BLACK HOLE ACCRETION DISKS

Lecture 7, Introduction to Black Hole Astrophysics

Hsiang-Yi Karen Yang, NTHU, 4/13/2021

ANNOUNCEMENTS

- HW3 solutions will be posted on iLMS tomorrow at 13:30.
- Please search for black hole news for the oral presentation and paste the news link here:

https://docs.google.com/spreadsheets/d/1_aYyMj1wf_uGheZ7zp_hvthmy4mdmPwIxFDdZOMG-nc/edit?usp=sharing

- Please start forming a team of 3 people for the final report. Choose a team leader and enter your names on iLMS -> 小組專區

PREVIOUS LECTURE…

- Evolution of a star is largely determined by its ***mass***
  - All stars go through the ***main sequence*** phase of H burning
  - If M < 8 M_{sun}, M_{core} < 1.4 M_{sun}
    star -> red giant -> planetary nebula -> WD
  - If 8 M_{sun} < M < 20 M_{sun}, 1.4 M_{sun} < M_{core} < 2-3 M_{sun}
    star -> supergiant -> core-collapse (Type II) supernova -> NS
  - If 20 M_{sun} < M, 3 M_{sun} < M_{core}
    star -> supergiant -> core-collapse (Type II) supernova -> BH
- Neutron stars
  - Properties & extreme conditions
  - Different types -- pulsars, magnetars
  - Internal structure & the unknown EOS of matter in the core – can be probed by the NICER X-ray mission by observing pulsars

PREVIOUS LECTURE…

- Formation of stellar-mass BHs
  - Mass distributions of smbhs are determined by (1) initial mass function of star formation, and (2) core mass after supernova explosions
  - Supernova models predict a ***mass gap*** of smbhs in the range of ***~50-150 M_{sun}***
  - Some smbhs found by GWs are within this gap, challenging current theoretical models
- Evolution of binary stars
  - ***Mass transfer*** is an important process for (1) solving the binary paradox (ex: Agol), (2) explaining the emission of X-ray binaries by accretion (ex: Cygnus X-1)
  - Understanding the evolution of binary systems is crucial for predicting the numbers of BH-BH, NS-NS, or BH-NS merger events that generate GWs

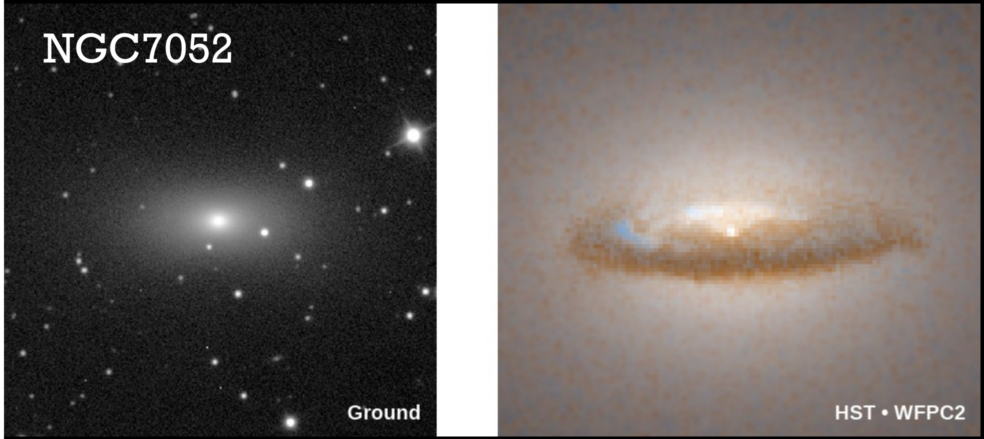
IMPORTANT FACTS FROM PREVIOUS LECTURES

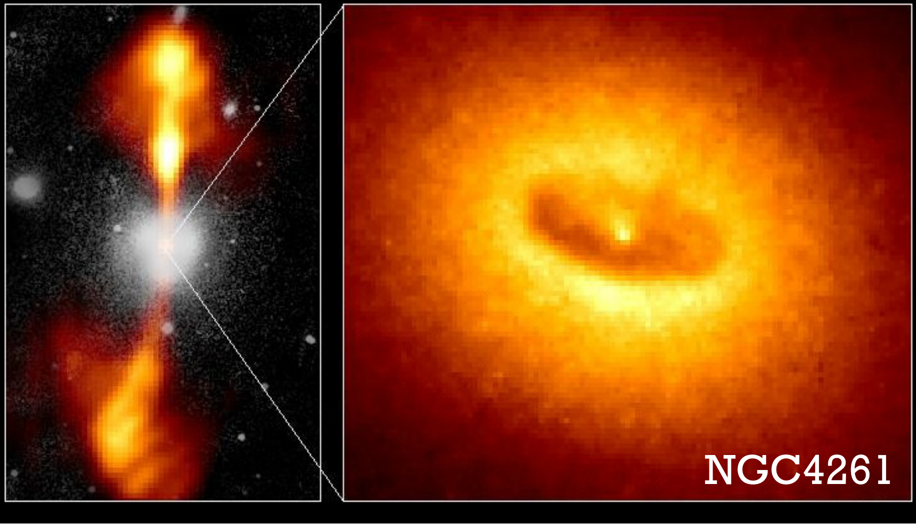
- BHs come in two flavors: stellar-mass BHs (smbhs) and supermassive BHs (SMBHs)
- BHs themselves do not shine, but the accretion disks can shine (e.g., X-ray binaries, quasars)
- Accretion disks are powerful engine in the universe
  - They can convert gravitational energy into radiation with high efficiencies, $\varepsilon \sim 5\text{-}40\%$
  - They can produce relativistic jets (Week 11)
  - The radiation and jets from SMBHs can significantly impact the galaxy formation (Week 12)

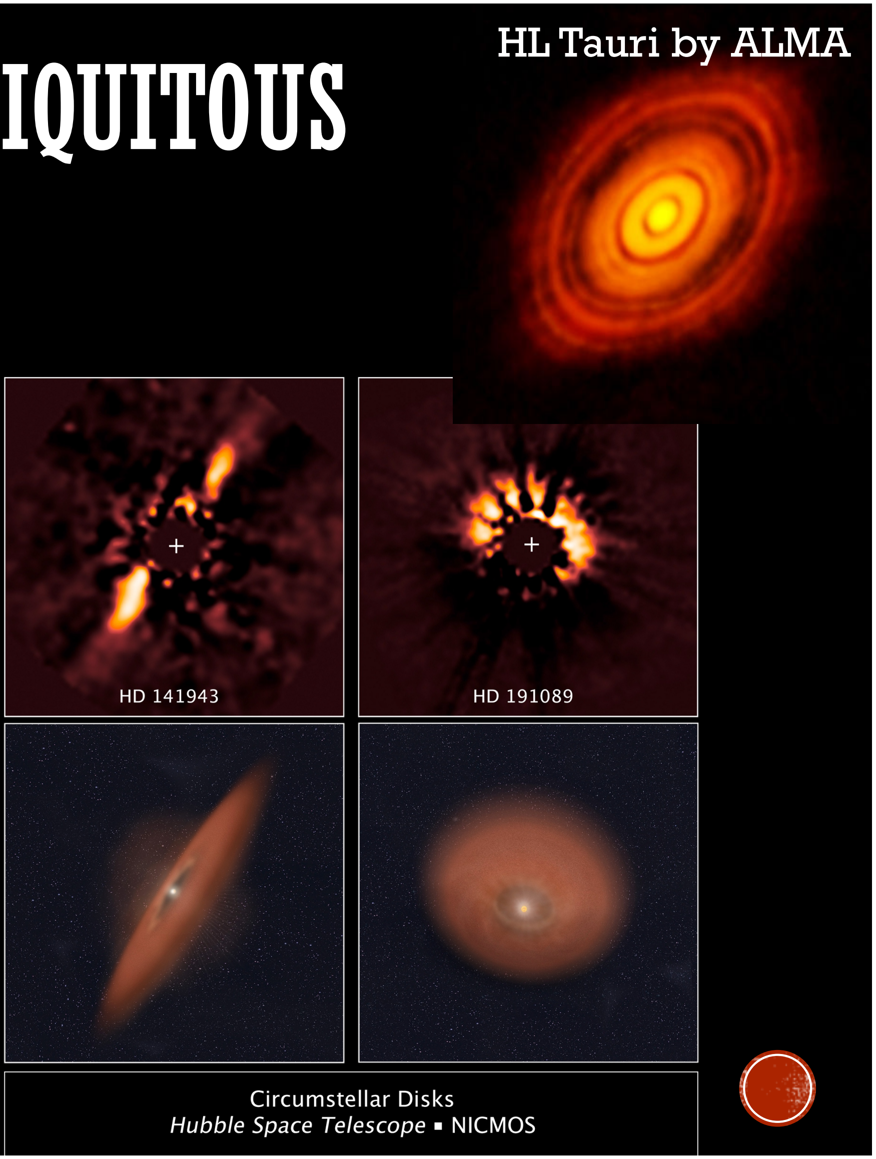
THIS LECTURE

- Overview of accretion disks
- The Eddington limit
- If no angular momentum: Bondi (spherical) accretion
- When there is angular momentum
  - How the disks are formed
  - Angular momentum problem and how to resolve it
- Three types of accretion disks depending on mass accretion rates
- Comparing the theory with observations

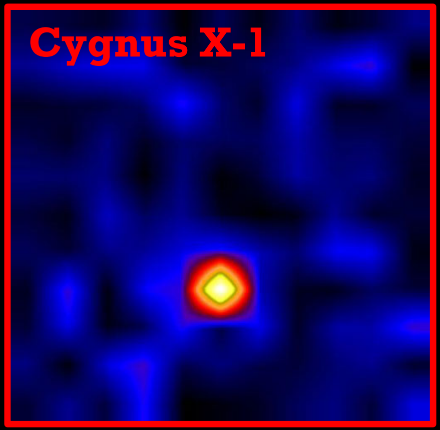
ACCRETION DISKS ARE UBIQUITOUS

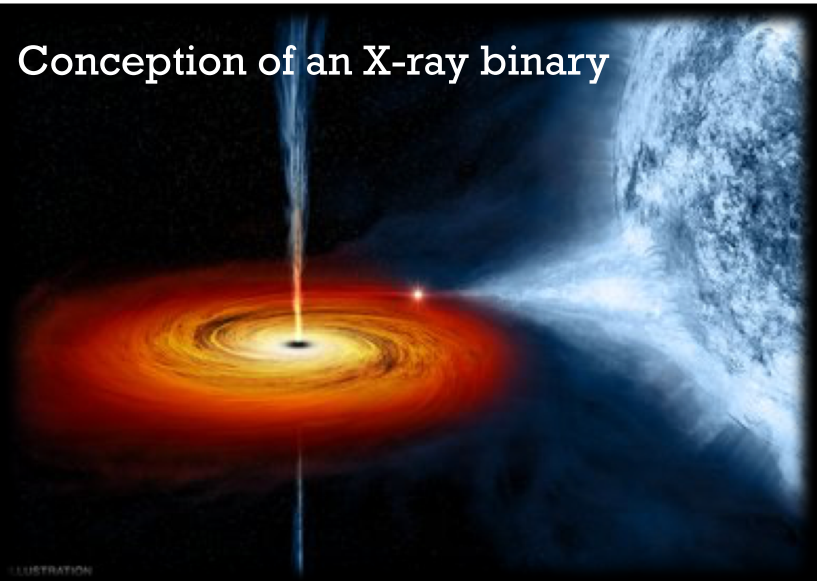


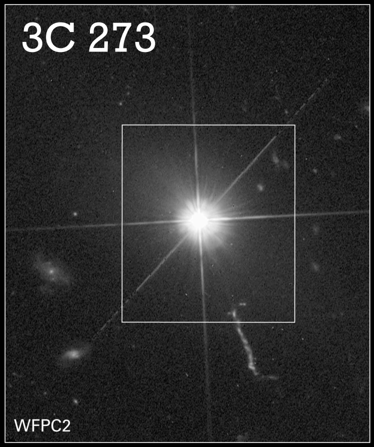


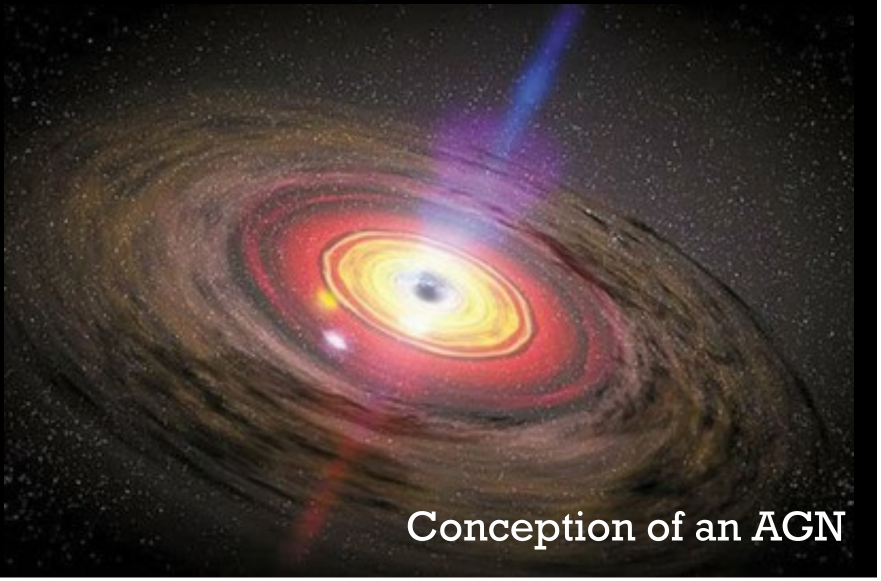

HL Tauri by ALMA

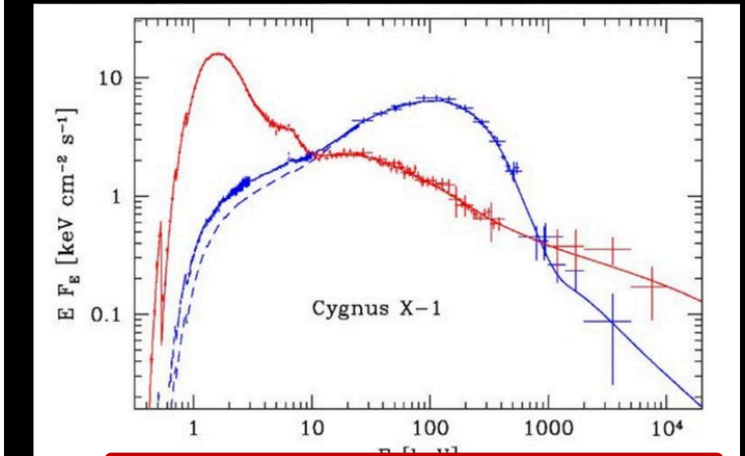
Circumstellar Disks
Hubble Space Telescope ▪ NICMOS

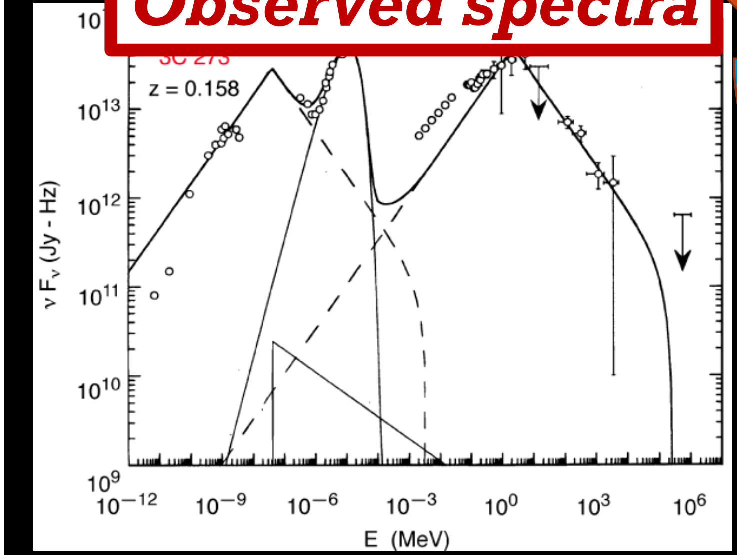

Cygnus X-1


Conception of an X-ray binary
ILLUSTRATION

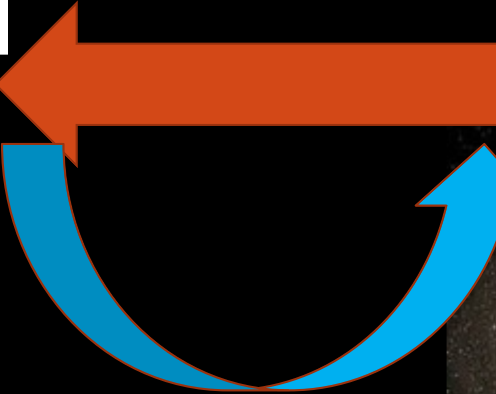

3C 273
WFPC2


Conception of an AGN

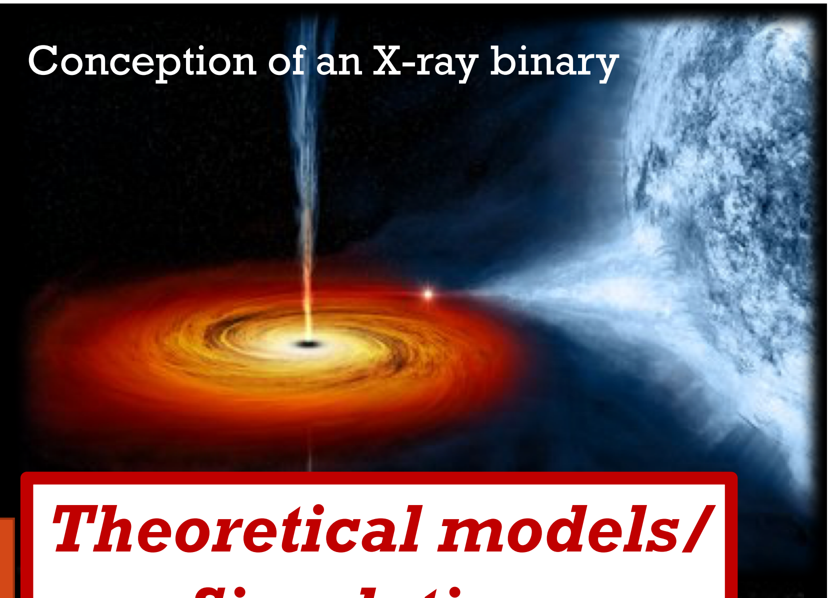


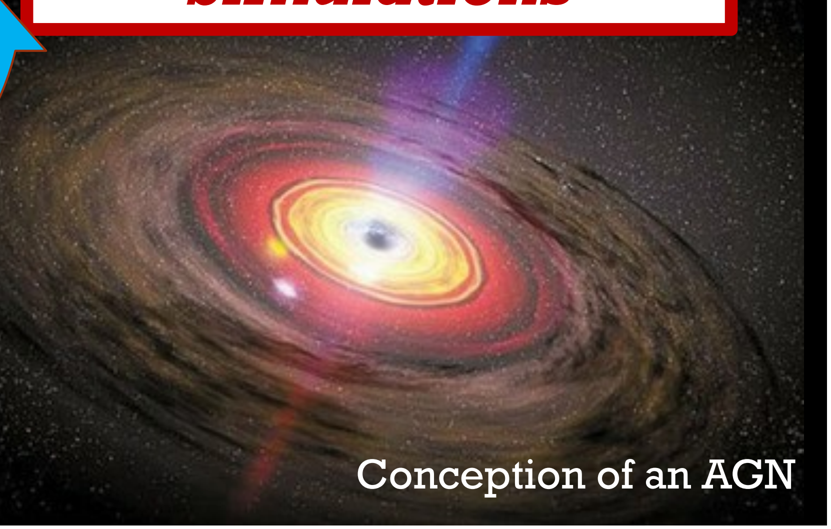


Observed spectra



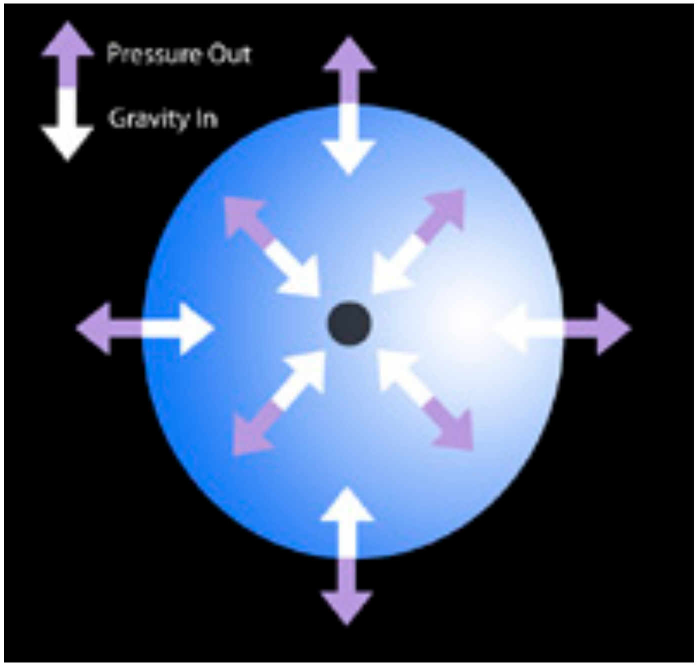
Theoretical models/ Simulations


Conception of an X-ray binary


Conception of an AGN

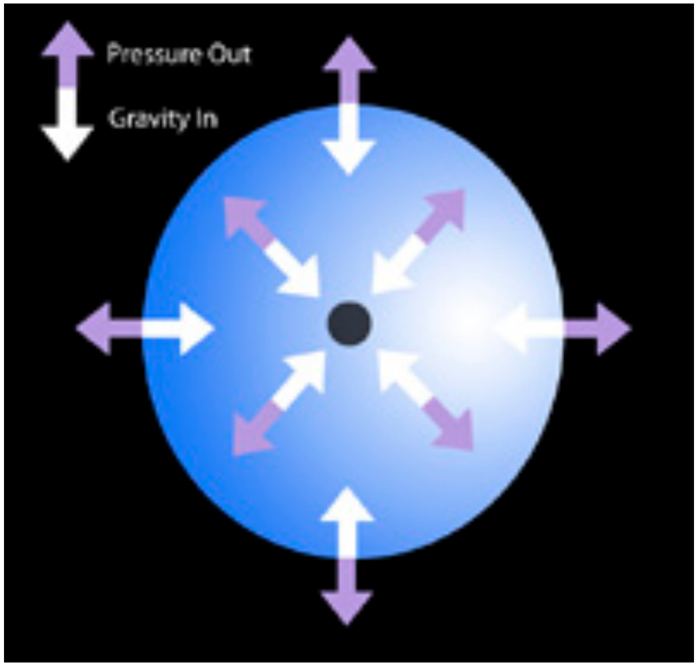
THEORIES OF BLACK HOLE ACCRETION

THE EDDINGTON LIMIT



- There is a limit to how fast mass can be dumped onto a BH – “***Eddington limit***”
- As materials accrete, they could efficiently turn their gravitational energy into radiation
- ***Pressure force from the intense radiation*** would push outward and halt the accretion

THE EDDINGTON LIMIT



- Materials infall due to gravity: $F_{grav} = \frac{GMm_p}{r^2}$
- Outward pressure force from radiation:

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

- If ***gravity*** wins, materials could flow inward; if ***radiation force*** wins, materials would be blown away
- There is a maximum luminosity for a given BH mass, i.e., the ***Eddington luminosity***:

$$L_{Edd} = \frac{4\pi GMm_p c}{\sigma_T} = 1.4\times10^{31}\left(\frac{M_{BH}}{M_{sun}}\right)\text{W}$$

($L_{sun} \sim 4 \times 10^{26}$ W)

THE EDDINGTON LIMIT

- Eddington luminosity:

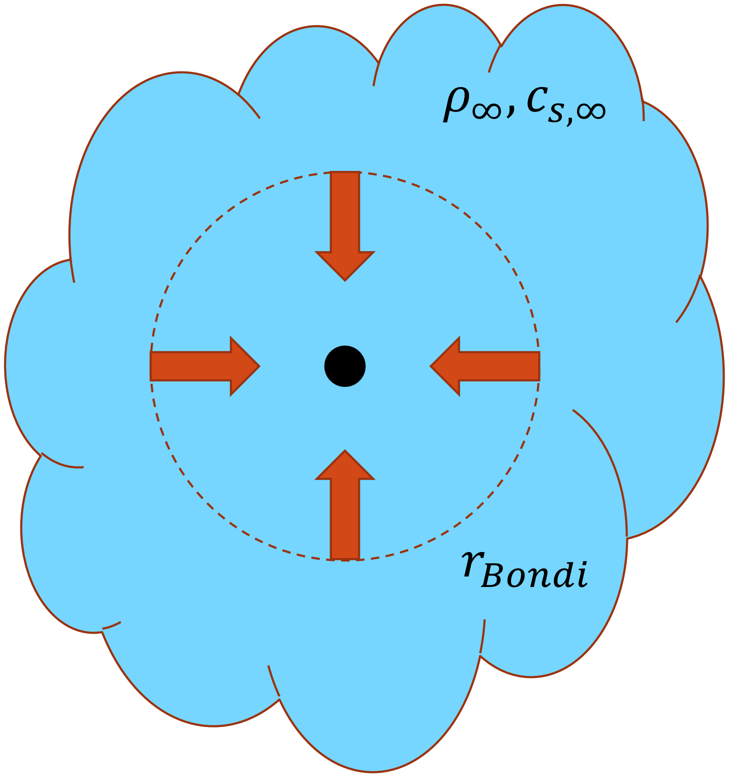
$$\boxed{L_{Edd} = 1.4\times10^{31}\left(\frac{M_{BH}}{M_{sun}}\right)\mathrm{W}}$$

- Associated with the critical luminosity we could define the ***Eddington accretion rate***:

$$\boxed{\dot{M}_{Edd} \equiv \frac{L_{Edd}}{\varepsilon c^2} = 2\times10^{-8}\left(\frac{M_{BH}}{M_{sun}}\right)\left(\frac{\varepsilon}{0.1}\right)^{-1} M_{sun}yr^{-1}}$$

- For the quasar 3C 273, M_{BH}~0.9x10^{9}M_{sun}, L~10^{39}W => L_{Edd} ~ 1.3x10^{40} W, L ~ 8% x L_{Edd}
- For most observed sources, the Eddington limit is respected
- Important because it determines the maximum rate BHs can accrete and grow! (Week 13)

THE SIMPLEST CASE – BONDI ACCRETION



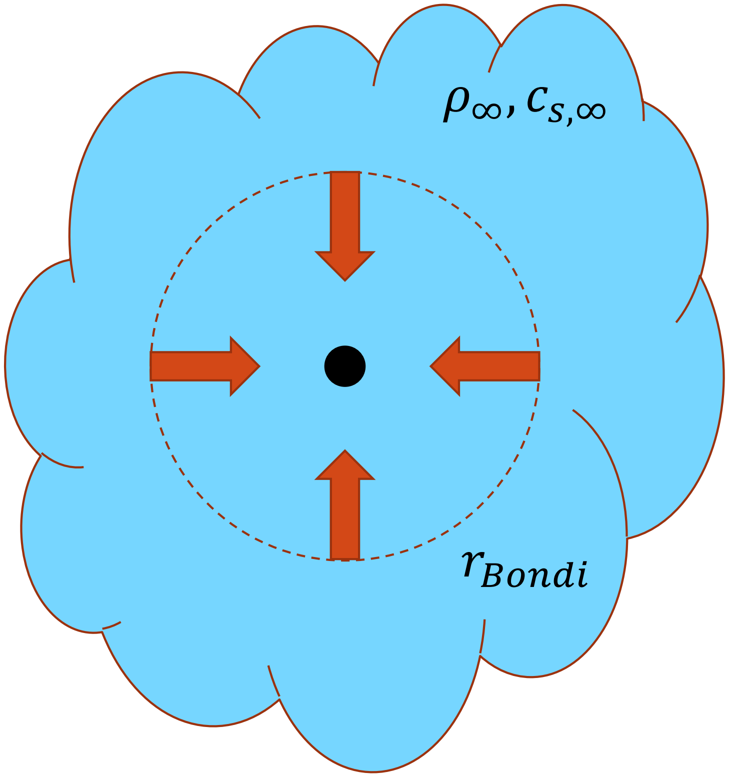
- Bondi (1952): Spherical accretion from fluids with ***no angular momentum*** and ***no magnetic field***
- Bondi accretion rate = accretion rate when reaching steady state:

$$\dot{M}_{BH} = \frac{\pi G^2 M^2 \rho_\infty}{c_{s,\infty}^3}$$

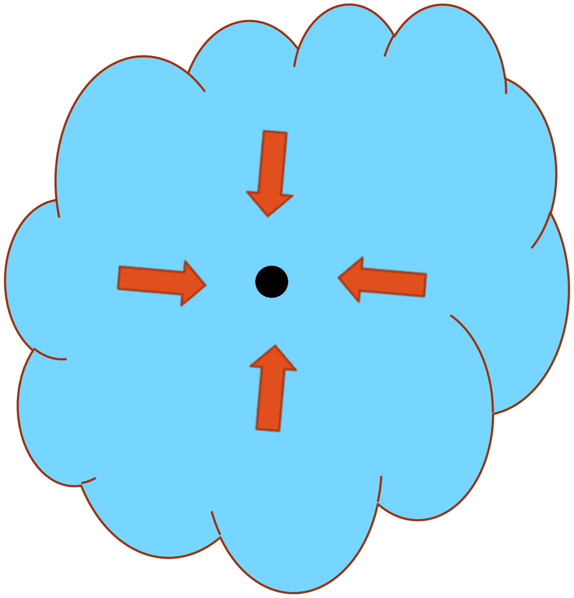
- Bondi radius = radius within which gravity from BH dominates thermal gas pressure:

$$r_{Bondi} = \frac{2GM}{c_{s,\infty}^2}$$

THE SIMPLEST CASE – BONDI ACCRETION



- In cosmological simulations of galaxy formation, the Bondi accretion rate is often used to approximate the BH accretion because
  - The formula is simple
  - Bondi radius >> r_S so it is somewhat easier to resolve the Bondi radius (resolving r_S is hopeless!)
- However, it is an extremely ideal case!



(a) (b)

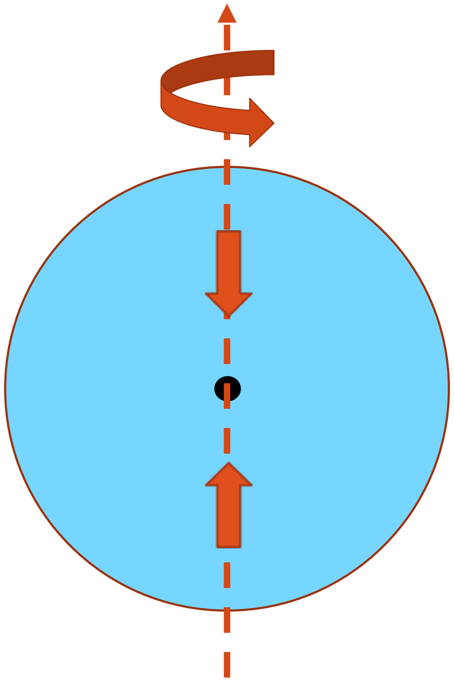
WHEN THERE IS ANGULAR MOMENTUM…

- As long as the accreting materials are not moving in the radial direction exactly, there would be nonzero net angular momentum
- If the angular momentum is conserved during the collapse, the orbital velocity would increase as radius decreases

$$L = mrv$$

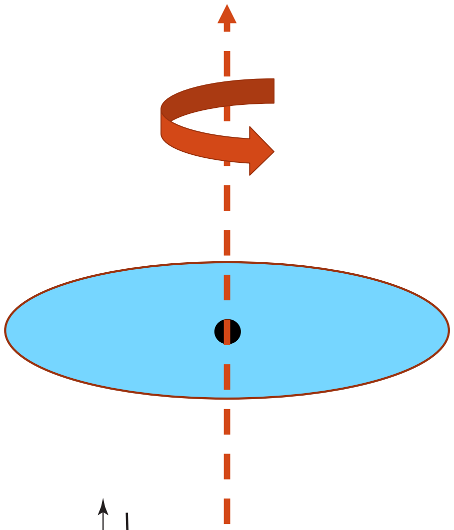
- This effect is dramatic because the range of scales involved in BH accretion can expand several orders of magnitude!

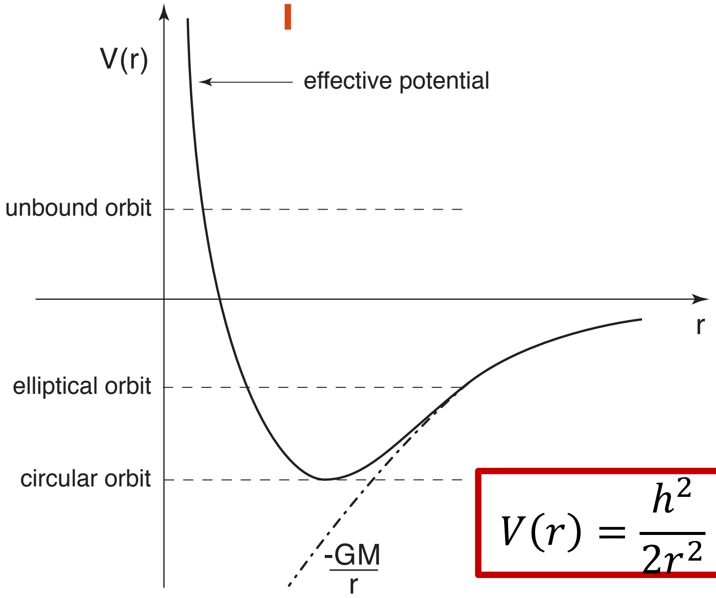
WHEN THERE IS ANGULAR MOMENTUM…



- Assuming the net angular momentum is pointing upward
- In the vertical direction, gravity would pull materials toward the equatorial plane
- This will proceed until gas pressure gradient is enough to oppose gravity (ignoring radiation pressure for now)
- ***Height of disk depends on gas pressure***
  - When gas pressure is small => thin disk
  - When gas pressure is non-negligible => thick disk

WHEN THERE IS ANGULAR MOMENTUM…

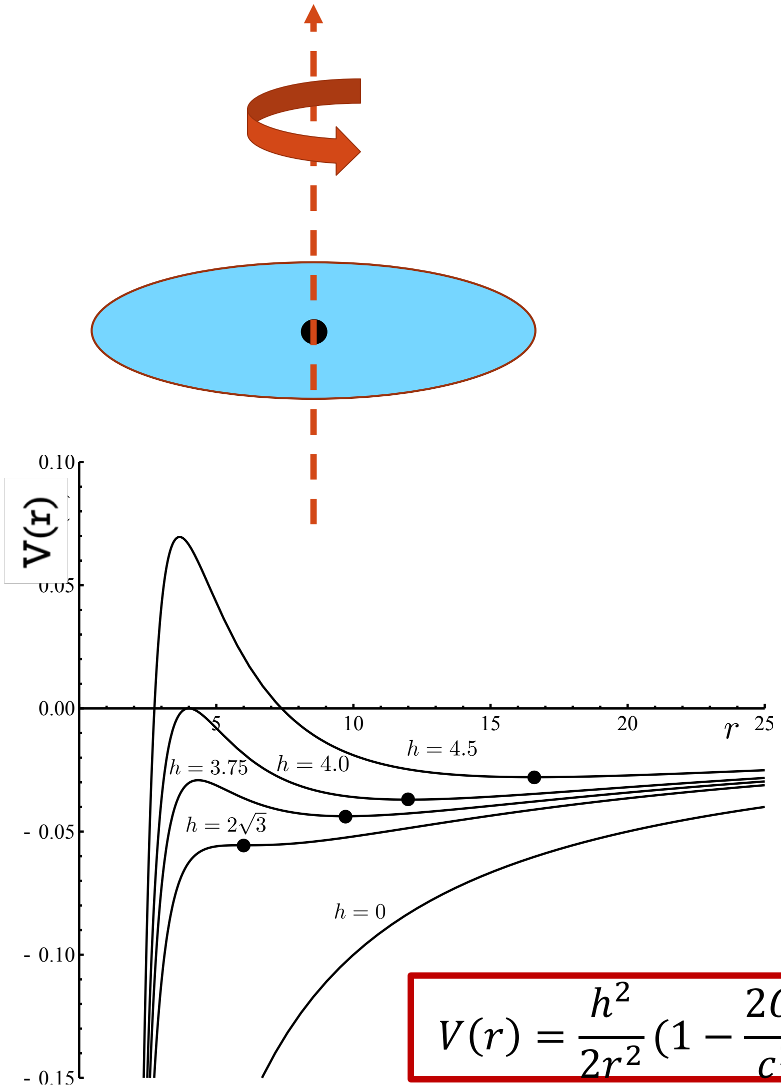




$$V(r) = \frac{h^2}{2r^2} - \frac{GM}{r}$$

- In the radial direction, recall that there is a ***centrifugal barrier*** when L /= 0
- The centrifugal barrier would stop materials from moving inward
- The initial angular momentum and energy of a gas parcel would determine the ***range of radius*** it can orbit the central mass

WHEN THERE IS ANGULAR MOMENTUM…



$$V(r) = \frac{h^2}{2r^2}\left(1 - \frac{2GM}{c^2 r}\right) - \frac{GM}{r}$$

- The centrifugal barrier is weaker when considering GR, but it only modifies the effective potential very close to the BH
- Most materials would settle down at radii much larger than the Schwarzschild radius
- Newtonian gravity is sufficient for treating the accretion physics unless very close to the BH

ACCRETION DISK

- It is naturally formed when materials with ***nonzero angular momentum*** fall onto the central object due to gravity
- The height of the disk is determined by the balance between gravity and gas pressure
- The radius of the disk is determined by the initial angular momentum and energy of the infalling materials
  - Larger angular momentum -> larger radius

BUT HOW DOES THE "ACCRETION" HAPPEN?

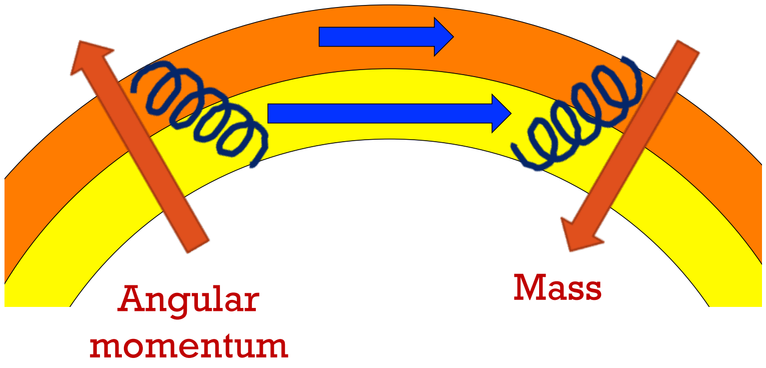
- There is an "***angular momentum problem***"
- Consider a parcel of gas with mass m orbiting a BH with mass M in a circular orbit, its velocity and angular momentum are:

$$V = \sqrt{\frac{GM}{r}}$$

$$L = mvr = m\sqrt{\frac{GM}{r}}r = m\sqrt{GMr}$$

- If angular momentum is conserved, r=constant => things would orbit forever without any accretion!
- To get closer to the BH, the piece of gas must ***lose its angular momentum***. But how?

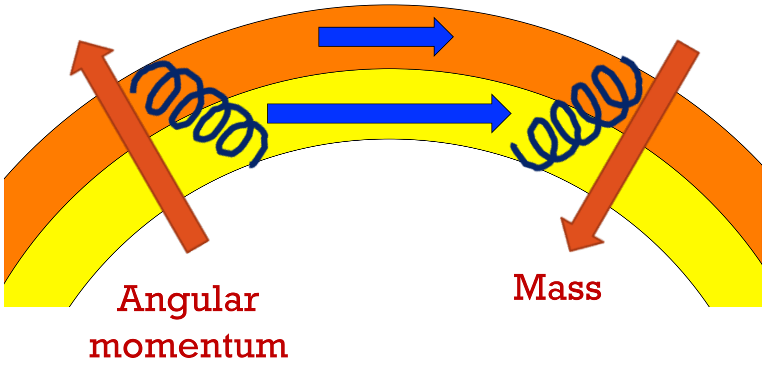
SHEARED FLOW (剪流)



$$V = \sqrt{\frac{GM}{r}}$$

- The accretion disk is a "***sheared flow***"
  - Orbital velocity increases as you move inwards
  - Rings of orbiting gas can "rub" against each other
- ***Viscosity* (黏度/內摩擦力)** is the ability of a gas/fluid to exchange momentum with neighboring gas/fluid if there is a shear flow
- So if gas has viscosity, then …
  - Inner/fast ring would be slowed down by outer/slow ring, and vice-versa
  - ***Angular momentum is transported outwards*** through the disk
  - The loss of angular momentum allows the ***gas to flow inwards***!
- Sources of viscosity remain unclear; may be related to magnetic tension acting like springs (jargon: the "magneto-rotational instability" or MRI)

SHEARED FLOW (剪流)



$$V = \sqrt{\frac{GM}{r}}$$

- The accretion disk is a "***sheared flow***"
  - Orbital velocity increases as you move inwards
  - Rings of orbiting gas can "rub" against each other

Magnetic-field induced viscosity allows angular momentum to be transported outward and mass to flow inward!

  - Inner/fast ring would be slowed down by outer/slow ring, and vice-versa
  - ***Angular momentum is transported outwards*** through the disk
  - The loss of angular momentum allows the ***gas to flow inwards***!
- Sources of viscosity remain unclear; may be related to magnetic tension acting like springs (jargon: the "magneto-rotational instability" or MRI)

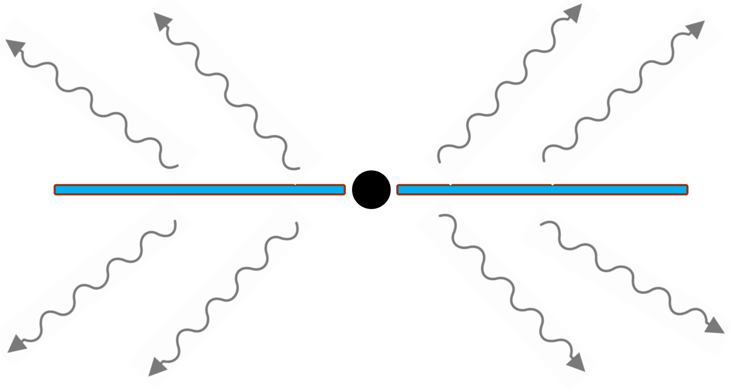
THREE TYPES OF ACCRETION DISKS

(I) STANDARD THIN DISKS

- Standard thin-disk model developed by Shakura & Sunyaev (1973) (GR version by Novikov & Thorne (1973))
- Proposed to explain ***highly accreting objects*** such as quasars and disk-dominated X-ray binaries
- Describes accretion disks when the accretion rate is high, i.e., when the ***Eddington ratio***:

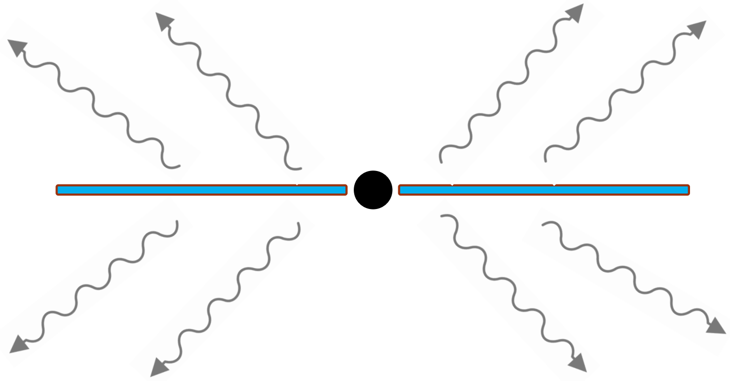
$$\boxed{0.01 \lesssim \dot{m} \equiv \frac{\dot{M}_{BH}}{\dot{M}_{Edd}} \lesssim 1}$$

(I) STANDARD THIN DISKS



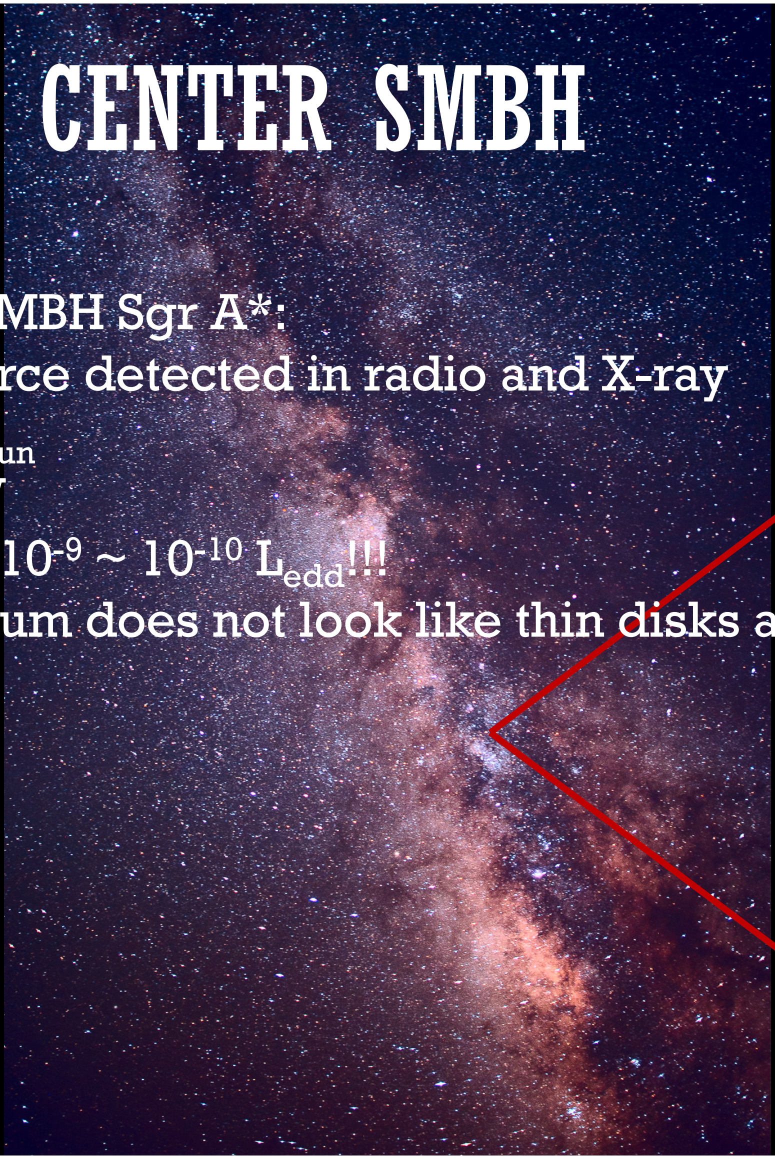
- Essential ingredients:
  - Assuming ***geometrically thin*** (H/R<<1) disks dramatically simplified the problem and allow for analytical solution as a function of r
  - By introducing a parametrized viscosity, angular momentum could be transported outward and mass could flow inward
  - Assuming the disk is ***radiatively efficient*** (heat generated by viscosity can be efficiently radiated away) => thermal pressure negligible => the disk could remain cold and thin
  - Assuming the disk is ***opaque*** (strong photon absorption), the emission could be approximated as ***thermal black-body radiation***

(I) STANDARD THIN DISKS

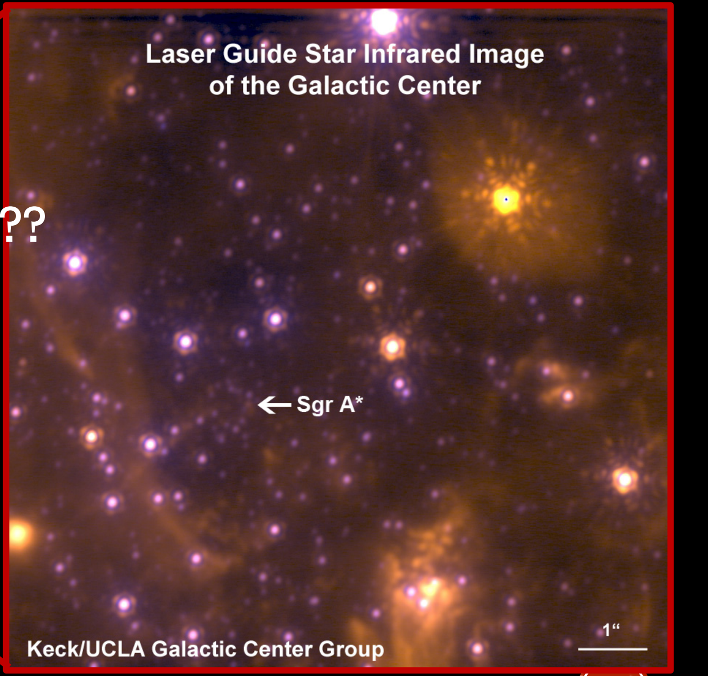


- Could derive total luminosity, radiative efficiency $\varepsilon \sim 5\text{–}40\%$, $T(r) \sim T_0 * r^{-3/4}$
- Characteristic temperature ***$T_0 \sim M_{BH}^{-1/4}$***
  - This is why disk emission from X-ray binaries peaks in X-ray and emission from SMBHs peaks in UV/optical!
- Disk ***spectrum*** can be computed as a superposition of black-body radiation with different T from different annuli
  - Could successfully explain observed spectra of ***highly-accreting objects*** such as quasars and disk-dominated X-ray binaries

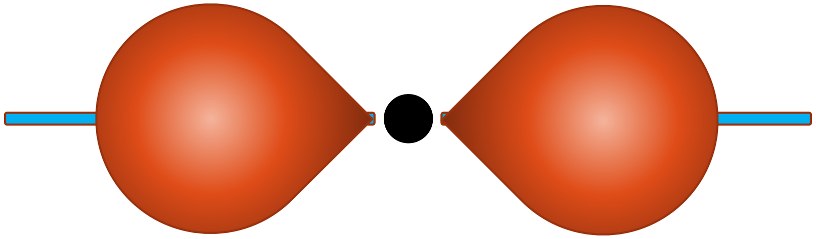
GALACTIC CENTER SMBH



The dormant SMBH Sgr A*:
Very weak source detected in radio and X-ray
$M_{BH} \sim 4\times10^{6}\ M_{sun}$
$L_{edd} \sim 5\times10^{37}$ W
$L_{obs} \sim 10^{28}$ W $\sim 10^{-9} \sim 10^{-10}\ L_{edd}$!!!
And the spectrum does not look like thin disks at all…??



(II) THICK DISKS

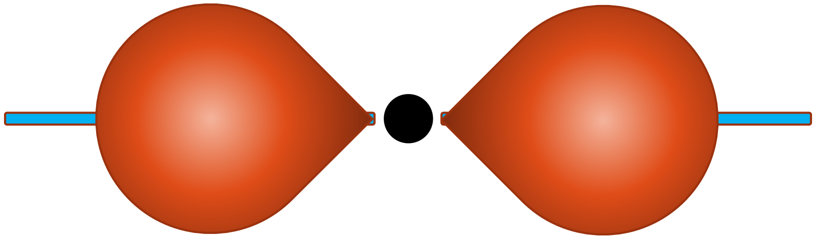


- Proposed to explain ***slowly-accreting objects*** like Sgr A*
- Describes accretion disks when accretion rate is low:

$$\boxed{\dot{m} \equiv \frac{\dot{M}_{BH}}{\dot{M}_{Edd}} \lesssim 0.01}$$

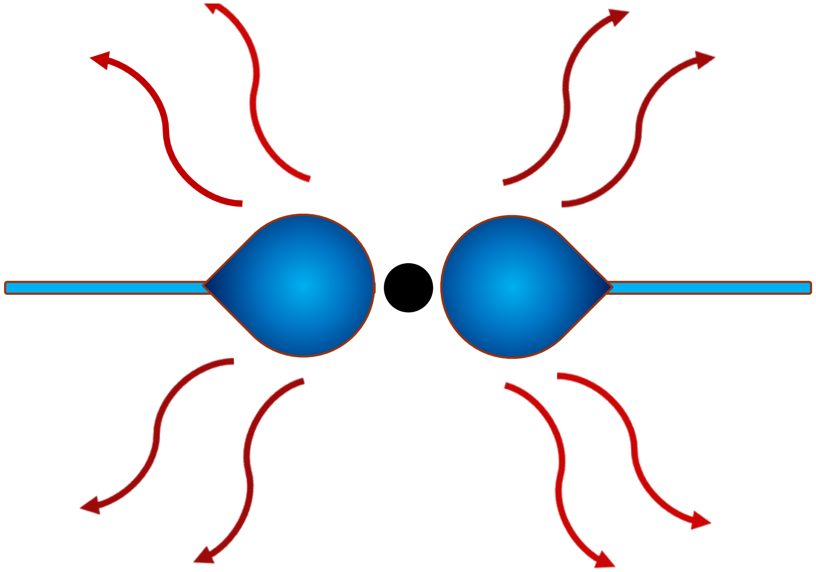
- Essential ingredients:
    - The accretion flow is ***radiatively inefficient***, so that heat generated by viscosity is stored within the flow => thermal pressure non-negligible => disk puffs up
    - The ***geometrically thick*** accretion flow is very hot (T~$10^{9\text{-}10}$ K), so often referred to as "***corona***"
    - Eventually the heat is advected (平流) or carried along as the gas is accreted onto the BH (jargon: "advection-dominated accretion flows" or ADAFs)
- Could derive gas density, temperature, etc, as a function of radius

HOW THICK DISKS SHINE?



- Thick disks are radiatively inefficient => ***low luminosity***
- Thick disks shine differently than think disks => ***different spectra***
  - The gas within thick disks is diffuse, hot, and ionized
  - These hot gas or corona can emit nonthermal emission (e.g., Bremsstrahlung emission, Compton scattering, synchrotron radiation)
- Successfully explain observed spectra of Sgr A*, some low-luminosity AGN, and corona-dominated X-ray binaries

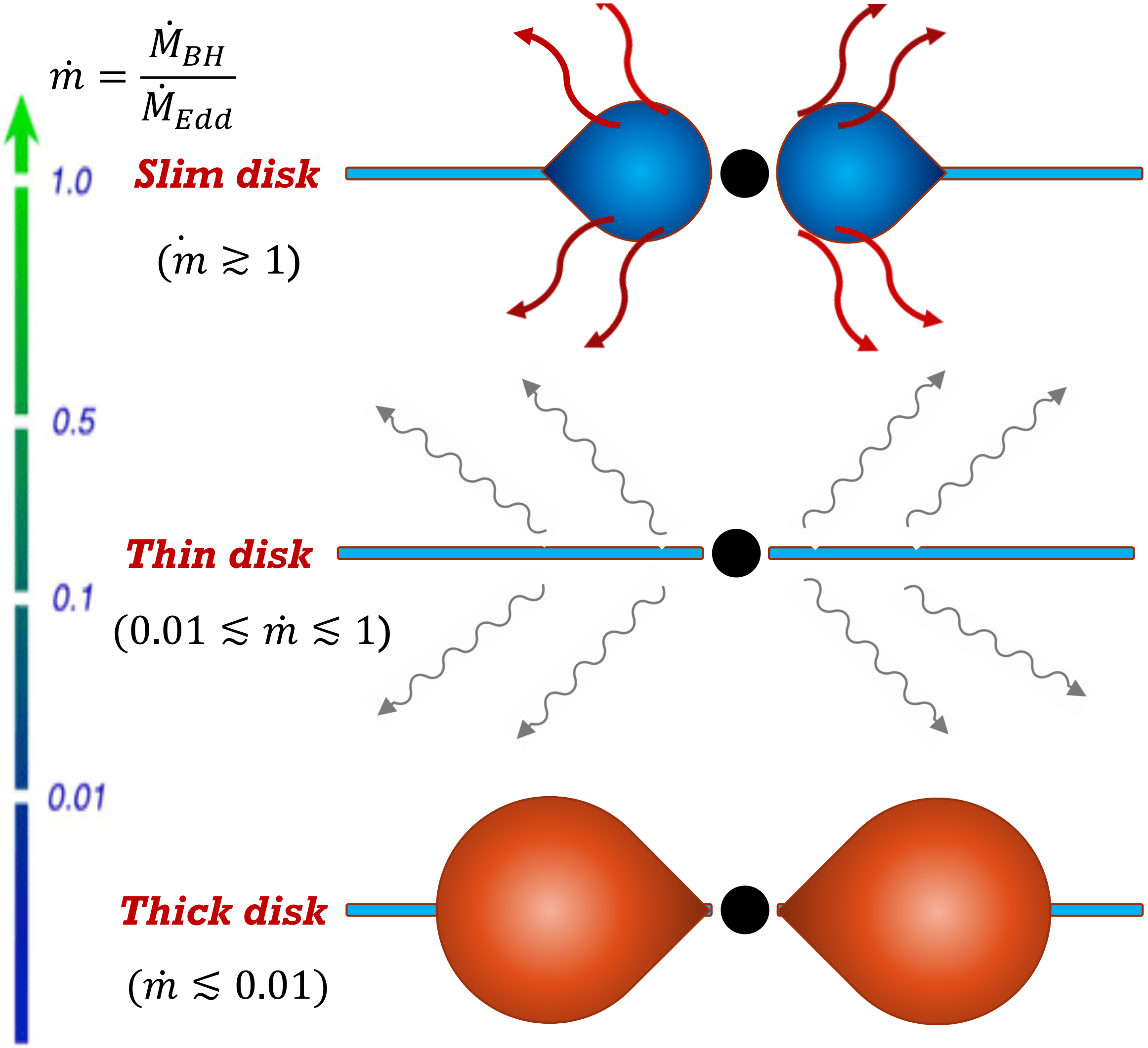
(III) SLIM DISKS



- Special case when $\boxed{\dot{m} \equiv \frac{\dot{M}_{BH}}{\dot{M}_{Edd}} \gtrsim 1}$

  i.e., "***super-Eddington accretion***"
- Essential ingredients:
  - Density is so high that photons are trapped and advected into the BH, so the radiative efficiency is lower than thin disks
  - Heat is partially radiated away so disk is ***slim***
  - Simulations show significant ***winds/outflows*** driven by radiation pressure
- Invoked to explain some objects with inferred super-Eddington accretion rates (e.g., some AGN, tidal disruption events (TDEs), and ultra-luminous X-ray sources (ULXs))

$$\dot{m} = \frac{\dot{M}_{BH}}{\dot{M}_{Edd}}$$



Slim disk

$(\dot{m} \gtrsim 1)$

- Radiatively less efficient than thin disks
- Radiation pressure driven winds
- Only occur in rare cases

Thin disk

$(0.01 \lesssim \dot{m} \lesssim 1)$

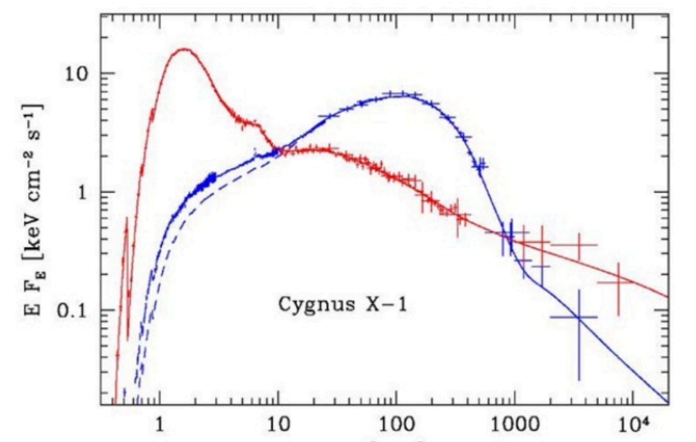
- Radiatively efficient
- Spectrum well described by superposition of black-body radiation
- Quasars, disk-dominated X-ray binaries

Thick disk

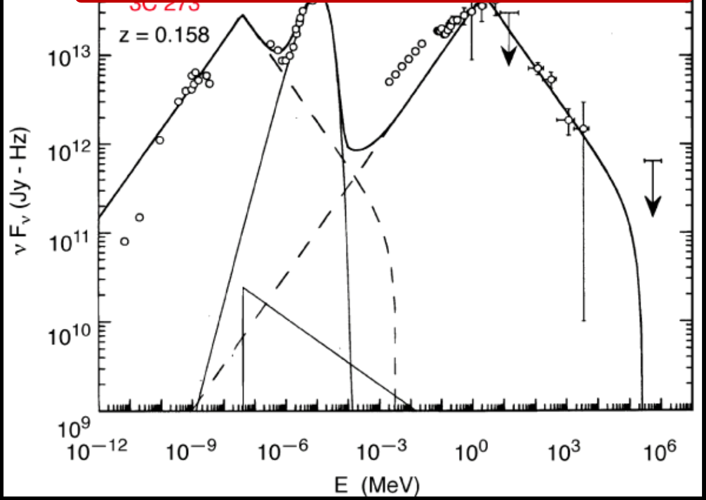
$(\dot{m} \lesssim 0.01)$

- Radiatively inefficient
- Accretion is hot – corona
- Spectrum described by nonthermal processes
- Sgr A*, low-luminosity AGN, corona-dominated X-ray binaries

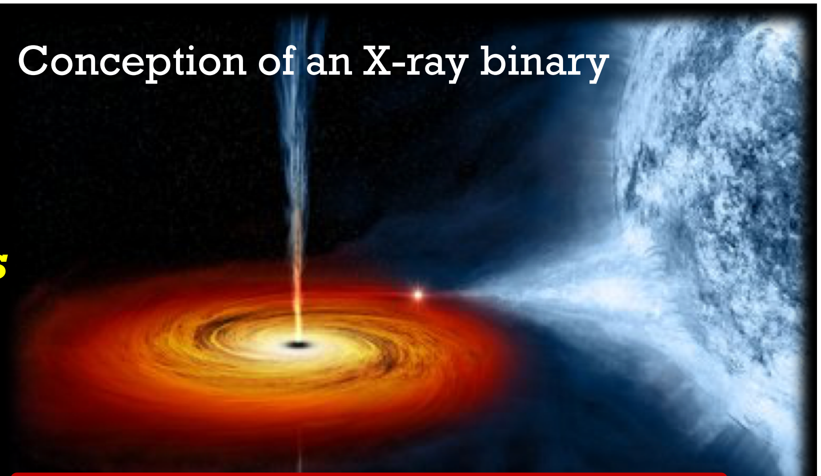
CONNECTING WITH OBSERVATIONS



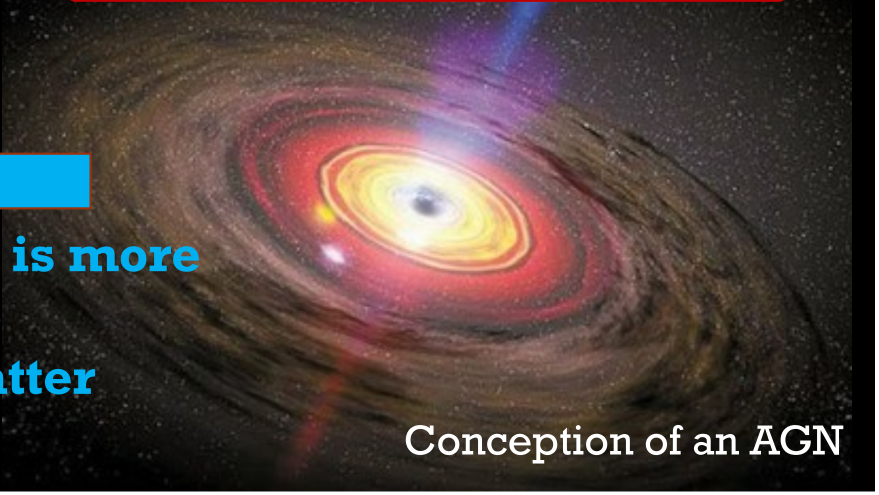
Observed spectra



*****X-ray binaries are micro-quasars***


Conception of an X-ray binary

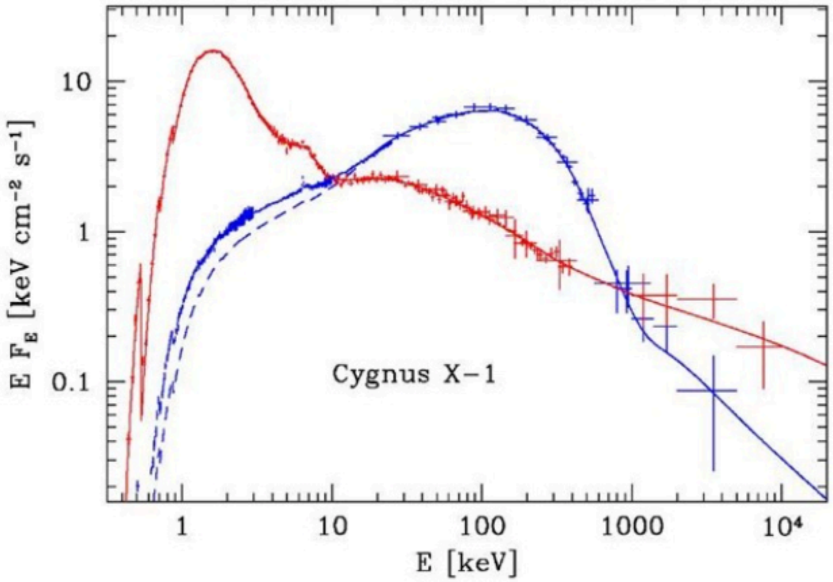
Theoretical models/ Simulations


Conception of an AGN

Spectra of AGN is more complex due to intervening matter (Week 9)

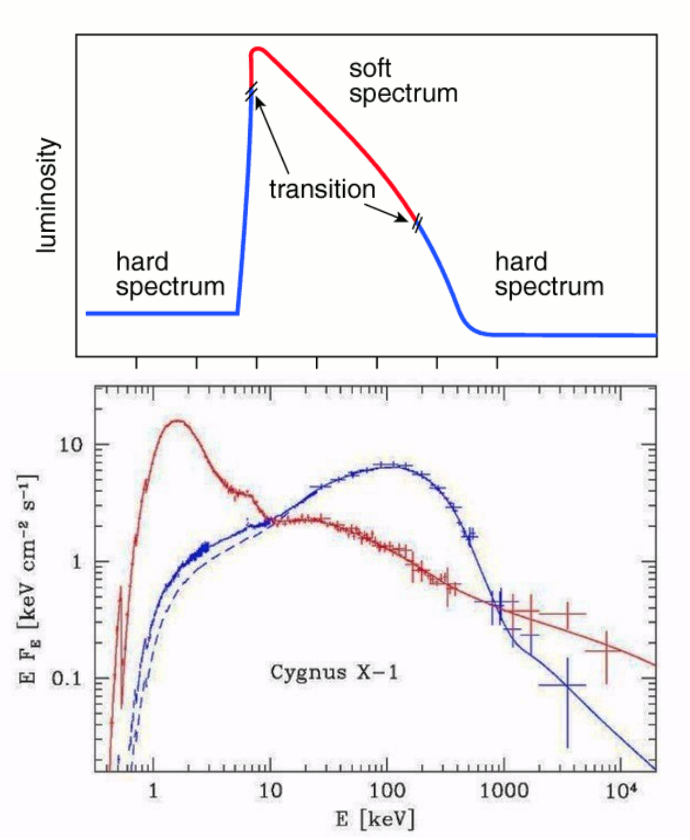
STATE TRANSITION OF X-RAY BINARIES

X-ray spectrum of Cygnus X-1



- X-ray binaries like Cygnus X-1 often show variation in their spectra on ~month timescales
- ***Red***: spectrum peaking in soft (low energy) X-rays => "***soft state***"
- ***Blue***: spectrum peaking in hard (high energy) X-ray => "***hard state***"
- There could be temporary, hybrid/intermediate states during their transition

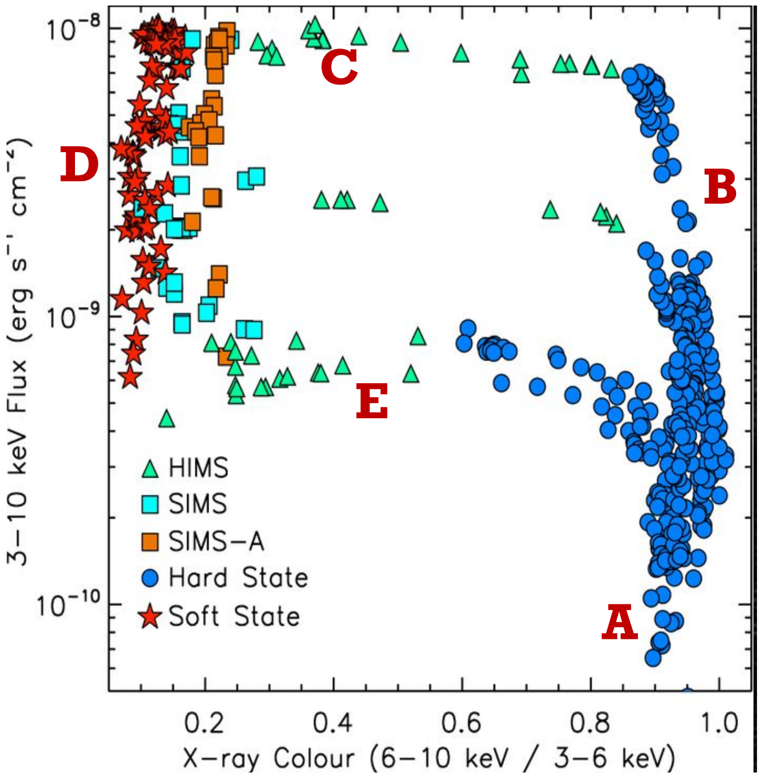
STATE TRANSITION OF X-RAY BINARIES



- Their luminosity also changes when their spectral change
- ***Soft state***: softer spectrum & higher luminosity
- ***Hard state:*** harder spectrum & lower luminosity

HARDNESS-INTENSITY DIAGRAM OF X-RAY BINARIES

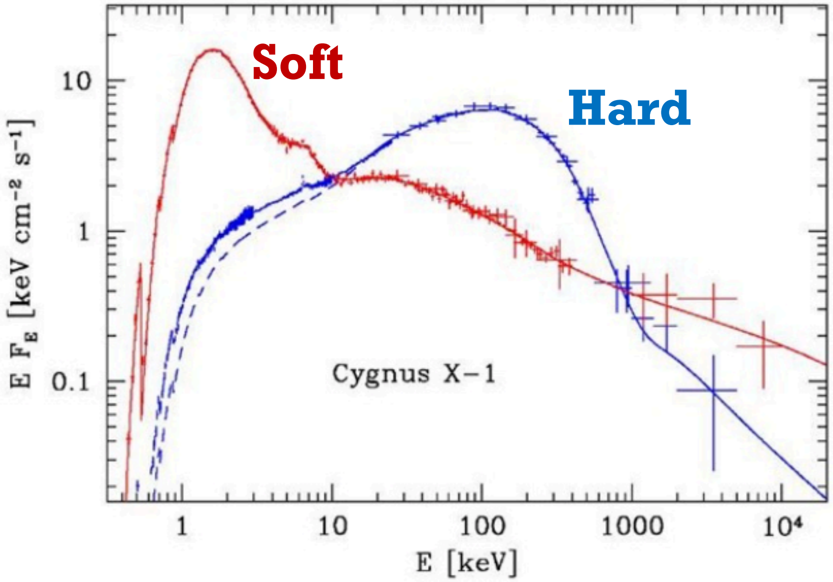
HID for GX339-4 (Plant+14)

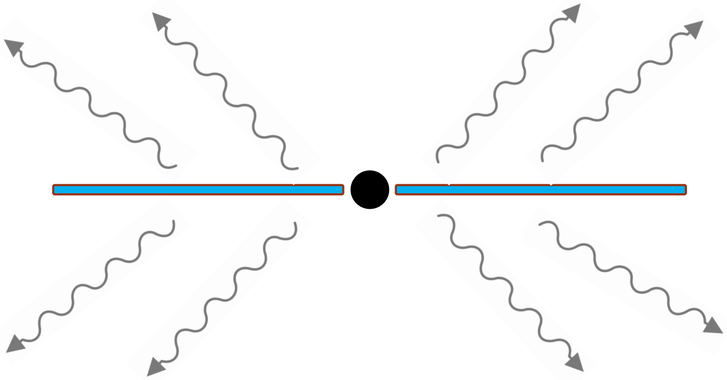


- ***Hardness-Intensity Diagram (HID)*** is often used to visualize state transitions of X-ray binaries
  - X axis: ratio of hard to soft X-ray photon counts
  - Y axis: X-ray luminosity
- A typical cycle would go from quiescent (A) -> hard state (B) -> transition (C) -> soft state (D) -> transition (E) -> quiescent (A)
- This is also called the "***q-diagram***"

SOFT STATE

X-ray spectrum of Cygnus X-1

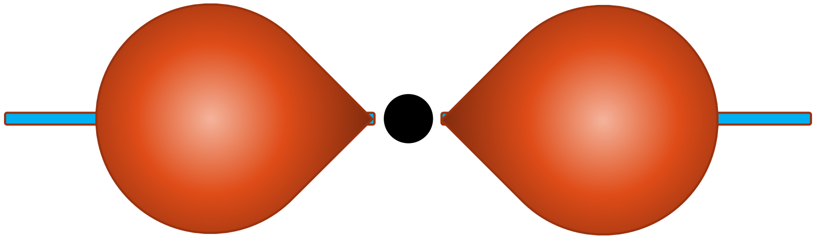




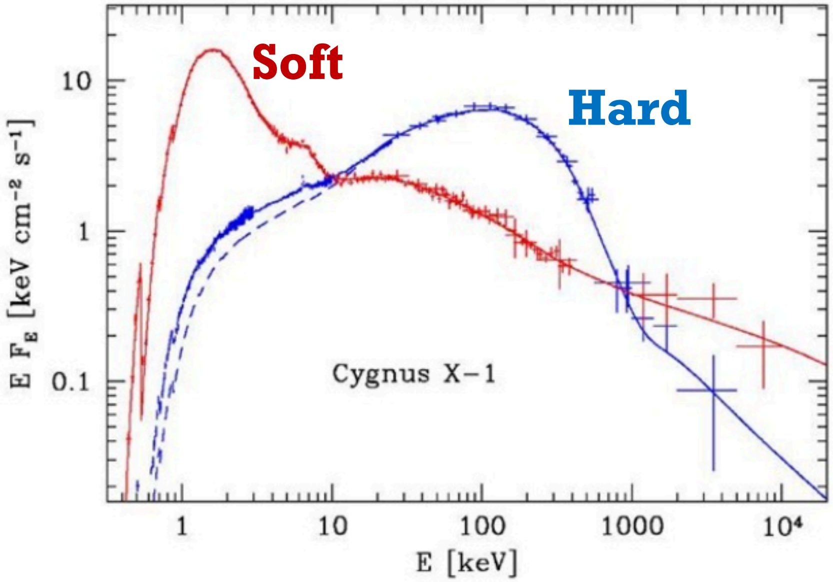
- The spectrum at the soft state can be described by thermal, superposed black body radiation
- The emission can be fit with the ***radiatively efficient thin-disk*** model
- The BH is accreting at ***high accretion rates***:

$$\boxed{0.01 \lesssim \dot{m} \equiv \frac{\dot{M}_{BH}}{\dot{M}_{Edd}} \lesssim 1}$$

HARD STATE



X-ray spectrum of Cygnus X-1

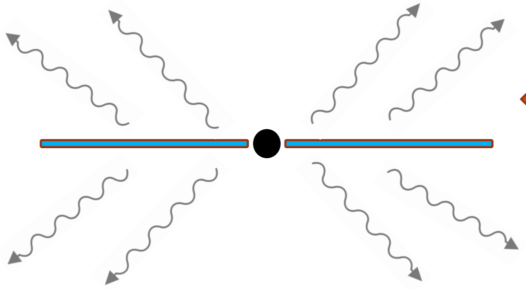


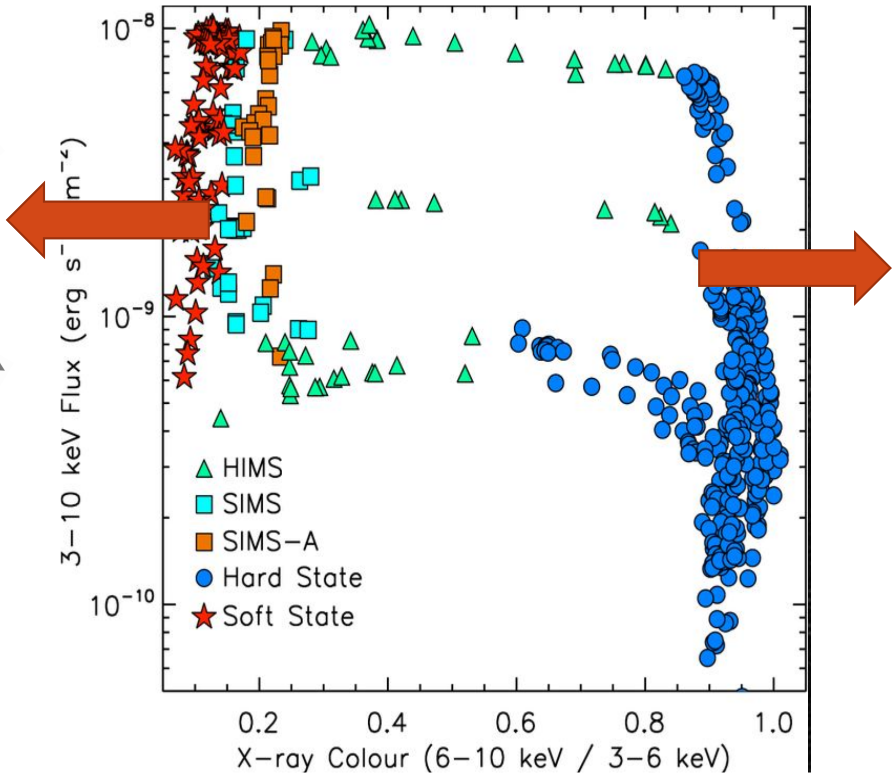
- The spectrum at the hard state can be described by nonthermal emission of a hot corona
- The emission can be fit with the ***radiatively inefficient thick-disk*** model
- The BH is accreting at ***low accretion rates***:

$$\boxed{\dot{m} \equiv \frac{\dot{M}_{BH}}{\dot{M}_{Edd}} \lesssim 0.01}$$

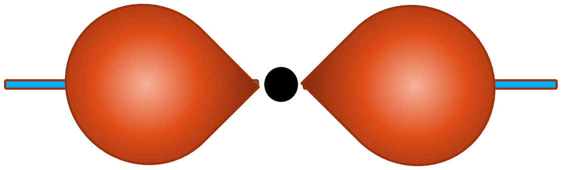
STATE TRANSITIONS

The “***high-soft***” state



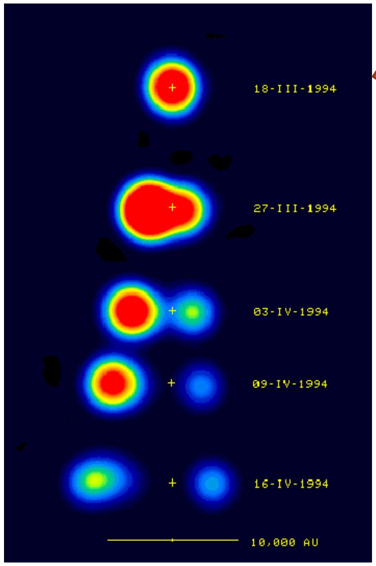


The “***low-hard***” state

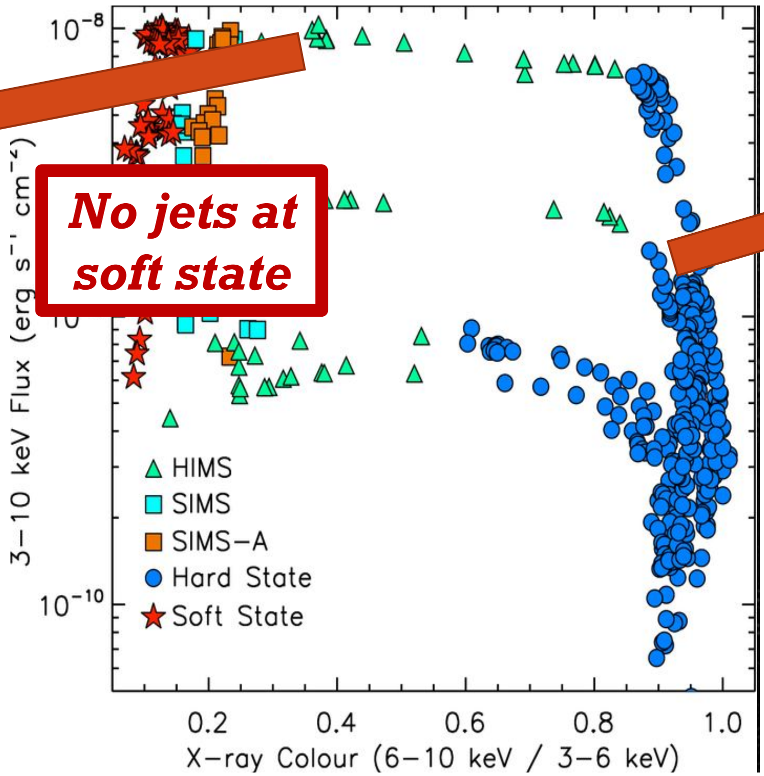


JETS AND STATE TRANSITIONS

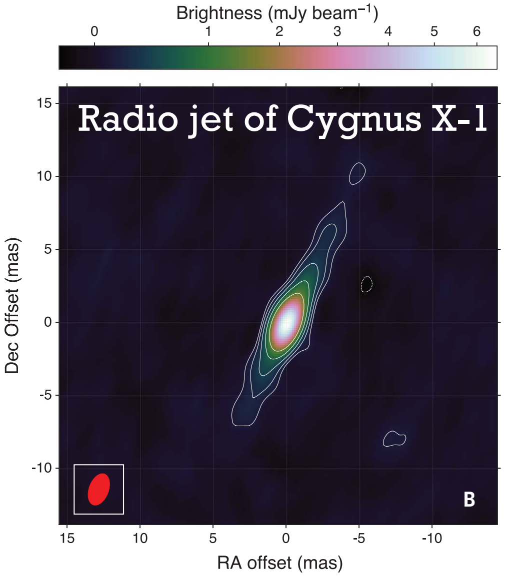
Moving blobs of
GRS1915+105



- ***Transient jets*** often observed during the transition from hard to soft state



No jets at soft state



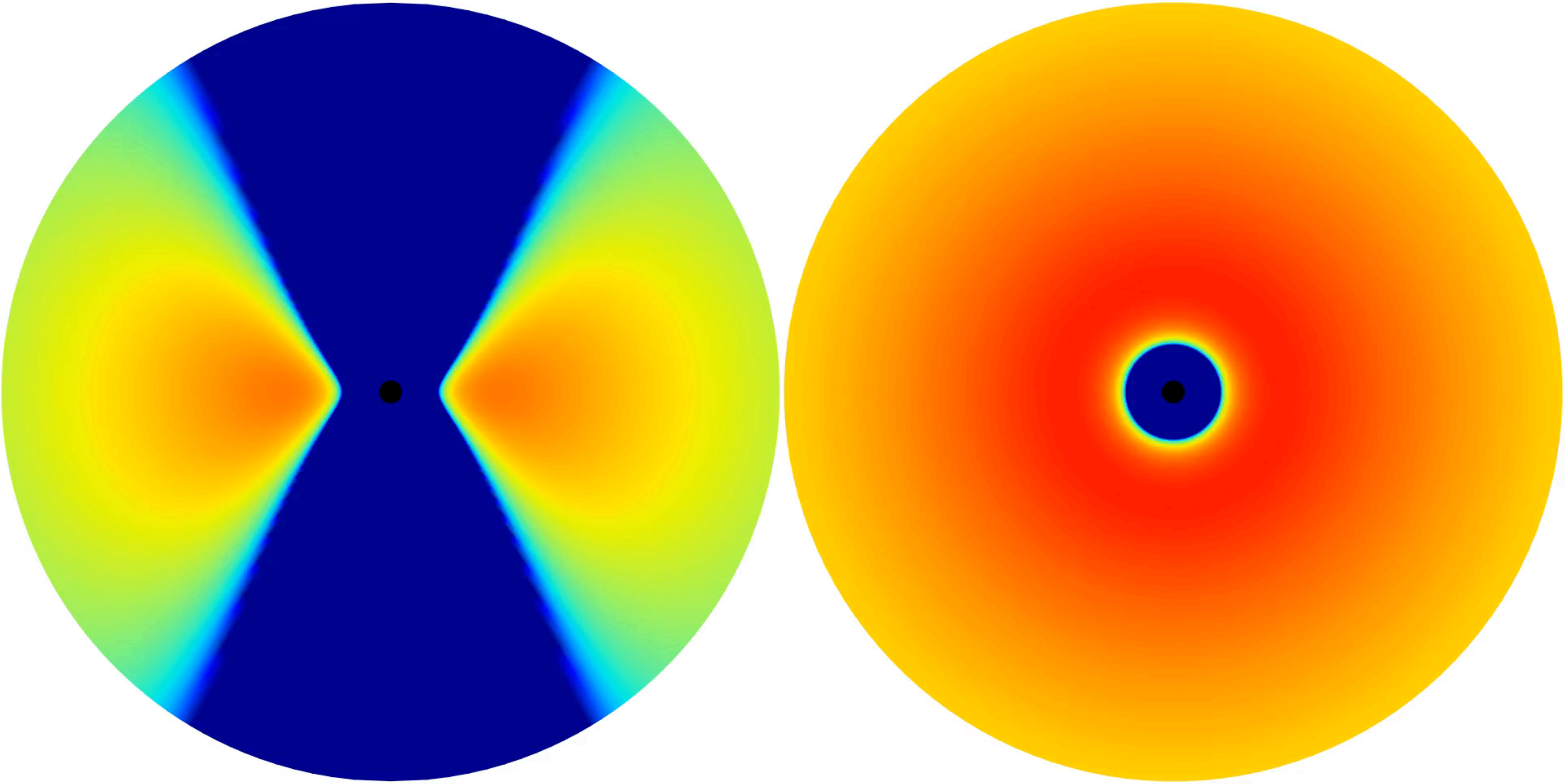
Radio jet of Cygnus X-1

- ***Steady, compact jets*** often observed during the hard state

MODERN TOOLS – GRMHD SIMULATIONS

NASA’s Pleiades Supercomputer

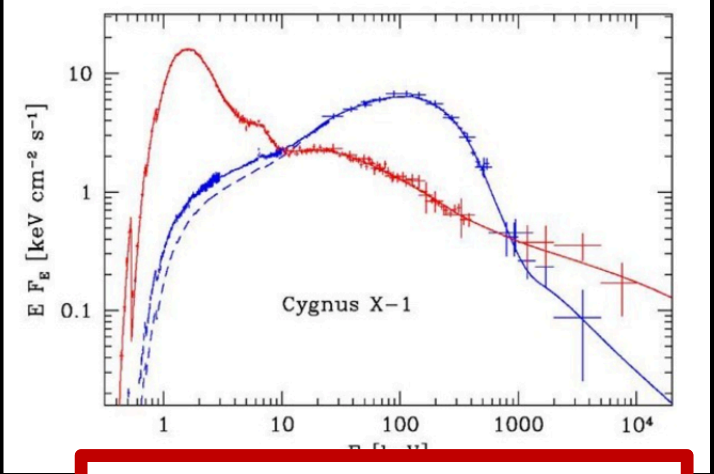
- Needed to capture all the complex processes such as turbulence, magnetic field, gas inflows and outflows, etc
- State-of-the-art general relativistic magnetohydrodynamic (***GRMHD***) simulation of the M87 accretion disk (https://www.youtube.com/watch?v=pjJlA4AjHiQ)



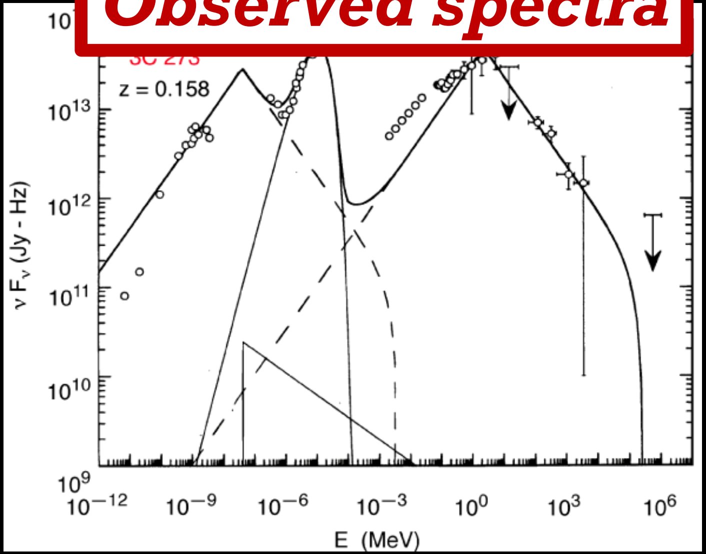
MODERN TOOLS – GRMHD SIMULATIONS

NASA's Pleiades Supercomputer

- These simulations have very high resolutions and include multiple physical processes => extremely ***computationally expensive***!!!
- We've come a long way, and these simulations are very helpful for our understanding of accretion disks, but…

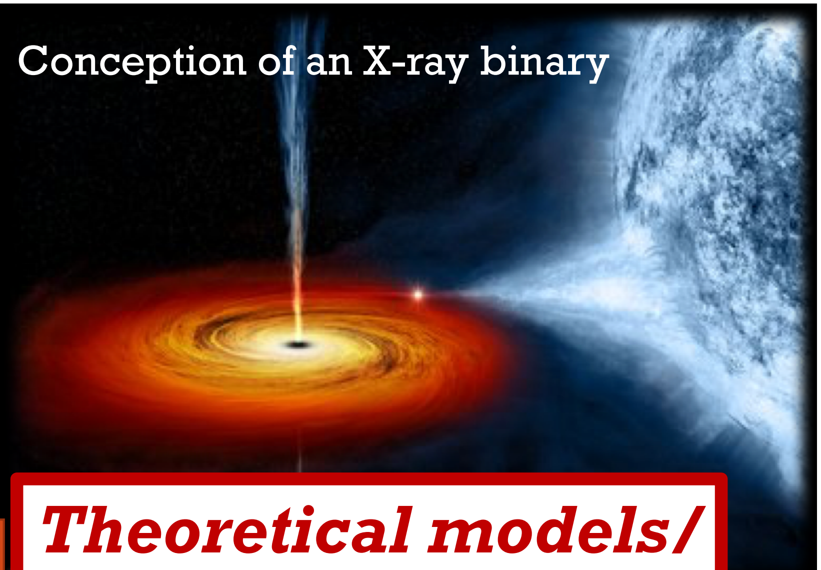


Observed spectra

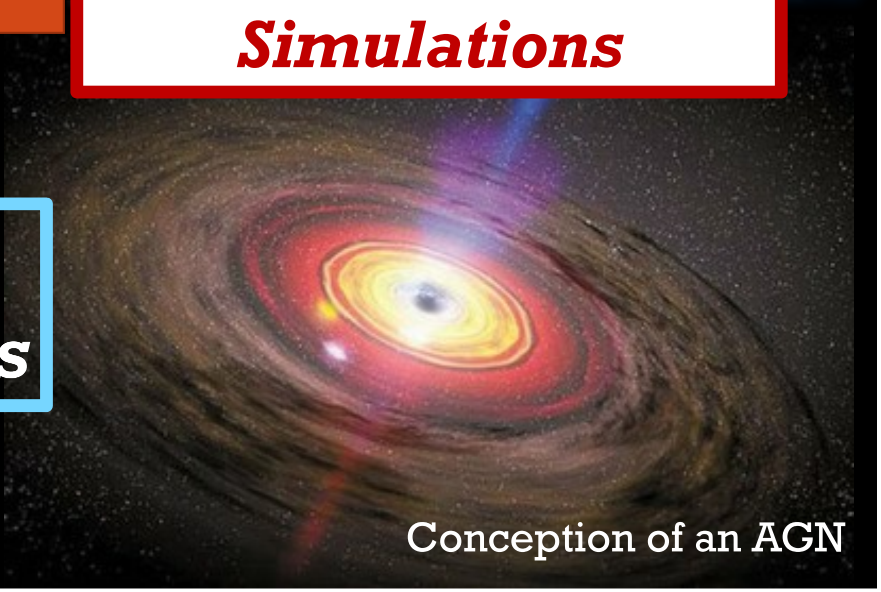


GRRMHD simulations

Theoretical models/ Simulations



Conception of an X-ray binary



Conception of an AGN

AN INCOMPLETE LIST OF OPEN QUESTIONS…

- Do the simulations agree with theoretical predictions?
- What is the nature of viscosity in accretion disks?
- What are the roles of magnetic field in the accretion disks and the formation of jets?
- What is the structure of the corona and how does it depend on the mass accretion rate?
- Are SMBHs simply scaled-up version of the smbhs?
- …

SUMMARY

- The ***Eddington limit*** – the maximum luminosity a body can achieve due to the competition between radiation pressure force and gravity
- Accretion properties depend on ***angular momentum*** and ***mass accretion rates***
- When no angular momentum -> spherical ***Bondi accretion***; when there is angular momentum -> accretion disks
- Solution of the angular momentum problem: ***outward angular momentum transport due to viscosity*** in shear flows, which allows mass to flow inward
- ***Three types (slim, thin, and thick) of accretion disks*** depending on the mass accretion rate
- X-ray binaries exhibit ***state transitions*** between X-ray hard and soft spectra, corresponding to transitions between thin and thick accretion disks due to varying accretion rates

ORAL PRESENTATION – SOME REMINDERS

- Each student shall give a ***10-15 minute presentation*** including Q&A. I will give signals when it is ***10*** and ***13*** minutes.
- The presentation should include what this news is about, why it is important/interesting, how they reach the conclusion, and what you think about their work
- Grading will take into account scores from the audience, the TA, and the instructor
  - Please be ***consistent***!!
- This is an opportunity for everyone to learn from each other's talk!
- In the Comments section at the end, please provide encouragements and ***constructive criticism***

PRESENTATIONS 4/13

- Casting Doubt on a Nearby Black Hole by Lin, Yen-Hsing 林彥興
- Extreme black holes have hair that can be combed by Liu, I-Fan 劉一璠

https://qrgo.page.link/mYQTm

https://qrgo.page.link/MvKGK