



# Prve fotografije crnih rupa - kako videti nevidljivo -

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*„Najbliži svemiru - park tamnog neba Vidojevica“  
Prokuplje, 5. decembar 2023.*

Deo aktivnosti AD Alfa u 2022/23. godini realizuju se u okviru projekta „Kako dohvatiti zvezde“, uz podršku Centra za promociju nauke



# Nobelova nagrada za fiziku 2020. godina

- **Rodžer Penrouz (*Roger Penrose*)**  
Rođen 8. avgusta 1931. Engleski fizičar, matematičar, filozof nauke. Prof. emeritus na Univerzitetu u Oksfordu.
- **Rajnhard Gencel (*Reinhard Genzel*)**  
Rođen 24. marta 1952. Nemački astrofizičar, ko-direktor Maks Plankovog instituta za vanzemaljsku fiziku. Prof. emeritus na Univerzitetu Berkley, Kalifornija.
- **Andrea Gez (*Andrea Ghez*)**  
Rođena 16. juna 1965. Američka astronomkinja i profesorka na Departmanu za fiziku i astronomiju na UCLA.

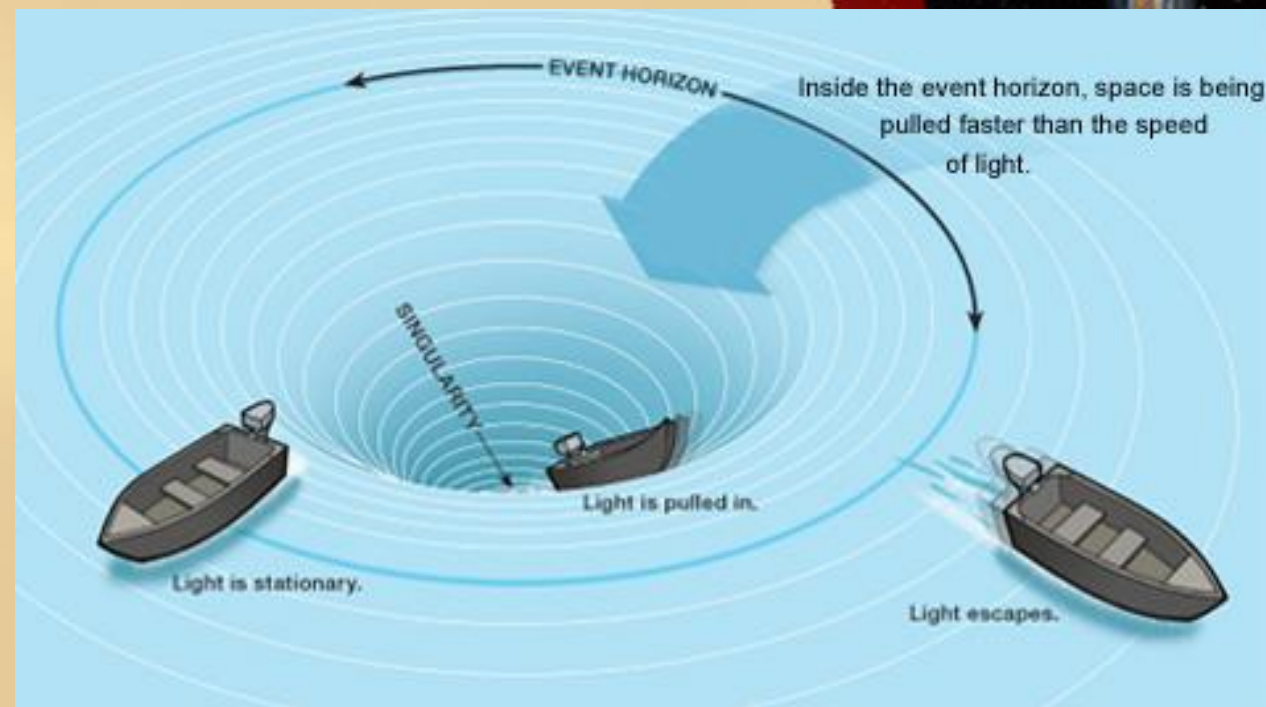
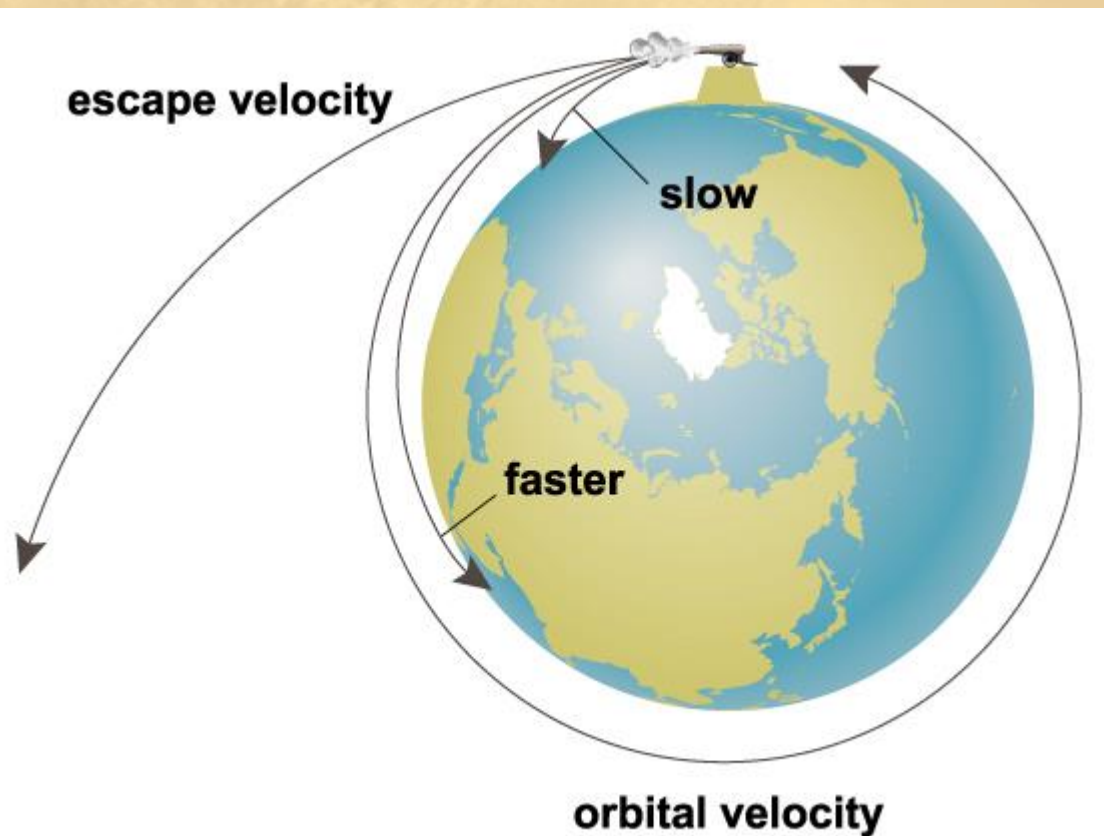


# Šta je to crna rupa?

- Objekat čije je gravitaciono polje toliko jako da nijedan oblik materije ili zračenja ne može da „pobegne“ iz nje
- Prema opštoj teoriji relativnosti mesto u kome je prostor-vreme beskonačno zakrivljeno
- **Džon Viler (1967)** prvi put pojam „crna rupa“
  - Grafički opis ideje koja je stara 200+ godina



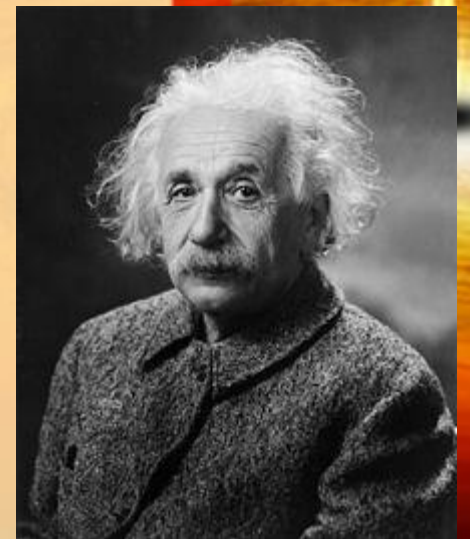
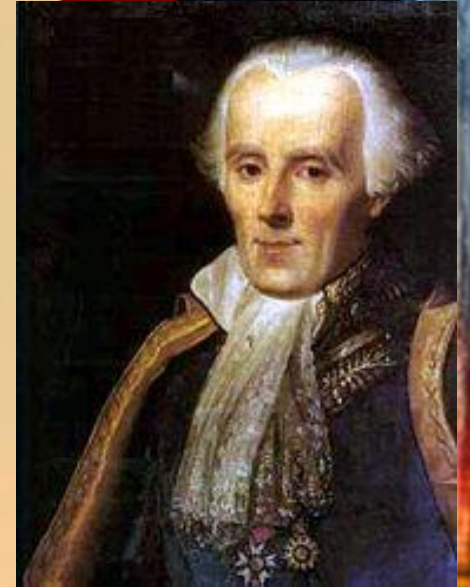
# „Ne može da 'pobegne' iz nje“?



Izvor: Answers magazine.

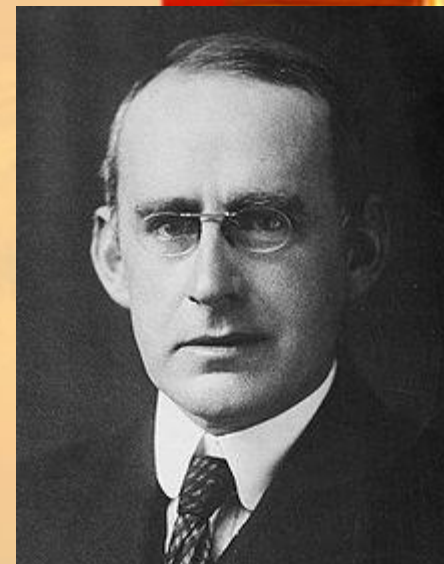
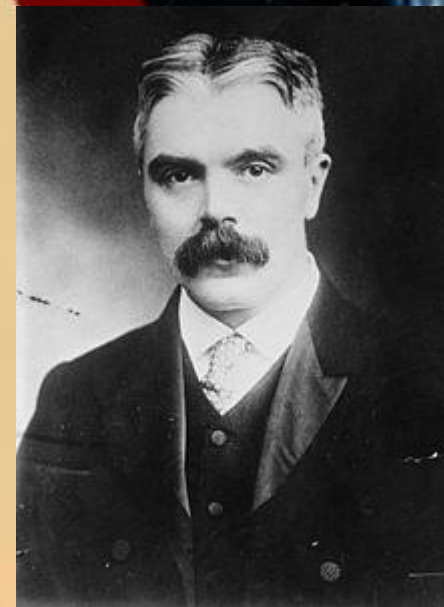
# Šta je to crna rupa?

- Prva ideja: **Džon Mičel**, 1783. godine (Kembridž)
  - Ako je zvezda dovoljno masivna i gusta; smatrao je da postoji mnogo takvih zvezda ali ne mogu da se vide već samo **detektuje efekat** njihove gravitacije
- Slična ideja: **Pjer Laplas**, nekoliko godina kasnije
  - Smatrao da malo znamo o prirodi svetlosti da bi mogli da pretpostavimo kako na nju **deluje gravitacija** i da nije sasvim na mestu izjednačiti svetlost sa topovskom đuladi u Njutnovoj teoriji gravitacije, jer je brzina svetlosti konstantna
- **Albert Ajnštajn**, novembar 1915. godine
  - **Opšta teorija relativnosti**

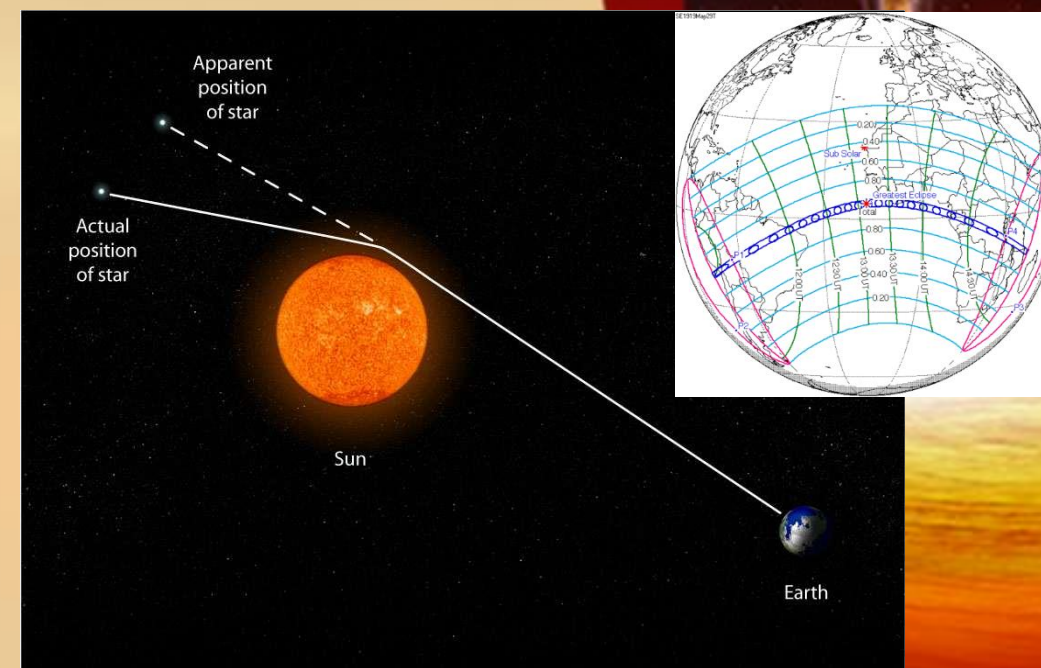
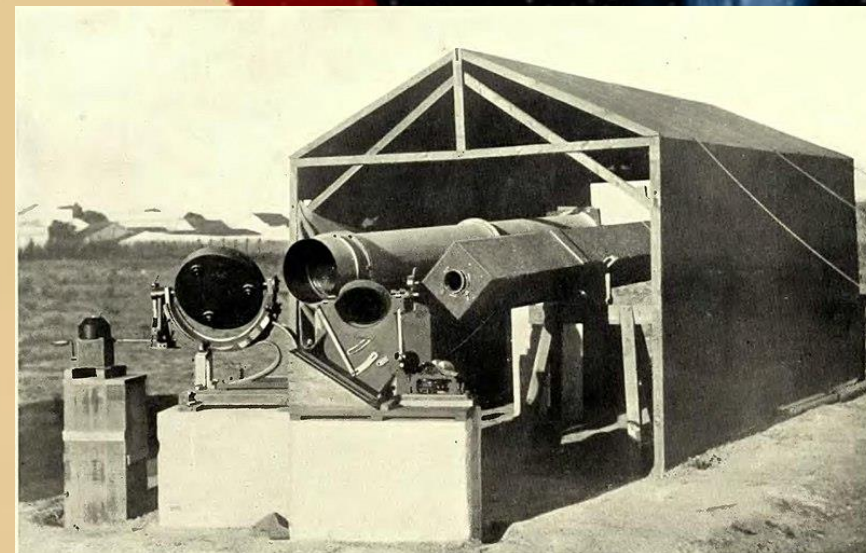


# Skretanje svetlosti

- Pomračenje Sunca: 29. maj 1919. godine
  - Britanski astronomi Frenk Dajson i Artur Edington
  - Zapadna Afrika, ostrvo Prinsipe  
(manje od dva ostrva države Sao Tome i Prinsipe, 136 km<sup>2</sup>, danas 5000 stanovnika)
- Prva ideja o skretanju svetlosti: **Johan Džordž fon Soldner** (1801), iz Njutnove gravitacije
- Prvi Ajnštajnovi proračuni (1911) - **pogrešni** (rezultati približni Njutnovoju teoriji)
  - Pokušaj merenja pomračenja 1912. god. iz Brazila - oblačno!
- Očekivani rezultati - **gravitaciono sočivo**, skretanje **1,75 lučnih sekundi** (2 puta više od Njutnove teorije gravitacije)

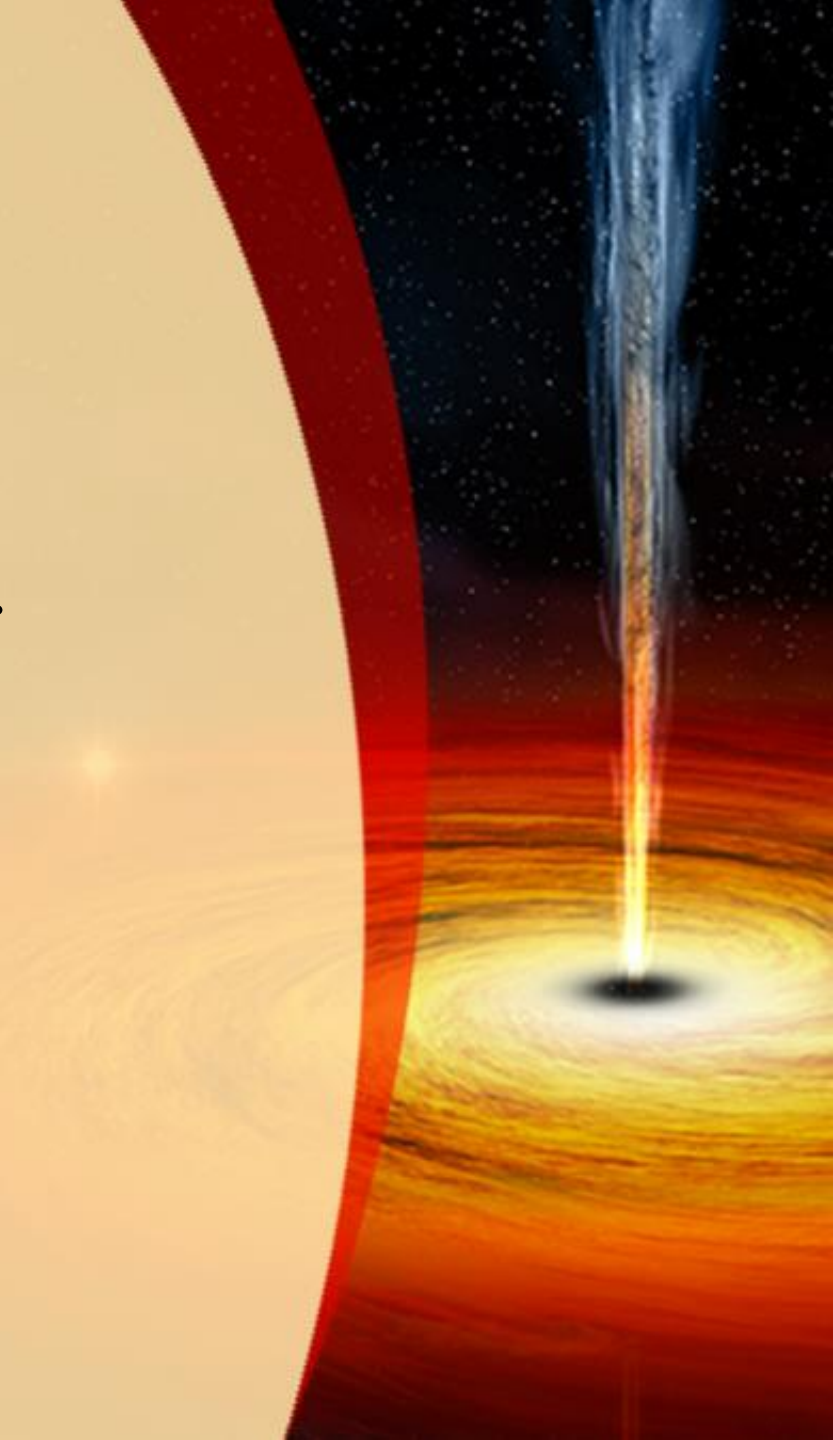


# Edingtonov eksperiment



# Šta je to crna rupa?

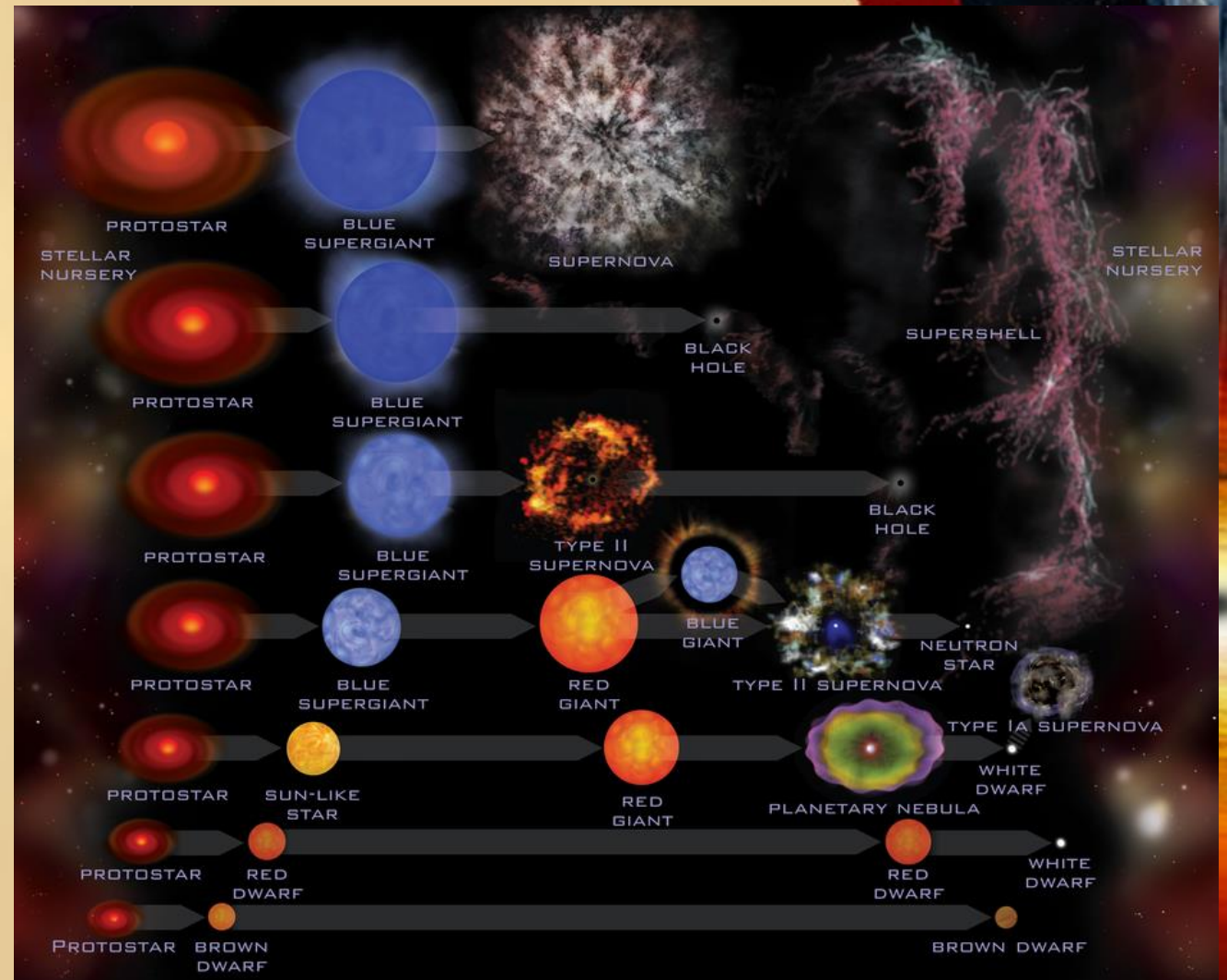
- Nekoliko nedelja kasnije
  - Karl Švarcšild - rešenja Ajnštajnovih jednačina koja pokazuju kako masivna tela savijaju prostor-vreme.
- Kasnija istraživanja
  - Crna rupa - okružena horizontom događaja
  - Veća masa → veća crna rupa
    - masa Sunca → prečnik horizonta događaja oko 3 km
    - masa Zemlje → 9 mm





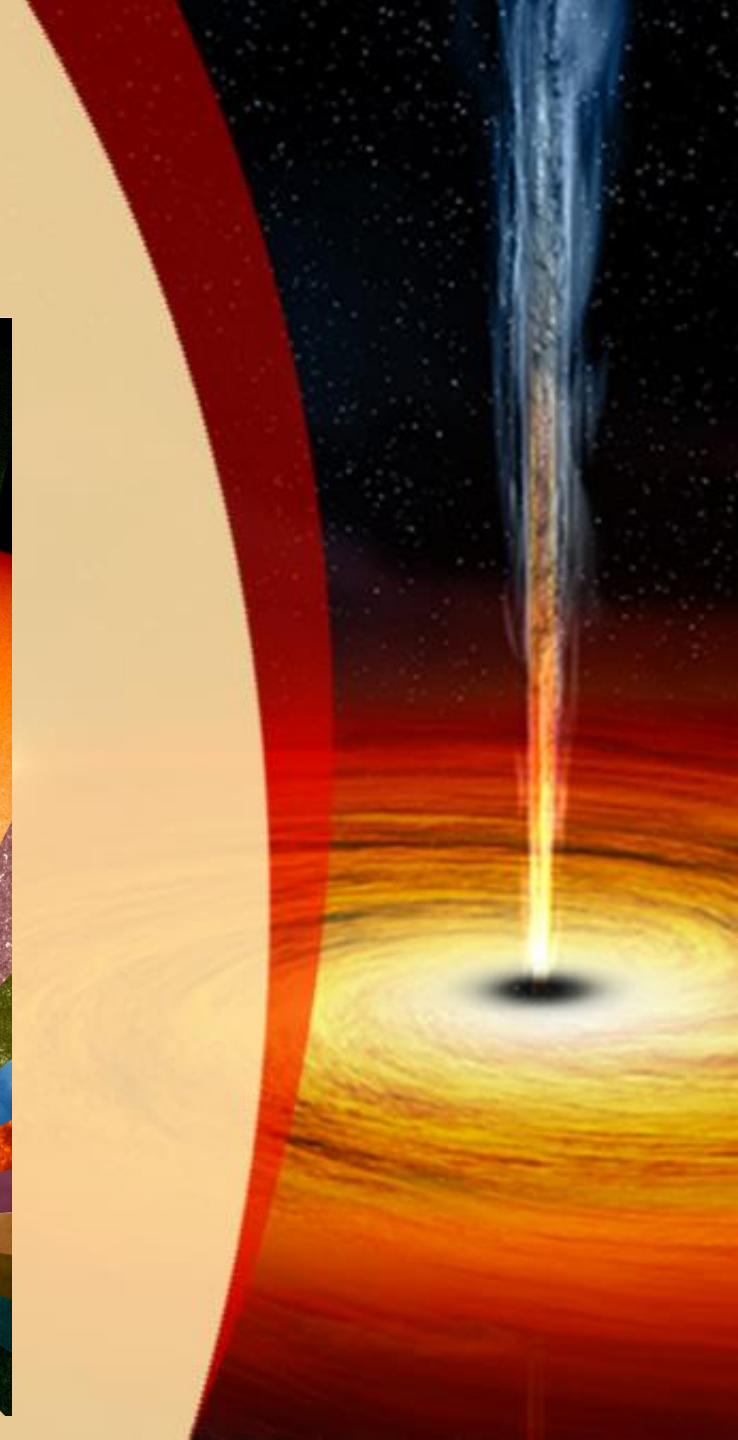
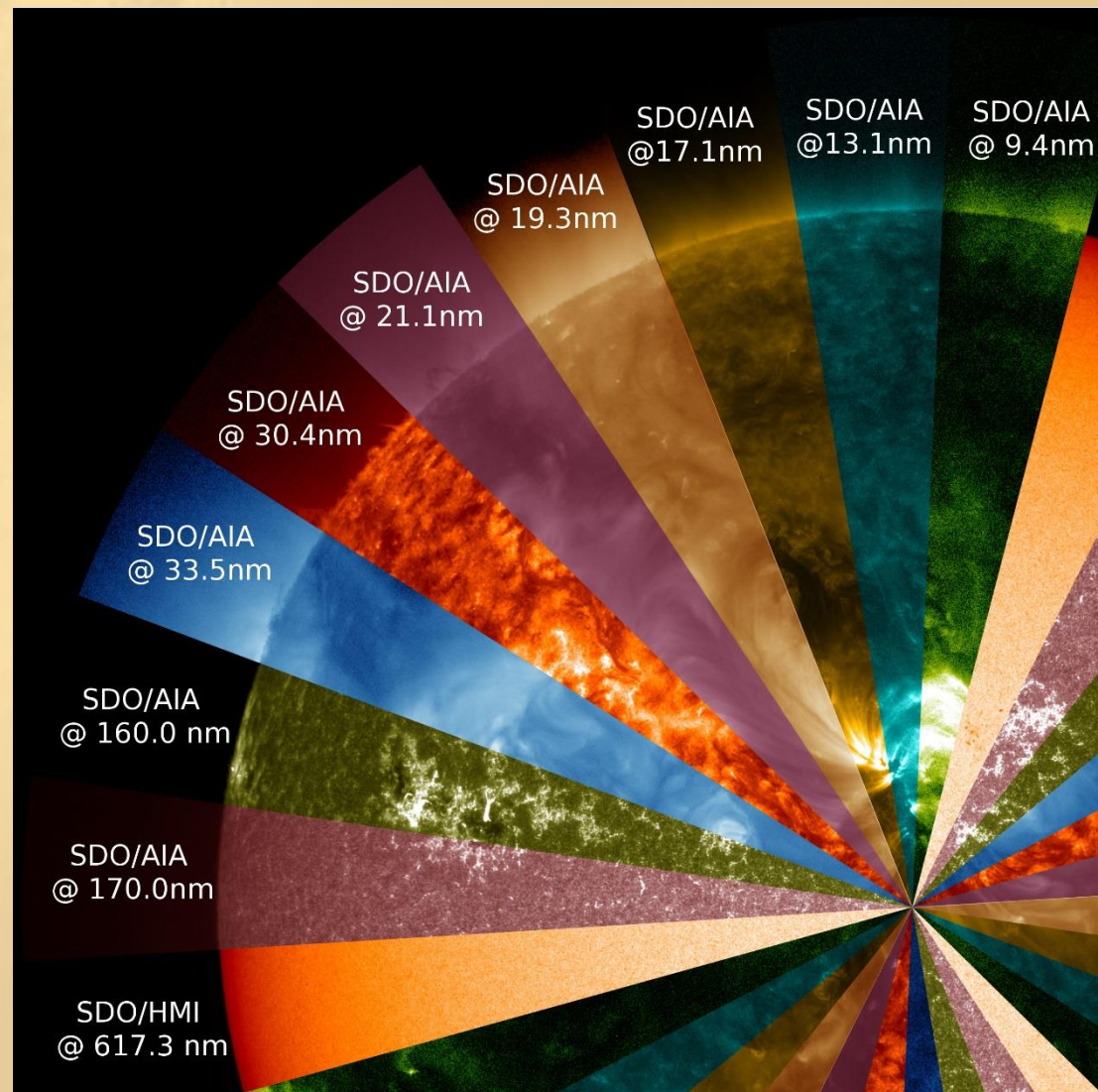
# Kako nastaju crne rupe?

- Robert Openhajmer (1930)
  - Prva izračunavanja - gravitacioni kolaps masivnih zvezda
- Do 1960+ godine
  - Smatrano da su ova rešenja samo teorijske analize idealne situacije (zvezda i crna rupa savršeno sferne i simetrične)
- Rodžer Penrouz (1964)
  - Prvo rešenje za realan slučaj kolapsirajuće zvezde!

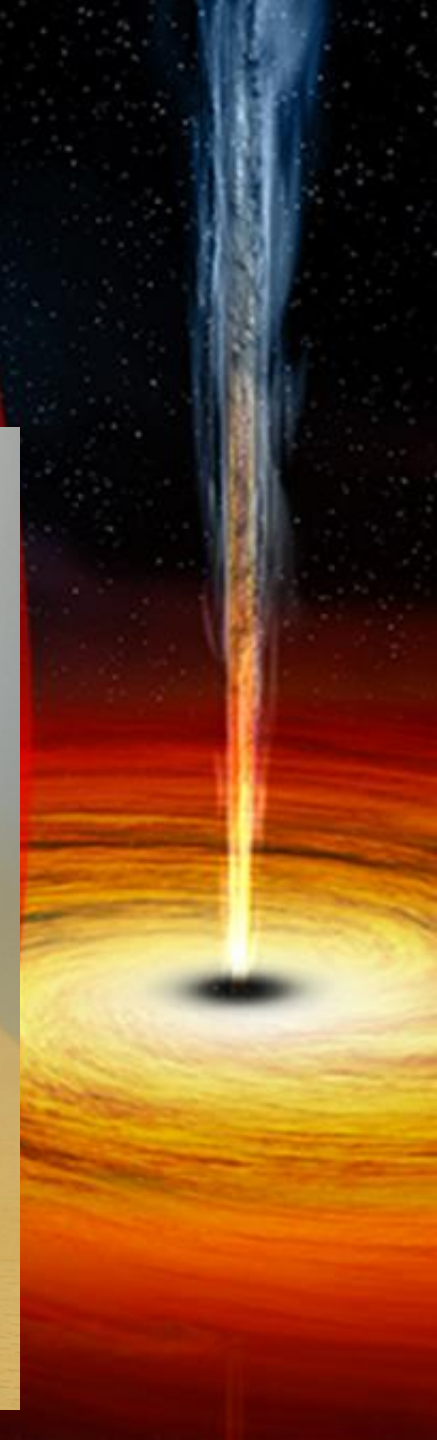




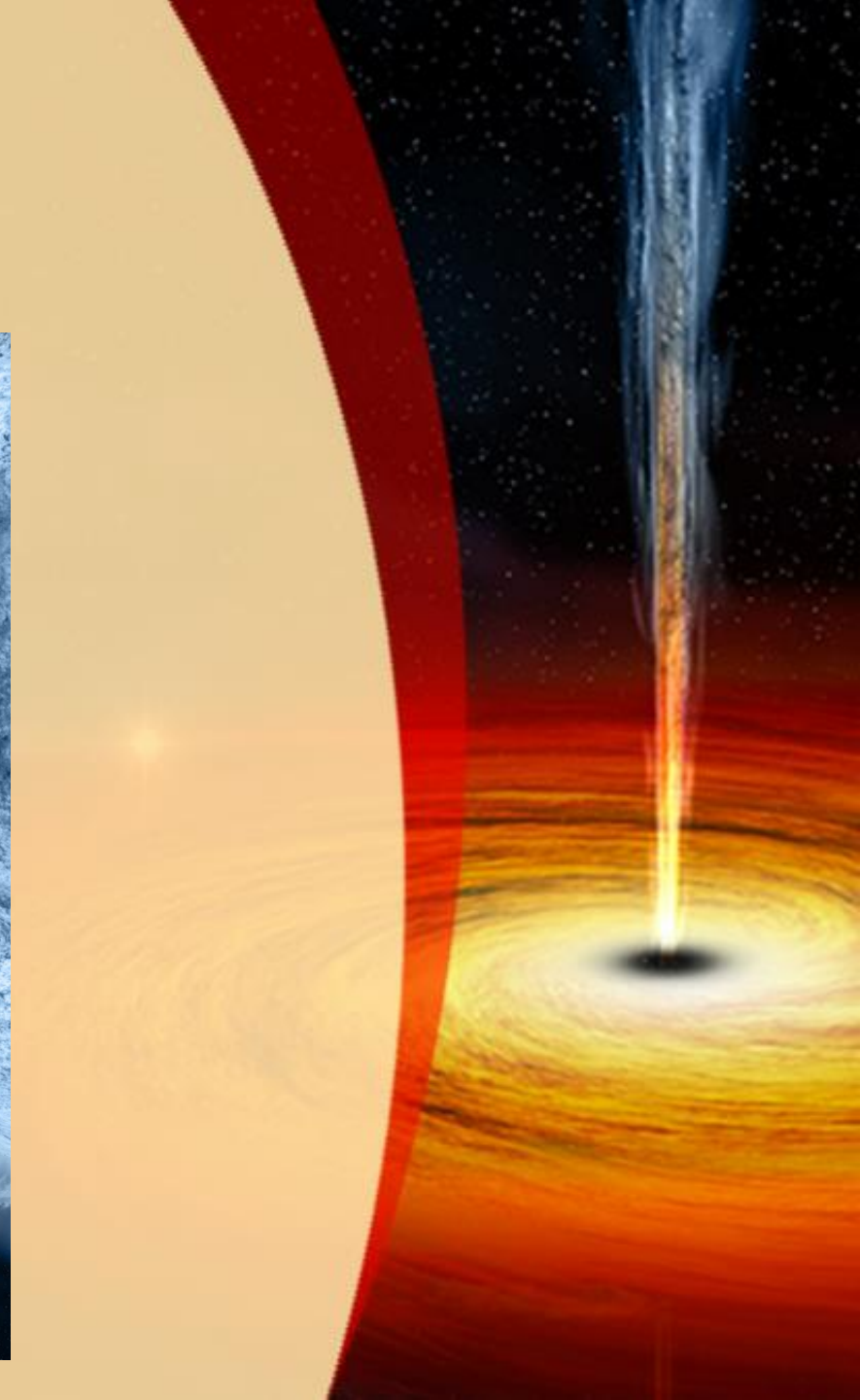
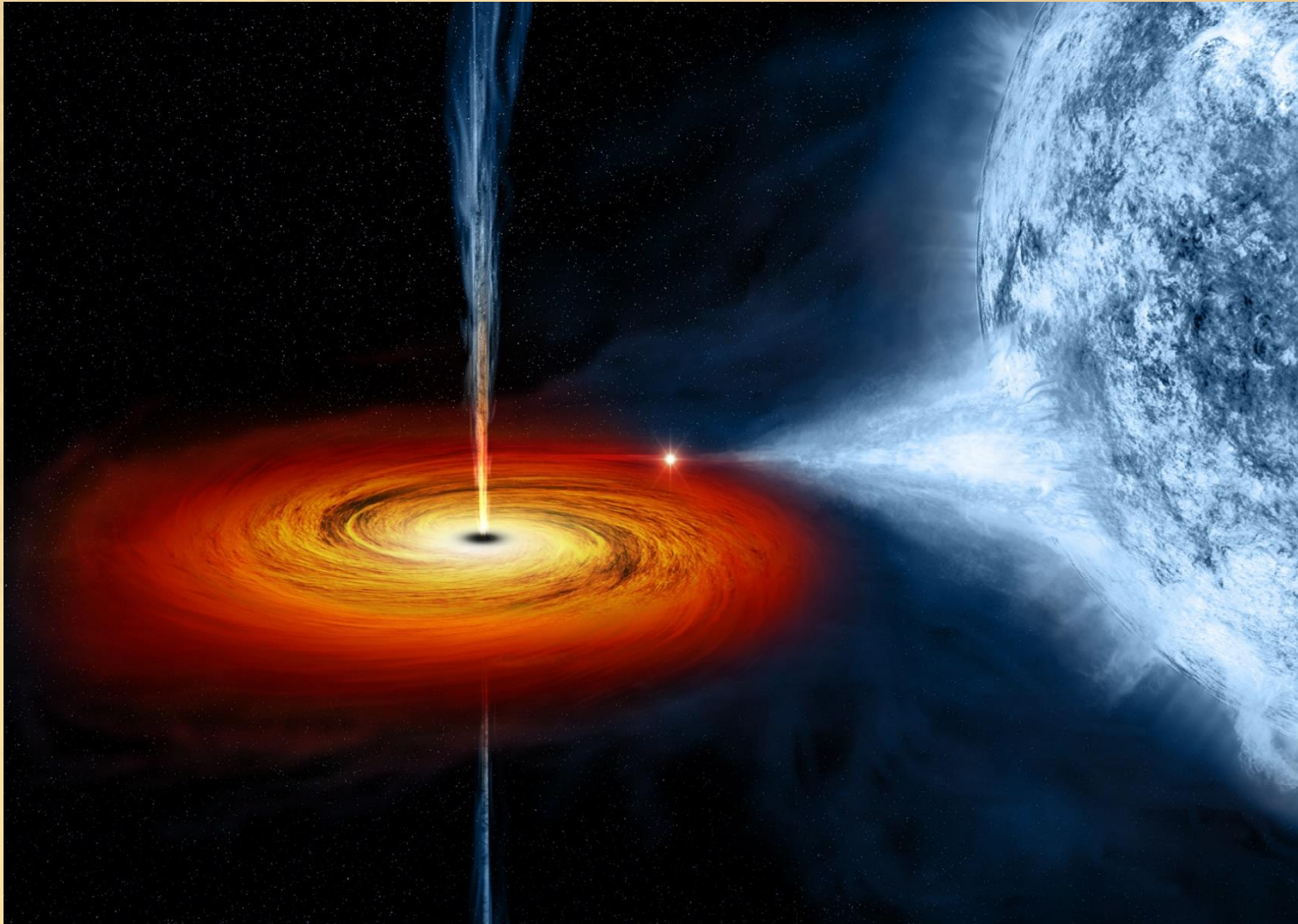
# Sunce na različitim „talasima“



# Ali, kako videti crnu rupu?

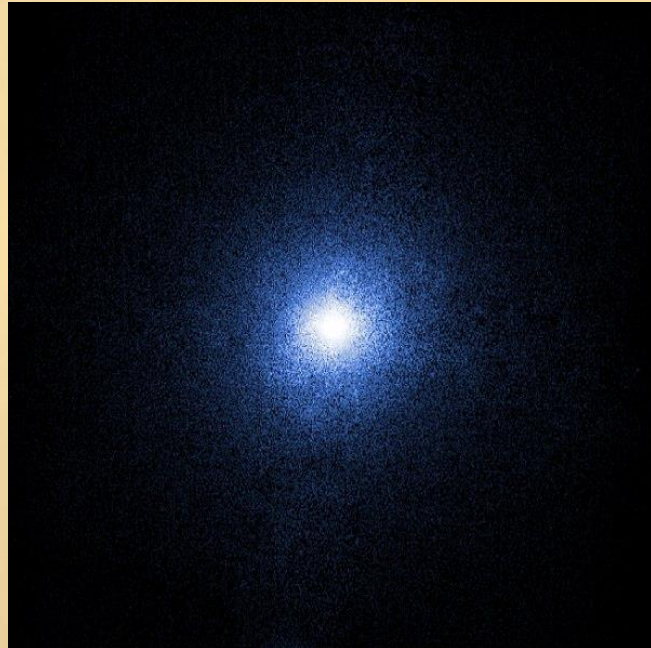
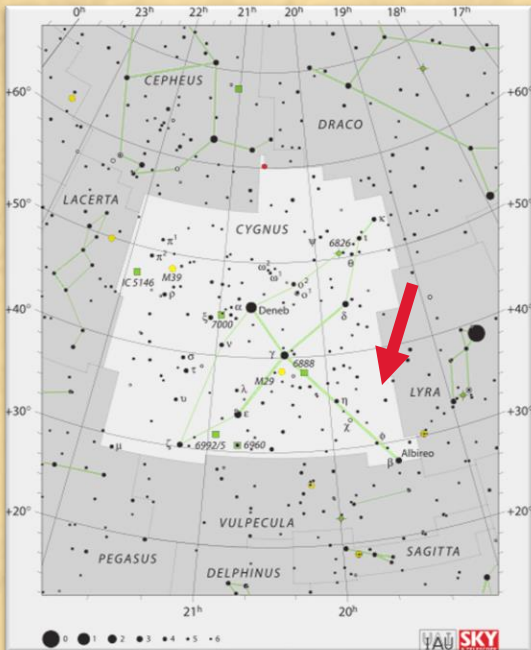


# Detekcija

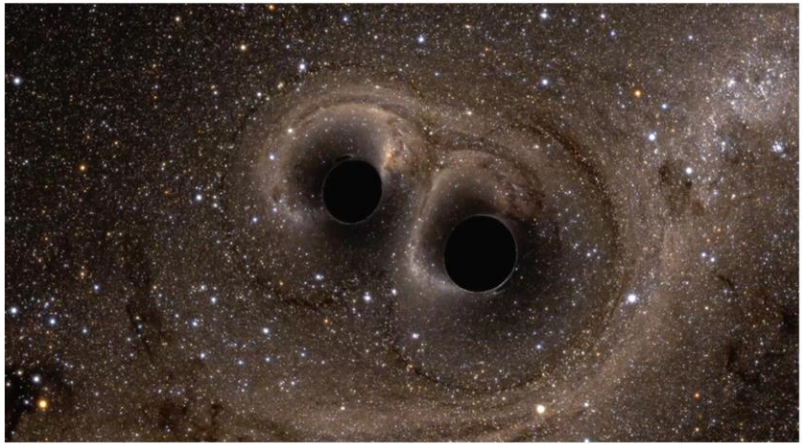


# Prvi kandidat *Cygnus X-1*

- Dvojni sistem, najveći deo zračenja emituje u X spektru
- Prvi kandidat *Cygnus X-1*
  - Otkrili: Luis Vebster, Pol Murdin i Čarls Bolton (1972)



# Sudar dve crne rupe...

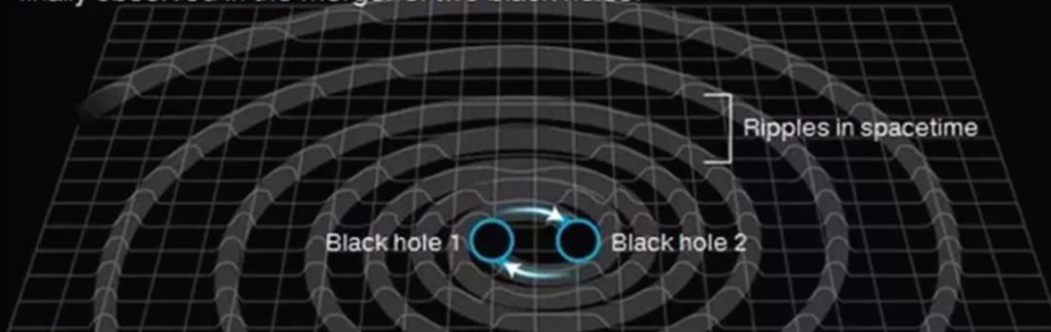


... gravitacioni talasi!

GW150914

## Ripples in spacetime

Theorized by Einstein, gravitational waves are finally observed in the merger of two black holes.



### Rotating giants

Two black holes rotate around each other before merging. The closer they get, the faster they spin. The energy from their spiralling and merger releases energy in the form of gravitational waves, or ripples in spacetime.

### Enormous energy

The result of the merger is a bigger black hole, though it's less massive than the two combined black holes. The equivalent of three solar masses is converted into energy, in the form of gravitational waves.

Solar mass



Black hole 1

36

Black hole 2

29

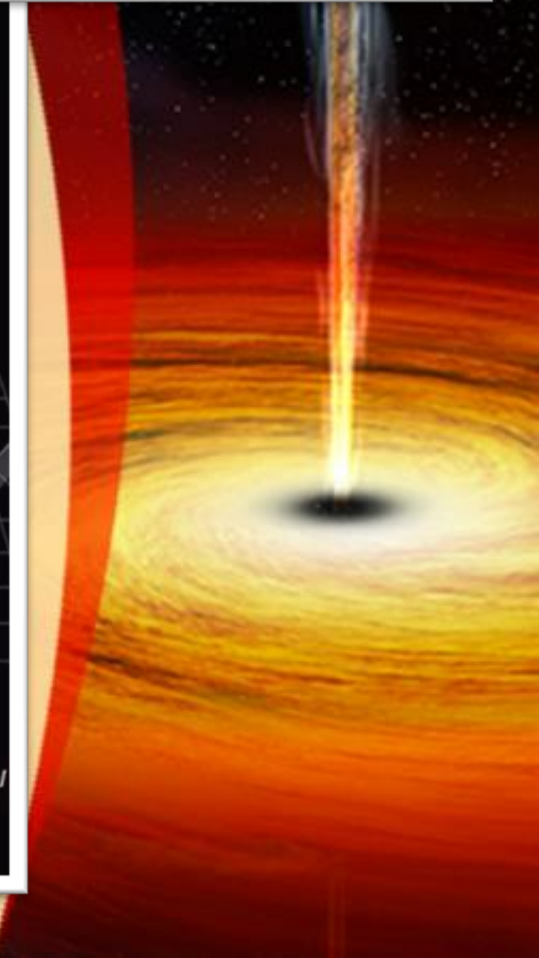
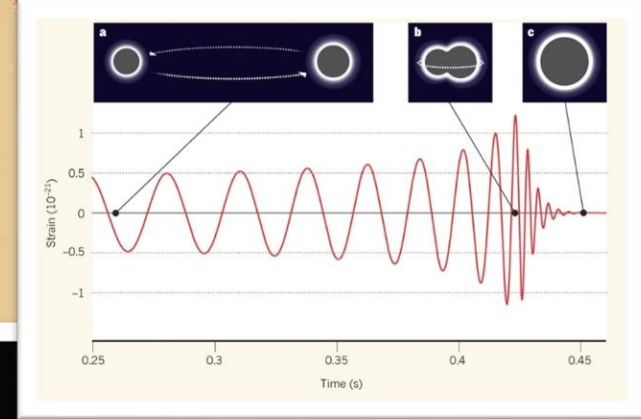
New black hole

62

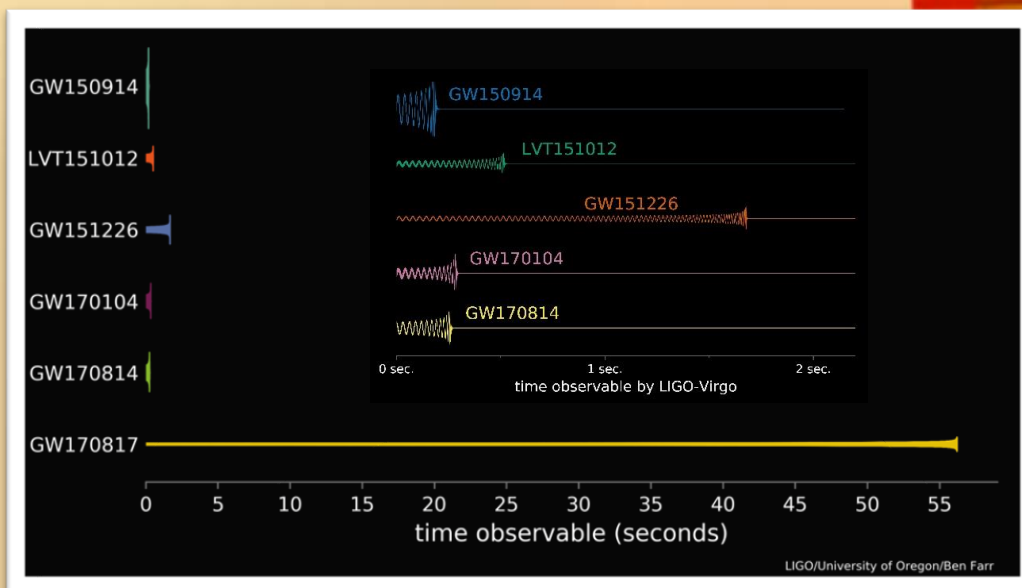
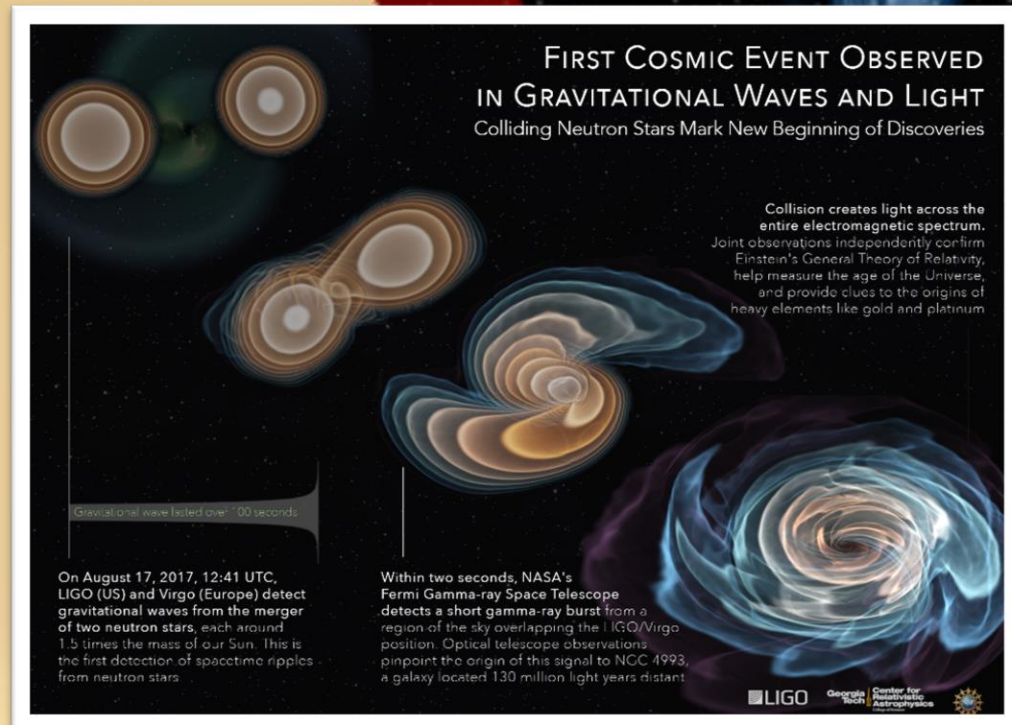
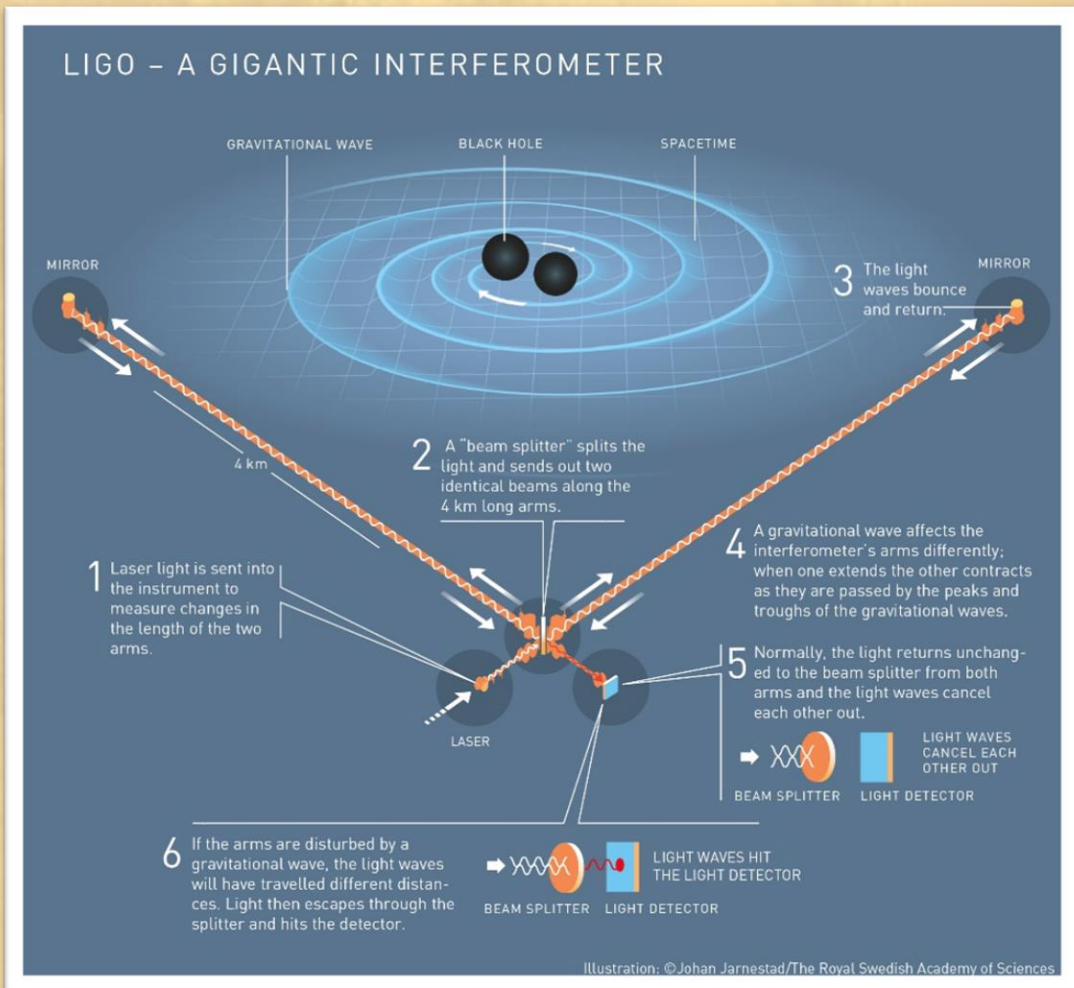
Gravitational waves

3

$$36 + 29 = 62 + 3$$



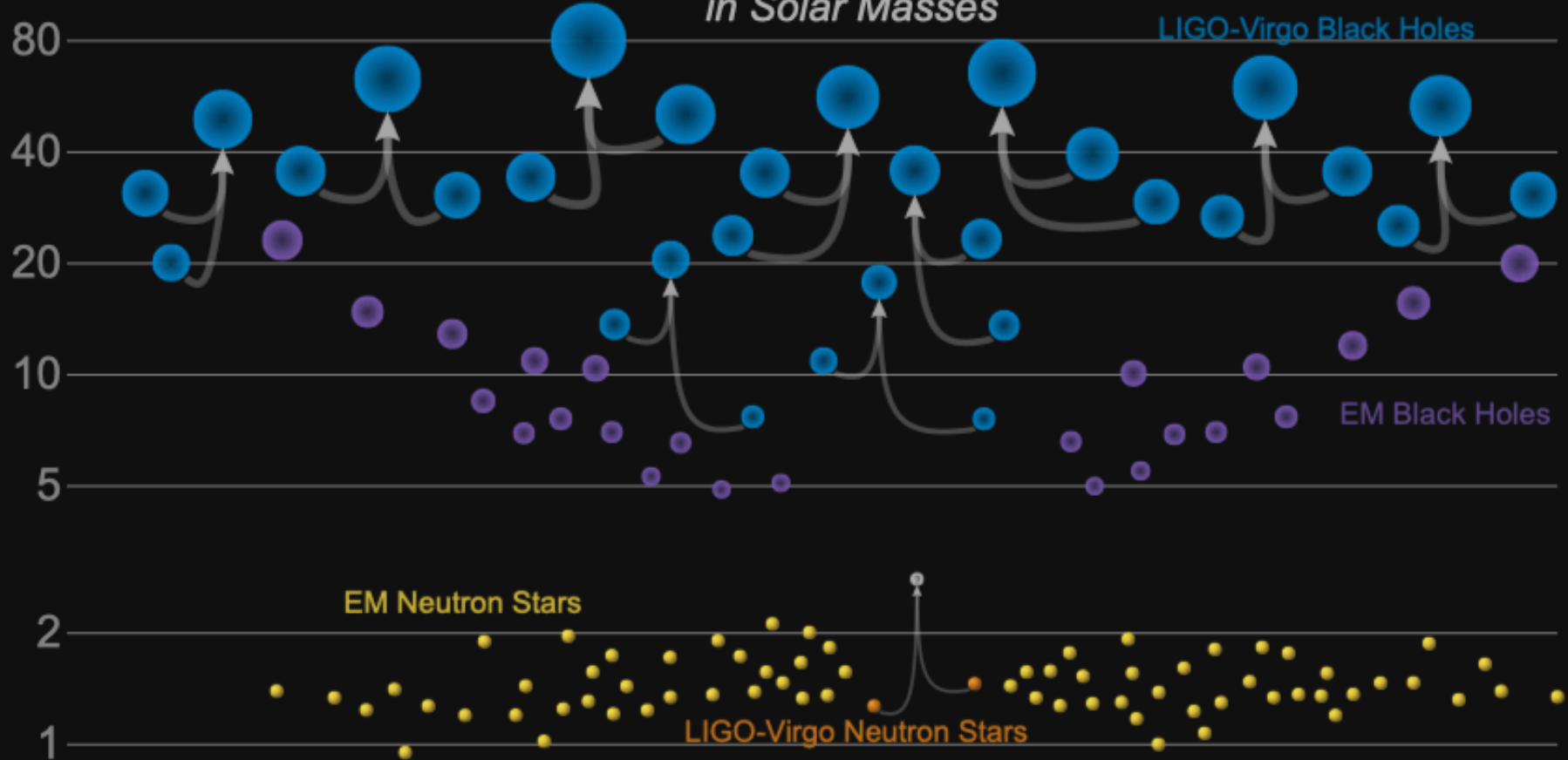
# Gravitacioni talasi





# Masses in the Stellar Graveyard

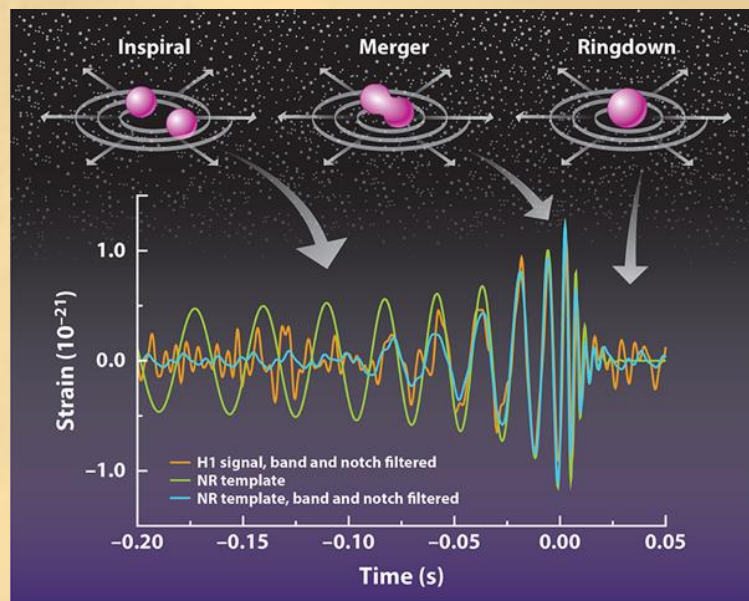
*in Solar Masses*



# Sudar dve neutronske zvezde

- Gravitacioni talasi

- GW170817
- GW170814
- GW170104
- GW151226
- GW150914
- ....



- Nobelova nagrada iz fizike
- za 2017. godinu

## GW170817

### Binary neutron star merger

A LIGO / Virgo gravitational wave detection with associated electromagnetic events observed by over 70 observatories.



Distance  
130 million light years

Discovered  
17 August 2017

Type  
Neutron star merger

12:41:04 UTC

A gravitational wave from a binary neutron star merger is detected.

gravitational wave signal  
Two neutron stars, each the size of a city but with the mass of the sun, collided into each other.

gamma ray burst

A short gamma ray burst is an intense beam of gamma ray radiation which is produced just after the merger.

+ 2 seconds

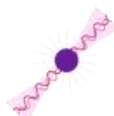
A gamma ray burst is detected.



GW170817 allows us to measure the expansion rate and the age of the universe directly using gravitational waves for the first time.



Detecting gravitational waves from a BNS event allows us to find out more about the structure of neutron stars.



This multimessenger event provides confirmation that neutron star mergers can produce short gamma ray bursts.



The observation of a kilonova allowed us to show that BNS mergers could be responsible for the production of all heavy elements, like gold, in the universe.



Observing both electromagnetic and gravitational waves from the event provides confirmation that gravitational waves travel at the same speed as light.

kilonova

Decaying heavy ions produce an optically bright kilonova, producing heavy metals like gold.

+10 hours 52 minutes

A new bright source of optical light is detected in a galaxy called NGC 4993, in the constellation of Hydra.

+11 hours 36 minutes

Infrared emission observed.

+15 hours

Bright ultraviolet emission detected.

+9 days

X-ray emission detected.

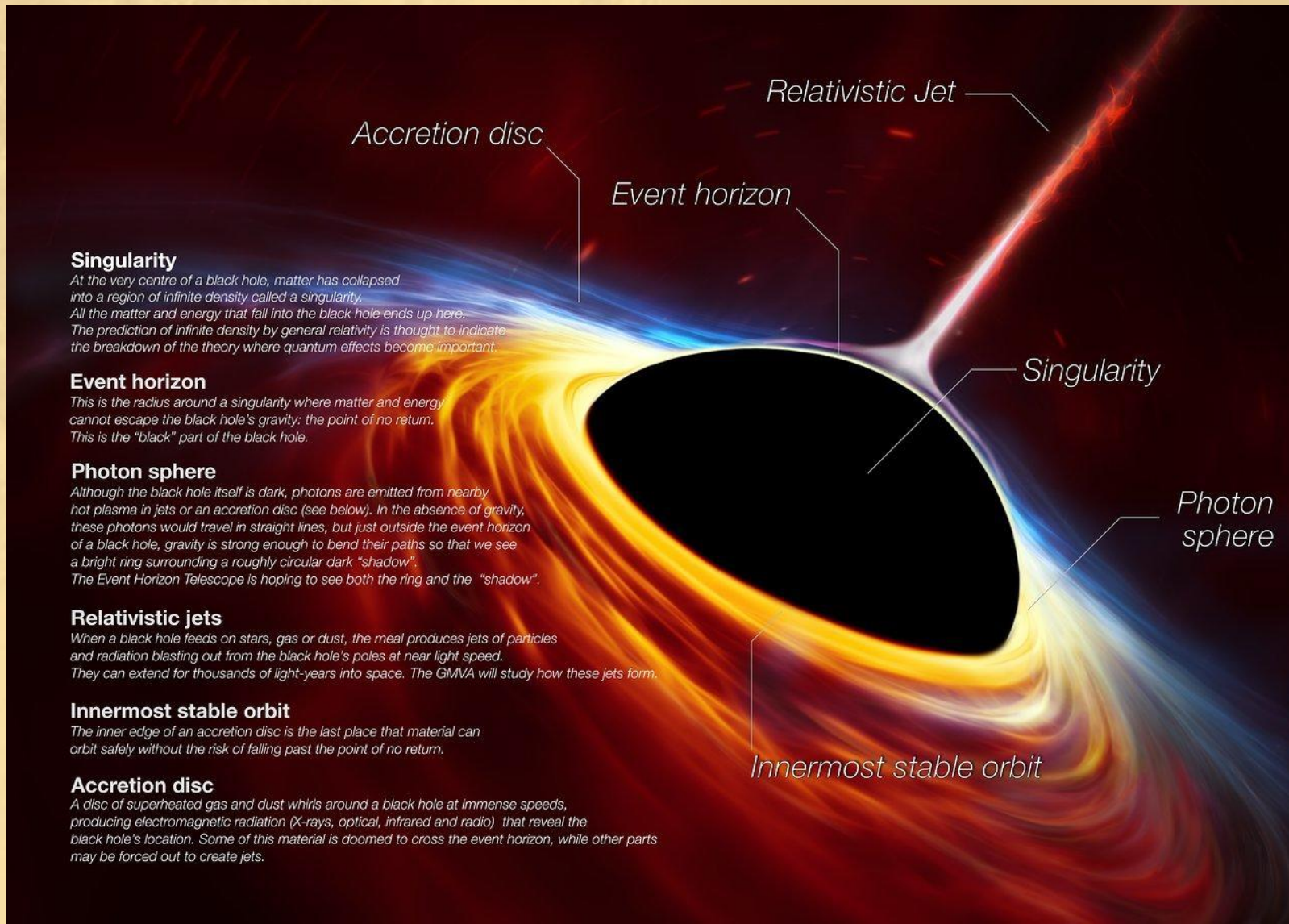
radio remnant

As material moves away from the merger it produces a shockwave in the interstellar medium - the tenuous material between stars. This produces an afterglow which can last for years.

+16 days

Radio emission detected.

# Struktura crne rupe



## 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

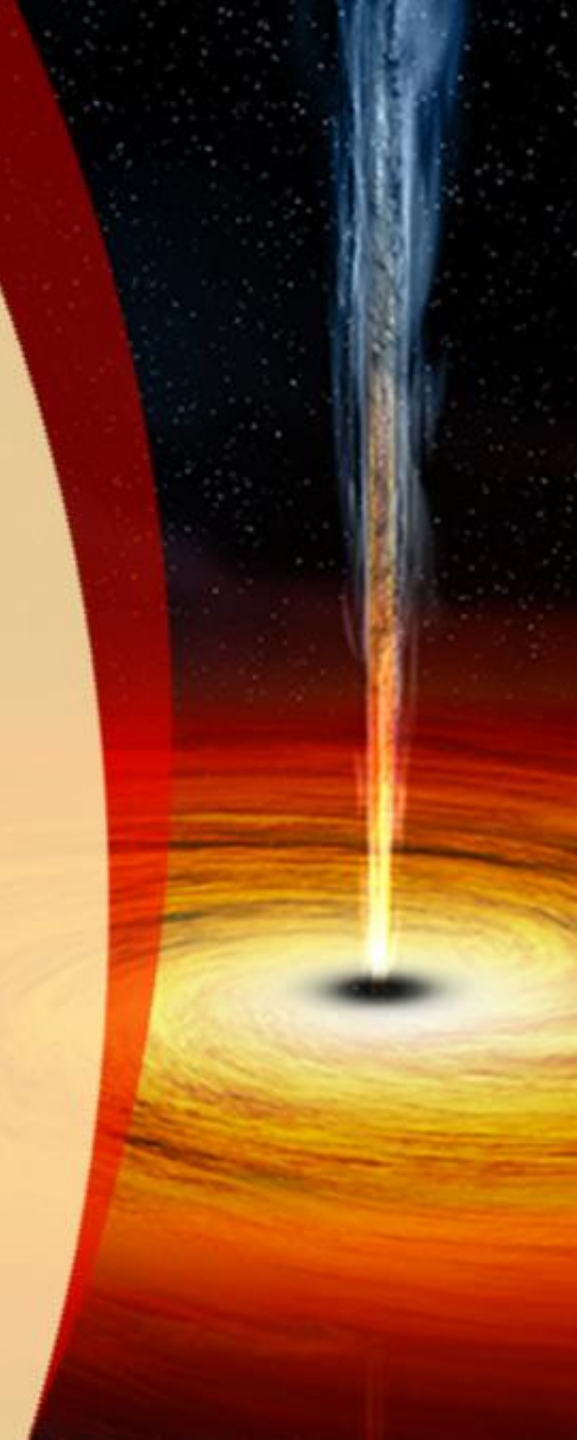
When a black hole feeds on stars, gas or dust, the meal produces jets of particles and radiation blasting out from the black hole's poles at near light speed. They can extend for thousands of light-years into space. The GMVA will study how these jets form.

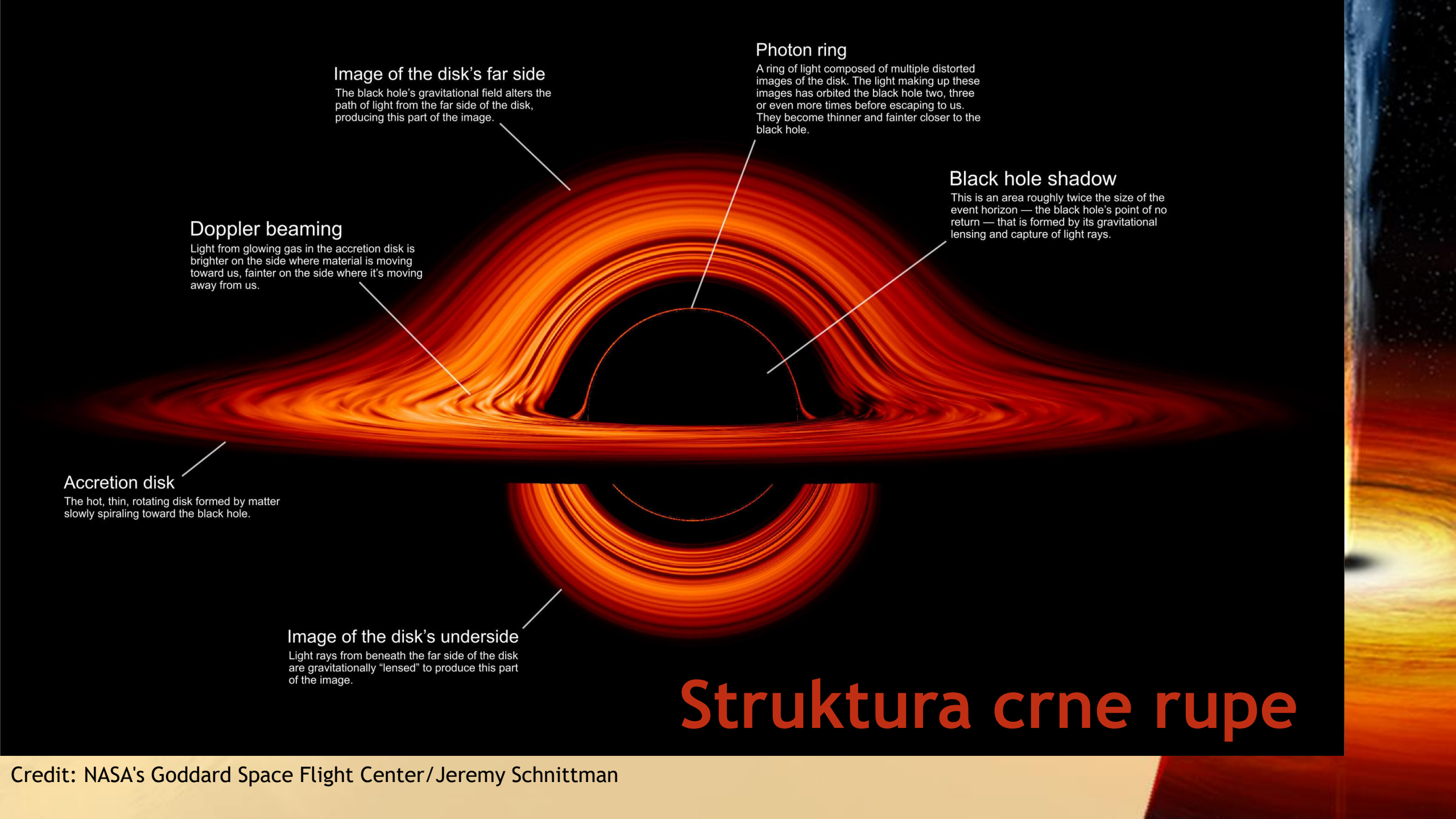
## Innermost stable orbit

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.





### Image of the disk's far side

The black hole's gravitational field alters the path of light from the far side of the disk, producing this part of the image.

### Photon ring

A ring of light composed of multiple distorted images of the disk. The light making up these images has orbited the black hole two, three or even more times before escaping to us. They become thinner and fainter closer to the black hole.

### Black hole shadow

This is an area roughly twice the size of the event horizon — the black hole's point of no return — that is formed by its gravitational lensing and capture of light rays.

### Doppler beaming

Light from glowing gas in the accretion disk is brighter on the side where material is moving toward us, fainter on the side where it's moving away from us.

### Accretion disk

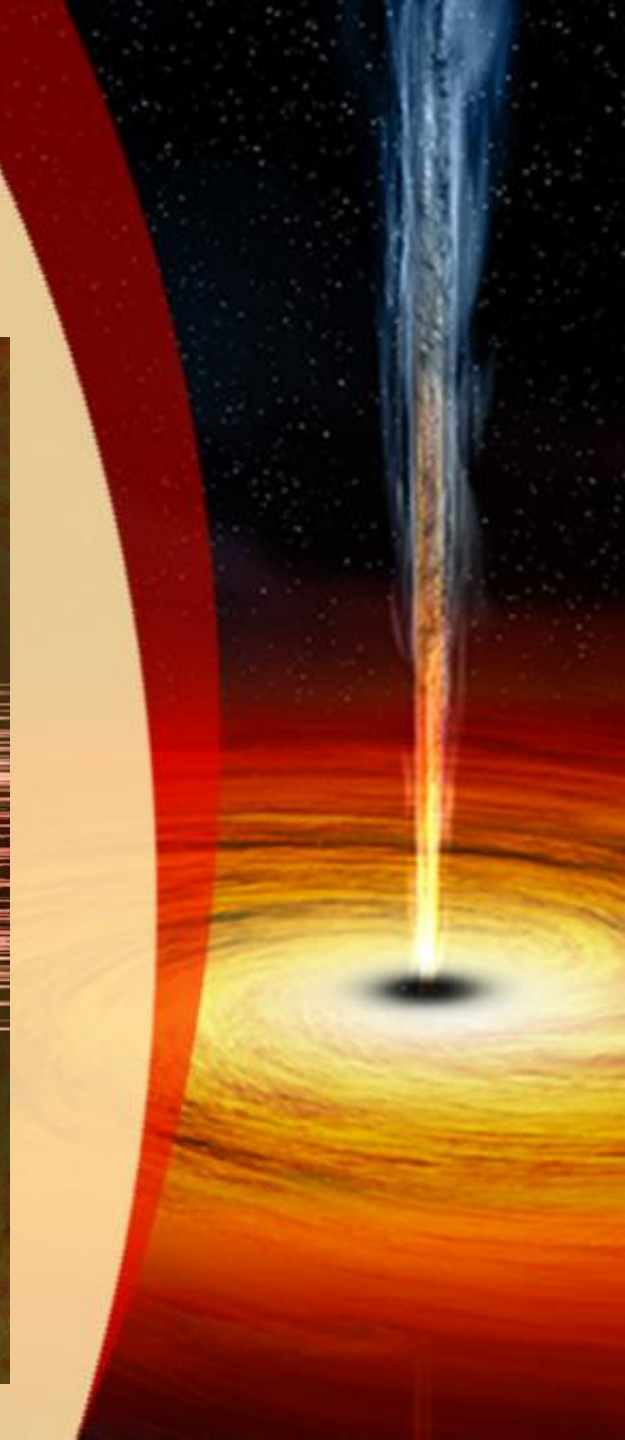
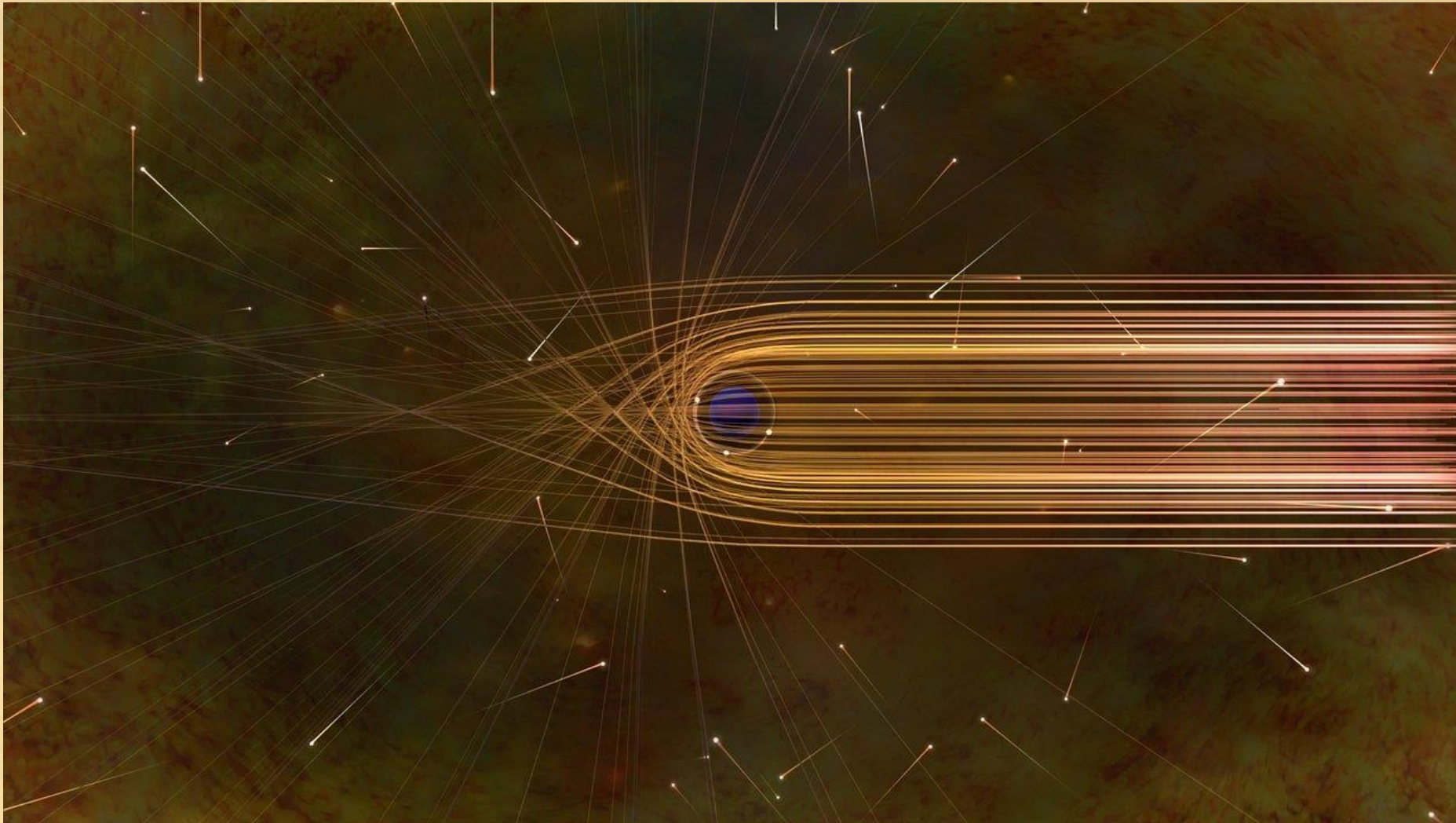
The hot, thin, rotating disk formed by matter slowly spiraling toward the black hole.

### Image of the disk's underside

Light rays from beneath the far side of the disk are gravitationally "lensed" to produce this part of the image.

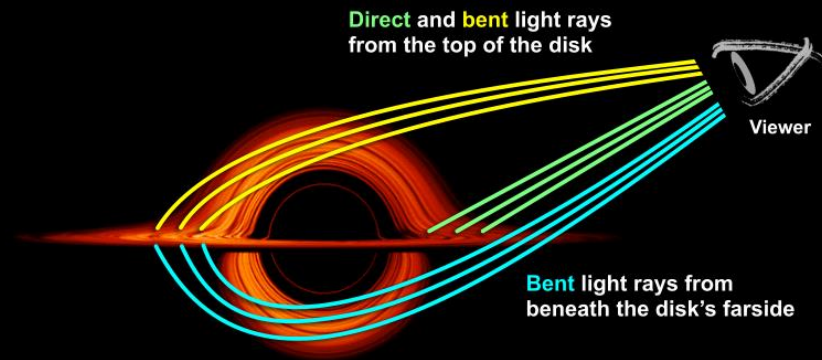
# Struktura crne rupe

# Opšta teorija relativnosti

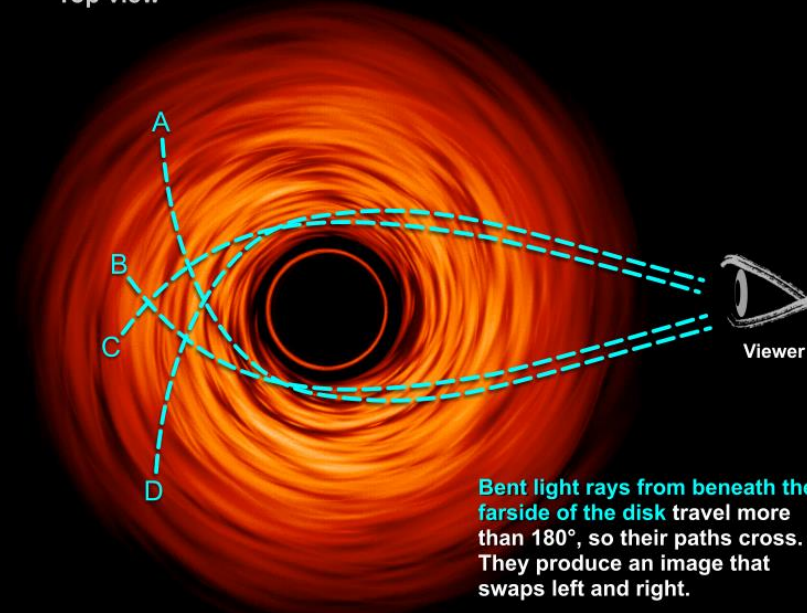


# Kako vidimo crnu rupu?

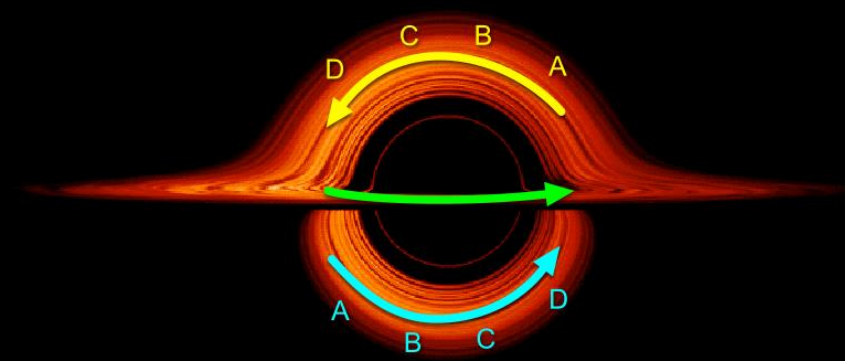
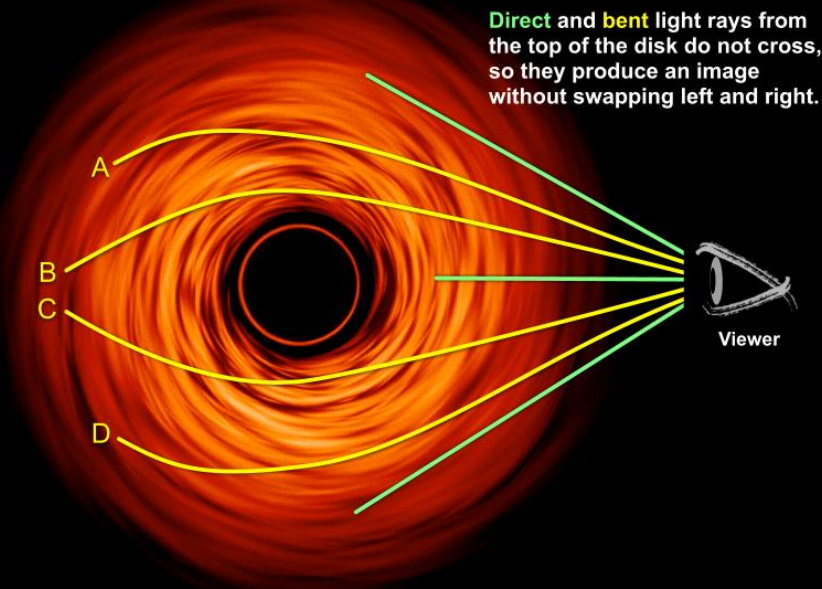
Side view



Top view

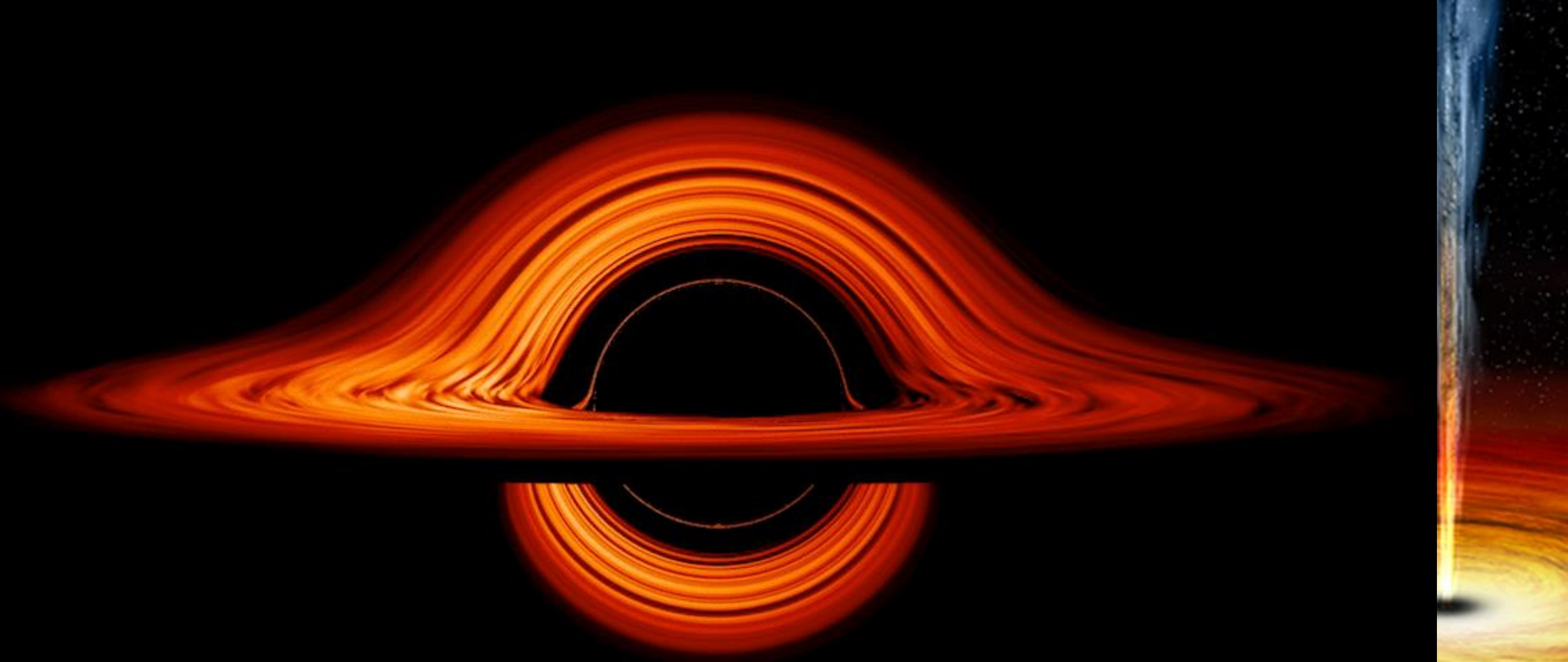


Top view



Apparent image and disk motion

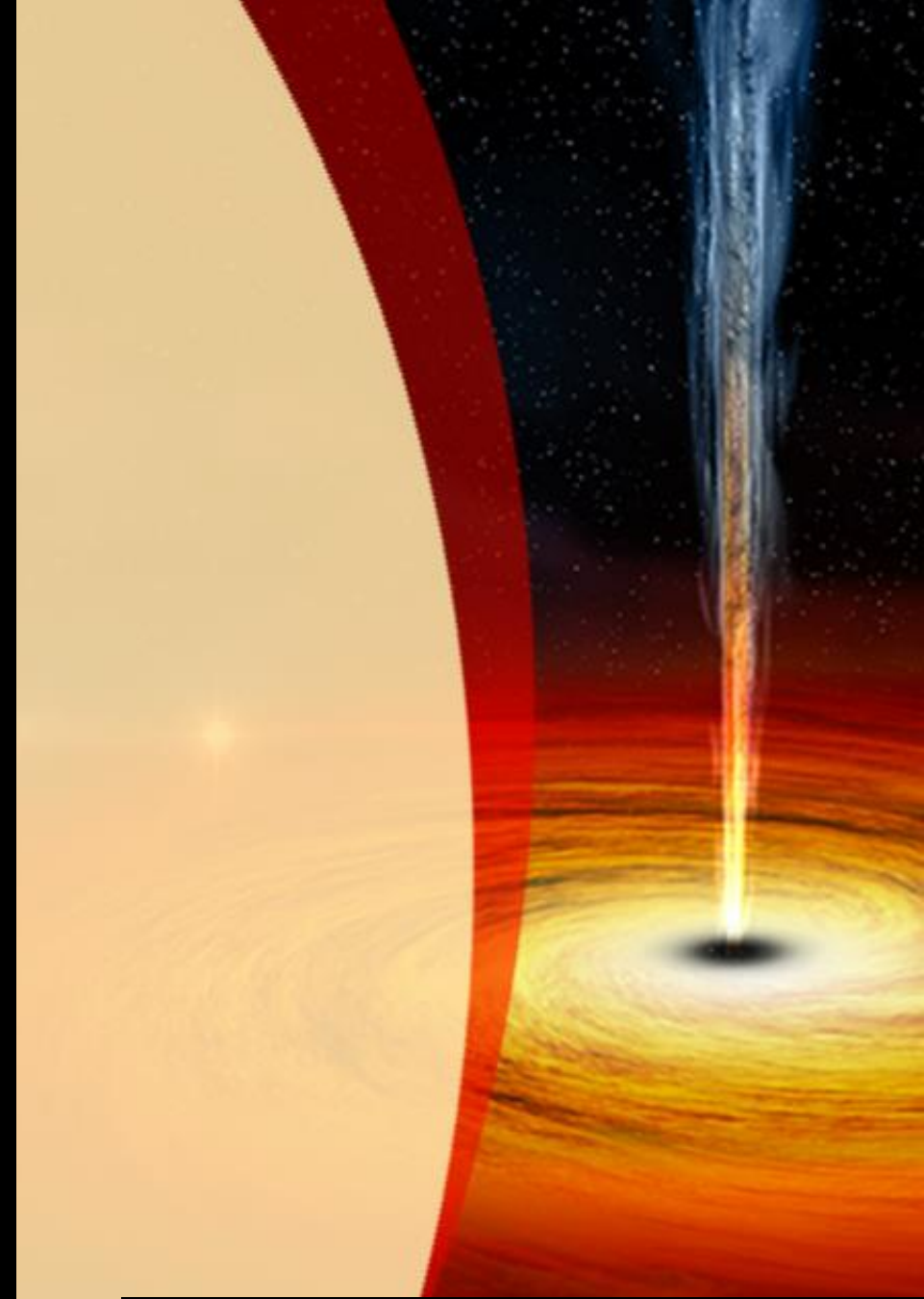
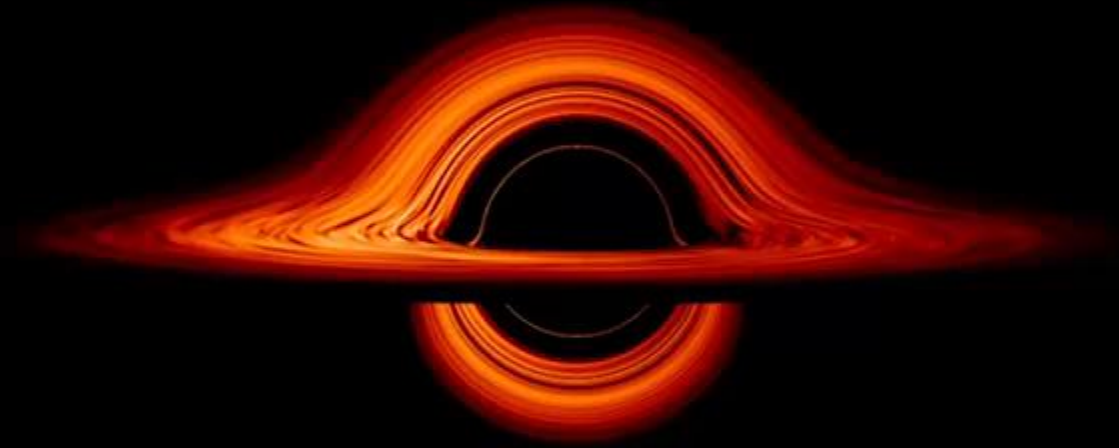




# Animacija ☺

Credit: NASA's Goddard Space Flight Center / Jeremy Schnittman

# Kako vidimo crnu rupu?



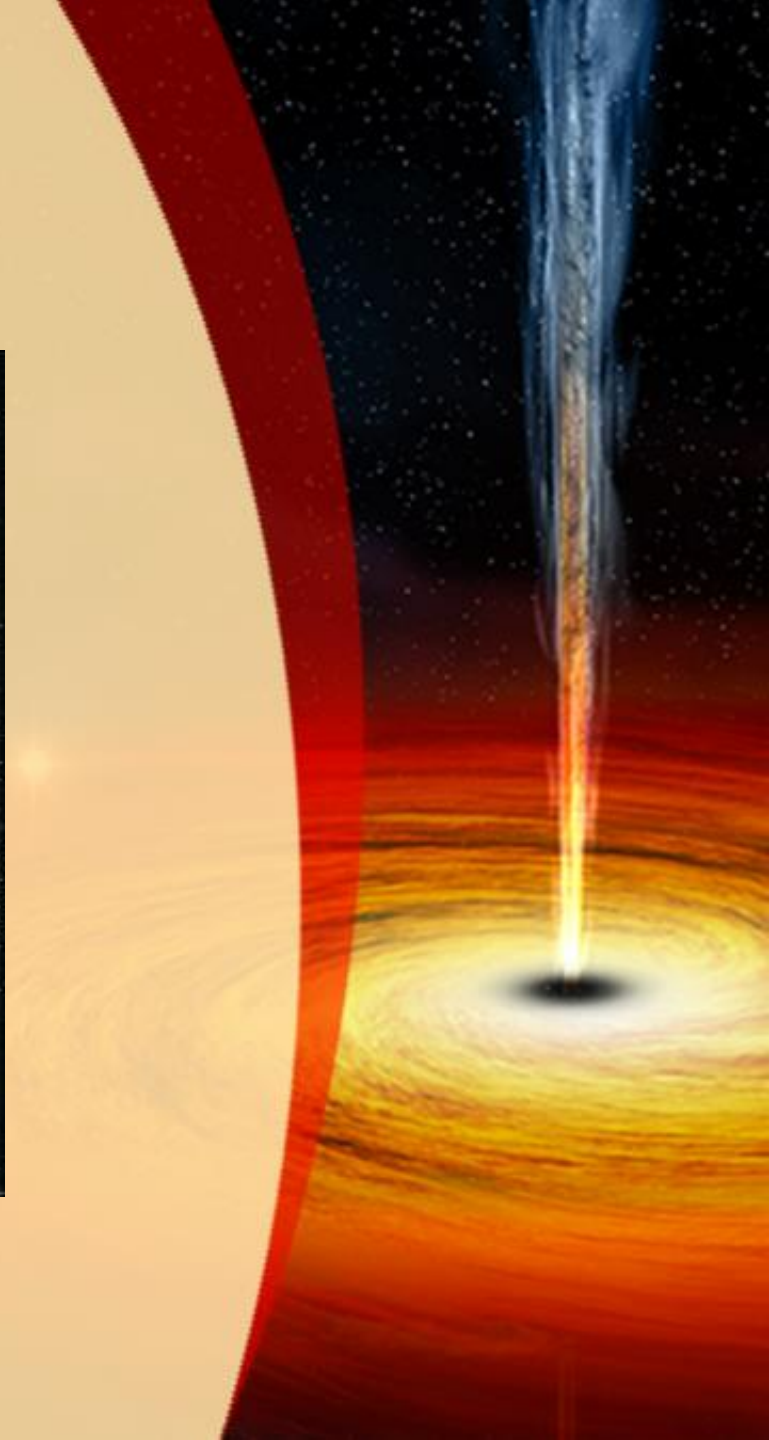
Izvor: NASA's Goddard Space Flight Center/Jeremy Schnittman  
<https://svs.gsfc.nasa.gov/13326>



## A može i ovako...



- Simulacija crne rupe objavljena 1979. godine (autor Jean-Pierre Luminet)



# Supermasivne crne rupe

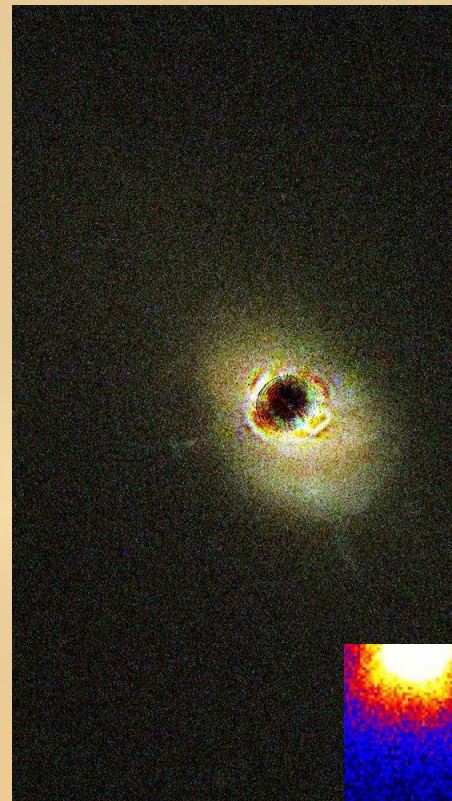
- U centru skoro svih galaksija
- U Mlečnom putu - lokacija *Strelac A* (najsnažniji radio izvor u našoj galaksiji)
- Akrecija materije u SMBH je proces odgovoran za energiju kvazara i drugih aktivnih galaksija

Vrsta	Masa [ $M_{\odot}$ ]	Veličina
Supermasivna	$10^5 - 10^{10}$	0,001 - 10 AJ
Srednjemasivna	$10^2 - 10^5$	$10^3$ km
Zvezdana	$< 10^2$	30 km
Mikro	$\ll M_{\odot}$	0,1 mm

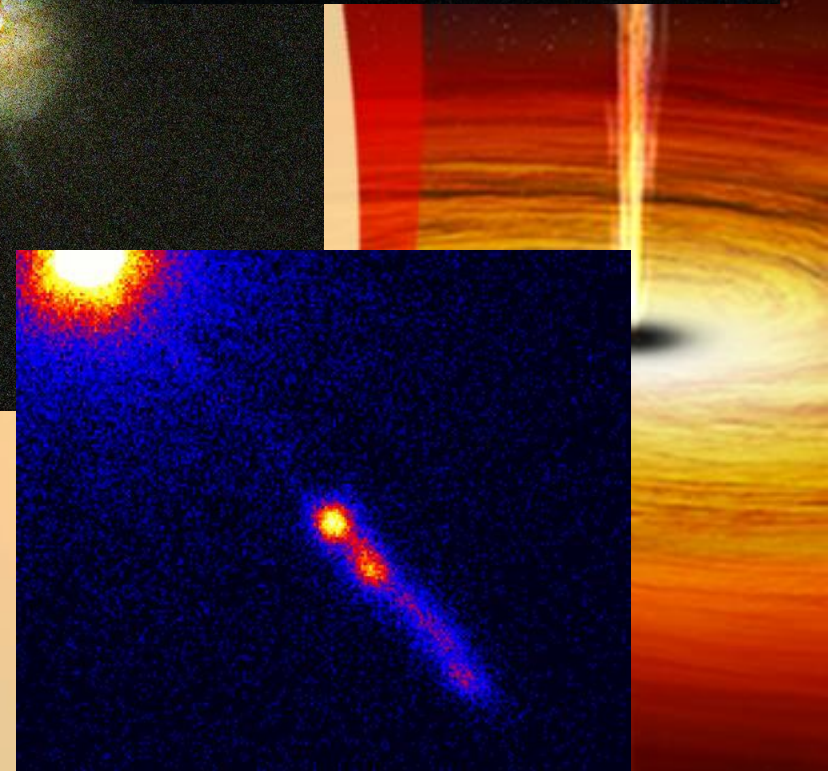
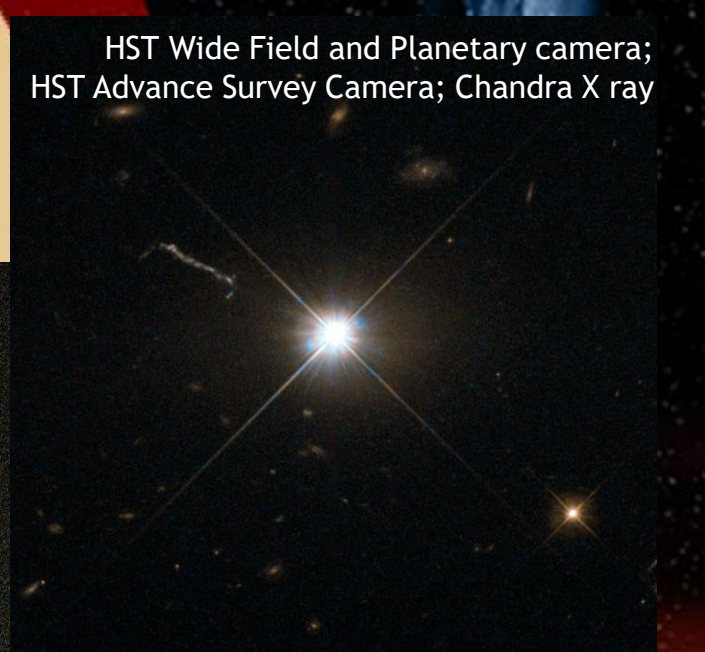


# Kvazari?

- *Quasi-stellar radio source*
- Godina 1963 - objekat 3C273
  - 2,5 milijardi svetlosnih godina
  - Najbliži kvazar, prvi detektovan; najsjajniji (VIS)
- Liče na zvezde, ali...
  - Na 30 ly - sjajan kao Sunce
- Neophodan jak izvor svetlosti!
  
- Ubrzo nakon otkrića zaključak:
  - Energija (svetlost) nastaje kad materija pada u masivnu crnu rupu

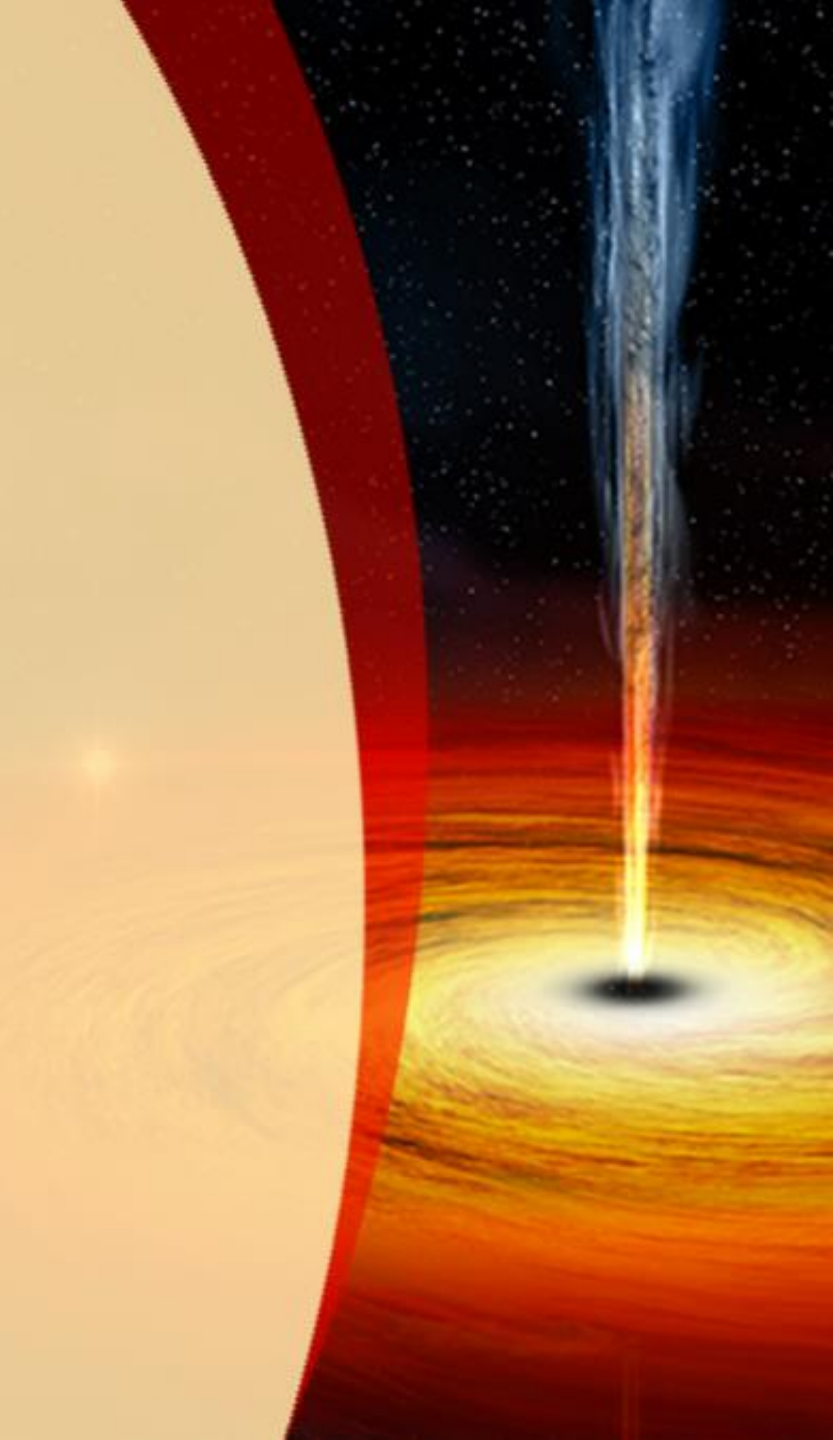


HST Wide Field and Planetary camera;  
HST Advance Survey Camera; Chandra X ray

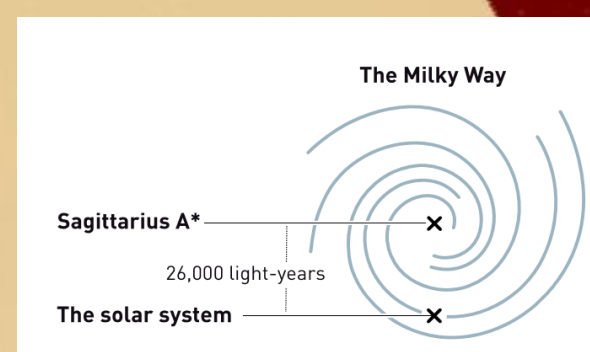


# Ne možemo da ih vidimo...

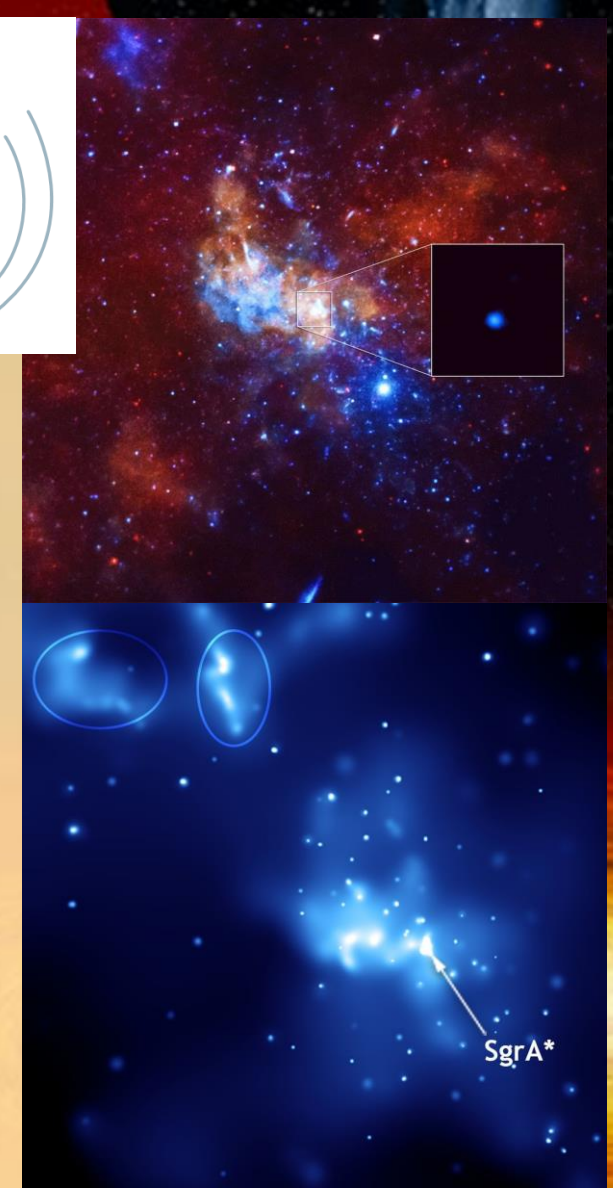
- ... ali znamo da postoje
  - Kretanje drugih objekata
- R. Gencel i A. Gez - nezavisne istraživačke grupe - istraživanje centra Galaksije
- Oblak međuzvezdanog gasa zaklanja najveći deo VIS zračenja iz centra
  - IC i radio teleskopi omogućili pogled
- Posmatrali orbite zvezda - najubedljiviji dokazi za postojanje nevidljivog supermasivnog objekta



# Sagittarius A\*

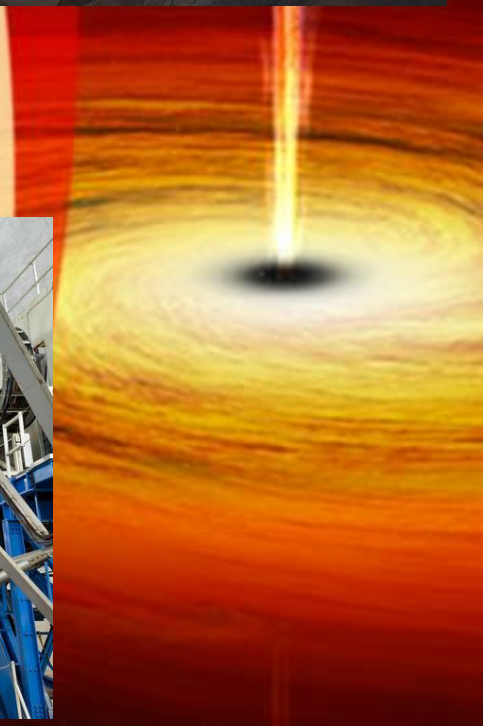
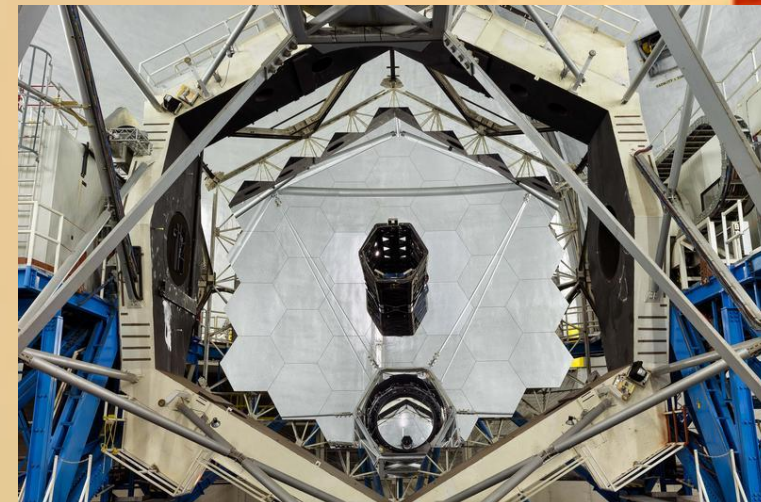
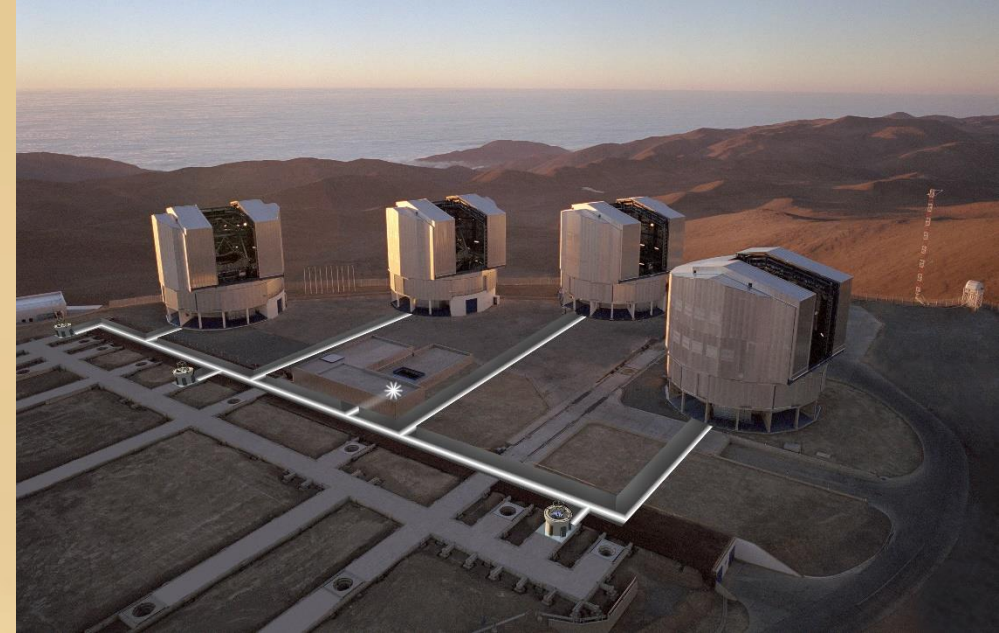


- Jak i kompaktan radio izvor u centru Galaksije
  - Blizu granice sazvežđa Strelac i Škorpija
- Još od otkrića kvazara - pretpostavka SMBH u centru velikih galaksija
  - masa par miliona do nekoliko milijardu masa Sunca
- Centar galaksije Harlow Shapley (pre 100 god)
  - Kasnije pokazano da je to Sag A\*
- 1990+ god
  - Projekti R. Gencel i A. Gez - posmatranje orbita zvezda u centru Mlečnog puta



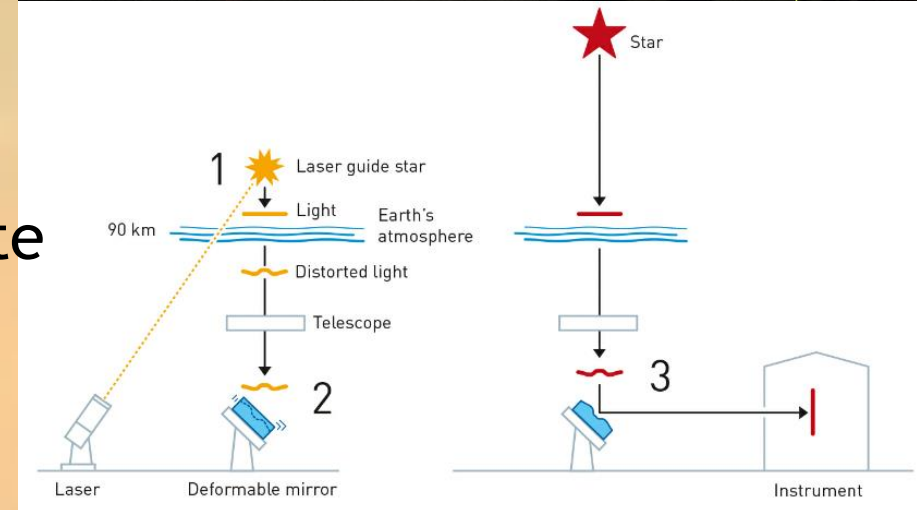
# Teleskopi

- R. Gencel i grupa
  - New Technology Telescope (La Silla mountain, Čile)
  - Very Large Telescope facility, VLT (Čile)
    - 4 teleskopa, najveći 8 metara (2 puta veći nego NTT)
- A. Genz i grupa
  - Keck opservatorija (Havaji)
    - Oko 10 metara (36 šestougaona segmenta)



# Zvezde pričaju priču

- Ogromni teleskopi ali problem - atmosfera
  - Adaptivna optika
- Istraživači pratili oko 30 sjajnih zvezda
  - 1 svetlosni mesec oko centra
    - velike brzine zvezda
  - Veća rastojanja - stabilnije i „standrdnije“ orbite
- Zvezda S2
  - Period 16 godina - mapirana cela orbita!
  - (Sunce 200 miliona godina)



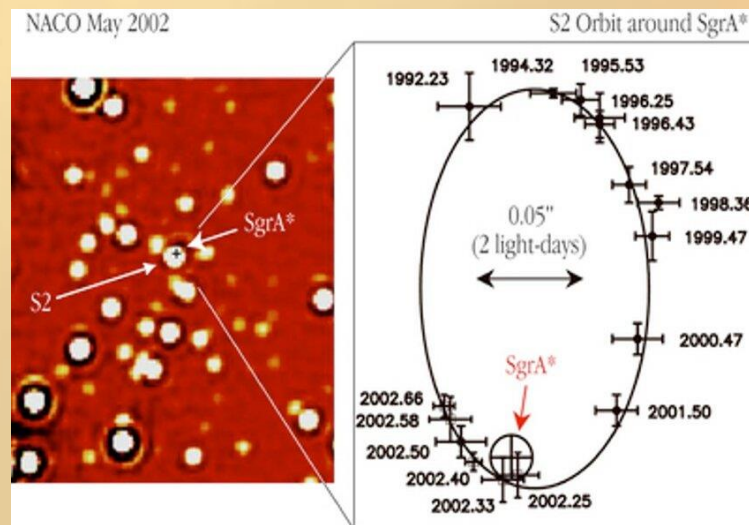
Scientific Background on the Nobel Prize in Physics 2020

# Zvezde pričaju priču

- Odlično poklapanje rezultata oba tima
  - SMBH 4 miliona masa Sunca
  - Oblast veličine Sunčevog sistema

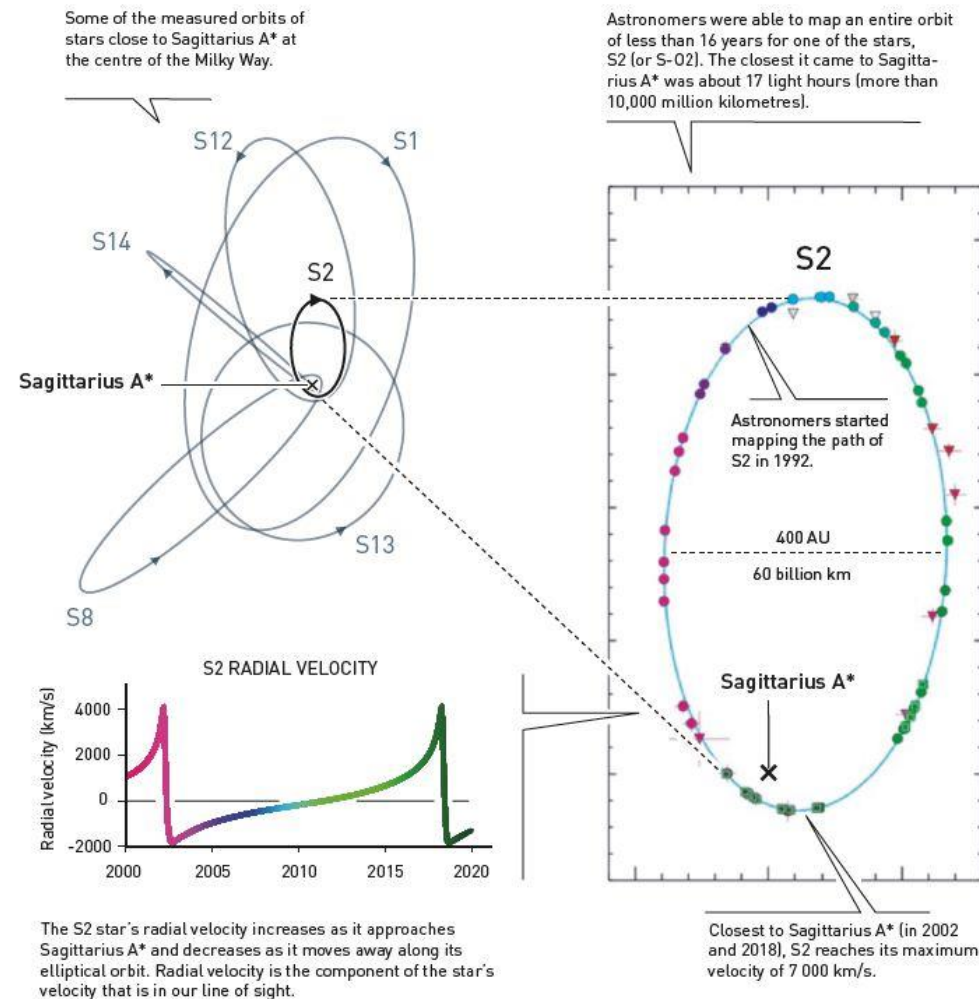
• ~~Možda je uskoro stvarno „vidimo“...~~

- videli smo je 😊



## Stars closest to the centre of the Milky Way

The stars' orbits are the most convincing evidence yet that a supermassive black hole is hiding in Sagittarius A\*. This black hole is estimated to weigh about 4 million solar masses, squeezed into a region no bigger than our solar system.

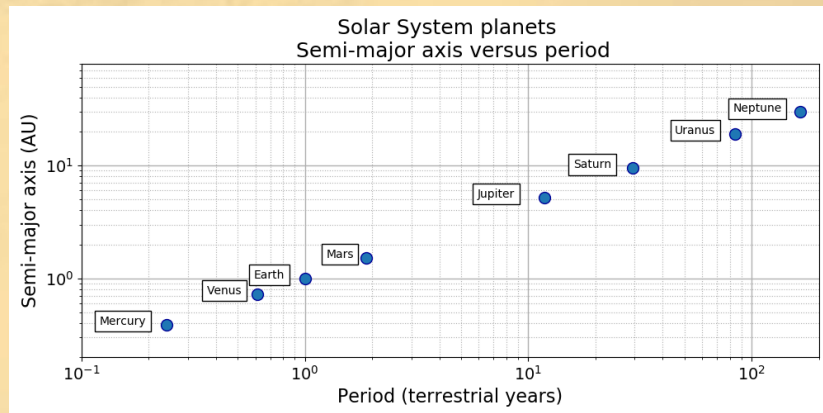
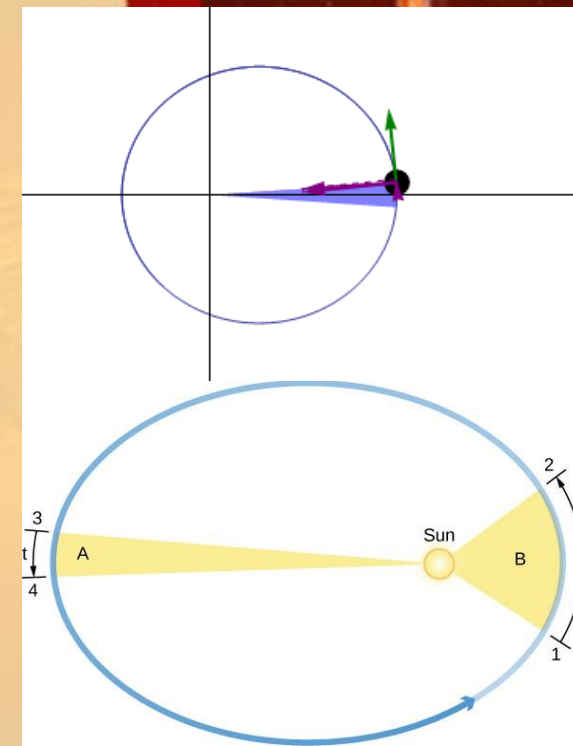
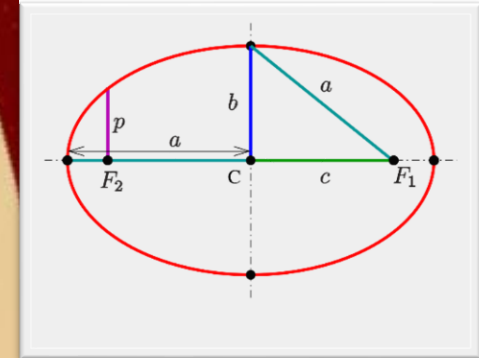
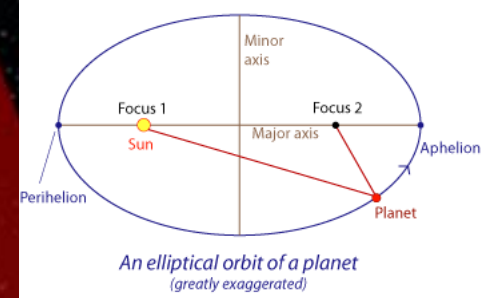




# Vežba - izračunajte masu SMBH

- Keplerovi zakoni

- Planete se oko Sunca kreću po eliptičkim putanjama, u čijoj se zajedničkoj žiži nalazi Sunce
- Radijus vektor planete u jednakim vremenskim intervalima opisuje jednake površine
- Kvadrati perioda ( $P$ ) obilaska planete oko Sunca srazmerni su kubovima velikih poluosa ( $a$ ) njihovih putanja

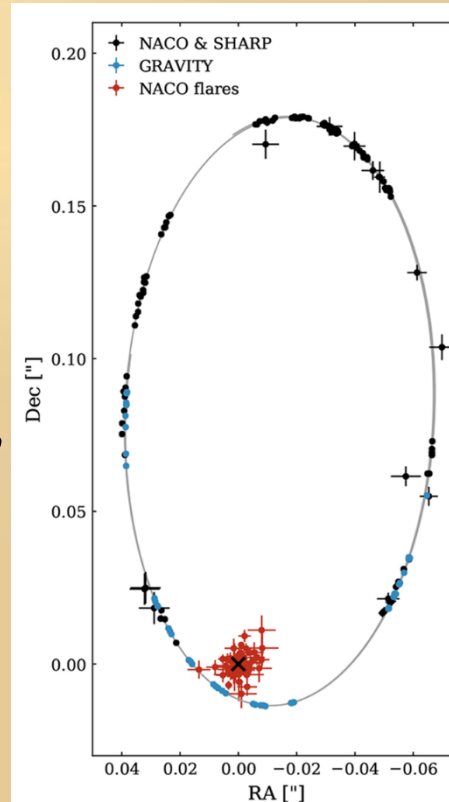


Modern data (Wolfram Alpha Knowledgebase 2018)

Planet	Semi-major axis (AU)	Period (days)	$\frac{R^3}{T^2}$ ( $10^{-6}$ AU <sup>3</sup> /day <sup>2</sup> )
Mercury	0.38710	87.9693	7.496
Venus	0.72333	224.7008	7.496
Earth	1	365.2564	7.496
Mars	1.52366	686.9796	7.495
Jupiter	5.20336	4332.8201	7.504
Saturn	9.53707	10775.599	7.498
Uranus	19.1913	30687.153	7.506
Neptune	30.0690	60190.03	7.504

# Vežba - izračunajte masu SMBH

- Levo - koordinate položaja zvezde S2
- Koordinatni početak - centar SMBH
- Kako?
  - Nacrtati tačke (i greške)
  - Nacrtati elipsu najpribližniju merenjima
  - Izmeriti veliku poluosu elipse
    - Arcsec prevesti u svetlosne dane ( $ld$ ),  
 $2 \text{ arcsec} = 28 \text{ ld}$
    - Izračunati srednju vrednost 😊



Date (year)	x (arcsec)	dx (arcsec)	y (arcsec)	dy (arcsec)
1992.226	0.104	0.003	-0.166	0.004
1994.321	0.097	0.003	-0.189	0.004
1995.531	0.087	0.002	-0.192	0.003
1996.256	0.075	0.007	-0.197	0.010
1996.428	0.077	0.002	-0.193	0.003
1997.543	0.052	0.004	-0.183	0.006
1998.365	0.036	0.001	-0.167	0.002
1999.465	0.022	0.004	-0.156	0.006
2000.474	-0.000	0.002	-0.103	0.003
2000.523	-0.013	0.003	-0.113	0.004
2001.502	-0.026	0.002	-0.068	0.003
2002.252	-0.013	0.005	0.003	0.007
2002.334	-0.007	0.003	0.016	0.004
2002.408	0.009	0.003	0.023	0.005
2002.575	0.032	0.002	0.016	0.003
2002.650	0.037	0.002	0.009	0.003
2003.214	0.072	0.001	-0.024	0.002
2003.353	0.077	0.002	-0.030	0.002
2003.454	0.081	0.002	-0.036	0.002

# Vežba - izračunajte masu SMBH

- Kako?

- ...

- Odrediti period ( $P$ )

- $A_{ell} = ab \cdot \pi$  -  $a$  i  $b$  sa slike, prethodni slajd

- $\Delta A = \frac{\Delta t}{P} \cdot A_{ell}$  - II Keplerov zakon

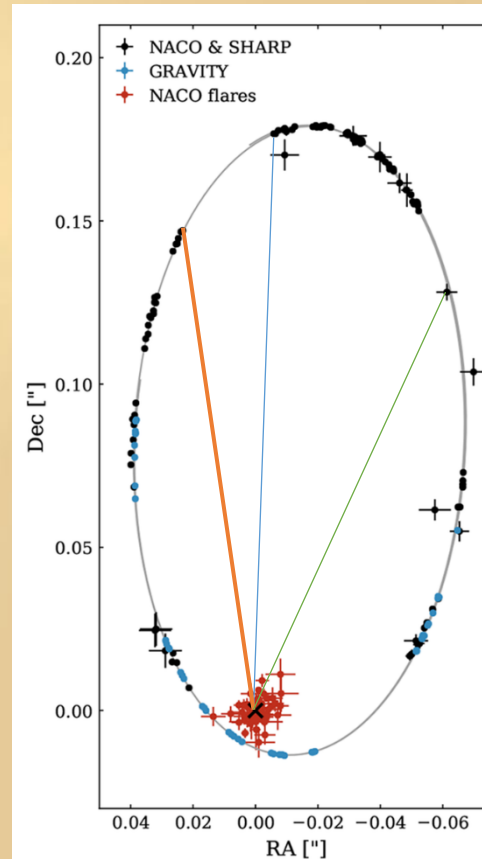
- Nepoznato  $\Delta A$ ,  $\Delta t$ ,  $A_{ell}$

- $\Delta A$  i  $\Delta t$  - sa slike (prethodni slajd, za svaki segment)
    - Nacrtati trougao i odrediti njegovu površinu (ponoviti više puta!)

- Izračunati masu SMBH

- III Keplerov zakon

- $P^2 = \frac{4\pi^2}{G(M+m_{S2})} a^3, M \gg m_{S2}$

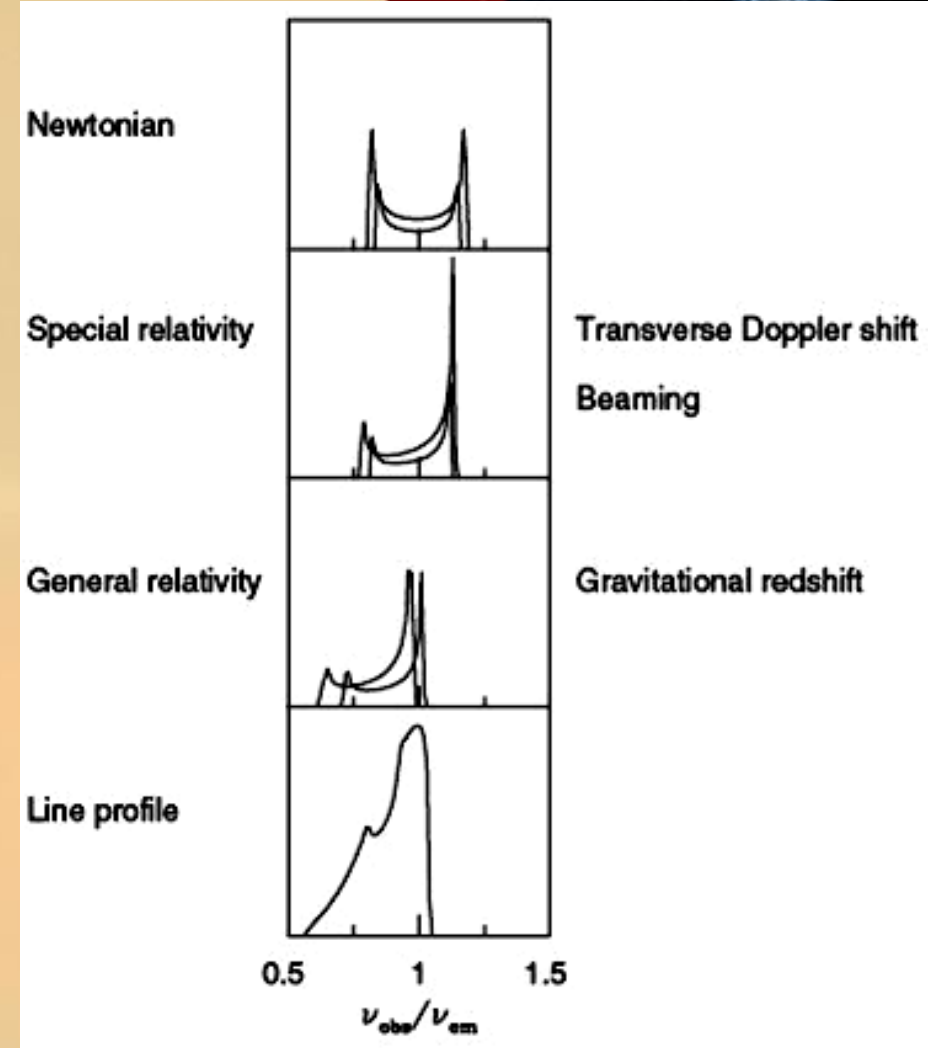
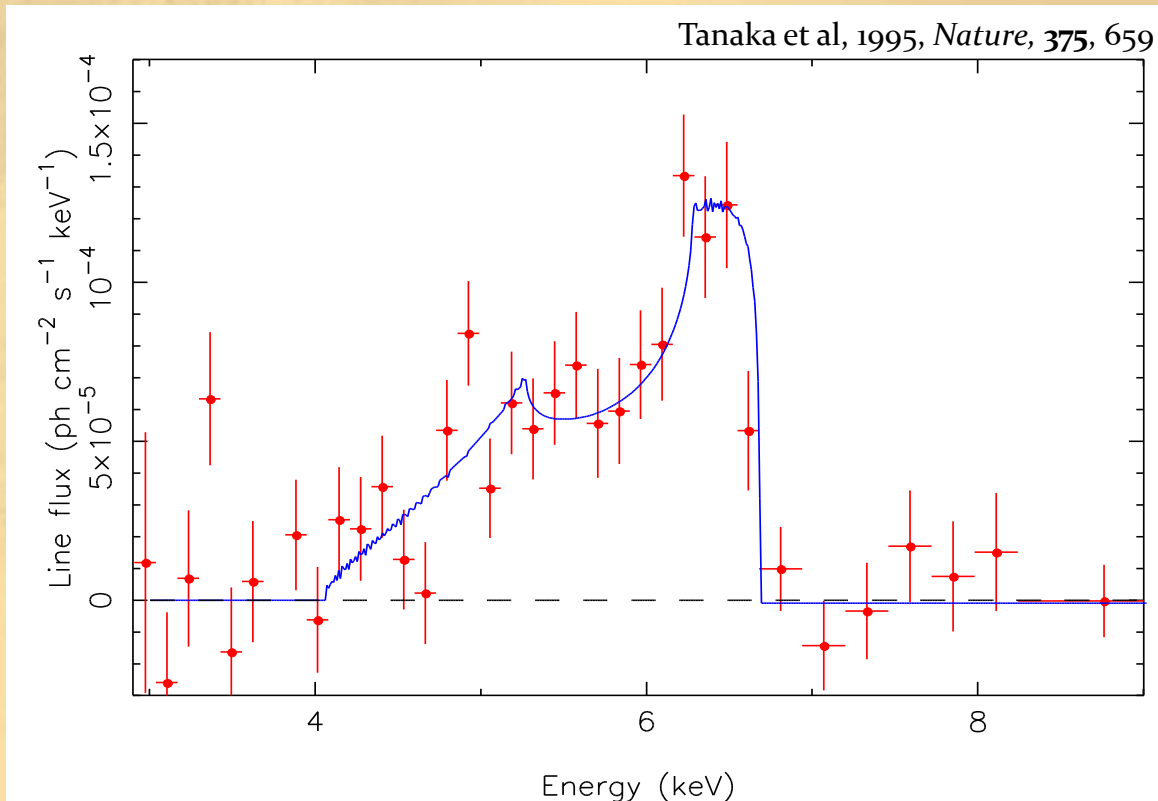


Date (year)	x (arcsec)	dx (arcsec)	y (arcsec)	dy (arcsec)
1992.226	0.104	0.003	-0.166	0.004
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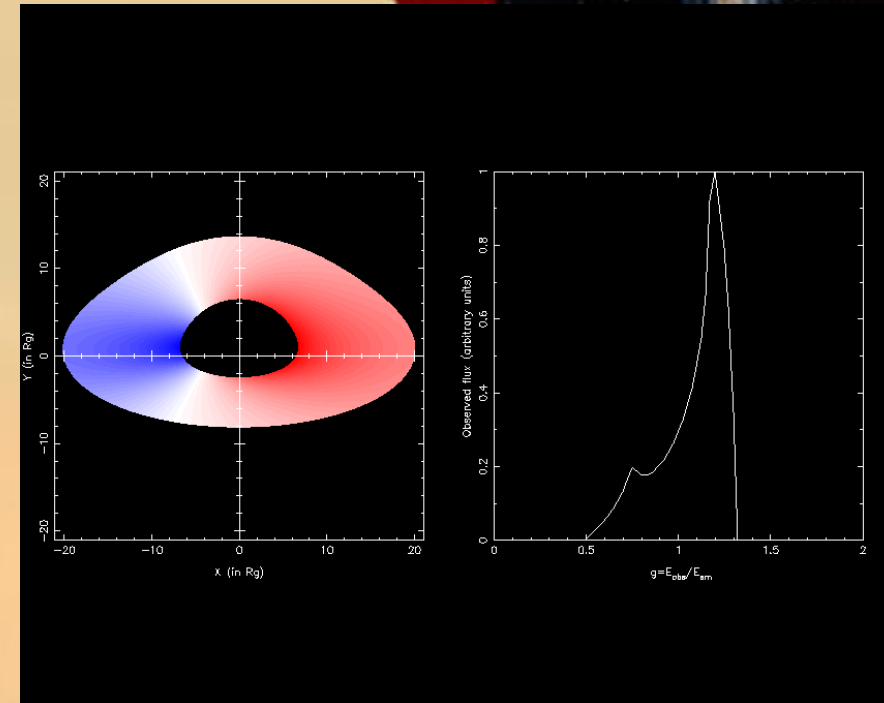
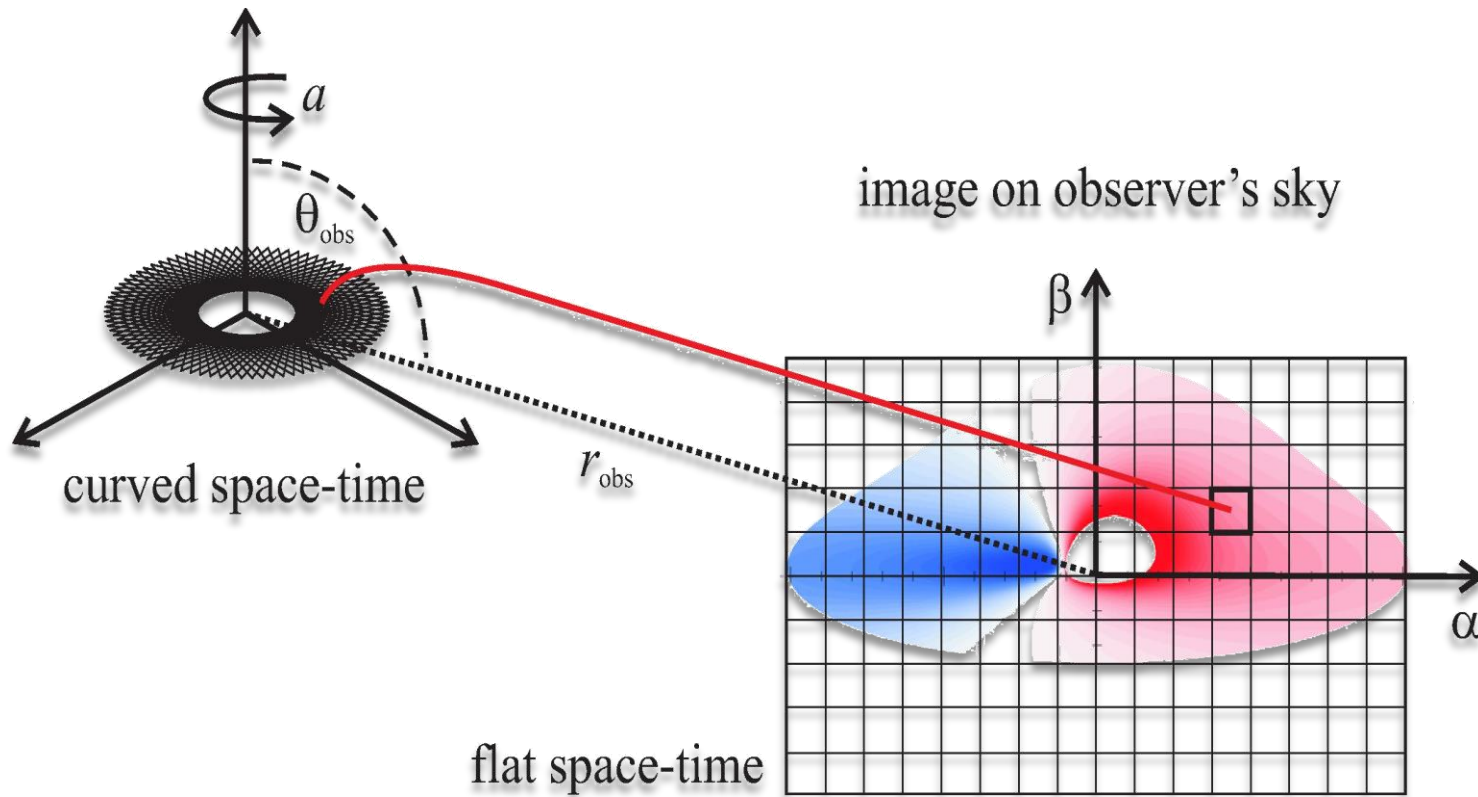
# Kako znamo da postoje?

Fabian, A. C. 2006, *AN*, 327, 943

- *Fe K $\alpha$*  linija u spektru



# Kako znamo da postoje?



M. Milošević, M.A. Pursiainen, P. Jovanović, L.Č. Popović, Int. J. Mod. Phys. A. 33 (2018) 1845016.

P. Jovanović, New Astron. Rev. 56 (2012), pp. 37 - 48.

L. Popović, P. Jovanović, E. Mediavilla, A.F. Zakharov, C. Abajas, J.A. Munoz, G. Chartas, ApJ 637 (2006), pp. 620 - 630.

L. Popović, E.G. Mediavilla, P. Jovanović, J.A. Munoz, A&A 398 (2003), pp. 975 - 982.

A. Čadež, C. Fanton, M. Calvani, New Astron. 3 (1998), pp. 647 - 654.

# Galaksija M87

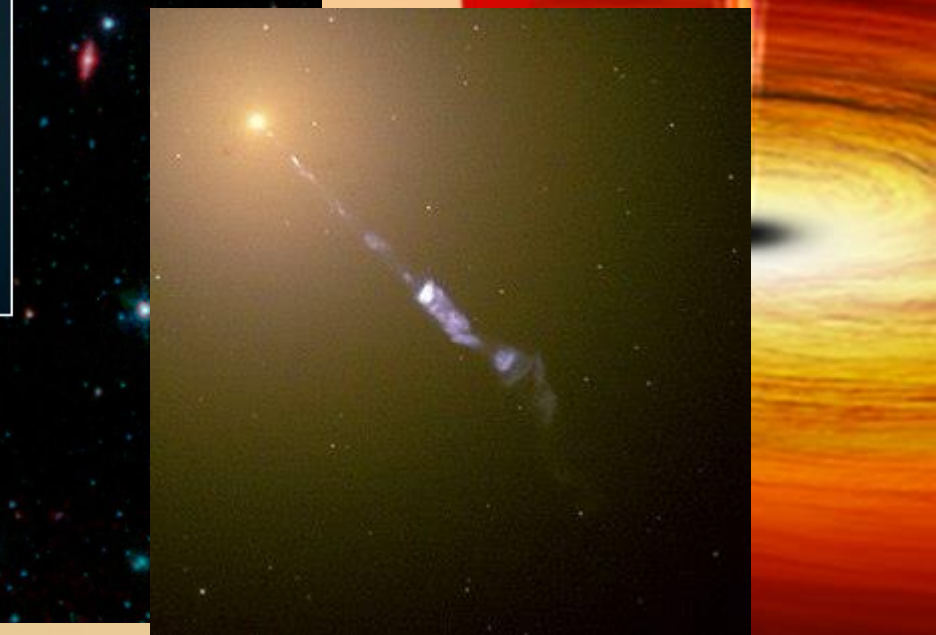
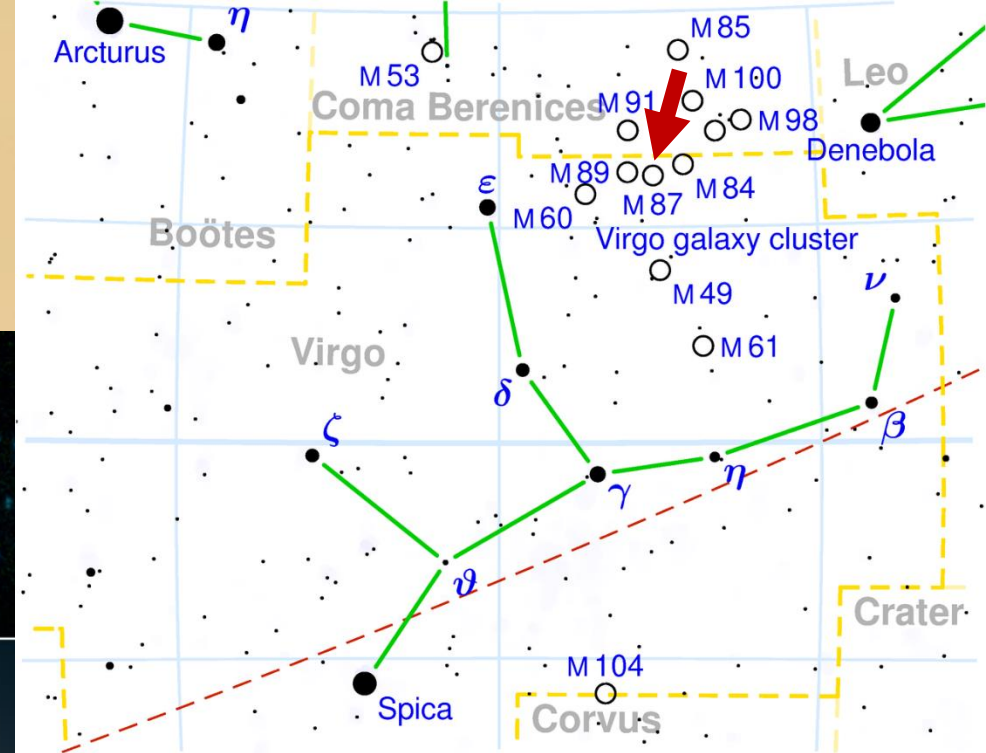
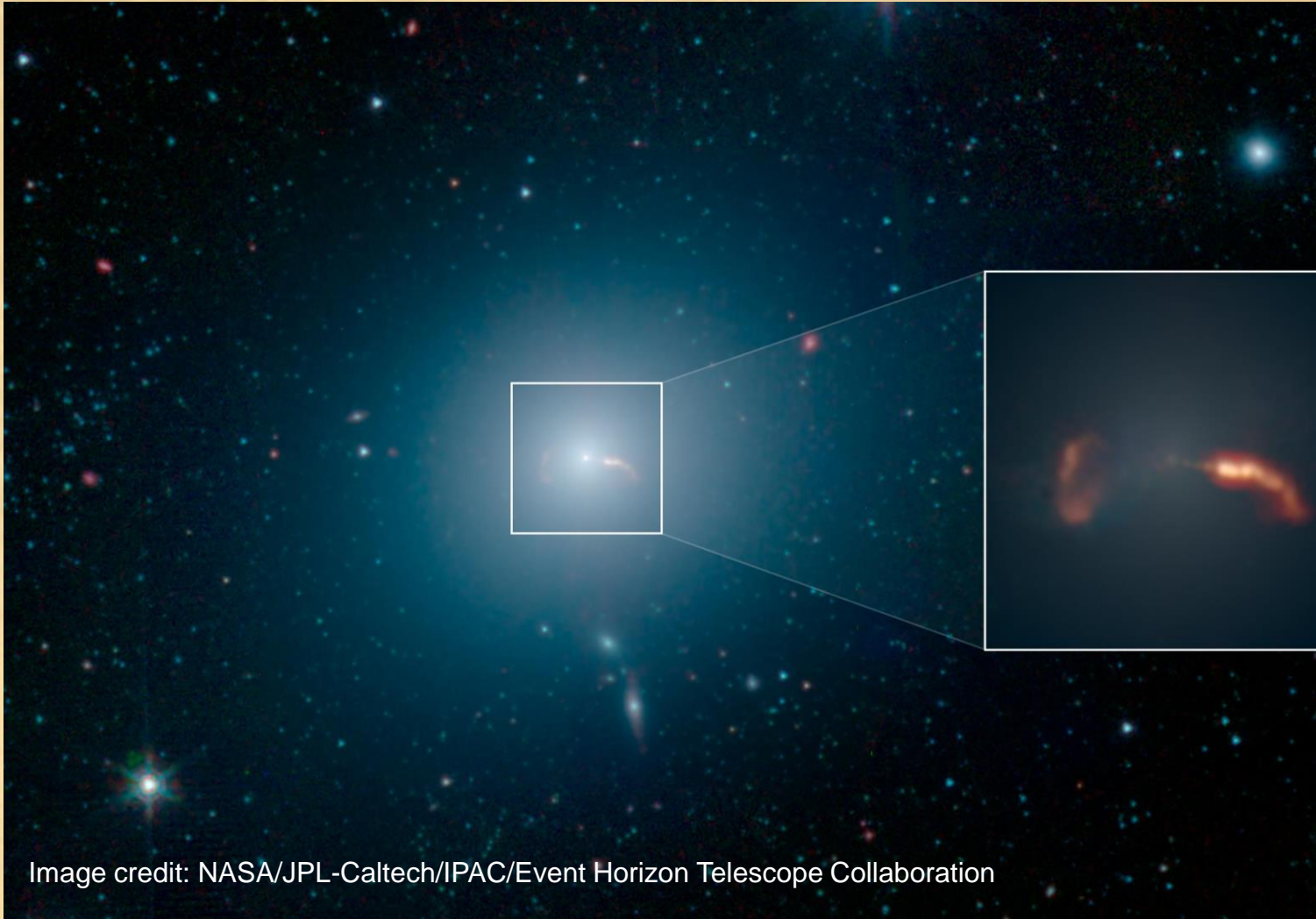


Image credit: NASA/JPL-Caltech/IPAC/Event Horizon Telescope Collaboration

NASA and The Hubble Heritage Team (STScI/AURA)

# Galaksija M87

- Daljina 52 miliona svetlosnih godina
- Dimenzije 125.000 x 100.000 s.g.
- Masa  $2,6 \cdot 10^{12} M_{\odot}$ , 4,5 puta masivnija od naše galaksije
- „jet“ (mlaz) 5.000 s.g.
- Ogroman broj zbijenih jata, 12.000; u Mlečnom putu 150-200

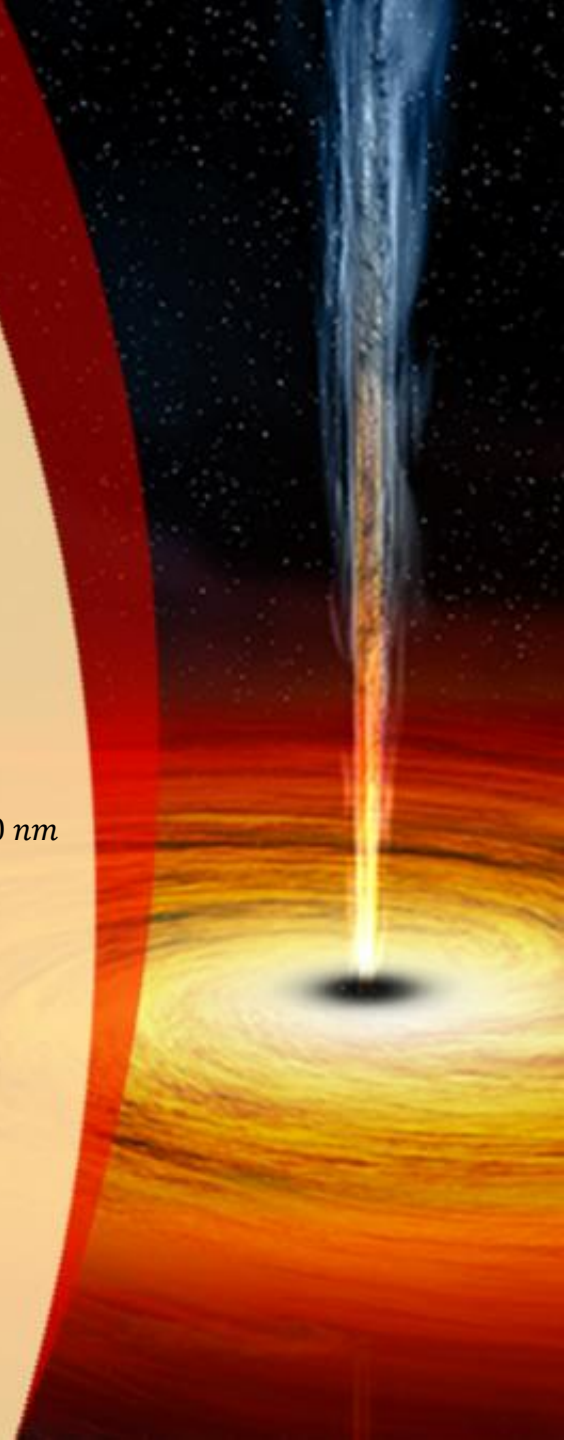


# Kako videti SMBH?

- Da bi kroz teleskop videli neki objekat potrebno je da prividne dimenzije tog objekta budu veće od razdvojne moći teleskopa
- Prosečne SMBH - otprilike 10x manja od mikrolučne sekunde!
- Takvim teleskopom mogla da se vidi jabuka na površini Meseca

$$\sin \alpha = 1,22 \frac{\lambda}{D}$$
$$\alpha = \frac{138}{D}$$

Za male uglove i VIS,  $\lambda = 550 \text{ nm}$   
 $D$  u milimetrima





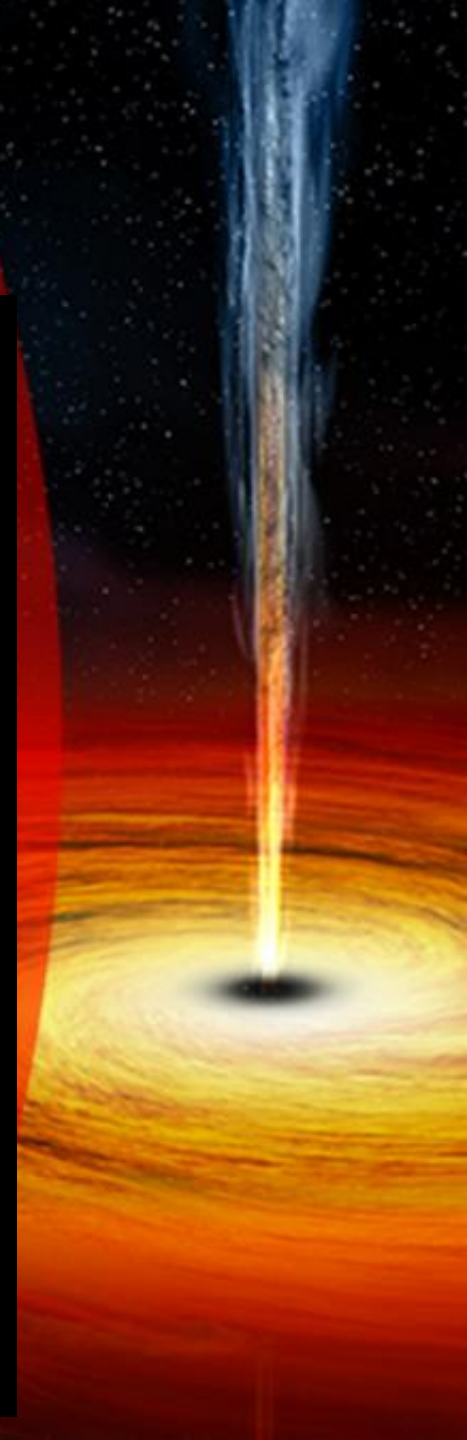
# Dimenzije & rastojanje



[https://www.youtube.com/watch?v=S\\_GVbuddri8](https://www.youtube.com/watch?v=S_GVbuddri8)

European Southern Observatory, NASA and The Hubble Heritage Team (STScI/AURA)

L. R. Weih & L. Razzolla  
(Goethe University Frankfurt)



# Teleskop veličine Zemlje

- Takav optički teleskop ne postoji ☹️
- Radio teleskop, tačnije radio interferometar
  - Početak 1946. godine
  - 1970-tih mogućnost povezivanja prijema radio signala iz celog sveta
  - Povezivanje antena zamenilo sinhronizovano spajanje snimljenih signala (korelacija)

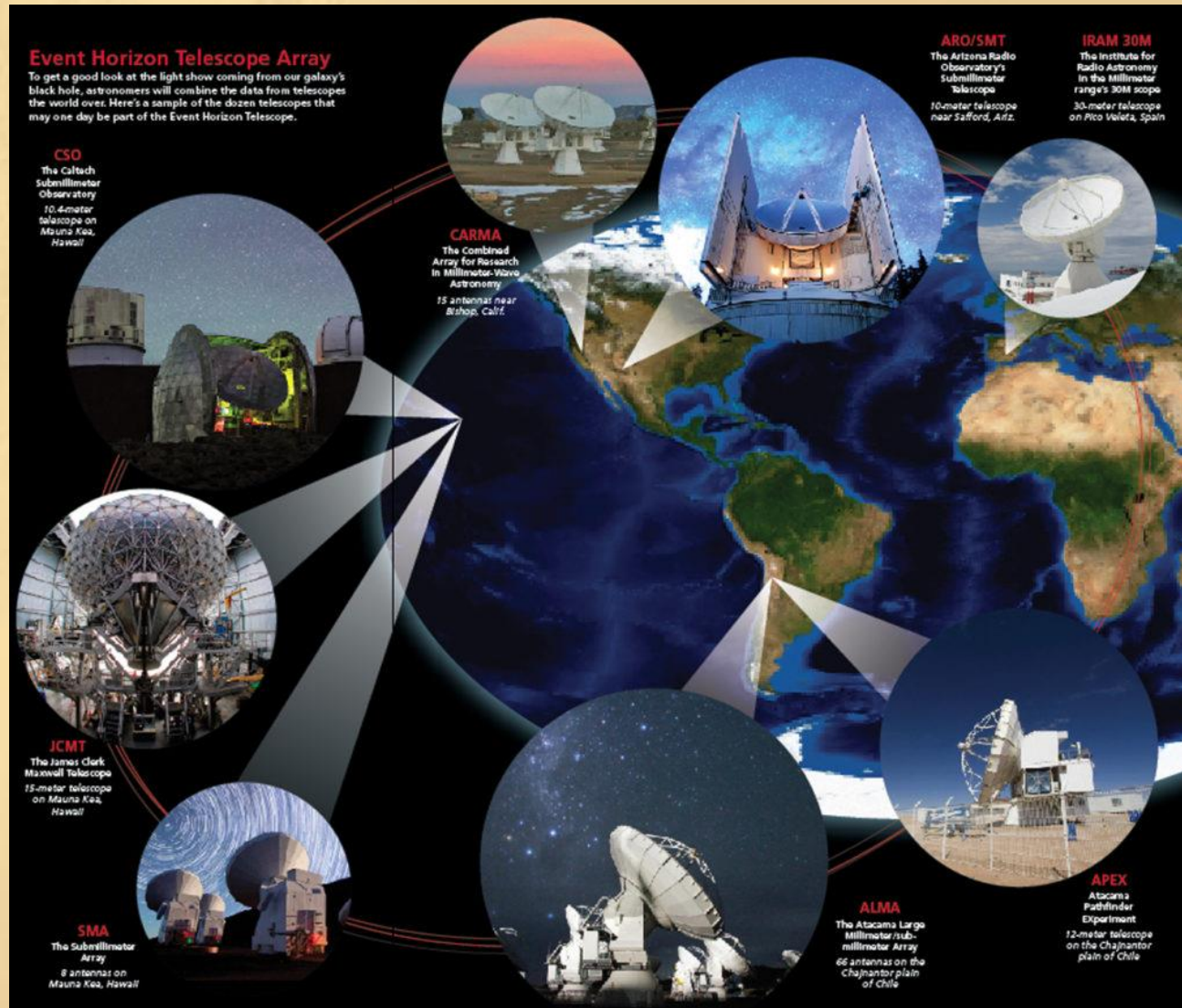


# Teleskop veličine Zemlje

- *Event Horizon Teleskop*, radi od 2007. godine
  - 8 radio teleskopa koji se nalaze na različitim kontinentima
- Atacama Large Millimeter/submillimeter Array (ALMA) u Čileu, South Pole Telescope (SPT) na Antarktiku, IRAM 30 metarski teleskop u Španiji itd.
- Mreža EHT teleskopa. **Žutom** bojom označene su stanice koje su korišćene 2017. i 2018. godine, **crvenom** oni teleskopi koji više nisu u upotrebi, **zeleno** su označeni teleskopi koji su se kasnije uključili u mrežu



# Event Horizon Teleskop



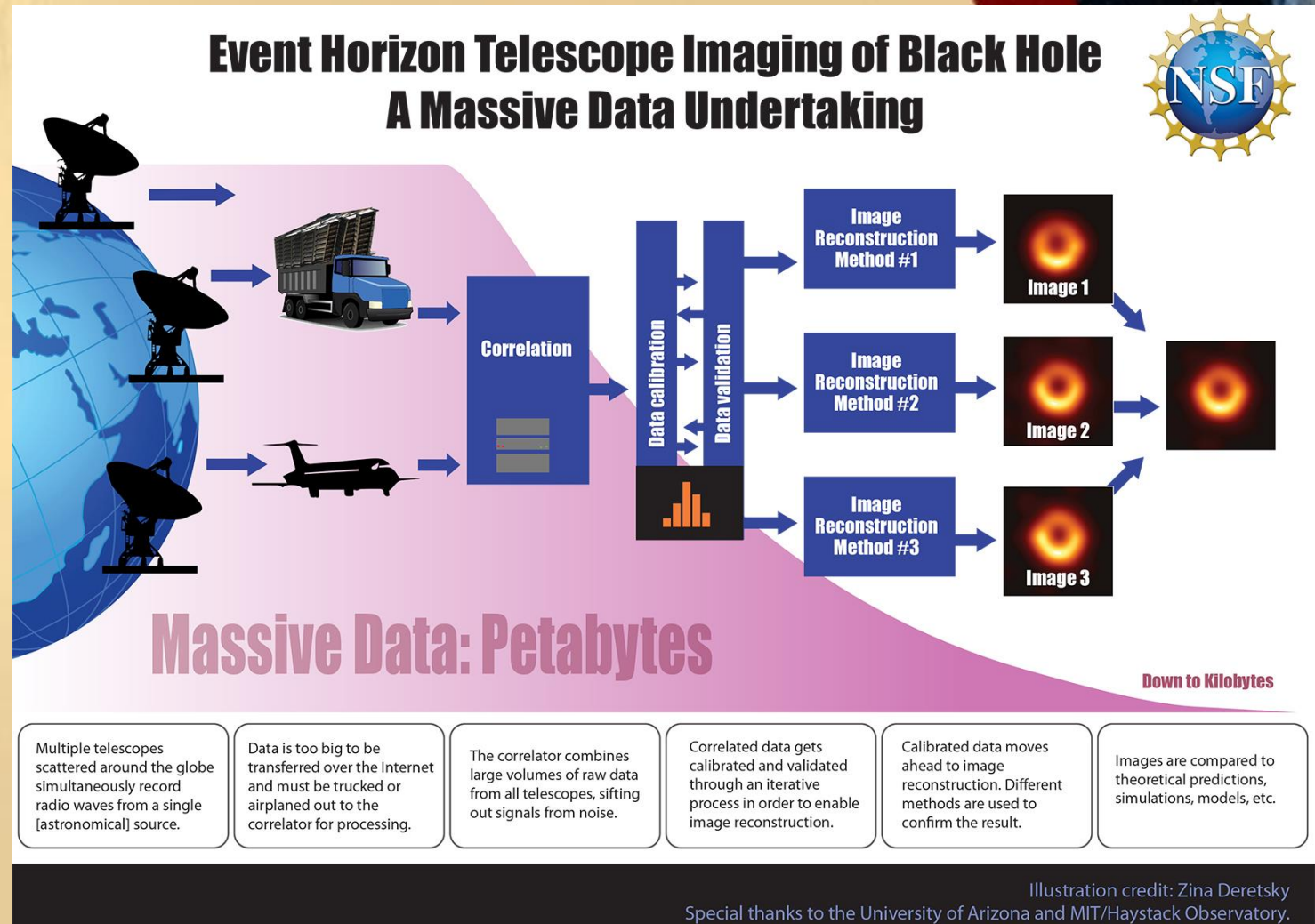
# Teleskop veličine Zemlje

- Rastojanja 160 m do 10.700 km
- Posle nekoliko godina pauze EHT ponovo uključen 4. aprila 2017. godine, posmatranje završilo 11. aprila
- Snimali su na talasnoj dužini 1,3 mm
- Za 5 dana svaki teleskop 900 TB podataka
- Obični HDD - 85% otkazalo zbog niskog pritiska (korišćeni diskovi punjeni helijumom i zatvoreni hermetički)



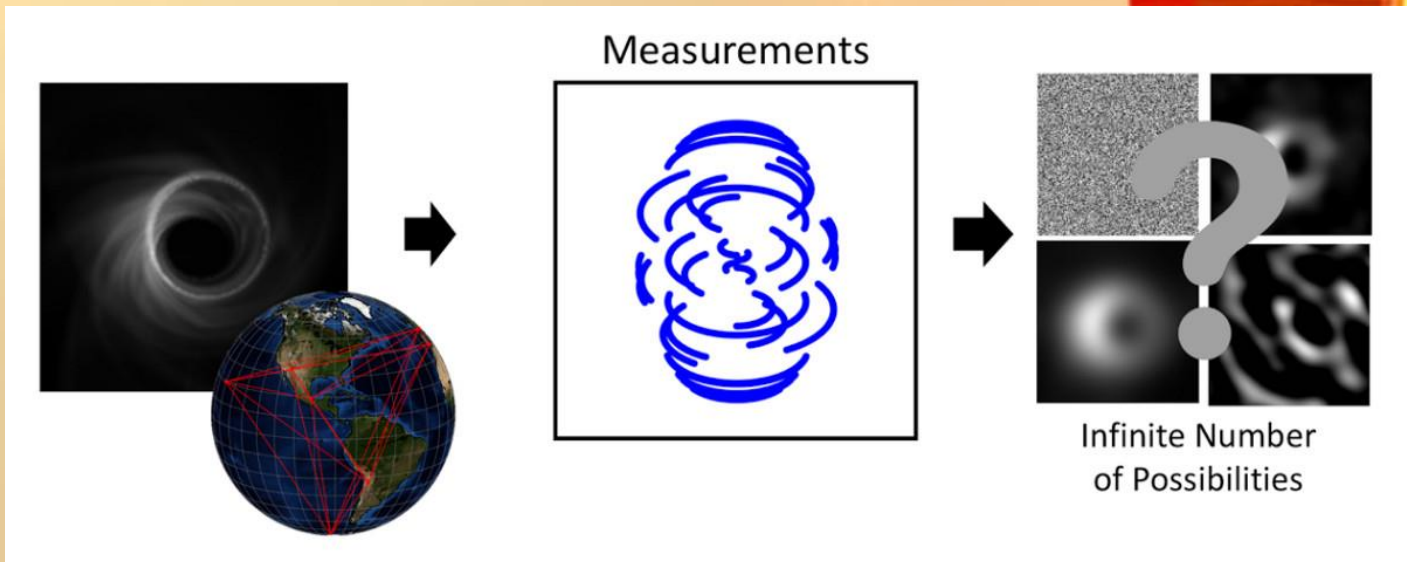
# Mnogo podataka 😊

- 200+ istraživača
- ½ tone hard diskova
- Opservatorija Mauna Kea
  - Oko 700 TB podataka
  - 8000 km od MIT
  - 50.400 sekundi (kamion + avion)
    - Brzina: 14 gigabajta/s (tj. 112 gigabita/s)
    - Najbrži internet: nekoliko gigabita/s 😊



# Big Data, AI, Mašinsko učenje

- Obrada i analize sačuvanih podataka pomoću superračunara
  - Max Planck institutu za radio astronomiju u Bonu, Nemačka,
  - MIT Haystack opservatoriji u SAD.
- Na ovakav način EHT postiže oko 2000 puta bolju rezoluciju od teleskopa Habl.



# “Žaba u bunaru”

Žabu koja je živela u okeanu, iznenada izbacila talas i prebacila u bunar. Na dnu bunara, ona sreće krastaču, tu rođenu, koja nikada iz njega nije izašla. Druga pita prvu:

- Odakle dolaziš?
- Dolazim iz okeana.
- Kakav je taj okean?
- Ogroman.

Krastača skoči pet centimetara.

- Je l' ovako veliki?
- Ne! Mnogo veći!

Ona skoči do dvadeset centimetara.

- Ovoliko veliki?

- Još veći!

Krastača skoči do polovine bunara.

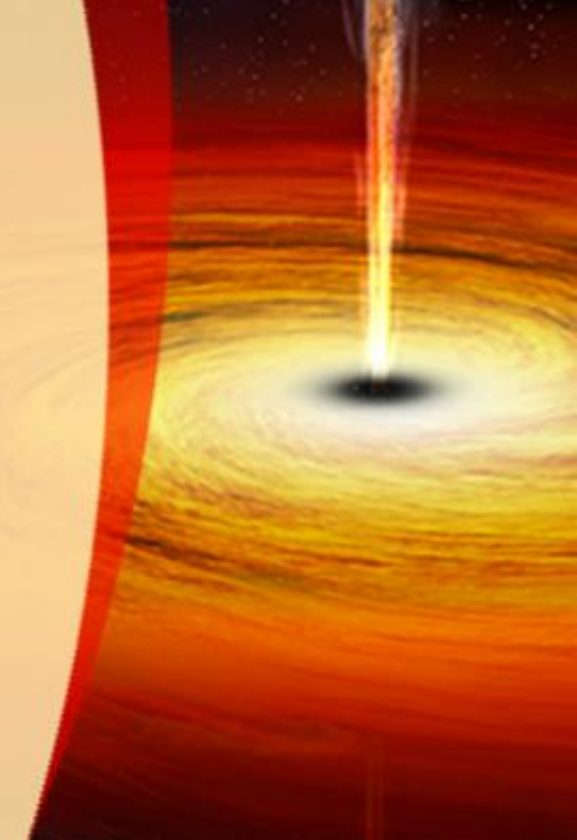
- Ovoliko?
- Ne!

Krastača pređe čitavo dno bunara.

- Ovoliko?
- Ne. Mnogo veći.

Potom krastača, uzviknuvši besno:  
“Lažljivice!” – ujede žabu.

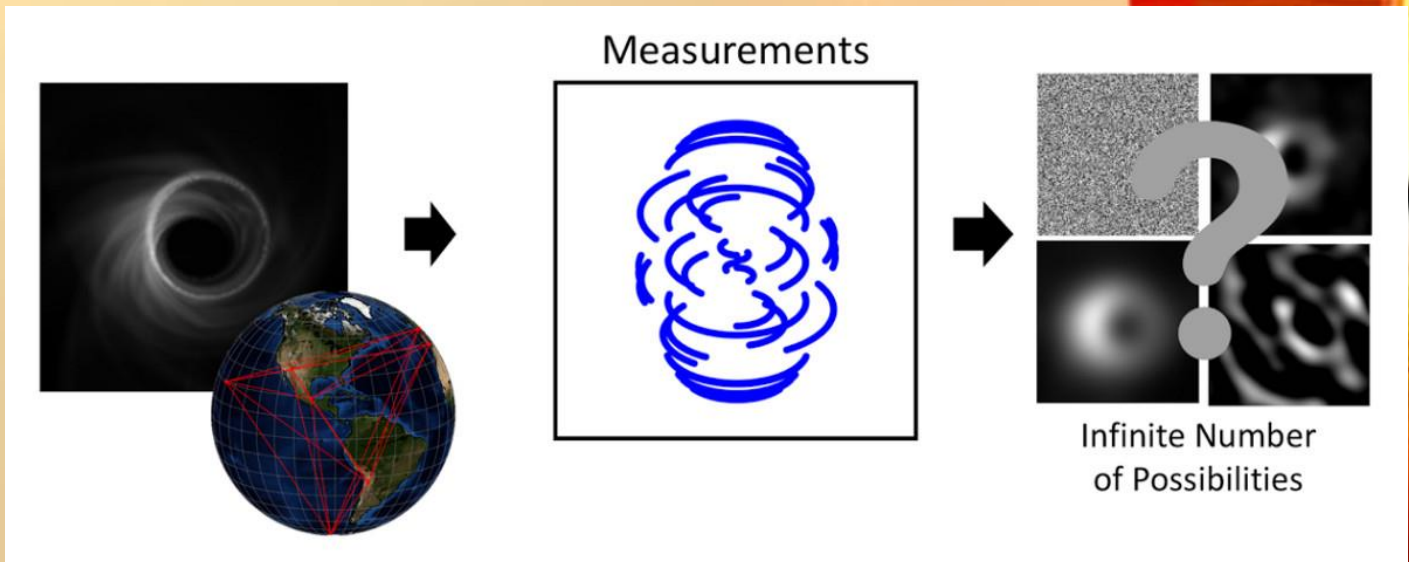
*“Mistični kabare”, Alejandro Hodorovski*



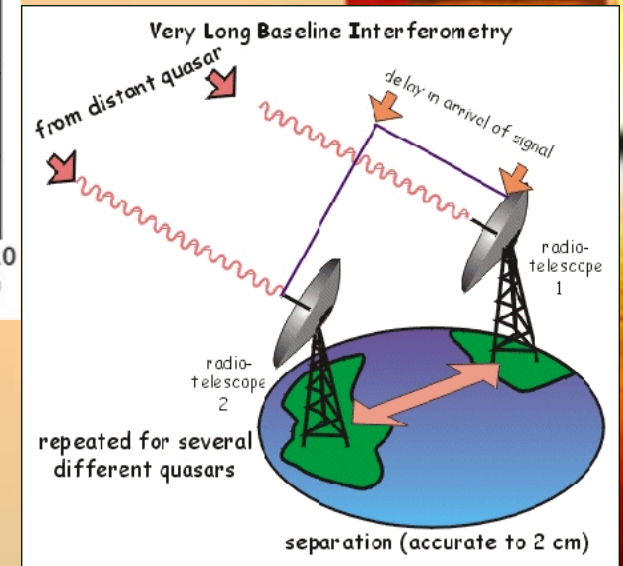
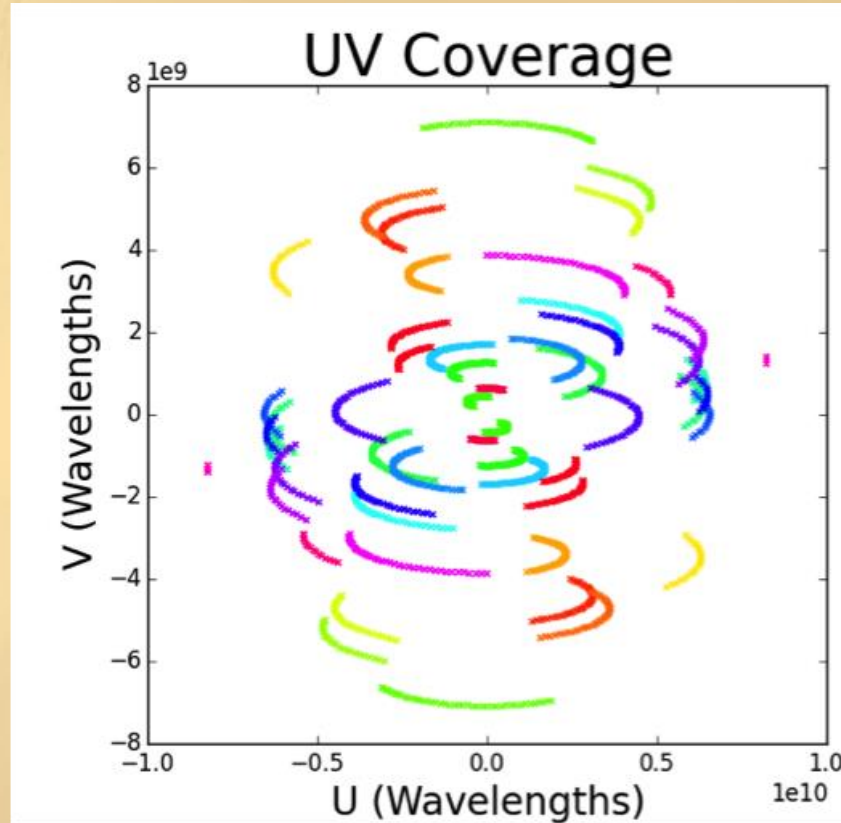
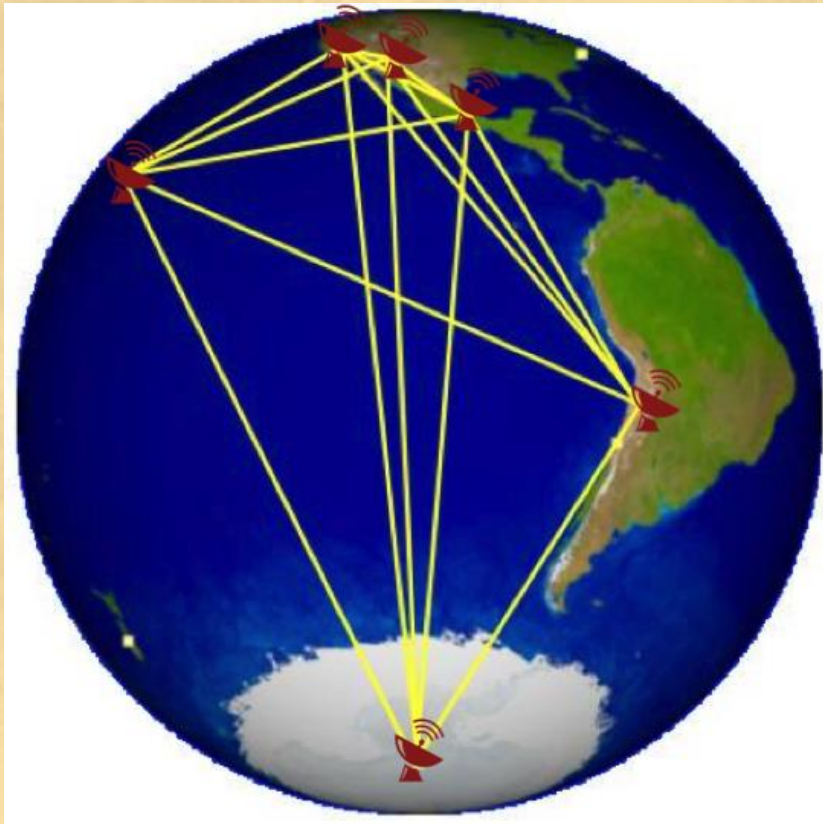


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# Big Data, AI, Mašinsko učenje



Katherine L. Bouman, Michael D. Johnson, Daniel Zoran, Vincent L. Fish, Sheperd S. Doeleman, William T. Freeman, *Computational Imaging for VLBI Image Reconstruction*, IEEE Conference on Computer Vision and Pattern Recognition (CVPR), 2016, pp. 913-922

<https://arxiv.org/abs/1512.01413>

# CHIRP (Continuous High-resolution Image Reconstruction using Patch priors)

Katherine L. Bouman, Michael D. Johnson, Daniel Zoran, Vincent L. Fish, Sheperd S. Doeleman, William T. Freeman, *Computational Imaging for VLBI Image Reconstruction*, IEEE Conference on Computer Vision and Pattern Recognition (CVPR), 2016, pp. 913-922

<https://arxiv.org/abs/1512.01413>

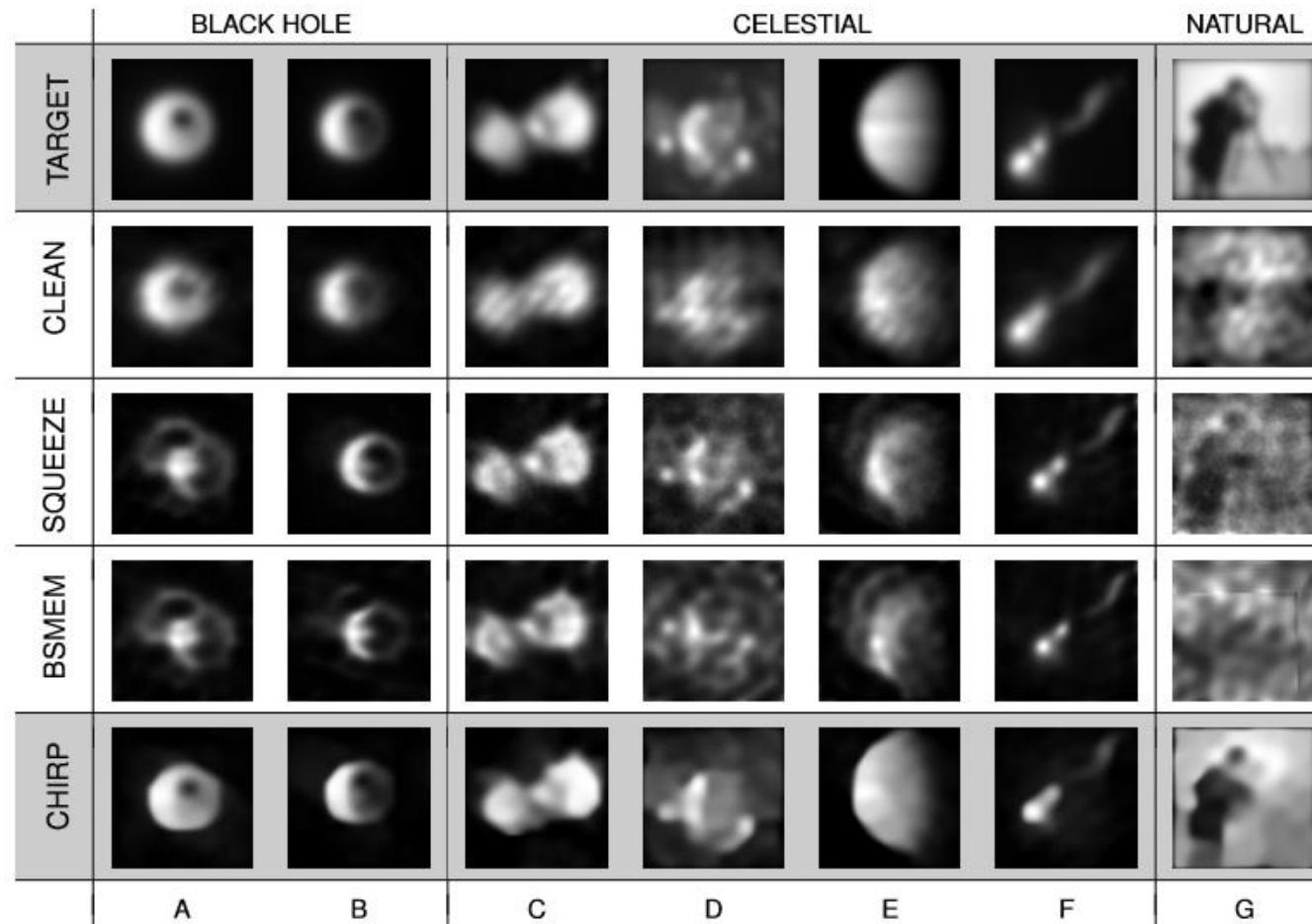
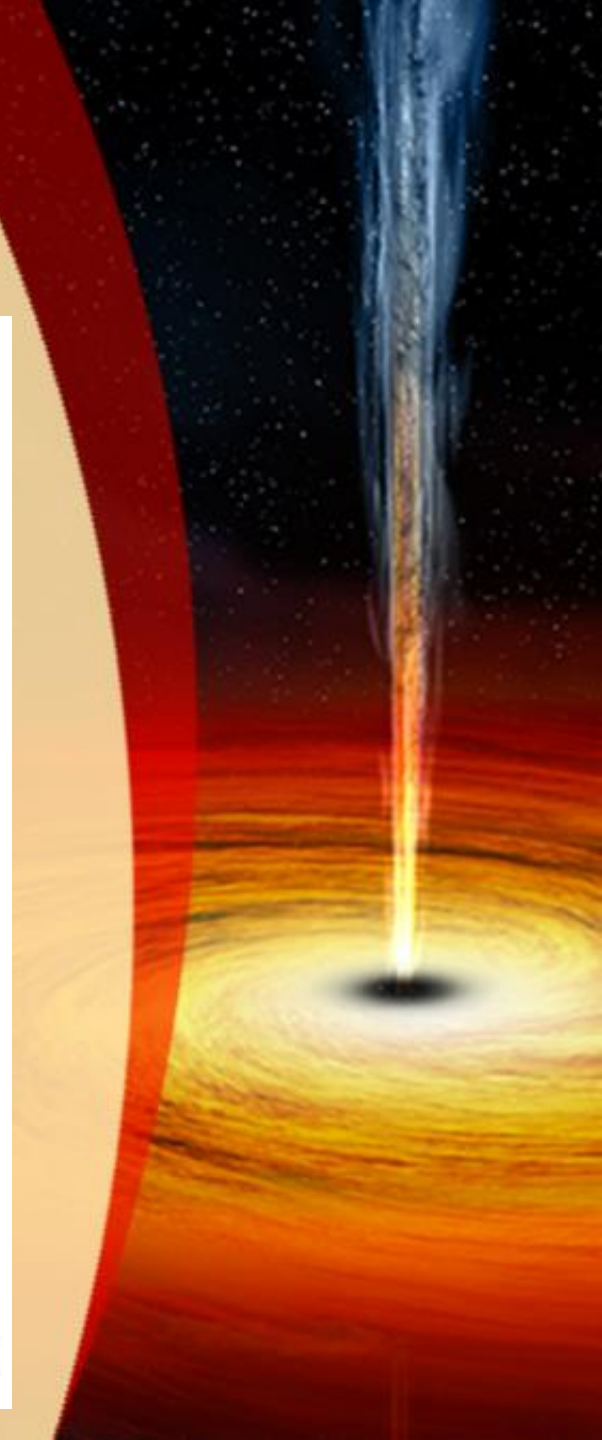
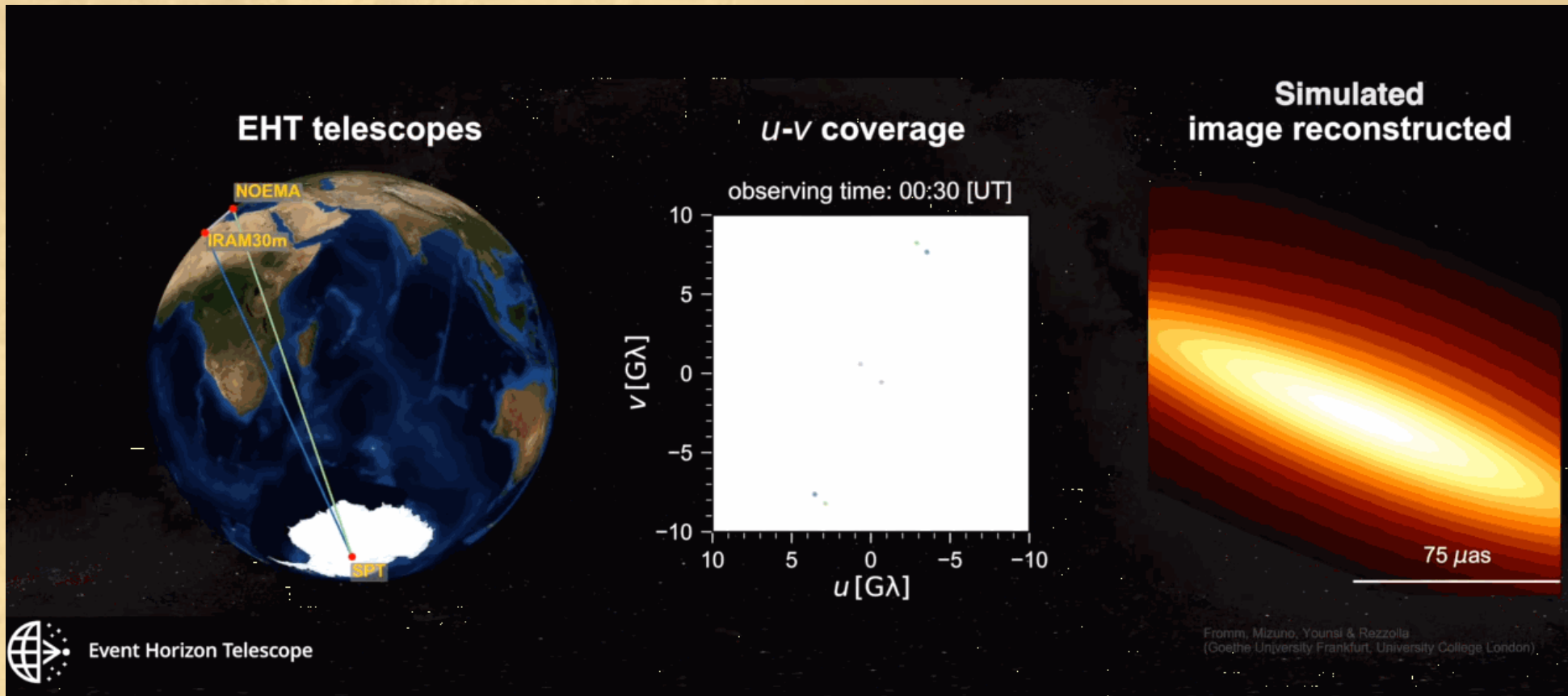


Figure 5. **Method Comparison:** Comparison of our algorithm, 'CHIRP' to three state-of-the-art methods: 'CLEAN', 'SQUEEZE', and 'BSMEM'. We show the normalized reconstruction of a variety of black hole (a-b), celestial (c-f), and natural (g) source images with a total flux density (sum of pixel intensities) of 1 Jansky and a  $183.82 \mu$ -arcsecond FOV. Since absolute position is lost when using the bispectrum, shifts in the reconstructed source location are expected. The 'TARGET' image shows the ground truth emission filtered to the maximum resolution intrinsic to this telescope array.

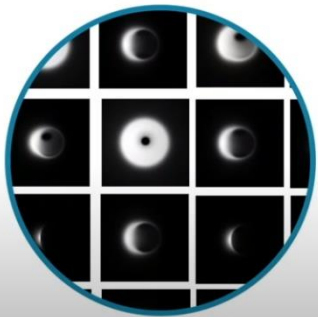


# Snimanje i rekonstrukcija

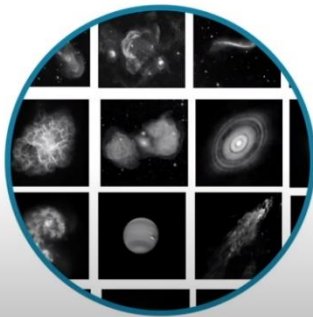


# Snimanje i rekonstrukcija

Different Types of Images → Different Features



Black Hole



Astronomical

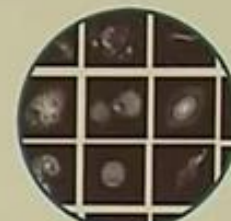


Everyday

Different Types of Images → Different Features



Black Hole

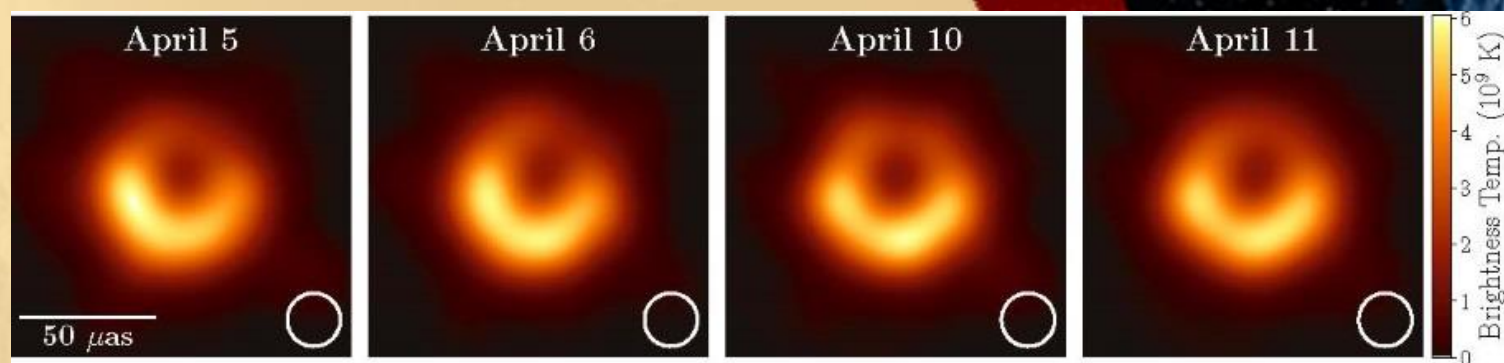


Astronomical

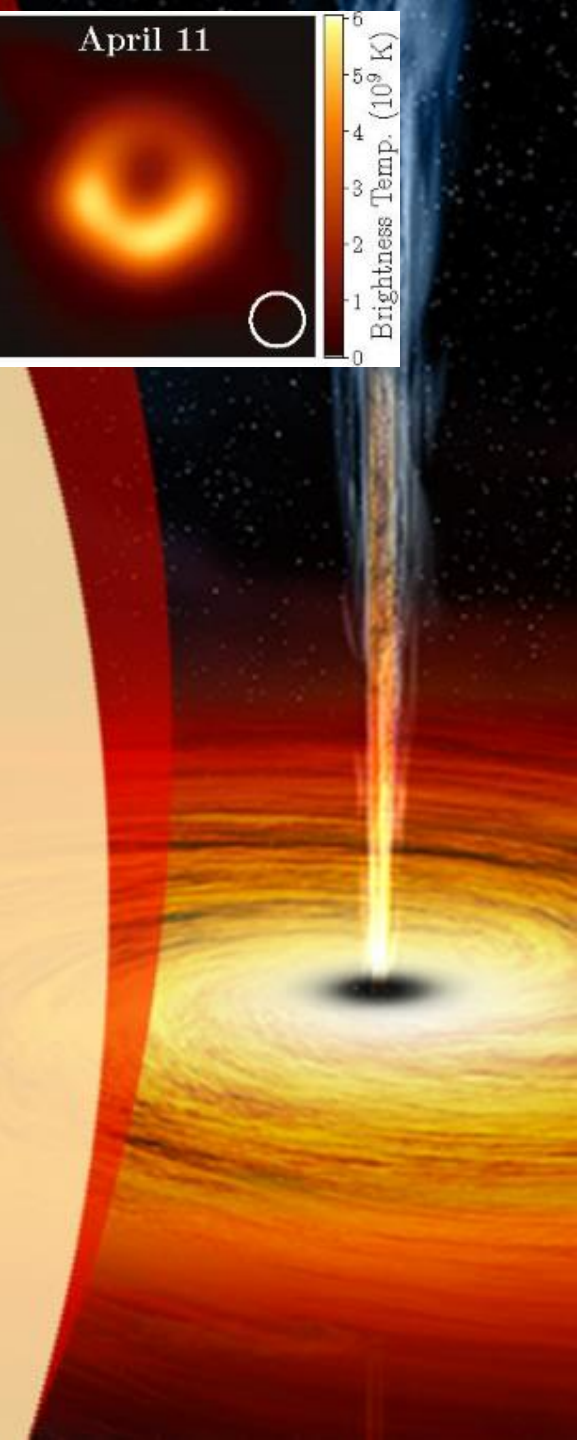


Everyday

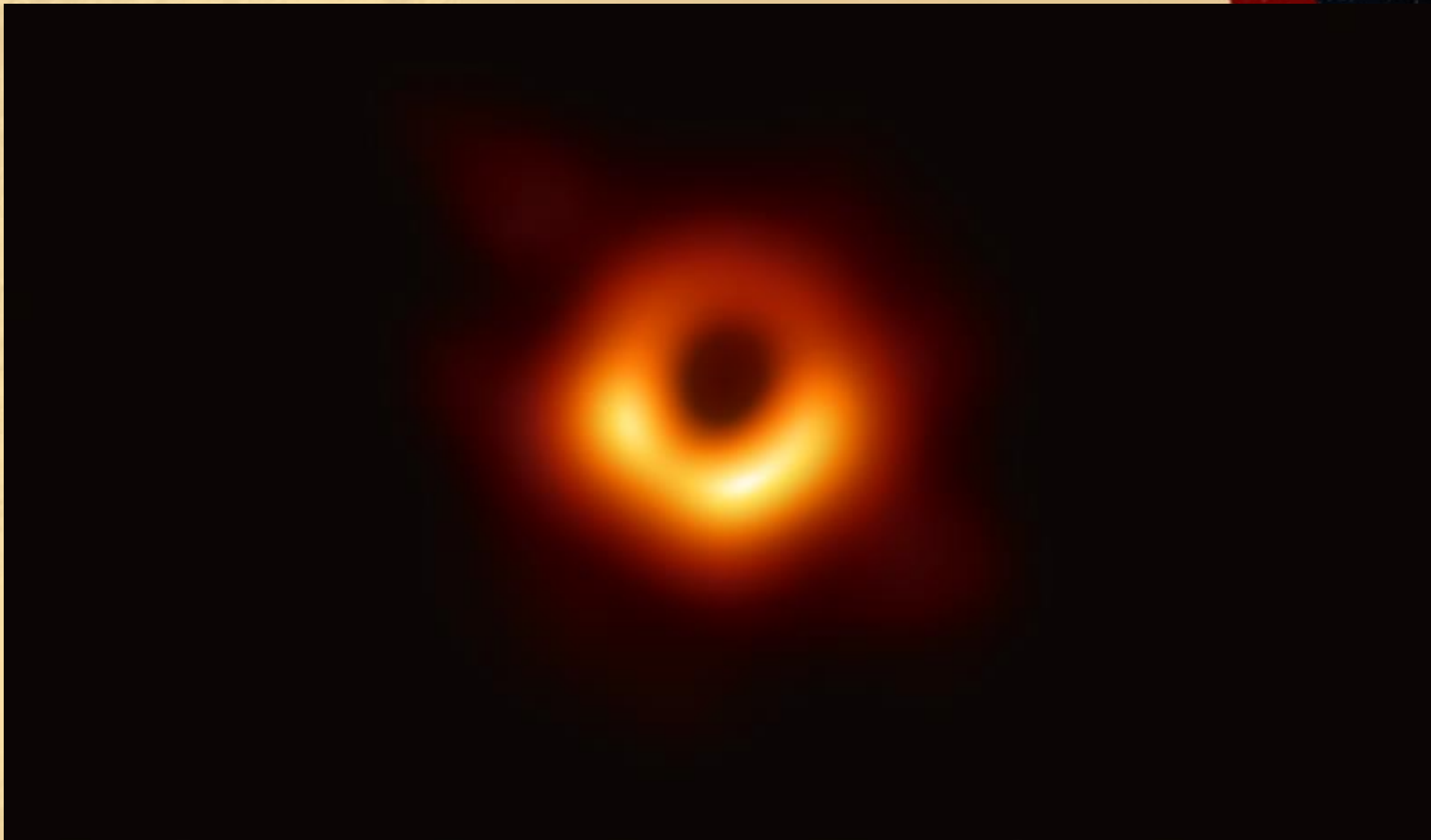
# SMBH



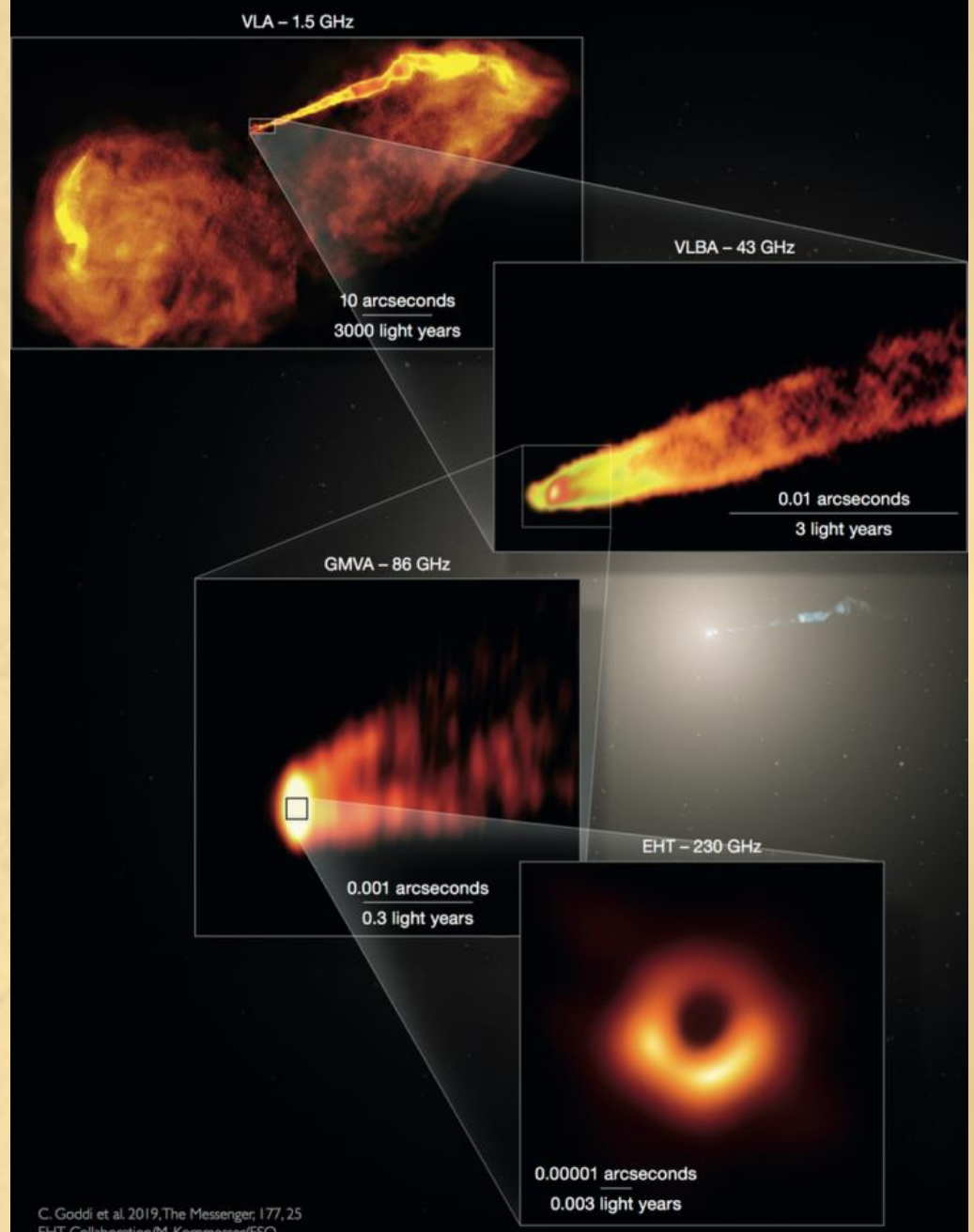
- Serije “fotografija” snimane 5, 6, 10 i 11 aprila 2017. godine, a svaka serija snimana je između 3 i 7 minuta.
- Jasno uočljiv sjajan prsten sa tamnom centralnom oblašću.
- Prečnik prstena iznosi 42, a debljina manje od 20 mikro-lučnih sekundi.
- Upoređivanjem dobijenih fotografija sa simulacijama dobijenim na osnovu magnetohidrodinamičke teorije relativnosti (GRMHD) - tzv. Kerova crnoj rupi, tj. nenaelektrisanjoj crnoj rupi koja rotira oko centralne ose.
- Procenjeno da horizont događaja ima dimenzije od 3,8 mikro-lučnih sekundi i da crna rupa rotira u smeru kazaljke na satu.



# SMBH u M87

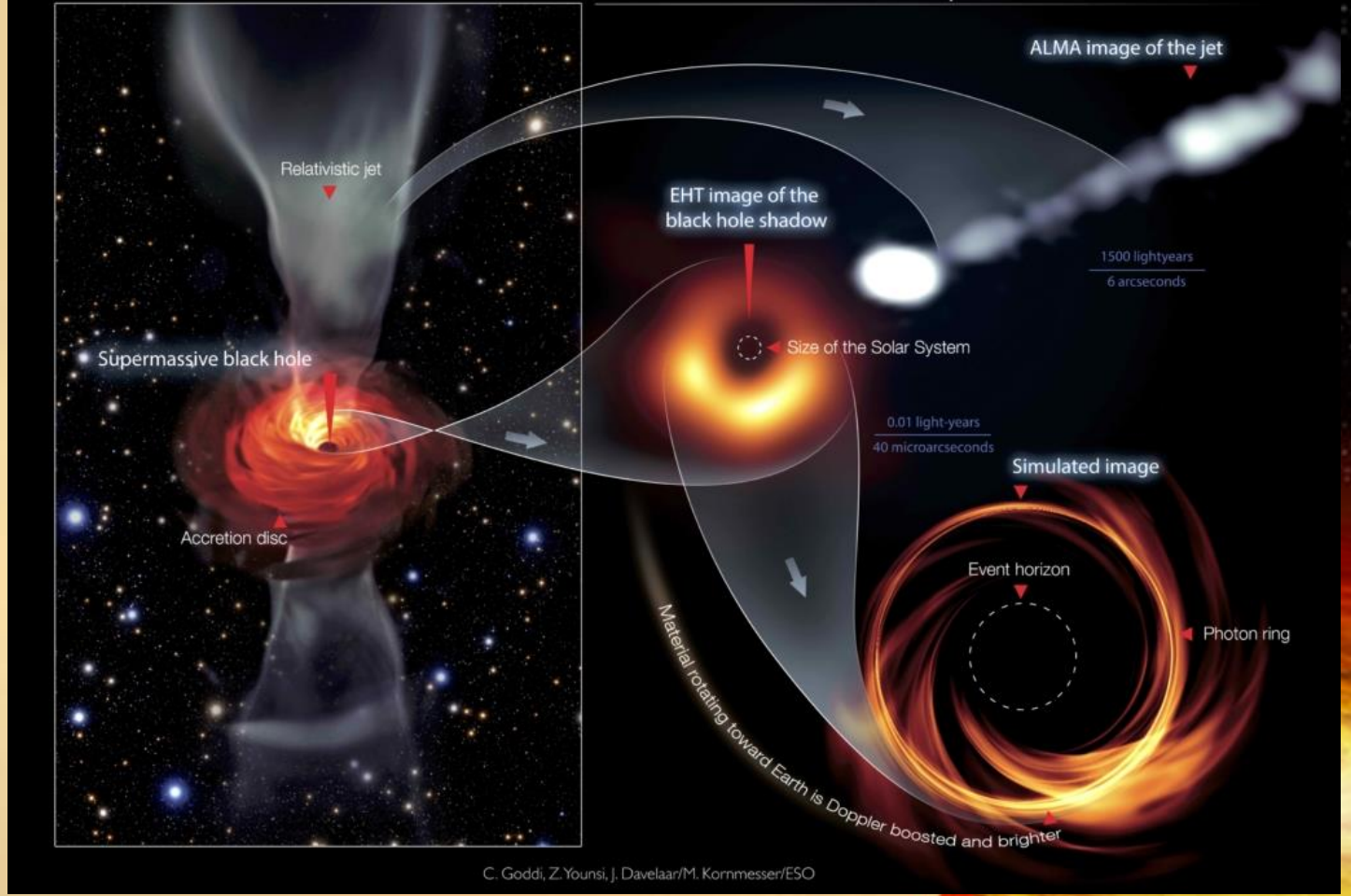


# The M87 Jet



C. Goddi et al. 2019, The Messenger, 177, 25  
EHT Collaboration/M. Kommesser/ESO

# M87 Black Hole – Event Horizon Telescope

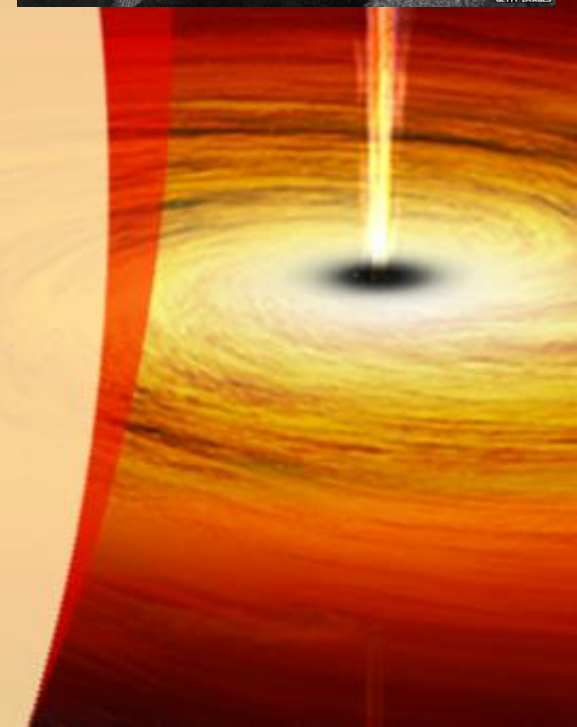
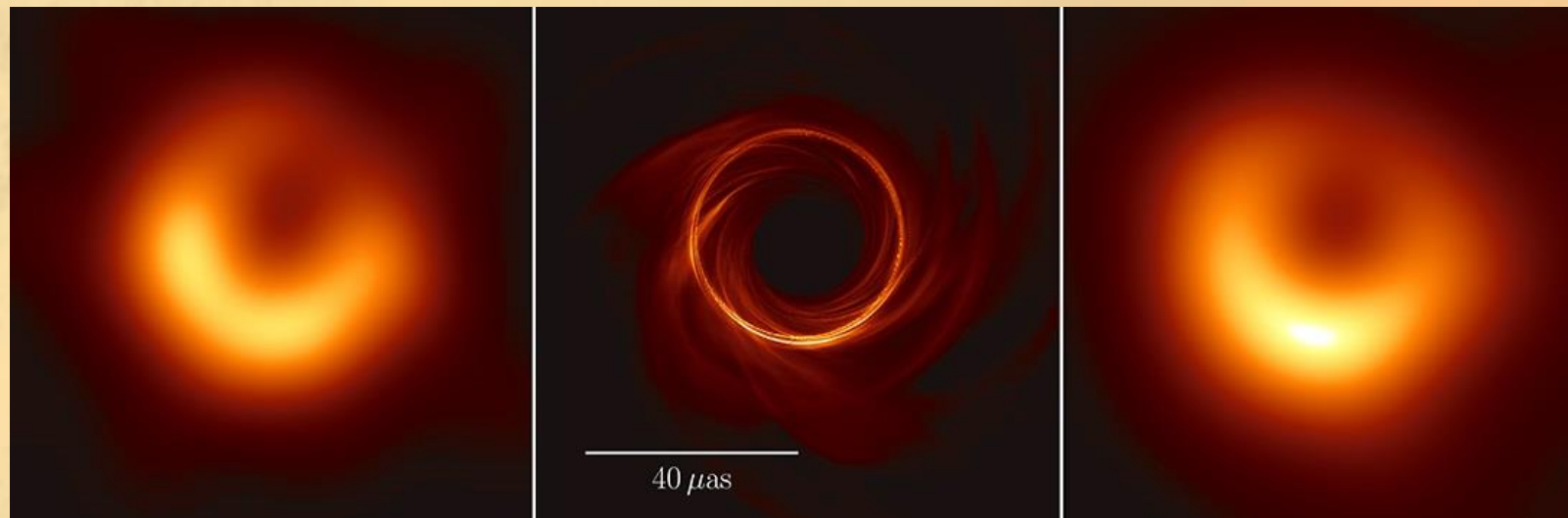
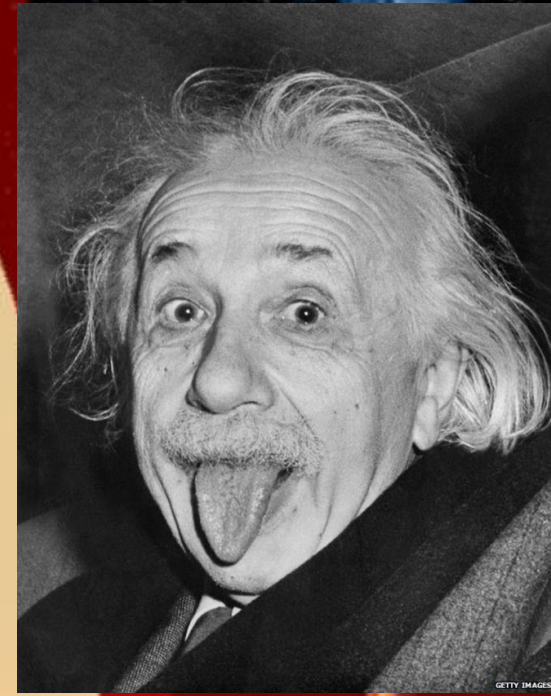


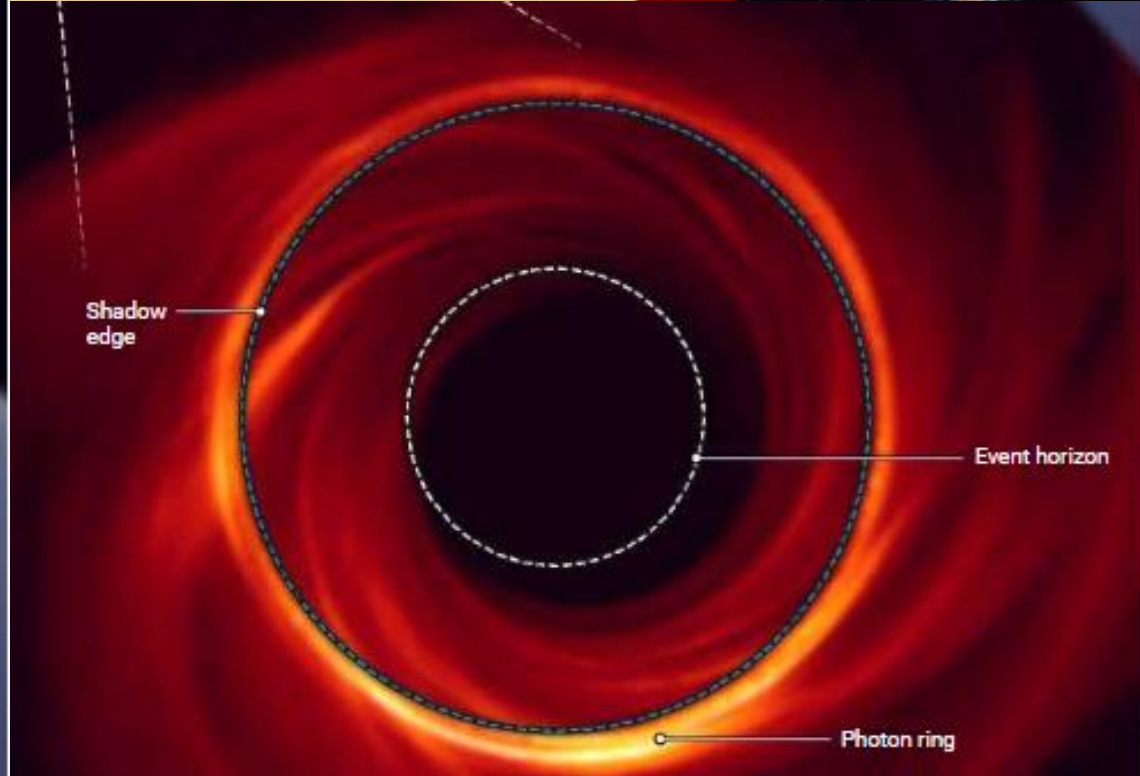
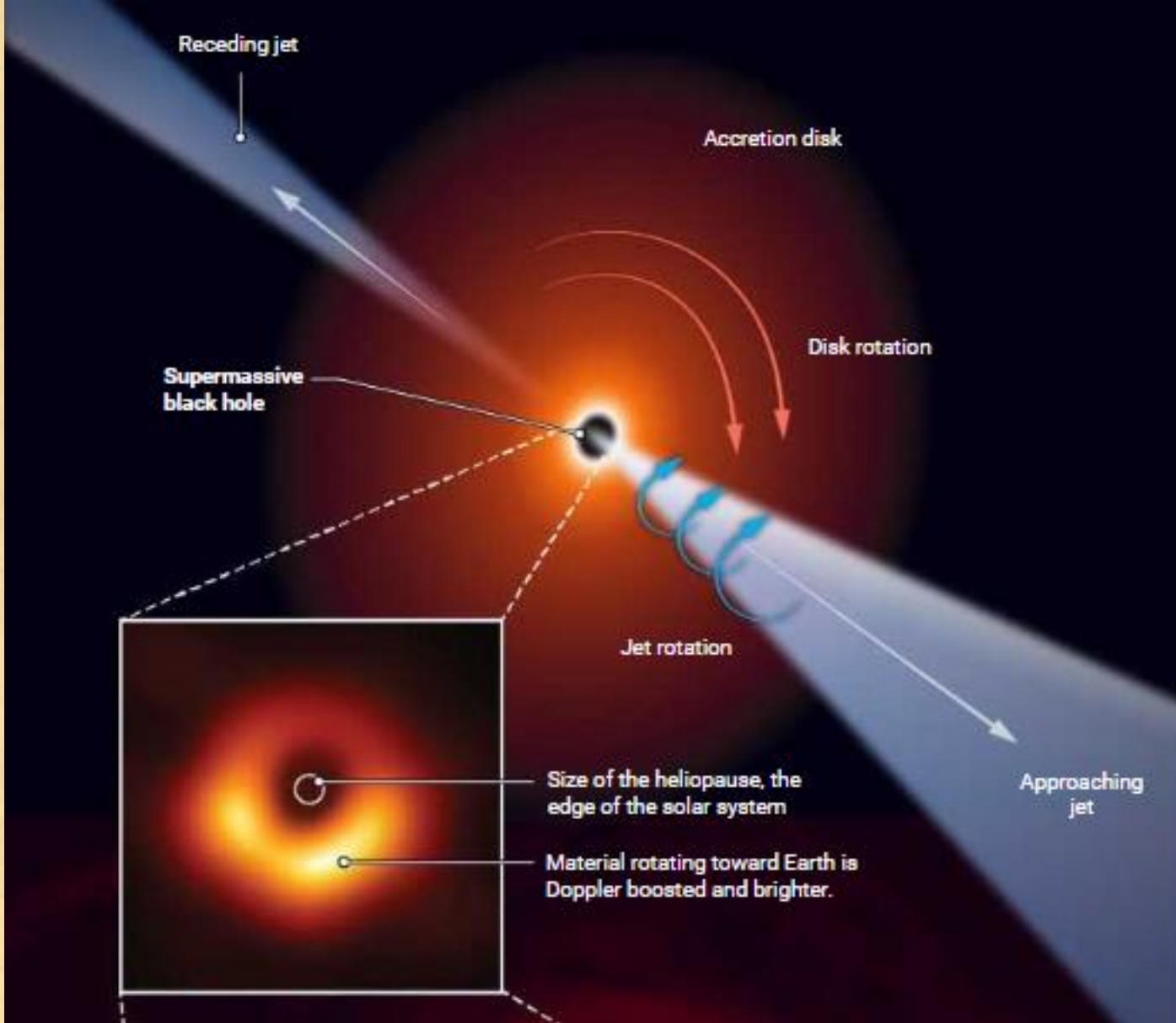
Rad: [C. Goddi et al. 2019, The Messenger, 177, 25](https://blackholecam.org/eh-t-m87-eso-messenger177/)  
Izvor: <https://blackholecam.org/eh-t-m87-eso-messenger177/>



# SMBH u M87

- Procena mase ove crne rupe, na osnovu ranijih posmatranja, kretala se u intervalu od 3,5 do 7,22 milijarde masa Sunca
- Na osnovu posmatranja EHT procenjeno da masa prve snimljene crne rupe iznosi **6,5 milijardi** masa Sunca.



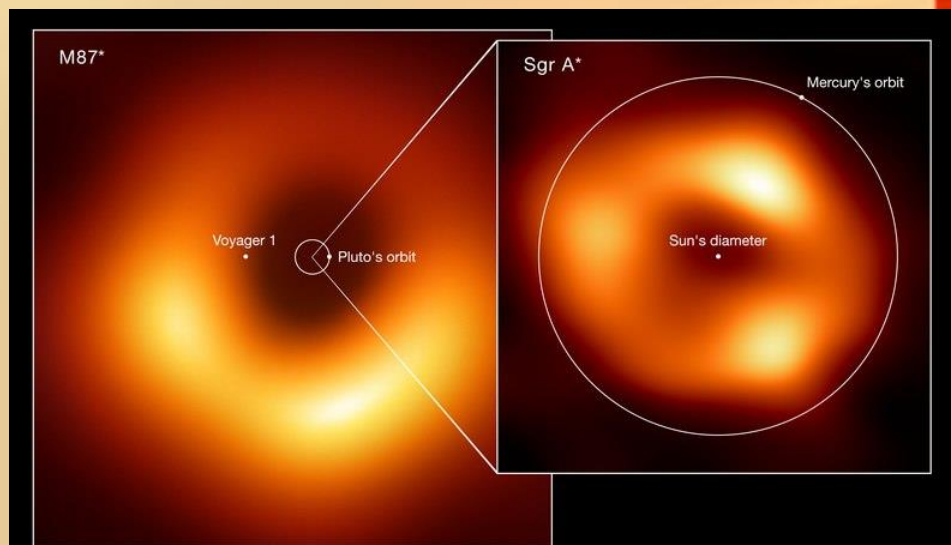


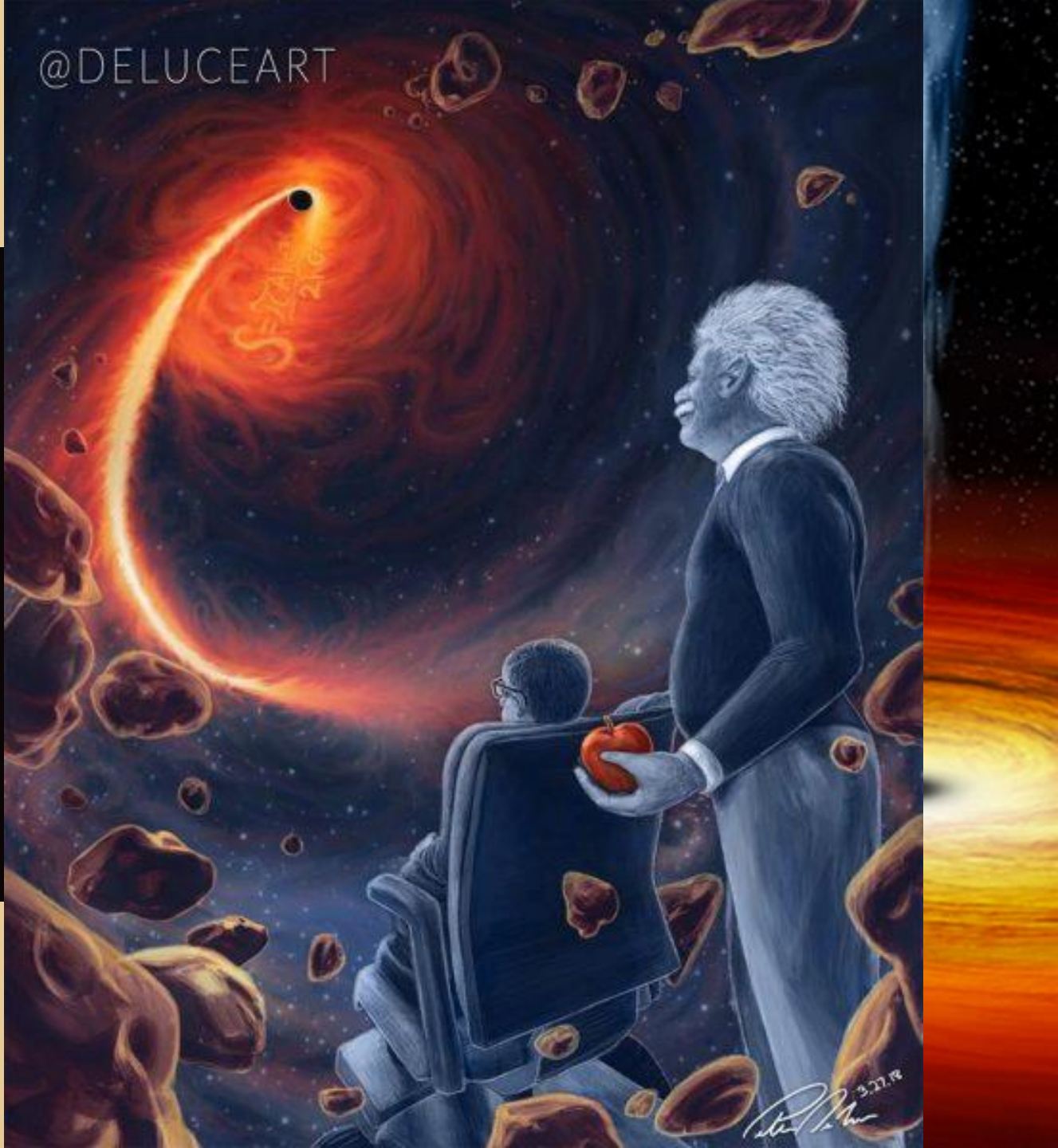
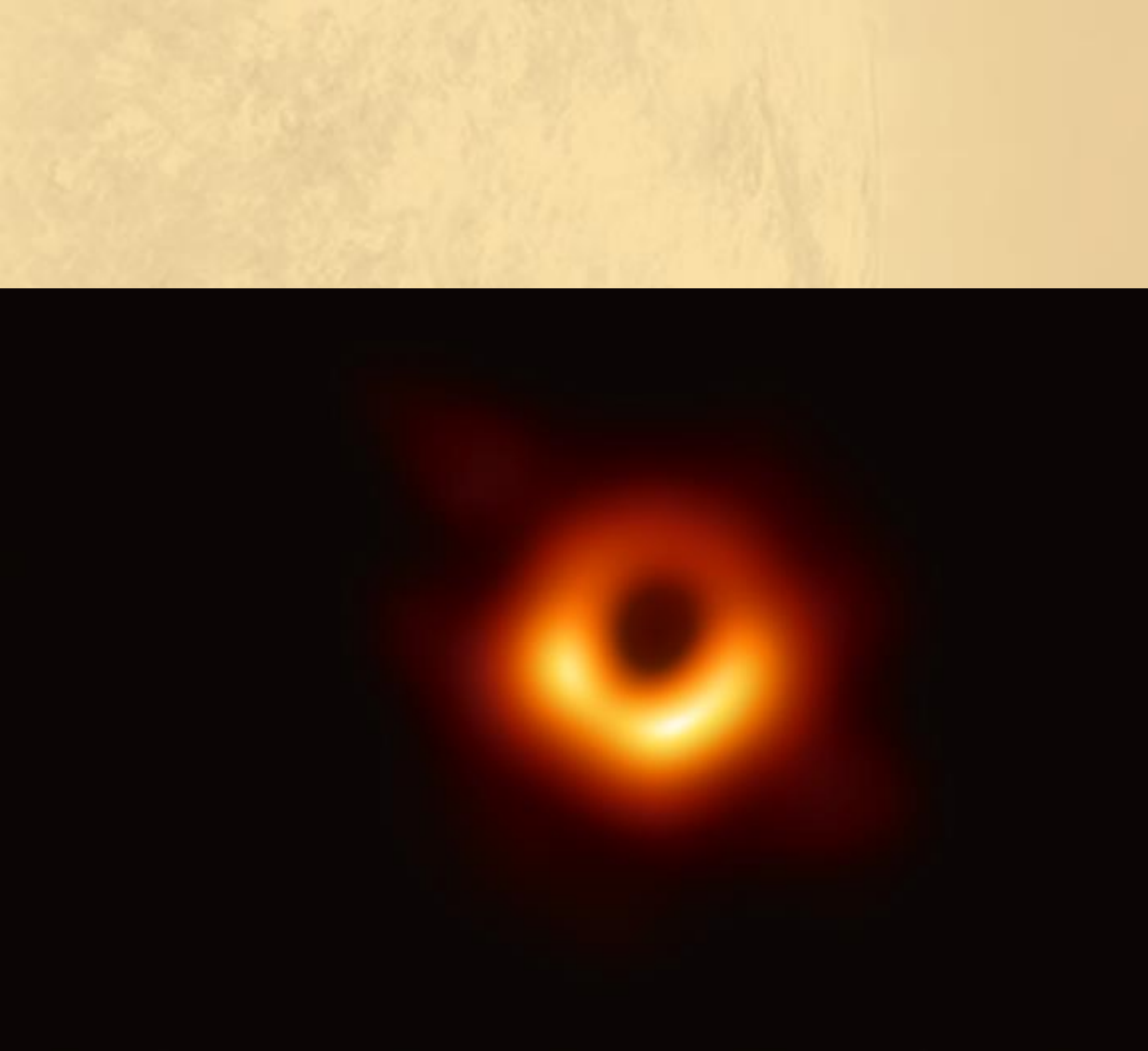
### Connecting the dots

Simulations (bottom) helped connect the EHT's fuzzy image (middle) to a physical model of M87's black hole (top), and suggest that the accretion disk spins clockwise.

# SMBH u Mlečnom putu

- Sagittarius A\*
- 12. maj 2022. godine
- 27.000 svetlosnih godina od nas
- Slične crne rupe
- Masa oko 4 miliona masa Sunca

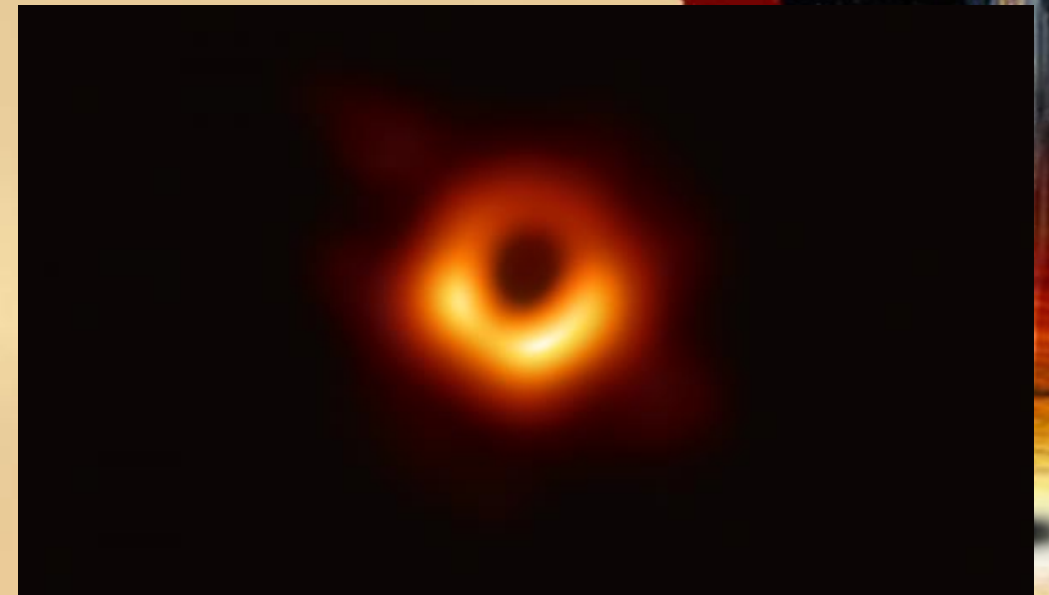
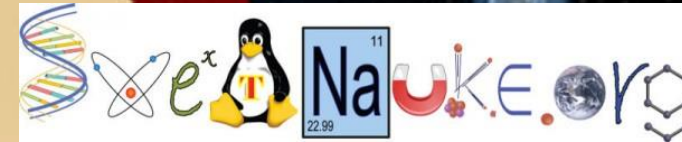




# Pitanja...



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Deo aktivnosti AD Alfa u 2022/23. godini realizuju se u okviru projekta „Kako dohvatiti zvezde“, uz podršku Centra za promociju nauke



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