Magnetohydrodynamic simulation code **CANS+** : Assessments and Applications

Yosuke Matsumoto[1]

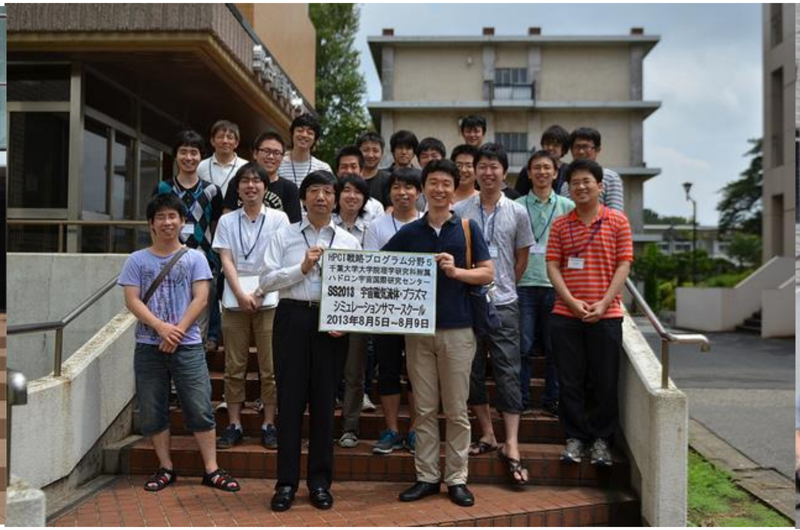
Y. Asahina[2], Y. Kudoh[1], T. Kawashima[2,3], J. Matsumoto[4], H. R. Takahashi[2], T. Minoshima[5], S. Zenitani[3], T. Miyoshi[6], & R. Matsumoto[1]

1. Department of Physics, Chiba University
2. CfCA, NAOJ
3. Division of Theoretical Astronomy, NAOJ
4. Astrophysical Big Bang Laboratory, RIKEN
5. MAT, JAMSTEC
6. Department of Physics, Hiroshima University

まつもと夏祭り

2012

2013



2014

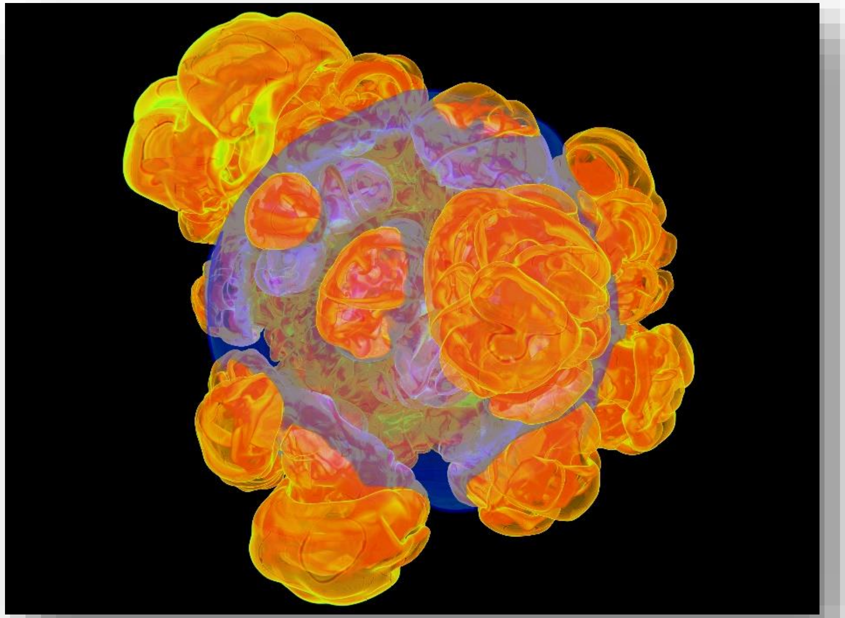
2015

2016

2017

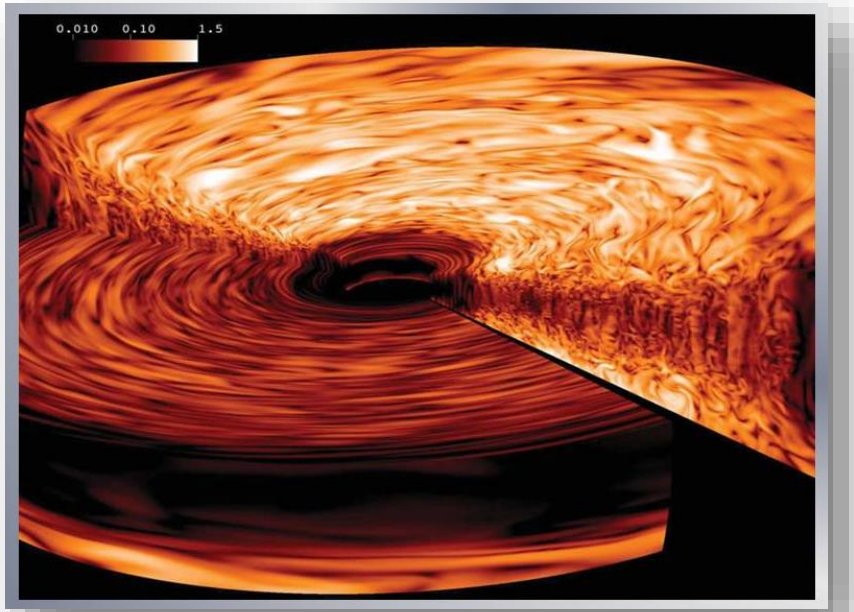
MHD simulations in plasma Astrophysics

FLASH



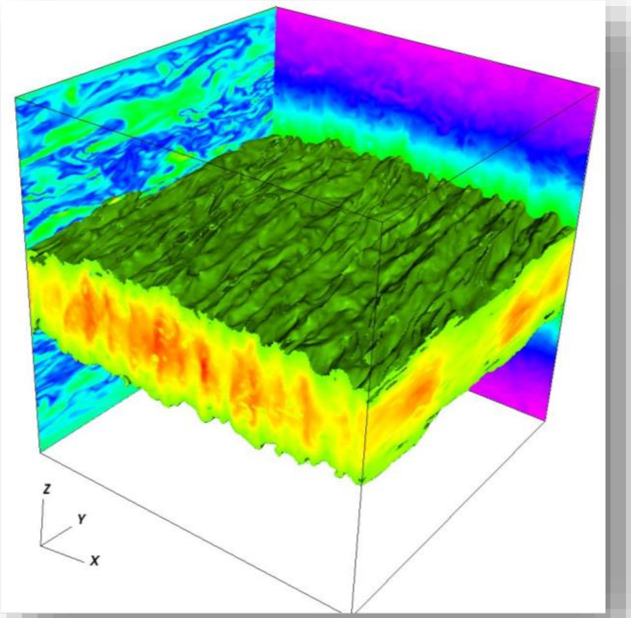
cf. Lee & Deane 09

PLUTO



cf. Mignone+ 07

Athena



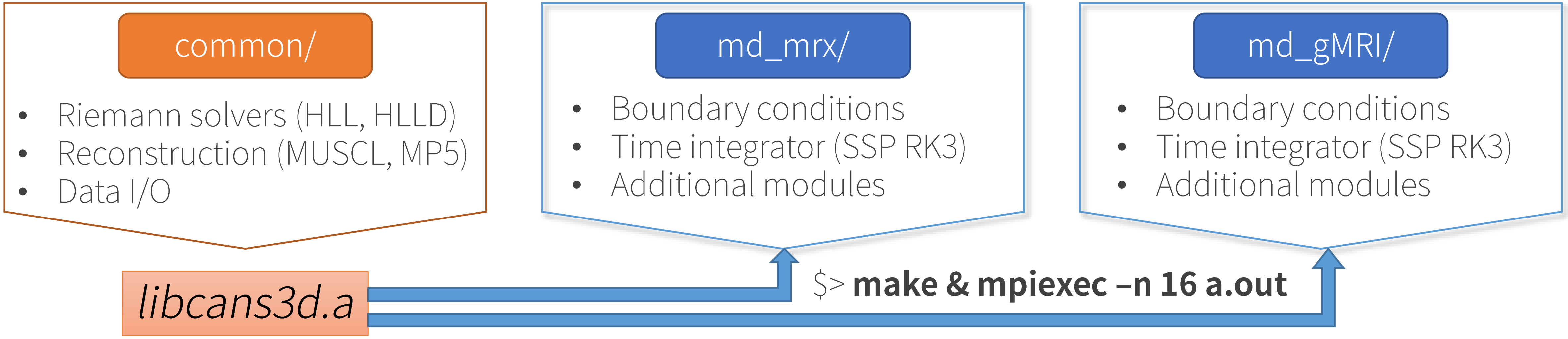
cf. Stone+ 08

Various public MHD codes for astrophysics. They are basically second-order accurate*.

(* PLUTO implements also 5th-order scheme based on FD.)

CANS & CANS+

- Coordinated Astronomical Numerical Software (CANS) was developed by T. Yokoyama (Univ. of Tokyo) & collaborators in 2002.
- **CANS+** was designed following the philosophy of CANS, but implements state-of-the-arts algorithms and parallelization
- **CANS+** adopt the modular way as in CANS including many physical problems and visualization tools by IDL procedures
- Documentation (Japanese) on the web site cans+ doc 検索



Basic eqs. & Algorithms

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \boldsymbol{v}) = 0,$$

$$\frac{\partial \rho \boldsymbol{v}}{\partial t} + \nabla \cdot (\rho \boldsymbol{v}\boldsymbol{v} + p_t \boldsymbol{I} - \boldsymbol{B}\boldsymbol{B}) = \rho \boldsymbol{g},$$

$$\frac{\partial \boldsymbol{B}}{\partial t} + \nabla \cdot (\boldsymbol{v}\boldsymbol{B} - \boldsymbol{B}\boldsymbol{v} + \psi \boldsymbol{I}) = -\nabla \times (\eta \boldsymbol{j}),$$

$$\frac{\partial e}{\partial t} + \nabla \cdot ((e + p_t)\boldsymbol{v} - \boldsymbol{B}(\boldsymbol{v} \cdot \boldsymbol{B})) = -\nabla \cdot (\eta \boldsymbol{j} \times \boldsymbol{B}) + \rho \boldsymbol{v} \cdot \boldsymbol{g},$$

$$\frac{\partial \psi}{\partial t} + c_h^2 \nabla \cdot \boldsymbol{B} = -\frac{c_h^2}{c_p^2}\psi,$$

$$\frac{\partial \boldsymbol{U}}{\partial t} + \sum_{s=x,y,z} \frac{\partial \boldsymbol{F}_s}{\partial s} = \boldsymbol{S}$$

$$\frac{\partial \bar{\boldsymbol{U}}_{(i,j,k)}}{\partial t} = -\sum_{s=i,j,k} \frac{\boldsymbol{F}^*_{(s+1/2)} - \boldsymbol{F}^*_{(s-1/2)}}{\Delta_s} + \boldsymbol{S}_{(i,j,k)}$$

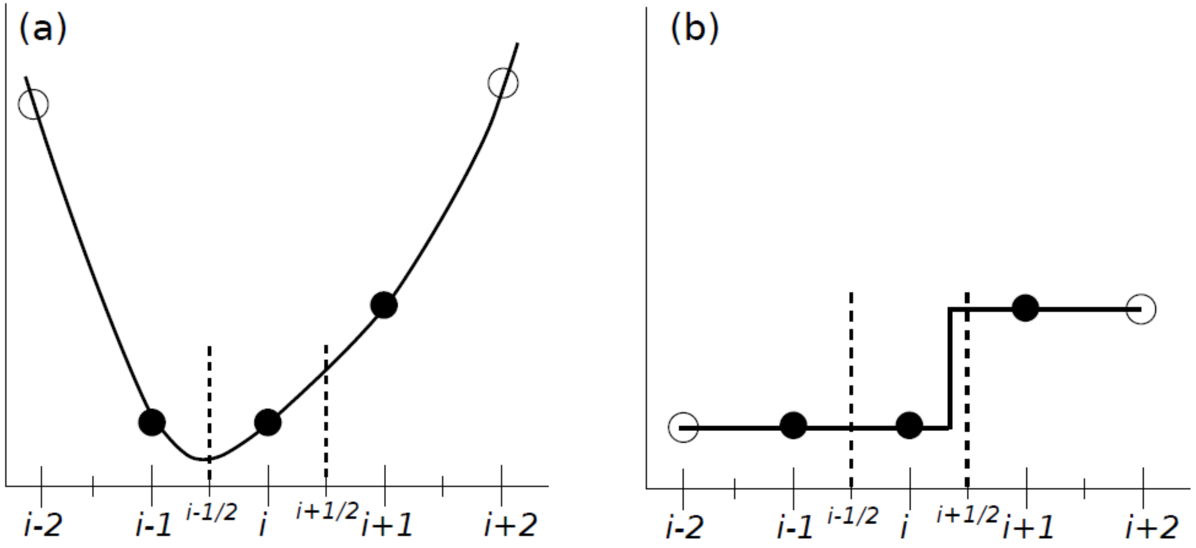
$\bar{\boldsymbol{U}}$ cell-averaged conservative vars.

$\boldsymbol{F}^*$ Numerical flux

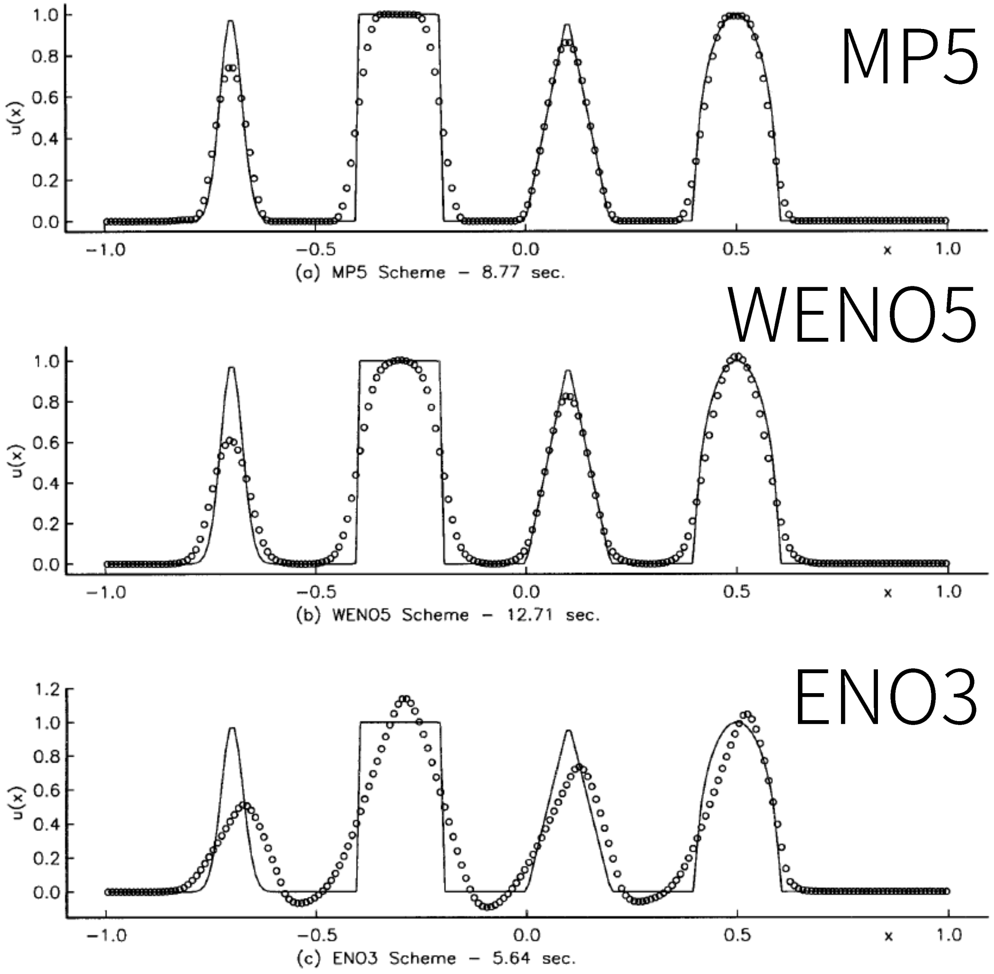
3 key features

- Godunov scheme: **F*** is given by the HLLD Approximate Riemann solver (Miyoshi & Kusano 05)
- High-resolution reconstruction: MP5 scheme (Suresh &Huynh 97)
- Hyperbolic divergence cleaning method (Dedner+ 02)

Monotonicity-preserving 5th-order (MP5) scheme (Suresh & Huhynh, JCP, 1997)



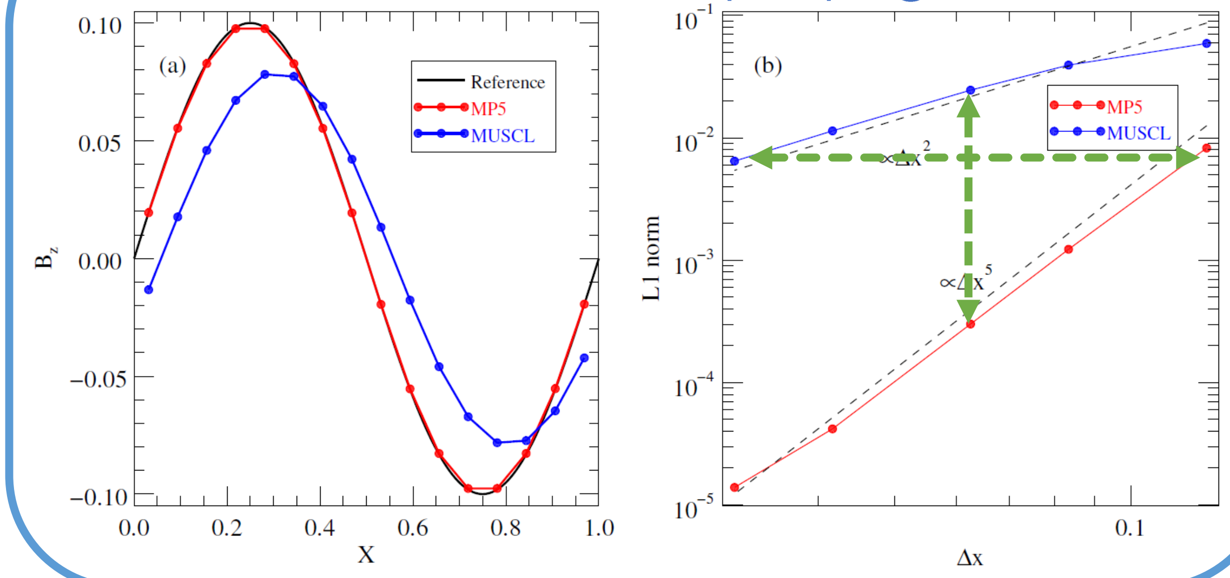
Linear advection



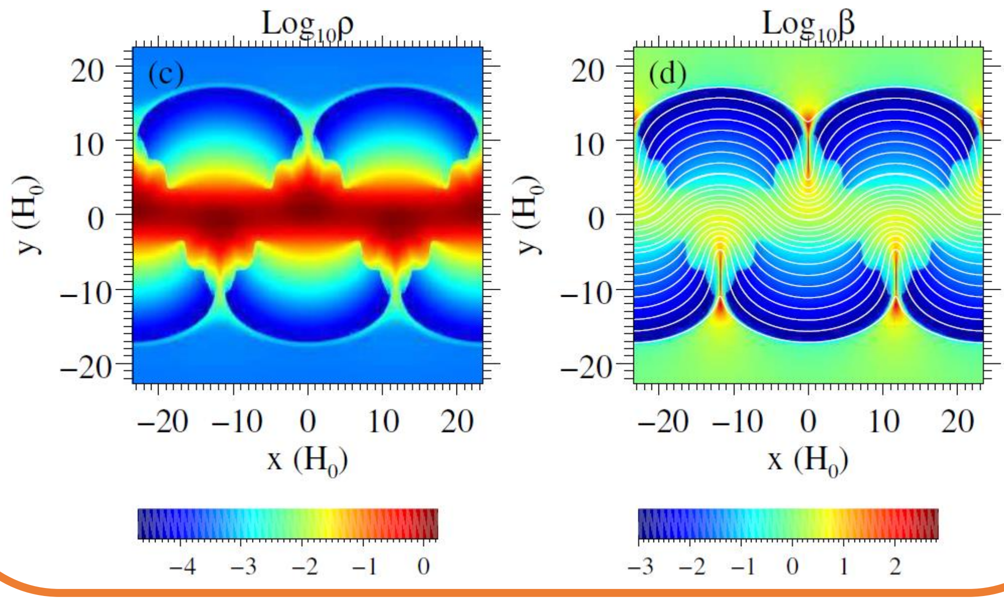
- 2nd-order TVD schemes cannot distinguish extremum and discontinuity -> strong damping of wave forms
- MP5 scheme using 5-point stencil can detect extrema while preserving monotonicity around discontinuities -> can handle turbulence & shocks simultaneously

Assessments of CANS+ capability

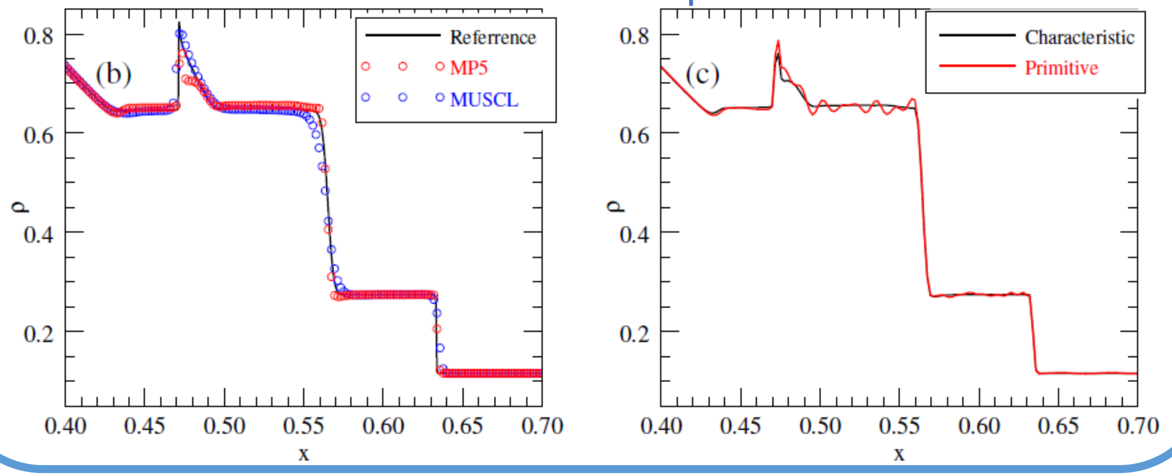
1D Alfven wave propagation



2D Parker instability



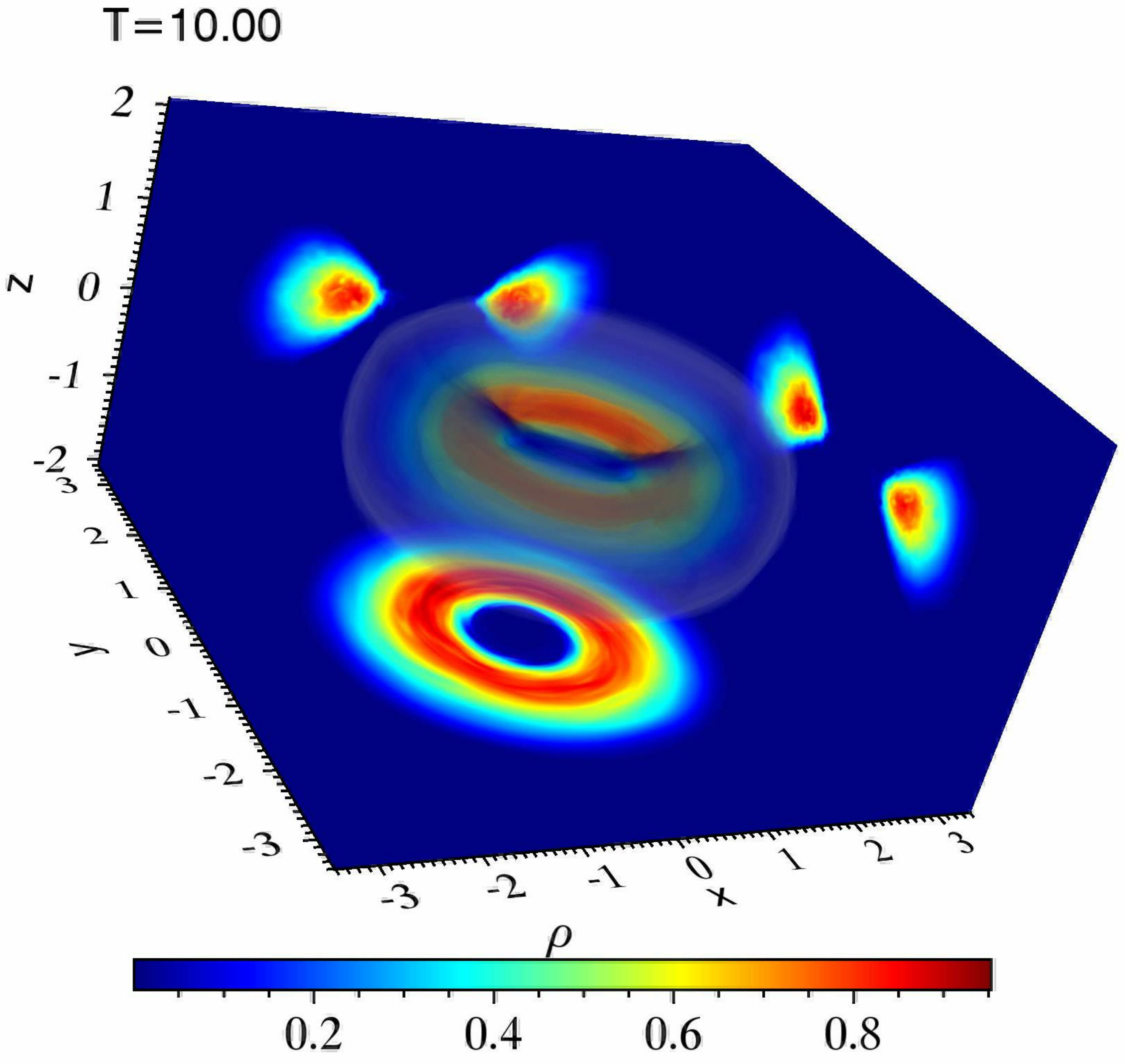
1D shock tube problem



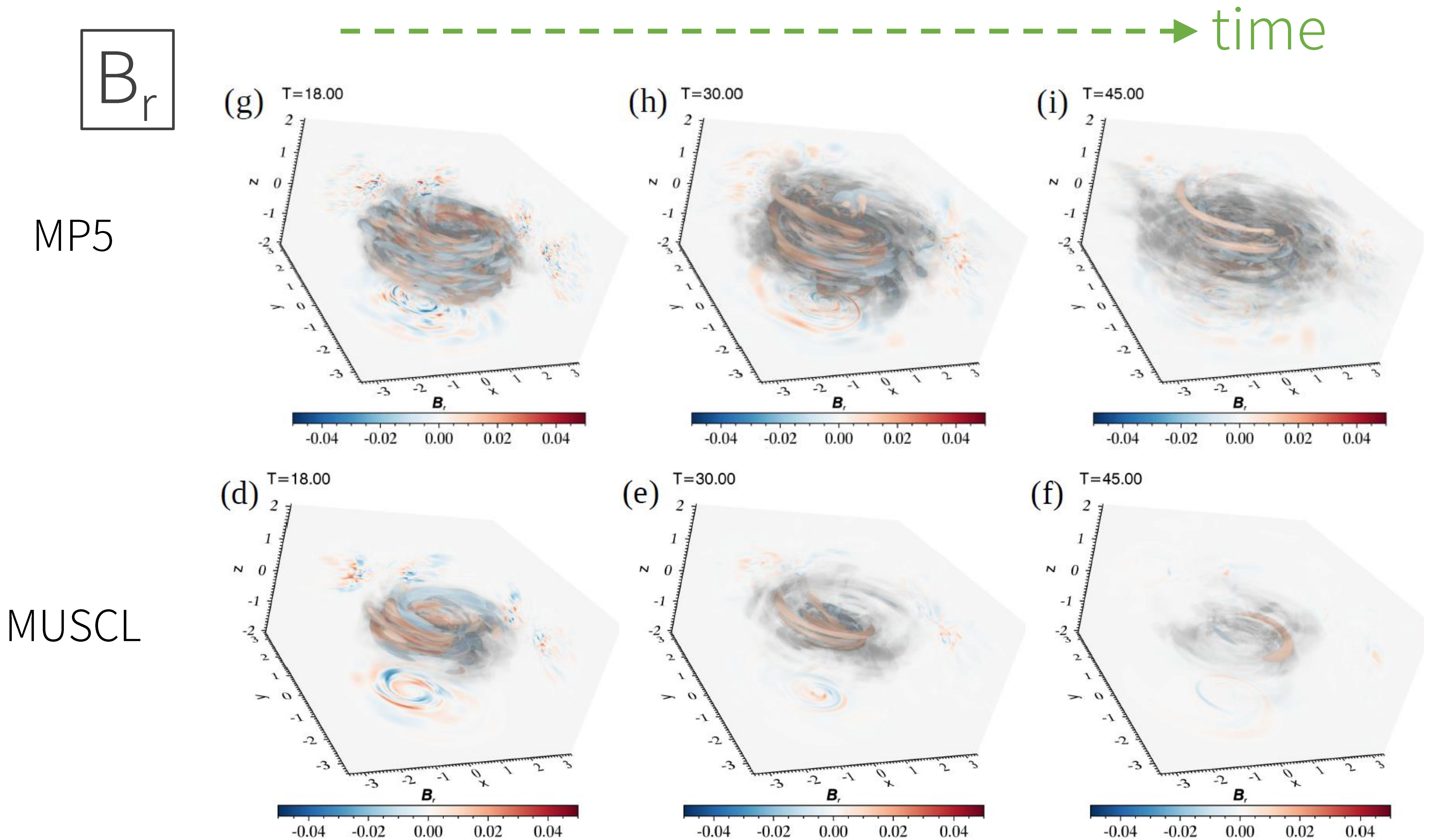
- 5th-order accurate in space for 1D wave propagation
- Monotonicity preservation in MHD shock tube problems
- Capable of solving very low-β ($=10^{-3}$) plasma
- Other problems (KHI, MRX, etc.)

3D global simulations of a black hole accretion disk

- Cylindrical coordinates
- Pseudo-Newtonian potential (Paczynski & Wiita 80)
- Initial toroidal B field
- $(n_r, n_\phi, n_z) = (256, 64, 264)$
- Long-term simulations: T=50 rotation periods
- MP5 vs. MUSCL (MC limiter)

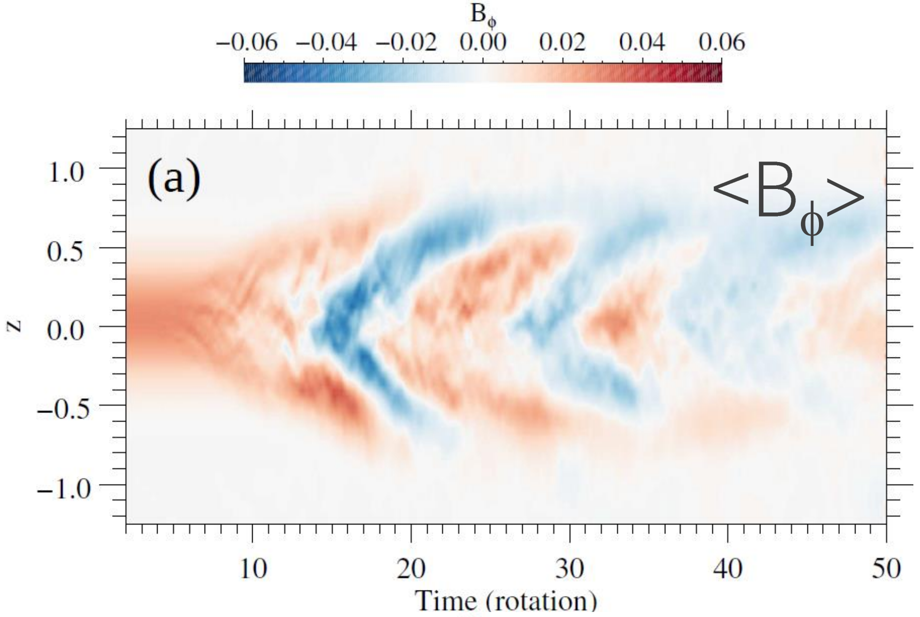


MRI development: MP5 vs. MUSCL

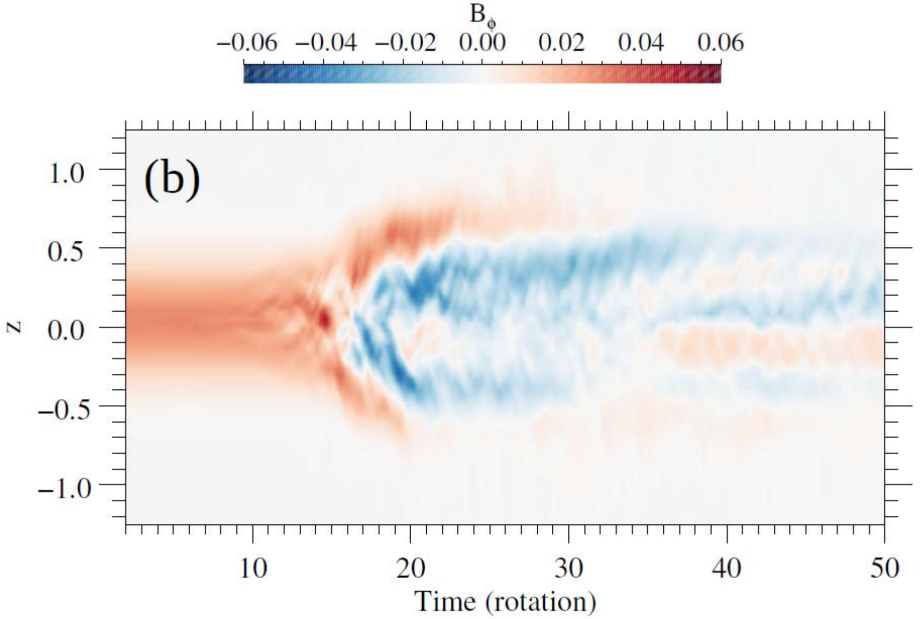


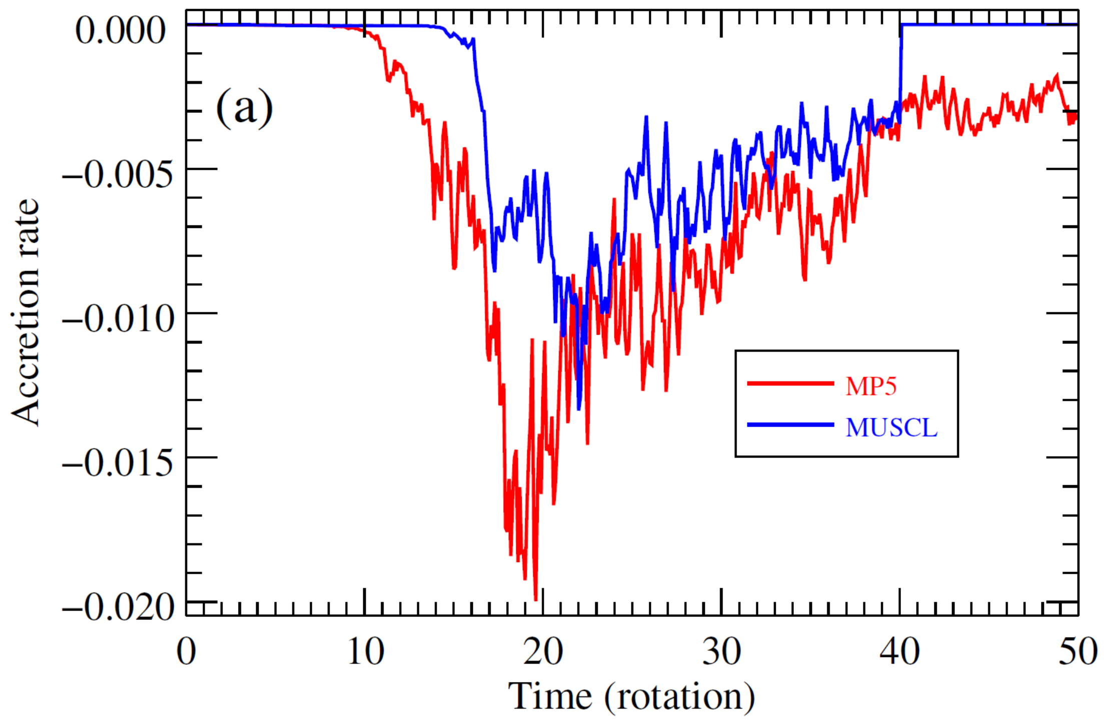
Magnetic dynamo & Mass accretion rate

MP5



MUSCL

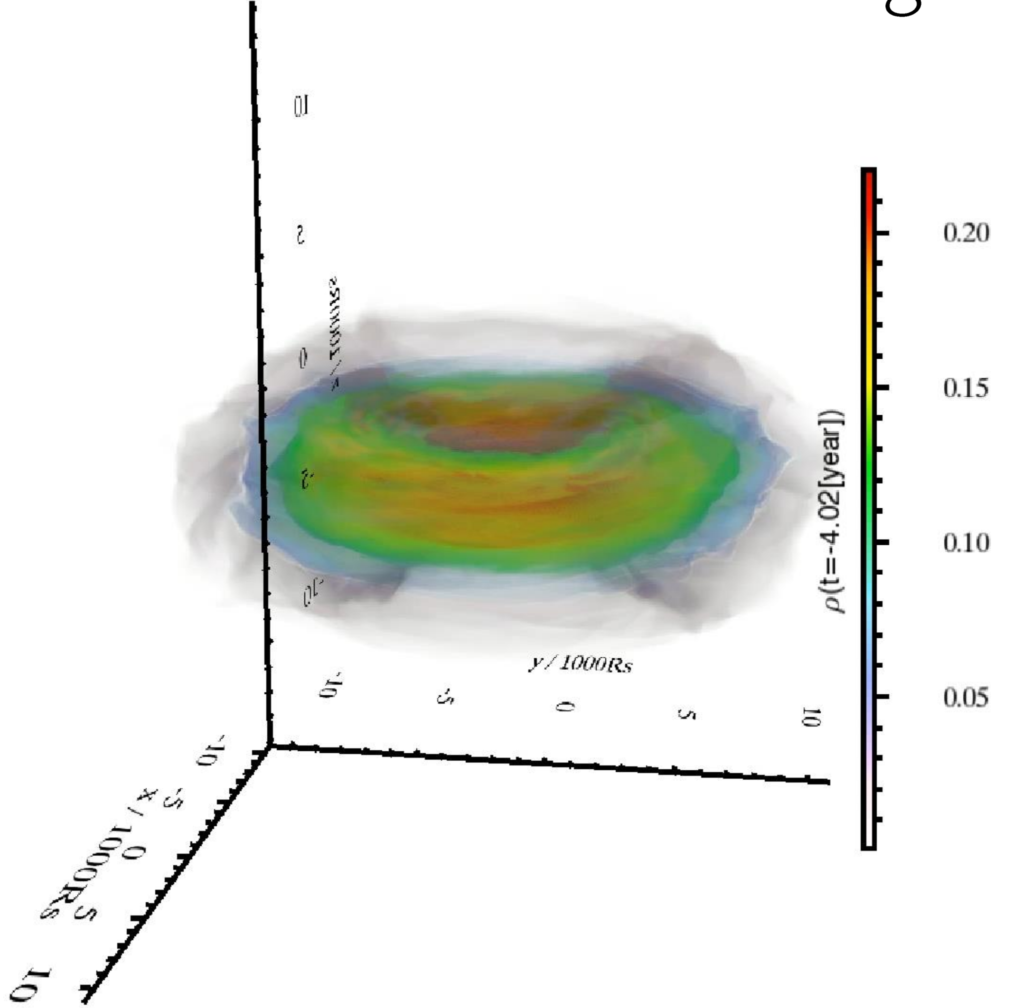




- Periodic reversals of B_ϕ in the disk center with T~10 for 50 rot. period in MP5 run
- Continuous mass accretion into the black hole in MP5 run

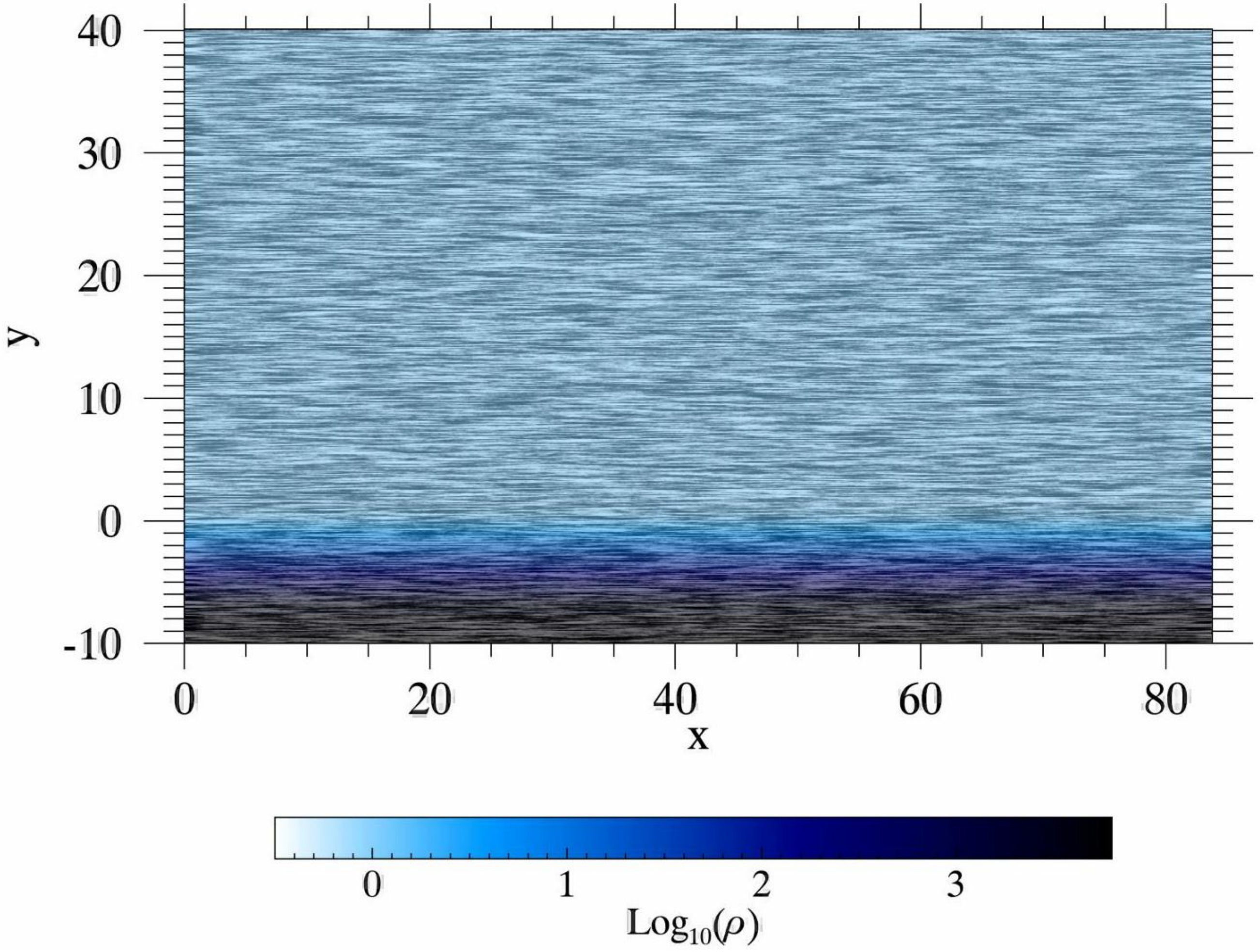
Ongoing studies using **CANS+**

G2 cloud interaction with Sgr A*



Kawashima, Matsumoto, & Matsumoto, *PASJ*, 2017

SW – Martian Ionosphere interaction



Seki, Matsumoto+, submitted to *Nature Commun.*

Summary

CANS+ is ...

- Capable of solving shock waves and turbulence simultaneously
- Robust in low-β plasma (>10^{-3})
- Scalable with >10^3 processes using MPI library and OpenMP
- Publicly available at

http://www.astro.phys.s.chiba-u.ac.jp/cans/doc

https://arxiv.org/abs/1611.01775