3D MHD SIMULATION TO REVEAL ANGULAR MOMENTUM TRANSPORT IN AN ACCRETION DISK

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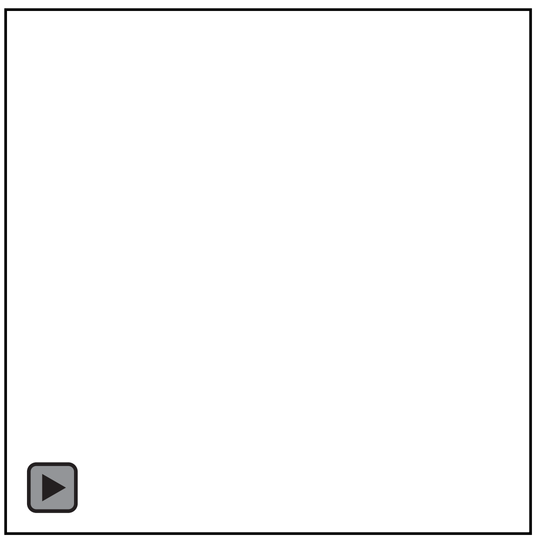
CONTENTS OF THIS TALK

- Introduction
  - Nature around the SgrA*
  - Importance of an accretion disk
  - Magneto-Rotational Instability
- Numerical Model
- Results
  - 3D structure of the accretion flow
  - Time evolution of the accretion flow
  - Entropy spiral structure
- Discussion
  - Origin of the spiral pattern
  - Correlation between the mass accretion rate and spiral arms
  - Current distribution in the spiral structures
- Summary

CURRENT ACTIVITY OF SGR A*

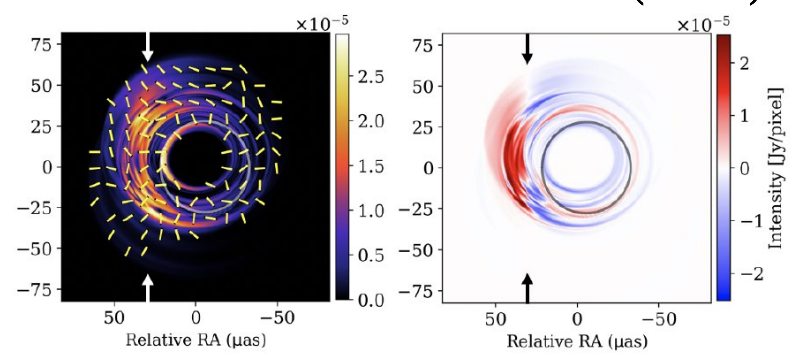
Srg A* ~ The central super massive black hole in the Milky Way

Mass : $4 \times 10^{6}\ M_{sun}$
Accretion rate : $10^{-7\sim-9}\ M_{Edd}$



According to the Low-activities, accretion flow of Sgr A* seems to be MAD or slow spin SANE-like plasma. (Ressler + 2020, Thuneto + 2020b).

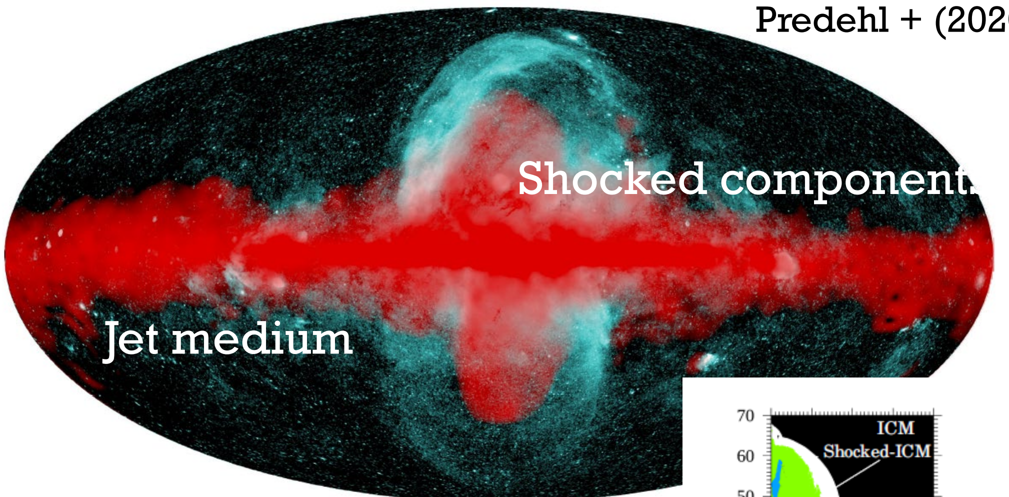
Tsuneto + (2020b)



PAST ACTIVITIES OF SGR A*

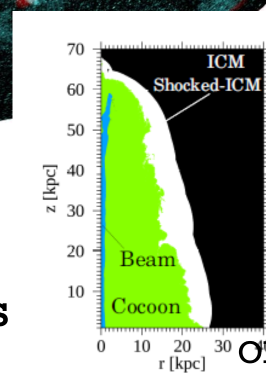
eROSITA found the X-ray bubbles surrounding the Fermi bubble

Predehl + (2020)



Red: γ-ray , Cyan: 0.6-1 keV

Similar structure to the jets in the galaxy clusters



Ohmura + (2020)

The proposed mechanism of the Fermi bubble

- Starburst
- Past activities of Sgr A*

According to the correlation between Fermi bubble and eROSITA bubble, they conclude that both bubbles are formed by past activities of Sgr A*.

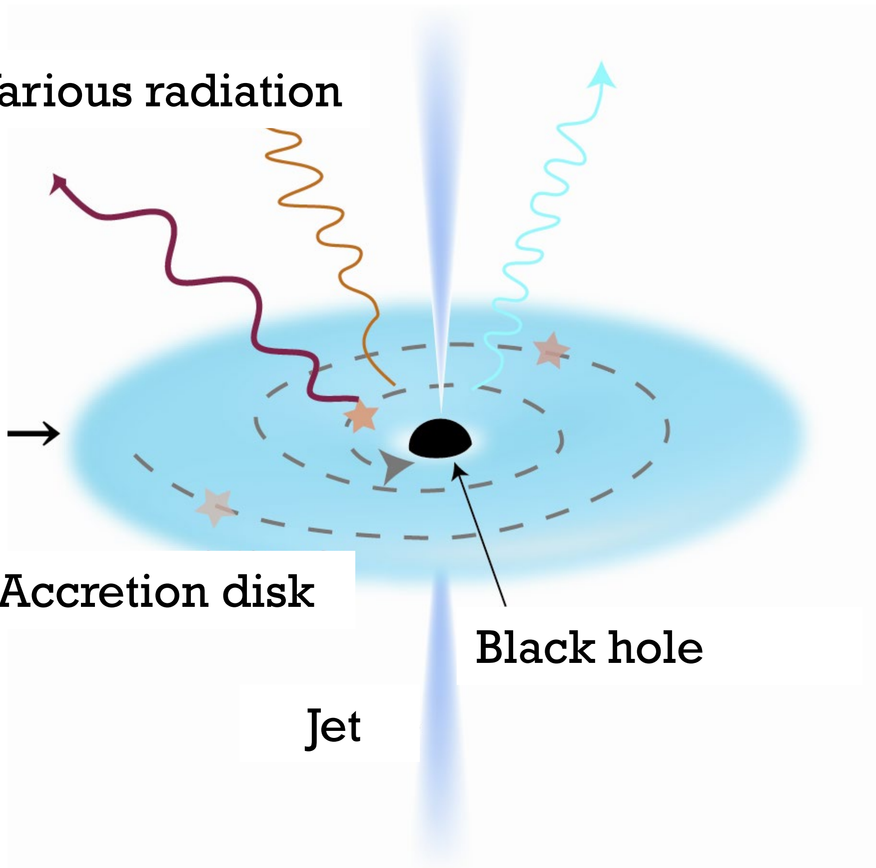
In the past,
standard accretion process becomes important – such as RIAF/SANE evolution.

THE ORIGIN OF THE ANGULAR MOMENTUM TRANSPORT

High energy activities such as jets and flares
～Gravitational energy of the black hole through an accretion disk

Accretion disk ~ Differential rotation
→Require the mechanism of angular momentum transport

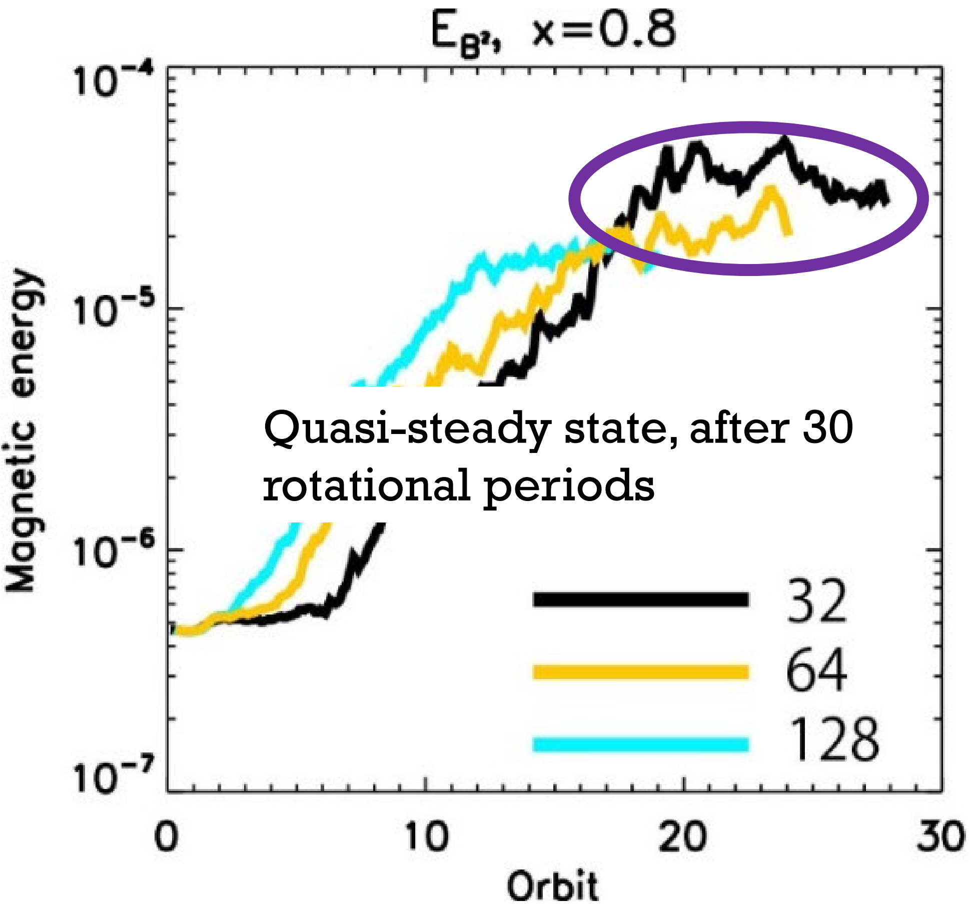
→



Origin of the viscosity
＝Magnetic turbulence made by Magneto-Rotational Instability

Numerical results show resolution dependence.

RESOLUTION STUDY OF SATURATION LEVEL



Machida + in preparation

High resolution study

- Firster Mass accretion

⇒Amplification of small-scale turbulence.

- Anti-correlation of the saturation levels of magnetic energy

⇒ Amplified magnetic fields are dissipated in the small scale.

PURPOSE OF THIS TALK

We study the dependence of the disk structure on the resolution in a quasi-steady state (~30 rotational period at pressure maximum).

CANS+

--Coordinated Astronomical Numerical Software +

(Matsumoto et al. 2019)

- HLLD method (Miyoshi and Kusano 2005)
- The ***third order*** Runge-Kutta method for time integration
- **The fifth order spacial integration** by MP5 method
- div B cleaning by 9 wave method

⇒ azimuthal 64 meshes ≒ 160 meshes of 2nd order results

INITIAL SET UP AND BASIC EQUATIONS

Basic equations

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

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

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

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

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

Parameter

Pressure maximum	$r_0 = 40\ r_g$
Angular momentum	$L = L_0$ constant
Plasma β	$\beta \equiv P_{gas}/P_{mag} = 100$ at $r = r_0$
Heat ratio	$\gamma = 5/3$
Sound speed	$c_s = 0.01\ c$

Unit

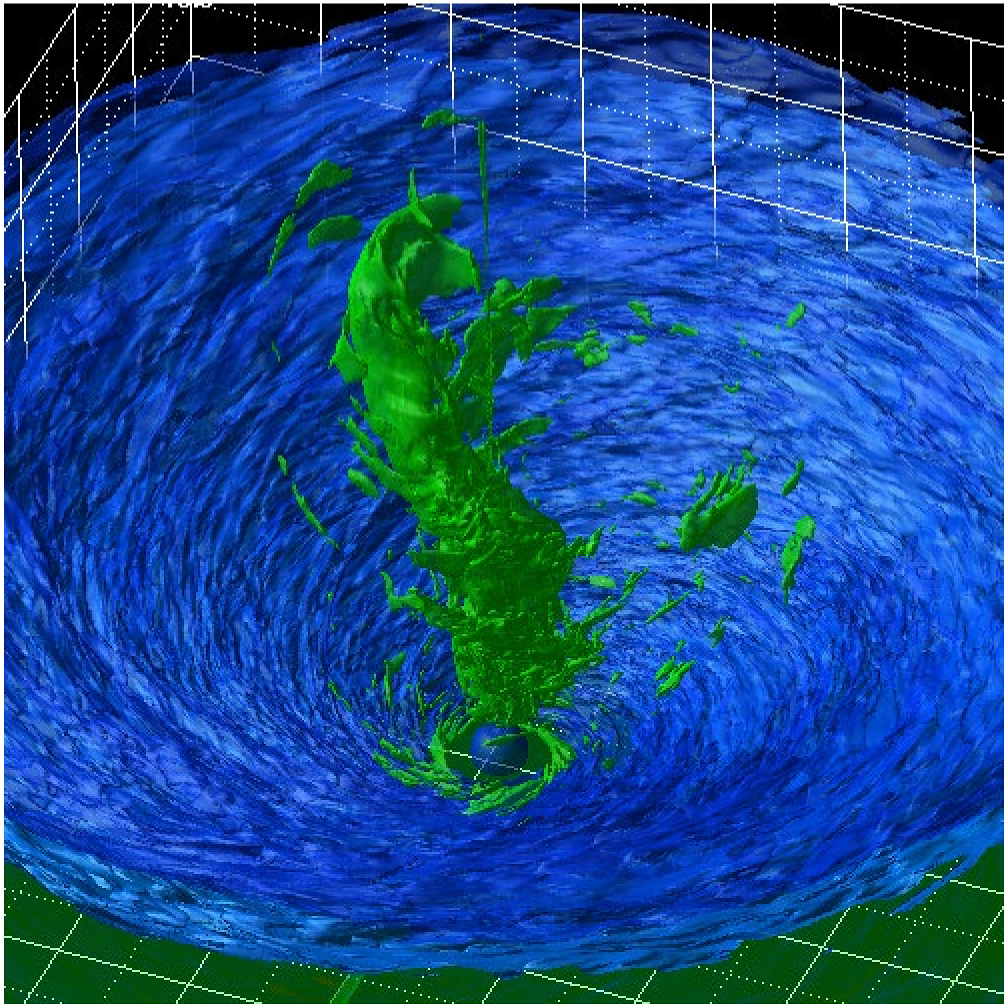
Length	r_g	$4.0 \times 10^6 (M/10M_{sun})$ cm
Velocity	c	2.99×10^{10} cm s^{-1}
Time	t_0	$10^{-4}(M/10M_{sun})$ sec
Temperature	T_0	1.1×10^{13} K

Number of grids

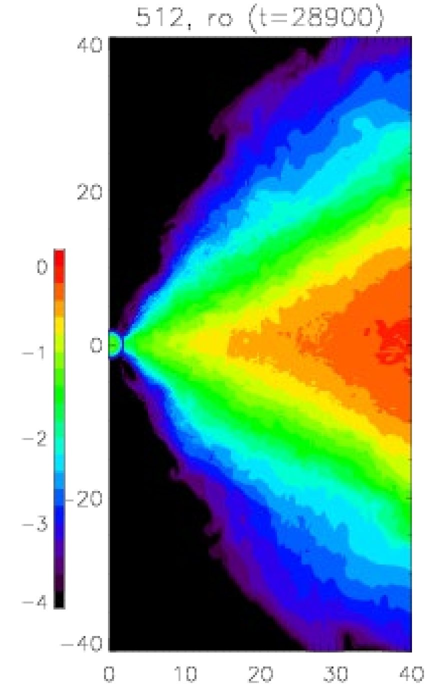
$(N_r, N_z) = (774, 774)$
$N_\varphi = 64, 128, 512, 1024$

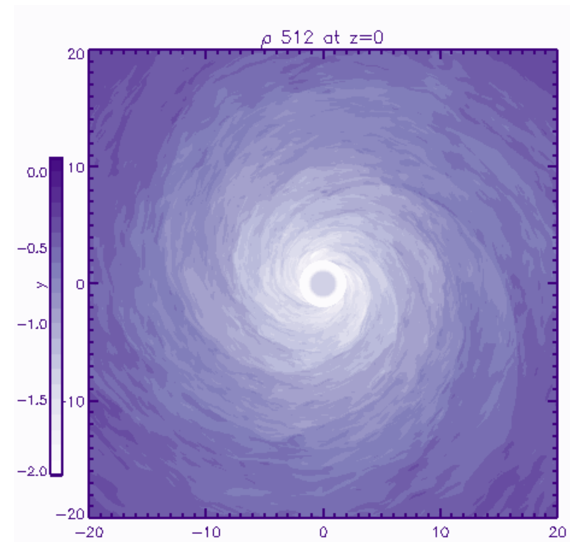
Here, we show the results of HM512 and LM64.

GLOBAL STRUCTURE



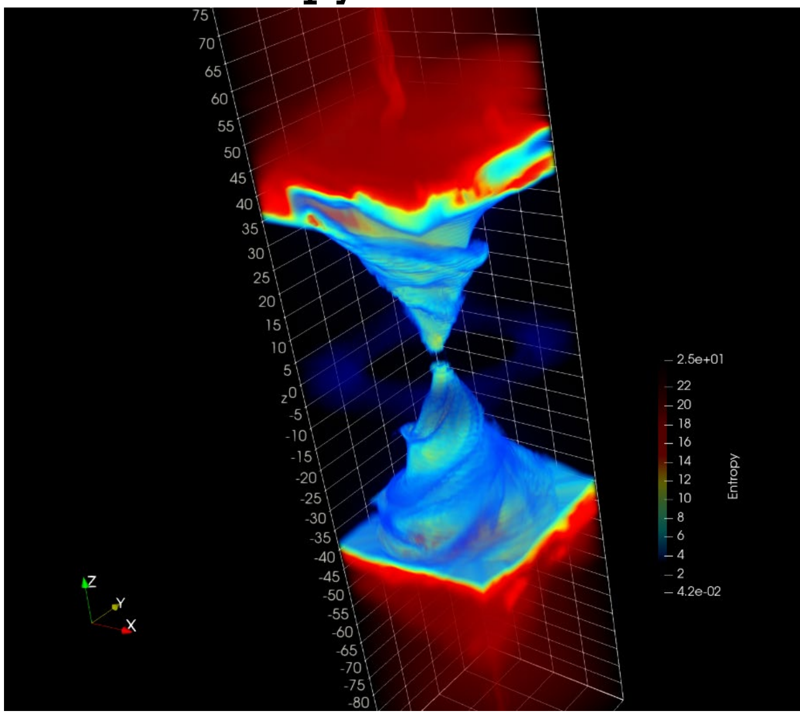
Blue surface : density,
Green surface: Outflow velocity (Vz>0)



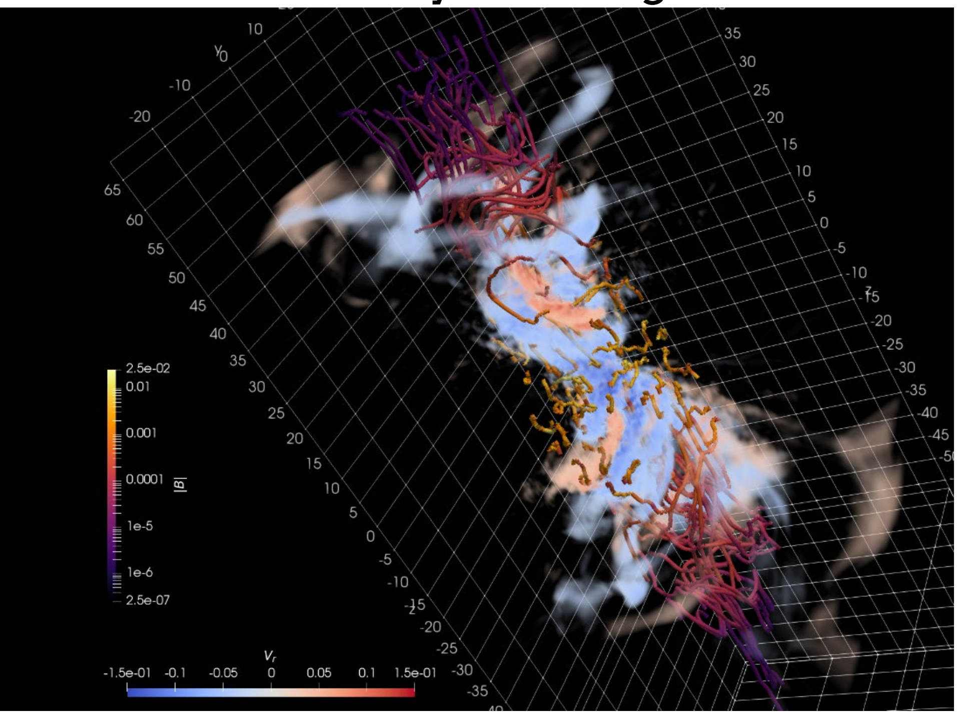


OUTFLOW FEATURE FROM THE BLACK HOLE

Entropy



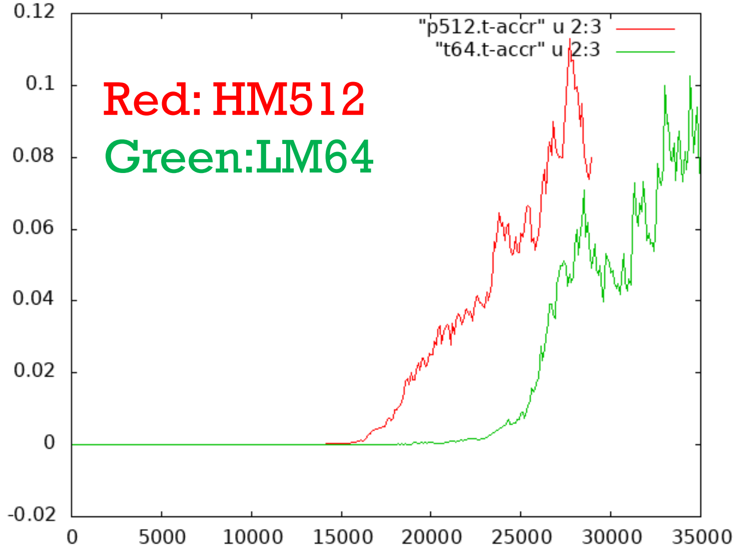
Radial velocity with magnetic fields



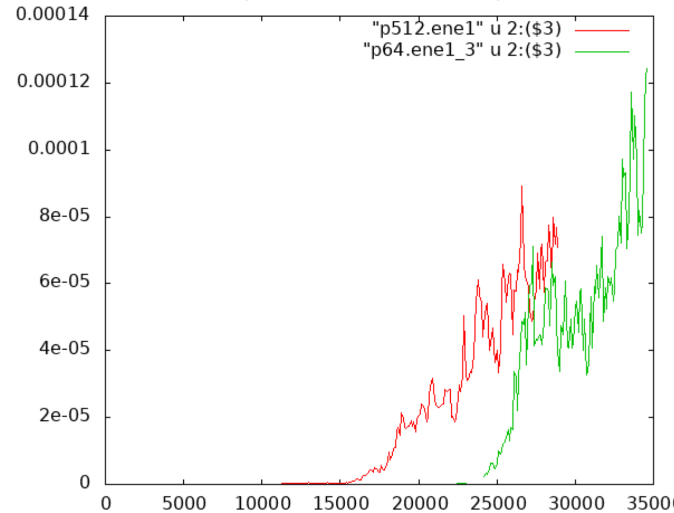
Near the center, vertical magnetic fields are formed with the outflowing and infalling flows.

TIME EVOLUTION OF ACCRETION RATE

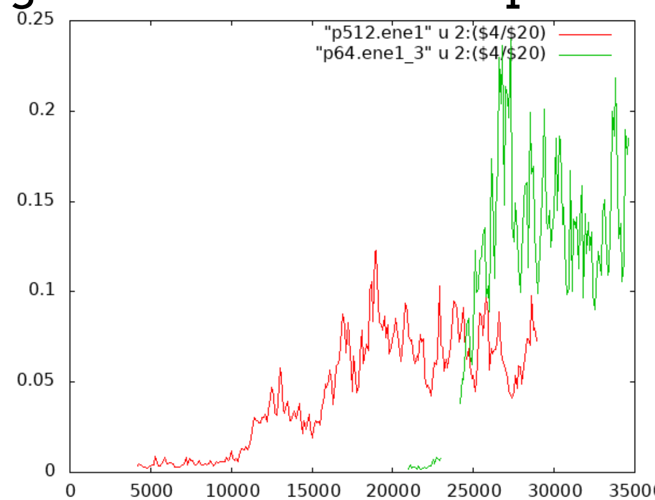
Mass Accretion Rate



Magnetic energy



Angular momentum transport rate



High resolution model shows firster growth of magnetic energy by MRI.
It leads firster mass accretion.

Saturation values

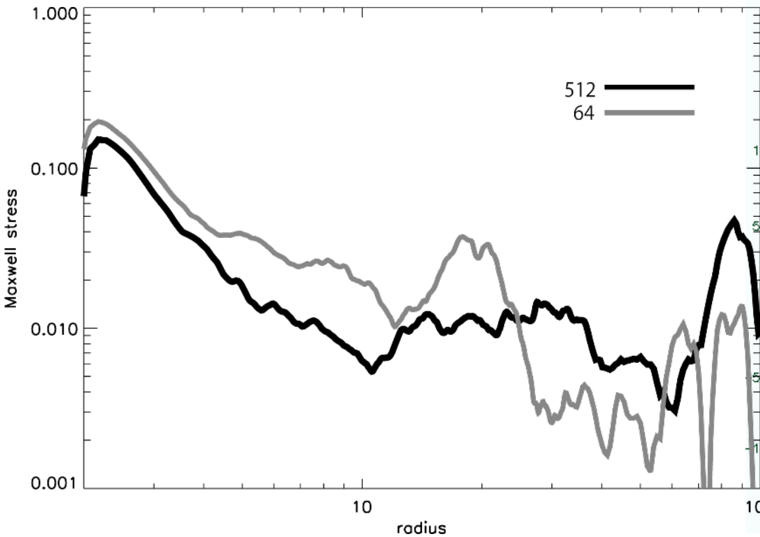
plasma β : HM512 ~5, LM64~ 2

AM. Transport α: HM512~ 0.07, LM64~0.15

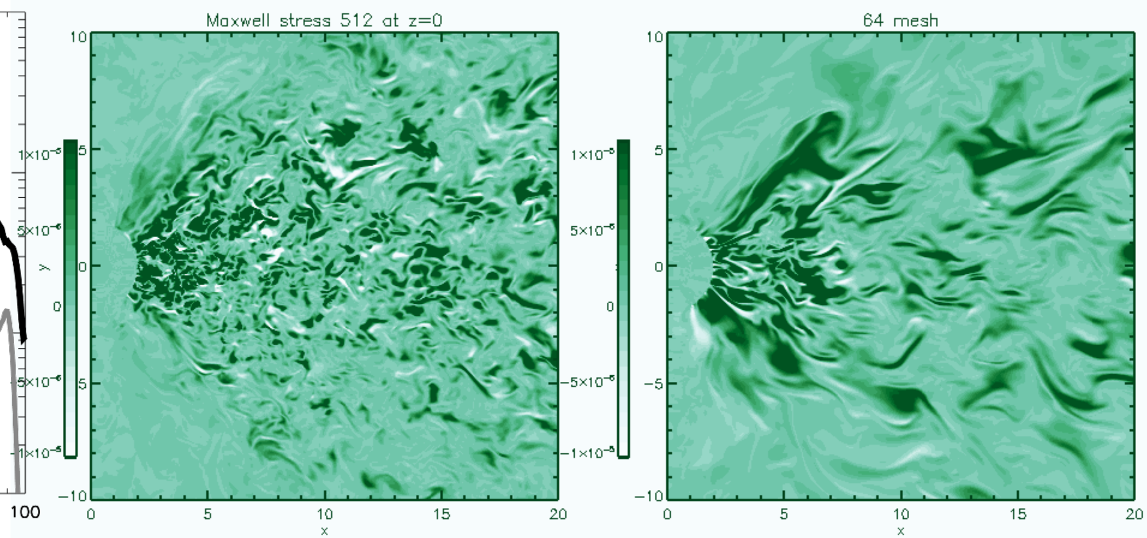
Local turbulence is fully developed, but it does not lead global accretion.

ANGULAR MOMENTUM TRANSPORT RATE ~MAXWELL STRESS DISTRIBUTION

-<BrBφ>/<P>



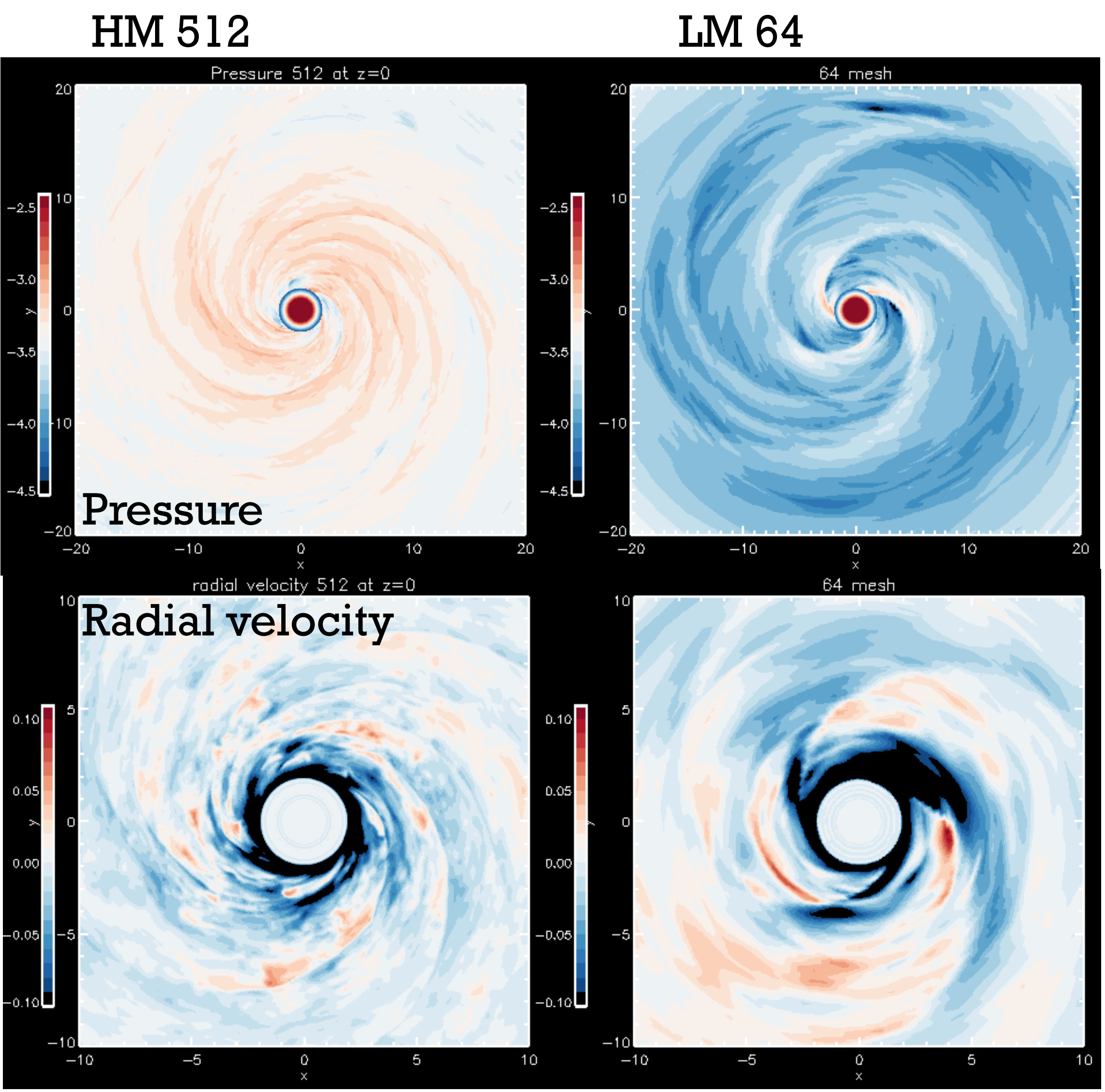
HM512 LM64



(Left) Radial profile of the angular momentum transport rate. Maxwell stress and gas pressure is averaged in the azimuthal direction.

(Middle and Right) The r-z slice of the Maxwell stress.

SPIRAL DISCONTINUITIES



Spiral Structure:

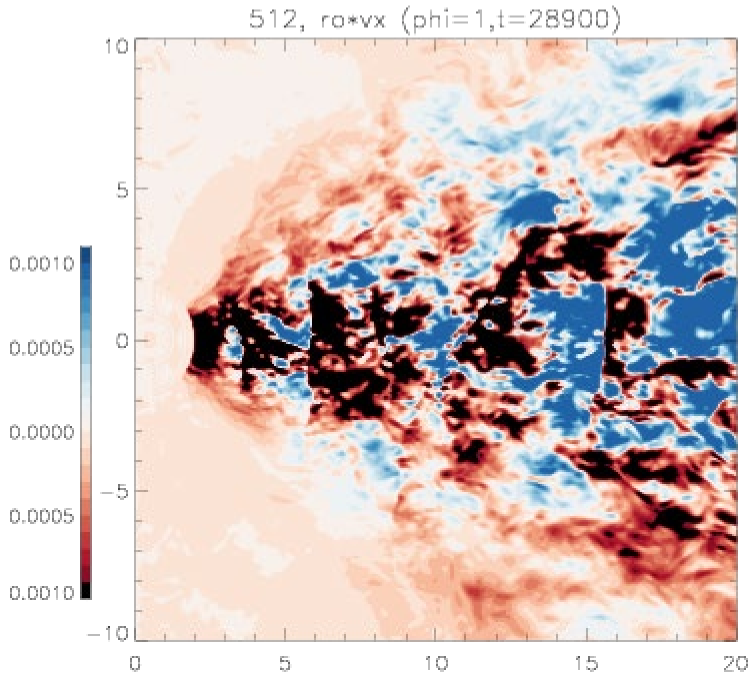
HM: Sharp discontinuity
LM: Smooth

Boundary : the direction of radial velocity changes

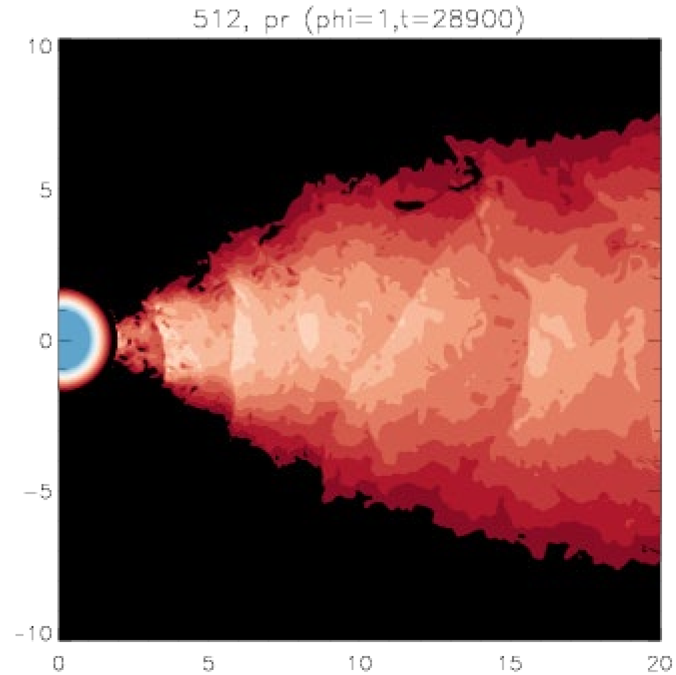
⇒ Inflow and outflow region clearly separated.

MOMENTUM DISTRIBUTION (RZ-PLANE)

Momentum of the radial direction



Pressure

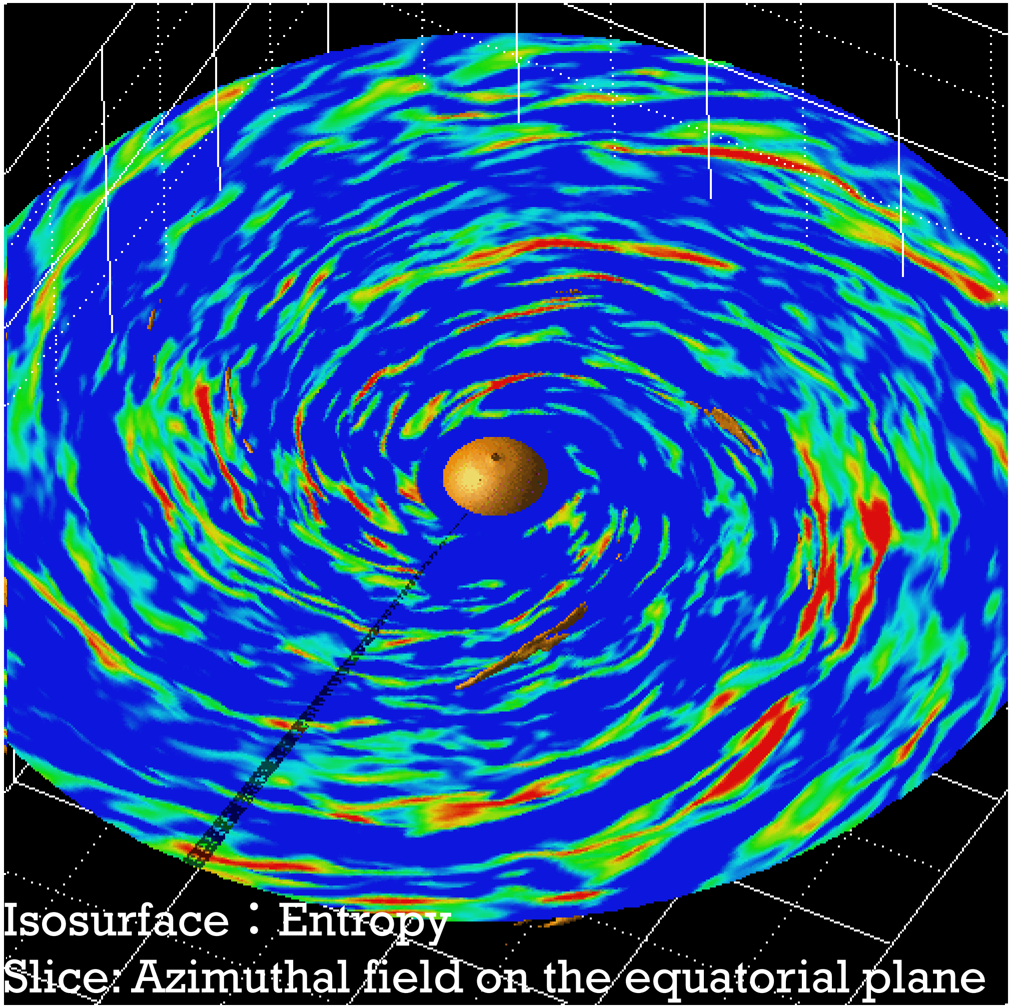


Both plots show the clear discontinuities around r~4, 6, 12 and 16 whose height are roughly 4~6 rg.

What is the origin of these discontinuities?

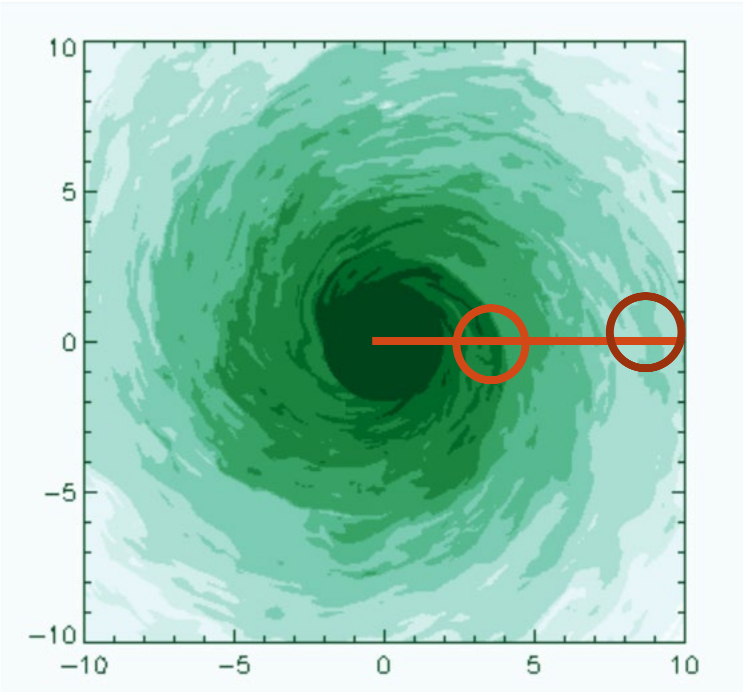
Can we observe the standing shock in the MRI turbulent disk?

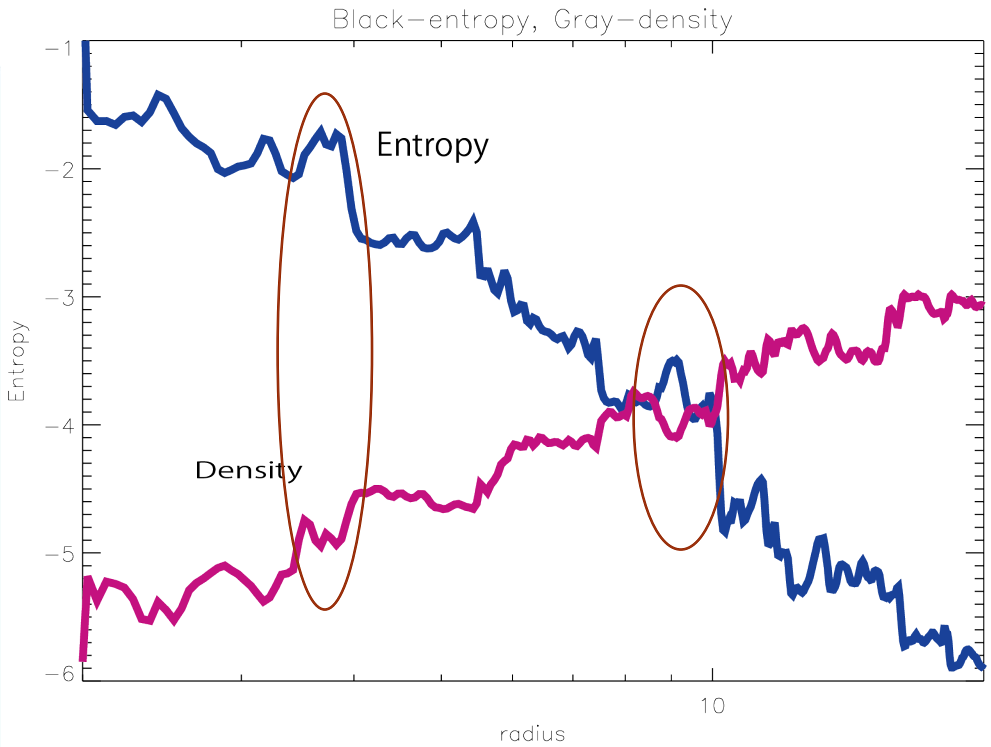
VOLUME RENDERING IMAGE OF ENTROPY



Entropy discontinuities are formed along the spiral structure observed in the density, velocity and pressure.

ENTROPY AND DENSITY DISTRIBUTION ACROSS THE DISCONTINUITY

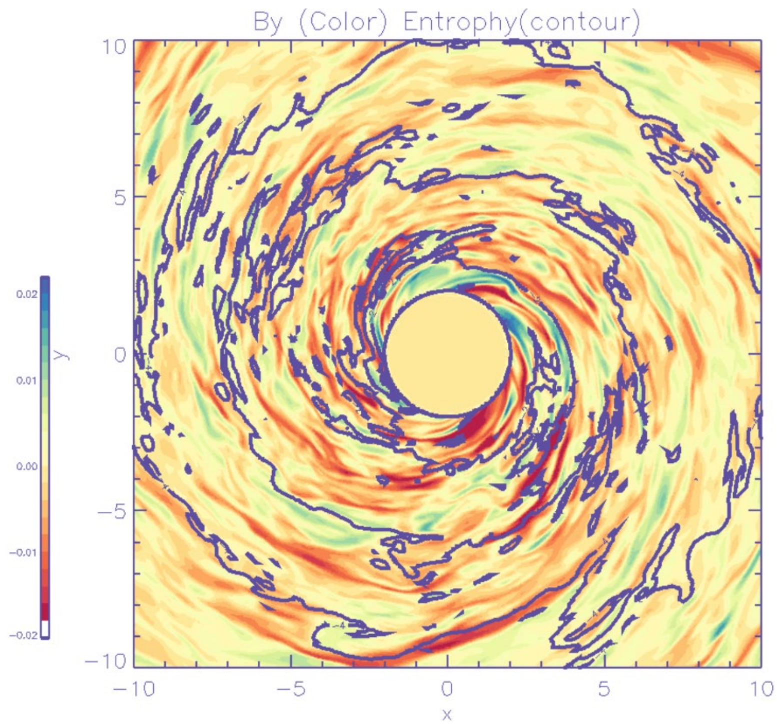


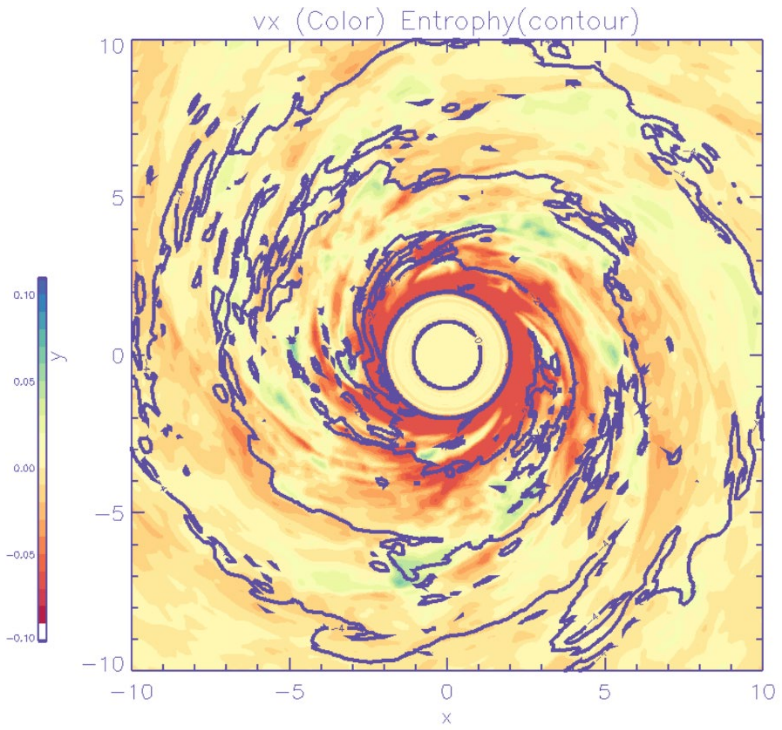


Inside the high entropy spiral, density suddenly decreases.

⇒ Discontinuity does not form by Spiral Shock.

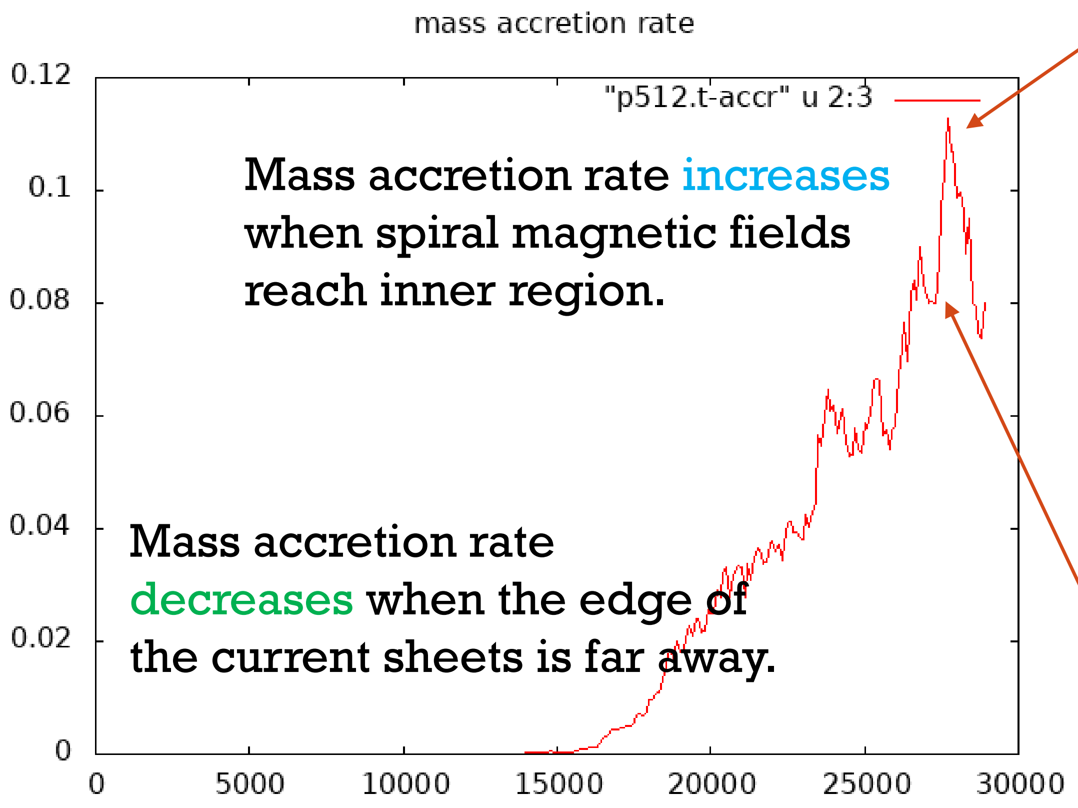
SPIRAL STRUCTURE ALONG THE MAGNETIC FIELDS

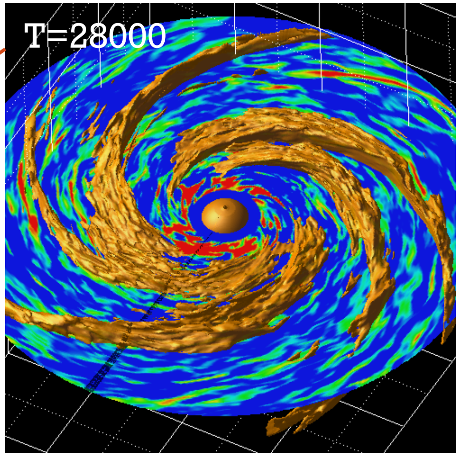


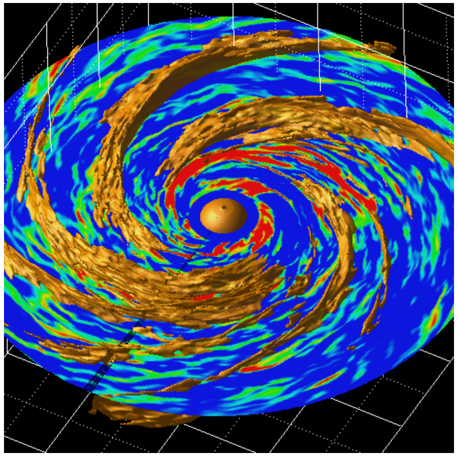


Entropy spirals are aligned with the magnetic fields. The direction of radial velocity becomes opposite across the spiral discontinuities.

CORRELATION BETWEEN SPIRAL STRUCTURE AND MASS ACCRETION RATE



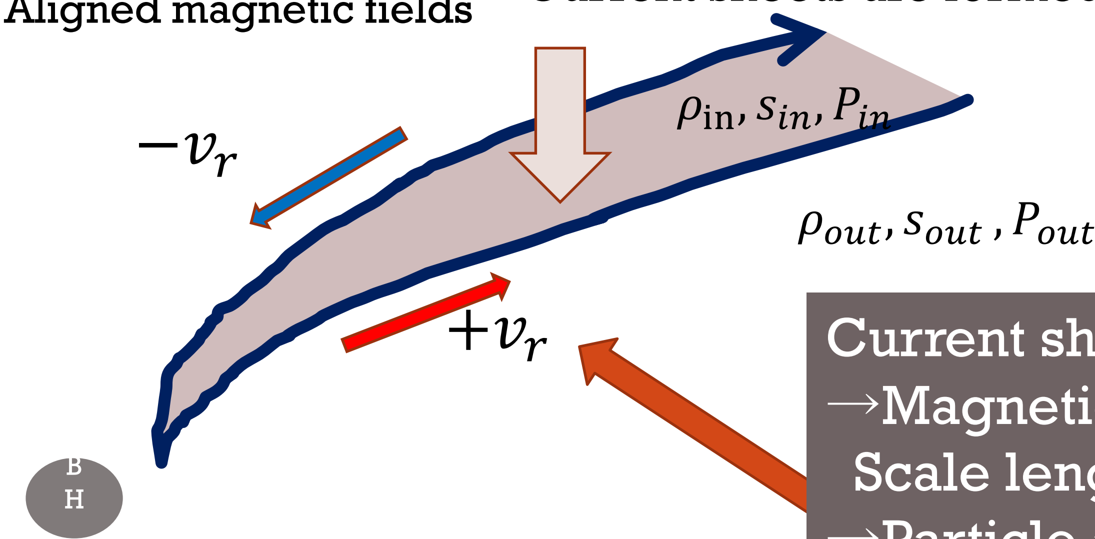




SCHEMATIC DRAWING OF SPIRAL ARMS

Aligned magnetic fields

Current sheets are formed.



Current sheets
→Magnetic reconnection
Scale length is ~5 rs
→Particle acceleration happened？

Small scale turbulent edges are formed.
radial scale : 0.3-0.5 rs, azimuthal scale ~5rs, vertical scale ~ 1-2 rs
→ turbulent energy ＞ magnetic tension ⇒ dissipate
turbulent energy ＜ magnetic tension
⇒Elongated by rotational motion ⇒ Spiral arms are formed.

Heating by Ohmic dissipation ⇒ Entropy walls are formed.

SUMMARY

- We investigate the resolution study for MRI in the accretion disk.
- According to the higher order accuracy of spacial resolution code, CANS+, we can resolve the global spiral structure inside the magnetically turbulent accretion disk.
- Spiral arms made by magnetic fields guide the mass accretion.
- Strong current sheets are formed in the spiral arm. The non-thermal particles can be accelerated around

THANK YOU FOR YOUR ATTENTION!