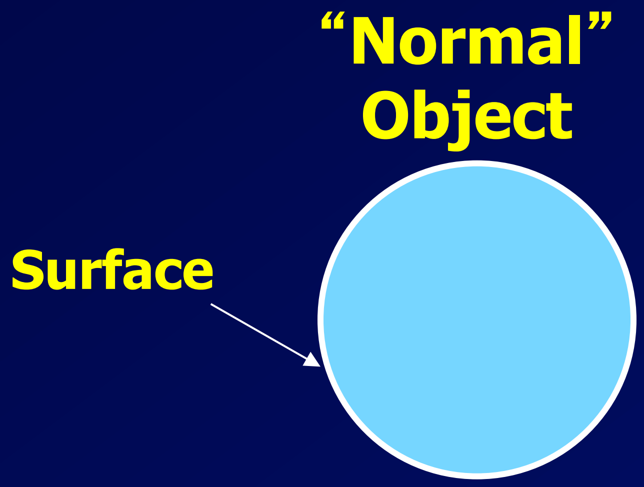
General Relativity and Astrophysical Black Holes

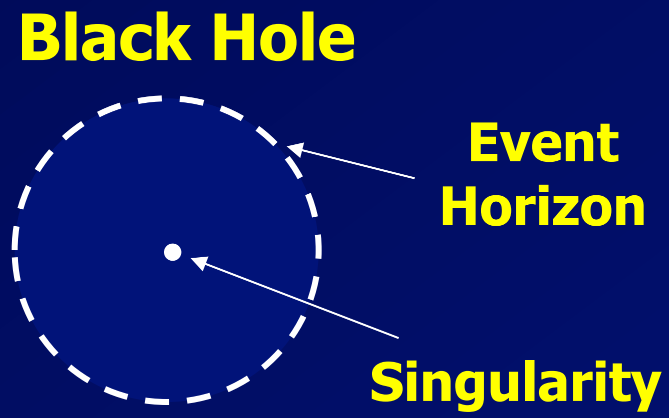
Ramesh Narayan

2015: Centenary of Schwarzschild's Solution

- Schwarzschild discovered the first exact solution of the nonlinear equations of GR in **December 1915**
  - Just a few weeks after Einstein's GR **(Nov 1915)**
  - Schw was in the Russian Front (1st WW) – died '16
- Einstein wrote:
  - "I have read your paper with the utmost interest. I had not expected that one could formulate the exact solution of the problem in such a simple way."
- It took physicists many years to understand the key properties of Schwarzschild's solution
- Today we know that it describes a **Black Hole**
- **2015:** Centenary of the first Black Hole solution

What Is a Black Hole?





- **Black Hole:** Ultimate victory of gravity
- Matter is crushed to a **SINGULARITY**
- Surrounding this is an **EVENT HORIZON**
- **One-way membrane: things can fall in but nothing can get out**

$$R_s = \frac{2GM}{c^2} = 2.95\left(\frac{M}{M_\odot}\right)\text{ km}$$

Exact Black Hole Solutions

- Schwarzschild (1915): M
- Reissner-Nordstrom (1916-18): M, Q
- Kerr (1963): M, J
- Kerr-Newman (1965): M, J, Q

- No other BH solution known. In fact, the No-Hair Theorem states that this is a complete catalog of all BH solutions

The Black Hole of Classical GR is Extremely Simple

- Mass: **M**
- Spin: $\mathbf{a_*}$ $\mathbf{(J = a_* G M^2 / c)}$
- Charge: Q

The Black Hole of Classical GR is Extremely Simple

- Mass: **M**
- Spin: $\mathbf{a_*}$ $\mathbf{(J = a_* G M^2/c)}$
- ~~Charge: Q~~

Classical vs Quantum BHs

- General Relativity involves only classical physics
- The BHs that arise in this theory are classical physics objects
- Merging GR with Quantum Mechanics is a major goal of present-day research
- Quantum BHs have weird properties
  - Hawking radiation
  - Singularity → Fuzzball? (Mathur)
- Outside the scope of this talk

Astrophysical Black Holes

- Black Holes are so bizarre one feels they should not be allowed by Nature
  - Einstein was never comfortable with BHs
- Surprisingly, two distinct varieties of BHs are common in the universe:
  - Stellar-mass BHs: **$M \sim 5$–$20\ M_\odot$**
  - Supermassive BHs: **$M \sim 10^6$–$10^{10}\ M_\odot$**

X-ray Binaries

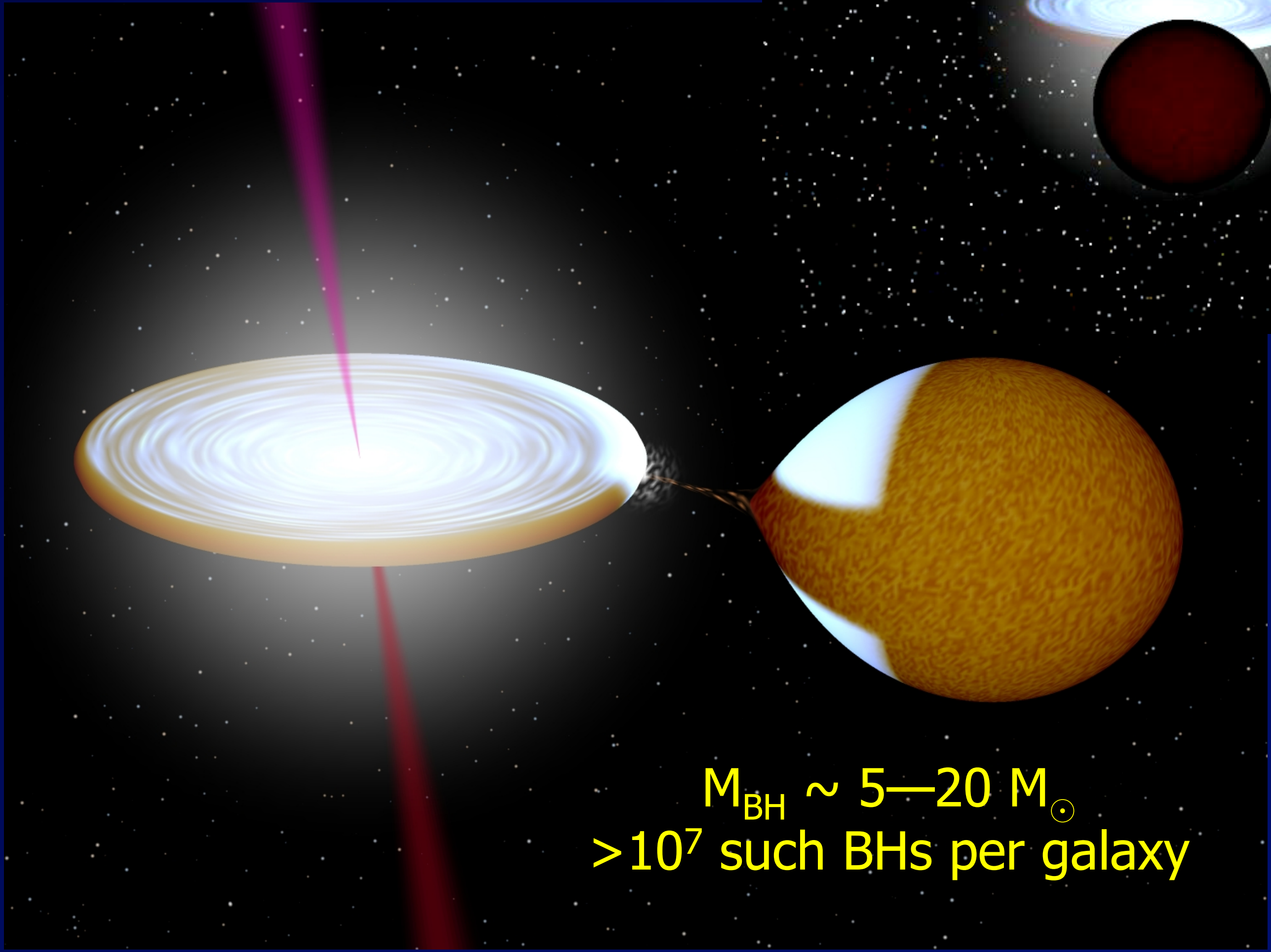


Image credit: Robert Hynes

Galactic Nuclei

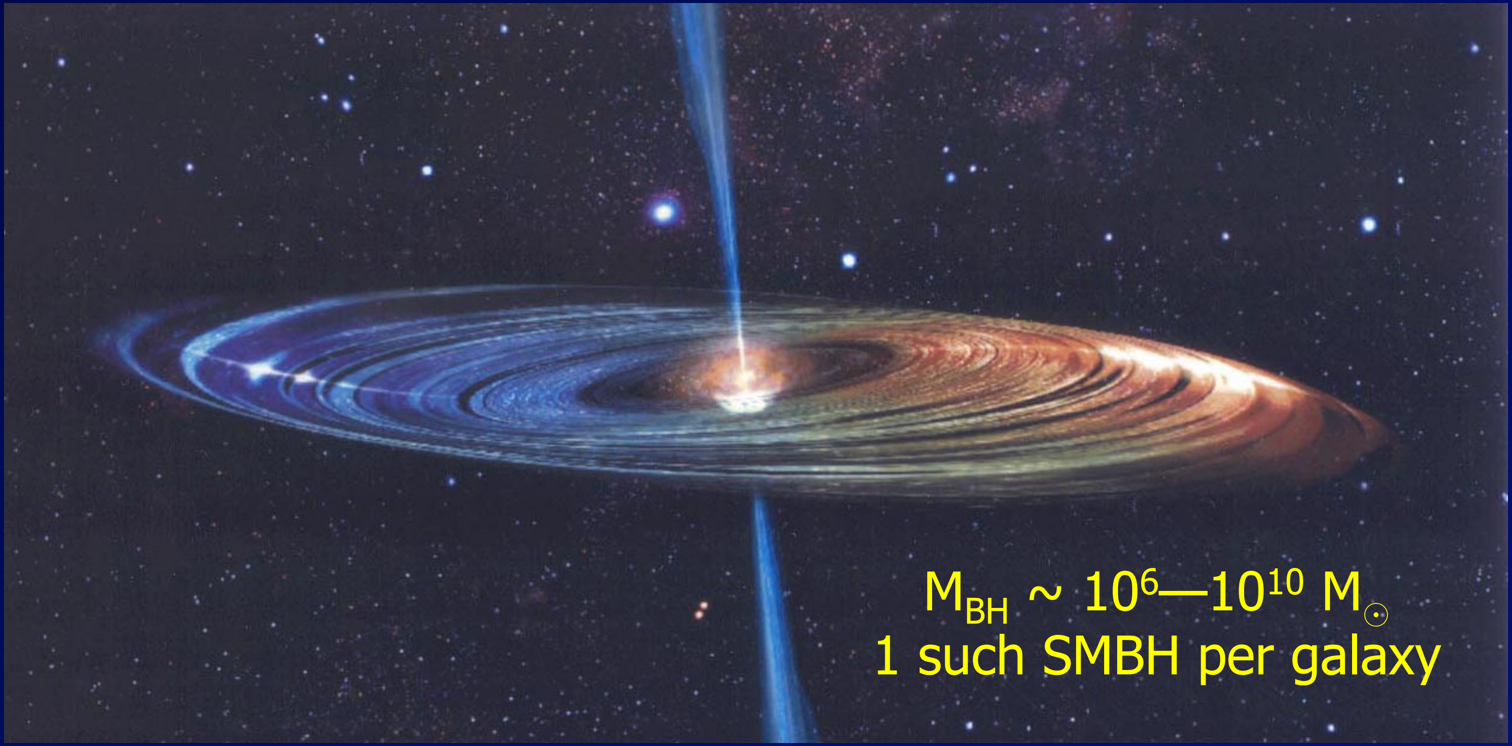


Image credit: Lincoln Greenhill, Jim Moran

How Do We Know They are Black Holes?

- Criteria used to identify astrophysical BHs
  - Must be compact: radius < few x R_S
  - Must be massive: $M >$ several $M_\odot$, i.e., too massive to be a Neutron Star ($M_{NS,crit} \leq 3M_\odot$)
- These are strong reasons for thinking that our candidates are BHs, but not foolproof…

Outline of Topics

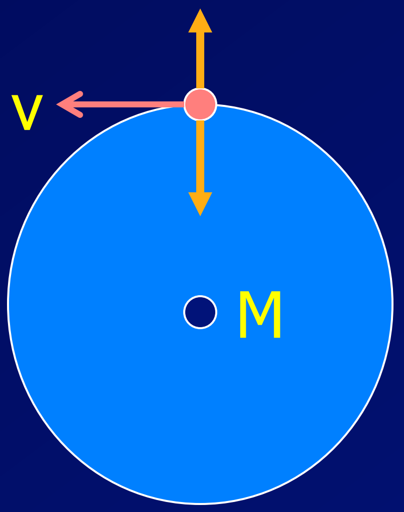
- Measuring Mass M
- Measuring Spin a_*
- Penrose Process – Relativistic Jets
- Evidence for the Event Horizon
- Strong Gravity – Event Horizon Telescope
- Evidence for the Singularity?
- Testing the No-Hair Theorem?

Measuring Mass: M

Measuring Mass in Astronomy

The best mass estimates in astronomy are **dynamical**: a test particle in a circular orbit satisfies (by Newton's laws):

$$\boxed{\begin{aligned} \frac{GM}{r^2} &= \frac{v^2}{r} \\ M &= \frac{v^3 P}{2\pi G} \end{aligned}}$$



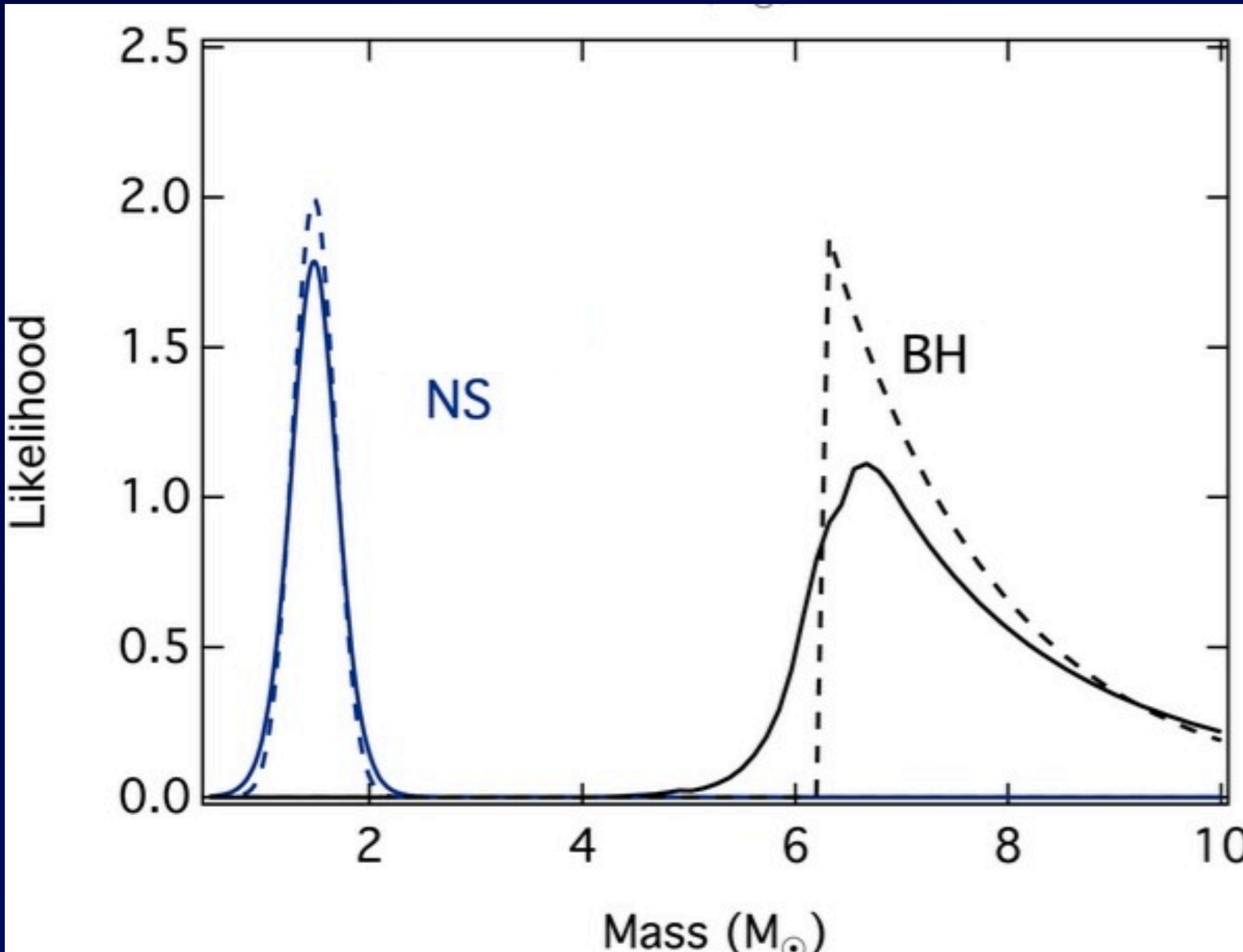
If ***v and P*** are measured, we can obtain ***M***

Earth-Sun: *v*=30 km/s, P=1yr → $M_\odot$=2x10^{33} g

Masses of stellar-mass BHs in binaries are measured by studying the motions of the companion stars

Table of BH Masses in XRBs

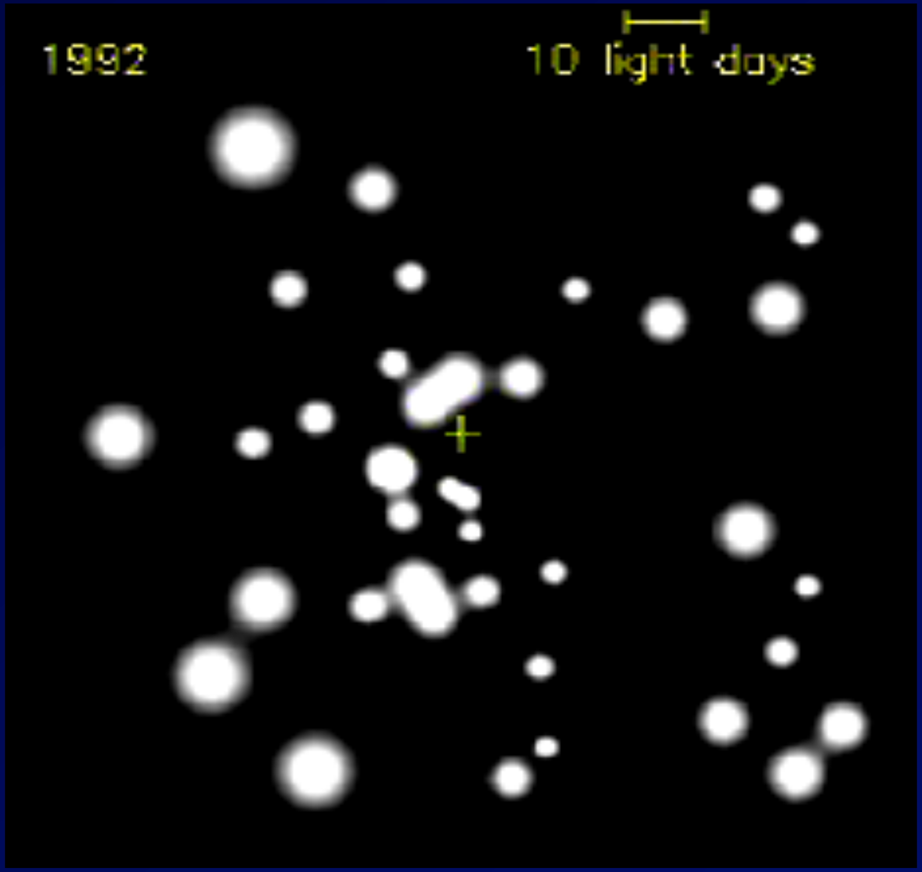
Binary	BH Mass ($M_\odot$)
LMC X-1	9.4—12.4
Cyg X-1	14.0—16.9
4U1543-47	8.4—10.4
M33 X-7 (eclipse)	14.2—17.1
GRO J0422+32	3.2—13.2
LMC X-3	6.4—7.6
A0620-00	6.3—6.9
GRO J1655-40	5.8—6.8
XTE J1650-500	>2.2
GRS 1124-683	6.5—8.2
SAX J1819.3-2525	6.8—7.4
GRS 1009-45	6.3—8.0
H1705-250	5.6—8.3
GS 2000+250	7.1—7.8
GS 1354-64	>5.4
GX 339-4	>5.3
GS 2023+338	10.1—13.4
XTE J1118+480	6.5—7.2
XTE J1550-564	8.5—9.7
XTE J1859+226	7.6—12.0
GRS 1915+105	9.5—10.7

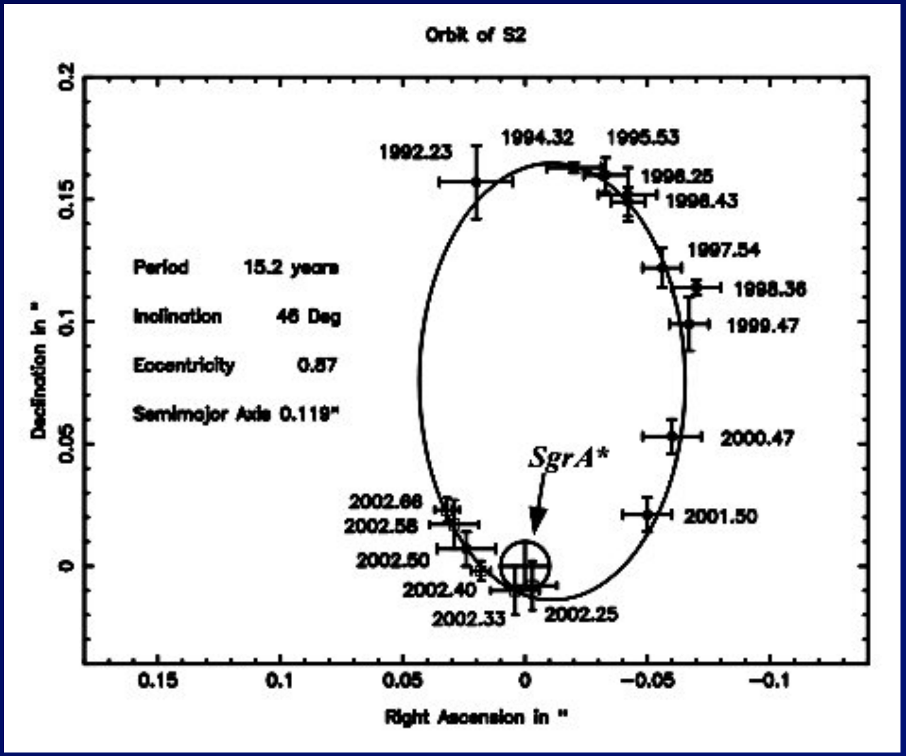


Minimum **BH** mass **~ 5$M_\odot$** Maximum **NS** mass **~ 2$M_\odot$**

Özel et al. (2010, 2012); Bailyn et al. (1998)

Motions of Stars at the Galactic Center



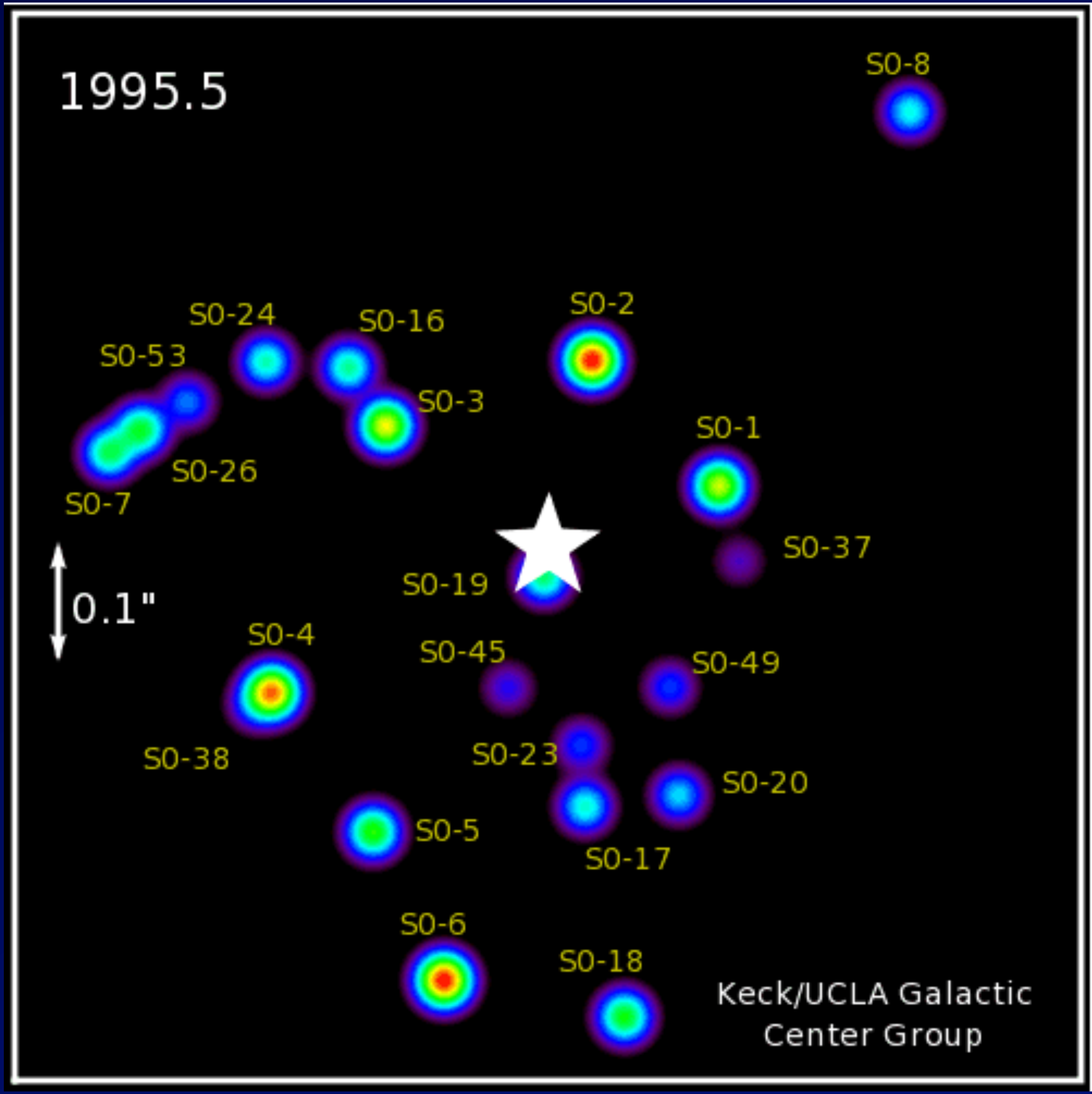


Schödel et al. (2002)

Motions of Stars at the Galactic Center

Ghez et al. (2005)

$M_{BH} = 4.5 \times 10^6 \ M_\odot$



Supermassive Black Holes in Other Galactic Nuclei

- Virtually every galaxy has a supermassive black hole (SMBH) at its center
- BH masses measured in several cases, though not as cleanly as in the case of our own Galaxy
  - $M_{BH} \sim 10^6$—$10^{10} M_\odot$

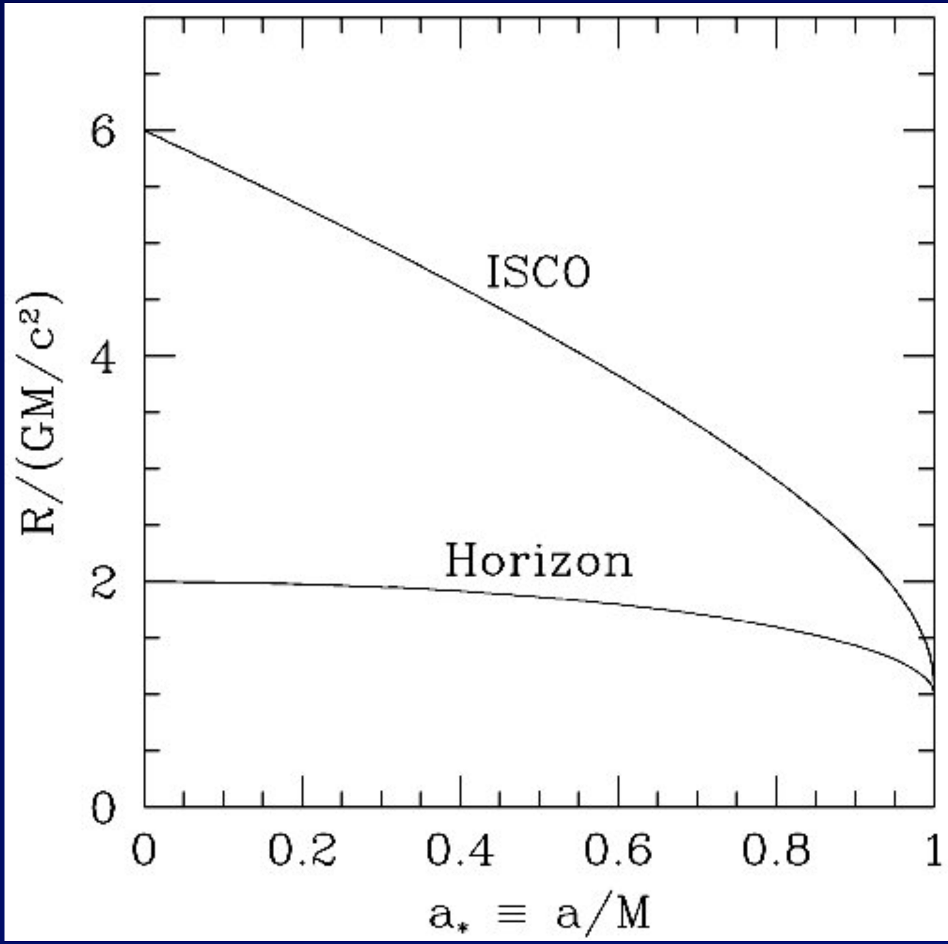
Measuring Spin: a_*

Estimating Black Hole Spin

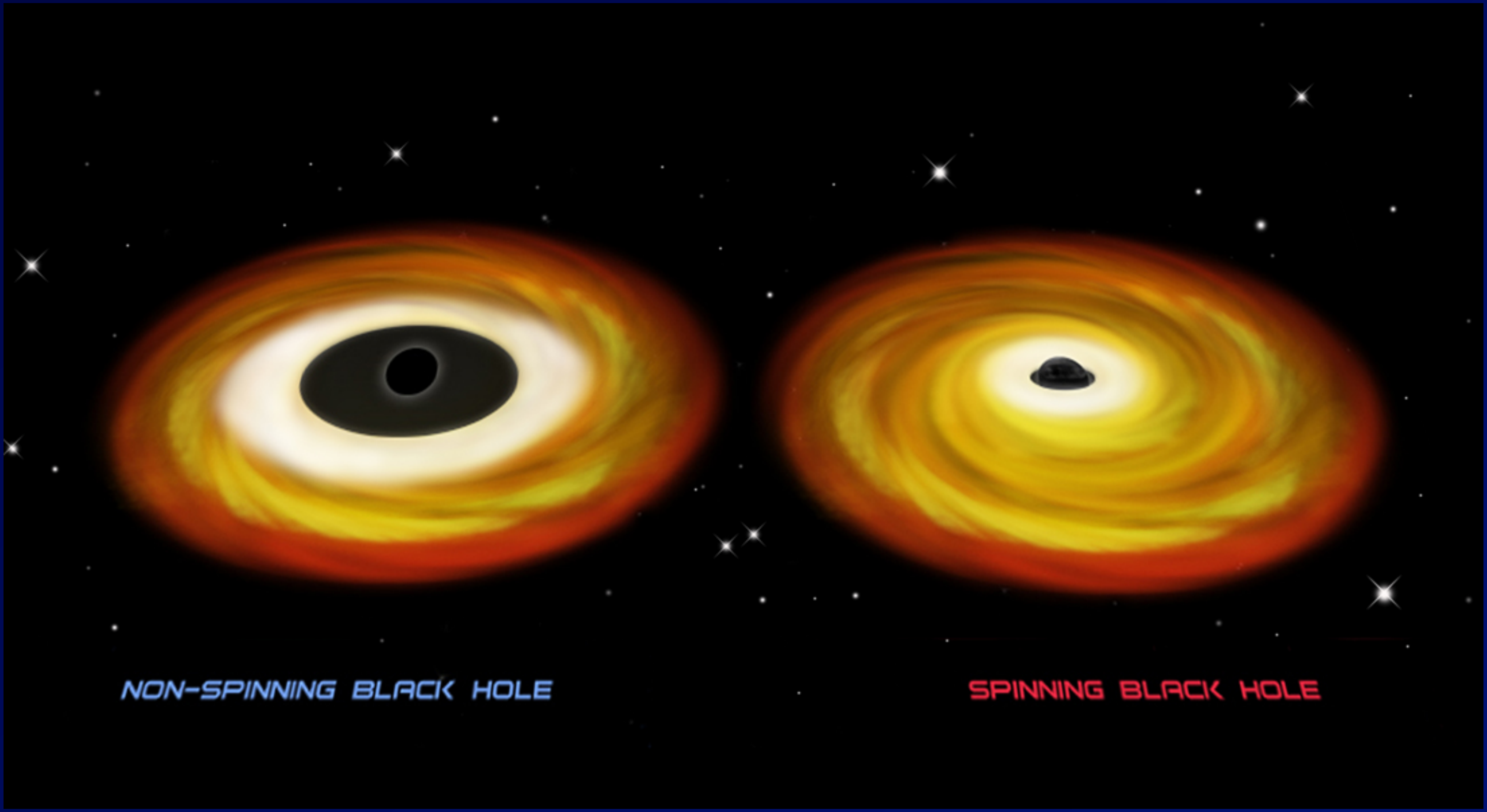
- X-Ray Continuum Spectrum ✔ ✔
- Relativistically Broadened Iron Line ✔
- Quasi-Periodic Oscillations **?**

Innermost Stable Circular Orbit (ISCO)

- R_{ISCO}/M depends on the value of a_*
- Not a small effect
- Full factor of 6 variation in R_{ISCO} as a_* goes from 0 to 1
- Inner edge of accrn disk is at R_{ISCO}



The Basic Idea



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

Measure radius of hole using various observables

Continuum-Fitting: BHXRBs: Full Range of Prograde Spins

Source Name	BH Mass ($M_\odot$)	BH Spin (a_*)
A0620-00	6.3—6.9	0.12 ± 0.19
H1743-322	6—9	0.2 ± 0.3
LMC X-3	6.4–7.6	0.25 ± 0.2
XTE J1550-564	8.5—9.7	0.34±0.24
GRO J1655-40	5.8—6.8	0.70 (± 0.1)
4U1543-47	8.4—10.4	0.80 (± 0.1)
M33 X-7	14—17	0.84 ± 0.05
LMC X-1	9.4—12.4	0.92 ± 0.06
Cyg X-1	14—16	> 0.95
GRS 1915+105	9.5—10.7	(> 0.95)

Shafee et al. (2006); McClintock et al. (2006); Davis et al. (2006); Liu et al. (2007,2009); Gou et al. (2009,2010,2011,2014); Steiner et al. (2011,2012,2014)

What About Supermassive Black Hole Spins?

- Continuum-fitting method works very well in the case of stellar-mass BHs
- Not easy to apply to supermassive BHs
- Iron line method is better for SMBHs
  - Very promising method
  - But consistency not yet established…

BH Spin and the Penrose Process

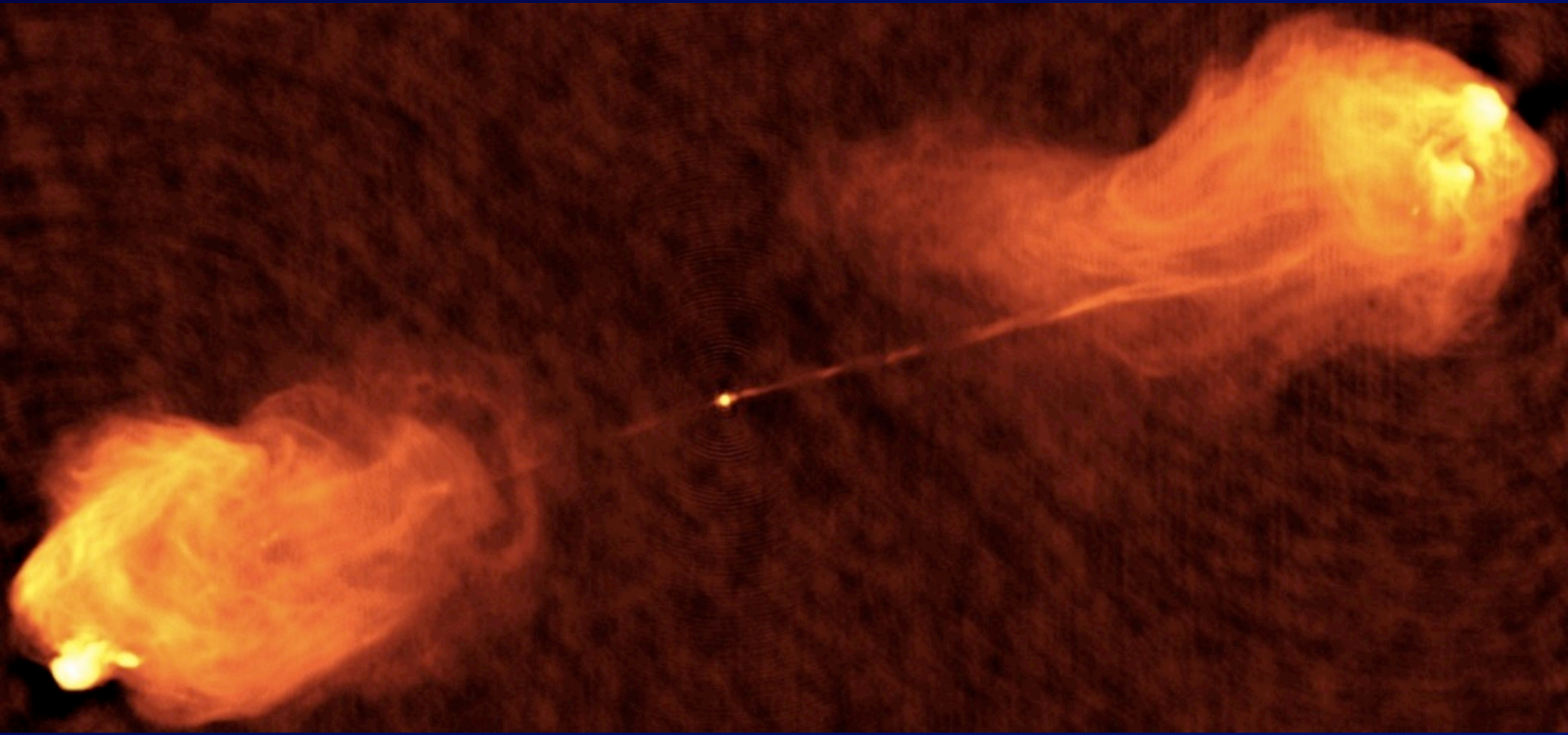
Penrose Process

- A spinning BH has free energy that can in principle be extracted (Penrose 1969)
  - Frame-dragging – ergosphere
  - Penrose: Thought experiment with particles
  - Extension with magnetic fields (Wagh & Dadhich 1989)
  - Probably not important in astrophysics
- But magnetized accretion disks (MHD) plus frame-dragging is promising (Ruffini & Wilson 1975; Blandford & Znajek 1977)

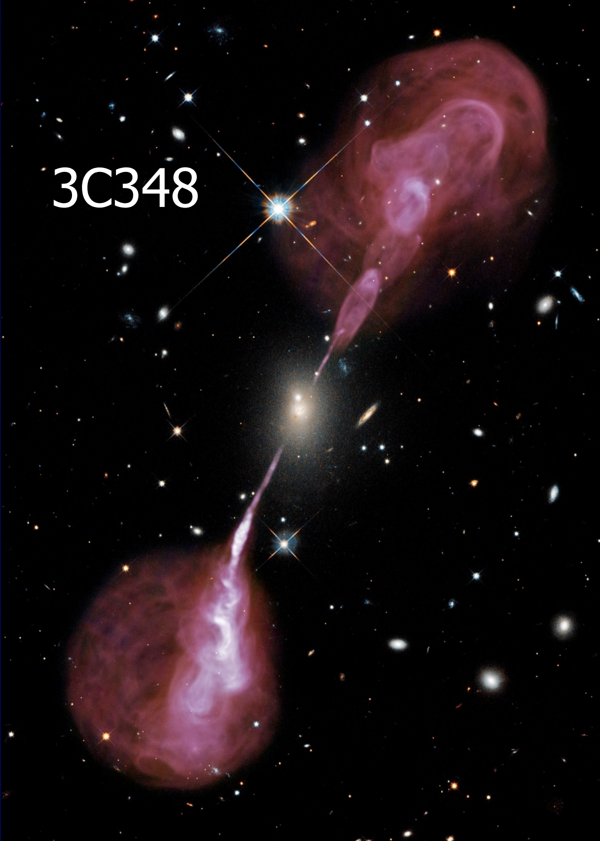
Relativistic Jets

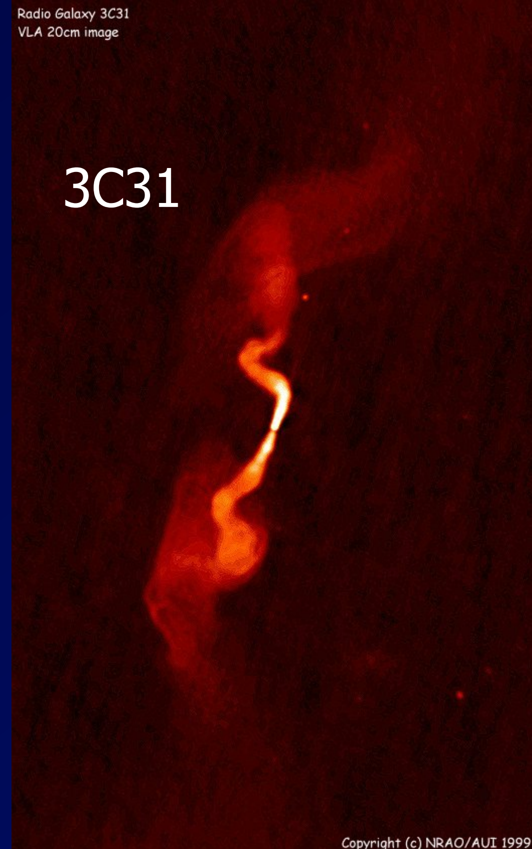
- Accreting BHs produce violent ejections of gas and magnetic field in jets
- Jets often move close to the speed of light: Relativistic Jets
- What is the power source?
- Could be BH spin energy extracted via a generalized Penrose Process (Ruffini & Wilson 1975; Blandford & Znajek 1977)
- Confirmed: Simulations, Observations

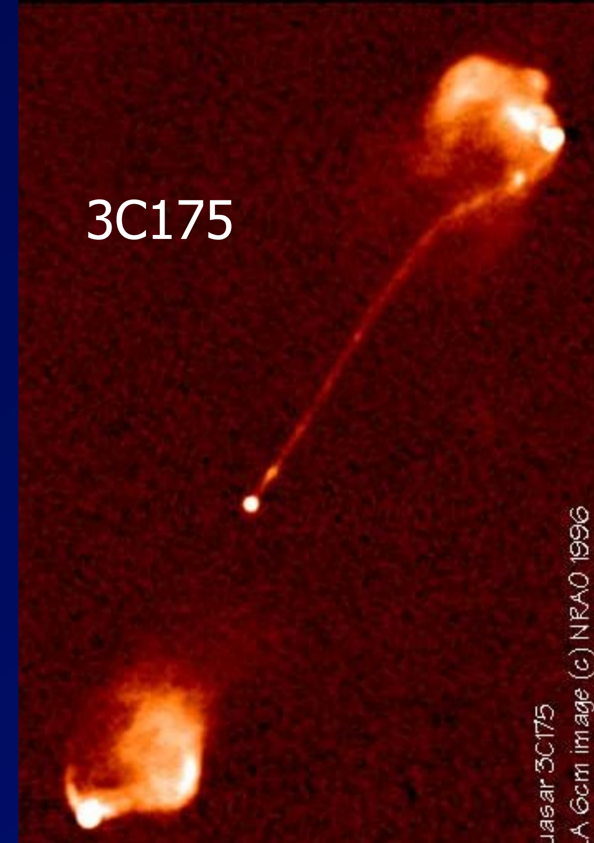
Relativistic Jets



Radio image of Cygnus A
Image credit: C. Carilli & R. Perley, NRAO


3C348


Radio Galaxy 3C31
VLA 20cm image
3C31
Copyright (c) NRAO/AUI 1999


3C175
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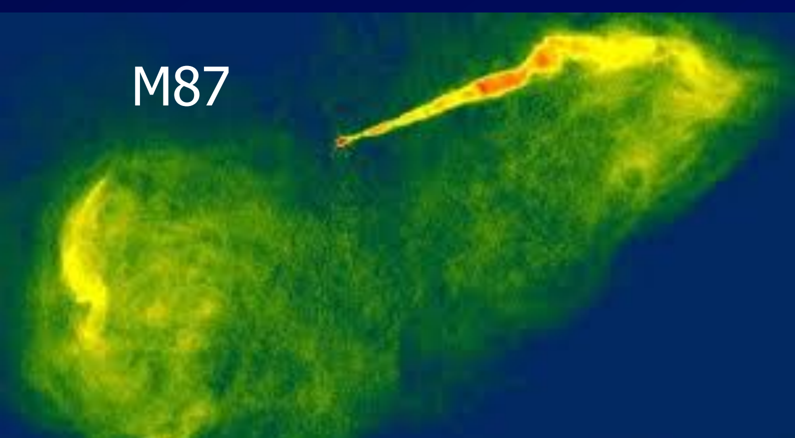
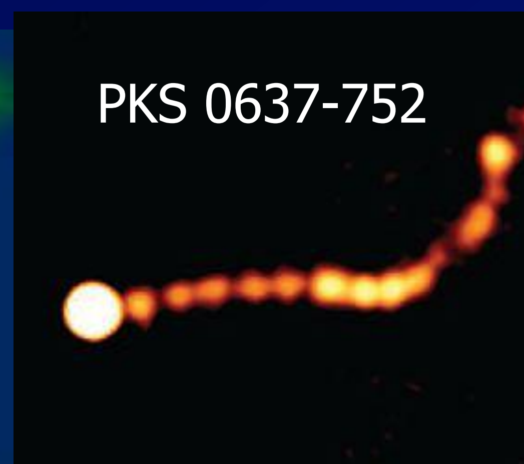
A 6cm image (c) NRAO 1996


M87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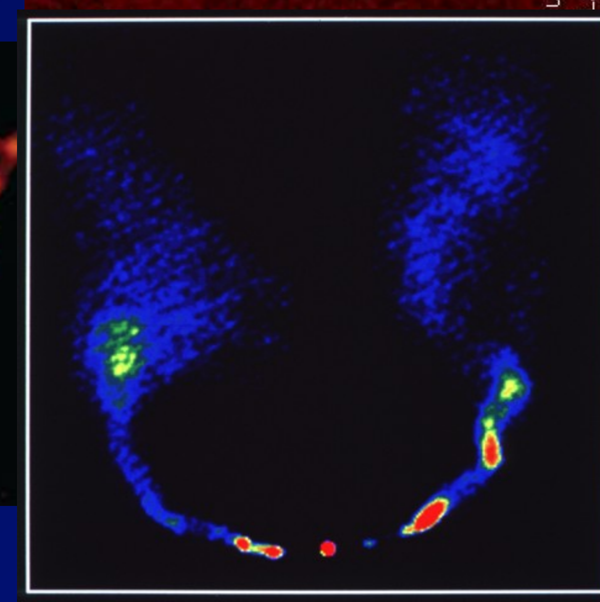
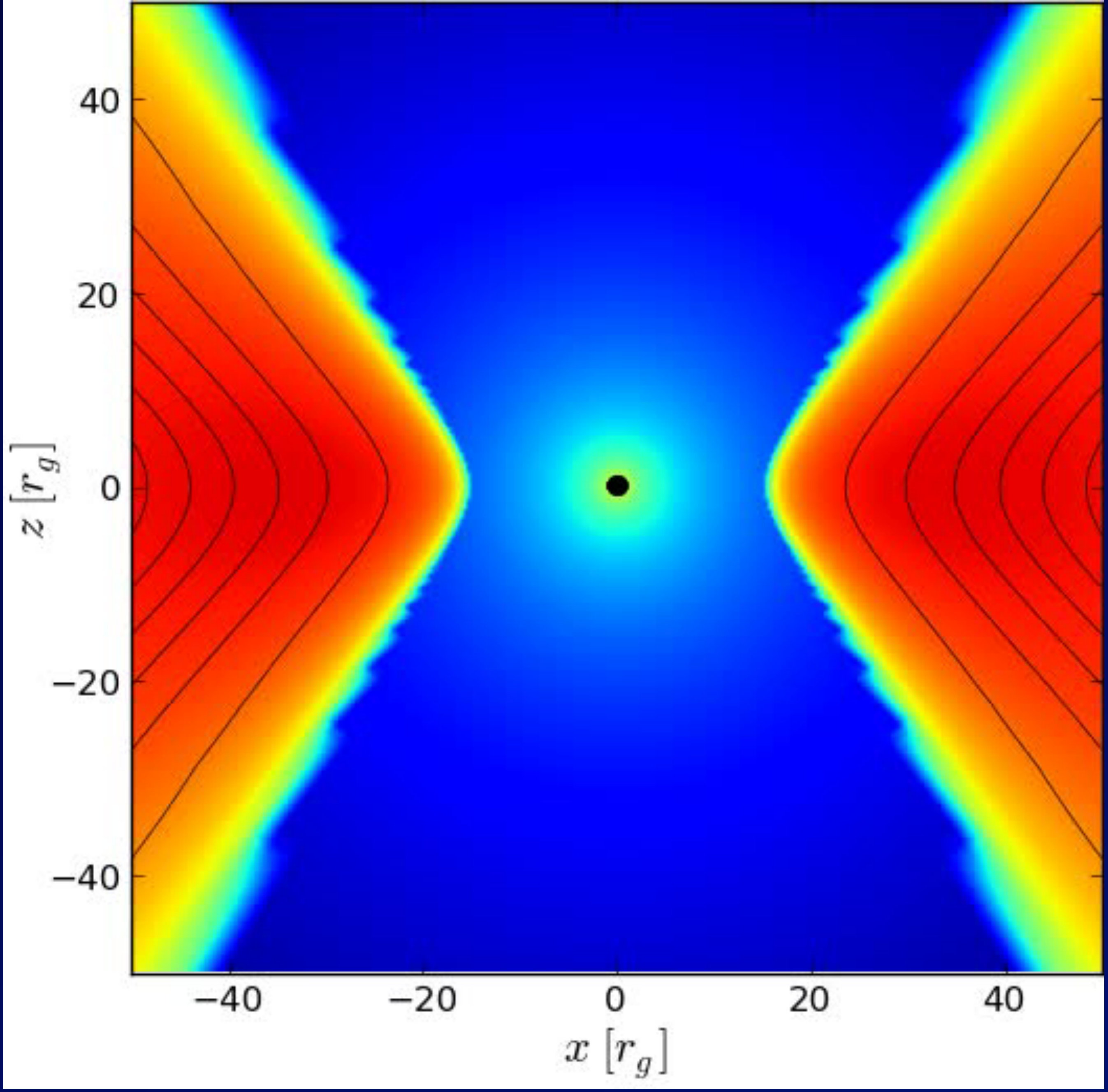
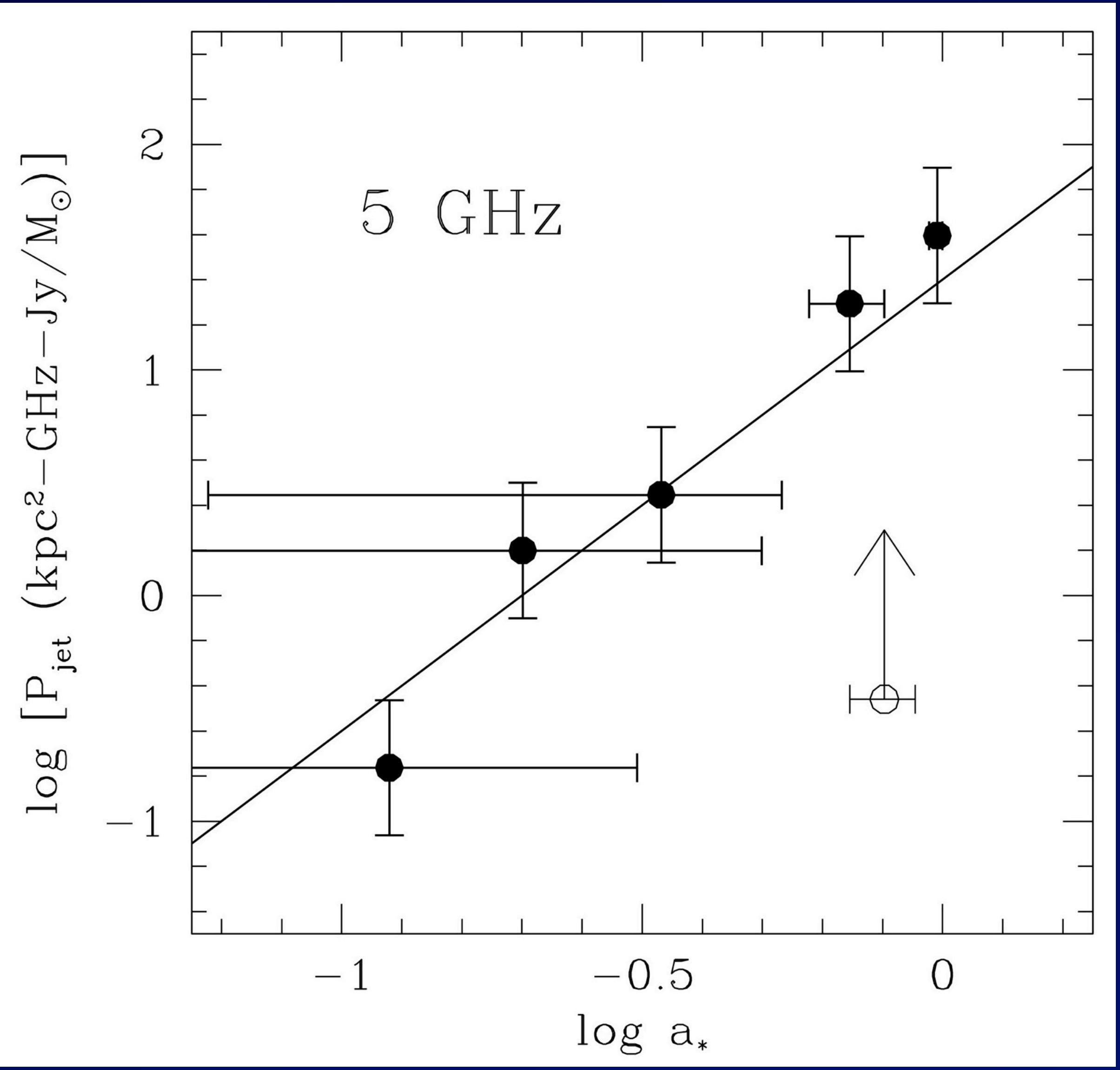




Tchekhovskoy (2011)

A Suggestive Correlation



5 transient BH XRBs have both ballistic jet ejections and spin estimates

Show good correlation

Narayan & McClintock (2012)
Steiner, McClintock & Narayan (2012)

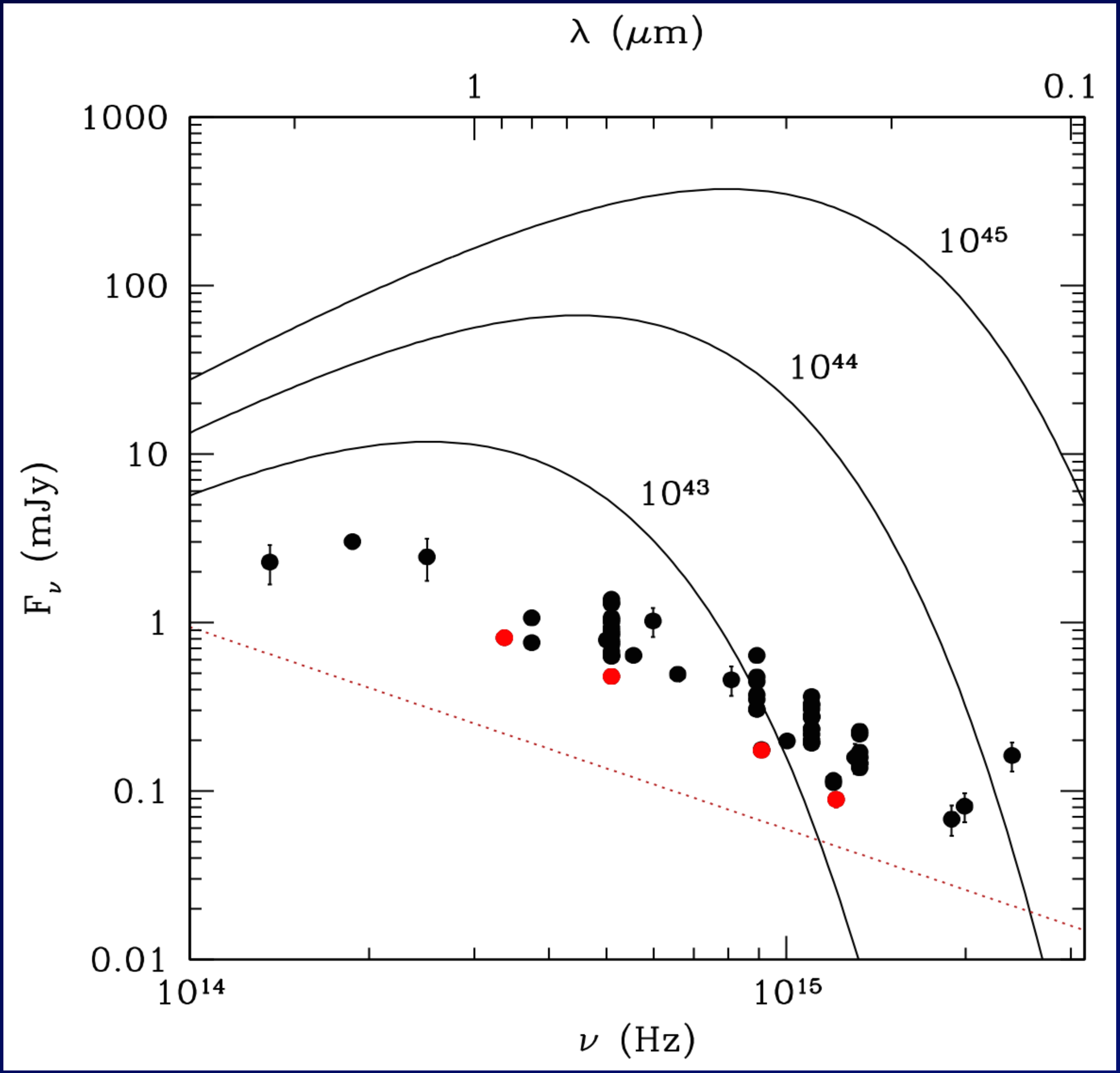
Evidence for the Event Horizon

Event Horizon

- Can we prove that astrophysical BHs have Event Horizons?
- **Yes**: There have been several successful tests ("proofs")
  - Stellar-mass BHs in XRBs
  - SMBH in our Galactic Center
- Latest test: SMBH in the nearby galaxy M87 (Broderick et al. 2015)

Outline of the "Proof"

- M87 has an active nucleus (M87*) with a powerful relativistic jet: 10^{44} erg/s
- To produce such a jet, the mass accretion rate must be $>10^{-3}$ Eddington
- If the compact object has a hard surface, we expect luminosity $L >$ few x 10^{43} erg/s
- Observational limits are well below this
- → No surface → M87* has Event Horizon

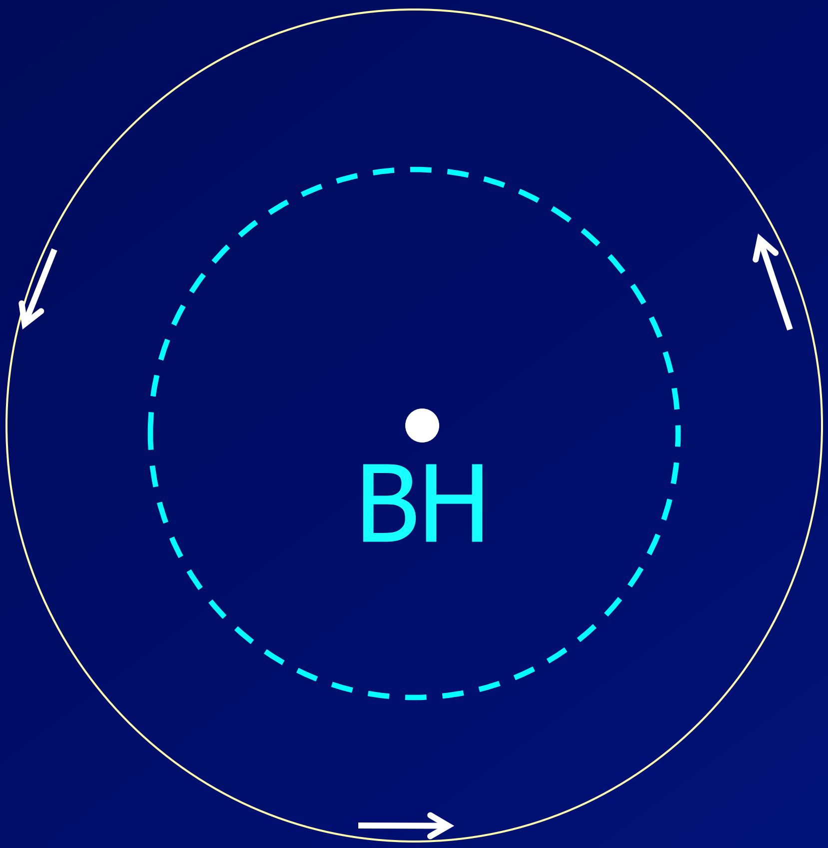


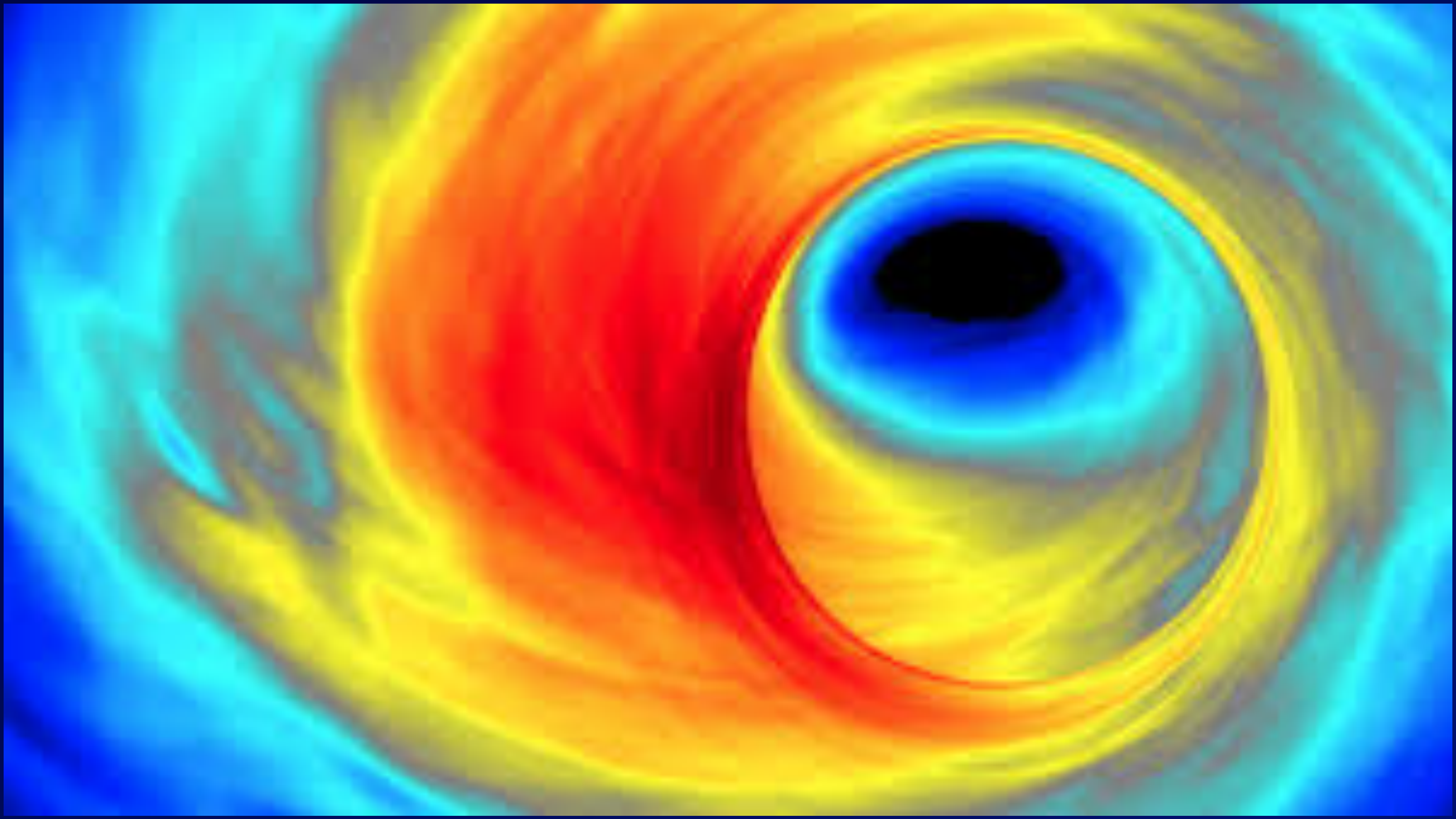
Broderick et al. (2015)

Observing Strong Gravity in Action: Event Horizon Telescope

Photon Orbit around a BH

- Close to a BH, photon orbits are sufficiently bent that one can have closed orbits
- Testable prediction of GR in strong gravity





Computer simulation of gas accreting on the supermassive BH at the center of our Galaxy (Scott Noble)

How Feasible is BH Imaging?

- The best candidate is Sgr A*, the supermassive BH at our Galactic Center
  - Angular size: few x 10^{-10} radians
- Imaging Sgr A* is very challenging – needs a telescope with a **HUGE** aperture
  - Optical radiation: few km diameter
  - Infrared: 10—100 km
  - Millimeter waves: Earth diameter
  - Meter waves: 1000 Earth diameters

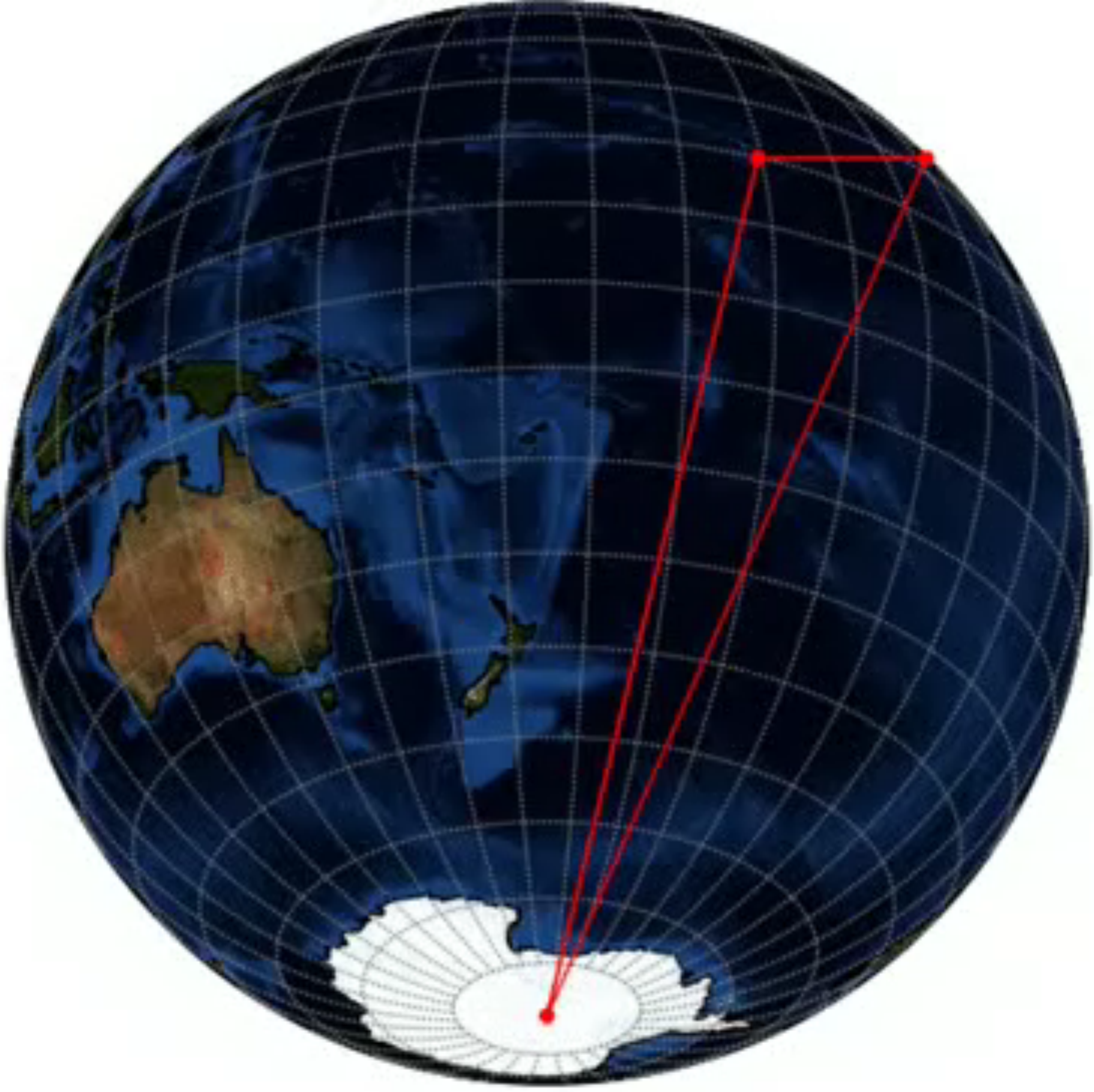
Event Horizon Telescope

A world-wide array of telescopes working at λ≈1mm can resolve emission near the BH at our Galactic Center

First steps have already been taken, and no technical hurdles are anticipated

Within the next few years, the EHT will obtain crude images of the accretion flow

Should see the "shadow of the BH" (photon orbit)



Other Goals for the Future

Singularity

- Singularity Theorems (Penrose, Hawking): Singularities inevitable in GR
- BHs have singularities, but they are hidden behind the event horizon
- Naked singularity solutions of GR are known (Joshi et al.)
- Could we detect a naked singularity?!
  - Would verify the Singularity Theorems
  - Would be a window into Quantum Gravity

No-Hair Theorem

- Can we test the No-Hair Theorem?
- We need to first measure M and a_*
- Then we must verify that no additional parameter is needed to fit observations
- Not within reach at this time
- With luck, the Event Horizon Telescope might get some results

Summary

- GR leads inevitably to BH solutions (M, a_*, Q)
- Astronomers have discovered many BHs in the universe
  - X-ray binaries: 5—20 $M_\odot$ ($\gtrsim 10^7$ per galaxy)
  - Galactic nuclei: $10^{6\text{-}10}$ $M_\odot$ (1 per galaxy)
- Astrophysical BHs provide us with an opportunity to observe/test GR in the regime of strong gravity
  - Spinning BHs – Penrose Process – Relativistic Jets ✔
  - (Circumstantial) Evidence for the Event Horizon ✔
  - Photon orbit – Event Horizon Telescope ~
  - Observe a Singularity **x**
  - Test No-Hair Theorem **x**