Supermassive black holes

Where do they live? How to find them?

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Sormano, 26 March 2026

What is a black hole?

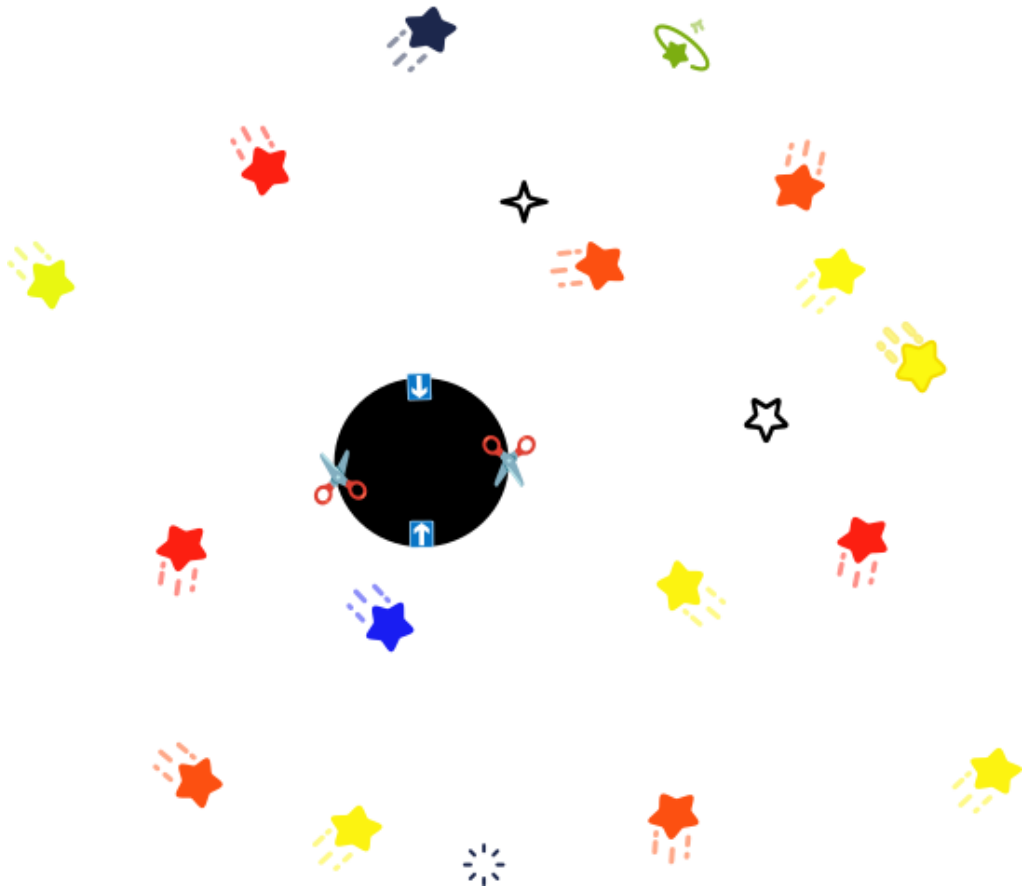




In English we say things like:

- "My car is a black hole. It just sucks up money."
- "I can't get a mobile phone signal at home. I live in a black hole."

Black holes in Physics

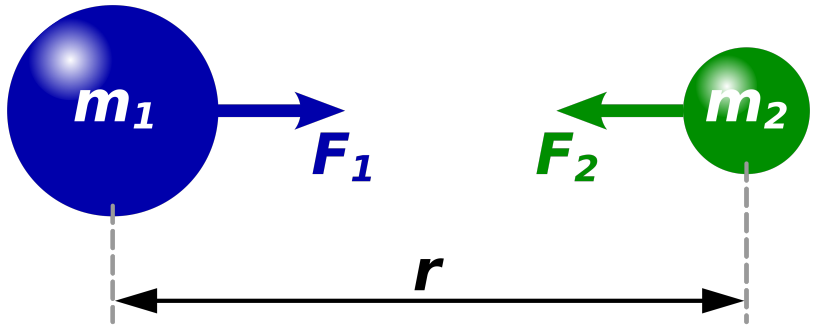


A black hole (BH) is a one-way hole cut out of space:
anything that crosses the boundary of the BH is gone forever!
It loses contact with the rest of the Universe.

What magical scissors can cut out such a hole?

What causes a black hole? Gravity!

Isaac Newton (1667, 1687): universal law of gravitation



$$F_1 = F_2 = G \frac{m_1 \times m_2}{r^2}$$

credit: Dennis Nilsson

The Earth pulls us. We pull the Earth.

If we wanted to escape the Earth we could either

- use a rocket to accelerate upwards, or
- jump very hard (11 km/s – escape velocity).

If we squeezed the earth into a smaller radius, we'd have to jump even harder.

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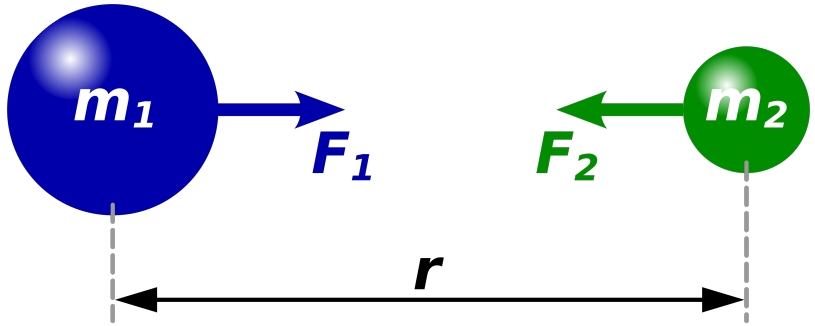

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credit: Dennis Nilsson

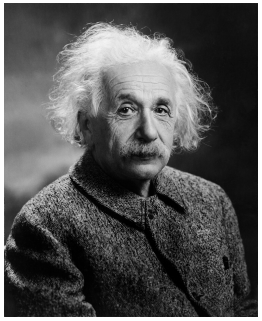
John Michell (1784), Pierre-Simon Laplace (1796):

Escape speed from Sun (r=7 million km) is $\sim$ 600 km/s.

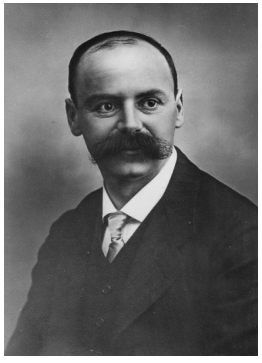
If we compressed the Sun to a radius of 3 km, then the escape speed would be 0.3 million km/s = the speed of light!
The sun would be invisible.

Beyond Newton

Two important results from 1915:



Albert Einstein (1879-1955) publishes his general theory of relativity



Karl Schwarzschild (1873-1916) finds the first solution to Einstein's theory.

Schwarzschild finds that **nothing** can escape from radii

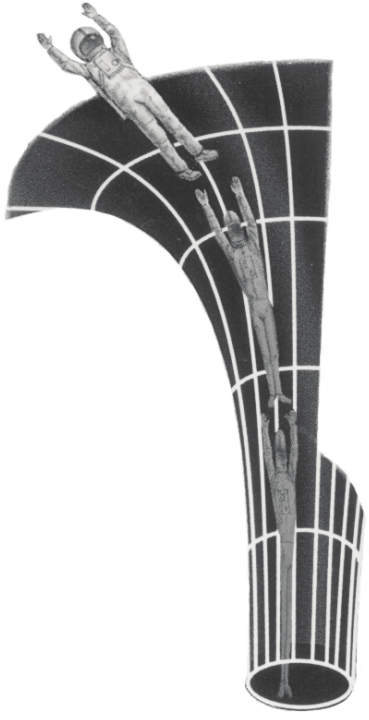
$$r < \frac{2GM}{c^2},$$

the **Schwarzschild radius**.
Consistent with Michell/Laplace calculations using Newtownian theory.

Manholes versus funnels

Unlike a manhole cut in the ground (or a Portal), the gravitational force from a black hole becomes stronger the closer we approach.





Black holes (BHs) spaghettify matter.

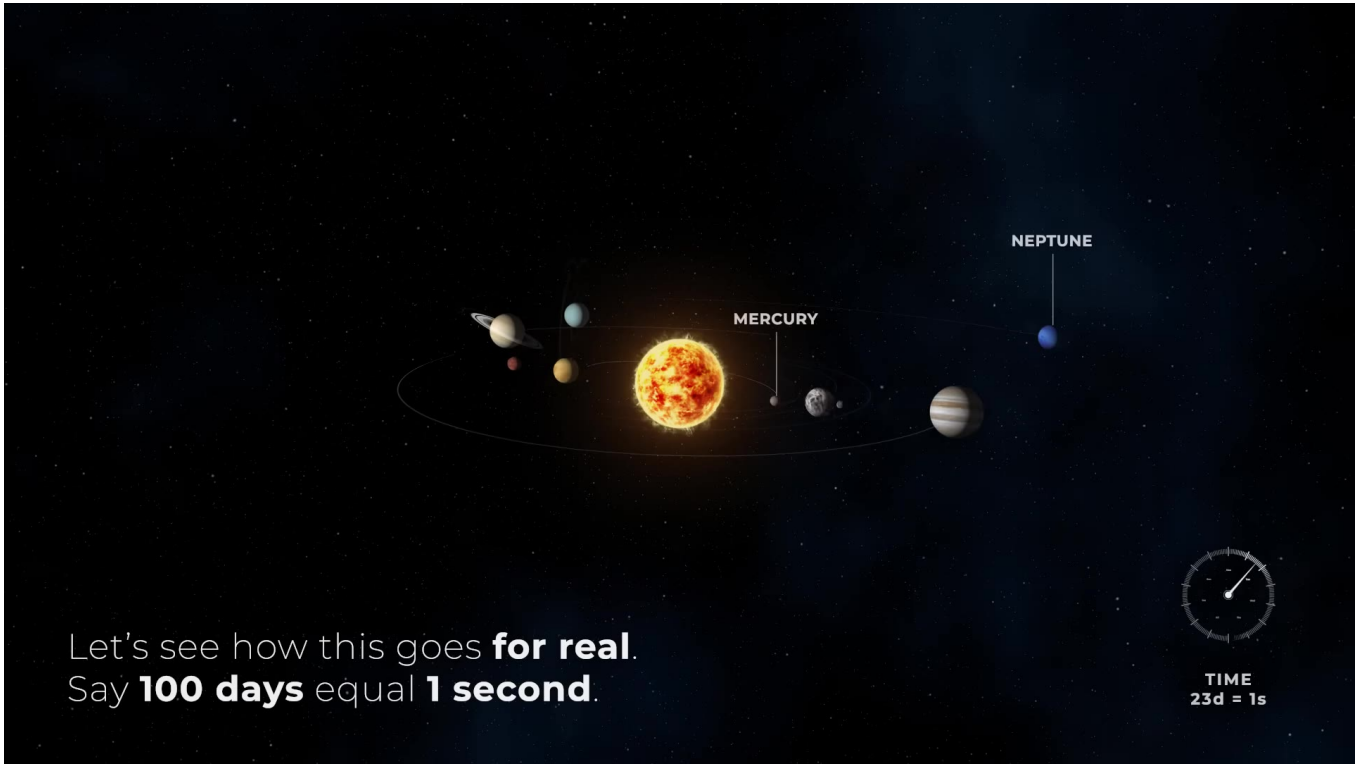
Do black holes (BHs) swallow *everything*?



Answer: no! They are hungry but their mouths are small.

Interlude: our solar system

Planets are continually falling towards the sun... *and missing*!



After Effects Tips & Treats - by Julien Schickel

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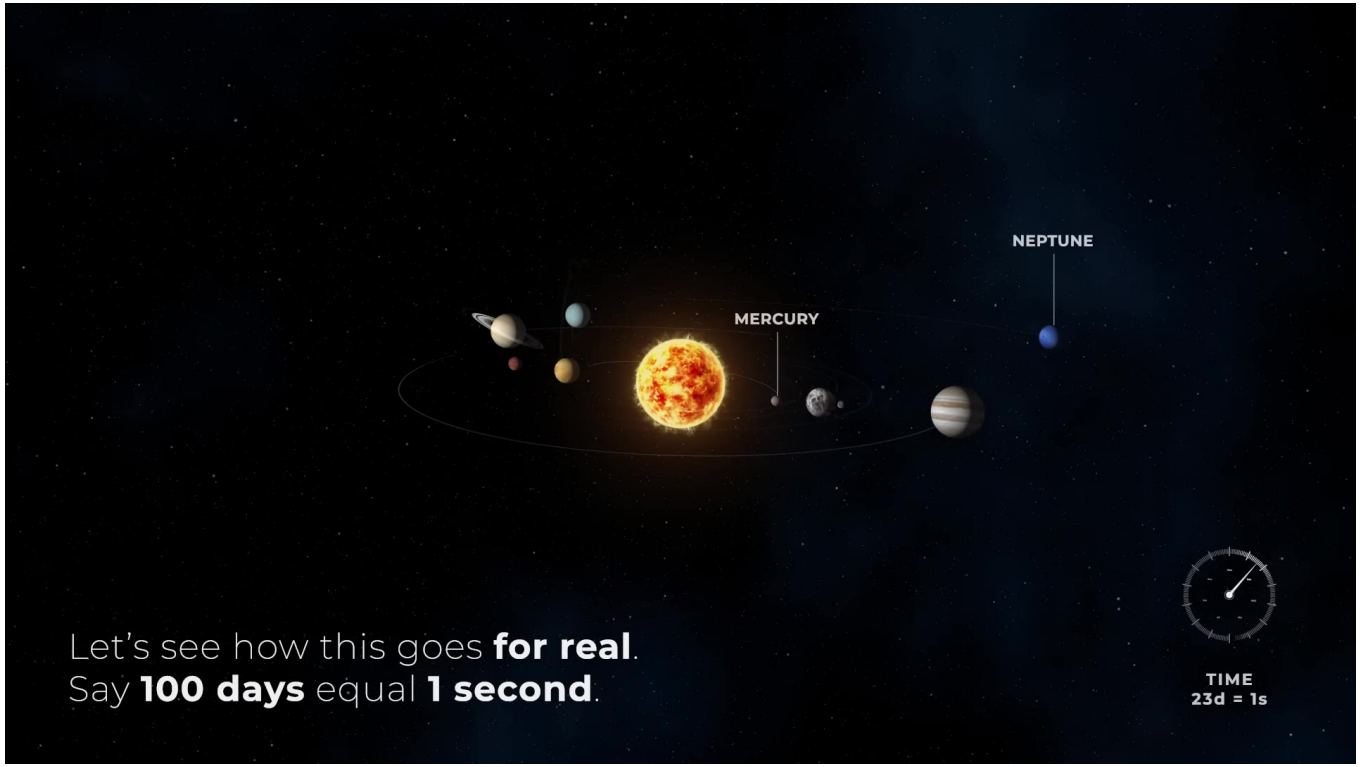


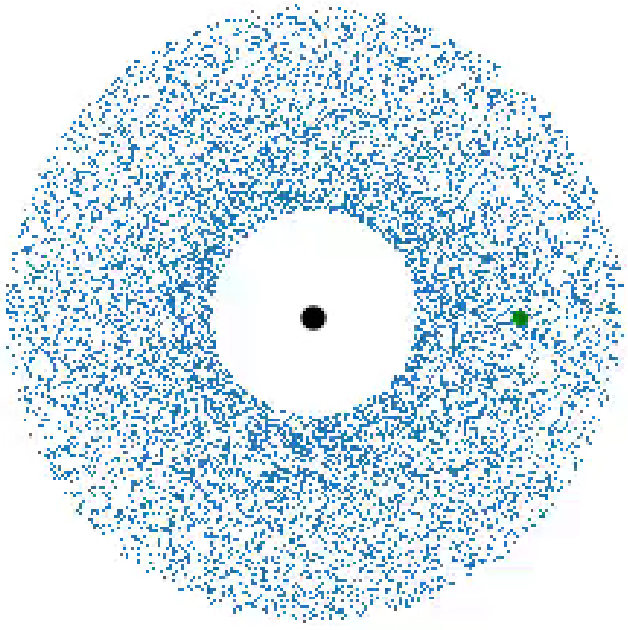
After Effects Tips & Treats - by Julien Schickel

If we replaced the Sun by a BH of the same mass...
...we would die..
but the planets would continue on their orbits.

BH will eat anything that falls directly onto it,
but its radius is only 3km!

How *do* black holes eat? Accretion discs

Gas settles onto circular orbits around BH.



I am a particle of gas (•).
Gas inside me moves faster.
Gas outside moves slower.
Friction → heat → energy lost by radiation.
I'll drift inwards (and speed up!).

Eventually I'll drift down to edge of BH and fall over.

Remember $E = mc^2$?
Here total energy released as radiation is $(\Delta E) \simeq 0.1(\Delta m)c^2$.
Accretion onto BH is $\sim 10\%$ efficient.

How do black holes eat? Accretion discs

Here is a simulation of this process:



credit: z136_A1

Supermassive black holes?

What is a "supermassive" black hole?

Mass of Sun:
$M_\odot \simeq 2 \times 10^{30}$ kg $= 2\underbrace{000000000000000000000000000000}_{30\ 0's}$ kg.

This $M_\odot$ is what most astronomers use as their unit of mass.

When they run out of fuel, stars more massive than about 20 $M_\odot$ collapse to form BHs of about 10 $M_\odot$.

These are called "stellar-mass" black holes.
They are not "supermassive".

Astronomers have long suspected that even bigger black holes to exist.

The evidence for "supermassive" black holes



1963: Maarten Schmidt discovers the first QSO (quasi-stellar object).

It looks like a star,
but it has a large redshift.
$\Rightarrow$ it is faraway (Hubble's law)
$\Rightarrow$ it must be very luminous.

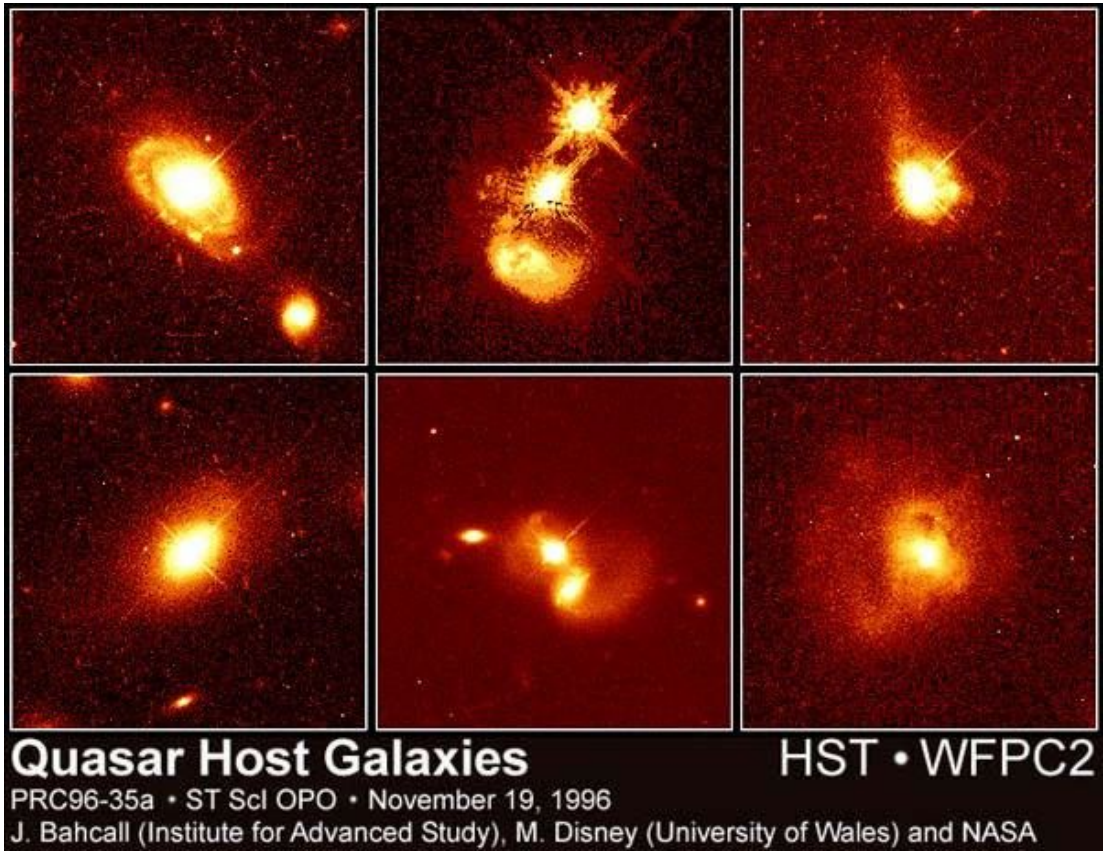
Some QSOs vary on timescales of hours
$\Rightarrow$ they must be compact.

Idea: QSOs are accretion disks surrounding BHs,
whose masses are millions to billions $M_\odot$.

The most natural location for these **supermassive BHs** is at the centres of galaxies.

Taking a closer look at QSOs

1996: Hubble Space Telescope shows that QSOs are located in galaxy centres.



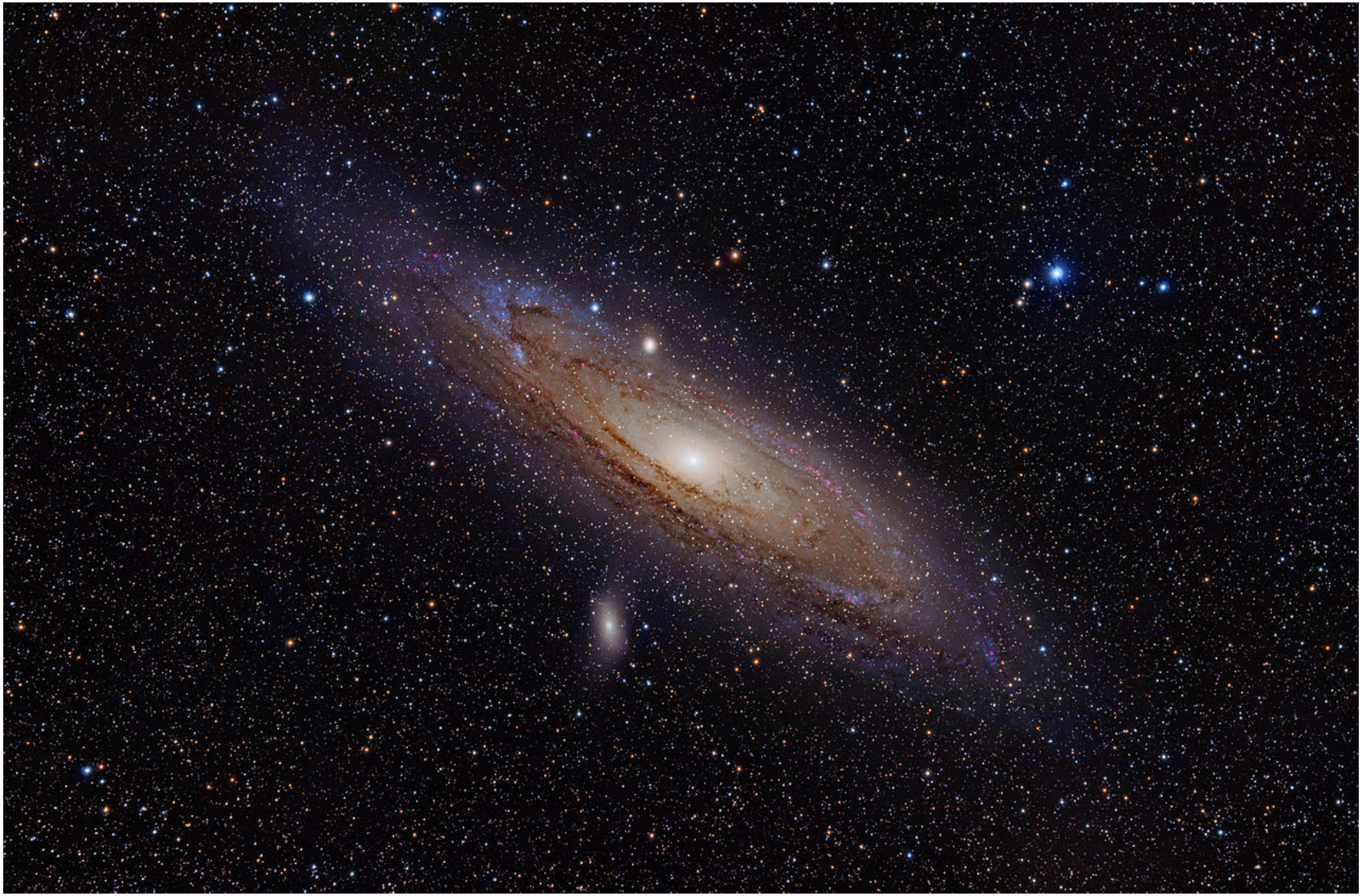
When we look back in the past at faraway galaxies, we find that there used to be many more QSOs than there are today.

There must be (starved) supermassive BHs in nearby galaxies!

Nearby galaxies

Nearby galaxies

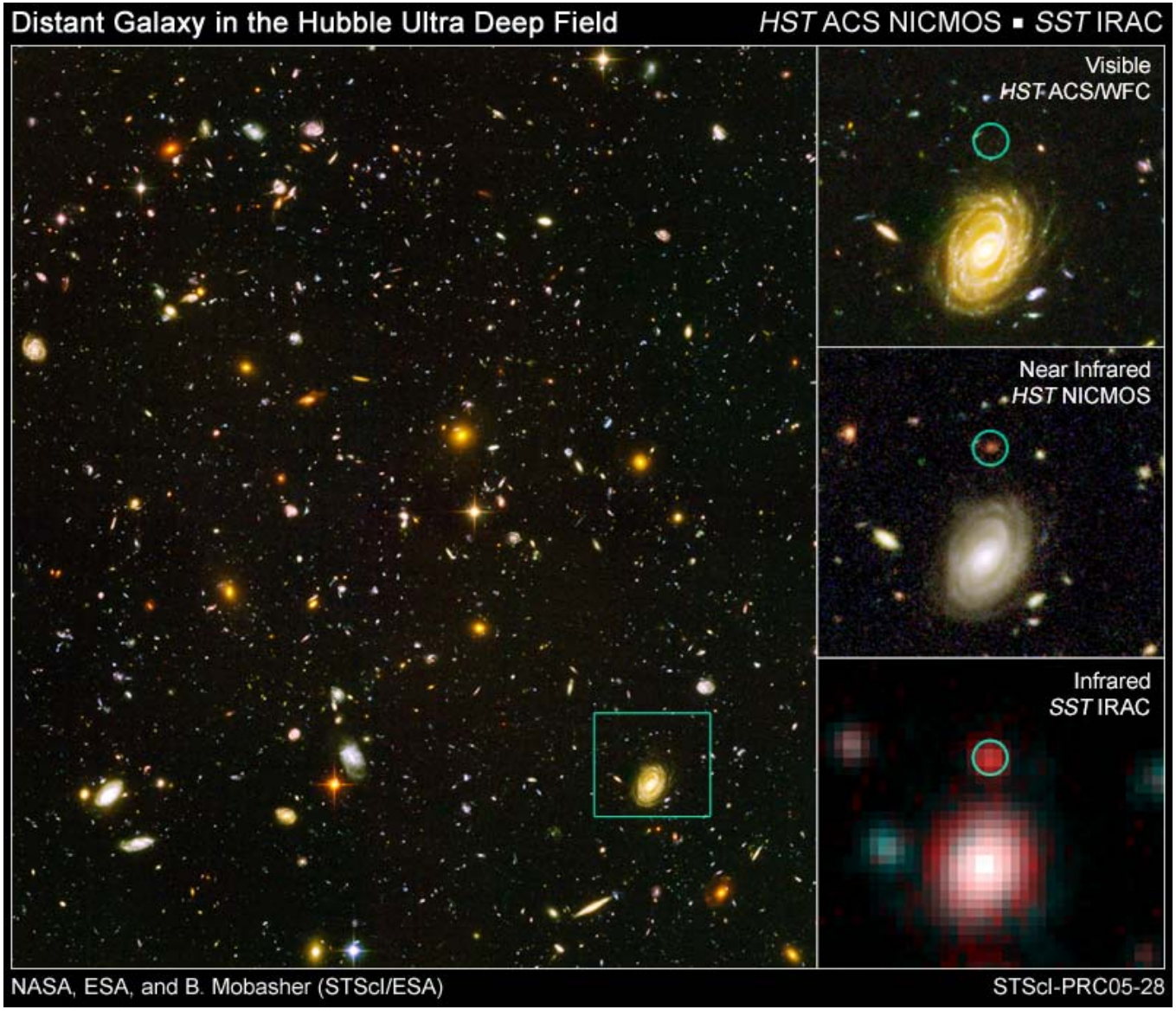
Here is the Andromeda galaxy (M31), our nearest large neighbour



It is about 2.5 million light years away and 100 thousand across.

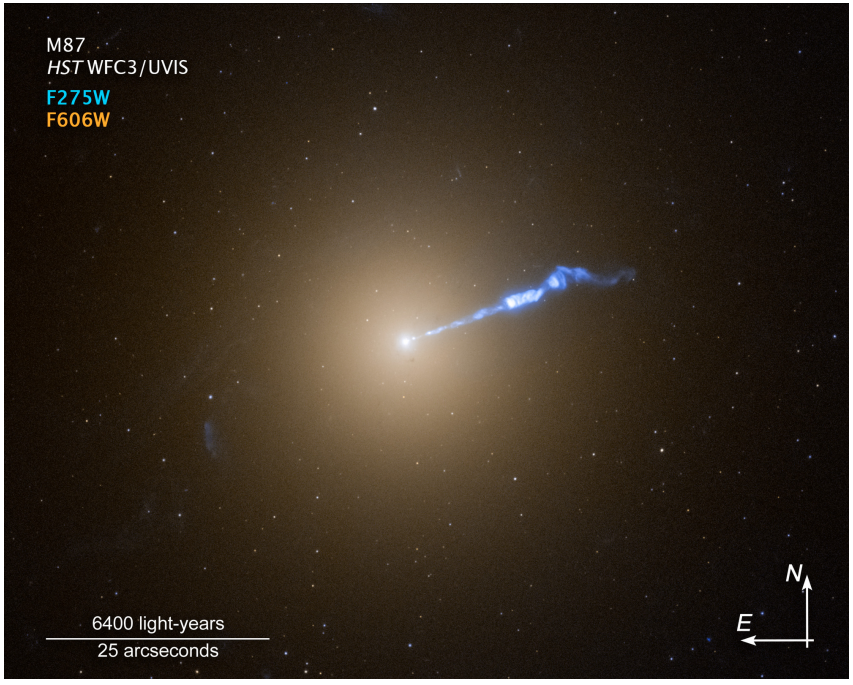
Galaxies

Galaxies exist as far as our telescopes can see:



Galaxies: active

Some nearby galaxies have **jets** shooting out from their centres:



NASA, ESA, STScI, Alec Lessing (Stanford University), Michael Shara (AMNH); Acknowledgment: Edward Baltz (Stanford University); Image Processing: Joseph DePasquale (STScI)



ESO/WFI (Optical); MPIfR/ESO/APEX/A.Weiss et al. (Submillimetre); NASA/CXC/CfA/R.Kraft et al. (X-ray)

Galaxies: our own

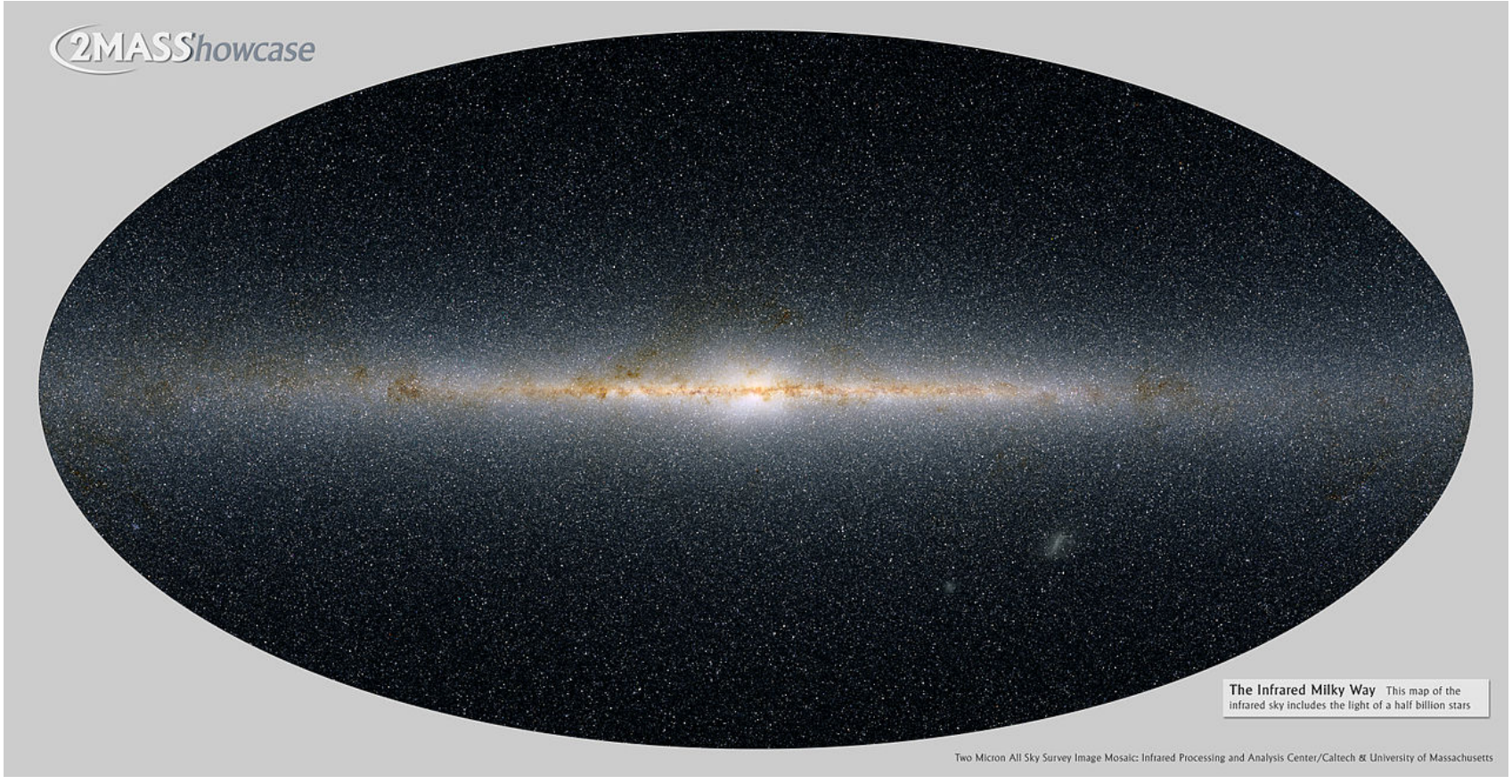
We live inside a disc galaxy, the Milky Way:



Dust!

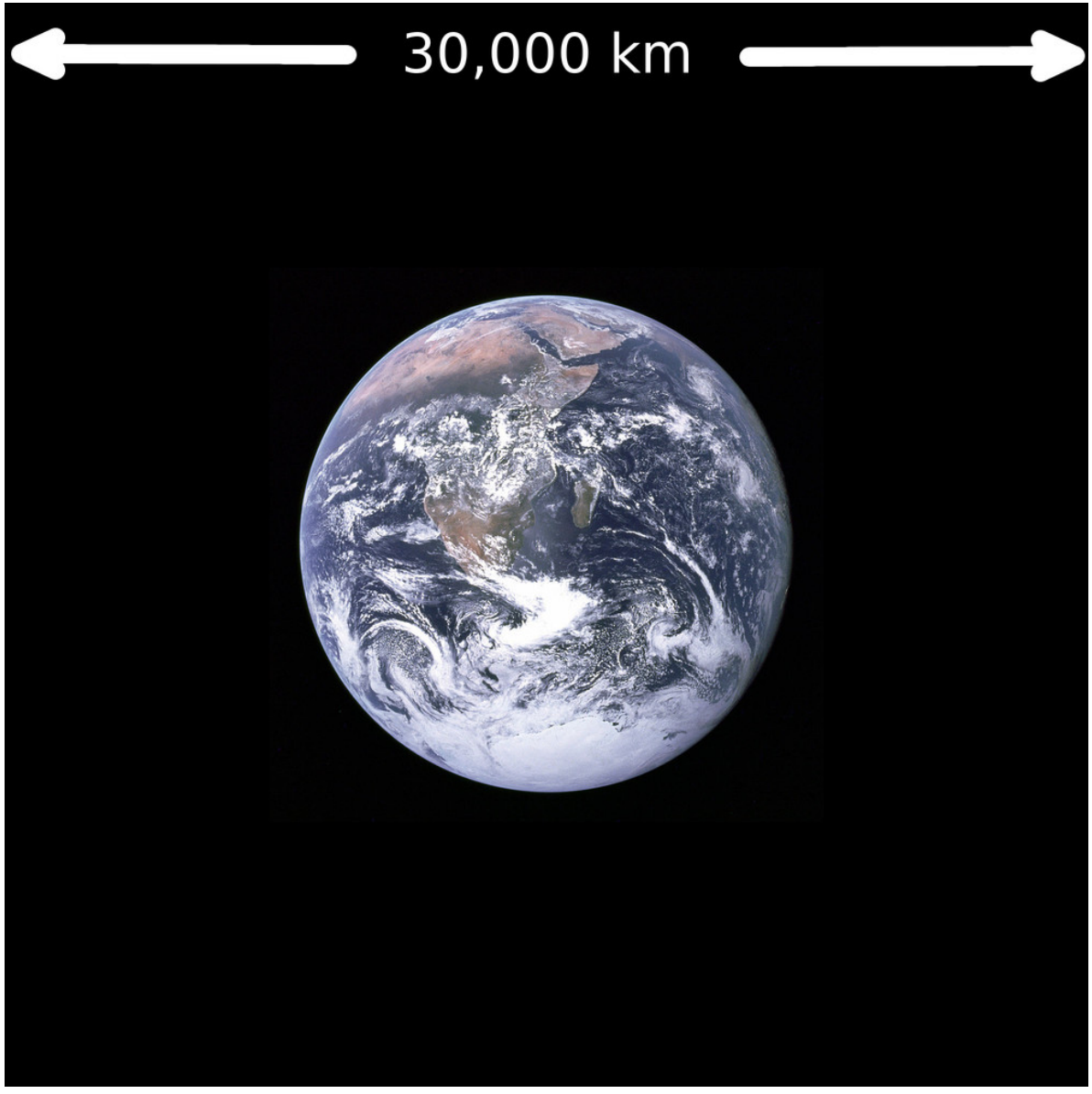
Galaxies: our own

Most of the visible light is obscured by dust, but the view becomes clearer if we look at infra-red wavelengths



We will come back to our own Galaxy soon...

Our Galaxy in more detail



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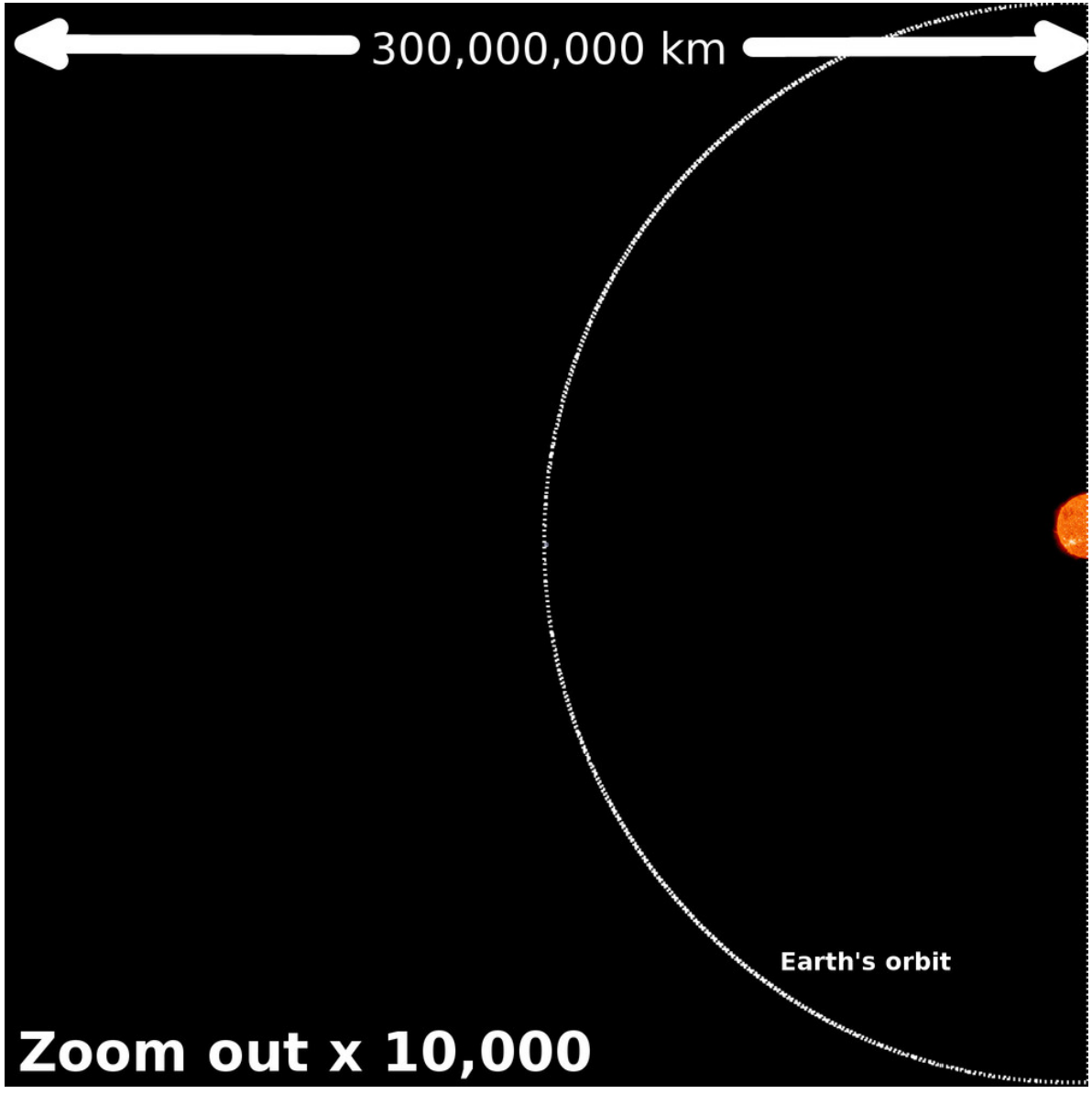

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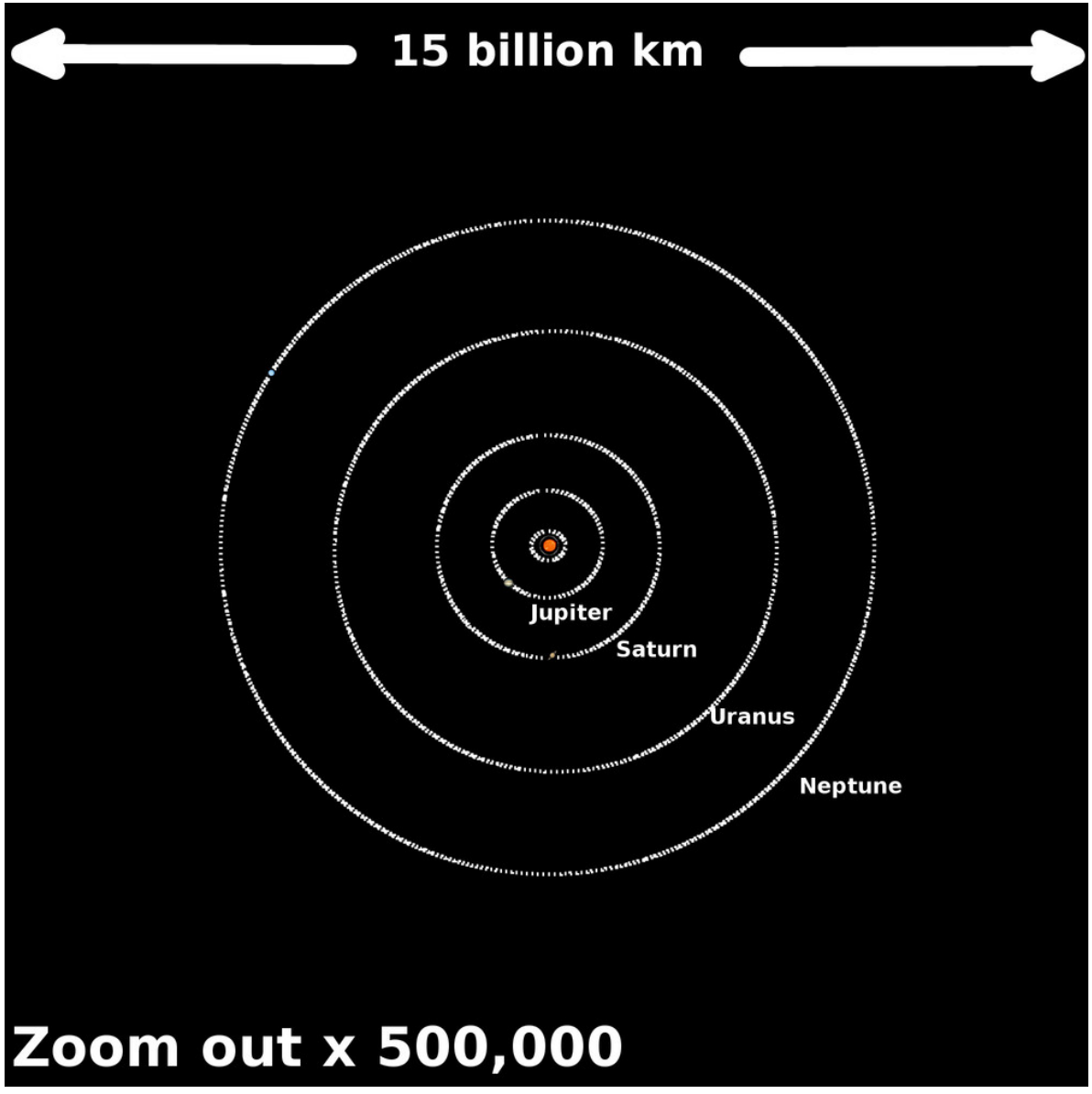

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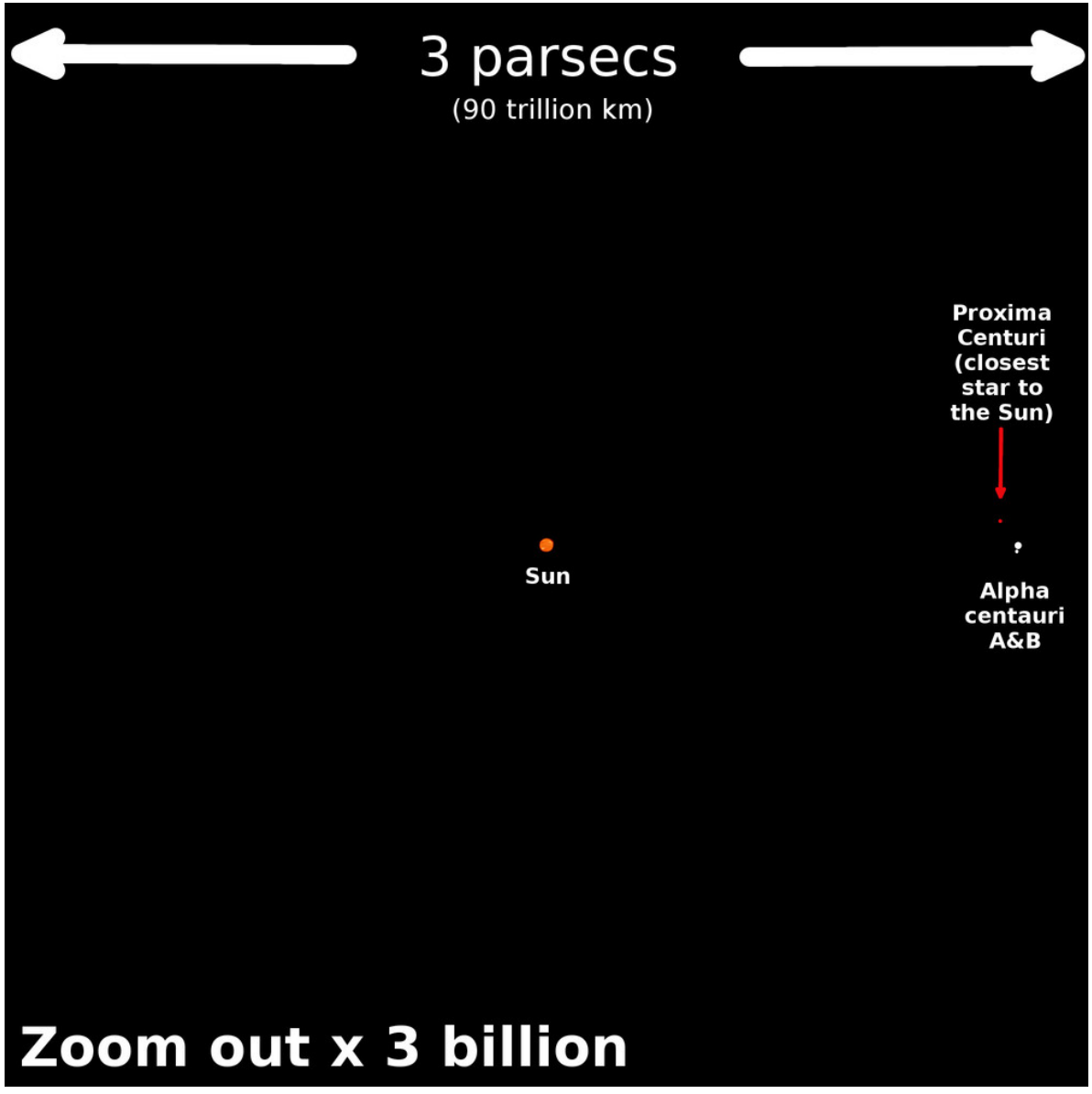

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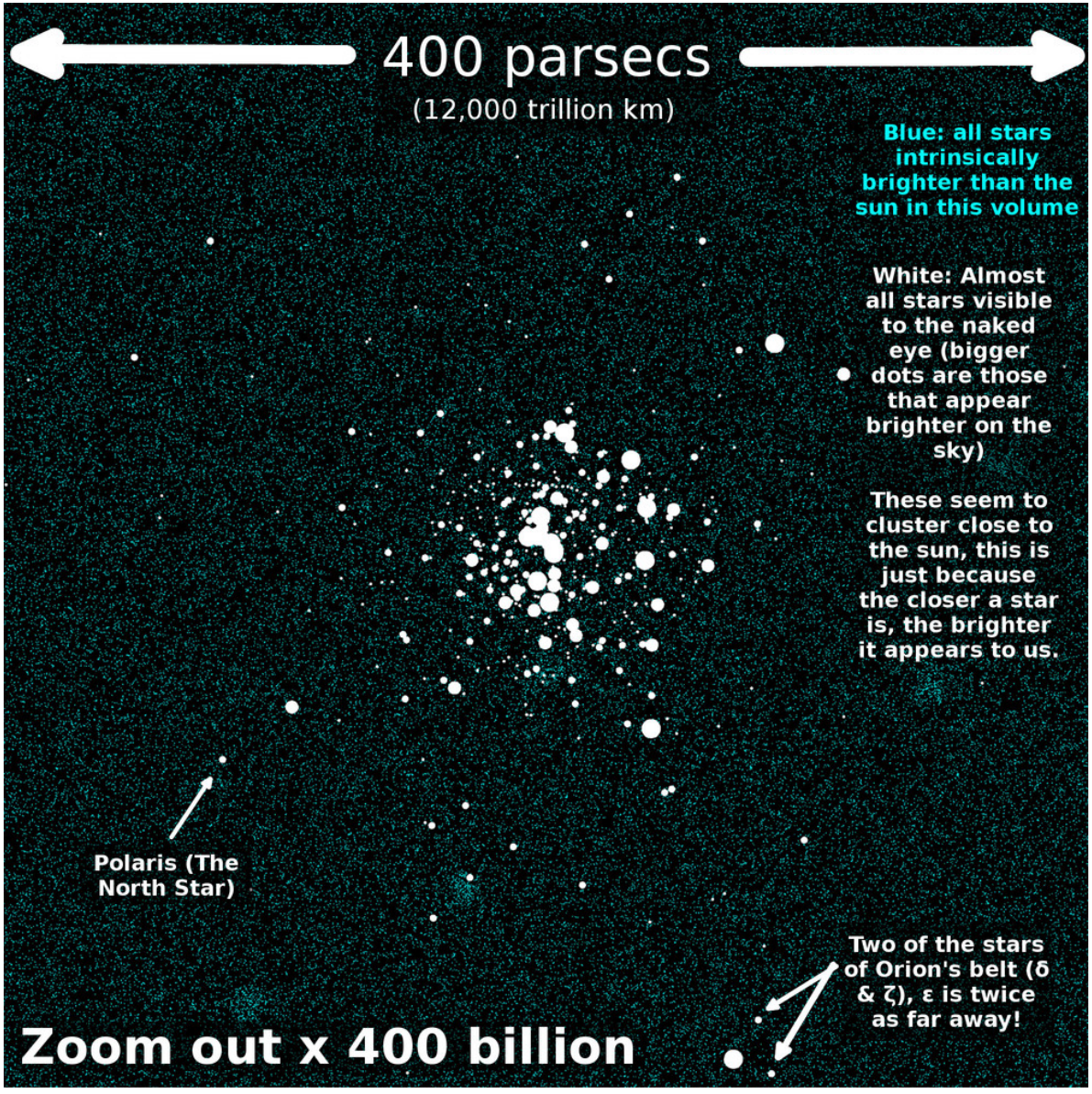

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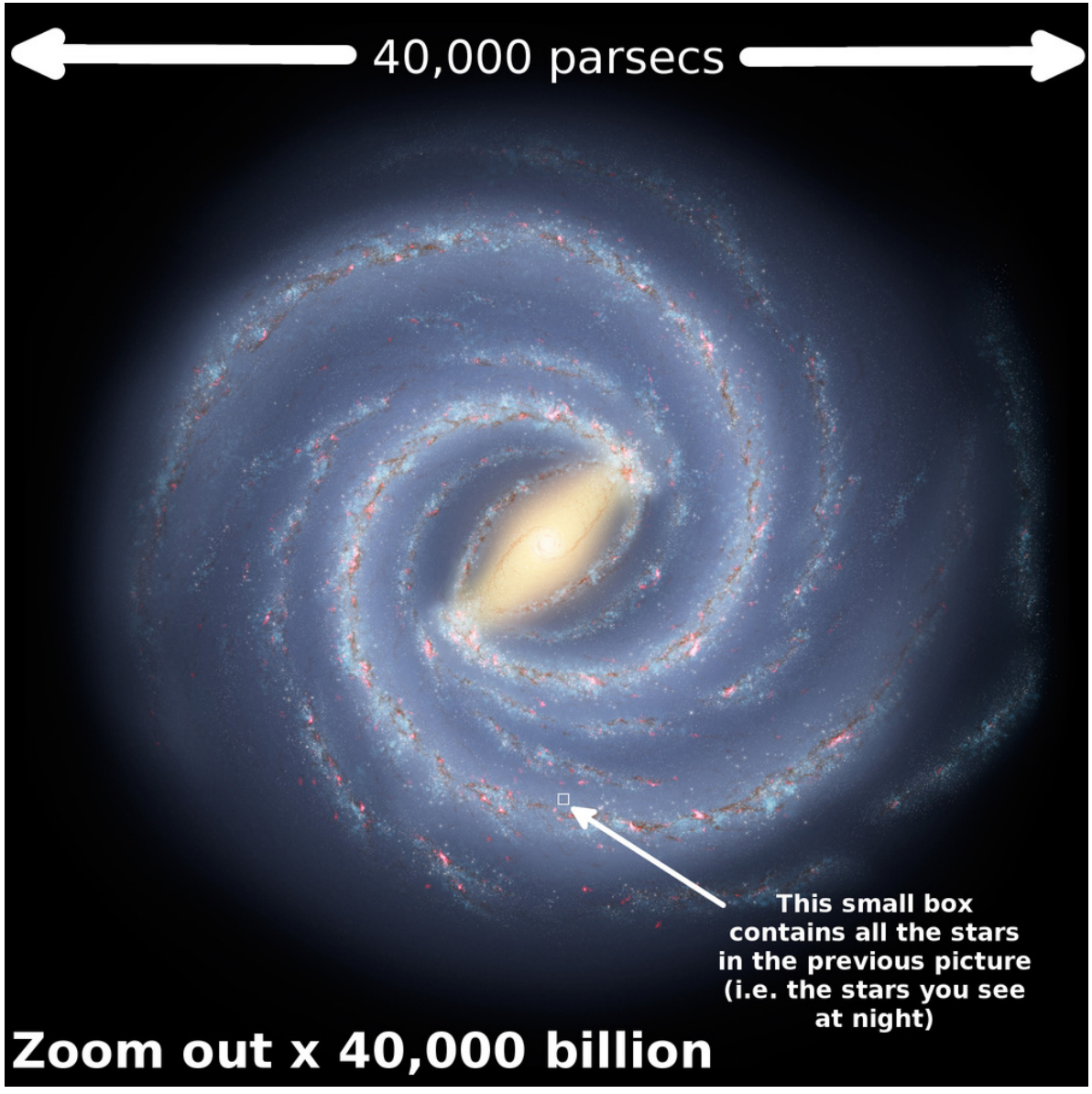
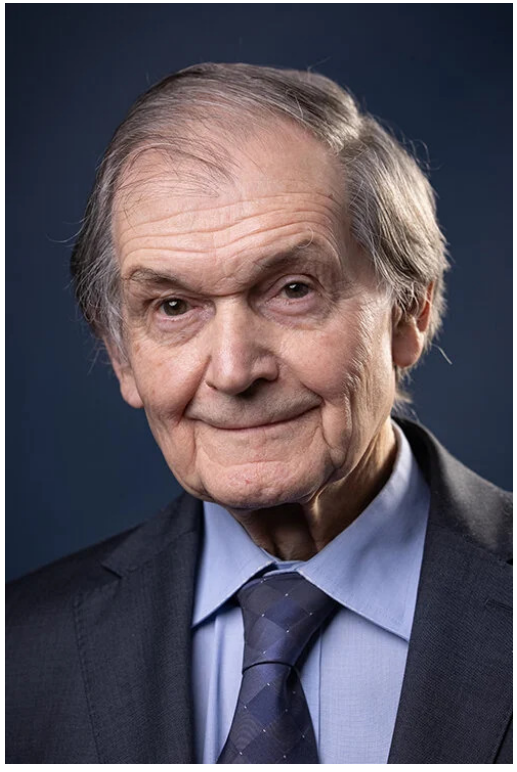


Finding supermassive black holes in nearby galaxies

The supermassive black hole at the centre of our Galaxy

2020 Nobel Prize: Reinhard Genzel, Andrea Ghez, Roger Penrose



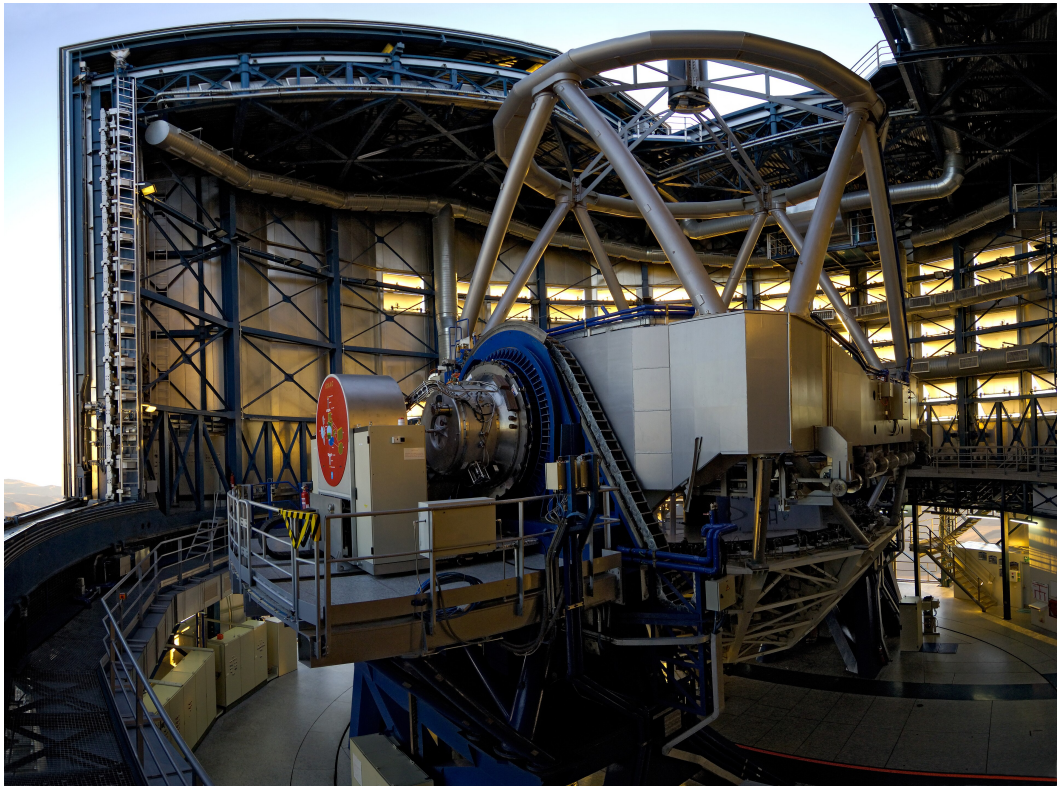


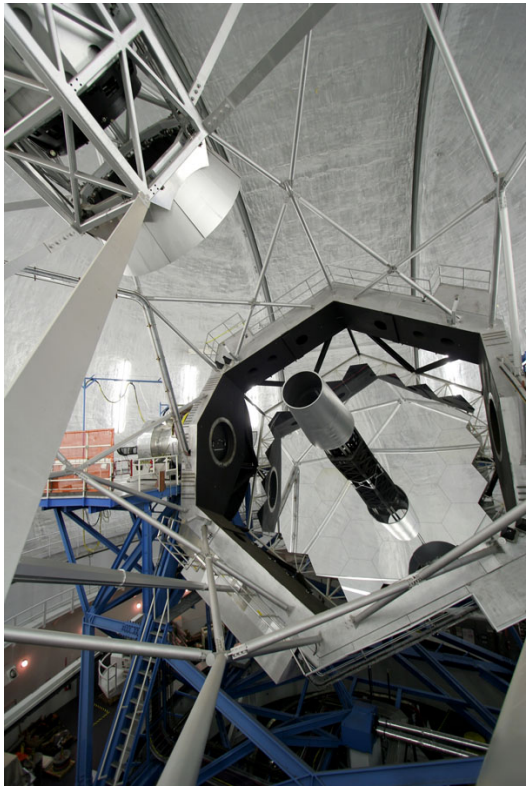
Penrose: mathematics of black holes.

Genzel/Ghez: detection of BH at centre of Milky Way.

The supermassive black hole at the centre of our Galaxy

8m VLT (left) and 10m Keck (right) telescopes:





Big telescopes have high sensitivity and high resolution.

Zooming in on the centre of our Galaxy

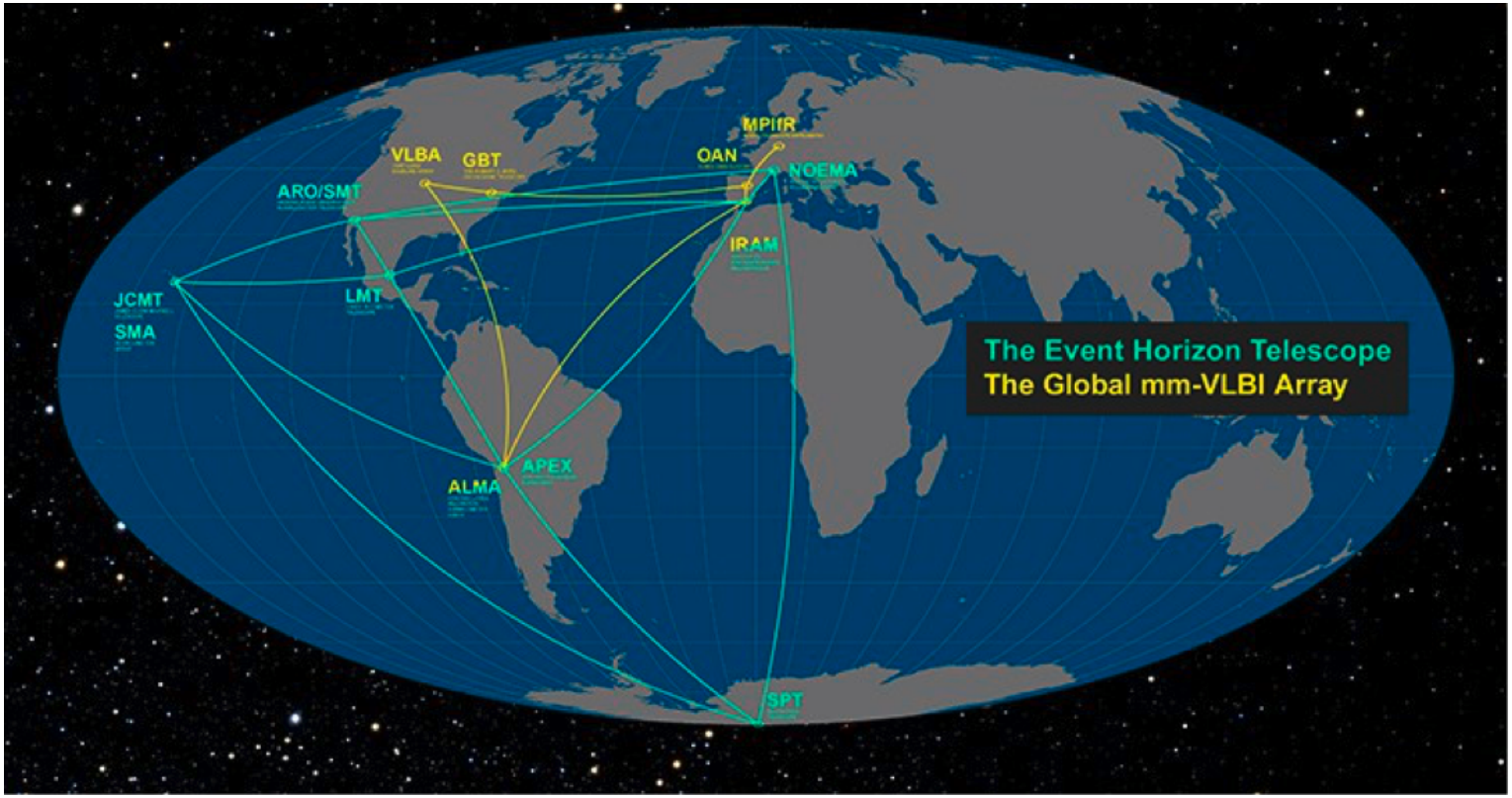


credit: ESO

Zooming in even more: the Event Horizon Telescope

To explain the motion of the S stars they need to include a very compact dark object of 4.2 million $M_\odot$ at a precise location.

With a bigger telescope we could zoom in on this precise location!

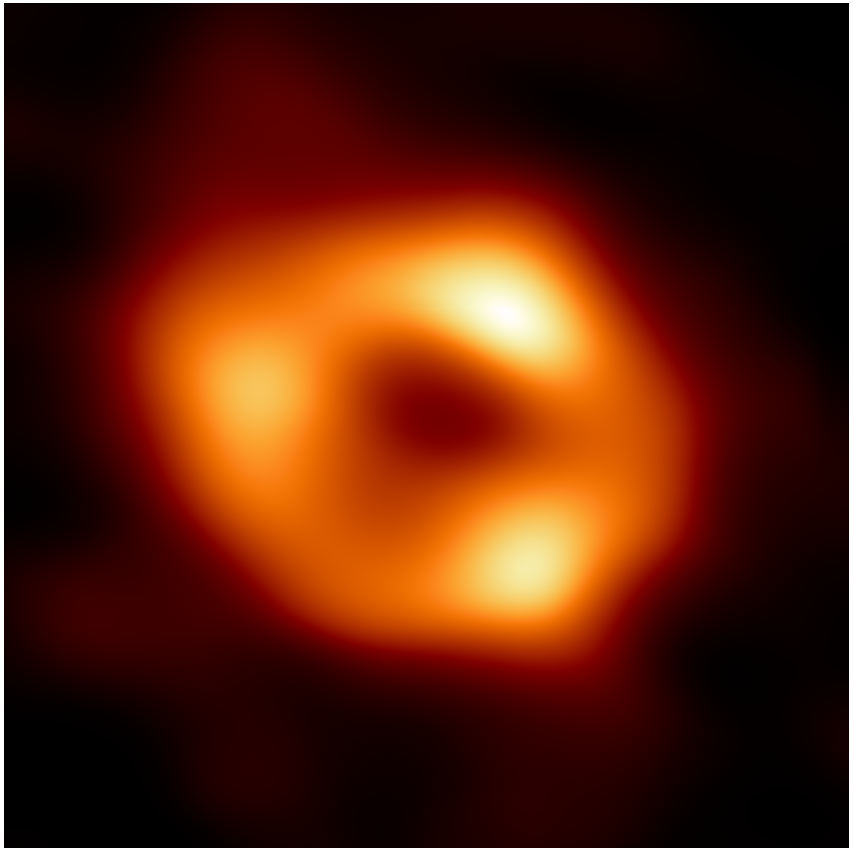


credit: ESO/O. Furtak

The bigger the telescope, the higher the resolution.
We can make a telescope the size of the earth using *interferometry*.

EHT picture

Here is what EHT sees when it zooms in:

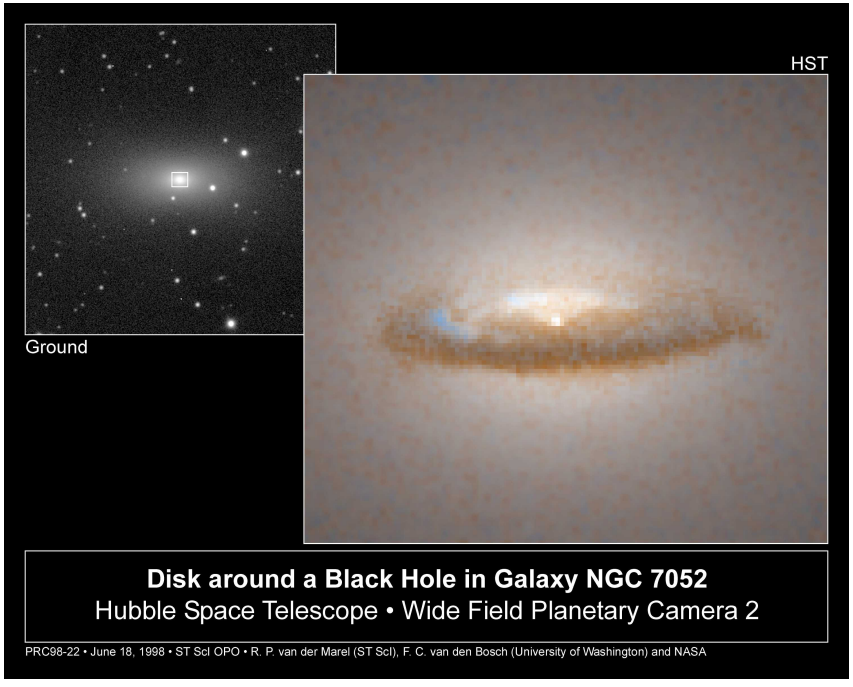


credit: EHT

It has the same size on the sky as a doughnut on the Moon.
It agrees with predictions from general theory of relativity.

Other galaxies

Some galaxies have central gas discs:



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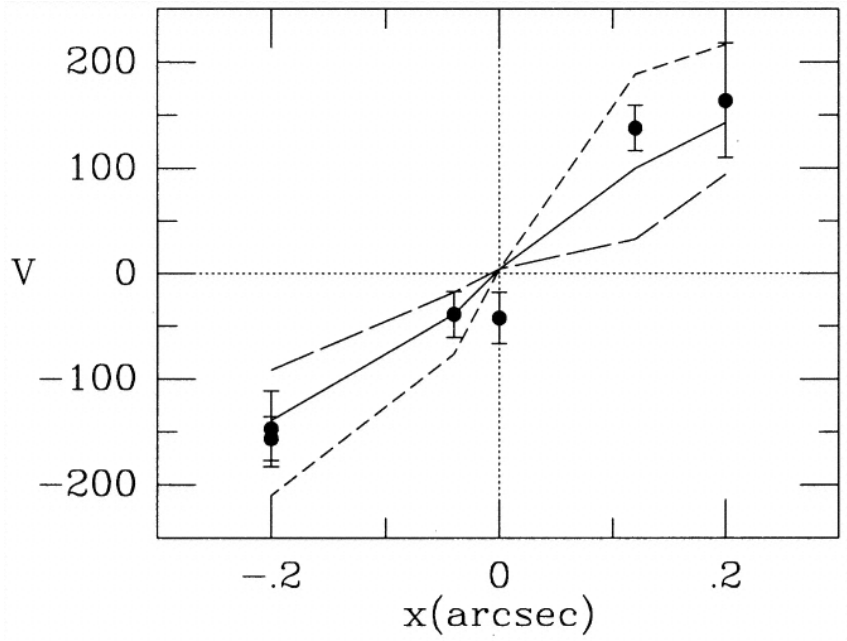

credit: van der Marel & van den Bosch (1998)

We can measure how the gas speed varies across the disc.
Our understanding of centripedal acceleration [$v^2 = GM(< r)/r$] lets us calculate the enclosed mass, $M(< r)$.

Long-dashed: prediction with $M_\bullet = 0$
Short-dashed: prediction assuming $M_\bullet$ is 1 billion $M_\odot$
Solid: Goldilocks model with $M_\bullet = 0.3$ billion $M_\odot$.

Other galaxies: stars

All galaxies have stars.
We can think of stars in galaxies like gas atoms in stars:

- gravity wants to pull the stars together, but
- stars' velocities are like a pressure force that wants to make the galaxy expand.

The two are in balance.

Other galaxies: stars

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In 1995 I joined the "Nuker" team, who were using the Hubble Space Telescope to investigate the centres of nearby galaxies.

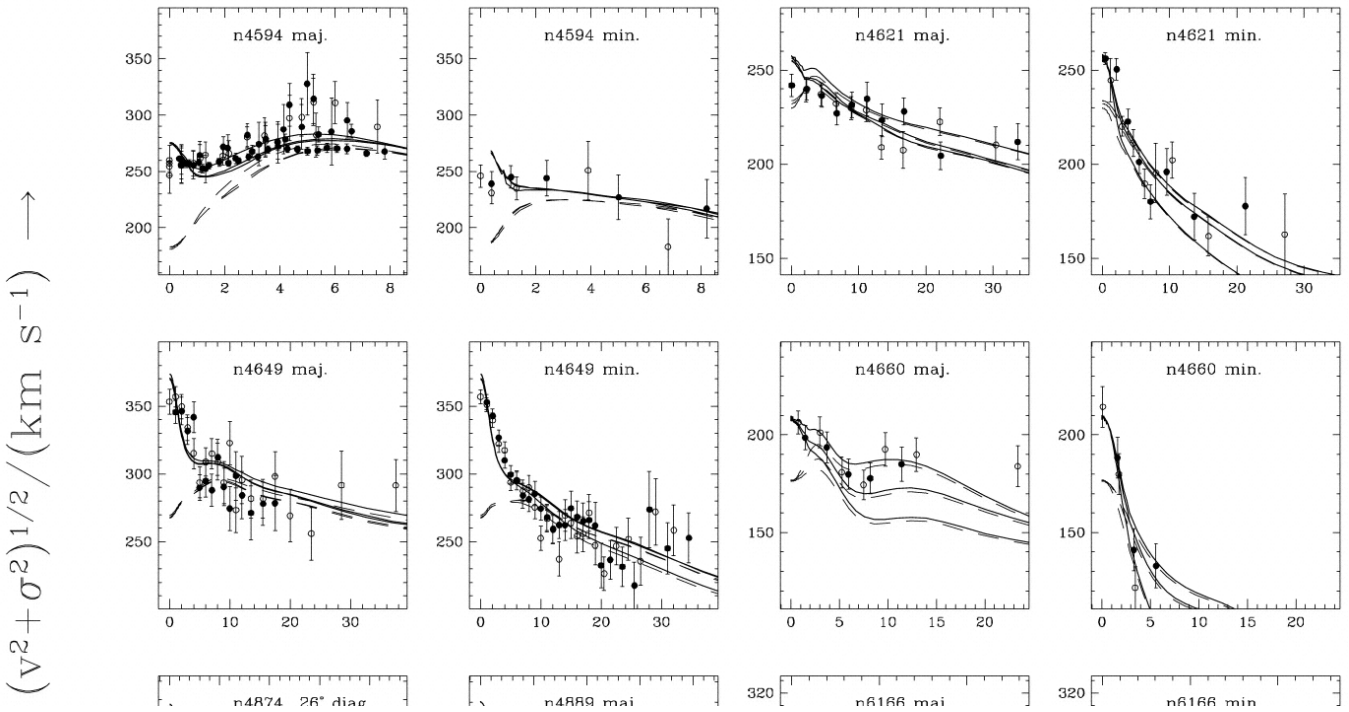
We wanted to use stellar kinematics to look for black holes.

We decided to explain the observations by building dynamical models making the simplest, most natural assumption about the "pressure" force.

What did we find?

(JM et al 1998)

To our surprise, almost every galaxy required a central BH to make balance the "pressure" force from stars' velocities.



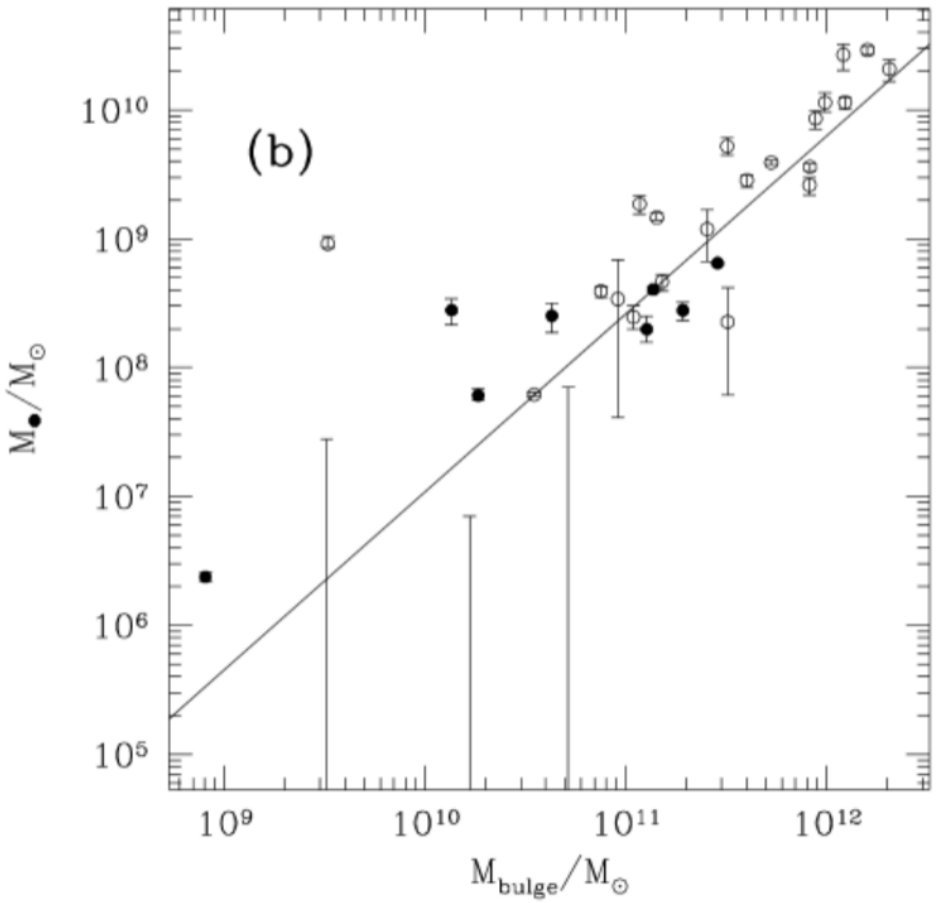
Plot of "velocity pressure" versus distance from centre.
Dashed curve: model prediction for $M_\bullet = 0$.
Solid curve: model prediction with best-fit $M_\bullet$.

This made us nervous!

What did we find?

(JM et al 1998)

We also found that the ratio $M_\bullet / M_{galaxy}$ was about 0.5%:

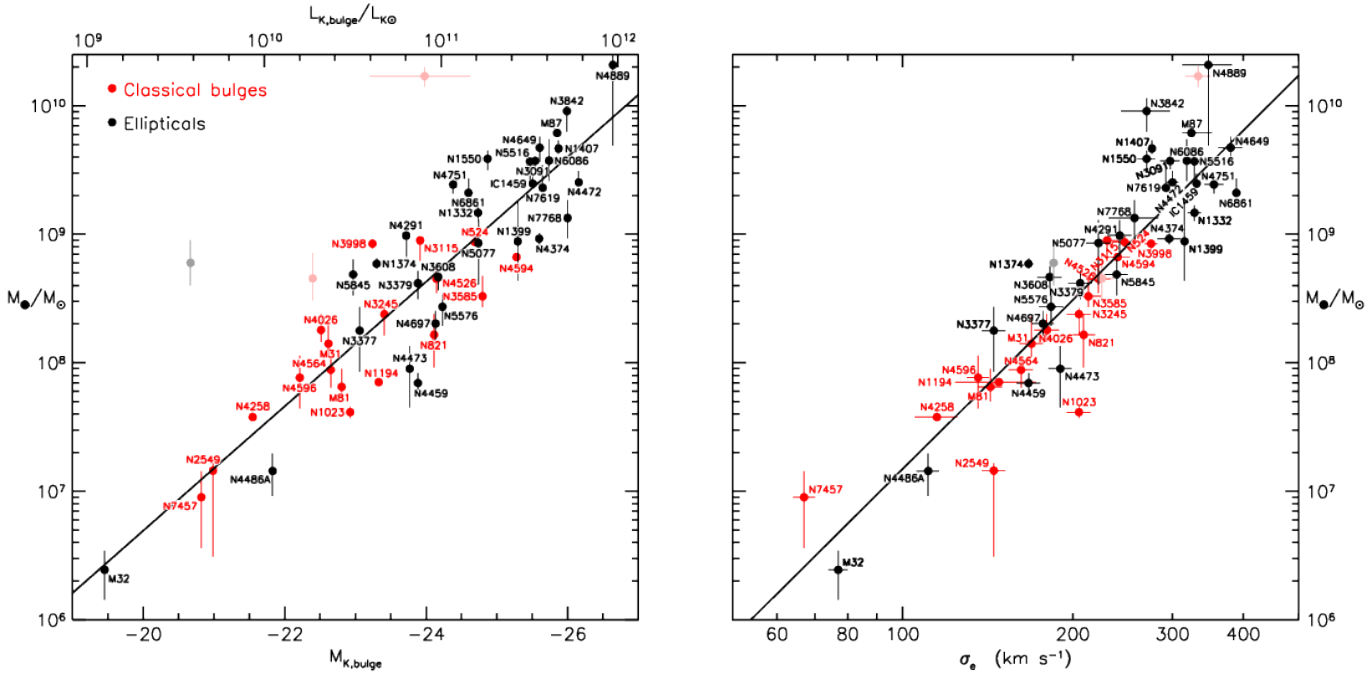


This made us nervous!

Nearby galaxies: a more modern census
(Kormendy & Ho 2013)

We've since discovered that our assumption about the velocity pressure was slightly too simple.

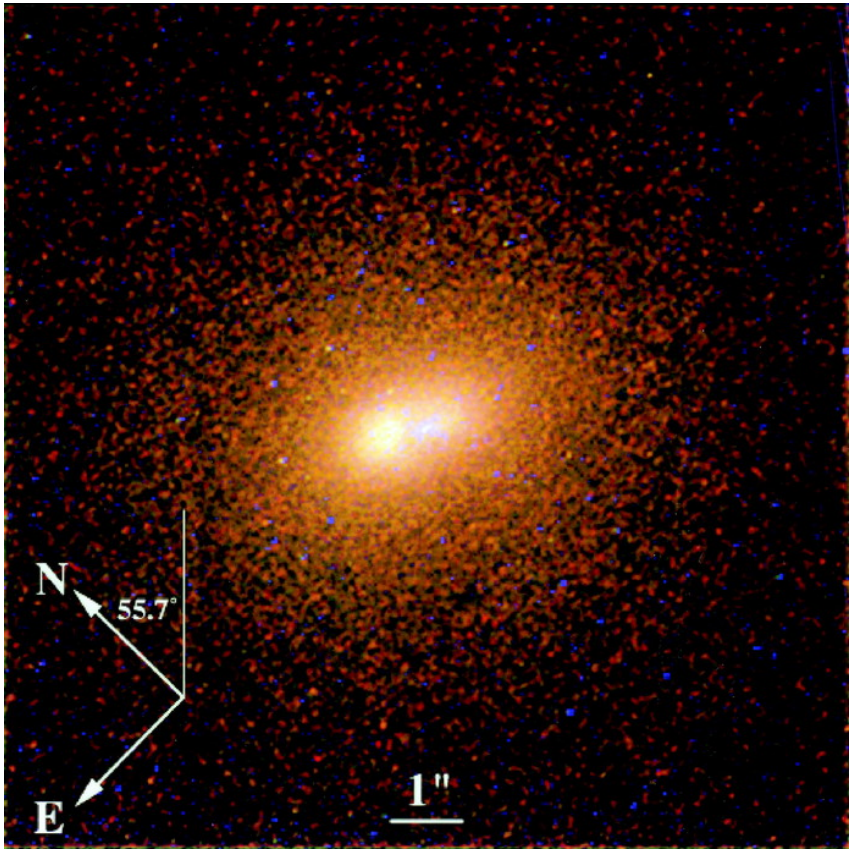
But it is true that almost all nearby galaxies have supermassive BHs, with $M_\bullet / M_{\rm galaxy} \simeq 0.2\%$ (versus 0.5%).



More modern examples

(Brown+JM 2013; JM ongoing; others)

Here's the central few thousand light years of Andromeda.



(Lauer et al 1998, 2012)

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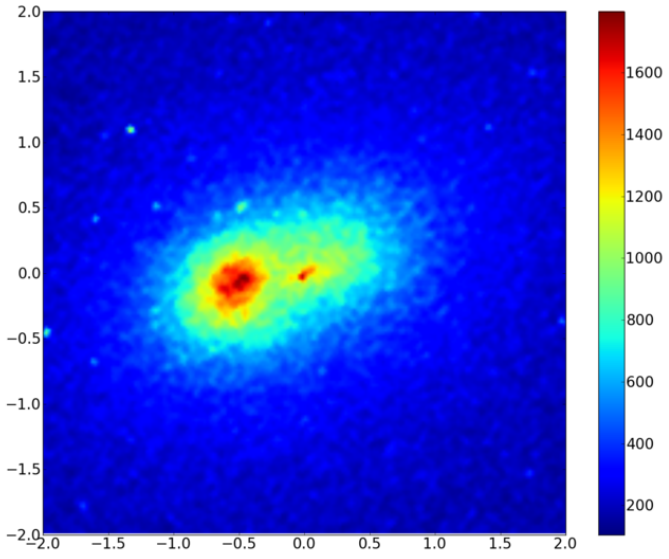

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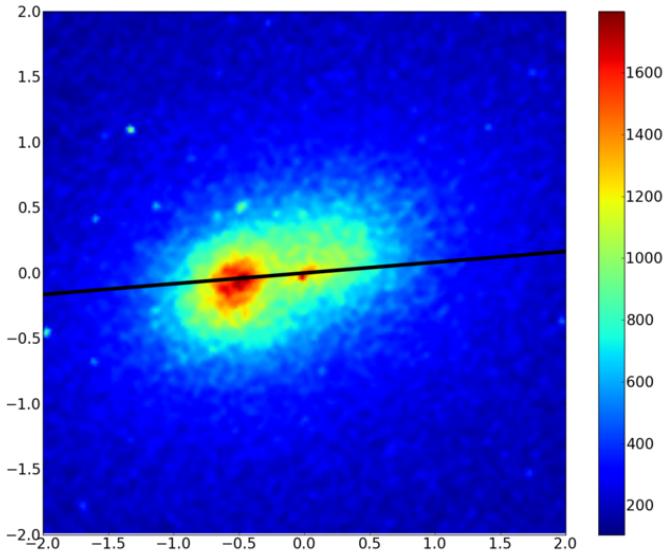

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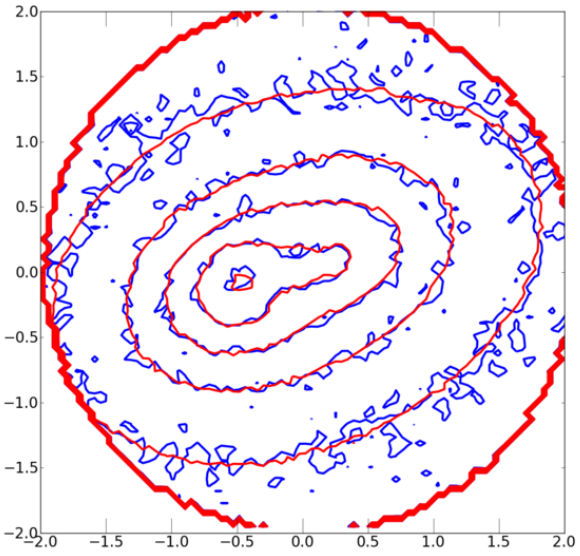
More modern examples

(Brown+JM 2013; JM ongoing; others)

We relax our "pressure" assumption,
assuming only that the centre of the galaxy is in a steady state.

First we try with $M_\bullet = 0$.
Then we increase $M_\bullet$ until we find a good match.



We match the galaxy image

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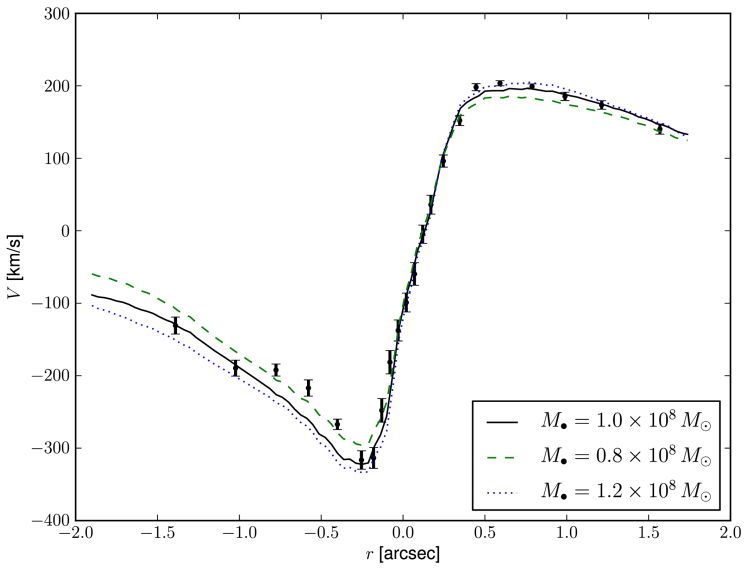

We match the galaxy image
..and its velocity field,

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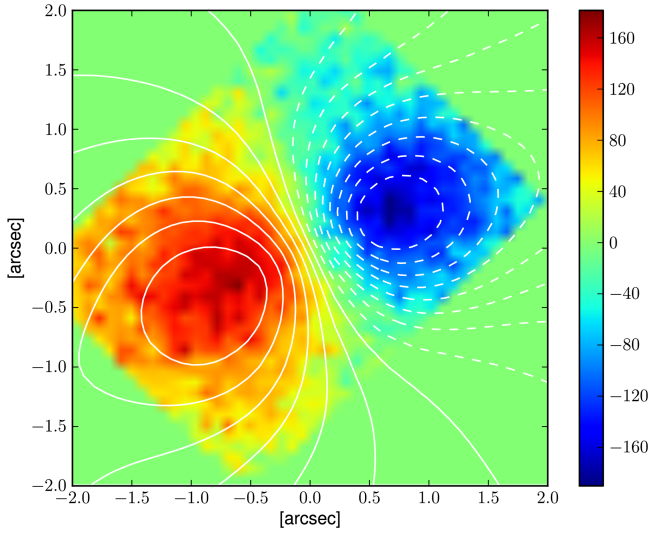
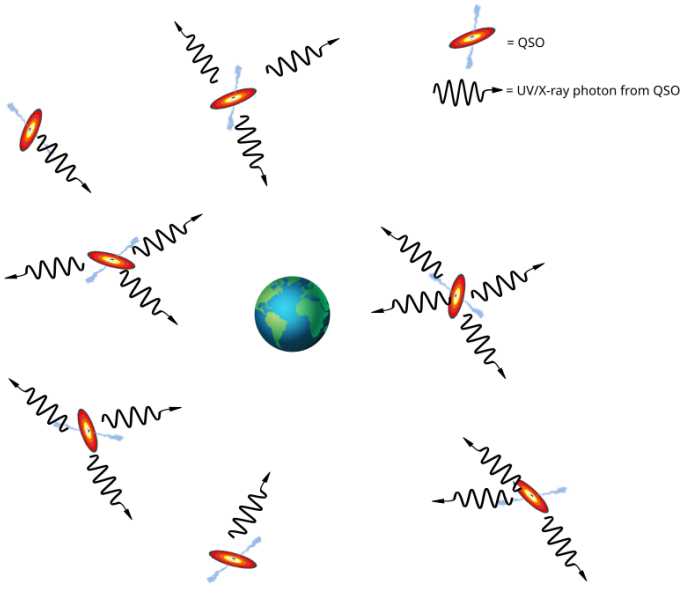


We match the galaxy image
..and its velocity field,
..in detail...
for $M_\bullet = 100$ million $M_\odot$.

Putting these result in context

Sołtan's (1982) argument

QSOs must come and go. But their light lives on.
Remember $\Delta E = 0.1(\Delta m)c^2$ for accretion discs?



Take a huge box containing many many galaxies and QSOs.

Use X-ray radiation around earth to estimate ΔE in box.

$\rightarrow \Delta m =$ mass of QSO engines

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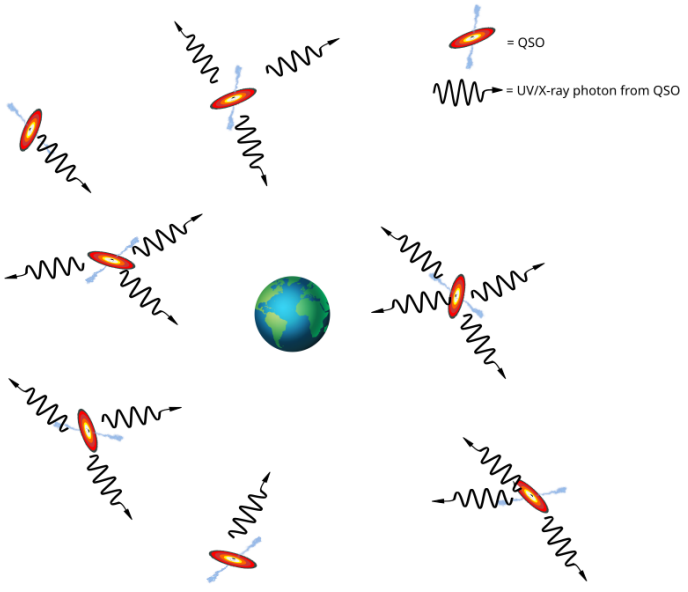

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Compare this to the mass obtained by assuming every galaxy has $M_\bullet = 0.2\%\, M_{\text{galaxy}}$.
They agree! **Every galaxy is a dormant QSO!**

Summary and open questions

Black holes

There are at least two types of BHs in the Universe:

1. stellar mass BHs ($M = 10\,M_\odot$ to $\sim 100\,M_\odot$)
   - these are the ashes of very massive stars

2. "Supermassive" BHs ($M =$ million to billions $M_\odot$)
   - every (large-ish) galaxy has one
   - the bigger the galaxy, the bigger the BH, with $M_\bullet / M_{galaxy} = 0.2\%$.
   - these are the engines that power QSOs, jets etc

Black holes

There are at least two types of BHs in the Universe:

1. stellar mass BHs ($M = 10\,M_\odot$ to $\sim 100\,M_\odot$)
   - these are the ashes of very massive stars
2. "Supermassive" BHs ($M =$ million to billions $M_\odot$)
   - every (large-ish) galaxy has one
   - the bigger the galaxy, the bigger the BH, with $M_\bullet / M_{galaxy} = 0.2\%$.
   - these are the engines that power QSOs, jets etc

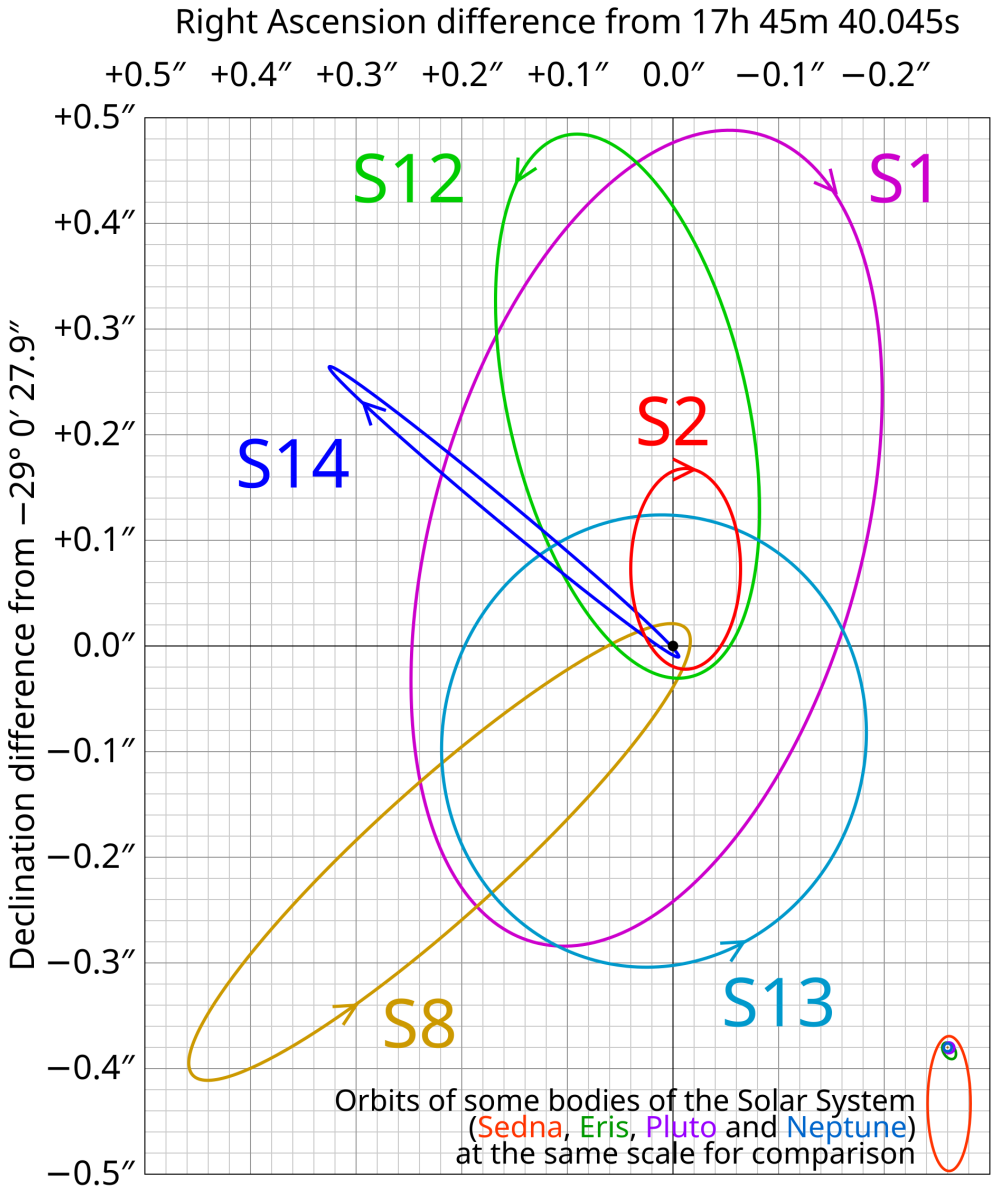
Unanswered questions

1. Are there intermediate-mass BHs? (hundreds to million $M_\odot$?)
2. What are the seeds from which supermassive BHs grow?
3. Why is there a correlation?
   - Vast difference in lengthscales!
   - Jets in QSO phase regulate joint growth of galaxy and BH?
4. How to feed gas to the BH? Gastrophysics.

How to feed BHs?

Gastrophysics!

Orbits at the Galactic centre



Mass of 4.2 million solar!