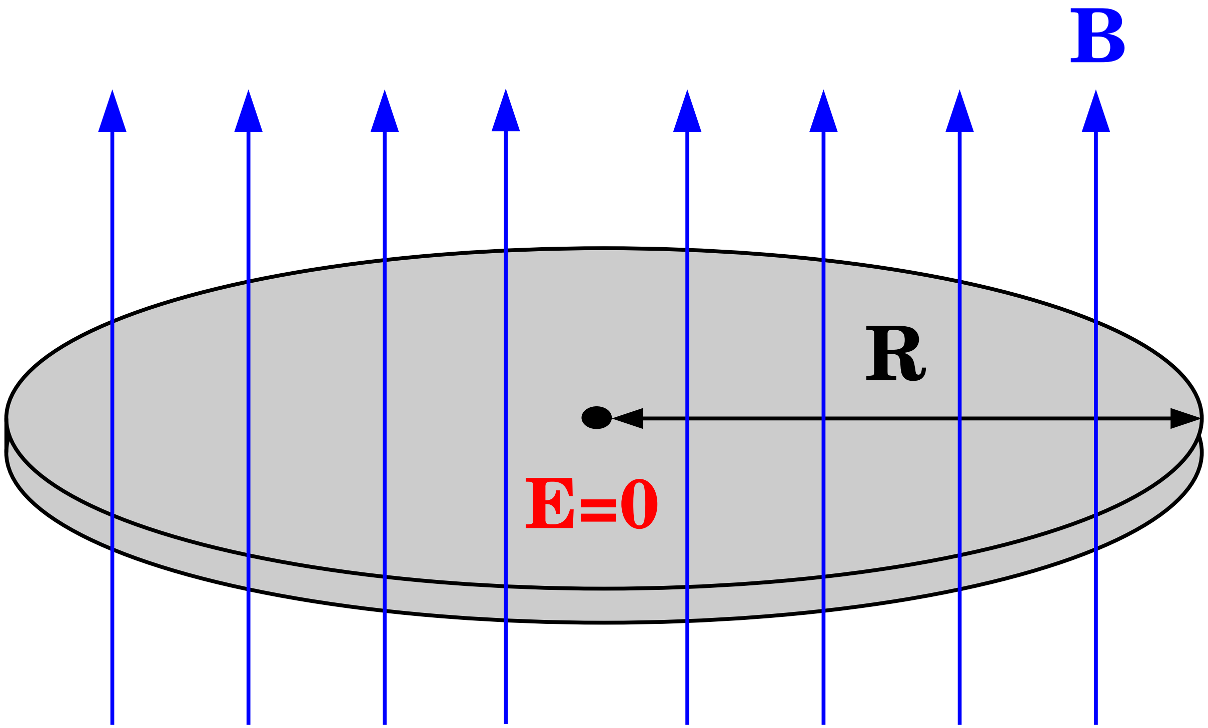
- Relativistic outflows
- Pair creation
- Non-thermal radiation
- GR effects (Lense-Thirring, curvature, etc...)

Extreme plasma astrophysics

Electrodynamics of relativistic magnetospheres

Static, perfectly conducting disk
Uniform B field

Reviews, e.g., Cerutti & Beloborodov 2017



=> Electric field E=0

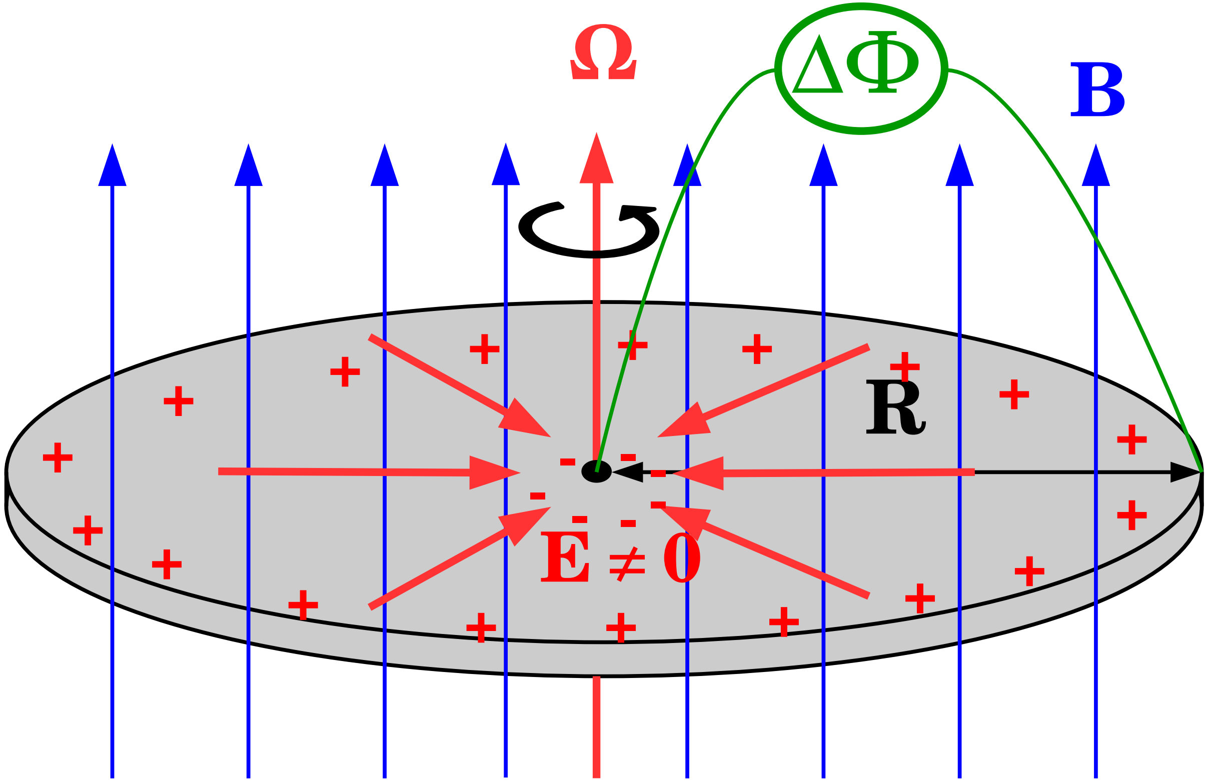
A familiar analogy: Faraday's disk

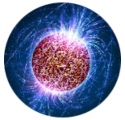
Rotating, perfectly conducting disk : Contant angular velocity **Ω**
Uniform B field

M87*

$r_g \sim 60$ AU
$B \sim 100$ G
$a \sim 1$

Potential drop
$\Delta\Phi \sim 10$ EV





Crab

$r_* \sim 10$ km
$B \sim 10^{12}$ G
$P \sim 33$ ms

Potential drop
$\Delta\Phi \sim 1$ EV

Induced electric field **$E = -V \times B/c = -(\Omega \times R) \times B/c$.** The disk is **polarized**.
=> Potential difference between the center and the outer radius

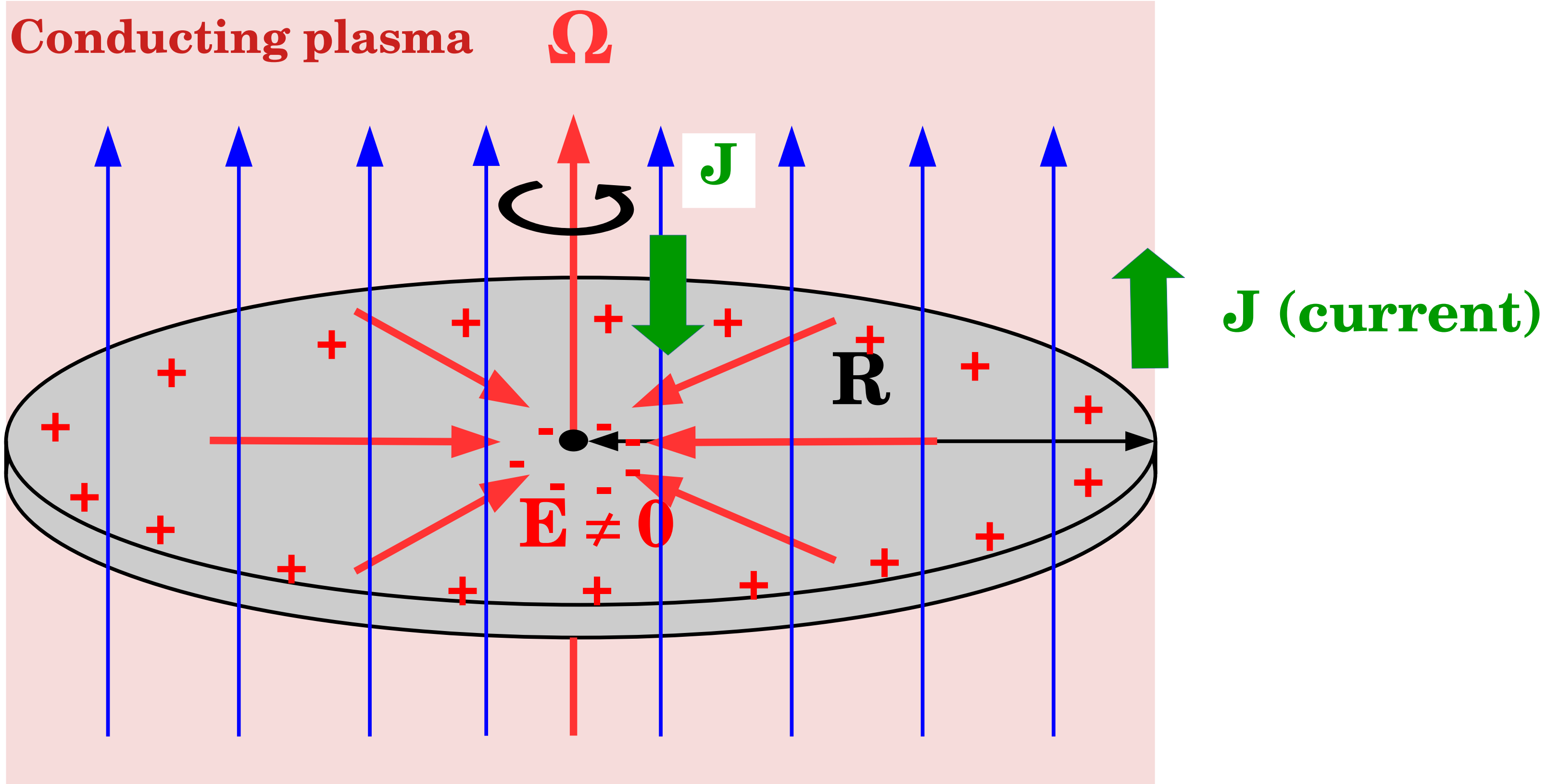
A familiar analogy: Faraday's disk

Current flow, Ampère law => **Toroidal field** !

M87*

$r_g \sim 60$ AU
B ~ 100 G
a ~ 1

Current I
$I \sim J \times r_g^2 \sim 10$ PA



A familiar analogy: Faraday's disk

Current flow, Ampère law => **Toroidal field** !

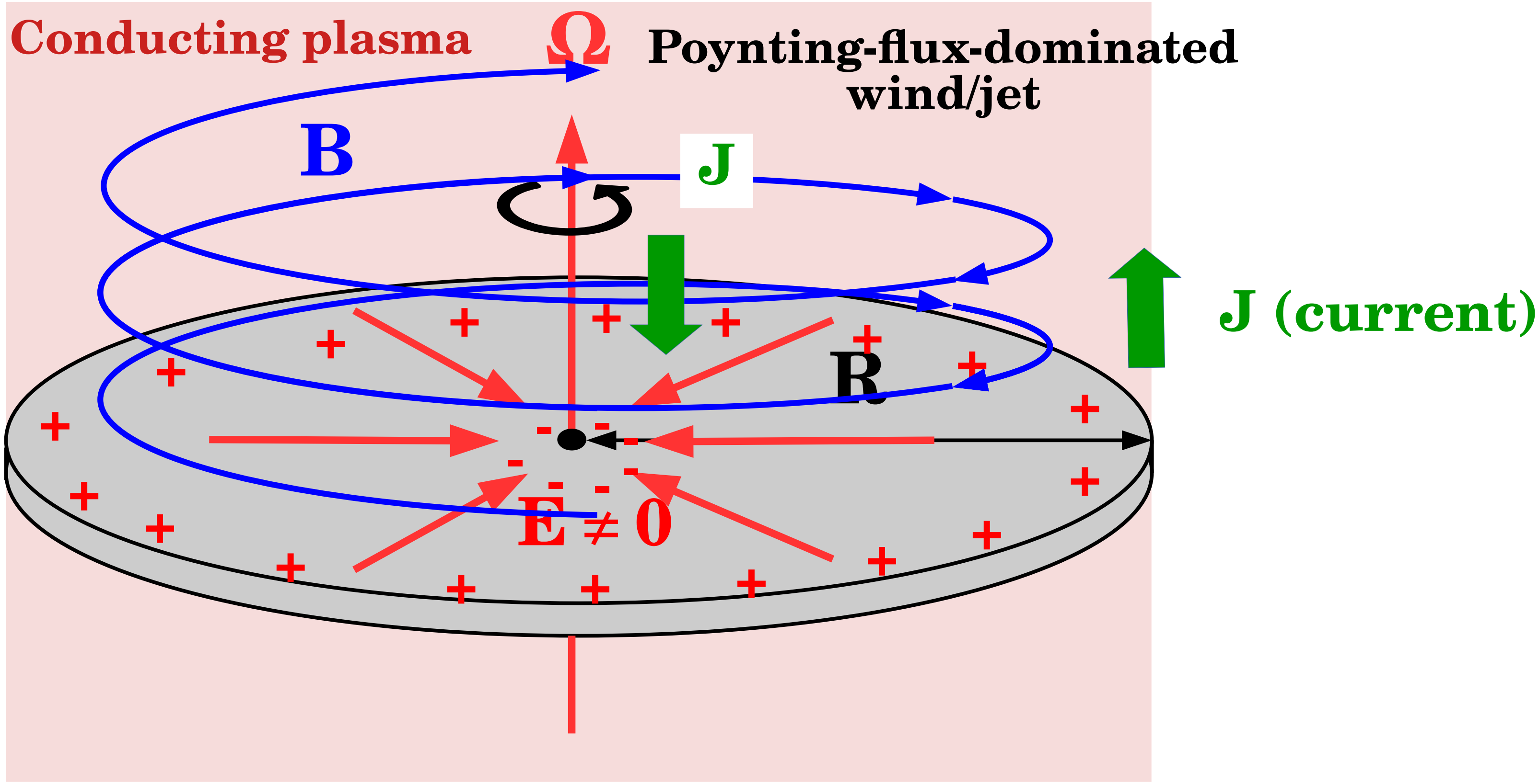
Poynting flux

$$\boxed{L_0 = \frac{1}{2c}\Psi_0^2\Omega^2}$$

$$\Psi_0 = B_0 R_0^2/2$$

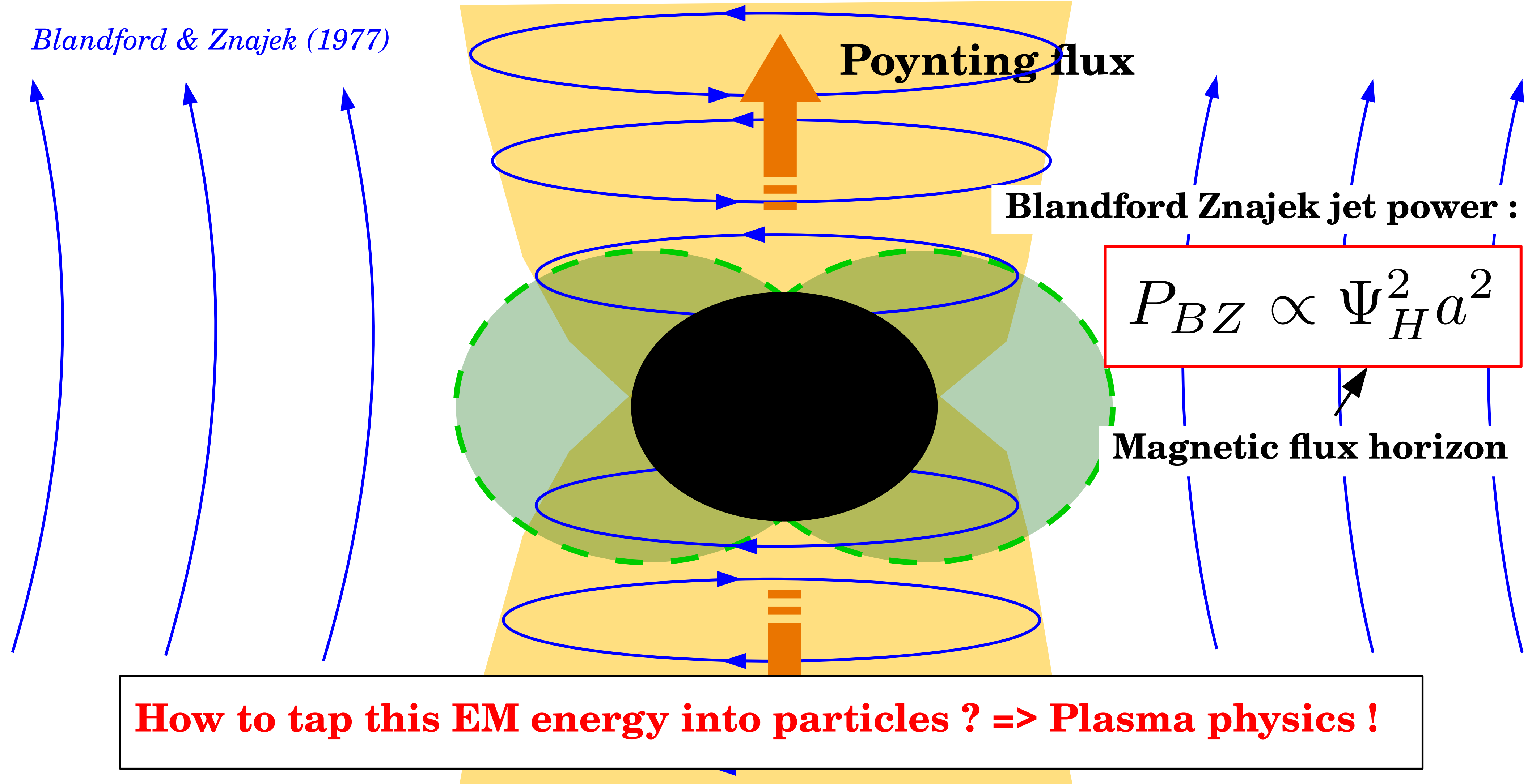
M87*

r_g ~ 60 AU
B ~ 100 G
=> L_0~10^{36} W



Magnetic torque slows down the disk => Electromagnetic spin down

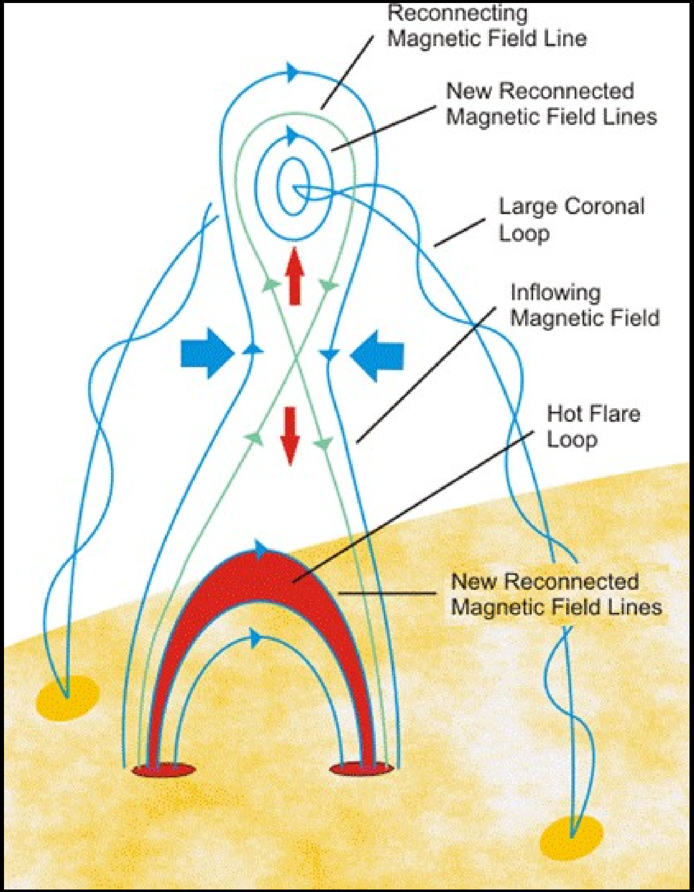
Electromagnetic extraction of the black hole spin



Particle acceleration processes

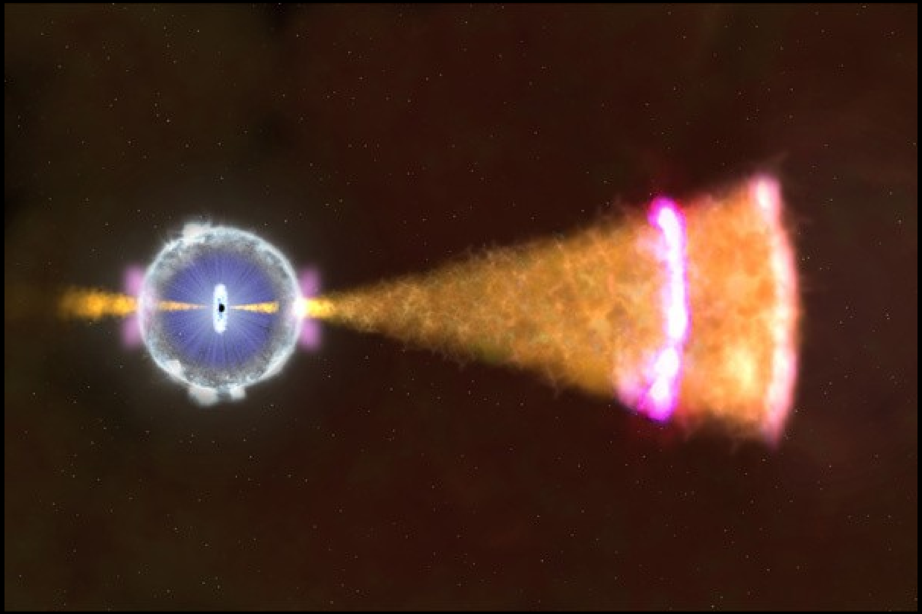
Magnetic reconnection

Magnetic energy => Particles

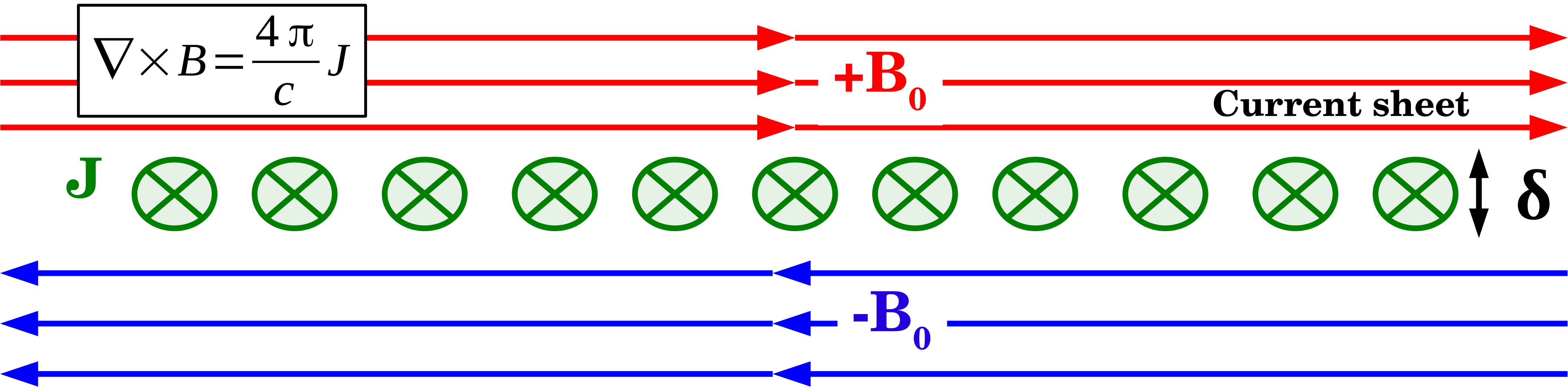


Shocks

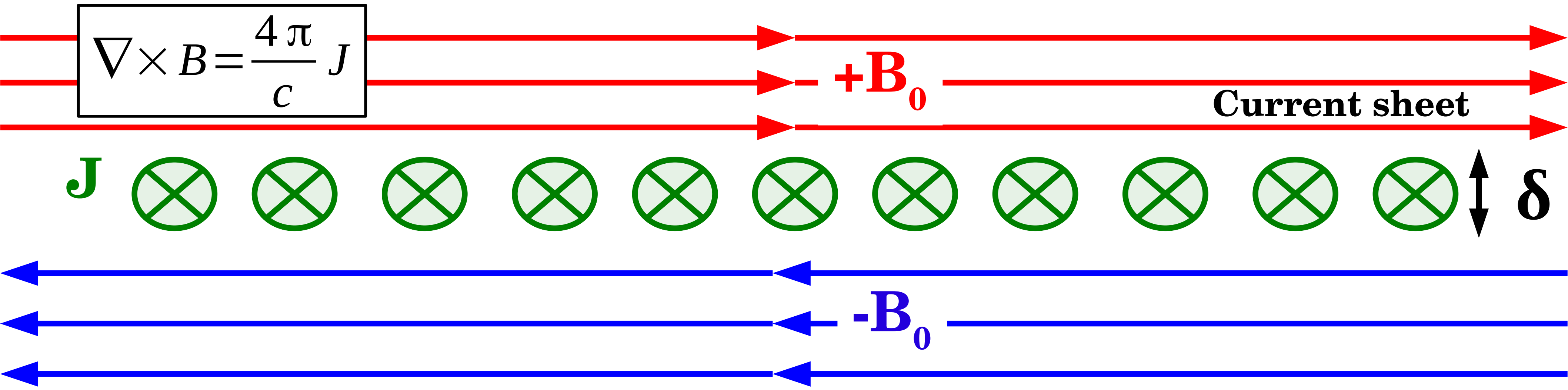
Flow kinetic energy => Particles

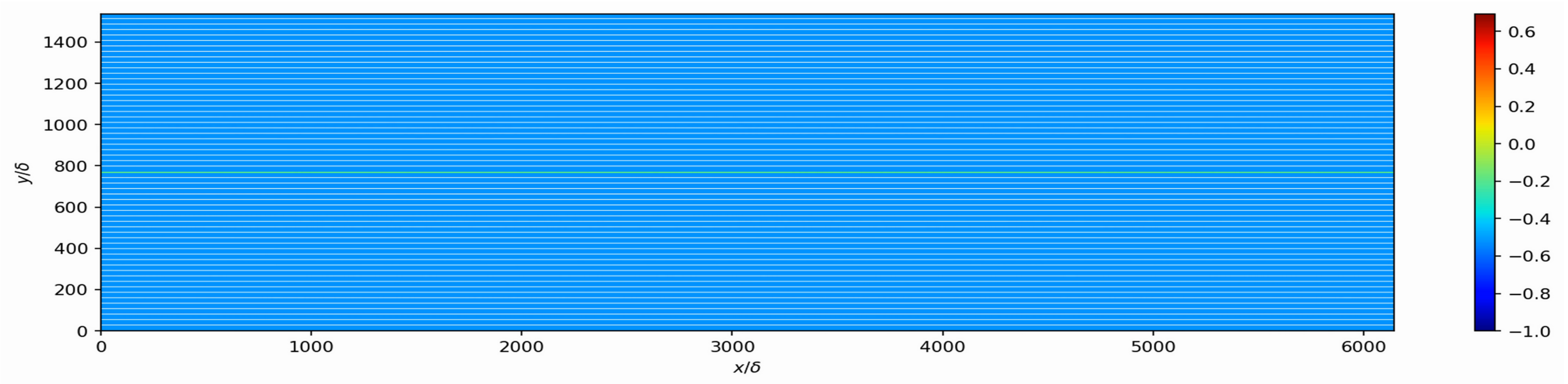


(Relativistic) magnetic reconnection

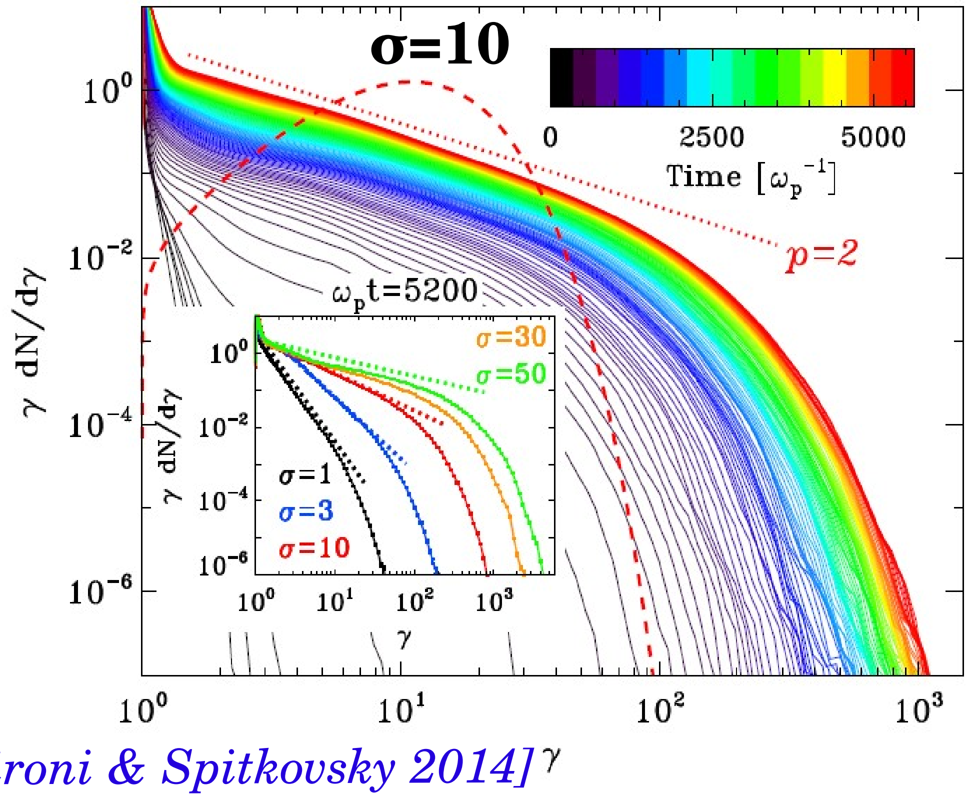


(Relativistic) magnetic reconnection

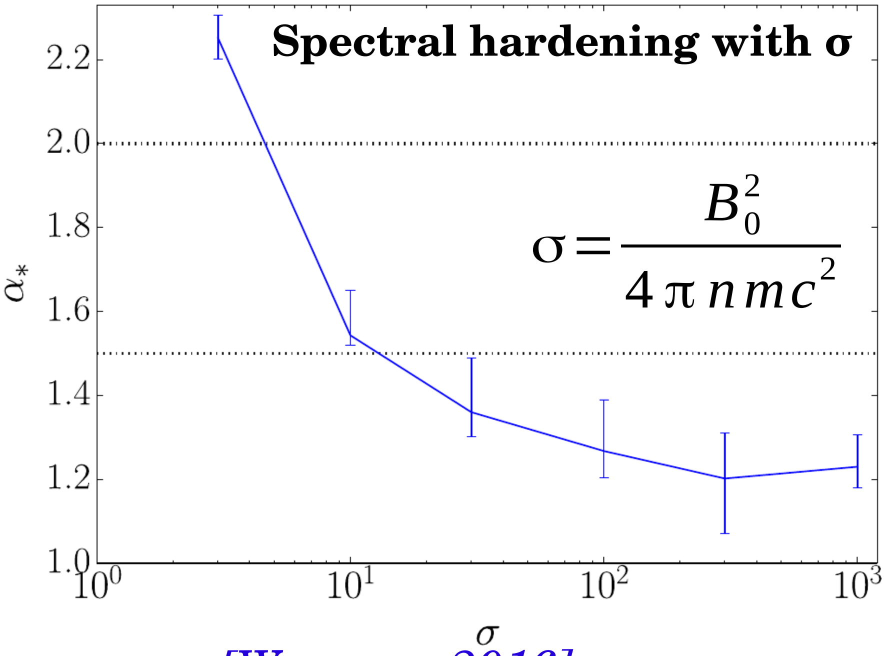




A very efficient non-thermal acceleration process



[Sironi & Spitkovsky 2014]

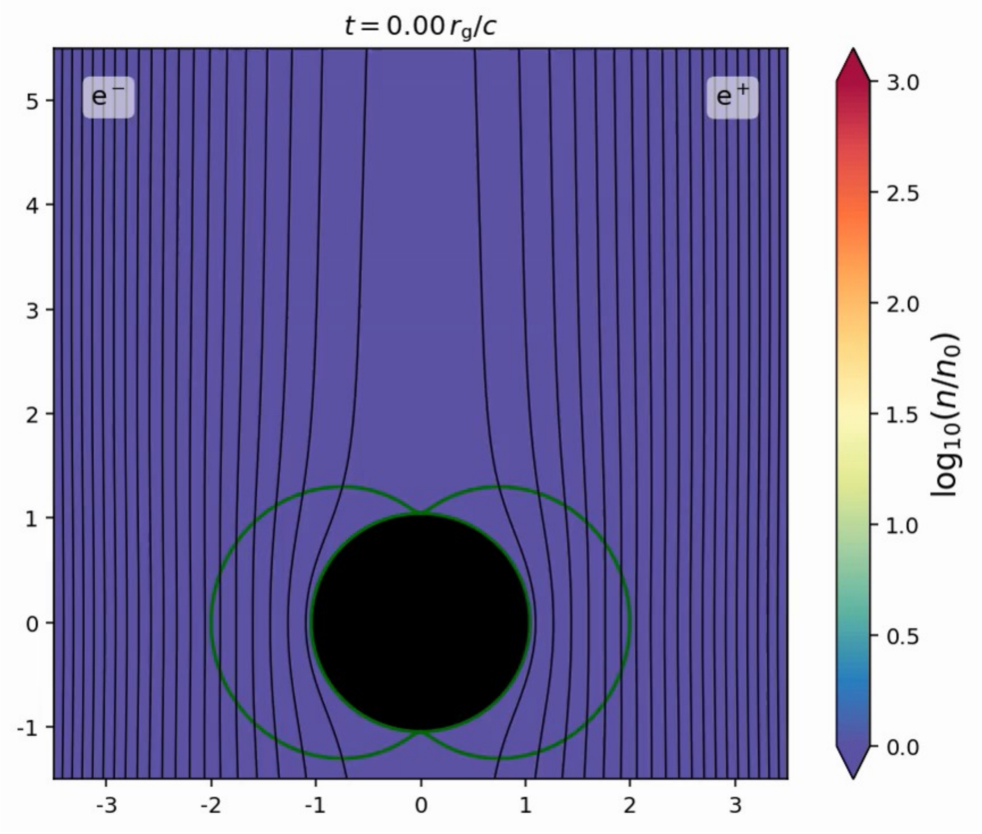


[Werner + 2016]

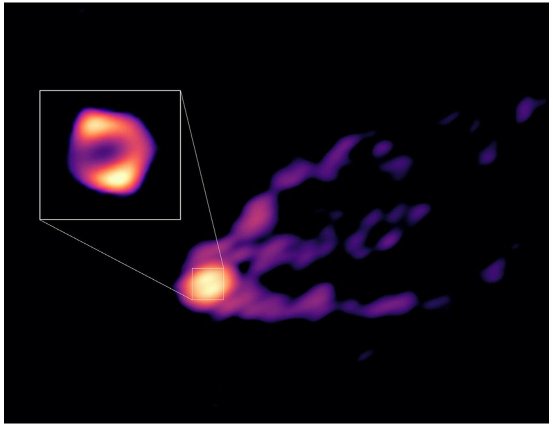
Reconnection proceeds at **10 % the speed of light** (i.e., **it is fast !**)
Broad, hard power-law spectra
Energy limitation : **radiative cooling & pair production**

Reconnection in relativistic magnetospheres

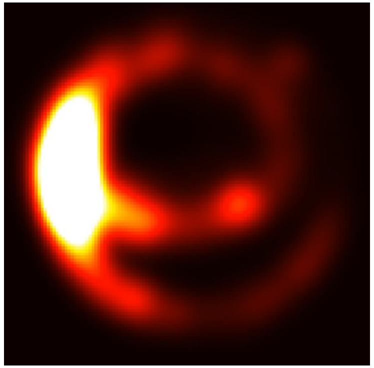
Black holes



Radio image



Synthetic synchrotron image

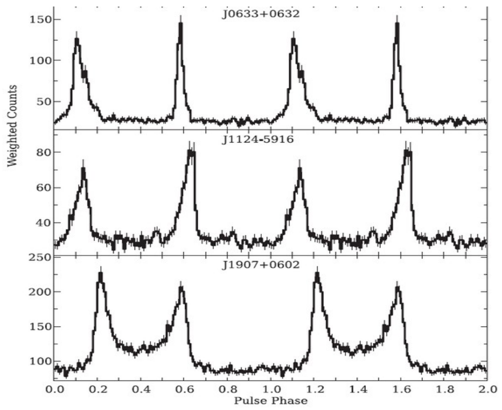


Reconnection consumes **>10 % of the Poynting power**

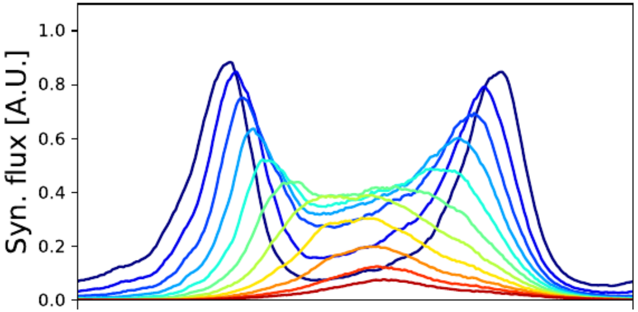
[Parfrey + 2019]

Reconnection in relativistic magnetospheres

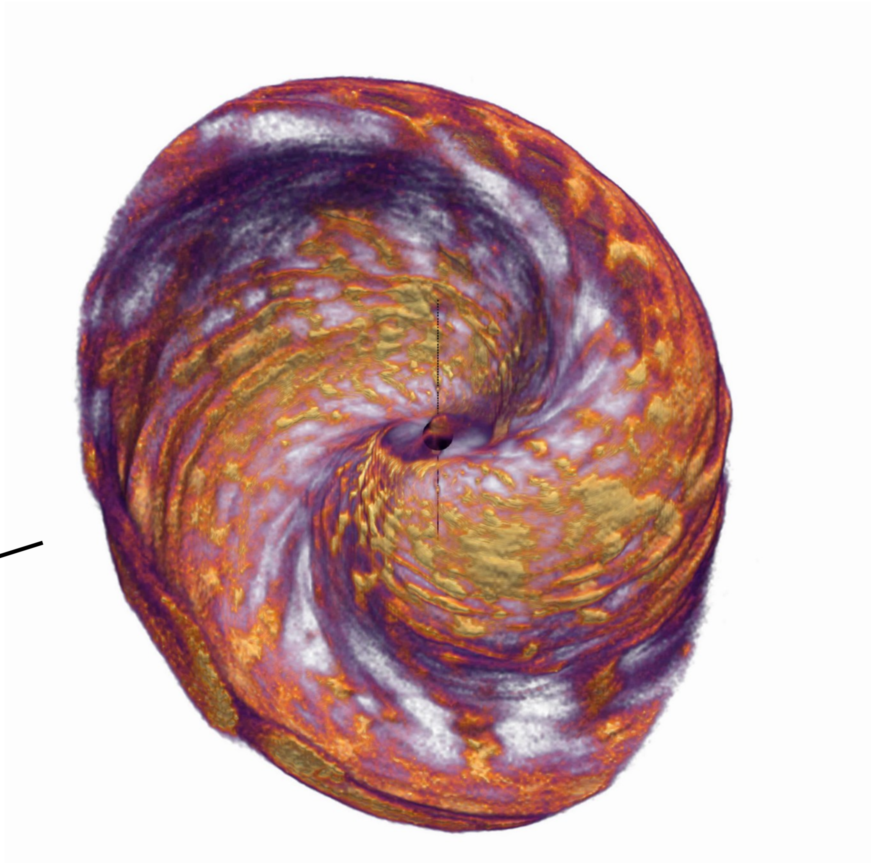
Fermi-LAT pulse profiles



Synthetic pulse profiles



Pulsars



Reconnection consumes **>10 % of the Poynting power**

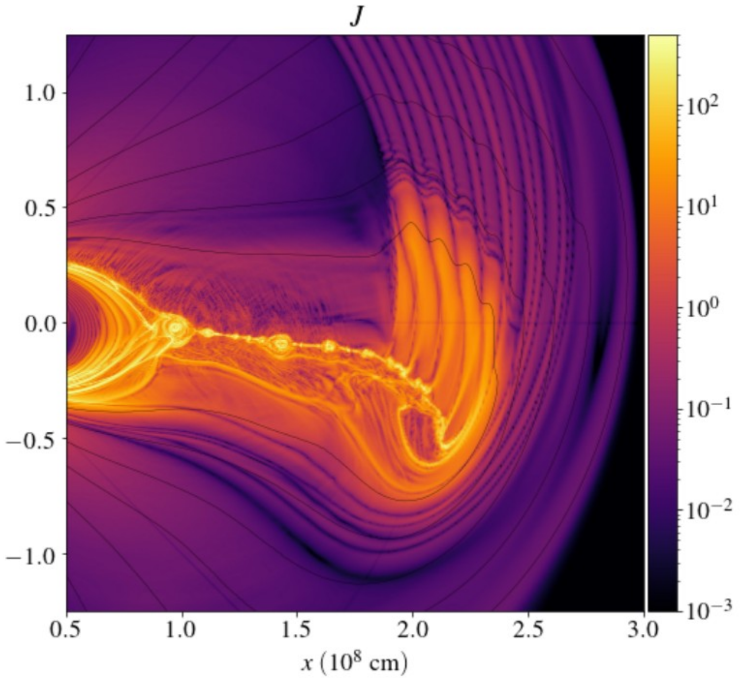
[Cerutti + 2025]

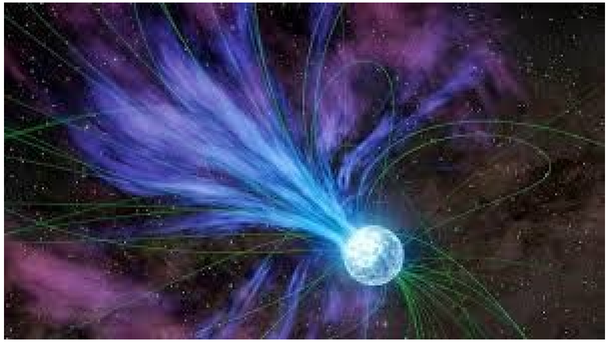
Reconnection in relativistic magnetospheres

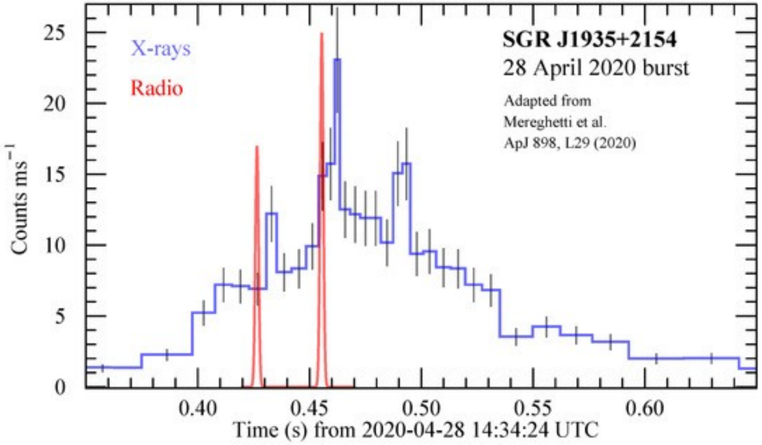
Magnetar flares / Fast Radio Bursts?

Supercritical fields: $B \gg B_{QED}$

=>Energy reservoir in the B field



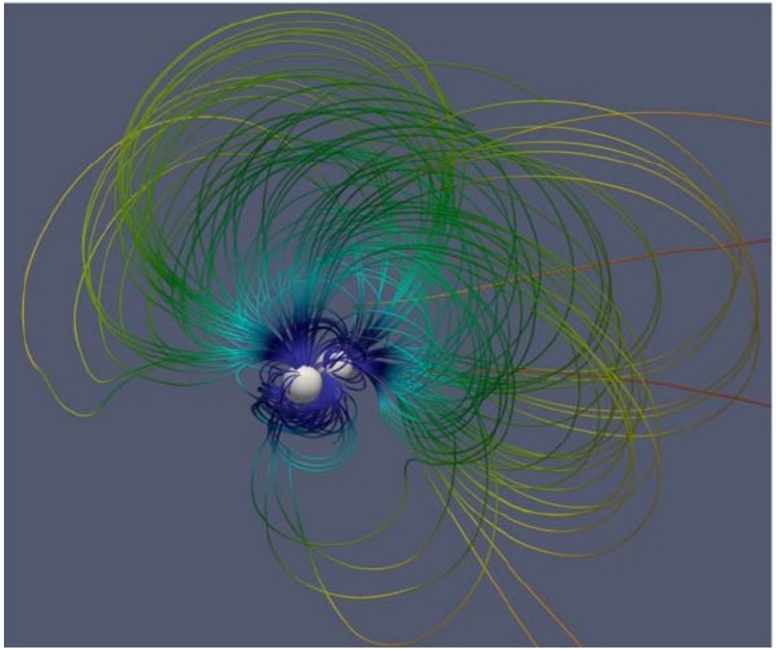




[Yuan + 2020]

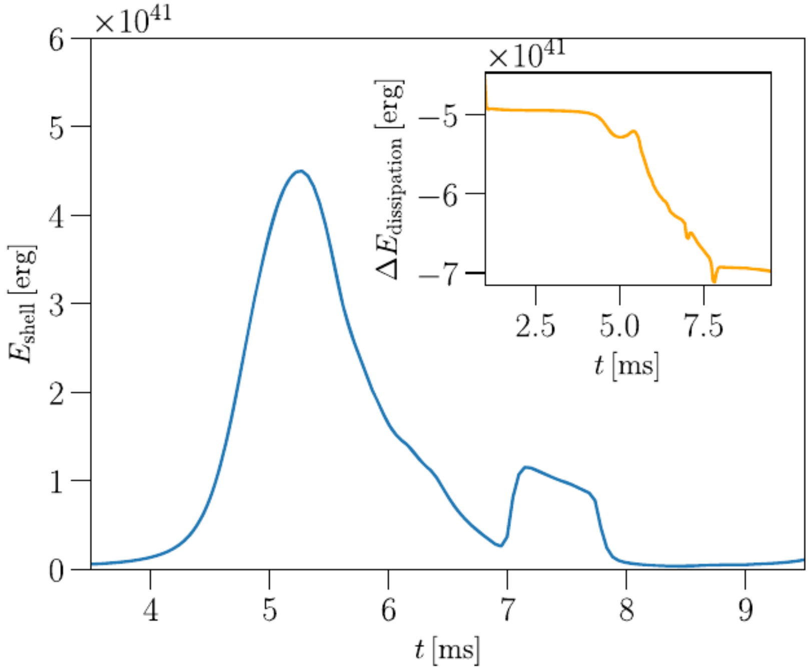
Reconnection in relativistic magnetospheres

Binary compact object



[Most & Philippov 2020]

Precursor electromagnetic emission to mergers



Perspectives

- **Black holes** and **neutron stars** beating hearts of the violent and energetic Universe
- Fantastic playgrounds for studying physics under **extreme conditions**
- Emergence of the « **Extreme Plasma Astrophysics** » subfield QED×Plasmas×General Relativity (IN2P3×INP×INSU), superb interdisciplinary field
- Synergies with **multimessenger astrophysics** and large sky surveys (SKA, LSST, CTA, LIGO-Virgo, …)
- Theory is (slowly) catching up with observations mostly driven by rapid progress in sophisticated **plasma simulations.**
- Multiscale processes, scale separation issue. Exascale computing is the next frontier.