Will not follow the subsubsections in the book exactly.

Two additional key references:

*** Accretion Power in Astrophysics, Frank, King, & Raine, Cambridge Univ. Press, 2002**

*** Hot Accretion Flows around Black Holes, Yuan & Narayan, 2014, ARA&A**

Video lectures given by Prof. Feng Yuan (SHAO)!

- What is Eddington luminosity? Can it be surpassed? If yes, how?
- What are the equations to be considered in the cases of HD and MHD accretion disks, respectively?
- Why is viscosity important in the accretion process? Which types of viscosities do you know about?
- What are the main features of the standard thin disk?
- What are the main features of the slim disk?
- What are the main differences between ADAF and LHAF?

Write your brief answers to these questions
using your own words
after this chapter is finished.

http://mooc.chaoxing.com/course/2524589.html

Formation and Co-Evolution of Galaxies and Supermassive Black Holes

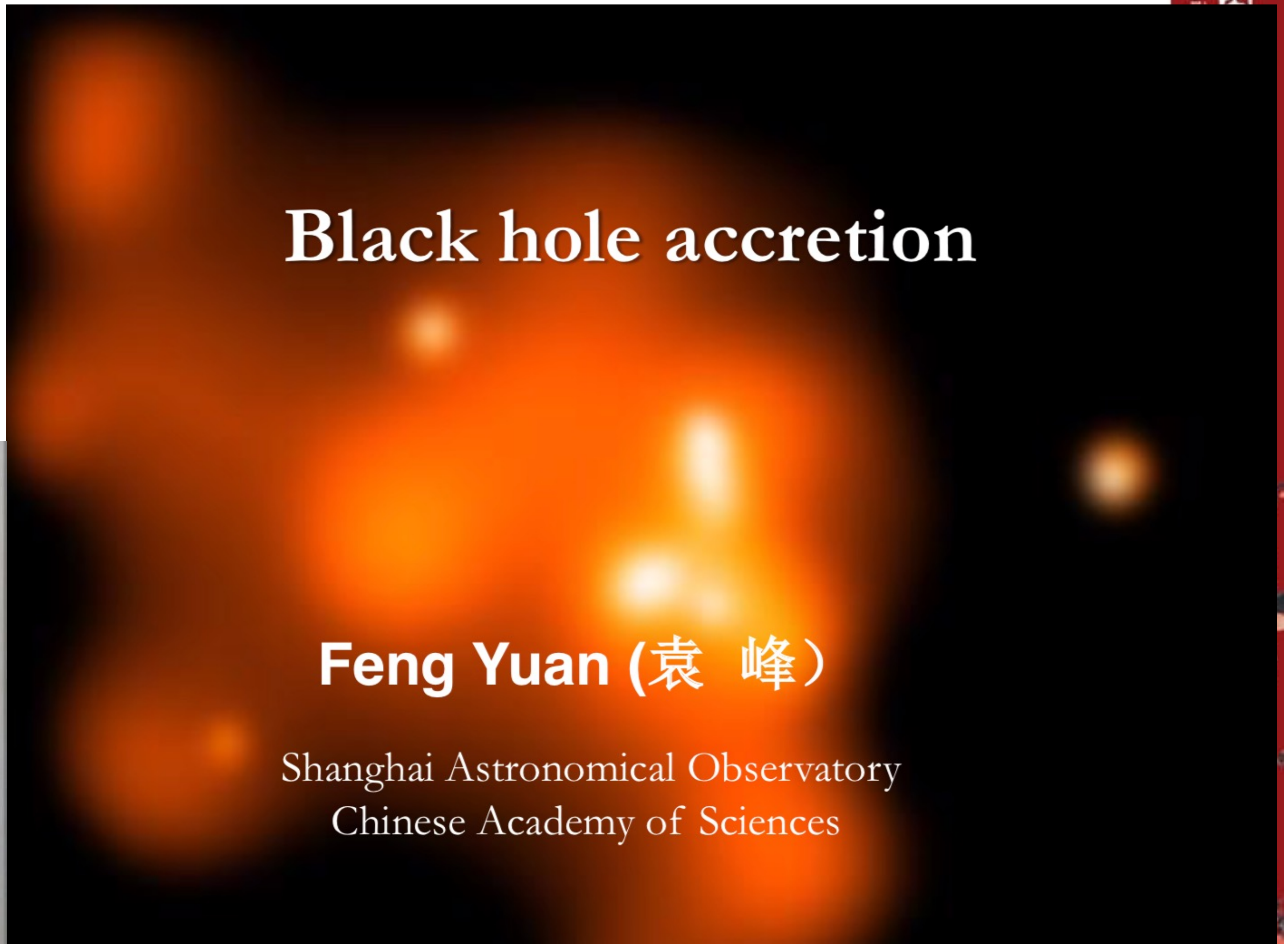
Prof. Niel Brandt : An Observational Overview of Active Galactic Nuclei

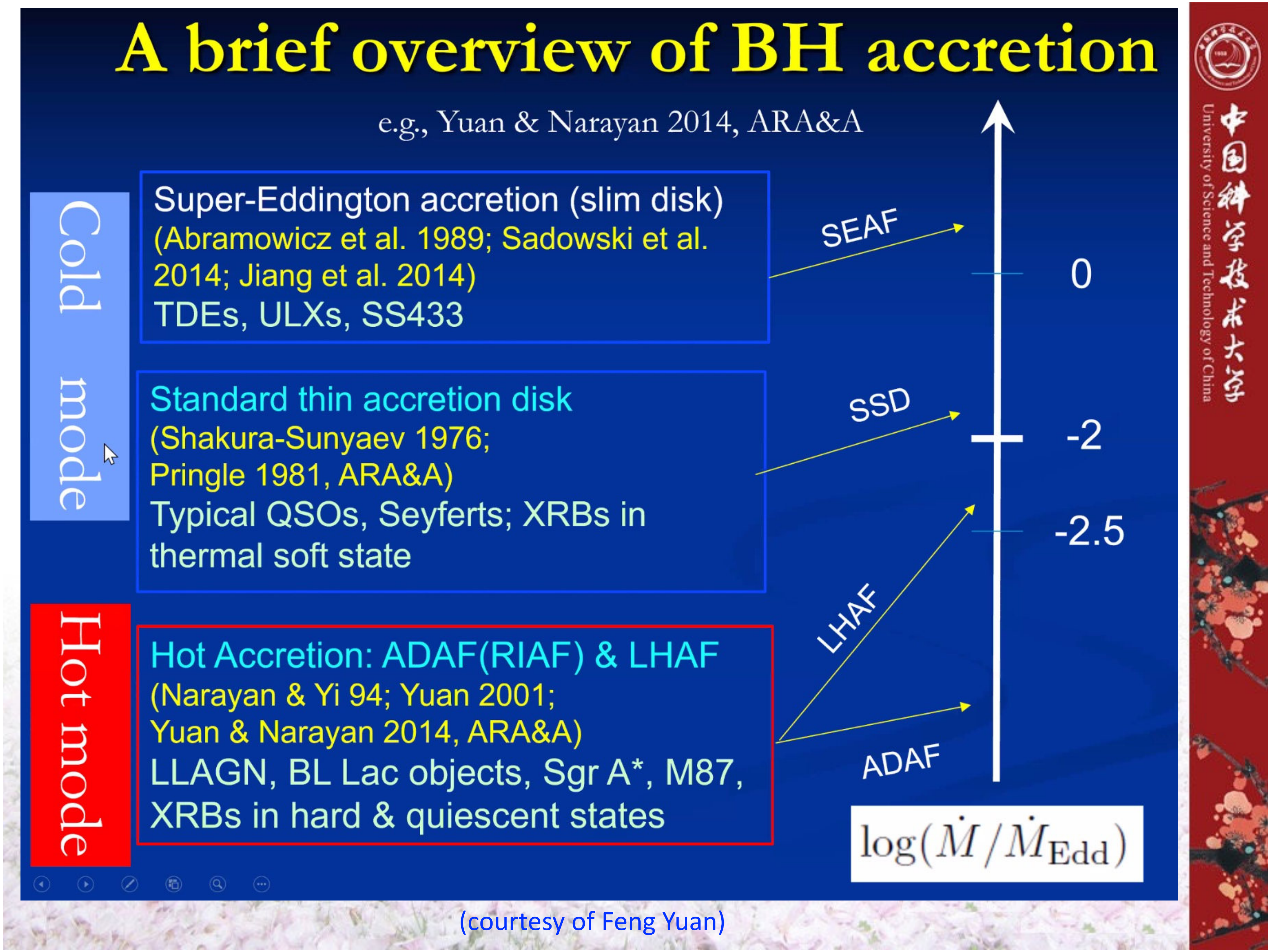
Prof. Luis C.Ho: The Galaxy Population (Properties, Origin, Evolution, Connection to SMBHs)

Prof. Houjun Mo : Cosmology and Galaxy Formation

Prof. Feng Yuan : Black hole accretion

中国科学技术大学
University of Science and Technology of China


Black hole accretion
Feng Yuan (袁 峰）
Shanghai Astronomical Observatory
Chinese Academy of Sciences



(courtesy of Feng Yuan)

4 Accretion disks

- Accretion disks (ADs):

  - very efficient accretion processes

  - fundamental and common physical processes in the universe

    * protostars; planet formation

    * various types of binary stars: LMXBs and HMXBs

    * dwarf novae or cataclysmic variables; classical novae

    * Gamma-ray bursts

    * AGNs

- ADs in galactic centers:

  - naturally formed by infalling gas that sinks into the central plane of the galaxy while retaining most of its angular momentum

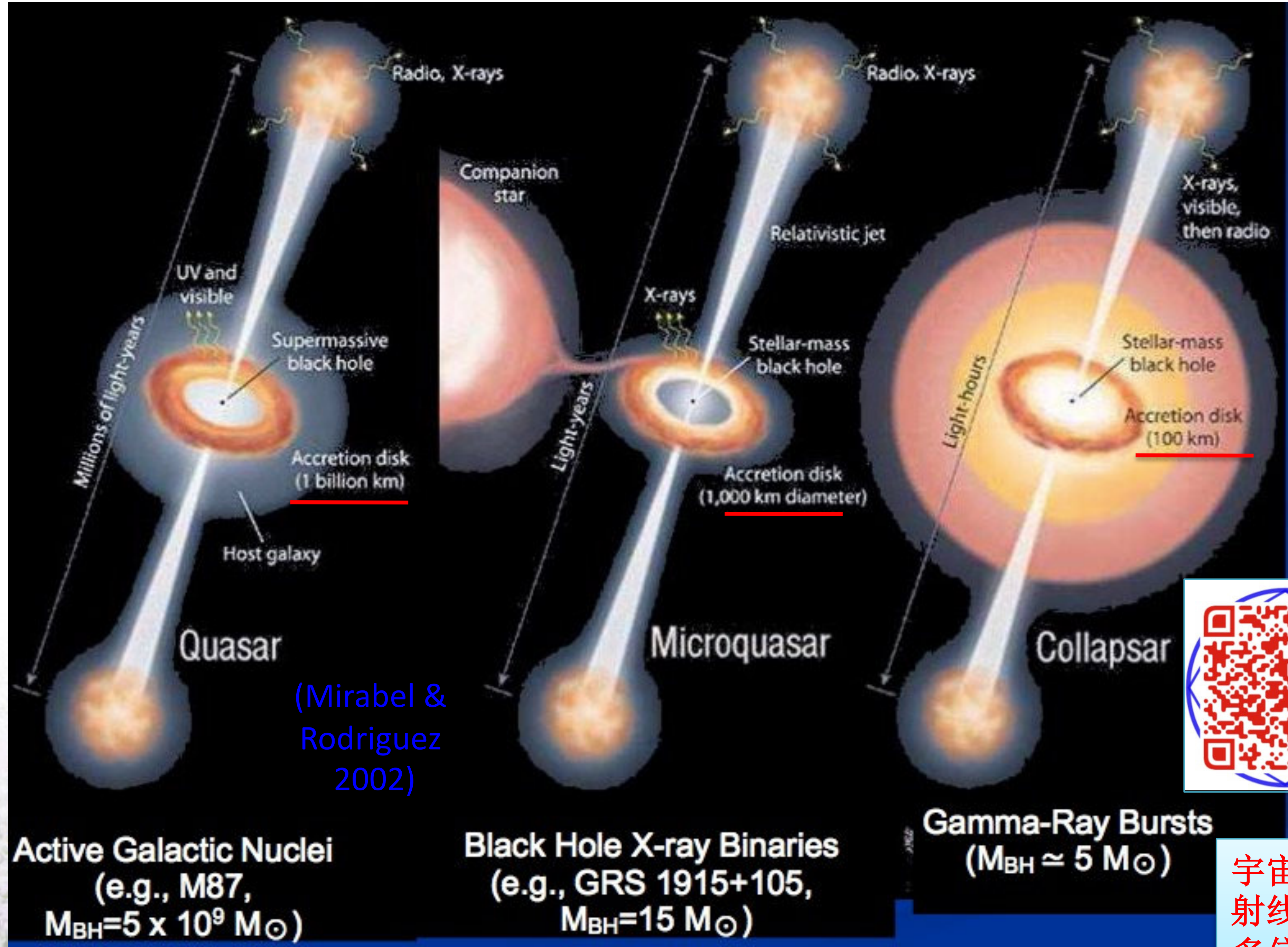
  - assumption: viscosity transfers gas angular momentum outward to allow it spiral into the center, losing a considerable % of grav. energy on the way

  - this lost grav. energy:

    * convert into EM radiation (extremely high efficiency up to ~42%)

    * convert into gas kinetic energy, gas blown away from the disk

    * heat gas to very high T, causing much of energy to be advected into BH



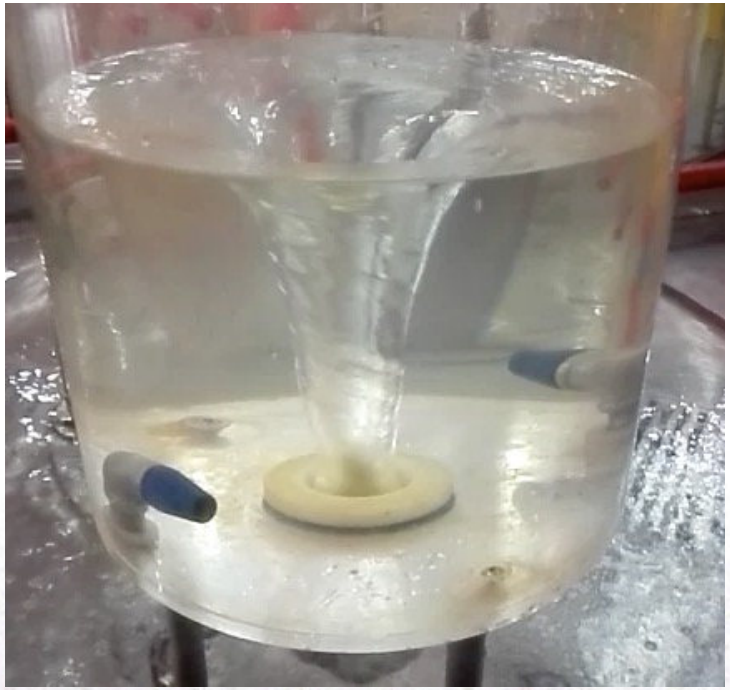
(Mirabel & Rodriguez 2002)

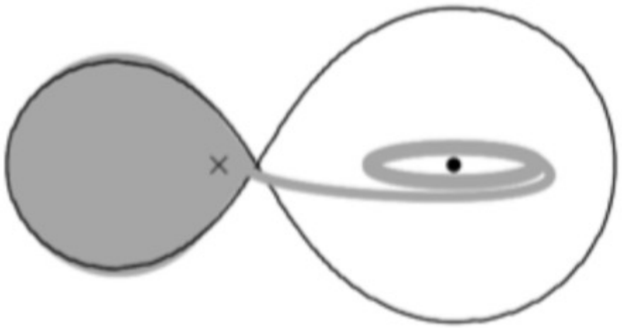
- Common key ingredients: BH, AD, jets at different scales

宇宙伽玛射线暴的多信使研究

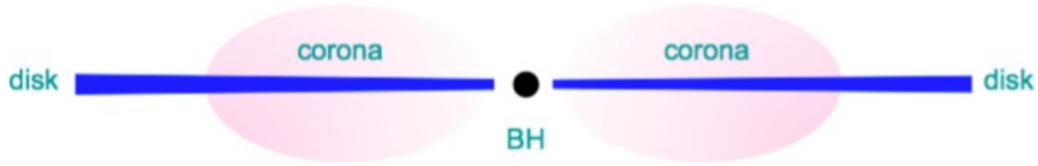
daily-life "accretion" @ Hefei Sci. & Tech. Museum

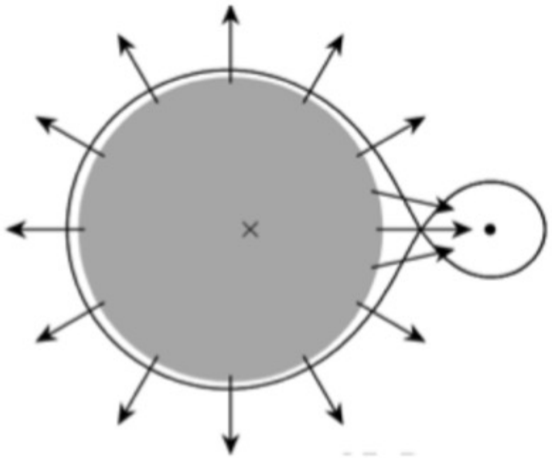
daily-life "accretion" @ Hefei Sci. & Tech. Museum



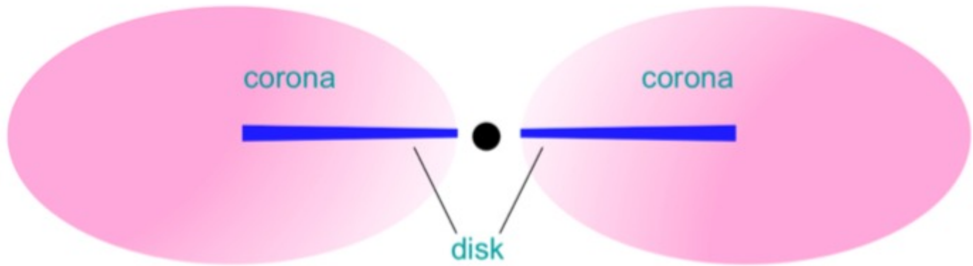


LMXB

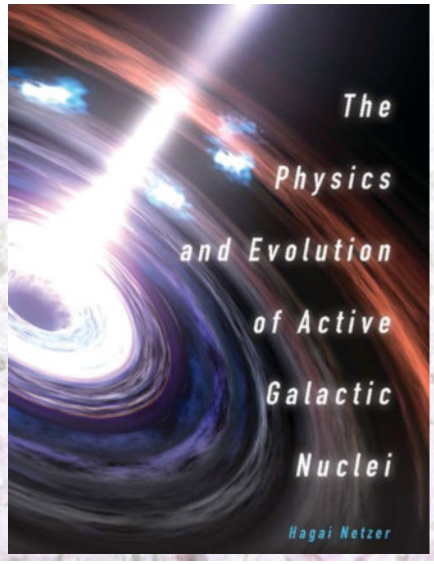




HMXB



AGN？



- ADs: hydrodynamics (HD) --- simplest case

  - continuity equation:

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

mass conservation

  - momentum equation:

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

mom. conservation

where the Lagrangian derivative:

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

going with the flow element

  - energy equation:

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

energy conservation

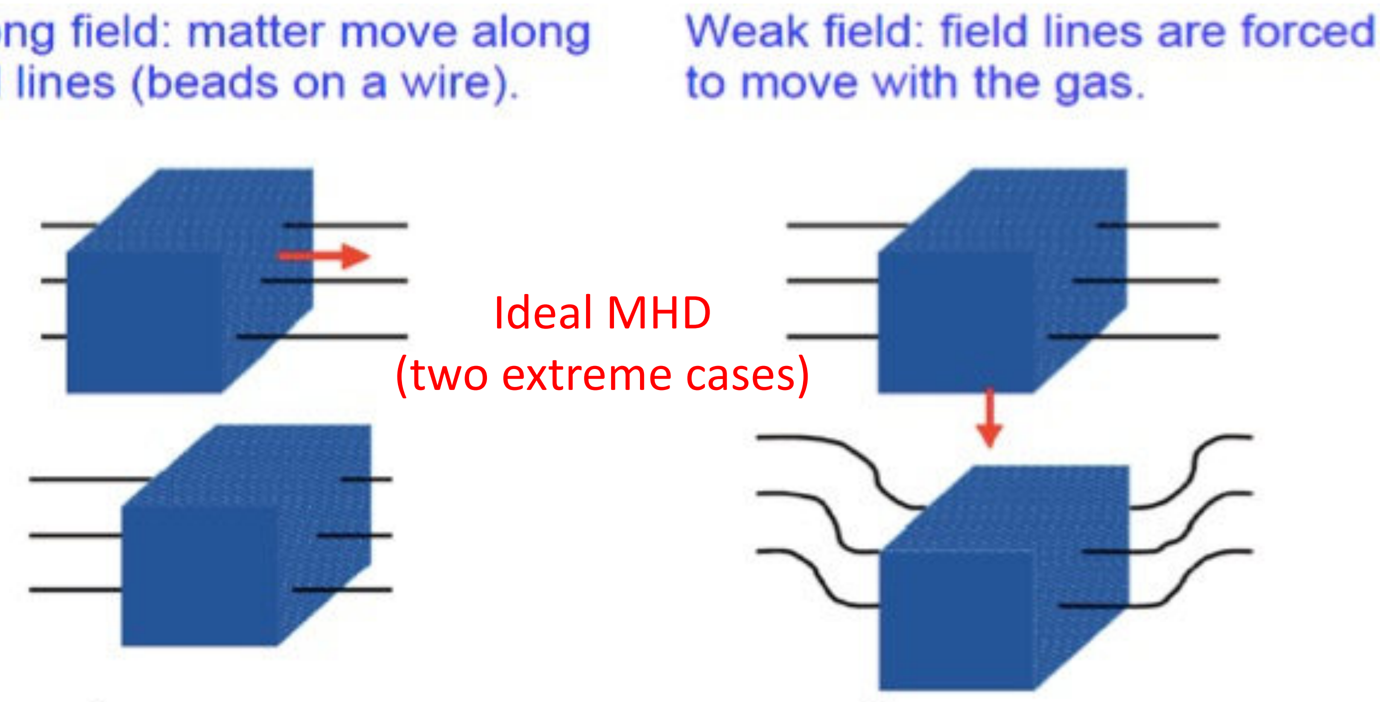
  - equation of state:

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

physical properties (ideal gas)

  - boundary conditions: differential --> algebra equations --> easier to solve

- ADs: magnetohydrodynamics (MHD) --- HD + **magnetic field**
  - HD + Lorentz force (← Maxwell equations)
  - need one additional equation to evolve the magnetic field
    * Faraday's law (induction equation): $$\frac{\partial \boldsymbol{B}}{\partial t} = -c\nabla \times \boldsymbol{E}$$
  - assume ideal MHD: gas is a perfect electric conductor (i.e., no resistance)
    * the induction equation can be written as: $$\frac{\partial \boldsymbol{B}}{\partial t} = \nabla \times (\boldsymbol{v} \times \boldsymbol{B})$$



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

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

- ADs: viscosity holds the key

  - viscous flow (Navier-Stokes viscosity – NS viscosity)

    * Euler's equation and viscous stress tensor:

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

  - physical interpretation: diffusion of momentum – momentum exchange across velocity gradient

  - NS viscosity too small, so we need an 'anomalous' one: alpha-viscosity

    * assumed to be constant in the case of HD

    * MHD simulations give diverse results on alpha

    * alpha increases with the net magnetic flux, ranging from ~0.01-1

  - disk properties that can affect viscosity:

    * local microphysics (e.g., specific atomic or molecular processes)

    * local or global turbulence

    * magnetic field strength and structure

  - results show that the higher the viscosity, the larger is the radial velocity of the inflowing gas; and the inward velocity is much less than the sound speed (i.e., the radial inflow is subsonic)

Corona-heated Accretion-disk Reprocessing: A Physical Model to Decipher the Melody of AGN UV/Optical Twinkling

Mouyuan Sun[1,2,3], Yongquan Xue[2,3], W. N. Brandt[4,5,6], Wei-Min Gu[1], Jonathan R. Trump[7], Zhenyi Cai[2,3], Zhicheng He[2,3], Da-bin Lin[8], Tong Liu[1], and Junxian Wang[2,3]

The Astrophysical Journal, 891:178 (21pp), 2020 March 10

Abstract

Active galactic nuclei (AGNs) have long been observed to "twinkle" (i.e., their brightness varies with time) on timescales from days to years in the UV/optical bands. Such AGN UV/optical variability is essential for probing the physics of supermassive black holes (SMBHs), the accretion disk, and the broad-line region. Here, we show that the temperature fluctuations of an AGN accretion disk, which is magnetically coupled with the corona, can account for observed high-quality AGN optical light curves. We calculate the temperature fluctuations by considering the gas physics of the accreted matter near the SMBH. We find that the resulting simulated AGN UV/optical light curves share the same statistical properties as the observed ones as long as the dimensionless viscosity parameter α, which is widely believed to be controlled by magnetohydrodynamic (MHD) turbulence in the accretion disk, is about 0.01–0.2. Moreover, our model can simultaneously explain the larger-than-expected accretion disk sizes and the dependence of UV/optical variability upon wavelength for NGC 5548. Our model also has the potential to explain some other observational facts of AGN UV/optical variability, including the timescale-dependent bluer-when-brighter color variability and the dependence of UV/optical variability on AGN luminosity and black-hole mass. Our results also demonstrate a promising way to infer the black-hole mass, the accretion rate, and the radiative efficiency, thereby facilitating understanding of the gas physics and MHD turbulence near the SMBH and its cosmic mass growth history by fitting the AGN UV/optical light curves in the era of time-domain astronomy.

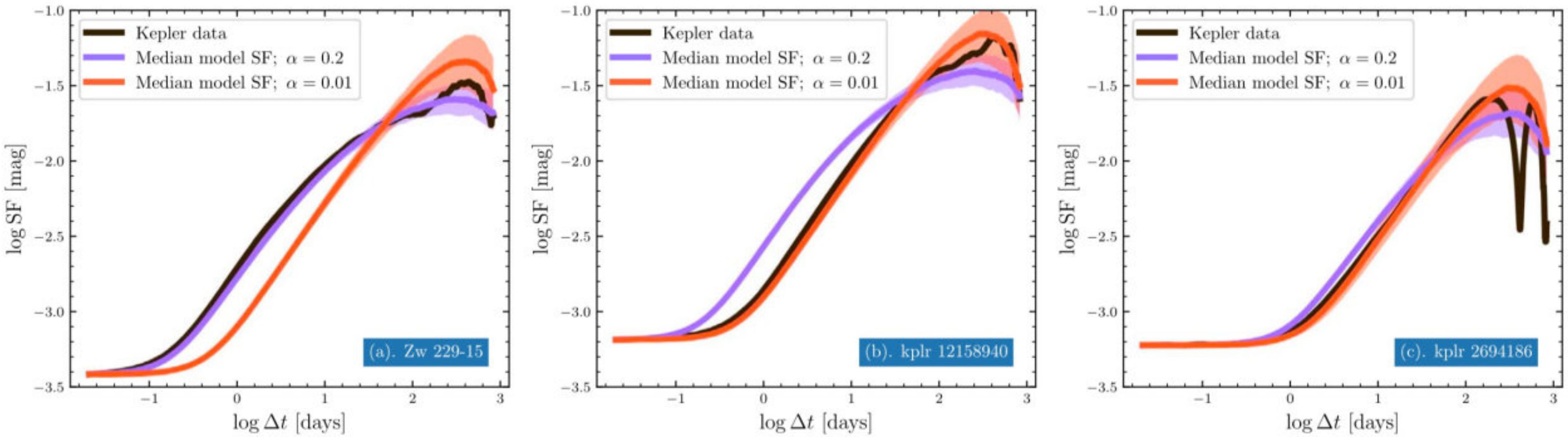


Figure 18. The SFs for the three *Kepler* AGNs. In each panel, the black thick curve represents the observed SF; the purple and orange thick curves correspond to our CHAR model with $\alpha = 0.2$ and $\alpha = 0.01$, respectively; the corresponding shaded regions indicate the 1σ uncertainties, which account for the photometric noise and sampling effects. The SFs show some dips or peaks at the long-timescale ends. This is simply because the light-curve durations are too short to constrain the long-timescale variability. For kplr 2694186, the observed SF has a dip feature around $\Delta t = 400$ days, which indicates periodicity in this source. However, this might be caused by instrumental effects (Smith et al. 2018a). Note that when generating the model light curves, our simulations include the same time-sampling issues and photometric errors as the SFs calculated from the real data.

- ADs: magneto-rotational instability (MRI)

  - MRI --> viscosity fluctuation --> accretion rate fluc. --> L fluc.

  - Rayleigh criteria for unmagnetized rotating disks:

    * unstable if $\frac{d(\Omega R^2)}{dR} < 0$, which is experimentally confirmed

    * all astrophysical disks should be stable based on this criteria

  - include a vertical, well-coupled magnetic field and change the criteria qualitatively:

    * unstable if $\frac{d\Omega}{dR} < 0$

    * all astrophysical disks should be unstable! – MRI (B: not too strong/weak)

  - resulted MHD turbulence: responsible for transport of angular momentum

  - MRI can amplify magnetic field

- ADs: very complicated to find the exact solutions

  - involve HD, MHD, viscosity, and MRI

    * resort to numerical simulations, still extremely challenging

  - consider some simplified cases

    * e.g., no magnetic field

nature astronomy

Article | Published: 30 June 2022

H_2O MegaMaser emission in NGC 4258 indicative of a periodic disc instability

Willem A. Baan, Tao An, Christian Henkel, Hiroshi Imai, Vladimir Kostenko & Andrej Sobolev

Nature Astronomy (2022) | Cite this article

Abstract

H_2O MegaMaser emission may arise from thin gas discs surrounding the massive nuclei of galaxies such as NGC 4258, but the physical conditions responsible for the amplified emission are unclear. A detailed view of these regions is possible using the very high angular resolution afforded by space very long baseline interferometry (SVLBI). Here we report SVLBI experiments conducted using the orbiting RadioAstron Observatory that have resulted in detections of the H_2O 22 GHz emission in NGC 4258, with Earth–space baselines of 1.3, 9.5 and 19.5 Earth diameters. Observations at the highest angular resolutions of 11 and 23 μas show distinct and regularly spaced regions within the rotating disc, at an orbital radius of about 0.126 pc. These observations at three subsequent epochs also indicate a time evolution of the emission features, with a sudden rise in amplitude followed by a slow decay. The formation of these emission regions, their regular spacing and their time-dependent behaviour appear consistent with the occurrence of a periodic magneto-rotational instability in the disc. This type of shear-driven instability within the differentially rotating disc has been suggested to be the mechanism governing the radial momentum transfer and viscosity within a mass-accreting disc. The connection of the H_2O MegaMaser activity with the magneto-rotational instability activity would make it an indicator of the mass-accretion rate in the nuclear disc of the host galaxy.

安涛（上海天文台）：

【科研进展】著名的漩涡星系NGC4258，对，就是那个通过水脉泽精确测量超大黑洞质量的明星星系，又有了新发现！天文学家找到周期性吸积盘不稳定性的观测证据。

由Willem Adrianus Baan教授领导的一个国际团队利用最高分辨率的空间VLBI对黑洞周围的吸积盘中的水超脉泽进行了多次观测（水超脉泽存在于这个气体盘中最致密的气体云中），成功探测到多个随吸积盘旋转的致密云团，这些云团在速度上呈现出有规律的变化。这些观测特征与吸积盘中发生的磁旋转不稳定性相一致。长期以来，有理论研究认为，吸积盘中的校差旋转会驱动产生剪切不稳定性，吸积盘通过这种类型的不稳定性调节径向动量传递和粘滞。这不仅创造了VLBI最高分辨率的记录，达到11微角秒，能够分辨出这个星系中62个天文单位大小的天体的结构（这个尺度相当于从太阳到海王星距离的两倍），而且还代表了空间VLBI在黑洞吸积盘研究领域的一个突破，使人们能够首次了解到吸积盘的最精细的动力学特性。

- Classification of AGN disks and ADs in general:

  - based on shape: thin, slim, and thick disks (depend on mass accretion rate)

    * whether being optically thin or thick, depending on column density (or surface density) and level of ionization of the gas

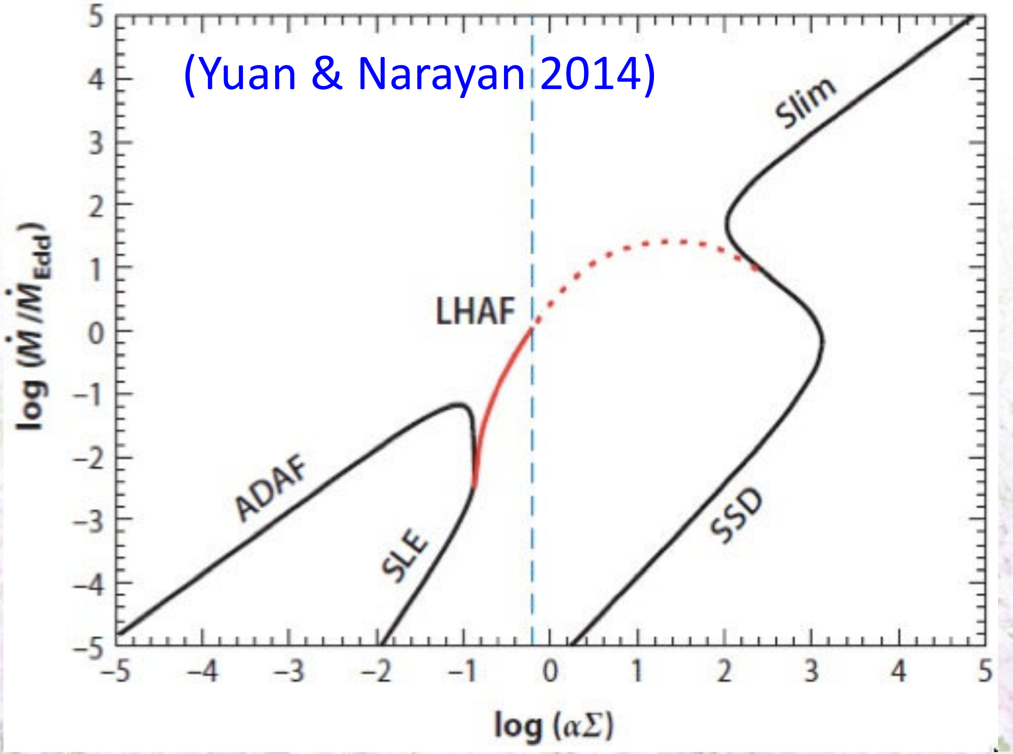
    * optical depth of AGN disks during fast accretion is very large

- Optically thick, geometrically thin ADs:

  - receive most attention

  - easier to treat analytically and numerically

  - a full solution can be used to calculate the emergent disk spectrum and to compare it with observations



- hot vs. cool
- optically thin vs. thick
- high vs. low accretion rate

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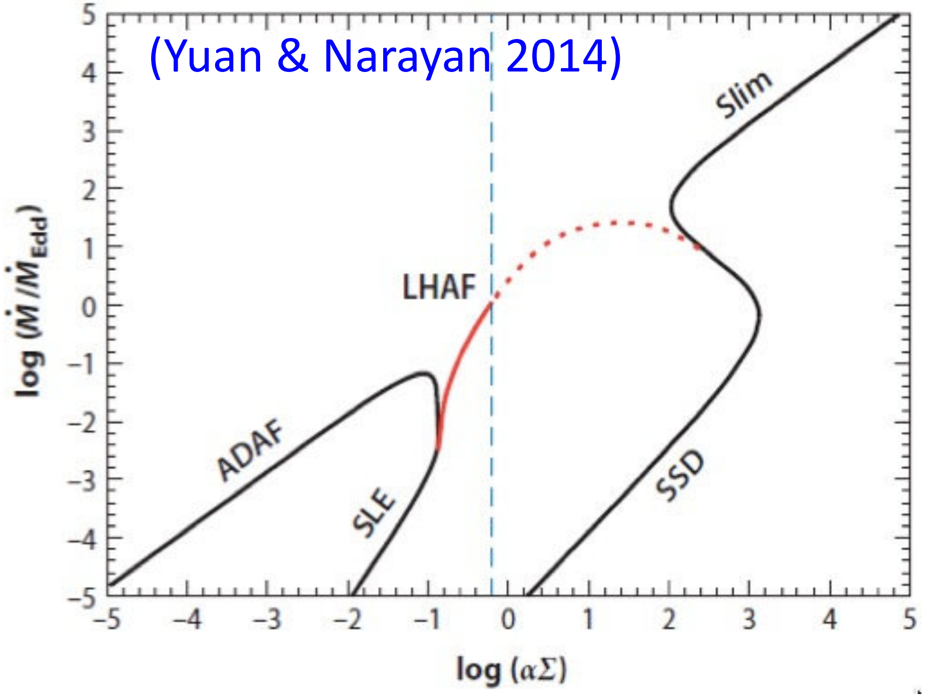
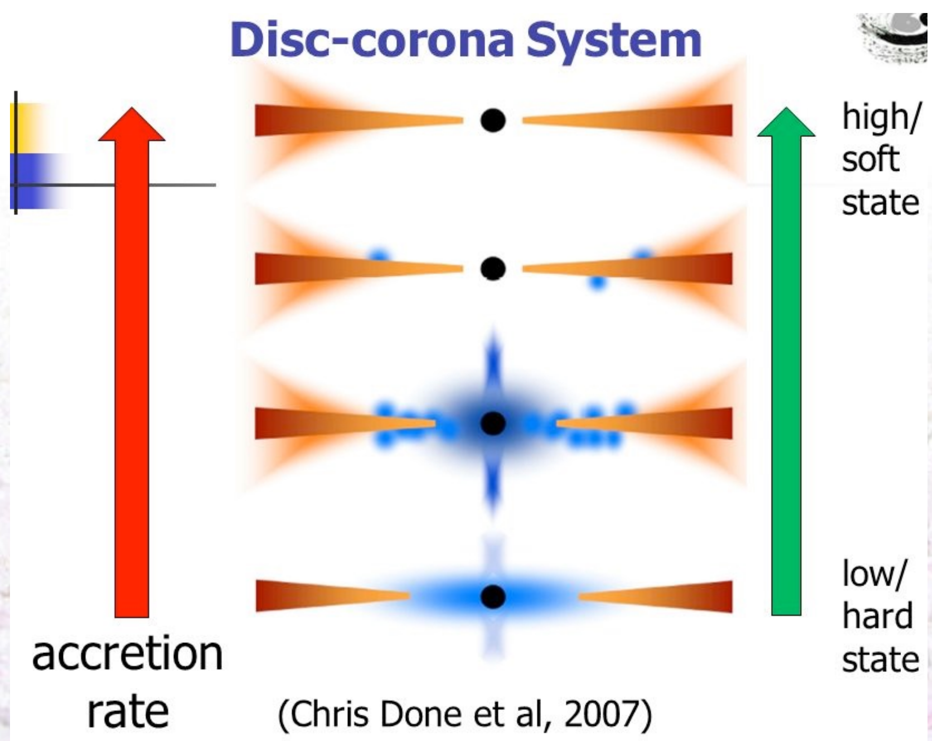


- temperature
- optical depth
- accretion rate
- thickness
- surface density
- radiative efficiency



4.1 Optically thick, geometrically thin ADs

- Optically thick, geometrically thin ADs:
  - likely to form over a large range of conditions in galactic nuclei during times when large amounts cold gas are falling toward the center
  - properties governed by fundamental parameters:
    * accretion rate, BH mass, and BH spin
    * determine disk geometry, gas T everywhere, overall L, emitted spectrum

- Measure accretion rate in units of normalized accretion rate L/L_{Edd}
  - not very accurate definition: accretion rate related to observed L via efficiency, so depending on BH spin; taking $\eta \sim 0.1$ for general discussion

H(r)

- Standard optically thick, geometrically thin AD:

  - approximated as a combination of multiple adjacent rings where all released grav. energy can be radiated locally as a perfect blackbody

  - characterized by 0.01 <~ L/L_{Edd} <~ 0.3

    * exact upper limit depends on disk shape and its deviation from a simple thin structure (definition of thin: thickness over radius well below 0.1)

    * lower limit determined by disk viscosity and radiation efficiency

  - major assumptions:

    * accreted gas moves inward slowly while retaining circular orbital motion

    * the motion of a particle in the ring is coupled to the motion of gas particles just outside and just inside its location through some kind of friction or viscosity (friction between adjacent rings determined by viscosity)

  - viscous time scale (i.e., the radial drift time through the disk) t_{vis}:

    * some typically assumed values give t_{vis}~1e4 yr at $r=100r_g$

    * faster AGN variability seen: other mechanisms affecting disk L needed

we write an expression for the *viscous time scale*, t_{vis}, which is the radial drift time through the disk,

$$t_{\mathrm{vis}} \simeq \frac{r}{v_r} \simeq \frac{2r^2}{3\nu}. \tag{4.33}$$

The additional time scales that can provide some explanation to the optical–UV continuum variations are as follows:

The sound-crossing time scale:

$$t_s \simeq \frac{0.3 M_8}{\sqrt{T/10^4}} \frac{r}{r_g} \text{ yr} \tag{4.36}$$

The dynamical time scale:

("free fall")

$$t_{\mathrm{dyn}} \simeq 0.005 M_8 \left[\frac{r}{r_g}\right]^{2/3} \text{ yr} \tag{4.37}$$

The thermal time scale:

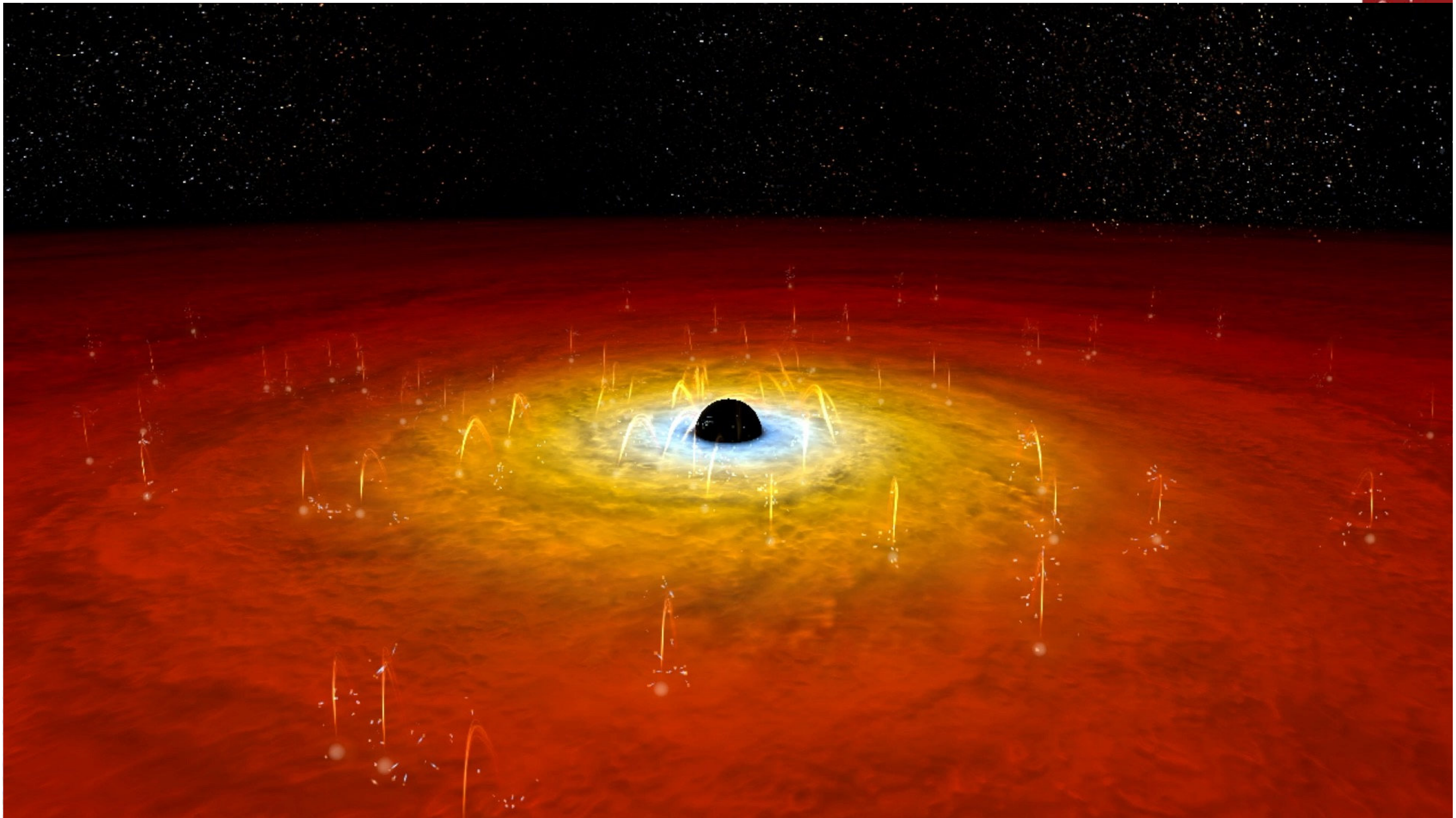
("fall with friction")

$$t_{\mathrm{th}} = t_{\mathrm{dyn}}/\alpha \tag{4.38}$$

The light-crossing time scale:

$$t_l \simeq 0.016 M_8 \frac{r}{r_g} \tag{4.39}$$

The light-crossing time scale is relevant to the case of an irradiated disk, which is discussed later. The other time scales are important in various cases involving instabilities in the disk.



Equations

- Mass conservation: $\dot{M} = 4\pi r H \rho v_r$

(P. gradient centrifugal gava. force accerlation)

- Momentum: $\frac{1}{\rho}\frac{dP}{dr} - (\Omega^2 - \Omega_k^2) r + v_r \frac{dv_r}{dr} = 0$
- Angular momentum: $\dot{M}(l - l_0) = 4\pi r^2 H \alpha P$

(2nd thermaldynamics law: TdS=dQ heat change viscous heating radiation loss)

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

Here the vertical radiation flux is:

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

Energy equation

- When effective optical depth >>1, radiative flux:

$$F(z) = \frac{-16\sigma T^3}{3\kappa_R \rho}\frac{\partial T}{\partial z}$$

(assume Roseland opacity)

- We should have: $$\frac{\partial F}{\partial z} = Q^+$$

E dissipation rate/area

- Integrate it, we have: $$\frac{-4\sigma T_c^4}{3k_R \rho H} = D(R)$$

- So:

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

(Tc: T at disk equator)

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

$$\frac{H_0}{r} = \frac{v_s}{v_K}$$

$$v_s \sim \sqrt{\frac{P}{\rho}}$$

$$v_s \ll v_K$$

A thin disk

Keplerian rotaion:

$$\text{Momentum:}\quad \frac{1}{\rho}\frac{dP}{dr} - (\Omega^2 - \Omega_k^2)r + v_r\frac{dv_r}{dr} = 0$$

Radiation

- We should have: $\sigma T^4(R) = D(R)$ [Compare with: $\frac{4\sigma}{3\tau}T_c^4 = D(R)$]

(T: T at disk surface)

- 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,

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

Shakura-Sunyaev solution

Under assumptions of:

1) gas pressure dominated; P=nKT
2) \alpha-viscosity; $\nu = \alpha' v_s H$ $\alpha = \frac{3\alpha'}{2}$
3) Roseland opacity well approximated by Kramer's law (powerlaw)

$$\Sigma = 5.2\alpha^{-4/5}\dot{M}_{16}^{7/10} m_1^{1/4} R_{10}^{-3/4} f^{14/5}\ \mathrm{g\ cm^{-2}},$$
$$H = 1.7\times10^{8}\alpha^{-1/10}\dot{M}_{16}^{3/20} m_1^{-3/8} R_{10}^{9/8} f^{3/5}\ \mathrm{cm},$$
$$\rho = 3.1\times10^{-8}\alpha^{-7/10}\dot{M}_{16}^{11/20} m_1^{5/8} R_{10}^{-15/8} f^{11/5}\ \mathrm{g\ cm^{-3}},$$
$$T_c = 1.4\times10^{4}\alpha^{-1/5}\dot{M}_{16}^{3/10} m_1^{1/4} R_{10}^{-3/4} f^{6/5}\ \mathrm{K},$$
$$\tau = 190\alpha^{-4/5}\dot{M}_{16}^{1/5} f^{4/5},$$
$$\nu = 1.8\times10^{14}\alpha^{4/5}\dot{M}_{16}^{3/10} m_1^{-1/4} R_{10}^{3/4} f^{6/5}\ \mathrm{cm^2\ s^{-1}},$$
$$v_R = 2.7\times10^{4}\alpha^{4/5}\dot{M}_{16}^{3/10} m_1^{-1/4} R_{10}^{-1/4} f^{-14/5}\ \mathrm{cm\ s^{-1}},$$
$$\text{with } f = \left[1-\left(\frac{R_*}{R}\right)^{1/2}\right]^{1/4}.$$

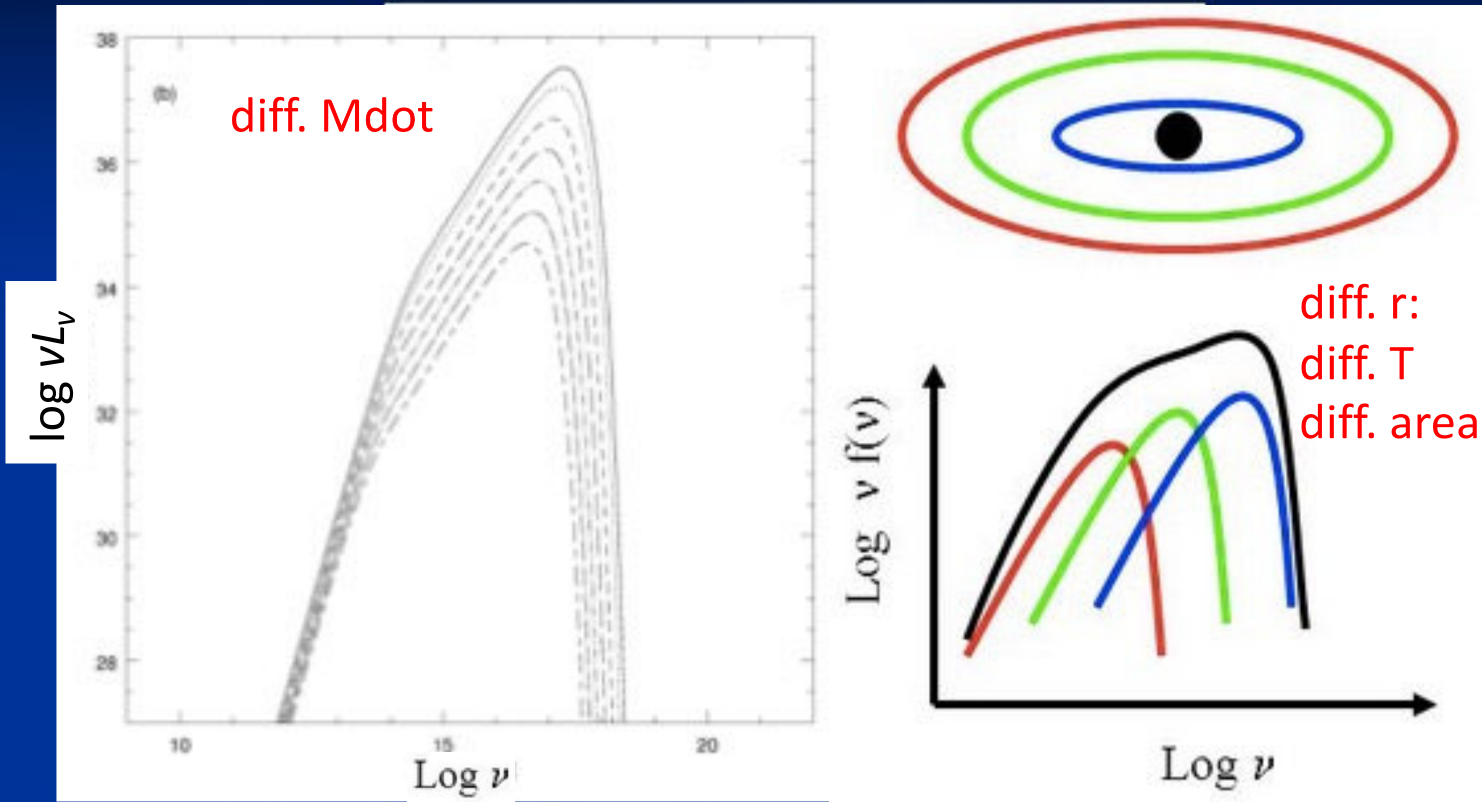
known Mbh & Mdot

$$T\left(\frac{r}{r_g}\right) \propto M_8^{-1/4}\left[\frac{\dot{M}}{\dot{M}_{\mathrm{Edd}}}\right]^{1/4}\left[\frac{r}{r_g}\right]^{-3/4} f(r)$$

$$f(r) = 1-\left(\frac{r_{\mathrm{in}}}{r}\right)^{1/2}$$

- Such disks emit most of E in UV for AGNs, while X-rays for stellar BHs: ~$M^{-1/4}$
- Multi-temperature blackbody emission: temperature ~$r^{-3/4}$

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.

$$\dot{M}_\odot \simeq 2.6 \left[\frac{L_{5100,45}}{\cos i} \right]^{3/2} M_8^{-1}$$

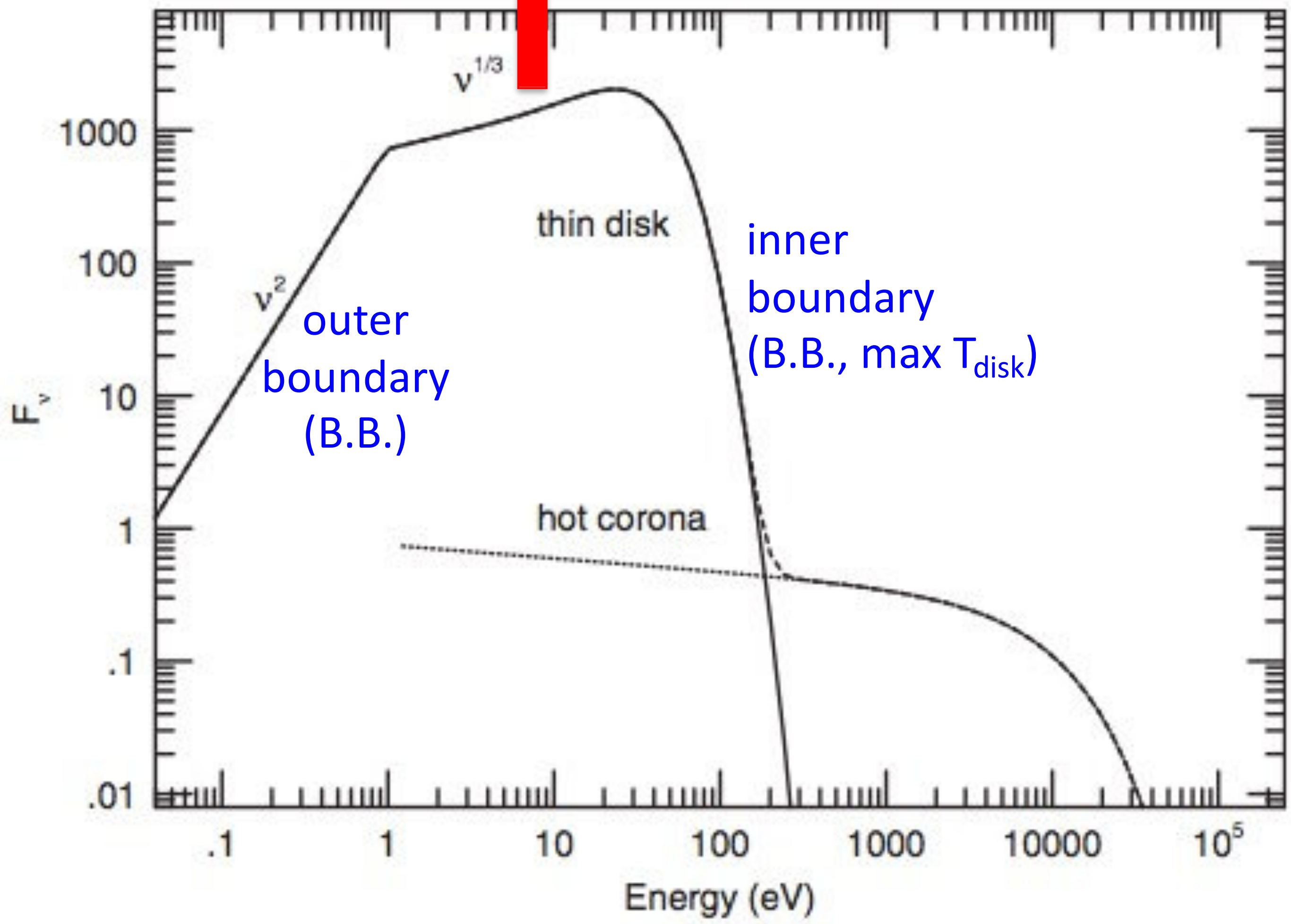
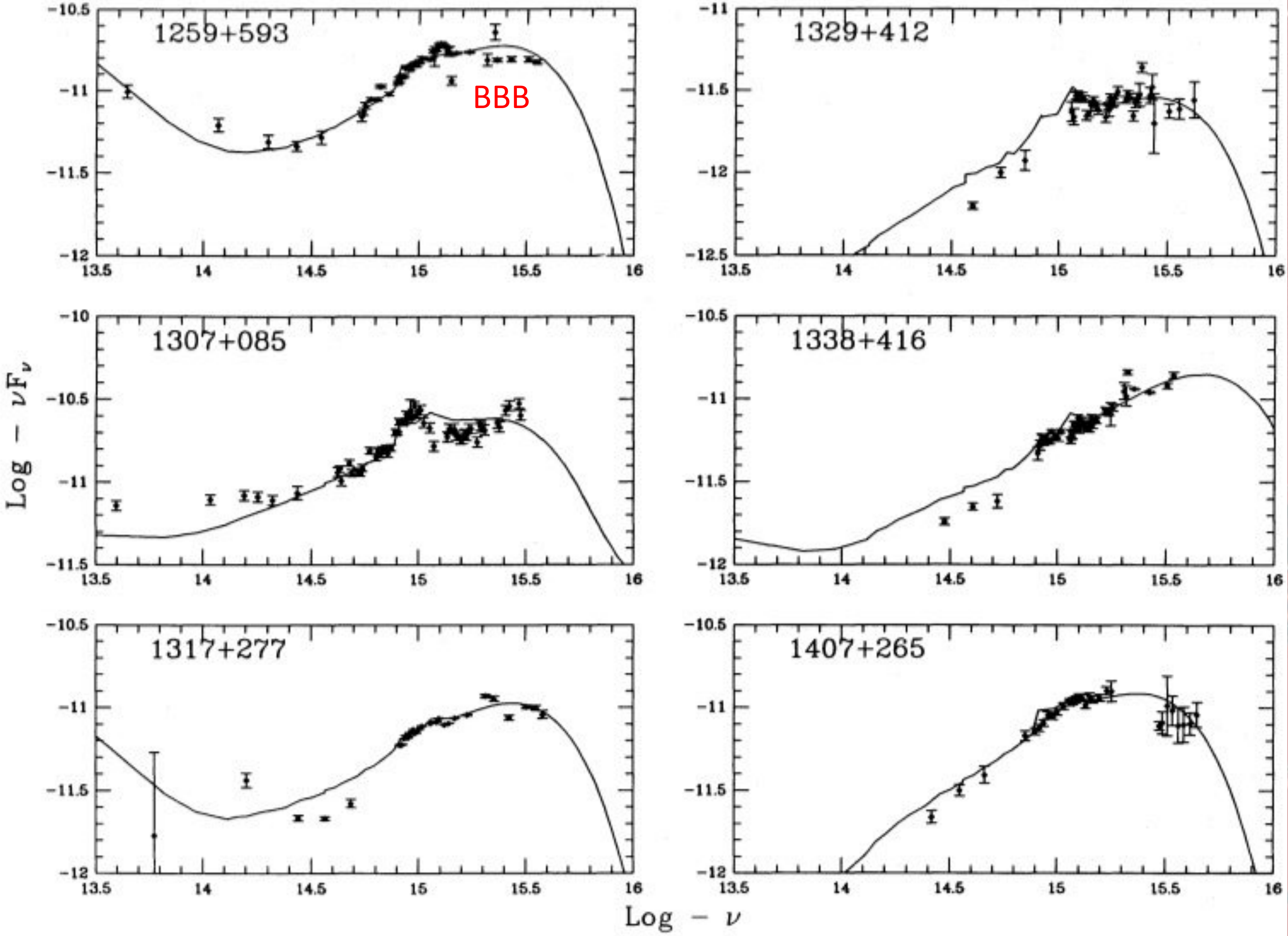


Figure 4.3. A schematic of a combined disk–corona spectrum. The maximum temperature of the geometrically thin, optically thick accretion disk is $T_{max} = 10^5$ K, and its outer boundary temperature is determined by the conditions at the self-gravity radius. The disk is surrounded by an optically thin corona with $T_{cor} = 10^8$ K.

SSD + powerlaw + recombination + starlight



(Sun & Malkan 1989: use thin ADs to fit UV-opt-IR SEDs of 60 QSOs and AGNs)

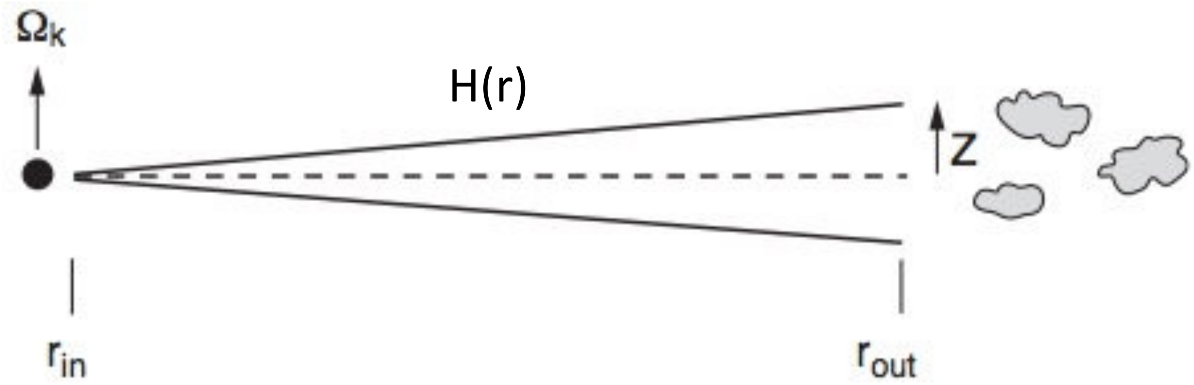


Figure 4.1. Definitions of basic disk parameters. The inner boundary of the disk is assumed to be the location of the ISCO. The outer boundary, r_{out}, is the self-gravity radius of the disk beyond which it breaks into self-gravitating blobs (courtesy of K. Sharon).

- r_{ISCO} (r_{ms}) provides a good approximation for r_{in} and its exact value depends on BH spin as mentioned before
- r_{out} is more difficult to define and is a function of the pressure and gravity at large distances

  - fate of outward-going angular momentum

    * result in expansion of the outer parts of the disk

    * some of this momentum may be transferred to gas and stars in regions far away from the BH

    * the inner torus in AGNs may be influenced by this process

- Assumption that all released grav. energy can be radiated locally as a perfect blackbody must break down at some point:

  - e.g., the disk density may be too low to radiate away all locally released energy on local dynamical time

    * local T increases and the assumption of a thin, gas-pressure-dominated disk no longer holds, resulting in radiation-inefficient flows

- Self-gravity becomes important (i.e., >BH gravity) far enough from BH:

  - the disk breaks into small fragments at corresponding radii (i.e., r_{out})

- r_{in}, H(r), and r_{out} completely specify the thin-disk geometry:

  - typical disk mass ~3e5 Msun for M_{BH}=1e8 Msun

    * typical time for such an entire disk to be accreted ~1e6 yr (efficiency~0.1, L/L_{Edd}=0.1) → "accretion episode"

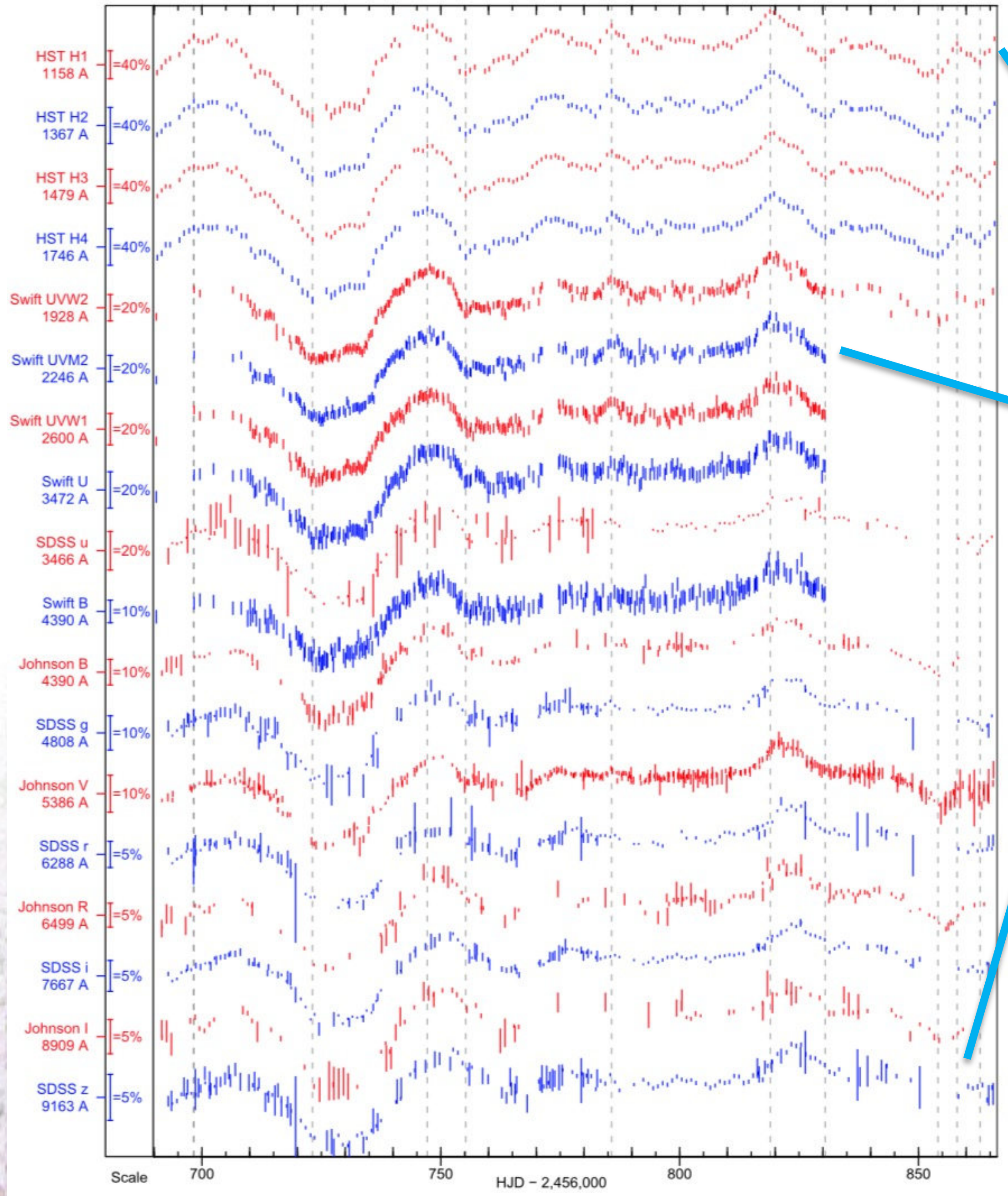
    * need several hundreds accretion episodes lasting about 1e6 yr each to double the mass of such a BH (though real situation being more complex)

    * important implications regarding growth times and modes of SMBHs

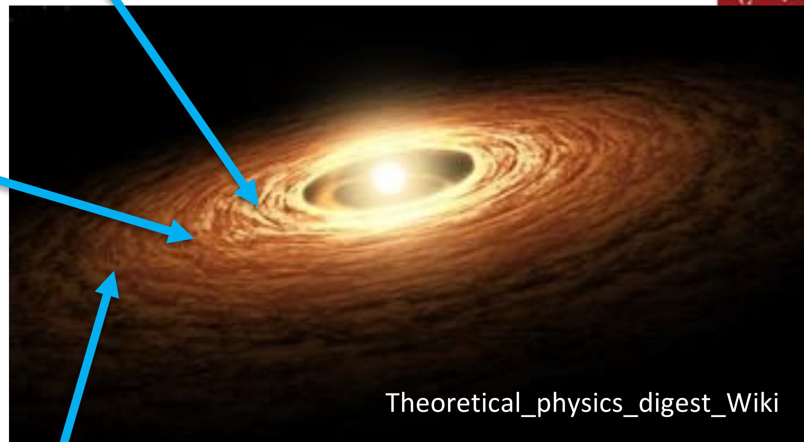
- Viewing angle dependences need to be considered when, e.g., attempting to derive total disk L from a single line-of-sight SED measurement (anisotropic disk emission)

AGN Accretion Disk Sizes

AGN STORM; Fausnaugh+16



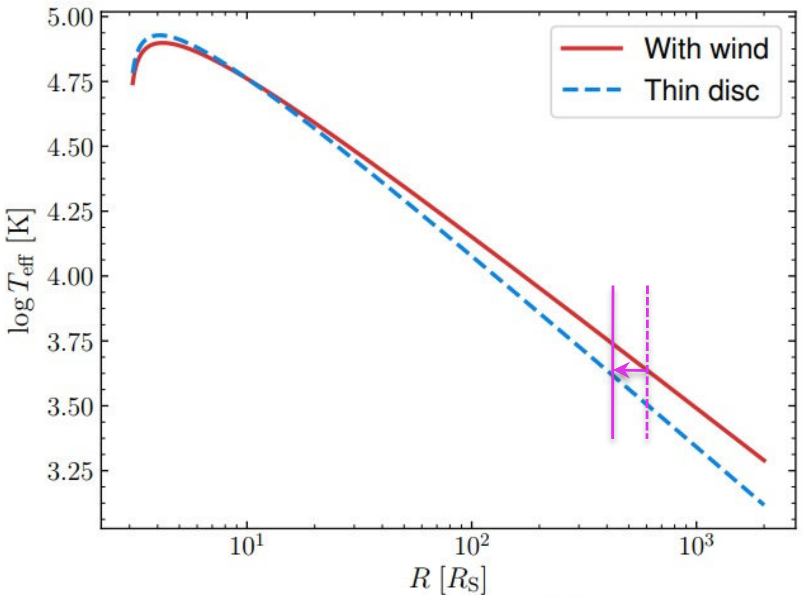
Reprocessing scenario: continuum RM

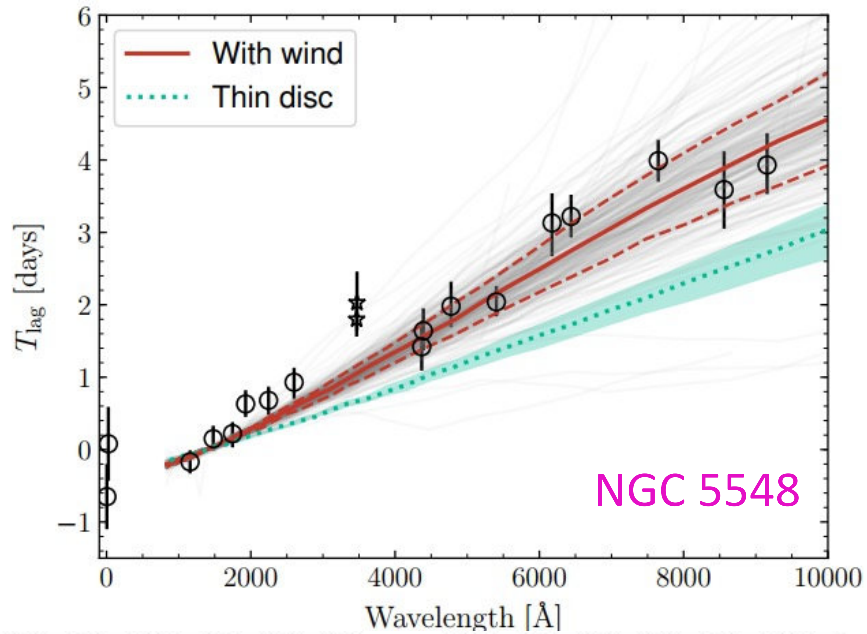


Disk temperature decreases with increasing radius

Time lags indicate the disk sizes

Winds can 'blow up' AGN accretion disc sizes



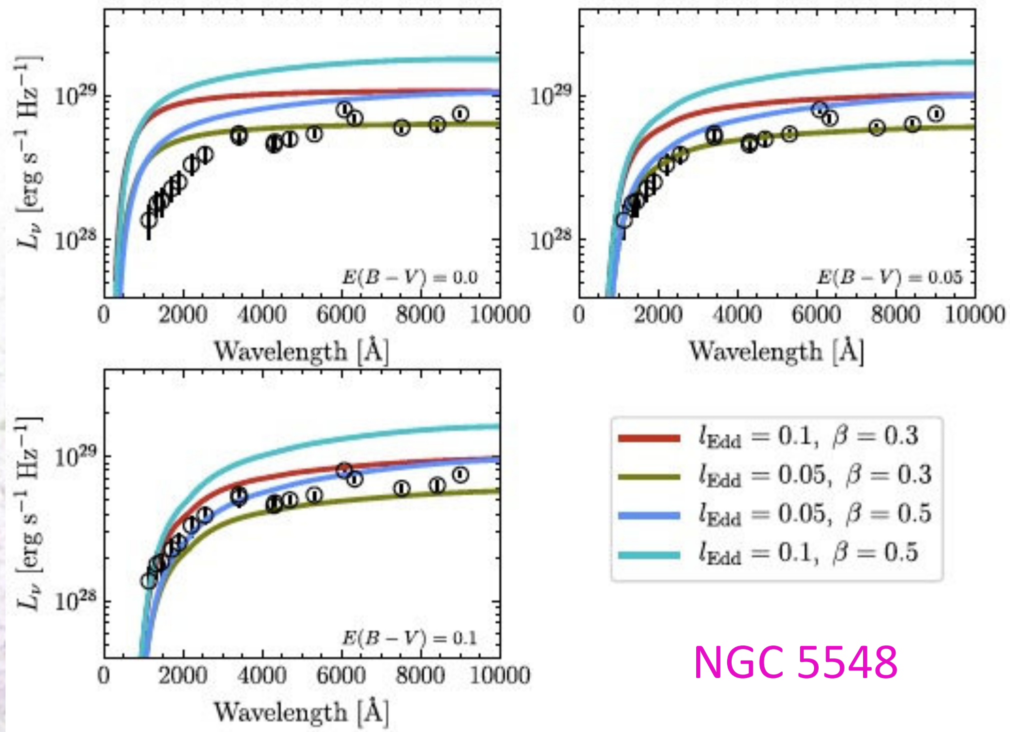


$$\dot{M} = \dot{M}_0 r^{\beta}$$

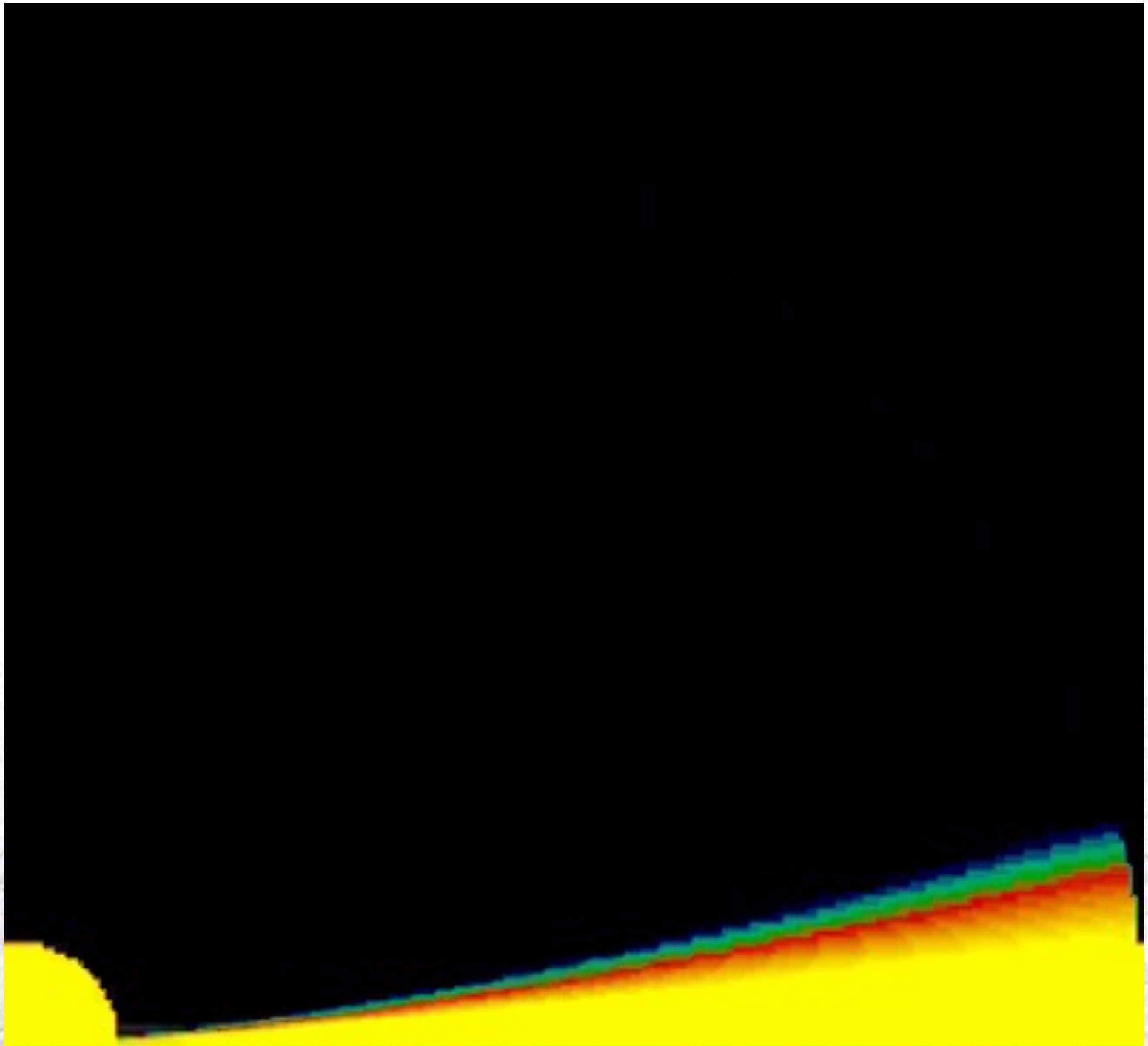
$$T_{\rm eff} = \left\{ \frac{3GM_{\rm BH}\dot{M}_0(1-\sqrt{3r_{\rm in}/r})}{8\pi\sigma R_S^3} \right\}^{\frac{1}{4}} r^{\frac{\beta-3}{4}}$$

The wind mass rate is ~ 0.6 Msun per year; this is consistent with the observed mass rate.

(Sun, Xue +2019)



Mass outflows from accretion disks



(Proga, Stone & Drew 1998, 1999)

4.2 Real AGN disks

- Real AGN disks could be quite diff. from the simple standard thin ADs:
  - strong magnetic fields:
    * affect physics and structure of the systems
    * provide an important source of viscosity and may drive massive winds from disk surface
  - very hot coronae (>1e7 K):
    * give rise to strong X-ray radiation that hits disk surface and changes local energy balance
  - disk-corona models: used extensively but details still not well understood

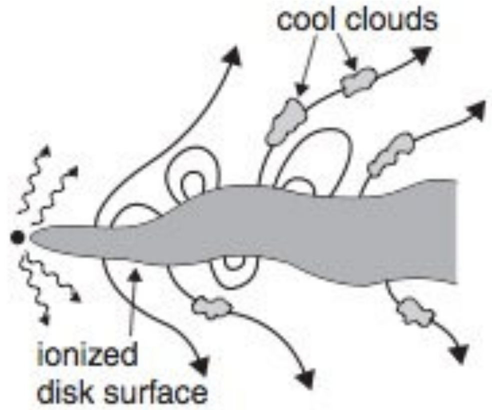


Figure 4.4. Complex magnetic disks may include a nonuniform geometry like the one shown schematically in this diagram. Winds and cool blobs can flow from the surface of the disk along the magnetic field lines. Such gas is exposed to the central radiation field at some height above the disk surface and can be driven in the radial direction by radiation pressure force (courtesy of K. Sharon).

4.2.1 Comptonization and the disk corona

- More realistic calculations of disk atmospheres include several processes that affect the emergent spectrum:

  - consider T gradient across disk and T increase in atmosphere

    * T increase + large Compton depth lead to Comptonization of softer-emitted photons and a considerable hardening of emitted spectrum (fig.)

  - hot, dilute gas/corona around thin ADs:

    * needed to explain AGN X-ray radiation

    * where soft disk-emitted photons are IC upscattered to X-rays

    * conditions for hot corona formation still unknown

      - one possibility: large vertical density gradient $\rightarrow$ some accretion proceeds via lower-density, outer layers of disk $\rightarrow$ large energy dissipation and sharp T rise $\rightarrow$ expansion of outer layers and creation of hot corona

        * even <1% of total accretion power released in corona $\rightarrow$ T~1e8K

        * such coronae radiate through free-free processes, dominating hard X-ray emission

    * explain X-ray obs. (E index~1, i.e., Gamma~2) of many AGNs, but not all

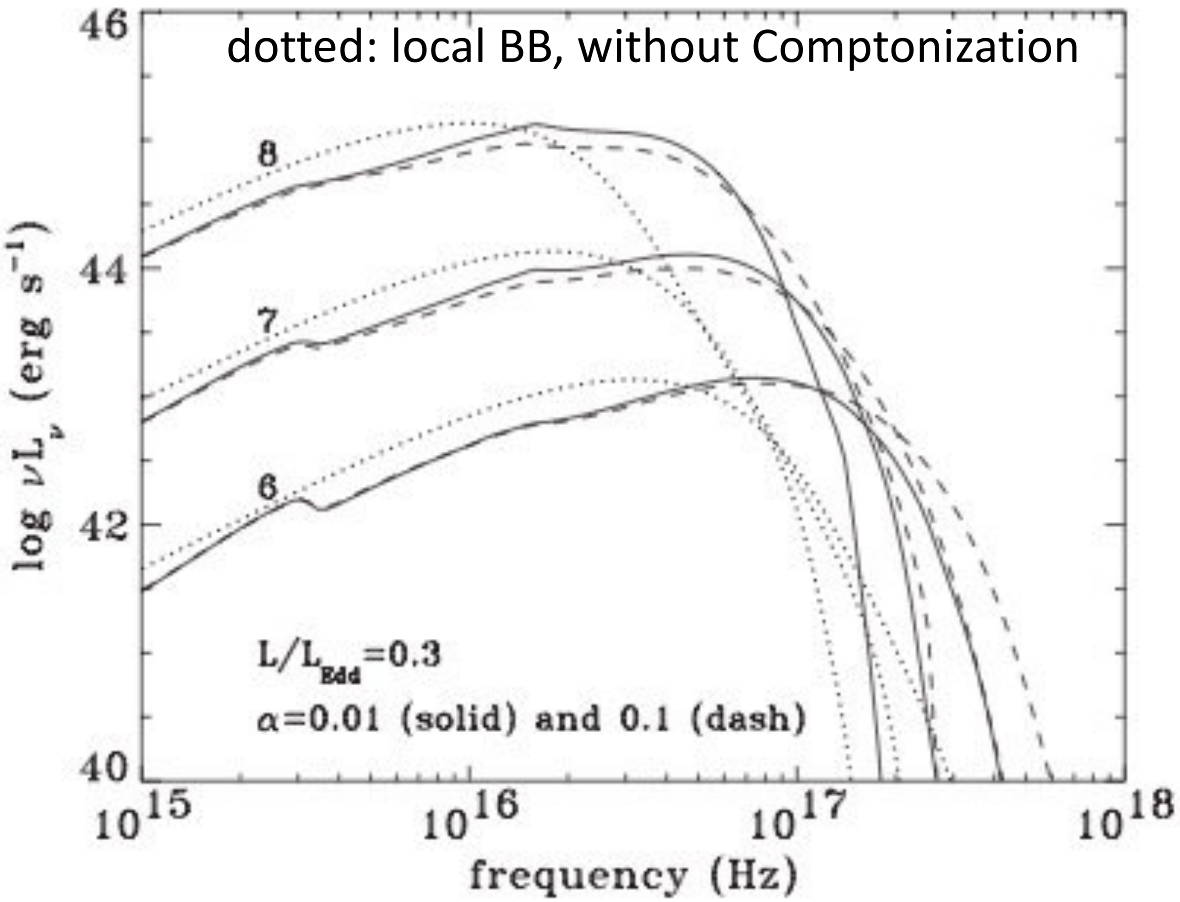


Figure 4.5. Calculated spectra of three accretion disks around BHs with $M_{BH} = 10^6$, 10^7, and $10^8\ M_{\odot}$, all with $L/L_{Edd} = 0.3$. The viewing angle of the disk is 60 degrees. The dotted lines show the much softer simple spectra obtained by assuming a combination of blackbodies without Comptonization (from Hubeny et al., 2001, reproduced by permission of the AAS).

Comptonization: hardening, but still not enough --> corona

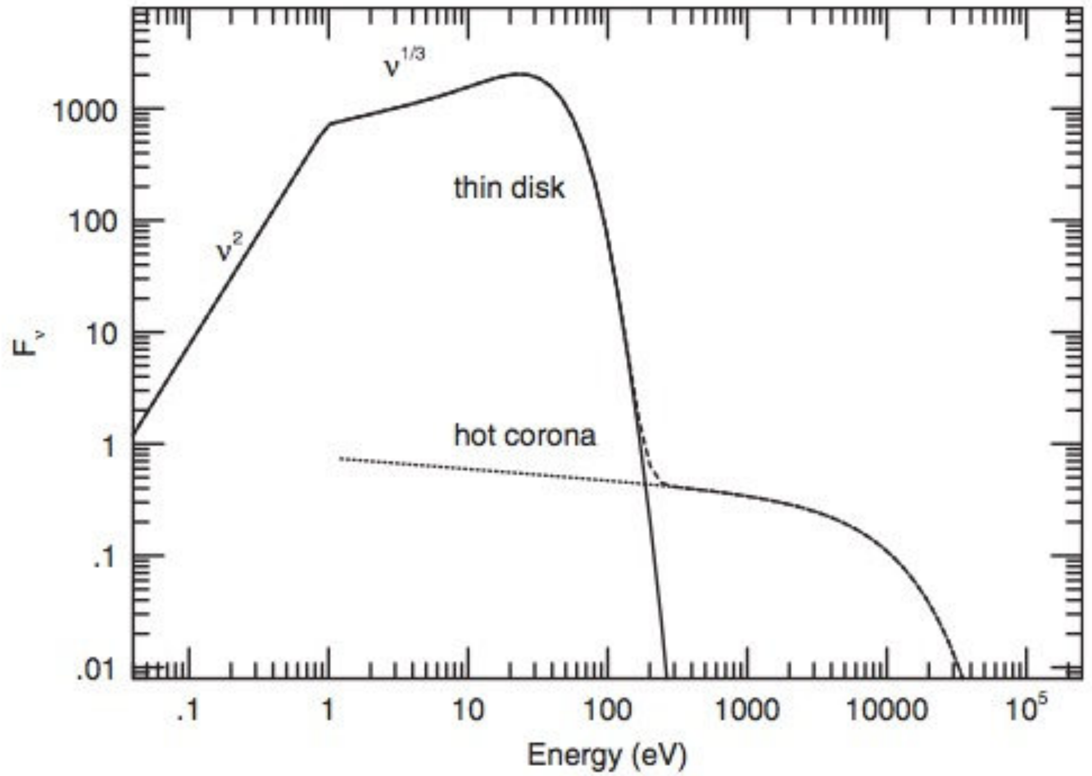


Figure 4.3. A schematic of a combined disk–corona spectrum. The maximum temperature of the geometrically thin, optically thick accretion disk is $T_{\max} = 10^5$ K, and its outer boundary temperature is determined by the conditions at the self-gravity radius. The disk is surrounded by an optically thin corona with $T_{\rm cor} = 10^8$ K.

variability: corona size << disk size

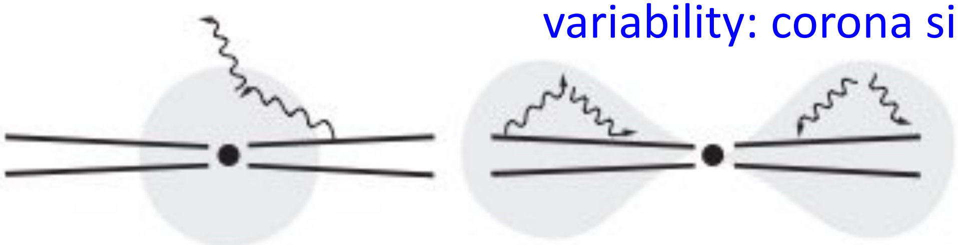
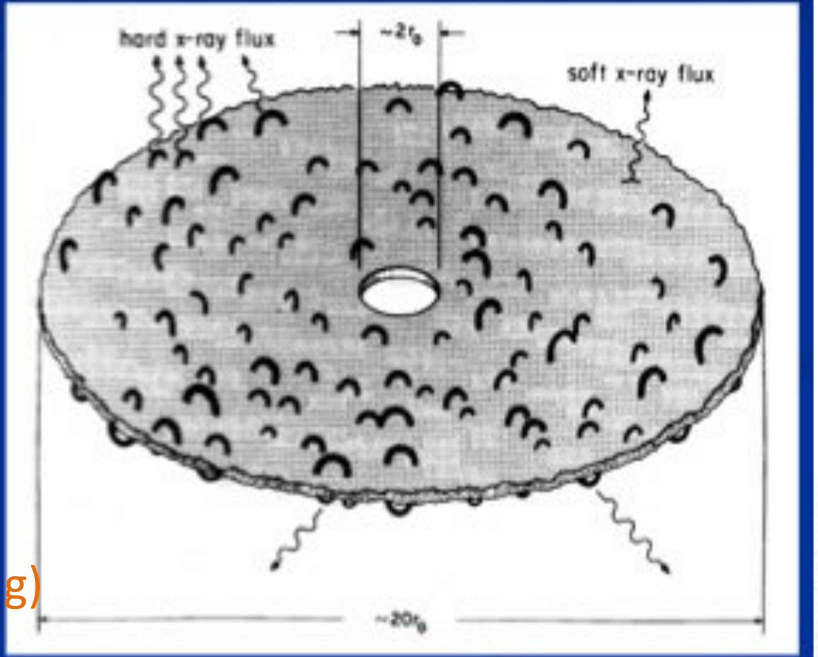
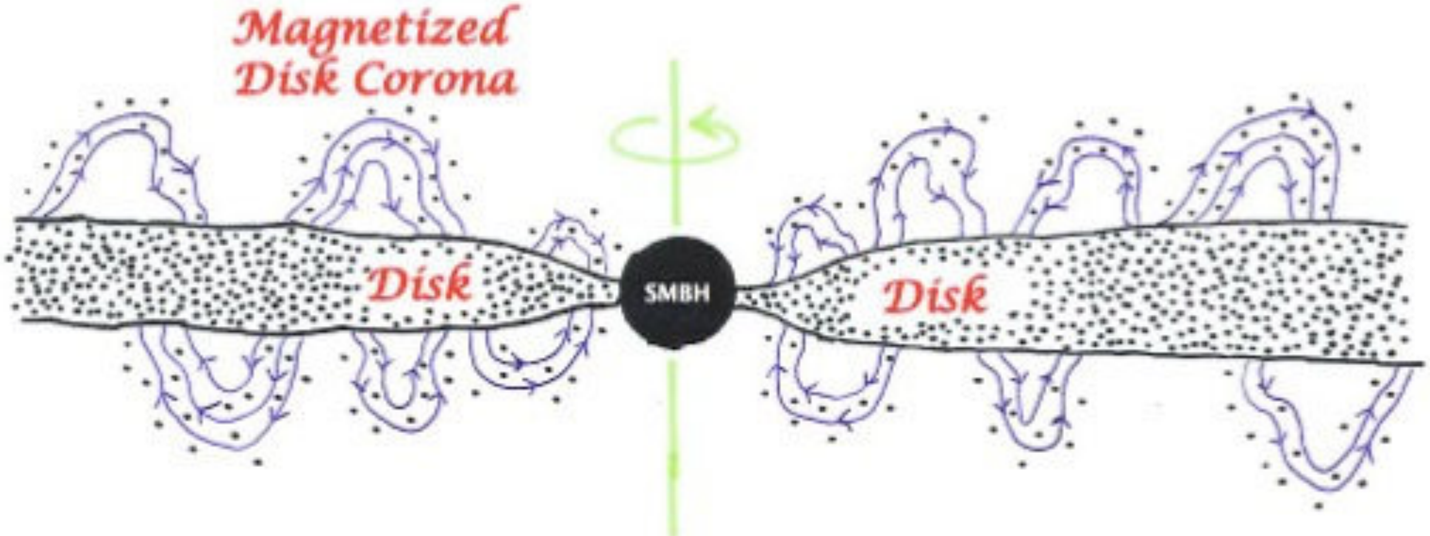


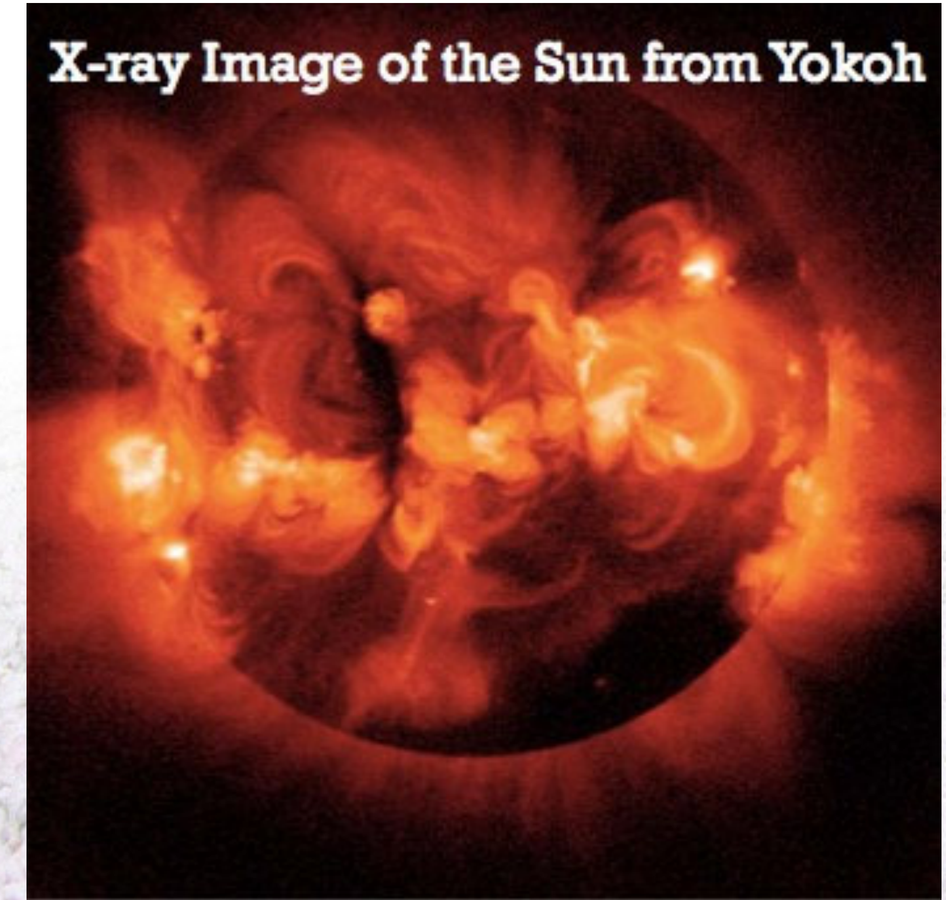
Figure 4.6. Two schematic disk–corona structures showing possible locations of the corona and the scattering geometry of the disk-produced and corona-produced photons.

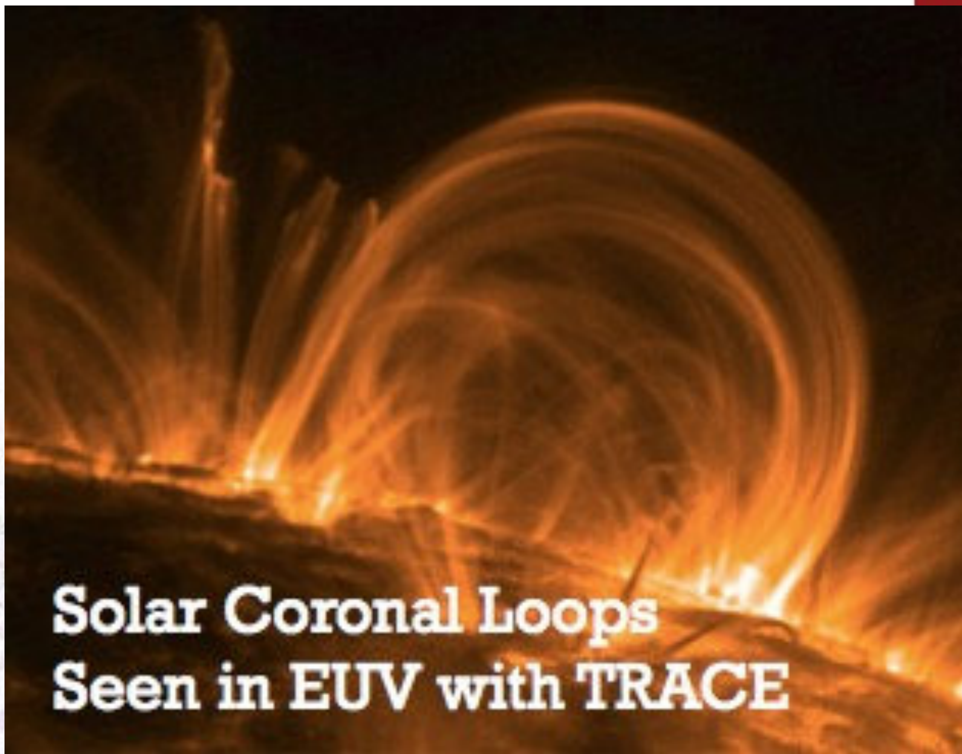
Disc-corona model

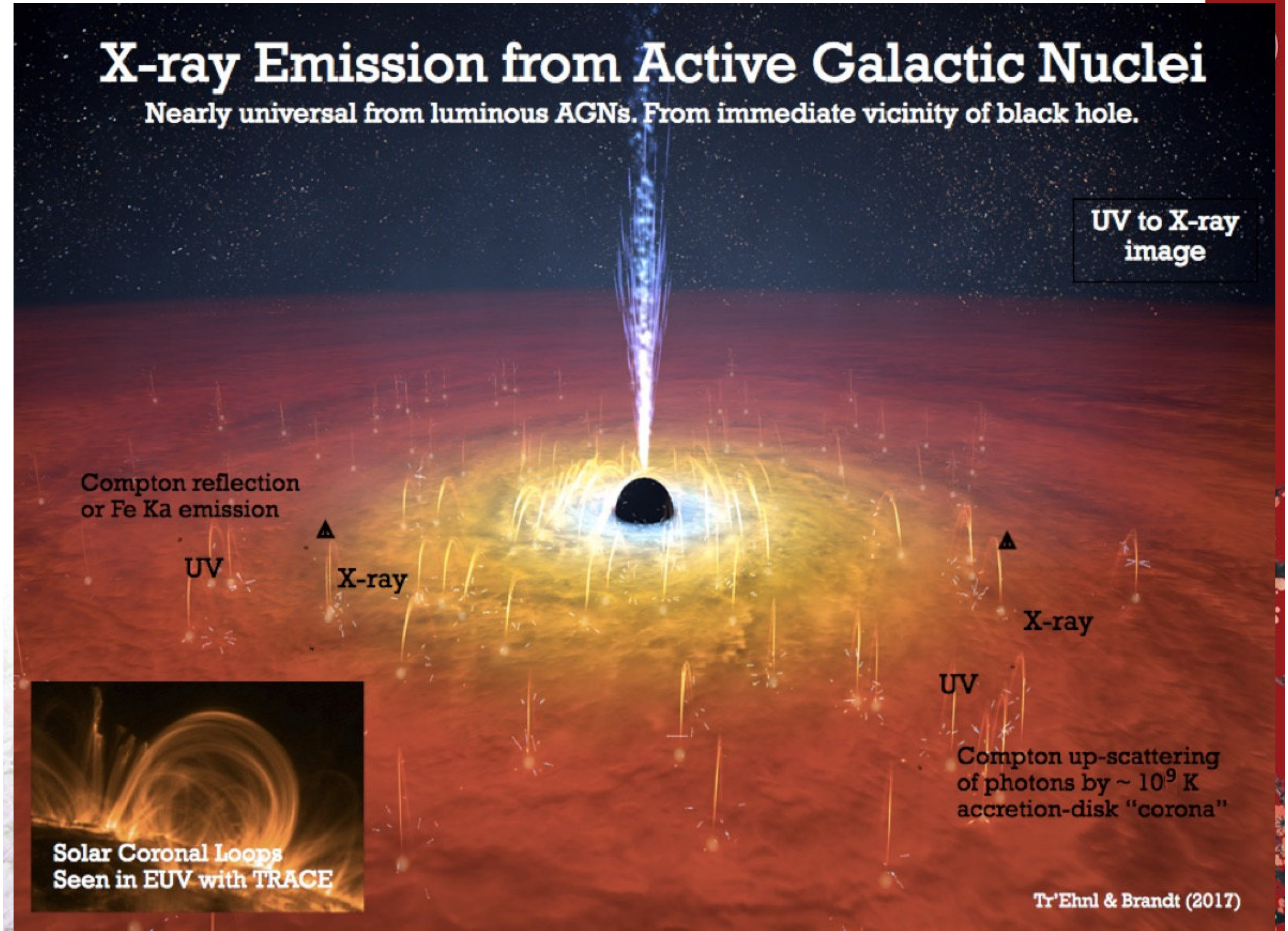
- Motivation
  - To explain X-ray radiation
  - Analogy with solar corona
- Formation mechanism of corona
  - Emergence of magnetic field from disk to corona
  - Magnetic reconnection heating (mag. E → thermal E, heating)
- MHD simulation to Corona:
  - Magnetically supported
  - High temperature

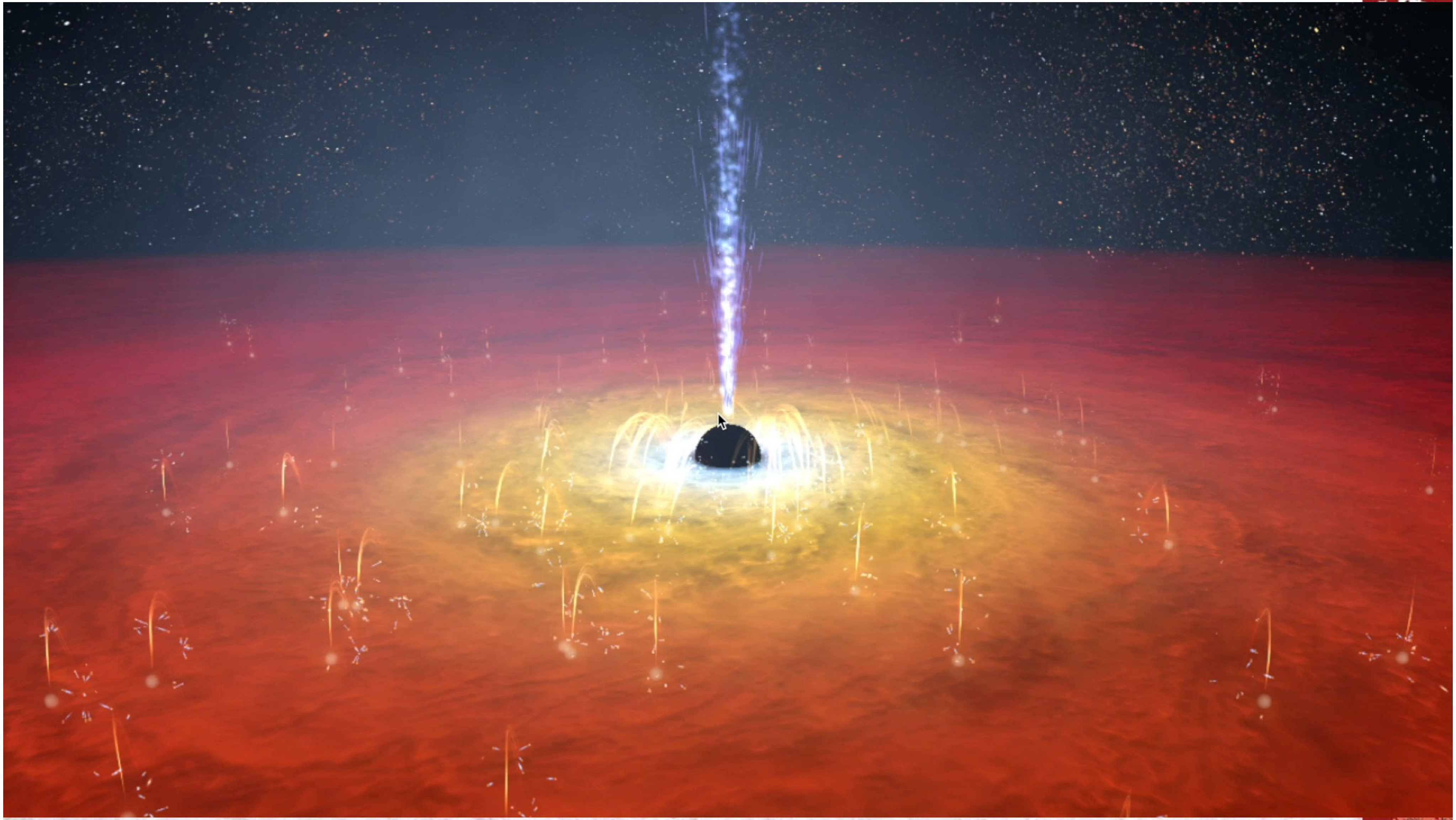



Magnetized
Disk Corona
Disk
SMBH
Disk


X-ray Image of the Sun from Yokoh


Solar Coronal Loops
Seen in EUV with TRACE


X-ray Emission from Active Galactic Nuclei
Nearly universal from luminous AGNs. From immediate vicinity of black hole.
UV to X-ray image
Compton reflection or Fe Ka emission
UV
X-ray
X-ray
UV
Compton up-scattering of photons by ~ 10^9 K accretion-disk "corona"
Solar Coronal Loops Seen in EUV with TRACE
Tr'Ehnl & Brandt (2017)



4.2.2 Irradiated disks

- External radiation sources can illuminate the disk and change the local energy balance
- Important examples are illumination by an X-ray-emitting corona and the irradiation of the outer areas of a flaring disk by its inner part
- Calculation of the spectrum of irradiated disks:

- complicated due to unknown geometry and the combination of external sources of energy and locally dissipated energy

- the simplest case: external point source of radiation is located along BH rotational axis at a height H_*

  * when $H_* >> H(r)$, have the same SED as the standard thin AD (some part shows disk SED with $L_\nu \propto \nu^{1/3}$) under numerous assumptions

  * when $H_* << H(r)$, reprocessing is important at the outskirt of the system; can produce an SED with a typically observed slope in opt.-UV spectrum

- Most important cases of irradiated AGN disks: illumination of optically emitting ADs by an external X-ray source such as a disk corona

  - alter significantly disk structure, local level of ionization, local T, and consequently, local emitted spectrum

    * hard corona photons can escape or be absorbed by cool AD
    * soft disk photons can be absorbed by corona or escape freely

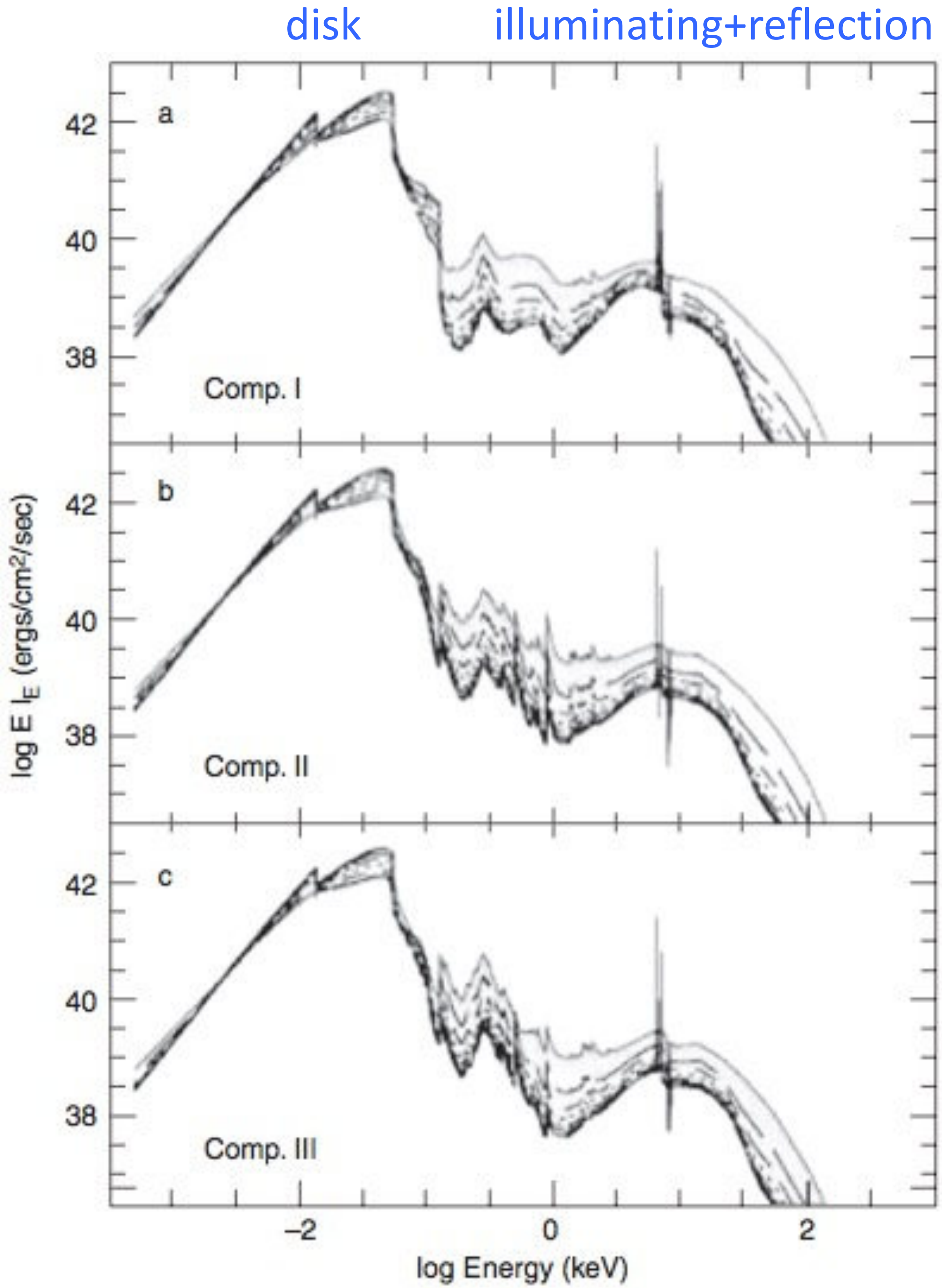


Figure 4.7. Various models illustrating the spectra of X-ray-illuminated accretion disks under different conditions (Rozanska and Madej, 2008; reproduced by permission of John Wiley & Sons Ltd.).

Corona-heated Accretion-disk Reprocessing (CHAR) Model

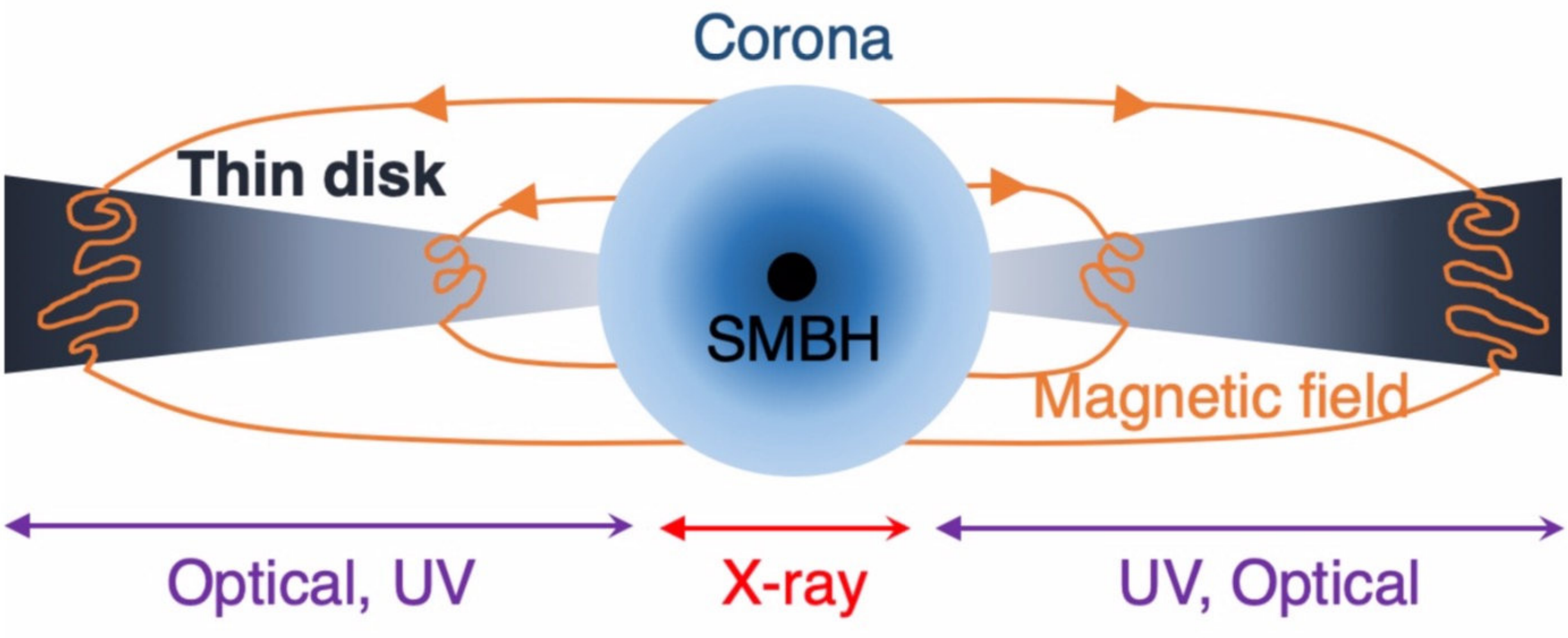


Figure 1: **Illustration of our corona-driven temperature-fluctuation model. The accretion disc (gray) and the corona (light blue) are tightly coupled by the magnetic fields (orange curves). Note that the disc might extend to the innermost stable radius; these inner regions have negligible contribution to the UV/optical variability discussed here. MHD flares in the corona can affect MHD turbulence and alter the heating rate in the accretion disc. As a result, the disc temperature fluctuates in response to the variable heating rate. The temperature fluctuations can be determined by solving the equation for thermal-energy conservation.**

(Sun, Xue et al. 2020)

- Nomenclature adopted in the field of X-ray astronomy:

  - reflection: radiation whose origin is outside the disk, being either scattered or else absorbed and reemitted by the gas in the disk
  - disk emission: radiation from the disk material itself, with the energy source being the external radiation field, but the emission frequency depends on the specific atomic processes

    * the absorption and emission frequencies can be very different
    * X-ray fluorescence lines belong to this category

4.3 Slim and thick accretion disks

- Larger accretion rates can result in large optical depths and inefficient emission since the accretion (inflow) timescale can be shorter than the time it takes for the radiation to diffuse to the disk surface

  - photons created in radiation-pressure-dominated regions of such disks are trapped in the accretion flow and advected onto the BH

  - higher T leads to slim or thick ADs

  - low radiation efficiency with $\epsilon_r < \eta$.

- Some slim-disk models give the relation between total L and normalized accretion rate: $L = a(1 + b \ln \dot{m}) M_{BH}$ (where $\dot{m} = \dot{M}/\dot{M}_{\rm Edd}$)

One-dimensional Dynamics: energy advection

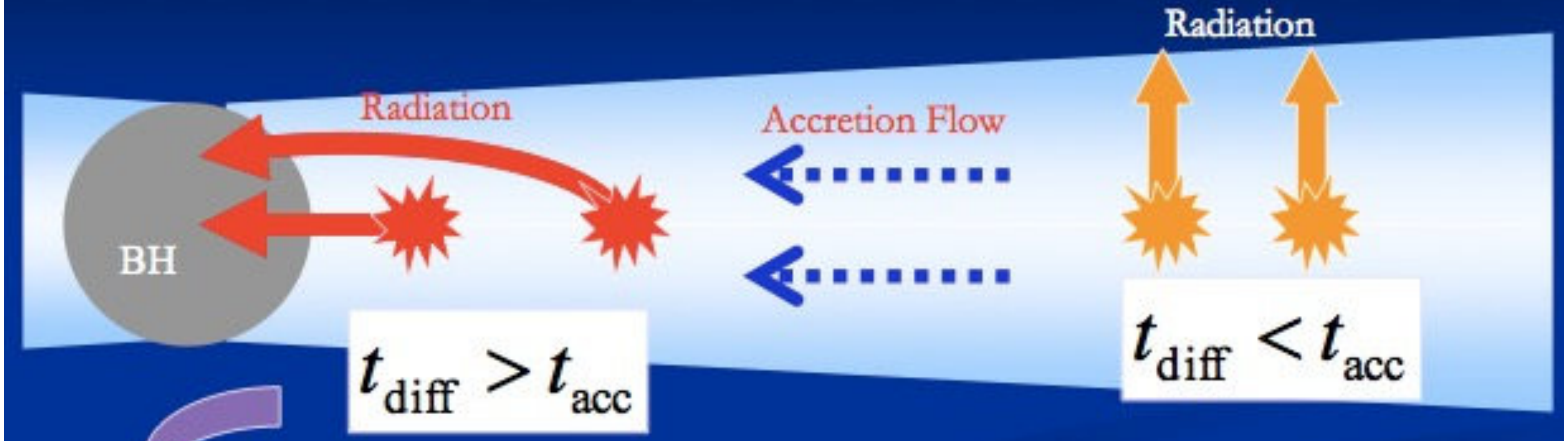
- Recall energy eq:

heat change — viscous heating — radiation loss

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

- When accretion rate is above Eddington, advection becomes 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



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

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

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

So photon-trapping occur in the super-Eddington flow

Self-similar solution

Wang & Zhou 1999; Belodorodov 2003 (not accurate solutions)

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

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

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

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

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

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

Strong advection assumption

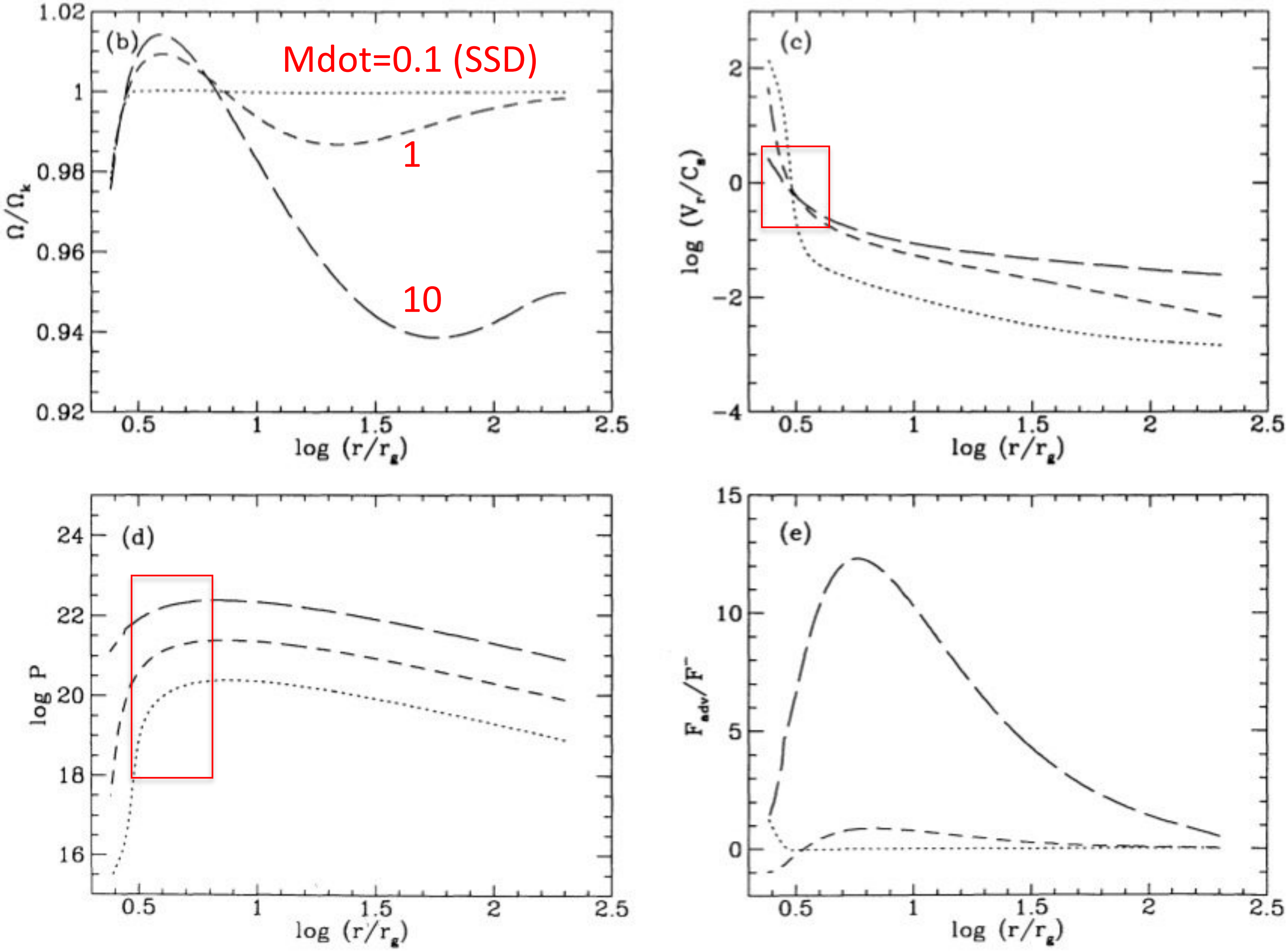
$$H\rho v_r T \frac{dS}{dr} = H\alpha P r \frac{d\Omega}{dr} - F^-$$

Global solution

(solve diff. equ. for accurate solutions)

- Three boundary conditions to be satisfied
  - Outer boundary condition (temperature, density, radial velocity); (starting status of accretion at outer radius)
  - sonic point condition (singularity: dv/dr=0/0); $r\frac{d\Omega}{dr}$
  - inner boundary condition (horizon of the BH)
- Solving two-point boundary value problem: difficult

One-dimensional global solution



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

Chen & Taam 1993

Slim disks: Radiation

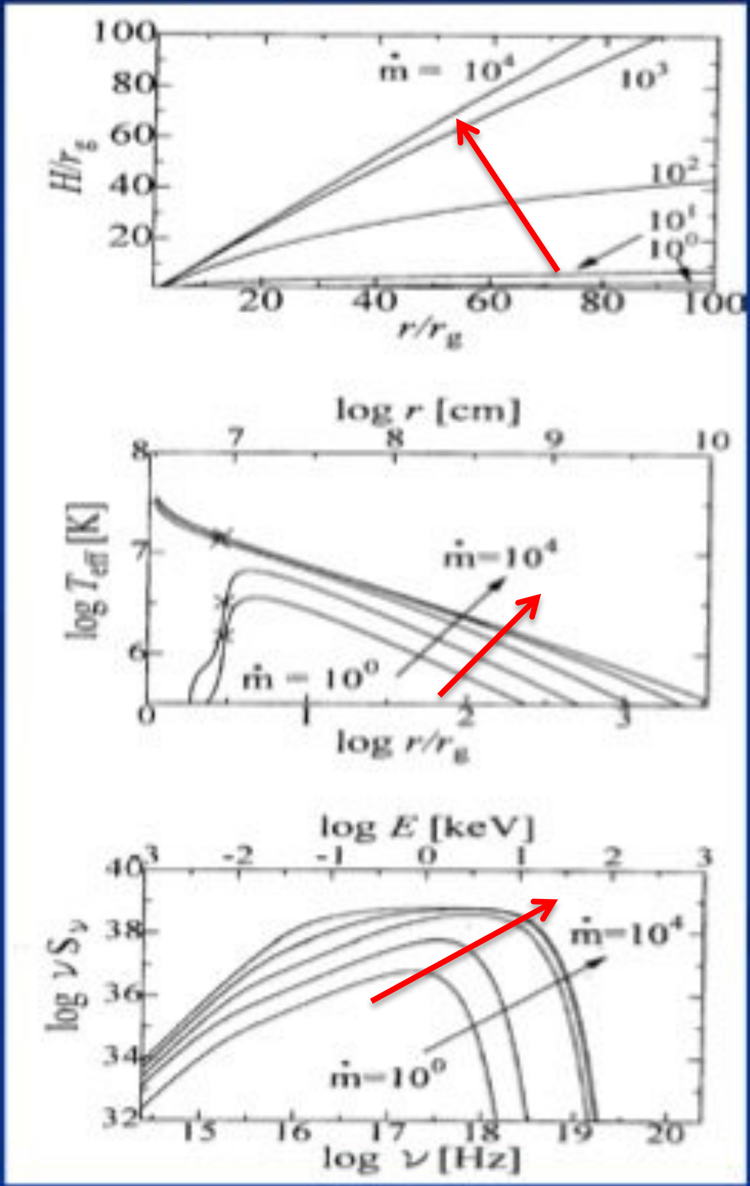
- Because of advection, we have

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

different from the thin disk.

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

(disk vs. spherical accretion)

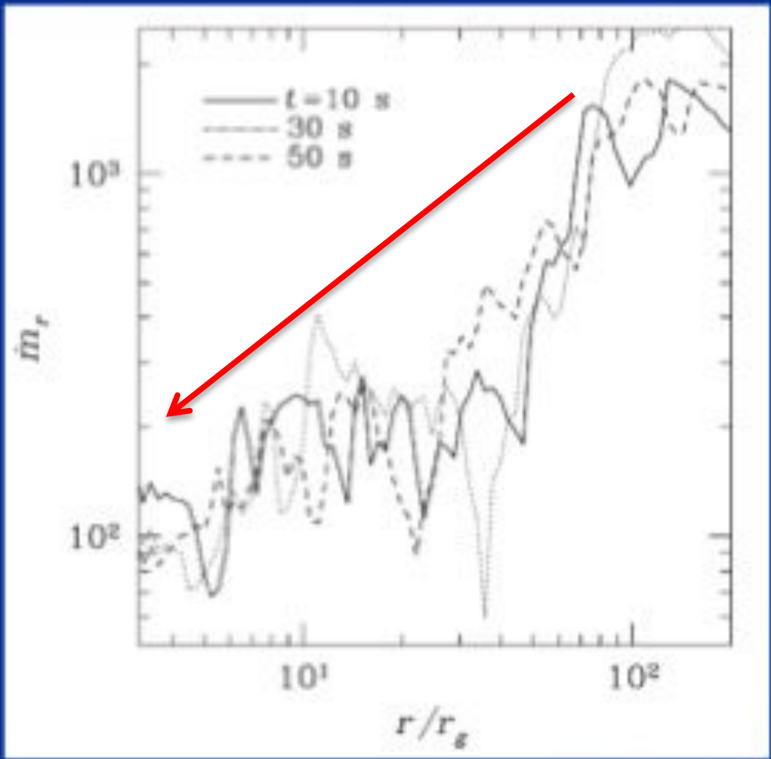


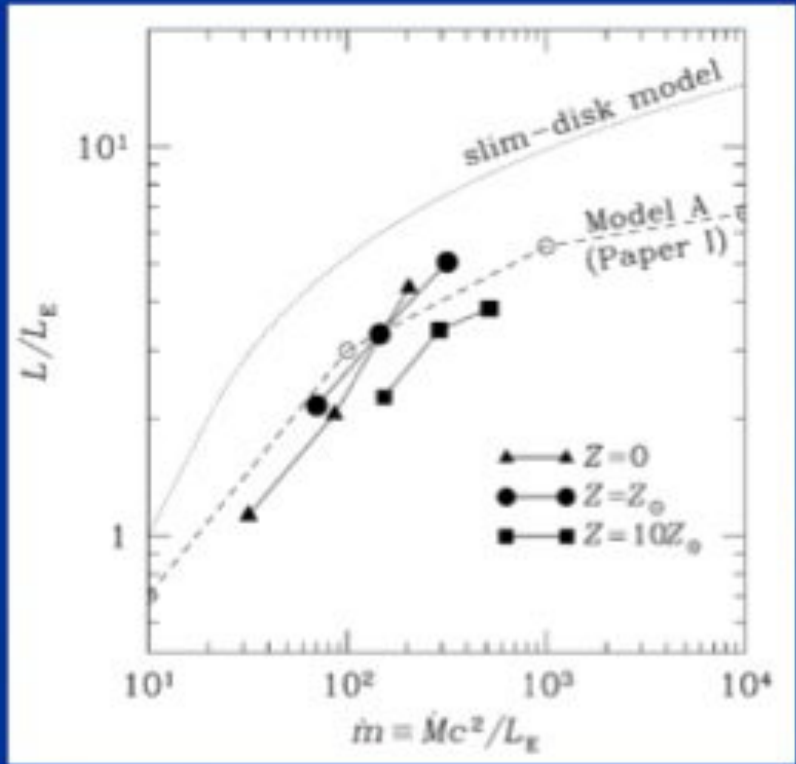
2D Radiative HD simulations (I)

Ohsuga et al. 2005; Yang et al. 2013

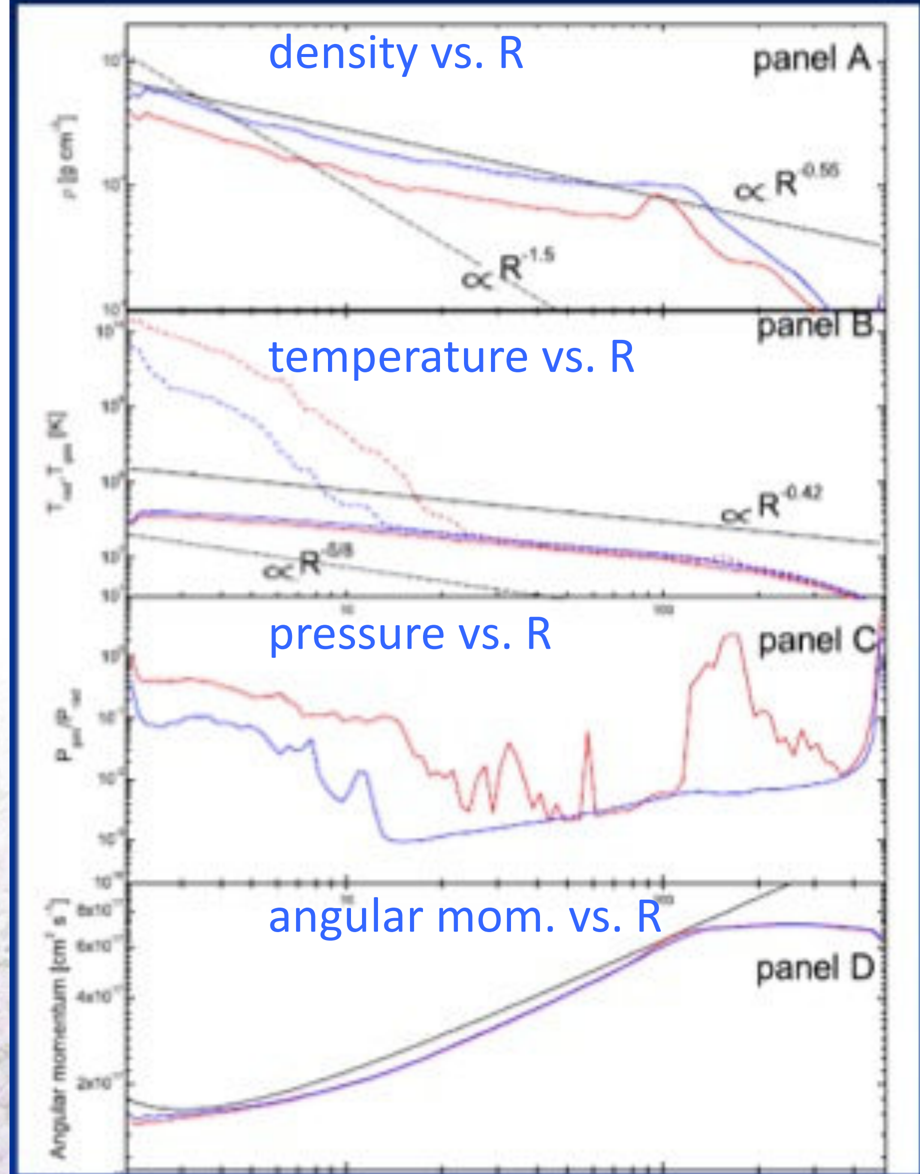
- Accretion rate decreases inward: mass outflow
  - Radiation or convection driven?
- Radiation is highly anisotropic

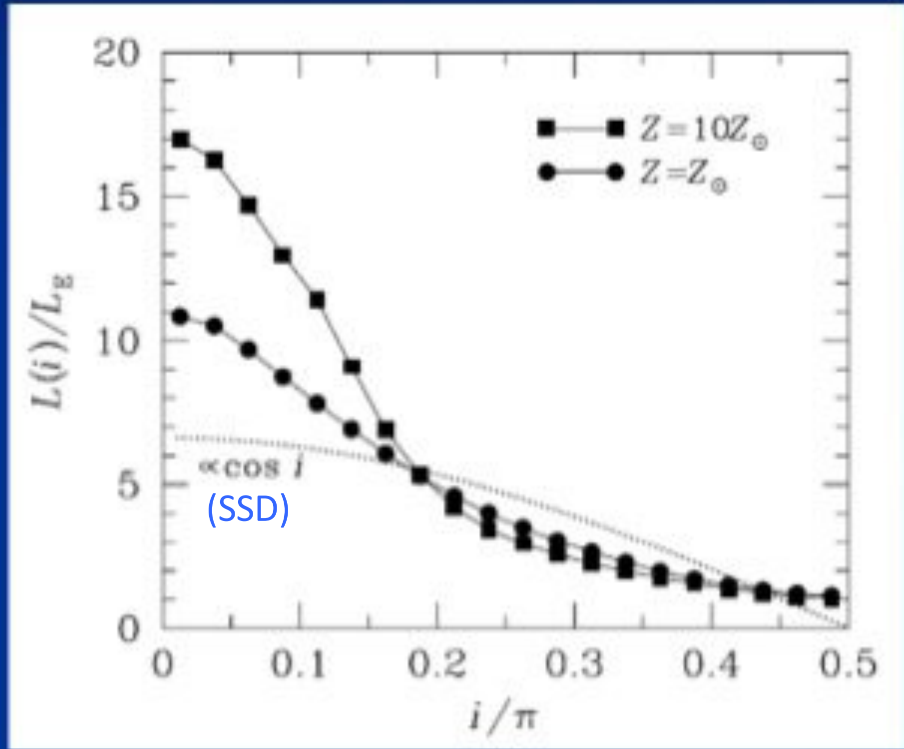
(Mdot not constant!)





2D Radiative HD simulation (II)





anisotropic radiation:
higher angle dependence
for slim disks than SSD

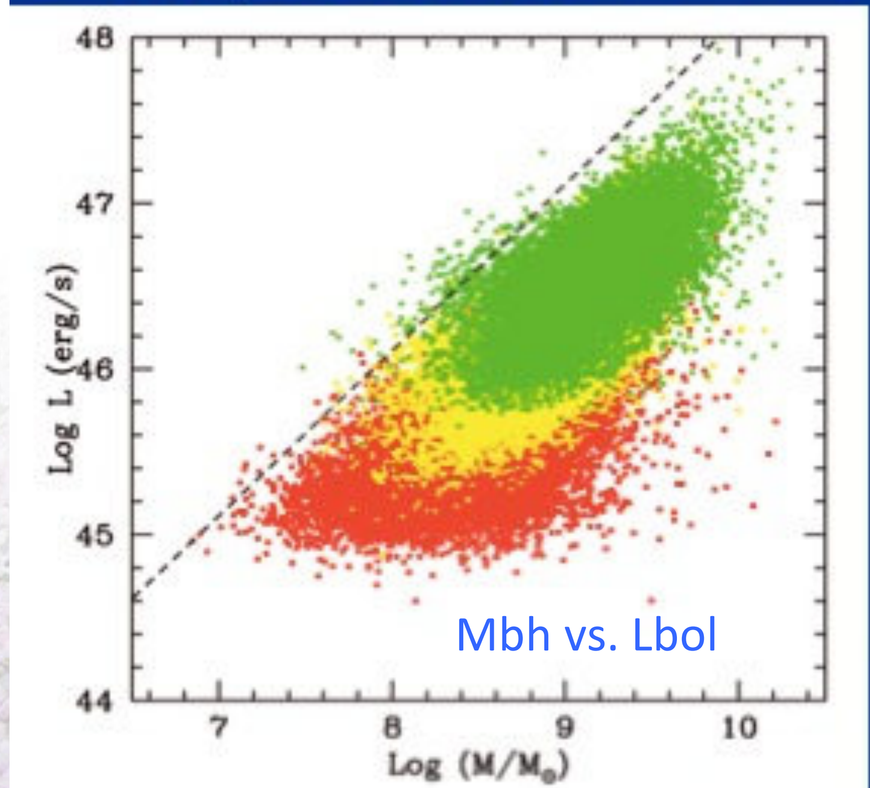
中国科学技术大学

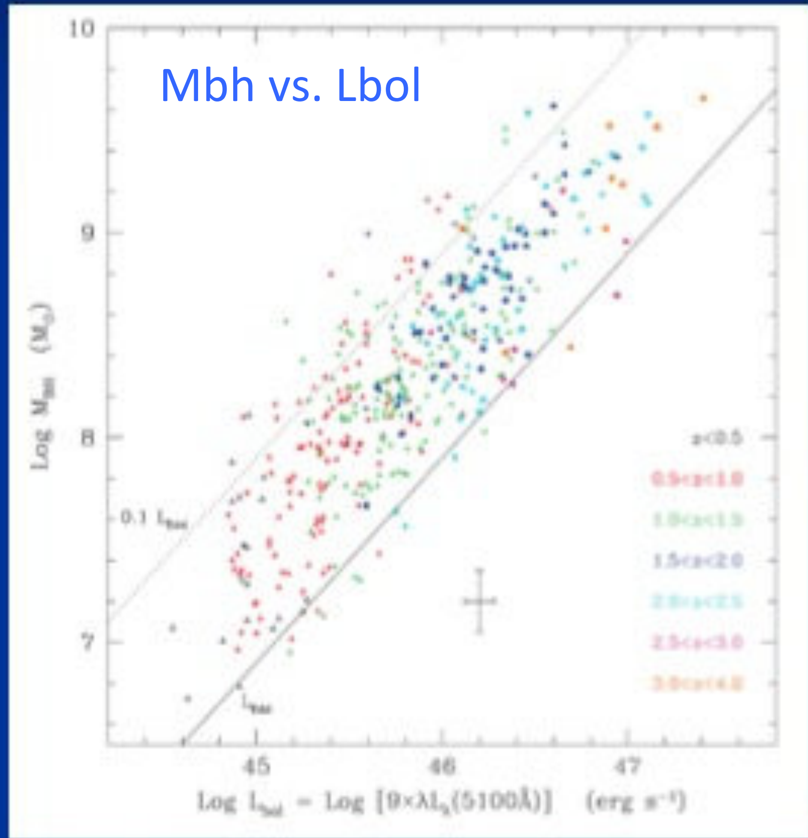
Possible Applications

- Narrow line Seyfert 1 (Mineshige et al. 2000)
- Ultraluminous X-ray sources (Watarai et al. 2001)
- SS433
- Some AGNs (very large mass, luminous, high-z quasars)

Sub-Eddington puzzle

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





Steinhardt & Elvis 2010

Kolleier et al. 2006

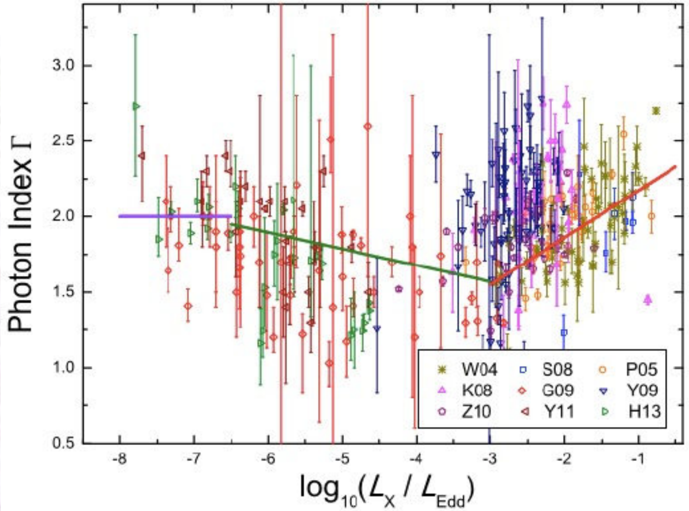
Super-Eddington Accreting Massive Black Holes as Long-Lived Cosmological Standards

Jian-Min Wang,[1,2,*] Pu Du,[1] David Valls-Gabaud,[3,1,2] Chen Hu,[1] and Hagai Netzer[4]
[1]*Key Laboratory for Particle Astrophysics, Institute of High Energy Physics, CAS, 19B Yuquan Road, Beijing 100049, China*
[2]*National Astronomical Observatories of China, CAS, 20A Datun Road, Beijing 100020, China*
[3]*LERMA, CNRS UMR 8112, Observatoire de Paris, 61 Avenue de l'Observatoire, 75014 Paris, France*
[4]*School of Physics and Astronomy and The Wise Observatory, The Raymond and Beverley Sackler Faculty of Exact Sciences, Tel-Aviv University, Tel-Aviv 69978, Israel*
(Received 27 August 2012; published 19 February 2013)

Super-Eddington accreting massive black holes (SEAMBHs) reach saturated luminosities above a certain accretion rate due to photon trapping and advection in slim accretion disks. We show that these SEAMBHs could provide a new tool for estimating cosmological distances if they are properly identified by hard x-ray observations, in particular by the slope of their 2–10 keV continuum. To verify this idea we obtained black hole mass estimates and x-ray data for a sample of 60 narrow line Seyfert 1 galaxies that we consider to be the most promising SEAMBH candidates. We demonstrate that the distances derived by the new method for the objects in the sample get closer to the standard luminosity distances as the hard x-ray continuum gets steeper. The results allow us to analyze the requirements for using the method in future samples of active black holes and to demonstrate that the expected uncertainty, given large enough samples, can make them into a useful, new cosmological ruler.

$$L_\bullet = \ell_0(1 + a \ln \dot{m}_{15}) M_\bullet, \quad (1)$$

where $\ell_0 \approx 5.29 \times 10^{38}$ erg s$^{-1} M_\odot^{-1}$, and $a \approx 0.476$ [7]. For reference, at $\dot{m} = 15$ the saturated luminosity is $\sim 4.20 L_{\rm Edd}$. Thus, at a given black hole mass, SEAMBHs are radiating basically at a constant luminosity which, as shown below, can therefore be used to deduce cosmological distances.



- Spectra of thick ADs can differ substantially
- Such thick ADs:

- may have narrow funnels, along BH rotational axis, and geometrically thick, optically thick structure
- gas T along walls of funnel can be very high, resulting in a hard X-ray-dominated spectrum in the general direction of BH axis
  * larger viewing angle spectrum is much softer, with most of radiation emitted in optical part of spectrum
  * such disks may look very different for observers at diff. viewing angles
- gas surrounding such disks may also be exposed to different radiation fields in different directions, which would affect its T and level of ionization in a geometrically dependent fashion

4.4 Radiatively inefficient accretion flows

- Optically thick, geometrically thin ADs: cooling-dominated flows

  - cooling mostly due to high-E electrons with high radiative efficiency

    * cooling efficiency in most cases ~ electron density squared

    * SSD: high enough densities → cooling very efficient (< inflow timescale)

- ADs with very low accretion rates:

  - much lower densities → cooling timescale >= or >> inflow timescale

  - extremes cases of very low density:

    * cooling very inefficient

    * particles retain dissipated grav. energy for a long time

    * T rises to virial T (1e12K/r) and advected into BH without releasing E

    * called ADAFs: advection-dominated accretion flows

      - a more general term: radiatively inefficient accretion flows (RIAFs)

    * ions and electrons can have very different T (T_ion >> T_e by ~2 orders)

      - low density → less Coulomb collisions that share kinetic E

      - electrons are more efficient coolants

- Additional RIAFs: ADIOS (advection-dominated inflow outflow solution) and CDAF (convection-dominated accretion flow) truncated disks

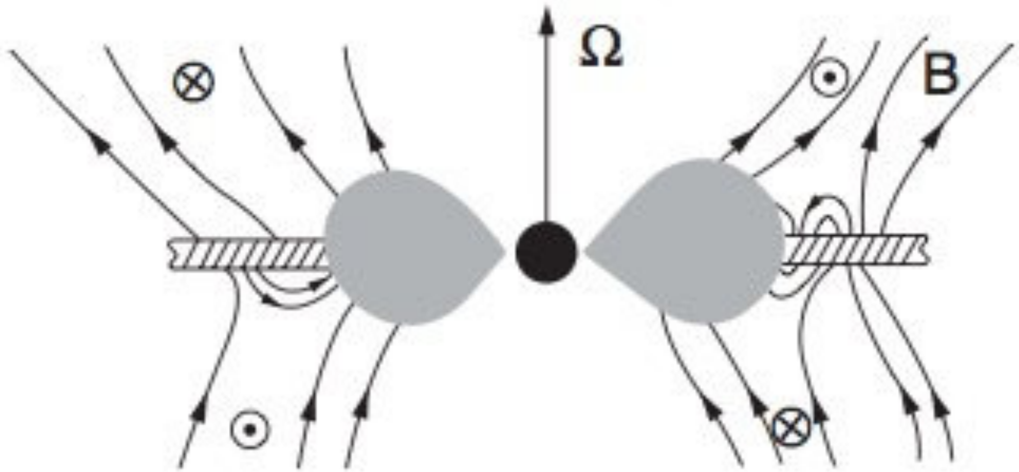
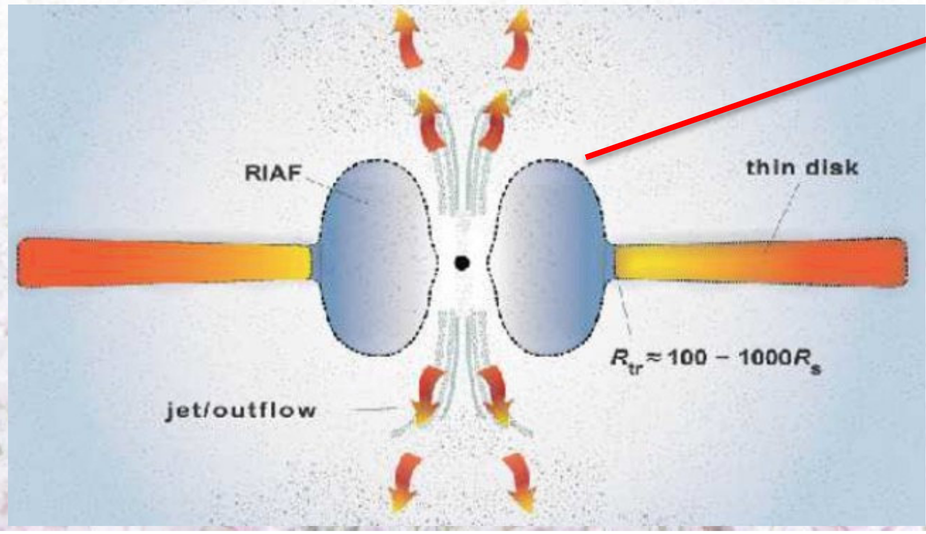
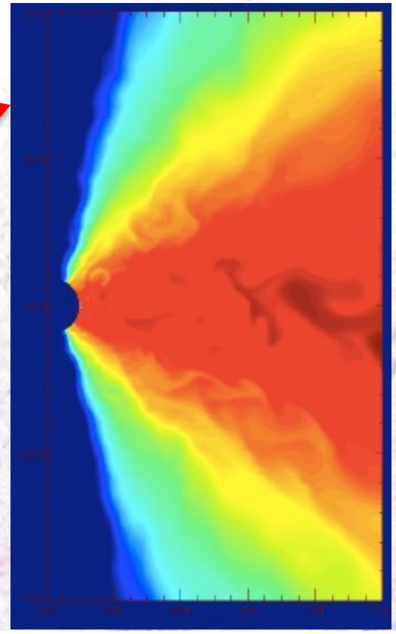


Figure 4.8. Two-temperature disks are similar to the standard optically thick, geometrically thin accretion disks far from the BH. Their very low accretion rate results in low densities and inefficient cooling in the inner parts. The gas in these regions cannot radiate away the released gravitation energy. It heats to very high temperatures, which results in a significant increase in the thickness of the disk. A large fraction of the released energy is advected to the center, and the mass-to-radiation conversion efficiency drops significantly.





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LETTERS

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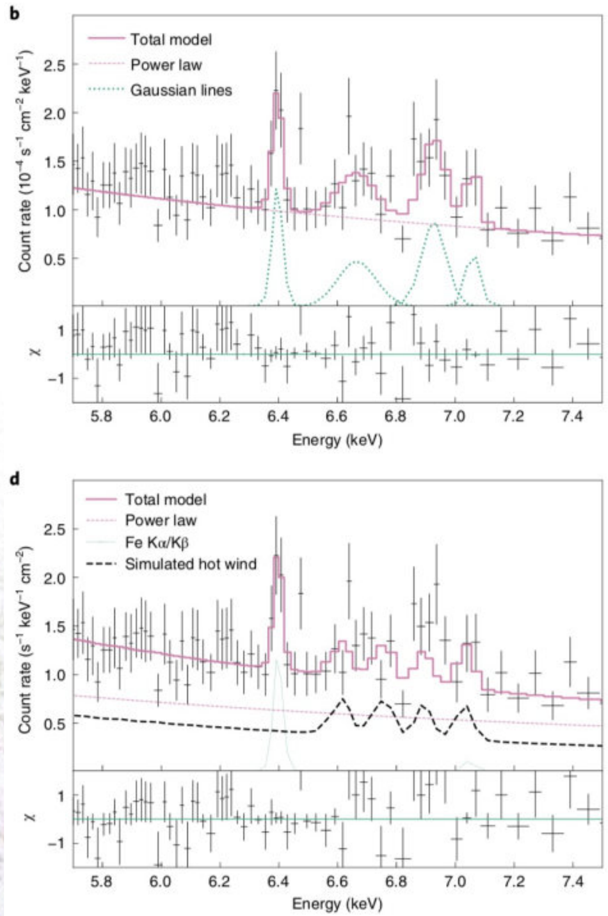
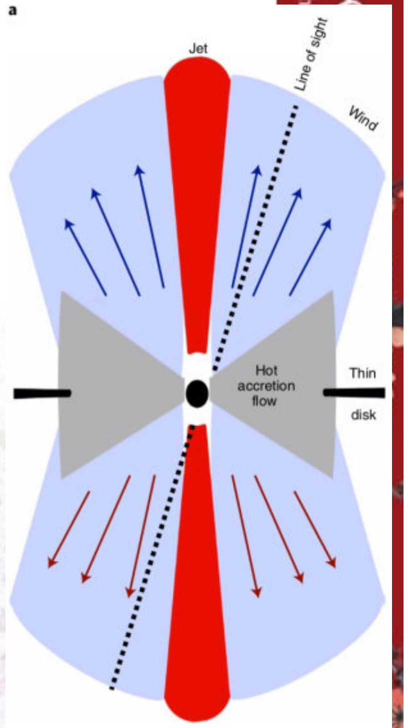
An energetic hot wind from the low-luminosity active galactic nucleus M81*

Fangzheng Shi[1,2], Zhiyuan Li[1,2] ✉, Feng Yuan[3,4] ✉ and Bocheng Zhu[3,4]

For most of their lifetime, super-massive black holes (SMBHs) commonly found in galactic nuclei obtain mass from the ambient medium at a rate well below the Eddington limit[1], which is mediated by a radiatively inefficient, hot accretion flow[2]. Both theory and numerical simulations predict that a strong wind must exist in such hot accretion flows[3–6]. The wind is of special interest not only because it is an indispensable ingredient of accretion but also, perhaps more importantly, because it is believed to play a crucial role in the evolution of the host galaxy via the so-called kinetic mode active galactic nucleus feedback[7,8]. Observational evidence for this wind, however, remains scarce and indirect[9–12]. Here we report the detection of a hot outflow from the low-luminosity active galactic nucleus in M81, based on Chandra high-resolution X-ray spectroscopy. The outflow is evidenced by a pair of Fe XXVI Lyα lines redshifted and blueshifted at a bulk line-of-sight velocity of $\pm 2.8\times 10^3$ km s^{-1} and a high line ratio of Fe XXVI Lyα to Fe XXV Kα implying a plasma temperature of 1.3×10^8 K. This high-velocity, hot plasma cannot be produced by stellar activity or the accretion inflow onto the SMBH. Our magnetohydrodynamical simulations show that, instead, it is naturally explained by a wind from the hot accretion flow, propagating out to $\gtrsim 10^6$ times the gravitational radius of the SMBH. The kinetic energy and momentum of this wind can significantly affect the evolution of the circumnuclear environment and beyond.





One-dimensional equations

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

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

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

energy

internal E — P term — viscosity heating — radiation cooling

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

Two-T:

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

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

viscous heating — collision gain — radiation loss

(delta: % of viscous heating that goes to e^-, unknown, depend on microphysics)

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:

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

C_s~(P/rou)^0.5

- Sub-Keplerian rotation: pressure-gradient support
- High temperature: $T \sim \frac{GMm_p}{6kR} \sim \frac{10^{12}}{r}$ (Virial)
- Geometrically thick: $(H = \frac{c_s}{\Omega_k} \sim R)$ ~spherical
- 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:

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

heat change viscous heating radiation loss

- 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:

heat change / viscous heating / collision loss

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

internal E gradient / compression work

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

dQ=dU+PdV

So we have:

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

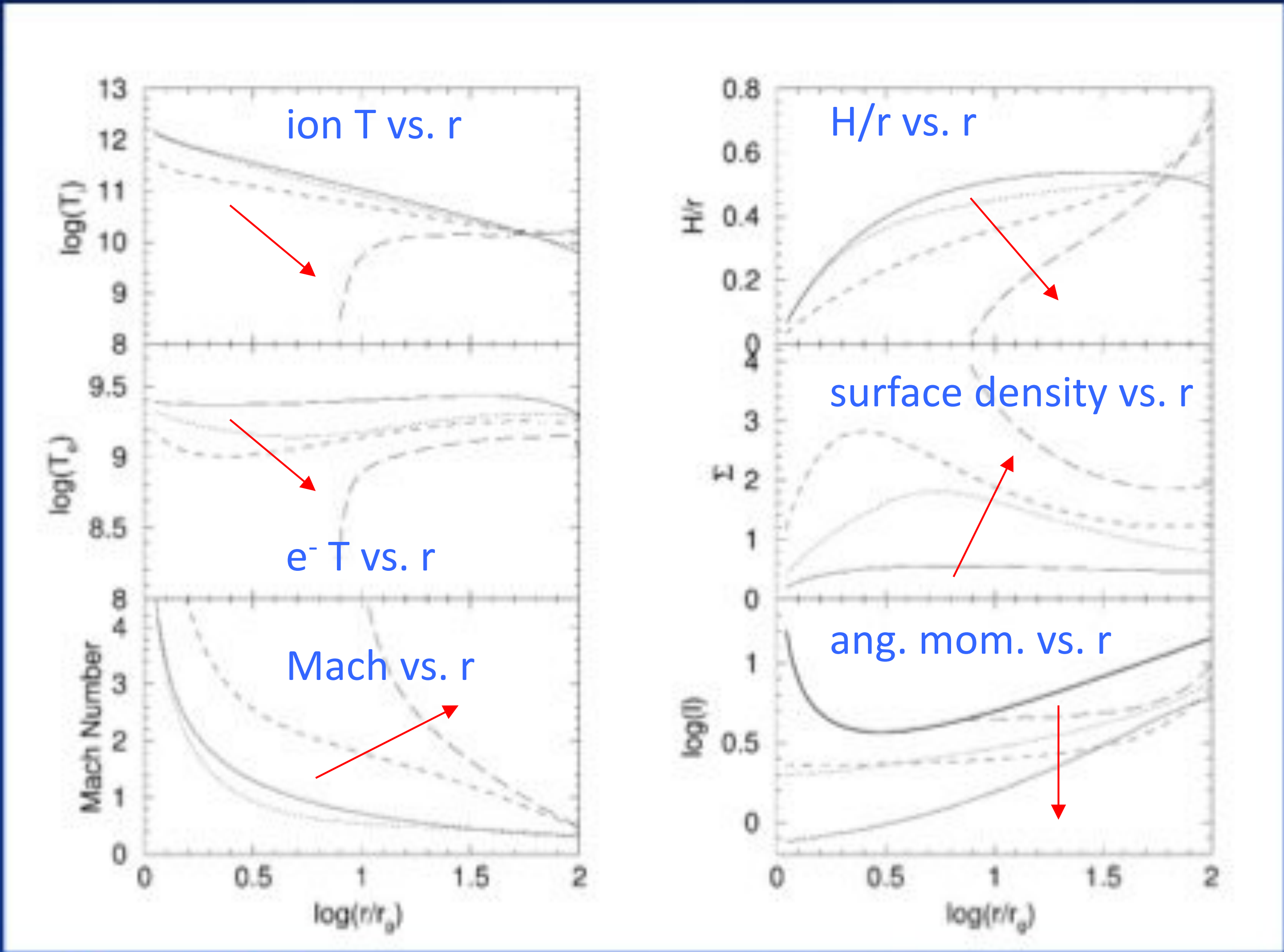
(de/dr<0: heating; starting hot, becoming hotter)

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 (cf. advection is a cooling term in ADAFs)

Global Solutions of hot accretion flow

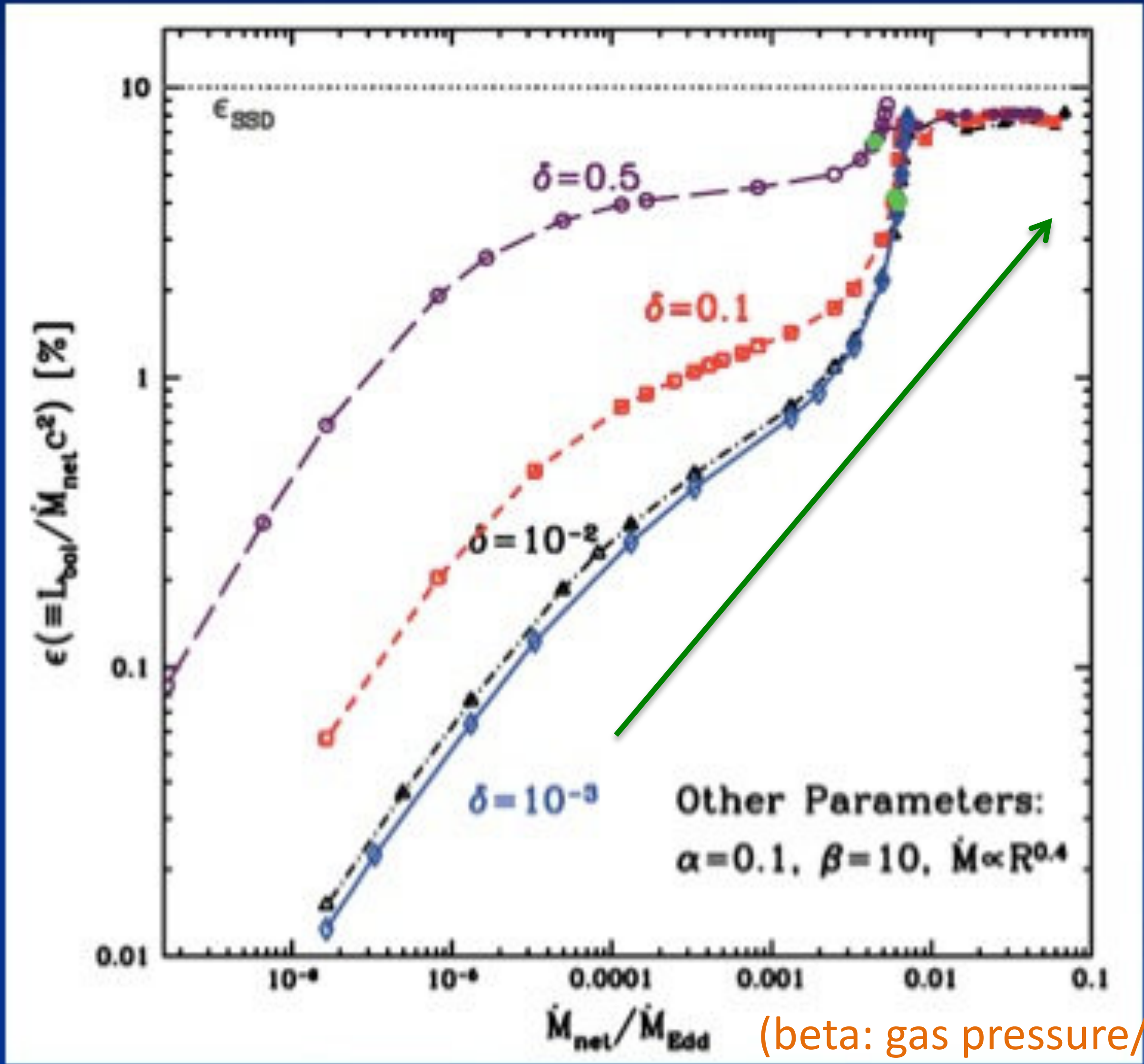


Yuan 2001

- α=0.3; $M_{BH} = 10M_{\odot}$
- 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



delta: fraction of viscous heating that goes to electrons

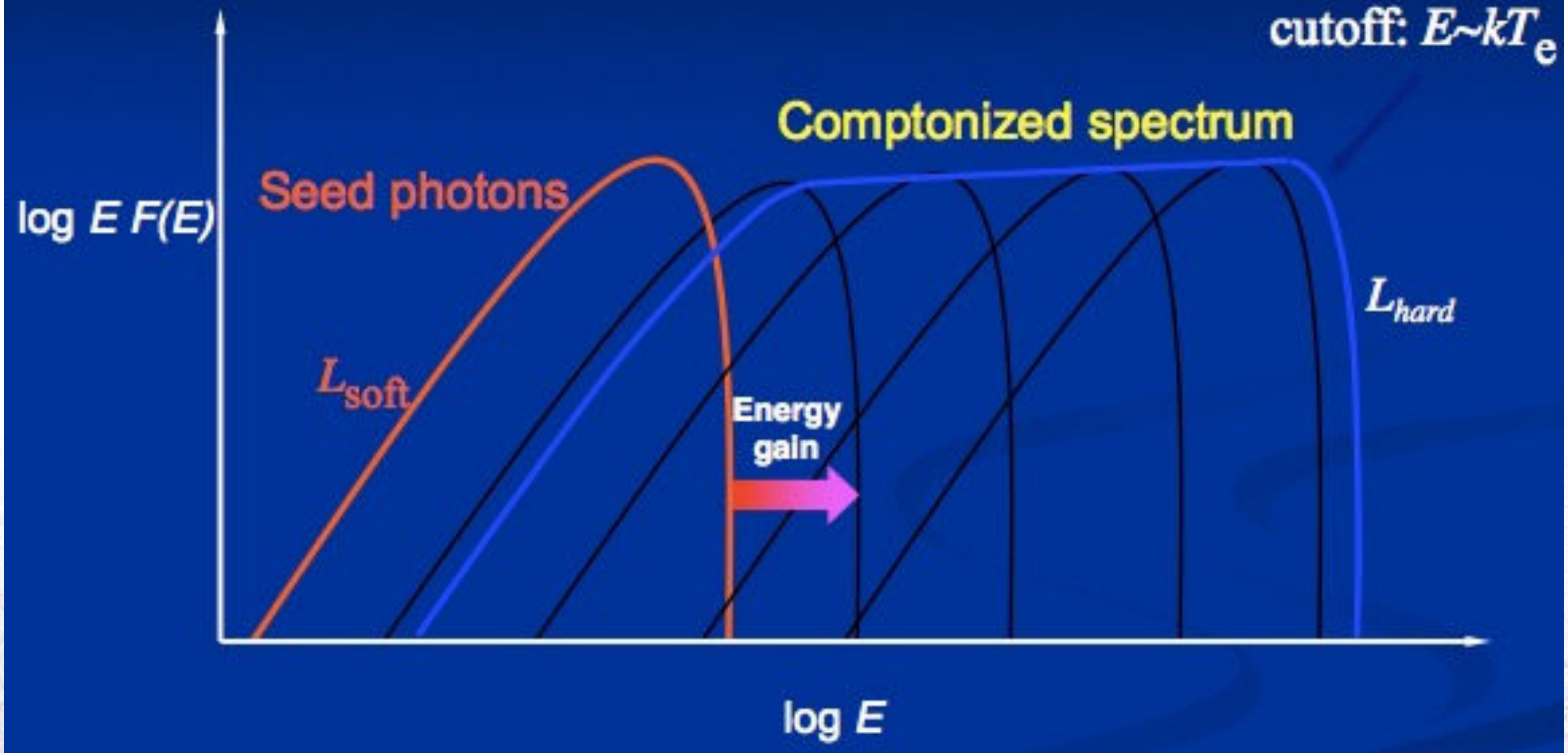
(beta: gas pressure/B pressure)

Radiative processes

(optically thin, no longer BB)

- Synchrotron emission:
  - relativistic electrons & B field (described by a parameter β); (beta: gas pressure/B pressure)
  - 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

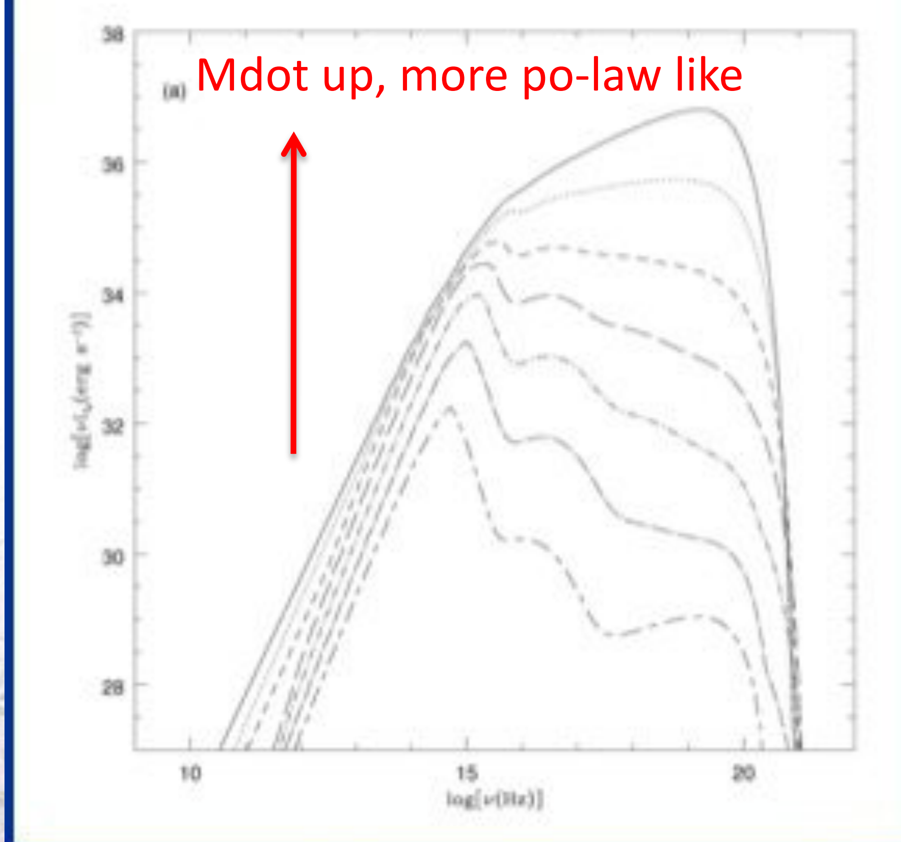
Thermal Comptonization



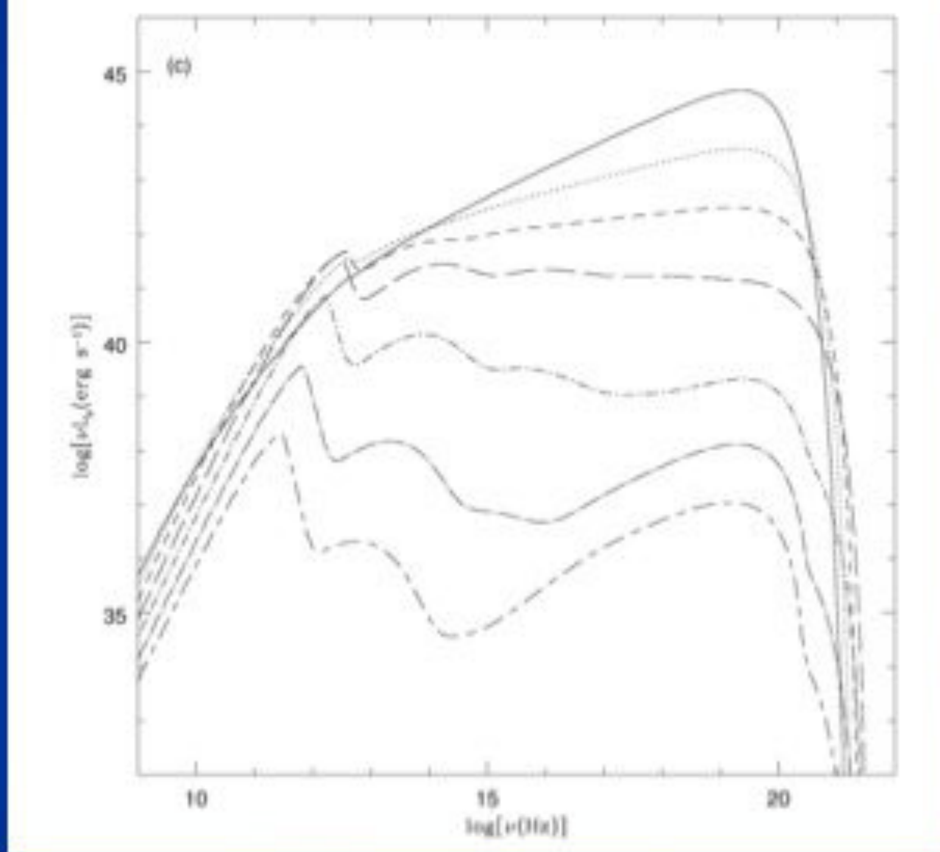
The photon index is a function of kT_e and τ (Thomson optical depth).

Emitted Spectrum

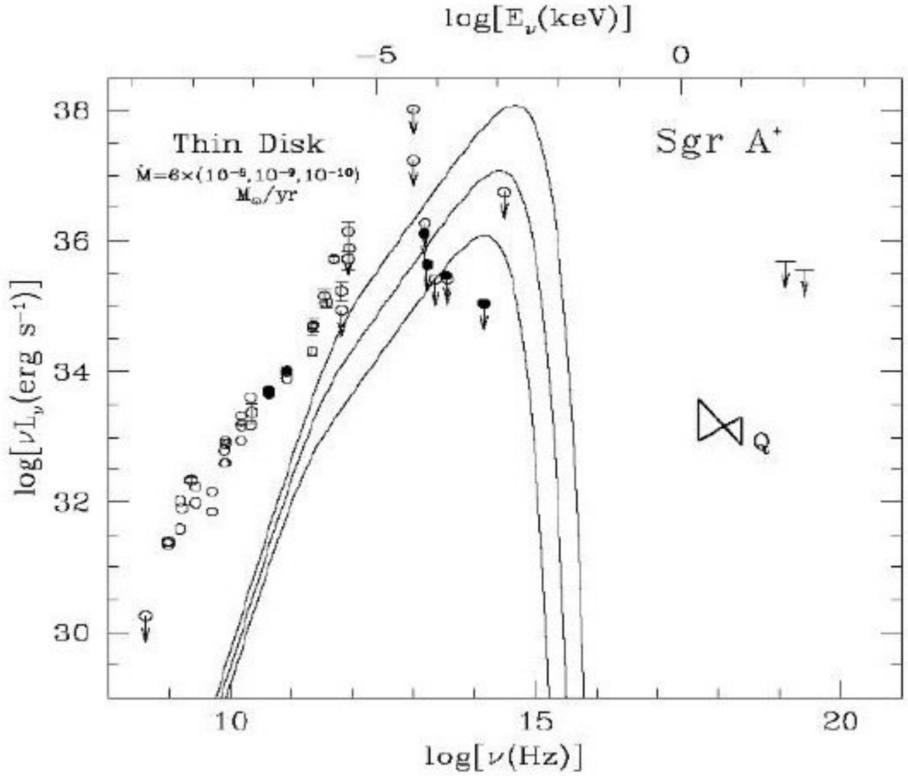
three humps: syn. ICS Brem.



Stellar-mass BH

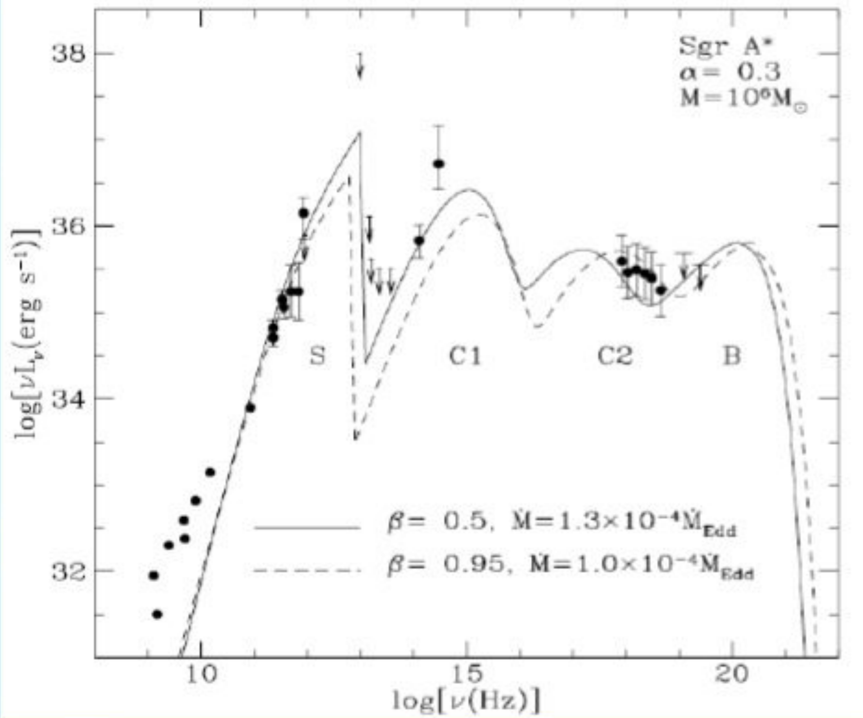


Supermassive BH



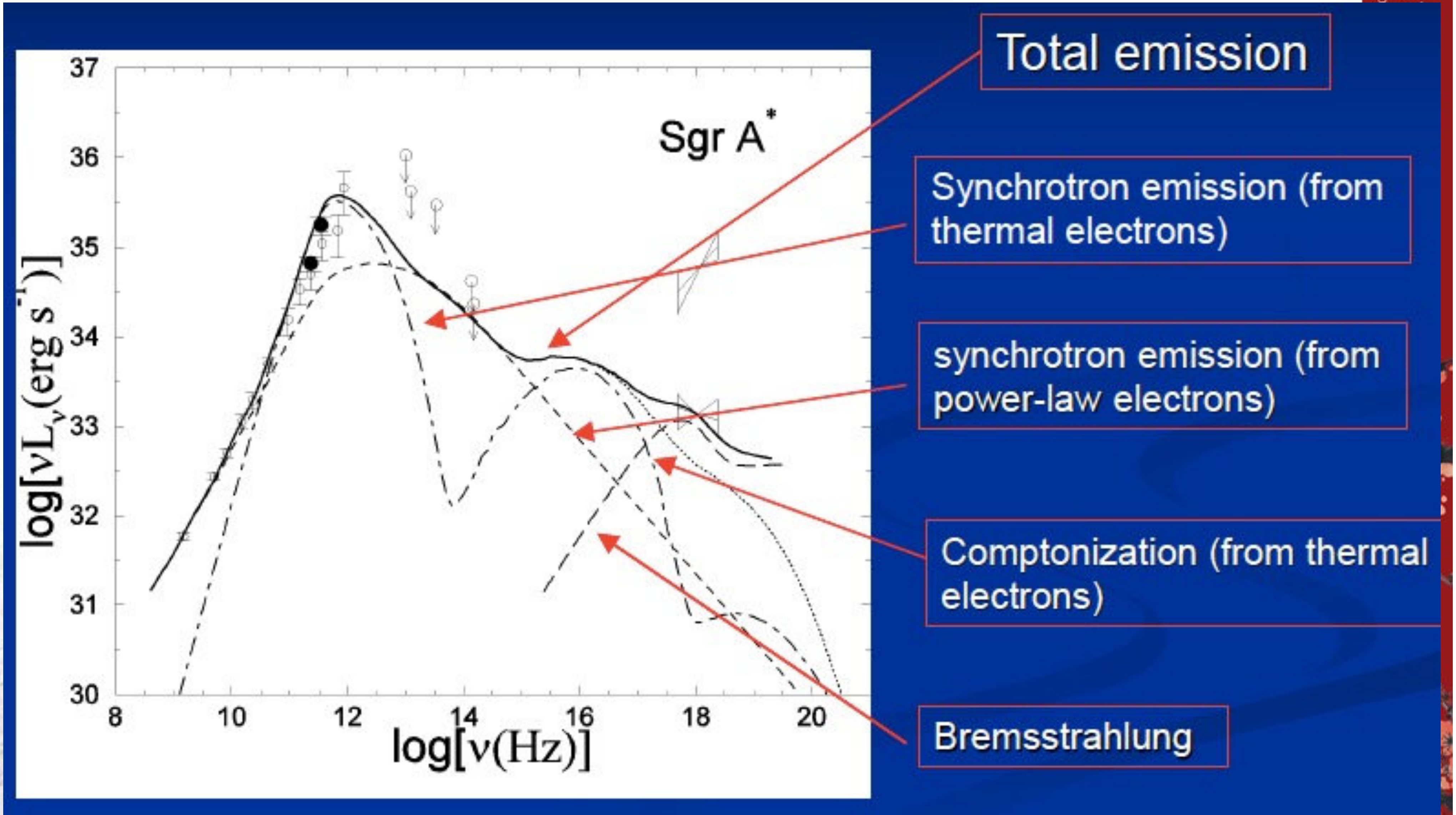
Sgr A* as an example:
SSD vs. ADAF

early ADAFs can explain:
- radiative efficiency
- broadband SED roughly



Narayan, Yi & Mahadeven 1995, Nature

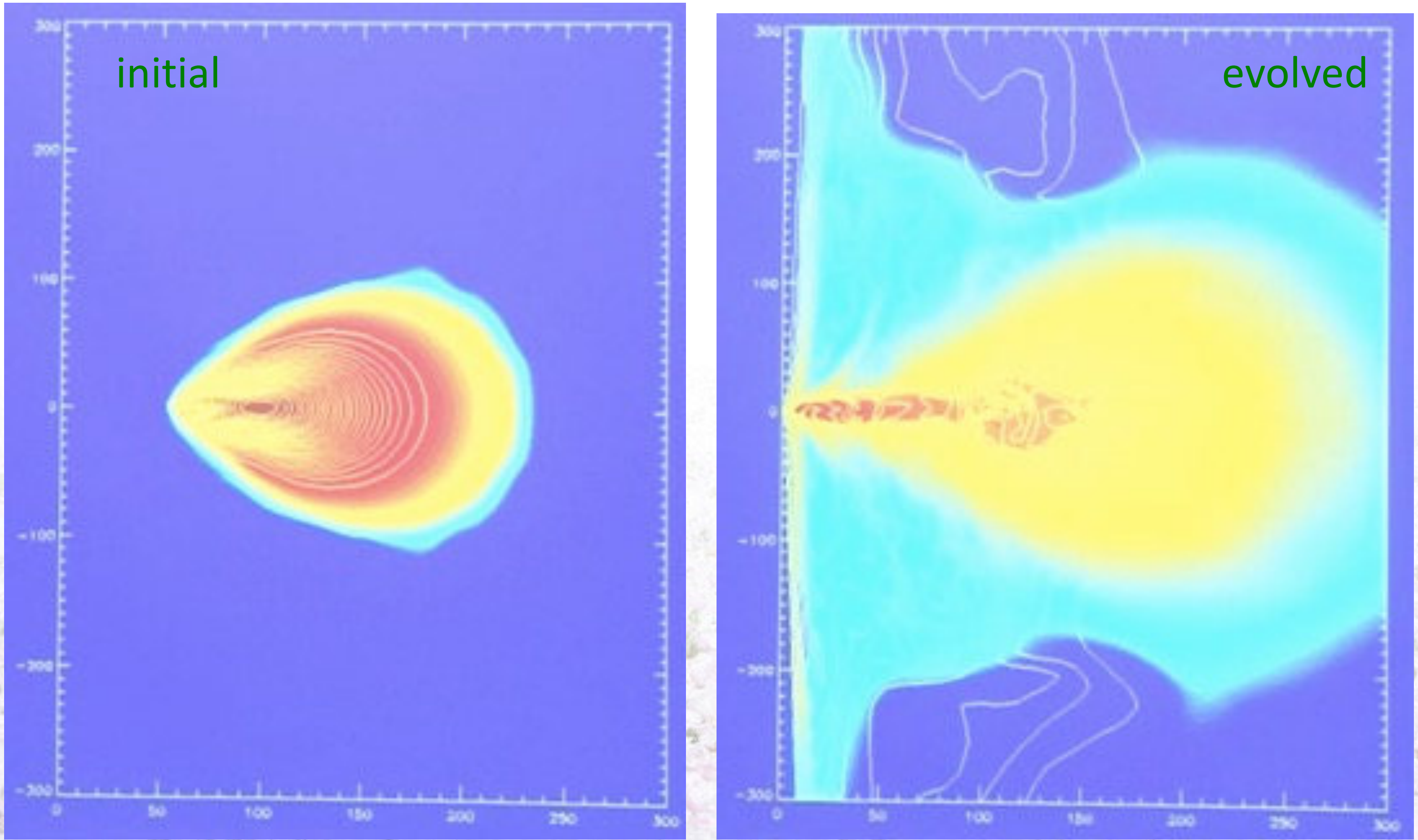
more advanced ADAF models



- Stability analyses for hot ADs:
  - $viscous stability: all hot ADs are viscously stable
  - convective stability:
    - * without B field, unstable, convective instability drives winds
    - * with B field, more realistic, stable, as MRI changes dynamics of hot ADs
  - thermal stability:
    - * stable for long-wavelength perturbations
    - * debates on short-wavelength perturbations: stable vs. unstable
    - * consequence of thermal instability:

- When $\dot{M} < 0.2\alpha\dot{M}_{Edd}$, no problem (growth timescale > accretion timescale)
- When $\dot{M} > 0.2\alpha\dot{M}_{Edd}$, growth timescale < accretion timescale,
  → Two-phase accretion flow! (cold dense clumps within hot dilute gas)

- Various complicated numerical simulations for hot ADs being carried out:
  - HD & MHD simulations:
    * mass accretion rate decreases inward
    * radial profiles of physical quantities are described by a powerlaw, consistent with self-similar solutions
    * viscosity~0.05-0.2, actually being quite diverse



(note: no global simulations for thin disks yet)

- Various complicated numerical simulations for hot ADs being carried out:

  - GRMHD simulations: B field configuration and strength in three regions:

    * jet: - B strongest, quite ordered, large-scale poloidal B field

      - magnetic energy density > gas rest (mass) energy

    * corona: - no significant difference btw corona T and disk T (unlike SSD)

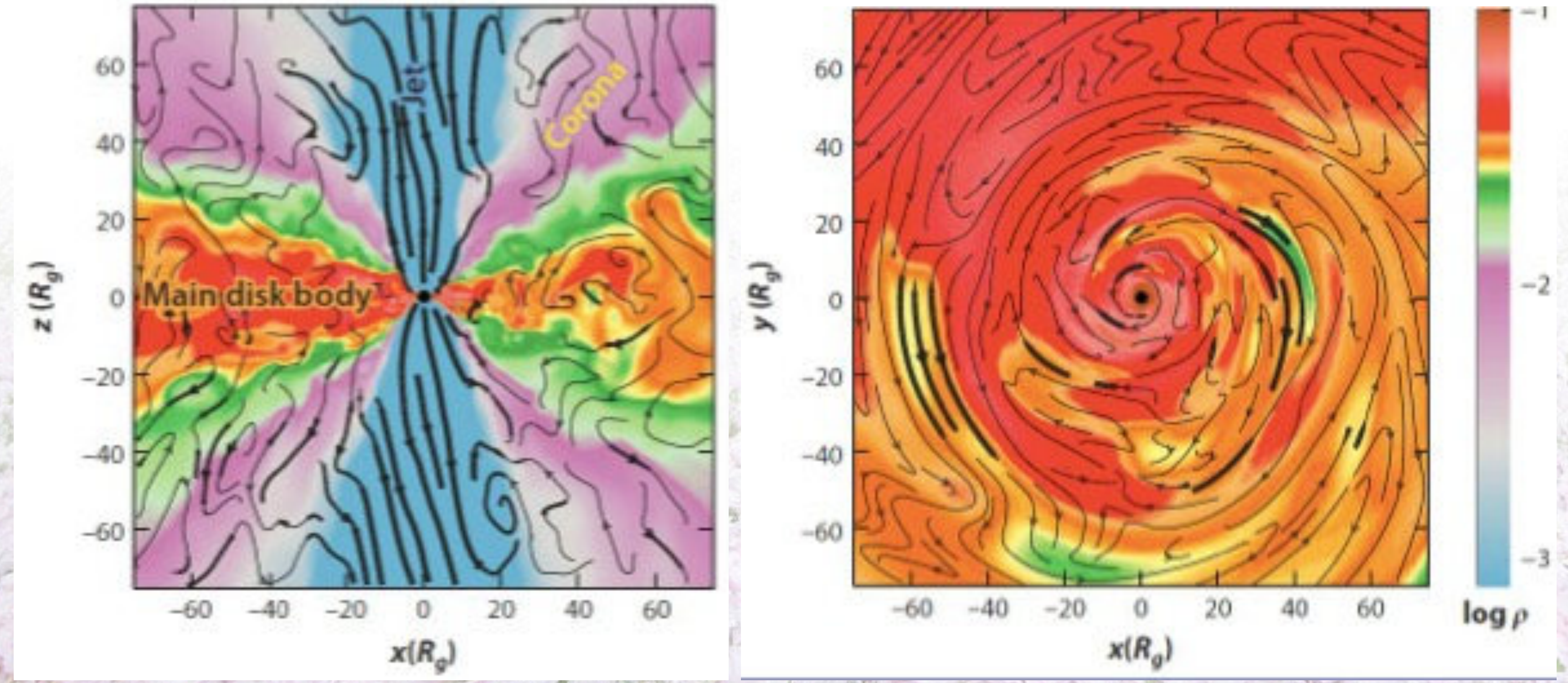
      - B strong; less ordered, turbulent, toroidal B field

      - magnetic pressure ~ gas pressure

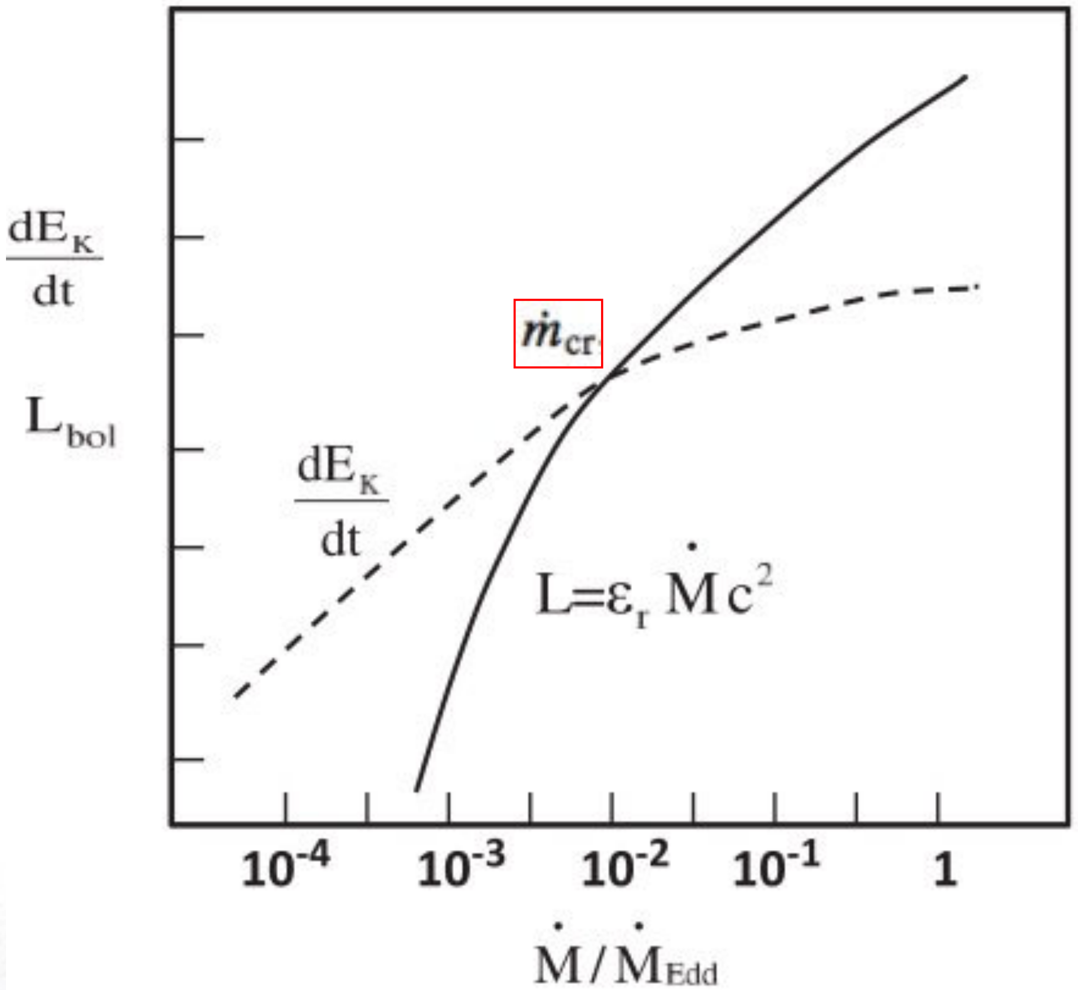
    * main disk body: - B weak, very turbulent

      - magnetic pressure ~ 0.1*gas pressure

now: GRRMHD!



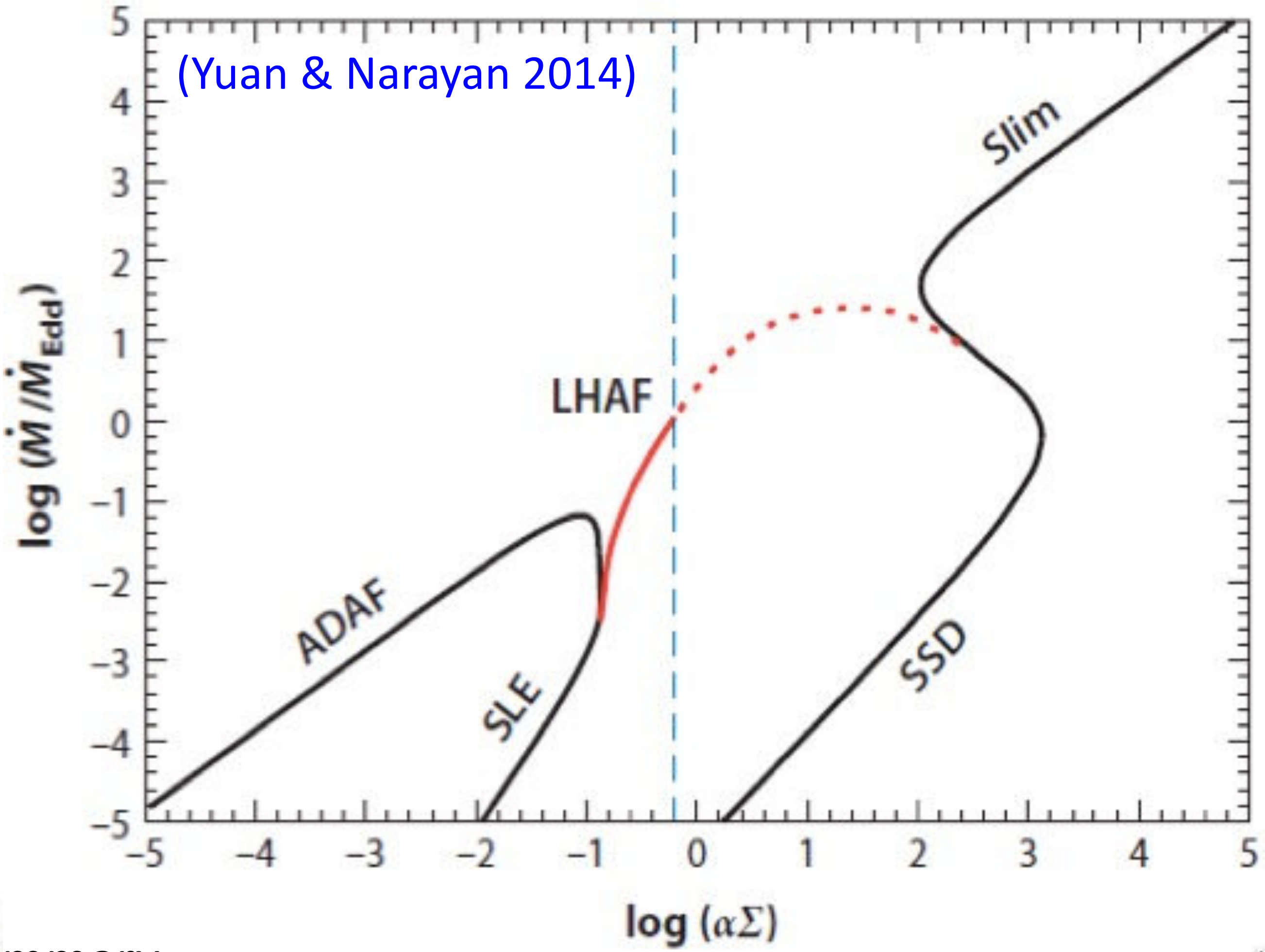
- When RIAFs involve mass loss through winds/outflows:
  - a large fraction of grav. E of inflowing gas converted to kinetic E of wind
  - such wind can leave BH on a short timescale, and move through galactic ISM or perhaps even IGM in a cluster of galaxies, delivering much of its kinetic E to the surrounding gas
    * sometimes this surrounding gas heated to emit X-rays, so can measure L_X to estimate the kinetic E of the outflow
    - some well-documented cases: $dE_K/dt > L_{bol}$
- AGN modes: cold and hot modes --- another classification
  - radiative/AGN/QSO mode: radiation-dominated processes, high L/L_{Edd}
  - radio/jet/kinetic/maintenance mode:
    most of the released E is kinetic E, low L/L_{Edd}, observations show that such flows often associated with powerful radio jets



$$\epsilon_r = \begin{cases} \eta & \text{if } \dot{m} > \dot{m}_{cr} \\ \eta \left(\frac{\dot{m}_{cr}}{\dot{m}}\right)^p & \text{if } \dot{m} \le \dot{m}_{cr} \end{cases}$$

(p~-1.0 to -0.5)

Figure 4.9. Schematic of the two modes of accretion in AGNs. The radiation power, L_{bol}, and the kinetic energy power, dE_K/dt, are plotted against the normalized accretion rate, $\dot{m} = \dot{M}/\dot{M}_{Edd}$. The transition from the radiative (AGN) mode to the kinetic energy (radio) mode is at $\dot{m} = \dot{m}_{cr}$, which, in this example, corresponds to $\dot{m} \approx 0.01$. The mass-to-radiation conversion efficiency ϵ_r (Equation 4.64) approaches at high accretion rates the radiation conversion efficiency η.



- Brief summary:

  - Accretion rate: Slim>SSD>LHAF>ADAF (holds the key)
  - Temperature: ADAF~LHAF>>Slim>SSD (hot: virial T 1e12K/r; cold: 1e6-7 K)
  - Thickness: ADAF (like spherical)~LHAF>Slim>SSD
  - Surface density: Slim>SSD>LHAF>ADAF
  - Optical depth: Slim>SSD>LHAF>ADAF
  - Radiation efficiency: SSD>Slim>LHAF>ADAF

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The Accretion Flow in M87 is Really MAD

Feng Yuan[1,2,4], Haiyang Wang[3], and Hai Yang[1,2]
[1] Shanghai Astronomical Observatory, Chinese Academy of Sciences, Shanghai 200030, People's Republic of China; fyuan@shao.ac.cn
[2] University of Chinese Academy of Sciences, 19A Yuquan Road, Beijing 100049, People's Republic of China
[3] Department of Physics, Fudan University, Shanghai 200433, People's Republic of China
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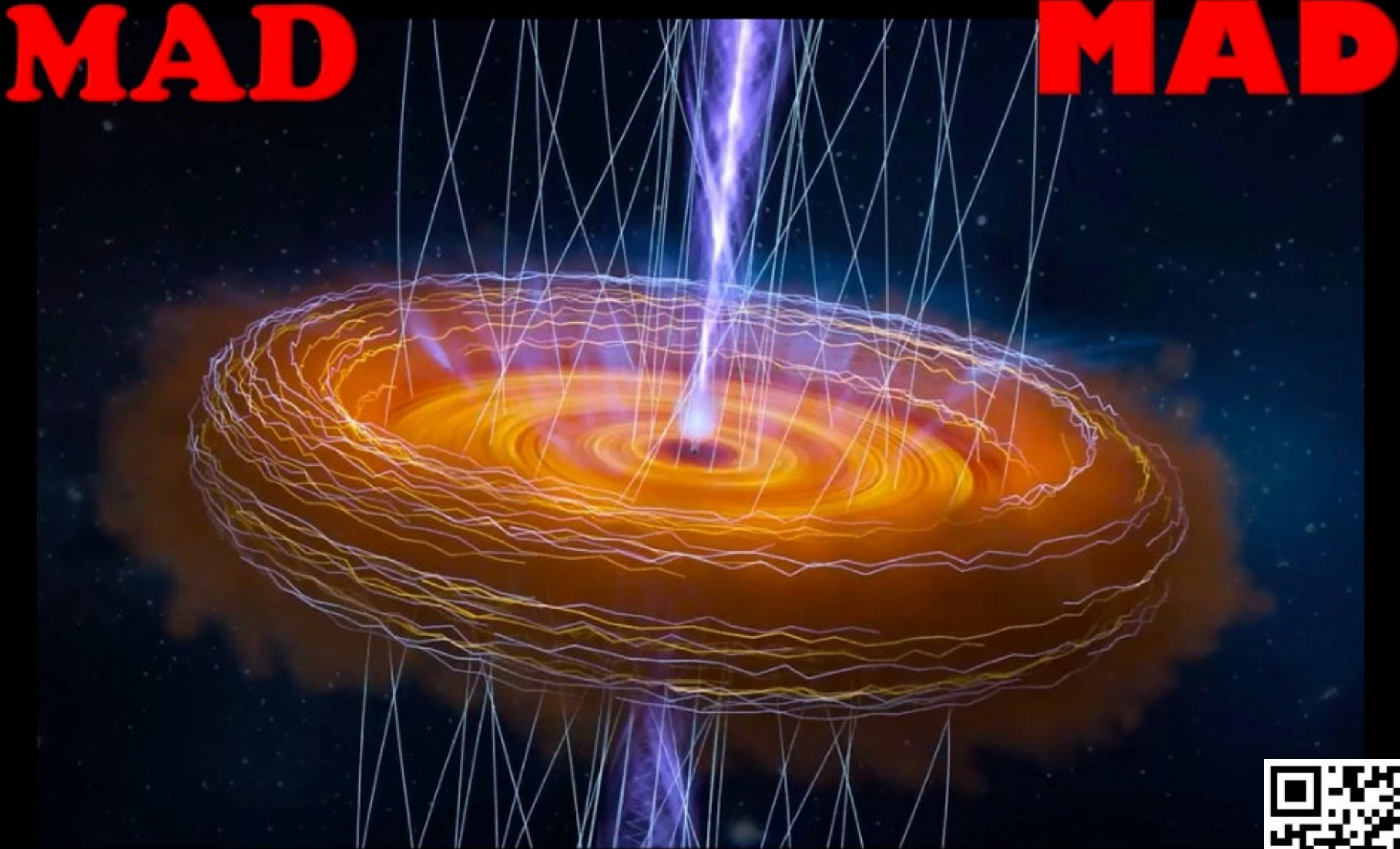
Abstract

The supermassive black holes in most galaxies in the universe are powered by hot accretion flows. Both theoretical analysis and numerical simulations have indicated that, depending on the degree of magnetization, black hole hot accretion flow is divided into two modes, namely SANE (standard and normal evolution) and MAD (magnetically arrested disk). It has been an important question which mode the hot accretion flows in individual sources should belong to in reality, SANE or MAD. This issue has been investigated in some previous works but they all suffer from various uncertainties. By using the measured rotation measure (RM) values in the prototype low-luminosity active galactic nuclei in M87 at 2, 5, and 8 GHz along the jet at various distances from the black hole, combined with three-dimensional general relativity magnetohydrodynamical numerical simulations of SANE and MAD, we show in this paper that the RM values predicted by MAD are well consistent with observations, while the SANE model overestimates the RM by over two orders of magnitude and thus is ruled out.

“疯狂”的黑洞磁囚禁吸积盘



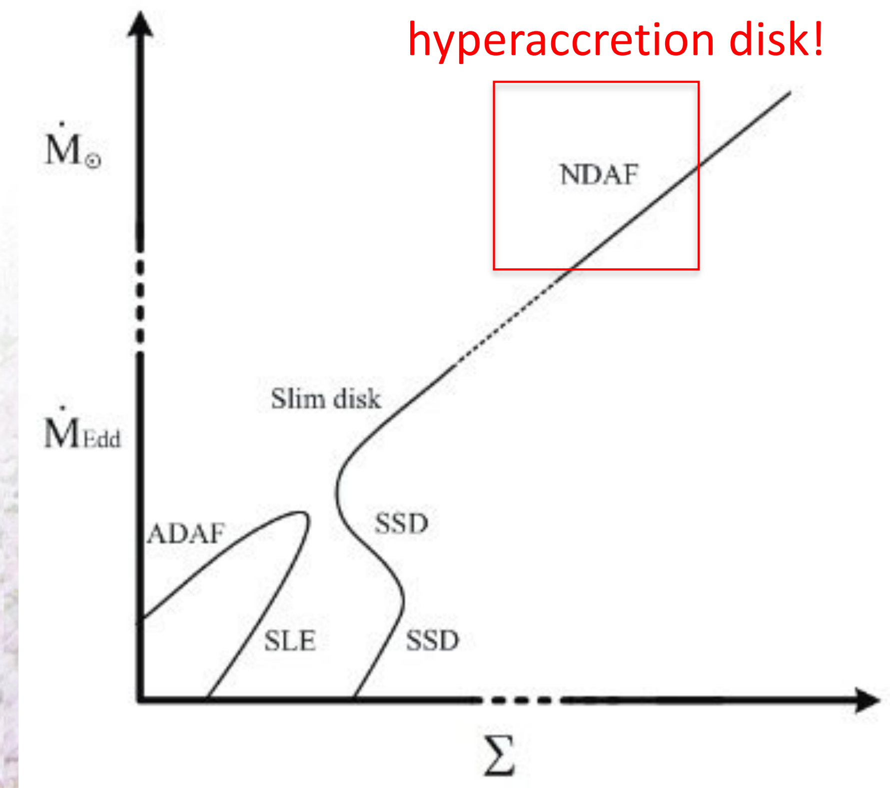
(WHU)

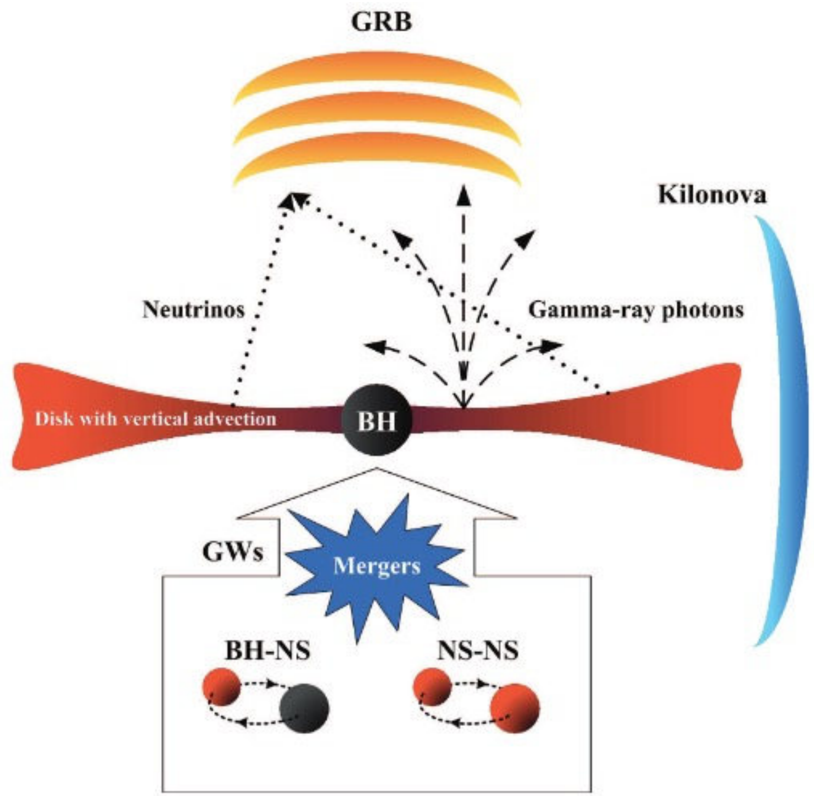
Neutrino-dominated accretion flows as the central engine of gamma-ray bursts

Tong Liu[a,b], Wei-Min Gu[a], Bing Zhang[b,c,d]

Abstract

Neutrino-dominated accretion flows (NDAFs) around rotating stellar-mass black holes (BHs) are plausible candidates for the central engines of gamma-ray bursts (GRBs). NDAFs are hyperaccretion disks with accretion rates in the range of around 0.001-10 $M_\odot$ s^{-1}, which have high density and temperature and therefore are extremely optically thick and geometrically slim or even thick. We review the theoretical progresses in studying the properties of NDAFs as well as their applications to the GRB phenomenology. The topics include: the steady radial and vertical structure of NDAFs and the implications for calculating neutrino luminosity and annihilation luminosity, jet power due to neutrino-antineutrino annihilation and Blandford-Znajek mechanism and their dependences on parameters such as BH mass, spin, and accretion rate, time evolution of NDAFs, effect of magnetic fields, applications of NDAF theories to the GRB phenomenology such as lightcurve variability, extended emission, X-ray flares, kilonovae, etc., as well as probing NDAFs using multi-messenger signals such as MeV neutrinos and gravitational waves.





4.5. Further reading

Standard α-disks: The seminal paper on the physics of α-disks is Shakura and Sunyaev (1973). Optically thick, geometrically thin disks are discussed in numerous books and articles. The treatment adopted here is similar to the one discussed in greater detail in Frank et al. (1985). A useful comprehensive review is given in Blaes (2007). State-of-the-art calculations of thin-disk spectra can be found in Blaes et al. (2001), Hubeny et al. (2001), Davis et al. (2007), and references therein. Davis and Laor (2011) describe the method to estimate a BH accretion rate regardless of its spin.

Comptonization and disk corona: See Reynolds and Nowak (2003), and references therein.

X-ray emission from irradiated disks: For the general geometry, see Blaes (2007). For X-ray features, see Reynolds and Nowak (2003), Ross and Fabian (2005), Dovčiak et al. (2004), Rozanska and Madej (2008), Cao (2009), and references therein.

Slim and thick accretion disks: There are relatively few calculations of such disks and their spectra; see, for example, Madau (1988), Kawaguchi et al. (2001), and Wang and Netzer (2003). For super-Eddington accretion, and the connection to NLS1s, see Collin and Kawaguchi (2004), and references therein.

RIAFs: The physics of various advection-dominated flows is discussed in numerous papers, including many that are not related to accretion onto massive BHs. Useful comprehensive descriptions with many additional references are Narayan and McClintock (2008) and Cao (2010).

Find newer further reading by yourself!