Advection-Dominated Accretion in Low-Luminosity Black Holes

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20-Year Collaboration with Jeff McClintock

- **My closest collaborator by far**
- About 65 papers (50 refereed) over the time period 1996–2014
  - ADAF model of BH X-ray binaries
  - BH: Event Horizon, spin, mass distribution
- Many students: Ann Esin, Kristen Menou, Eric Zimmerman, Rebecca Shafee, Bob Penna, Sasha Tchekhovskoy, Jack Steiner
- Many postdocs…

Accretion Disk Theory: Analytical Models

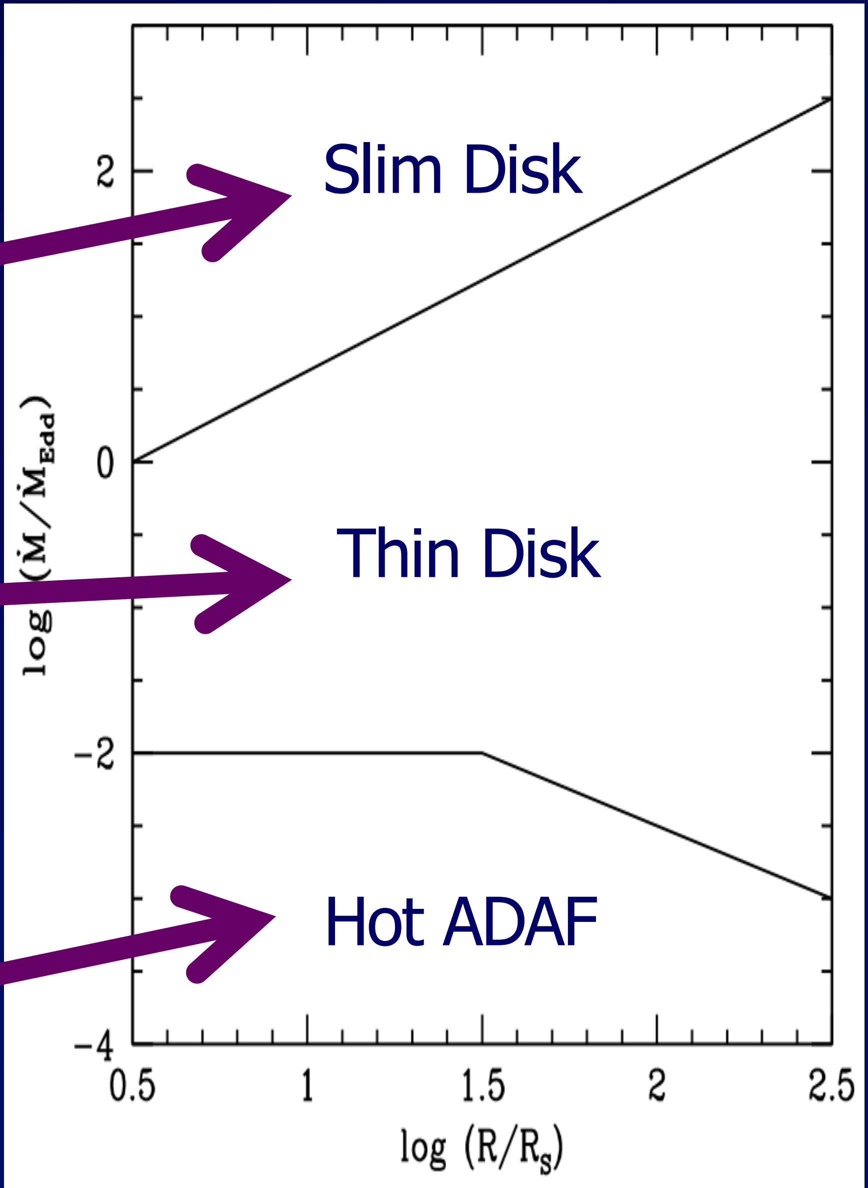
- 1D accretion models have been developed by simplifying the equations (Shakura & Sunyaev 1973; Novikov & Thorne 1973; Narayan & Yi 1994, 1995; Abramowicz et al. 1988, 1995;…)
- These models provide a lot of insight
- Three regimes of accretion have been identified, distinguished by $Mdot/Mdot_{Edd}$

Accretion Regimes

Super-Eddington Accretion, Slim Disk, ADAF (Abramowicz+ 89; Sadowski+ 15)
Radiation-dominated: ULX, SS433

Thin Accretion Disk: radiatively efficient (Shakura-Sunyaev, Novikov-Thorne 73)
Radiation-dominated: BH XRB soft state

ADAF, RIAF, Hot Accretion (Ichimaru 77; Rees et al. 82; Narayan& Yi 94, 95; Abramowicz+ 95; Yuan & Narayan 14)
Hot, two-temperature, radiatively inefficient: BH XRB low/quiescent state



Advection-Dominated Accretion Flow (ADAF)

$$TdS = dQ = Q^{+} - Q^{-}$$

$$\rho T \frac{ds}{dt} = q^{+} - q^{-}$$

$$\rho v_r T \frac{ds}{dr} = q^{+} - q^{-}$$

$$q^{\mathrm{adv}} = q^{+} - q^{-}$$

- Thin accretion disk
  Radiatively efficient

  $$q^{+} \approx q^{-} \gg q^{\mathrm{adv}}$$

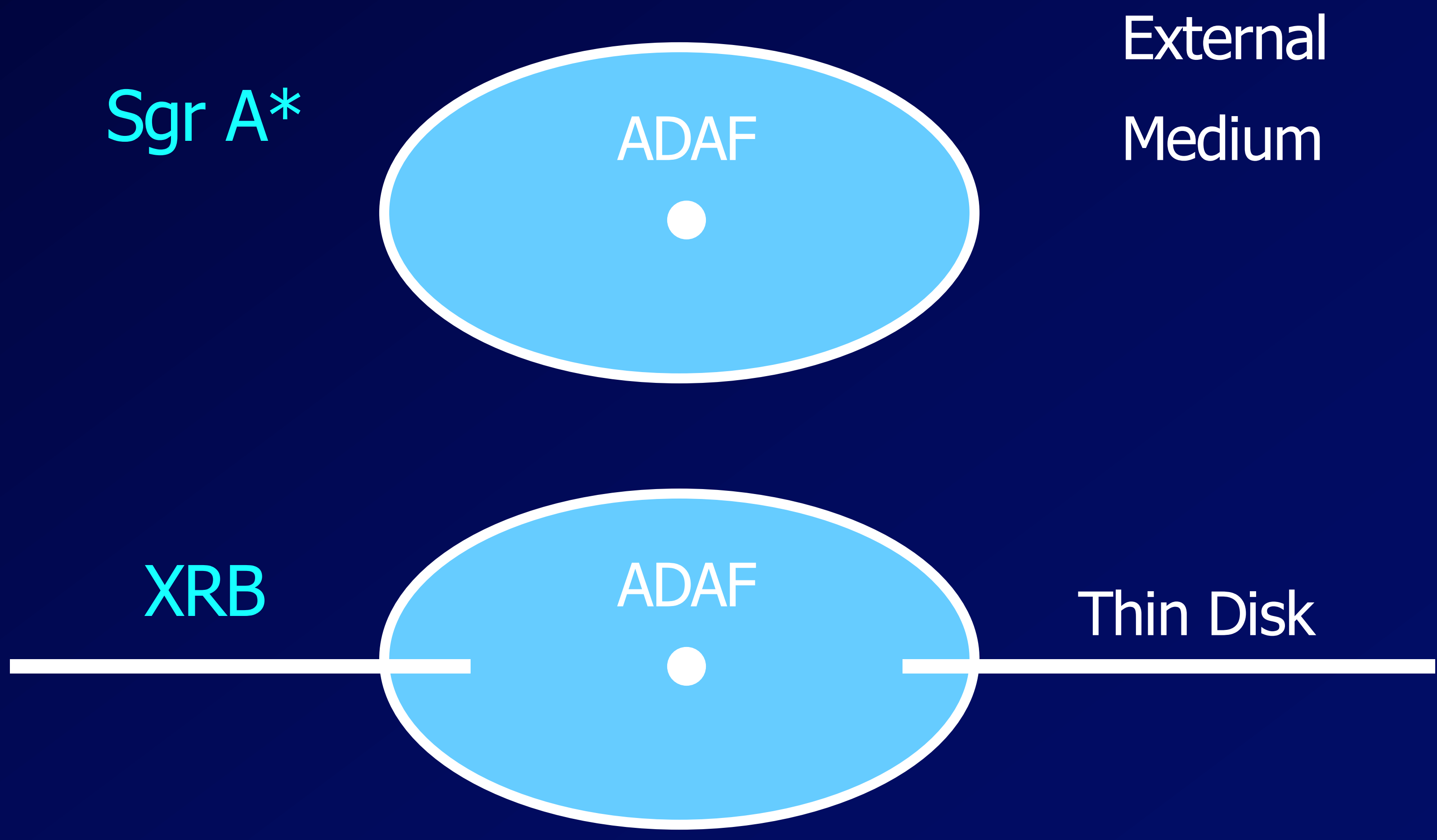
- Advection Dominated Accretion Flow (ADAF)
  Radiatively inefficient

  $$q^{+} \approx q^{\mathrm{adv}} \gg q^{-}$$

Properties of Hot ADAFs

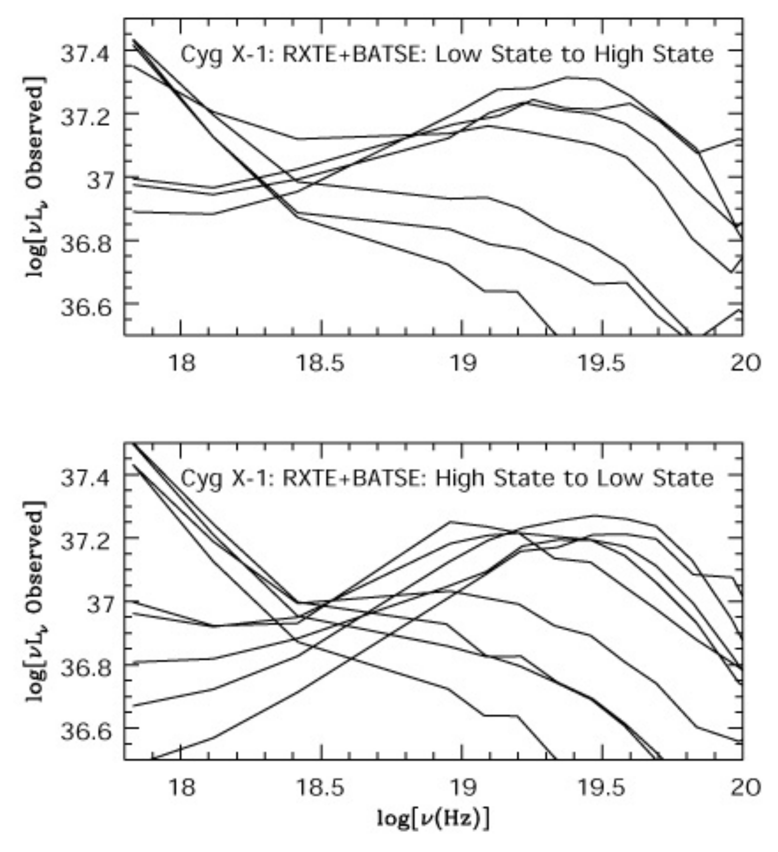
- Radiatively inefficient (particles meet infrequently)
- Optically thin: radiates via synchrotron, bremsstrahlung, inverse Compton
- Relevant for low-Mdot accretion sources
- Two-temperature: $T_i \sim 10^{12}K/r$, $T_e \sim 10^{10-11}K$
- Geometrically thick
- Has powerful jets and winds

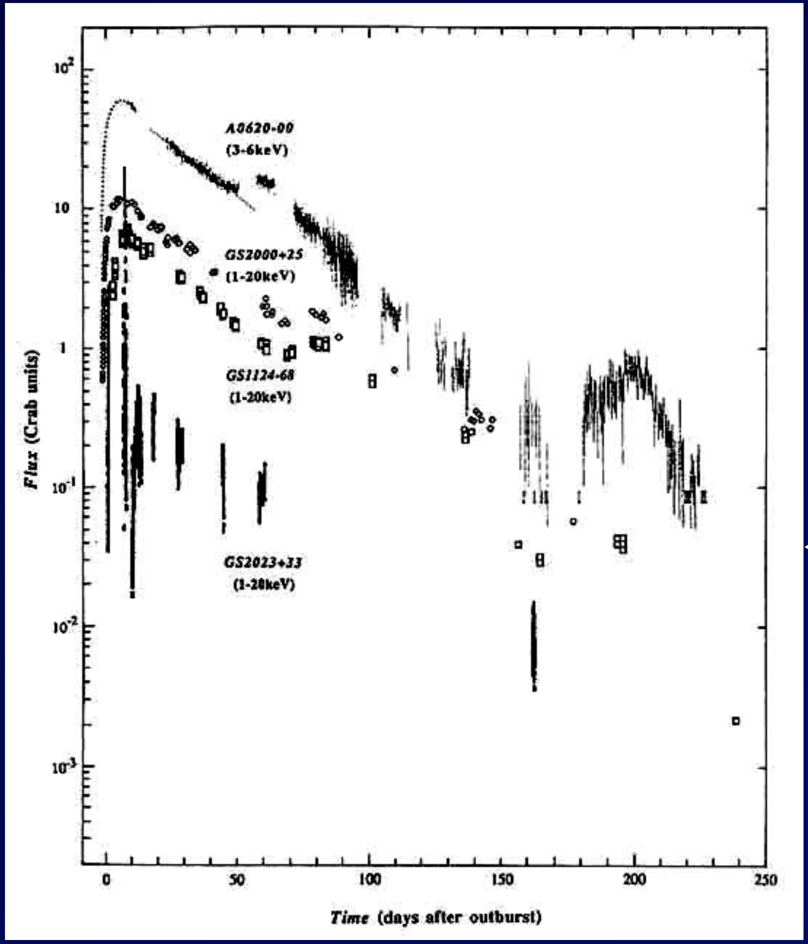
Geometry of ADAF Model



Cyg X-1

- High Soft state: thin disk
- Low state: no thin disk: kT>100 keV



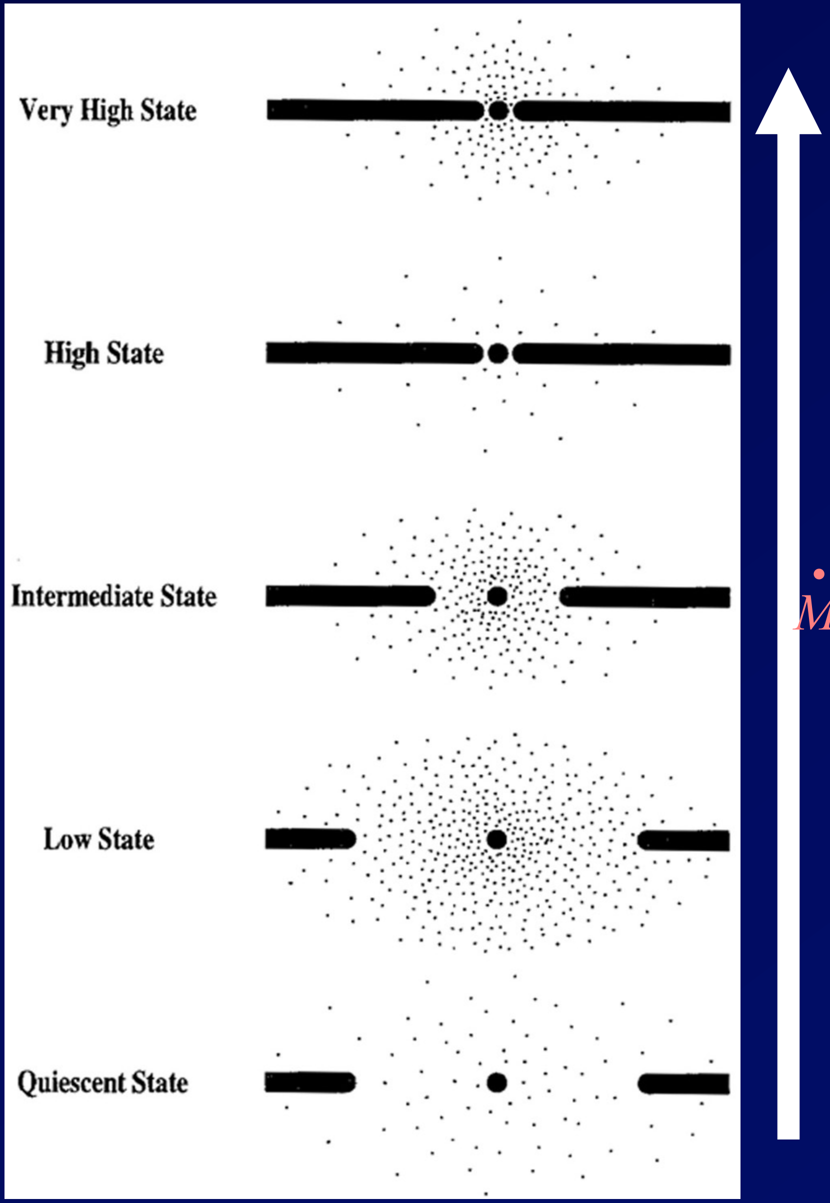


Soft X-ray Transients

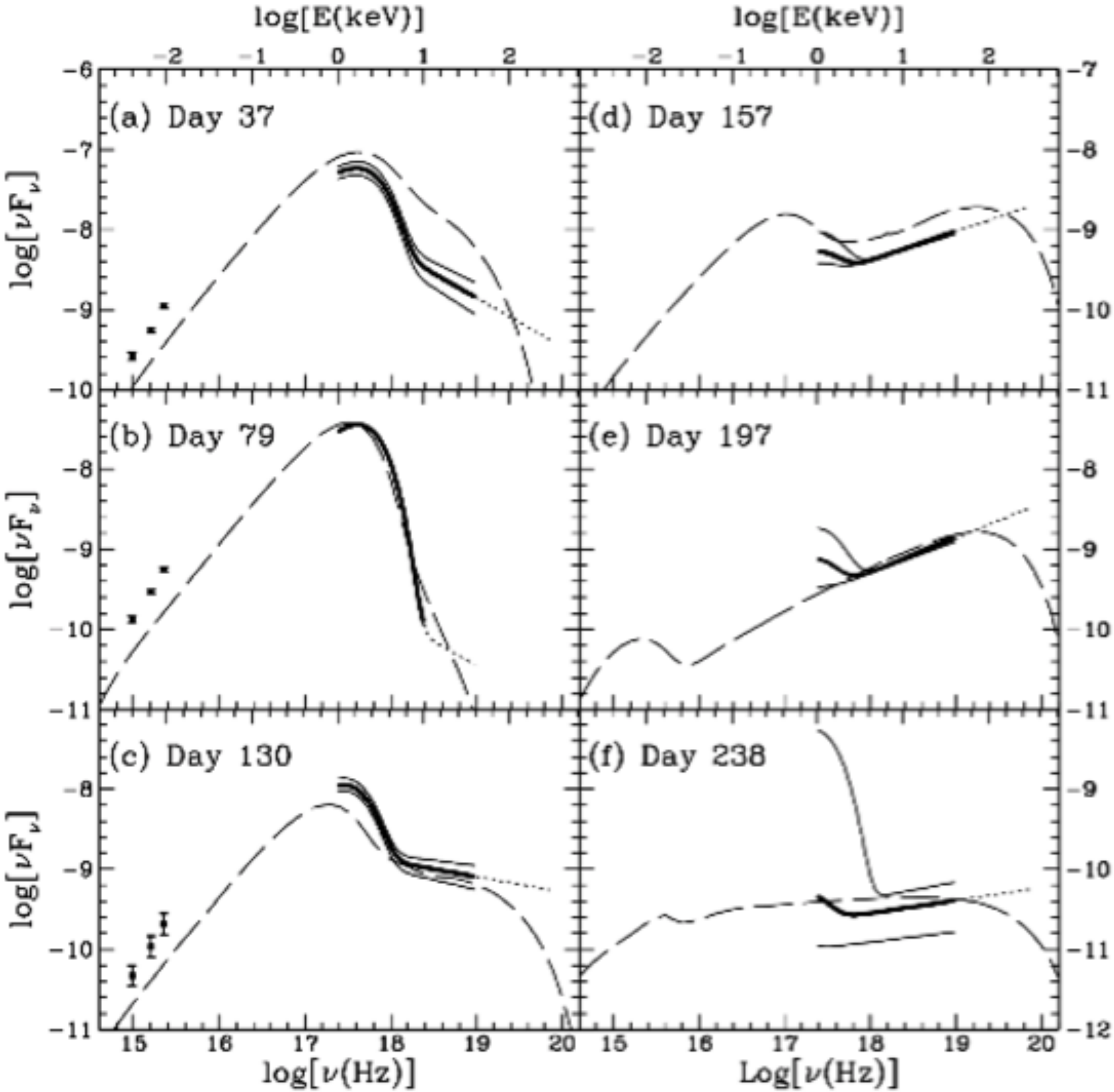
- Go through a very wide range of Mdot during transient outburst
- Sweep through spectral states via state changes

A Paradigm for Dim BHs

- Esin, McClintock & Narayan (1997): When Mdot falls below a few percent of Eddington, a hole opens up in the thin disk, and the inside is filled with a hot ADAF
- As Mdot decreases further, the hole grows bigger and radiative efficiency drops significantly



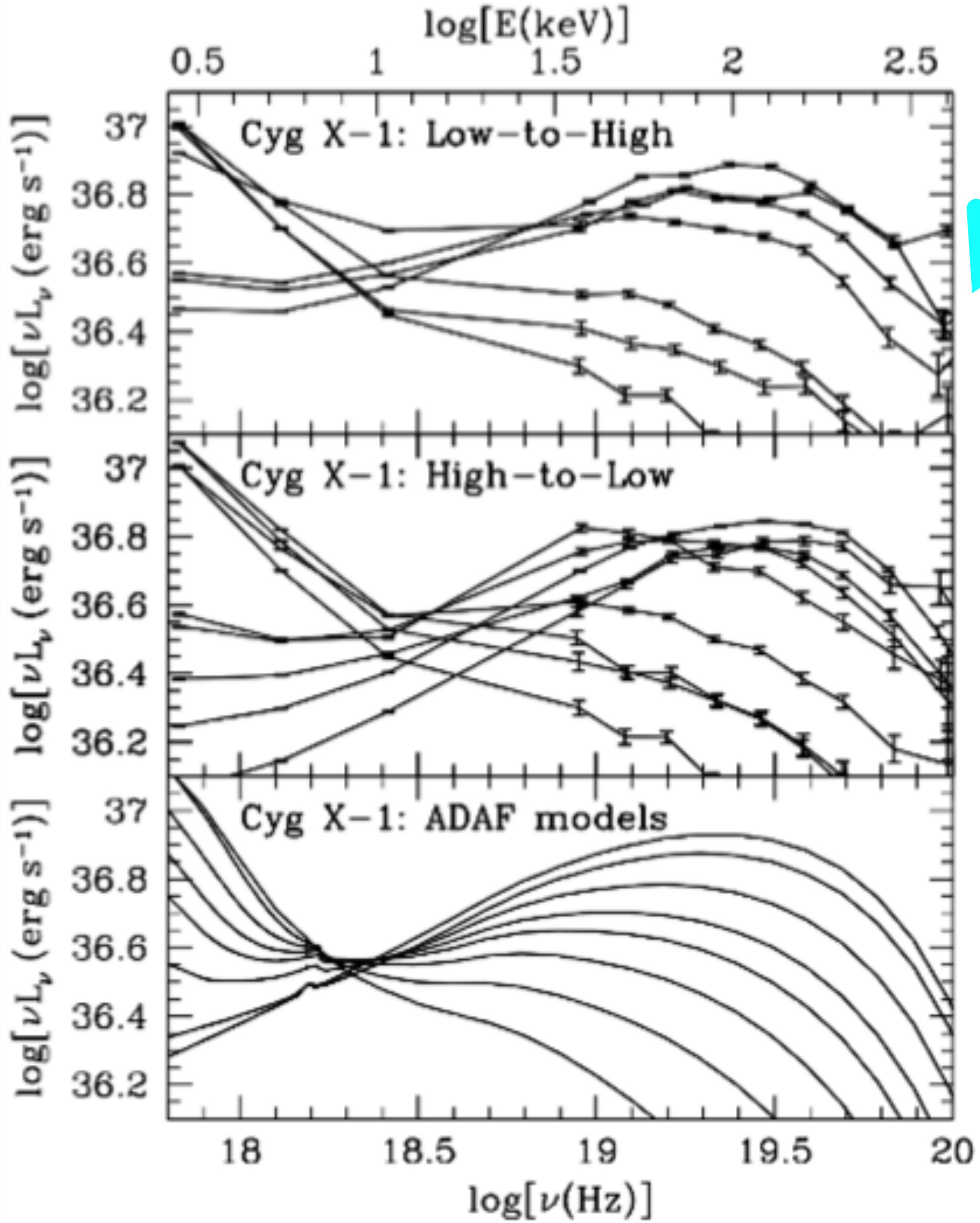
Esin et al.(1997)



Theoretical model spectra of a 6 M⊙ BH accreting at different Mdot

Compared to data on Nova Muscae 1991

Esin+ 1997



ADAF model of state transition in Cyg X-1 (Esin et al. 1998)

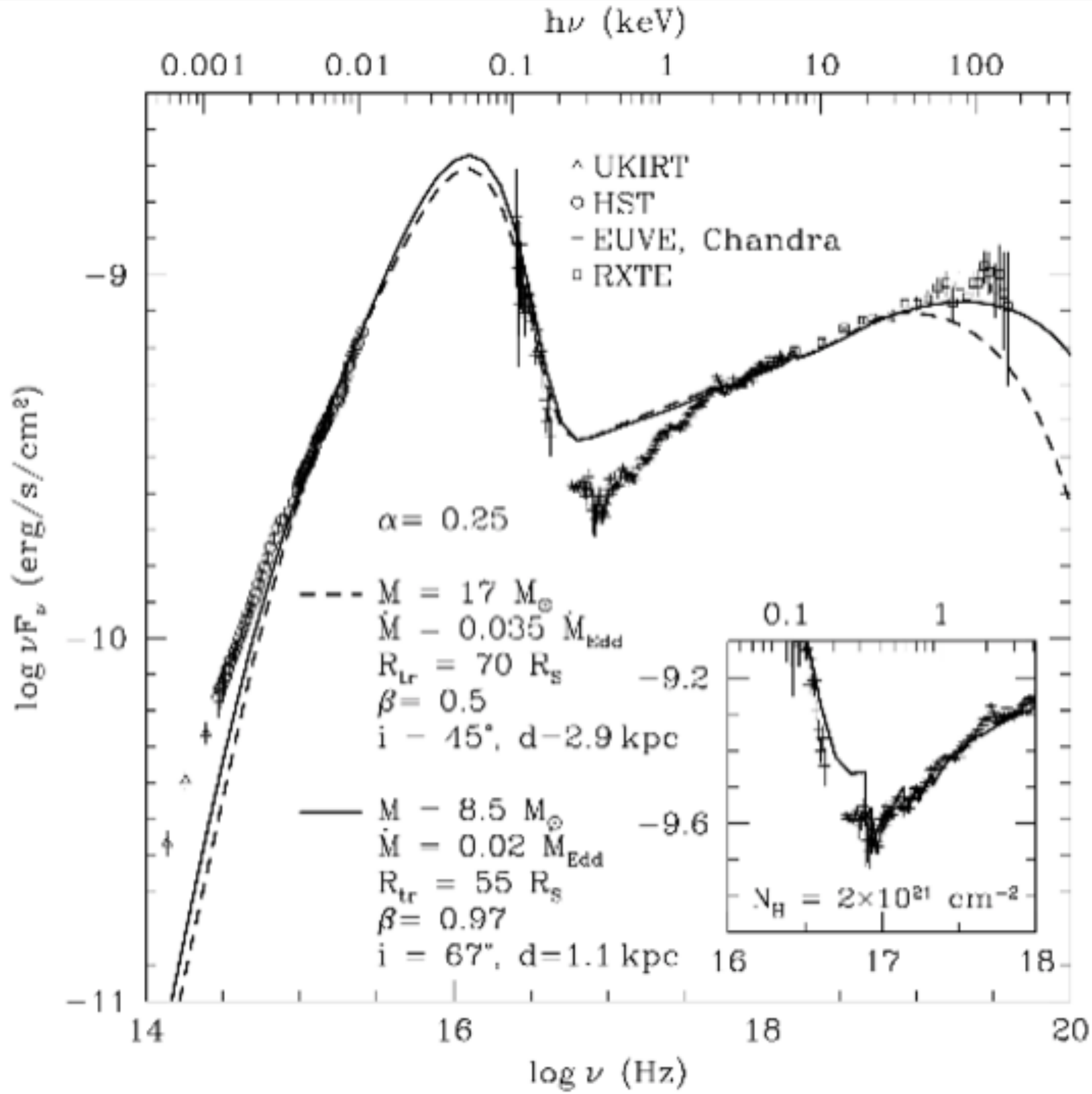
Other ADAF-related work on BH XRBs:

N, McClintock & Yi (1996)
N, Barret & McClintock (97)
Hameury et al. (97)
Menou et al. (99)
Esin et al. (2000, 2001)

Clues from timing:
Gilfanov et al. (1999)

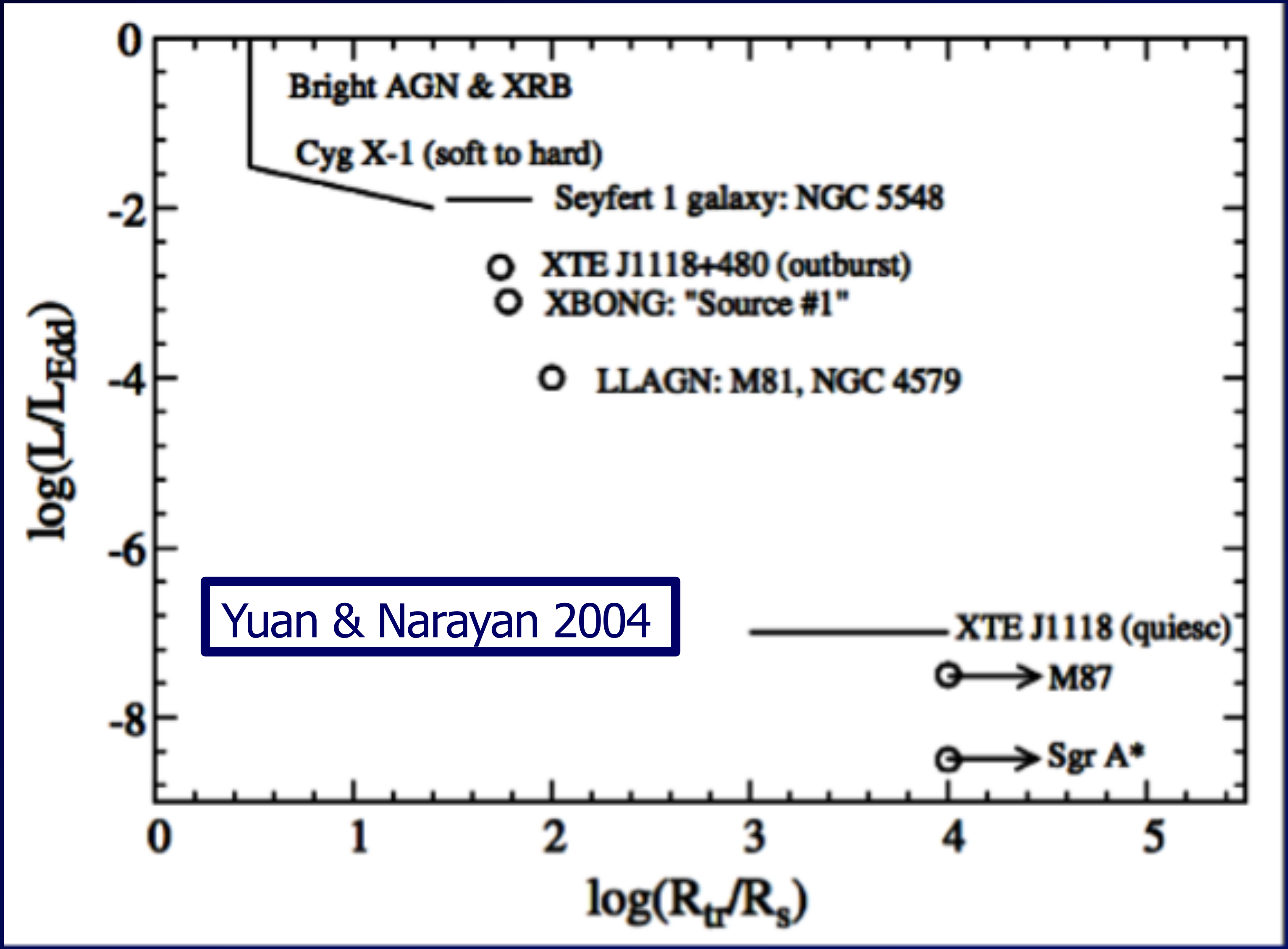
Conflicting evidence from X-ray reflection

Hysteresis is unexplained



ADAF model of XTE J1118+480

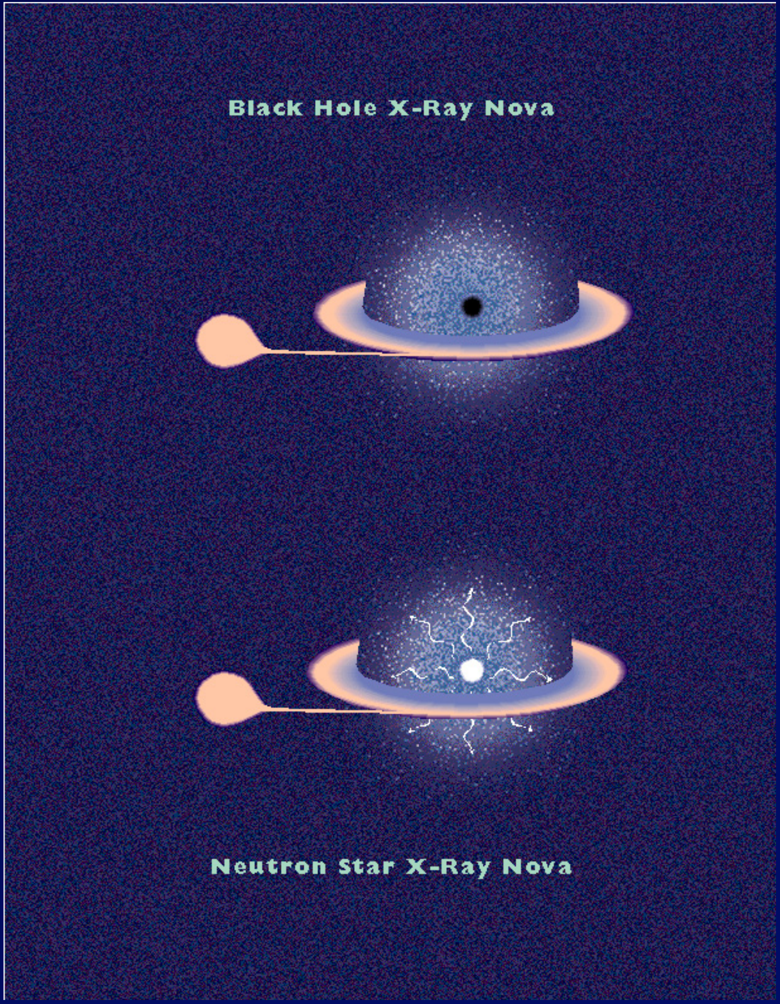
Esin, McClintock et al. (2001)



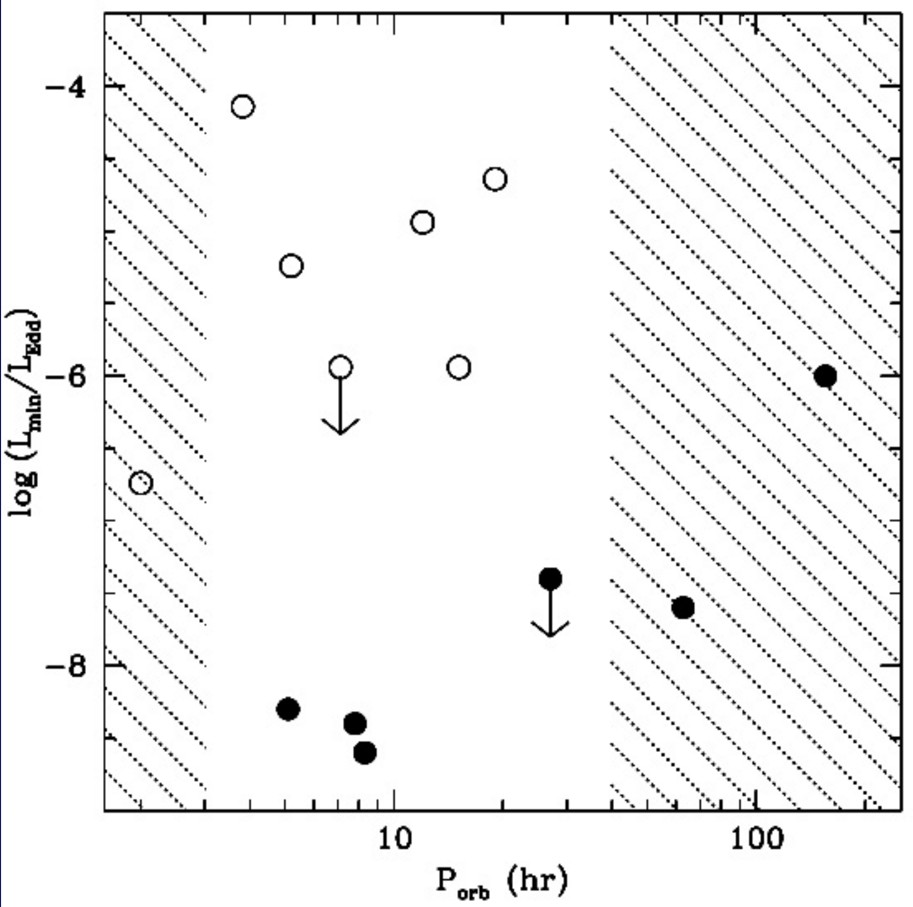
Guess (based on observations) of how the transition radius R_{tr} varies with L/L_{Edd} (or equivalently Mdot)

Using ADAFs to Test for the Event Horizon

- Narayan, Garcia & McClintock (1997) suggested comparing quiescent BH SXTs (or X-ray Novae) with quiescent NS SXTs
- If both systems accrete via a radiatively inefficient mode (ADAF), then NS SXTs should be significantly brighter than BH SXTs, since NSs will radiate the advected energy from their surfaces, whereas BHs will swallow the energy
- Results: Narayan et al. (1997), Asai et al. (1998), Chen et al. (1998), Menou et al. (1999), **Garcia, McClintock, Narayan et al. (2001)**



Chandra Results on Quiescent SXTs



Garcia et al. (2001):

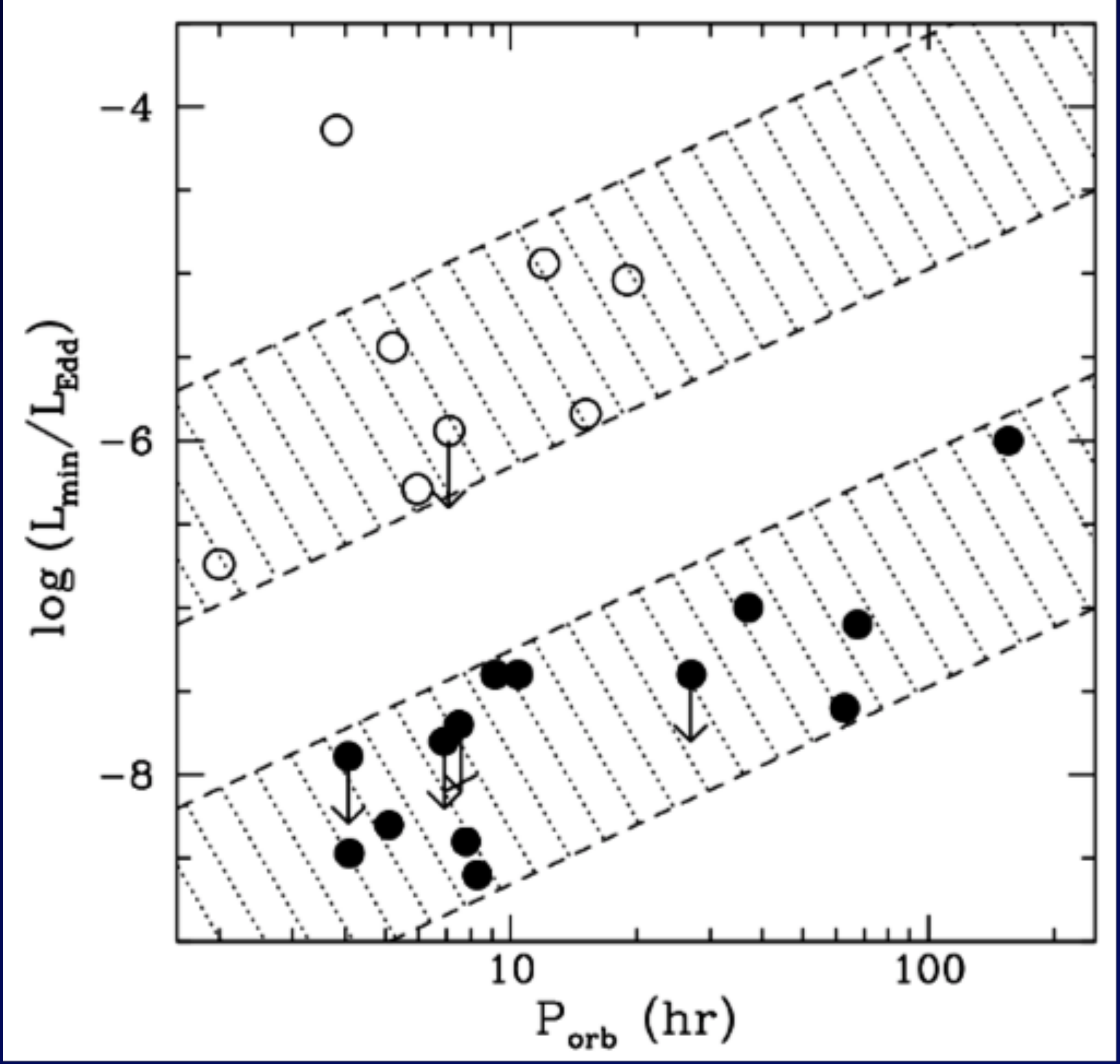
Chandra data!

BH SXTs are more than 100 times fainter than NS SXTs

Such a large difference is expected **IF**:

(1) The accretion is radiatively inefficient, **AND**

(2) BHXN have event horizons and NSXN have surfaces



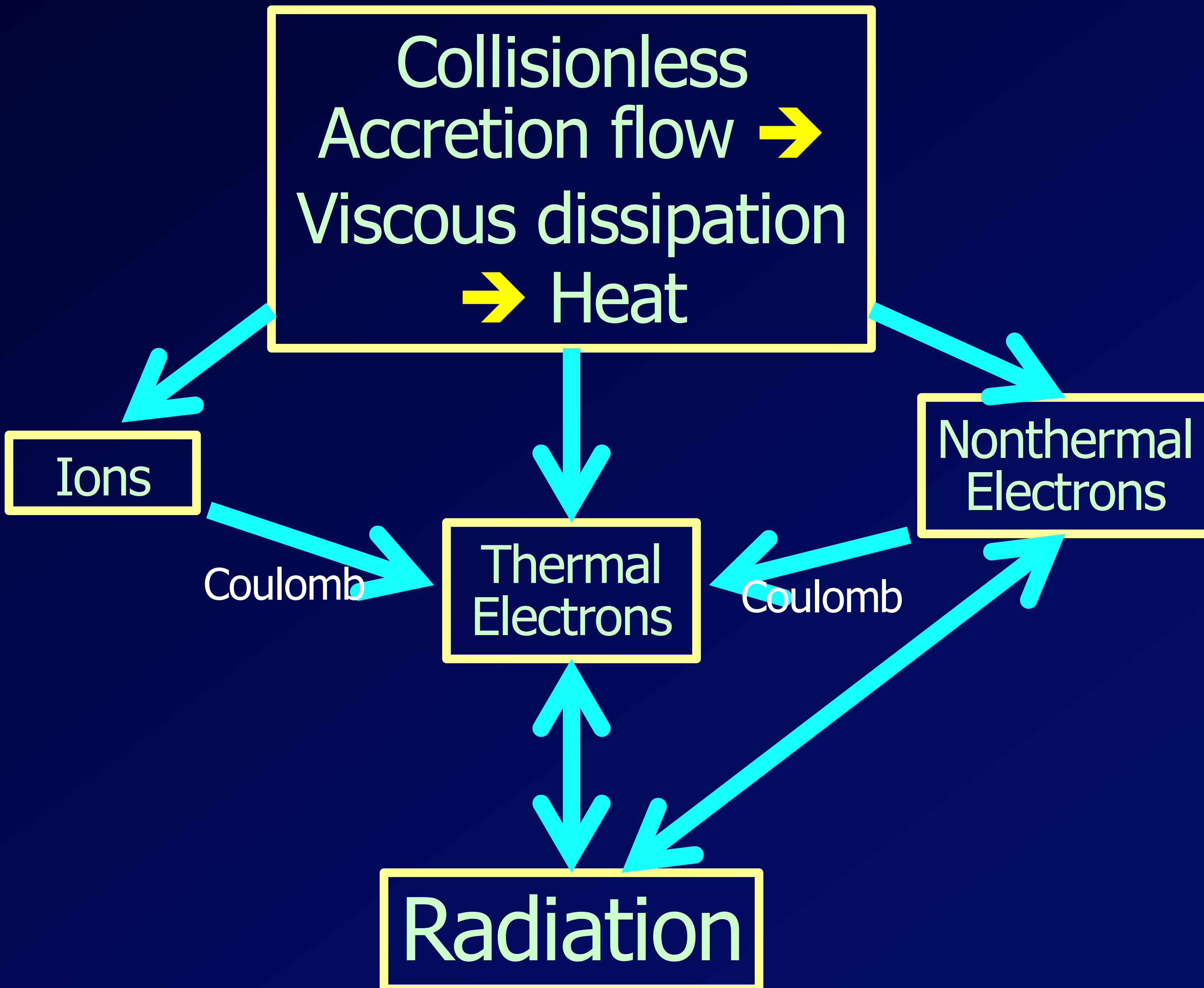
Narayan & McClintock (2008)

Black Holes Really Are Black!!

- If we see a dim BH SXT, we might think that it is dim simply because very little gas reaches the center
- But, when a nearly identical NS SXT is 100+ times brighter, we know that it is more than just gas supply
- Most straightforward interpretation: quiescent BH SXTs are much dimmer than NS SXTs because they swallow the gas, and heat energy, through the **Event Horizon**
- If this interpretation is correct, then the X-ray data imply that black holes really are really black!

ADAF Thermodynamics is Highly Uncertain

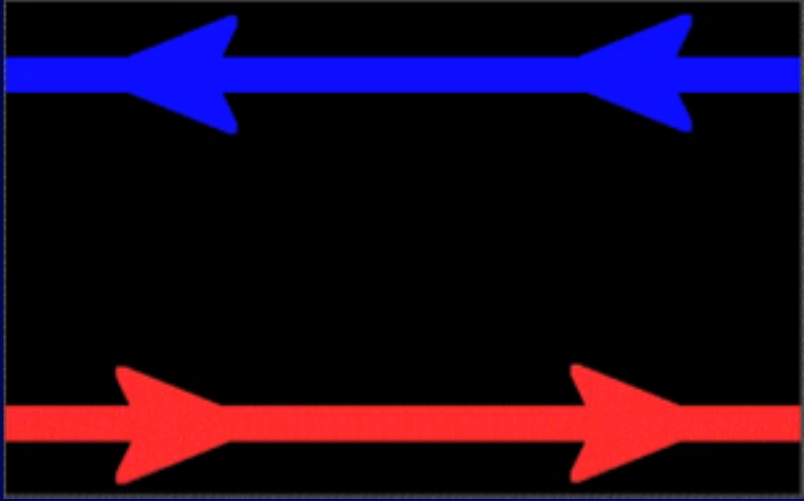
- The plasma is collisionless
  - Electrons/protons do their own thing
- Non-equilibrium: Two-temperature
- Each particle remembers its heating history and radiates accordingly
- We need to understand plasma heating processes to make good models


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

Simulating Fundamental Plasma Processes

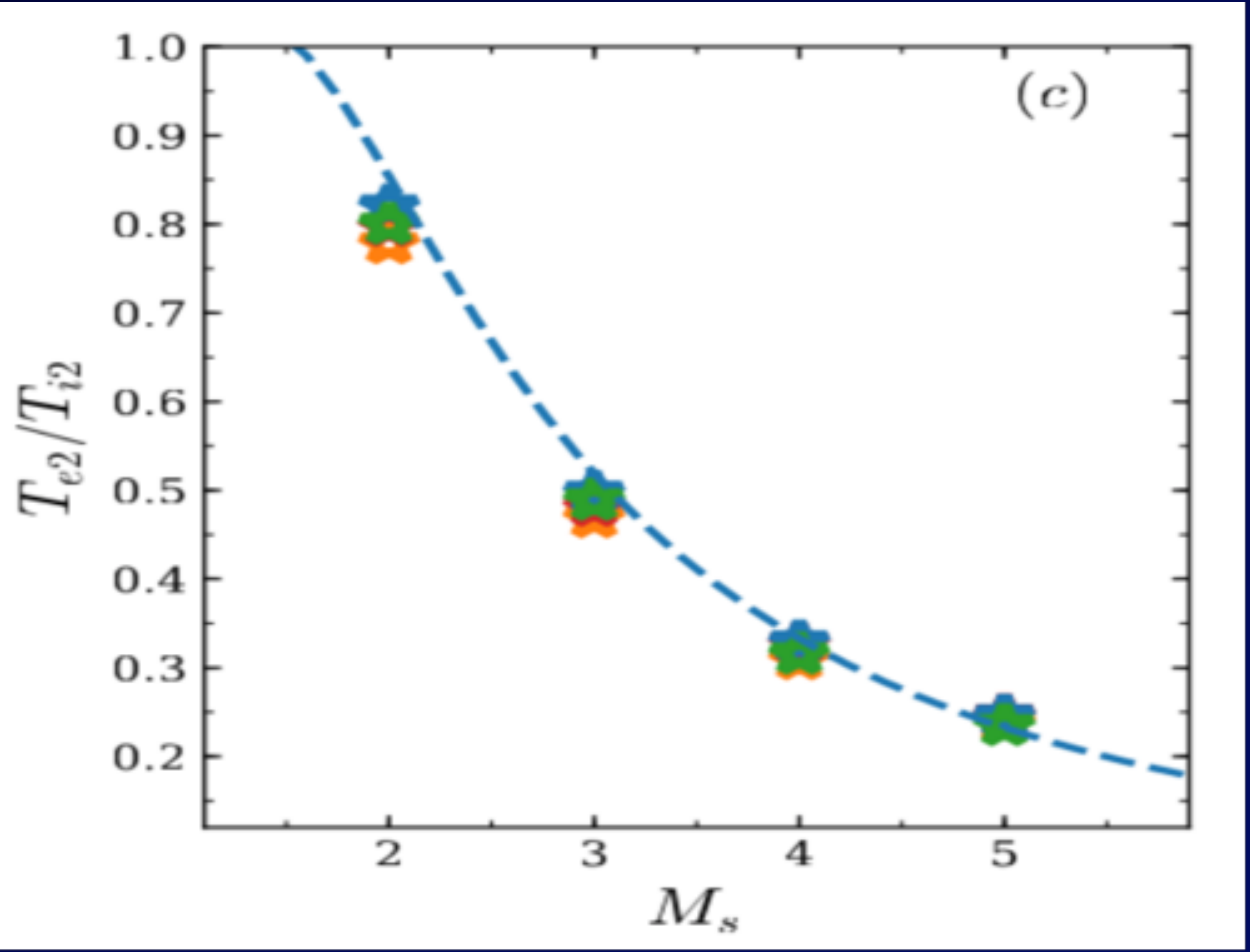
- So far, ADAF models have used toy prescriptions for particle heating, based on guesses, or clues from observations
- Now, people are beginning to study particle heating via detailed Particle-in-Cell (PIC) simulations (billions of particles)
  - Spitkovsky, Sironi, Li, Uzdensky, …
  - Xinyi Guo, Michael Rowan

Magnetic Reconnection



Rowan, Sironi & Narayan (2017)

Electron vs Ion Heating in Low Mach Number Shocks



$\delta_e/(1-\delta_e)$ vs Shock Mach Number

Guo, Sironi & Narayan (2018a,b)

Numerical Simulations of Black Hole Accretion

- Numerical simulations of BH accretion can include all the complex physics that purely analytical methods cannot handle
  - Multi-dimensional → **2D/3D Hydrodynamics**
  - General Relativity (**BH**) → **2D/3D GRHD**
  - Magnetic field (**MRI**) → **GRMHD**
  - Radiation → **GRRMHD**
  - More Thermal Physics → **Plasma processes**
  - Nonthermal Physics → **Plasma processes**

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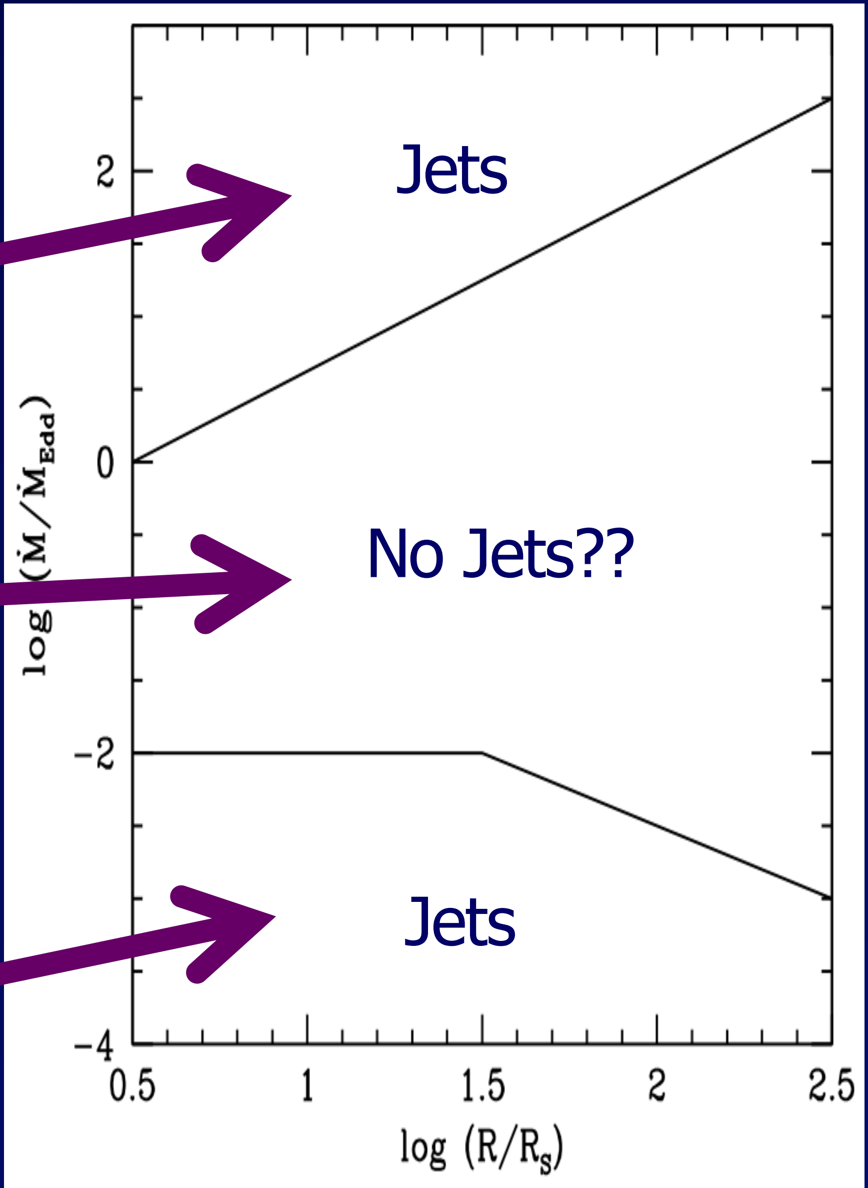


MOVIE

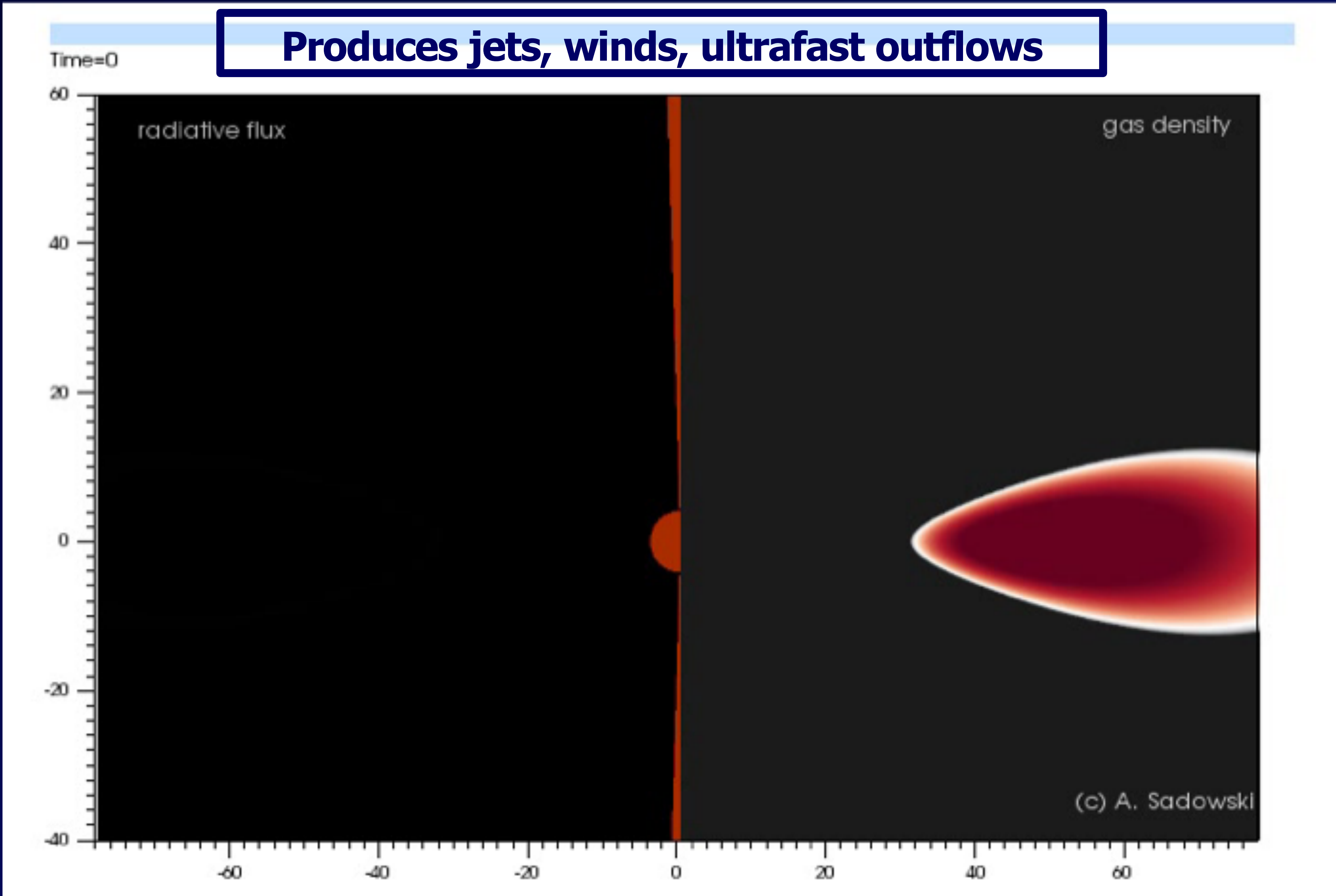
3D GRMHD simulation
(Tchekhovskoy+ 2011,12)

Non-radiating ADAF around a rapidly spinning BH accreting in the MAD state

A really Powerful Jet

Clear evidence for energy (and angular momentum) outflow from the BH

GRRMHD simulation: $M=10M_\odot$, $a_*=0$, $\dot{M}=10\dot{M}_{Edd}$,
(Sądowski et al. 2015: KORAL) **(ULX)**



ADAFs and Jets

- Both kinds of ADAF happily produce powerful outflows and jets
- The most powerful and most relativistic jets are obtained when
  - the BH spins rapidly, and
  - strong magnetic field around BH
  - Blandford-Znajek (1977) process