Bizarre eating habits of the Black Hole in the center of the Milky Way

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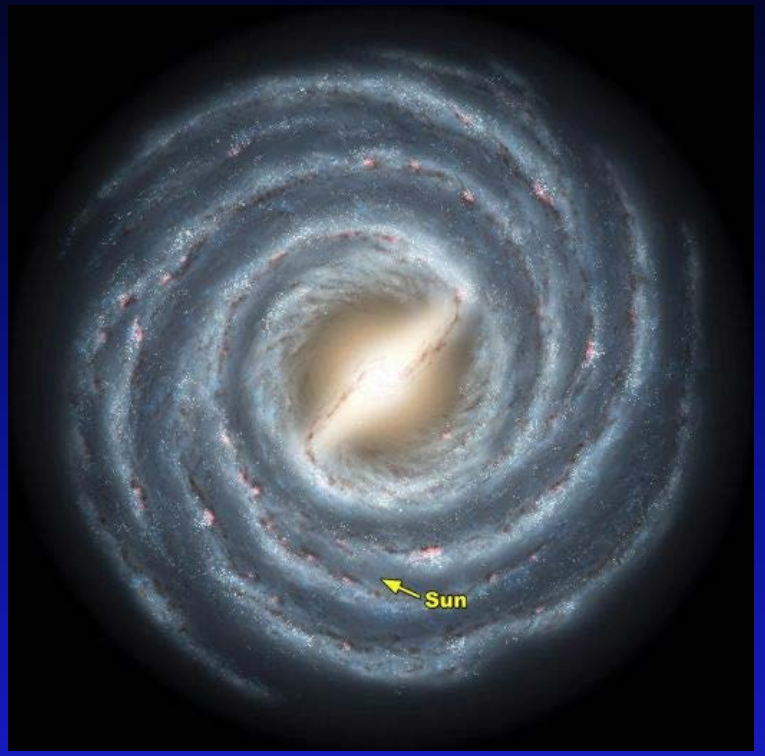
12 Feb 2012

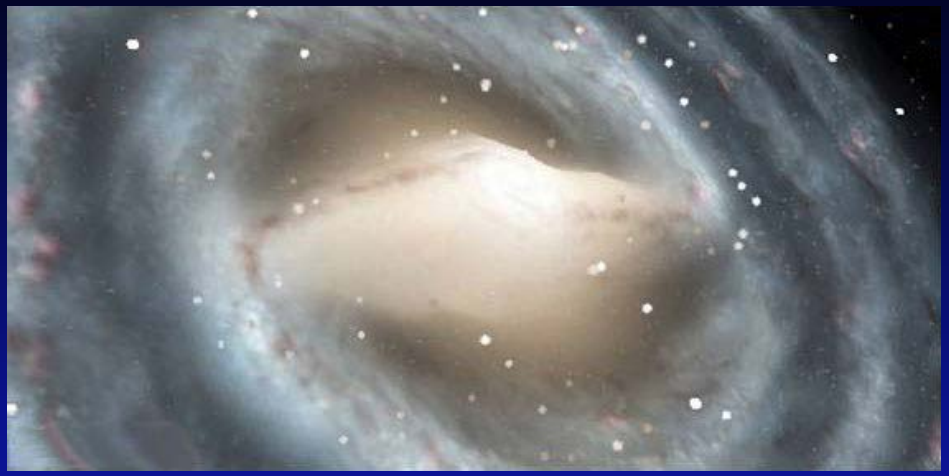
The Milky Way galaxy



A typical spiral galaxy is our home:

100.000 light years across collection of
dust + gas + 400 billion stars rotating around the center
Distance to the center – 26.000 light years

Zoom-in on the center



Bulge – dense collection
of stars 10.000ly across

Dust – absorbs all optical light

Bright stellar light +
extreme amounts of dust
have long been obscuring the very center

But clues on some unusual activity
were accumulating

Unusual activity in the center

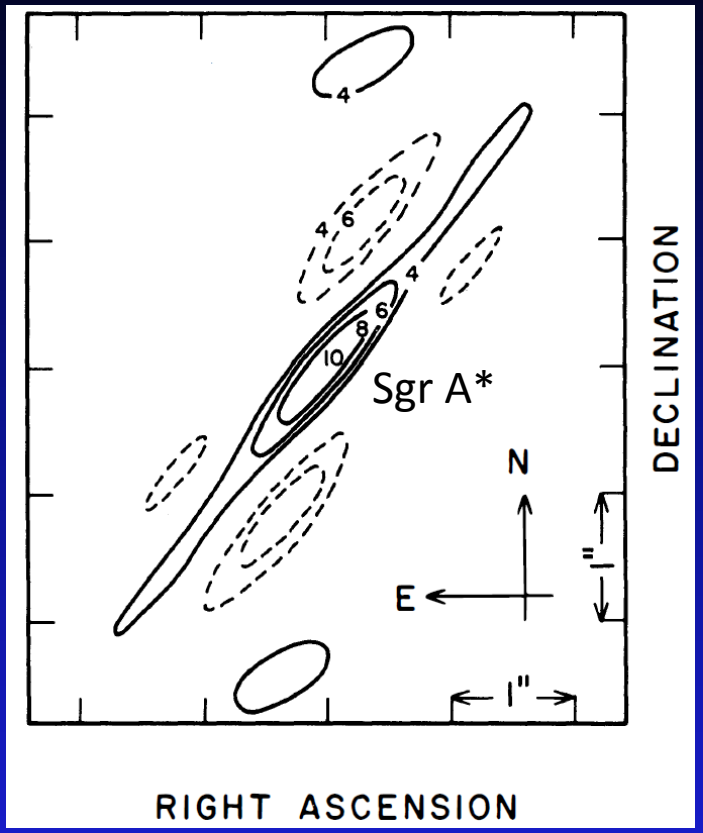
Radio source Sgr A*

(named after constellation Sagittarius)

300 light years

First observed by Jansky in 1932

(found to interfere with radio transmission)



8 light months

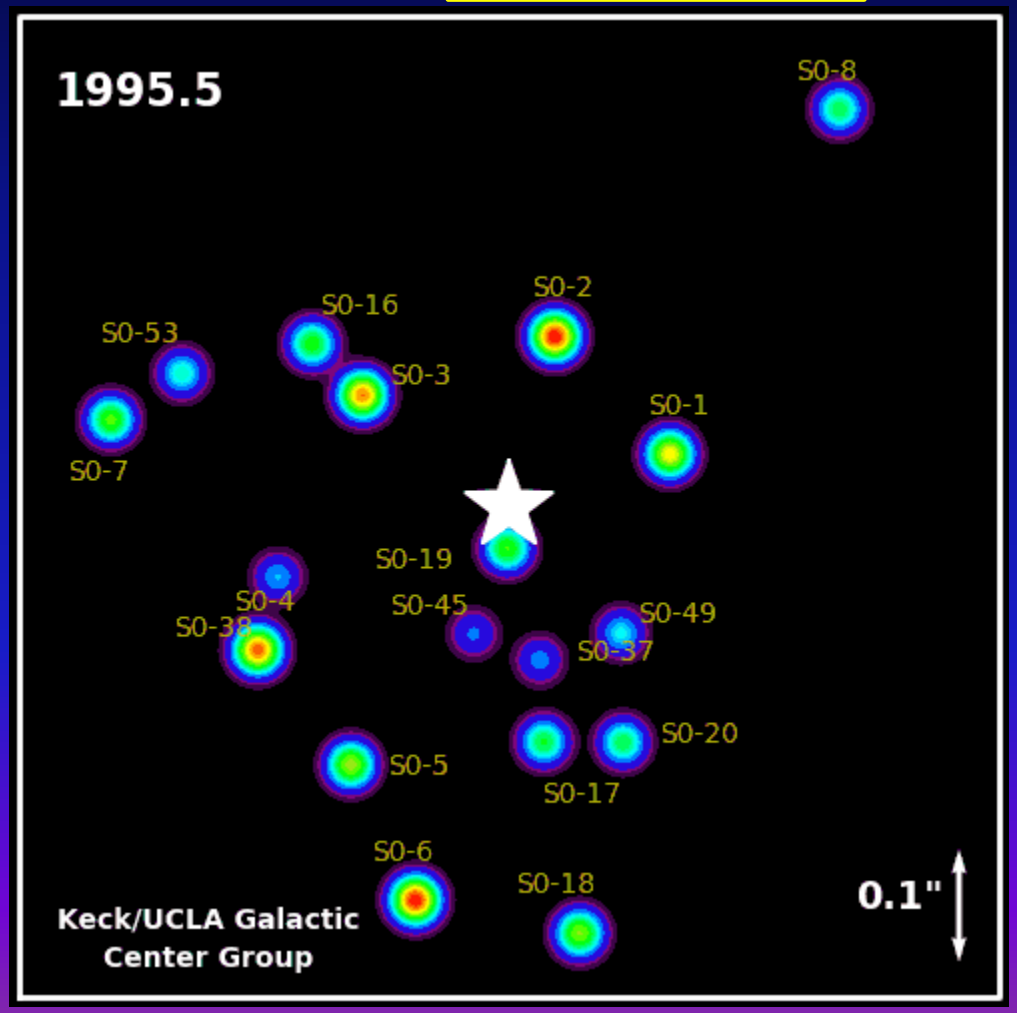
A very bright central core is identified later

by Balick & Brown 1971

Dark mass found

Stars orbit a central location:

black hole 4mln times more massive than Sun



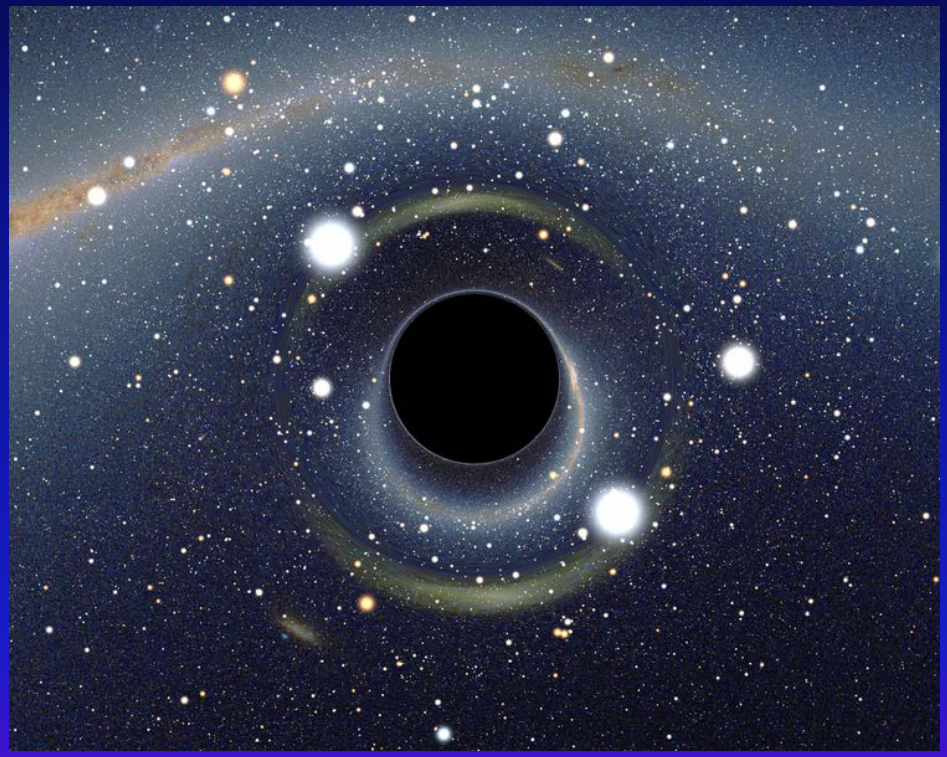
IR observations from 1990s

Closest stars reach speed 5000km/s – 1000x the speed of fastest projectiles

Shortest orbit – 12 years, things change on human timescale

What is a black hole (BH)?

A region of space having a gravitational field so intense that no matter or radiation can escape.



Characterized by gravitational radius R_g

R_g=30x distance to the Moon for Galactic Center black hole

Also, BH: a figurative place of emptiness or aloneness
(a lonely beast in the center of the Milky Way!)

Could it be something other than a BH?

Not really

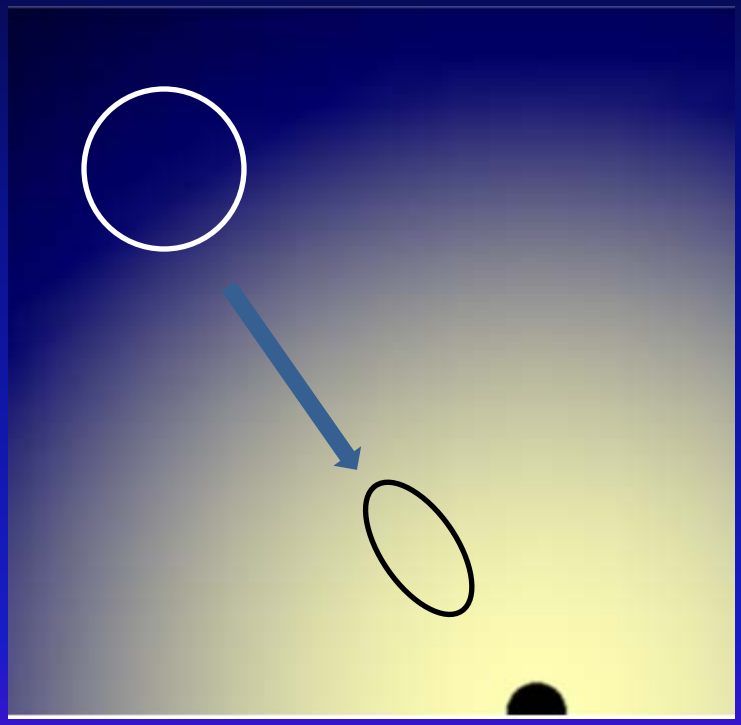
Stellar orbits come as close as $4000R_g$,
thus the central mass is constrained to a very small volume

- No stable single object has such a large mass (4mln solar masses) – will collapse into the BH
- A collection of stars put together within a small volume will not stay together – some will get kicked out, the rest will collapse into the BH

However, scientists are never 100% sure ☺

So, why does it emit light?

The BH itself doesn't emit light, but the infalling gas does emit



1. A BH pulls a clump of gas
2. The clump gets compressed
3. Compression causes heating
   (similar to pumping air into a tire)
4. Hot gas emits light (+ radiowaves, X-rays)

How hot does the gas get?

1. BH can accelerate particles to the speed of light
2. Rest mass energy gets converted into heat as $E=mc^2$
3. Achieved temperature is up to 1bln K – 100.000x that in the center of the Sun

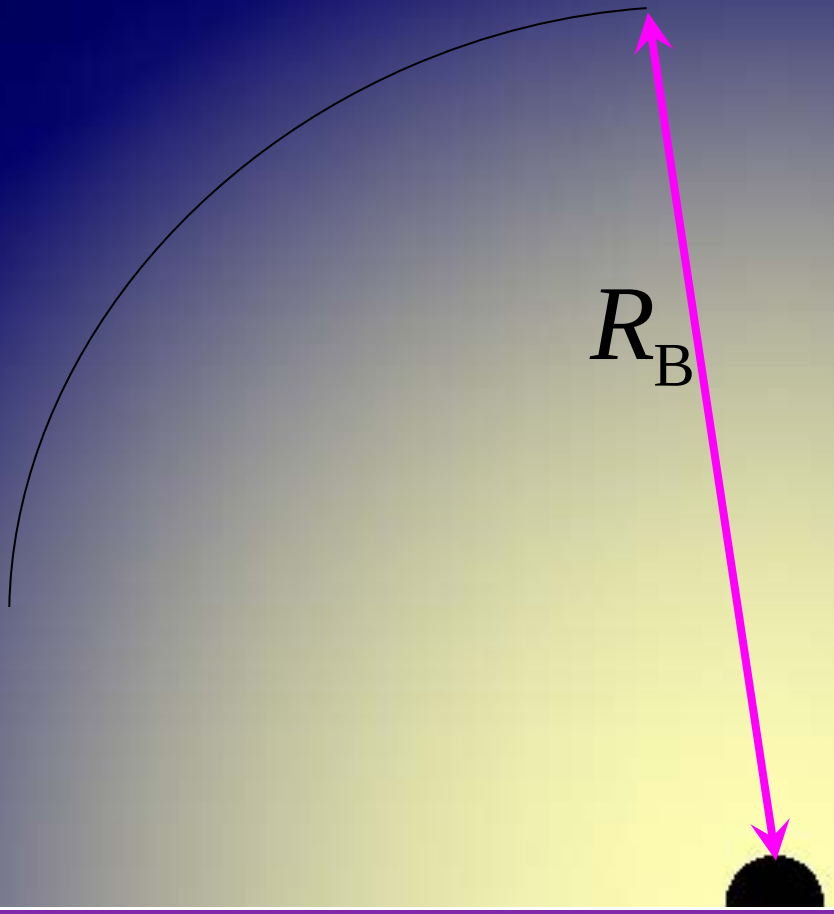
The process of gas infall onto the BH is called accretion

The properties of accretion

Characterized by Bondi radius R_B, where particle thermal energy equals gravitational energy:
once within R_B, the matter is pulled in

Accreting gas heats up due to compression

Vary dependent on gas supply

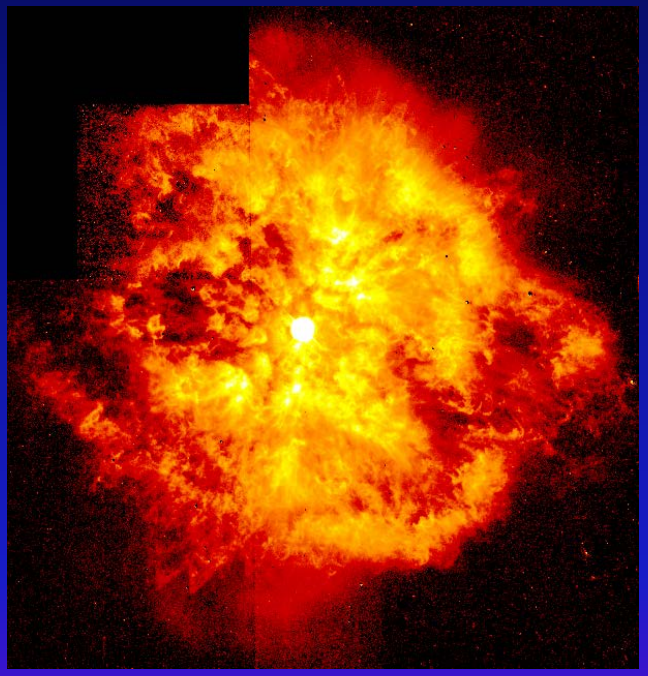


From where does the gas originate?

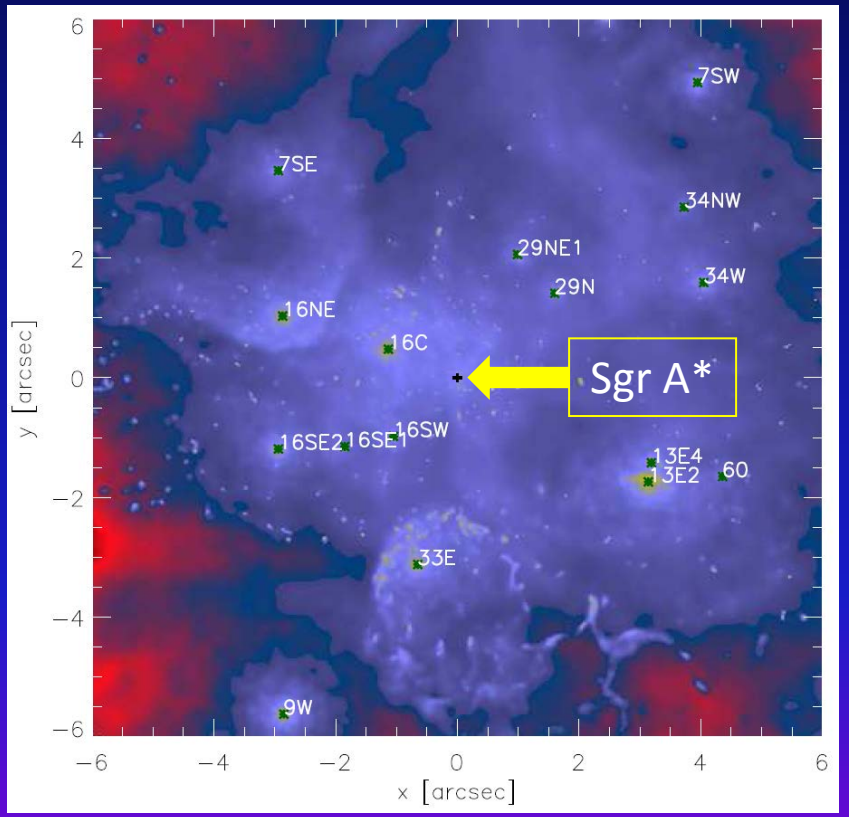
At present epoch – from stellar winds

Wolf-Rayet star ~ 20 solar masses,
violent expulsion of winds ~ 3 Earth masses per year

Cuadra et al 2008



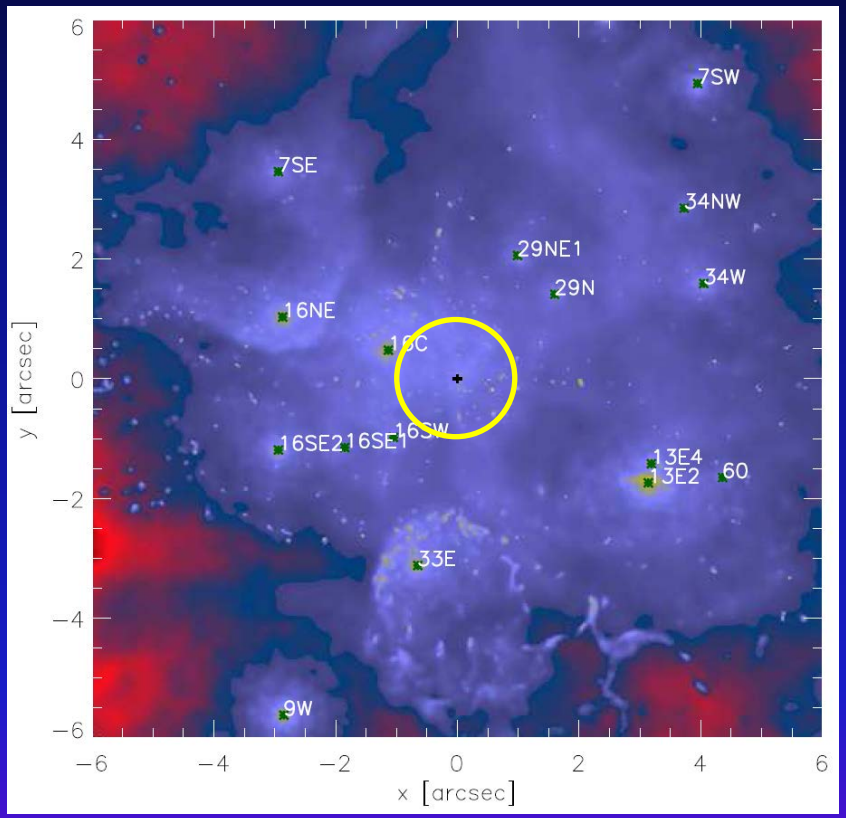
Wind velocity up to 2000km/s



Winds from several stars collide
and heat the gas to 10mln K

Does the BH monster eat all that gas?

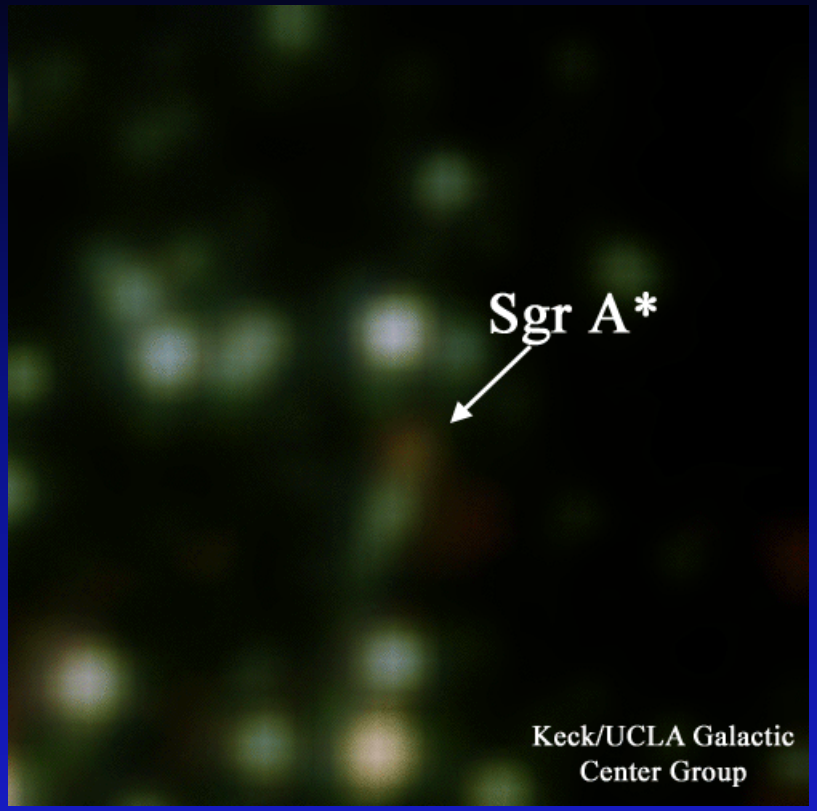
No, most of it escapes the pull of the black hole



BH can only pull gas within “Bondi radius”
1’’=50light days = 1trln km

At least 99% of gas escapes
being served for dinner

Light from the BH (accretion flow)

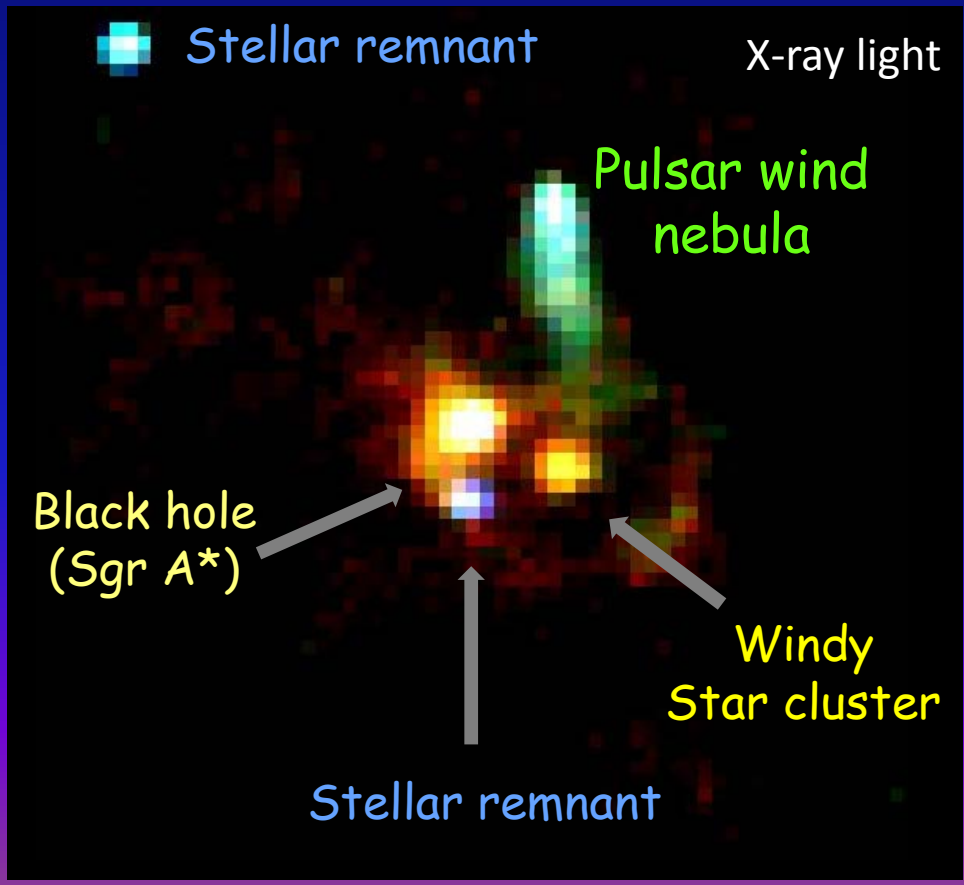


IR light – twinkling red spot in the center
(the rest are stars distorted by the atmosphere)

Radio – can image features of gravitational radius size!

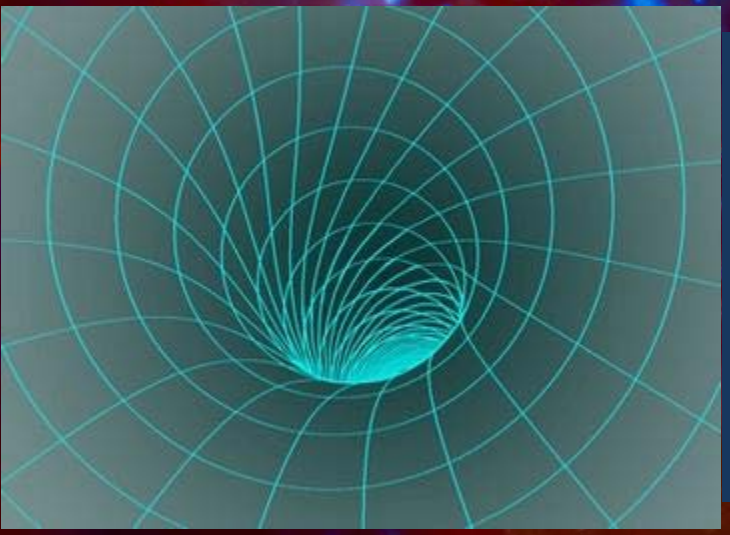
Seeing through gas and dust:

- Radio & IR – wavelengths larger than particle size
- X-rays – penetrate through dust, partially absorbed by dust & gas



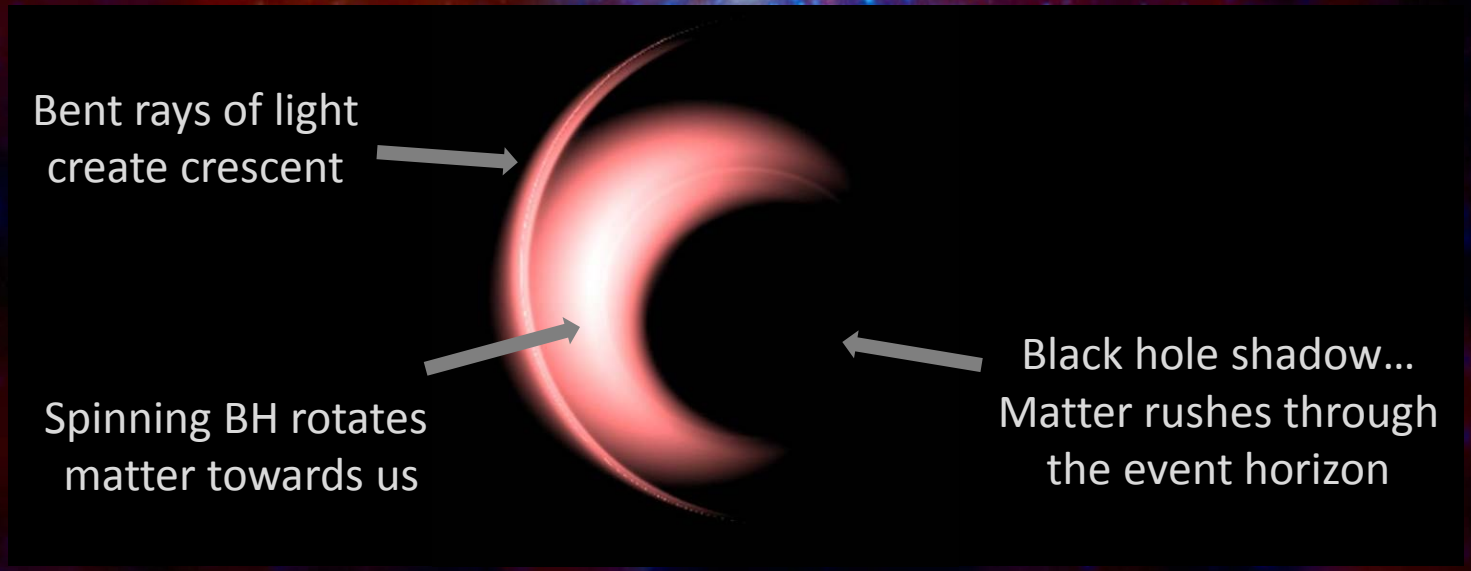
Spacetime distortions near the BH

Observed in 2008+ with radio interferometers



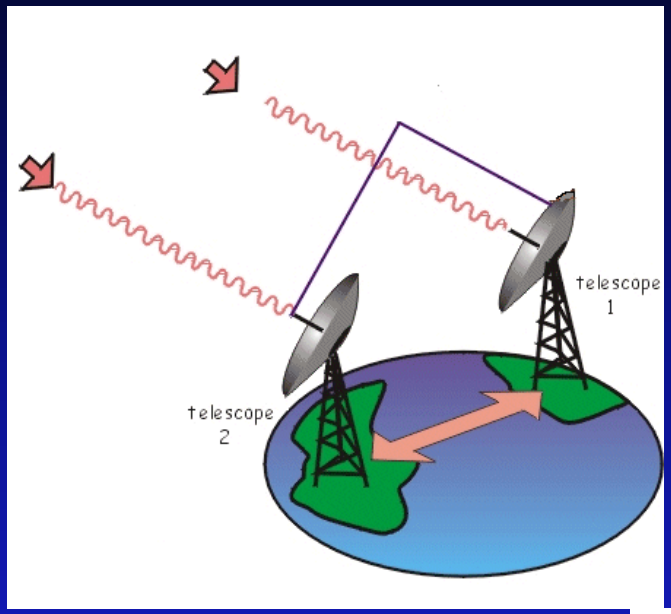
Black holes:

- ✓ Bend the rays of light
- ✓ Spin and swirl matter around
- ✓ Suck gas through the event horizon, so that it stops emitting light



Very Long Baseline Interferometry

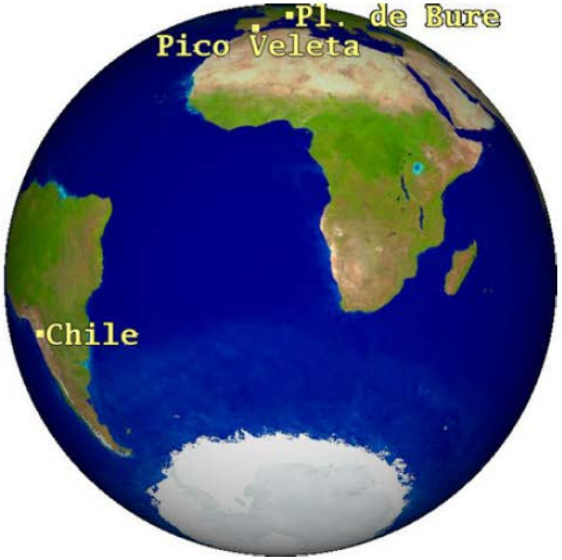
A pair of telescopes at different sites on Earth (or in space!)



VLBI

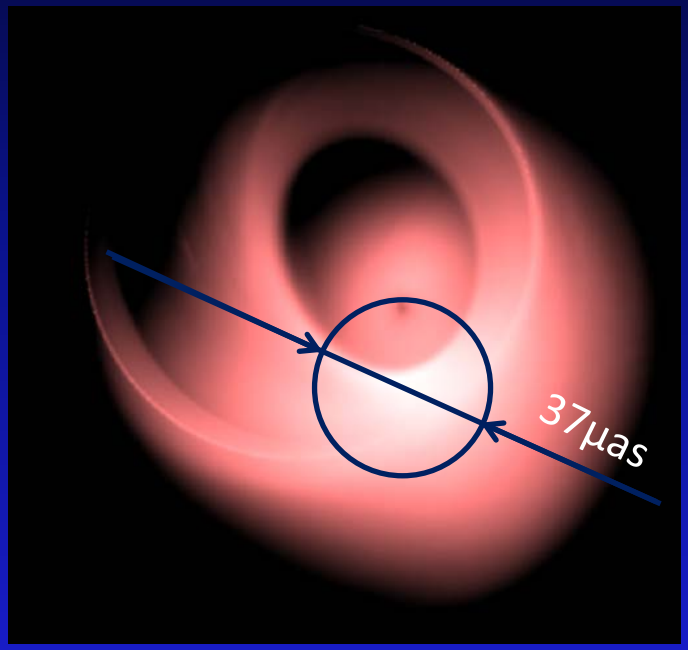
- ✓ Two telescopes 300-10.000km apart
- ✓ Observe separately, then data are correlated to find source size
- ✓ Usage of several telescopes allows us to reconstruct image

Telescopes in Hawaii, Arizona and California are operating in VLBI mode now!

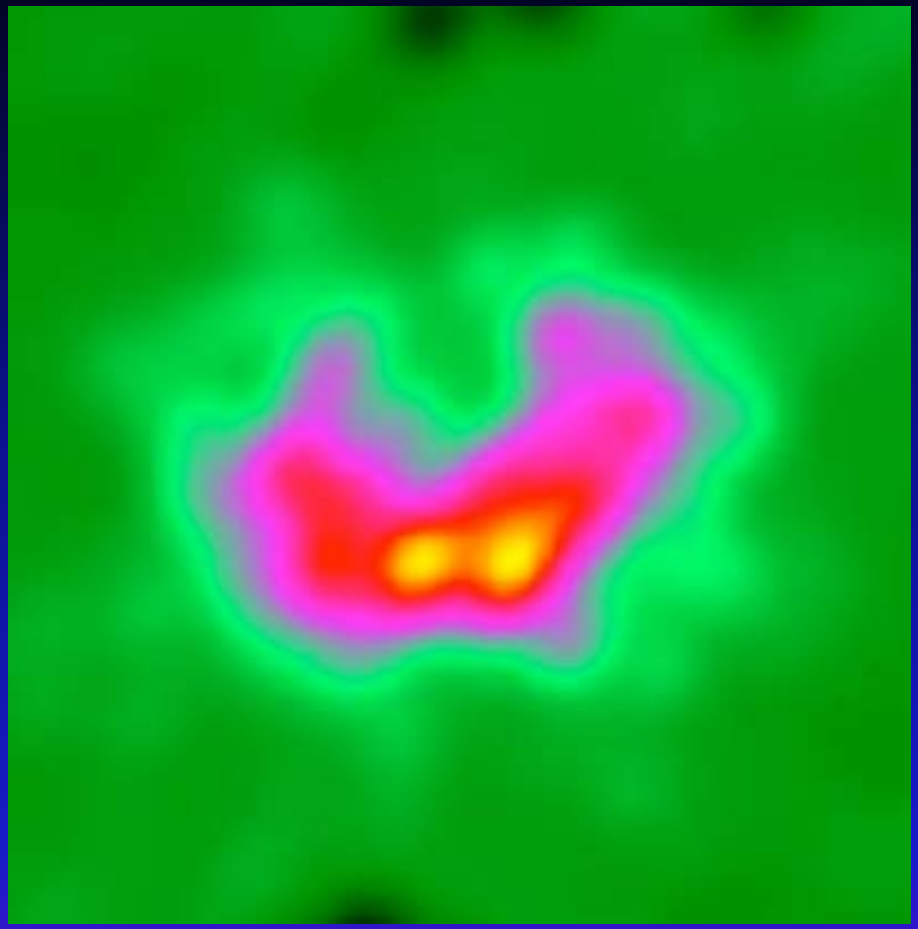


Spacetime distortions near the BH

37microarcsec size on Hawaii-Arizona baseline
Doeleman et al. 2008, Nature



Size of the image along certain axis – consistent with models of gas flow close to the black hole



With 7 stations working (2014-2015) one can reconstruct the image

Event Horizon Telescope

The images are too dim!

If all captured material were to fall onto the BH,
then that material would emit lots of radio/IR/X-rays before falling,
much larger than the observed emission

Observations suggest only 1% of mass captured within R_B
falls onto the BH, the rest somehow escapes…

99.99% of material tricks the starving BH

How does the gas trick the BH?

Sacrifice a few particles to save the rest

Hot particles near BH

Heat flux

Cold particles at R_B

Escape

- ✓ Particles heat up on the way to BH
- ✓ If those near the BH could transfer heat to cold particles at R_B, then those particles would have enough energy to escape!
- ✓ Those near the monster do transfer heat out via "conduction" – they have little energy left and are swallowed, but particles far away can escape

How does conduction work?

It equilibrates temperature
like “down-to-Earth” conduction through building walls

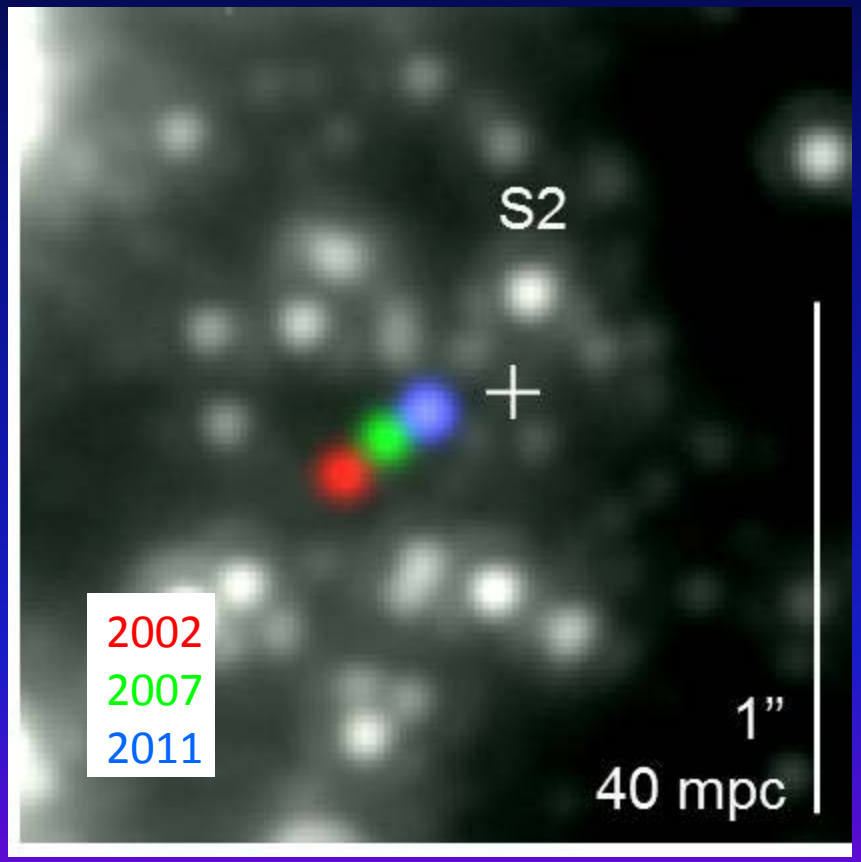
Electrons can freely move
in very rarified hot gas (plasma) near Sgr A*

Those electrons get energy in hot inner regions
and deposit it in cold outer regions

Dinner will eventually arrive… in 2013!

A dense cold cloud on the way to the GC

Gillessen et al. 2012, Nature



Position of the cloud in various epochs

The cloud

- ✓ Mass about 3x Earth mass
- ✓ Much denser and cooler than surrounding gas – can’t resist BH pull
- ✓ Likely to lead to substantial inflow

- ✓ The cloud fell 26.000 years ago, but light took that time to reach us

Here is how it falls

A gas cloud on its way into the super-massive black hole in the Galactic Centre

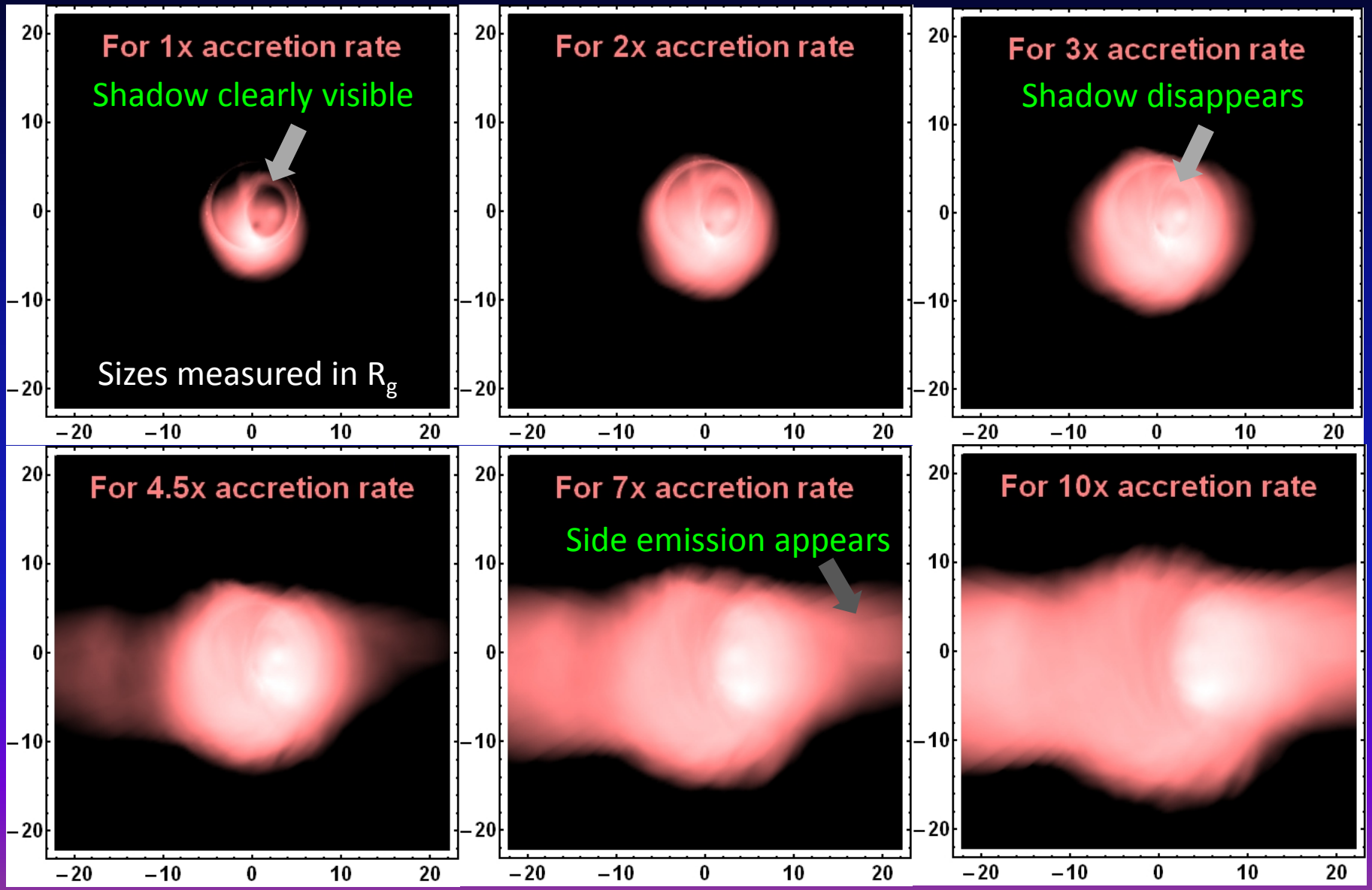
S. Gillessen, R. Genzel, T. Fritz, E. Quataert, C. Alig, A. Burkert, J. Cuadra, F. Eisenhauer, O. Pfuhl, K. Dodds-Eden, C. Gammie, T. Ott
Nature, Dec. 2011

MPE

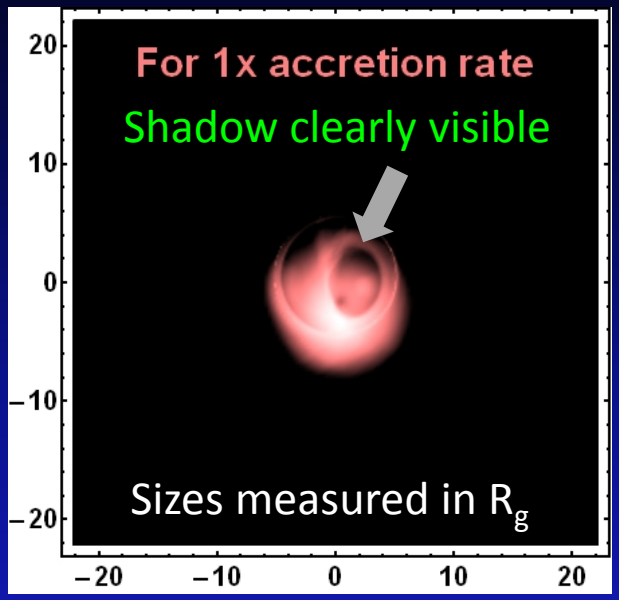
Simulation by: M. Schartmann, A. Burkert, C. Alig, S. Gillessen, R. Genzel
using PLUTO 3.1.1 (Mignone et al. 2007)

How will the BH shadow change?

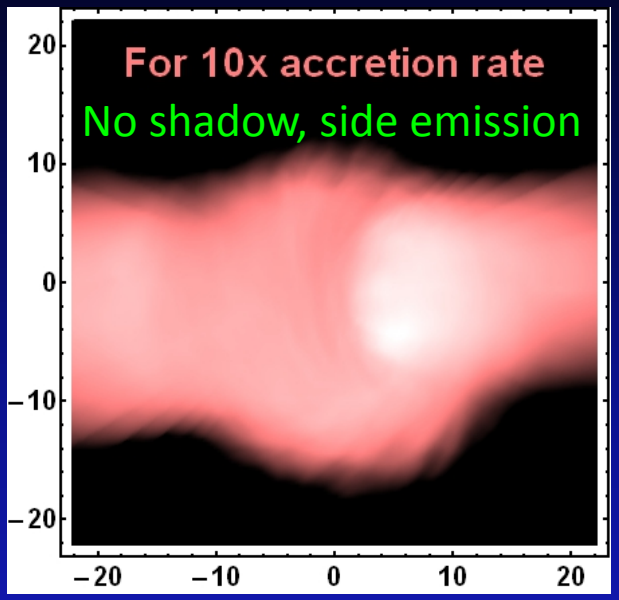
Accretion rate from the cloud may be 10x larger…



How will the BH shadow change?



VS



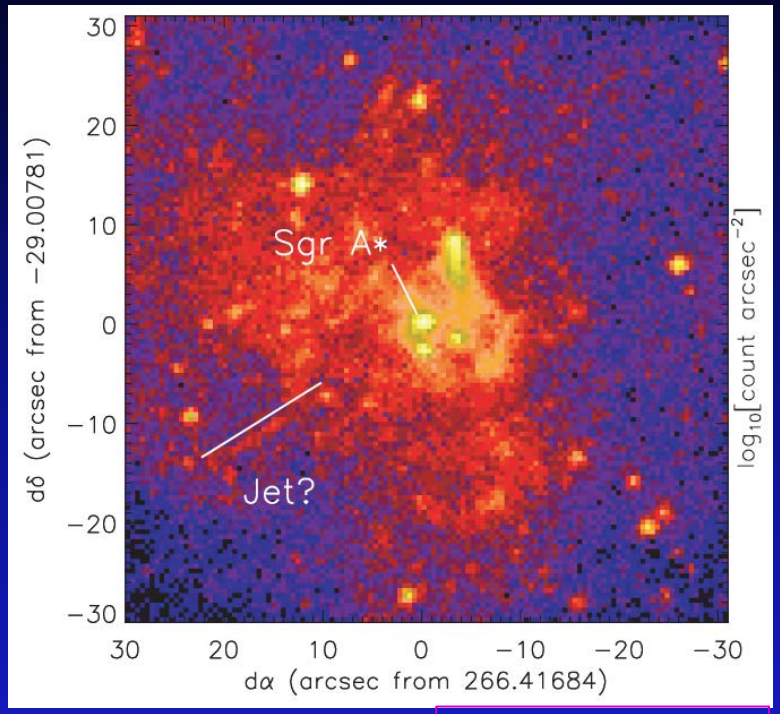
Why changes happen (1x -> 10x accretion rate)?

- ✓ Gas radiates in larger volume – can't spot the shadow
- ✓ Large amount of gas obscures its own emission
- ✓ Hot gas expelled along the polar axis (jet) – side emission

By the time the radio telescopes are ready, the shadow may disappear

Jet from previous epochs is observed

Size of jet feature – 2 light years



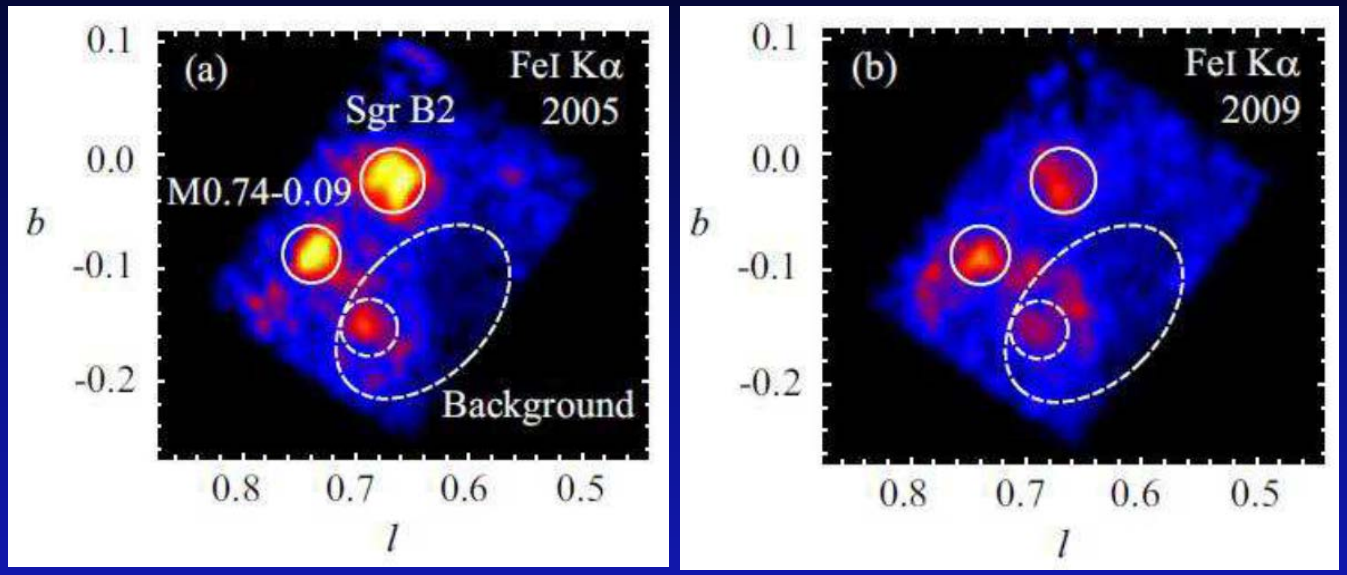
Muno et al. 2008

Jet feature 2 light years across could originate 2-30 years ago

What will happen in 2013+ was also happening in the past:
periods of active accretion are frequent

“Light echo” episode ~300yrs ago

BH accretion irradiated an outside cloud, which started to shine

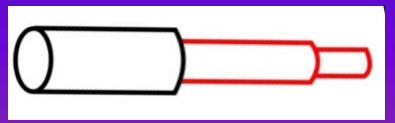


Short timescale

BH activity

Nobukawa et al. 2011

- ✓ About 300yrs ago the BH was accreting a lot of gas
- ✓ X-ray luminosity of that gas was 1mln times larger
- ✓ BH is not shining anymore, but the reflected light just reached us



Accretion 1mln times brighter!?

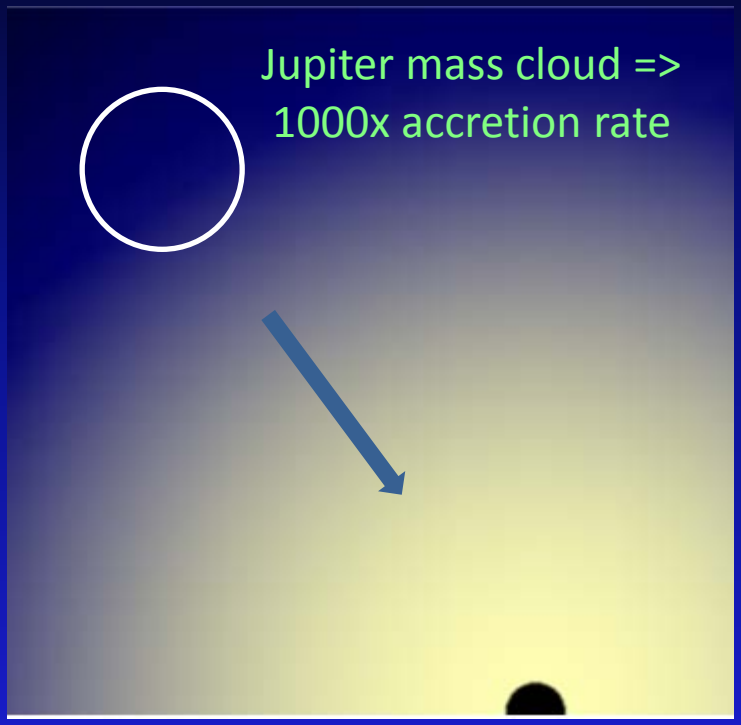
1000x accretion rate from a bigger cloud/stellar winds

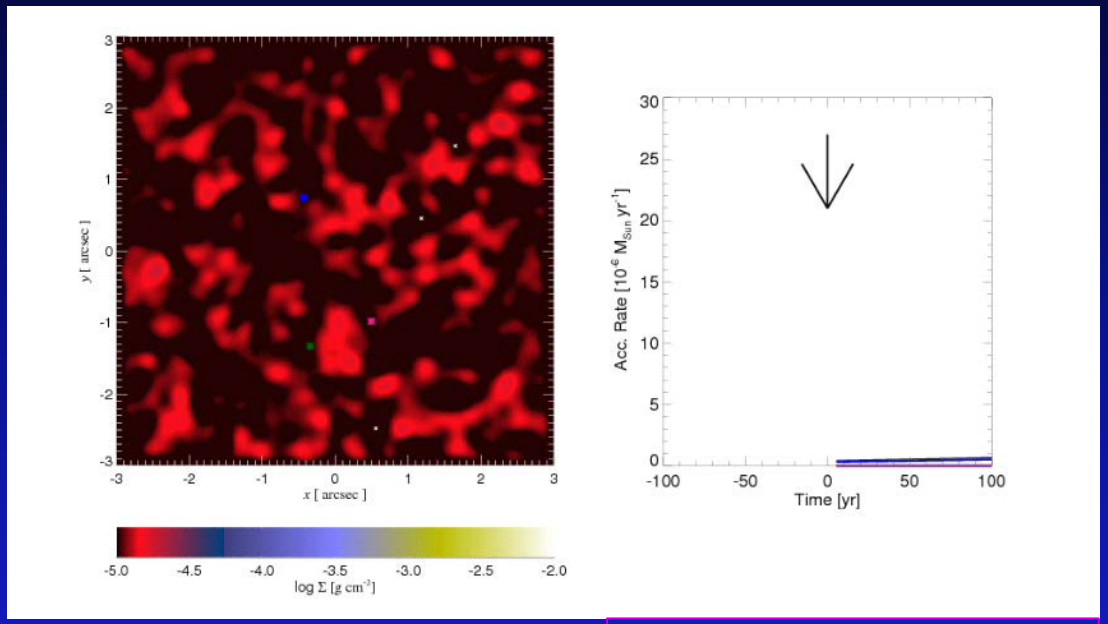
See Mathematica presentation:

- Emission is proportional to the number of collisions
- The number of collision is proportional to the number of particles squared

Competing hypotheses

External cloud or stellar winds activity?





Cuadra, Nayakshin et al. 2005

However, feeding from the cloud is long…

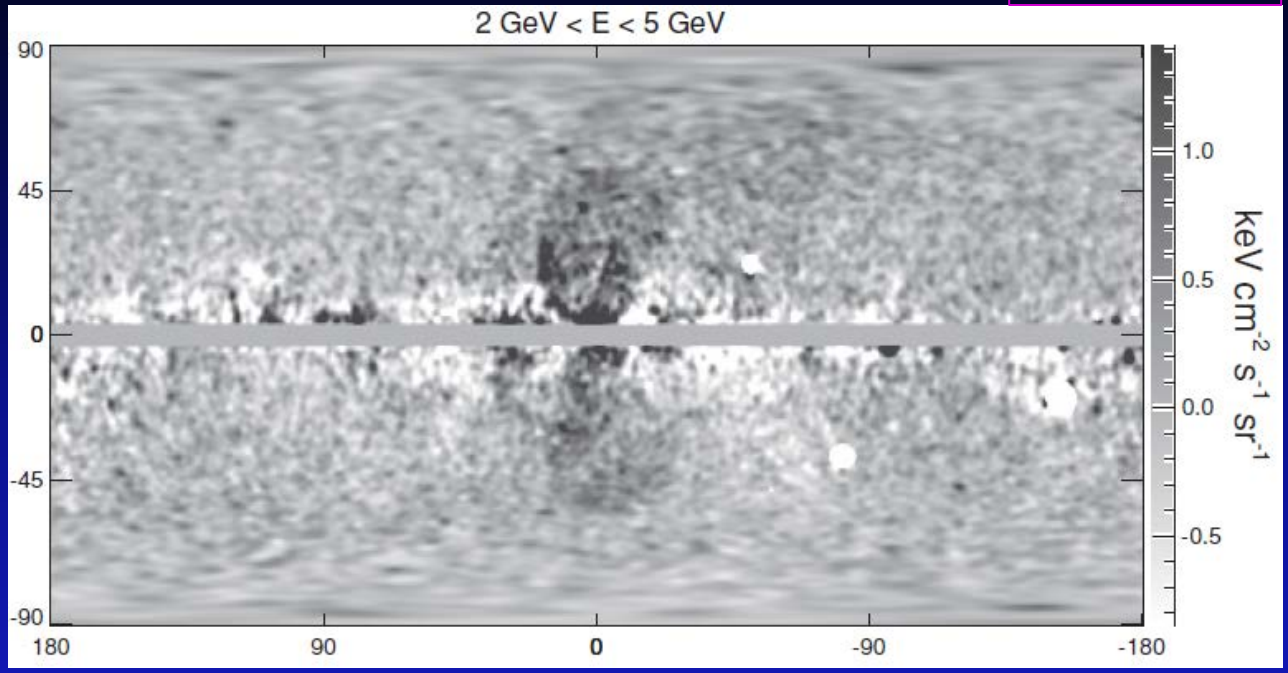
Can't reproduce the short timescale of irradiation fading

Stellar winds produce quickly changing accretion

Can't reproduce the magnitude of the event (1000x times)

Even more dramatic past: Fermi bubbles?

Su et al. 2010



Galaxy in gamma-ray view

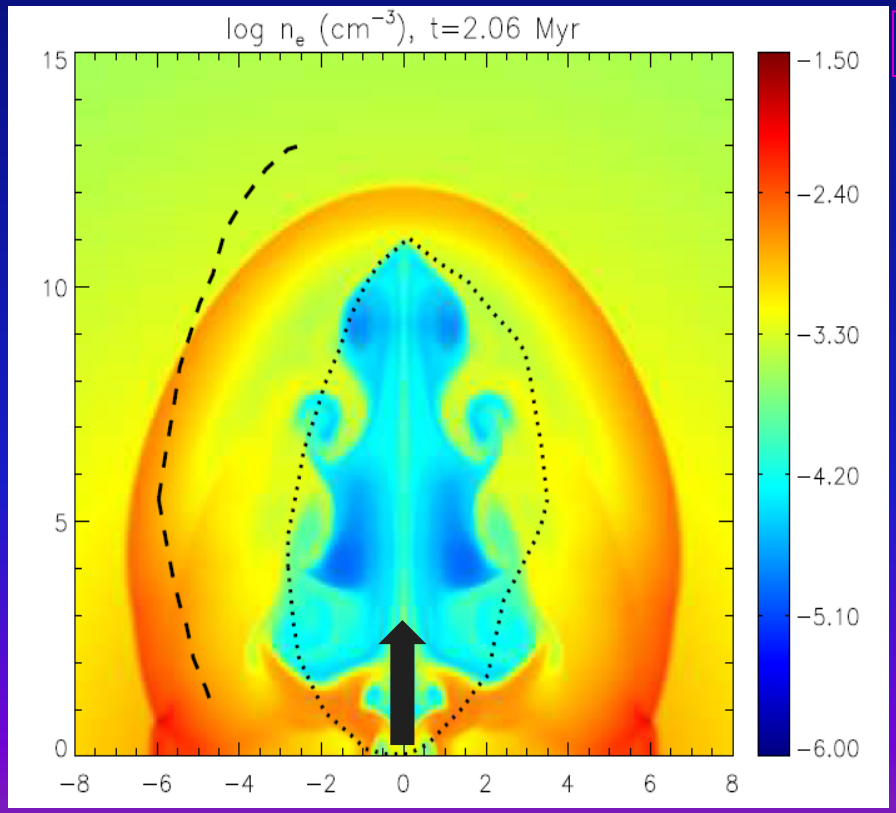
- ✓ Huge structure on the galactic scale – Fermi bubbles
- ✓ Bubbles originate in the Galactic center
- ✓ Likely originates several mln years ago

Jet ejected from the BH could have blown the bubbles

Yes, the BH could be that powerful

Numerical simulations:

- ✓ Scientists setup the problem on a supercomputer
- ✓ BH + as much gas as it could eat
- ✓ "Simulate" evolution of BH + gas (or just outflowing gas)
  "leftover" gas gets expelled and blows bubbles



Guo & Mathews 2011

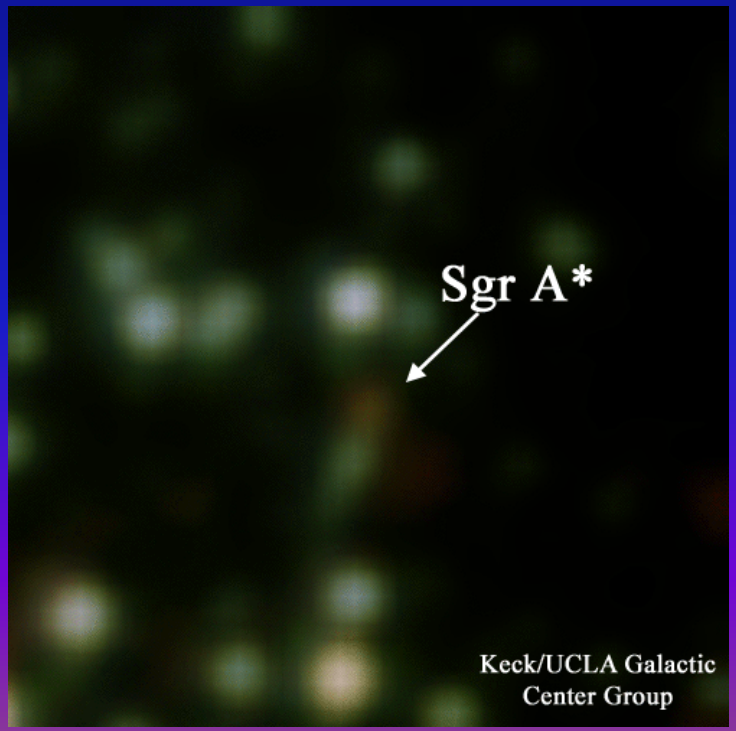
Numerical simulations indicate the BH could blow bubbles over a period of 0.5mln years about 5mln years ago swallowing an Earth mass per hour

The jet could be visible with a naked eye

Fortunately, the BH will not shoot the jet towards us – we'd be fried otherwise!

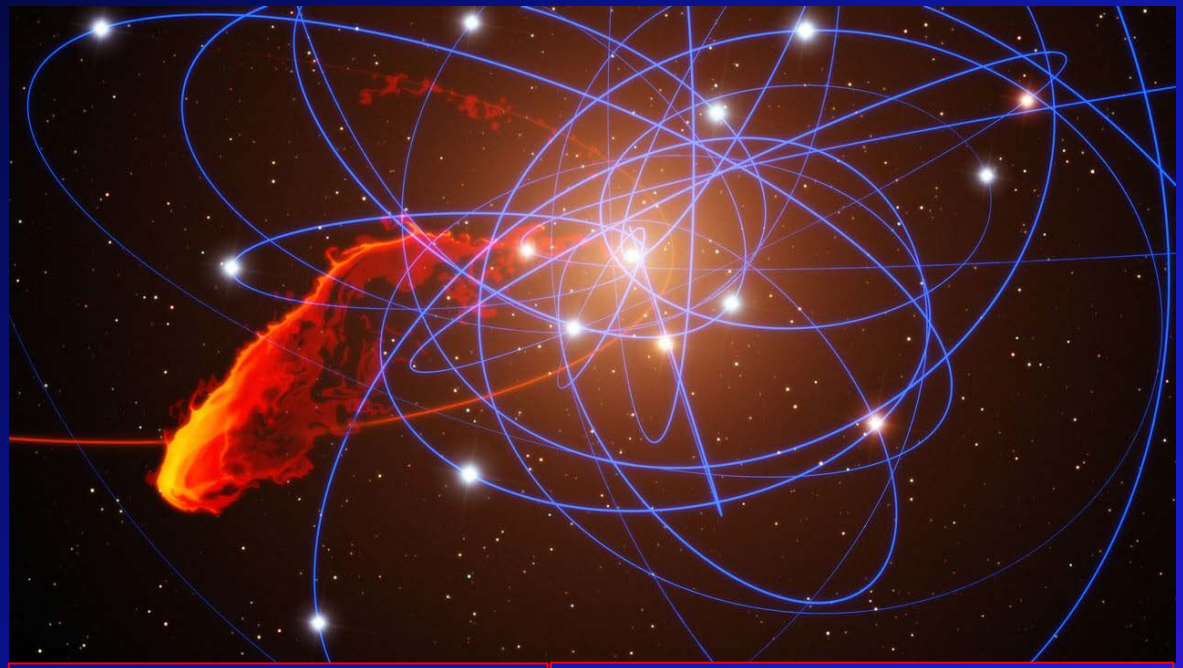
Mysterious Sgr A* black hole

- The topic of continuous amazement
  even among professional astronomers
- Gradually reveals its surprised
- Astronomers can directly look at it to observe the BH shadow
- Gas can trick the starving BH at present and avoid being swallowed
- The monster was feasting some time in the past
  and will be having a snack in the near future



Disrupted cloud of gas

NOW on the way to the BH,
closest approach at 2013, tidally disrupted



Gillessen et al. 2012, Nature | Image Credit: ESO/MPE/Marc Schartmann

10^{34}erg/s X-ray flare from shock

But small fraction of mass in the accretion flow within 0.5’’

No long-term consequences!?

Why do regimes switch?

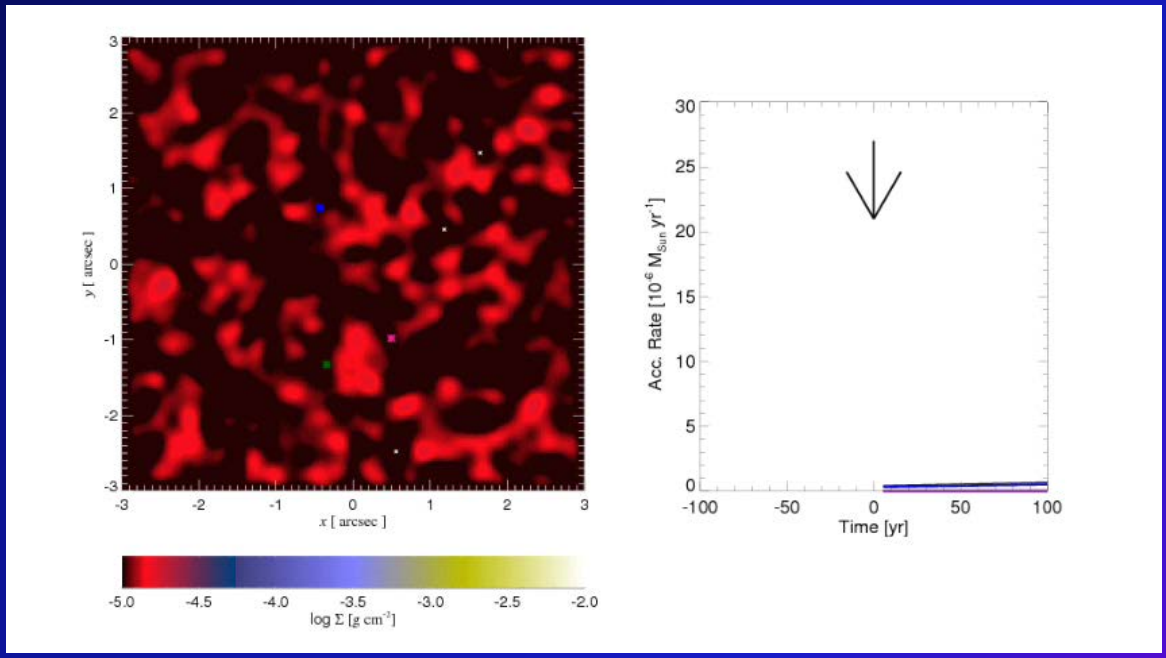
Amplified natural variability

Natural variability:
colliding winds,
orbits of stars

Cuadra, Nayakshin et al. 2005

Timescales as short as 10yrs!

Sound crossing time 60yrs



Sgr A* region is on the brink of cooling down

Cuadra, Nayakshin et al. 2005

$t_{cooling} \sim t_{dynamic}$

Early simulations of colliding winds exhibited run-away cooling

Sgr A* region is on the brink of being collisional

Shcherbakov & Baganoff 2010

$\lambda_{mfp} \sim r_B$

Conduction is suppressed when $\lambda_{mfp} < r_B$

Lots of molecular gas at >1pc ready to accrete

Alexander 2005 (review)

When the inner pressure is low, the gas may pour in