Accretion Physics

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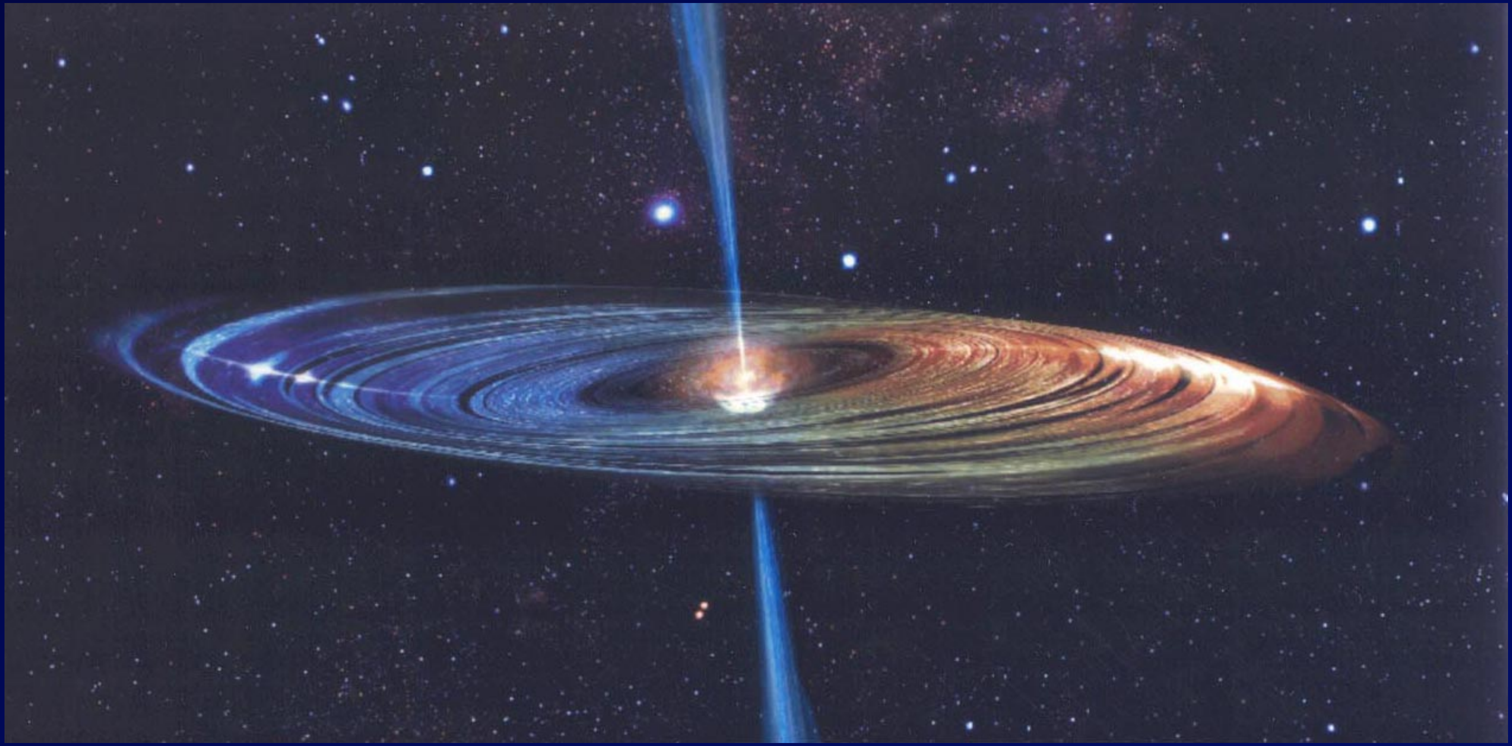
Black Hole Accretion: Highly Energetic Process Makes Relativistic Jets



Artist's Image (credit: Lincoln Greenhill, Makoto Inoue, Jim Moran)

Review Articles

- Black Hole Accretion: Narayan & Quataert, Sci. 307, 77-80 (2005)
- Hot Accretion Flows around Black Holes: Yuan & Narayan, ARAA 52, 529-588 (2014)

Accretion Disk

- Gas with angular momentum goes into orbit at a large radius around the BH
- Gas spirals in towards the center via a sequence of near-circular orbits
- Substantial amount of gravitational energy is released as heat
- Energy comes out as radiation, jets
- The **EHT** makes this a timely subject

Angular Momentum & Energy

- Consider circular Keplerian orbits (to fix ideas):
- Specific angular momentum decreases inward
  ➔ gas must lose angular momentum to spiral in

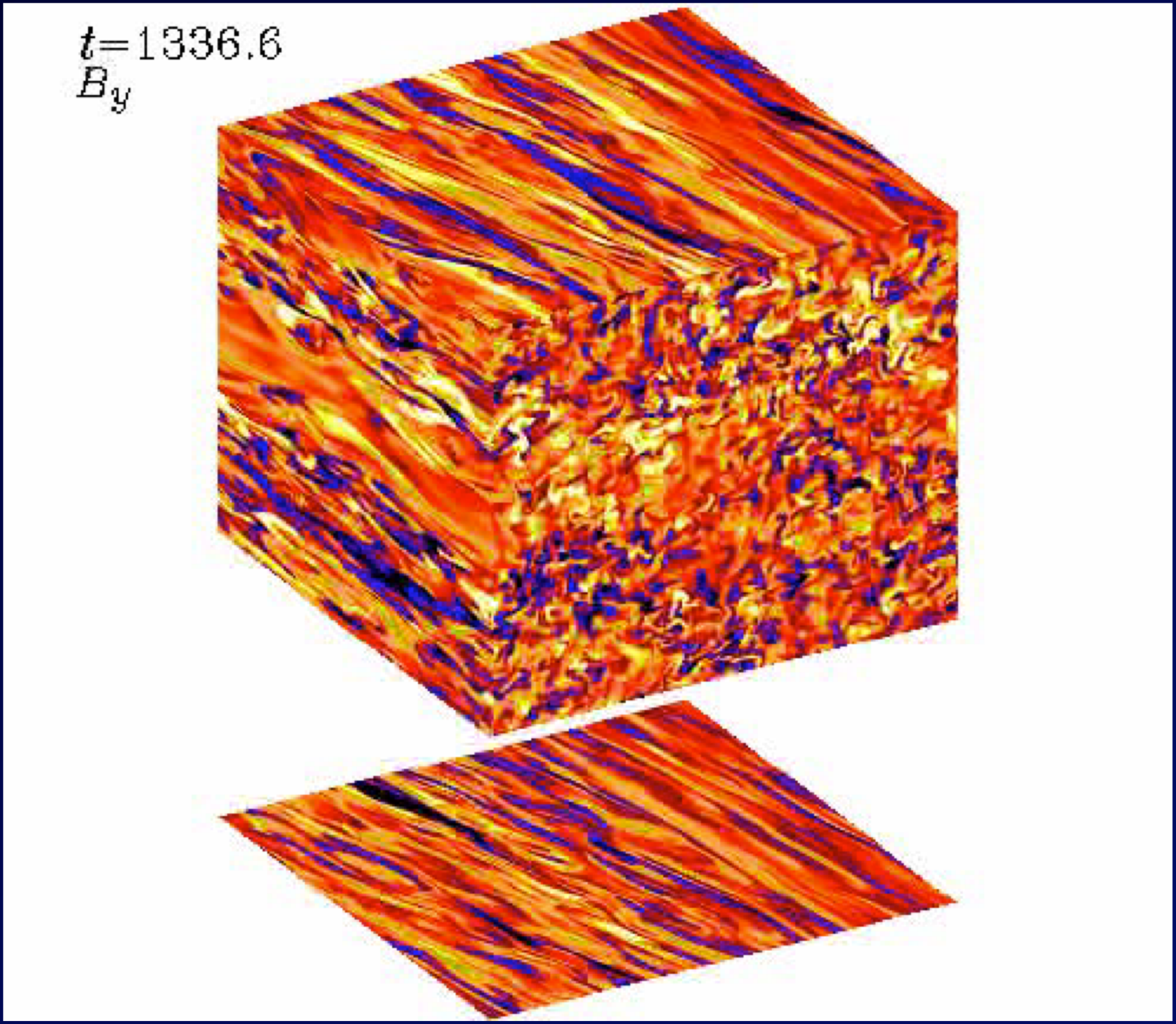
$$l = \sqrt{GMr}$$

- Binding energy increases inward
  ➔ gas must get rid of energy to remain Keplerian

$$e = GM / 2r$$

Angular Momentum Transport

- "Viscosity" in the gas can transport ang. mmtm outward, thus allowing accretion
- But microscopic viscosity is too weak
- Major Breakthrough: Magnetorotational instability (MRI: Balbus & Hawley 1991)
  - Weak magnetic field in a differentially-rotating disk causes MRI
  - Nonlinear development of MRI gives turbulence and angular mmtm transport



Movie Credit: Axel Brandenburg

Importance of Numerical Computations

- Numerical simulations are vital
  - Magnetic fields (MHD, MRI, and beyond)
  - Nonlinear turbulence
  - General relativity: Kerr metric
  - Webinar: Charles Gammie
- Ray-tracing in curved space-time
  - Webinar: Chi-Kwan Chan

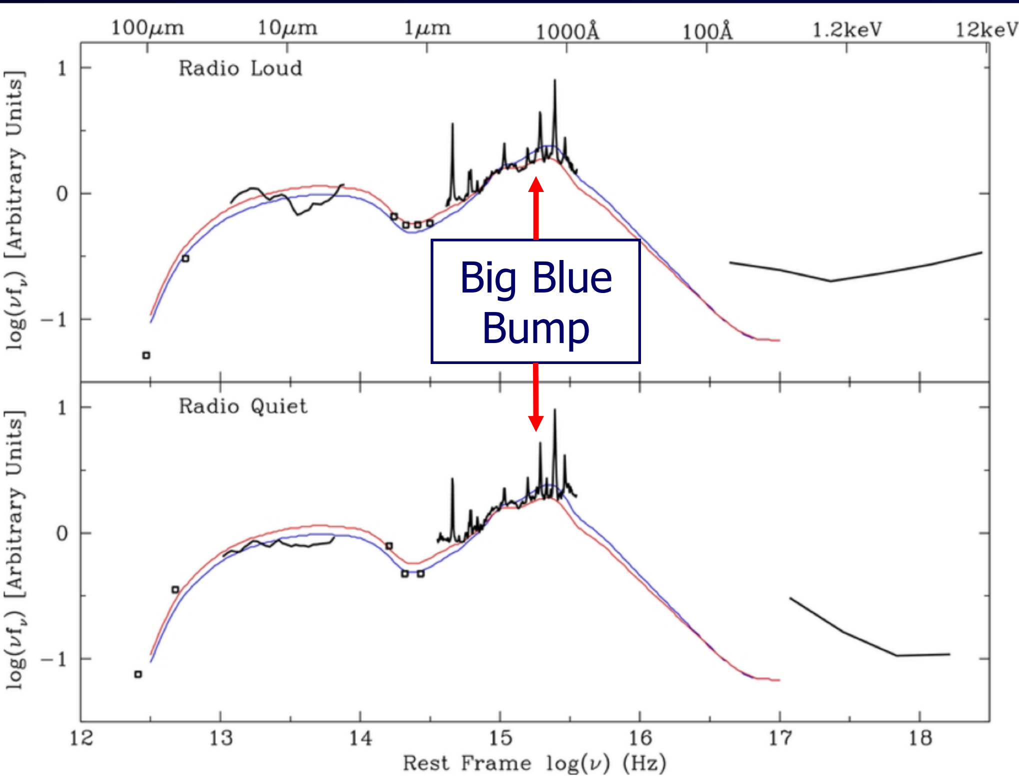
What About Energy?

- Accretion down to the center releases a lot of energy: ~GM/2r
- This energy appears as heat (viscous dissipation into heat is unavoidable)
- Under favorable cases, the hot gas will simply radiate away all the heat
- We then have a Thin Accretion Disk

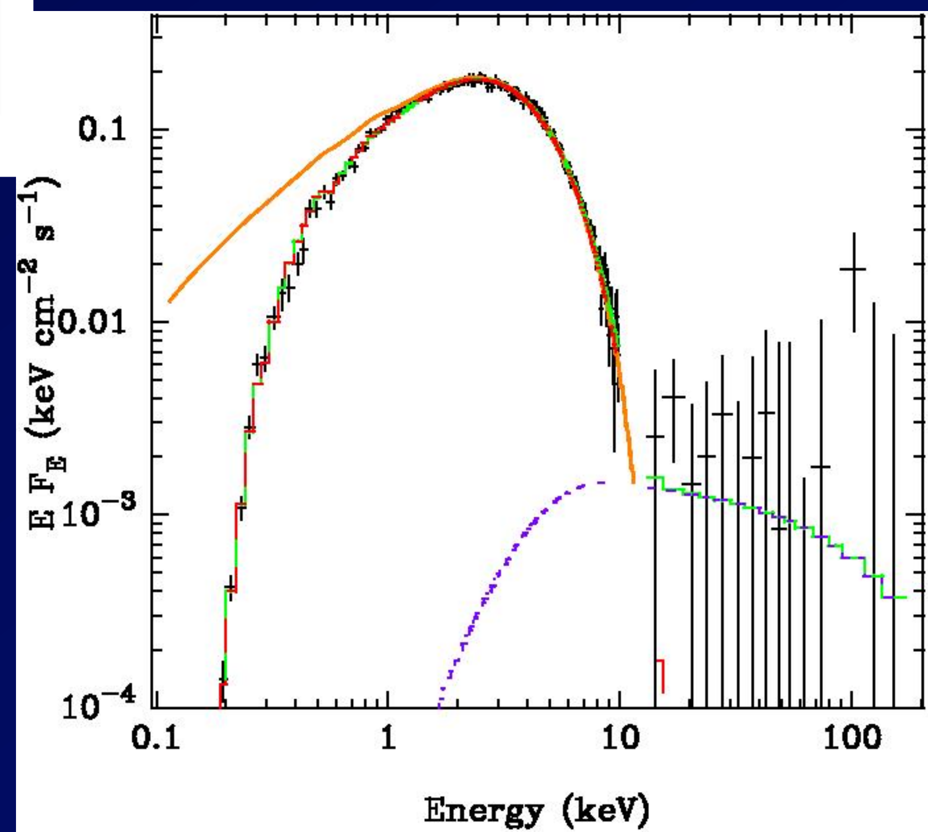
Thin Accretion Disk Model

(Shakura & Sunyaev 1973; Novikov & Thorne 1973)

- Geometrically thin: H ? R
  - Cool gas: c_s ? v_K, p ? ?v_K^2 (gas pressure is negligible)
  - Keplerian rotation: ? = $?_K$
  - Radiatively efficient: $L_{acc} \sim 0.1$ Mdot c^2
- Optically thick --- blackbody-like radiation
  - multi-color blackbody spectrum
- Quasars, X-ray binaries in the “soft state”



Typical spectra of luminous quasars. The Big Blue Bump in the spectrum is believed to be from a thin disk.



Thermal bump in spectrum of X-ray Binary LMC X-3 in the soft state. Modeled well with a thin disk.

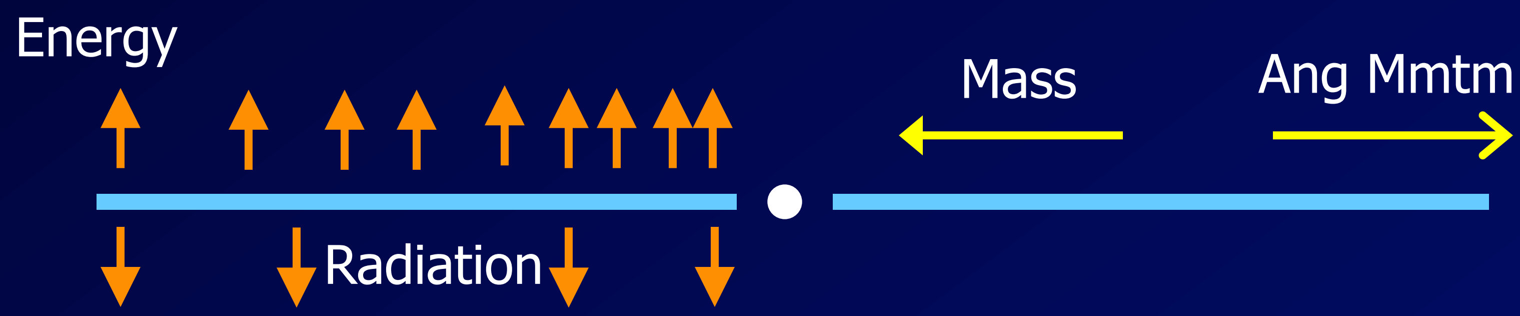
Eddington Limit

$$L_{\rm Edd} = \frac{4\pi GMc}{\kappa} = 10^{38}\,\frac{M}{M_\odot}\,{\rm erg\,s^{-1}}$$

$$\dot{M}_{\rm Edd} = \frac{L_{\rm Edd}}{0.1c^2} \approx 2\times 10^{-8}\left(\frac{M}{M_\odot}\right) M_\odot{\rm yr}^{-1}$$

- Mdot_{Edd} is estimated here assuming a fiducial radiative efficiency of 10%

Can a Disk Exceed the Eddington Mass Accretion Rate?



- As the disk luminosity approaches L_{Edd} , radiation pressure puffs up the disk vertically
- No longer geometrically thin
  - Thin Disk Model becomes inconsistent
- Does this mean $Mdot > Mdot_{Edd}$ is impossible?
- Will the disk just blow itself apart?

Advection Saves the Day

- When Mdot > $Mdot_{Edd}$, ~$1L_{Edd}$ worth of luminosity is radiated from the disk surface
- Rest of the energy remains trapped in the gas and is "advected" with the gas
- Advection-dominated accn flow (ADAF)
- Another name: Radiatively Inefficient Accn
- Internal energy: large radiation pressure
- Geometrically thick disk
- Heavy mass loss expected

Two Solutions to Energy Problem
→ Two Kinds of Accretion

Radiatively Efficient
Thin Accretion Disk

Most of the heat energy is radiated

$$L_{\rm rad} \sim 0.1 \dot{M} c^2$$

Advection-Dominated
ADAF
Radiatively Inefficient

Most of the heat energy is retained in the gas

$$L_{\rm rad} \ll 0.1 \dot{M} c^2$$

$$L_{\rm adv} \sim 0.1 \dot{M} c^2$$

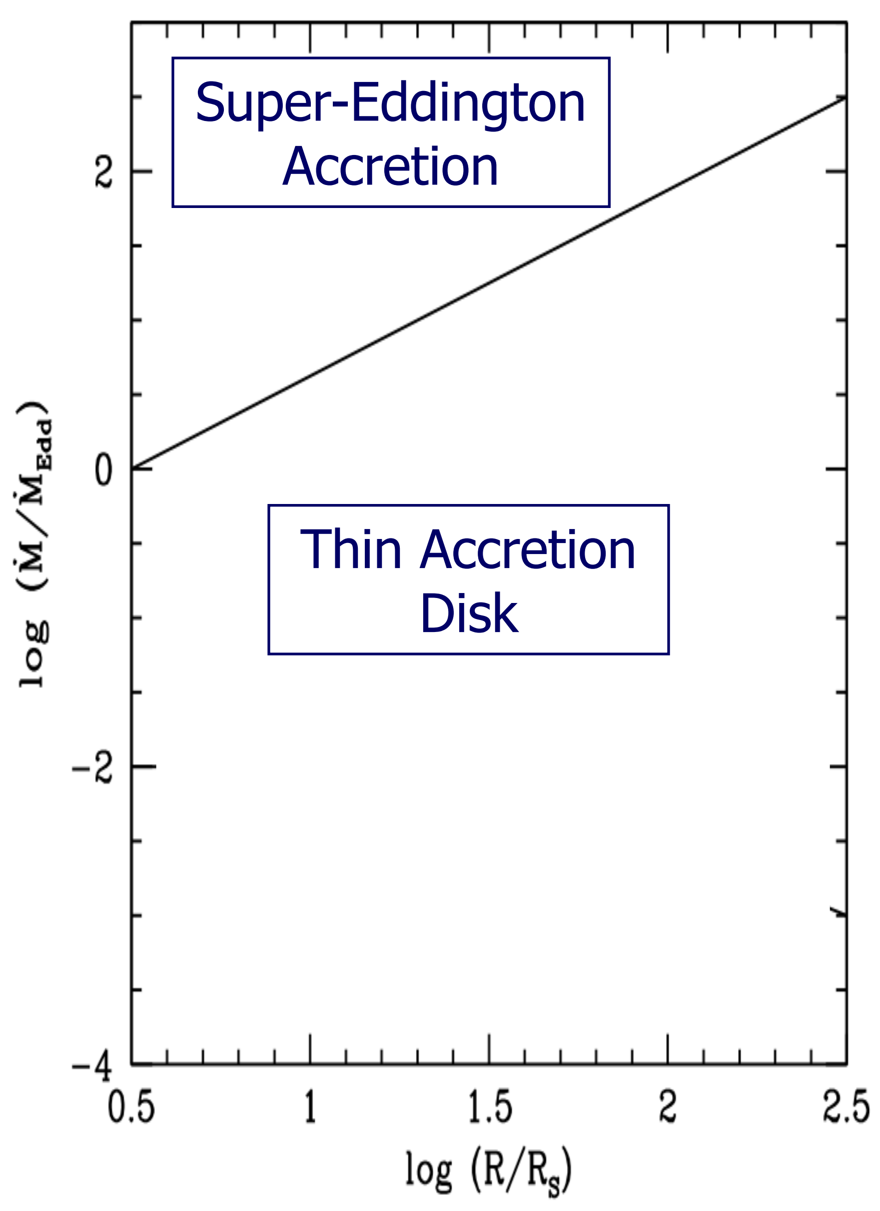
Two Distinct Accretion Regimes

Looks like a simple story:

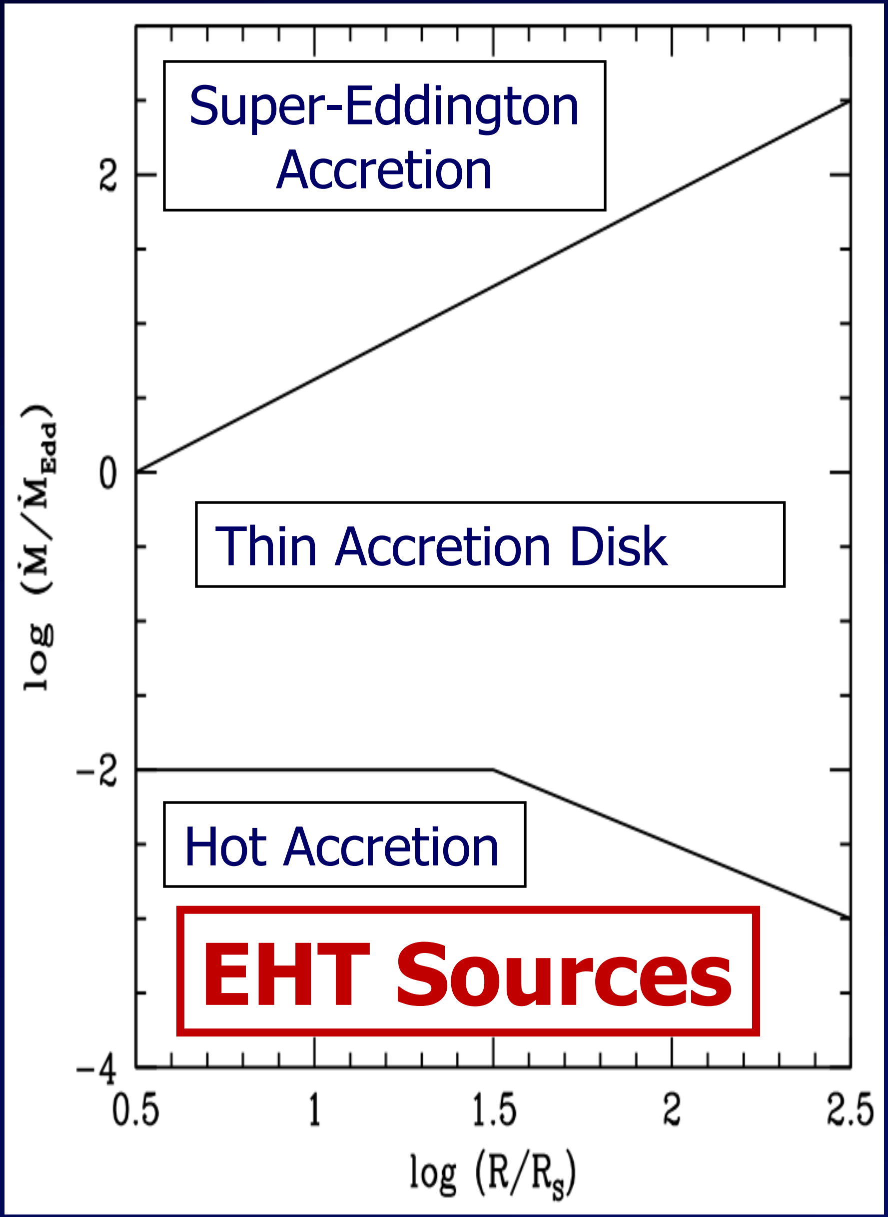
Radiatively efficient thin disk when $F_{local} < F_{Edd}$

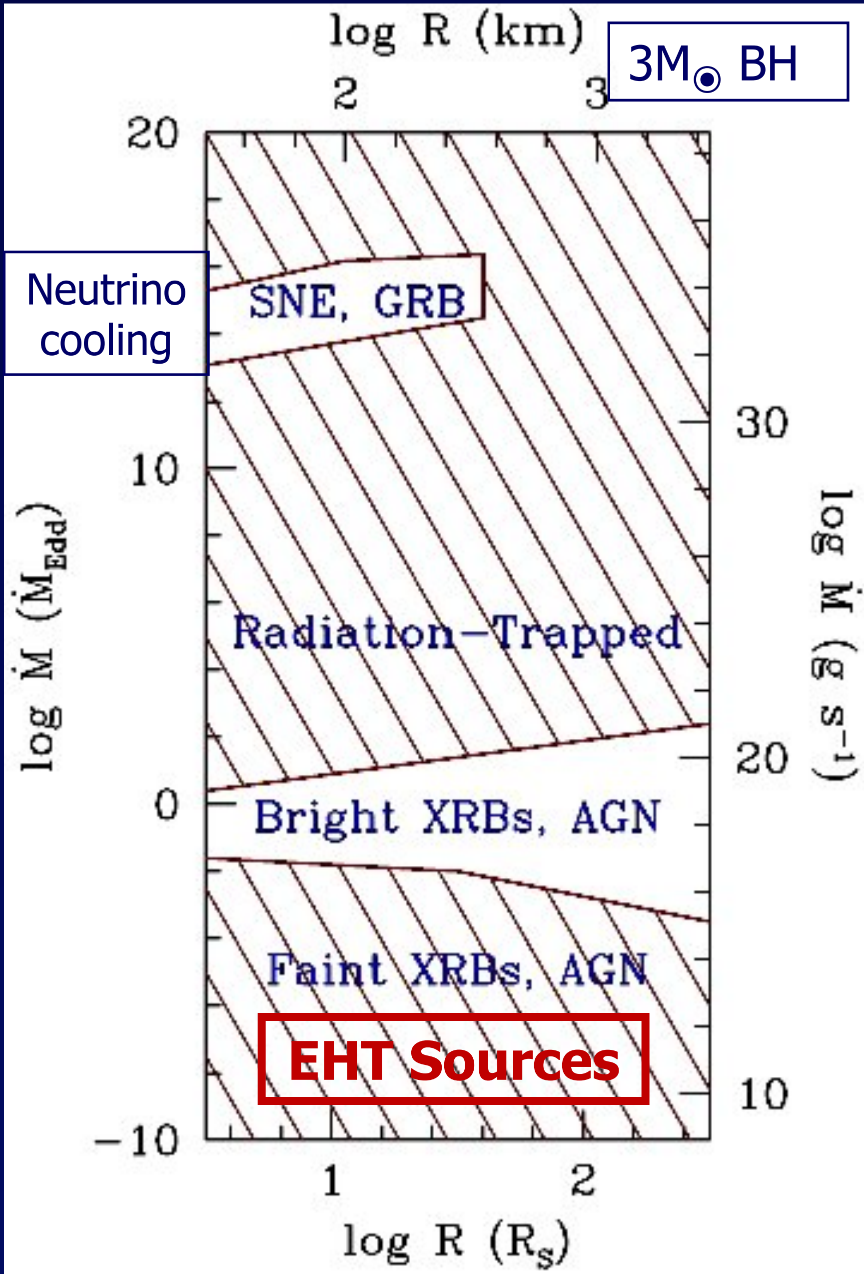
Advection-dominated thick disk otherwise

Actually, the story is much more interesting!



Accretion Regimes

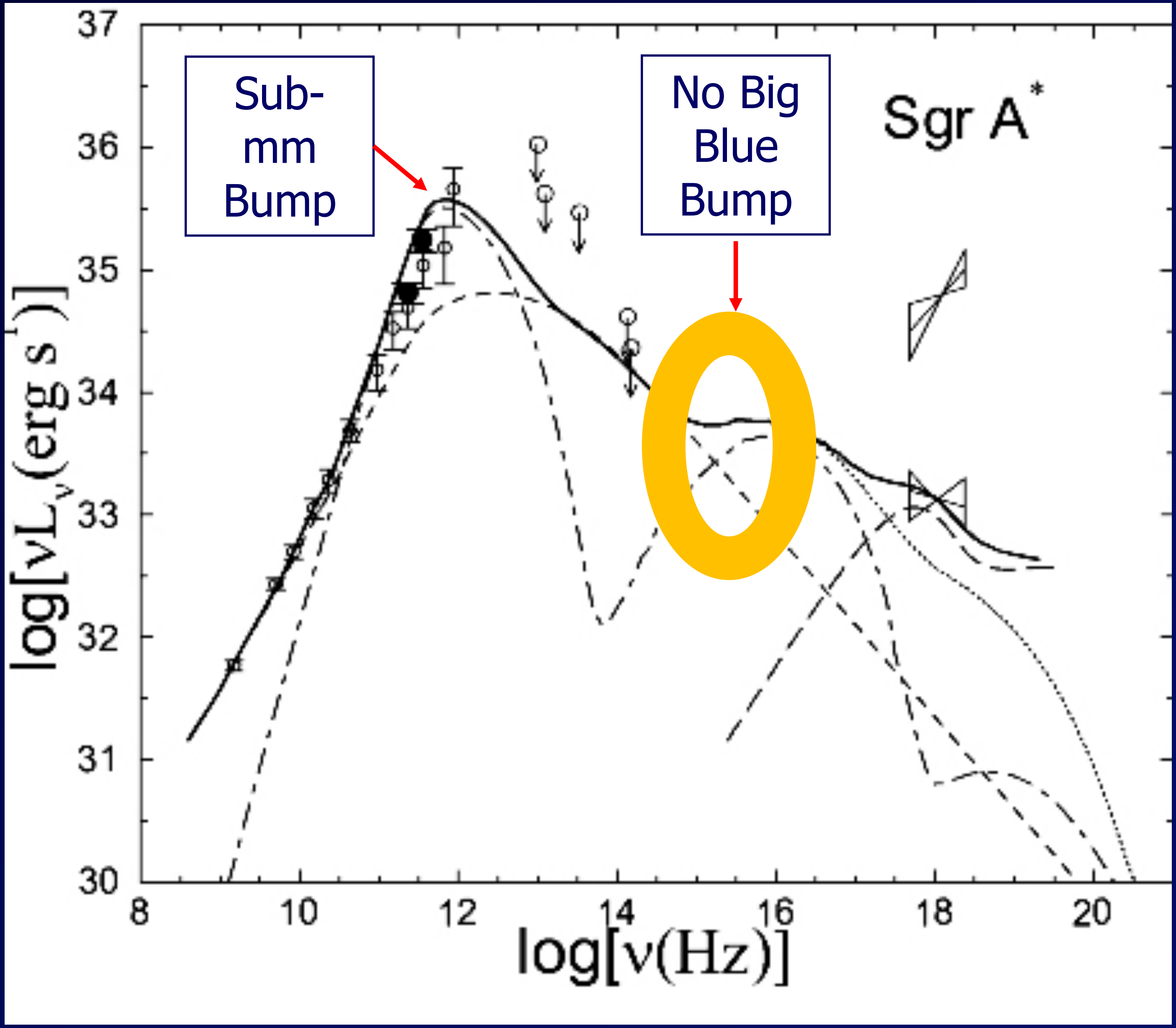




Narayan & Quataert (2005)

A Surprise at Low Mdot

- For Mdot $\ll$ $Mdot_{Edd}$, the thin disk model is perfectly good (very very thin)
- But Nature doesn't like this model!
- When Mdot $\lesssim$ 0.01 $Mdot_{Edd}$, both supermassive and stellar-mass BHs seem to switch to a Hot Accretion Flow
- Thermal Big Blue Bump goes away, and a very different spectrum appears



Galactic Center BH: Sagittarius A*

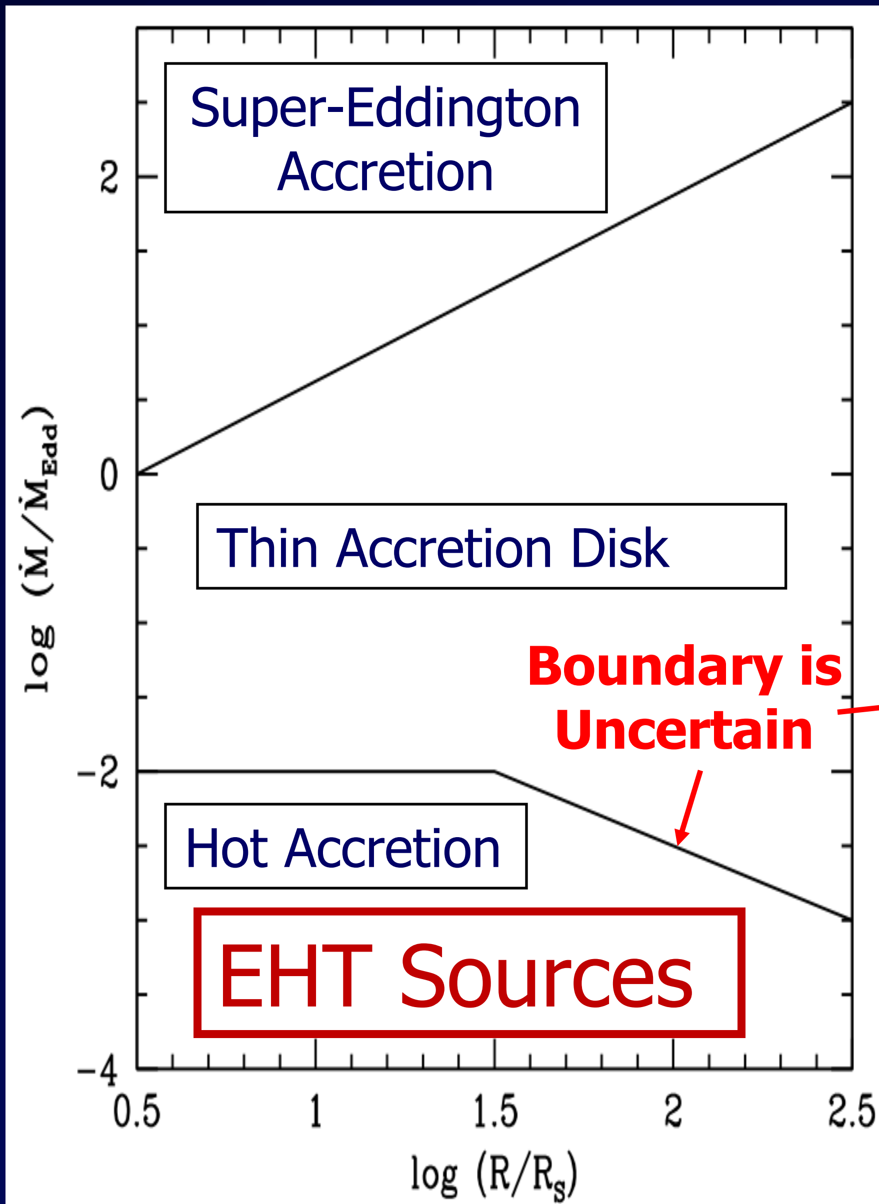
Theory: A Hot Accretion Flow Solution Appears at Low Mdot

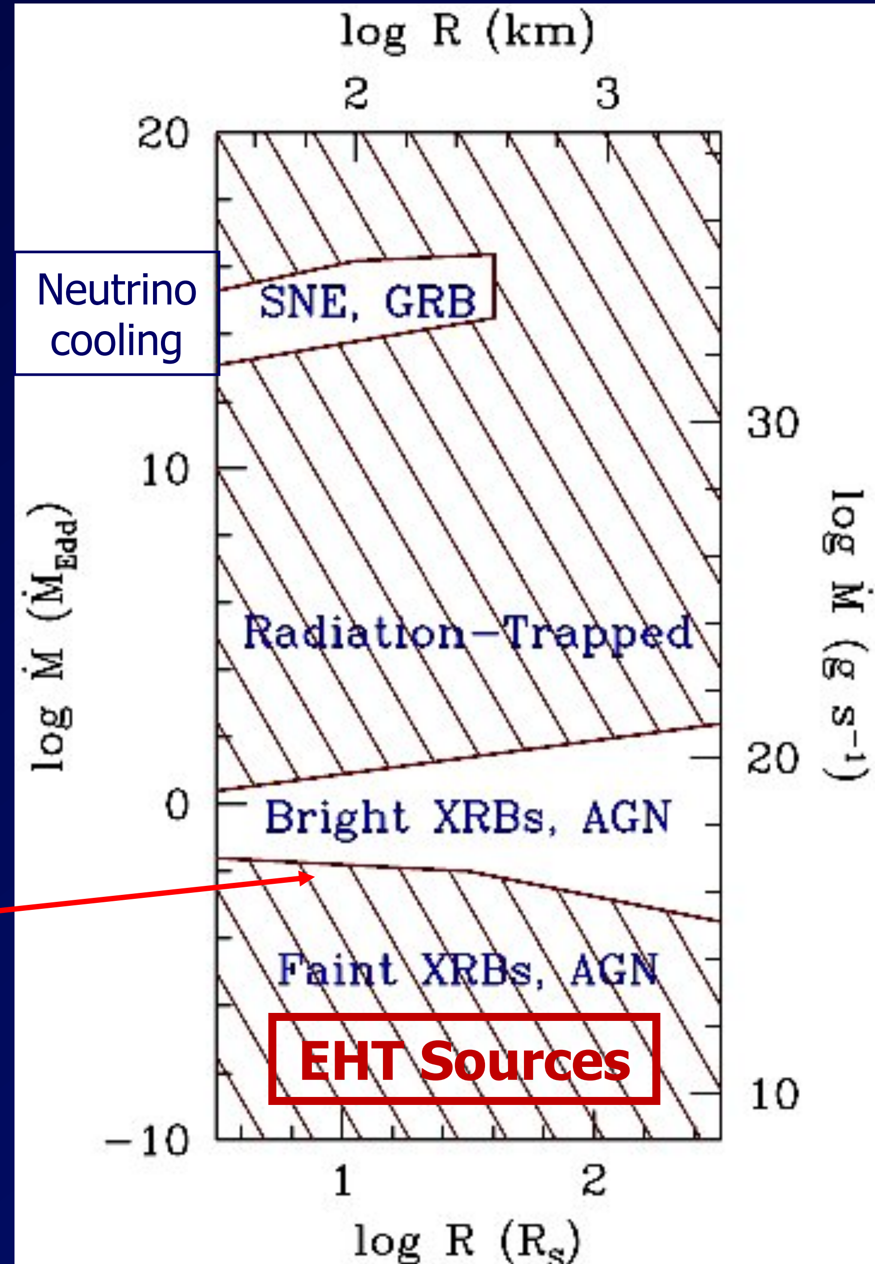
- For Mdot $\lesssim$ 0.01 $\mathrm{Mdot}_{\mathrm{Edd}}$, a new accretion solution appears which
  - is advection-dominated (ADAF)
  - contains very hot gas (virial temperature)
  - is geometrically very thick
  - is optically thin
- The thin disk solution is still allowed, and is perfectly viable!

So Why Does Nature Prefer Hot Accretion at Low Mdot?

- Nature seems to be just waiting for the hot solution to appear and switches to it immediately
- But why is this the case?
- There is no really good answer
- It is also not clear how quickly the transition can happen

Accretion Regimes



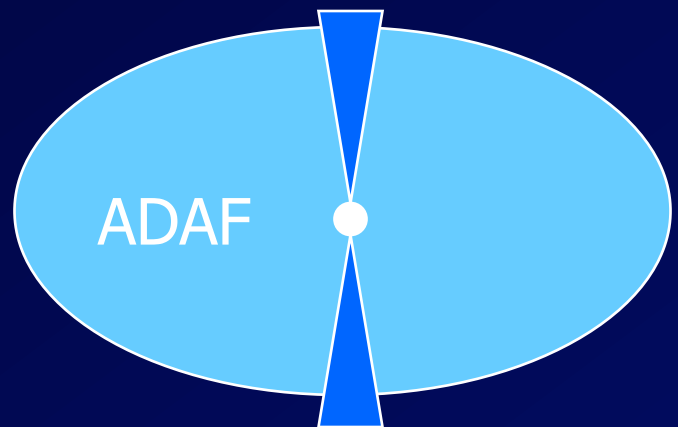


Narayan & Quataert (2005)

Hot Accretion Flow Geometry

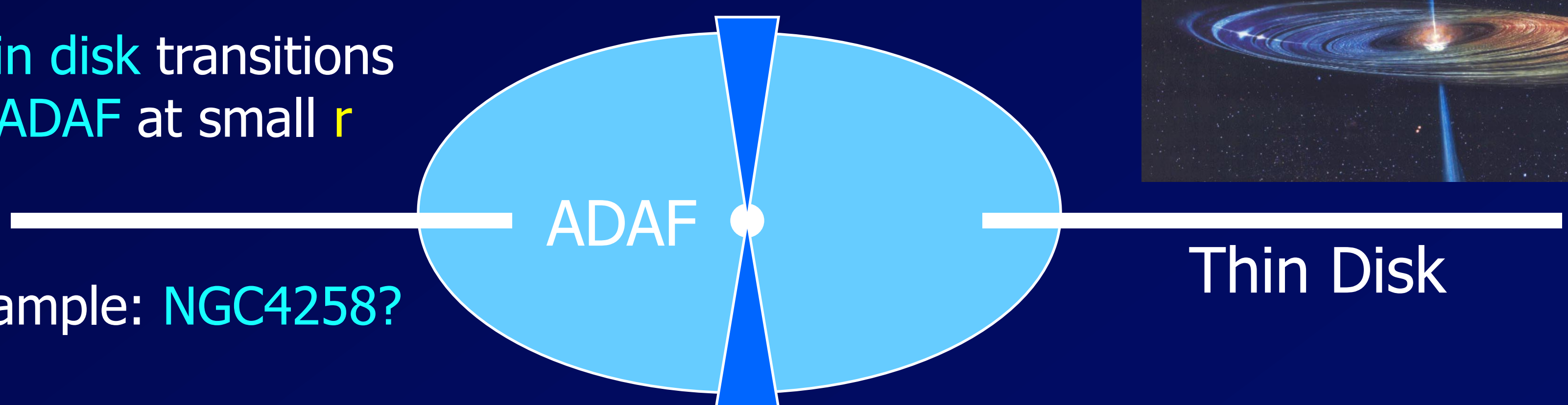
Pure ADAF -- no thin disk at all

Examples: Sgr A*, perhaps M87



Thin disk transitions to ADAF at small r

Example: NGC4258?



Hot Accretion Flow Properties

- ADAF: Radiatively inefficient
- Energy stored in gas (gas/mag pressure)
- Gas becomes very hot: $T \sim 10^{12} K/r$
- Disk is geometrically thick: $h \sim r/2$
- Density becomes very low: $\rho \sim T^{-3/2}$
- Optically thin: $\tau_{es} \ll 1$ (we can see the BH!)
- Cooling rate is low: even though T is large, ρ is very small (brems: $\rho T^{1/2}$)
- Low cooling → radiatively inefficient

Two-Temperature Plasma

- At the very low ρ found in a hot accretion flow, the plasma is collisionless
- Likely to become two-temperature with $T_e \ll T_i$ (e.g., $T_i \rightarrow 10^{12}$K, $T_e < 10^{11}$K)
- This enhances radiative inefficiency
- Can the EHT "prove" that the plasma in M87, Sgr A* is two-temperature?

Radiation from a Hot ADAF

- Hot electrons with temperature $>10^{10}$K radiate primarily via
  - Synchrotron
  - Bremsstrahlung
  - Comptonization:
    - Synchrotron self-Compton
    - External soft photons (if there is an outer disk)
- Ions ($>10^{11}$K) hardly radiate (pions?)

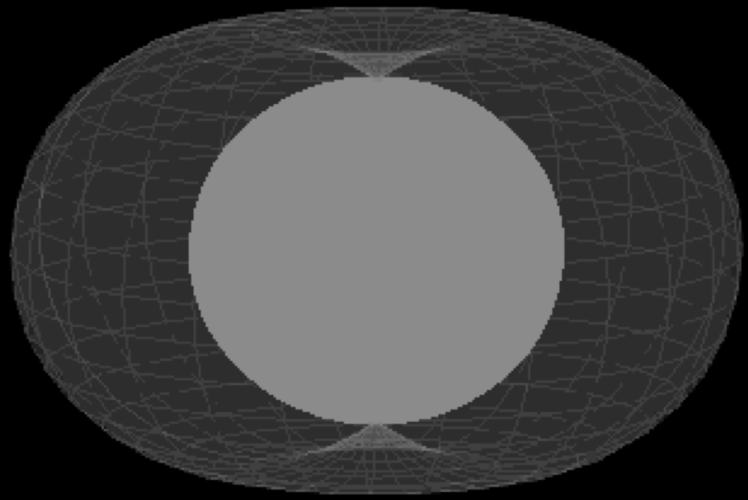
Energy Problem: To Accrete or Not?

- Without radiative cooling, accretion energy is stored as pressure (gas, B)
- Gas is only weakly bound to the BH: pressure balances gravity
- Two limits of energy advection:
  - All the gas accretes into the BH
  - (Almost) all the gas is ejected
- The truth is probably in between
- Waiting for simulations to give the answer

ADAFs and Relativistic Jets

- Numerical simulations show that hot accretion flows produce powerful relativistic jets
- Physics consistent with Blandford & Znajek (1977): B plus BH spin

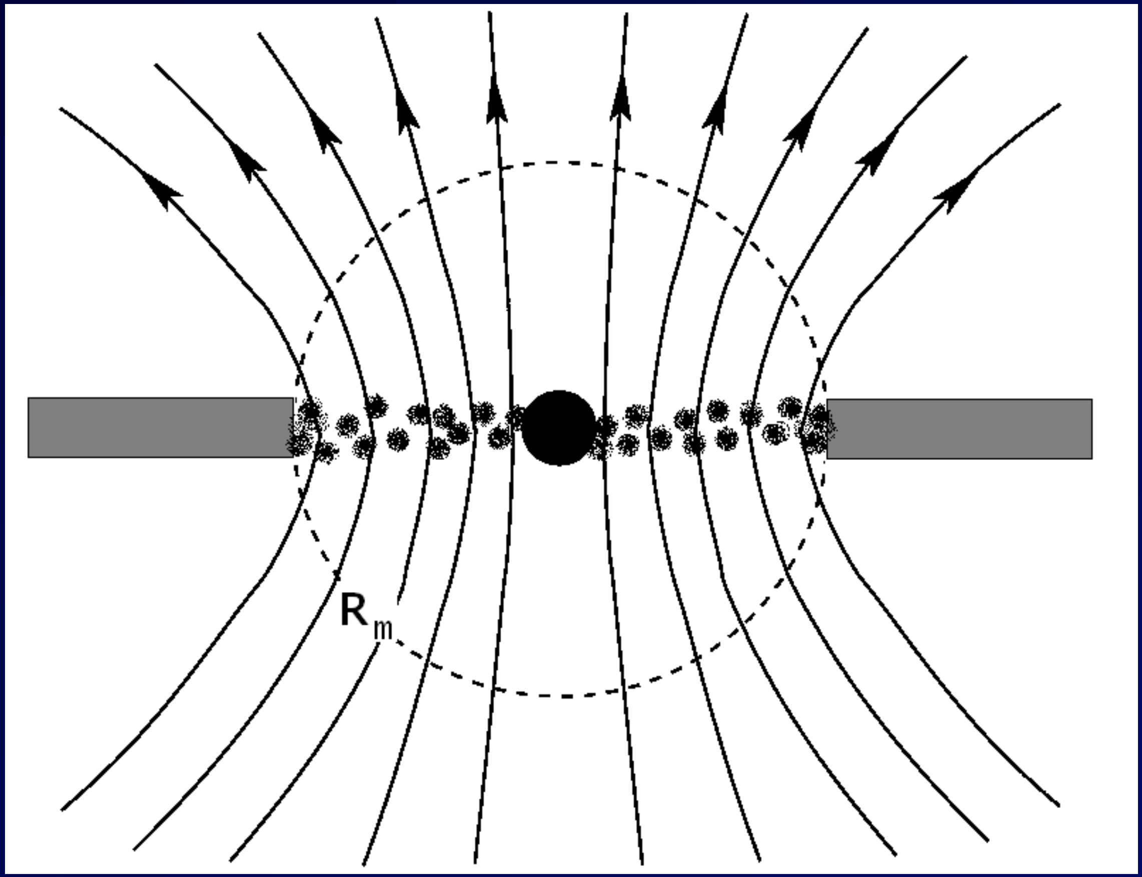
$$P_{\rm jet} \approx \Phi_{\rm BH}^2 a_*^2$$



Semenov et al. (2004)

Black Hole Spin Energy!

- P_{jet} = 1.4 Mdot c^2 for a simulation with a_*=0.99 (Tchekhovskoy 2011)! How?!
- Jet derives most (all?) of its power from the spin energy of the BH
- Can we have arbitrarily large jet power (100 Mdot c^2) by simply increasing B?
- No! There is a limiting field strength: Magnetically Arrested Disk (MAD)



MAD: The field is as strong as it can be and yet permit gas to accrete. Accretion with weaker fields is called SANE

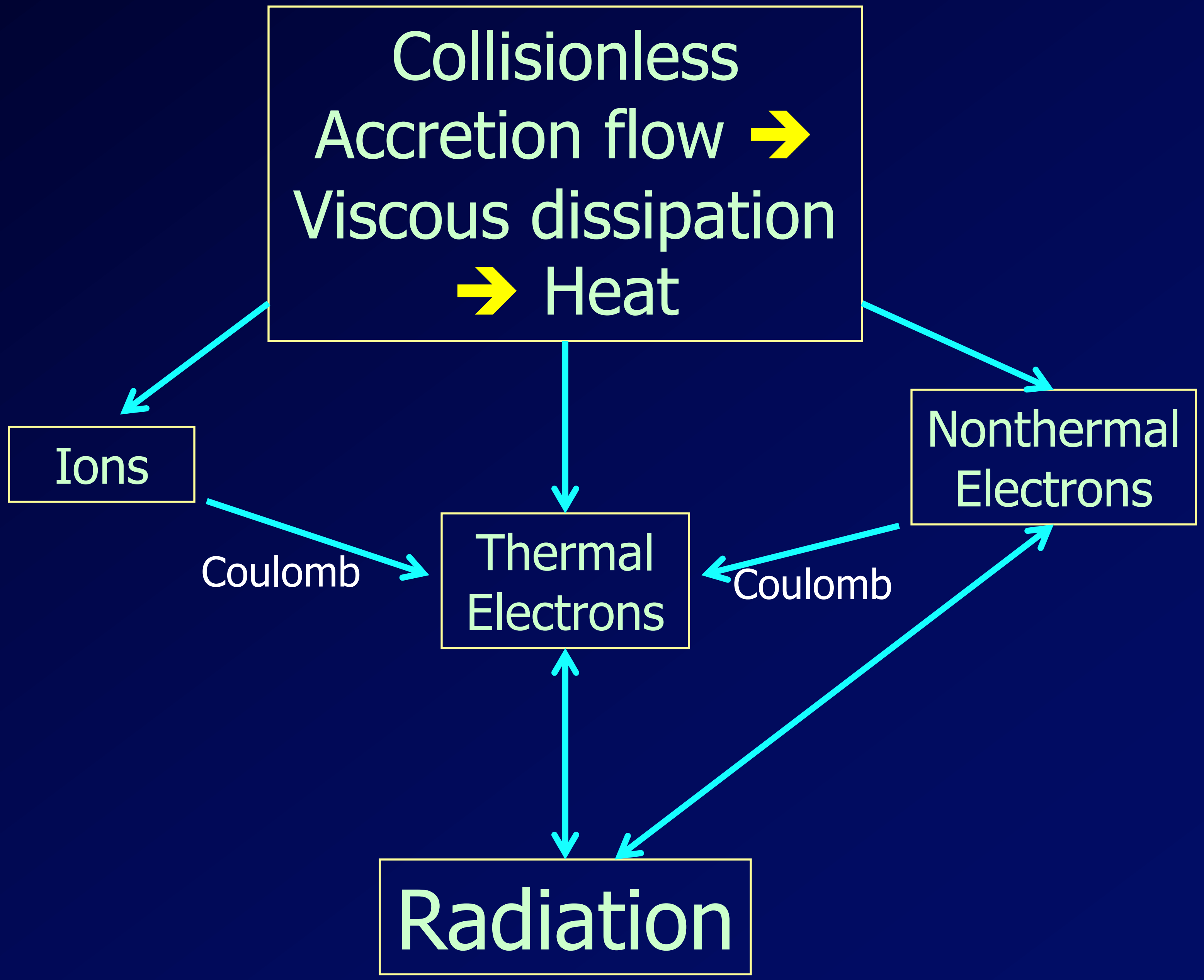
$$\phi_{\mathrm{MAD}} = \Phi_{\mathrm{BH}} / \sqrt{\dot{M} r_g^2 c} \approx 50$$

EHT and Jets

- Can observations with the EHT “prove” that the jet in M87 is powered by the Blandford & Znajek mechanism?
- Can observations with the EHT “explain” why Sgr A* apparently has no jet (or at best a very weak one)?

Hot Accretion Thermodynamics is Highly Uncertain

- Plasma in a Hot ADAF is collisionless
  - Electrons/protons do their own thing
- Non-equilibrium: Two-temperature + …
- Each particle remembers its heating history and radiates accordingly
- We need to understand plasma heating processes to interpret observations
- Both a curse and an opportunity


Collisionless
Accretion flow →
Viscous dissipation
→ Heat
Ions
Thermal
Electrons
Nonthermal
Electrons
Coulomb
Coulomb
Radiation

Particle Heating/Acceleration

- Multiple heating/acceleration channels
  - Compression, shear, instabilities
  - Turbulent cascade and dissipation
  - Magnetic reconnection
  - Shocks

Upcoming Webinars

- Gammie: GRMHD Numerical Simulations
- Chan: Ray Tracing
- Quataert: Subgrid/Plasma Physics
- Berti: Kerr Black Hole and Beyond

Concluding Comments

- This webinar gave a broad survey of
  - Accretion Physics, esp. Hot Accretion Flows
  - Connection to Relativistic Jets
- The EHT has triggered renewed interest
  - EHT motivates re-examining our ideas
  - EHT can test our understanding
  - EHT can/will come up with surprises

Please Complete the Survey!

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