TESTING GR WITH BLACK HOLES: EVIDENCE FOR THE EVENT HORIZON

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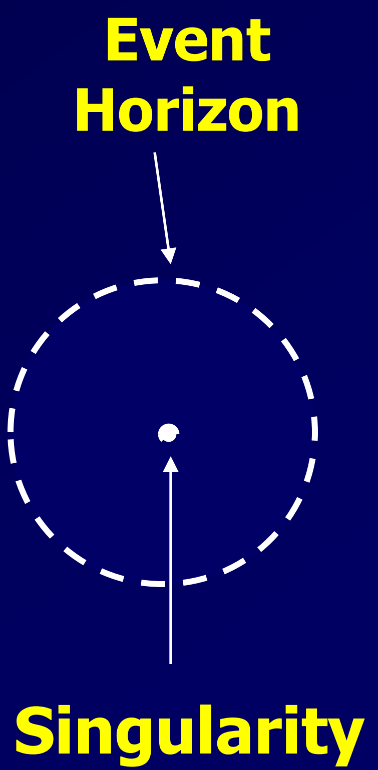
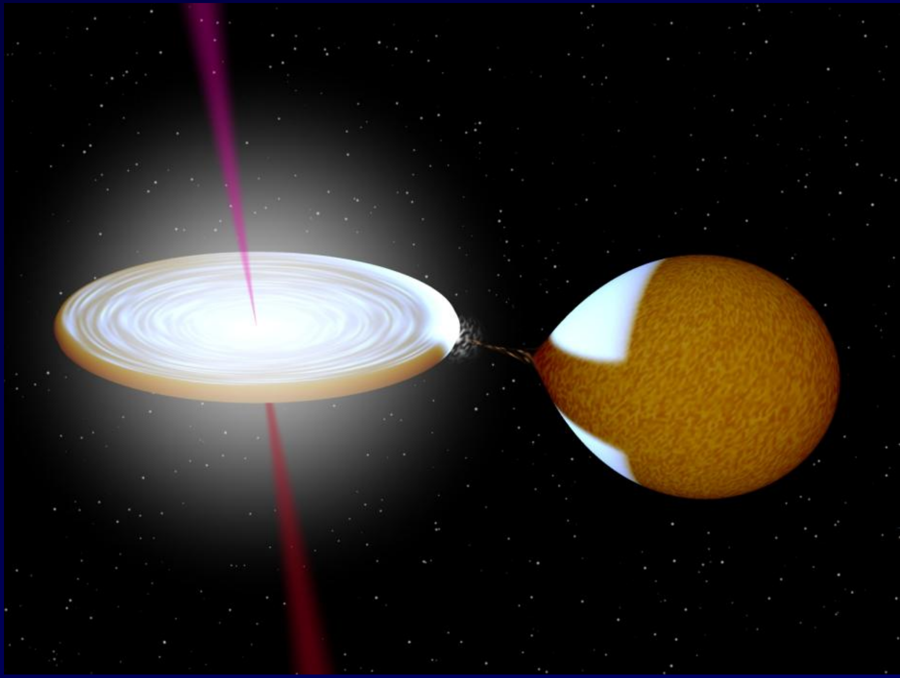
Testing Theories of Gravity: Quantitative vs Qualitative

- Many tests of gravity are quantitative: Metric, No-Hair Theorem, etc.
- But gravity theory makes some **amazing qualitative predictions**
- **Black Hole Event Horizon**
- Does the Event Horizon really exist?
- Verifying the Event Horizon would be a Qualitative but Deep Test of Gravity



In Search of the Event Horizon



- Accretion flows are very useful, since inflowing gas reaches the center and “senses” the nature of the central object
- X-ray binaries have an additional advantage --- we can compare **NS** and **BH** systems --- event horizon vs hard surface

Evidence for the Event Horizon

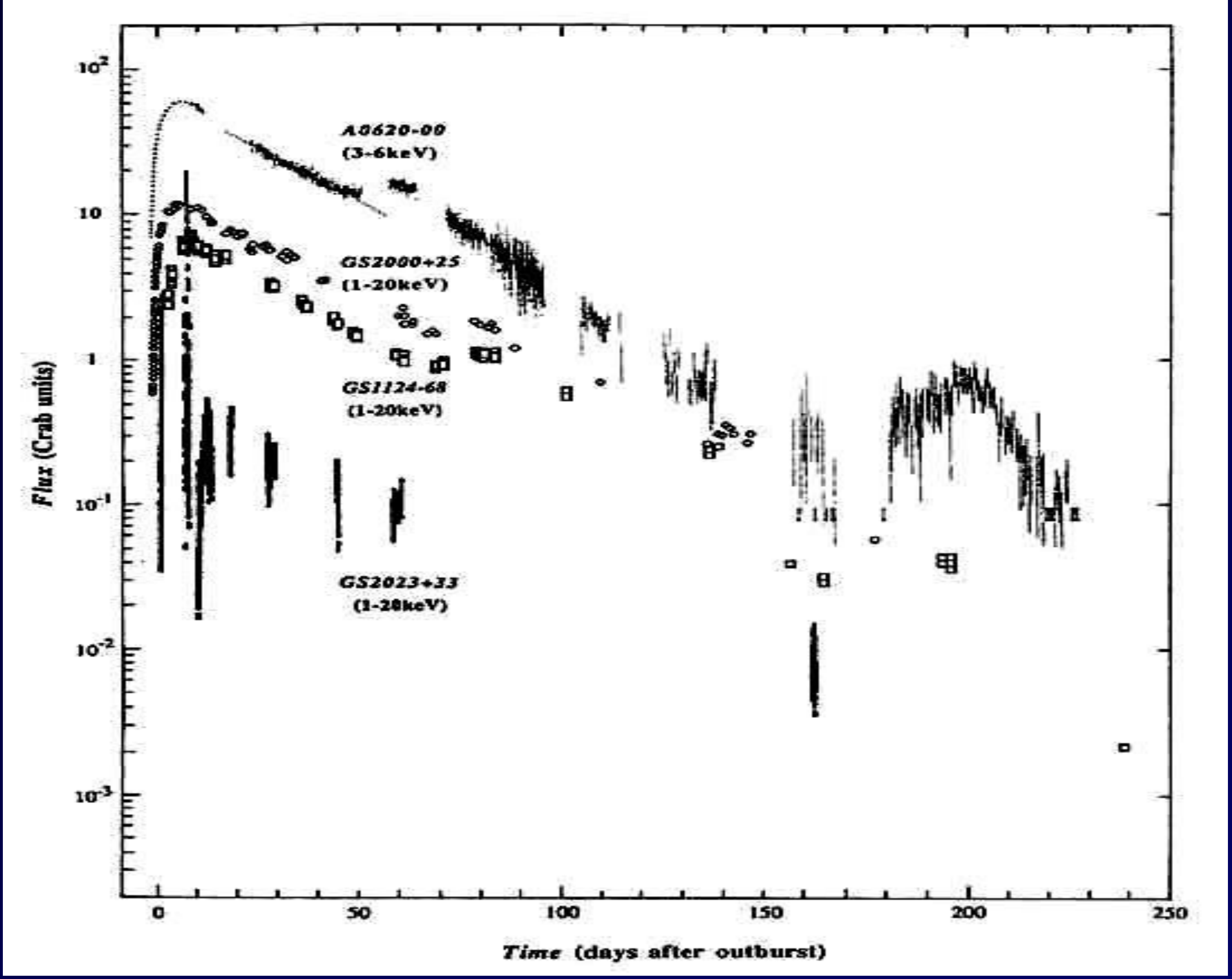
- ✔ Differences in quiescent luminosities of XRBs (Narayan, Garcia & McClintock 1997; Garcia et al. 2001; …)
- !! Differences in Type I X-ray bursts between NSXRBs and BHXRBs (N & Heyl 2002; Remillard et al. 2006)
- X-ray colors of XRBs (Done & Gierlinsky 2003)
- Thermal surface emission of NSXRBs and BHXRBs (McClintock, Narayan & Rybicki 2004)
- ✔ Infrared flux of Sgr A* (Broderick & Narayan 2006, 2007; Broderick, Loeb & Narayan 2009)

Physics of Accretion

- Gas with angular momentum goes into orbit at a large radius around the BH
- Slowly spirals in by viscosity (magnetic fields) and falls onto central object: M, R
- Potential energy is converted to
  - Orbital KE ≈ GM/2R ≈ 50% of PE
  - Thermal energy ≈ 50% of PE
- What happens to the two forms of energy?

Case I: Radiatively Inefficient Accretion

- Many accretion systems are radiatively inefficient (advection-dominated: ADAF)
  - Accretion luminosity: L_{acc} □ $L_{thermal}$
    i.e., L_{acc} □ 0.1 Mdot c^2
- What happens to the remaining energy?
  - If BH, energy disappears through EH
  - If NS, released from the surface of the accreting object when gas crashes on it: $L_{surface} \approx$ GMMdot/R ≈ 0.2 Mdot c^2 □ L_{acc}

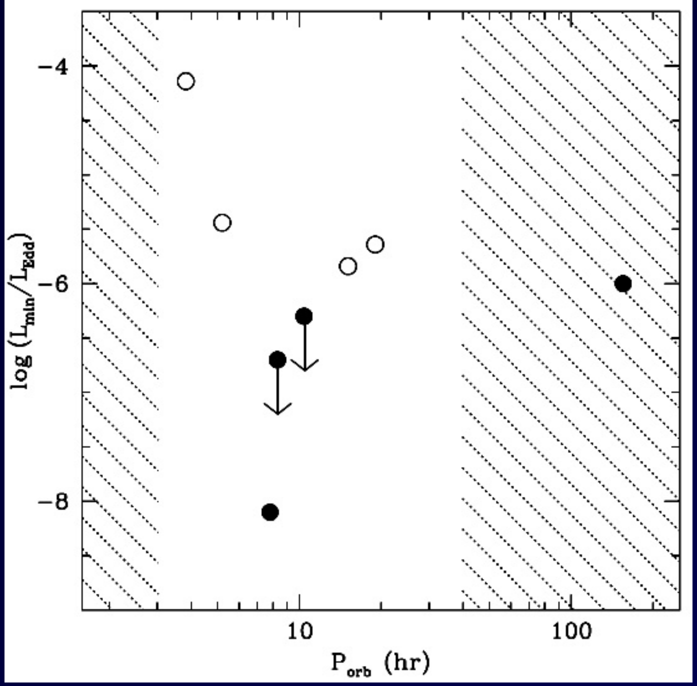


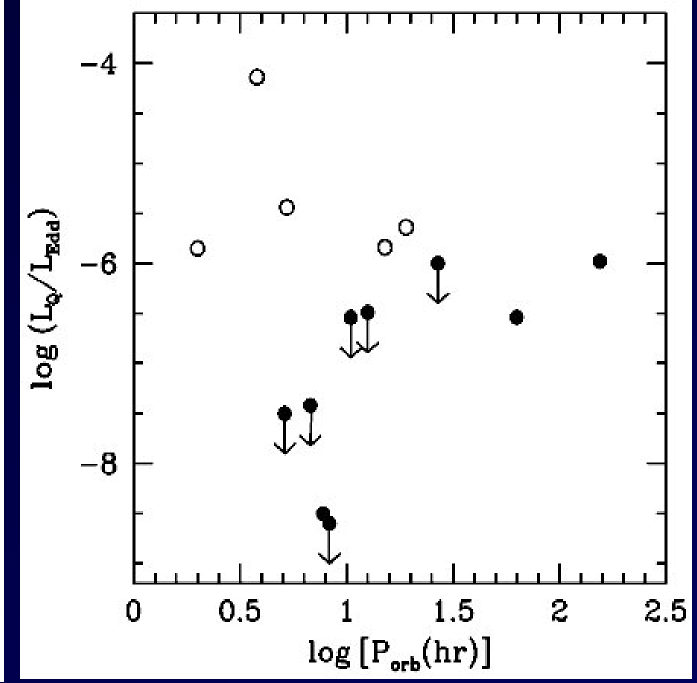
Light Curves of Transient X-ray Binaries

Event Horizon in XRBs

- Look at BH and NS XRBs in quiescence (Narayan & Yi 1995; Narayan, Garcia & McClintock 1997; Menou et al. 1999; Garcia et al. 2001; McClintock et al. 2003)
- Accretion is known to be advection-dominated (N, McClintock & Yi 1996), so we expect
  - BH: $L_{BH} = L_{acc}$ □ 0.1Mdot c^2
  - NS: $L_{NS} = L_{acc} + L_{surface} \approx 0.2$ Mdot c^2 □ L_{BH}
- Therefore, if BH candidates in XRBs have EHs, they should be much fainter than NSs
- **They sure are!!**

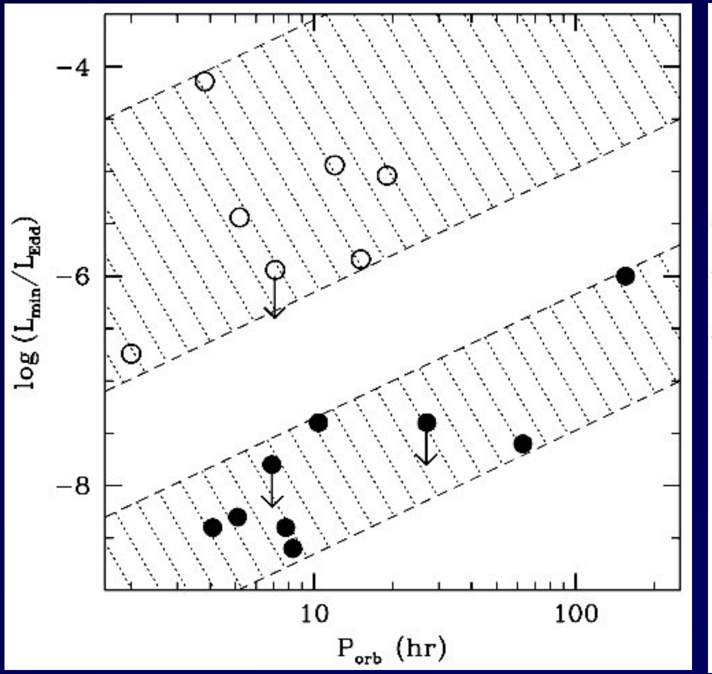
1997

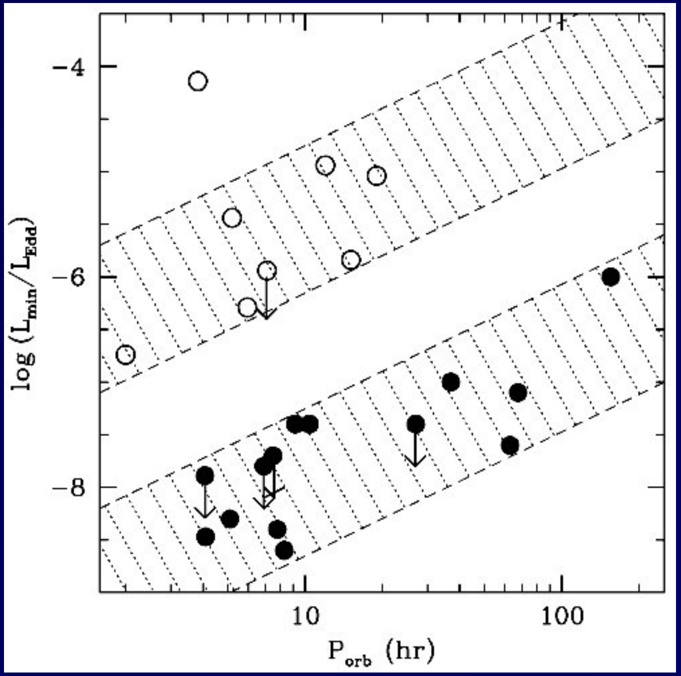




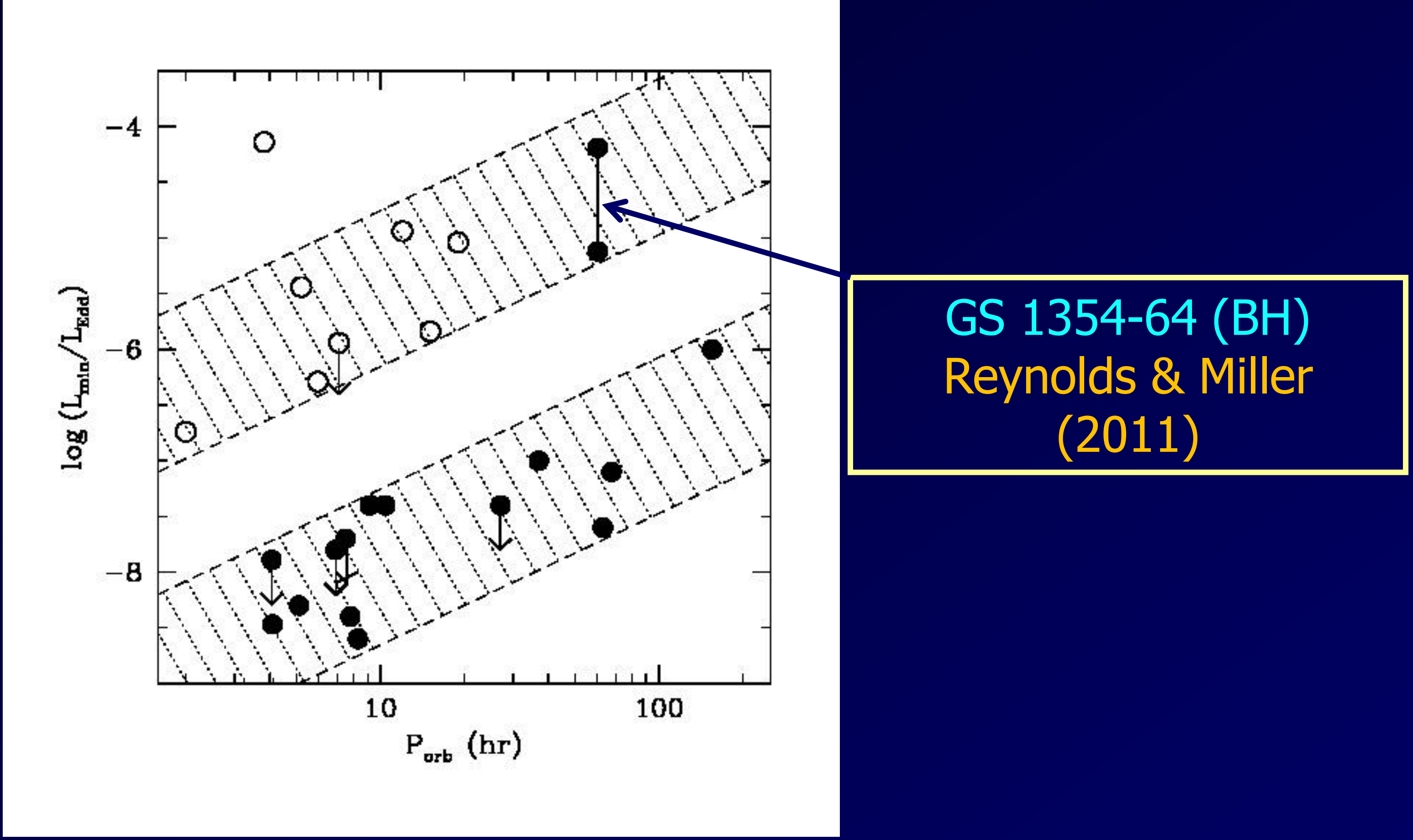
2000

2002

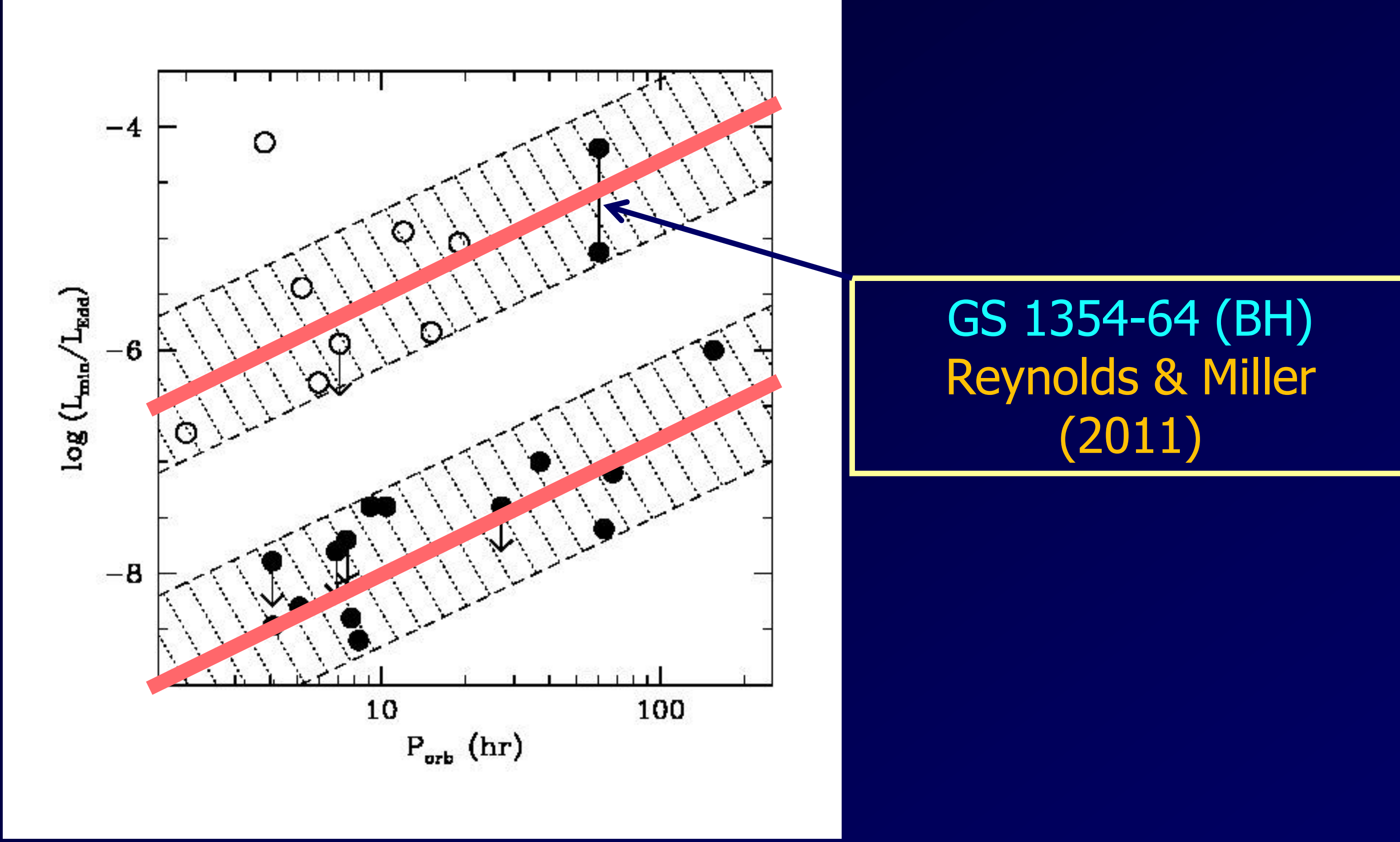




2007



- Transient XRBs in quiescence have ADAFs (N, M & Yi 96)
- Binary period P_{orb} determines Mdot (Lasota & Hameury 1998; Menou et al. 1999)
- At each P_{orb}, we see that L/L_{Edd} is much lower for BH systems. True also for raw L values. (Garcia et al. 2001; McClintock et al. 2003; …)



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Two Key Assumptions

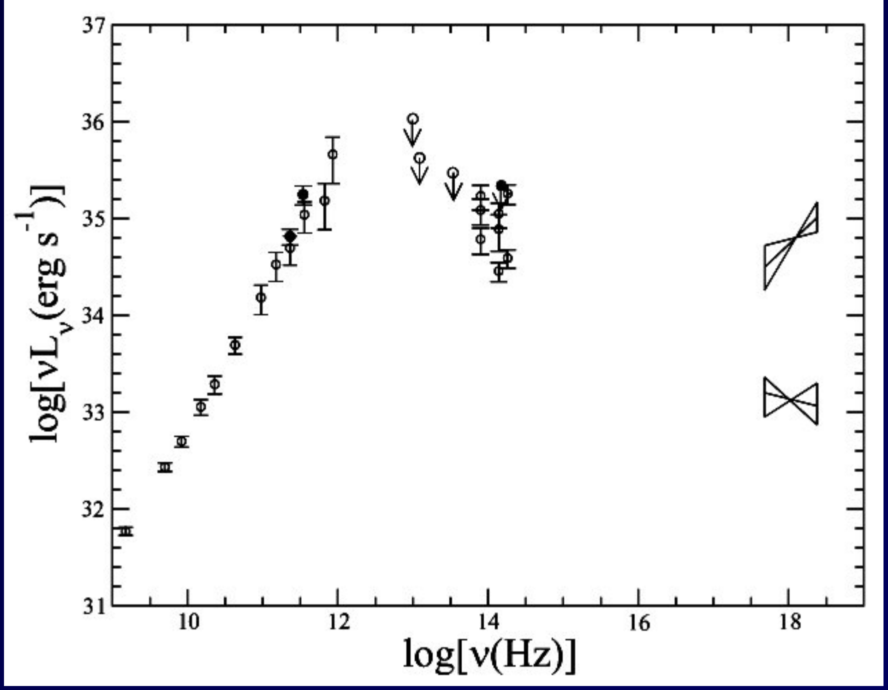
- Our evidence for the EH from quiescent XRBs requires BH and NS systems to have radiatively ineff. accretion (ADAF)
- Also, P_{orb} has to be a good proxy for Mdot
- Both assumptions are very reasonable
- But the argument would be stronger if we could avoid these assumptions
- We can do this at the Galactic Center

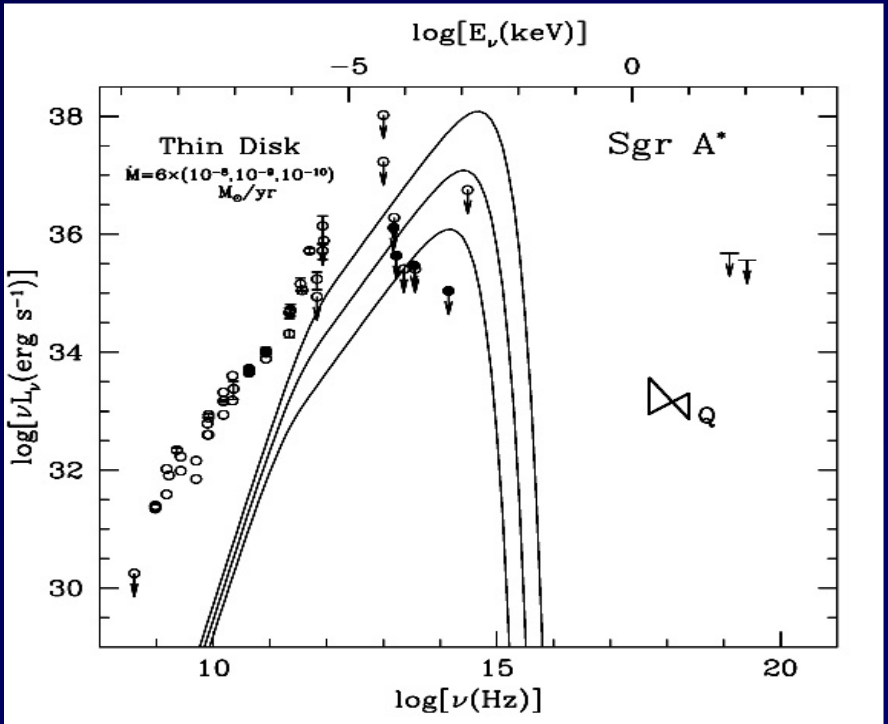
Black Hole Candidate at the Gal. Ctr.: Sagittarius A

- Dark mass ~ $4 \times 10^6\ M_\odot$ at the Galactic Center
- Compact radio source Sgr A* is associated with the dark mass (Reid & Brunthaler 2005)
- Sgr A* is very compact: $< 10GM/c^2$ (Doeleman)
- Sgr A* is ultra-dim: $L \sim 10^{36}$ erg/s
- Minimum accretion rate: $Mdot_{min} = 10^{-10}\ M_\odot yr^{-1}$

Luminosity and Spectrum of Sgr A*

- Sgr A* is a very dim source. It has a luminosity of only ~10^{36} erg/s
- Most of the luminosity comes out in the sub-mm
- Most likely we have an ADAF (Narayan, Yi & Mahadevan 1995)
- But we won't use this fact





Case II: Radiatively Efficient Accretion

- If the accretion system is radiatively efficient (e.g., standard thin disk)
  - Accrn lum: $L_{acc} \approx L_{thermal} \approx 0.1$ Mdot c^2
- What happens to the remaining energy?
  - If BH, energy disappears through EH
  - If we have an object with a surface: $L_{surface} \approx L_{KE} \approx 0.1$ Mdot $c^2 \approx L_{acc}$
  - (Recall, for ADAF: $L_{surface}$ □ L_{acc})

The Radiation we see in Sgr A* is from the Accretion Disk

- Any "surface" in Sgr A* will produce optically thick radiation (opaque to its own radiation)
- Measured mm/sub-mm flux, coupled with small angular size, implies high brightness temperature: $T_B > 10^{10}$ K. Requires gas temperature $\geq 10^{10}$ K.
- Optically thick emission at this temperature would peak in γ-rays (and outshine the universe!!)
- Therefore, the radiation from Sgr A* must be emitted by gas that is optically thin in IR/X-rays/γ-rays
- ➔ Sub-mm radiation is from the accretion flow

*Is there any "Surface" Luminosity from Sgr A**

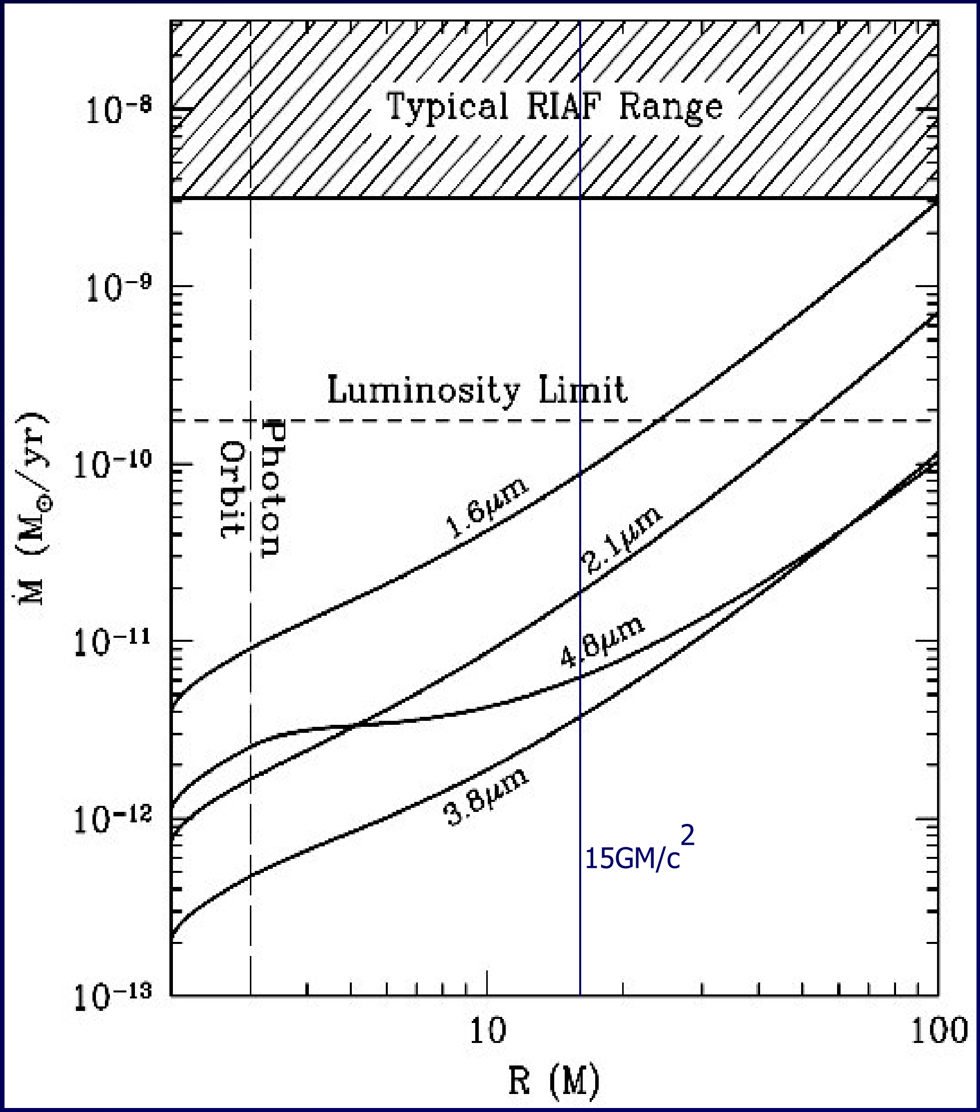
- The surface luminosity is expected to be

  $L_{\mathbf{surface}} \approx L_{acc}$ (at least, could be much more)

- Since we know $L_{acc} \approx 10^{36}$ erg/s, we predict: $L_{surface} \approx 10^{36}$ erg/s (perhaps □10^{36} erg/s)
- Moreover, surface should be optically thick (blackbody-like emission) and for likely radii R of the surface, radiation should be in Infrared
- **No Sign of this Radiaton**

Maximum Mdot from IR Flux Limits

- IR flux limits place stringent constraints on accretion onto a surface
- Limits are well below minimum possible Mdot in Sgr A*
- Therefore, Sgr A* cannot have a surface
- **➔ has Event Horizon**



Broderick & Narayan (2006, 2007)

Broderick, Loeb & Narayan (2009)

Summary of the Argument

- The observed sub-mm emission in Sgr A* is definitely from the accretion flow
- Radiation is way too hot to be from the "surface" of a compact object
- If Sgr A* has a surface we expect at least $\sim 10^{36}$ erg/s from the surface
- This should come out in the IR, but measured limits are ~100 times lower
- Therefore, Sgr A* cannot have a surface

Can Strong Gravity Provide a Loophole?

- Under all reasonable conditions, the radius of the surface must be larger than $(9/8)R_S$ (Buchdahl 1959) → grav. redshift < 3
- In some very unusual models (gravastar, dark energy star), it is possible to have a smaller radius: $\mathbf{R = R_S + \Delta R, \Delta R \ll R_S}$
- Extreme relativistic effects are expected

Effects of Strong Gravity

- Radiation may take forever to get out
- Surface emission may be redshifted away
- Emission may not be blackbody radiation
- Emission may be in particles, not radiation
- Surface may not have reached steady state

It is easily shown that none of these effects can get around the observational evidence

One Key Assumption

- Our argument for an EH in Sgr A* makes only one important assumption
  - It assumes that the source is accreting and sub-mm radiation is produced by accretion
- The only way out of an Event Horizon is to say that Sgr A* is powered by something other than accretion

Summary

- By now, there is a variety of astrophysical evidence – two were presented here -- for the reality of **BH Event Horizons**
- Each argument by itself is pretty strong
- Combined, the evidence is **Very Strong**
- Virtually impossible to get around…

A Question for Physicists!

- Can we say that the search for the Event Horizon is a done deal?
- Can we chalk up a victory for gravity and move on?
- If "NO", what else must we do?
- We need guidance on when we can claim victory…

(Narayan & McClintock: New Astron. Rev., 51, 733, 2008)