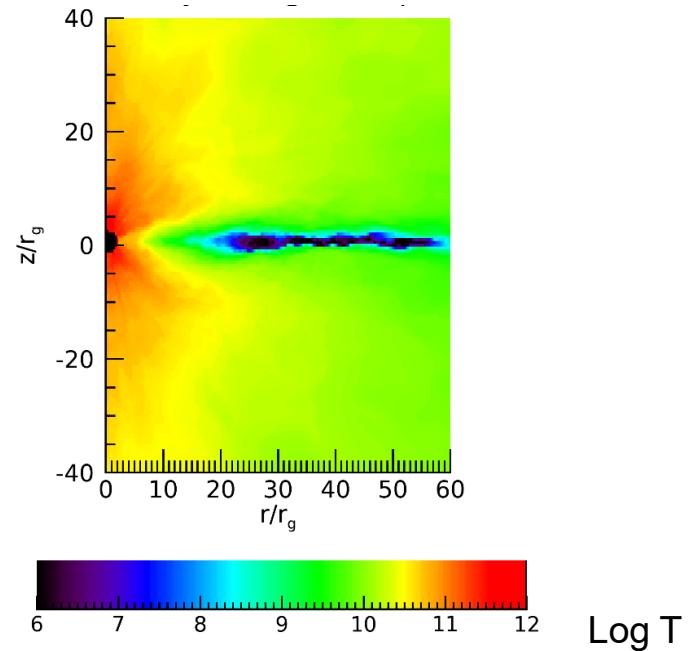
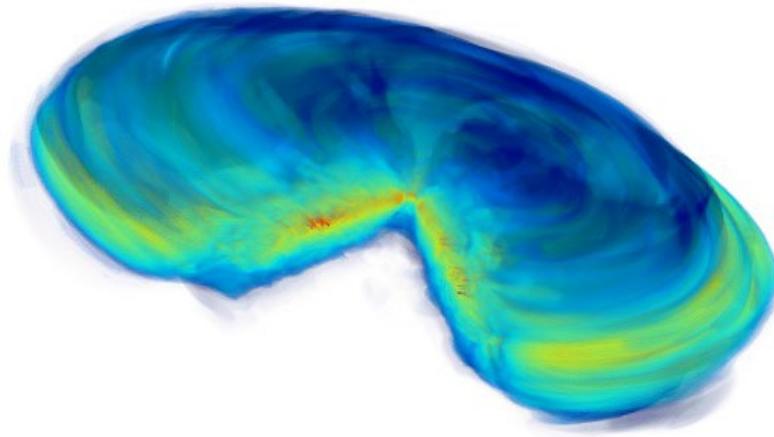


セイファート銀河におけるX線放射領域 形成の磁気流体モデル

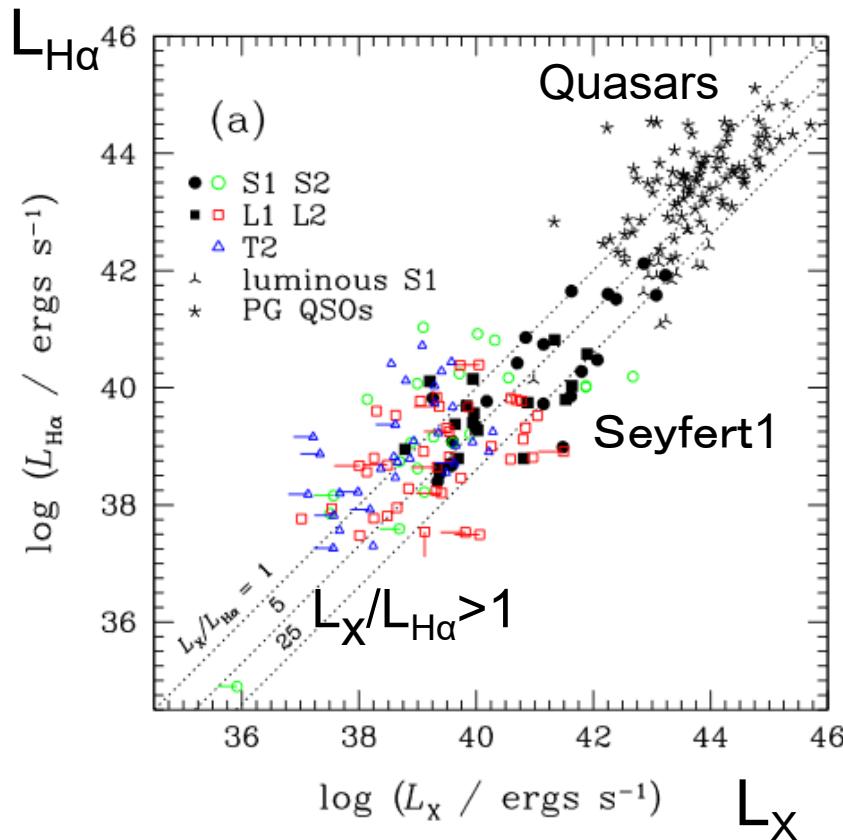


松元亮治、五十嵐太一(千葉大)

高橋博之(中部大)、大須賀健(筑波大)、加藤成晃(理研)

セイファート銀河のX線光度

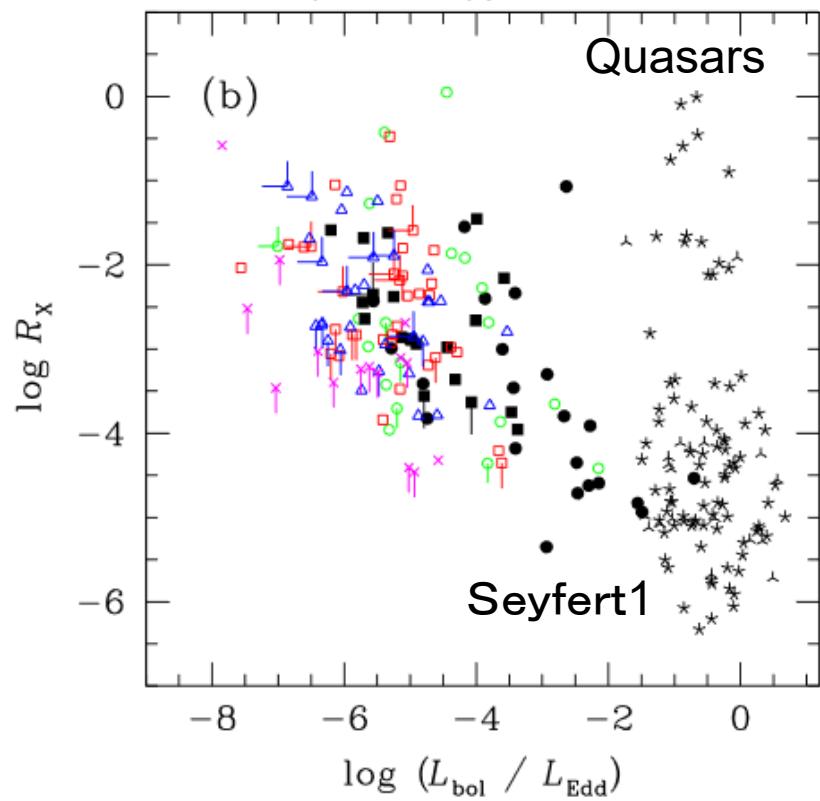
Nuclear Activity in Nearby Galaxies



Quasars and Seyfert
Galaxies are X-ray Bright

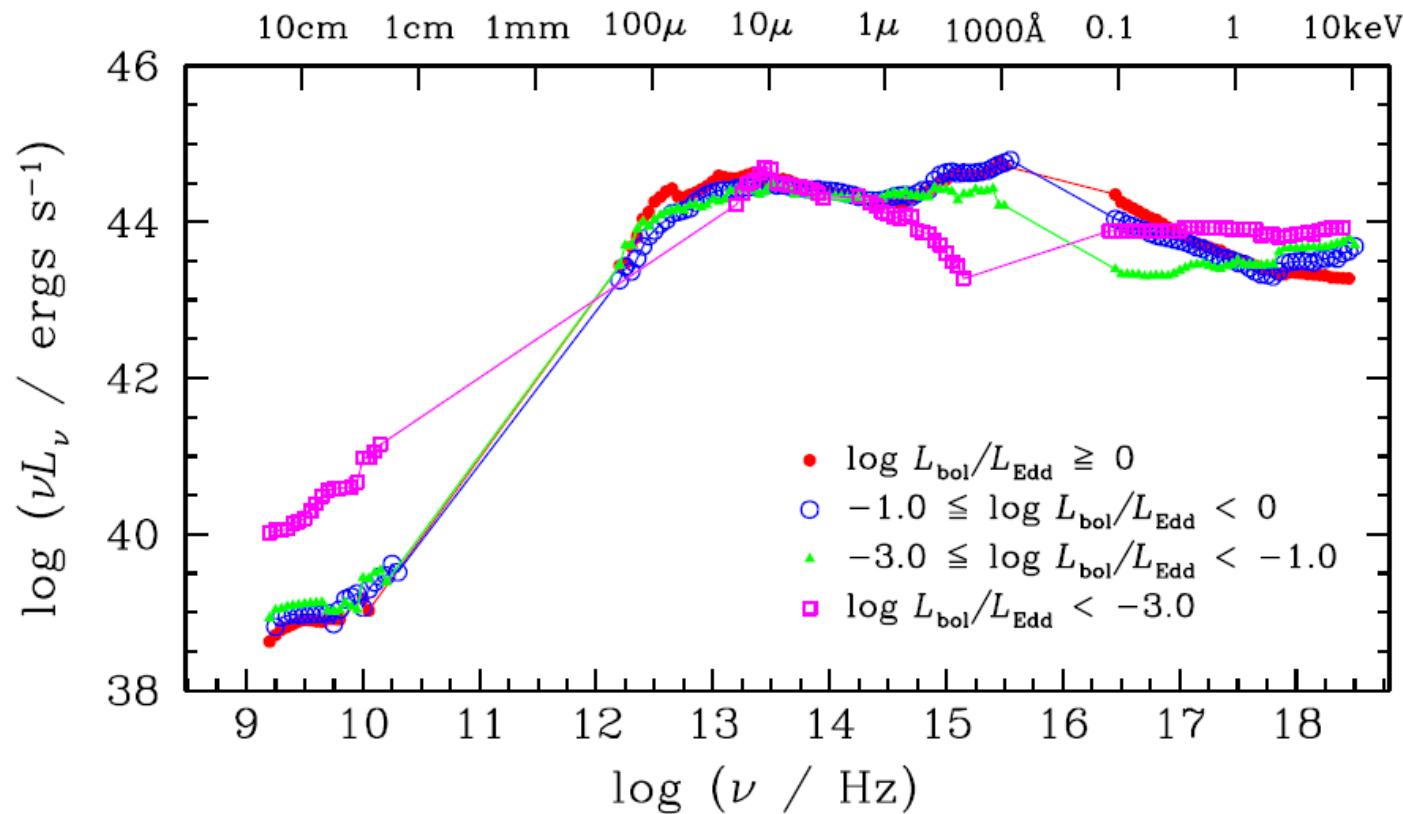
Radio Loudness

$$R_X \equiv \nu L_\nu(5 \text{ GHz})/L_X$$



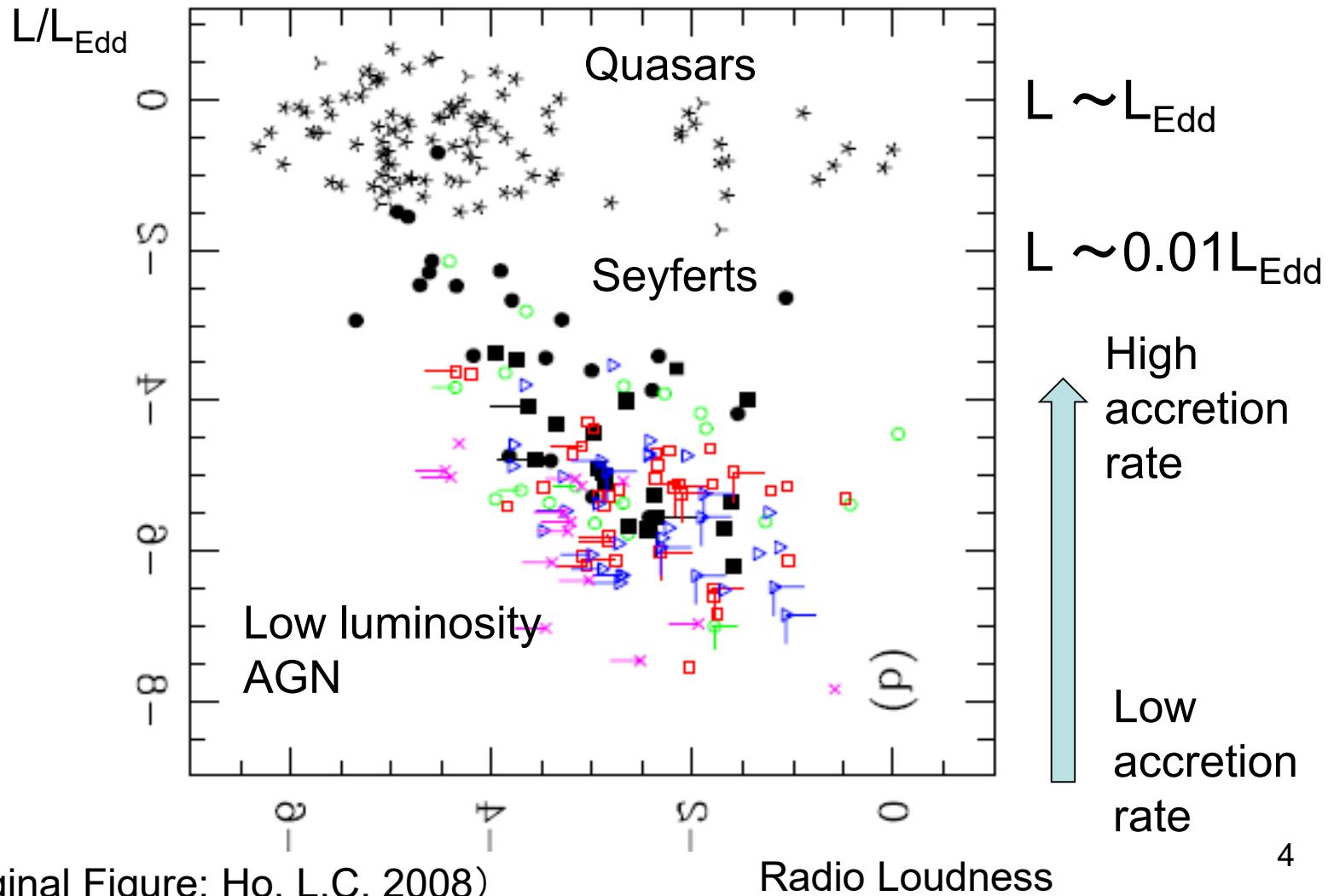
Ho, L.C. (2008) ARAA

1μmで規格化した輻射スペクトル

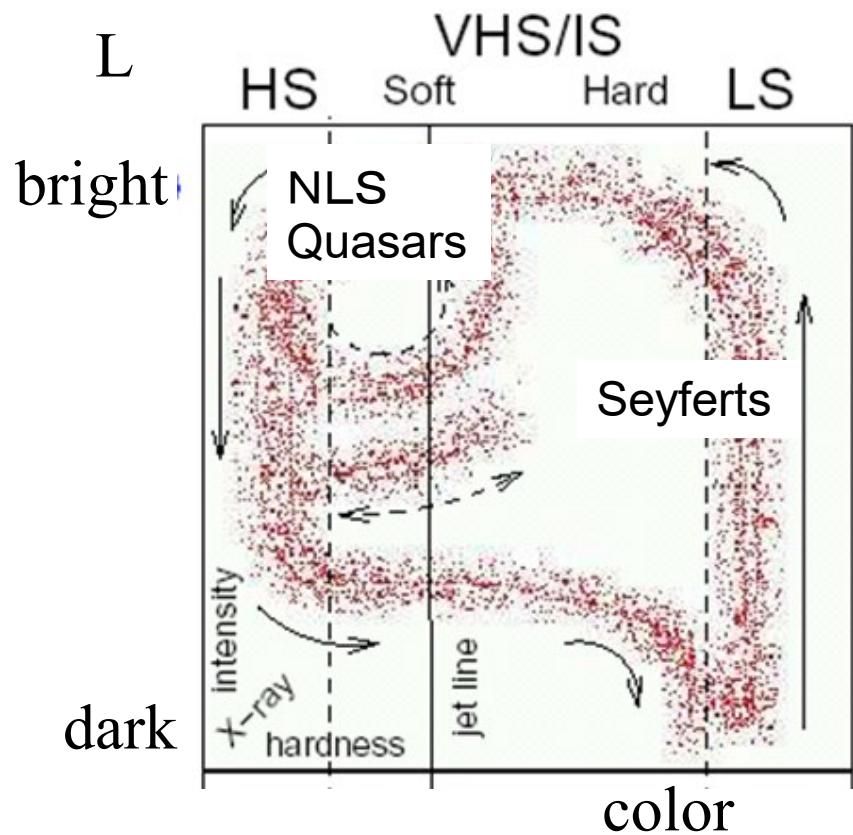


Ho, L.C. (2008) ARAA

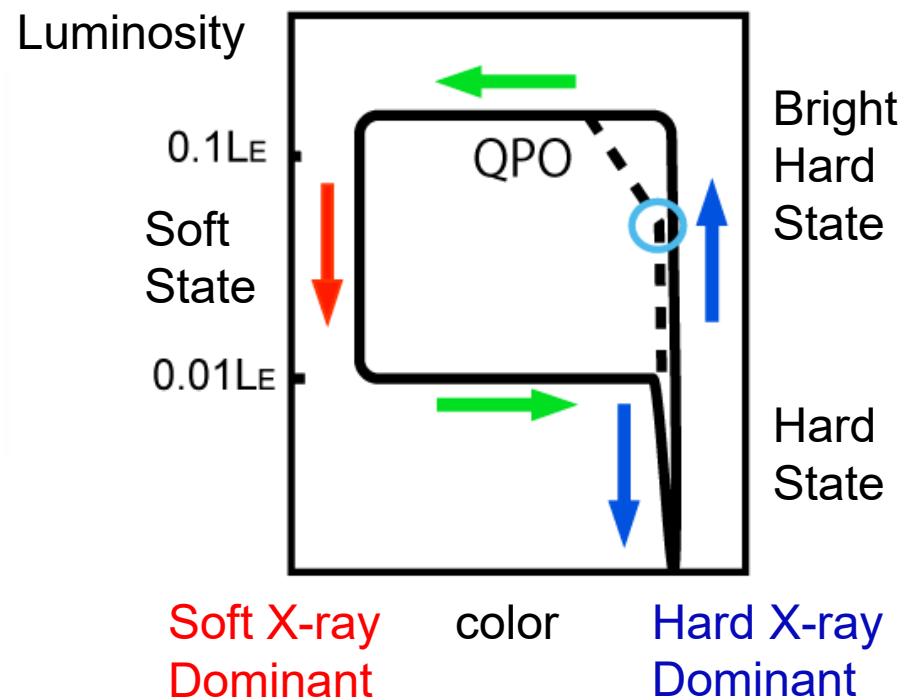
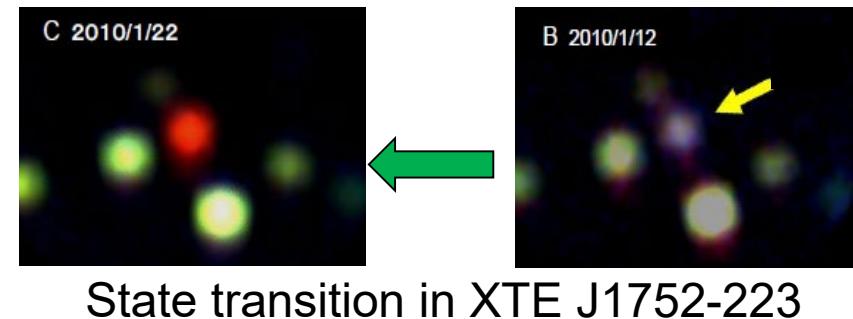
AGNの進化経路？



ブラックホール候補天体の色・光度図



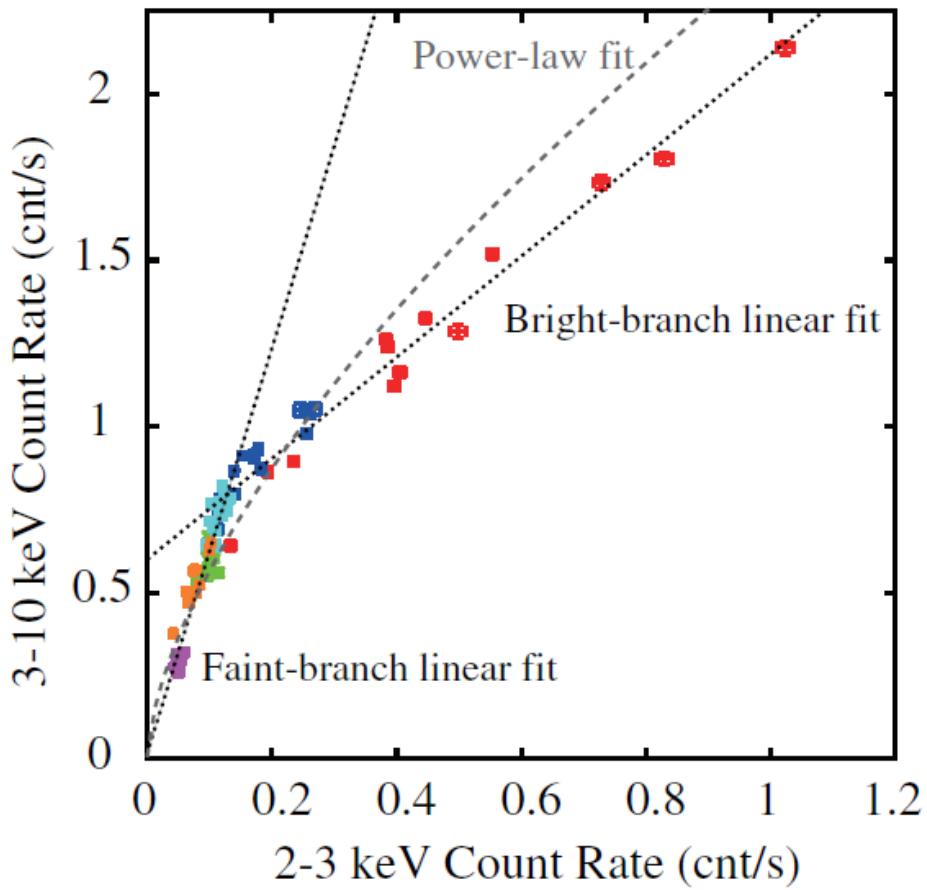
Fender, Belloni, Gallo 2004



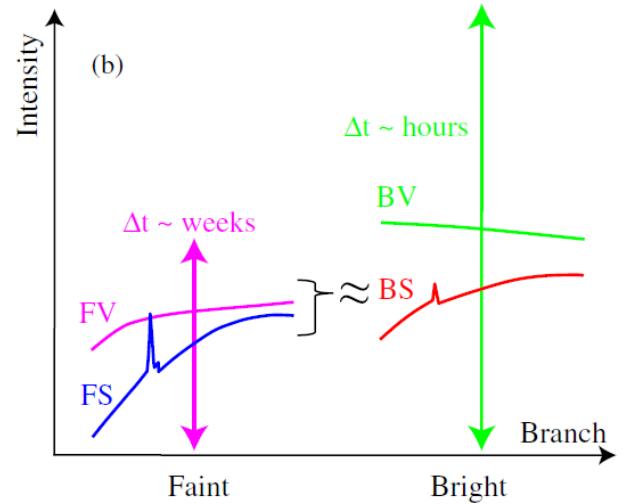
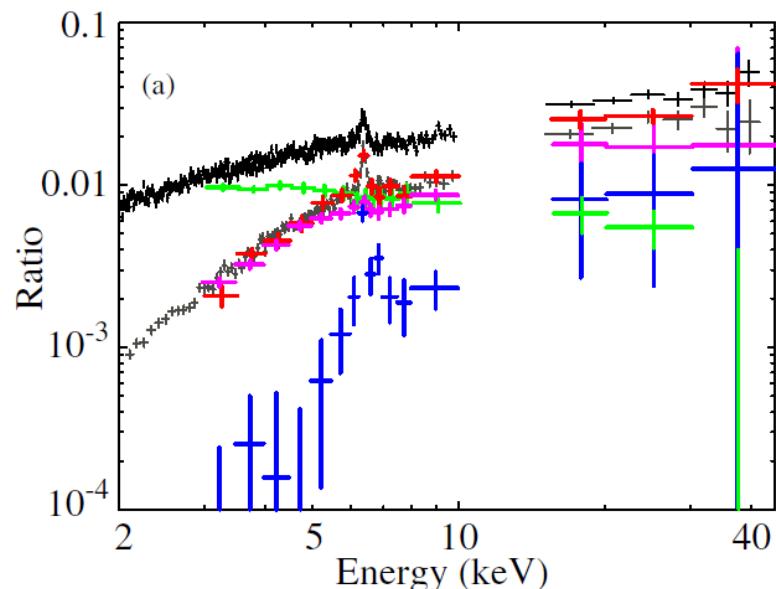
セイファート銀河で観測された 状態遷移

Noda et al. ApJ 794, 2, (2014)

「すざく」衛星によるI型セイファート銀河 NGC3227の観測結果：軟X線超過領域の出現

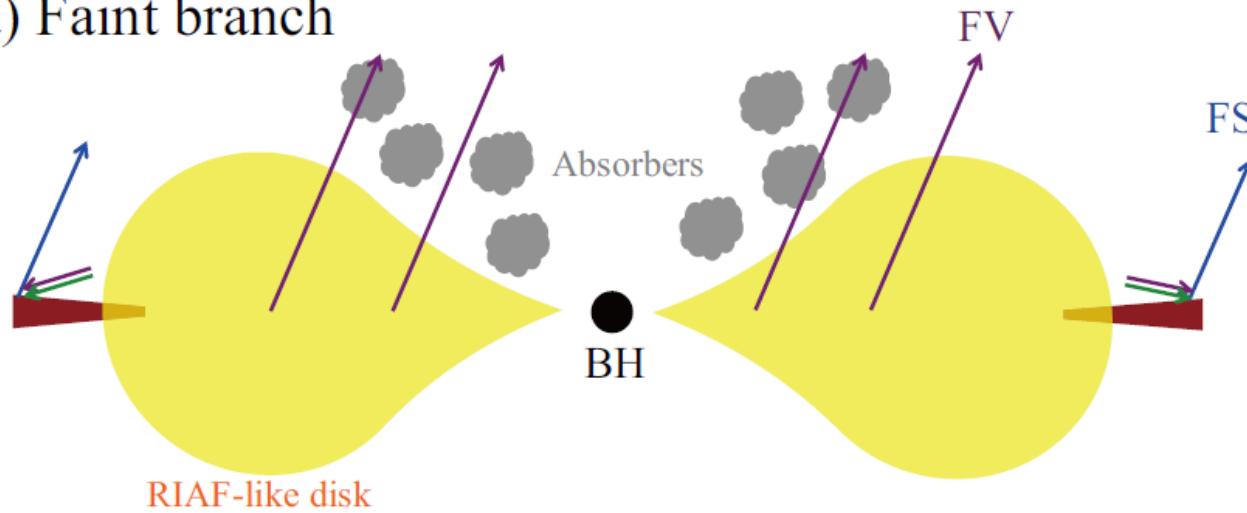


Noda+ 2014

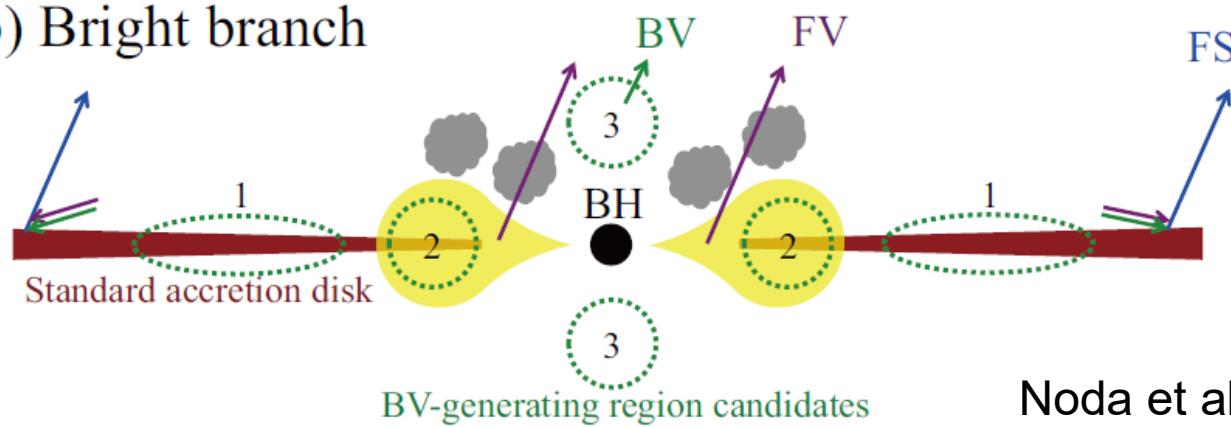


セイファート銀河のエンジンの模式図： 軟X線超過領域はどこにあるか？

(a) Faint branch



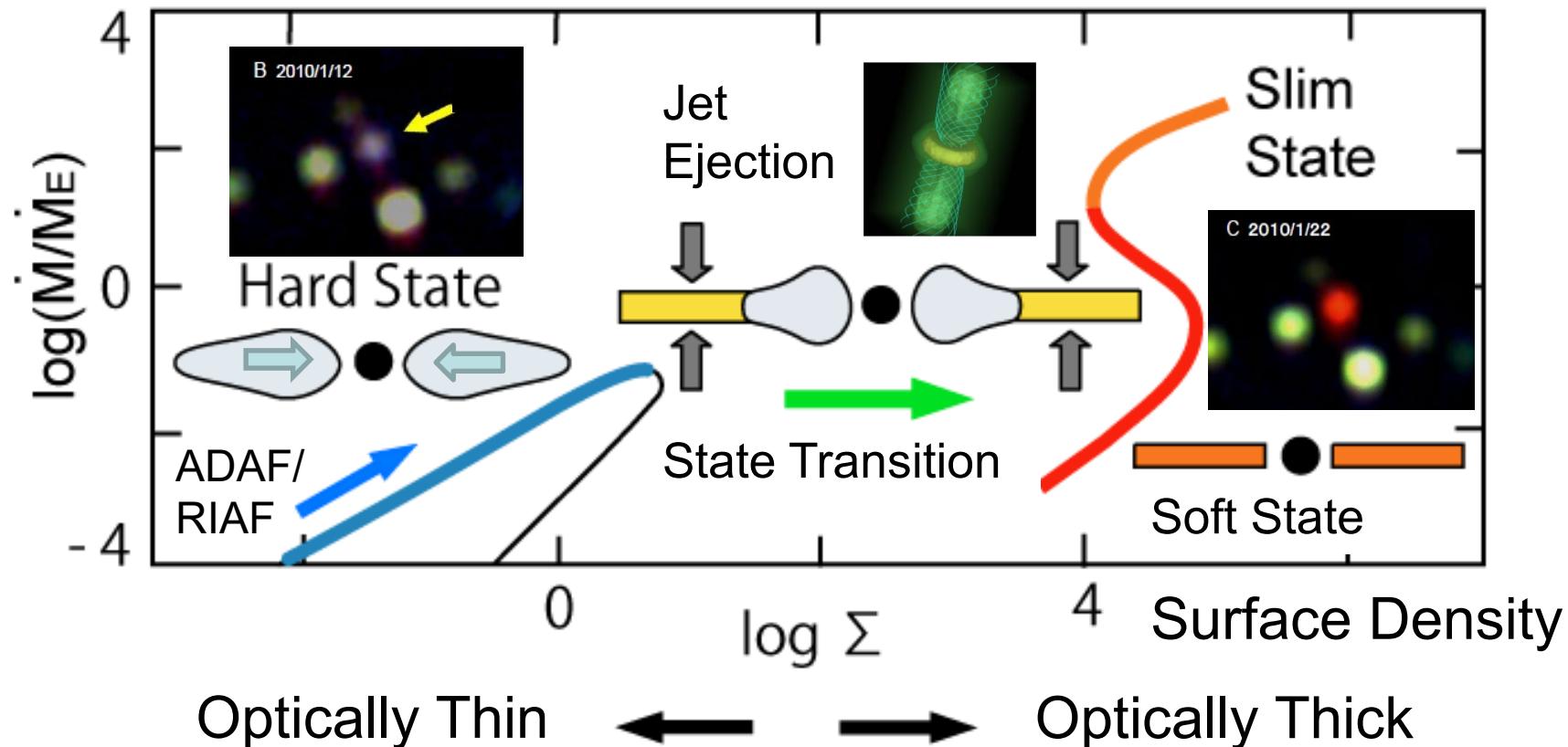
(b) Bright branch



Noda et al. 2014

状態遷移の理論モデル

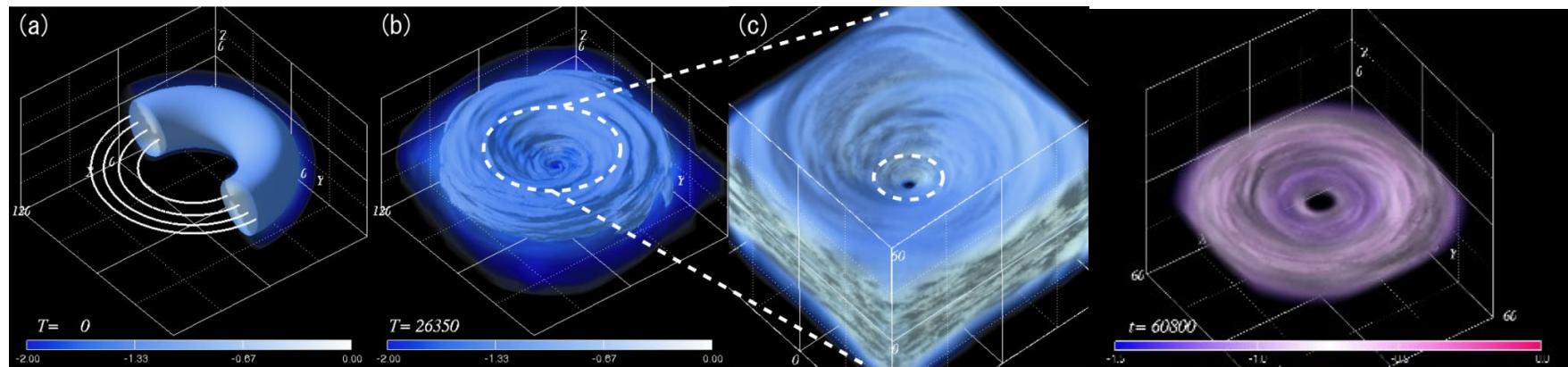
Accretion Rate



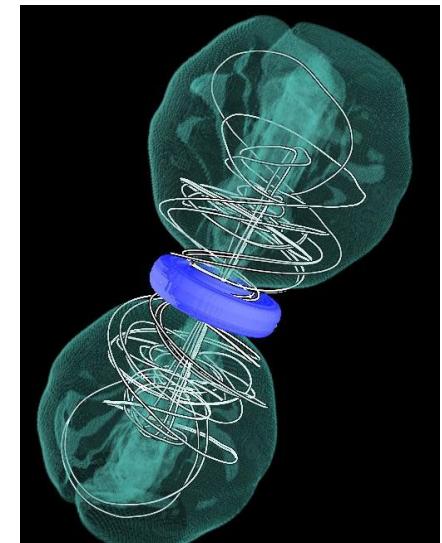
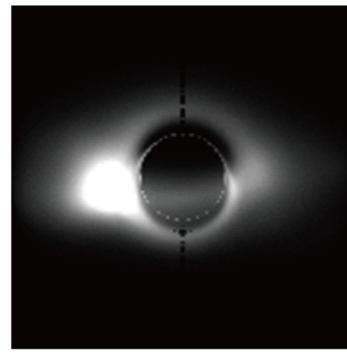
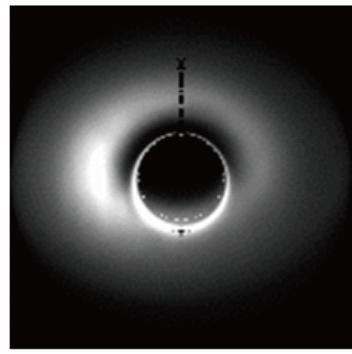
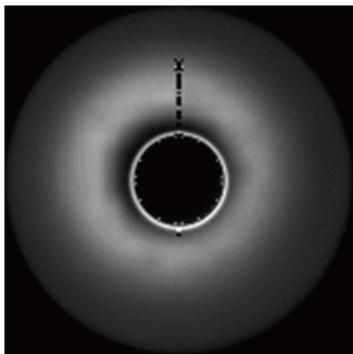
ブラックホール降着流の熱平衡曲線
(Abramowicz et al. 1995)

明るいハードステートの 輻射磁気流体シミュレーション

ブラックホール降着円盤の大局的 3次元磁気流体シミュレーション



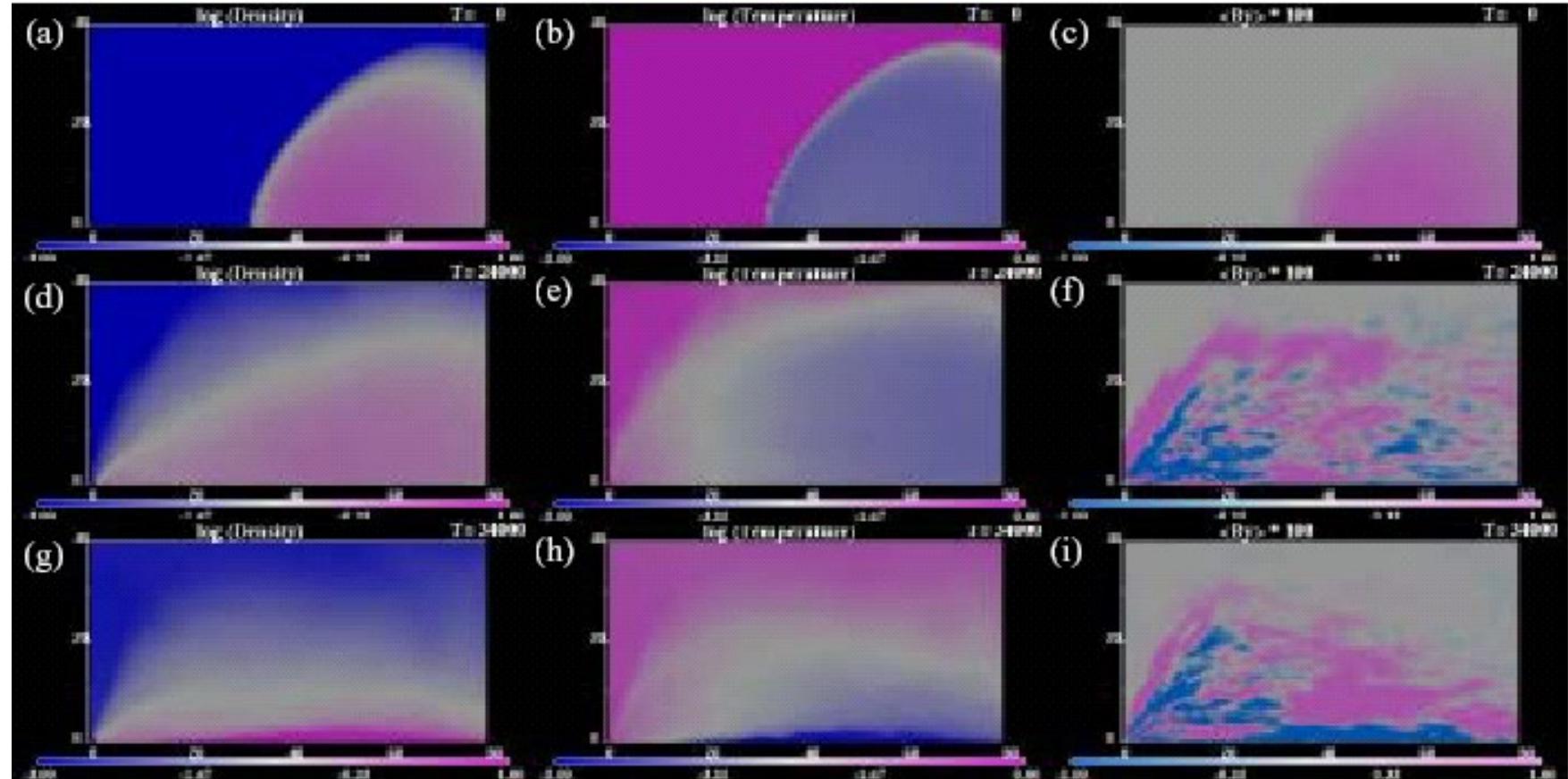
Machida et al. 2003



Machida, M. Bursa

Y.Kato

輻射冷却を考慮した3次元磁気流体計算



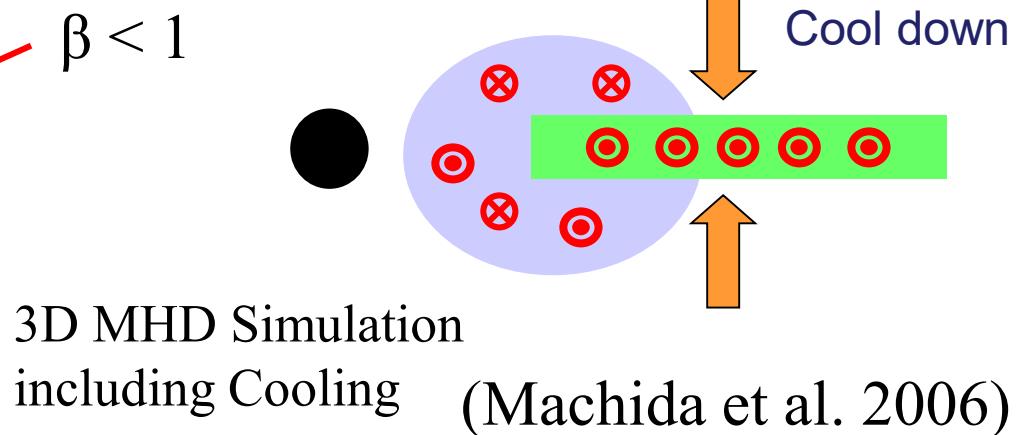
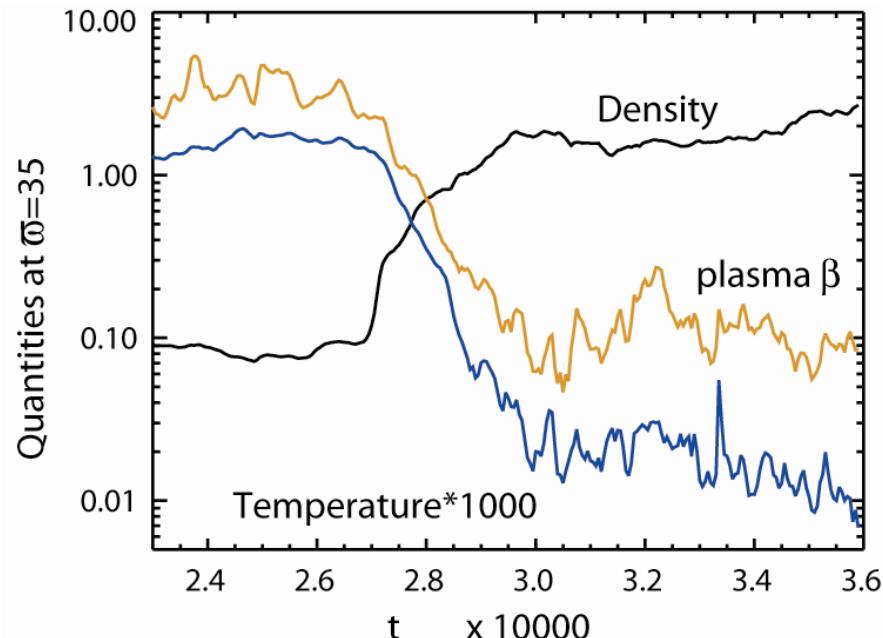
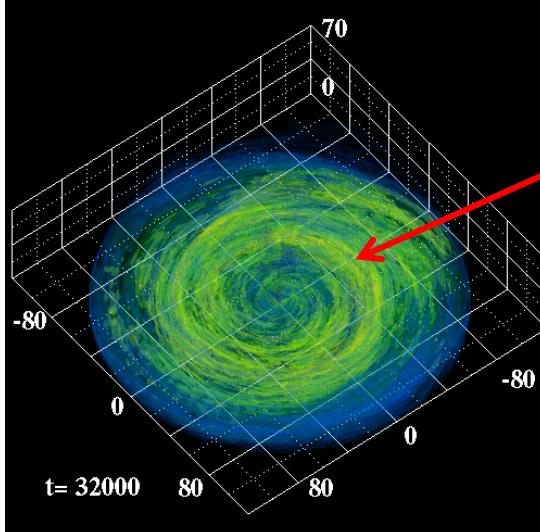
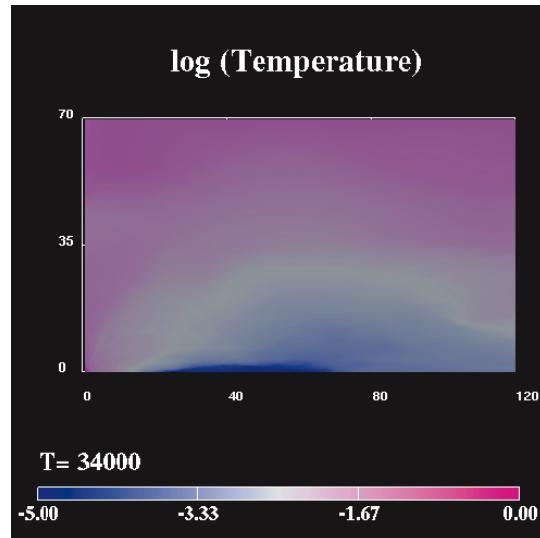
density

temperature

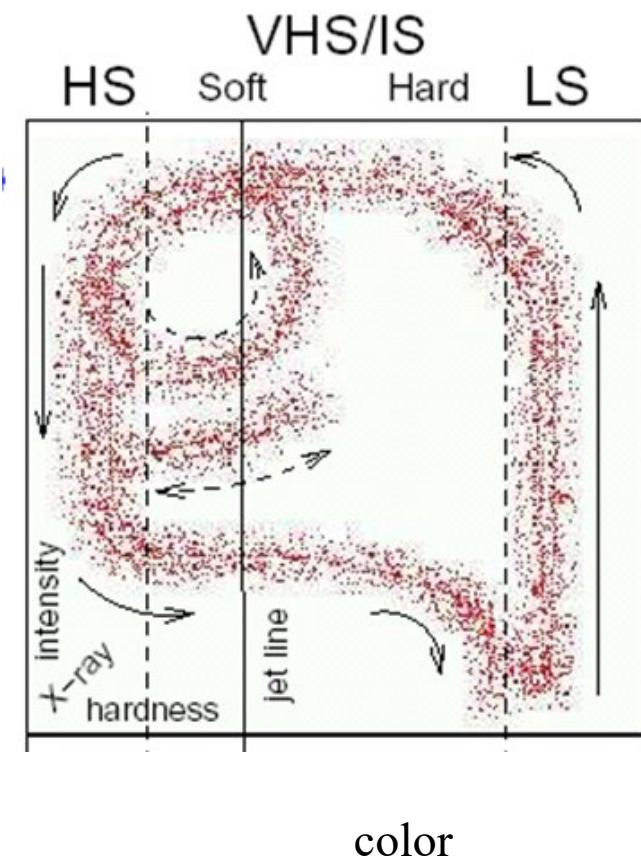
Toroidal field

Machida et al. 2006

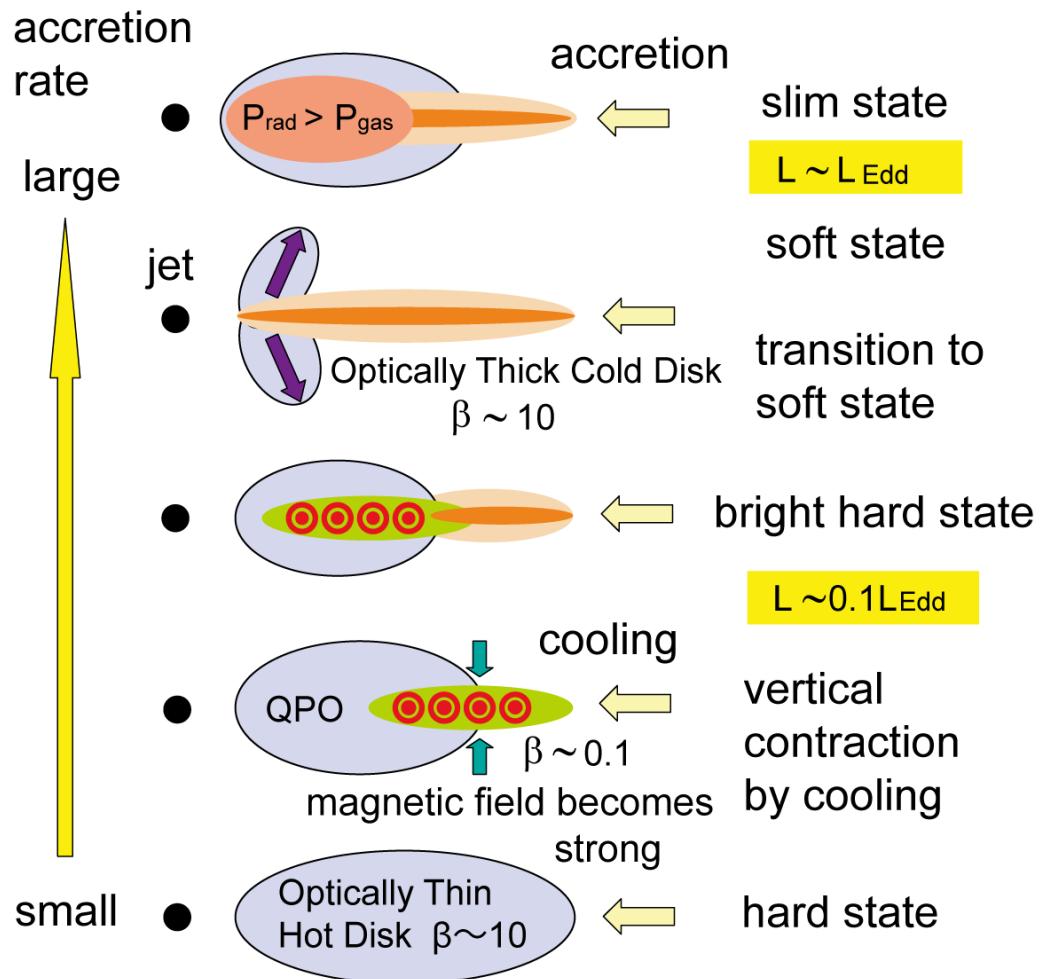
磁気圧で支えられた円盤の形成



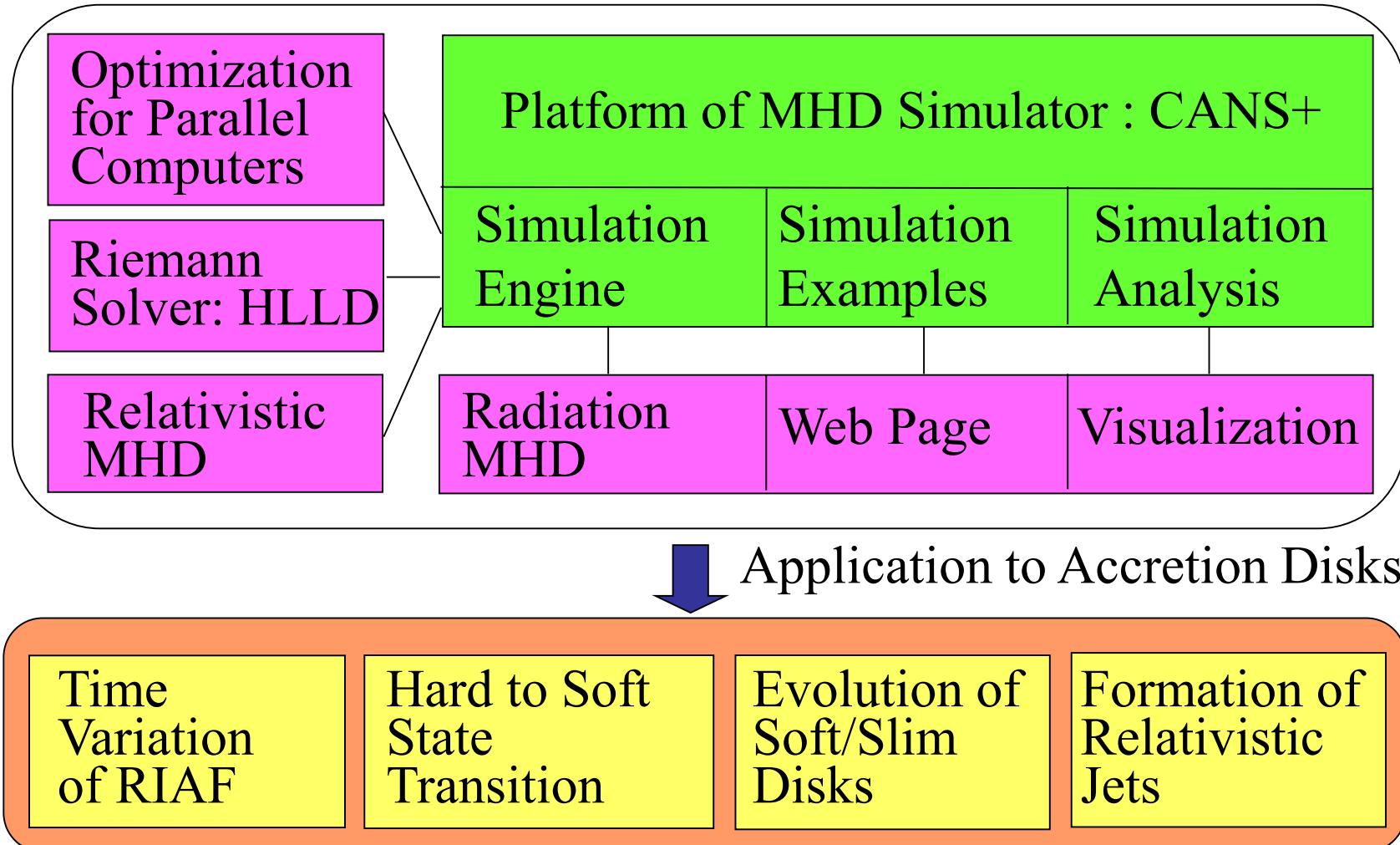
降着率変動に伴うブラックホール降着流の進化



Fender, Belloni, Gallo 2004

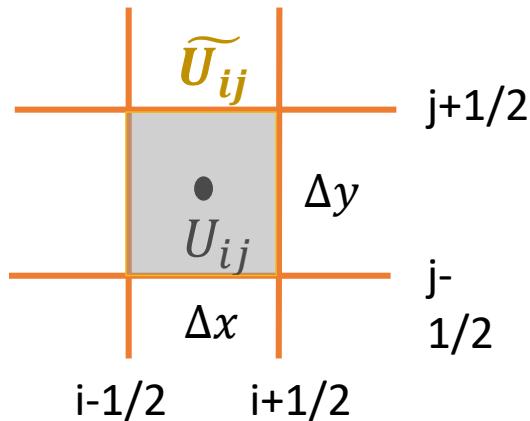


降着円盤シミュレータの改訂



Numerical Scheme adopted in CANS+

Finite Volume Method



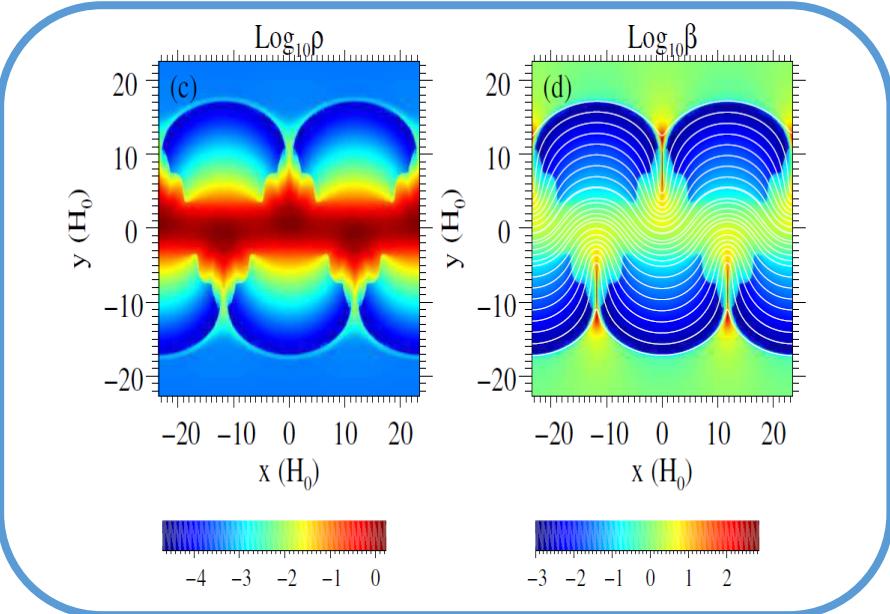
$$\frac{\partial U}{\partial t} = -\frac{\partial F}{\partial x} - \frac{\partial F}{\partial y}$$

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

\widetilde{U}_{ij} : Cell Average F^* : Numerical Flux

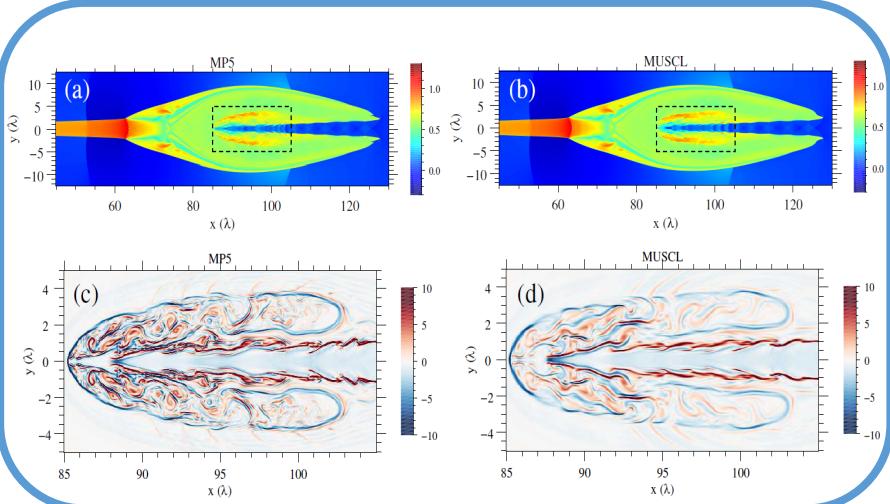
- Numerical Flux F^* is obtained by HLLD approximate Riemann solver (Miyoshi & Kusano 05)
- Higher order MP5 scheme (Suresh & Huynh 97)
- $\text{div } \mathbf{B} = 0$: Hyperbolic cleaning method (Dedner+ 02)

Application of CANS+



Parker Instability

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



Magnetic Reconnection
Can resolve shocks,
discontinuities, and
turbulence

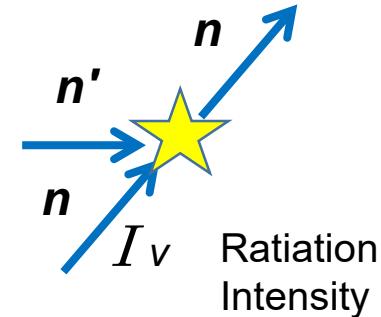
6000×1500 mesh

輻射磁気流体コードCANS+Rへの拡張

Takahashi&Ohsuga (2013,2014)によるM1コードの非相対論版

- Equation of Radiative Transfer

$$\left(\frac{1}{c} \frac{\partial}{\partial t} + \mathbf{n} \cdot \nabla \right) I_\nu(t, \mathbf{r}, \mathbf{n}) = -\sigma_\nu I_\nu(t, \mathbf{r}, \mathbf{n}) \\ + \sigma_\nu S_\nu(t, \mathbf{r}, \mathbf{n}) + \sigma_{\nu,s} \int g(\mathbf{n}, \mathbf{n}') I_\nu(t, \mathbf{r}, \mathbf{n}') d\mathbf{n}'$$



- Moment Equations

$$\frac{\partial E_\nu}{\partial t} + \nabla \cdot \mathbf{F}_\nu = S(E_\nu) \\ \frac{\partial \mathbf{F}_\nu}{\partial t} + c^2 \nabla \cdot \mathbb{P}_\nu = S(\mathbb{P}_\nu)$$

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

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

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

- M1 Closure

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

χ : Eddington Factor

CANS+Rの基礎方程式

Resistive MHD

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

$$\frac{\partial \rho \mathbf{v}}{\partial t} + \nabla \cdot (\rho \mathbf{v} \mathbf{v} - \mathbf{B} \mathbf{B} + P \mathbf{I}) = \rho \nabla \phi_{\text{PN}} - \mathbf{S}(\mathbb{P}_r)$$

$$\frac{\partial E}{\partial t} + \nabla \cdot [(E + P \mathbf{I}) \mathbf{v} - \mathbf{B}(\mathbf{B} \cdot \mathbf{v})] = -\nabla \cdot (\eta \mathbf{j} \times \mathbf{B}) + \rho \mathbf{v} \cdot \nabla \phi_{\text{PN}} - c \mathbf{S}(E_r)$$

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

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

Radiation

$$\frac{1}{c^2} \frac{\partial \mathbf{F}_r}{\partial t} + \nabla \cdot \mathbb{P}_r = \mathbf{S}(\mathbb{P}_r)$$

$$\frac{\partial E_r}{\partial t} + \nabla \cdot \mathbf{F}_r = c \mathbf{S}(E_r)$$

Pseudo-Newtonian potential

$$\phi_{\text{PN}} = -\frac{GM}{R - r_s}$$

Source term

$$\mathbf{S}(\mathbb{P}_r) = \rho \kappa_{\text{ff}} \frac{\mathbf{v}}{c} (a_r T^4 - E_r) - \rho (\kappa_{\text{ff}} + \kappa_{\text{es}}) \frac{1}{c} [\mathbf{F}_r - (\mathbf{v} \mathbf{E}_r + \mathbf{v} \cdot \mathbb{P}_r)]$$

$$S(E_r) = \rho \kappa_{\text{ff}} (a_r T^4 - E_r) + \rho (\kappa_{\text{ff}} - \kappa_{\text{es}}) \frac{\mathbf{v}}{c} \cdot [\mathbf{F}_r - (\mathbf{v} \mathbf{E}_r + \mathbf{v} \cdot \mathbb{P}_r)]$$

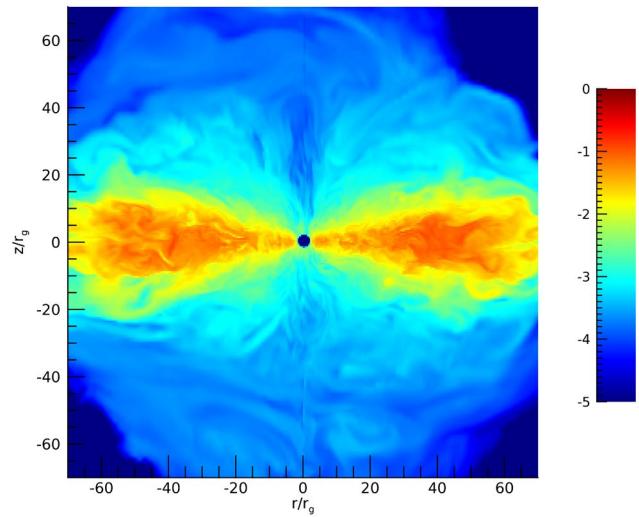
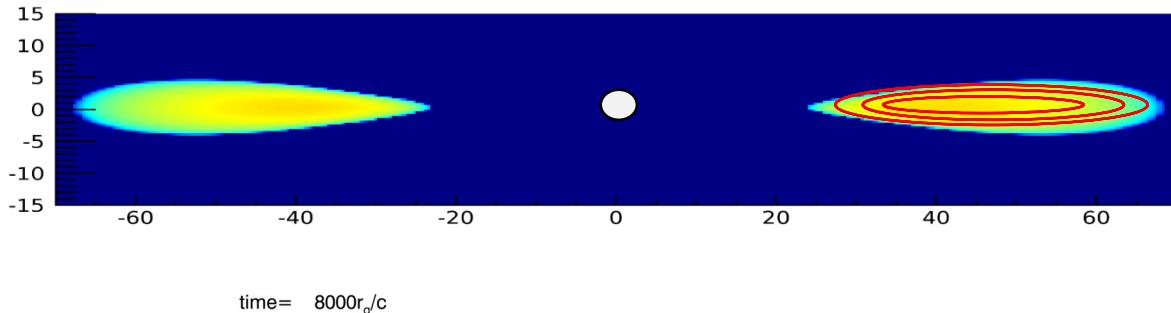
Electron Scattering Opacity

$$\kappa_{\text{es}} = \frac{\sigma_T}{m_p} = 0.4$$

Free-Free Absorption Opacity

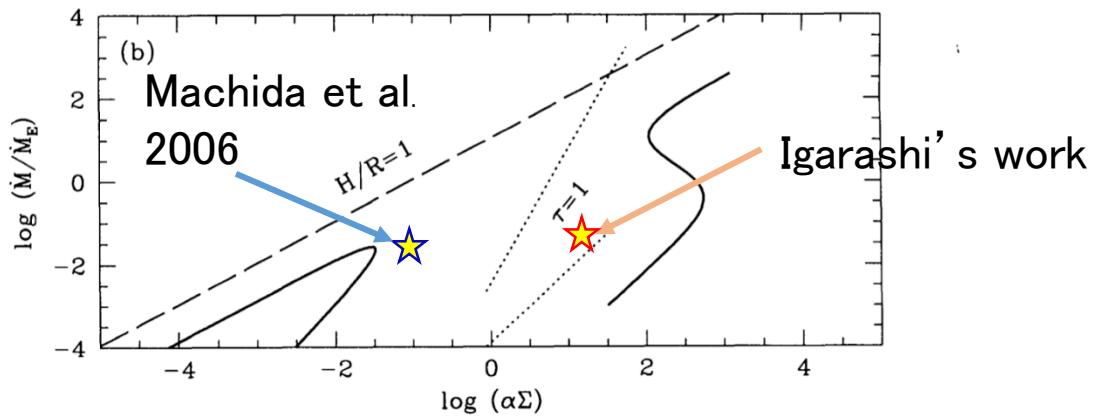
$$\kappa_{\text{ff}} = 1.7 \times 10^{-25} m_p^{-2} \rho T_{\text{gas}}^{-3.5}$$

ブラックホール降着流におけるハード・ソフト 状態遷移シミュレーション: 初期条件



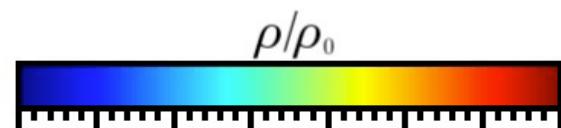
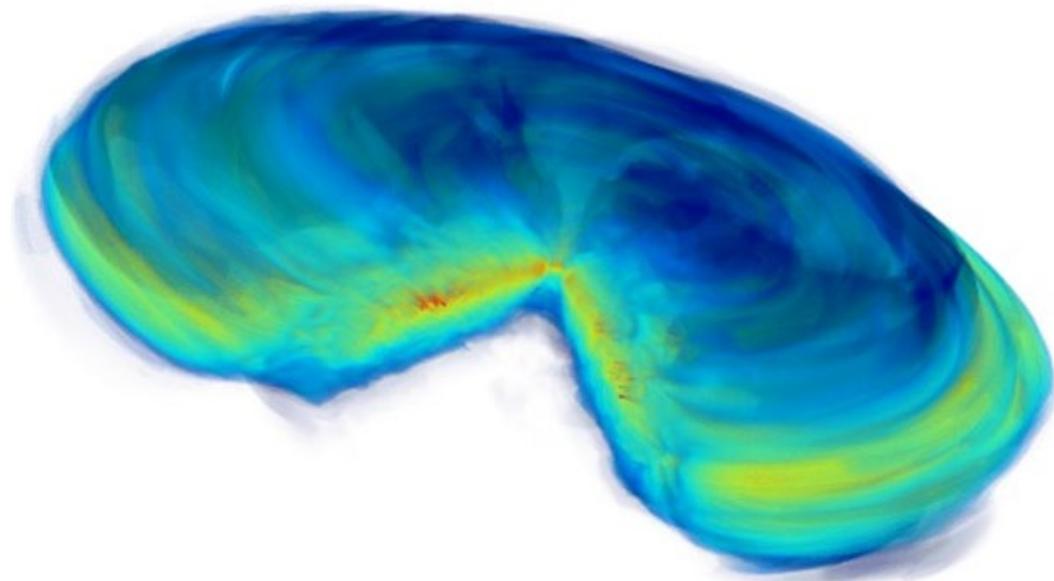
輻射冷却を含めずに準定常な高温
降着流(RIAF)が形成されるまで計算

初期密度分布と磁力線
($\beta = P_{\text{gas}}/P_{\text{mag}} = 10 @ 40r_s$)
円筒座標系
($N_r, N_\varphi, N_z = (401, 32, 411)$)
 $M = 10M_\odot$



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

3次元密度分布の時間発展

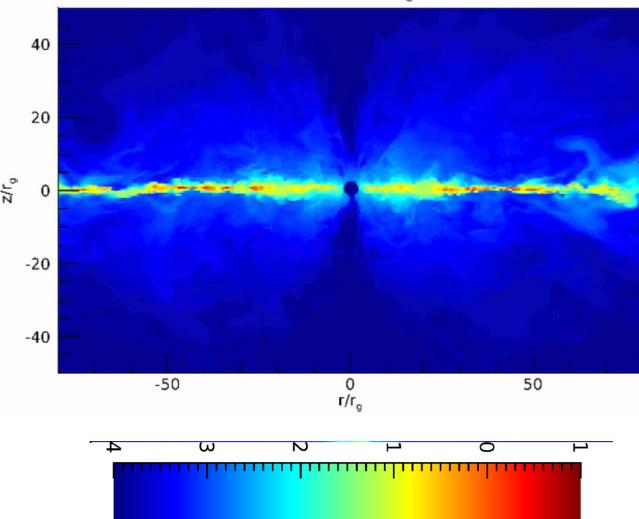


-4.0 -3.5 -3.0 -2.5 -2.0 -1.5 -1.0 -0.5

Snap Shot in r-z plane @ t=2.55s

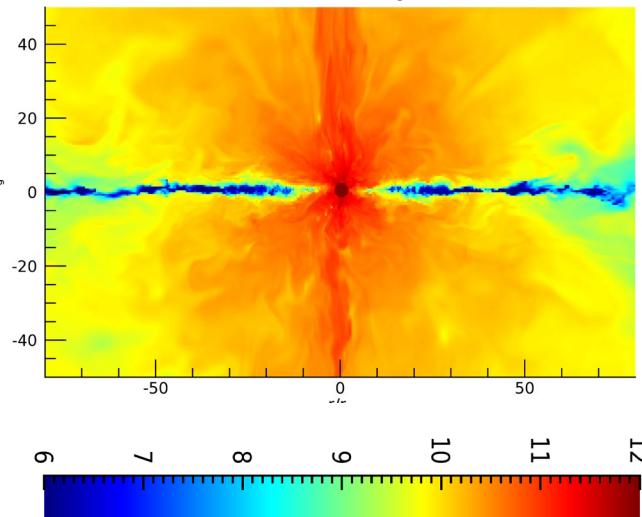
密度

time= 25600 r_g/c



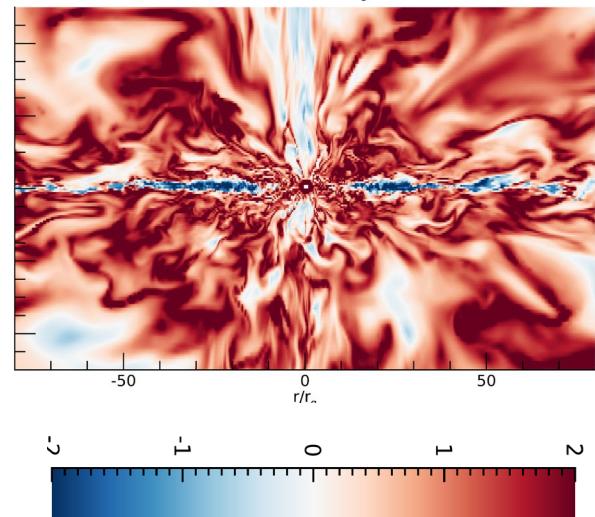
温度

time= 25500 r_g/c



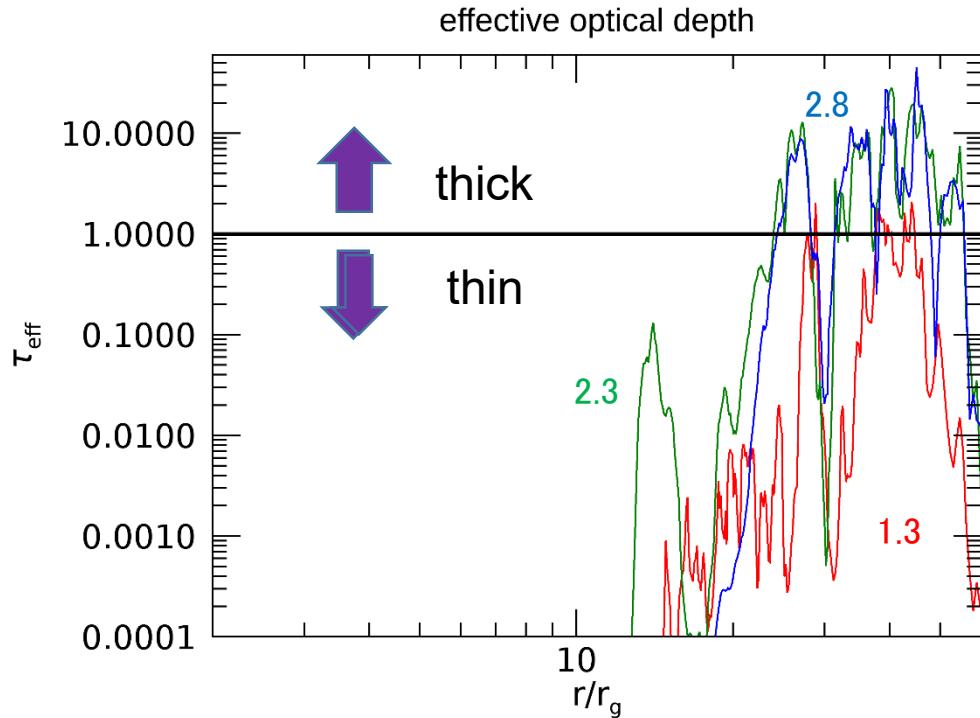
プラズマ β

time= 25500 r_g/c



- ブラックホール近傍($r < 10r_s$): 高温低密度、光学的に薄い、 $\beta \sim 10$
- 遠方($r > 20r_s$): 低温高密度、光学的に厚い $\beta < 1$
- 中間領域 ($10r_s < r < 20r_s$): $\sim 10^8 K$ 、光学的に薄い、 $\beta \sim 0.01$
- 光度 $L \sim 0.1 L_{Edd}$ 明るいハードステートに対応

光学的厚さの分布

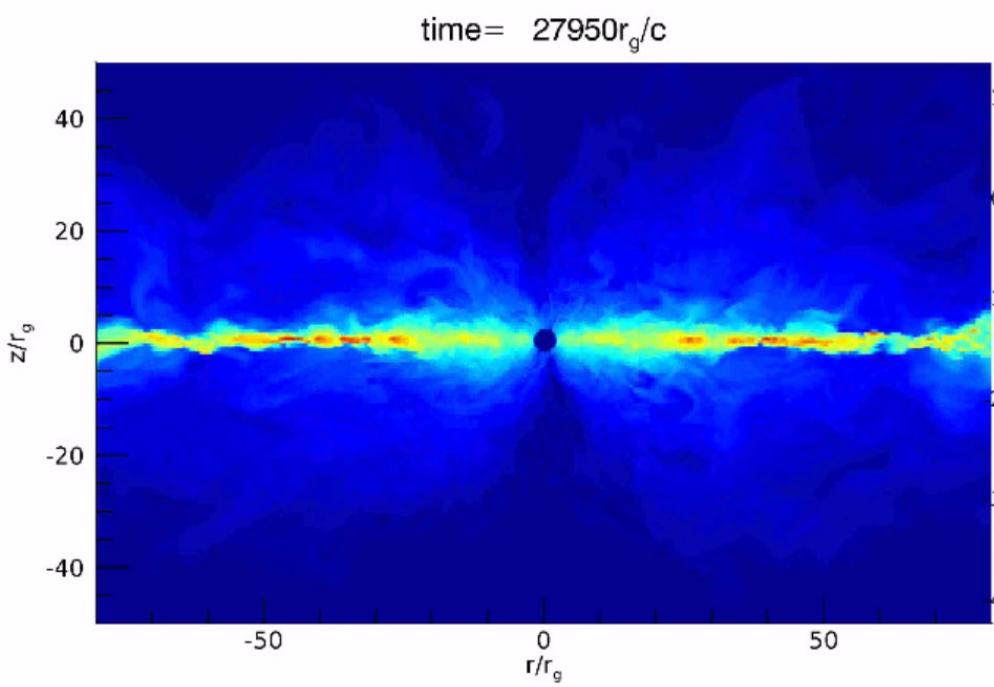


Effective optical depth

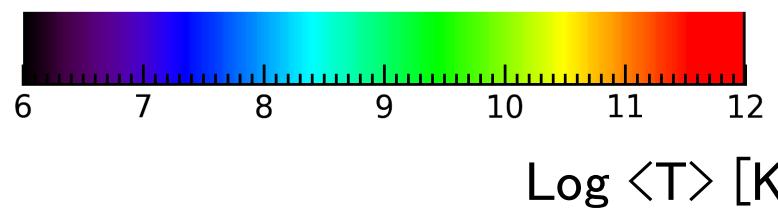
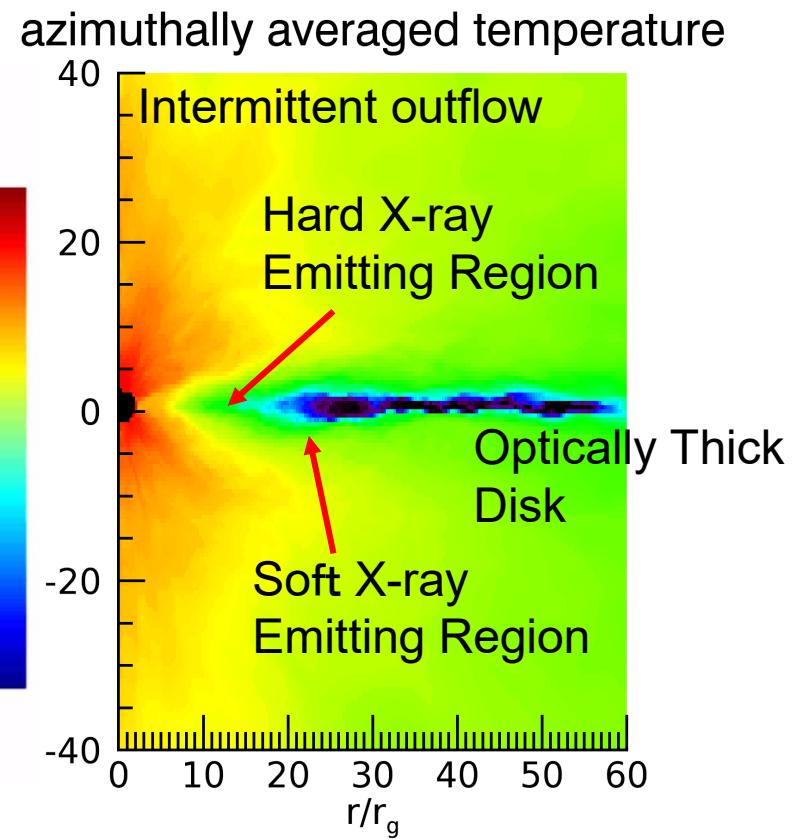
$$\tau_{\text{eff}} = \sqrt{\tau_{\text{abs}}(\tau_{\text{sca}} + \tau_{\text{abs}})}$$
$$\tau = \int_0^{50r_g} \rho \kappa dz$$

- Outer region ($r > 20r_s$) は光学的に厚くなる ($\tau_{\text{eff}} > 1$)
- ブラックホール近傍 ($r < 10r_s$) は光学的に薄い

Numerical Results at 3sec for $10M_{\odot}$ Black Hole



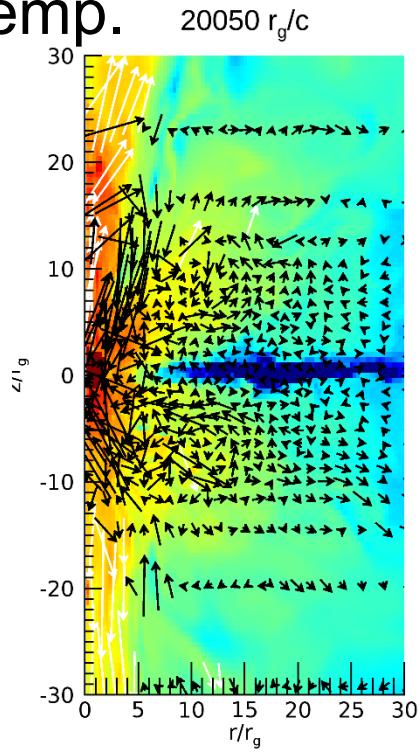
Density Distribution



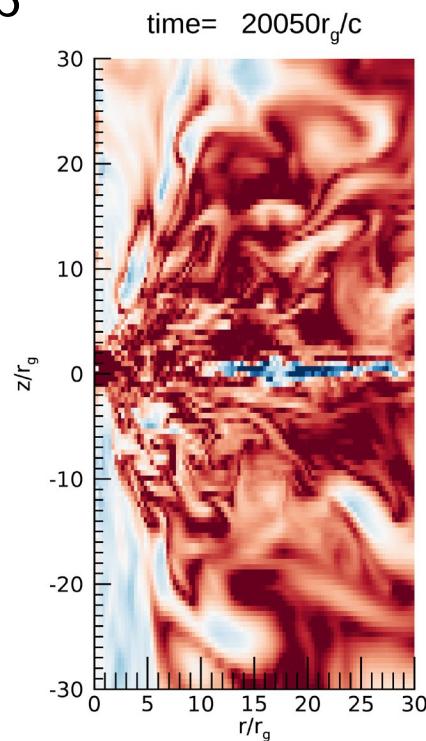
Log $\langle T \rangle$ [K]

ジェットの噴出: Snap shot @2.005 s

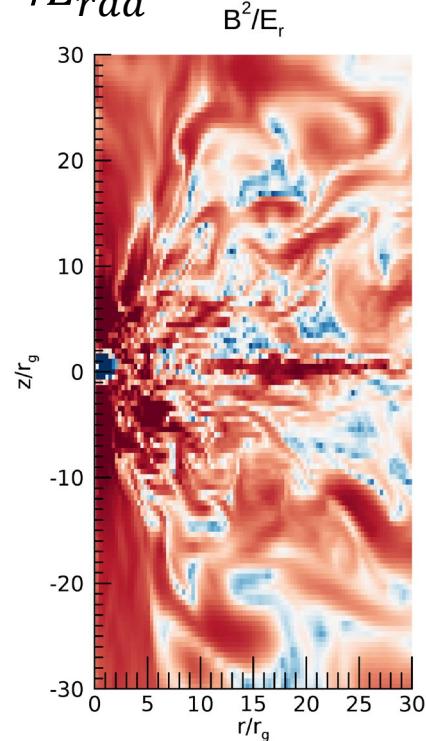
Temp.



β

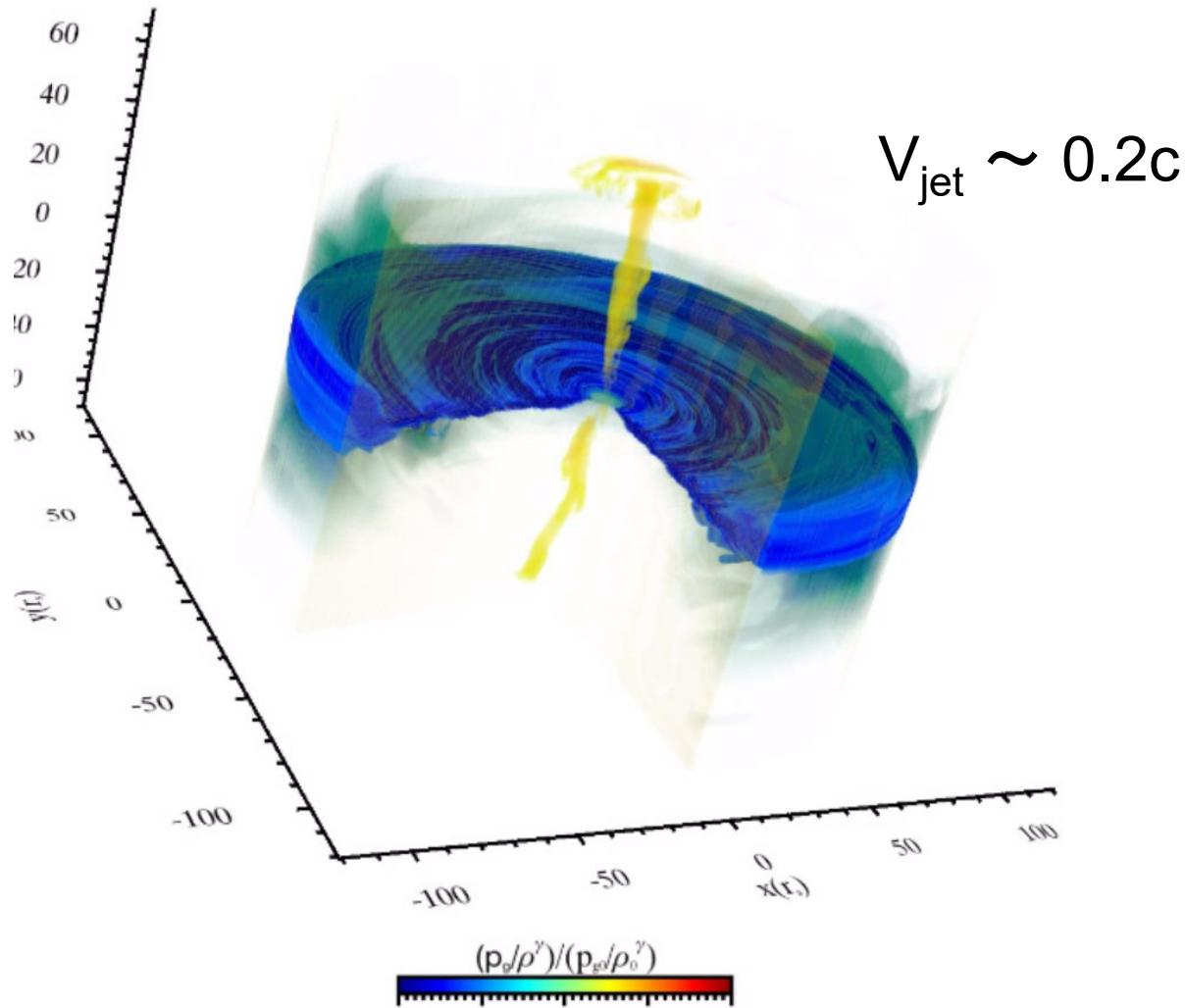


B^2/E_{rad}

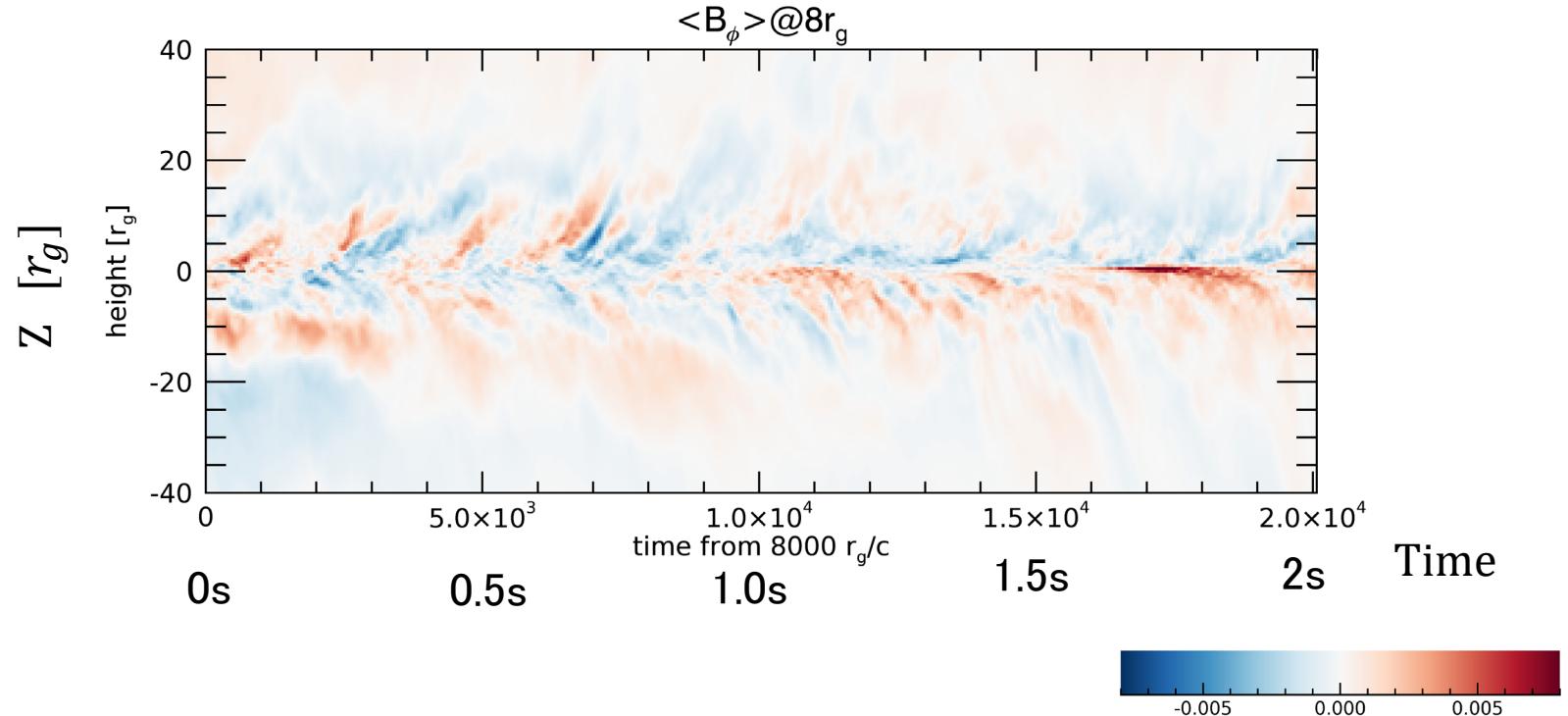


- Subrelativistic jet の噴出: Opening angle : $\theta = 15^\circ$
- 回転軸付近は高温、磁気圧優勢
- 輻射圧はジェット加速には寄与していない

間歇的なジェット噴出

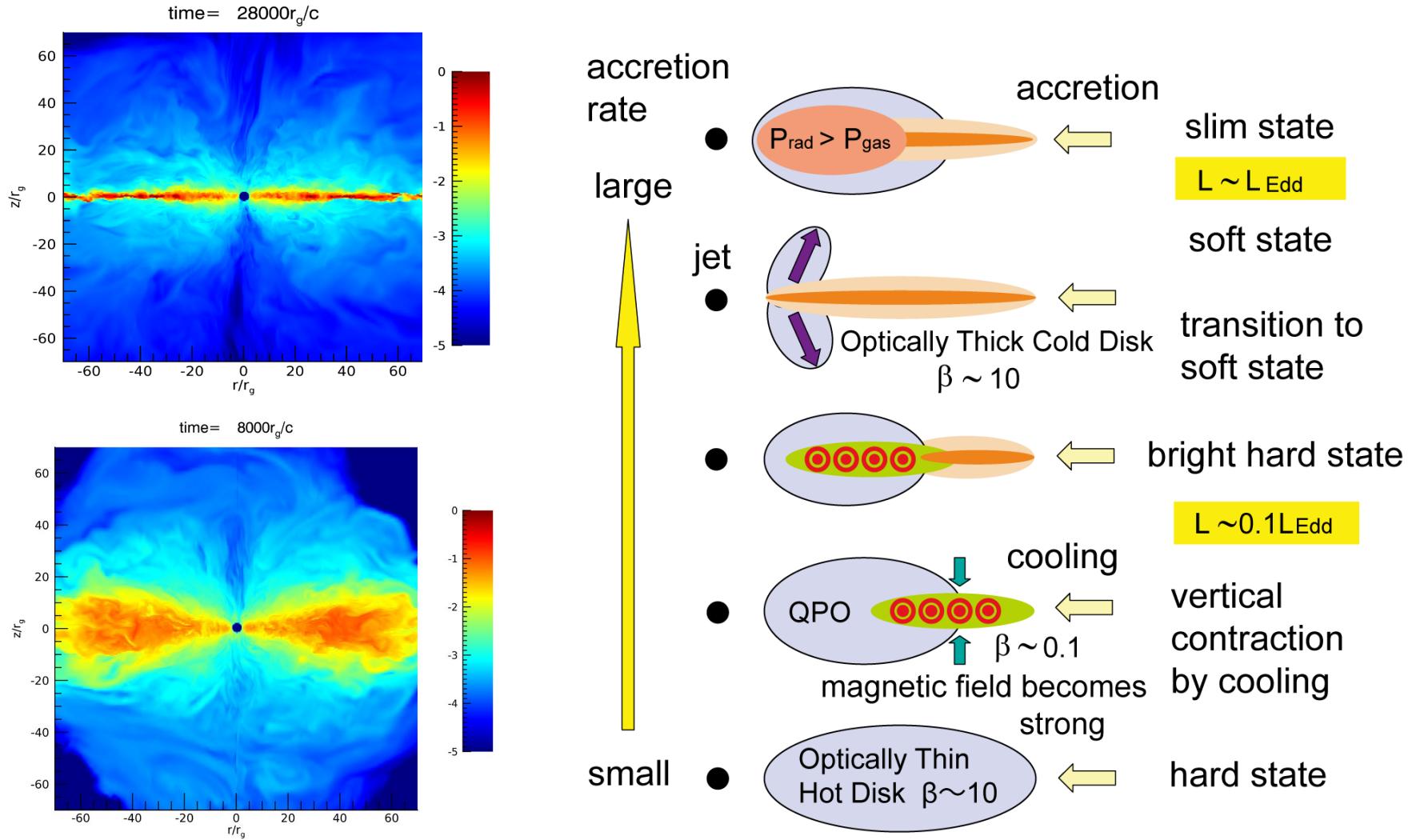


方位角磁場の時間変化: Butterfly Diagram



- $r=8rs$ における方位角磁場
- 3–5Hzの準周期振動
- ハード・ソフト状態遷移中に観測される1–10HzのQPOに対応？

ブラックホール降着流の時間変化



まとめ

- ・セイファート銀河のエンジンは巨大ブラックホールへのサブエディントン降着と考えられる
- ・セイファート銀河中心ブラックホールへの降着率がRIAFの上限以上になると激しく時間変動する軟X線放射領域が形成される
- ・この軟X超過領域は明るいハードステート円盤と考えられる
- ・非相対論的な輻射磁気流体コードCANS+Rを適用することにより、明るいハードステート円盤の輻射磁気流体シミュレーションを行った
- ・明るいハードステートではブラックホール近傍の光学的に薄い高温円盤と遠方の光学的に厚い円盤、その中間の磁気圧で支えられた円盤が共存する
- ・中心天体が超大質量ブラックホールの計算を実施予定

END