ASTROPHYSICAL BLACK HOLES: WHAT CAN THEY TELL US ABOUT GRAVITY?

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Good News – The Universe is Full of Black Holes!

- From theory: Neutron stars, strange stars, or other kinds of compact objects cannot be more massive than $\sim 3M_{\odot}$
- Observations: The most massive neutron star discovered so far is $\sim 2M_{\odot}$
- Any compact relativistic object with mass $> 3M_{\odot}$ MUST BE A BLACK HOLE
- Huge numbers of these in the Universe

X-ray Binaries

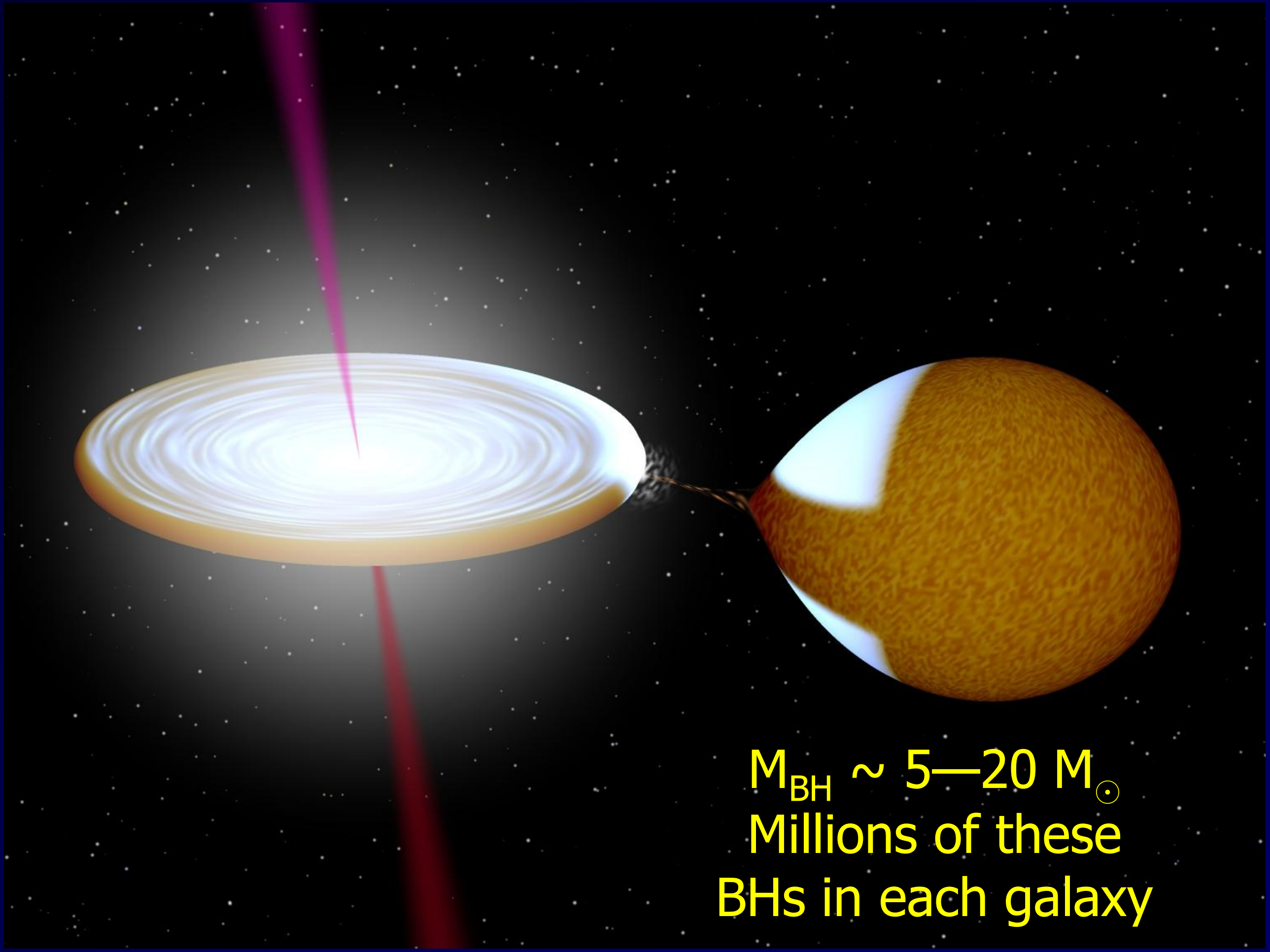


Image credit: Robert Hynes

Galactic Nuclei

Image credit: Lincoln Greenhill, Jim Moran

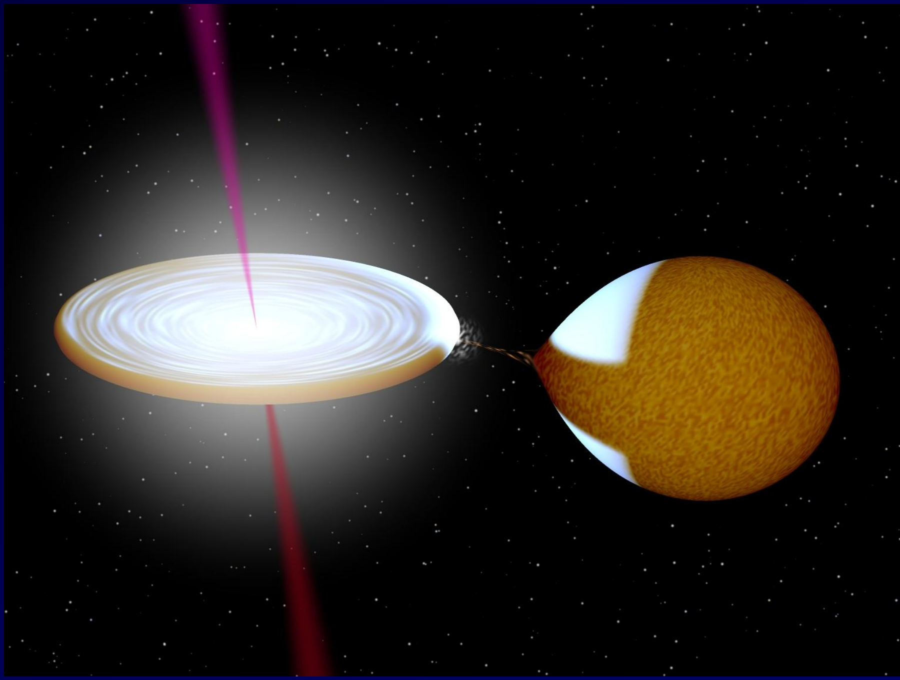
What Makes Black Holes so Special?

- From the point of view of (classical) gravity, two unique features:
  - Black holes have Event Horizons
  - Black holes have only two hairs: M, $a_* = a/M$ (No Hair Theorem)

I. Are Astrophysical Black Holes Really Black Holes?

- We know that astrophysical BHs are:
  - Compact: $\mathbf{R \lesssim few\ R_S}$
  - Massive: $\mathbf{M \gtrsim 3M_\odot}$ (not neutron stars)
- But can we be sure that they are really BHs?
- Can we find independent evidence that **BH** candidates actually possess **Event Horizons** ?

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:
  - Can distinguish Event Horizon vs Stellar Surface
- X-ray binaries: We can compare **NS** systems (surfaces) with **BH** systems (no surfaces?)

Signatures of the Event Horizon

√ ▪ Differences in quiescent luminosities of XRBs (Narayan, Garcia & McClintock 1997; Garcia et al. 2001; McClintock et al. 2003;…)

√ ▪ Differences in Type I X-ray bursts between NSXRBs and BHXRBs (Narayan & Heyl 2002; Tournear et al. 2003; Yuan, Narayan & Rees 2004; Remillard et al. 2006)

▪ Differences in X-ray colors of XRBs (Done & Gierlinsky 2003)

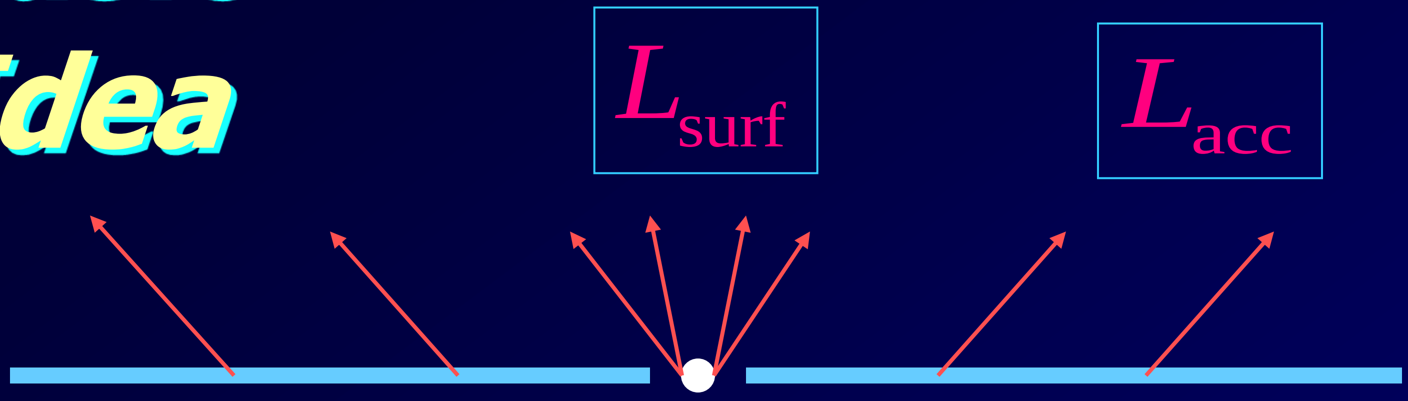
▪ Differences in thermal surface emission of NSXRBs and BHXRBs (McClintock, Narayan & Rybicki 2004)

√ ▪ Infrared flux of Sgr A* (Broderick & Narayan 2006, 2007, 2009)

Physics of Accretion

- Gas with angular momentum goes into orbit at a large radius around the BH
- Slowly spirals in by "viscosity" (magnetic stresses) and falls into the BH at the center
- Potential energy is converted to orbital kinetic energy and thermal energy:
- Thermal energy is radiated
- A good fraction of this luminosity comes from the surface of the central object

Basic Idea



- The surface luminosity from the central star is predicted to be always important: $\mathbf{L_{surf} \gtrsim L_{acc}}$
- Unless there is no surface…
- We look for systems that have negligible surface luminosity → these must be **BHs**
- Has the potential to be a robust argument since it just uses energy conservation

How Much Luminosity from the Surface?

- In a Newtonian analysis, if the accretion disk extends down to the radius of the central star R_*, the binding energy of
  - circular orbit at R_* is $GM/2R_*$
  - material on stellar surface is $\sim GM/R_*$

$$\boxed{\begin{gathered} L_{\mathrm{acc}} = GM\,\dot{M}/2R_* \\ L_{\mathrm{surf}} \sim GM\,\dot{M}/2R_* = L_{\mathrm{acc}} \end{gathered}}$$

Relativistic Case

Energy per unit mass

At infinity: $e_\infty = 1$

Circular orbit at radius r$_*$: $e_{\rm acc}(r_*)$

At rest on stellar surface: $e_{\rm surf}(r_*)$

Luminosity

(radiatively efficient)

Accretion: $L_{\rm acc} = \left[1 - e_{\rm acc}(r_*)\right]\dot{M}$

Surface: $L_{\rm surf} = \left[e_{\rm acc}(r_*) - e_{\rm surf}(r_*)\right]\dot{M}$

Schwarzschild "Star"

$r_* = r_{ISCO} = 6M$

$L_{\rm acc} = 0.0572\,\dot{M}$

$L_{\rm surf} = 0.1263\,\dot{M}$

$r_* = r_{\rm Buchdahl} = (9/4)M$

$L_{\rm acc} = 0.0572\,\dot{M}$

$L_{\rm surf} = 0.6095\,\dot{M}$

$r_* = r_{\rm gravastar} \approx 2M$

$L_{\rm acc} = 0.0572\,\dot{M}$

$L_{\rm surf} \approx 0.9428\,\dot{M}$

Often the Situation is Even Better

- In many systems, the accretion flow is radiatively inefficient (Advection-Dominated Accretion Flow: ADAF)
- Then L_{acc} is very much smaller

$$L_{\text{acc}} \ll \left[1 - e_{\text{acc}}(r_*)\right]\dot{M}$$

$$L_{\text{surf}} = \left[1 - e_{\text{surf}}(r_*)\right]\dot{M} \gg L_{\text{acc}}$$

Orders of magnitude difference possible

Luminosities of Quiescent XRBs

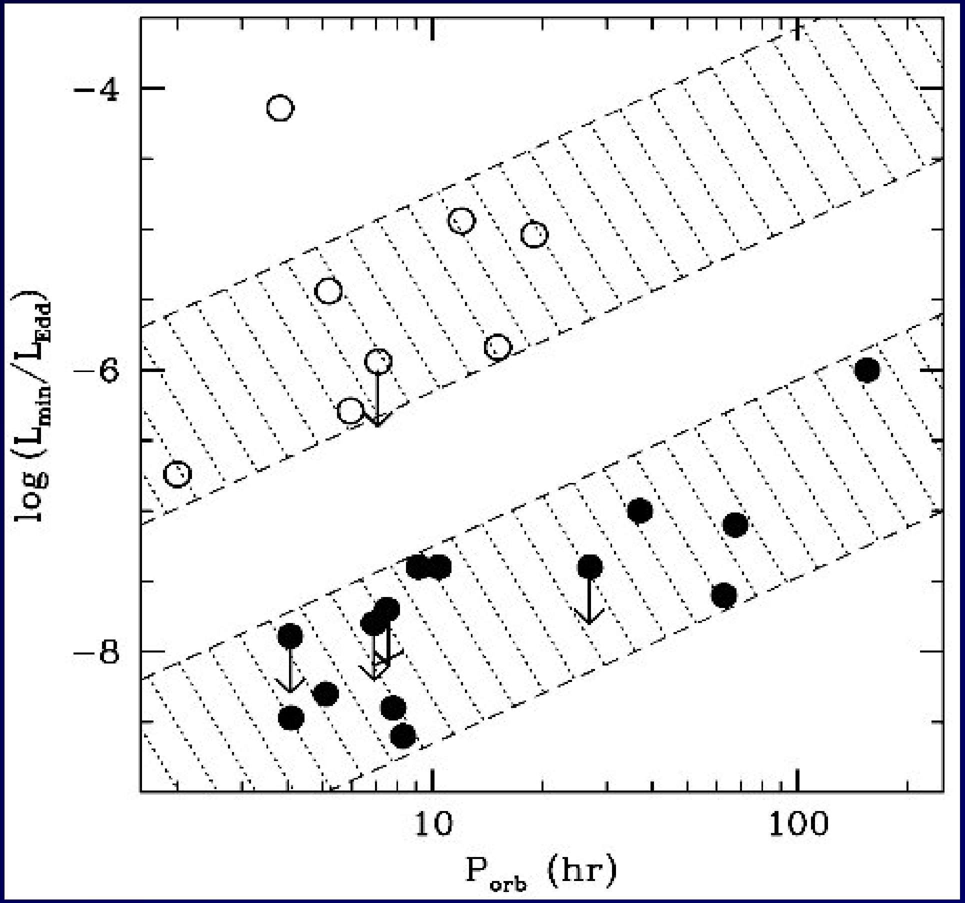
Extremely strong signal in the data

There is no question that quiescent BHs are orders of magnitude fainter than NSs

Perfectly natural if BHCs have Event Horizons

The effect was predicted!

Other explanations are very contrived



Narayan, Garcia & McCltintock (1997)
Garcia et al. (2001)…

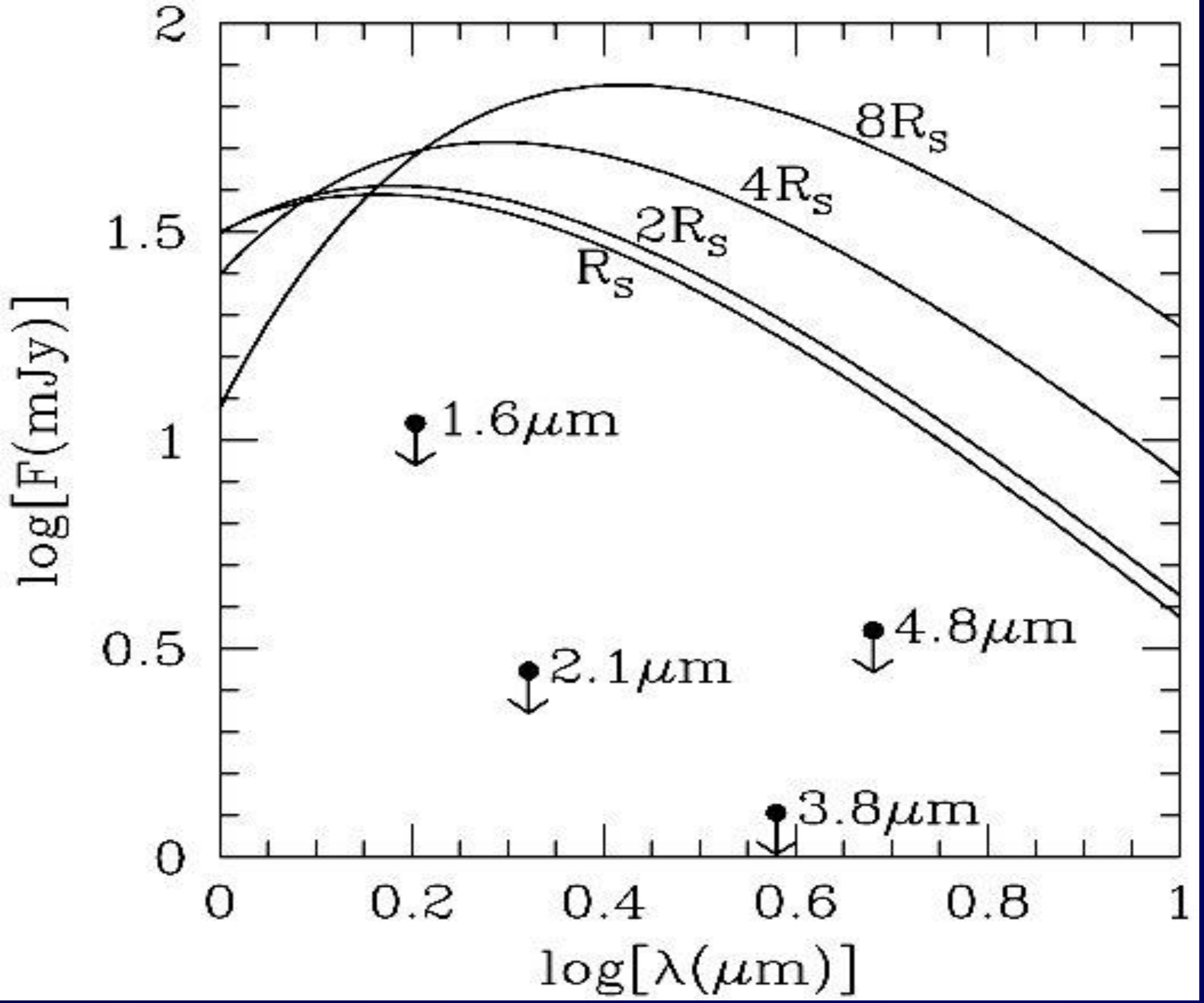
Another Test: The Black Hole at the Center of Our Galaxy

Name: Sagittarius A*

Mass $\sim 4 \times 10^6\ M_\odot$ (inferred from stellar motions)

Is There Any "Surface" Emission from Sgr A?*

- The surface luminosity is expected to be $\mathbf{L_{surf}} \gtrsim \mathbf{L_{acc}}$ (very likely $\mathbf{L_{surf}} \gg \mathbf{L_{acc}}$)
- Since we know $\mathbf{L_{acc} \sim 10^{36}}$ **erg/s**, we expect: $\mathbf{L_{surf}} \gtrsim \mathbf{10^{36}}$ **erg/s** (or $\gg \mathbf{10^{36}}$ **erg/s**)
- For typical radii $\mathbf{R_*}$ of Sgr A*'s "surface" the radiation is predicted to come out in the IR
- But there is no sign of this radiation

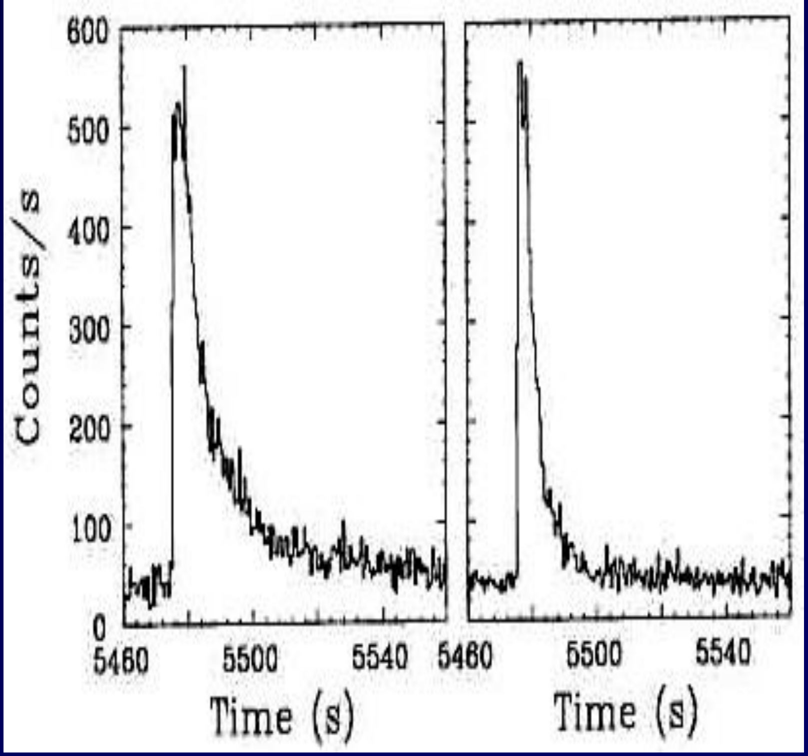


Based on Broderick & Narayan (2006)

All four IR bands have flux limits well below the predicted flux even though model predictions are very conservative (e.g., assume radiatively efficient)
→ Sgr A* cannot have a surface → Event Horizon → Black Hole

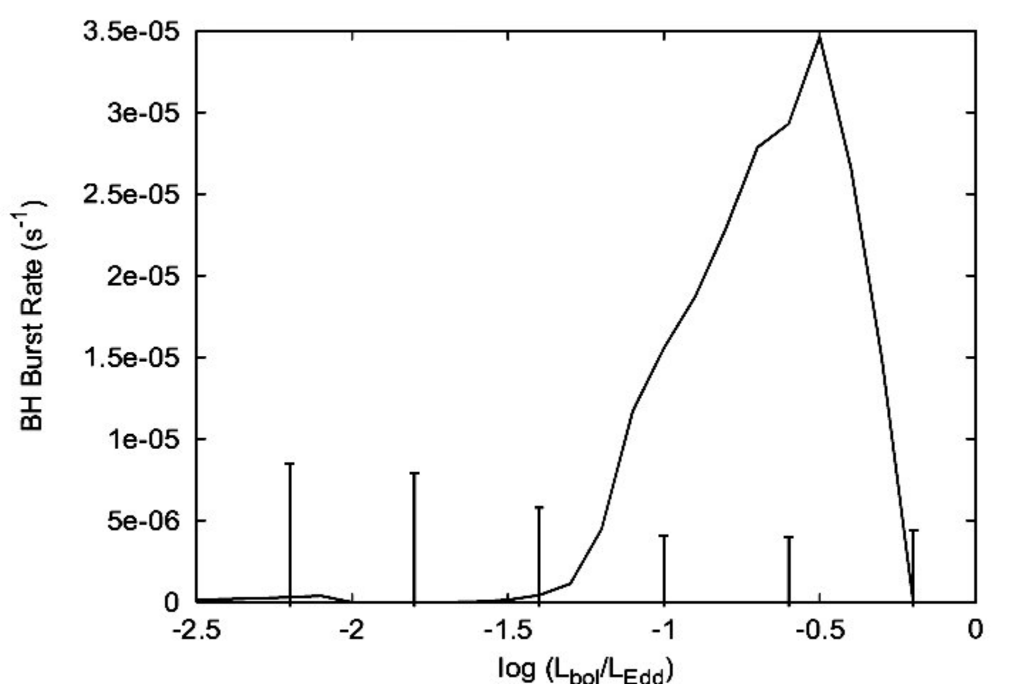
Type I X-ray Bursts

- Discovered by Grindlay et al. (1976)
- Very common in XRBs
- Sudden brightening, once every several hrs; lasts about 10-100 s
- Physics understood: unstable nuclear burning of accreted gas



No Type I Bursts in BHs!!

- No BH candidate has ever exhibited a Type I burst
- Obvious explanation: They have event horizons, so material cannot pile up, no nuclear instability
- Quantitative analysis: Lack of bursts is very significant (90% conf. limits are shown)



Narayan & Heyl (2002)

Tournear et al. (2003)

Remillard, Lin, Cooper, N (2006)

Can Strong Gravity Provide a Loophole?

- In some very unusual models of compact stars (e.g., gravastar, dark energy star), it is possible to have a surface at a very small radius:
  $R_* = 2M + \Delta R,\ \Delta R \ll 2M$
- Extreme relativistic effects are expected
- Can relativity hide surface emission? **NO!!**

For More Details

Please see

Narayan & McClintock: New Astronomy Reviews, 51, 733-751 (2008)

Let us Accept that Astrophysical BH Candidates have no Surfaces

- Does this prove that these objects have Event Horizons?
- Not really – there are other options, but they are even more bizarre!

They Could be Wormholes?

- Damour & Solodukhin (2007)
- Wormholes can “look” just like BHs
- Accreting gas falls and then bounces back
- If bounce-back time is long enough, then cannot distinguish a Wormhole from a BH
- But it requires: $\lambda \ll \exp[-10^{15}]$
- Is such an extreme value reasonable?
- Does accreted mass modify the solution?

Black Hole Mimickers

- Lemos & Zaslavskii (2007, 2008,…)
- Best to worst BH mimickers:
  - Wormholes on basis of extremal BHs
  - Wormholes on basis of quasi-BHs
  - Wormholes on non-extremal BHs
  - Gravastars
- “Extremal systems are unlikely, while non-extremal are poor mimickers”

Could They be Naked Singularities?

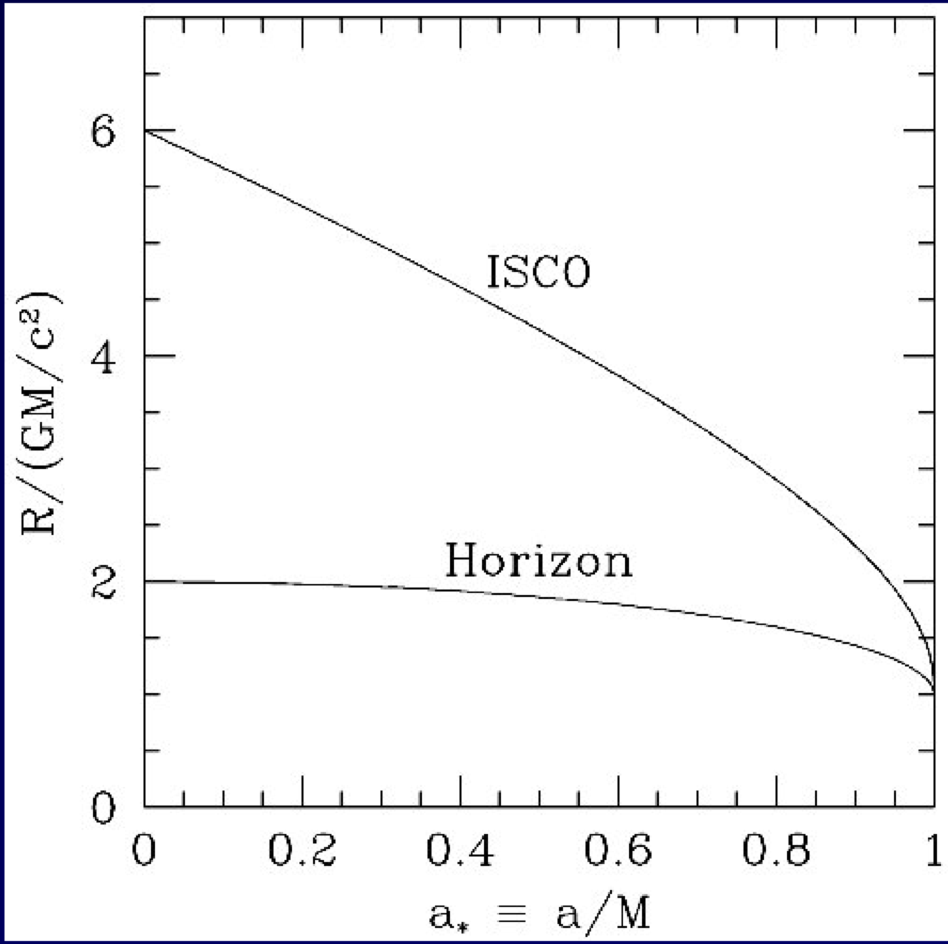
- E.g., Kerr solution with a*>1 (super-spinars): Bambi & Freese (2009), Bambi et al. (2009, 2010,…)
- Q: Are naked singularities consistent with the lack of "surface radiation"?
  - Seems unlikely…
  - If we can see down to the singularity, surely we will observe continued emission from gas right down to the center
  - The object should be very bright…

II. Is the No-Hair Theorem True?

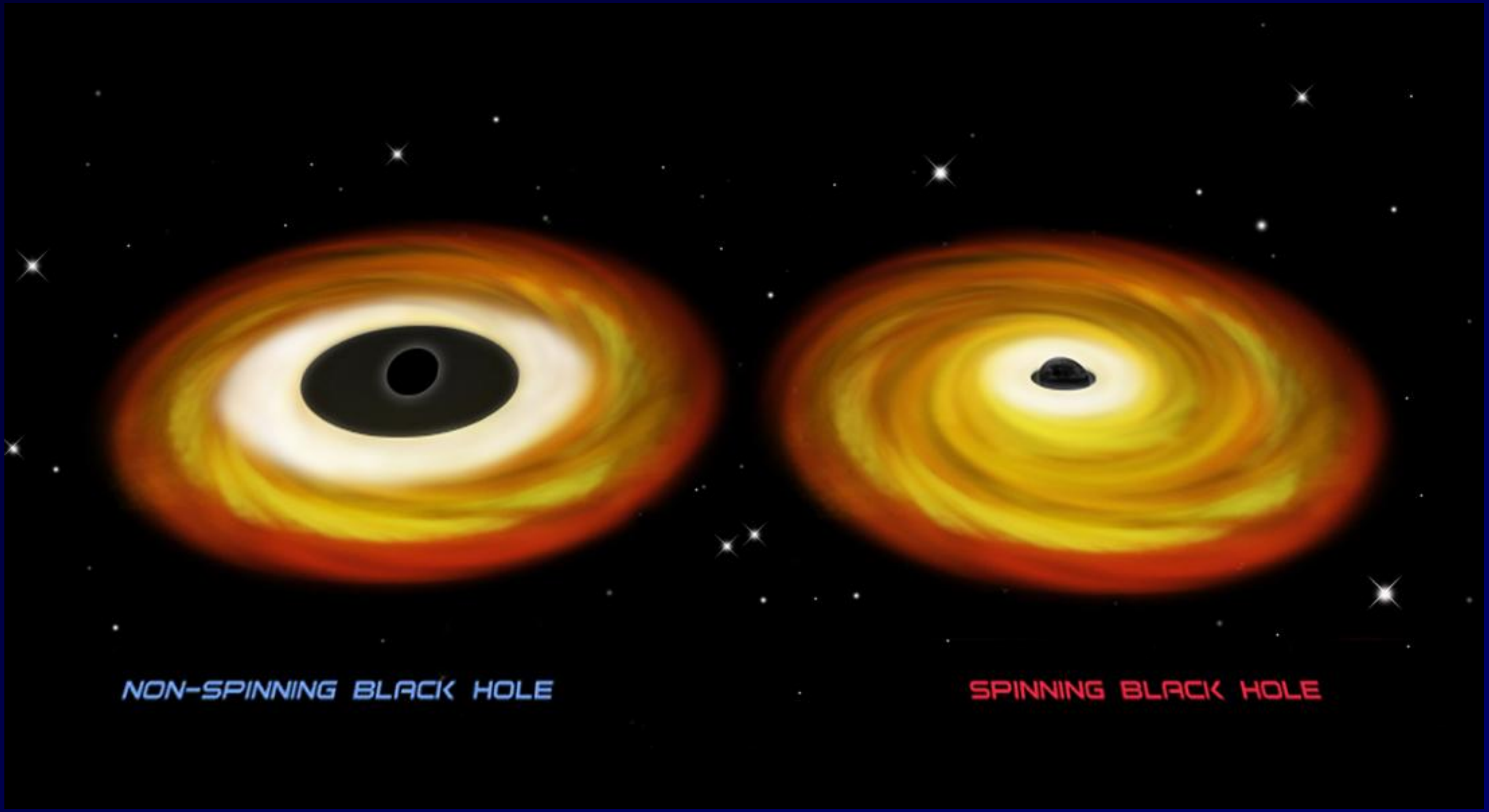
- Can we test the **No-Hair Theorem**?
- Here is one way to do it:
  - Choose a suitable astrophysical BH
  - Measure **M**, $\mathbf{a}_*$ as precisely as possible
  - Make additional observations of space-time
  - Check whether all observables are consistent with the Kerr metric: **M**, $\mathbf{a}_*$
- We have M, and we are just getting a_*

Innermost Stable Circular Orbit (ISCO)

- R_{ISCO}/M depends on the value of a_*
- If we can measure R_{ISCO}, we will obtain a_*
- Note factor of 6 variation in $\mathbf{R_{ISCO}}$
- **Especially sensitive** as $a_* \rightarrow 1$



The Basic Idea



Accretion disk has a dark central "hole" with no radiation

Measure radius of hole by estimating area of the bright inner disk

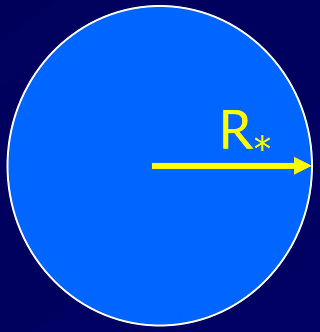
Measuring the Radius of a Star

- Measure the flux F received from the star
- Measure the temperature T_* (from spectrum)

$$L_* = 4\pi D^2 F = 4\pi R_*^2 \sigma T_*^4$$

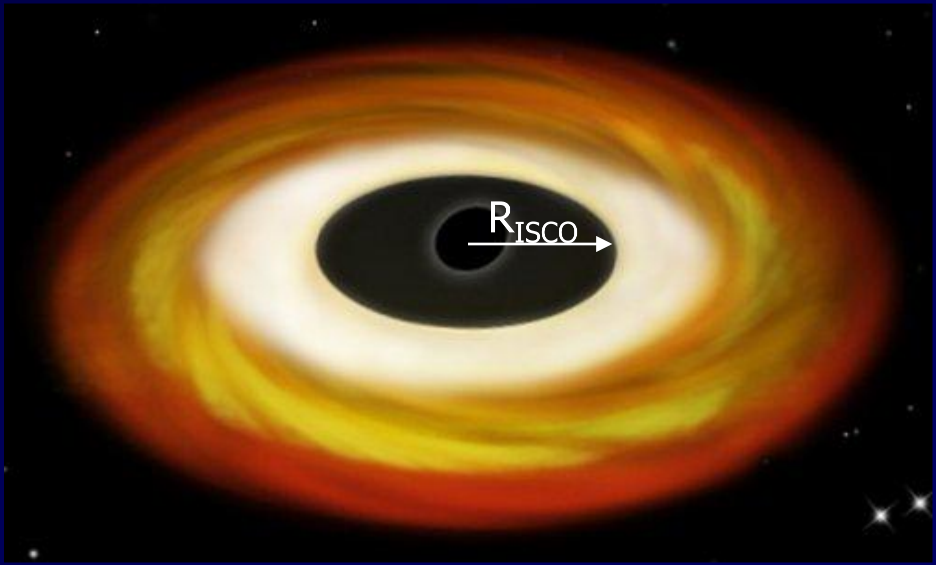
$$\Delta\Omega = \frac{\pi R_*^2}{D^2} = \frac{\pi F}{\sigma T_*^4}$$

$$R_* = D\sqrt{\frac{\Delta\Omega}{\pi}} = 37.5\frac{L_*^{1/2}}{T_*^2} \quad (\mathrm{cgs})$$



Measuring the Radius of the Disk Inner Edge

- We want the radius of the "hole" in the disk emission
- Same principle as for a star
- From X-ray data we obtain **F_X** and **T_X** → **$\Delta\Omega$**
- Knowing distance **D** and inclination ***i*** we get **R_{ISCO}** (some geometrical factors)
- From **R_{ISCO}/M** we get **a_***



Zhang et al. (1997); Li et al. (2005); Shafee et al. (2006); McClintock et al. (2006); Davis et al. (2006); Liu et al. (2007); Gou et al. (2009,2010); …

BH Masses and Spins

Source Name	BH Mass ($M_\odot$)	BH Spin (a_*)
A0620-00	6.3—6.9	0.10 ± 0.20
LMC X-3	5.9—9.2	~0.25
GRO J1655-40	6.0—6.6	0.70 ± 0.05
M33 X-7	14.2—17.1	0.77 ± 0.05
4U1543-47	7.4—11.4	0.80 ± 0.05
LMC X-1	9.0—11.6	0.92 ± 0.06
GRS 1915+105	10—18	0.99 ± 0.01

Shafee et al. (2006); McClintock et al. (2006); Davis et al. (2006); Liu et al. (2007); Gou et al. (2009, 2010)

Status of This Enterprise

- We and others are pushing hard to measure as many a_* values as we can, as accurately as possible
- It is hard work, and we may never achieve enough precision for the results to be useful for fundamental physics, i.e., Testing the No-Hair Theorem
- We intend to keep trying…

But We Need Ideas

- The only idea we have to test the No-Hair Theorem is the following:
  - Measure a_* with great precision using more than one method, e.g., our method and the fluorescent iron line method
  - Check for consistent values of a_*
  - Inconsistency might imply that the No-Hair Theorem is invalid (but equally well, our models could be wrong!)

Are There Any Consistent Black Hole Solutions that are Not Kerr?

- Vacuum BH solutions are still basically Kerr, even in general f(R) gravity (Psaltis et al. 2008)
- It looks like the No-Hair Theorem is a very robust feature of classical gravity
- Are there gravity theories with BH solutions different from Kerr?

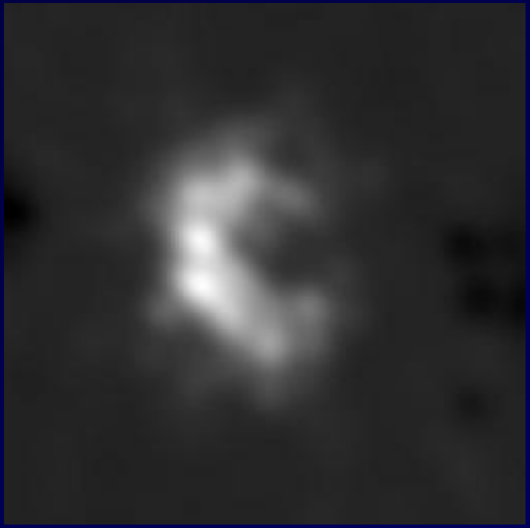
Vacuum Solutions with General Moments

- Manko & Novikov (1992)
- Class of solutions with general moments
- But all their vacuum solutions appear to have naked singularities
- These will be ruled out if we succeed in ruling out naked singularities
- Johanssen & Psaltis (2010) propose ways of checking the quadrupole moment

Sgr A* is optimal for testing the No-Hair Theorem via Imaging

Radio interferometric observations in the sub-millimeter band have the potential to resolve the image of the radiating gas on the scale of the Event Horizon

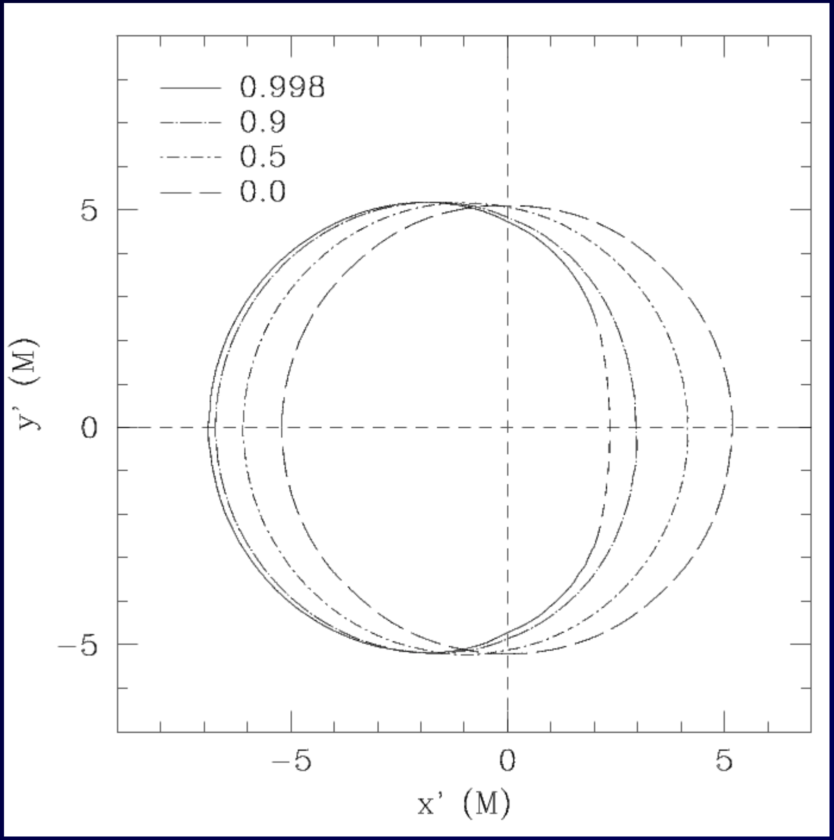
The shape of the image is sensitive to the quadrupole moment of the exterior space-time

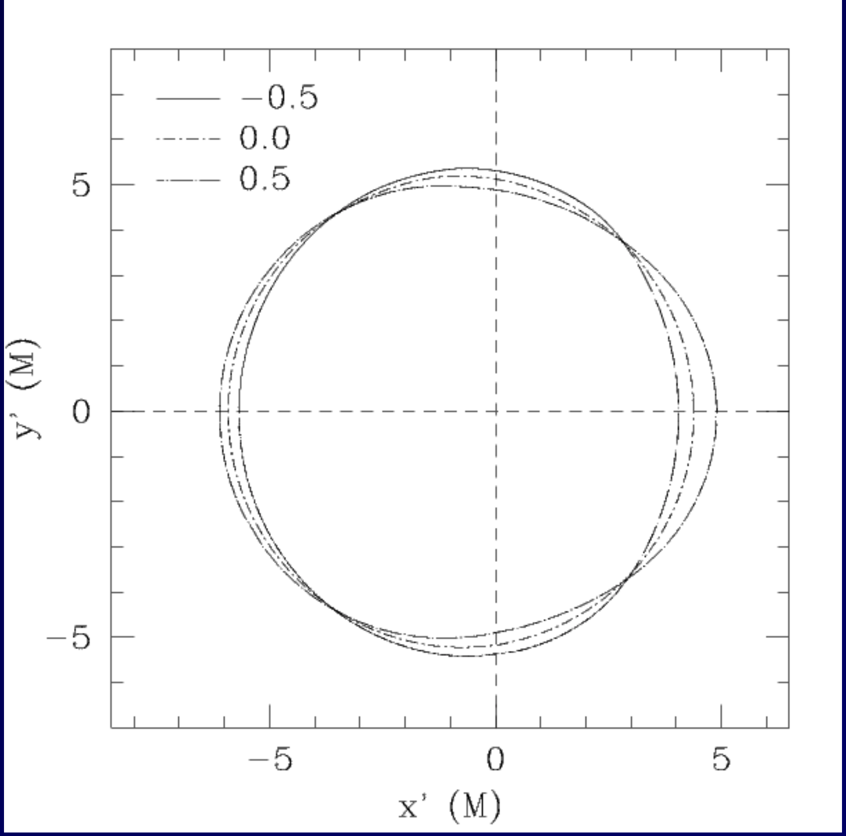


Fish & Doeleman 2009

7-telescope array

13-telescope array





Displacement measures spin. Asymmetry measures quadrupole deviation (Johannsen & Psaltis 2010)

Summary: Event Horizon

- Astrophysical BHs do not have surfaces
- Suggests they have Event Horizons
- But they might be Wormholes…
- Or Naked Singularities…
- Should be possible to rule these out

Summary: Black Hole Spin

- We are beginning to make credible measurements of BH spin
- Testing the No-Hair Theorem is next
- Problem: we lack concrete BH solutions that are different from Kerr
- Solutions with general moments exist, but they seem to have Naked Singularities…