Black hole accretion

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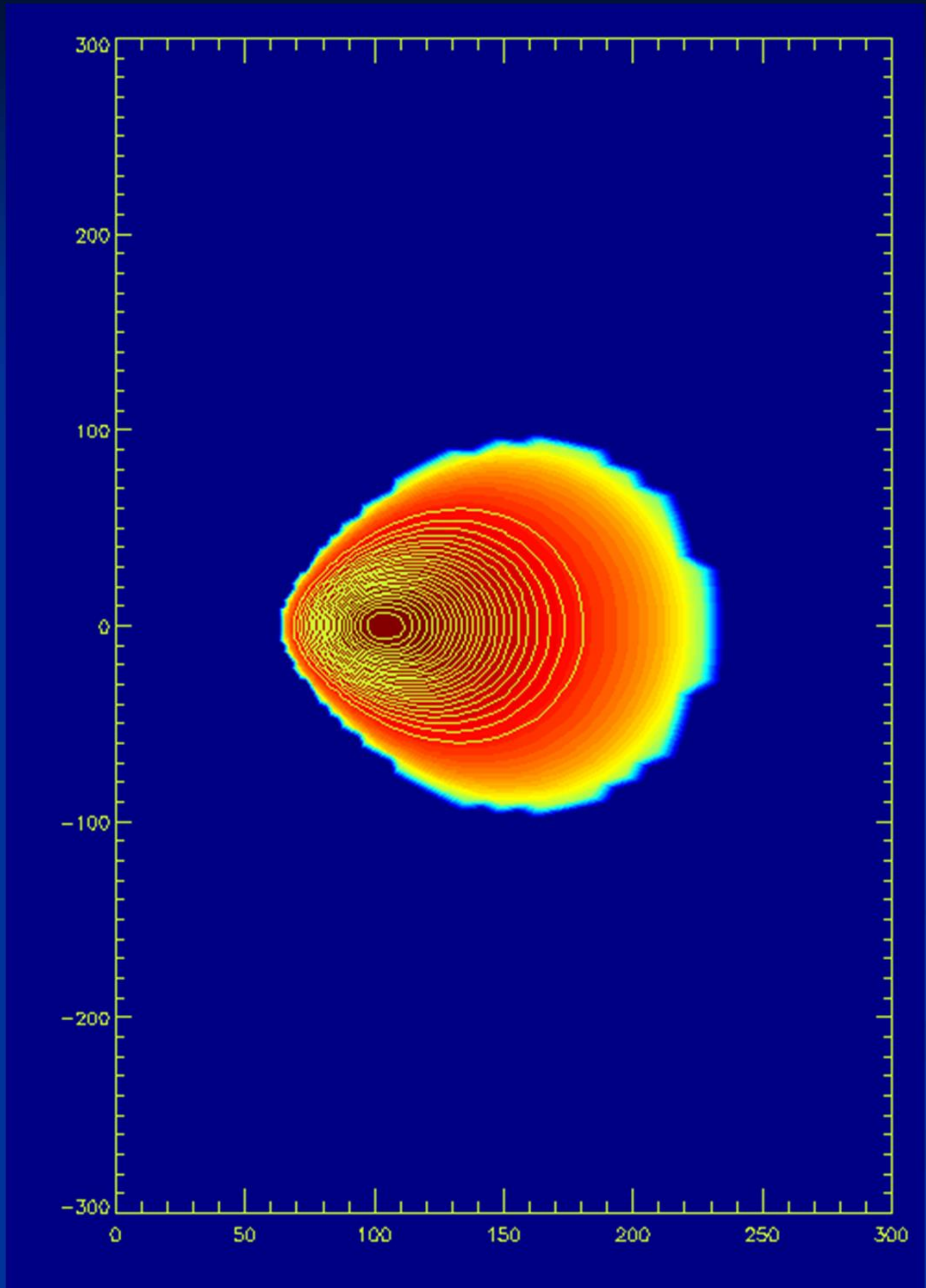
Outline

- Chapter 1: Introduction to some basic concepts 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: Wind and jet
- Chapter 6: AGN feedback

References

- 《Accretion power in astrophysics》： Frank, King & Raine; Cambridge University Press, 2002
- 《Hot accretion flows around black holes》： Yuan & Narayan 2014, ARA&A, 52, 529

Chapter 1:
Introduction to some basic concepts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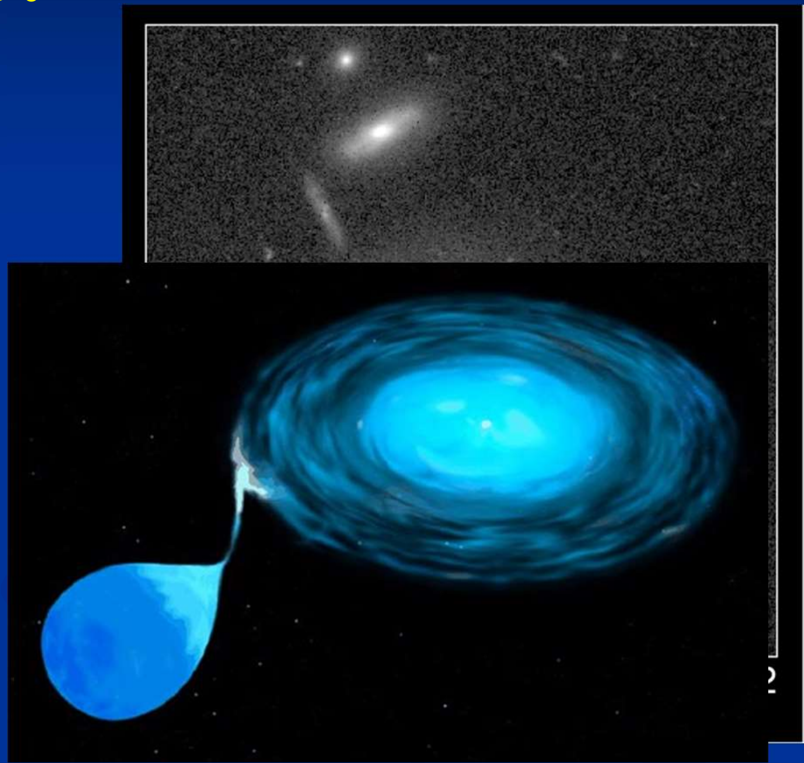
How common is accretion in the universe?



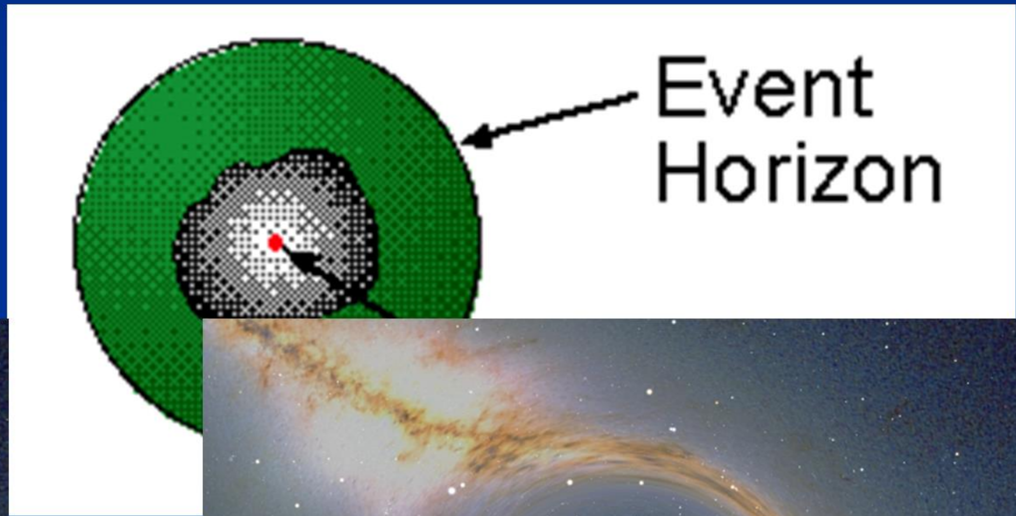
- Active galactic nuclei
- Black hole X-ray binaries
- Gamma-Ray burst
- Star formation
- Planet formation
- Cooling flow in galaxy and galaxy clusters

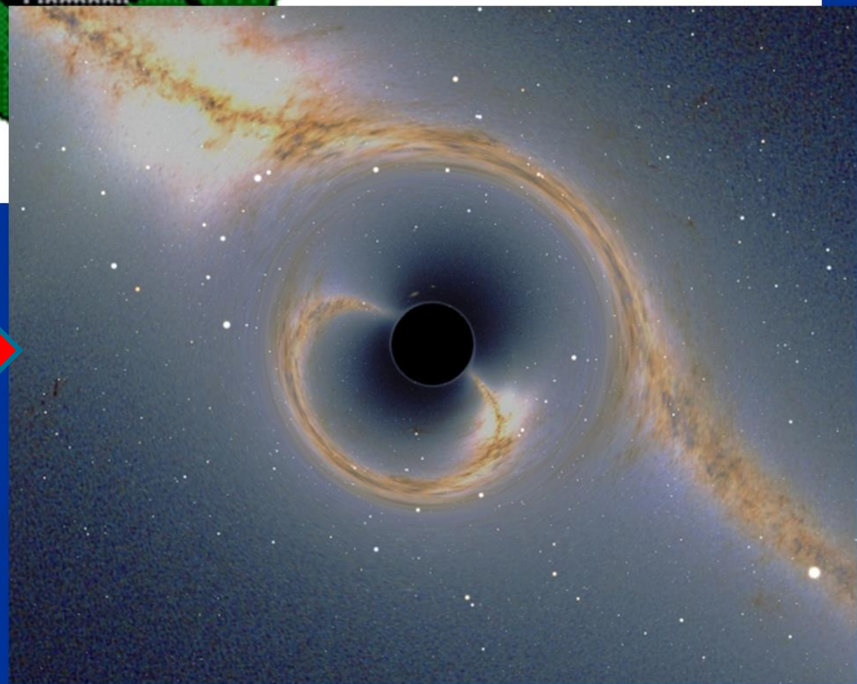
——A fundamental & common physical process

1.1 Some basic concepts

1.1 Black Hole

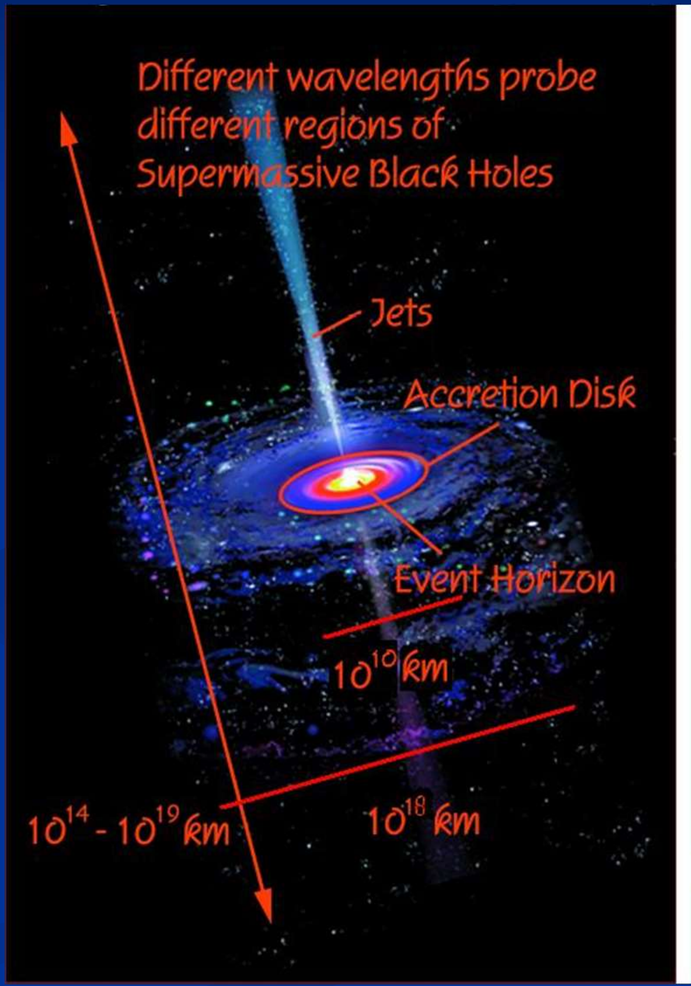
- Prediction of GR
- "Structure" →
- No-hair theorem





Accretion

- Rotating gas surrounding the black hole falls onto the center due to the gravitational force
- Gravitational energy → thermal energy
- Thermal energy → radiation



Accretion rate and radiative efficiency

- Mass accretion rate
- Efficiency of accretion:

$$L = G M_{BH} \dot{M} / \mathrm{R};$$

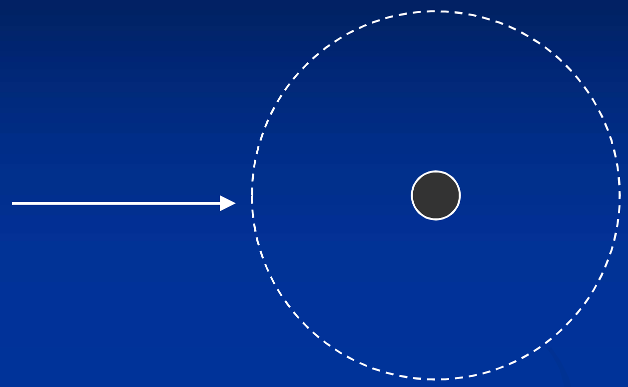
if R=6GM/c^2 (ISCO),

$$\mathrm{L} = 1/6\ \dot{M} c^2$$

- As comparison, efficiency of nuclear reaction is only 0.007
- Thermal temperature: $T_{th} = G M m_p / 3\mathrm{kR}$

Bondi accretion

- **Bondi radius:**



grav. energy = thermal energy

$$\Rightarrow \quad R_A \approx \frac{GM}{c_s^2}$$

- **Mass accretion rate:**

$$\dot{M}_{captured} \approx 4\pi R_A^2 \rho c_s \,\Big|_{R \approx R_A}$$

Eddington Luminosity

- Grav. Force: $$\frac{GMm}{r^2}$$
- Radiation force: $$\frac{\sigma L}{4\pi r^2 c}$$
- Eddington limit: $$L_{Edd} = \frac{4\pi GMmc}{\sigma}$$
- spherical accretion and disk accretion

1.2 HD and MHD

Hydrodynamics

- Continuity equation:

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

- Momentum equation:

(Euler equation)

$$\rho \frac{d\boldsymbol{v}}{dt} = -\nabla P - \rho \nabla \Phi$$

where the Lagrangian derivative:
（随体导数）

$$\frac{d}{dt} \equiv \frac{\partial}{\partial t} + \boldsymbol{v} \cdot \nabla$$

- Energy equation:

$$\rho \frac{\mathrm{d}(e/\rho)}{\mathrm{d}t} = -P \nabla \cdot \boldsymbol{v}$$

- Equation of state:

$$P = \frac{\rho}{\mu m_p} kT$$

Magnetohydrodynamics(MHD)

- Hydrodynamics + Lorentz force
- Need one more equation to evolve the magnetic field

Faraday's law: $$\frac{\partial B}{\partial t} = -c\nabla \times \boldsymbol{E}$$

- Ideal MHD: gas is a perfect electric conductor

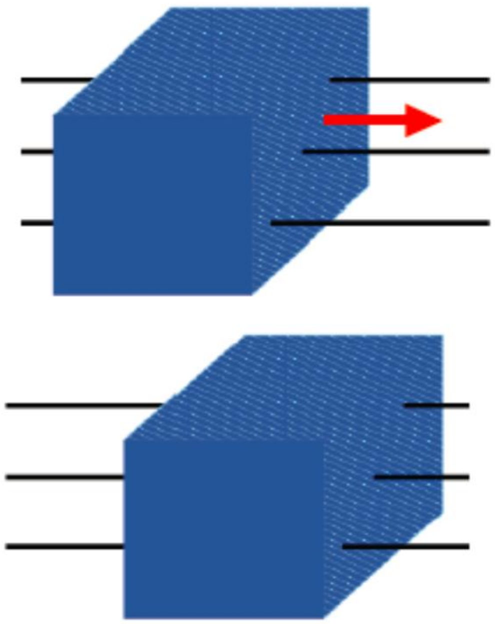
In the co-moving frame: $$\boldsymbol{J}' = \sigma \boldsymbol{E}' \xrightarrow{\sigma \to \infty} \boldsymbol{E}' = 0$$

transforming to the lab frame: $$\boldsymbol{E} = \boldsymbol{E}' - \frac{1}{c}\boldsymbol{v} \times \boldsymbol{B} = -\frac{1}{c}\boldsymbol{v} \times \boldsymbol{B}$$

So we have the induction equation: $$\frac{\partial B}{\partial t} = \nabla \times (\boldsymbol{v} \times \boldsymbol{B})$$

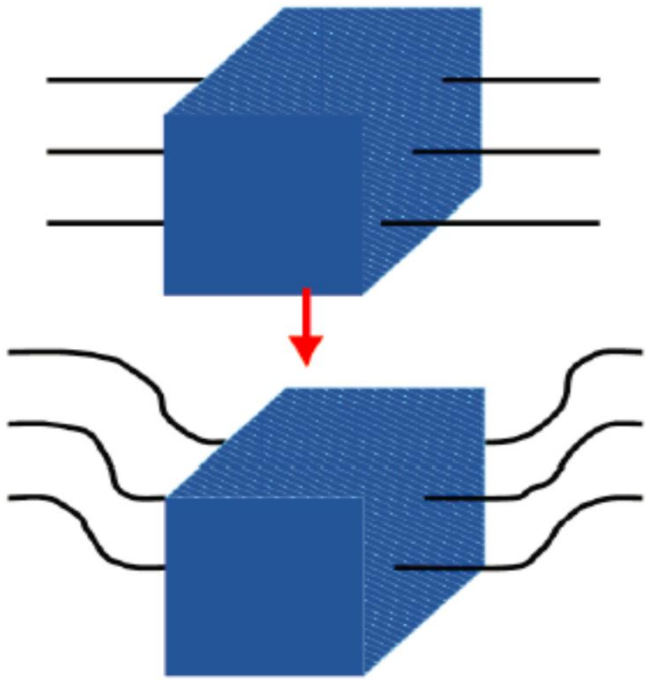
Ideal MHD

Strong field: matter move along field lines (beads on a wire).



$$\frac{|B|^2}{8\pi} >> P_{gas} + \rho|\mathbf{v}|^2$$

Weak field: field lines are forced to move with the gas.



$$\frac{|B|^2}{8\pi} << P_{gas} + \rho|\mathbf{v}|^2$$

1.3 Viscosity & MRI

Viscous flow (Navier-Stokes viscosity)

Euler's equation:

$$\frac{\partial(\rho \boldsymbol{v})}{\partial t} + \nabla \cdot (\rho \boldsymbol{v}\boldsymbol{v} + P\mathsf{I}) = \nabla \cdot \boldsymbol{\sigma}$$

Viscous stress tensor: (Laundau & Lifshitz, 1959)

$$\sigma_{ij} = \rho\nu\left(\frac{\partial v_i}{\partial x_j} + \frac{\partial v_j}{\partial x_i} - \frac{2}{3}\delta_{ij}\nabla \cdot \boldsymbol{v}\right)$$

Physical interpretation:

"Diffusion" of momentum: momentum exchange across velocity gradient.

Reynolds number:

$$\mathrm{Re} \equiv \frac{VL}{\nu}$$

viscosity unimportant when Re>>1.

Viscous torque in shearing flow

- Stress:

$$\sigma_{xy} = -\eta \frac{dv_x}{dy} = -\rho\nu \frac{dv_x}{dy} = -\rho\nu R\Omega'$$

η:Dynamic viscosity
ν: Kinematic viscosity

- Viscous Torque: $G(R) = 2\pi R\nu\Sigma R^2\Omega'$
- The working by the net torque:

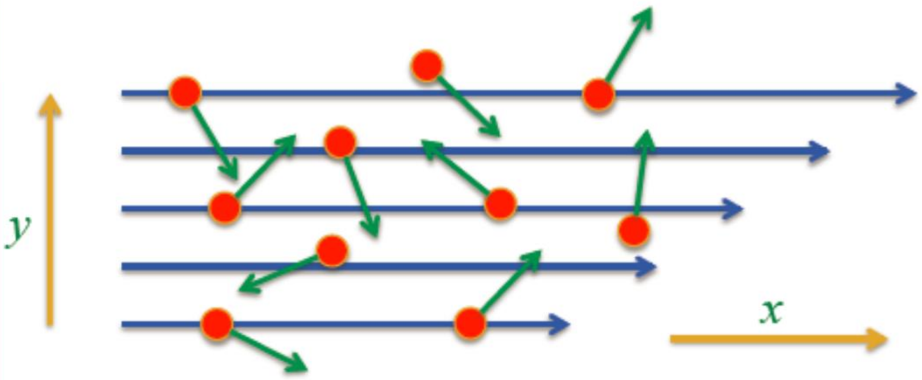
$$\Omega \frac{\partial G}{\partial R} dR = [\frac{\partial}{\partial R}(\mathrm{G}\Omega) - G\Omega']\mathrm{dR}$$

- The former is convection of rotational energy while the latter is the real local rate of loss of mechanical energy to gas. The rate per unit surface area:

$$D(R) = \frac{G\Omega' dR}{4\pi R dR} = \frac{1}{2}\nu\Sigma(R\Omega')^2$$

NS viscous stress: too small

Momentum flux: $$\sigma_{ij} = \rho\nu\left(\frac{\partial v_i}{\partial x_j} + \frac{\partial v_j}{\partial x_i}\right)$$



Exchange of x momentum due to thermal motion in y and molecular collisions

$$\sigma_{xy} \sim \rho v_{\rm th}\left(\frac{dv_x}{dy}\lambda_{\rm mfp}\right)$$

$$\Rightarrow \nu \sim \frac{1}{3}\lambda_{\rm mfp}v_{\rm th}$$

$$\left(\sigma_{xy} = -\eta\frac{dv_x}{dy} = -\rho\nu\frac{dv_x}{dy}\right)$$

Most astrophysical flows are inviscid:

$$\mathrm{Re} = \frac{VL}{\nu} \sim \frac{V}{v_{\rm th}}\frac{L}{\lambda_{\rm mfp}}$$

$$V \gtrsim v_{\rm th}$$

$$L \gg \lambda_{\rm mfp}$$

So we need `anomalous' viscosity

α –Viscosity: $$T_{R\phi} = \alpha P$$

In this case, we have:

$$G(R) = 2\pi R^2 H T_{R\phi}$$

$$D(R) = \frac{G\Omega' dR}{4\pi R dR} = \mathrm{R} H T_{R\phi} \Omega'$$

MRI (Magnetorotational instability)

Balbus & Hawley 1991 (***SHAW Prize of Astronomy in 2013!***)

- Rayleigh criterio for unmagnetized rotating disks:

Unstable if: $$\frac{d(\Omega R^2)}{dR} < 0$$

Confirmed experimentally (Ji et al. 2006)

All astrophysical disks should be stable against this criterion

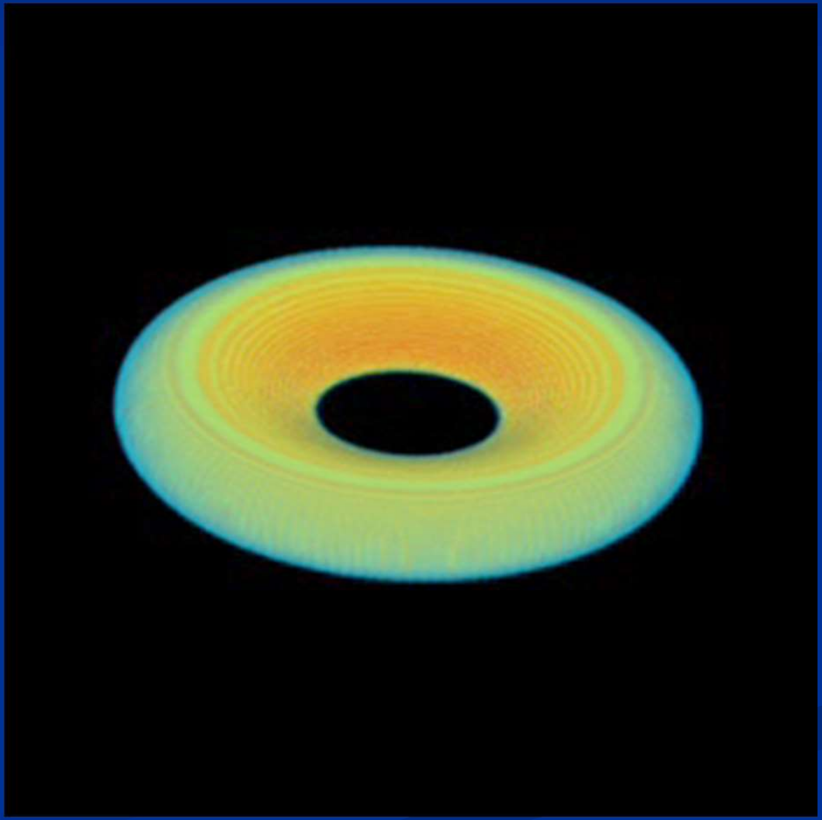
- Including a vertical, well-coupled magnetic field qualitatively changes the criterion:
- Unstable if: $$\frac{d\Omega}{dR} < 0$$ (Balbus & Hawley 1991)

All astrophysical disks should be unstable!

MRI (Magnetorotational instability)

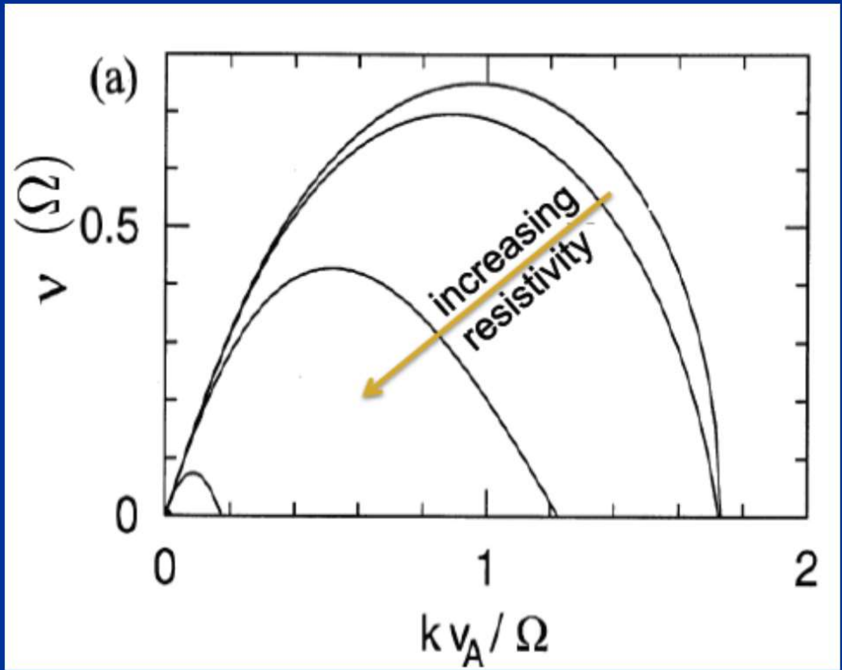
---mechanism of angular momentum transfer

- MRI can amplify magnetic field (why?)
- Resulted MHD turbulence is responsible for the transport of angular momentum.
  - Maxwell stress
  - Reynolds stress



MRI (Magnetorotational instability)

Dispersion relation:



Fatest growth rate: Ω

- Most unstable wavelength:

$$\lambda \sim \frac{2\pi v_A}{\Omega}$$

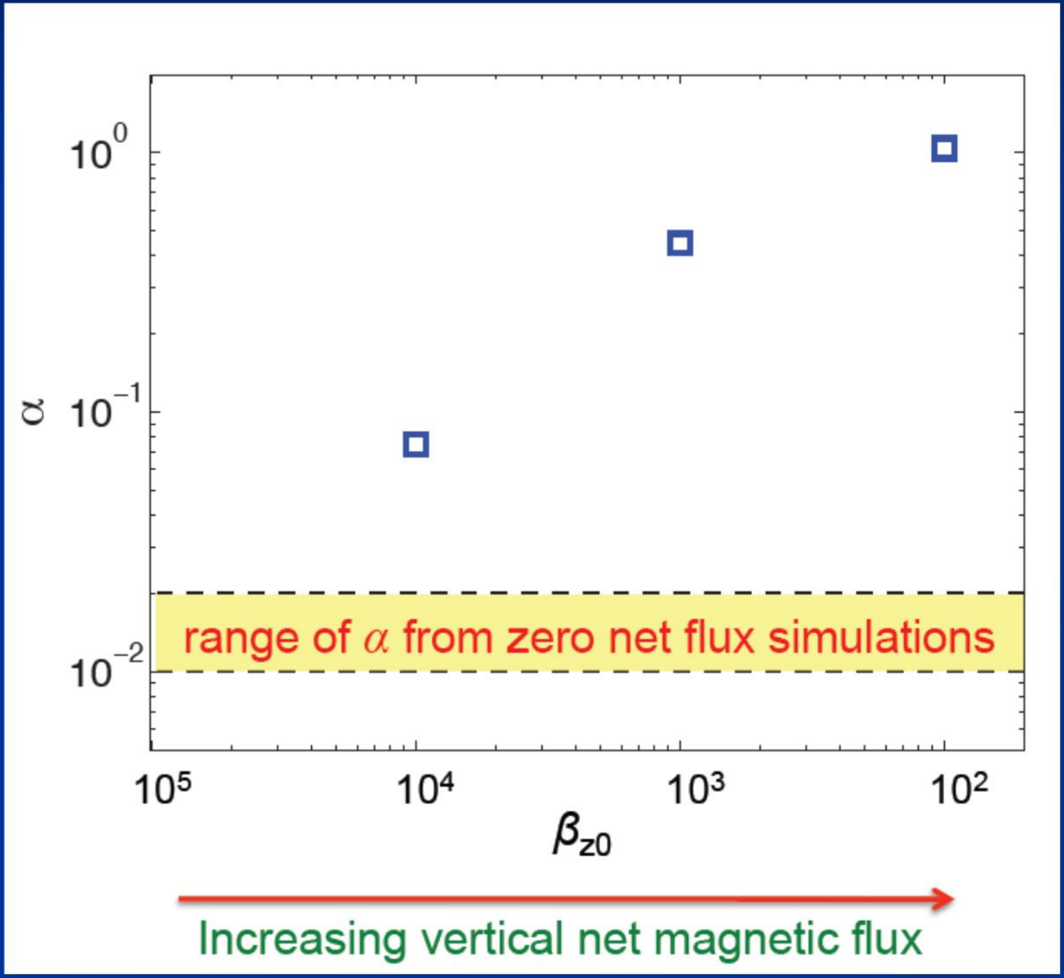
- To be fit into the disk, require:

$$\lambda \lesssim H = \frac{c_s}{\Omega}$$

$$\Rightarrow \quad v_A \lesssim c_s/2\pi$$

$$\Rightarrow \quad \beta_0 \equiv \frac{P_{\rm gas}}{P_{\rm mag}} \gtrsim 8\pi^2$$

What is the value of α?



Bai & Stone 2013

- MHD simulation result: diverse……
- The value of α increases with the net magnetic flux, ranging from 0.01→1

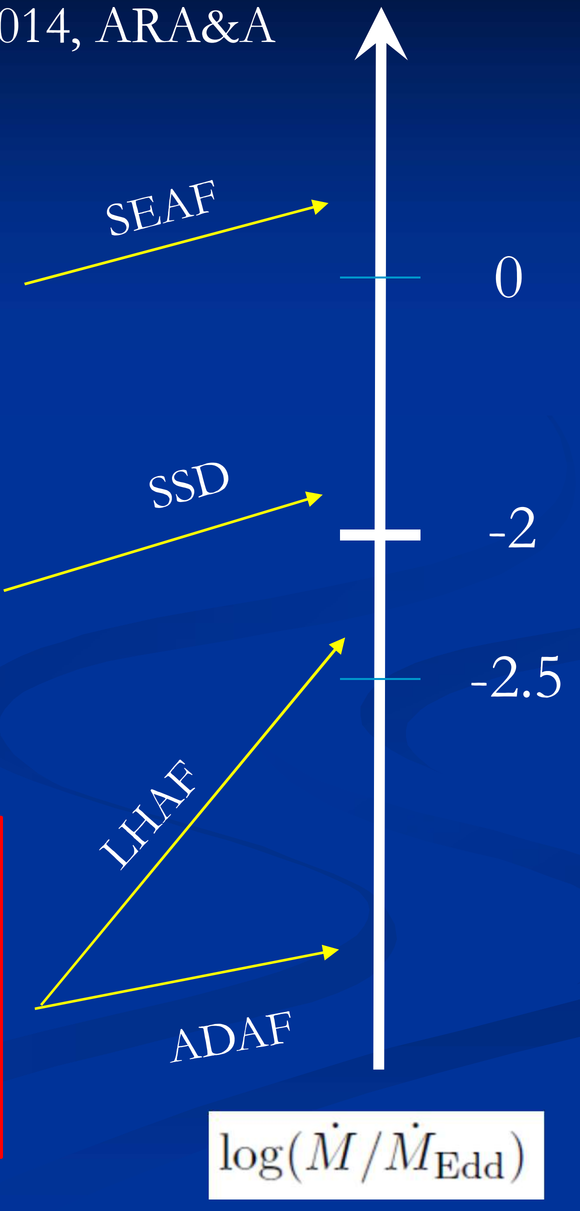
Accretion modes: cold & hot

Pringle 1981, ARA&A; Yuan & Narayan 2014, ARA&A

Super-Eddington accretion (slim disk)
(Abramowicz et al. 1989; Sadowski et al. 2014;
Jiang et al. 2014)
TDEs, ULXs, SS433

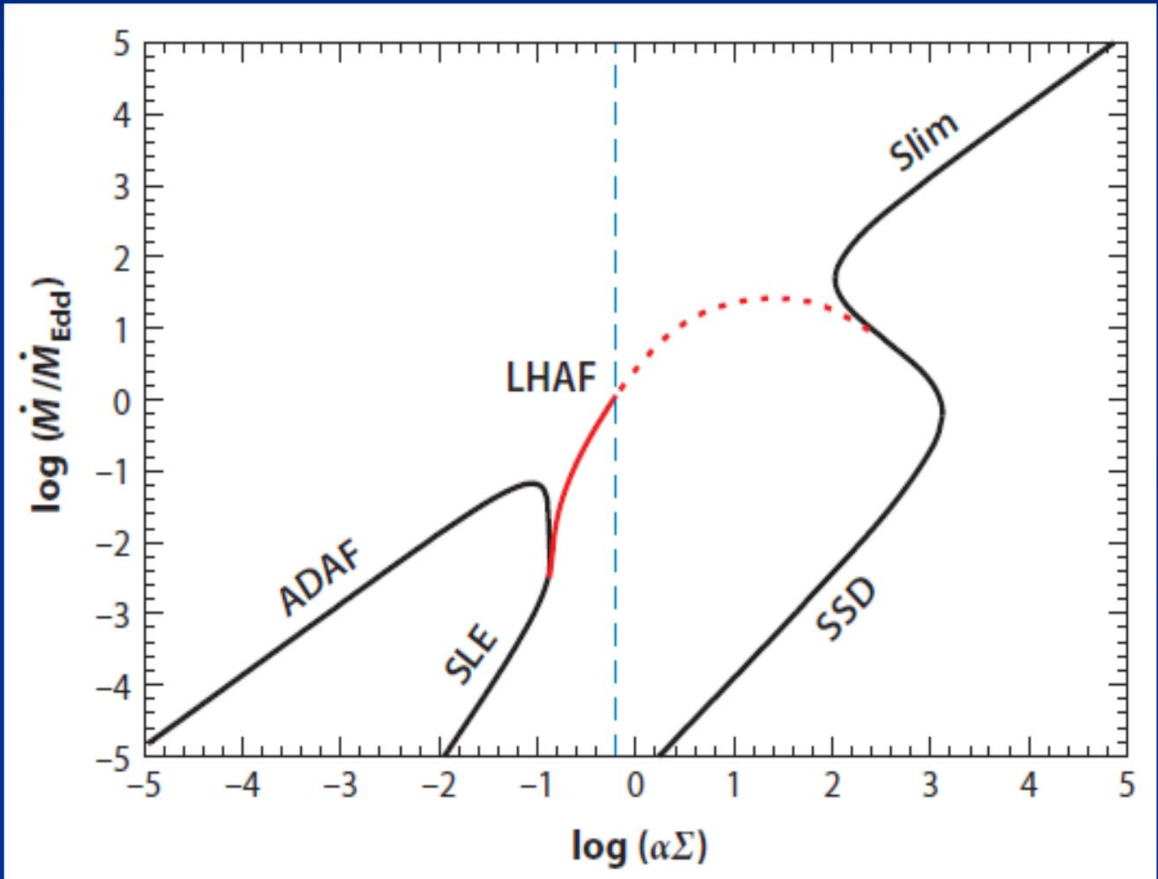
Standard thin accretion disk
(Shakura-Sunyaev 1976;
Pringle 1981, ARA&A)
Typical QSOs, Seyferts; XRBs in thermal
soft state

Hot Accretion: ADAF(RIAF) & LHAF
(Narayan & Yi 94; Yuan 2001;
Yuan & Narayan 2014, ARA&A)
LLAGN, BL Lac objects, Sgr A*, M87
XRBs in hard & quiescent states



Chapter 2:
The standard thin disk and slim disk

Thermal equilibrium of all accretion models



Yuan & Narayan 2014

Two series of solutions: Hot & cool

2.1 The standard thin disk

Equations

- Mass conservation： $\dot{M}=4\pi r H\rho v_r$
- Momentum： $\frac{1}{\rho}\frac{dP}{dr}-(\Omega^2-\Omega_k^2)r+v_r\frac{dv_r}{dr}=0$
- Angular momentum: $\dot{M}(\mathrm{l}-l_0)=4\pi r^2 \mathrm{H}\alpha\mathrm{P}$
- Energy equation： $H\rho v_r T\frac{dS}{dr}=H\alpha Pr\frac{d\Omega}{dr}-F^-$

  Here the vertical radiation flux is:

$$F^- = \frac{c}{k\rho}\frac{aT^4}{3H}$$

Energy equation

- When effective optical depth >>1, radiative flux: $$F(z) = \frac{-16\sigma T^3}{3\kappa_R \rho} \frac{\partial T}{\partial z}$$
- We should have: $$\frac{\partial F}{\partial z} = Q^+$$
- Integrate it, we have: $\frac{-4\sigma T_c^4}{3k_R \rho H} = \mathrm{D(R)}$
- So:

$$\frac{4\sigma}{3\tau} T_c^4 = D(R)$$

Overview of the thin disk model

- Cool: ~10^6 K → Geometrically thin & Keplerian rotation
- Slow radial velocity
- "Optically thick":
- Spectrum: black body spectrum
- Radiative efficiency is high, ~0.1

A thin disk

Radiation

- We should have: $\sigma T^4(R) = D(R)$ [Compare with: $\frac{4\sigma}{3\tau} T_c^4 = D(R)$]
- Thus: $$T(R) = \left\{ \frac{3GM\dot{M}}{8\pi R^3 \sigma} \left[1 - \left(\frac{R_*}{R} \right)^{1/2} \right] \right\}^{1/4}$$
- Emitted spectrum:

$$I_\nu = B_\nu[T(R)] = \frac{2h\nu^3}{c^2(e^{h\nu/kT(R)} - 1)} (\text{erg s}^{-1} \text{ cm}^{-2} \text{ Hz}^{-1} \text{ sr}^{-1})$$

- Integrate over radius,

$$F_\nu = \frac{4\pi h \cos i \, \nu^3}{c^2 D^2} \int_{R_*}^{R_{\text{out}}} \frac{R \, \mathrm{d}R}{e^{h\nu/kT(R)} - 1}$$

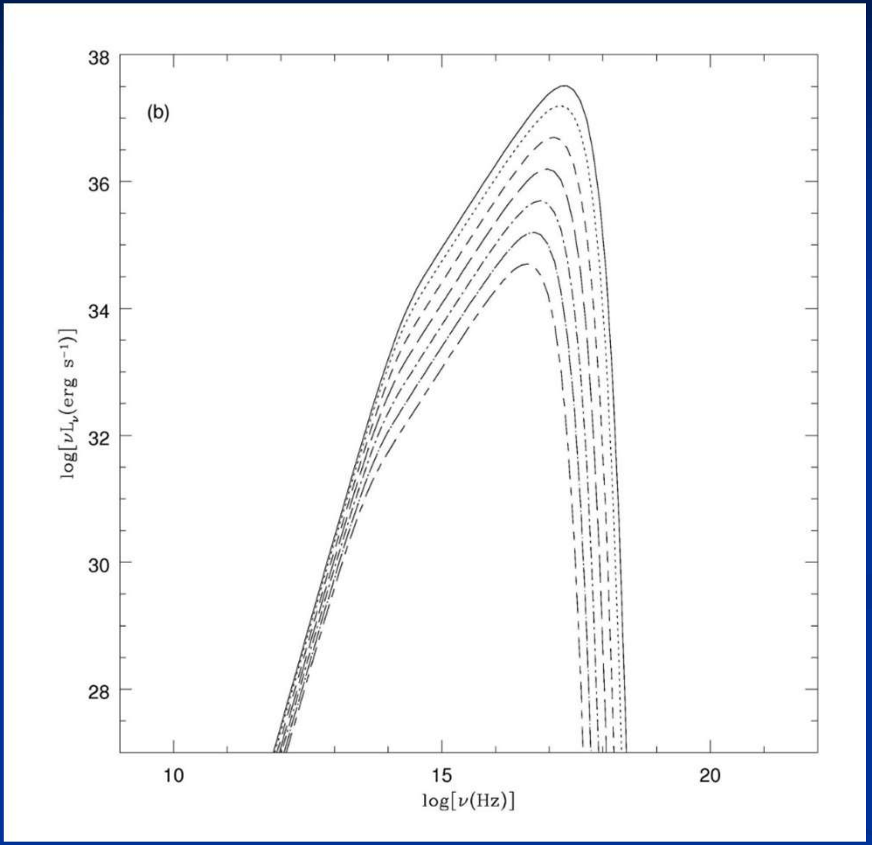
Shakura-Sunyaev solution

Under assumptions of:

1) gas pressure dominated;
2) \alpha-viscosity;
3) Roseland opacity well approximated by Kramer's law

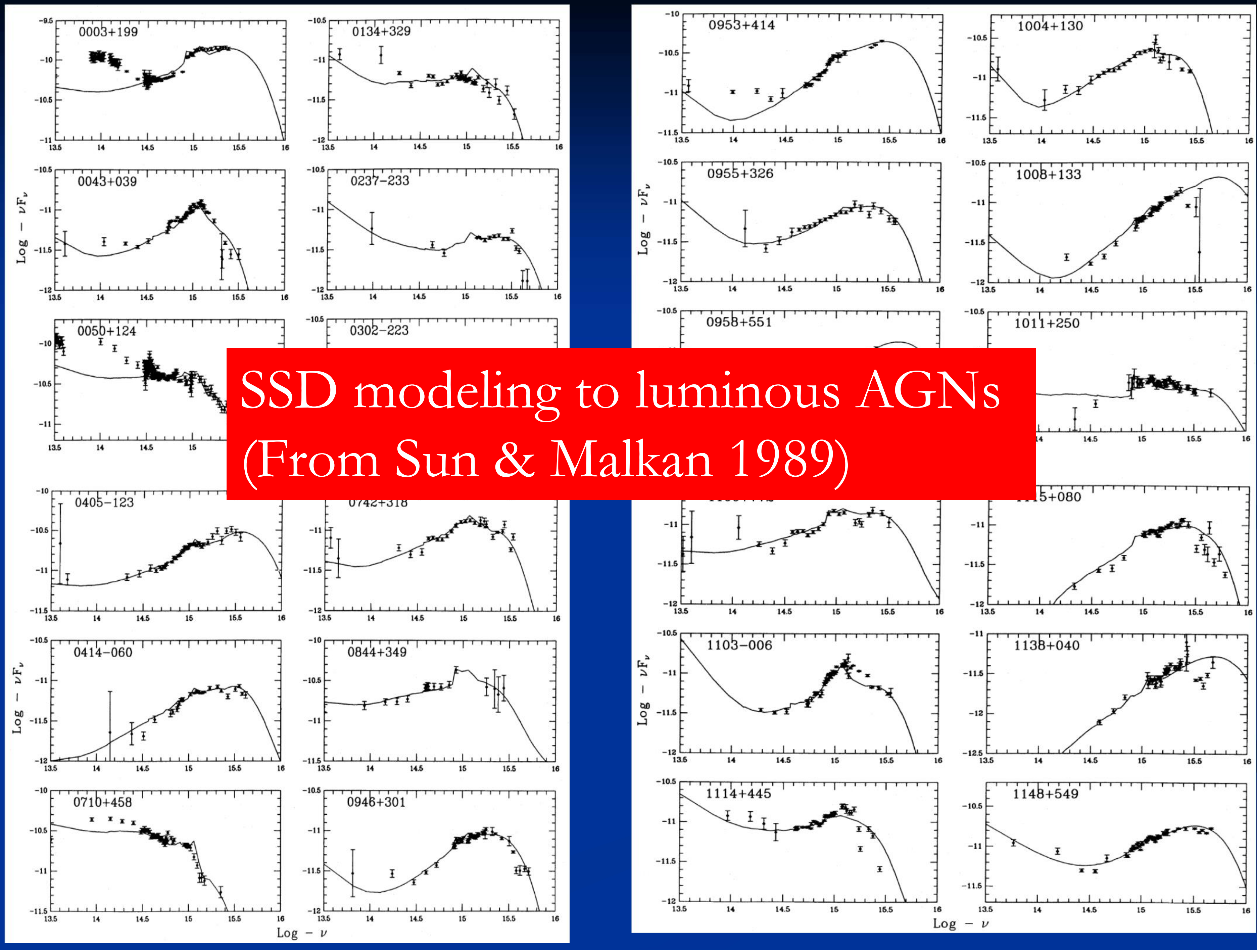
$$
\begin{aligned}
\Sigma &= 5.2\alpha^{-4/5}\dot{M}_{16}^{7/10}m_1^{1/4}R_{10}^{-3/4}f^{14/5}\,\mathrm{g\ cm^{-2}},\\
H &= 1.7\times 10^{8}\alpha^{-1/10}\dot{M}_{16}^{3/20}m_1^{-3/8}R_{10}^{9/8}f^{3/5}\,\mathrm{cm},\\
\rho &= 3.1\times 10^{-8}\alpha^{-7/10}\dot{M}_{16}^{11/20}m_1^{5/8}R_{10}^{-15/8}f^{11/5}\,\mathrm{g\ cm^{-3}},\\
T_c &= 1.4\times 10^{4}\alpha^{-1/5}\dot{M}_{16}^{3/10}m_1^{1/4}R_{10}^{-3/4}f^{6/5}\,\mathrm{K},\\
\tau &= 190\alpha^{-4/5}\dot{M}_{16}^{1/5}f^{4/5},\\
\nu &= 1.8\times 10^{14}\alpha^{4/5}\dot{M}_{16}^{3/10}m_1^{-1/4}R_{10}^{3/4}f^{6/5}\,\mathrm{cm^2\,s^{-1}},\\
v_R &= 2.7\times 10^{4}\alpha^{4/5}\dot{M}_{16}^{3/10}m_1^{-1/4}R_{10}^{-1/4}f^{-14/5}\,\mathrm{cm\ s^{-1}},\\
\text{with } f &= \left[1-\left(\frac{R_*}{R}\right)^{1/2}\right]^{1/4}.
\end{aligned}
$$

Emitted spectrum of a standard thin disk

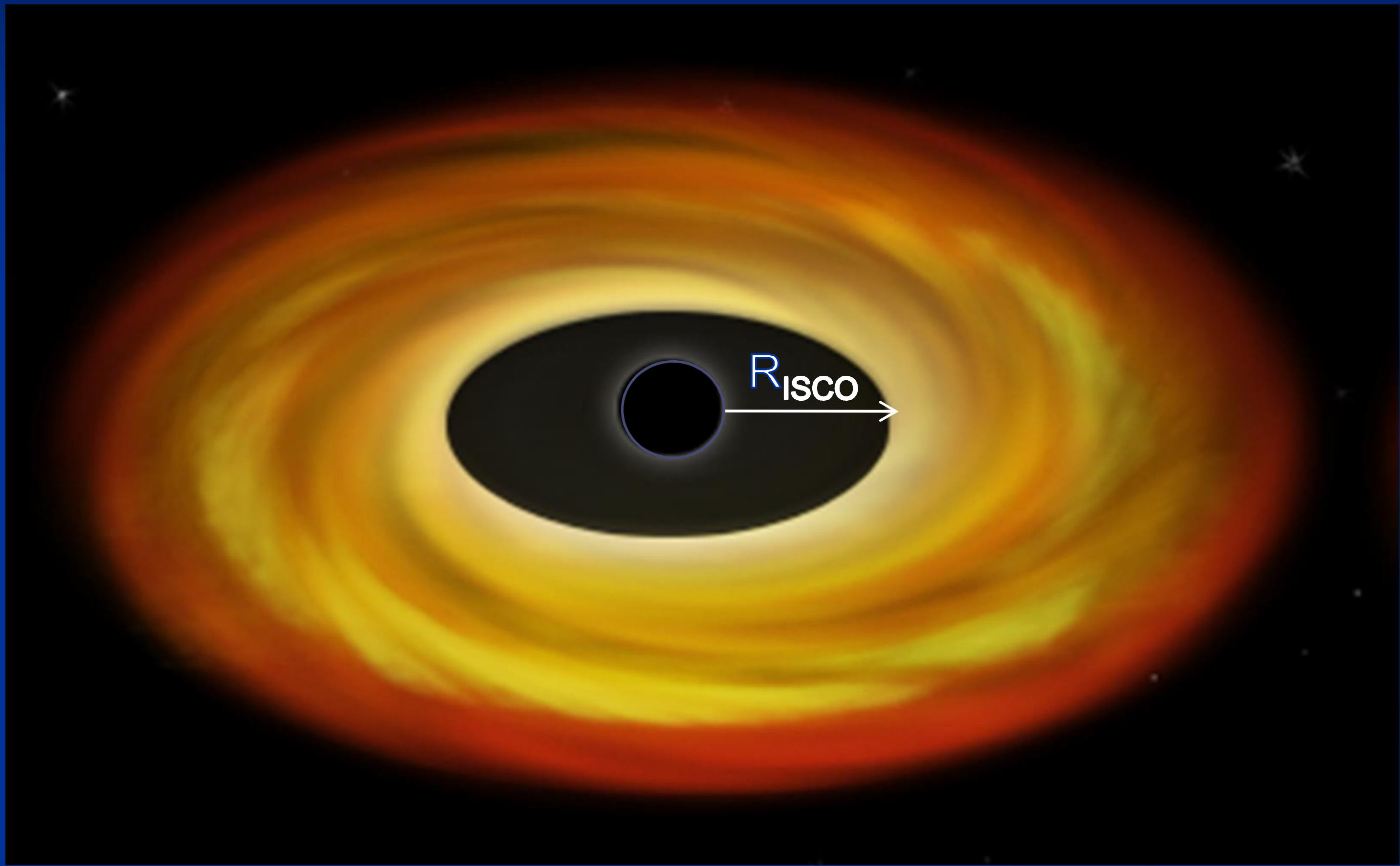


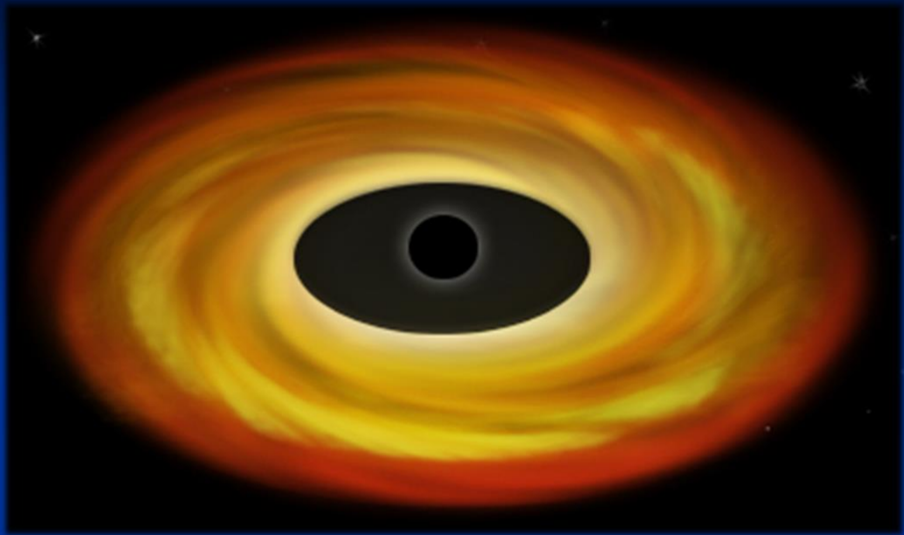
Note that within a radius, the main opacity mechanism is no longer Kramers' opacity, but electron scattering. Since it is no longer involves the microscopic inverse of the processes emitting the radiation (free-free and bound-free) the emergent radiation need not be precisely blackbody, even for quite large optical depth.

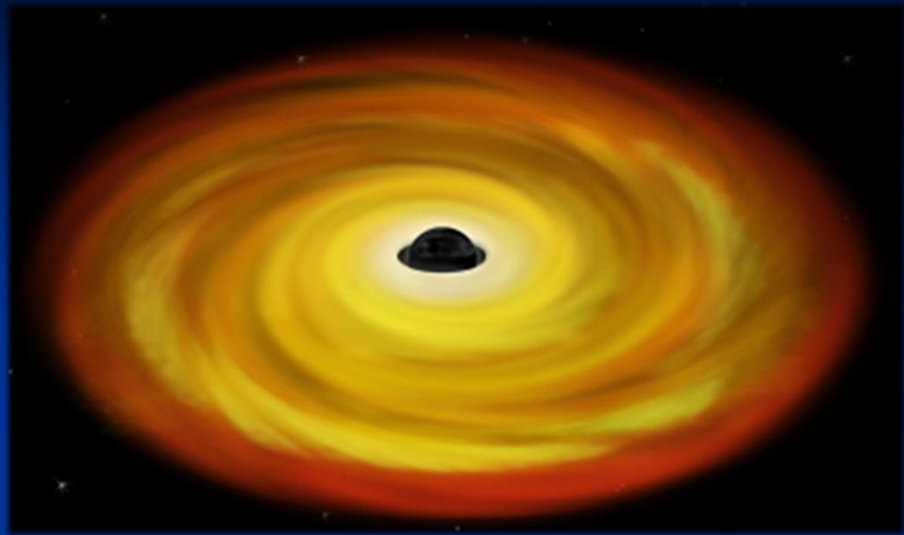
SSD modeling to luminous AGNs (From Sun & Malkan 1989)



Measuring the Inner Disk Radius







$a_* = 0$

$R_{ISCO} = 6M\ G/c^2$

(90 km)

for $M = 10\ M_\odot$

$a_* = 1$

$R_{ISCO} = 1M\ G/c^2$

(15 km)

Measuring R_{ISCO}

Radius R of a Star

$L = 4\pi D^2 F = 4\pi R^2 \sigma T^4$

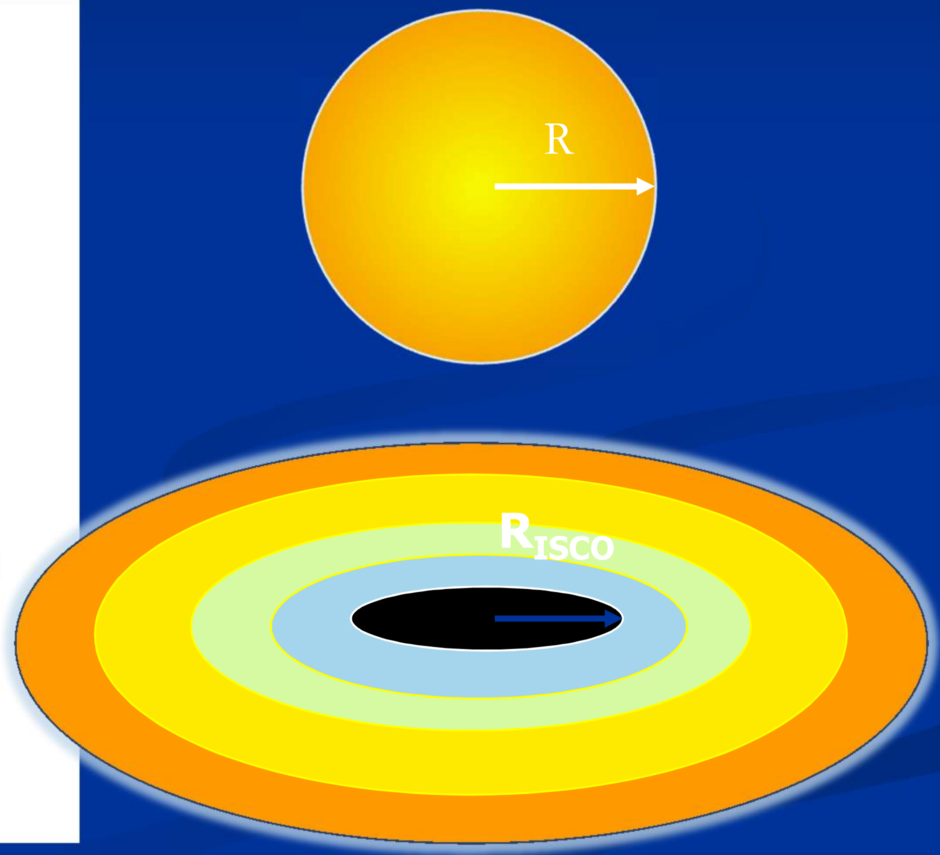
Solid angle: $(R/D)^2 = F/\sigma T^4$

$D \rightarrow$ R

Radius R_{ISCO} of Disk Hole

F and $T \rightarrow$ solid angle

D and $i \rightarrow$ R_{ISCO}



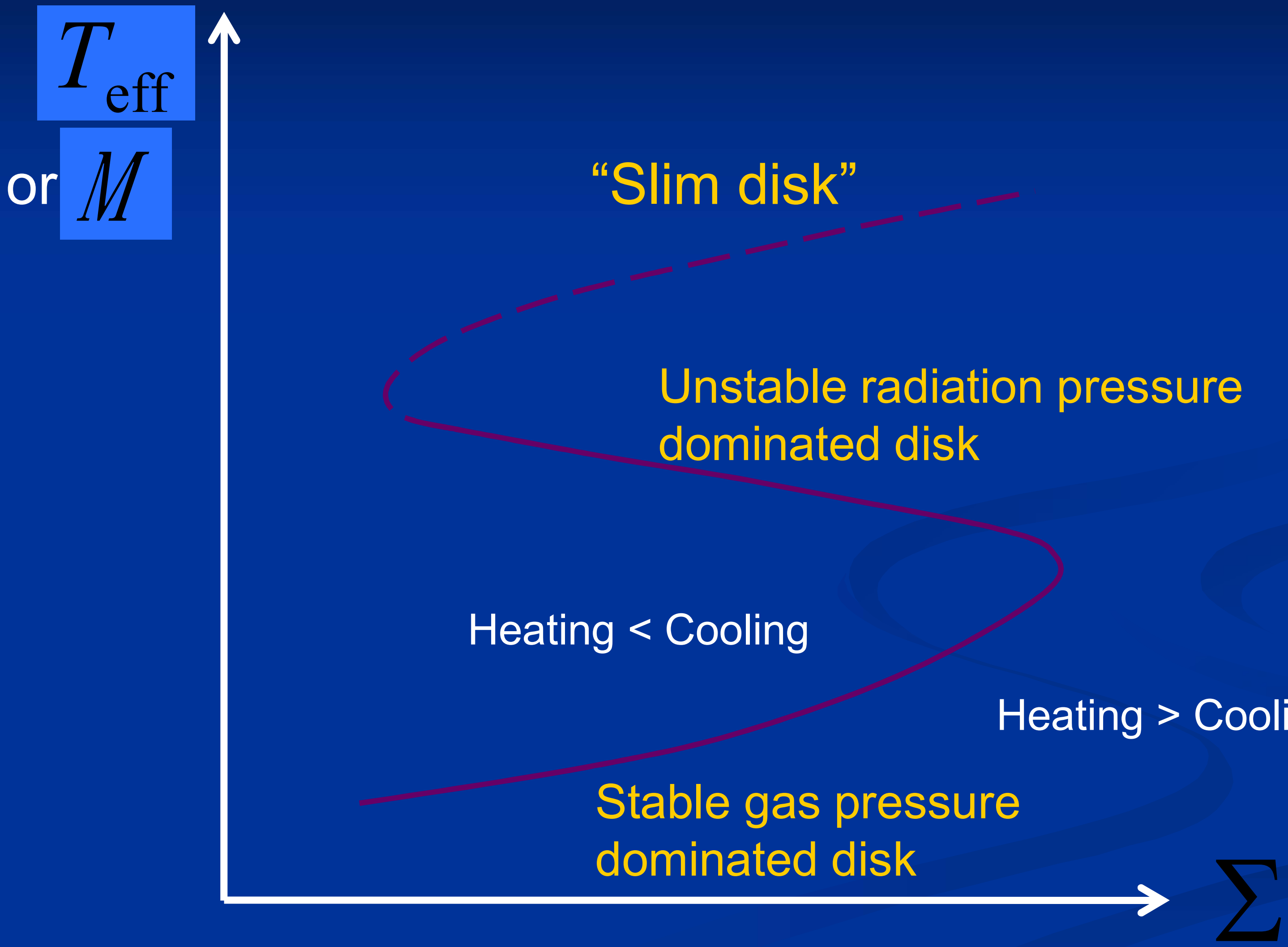
R_{ISCO} and **M** $\longrightarrow$ a_*

Requirements for the X-ray Continuum Fitting Method

Zhang, Cui & Chen 1997

- Spectrum dominated by accretion disk component
- Theoretical profile of disk flux F(R) : NT73
- Thin disk: H/R equivalent to $L/L_{Eddington} < 0.3$
- Accurate estimates of M, D, i
  - Assume alignment of BH spin and orbital angular momentum
- Disk atmosphere model of spectral hardening
  - *(Davis et al. 2005, 2006, 2009; Davis & Hubeny 2006; Blaes et al. 2006)*

Thermal and viscous stability



Thermal stability: an open issue

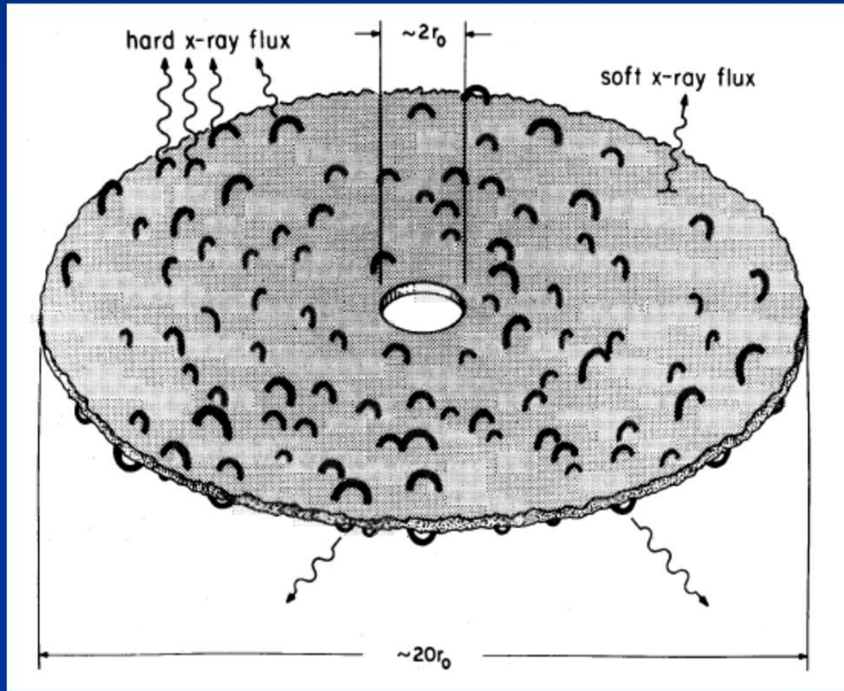
- Observations to the soft state of BHBs show that they are stable!
- RMHD simulations:
  - Hirose, Krolik & Blaes (2009): thermally stable
  - Jiang, Stone & Davis (2013): thermally unstable
  - So it is not understood how to explain observations

Other problems of thin disk model

- Micro-lensing result (Morgan et al. 2010)
  - ‘observed’ size is a factor of 4 larger than predicted
- Under-predict the UV spectrum of AGN (Zheng et al. 1997)
- $\alpha_{FUV} - \mathrm{M_{BH}}$ space not consistent with model (Shang et al. 2005)
- Hard to explain the simultaneous variability at various waveband (Krolik et al. 1991)
- Emission line intensities not consistent with theoretical prediction (Bonning et al. 2013)
- Wind must exist

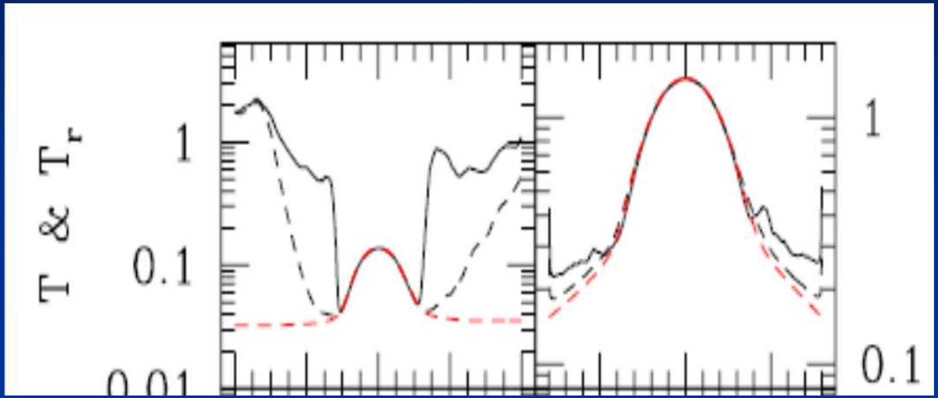
Disc-corona model

- Motivation
  - To explain X-ray radiation
  - Analogy with solar corona
- Formation mechanism of corona
  - Emergence of magnetic field from disk to corona
  - Magnetic reconnection heating
- MHD simulation to Corona:
  - Magnetically supported
  - High temperature

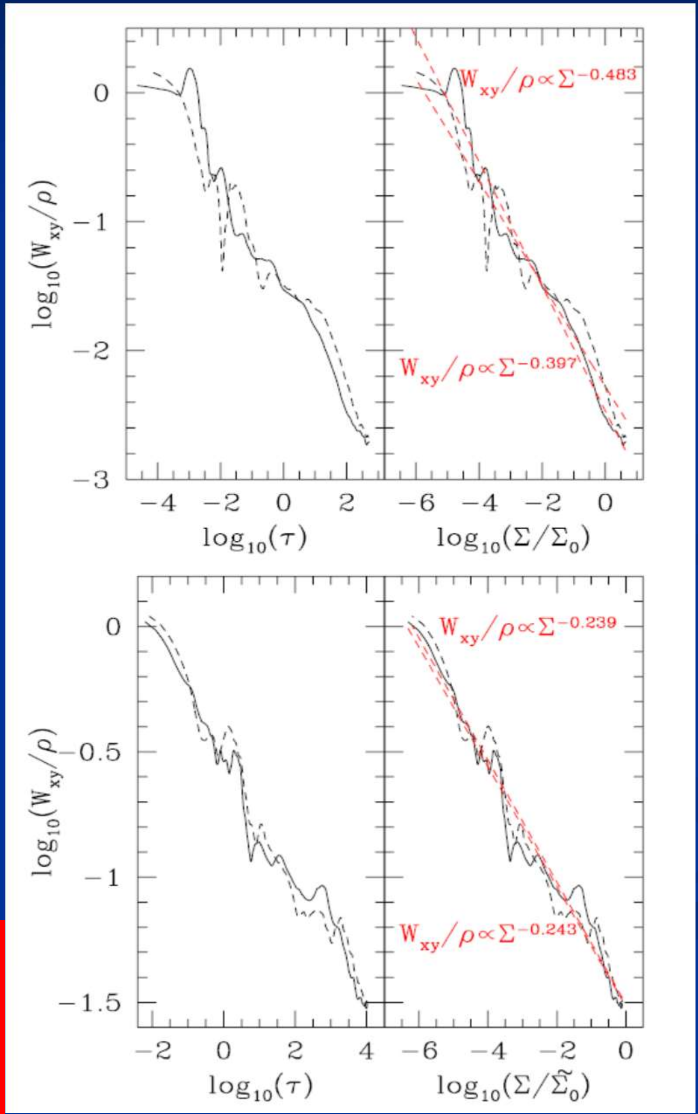


Radiative MHD simulation of corona

Jiang, Stone & Davis 2014



Low Σ high Σ



Low Σ

high Σ

- The strength of the corona depends on surface density of the disk!
- Temperature of corona can be 30 times higher than that of the disk;

Profiles of the stress per unit mass produced by MRI turbulence as a function of optical depth measured from the disk surface (left panels) and the disk surface density (right panels).

2.2 Slim disks

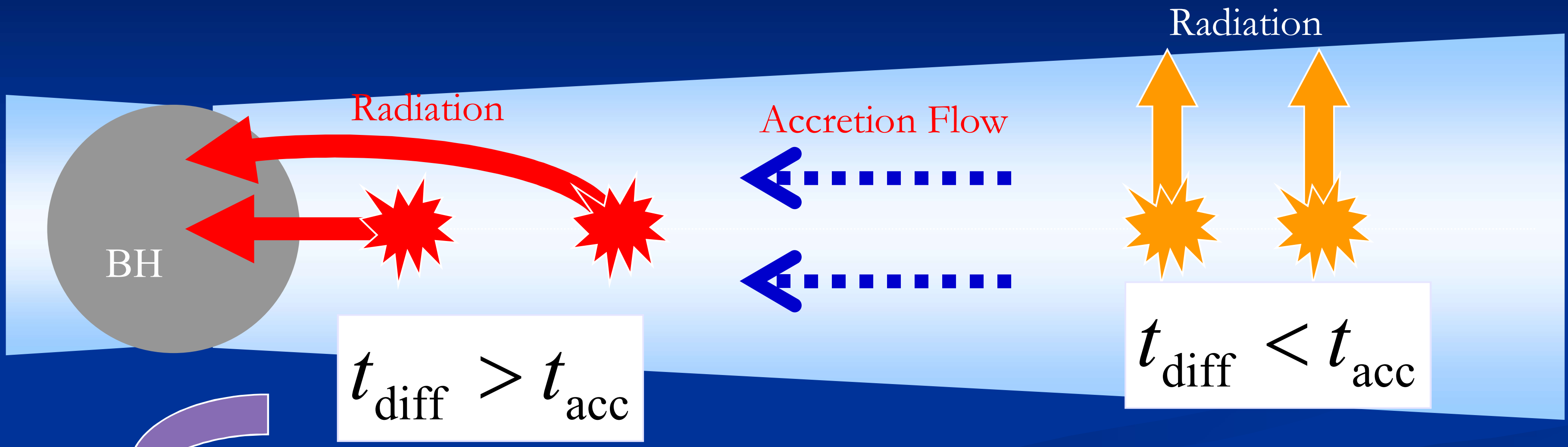
One-dimensional Dynamics: energy advection

- Recall energy eq:

$$H\rho v_r T\frac{dS}{dr}=H\alpha P r\frac{d\Omega}{dr}-F^-$$

- When accretion rate is above Eddington, advection because dominant ("photon trapping" effect). This is because viscous heating increases faster than radiative cooling.
- Thus T is much higher and the disk is slim

Photon Trapping



$$\frac{r}{r_S} < \left(\frac{\dot{M}}{L_E c^2}\right)\left(\frac{H}{r}\right)$$

$$t_{diff} \sim \frac{H}{\tau c}; \quad t_{acc} \sim \frac{r}{v_r}$$

$$\left(\frac{R_{\mathrm{tr}}}{r_g}\right) = \frac{\kappa_{\mathrm{es}} \dot{M}}{\pi c}\left(\frac{H}{r}\right) = 7.2 \times 10^2 \left(\frac{\dot{m}}{50}\right)$$

So photon-trapping occur in the super-Eddington flow

Self-similar solution

Wang & Zhou 1999; Belodorodov 2003

$$P = \left(\frac{\xi f}{n}\right)^{1/2} \frac{\dot{M}\Omega_K}{4\pi\alpha r} \propto r^{-5/2} ,$$

$$\rho = \frac{\gamma_0^2}{4\pi\alpha}\left(\frac{\xi^3}{n^3 f}\right)^{1/2} \frac{\dot{M}}{\Omega_K r^3} \propto r^{-3/2}$$

$$v_r = \frac{n\alpha}{\xi\gamma_0} r\Omega_K \propto r^{-1/2} ,$$

$$\frac{H}{r} = \frac{1}{\gamma_0}\left(\frac{nf}{\xi}\right)^{1/2} = \text{constant} ,$$

$$\Omega = \frac{\Omega_K}{\gamma_0} \propto r^{-3/2} ,$$

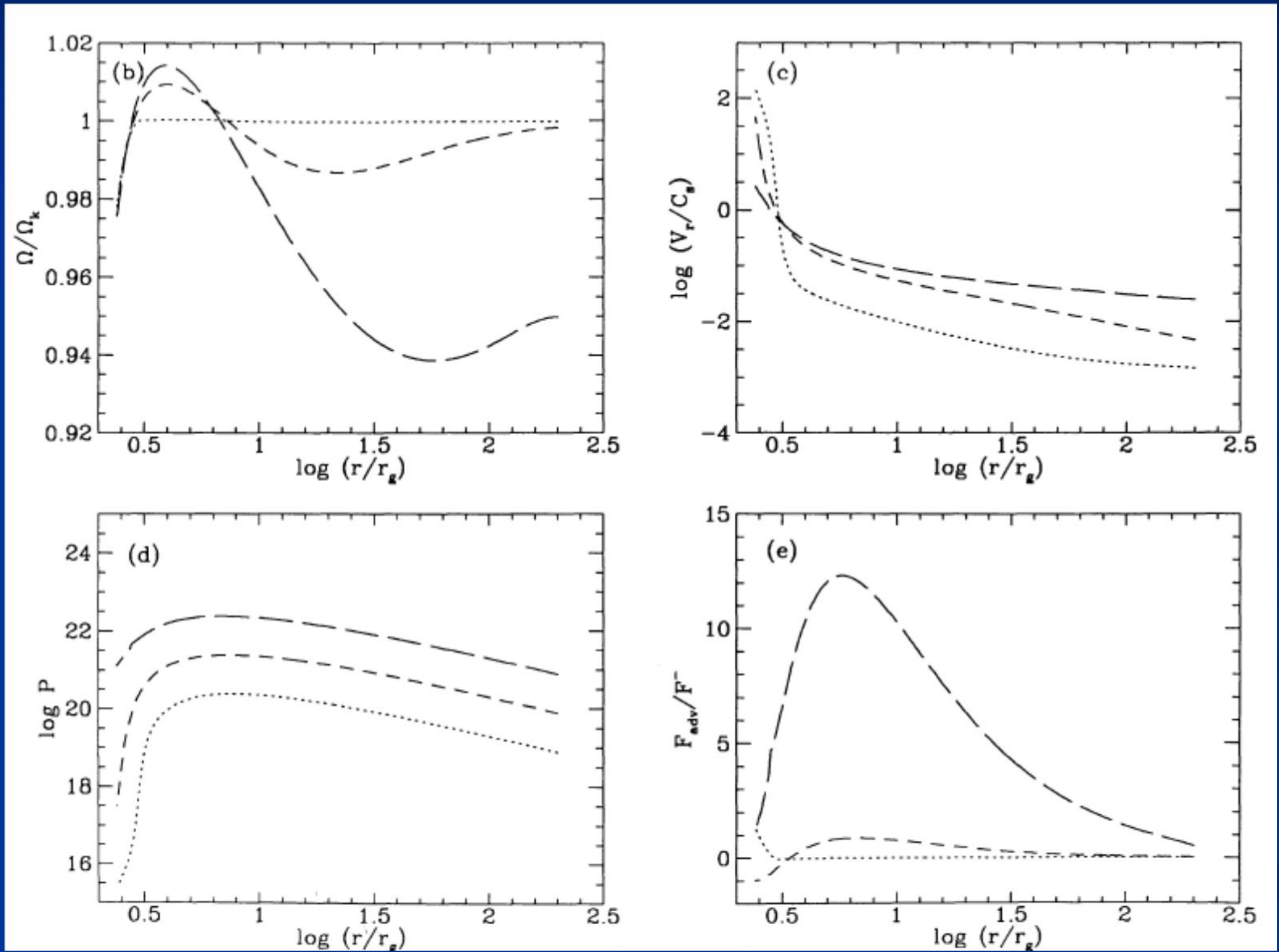
$$c_s = \left(\frac{nf}{\xi}\right)^{1/2} \frac{r\Omega_K}{\gamma_0} \propto r^{-1/2} ,$$

Strong advection assumption

Global solution

- Three boundary conditions to be satisfied
  - Outer boundary condition (temperature, density, radial velocity);
  - sonic point condition (singularity: dv/dr=0/0);
  - inner boundary condition (horizon of the BH)
- Solving two-point boundary value problem:
  - shooting
  - relaxation

One-dimensional global solution



$\dot{M}=0.1,1,10$

Chen & Taam 1993

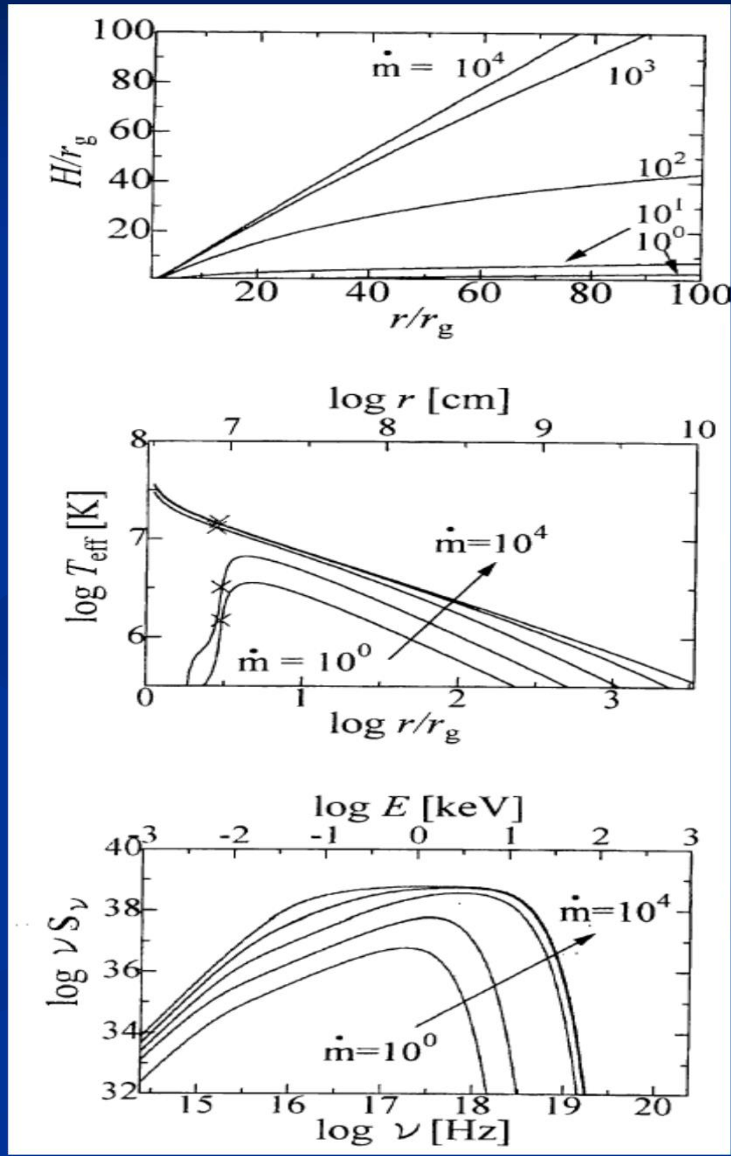
Slim disks: Radiation

- Because of advection, we have

$$T_{\rm eff}^4 \propto \frac{T_c^4}{\tau} \propto \frac{p}{\rho H} \propto r^{-2}$$

different from the thin disk.

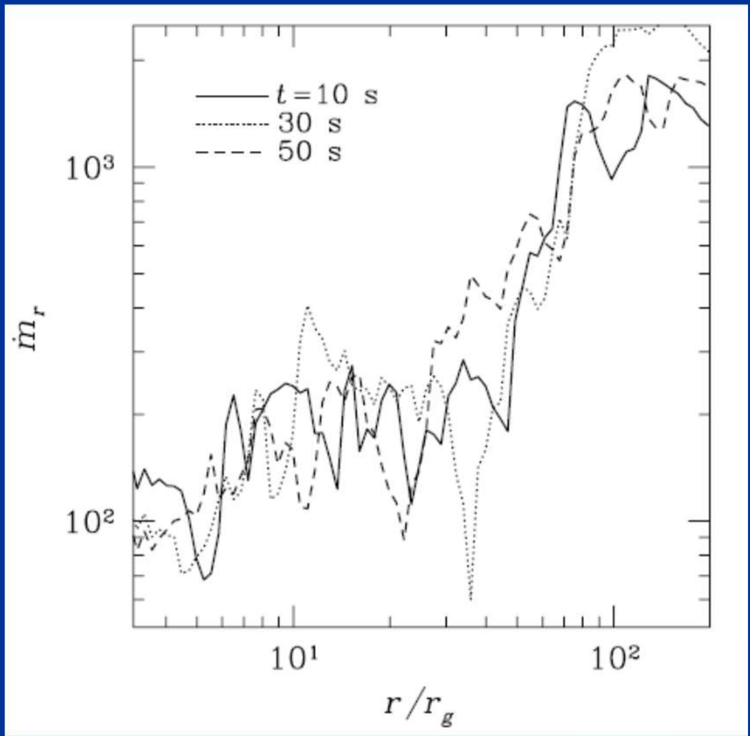
- Thus spectrum also changes
- Radiative efficiency lower than thin disk
- Luminosity: can be much higher than Eddington!

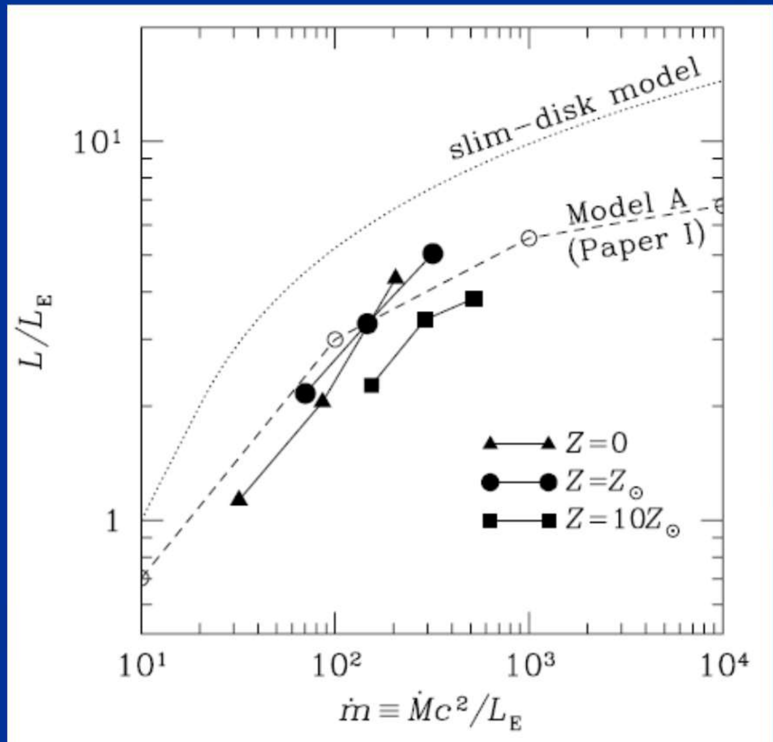


Radiative HD simulations (I)

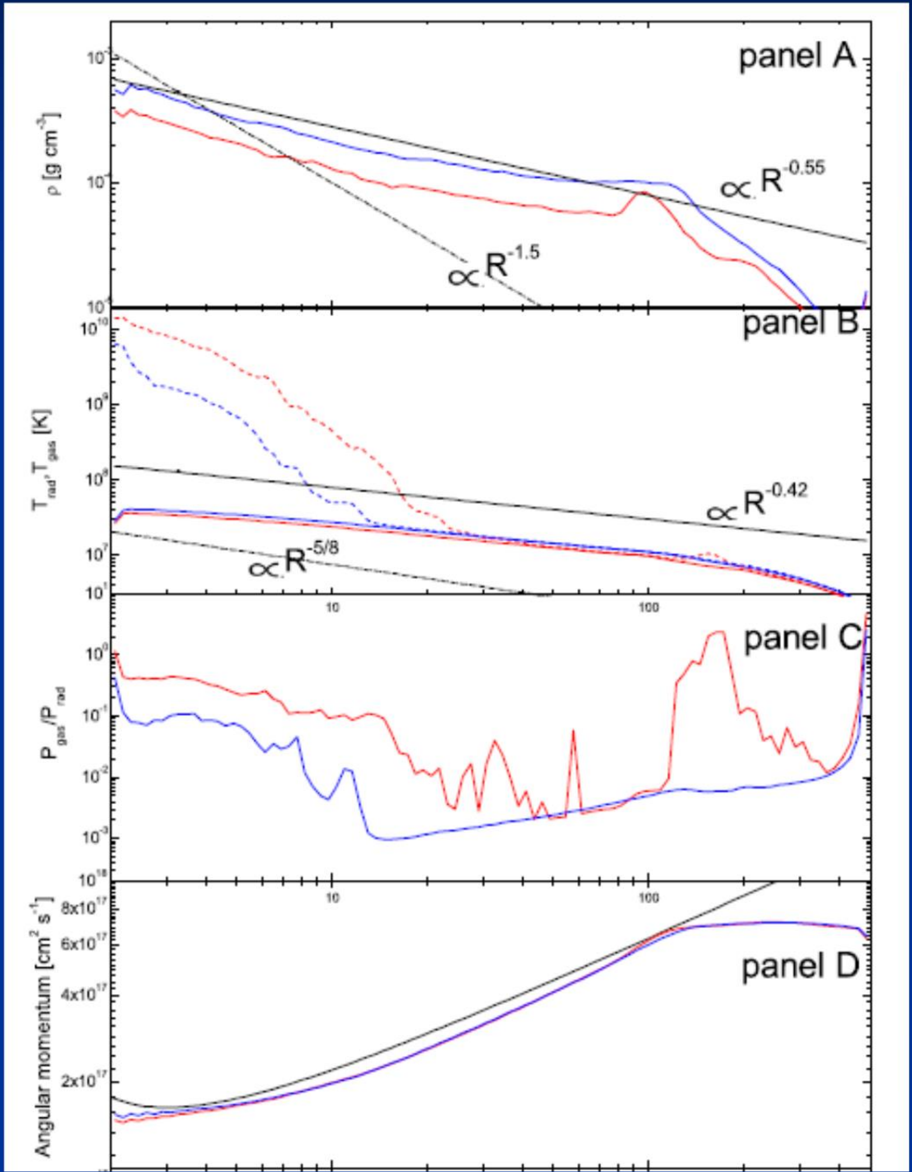
Ohsuga et al. 2005; Yang et al. 2013

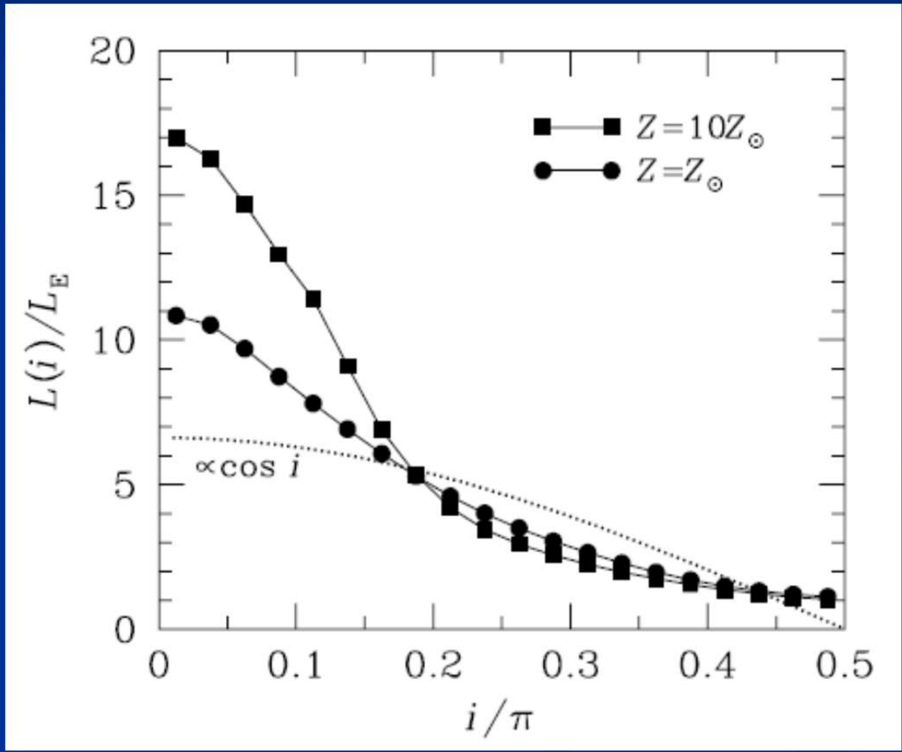
- Accretion rate decreases inward: mass outflow
  - Radiation or convection driven?
- Radiation is highly anisotropic



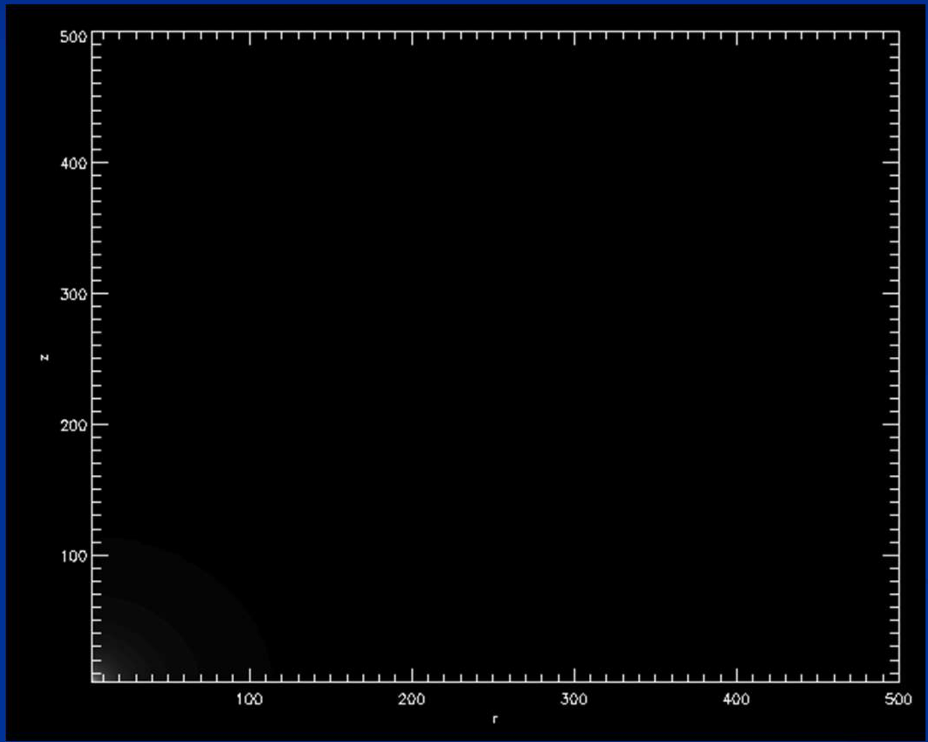


Radiative HD simulation (II)





Movie of slim disk simulation

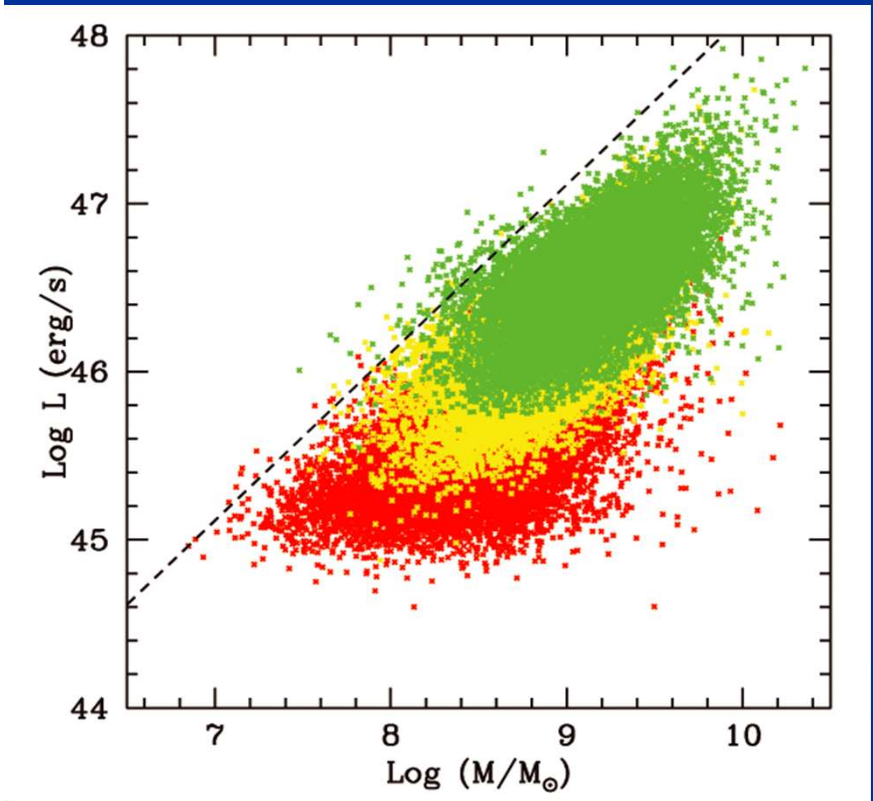


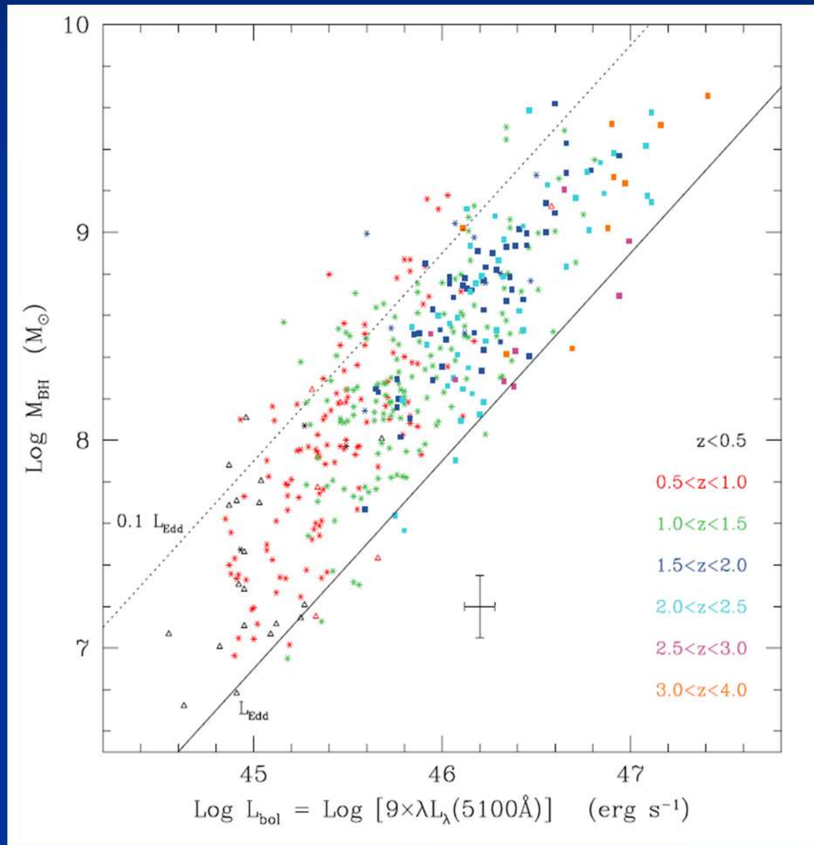
Possible Applications

- Narrow line Seyfert 1 (Mineshige et al. 2000)
- Ultraluminous X-ray sources (Watarai et al. 2001)
- SS433
- Some AGNs

Sub-Eddington puzzle

- Slim disk: super-Eddington
- Observational results →
- Why? Feedback? unknow





Kolleier et al. 2006

Steinhardt & Elvis 2010