Accretion disks simulations on the GPU partition of Kraken

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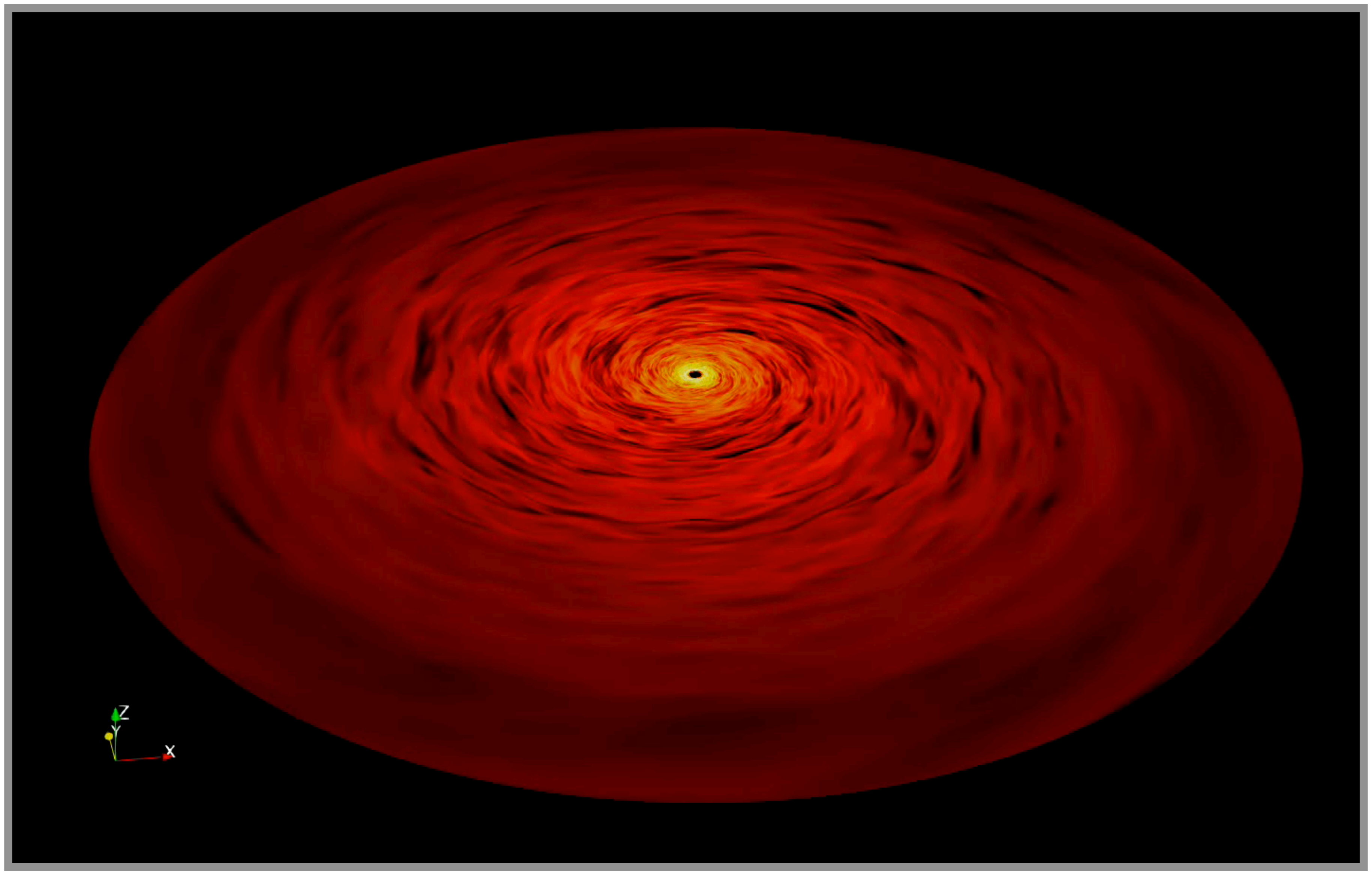
ORIGINES

Accretion disks

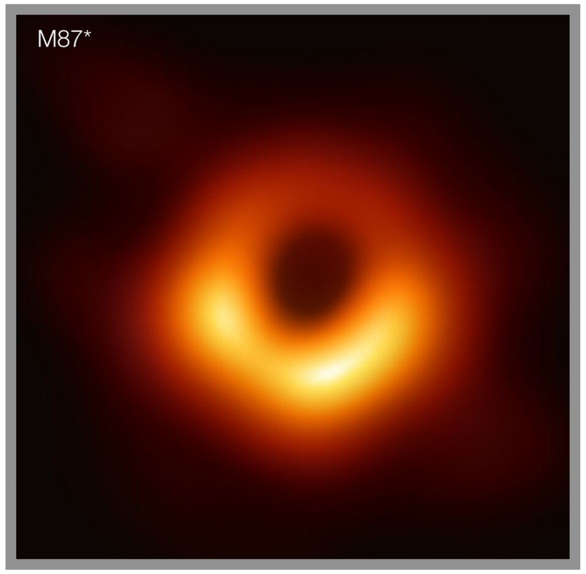
Disks of matter (plasma, gas, dust) orbiting a central object



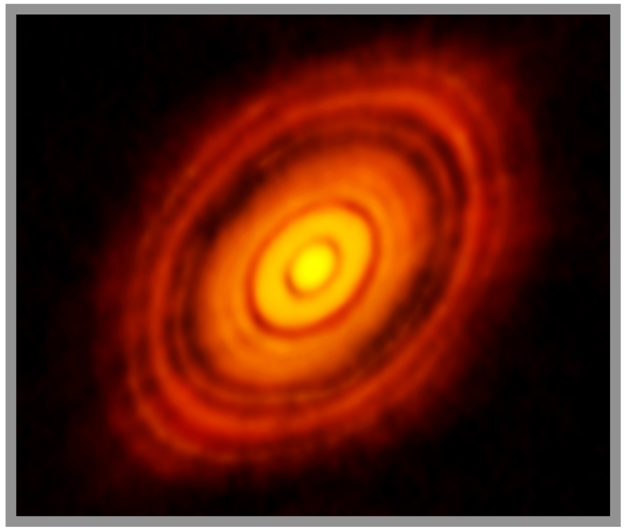
Diversity of accretion disks

Accretion disks are ubiquitous in astrophysics

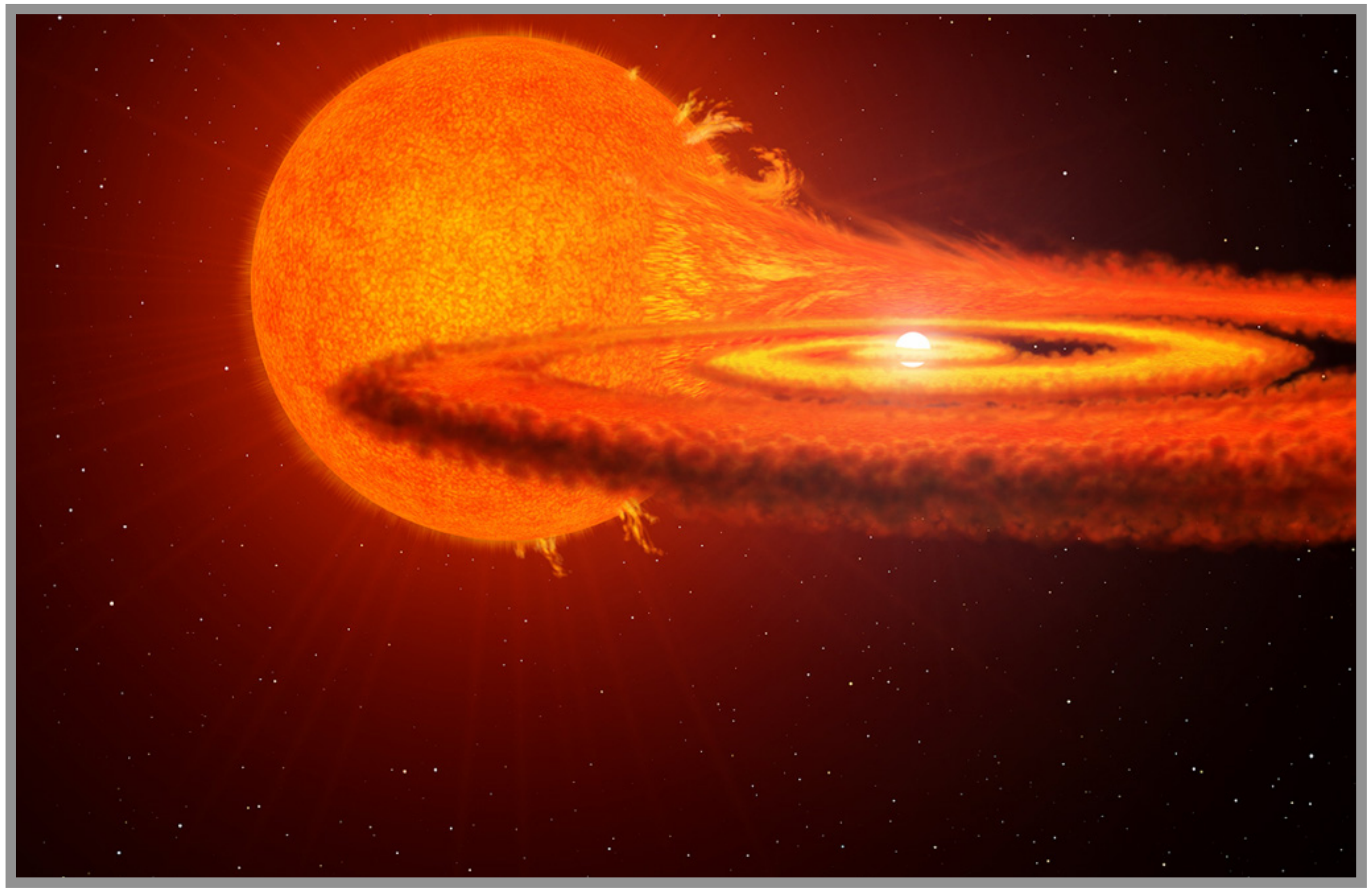
Supermassive black holes at the center of galaxies



Protoplanetary disks



Accreting binaries with a compact object (black hole, neutron star or white dwarf)



Why do we care about accretion disks ?

- Accretion disks the most powerful emitter of light in the Universe !

At least 10 times more efficient than nuclear fusion at converting mass into energy

Recent observation of an accretion disk around a supermassive black hole only 800 million years after the Big Bang !
(Bosman et al. 2024)

(age of the Universe is ~14 billions years)

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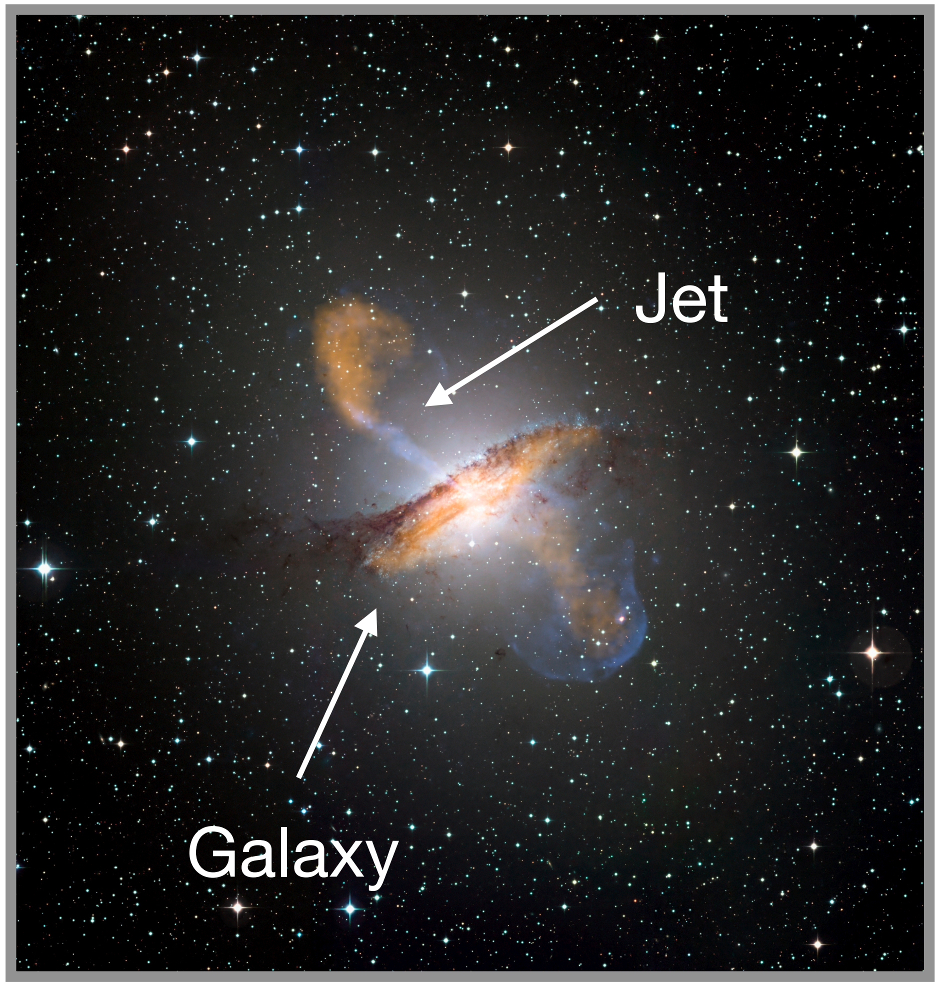
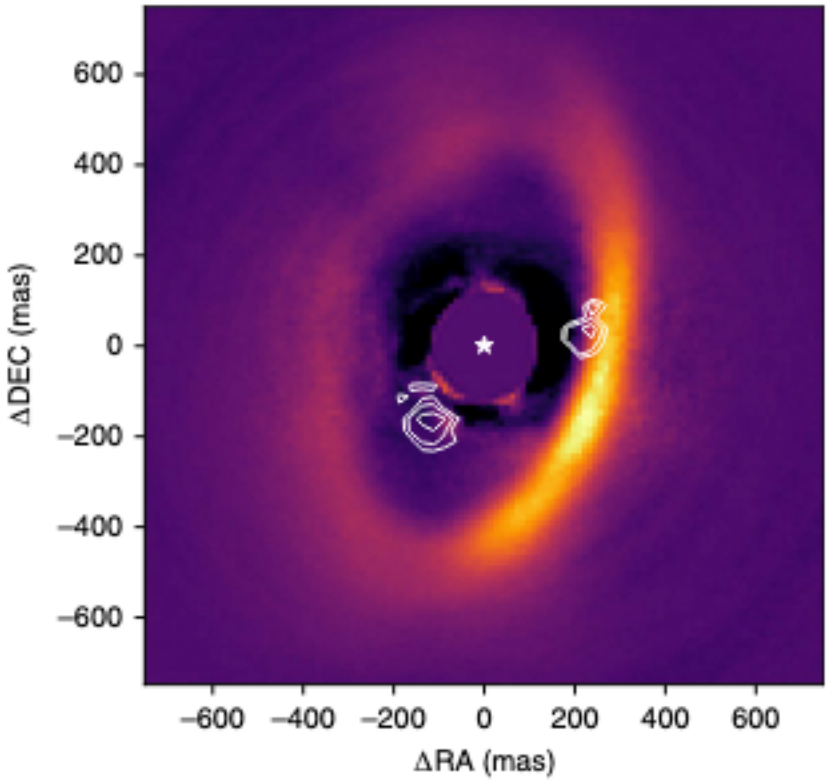
- Accretion disks are responsible for very large scale outflows



Jet is at least a million times larger than the accretion disk !

Why do we care about accretion disks ?

- Accretion disks the most powerful emitter of light in the Universe !
- Accretion disks are responsible for very large scale outflows
- Accretion disks are the birth place of planets



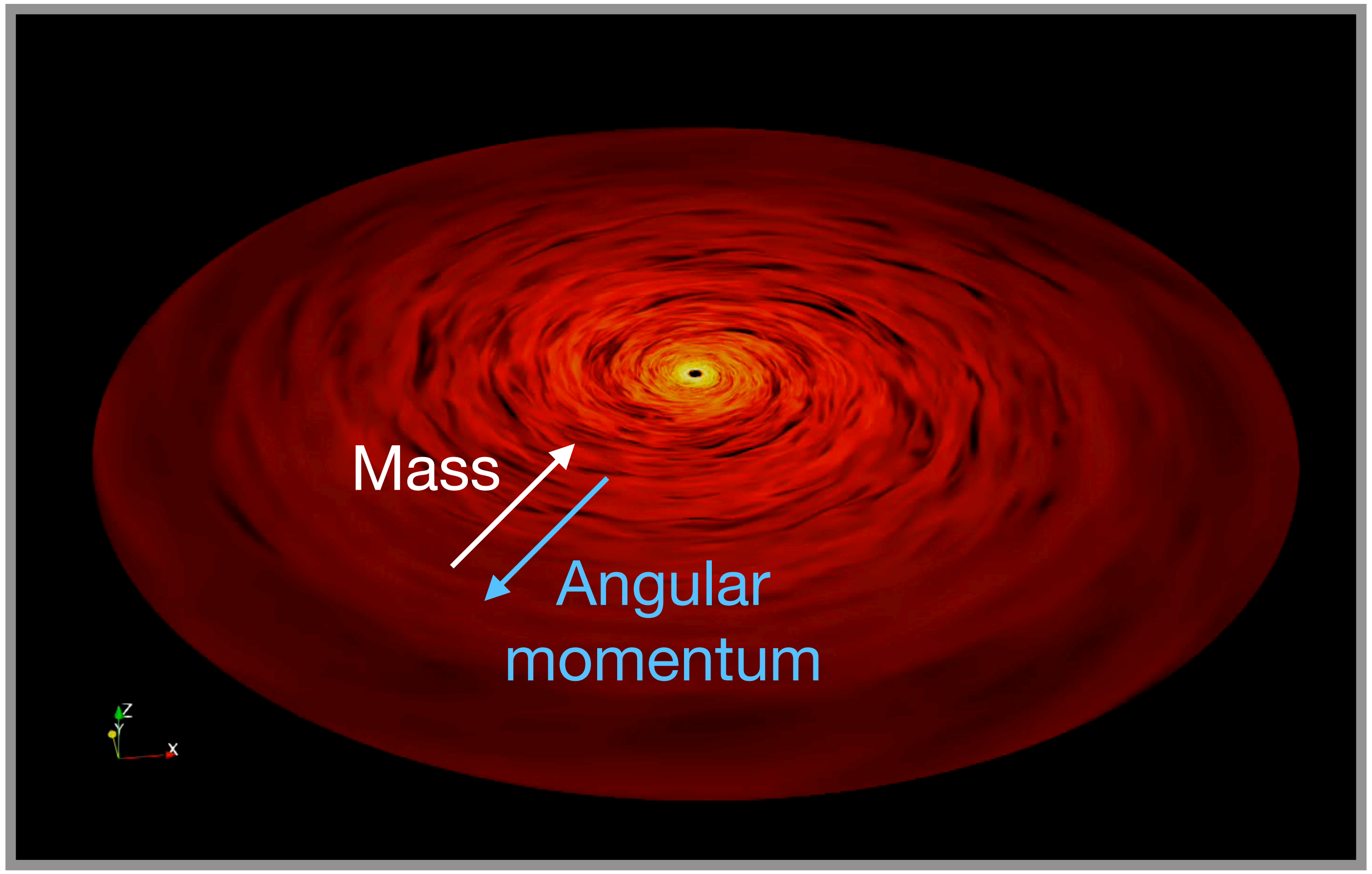
Planets have been now directly observed in one disk !
(Haffert et al. 2019)

Open questions on accretion disks

- How do accretion disks accrete ?

Need to transport angular momentum (rotation) outward but how ?

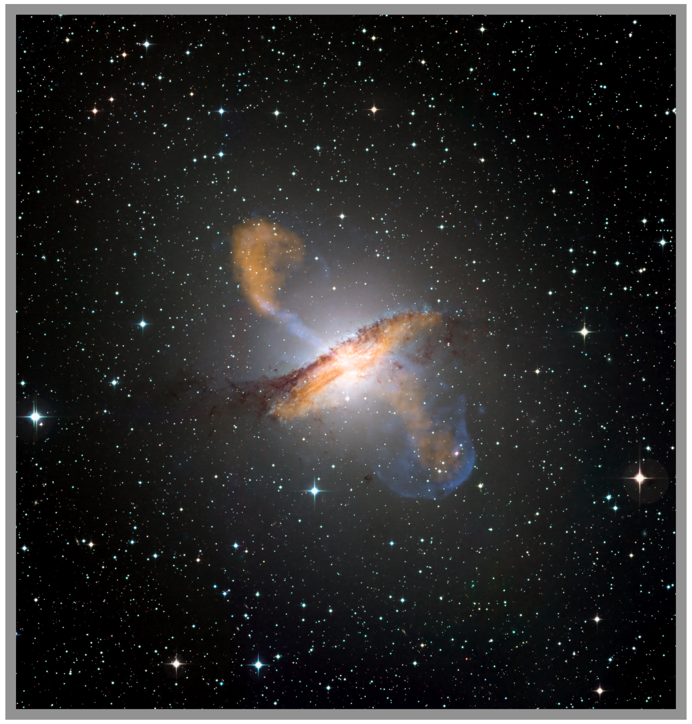
Main paradigm is magnetic turbulence !

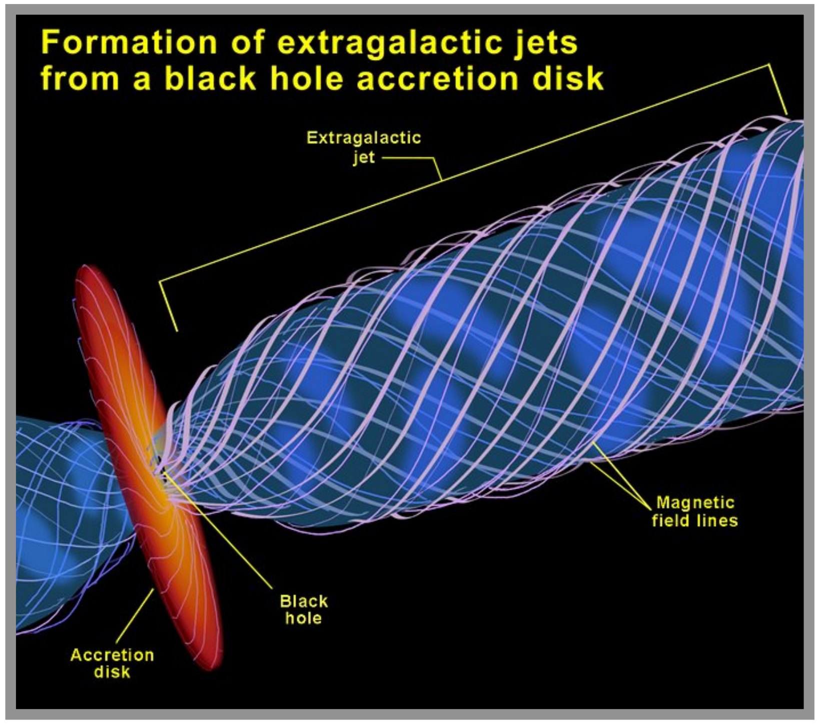


Open questions on accretion disks

- How do accretion disks accrete ?

- How can accretion disks produce large-scale outflows ?

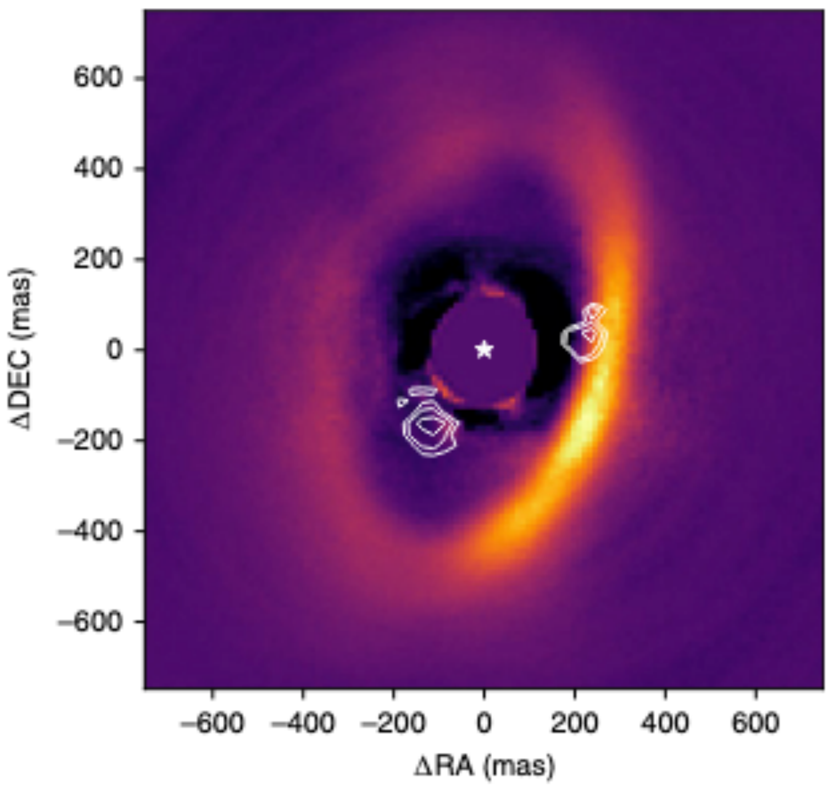




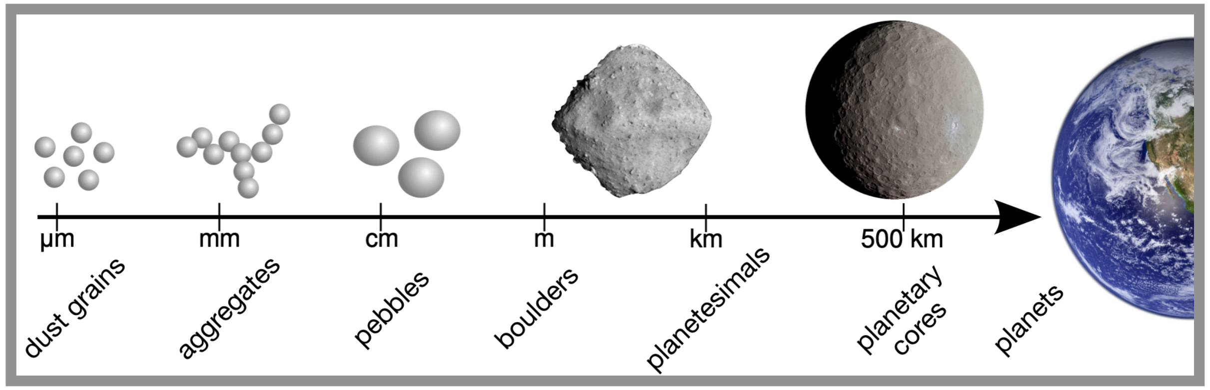
Again, main paradigm is magnetic field !

Open questions on accretion disks

- How do accretion disks accrete ?
- How can accretion disks produce large-scale outflows ?
- How planets form in accretion disks ?



How to grow from dust to pebbles
to planetesimals to planets ?



How do we study accretion disks ?

Need to model a fluid on large-scales under the influence of gravity, radiation and magnetic fields

We use the theory framework of the magneto-hydrodynamics (MHD)

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$$\partial_t \begin{pmatrix} \rho \\ \rho \mathbf{v} \\ E + \rho\Phi \\ \mathbf{B} \end{pmatrix} + \nabla \cdot \begin{pmatrix} \rho \mathbf{v} \\ \rho \mathbf{v}\mathbf{v} - \mathbf{B}\mathbf{B} + P \cdot \mathbf{Id} \\ (E + P + \rho\Phi)\mathbf{v} - \mathbf{B}(\mathbf{v} \cdot \mathbf{B}) \\ \mathbf{v}\mathbf{B} - \mathbf{B}\mathbf{v} \end{pmatrix}^T = \begin{pmatrix} 0 \\ -\rho\nabla\Phi \\ 0 \\ 0 \end{pmatrix}$$

MHD equations are non-linear, need for numerical simulations !

$$\partial_t \mathbf{U} + \nabla \cdot \mathbf{F} = \mathbf{S}$$

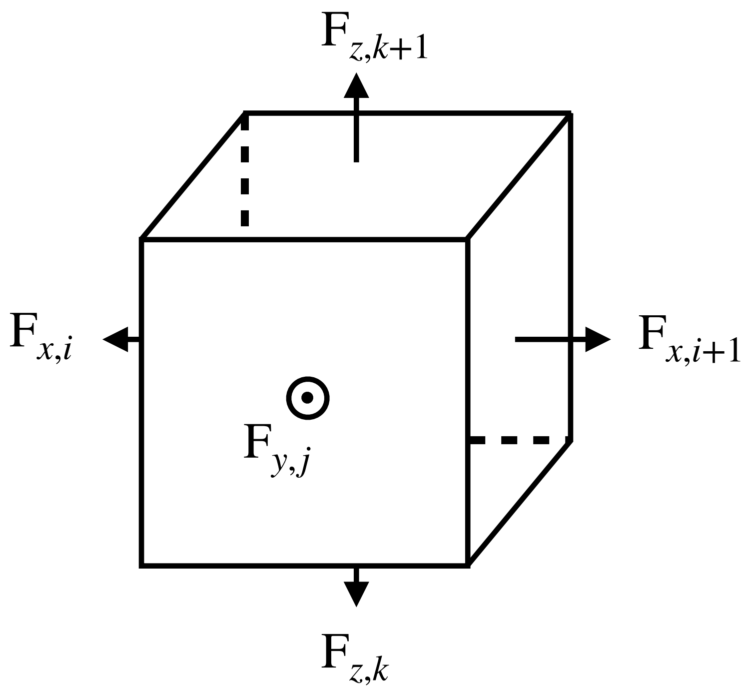
where U is the set of fluid conserved variables, F is the flux for each variable and S is a source term

Finite volume method

$$\partial_t \mathbf{U} + \nabla \cdot \mathbf{F} = \mathbf{S}$$

Very suitable for a finite volume method !

$$\partial_t \int_{\mathcal{V}} \mathbf{U} dV + \int_{\mathcal{S}} \mathbf{F} \cdot dS = \int_{\mathcal{V}} \mathbf{S} dV$$



1. Discretize the grid into finite volumes
2. Average variables over volumes
3. Compute fluxes through the faces of the volume
4. Compute source terms
5. Evolve variables

IDEFIX code

We developed at IPAG an MHD radiative finite-volume code called IDEFIX
(Lesur et al. 2023)

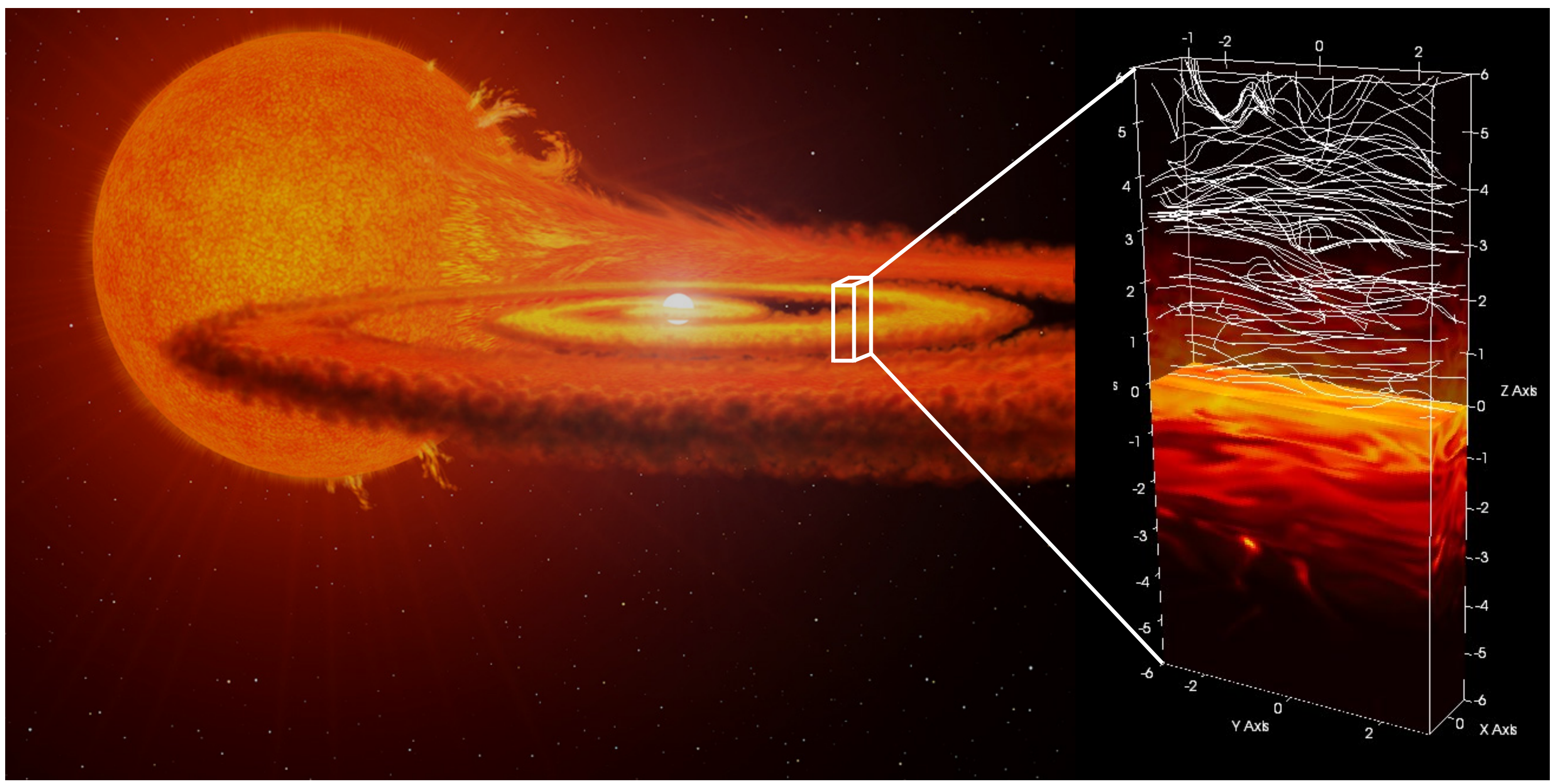
IDEFIX is an open-source C++ code using the Kokkos Library for performance portability so that it is **performant on CPUs and GPUs**

Performance on a single Intel Cascade Lake CPU core is 0.62e6 cells update per seconds

Performance on a H100 on Jean-Zay is ~2e8 cells update per seconds
For a 1000^3 grid, one whole domain update every 5 seconds

My experience on GRICAD

I have been using GRICAD since beginning of my PhD in 2016
to study the turbulent angular momentum transport in disks



Back then, we did
local simulations !

However, realized we need global simulations because vertical
winds can transport angular momentum too !
(Scepi et al. 2018b)

Project on KRAKEN

1. Test IDEFIX on the H100 GPUs of Kraken

IDEFIX performs very well on a single H100 GPU node
Same performance as on the H100 GPUs of Jean-Zay !

However, I was unable to run it across several nodes…
Code would crash because of IB connection issues

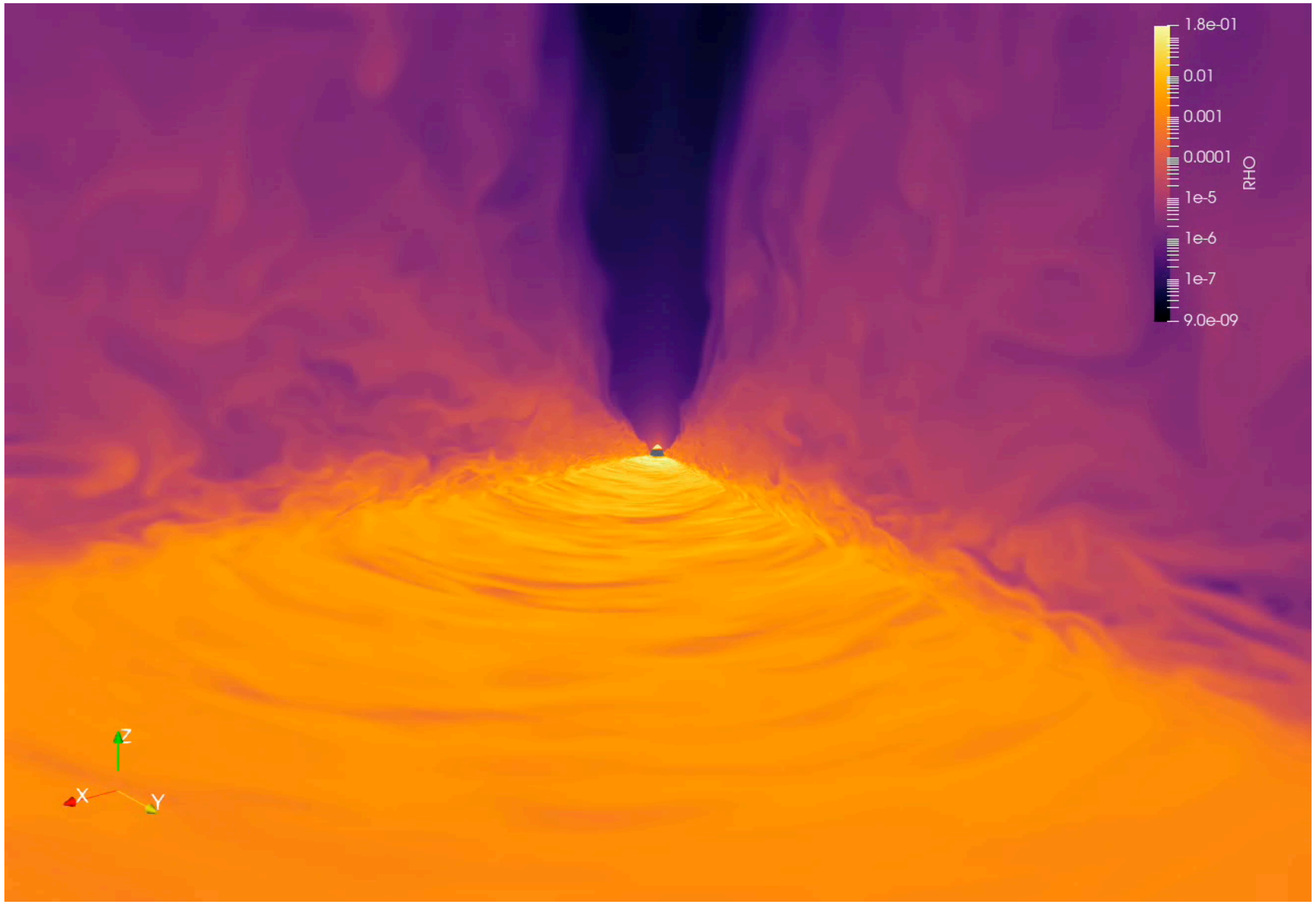
```
"ib_mlx5_log.c Transport retry count exceeded on ibp195s0:1"
```

Also hard to compile version of Idefix with Python Interface using pybind11…
Using Nix and Guix can be quite heavy for our usage
Could use a lighter option like module

Project on KRAKEN

1. Test IDEFIX on the H100 GPUs of Kraken

2. Start global simulation of accretion disk



Thank you !