Towards exascale simulations of warped magnetized discs around black holes

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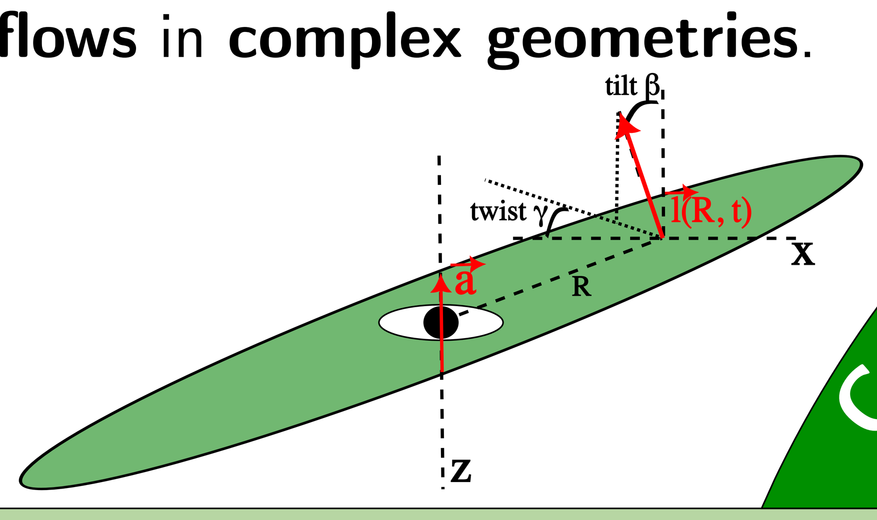
Context & Goals

Accretion discs around black holes warp, and may even **break**, under the influence of relativistic torques: this is the **Bardeen-Petterson effect**. **When does the disc break ? What is the accretion rate?**

The gas is ionized, and **material is likely expelled from the midplane** (Blandford-Znajek and Blandford-Payne mechanisms).

Our goal is to carry **high-resolution** (~10^9-10^{10} particules), **multi-physics simulations** of an accretion disc around a black hole.

We need to resolve **global and local flows** in **complex geometries**.



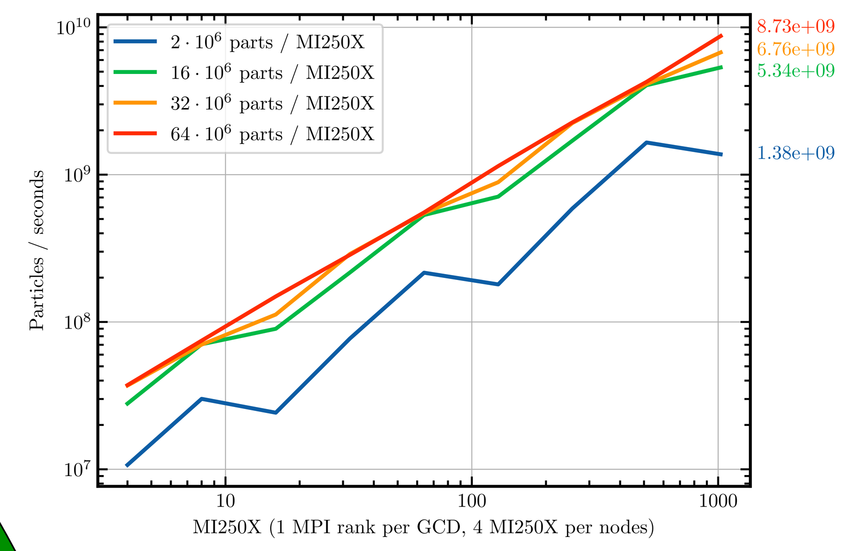
Methods

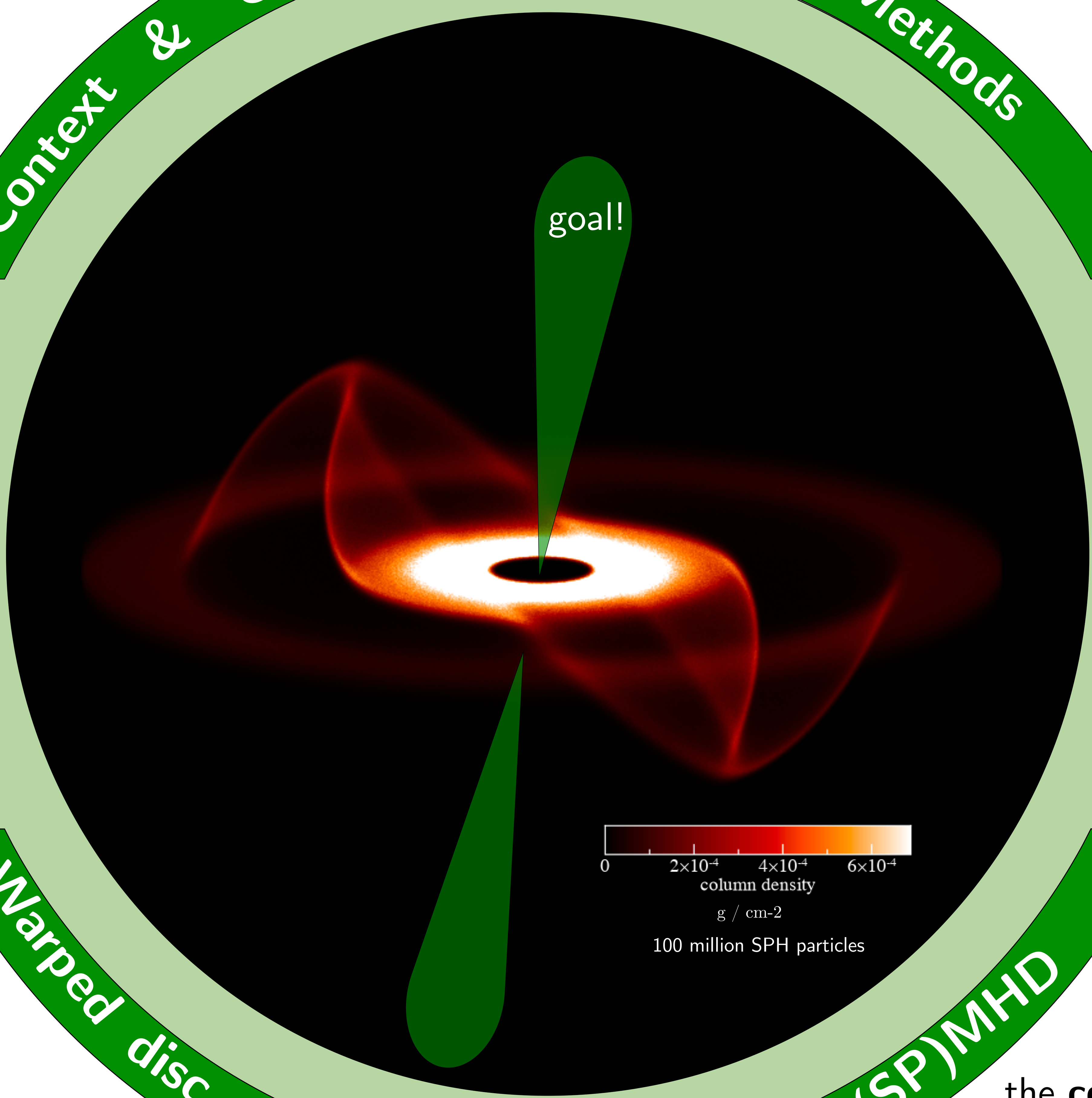
Shamrock is a new **multi-GPU** astrophysics code. It is written in templated C++17 and uses SYCL and MPI.

We use the **Smooth Particule Hydrodynamics (SPH)** method. Simulations are carried in 3D.

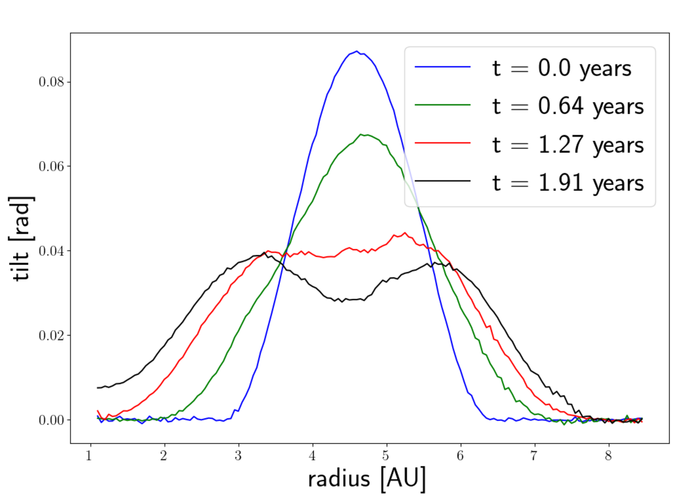
Dissipation is accounted for as a viscosity term parametrized by a constant α: $\nu = \alpha c_s H$ (Shakura & Suneyev 1973).

The disc is **thin** and **non self-gravitating**.

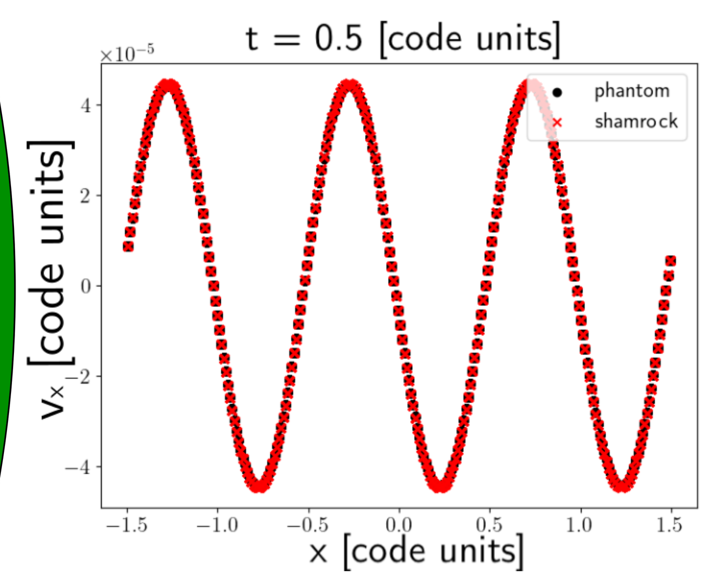




Warp test



MHD test



Warped disc structure

By linearly perturbing the equations, we know that there are 2 regimes of evolution for a small amplitude warp:

➡ **Diffusing regime** $\alpha > H/R$ (Papaloizou & Pringle 1983)

➡ **Bending wave regime** $\alpha \leq H/R$ (Papaloizou & Lin 1995). In this regime,

$$\Sigma R^2 \Omega \frac{\partial \boldsymbol{l}}{\partial t} = \frac{1}{R}\frac{\partial \boldsymbol{G}}{\partial R} + \boldsymbol{T},$$

$$\frac{\partial \boldsymbol{G}}{\partial t} - \left(\frac{\Omega^2 - \kappa^2}{2\Omega}\right) \boldsymbol{l} \times \boldsymbol{G} + \alpha \Omega \boldsymbol{G} = \Sigma R^3 \Omega \frac{c_s^2}{4} \frac{\partial \boldsymbol{l}}{\partial R}.$$

(SP)MHD

To deal with magnetic monopoles, we use a divergence cleaning method:

the **constrained hyperbolic-parabolic divergence cleaning** (Tricco 2016):

$$\frac{d\mathbf{B}}{dt} = -\mathbf{B}(\nabla \cdot \mathbf{v}) + (\mathbf{B} \cdot \nabla)\mathbf{v} - \nabla \psi$$

$$\frac{d\psi}{dt} = -c_h^2 (\nabla \cdot \mathbf{B}) - \frac{\psi}{\tau}$$

Perspectives

Ready to run simulations on large clusters (Adastra, Lumi)!

More physics to come!
- post-newtonian corrections at orders 1 and 2.5
- addition of non-ideal MHD terms to the solver
- investigation of prescriptions of viscosity and its physical origin in SPH simulations
- try different methods to enforce $\nabla \cdot \mathbf{B} = 0$, for instance Clebsch decomposition

Key Takeaways

We are ready to launch exascale simulations

The methods developed can be applied in **a variety of other contexts,** including **planet-forming discs** which are also ionized, and known from observation to be warped in great proportion.

⚠ Caveats

Limits of the α disc model

Symmetry breaking of the current $\nabla \cdot B = 0$ enforcement method