Title: Black Hole Spin

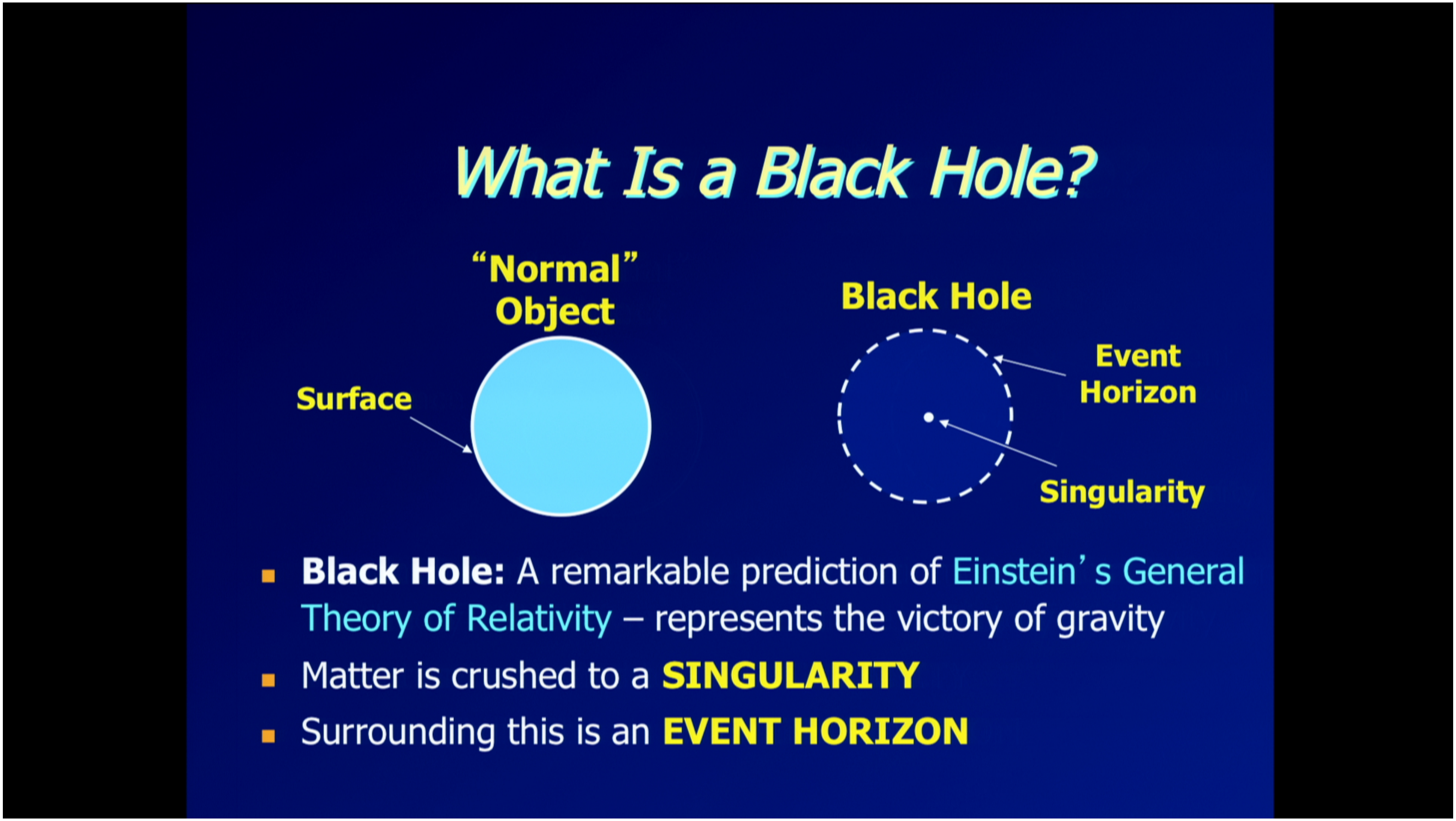
Date: Feb 29, 2012  02:00 PM

URL: http://pirsa.org/12020130

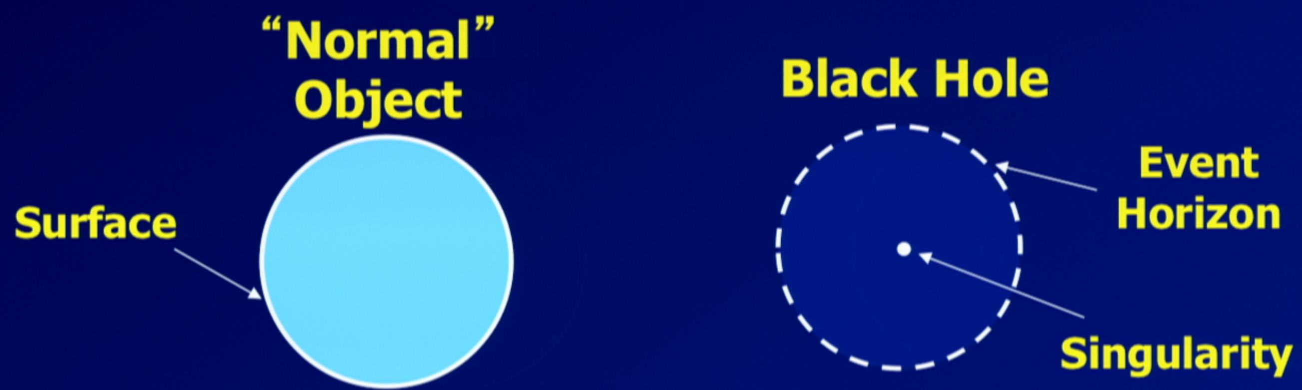
Abstract: Astrophysicists have discovered two varieties of black holes in the universe: stellar-mass black holes with masses in the range 5 to 20 solar masses, and supermassive black holes with masses in the range million to several billion solar masses. While black hole masses have been measured for many years, only recently have methods been developed for measuring black spin. With this advance, it is possible to investigate what effect spin has on observational properties of black holes.<br>

# Black Hole Spin

Ramesh Narayan


What Is a Black Hole?
"Normal" Object
Surface
Black Hole
Event Horizon
Singularity
Black Hole: A remarkable prediction of Einstein's General Theory of Relativity – represents the victory of gravity
Matter is crushed to a SINGULARITY
Surrounding this is an EVENT HORIZON

## *What Is a Black Hole?*




- **Black Hole:** A remarkable prediction of Einstein's General Theory of Relativity – represents the victory of gravity
- Matter is crushed to a **SINGULARITY**
- Surrounding this is an **EVENT HORIZON**

# The Event Horizon

- The event horizon is a one-way membrane
- Matter/Energy can fall in, but nothing gets out, not even light
- Region inside event horizon is causally cut-off from outside
- **Radius of EH = Schwarzschild Radius:**

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

# The Event Horizon

- The event horizon is a one-way membrane
- Matter/Energy can fall in, but nothing gets out, not even light
- Region inside event horizon is causally cut-off from outside
- **Radius of EH = Schwarzschild Radius:**

$$R_s = \frac{2GM}{C^2} = 2.95\left(\frac{M}{M_e}\right)\text{km}$$

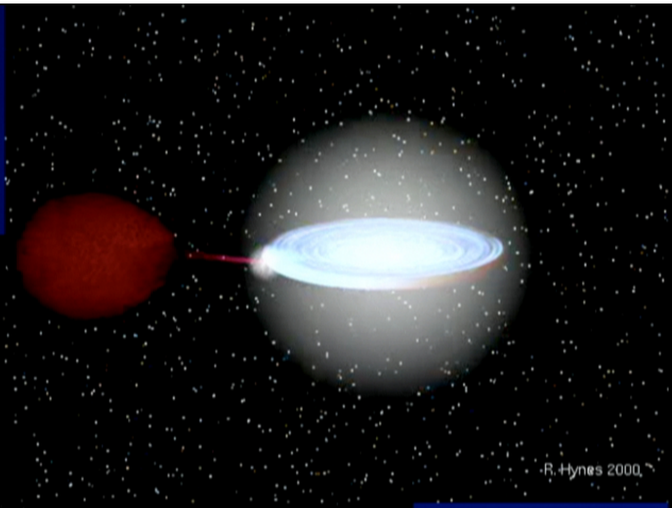
# How Massive Can a BH Be?

- A BH can have any mass above ~$10^{-5}$ g (Planck mass $(hc/G)^{1/2}$ --- quantum gravity limit)
- Unclear if very low-mass BHs form naturally
- BHs more massive than ~$3M_\odot$ are very likely:
  - Form quite naturally by gravitational collapse of massive stars at the end of their lives
  - No other stable equilibrium available at these masses
- Enormous numbers of such BHs in the universe

# How Massive Can a BH Be?

- A BH can have any mass above $\sim 10^{-5}$ g (Planck mass $(hc/G)^{1/2}$ --- quantum gravity limit)
- Unclear if very low-mass BHs form naturally
- BHs more massive than $\sim 3M_{\odot}$ are very likely:
  - Form quite naturally by gravitational collapse of massive stars at the end of their lives
  - No other stable equilibrium available at these masses
- Enormous numbers of such BHs in the universe

# X-ray Binaries



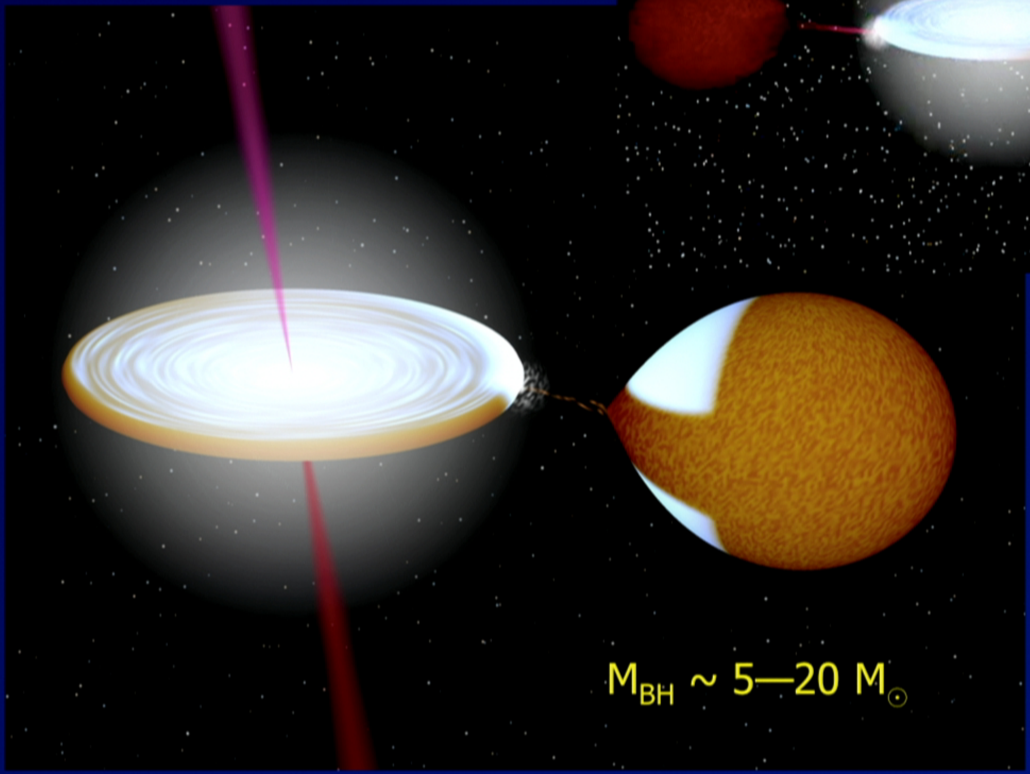




Image credit: Robert Hynes

# X-ray Binaries

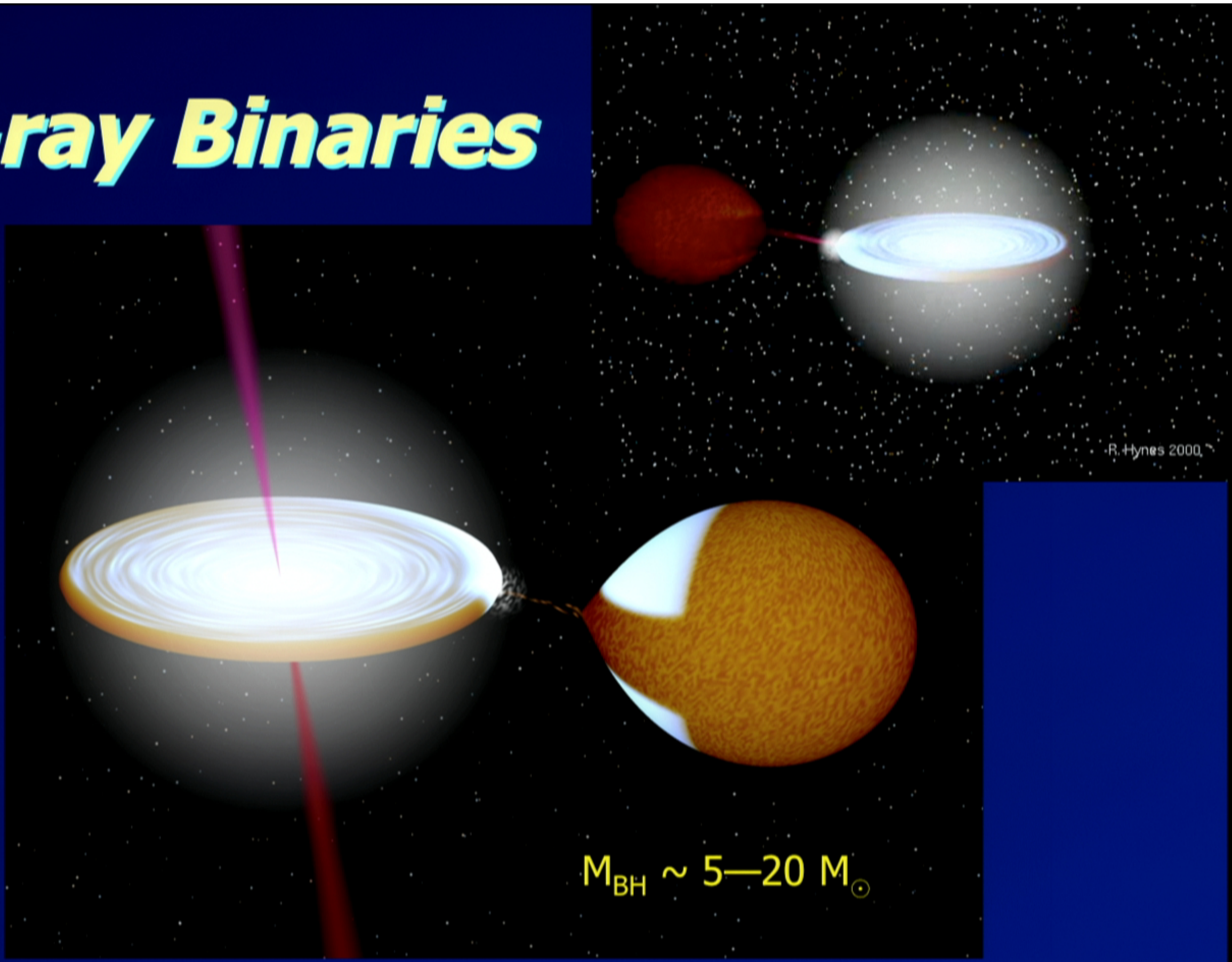



Image credit: Robert Hynes

# A Black Hole is Extremely Simple

- Mass: **M**
- Spin: **$a_*$ ($J=a_*GM^2/c$)**
- Charge: Q

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

# A Black Hole is Extremely Simple

- Mass: **M**
- Spin: **$a_*$ ($J=a_*GM^2/c$)**
- Charge: Q

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

# Masses of Stars in Binaries

Observations give

**$v_r$** : radial velocity of secondary

**P** : orbital period of binary

These two quantities give the mass function (Newton's Laws):

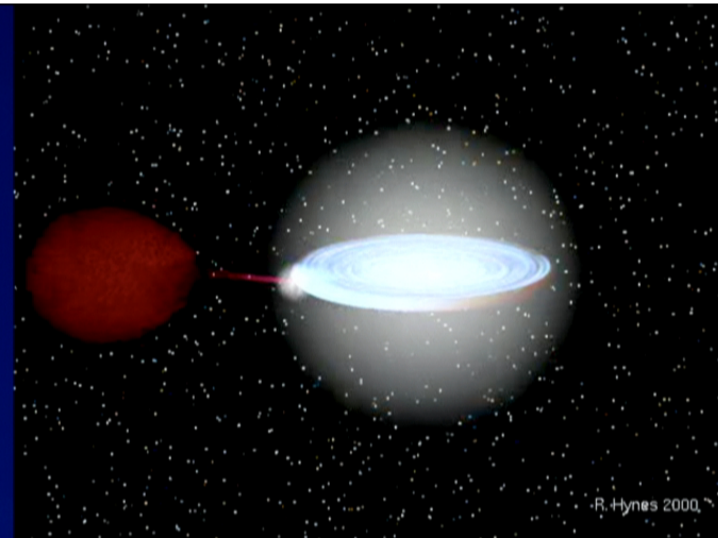
$$f(M) = \frac{v_r^3 P}{2\pi G} = M_X \frac{\sin^3 i}{(1 + M_s / M_X)^2}$$

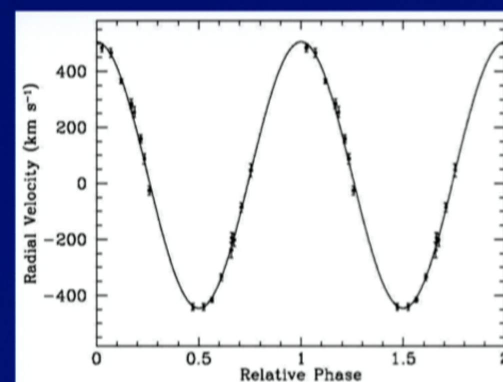
Often, $M_s \ll M_X$, so finite $M_s$ is not an issue for measuring $M_X$

The inclination ***i*** is more serious :

Various methods to estimate it

Eclipsing systems are best



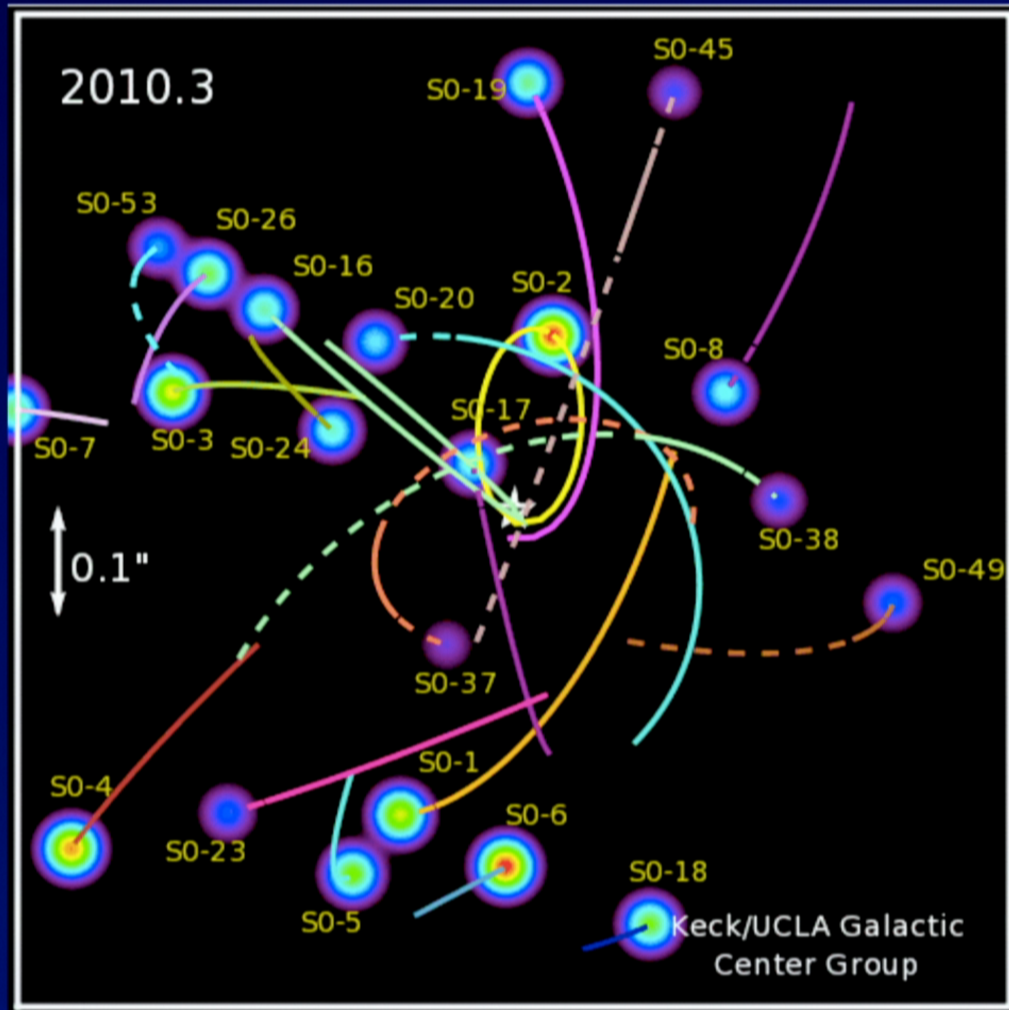




GRS 1009-45
Filippenko et al. (1999)

| 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 | 5.9—9.2 |
| A0620-00 | 6.3—6.9 |
| GRO J1655-40 | 6.0—6.6 |
| 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 | 10—18 |

| 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 | 5.9—9.2 |
| A0620-00 | 6.3—6.9 |
| GRO J1655-40 | 6.0—6.6 |
| 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 | 10—18 |

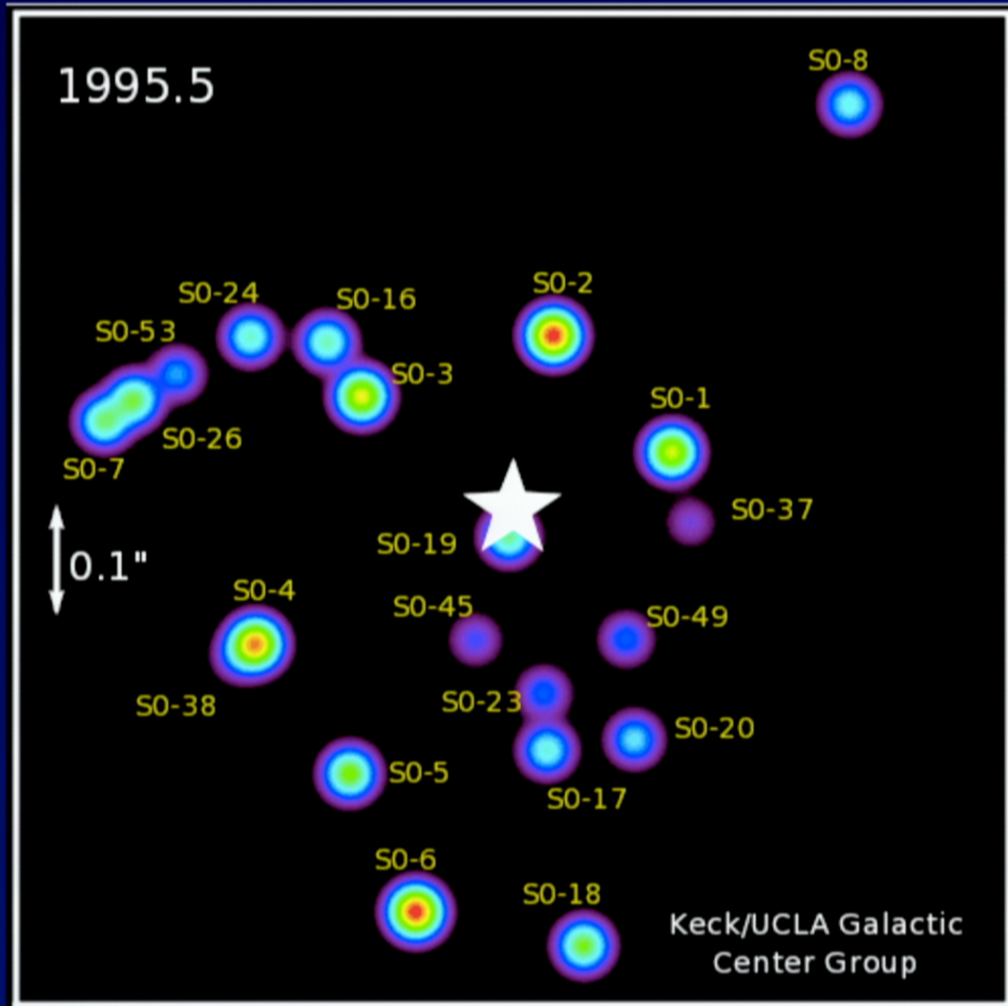
# Stellar Dynamics at the Galactic Center




Schodel et al. (2002)
Ghez et al. (2005)

**$M=4.5\times10^{6}\ M_{\odot}$**

# Stellar Dynamics at the Galactic Center




Schodel et al. (2002)
Ghez et al. (2005)

**$M = 4.5 \times 10^6\ M_\odot$**

# Supermassive Black Holes in Other Galactic Nuclei

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

# Supermassive Black Holes in Other Galactic Nuclei

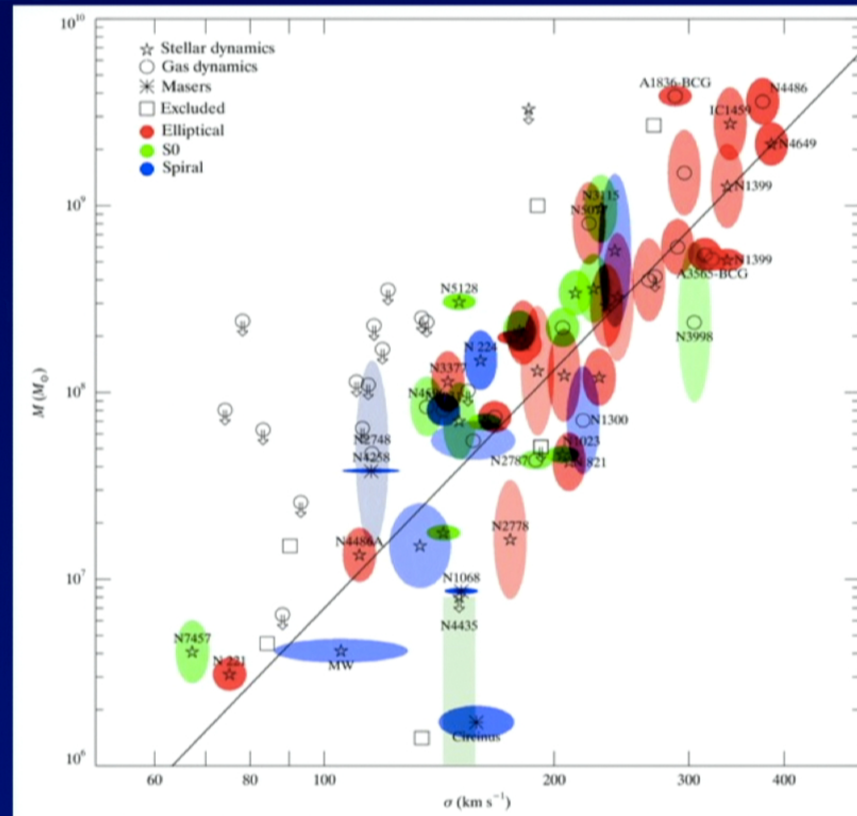
- BHs identified in nuclei of many other galaxies
- BH masses obtained in several cases, though not as cleanly as in the case of our own Galaxy
  - $M_{BH} \sim 10^6 — 10^{10} M_{\odot}$
- Virtually every galaxy has a supermassive black hole (SMBH) at its center!

# The $M_{BH}$-$\sigma$ Relation

There is a remarkable correlation between the mass of the central supermassive black hole and the velocity dispersion of the stars in the galaxy: **$M_{BH}$-$\sigma$** relation

There is also a relation between **$M_{BH}$** and galaxy luminosity **L**

Important clue on the formation/evolution of SMBHs and galaxies



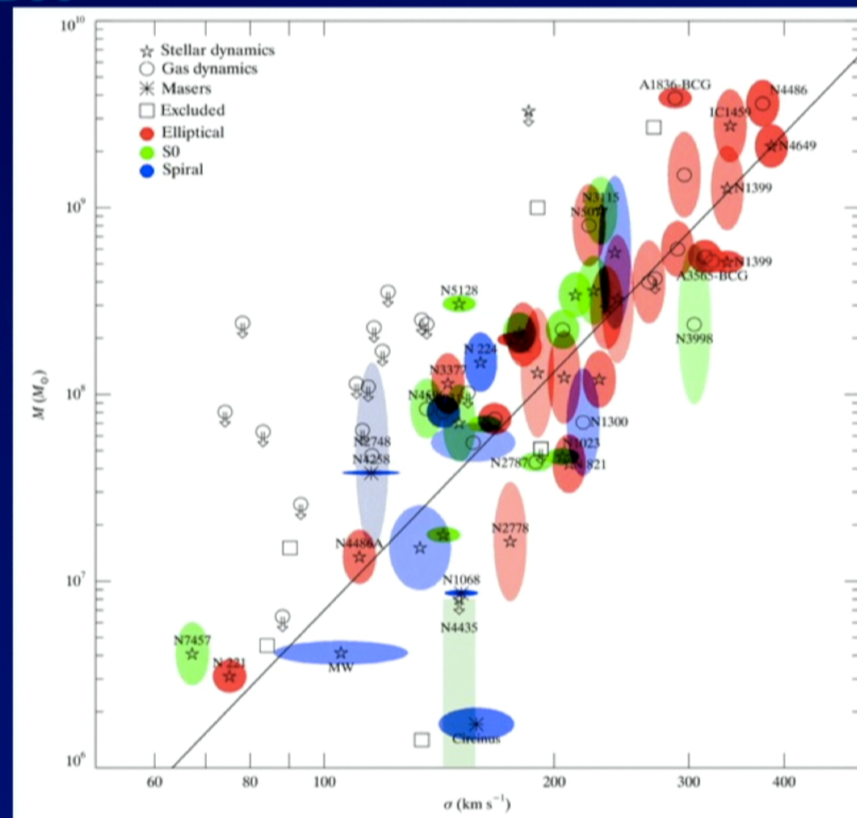

Gultekin et al. (2009)

# The $M_{BH}$-$\sigma$ Relation

There is a remarkable correlation between the mass of the central supermassive black hole and the velocity dispersion of the stars in the galaxy: **$M_{BH}$-$\sigma$** relation

There is also a relation between **$M_{BH}$** and galaxy luminosity **L**

Important clue on the formation/evolution of SMBHs and galaxies



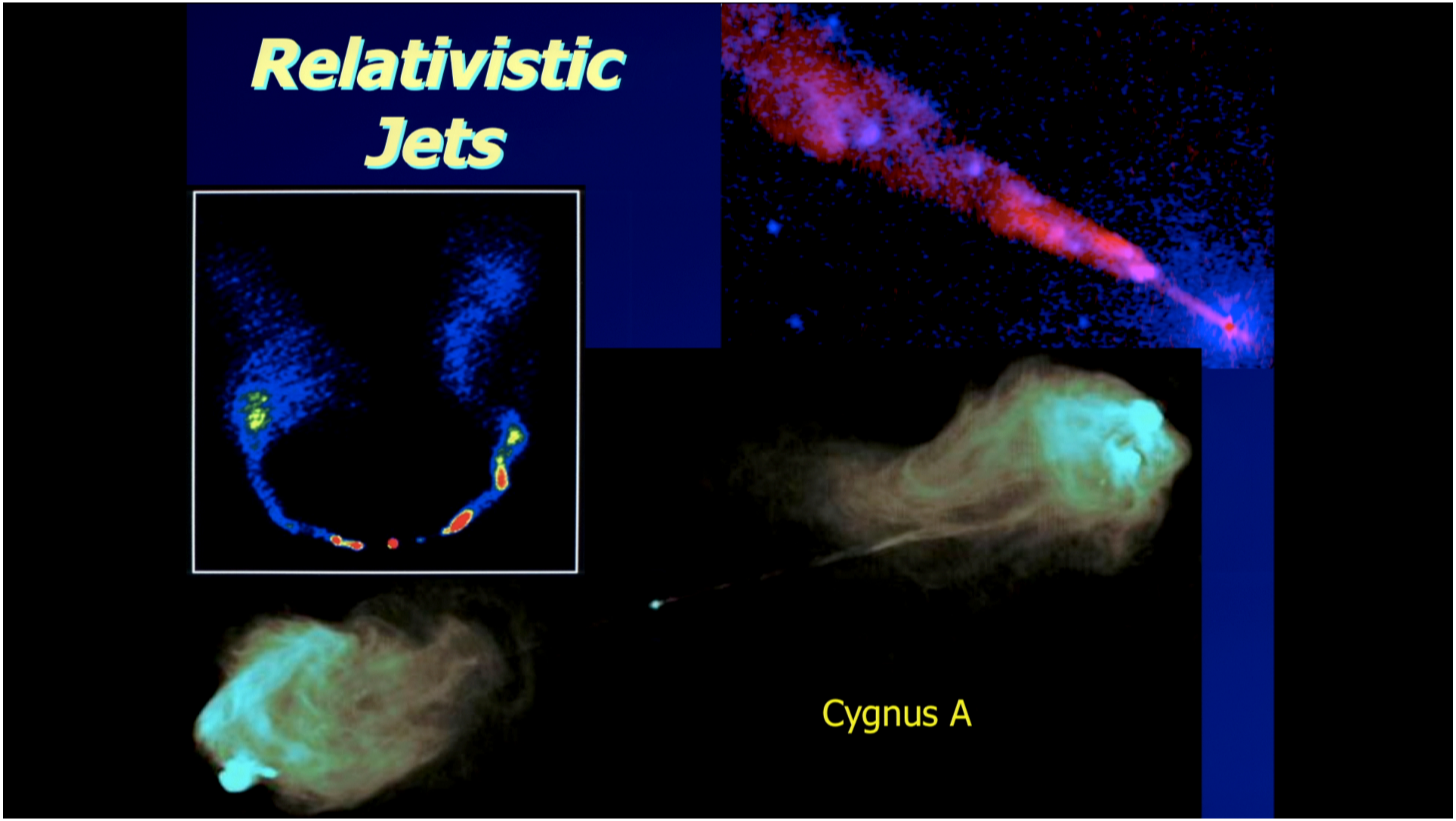

Gultekin et al. (2009)

# Why are BHs and Host Galaxies Correlated?

- Galaxies merge and grow during the evolution of the Universe
- During a merger, the two central BHs come together, merge and become “Active”
- The Active BH is very powerful and causes a huge disruption in the surrounding galaxy
- In the process, it is proposed that the galaxy’s properties are controlled by the BH

# How Can an Active BH Have so much Effect?

- A BH is extremely tiny compared to the surrounding galaxy (factor $10^9$ in scale)
- Yet it is apparently able to have a profound effect on the entire galaxy
- How does it do it?
- It is believed to be through energetic ejections: Relativistic Jets
- Radiation may also have an effect

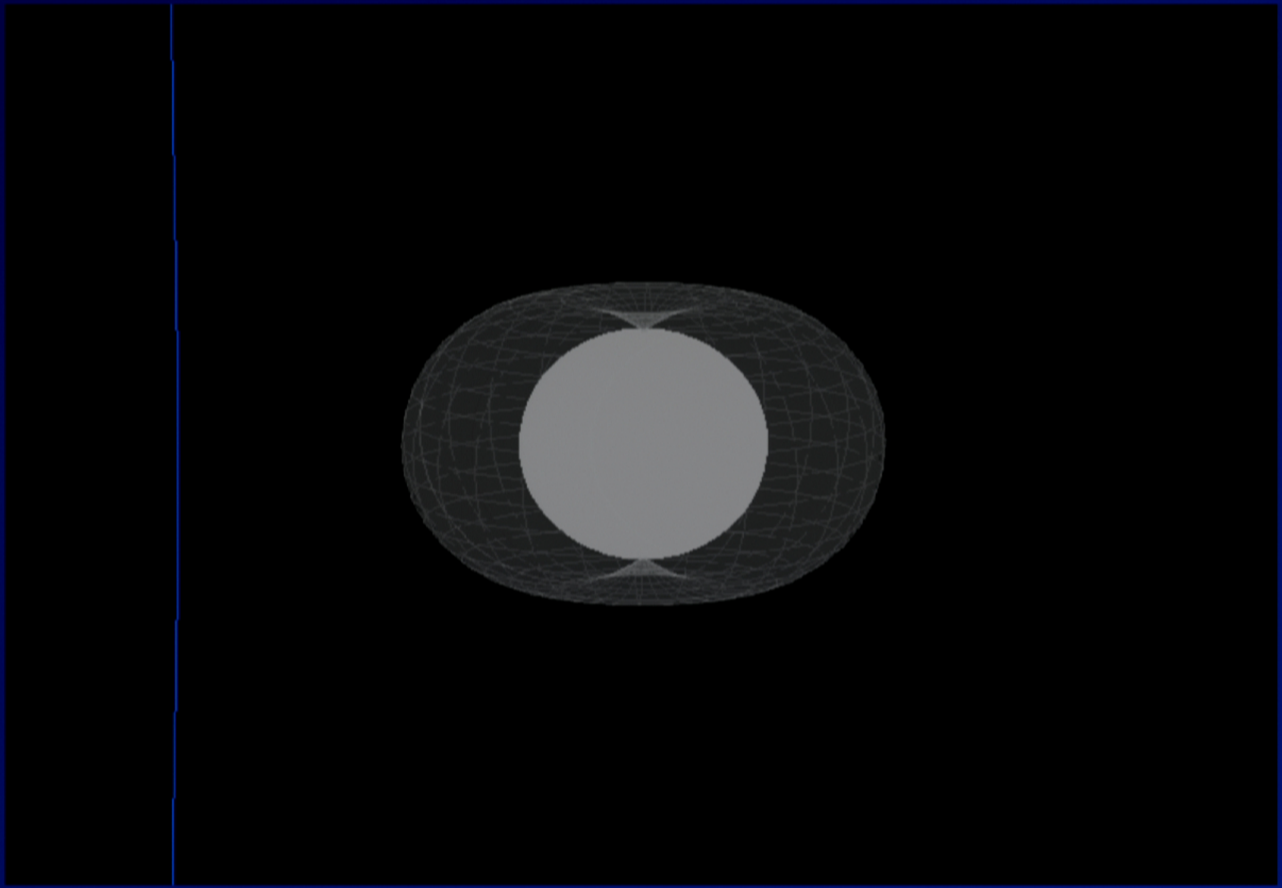

Relativistic
Jets
Cygnus A

# What is the Power Source Behind Relativistic Jets?

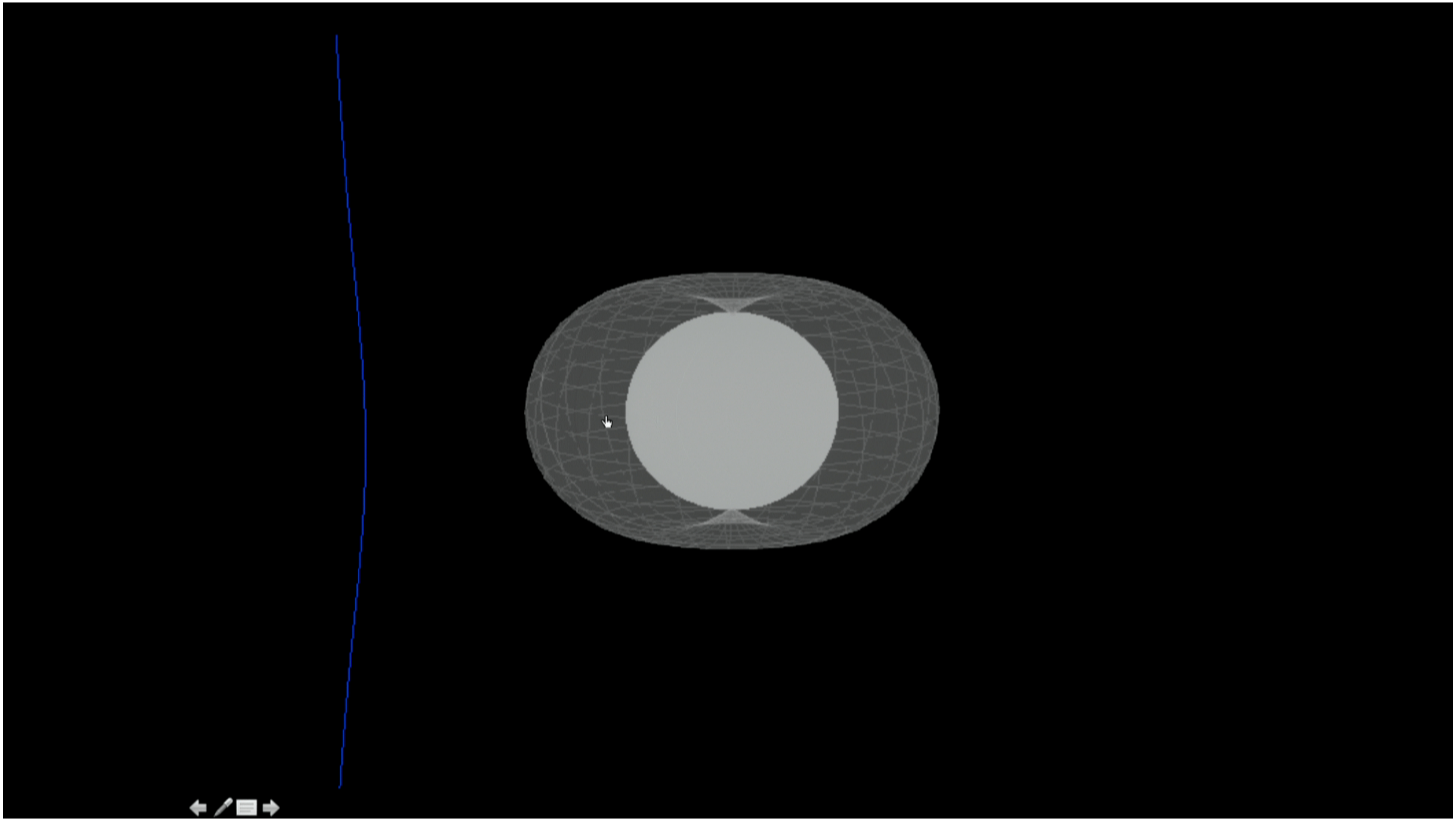
- **Probably the Second Hair!**
- Could it be that jets get their power directly from the BH?
- Not as crazy as it sounds
- A spinning BH does not just eat stuff
- It can also give back energy (at least when it is in a good mood!)

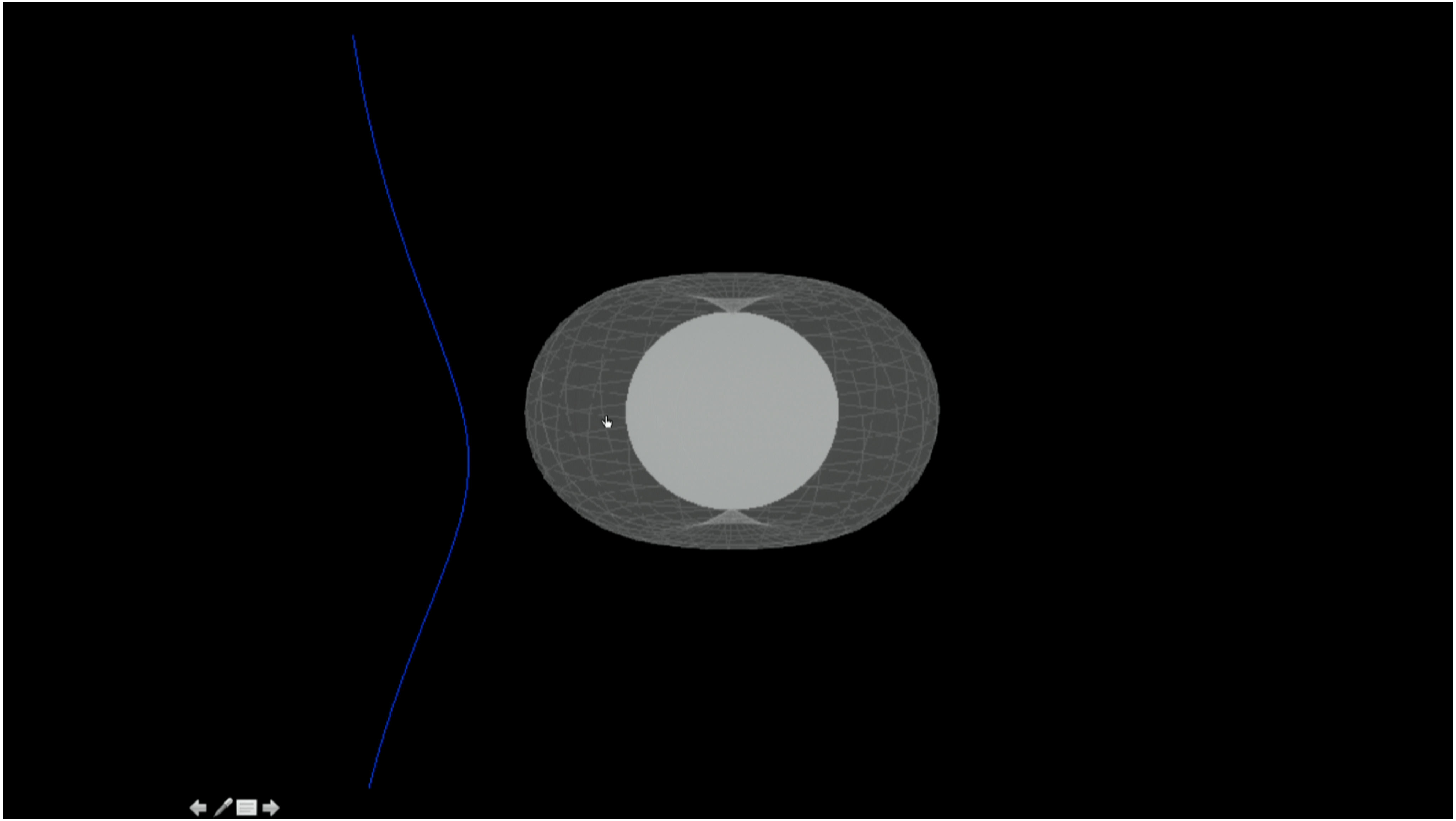
# Energy from a Spinning Black Hole

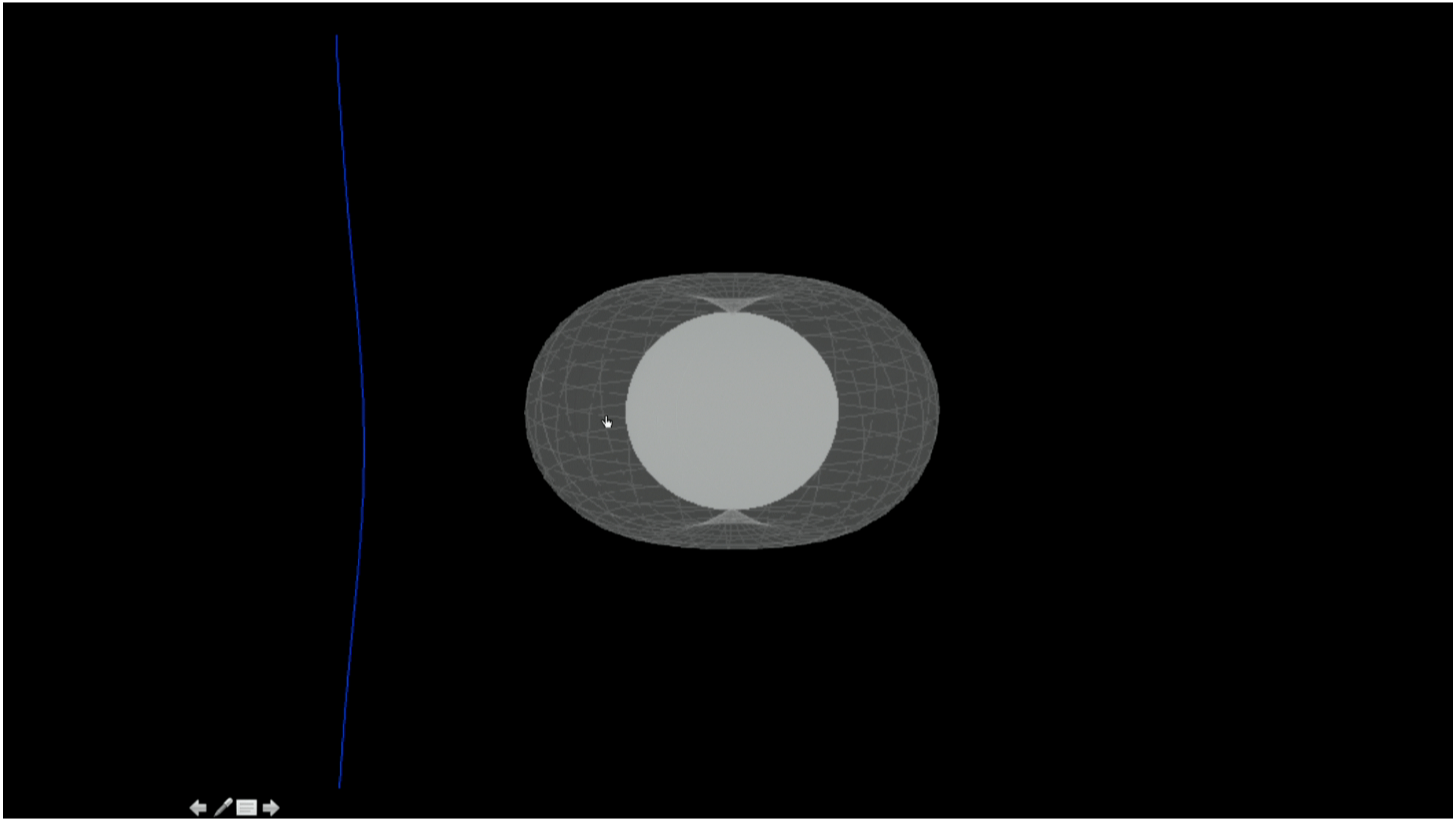
- A spinning BH has free energy that can in principle be extracted (Penrose 1969)
- The BH is like a flywheel
- This might explain relativistic jets
- But how does Nature "grip" the BH and access the rotational energy?!
- Most likely through magnetic fields via the mechanism of frame-dragging

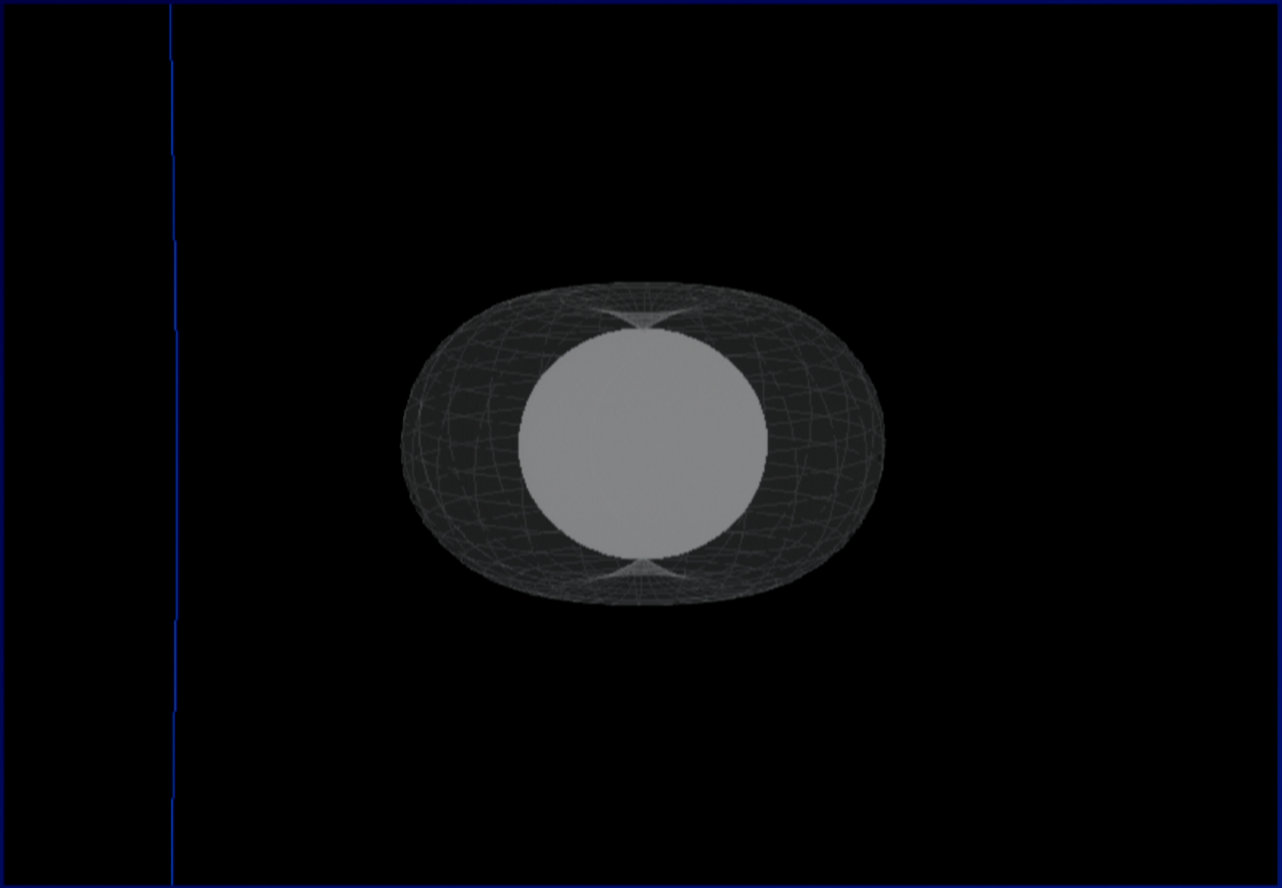


Semenov et al. (2004)





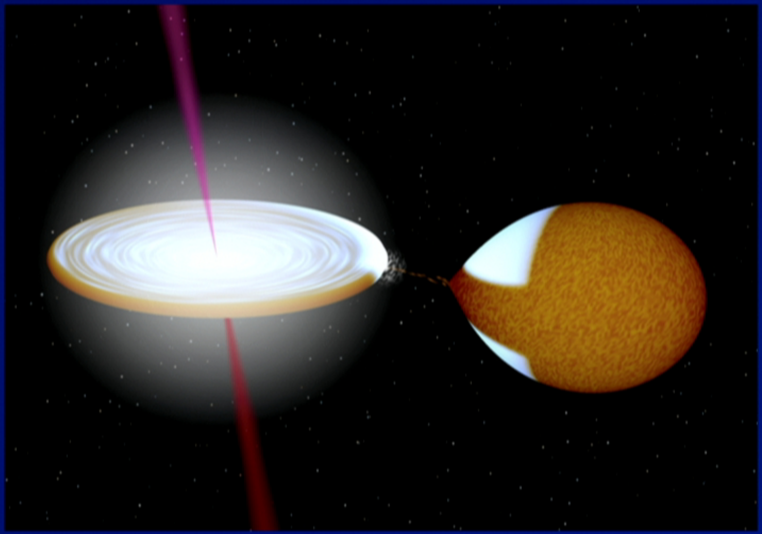




Semenov et al. (2004)

# Mass is Easy, Spin is Hard

- **Mass** can be measured in the Newtonian limit using test particles (e.g., stellar companion) at large radii
- **Spin** has no Newtonian effect
- To measure spin we must be in the regime of strong gravity, where General Relativity operates
- Need test particles at small radii
- Fortunately, we have the gas in the accretion disk…

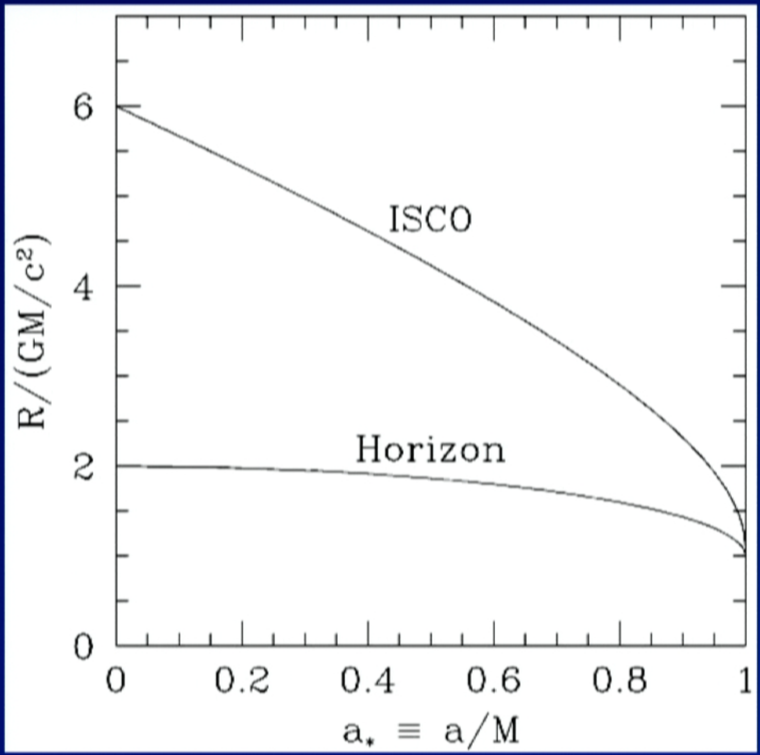


# Circular Orbits

- 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 $R \geqslant 6M$
- $R=6M$ is the innermost stable circular orbit, or **ISCO**, of a non-spinning BH
- For spinning BHs $R_{ISCO}$ is smaller

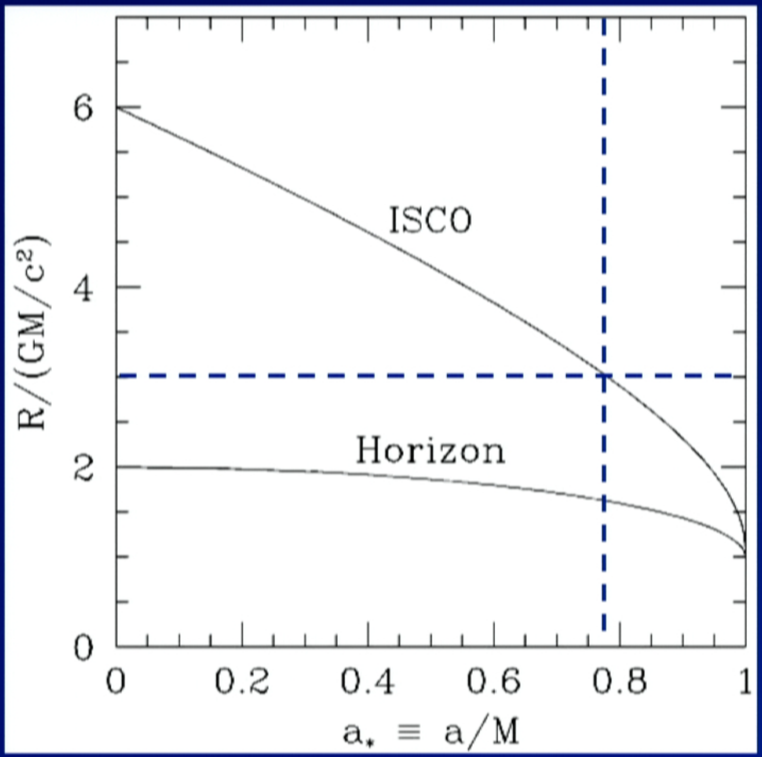
# Innermost Stable Circular Orbit (ISCO)

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

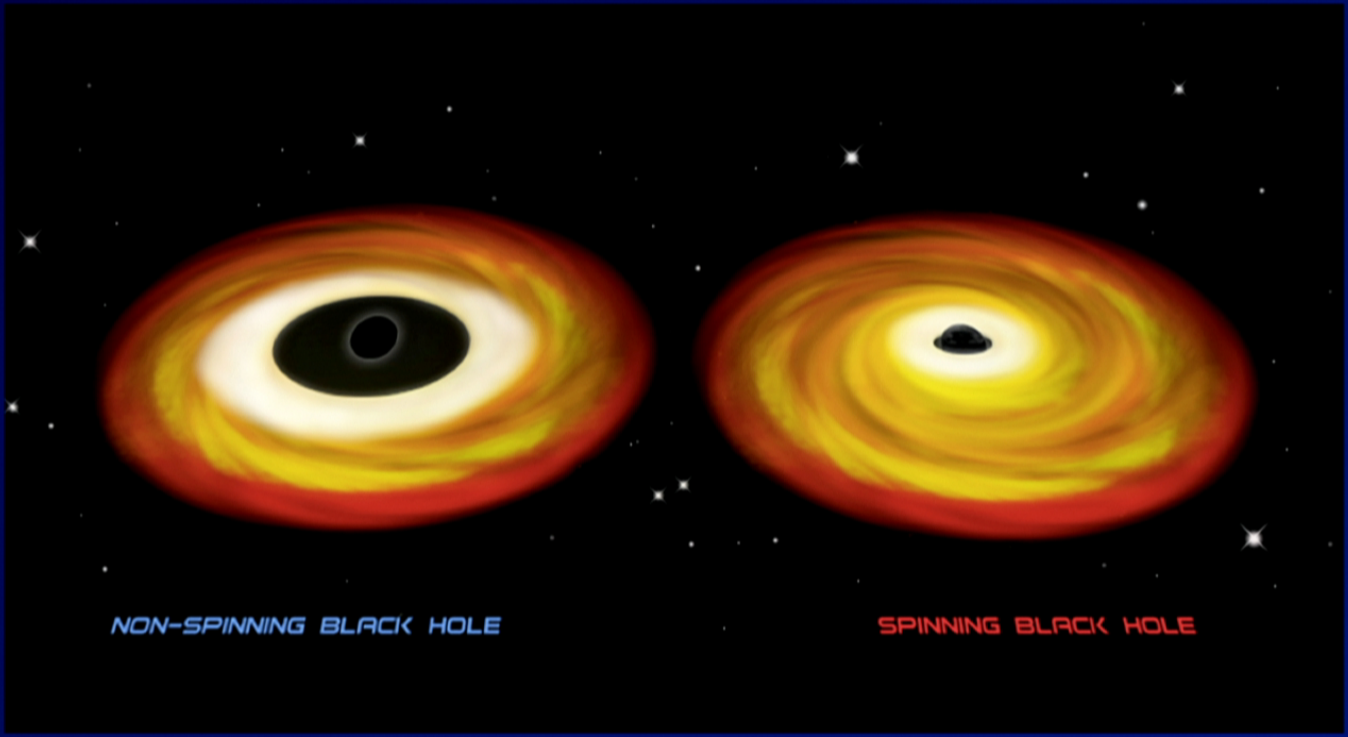


# Innermost Stable Circular Orbit (ISCO)

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



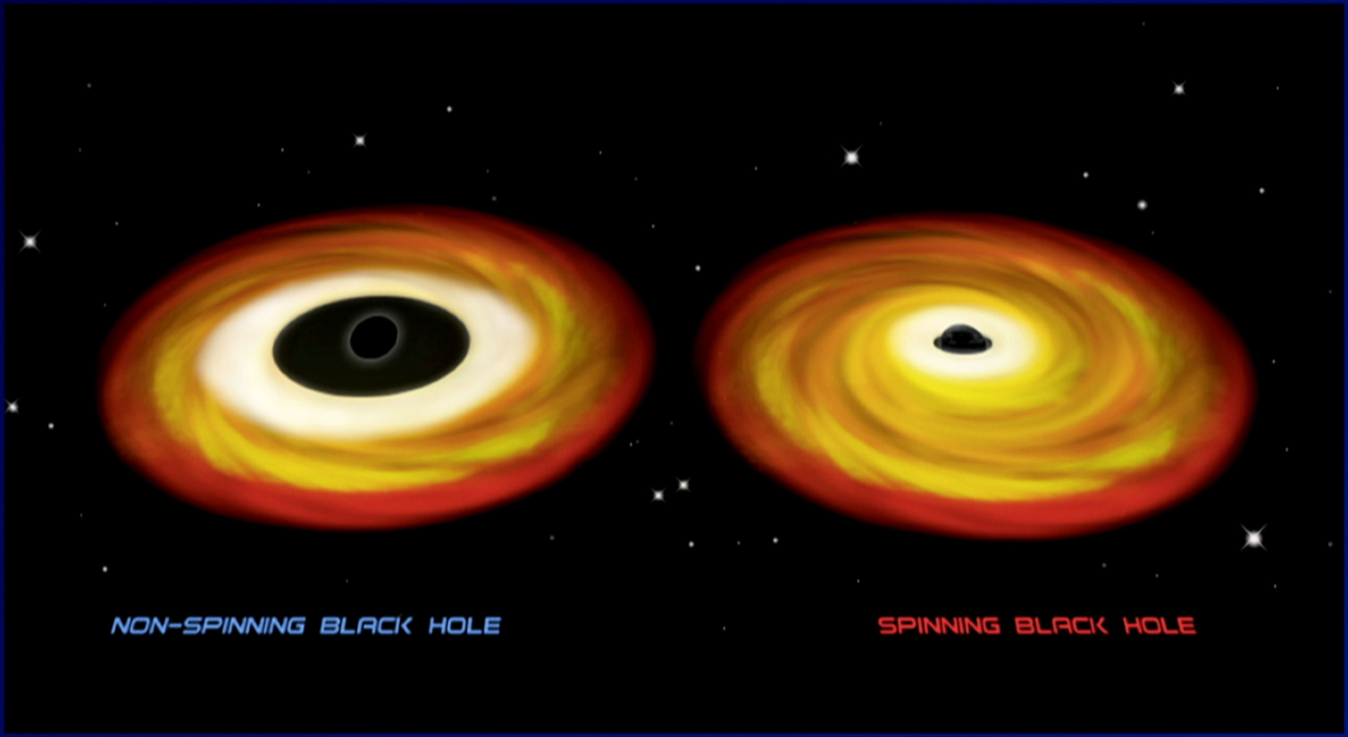
# The Basic Idea




Accretion disk will have a dark hole inside the ISCO

Measure radius of hole via observations ➔ $a_*$

# The Basic Idea




Accretion disk will have a dark hole inside the ISCO

Measure radius of hole via observations → $a_*$

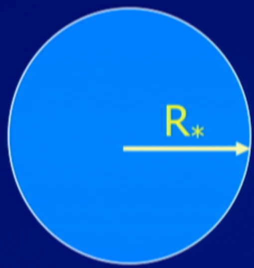
# Measuring the Radius of a Star

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

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

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

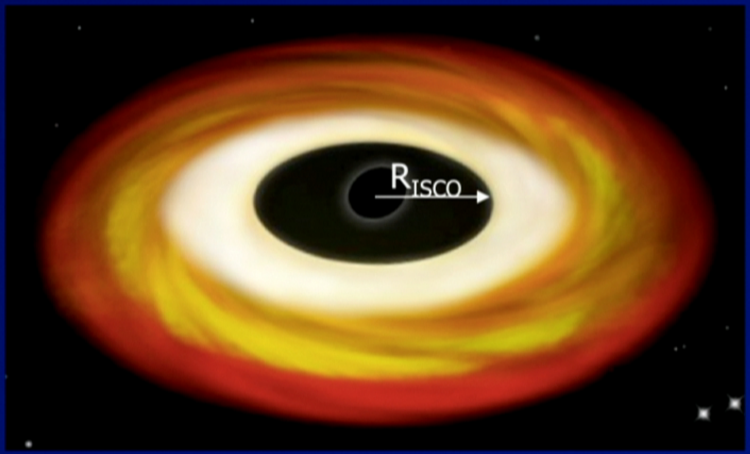
$$R_* = D\sqrt{\frac{\Delta\Omega}{\pi}} = 37.5\,\frac{L_*^{1/2}}{T_*^2} \quad (\text{cgs})$$




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



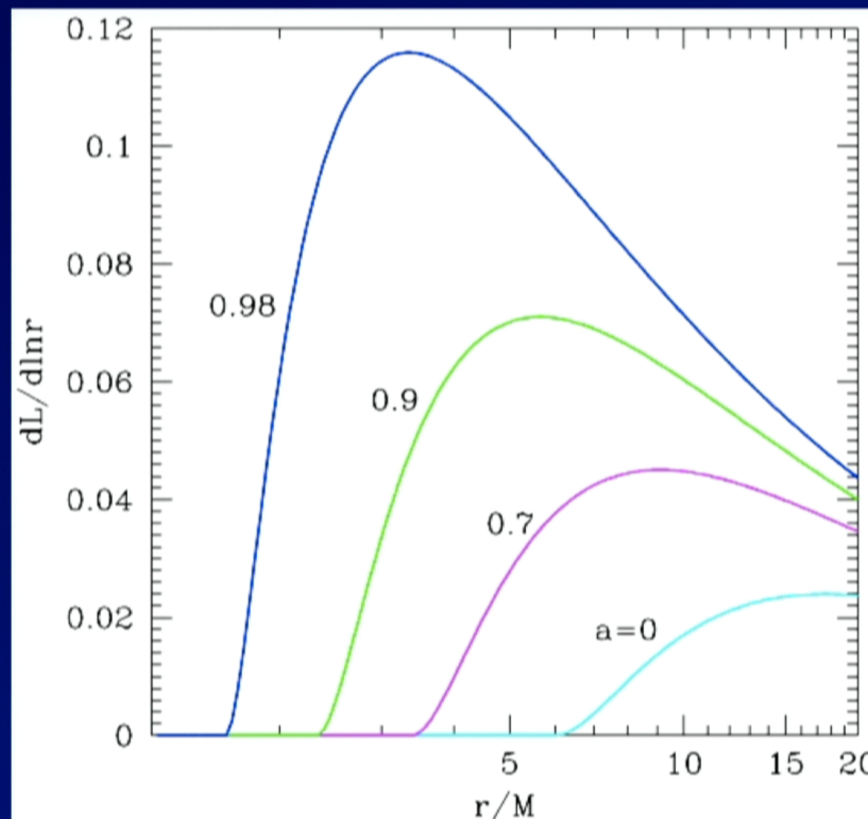

Zhang et al. (1997); Li et al. (2005); Shafee et al. (2006); McClintock et al. (2006); Davis et al. (2006); Liu et al. (2007); Gou et al. (2009,2010); Steiner et al. (2010,2011); ...

# General Relativistic Disk Model: Novikov & Thorne (1973)

L(r) peaks at a progressively smaller radius as the dimensionless BH spin parameter $a_*$ increases

For a given $L_{tot}$, the spectrum is hotter for larger $a_*$

Thus, luminosity plus spectrum ➔ $a_*$

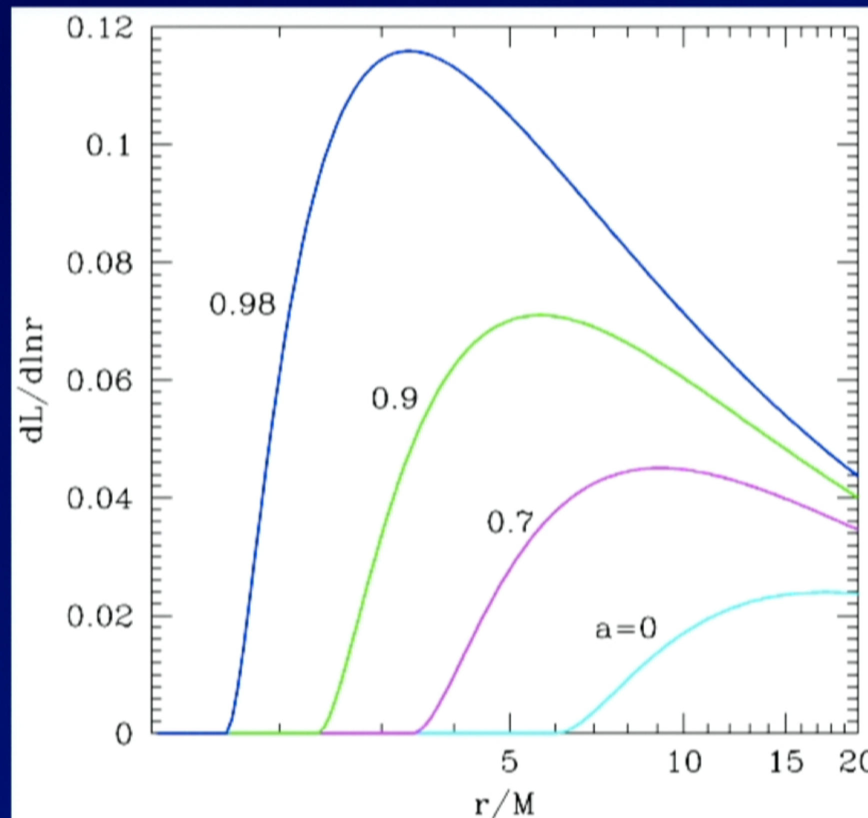


# General Relativistic Disk Model: Novikov & Thorne (1973)

L(r) peaks at a progressively smaller radius as the dimensionless BH spin parameter $a_*$ increases

For a given $L_{tot}$, the spectrum is hotter for larger $a_*$

Thus, luminosity plus spectrum → $a_*$

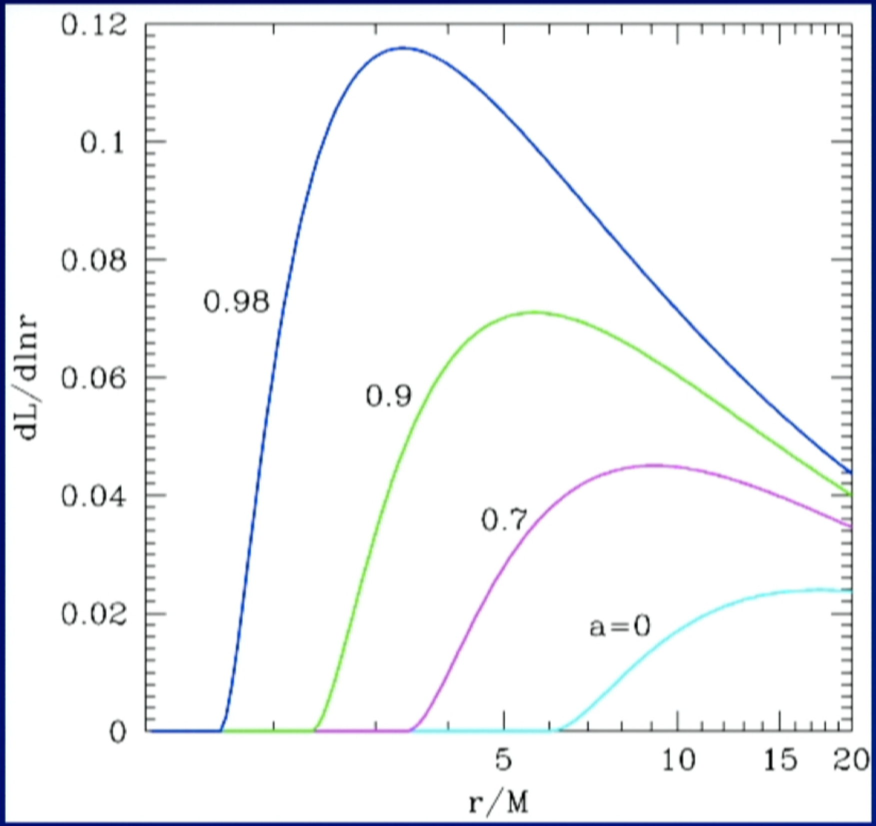


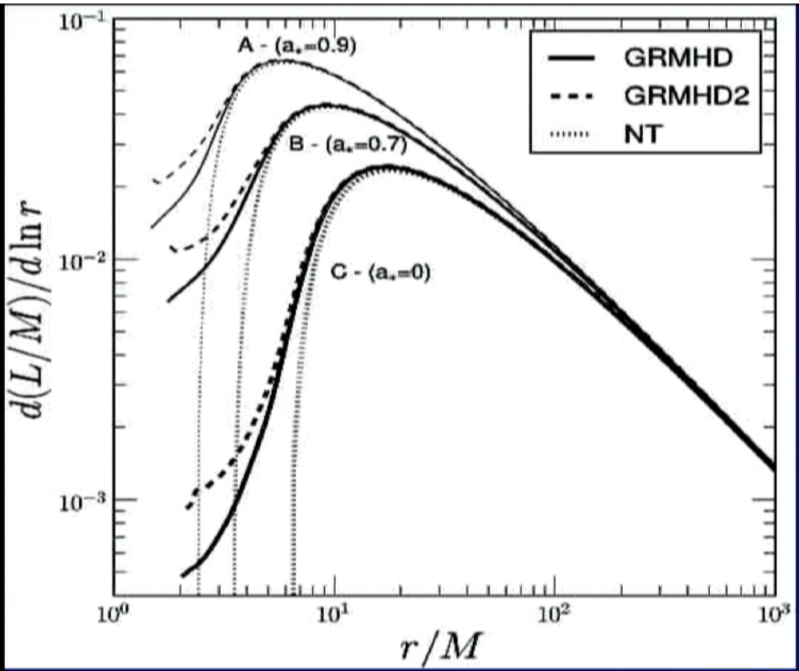
# General Relativistic Disk Model: Novikov & Thorne (1973)

L(r) peaks at a progressively smaller radius as the dimensionless BH spin parameter $a_*$ increases

For a given $L_{tot}$, the spectrum is hotter for larger $a_*$

Thus, luminosity plus spectrum → $a_*$






# How Good is the NT Model?

Check using GRMHD simulations of thin accretion disks

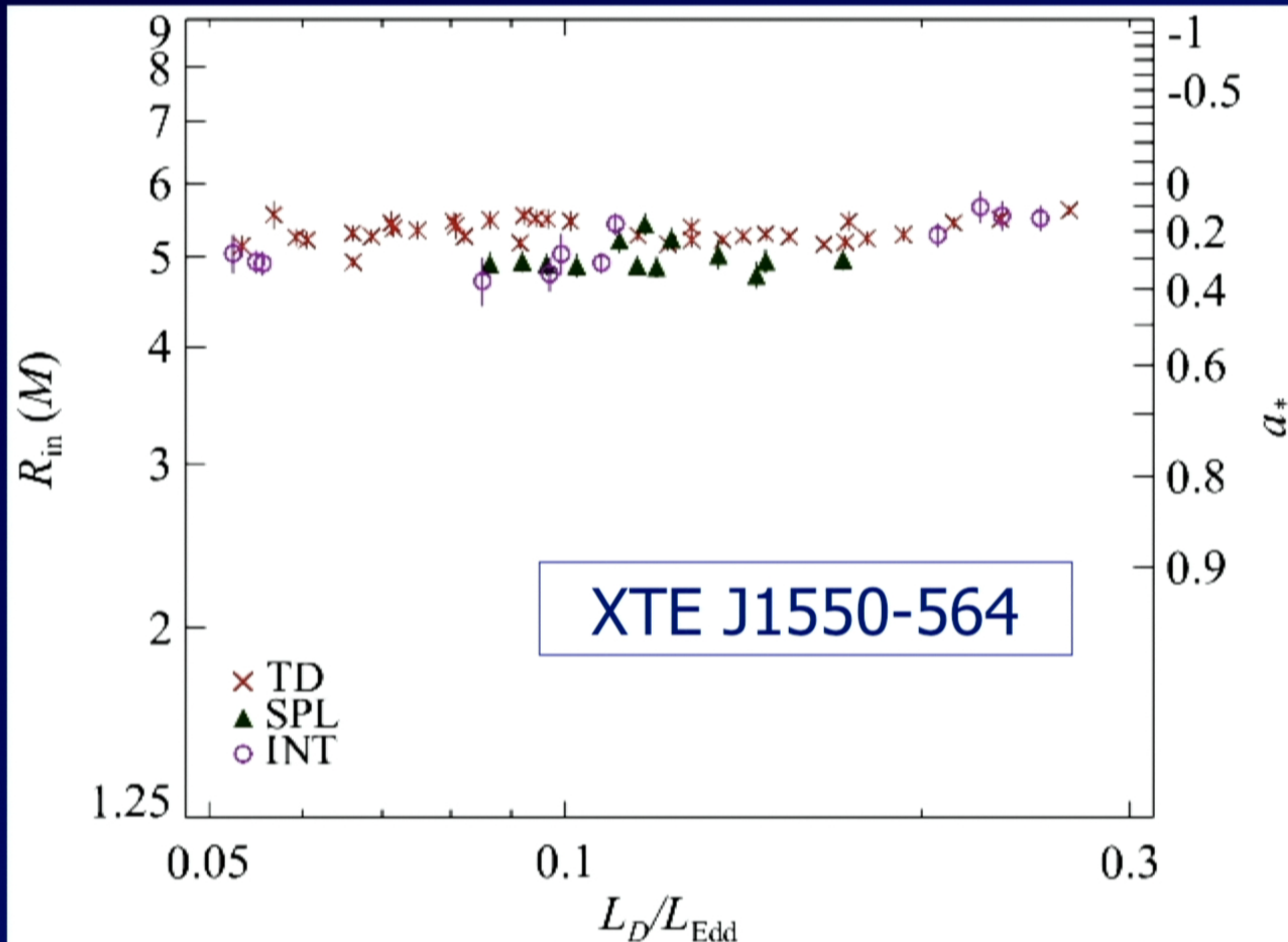
Luminosity profile agrees: GRMHD simulation vs NT model

There is some emission in the plunging region, but not a lot

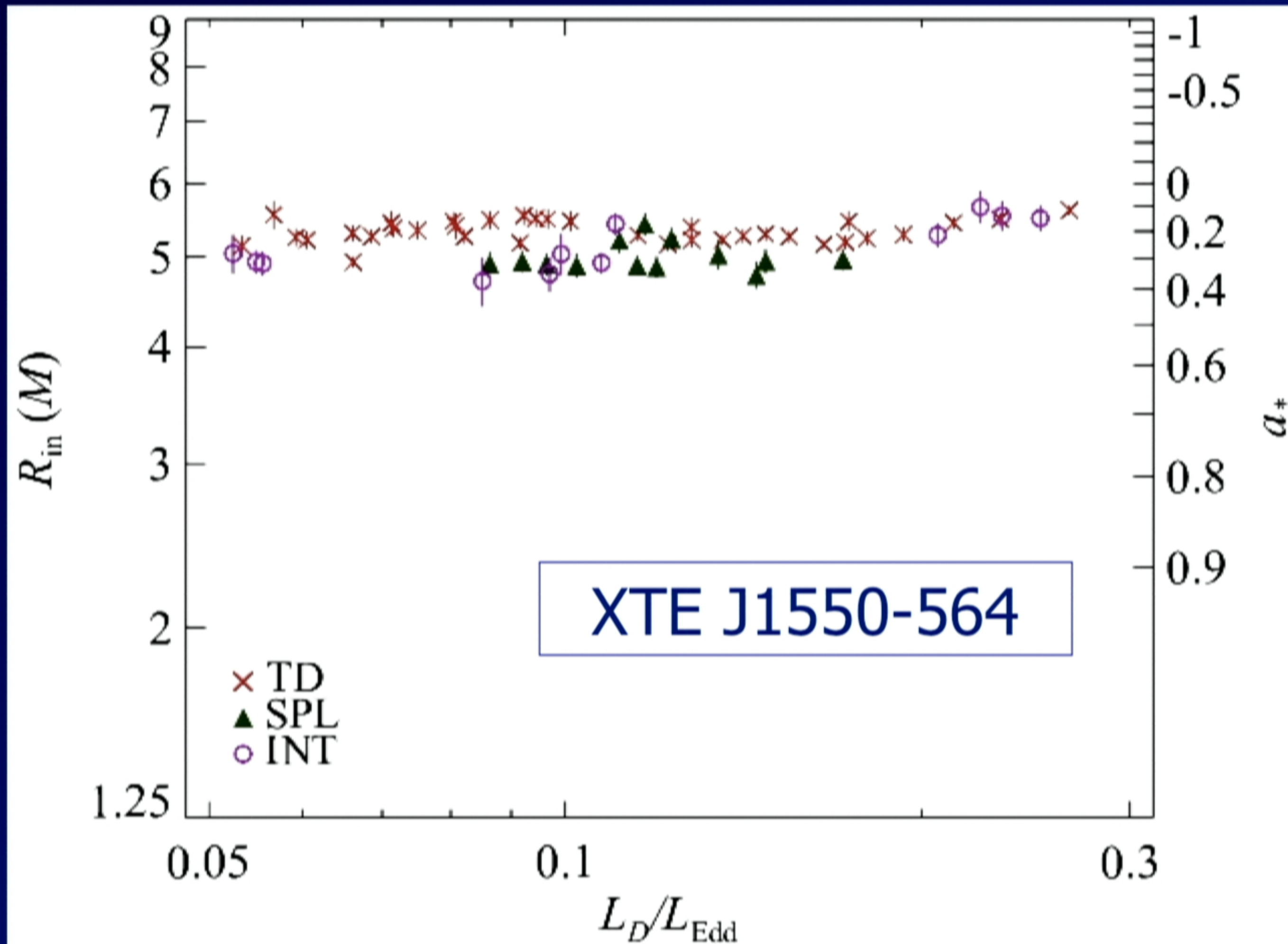
Penna et al. (2010); Kulkarni et al. (2011); Zhu et al. (2012)

# How Well Does It Work in Practice?

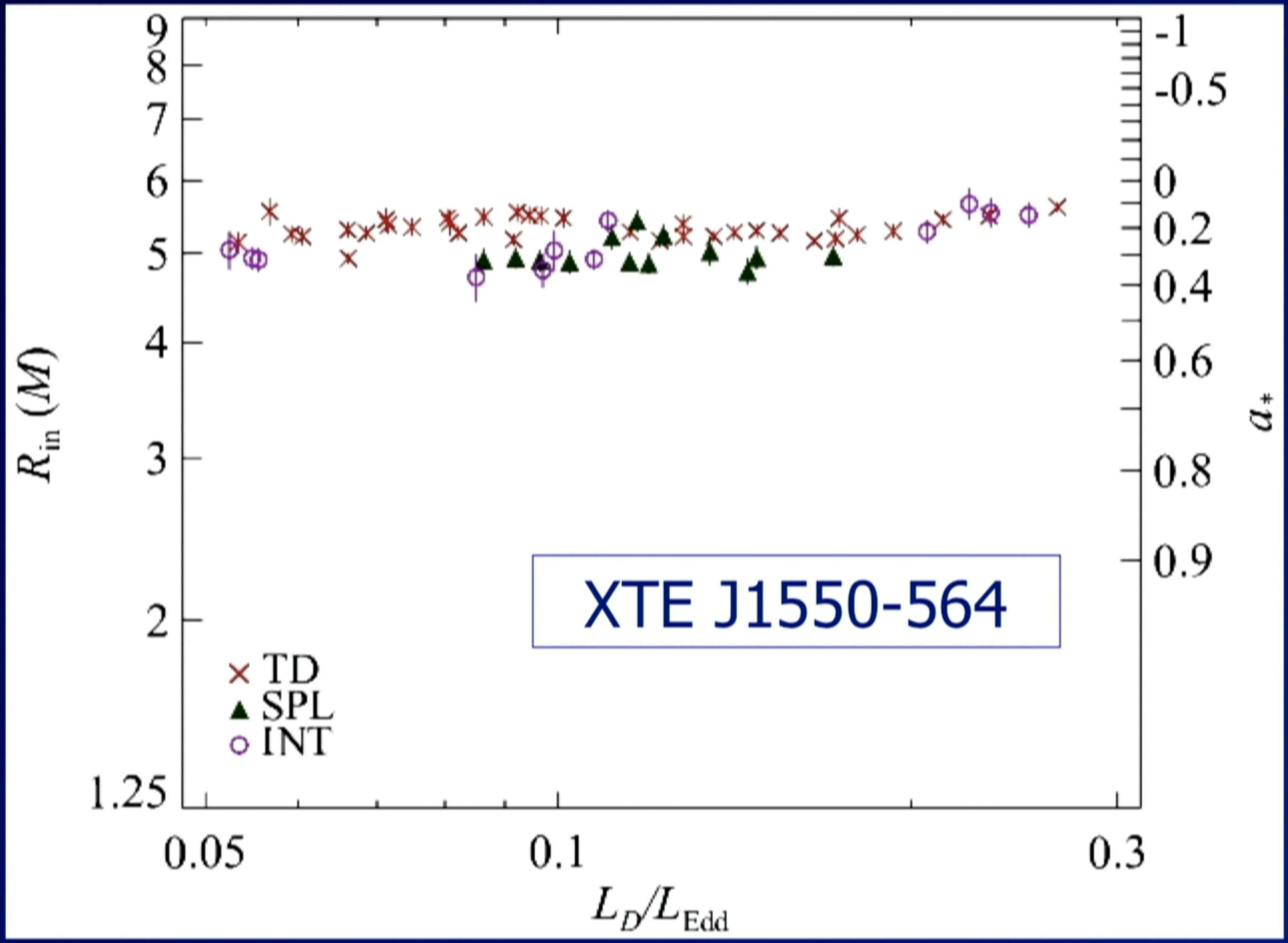
- We have observed the same object at different times and different luminosities, using different instruments
- Obtain consistent estimates of $R_{ISCO}$ and $a_*$
- Strong suggestion that the continuum-fitting method is robust




Estimates of disk inner edge $R_{in}$ and BH spin parameter $a_*$ from **35** TD (superb) and **25** SPL/Intermediate (so-so) data (**Steiner et al. 2010**)




Estimates of disk inner edge $R_{in}$ and BH spin parameter $a_*$ from **35** TD (superb) and **25** SPL/Intermediate (so-so) data (**Steiner et al. 2010**)




Estimates of disk inner edge $R_{in}$ and BH spin parameter $a_*$ from **35** TD (superb) and **25** SPL/Intermediate (so-so) data (**Steiner et al. 2010**)

# BH Spin Measurements via Continuum-Fitting

| Source Name | BH Mass ($M_\odot$) | BH Spin ($a_*$) |
|---|---|---|
| A0620-00 | 6.3—6.9 | 0.12 ± 0.19 |
| LMC X-3 | 5.9—9.2 | ~0.25 |
| XTE J1550-564 | 8.5—9.7 | 0.34±0.24 |
| GRO J1655-40 | 6.0—6.6 | 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 | 9.4—12.4 | 0.92 ± 0.06 |
| Cyg X-1 | 14.0—16.9 | > 0.92 |
| GRS 1915+105 | 10—18 | > 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); Steiner et al. (2010)

# BH Spin Measurements via Continuum-Fitting

| Source Name | BH Mass ($M_\odot$) | BH Spin ($a_*$) |
|---|---|---|
| A0620-00 | 6.3—6.9 | 0.12 ± 0.19 |
| LMC X-3 | 5.9—9.2 | ~0.25 |
| XTE J1550-564 | 8.5—9.7 | 0.34±0.24 |
| GRO J1655-40 | 6.0—6.6 | 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 | 9.4—12.4 | 0.92 ± 0.06 |
| Cyg X-1 | 14.0—16.9 | > 0.92 |
| GRS 1915+105 | 10—18 | > 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); Steiner et al. (2010)

# BH Spin and Jets

- Now that we finally have measurements of BH spin, is there any indication that Jets are powered by BH rotation?
- **YES!!** We now have the first evidence!

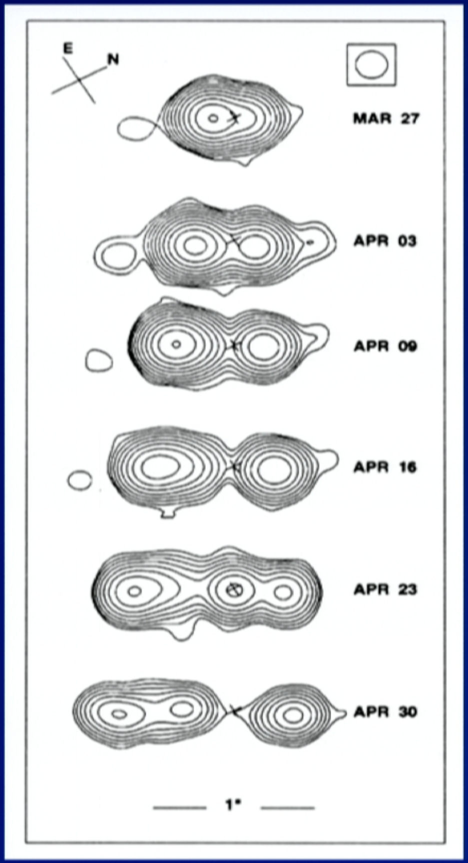
# Micro-Quasar
# GRS 1915+105

GRS 1915+105 has spectacular relativistic jets

Blobs of material are seen to flow out relativistically with

v = 0.92c  or $\Upsilon$=2.6

Mirabel & Rodriguez (1994)



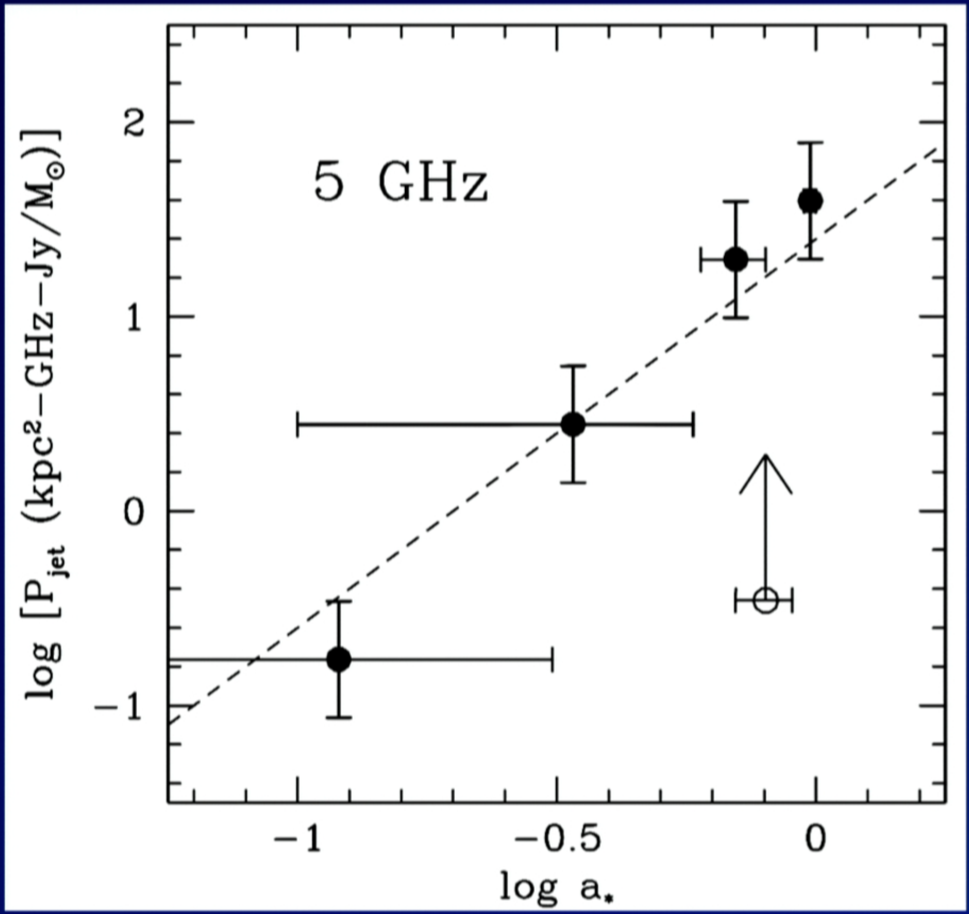
# Proxy for Jet Power

- Take observed radio flux $\nu S_\nu$ at a standard frequency: $\nu$ =5 GHz
- Multiply by square of distance: $D^2$
- Divide by BH mass M

$$P_{\rm jet} = \left(\nu S_\nu\right)_{5GHz} D^2 / M$$

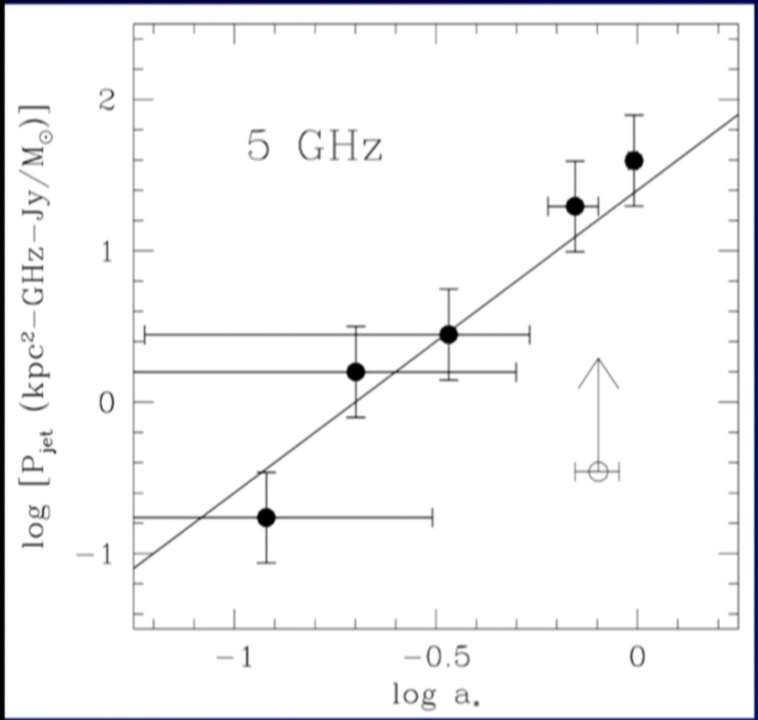
- This is our proxy for jet power
- Based entirely on observational data

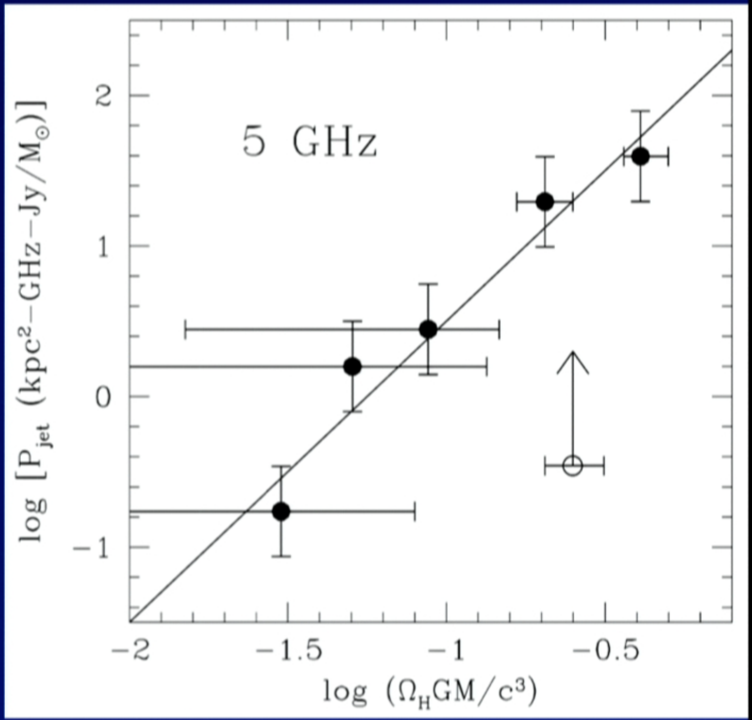
# A Very Suggestive Correlation



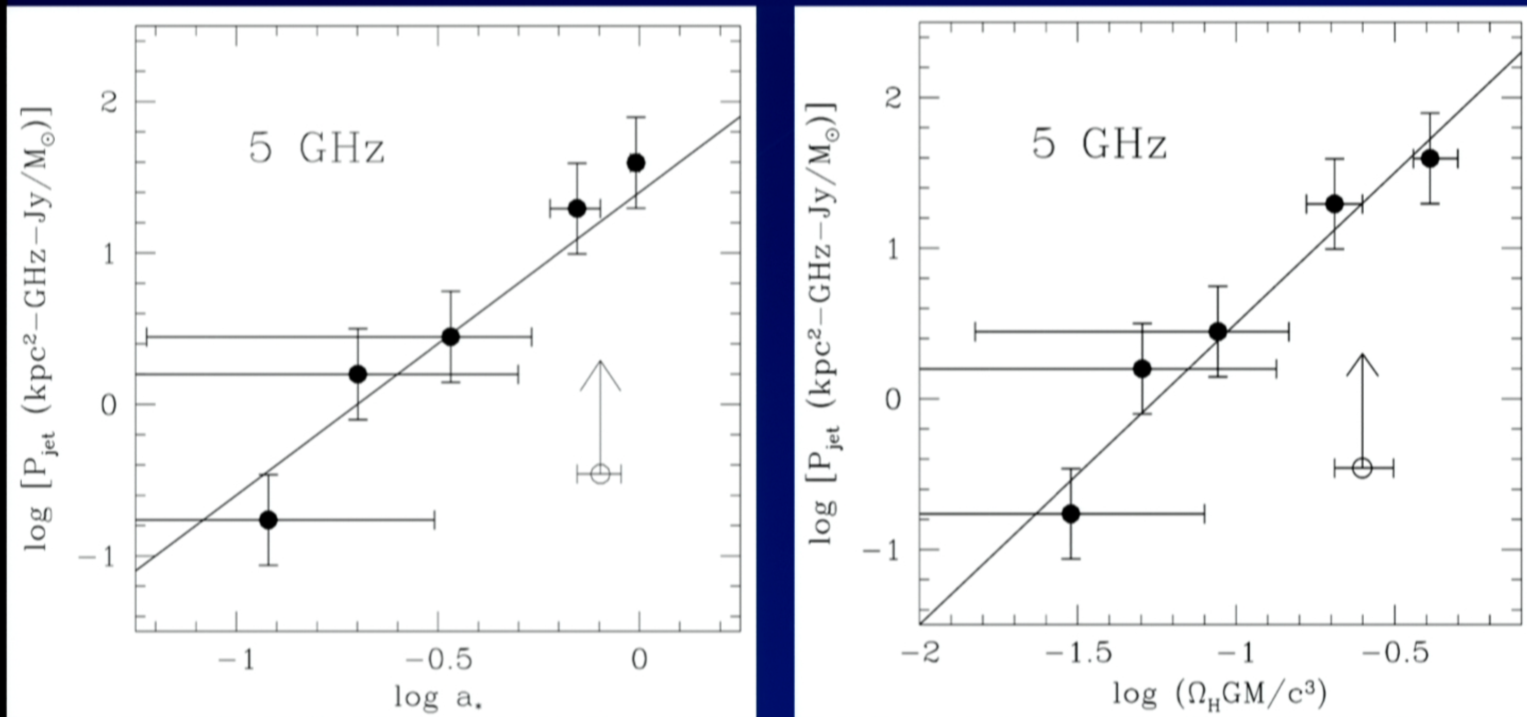

Four transient BH XRBs have both ballistic jet ejections and spin estimates

Narayan & McClintock (2012)

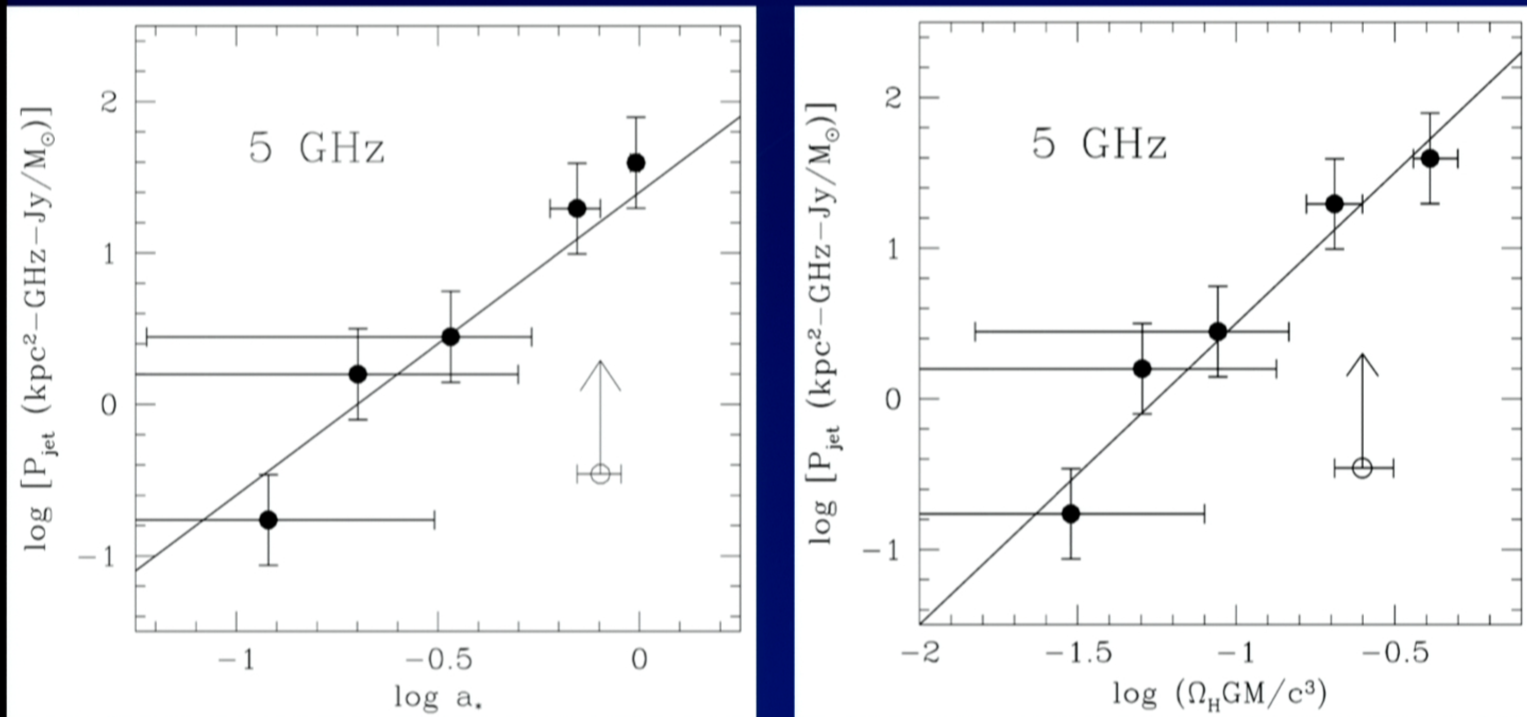


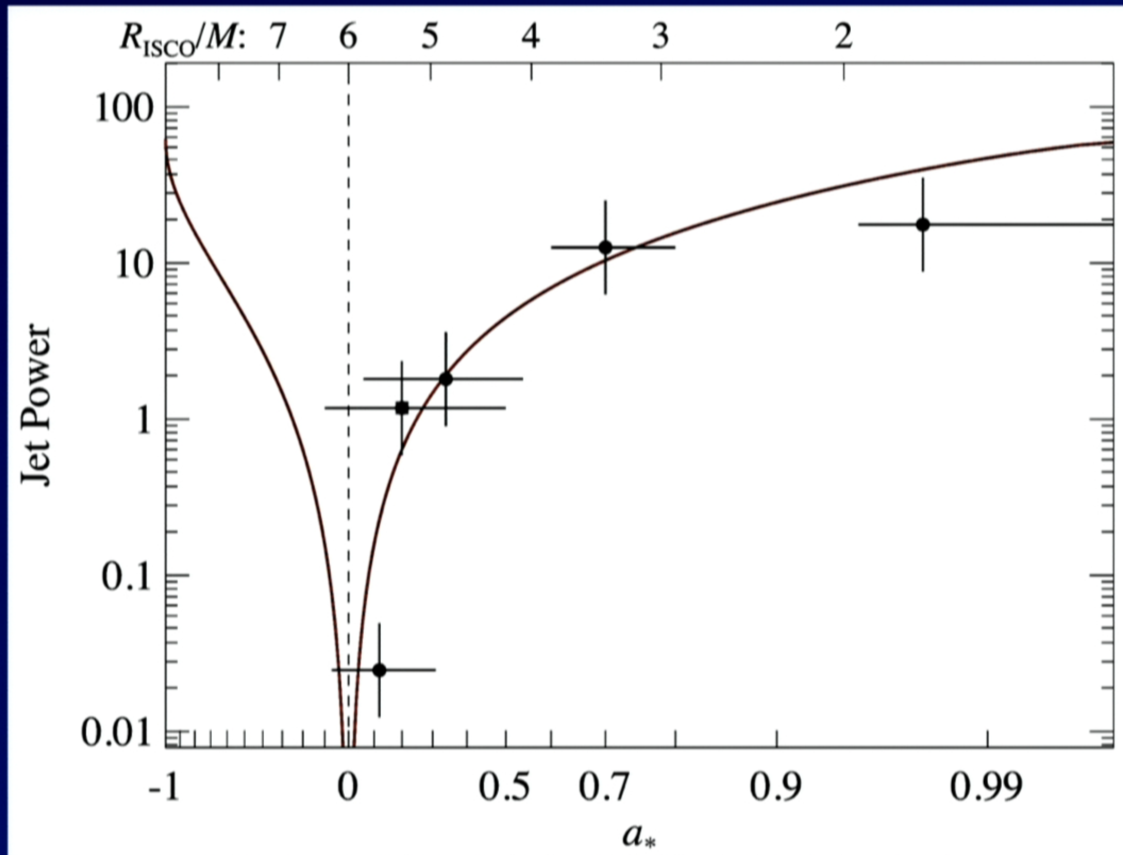

We now have a fifth object with both a ballistic jet and a spin estimate: H1743-322 (Steiner & McClintock 2012)
Fits within the previous correlation perfectly!!
Now our correlation consists of **FIVE objects**!!




We now have a fifth object with both a ballistic jet and a spin estimate: H1743-322 (Steiner & McClintock 2012)
Fits within the previous correlation perfectly!!
Now our correlation consists of **FIVE objects**!!




We now have a fifth object with both a ballistic jet and a spin estimate: H1743-322 (Steiner & McClintock 2012)
Fits within the previous correlation perfectly!!
Now our correlation consists of **FIVE objects**!!




Another representation of the same data (Steiner et al. 2012)

Since the primary observable is $R_{ISCO}$, we show Jet Power vs $\log(R_{ISCO})$

# What Does It Mean?

- One could think of many reasons why the correlation may be absent or washed out:
  - Jet power may not be correlated with BH spin
  - Radio power not correlated with jet power
  - BH spin measurements could be wrong
- **Despite all these possibilities, we see a strong correlation!!**
- Presumably none of the possibilities listed in the blue bullets is true

# Are Astrophysical BH Candidates Really BHs?

- True they are compact and massive
- But do they have Event Horizons?
- Can we test this via observations?
- Surprisingly, the answer is **YES!!**
- Multiple tests have been devised, and all evidence points to the reality of Black Holes and Event Horizons

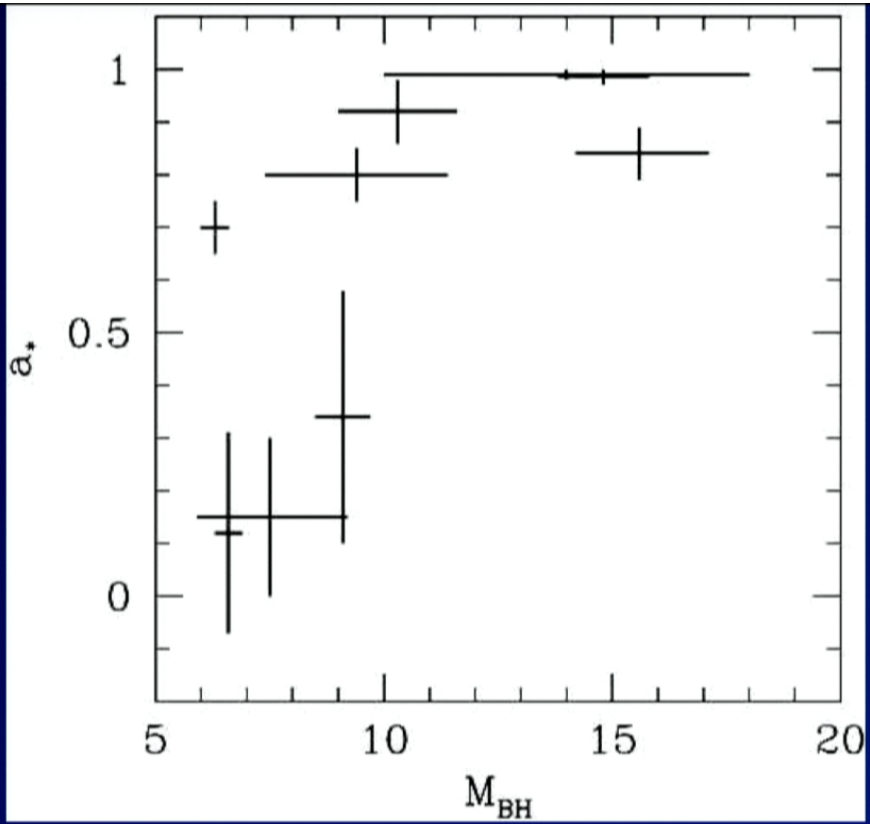
# Summary

- Many astrophysical BHs have been discovered during the last ~20 years
- There are two distinct populations:
  - X-ray binaries: 5—20 $M_\odot$ ($\gtrsim 10^7$ per galaxy)
  - Galactic nuclei: $10^{6-10}$ $M_\odot$ (1 per galaxy)
- BH spin estimates are now available
  - Evidence that Jets derive power from BH Spin
- Next frontier: The No-Hair Theorem

# BH Spin Measurements via Continuum-Fitting

| Source Name | BH Mass ($M_\odot$) | BH Spin ($a_*$) |
|---|---|---|
| A0620-00 | 6.3—6.9 | 0.12 ± 0.19 |
| LMC X-3 | 5.9—9.2 | ~0.25 |
| XTE J1550-564 | 8.5—9.7 | 0.34±0.24 |
| GRO J1655-40 | 6.0—6.6 | 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 | 9.4—12.4 | 0.92 ± 0.06 |
| Cyg X-1 | 14.0—16.9 | > 0.92 |
| GRS 1915+105 | 10—18 | > 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); Steiner et al. (2010)


1
0.5
0
a*
5
10
15
20
M_BH