Athena++
a New RMHD Simulation Code with Adaptive Mesh Refinement

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The Athena++ Project

- Completely redesign **Athena** (Stone et al. 2008) from scratch
- Flexible coordinates: **non-uniform spacing, Spherical**…
- Static / **Adaptive Mesh Refinement (AMR)**
- Support various physical processes (not limited to star formation)
  - MHD(CT), **self-gravity, radiation, general relativity**…
- Highly parallelized: **Z-ordering & dynamic scheduling**
- **Hybrid parallelization**: MPI + OpenMP
- High performance: **vectorization**, memory hierarchy, etc.
- **Parallel IO with MPI/HDF5**, support standard software (VisIt)
- Easy-to-use, easy-to-learn, easy-to-maintain: documents & tests
- Support various architectures; Intel, **IBM BG/Q, Xeon Phi** etc.

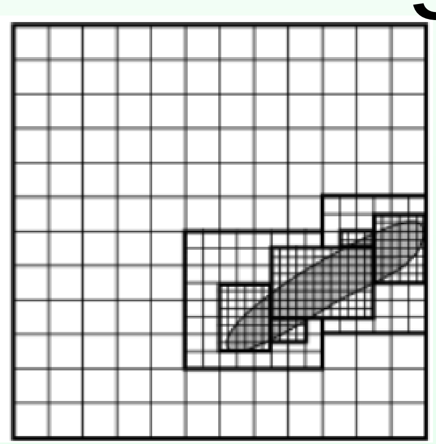
RED: New (or improved) features in Athena++

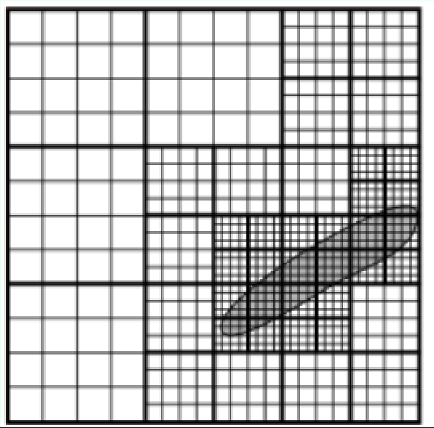
Comparison with Predecessors

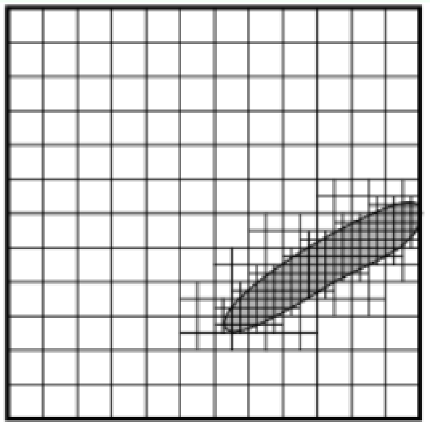
	ZEUS (1992)	Athena (2008)	Athena++ (2016)
Coordinates	Cart. Cyl. Sph.	Cart. Cyl. (Sph.)	**Cart. Cyl. Sph. GR**
Mesh Spacing	Arbitrary	Fixed	**Arbitrary**
Refinement	-	Static Only	**Static + Adaptive**
MHD	Operator-Split+CT	Riemann sol. + CT	**Riemann sol. + CT**
Radiation	VEF / FLD	(M1+RSL / VEF / Direct)	**VEF / Direct**
Refinement	-	Static Only	**Static + Adaptive**
Parallelization	Flat MPI	Flat MPI	**MPI + OpenMP**
Other features	Non-ideal MHD	Self-gravity (w/FFT, uniform only)	**Self-gravity on AMR** **Non-ideal MHD** **Chemical Reactions** **Parallel I/O (HDF5)**

(Figures are from Matsumoto -san's presentation, thanks!)

AMR Design: Grid Structure







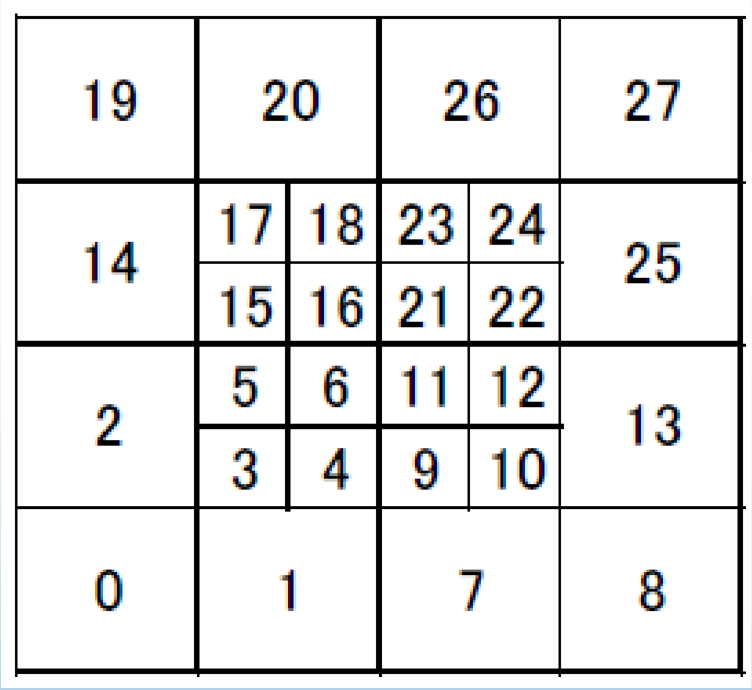
	(A) Block (Patch) Based	(B) Oct-Tree-Block Based	(C) Cell(Tree)-Based
Pros	High adaptivity **Uniform within block** **Use of existing scheme**	**Simple relation btw blocks** **Uniform within block** **Use of existing scheme** Parallelization by space-filling curve	Highest adaptivity Logically beautiful Parallelization by space-filling curve
Cons	Grids are not unique **Non-trivial grid generation** **Complex parallelization**	Lower adaptivity (depending on block size)	**Performance Issue** **Complicated grids** **(non-trivial neighbor cell)** **Hard to write,read,analyze**
Examples	Original: Berger & Colella 1989 Orion, PLUTO(Chombo), Enzo, **Athena SMR**,…	FLASH(PARAMESH) Nirvana, SFUMATO,…	RAMSES, ART

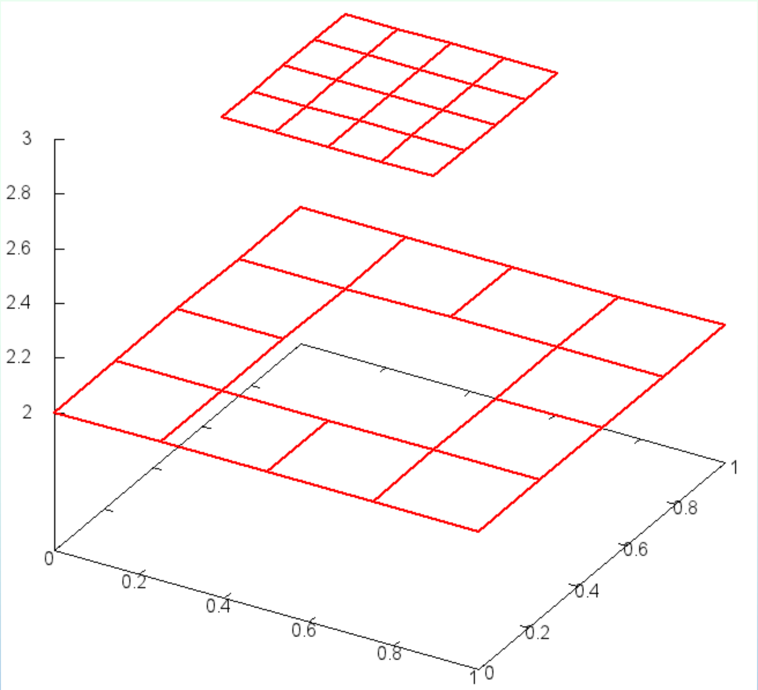
More about AMR Grids

Meshblocks are stored in (a part of) oct-tree and numbered by Z-ordering→not ideal, but good balance btw cost & performance

Shared time stepping only (at least for now)

Do not solve overlapping regions: level-interactions are only at the level boundaries → minimize inter-level dependencies



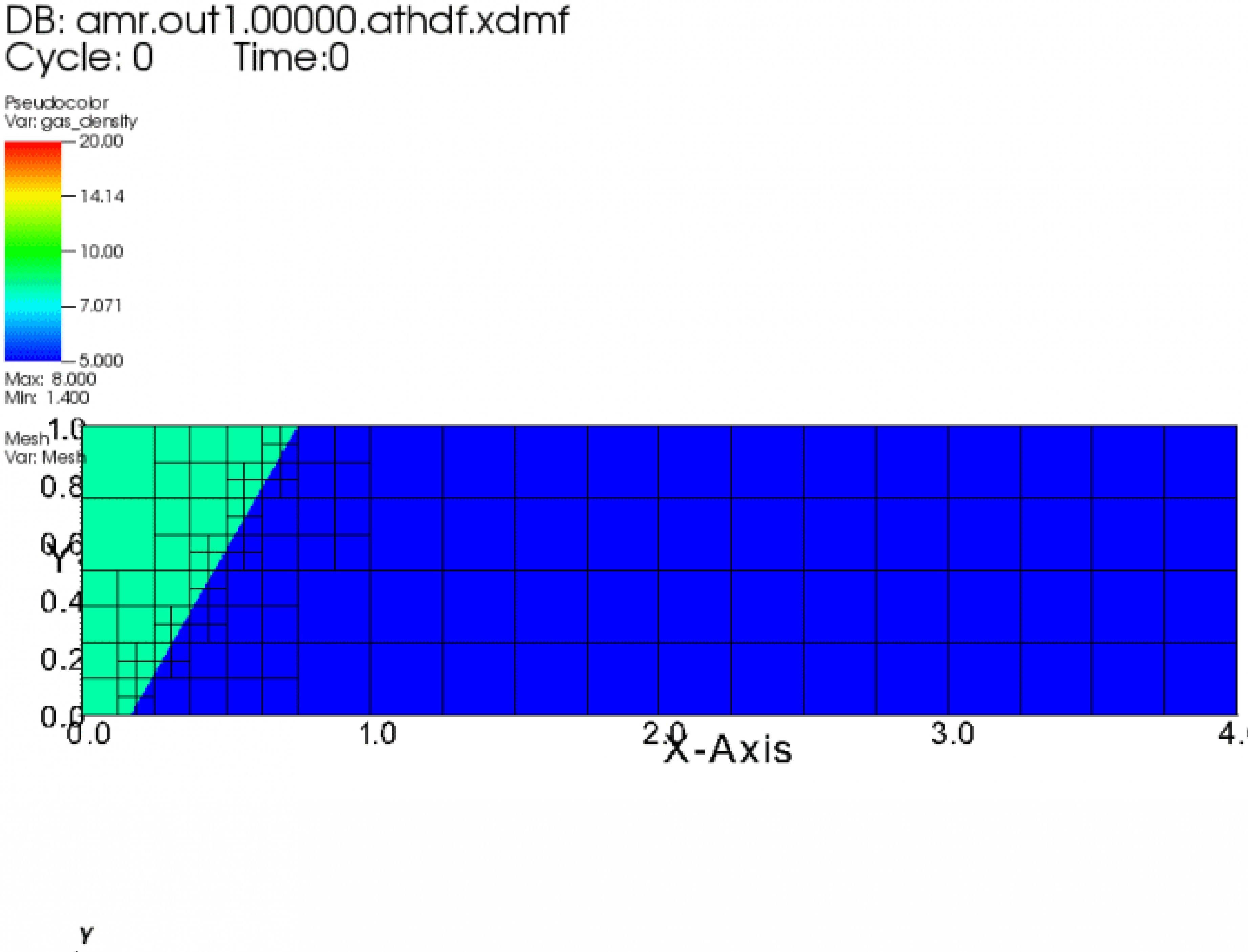


Adaptive Mesh Refinement

- Implemented in a week based on the SMR
  - The Black Friday is the official birthday

- "AMR part" is only less than 1000 lines
  - "SMR part" is much longer, sharing most codes

- Low overhead, almost as fast as uniform grids, at least on a single core.



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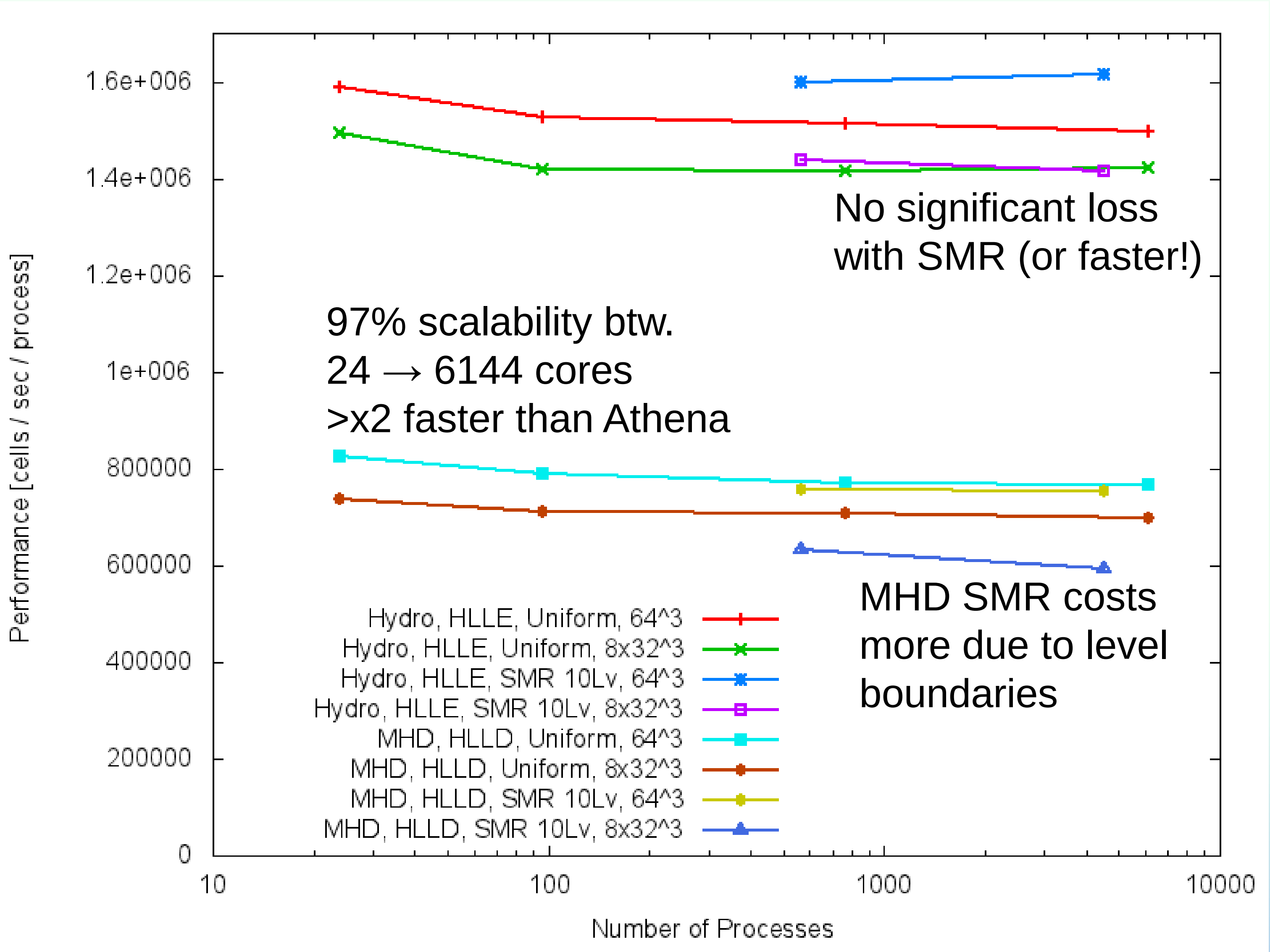
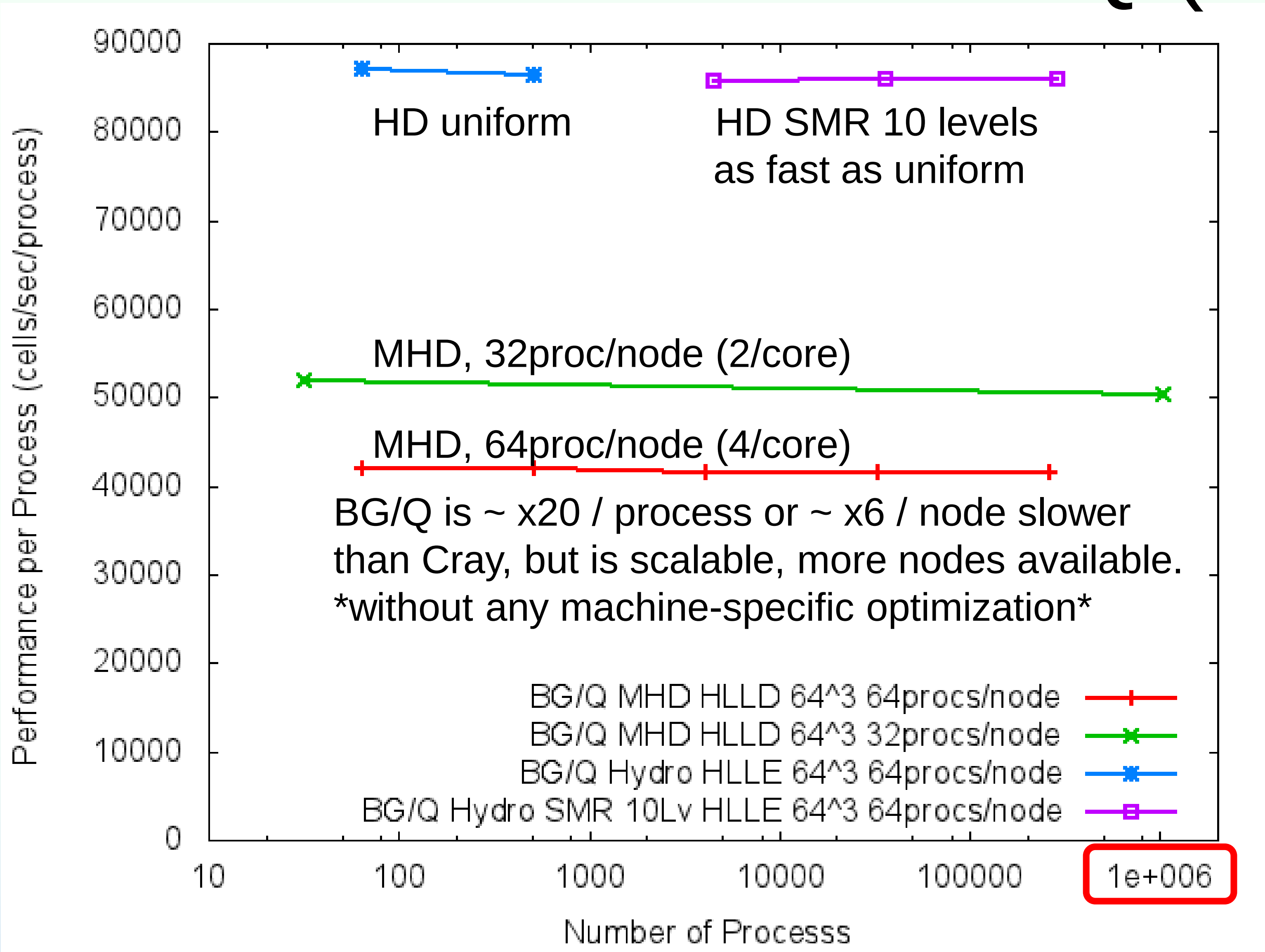
Pseudocolor
Var: gas_density
20.00
14.14
10.00
7.071
5.000
Max: 8.000
Min: 1.400
Mesh
Var: Mesh
1.0
0.8
0.6
0.4
0.2
0.0
Y
0.0
1.0
2.0
3.0
X-Axis
Y

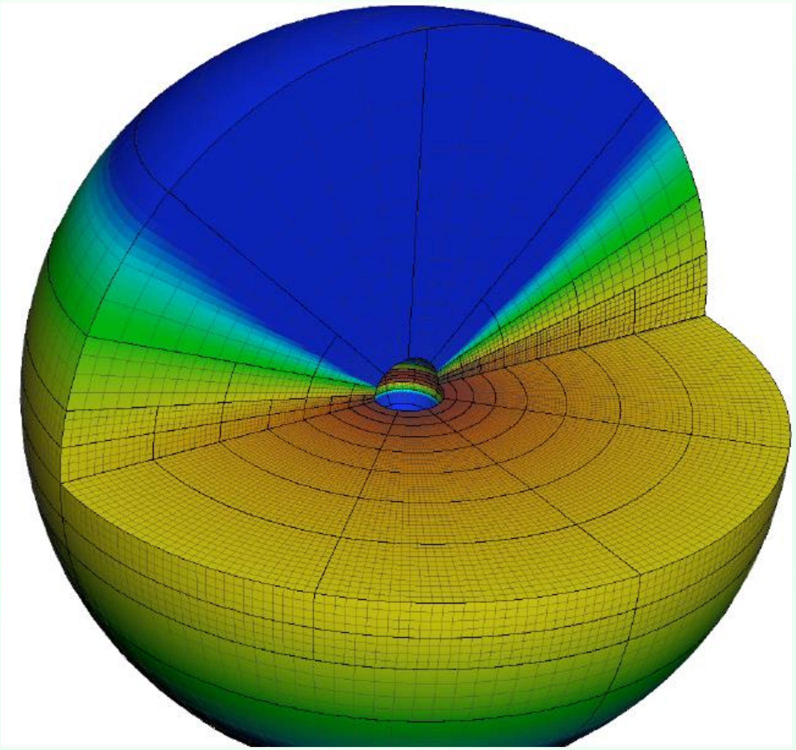
Performance on NAOJ Cray XC30

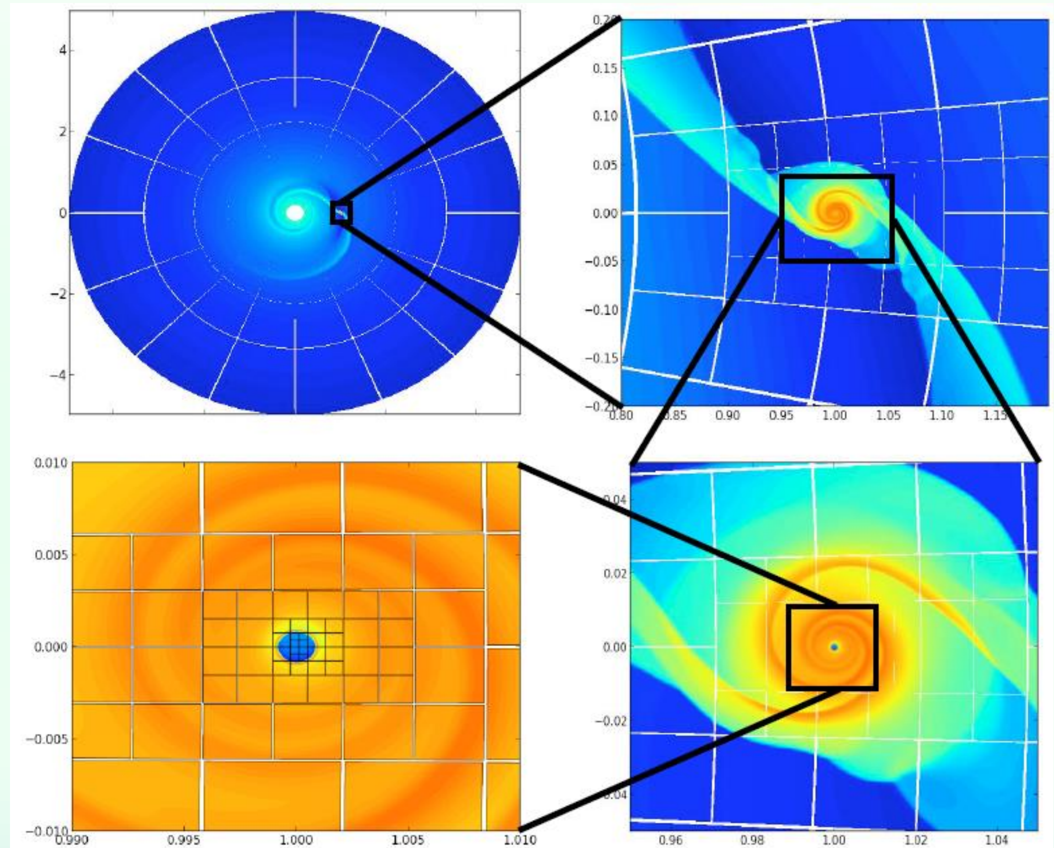


Performance on IBM BG/Q (Mira)



Planet-Disk Interaction



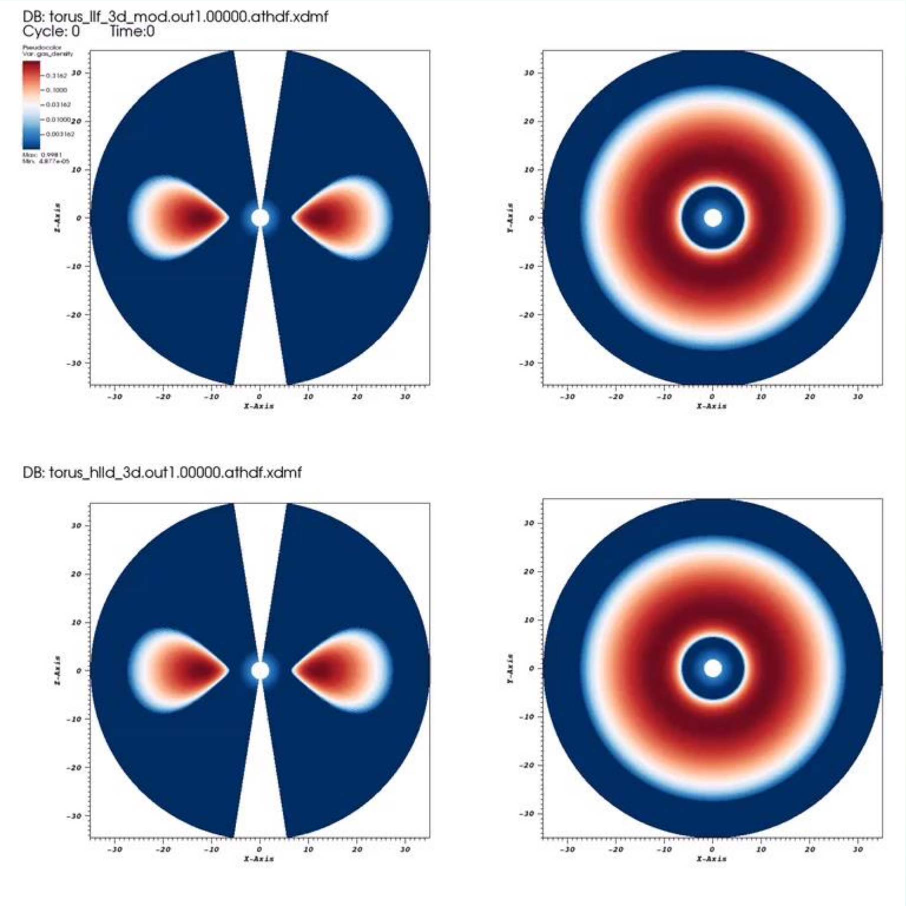


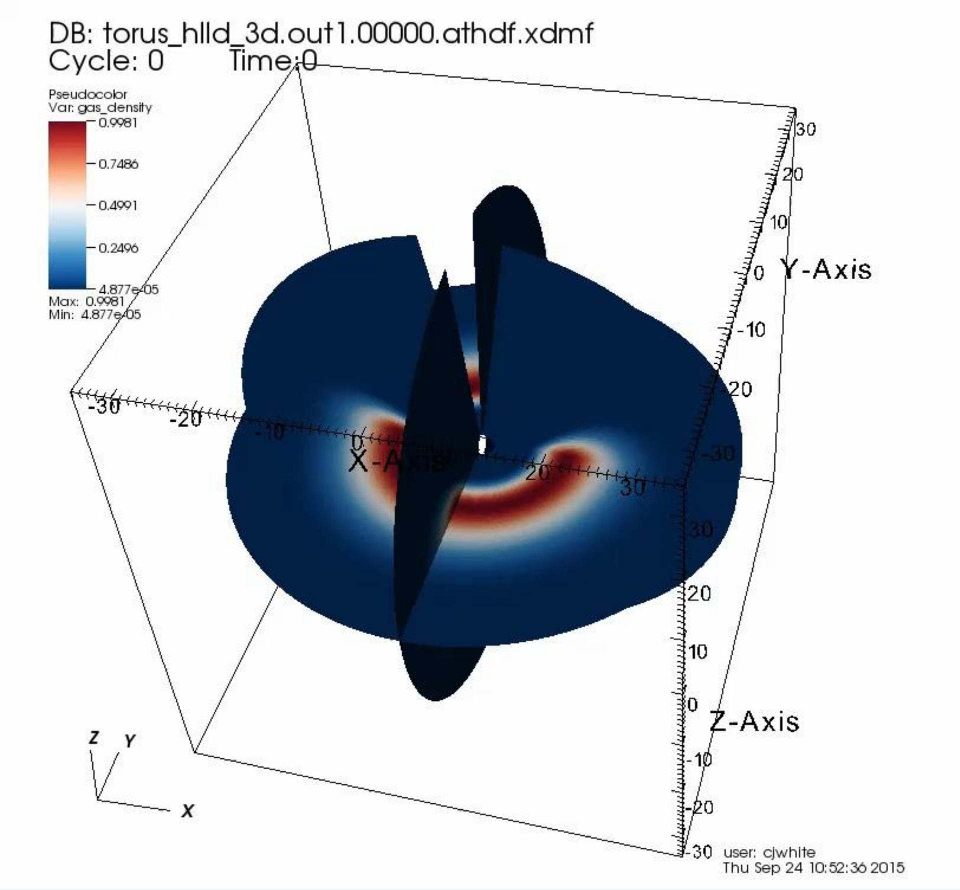
(Figures provided by Zhaohuan Zhu)

Planet-disk interaction simulation in 3D spherical coord. with SMR
SMR allows us to resolve the small scale circumplanetary disk while covering the whole disk with an affordable cost.

(A related paper & NASA PR: http://hubblesite.org/newscenter/archive/releases/2015/40/)

GRMHD accretion Torus

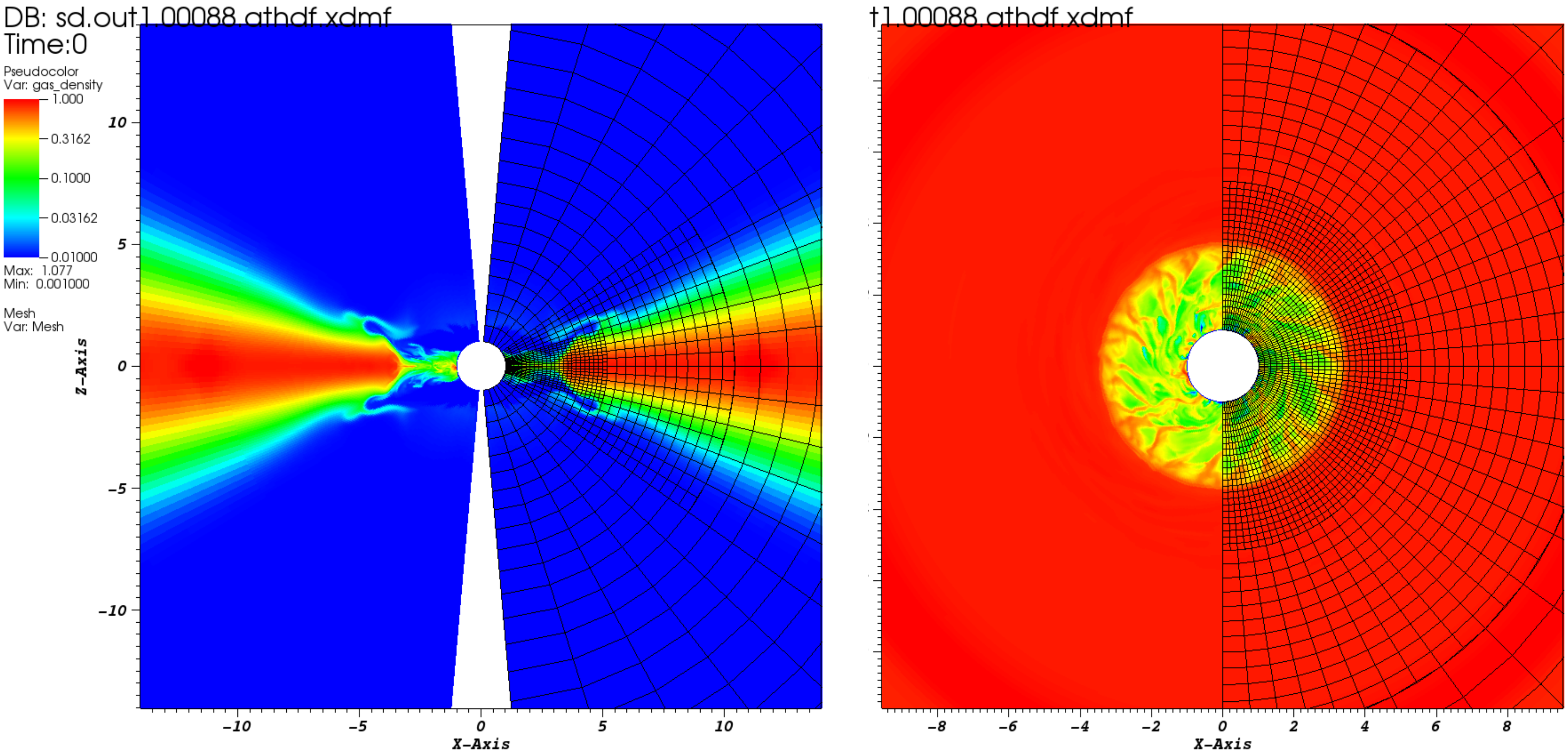




GRMHD (fixed-metric) simulations (by C. White, arXiv:1511.00943) any Riemann solver can be used → more accurate (and faster) than other codes using LLF. Costs ∼x2.7 (HD) - x4.6 (MHD).

Star-Disk Interaction

note: showing coarsely sampled mesh



Non-uniform mesh (r: cosh, θ: compressed near mid-plane)
+ SMR save a lot of computational time (960 cores -> 400 cores)
The magnetic interchange instability is developing.

Plan

- Now we are cleaning up the code and preparing documentation
- Public distribution on the website: soon, hopefully before April (I feel terribly sorry that we could not make it before this UM)
- Method Paper: soon, hopefully before April
- The first public version (1.0) will include:
  - HD and MHD (including special relativity)
  - SMR and AMR
  - Flexible coordinate systems

  →GR and Radiation will not be included in the first release
- New features being implemented:
  - Self-gravity (~summer)
  - Chemistry (on going)
  - Non-ideal MHD (AD, Hall, Ohmic; on going)
  - Particles (dust, planetesimal, etc.; on going)

Summary

New AMR MHD code Athena++

- Good performance in hydro / MHD, uniform / AMR without machine-specific optimization (except #pragma simd)
- Versatile: can be used for from protoplanetary disks, star formation to general relativistic BH disks.
- Carefully designed and tested; we even found two bugs in Intel C++ Compiler and one in Cray MPI.
- Current plan: make it public and publish a method paper as soon as possible, hopefully in 2 months
- Planning to have a support website in Japanese and hold a hands-on school