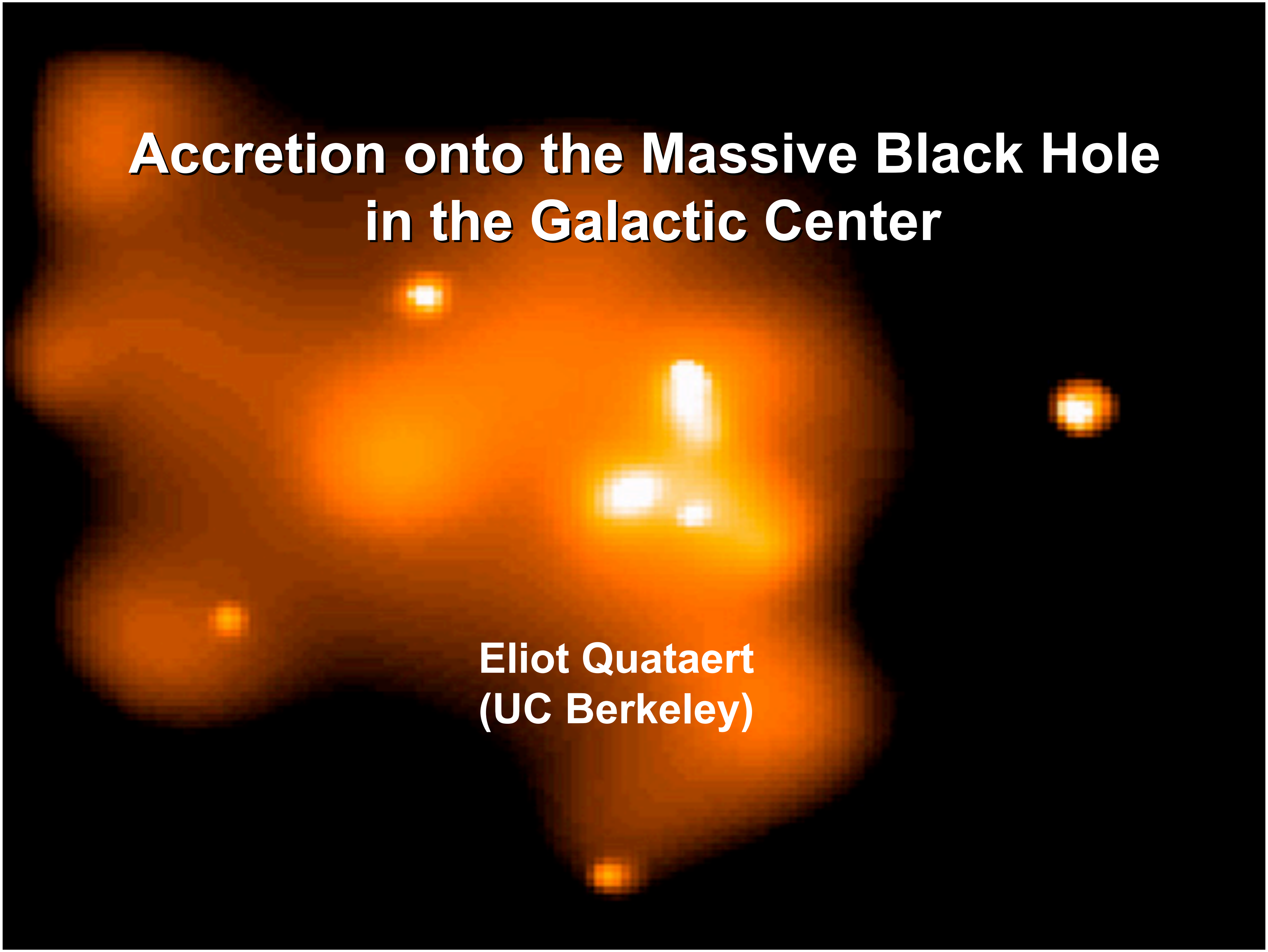


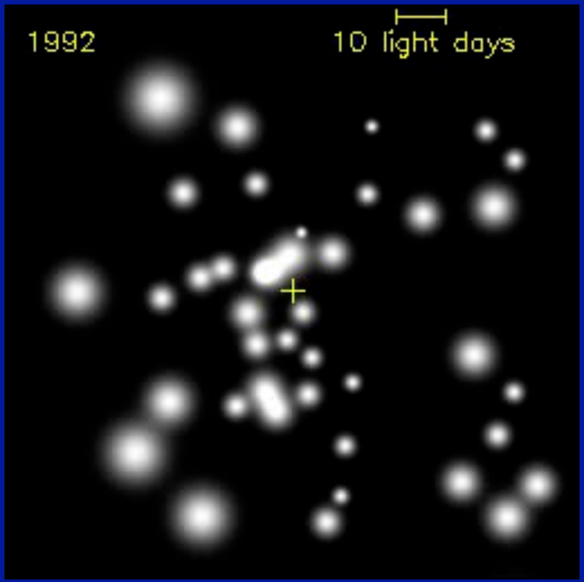
Accretion onto the Massive Black Hole in the Galactic Center

Eliot Quataert
(UC Berkeley)

Why focus on the Galactic Center?

- Best evidence for a BH (stellar orbits)
  - $M \approx 4 \times 10^6 M_\odot$
- Largest BH on the sky (horizon ≈ 8 μ")

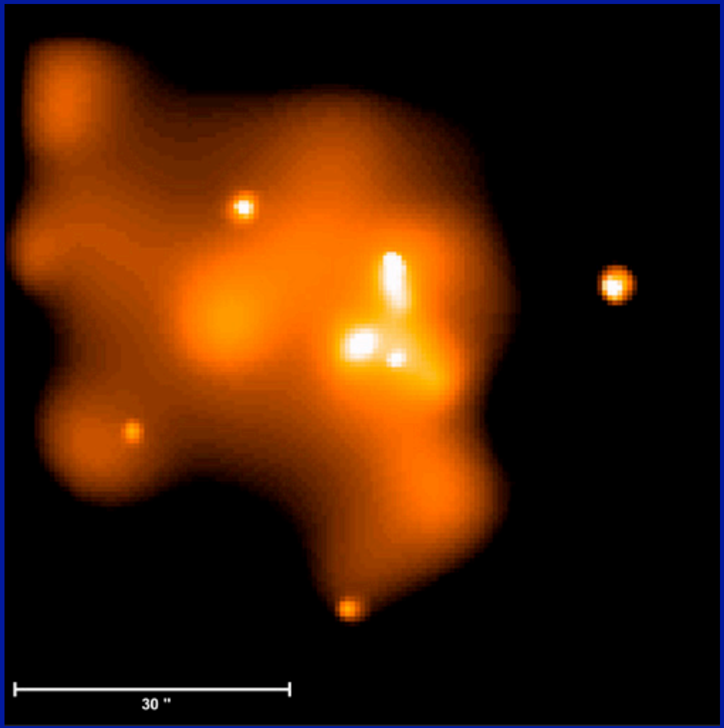
GR!
  - VLBI imaging of horizon in ~ 5-10 yrs
- X-ray & IR variability probes gas at ~ R_s



Genzel; Ghez

- Extreme low luminosity ($L \sim 10^{-9} L_{EDD}$) illuminates accretion physics
- Most detailed constraints on ambient conditions around BH
  - Feeding the (rather weak, and actually not that impressive) “monster”
  - Stellar dynamics & star formation in Galactic Nuclei
  - Binary BHs
- Useful laboratory for other BH systems

Outline



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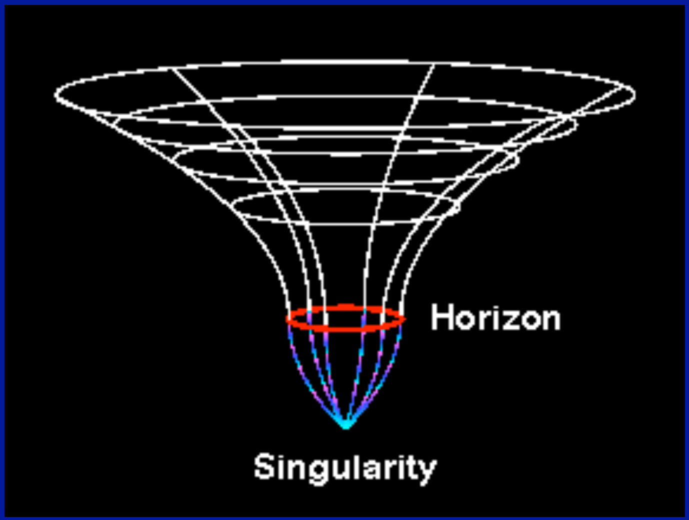
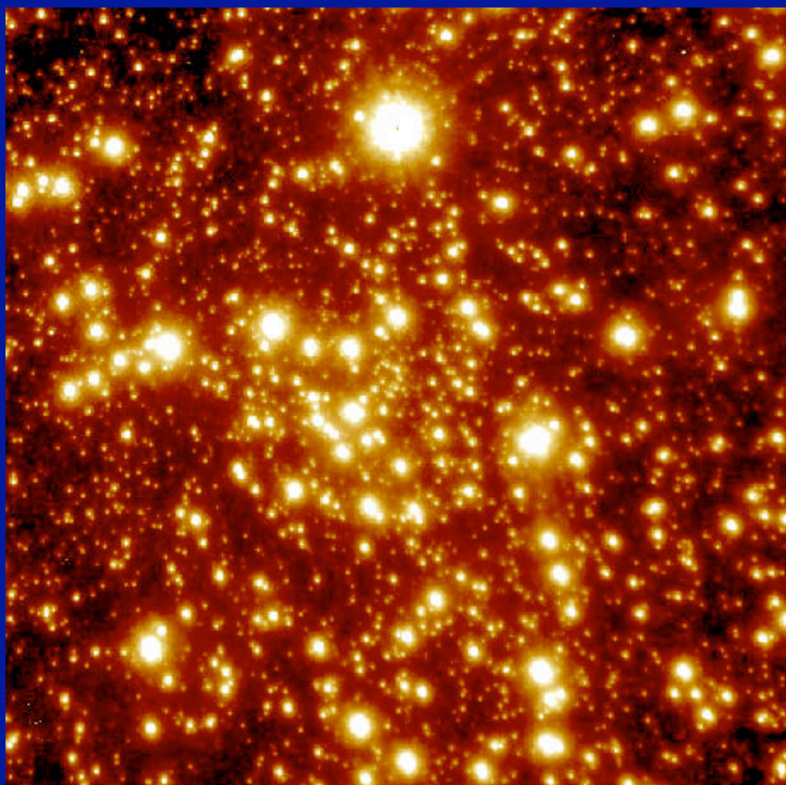


How does the gas get from the surrounding medium to the BH?

What determines the accretion rate, radiative efficiency, and observed emission from the BH?

Fuel Supply

IR (VLT) image of central ~ pc

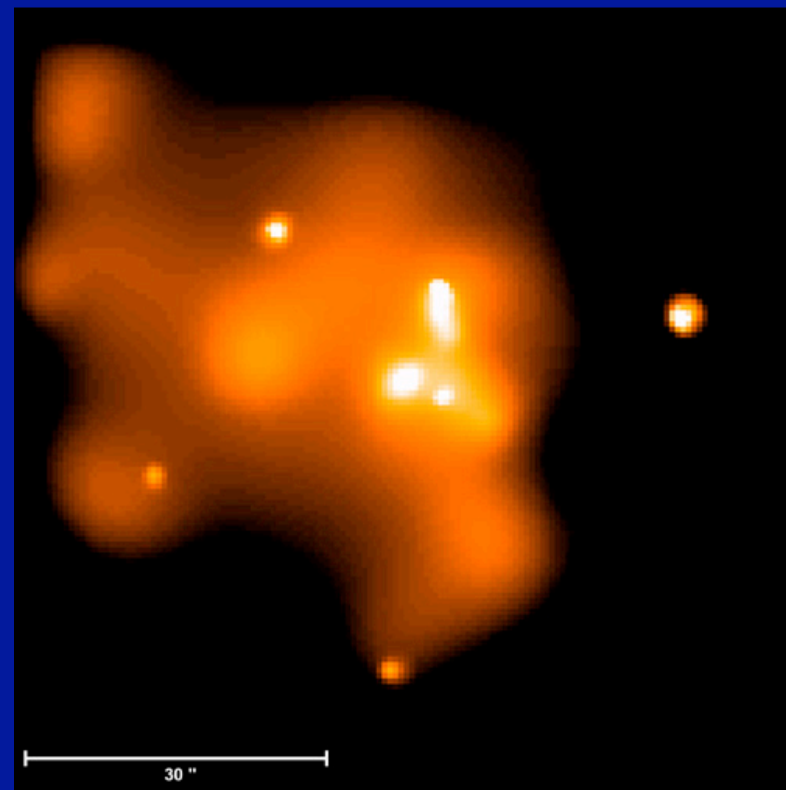


Genzel et al.

Young cluster of massive stars in the central ~ pc loses ~ 10^{-3} $M_\odot$ yr^{-1} (≈ 2-10" from BH)

1" = 0.04 pc ≈ 10^5 R_S @ GC

***Chandra* image of central ~ 3 pc**

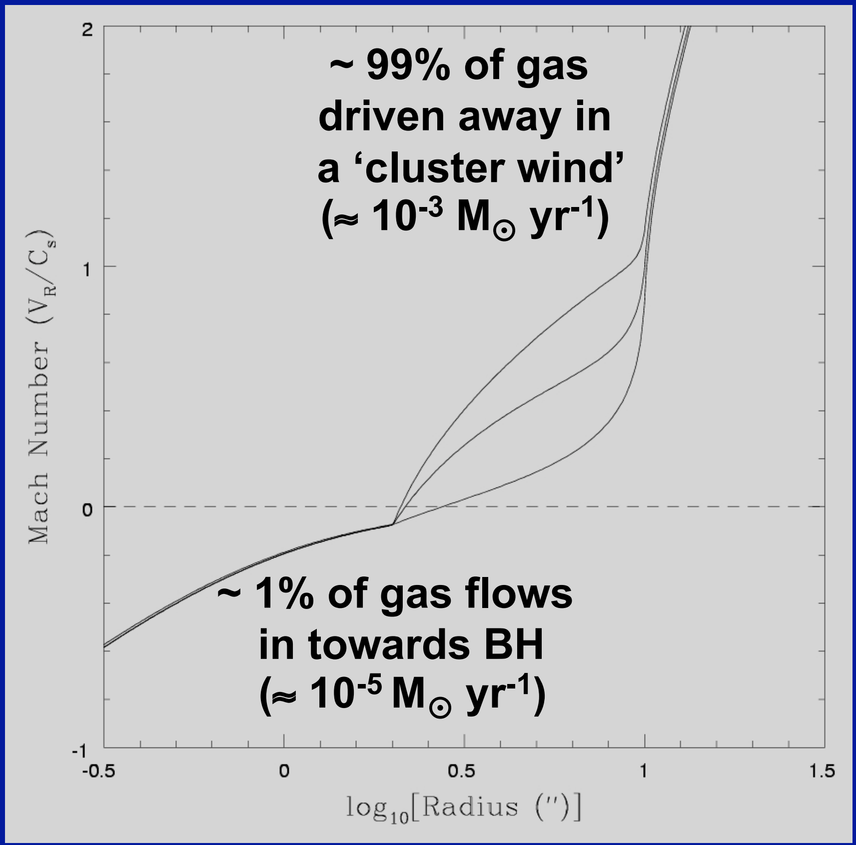


Baganoff et al.

Hot x-ray emitting gas (T = 1-2 keV; n = 100 cm^{-3}) produced via shocked stellar winds

1D Simulation of Gas Flow in Central Parsec "Cluster Wind" + Accretion onto BH

Radial Velocity



$\dot{M}_{stars} \approx 10^{-3} M_\odot yr^{-1}$ $V_{winds} \approx 10^3$ km/s

BHs 'sphere of influence'

Bondi Accretion Radius $R_A \approx \frac{GM}{c_s^2} \approx 1''$

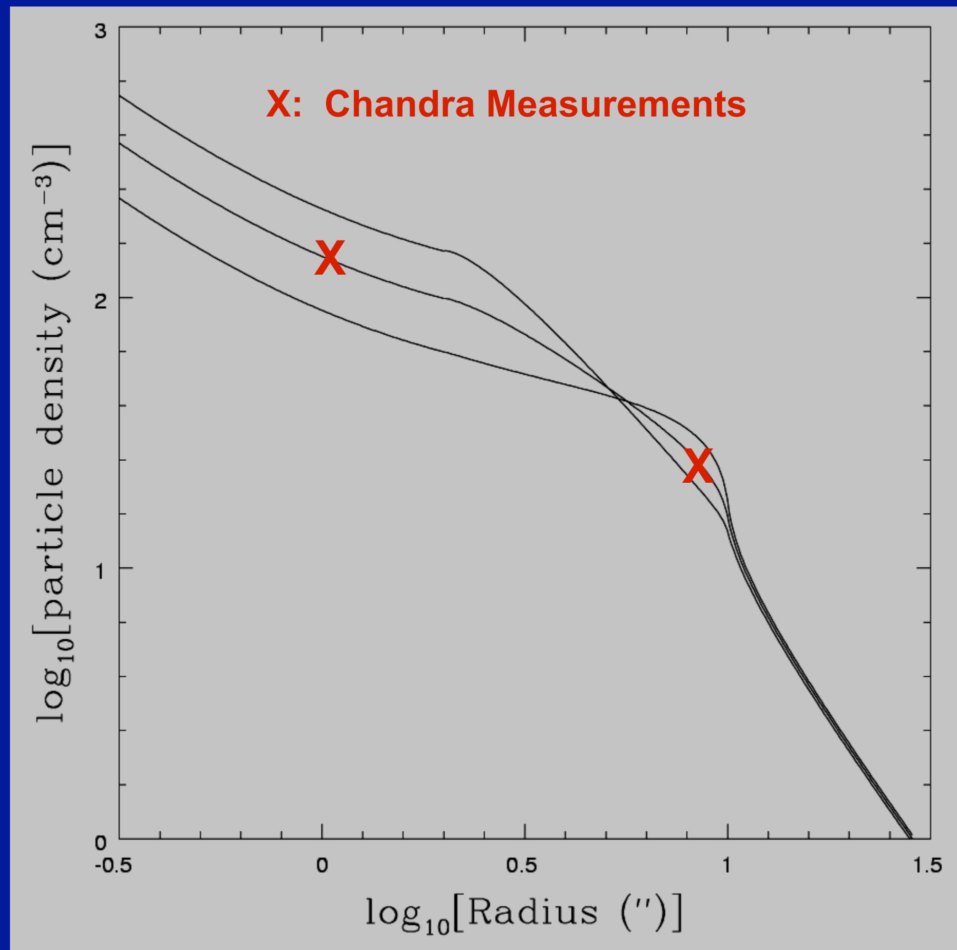
$$M_{captured} \approx 4\pi R_A^2 \rho c_s |_{R \approx R_A}$$

observed ρ & T ⇒ $\dot{M} \approx 10^{-5} M_\odot yr^{-1}$

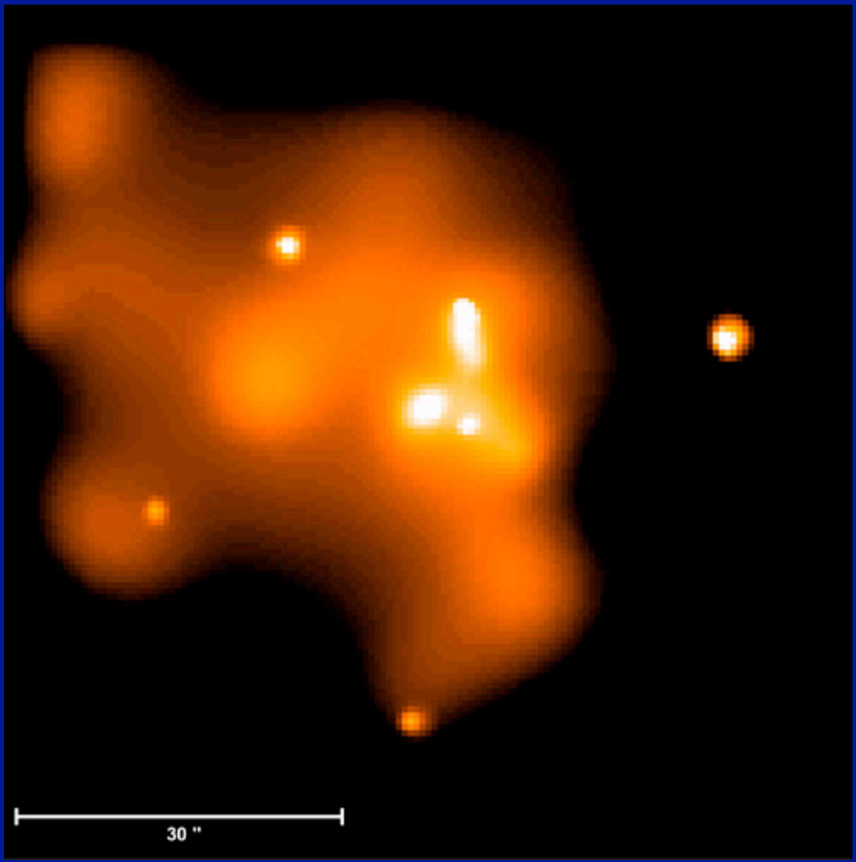
Predicted Density

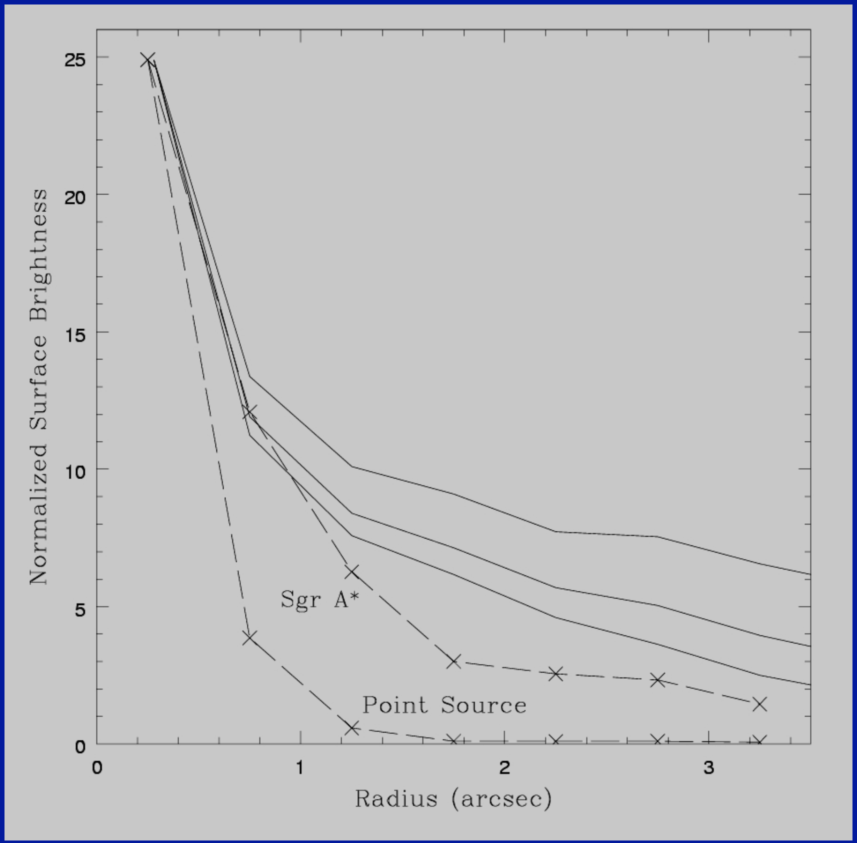
Temperature of observed gas rises from ~ 1-2 keV at 10” to ~4-5 keV at 1”

Consistent with gas being heated and compressed as it moves deeper in the potential well of the BH



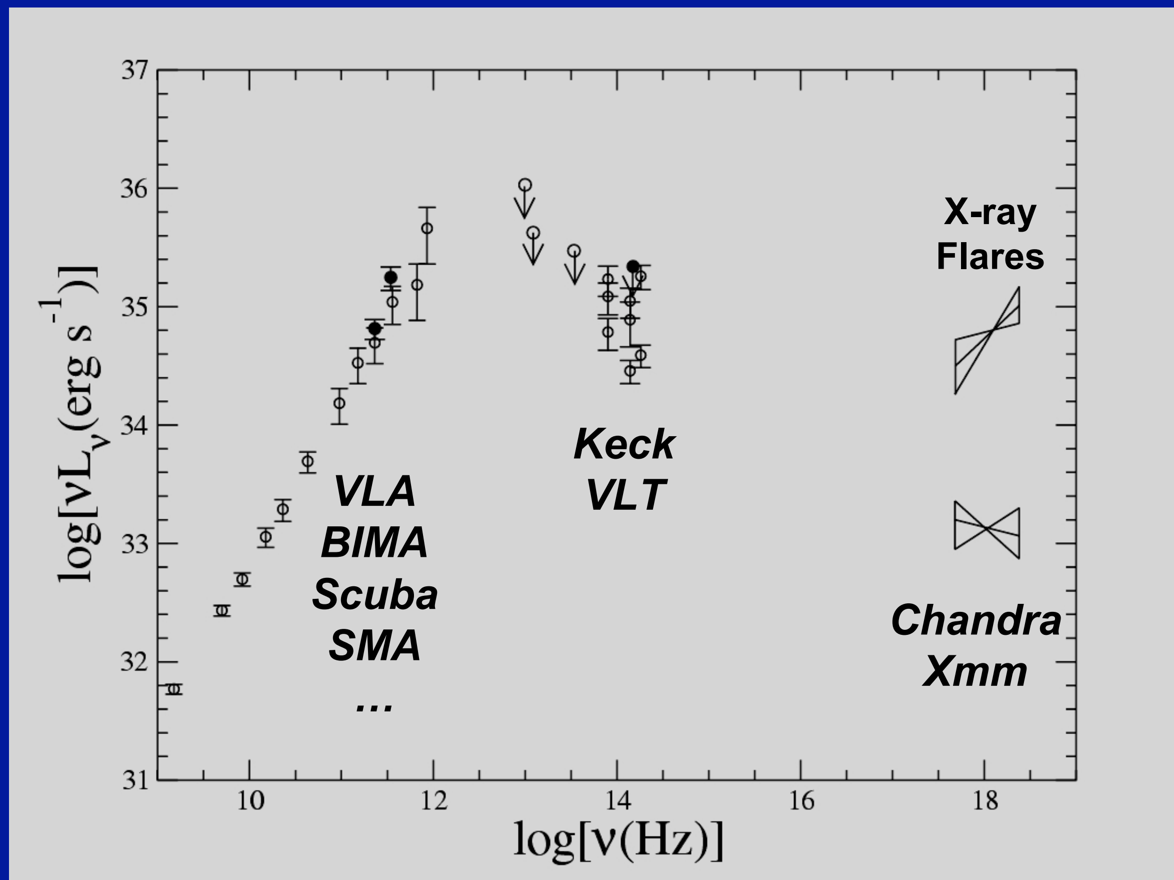
Predicted X-ray Surface Brightness Compared to Observations





Extended X-ray source coincident w/ the BH is a signature of gas being gravitationally captured from the surrounding star cluster (ala Bondi)

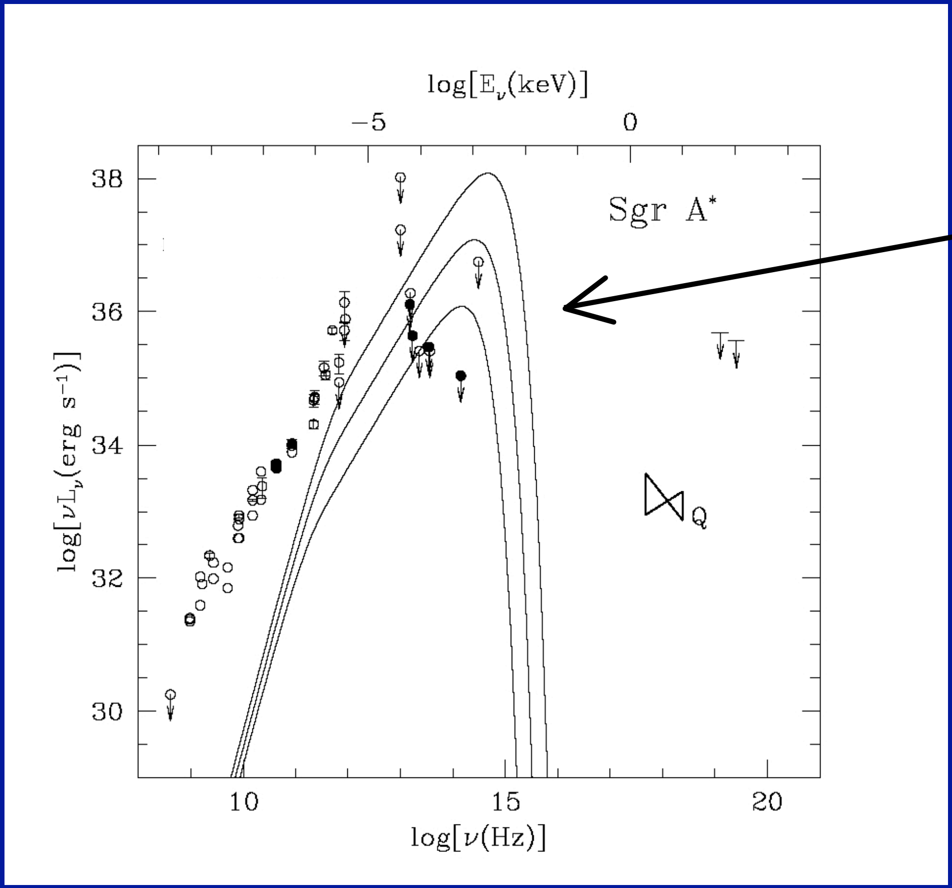
Total Luminosity ~ 10^{36} ergs s^{-1}
~ 100 $L_{\odot}$ ~ 10^{-9} L_{EDD} ~ 10^{-6} $\dot{M} c^2$



Extensive Linear & Circular Polarization Data In Radio

Inferred efficiency <<<<< ~ 10% efficiency in luminous BHs

Arguments Against Accretion at smaller radii proceeding via an Optically Thick, Geometrically Thin Disk, as in Luminous AGN



1. inferred low efficiency

2. where is the expected blackbody emission?

$$\dot{M}_{disk} < 10^{-10} M_{\odot} yr^{-1}$$

3. observed gas on ~ 1” scales is primarily hot & spherical, not disk-like (w/ $t_{cool} >> t_{flow}$)

4. absence of stellar eclipses argues against $\tau >> 1$ disk (Cuadra et al. 2003)

Radiatively Inefficient Accretion Flow

(e.g., Ichimaru 1977; Rees et al. 1984; Narayan & Yi 1994)

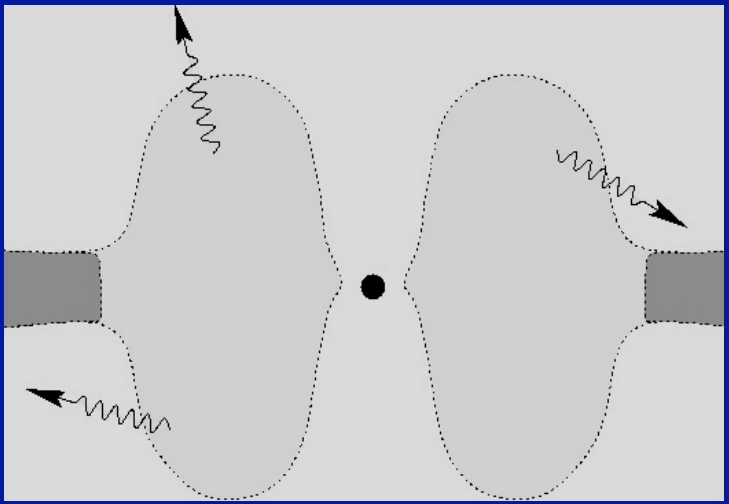
- At low densities (accretion rates), cooling is inefficient

$$L << 0.1\dot{M}c^2$$

$$kT \sim \frac{GMm_p}{R}$$

grav. pot. energy stored as thermal energy instead of being radiated

- Hot optically thin collisionless plasma near BH



$T_p \sim 10^{12}$ K

$T_e \sim 10^{10}$-10^{11} K

(particles likely nonthermal)

e-p collision time >> inflow time

- Initial Models (ADAFs) had

(e.g., Narayan & Yi 1994)

$$\dot{M}_{BH} \sim \dot{M}_{captured}$$

Efficiency ~ 10^{-6}

Low efficiency because electron heating is assumed to be very inefficient (electrons radiate, not protons)

- Very little mass supplied at large radii accretes into the black hole (outflows/convection suppress accretion)

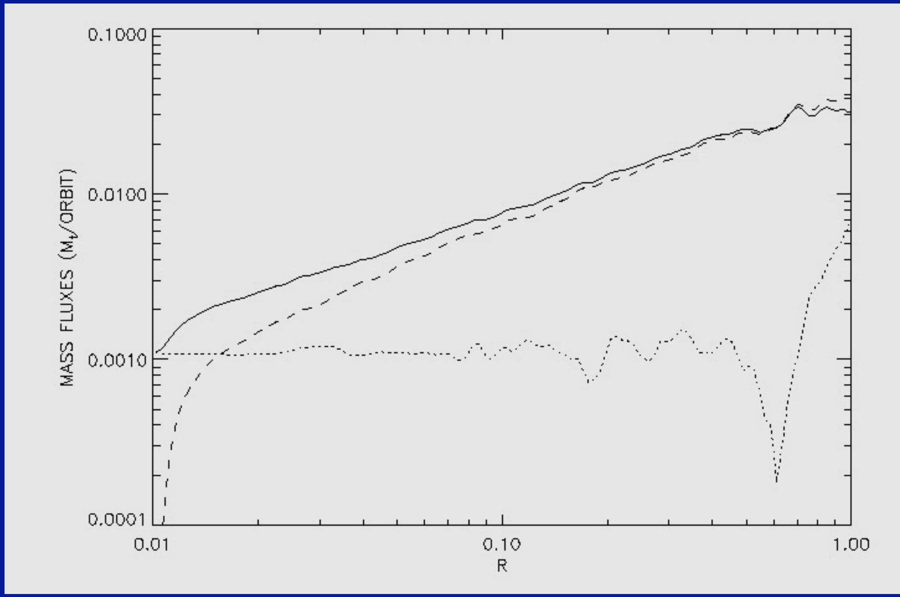
(e.g., Igumenschev & Abramowicz 1999, 2000; Stone et al. 1999; Blandford & Begelman 1999; Narayan et al. 2000; Quataert & Gruzinov 2000; Stone & Pringle 2001; Hawley & Balbus 2002; Igumenschev et al. 2003; Pen et al. 2003)

$$\dot{M}_{BH} \sim \dot{M}_{captured} \frac{R_{in}}{R_{out}} \sim 10^{-5} \dot{M}_{captured}$$

very little radiation because very little gas makes it to the BH

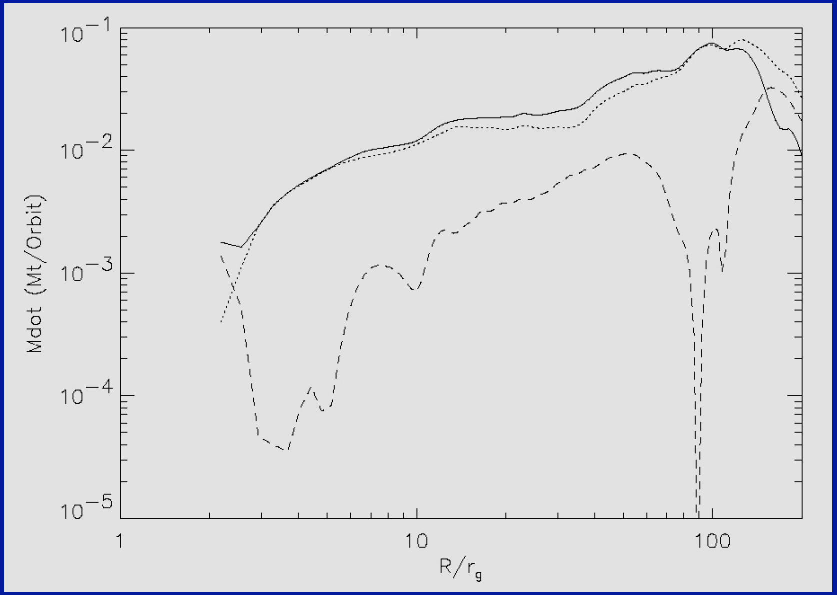
Numerical Simulations

Hydrodynamic



(Igumenshchev & Abramowicz 1999, 2000; Stone et al. 1999)

MHD



(Stone & Pringle 2001; Hawley & Balbus 2002; Igumenshchev et al. 2003)

Theoretical Aside:

If magnetic field is “weak” (β > ~ 10), convection dominates flow dynamics

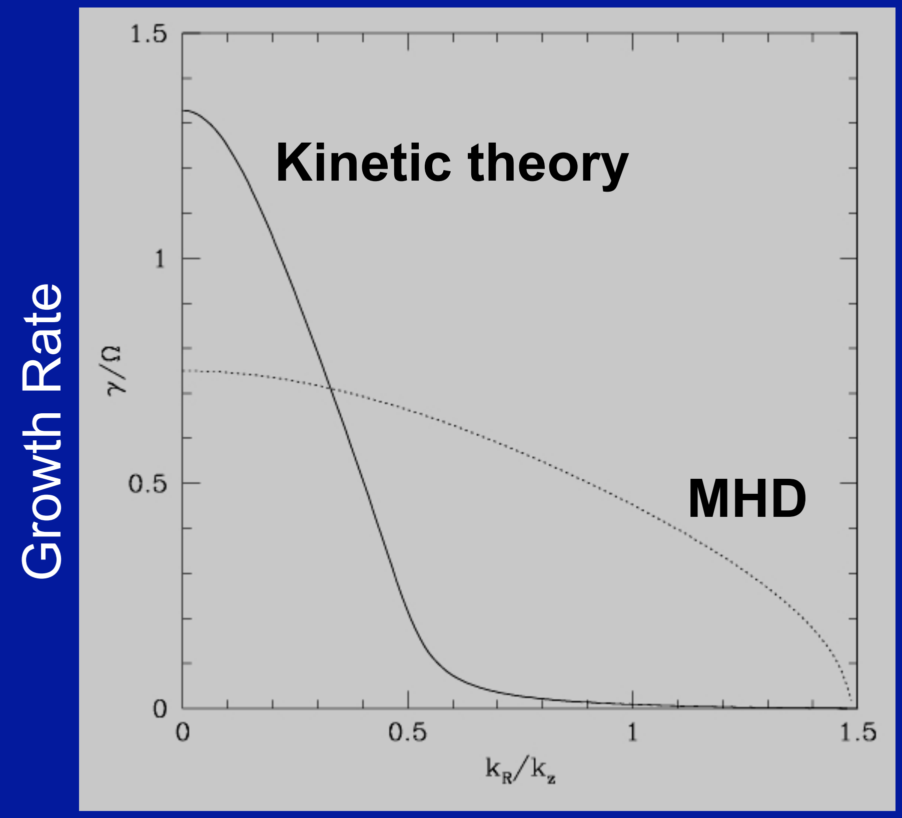
If magnetic field is stronger (β ~ 1), MHD turbulence dominates

(Narayan, Quataert, Igumenshchev, & Abramowicz 2002)

Are the Simulations Relevant to an Intrinsically Collisionless System?

- Perhaps, but …
- Physics of angular momentum transport is different in collisionless plasmas
- Kinetic simulations in progress

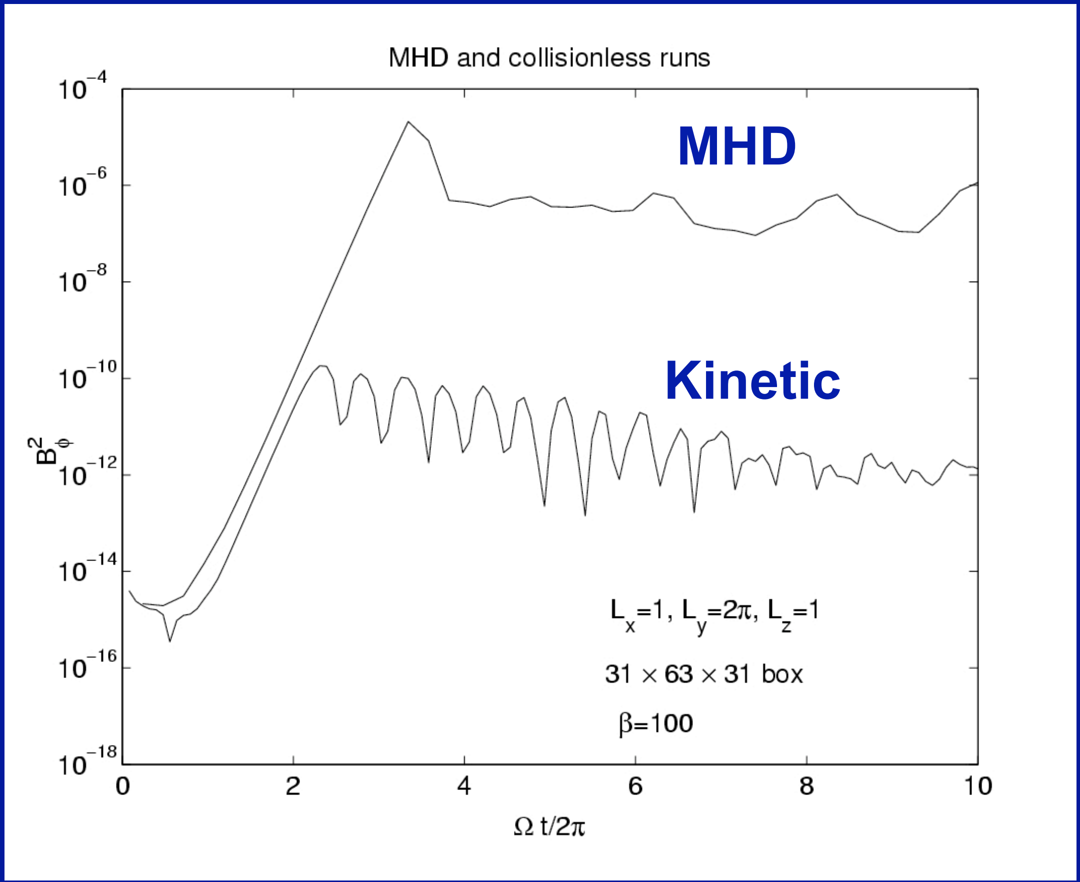
Magnetorotational instability



Wavevector

Quataert, Dorland, & Hammett 2002

Preliminary Nonlinear Kinetic Sims



Magnetic Energy

Sharma, Hammett, Quataert, & Stone

Time (Orbital Periods)

Kinetic sims initially saturate at much lower field strength (due to anisotropic pressure tensor)

Further nonlinear evolution unclear (work in progress …)

Overall Energetics

- very little mass available at large radii accretes into the BH

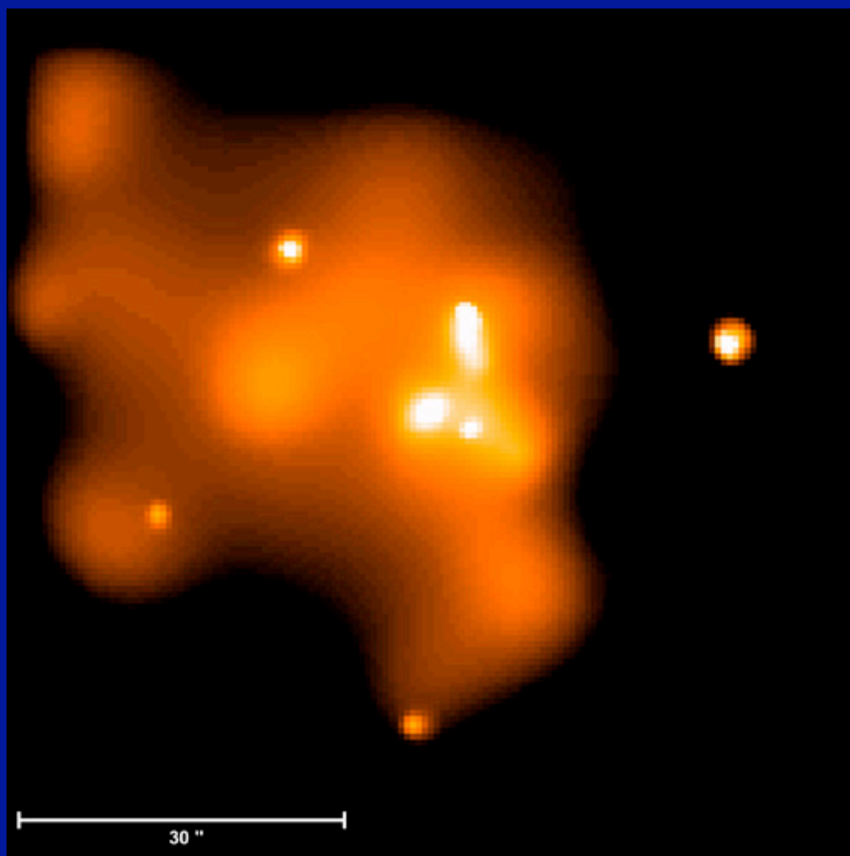
$$\dot{M}_{BH} \sim \dot{M}_{captured} \frac{R_{in}}{R_{out}} \sim 10^{-5} \dot{M}_{captured}$$

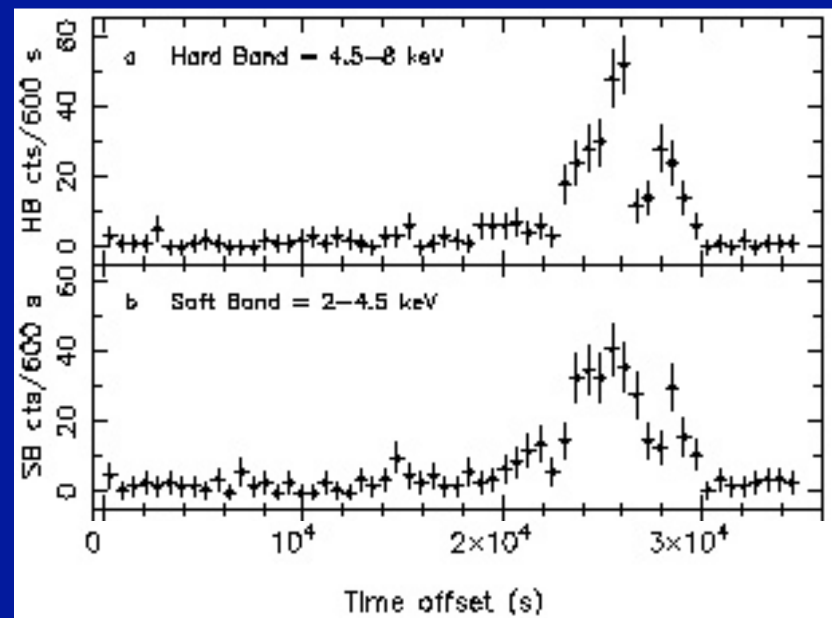
$$L_{observed} \sim 10^{-6} \dot{M}_{captured} c^2 \sim 0.1 \; \dot{M}_{BH} c^2$$

- low accretion rate confirmed by detection of ~ 10% linear polarization in the radio emission from the Galactic Center (QG 2000; Agol 2000; Bower et al. 2003)
  - Faraday Rotation (< 10^6 rad/m^2) constrains the plasma density near the BH

$$\dot{M}_{BH} < 10^{-8} M_{\odot} yr^{-1} << \dot{M}_{captured}$$

X-ray Emission: Quiescent + Flares





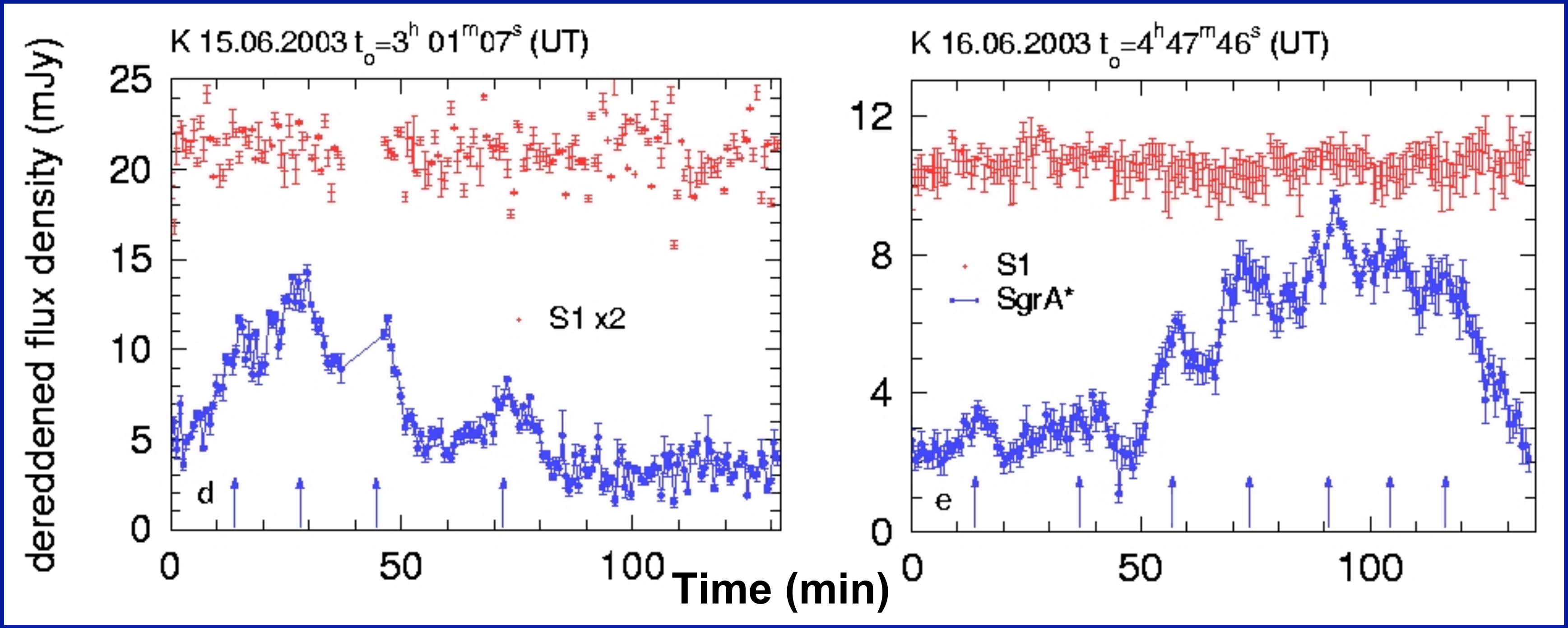
Orbital period at $3R_S$ = 28 min

Several times a day X-ray flux increases by a factor of ~ few-50 for ~ an hour

timescale ⇒ emission arises close to BH ~ 10 R_S

Variable IR Emission

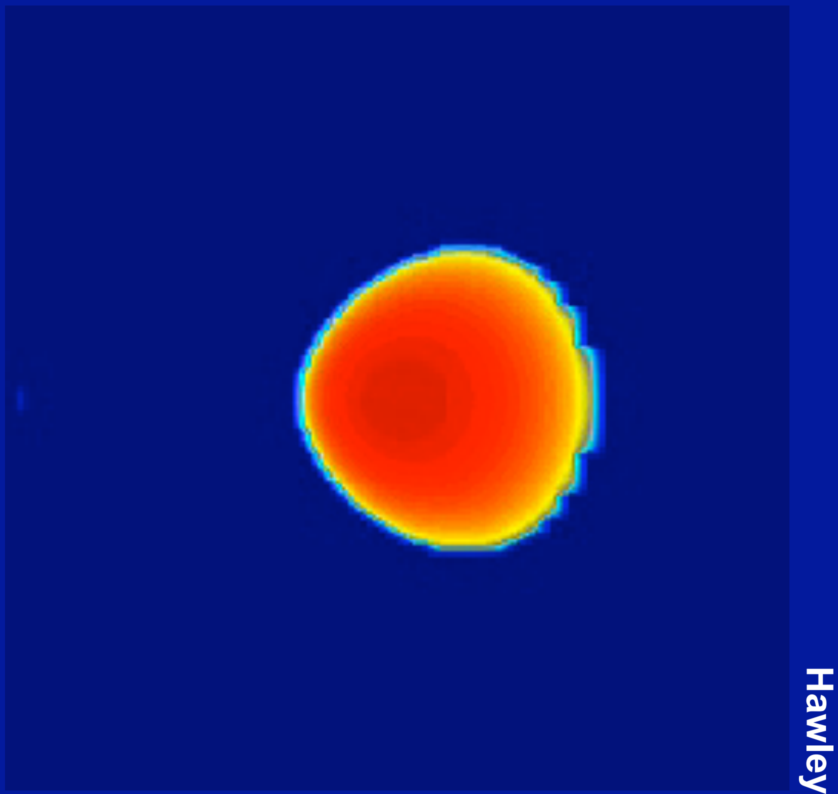
(Genzel et al. 2003; Ghez et al. 2003)



Genzel et al. 2003

Light crossing time of Horizon: 0.5 min

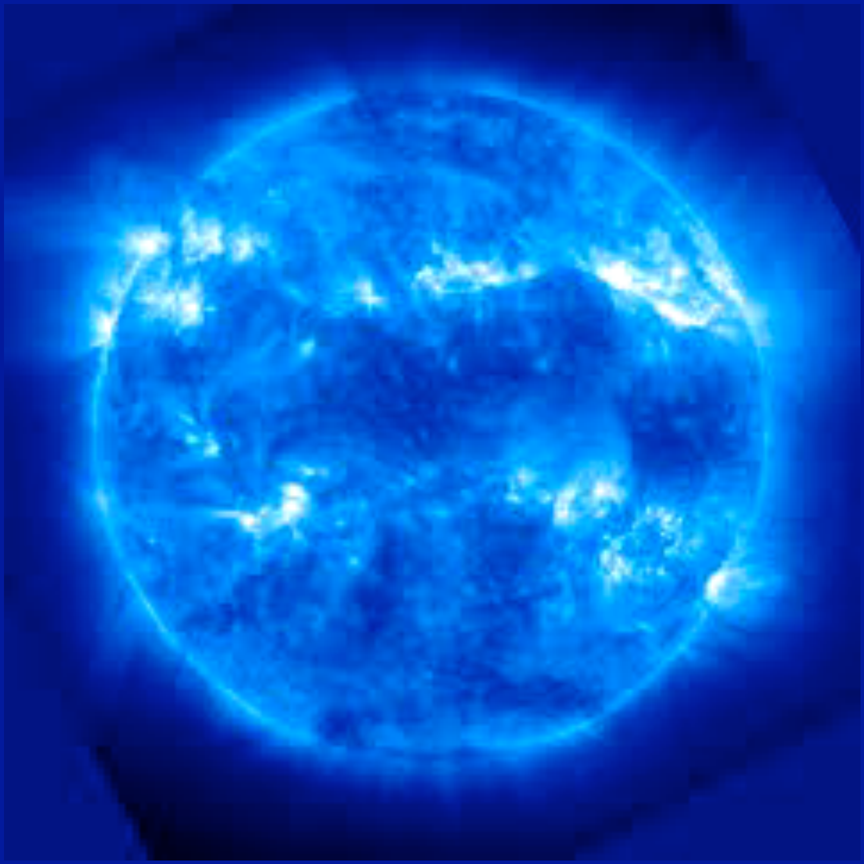
Orbital period at $3R_S$ (last stable orbit for a = 0): 28 min



Accretion flow is highly time-dependent, with fluctuations in density, temperature, dissipation of magnetic & kinetic energy, etc.

suggests observed variability due to turbulent plasma very close to horizon

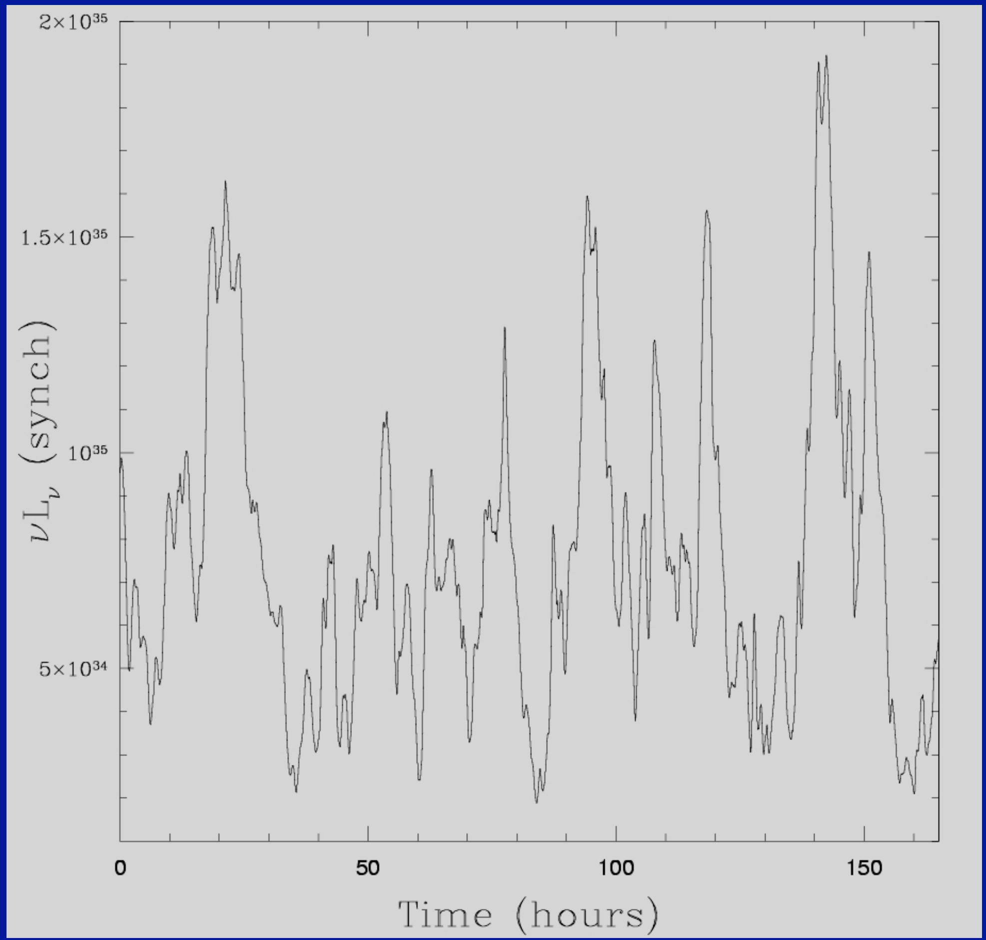
Analogy: Solar Corona



SOHO Movie of Active Regions (UV)
(Solar & Heliospheric Observatory)

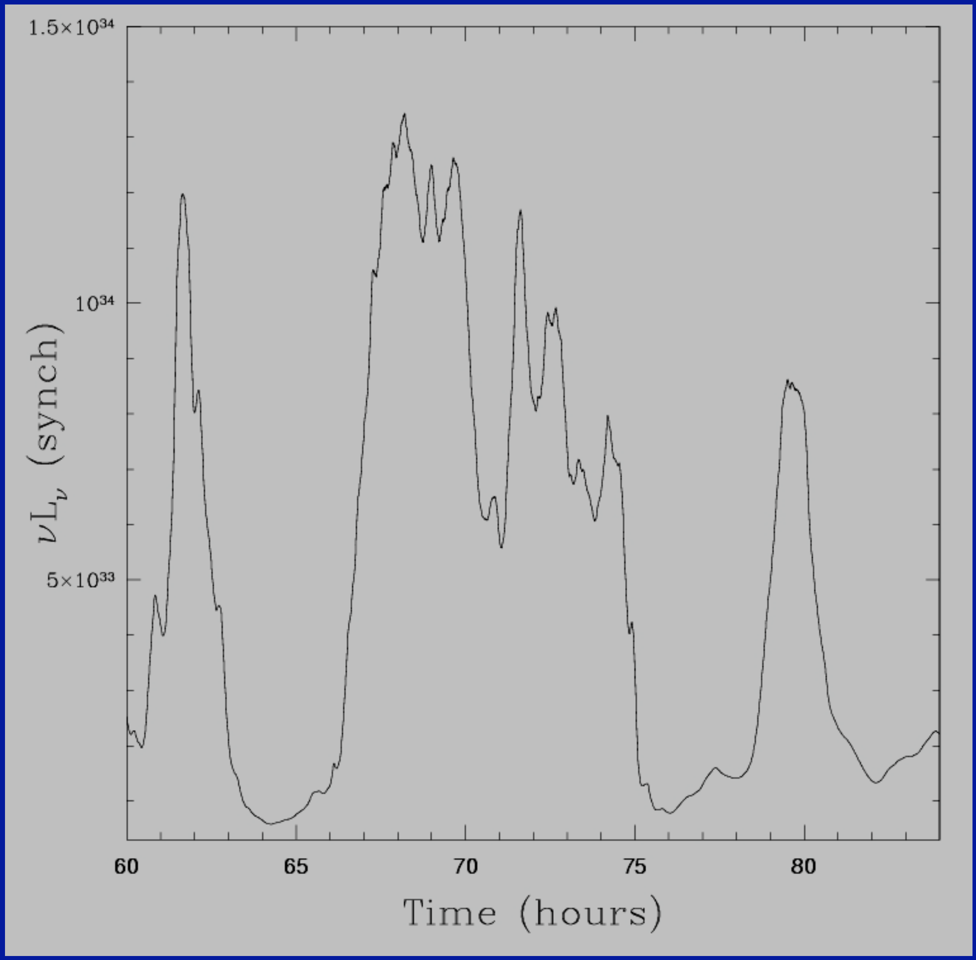
Synchrotron Emission from MHD Simulations

1mm/300 GHz (thermal; optically thin)



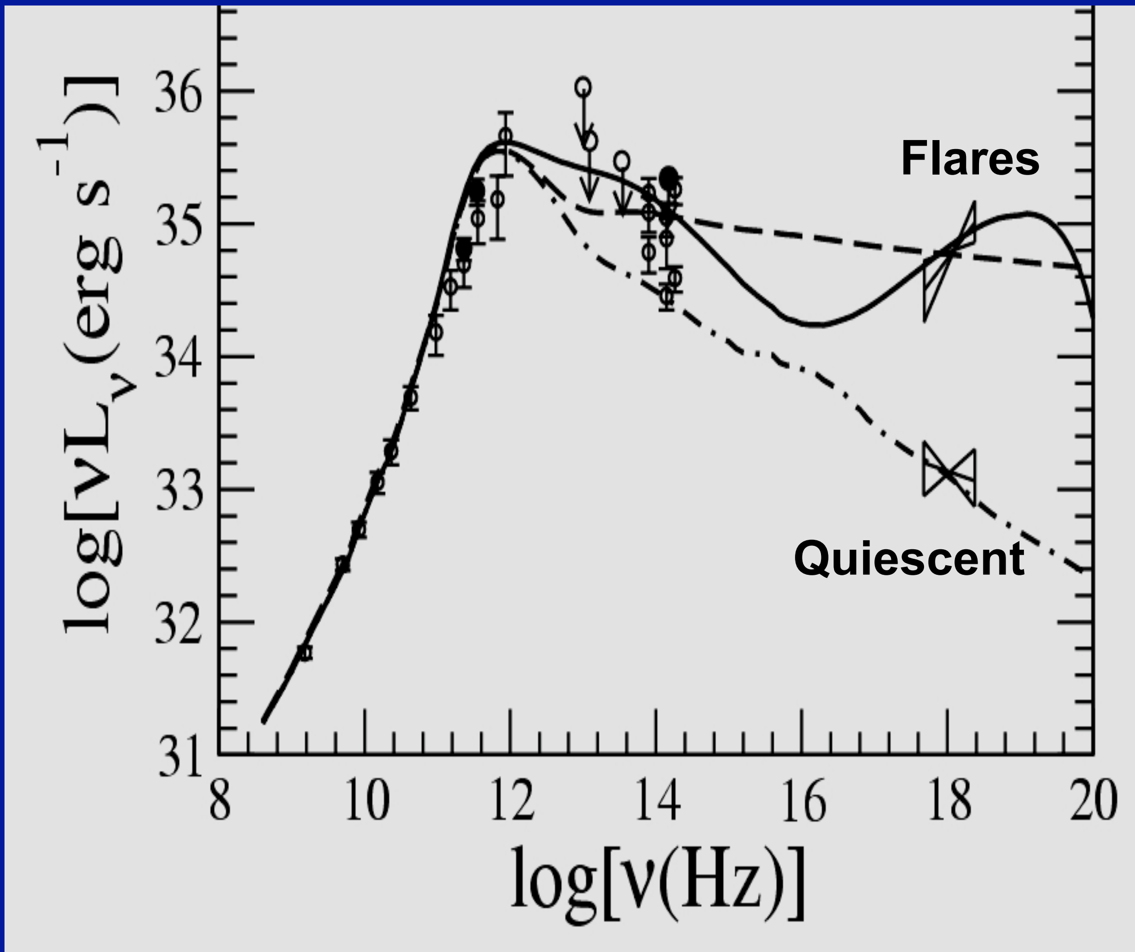
Goldston, Quataert, & Igumenshchev 2004

A Day in the Life of Sgr A*



Factors of ~ 2-5 variability over several hours

Final Ingredient: Particle Acceleration

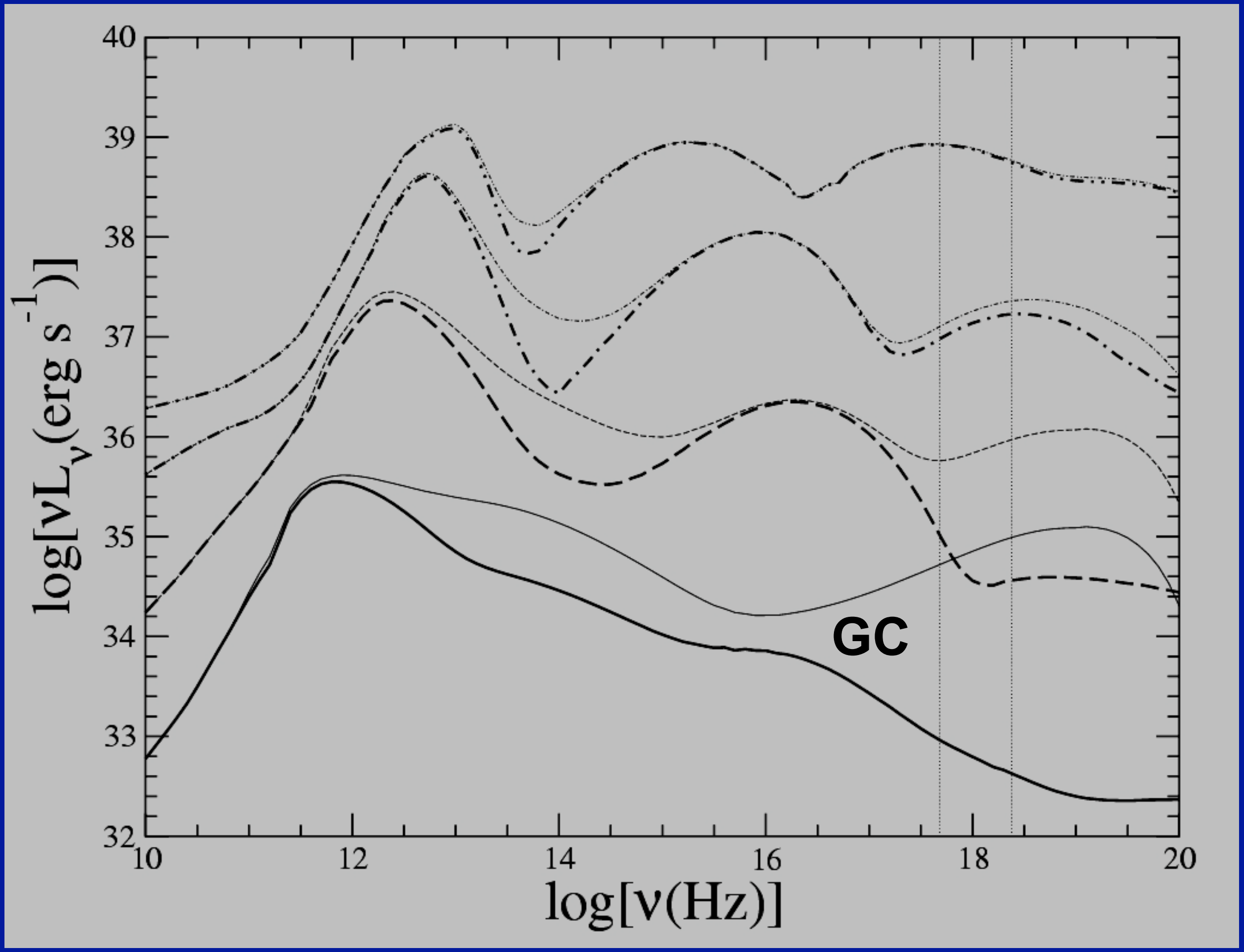


assume that close to BH ~ 10% of electron thermal energy transiently dumped into a power law tail

IR: synchrotron from $\gamma \sim 10^3$ e^-
X-rays: synch. from $\gamma \sim 10^5$ e^-

Prominence of nonthermal emission unsurprising because of collisionless magnetized two-temperature turbulent plasma

Why our Galactic Center?



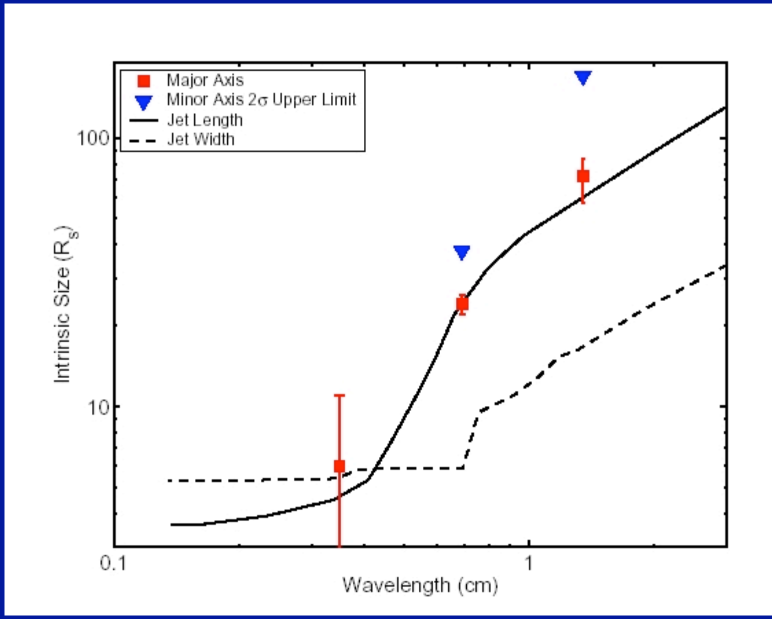
Key is L <<<<< L_{EDD}: analogous 'flares' harder to detect in more luminous systems because they are swamped by emission from the bulk (~ thermal) electrons (next best bet is probably M32)

Inward Bound

- GC horizon: $R_S \approx 10^{12}$ cm $\approx 4\text{x}10^{-13}$ rad $\approx 8\ \mu$-arcsec
- GC is largest BH on the sky!
- can plausibly be directly imaged with VLBI at mm λ's in the next ~ 5 years

Size of Sgr A*

Observed Size (R_S)



Bower et al. 2004

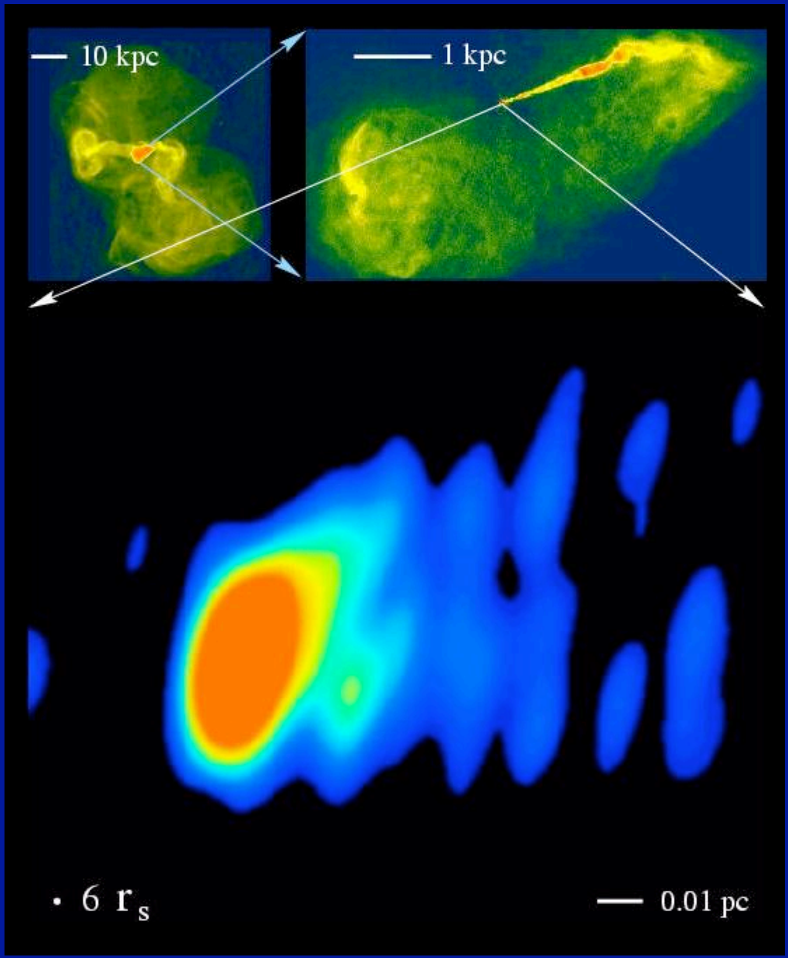
Wavelength (cm)

Simple extrapolation
Size ⇒ Horizon as λ ⇒ 1mm

Inward Bound

Shep Doeleman & collaborators have achieved 34μ" at 1.3 mm on 3C279 (~ $4R_S$ for Sgr A*)

M87 at 7 mm (R_S 2 x smaller on sky)



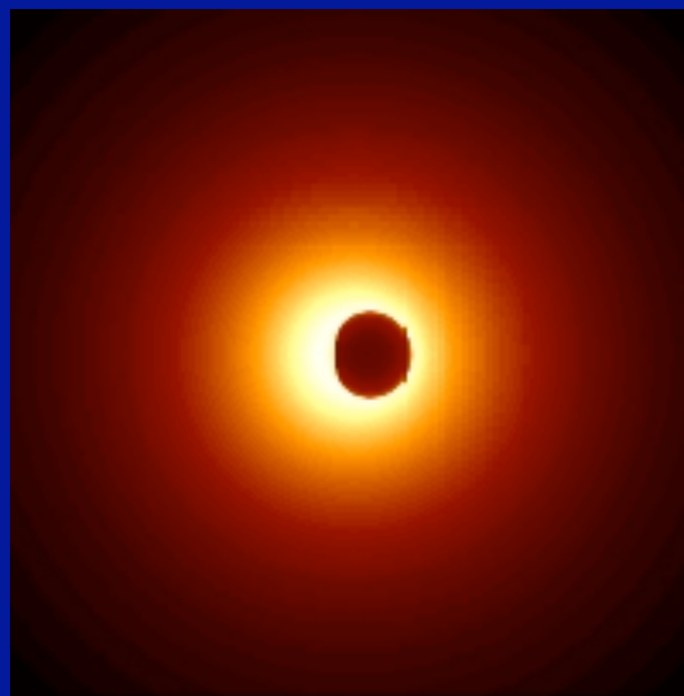
Biretta et al. 1999

— 30 R_S

Toy Models Predict a True "Black Hole"

(light bending, grav. redshift, photons captured by BH, …
⇒ suppression in observed flux from near the BH)

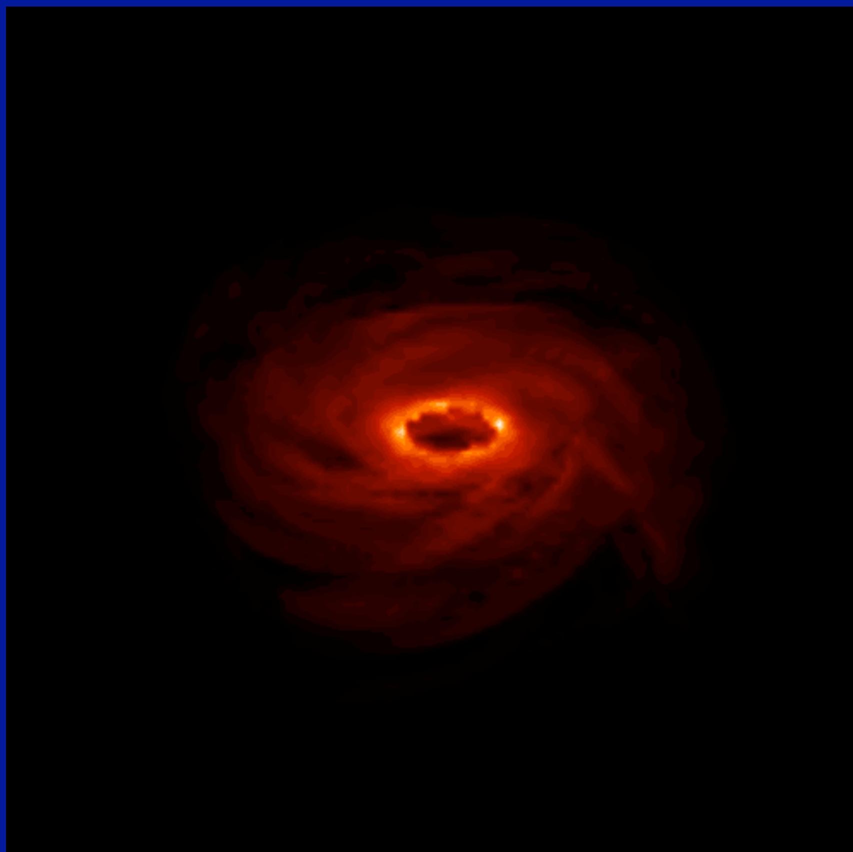
$\approx 10\ R_S$



Falcke et al. 2000; based on Bardeen 1973
also Broderick & Blandford 2003

Work in Progress: “Realistic” Images from Simulations

$\approx 10\ R_S$



Newtonian: No GR Transport Yet

Encouraging: emission strongly peaked near BH where GR effects important

Emission from very small radii also implied by rapid variability

A ‘Concordance’ Model of Sgr A*

- Stars supply ~ 10^{-3} $M_\odot$ yr^{-1} to the central pc of the GC
- ~ 10^{-5} $M_\odot$ yr^{-1} captured by the BH
  - supported by extended X-ray source coincident w/ BH
- ~ 10^{-8} $M_\odot$ yr^{-1} (or perhaps less) accretes onto the BH via a hot radiatively inefficient accretion flow (efficiency > 10^{-3})
  - most mass driven away rather than accreting onto BH
  - supported by detection of polarization in mm emission
- Variable IR & X-ray Emission
  - nonthermal synchrotron radiation from accelerated electrons
  - unique probe of gas dynamics and particle accel. very close to BH
  - encouraging for project of imaging horizon of BH