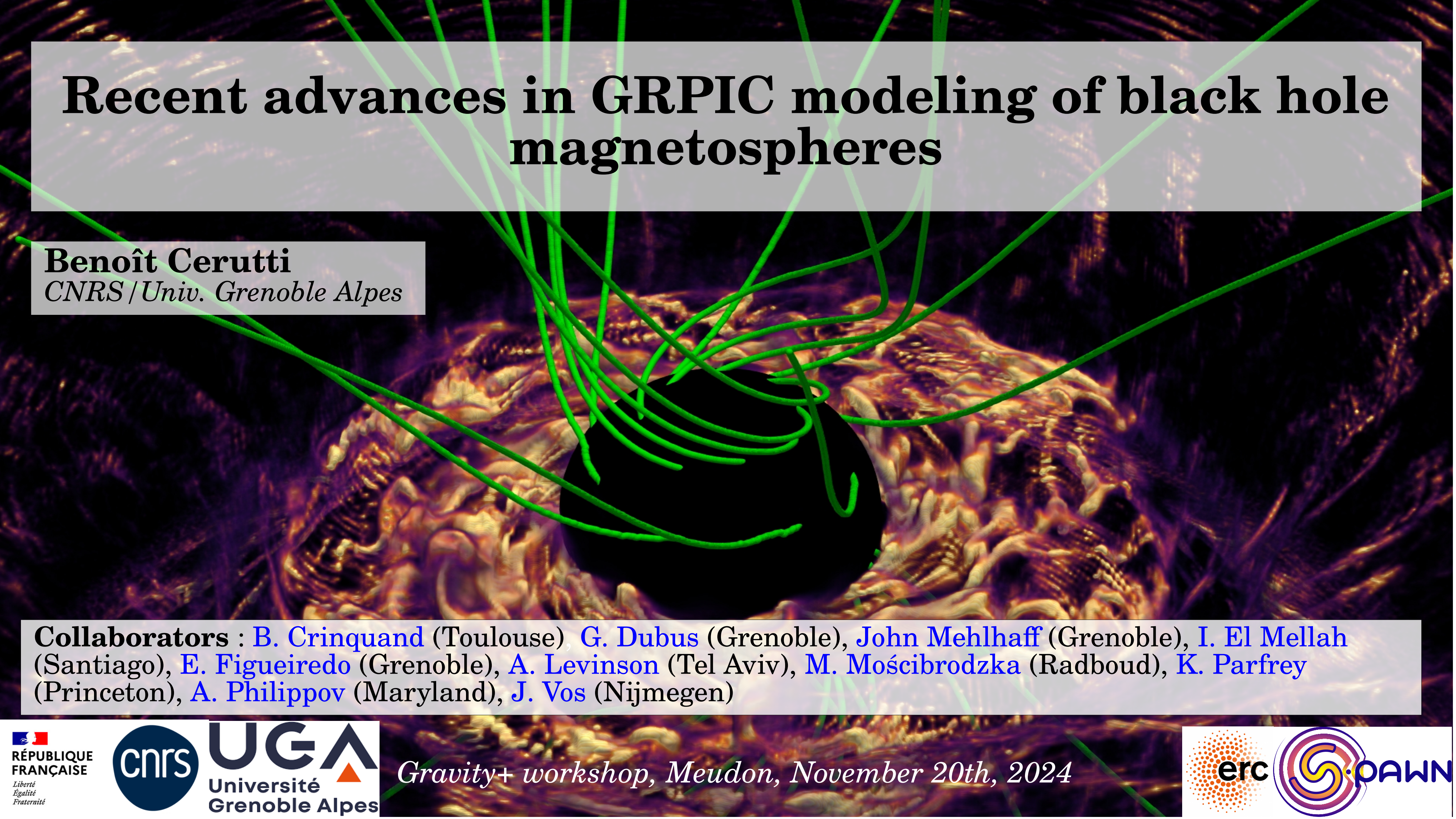

# Recent advances in GRPIC modeling of black hole magnetospheres


**Benoît Cerutti**
*CNRS/Univ. Grenoble Alpes*


**Collaborators** : B. Crinquand (Toulouse), G. Dubus (Grenoble), John Mehlhaff (Grenoble), I. El Mellah (Santiago), E. Figueiredo (Grenoble), A. Levinson (Tel Aviv), M. Mościbrodzka (Radboud), K. Parfrey (Princeton), A. Philippov (Maryland), J. Vos (Nijmegen)

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UGA Université Grenoble Alpes

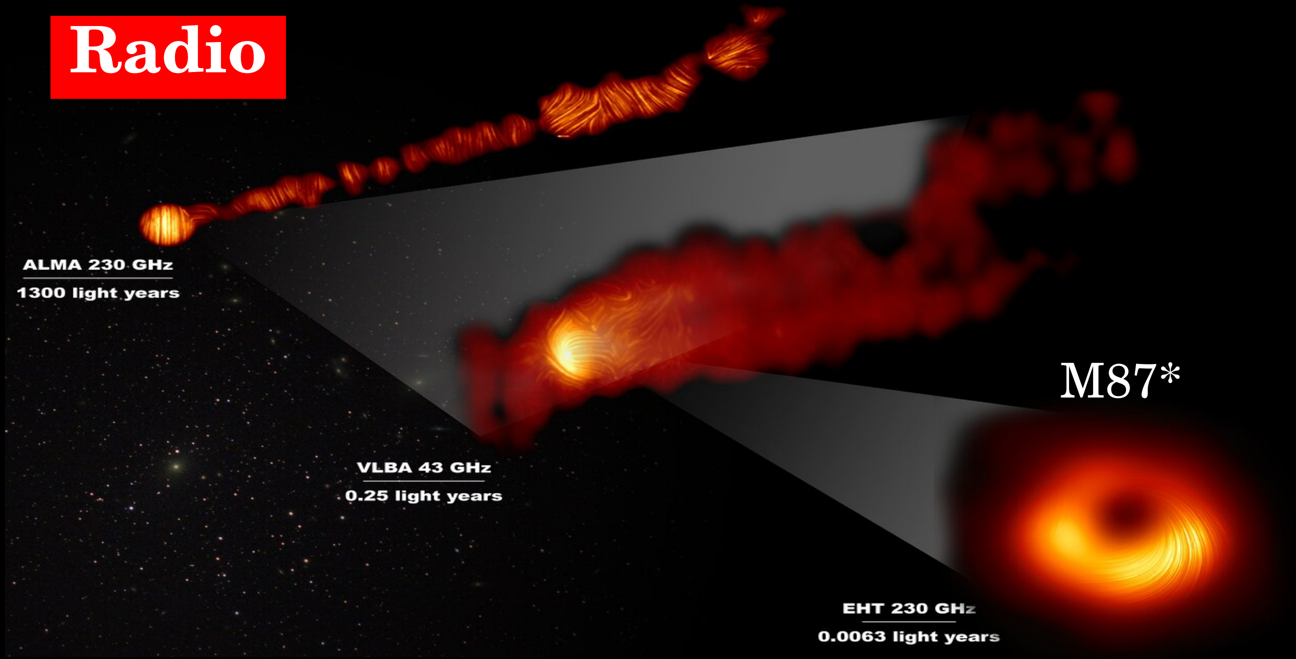
*Gravity+ workshop, Meudon, November 20th, 2024*

erc SPAWN

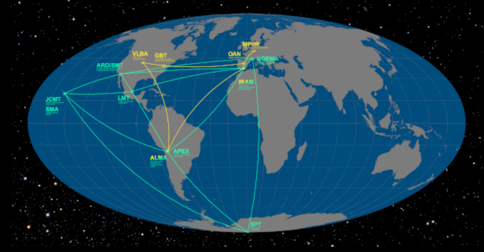
# Black hole horizon-scale observations

EHT collaboration (M87*, SgrA*)

**Radio**




Event Horizon Telescope



SgrA*

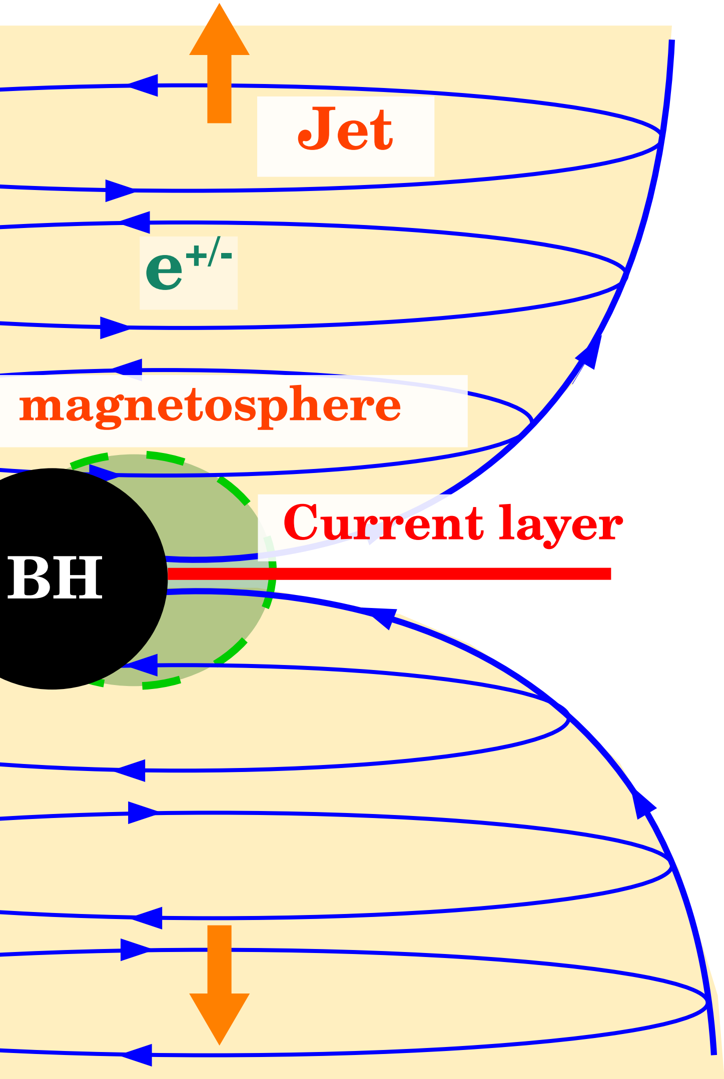
Gravity@VLT

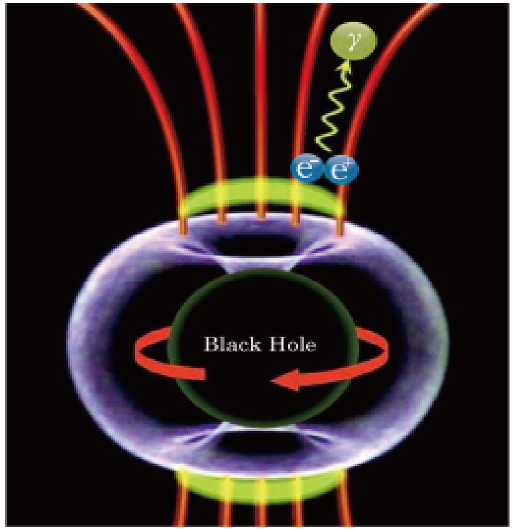
**IR**

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

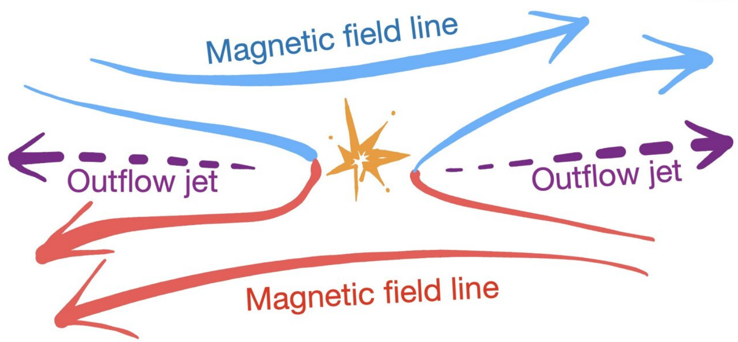
**How do black hole jets form ?**
**What is the origin of particle acceleration ?**

# A (naive) global picture



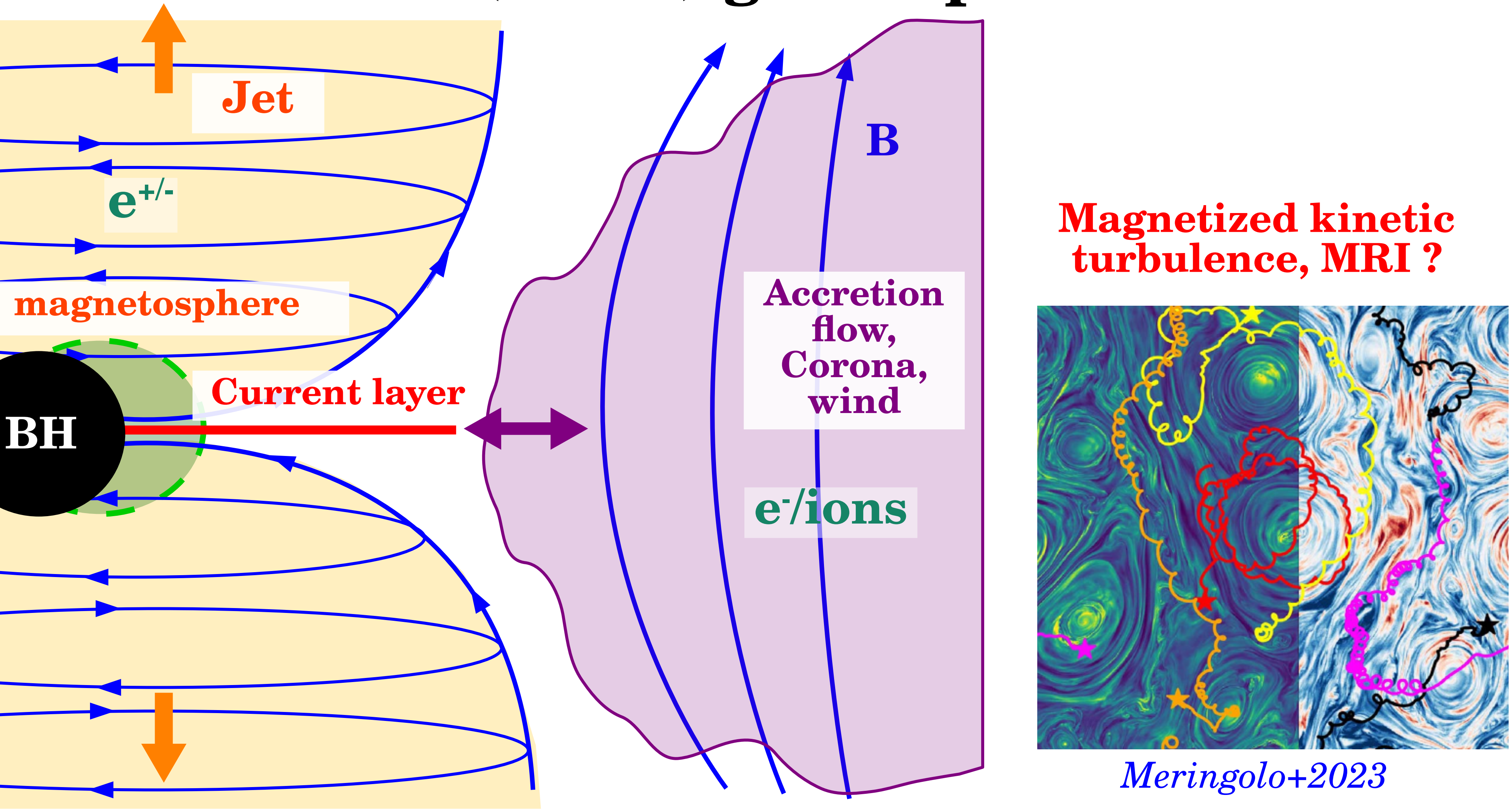




**Spark gap ?**

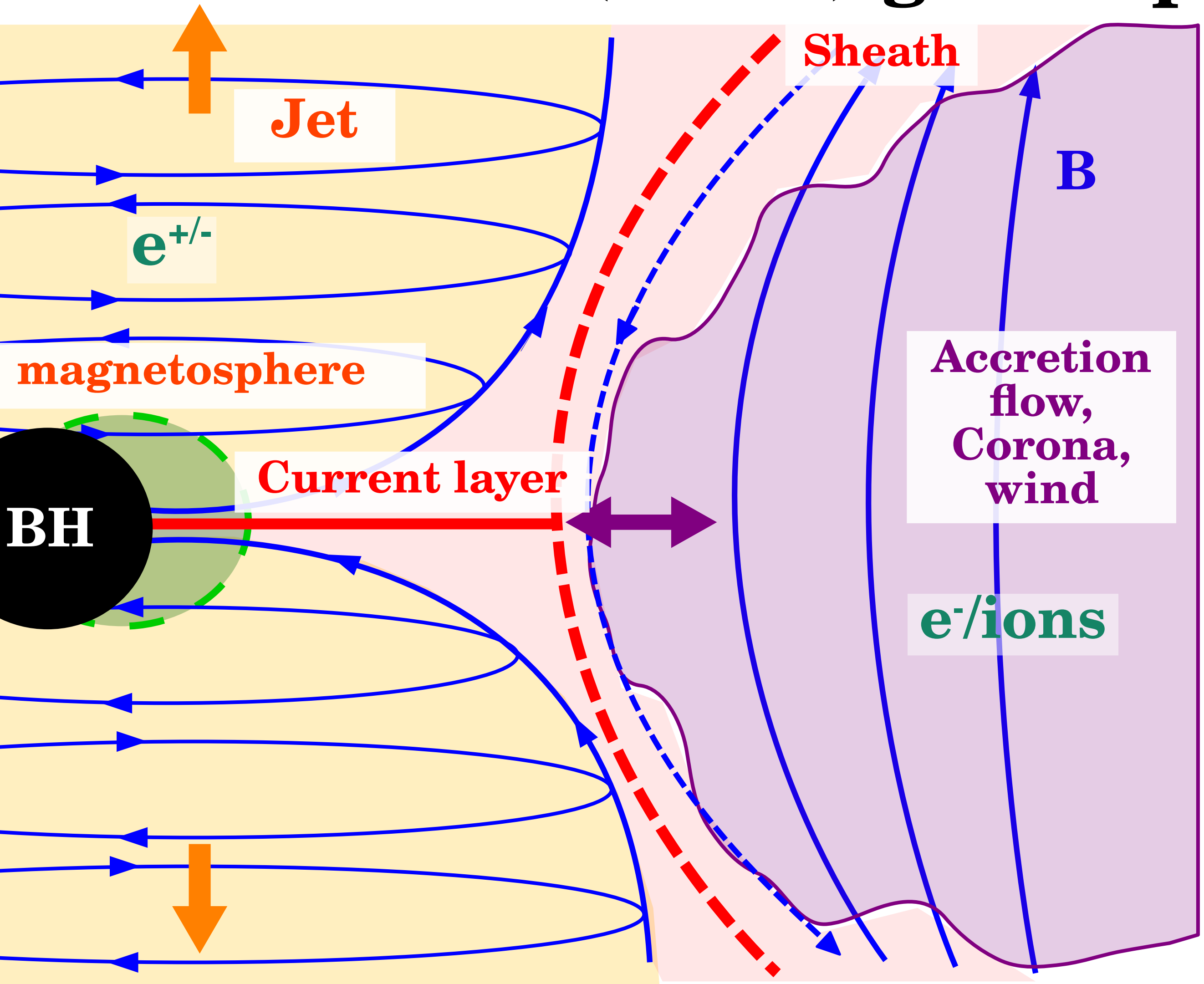



**Magnetic reconnection ?**

# A (naive) global picture

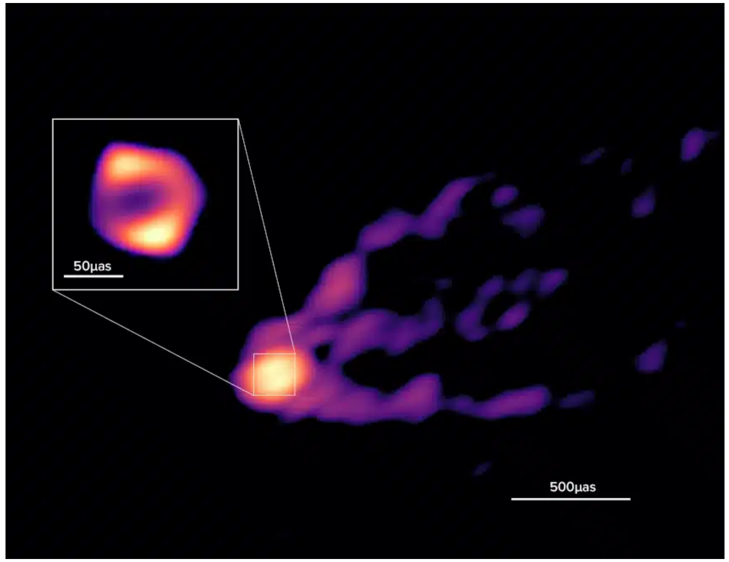


# A (naive) global picture

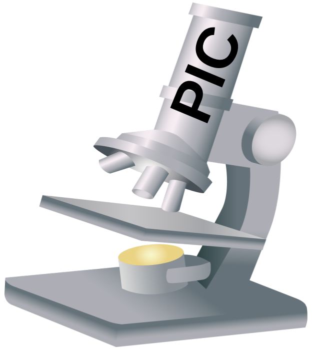



**(Asymmetric) magnetic reconnection ?**

**Shear flows, shocks, Kelvin-Helmholtz, Rayleigh Taylor ?**



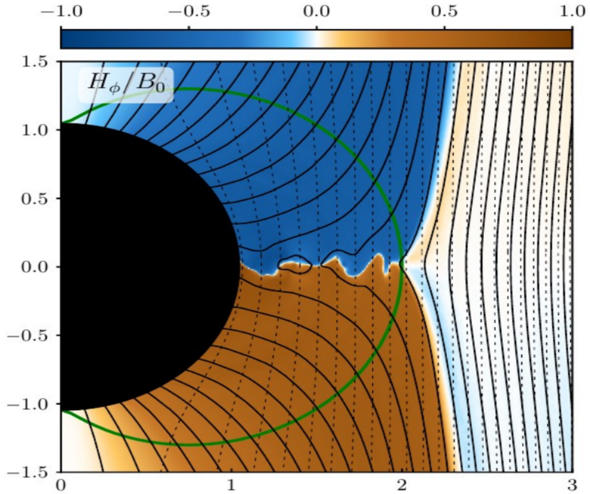

*Lu+2023*




# Particle-in-cell simulations

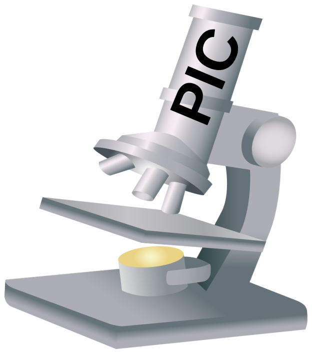
## Relativistic, ultra-magnetized, collisionless plasmas

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




*Parfrey, Philippov, Cerutti (2019)*

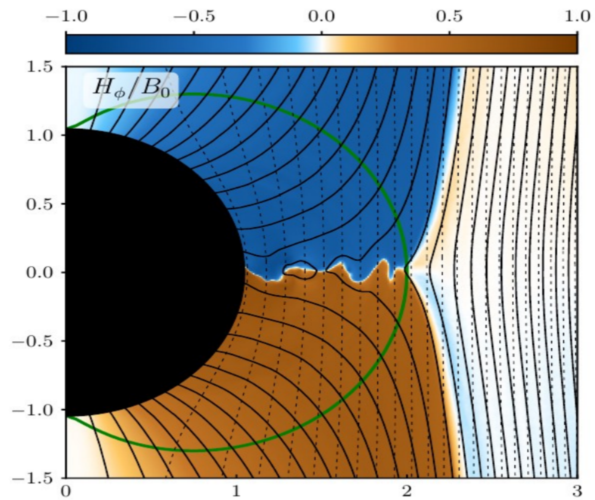
# Particle-in-cell simulations




**Relativistic, ultra-magnetized, collisionless plasmas**

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

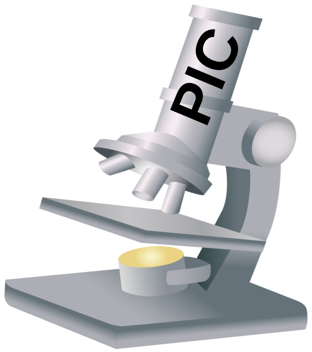
- Ab-initio modeling of plasmas
- Particle acceleration, radiation, pair creation
- Model observables




*Parfrey, Philippov, Cerutti (2019)*

**Theoretical model** ⟷ **Observations**

# Particle-in-cell simulations

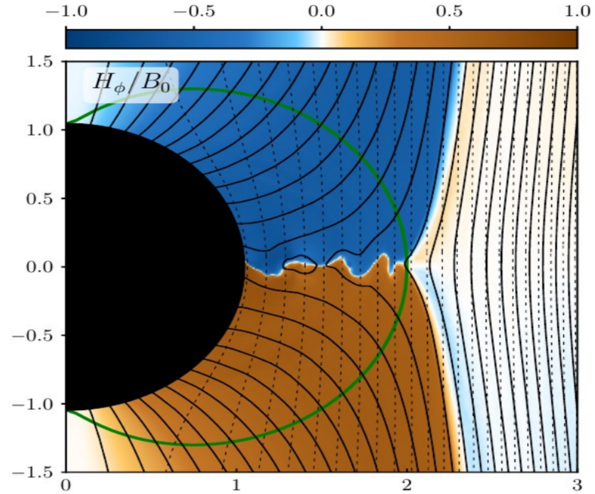



**Relativistic, ultra-magnetized, collisionless plasmas**

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

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

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

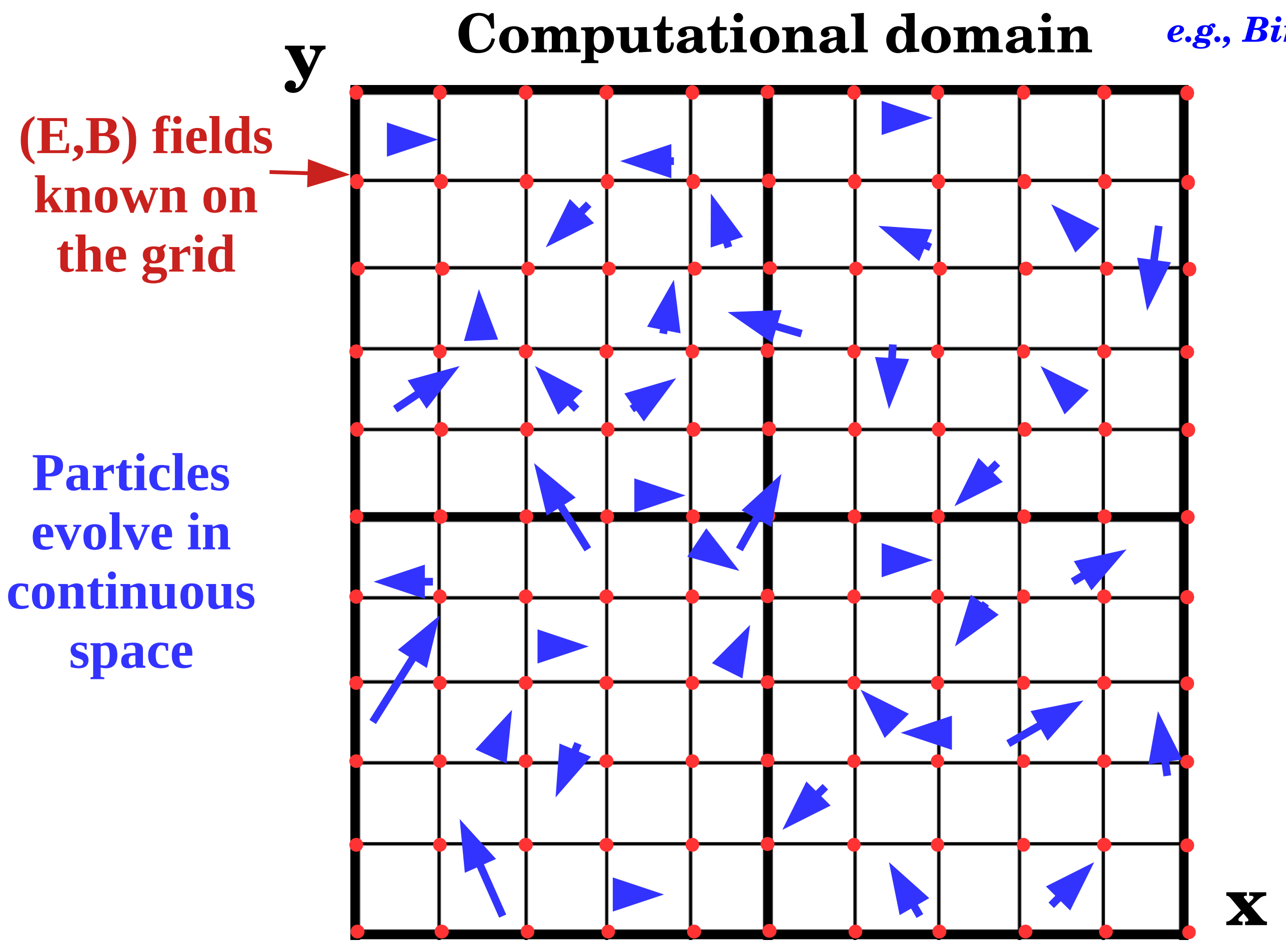


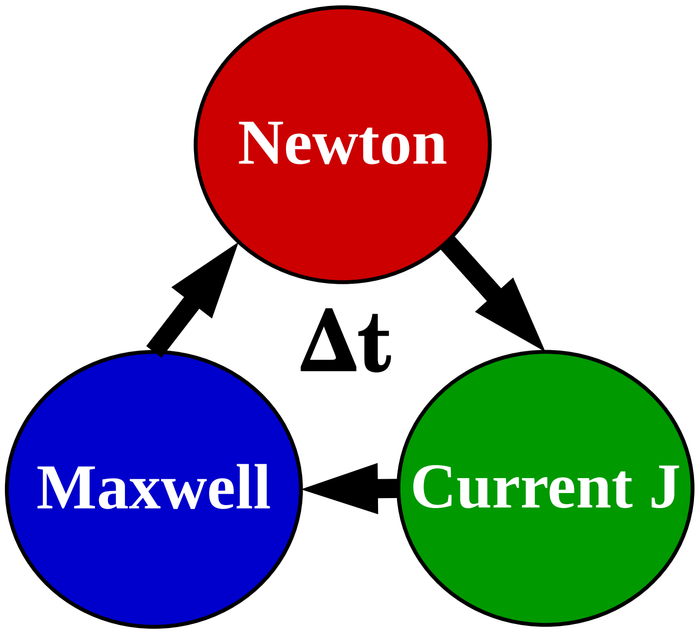

*Parfrey, Philippov, Cerutti (2019)*

**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

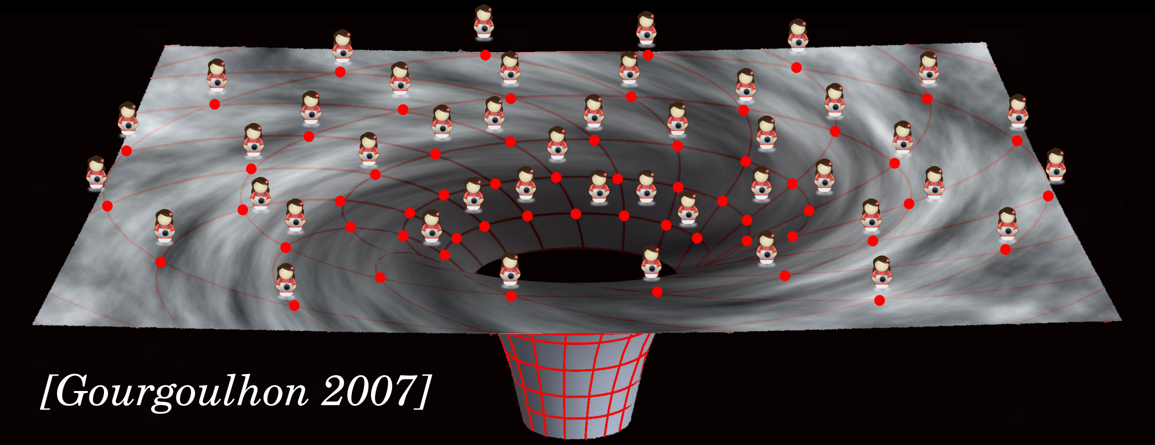
## General Relativity : 3+1 formalism

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

**$\alpha$** is the “lapse function”
**$\beta^i$** 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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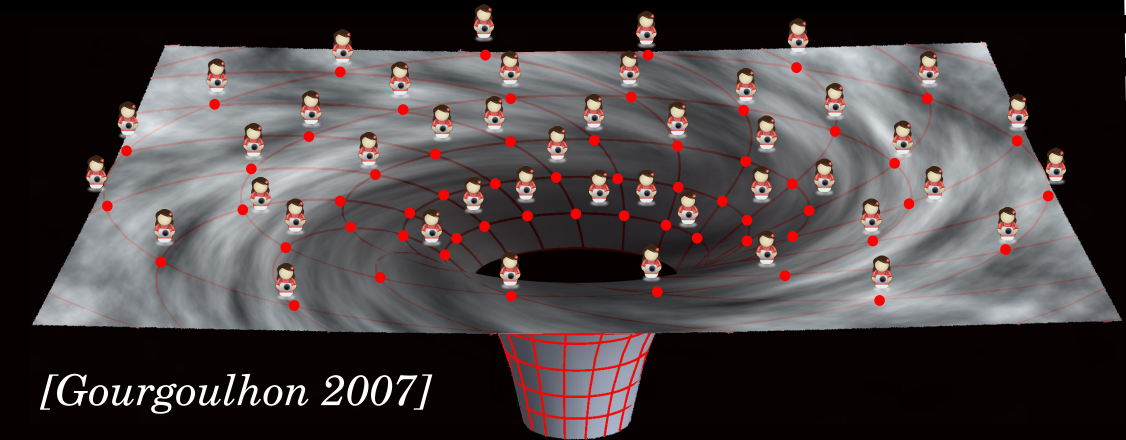
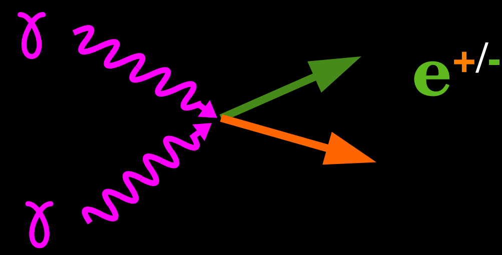


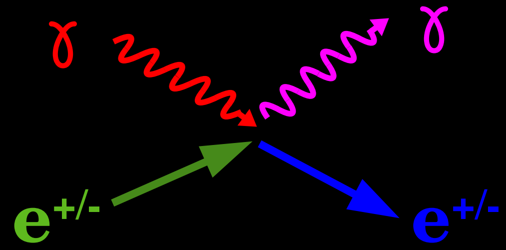
*[Gourgoulhon 2007]*

## Radiative transfer : Monte Carlo

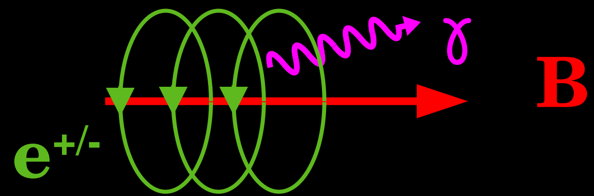
Full differential cross sections from QED




Pair creation

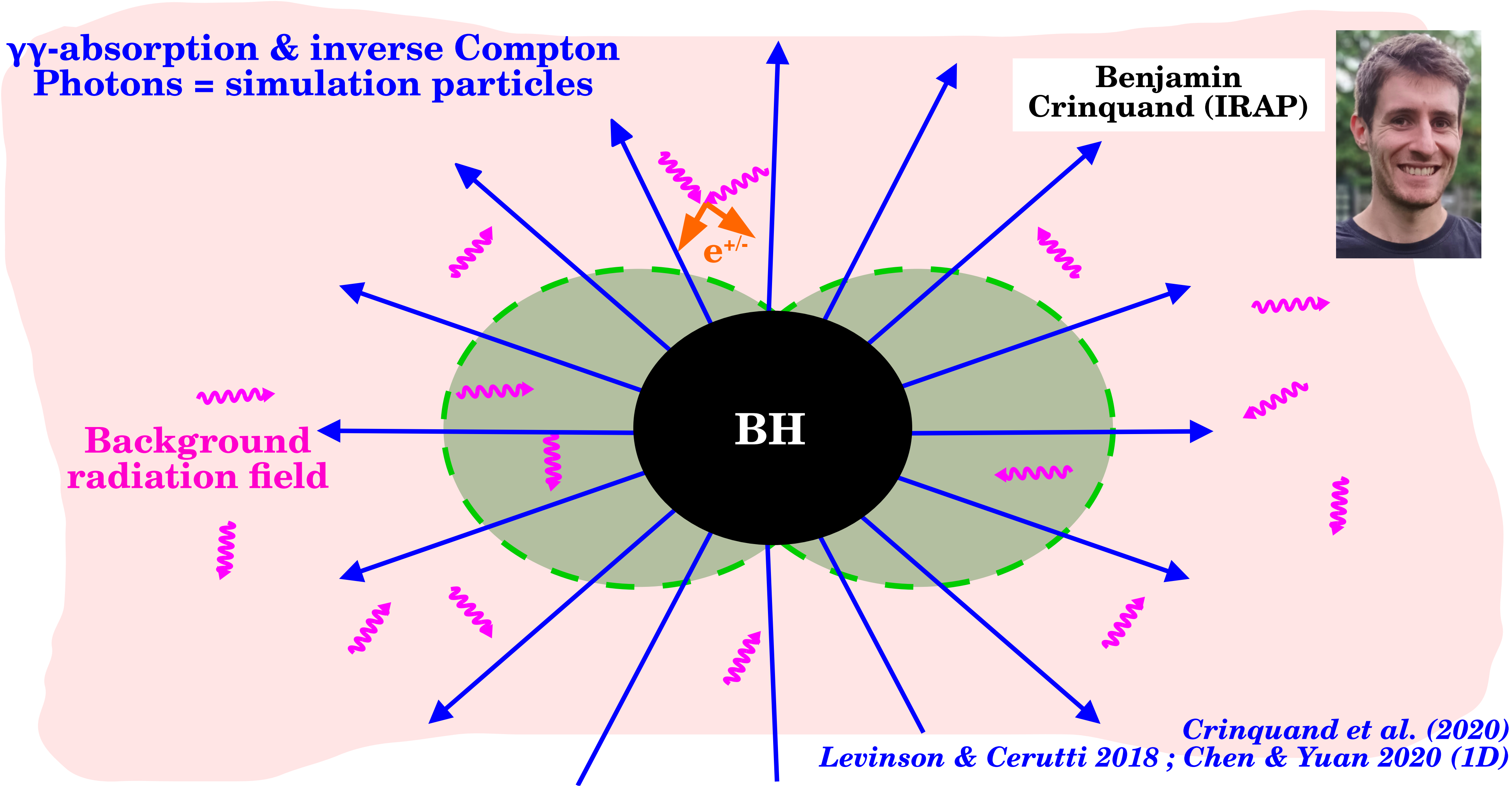



Inverse Compton




Synchrotron

# Num Exp#1 : Spark gap dynamic and BZ activation

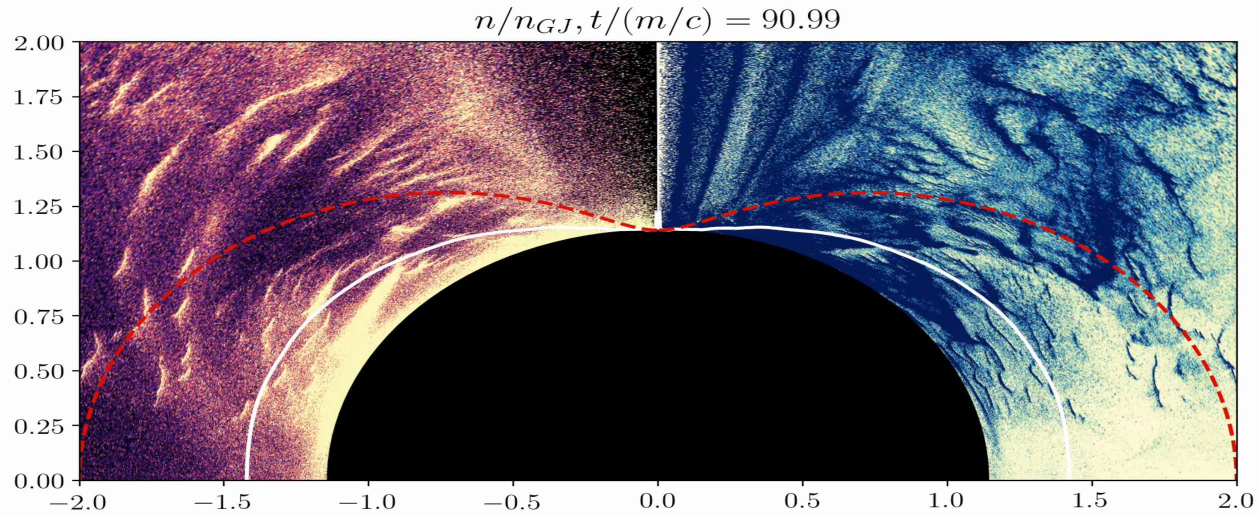



Benjamin Crinquand (IRAP)

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

# Spark-gap dynamics and pair creation

## Magnetic field = pure monopole



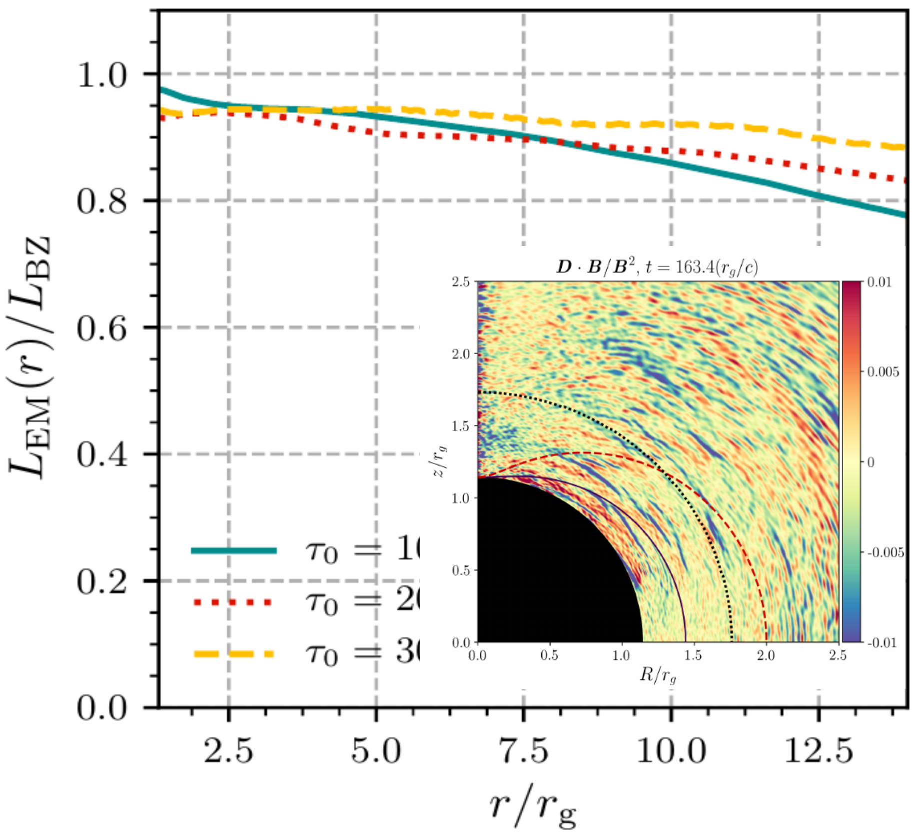

**Gap size determined by the photon mean-free path**

**Low plama multiplicity, i.e., few pairs from primary particles**

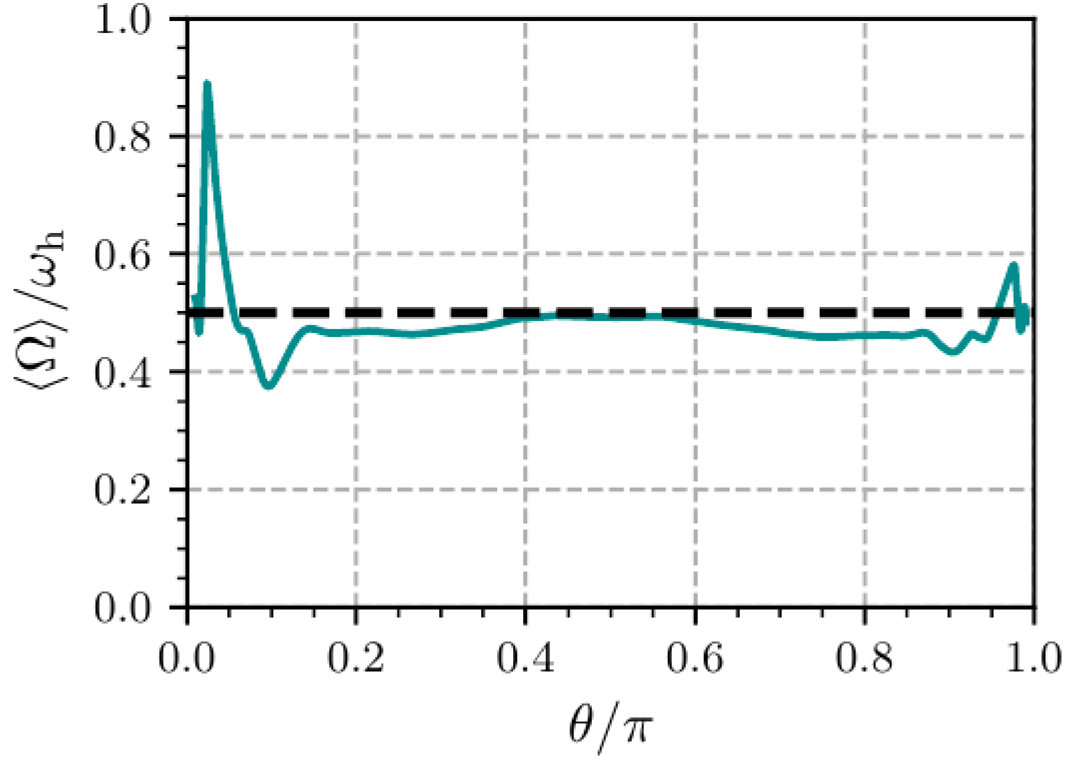
*Crinquand, et al. (2020)*

# Blandford-Znajek jet activation

**Poynting flux**

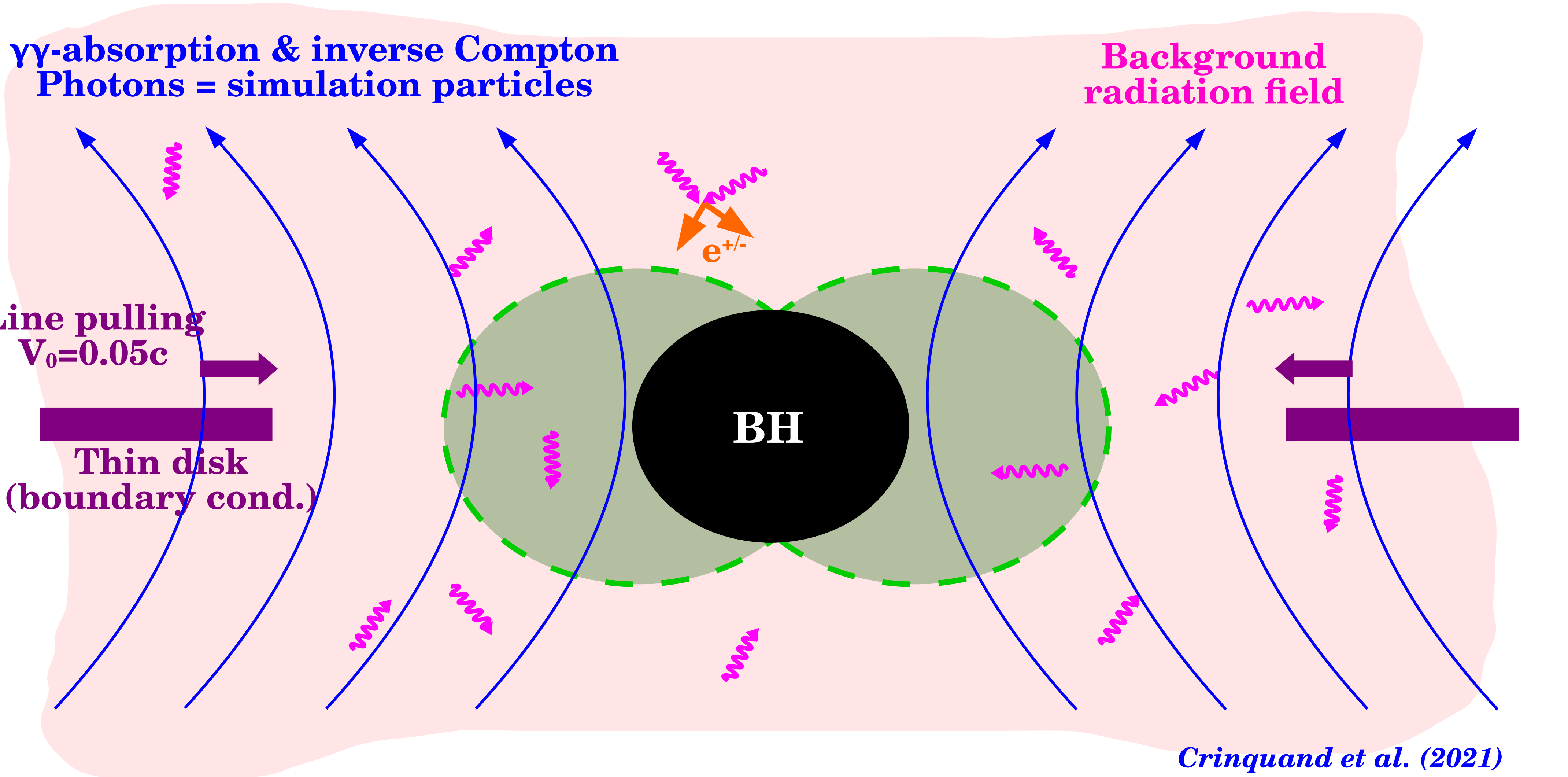



**Field line angular velocity**

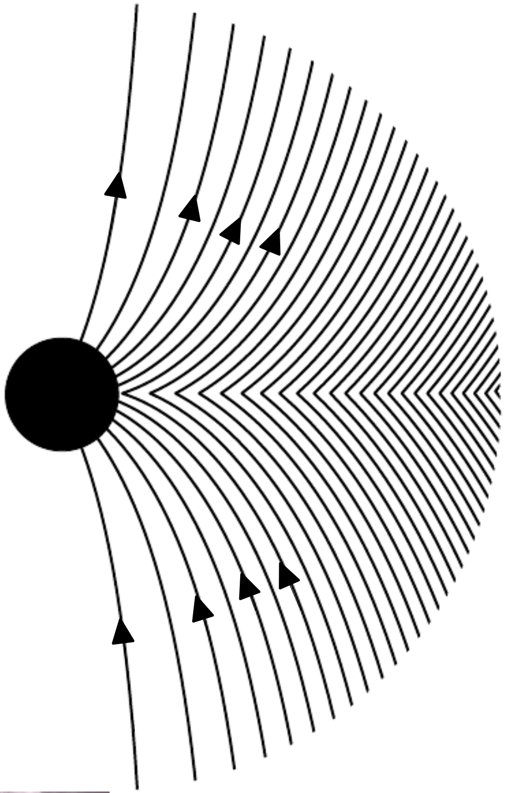


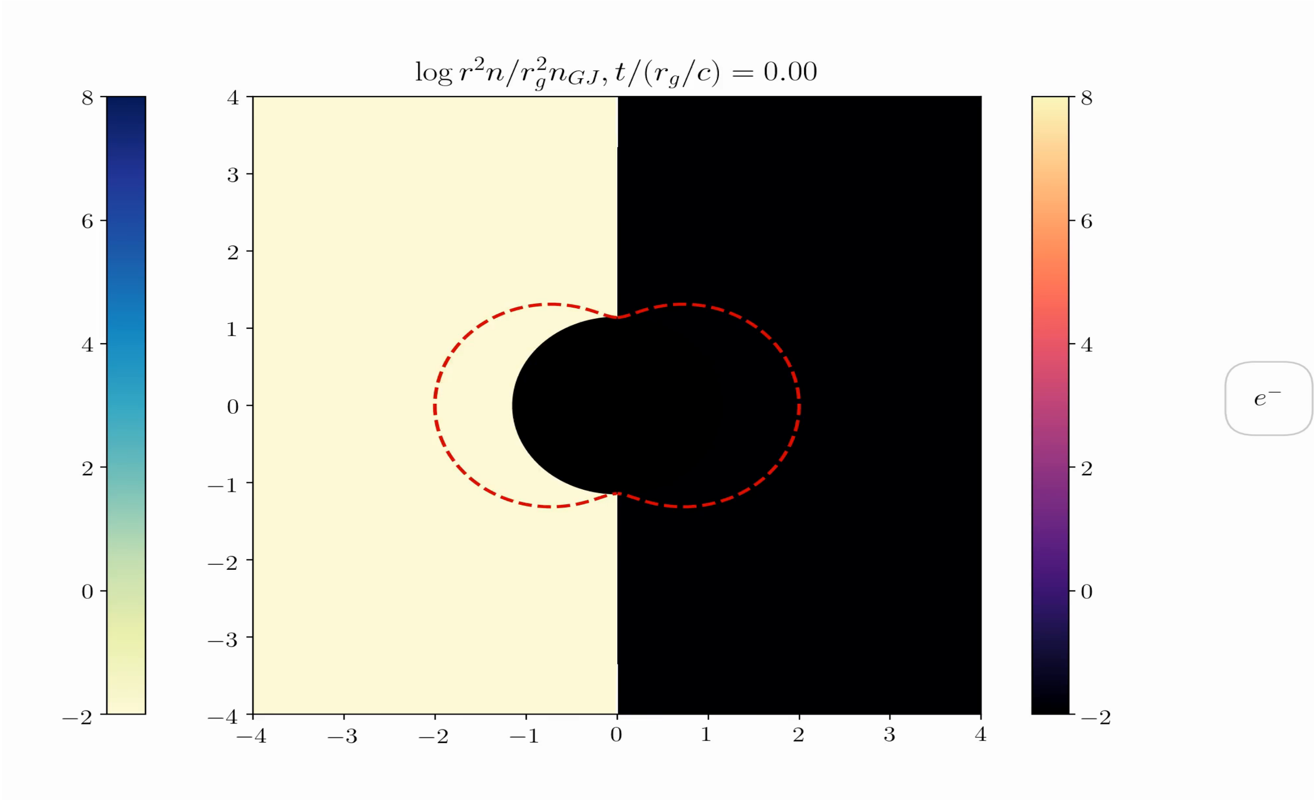

**Force-free like state with finite 5-10 % dissipation → particle acceleration (gap)**

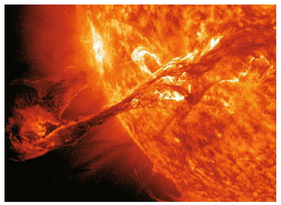
# Num Exp#2: Spark gap and ergospheric reconnection



# Paraboloidal configuration (spark gap & reconnection)

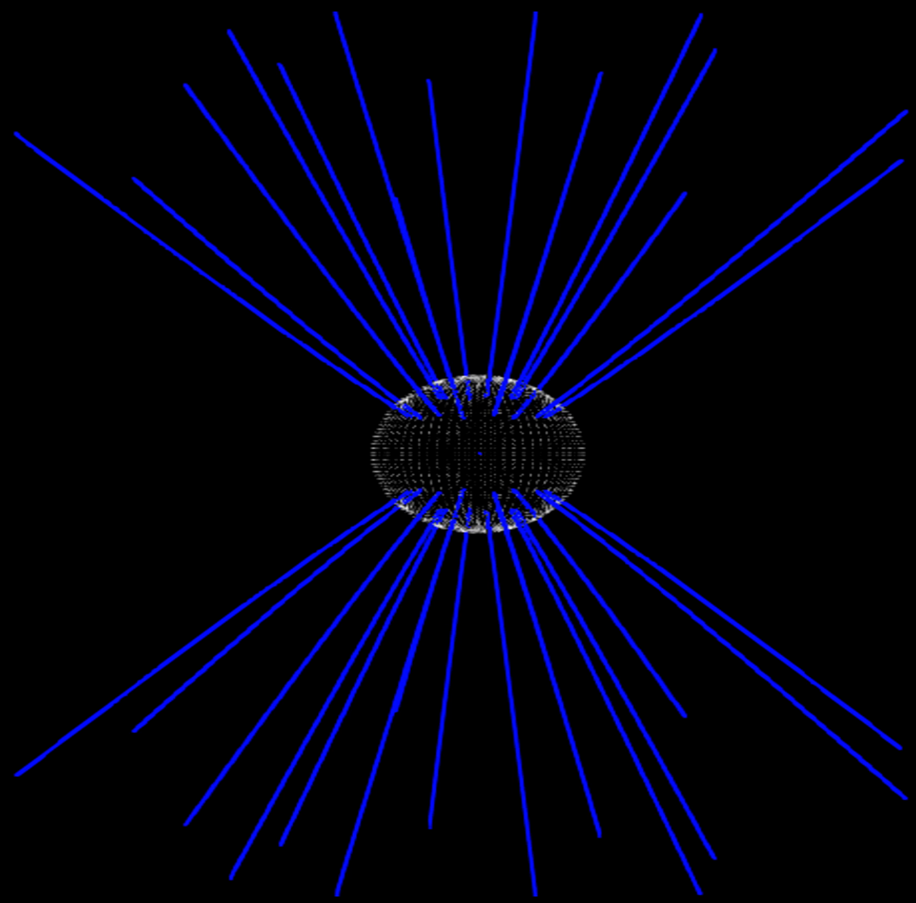




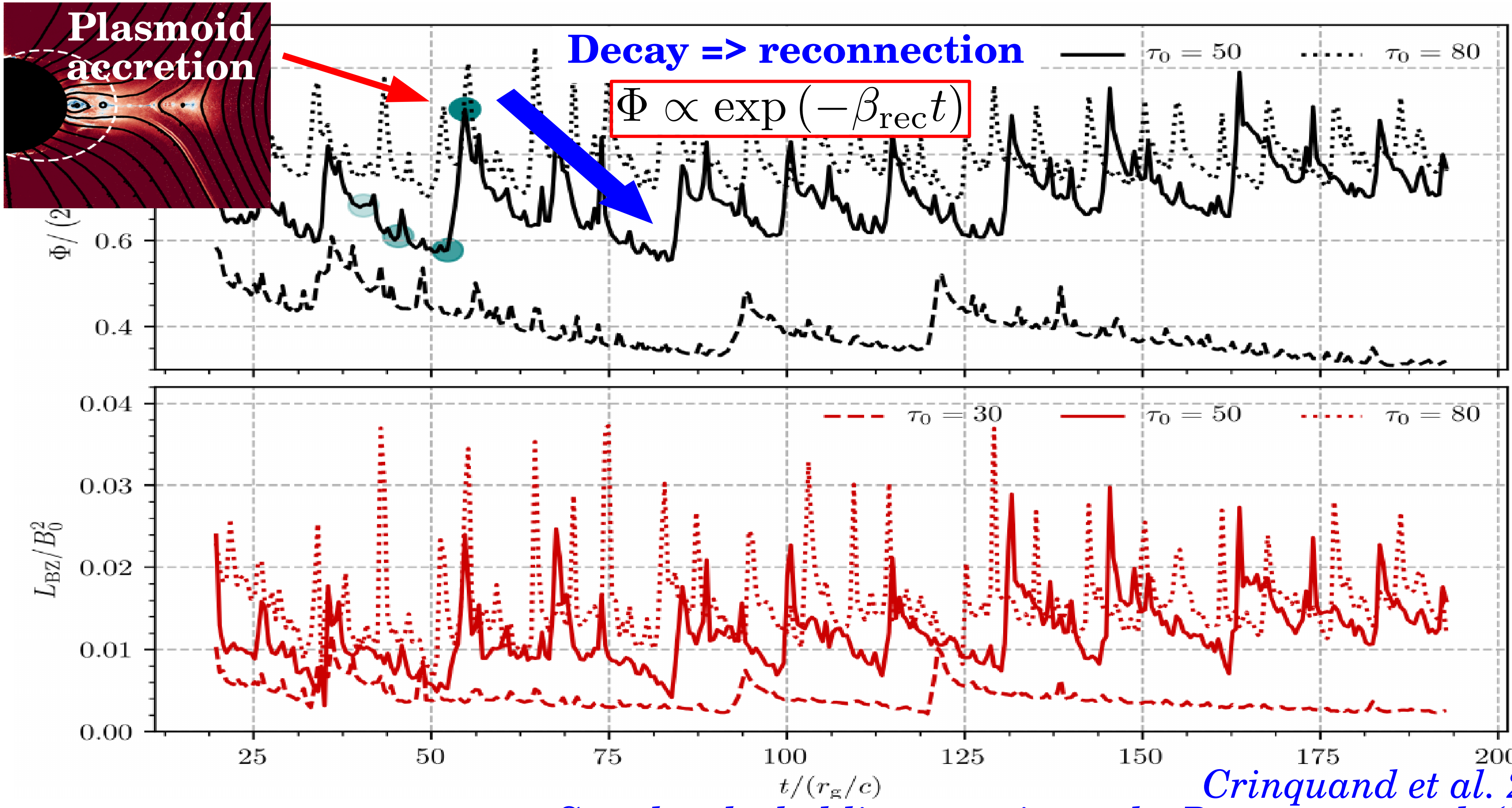



*Crinquand et al. 2021*

# Extension to full 3D



# Magnetic flux is regulated by reconnection

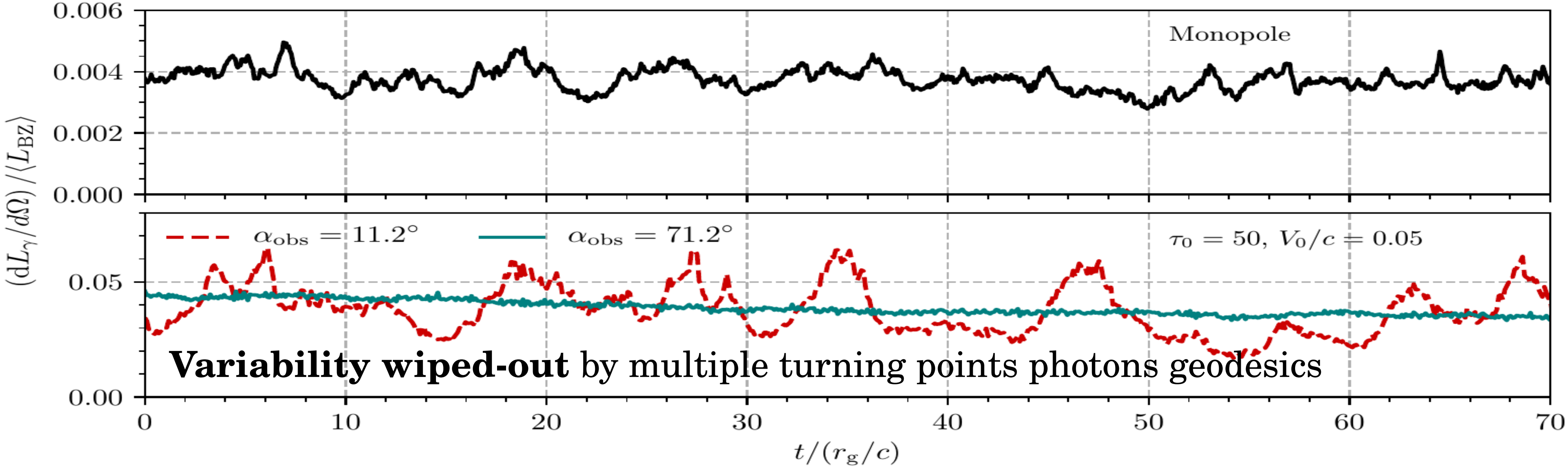



*Crinquand et al. 2021*

*See also the balding experiment by Bransgrove et al. (2021)*

# High efficiencies but weak γ-ray variability

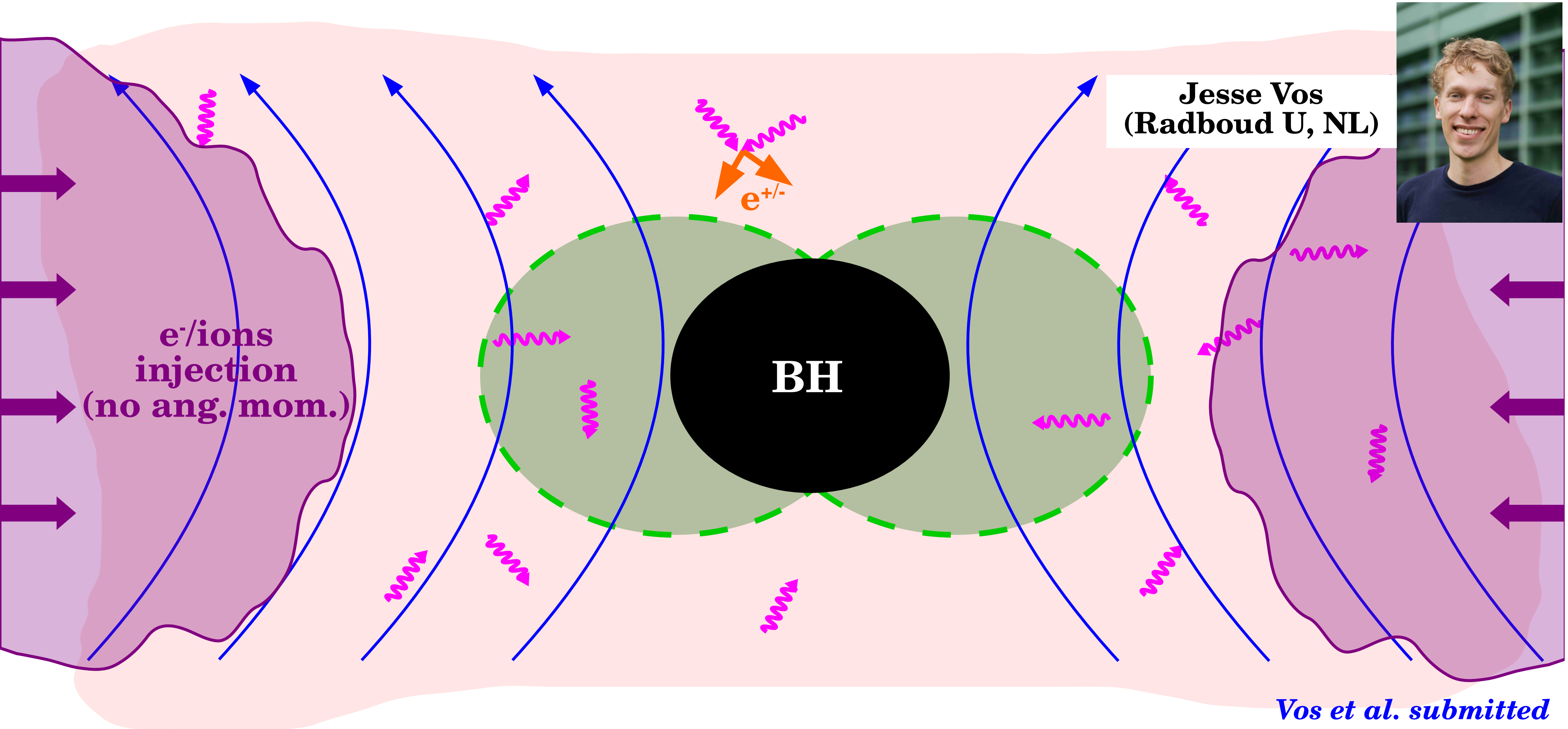
**Optically thin radiation = ray-tracing with GeoKerr (*Dexter & Agol 2009*)**




- ✅ High-radiative efficiency : ~**5%** $L_{BZ}$ polar-caps, ~**40%** $L_{BZ}$ current sheet
- ❌ Variability is too weak (~ 50% level) => need for **external forcing ?** (e.g., sudden change is the magnetic flux, radiation field)

*Crinquand et al. 2021*

# Num Exp#3: Spark gap and ergospheric reconnection and accretion

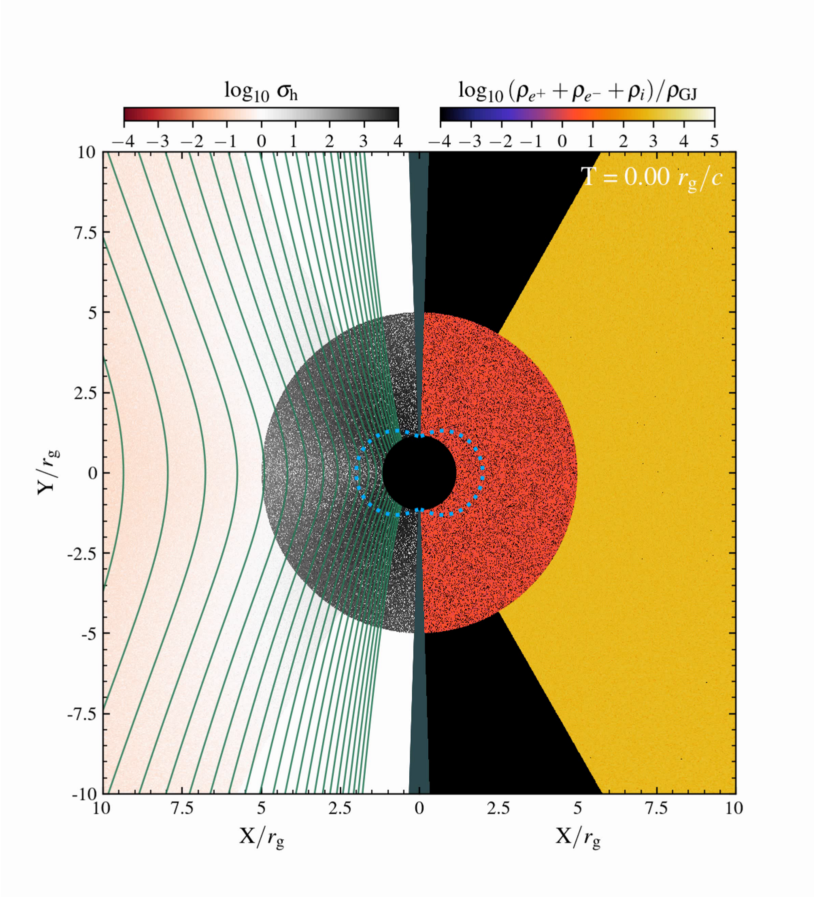



Jesse Vos
(Radboud U, NL)

*Vos et al. submitted*

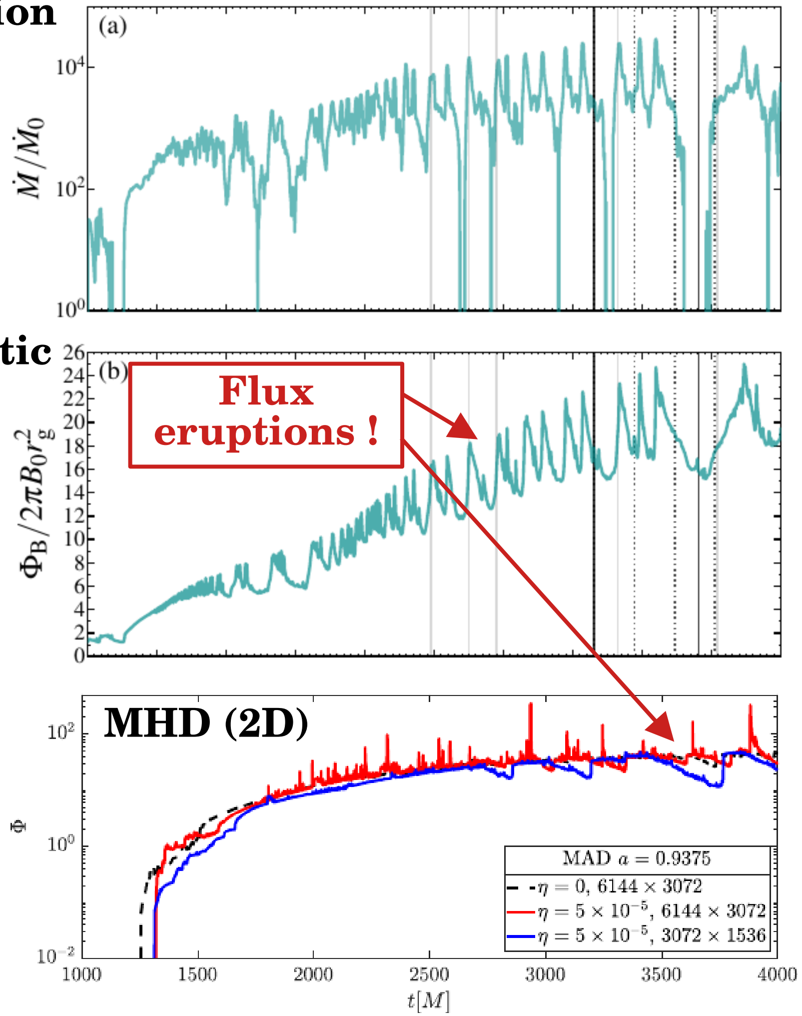
# A (2D) MAD-like state is reproduced

**See also Galishnikova et al. 2023**



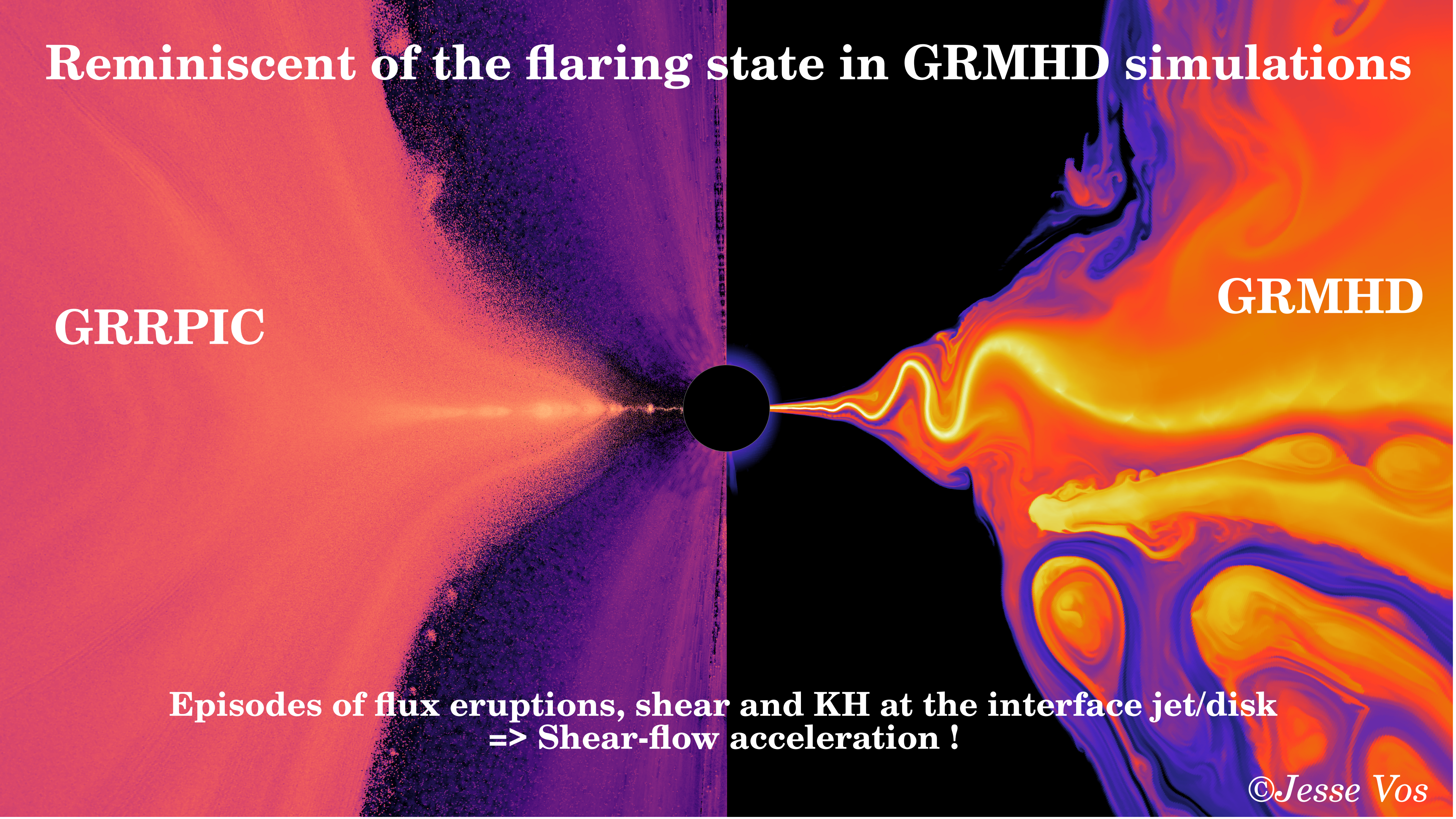

**Accretion rate**

**Magnetic flux**

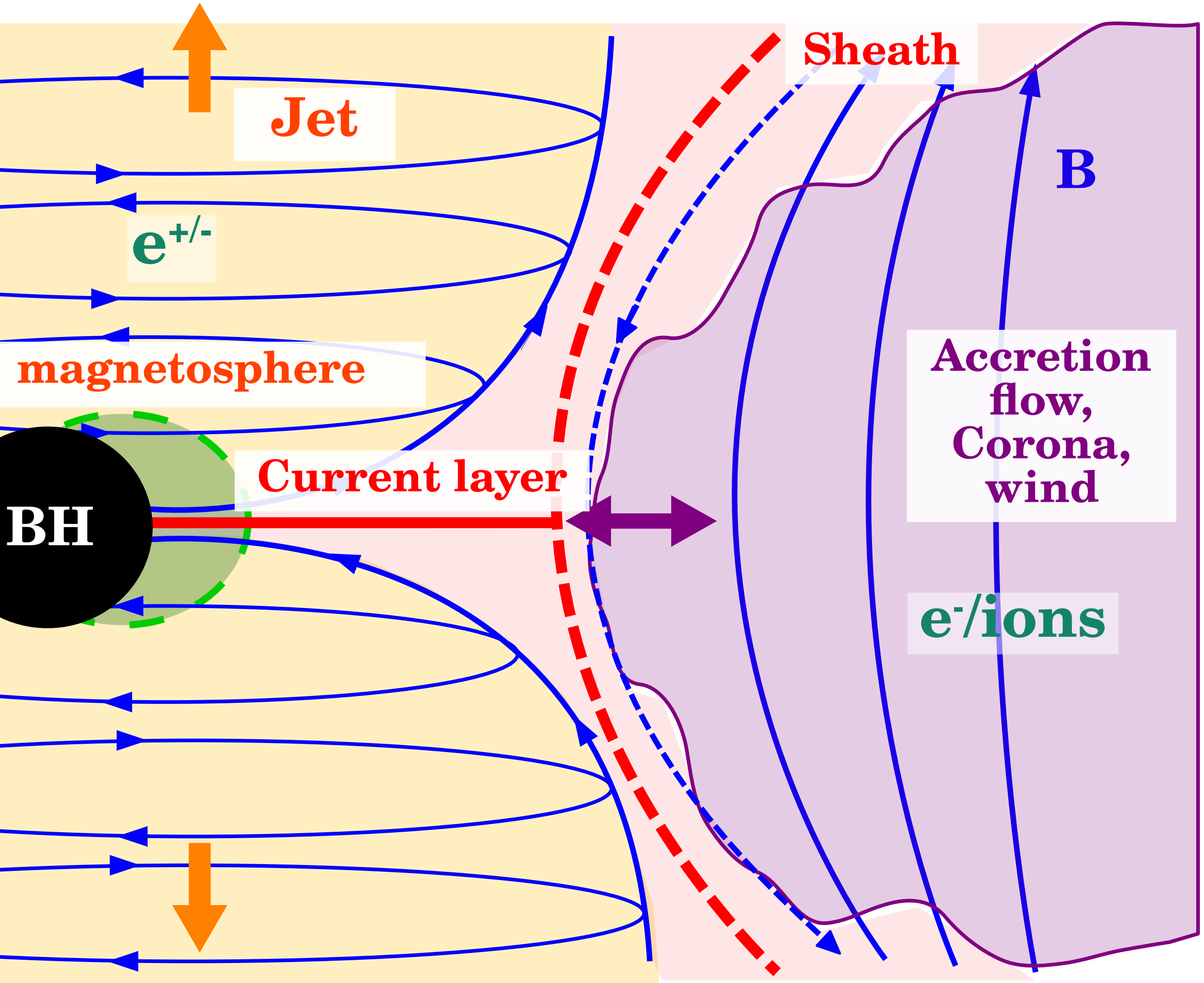



***Vos et al. submitted***

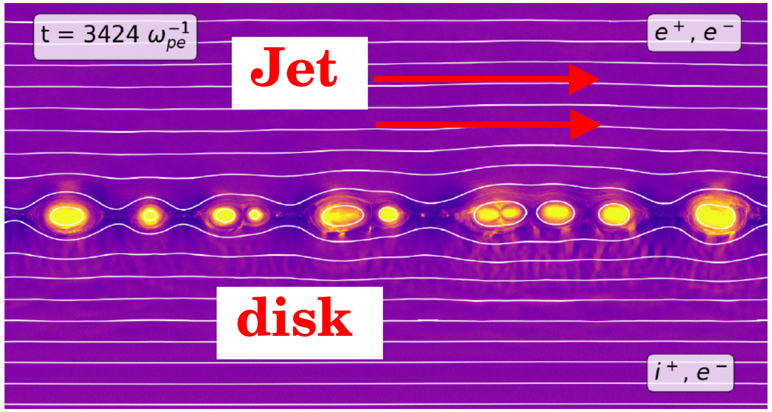
***Ripperda+ 2020***


Reminiscent of the flaring state in GRMHD simulations
GRRPIC
GRMHD
Episodes of flux eruptions, shear and KH at the interface jet/disk
=> Shear-flow acceleration !
©Jesse Vos

# Dissipation driven by global instabilities (KH, RT)




**(Asymmetric) magnetic reconnection ?**




Reconnection and particle acceleration driven by the dense side (accretion flow)

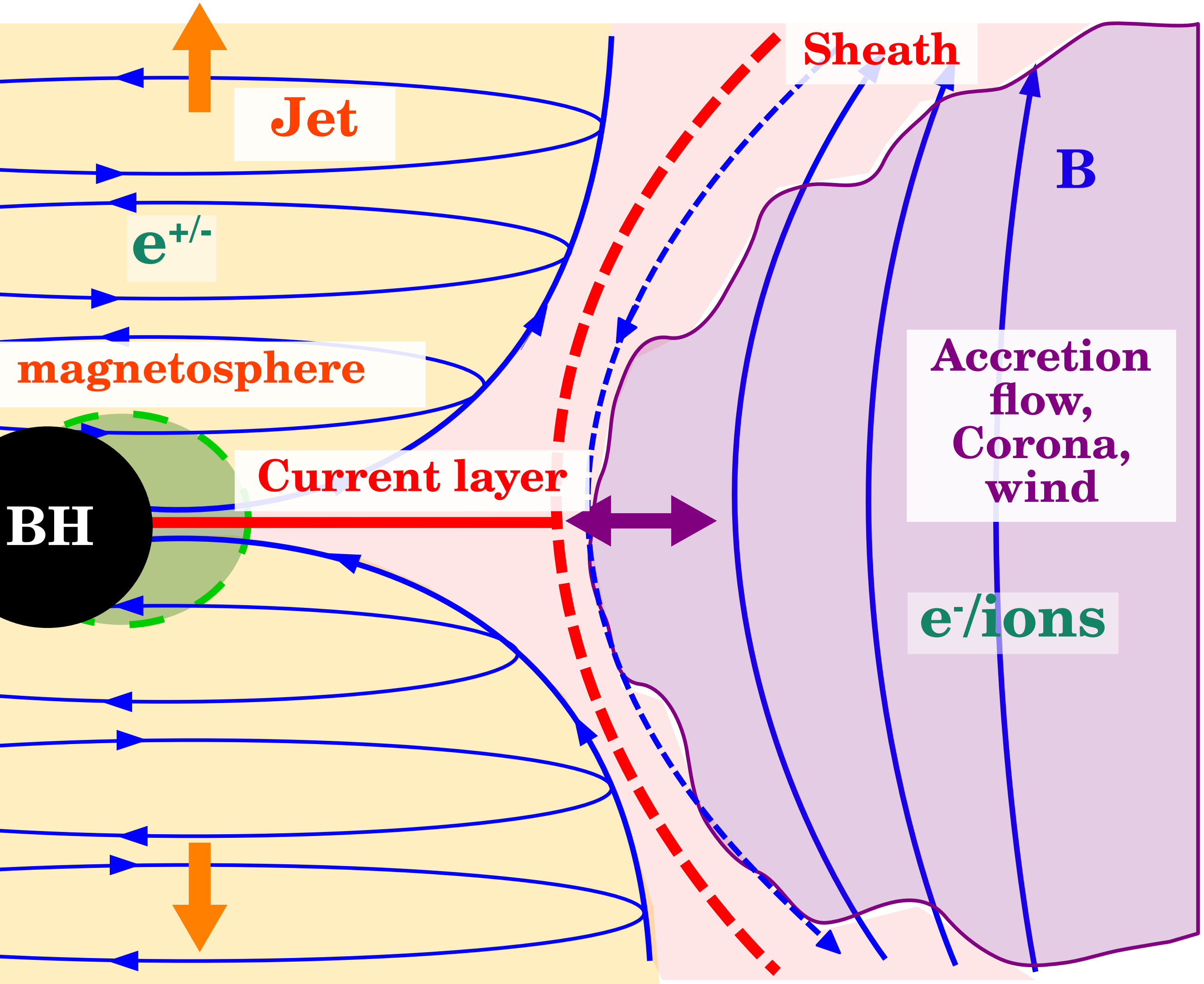
**=> Weak acceleration !**

**=> Particle injection ?**

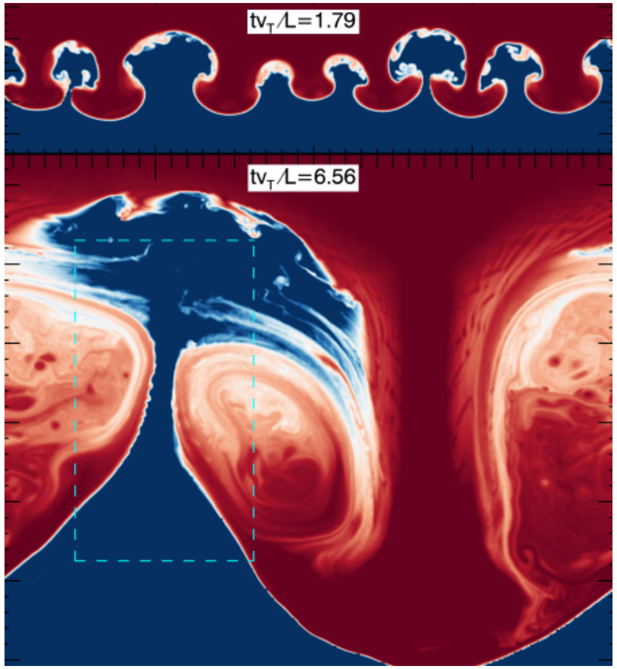
A **velocity shear** makes it worse !

***Figueiredo et al. (2024)***

# Dissipation driven by global instabilities (KH, RT)



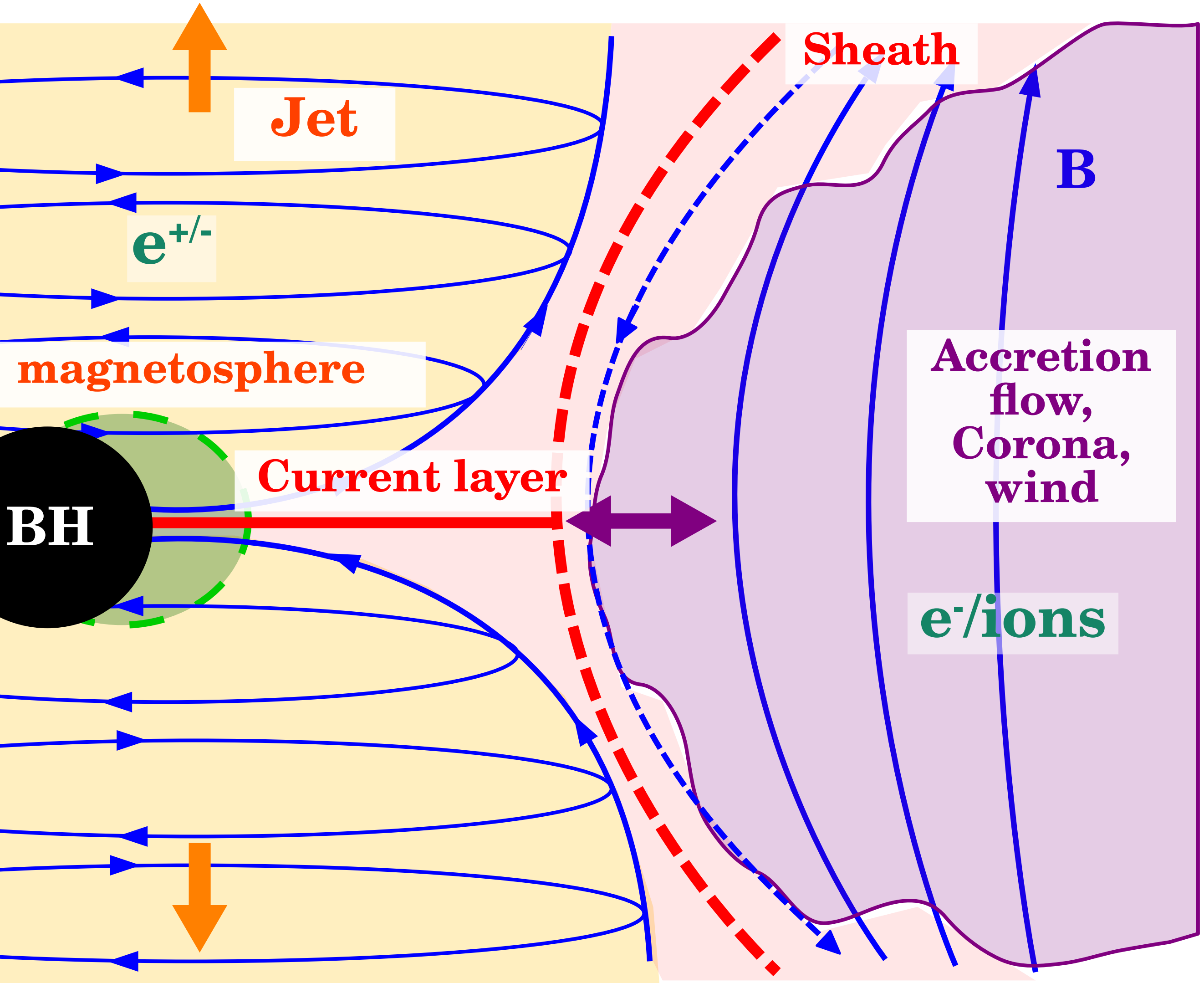

RT-driven reconnection



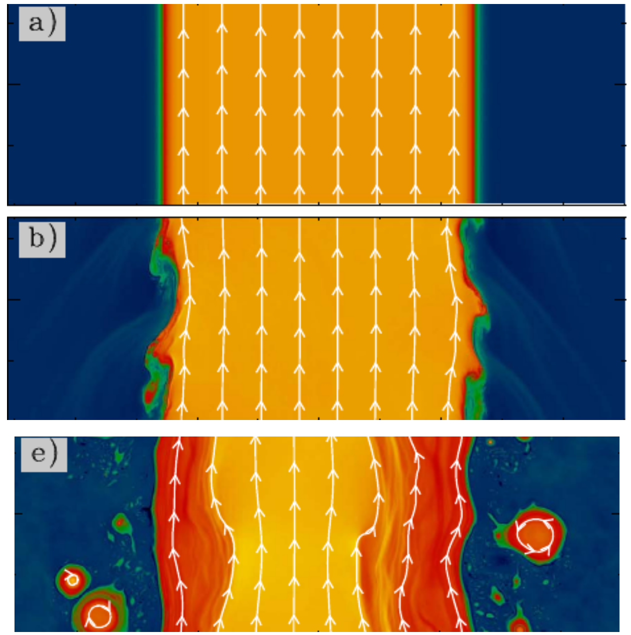

=> Particle acceleration !
Quenched due to asymmetries ?

*Zhdankin et al. 2024*

# Dissipation driven by global instabilities (KH, RT)



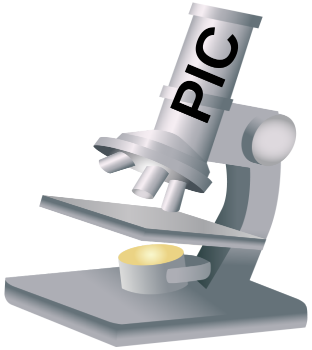

**KH-driven reconnection + shear-flow acceleration**




Reconnection : **Injection** mechanism for shear-flow acceleration

***Sironi et al. 2021***

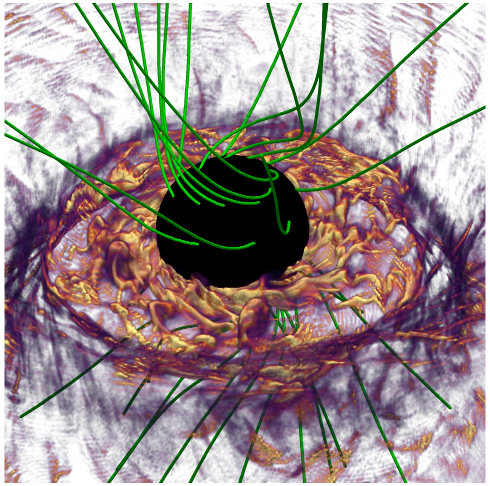
# The scale separation challenge



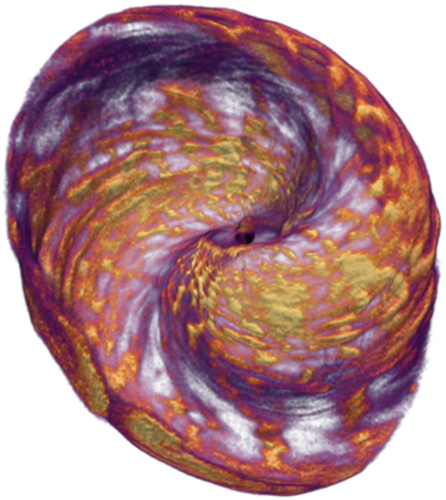

PIC must resolve plasma kinetic scales (~particle Larmor radius scale $R_L$)

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 ...**




**Overview**

This workshop aims at bringing together world experts in the field of relativistic plasma astrophysics to discuss recent progress in the understanding of magnetized plasmas surrounding neutron stars and black holes and related astrophysical phenomena from an observational, theoretical and computational perspectives.

**Important dates**

Conference dates: Sunday April 6, 2025 - Friday April 11, 2025.

Application and abstract submission: September 16, 2024 - December 1, 2024.

Notification to all applicants: December 15, 2024.

**Registration fee**

The registration fee is fixed to a flat rate of **300€** (taxes included). It will cover all expenses during your stay in Les Houches (meals and accommodation). Payment can be made by credit card, bank transfer or purchase order. A link to the online payment platform (Azur-Colloque) will be available soon.

**Confirmed invited speakers**

- Andrei Beloborodov, Columbia University, USA
- Roger Blandford, Stanford University, USA
- Arache Djannati-Ataï, APC/CNRS, France
- Gwenael Giacinti, Tsung-Dao Lee Institute, China
- Hayk Hakobyan, Columbia University, USA
- Yuri Lyubarsky, Ben-Gurion University of the Negev, Israel
- Monika Mościbrodzka, Radboud University, Netherlands
- Kohta Murase, Penn State, USA
- Cherry Ng, LPC2E/CNRS, France
- Nanda Rea, CSIC-ICE, Spain
- Bart Ripperda, CITA-University of Toronto, Canada
- Dmitri Uzdensky, University of Oxford, UK
- Alexandra Veledina, University of Turku, Finland
- Yajie Yuan, Washinton Univeristy, USA

**Pre-registration & abstract submission : Dec 1 !**

SOC :
- B. Cerutti (chair)
- B. Crinquand
- N. Globus
- C. Guépin
- A. Levinson
- K. Parfrey
- A. Philippov

https://r-magnetosphere.sciencesconf.org/

# Conclusions

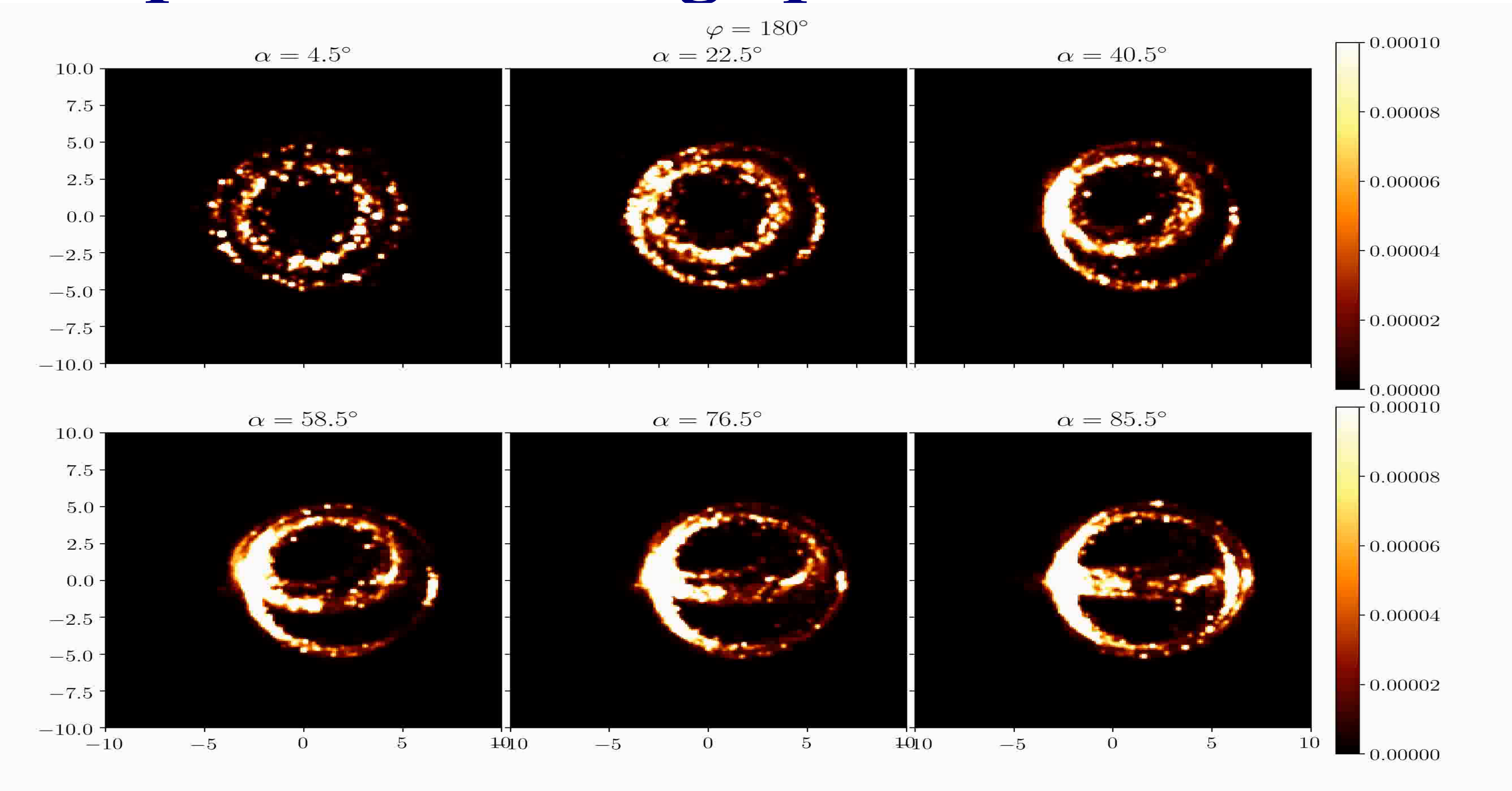
- There is a **urgent need** to better understand the behavior of plasma near black holes (EHT and Gravity observations)
- The **(GR)(R)PIC method** has become a successful tool to explore these processes from first principles.
- The study of black hole magnetospheres show how strongly connected microscopic and system size are connected. **Global simulations needed.**
- **Magnetic reconnection** accelerates particles efficiently and regulates the magnetic flux on the BH horizon
- The **ergospheric current sheet** is a bright source of non-thermal synchrotron radiation (10 % of the jet power)
- ***Caveat* : small scale separation** is a strong limitation of the predictive power of PIC simulations

  => Need for innovative numerical techniques (hybrid, GPU, …)

# Questions & challenges

- Multiscale challenges, how do the kinetic scales feedback on the large scales, and vice-versa?
- What is the connection between the magnetosphere and the accretion flow?
- How much (kinetic) physics do we need? What dissipative processes are at work?
- What is the origin of SgrA* IR-X-ray flares ?
- What is the origin of the jet sheath emission? How to interpret the wide jet base observed in M87*? Gamma-ray flares ?
- Is reconnection in the magnetosphere powerful enough to explain the non-thermal flux near the horizon?
- How are electrons heated in the accretion flow? Role of kinetic turbulence, shear flows, reconnection, shocks?
- How close to a MAD accretion mode observed in GRMHD can be modeled with GRPIC?

# Hotspots due to large plasmoid formation




**=> Prediction for ngEHT observations**