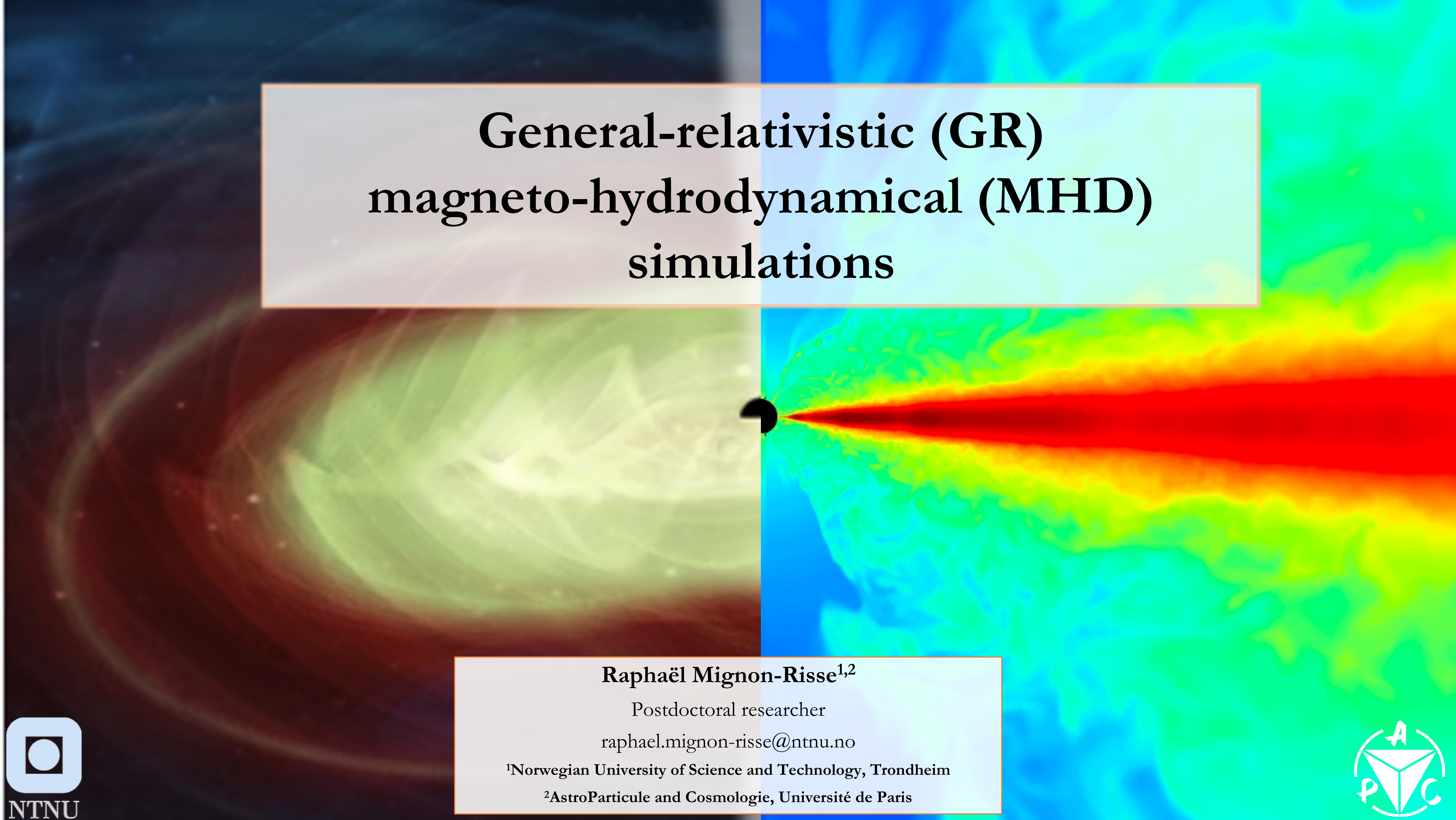

General-relativistic (GR) magneto-hydrodynamical (MHD) simulations

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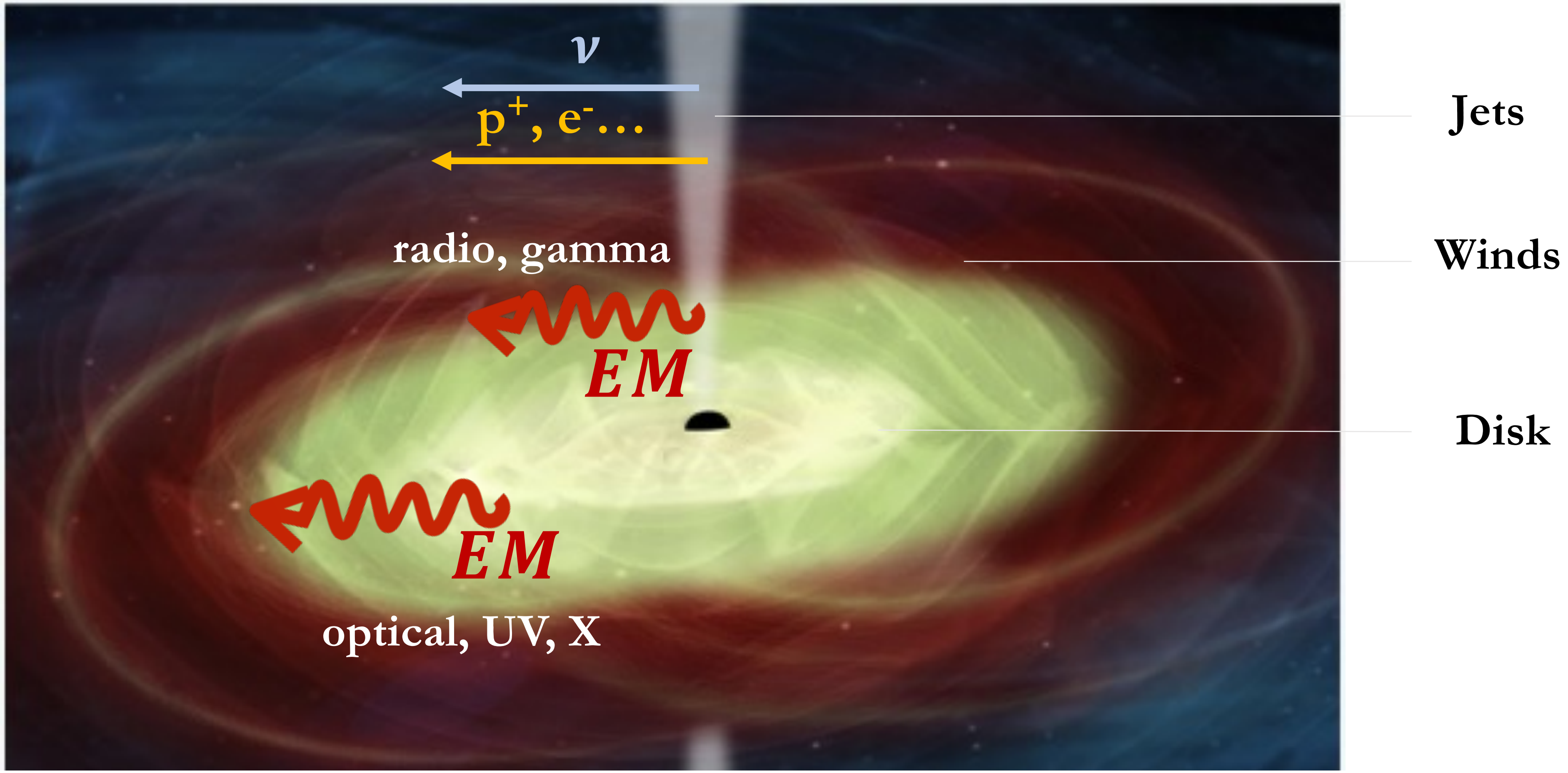
NTNU

The multi-messenger view of black holes



Impact of the BH of any of these structures and on their interplay, dynamics, variability
→ GR

Objective of this talk:

give you the relevant informations for those
willing to start using/collaborating on GRMHD simulations

What does a GRMHD code do? example with GR−AMRVAC

- **Assume a given black hole spacetime metric: « Schwarzschild » / « Kerr »**
- **In General Relativity, spacetime is 4D : go to 3+1 D**
- **Solve local conservation of the stress-energy tensor and matter current density:**

1. Mass, momentum (, energy) conservation with additional terms from the metric
2. Same form as in classical hydrodynamics !

- **What is GRMHD used for?**

General-relativistic Simulations of Four States of Accretion onto Millisecond Pulsars

First M87 Event Horizon Telescope Results. VIII. Magnetic Field Structure near The Event Horizon

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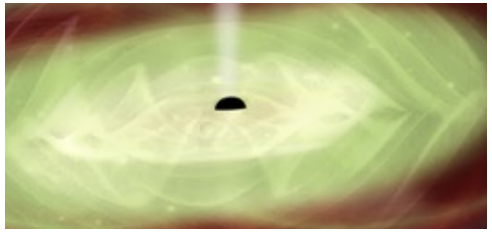
Jet Launching in Resistive GR-MHD Black Hole–Accretion Disk Systems

Beamed Emission from a Neutron-star ULX in a GRRMHD Simulation

RELATIVISTIC DYNAMICS AND MASS EXCHANGE IN BINARY BLACK HOLE MINI-DISKS

…

MHD is an approximation



- Standard approach to the BH accretion problem

- **Fluid approach:**
  - ➢ macroscopic behaviour : distances $\gtrsim R_S = 2\frac{GM}{c^2} \approx 3\ \frac{M}{M_\odot}$ km, timescales $\gtrsim R_S/c$,
  - ➢ maxwellian distribution of particles (= thermal equilibrium ← high collision rate)

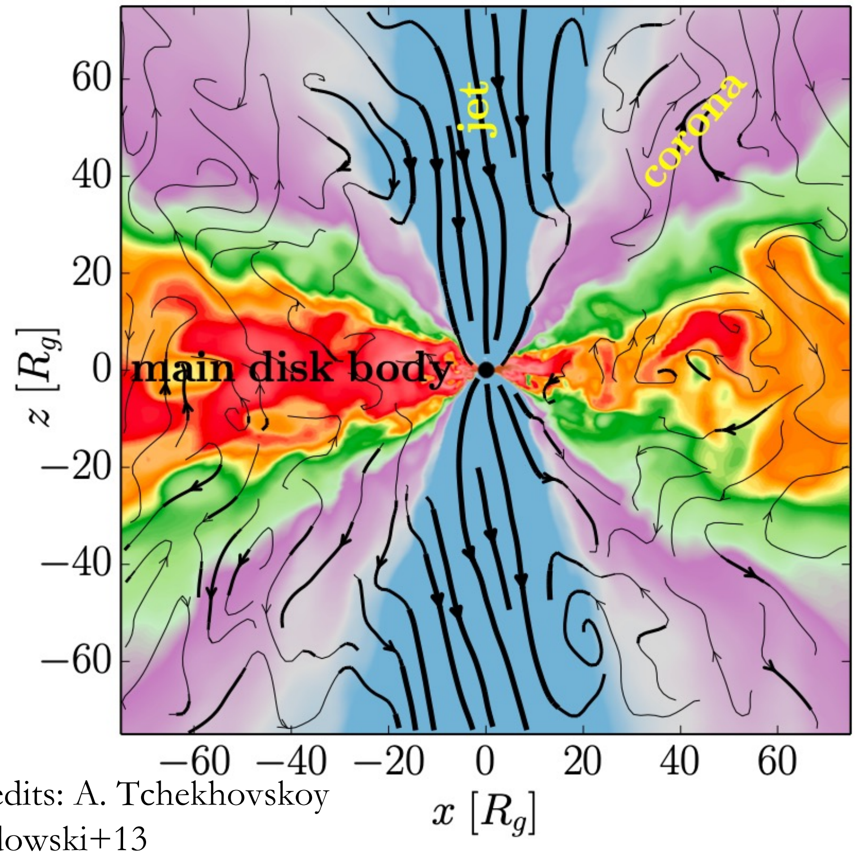
- **One-fluid model:**
  - ➢ If jet: composition (lepton pairs or hadrons) has no impact on the dynamics

- **ideal MHD:**
  - ➢ perfect coupling between fluid and magnetic fields
  - ➢ assume the plasma is fully ionized
  - ➢ reconnection only occurs through numerical errors

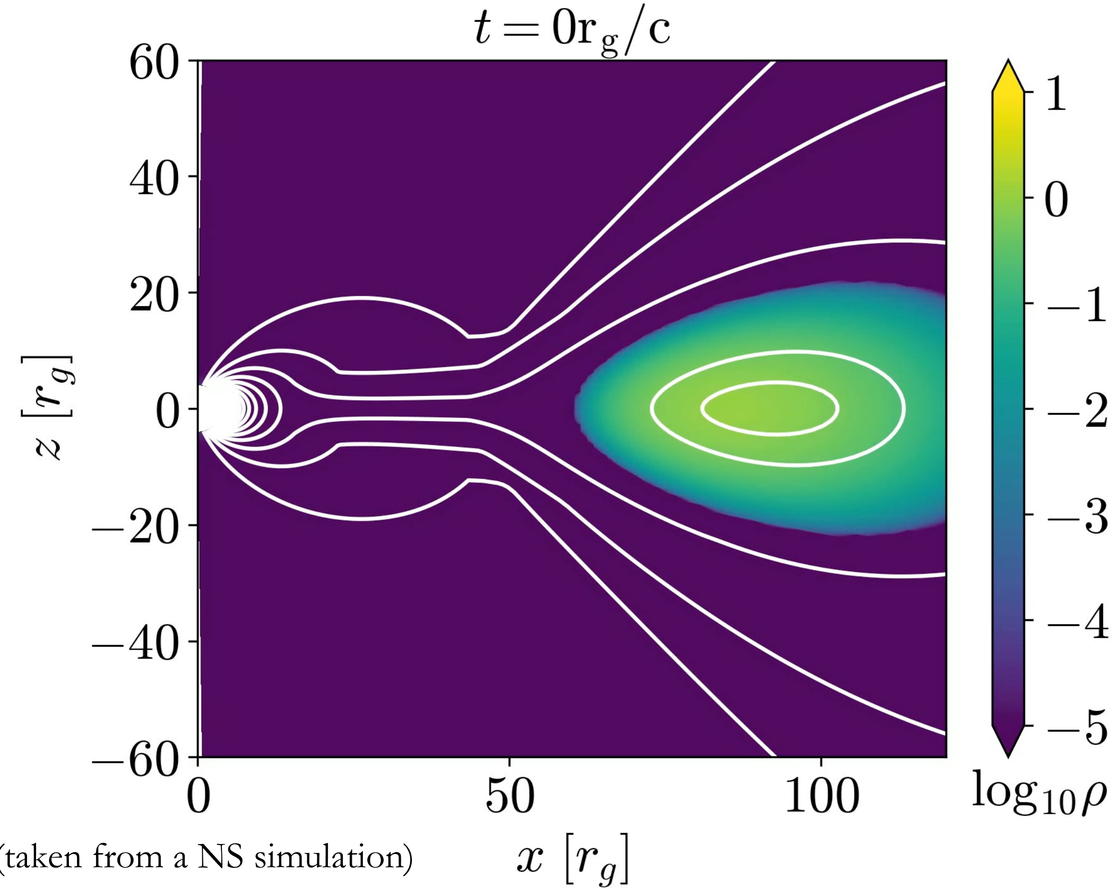
A standard setup: an MRI-unstable torus

- Initial torus in hydrostatic equilibrium, unstable to the magneto-rotational instability (Balbus & Hawley, 1991):
  - ➢ angular momentum transport via Maxwell (>) and Reynolds' stress
- Only exact & analytical setup for 3D GR simulations (Fishbone & Moncrief 1976)

- (constant angular momentum) torus ≠ equilibrium structure or a realistic disk /!\



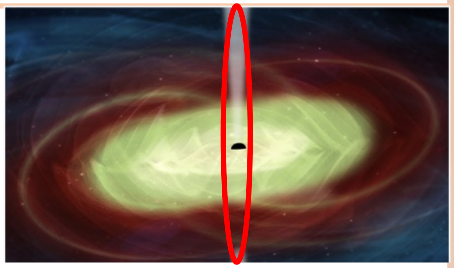
Credits: A. Tchekhovskoy
Sadowski+13

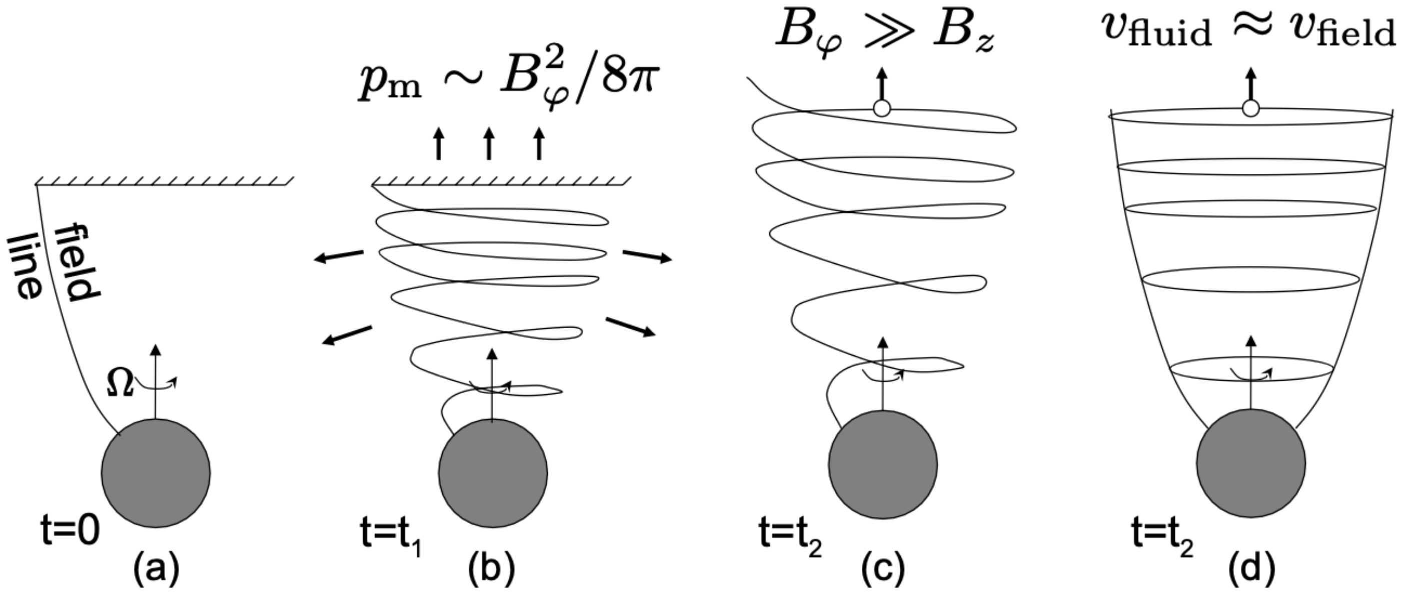


(taken from a NS simulation)

The Blandford-Znajek mechanism

- Only outflow mechanism proper to black holes
- Spinning black holes drag in rotation their spacetime and the magnetic field along with it





Credits: Tchekhovskoy+12

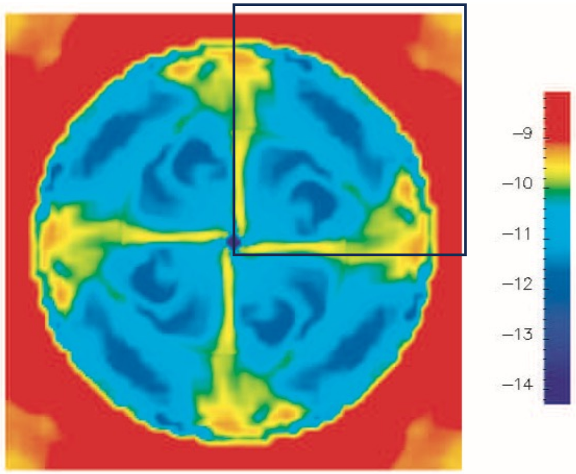
$$P_{jet} \approx 2.5 \left(\frac{a_*}{1+\sqrt{1-a_*^2}}\right)^2 \left(\frac{\Phi}{\Phi_{MAD}}\right)^2 \dot{M}_{BH}c^2$$

e.g. Yuan & Narayan 2014

- Maximal for highly-spinning BHs and high magnetic flux threading the BH horizon
- P_{jet} can exceed $\dot{M}_{BH}c^2$? Energy extraction from BH (Penrose 1969)

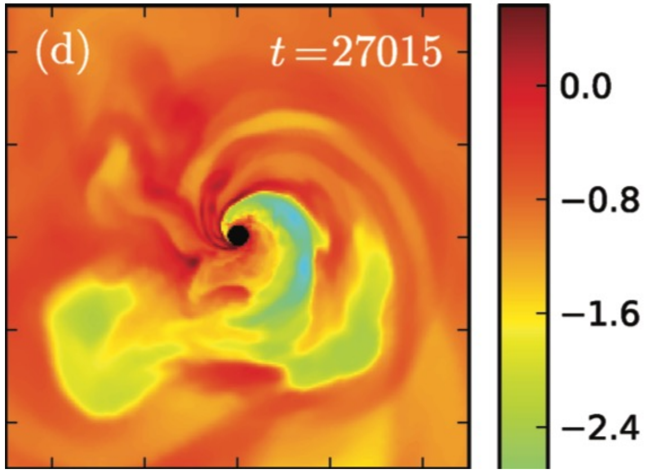
Magnetically-arrested disks (« MAD »)

- High magnetic flux advected to the BH horizon and stops accretion (→ MAD, Igumenshchev+03)



Igumenshchev+03: 3D MHD
(periodic boundaries azimuthally)

Tchekhovskoy+11: 3D GRMHD
with HARM



- Accretion occurs via interchange/Rayleigh-Taylor instabilities
- Renewed interest (e.g. Tchekhovskoy+12) because of jet launching

$$P_{\rm jet} \approx 2.5 \left(\frac{a_*}{1+\sqrt{1-a_*^2}}\right)^2 \left(\frac{\Phi}{\Phi_{\rm MAD}}\right)^2 \dot{M}_{\rm BH} c^2$$

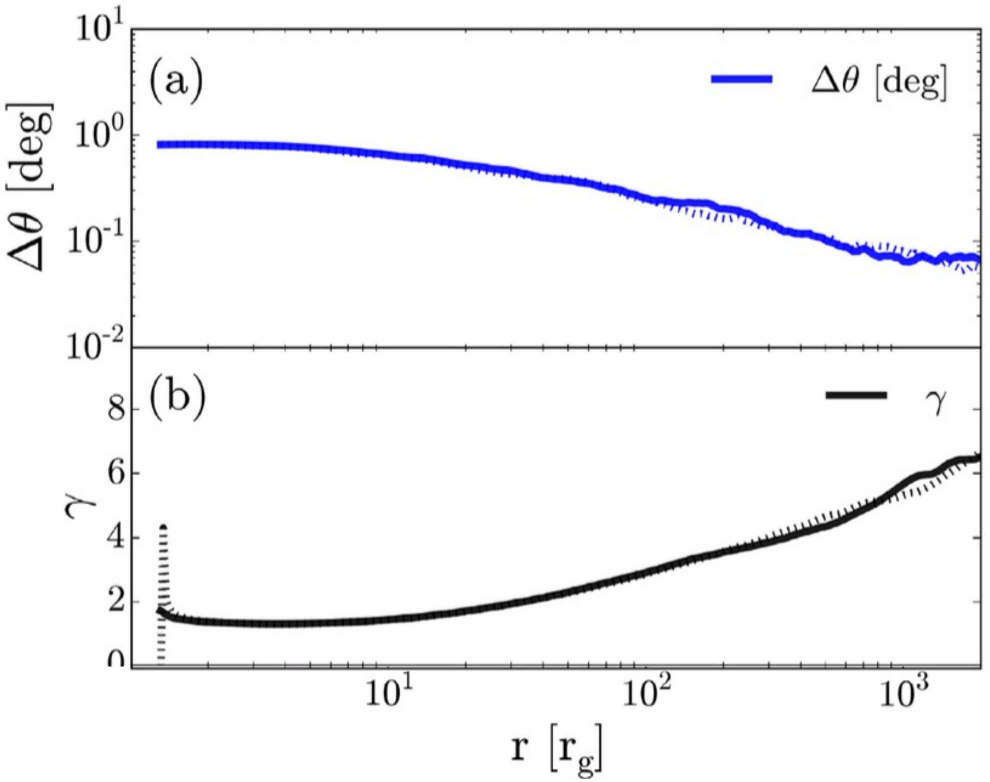
Implications for the jet:

- $P_{\rm jet} \propto \dot{M}_{\rm BH} c^2$, independent on the initial magnetic flux in MAD state because flux saturates

Outcomes of interest

- Parabolic jet shape (e.g. Nakamura+18)

- Opening angle & collimation
  - ➢ jet collimated by disk wind (e.g. Liska+20)



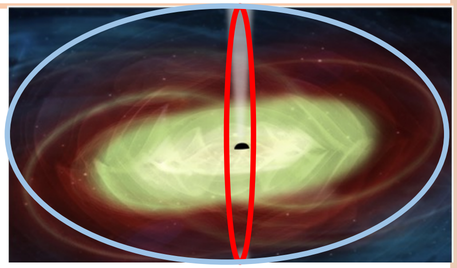
Liska+20: 3D GRMHD with H-AMR
initial purely <u>toroidal</u> B

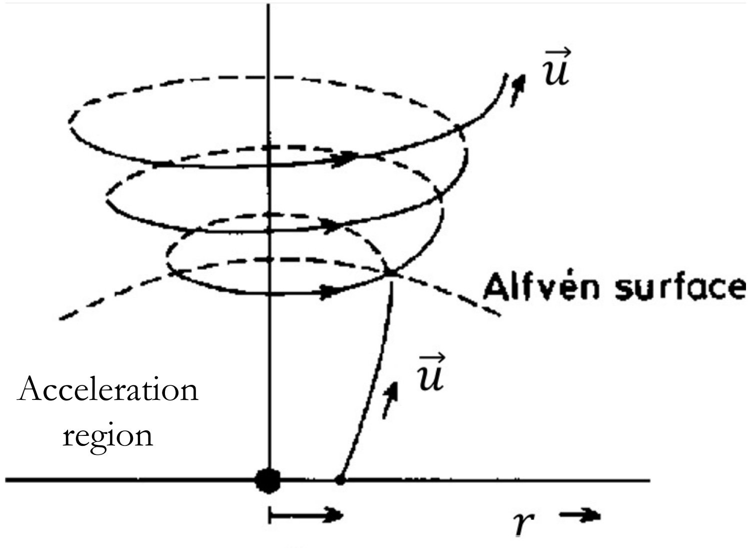
- Lorentz factor $\Gamma \gtrsim 10$ reached but:
  Γ depends on the mass load $\dot{M}_{\rm jet}$: $P_{\rm jet} \approx \Gamma\, \dot{M}_{\rm jet}\, c^2$
  No pair creation and density too low in the jet → artificial density floor
  - ➢ Maximal Γ reached depends on this density floor

- B field strength: normalized to the thermal pressure via the plasma β variable

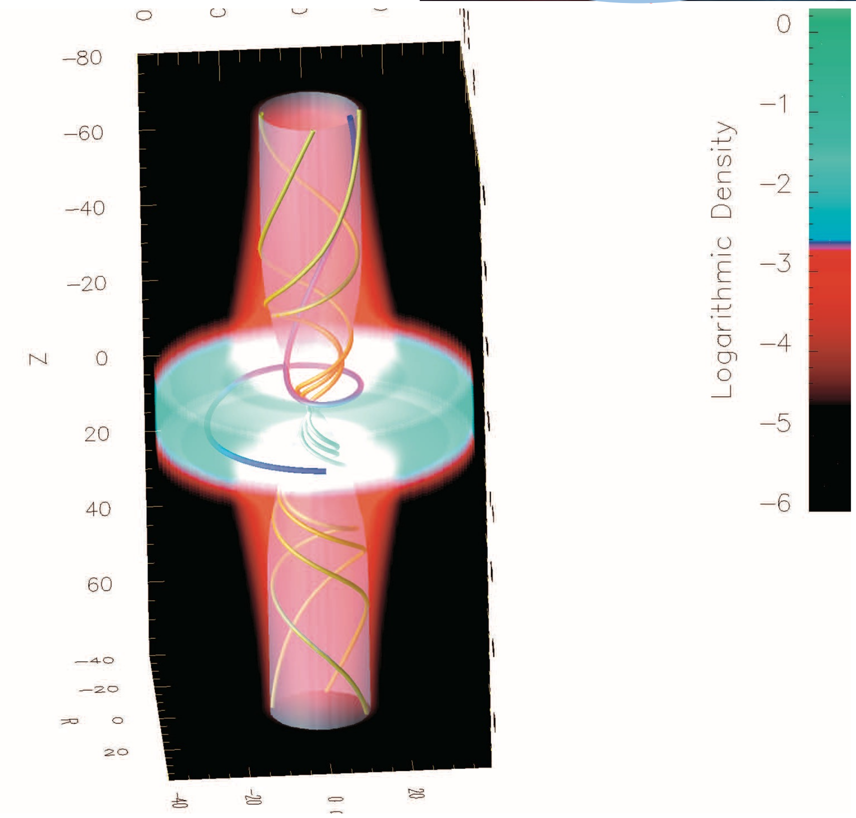
Other outflows are disk-based

- Magneto-centrifugal mechanism (Blandford & Payne 1982): « bead on a wire »





Credits: Spruit, 1996

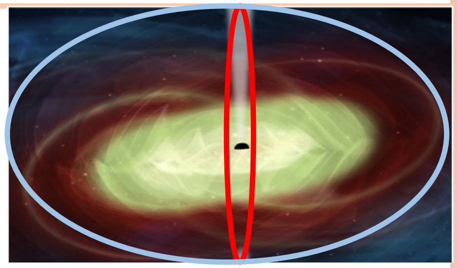


- collimation from toroidal component of B
- Lorentz factor Γ~a few (e.g. Porth & Fendt 2010: RMHD with `PLUTO`)
- Can collimate the BZ jet

Casse & Keppens 2004: no GR, with a previous version of `MPI-AMRVAC`

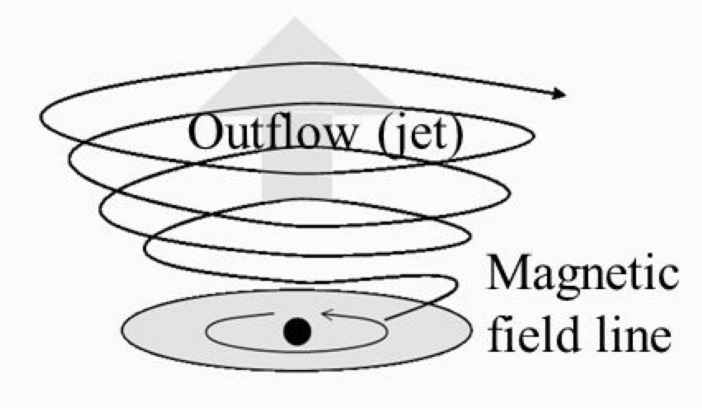
- Presence in GRMHD simulations: Dihingia+21 with `BHAC`, but see Qiang+18 with `rHARM`)

Other outflows are disk-based

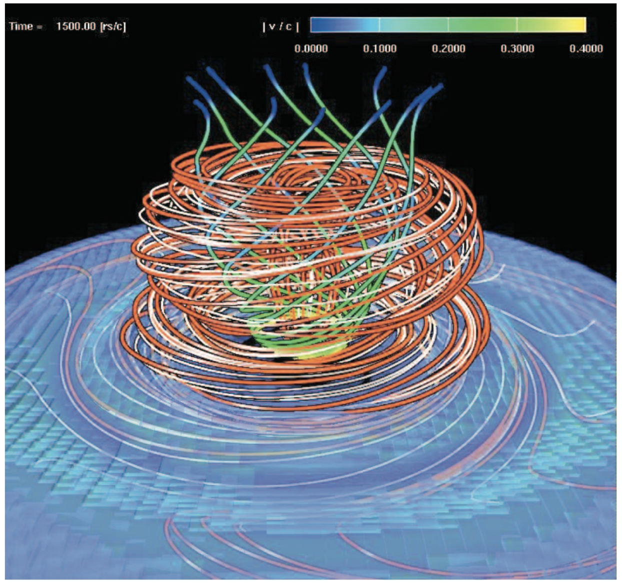


- Magnetic tower flow (Shibata & Uchia 1985, 1986, Lynden-Bell, 1997, 2003, Kato+04…)

$$\underbrace{\mathbf{J}\times\mathbf{B}}_{\text{Lorentz force}} = \underbrace{\boldsymbol{\kappa}\frac{B^2}{\mu_0}}_{\text{magnetic tension}} - \underbrace{\nabla_\perp\left(\frac{B^2}{2\mu_0}\right)}_{\text{magnetic pressure}}$$



Credits: Spruit, 1996

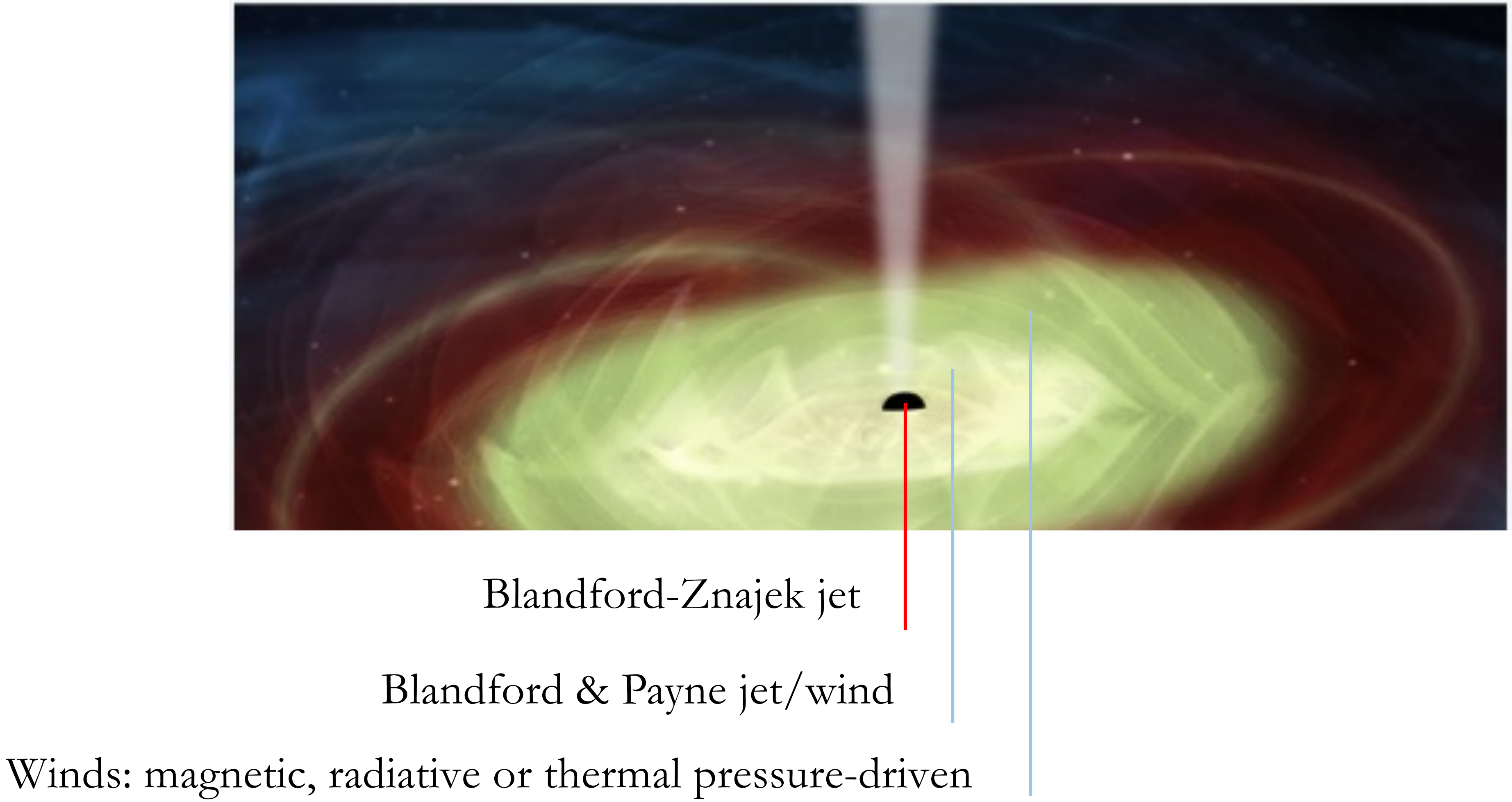


Kato+04
MHD+pseudo-Newtonian potential

- collimation from external (ambient) pressure
- Maximal velocity ~0.2c
- Can collimate the BZ jet

- Others: thermal/radiative outflows: driven by thermal pressure gradients or radiative pressure

Recap: outflows from black holes

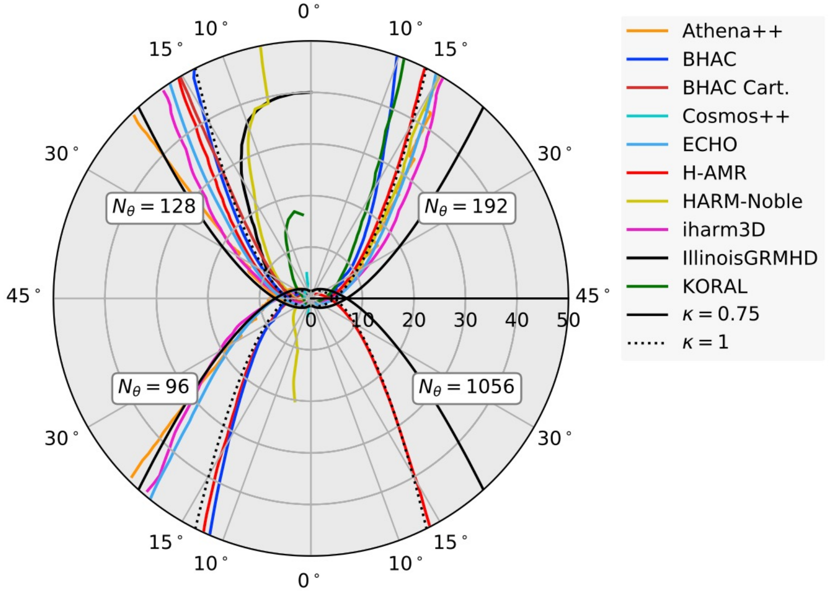


- Co-existence and even interplay (collimation?)
- Except for BZ, mechanisms plausibly universal: X-ray binaries (e.g. Liu+22), protostellar disks (e.g. Mignon-Risse+21)…

The landscape of codes

- Non-exhaustive list of widely used codes:
  - `Athena++` (Stone+08)
  - `BHAC` (Porth+17), `GR-AMRVAC` (Casse+17), based on `MPI-AMRVAC` (Keppens+12)
  - `Cosmos++` (Anninos+05, Fragile+12,+14)
  - `ECHO` (Londrillo & Del Zanna, 2000, 2004)
  - `H-AMR`, `HARM` (Gammie+03, Noble+06,+09), `cuHARM` (Bégué+23)
  - `IllinoisGRMHD` (Etienne+15)
  - `KORAL` (Sadowski+13,+14)

- C/Fortran, adaptive-mesh refinement and same numerical methods
- Tested codes (9) agree on the BH-torus problem
  → EHT code comparison, see Porth+19:

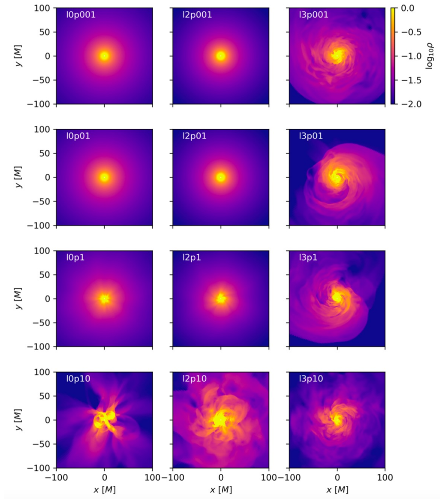


- Computing resources: ~~laptop~~ local/(inter)national clusters

- Comment on open-access:
  - public versions often lagging the latest developments
  - various branches of the code, corresponding to various developers/teams
  - **steep** learning curve. Contact the authors or us (APC: P. Varniere, F. Casse, RMR)

Limitations from…

- Initial conditions:
  - ➢ out of (magnetic) equilibrium
  - ➢ disconnected from large scales (some efforts in this direction: Olivares+23)
    → what consequences for the magnetic flux??
  - ➢ limited mass reservoir → limits the maximal duration of the simulation



Olivares+23: GRHD with BHAC

- Physics: knowledge on the accretion/ejection processes:
  - ➢ SANE (Standard And Normal Evolution): BH magnetosphere has no impact on the accretion
  - ➢ MAD (Magnetically Arrested Disk): magnetic flux accumulation forms a magnetic barrier
  - ➢ ADAF (Advection-Dominated Accretion Flow), RIAF (Radiatively Inefficient Accretion Flow), CDAF (Convection-…), ADIOS (Adiabatic Inflow-Outflow Solution)…

  - ➢ Angular momentum transport: MRI? something else? (e.g. outflows)

Limitations from…

- <u>Background</u> metric: no self-gravity

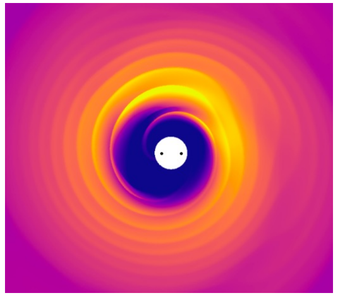
- In general, <u>stationary</u> metric: no motion of the compact object nor spin precession
  But gravitational wave source ⟺ dynamical spacetime
  Exceptions: `HARM` (Noble+12), `GR-AMRVAC` (Casse+17, Mignon-Risse+22), `IllinoisGRMHD` (Etienne+15)

Explaining temporal variations in the jet position angle of the blazar OJ 287 using its binary black hole central engine model

Dey+21

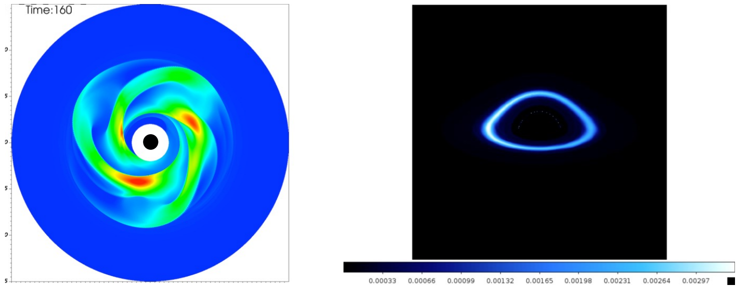
Neutrino Emissions of TXS 0506+056 caused by a Supermassive Binary Black Hole Inspiral?

Jaroschewski+23



Mignon-Risse+23

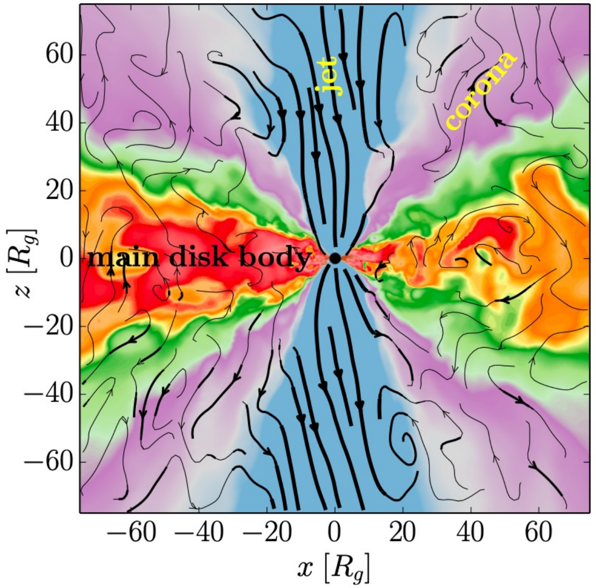
- Fluid properties in fluid frame ≠ emission seen from Earth
  → need GR ray-tracing step
  Ex.: `BOTHROS` (e.g. D'Ascoli+18), `BHOSS` (e.g. Olivares+20),
  `GYOTO` (Vincent+11, e.g. Varniere+18, Mignon-Risse+21…)



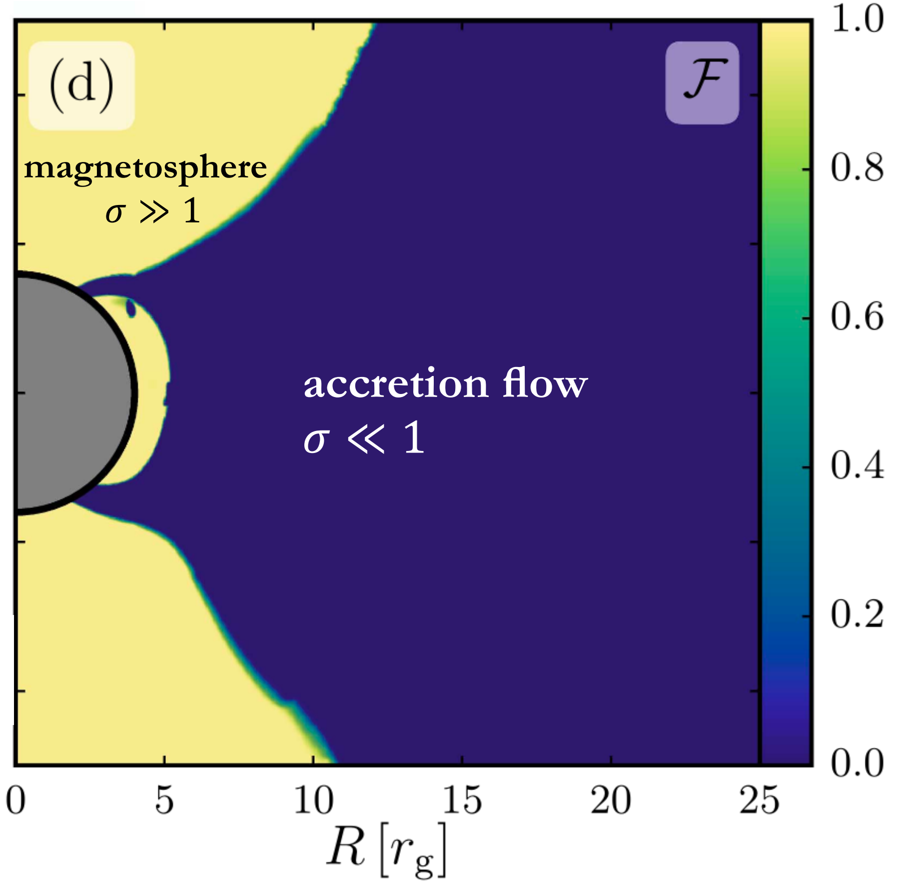
Mignon-Risse+21

Beyond… single fluid approaches: hybrid « force-free »

- At high magnetization, small errors in the magnetic fields yield large errors/crashing for the fluid dynamics
  - Pb in BH magnetospheres
  - Alternative: couple the MHD to a « force-free » approach designed for highly magnetized regions with $\sigma \gg 1$



Credits: A. Tchekhovskoy
Sadowski+13



Parfrey & Tchekhosvkoy 2017

For neutron stars :
- Parfrey & Tchekhovskoy 2017 in HARM
- Das+22 in BHAC

Beyond… fluid approaches: kinetic methods

- Spatial scales: BH horizon $R_S \approx 3\times10^9 \frac{M}{10^6 M_\odot}$ m

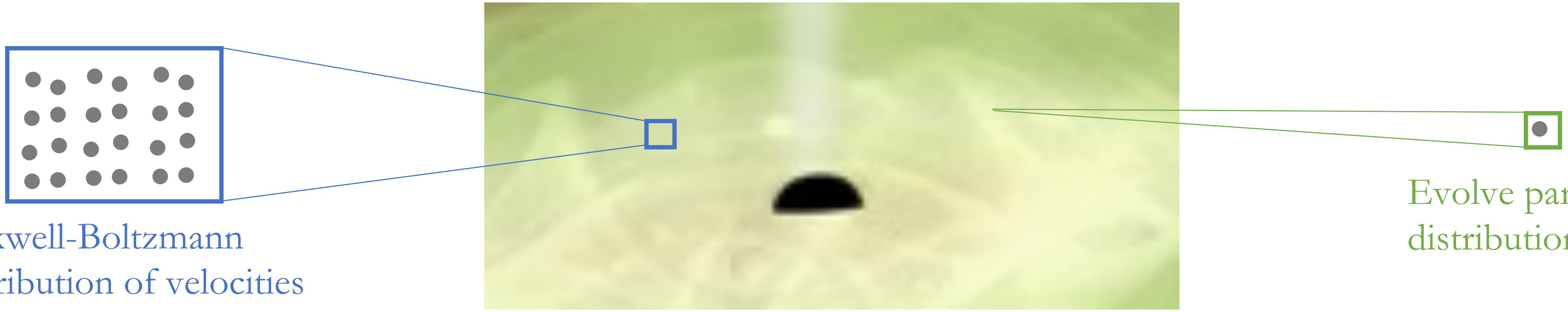
  Accretion disk $\sim 100 - 1000\ R_S$

- Timescales: $R_S/c \sim 10$s

- Spatial scale: skin depth $\lambda_e = c/\varpi_e \sim 300$m

- Timescale: electron plasma frequency ϖ_e

  $\rightarrow \tau \sim 1/\varpi_e \sim 10^{-6} \left(\frac{n_e}{10^4\,\mathrm{cm}^{-3}}\right)$ s



Maxwell-Boltzmann distribution of velocities

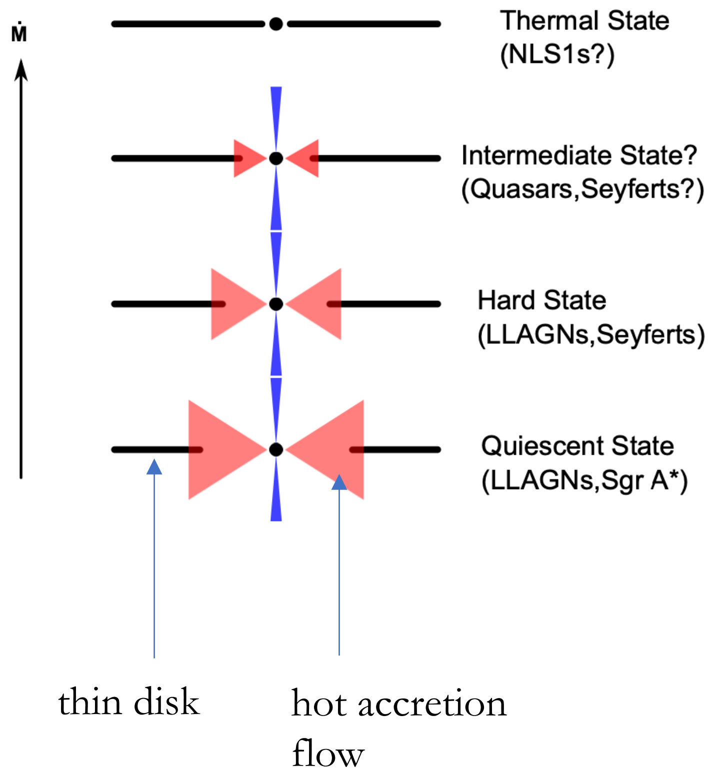
Evolve particle velocity distribution function

- MHD-PIC methods:
  - ➢ Confine the kinetic model to some regions (Daldorff+14)
  - ➢ For (Cosmic ray) particle acceleration in shocks (Bai+15 in `Athena`)
- Particle-in-[MHD]-Cells (Casse+18, Van Marle+18 in `MPI-AMRVAC`)
  - ➢ Interplay between thermal plasma and supra-thermal particles (cosmic rays)

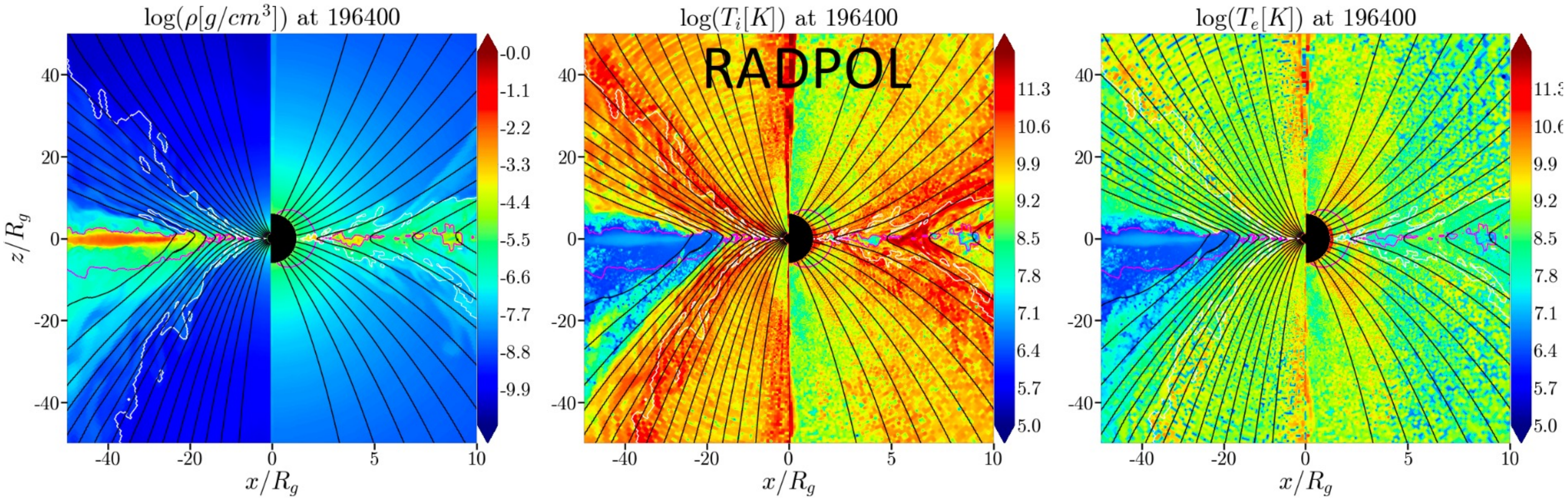
❑ Only classical so far, not relativistic yet

Beyond… GRMHD: GR-**R**-MHD

- Rare examples of GR R MHD (e.g. KORAL: Sadowski+13, ATHENA++: White+23, cuHARM: D. Bégué's talk)
- Note: « on-the-fly » radiative transport problem often simplified to be tractable → fluid descriptions
- 10-30 times more computationally expensive (Dexter+21) ≫ days



Credits: Narayan & McClintock 2008



Liska+22: two-temperature GR-R-MHD

Beyond… ideal MHD: resistivity, diffusion

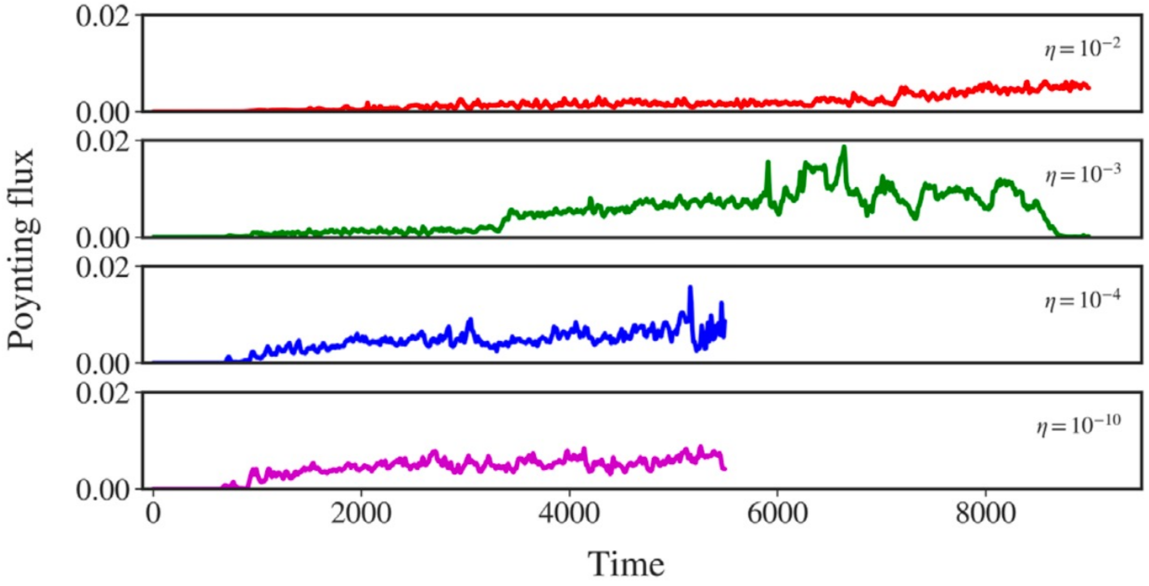
- Resistive effects allow:
  the flow to be accreted through the field lines
  disk matter to be loaded onto the jet
  fields line to reconnect (and to control this!) and more generally the field topology to evolve

- Ohm's law: $$\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B} = \eta \boldsymbol{J}$$

$$\eta(r,\theta) = \eta_0 \exp\left[-2\left(\frac{\alpha}{\alpha_\eta}\right)^2\right]$$

- Resistivity implemented in a few codes:
  ECHO (Bucciantini & Del Zanna, 2014),
  HARM (Qian+18), BHAC (Ripperda+19)…

➢ Complex interplay of magnetic reconnection (↘), Ohmic heating (↗), magnetic diffusion (↗) (Vourellis+19)



Vourellis+19: resistive GRMHD

Conclusions

- BH jet launching from **BZ mechanism,** currently favored to explain radio-loud AGNs, widely studied

- **Limited variety of initial conditions**, mostly corresponding to « hot accretion flows » (Yuan & Narayan 2014) rather than historically-standard thin disks (Shakura & Sunyaev 1973)

- **GRMHD codes are numerous, mature, similar** → they qualitatively agree on the BH accretion problem
  - **but steep learning curve**

- Keep in mind the (**MHD) approximations**
  - **or go beyond** : GR-**R**-MHD, resistive MHD, coupling to force-free or PIC…
  - is GR/R needed for your problem?

Some references

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THE ASTROPHYSICAL JOURNAL LETTERS, 851:L34 (7pp), 2017 December 20 https://doi.org/10.3847/2041-8213/aa9c85

General-relativistic Simulations of Four States of Accretion onto Millisecond Pulsars

Kyle Parfrey[1,2,5] and Alexander Tchekhovskoy[1,2,3,4,6]

MNRAS 000, 1–14 (2022) Preprint 11 January 2022 Compiled using MNRAS LaTeX style file v3.0

Disk Tearing Leads to Low and High Frequency Quasi Periodic Oscillations in a GRMHD Simulation of a Thin Accretion Disk

G. Musoke,[1★] M. Liska,[2] O. Porth,[1] Michiel van der Klis,[1] Adam Ingram [3]

THE ASTROPHYSICAL JOURNAL LETTERS, 910:L13 (43pp), 2021 March 20 https://doi.org/10.3847/2041-8213/abe4de

First M87 Event Horizon Telescope Results. VIII. Magnetic Field Structure near The Event Horizon

The Event Horizon Telescope Collaboration
(See the end matter for the full list of authors.)

THE ASTROPHYSICAL JOURNAL, 859:28 (24pp), 2018 May 20 https://doi.org/10.3847/1538-4357/aabd36

Jet Launching in Resistive GR-MHD Black Hole–Accretion Disk Systems

Qian Qian (钱前)[1], Christian Fendt, and Christos Vourellis[1]

THE ASTROPHYSICAL JOURNAL LETTERS, 917:L31 (7pp), 2021 August 20 https://doi.org/10.3847/2041-8213/ac1859

Beamed Emission from a Neutron-star ULX in a GRRMHD Simulation

David Abarca[1], Kyle Parfrey[2], and Włodek Kluźniak[1]

THE ASTROPHYSICAL JOURNAL, 838:42 (20pp), 2017 March 20 https://doi.org/10.3847/1538-4357/aa63f3

Relativistic Dynamics and Mass Exchange in Binary Black Hole Mini-disks

Dennis B. Bowen[1], Manuela Campanelli[1], Julian H. Krolik[2], Vassilios Mewes[1], and Scott C. Noble[3]

Beyond… fluid approaches: kinetic methods

- MHD-PIC method: (Daldorff+14, Makwana+17)
  - ➢ MHD gives initial and boundary conditions to plasma ; MHD updated based on PIC variables
- MHD-PIC method for (Cosmic ray) particle acceleration in shocks (Bai+15 in `Athena`)
  - ➢ CRs: Lagrangian particles obeying the Lorentz force; momentum + energy feedback onto fluid
  - ➢ Ions+electrons = « thermal » fluid
- Particle-in-[MHD]-Cells (Casse+18, Van Marle+18 in `MPI-`**`AMR`**`VAC`)
  - ➢ Interplay between thermal plasma and supra-thermal particles (cosmic rays)

$$\frac{\partial \rho \mathbf{v}}{\partial t} + \nabla \cdot \left(\rho \mathbf{v} \otimes \mathbf{v} - \frac{\mathbf{B} \otimes \mathbf{B}}{4\pi} + P_{\rm tot}\, 1_3 \right) = - \underline{\mathbf{F}_{\rm part}}$$

$$\frac{\partial e}{\partial t} + \nabla \cdot \left((e + P_{\rm tot})\mathbf{v} + (\mathbf{E} - \mathbf{E}_0) \times \frac{\mathbf{B}}{4\pi} \right) = - \underline{\mathbf{u}_{\rm part} \cdot \mathbf{F}_{\rm part}}$$

$$c\mathbf{E} = -((1 - R)\mathbf{v} + \underline{R\, \mathbf{u}_{\rm part}}) \times \mathbf{B}$$

$$\frac{\partial \mathbf{p}_j}{\partial t} = q_j \left(\mathbf{E} + \frac{\mathbf{u}_j}{c} \times \mathbf{B} \right)$$

Casse+18

➢ Can be applied to scales ≫ microscopic (PIC scales)

❑ Only classical so far, not relativistic yet