Black hole accretion

Feng Yuan (袁　峰）

Shanghai Astronomical Observatory
Chinese Academy of Sciences

Outline

- Chapter 1: Introduction to some basic concepts of accretion and Review of accretion models
- Chapter 2: The standard thin disk and slim disk
- Chapter 3: Hot accretion flow: dynamics & radiation
- Chapter 4: Hot accretion flow: applications
- Chapter 5: Formation of outflow and jet
- Chapter 6: AGN interaction with ISM

Chapter 3:
Hot accretion flow: dynamics and radition

3.1 One-dimensional dynamics

One-dimensional equations

One-T:

$$\frac{d}{dR}(\rho R H v) = 0,$$

$$v\frac{dv}{dR} - \Omega^2 R = -\Omega_K^2 R - \frac{1}{\rho}\frac{d}{dR}(\rho c_s^2),$$

$$v\,\frac{d(\Omega R^2)}{dR} = \frac{1}{\rho R H}\frac{d}{dR}\left(\nu\rho R^3 H\frac{d\Omega}{dR}\right)$$

$$\rho v\left(\frac{de}{dR} - \frac{p}{\rho^2}\frac{d\rho}{dR}\right) = \rho\nu R^2\left(\frac{d\Omega}{dR}\right)^2 - q^-,$$

Two-T:

$$q^{\rm adv,i} \equiv \rho v\left(\frac{de_i}{dR} - \frac{p_i}{\rho^2}\frac{d\rho}{dR}\right) \equiv \rho v\frac{de_i}{dR} - q^{i,c} = (1-\delta)q^+ - q^{\rm ie},$$

$$q^{\rm adv,e} \equiv \rho v\left(\frac{de_e}{dR} - \frac{p_e}{\rho^2}\frac{d\rho}{dR}\right) \equiv \rho v\frac{de_e}{dR} - q^{e,c} = \delta q^+ + q^{\rm ie} - q^-.$$

Self-similar solution

Narayan & Yi 1994;1995; Yuan, Bu & Wu (2012)

Assuming power-law scaling with radius for physical quantities:

$$v \simeq -1.1 \times 10^{10}\, \alpha r^{-1/2} \quad \mathrm{cm\ s^{-1}},$$

$$\Omega \simeq 2.9 \times 10^{4}\, m^{-1} r^{-3/2} \quad \mathrm{s},$$

$$c_s^2 \simeq 1.4 \times 10^{20}\, r^{-1} \quad \mathrm{cm^2\ s^{-2}},$$

$$n_e \simeq 6.3 \times 10^{19}\, \alpha^{-1} m^{-1} \dot{m}\, r^{-3/2} \quad \mathrm{cm^{-3}},$$

$$B \simeq 7.8 \times 10^{8}\, \alpha^{-1/2} m^{-1/2} \dot{m}^{1/2} r^{-5/4} \quad \mathrm{G},$$

$$p \simeq 1.7 \times 10^{16}\, \alpha^{-1} m^{-1} \dot{m}\, r^{-5/2} \quad \mathrm{g\ cm^{-1}\ s^{-2}},$$

$$q^{+} \simeq 5.0 \times 10^{21}\, m^{-2} \dot{m}\, r^{-4} \quad \mathrm{ergs\ cm^{-3}\ s^{-1}},$$

$$\tau_{\mathrm{es}} \simeq 24\, \alpha^{-1} \dot{m}\, r^{-1/2},$$

Main features

- Large radial velocity:

$$v_r \sim \frac{\alpha c_s H}{R}$$

- Sub-Keplerian rotation: pressure-gradient support
- High temperature: $T \sim \frac{GMm_p}{6kR} \sim \frac{10^{12}}{r}$ (virial, why?)
- Geometrically thick: $(H = \frac{c_s}{\Omega_k} \sim R)$
- Optically thin (because of large radial velocity)
- Two-temperature: $T_i \gg T_e$
  - coupling between ions and electrons not strong enough
  - plasma collective behavior also too weak

Radiative efficiency is low when $\dot{M}$ is small

- outflow
- The energy equation of the accretion flow:

$$\rho \upsilon T \frac{ds}{dr} \equiv q_{adv} = q^{+} - q^{-}$$

- For the standard thin disk, we have,

$$q^{+} \approx q^{-} >> q_{adv}$$

- For ADAFs, we have,

$$q^{+} \approx q_{adv} >> q^{-}$$

- physics:
  - the density of the accretion flow is very low so: radiation timescale >> accretion timescale.
  - So most of the viscously dissipated energy is stored in the accretion flow and advected in to the black hole rather than radiated away.

The critical accretion rate of ADAF

- With the increasing of $\dot{M}$, cooling increases faster than the viscous dissipation and advection
- So there exists a critical accretion rate of ADAF, determined by

$$q^+ = q^- \rightarrow \dot{M}_{crit,ADAF} \sim \alpha^2 \dot{M}_{Edd}$$

What will happen when $\dot{M} > \dot{M}_{crit,ADAF}$?

Extension of ADAF to higher $\dot{M}$: LHAFs

Yuan 2001, MNRAS

The energy equation of accretion flow:

$$\rho \upsilon T_i \frac{ds_i}{dr} \equiv q_{adv,i} = q^+ - q_{ie}$$

$$q_{adv} \equiv \rho \upsilon T_i \frac{ds_i}{dr} \equiv \rho \upsilon \frac{d\varepsilon_i}{dr} - q^c$$

So we have:

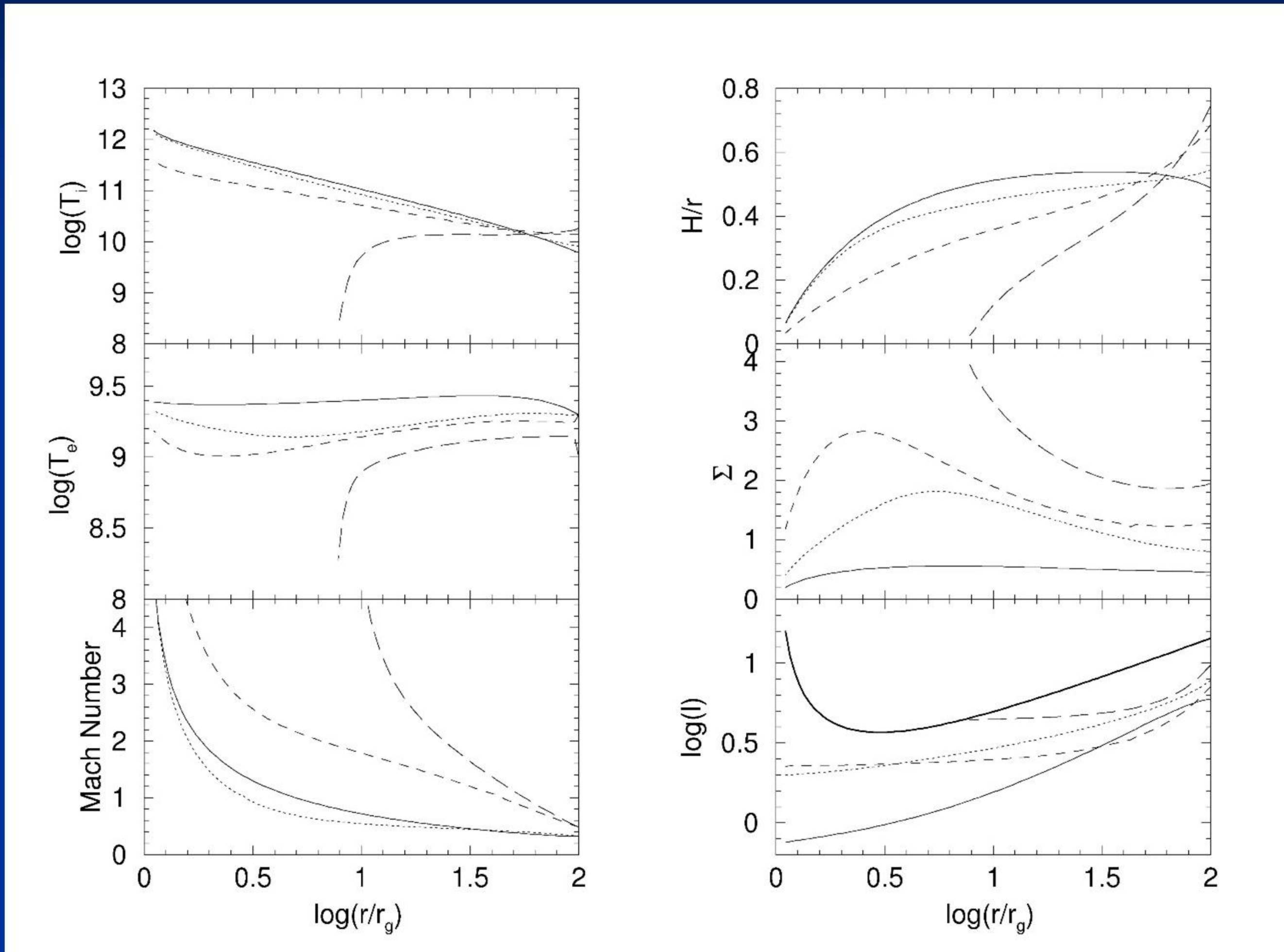
$$\rho \upsilon \frac{d\varepsilon_i}{dr} = q^+ + q^c - q_{ie}$$

So there exists another critical rate $\dot{M}_{crit,LHAF}$, determined by:

$$q^+ + q^c = q_{ie} \rightarrow \dot{M}_{crit,LHAF} \sim 0.6\, \alpha \dot{M}_{Edd}$$

Below $\dot{M}_{crit,LHAF}$, the solution is called LHAF, in which advection is a heating term

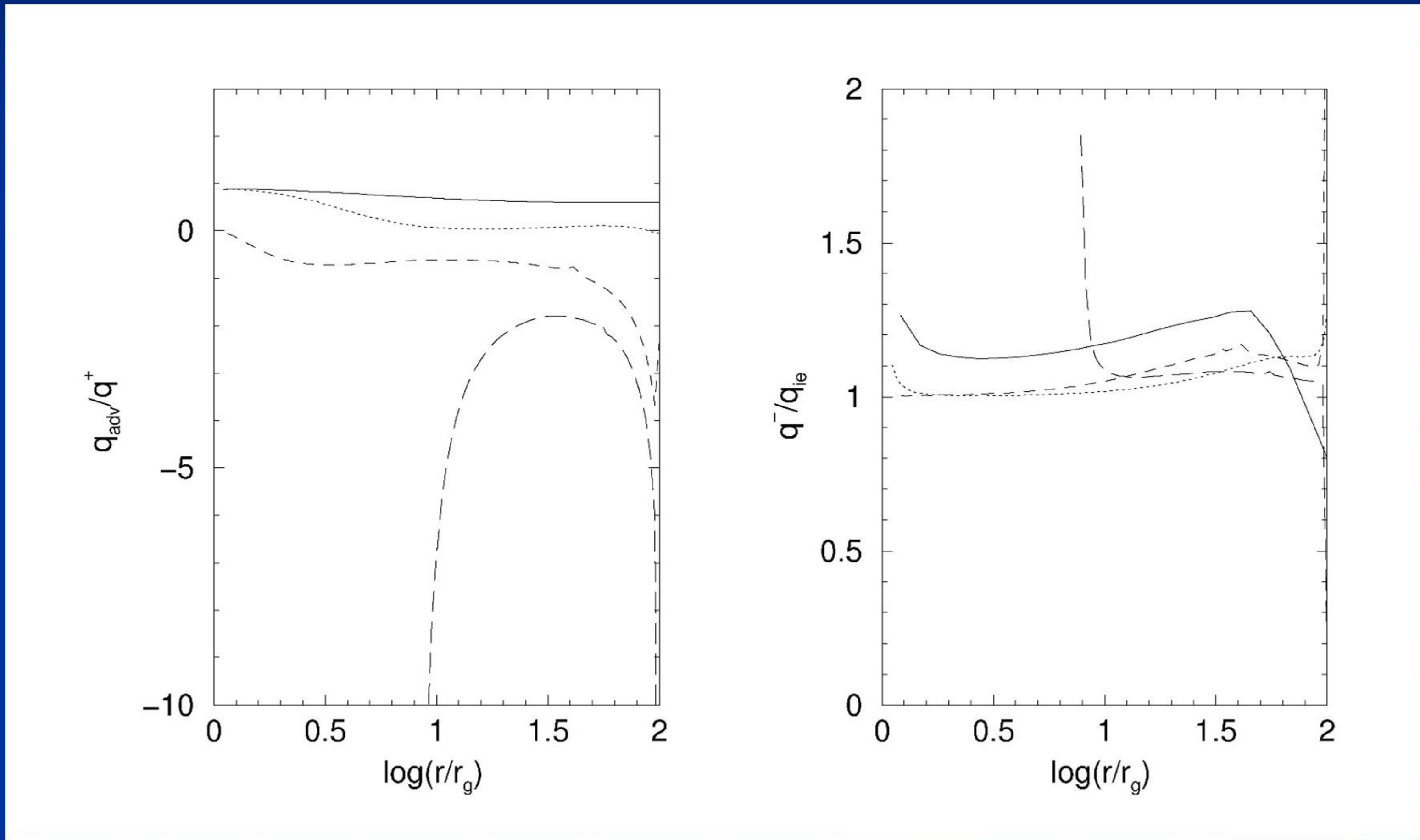
Global Solutions of hot accretion flow



Yuan 2001

- α=0.3; $M_{BH} = 10 M_{\bullet}$
- Accretion rates are: 0.05(solid; ADAF); 0.1 (dotted; critical ADAF); 0.3 (dashed; type-I LHAF) 0.5 (long-dashed; type-II LHAF)

Global Solutions: Energetics

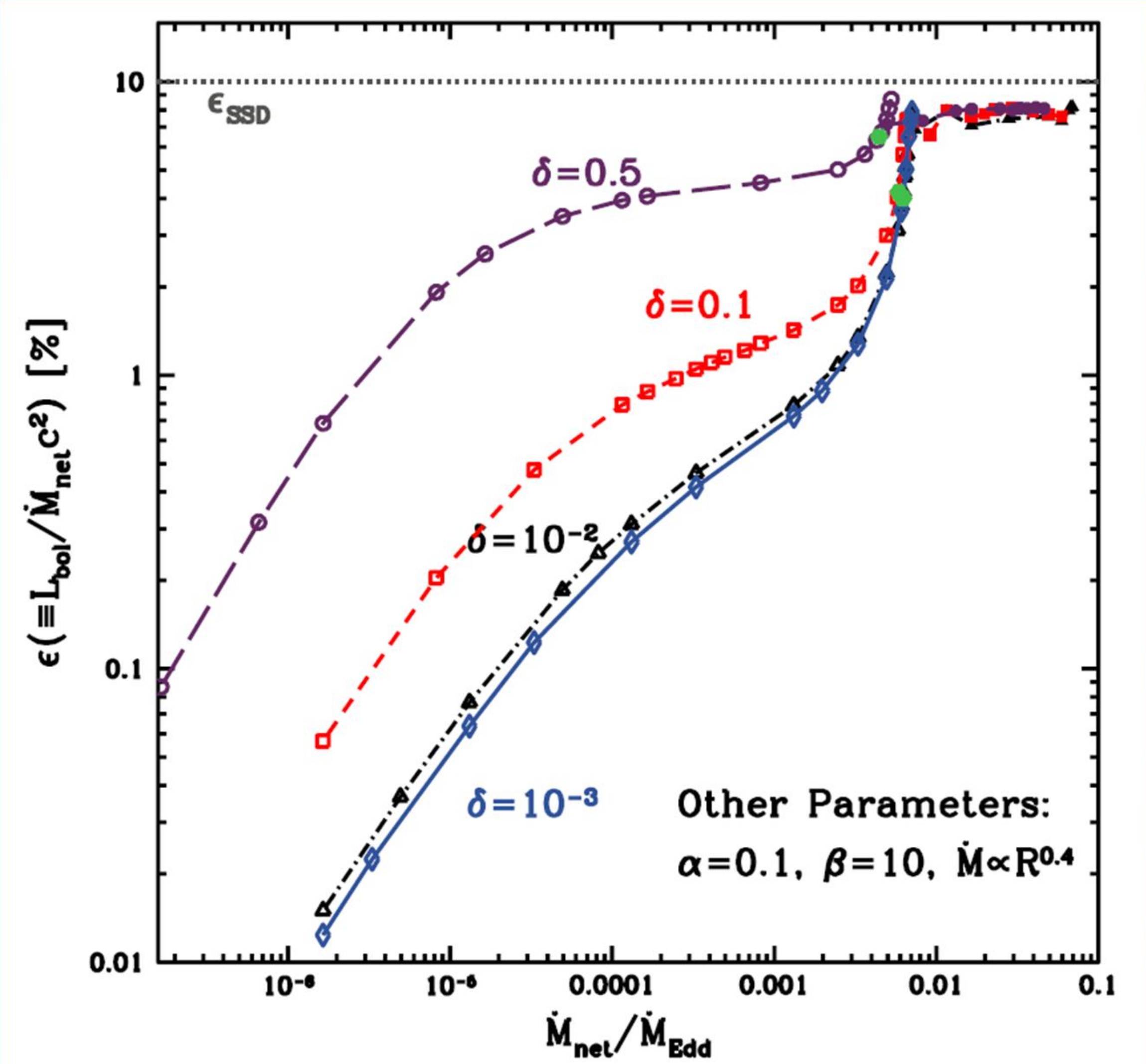


Yuan 2001

- Accretion rates are: 0.05(solid; ADAF); 0.1 (dotted; critical ADAF); 0.3 (dashed; type-I LHAF) 0.5 (long-dashed; type-II LHAF)

Radiative efficiency of ADAF & LHAF

Xie & Yuan 2012

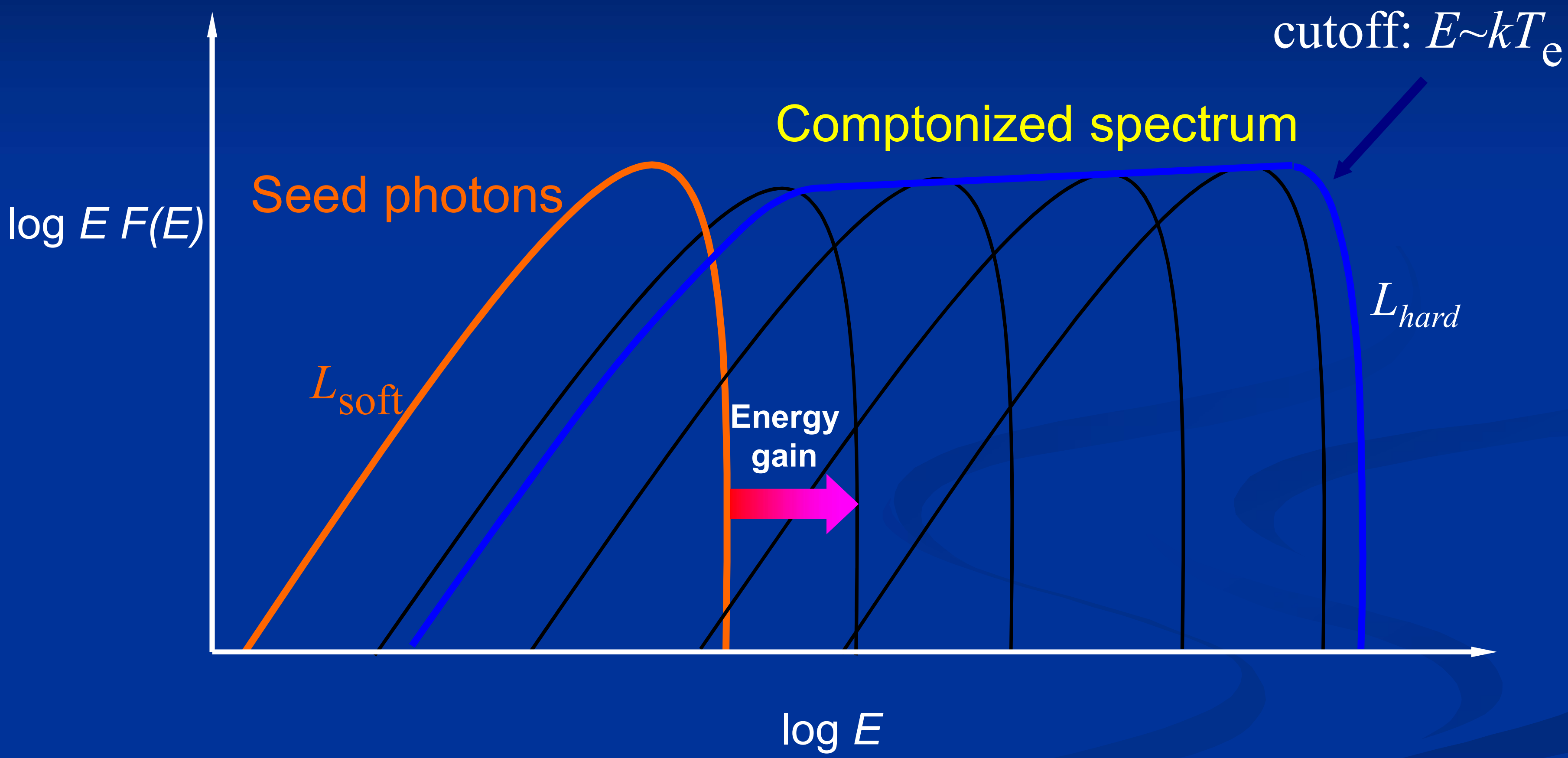


3.2 Radiation

Radiative processes

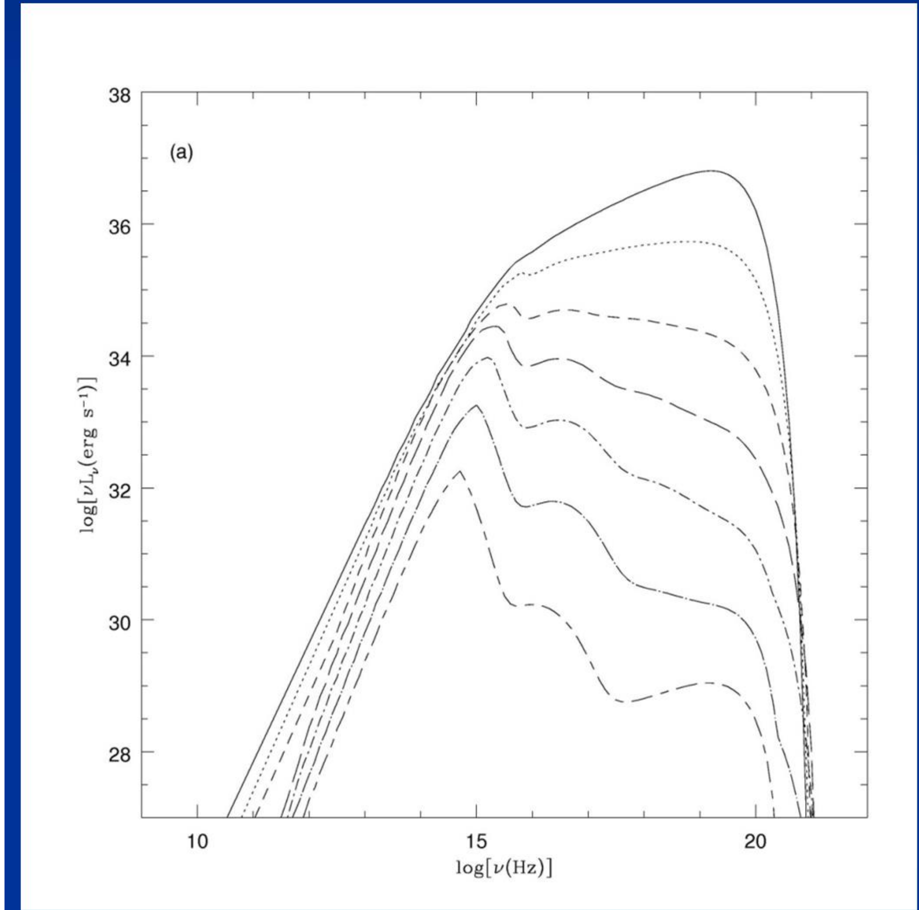
- Synchrotron emission:
  - relativistic electrons & B field (described by a parameter β);
  - Maxwell distribution
  - Self-absorption of synchrotron emission
- Bremsstrahlung radiation
- Comptonization
  - seed photons are synchrotron & Brem. photons
- Misc:
  - Gamma-ray emission by the decay of neutral pions created in proton-proton collisions

Thermal Comptonization

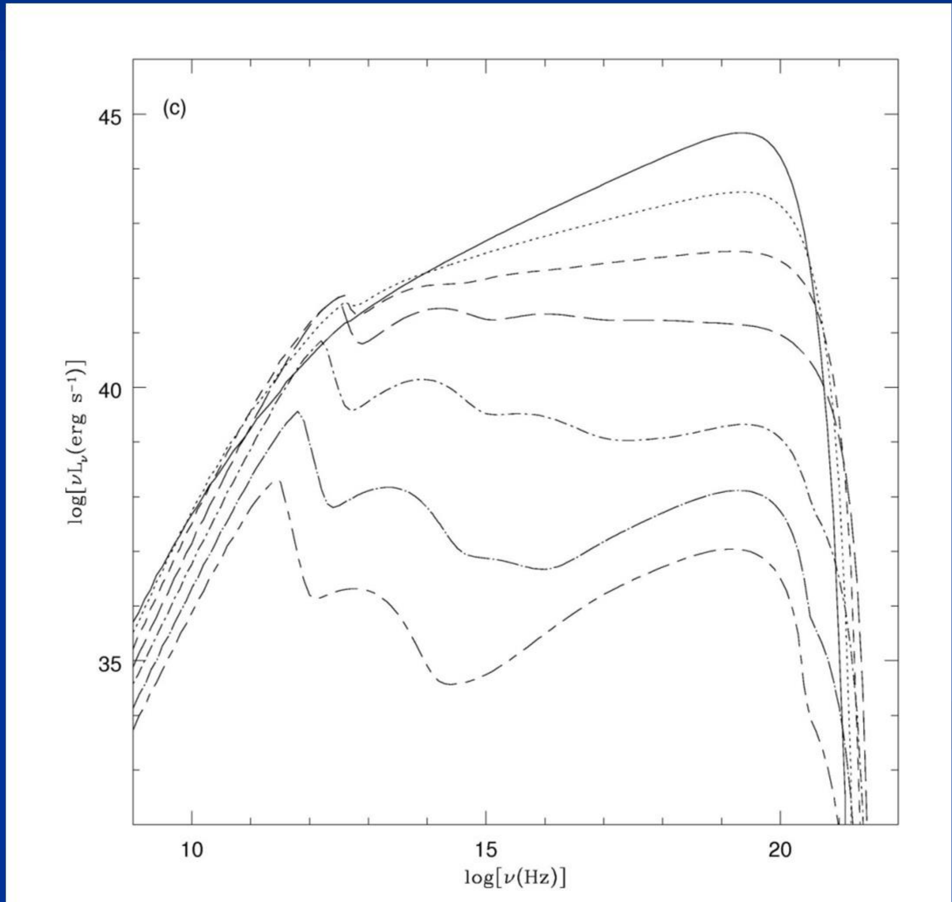


The photon index is a function of kT_e and τ (Thomson optical depth).

Emitted Spectrum



Stellar-mass BH



Supermassive BH

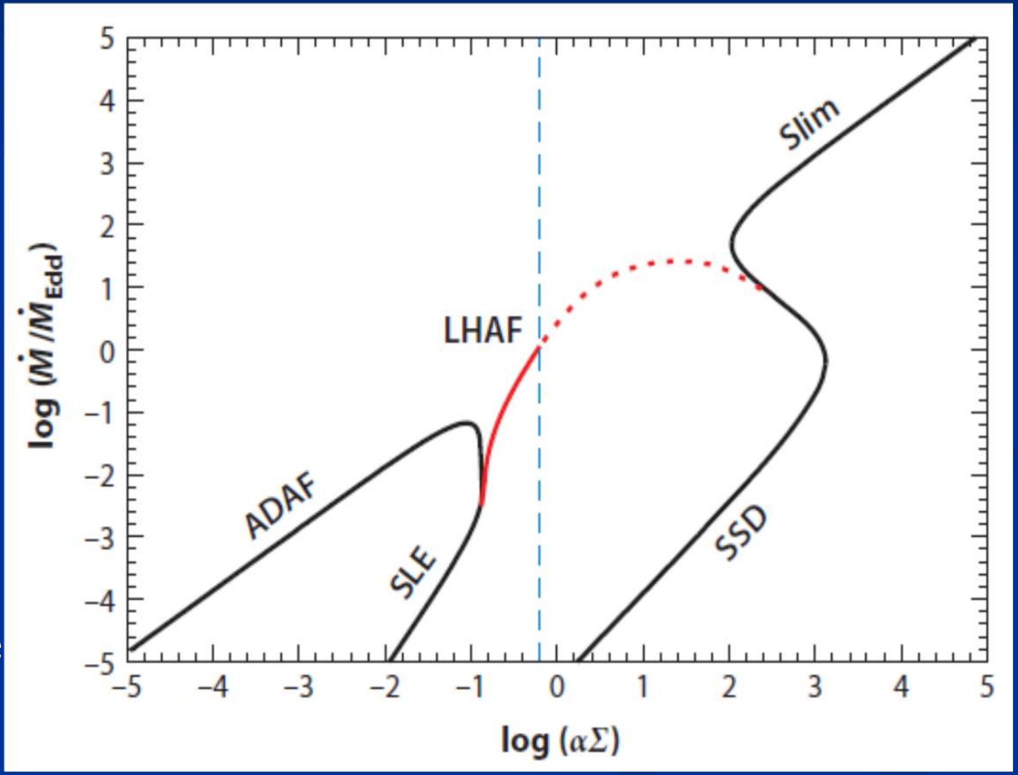
3.3 Stability

The thermal equilibrium curve of accretion solutions: local analysis

- Following the usual approach, we adopt the following two assumptions

$$\Omega = \Omega_k \qquad Q_{adv} \equiv \frac{\dot{M}}{2\pi R^2}\frac{P}{\rho}\xi$$

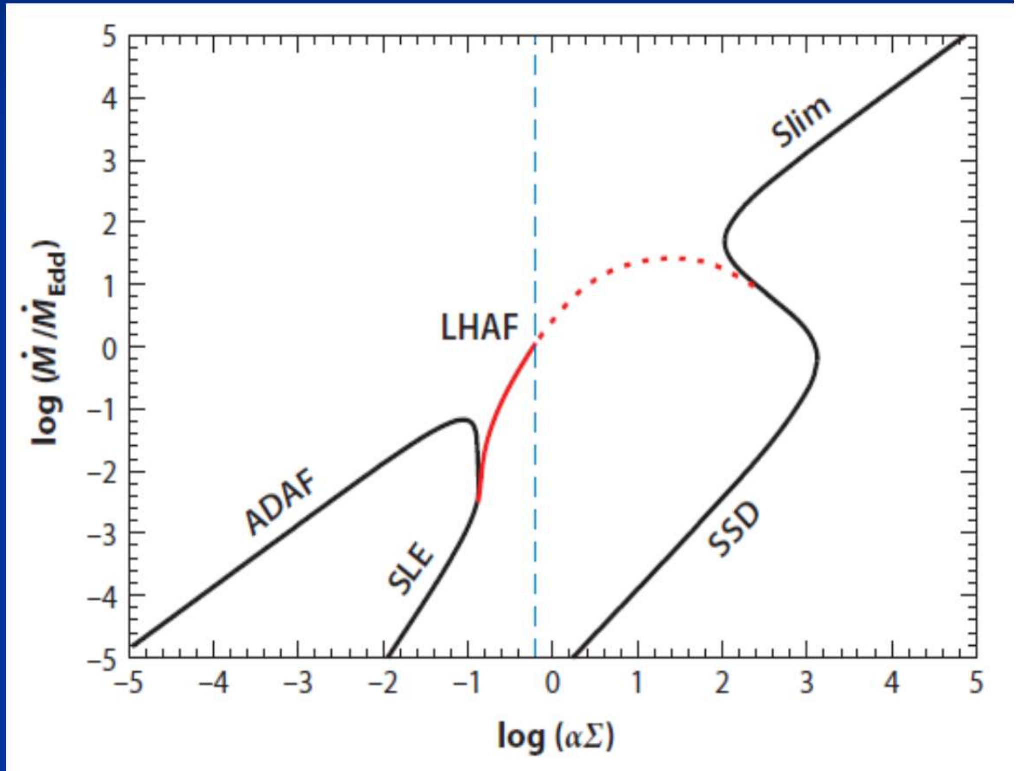
- solving the algebraic accretion equations, setting ξ to be positive and negative to obtain different accretion solutions.



Yuan & Narayan 2014

Viscous stability

- All three solutions are viscously stable since their positive slopes.



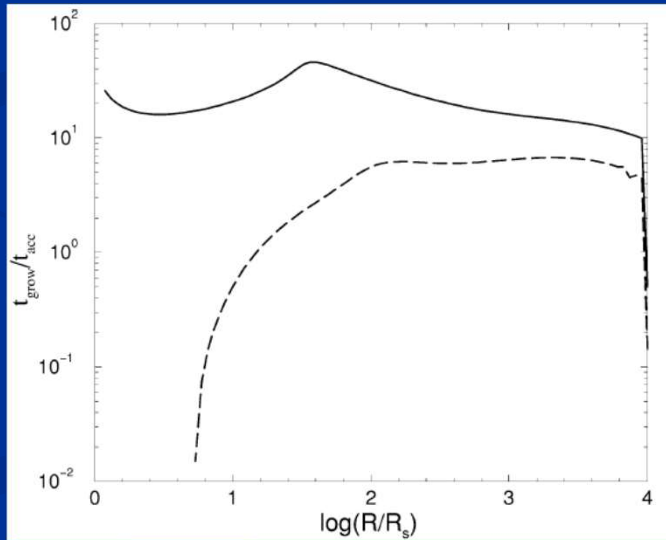
Convective stability

- Without B field (academic case): unstable
  - entropy increases inward
  - Convective instability drives winds
- With B field (more realistic case): stable (Yuan, Bu & Wu 2012; Narayan et al. 2012)
  - This is because MRI changes the dynamics of hot accretion flow (Stone, Pringle 2001; Hawley & balbus 2002)

Thermal stability

- Stable for long-wavelength perturbation since the slope is positive
- Short-wavelength perturbation: debate
  - Stable (Wu & Li 1996; Wu 1997)
  - Unstable (Manmoto et al,. 1996; Kato et al. 1996, 1997; Yuan 2003)
- Consequence of thermal stability
  - When $\dot{M} < 0.2\alpha\dot{M}_{Edd}$, no problem
  - When $\dot{M} > 0.2\alpha\dot{M}_{Edd}$, growth timescale < accretion timescale,

    → Two-phase accretion flow?!



3.4 Numerical simulations

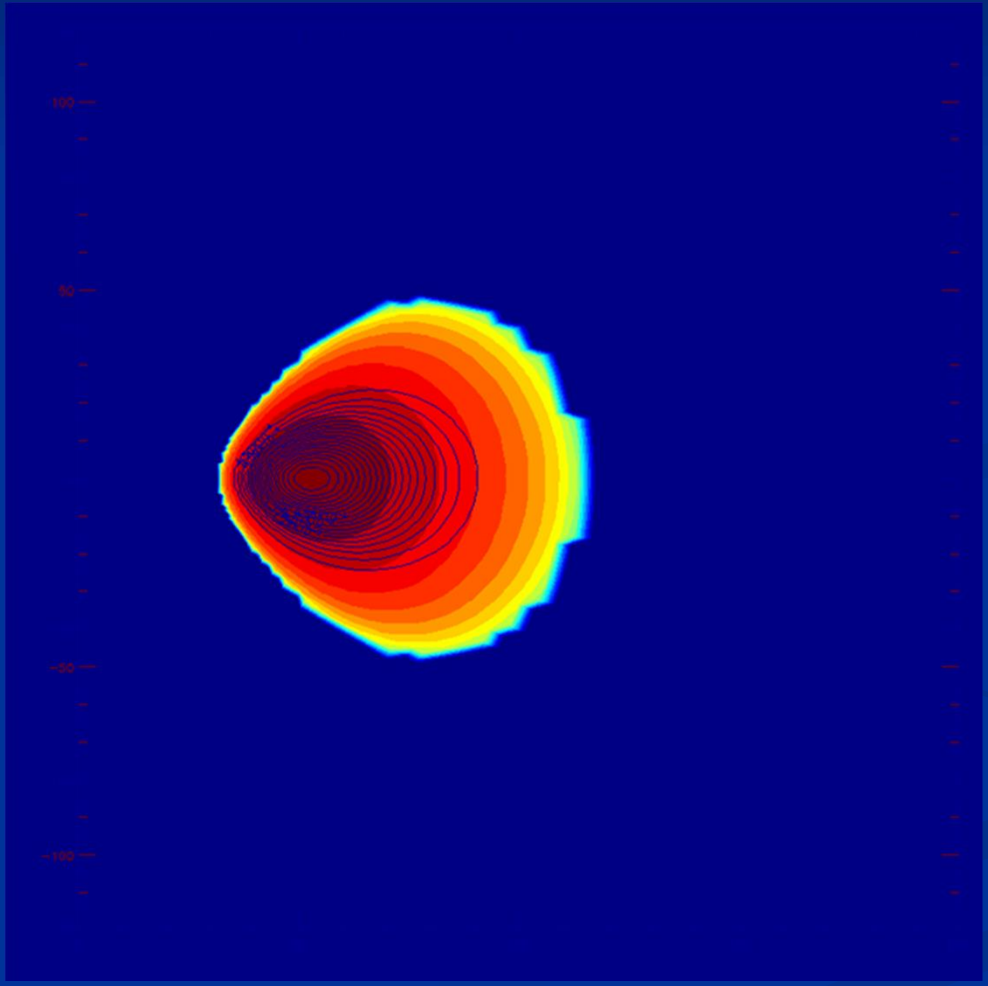
HD & MHD simulations: overview

- The mass accretion rate decreases inward
- The radial profiles of physical quantities are described by a power-law, consistent with the self-similar solution.
- Values of parameters:

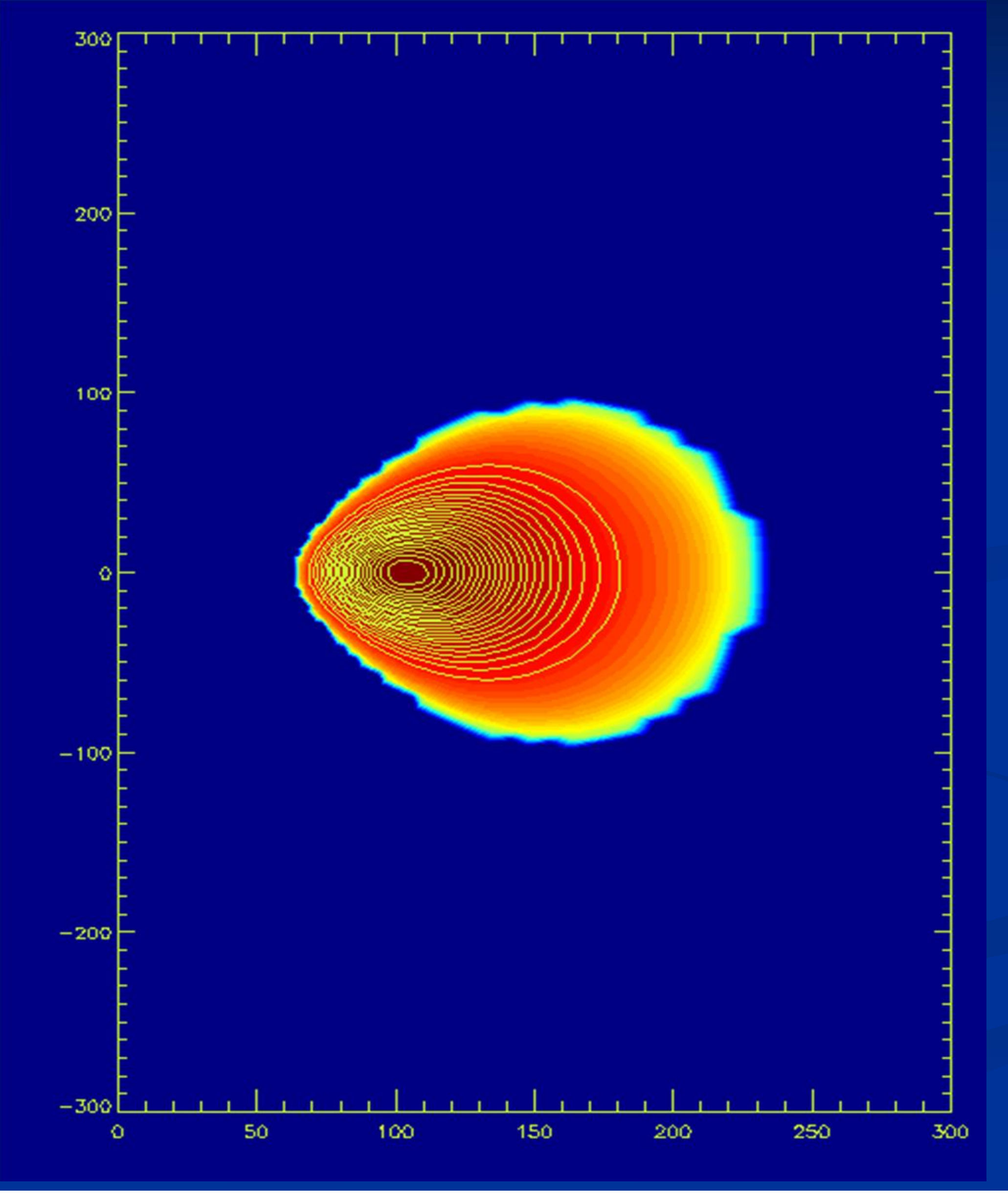
$\alpha \sim 0.05 - 0.2; \alpha\beta \sim 0.5$

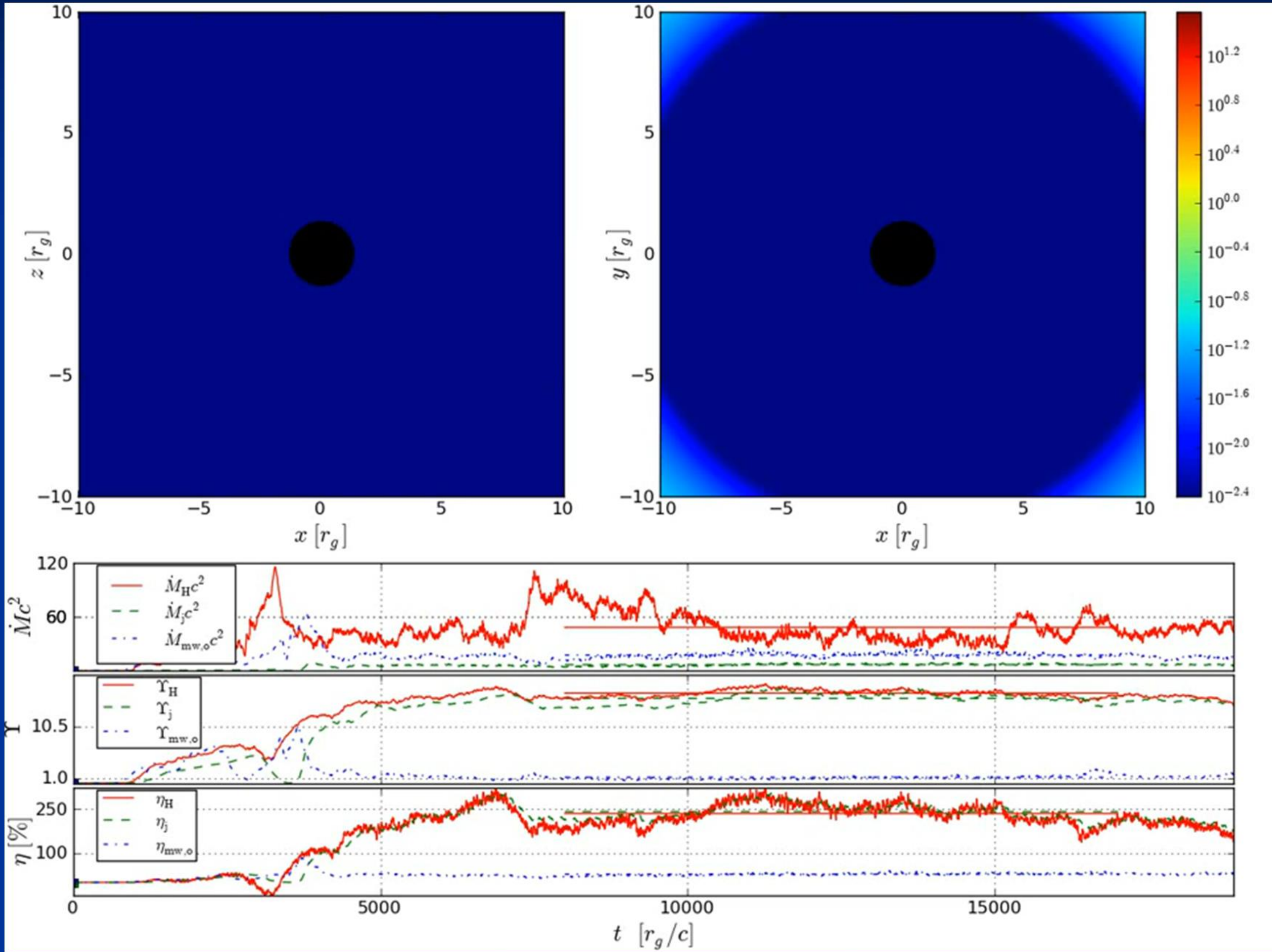
(α is actually quite diverse, depend on shearing box or global, net flux, resolution et al.)

MHD simulation: initial condition



MHD simulation: movie

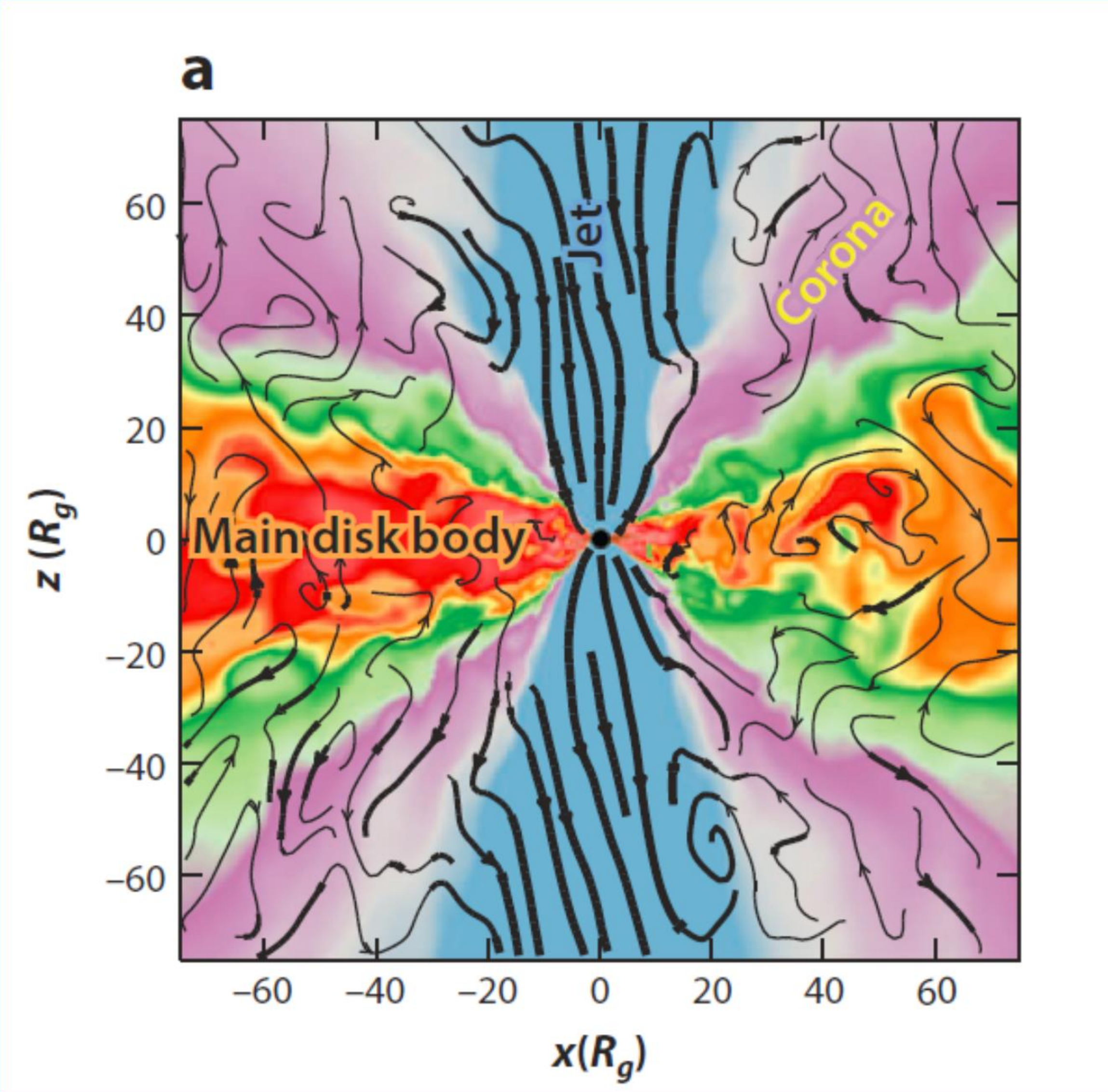




$z\ [r_g]$
$x\ [r_g]$
$y\ [r_g]$
$\dot{M}c^2$
$\dot{M}_{\rm H}c^2$
$\dot{M}_{\rm j}c^2$
$\dot{M}_{\rm mw,o}c^2$
Υ
$\Upsilon_{\rm H}$
$\Upsilon_{\rm j}$
$\Upsilon_{\rm mw,o}$
$\eta\ [\%]$
$\eta_{\rm H}$
$\eta_{\rm j}$
$\eta_{\rm mw,o}$
$t\ [r_g/c]$

Snapshot of GRMHD simulation

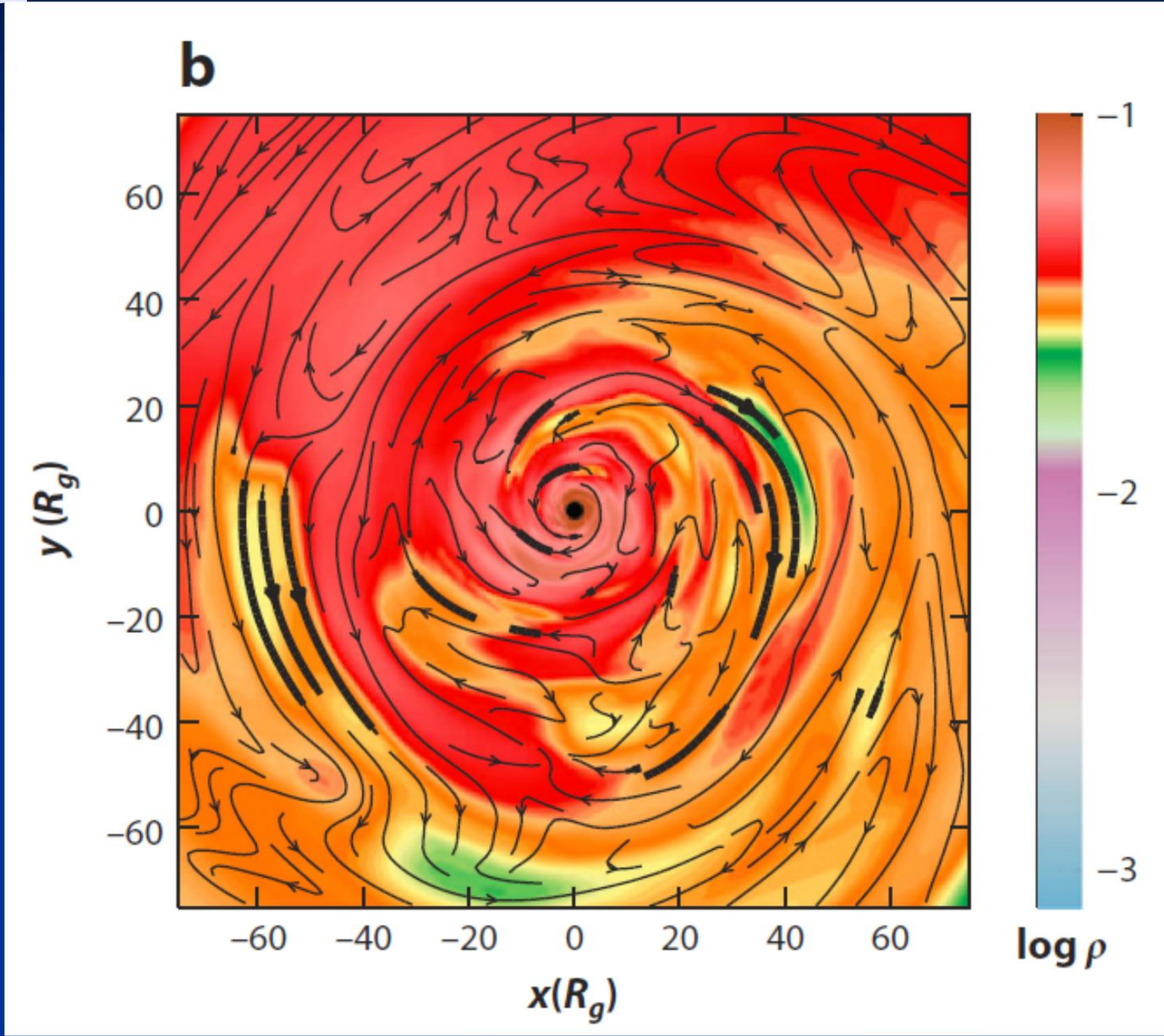
Yuan & Narayan 2014; courtesy of A. Tchekhovskoy



B field configuration and strength in three regions:

1. **Main disk body:**
2. **Corona**
3. **jet**

Snapshot of GRMHD simulation



Yuan & Narayan 2014; courtesy of A. Tchekhovskoy