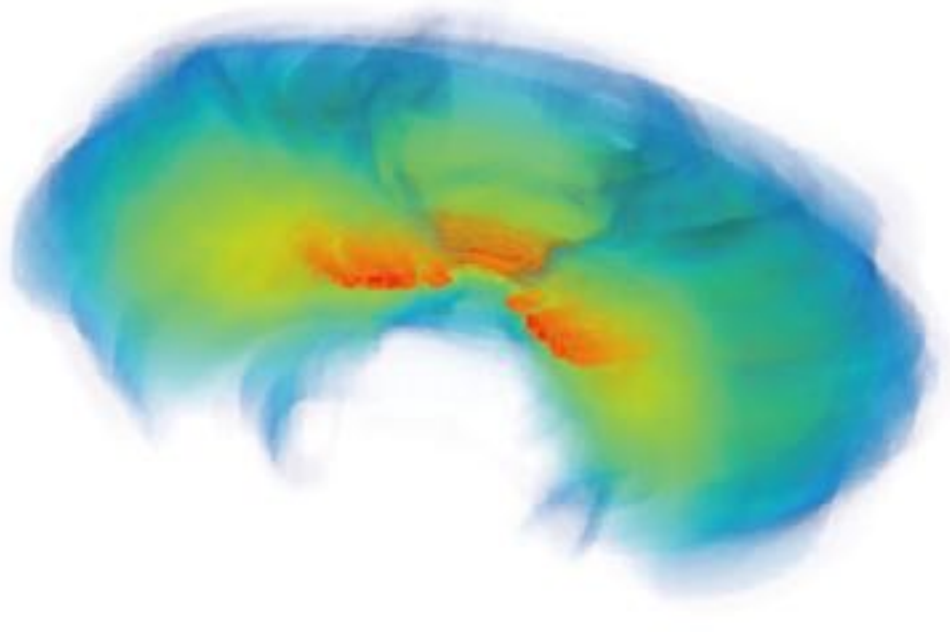
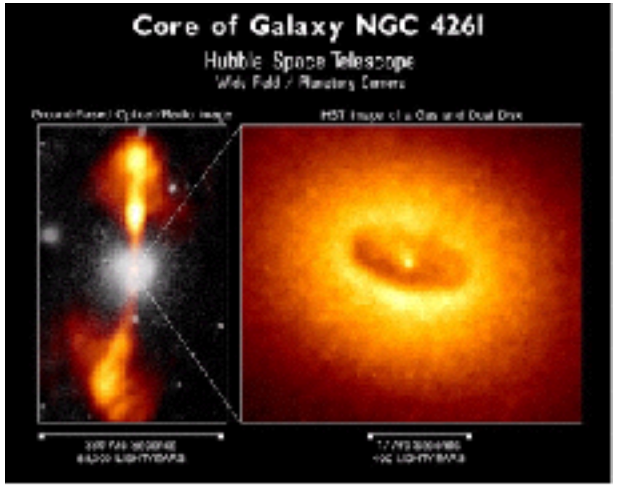
EASW8 August 1, 2018@Daejeon

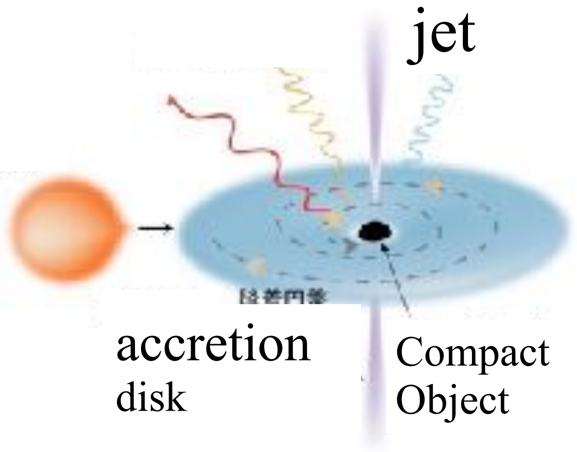
Radiation Magnetohydrodynamic Simulations of Black Hole Accretion Disks

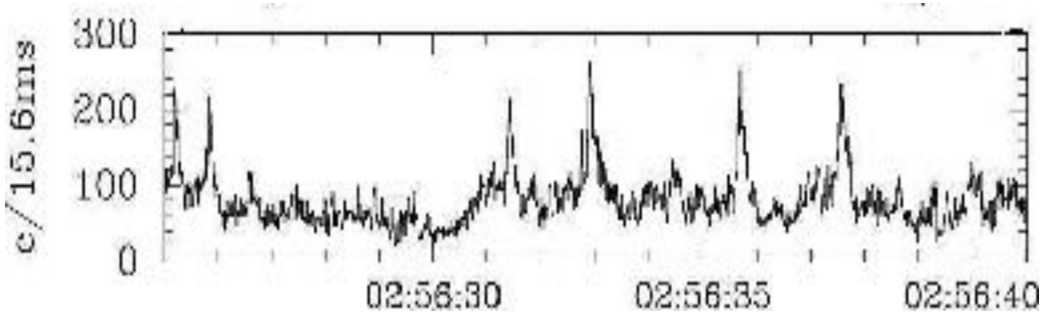


Ryoji Matsumoto (Chiba University)

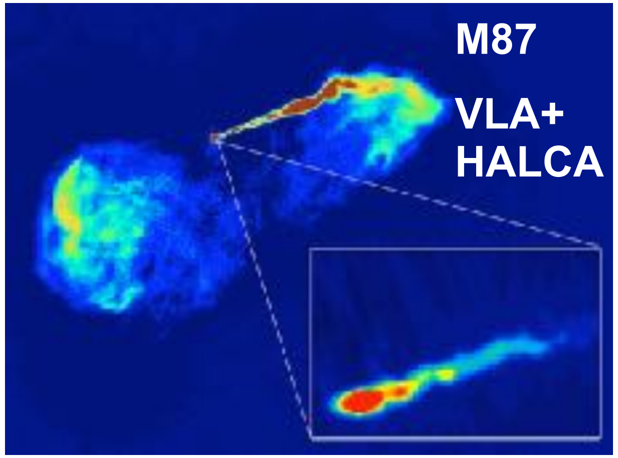
Activities Driven by Accretion onto a Black Hole



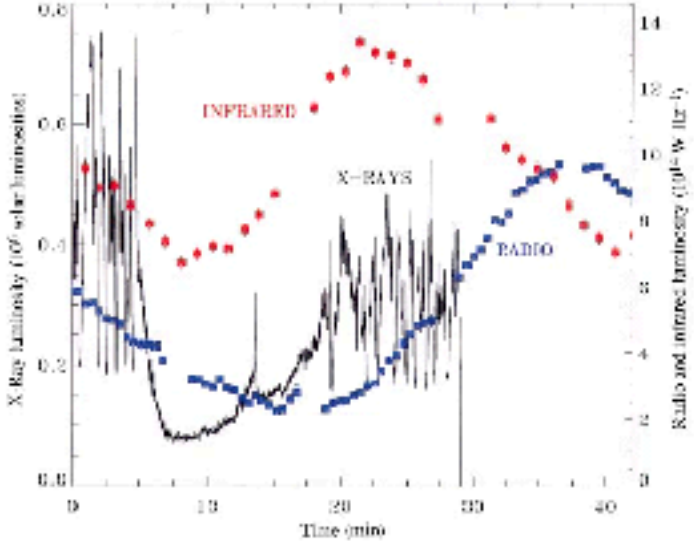




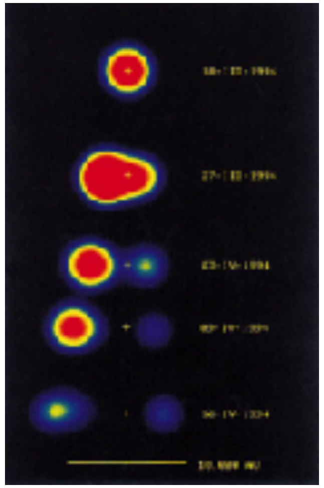
X-ray light curve of Cyg X-1 (Negoro 1995)



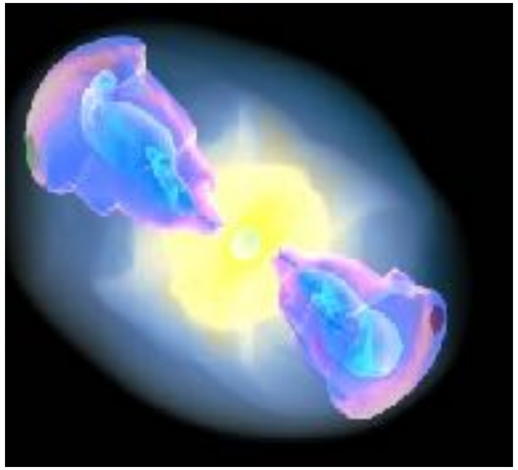
Active Galactic Nuclei



Microquasar GRS1915+105

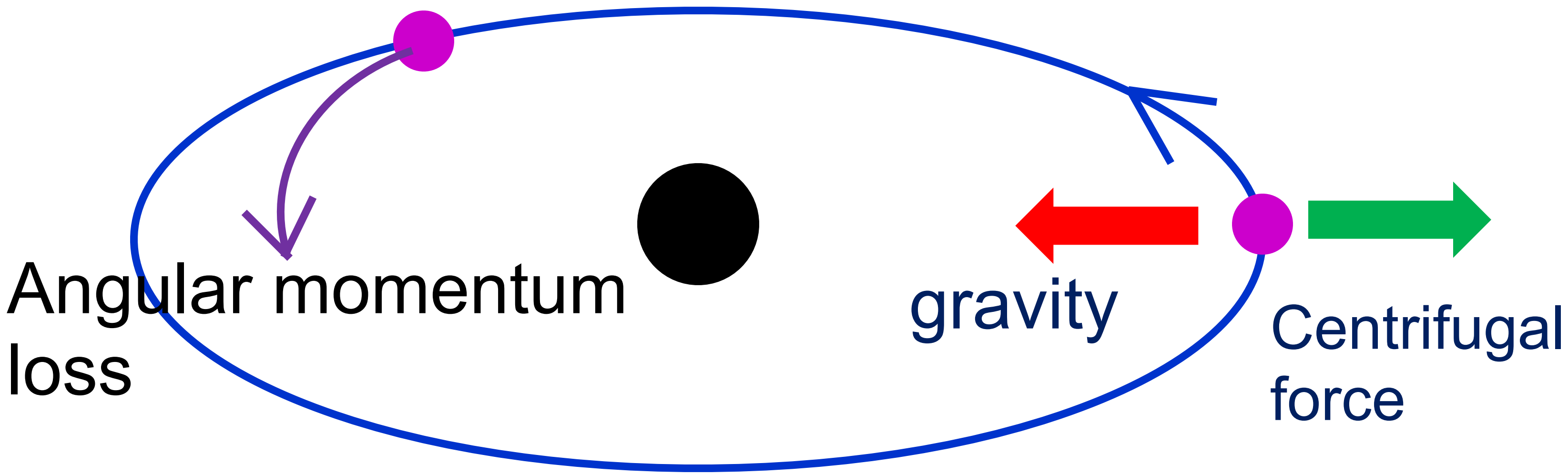


Mirabel and Rodriguez 1998



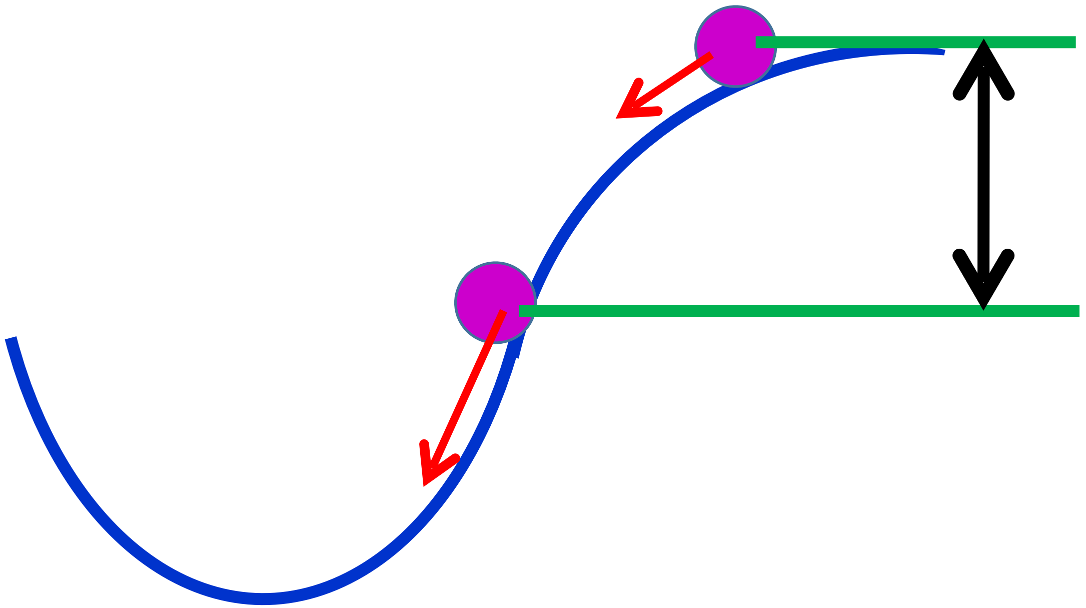
Gamma Ray Burst

Rotation around a Gravitating Object



When matter with angular momentum infalls toward a gravitating object, it forms a rotating disk. Accretion becomes possible when angular momentum is extracted.

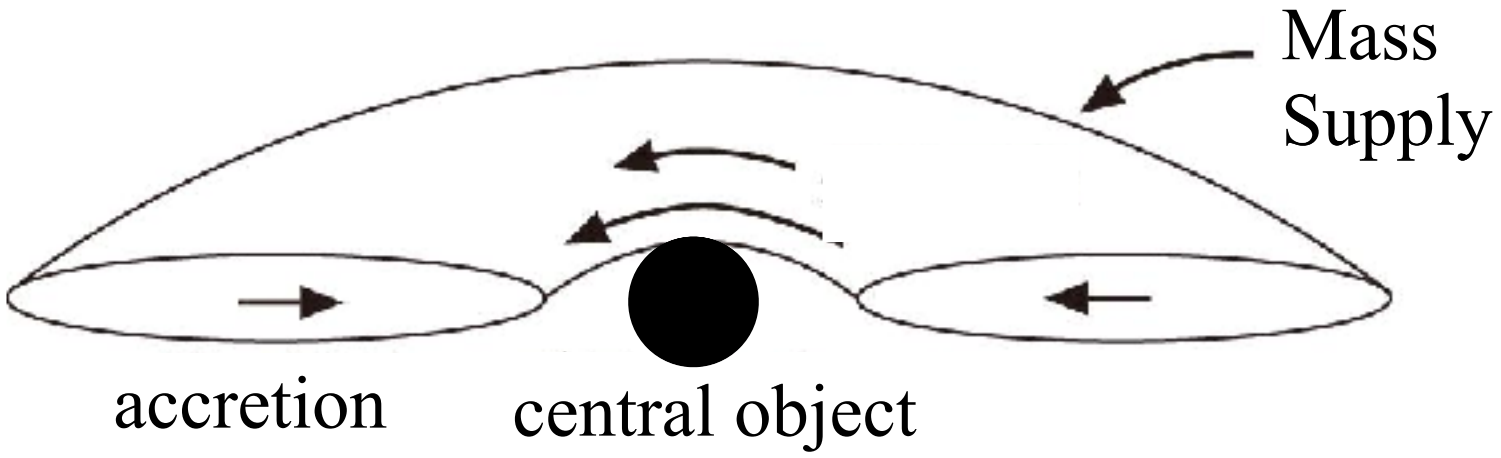
Release of Energy by Mass Infall



This difference of the potential energy is converted to other energy

The released gravitational energy approaches $E=mc^2$ when the central object is a black hole (more efficient than nuclear fusion)

Angular Momentum Transport in Accretion Disks

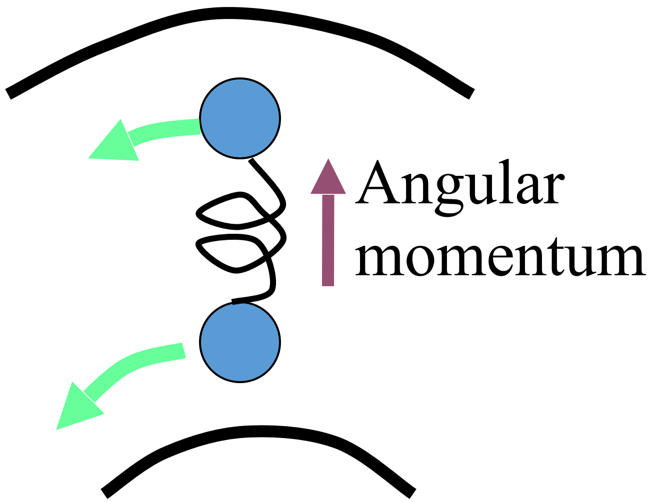


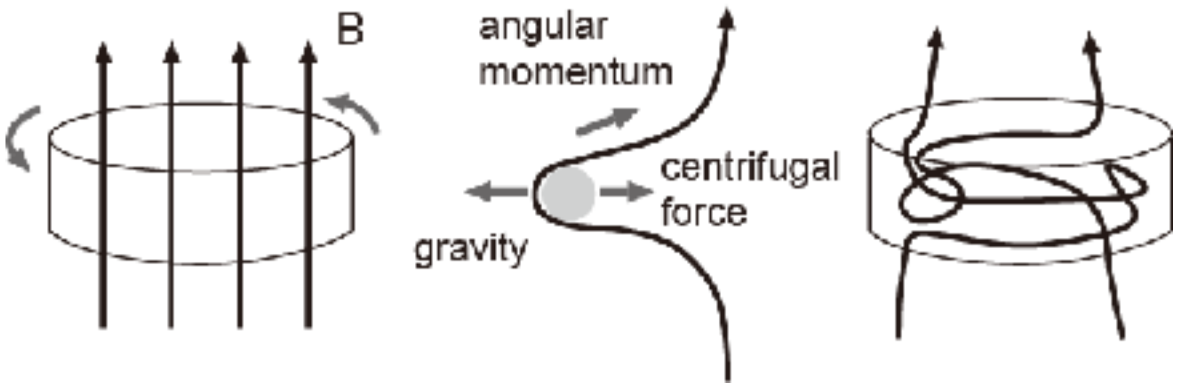
Rotating gas should lose angular momentum to accrete

Standard theory of accretion disk assume $T_{r\phi} = \alpha P$

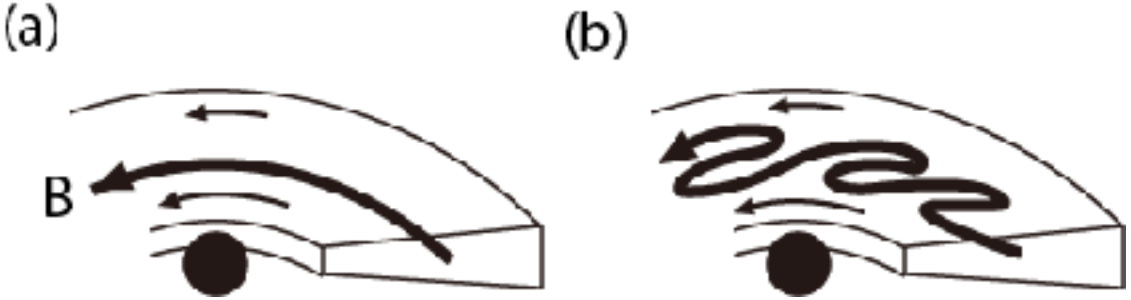
- Interval of dwarf nova outbursts indicate $\alpha = 0.01 \sim 0.1$
- In hydrodynamical disks $\alpha = O(0.001)$ too small !

Magneto-rotational Instability (MRI) in Differentially Rotating Disks

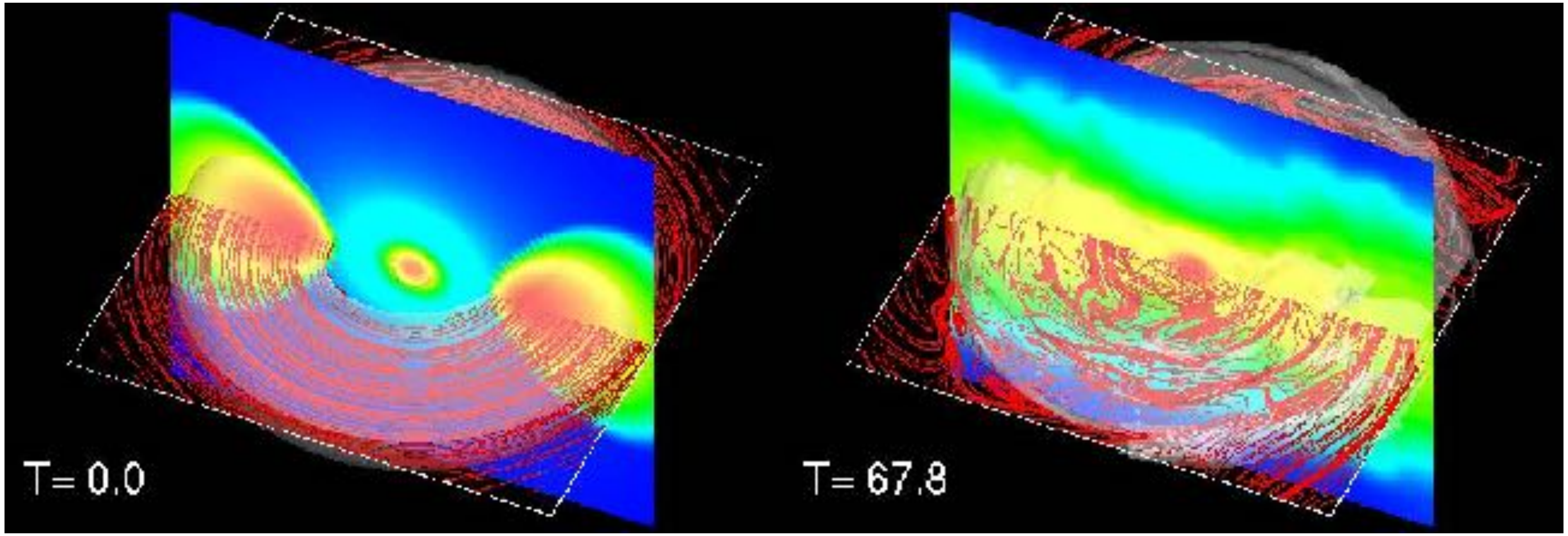




Balbus and Hawley (1991), Velikhov (1959)



Global 3D MHD Simulation of Differentially Rotating Torus



Initial Condition

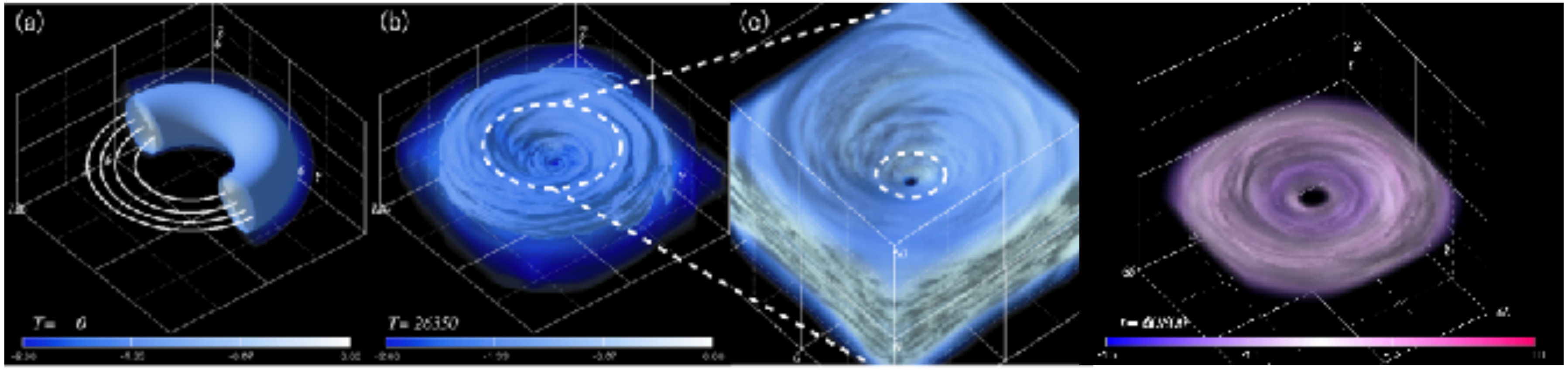
β = Pgas/Pmag=100

After 10 Rotation Period

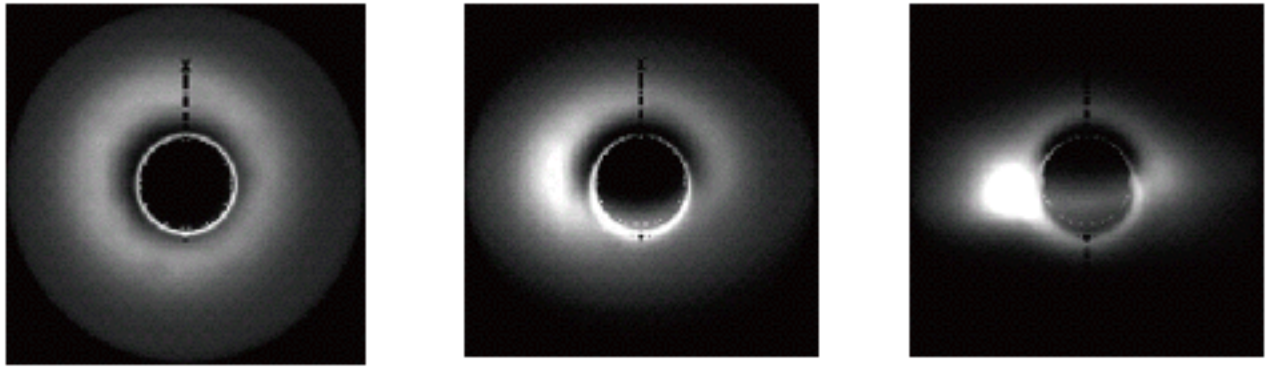
200*64*240 grid points

Matsumoto 1999

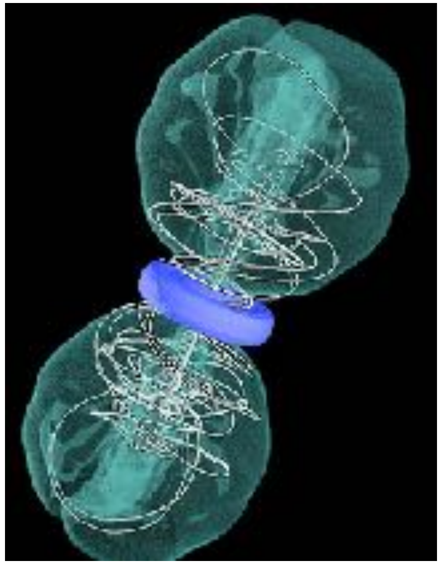
Global Three-dimensional Magnetohydrodynamic Simulations



Machida et al. 2003



Machida, M. Bursa

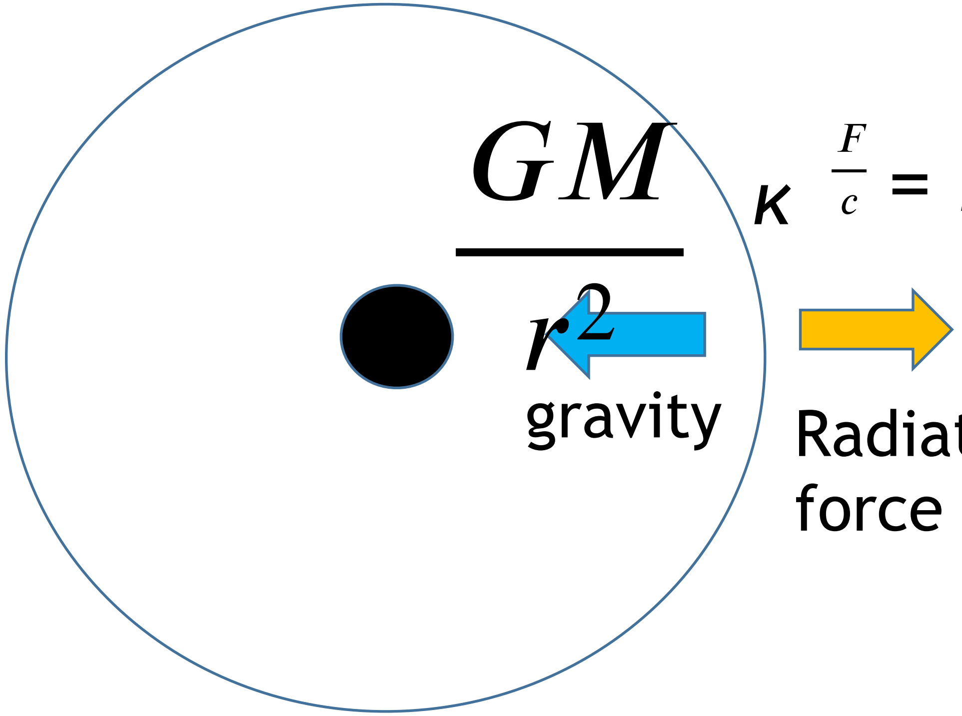


Y.Kato

How Bright a Black Hole can Shine ?

- Eddington Luminosity

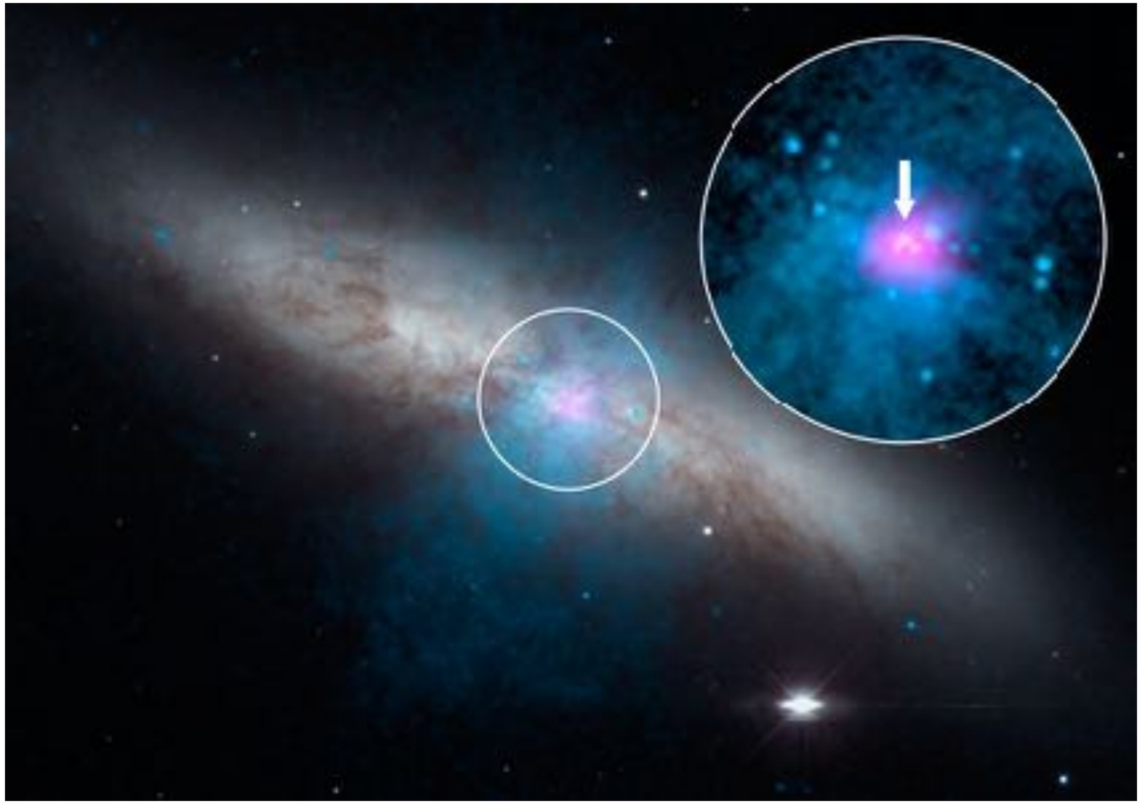
$\frac{GM}{r^2}$ κ $\frac{F}{c}$ = κ



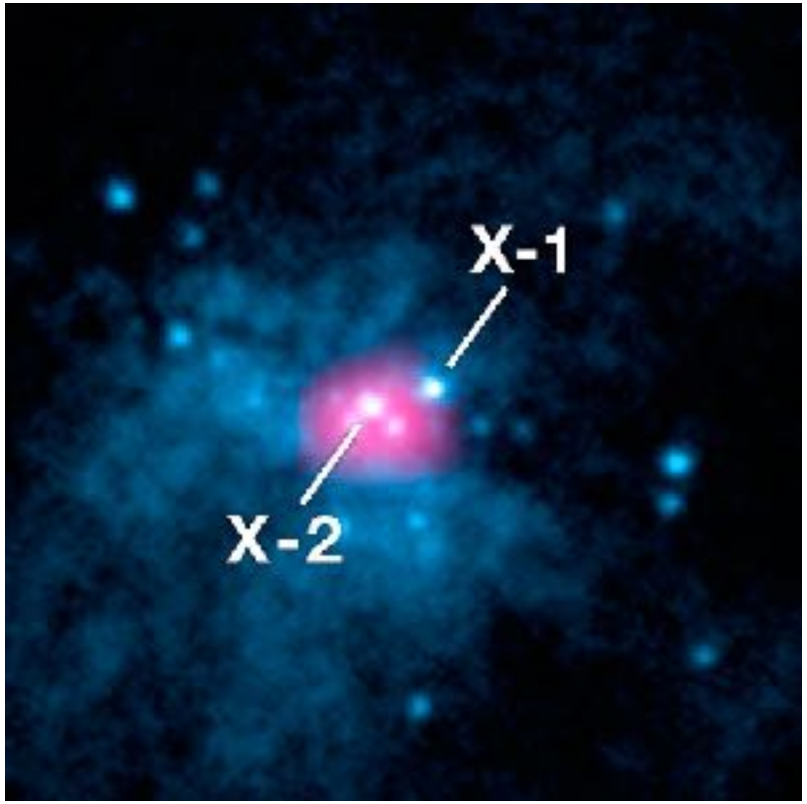
$L_{\rm Edd}$ = = 10^{38} $\frac{M}{M_\odot}$ erg/s

$\dot{M}_{\rm Edd}$ = = 10^{17} $\frac{M}{M_\odot}$ g/s

Ultraluminous X-ray Sources



Composite image of M82 Galaxy



X-ray image of the core region

X-ray: NASA/CXC/Univ. of Toulouse/M.Bachetti et al, Optical: NOAO/AURA/NSF

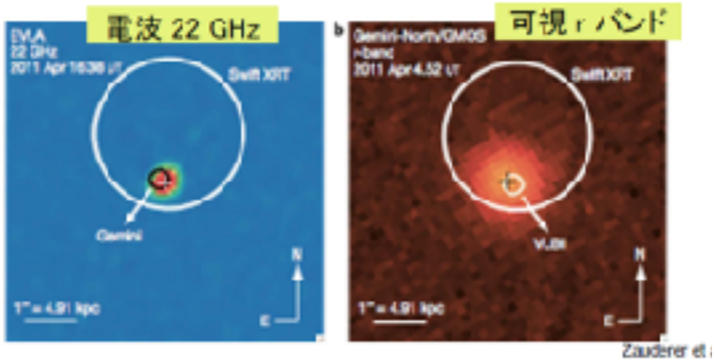
$L > 10^{41}$erg/s

M82 X-2 has been found to be a pulsar, whose mass is less than 2 solar mass: $L \gg L_{Edd}$

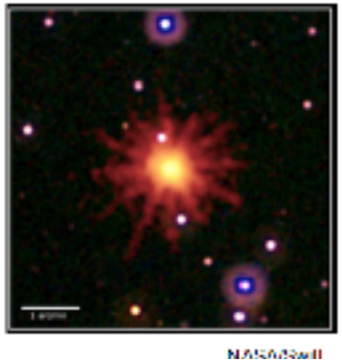
M82 X-1 can be a black hole

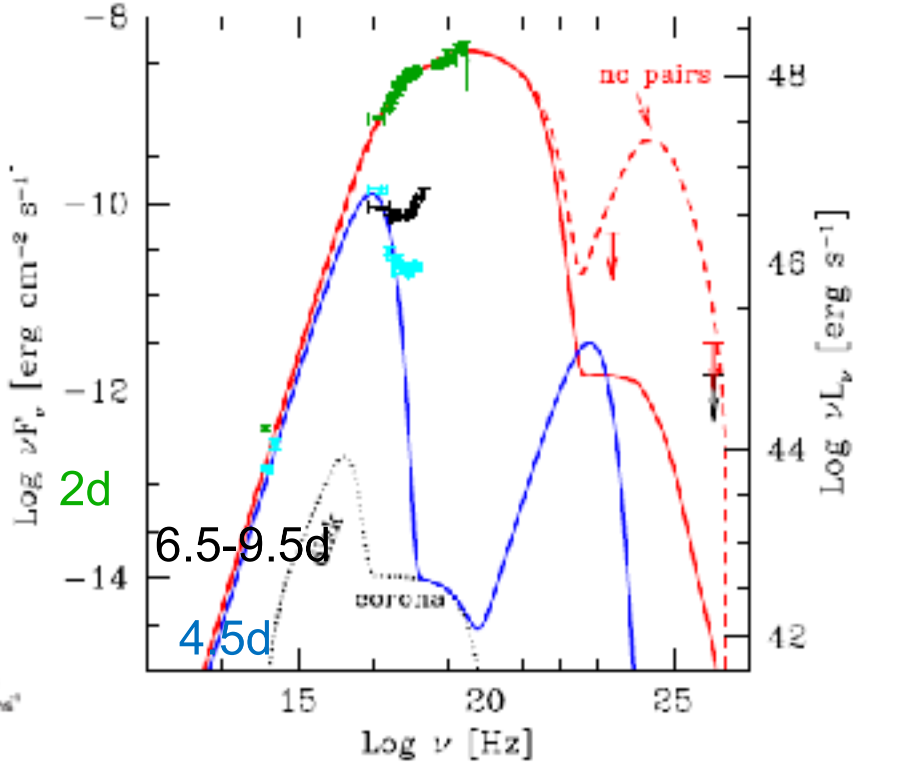
Tidal Disruption Event: Swift J1644+57

- Found by Swift satellite on March 28, 2011
- The source is identified with a radio source in a galaxy with z=0.3534



Swift (X 可視)



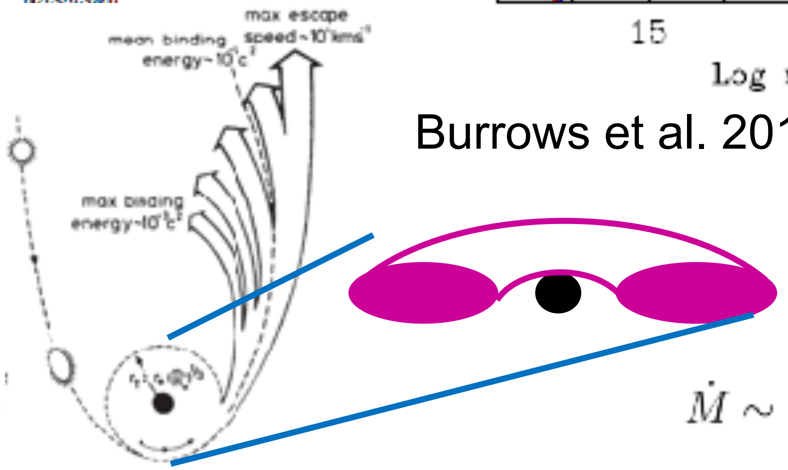


Burrows et al. 2011, Nature 476, 421

- Black Hole Mass : $10^6 M_\odot$

  $L_X \sim 10^{48}$ erg/s >> $L_{Edd} \sim 10^{44} M_6$ erg/s

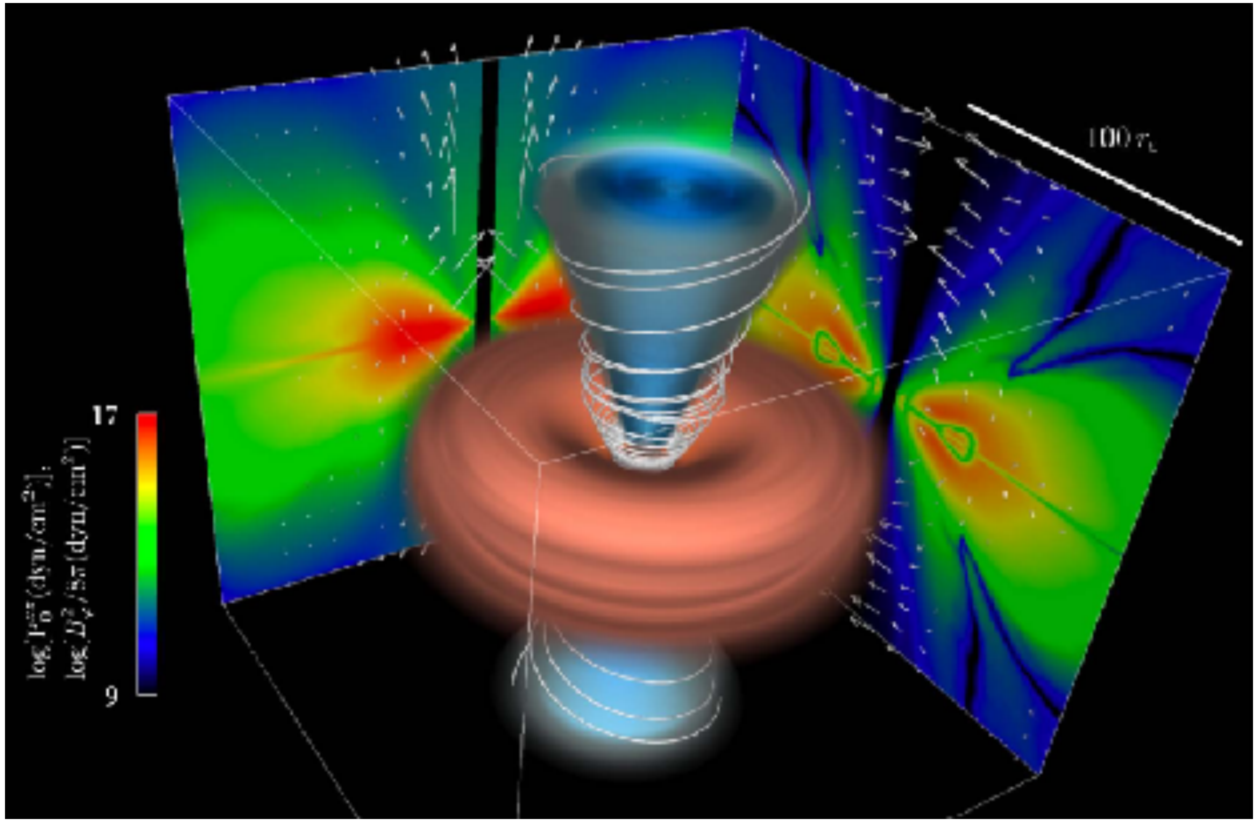
- Stayed in Super Eddington State over one year



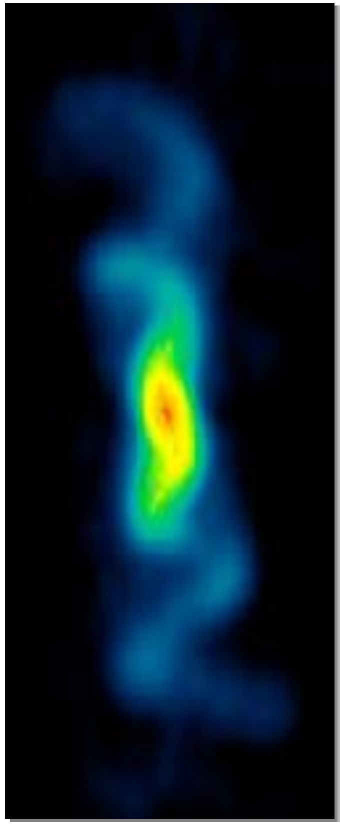
Rees (1988)

$$\dot{M} \sim \frac{1}{3}\frac{M_*}{t_{\rm fallback}}\left(\frac{t}{t_{\rm fallback}}\right)^{-5/3}$$

Global Radiation MHD Simulation of Supercritical Accretion onto a Black Hole



Takeuchi, Ohsuga, and Mineshige 2010



SS433

Axisymmetric 2D Radiation MHD Simulation

Basic Equations (Flux Limited Diffusion)

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

$$\rho \frac{\partial \mathbf{v}}{\partial t} + \rho(\mathbf{v} \cdot \nabla)\mathbf{v} = -\nabla p + \frac{(\nabla \times \mathbf{B}) \times \mathbf{B}}{4\pi} + \rho \mathbf{g} + \frac{\kappa + \sigma}{c}\mathbf{F}_0$$

Radiative Force

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B} - \eta \nabla \times \mathbf{B})$$

$$\frac{\partial \rho \varepsilon}{\partial t} + \nabla \cdot (\rho \varepsilon \mathbf{v}) + p \nabla \cdot \mathbf{v} = Q_J + Q_{vis} - 4\pi\kappa B + c\kappa E_0$$

$$\frac{\partial E_0}{\partial t} + \nabla \cdot (E_0 \mathbf{v}) = -\nabla \cdot \mathbf{F}_0 + 4\pi\kappa B - c\kappa E_0 - \nabla \mathbf{v} : \mathbf{P}_0$$

Ohsuga et al. 2005, 2006

Flux Limited Diffusion

$$\boldsymbol{F}_0 = -\frac{c\lambda}{\chi}\nabla E_0,$$

$$\lambda = \frac{2 + \mathcal{R}}{6 + 3\mathcal{R} + \mathcal{R}^2},$$

$$\mathcal{R} = |\nabla E_0|/(\chi E_0)$$

$$\mathbf{P}_0 = \mathbf{f} E_0,$$

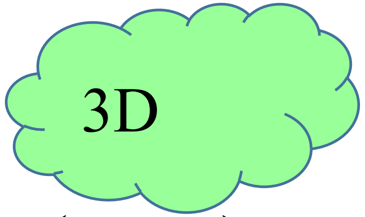
$$\mathbf{f} = \frac{1}{2}(1 - f)\mathbf{I} + \frac{1}{2}(3f - 1)\boldsymbol{nn},$$

Eddington Tensor

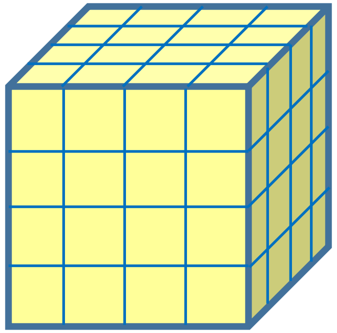
f : Eddington Factor

From HD/MHD to Radiation MHD

HD



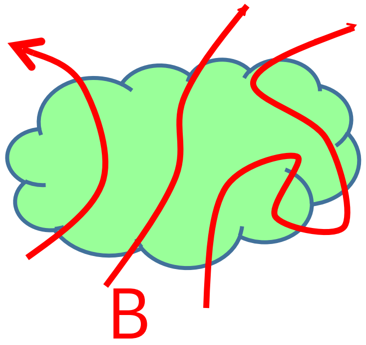
3D Mesh
Finite Difference



$\rho(t,x,y,z)$, $\boldsymbol{v}(t,x,y,z)$, $P(t,x,y,z)$

Cost $\propto N^3 \times N_{step}$

MHD



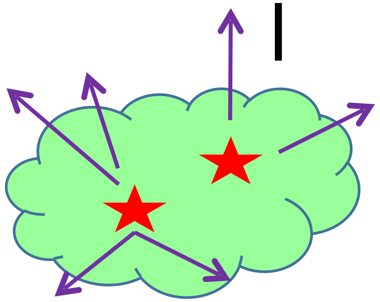
$+\boldsymbol{B}(t,x,y,z)$

Flux Limited Diffusion → M1

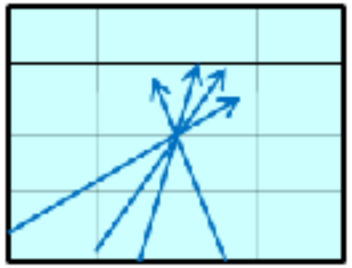
Solve Radiation Transfer

$$\frac{1}{c}\frac{\partial I}{\partial t} + \mathbf{n}\cdot\nabla I = \eta - \chi I$$

Radiation MHD

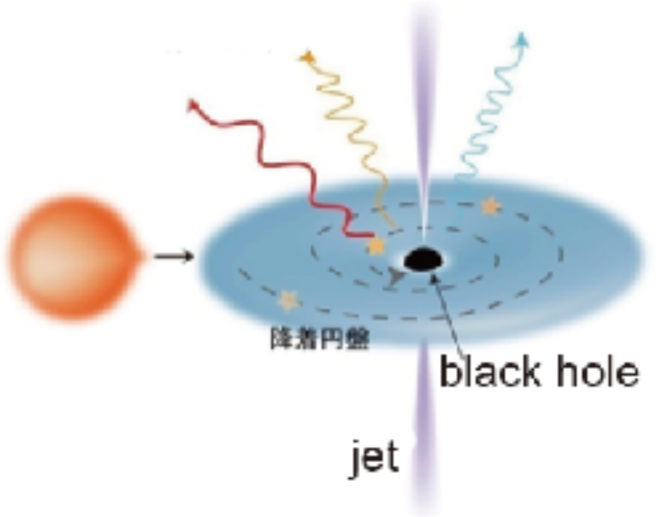


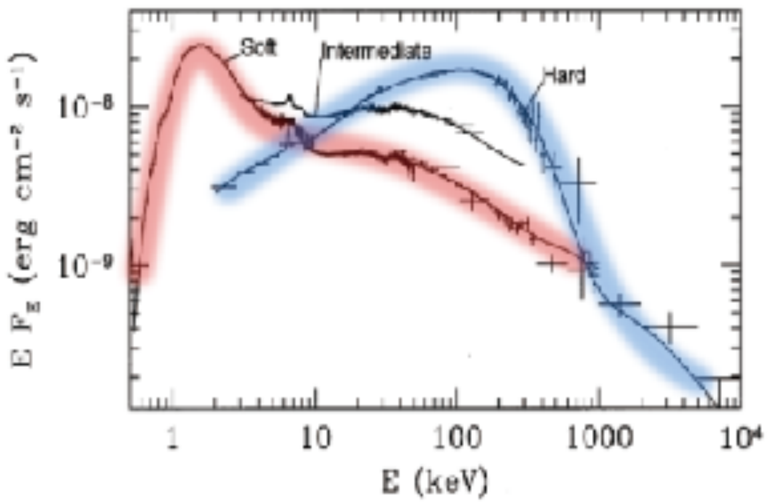
+ I $(t,x,y,z,\nu,\theta,\phi)$



$N^6 \times N_{step}$

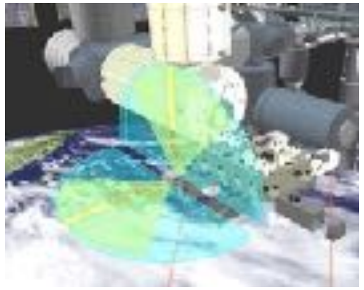
State Transitions of Black Hole Candidates

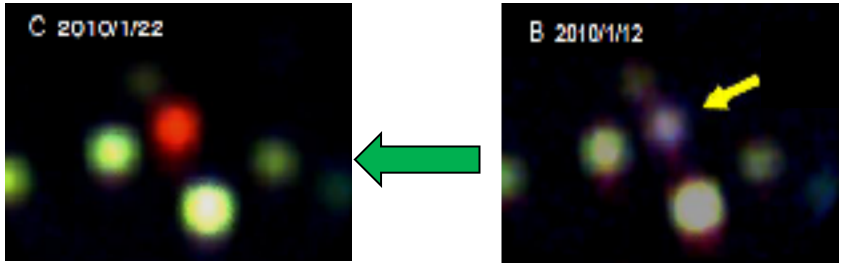


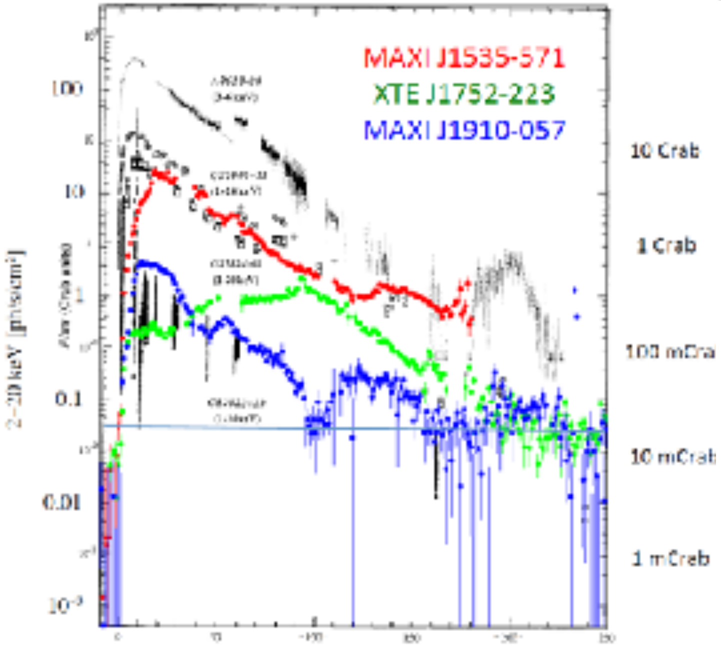


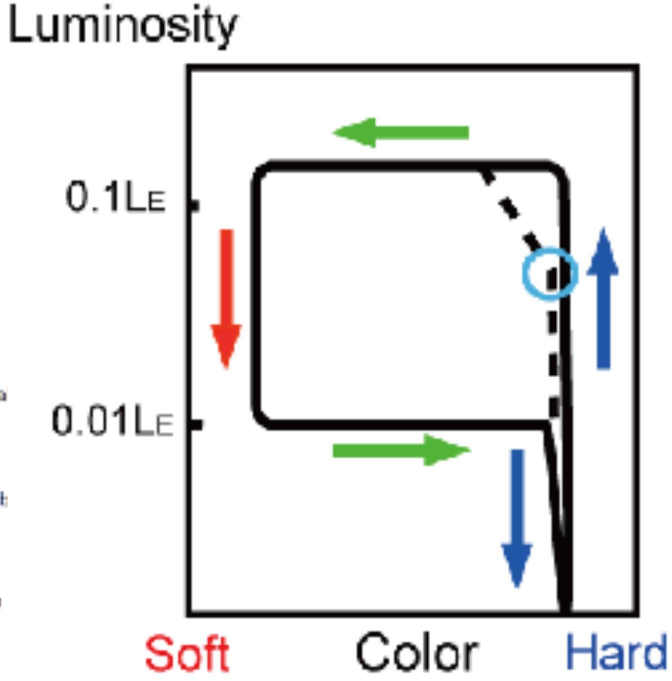
X-ray Spectrum of Cyg X-1（Gierlinski 1999）

All sky X-ray Monitor MAXI@RIKEN





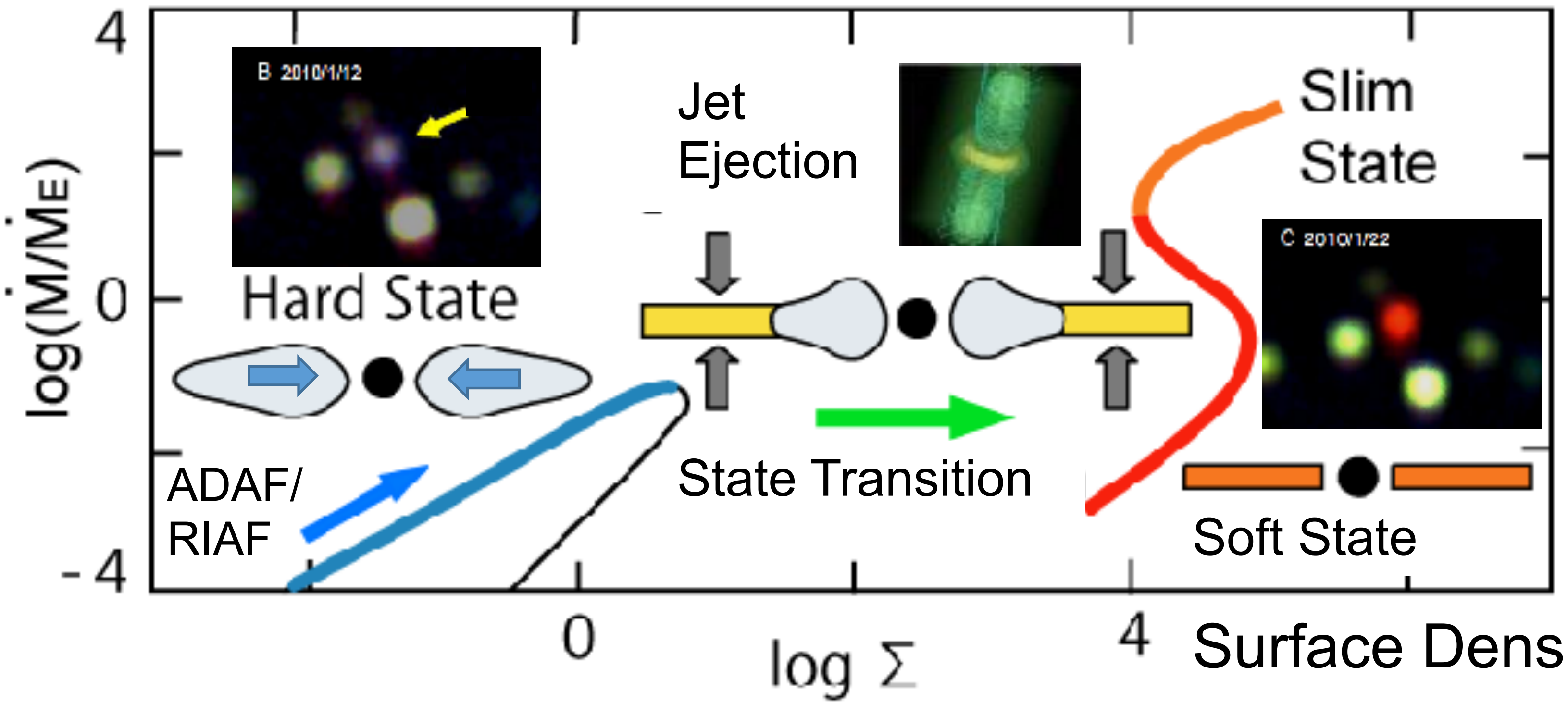




Evolution of a black hole candidate during outburst.
Dashed curve shows the trajectory XTE J1752-223

Theoretical Model of State Transition

Accretion Rate

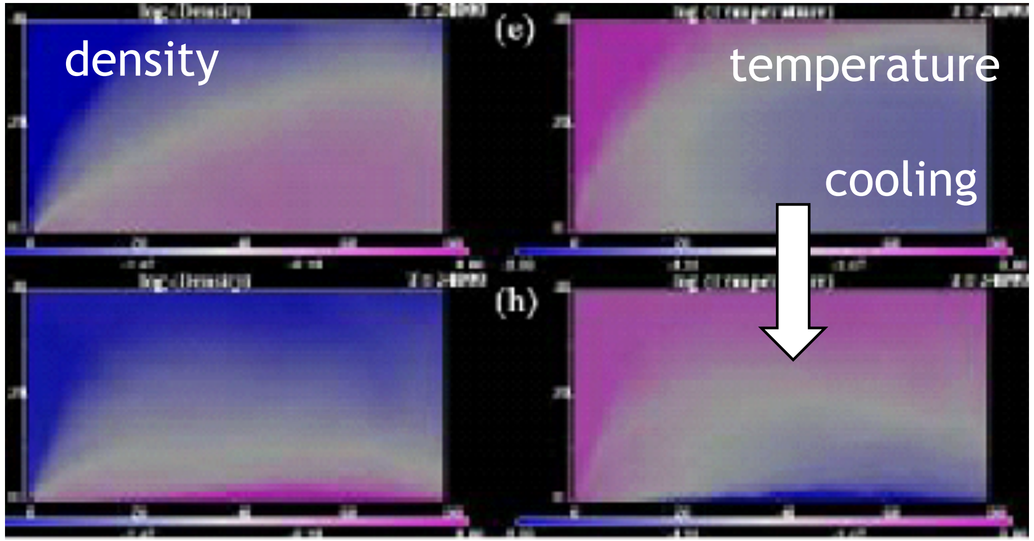


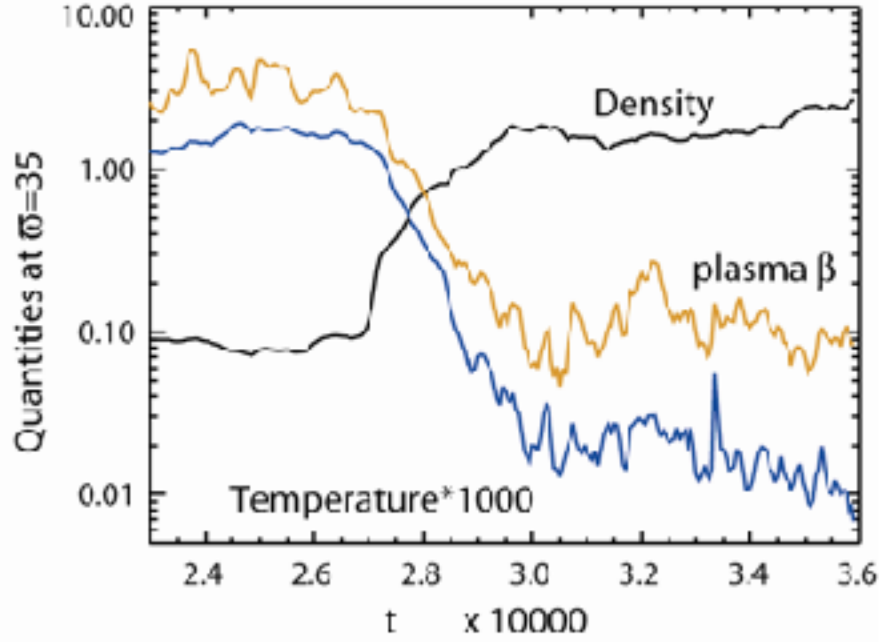
Surface Density

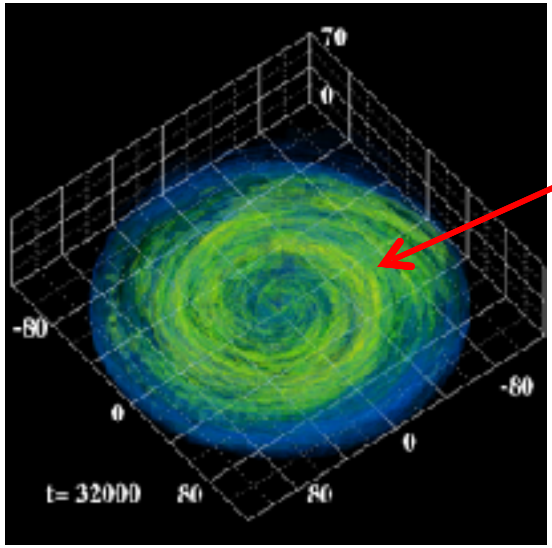
Optically Thin ⟵ ⟶ Optically Thick

Thermal Equilibrium Curves of Accretion Flows
(Abramowicz et al. 1995)

Global 3D MHD Simulation including Optically Thin Cooling

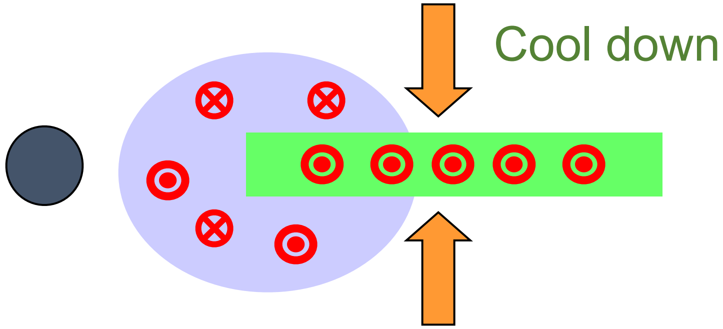






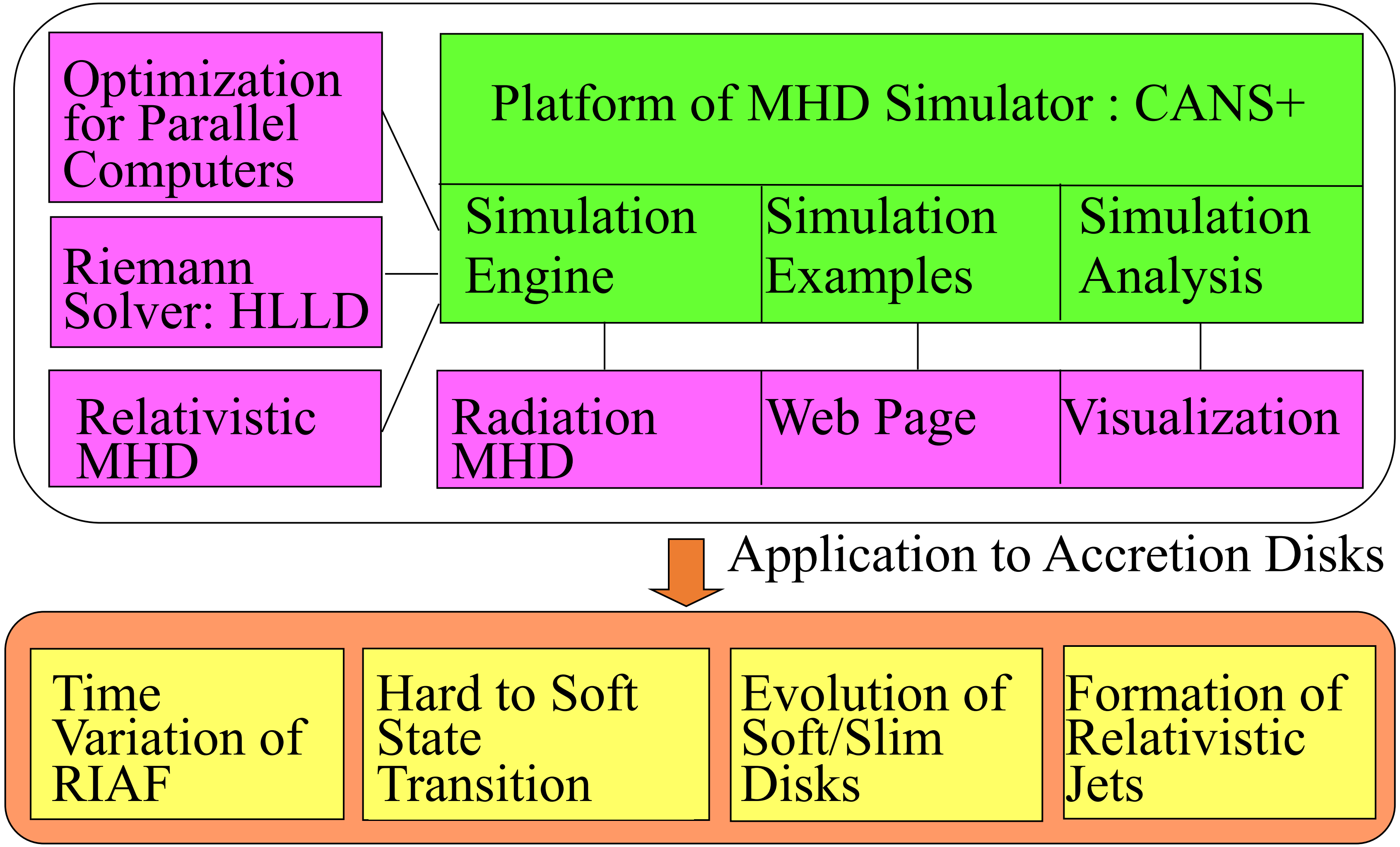
$\beta < 1$

Formation of magnetically supported disk ($\beta = P_{gas}/P_{mag} << 1$)



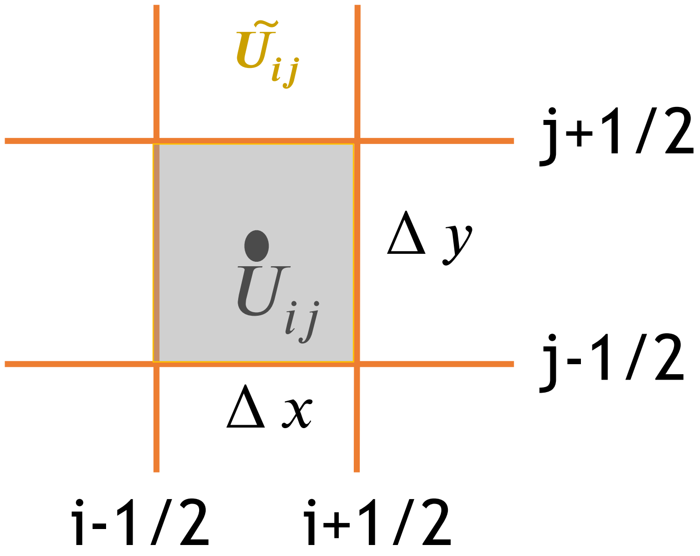
Machida et al. 2006

Revision of Magnetohydrodynamic Simulator for Accretion Disks



Numerical Scheme adopted in CANS+

Finite Volume Method



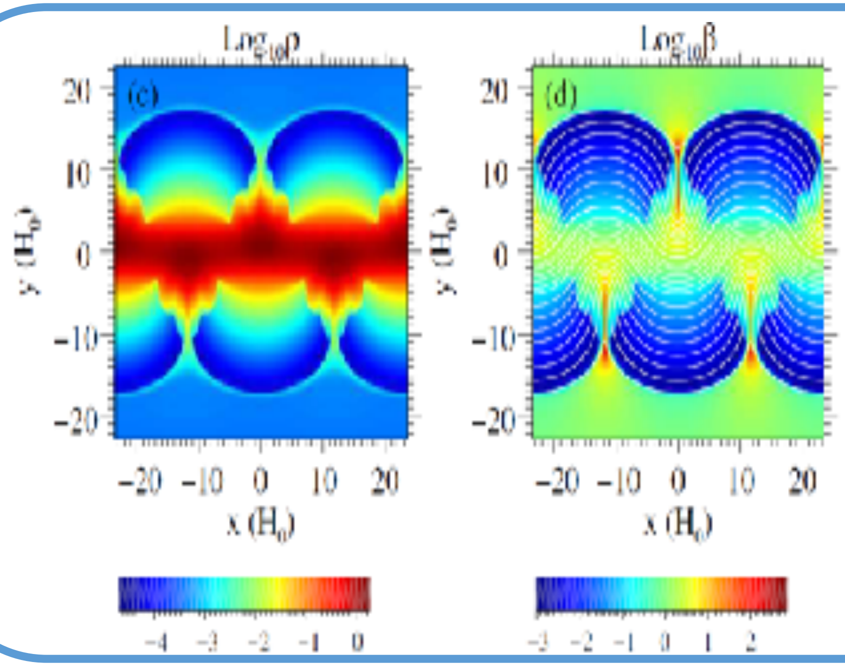
$$\frac{\partial U}{\partial t} = -\frac{\partial F}{\partial x} - \frac{\partial F}{\partial y}$$

$$\frac{\partial \tilde{U}_{ij}}{\partial t} = -\frac{F^*_{i+\frac{1}{2}} - F^*_{i-\frac{1}{2}}}{\Delta\, x} - \frac{F^*_{j+\frac{1}{2}} - F^*_{j-\frac{1}{2}}}{\Delta\, y}$$

: Cell Average : Numerical Flux

- Numerical Flux F* is obtained by HLLD approximate Riemann solver (Miyoshi & Kusano 05)
- Higher order MP5 scheme (Suresh &Huynh 97)
- div B=0 : Hyperbolic cleaning method (Dedner+ 02)

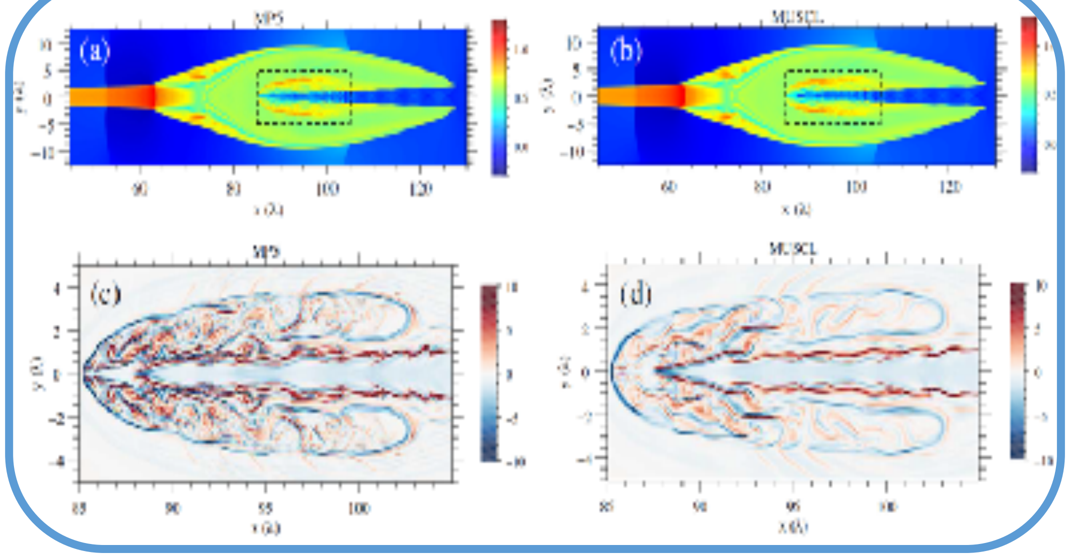
Application of CANS+



Parker Instability
can simulate low-β region
($\beta = P_{gas}/P_{mag} = 10^{-3}$)

Vx

Jz



Magnetic Reconnection
Can resolve shocks, discontinuities, and turbulence

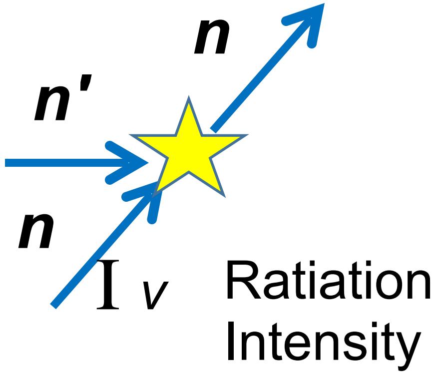
6000×1500 mesh

Extension of CANS+ to Radiation MHD Code: Non-Relativistic Version of M1 Code Developed by Takahashi and Ohsuga (2013)

- Equation of Radiative Transfer

$$\left(\frac{1}{c}\frac{\partial}{\partial t}+\boldsymbol{n}\cdot\nabla\right)I_\nu(t,\boldsymbol{r},\boldsymbol{n})=-\sigma_\nu I_\nu(t,\boldsymbol{r},\boldsymbol{n})$$

$$+\sigma_\nu S_\nu(t,\boldsymbol{r},\boldsymbol{n})+\sigma_{\nu,s}\int g(\boldsymbol{n},\boldsymbol{n}')I_\nu(t,\boldsymbol{r},\boldsymbol{n}')d\boldsymbol{n}'$$



- Moment Equations

$$E_\nu(t,\boldsymbol{r})=\frac{1}{c}\int I_\nu(t,\boldsymbol{r},\boldsymbol{n})d\boldsymbol{n}$$

$$\boldsymbol{F}_\nu(t,\boldsymbol{r})=\int \boldsymbol{n}\, I_\nu(t,\boldsymbol{r},\boldsymbol{n})d\boldsymbol{n}$$

$$\overleftrightarrow{\boldsymbol{P}}_\nu(t,\boldsymbol{r})=\frac{1}{c}\int \boldsymbol{n}\boldsymbol{n}\, I_\nu(t,\boldsymbol{r},\boldsymbol{n})d\boldsymbol{n}$$

- M1 Closure

$$\overleftrightarrow{\boldsymbol{P}}_\nu=\left(\frac{1-\chi}{2}\overleftrightarrow{\boldsymbol{I}}+\frac{3\chi-1}{2}\boldsymbol{n}\boldsymbol{n}\right)E_\nu$$

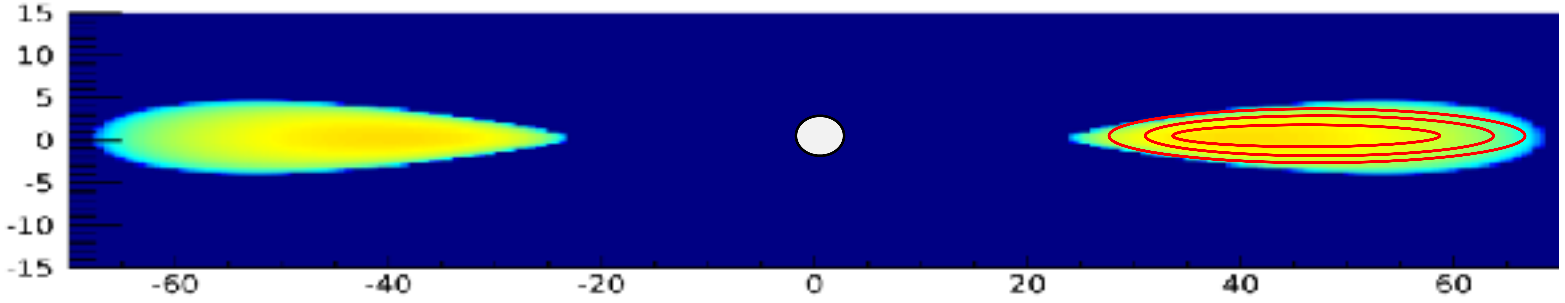
χ : Eddington Factor

Radiation Source Terms

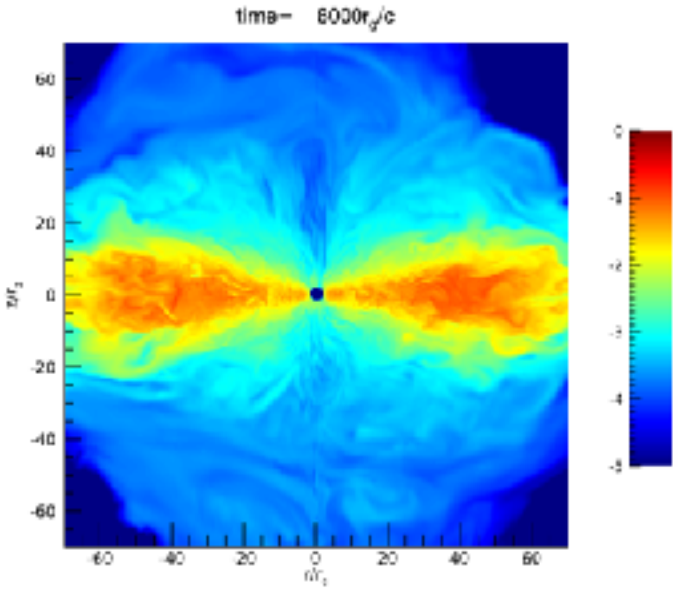
$$S_0 = \rho\kappa_{\rm ff}\left(\frac{4\pi B}{c} - E_{\rm rad}\right) + \rho\left(\kappa_{\rm ff} - \kappa_{\rm es}\right)\frac{\boldsymbol{v}}{c^2}\cdot\left[\boldsymbol{F}_{\bf rad} - \left(\boldsymbol{v}E_{\rm rad} + \boldsymbol{v}\cdot\mathbf{P}_{\rm rad}\right)\right]$$

$$\boldsymbol{S}_1 = \rho\kappa_{\rm ff}\frac{\boldsymbol{v}}{c}\left(\frac{4\pi B}{c} - E_{\rm rad}\right) - \rho(\kappa_{\rm ff} + \kappa_{\rm es})\frac{1}{c}\left[\boldsymbol{F}_{\bf rad} - (\boldsymbol{v}E_{\rm rad} + \boldsymbol{v}\cdot\mathbf{P}_{\rm rad})\right]$$

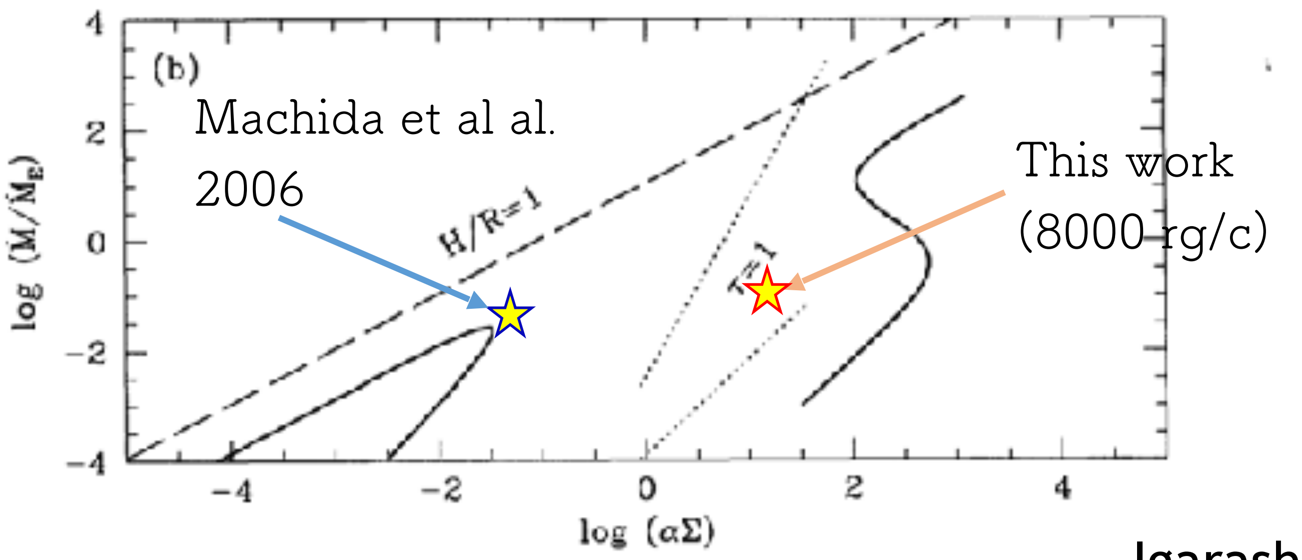
Initial Setup of the Radiation MHD Simulations of Hard-to-Soft Transition in Black Hole Accretion Disks



Initial density distribution and magnetic field lines



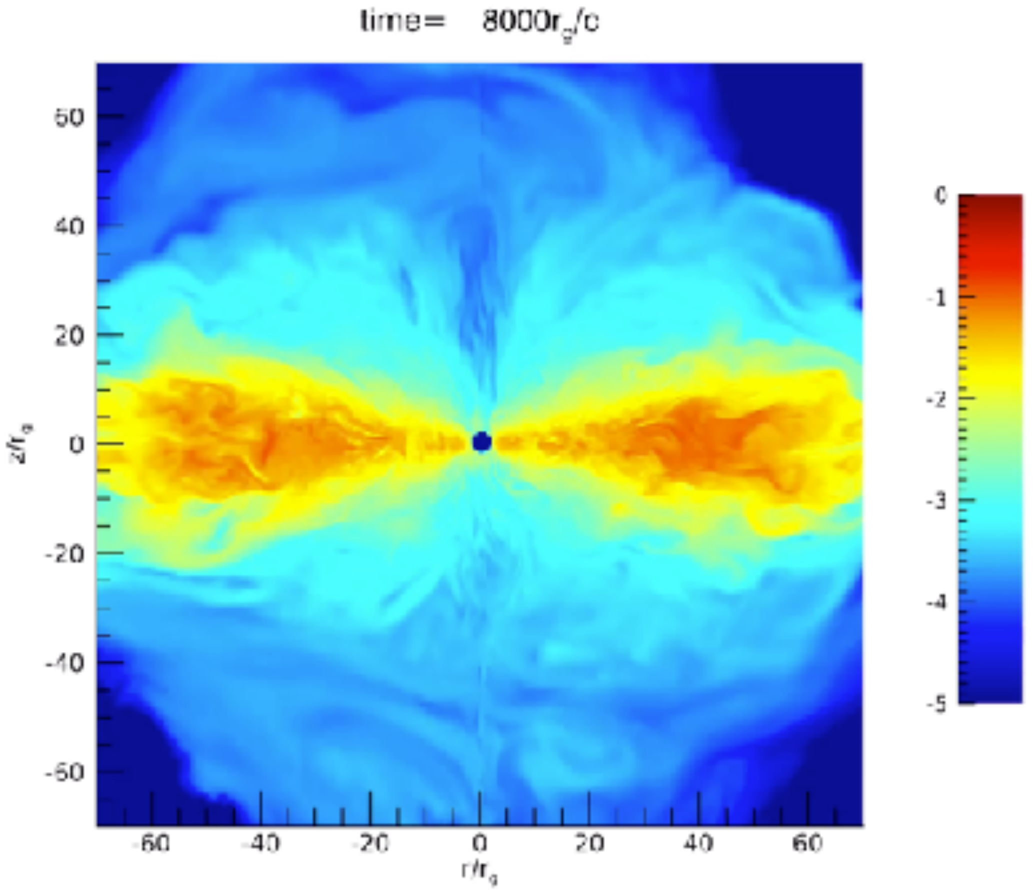
Density distribution of hot accretion Flow obtained by not including cooling

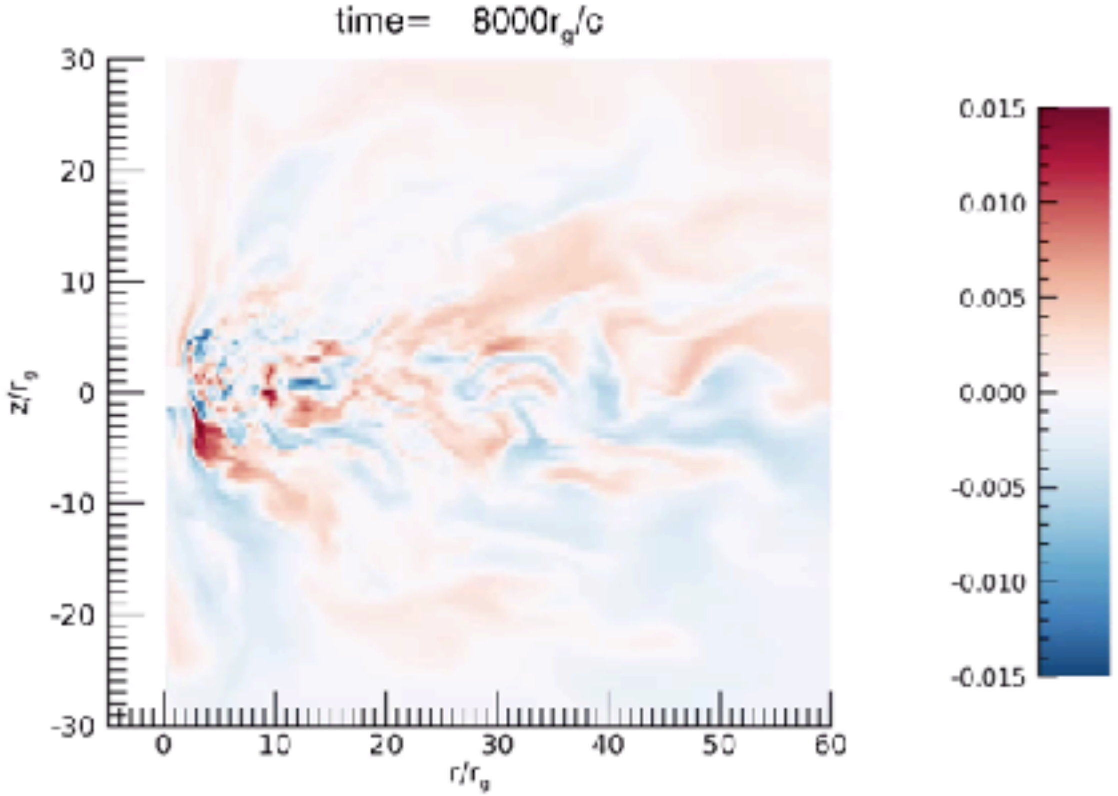


Location in Σ-accretion rate plane when cooling is switched on

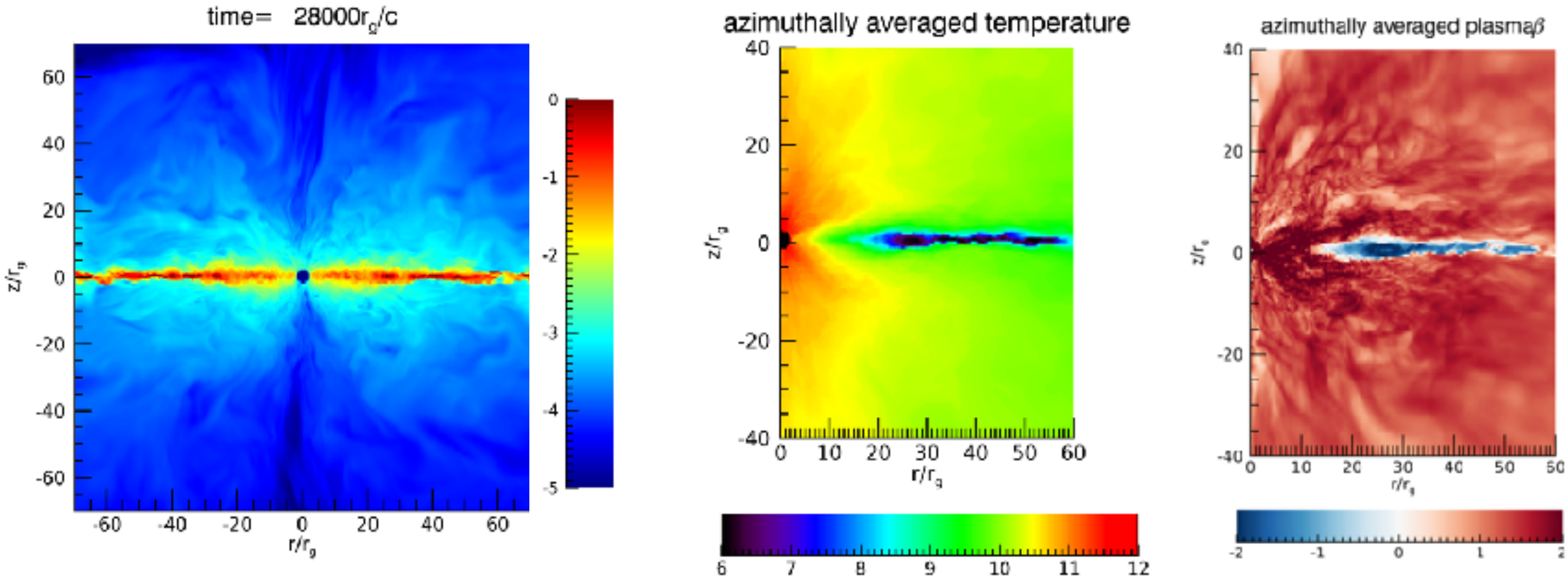
Igarashi et al. 2018 in prep.

Time Evolution of Density and Azimuthal Magnetic Field





Numerical Results at t=$28000r_g/c$



Density

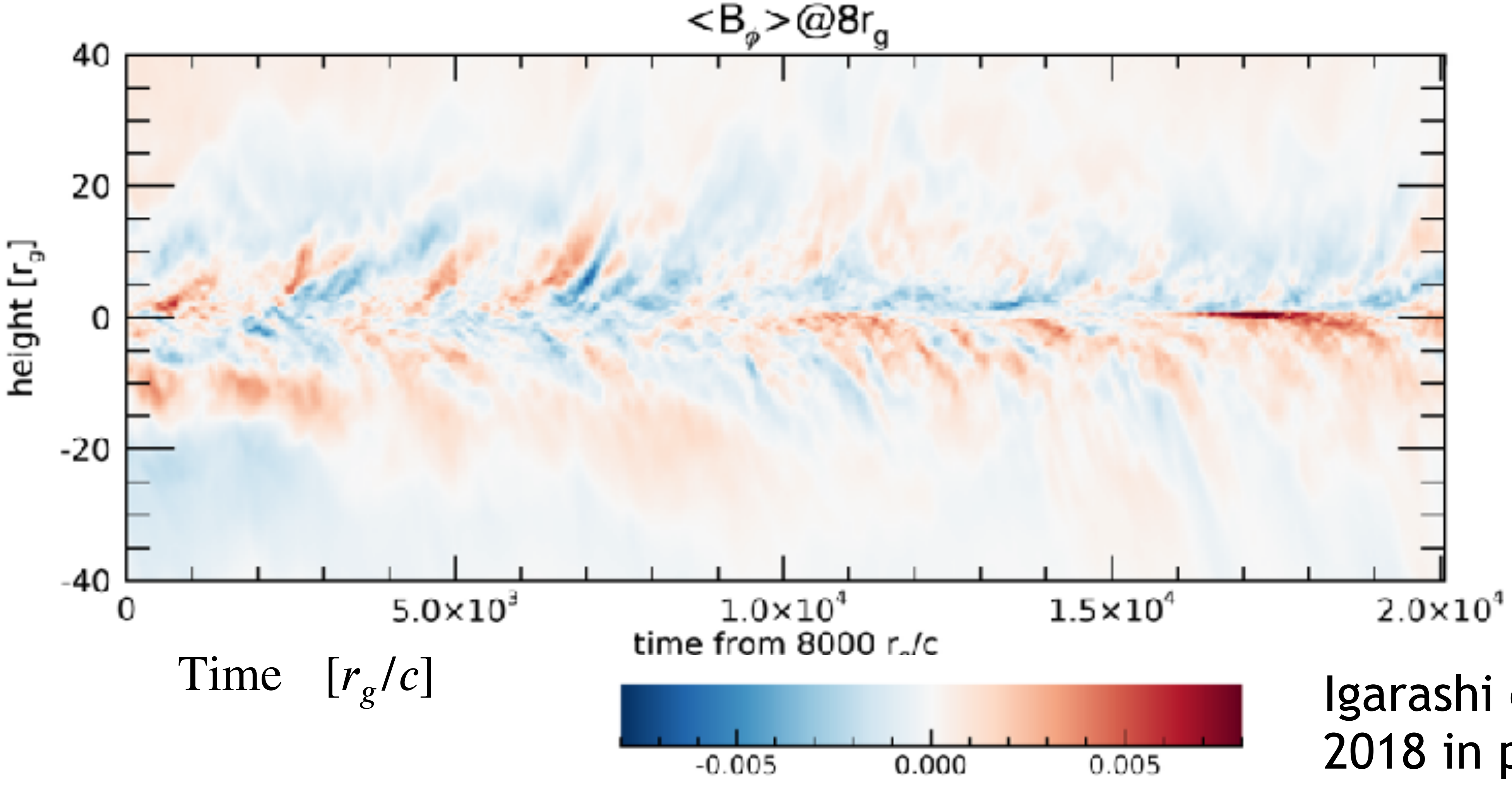
Log <T> [K]

Log < β >

Distribution

Igarashi et al. 2018 in prep

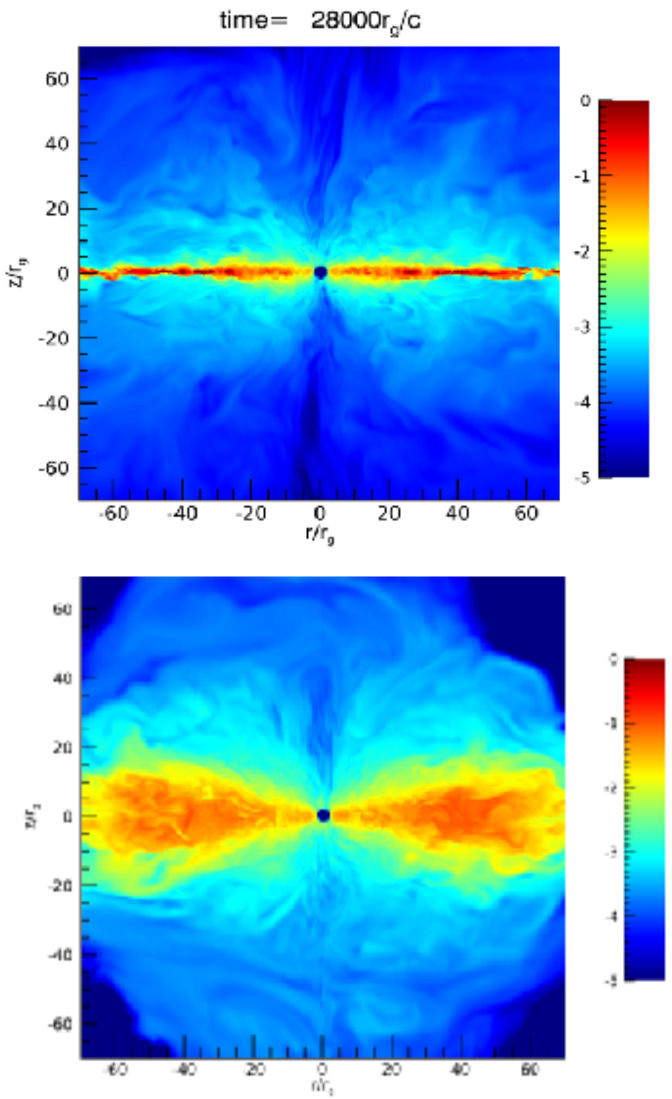
Butterfly Diagram at $r=8r_g$

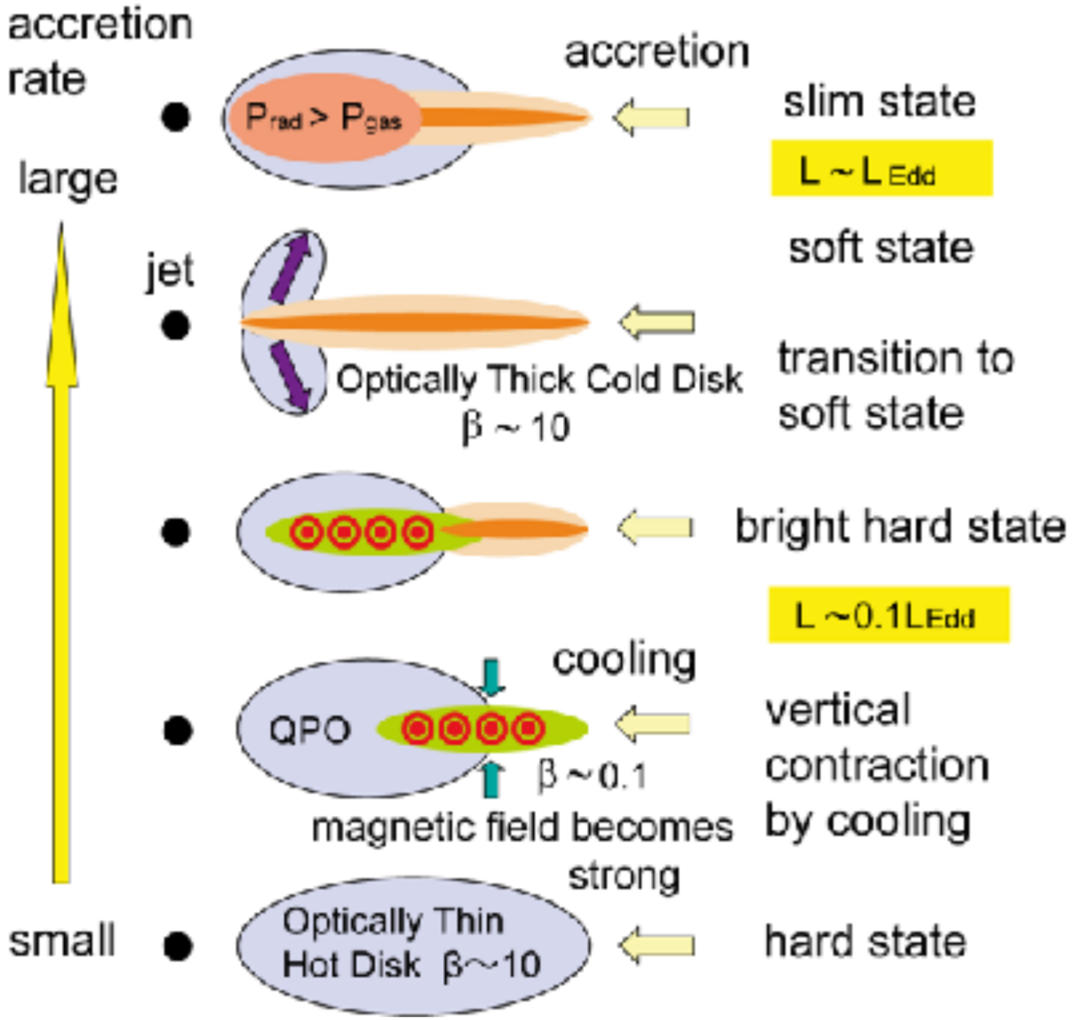


Igarashi et al.
2018 in prep.

Evolution of Black Hole Accretion Disks

L





Summary

- Three-dimensional radiation magnetohydrodynamic code based on the M1 closure scheme has been applied to simulate the hard-to-soft transition in black hole accretion flows
- When the accretion rate is 10% of the Eddington accretion rate, hot, optically thin disk near the black hole and the cool, optically thick disk in the outer region coexist
- This state corresponds to the luminous hard state observed during the hard-to-soft transition
- Quasi-periodic dynamo with frequency 10Hz is excited in the inner hot disk. This can be the origin of low frequency quasi-periodic oscillations observed during the hard-to-soft transition