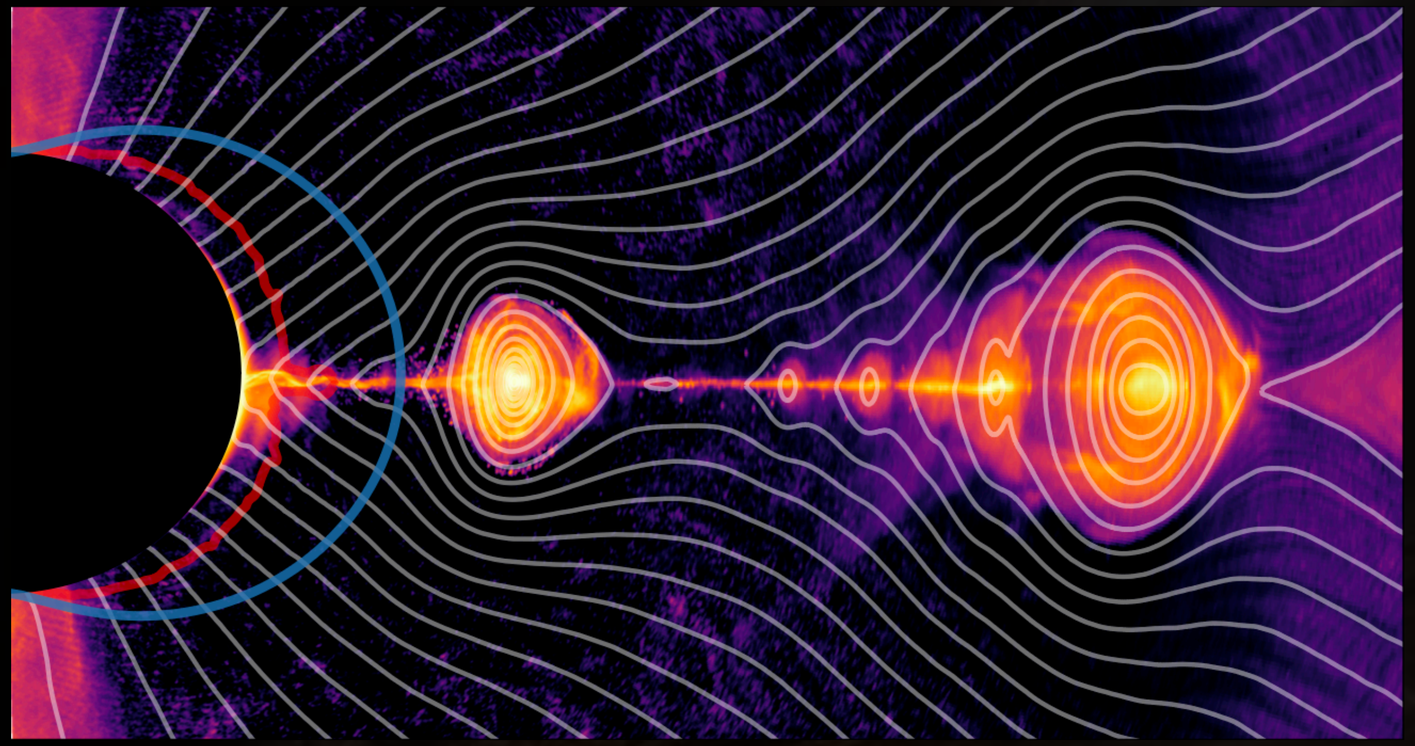
A Kinetic Approach for Astrophysical Relativistic Plasmas



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RAGtime - Relativistic Astrophysics Group Meeting
Opava, November 2026

Einstein Telescope

Event Horizon Telescope

ITP Institute for Theoretical Physics

GOETHE UNIVERSITÄT FRANKFURT AM MAIN

UNIVERSITÀ DELLA CALABRIA

Astrophysical context



EHT Collaboration 2019, 2022

- How and where are the relativistic particles accelerated?
- How and where is the magnetic energy dissipated?
- What is the ratio of temperature between species?
- What is the role of positrons and/or protons?
- …

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Our numerical approach:

➡ GRPIC kinetic simulations;

➡ 3+1 spacetime decomposition $(\alpha, \beta^i, \gamma_{ij})$;

➡ Axisymmetric and stationary spacetime.

Particle equations of motion

$$\frac{1}{c}\frac{dx^i}{dt} = \frac{\alpha}{\Gamma}\gamma^{ij}u_j - \beta^i$$

$$\frac{1}{c}\frac{du_i}{dt} = \mathcal{O}_{Metric} + \mathcal{O}_{Lorentz}$$

Maxwell equations

$$\frac{\partial B^i}{\partial t} = -c\left(\nabla \times \boldsymbol{E}\right)^i$$

$$\frac{\partial D^i}{\partial t} = c\left(\nabla \times \boldsymbol{H}\right)^i - 4\pi J^i$$

the Frankfurt Particle-In-Cell code for stationary and axisymmetric black-hole spacetimes

Meringolo2025+ ApJL 992 (1) L8

Meringolo & Rezzolla 2026 ASCOM 101154

Imbrogno2026+ (in Prep.)

Abdulkhamidov2026+ (in Prep.)

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Particles four-velocities

Maxwell equations

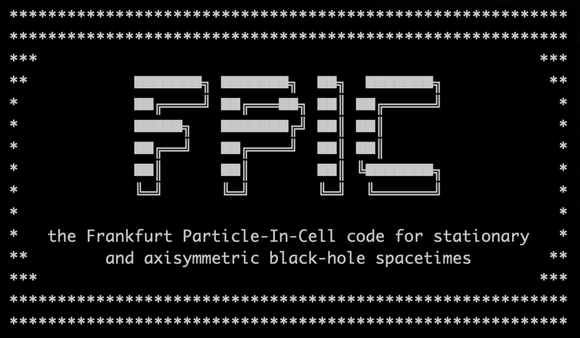
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Fields as measured by FIDOs (fiducial observers)

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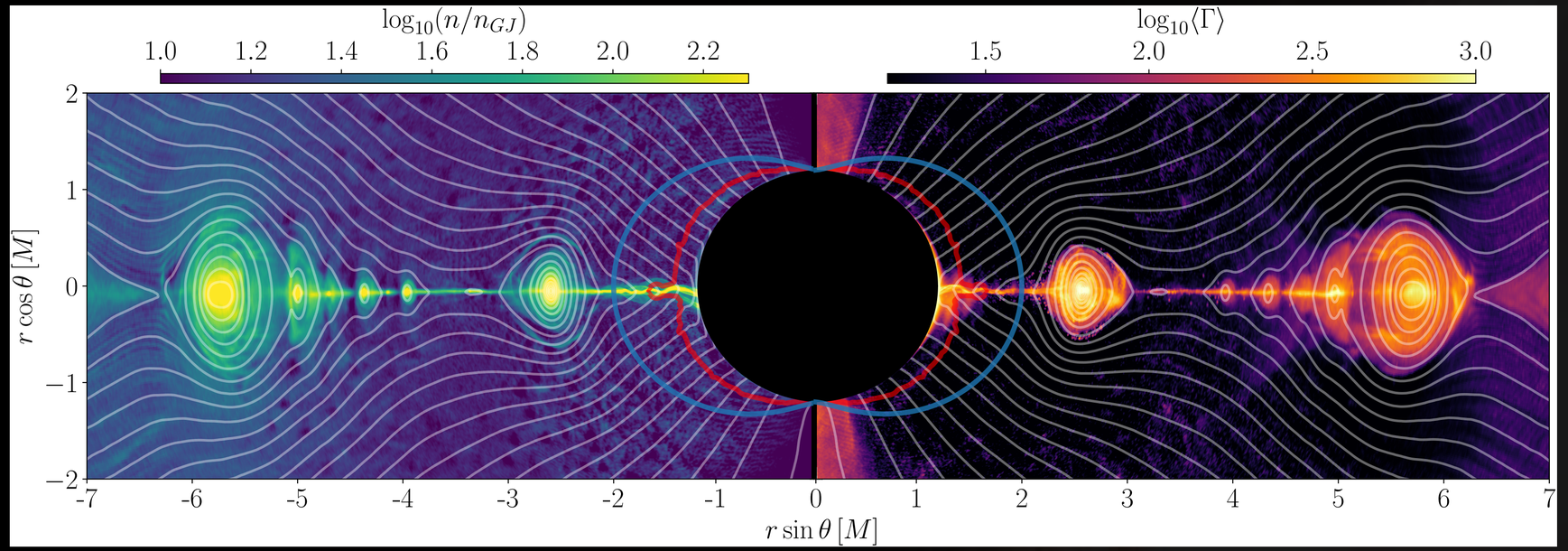
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PIC simulations in non-flat spacetimes

Particles number density

Cell-averaged Lorentz factor



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Magnetic IC: split monopole

12 different spins: $a_* \in \{0.1, 0.999\}$

Kerr-Schild coordinates

Pair plasma injection

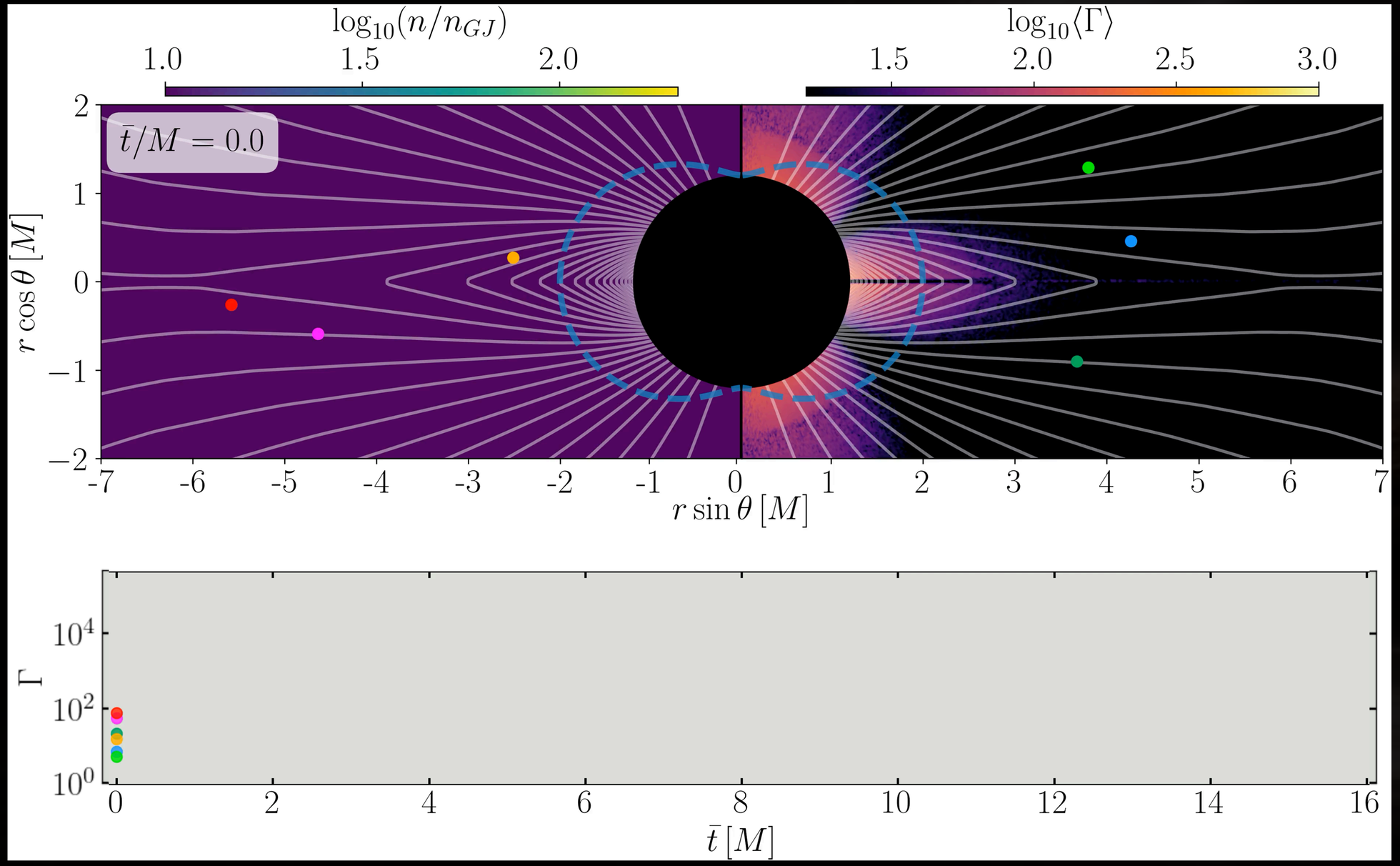
We are in force-free regime:

$$\left[\sigma := \frac{B^2}{4\pi nm}\right] \gg 1$$

$$\left[n_{GJ} := \frac{\Omega_h B_0}{4\pi ce}\right] \ll n$$

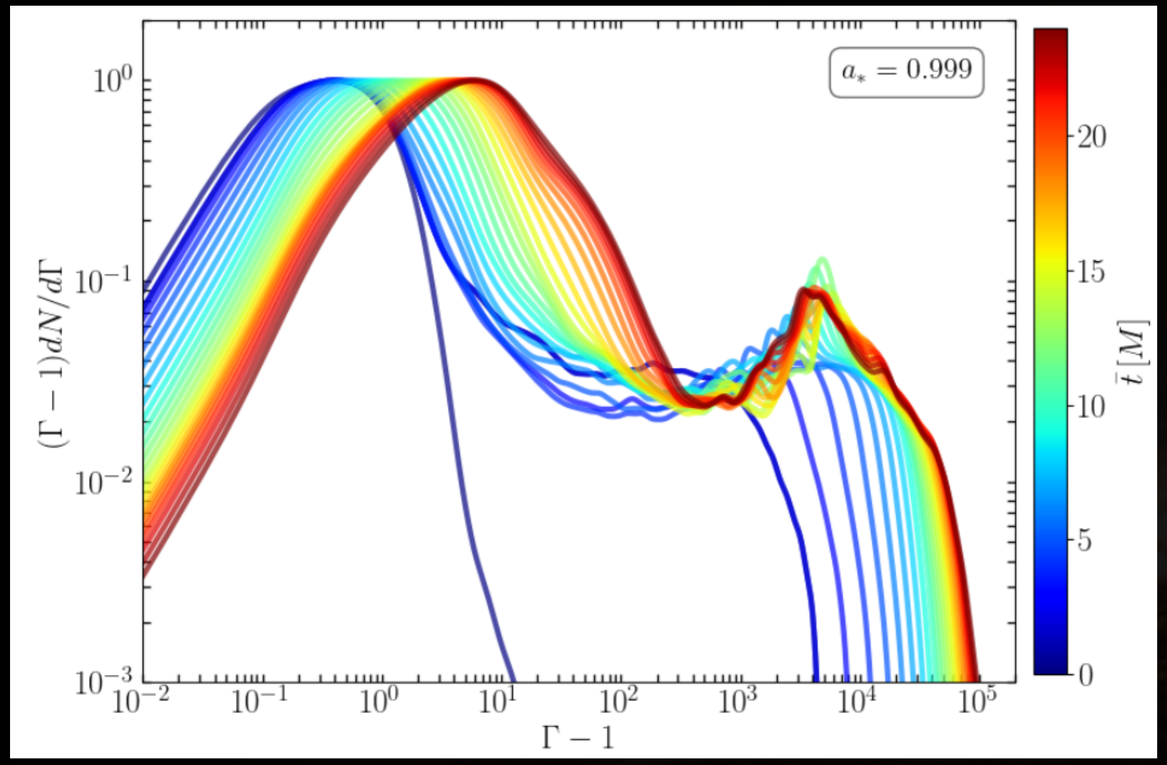
- A current sheet develops at the equatorial plane, where magnetic reconnection takes place;
- A chain of plasmoids forms in the layer. They merge, forming big structures in a stationary regime;
- Magnetic reconnection is the main responsible for particles acceleration, which acquire high Lorentz factors inside plasmoids.

PIC simulations in non-flat spacetimes



Particles energy spectra

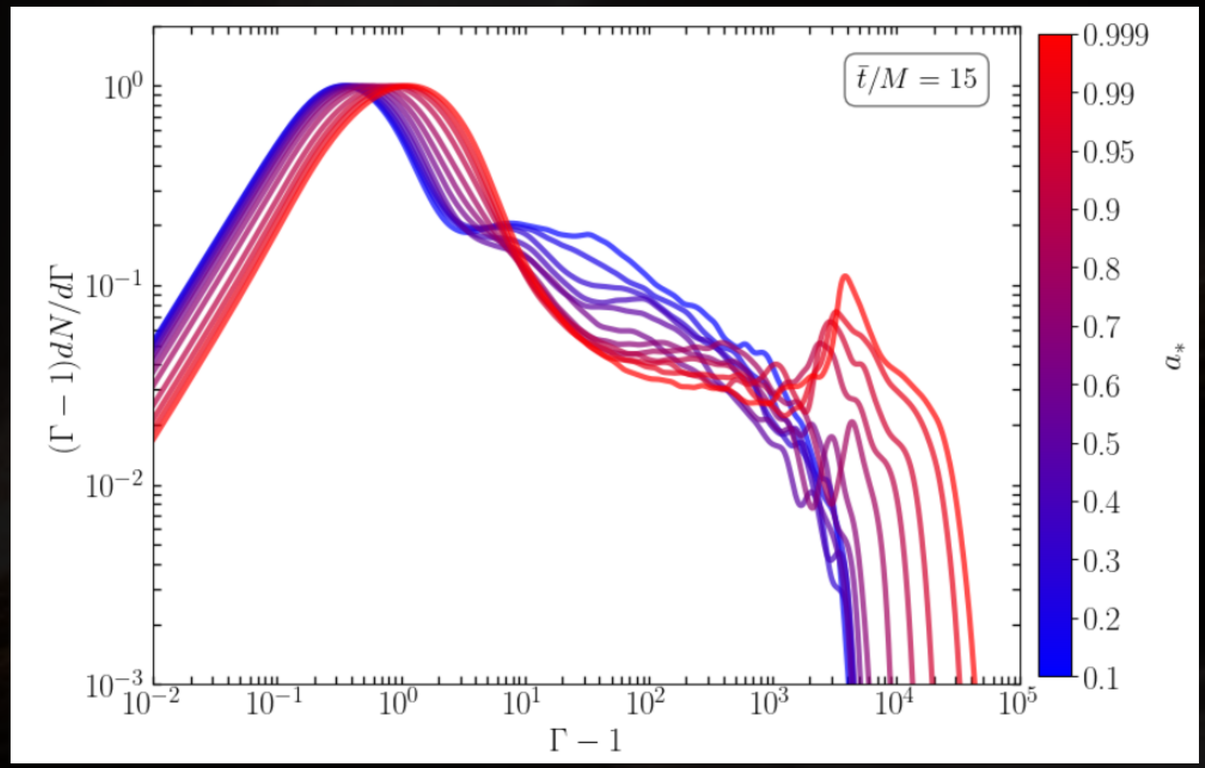
Time evolution of energy spectra (fixed spin)



Thermal particles

Non-thermal particles

Energy spectra for different spins (fixed time)

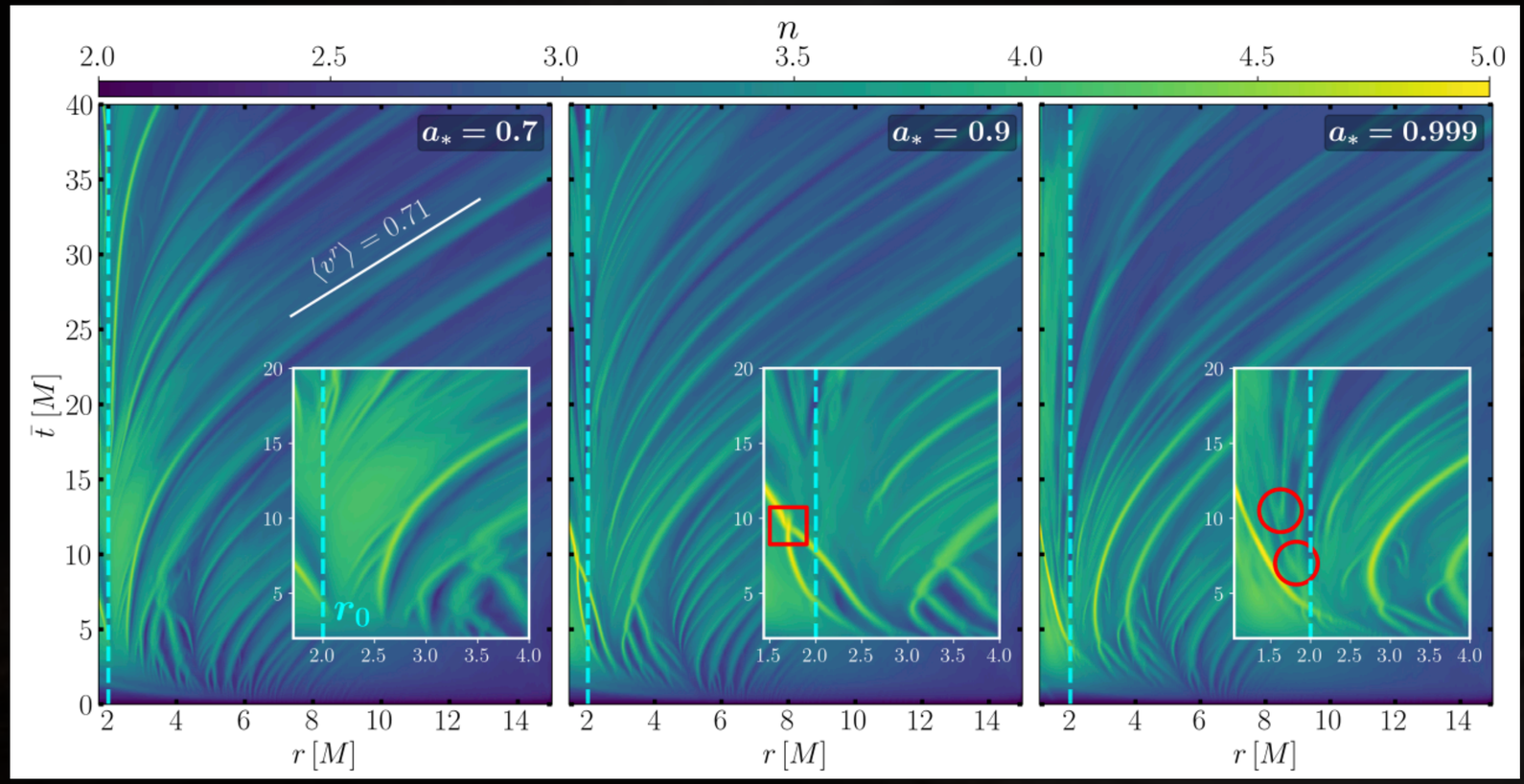


High-energetic particles increase with increasing spin

Plasmoids dynamics

- Spacetime diagram shows the genesis of plasmoids at the equatorial plane and their evolution;
- In general, plasmoids formed inside the ergoregion move toward the event horizon and fall into the BH with a relatively small radial velocity;
- Those born outside are ejected from the magnetosphere and accelerated to relativistic velocities, up to $\langle v^r \rangle \sim 0.7$

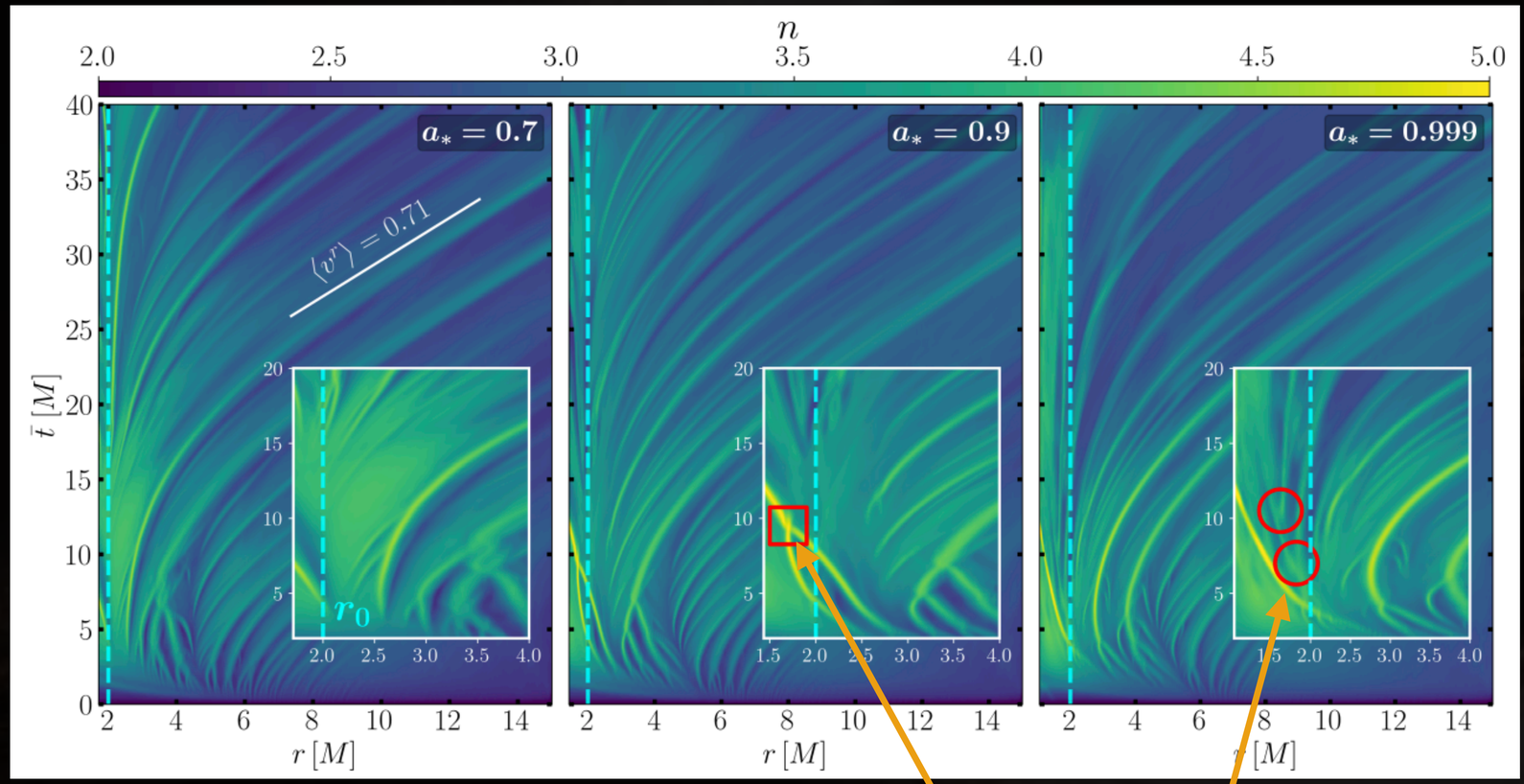
Spacetime diagram of the number density



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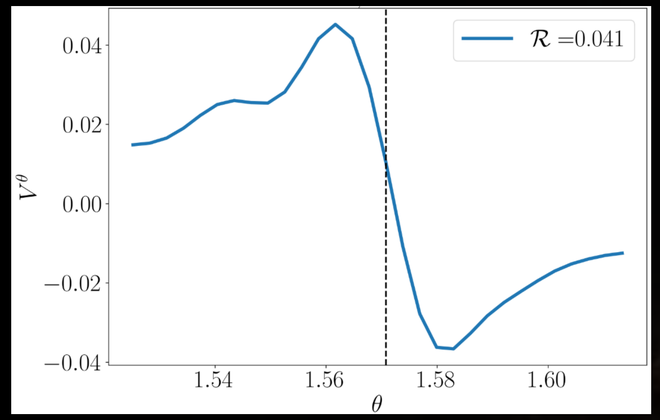


Inside the ergosphere, plasmoids can collide or split

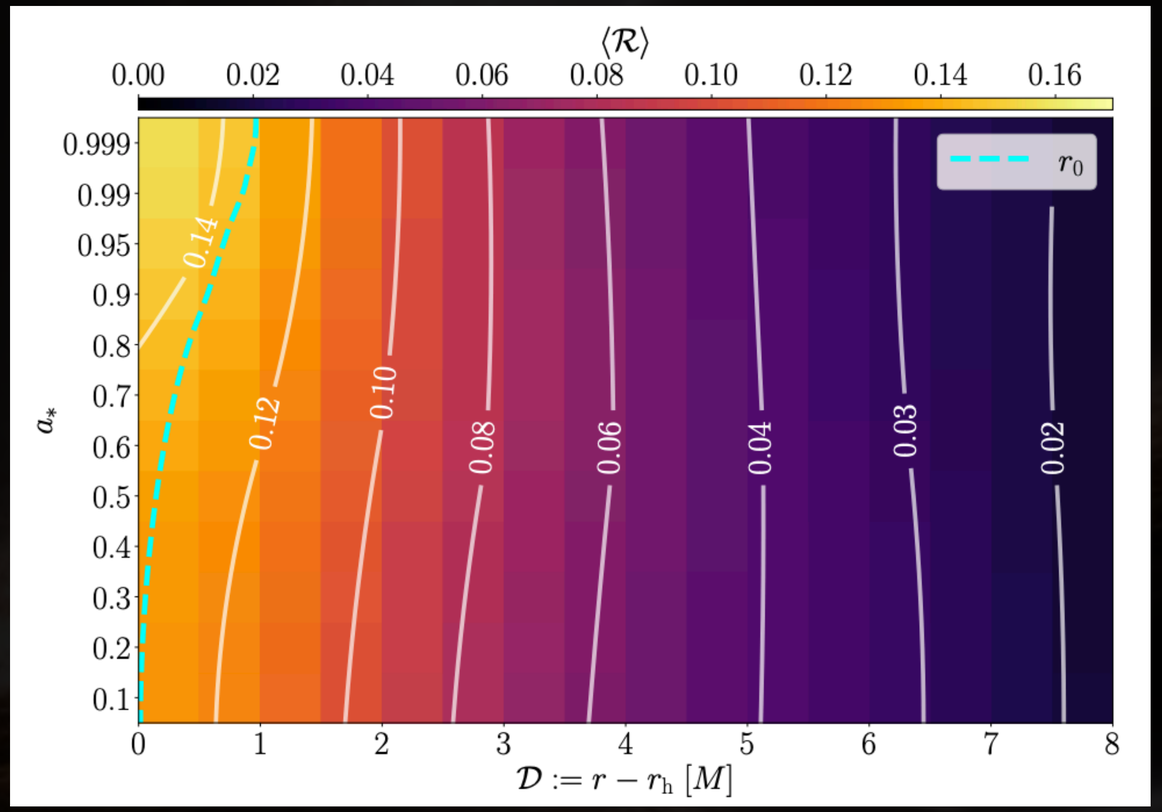
Reconnection rate in curved spacetimes: v1

We define the magnetic reconnection rate as the "jump" in the polar drift velocity across the current sheet at the X-point:

$$\begin{cases} \mathcal{R} := \frac{1}{2}\Delta V^{\theta} \\ V^{i} := \sqrt{\gamma}\,\eta^{ijk}\,D_j B_k / B^2 \end{cases}$$



Averaged reconnection rate



Meringolo et al. 2025 ApJL 992, L8

- The majority of the reconnection events take place near the BH and increase as a function of the spin;
- For any spin, the largest rate is always attained in the ergosphere (marked with a cyan dashed line);
- It reaches a maximum value of ~ 0.15 for the maximally spinning BH considered with $a_* = 0.999$.

Generalized Ohm's law in curved spacetimes

PRELIMINARY RESULTS!

Starting from the moments of the distribution function for each species "s",
we derive a kinetic general-relativistic Ohm's law:

$$D^j = -\sum_s \left[\frac{1}{N}\eta_{ilk}\,\gamma^{ij}\,\boldsymbol{V}_s^l\,\boldsymbol{B}^k\right] + \sum_s \left[\frac{q_s}{m_s N}\nabla_0 \boldsymbol{\Pi}_s^{0j}\right] + \sum_s \left[\frac{q_s}{m_s N}\nabla_i \boldsymbol{\Pi}_s^{ij}\right]$$

"Ideal" $D^j_{\boldsymbol{V}\times\boldsymbol{B}}$ — "Non-ideal" $D^j_{\nabla\cdot\boldsymbol{\Pi}}$

The evolved electric field $\tilde{D}^j$ can be totally reconstructed from the moments:

$$\tilde{D}^j \simeq D^j_{\boldsymbol{V}\times\boldsymbol{B}} + D^j_{\nabla\cdot\boldsymbol{\Pi}}$$

Pressure tensor $\boldsymbol{\Pi}_s^{\mu\nu} := \int p_s^\mu\, p_s^\nu\, f_s \frac{d^3p}{\sqrt{\gamma}}$

Weighted current density $V^j := \frac{q_s^2}{m_s}\int p_s^j\, f_s \frac{d^3p}{\sqrt{\gamma}}$

Weighted number density $N := \frac{q_s^2}{m_s}\int \frac{f_s\, u_s^0}{\Gamma}\frac{d^3p}{\sqrt{\gamma}}$

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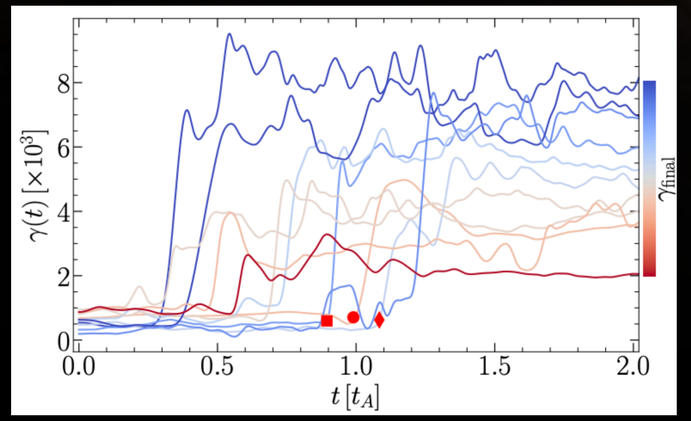
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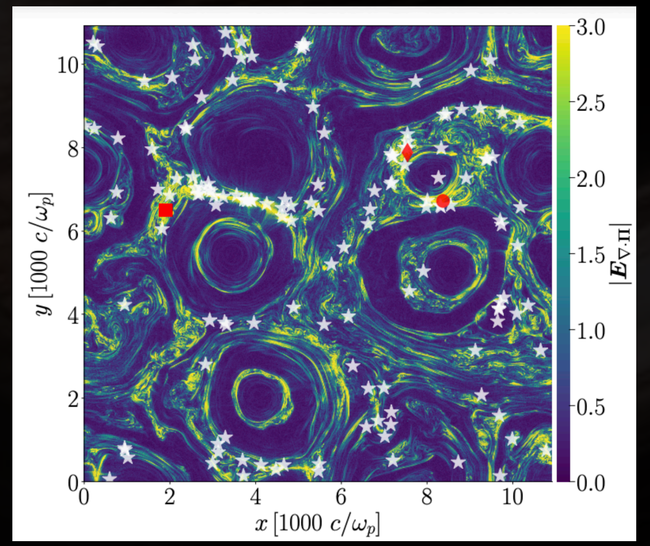
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As in flat-spacetime PIC simulations, this electric field is the responsible for particle accelerations





Meringolo et al. 2026 PRD Letters (in Press)

Reconnection rate in curved spacetimes: v2

PRELIMINARY RESULTS!

An equivalent definition of reconnection rate used in plasma community is

$$\mathscr{R} := \frac{|D^{\varphi}_{\rm tot}|_{\rm XP}}{\langle B_{\rm up}\rangle_{\rm rms}}$$

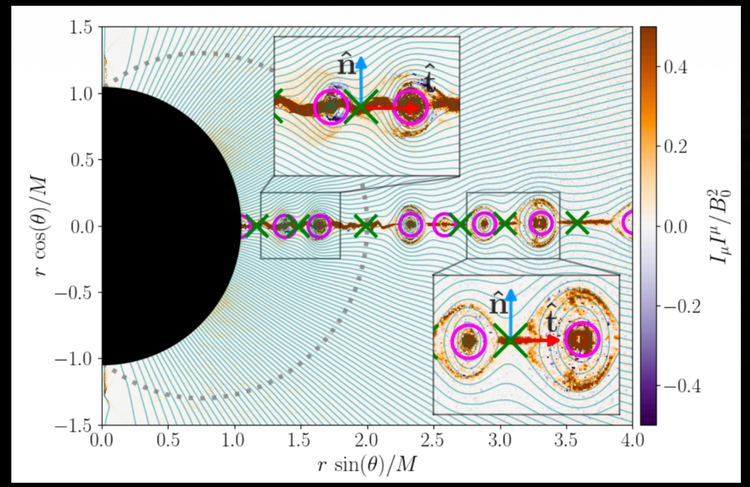
Meringolo et al. 2026
In Progress

$D^{\varphi}_{\rm XP}$ is the reconnecting electric field at the X-points

$\langle B_{\rm up}\rangle_{\rm rms} := \langle\sqrt{\gamma_{rr}(B^r)^2 + \gamma_{\theta\theta}(B^\theta)^2}\rangle_{\rm rms}$ is the magnetic field around the X-point

To find the X-points and O-points:

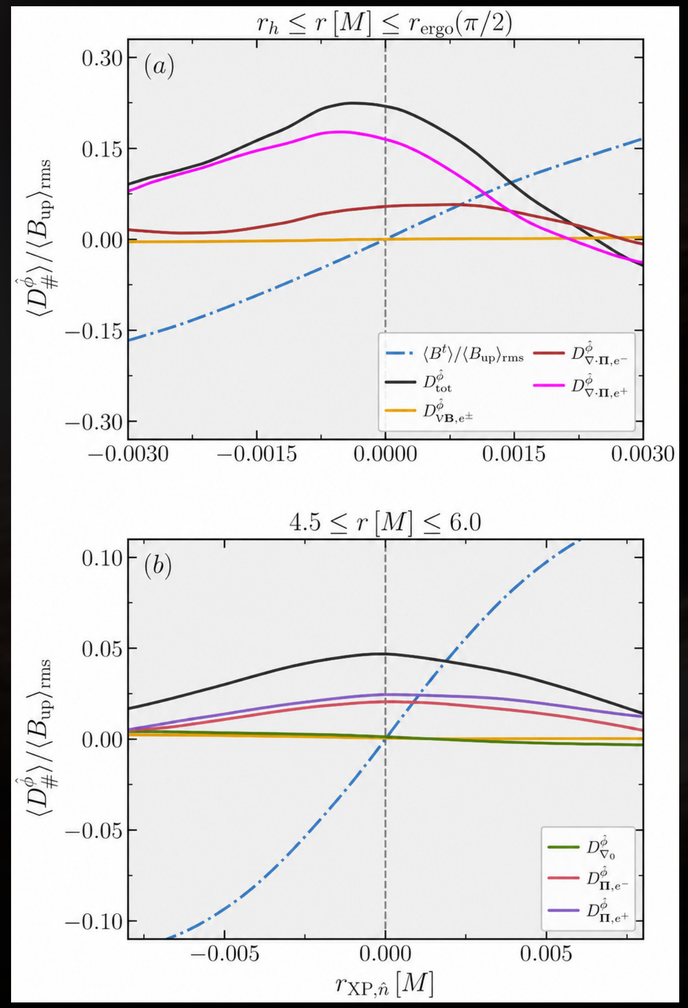
$$\begin{cases} B^r = 0 \\ B^\theta = 0 \\ \det(H^\mu_\nu) \end{cases} \begin{cases} < 0 : \text{X-point} \\ > 0 : \text{O-point} \end{cases}$$



Hessian matrix $H^\mu_\nu := \gamma^{\mu\sigma} D_\sigma D_\nu A_\phi$

Covariant derivative

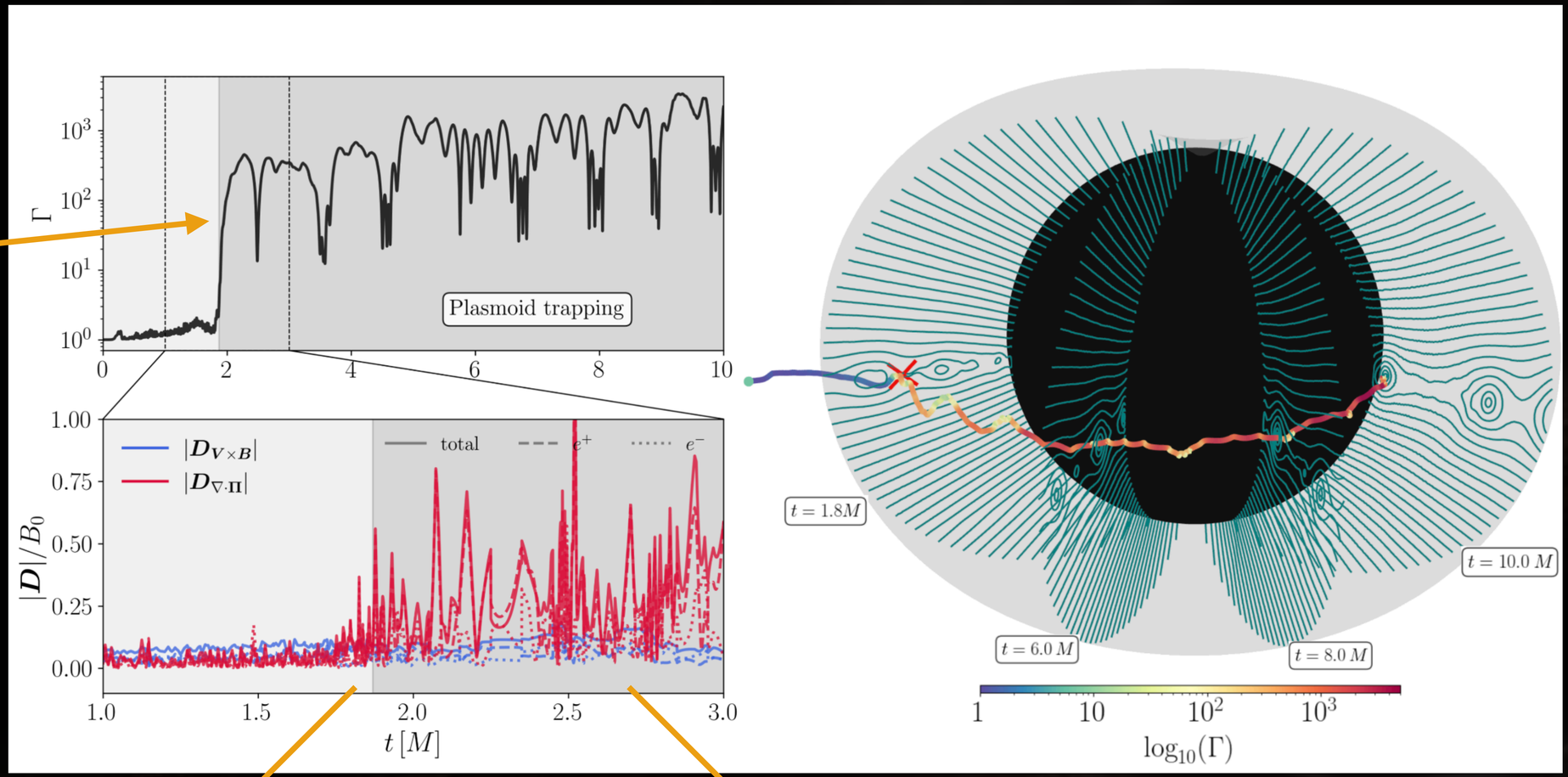
Vector potential



Particle acceleration

PRELIMINARY RESULTS!

Inside the ergosphere, particles can experience strong acceleration, and a sudden increase in Lorentz factor



- At t~1.8 M the particle crosses an X-point where magnetic reconnection takes place.
- Here the non-ideal electric field (red) dominates over the ideal one (blue)

- Following the initial sudden acceleration, the particle remains trapped within the plasmoid, gaining further energy through second-order Fermi-like processes before falling into the black hole.

Blandford-Znajek mechanism

$P_{BZ} = \int (T^r_0)_{\rm EM} \sqrt{-g}\, d\theta\, d\phi$ is the Blandford-Znajek luminosity, and can be generically expressed as:

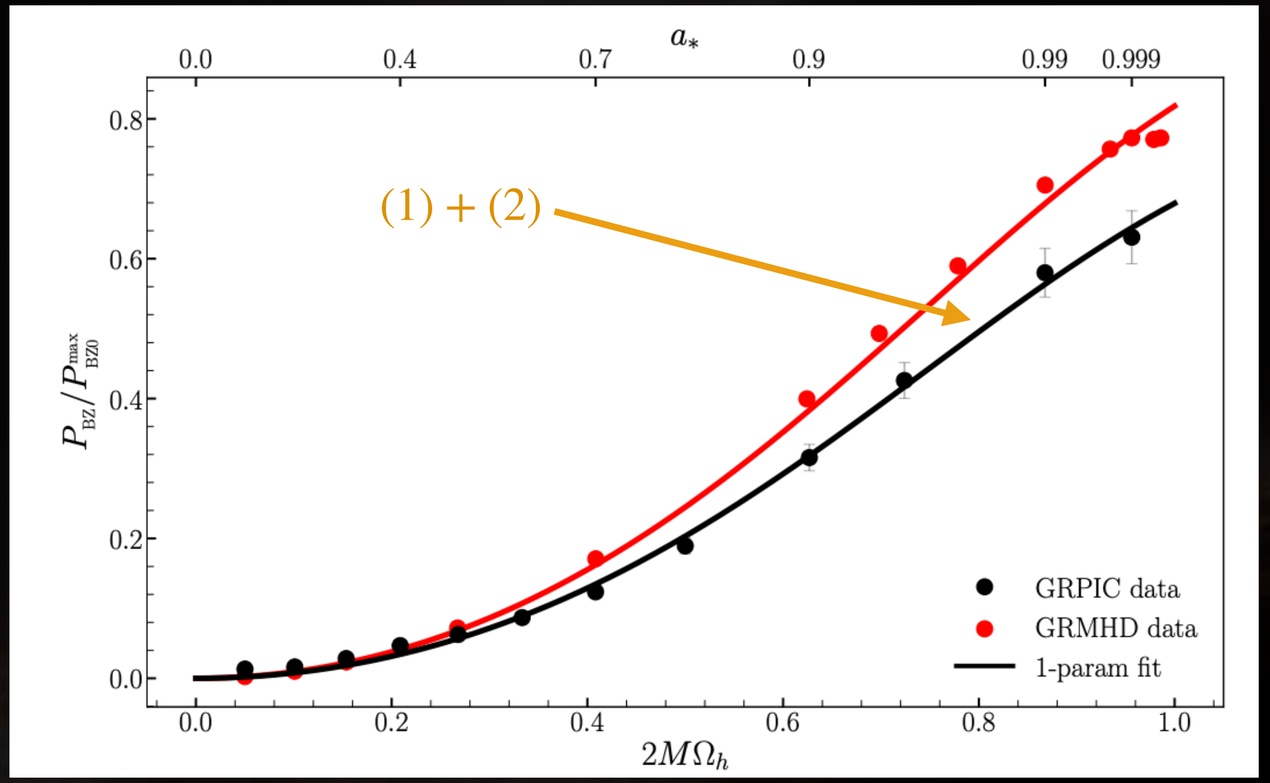
$$P_{BZ} = \frac{k}{4\pi} \Phi_h^2 F(\Omega_h) \quad (1)$$

Magnetic flux

$$\Phi_h = \int |B^r| \sqrt{-g}\, d\theta\, d\phi$$

Angular velocity

$$\Omega_h = \frac{2a_*}{1 + \sqrt{1 - a_*^2}}$$



Meringolo et al. 2025 ApJL 992, L8

Combining analytic techniques and perturbation theory one gets:

$$F_{\rm analytic}(\Omega_h) = \Omega_h^2 \left[1 + \tilde{\alpha}(M\Omega_h)^2) + \tilde{\beta}(M\Omega_h)^4 + \tilde{\gamma}\,|M\Omega_h|^5 + (\tilde{\delta} + \tilde{\epsilon}\log|M\Omega_h|)(M\Omega_h)^6\right] + \mathcal{O}(M^9\Omega_h^9) \quad (2)$$

GRPIC and GRMHD results are compatible with analytic predictions and can be rescaled via a single coefficient.

Recap and take-home message

- We presented fully-kinetic GRPIC simulations by using the FPIC code, modeling relativistic plasmas in a stationary and axisymmetric spacetime described by the Kerr metric;

- We computed the reconnection rate by using different approaches obtaining consistent results. We expressed reconnection in terms of the BH spin and the distance from the event horizon;

- Inside the ergoregion, negative-energy particles can be created and accreted, leading to the Penrose-process;

- The measured Blandford-Znajek power shows excellent agreement with the high-order predictions coming from perturbation theory, and GRMHD simulations

- We propose a generalized kinetic Ohm's law for electric fields in curved spacetimes. The non-ideal term is strong at the X-point where reconnection takes place, driving particle acceleration.

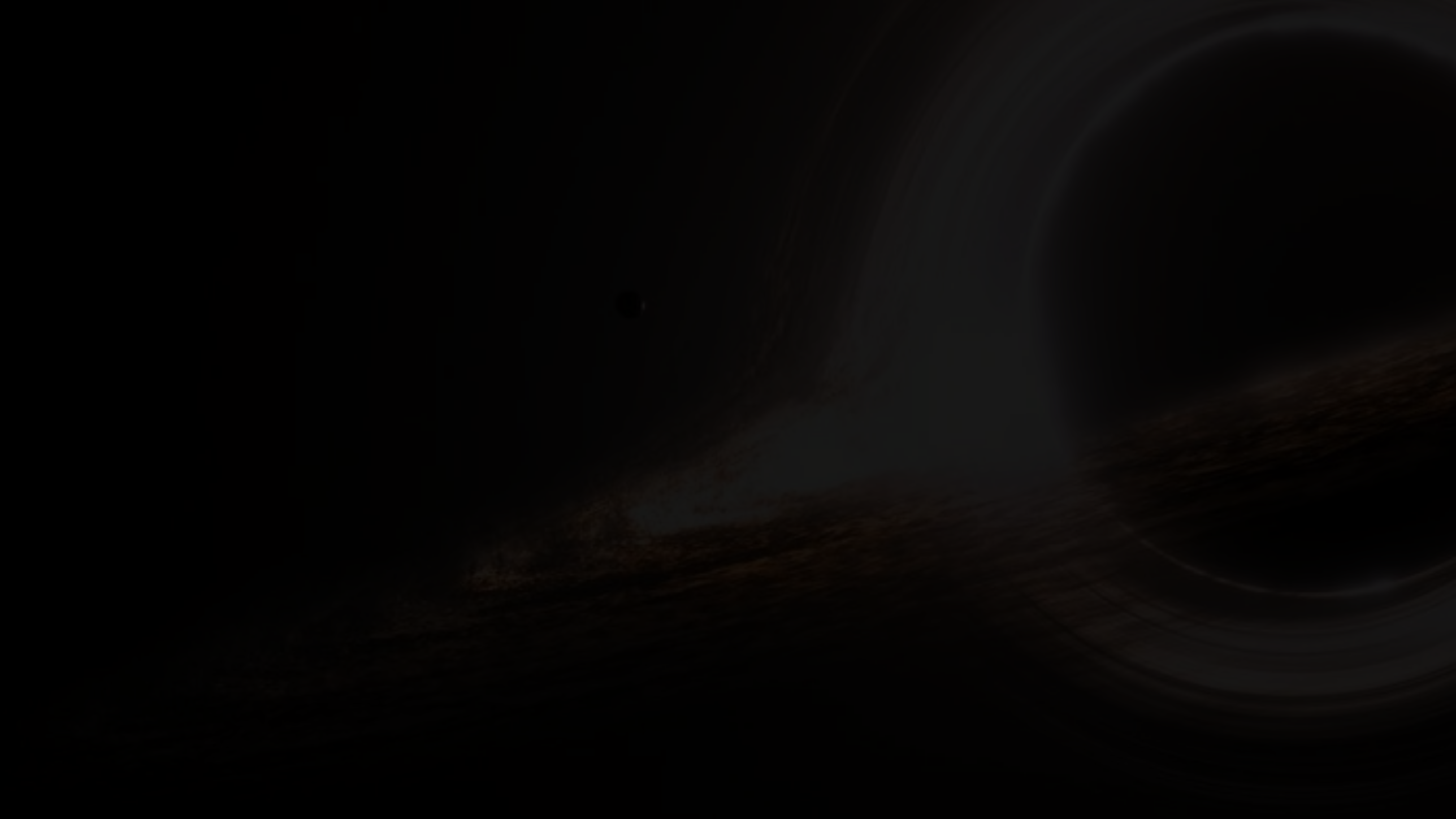
In astrophysics, kinetic models have the potential to answer the most fundamental theoretical questions:

- Magnetic reconnection and energy conversion;
- Dissipation of turbulence at kinetic scales;
- Particle acceleration mechanisms;
- Multi-species plasma modelling;
- …

Thanks for your attention!



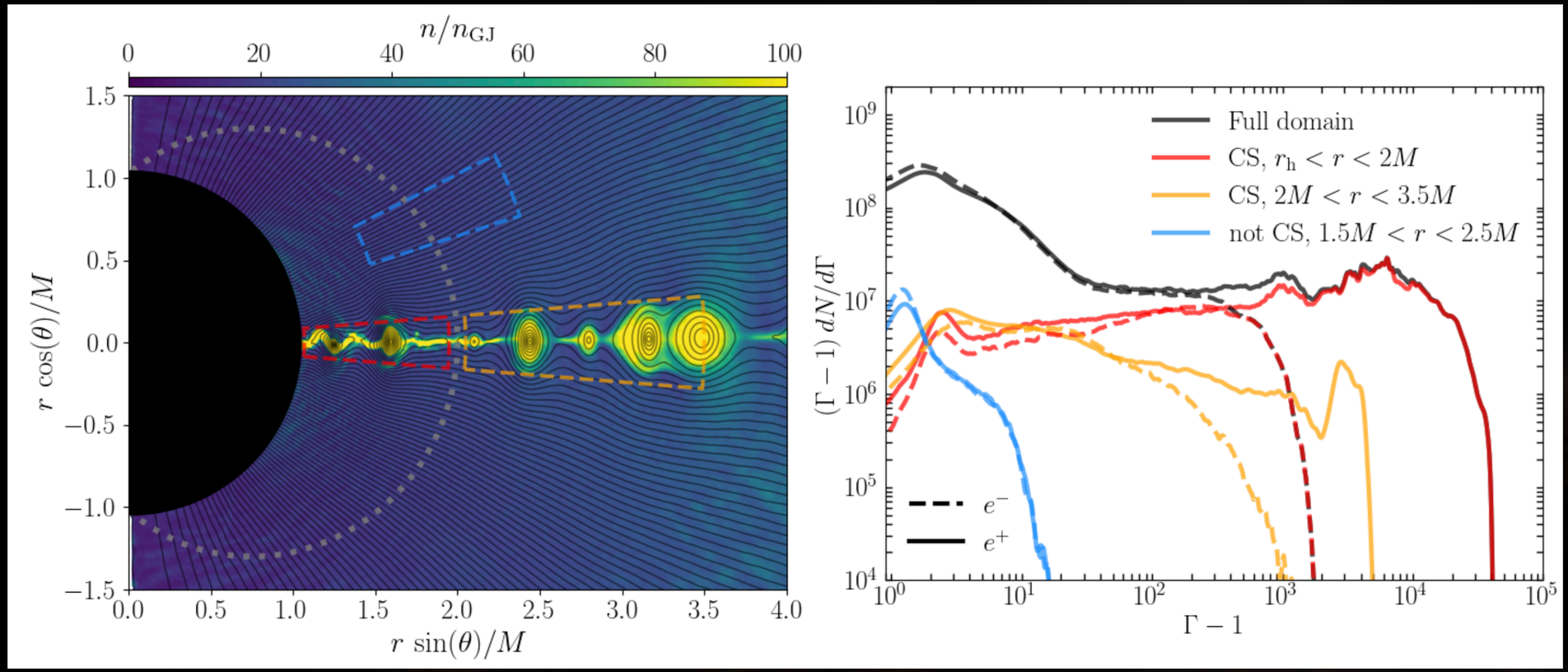
Turbulent Starry Night



Particles energy spectra

EXTRA SLIDE

$$a_* = 0.999$$

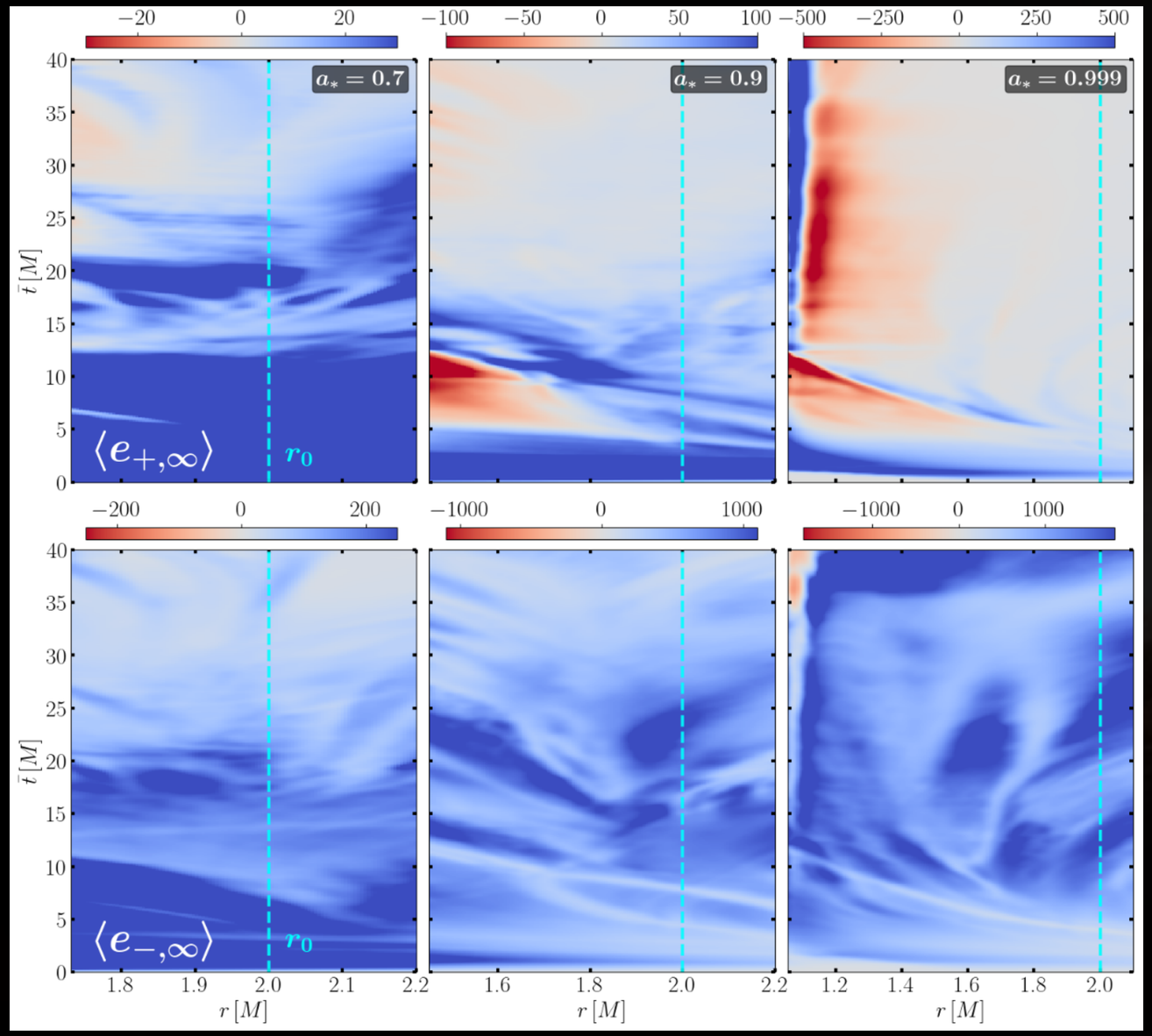


Magnetic reconnection is the primary source of non thermal particles, and most energetic ones are located inside the current sheet;

Inside the ergo-regions along the current sheet, the acceleration is the highest, thanks to a nonlinear combination of reconnection and strong gravity.

Energy at infinity for particles

EXTRA SLIDE



Inside the ergosphere particles can show negative energy at infinity $e_\infty < 0$, where:

$$e_\infty := \alpha\sqrt{1 + \gamma^{ij} u_i u_j} - \beta^r u_r$$

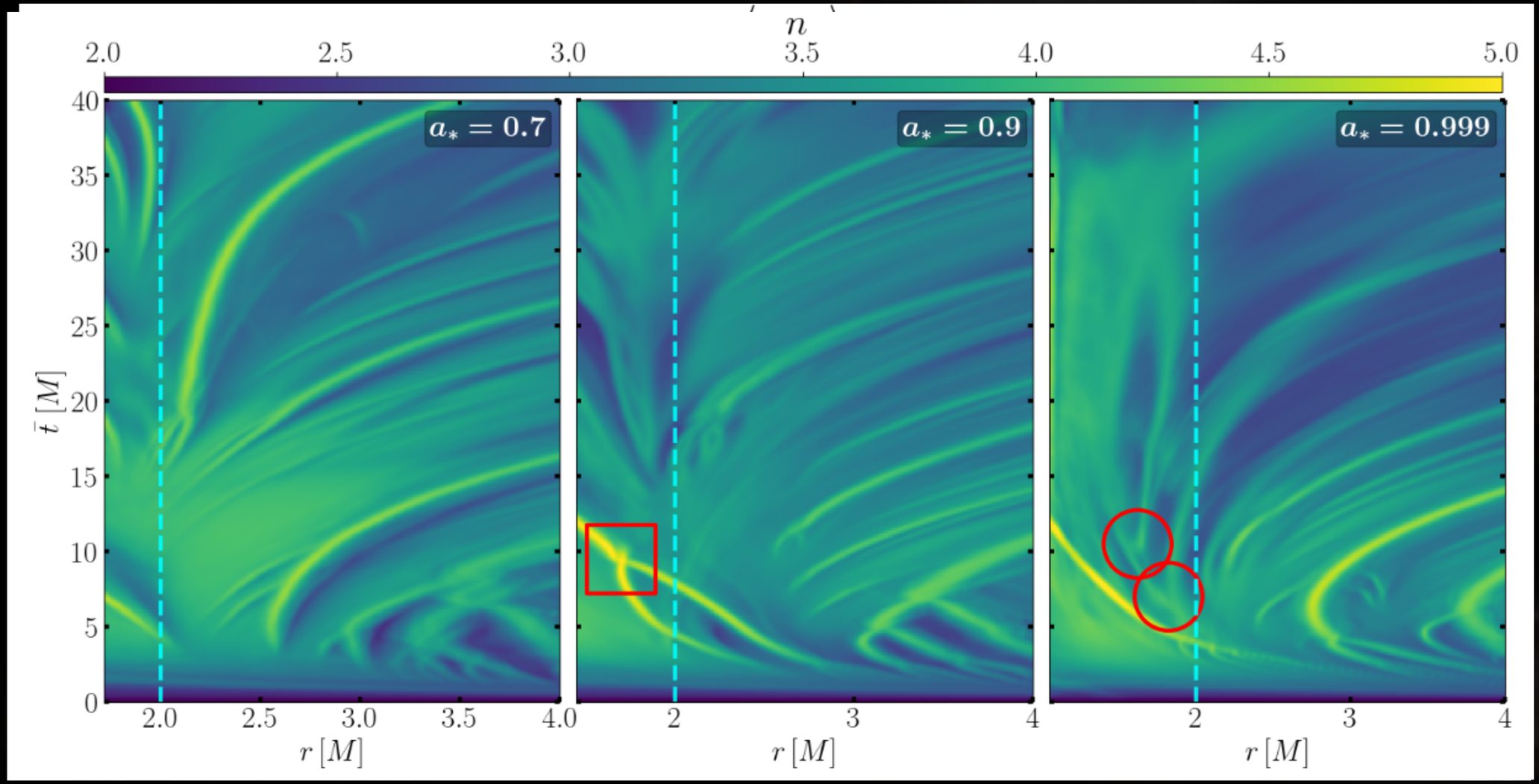
We define cell-averages as:

$$\langle e_\infty \rangle(\boldsymbol{x}, t) := \frac{\int f(\boldsymbol{x}, \boldsymbol{v}, t)\, e_\infty\, d^3v}{\int f(\boldsymbol{x}, \boldsymbol{v}, t)\, d^3v} \simeq \frac{\sum_k w_k\, e_{\infty,k}}{\sum_k w_k}$$

When particles with negative energy cross the horizon, the Penrose process is active, extracting energy from the black hole.

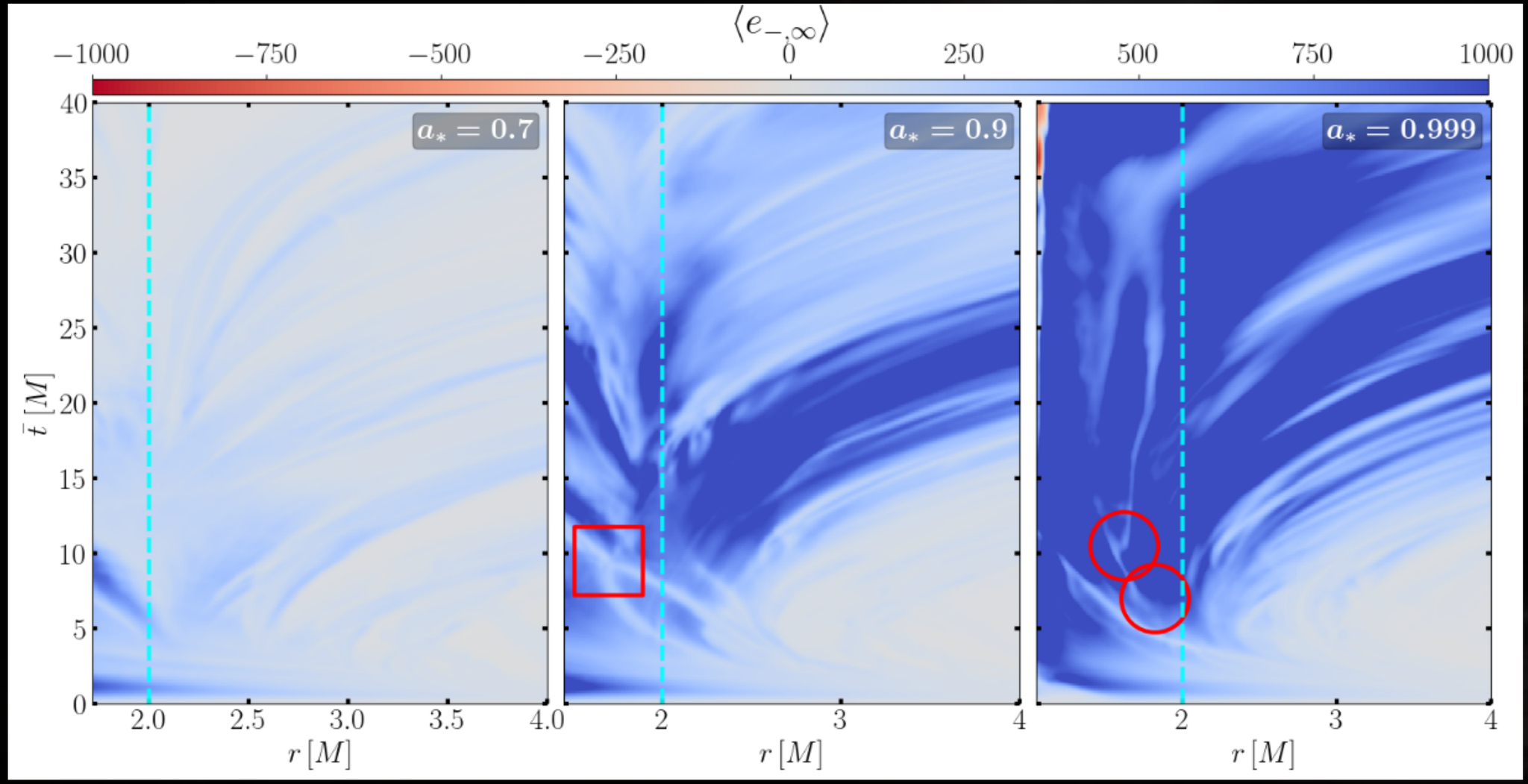
Plasmoids dynamics

EXTRA SLIDE



Plasmoids dynamics

EXTRA SLIDE

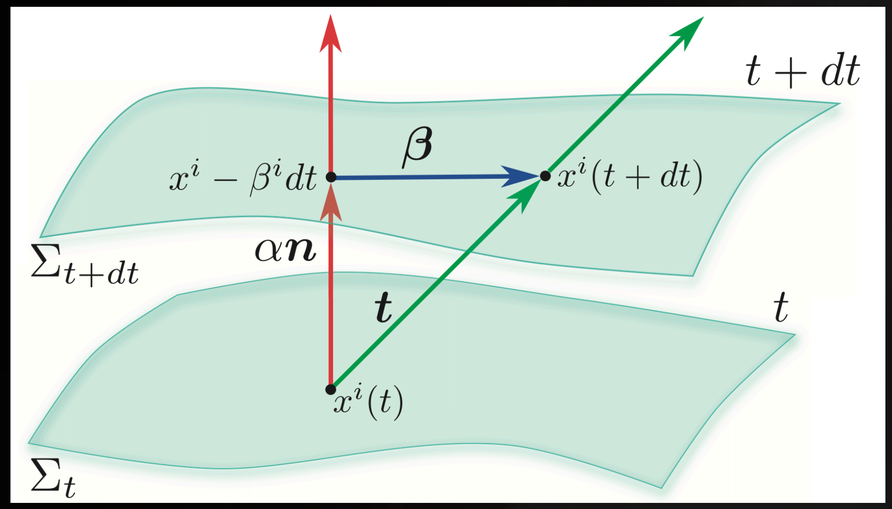


GRPIC approach

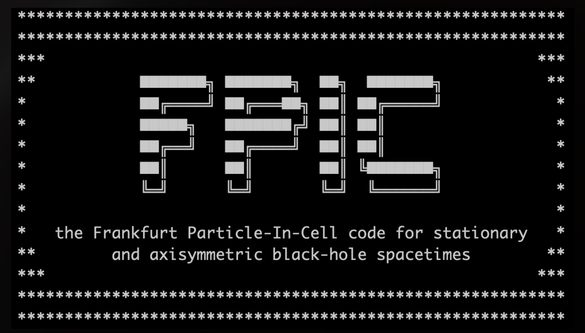
EXTRA SLIDE

We adopt the 3+1 formalism

- spatial metric: γ_{ij}
- lapse function: α
- shift vector: β^i



Credits: Rezzolla, Zanotti, Relativistic Hydrodynamics



Meringolo25+ ApJL, 992 (1) L8

Meringolo & Rezzolla 26, ASCOM, 101154

Imbrogno+ (in Prep.)

Abdulkhamidov+ (in Prep.)

Maxwell equations

$$\begin{cases} \partial_t B^i = -\underbrace{\dfrac{1}{\sqrt{\gamma}}\eta^{ijk}\partial_j\left[\alpha D_k + \sqrt{\gamma}\,\eta_{klm}\beta^l B^m\right]}_{\nabla\times \boldsymbol{E}} \\ \partial_t D^i = \underbrace{\dfrac{1}{\sqrt{\gamma}}\eta^{ijk}\partial_j\left[\alpha B_k - \sqrt{\gamma}\,\eta_{klm}\beta^l D^m\right]}_{\nabla\times \boldsymbol{H}} - 4\pi\left[\alpha j^i - \rho\beta^i\right] \\ 4\pi\rho = \dfrac{1}{\sqrt{\gamma}}\partial_j\left(\sqrt{\gamma}D^j\right) \\ 0 = \dfrac{1}{\sqrt{\gamma}}\partial_j\left(\sqrt{\gamma}B^j\right) \end{cases}$$

Particle equations of motions

$$\begin{cases} \dfrac{1}{c}\dfrac{dx^i}{dt} = v^i = \dfrac{\alpha}{\Gamma}\gamma^{ij}u_j - \beta^i \\ \dfrac{1}{c}\dfrac{du_i}{dt} = \underbrace{-\Gamma\partial_i\alpha + u_j\partial_i\beta^j - \dfrac{\alpha}{2\Gamma}u_l u_m\partial_i\gamma^{lm}}_{\mathcal{O}^g} + \underbrace{\dfrac{q\alpha}{mc^2}\left(\gamma_{ij}D^j + \dfrac{\sqrt{\gamma}\eta_{ijk}\gamma^{jl}u_l B^k}{\Gamma}\right)}_{\mathcal{O}^{\rm em}} \end{cases}$$

B^i, D^i are fields as measured by FIDOs (fiducial observers) with 4-velocity orthogonal to the hypersurface of constant time, i.e., $n_\mu \gamma^{\mu\nu} = 0$