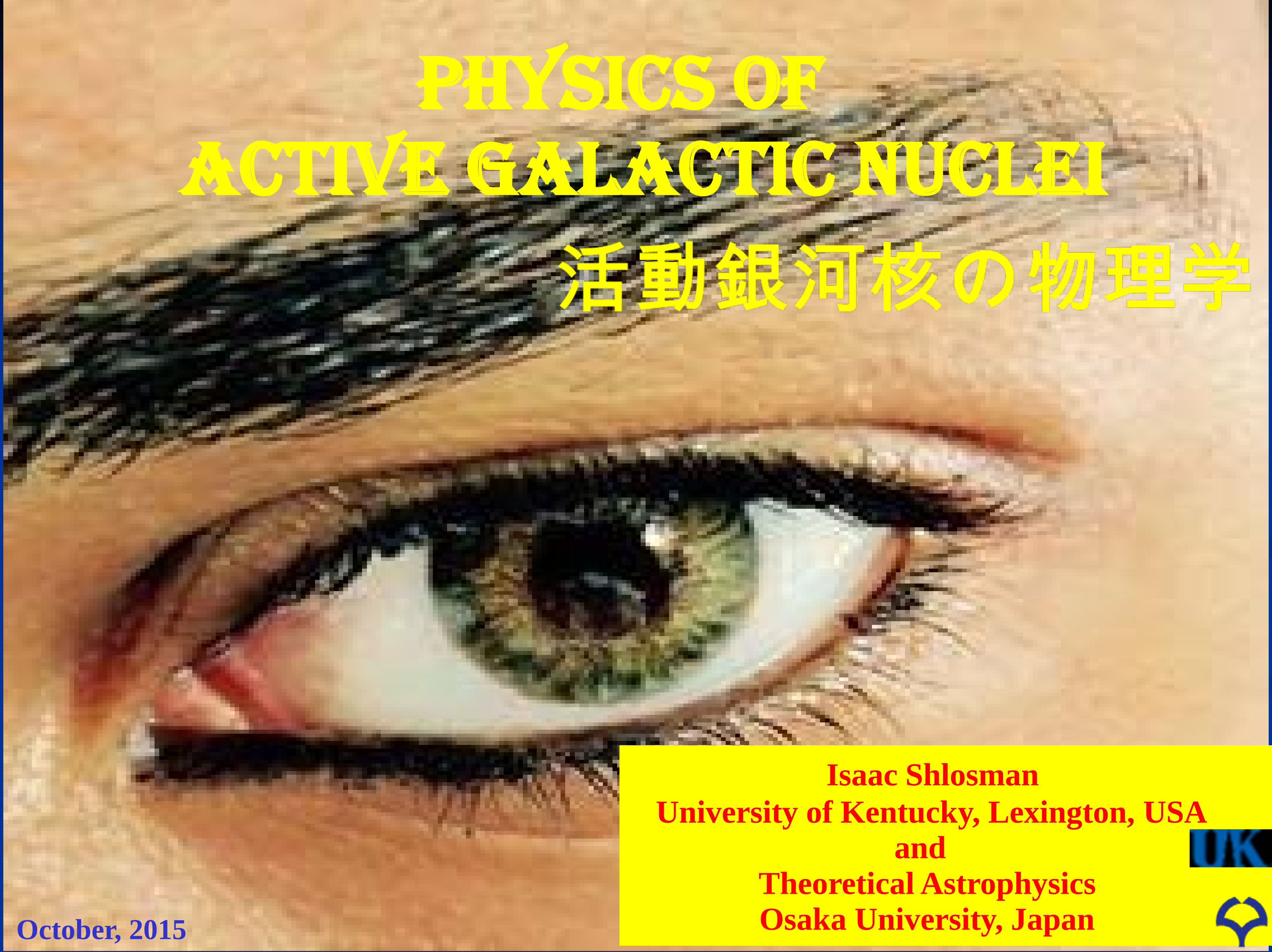


PHYSICS OF ACTIVE GALACTIC NUCLEI

活動銀河核の物理学

Isaac Shlosman
University of Kentucky, Lexington, USA
and
Theoretical Astrophysics
Osaka University, Japan

October, 2015

LECTURE 2:
SUPERMASSIVE BLACK HOLES AND ACCRETION PROCESSES

Relativity and black holes

Spherical accretion on BHs and why do we need supermassive BHs

Disk accretion on BHs:
geometrically-thin and thick disks: ADAF, ADIOS, CDAF, etc.

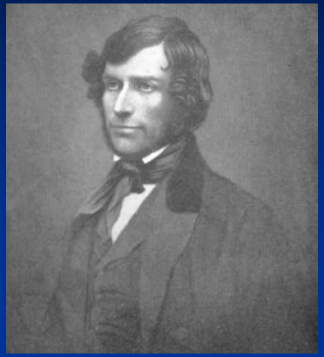
The central engine of AGN

BLACK HOLES

❖ First mentioning of a black hole in history (1783):

If the semi-diameter of a sphere of the same density as the Sun were to exceed that of the Sun in the proportion of 500 to 1, a body falling from an infinite height towards it would have acquired at its surface greater velocity than that of light, and consequently supposing light to be attracted by the same force in proportion to its vis *inertiae*, with other bodies, all light emitted from such a body would be made to return towards it by its own proper gravity.

John Michell (1724-1793)
English clergyman and natural philosopher



John Michell

Karl Schwarzschild

$$\frac{1}{2} v^2 = \frac{GM}{R}$$

are there objects with $\frac{2GM}{Rc^2} \geq 1$?

Laplace (1896) in 1st and 2nd edition of his book, then removed this note….
Karl Schwarzschild (1916) in a letter to Einstein from the front….
1st nontrivial stationary solution to Einstein eqs.

BLACK HOLES

A black hole is completely specified by their

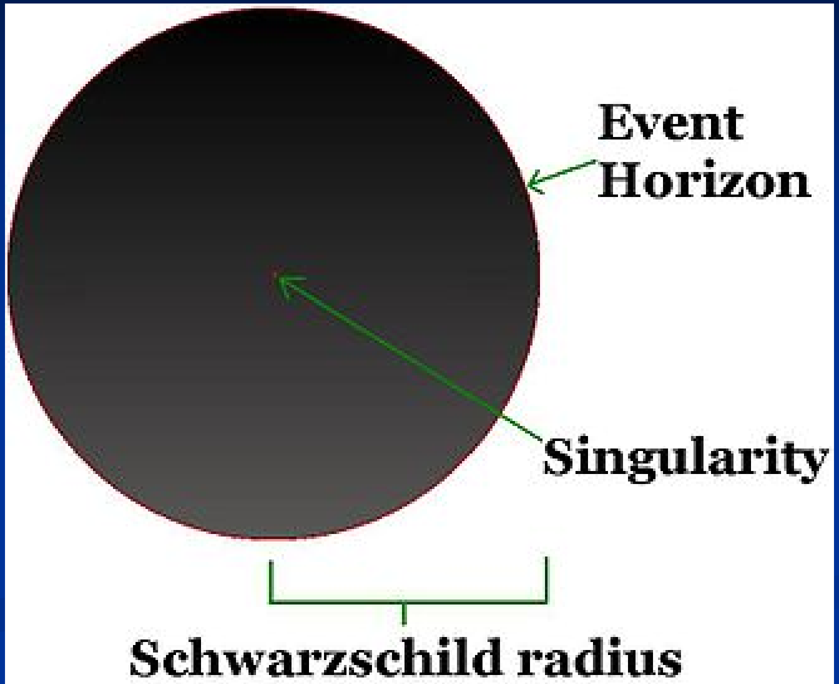
masses M

angular momentum J

charge Q (likely = 0)

Black holes have no hair!

theorem by J.A. Wheeler



- Schwarzschild black hole: J=0, Q=0
  - → spherically-symmetric with radius $R_\bullet = 2GM/c^2$

Schwarzschild solution:

$$ds^2 = g_{\mu\nu}dx^\mu dx^\nu = -(1-2M/r)\,dt^2 + \frac{dr^2}{1-2M/r} + r^2 d\Omega^2 \,,$$
$$d\Omega^2 = d\theta^2 + \sin^2\theta\, d\varphi^2 \,,$$

→smallest stable orbit at $R_{min} = 3R_\bullet$

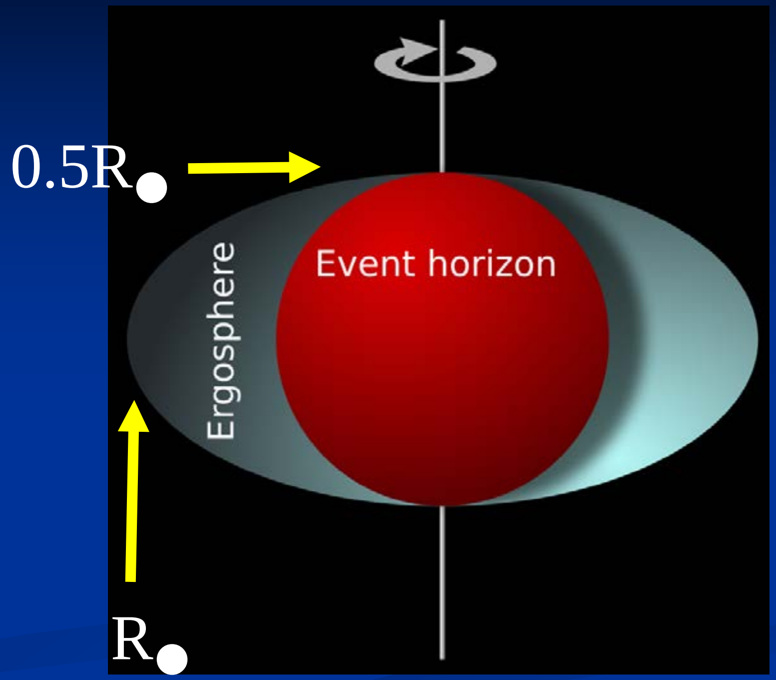
→minimal orbital period for $M_\bullet \sim 10^{7\text{-}8} M_\odot$ → few hours (variability)

singularity!

BLACK HOLES

- Kerr (1963) black hole: axisymmetric → parameter J

$$ds^2 = -dt^2 + (r^2 + a^2)\sin^2\theta d\varphi^2 + \frac{2Mr(dt - a\sin^2\theta d\varphi)^2}{r^2 + a^2\cos^2\theta} + (r^2 + a^2\cos^2\theta)\left(d\theta^2 + \frac{dr^2}{r^2 - 2Mr + a^2}\right).$$



Kerr black hole

1st law of black hole physics: the increase of the BH mass is the sum of all energies added to the BH

2nd law of black hole physics: the total area of the horizon cannot decrease

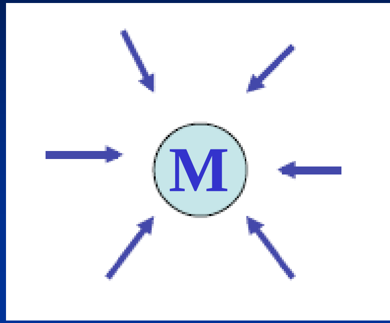
Lense-Thirring effect: dragging of intertial frames
→ objects in the ergosphere cannot be at rest with respect to observer at ∞

ACCRETION ONTO BLACK HOLES

- Spherical accretion: Bondi-Hoyle solution

  Steady-state spherical inflow under gravity (at rest at ∞)

  → mass conservation equation



$$\nabla \cdot (\rho \underline{u}) = 0 \qquad \text{eq.(1)}$$

$$\int_V \nabla \cdot (\rho \underline{u}) dV = \int_s \rho \underline{u} \cdot d\underline{S} \;\Rightarrow\; 4\pi r^2 \rho u = \text{constant} = \dot{M} \qquad \text{eq.(2)}$$

mass inflow rate

→steady-state momentum (Euler) equation:

$$(\underline{u} \cdot \underline{\nabla})\underline{u} = -\frac{1}{\rho}\underline{\nabla} p - \underline{\nabla}\psi \qquad \text{eq.(3)}$$

point mass gravity

$$u\frac{\partial u}{\partial r} = -\frac{1}{\rho}\frac{\partial p}{\partial r} - \frac{GM}{r^2} \qquad \text{eq.(4)}$$

$$\frac{\partial}{\partial r}\left(r^2 \rho u\right) = 0 \;\Rightarrow\; 2r\rho u + r^2 u\frac{\partial \rho}{\partial r} + r^2 \rho \frac{\partial u}{\partial r} = 0 \;\Rightarrow\; -\frac{1}{\rho}\frac{\partial \rho}{\partial r} = \frac{2}{r} + \frac{1}{u}\frac{\partial u}{\partial r}$$

But
$$\frac{1}{\rho}\frac{\partial p}{\partial r} = \frac{1}{\rho}\frac{\partial p}{\partial \rho}\frac{\partial \rho}{\partial r} = c_s^2 \frac{1}{\rho}\frac{\partial \rho}{\partial r}$$

ACCRETION ONTO BLACK HOLES

❖ Spherical accretion: Bondi-Hoyle solution

eq.(4): $$u\frac{\partial u}{\partial r} = -\frac{1}{\rho}\frac{\partial p}{\partial r} - \frac{GM}{r^2}$$ → $$\left(u^2 - c_s^2\right)\frac{\partial(\ln u)}{\partial r} = \frac{2c_s^2}{r}\left(1 - \frac{GM}{2c_s^2 r}\right)$$

So at $r_s = GM/2c_s^2$ *u* is a maximum/minimum

or u = c_s → sonic transition happens at r_s

c_s= const. → *T* determines the sonic point

density at the sonic point: $$\rho_s = \frac{\dot{M}}{4\pi r_s^2 c_s}$$

Definition of accretion radius: $r_{acc} = \frac{2GM}{c_s^2}$ → $$\mathbf{r_{acc} = \frac{2GM}{c^2+v^2}}$$

If M moving with speed v

ACCRETION ONTO BLACK HOLES

- Spherical accretion: Bondi-Hoyle solution

Insert r_{acc} into $\dot{M}$

$$\dot{M} \sim \frac{4\pi\rho G^2 M_\bullet^2}{(c^2 + v^2)^{3/2}}$$

accretion rate

$$\dot{M} \sim 6 \text{ x } 10^{-16} \left(\frac{M_\bullet}{1M_\odot}\right)^2 M_\odot/\mathrm{yr}$$

for $T=10^4$ K

$v=0$

$\rho = 10^{-24}$ g/cm^3

ACCRETION ONTO BLACK HOLES

❖ Eddington limit

For an AGN with observed bolometric luminosity L → estimate minimum $M_{\bullet}$

→ spherically-symmetric accretion, fully ionized H

Flux at distance r

$$F = \frac{L}{4\pi r^2}$$

Corresponding radiation pressure on free electrons

$$P_{rad} = \frac{L}{4\pi r^2 c}$$

→ using minimum cross section (Thomson) $\sigma_T = 6.65 \text{ x } 10^{-25}\ \text{cm}^2$

Resulting outward radiation force on a single electron:

$$f_{rad} = \frac{L\sigma_T}{4\pi r^2 c}$$

ACCRETION ONTO BLACK HOLES

- Eddington limit

Balancing by gravity per proton (WHY?): $f_{grav} = \frac{GMm_p}{r^2}$

$$\boxed{L = \frac{4\pi G c m_p}{\sigma_T} M = 1.3 \text{ x } 10^{38} \left(\frac{M}{M_\odot}\right) \text{ erg/s}}$$

The Eddington luminosity

Inverting this formula and using AGN luminosity:

$$\boxed{M_\bullet = 8 \text{ x } 10^5 \left(\frac{L}{10^{44} \text{erg/s}}\right) M_\odot}$$

this is minimum mass

Need supermassive BHs to explain the AGN luminosity! → SMBH

ACCRETION ONTO BLACK HOLES

❖ Fueling AGN To pro ... /s

Need ... this gas must be accreted?

Define efficiency of e ... $L = \eta \dot{M} c^2$

Mass δm accretes fro ...

Available energy to sp ... $= \frac{GM_\bullet \dot{M}}{r}$

This is an uppe ... radiation!

Energy/mass: $E_{pot} = \frac{\quad}{r}$ → for neutron star (1 $M_\odot$, 10 km) ~ 1.4×10^{20} erg/gm

→ for black hole (1 $M_\odot$, 3 km) ~ 4.6×10^{20} erg/gm

but no hard surface! How can it radiate?

ACCRETION ONTO BLACK HOLES

❖ Spectra of AGN: two options

Energy of each proton is turned directly into heat by a shock at the surface or horizon:

$$\frac{GM}{r} \rightarrow \frac{3kT}{m_p} \rightarrow Ts \sim 1 \times 10^{12}\ K \qquad \text{for neutron star}$$

$$\rightarrow \quad \sim 3 \times 10^{12}\ K \qquad \text{for any mass BH}$$

Energy of each proton is thermalized and radiated away as a blackbody (at Eddington luminosity)

$$L_E = 4\pi r^2 \sigma T^4$$

$$\rightarrow T_{bb} \sim 10^7\ K \quad \text{for neutron star}$$

$\sim 10^5$ K for SMBH of $10^8\ M_\odot$ → $R_s = 2GM_\bullet / c^2 \sim 3 \times 10^{13}$ cm

SMBH are expected to radiate from optical/UV → X-rays → γ rays !
Great fit to observations of AGN!

ACCRETION ONTO SUPERMASSIVE BLACK HOLES

❖ Fueling AGN

If L ~ L(Eddington) → SMBH grows exponentially!

$$L = \frac{GM_{\bullet}\dot{M}}{r} \quad \Longleftrightarrow \quad L_{edd} = \frac{4\pi G c m_p}{\sigma_T} M_{\bullet}$$

$$\left.\begin{aligned} \frac{1}{M_{\bullet}}\, dM_{\bullet} &= \text{const. x } dt \\ M_{\bullet} &= M_{0\bullet}\, e^{t/t(Sal)} \end{aligned}\right\} \rightarrow t_{Sal} = \frac{\eta \sigma_T c}{4\pi G m_p} \sim 4.5\, \eta_{0.1}\, 10^7 \text{ yr}$$

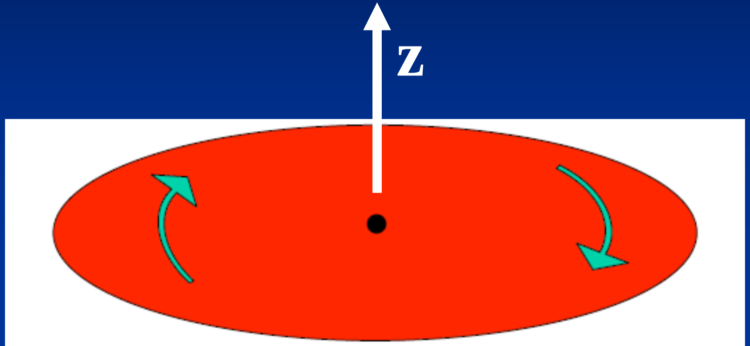
Salpeter (1964) *e*-folding time
for the BH growth at the Eddington rate

ACCRETION ONTO SUPERMASSIVE BLACK HOLES

❖ Disk accretion: Shakura-Sunyaev-Novikov-Thorne solution → geometrically-thin disks

$$\Sigma = \int_{-\infty}^{\infty} \rho dz \approx 2H\langle\rho\rangle$$

Σ = surface density of a disk
with a half-thickness H
in **cylindrical** coordinates R, φ, z



accretion disks are universal mechanism to get rid of J

$v_\varphi = v_K = (GM_\bullet/R)^{1/2}$ rotation velocity is Keplerian
→ disk is supported by rotation only

radial pressure gradient → neglect

For gas to move inward → $J/M = \mathbf{R} \times \mathbf{v} = (GM_\bullet R)^{1/2}$ must move out!
→ needs (coefficient of kinematic) viscosity ν !
$\nu \sim v_T \lambda$ → thermal velocity x mean free path
→ assume viscous torque G(R) between neighboring disk rings

ACCRETION ONTO SUPERMASSIVE BLACK HOLES

❖ Disk accretion: Shakura-Sunyaev-Novikov-Thorne solution → geometrically-thin disks

Assume G(R) viscous torque between neighboring disk rings:

$G(R) = 2\pi R\, \Sigma R^2\, \nu\Omega'$ where $\Omega' = d\Omega/dR$

$Rd\Omega/dR$ ← shear

analog of thin accretion disk

$\Omega=(GM_\bullet/R^3)^{1/2}$ → angular velocity in Keplerian disk

Net torque on a disk ring between R and $R+\Delta R$ is

$$G(R+\Delta R) - G(R) = \frac{\partial G}{\partial R}\Delta R \qquad \text{eq.(5)}$$

Torque does work at a rate:

$$\Omega\frac{\partial G}{\partial R}\Delta R = \left[\underbrace{\frac{\partial}{\partial R}(G\Omega)}_{\text{transport of rotational energy}} - \underbrace{G\Omega'}_{\text{dissipation per unit area}}\right]\Delta R \qquad \text{eq.(6)}$$

ACCRETION ONTO SUPERMASSIVE BLACK HOLES

❖ Disk accretion: geometrically-thin disks → viscous torque

Now, assume that the gas in the disk has a small radial velocity v_R

$$R\frac{\partial \Sigma}{\partial t} + \frac{\partial}{\partial R}(R\Sigma v_R) = 0$$

eq.(7)

equation of the mass conservation in the disk (continuity eq.)

$$R\frac{\partial}{\partial t}(\Sigma R^2 \Omega) + \frac{\partial}{\partial R}(R\Sigma v_R R^2 \Omega) = \frac{1}{2\pi}\frac{\partial G}{\partial R}$$

eq.(8)

equation of *J* conservation in the disk

combine

$$R\frac{\partial \Sigma}{\partial t} = -\frac{1}{2\pi}\frac{\partial}{\partial R}\left[\frac{1}{(R^2\Omega)'}\frac{\partial G}{\partial R}\right]$$

eq.(9)

$G(R) = 2\pi R\, \Sigma R^2\, \nu\Omega'$

$$\boxed{\frac{\partial \Sigma}{\partial t} = \frac{3}{R}\frac{\partial}{\partial R}\left[R^{1/2}\frac{\partial}{\partial R}(\nu\Sigma R^{1/2})\right]}$$

eq.(10)

insert into eq.(7)

$$u_R(R,t) = -\frac{3}{\Sigma R^{1/2}}\frac{\partial}{\partial R}(\nu\Sigma R^{1/2})$$

ACCRETION ONTO SUPERMASSIVE BLACK HOLES

❖ Disk accretion: geometrically-thin disks → timescales

$$\frac{\partial^2}{\partial R^2} \longrightarrow \frac{1}{R^2}$$

$$t_{\rm acc}^{-1} = \frac{1}{\Sigma}\frac{\partial \Sigma}{\partial t}$$

$t_{visc} \sim R^2/\nu$ viscous timescale is extremely long! Need "anomalous" viscosity!

$t_{dyn} \sim R/v_K \sim \Omega^{-1} \sim (R^3/GM_\bullet)^{1/2}$ dynamical timescale

$$t_{th} \sim \Sigma c_s^2/D(R) \sim R^3 c_s^2/GM_\bullet \nu \sim \frac{R^2}{\nu}\frac{c_s^2}{v_K^2} \sim \frac{H^2}{R^2}\, t_{visc}$$

→ $\boxed{t_{dyn} < t_{th} < t_{visc}}$

ACCRETION ONTO SUPERMASSIVE BLACK HOLES

❖ Disk accretion: geometrically-thin disks → **example**

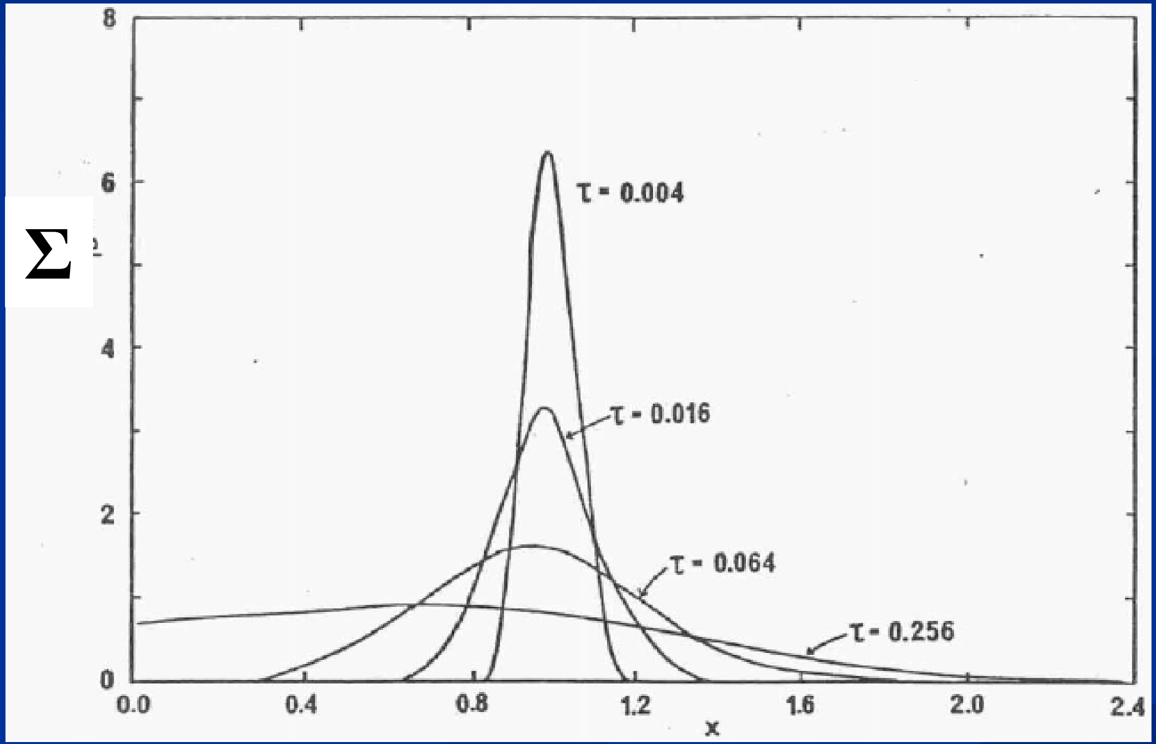
Assume an infinitesimally thin ring with mass *m* and radius R_0 → $x=R/R_0$; $\tau = t\,(12\nu/R_0^2)$

$$\Sigma(R, t=0) = \frac{m\delta(R-R_0)}{2\pi R_0}$$

solution

$$\Sigma(x,\tau) = \frac{m}{\pi R_0^2}\tau^{-1}x^{-1/4}\exp\left[-\frac{1+x^2}{\tau}\right] I_{1/4}\left(\frac{2x}{\tau}\right)$$

where $I_{1/4}$ is modified Bessel function



x=R/R$_0$

viscous evolution of thin ring

At later time, the ring moves inward, but has a long tail to large *R*
→ most material is accreted, but some escapes with large *J*

ACCRETION ONTO SUPERMASSIVE BLACK HOLES

❖ Disk accretion: geometrically-thin disks → steady-state

Steady-state radial momentum conservation equation:

$$u_R \frac{\partial u_R}{\partial R} - \frac{u_\phi^2}{R} + \cancel{\frac{1}{\rho}\frac{\partial P}{\partial R}} + \frac{GM_\bullet}{R^2} = 0$$

$$\frac{1}{\rho}\frac{\partial P}{\partial z} = -\frac{GM_\bullet z}{R^3}$$ vertical hydrostatic equilibrium → $H \sim c_s\,(GM_\bullet/R^3)^{-1/2} \sim c_s\,\Omega^{-1} \sim (c_s/v_\varphi)\,R$

$$\dot{M} = -2\pi R \Sigma u_R$$ mass conservation → mass inflow rate (accretion rate) ← $\partial\Sigma/\partial t = 0$

$$-\nu\Sigma \frac{\partial \Omega}{\partial R} = -\Sigma u_R \Omega - \frac{C}{2\pi R^3}$$ integrating equation of J conservation

→ $C = \dot{M}\,(GM_\bullet R_0)^{1/2}$ – constant of integration

$$\boxed{\nu\Sigma = \frac{\dot{M}}{3\pi}\left[1 - \left(\frac{R_0}{R}\right)^{1/2}\right]}$$

where $R_0 = 3R_\bullet$ is the innermost stable orbit around BH

ACCRETION ONTO SUPERMASSIVE BLACK HOLES

❖ Disk accretion: geometrically-thin disks → emission

Dissipation rate of rotational kinetic energy per per unit time per unit area

$$D(R) = \frac{G\Omega'}{4\pi R} = \frac{1}{2}\nu\Sigma(R\Omega')^2 = \frac{9}{8}\nu\Sigma\frac{GM}{R^3}$$

for Keplerian disk

$$D(R) = \frac{3GM\dot{M}}{4\pi R^3}\left[1 - \left(\frac{R_0}{R}\right)^{1/2}\right]$$

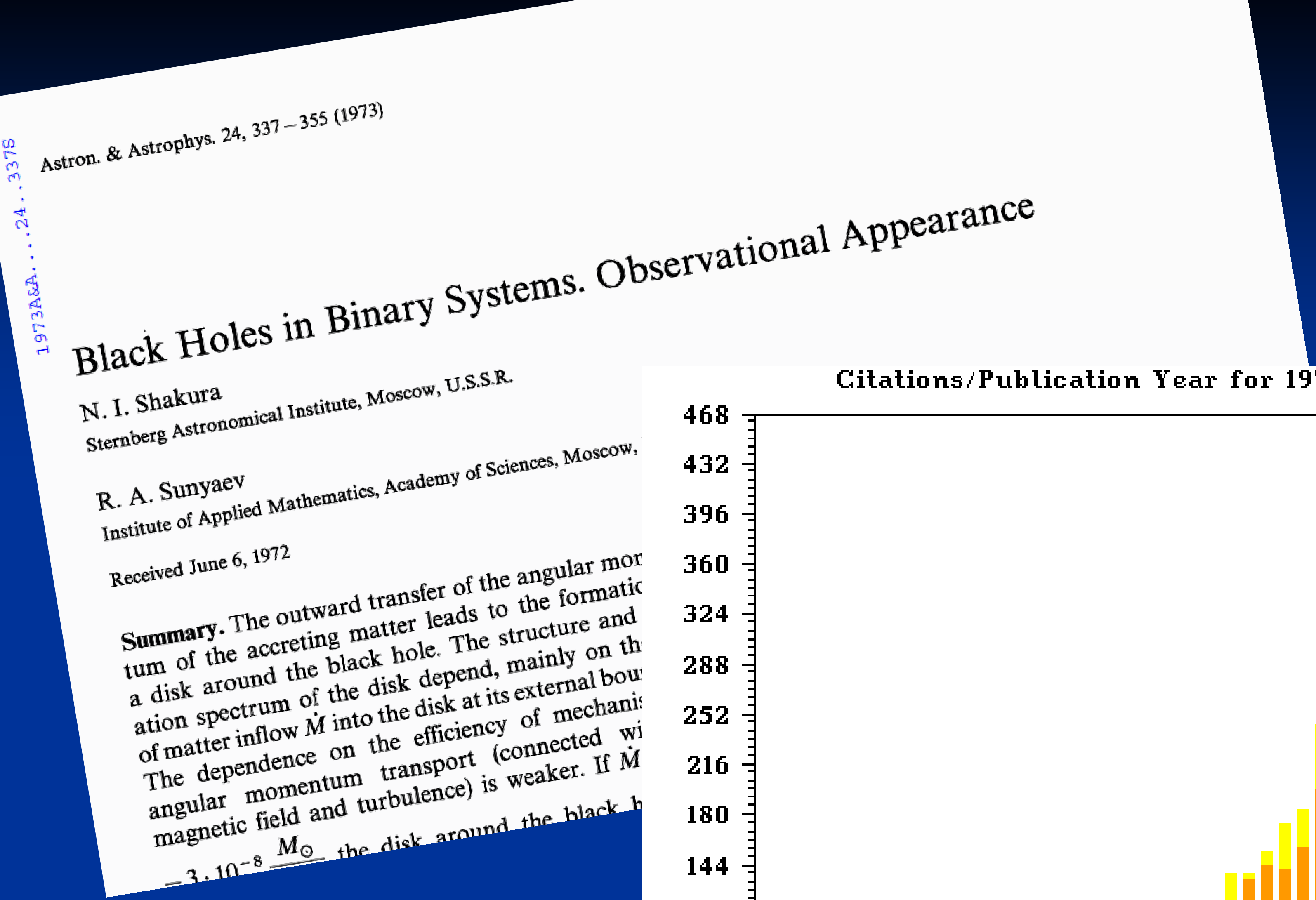
no dependency on viscosity!

$$L_{\rm disk} = \int_{R_0}^{\infty} D(R) 2\pi R dR = \frac{1}{2}\frac{GM\dot{M}}{R_0}$$

only $0.5E_{pot}$ → the rest is sucked in by the BH

If accretion disk optically thick (blackbody) → emissivity B(T) ~ σT^4 → $T \sim R^{-3/4}$

Accretion disk spectrum: $$S_\nu \propto \int_{R_{\rm in}}^{R_{\rm out}} B_\nu[T(R)] 2\pi R dR$$



Astron. & Astrophys. 24, 337 – 355 (1973)

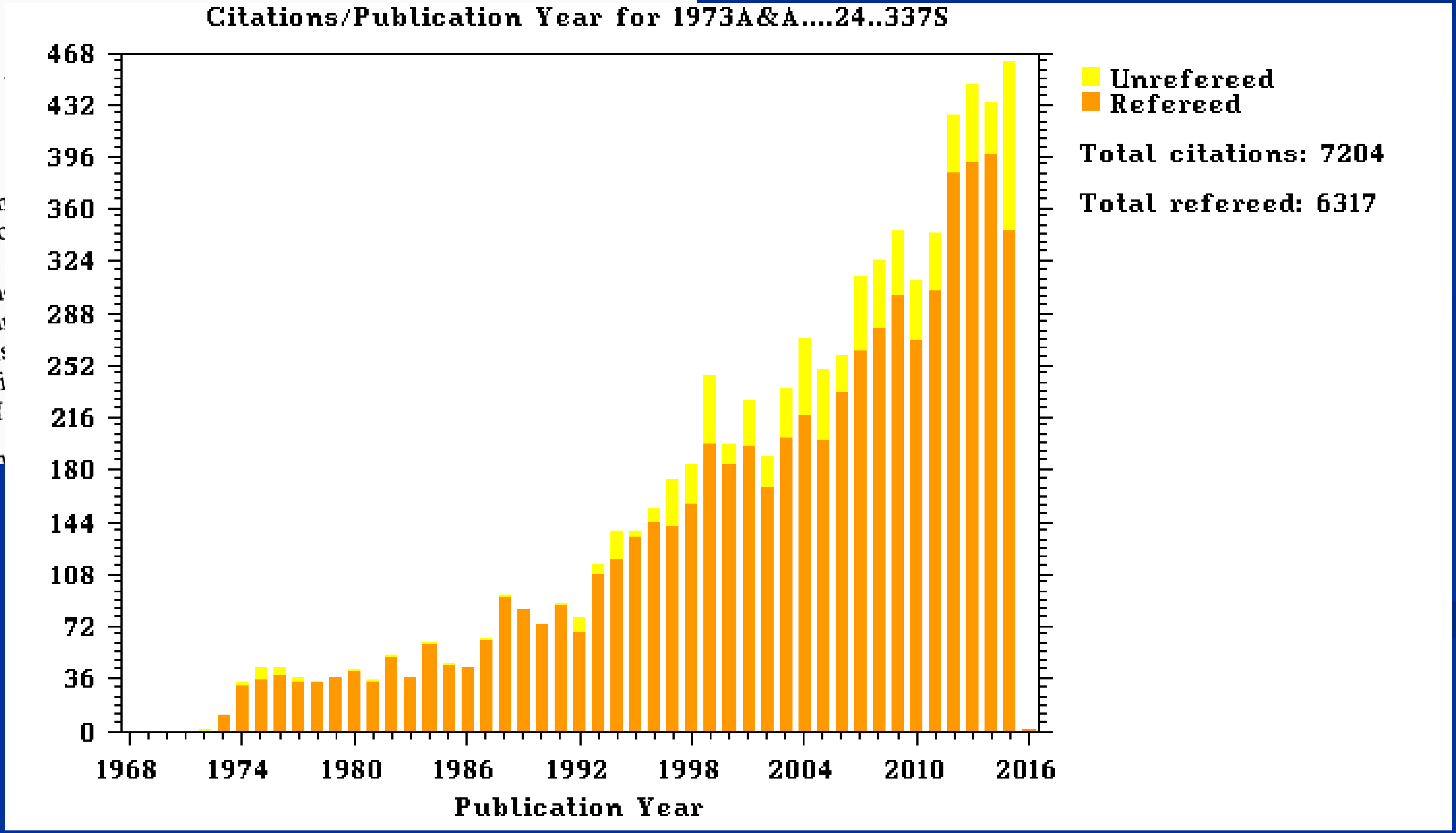
Black Holes in Binary Systems. Observational Appearance

N. I. Shakura
Sternberg Astronomical Institute, Moscow, U.S.S.R.

R. A. Sunyaev
Institute of Applied Mathematics, Academy of Sciences, Moscow,

Received June 6, 1972

Summary. The outward transfer of the angular mom
tum of the accreting matter leads to the formatio
a disk around the black hole. The structure and
ation spectrum of the disk depend, mainly on th
of matter inflow $\dot{M}$ into the disk at its external bou
The dependence on the efficiency of mechanis
angular momentum transport (connected wi
magnetic field and turbulence) is weaker. If $\dot{M}$
$\dot{M} \approx 3 \cdot 10^{-8} \frac{M_\odot}{\ }$ the disk around the black h



ACCRETION ONTO SUPERMASSIVE BLACK HOLES

❖ Disk accretion: geometrically-thin disks → emission

Viscosity responsible for energy-to-radiation conversion

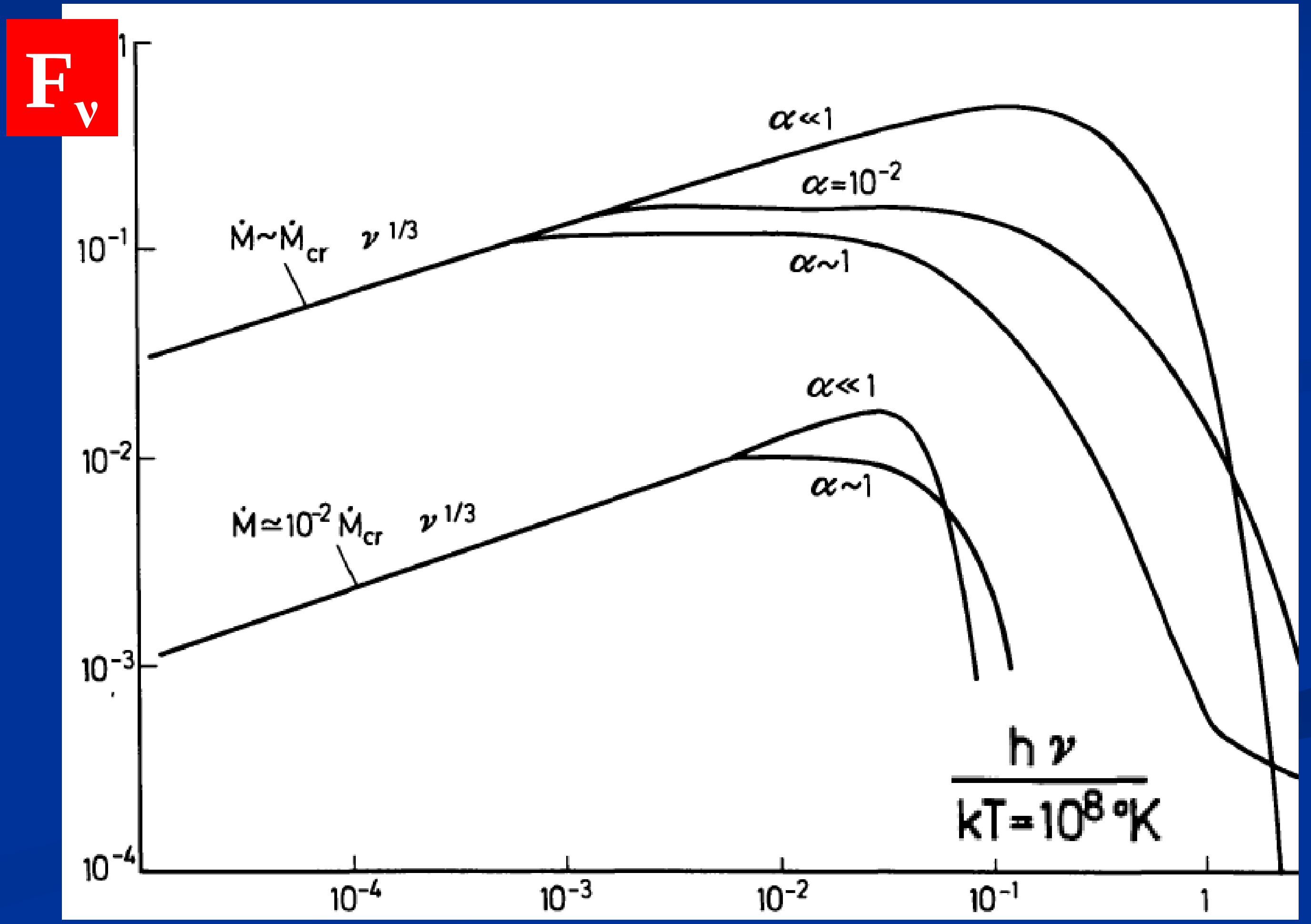
$$S_\nu \propto \int_{R_{\rm in}}^{R_{\rm out}} B_\nu[T(R)]2\pi R dR$$

$\boxed{\nu = \alpha\, c_s\, H}$ (Shakura & Sunyaev 1973)

→ definition of α - viscosity
→ [ν] = cm²/s α - dimensionless

Remember: $\nu \sim \lambda\, v_T \rightarrow \alpha\, c_s\, H$

$\lambda \leq H$ and $v_T \leq c_s \rightarrow \alpha \leq 1$



Spectra of geometrically-thin, optically-thick accretion disks

ACCRETION ONTO SUPERMASSIVE BLACK HOLES

❖ Disk accretion: geometrically-thin disks → spin up of the BH

Accretion of angular momentum *J*

$$\dot{J} \sim \dot{M}\,(GM_{\bullet}R_0)^{1/2}$$

photon emission limits *J* for the BH

Dimensionless angular momentum $\boxed{a = \frac{cJ}{GM_{\bullet}^2}}$ where $0 \leq a \leq 1$

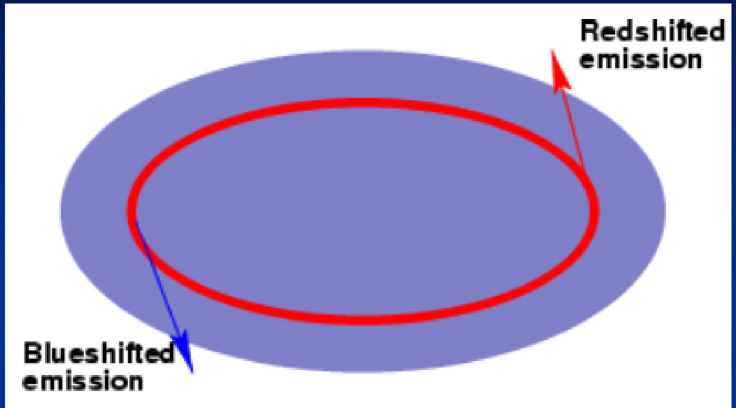
ACCRETION ONTO SUPERMASSIVE BLACK HOLES

❖ Disk accretion: evidence for SMBHs from X-ray spectroscopy

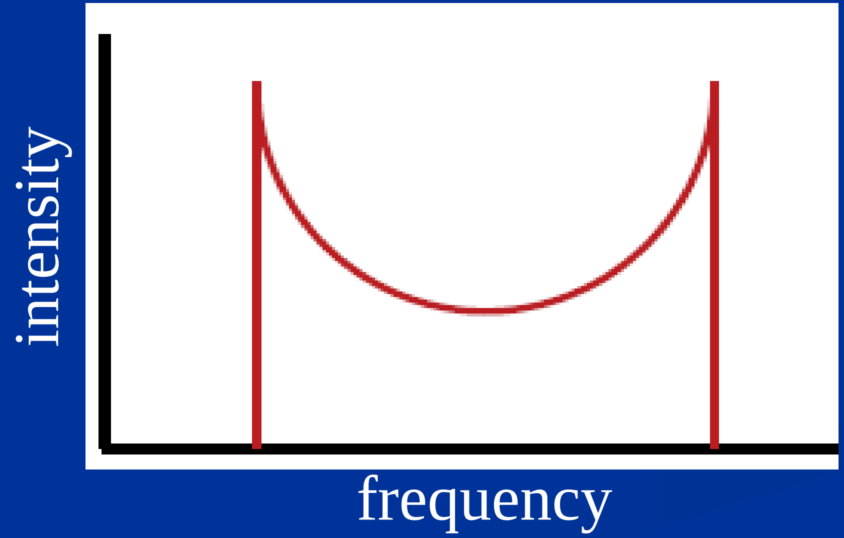
Measuring spectral line profiles from the inner disk

Fe lines in X-rays

Newtonian case ONLY!



$$\frac{\Delta \nu}{\nu} = \frac{v_{obs}}{c}$$



double-horned line profile from a single ring in the disk

ACCRETION ONTO SUPERMASSIVE BLACK HOLES

❖ Disk accretion: evidence for SMBHs from X-ray spectroscopy

Fe lines in X-rays
relativistic case → several effects

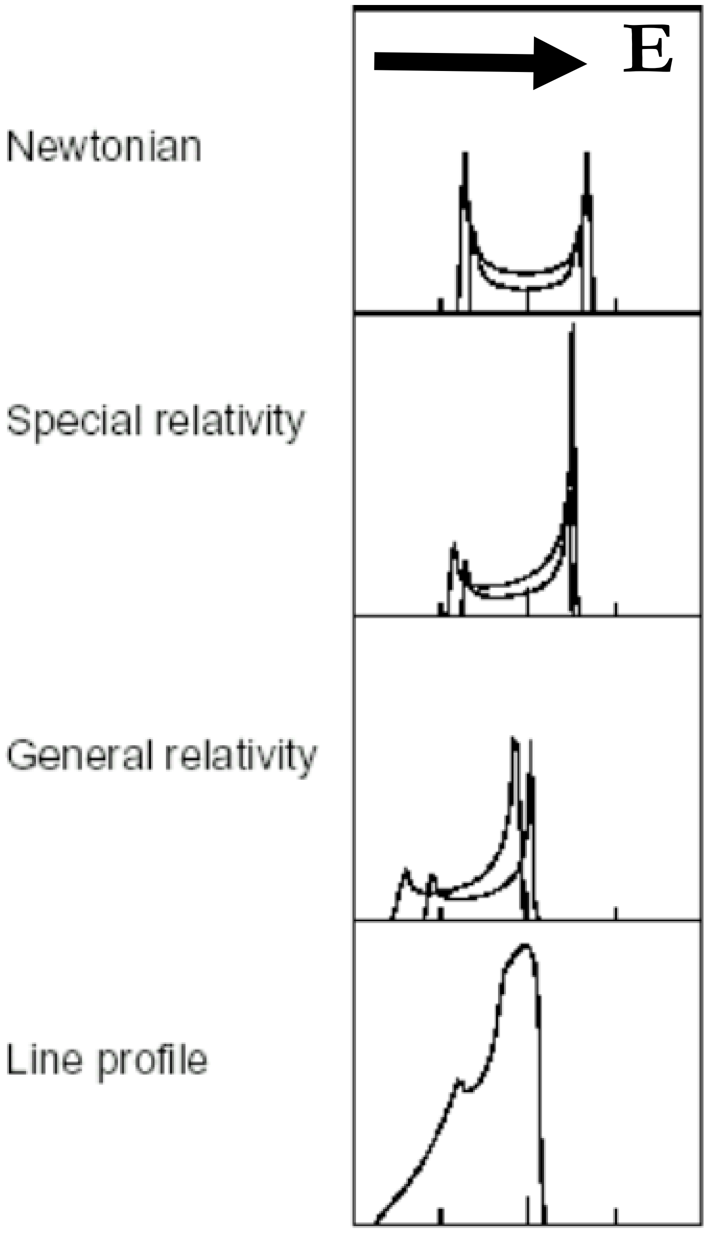
Transverse Doppler effect:
moving clock slows down →
observed ν is reduced compared to the rest frame by $(1 - v^2/c^2)^{-1/2}$

Beaming:
boosts blue wing of the line, attenuates red wing

Gravitational redshift:
more shift to lower energies

Integrate over all radii and predict:

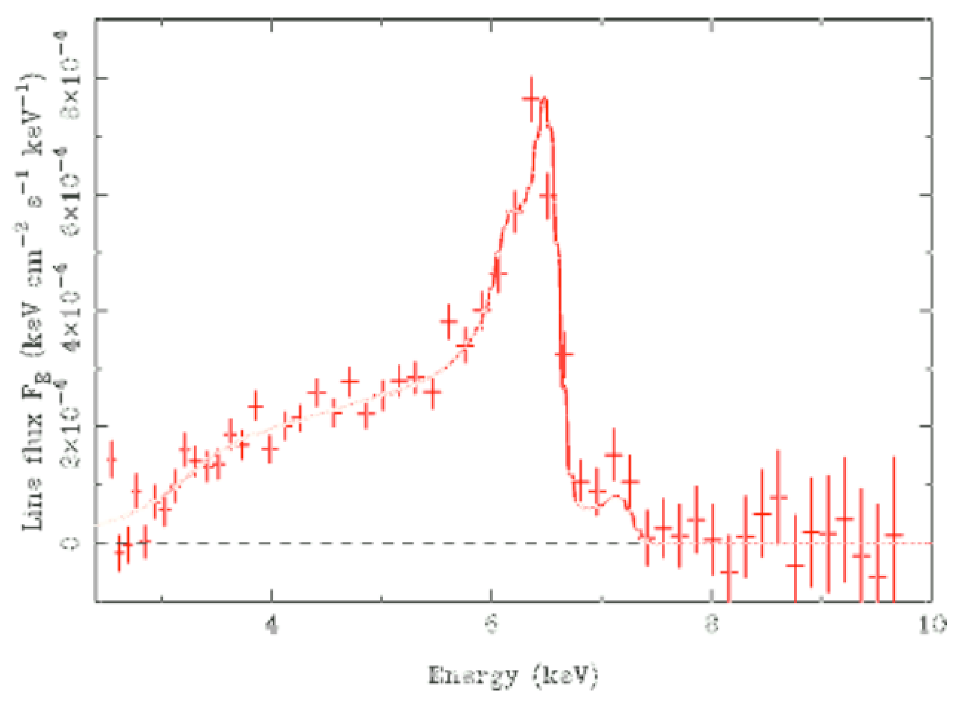
broad, asymmetric line profile with a sharp cutoff at high E

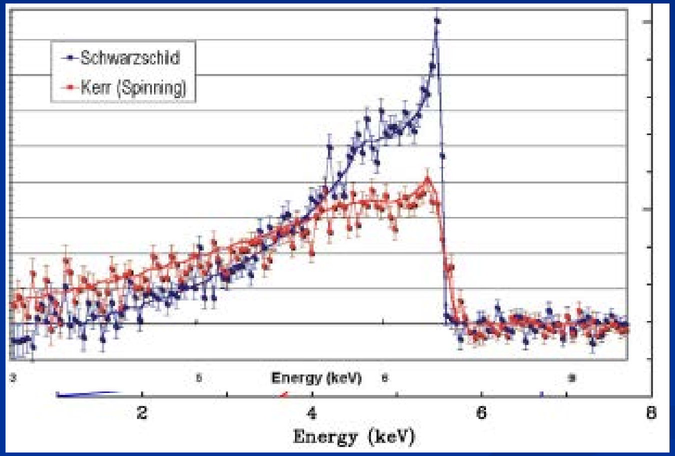


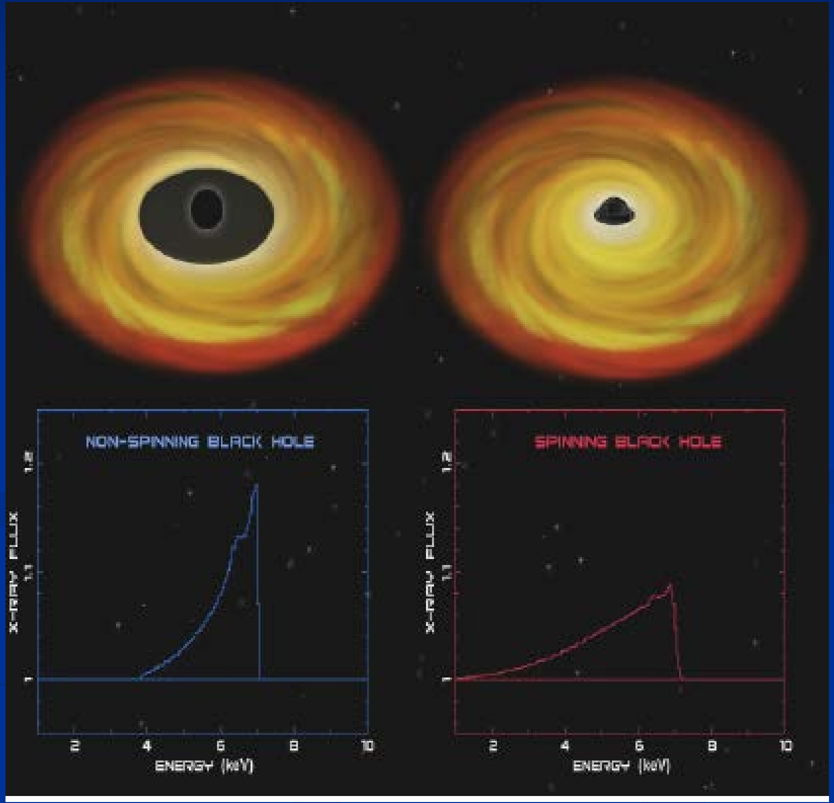
ACCRETION ONTO SUPERMASSIVE BLACK HOLES

❖ Disk accretion: evidence for SMBHs from X-ray spectroscopy

Fe lines in X-rays → observations







Fe line profile for Seyfert galaxy MCG-6-30-15 using XMM-Newton

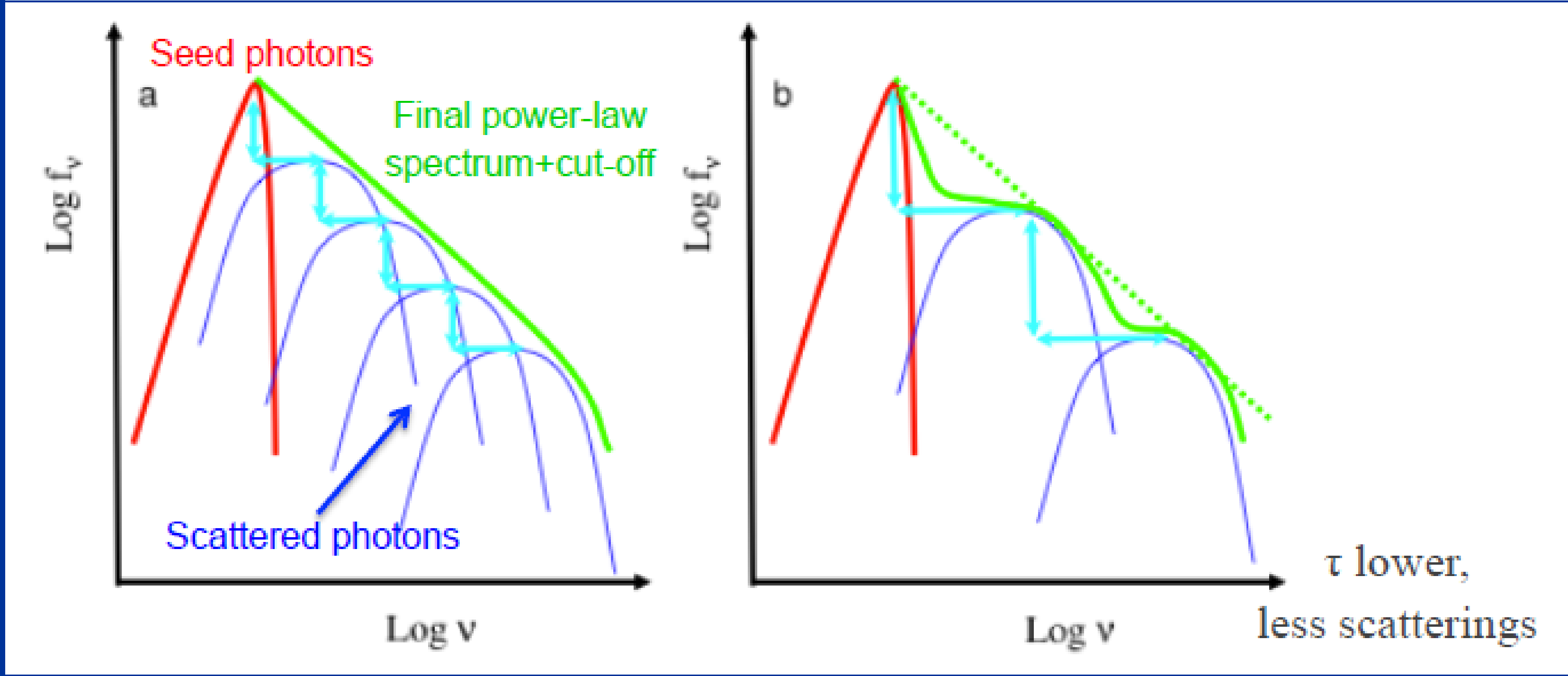
Fe line profile: often extremely broad
→ detailed modeling of the line shape
→ rapidly spinning SMBH

Best proof to date of presence of SMBHs in AGN!

ACCRETION ONTO SUPERMASSIVE BLACK HOLES

❖ Disk accretion: comptonization

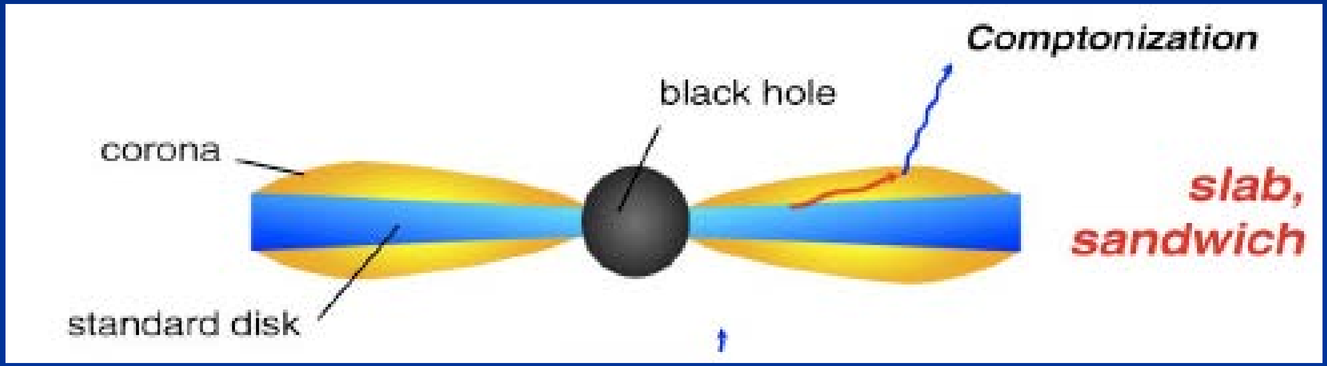
Seed photons are up-scattered, then become the "new" seed photons for following scatterings ➔ the overall spectrum resembles that of a powerlaw
Thermal Comptonization: electrons have a Maxwellian distribution. Cut-off in the powerlaw when the process of transferring energy from electrons to photons is not efficient anymore ($E_{cut\text{-}off} \approx kT_{electrons}$)



ACCRETION ONTO SUPERMASSIVE BLACK HOLES

❖ Disk accretion: evidence for SMBHs from X-ray spectroscopy

Compton and inverse Compton effects

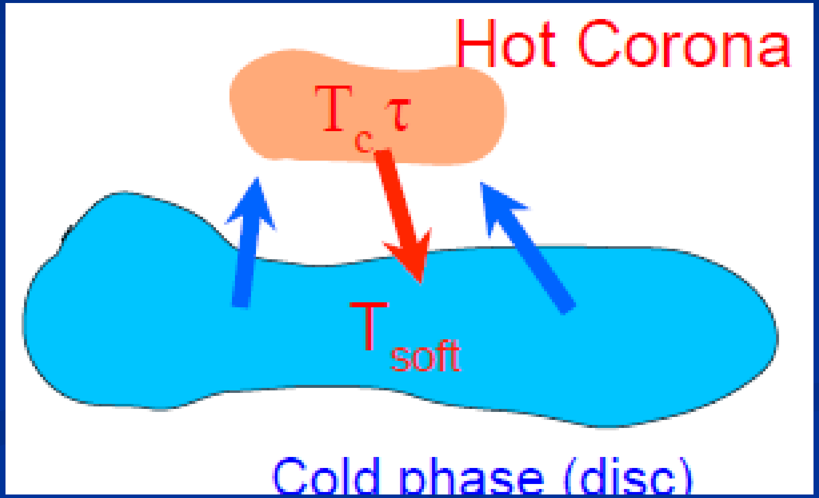


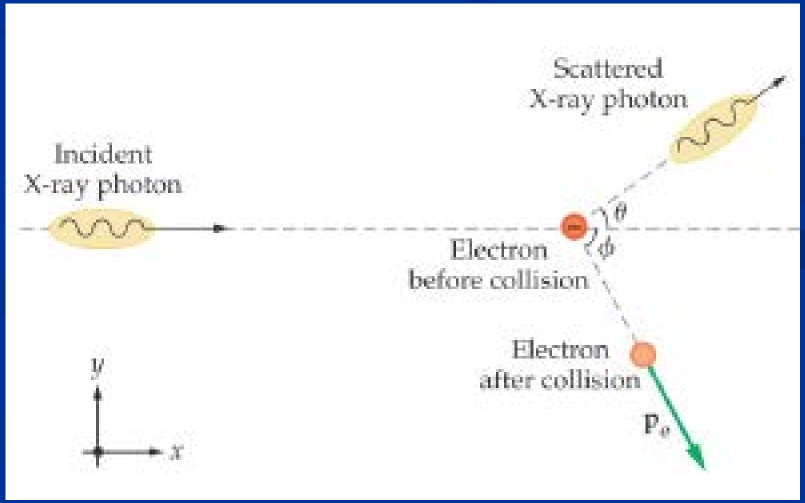
$$\Delta E = E' - E \simeq -\frac{E^2}{m_e c^2}(1 - \cos\theta)$$

For non-stationary electron:

$\Delta E < 0 \rightarrow$ Compton

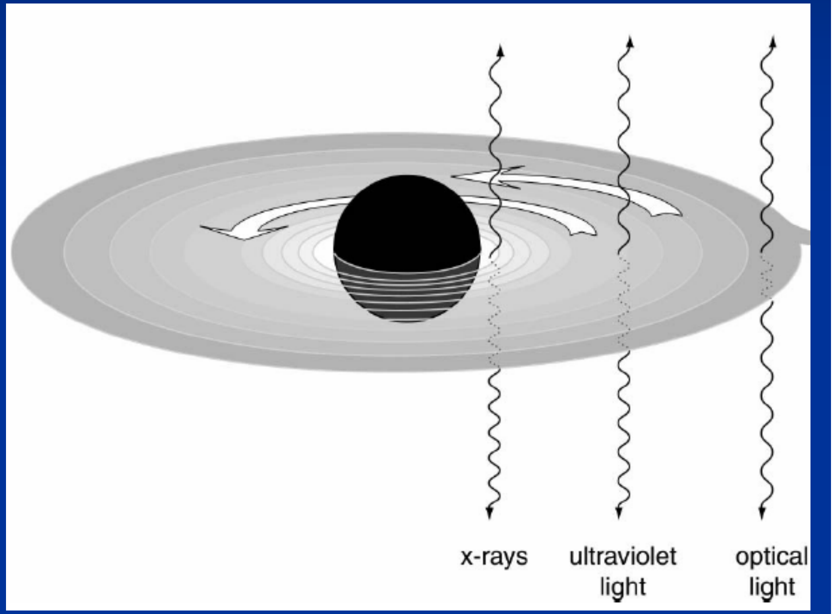
$\Delta E > 0 \rightarrow$ Inverse Compton

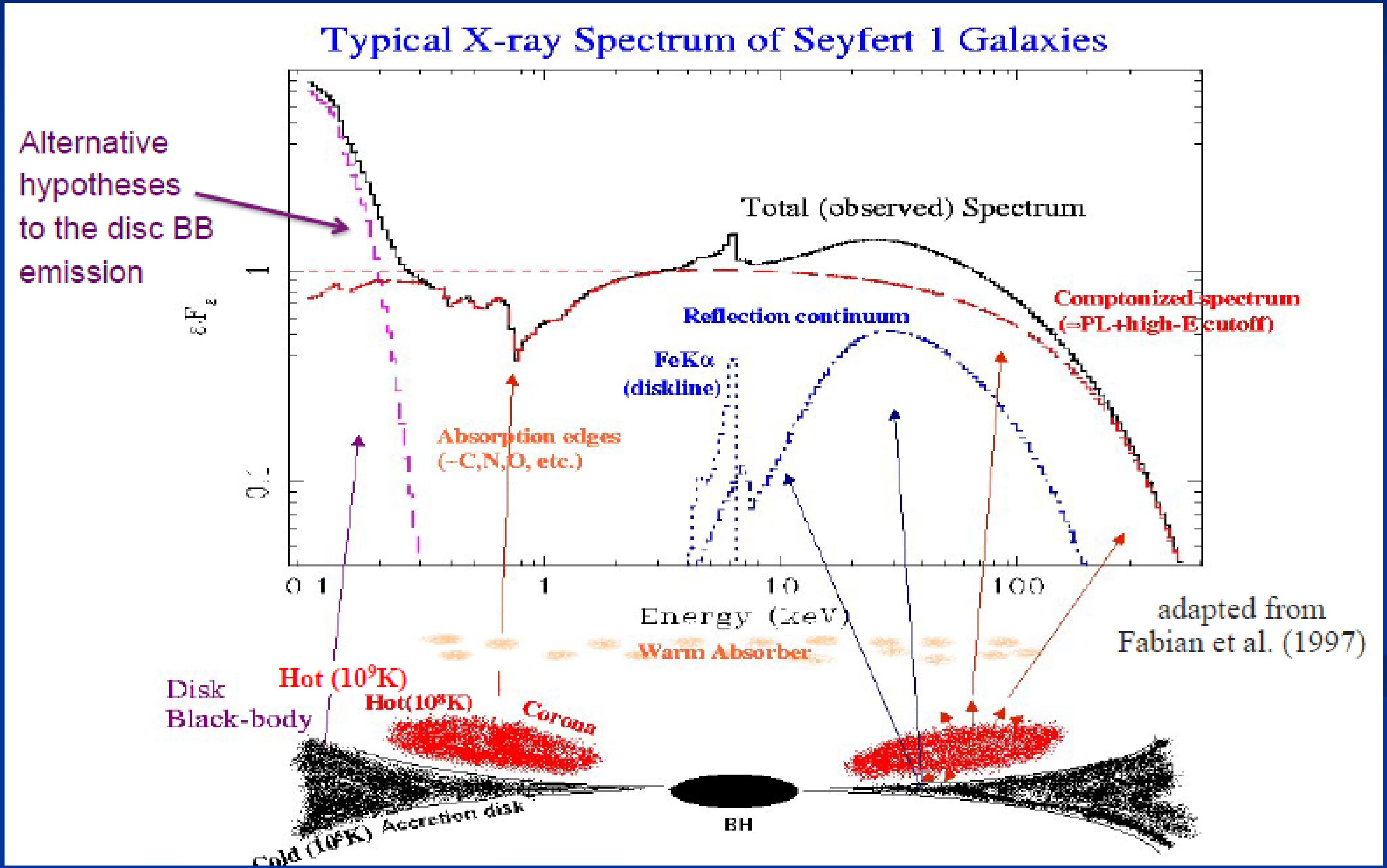




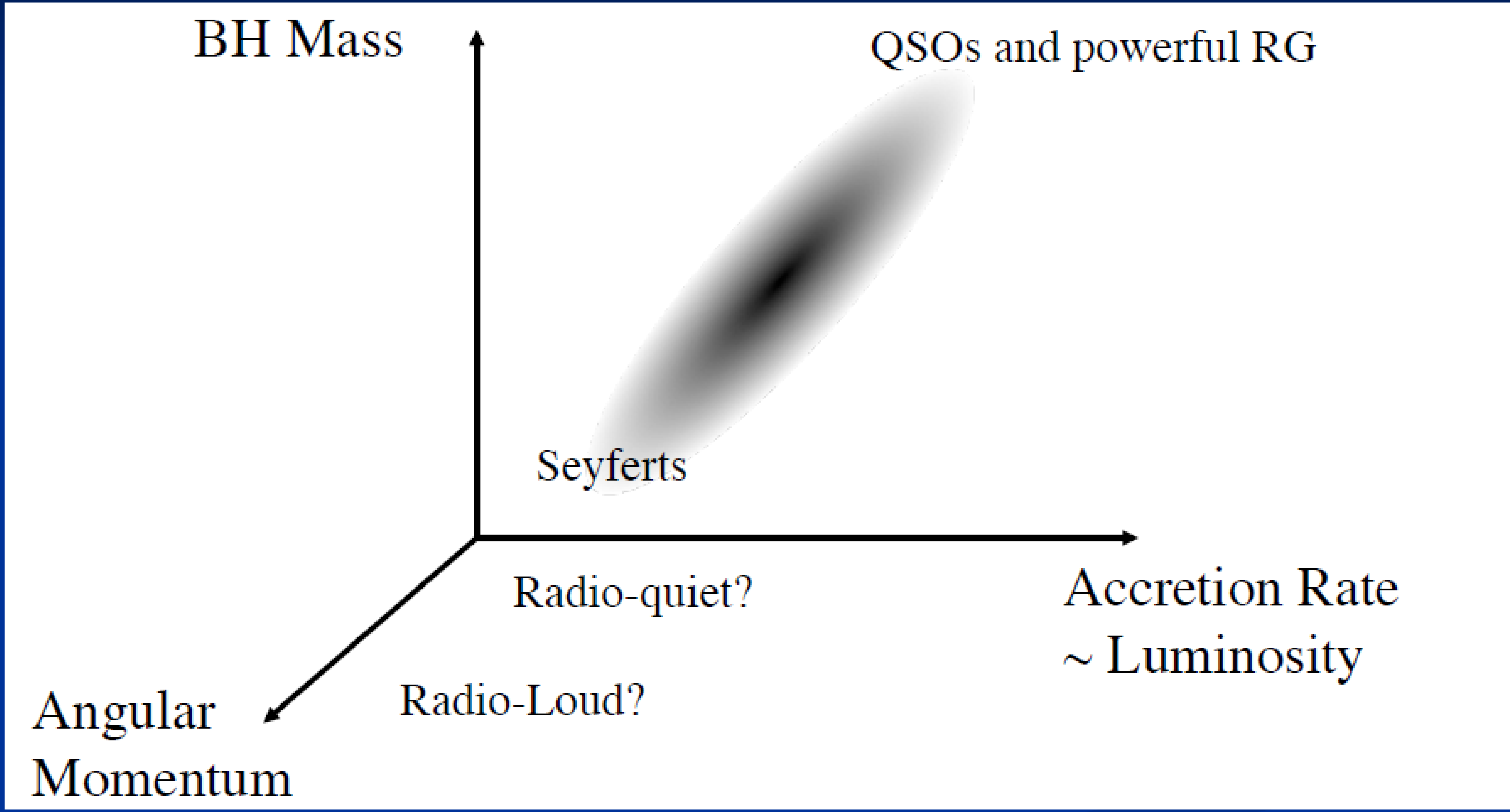
ACCRETION ONTO SUPERMASSIVE BLACK HOLES

❖ Disk accretion: geometrically-thin disks → thermal emission





AGN: Physical Classification



In addition, dependence on the viewing angle

EFFICIENCY OF ENERGY-TO-RADIATION CONVERSION

- $L = \eta\, \dot{M} c^2$

Gas falls in to the last stable orbit at $3R_0$

Efficiency of potential energy-to-radiation conversion (Newtonian, but OK)

$$\eta = \frac{GM_\odot \dot{M}}{6GM_\odot/c^2}\frac{c^{-2}}{\dot{M}} \sim 0.17$$

Actually, Schwarzschild BH: $\eta \sim 0.06$

Kerr BH: ~ 0.42

Taking $\eta \sim 0.1$

$$\dot{M} \sim 10^{46}\ \mathrm{erg/s}\ /0.1\, c^2 \sim 10^{26}\ \mathrm{g/s} \sim 2\ M_\odot/\mathrm{yr}$$

HST image of gas accreting onto SMBH in elliptical galaxy NGC 4261

EFFICIENCY OF ENERGY-TO-RADIATION CONVERSION

❖ Slim disks: non-Keplerian angular momentum

Shakura & Sunyaev disks: all dissipated energy is
Radiated locally → viscous heating = radiative cooling

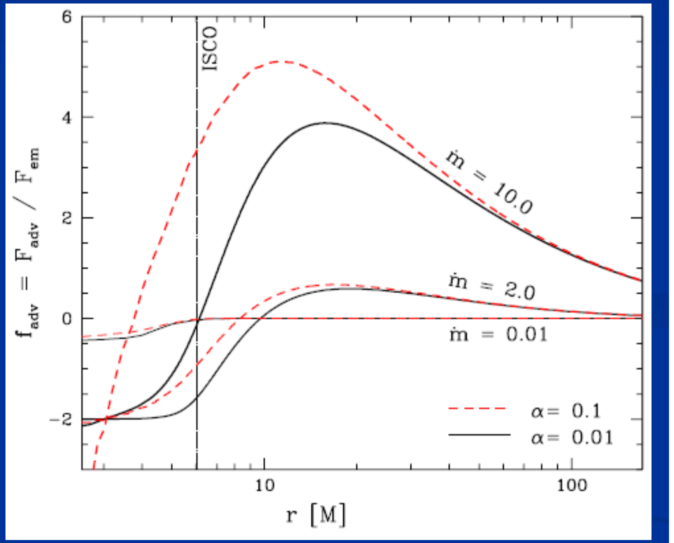
Good, if $\dot{M} << \dot{M}_{Edd}$

when $L > 0.3L_{Edd}$ → v_R and H increase

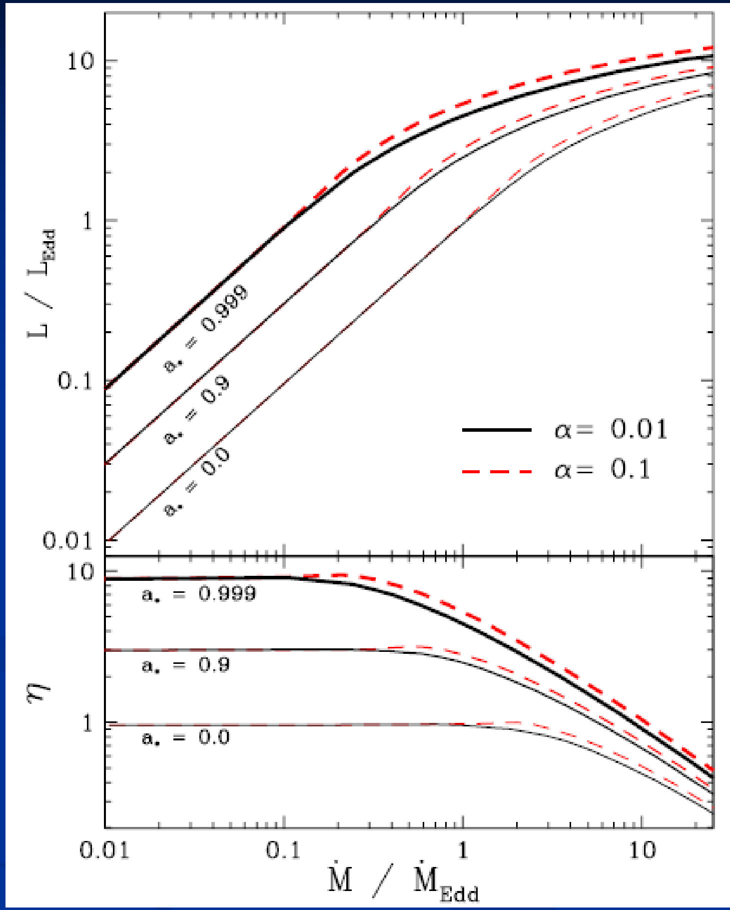
additional cooling: advection

Why?

→ photons have no time to escape



Advective-to-radiation fluxes as a function of $\dot{M}$



Sadowski (2011)

Still slim disks are luminous and radiation efficient →$\eta \sim 0.006 - 0.6$

ACCRETION ONTO SUPERMASSIVE BLACK HOLES

❖ Thick disk accretion: Advection Dominated Accretion Flow (ADAF)

Lightman, Eardley, Rees (1970s), Narayan & Yi (1990s), Abramowicz (1990s)

Nearly **all** viscosity-dissipated energy is carried (advected) into the SMBH and not radiated away → dominated by gas pressure!

Two effects:

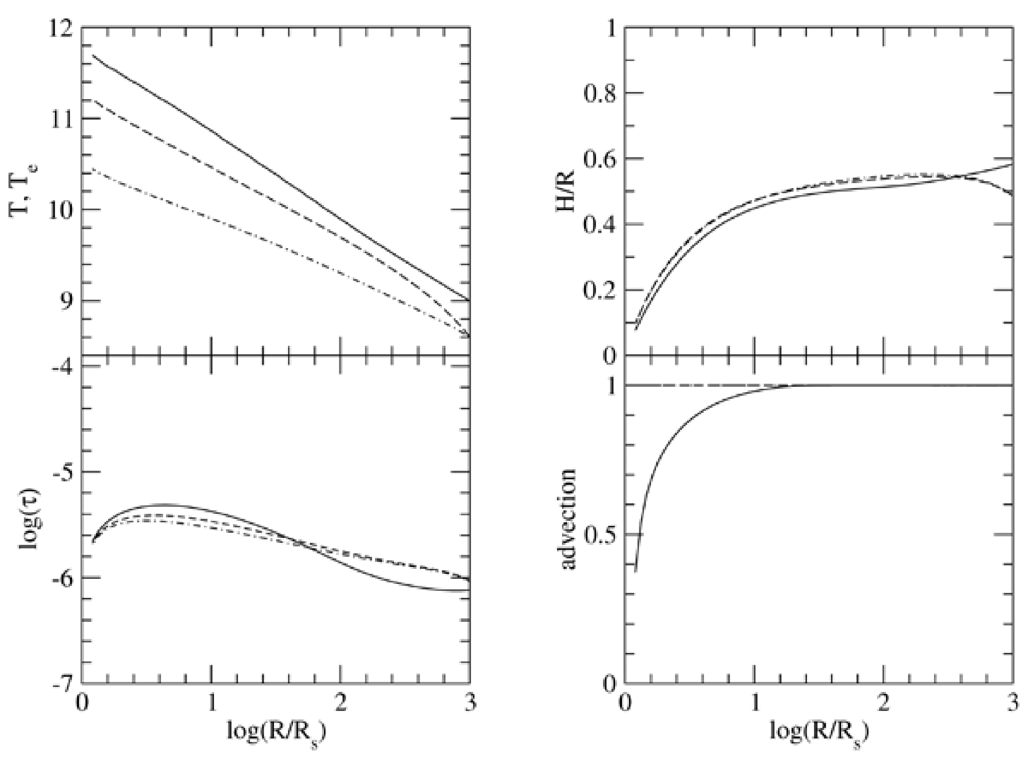
→dissipated E cannot be radiated locally→ low L

→rotation is not Keplerian, but….

Hot disk with $c_s \sim v_K$; $v_R \sim \alpha\, v_K\, (H/R)^2 \sim 0.1\text{-}0.3\, v_K$

$$t_{acc} \sim R/v_R \sim t_{ff}/\alpha$$

Low-density gas → very long cooling time → optically-thin!



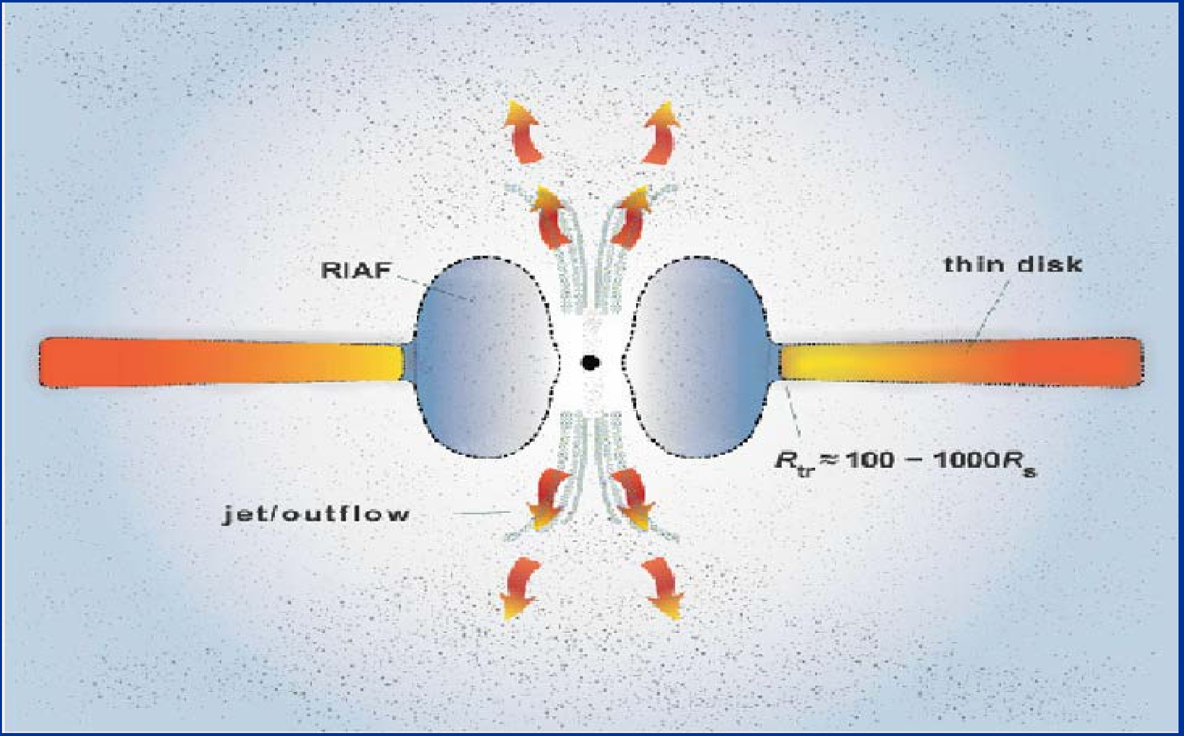
Abramowicz and Fragile (2013)

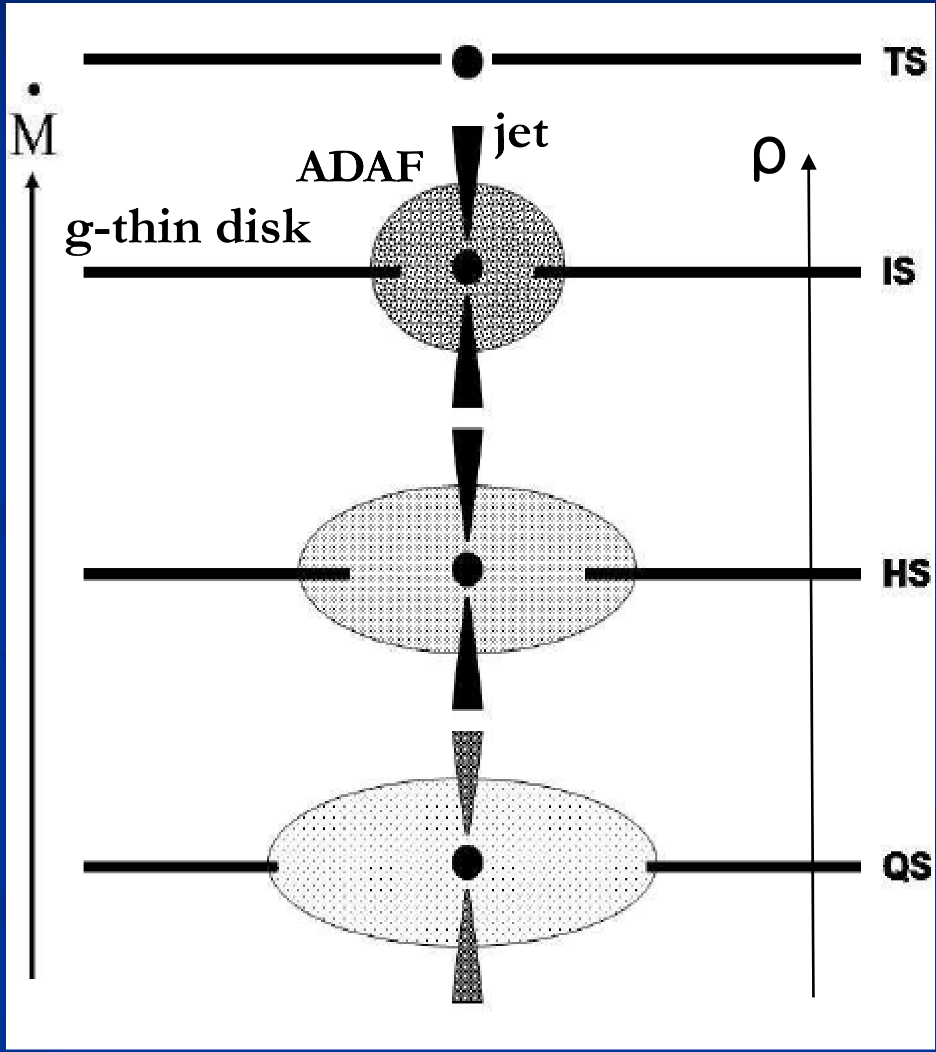
ACCRETION ONTO SUPERMASSIVE BLACK HOLES

❖ Thick disk accretion: ADAF→Radiatively-Inefficient Accretion Flow (RIAF)

Low-luminosity AGN

$L < 0.01\ L_{Edd}$





ACCRETION ONTO SUPERMASSIVE BLACK HOLES

❖ Thick disk accretion: Convection Dominated Accretion Flow (CDAF)

Quataert and Gruzinov (2002)

Much of viscosity-dissipated energy is carried (advected) into the SMBH and not radiated away

→ convection carries energy to large *R*, but not to ∞

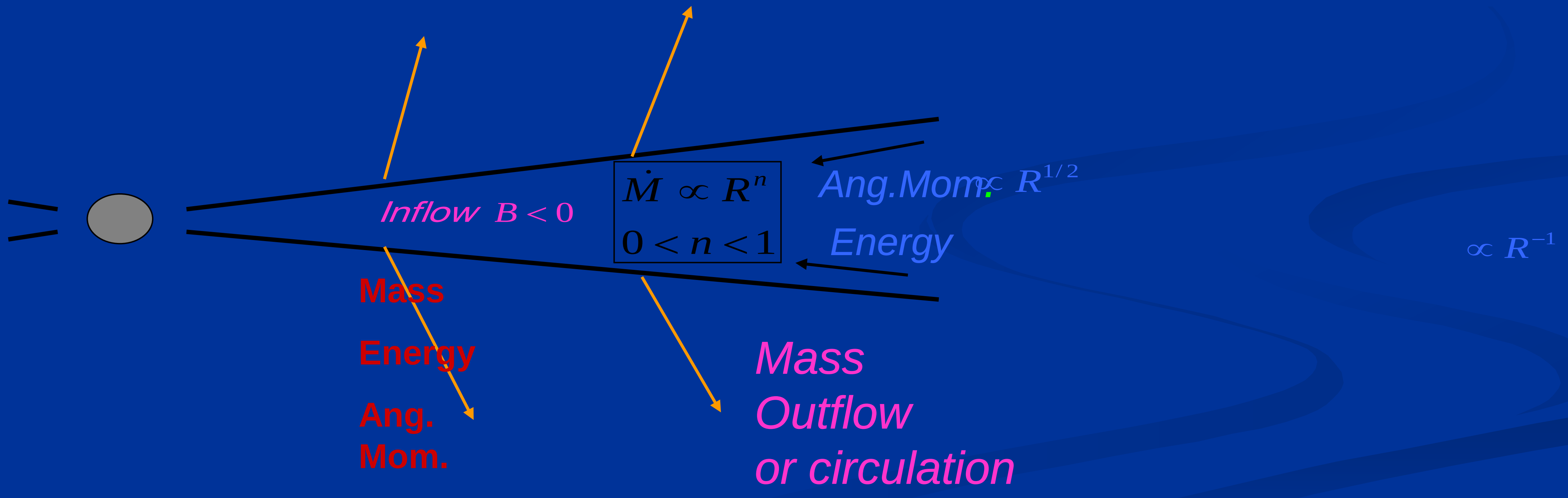
→ SMBH grows slowly!

Accretion onto Supermassive Black Holes

❖ Thick disk accretion: Advection Dominated Inflow-Outflow Solution (ADIOS)

Blandford & Begelamn (1999, 2004)

Most of gas is driven away → only small amount accretes on the SMBH
→ SMBH grows slowly!



CONCLUSIONS FOR TALK 2

- Accretion disk physics is fundamental because it is basically the black hole physics
- AGN emerges as a diverse class of objects even when the central engine is only supermassive black holes
- We have observational confirmation that SMBHs reside in the AGN and power them in various ways
- The detailed physics of accretion flows is only now being understood as complicated, which has many solutions → thin and thick disks, ADAFs, CDAFs, ADIOS, etc…
- Still unsolved are many details, and especially that of what is the source of fuel which powers SMBHs