Black Hole Astrophysics

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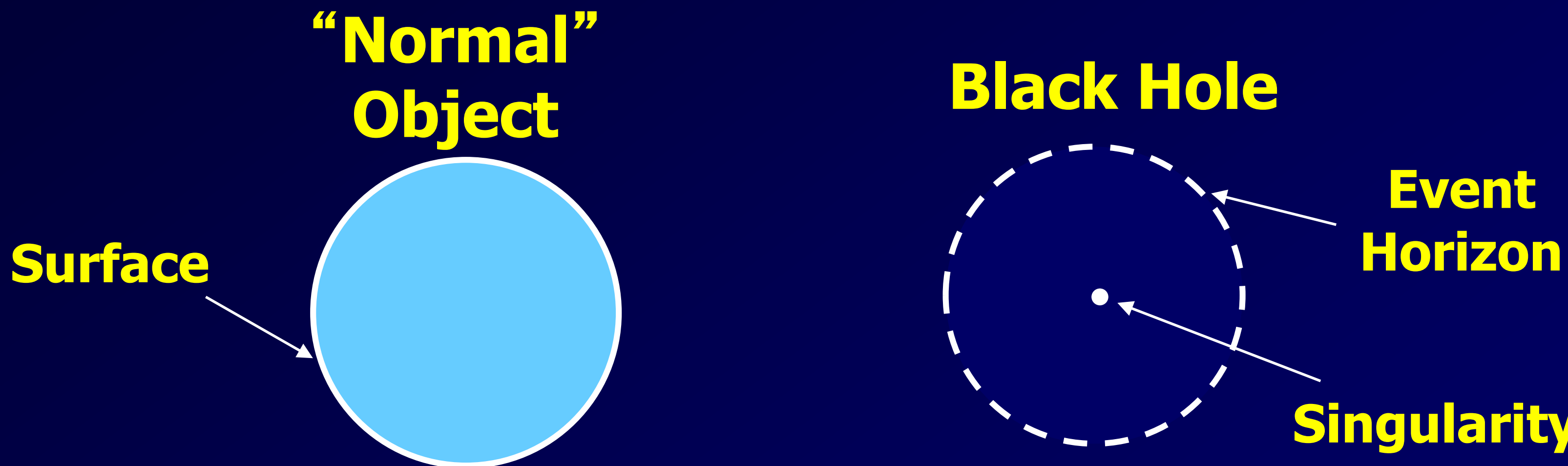
What Is a Black Hole?



- Prediction of Einstein’s General Theory of Relativity
- Matter is crushed to a **SINGULARITY**
- Surrounding this is an **EVENT HORIZON**

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

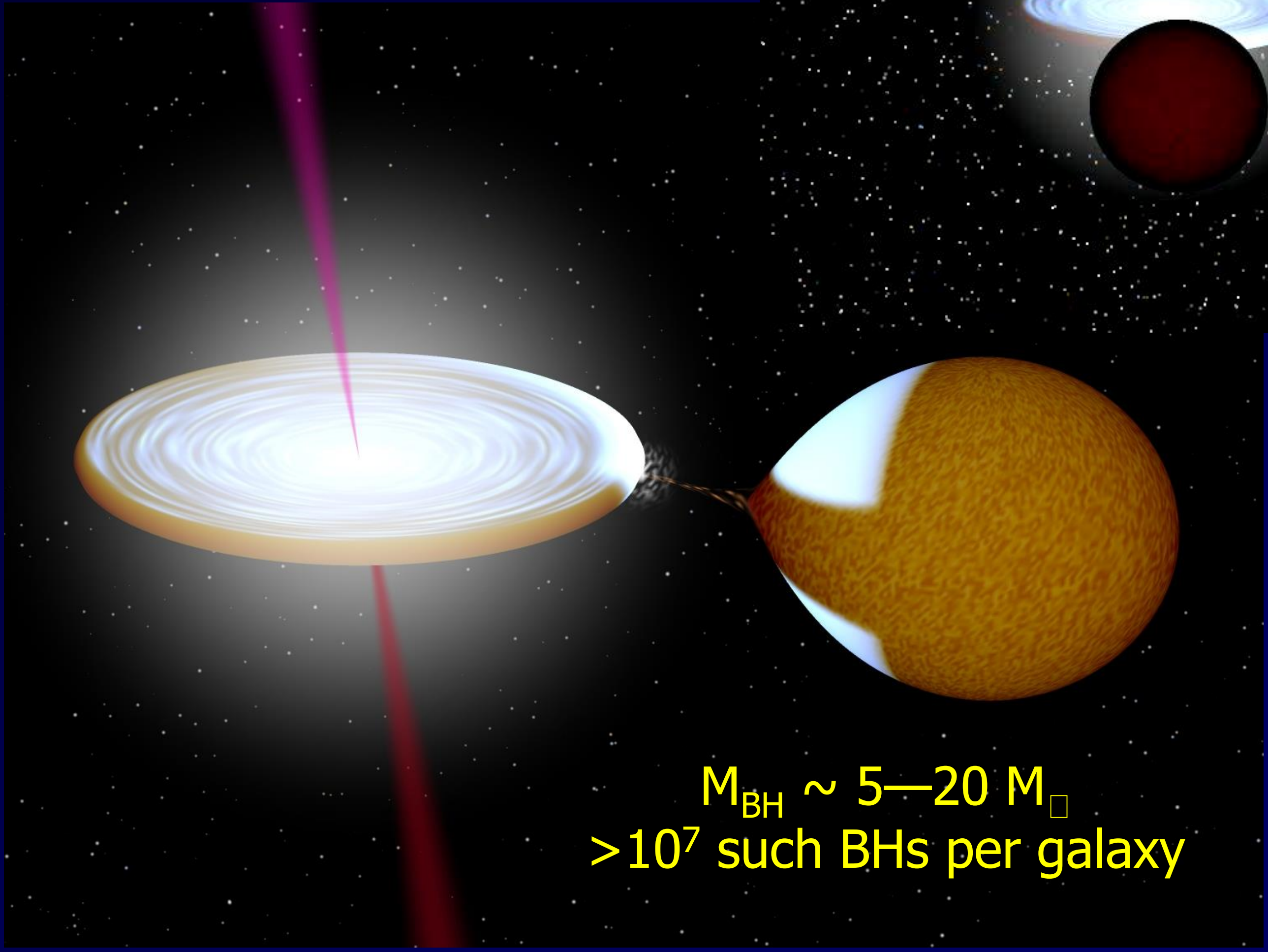
Classical vs Quantum BHs

- General Relativity involves 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
  - Information Paradox
- Outside the scope of this talk

Astrophysical Black Holes

- Black Holes are so bizarre one feels they should not be allowed by Nature
- But in fact, two distinct varieties of BHs are common in the universe:
  - Stellar-mass BHs: **$M \sim 5\text{–}20\ M_{\odot}$**
  - Supermassive BHs: **$M \sim 10^{6}\text{–}10^{10}\ M_{\odot}$**

X-ray Binaries



$M_{BH} \sim 5\text{—}20\ M_{\odot}$

$>10^7$ such BHs per galaxy

Image credit: Robert Hynes

Galactic Nuclei

Image credit: Greenhill – Inoue – 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…
- Aside: It is possible to do better – "prove" that the objects have Event Horizons

A Black Hole is Extremely Simple

- Mass: **M**
- Spin: Angular Momentum **J**
- Charge: Q

A Black Hole has no Hair! (No Hair Theorem)

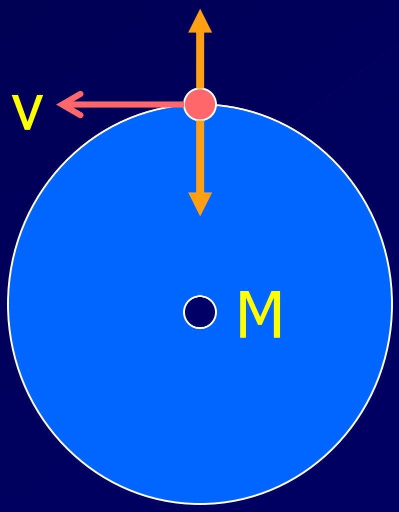
Outline of Topics

- Measuring Mass M
- Measuring Spin a_* ($J = a^* GM^2/c$)
- Penrose Process – Relativistic Jets
- Strong Gravity – Event Horizon Telescope

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):



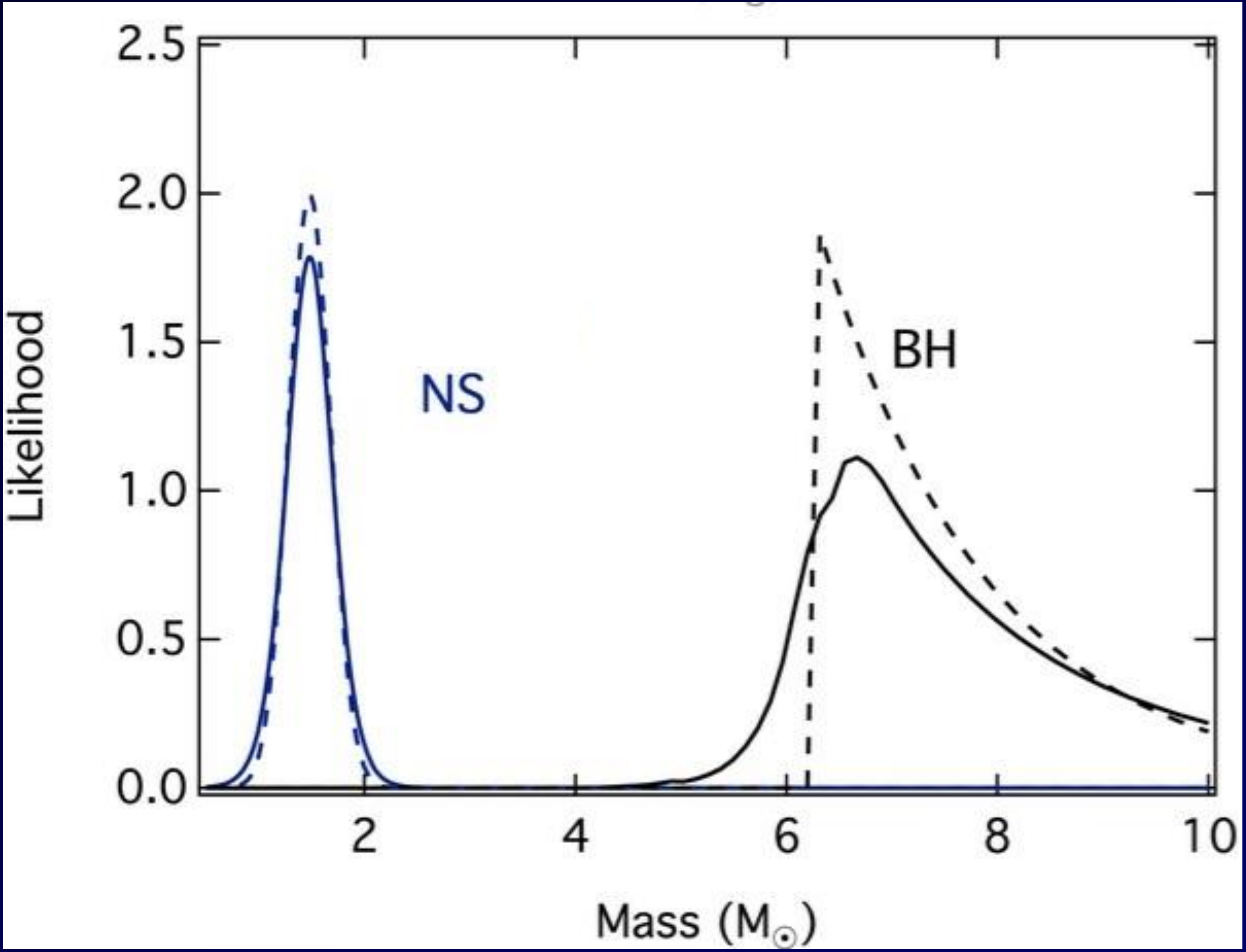
$$\frac{GM}{r^2} = \frac{v^2}{r}$$

$$M = \frac{v^3 P}{2\pi G}$$

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

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

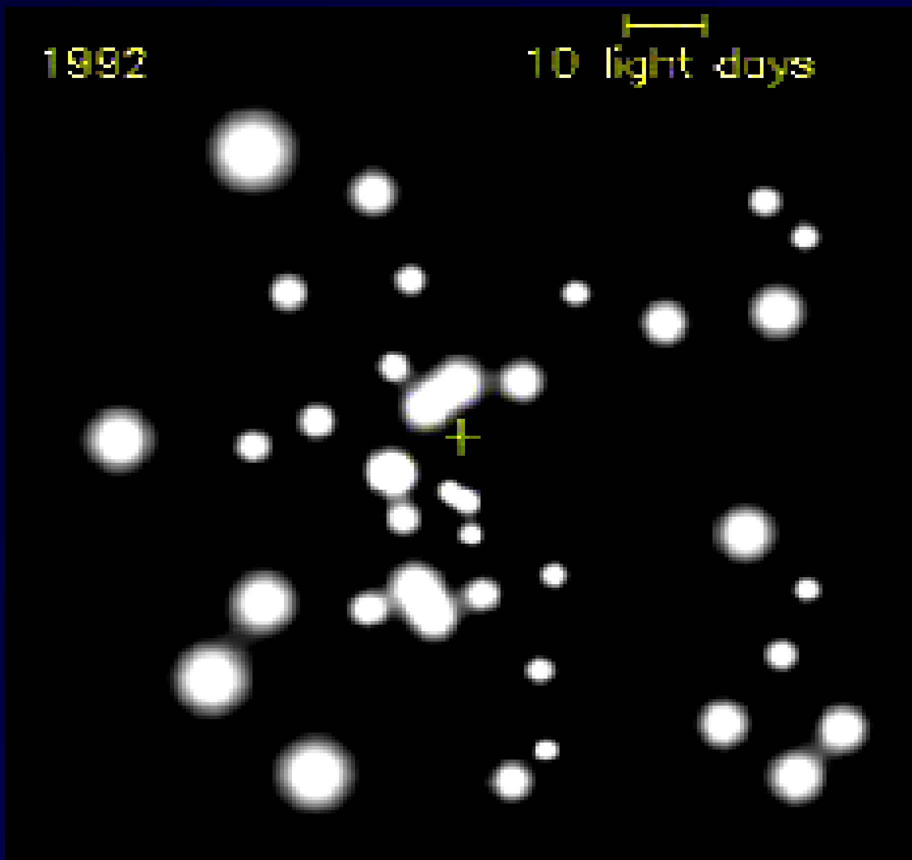
Masses of stellar-mass BHs in binaries are measured by studying the motions of the companion stars

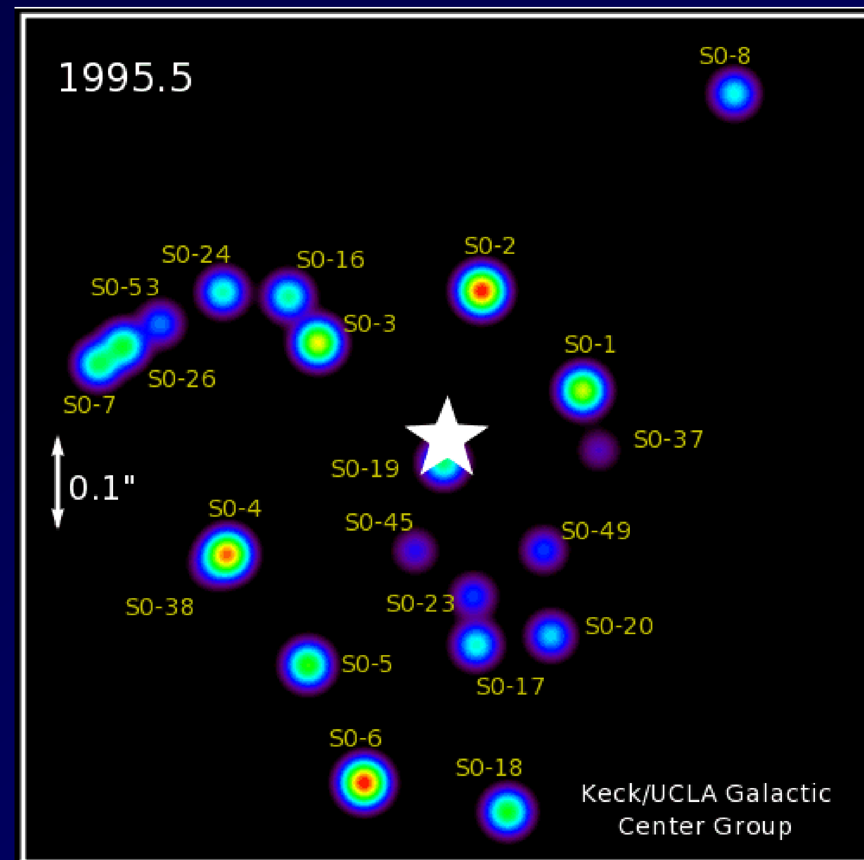


Minimum **BH** mass **~ 5M**□ Maximum **NS** mass **~ 2M**□

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

Motions of Stars at the Galactic Center





Schödel et al. (2002)

$M_{BH}=4.5\times10^{6}\ M_{\odot}$

Ghez et al. (2005)

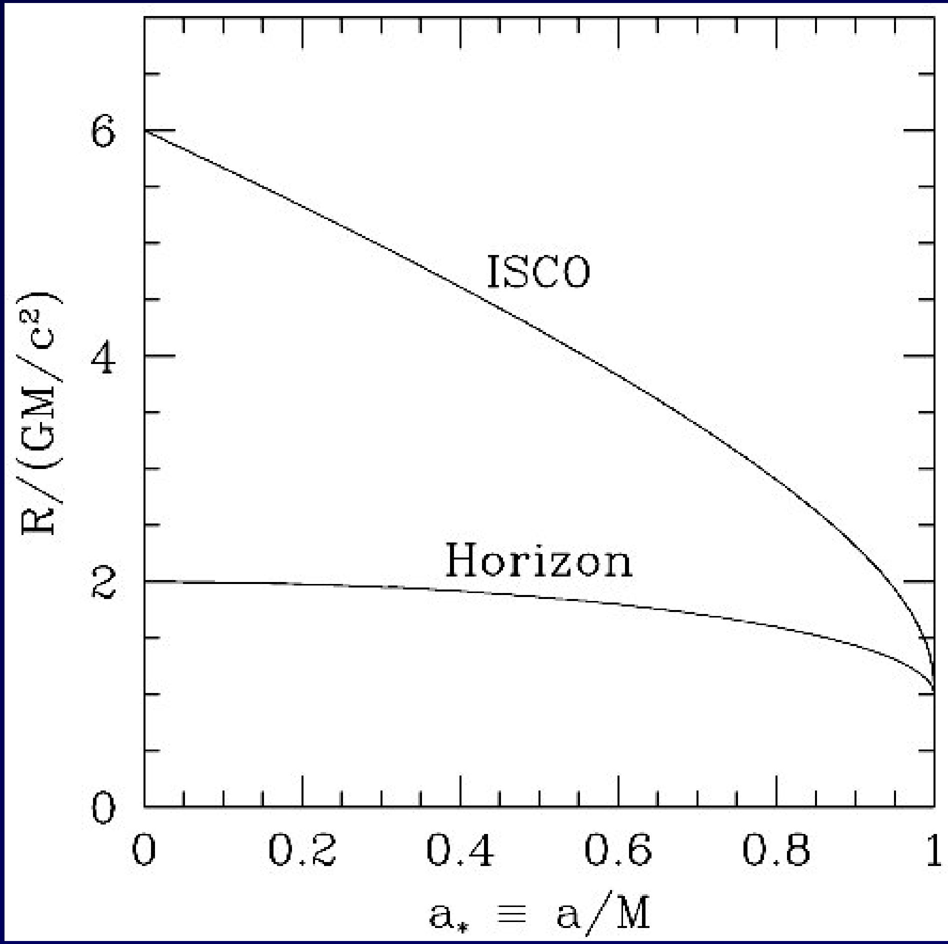
Measuring Spin: a_*

Circular Orbits

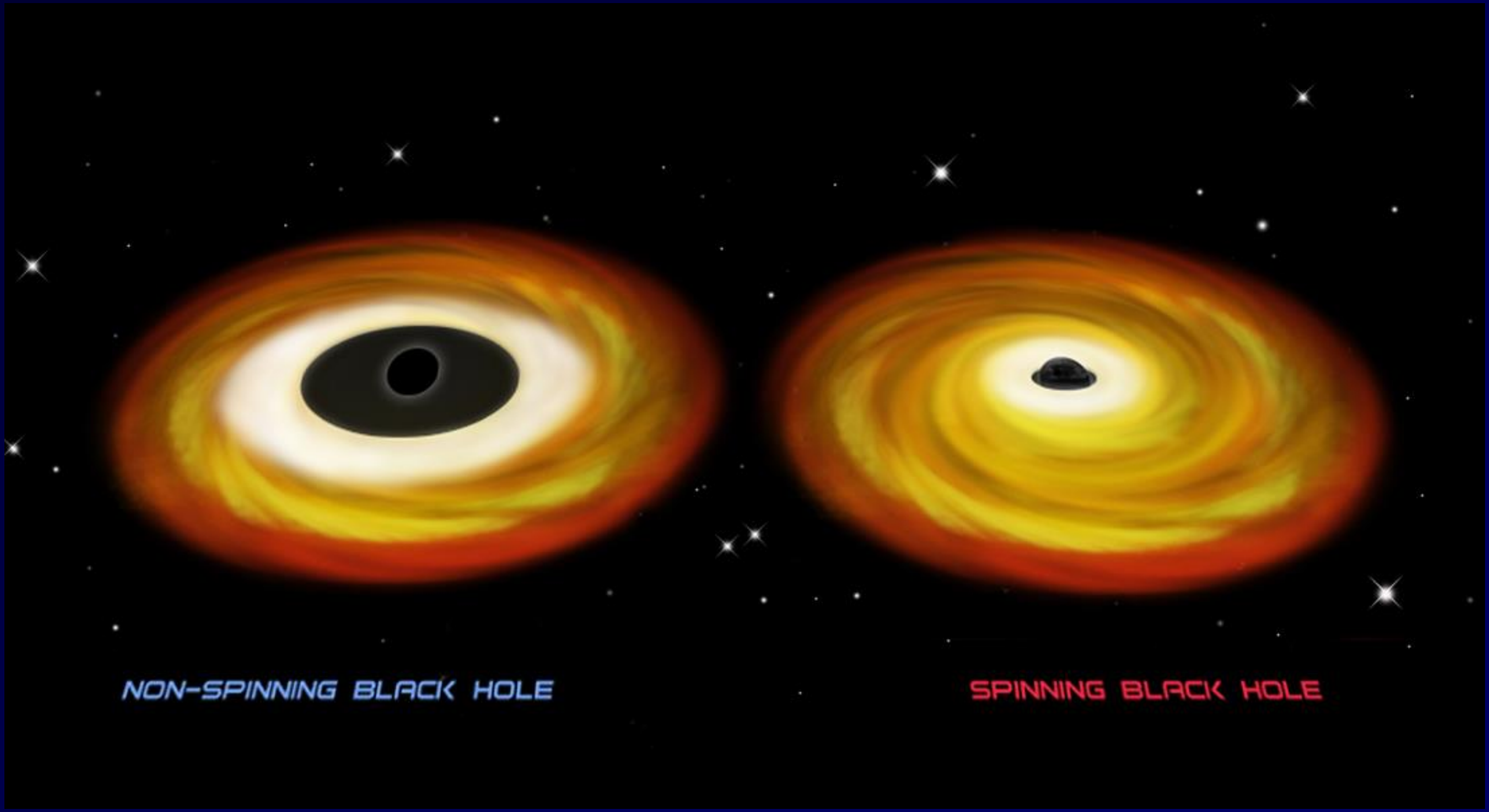
- In Newtonian gravity, stable circular orbits are available at all R
- Not true in General Relativity
- For a non-spinning BH (Schwarzschild metric), stable orbits only for R □ $6GM/c^2$
- $R=6M$ is the innermost stable circular orbit (**ISCO**) of a non-spinning BH
- The radius of the ISCO (R_{ISCO}) depends on the BH spin

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 negligible radiation

Measure radius of hole using various observables

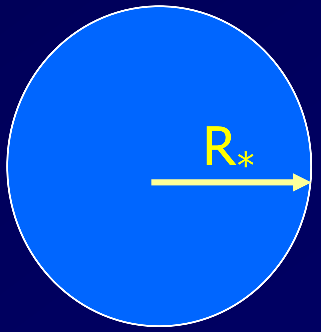
Measuring the Radius of a Star

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

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

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

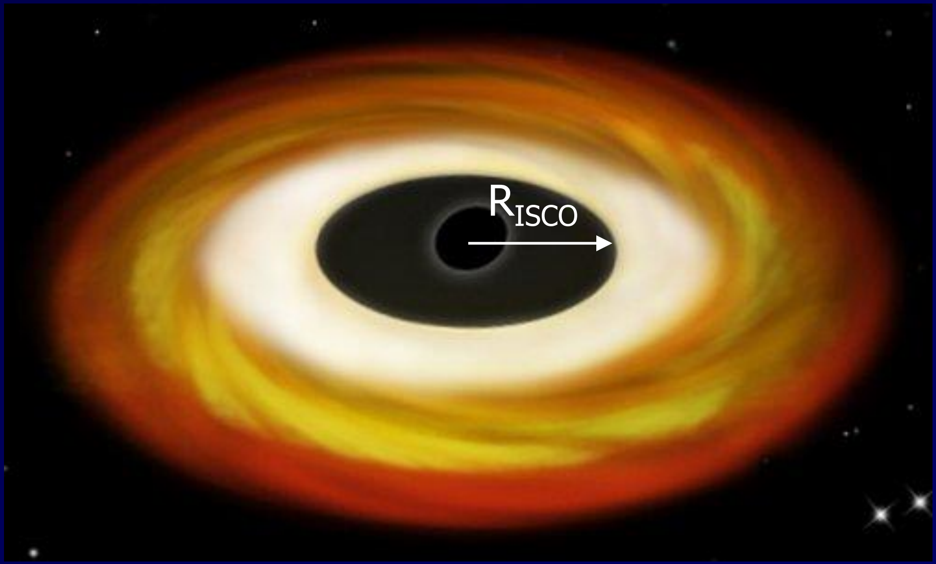
$$R_* = D\sqrt{\frac{F}{s T_*^4}}$$



- A smaller star has to be hotter to produce the same luminosity

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 $\mathbf{F_X}$ and $\mathbf{T_X}$ → $\mathbf{\Delta\Omega_{bright}}$
- Knowing distance **D** and inclination $\boldsymbol{i}$ we get $\mathbf{R_{ISCO}}$ (some geometrical factors)
- From $\mathbf{R_{ISCO}/M}$ we get $\mathbf{a_*}$



- 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. (2009,2010,2011); Steiner et al. (2010,2011) …

BHXRB: Spin Measurements

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 ± 0.25
XTE J1550-564	8.5—9.7	0.34±0.24
GS 1124-683	9.6—13.1	0.63 ± 0.17
GRO J1655-40	5.8—6.8	0.70 (± 0.1)
4U1543-47	8.4—10.4	0.80 (± 0.1)
M33 X-7	14.2—17.1	0.84 ± 0.05
LMC X-1	9.5—12.3	0.92 ± 0.06
GRS 1915+105	10.5—14.3	> 0.95
Cyg X-1	13.8—15.8	> 0.98

Shafee et al. (2006); McClintock et al. (2006); Davis et al. (2006); Orosz et al. (2007,2009,2011); Liu et al. (2007,2009); Gou et al. (2009,2010,2011,2014); Steiner et al. (2011,2012,2014) ; Reid et al. (2014); Wu et al. (2016); Chen et al. (2016)

BH Spin and the Penrose Process

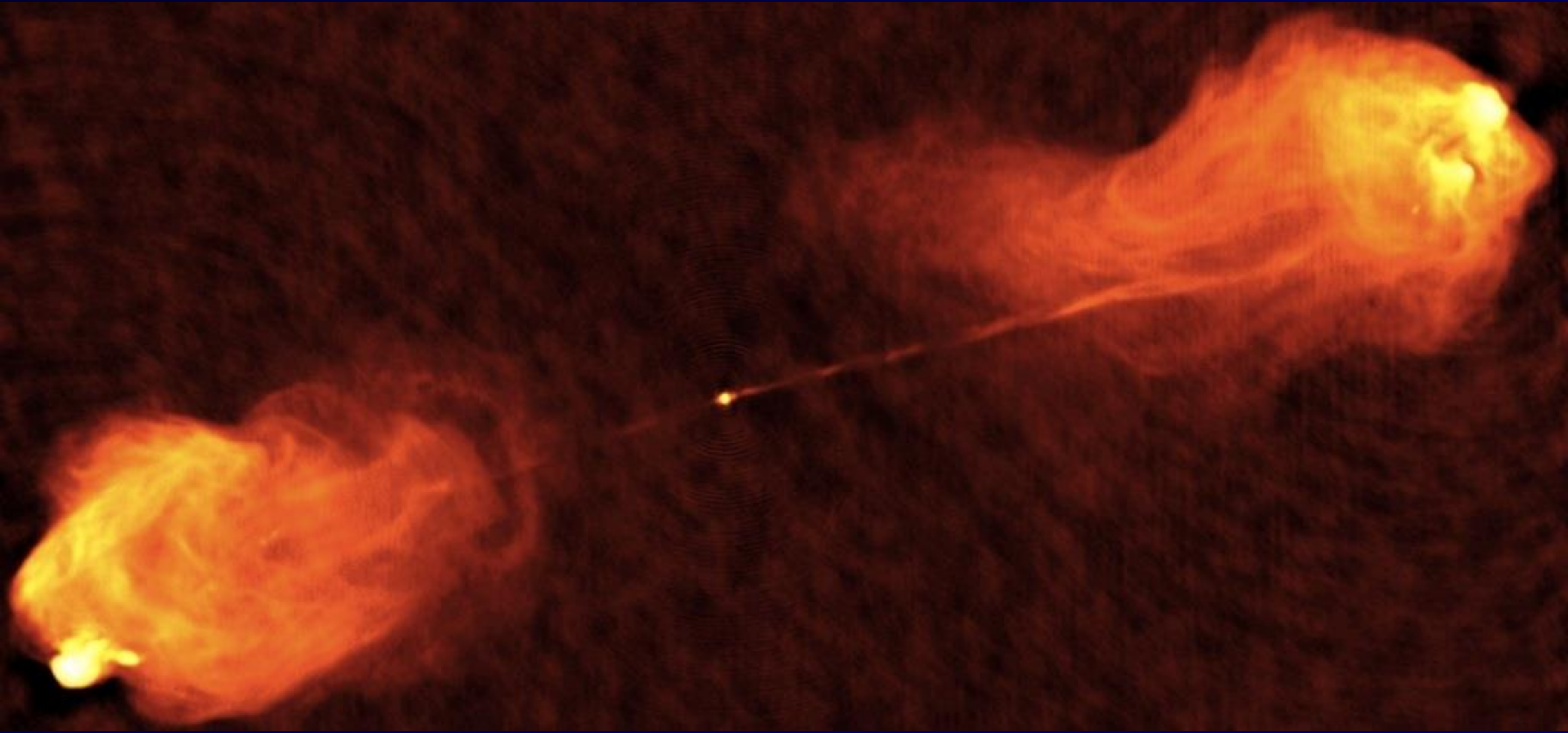
Accretion Power

- Whatever falls into a BH is lost forever
- However, while flowing in, the gas in an accretion disk becomes very hot
- The disk radiates prodigiously: radio, infrared, optical, UV, X-ray, gamma-ray **(QUASARS)**
- Over the history of the universe, BHs have produced as much radiation as all the stars combined!!

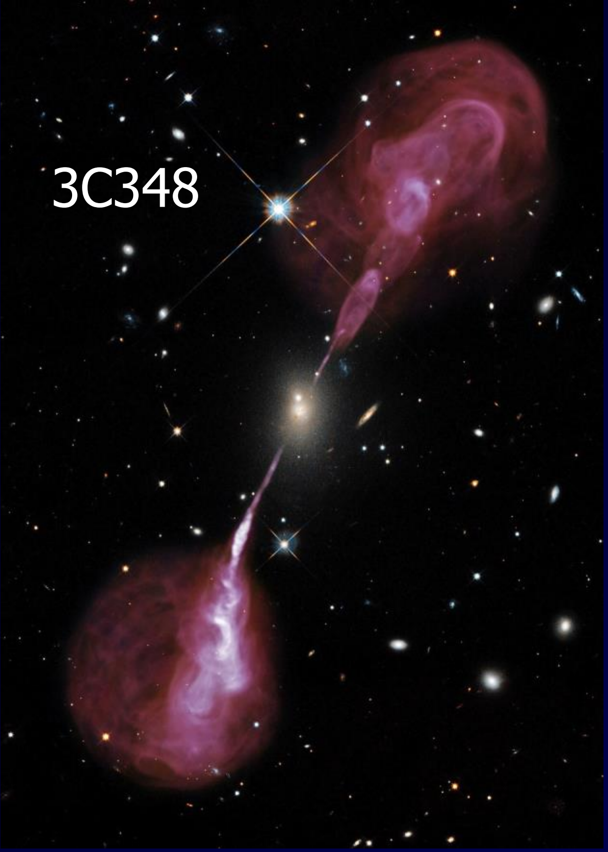
BHs Also Produce Jets

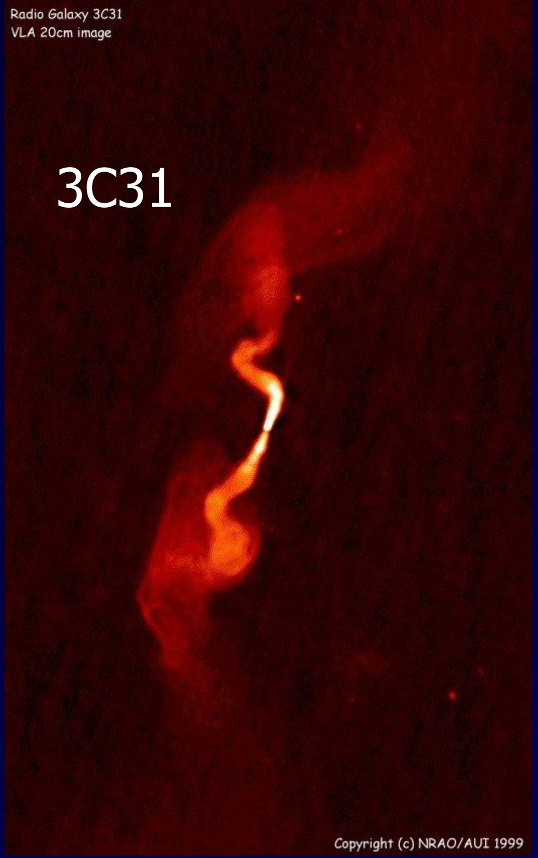
- Accreting BHs produce violent ejections of gas and magnetic field in jets
- Jets often move close to the speed of light: Relativistic Jets
- Jets can be extremely powerful, rivaling the radiation from the disk

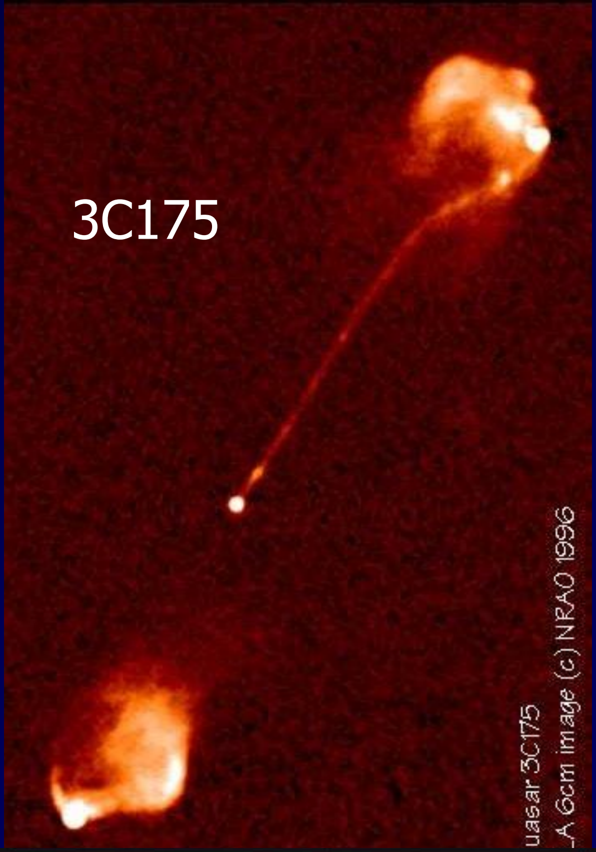
Relativistic Jets



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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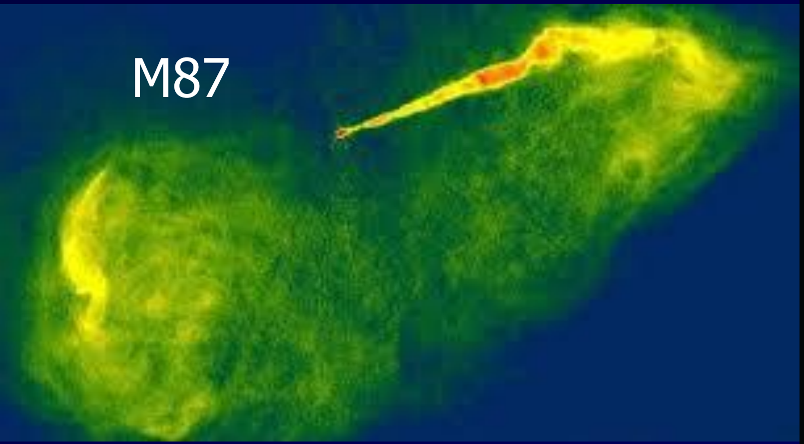
_A 6cm image (c) NRAO 1996


M87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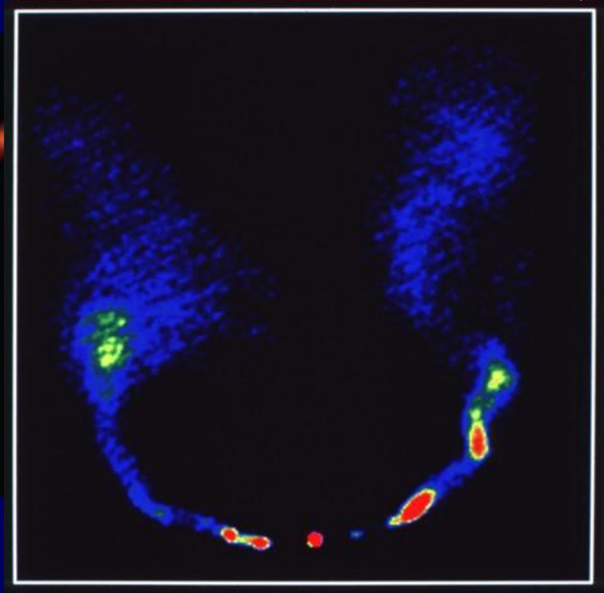


X-ray Binary "Micro-Quasar" GRS 1915+105

GRS 1915+105

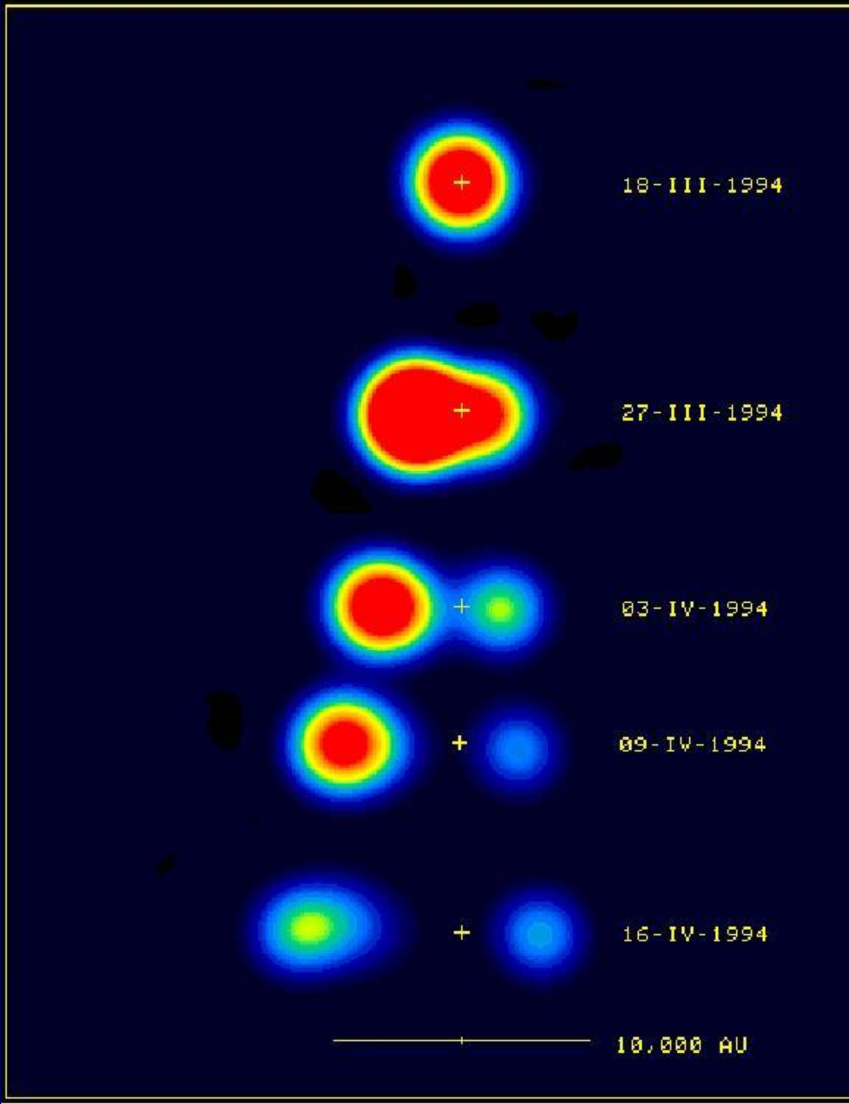
Blobs of material are seen to flow out with apparent speed >c

Superluminal Motion

Infer relativistic motion with

v = 0.92c or Y=2.6

Mirabel & Rodriguez (1994)

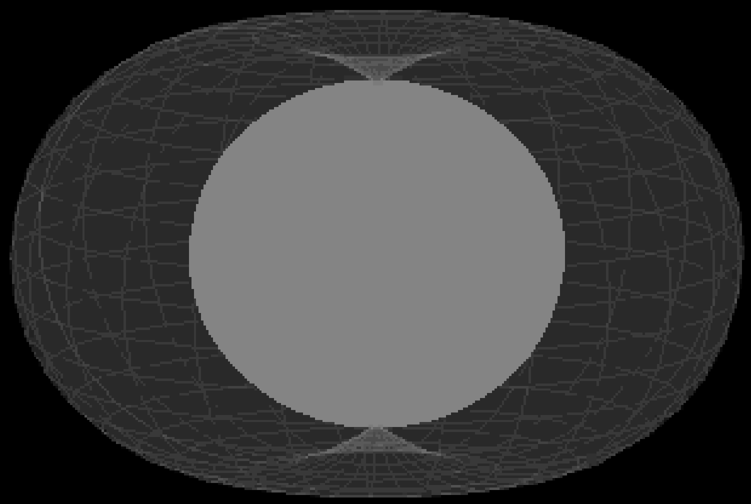


How Are Jets Produced?

- It has for long been conjectured that jets may be produced by spinning BHs
- There is growing evidence that this idea is actually correct
  - Simulations ✓
  - Observations ?

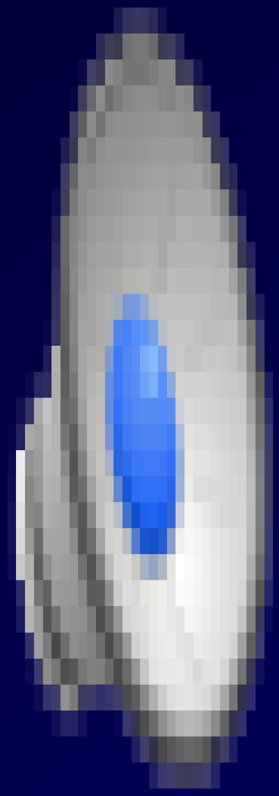
Penrose Process

- A spinning BH has free energy that can in principle be extracted (Penrose 1969)
  - Frame-dragging and the ergosphere
- Penrose came up with a thought expmnt with particles to demonstrate the principle
  - Probably not important in astrophysics
- But magnetized accretion disk (MHD) plus frame-dragging is promising (Ruffini & Wilson 1975; Blandford & Znajek 1977)



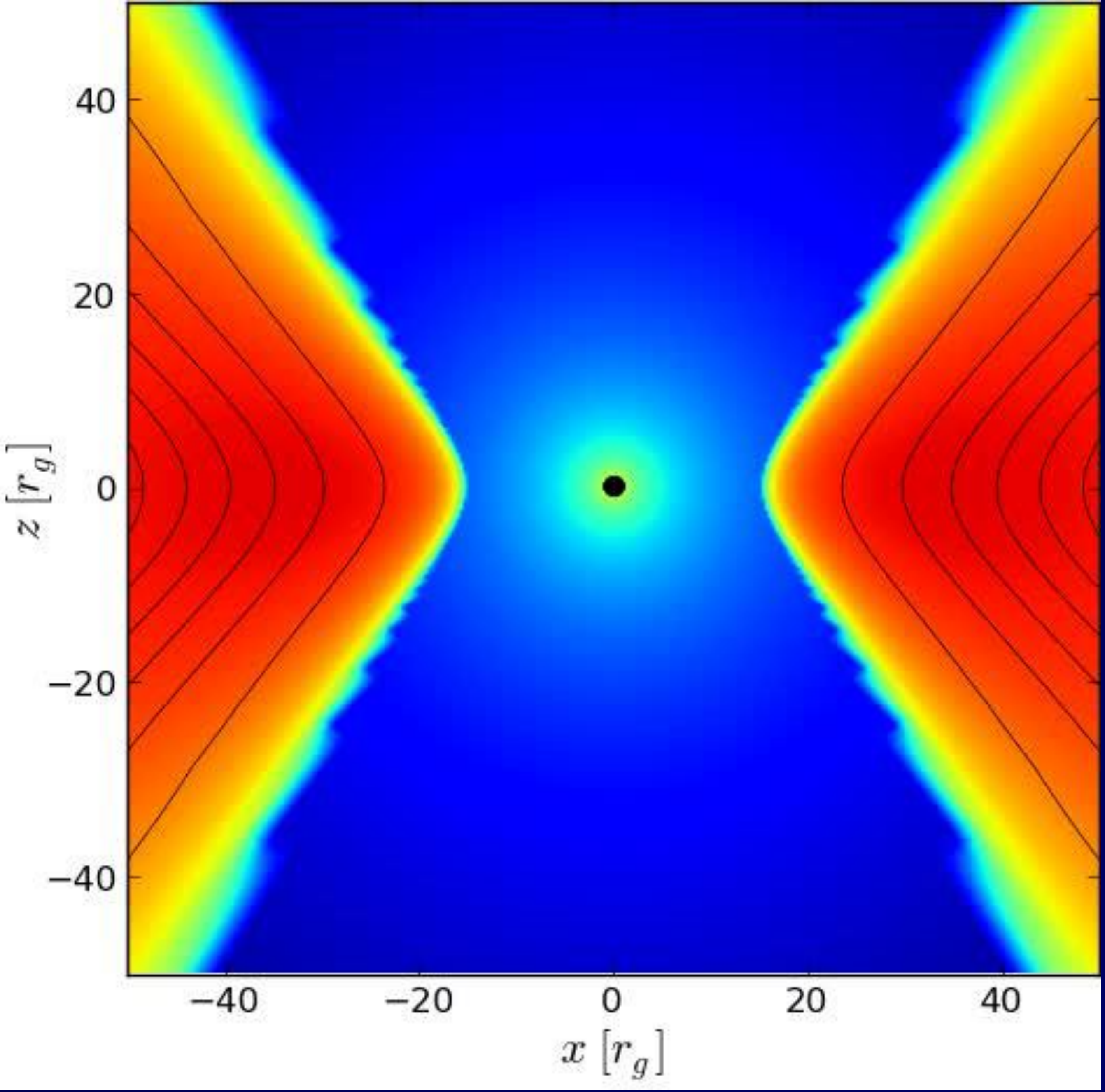
Semenov et al. (2004)

MOVIE



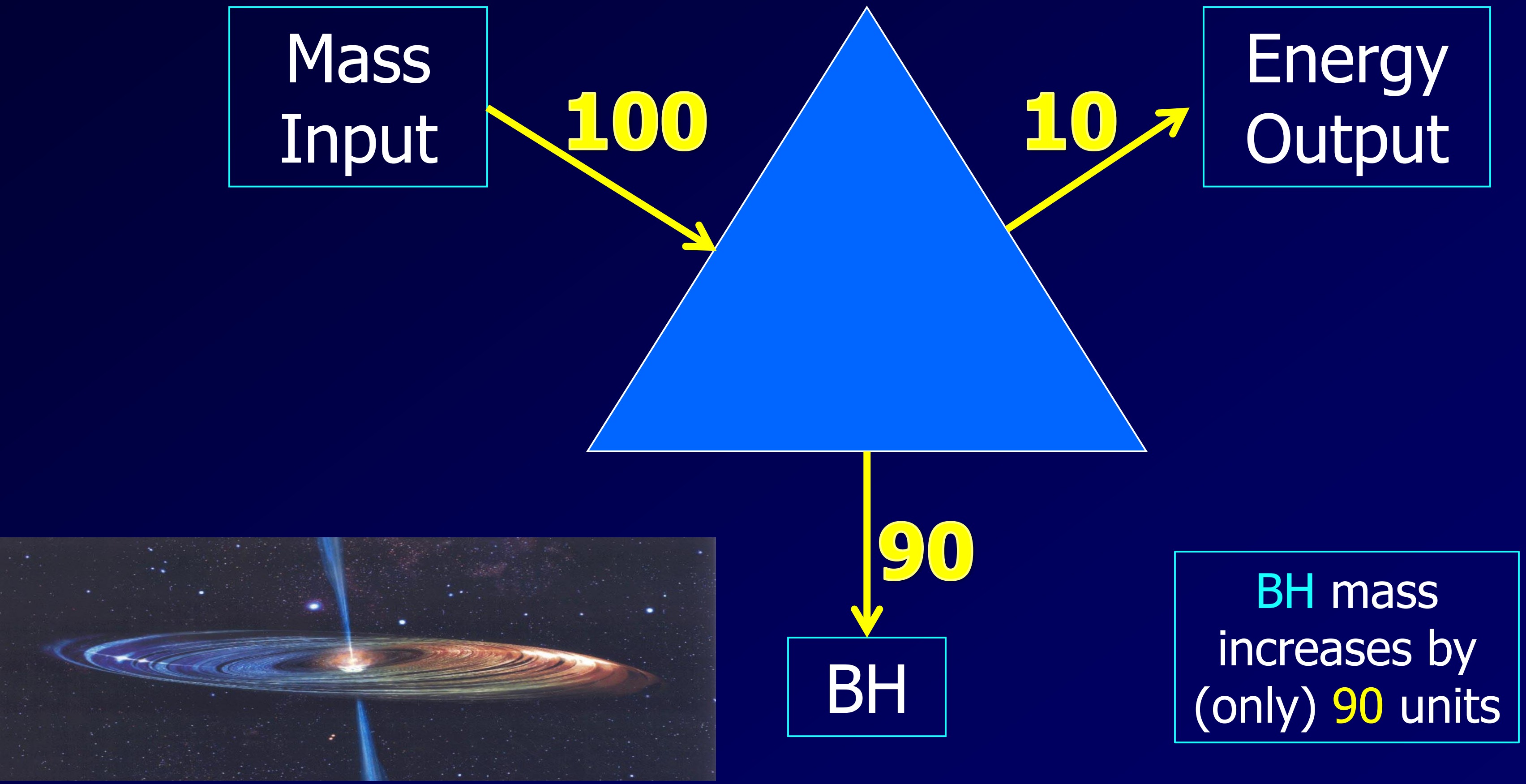
3D GRMHD simulation
(Tchekhovskoy 2011+)

Clear evidence in simulations for energy and angular momentum outflow from the BH

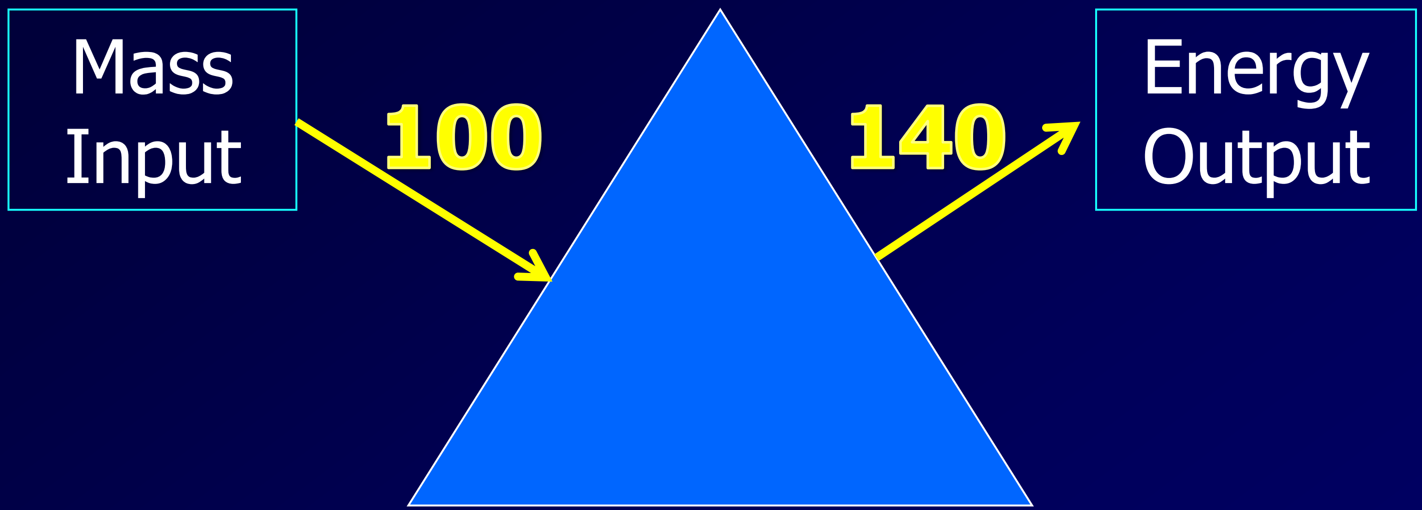


Tchekhovskoy (2011)

Typical Accretion System

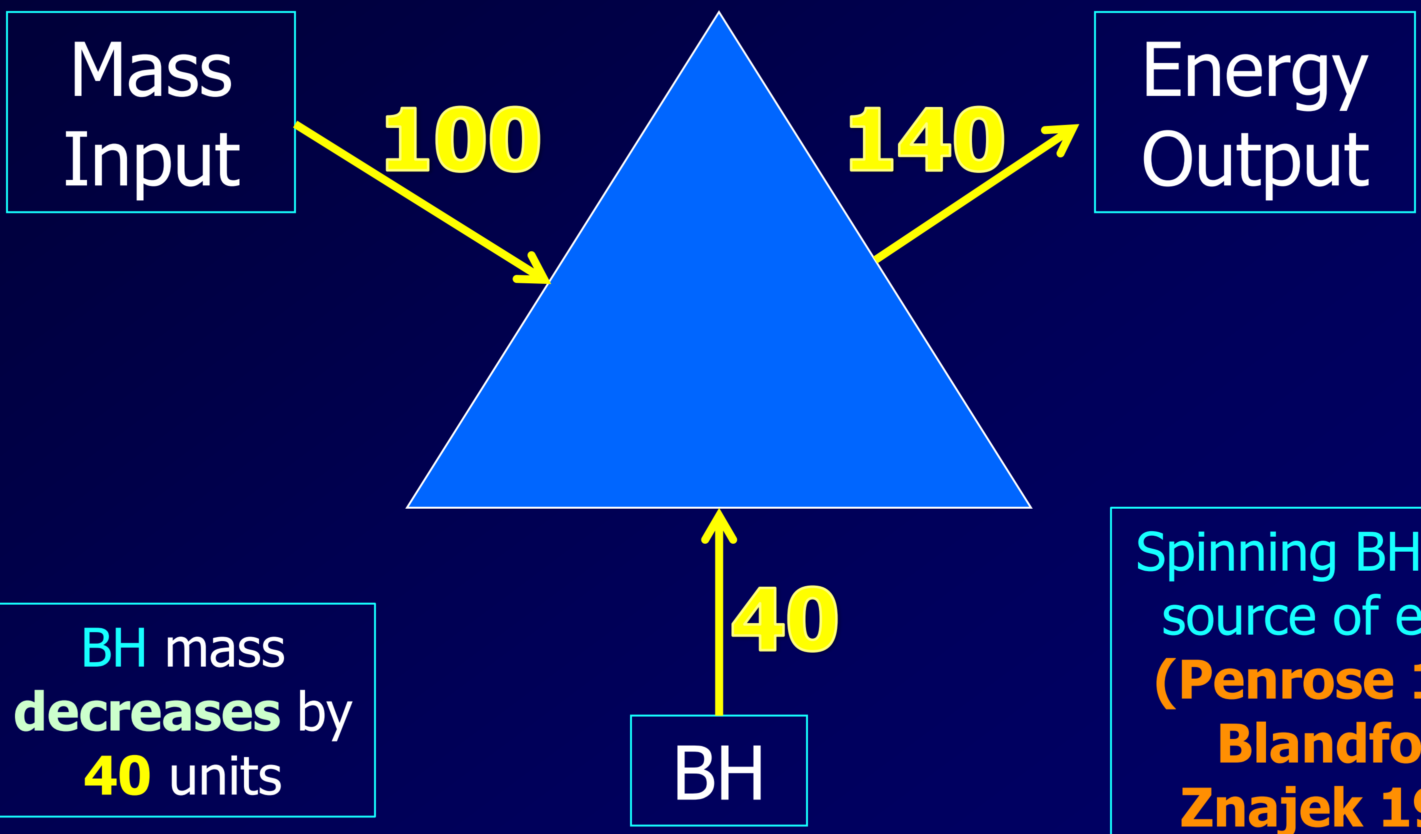


Tchekhovskoy et al. (2011) Simulation



What's going on?!
Doesn't this violate some fundamental law of nature?!

Tchekhovskoy et al. (2011) Simulation



BH mass **decreases** by **40** units

Spinning BHs are a source of energy **(Penrose 1969; Blandford-Znajek 1977)**

The BH is Losing Mass!

- Our BH eats matter but loses mass!
- Doesn't this violate the concept of a horizon: stuff falls in, nothing gets out?
- **No**: The quantity that has to increase with time is not BH mass M, but event horizon area A ("Area Theorem")

$$A=8\pi (GM/c^2)^2 [1+(1-a_*^2)^{1/2}]$$

- A BH can lose mass ($dM/dt<0$) and spin ($da_*/dt<0$) in such a way that $dA/dt>0$

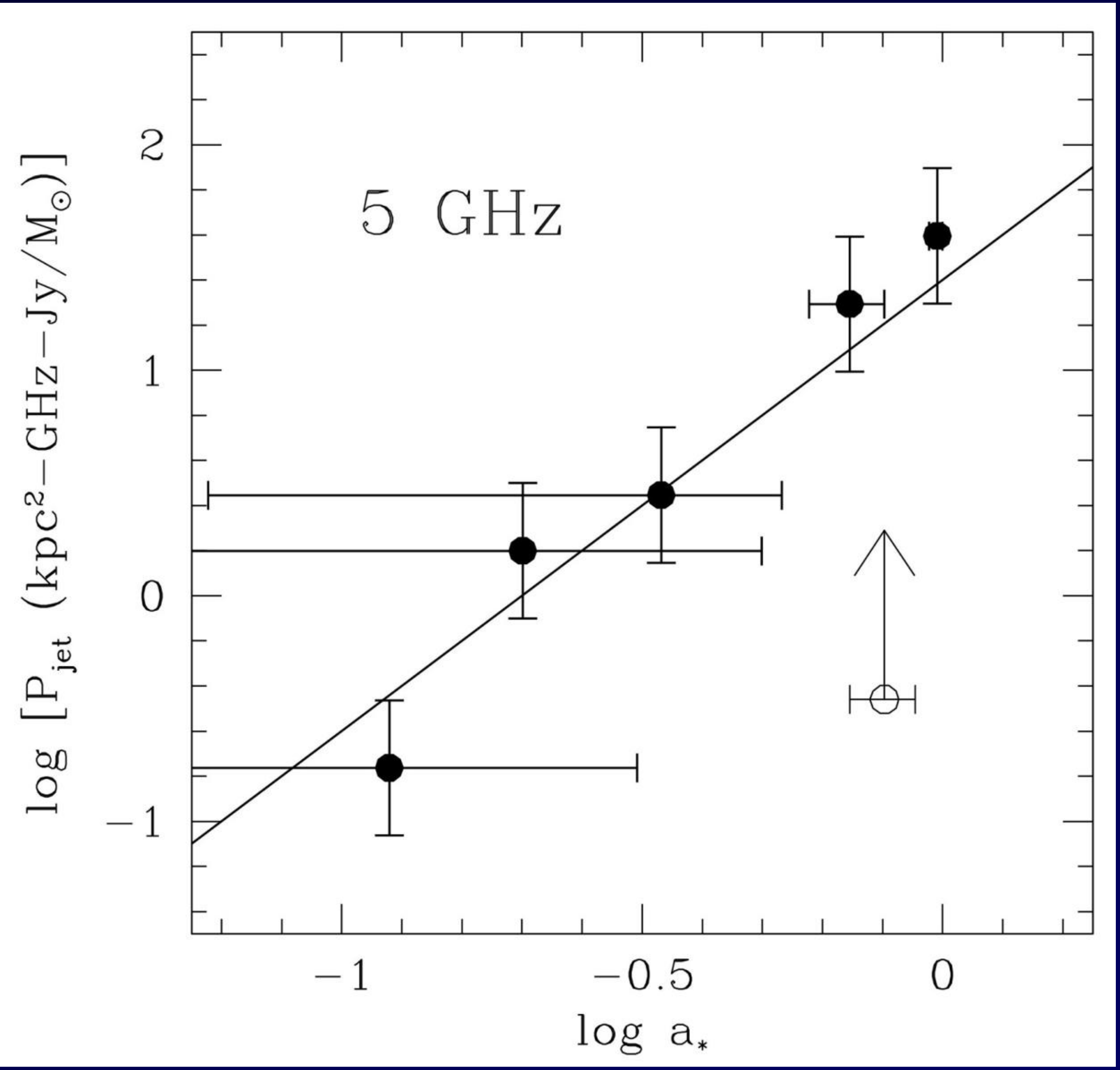
Area = Entropy

- Bekenstein & Hawking showed that the entropy of a BH is proportional to the area of its event horizon

$$S_{\mathrm{BH}} = \frac{2pc^3k}{Gh}A$$

- Thus, the Area Theorem can be reinterpreted as a manifestation of the Second Law of Thermodynamics

A Suggestive Correlation



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

There is a correlation

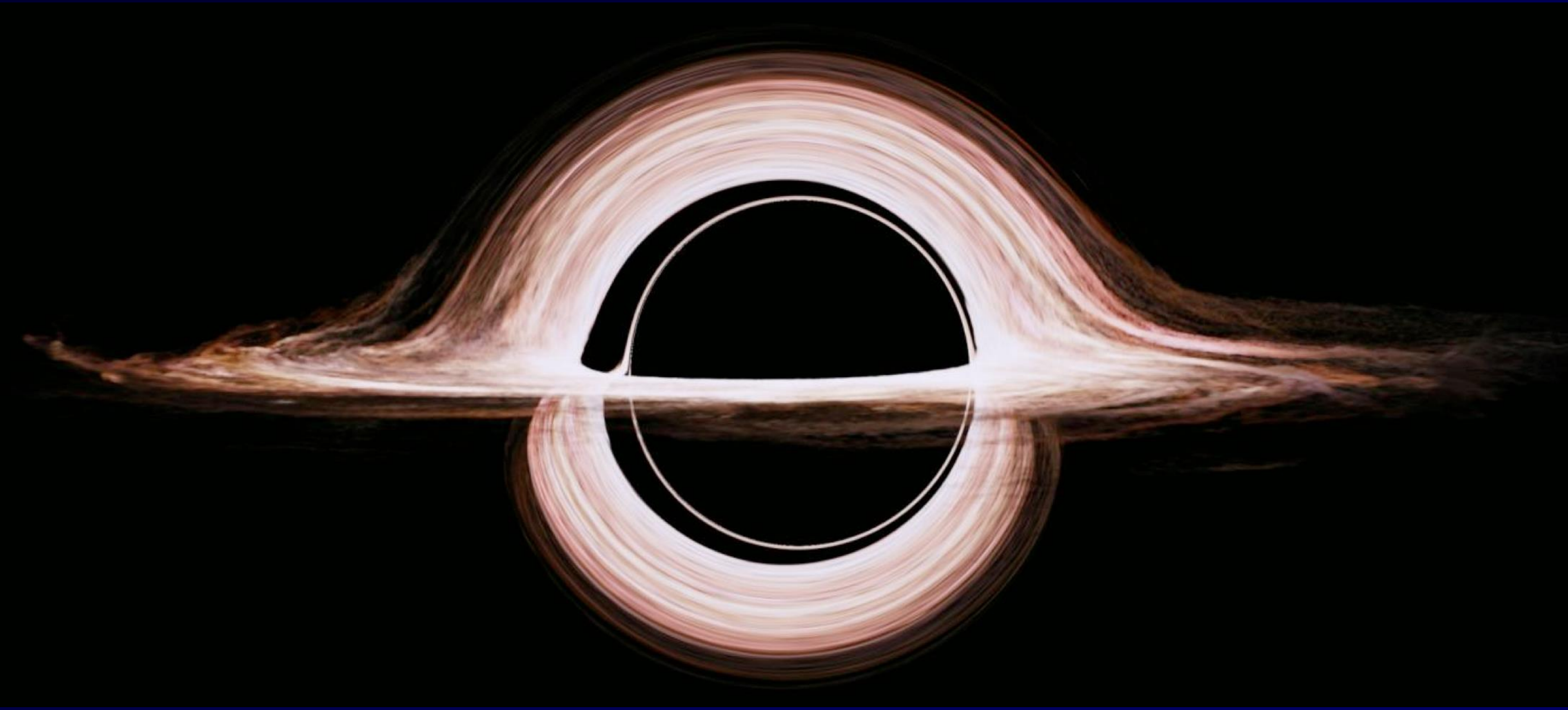
But small sample

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

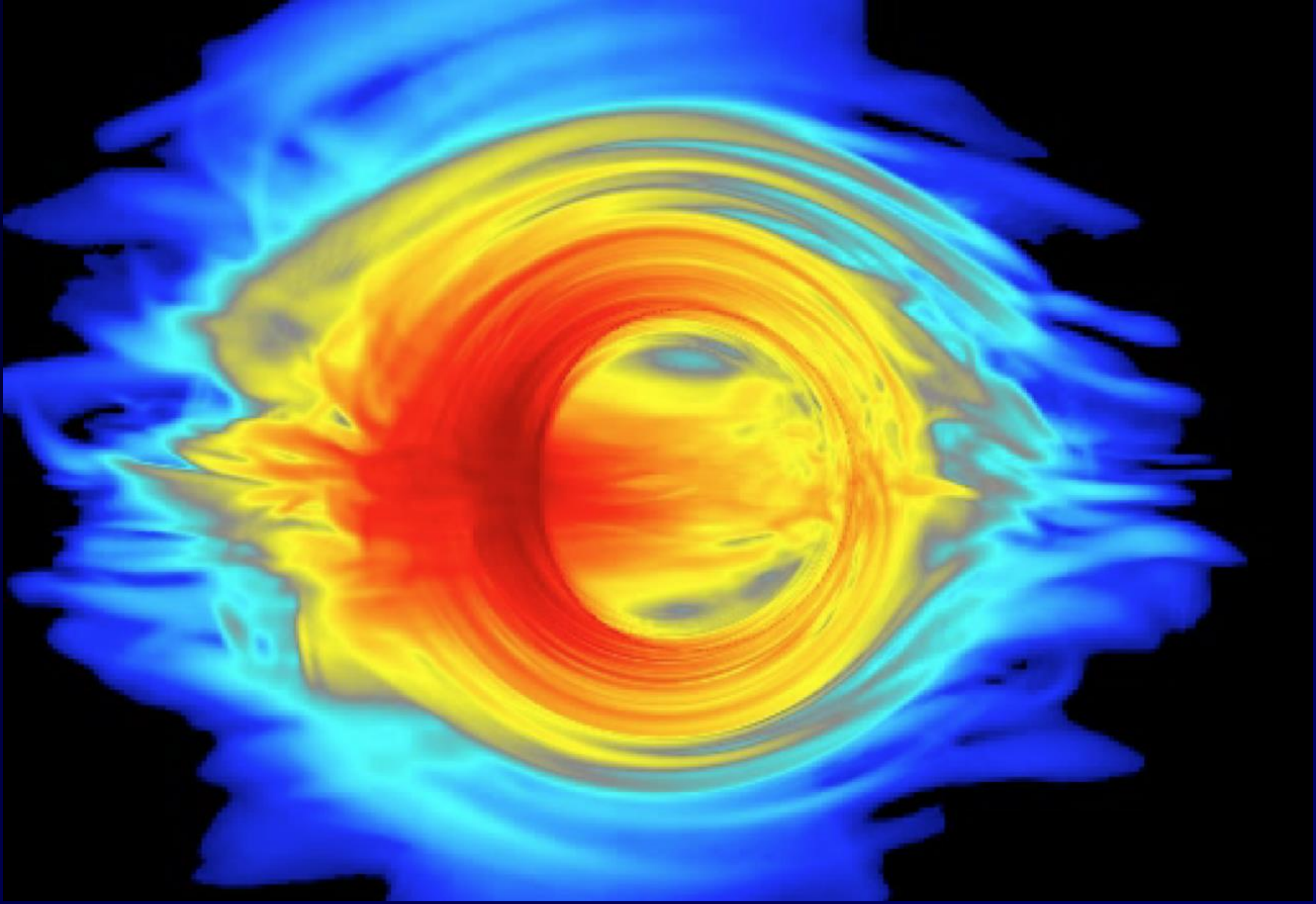
Imaging a Black Hole: Event Horizon Telescope

Image of a Black Hole

- An isolated BH is completely dark
- But an accreting BH produces radiation
- If we could obtain an image of an accreting BH, what would it look like?
- Depends of course on the details of the accretion flow, but we have some idea of what to expect

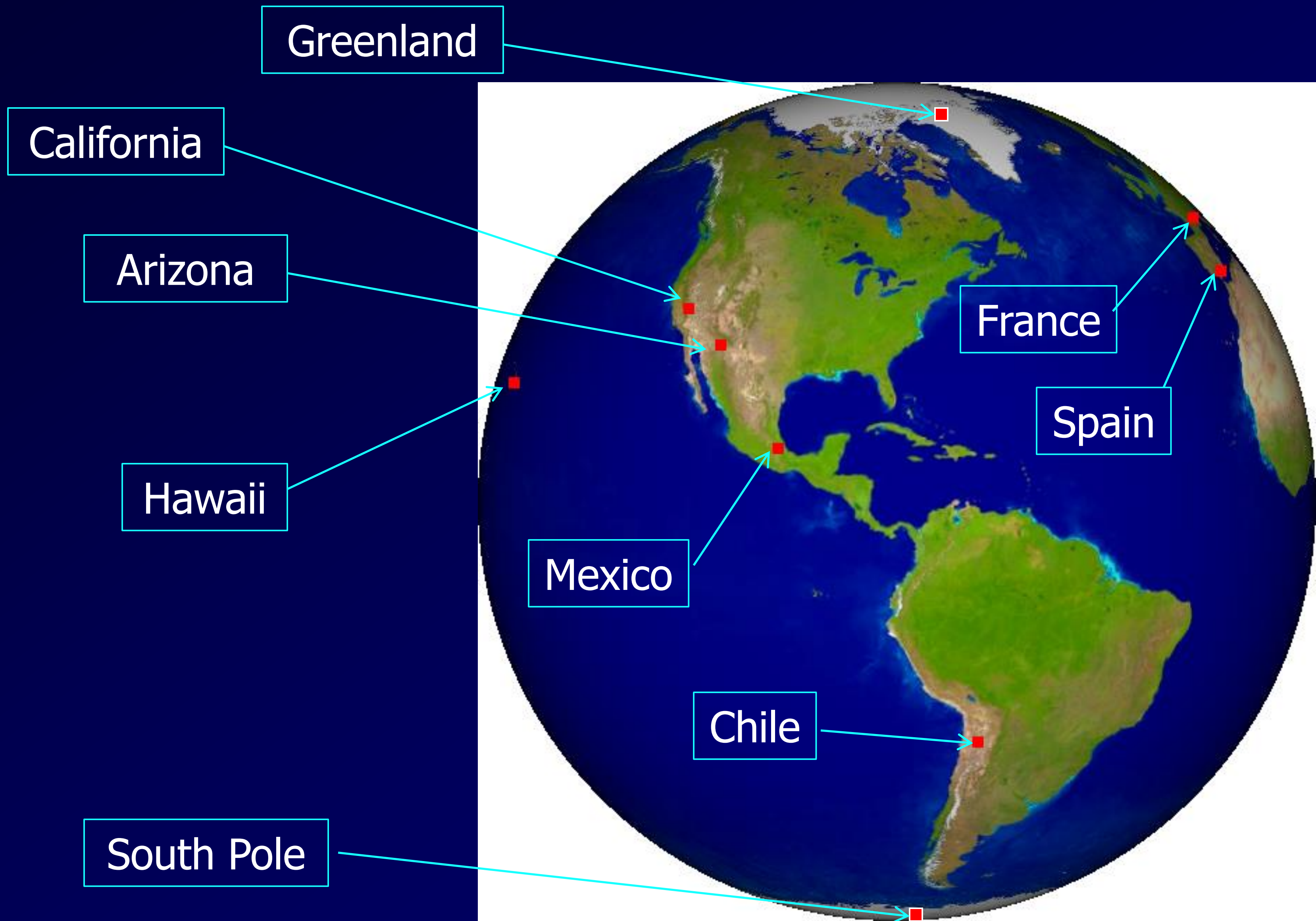


"Interstellar" (Movie 2015)



Computer simulated image of gas accreting at the Galactic Center (Dolence, Gammie, Noble, et al.)

Event Horizon Telescope: An Interferometer at λ=1.3mm



Summary

- The BH was initially a purely theoretical concept that nobody took seriously
  - Einstein thought BHs cannot be real!!
- But many BHs have been discovered in recent years in different kinds of objects in the universe
- Two distinct populations:
  - Stellar-Mass BHs: 5—20 $M_{\square}$ ($\square 10^7$ per galaxy)
  - SuperMassive BHs: 10^{6-10} $M_{\square}$ (1 per galaxy)
- Relativistic Jets appear to derive power from BH Spin
  - Manifestation of the Penrose Process
- The Event Horizon Telescope is just around the corner