The first Black Hole images with the Event Horizon Telescope

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Very Long Baseline Interferometry

Max-Planck-Institut
für
Radioastronomie

Event Horizon Telescope

SFB1491

4th Graduate School on Plasma-Astroparticle Physics

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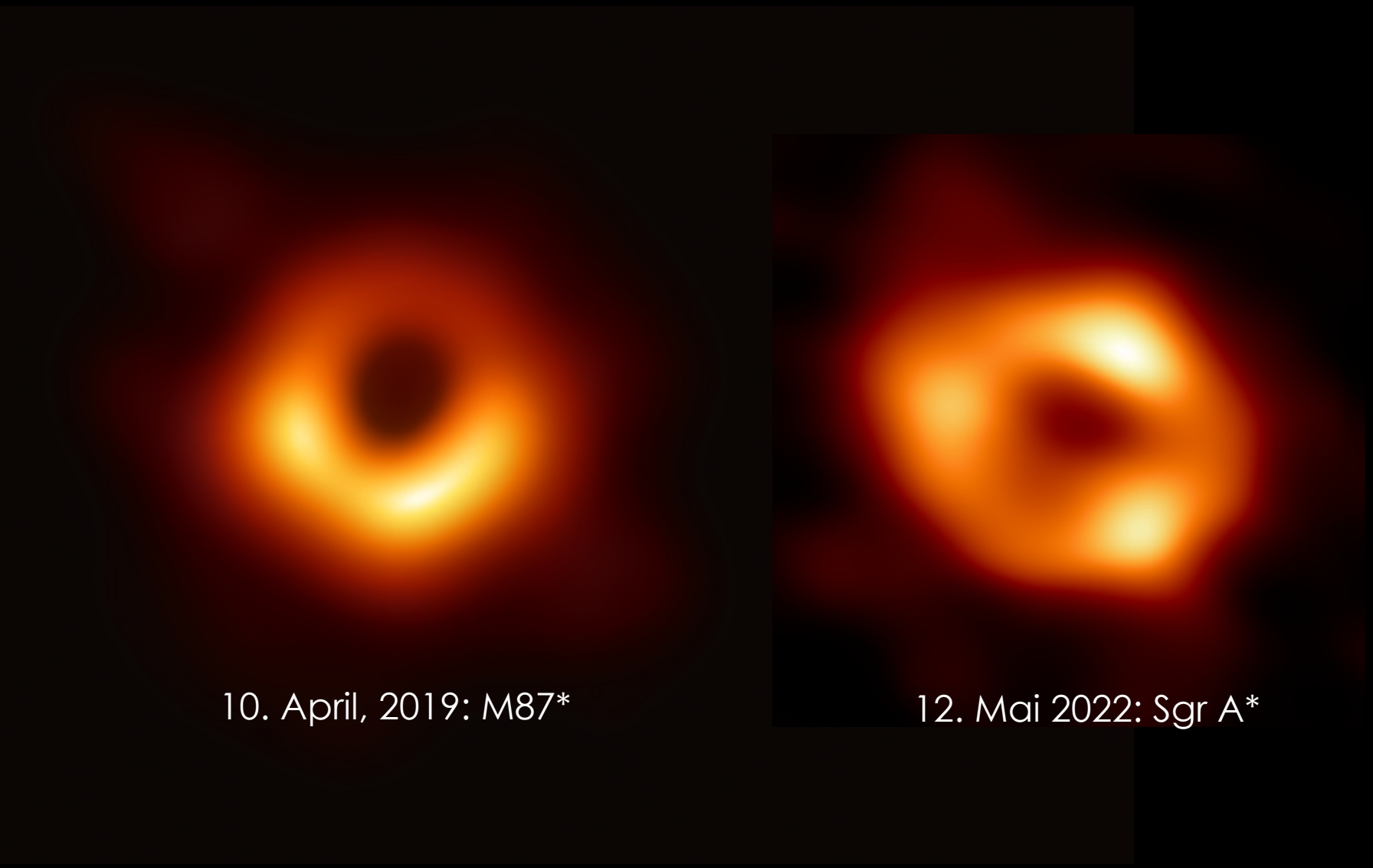
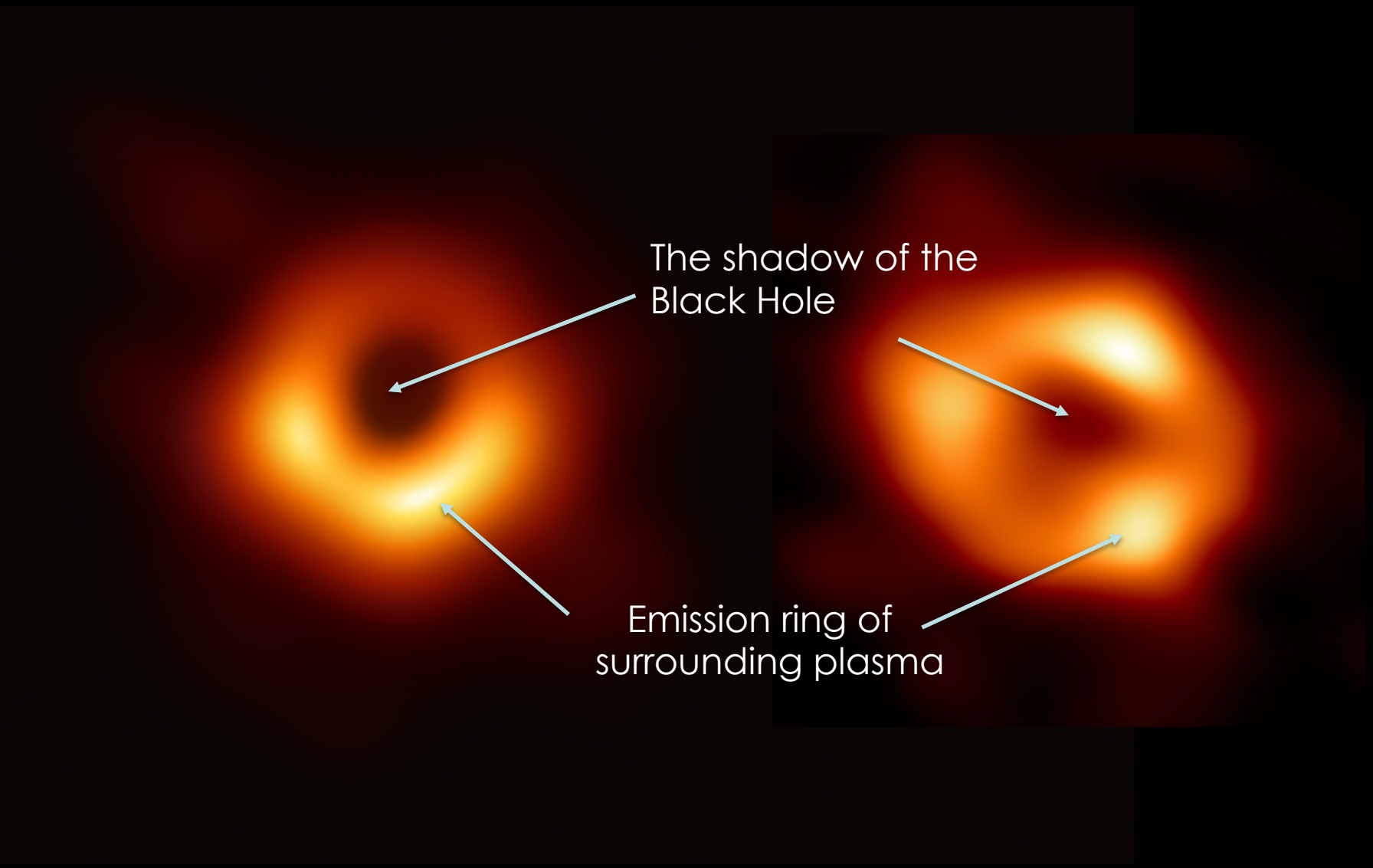
Physikzentrum Bad Honnef



10. April, 2019: M87*

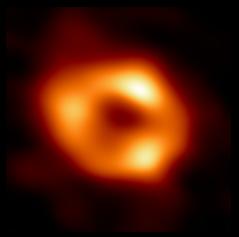
12. Mai 2022: Sgr A*


The shadow of the
Black Hole
Emission ring of
surrounding plasma

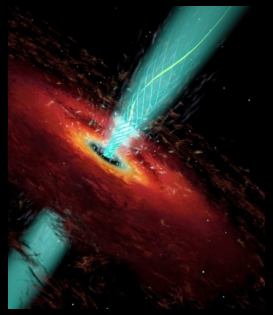
Plan for this talk

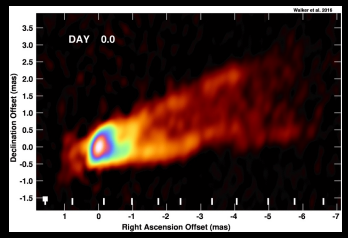
How to find a supermassive Black Hole in the Sky

EHT observations and
the EHT-images of Sgr A*



M87* and Sgr A* -
what do they have in common ?
What are the differences ?





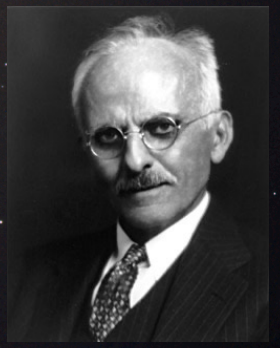
The future:
The ngEHT & supermassive binary Black Holes

How to find a supermassive Black Hole in the Sky ?

M87*

“a curious straight ray ... apparently connected with the nucleus by a thin line of matter”

Heber Curtis 1918



Many Questions

How are jets generated?

Do Black Holes exist?

Really?

Do we need Quantum physics
to explain the
complete phenomenon “black hole”?

How would an image of the shadow
of a black hole look like?

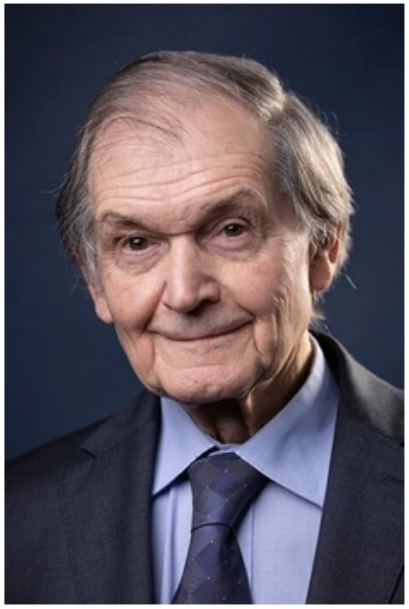
Is Einstein still and again right?

How to find a supermassive Black Hole in the Sky ?

Sgr A*

The closest supermassive black hole to home: Sgr A*

Nobel Prize in Physics 2020



© Nobel Prize Outreach. Photo: Fergus Kennedy

Roger Penrose

Prize share: 1/2

© Nobel Prize Outreach. Photo: Bernhard Ludewig

Reinhard Genzel

Prize share: 1/4

© Nobel Prize Outreach. Photo: Annette Buhl

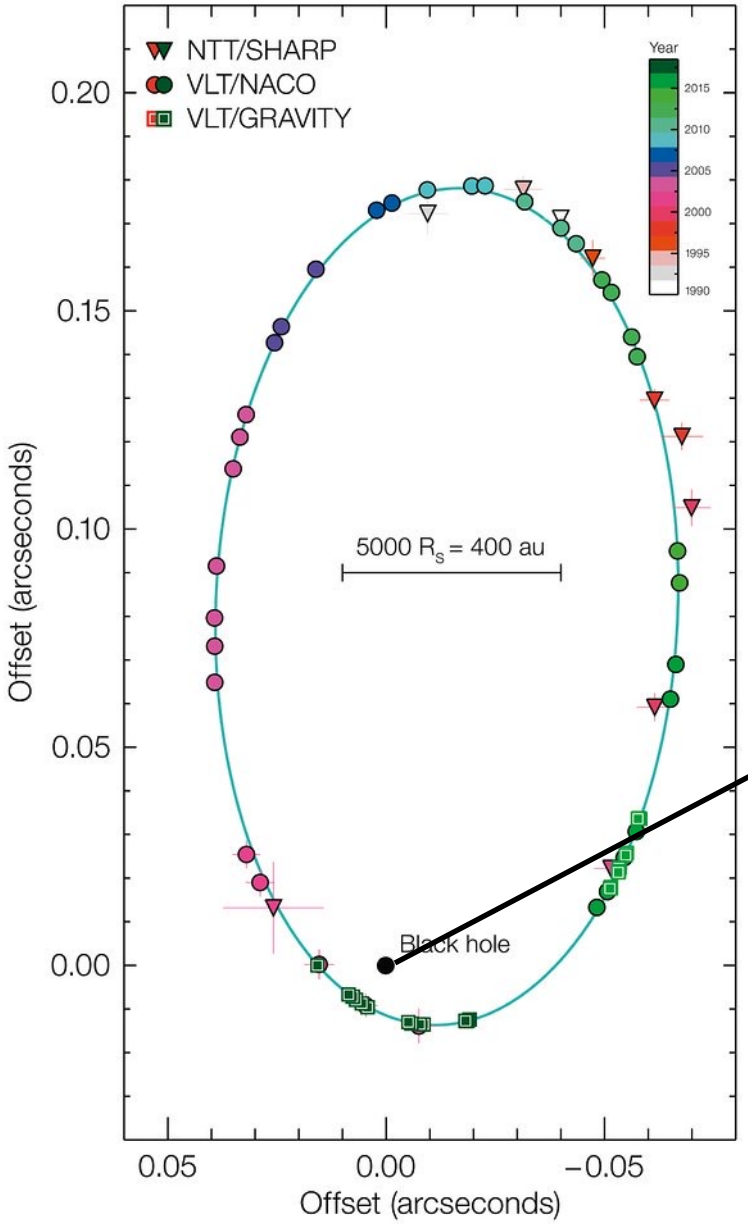
Andrea Ghez

Prize share: 1/4

The Nobel Prize in Physics 2020 was divided, one half awarded to Roger Penrose "for the discovery that black hole formation is a robust prediction of the general theory of relativity", the other half jointly to Reinhard Genzel and Andrea Ghez "for the discovery of a supermassive compact object at the centre of our galaxy"

Very Large Telescope (VLT) , Chile

Keck Telescopes in Hawaii. Credit: Keck Observatory



This diagram shows the motion of the star S2 around the supermassive black hole at the centre of the Milky Way. It was compiled from observations with ESO telescopes and instruments over a period of more than 25 years.

The star takes 16 years to complete one orbit and was very close to the black hole in May 2018. Note that the sizes of the black hole and the star are not to scale.

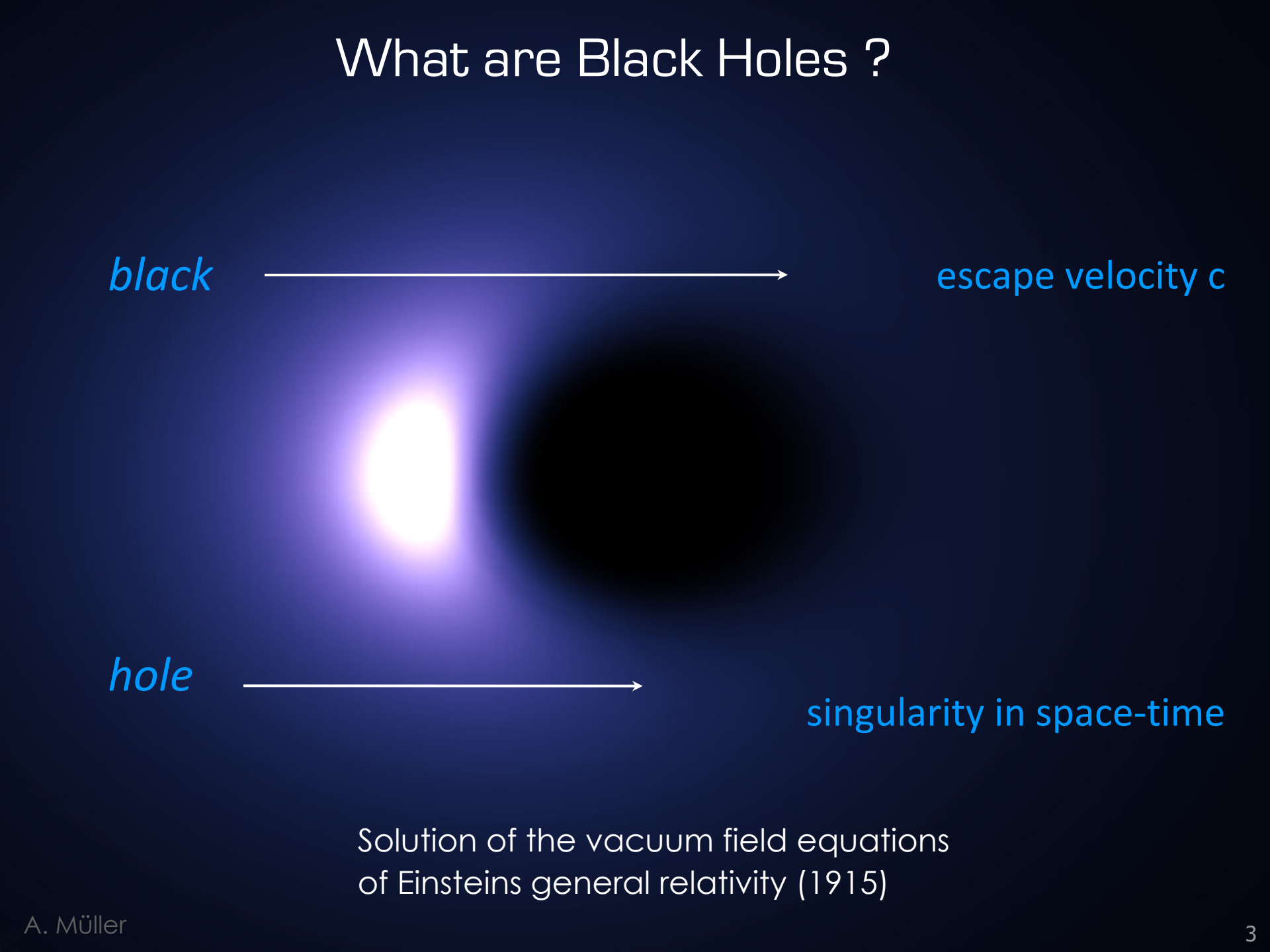
Credit: ESO/MPE/GRAVITY Collaboration

Ein supermassereiches, kompaktes Objekt.

Masse: 4.3 Mio. Sonnenmassen
Entfernung: 26 600 Lj

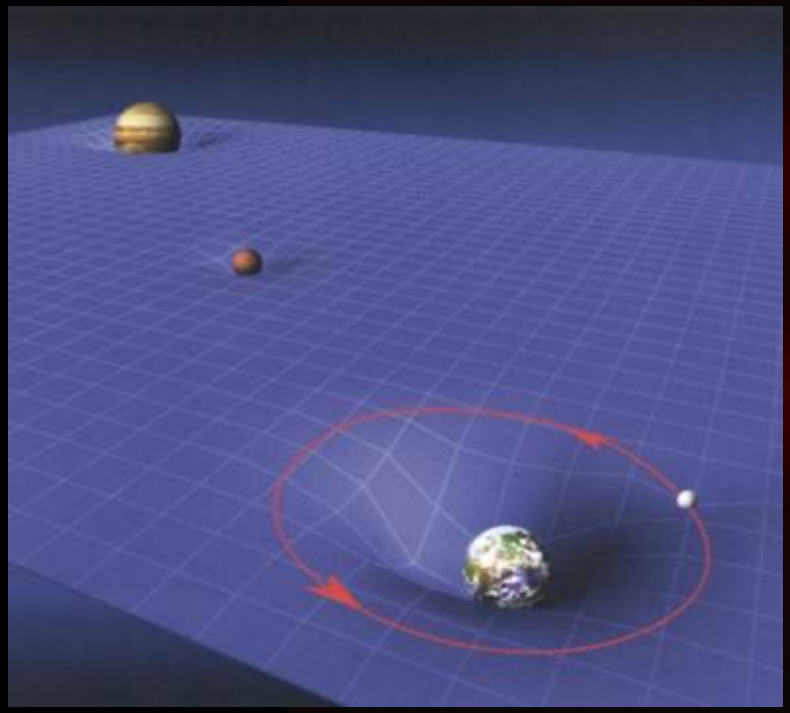
Genzel et al. 1997, 2000, 2003a, 2010; Ghez et al. 1998, 2000; Eckart et al. 1999, 2002; Gezari et al. 2002; Schödel et al. 2007; Schödel et al. 2003; Eisenhauer et al. 2005; Ghez et al. 2005b, 2008; Gillessen et al. 2009a, 2009b, 2017; Meyer et al. 2012; Boehle et al. 2016; Chu et al. 2018; Hees et al. 2019; O'Neil et al. 2019; Gravity Collaboration et al. 2021a

What are Black Holes ?



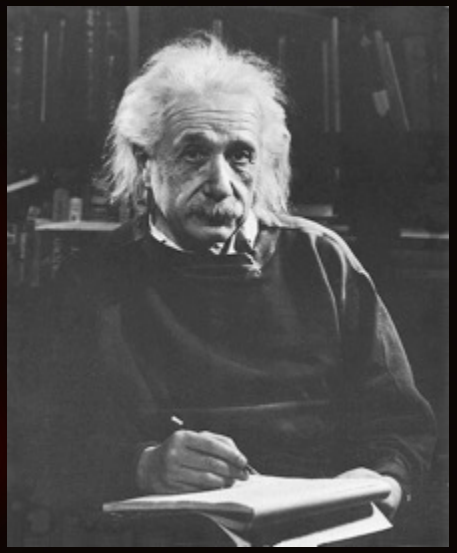
Solution of the vacuum field equations
of Einsteins general relativity (1915)

Space & time are bent, or curved, by matter.



This is **gravity**.

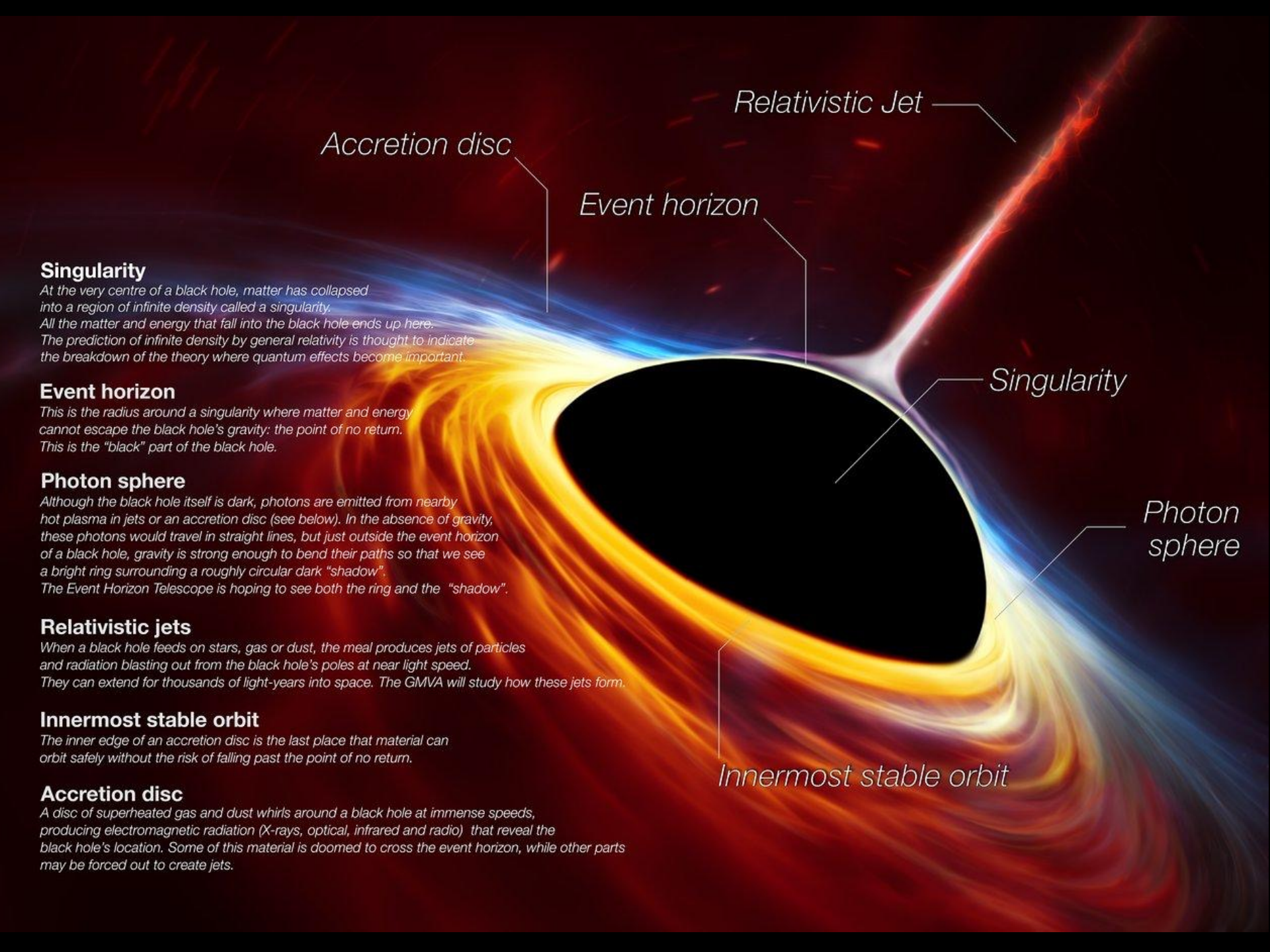
Planets, moons and baseballs go "as straight as they can."



"matter tells spacetime how to curve, and curved space tells matter how to move"

J.A. Wheeler

Black Holes are invisible,
because of Gravity.



Singularity
At the very centre of a black hole, matter has collapsed into a region of infinite density called a singularity. All the matter and energy that fall into the black hole ends up here. The prediction of infinite density by general relativity is thought to indicate the breakdown of the theory where quantum effects become important.

Event horizon
This is the radius around a singularity where matter and energy cannot escape the black hole's gravity: the point of no return. This is the "black" part of the black hole.

Photon sphere
Although the black hole itself is dark, photons are emitted from nearby hot plasma in jets or an accretion disc (see below). In the absence of gravity, these photons would travel in straight lines, but just outside the event horizon of a black hole, gravity is strong enough to bend their paths so that we see a bright ring surrounding a roughly circular dark "shadow". The Event Horizon Telescope is hoping to see both the ring and the "shadow".

Relativistic jets
When a black hole feeds on stars, gas or dust, the meal produces jets of particles and radiation blasting out from the black hole's poles at near light speed. They can extend for thousands of light-years into space. The GMVA will study how these jets form.

Innermost stable orbit
The inner edge of an accretion disc is the last place that material can orbit safely without the risk of falling past the point of no return.

Accretion disc
A disc of superheated gas and dust whirls around a black hole at immense speeds, producing electromagnetic radiation (X-rays, optical, infrared and radio) that reveal the black hole's location. Some of this material is doomed to cross the event horizon, while other parts may be forced out to create jets.

Why do we need an image of the black hole shadow in Sgr A*?

- Sgr A* is on a diet and has no jet – this is significantly different from M87*. It is important for us to figure out, whether the central machines in the Milky Way and in M87* operate differently.

- Black Holes are the extreme cases of strong Gravity – to understand better Gravity and its limits, we need to study Black Holes. M87* ist 1500 heavier than Sgr A* - is Einstein still right?

- Einsteins General Relativity does not work beyond the Event Horizon. By studying yet another Black Hole (Sgr A*) we hope to learn more about the physics that drive Black Holes.

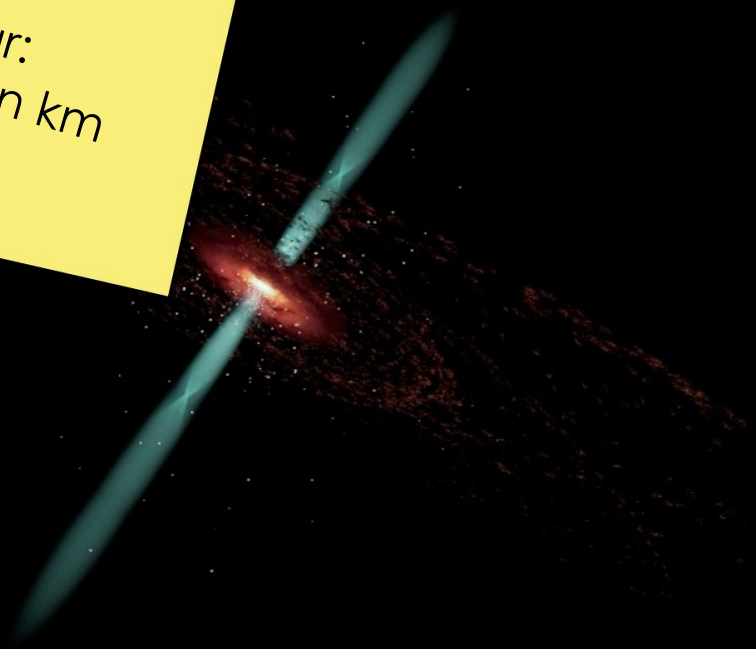
- And the big hope is – once we understand Black Holes better, we might also learn more about the beginning of our Universe.

Both Black Holes in Comparison: Jet, Accretion, etc.

Solar mass:
10^{30} kg

light year:
9.5 trillion km

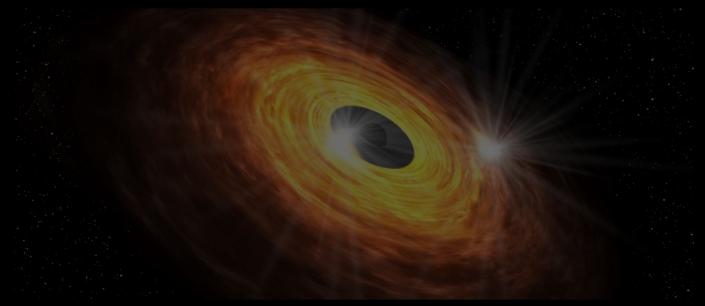
M87*



W. Steffen

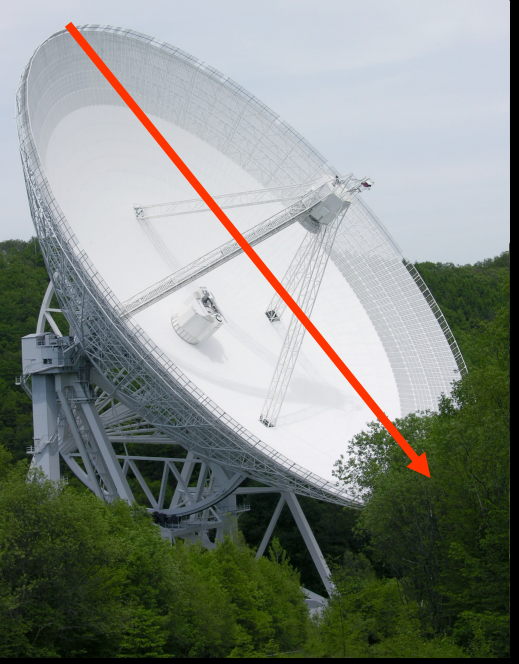
- 6.5 Billion solar masses
- 55 Mio light years distance
- spectacular jet
- being fed

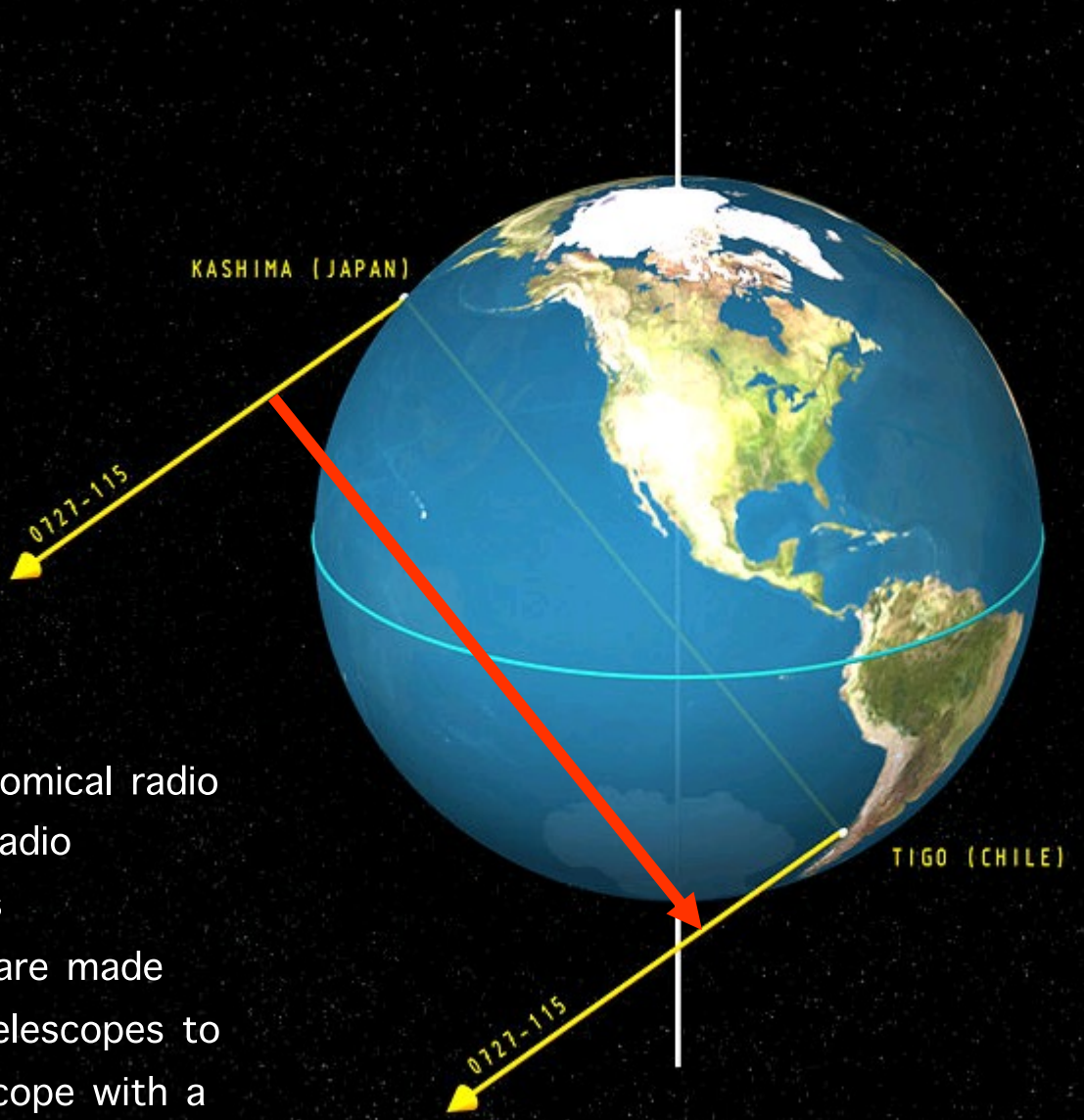
Sgr A*



- 4.3 Million solar masses
- 27 000 light years distance
- jet or no jet ?
- "on a diet"

Very Long Baseline Radio-Interferometry (VLBI)

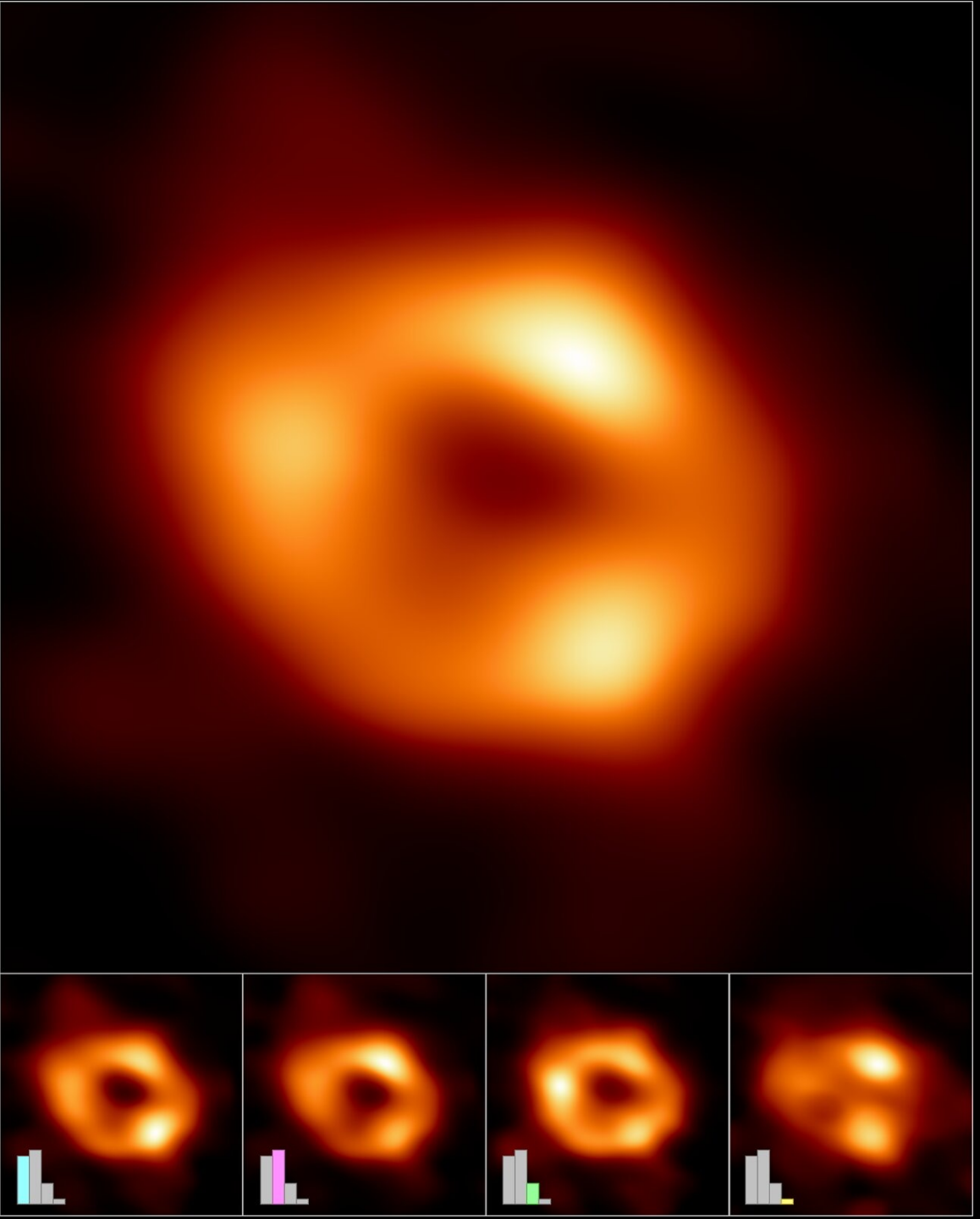




In VLBI a signal from an astronomical radio source is collected at multiple radio telescopes on Earth. This allows observations of an object that are made simultaneously by many radio telescopes to be combined, emulating a telescope with a size equal to the maximum separation between the telescopes.

Credit: ESO/M, Kornmesser

The observations took place in
April 2017, April 2018, April 2021, and 2022 !



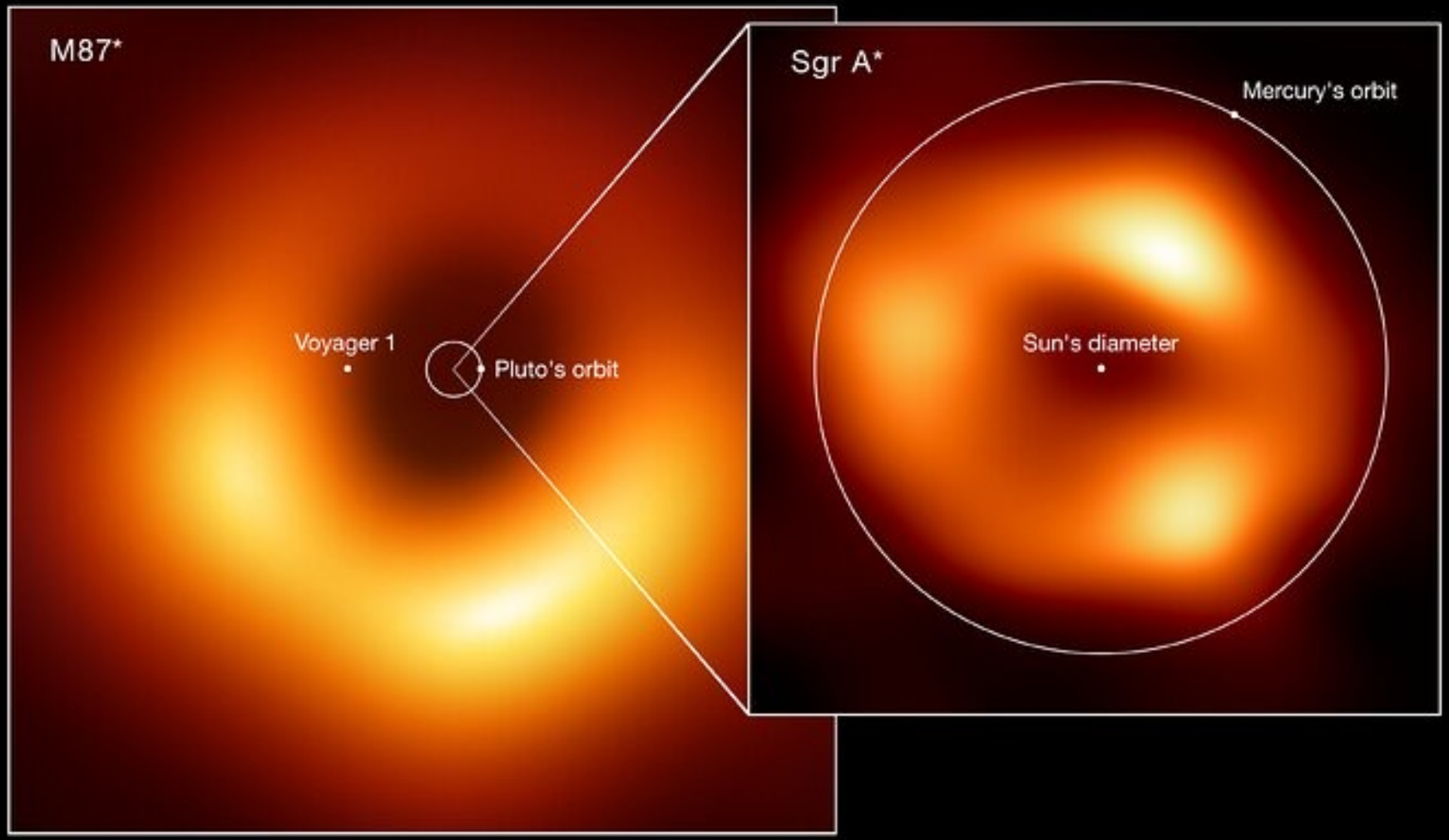
The main image of Sgr A* (top) was produced by averaging together thousands of images created using different computational methods.

These images can also be clustered into four groups based on similar features (bottom).

The bar graphs show the relative number of images belonging to each cluster.

As you can see, non-ring images (bottom right) are very rare.

Credit: EHT Collaboration



EHT Collaboration, Lia Medeiros

Voyager 1: currently at a distance of 22 Billion km from Earth

https://iopscience.iop.org/journal/2041-8205/page/Focus_on_First_Sgr_A_Results

First Sagittarius A* Event Horizon Telescope Results. I. The Shadow of the Supermassive Black Hole in the Center of the Milky Way

The Event Horizon Telescope Collaboration *et al.* 2022 *ApJL* **930** L12

First Sagittarius A* Event Horizon Telescope Results. II. EHT and Multiwavelength Observations, Data Processing, and Calibration

The Event Horizon Telescope Collaboration *et al.* 2022 *ApJL* **930** L13

First Sagittarius A* Event Horizon Telescope Results. III. Imaging of the Galactic Center Supermassive Black Hole

The Event Horizon Telescope Collaboration *et al.* 2022 *ApJL* **930** L14

First Sagittarius A* Event Horizon Telescope Results. IV. Variability, Morphology, and Black Hole Mass

The Event Horizon Telescope Collaboration *et al.* 2022 *ApJL* **930** L15

First Sagittarius A* Event Horizon Telescope Results. V. Testing Astrophysical Models of the Galactic Center Black Hole

The Event Horizon Telescope Collaboration *et al.* 2022 *ApJL* **930** L16

First Sagittarius A* Event Horizon Telescope Results. VI. Testing the Black Hole Metric

The Event Horizon Telescope Collaboration *et al.* 2022 *ApJL* **930** L17

https://eventhorizontelescope.org/for-astronomers/data

EHT Data Products

EHT Data Product Code	Title	Author(s)	Last Updated	Access Link(s)	Reference
2022-D02-03	Multi-wavelength Observations of Sgr A* During the 2017 EHT Campaign	The EHT MWL Science Working Group et al.	12 May 2022	CyVerse Data Commons (DOI: 10.25739/26fq-k306)	The EHT Collaboration et al. 2022b (Sgr A* Paper II)
2022-D02-01	First Sagittarius A* EHT Results: Calibrated Data	The EHT Collaboration et al.	12 May 2022	CyVerse Data Commons (DOI: 10.25739/m140-ct59)	The EHT Collaboration et al. 2022b (Sgr A* Paper II)
2022-D01-01	2017 EHT Observations: Complete L1 Data Products	The EHT Collaboration et al.	9 May 2022	ALMA Science Portal and CyVerse Data Commons (DOI: 10.25739/kat4-na03)	The EHT Collaboration et al. 2019c (M87 Paper III) & 2022c (Sgr A* Paper III)

THINGS TO DO:

- [ ] The details of the ring emission ?
- [ ] Are there further black holes suited for imaging?
- [ ] Einstein – how far does GR hold?
- [ ] Resolving the Ring
- [ ] What are the bright spots?
- [ ] What‘s the spin of Sgr A* and M87*?
- [ ] How about binary black holes?
- [ ] What is the closest pair?
- [ ] How to find these closest pairs ?
- [ ] How would the shadow of a SMBBH look like?
- [ ] Watching the merger „live“?
- [ ] Gravitational waves ...

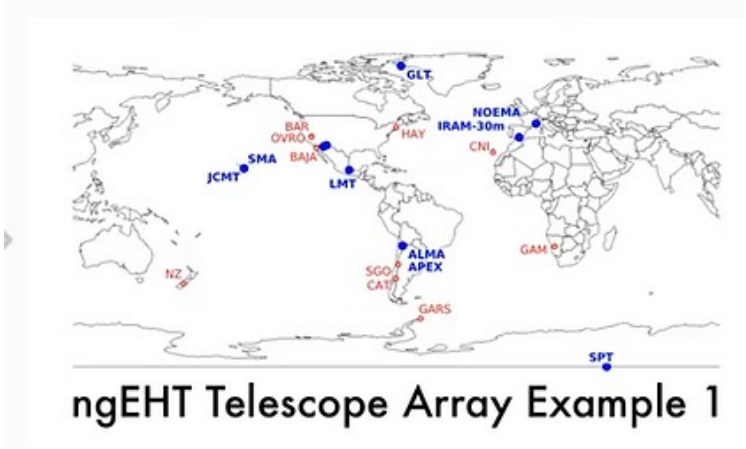
and of course the Singularity problem ...

https://www.ngeht.org/

Science with the ngEHT

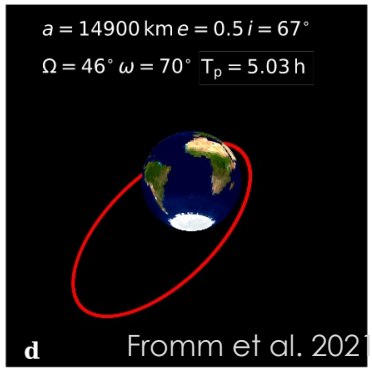
- Testing Einstein‘s Theory of General Relativity
- Mapping Magnetic Fields Near the Horizon
- Discovering the origin of Black Hole Jets

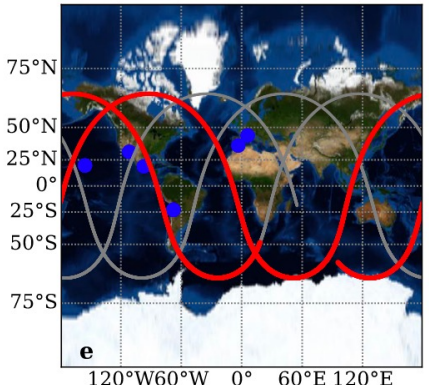
Image Credit: Ming-Tang Chen, IRAM & DiVertiCimes, Arash Roshaninesha, and Nick Conroy



ngEHT Telescope Array Example 1

The Next Generation Event Horizon Telescope





Mondbasis Alpha

Neue Pläne für eine Besiedlung des Mondes

Wie könnte die erste Mondbasis aussehen? So stellt die europäische Raumfahrtagen
Foster + Partners


Many thanks for your attention!
Looking forward to your questions ....
Binary Simulation: Nasa Goddard Space Flight Center