Les Trous Noirs Astrophysiques

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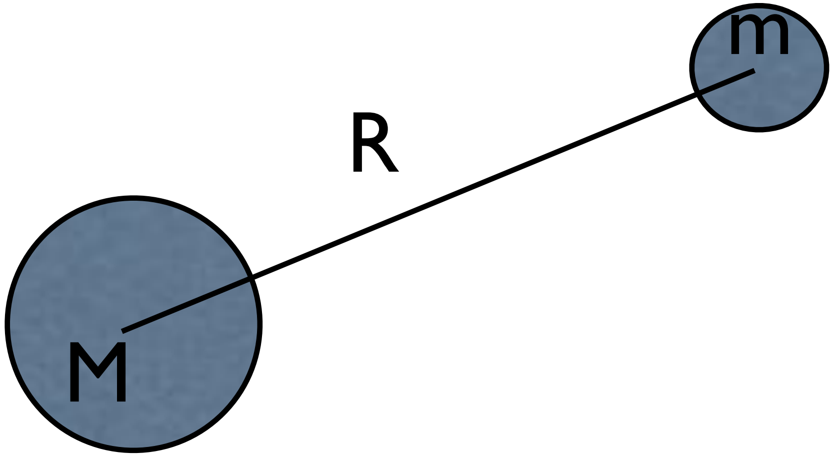
Outline

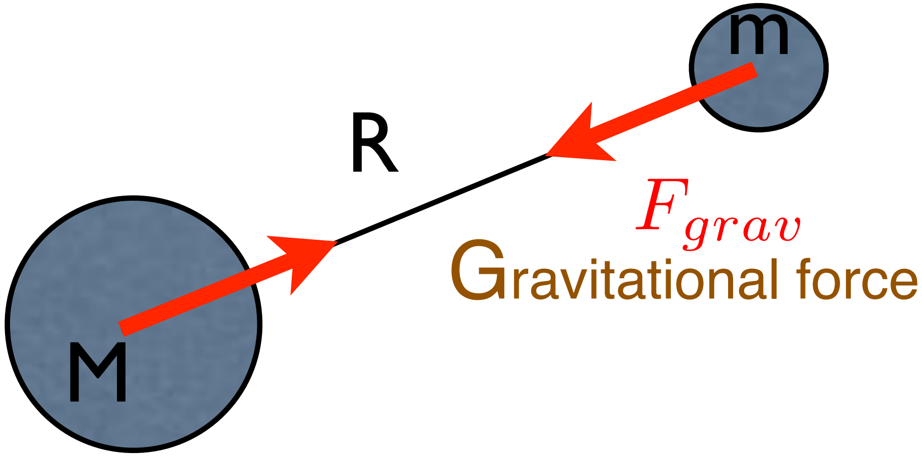
- Black holes: generalities
- The different types of astrophysical black holes
- Black hole environments (accretion disk, corona, jets,…)
- A promising future

Black Holes
Generalities

Newton and the Gravitation Law



Newton and the Gravitation Law



$$F_{grav} = m\,\mathcal{G}\,\frac{M}{R^2}$$

(gravitational) Constant

avec $g = \mathcal{G}\,\frac{M}{R^2}$

gravitational acceleration

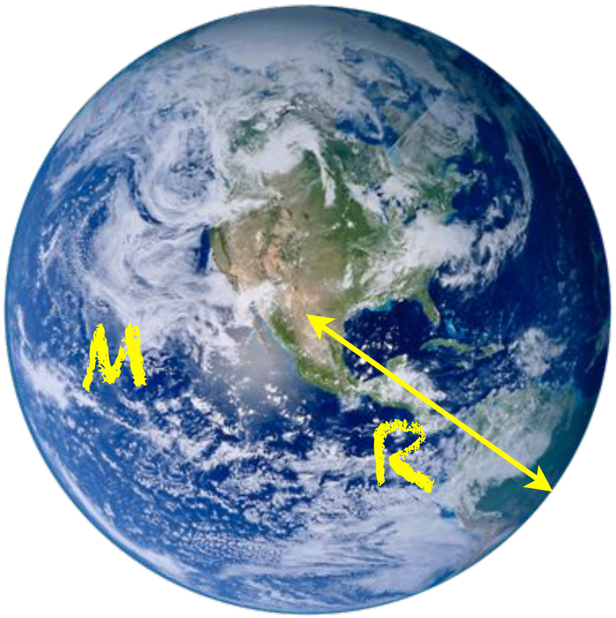
$$\mathcal{G} = 6.67384 \times 10^{-11} m^3.kg^{-1}.s^{-2}$$

On Earth g≈10 $m.s^{-2}$

Escape Velocity

The escape velocity can be computed from the Newton theory:

$$v_{esc} = \sqrt{2\mathcal{G}}\sqrt{\frac{M}{R}}$$



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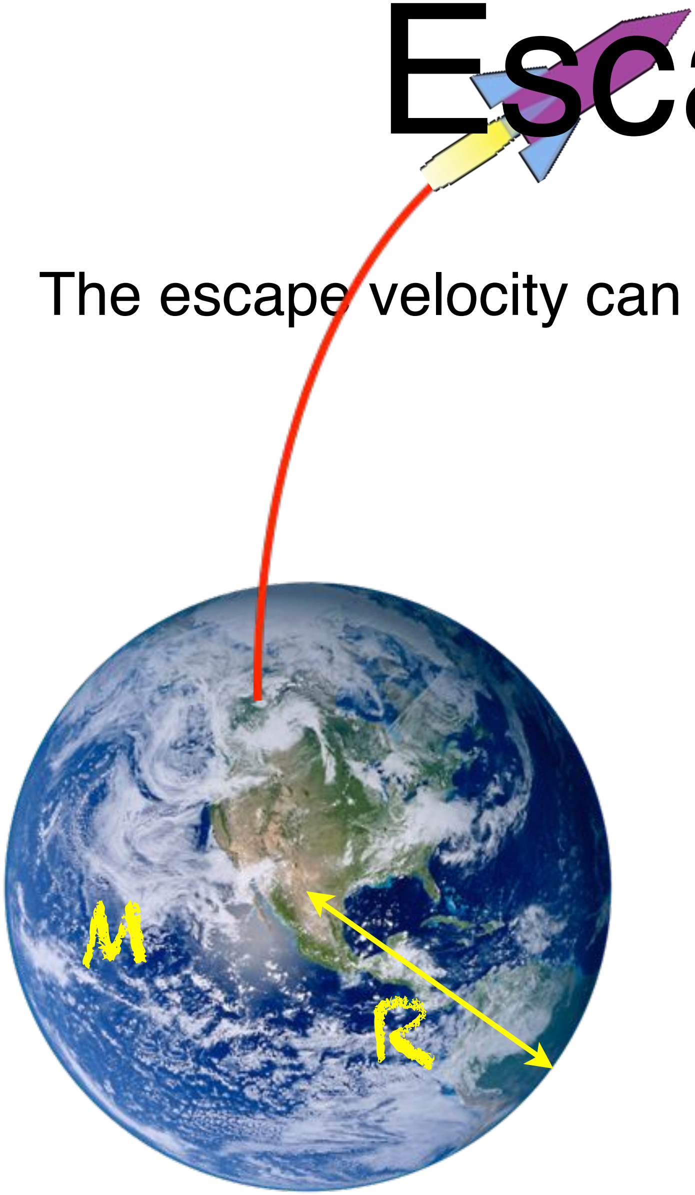

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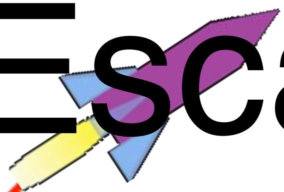

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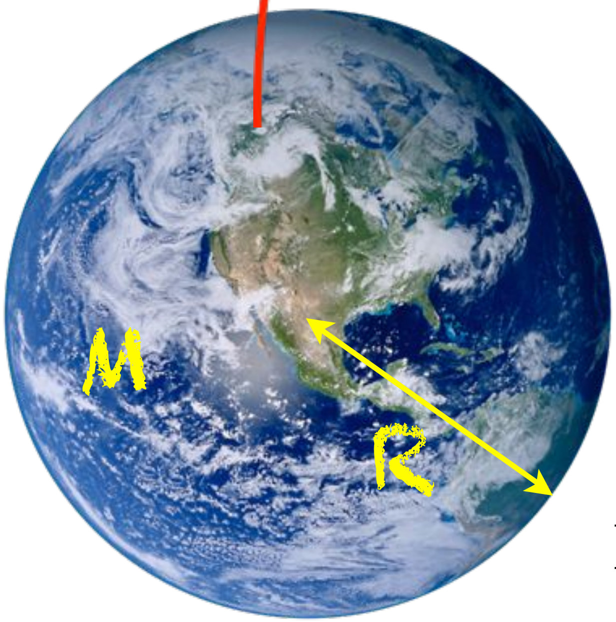

Numerical application

- for the Earth:

M_{earth}=6 10^{24} kg, R_{earth}= 6400 km $\Rightarrow$ **v_{esc} = 11 km/s**

- for the sun:

M_{sun}=2 10^{30} kg, R_{sun}= 700 000 km $\Rightarrow$ **v_{esc} = 615 km/s**

Black Hole Concept

An astrophysical object of mass M has a escape velocity $v_{esc}=c$ if its radius R is smaller than

$$v_{esc} = \sqrt{2\mathcal{G}}\sqrt{\frac{M}{R}}$$

$$\rightarrow \quad R < R_{lim} = \frac{2\mathcal{G}}{c^2}M = 2R_g$$

R_{lim}=Schwarzschild radius

R_g=gravitationnal radius

(same limit found from GR equations)

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(same limit found from GR equations)

Then even light cannot escape !

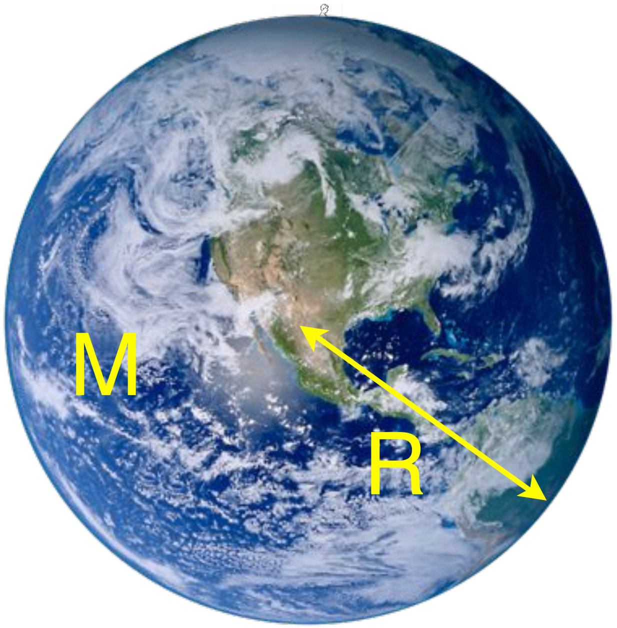
Numerical application

➡ for the Earth, R_{lim} = 9 mm

➡ for the Sun, R_{lim} = 3 km

Gravitation

A huge source of energy



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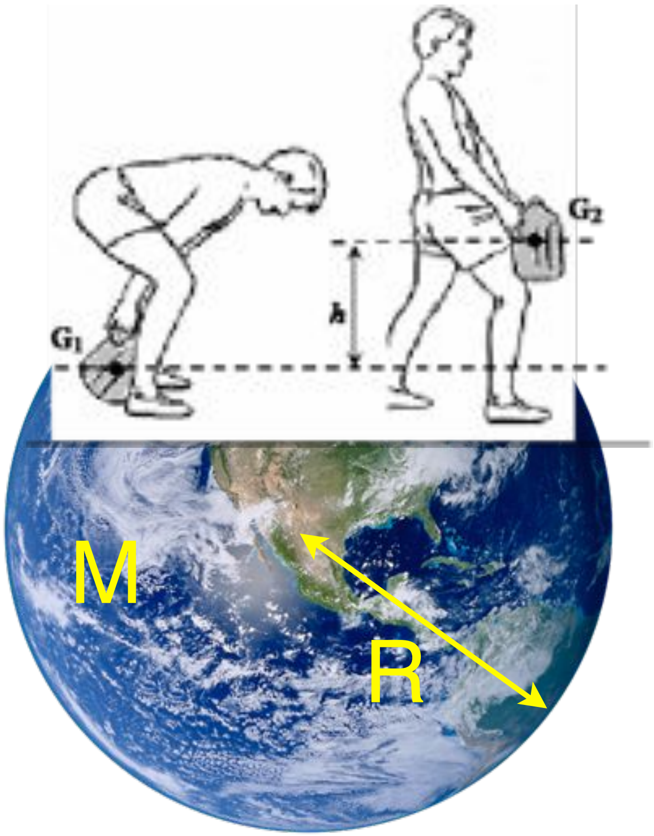
To lift a masse m at a height h above a celestial body of radius R and mass M, we need to provide:



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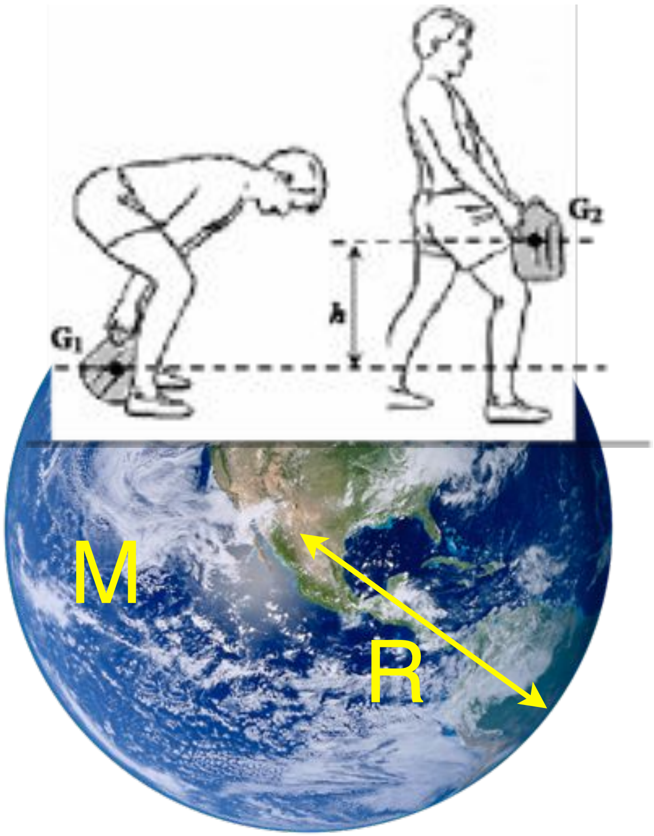
$$E_{grav} = F_{grav}h \quad = \frac{R_{lim}}{2R}\frac{h}{R}mc^2$$



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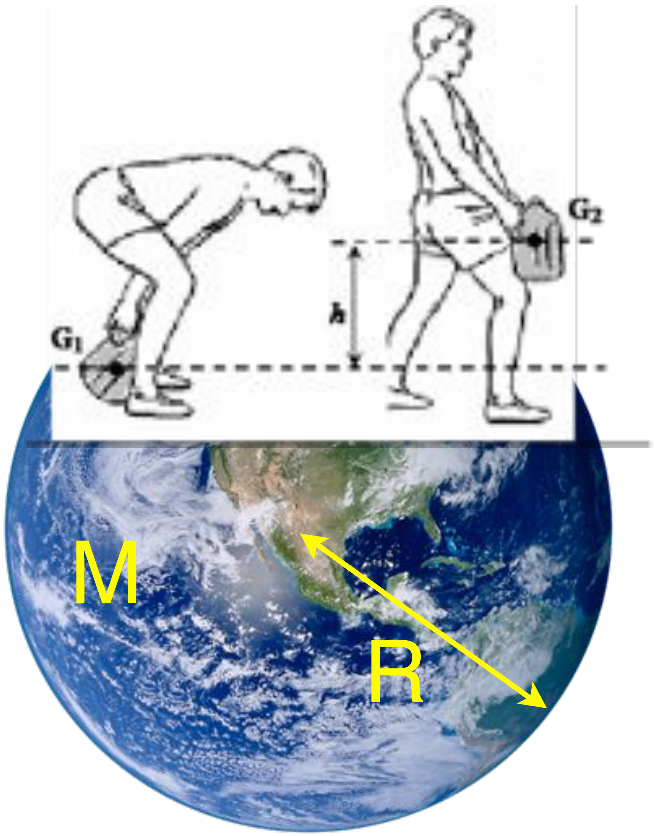

Numerical applications: m=1kg, h=1m

- E_{grav} = 10 Joules on Earth
- E_{grav} = 300 Joules on the Sun

For a black hole $R=R_{lim}$:

- $E_{grav} = 10^{12}$ Joules on a black hole of 10 M_{sun}

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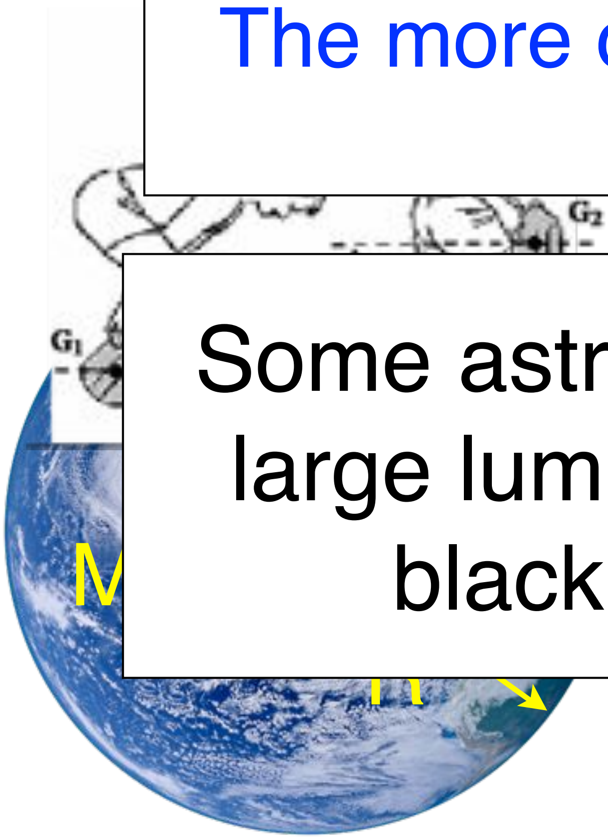


The more compact the object ($R \rightarrow R_{lim}$) the larger E_{grav}!

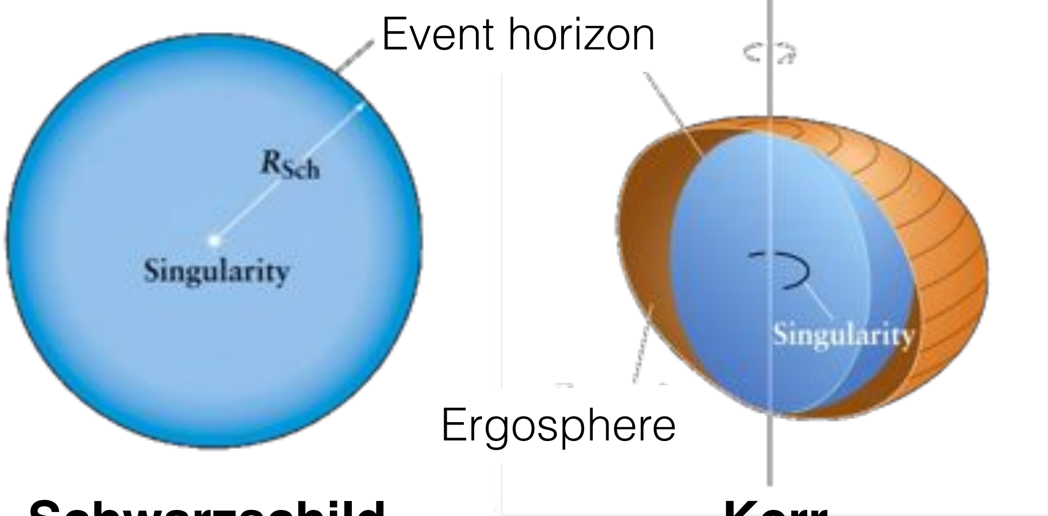
Some astrophysical objects radiate a so large luminosity that the presence of a black hole appears very likely!

- $E_{grav} = 10^{12}$ Joules on a black hole of 10 M_{sun}

Rotating Black Hole

A rotating BH is smaller than a non rotating one…

Non rotating | **Rotating**



Schwarzschild

$R_{EH}=R_{lim}$

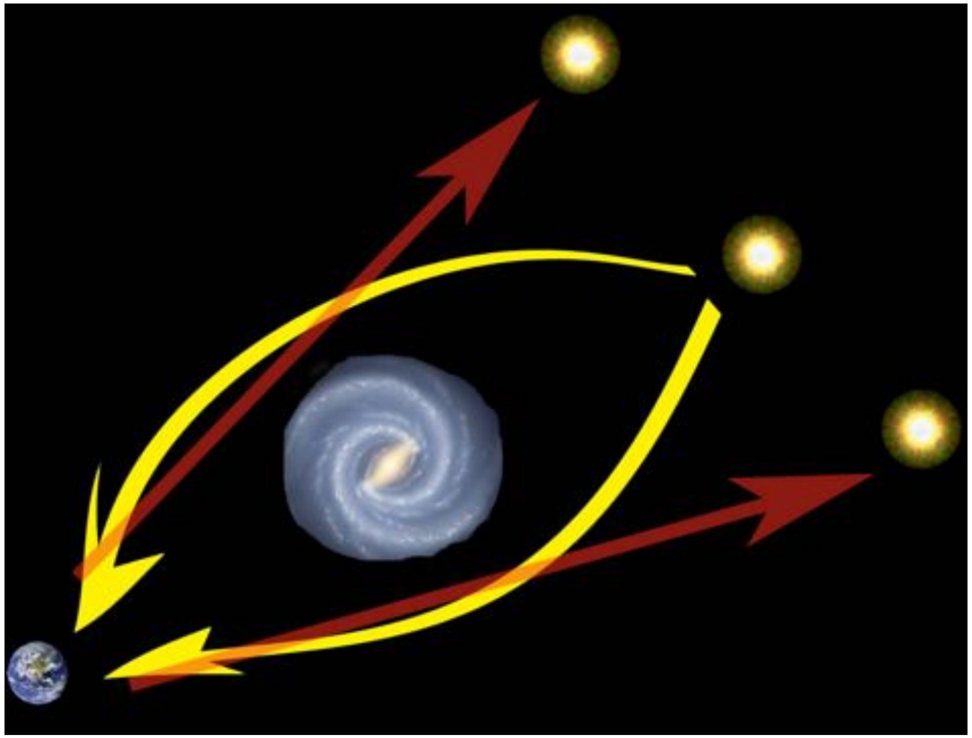
Kerr

$R_{lim}/2<R_{EH}<R_{lim}$

The more the BH rotates, the larger E_{grav}!

Funny effects…

Gravitational lensing



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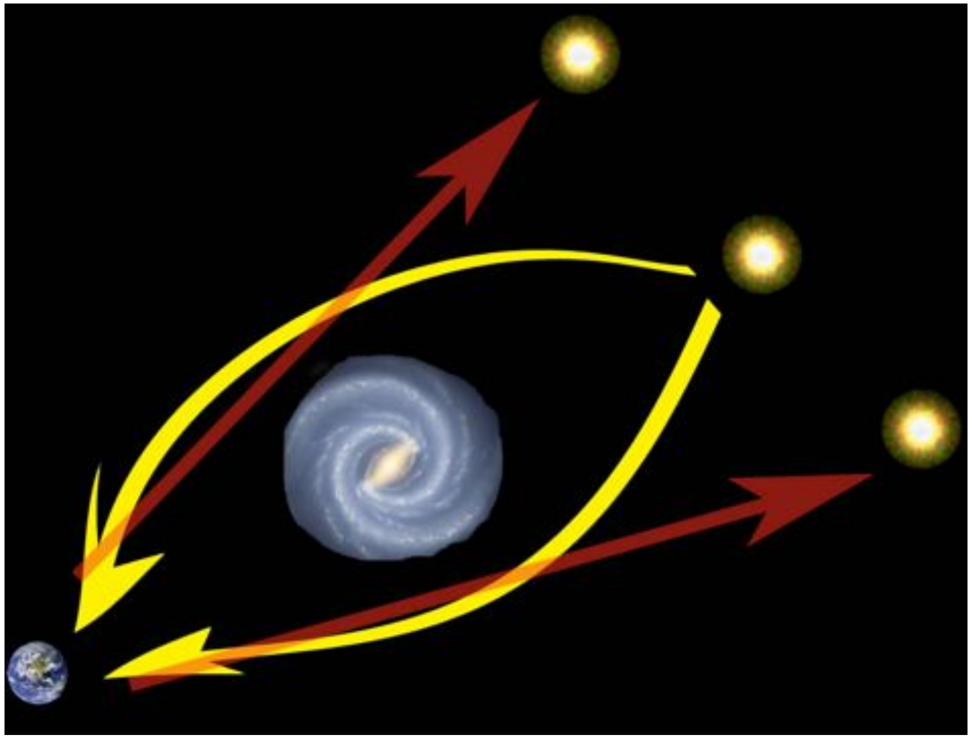
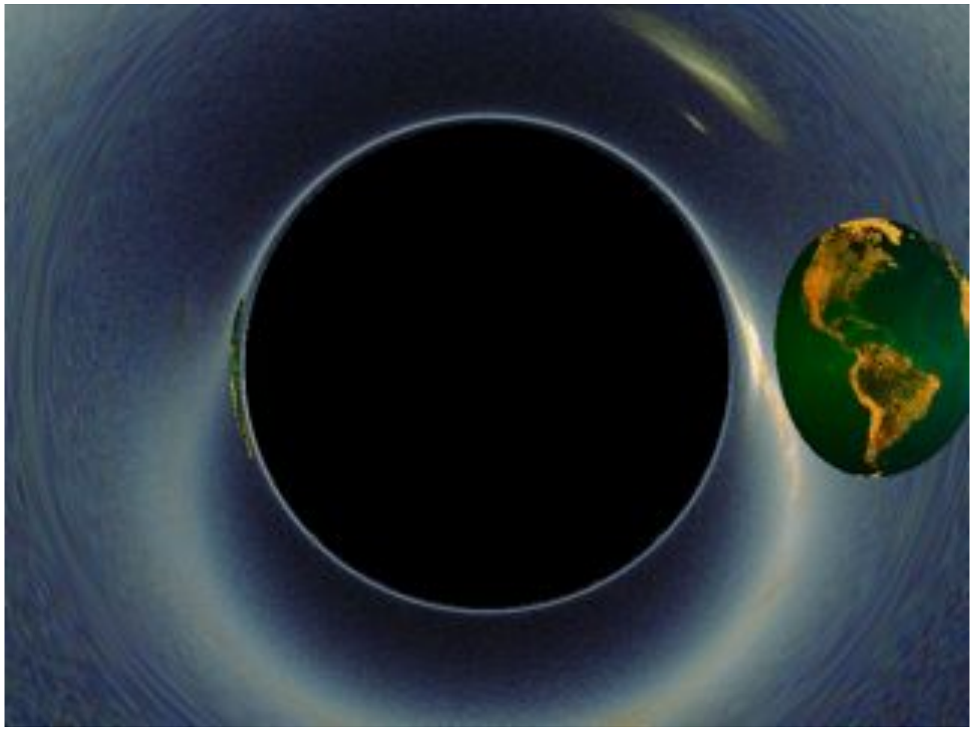


Amplified close to a black hole



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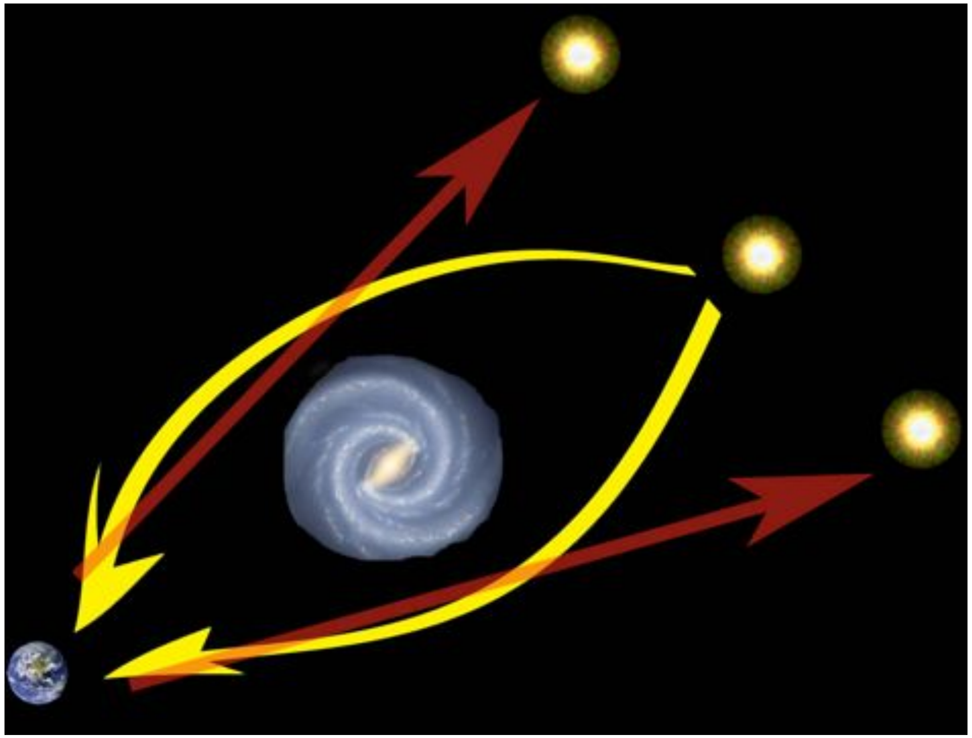

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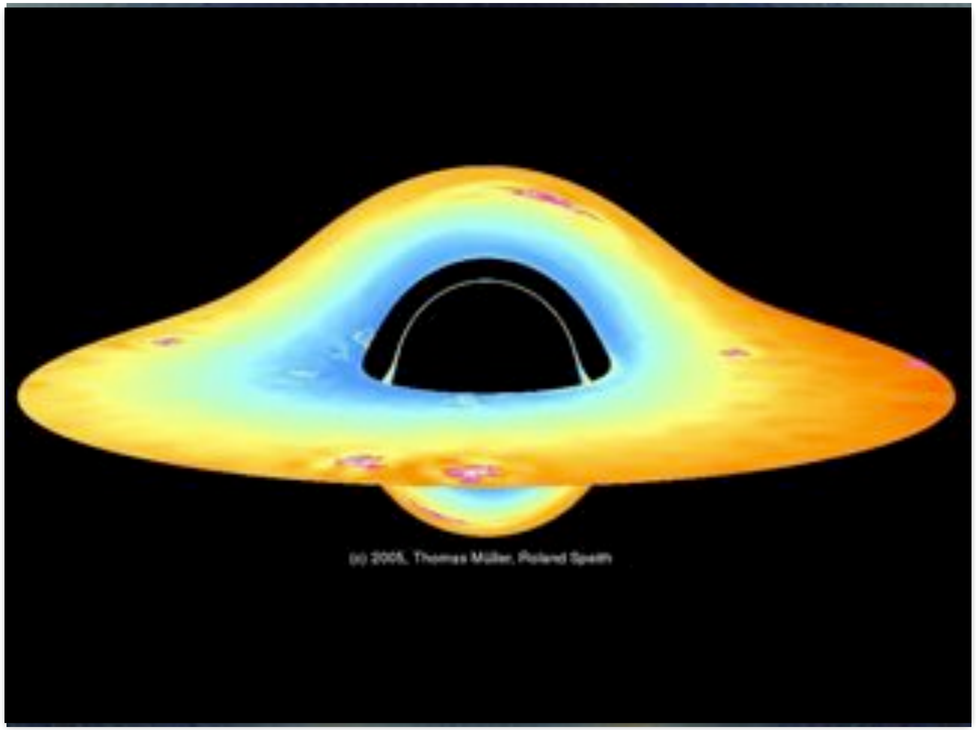
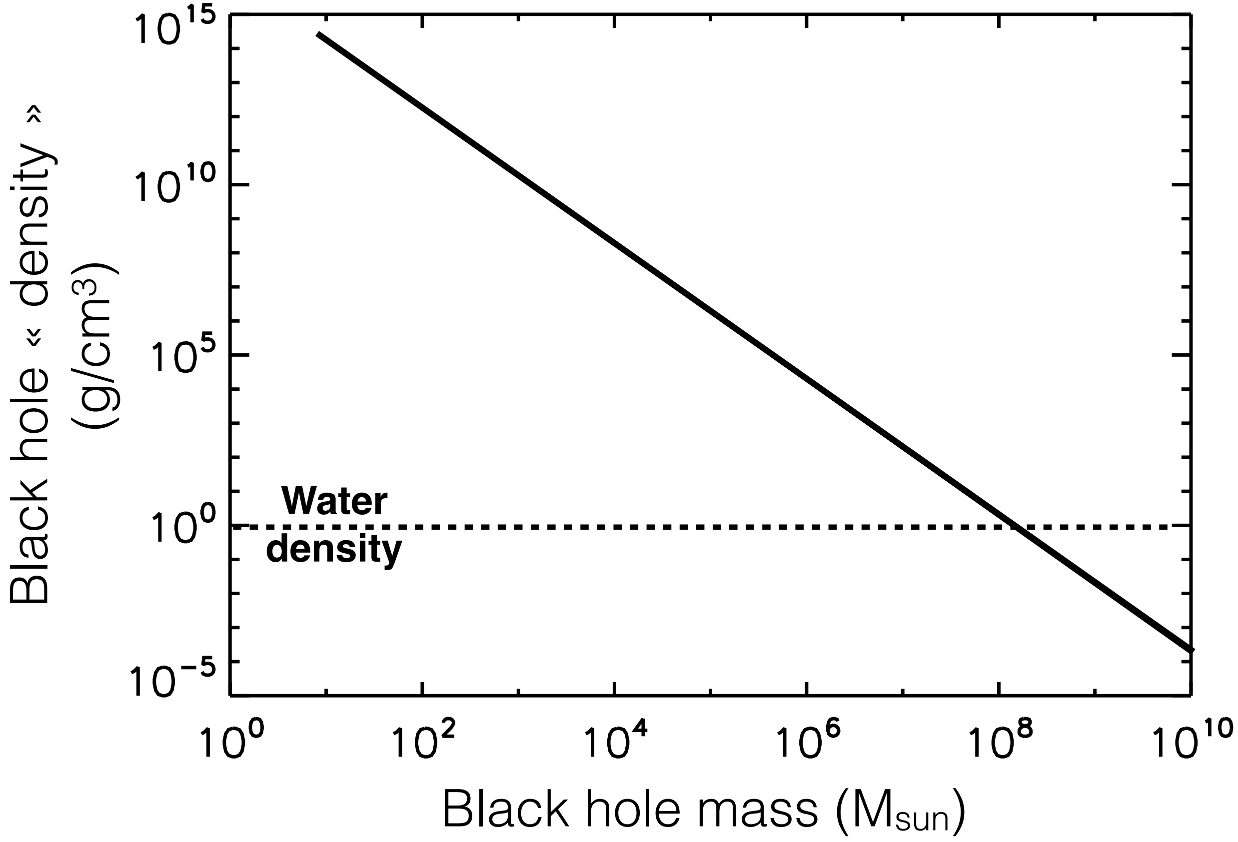


A wrong Idea…

Black hole does not always mean extreme density



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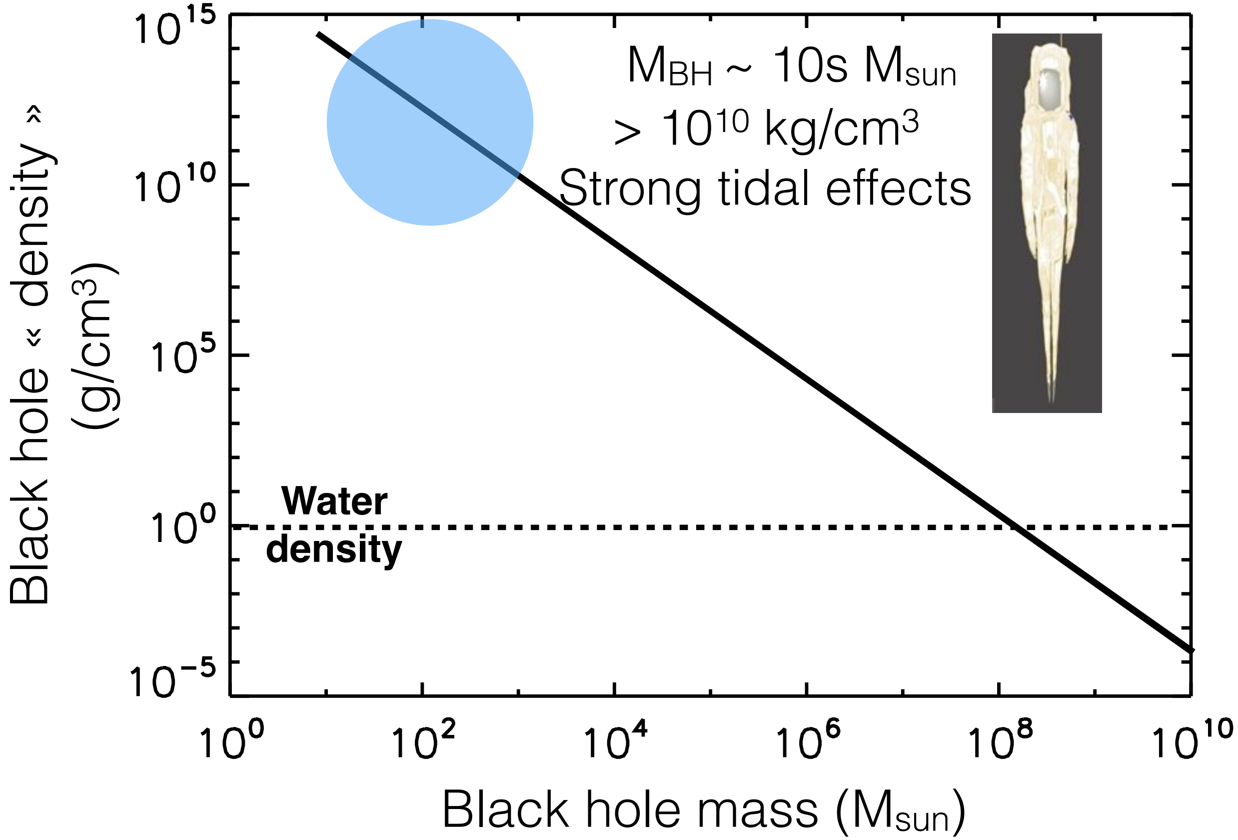

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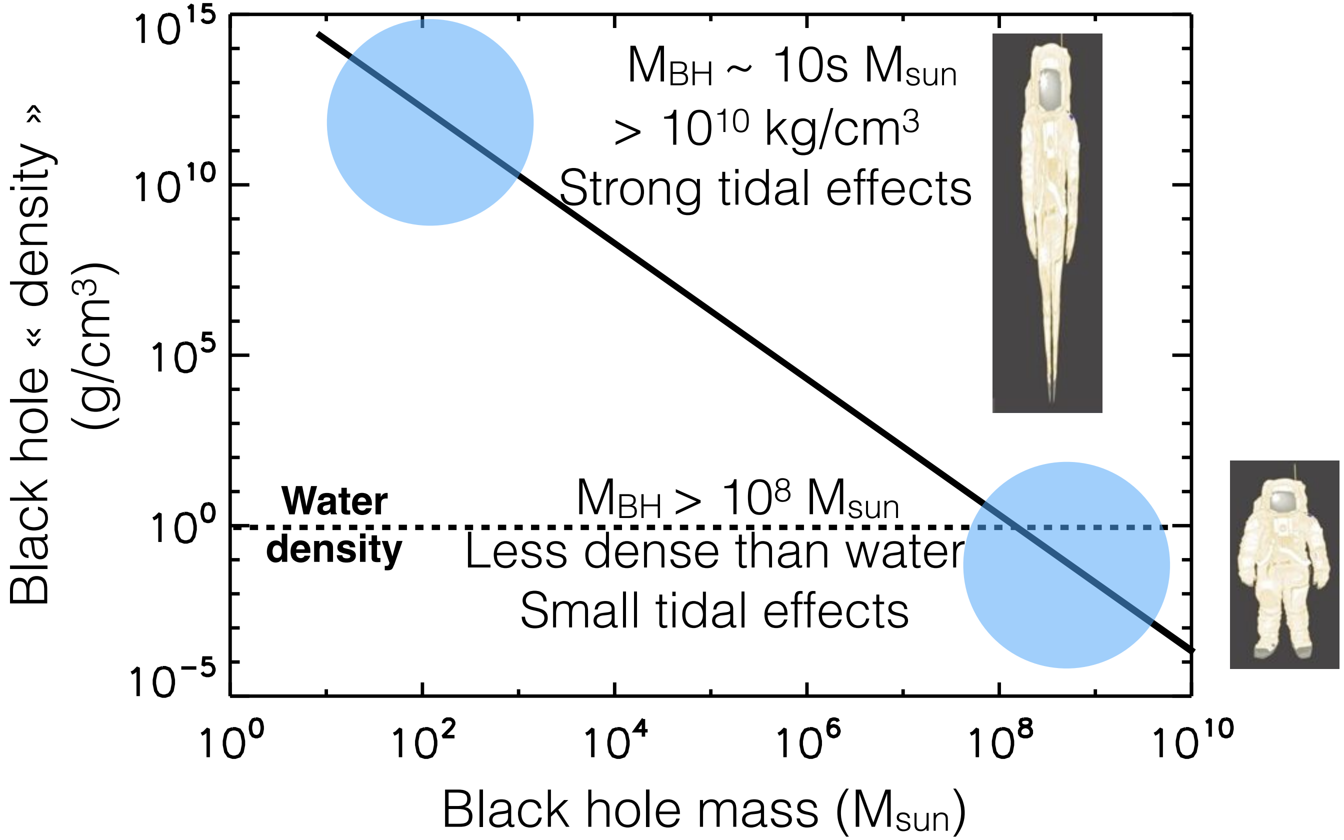
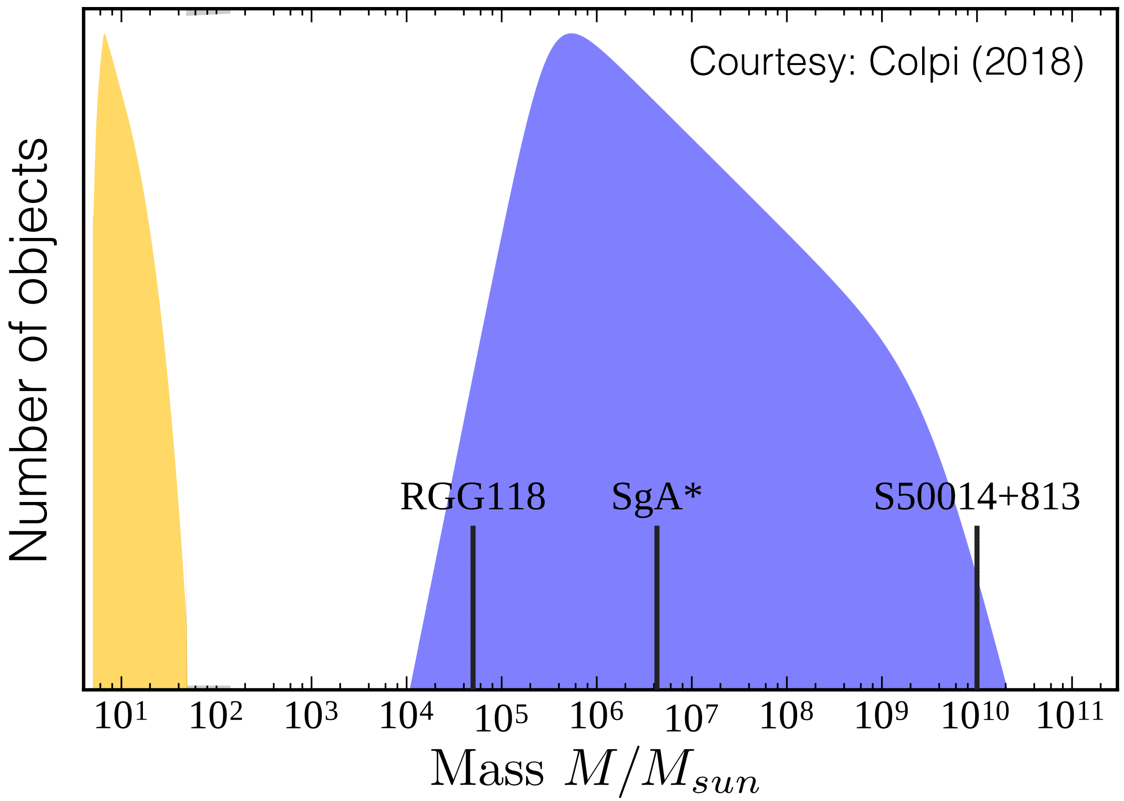


The Different Types of Astrophysical Black Holes

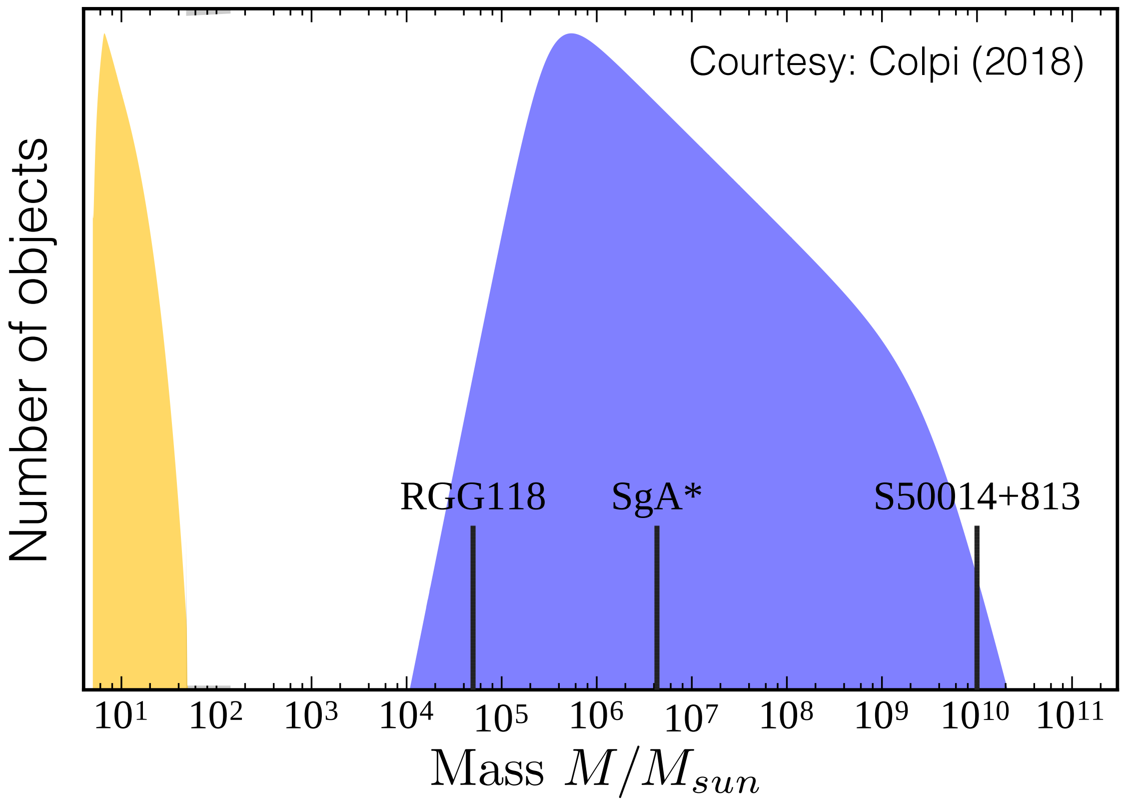
Two Main Types of Black holes



Two Main Types of Black holes

Stellar mass BH

Origin: Final product of dead stars



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- Binary system black hole + (donor) star

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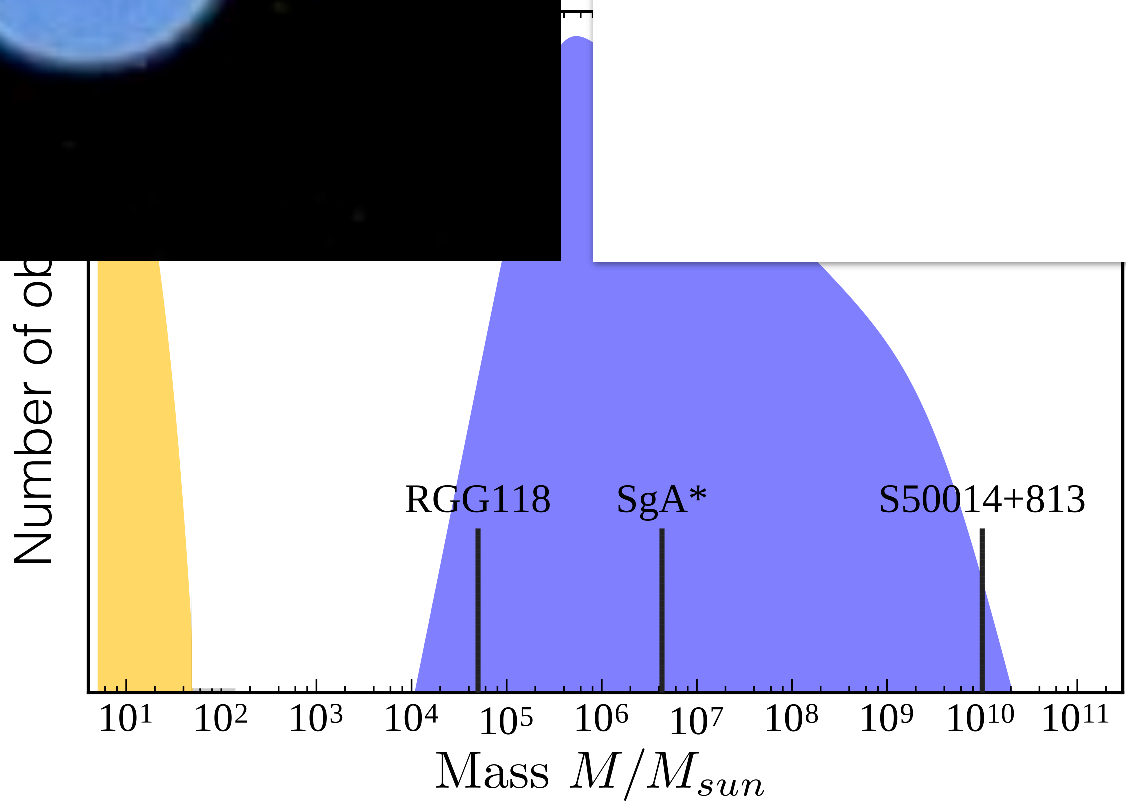

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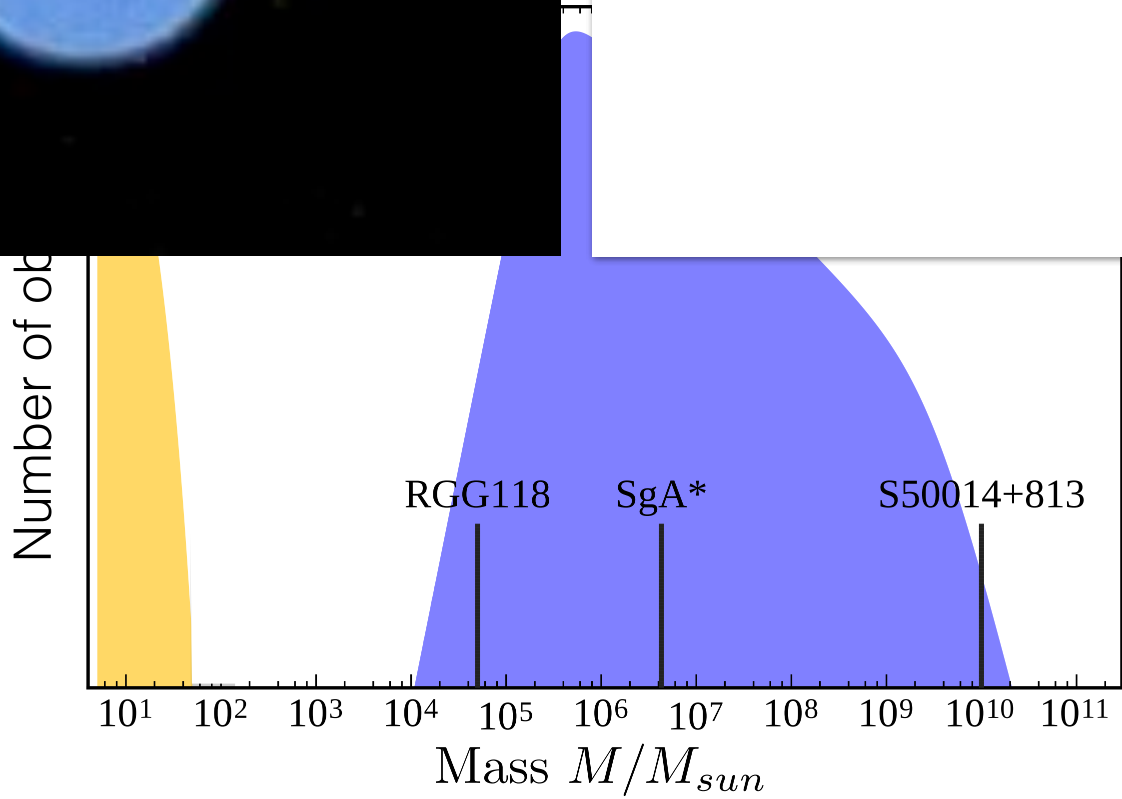

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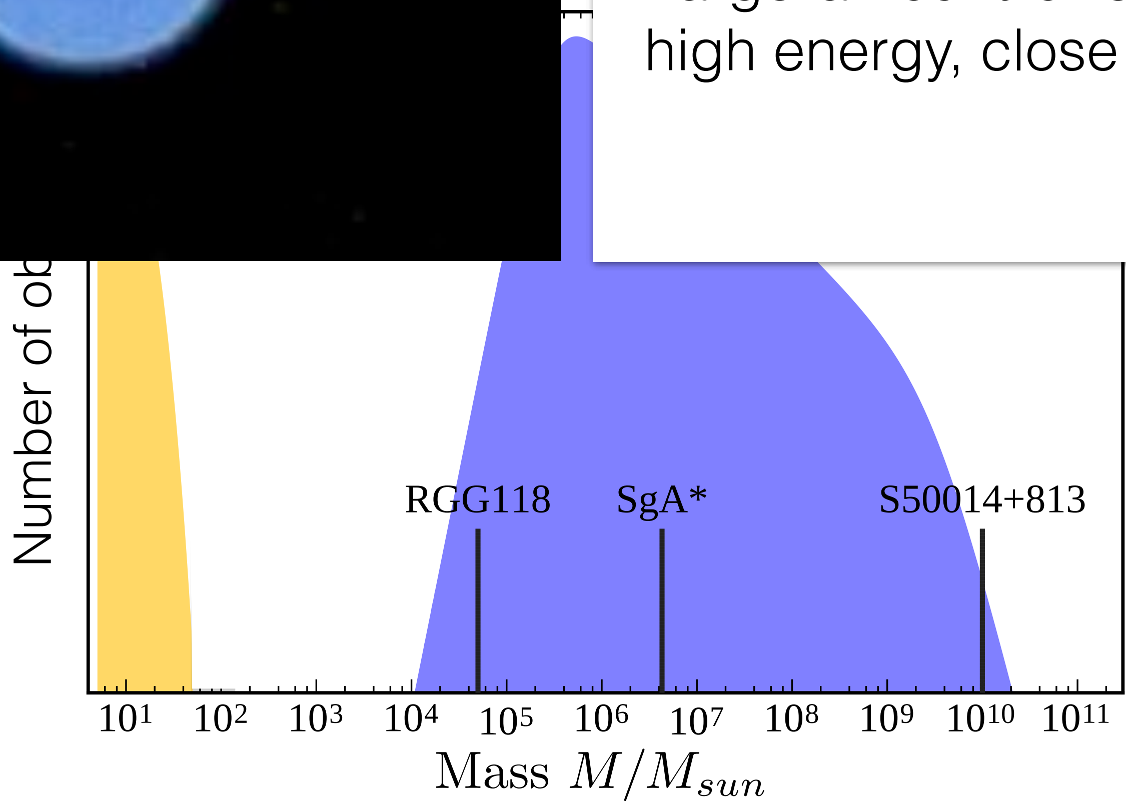

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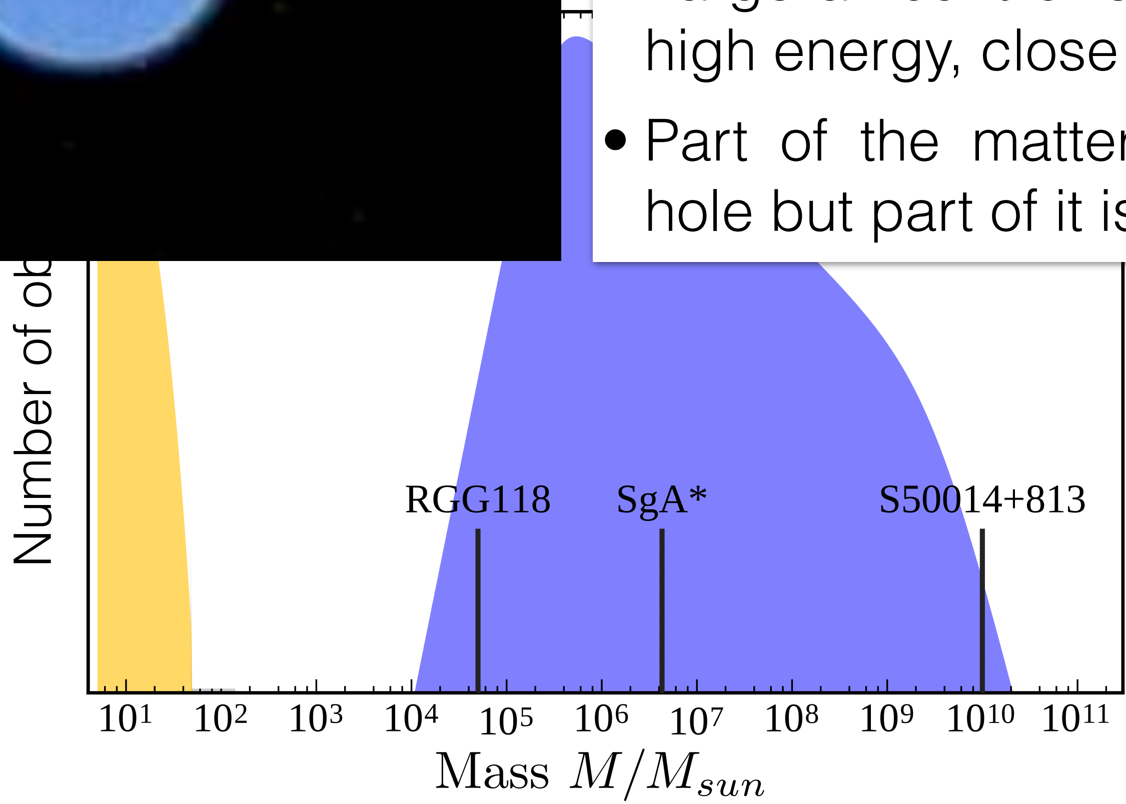

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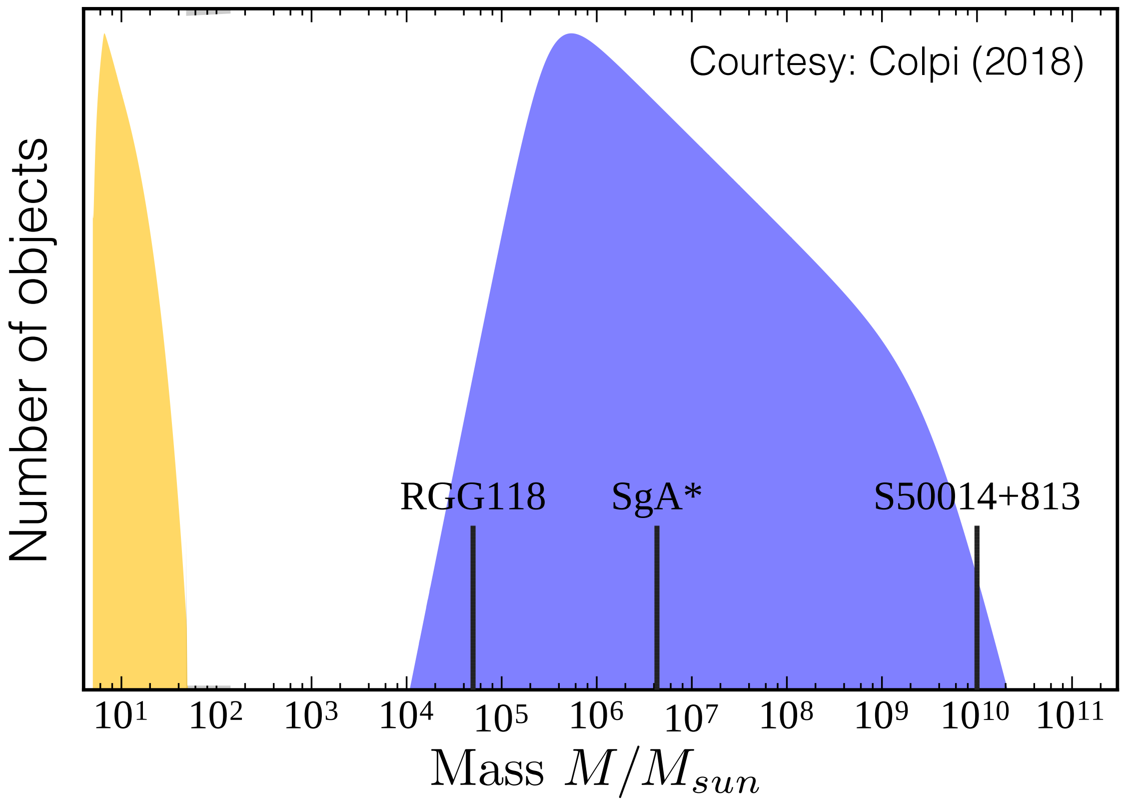

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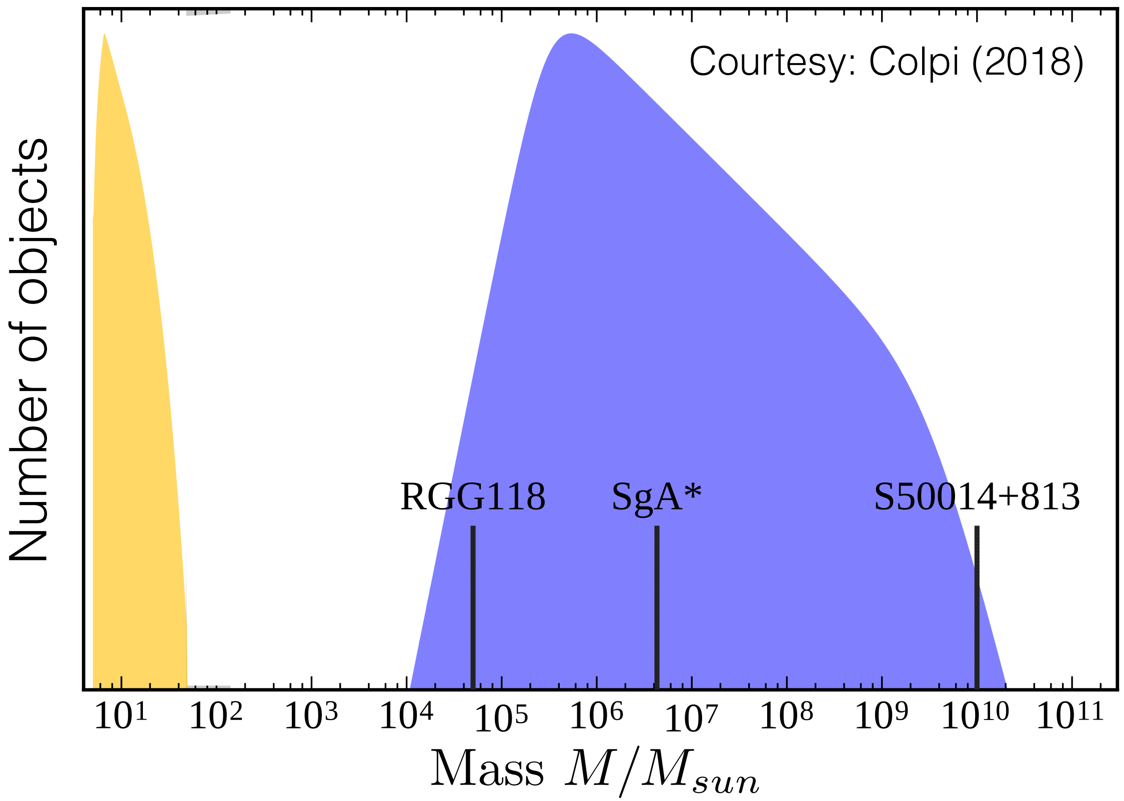

Super Massive BH

Origin: Not completely understood

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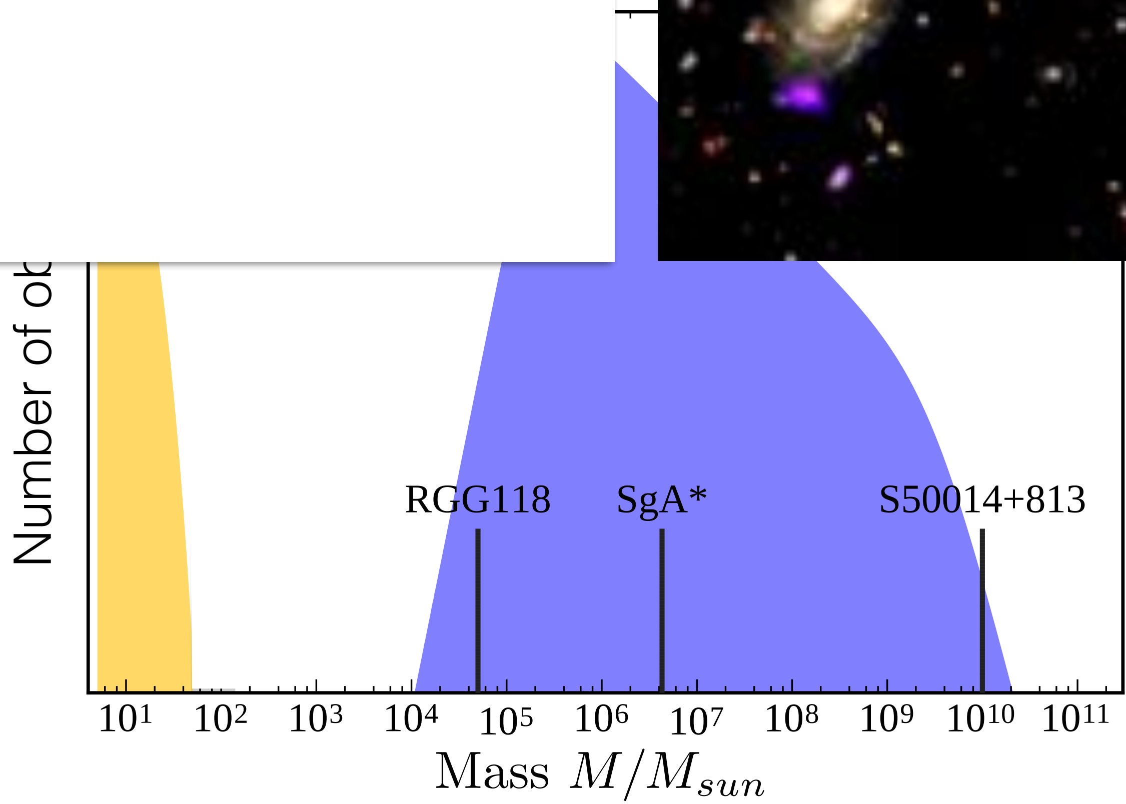

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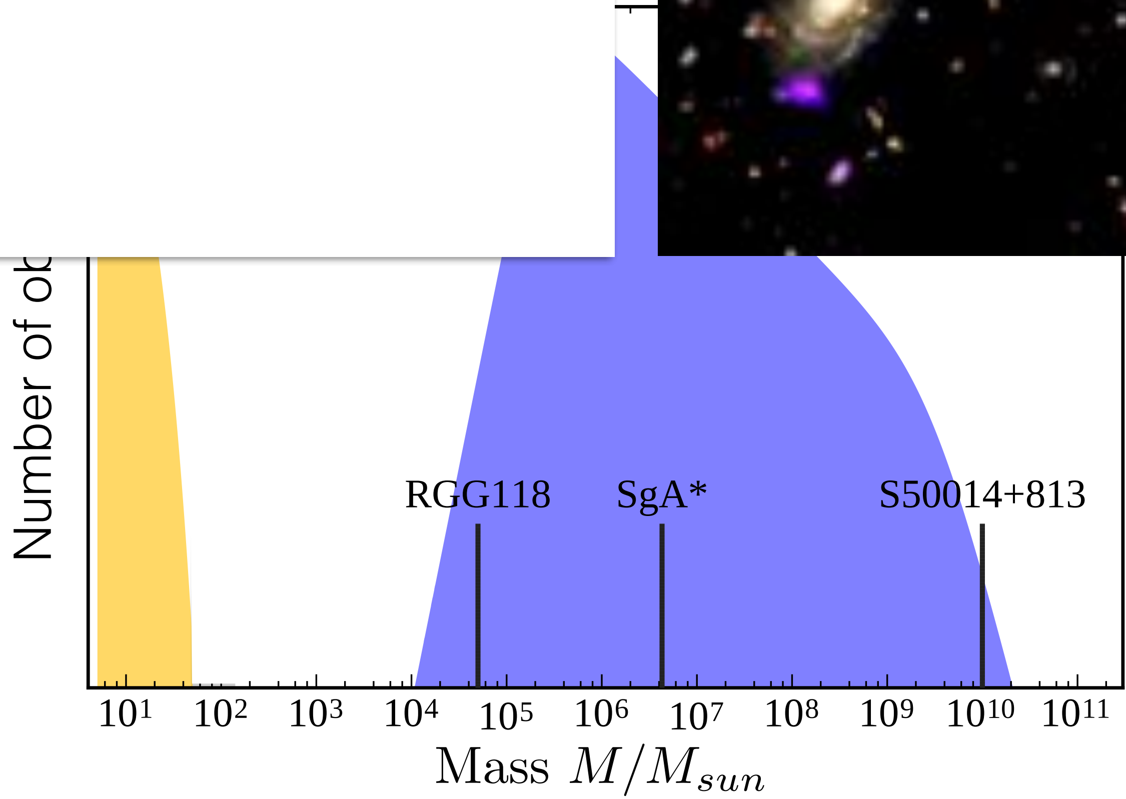

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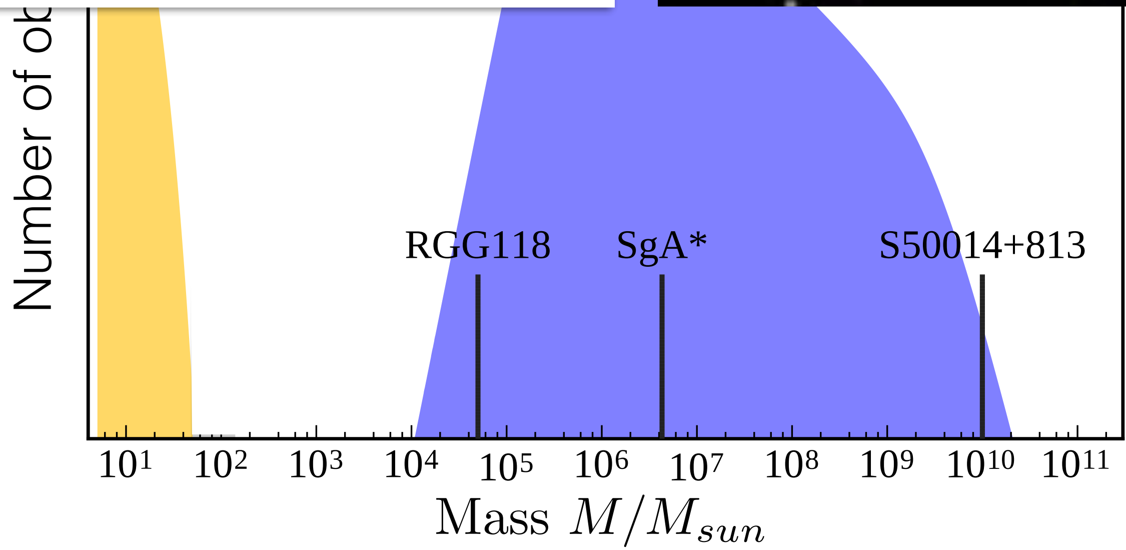

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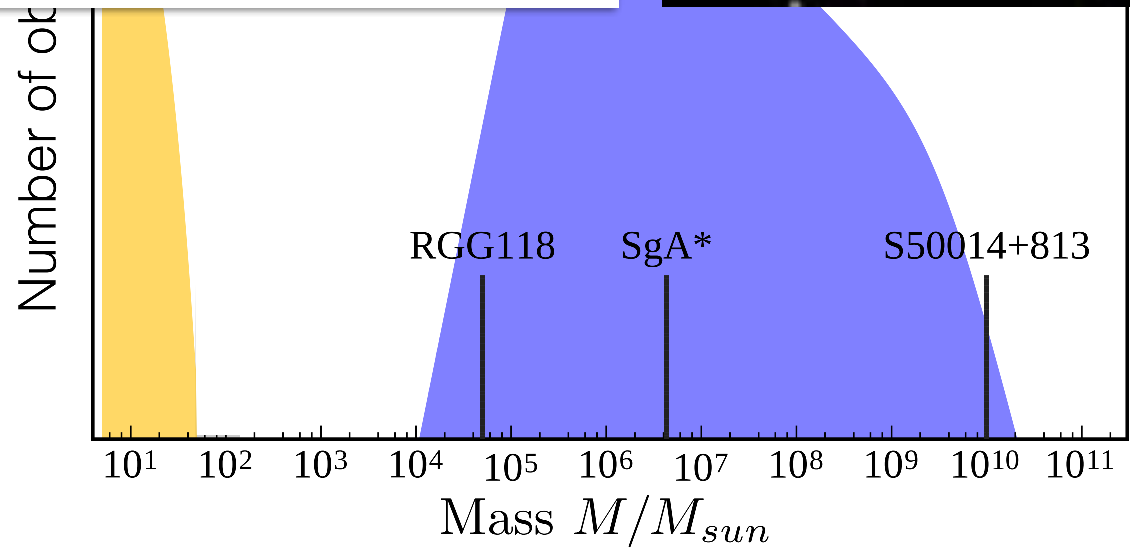

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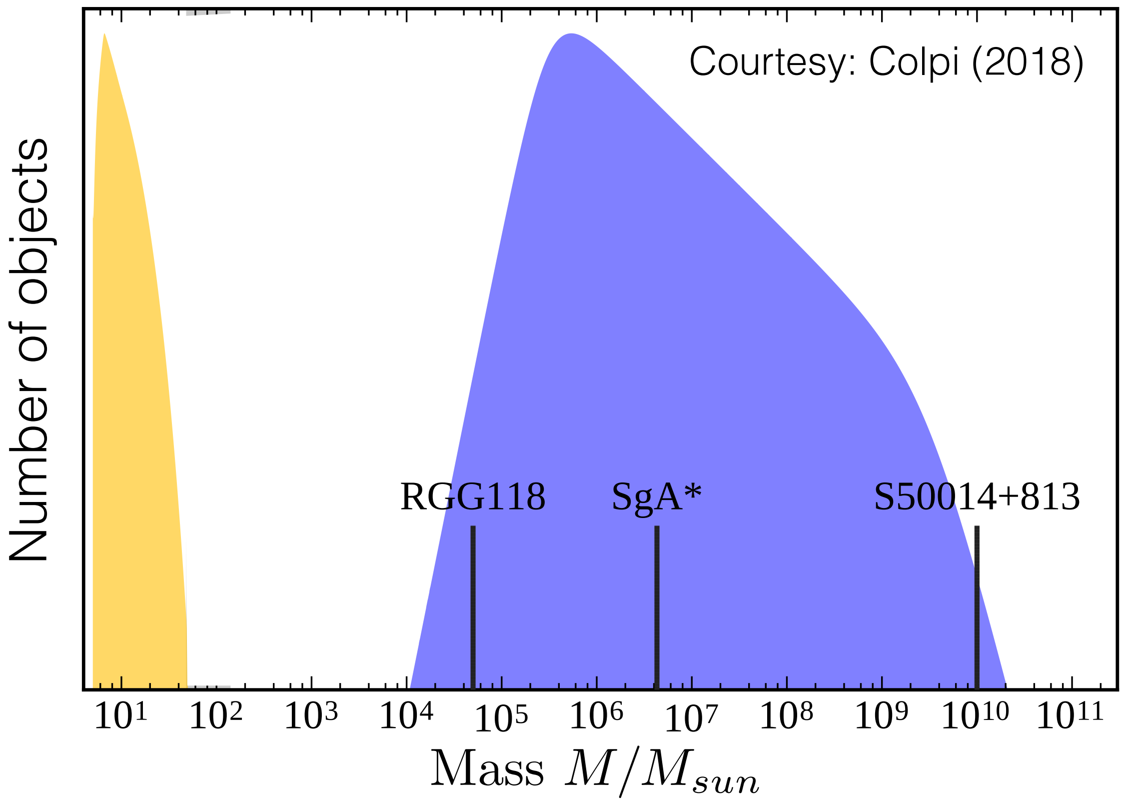
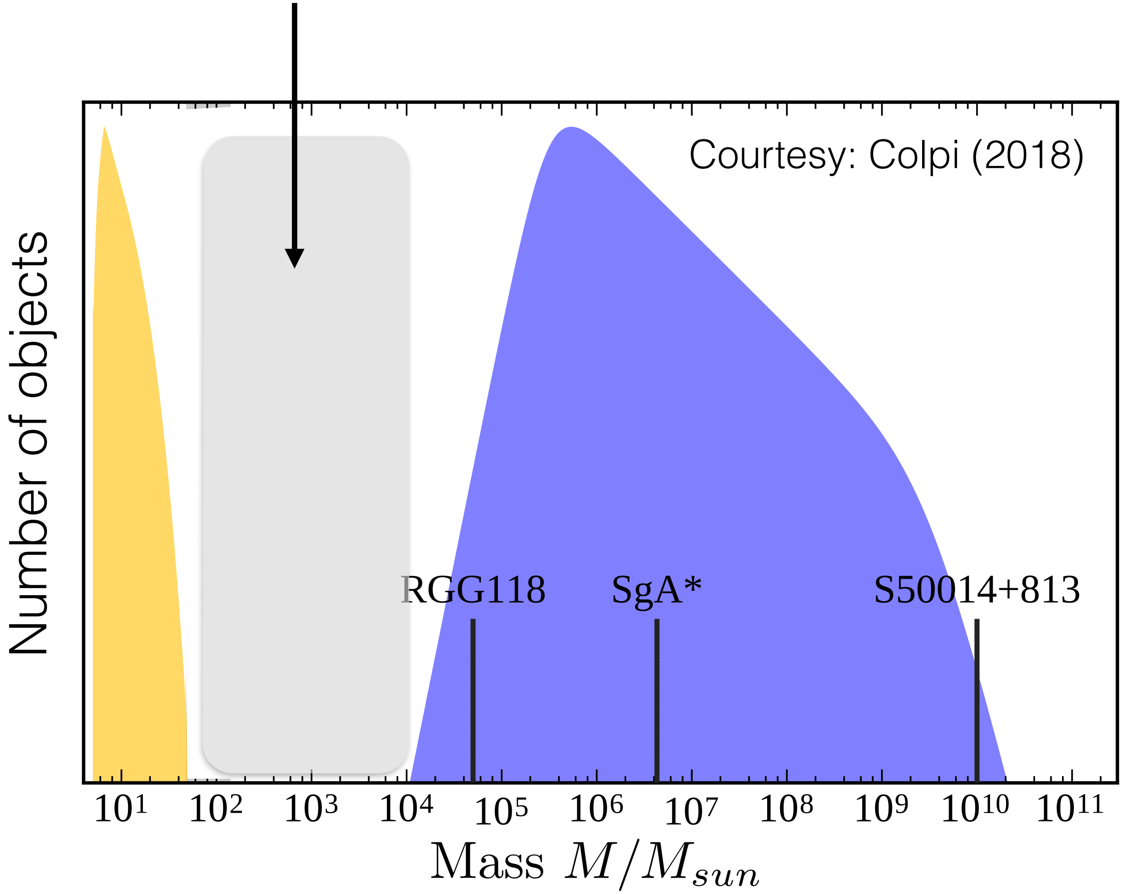


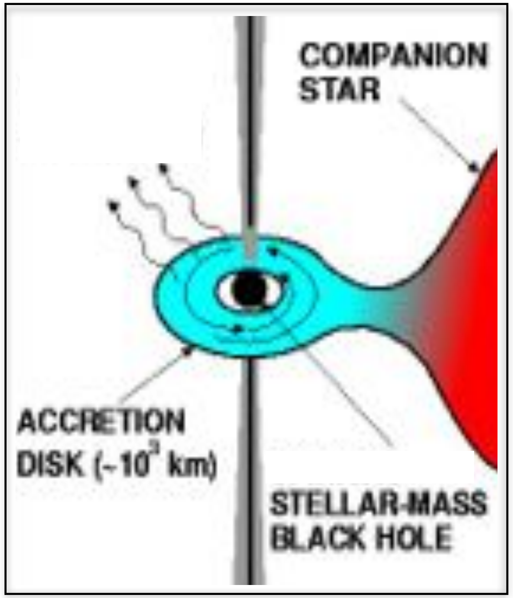
Two Main Types of Black holes

Intermediate mass black holes.
Their existence is still uncertain

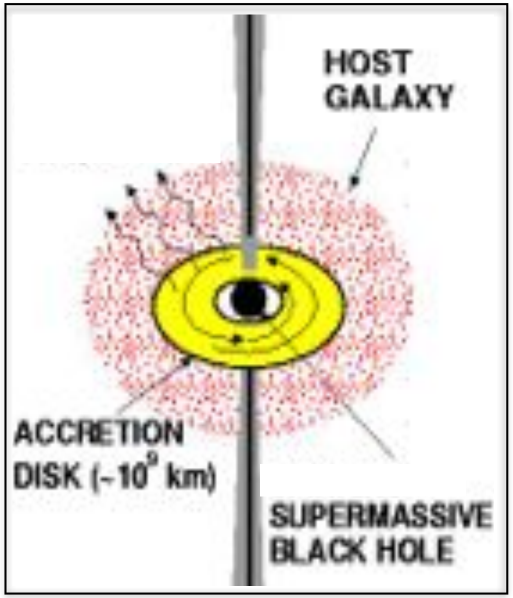


Fiducial numbers

Microquasar



Super massive BH



	Stellar mass	Super massive
BH Mass (M	10	10
Gravitational radius (km)	10	10
Typical Timescale (sec)	0,001	100-1000
Distance from earth (light year)	10 000	10
Luminosity	from quiescence to L	

$L = L_{Edd}$

Black hole's radiation expels → ← Black hole's gravity pulls in

$$L_{Edd} \simeq 10^6 L_{sun} \text{ for } 10 M_{sun}$$

$$L_{Edd} \simeq 10^{13} L_{sun} \text{ for } 10^8 M_{sun}$$

How do we measure their mass?

General idea:

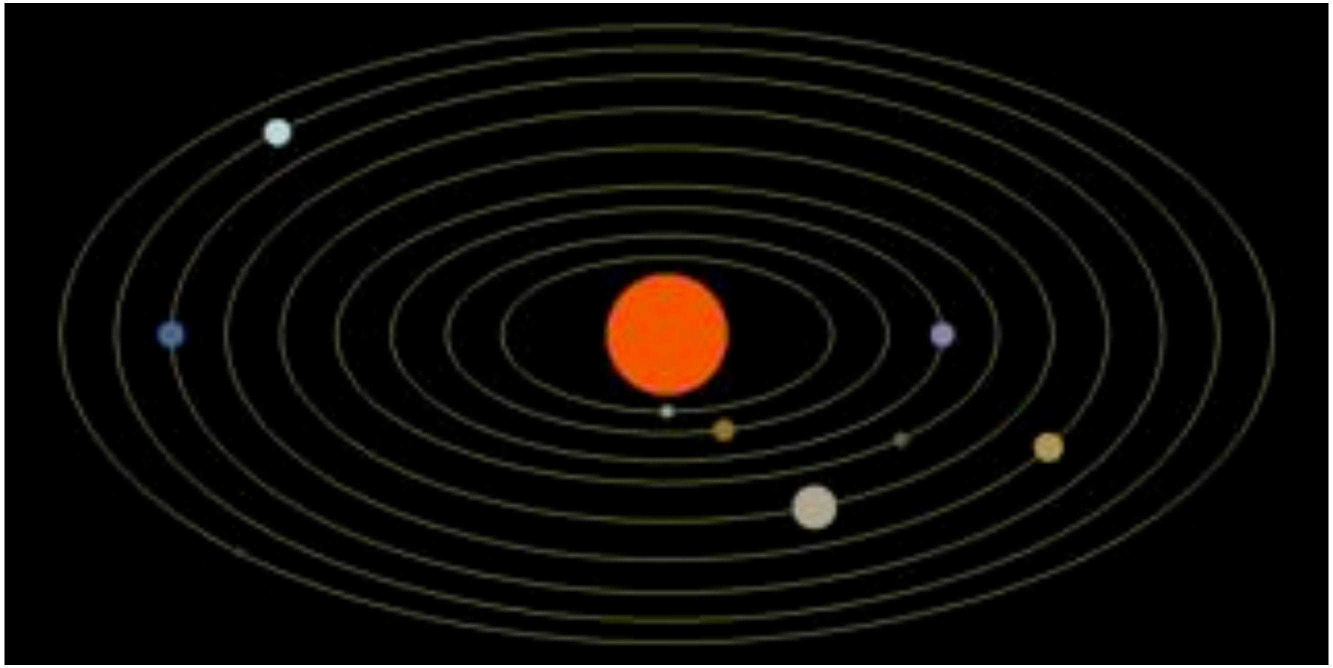
1. Observe something which rotates
2. Determine its velocity v
3. Determine the radius R of its orbit
4. Deduce the mass of the massive central object using a formula M(v,R)

Body in circular orbit of radius **R** around an object of mass **M** moves at the **Keplerian velocity**

$$V_K = \sqrt{\frac{\mathcal{G}M}{R}}$$

(Rem: see talk for mass measurement thanks to gravitational waves)

How do we measure their mass?



<u>3rd Kepler law</u>

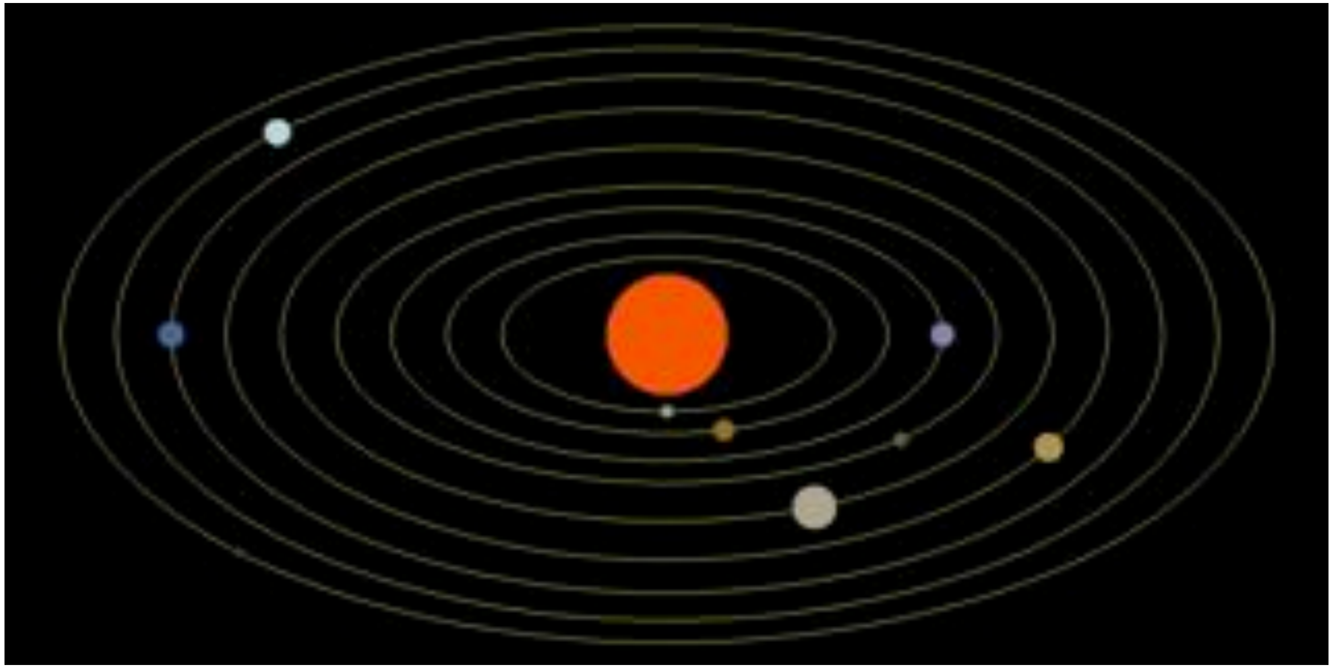
(in case of circular orbit, no inclination, $M_{star} \gg M_{planet}$)

Orbital period → P_{orb}

Keplerian velocity of the planet → $V^3_{K,planet}$

$$M_{star} \simeq P_{orb} V^3_{K,planet} / 2\pi\mathcal{G}$$

How do we measure their mass?



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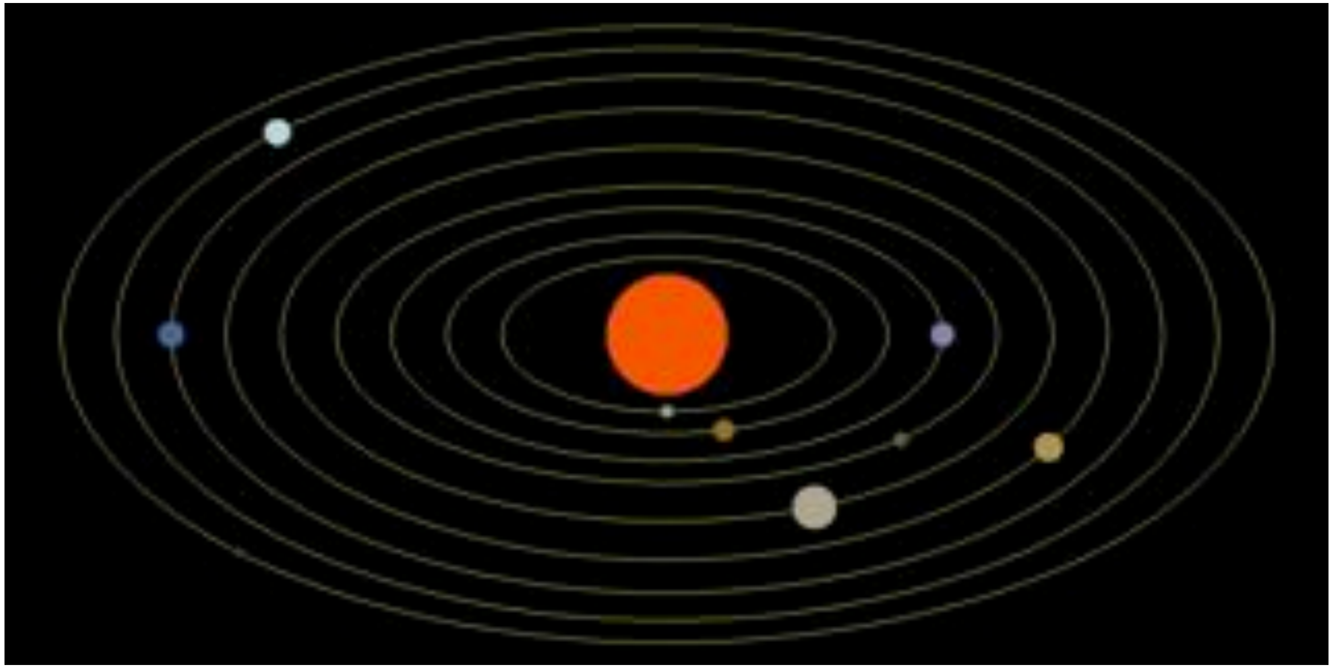


Numerical application: the case of the earth and the sun

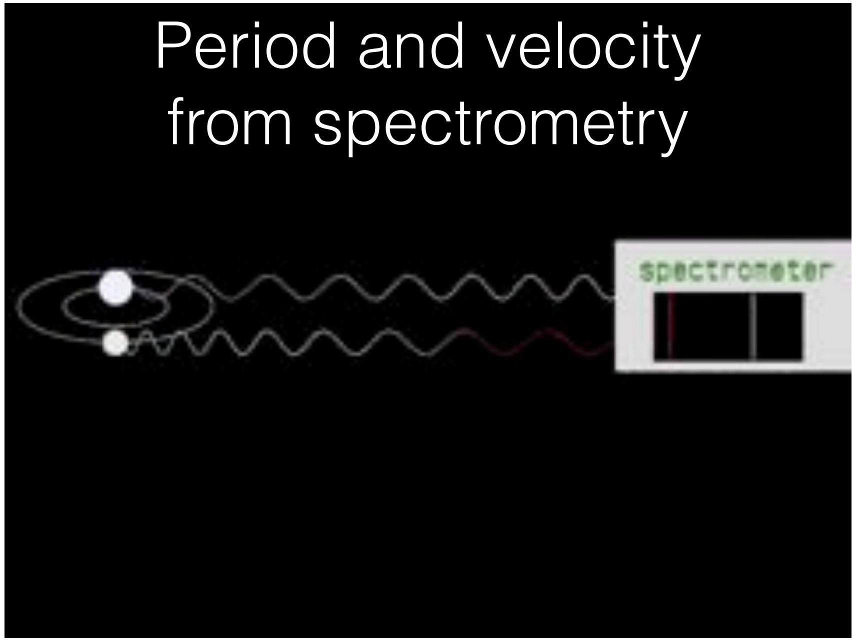
Eart orbital period: 1 year

Orbital radius: 150 millions of km

➧ $M_{sun} = 2\ 10^{30}$ kg

How do we measure their mass?

Microquasars



In general, objects of similar mass, on inclined orbit, …

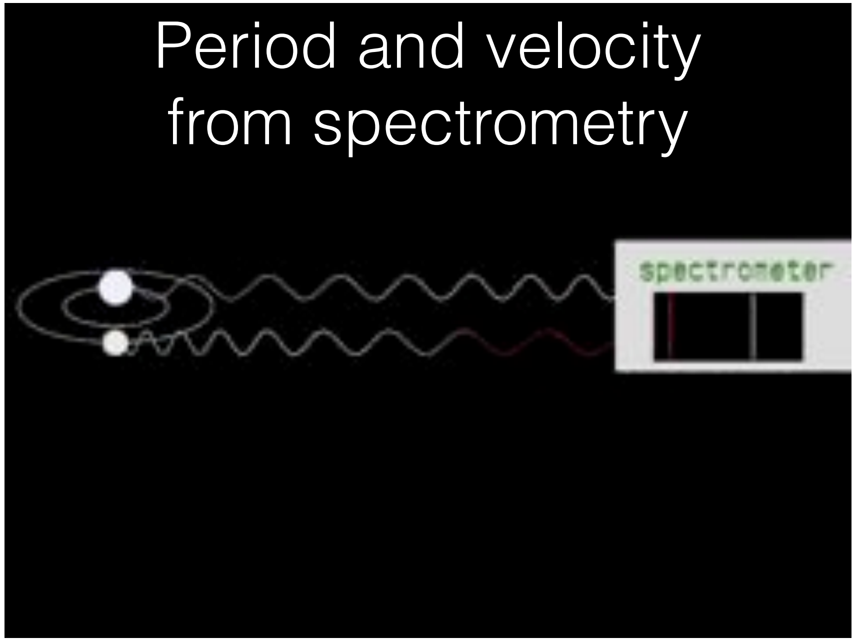
$$M_1 \sin^3 i/(1 + M_2/M_1)^2 = P_{orb} V^3_{K,M_2}/2\pi\mathcal{G}$$

Binary inclination

$$< M_1$$

How do we measure their mass?

Microquasars



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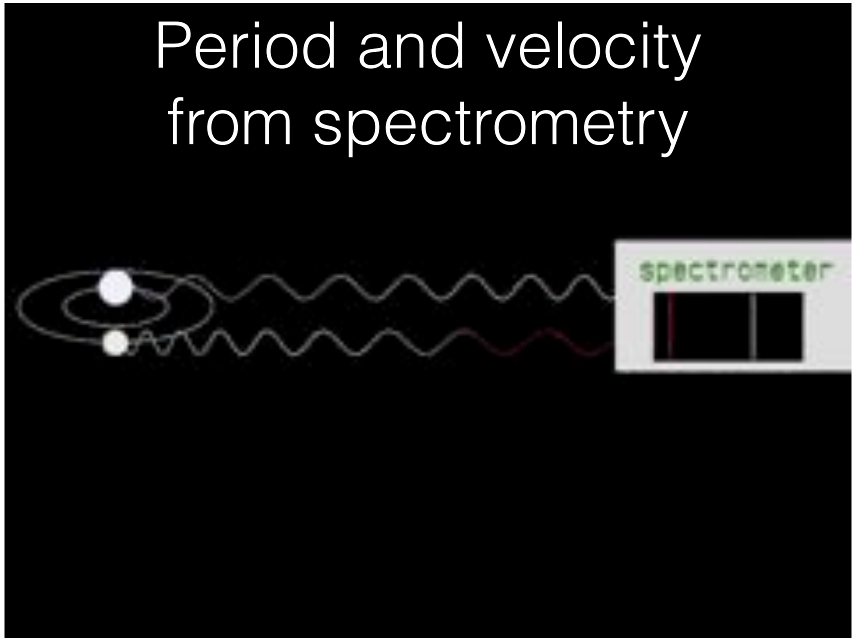

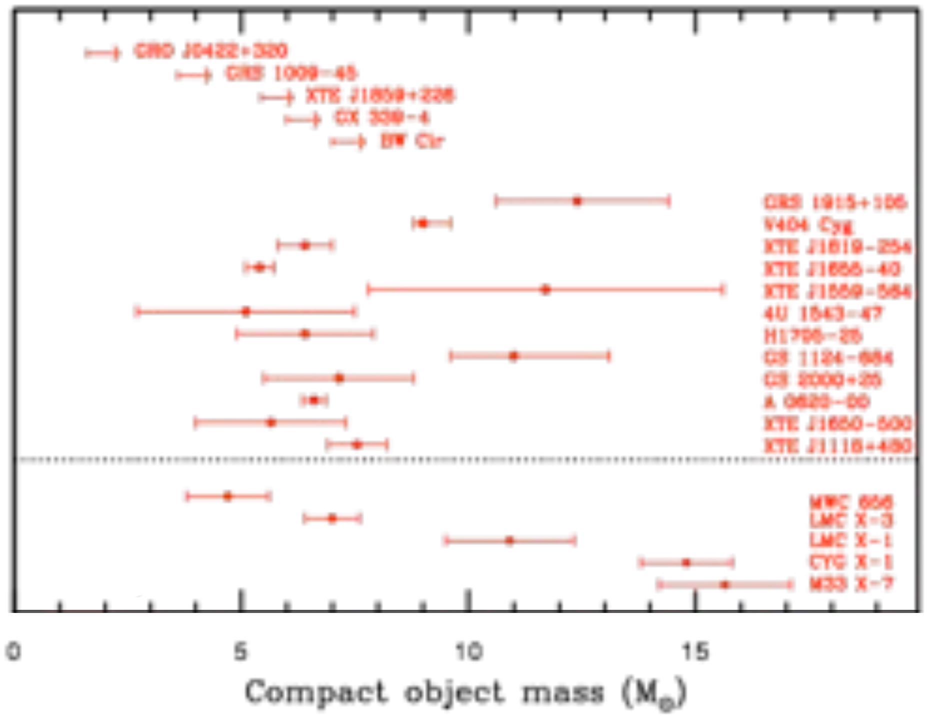

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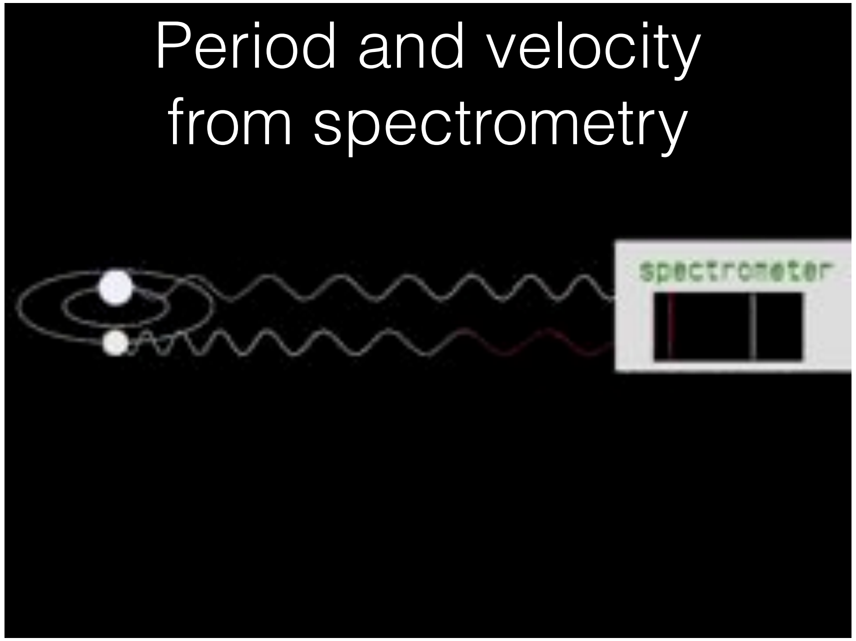
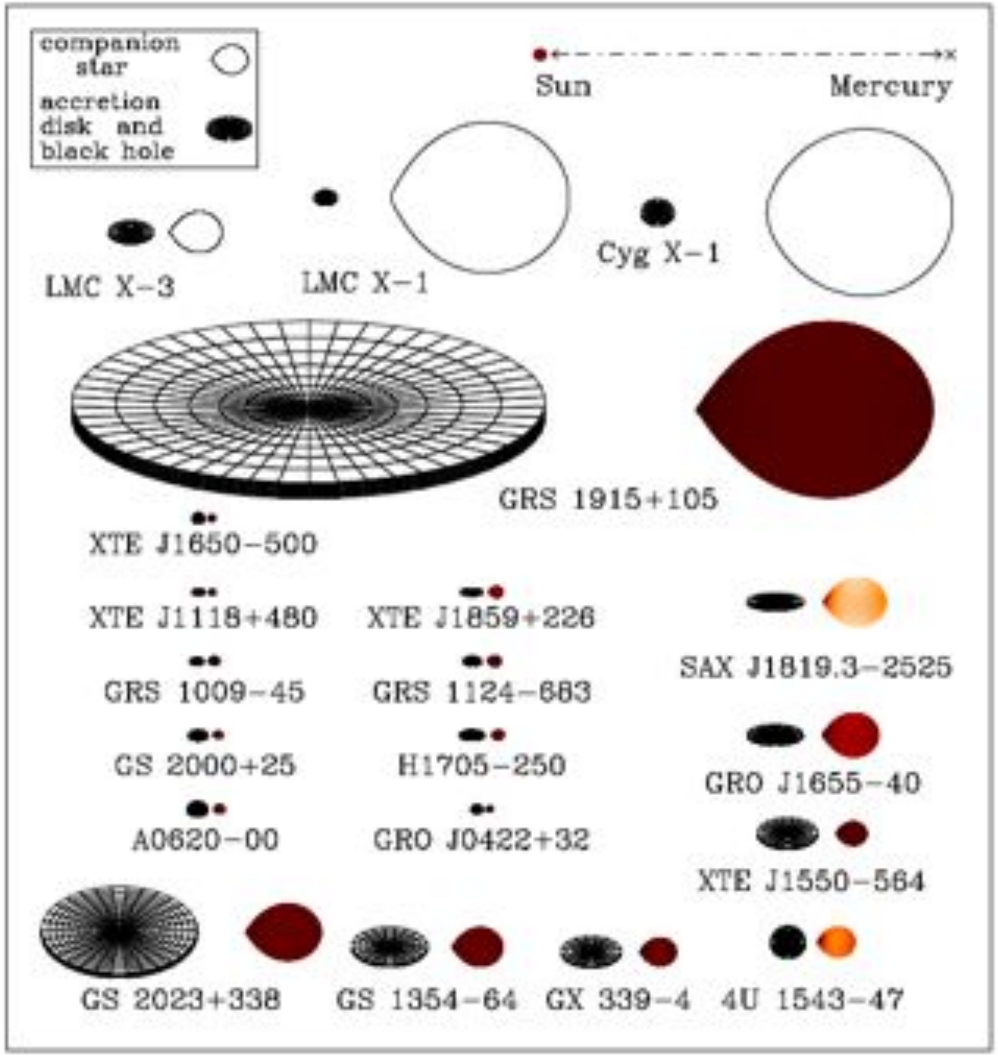


In general, objects of simi

$$M_1 \sin^3 i/(1 + M_2/M_1)^2 = P_{orb}$$

Binary inclination

$$< M_1$$



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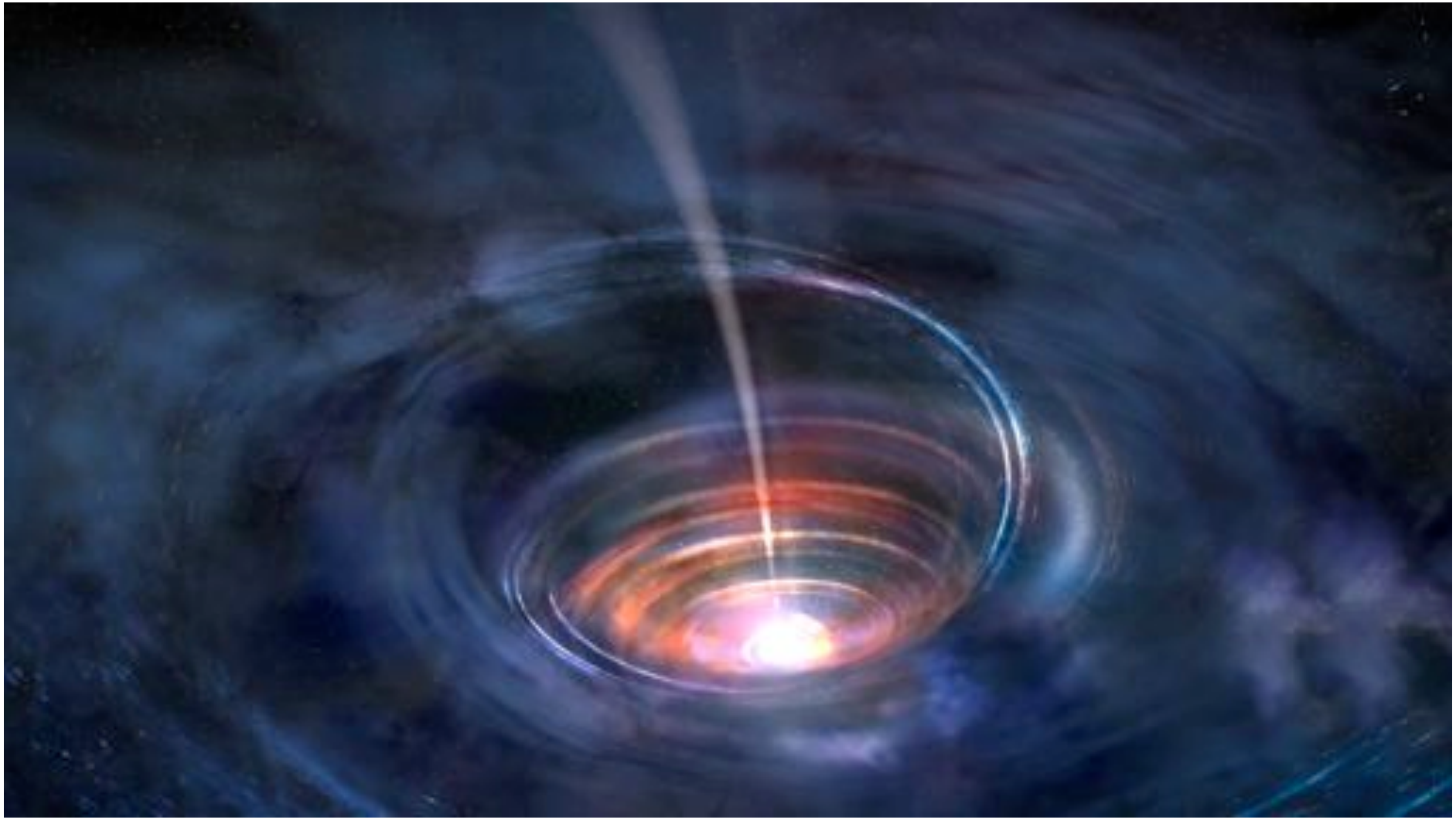
Super Massive Black Holes

« Reverberation Mapping »



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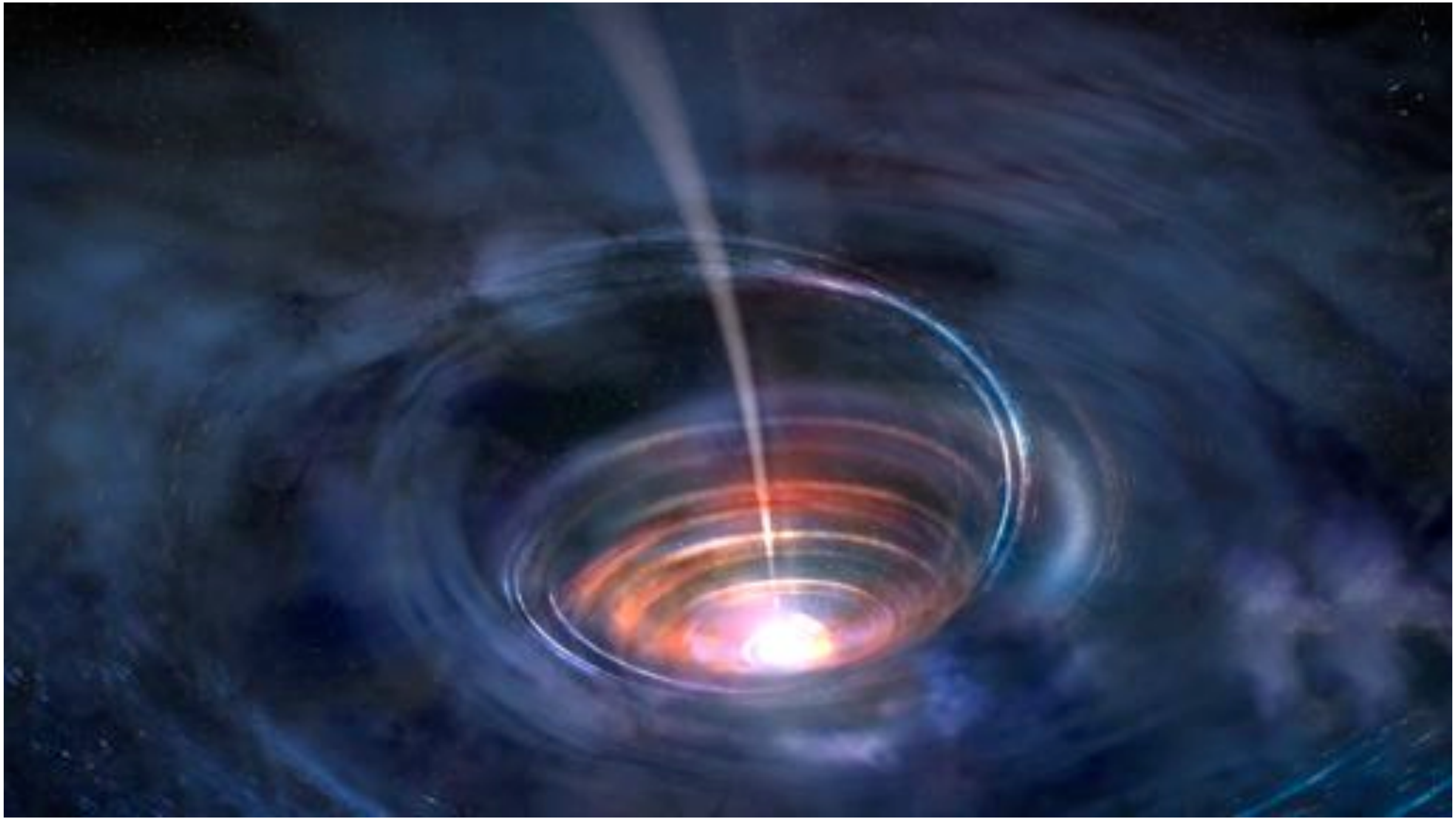

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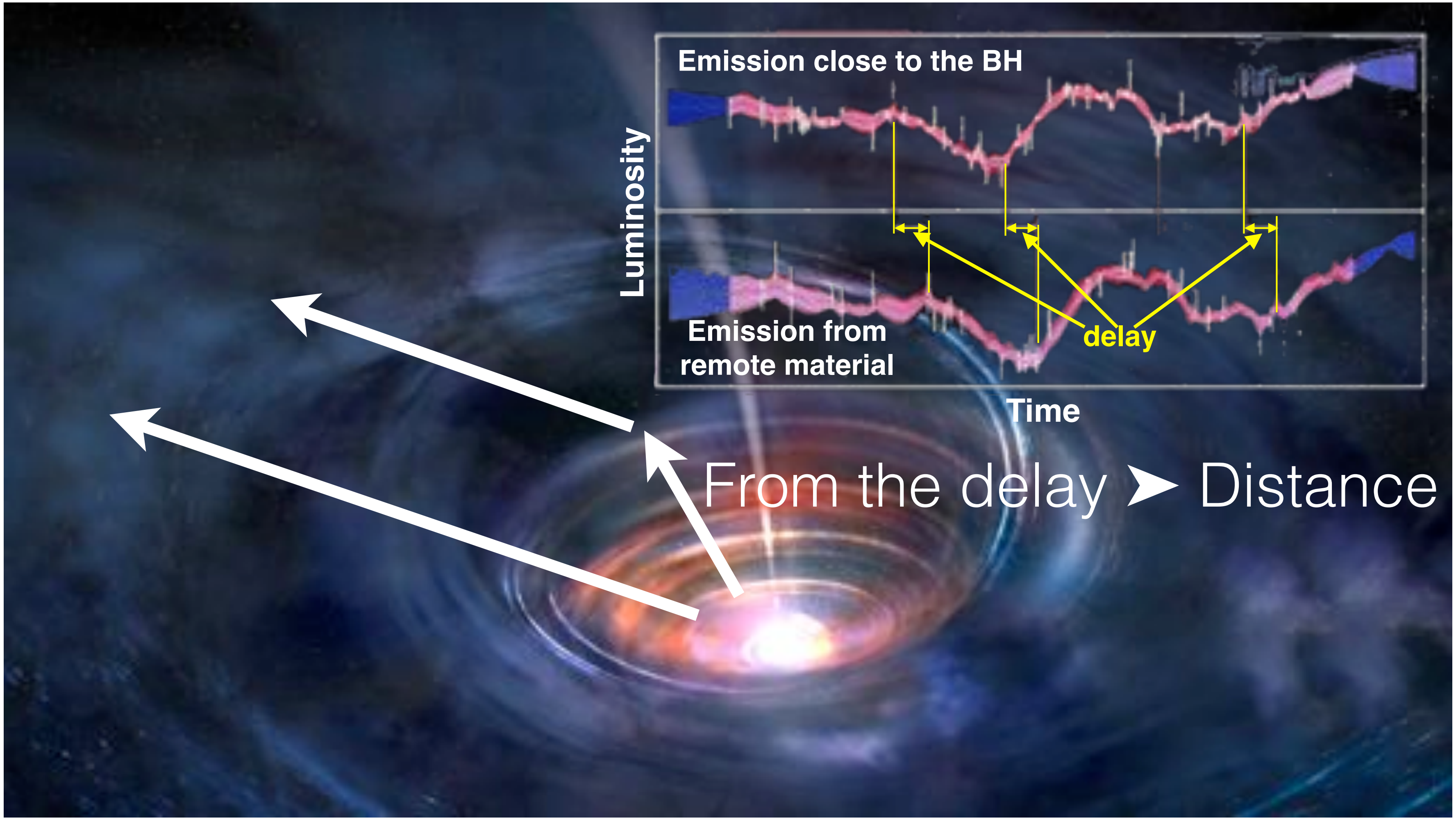

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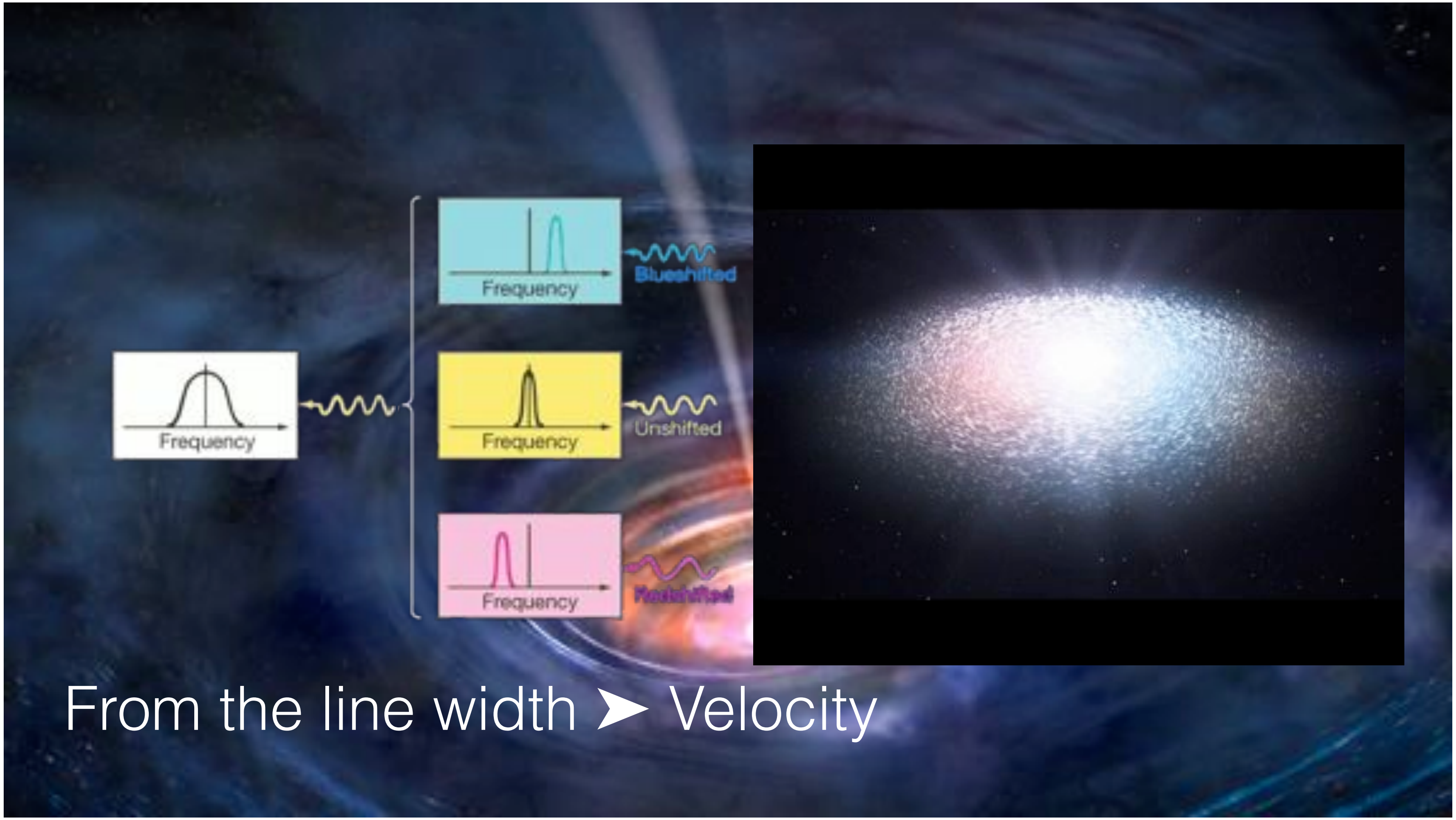

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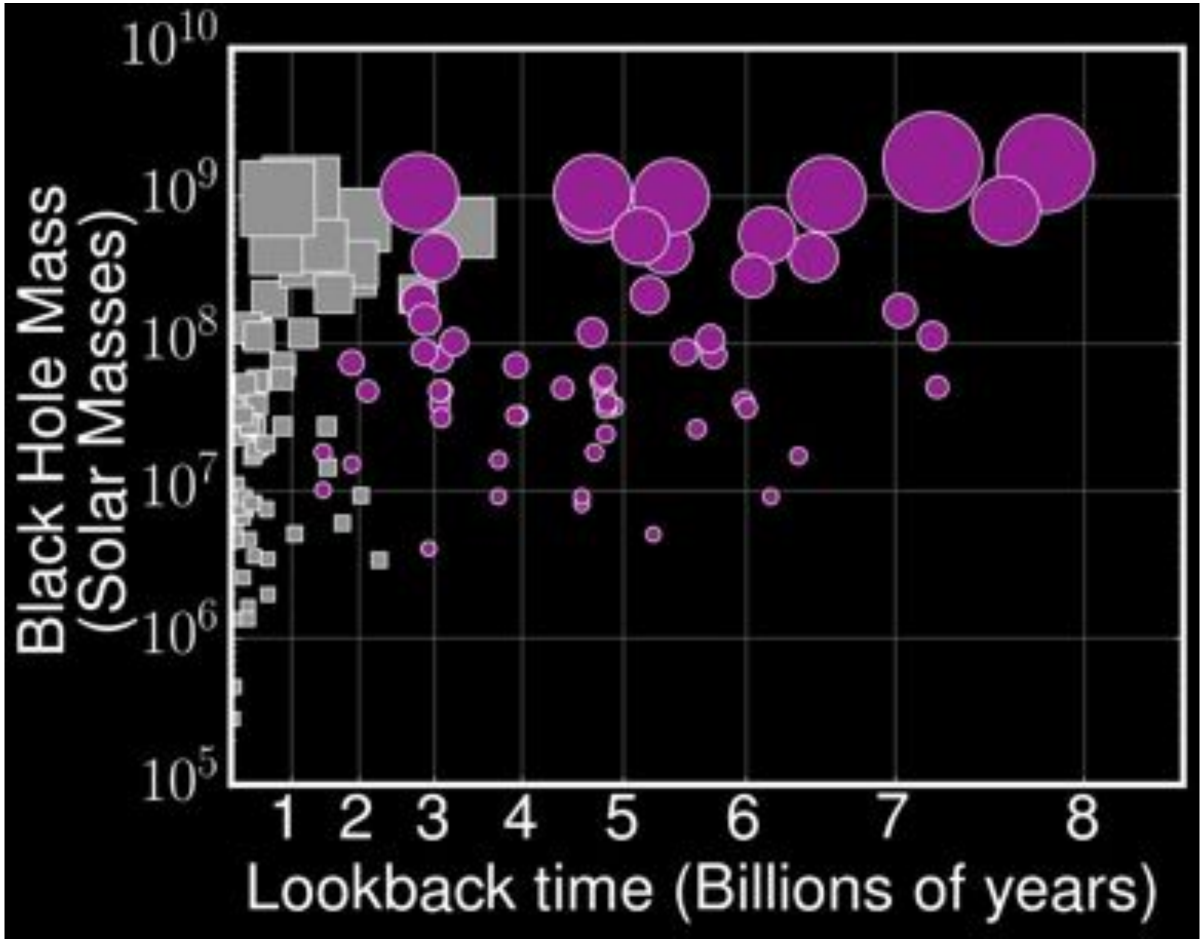
Super Massive Black Holes

« Reverberation Mapping »



Grier et al. (2017)

- SMBH in almost all galaxies…
- Super massive black holes already in place in the early universe

E.g. ULAS J1342 + 0928 has a 10^9 M_{sun} at a lookback time of 13 billions of years…

How do we measure their mass?

Super Massive Black Holes

Via direct measurements…

… e.g. Interferometry (GRAVITY)

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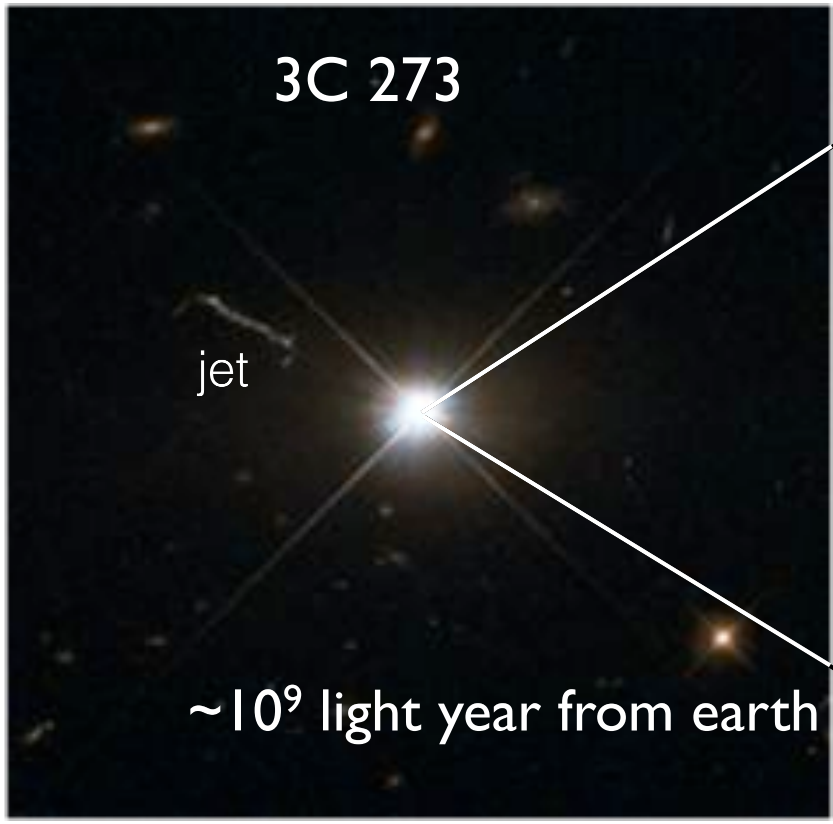
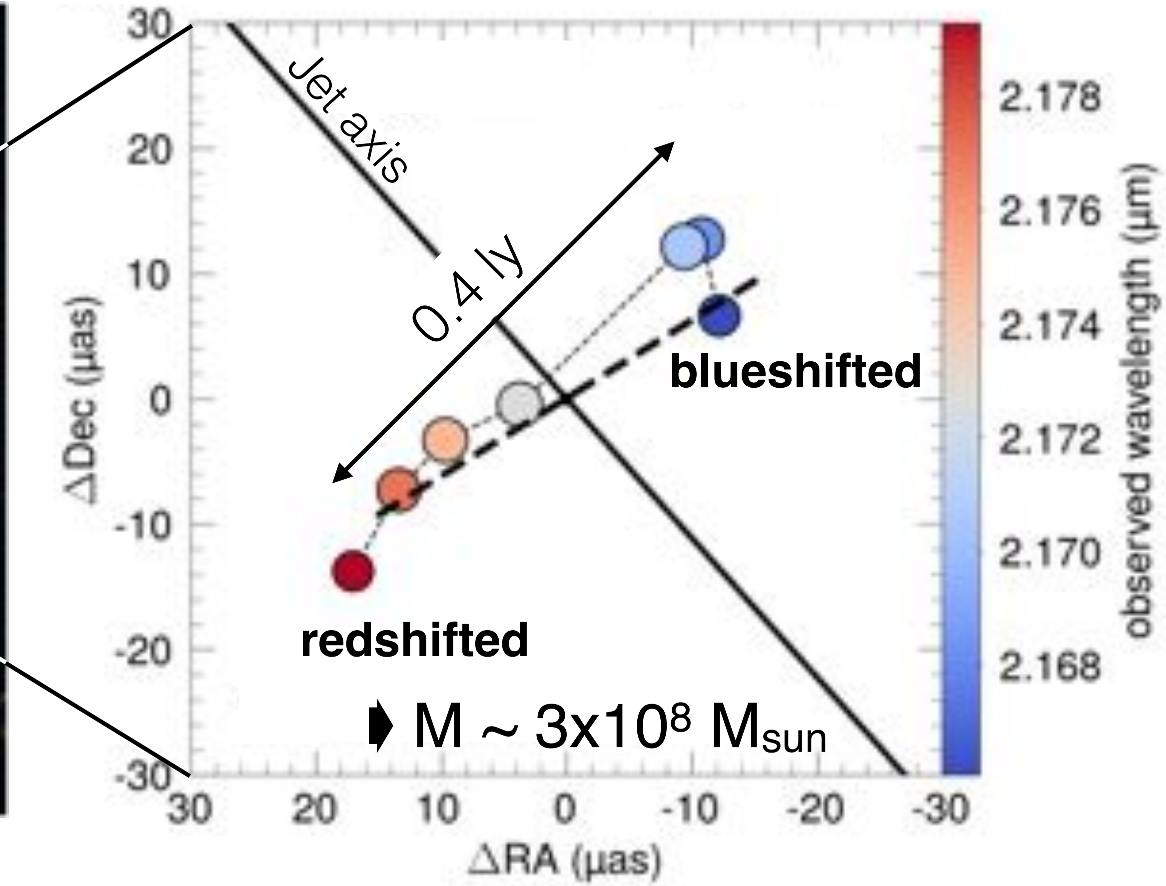


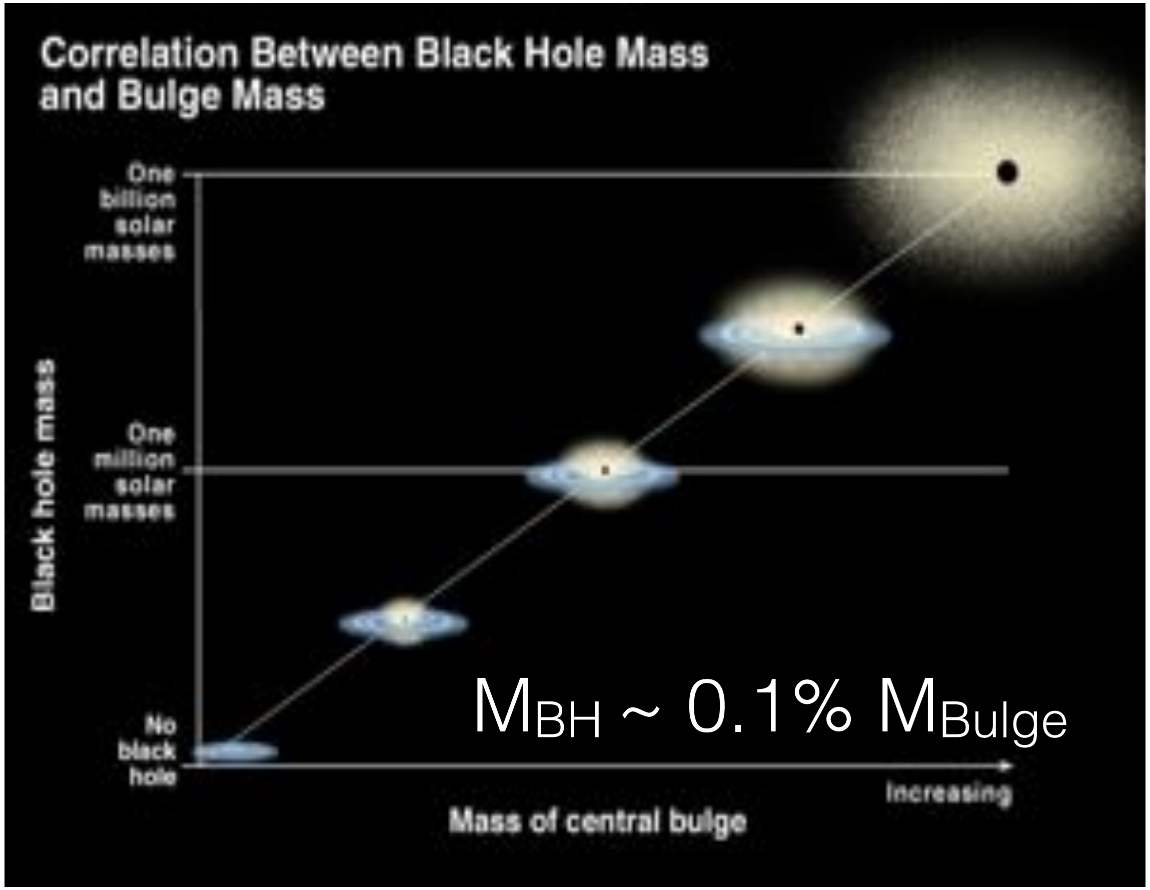


Sturm et al. (2018)

How do we measure their mass?

Super Massive Black Holes

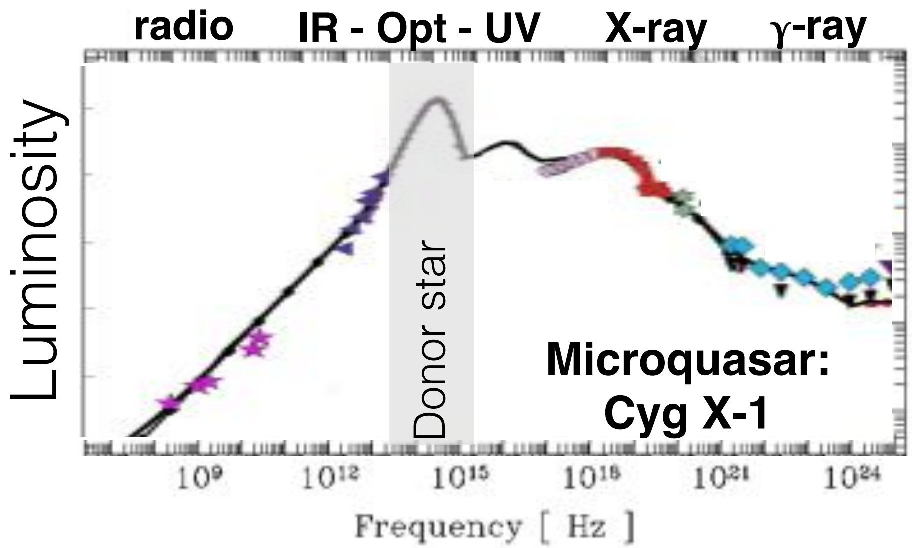
Phenomenological Relationship

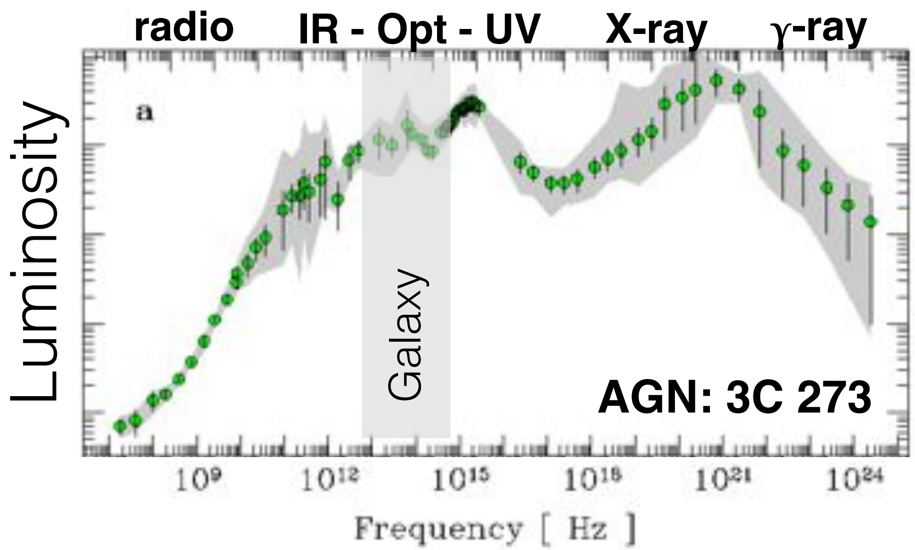


- BH mass related to bulge mass of the host galaxy
- BH growth and galaxy evolutions are related

Astrophysical Black Hole Environment

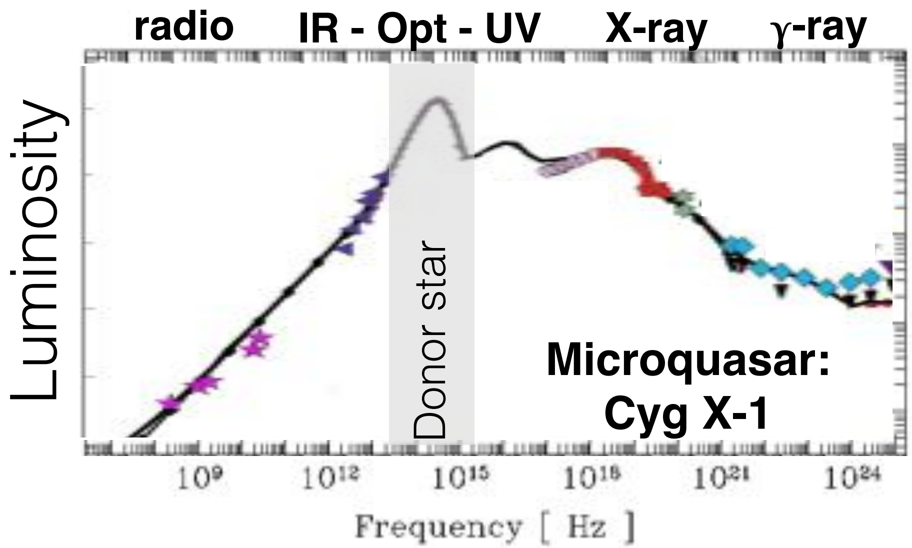
Broad Band Emission

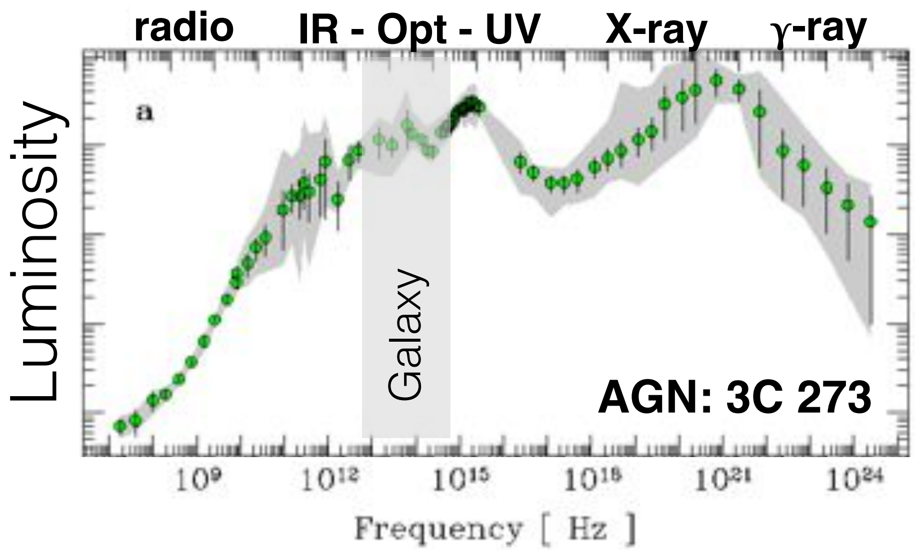




- From Radio to gamma-rays
- Luminosity dominated by high energy bands
- Several spectral components

Broad Band Emission





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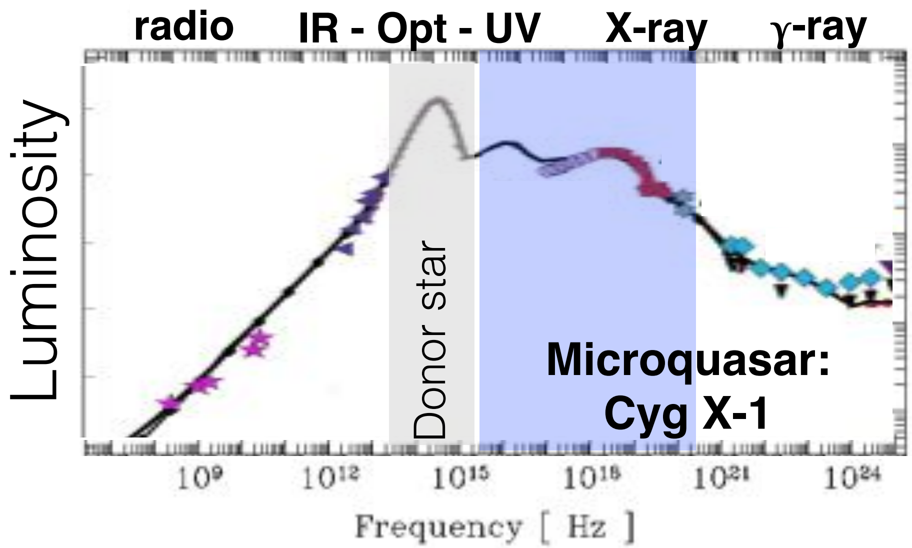

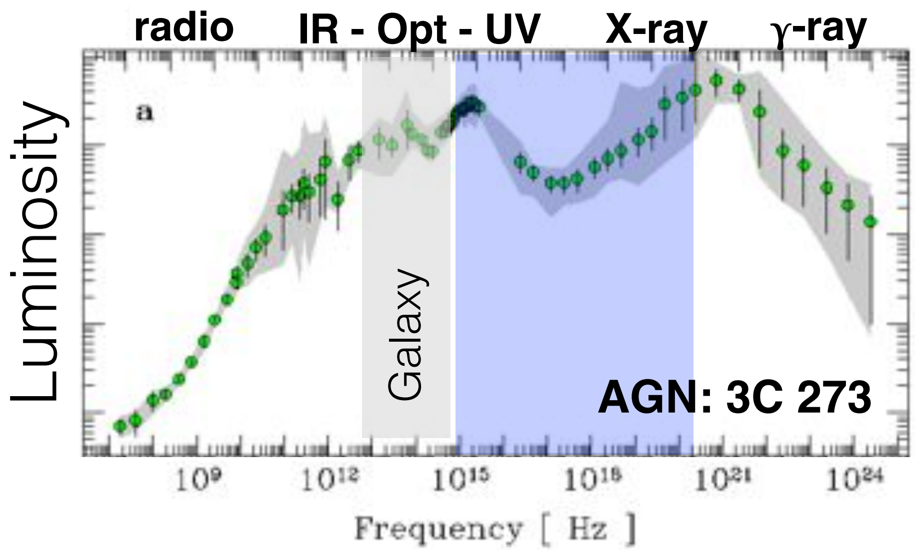

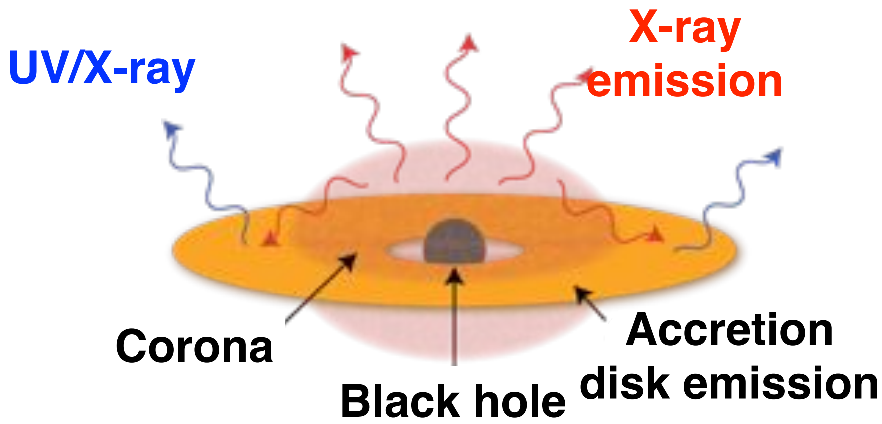

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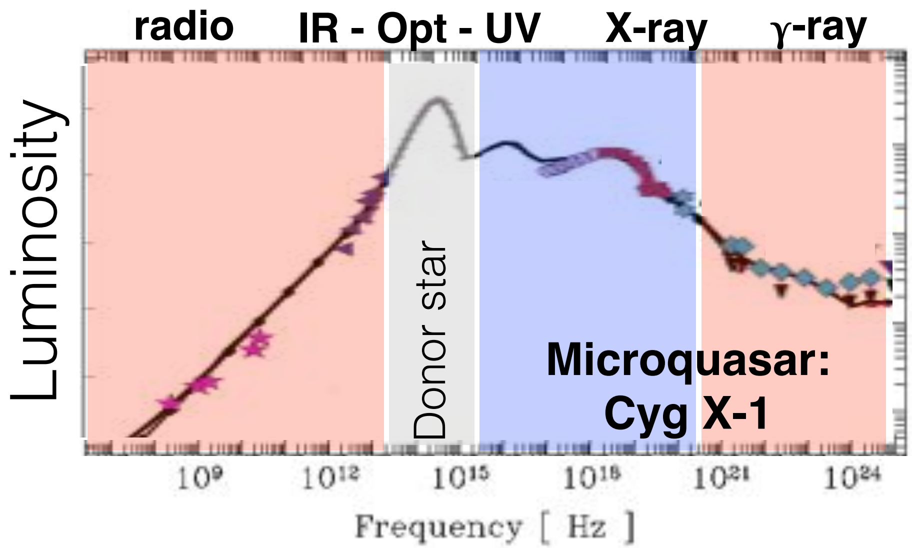
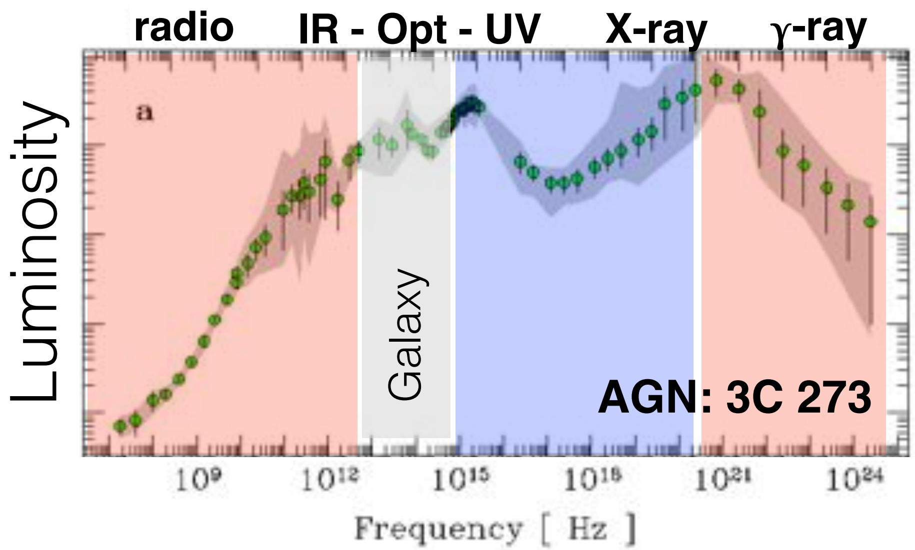
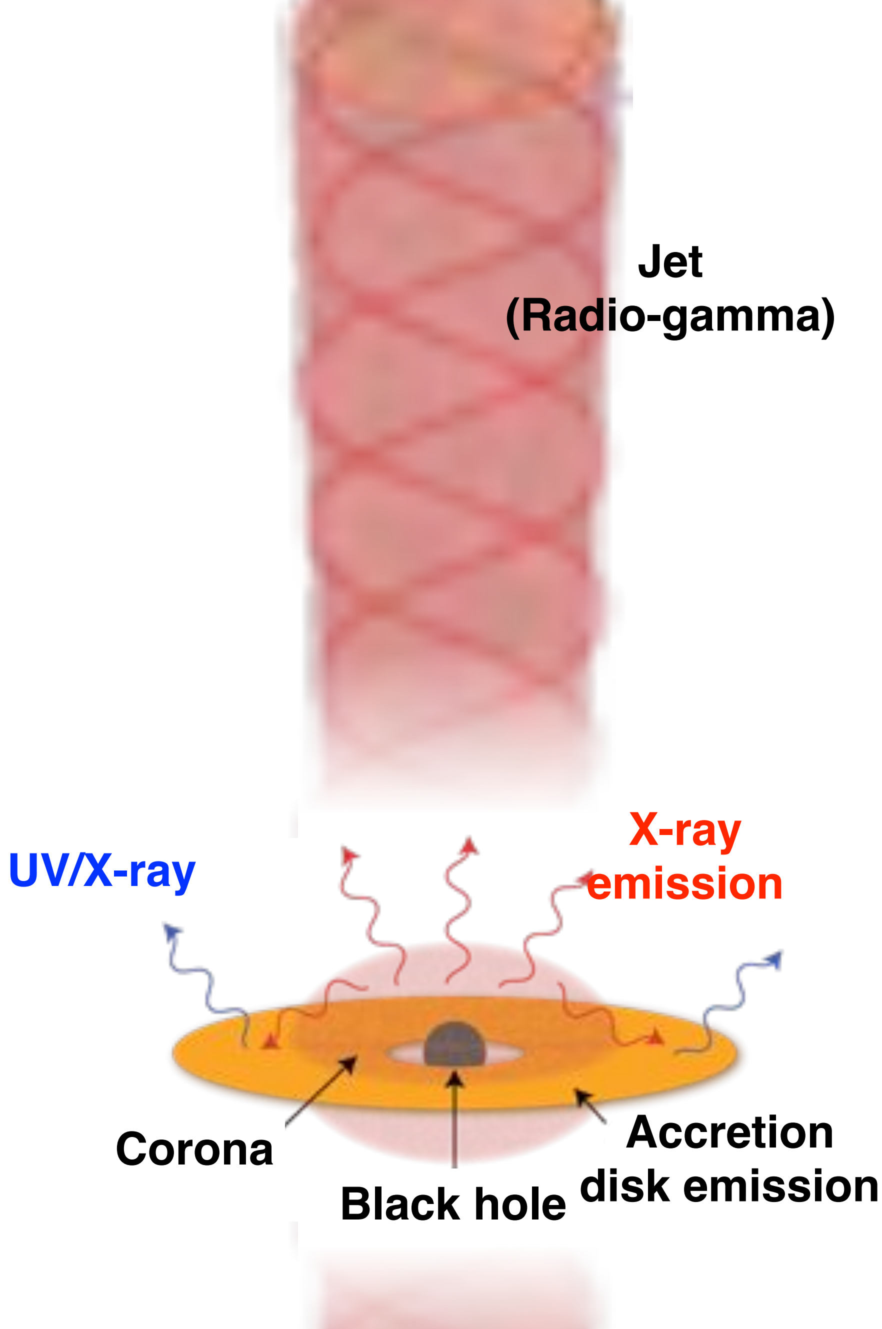




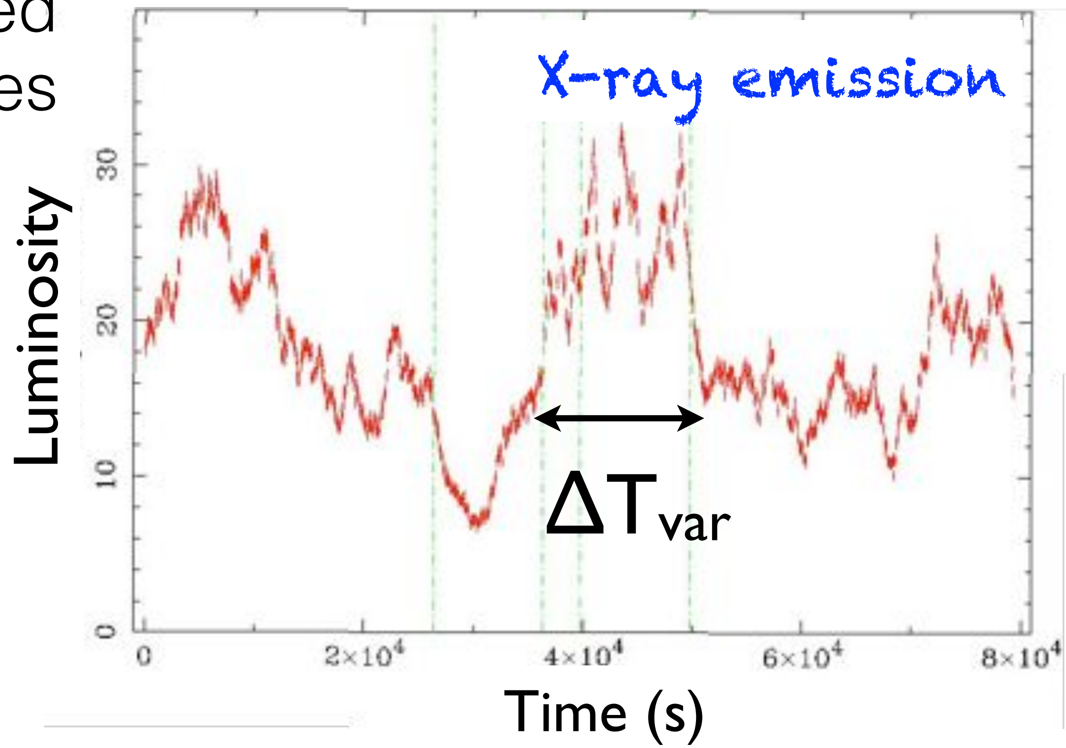


Powerful Accretion

Powerful Accretion

- The accreted matter is heated to large temperature and radiates in X and gamma-rays

- The fastest variabilities are observed at high energy (X, gamma)



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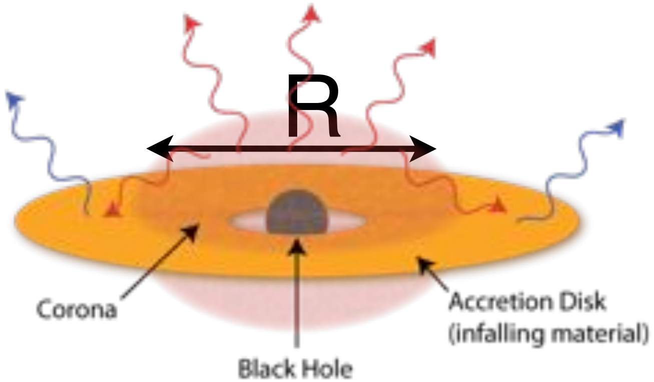
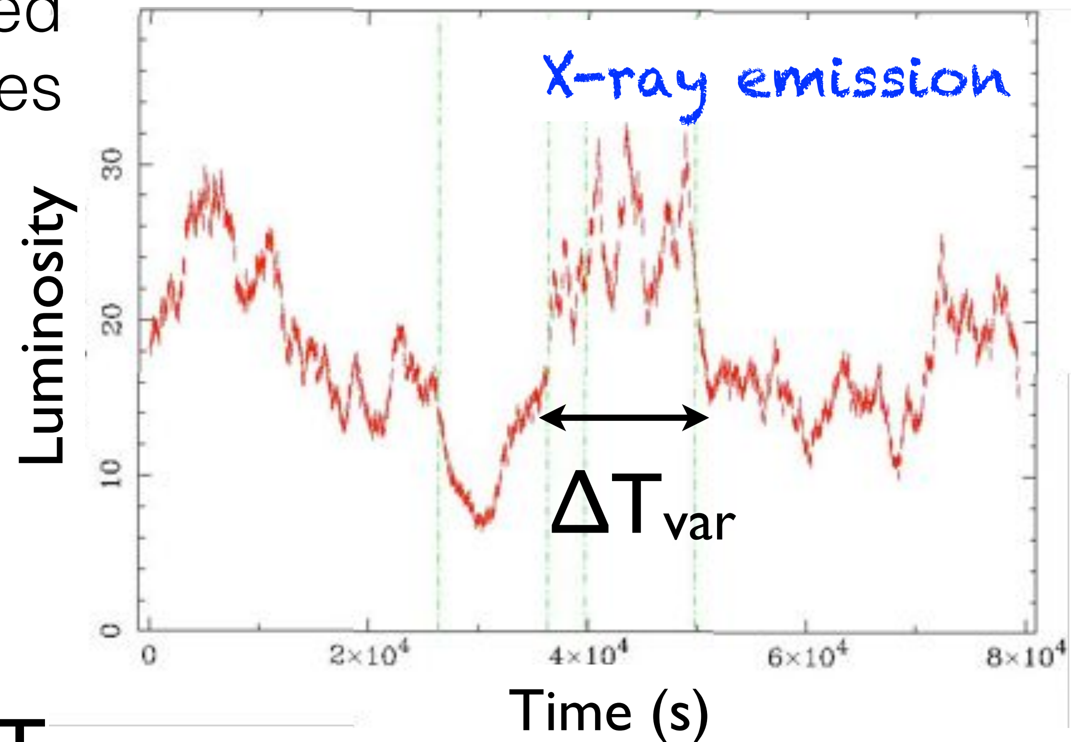
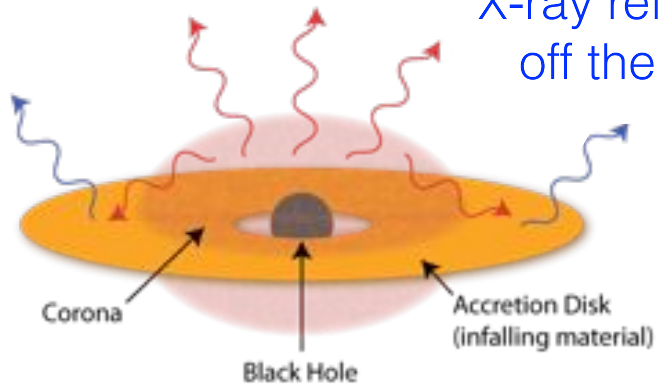


$$R < c\Delta T_{var}$$



⇨ Emitting regions are small, ~kms in microquasars, ~light-minutes (distance earth-Sun) in AGN

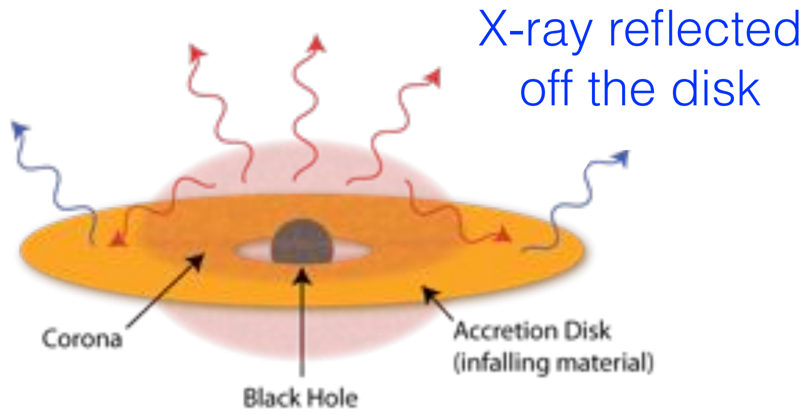
Reflection Component



X-ray reflected
off the disk

Reflection Component

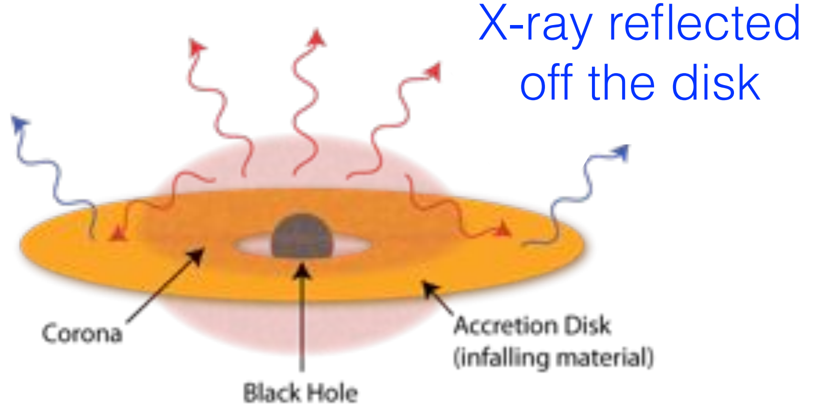
- Part of the X-ray emission is reflected on the accretion disk



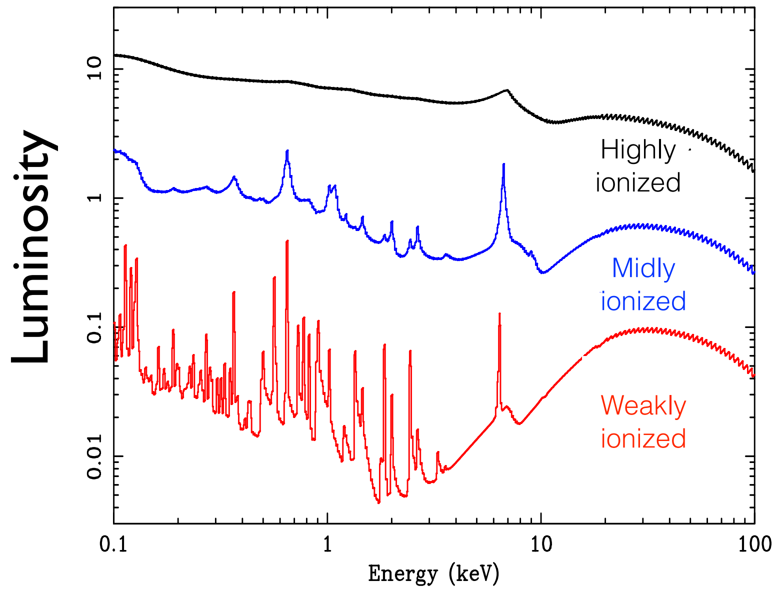
Reflection Component

- Part of the X-ray emission is reflected on the accretion disk

- The nature (ionisation, geometry) of the corona-disk is imprint in the reflection components



Ionisation effect



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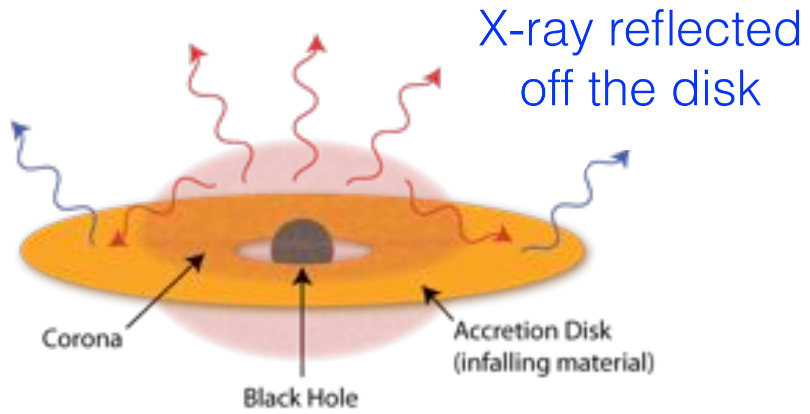

Reflection Component

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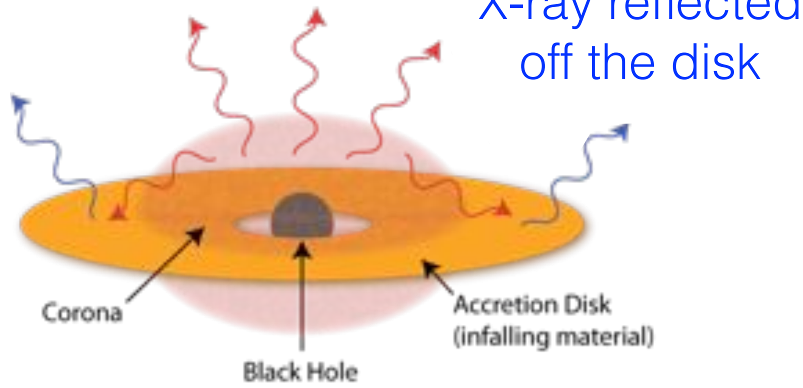
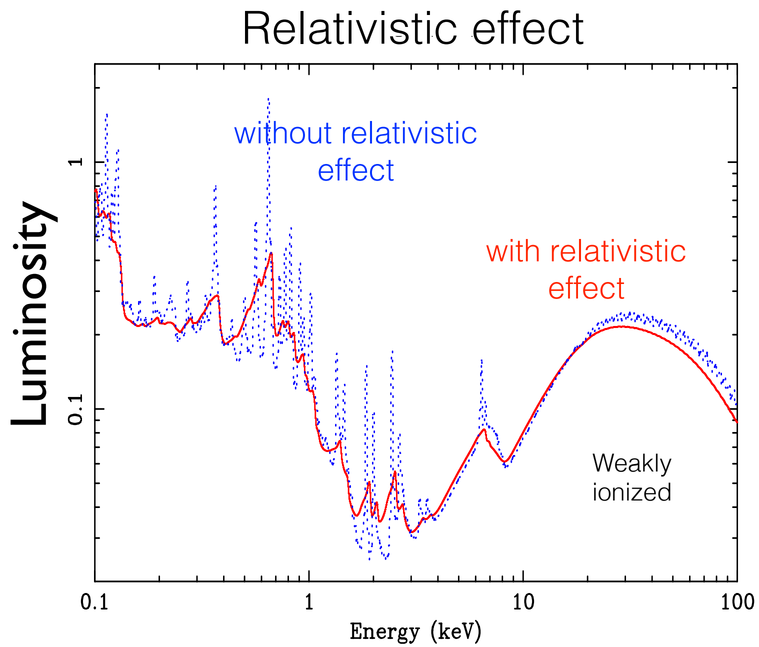
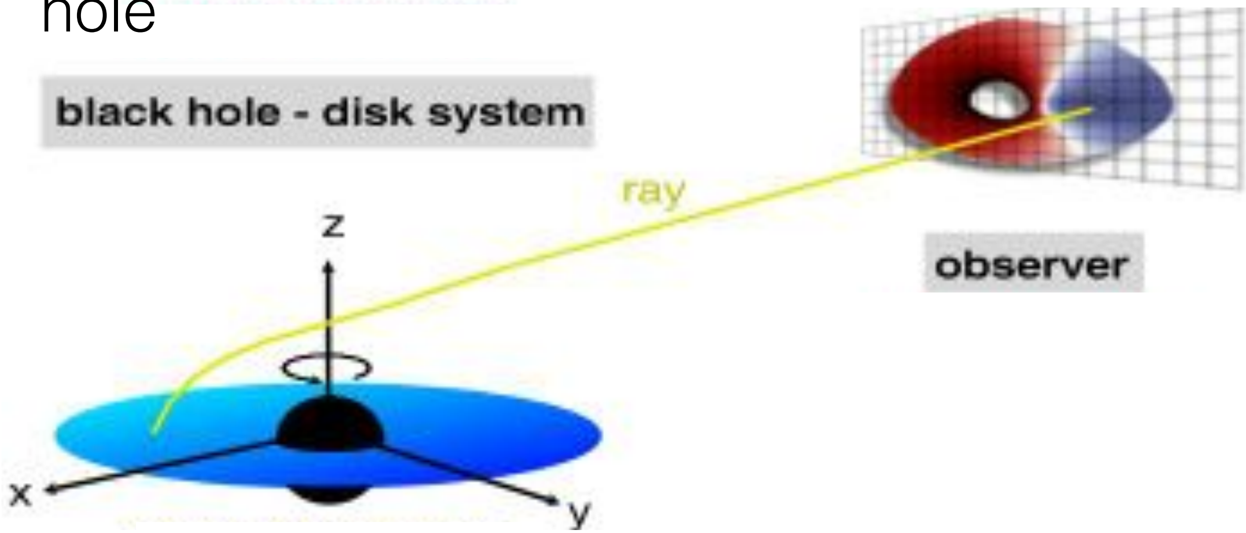
- The nature (ionisation, geometry) of the corona-disk is imprint in the reflection components

- … but also the relativistic effects when it is emitted close to the black hole







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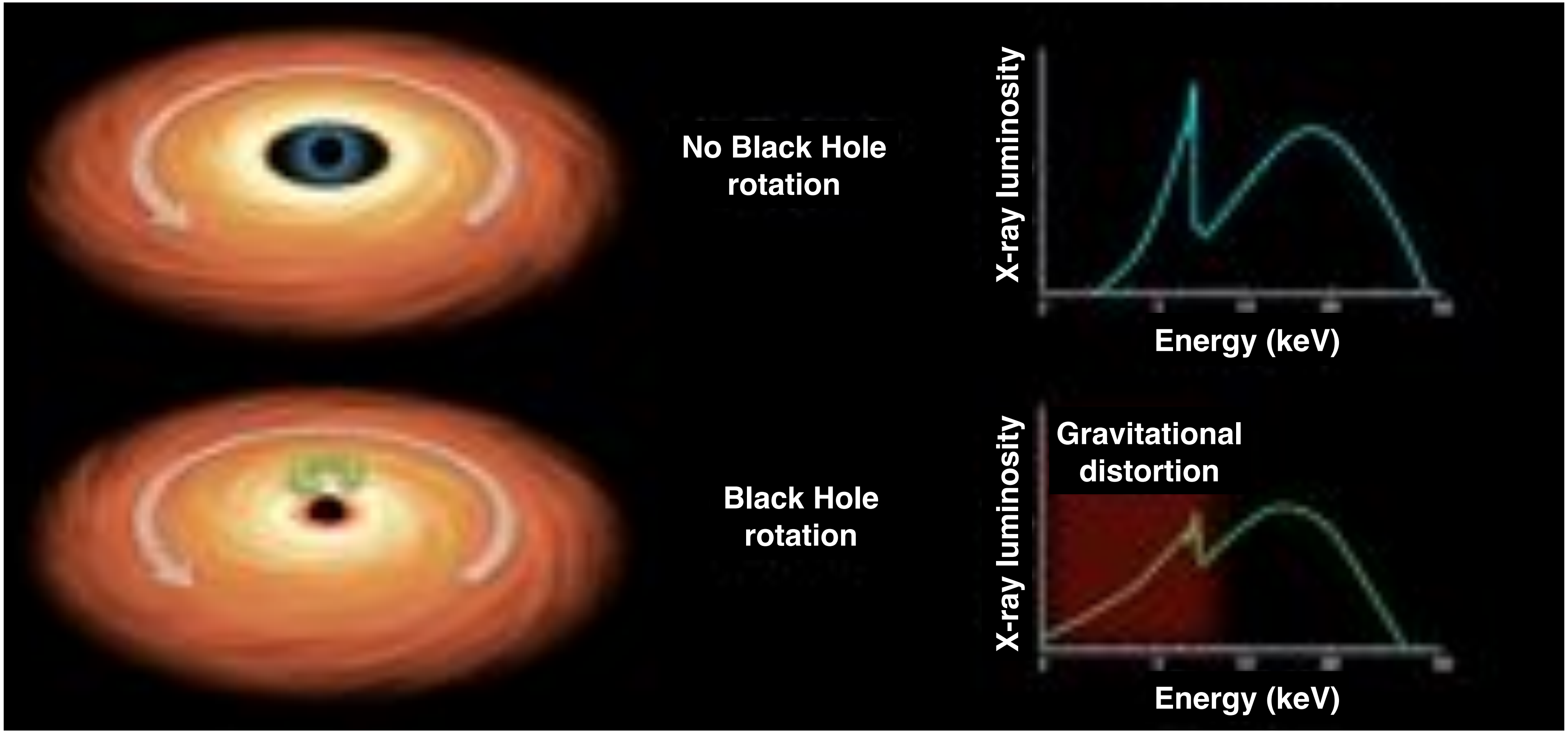

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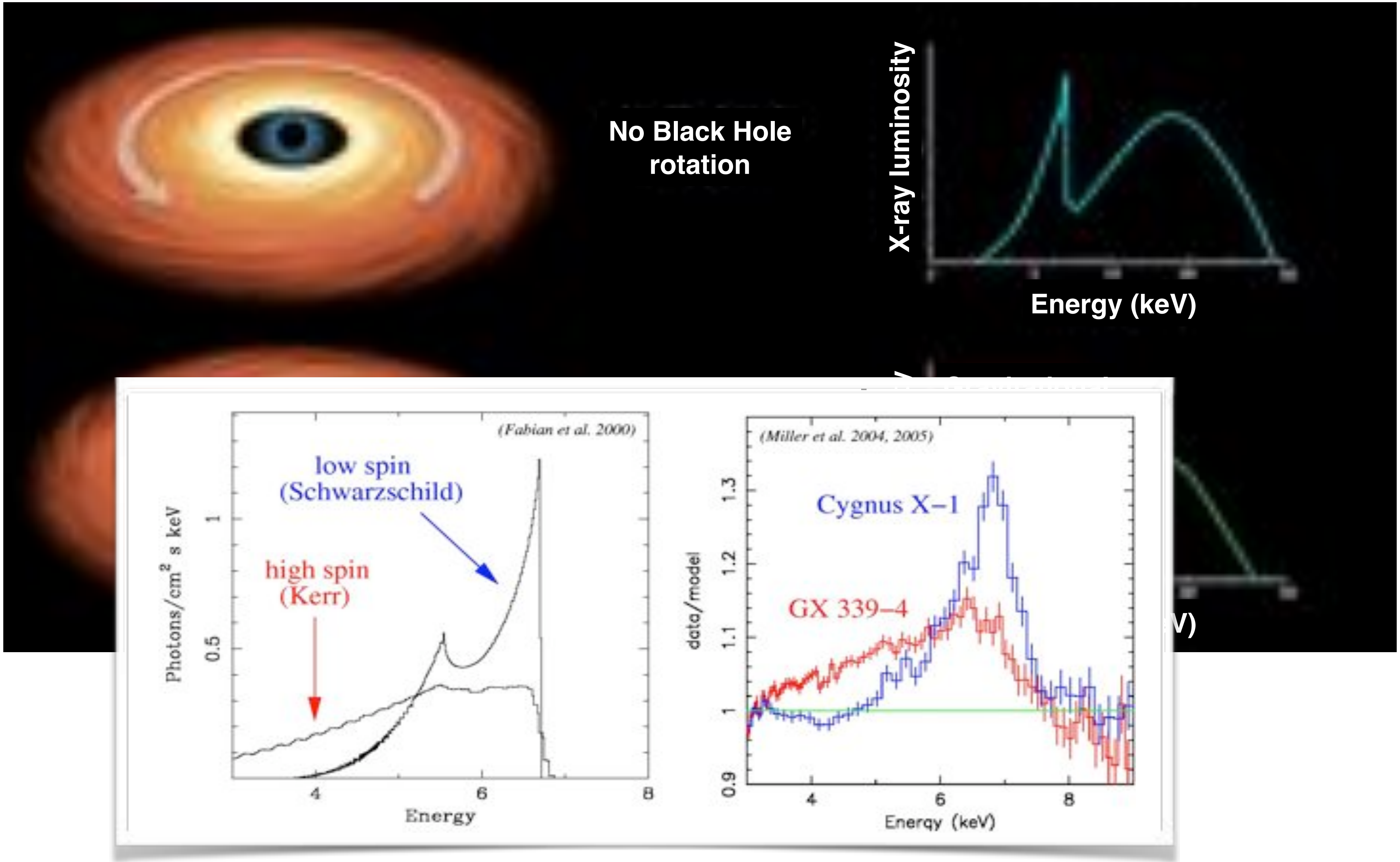
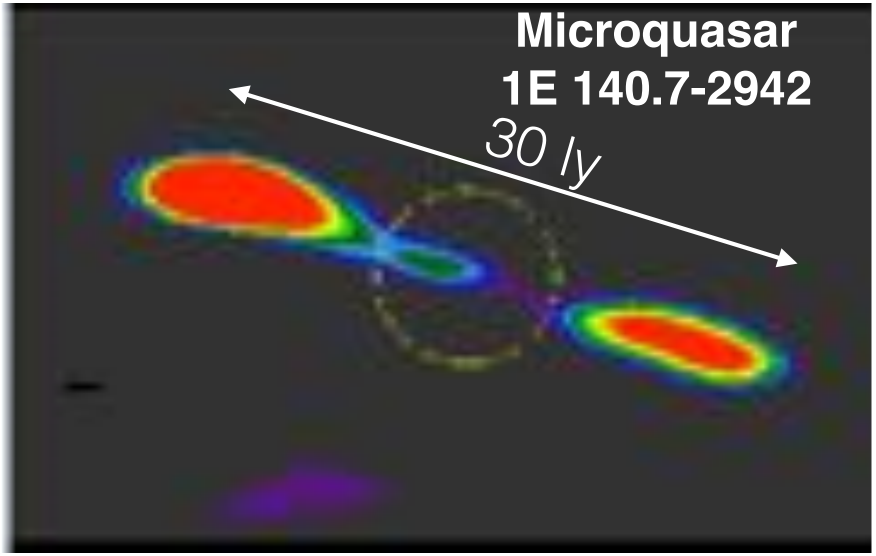
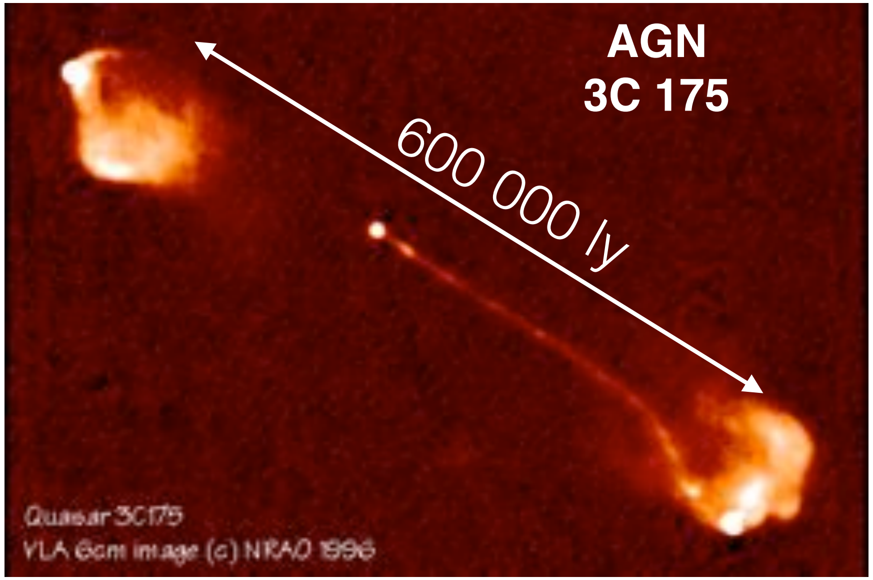


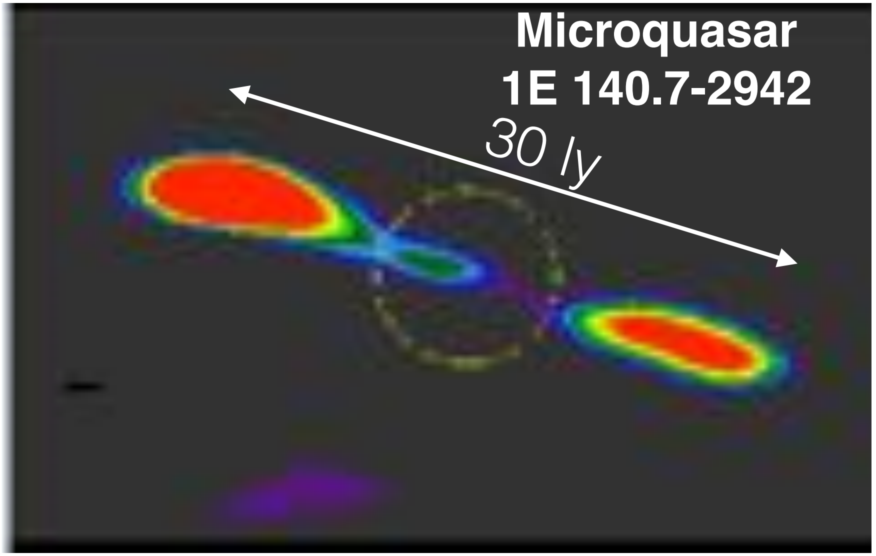
Powerful Ejections

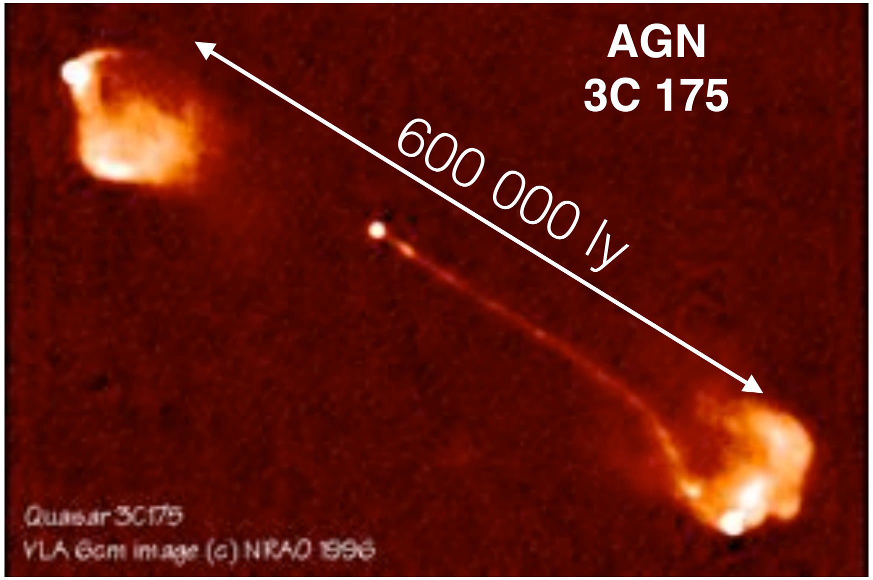




- X-ray binaries show powerful ejection during their outburst
- 10% of active galaxies have powerful jets
- Radio-Gamma ray emission indicating highly relativistic particles

Powerful Ejections





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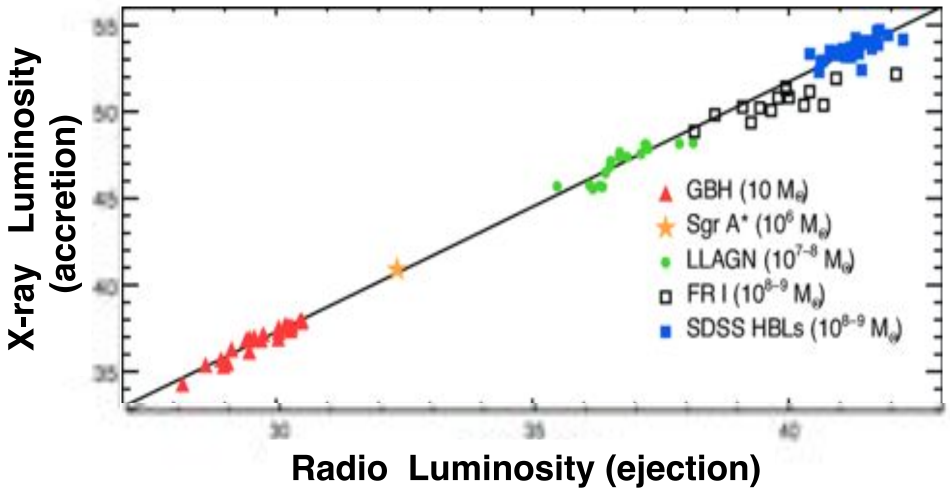
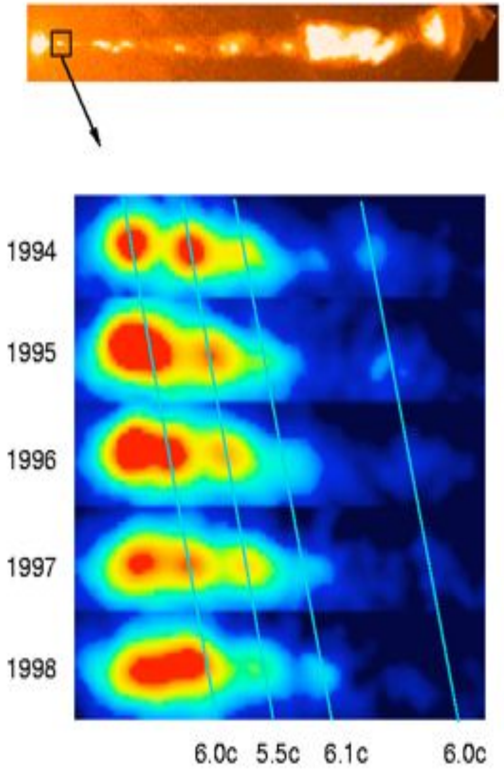


- Accretion and ejection processes are intimately related

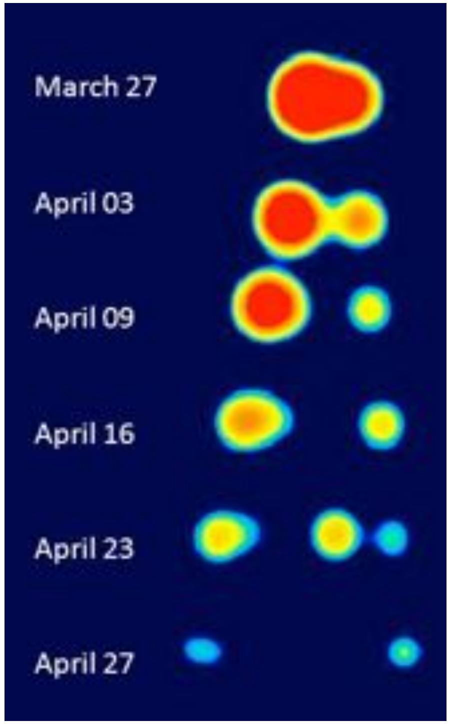
➨ talk by J. Ferreira

Superluminal motions

Radio galaxie M87



Microquasar
GRS 1915+105



1.7c

Superluminal motions

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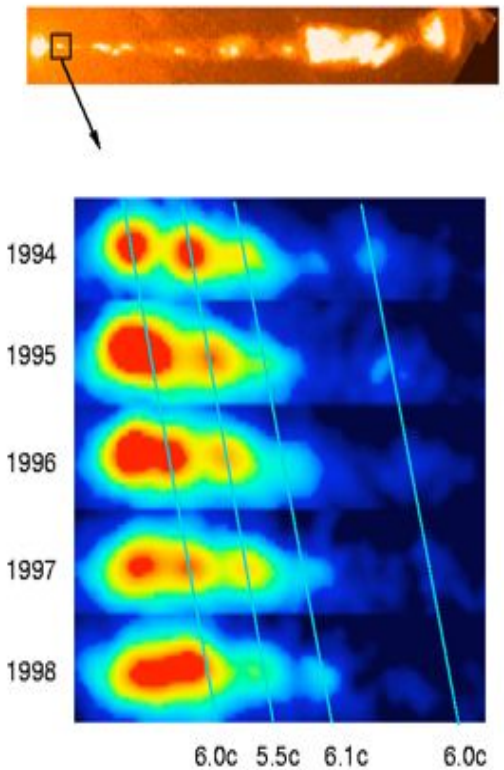

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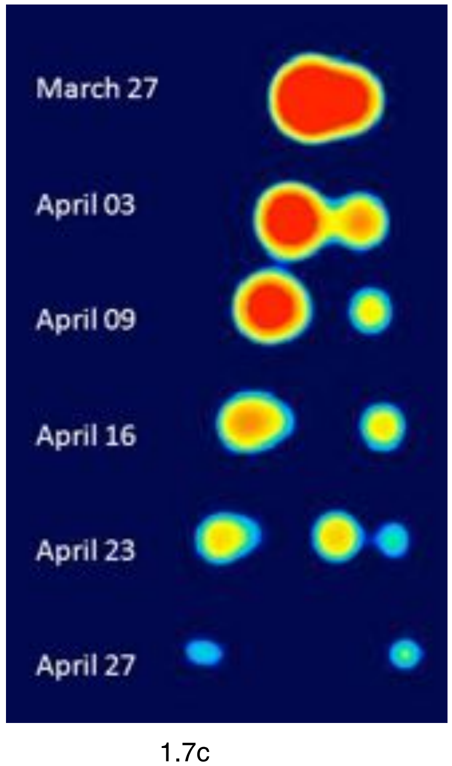
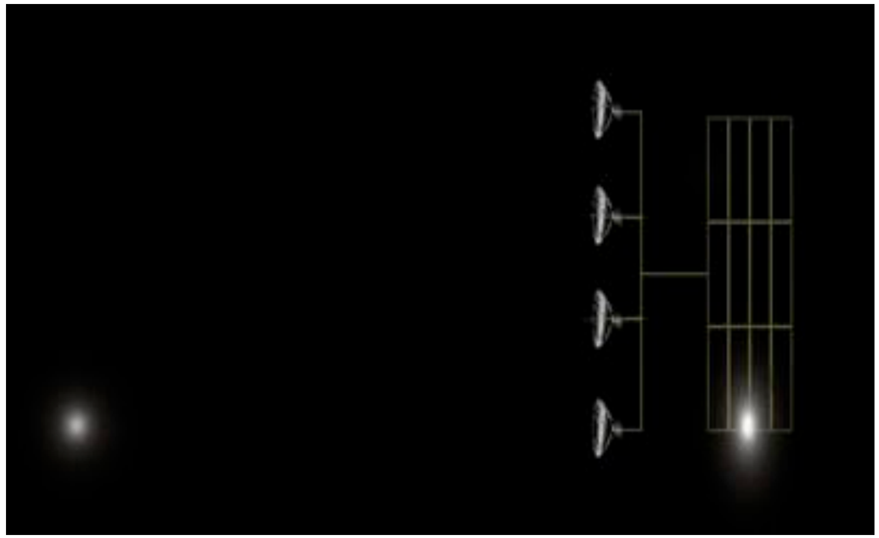
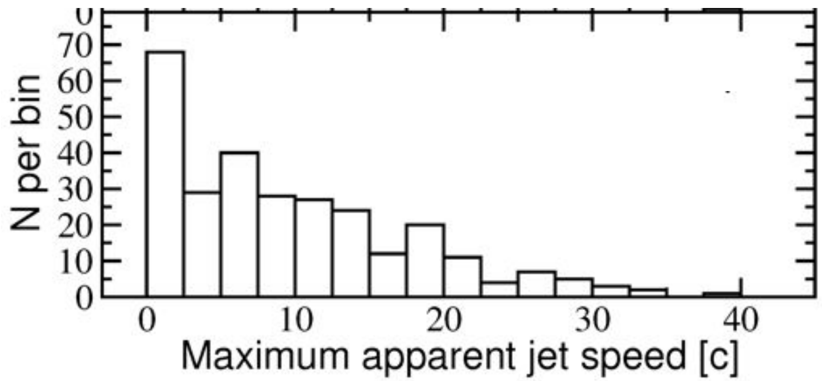
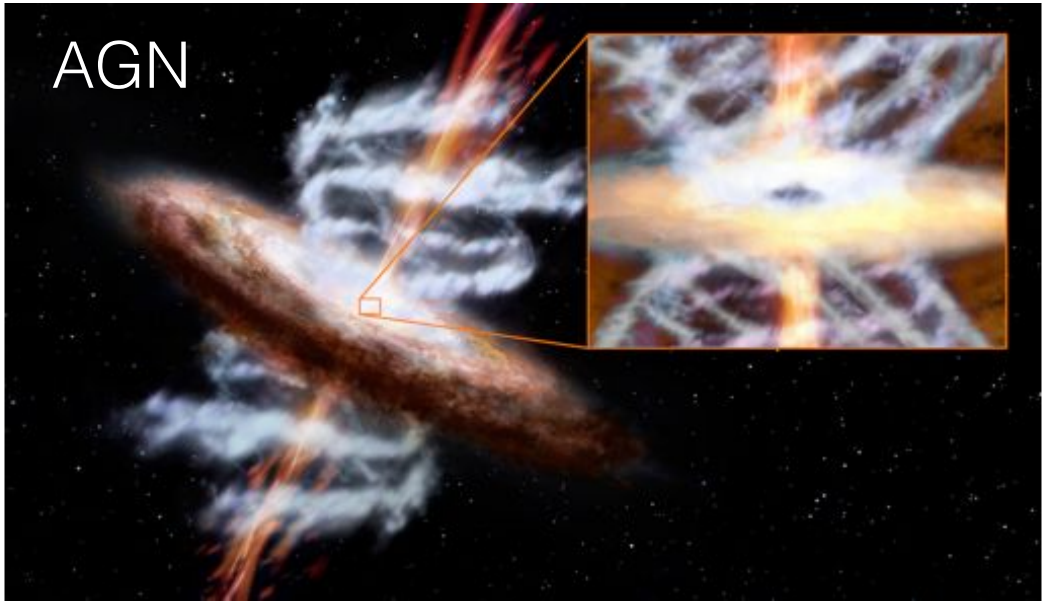




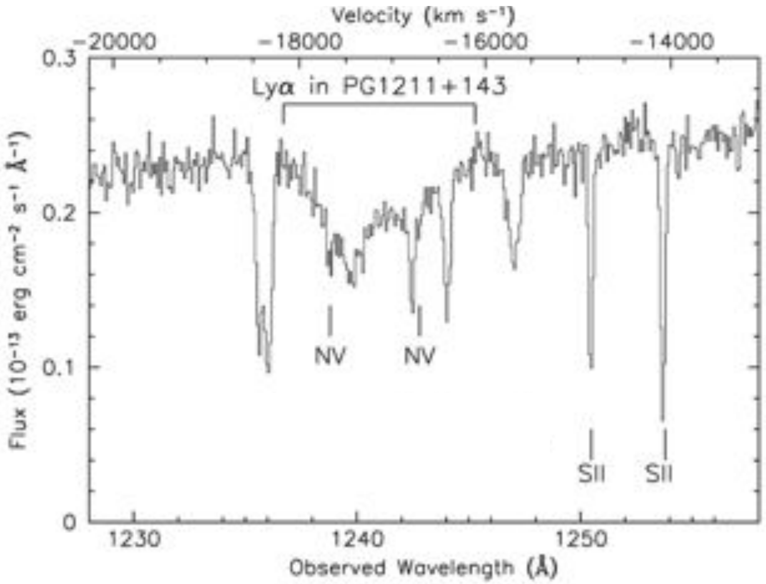


Projection effect when material moves close to speed of light close to the line of sight

Smooth Winds



- Blueshifted absorption lines signature of outflowing material at 1000s to 10 000s of km/s

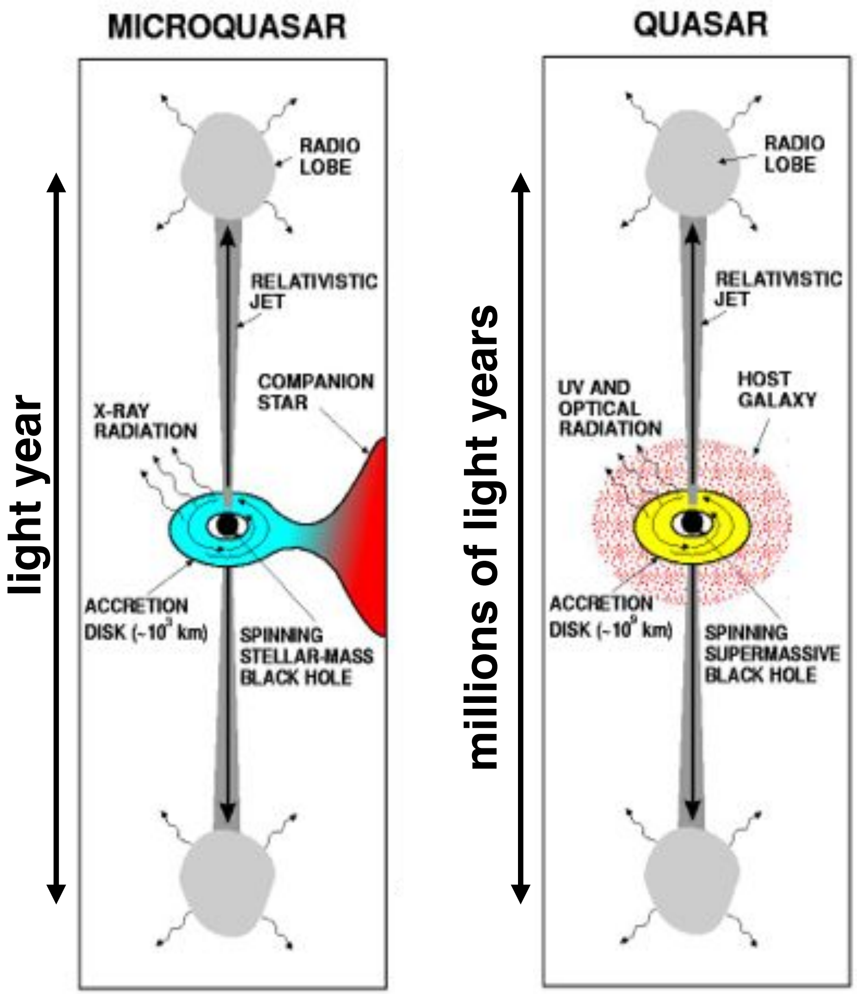


- Could have strong influence on the compact object evolution

Anatomy of an AGN in NGC 5548

Anatomy of an AGN in NGC 5548

Are Microquasars and AGN the same but on different scales?



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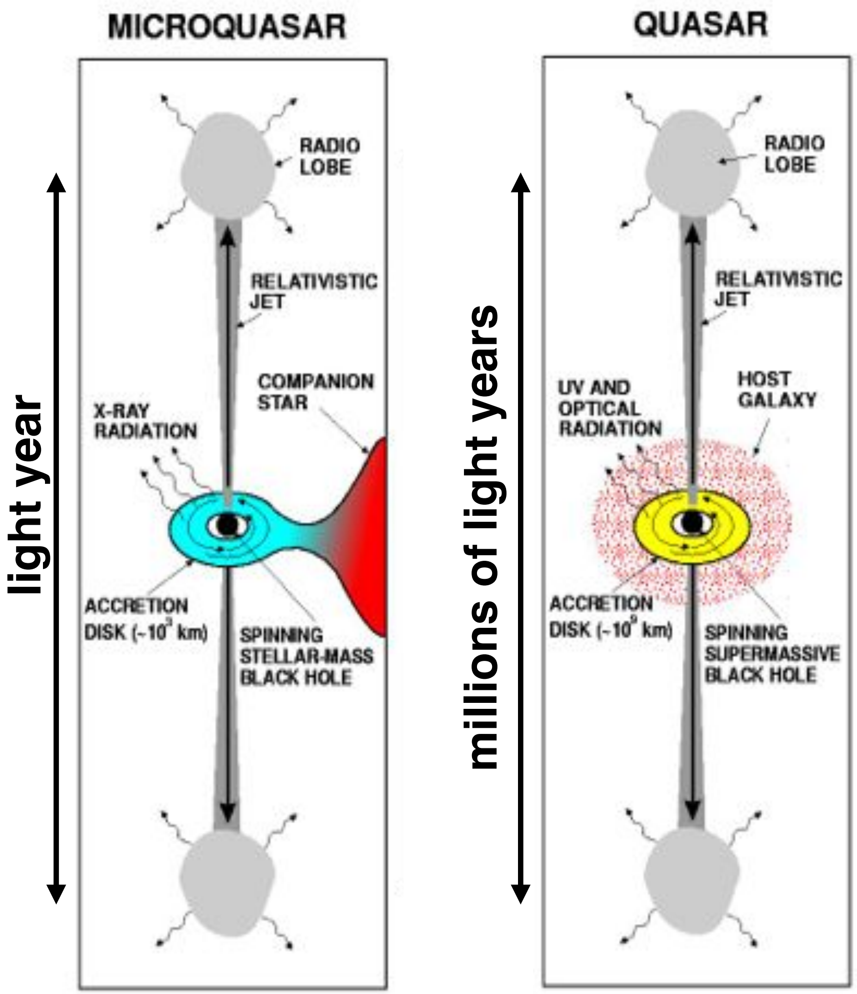

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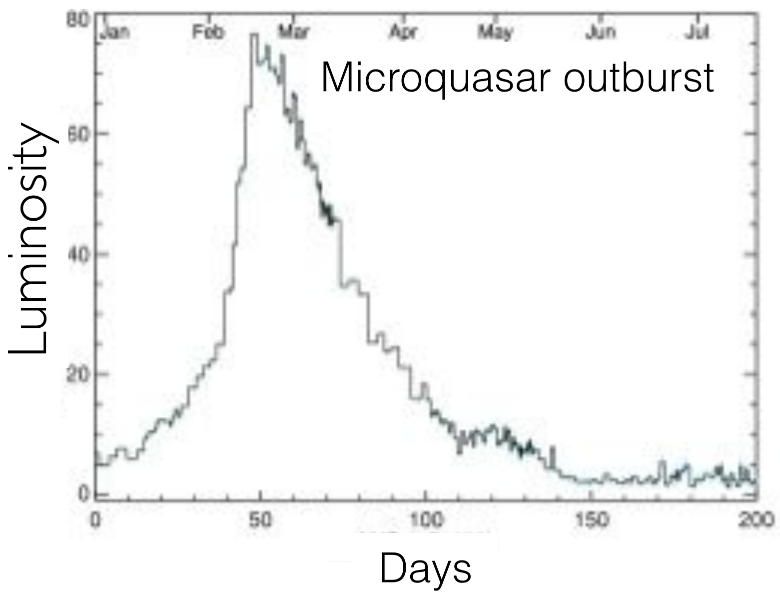

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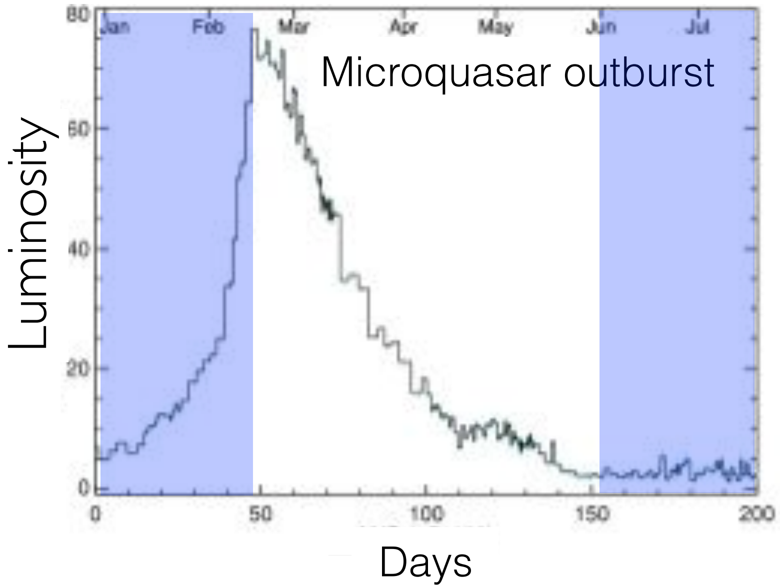

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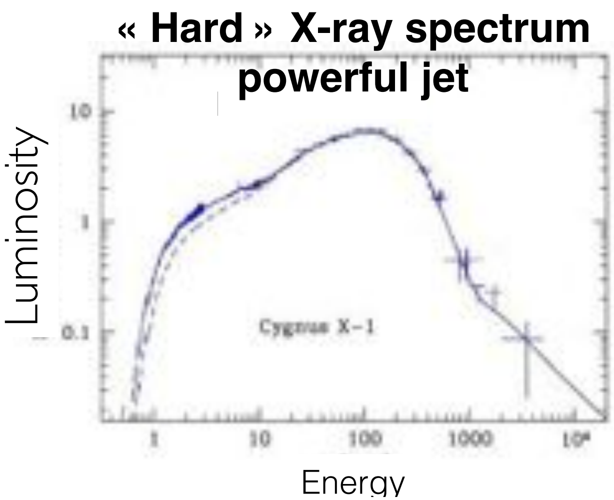

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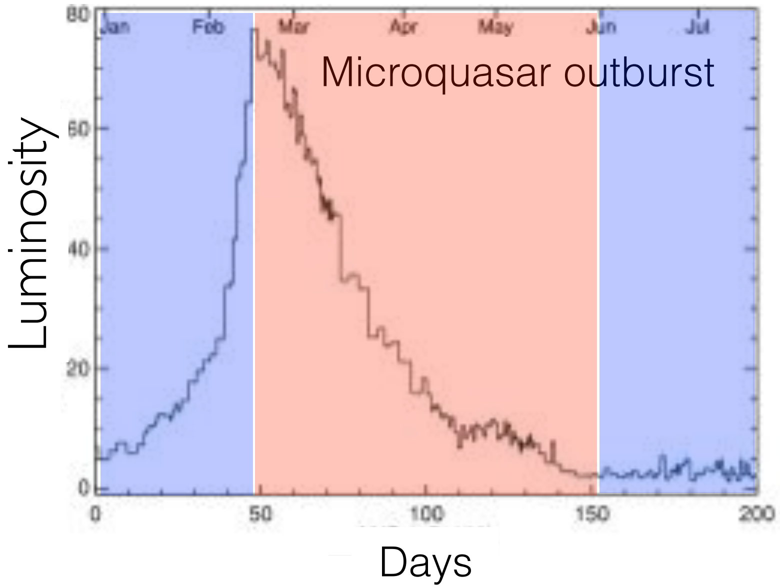

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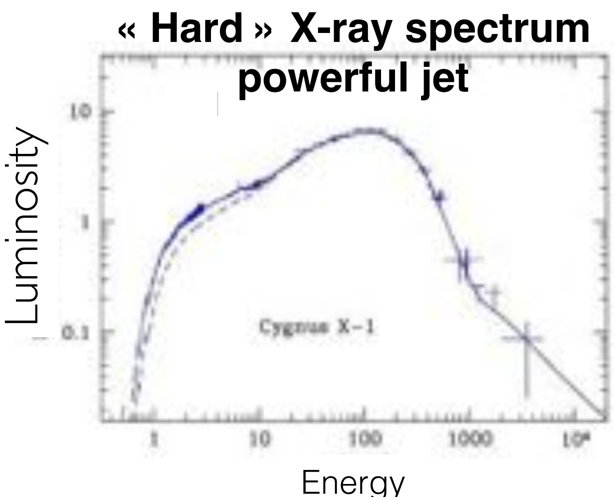

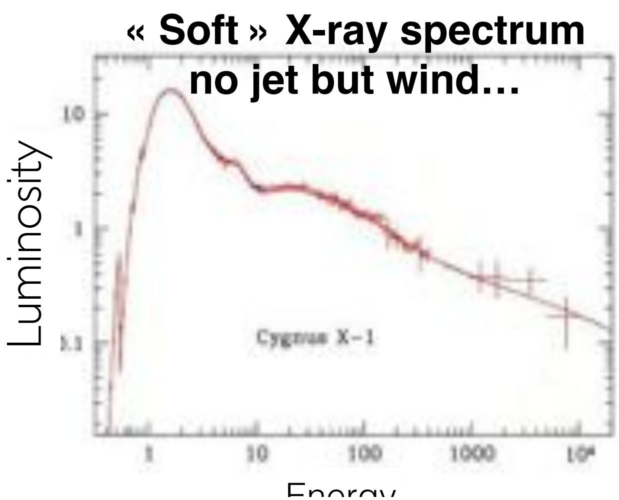

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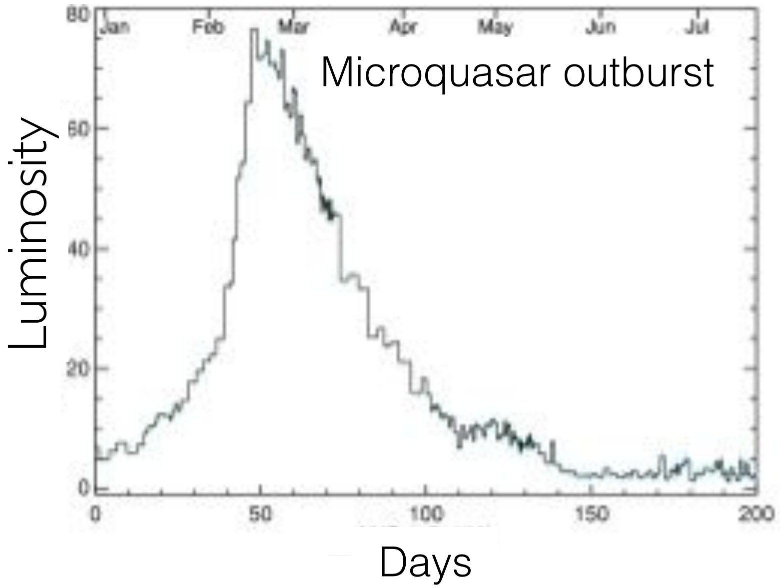
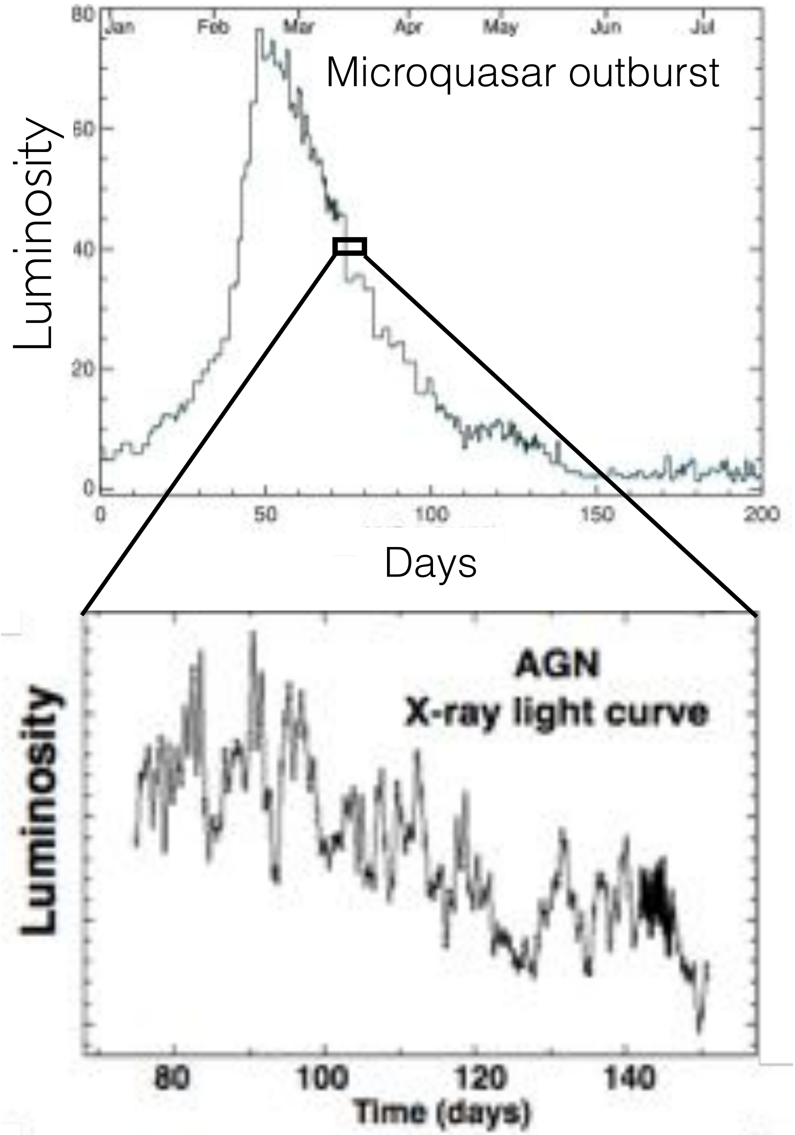


Are Microquasars and AGN the same but on different scales?



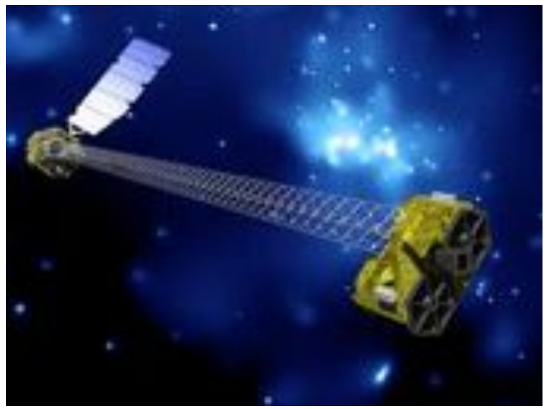
- 1 sec. of a microquasar lifetime corresponds to month/years of an AGN lifetime…
- AGN could be different snapshots of microquasars evolution during outburst

A Promising Future

Black holes under the « Microscope »

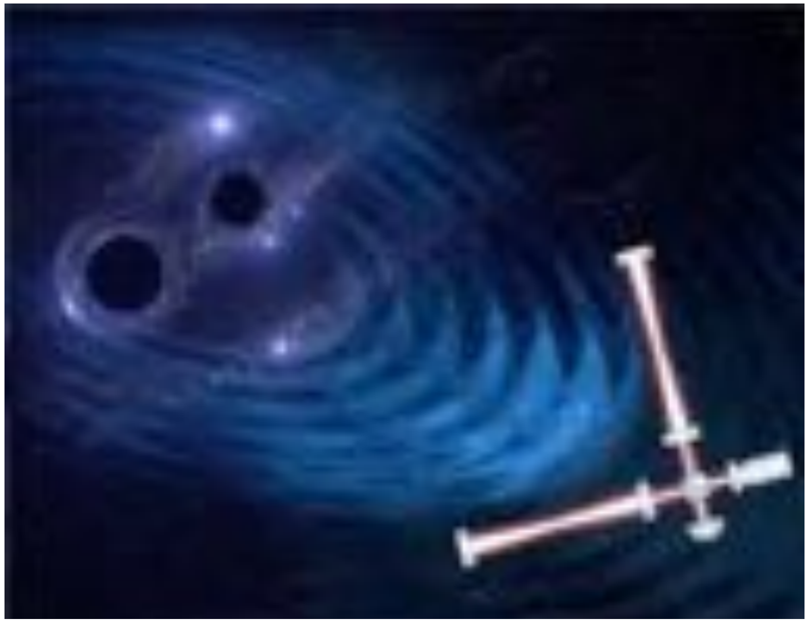
- The SMBH of our Milky Way
  - Multi wavelength observation of its environment
    - ➨ talk by M. Clavel
  - GRAVITY on VLTI
    - ➨ talk by K. Perraut

- GRAVITY, XMM, NuSTAR,… currently at work!



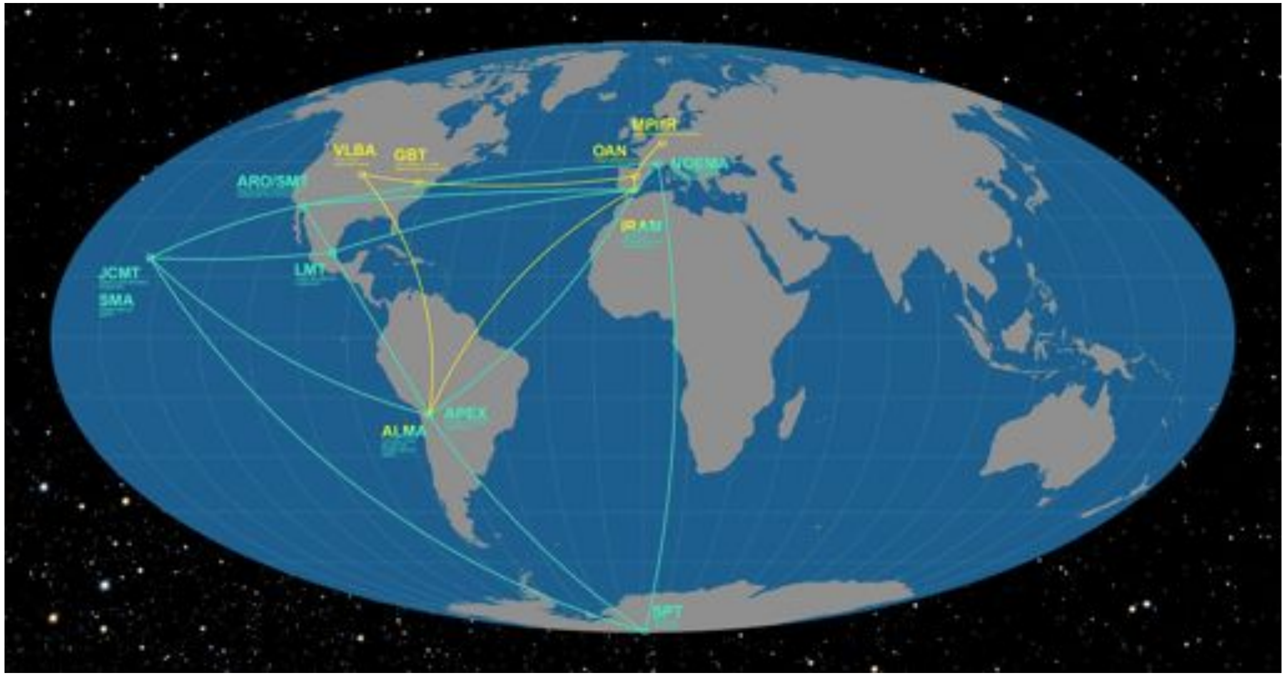
Black holes under the « Microscope »

- New instruments (a few examples):
  - Gravitational waves experiments open a new window to learn about BH properties in the Universe ➨ see tomorrow's talk



Black holes under the « Microscope »

- New instruments (a few examples):
  - Event Horizon Telescope (radio)



- Spatial resolution to resolve the event horizon of close SMBH
- Targets: SMBH of our Milky Way, Messier 87
- Goal: direct image of the BH shadow…

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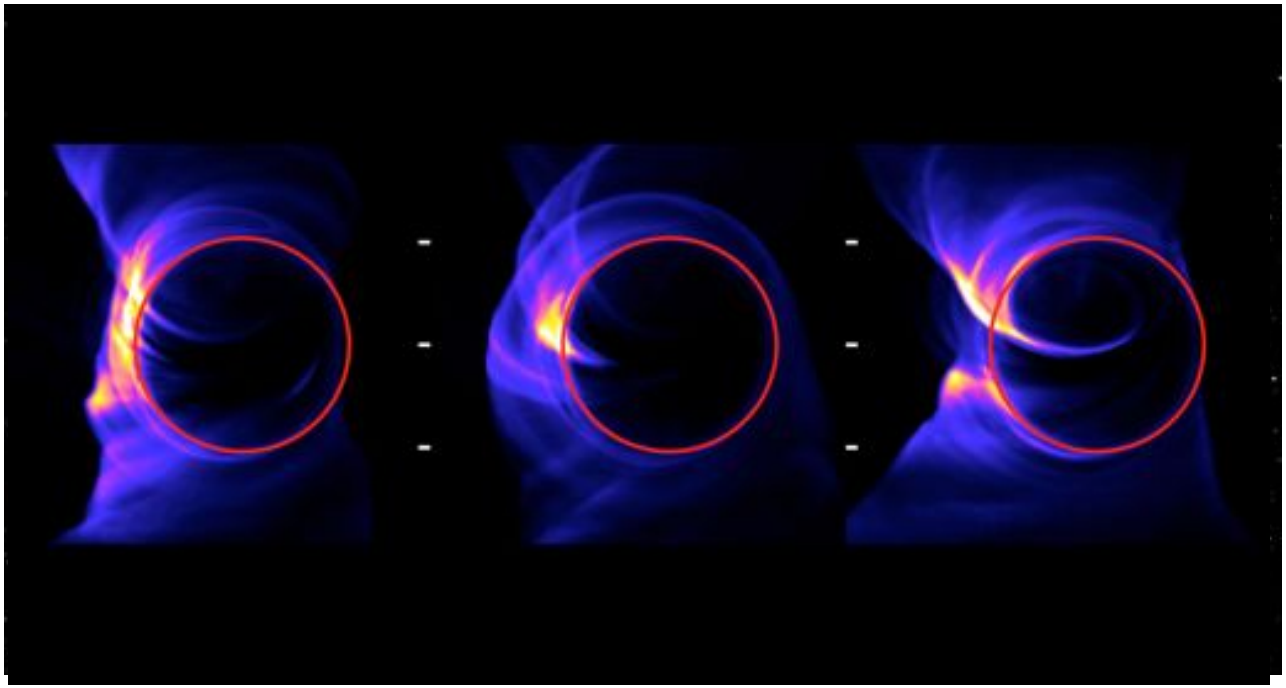

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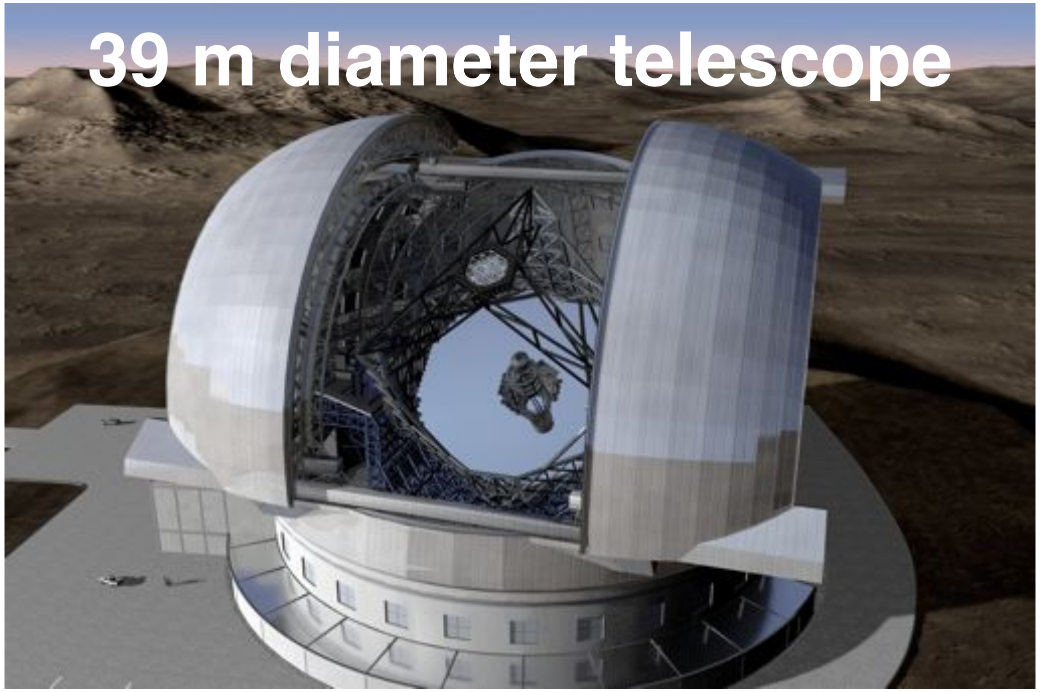
Black holes under the « Microscope »

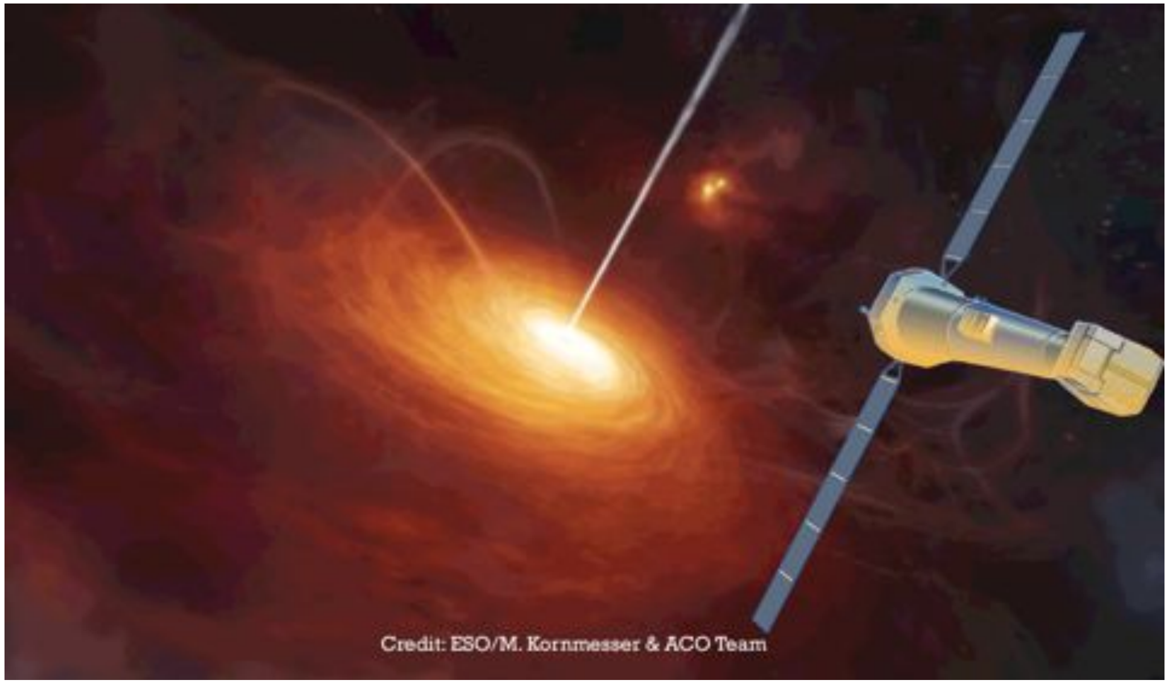
- New instruments (a few examples):
  - Extremely Large Telescope (Optical/IR)



- Large collecting area
- Targets: Spectroscopy of large samples of high-*z* AGN
- Goal: understand the formation of the SMBH
- First light: 2024

Black holes under the « Microscope »

- New instruments (a few examples):
    - Athena satellite (X-ray)



- Large collecting area, high spatial, spectral and timing resolution
- Targets: High-z AGN
- Goal: understand the formation of the SMBH.
- First light: 2030…

Stay Tuned!

Thanks!