High-resolution protoplanetary disk turbulence

Using Idefix on pre-exascale machines

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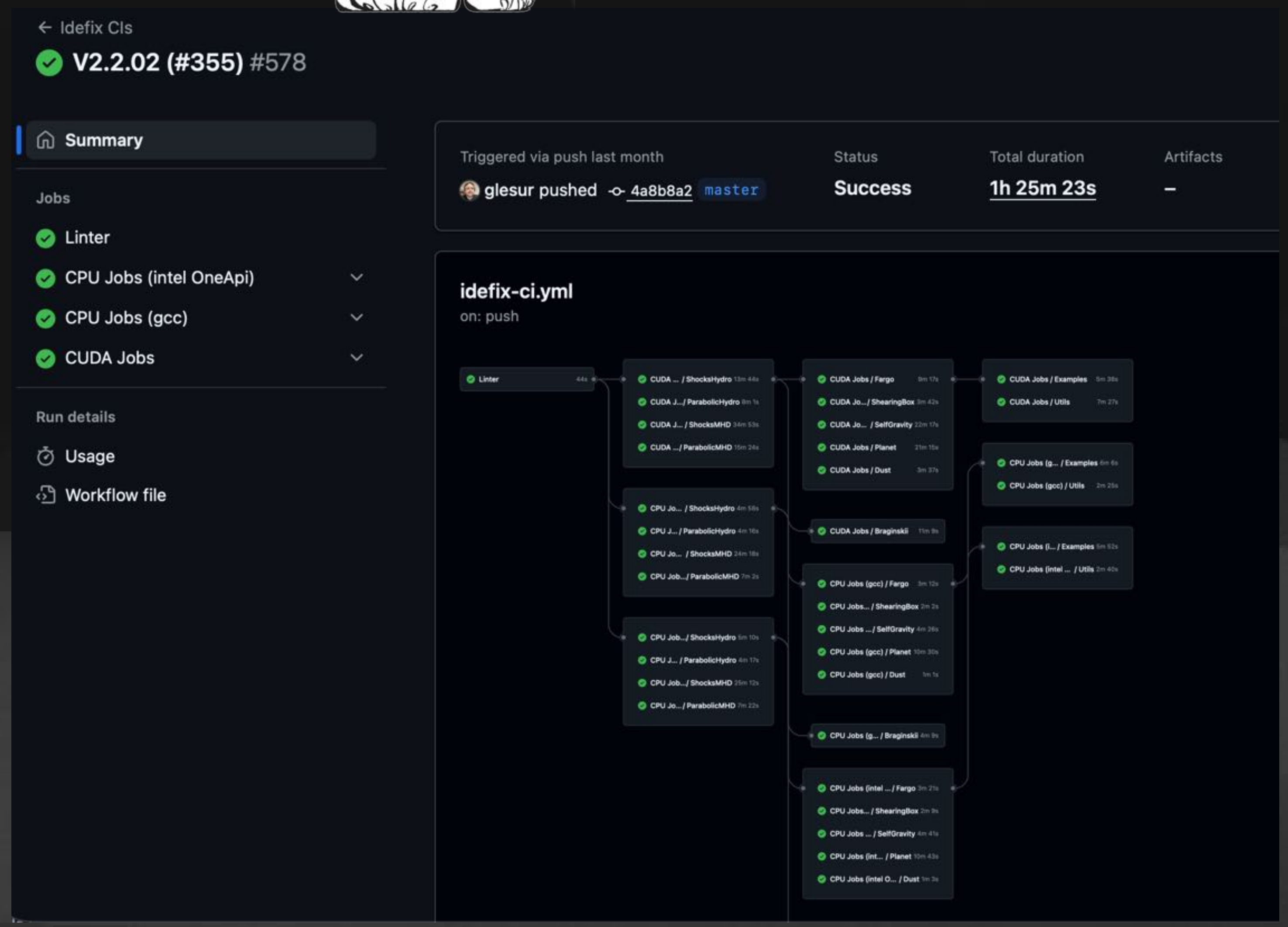
and the Idefix contributors

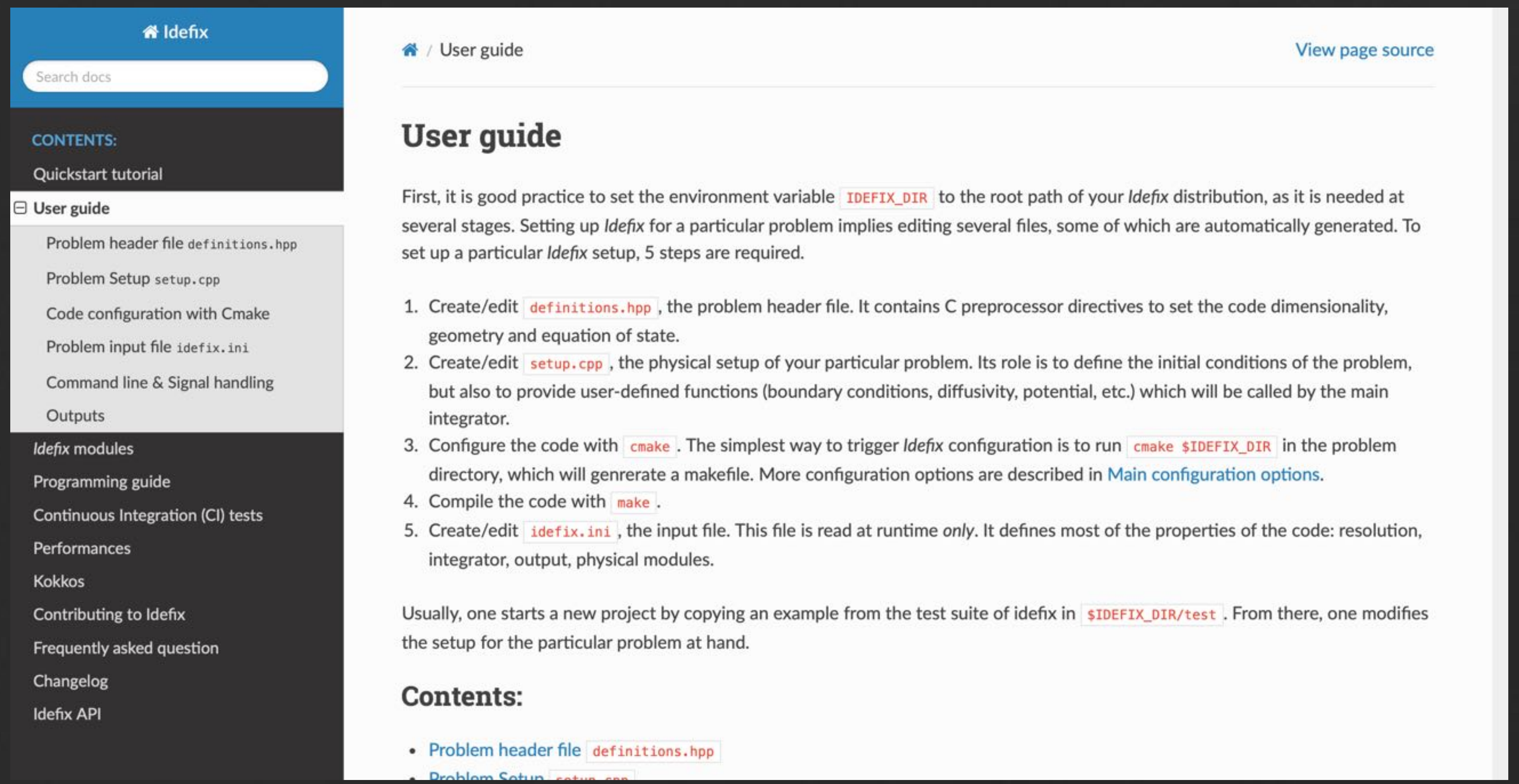
Université Grenoble Alpes
IPAG Institut de Planétologie et d'Astrophysique de Grenoble
MHD@EXASCALE Fast & efficient simulations for astrophysics
FRANCE 2030 PROGRAMME DE RECHERCHE ORIGINES

The Idefix code in a nutshell (I)

- Idefix = finite-volume Godunov code in C++ 17, relying on Kokkos
  - Aim: fast, smart and physicist-friendly
  - Constrained transport for the MHD module ($\nabla \cdot B = 0$)
  - No AMR, but non-cartesian stretched grids allowed
- Inputs, outputs and data structures are very similar to PLUTO: simplified setup portability
- Collaborative: pull requests, issues and discussions on the **public** GitHub repository
- Quality check: code validation for each PR on Nvidia GPUs and CPUs (intel & gcc compilers)
- Code under CECILL license, available on GitHub
- Method paper: Lesur+2023



Testing pipeline (GitHub actions)

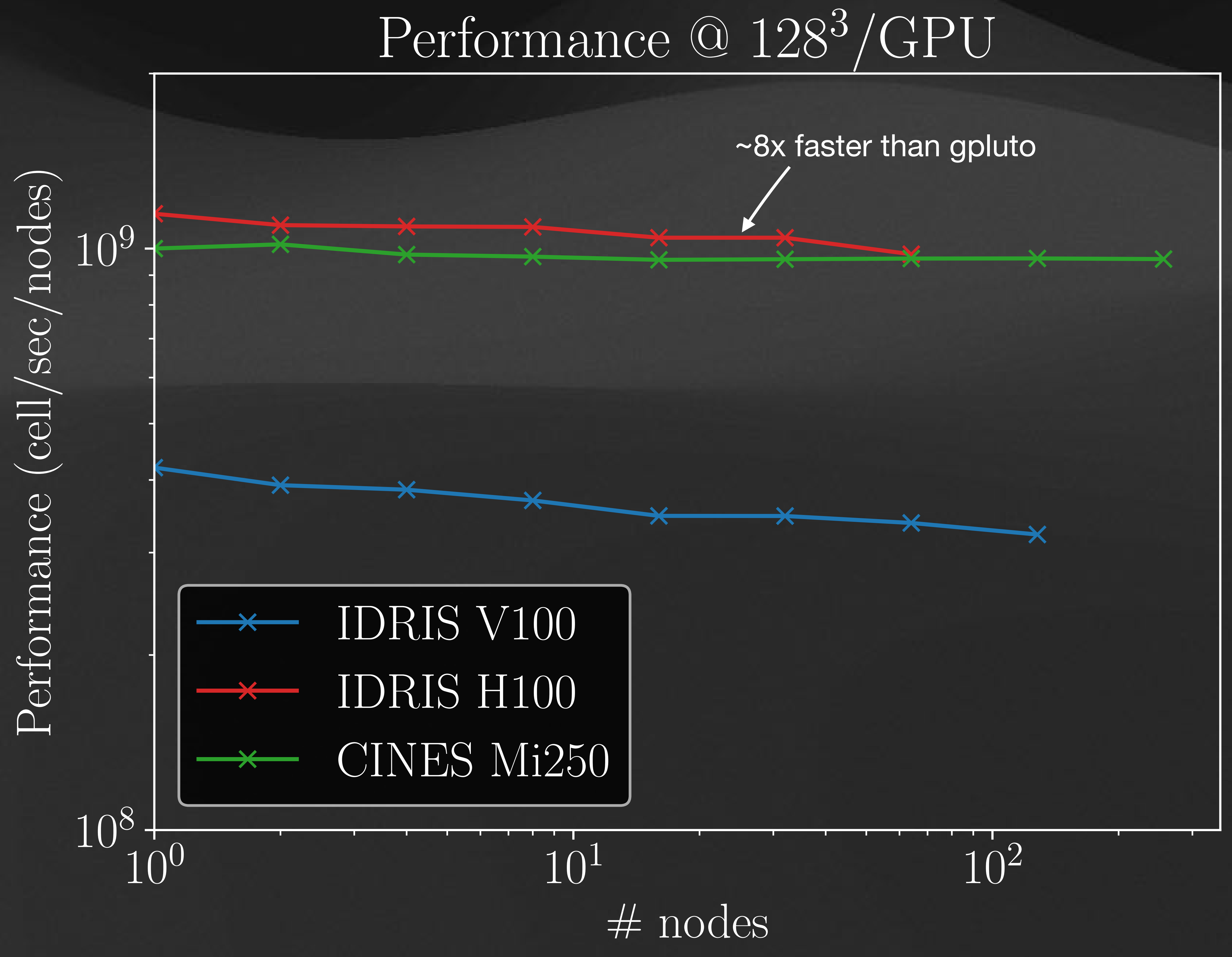


Automatically updated documentation

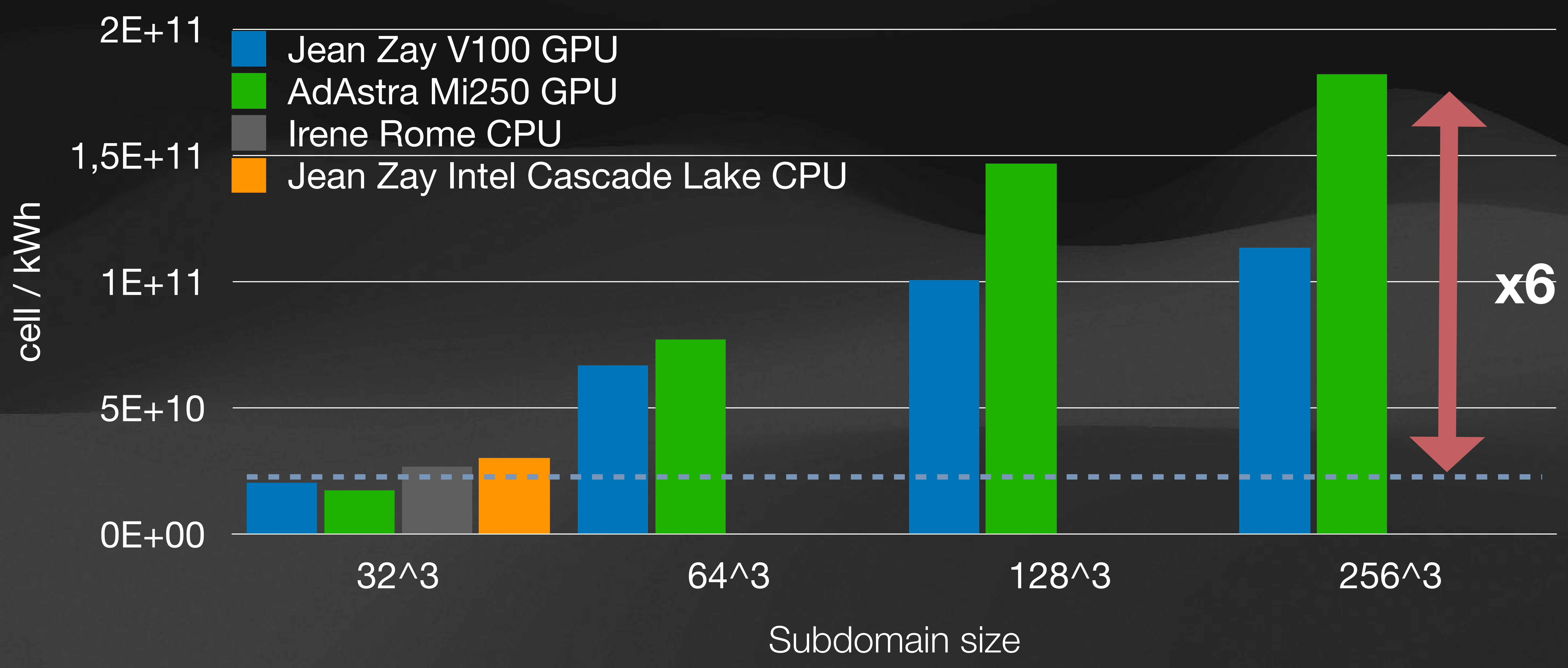
The Idefix code in a nutshell (II)

What does it give you?

Feature	Status
HD & MHD (Constrained transport)	public
Multiple Riemann solvers (Lax, HLL, HLLC/D, Roe)	public
Geometry (cartesian, cylindrical, spherical, polar)	public
Non-ideal MHD (Ohmic, Ambipolar, Hall)	public
MPI, MPI+OpenMP, MPI+Cuda, MPI+HIP, MPI+Sycl	public
Super time-stepping (RKL scheme:)	public
Orbital advection (FARGO)	public
Self gravity (Bicgstab)	public
Dust (particle approach)	on demand
Dust (fluid approach)	public
Radiative transfer (M1 scheme)	on demand
Python interface « pydefix »	public



Idefix Energy efficiency



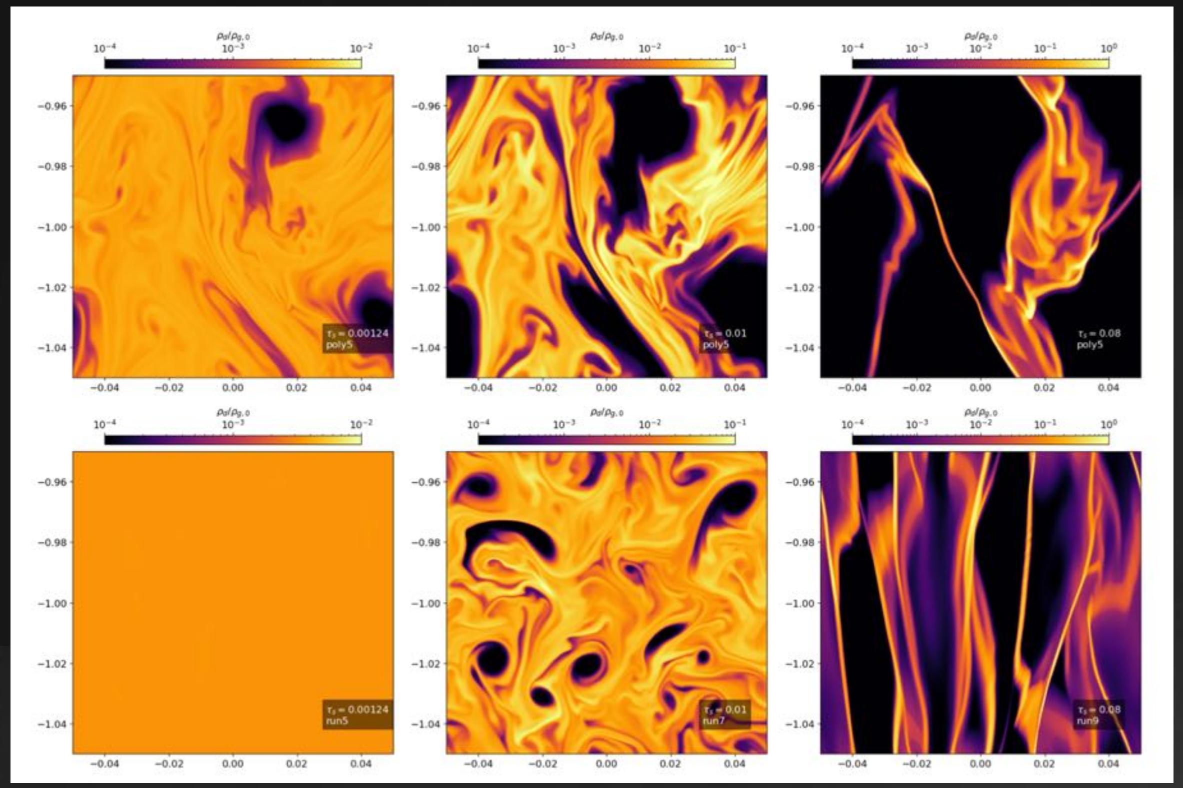
Running the same problem on a GPU is up to 6 times more energy efficient

but

Strong dependence on the domain size!

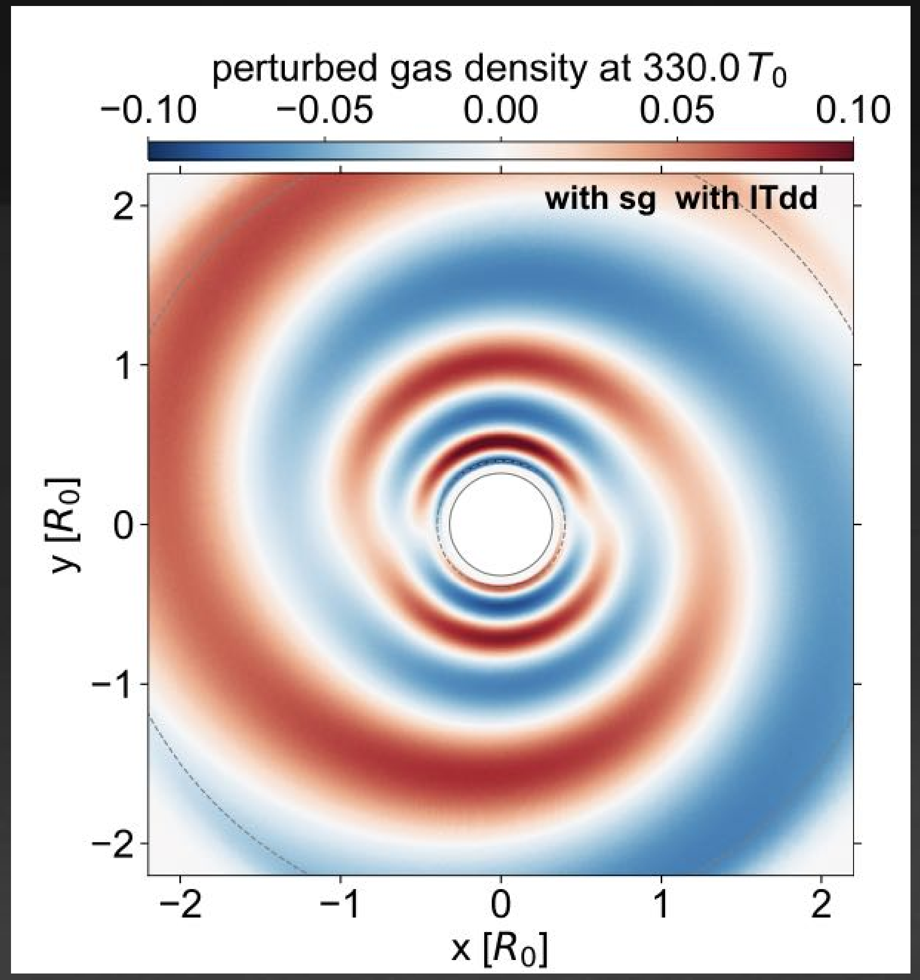
The Idefix code applications

Dust settling resonant drag instability



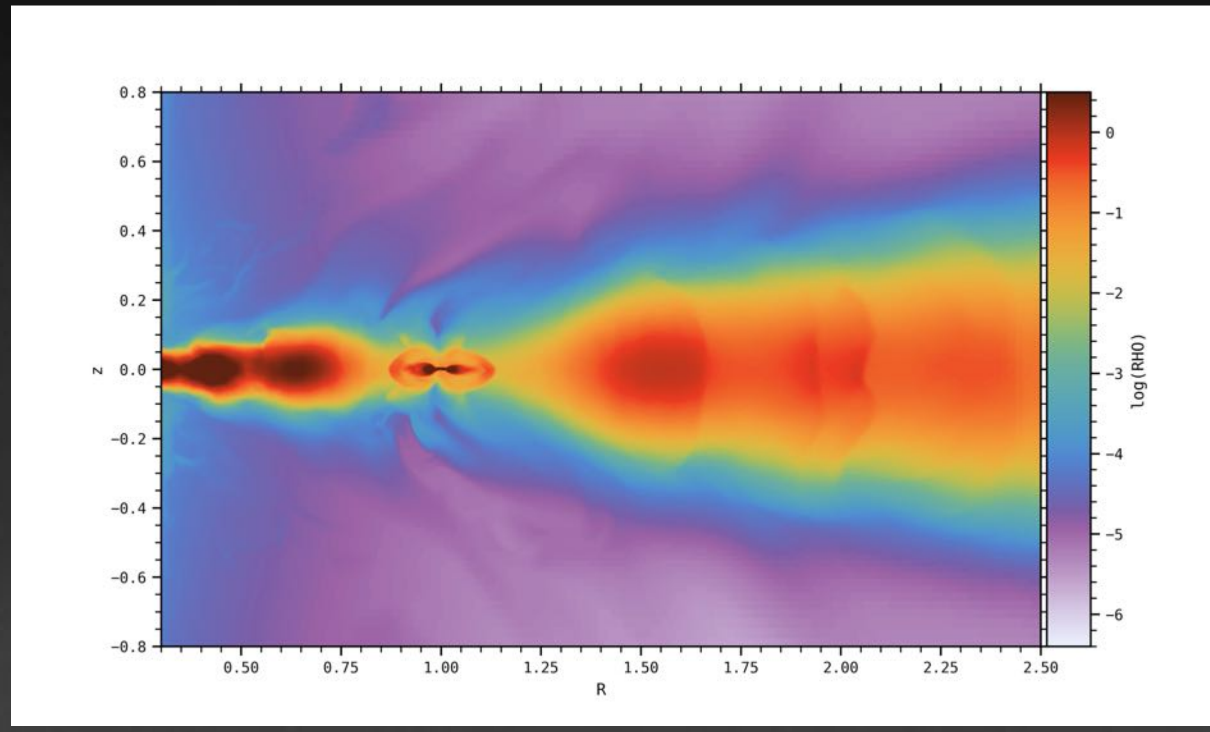
Aly & Paardekooper 2025

Reflex instability



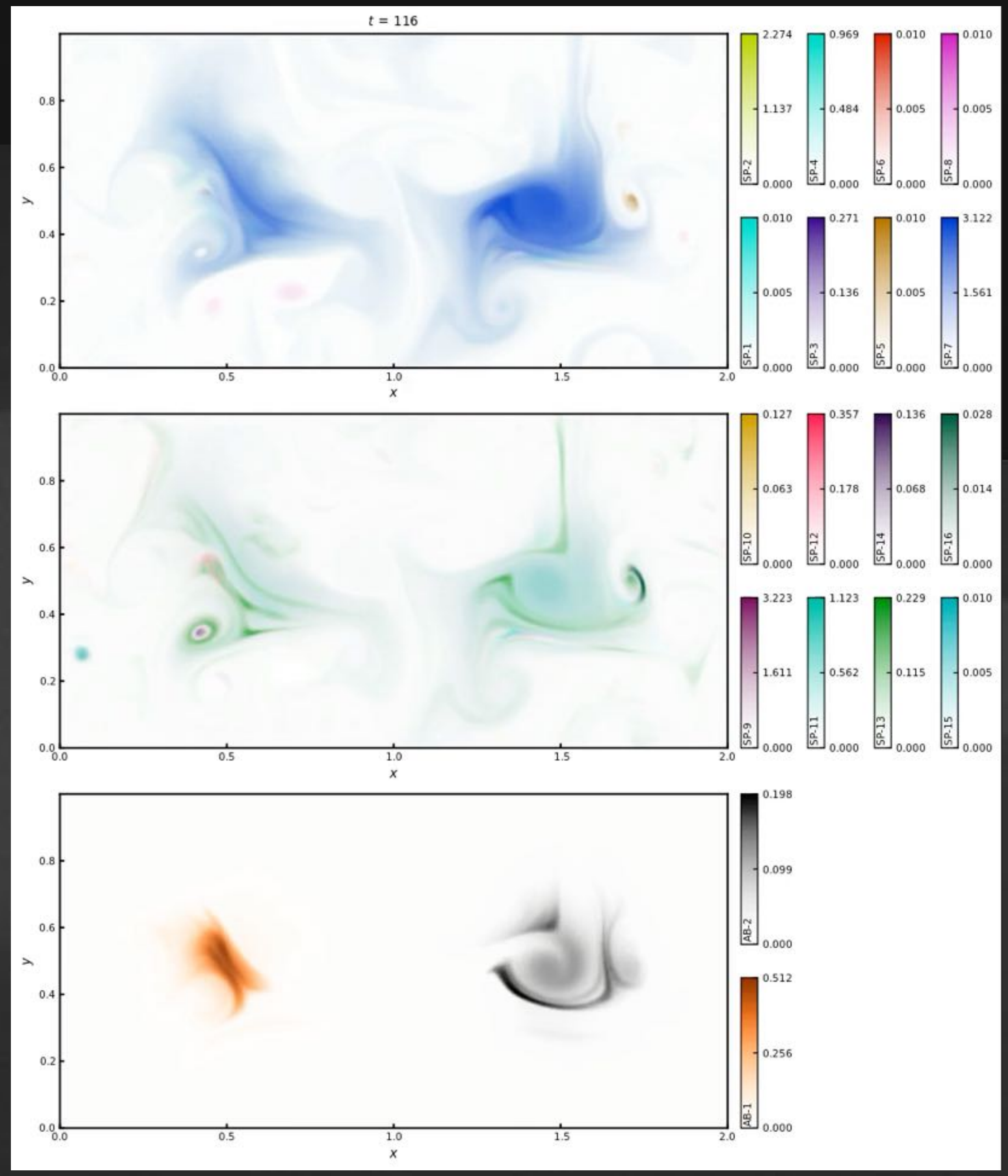
Crida+2025

Planet migration



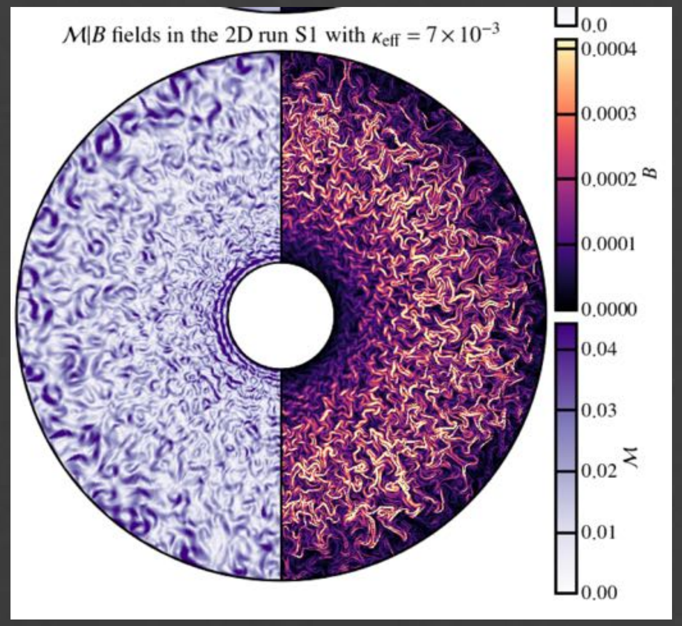
Wafflard-Fernandez+ 2025

Ecology: trophic network in turbulent flows (application to oceans+plankton)



Rincon+2025

Magneto-thermal instability in galaxy clusters

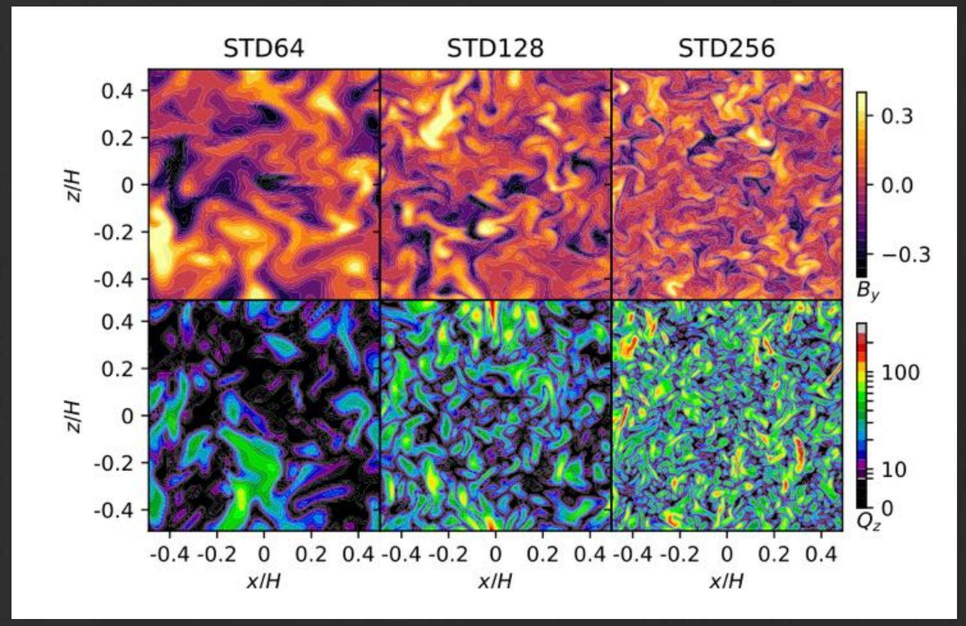


Kempf & Rincon 2025

Magnetospheric interaction

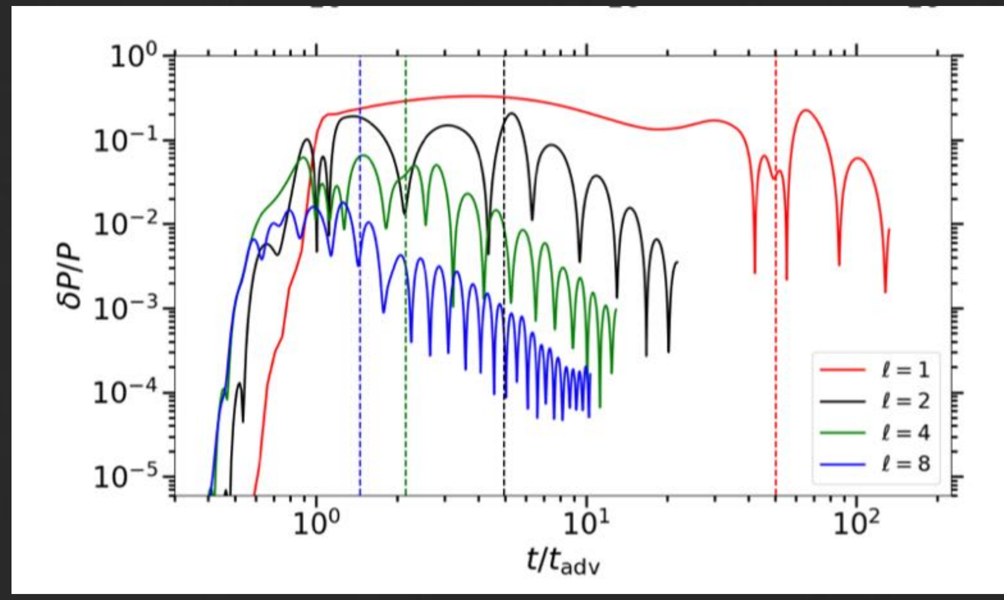
Lesur+2026

MRI turbulence



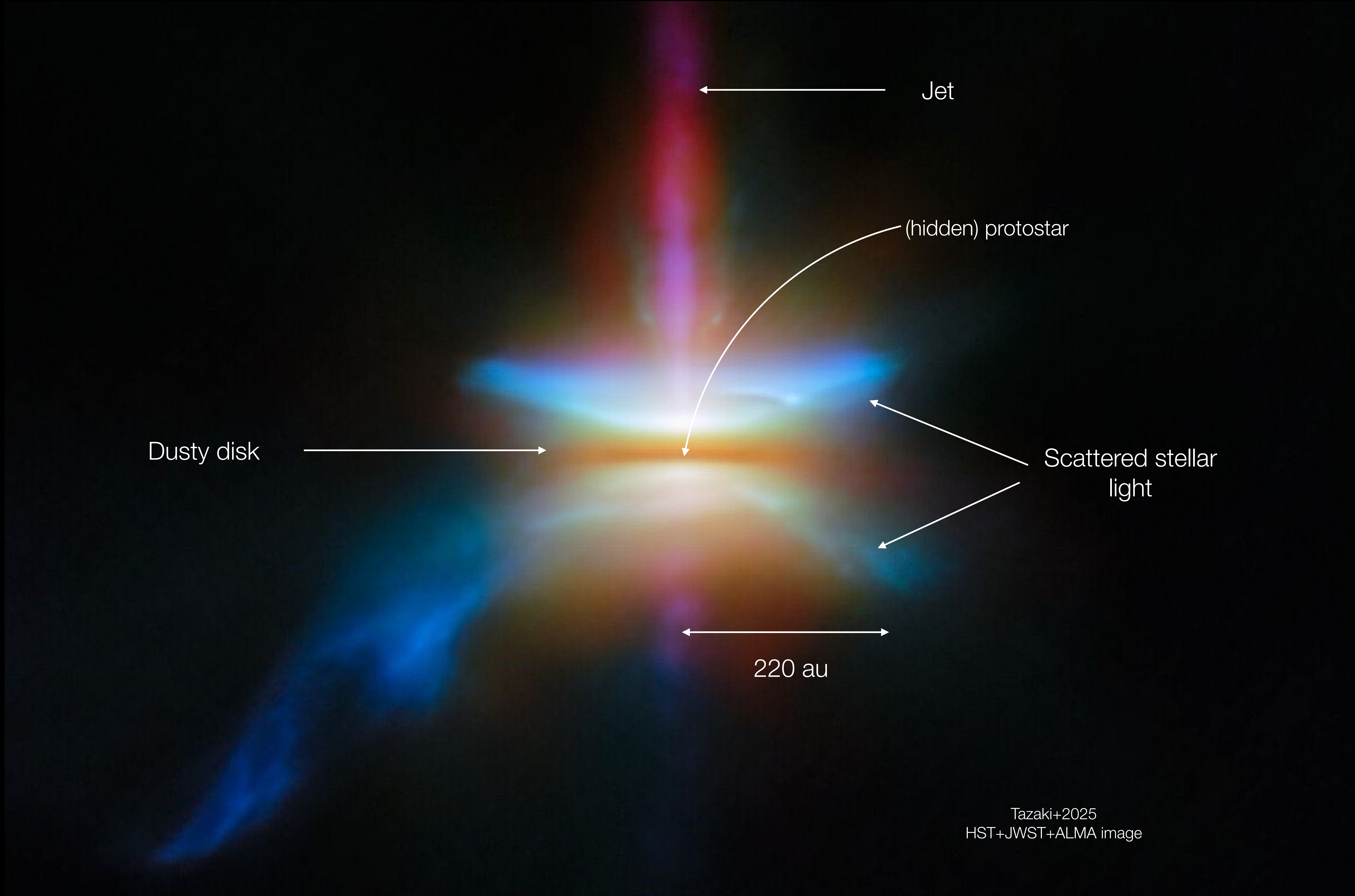
Jannaud & Latter 2025

Vortices in collapsing stars



Telman+2025

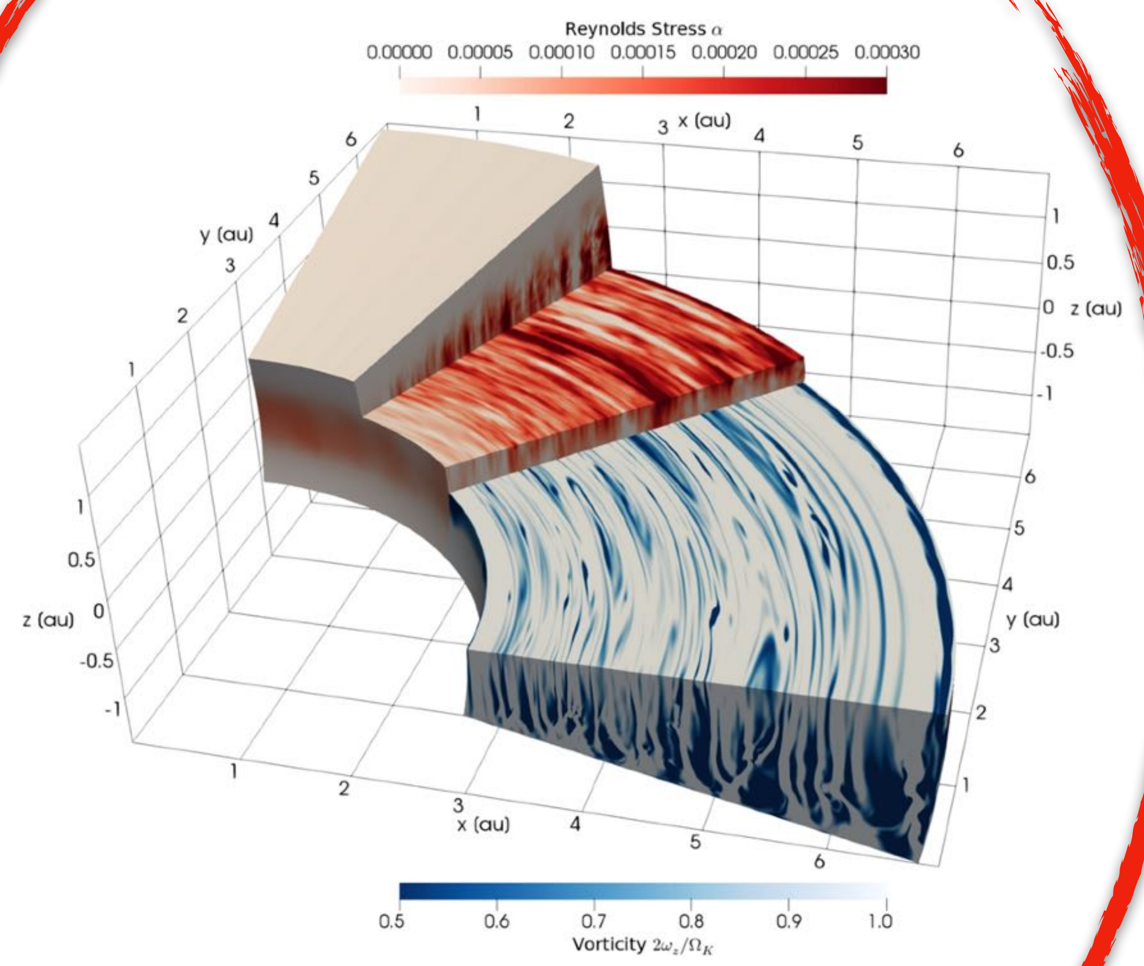
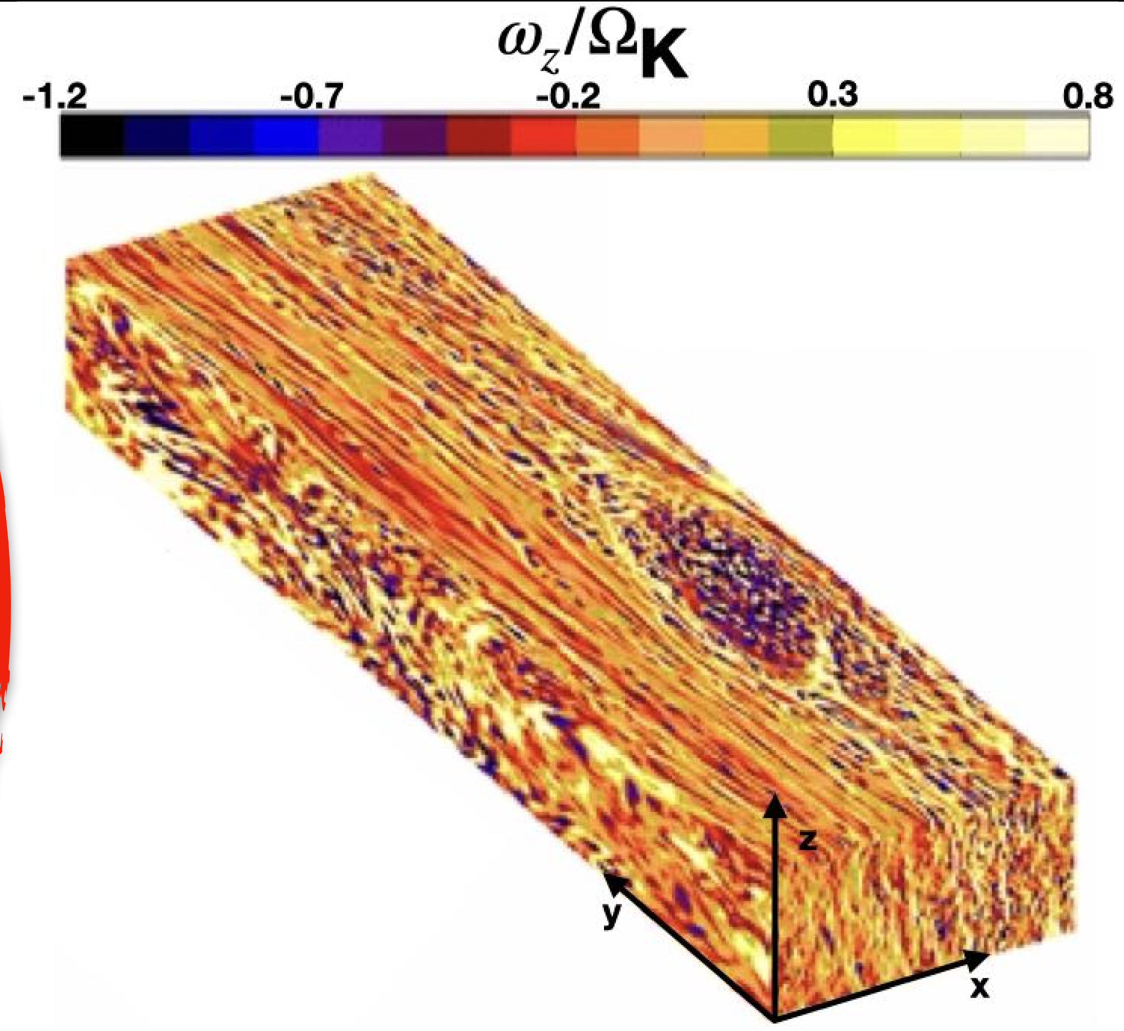
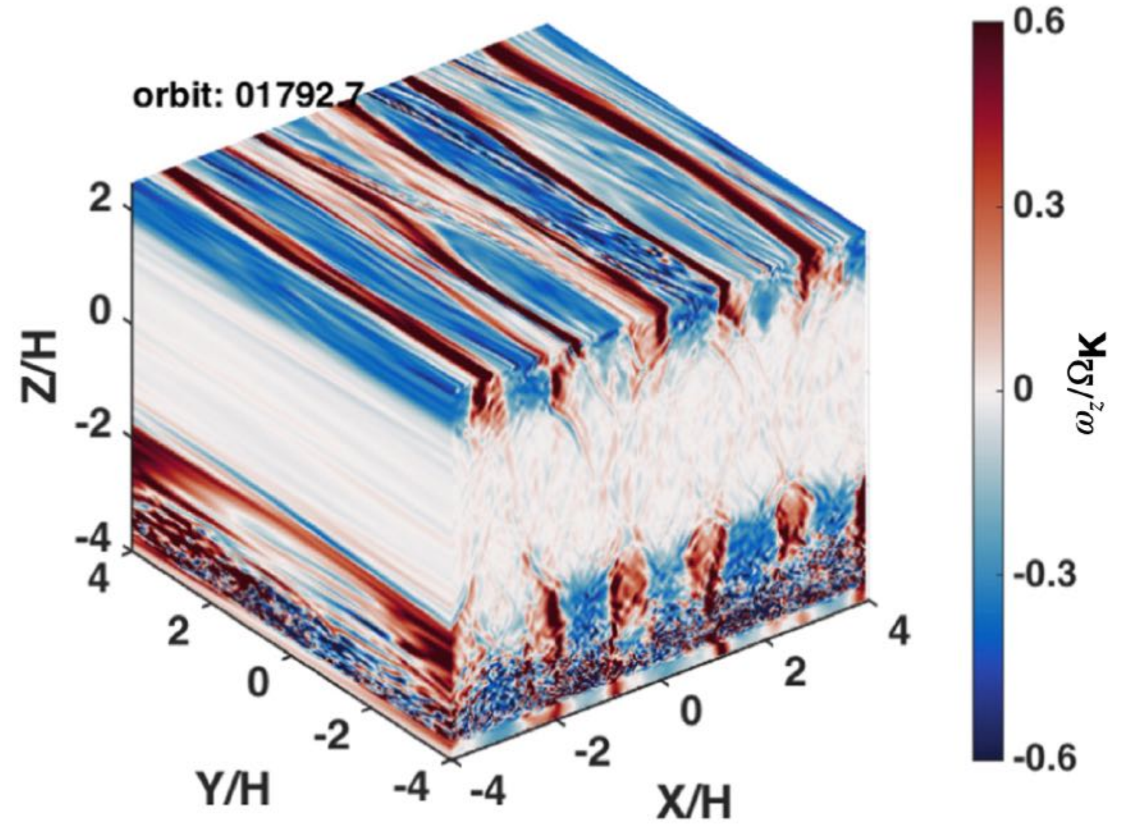
An application to protoplanetary disks



Jet
(hidden) protostar
Dusty disk
Scattered stellar
light
220 au
Tazaki+2025
HST+JWST+ALMA image

Hydrodynamical instabilities in disks

[Lesur+2023,PPVII]

Vertical Shear Instability	Convective Overstability	Zombie Vortex Instability
		
$\tau_{\rm cool}\Omega_{\rm K} \ll 1$	$\tau_{\rm cool}\Omega_{\rm K} \sim 1$	$\tau_{\rm cool}\Omega_{\rm K} \gg 1$
$q \neq 0$	$-1 < p/q < 1/(\gamma - 1)$	$\lvert z\rvert \gtrsim \sqrt{\gamma/(\gamma-1)}H$
$\alpha_{\rm S} \sim 10^{-4}$	$\alpha_{\rm S} \sim 10^{-3}$	$\alpha_{\rm S} \sim (10^{-5}\text{–}10^{-4})^{\dagger}$
Outcome: turbulence & vortices		

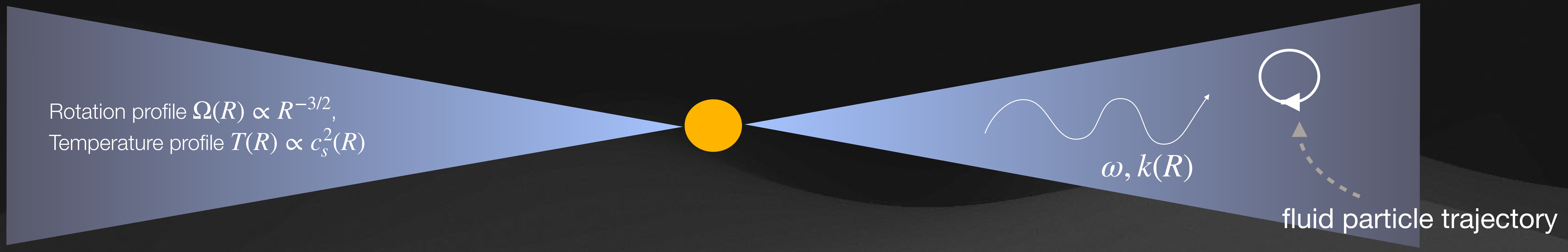
Fast cooling

Slow cooling

Isothermal perturbations

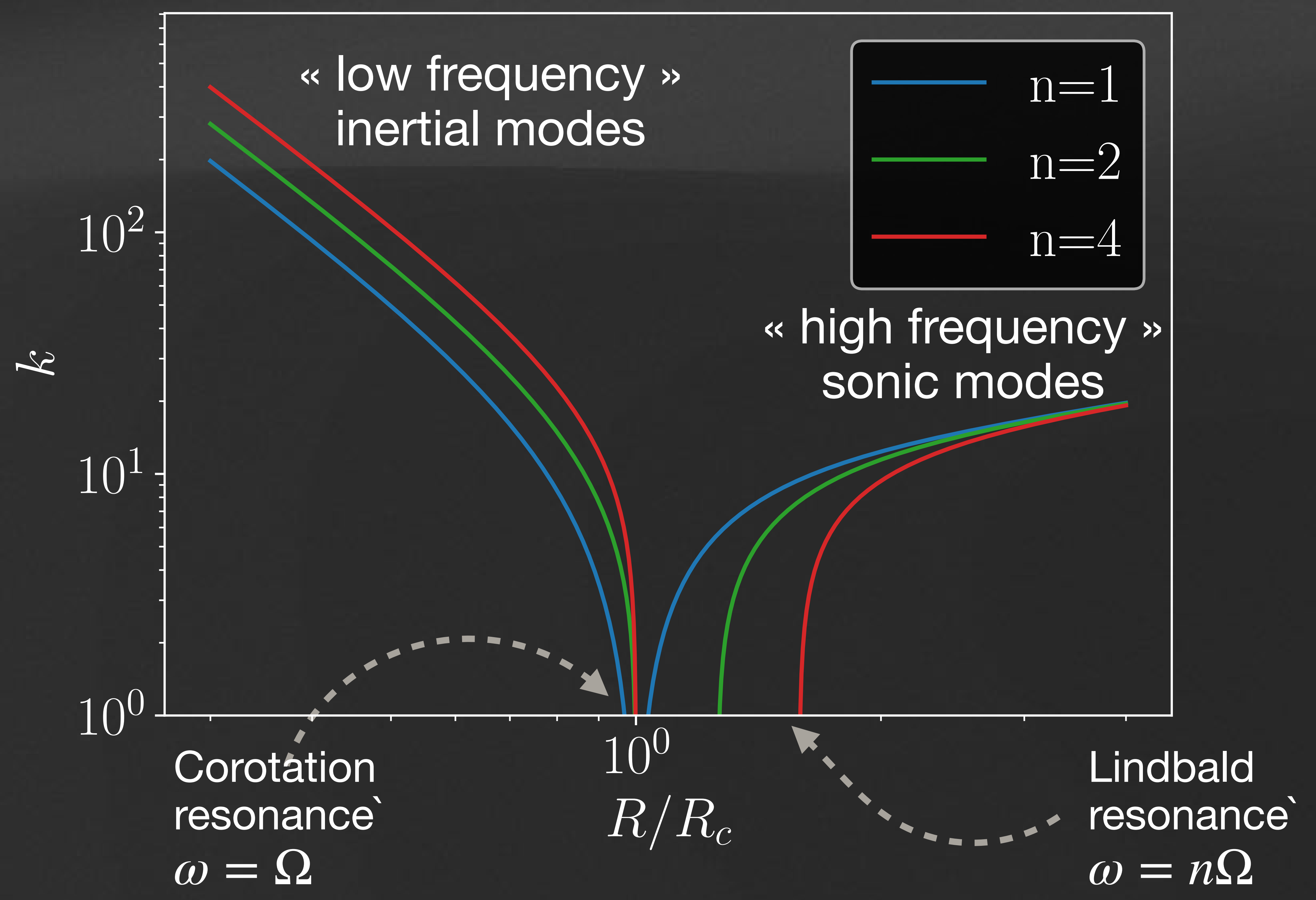
Adiabatic perturbations

Wave modes in an isothermal disk



- Dispersion relation in an isothermal disk:
  $(\omega^2 - n\Omega^2)(\omega^2 - \Omega^2) = (\omega c_s k)^2$ [Lubow & Pringle 1993]

vertical wavenumber



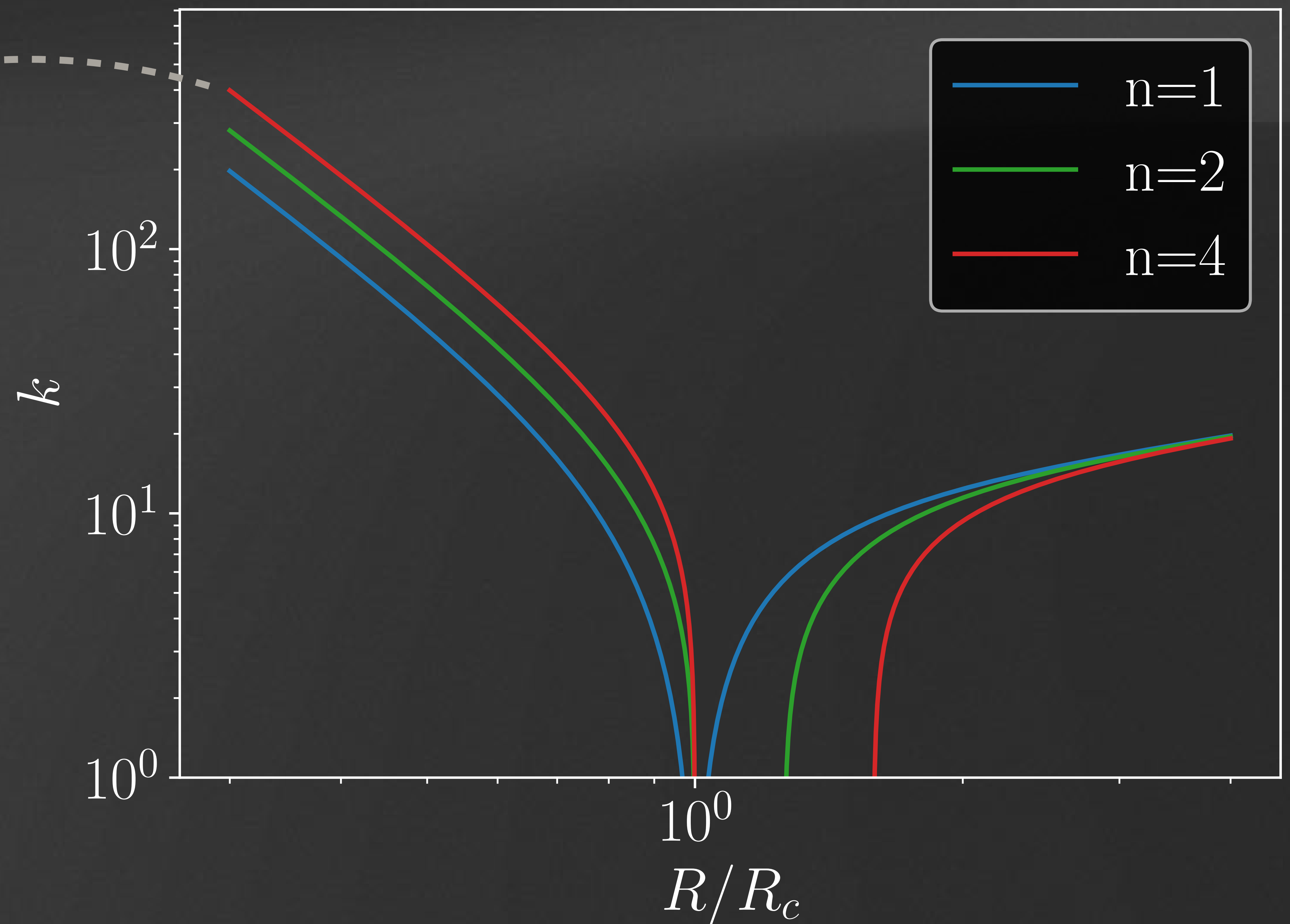
Vertical shear in disks

thermal wind equation $$\partial_z \Omega^2 = -\frac{1}{R\rho^2}(\partial_z \rho \partial_R P - \partial_R \rho \partial_z P)$$

→ Astrophysical disks are generally subject to a vertical shear

$$\omega = \frac{\sqrt{n}\Omega}{kH}(1 + ikHq)$$

vertical shear parameter



Overstable inertial modes
=
« Vertical shear instability »
(VSI)

Open questions about the VSI

- Theory predicts that large n modes should be the most unstable, is it the case in practice? How does the VSI saturates?
- Do large scale inertial modes survive in the non-linear regime?
- What happens at corotation resonance (where inertial modes should vanish?)
- Does it transport angular momentum?
- Does it generate long-lived vortices? [Richard, Nelson, Umurhan 2015]

EuroHPC Extreme scale project
~4000 GPUs used simultaneously for 2.5 months

Running on a pre-exascale machine

A long and winding road (I)

```
Gravity: central mass gravitational potential ENABLED with M=1
TimeIntegrator: using 3rd Order (RK3) integrator.
TimeIntegrator: Using adaptive dt with CFL=0.8 .
TimeIntegrator: will stop after 43.5 hours.
Main: Creating initial conditions.
Main: Cycling Time Integrator...
TimeIntegrator:             time |           cycle |        time step | cell (updates/s) | MPI overhead (%)
TimeIntegrator:     0.000000e+00 |               0 |     1.000000e-06 |              N/A |              N/A
TimeIntegrator:     1.593742e-05 |              10 |     2.593742e-06 |     1.228411e+11 |         6.229152
TimeIntegrator:     5.727500e-05 |              20 |     6.727500e-06 |     1.263376e+11 |         6.696973
TimeIntegrator:     1.644940e-04 |              30 |     1.744940e-05 |     1.260329e+11 |         6.868502
TimeIntegrator:     4.425926e-04 |              40 |     4.525926e-05 |     1.260741e+11 |         6.713010
TimeIntegrator:     1.163909e-03 |              50 |     1.173909e-04 |     1.258320e+11 |         6.739630
TimeIntegrator:     3.034816e-03 |              60 |     3.044816e-04 |     1.251714e+11 |         6.986361
TimeIntegrator:     6.519082e-03 |              70 |     3.555275e-04 |     1.245450e+11 |         7.566431
TimeIntegrator:     1.007368e-02 |              80 |     3.553797e-04 |     1.238352e+11 |         8.051875
TimeIntegrator:     1.362683e-02 |              90 |     3.552368e-04 |     1.236095e+11 |         8.408736
TimeIntegrator:     1.717857e-02 |             100 |     3.550985e-04 |     1.230930e+11 |         8.999555
TimeIntegrator:     2.072898e-02 |             110 |     3.549738e-04 |     1.191618e+11 |        10.278076
...
TimeIntegrator:     6.680007e-02 |             240 |     3.539673e-04 |     8.560018e+10 |        31.998791
TimeIntegrator:     7.033955e-02 |             250 |     3.539236e-04 |     8.455433e+10 |        32.354674
TimeIntegrator:     7.387860e-02 |             260 |     3.538831e-04 |     8.536546e+10 |        31.871857
TimeIntegrator:     7.741726e-02 |             270 |     3.538455e-04 |     8.451818e+10 |        32.560332
...
TimeIntegrator:     3.213042e-01 |             960 |     3.533728e-04 |     7.226361e+10 |        39.876328
TimeIntegrator:     3.248379e-01 |             970 |     3.533726e-04 |     7.318458e+10 |        39.556451
TimeIntegrator:     3.283717e-01 |             980 |     3.533725e-04 |     7.281833e+10 |        39.854619
TimeIntegrator:     3.319054e-01 |             990 |     3.533724e-04 |     7.167976e+10 |        40[illegible]
Main: Reached maximum number of integration cycles.
Main: Reached t=0.335439
Main: Completed in 10 minutes 53 seconds and 1000 cycles
Main: Perfs are 8.174090e+10 cell updates/second
MPI overhead represents 34% of total run time.
```

Diagnostic: GPU overheating due to algae growing in the cooling water pipes

A long and winding road (II)

```
MPICH ERROR [Rank 3284] [job id 6471201.0] [Mon Mar 25 16:22:20 2024] [nid006342] - Abort(1009397903) (rank 3284 in comm 0): Fatal error in PMPI_Waitall:
Other MPI error, error stack:
PMPI_Waitall(378)..............: MPI_Waitall(count=2, req_array=0x14bf148, status_array=0x7ffe3211d520) failed
MPIR_Waitall(167)..............:
MPIR_Waitall_impl(51)..........:
MPID_Progress_wait(201)........:
MPIDI_Progress_test(97)........:
MPIDI_OFI_handle_cq_error(1067): OFI poll failed (ofi_events.c:1069:MPIDI_OFI_handle_cq_error:Input/output error - UNDELIVERABLE)
...
srun: error: Node failure on nid005989
srun: Force Terminated StepId=6471201.0
slurmstepd: error: *** JOB 6471201 ON nid005280 CANCELLED AT 2024-03-25T16:29:07 DUE TO NODE FAILURE, SEE SLURMCTLD LOG FOR DETAILS ***
```

After two months of intense bug tracking and exchange with LUMI IT support…

failure rate […] is approximately 3 random GPU node failures per day observed (there are almost 3000 GPU nodes in total). This rough statistics gives at least some understanding of expected level of reliability or mean time to failure. In other words, current diagnosis is "bad luck".

→ a job on 1000s of GPUs is *expected to crash* over a 24 hours runtime

→(very) fast & reliable checkpointing system is mandatory

A long and winding road (III)

```
-rw-rw---- 1 lesurg l-ipag 2.2T Mar 29 22:13 data.0017.vtk
-rw-rw---- 1 lesurg l-ipag 2.2T Apr  6 00:10 data.0018.vtk
-rw-rw---- 1 lesurg l-ipag 2.2T Apr 23 04:52 data.0019.vtk
-rw-rw---- 1 lesurg l-ipag 2.2T Apr 25 17:49 data.0020.vtk
-rw-rw---- 1 lesurg l-ipag 2.2T May  4 22:06 data.0021.vtk
-rw-rw---- 1 lesurg l-ipag 2.2T May 11 23:29 data.0022.vtk
-rw-rw---- 1 lesurg l-ipag 2.2T May 29 17:21 data.0023.vtk
-rw-rw---- 1 lesurg l-ipag 2.2T Jun 11 06:51 data.0024.vtk
-rw-rw---- 1 lesurg l-ipag 2.2T Jun 23 06:52 data.0025.vtk
```

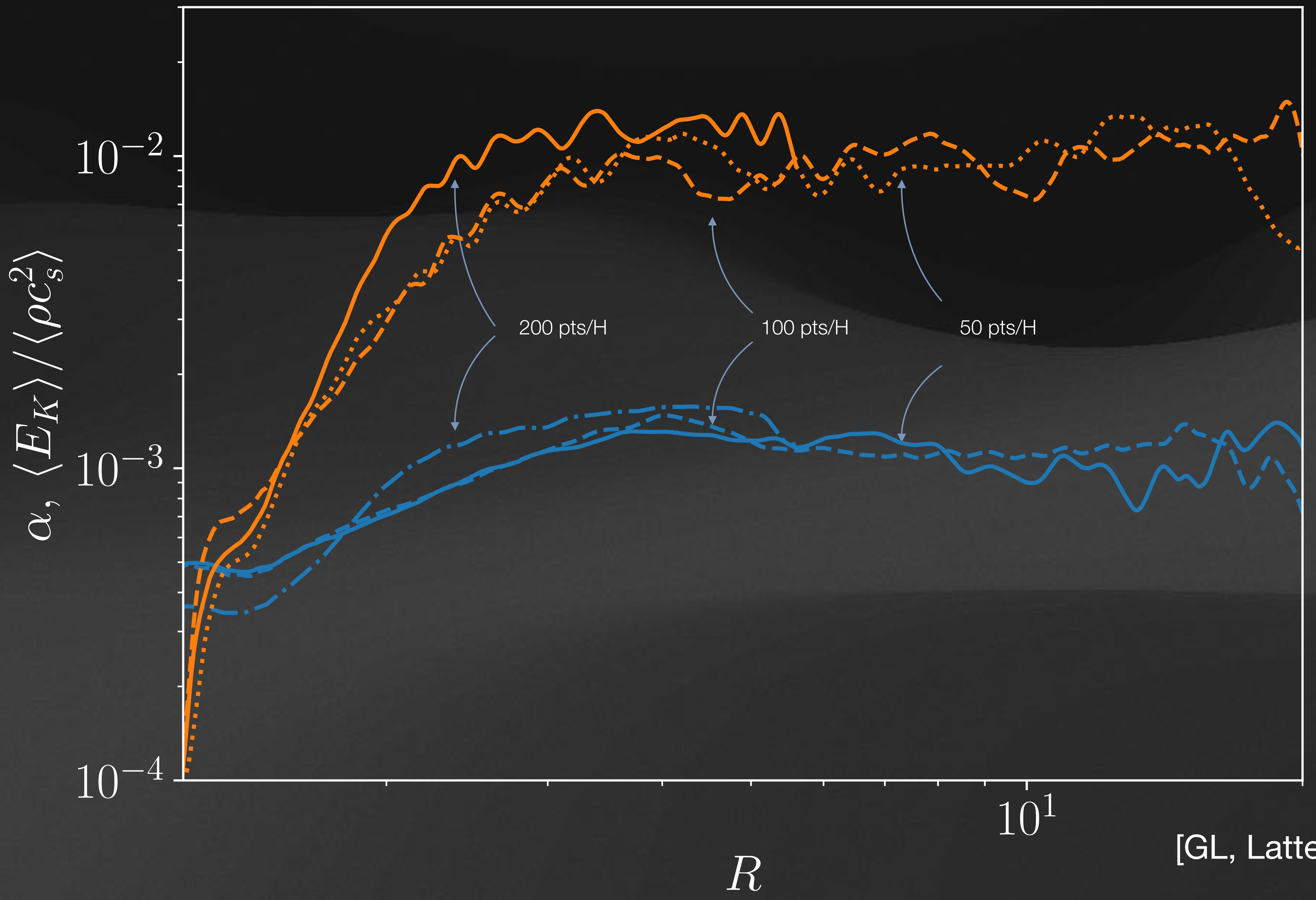
- Output snapshots are typically above 1TB
  (NB: idefix is efficient: ~5 minutes to write one of the above VTK file)
- We don’t have the ressources to directly load these files…

→ on-the-fly slicing and post-treatment

Some results!


Time=4994.369
Dust density
size=0.1mm, St=0.001
1.0e+00
0.1
0.01
0.001
0.0001
1e-5
1.0e-06
Dust3

Angular momentum transport & energetics

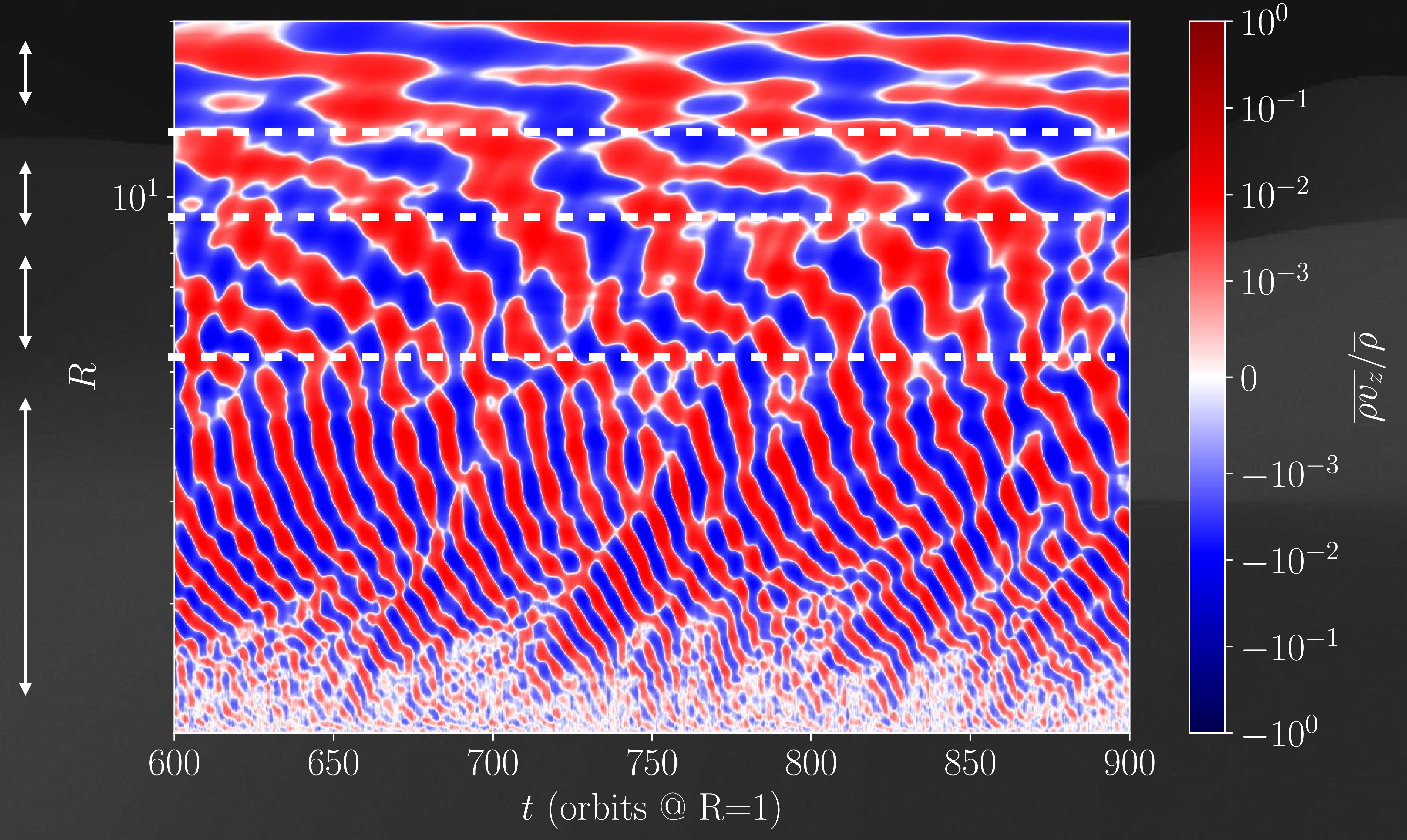


[GL, Latter & Ogilvie 2025]

- Convergence with resolution achieved
- Significant inner boundary « transition zone » with $\Delta R/R \sim 3$
- Gives $\alpha \sim 10^{-3}$

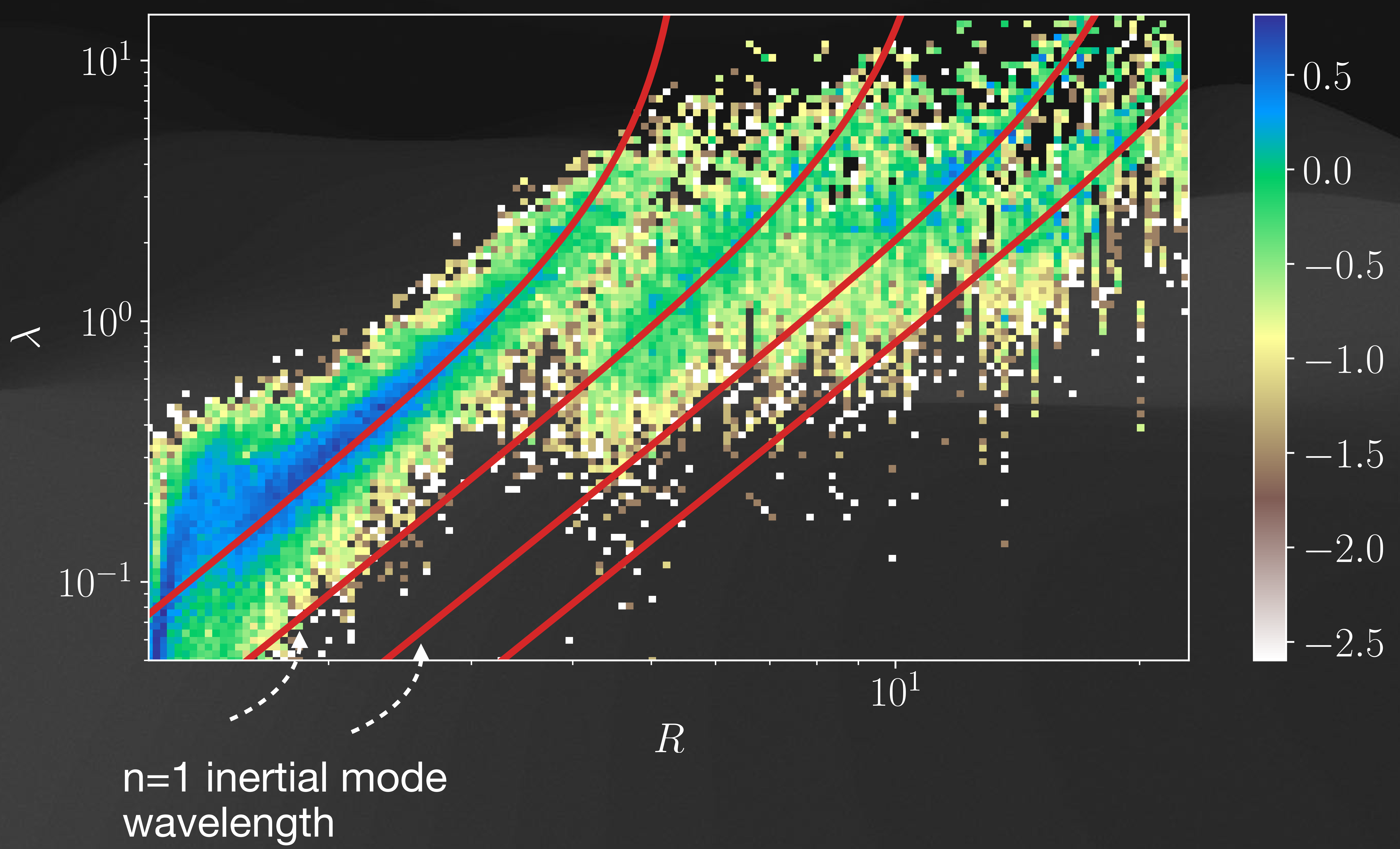
Wave pattern

wave regions

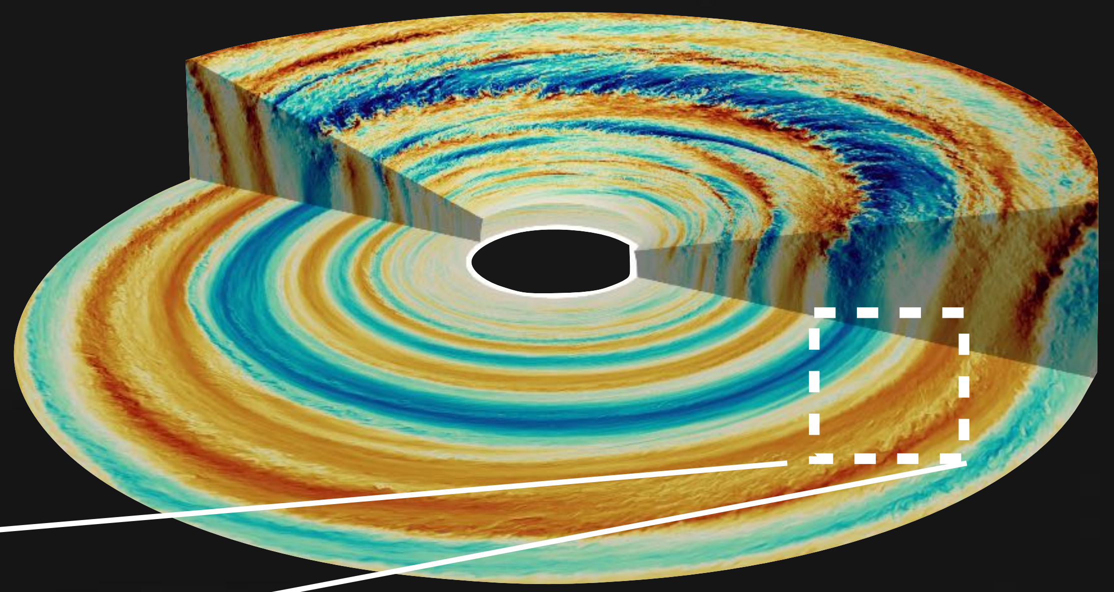


- The disk is divided into wave « zones » , each having a fixed frequency

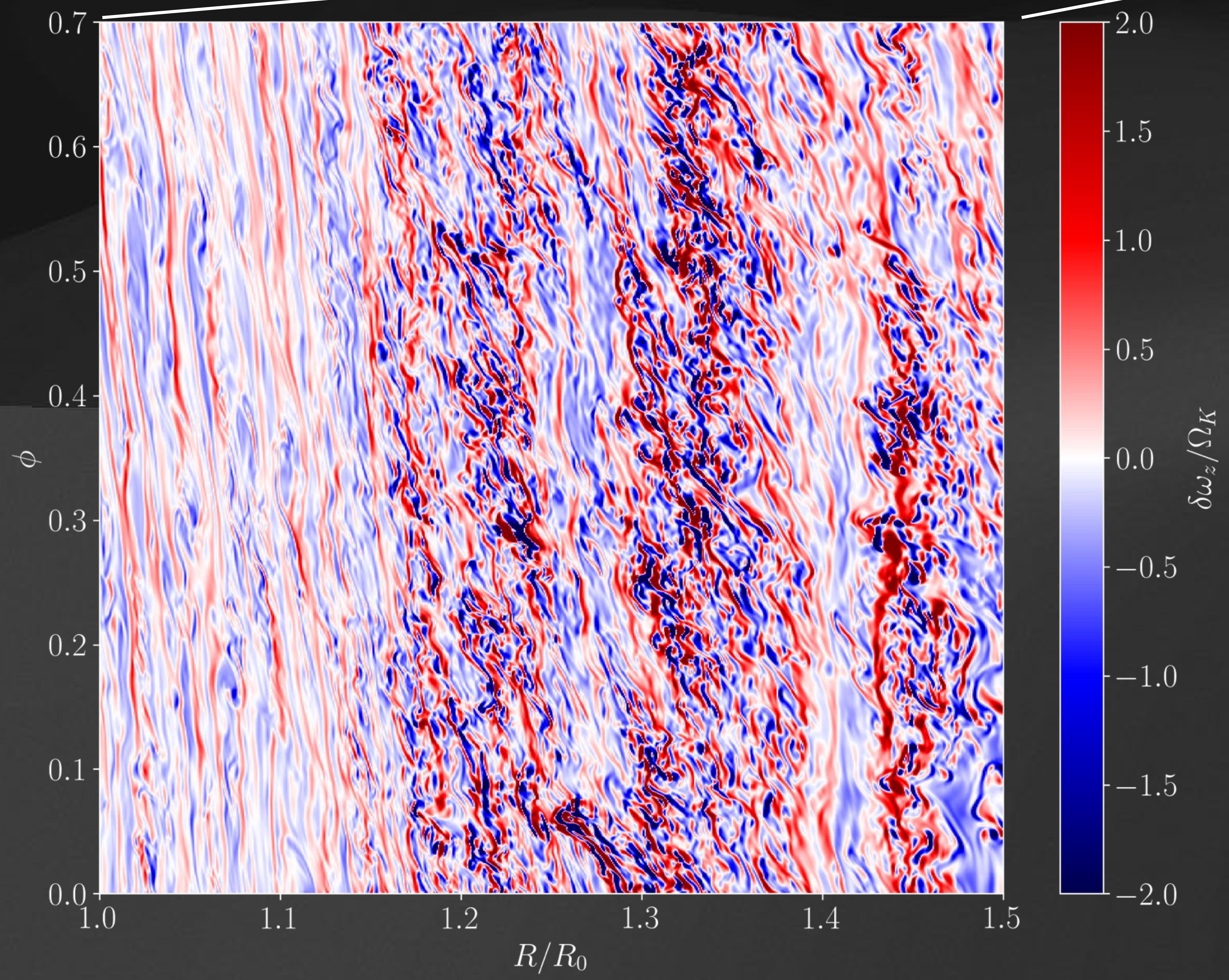
Wave pattern is n=1 inertial modes



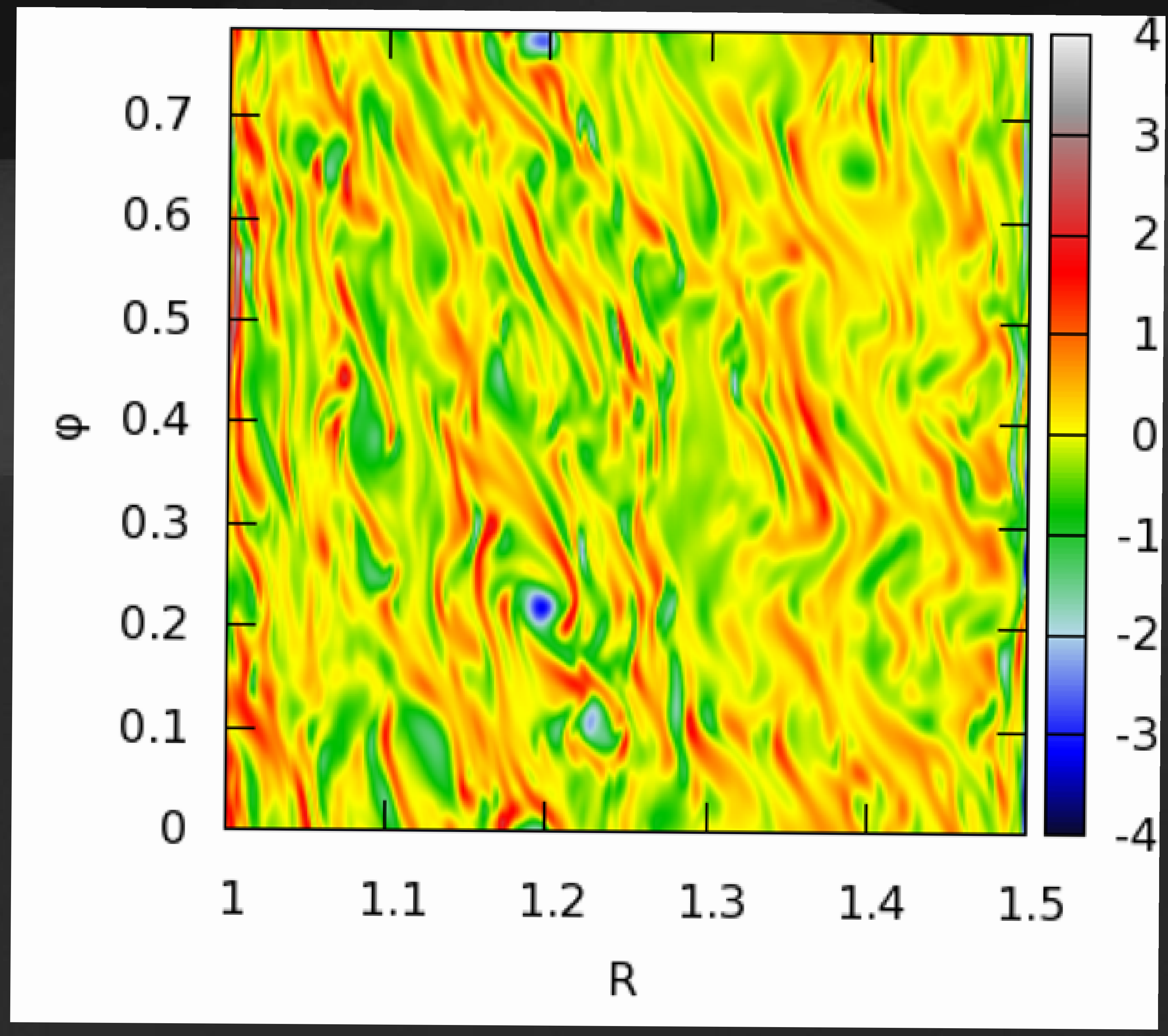
Vortices?



200 pts/H
[GL, Latter & Ogilvie 2025]



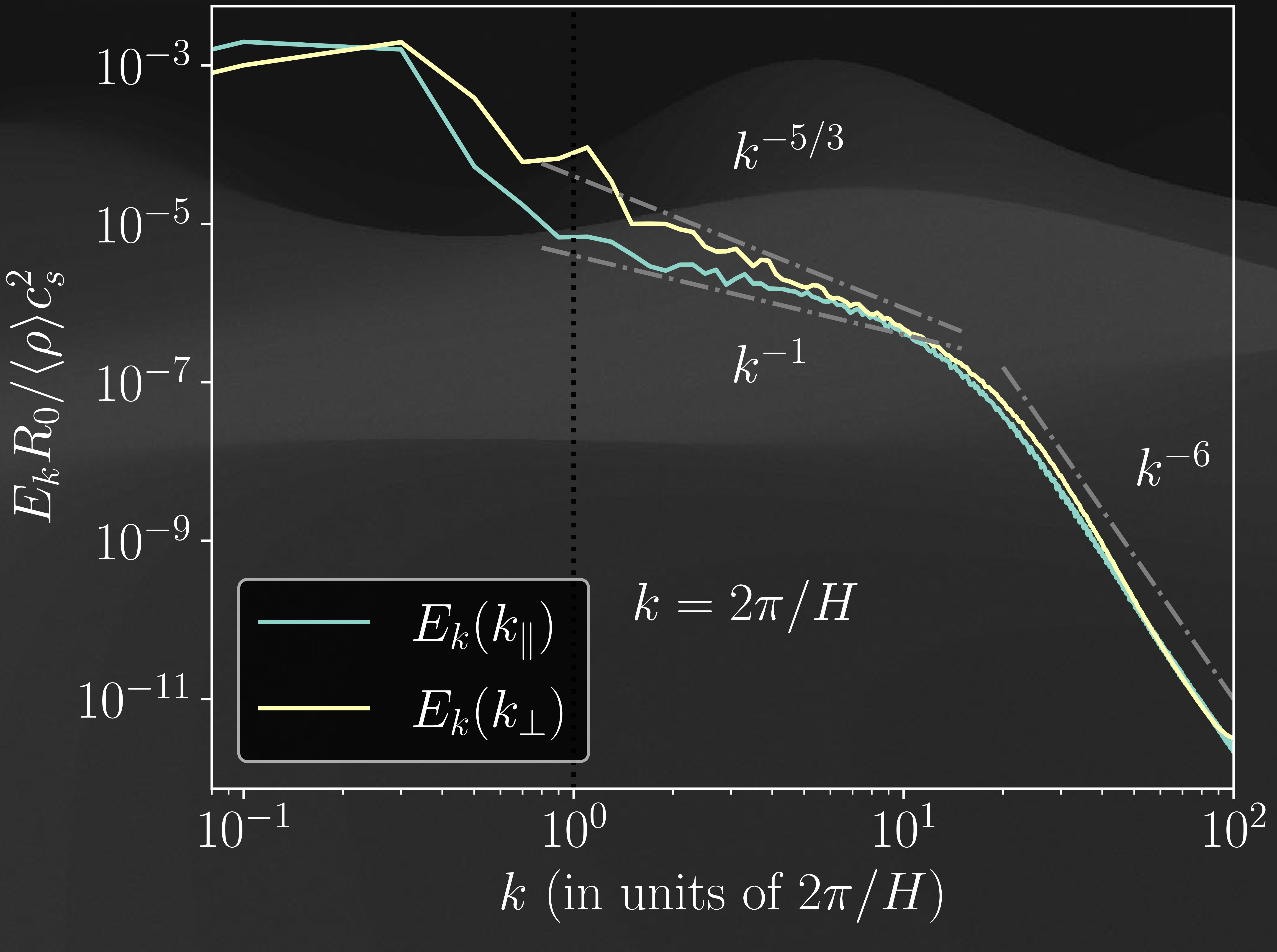
20 pts/H
[Richard, Nelson, Umurhan 2015]



Long-lived vortices seen in previous simulations are likely a low-resolution artefact

Turbulent spectrum

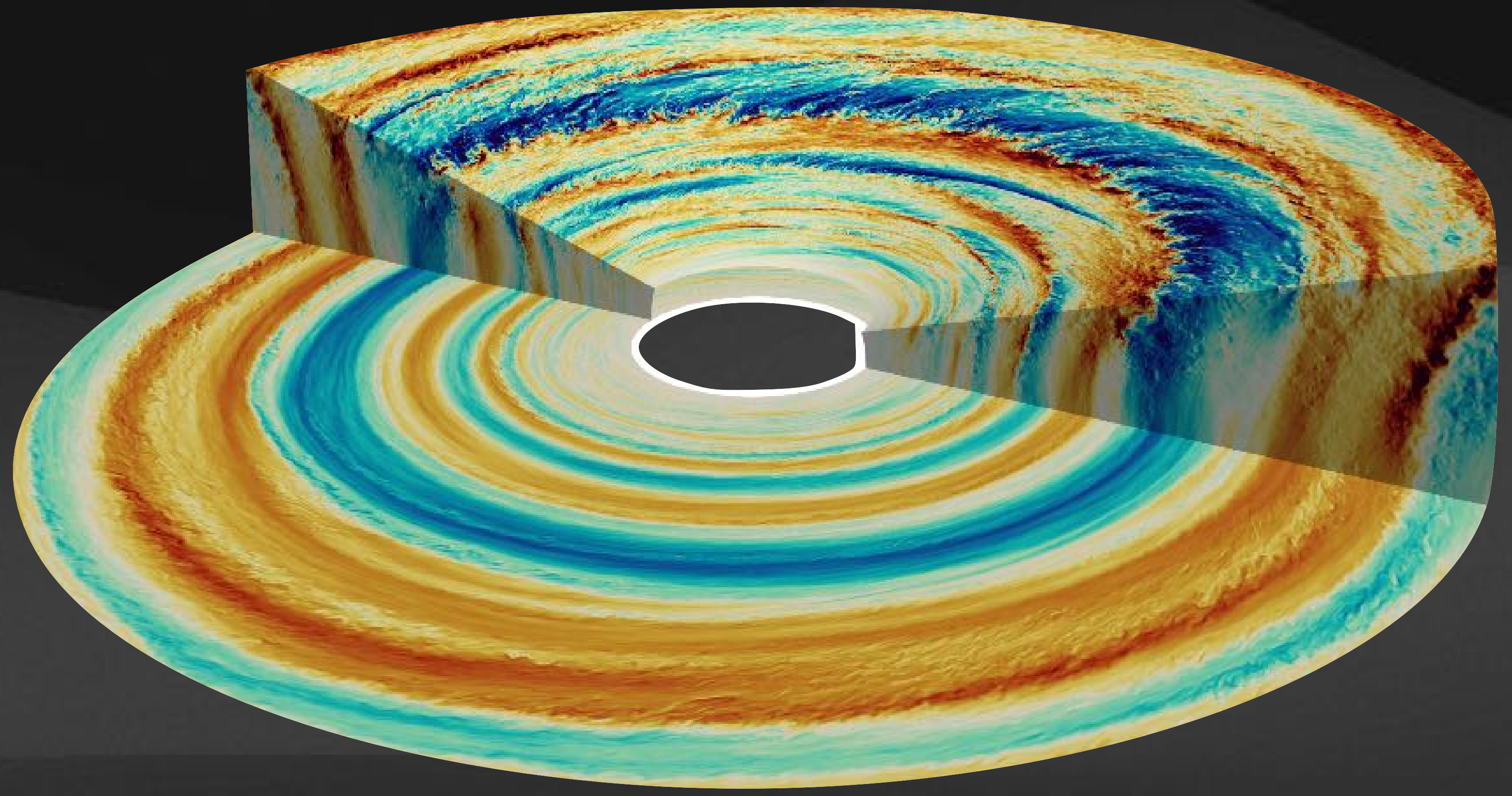
- Spectrum characteristic of critically-balanced rotating turbulence
  [Nazarenko & Schekochihin 2011]
- Grid dissipation → k^{-6}
- Still no proper Kolmogorov cascade despite resolution 200pts/H



Take home messages

Idefix is a production, versatile, exascale code for astrophysical flows

VSI turbulence produces large-scale n=0 inertial modes



Running on (pre)-exascale system is a burden because of high system failure rate and unexpected technological issues

Long-lived vortices disappear at high resolution