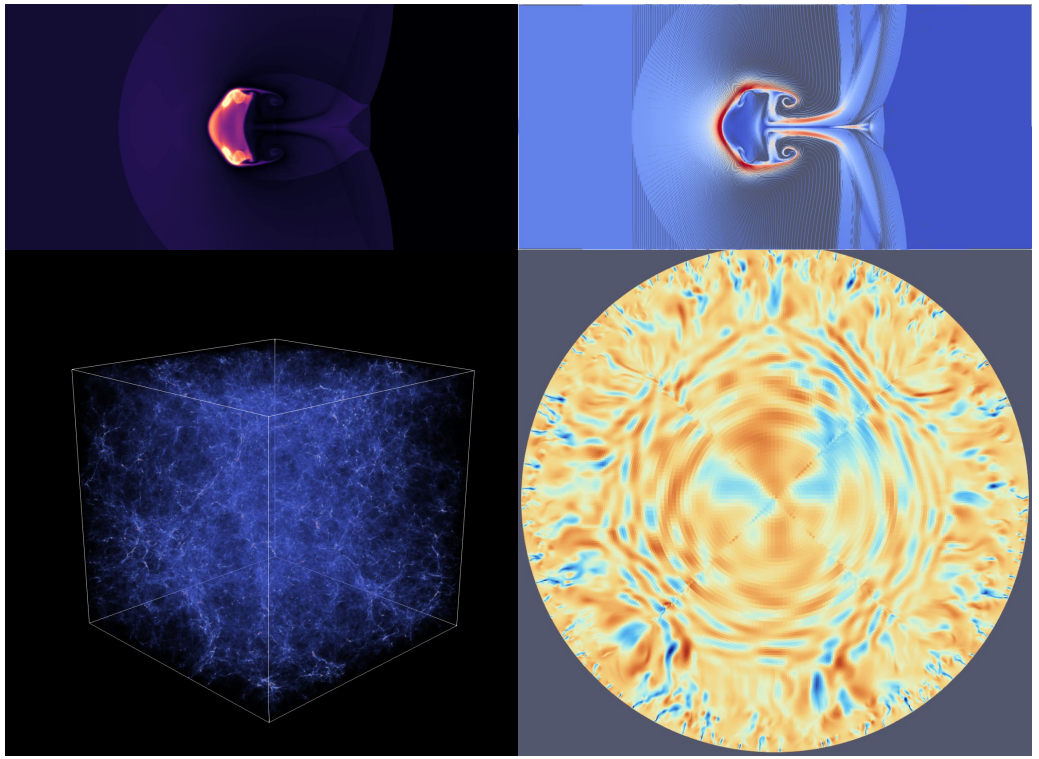
Dyablo:
An adaptive mesh refinement code at the era of Exascale computing



Journées de l'action spécifique numérique

15/12/2025

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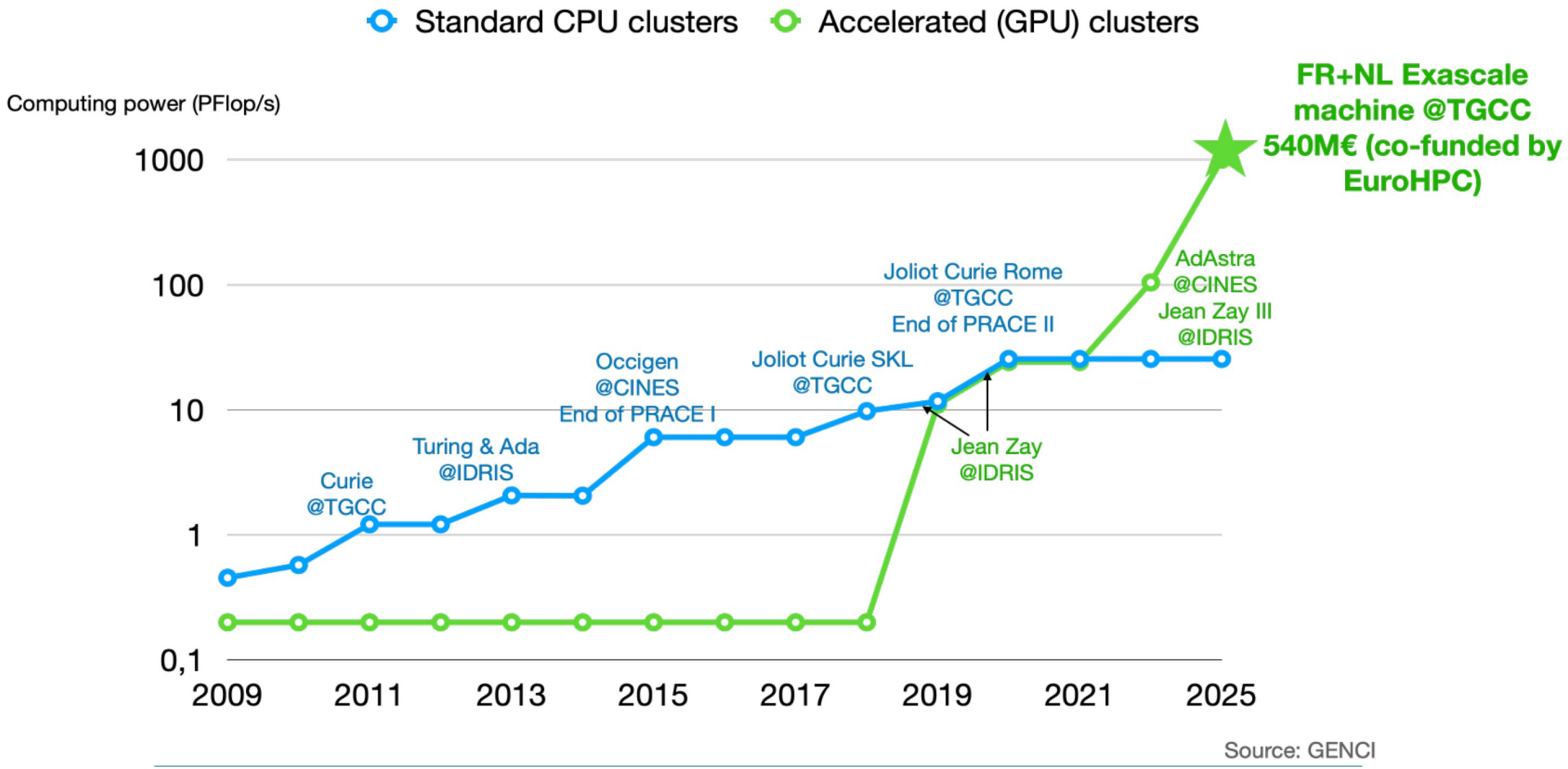
The problem with Exascale

(Thanks Julien)



Graph courtesy of G. Lesur/PEPR Origins

The problem with Exascale

Variety of architectures/vendors

- GPU is mandatory to reach target resolution/time-to-solution/efficiency
- Each vendor has their own formalism
- CUDA does not work on AMD, HIP does not work on Intel, etc.
- So what do we do ?
- The solution is performance portability:
  - Kokkos (Julien has talked about it before me)
  - SYCL (see Timothée's talk on Wednesday)
- Dyablo is an (one) answer to this.

Rank	System	Cores	Rmax (PFlop/s)	Rpeak (PFlop/s)	Power (kW)
1	**El Capitan** - HPE Cray EX255a, AMD 4th Gen EPYC 24C 1.8GHz, AMD Instinct MI300A, Slingshot-11, TOSS, HPE DOE/NNSA/LLNL United States	11,340,000	1,809.00	2,821.10	29,685
2	**Frontier** - HPE Cray EX235a, AMD Optimized 3rd Generation EPYC 64C 2GHz, AMD Instinct MI250X, Slingshot-11, HPE Cray OS, HPE DOE/SC/Oak Ridge National Laboratory United States	9,066,176	1,353.00	2,055.72	24,607
3	**Aurora** - HPE Cray EX - Intel Exascale Compute Blade, Xeon CPU Max 9470 52C 2.4GHz, Intel Data Center GPU Max, Slingshot-11, Intel DOE/SC/Argonne National Laboratory United States	9,264,128	1,012.00	1,980.01	38,698
4	**JUPITER Booster** - BullSequana XH3000, GH Superchip 72C 3GHz, NVIDIA GH200 Superchip, Quad-Rail NVIDIA InfiniBand NDR200, RedHat Enterprise Linux, EVIDEN EuroHPC/FZJ Germany	4,801,344	1,000.00	1,226.28	15,794
5	**Eagle** - Microsoft NDv5, Xeon Platinum 8480C 48C 2GHz, NVIDIA H100, NVIDIA Infiniband NDR, Microsoft Azure Microsoft Azure United States	2,073,600	561.20	846.84	

What is Dyablo ?

The outline:

- Modern code for the modeling of multi-scale/multi-physics astrophysical fluids
- Block-based AMR formalism
- Written in modern C++ (20 in a couple of days !)
- Relying on Kokkos for performance portability and MPI
- Open-source and community-centered
- Modern software engineering concepts
- Benefit from common needs between various astrophysics fields
- Let’s start from scratch and question everything “we do as we always did”

Open source and community centered

Open-source:

- Developments are made on CEA hosted gitlab: https://drf-gitlab.cea.fr
  - Anyone can create an account
  - Three repositories: Dyablo, pyablo, documentation
  - Protected branches (dev, main) are mirrored automatically on github: https://github.com/Dyablo-HPC/
  - Documentation is automatically built with readthedocs: https://dyablo.readthedocs.io/en/latest/
  - Collaboration on day-to-day basis via Slack
  - *Dyablo dev meeting* once every month

Collaboration:

- GINEA: Groupement d'Instrumentation Numérique pour l'Exascale en Astrophysique
- ERC Synergy WholeSun
- PEPR Numpex: Exa-DoST (PC3); Exa-DI (PC5) (see Julien's talk @11:00)
- PEPR Origins: MHD@Exascale (see Guillaume's talk @11:30)
- EUPEX (WP3)
- Moonshot CExA

Software engineering concepts

Separation of concerns

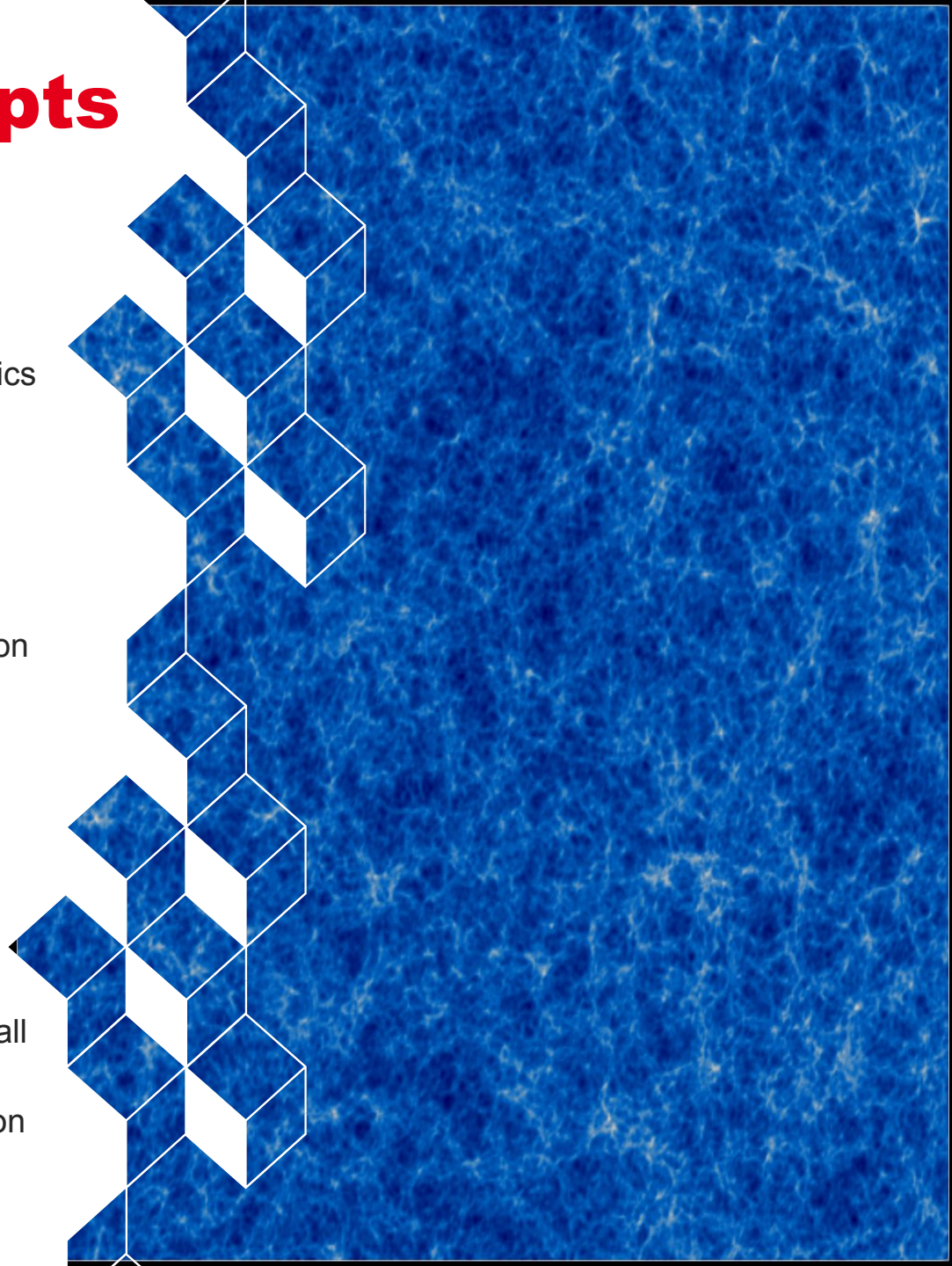
- Physicists implementations should not interfere with HPC
- Back-end implementation should be modifiable without rewriting the physics
- Interface between back-end and physics kernels should stay as stable as possible

High-level abstractions

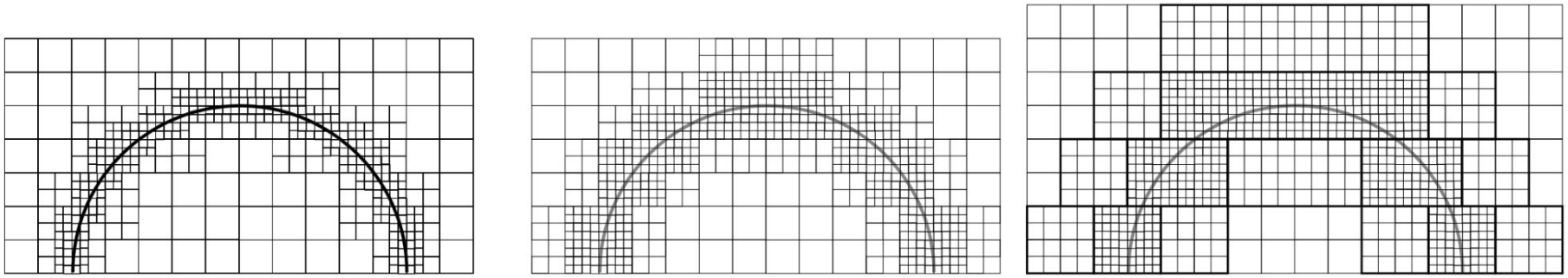
- Having access to high-level classes hides the complexity of implementation
- Easier implementation of physics without having to bother about memory layout/management
- Example: The `CellIndex` class manages neighbor finding for AMR

Modularity

- C++ templating + performance portability = long compilation times
- To avoid having to recompile the code (de)activating modules à la Pluto, all major features of Dyablo are *“plugins”*
- Plugins are compiled once and can be activated/deactivated at initialization instead of compilation.



Block-based AMR

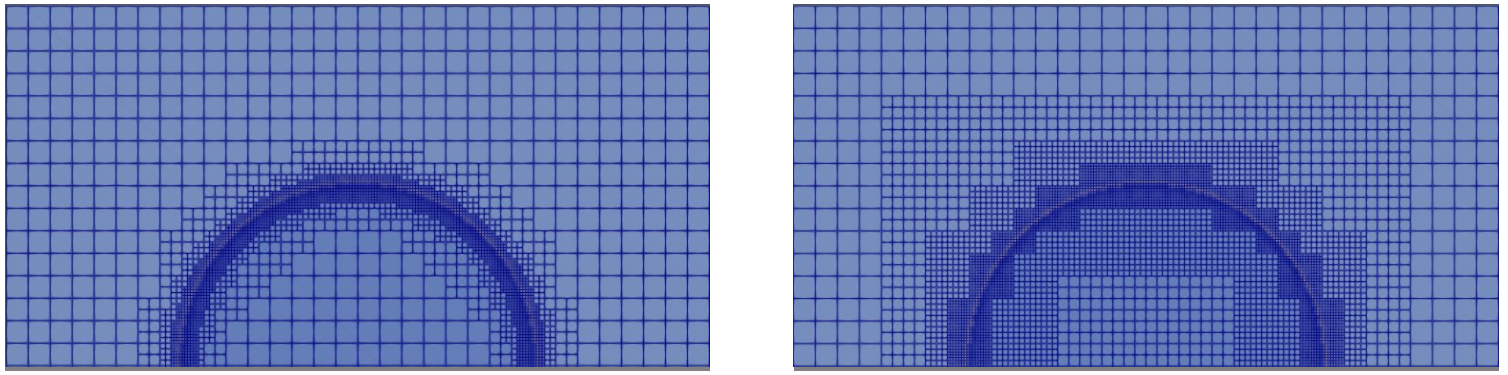


Source: Dunning et al. 2019; "Adaptive Mesh Refinement in the Fast Lane."

Advantages of block-based AMR:

- **Smaller tree:** AMR cycle is faster
- **Increased regularity**: More conformal faces = easier streamlining for the GPU
- Cell-based still possible by taking blocks of size 1

Cell-based
600k octants
600k cells

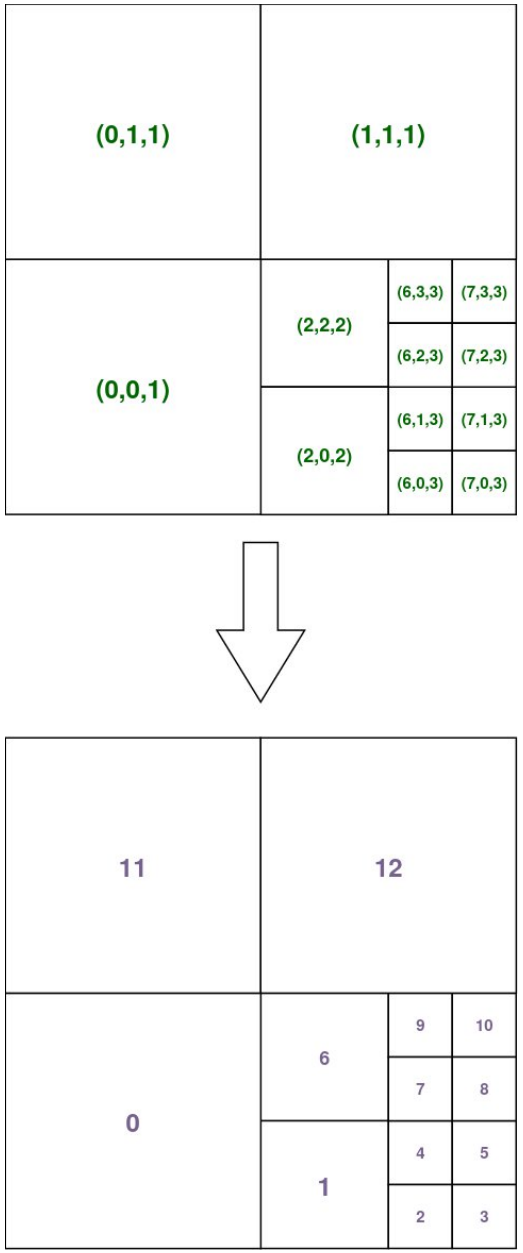


Block-based
18k octants
4x4x4 blocks
1100k cells

Hashmap based neighbor search

Memory layout:

- Linear octree: only the leaves (ie blocks) are stored
- Space-filling curve: octants are ordered along the Morton Z-curve
- All octants are referenced in a hashmap: (i, j, k, level) -> octant_id
- Looking for a neighboring octant is simply looking for matching keys in hashmap:
  - Construct the neighbor key, if it exists return the stored id
  - If not, construct the neighbor key at level-1
  - If still nothing, construct the neighbor key at level+1
- Allows the data to live at all times on GPU memory for computation



Plugins

Plugins are feature “bricks”

- Every aspect of the code that should be modular is made as a plugin
- Static inheritance and a *factory design pattern* to instantiate the plugins at runtime
- Plugins can simple simple objects:
  - Dt calculation, refinement criterion, IO backends, etc.
- Or more complex, multi-layered classes
  - HydroState + HLLC + Slope limiters + BoundaryConditions = Hydro policy
  - Hydro policy + RK2 scheme = Hydro_RK2 plugin
- Plugins are registered in generic factories at compile time
- And selected in .ini file at runtime

```
FACTORY_REGISTER( dyablo::HyperbolicUpdateFactory,
                  dyablo::HydroUpdate_RK2,
                  "HydroUpdate_RK2")
```

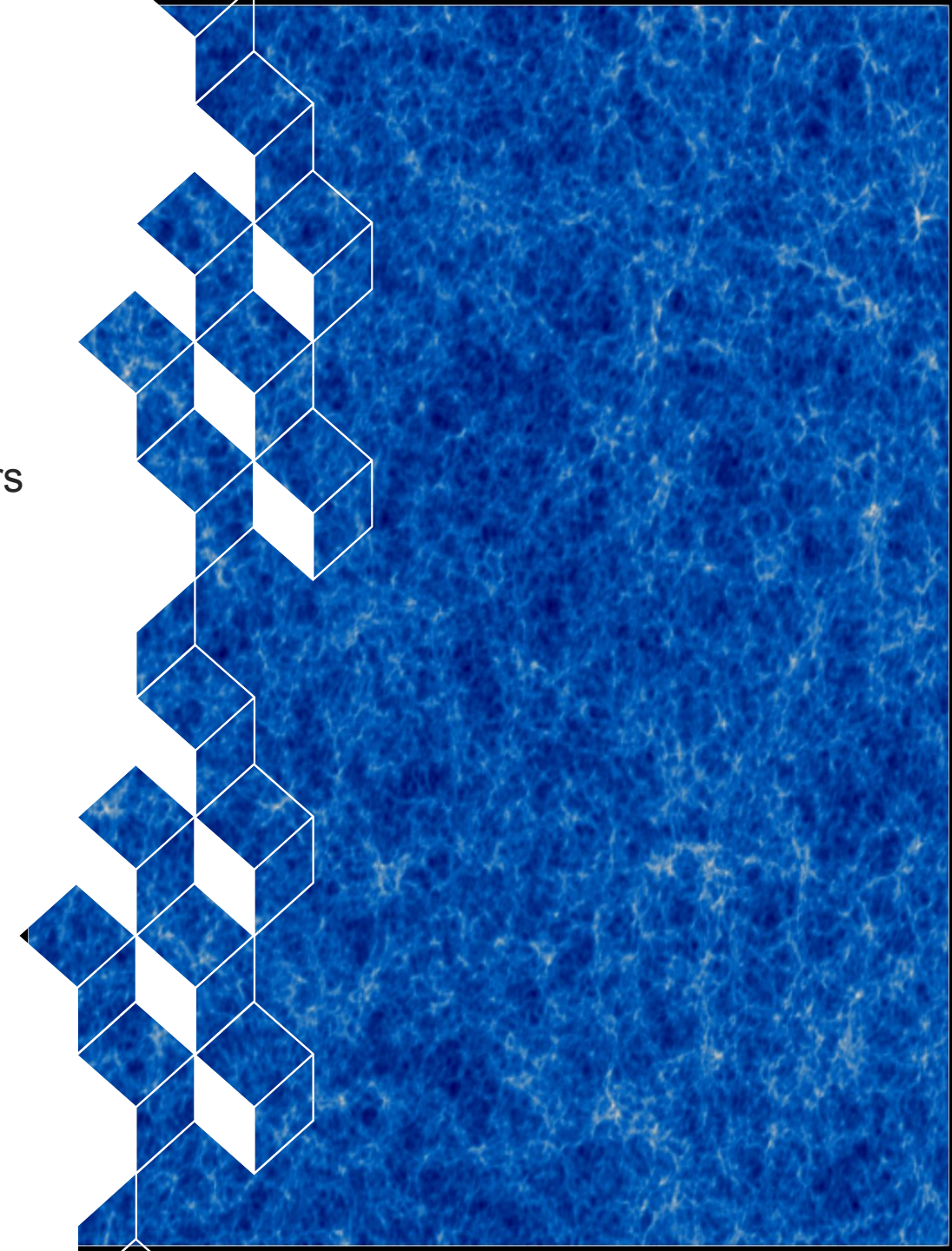
```
std::string godunov_updater_id =
  configMap.getValue<std::string>("hydro", "update", "HydroUpdate_hancock");
this->godunov_updater = HyperbolicUpdateFactory::make_instance( godunov_updater_id,
  configMap,
  this->m_foreach_cell,
  timers
);
```

```
[hydro]
update=HydroUpdate_RK2
```

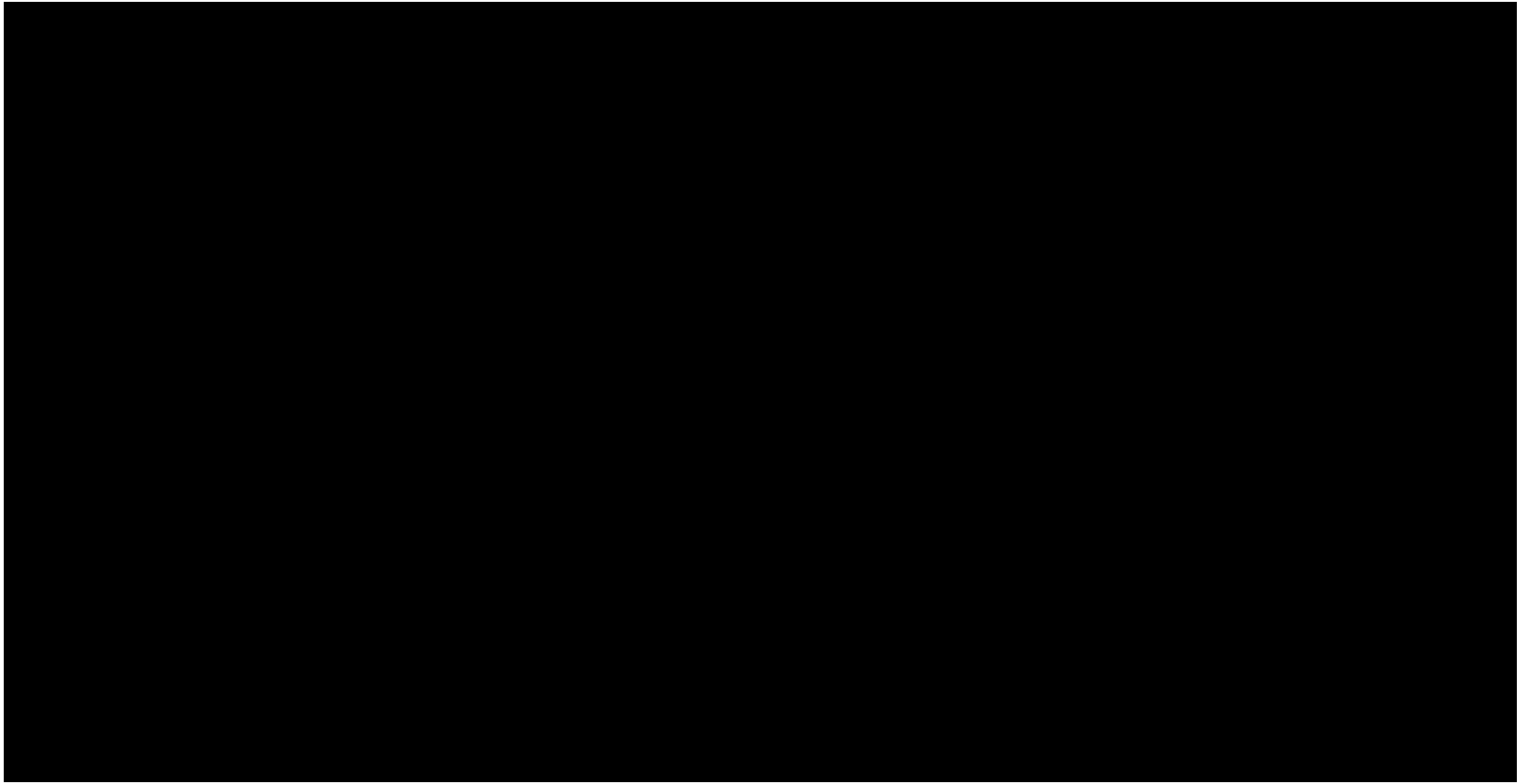
What is in Dyablo ?

Multiple branches:

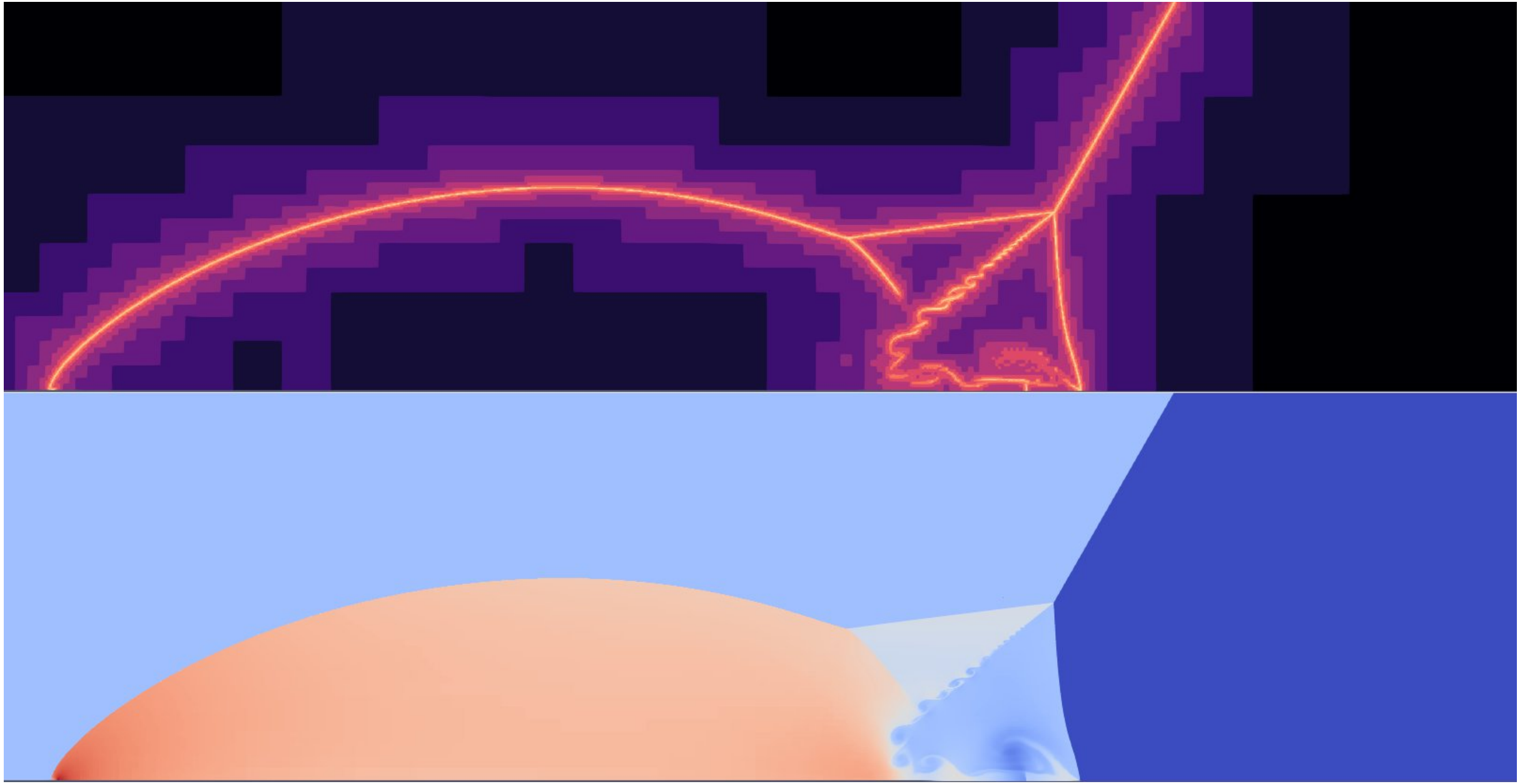
- Dev branch with common useful plugins:
  - Hydro/MHD(div cleaning)/RHD(M1 explicit) solvers
  - Thermal Conduction/Viscosity explicit parabolic solvers
  - (self) Gravity update with CG
  - Particles CIC, NGP, tracers
  - Source terms: basic cooling,
- Community branches:
  - Branches led by community applications
  - Two main community branches for now
- Feature branches:
  - Sub-branches made for implementing features



Double Mach reflection



Double Mach reflection



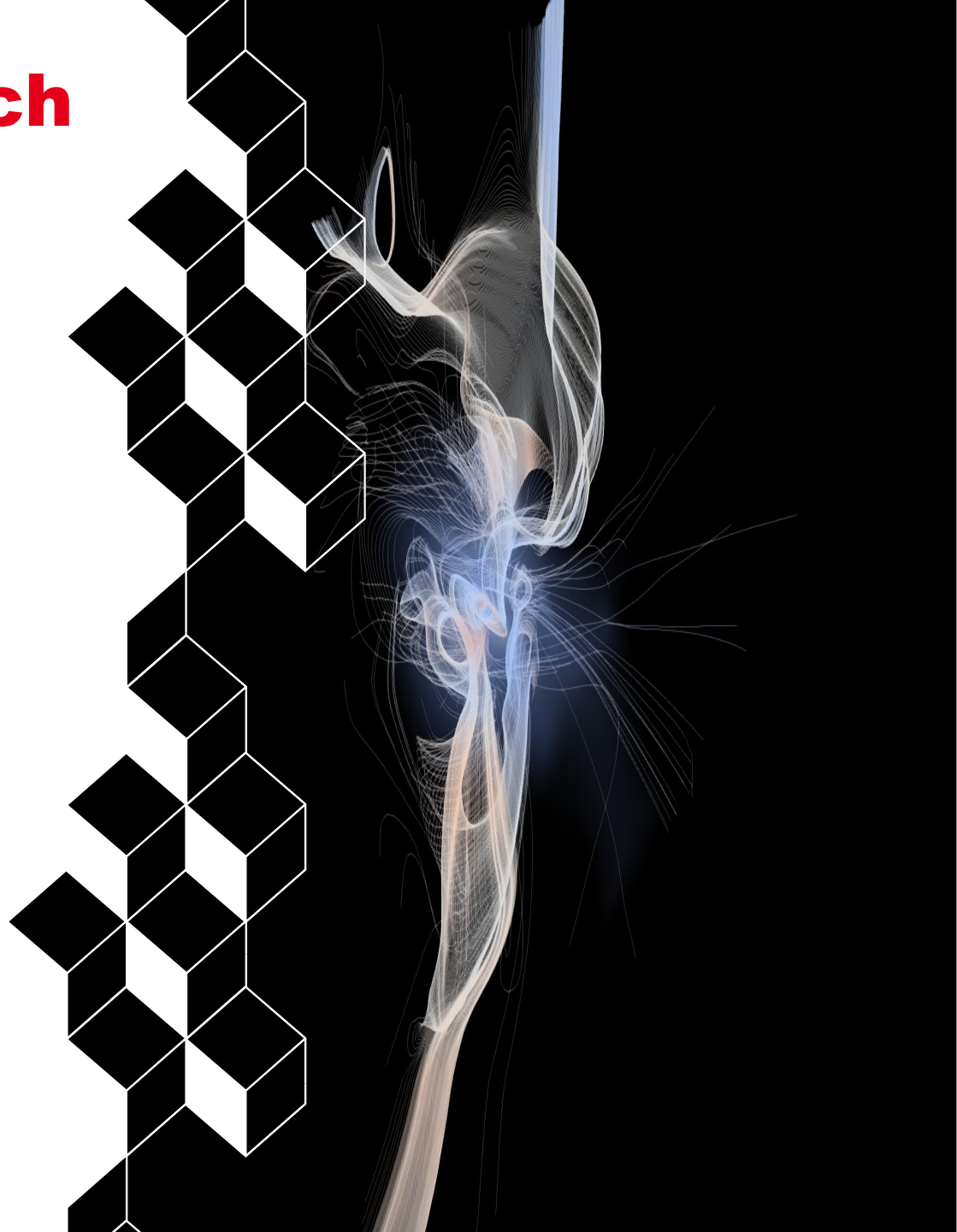
Developments: `cosmo` branch

Exclusive features:

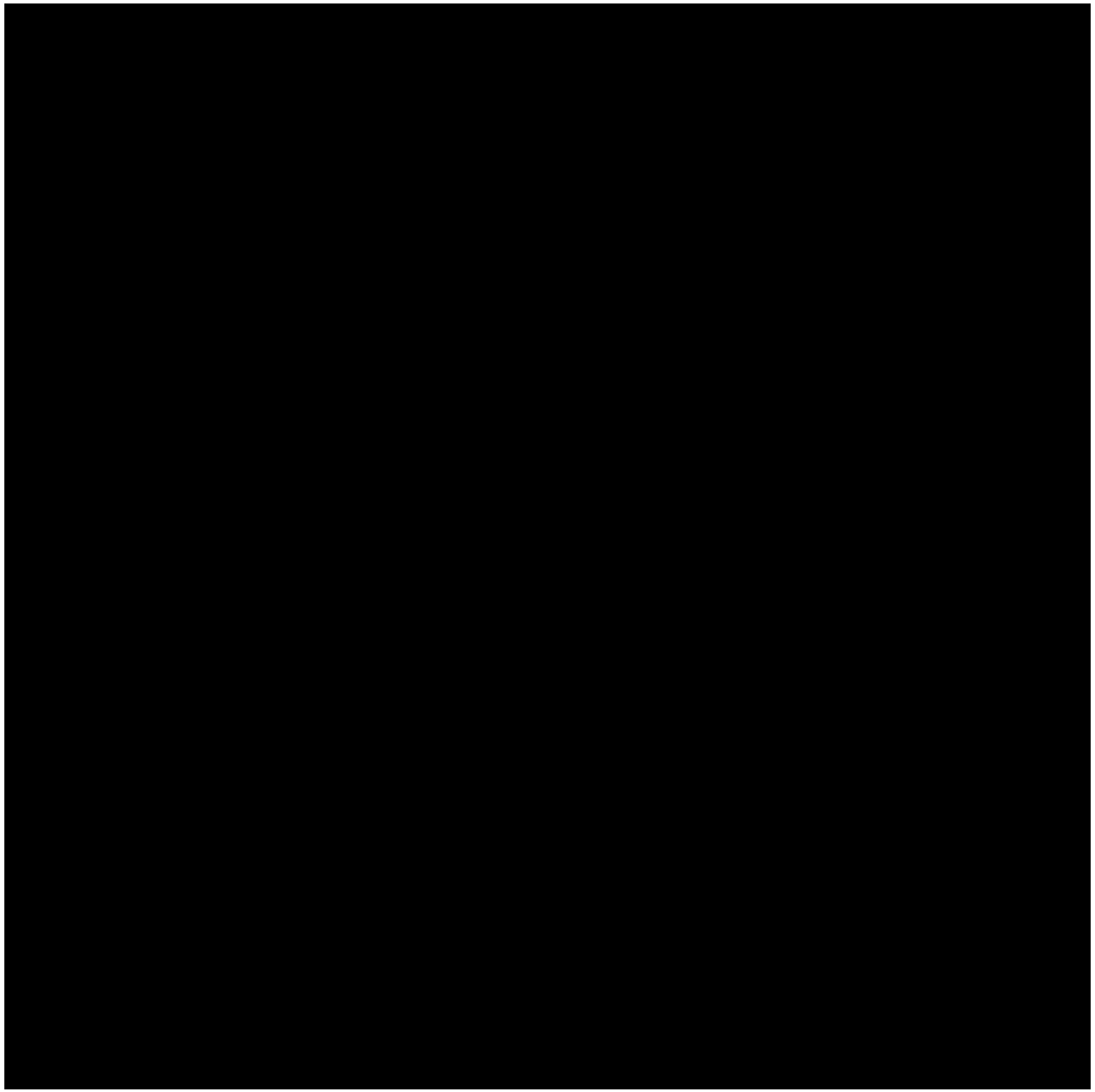
- **Hydro:** Pressure fix (not finalized)
- **Source Terms:** Cooling using Grackle public tables, turbulent forcing term (not finalized)
- **Particles:** Stellar feedback, Star formation
- **Gravity**: Multigrid Poisson solver
- **IOs:** Reading from Gadget snapshot (not finalized)

Contributors:

- Dominique Aubert – ObAS
- Michel-Andrès Breton – CEA Saclay
- Corentin Cadiou – IAP
- Olivier Marchal – ObAS



A first galaxy with Dyablo



Video courtesy of: Dominique Aubert, Michel-Andrès Breton, Corentin Cadiou, Olivier Marchal,

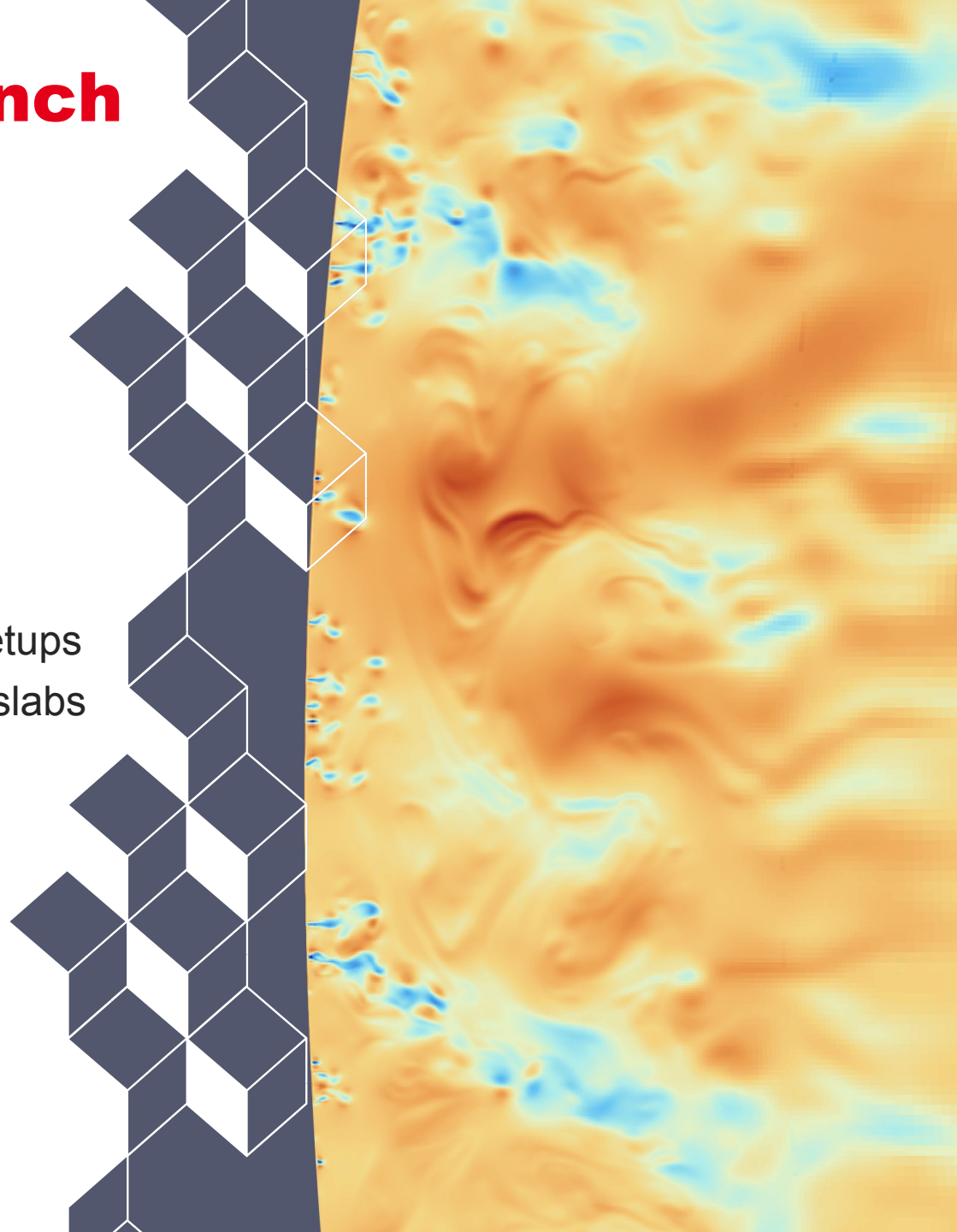
Developments: `wholesun` branch

Exclusive features:

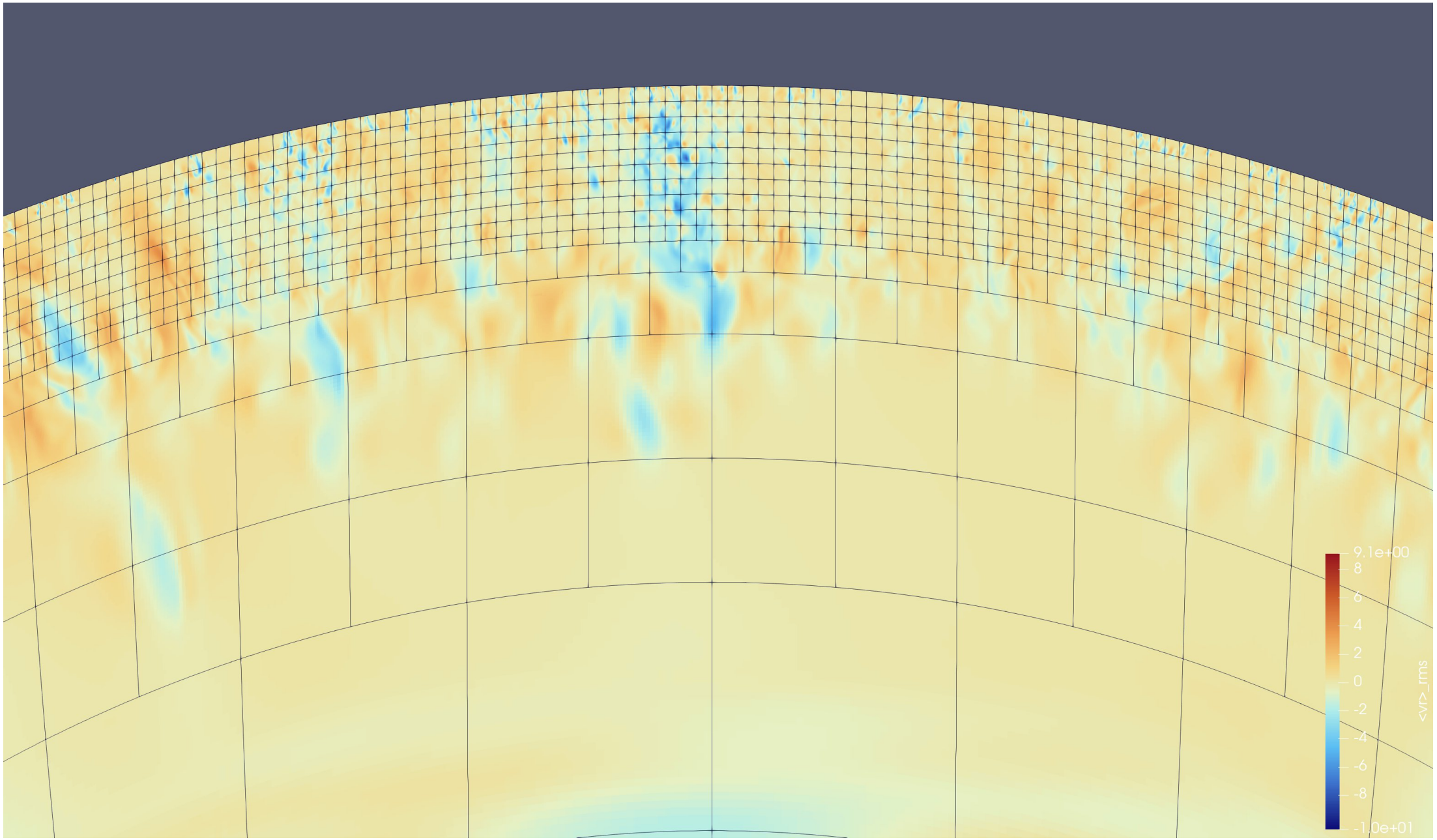
- **Geometry:** Isometric mappings (See Grégoire's talk on Wednesday)
- **MHD:** Five-Waves solver from MDLS
- **Source Terms:** Isothermal atmosphere cooling
- **Well-balancing:** Alpha-beta well balancing for radial setups
- **Setups:** Various setups for solar physics ranging from slabs to radial profiles

Contributors:

- Lucas Barbier – CEA Saclay
- Catherine Blume – University of Colorado Boulder
- Grégoire Doebele – CEA Saclay
- Adam Finley – ESTEC Leiden

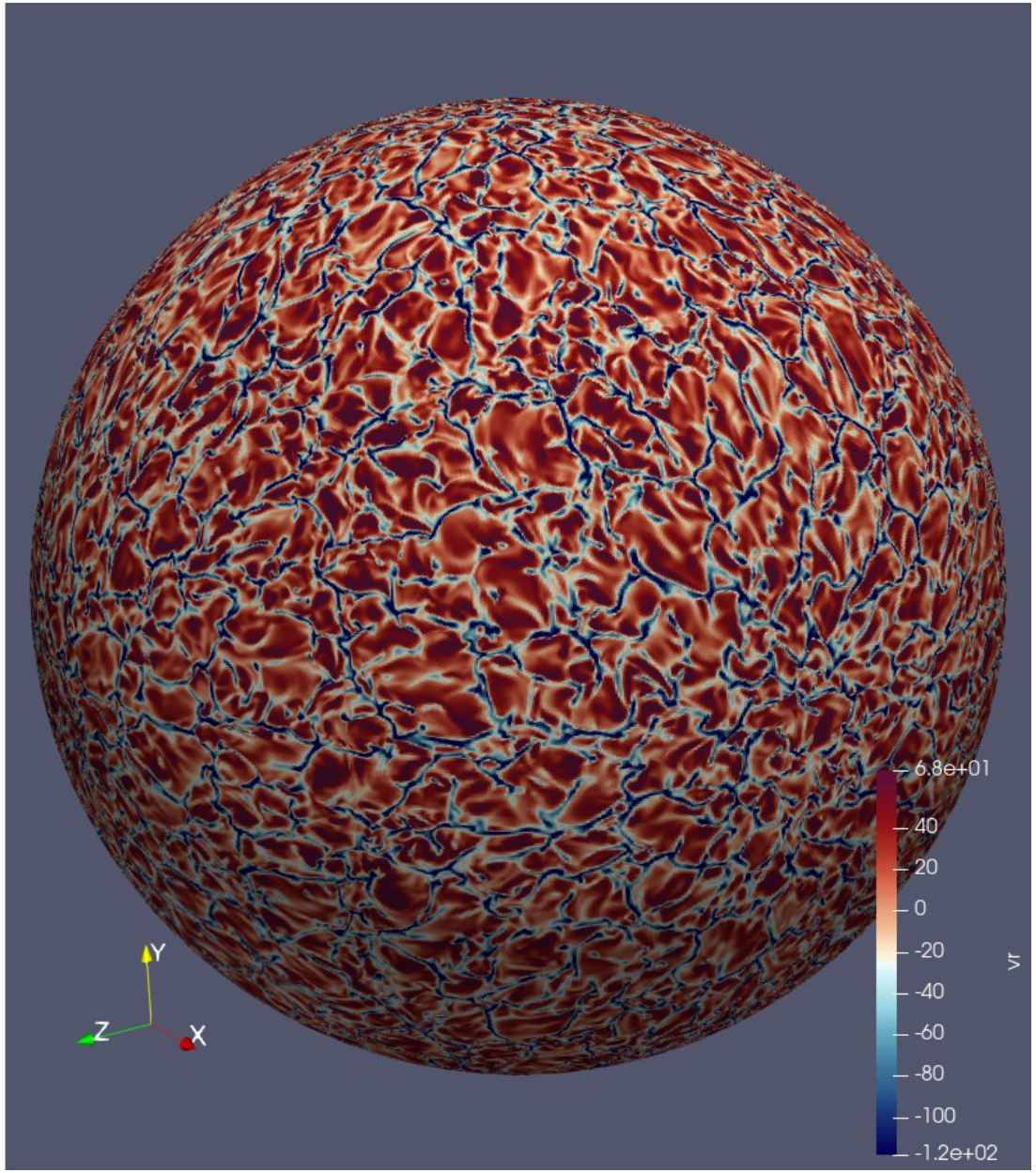


Solar-like setup with geometric module simulation (and AMR)



Edges indicate blocks, not cells ! Running on 1 h100 on Jean-Zay

Solar-like setup with geometric module simulation (in 3D)



$N = 512\text{^}3$ *fixed resolution run; 64 MI250X on AdAstra*

Developments: other branches

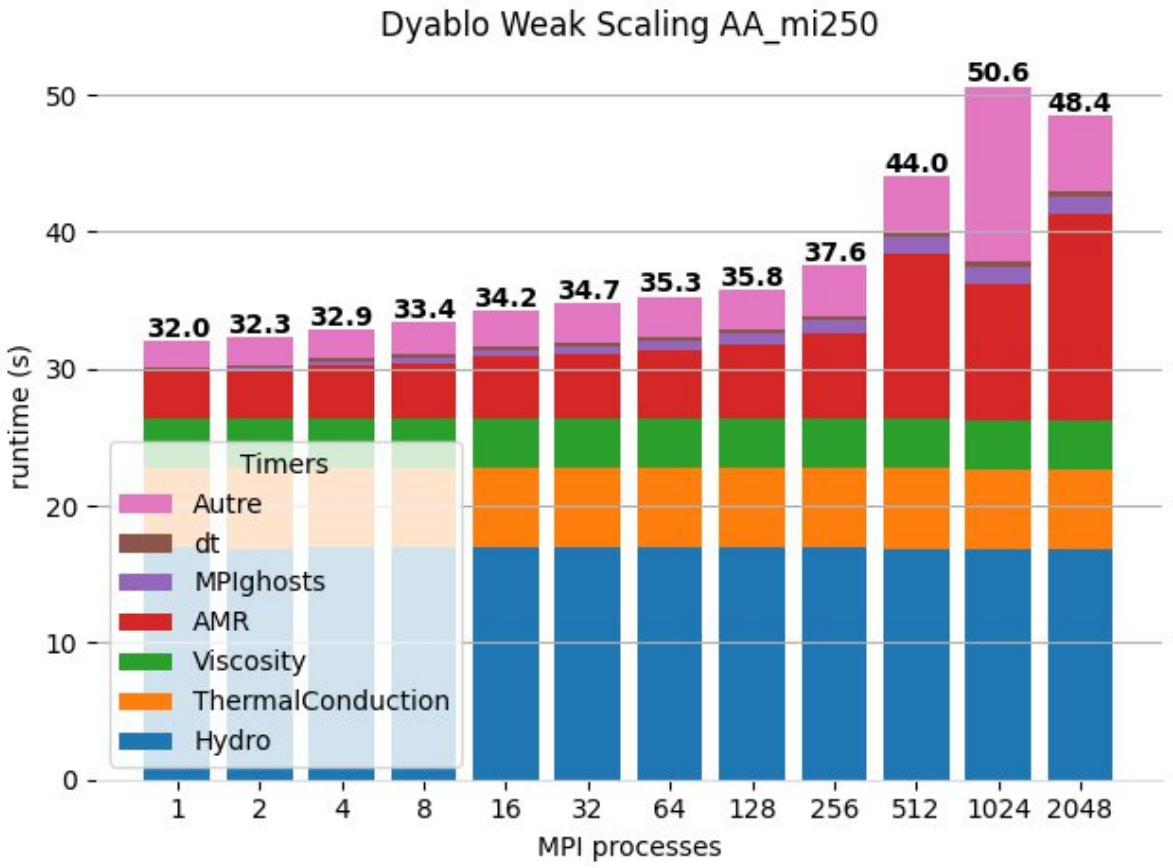
Other branches (development or future community):

- **Multigrid and TSC scheme:** Michel-Andrès Breton
- **Dust/ISM:** Benoît Commerçon, Leodasce Sewanou
  - Base for a future community branch (see maybe Leodasce's talk on Wednesday)
  - A collapse with barotropic equations has been tested in another branch -> Works but BG is killing the time-to-solution
- **Subgrid physics/comparison with Ramses:** Florent Bréhard, Mike Petrault, Jenny Sorce
- **Cosmic rays:** Yohan Dubois, San Han, Guillaume Tcherniatinsky
- **Core features** - Passive scalars, hierarchical timestepping, intermediate level storages: Maxime Delorme, Arnaud Durocher

What about exascale ?

Weak scaling benchmark:

- **Solar physics setup**: Navier-Stokes + Gravity + Viscosity + Thermal conduction
- 3-7 refinement levels: Max Resolution: 2048x2048x512
- 30.6Mcells per domain (1 GPU)
- 100 iterations
- No load-balancing
- Scalability tested on French infrastructures:
  - Up to 128 a100 on Jean-Zay
  - Up to 2048 mi250X on AdAstra (~60 billion cells)
- Data is quite old now (november 2023): needs to be updated.



Roadmap for Dyablo v1.0

MULTIGRID	PASSIVE SCALARS	HIERARCHICAL TIMESTEPPING	DOCUMENTATION	BENCHMARKING	DYABLO V1.0
• Integration of the multigrid branch • Adaptation of the general structure for intermediate level storage/communication	• Passive scalar advection regardless of scheme used	• Partial integration of levels • AMR cycle in the middle of an integration cycle	• Finalizing contributor guide • Doxygen/Breathe • CI integration	• Re-run of all benchmarks: hydro, MHD, cosmo, solar. • Comparison with state of the art	• Public tag • Method paper

A lot of work is still needed to reach a first stable official version of the code !

Current and future work

Peripheral developments/activities:

- **Numpex:**
  - ExaDOST (PC3): Sylvain Joube (postdoc) is working on a new solution for compressed AMD data-formats, visualization and analysis.
  - ExaDI (PC5): Dyablo and Samurai (Polytechnique/CMAP) are leading a working group on a series of benchmarks for modern AMR codes to pinpoint common difficulties
- CExA/PTC: Jean-François David (postdoc) is building analysis tools for the profiling and optimization of large kernels in Kokkos applications

Future work for the core team:

- Python front-end:
  - Being able to fully control the time-loop and let C++ handle the computations
- In-situ analysis:
  - Use the supercomputers to calculate diagnostics and first step analysis while the code is running

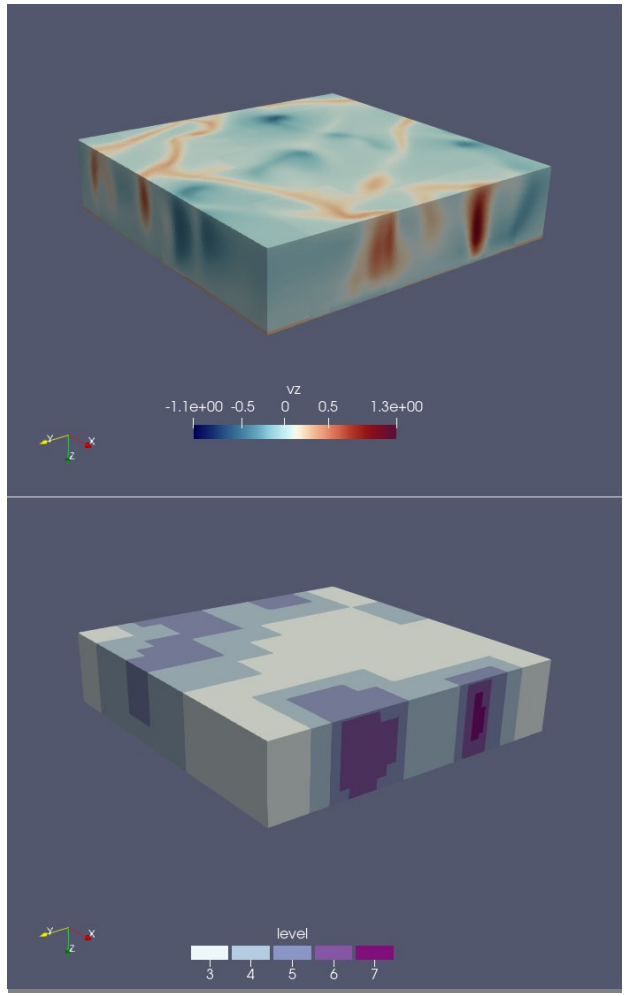
Thank you

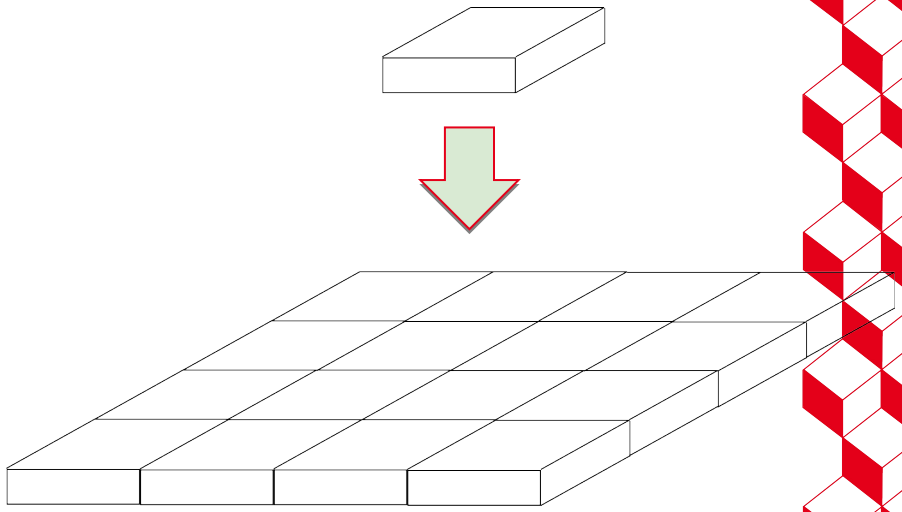
Weak scaling benchmarks

Use case

Solar convection slab :

- 3-7 refinement levels
  - Base resolution 128x128x32
  - Max resolution 2048x2048x512
  - 30.6M cells per domain
- Horizontal tiling per MPI process
- 100 iterations
- 1 AMR cycle per iteration
- No Load-balancing
- Scalability tested on Jean-Zay and Ad-Astra [Tier 1 french SC]
  - CPU : Intel CSL, AMD Genoa
  - GPU : v100, a100, MI250X
  - Tested up to 2048 GPUs ~62 billion cells

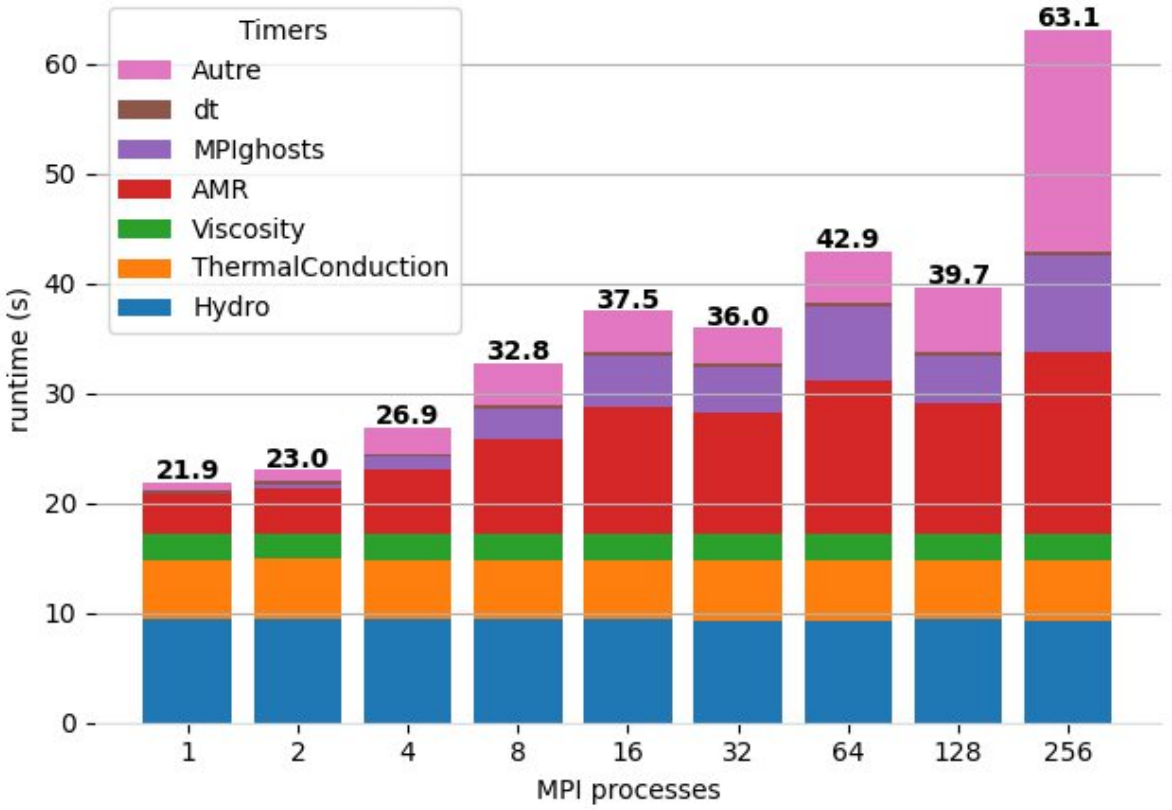




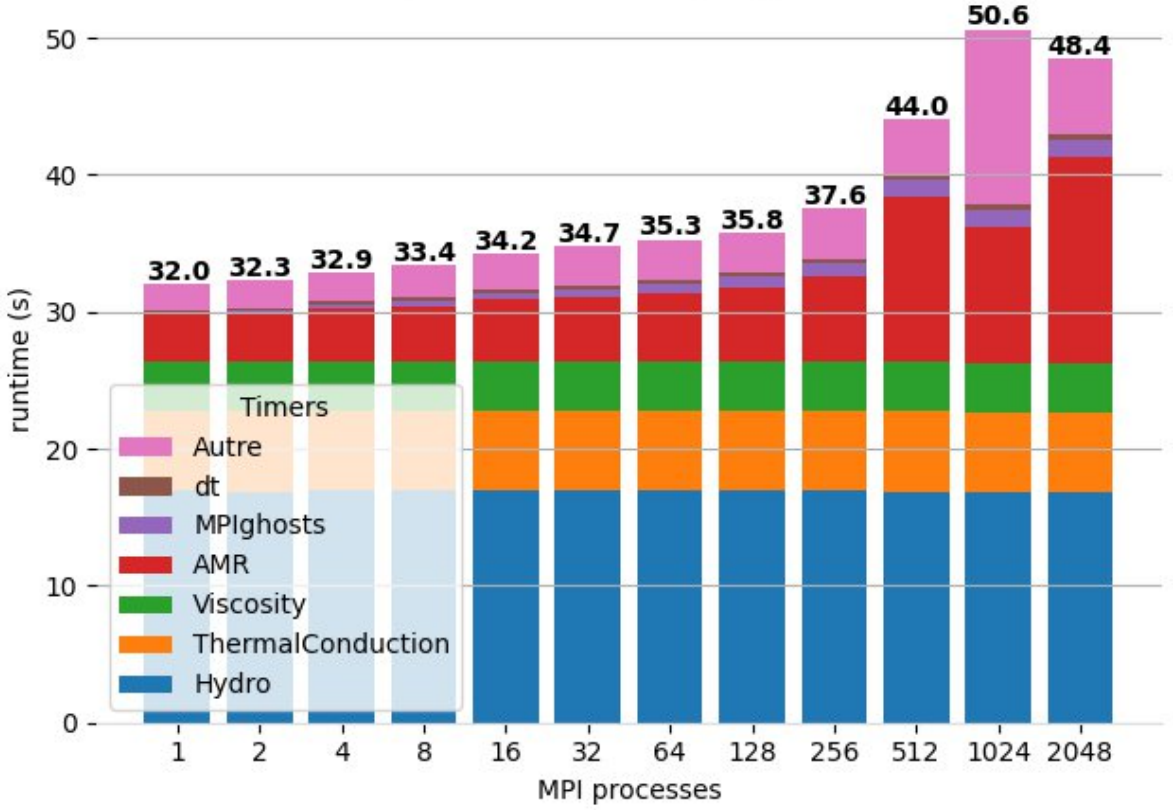
Replication on N MPI processes

Weak scalability for convection runs

Jean Zay GPU *(8 x Nvidia A100)*



Ad Astra GPU *(8 x AMD MI250x)*



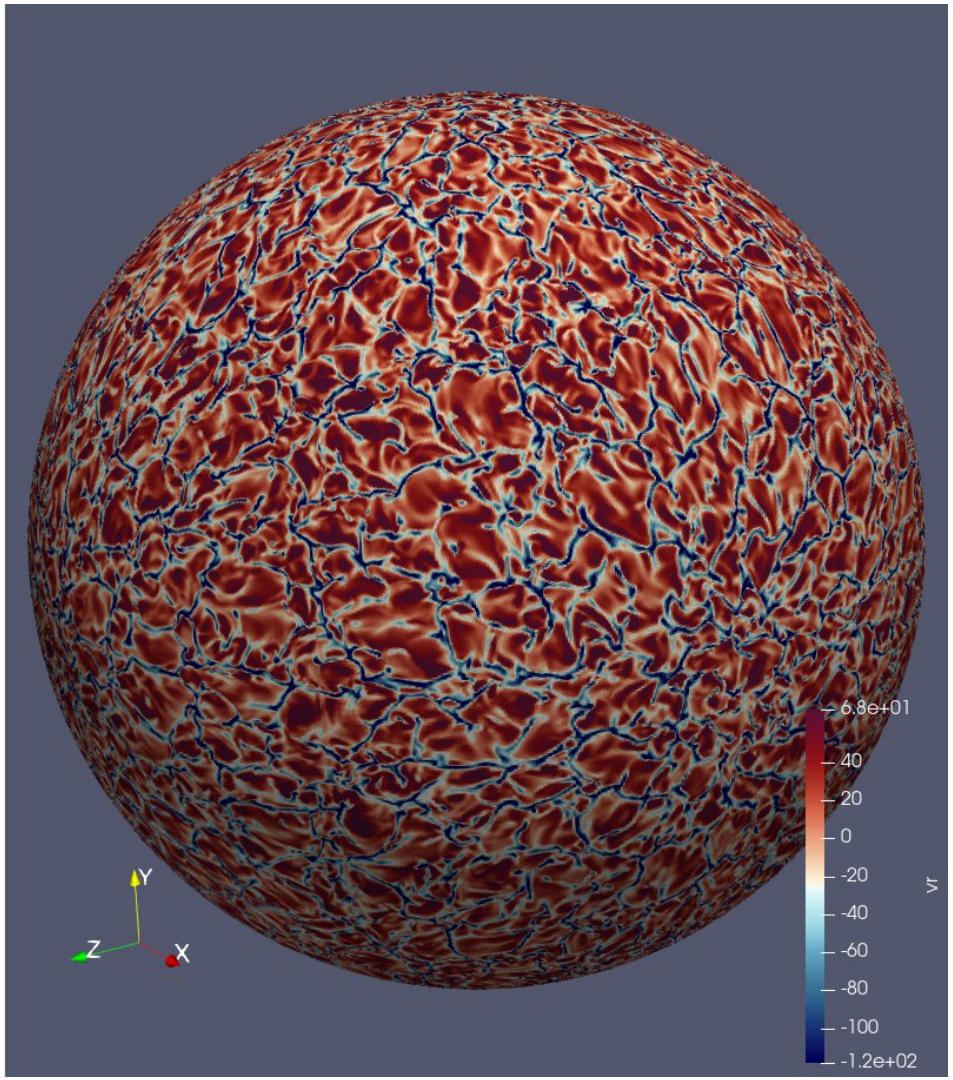
Strong scalability benchmark

Use case

Convection on a sphere:

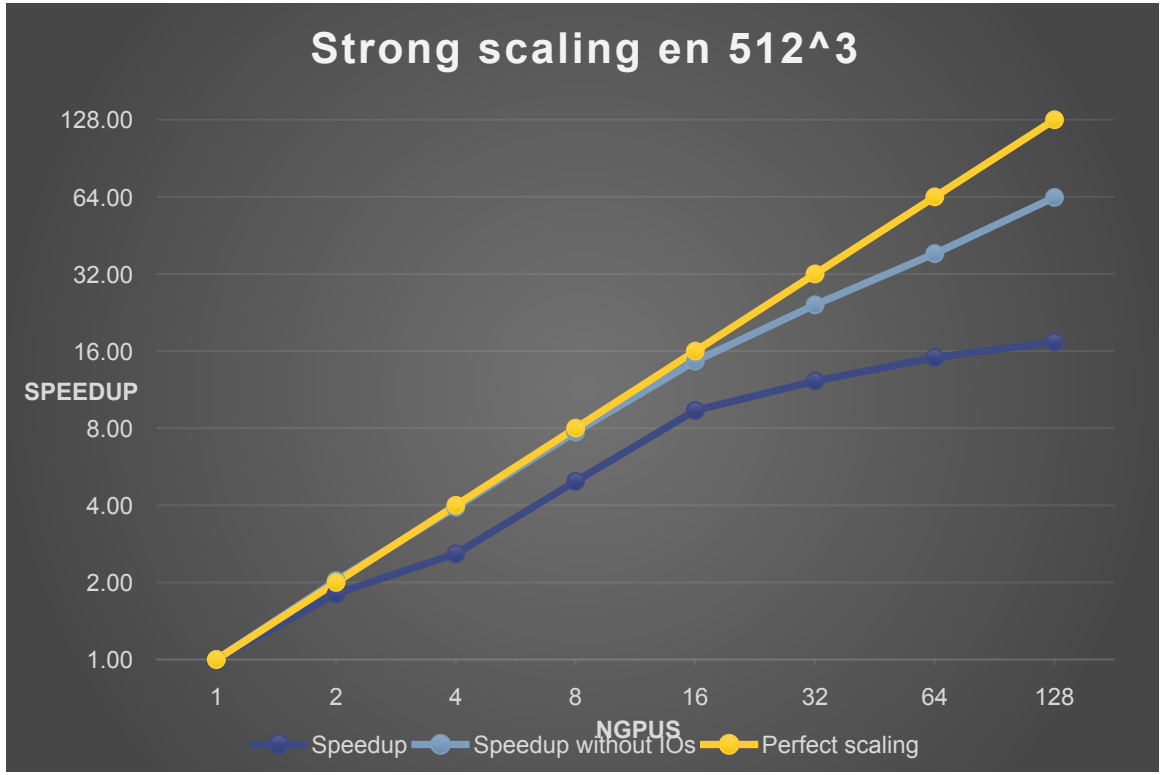
1. Equations:
    1. Navier-stokes
    2. Thermal conduction
    3. Gravity
    4. Heating at the center
2. Boundary conditions: Fixed energy flux at surface
3. 512^3 fixed resolution (130Mcells), solved on a radial mapping

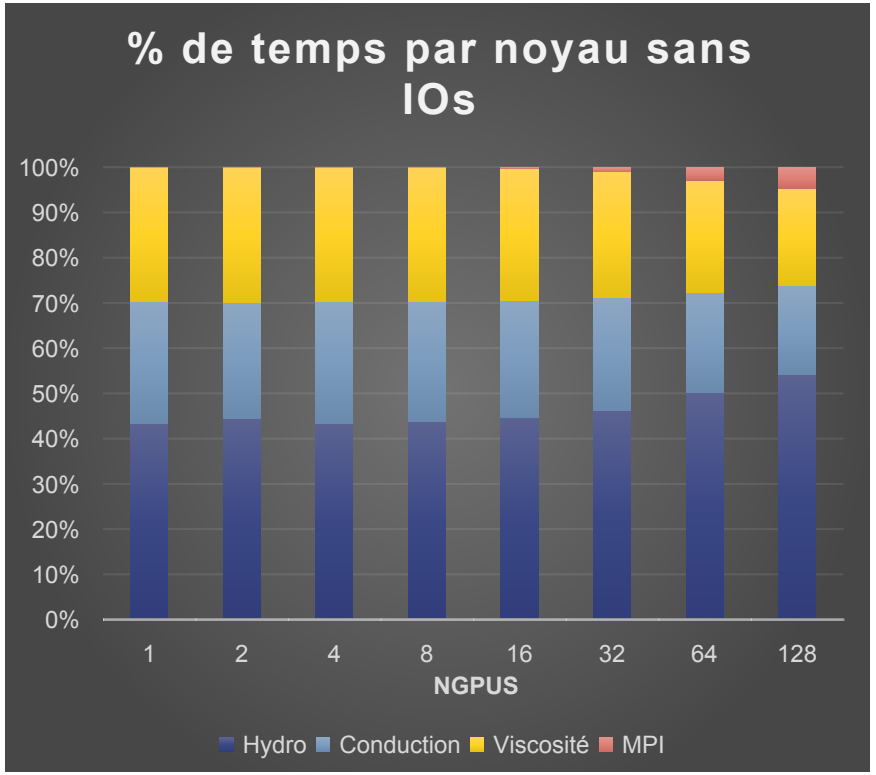
Warning: Geometry module is still very experimental and numbers should be taken with a pinch of salt.



Strong Scalability

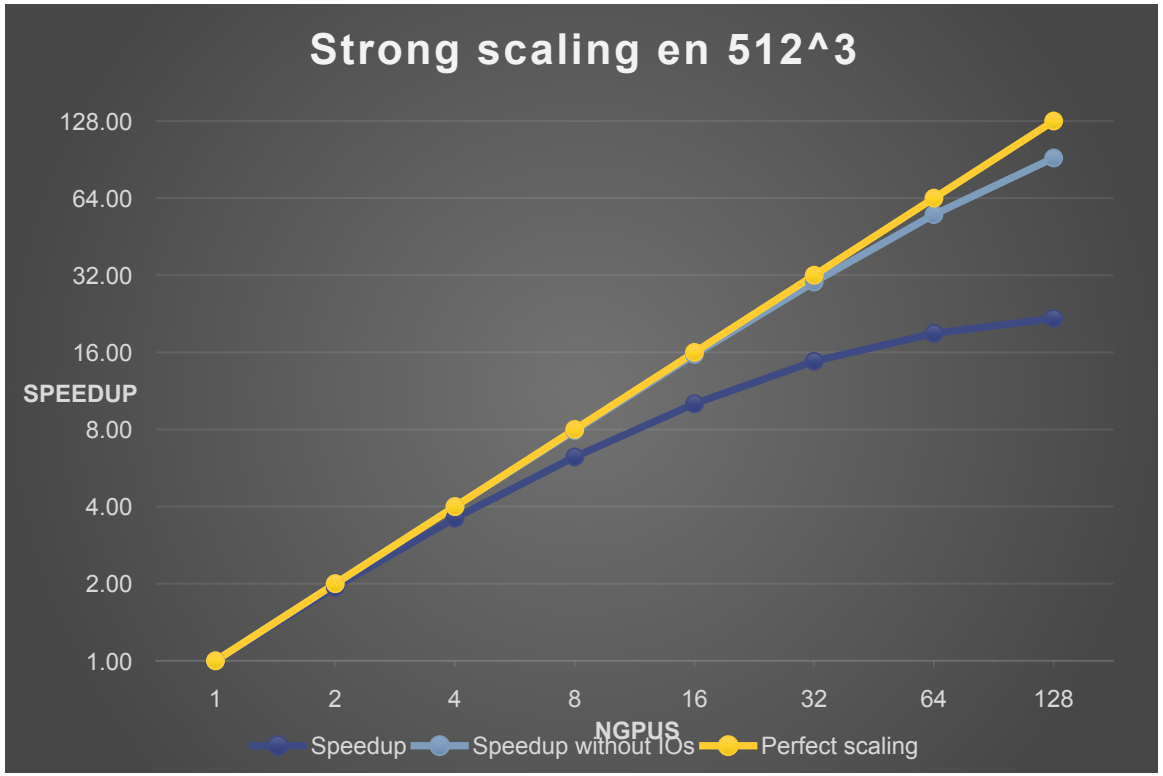
Jean-Zay H100

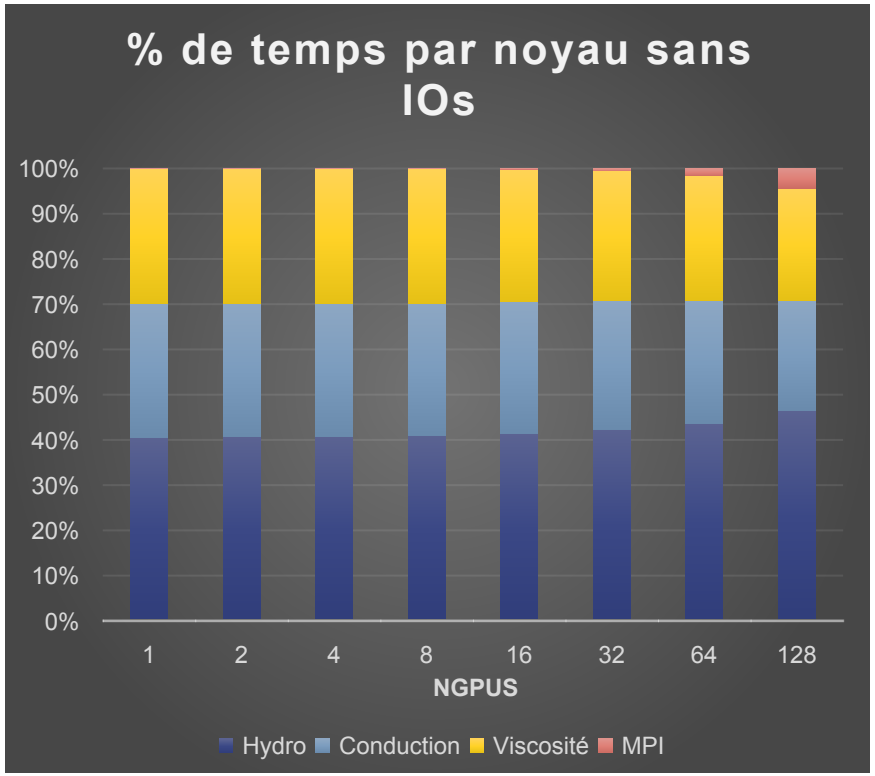




Strong Scalability

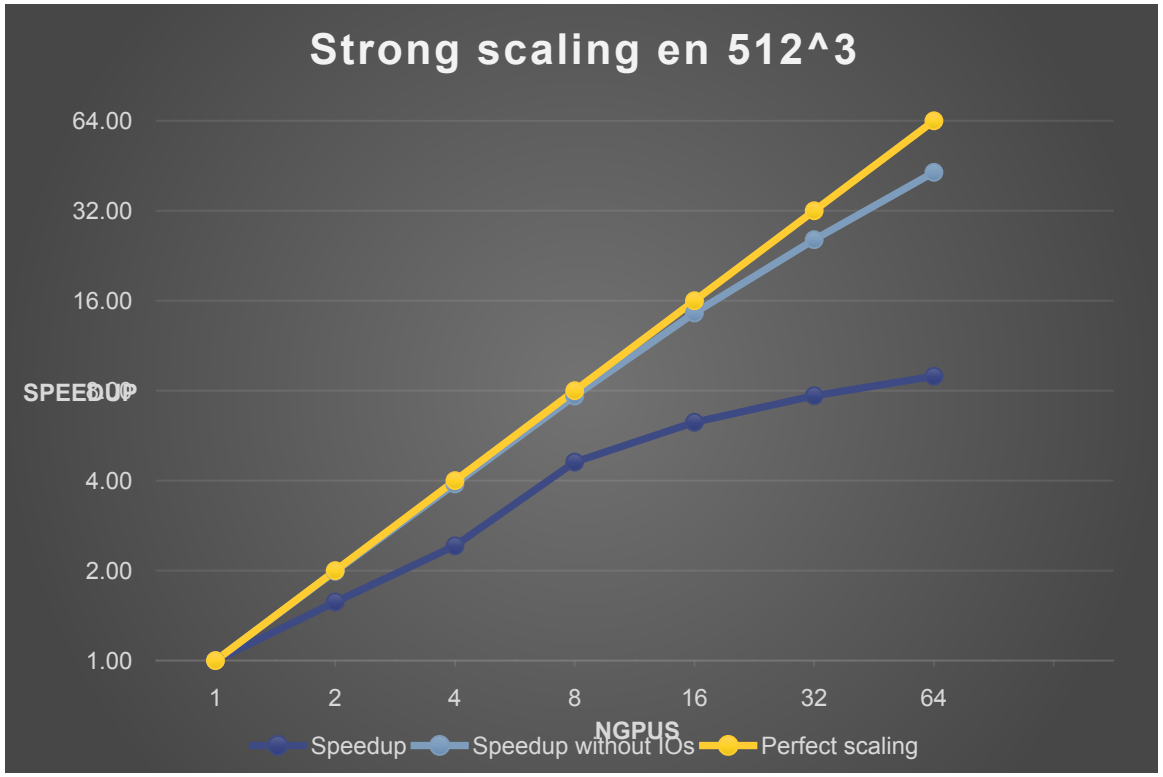
AD-Astra MI250X

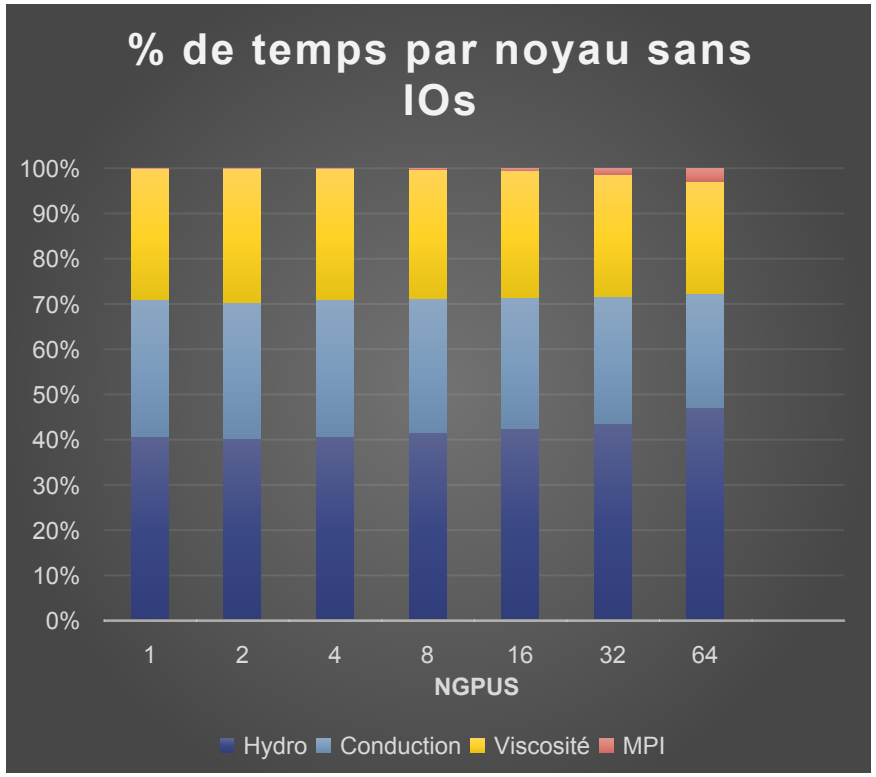




Strong Scalability

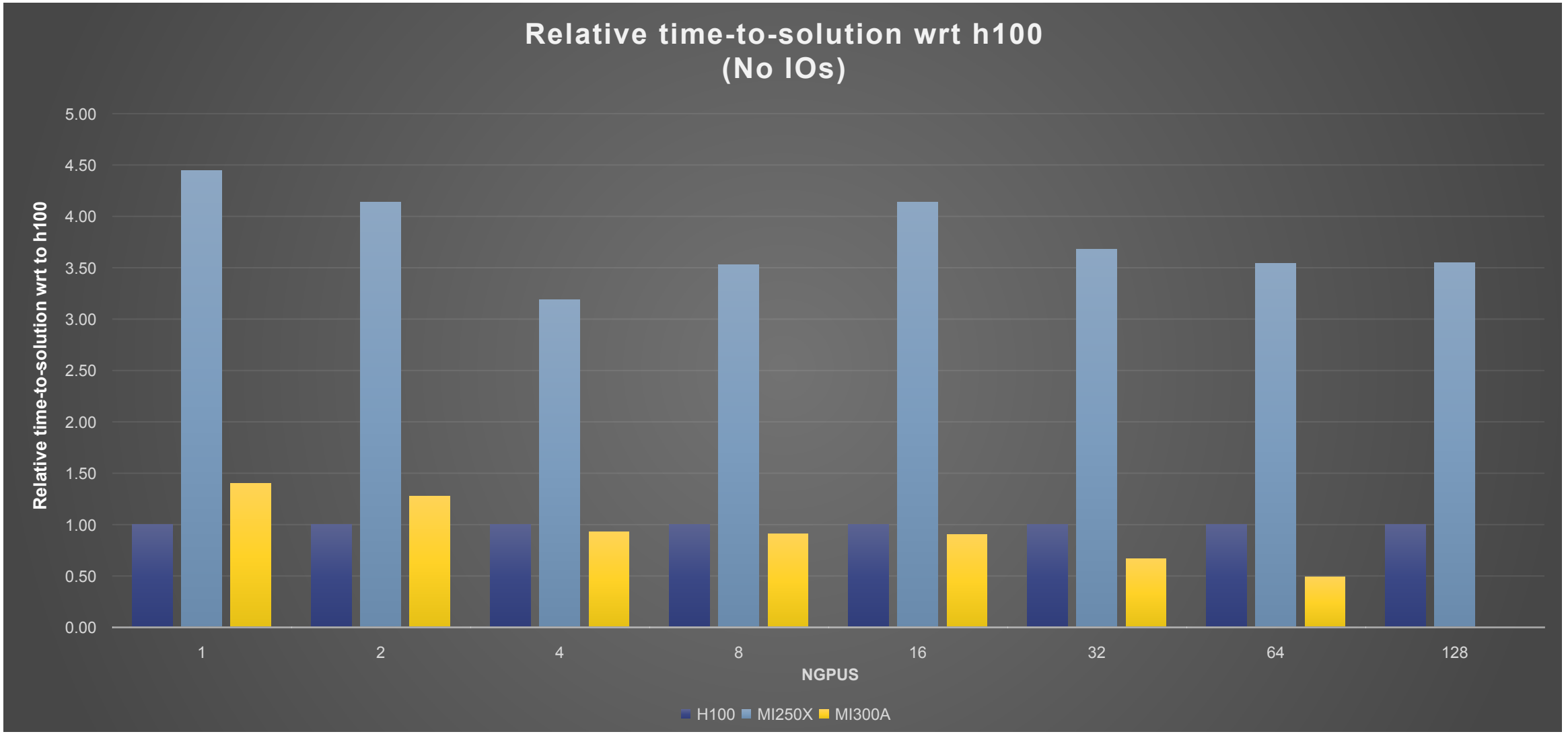
AD-Astra MI300A





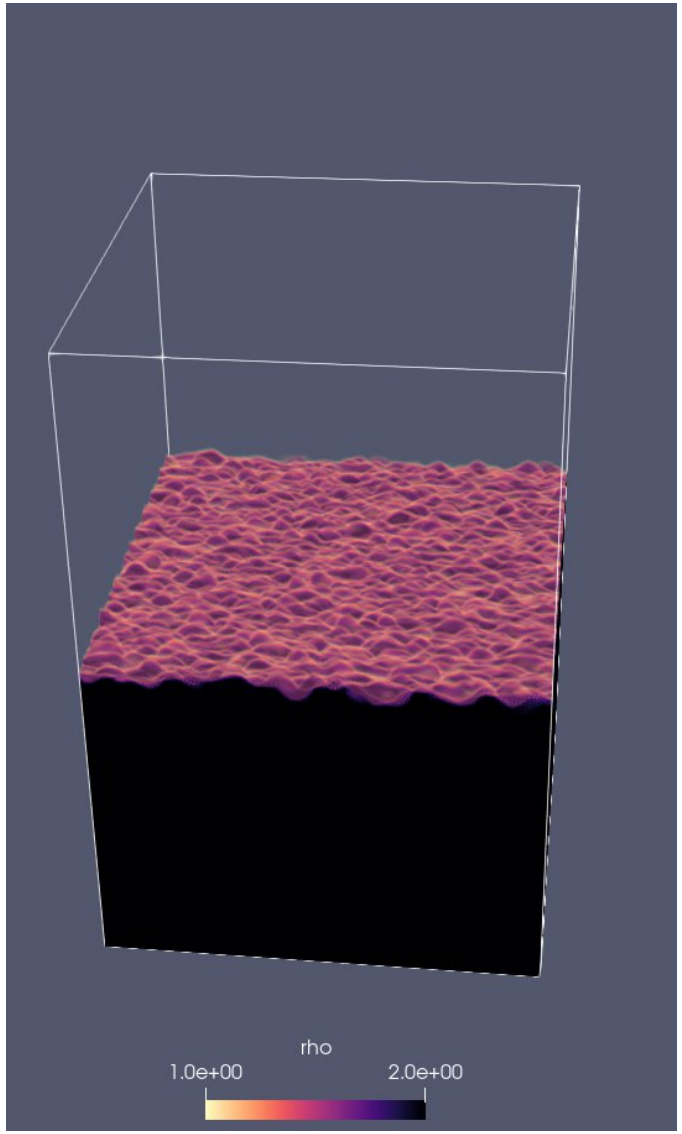
Strong Scalability

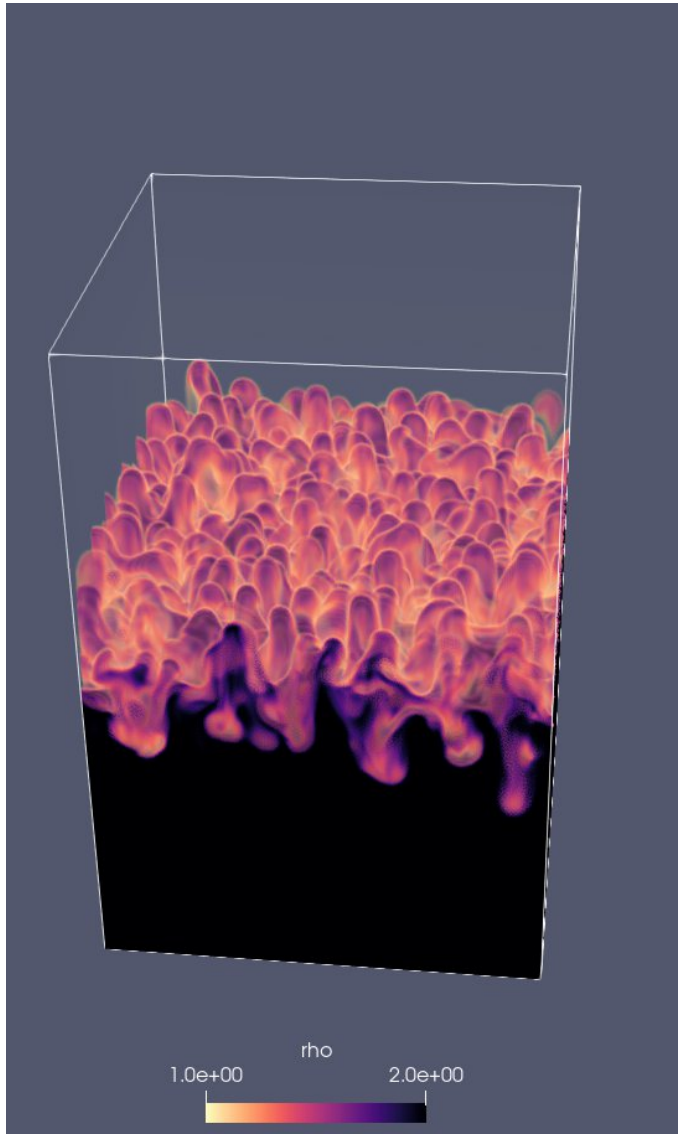
Architecture comparison



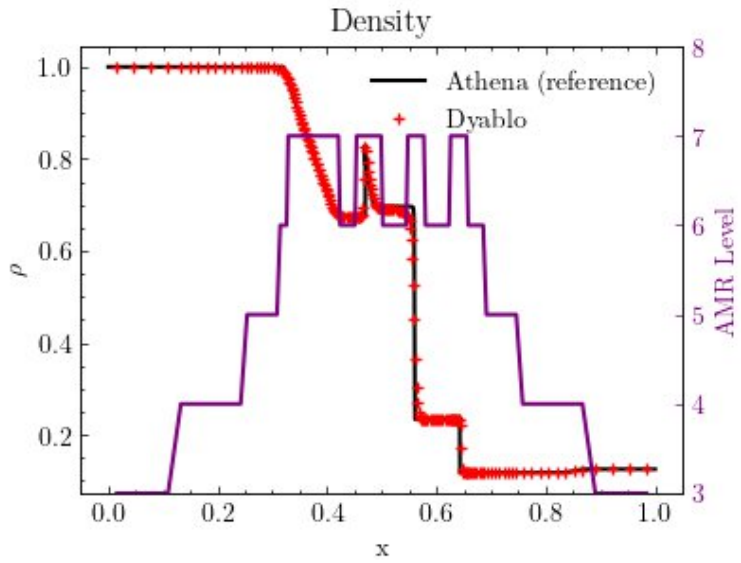
Cloud-shock interaction

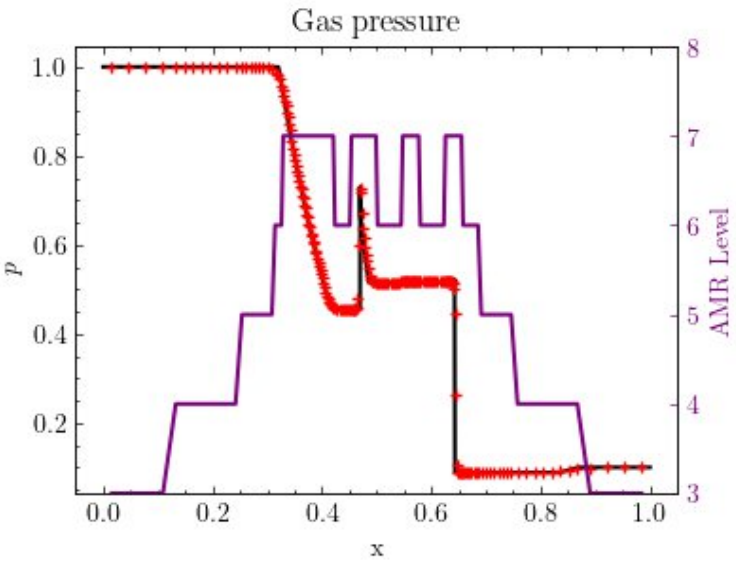
Rayleigh-Taylor 3D

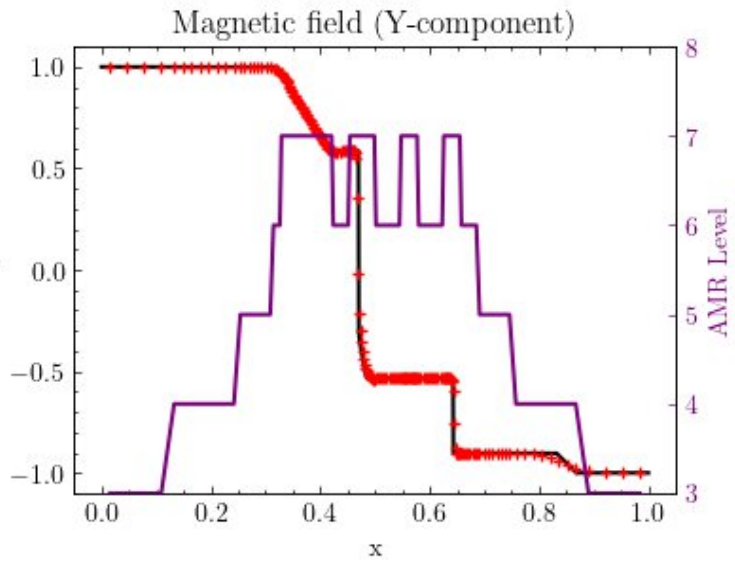




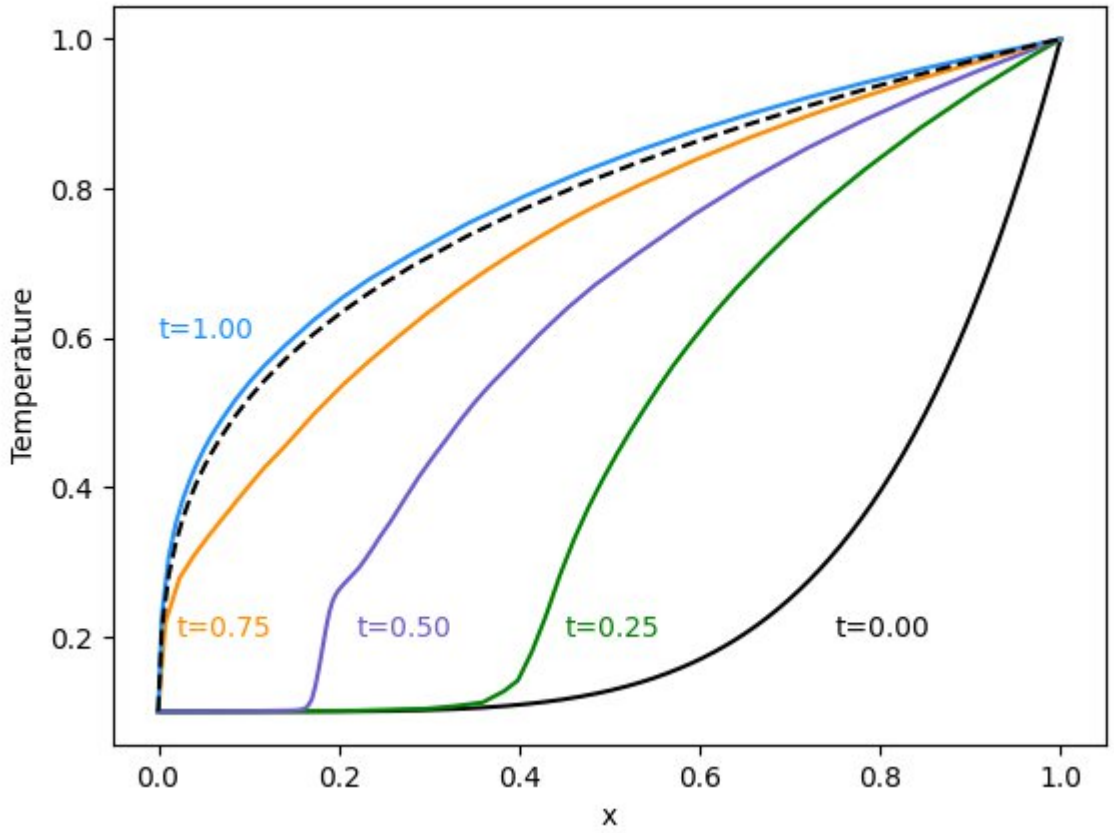
Brio-Wu


Density
Athena (reference)
Dyablo
ρ
AMR Level
x

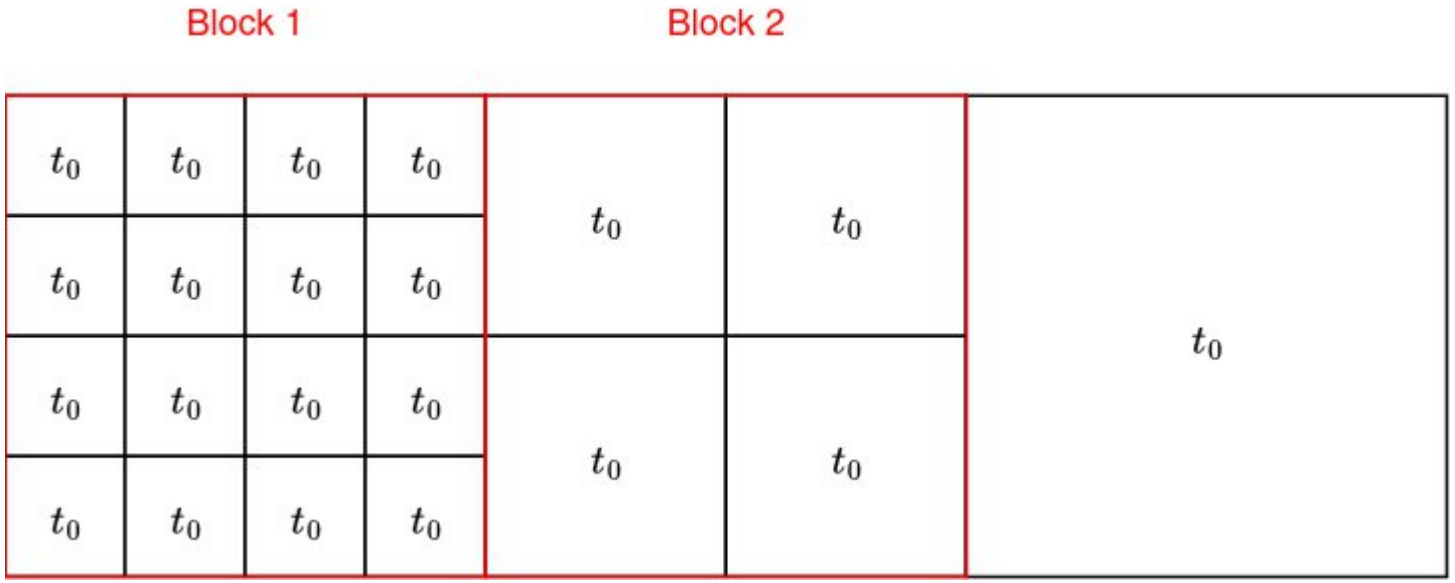

Gas pressure
p
AMR Level
x


Magnetic field (Y-component)
B_y
AMR Level
x

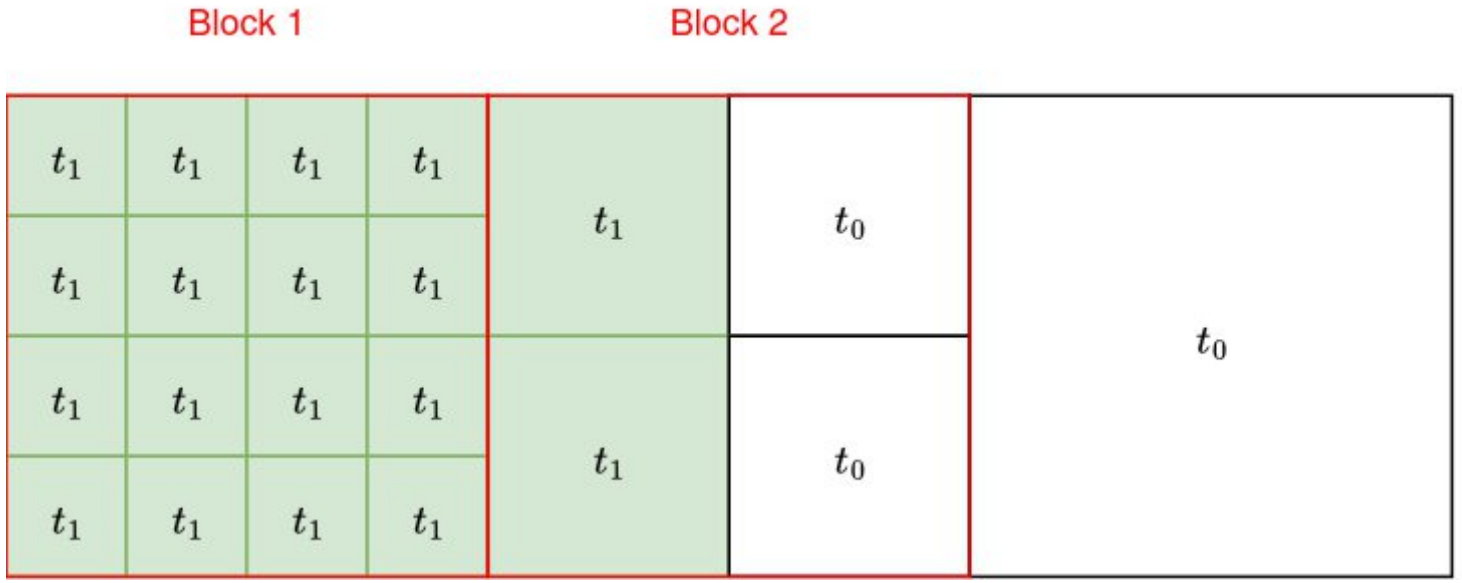
Heat conduction – Rempel et al 2016



Hierarchical Timestepping



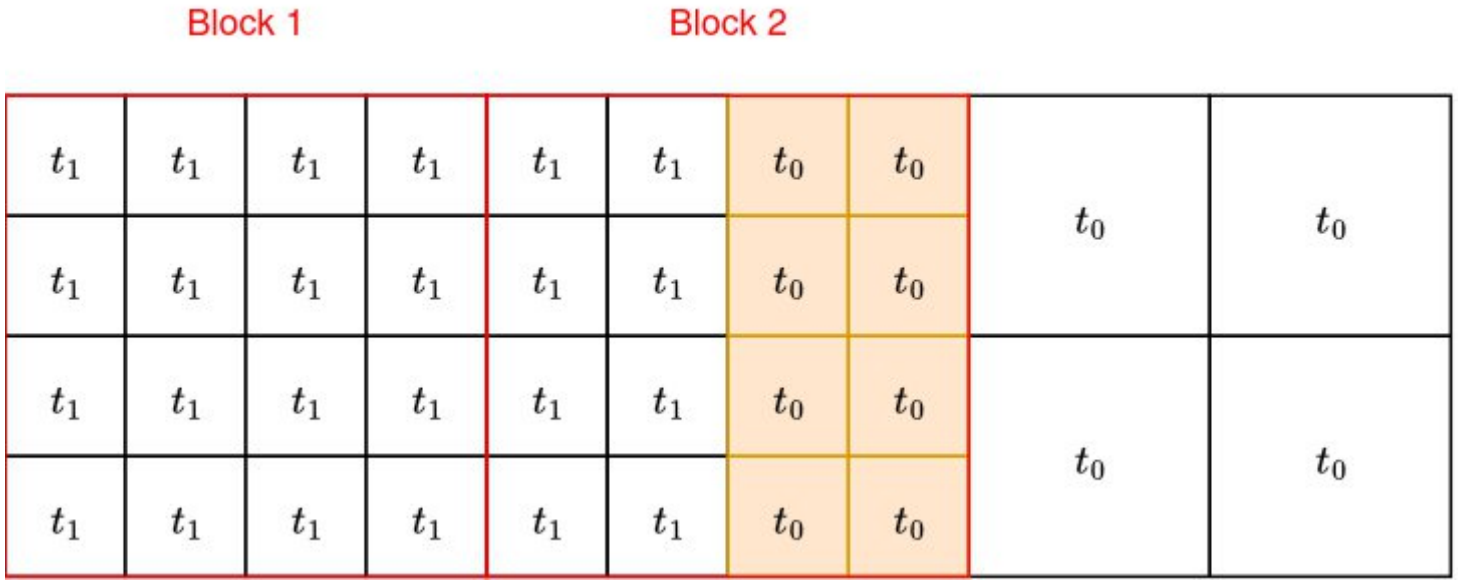
Hierarchical Timestepping



Advancing time

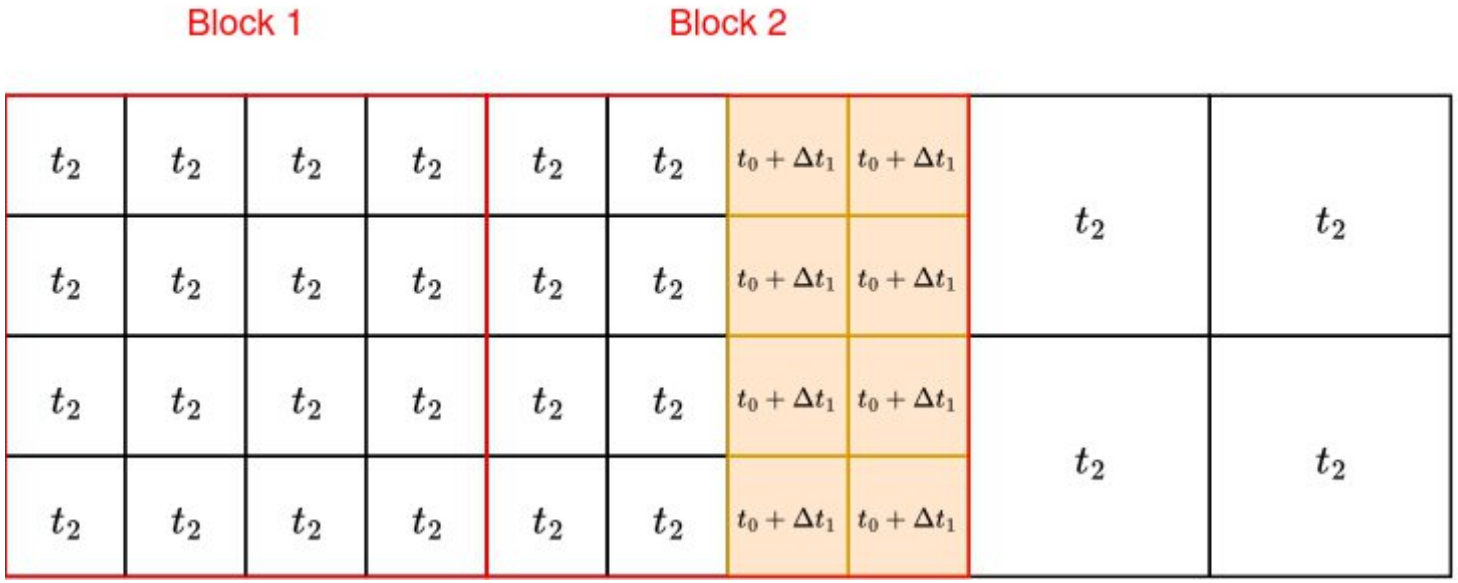
$t_1 = t_0 + \Delta t_0$

Hierarchical Timestepping



AMR Cycle

Hierarchical Timestepping



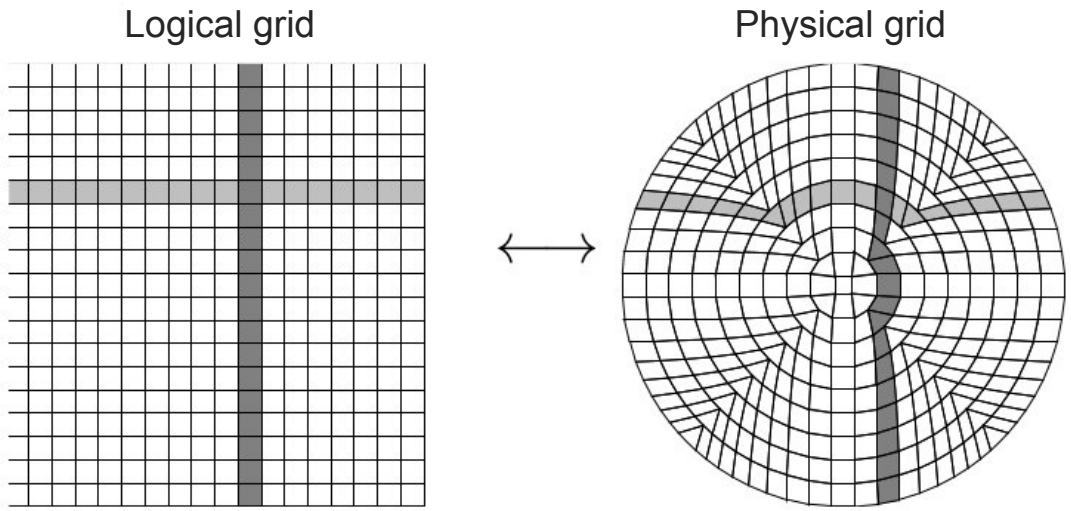
Advancing time

$$t_2 = t_1 + \Delta t_1$$

Geometry module

Isomorphism between a logical grid (cartesian) and a physical grid:

- Based on *Calhoun et al. 2008*: *"Logically Rectangular Grids and Finite Volume Methods for PDEs in Circular and Spherical Domains"*
- Easily to implement, hard to master
- One unique formulation for any type of geometry (no source terms)
- No singularity for spherical geometry
- Less variation in cell aspect-ratio for a given level



Geometry module

Some other examples

- All that is needed is a mapping from logical to physical
- The module calculates areas, volumes and projections accordingly