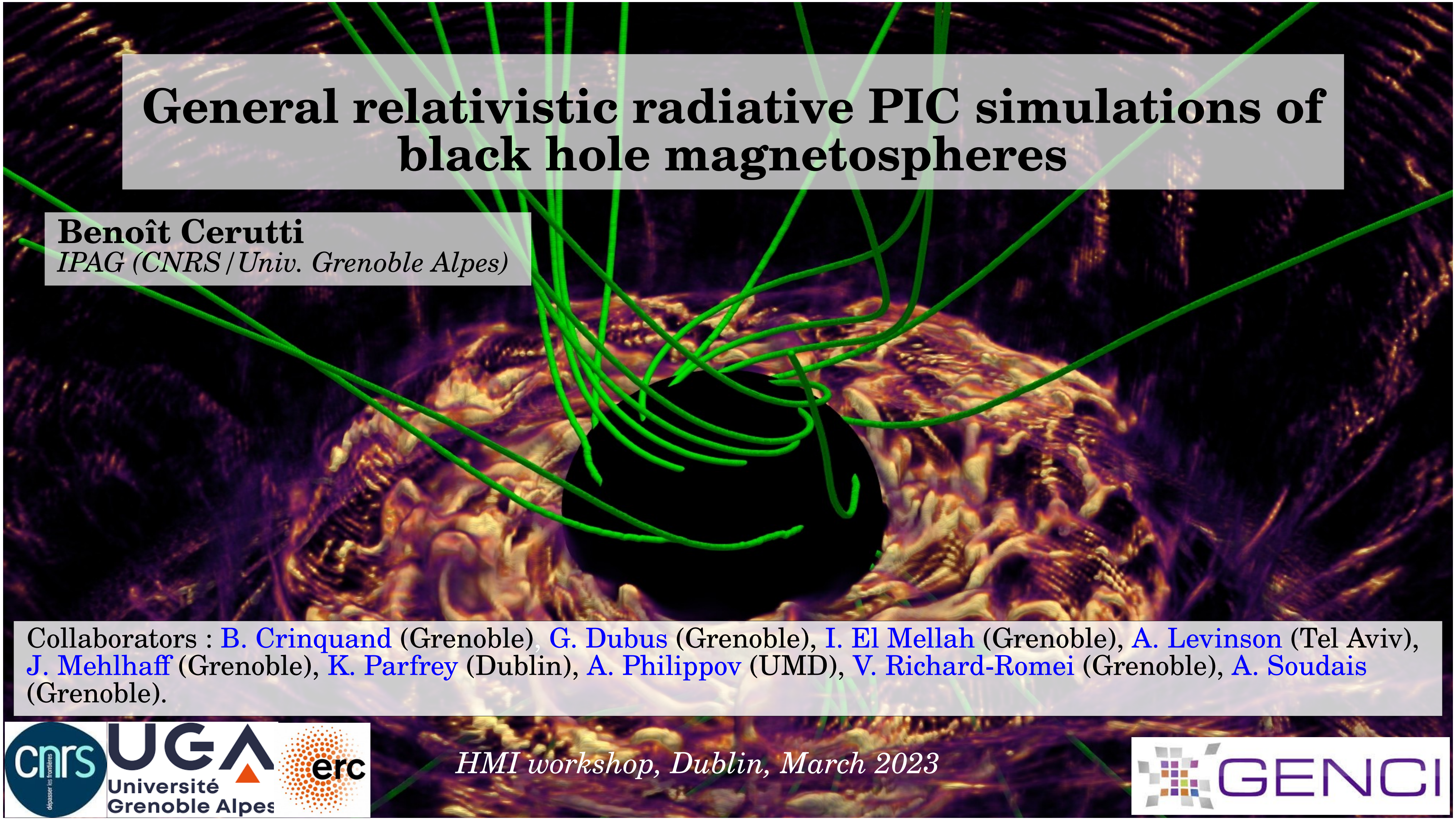
General relativistic radiative PIC simulations of black hole magnetospheres

Benoît Cerutti
IPAG (CNRS/Univ. Grenoble Alpes)



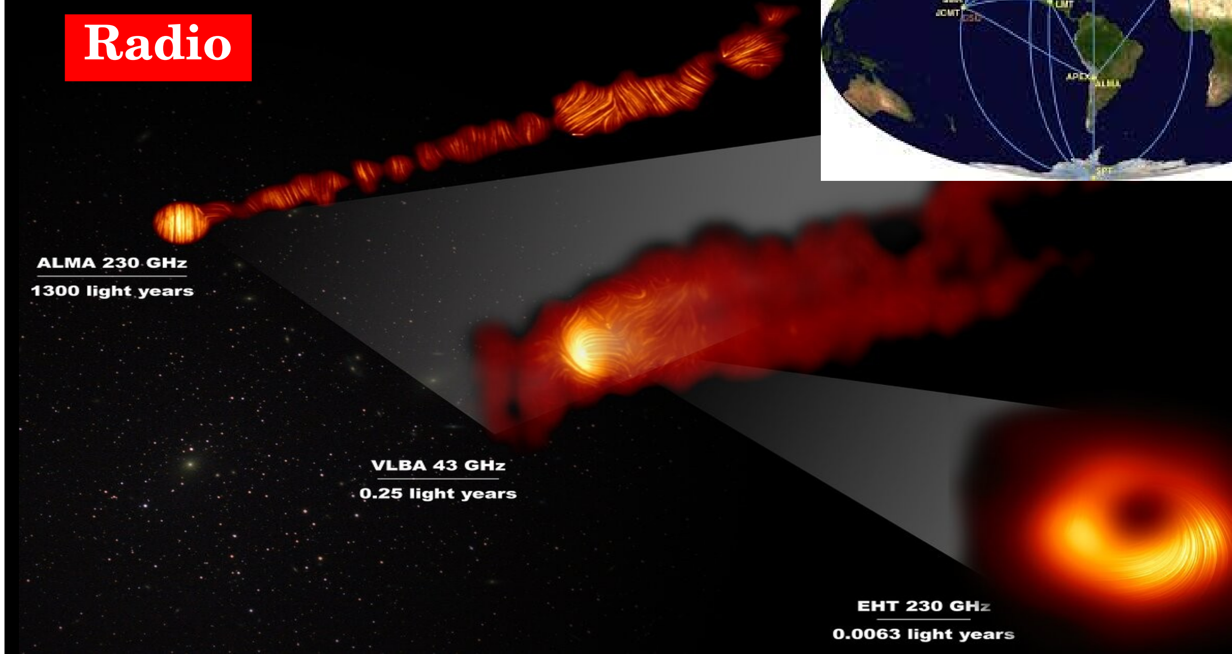
Collaborators : B. Crinquand (Grenoble), G. Dubus (Grenoble), I. El Mellah (Grenoble), A. Levinson (Tel Aviv), J. Mehlhaff (Grenoble), K. Parfrey (Dublin), A. Philippov (UMD), V. Richard-Romei (Grenoble), A. Soudais (Grenoble).

HMI workshop, Dublin, March 2023

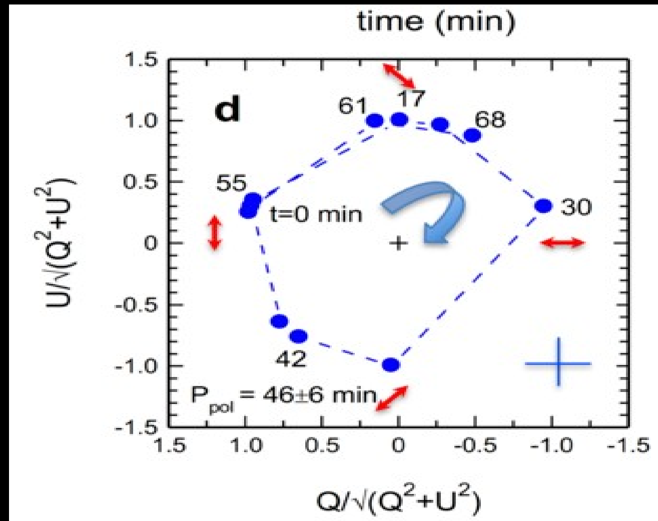
Horizon-scale observations

EHT collaboration (M87*, SgrA*)

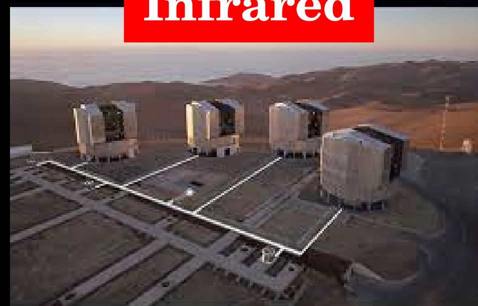
Radio



Gravity collaboration (SgrA*)



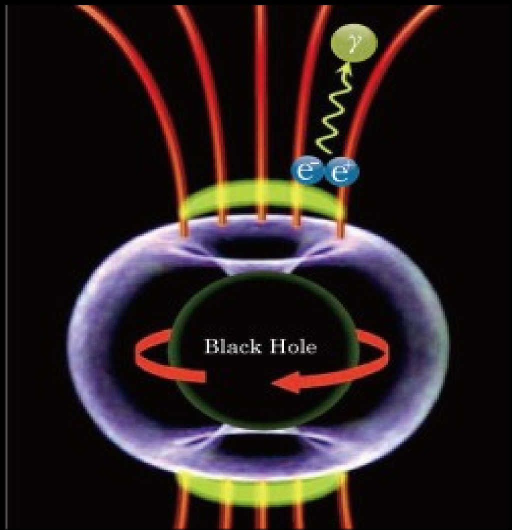
Infrared



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

A magnetospheric origin?

Relativistic magnetospheres



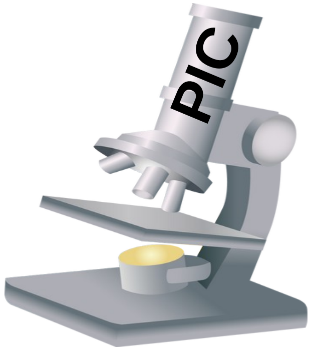
Magnetosphere
=
plasma + large-scale magnetic field

Closest region accessible to observations

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

Laboratories to probe physics under extreme conditions !
Multi-physics problem : plasma physics, general relativity, QED
Complex problem → need for simulations

Particle-in-cell simulations

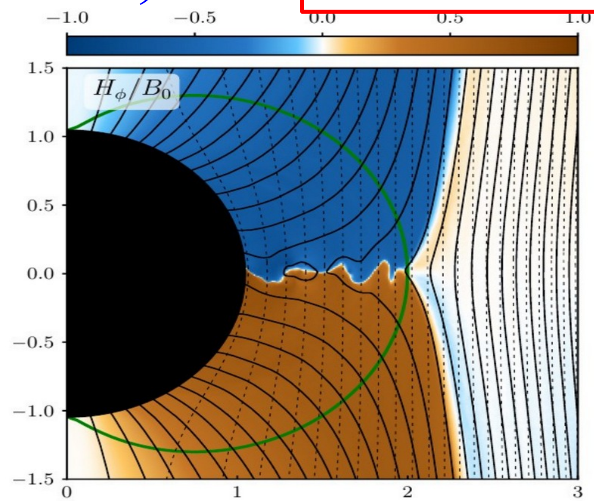


Relativistic, ultra-magnetized, collisionless plasmas

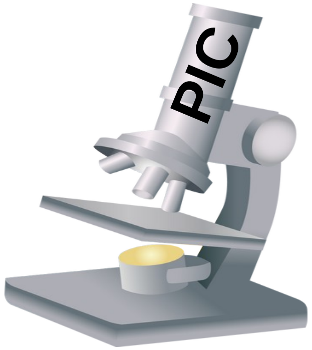
(General Relativistic) Radiative Particle-In-Cell simulations:
Plasma flow = discrete charged particles

Code : Zeltron *(Cerutti et al. 2013, Parfrey et al. 2019)*

Kenichi's talk



Parfrey, Philippov, Cerutti (2019)



Particle-in-cell simulations

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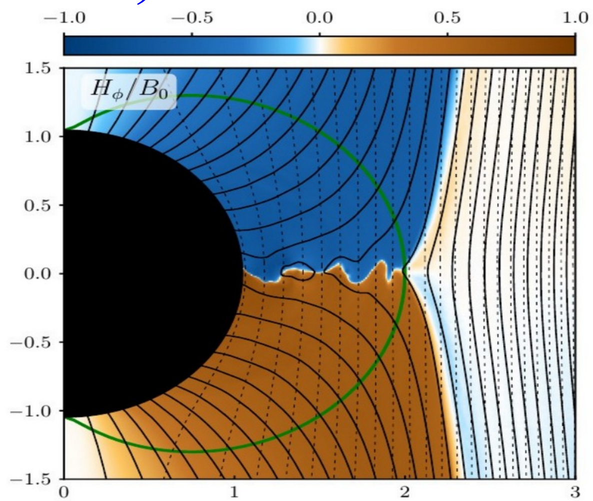
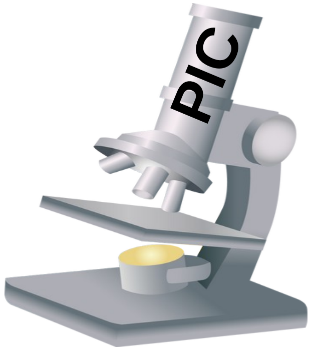
- Ab-initio modeling of plasmas
- Particle acceleration, radiation, pair creation
- Model observables



Parfrey, Philippov, Cerutti (2019)

Theoretical model ⟷ Observations

Particle-in-cell simulations



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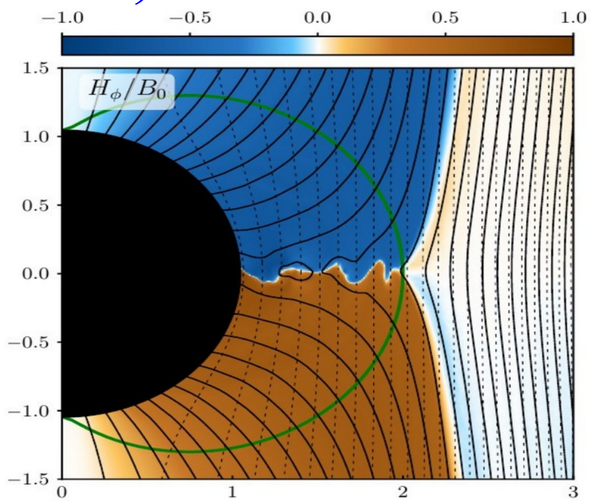
- Model observables

- Computationally expensive
- Short-term evolution, small scale-separation

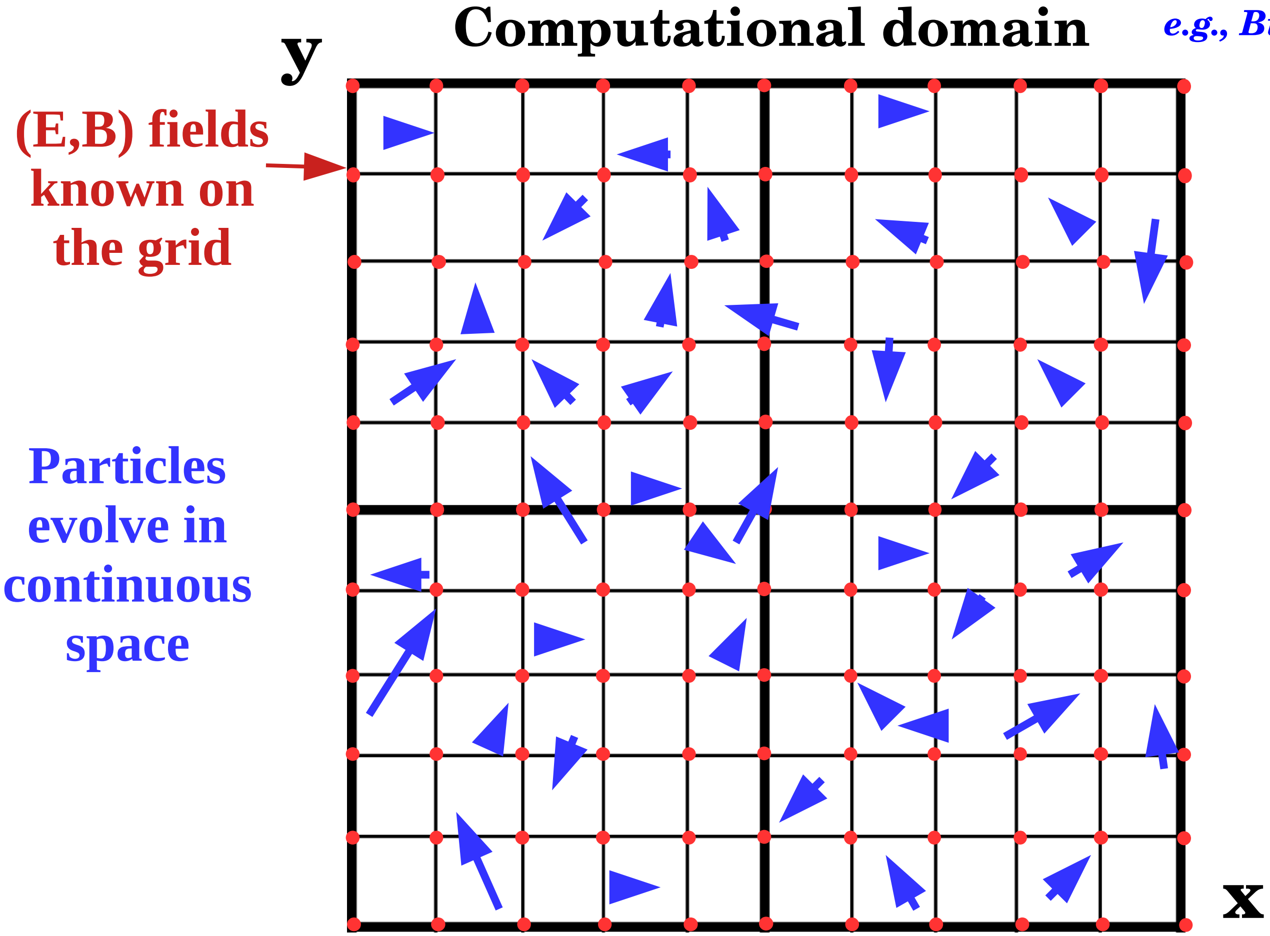


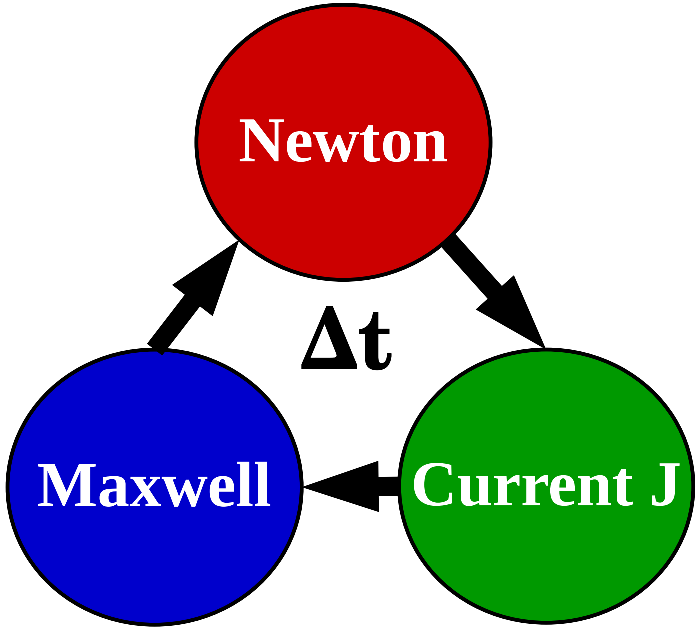
Parfrey, Philippov, Cerutti (2019)

Theoretical model ⟷ Observations

The particle-in-cell approach in a nutshell

e.g., Birdsall & Langdon 1991; Sironi & Cerutti 2017





Applications: shocks, reconnection, turbulence, magnetospheres...

General Relativistic Radiative PIC

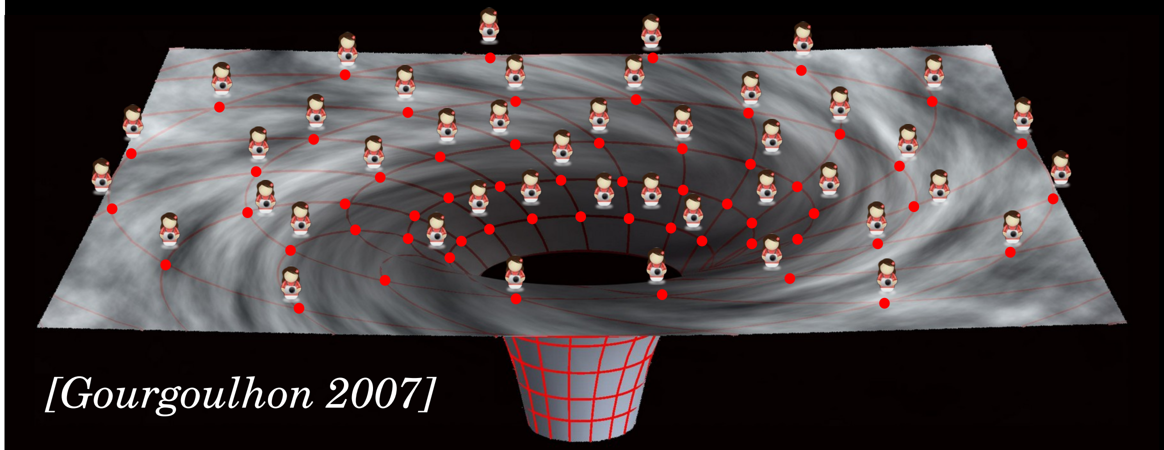
General Relativity : 3+1 formalism

$$ds^2 = -\alpha^2 dt^2 + \gamma_{ij}\left(dx^i + \beta^i dt\right)\left(dx^j + \beta^j dt\right)$$

α is the "lapse function"
β^i is the "shift vector"

Fiducial observer:
Locally at rest with respect to space time

- **<u>Fixed</u>** numerical grid



[Gourgoulhon 2007]

General Relativistic Radiative PIC

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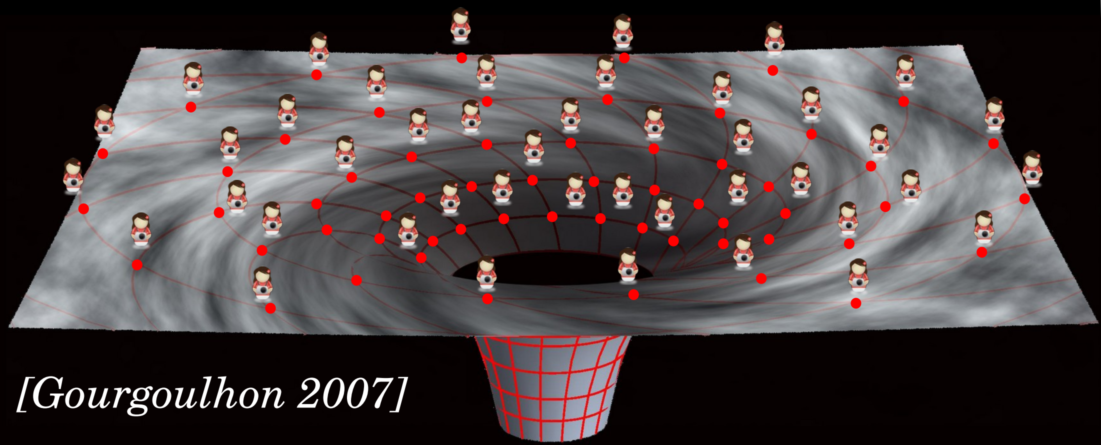
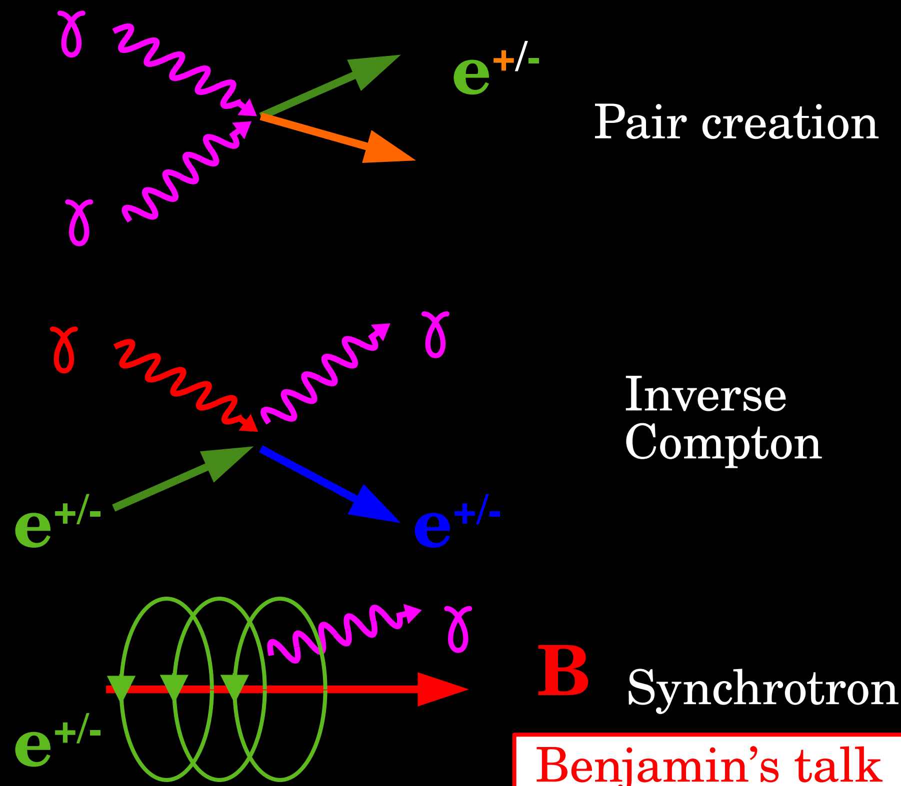


Radiative transfer : Monte Carlo

Full differential cross sections from QED

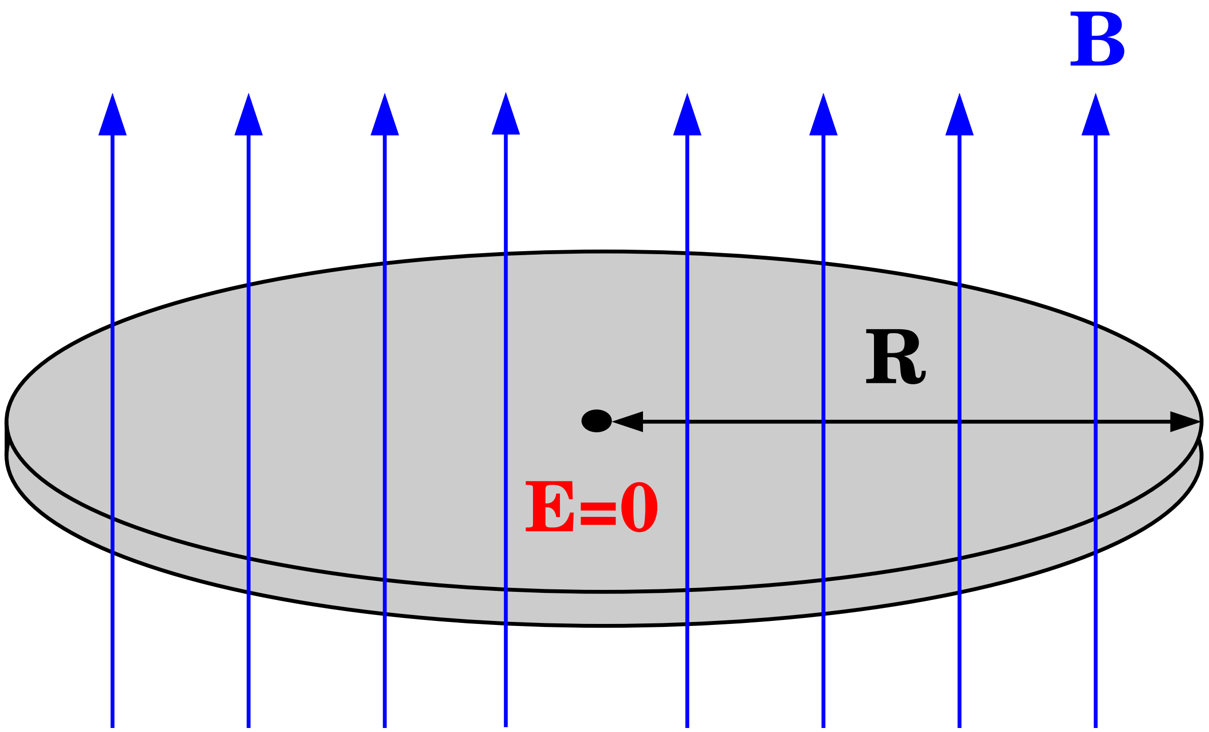


Benjamin's talk

Electrodynamics of relativistic magnetospheres

Static, perfectly conducting disk
Uniform B field

Reviews, e.g., Cerutti & Beloborodov 2017

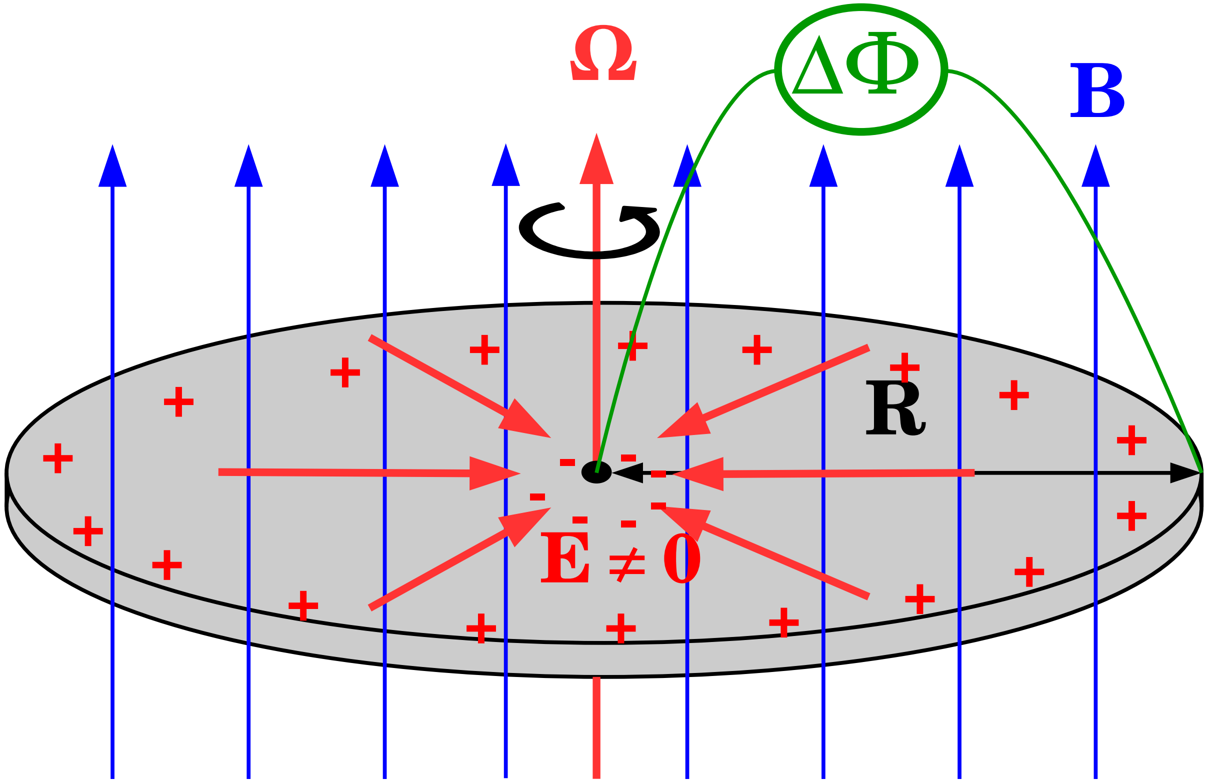


=> Electric field E=0

A familiar analogy: Faraday's disk

Rotating, perfectly conducting disk : Contant angular velocity **Ω**

Uniform B field

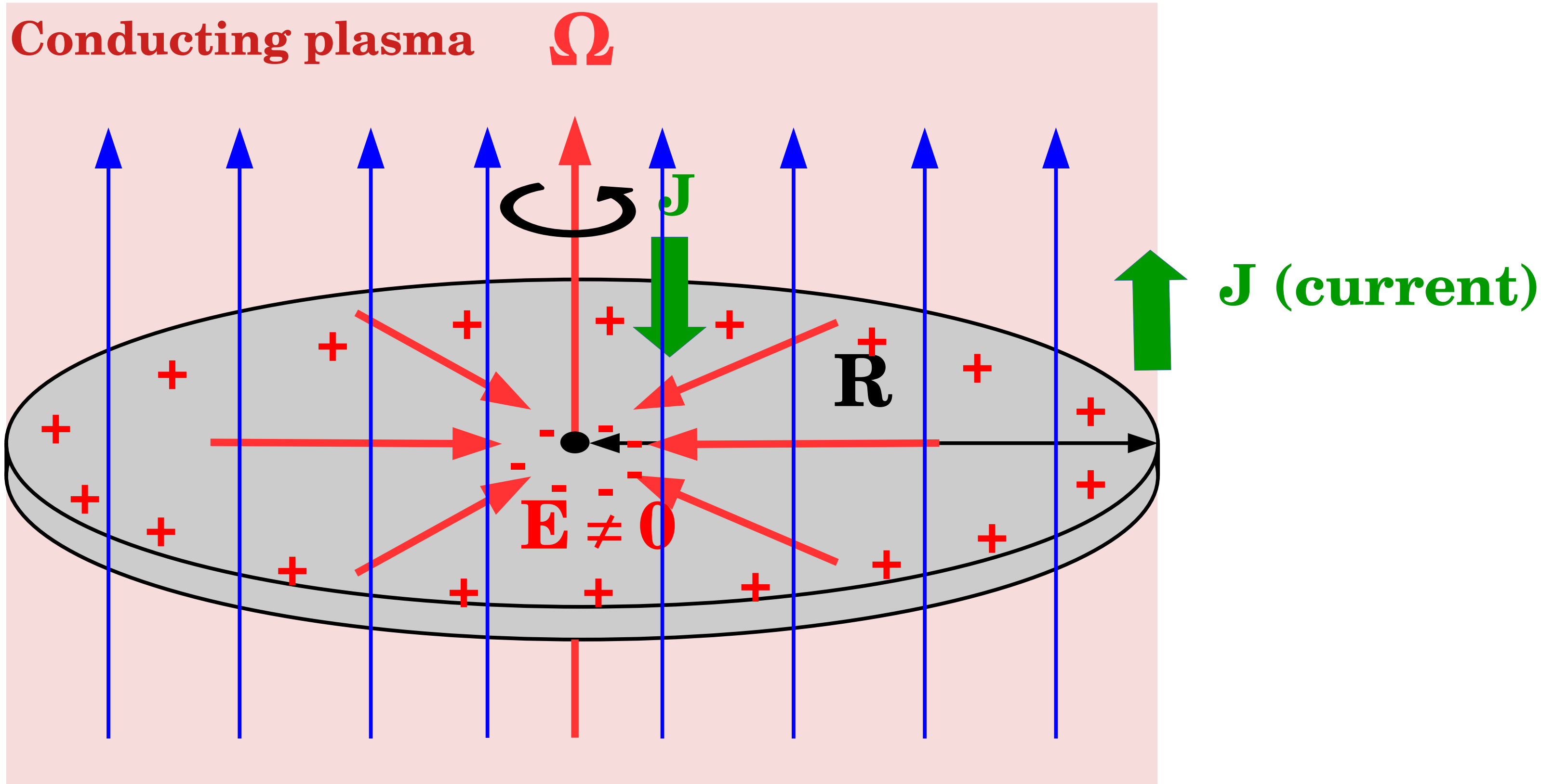


Induced electric field **E=-V×B/c=-(Ω×R)×B/c.** The disk is **polarized**.

=> Potential difference between the center and the outer radius

A familiar analogy: Faraday's disk

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



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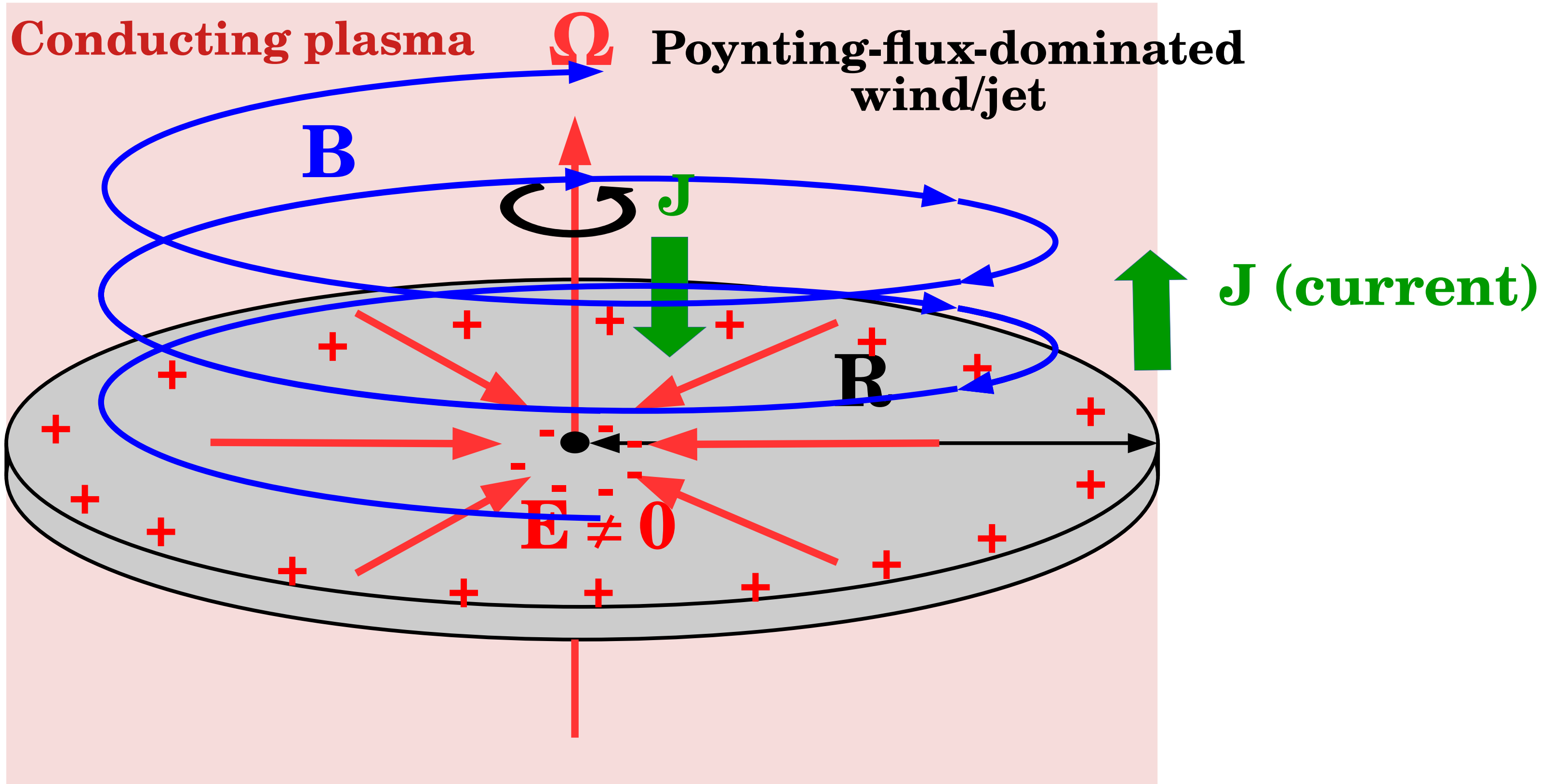
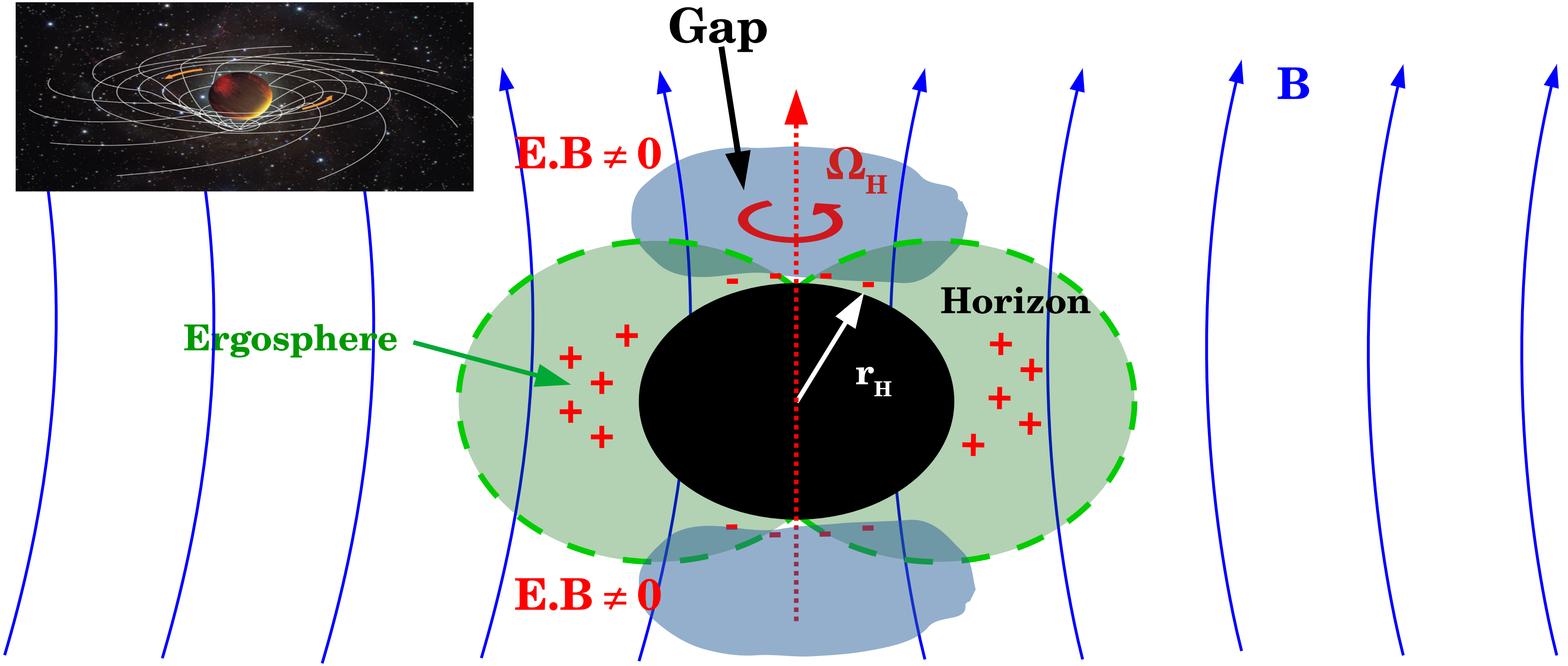


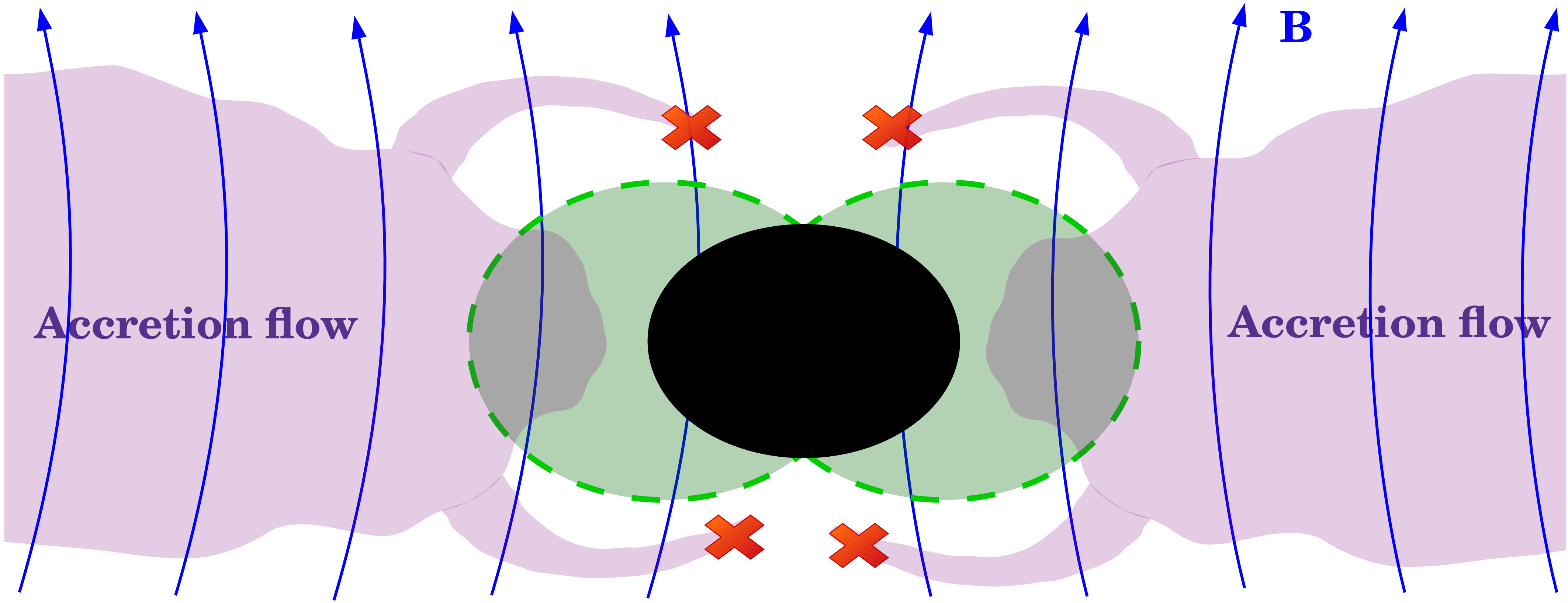
Magnetic torque slows down the disk => Electromagnetic spin down

In a black hole, where is the inductor ?

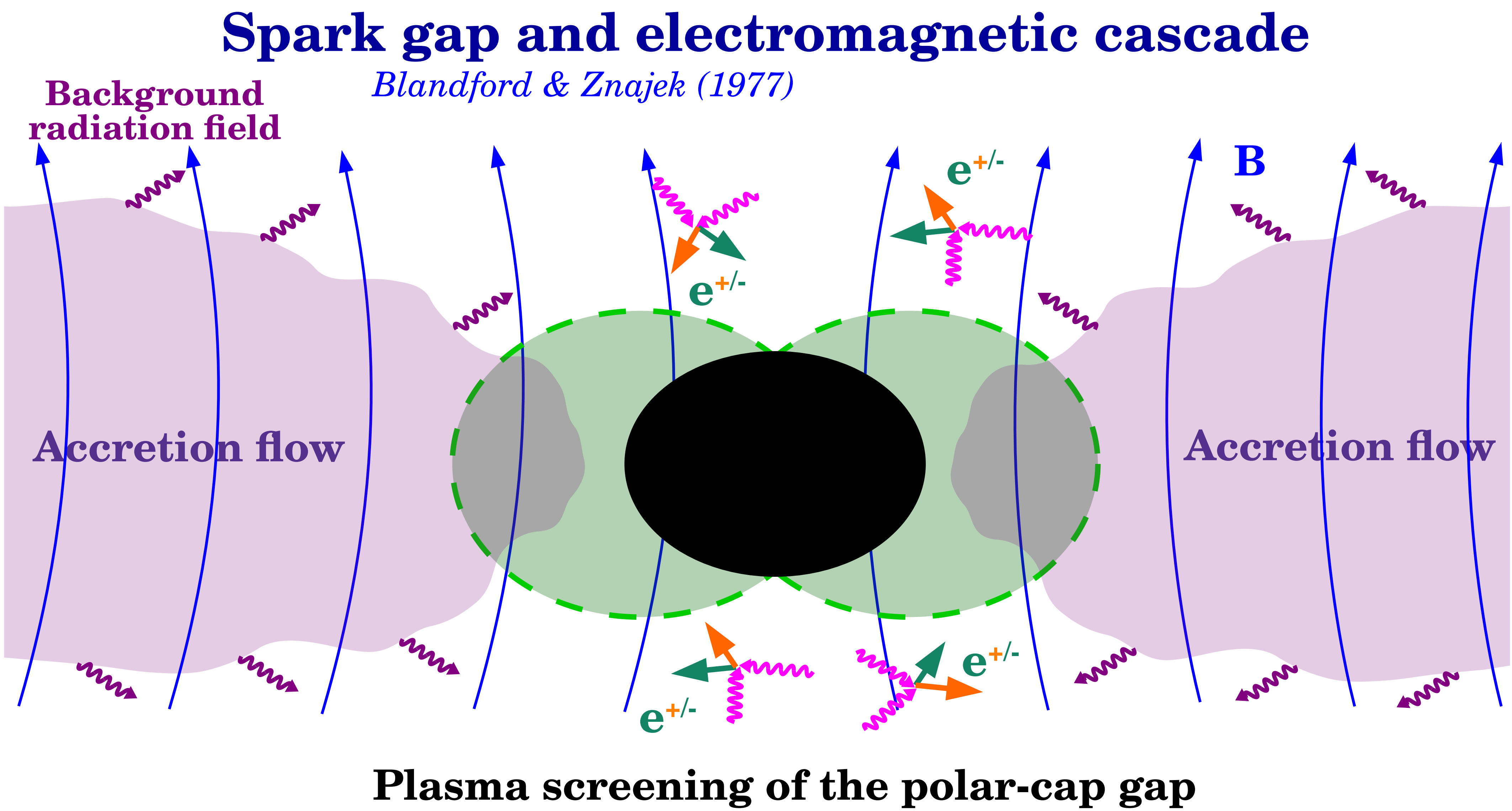


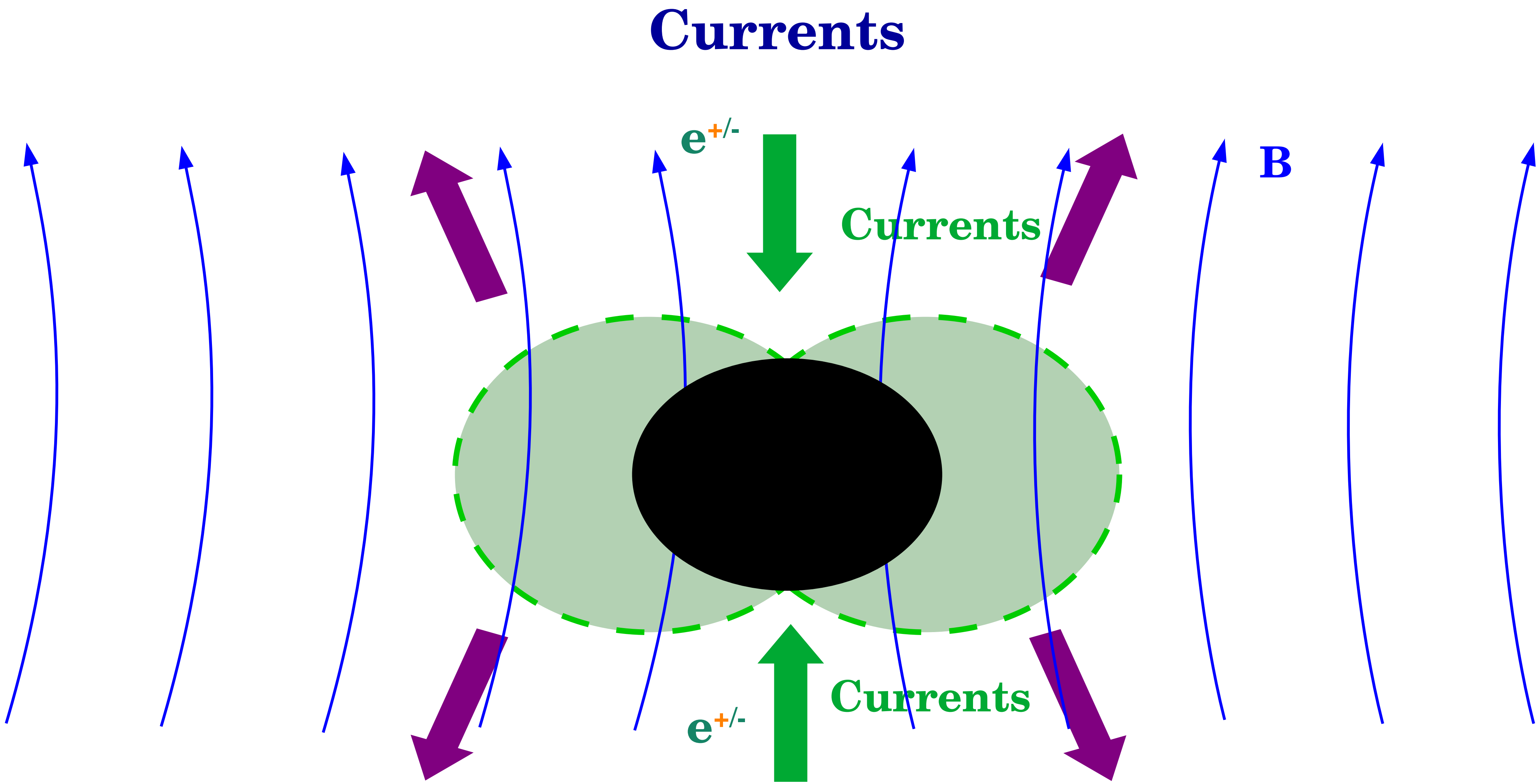
Frame-dragging induces a parallel electric field at the poles

Plasma loading

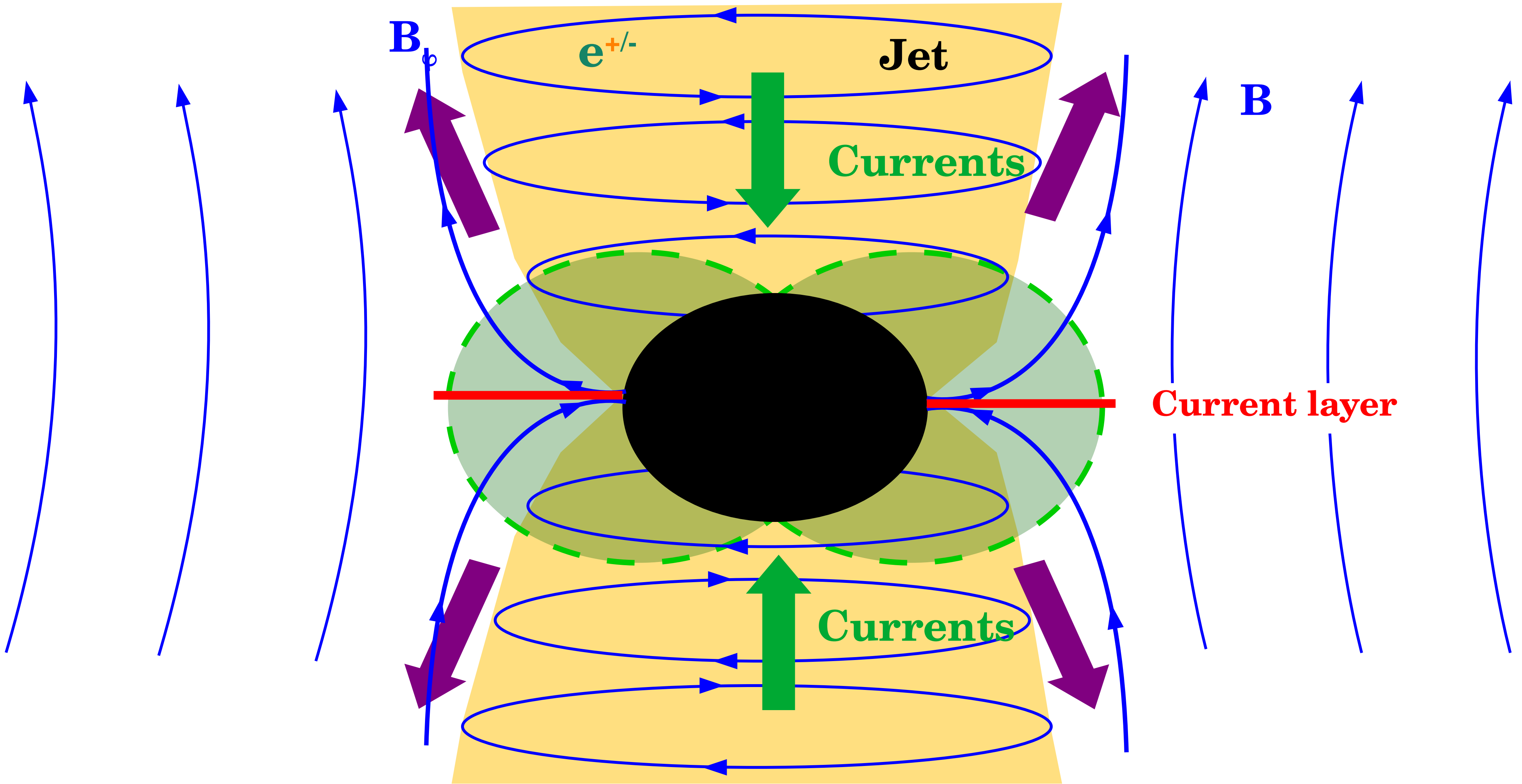


No direct feeding from the accretion flow => pair creation

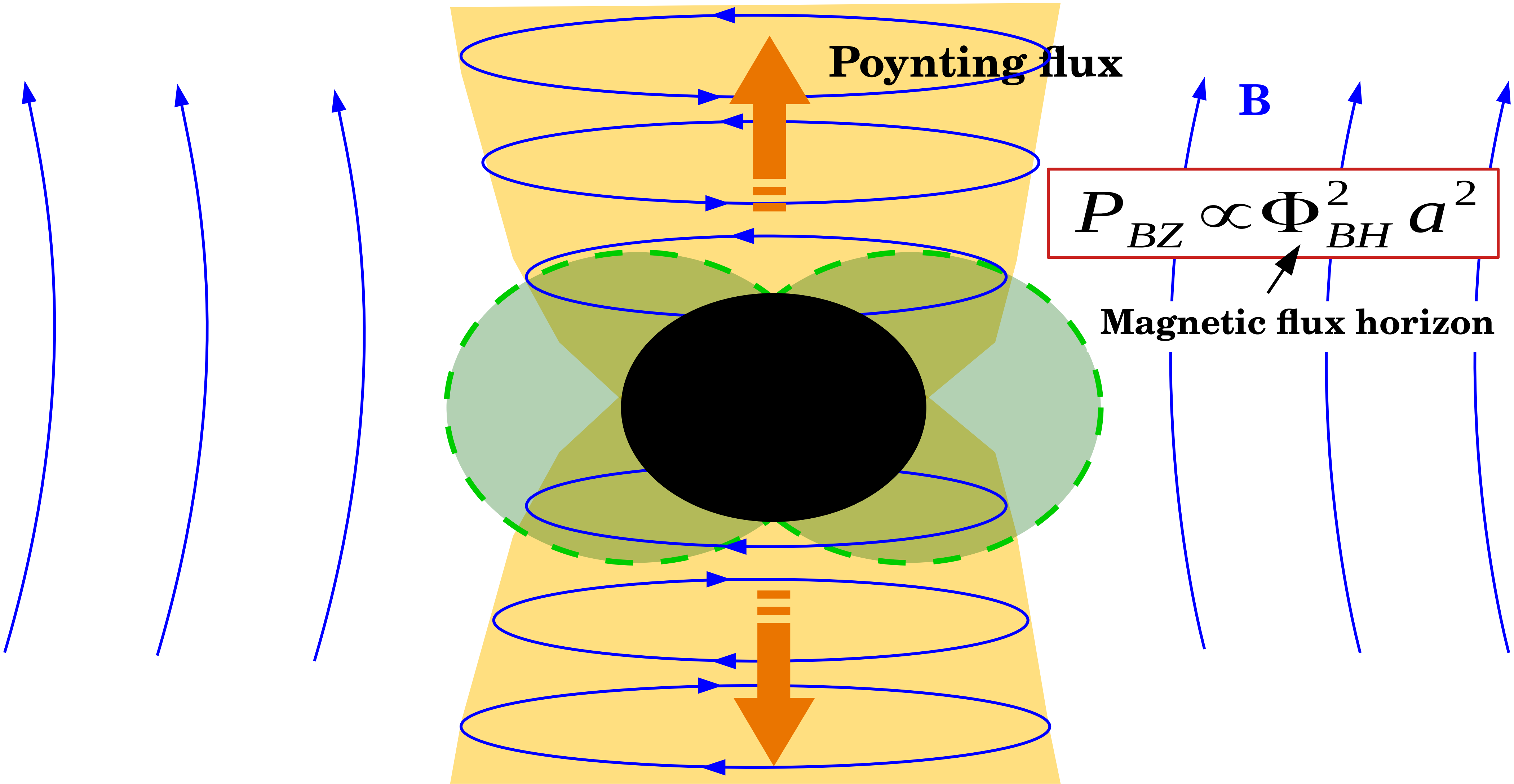

Spark gap and electromagnetic cascade
Blandford & Znajek (1977)
Background radiation field
B
e+/-
e+/-
e+/-
e+/-
Accretion flow
Accretion flow
Plasma screening of the polar-cap gap

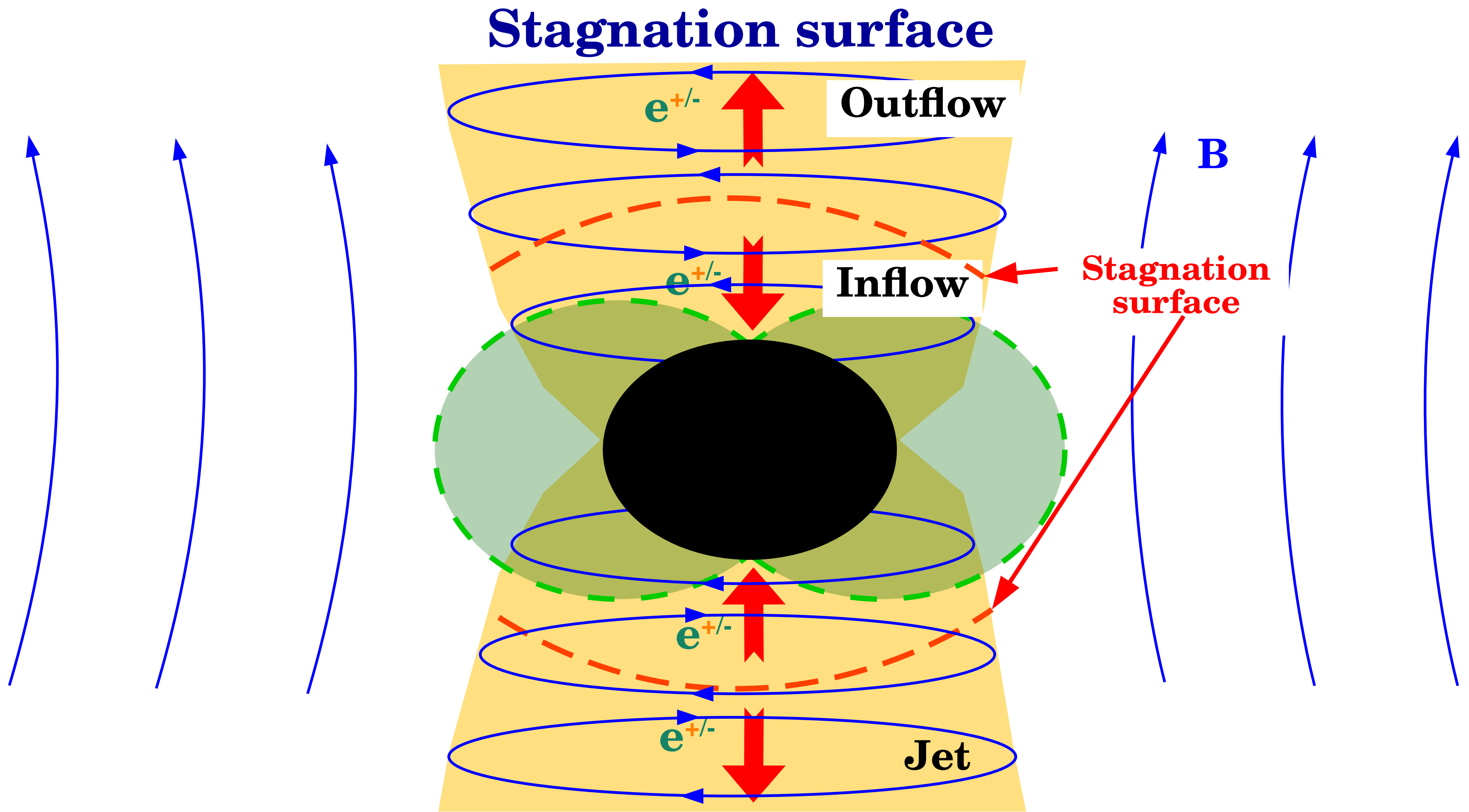

Currents
$e^{+/-}$
Currents
B
Currents
$e^{+/-}$

Blandford-Znajek jet & ergospheric current layer(s)



Electromagnetic extraction of the black hole spin

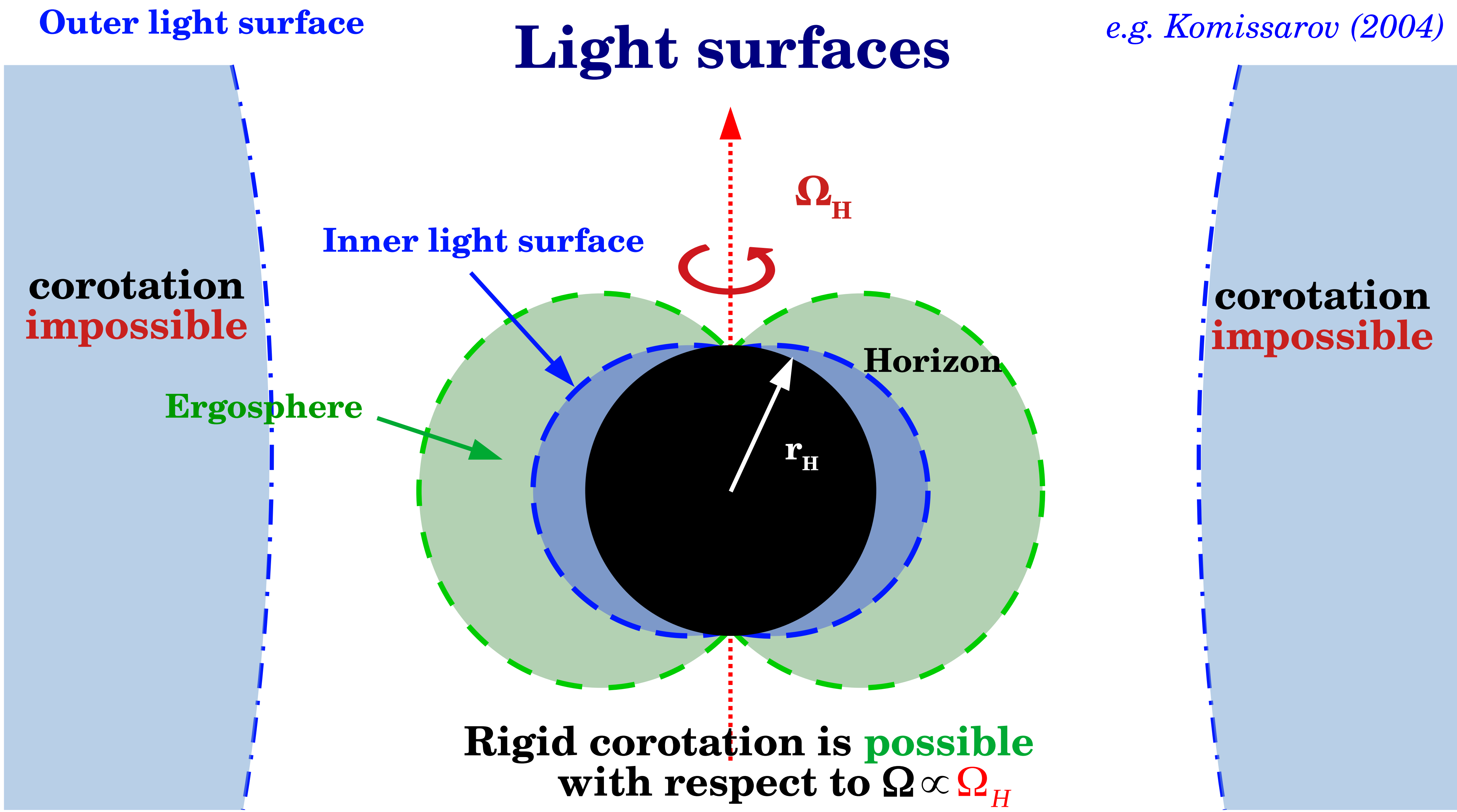




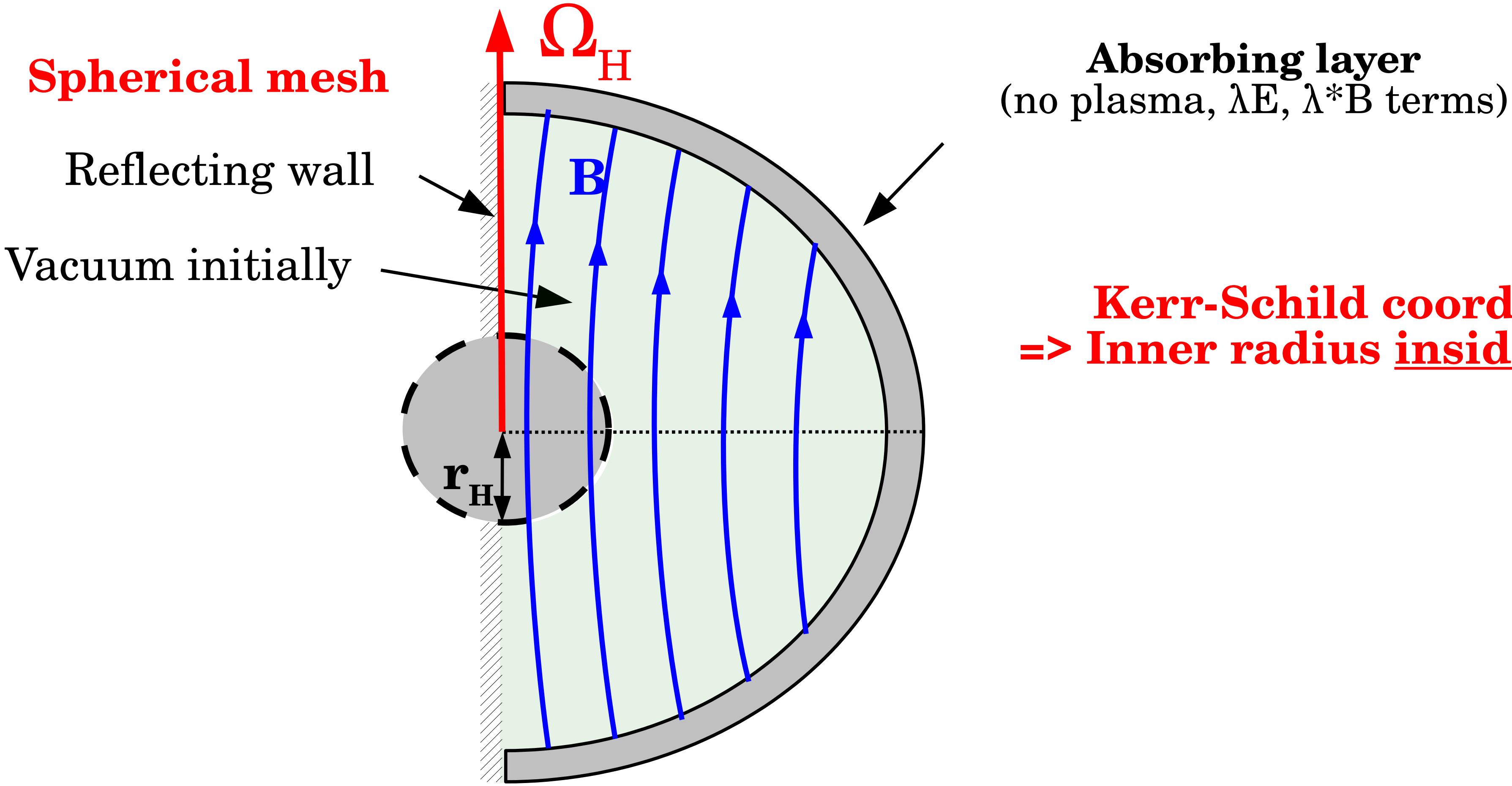
Stagnation surface
Outflow
e+/-
B
Inflow
e+/-
Stagnation surface
e+/-
e+/-
Jet

Light surfaces

e.g. Komissarov (2004)



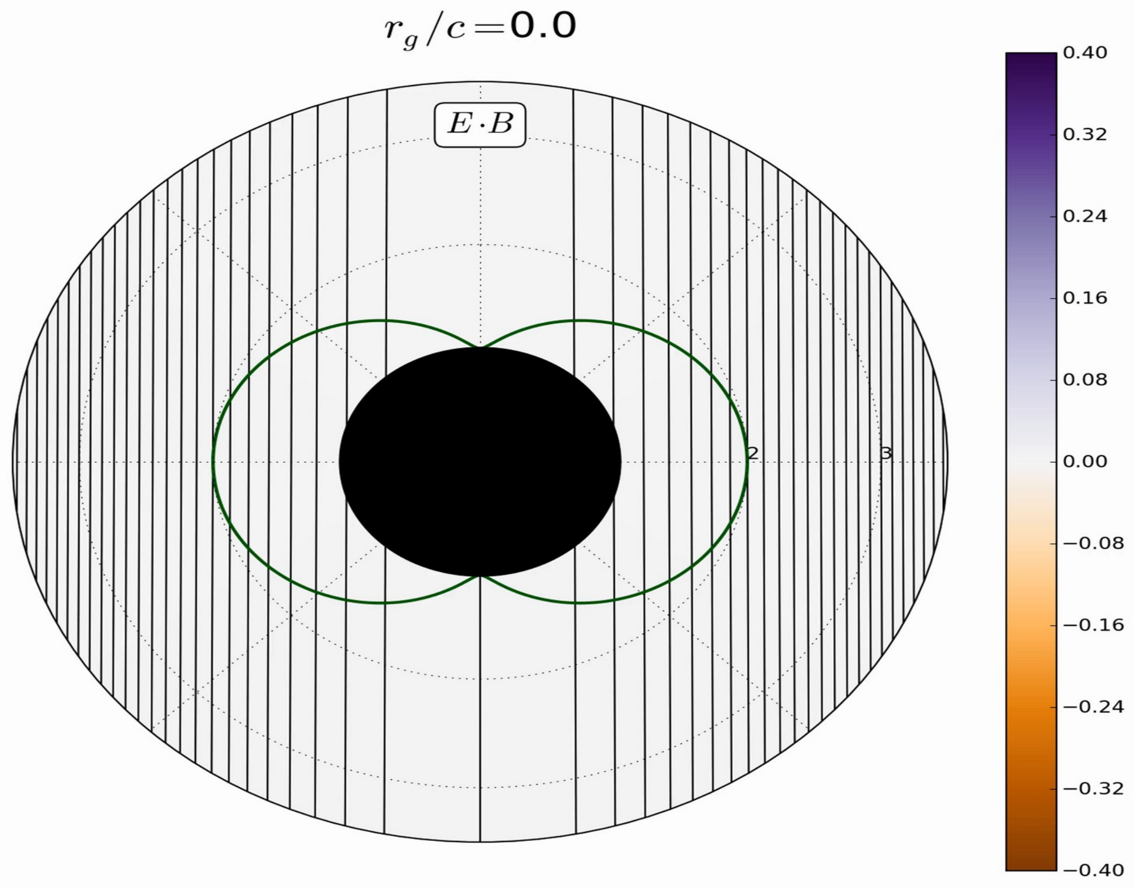
The numerical 2D axisymmetric setup

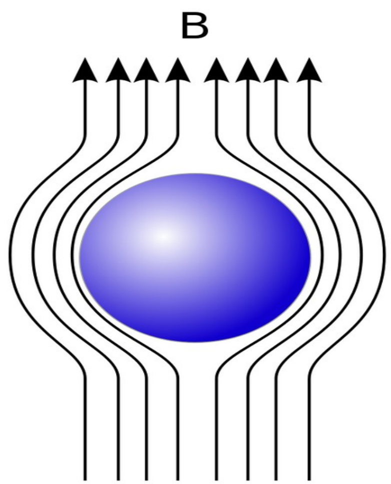


Kerr-Schild coordinates
=> Inner radius <u>inside</u> horizon

Test of Kerr hole in <u>vacuum</u> with uniform B field

For a~1, "Meissner" - like effect





$$\Psi_{\rm BH} = \pi r_{\rm H}^2 B_0 \left(1 - \frac{a^4}{r_{\rm H}^4}\right)$$

Wald 1974

King, Lasota & Kundt 1975

Plasma injection?

<u>First prescription :</u> No photons, ad-hoc injection

<u>Hypothesis</u>: **Force-free-ish** magnetosphere everywhere:

$$\rho \boldsymbol{E} + \boldsymbol{J} \times \boldsymbol{B} = 0,$$ Neglect plasma pressure and inertia

$$\boldsymbol{E} \cdot \boldsymbol{J} = 0$$

$$\boldsymbol{D} \cdot \boldsymbol{B} = 0\,.$$

Begin with **vacuum Wald fields** where D.B ≠ 0 and start injecting wherever:

$|D.B|/B^2 > \varepsilon_{D.B}$

Low supply: $\varepsilon_{D.B} = 10^{-2}$

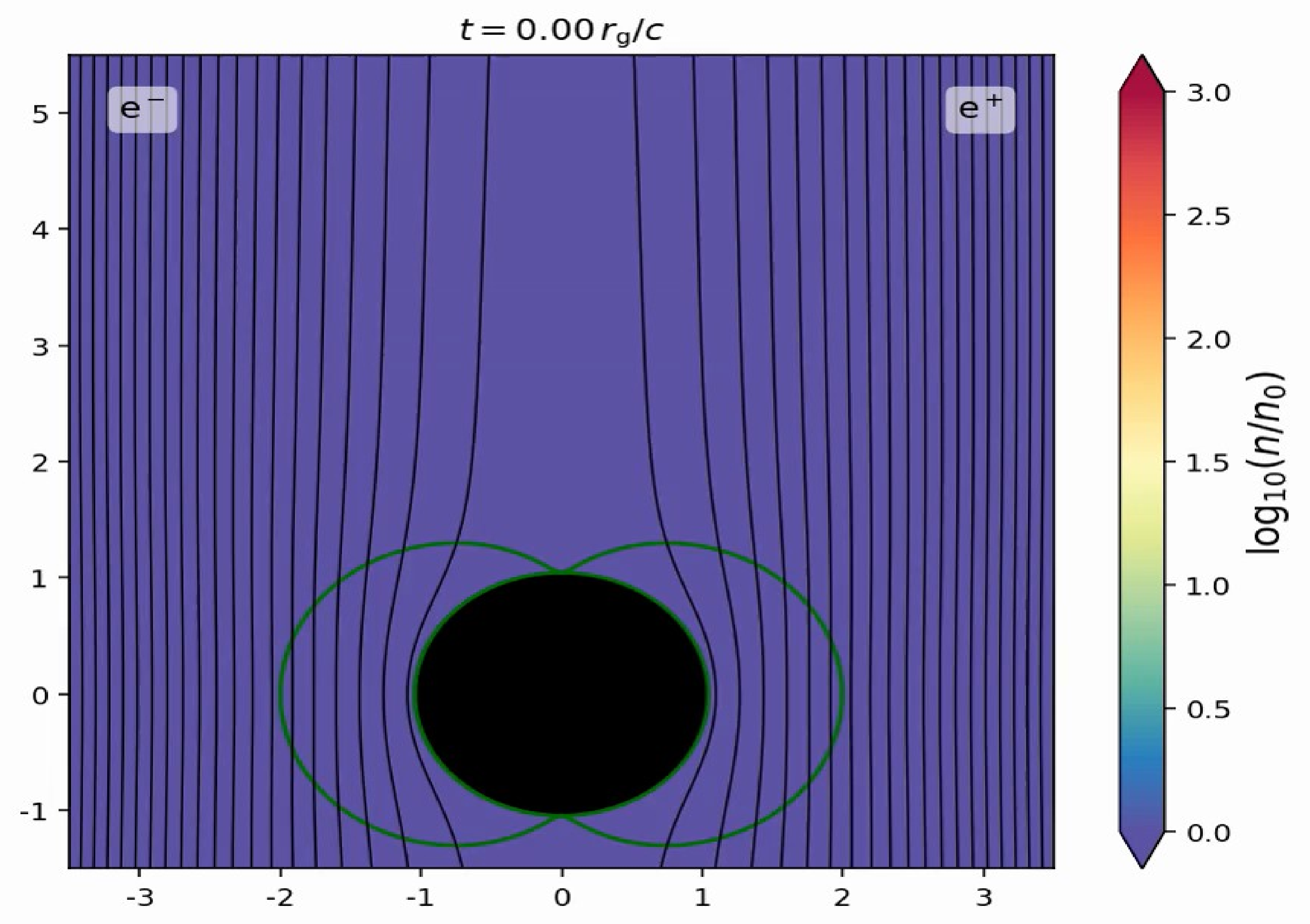
High supply: $\varepsilon_{D.B} = 10^{-3}$

e^+/e^- pairs injection:

$$\delta n_{\rm inject} = \frac{\mathcal{R}}{4\pi e} \frac{|\boldsymbol{D} \cdot \boldsymbol{B}|}{B},$$

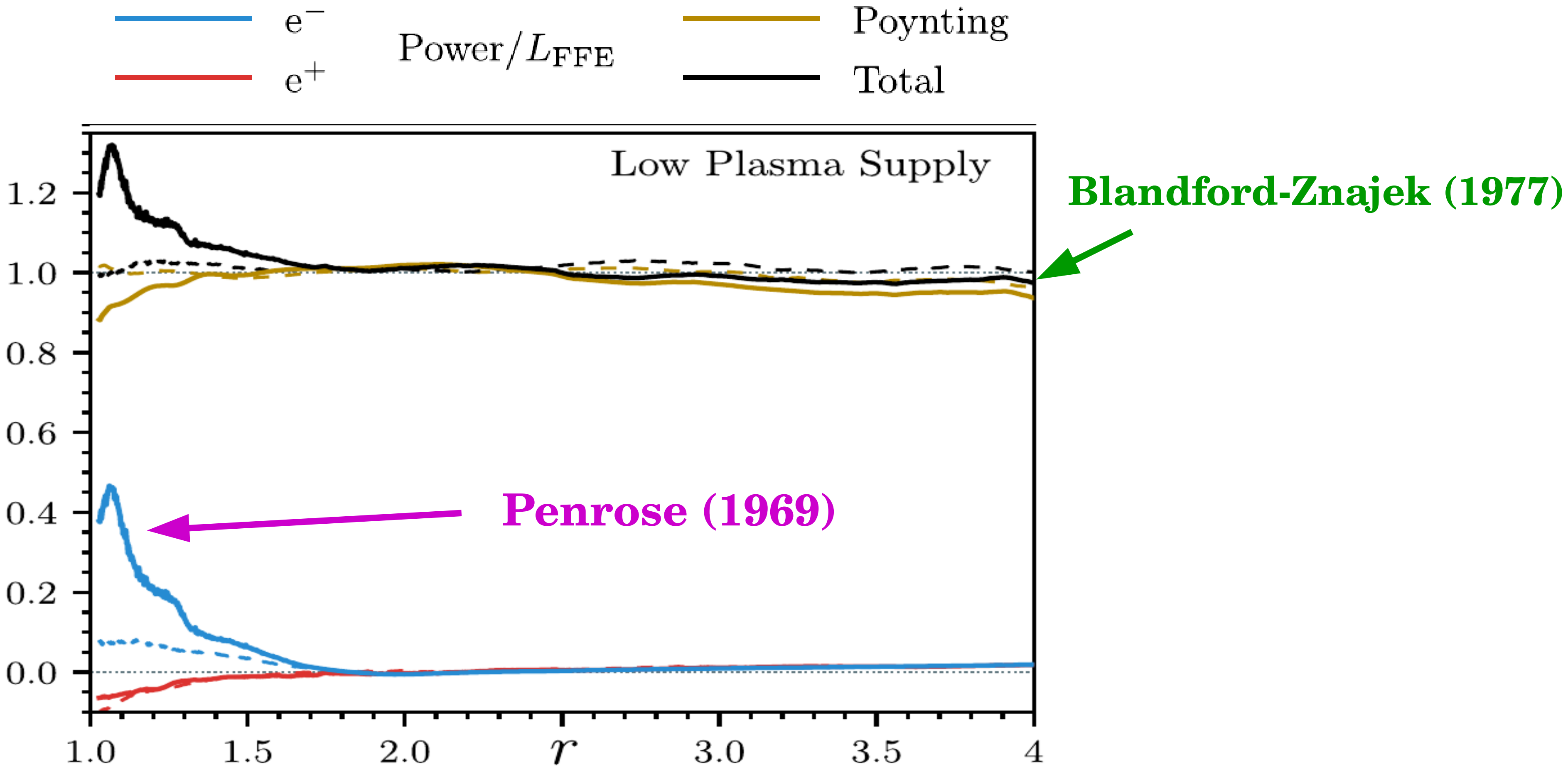
Ad-hoc plasma supply

Volume injection



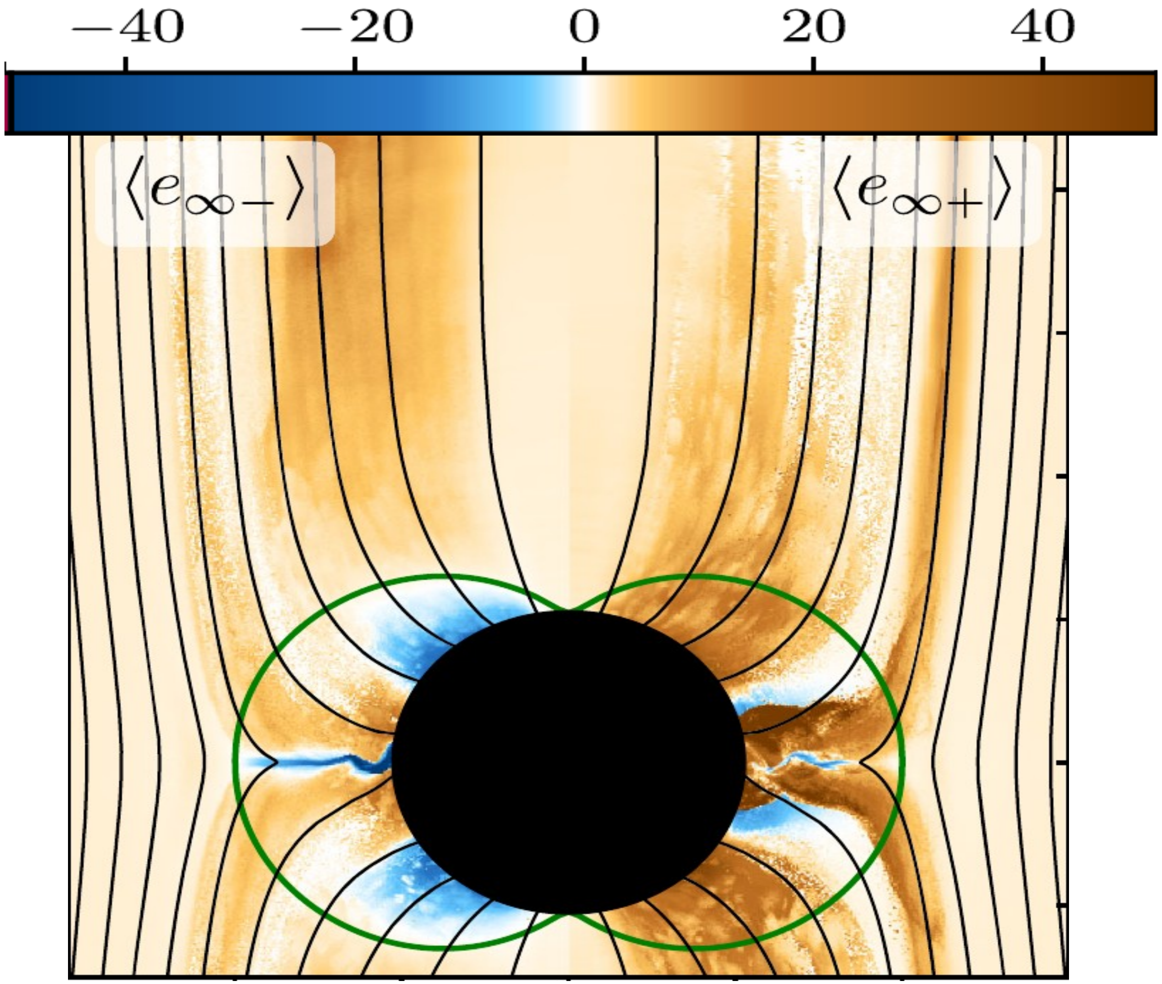
Parfrey et al. (2019)

Black-hole spin extraction



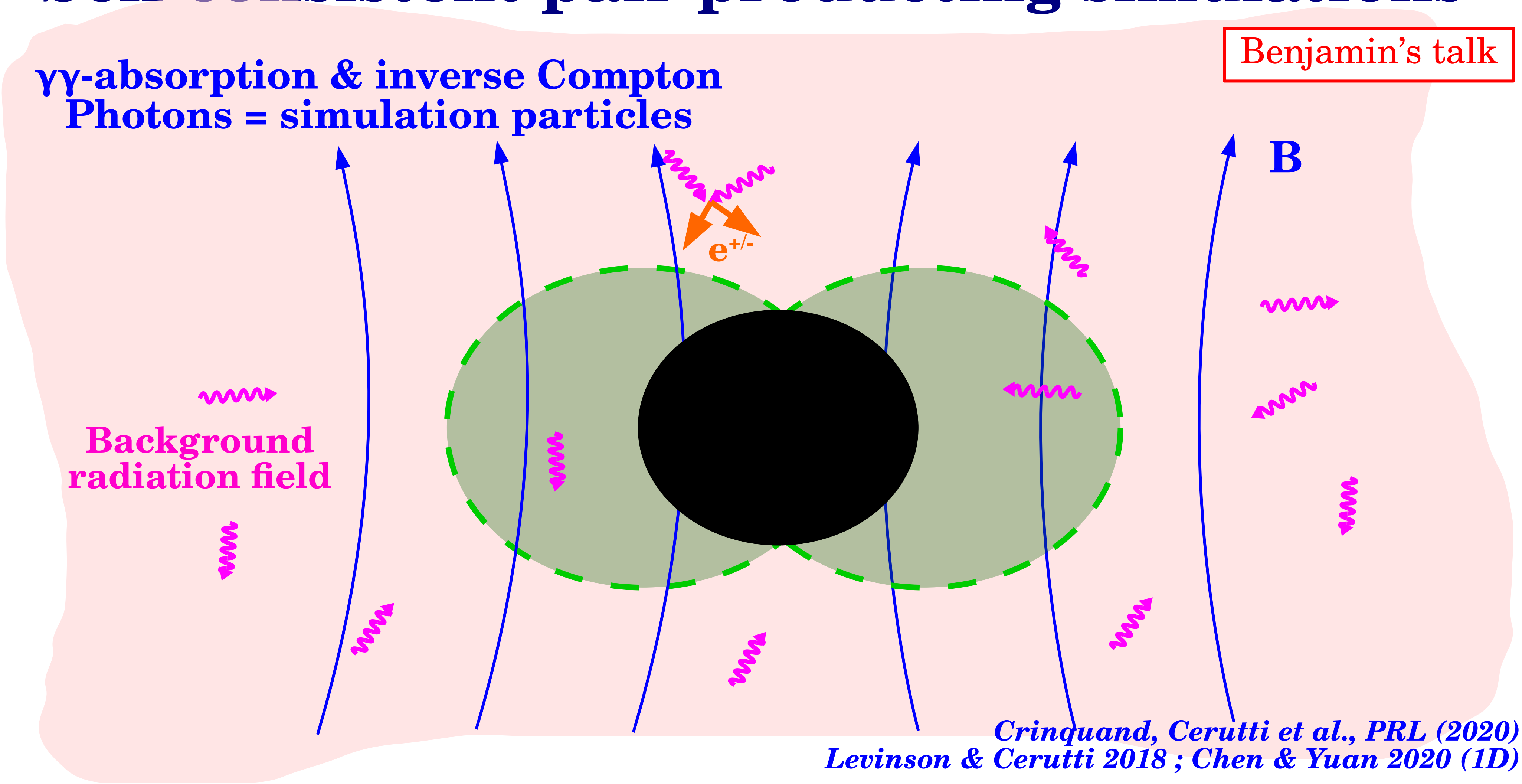
Parfrey et al. 2019

“Negative energy” particles



Parfrey et al. 2019

Self-consistent pair producing simulations

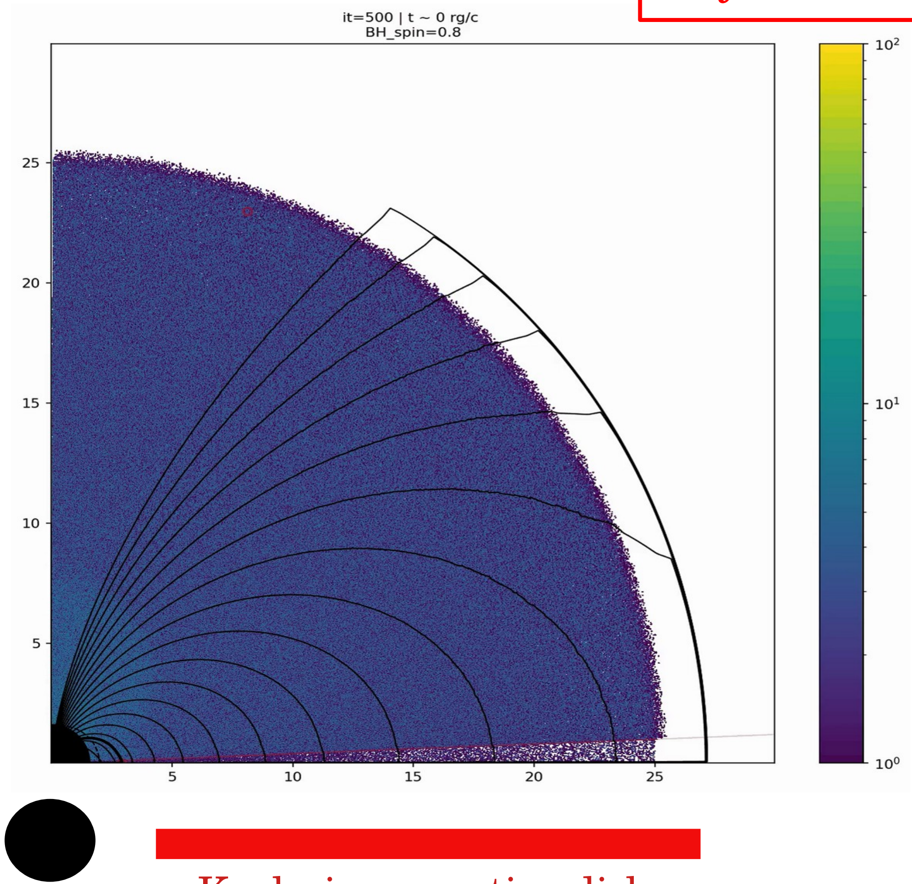


Crinquand, Cerutti et al., PRL (2020)
Levinson & Cerutti 2018 ; Chen & Yuan 2020 (1D)

Black-hole-disk interaction, coronal heating

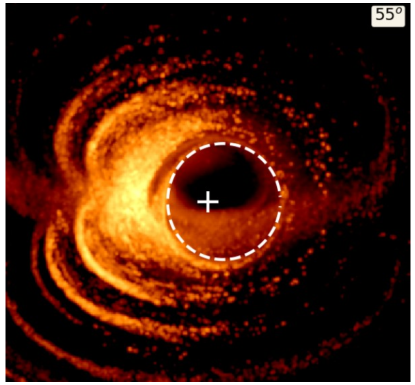
El Mellah et al. (2022, 2023 in prep)

Ileyk's talk

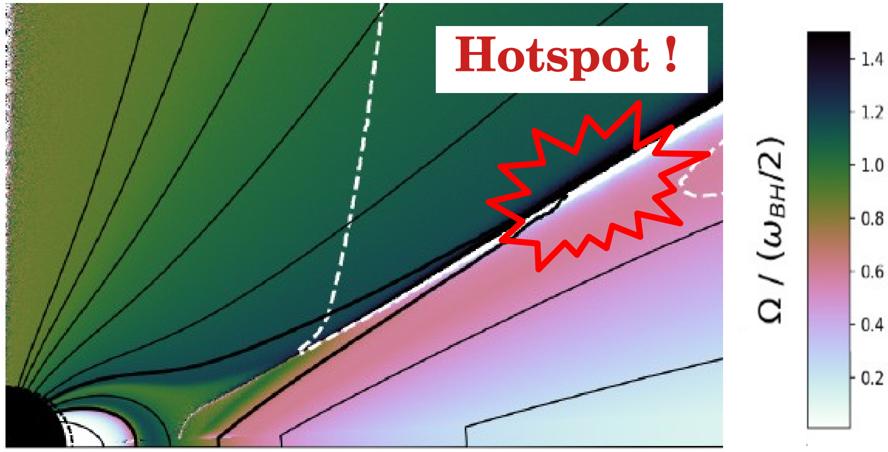


Kerr BH

Keplerian accretion disk



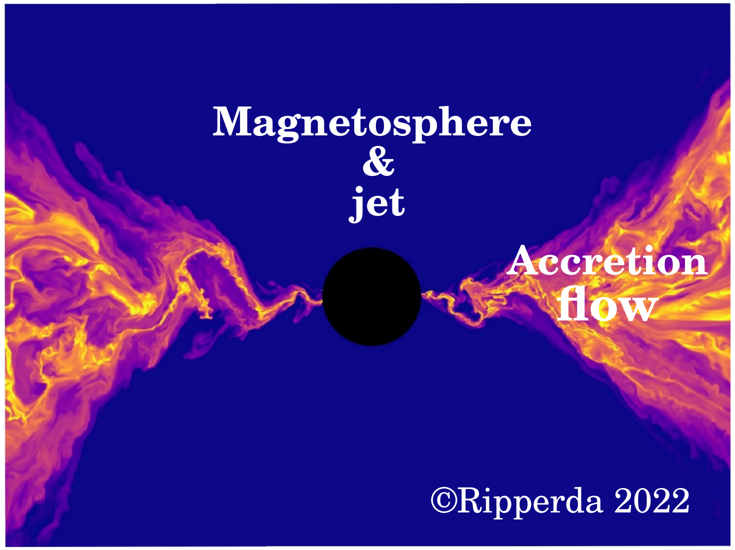
Synthetic synchrotron image



Elevated **above** the midplane and apparently **super-Keplerian**

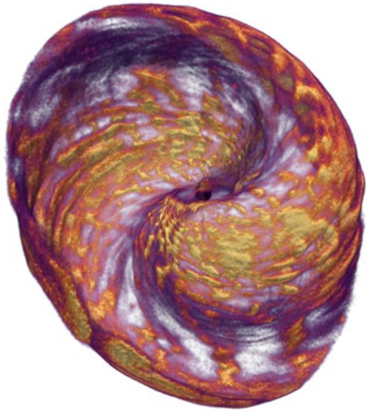
Perspectives

Magnetosphere & collisionless accretion flow



Alisa's talk

Binary BH-NS magnetospheres



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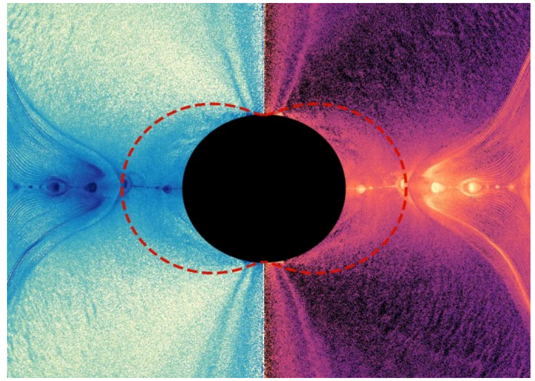
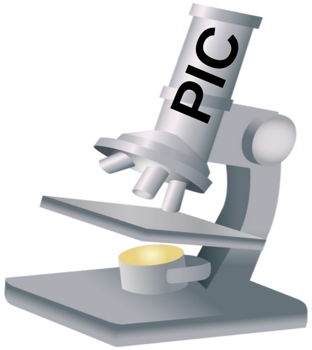


Electromagnetic precursor emission?

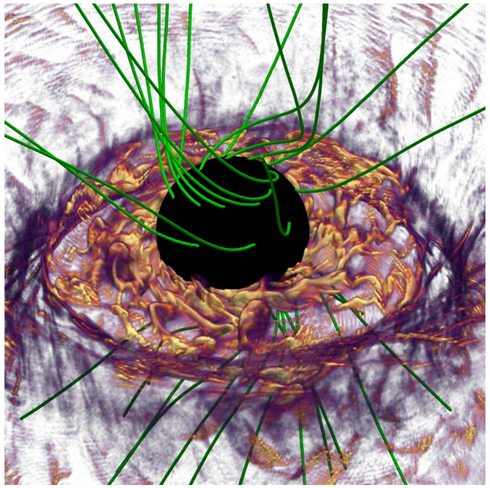
The scale separation challenge



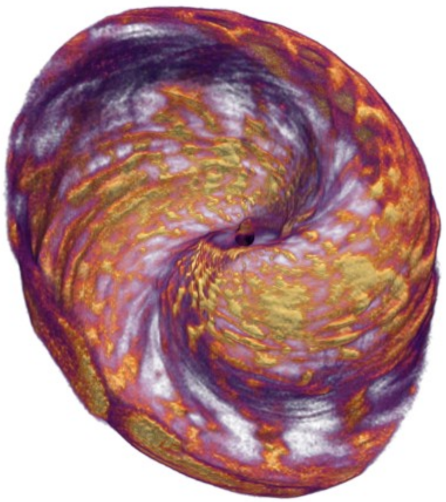
PIC must resolve plasma kinetic scales (~particle Larmor radius scale R_L)

In global PIC models, we must cheat because R_L<<< magnetosphere

Is it valid, does it make sense ?



e.g. M87*-SgrA*
$R_{BH}/R_L \sim 10^{10-14}$



e.g. Crab, ms pulsars
$R_{LC}/R_L \sim 10^6$

Is PIC always needed ?
=> Hybrid e.g., MHD+PIC methods, GPU acceleration, sub-grid model ...

Hybrid force-free/PIC simulations: aligned pulsar

Courtesy [Adrien Soudais]

$$\mathbf{J} = \mathbf{J}_{\rm PIC} \cdot (1 - f(\Psi)) + \mathbf{J}_{\rm FFE} \cdot f(\Psi)$$

- Domain separation criterion:

  Magnetic flux function $\Psi = \iint \mathbf{B} \cdot \mathrm{d}\mathbf{S}$

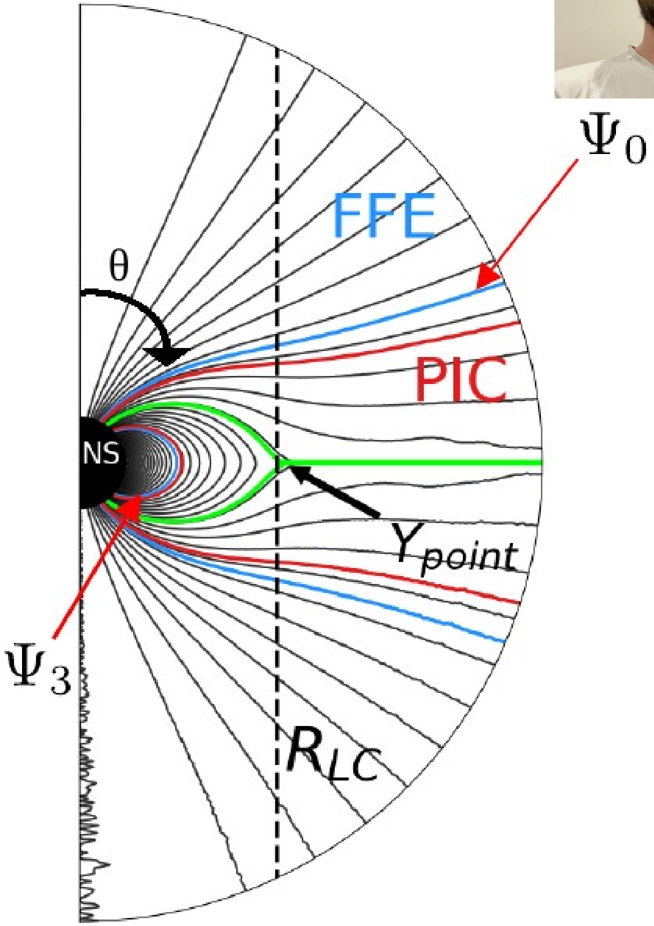
- Isocontours of Ψ = magnetic field lines
- Transition zone
- Separatrix inside the PIC domain

If $\Psi \in [\Psi_0, \Psi_3]$:

↳ PIC

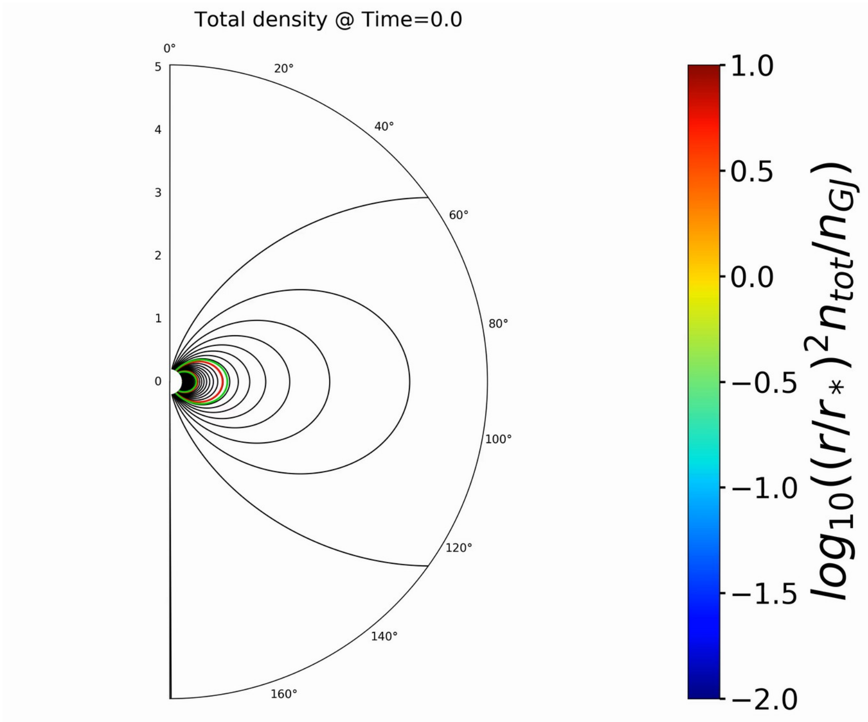
Else:

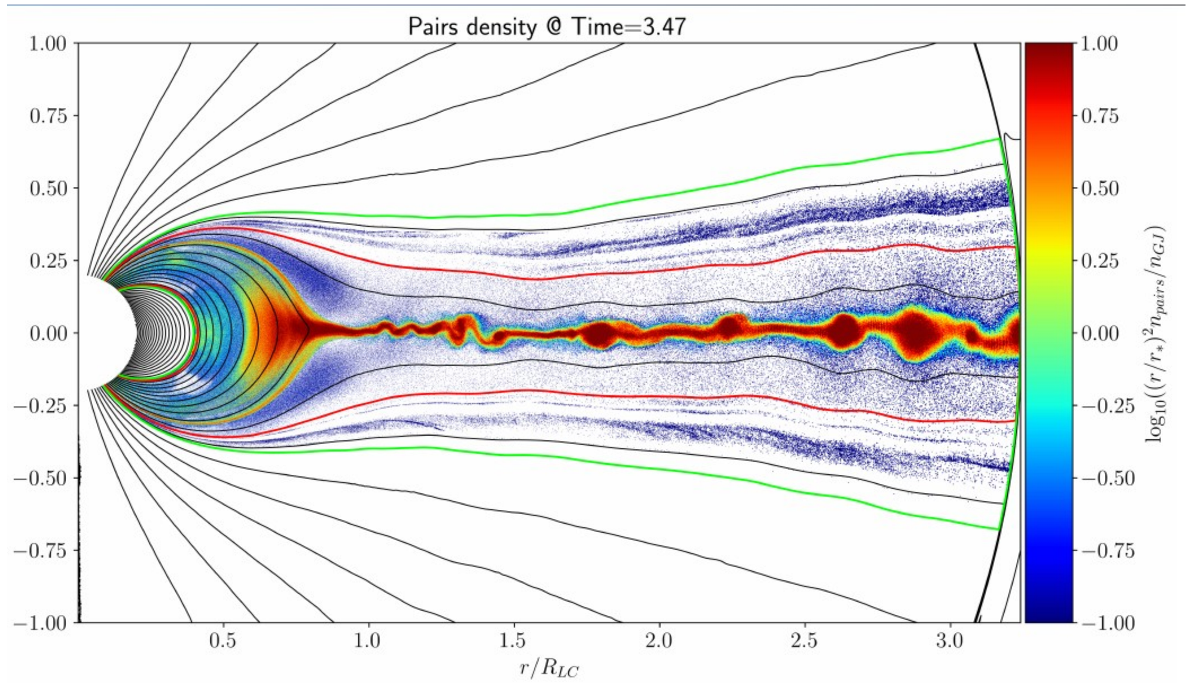
↳ FFE



Preliminary results

High-resolution simulation (4096×4096)





=> Switching to extreme resolutions with full ms-pulsar scales

Conclusions

- There is a **urgent need** to better understand the behavior of plasma near black holes and neutron stars (gamma-ray pulsars, EHT image of M87*, Sgr A*)
- The **PIC method** has become a successful tool to explore these processes from first principles.
- The study of relativistic magnetospheres show how strongly connected microscopic and system size are connected. **Global simulations needed.**
- **Magnetic reconnection** accelerates particles efficiently and regulates the magnetic flux on the BH horizon
- ***Caveat* : small scale separation** is a strong limitation of the predictive power of PIC simulations
  => Need for innovative numerical techniques (hybrid, GPU, …)