Astrophysical MHD Simulations with Athena++

Kengo Tomida
(Tohoku U.)

牧野さんと私

還暦おめでとうございます

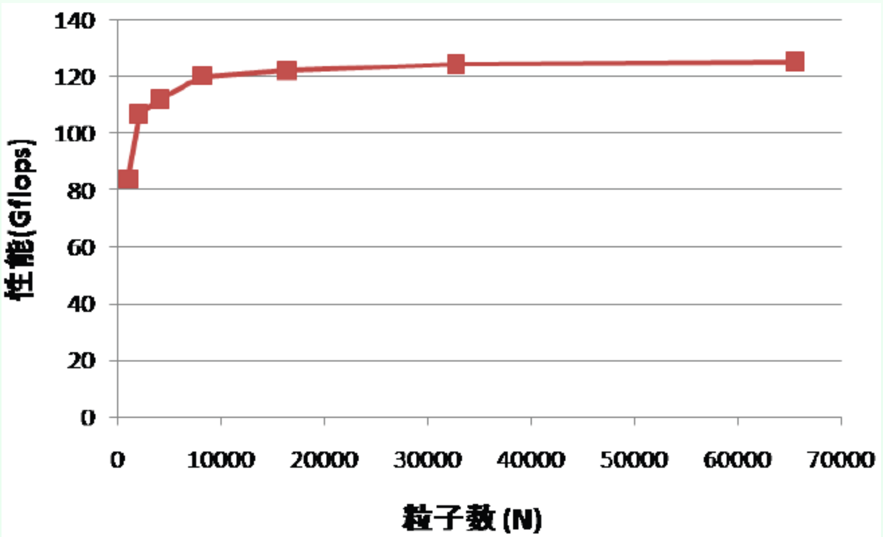
牧野さんとの出会い

- 最初にお会いしたのは京大宇宙物理学教室の集中講義
- 当時私は4年生で、春から総研大/国立天文台に入学予定
- 牧野さんは同時期に天文台に異動
  春からよろしくお願いします、と挨拶した

- 私は星形成の理論グループ（富阪さん）の所属
  → 牧野さんのグループとは「隣の研究室」という関係
- 富阪グループの学生はほぼずっと私一人
  → 学生が多く賑やかだった牧野グループとは対照的
- 牧野さんには色々お世話になりました

少し思い出話

（富田＆山崎 2008）



当時参加したN体の学校で似鳥さんからPhantom Grapeの話を聞いた。

→ 自分にも出来そうな気がしたので当時話題だったPS3搭載のCell Broadband Engineでやる。

→ PS3(自腹)にLinuxを入れて牧野さんに色々相談しながらN体計算コードを書いた。

⇒ Cell Speed Challenge 2008 自由課題部門 第1位

性能だけでなく精度（Cellは切り捨て）を議論したことも高く評価された。

	Cell B.E.	GRAPE-7	CUNBODY-1
最大粒子数	86400	24576	131072
ピーク性能 (Gflops)	125 (実測)	456 (理論値)	653 (実測)
チップ単価	2 万円 (推定)	36 万円 (Model600)	7 万 (GTX)
システム単価 (最小構成)	4 万円 (PS3)	45 万円〜 (ホスト込)	16 万円〜 (ホスト込)
消費電力	18W 本文参照	約 20W	約 200W?
価格対性能比 (円/Gflops)	320	987	245
電力対性能比 (W/Gflops)	0.14	0.04	0.31

Athena++

Athena++

- A new public MHD simulation code for astrophysics
- Developed in international collaboration led by Jim Stone @ IAS
- Paper：Stone, Tomida, White, and Felker, 2020, ApJS
- Flexible Coordinates: **variable spacing, Spherical, Cylindrical**…
- Static/**Adaptive Mesh Refinement (AMR)** with uniform timestep
- Robust MHD solver with approximate Riemann solver + CT
- Various physical processes for astrophysical applications
  - General Relativity, self-gravity, non-ideal MHD, EOS, radiation...
- High-performance and parallelization using **dynamic scheduling**
- **Hybrid parallelization**: MPI + OpenMP, auto load balancing
- **Parallel IO with MPI/HDF5**, supporting standard software
- Easy to use, easy to learn, and easy to maintain
- Strict quality control：Found bugs in compilers and libraries.

Dynamic Scheduling with TaskList

The ordering of computation is usually fixed at the time of programming

In Athena++, we split computation into small Tasks and put them in TaskList. TaskList defines the ordering and dependency between the Tasks.

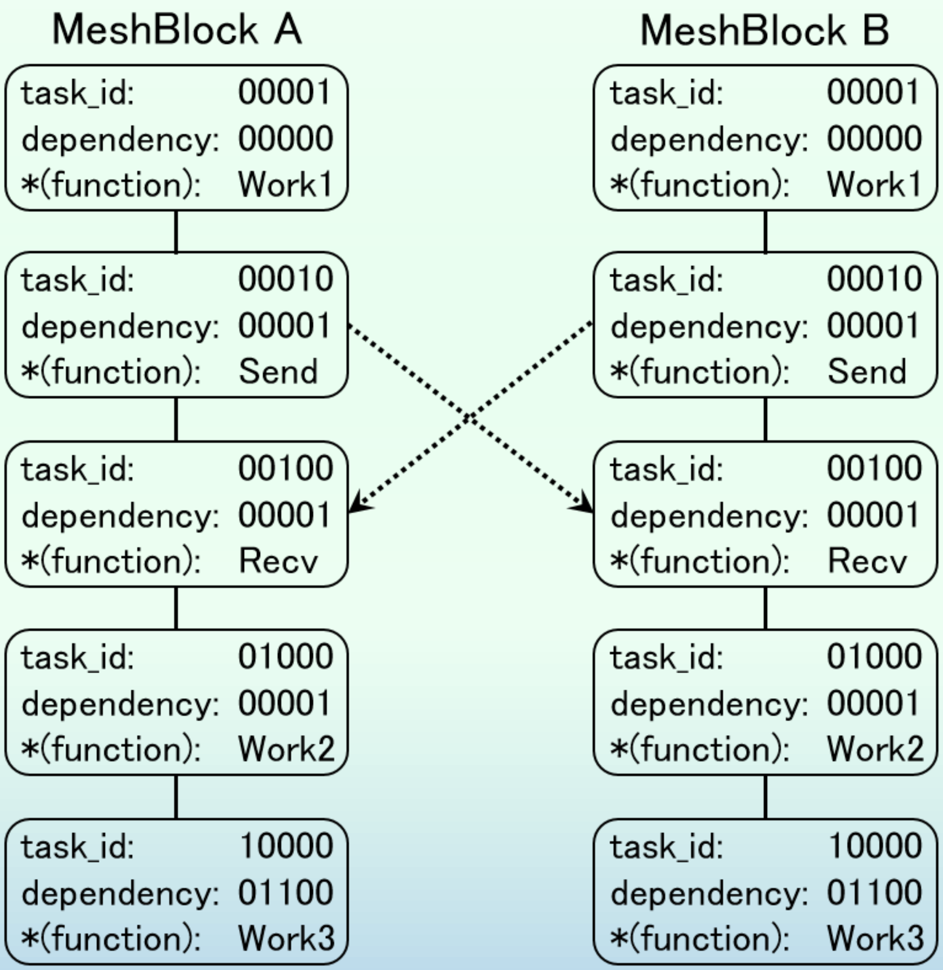
- Split implementation of Tasks and relations between Tasks

→ improve modularity and flexibility

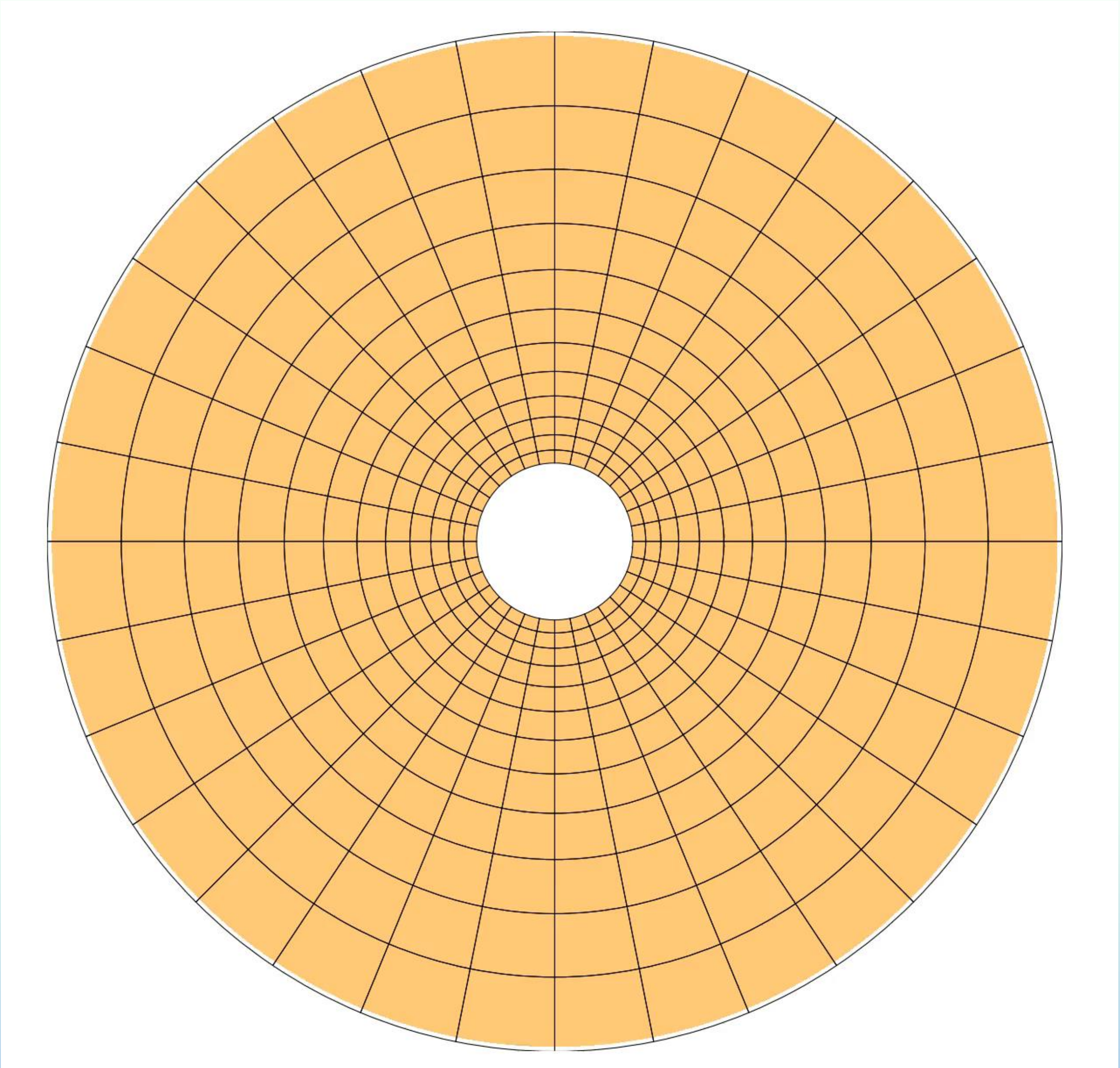
- The ordering of computation is determined dynamically at runtime

→ computation-communication overlap

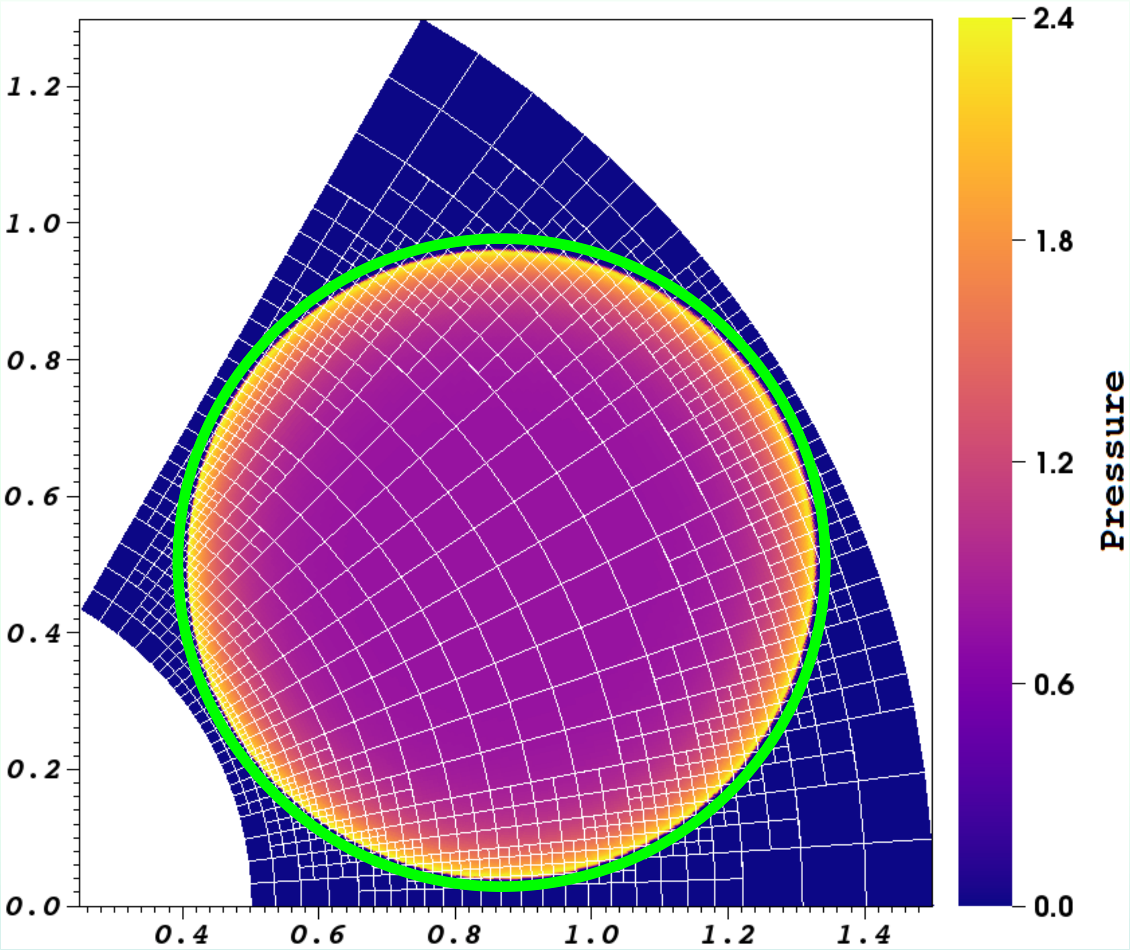
⇒ improve both development and simulation performance.

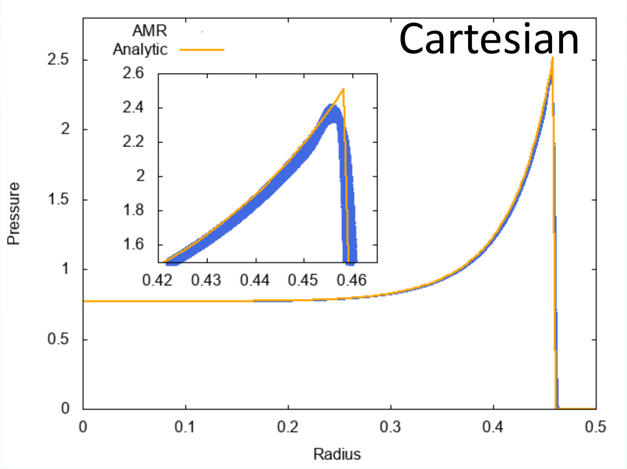


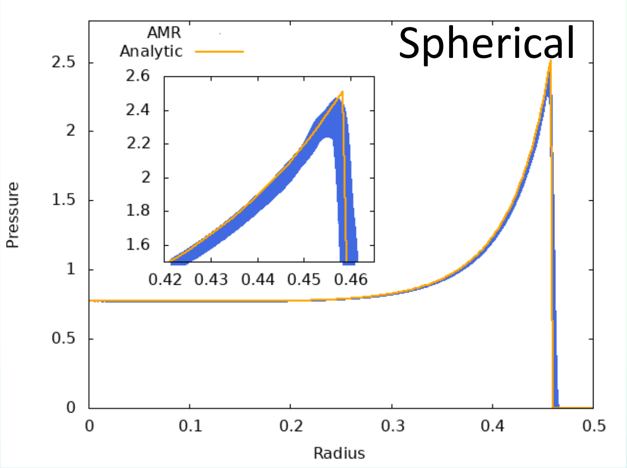
Athena++ Logo Demonstration



3D Blast Wave & Sedov-Taylor solution



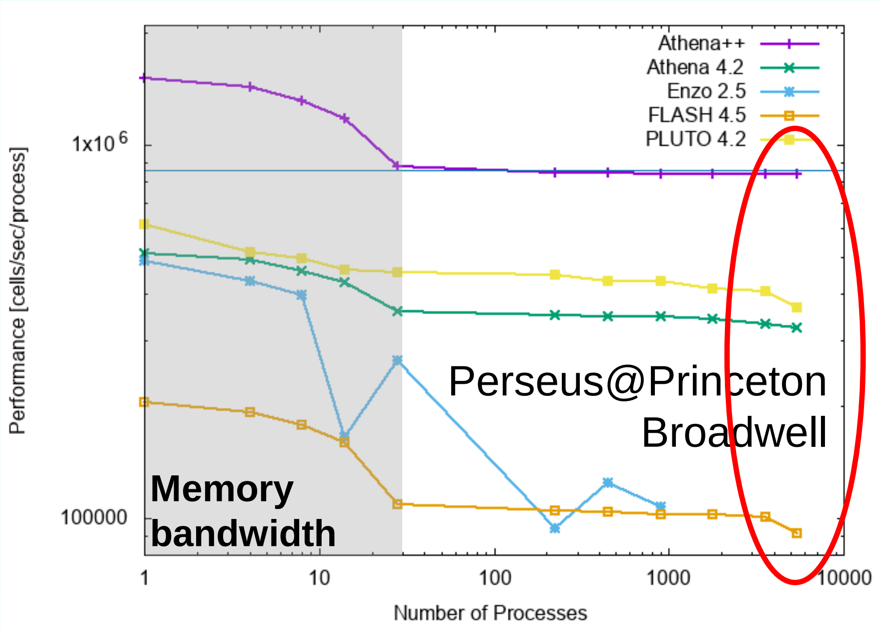


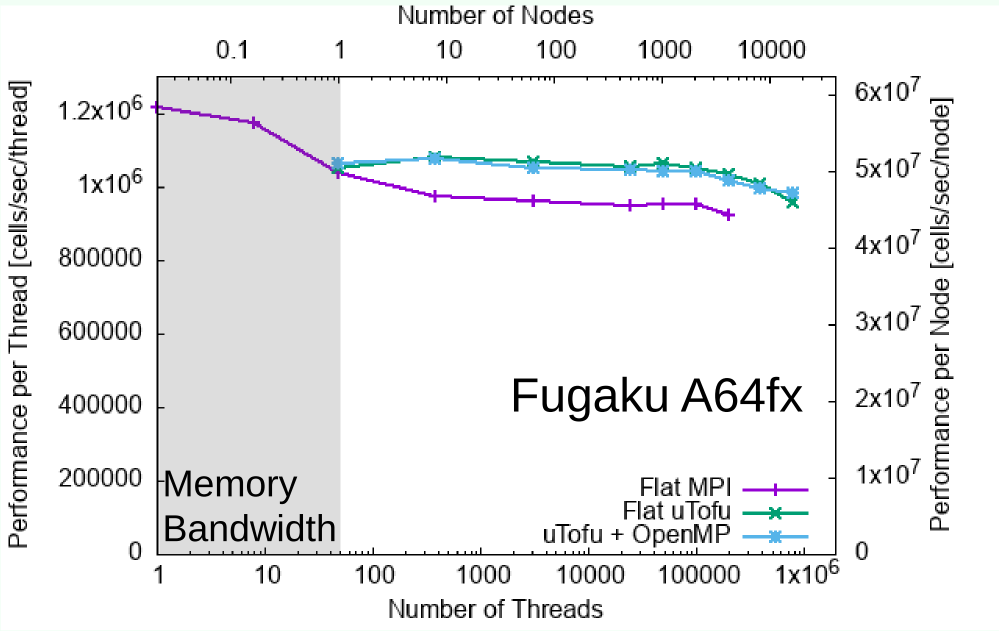


Offset Blast wave in 3D spherical polar coordinates

- Athena++ can maintain symmetry well (beware of optical illusion)
- And can reproduce the Sedov-Taylor solution reasonably well too

Athena++ Performance



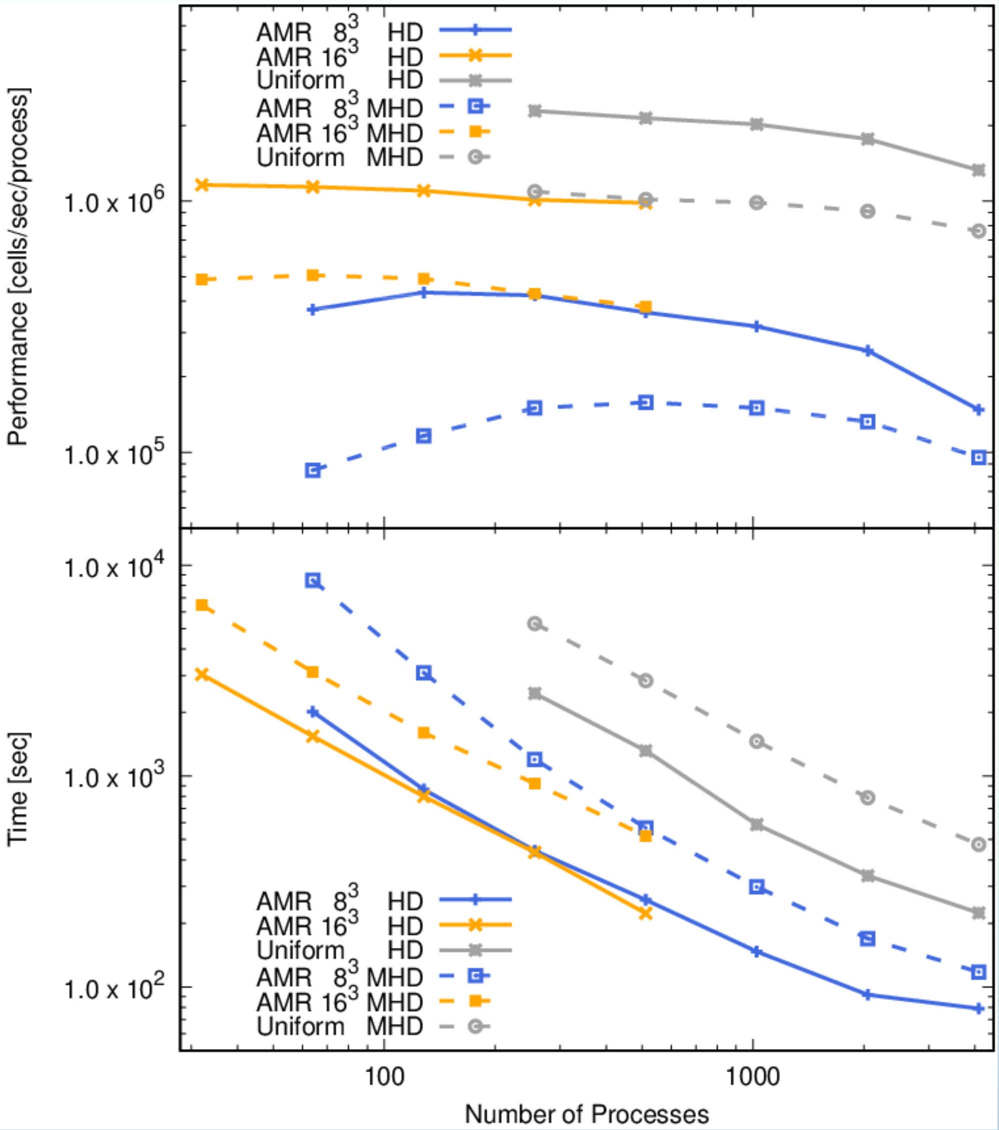


Weak scaling tests of ideal MHD using 64^3 cells / core

- >97% weak scalability up to >10,000 cores.
- >92% with more than half million threads on Fugaku.
- Faster than other public astrophysical MHD codes.
- We can do better than million$$$ projects if we do it right.

⇒ Athena++ is ready for the Exa-scale era.

AMR Strong Scaling



HD/MHD Blast wave tests

Uniform: 512^3

AMR: 3 levels with 8^3 and 16^3 MeshBlocks

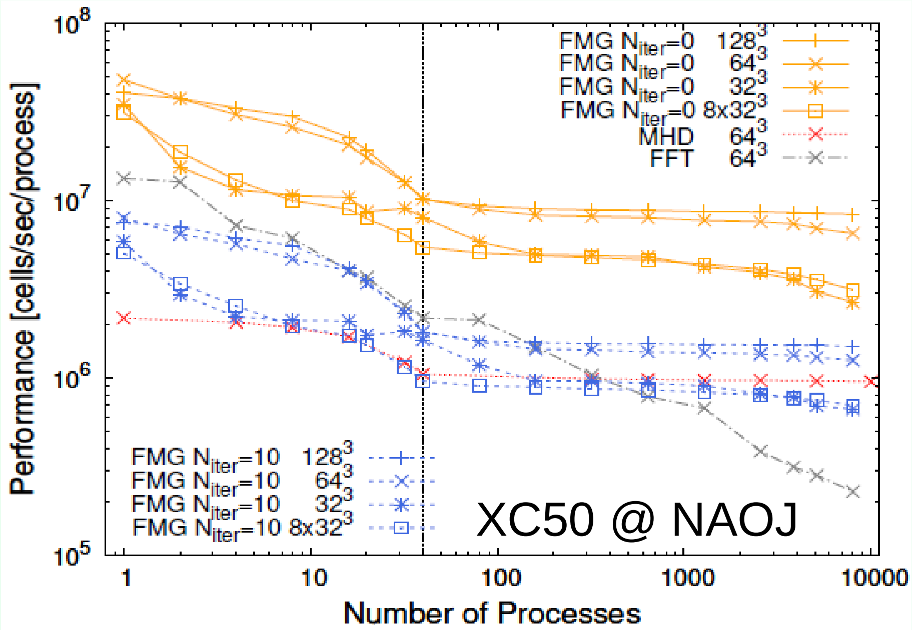
2nd-order PLM,

HLLE for HD, HLLD for MHD

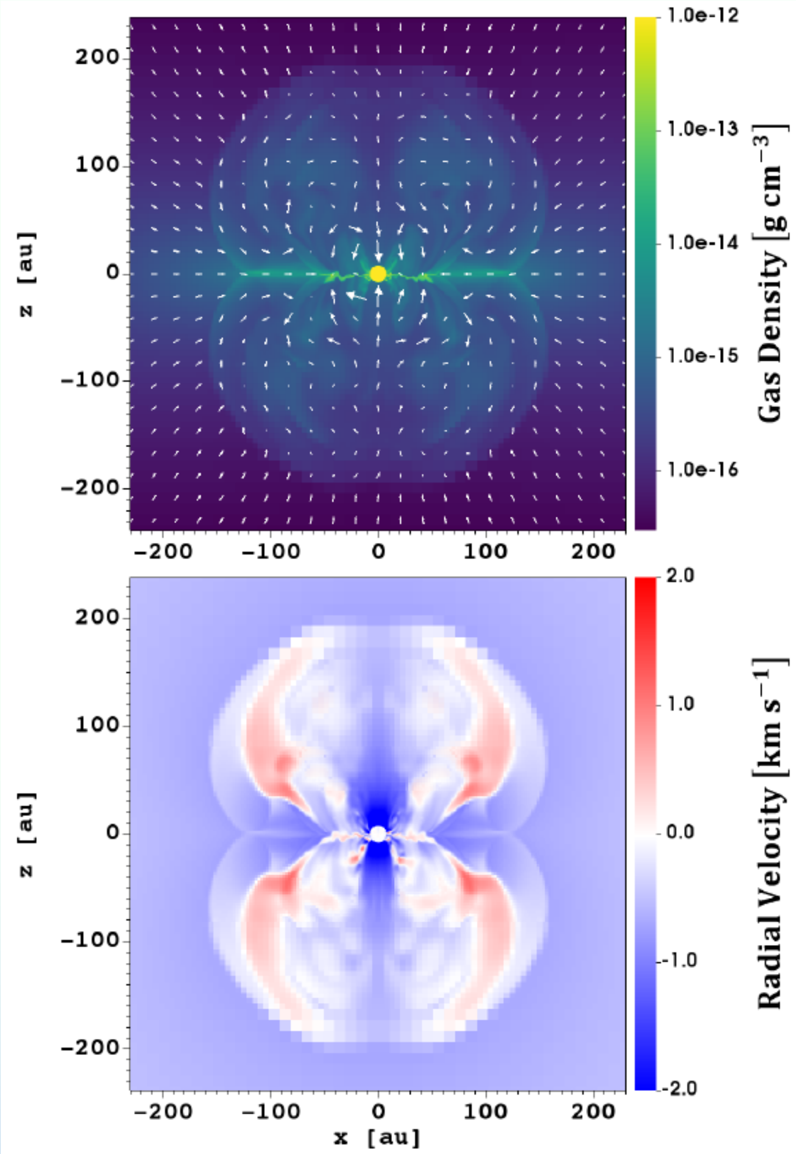
Cray XC50 @ NAOJ, Skylake

Half of the performance gain of AMR comes from the longer time step by derefining central hot gas with high sound speed.

Multigrid Self-Gravity Solver

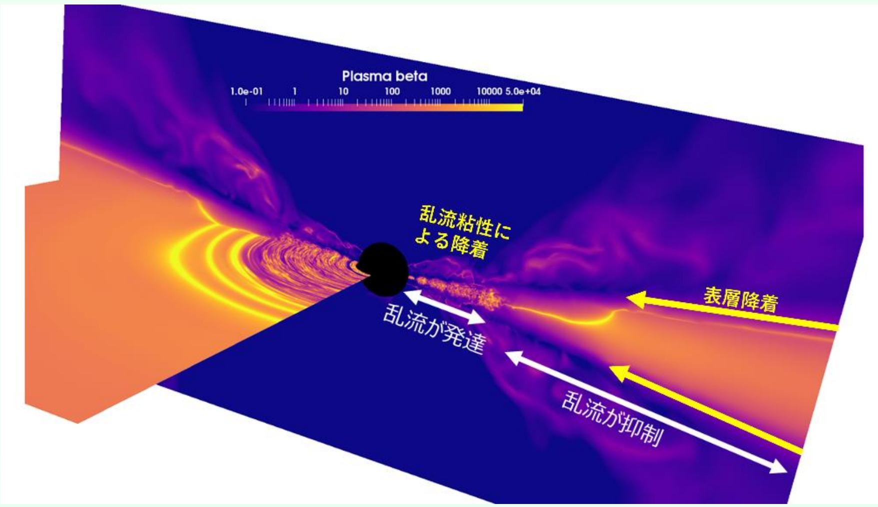


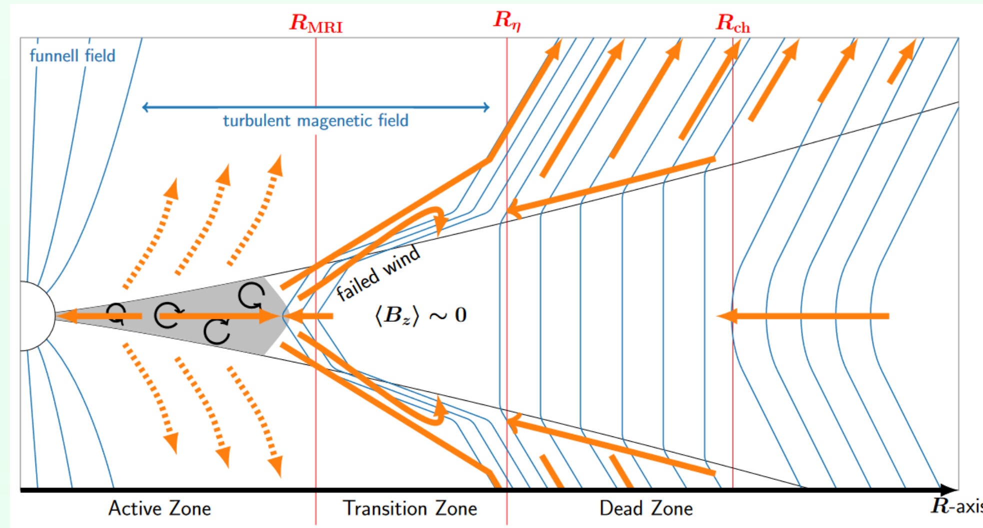
A new self-gravity solver using full multigrid. It is not trivial to develop a scalable gravity solver as it requires global communication. With dynamical scheduling in Athena++, we successfully developed an efficient solver. ↑ Now AMR star formation simulations are possible with Athena++. →
(Tomida and Stone, 2023, ApJS)



Scientific Projects

Protoplanetary Disks



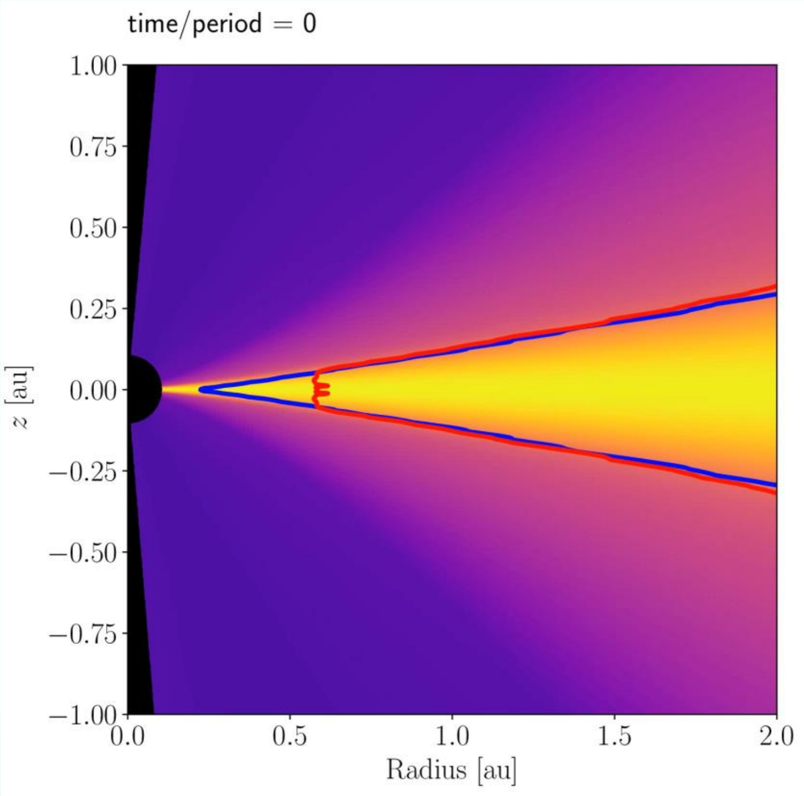


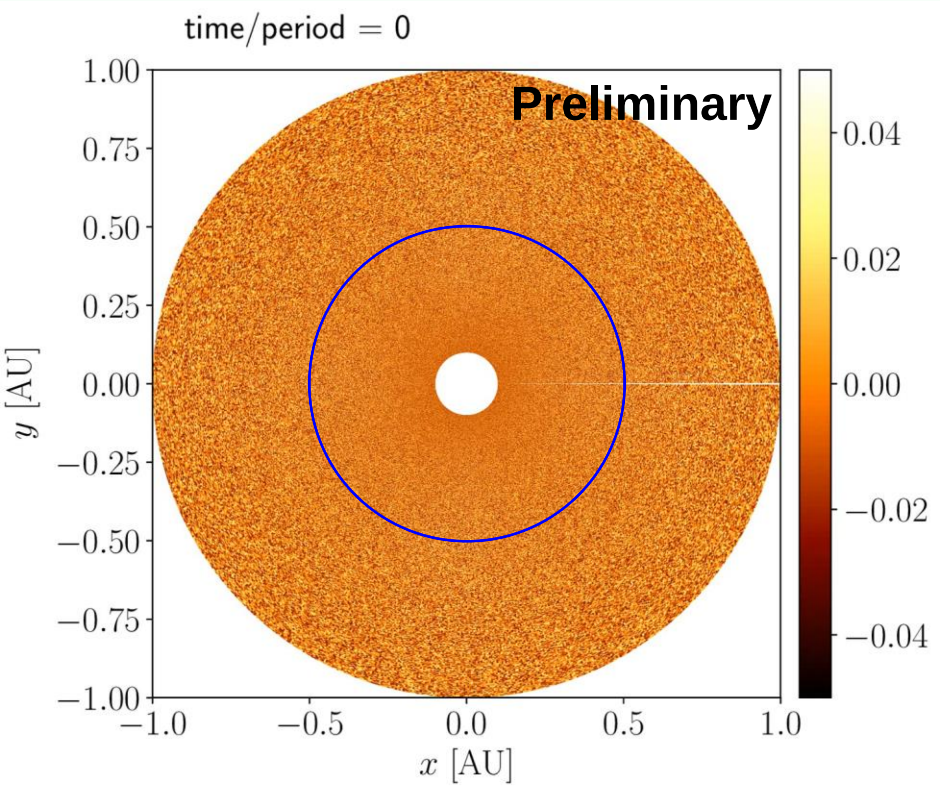
(Iwasaki et al. to be submitted)

High-resolution 3D global non-ideal MHD simulations of protoplanetary disks resolving MRI turbulence using Fugaku.
Rich disk structures are produced by interaction between non-ideal MHD effects + thermodynamics.
→ Realistic mass/flux transport in disks and planet formation site

(Iwasaki et al. in prep.
Mori et al. in prep.)

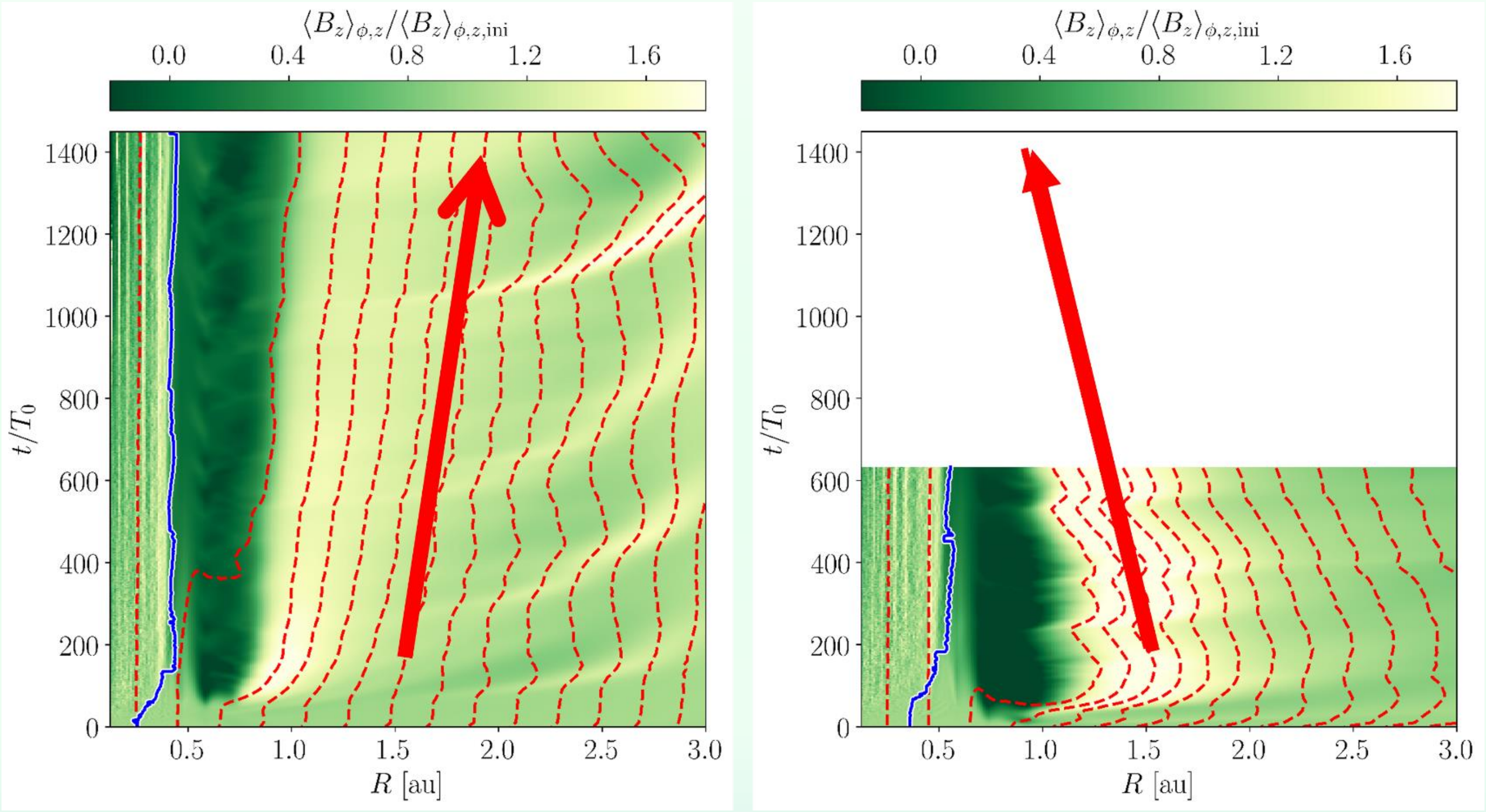
Protoplanetary Disks





3D Global non-ideal (OD+AD, Hall in progress) MHD simulations to determine the environment of planet formation.
Rich structure formation: active/dead zones, winds, rings, gaps, ...

Magnetic Flux Transport



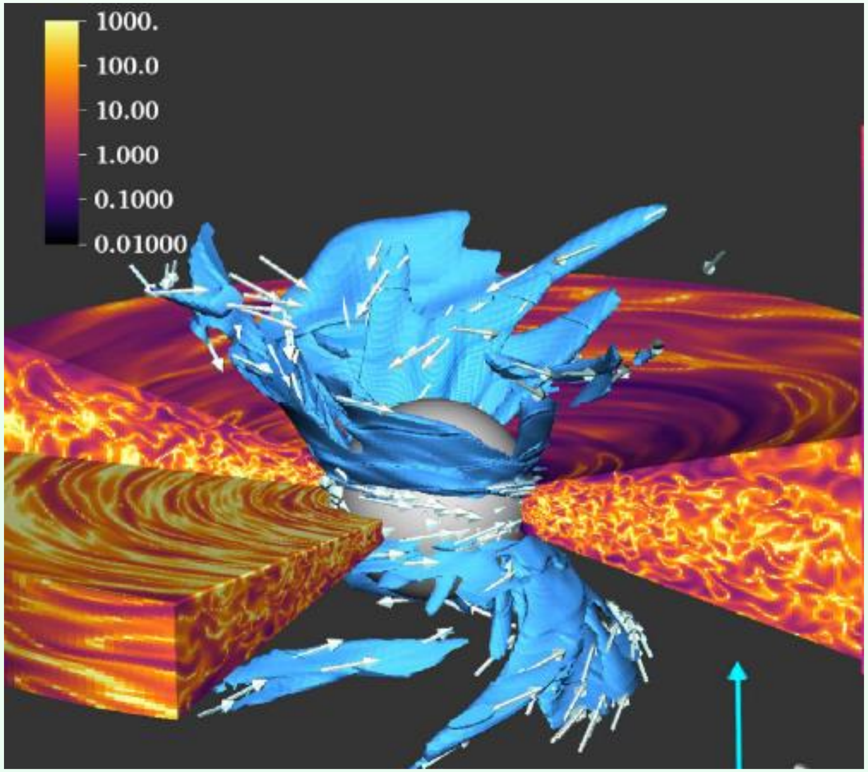
$d/g = 10^{-4}$ $d/g = 10^{-2}$

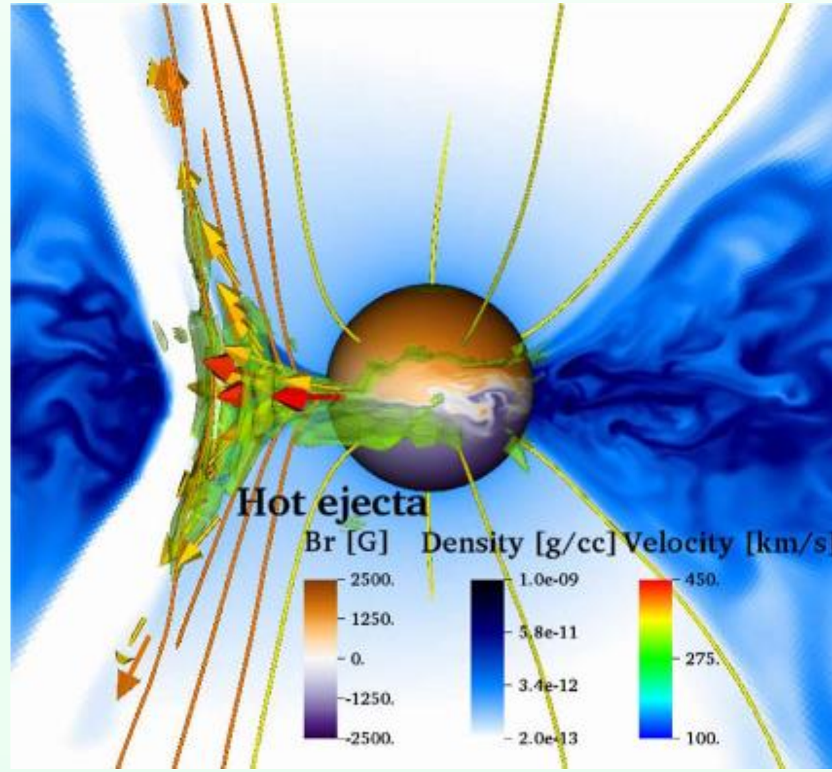
Magnetic flux transport is important in the context of the stellar magnetic flux as well as the structure and evolution of protoplanetary disks.

We found that relatively fast transport speed of a few × v_K, but the direction of the transport depends on the dust properties.

(Takasao et al. 2018, 2019, 2022)

Star Disk Interaction

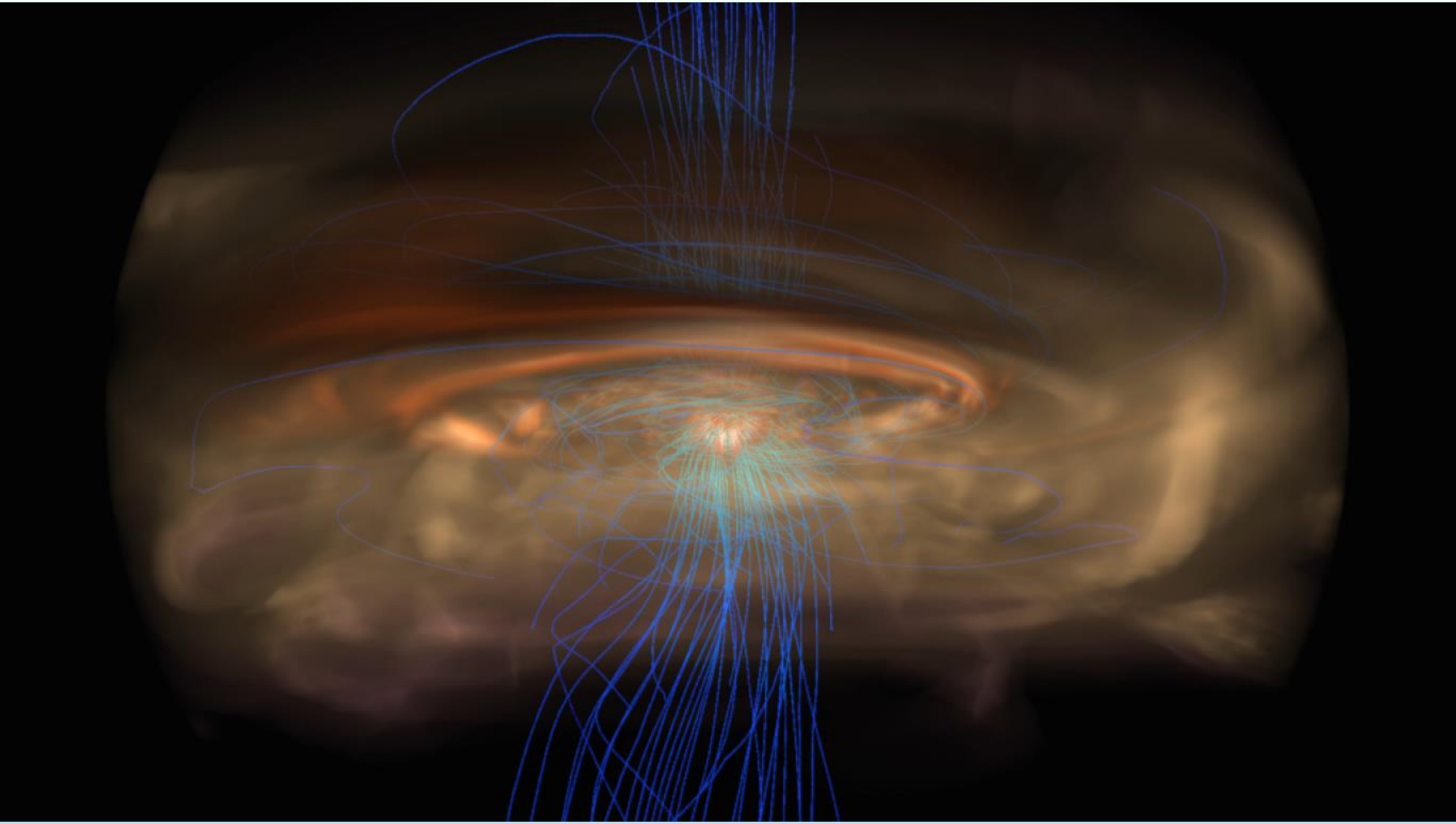




Left：Accretion flow onto a weakly magnetized protostar
fast accretion onto the high latitude region is realized even without magneto-sphere – failed wind loses ang. mom. and accretes.

Right：A new model of giant flares produced by reconnecting disk B-field can explain the observed energy release in giant flares

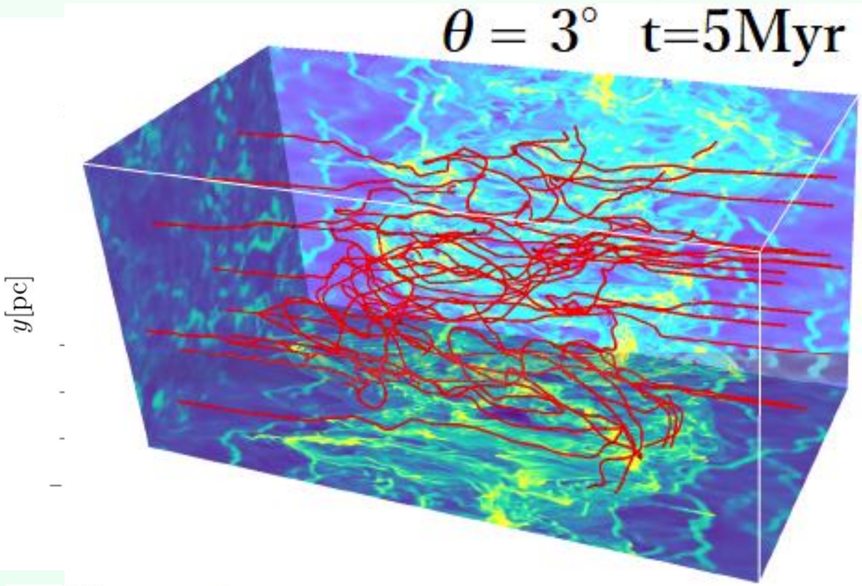
Professional Visualization

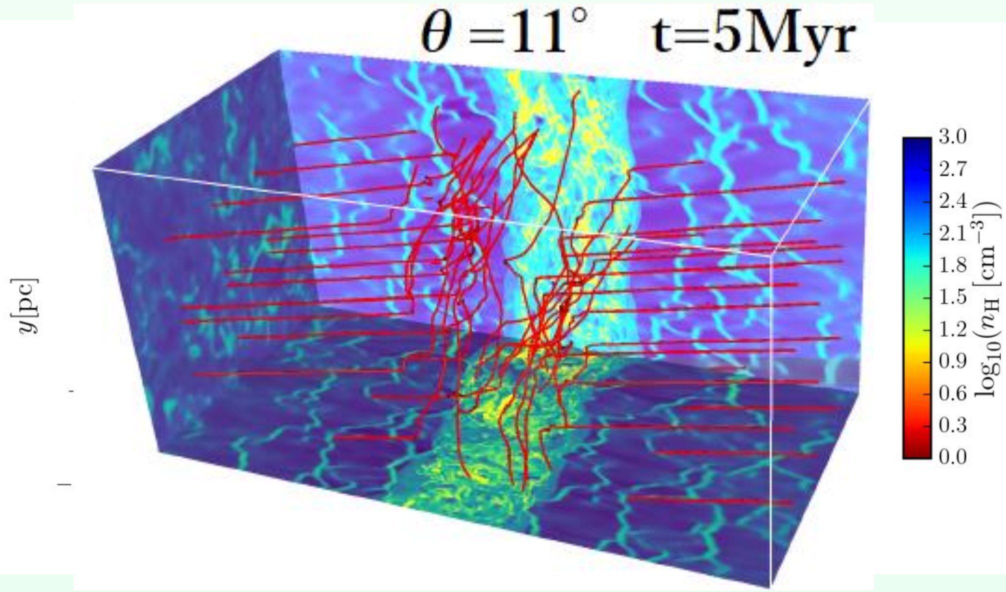


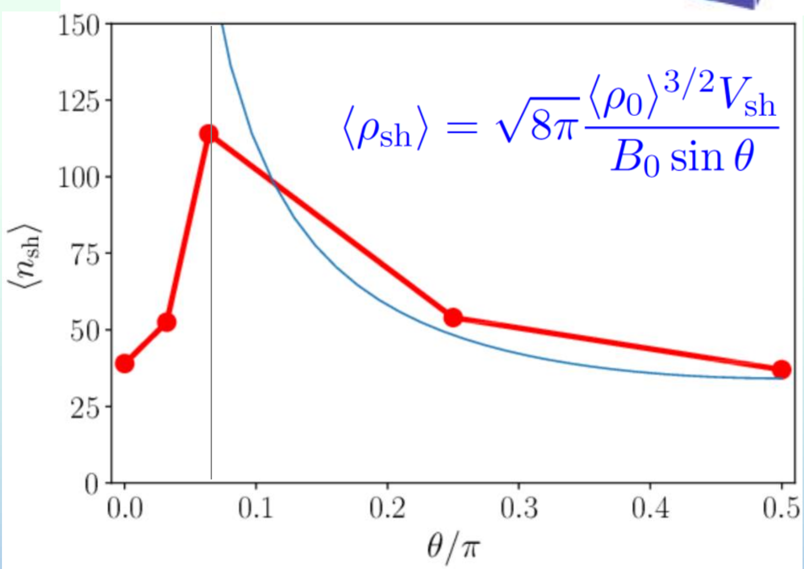
(Takasao et al. 2019, visualization by T. Takeda @ Vasa Entertainment)

(Iwasaki et al. 2019
Kobayashi et al. 2020, 2022, 2023)

Molecular Cloud Formation







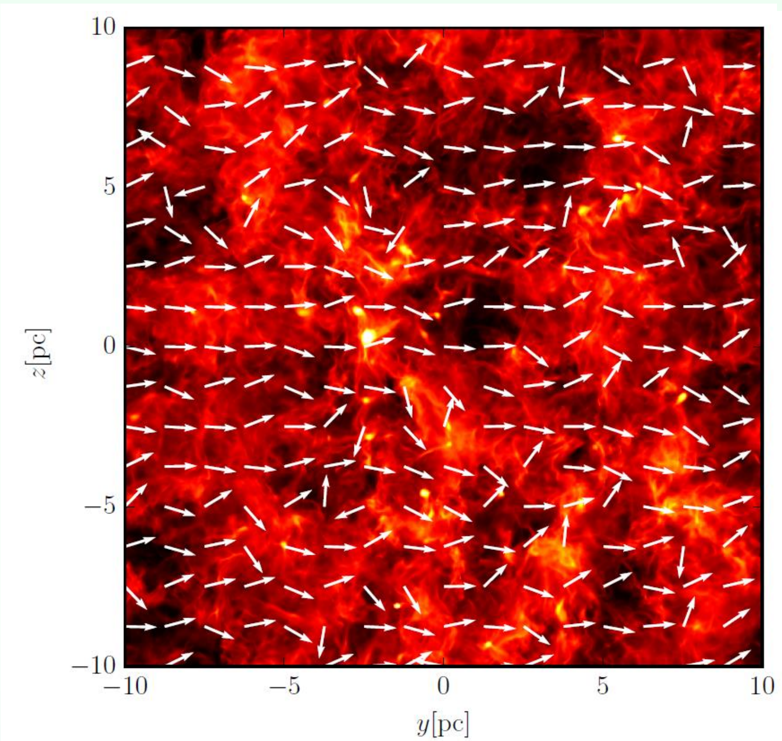
To study the first step of star formation, we simulated molecular cloud formation in converging flows (model of SN, spirals, galaxy merger, etc.).

Turbulence structure and cloud formation efficiency depends on magnetic fields.

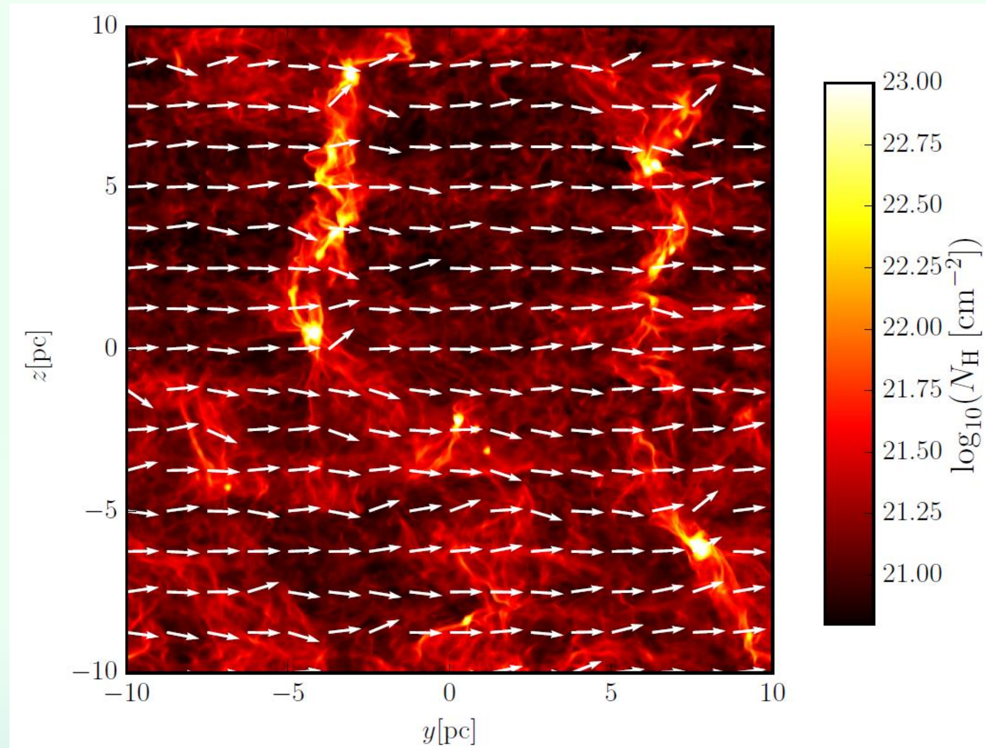
(Iwasaki & Tomida 2022)

Core / Filament Formation

θ=3˚ t=10Myr



θ=11˚ t=7.5Myr



Column density with and without self-gravity

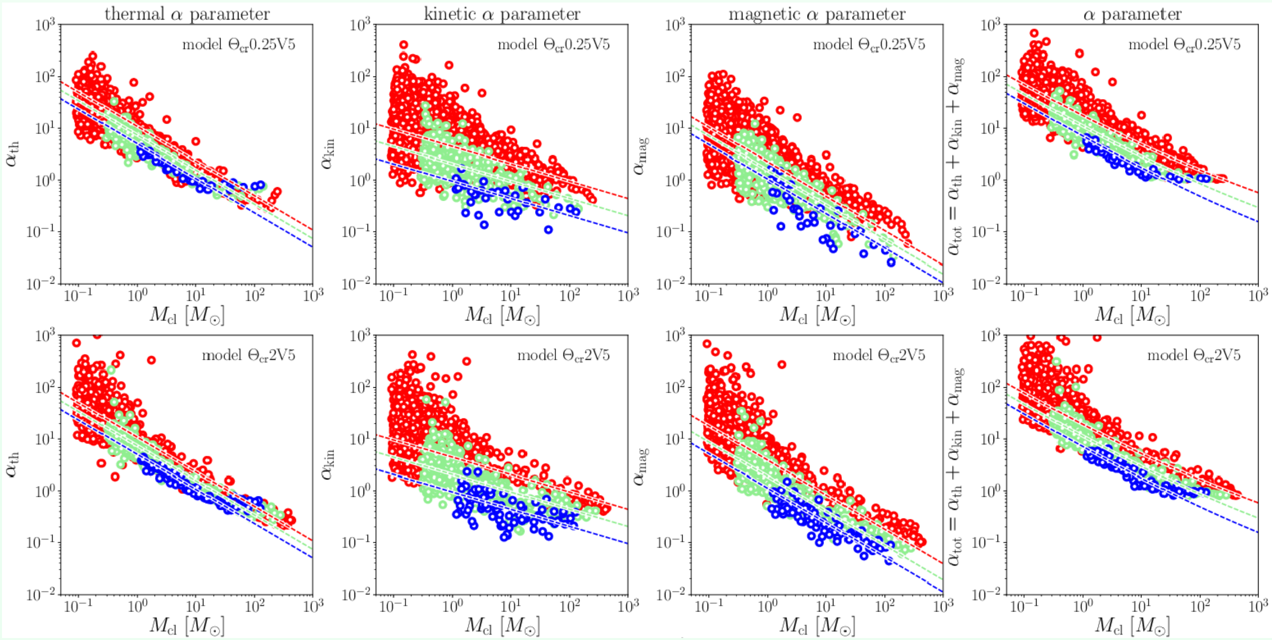
Left: super-Alfvenic turbulence suppresses coherent structure formation→cores/clumps

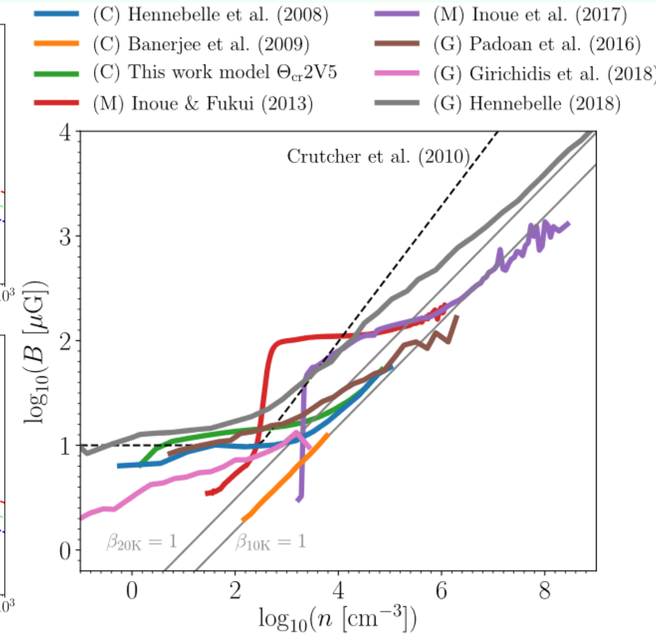
Right: filaments perpendicular to the field lines are formed

→ Self-gravity is (obviously) the key ingredient in the core/filament formation

(Iwasaki & Tomida 2022)

Universal Scaling Relations





We found that the virial parameters molecular cloud cores follow universal scaling relations (left, color = threashold densities **$10^{3.5,4,4.5}$**) regardless of the simulation setup.
We also found that the magnetic field vs density relations are more or less universal across different simulations (right)
→ The origin of the universality of star formation (e.g., IMF) ?

Galactic-Scale Star Formation

In order to understand star formation consistently across the scales, we need to model the whole galactic scale with appropriate physical processes.

With Athena++ and Fugaku, we have started a new project to simulate the whole galactic disk with very high resolution of a few pc, including **magnetic fields**, radiation and other processes.

We also plan to extract some molecular clouds formed in the galactic-scale simulation and perform zoom-in simulations of star and disk formation.

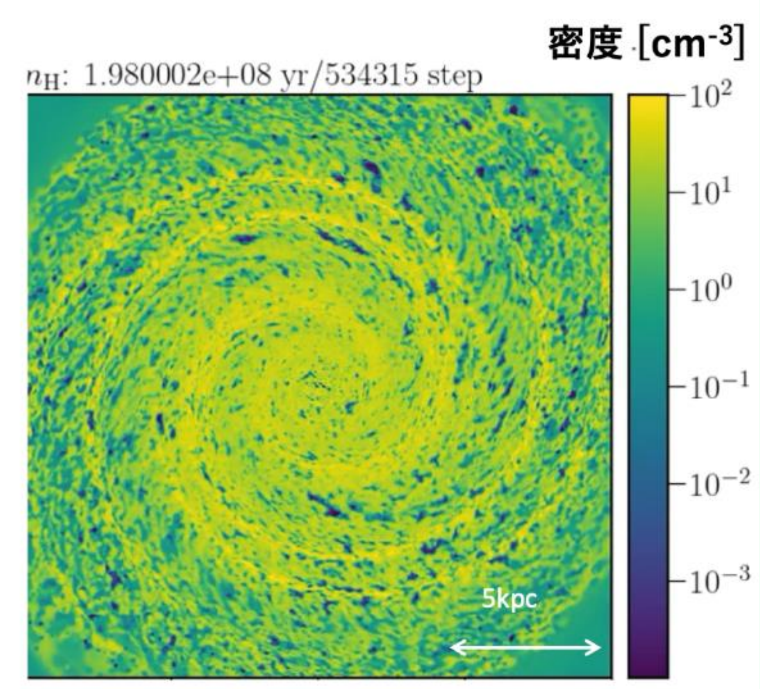
(Galactic) Disk to (Protoplanetary) Disks

NGC 7496 (PHANGS-JWST, Lee et al. arXiv:2212.02667) – now JWST + ALMA can directly resolve embedded star formation in other galaxies.

“Disk to Disks” Project

Global MHD simulations of star formation at the Galactic scale (led by Sugimura-san, in collaboration with Princeton)
→ 天の川プロジェクトの現代版

- Athena++ AMR
- Magnetic fields
- Appropriate heating/cooling
- Star formation feedback (currently random but star particles in progress.)
- Self-gravity (currently gas only, but live star/DM with particle-mesh in progress.)



“Test” simulation with 8pc resolution including magnetic fields and supernova feedback (Sugimura et al. in prep.)

- Consistently model the star formation environment at the Galactic scale
- Galactic-scale magnetic fields (dynamo, link to star formation)
- Prediction for next-generation observations (SKA, CMB foreground, etc.)

まとめ

- Athena++ (https://www.athena-astro.app/) は多様な物理をサポートしており、既に多様な宇宙物理学の問題に適用可能

→ 銀河・星形成・原始惑星系円盤・惑星形成・降着円盤・ジェット・超新星爆発・惑星大気・工学（燃焼流体）・・・

- 今後も継続して新機能が開発・公開される
- GPU対応（OpenACC）やKokkos版の開発(AthenaK)も進行中
- ユーザー/開発者コミュニティも成熟してきた
- 公開コードの中では一番性能を意識したコードと思われる

- 性能を意識するようになったのはCellでの経験があったから

→ 直接の学生ではありませんでしたが、牧野さんの近くで色々学び、良い影響を受けたと感謝しています。
引き続き、成果創出・次世代でもよろしくお願いします。

Thanks a lot!