The ins and outs of black holes: Accretion flows

Rodrigo Nemmen
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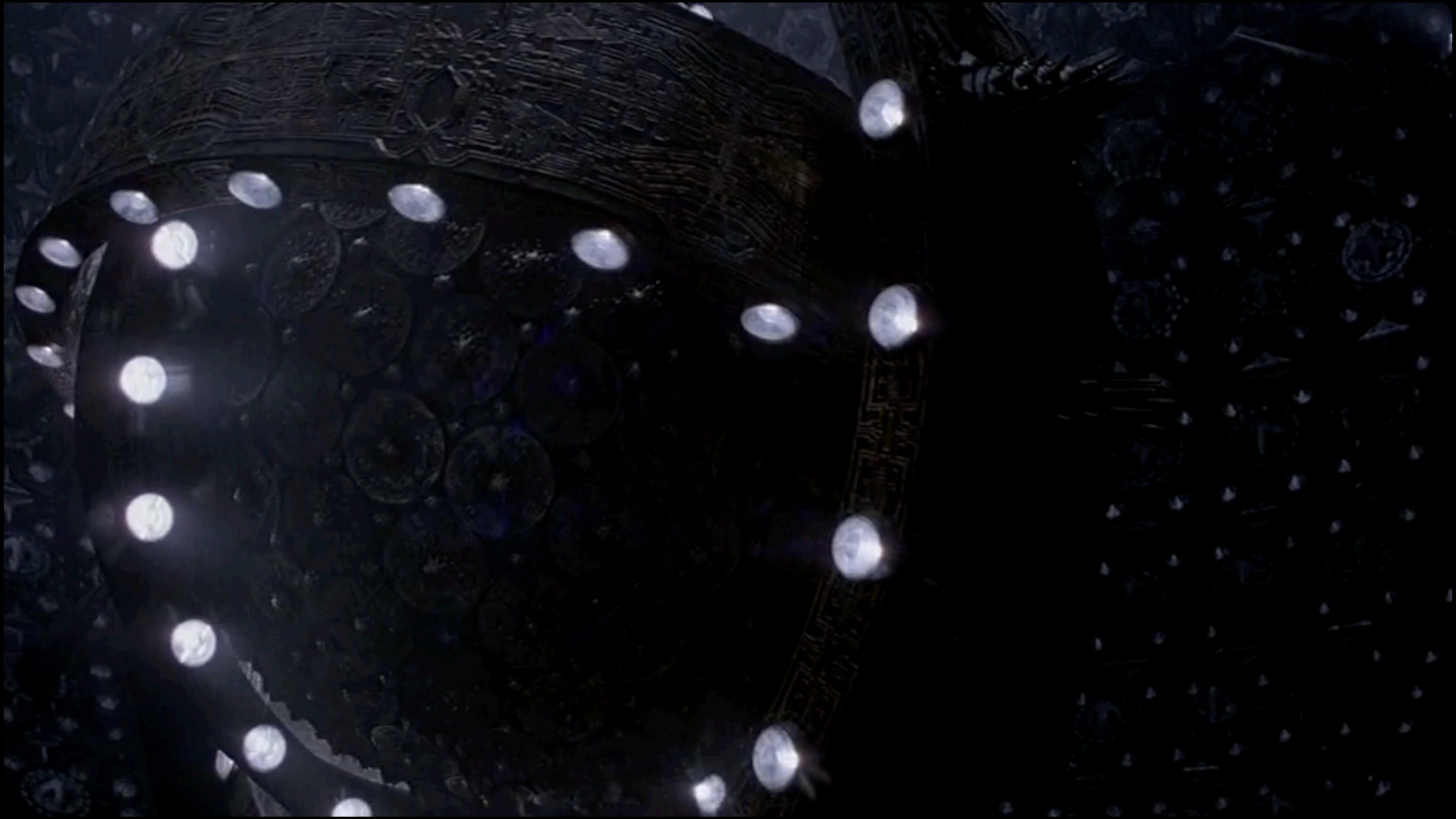
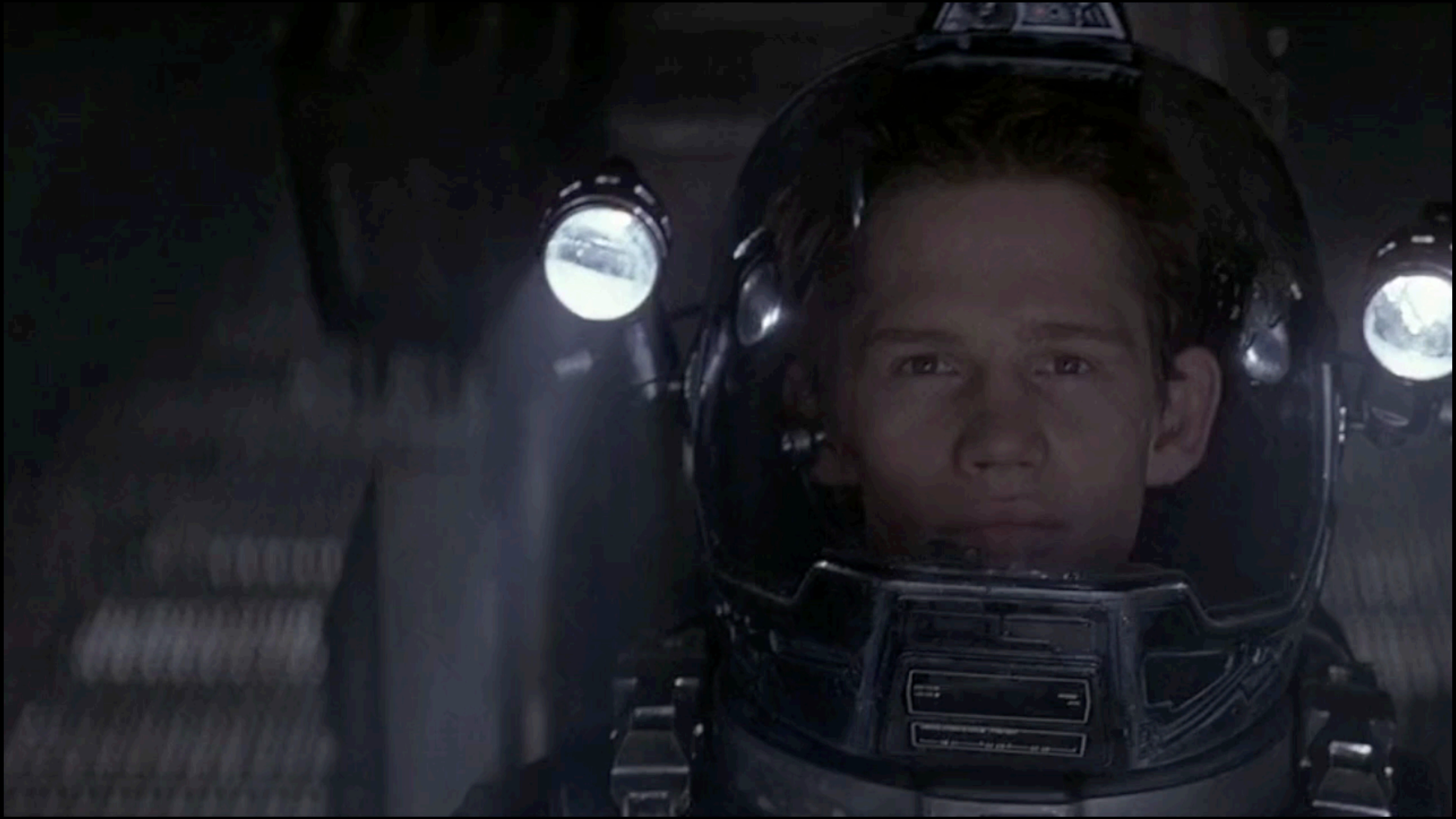
What happens when you feed a black hole?



Créditos: Paramount, Golar, Impact Pictures



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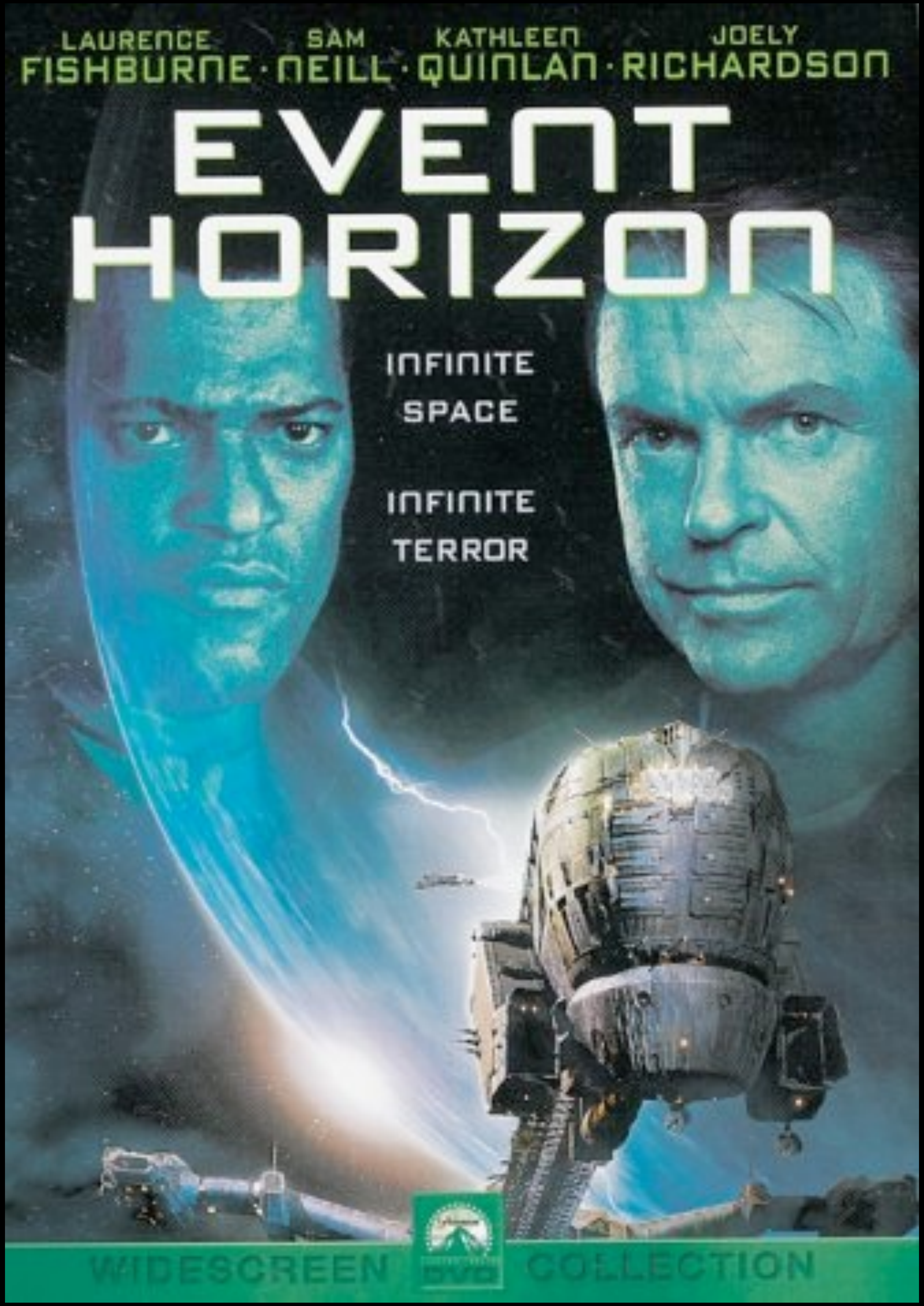


“O Enigma do Horizonte”
1997

Disks are ubiquitous in the universe

Blaes, SciAm

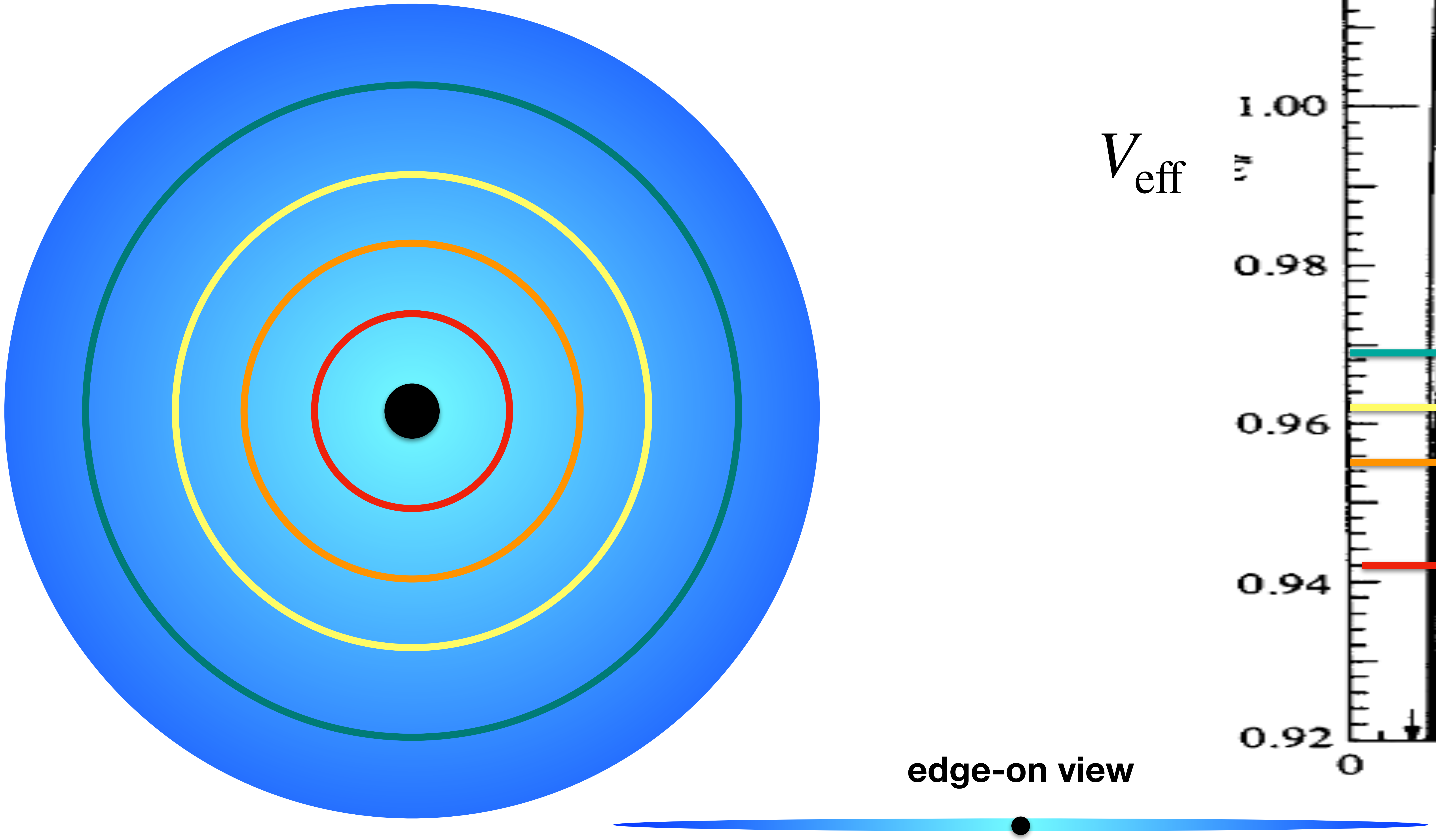
Effective potential and accretion disks

Effective potential for orbits around a Schwarzschild black hole

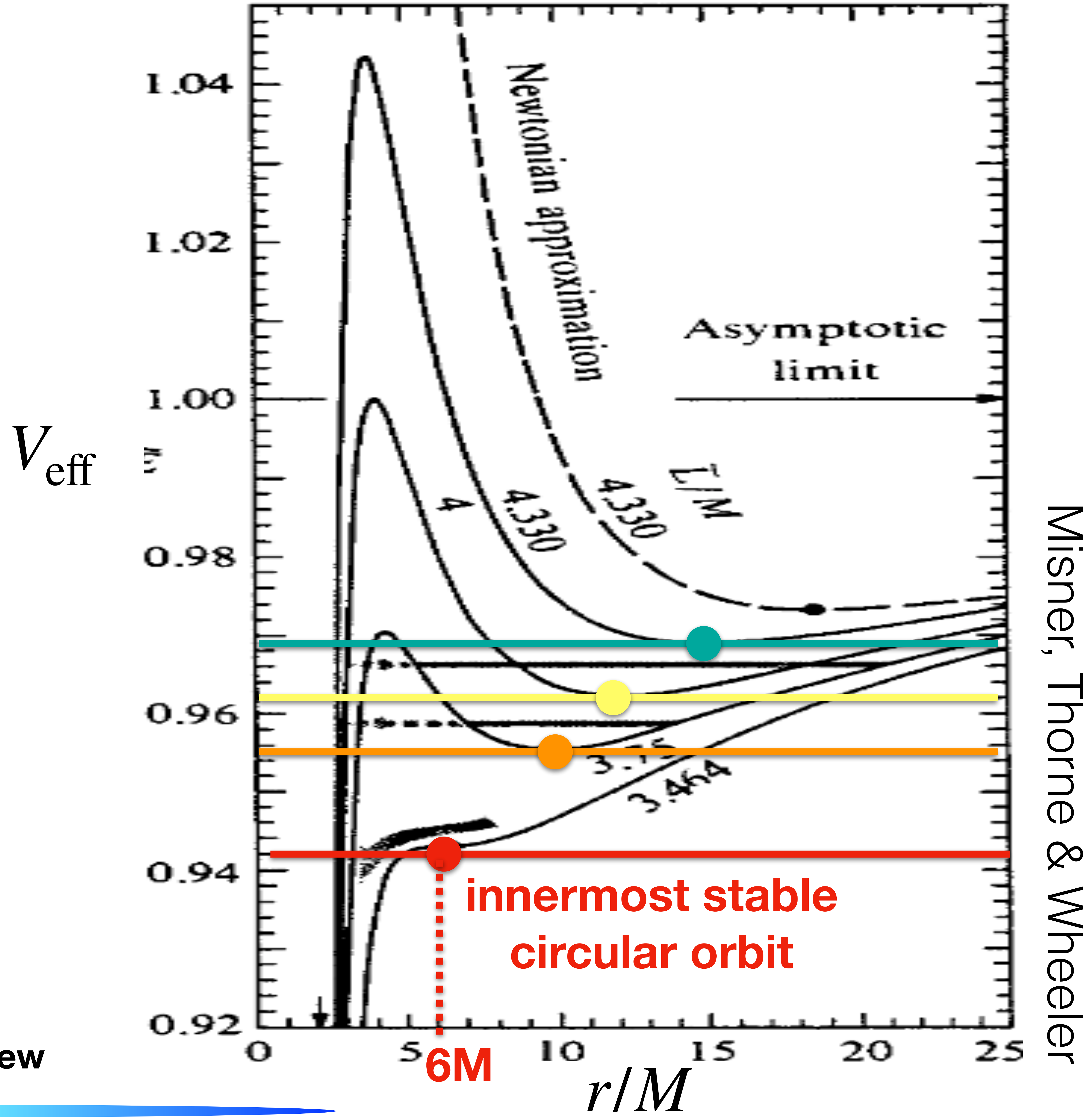
$$E = \frac{1}{2}\left(\frac{dr}{d\tau}\right)^2 + V_{\text{eff}}$$

effective potential

face-on view of accretion disk



edge-on view



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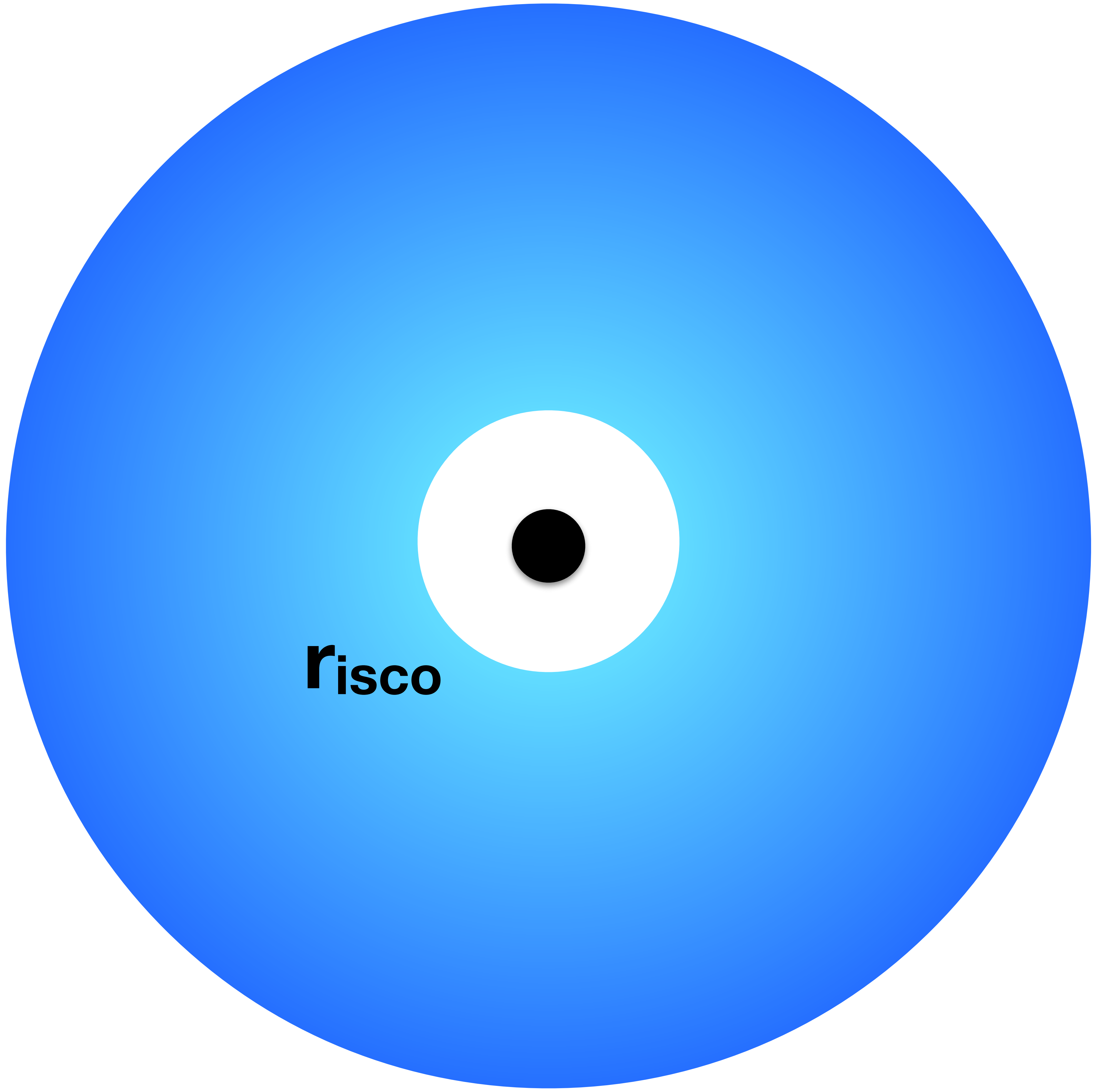
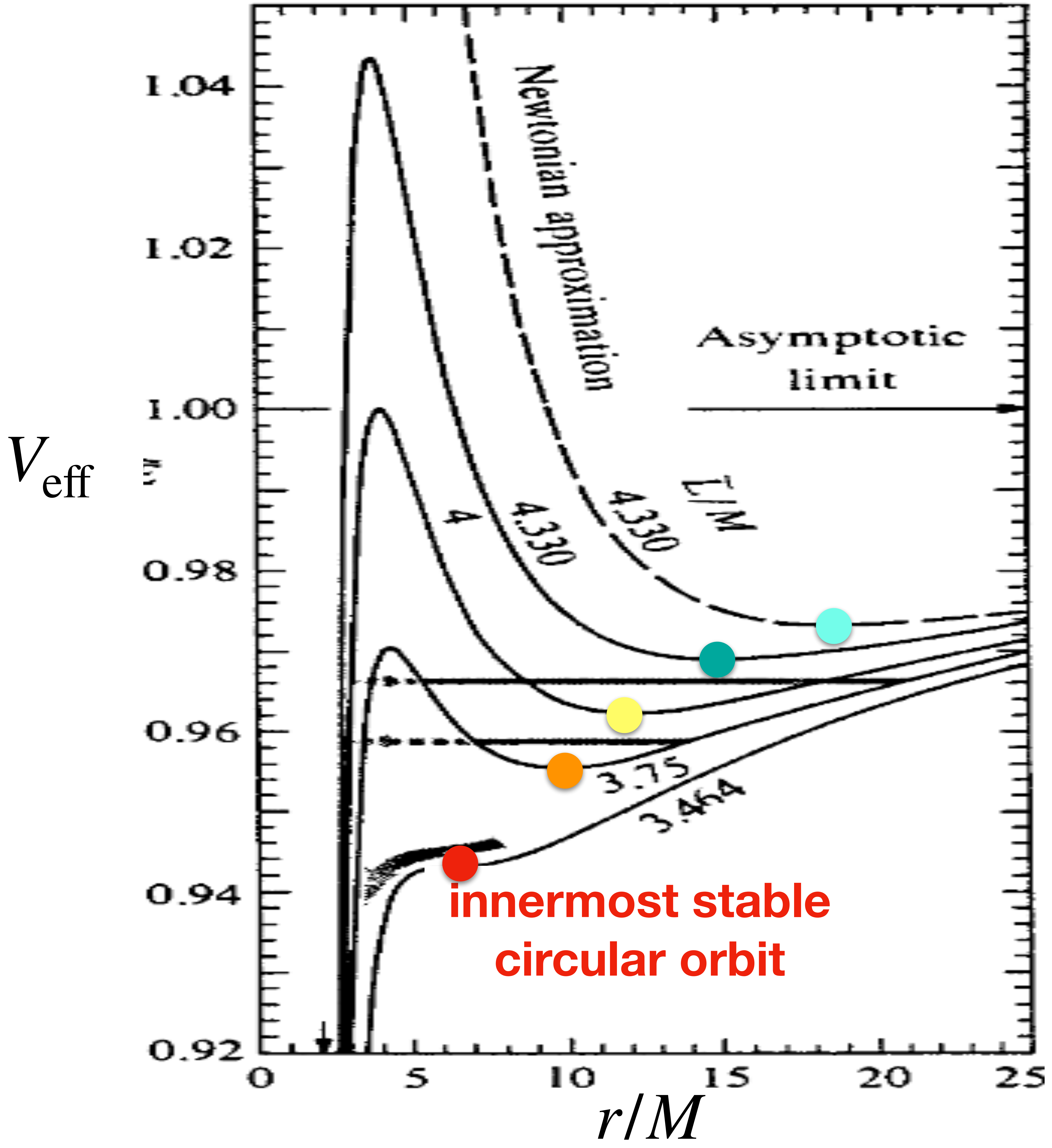
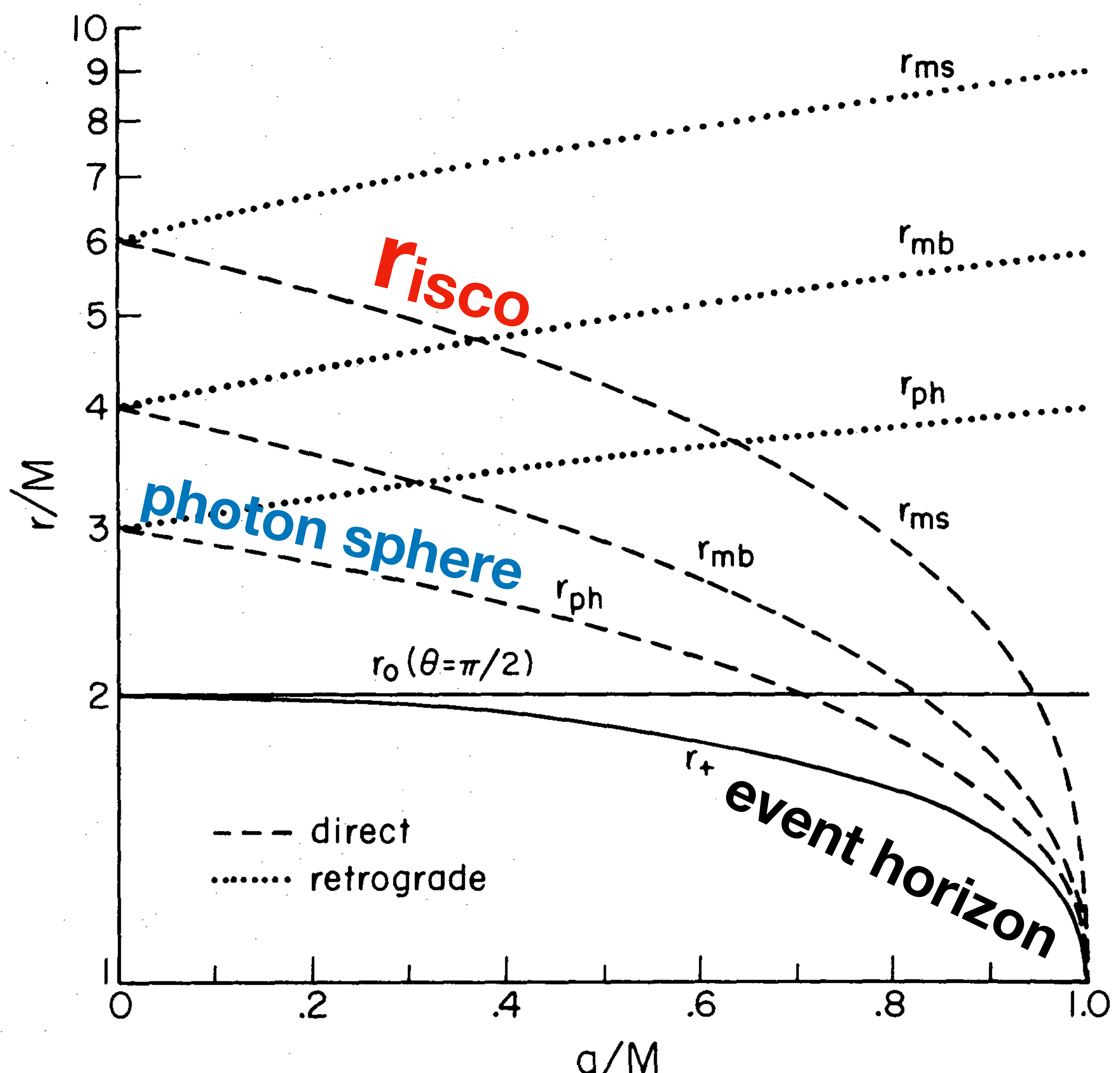




Misner, Thorne & Wheeler

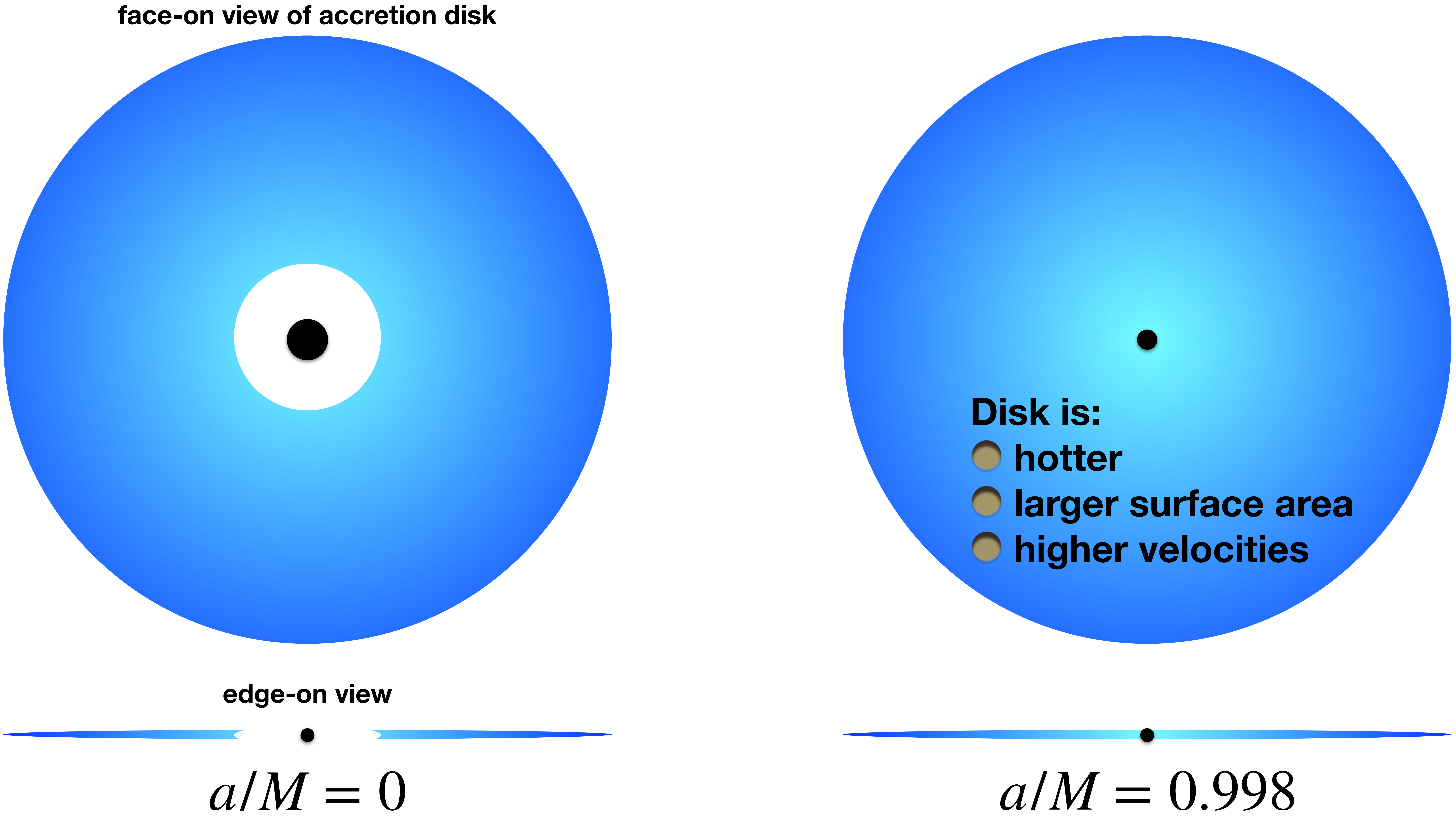
BH spin and accretion disks

ISCO radius depends on the BH spin

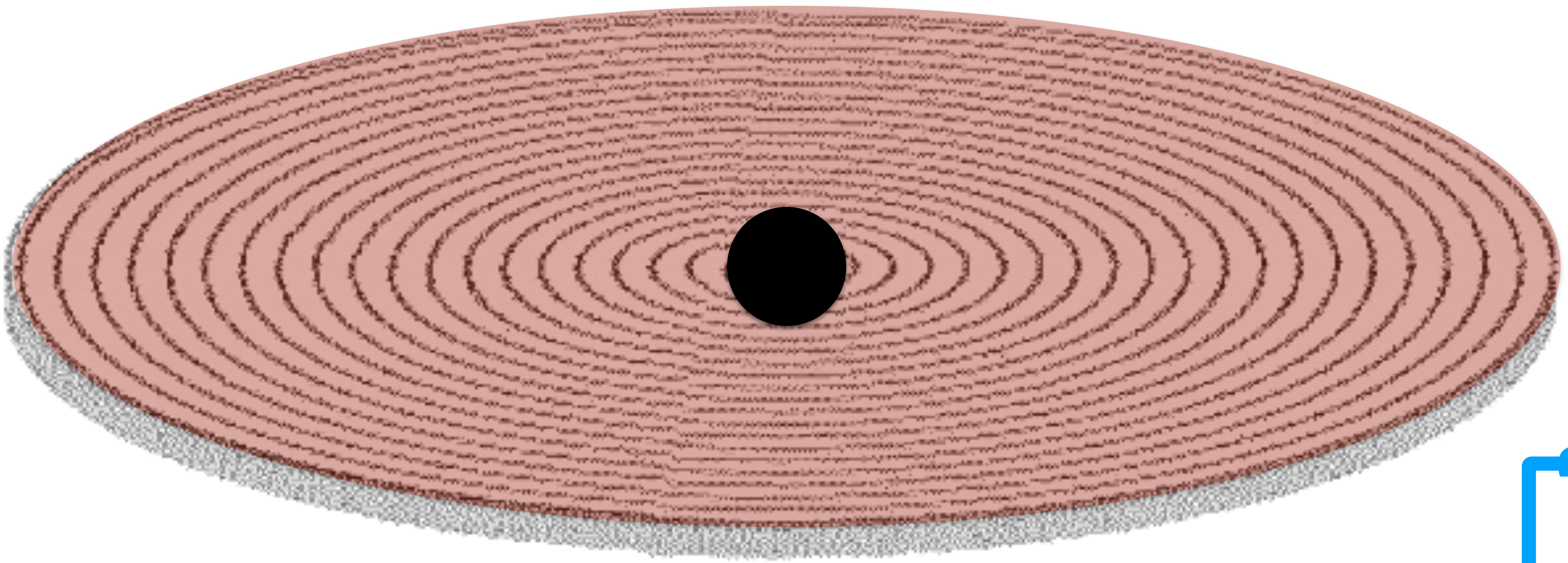


Bardeen+1973

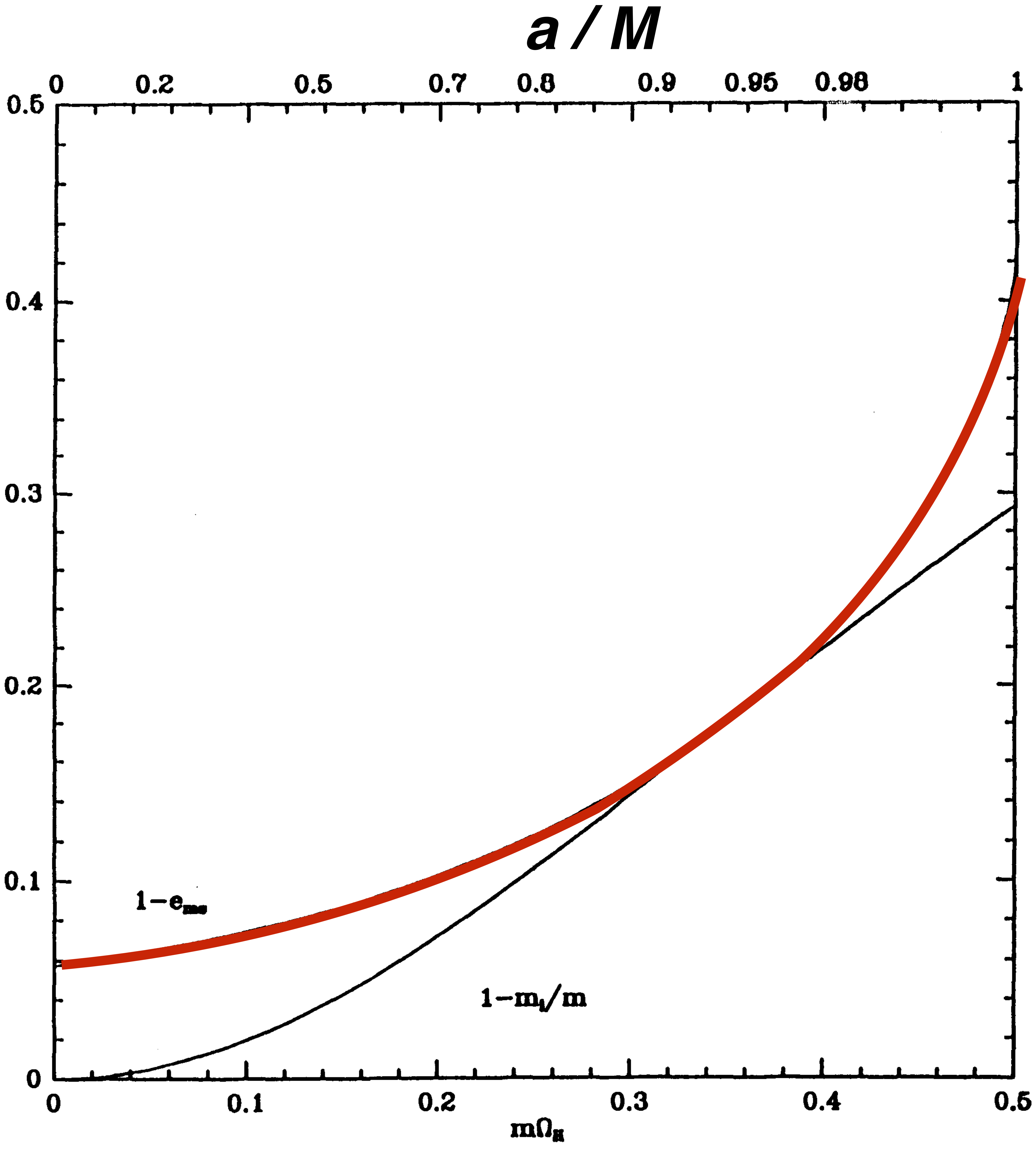
ISCO radius depends on the BH spin



Efficiency of black hole furnaces: accretion disks



efficiency of energy release η_{acc}



Blandford

Black hole spin leaves imprint on accretion disk

Faster, hotter, brighter

but gravitational redshift

Black hole accretion disks are the most efficient radiators in the universe

Release enormous amounts of light

Radiative efficiency:

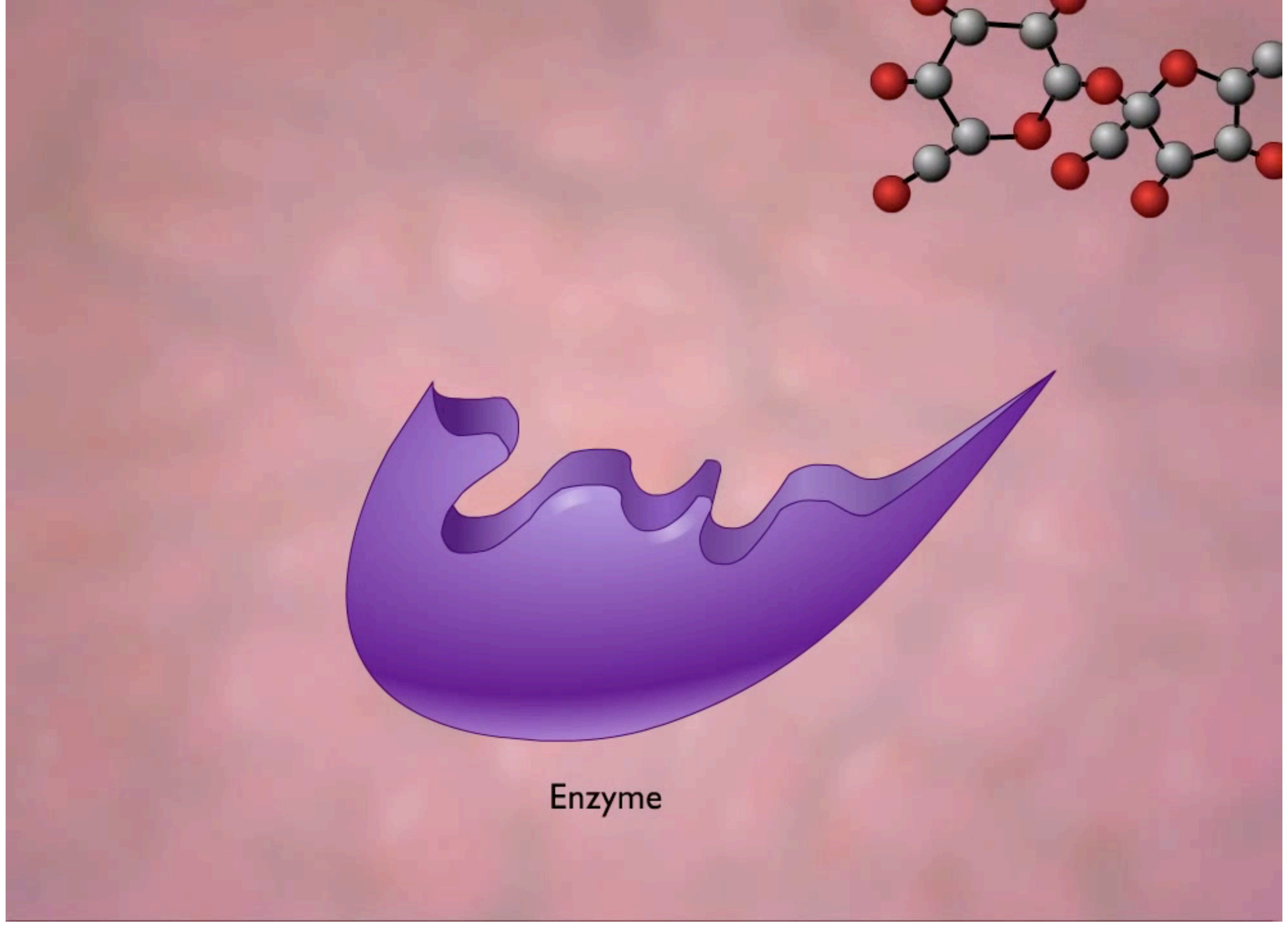
$$\eta_{\rm rad} = \frac{E_{\rm out}^{\rm rad}}{E_{\rm in}^{\rm gas}} = 10 - 40\%$$

Radiate across all eletromagnetic spectrum!

Credit: ESO

Sugar (sucrose) $C_{12}H_{22}O_{11}$

1g → 4 kcal= 16.2 kJ = 1e23 eV



$$\eta = \frac{E}{mc^2} = \frac{1.6 \times 10^{11}\mathrm{erg}}{9 \times 10^{20}\mathrm{erg}} = 2 \times 10^{-10}$$

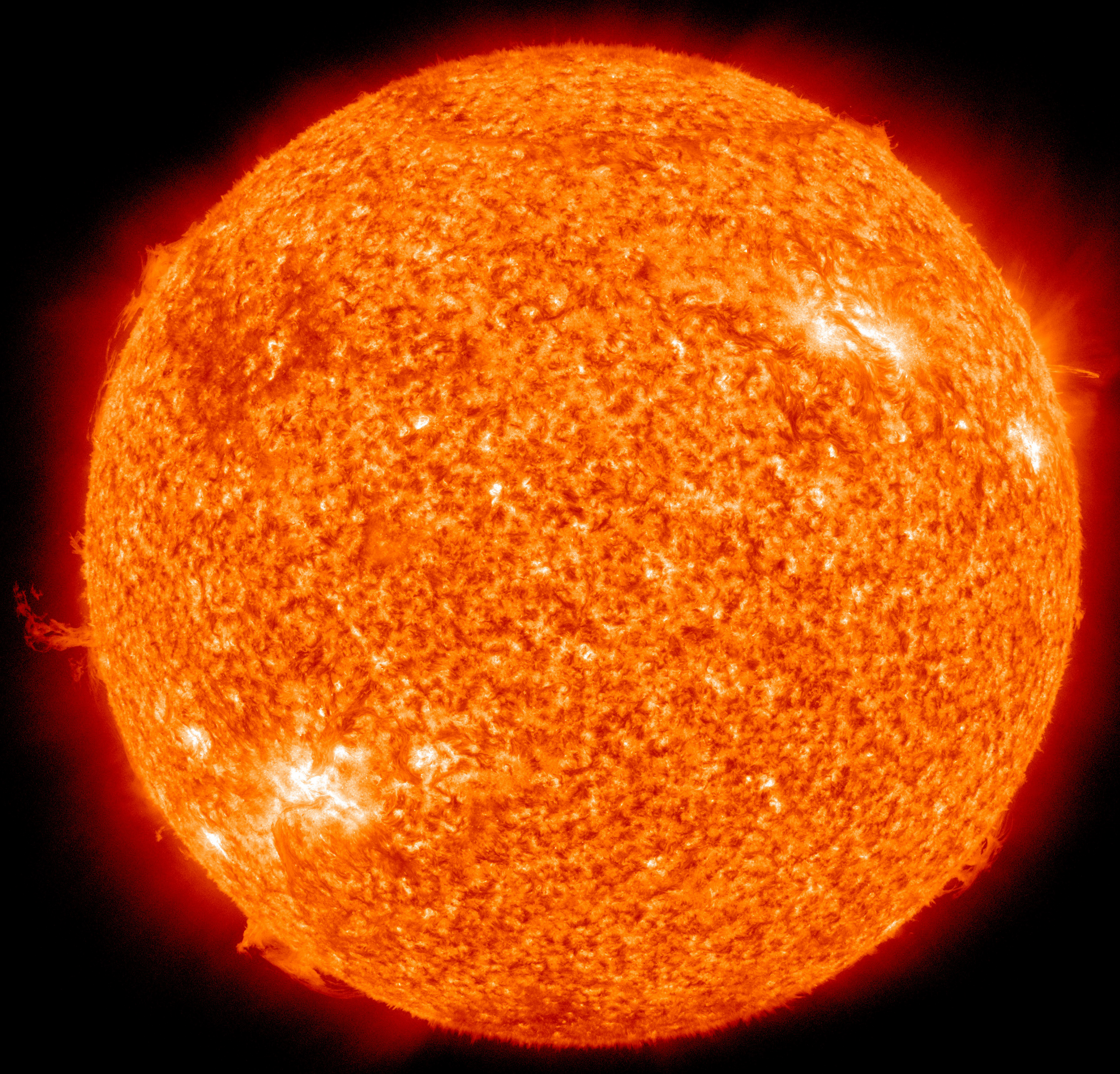
R. Nemmen

Itaipu Dam – 14 GW

$$\eta = \frac{mgh}{mc^2} = 10^{-14}\left(\frac{h}{100\ \mathrm{m}}\right)$$

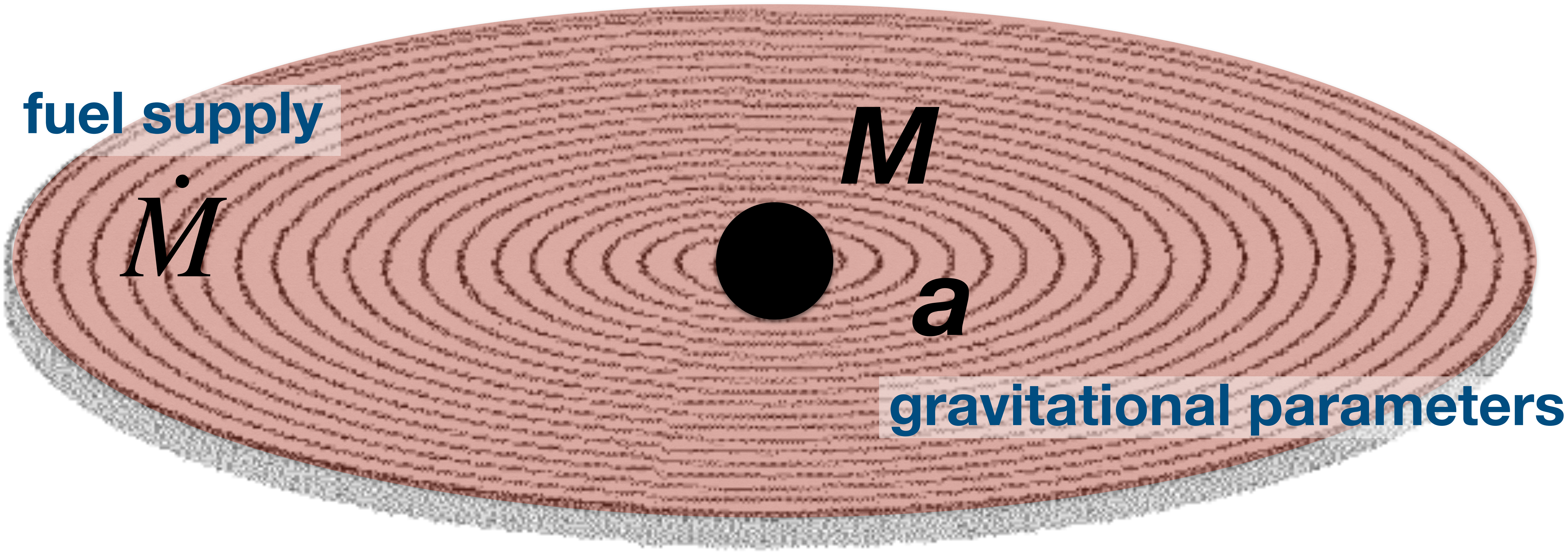
$$\eta = \frac{mv^2}{2mc^2} \sim 10^{-14}\left(\frac{v}{200\ \mathrm{km/h}}\right)^2$$

Nuclear fusion



$$\eta = 0.008 \times 0.1 \sim 8 \times 10^{-4}$$

Fundamental parameters of an accreting black hole



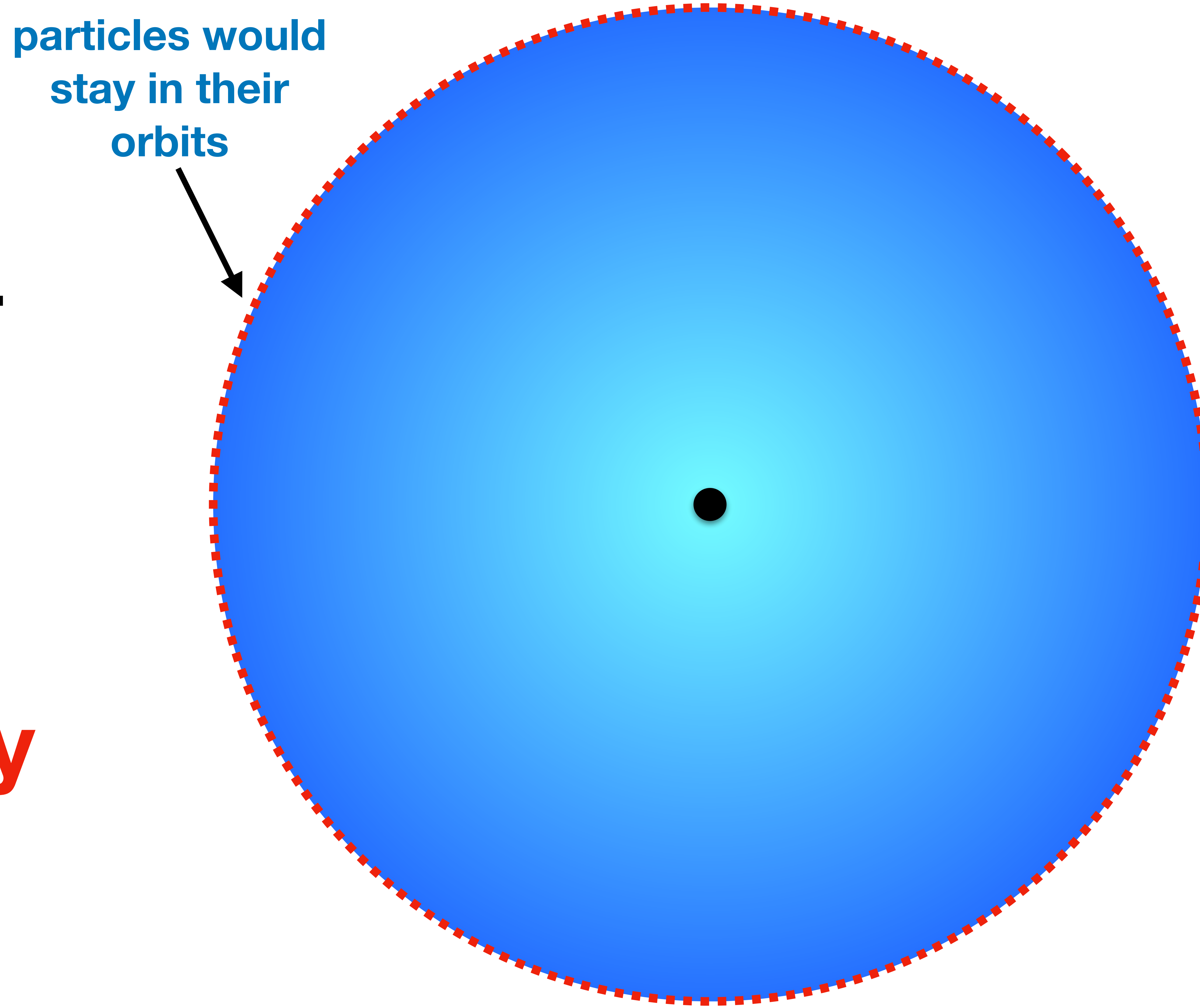
Theorist's dream: compute every property of the system from these numbers

Importance of angular momentum removal (viscosity)

Without a.m. removal, there would be no accretion (because $v_r = 0$)

Therefore no energy dissipation + radiation → conflict with observations

Accretion flows are fundamentally dissipative systems



Primer on fluid dynamics

Derive continuity equation

Equations of hydrodynamics

Conservation

of

Mass

$$\frac{D\rho}{Dt} + \rho\nabla \cdot \mathbf{v} = 0$$

from AGN course
accretion flows i

Rate of change
"following the fluid"

$$\frac{\mathrm{D}f}{\mathrm{D}t} = \frac{\partial f}{\partial t} + (\boldsymbol{u} \cdot \nabla)f.$$

Equations of hydrodynamics

Conservation of

Mass

$$\frac{D\rho}{Dt} + \rho\nabla \cdot \mathbf{v} = 0$$

Momentum

$$\rho\frac{D\mathbf{v}}{Dt} = -\nabla p - \rho\nabla\phi + \nabla \cdot \mathbf{T}$$

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Energy

$$\rho\frac{D(e/\rho)}{Dt} = -p\nabla\cdot\mathbf{v} + \mathbf{T}^2/\mu - \nabla\cdot\mathbf{F}_{\mathrm{rad}} - \nabla\cdot\mathbf{q}$$

Rate of change "following the fluid"

$$\frac{\mathrm{D}f}{\mathrm{D}t} = \frac{\partial f}{\partial t} + (\boldsymbol{u}\cdot\nabla)f.$$

Equations of hydrodynamics:
Momentum conservation

Cauchy momentum equation

$$\rho \frac{D\mathbf{v}}{Dt} = \nabla \cdot \sigma + \overbrace{\rho \mathbf{a}}^{\text{external forces}}$$

Rate of change "following the fluid"

$$\frac{Df}{Dt} = \frac{\partial f}{\partial t} + (\boldsymbol{u} \cdot \nabla) f.$$

Equations of hydrodynamics: Momentum conservation

Cauchy momentum equation

$$\rho \frac{D\mathbf{v}}{Dt} = \nabla \cdot \sigma + \overbrace{\rho \mathbf{a}}^{\text{external forces}}$$

Divergence of stress tensor

$$\nabla \cdot \sigma = \overbrace{-\nabla p}^{\text{pressure forces}} + \overbrace{\nabla \cdot \mathbf{T}}^{\text{viscous forces}}$$

Rate of change
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$$\frac{\mathrm{D}f}{\mathrm{D}t} = \frac{\partial f}{\partial t} + (\boldsymbol{u} \cdot \nabla) f.$$

Equations of hydrodynamics: Momentum conservation

Cauchy momentum equation

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Divergence of stress tensor

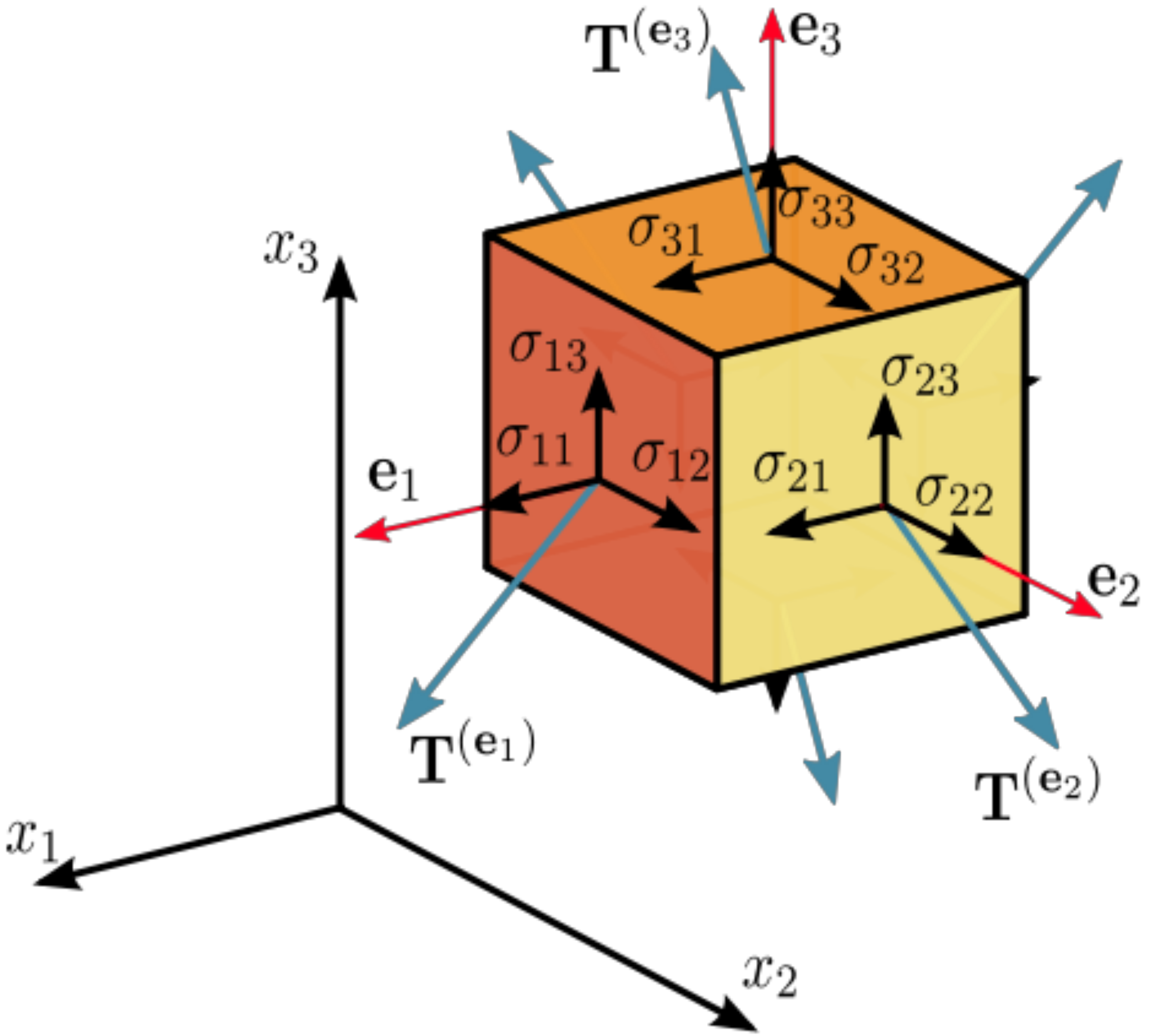
$$\nabla \cdot \sigma = \overbrace{-\nabla p}^{\text{pressure forces}} + \overbrace{\nabla \cdot \mathbf{T}}^{\text{viscous forces}}$$

$$\therefore \quad \overbrace{\rho \frac{D\mathbf{v}}{Dt}}^{\text{force / volume}} = \overbrace{-\nabla p}^{\text{pressure forces}} \overbrace{- \rho \nabla \phi}^{\text{gravity}} + \overbrace{\nabla \cdot \mathbf{T}}^{\text{viscous forces}}$$

Rate of change
"following the fluid"

$$\frac{\mathrm{D}f}{\mathrm{D}t} = \frac{\partial f}{\partial t} + (\boldsymbol{u} \cdot \nabla) f.$$

Equations of hydrodynamics: stress tensor



$$\boldsymbol{\sigma} = \sigma_{ij} = \begin{bmatrix} \sigma_{11} & \sigma_{12} & \sigma_{13} \\ \sigma_{21} & \sigma_{22} & \sigma_{23} \\ \sigma_{31} & \sigma_{32} & \sigma_{33} \end{bmatrix}$$

$$= \begin{bmatrix} \sigma_{xx} & \sigma_{xy} & \sigma_{x} \\ \sigma_{yx} & \sigma_{yy} & \sigma_{yz} \\ \sigma_{zx} & \sigma_{zy} & \sigma_{zz} \end{bmatrix}$$

$$\equiv \begin{bmatrix} \sigma_x & \tau_{xy} & \tau_{xz} \\ \tau_{yx} & \sigma_y & \tau_{yz} \\ \tau_{zx} & \tau_{zy} & \sigma_z \end{bmatrix}$$

orthogonal shear stresses

orthogonal normal stresses (pressure)

http://en.wikipedia.org/wiki/Stress_(mechanics)#/media/File:Components_stress_tensor_cartesian.svg

Equations of hydrodynamics:
Energy conservation

$$\overbrace{\rho\frac{D(e/\rho)}{Dt}}^{\text{rate of change in internal energy}} = -p\nabla\cdot\mathbf{v} + \overbrace{\mathbf{T}^2/\mu}^{\text{viscous heating}} - \overbrace{\nabla\cdot\mathbf{F}_{\rm rad}}^{\text{radiative cooling}} - \overbrace{\nabla\cdot\mathbf{q}}^{\text{thermal conduction}}$$

Rate of change
"following the fluid"

$$\frac{\mathrm{D}f}{\mathrm{D}t} = \frac{\partial f}{\partial t} + (\boldsymbol{u}\cdot\nabla)f.$$

Equations of hydrodynamics

Conservation of

Mass

$$\frac{D\rho}{Dt} + \rho \nabla \cdot \mathbf{v} = 0$$

Momentum

$$\rho \frac{D\mathbf{v}}{Dt} = -\nabla p - \rho \nabla \phi + \nabla \cdot \mathbf{T}$$

Energy

$$\rho \frac{D(e/\rho)}{Dt} = -p \nabla \cdot \mathbf{v} + \mathbf{T}^2/\mu - \nabla \cdot \mathbf{F}_{\mathrm{rad}} - \nabla \cdot \mathbf{q}$$

Plus:

- ⁕ equation of state
- ⁕ opacity description
- ⁕ viscosity

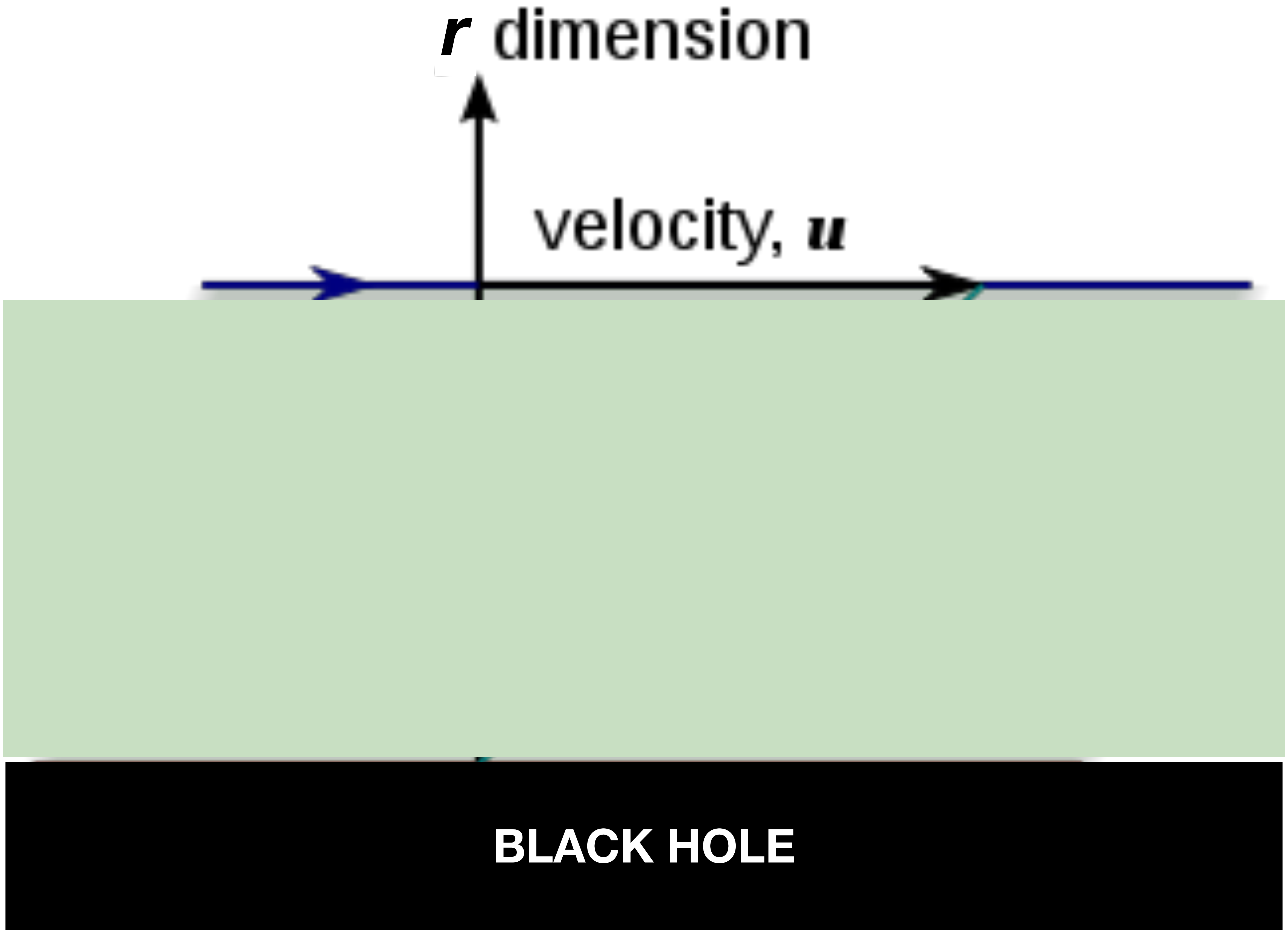
Flow Illustrator
https://www.youtube.com/watch?v=CFXS3MVFmvY

Nature of a.m. dissipation

BH accretion disks are a fancier version of Kepler's problem

$$\Omega = \frac{d\phi}{dt} = \left(\frac{M}{r^3}\right)^{1/2}$$

Differential rotation



http://en.wikipedia.org/wiki/Viscosity#/media/File:Laminar_shear.svg

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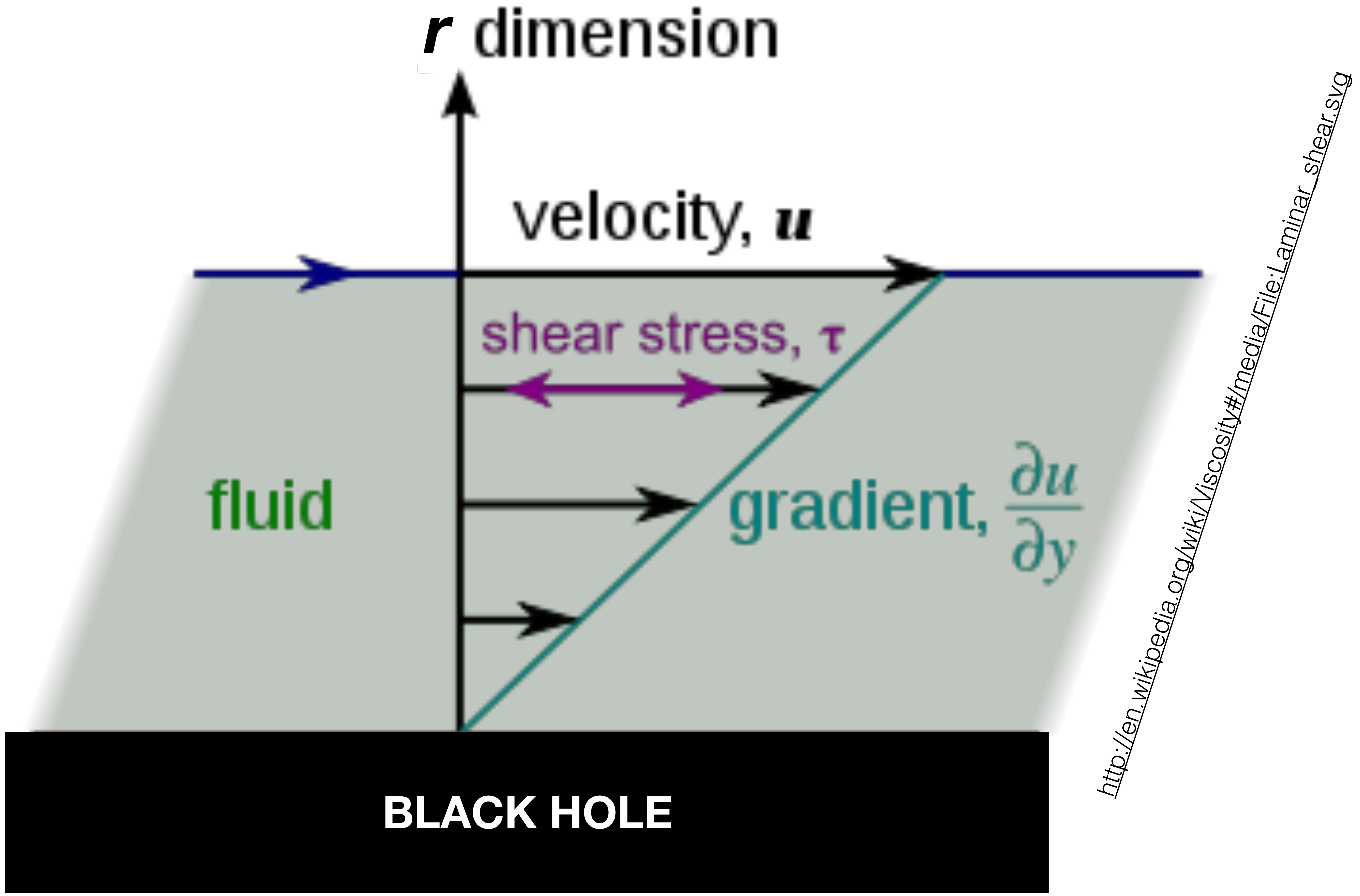


Shear stress → viscosity → energy dissipation

There was suspicion that hydrodynamic turbulence could drive accretion in the universe

Magnetorotational Instability (MRI) Experiment at Princeton

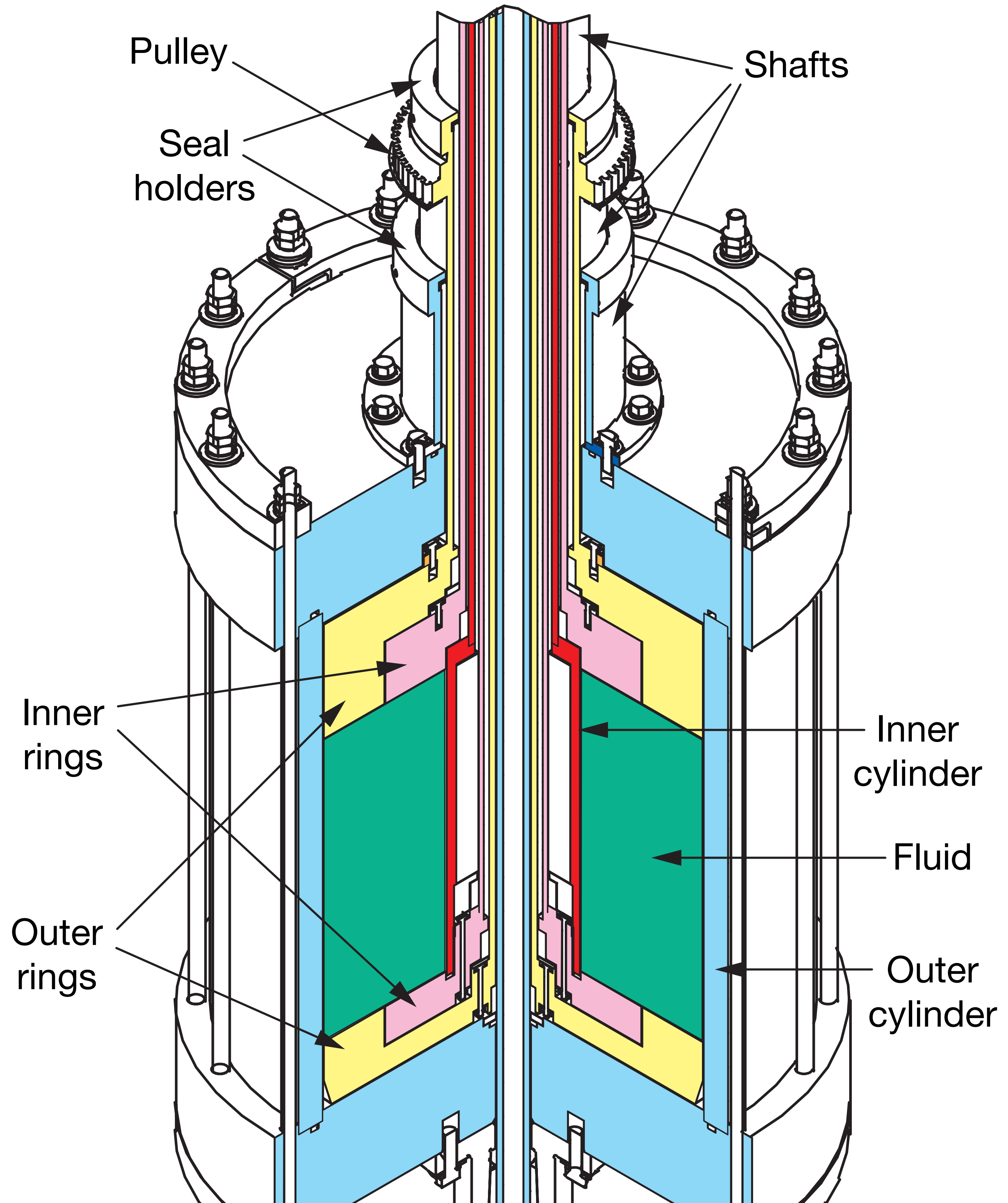
Goal: investigate nature of turbulence in *astrophysical* disks

http://mri.pppl.gov

Hydrodynamic turbulence cannot transport angular momentum effectively in astrophysical disks

Hantao Ji[1], Michael Burin[1]†, Ethan Schartman[1] & Jeremy Goodman[1]

The most efficient energy sources known in the Universe are accretion disks. Those around black holes convert 5–40 per cent of rest-mass energy to radiation. Like water circling a drain, inflowing mass must lose angular momentum, presumably by vigorous turbulence in disks, which are essentially inviscid[1]. The origin of the turbulence is unclear. Hot disks of electrically conducting plasma can become turbulent by way of the linear magnetorotational instability[2]. Cool disks, such as the planet-forming disks of protostars, may be too poorly ionized for the magnetorotational instability to occur, and therefore essentially unmagnetized and linearly stable. Nonlinear hydrodynamic instability often occurs in linearly stable flows (for example, pipe flows) at sufficiently large Reynolds numbers. Although planet-forming disks have extreme Reynolds numbers, keplerian rotation enhances their linear hydrodynamic stability, so the question of whether they can be turbulent and thereby transport angular momentum effectively is controversial[3–15]. Here we report a laboratory experiment, demonstrating that non-magnetic quasi-keplerian flows at Reynolds numbers up to millions are essentially steady. Scaled to accretion disks, rates of angular momentum transport lie far below astrophysical requirements. By ruling out purely hydrodynamic turbulence, our results indirectly support the magnetorotational



Magnetorotational instability (MRI)

First studied by Chandrasekhar 1963, Velikhov 1959

Only in 1991 Balbus & Hawley realized their importance and generality

THE ASTROPHYSICAL JOURNAL, 376:214–222, 1991 July 20

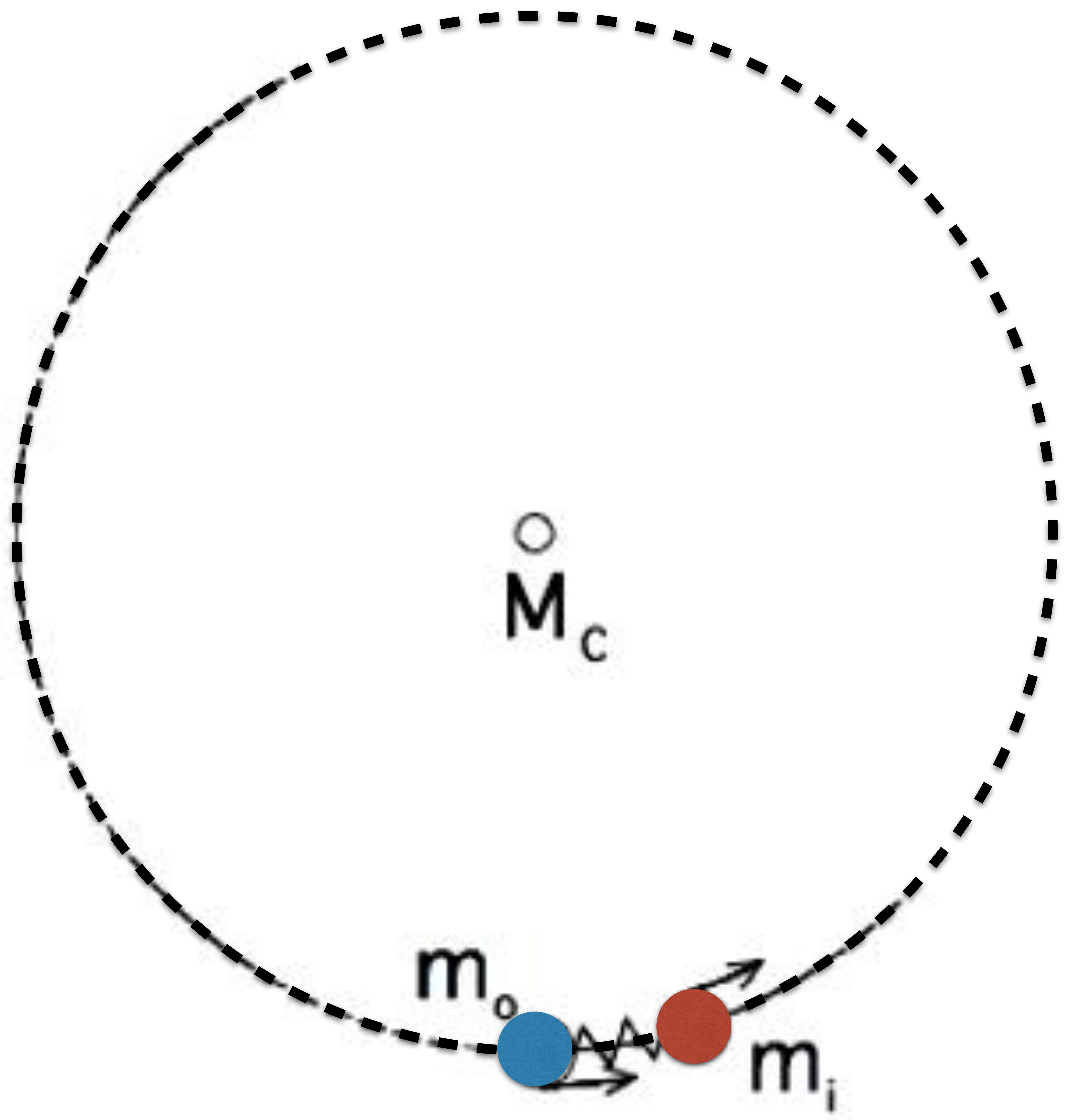
A POWERFUL LOCAL SHEAR INSTABILITY IN WEAKLY MAGNETIZED DISKS.
I. LINEAR ANALYSIS

STEVEN A. BALBUS AND JOHN F. HAWLEY
Virginia Institute for Theoretical Astronomy, Department of Astronomy, University of Virginia, P.O. Box 3818, Charlottesville, VA 22903
Received 1990 November 1; accepted 1991 January 16

ABSTRACT

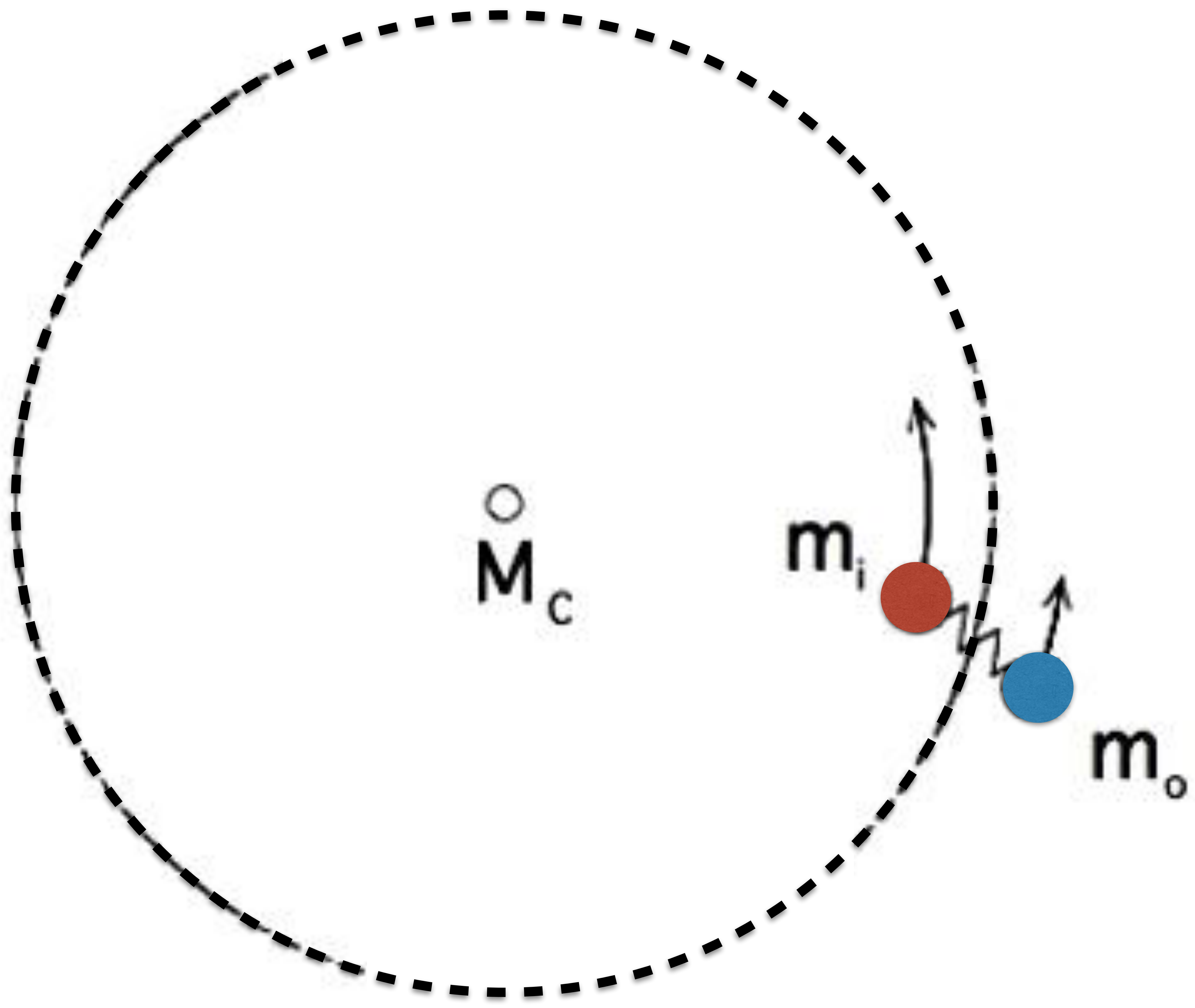
In this paper and a companion work, we show that a broad class of astrophysical accretion disk is dynamically unstable to axisymmetric disturbances in the presence of a weak magnetic field. Because of the ubiquity of magnetic fields, this result bears upon gaseous differentially rotating systems quite generally. This work presents a linear analysis of the instability. (The companion work presents the results of nonlinear numerical simulations.) The instability is local and extremely powerful. The maximal growth rate is of order

Analogy to understand magnetorotational instability (MRI)



http://www.scholarpedia.org/article/Magnetorotational_instability

Analogy to understand magnetorotational instability (MRI)



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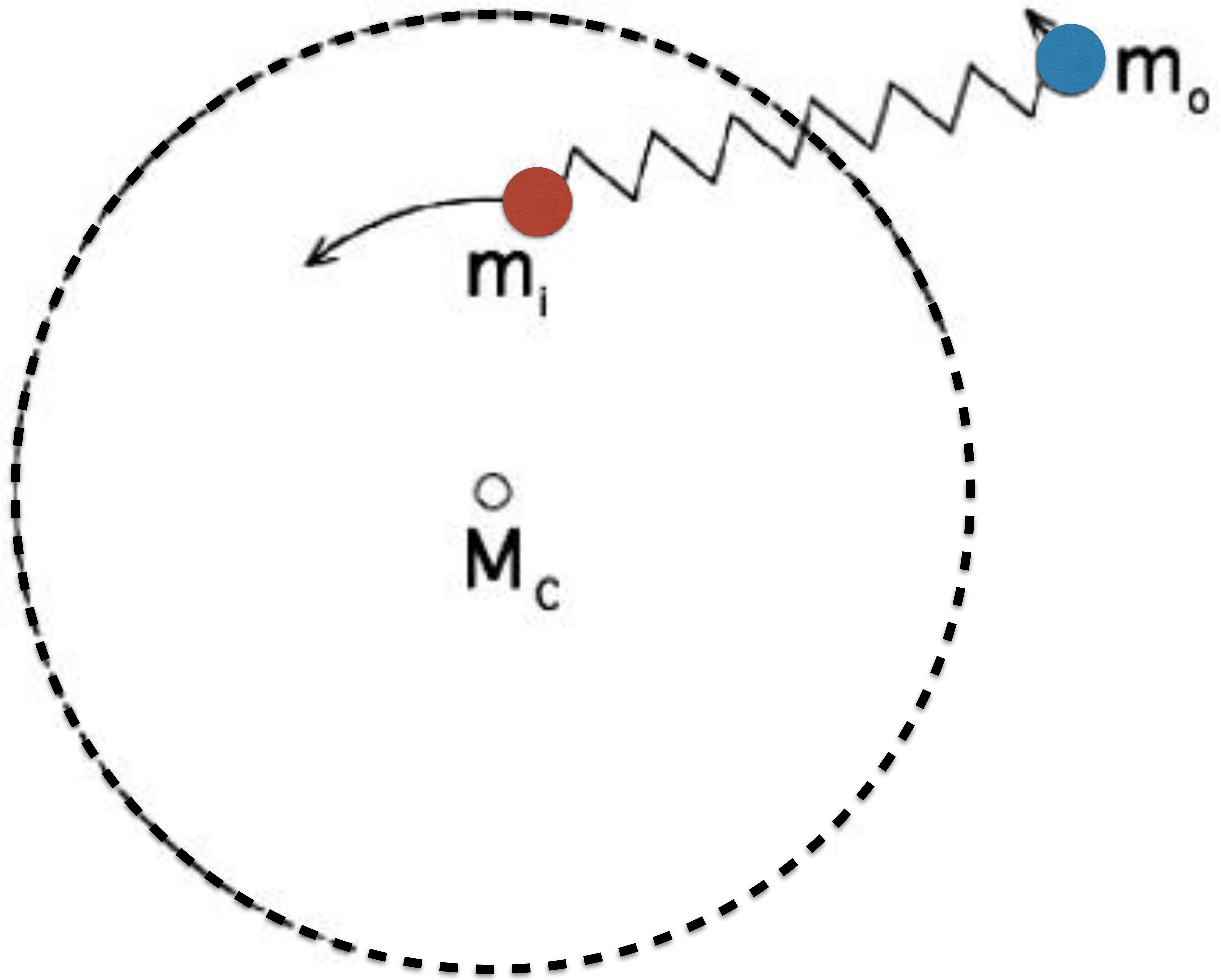

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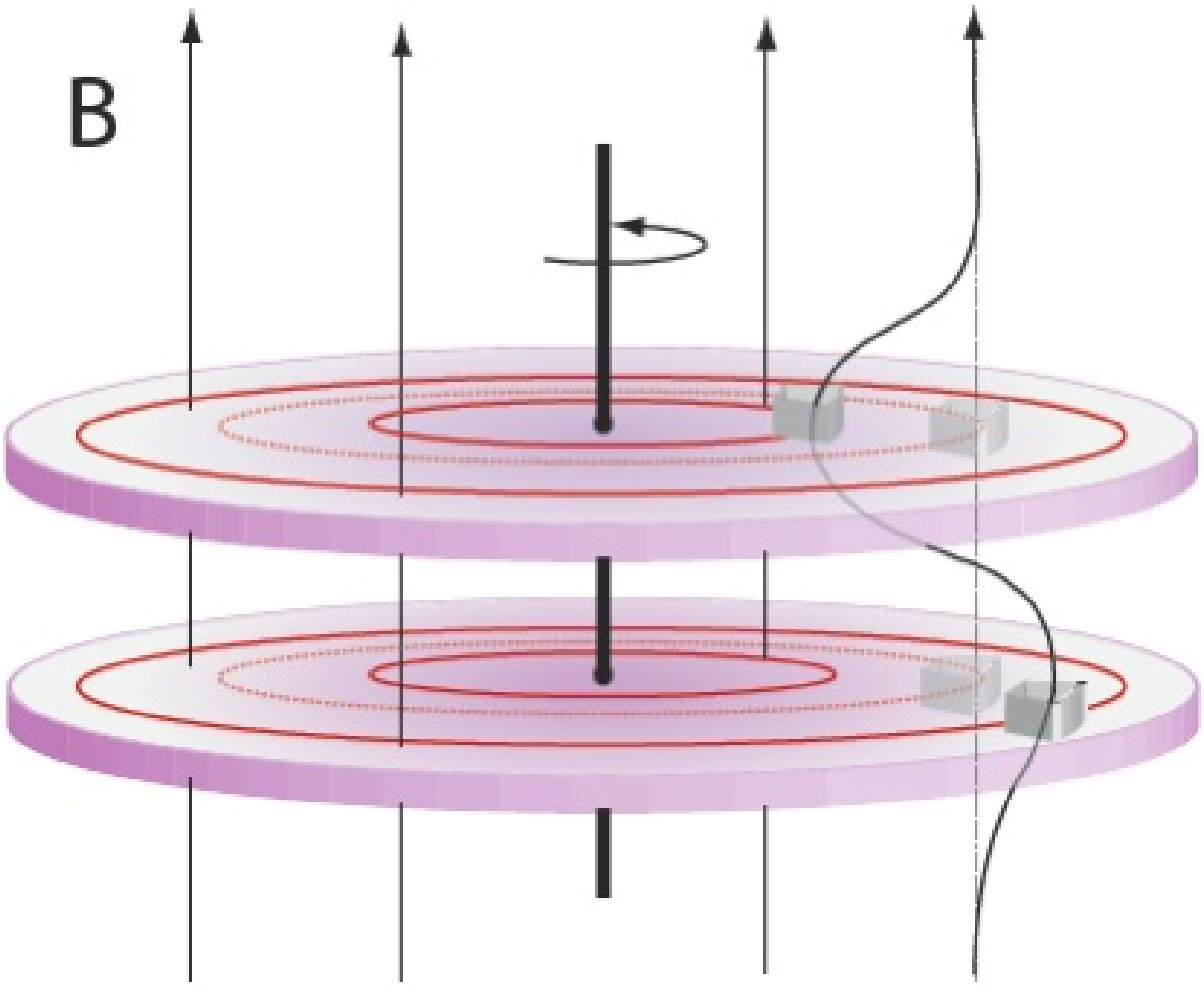
Magnetorotational instability (MRI)

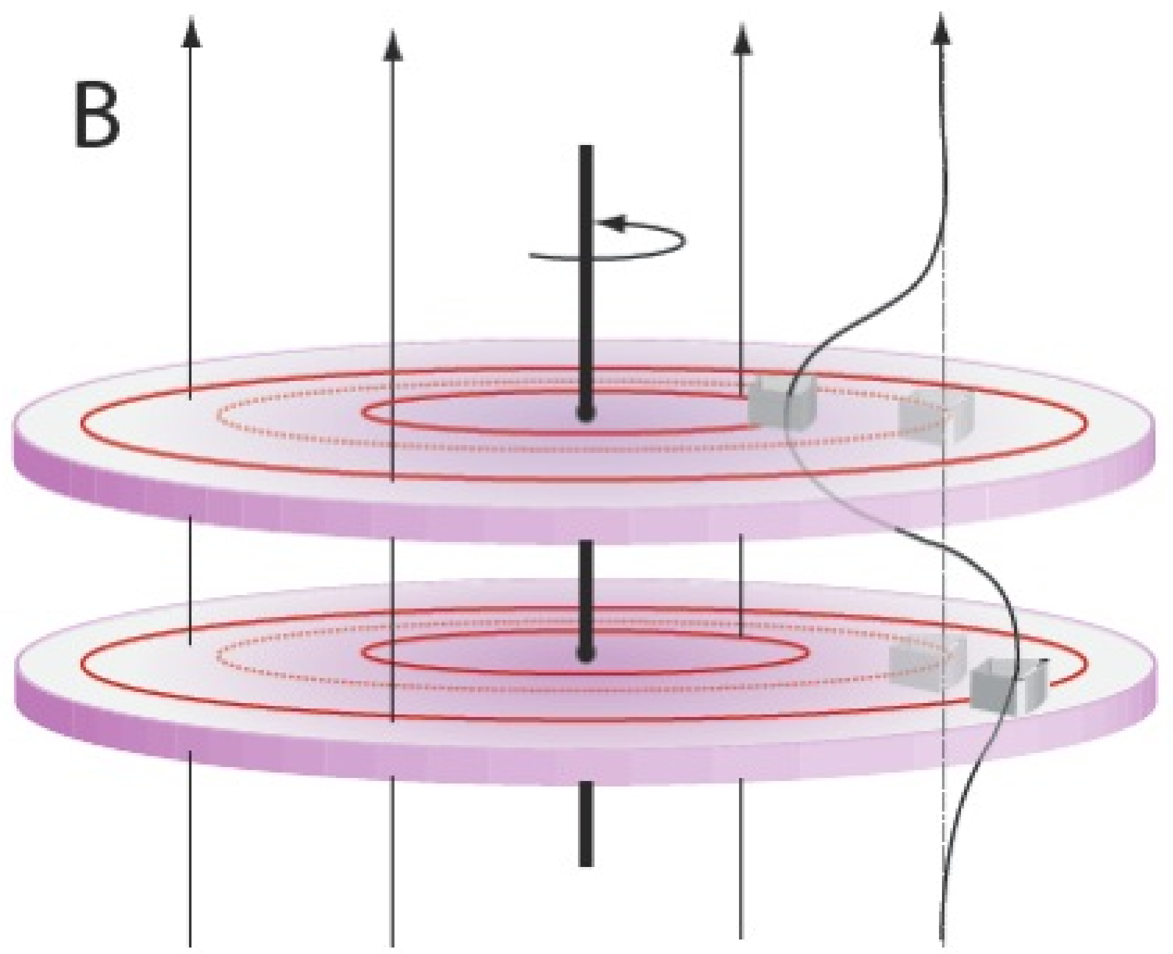


In reality, a magnetic field takes the place of a spring

Nick Murphy

Magnetic fields are the main agent removing a.m. in black hole disks

Can be modeled with pure hydrodynamics + effective viscosity (with limitations)



Application of hydrodynamics to accretion flows

Applying equations to accretion flows: approximations

Poloidal component of momentum equation

$$\overbrace{(\mathbf{v_p}\cdot\nabla)\mathbf{v_p}}^{\substack{\text{advection} \\ \text{(is } \boldsymbol{v_R} \text{ big?)}}} = -\overbrace{\frac{\nabla p}{\rho}}^{\substack{\text{pressure} \\ \text{support}}} - \overbrace{\nabla\Phi}^{\text{gravity}} + \overbrace{\Omega^2 R}^{\substack{\text{rotation} \\ \text{(is } \boldsymbol{v_\phi} \text{ big?)}}} + \overbrace{(\nabla\cdot\mathbf{T})_p}^{\text{viscosity}}$$

related to viscosity

Classifying accretion flow models

$$\cancel{\overbrace{(\mathbf{v_p}\cdot\nabla)\mathbf{v_p}}^{\text{advection (is } v_R \text{ big?)}}} = -\overbrace{\frac{\nabla p}{\rho}}^{\text{pressure support}} - \overbrace{\nabla\Phi}^{\text{gravity}} + \cancel{\overbrace{\Omega^2 R}^{\text{rotation (is } v_\phi \text{ big?)}}} + \cancel{\overbrace{(\nabla\cdot\mathbf{T})_p}^{\text{viscosity}}}$$

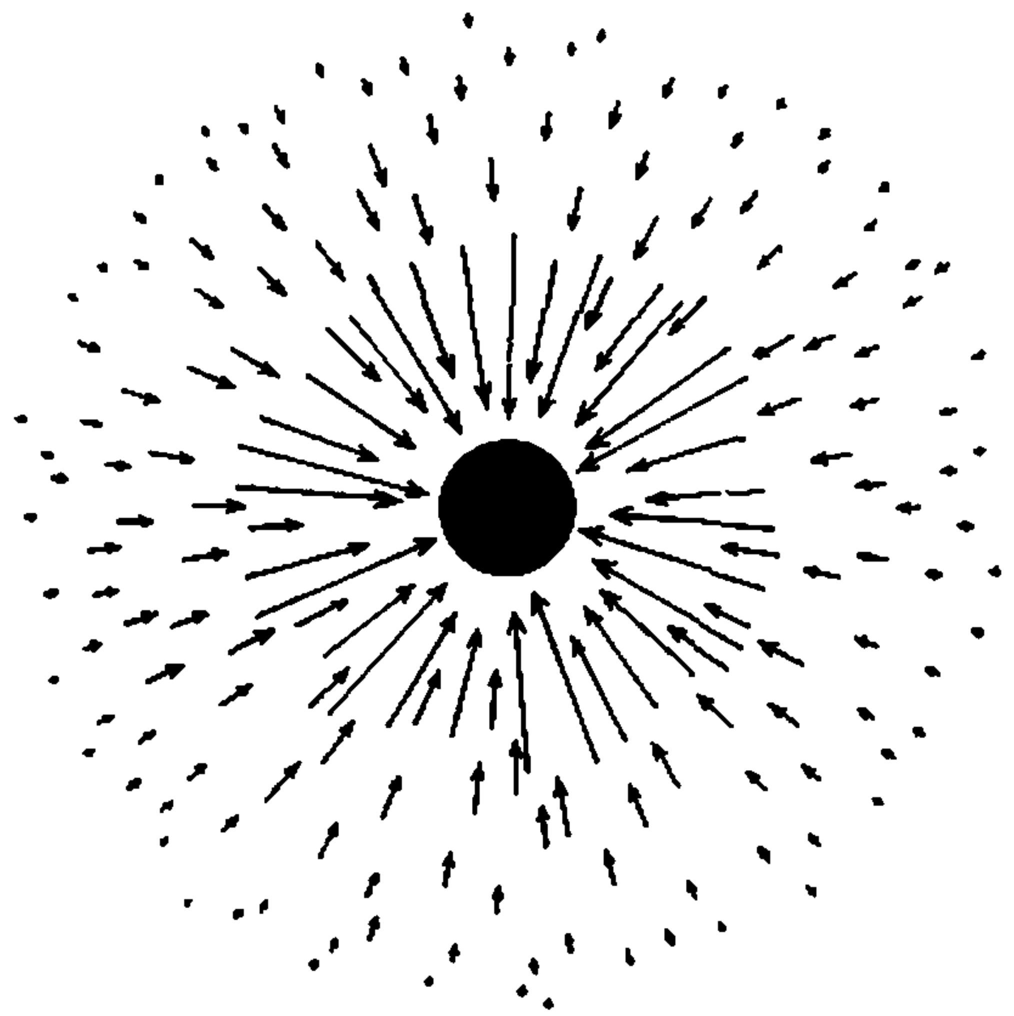
Stars, stellar envelopes & atmospheres

no accretion

Classifying accretion flow models

$$\underbrace{(\mathbf{v_p}\cdot\nabla)\mathbf{v_p}}^{\text{advection (is } v_R \text{ big?)}} = -\overbrace{\frac{\nabla p}{\rho}}^{\text{pressure support}} - \overbrace{\nabla\Phi}^{\text{gravity}} + \cancel{\overbrace{\Omega^2 R}^{\text{rotation (is } v_\phi \text{ big?)}}} + \cancel{\overbrace{(\nabla\cdot\mathbf{T})_p}^{\text{viscosity}}}$$

Spherical accretion: Bondi-Hoyle accretion



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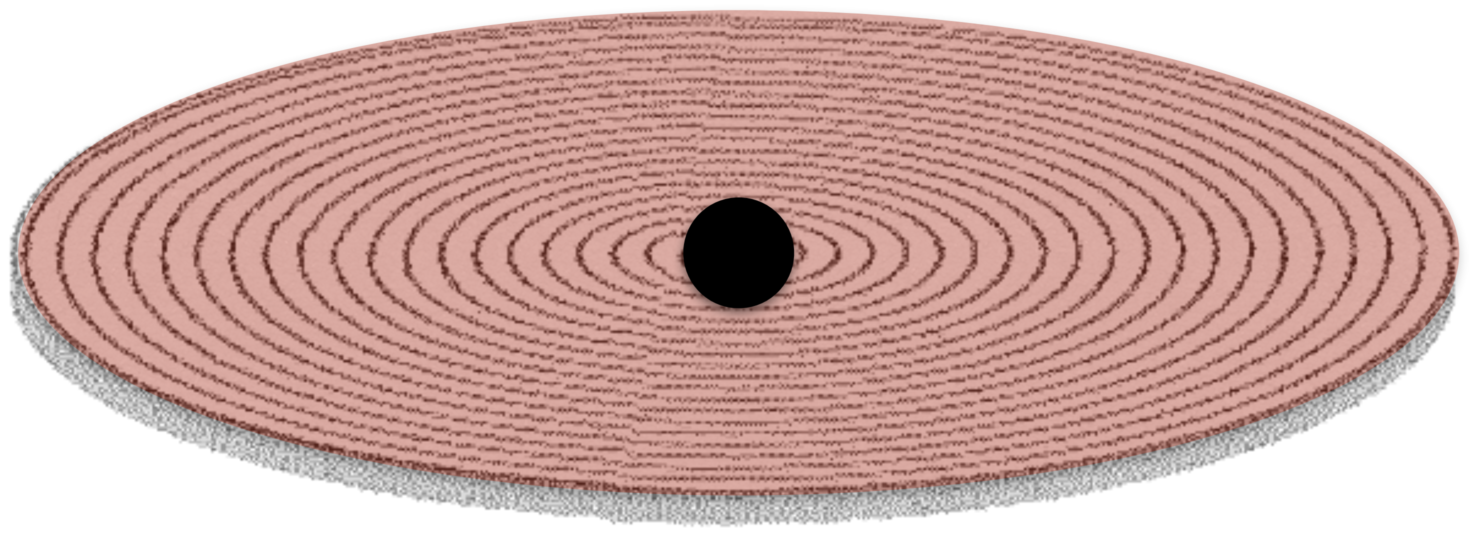

Thin accretion disks (quasi-Keplerian)

Classifying accretion flow models

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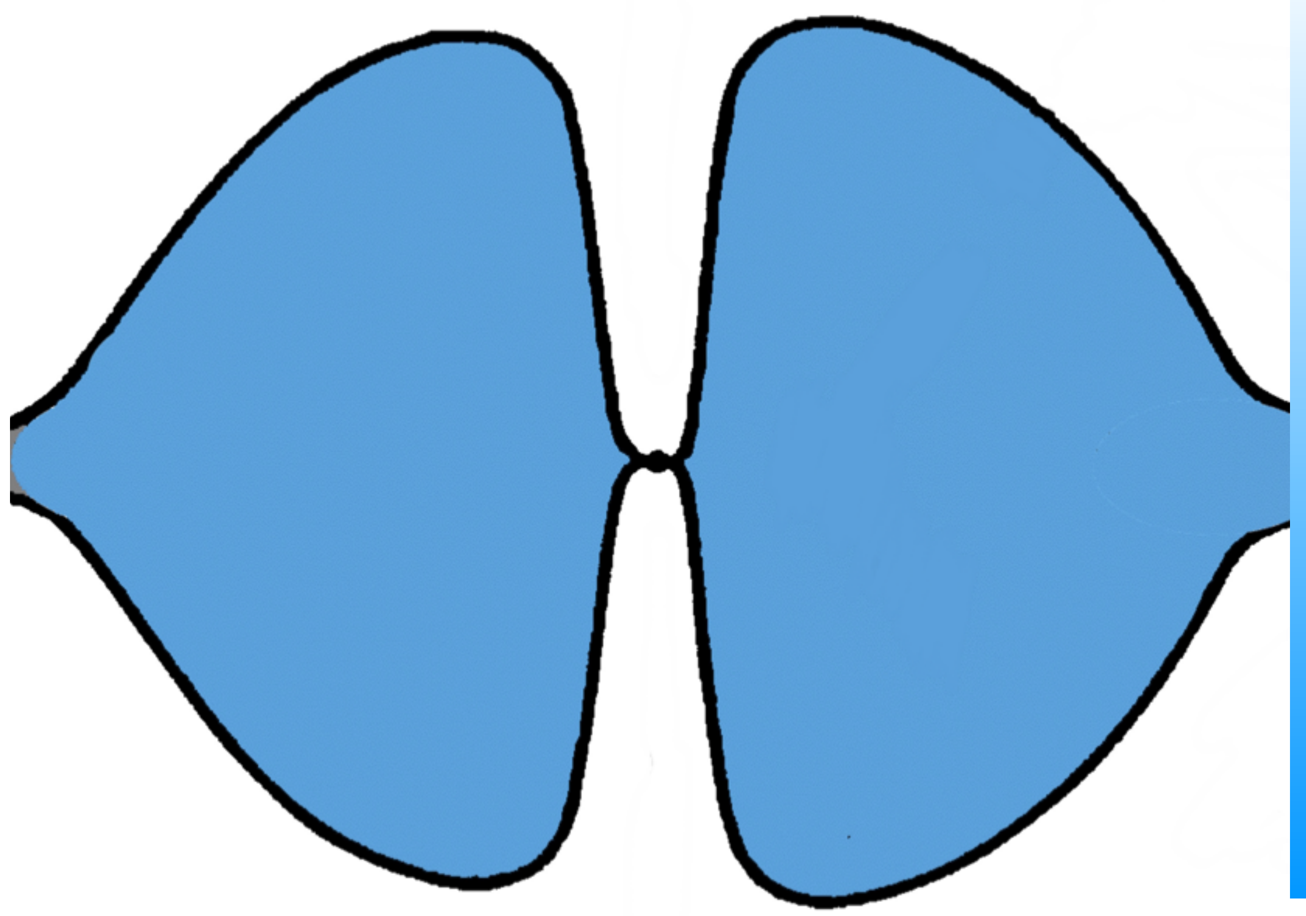
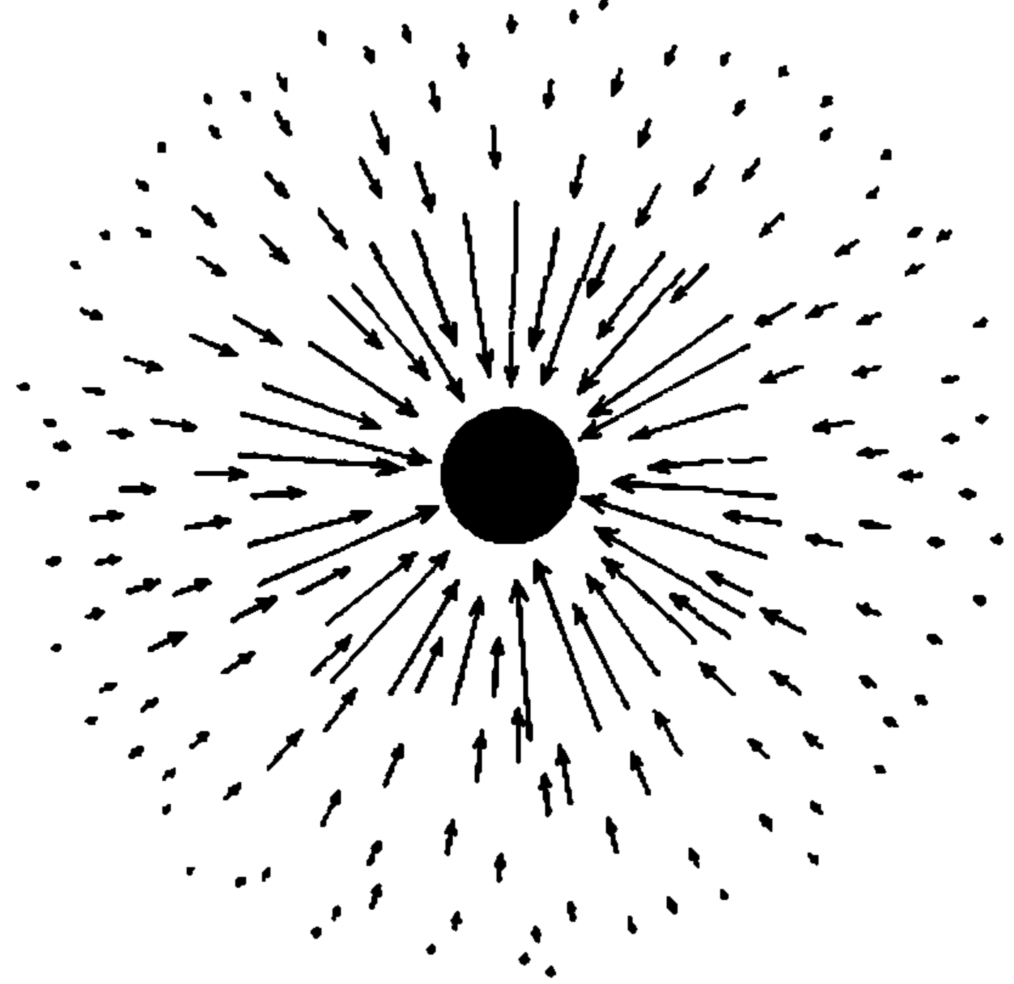
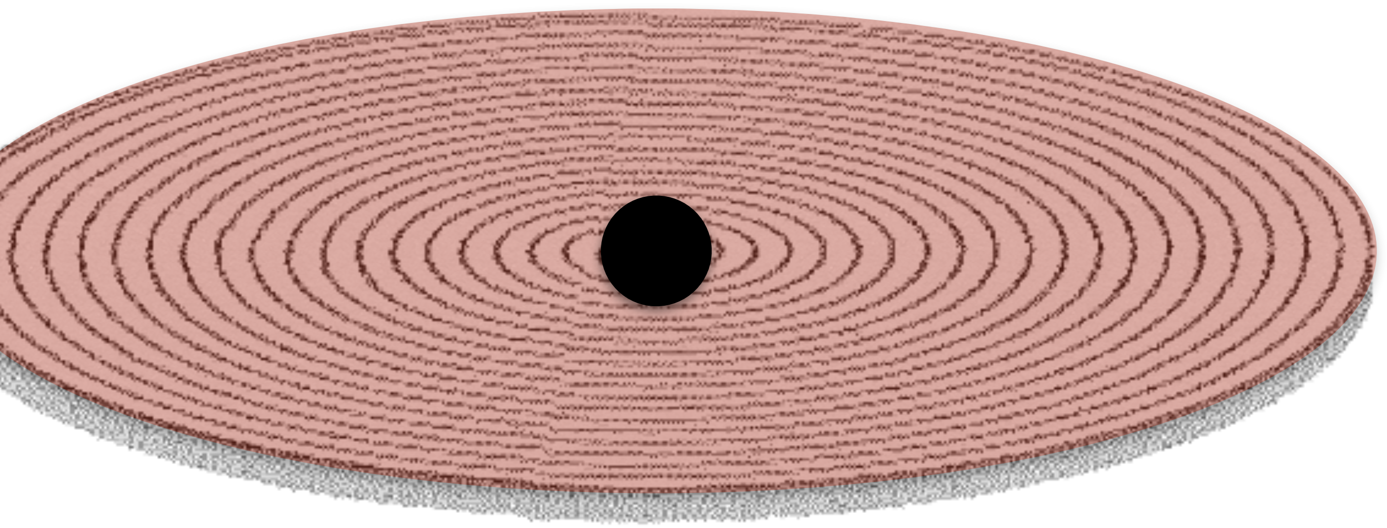


Radiatively inefficient accretion flows (RIAFs)

Spherical accretion:
Bondi-Hoyle accretion





Thin accretion disks
(quasi-Keplerian)

Radiatively
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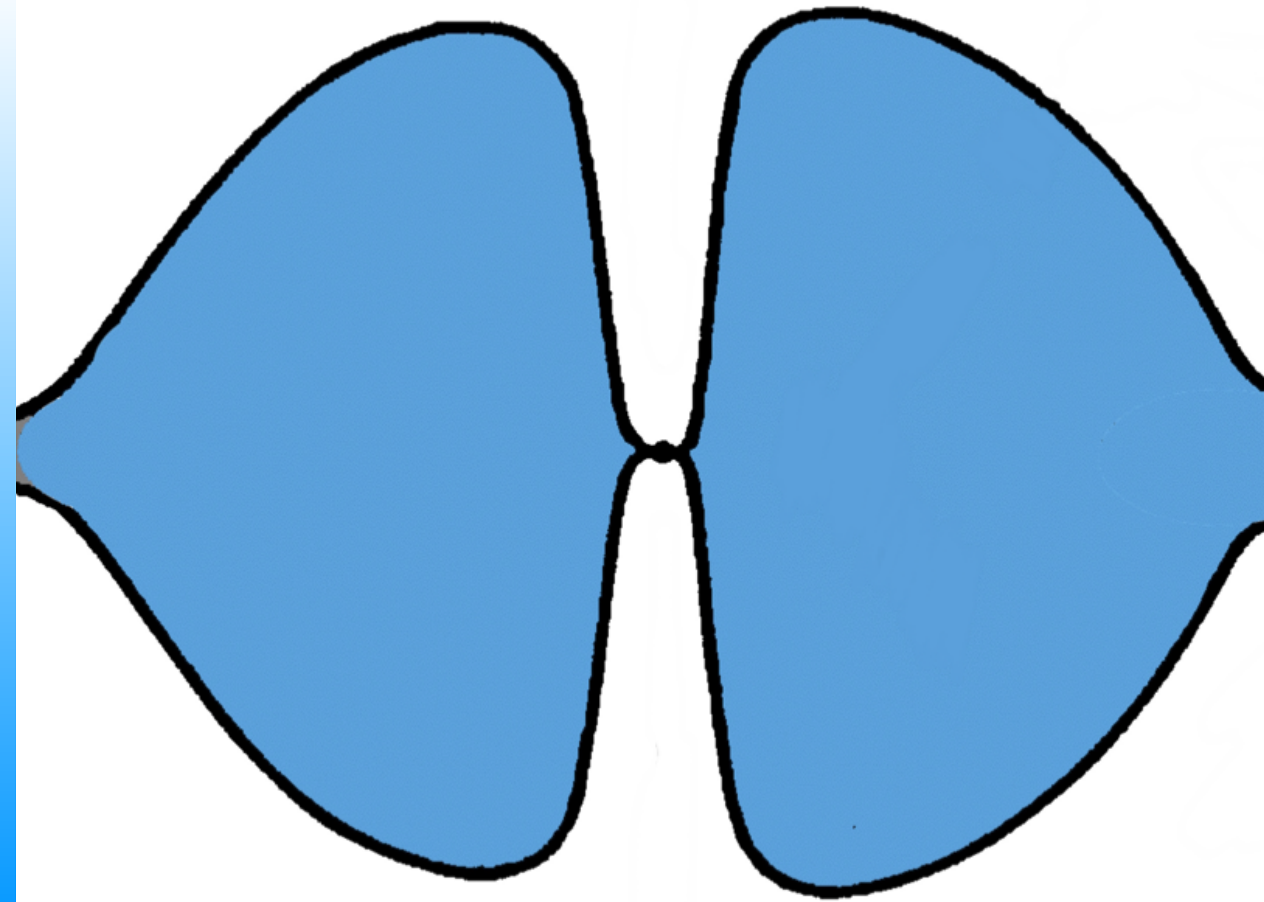


Towards a unified theory of black hole disks: preliminaries

Fundamental concept: Eddington luminosity

Equations of hydrodynamics:
Energy conservation

Compact version

$$\overbrace{\rho T \frac{\mathrm{D}S}{\mathrm{D}t}}^{\text{rate of increase of entropy/volume}} = \overbrace{q_+}^{\text{heating rate}} - \overbrace{q_-}^{\text{cooling rate}} = \overbrace{q_{\mathrm{adv}}}^{\text{advective cooling rate}}$$

Heat energy must go somewhere

$$\overbrace{q_+}^{\text{heat due to viscous dissipation}} = \underbrace{q_-}_{\text{radiative cooling}} + \underbrace{q_{\mathrm{adv}}}_{\text{advective cooling}}$$

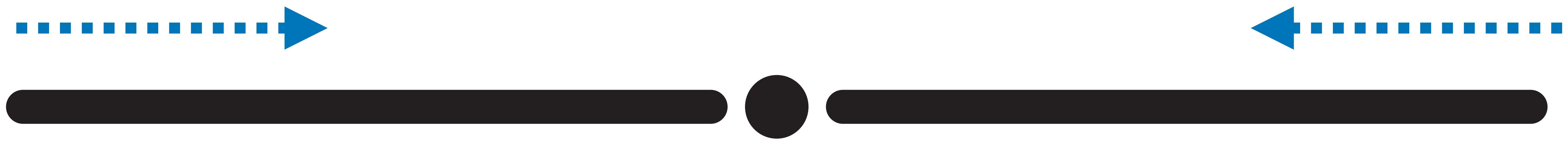
Advection of a car by a fluid

Simple description of an accretion disk

mass accretion rate

$\dot{M}/\dot{M}_{\mathrm{Edd}}$

h/r I

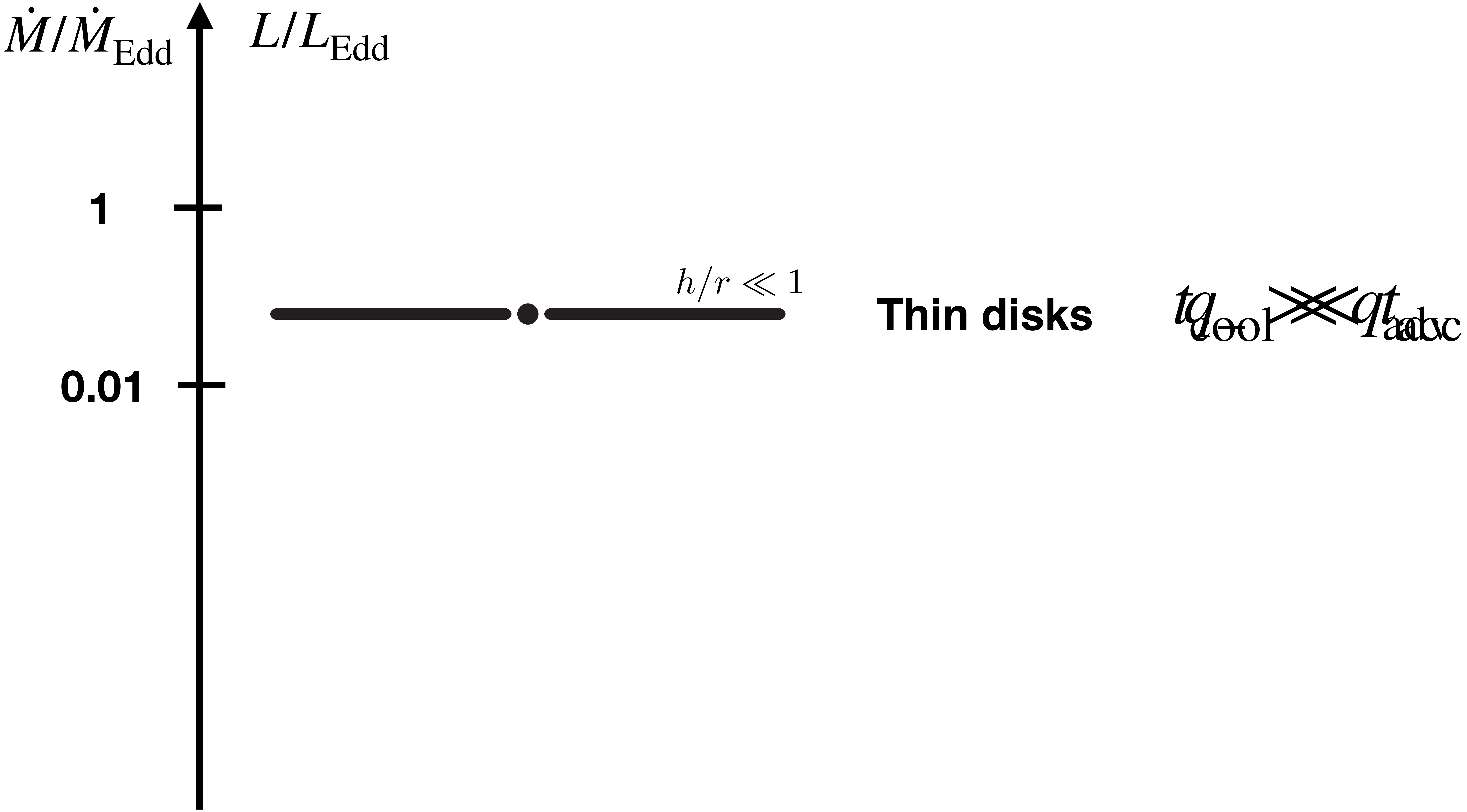


disk thickness

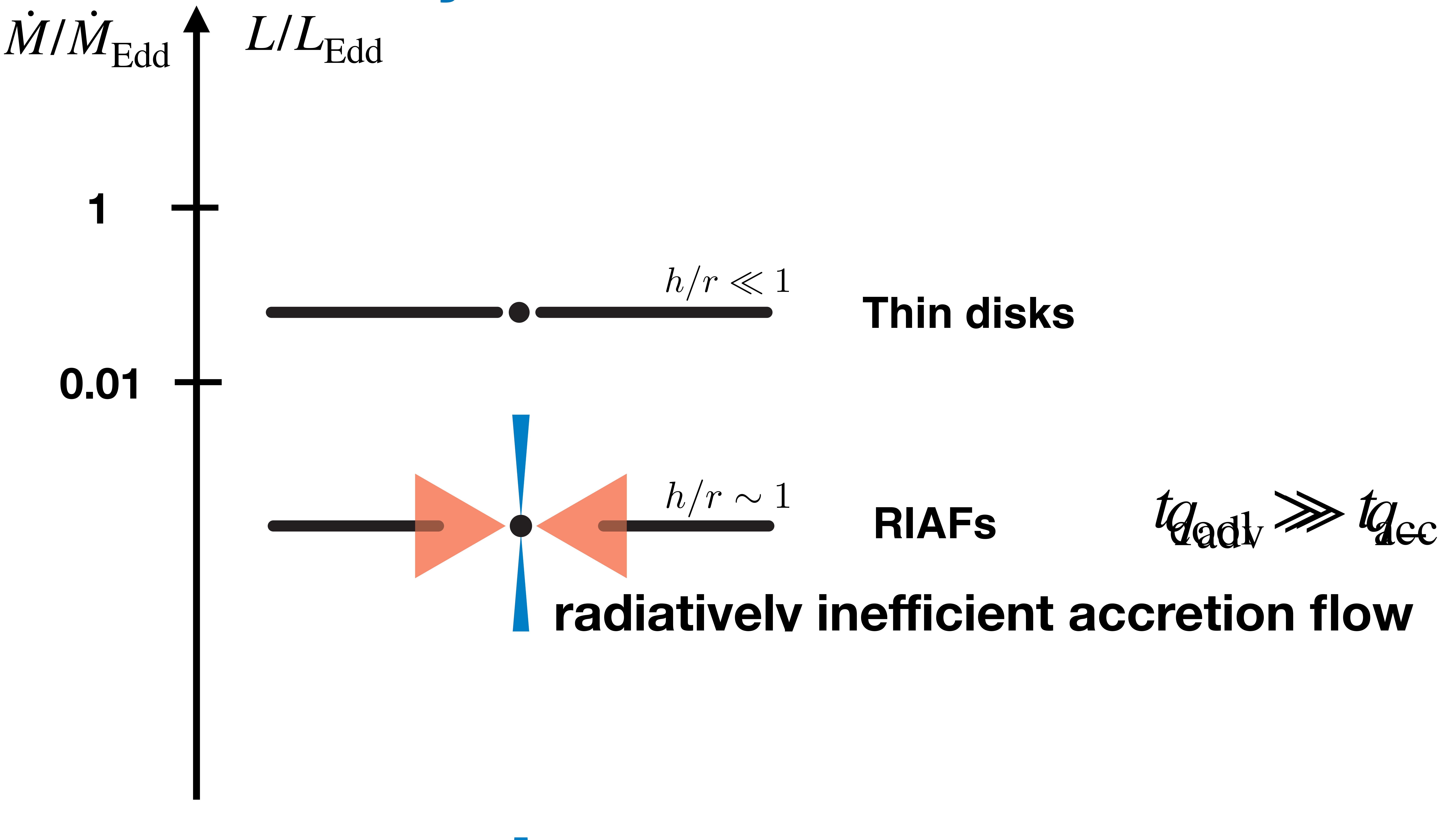
mass accr. rate related to gas density

$$\dot{M} = 4\pi r^2 \rho v_r$$

Unified theory of black hole accretion flows



Unified theory of black hole accretion flows



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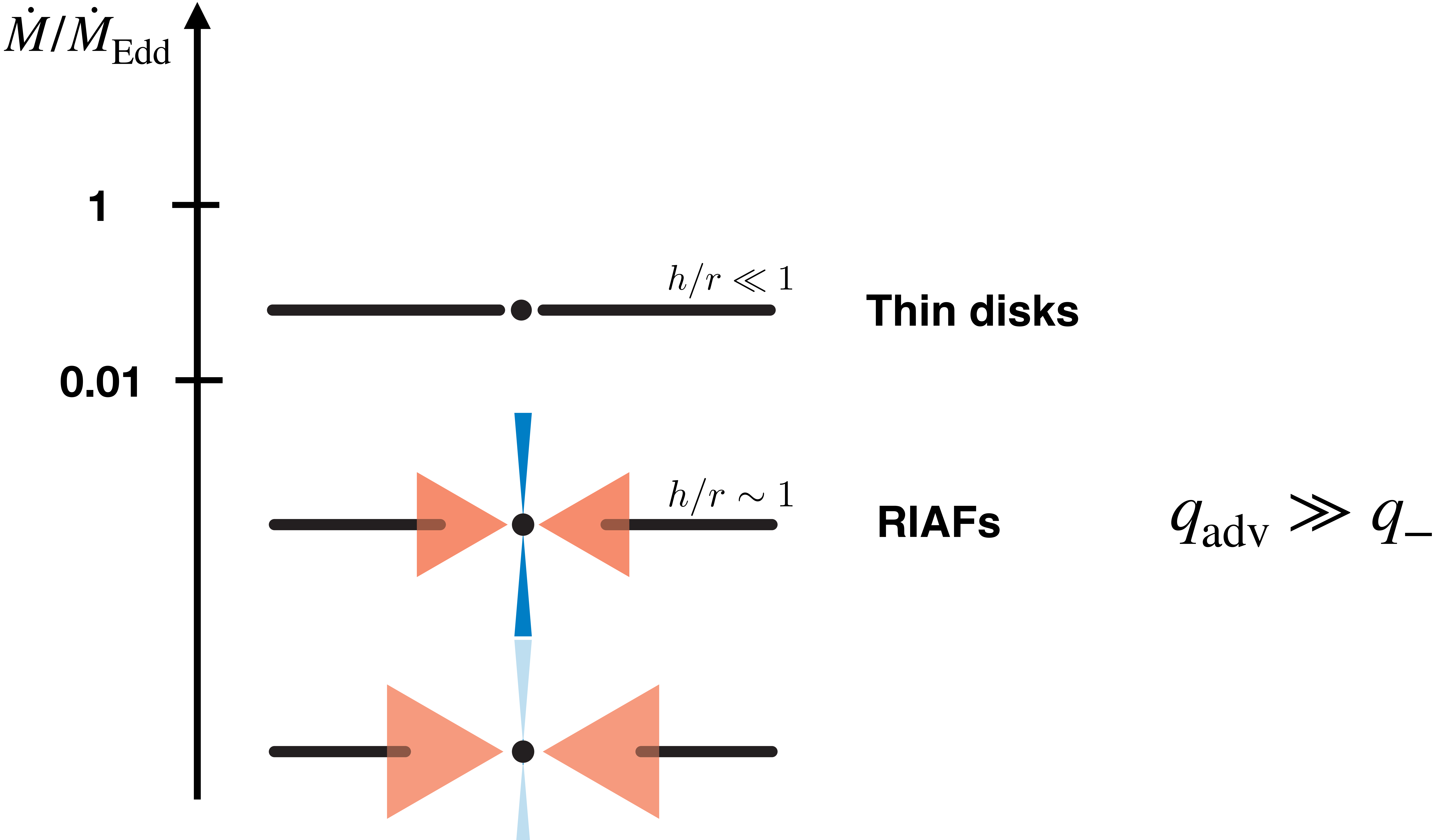
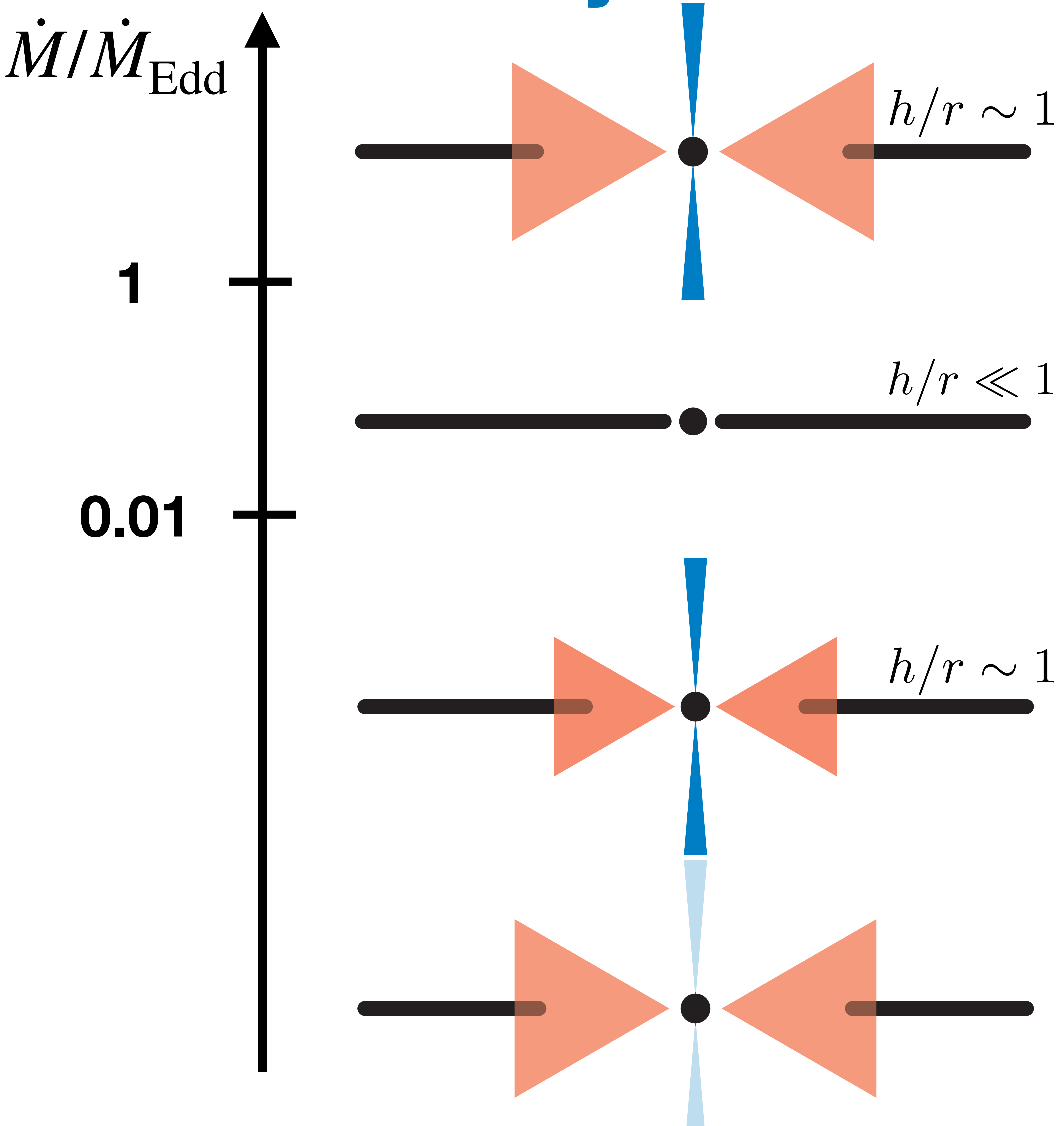


Unified theory of black hole accretion flows



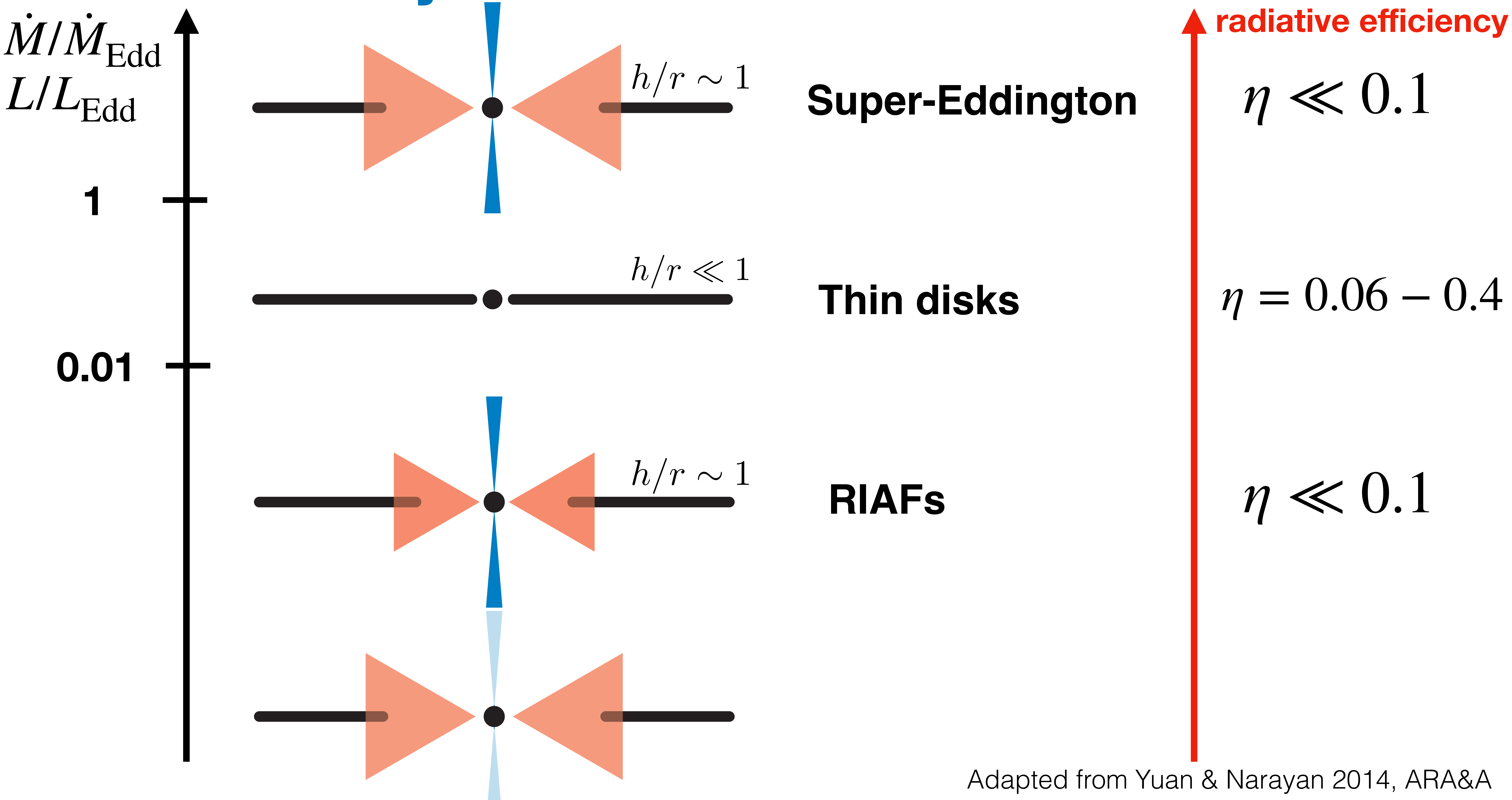
Super-Eddington $t_{\rm diffusion}^{\rm photon} \gg t_{\rm acc}$

Thin disks

RIAFs

Adapted from Yuan & Narayan 2014, ARA&A

Unified theory of black hole accretion flows



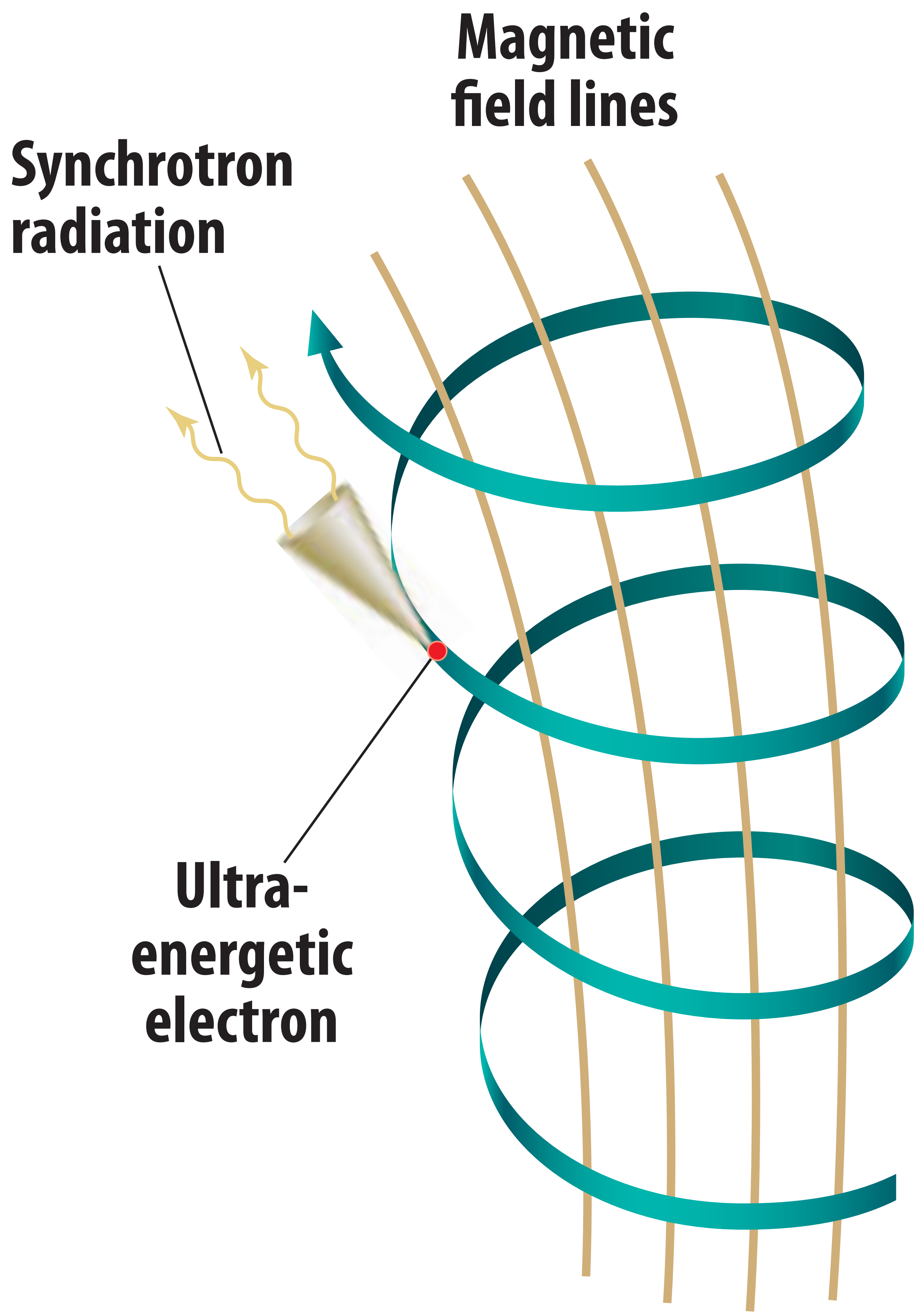
Adapted from Yuan & Narayan 2014, ARA&A

Electromagnetic radiation from accretion disks

what wavelengths?

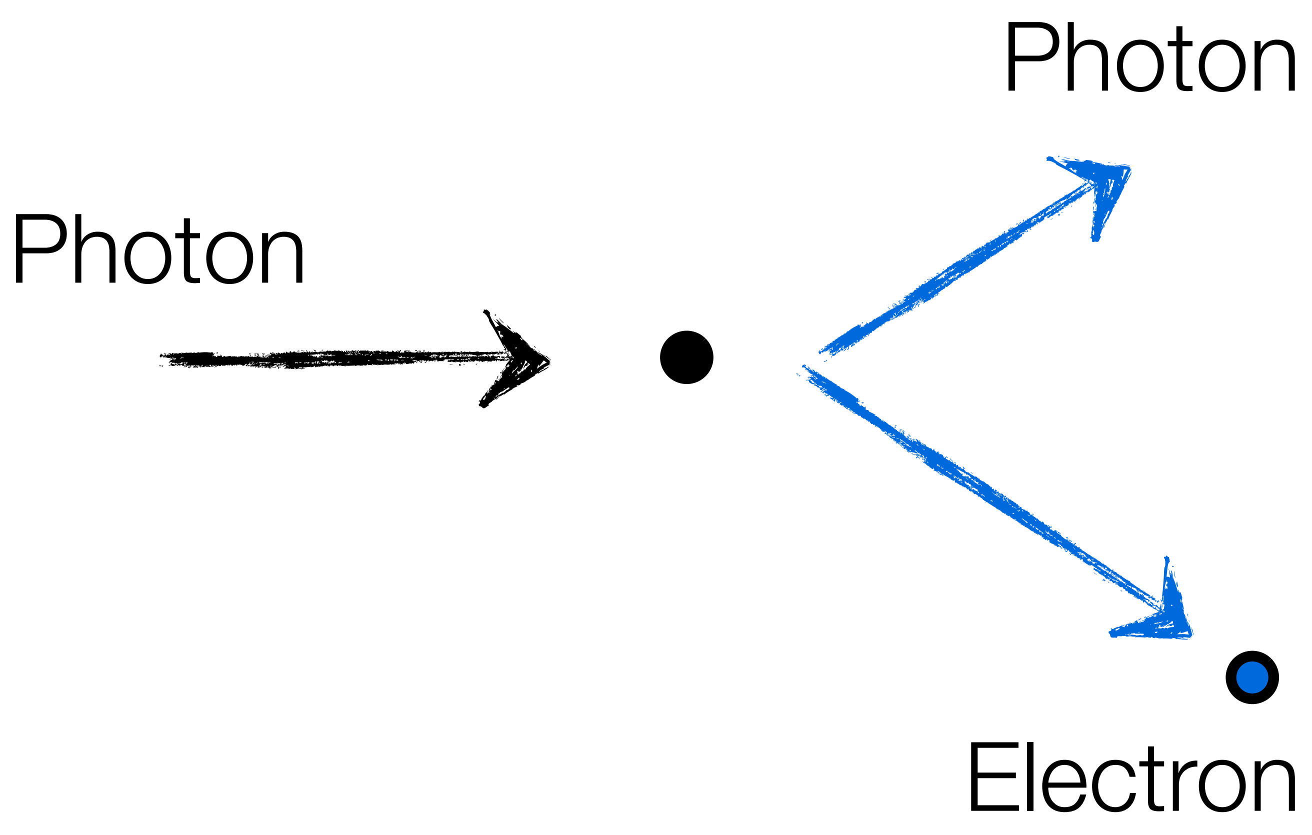
Important processes involving EM interactions in accretion disks

Synchrotron

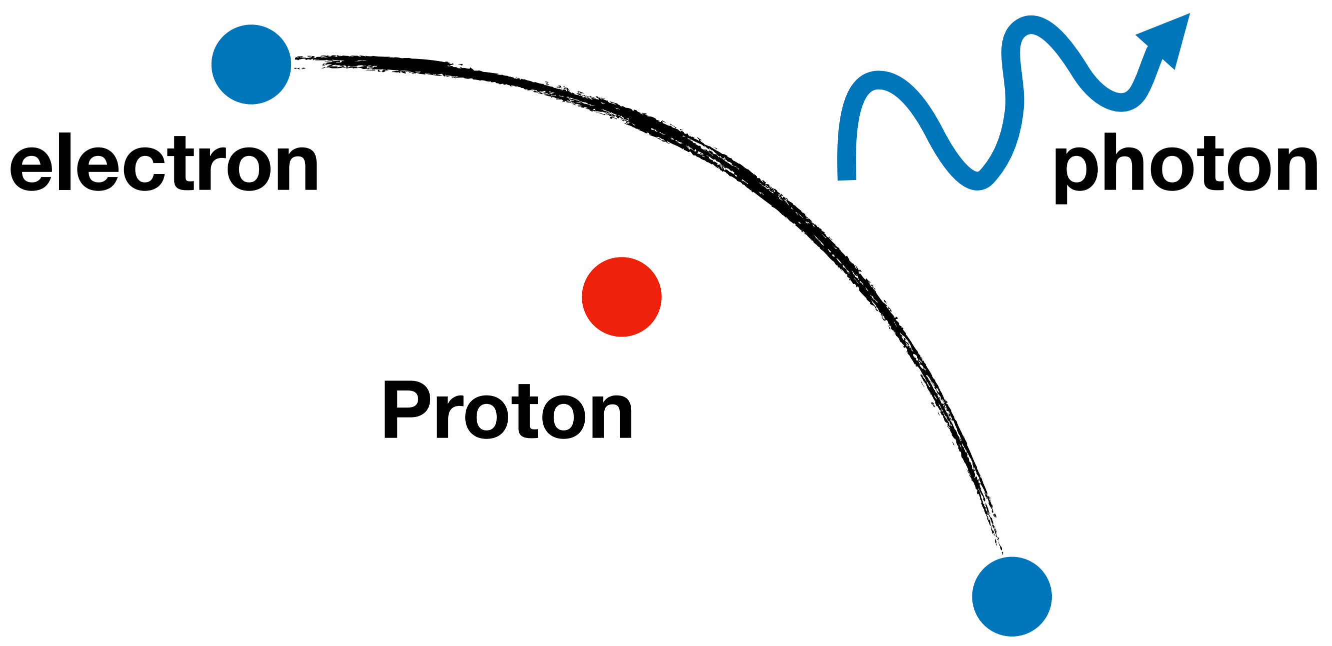


Begelman & Rees

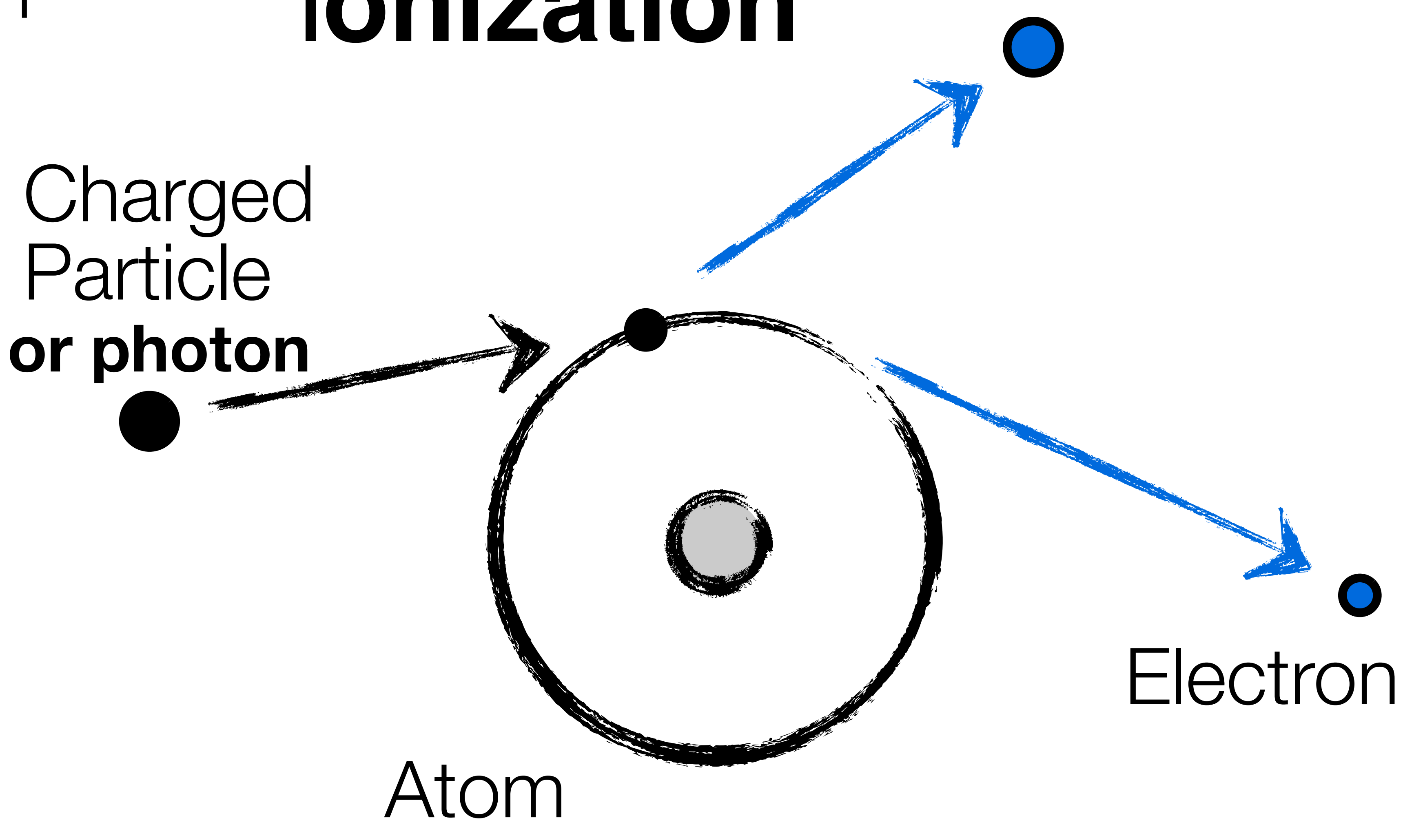
(inverse) Compton scattering



Bremsstrahlung

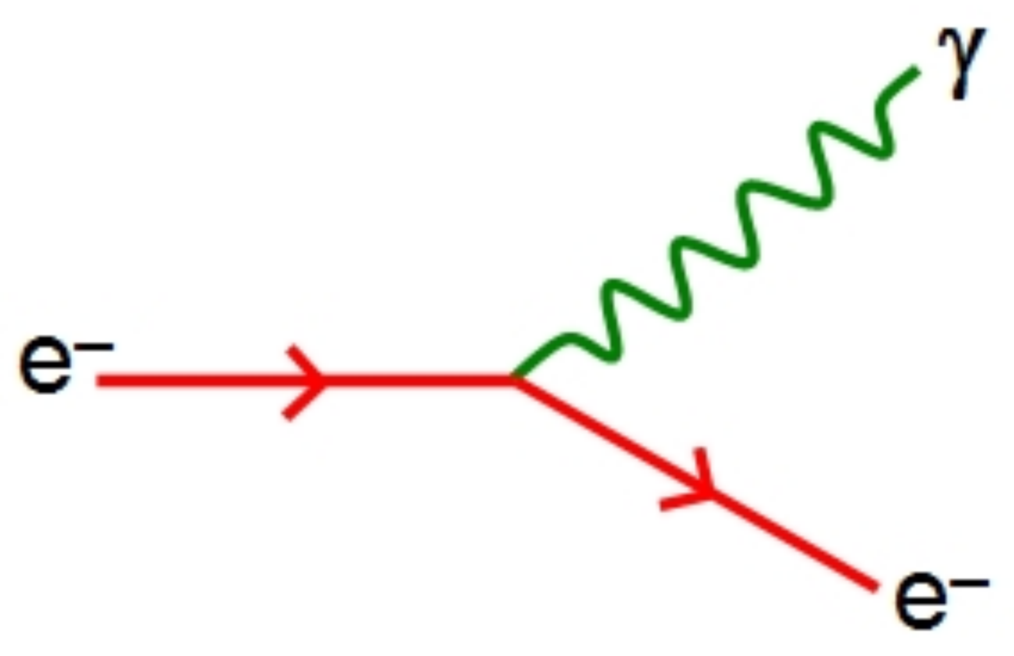


Ionization

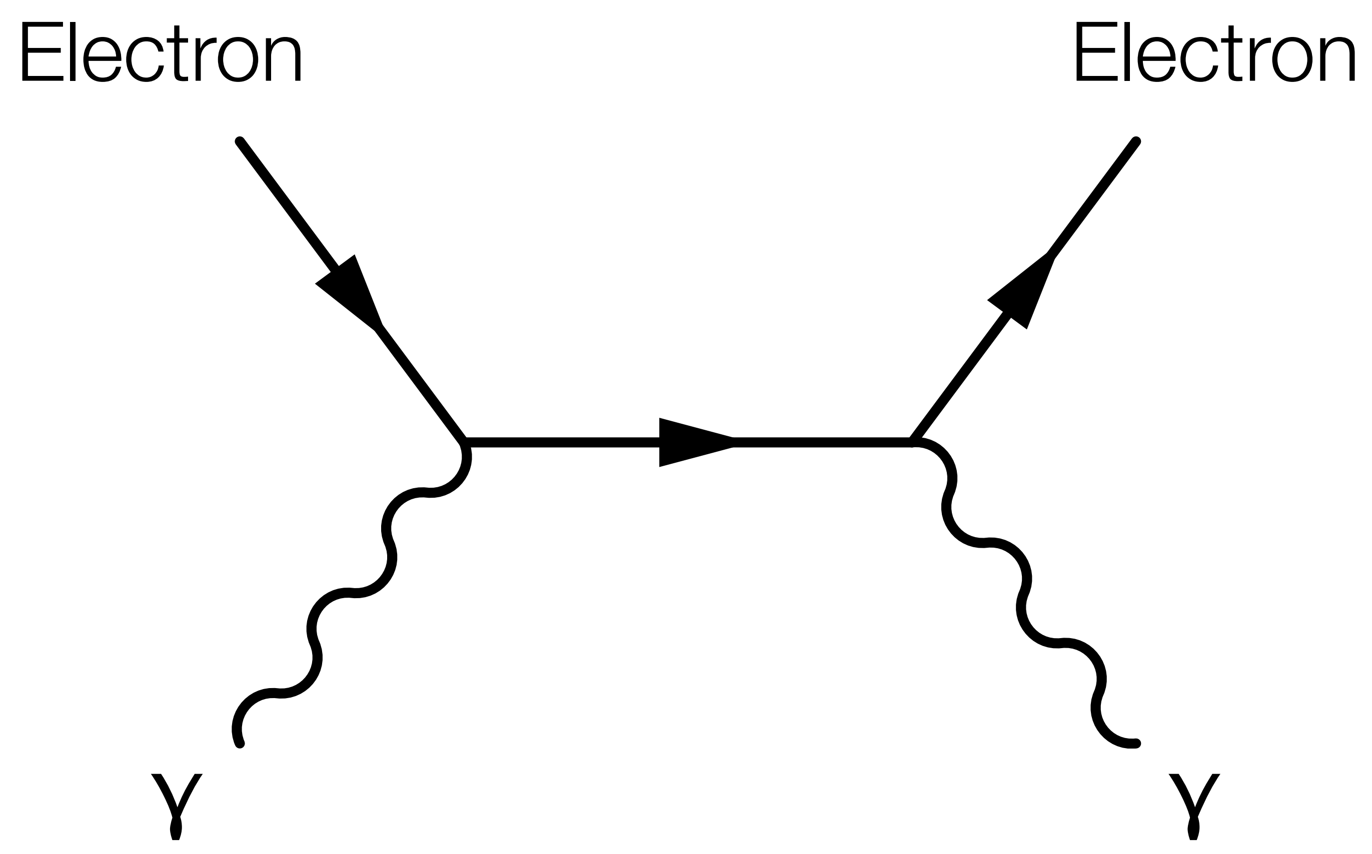


Feynman diagrams for EM interactions in accretion disks

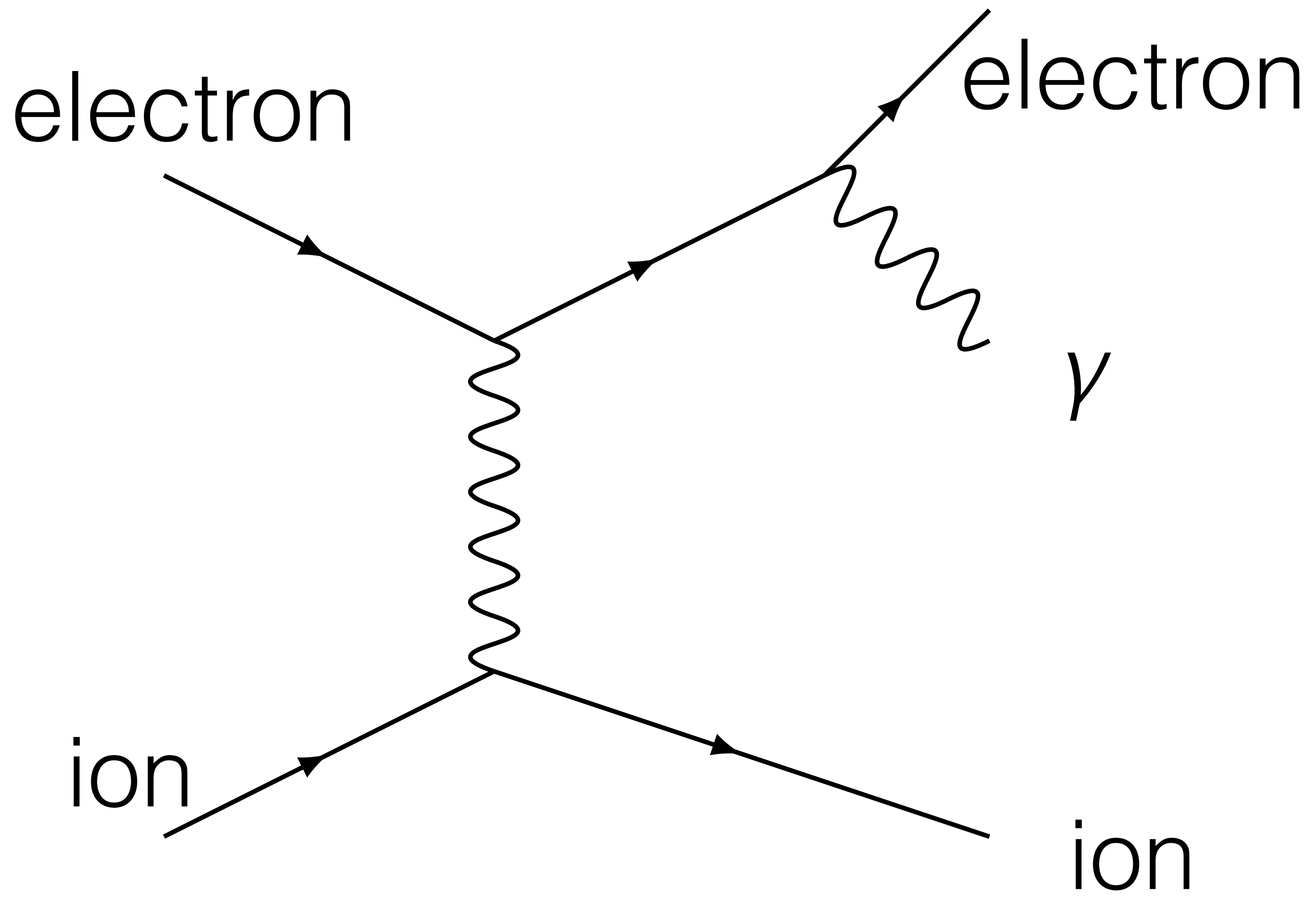
Synchrotron



(inverse) Compton scattering

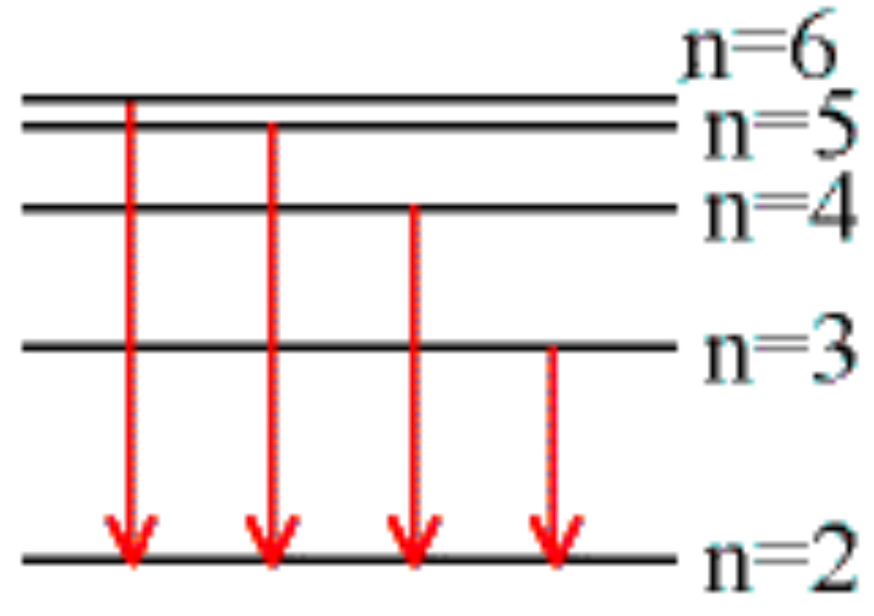


Bremsstrahlung

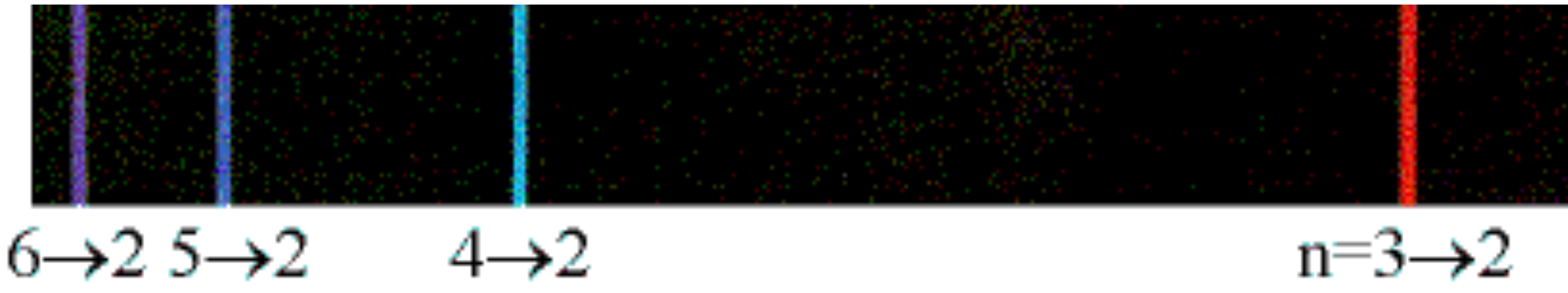


Line emission is also important

Hydrogen transitions



Line spectrum

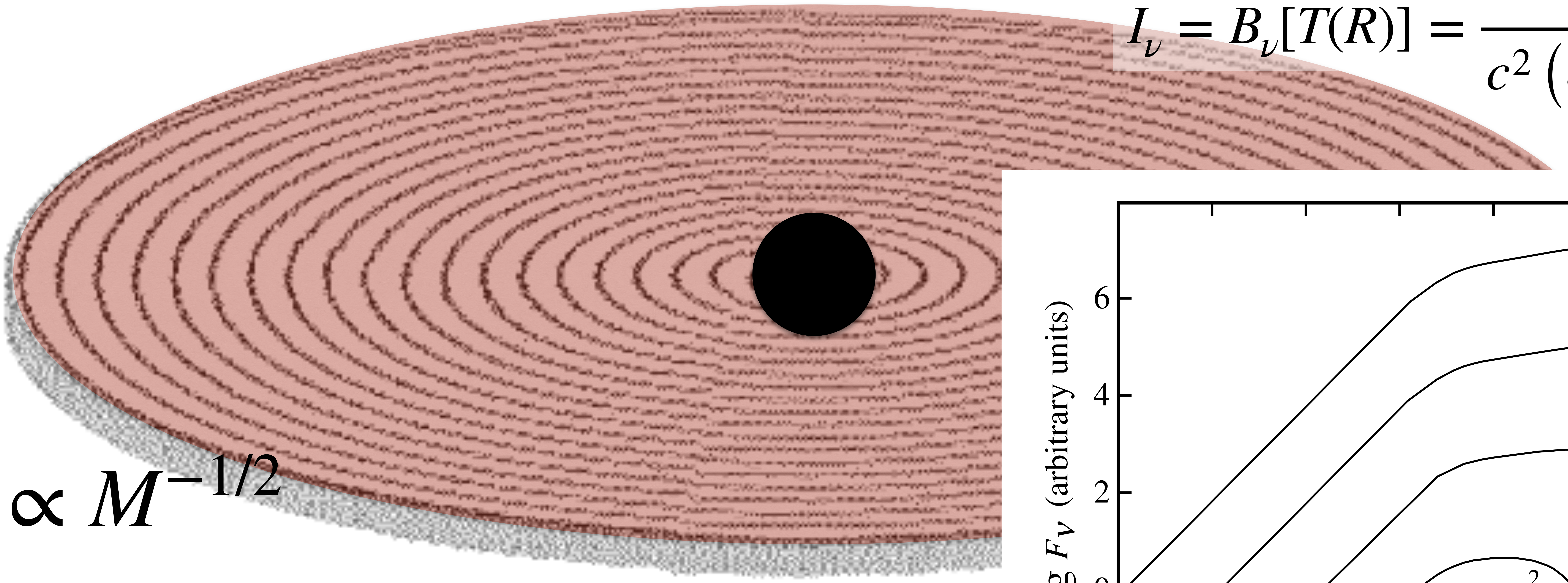


Thin disks

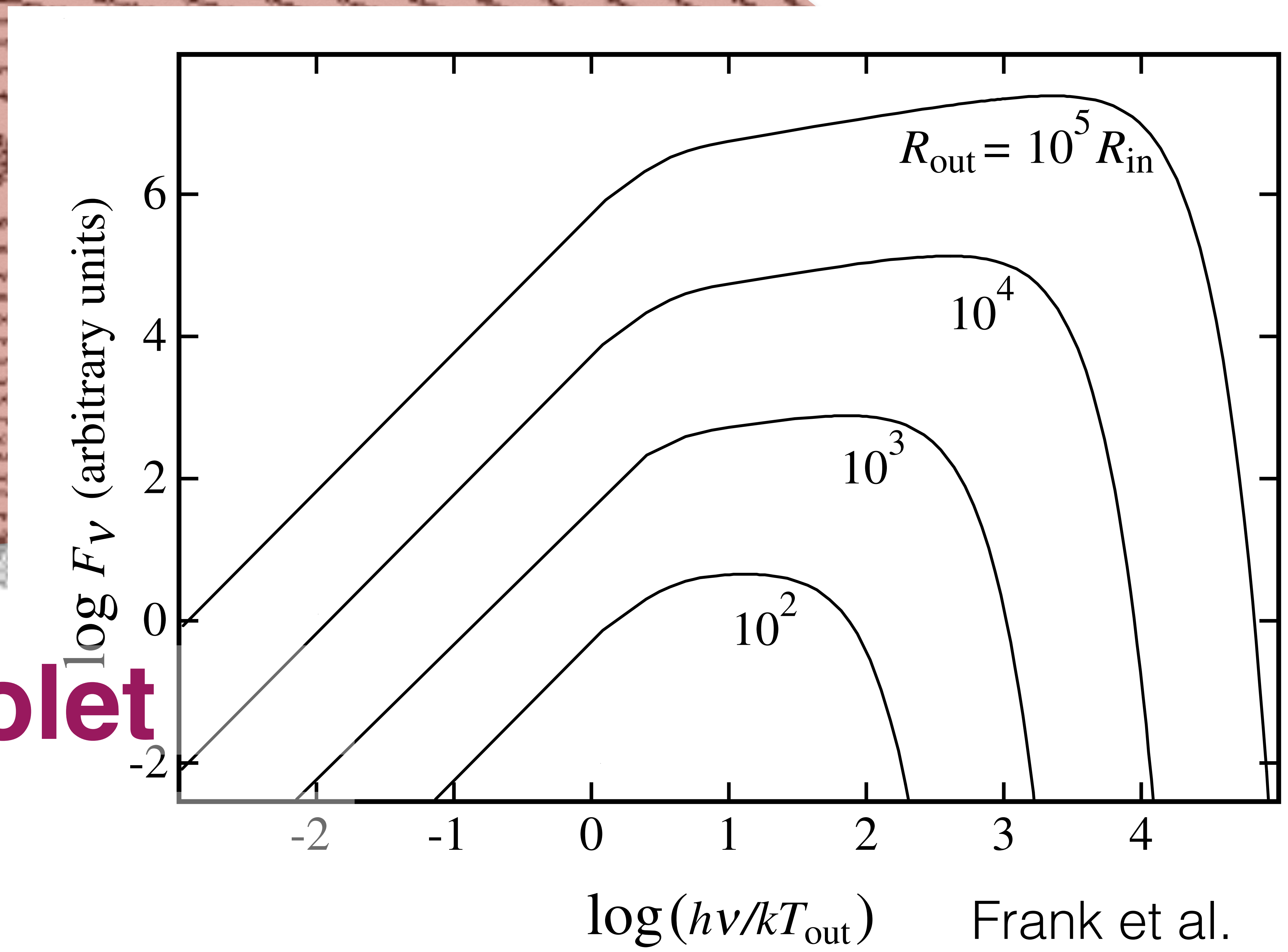
- ◆Very high densities
- ◆Gas is opaque
- ◆Photons thermalize locally with gas

→ Blackbody radiation

$$I_\nu = B_\nu[T(R)] = \frac{2h\nu^3}{c^2\left(e^{h\nu/kT(R)} - 1\right)}$$



$$T_{\max} \propto M^{-1/2}$$

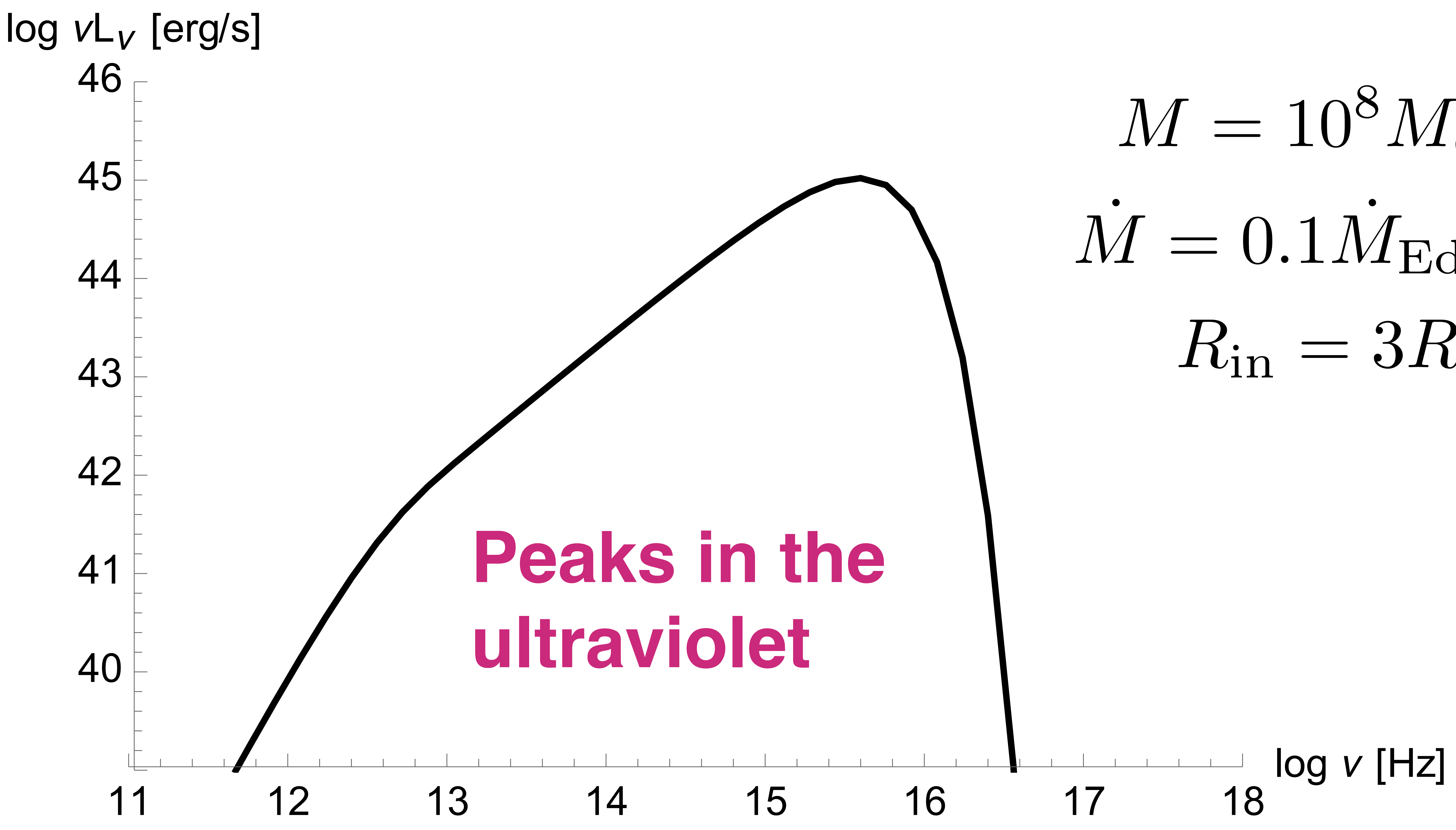


Frank et al.

$T \sim 10^5$ K, M=10^8 $M_{\rm Sun}$ peak ultraviolet

$T \sim 10^8$ K, M=10 $M_{\rm Sun}$ peak X-rays

EM spectrum of a thin disk



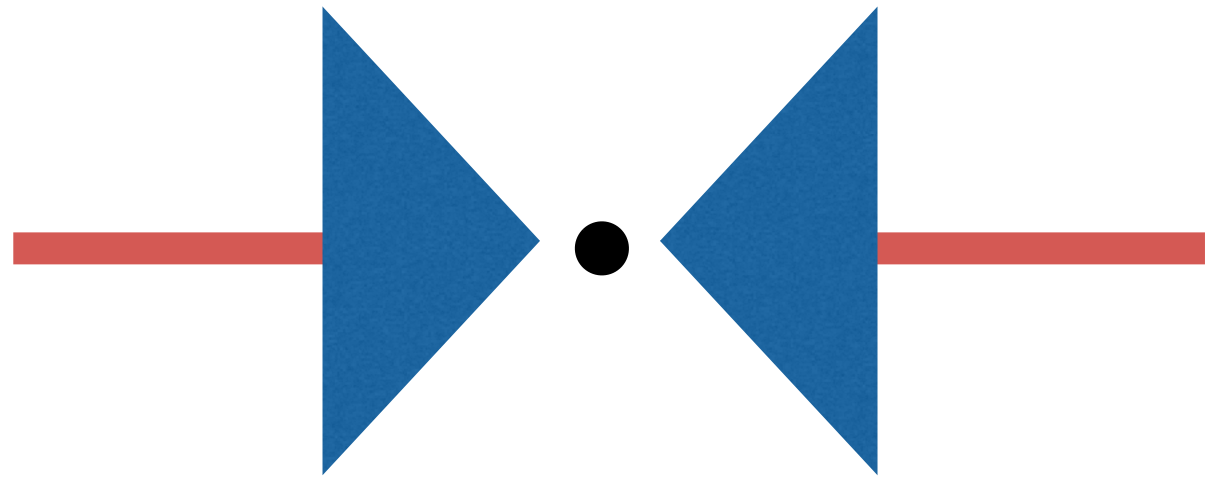
$$M = 10^8 M_\odot$$
$$\dot{M} = 0.1 \dot{M}_{\rm Edd}$$
$$R_{\rm in} = 3R_S$$

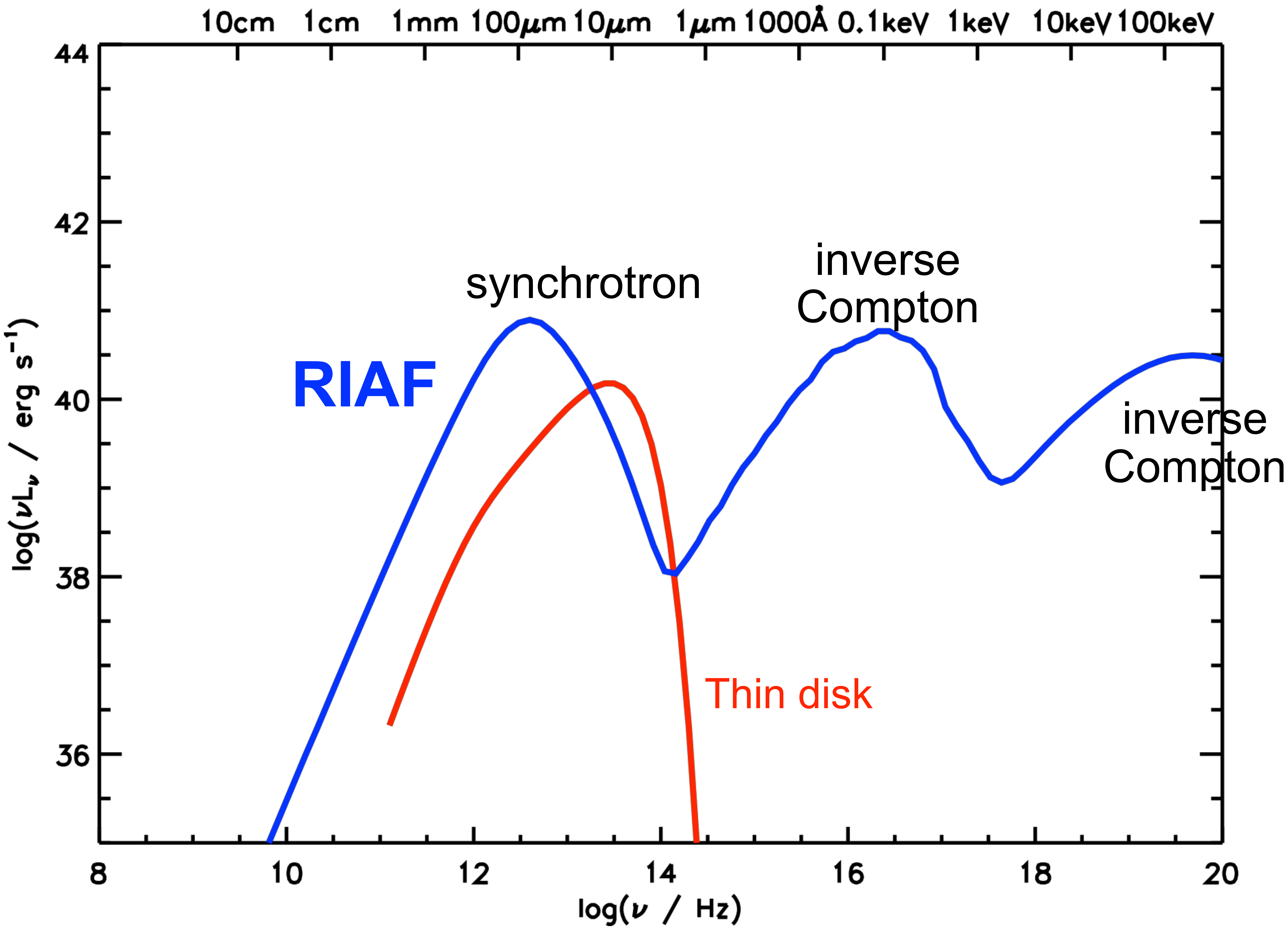
RIAFs

Optically thin (low densities)

Very hot
$T_i \sim 10^{12}\ (R_S/R)$ K
$T_e \sim 10^9 - 10^{11}$ K

EM spectrum of RIAF





$$L_{\rm IC} \propto \gamma^2 U_{\rm ph}$$

electron Lorentz factor

seed photons energy density

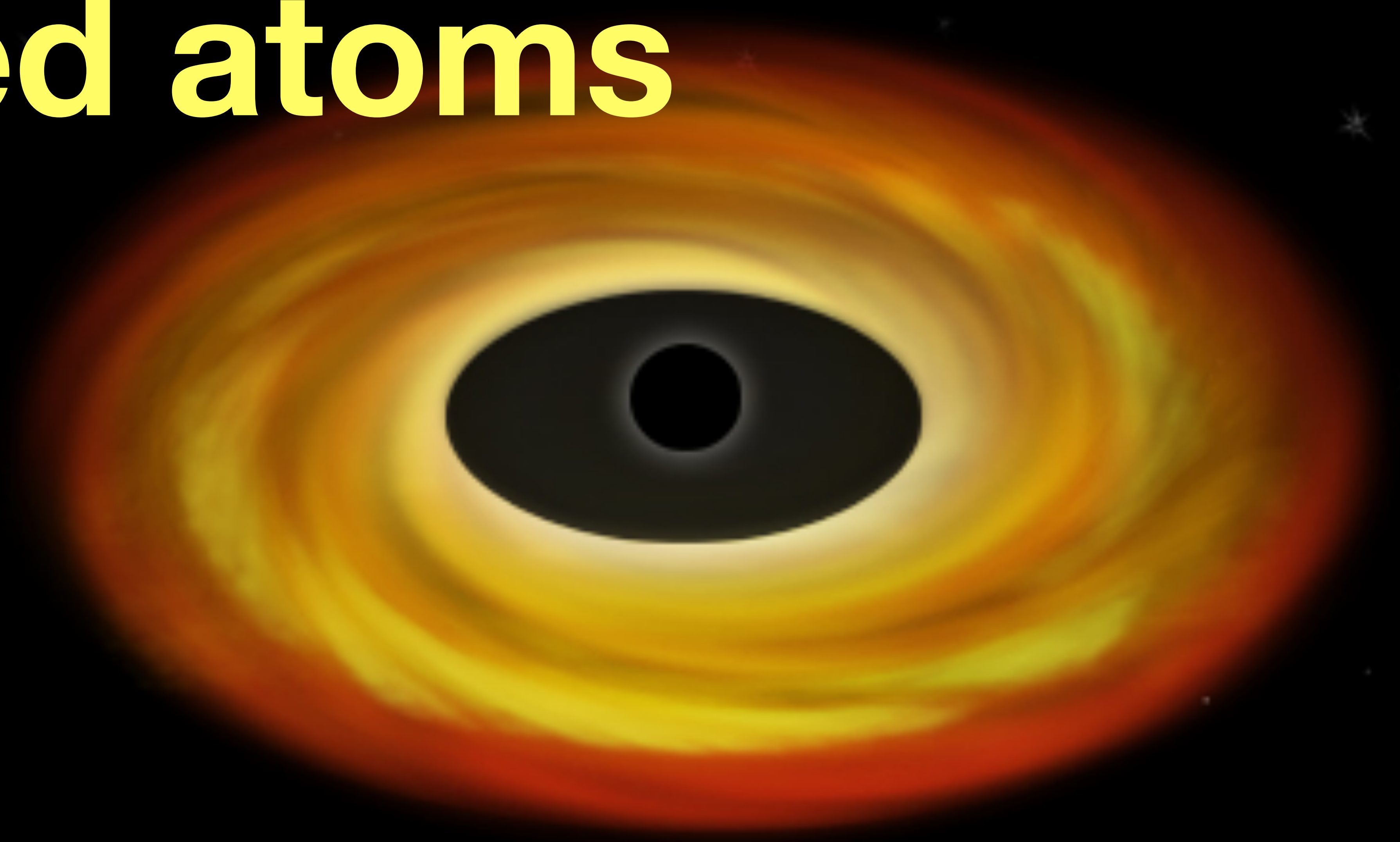
$$M = 10^8\, M_\odot$$

$$\dot{M}_{\rm out} = 0.001 \dot{M}_{\rm Edd} \qquad s = 0.3$$

$$R_{\rm tr} = 500 R_S \qquad \delta = 0.3$$

Model parameters

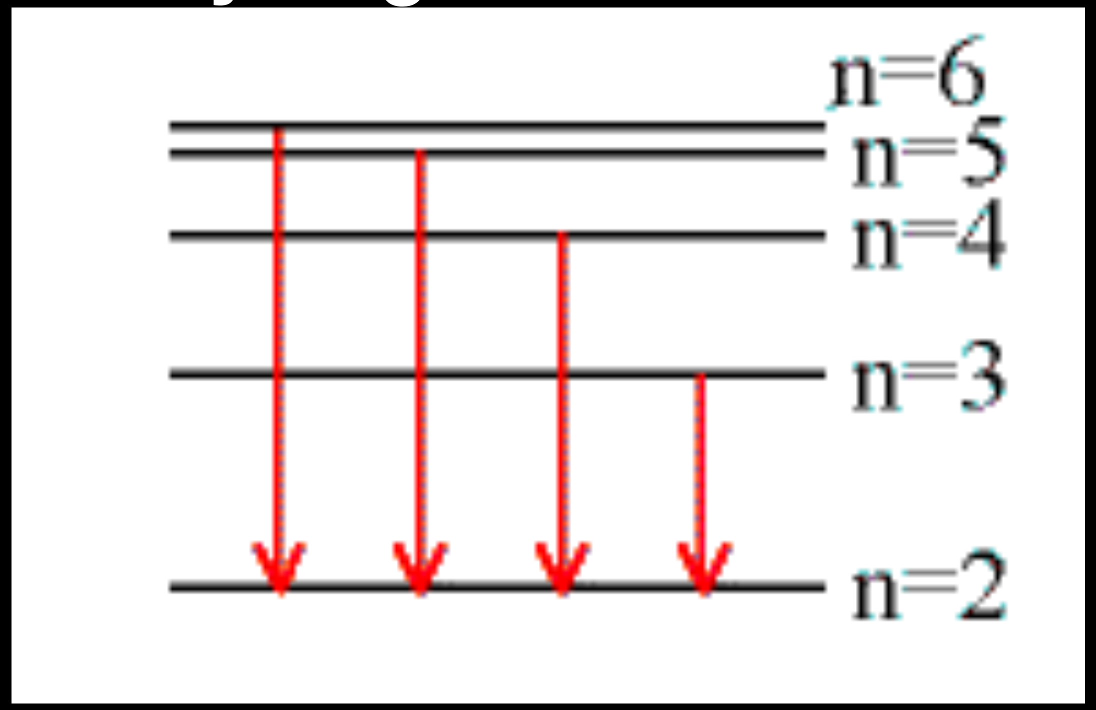
Disks can produce emission lines due to excited atoms



Disk has ionized nuclei which recombine with electrons

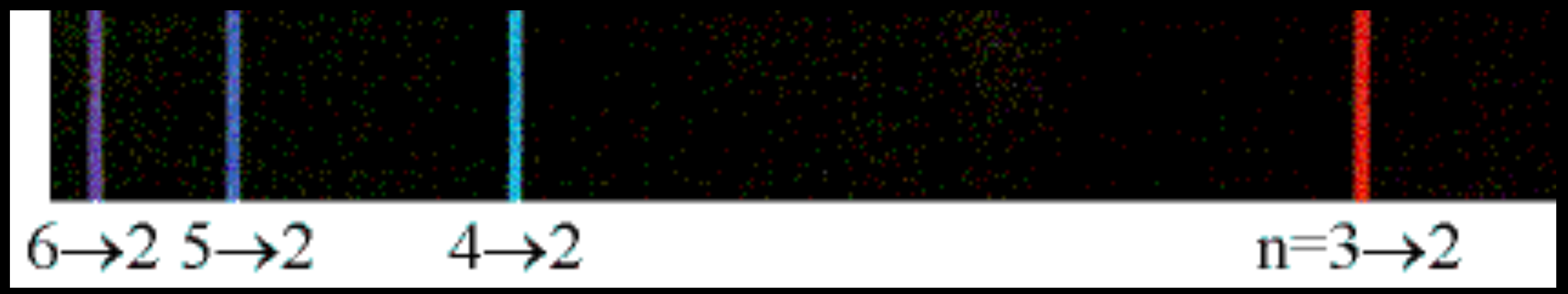
if disk is cool enough: excited electrons will decay to the ground level

Hydrogen transitions

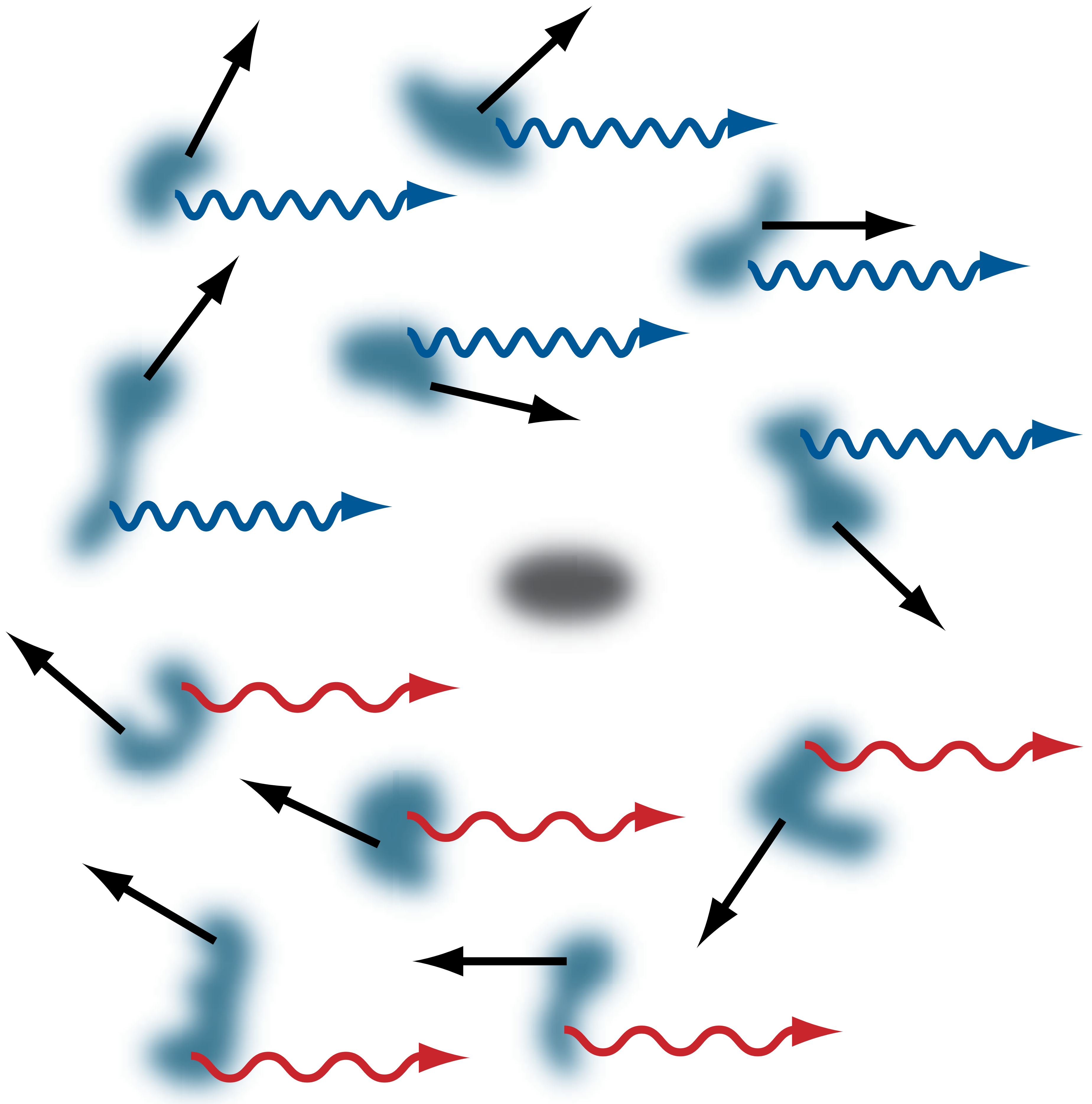


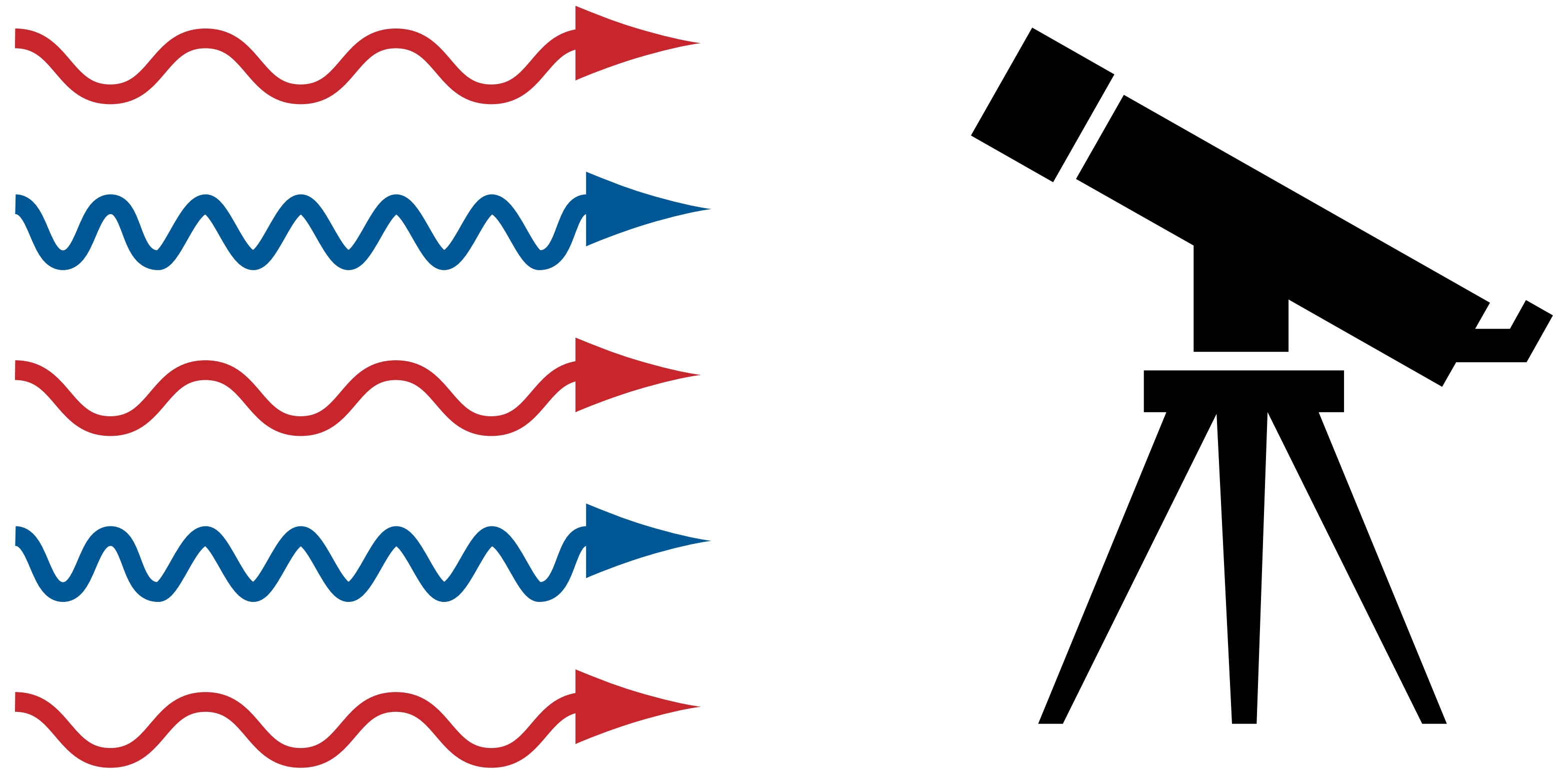
emission lines

info about disk composition, velocity, shape



Moving clouds emit spectral line

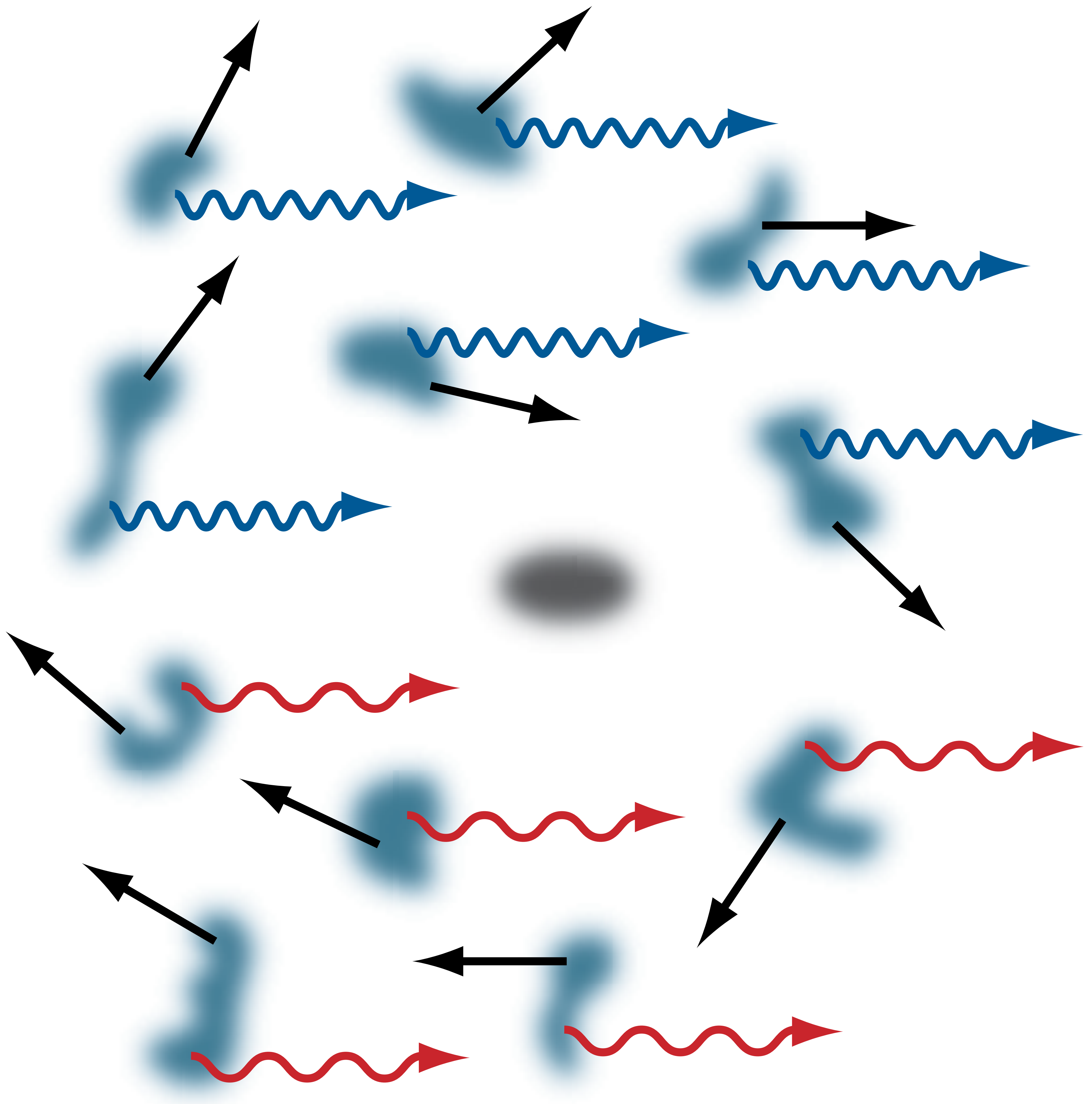




Observer measures line from
entire system

Begelman & Rees

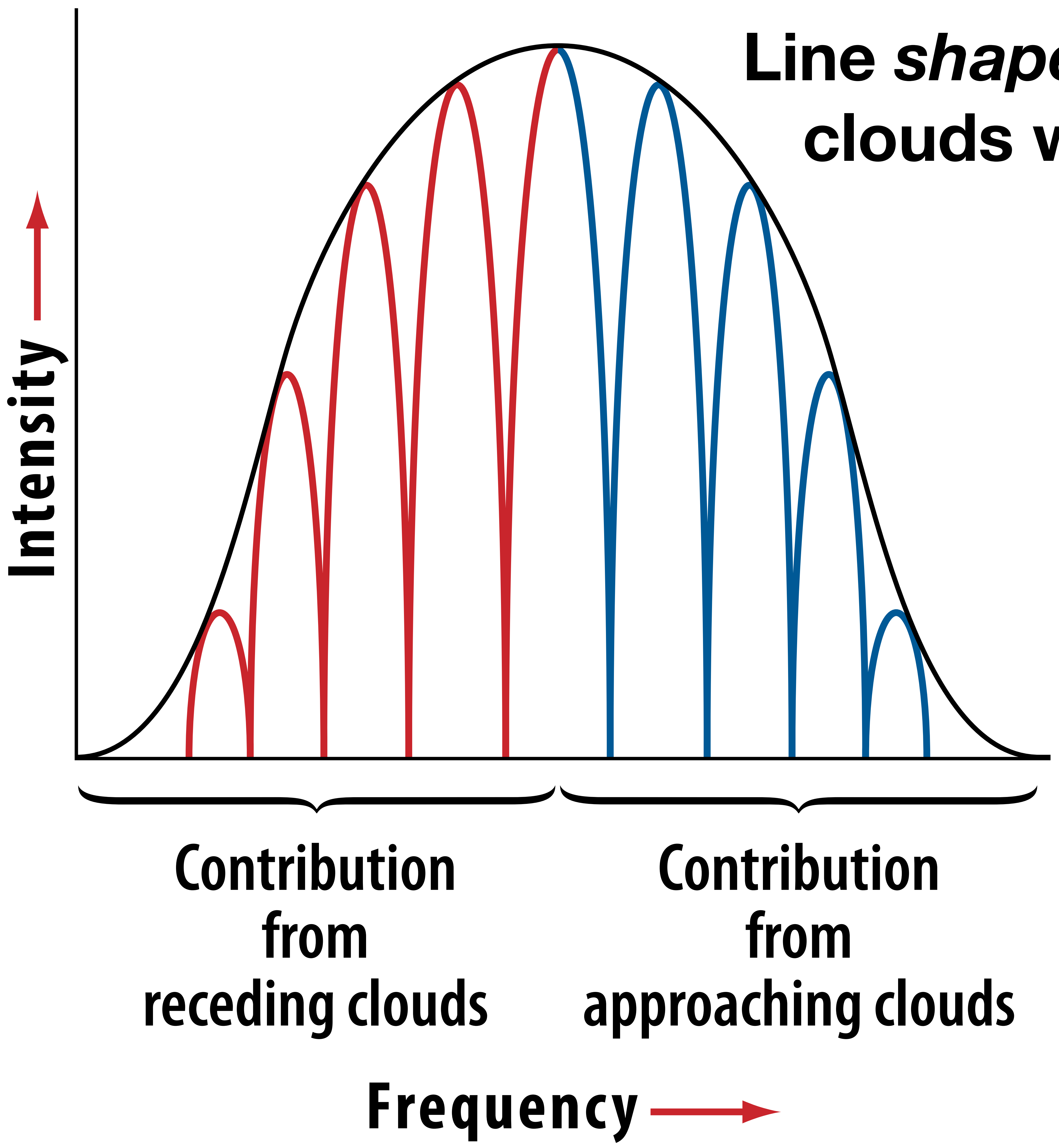
Moving clouds emit spectral line



Integrated spectrum

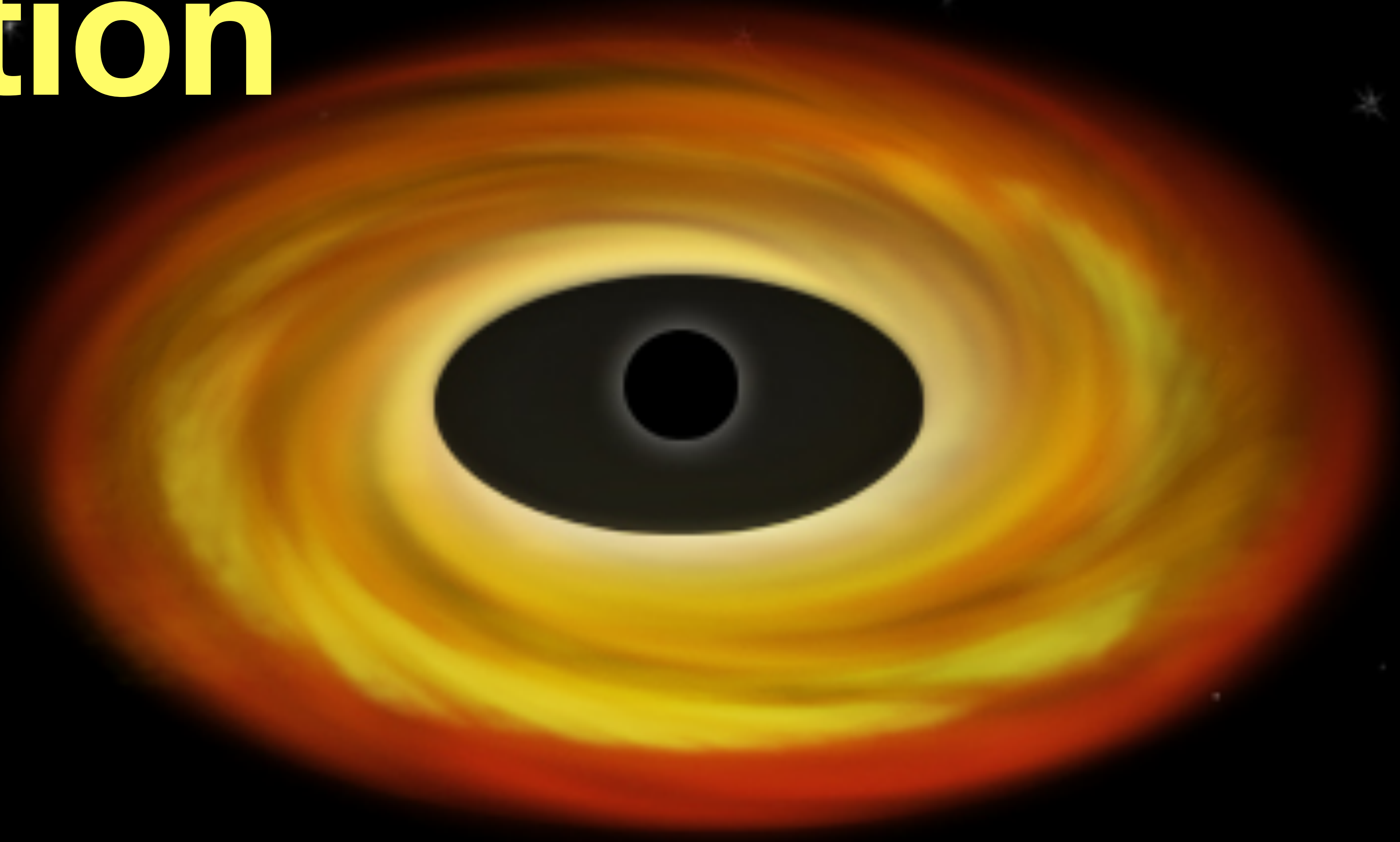
Line *much broader* than individual cloud

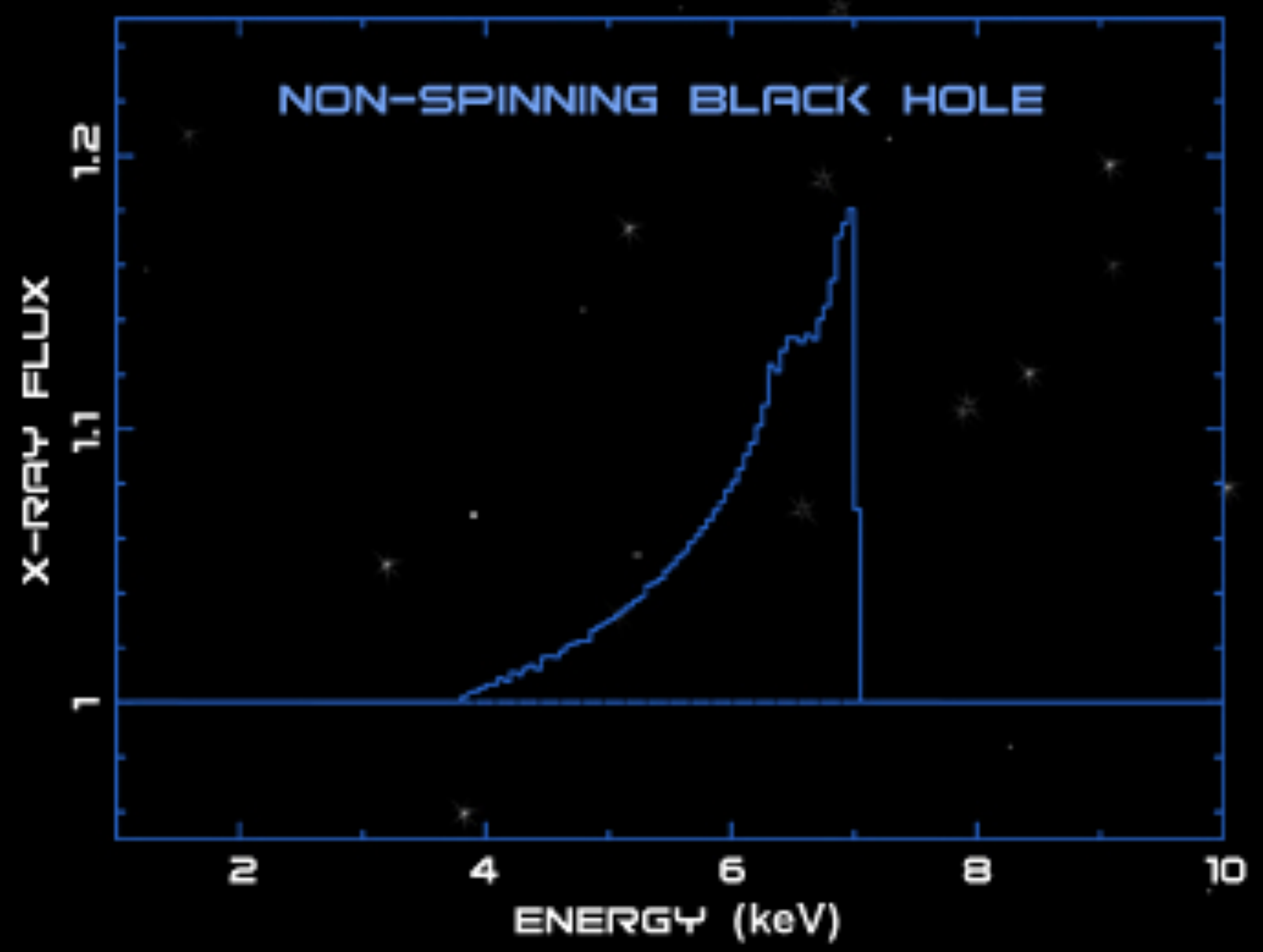
Line *shape*: number of clouds with different velocities



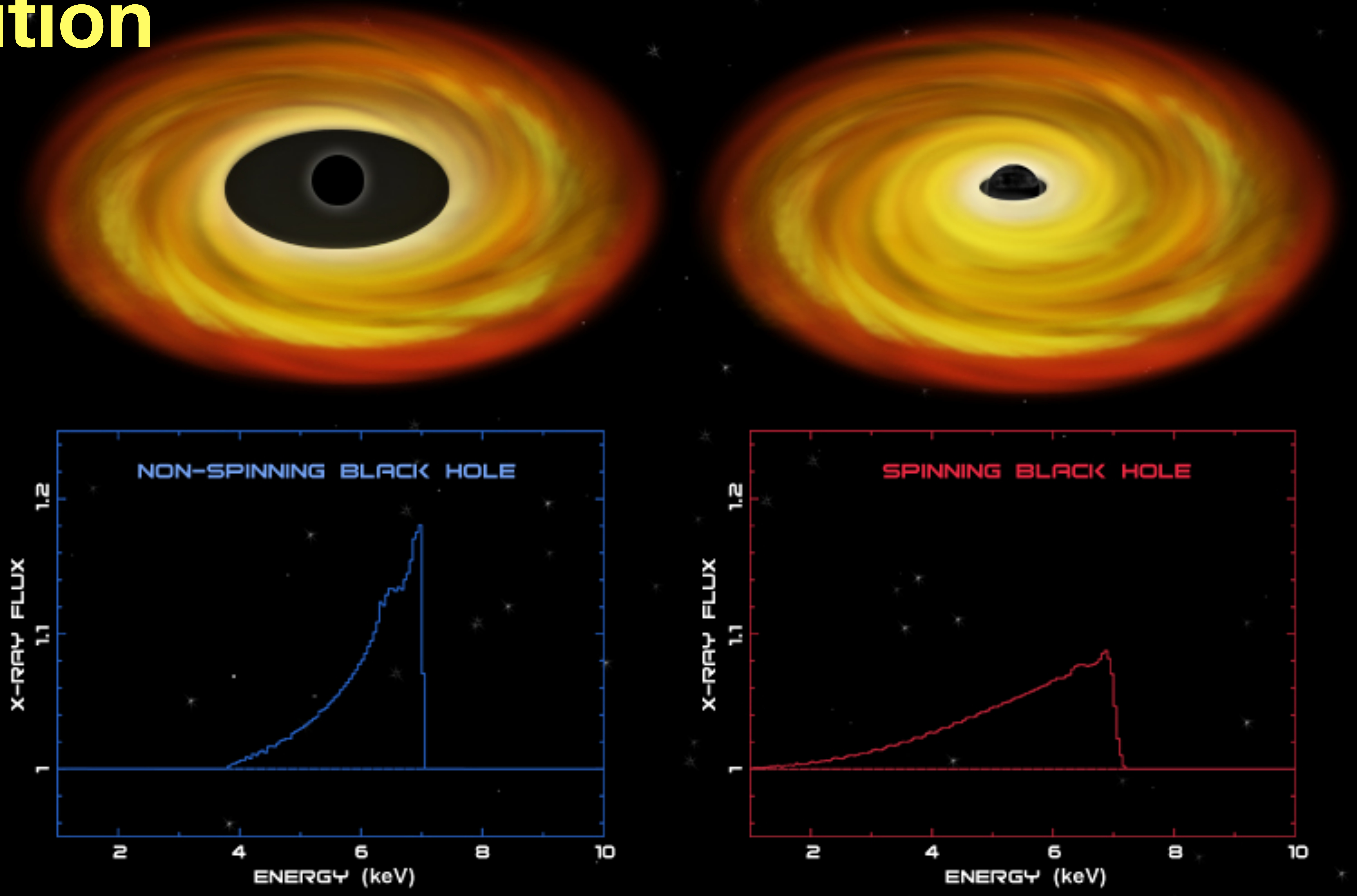
Begelman & Rees

Example: X-ray emission-line due to Fe Kα transition



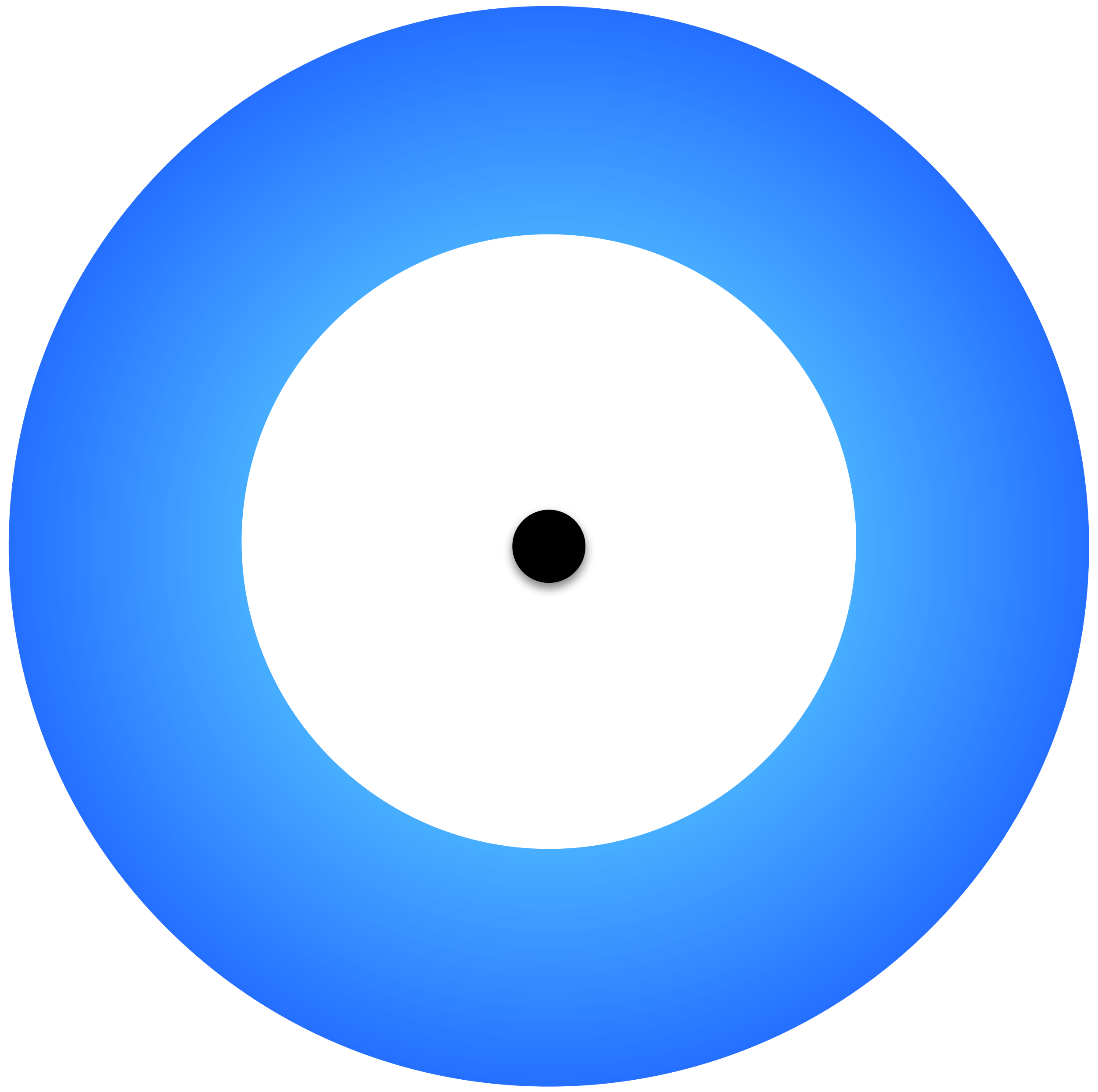


Example: X-ray emission-line due to Fe Kα transition



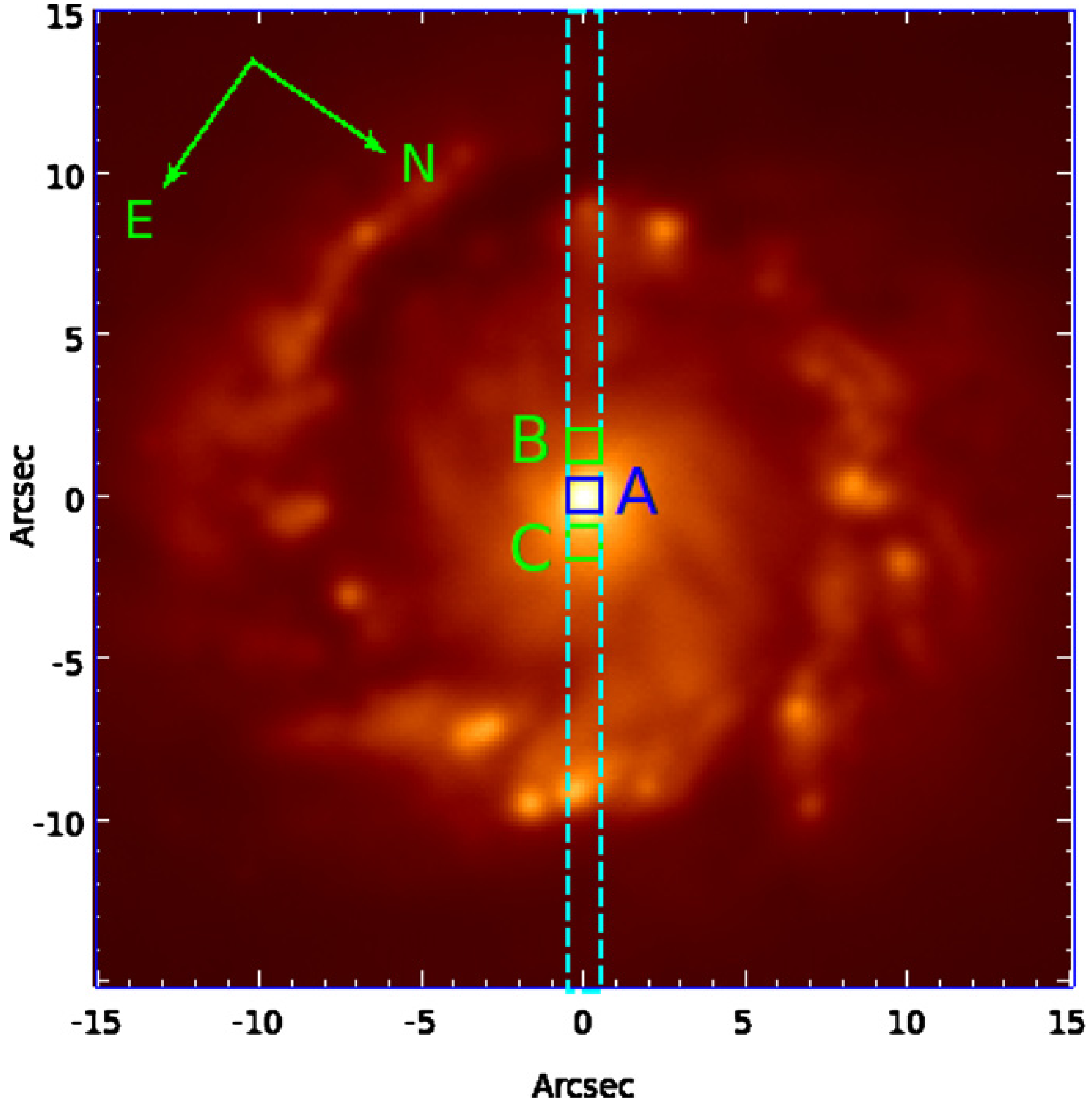
Emission-line signatures of black hole accretion disks in galactic nuclei

face-on view of accretion disk



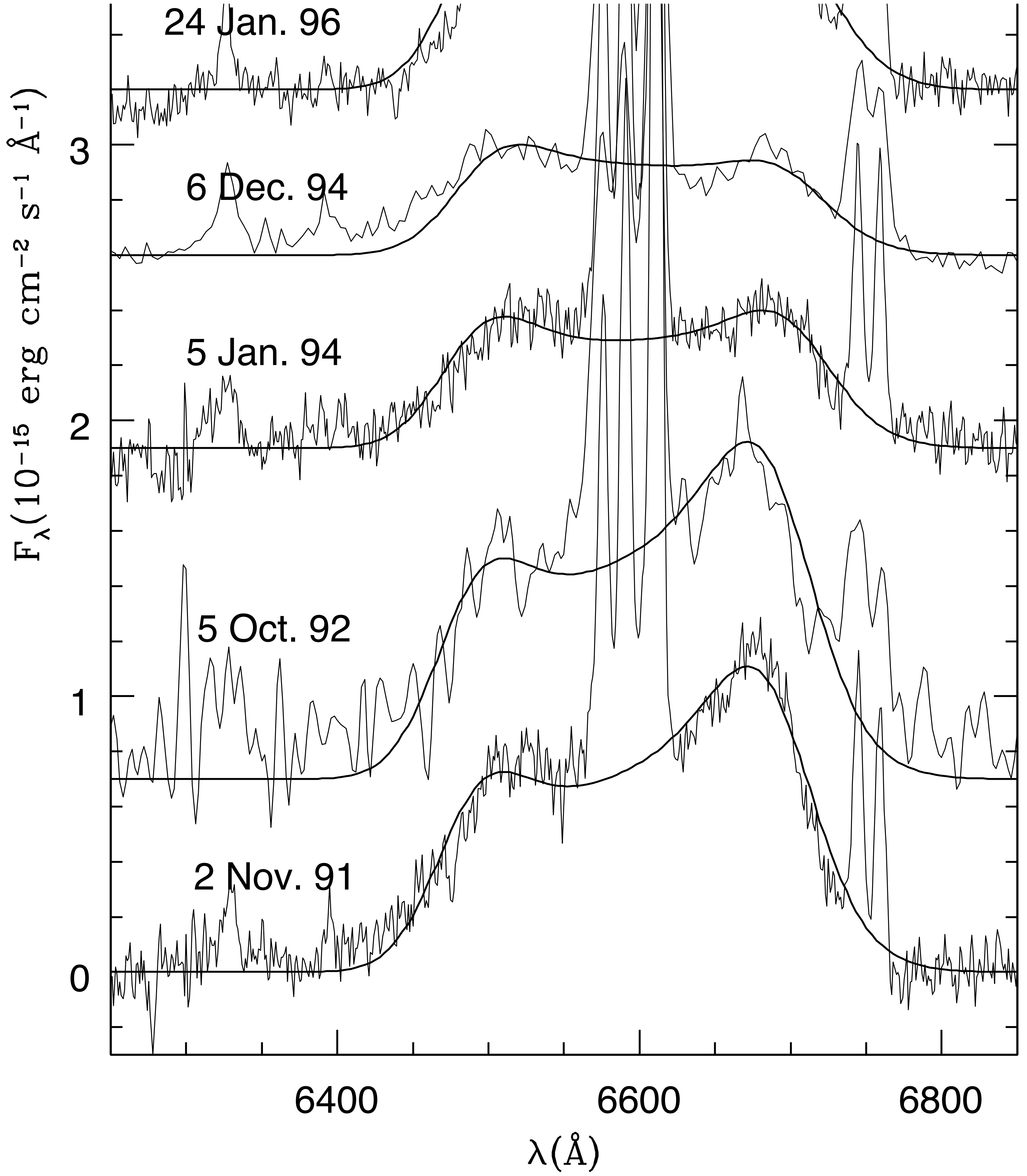
constrain on disk geometry
+ velocities

$$r > 200M$$



FWHM ≈ 10000 km/s

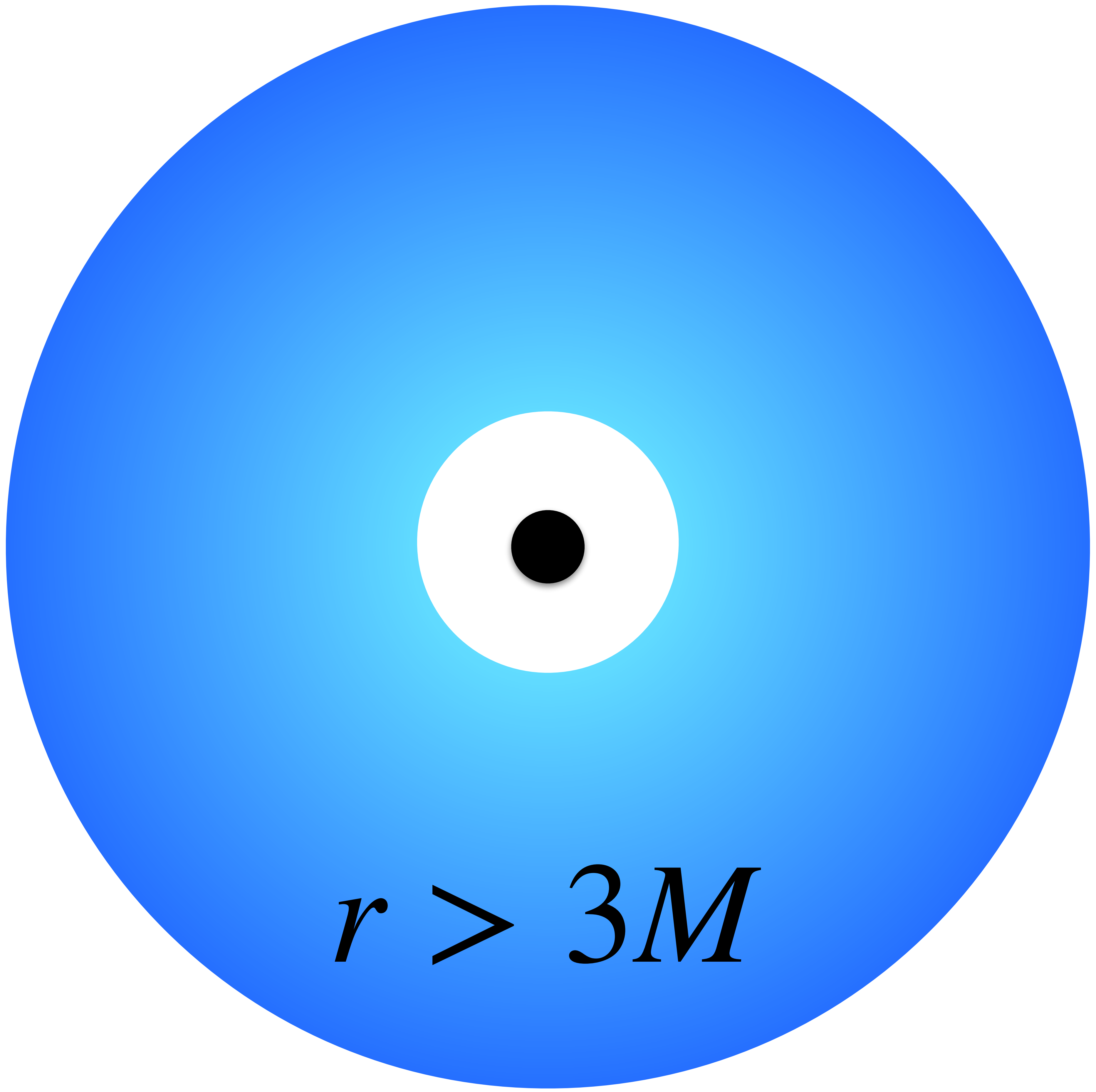
Schimoia, …, Nemmen+2012



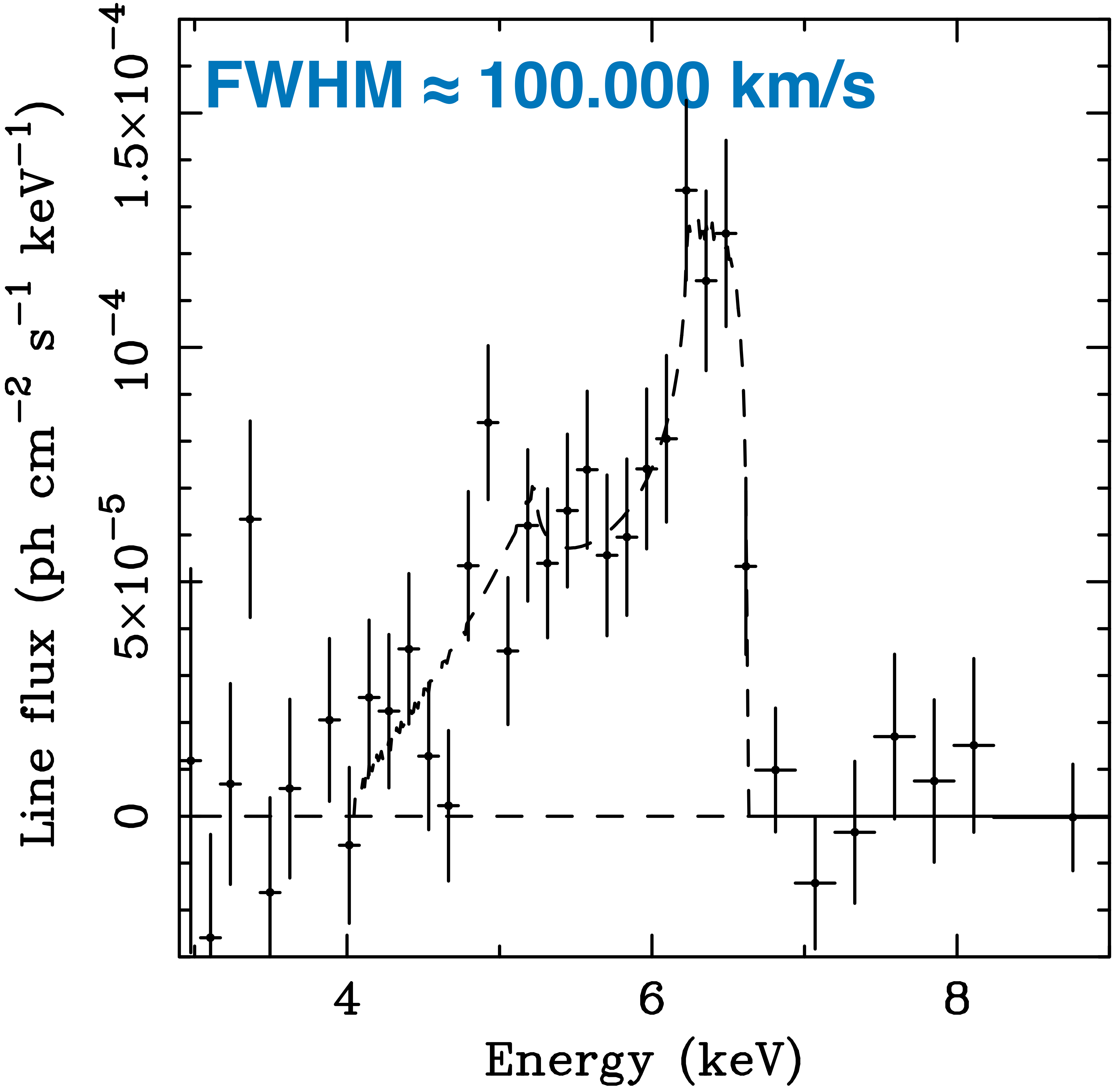
Storchi-Bergmann,
Nemmen+2003

Broad X-ray emission lines in a galactic nucleus

evidence for relativistic material around black hole



$M = 10^7 M_\odot$



Tanaka+1995, Nature

Gravitationally redshifted emission implying an accretion disk and massive black hole in the active galaxy MCG−6−30−15

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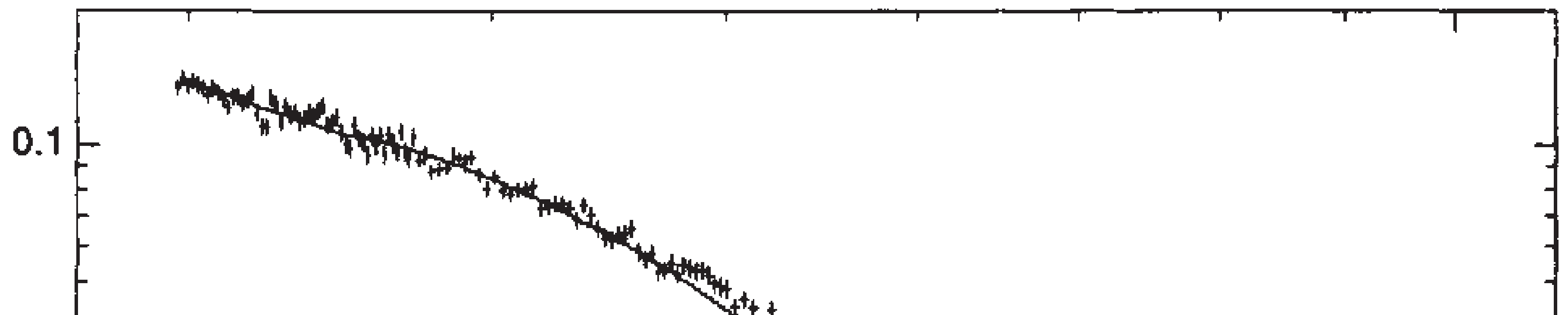
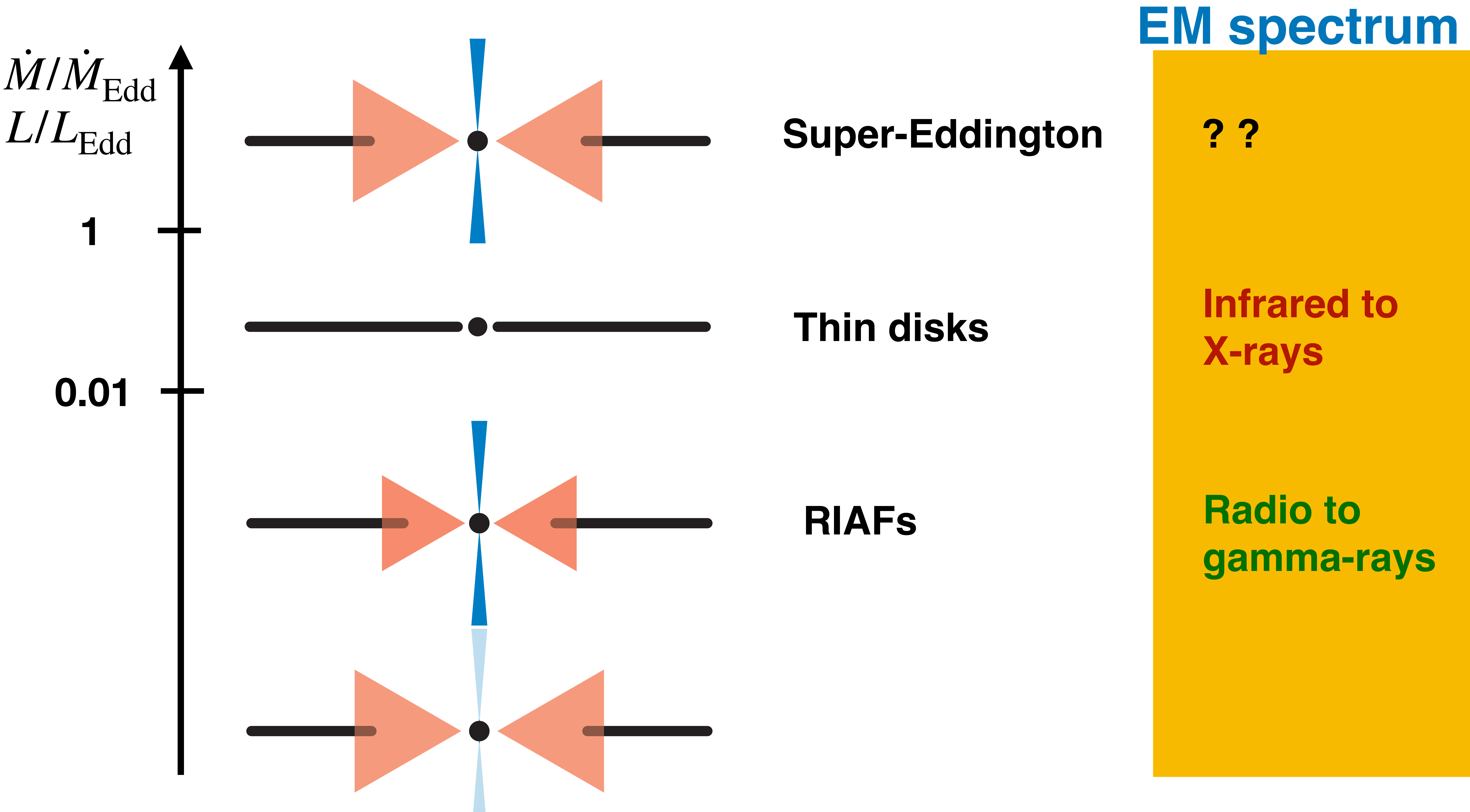
ACTIVE galactic nuclei and quasars are probably powered by the accretion of gas onto a supermassive black hole at the centre of the host galaxy[1], but direct confirmation of the presence of a black hole is hard to obtain. As the gas nears the event horizon, its velocity should approach the speed of light; the resulting relativistic

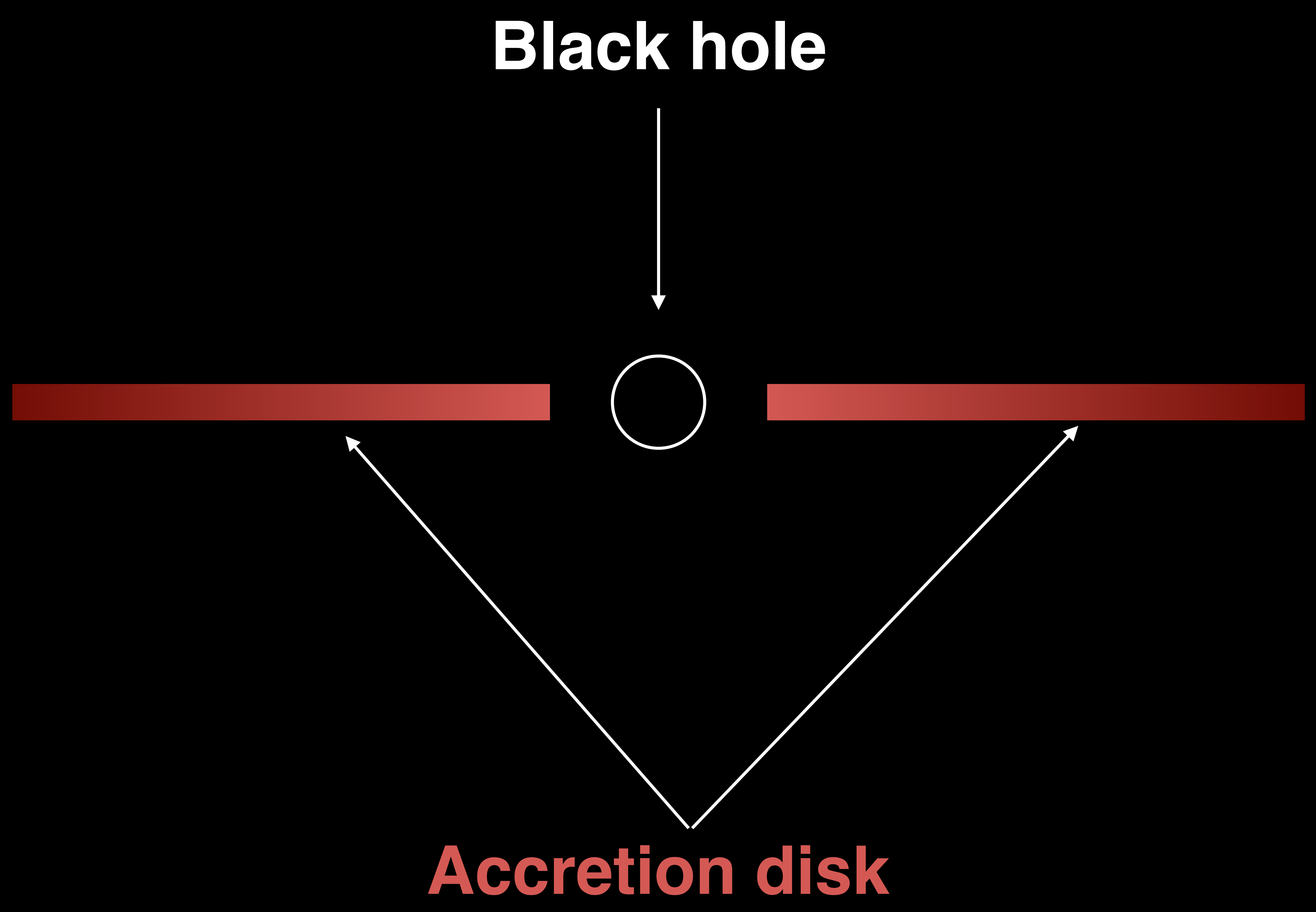
MCG−6−30−15 was observed by ASCA[17] on 23 July 1994 for approximately four days, with both the CCD (charge-coupled device) detectors (SIS) and gas-scintillation proportional counters (GIS) in operation. Here we present only the SIS data, which have the better energy resolution; the GIS and SIS data are entirely consistent. A complicating factor in the analysis of the integrated SIS spectra is the presence of features from highly ionized gas in the line of sight, the so-called warm absorber[18], which is now well established in this source[14,19,20]. Initially, then, we fitted the spectra in the range 0.4–10 keV with a model consisting of a power law emitter and photoionized absorber. This shows that the absorption only affects the spectrum below 2 keV, and therefore in analysing the line data we have restricted the energy range to 2.5–10 keV. Previous data from the Ginga satellite also showed[6] strong evidence for a reflection continuum component accompanying the iron-emission line. We have assumed a face-on slab subtending 2π sr at the X-ray source and calculated the reflection spectrum using the model of Lightman and White[8]. As expected from previous observations[6], the spectrum and residuals for the 3–10 keV continuum fit show a well defined excess in the residuals at ~6 keV (Fig. 1), most probably an iron Kα line, but much broader than the instrument resolution for a




EM spectrum
$\dot{M}/\dot{M}_{\rm Edd}$
$L/L_{\rm Edd}$
1
0.01
Super-Eddington
Thin disks
RIAFs
? ?
Infrared to X-rays
Radio to gamma-rays

The final frontier: Direct imaging of the accretion disk


Thorne, Warner, Paramount

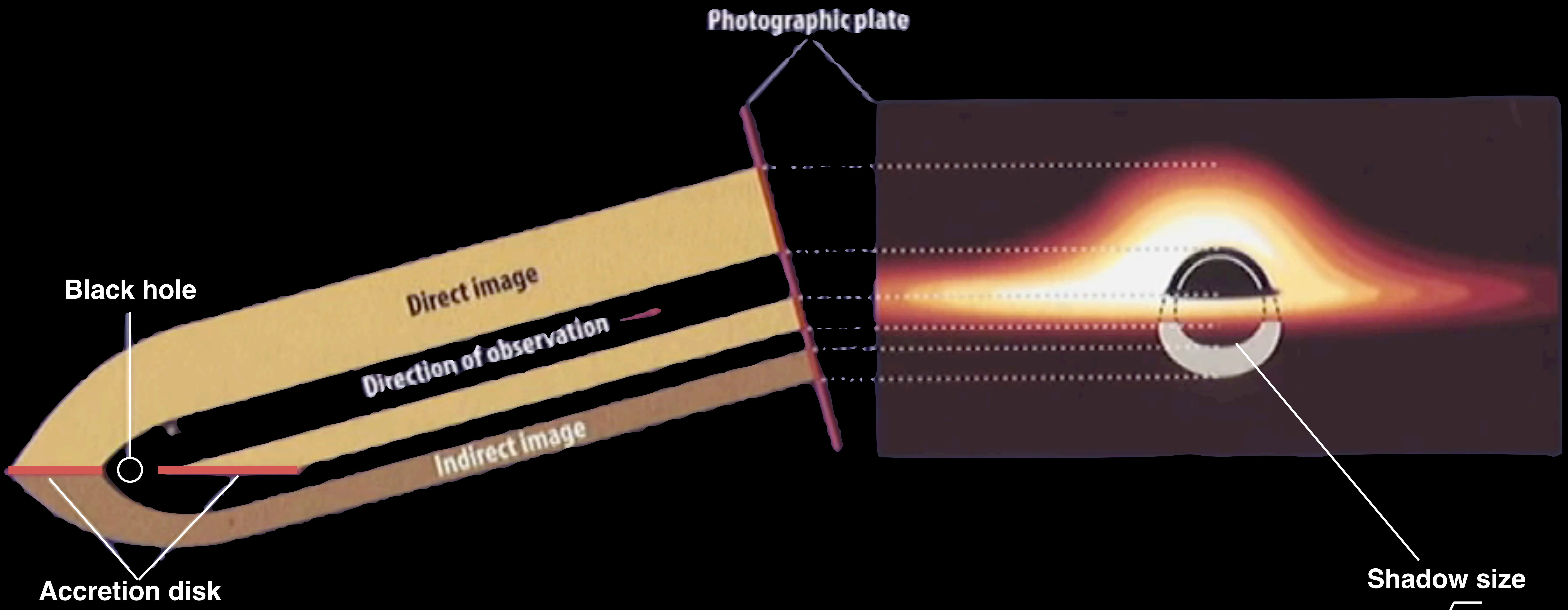


R. Nemmen

Bardeen 1973; Luminet 1979

Black hole casts apparent shadow on light from surrounding accretion flow

Weakly dependent on spin and inclination



$$R = 3\sqrt{3}M$$

Schwarzschild

Bardeen 1973; Luminet 1979

Next: outflows

Director’s cut

Back-of-the-envelope estimate of accretion disk luminosity

$L \sim 10^{10} L_{sun}$
$\sim 1 M_{Earth} c^2$
every 3 hours

$$M = 10^8 M_\odot$$

BLACK HOLE MASS

$$m = 1 M_\odot$$

MASS SUPPLY TO BLACK HOLE

FREE-FALL TIMESCALE

$$t_{\mathrm{ff}} = \sqrt{\frac{2r^3}{GM}}$$

$$\dot{m} \sim m/t_{\mathrm{ff}} = 10^{24}\ \mathrm{g\ s^{-1}}$$

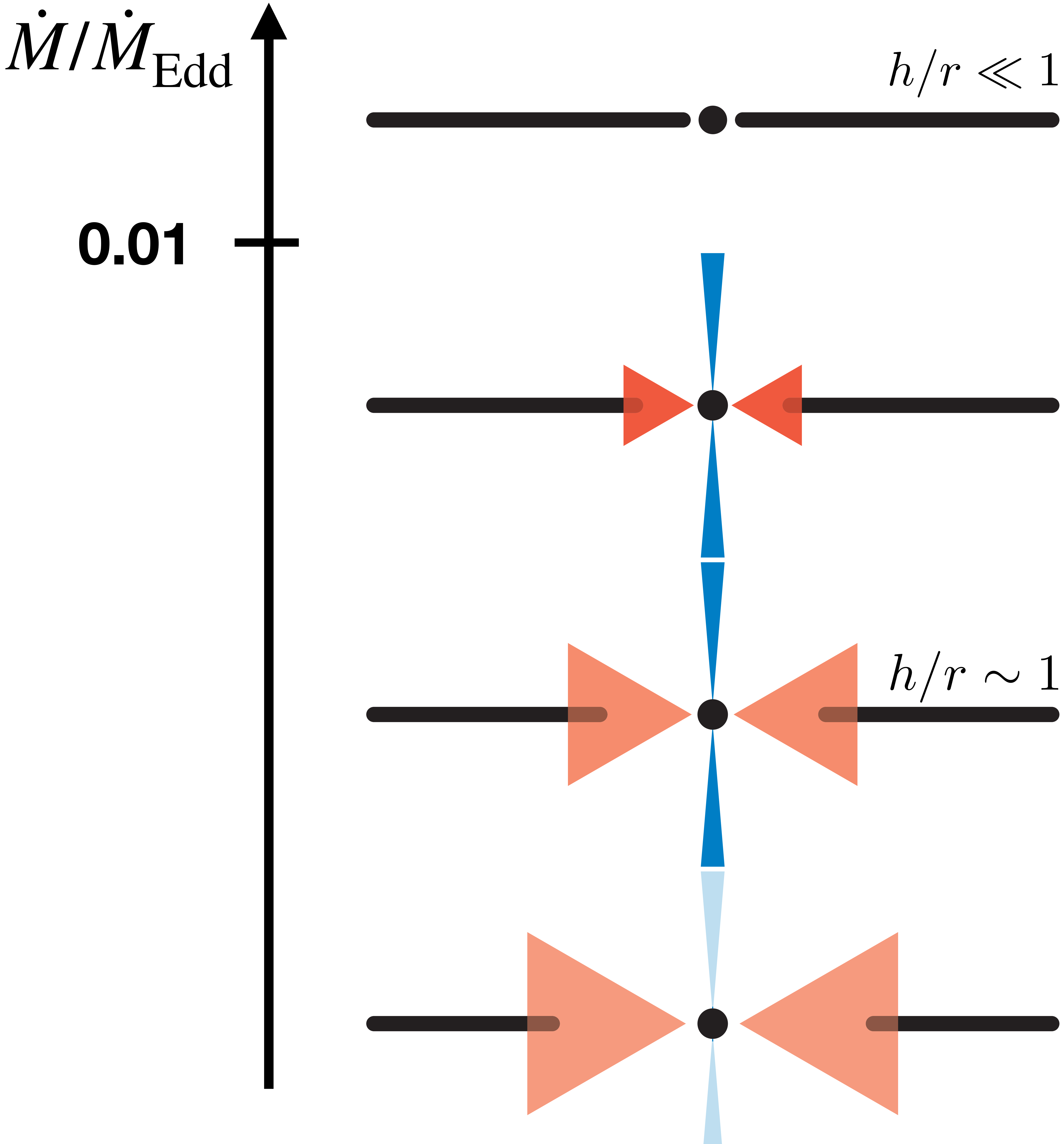
MASS OF ALL WATER ON EARTH

MASS ACCRETION RATE

$$L \sim 0.1 \dot{m} c^2 \sim 10^{44}\ \mathrm{erg\ s^{-1}}$$

LUMINOSITY

Unified theory of black hole accretion flows



Density related to accretion rate

$$\dot{M} = 4\pi r^2 \rho v_r$$

Changes in Mdot affect Coulomb interactions between electrons (which radiate) and ions (which get heat energy)

Therefore, rho affects cooling time

Adapted from Yuan & Narayan 2014, ARA&A