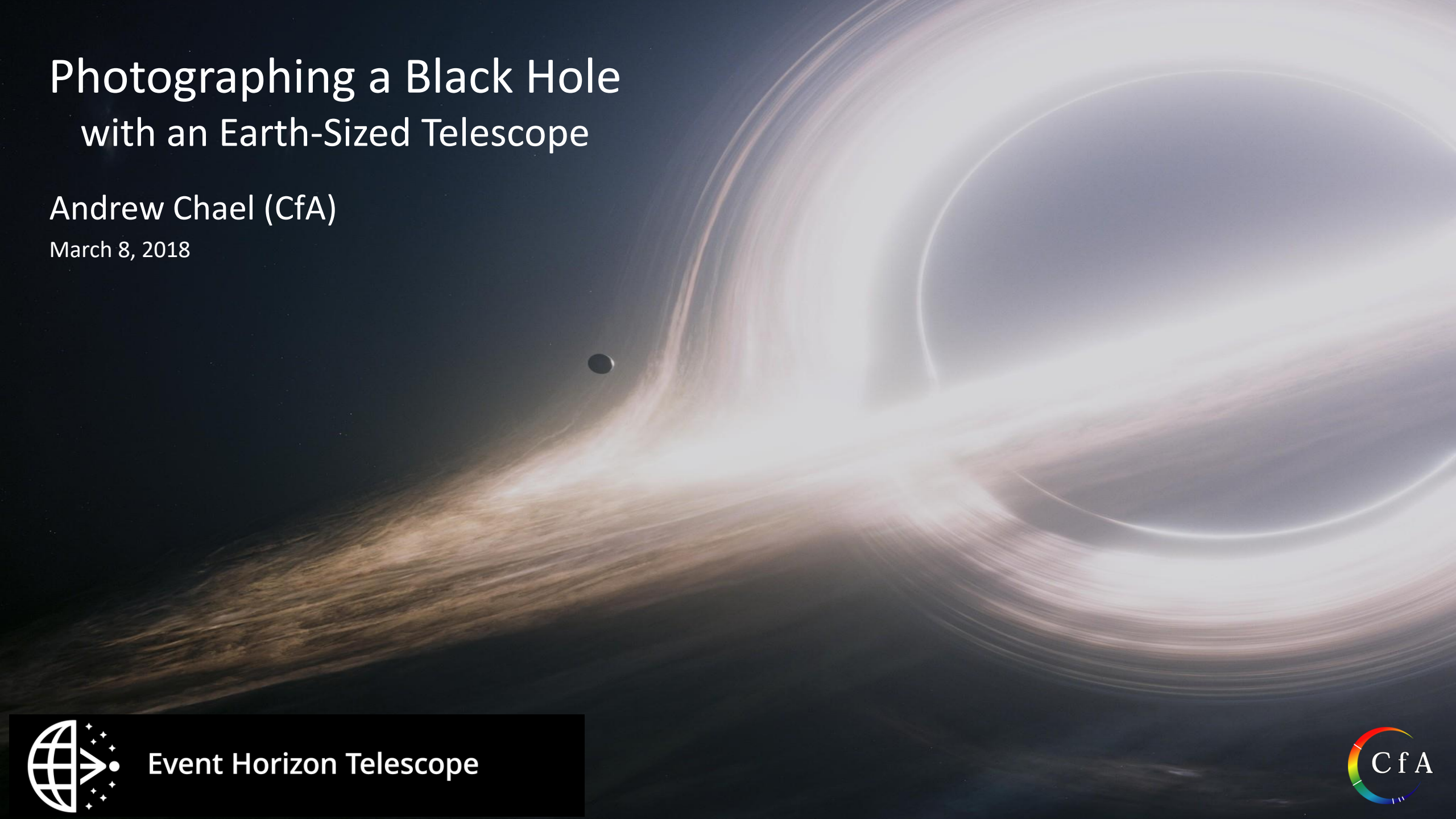
Photographing a Black Hole
with an Earth-Sized Telescope

Andrew Chael (CfA)

March 8, 2018



Event Horizon Telescope

CfA

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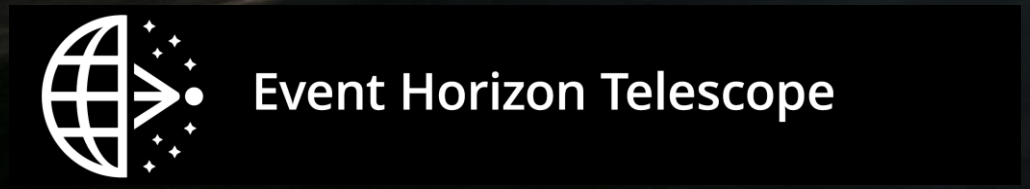
with an Earth-Sized Telescope

Andrew Chael (CfA)

March 8, 2018

work with: Katie Bouman, Michael Johnson, Lindy Blackburn, Sheperd Doeleman, Freek Roelofs, Vincent Fish, Kazu Akiyama
and
The Event Horizon Telescope Collaboration



Black Holes

Dark Stars

An object's escape velocity is

independent of its mass:

$$V_{\text{escape}} = \sqrt{\frac{2GM}{r}}$$

Once V_{escape} exceeds the speed of light (c), even photons will be trapped and the star will become dark!

Need to compress a mass M within the radius

$$\boxed{r = \frac{2GM}{c^2}}$$


PHILOSOPHICAL
TRANSACTIONS:

On the Means of Discovering the Distance, Magnitude, &c. of the Fixed Stars, in Consequence of the Diminution of the Velocity of Their Light, in Case Such a Diminution Should be Found to Take Place in any of Them, and Such Other Data Should be Procured from Observations, as Would be Farther Necessary for That Purpose. By the Rev. John Michell, B. D. F. R. S. In a Letter to Henry Cavendish, Esq. F. R. S. and A. S.

John Michell

Phil. Trans. R. Soc. Lond. 1784 **74**, 35-57, published 1 January 1784

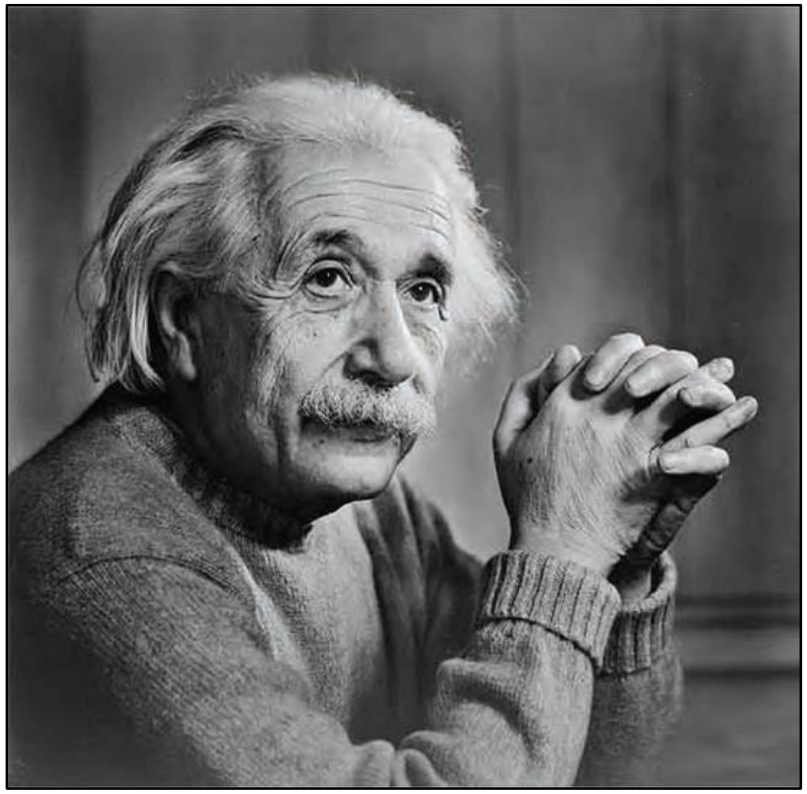
John Michell

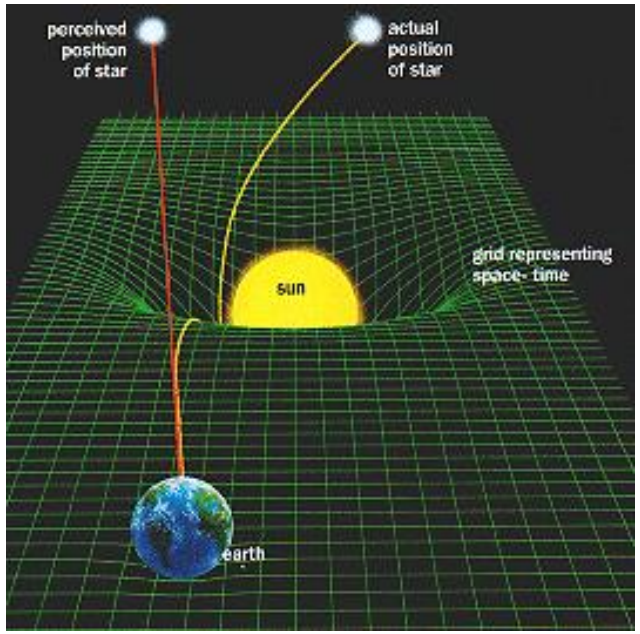
Philosophical Transactions of the Royal Society of London (1784)

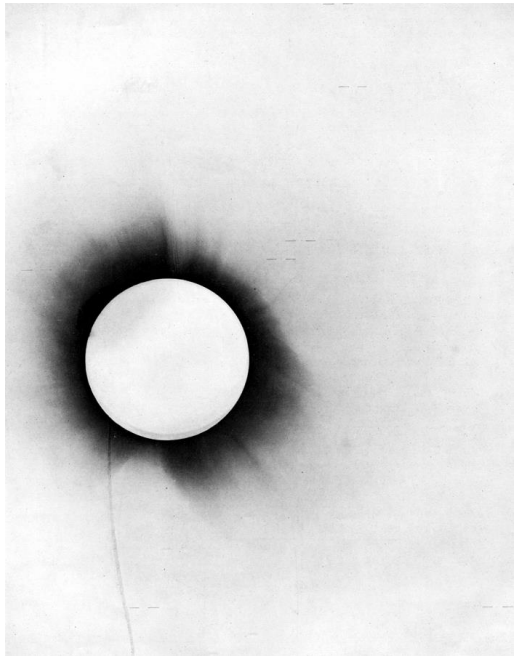
Black Holes

1915

$$G_{\alpha\beta} = \frac{8\pi G}{c^4} T_{\alpha\beta}$$



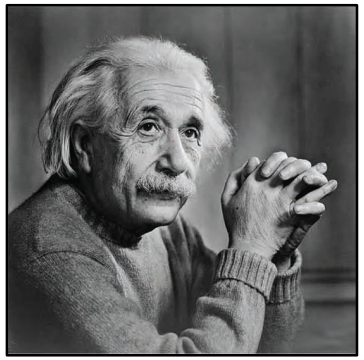




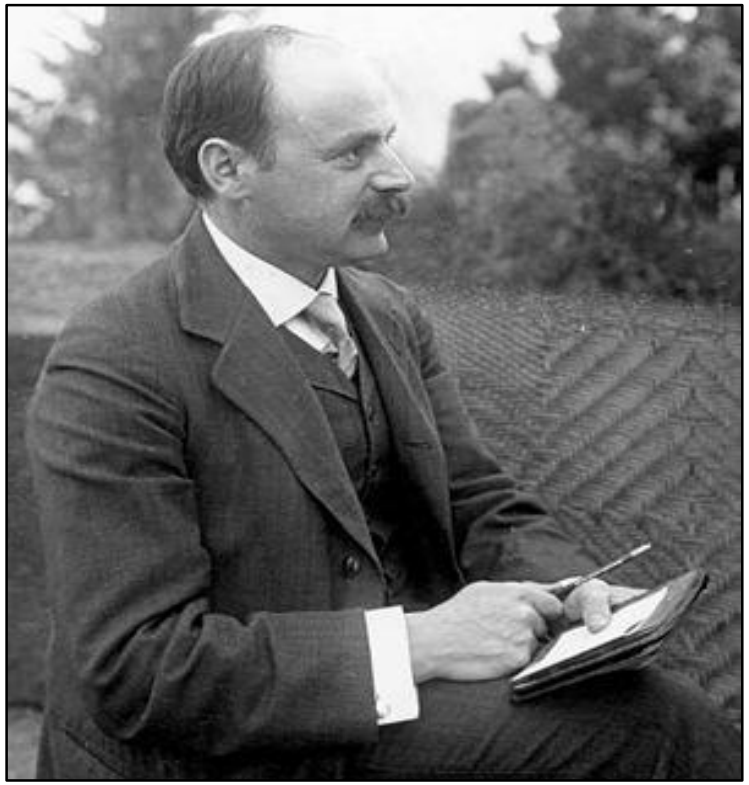
Albert Einstein publishes his general theory of relativity.
Predicts that light is affected by gravity

Black Holes

1915



1916



Karl Schwarzschild discovers the first non-trivial exact solution in GR

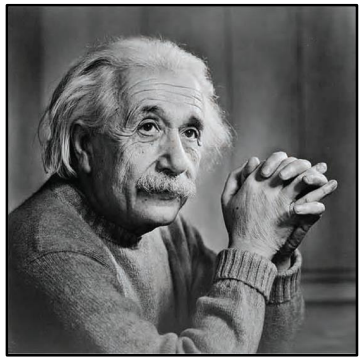
His solution depends on a particular radius, the “Schwarzschild radius”. Inside this radius, all matter must move toward the central singularity.

$$\boxed{r = \frac{2GM}{c^2}}$$

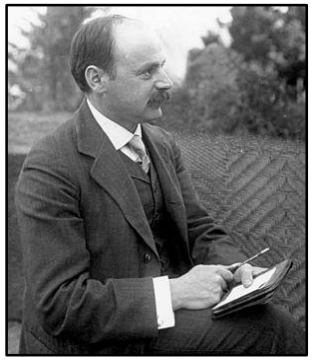
$$c^2\,d\tau^2 = \left(1 - \frac{r_\mathrm{s}}{r}\right) c^2\,dt^2 - \left(1 - \frac{r_\mathrm{s}}{r}\right)^{-1} dr^2 - r^2\left(d\theta^2 + \sin^2\theta\,d\varphi^2\right)$$

Black Holes

1915



1916

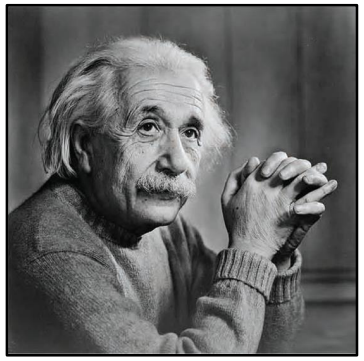


1916

David Hilbert publishes “The Foundations of Physics”
Gives the first calculation of how a black hole might appear to a distant observer
Predicts that it will cast a shadow with diameter 5.2 times the Schwarzschild radius

Black Holes

1915



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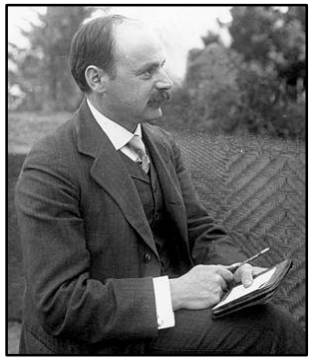
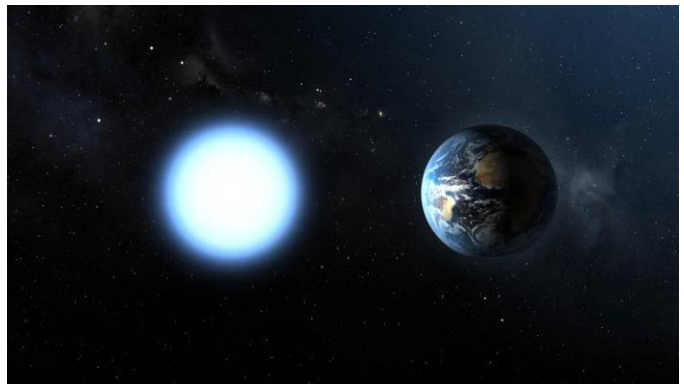


1916

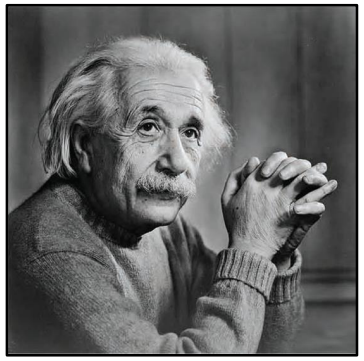
1931

Chandrasekhar discovers that white dwarfs have a maximum mass: $1.44 \times M_{\odot}$.

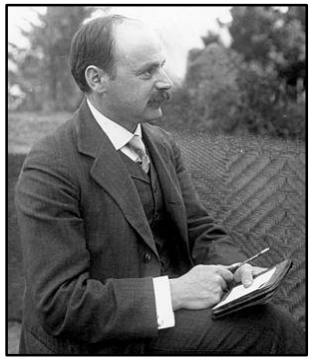


Black Holes

1915



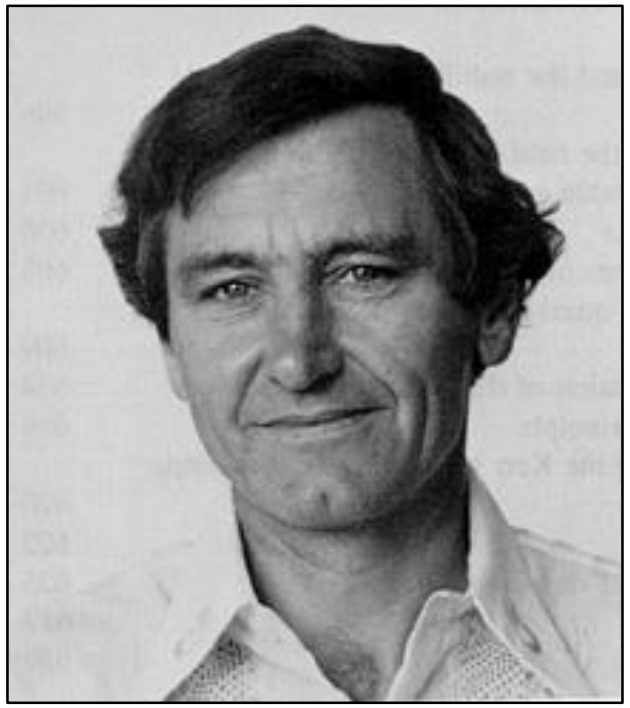
1916



1916

1931

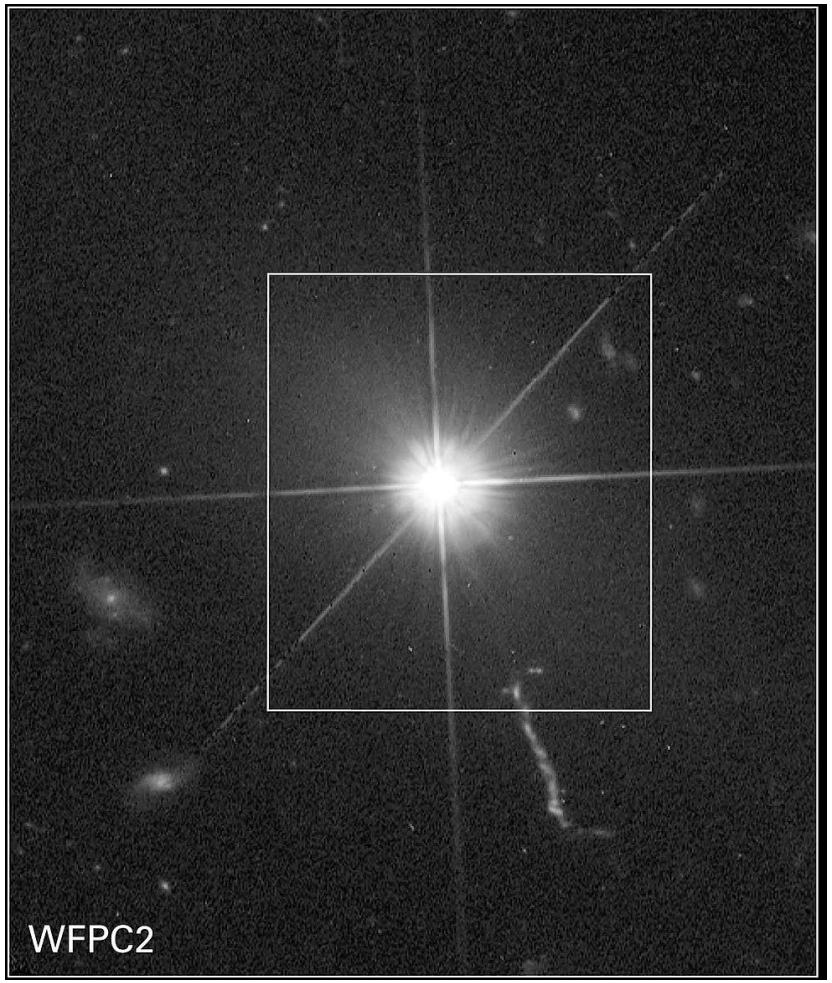
1963



Roy Kerr discovers the solution for a rotating black hole

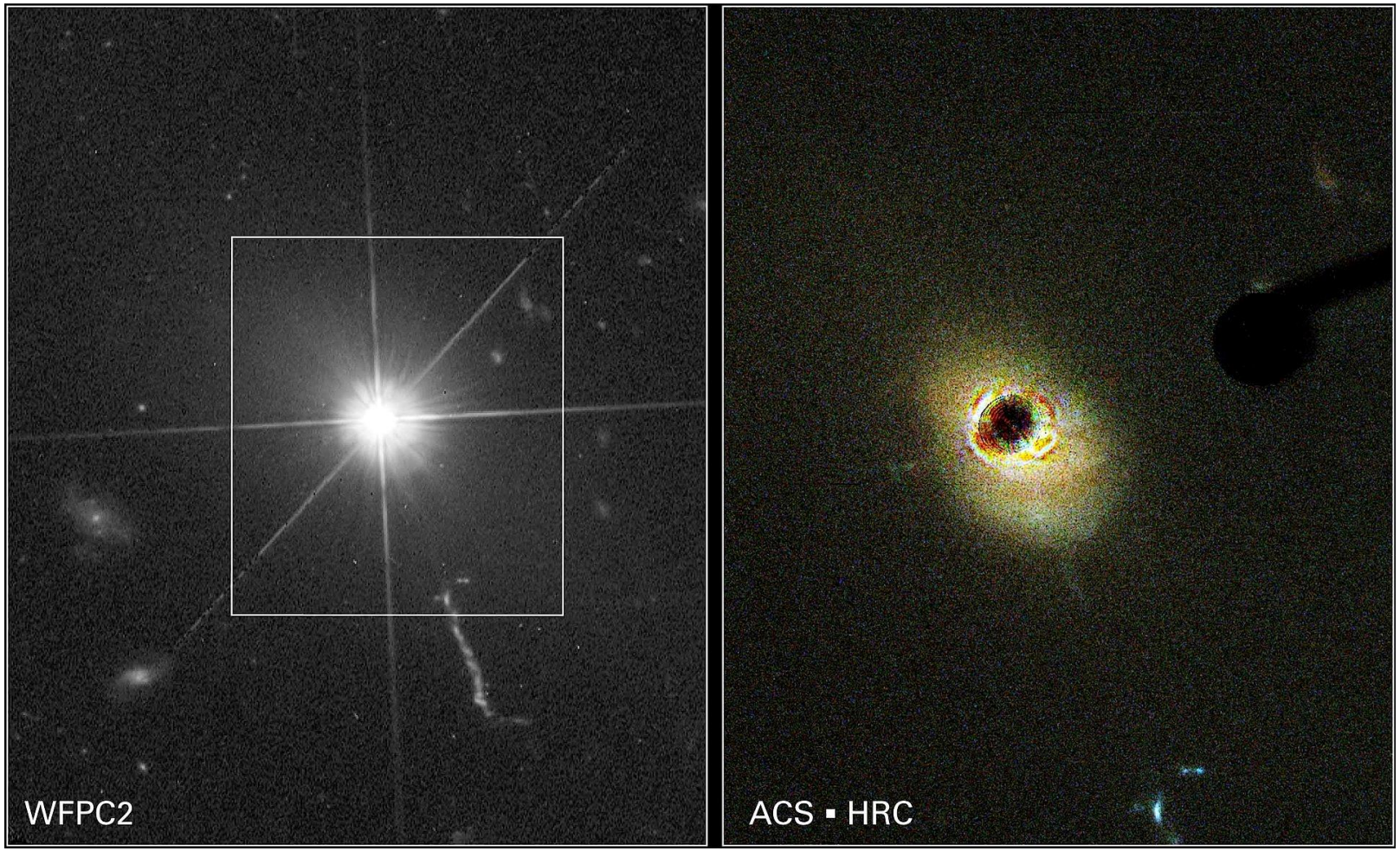
Provides an exact description of all astrophysical black holes (“no hair”)

Quasars – 1960s



NASA/ESA

Quasars – 1960s



NASA/ESA

Accretion Energy

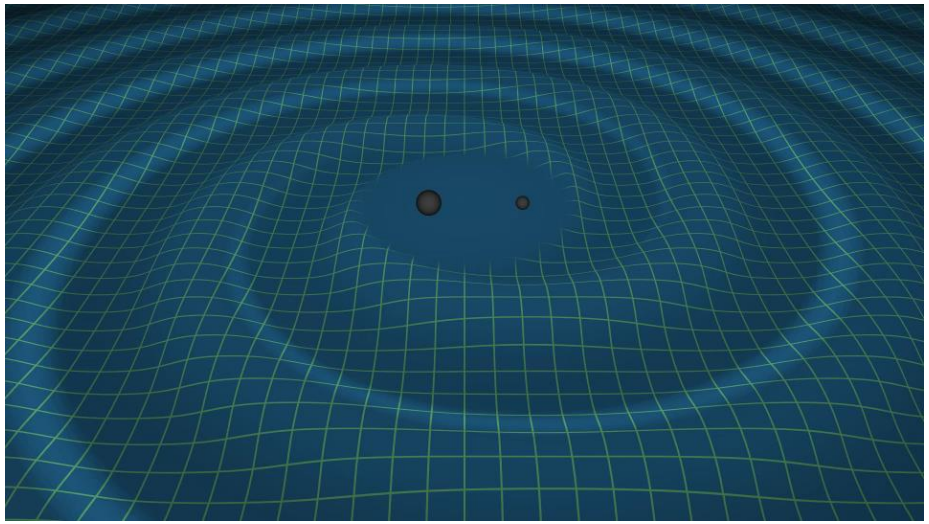
Accretion Power per unit mass:

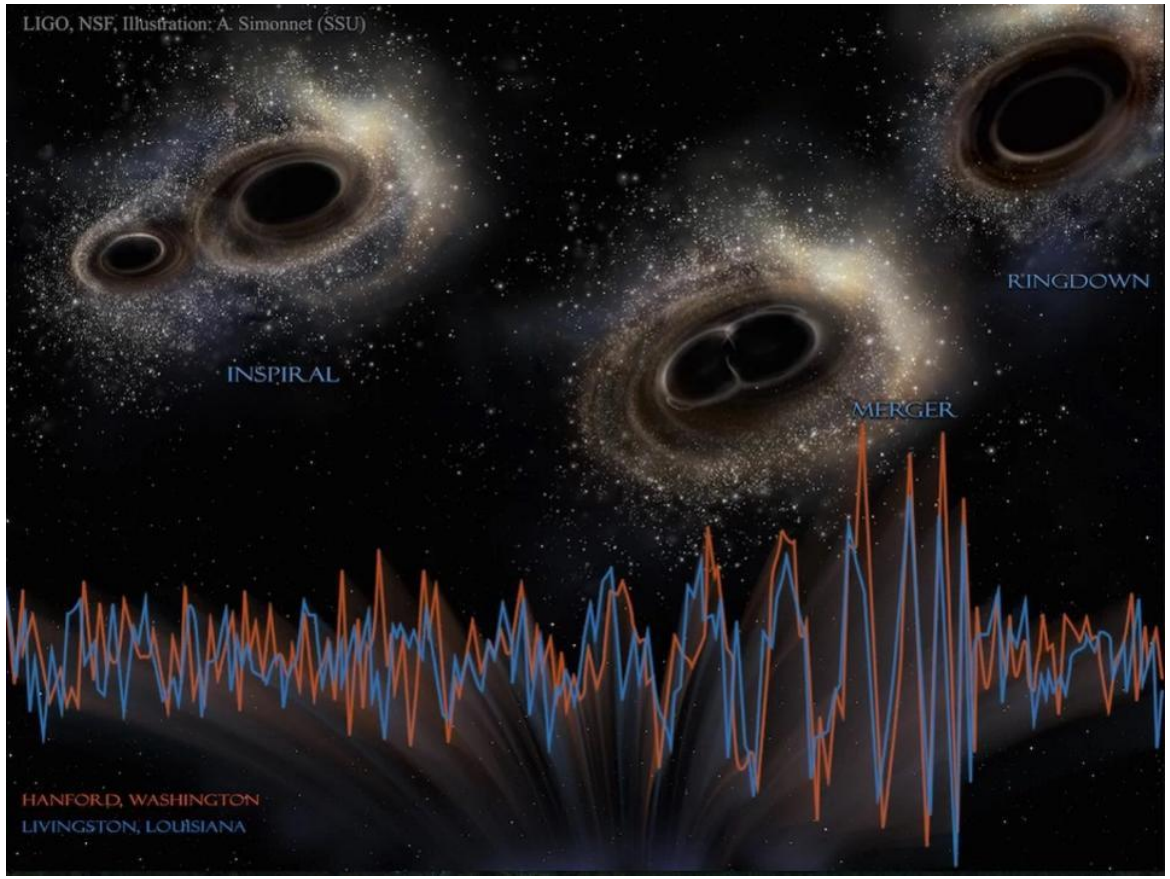
$$\Delta E/mc^2 = GM/Rc^2$$
$$= 1/2 \ \text{ at } \ R = R_{\text{Sch}}$$

For Nuclear Fusion:

$$\Delta E/mc^2 = 0.007$$

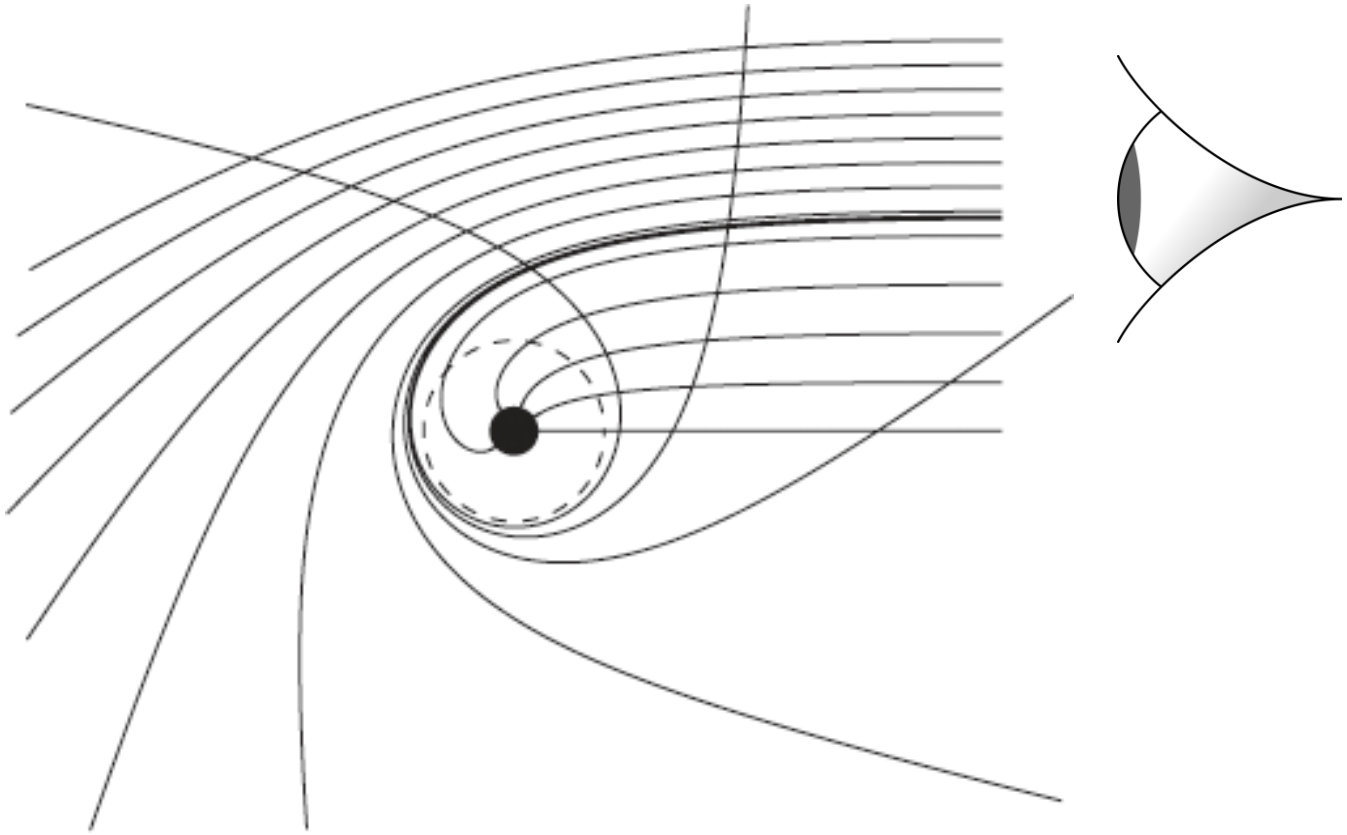
Gravitational Waves – 2015





LIGO/NSF

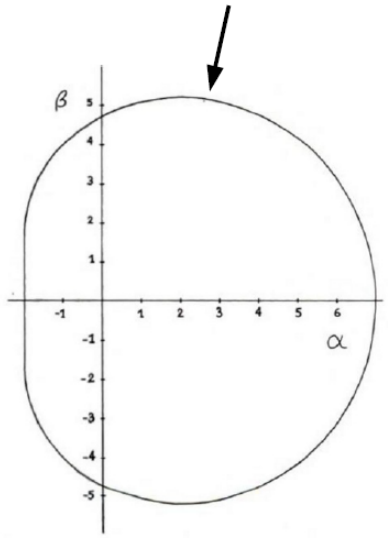
What would a black hole look like?



Thomas Muller

What would a black hole look like?

The black hole “shadow”
Changes by only ±4% with BH spin



Bardeen 1973

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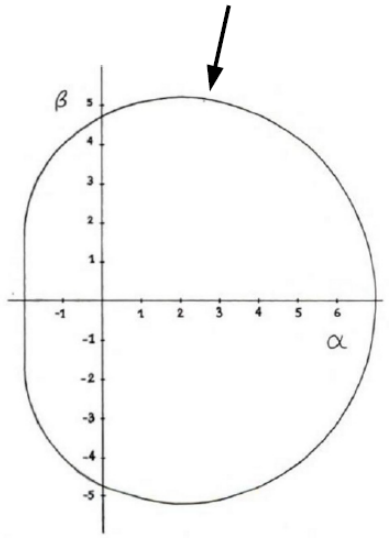
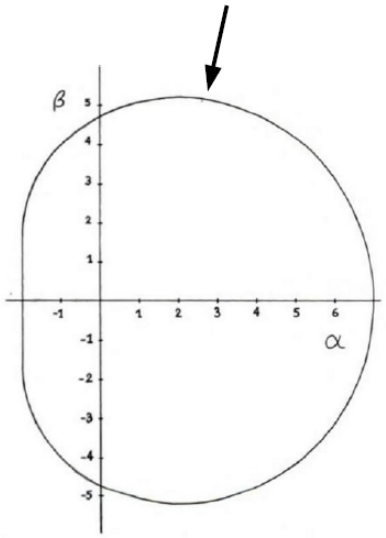


Bardeen 1973

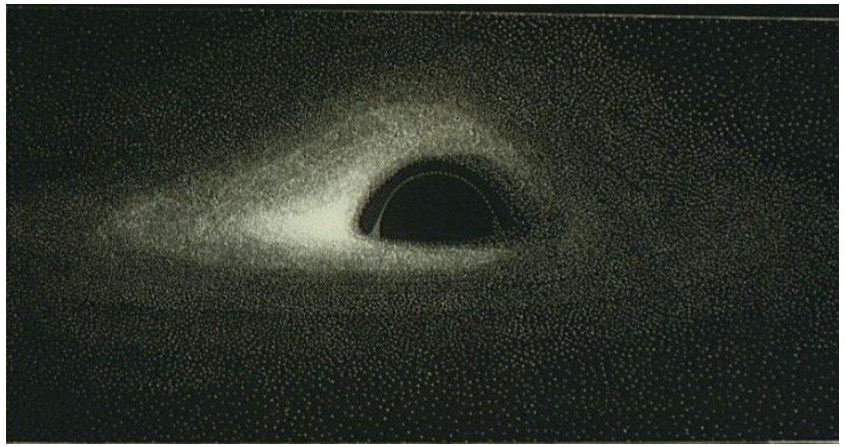
“It is conceptually interesting, if not astrophysically very important, to calculate the precise apparent shape of the black hole... Unfortunately, there seems to be no hope of observing this effect.” (Bardeen 1973,1974)

What would a black hole look like?

The black hole “shadow”
Changes by only ±4% with BH spin



Bardeen 1973



Luminet 1979

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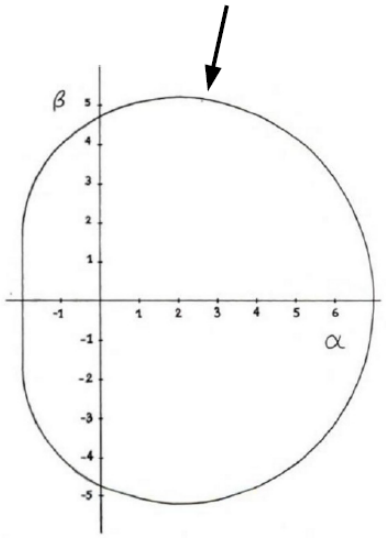
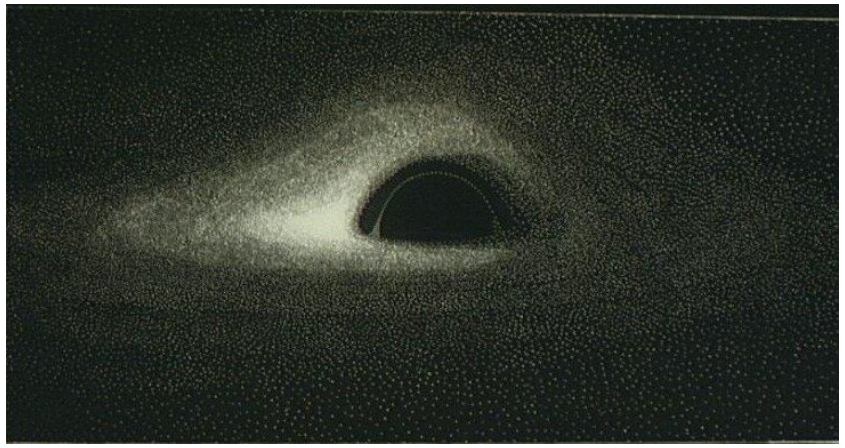


Bardeen 1973



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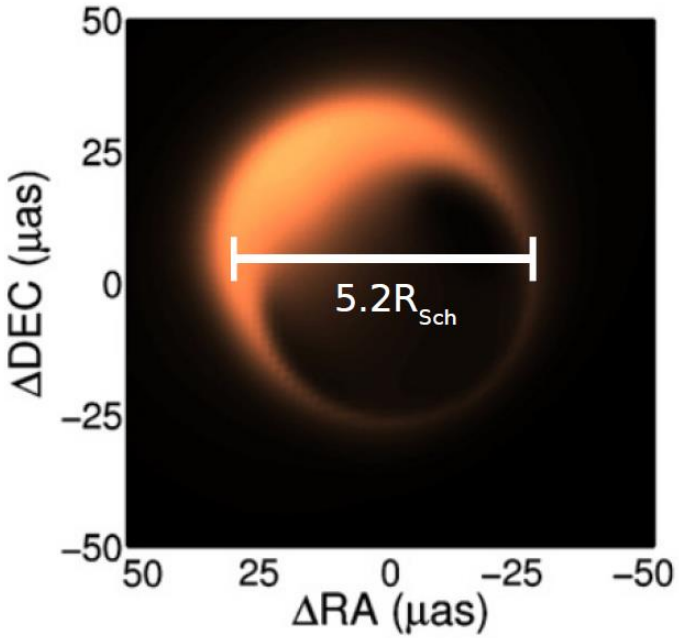


Broderick 2011

“It is conceptually interesting, if not astrophysically very important, to calculate the precise apparent shape of the black hole... Unfortunately, there seems to be no hope of observing this effect.” (Bardeen 1973,1974)

Jets and black hole feedback

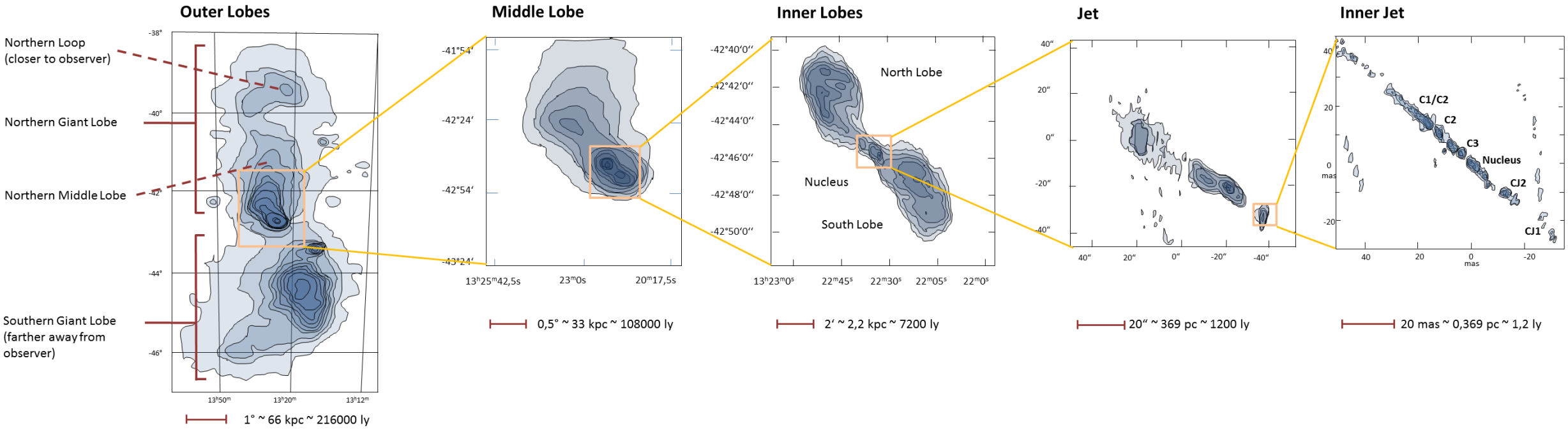
STScI/NASA

Jets and black hole feedback

STScI/NASA

Jets and black hole feedback

Jets and black hole feedback

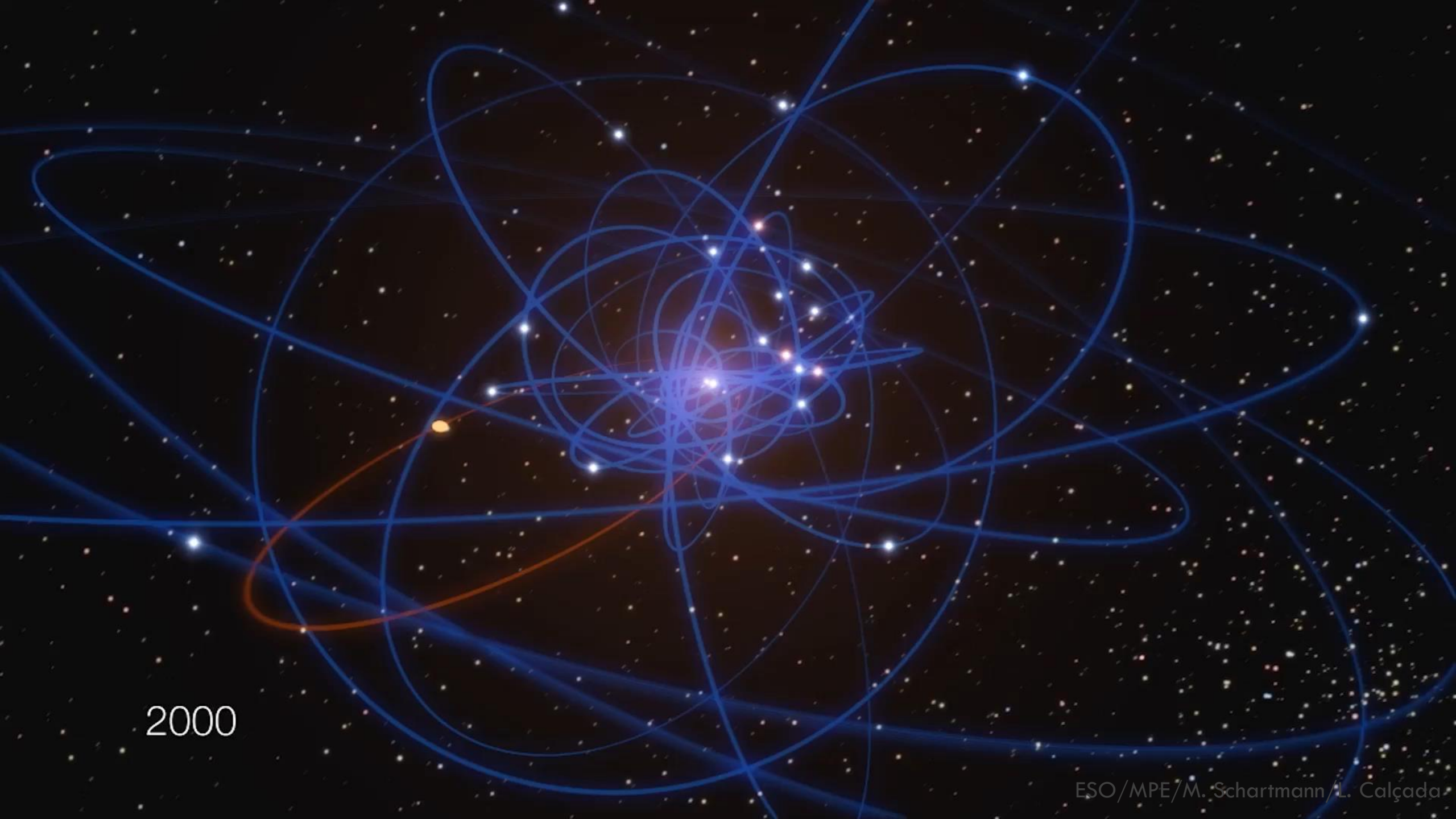


Roopesh Ojha

Sagittarius A*

26,000 Light Years Away

ESO/S. Gillessen and B. Gilli


2000
ESO/MPE/M. Schartmann/L. Calçada

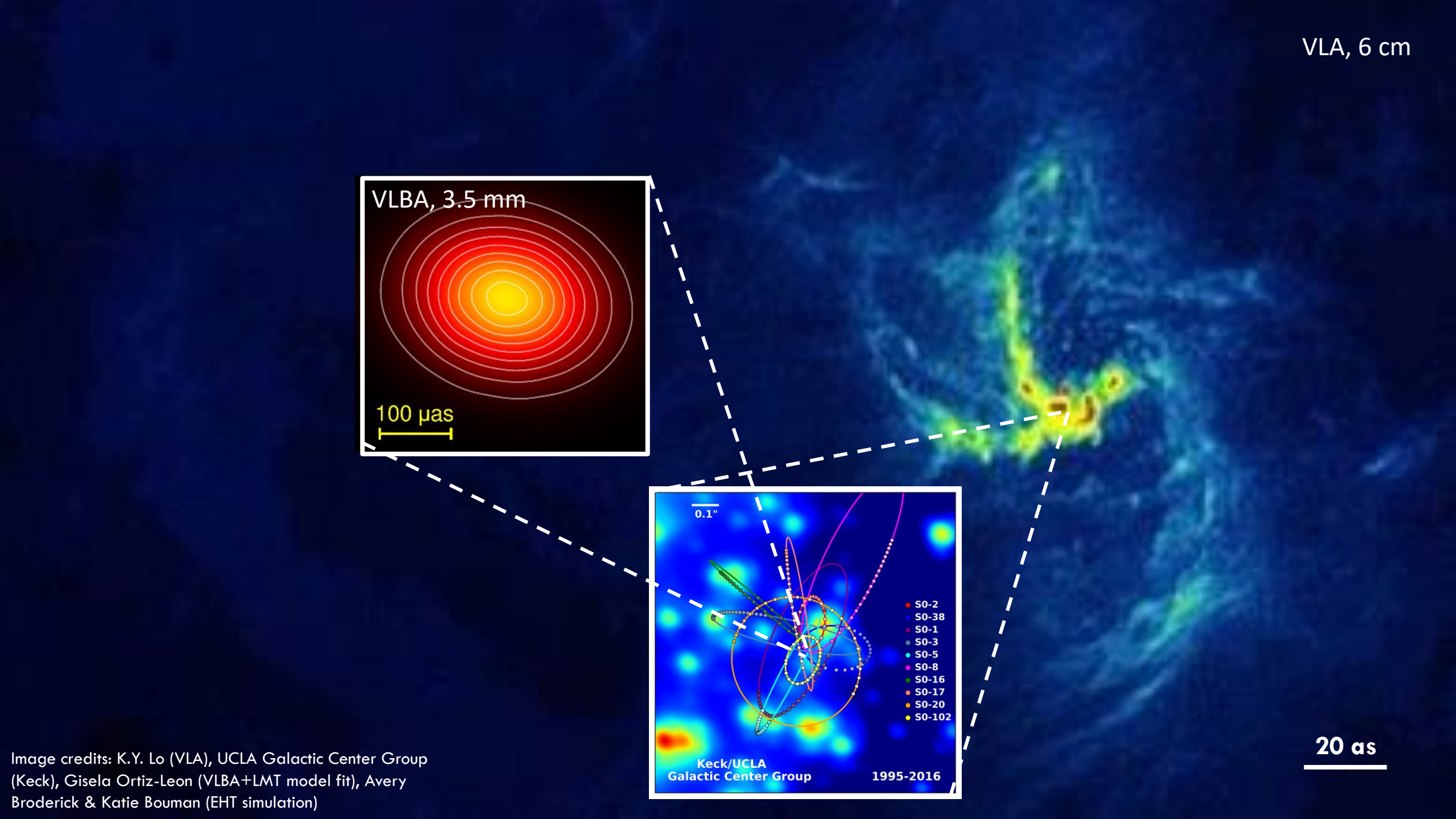
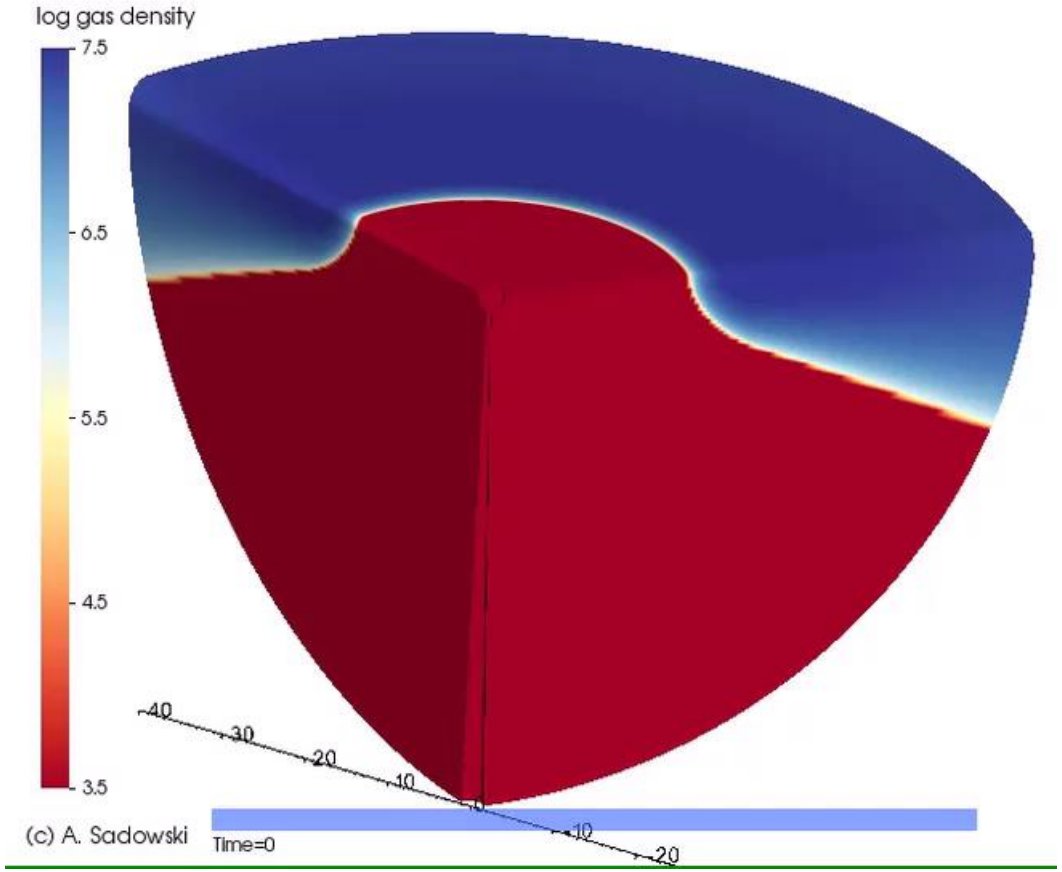


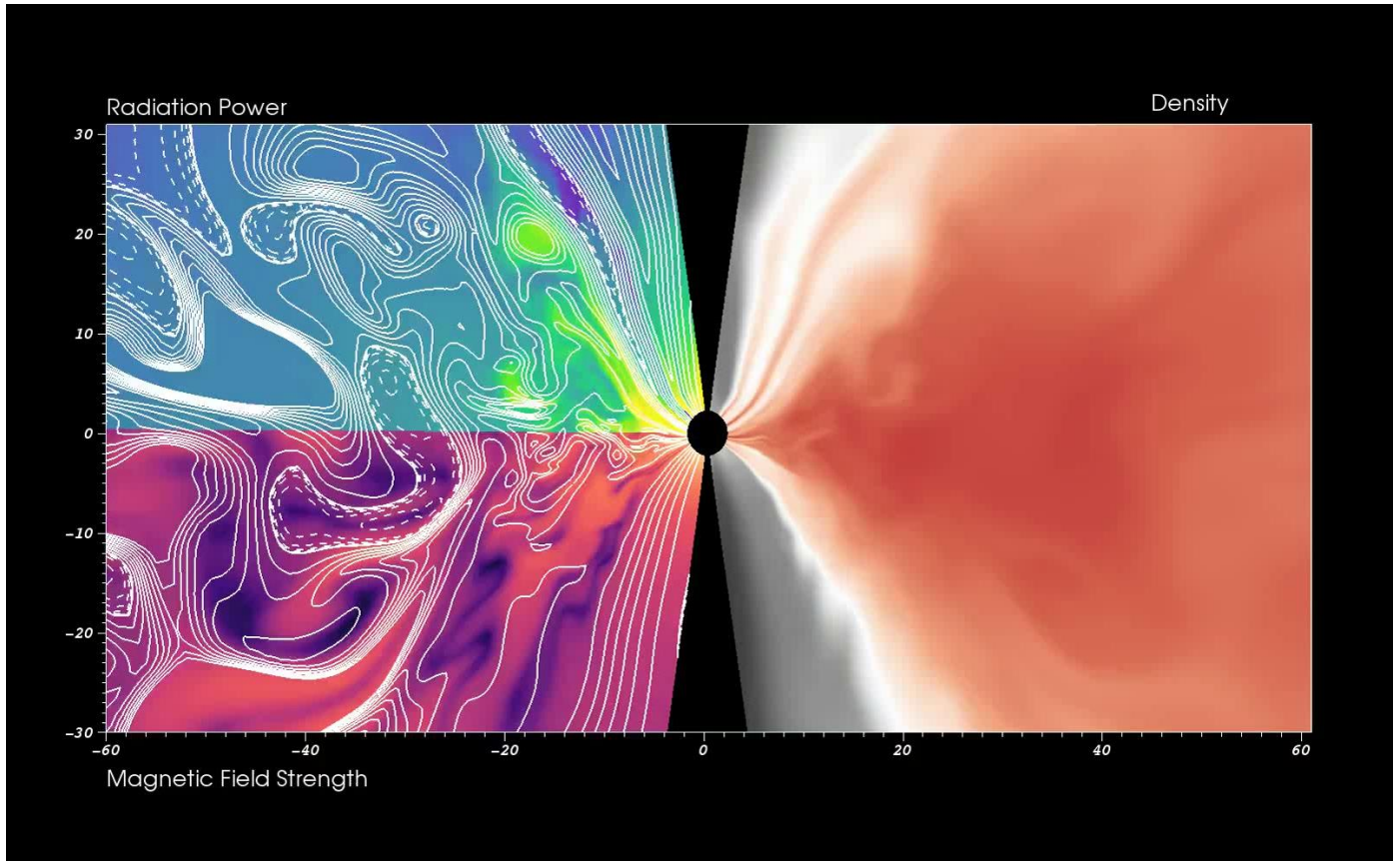
Image credits: K.Y. Lo (VLA), UCLA Galactic Center Group (Keck), Gisela Ortiz-Leon (VLBA+LMT model fit), Avery Broderick & Katie Bouman (EHT simulation)

Simulations of Sgr A*



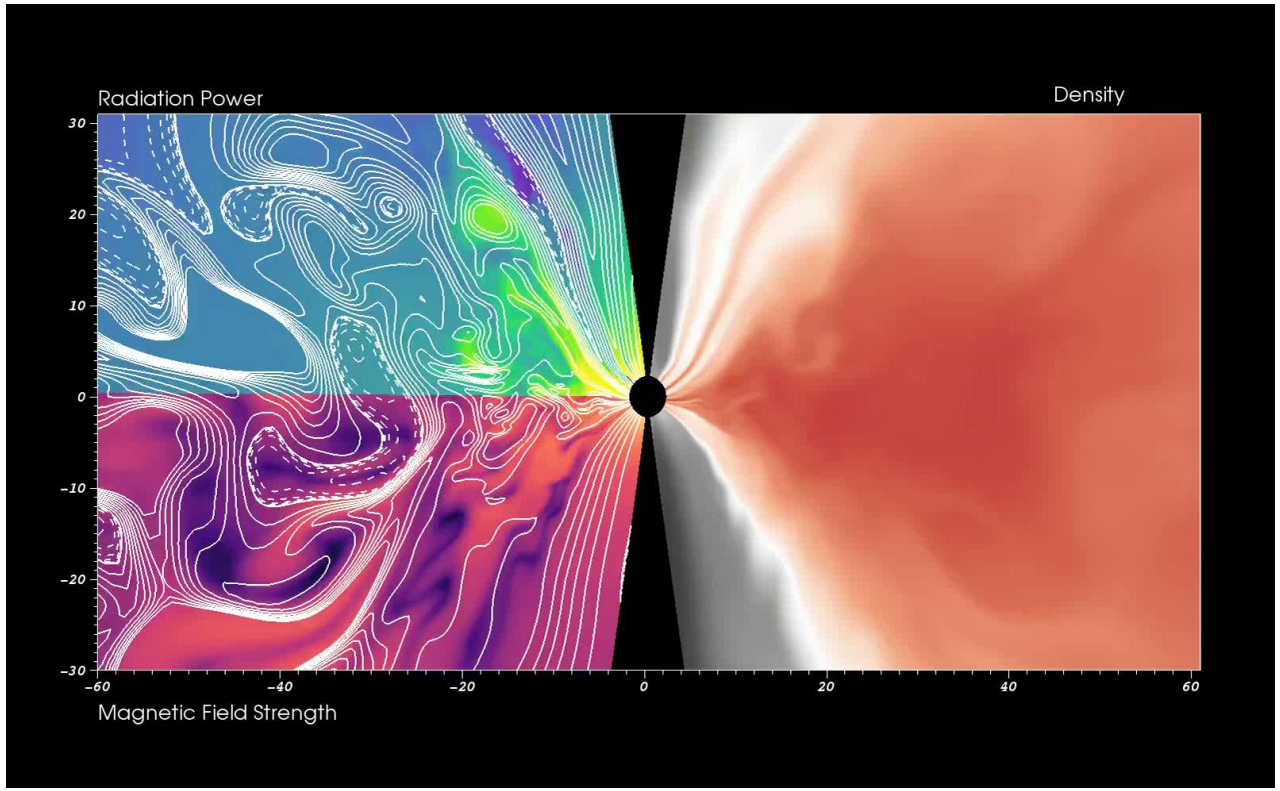
Sadowski 2016

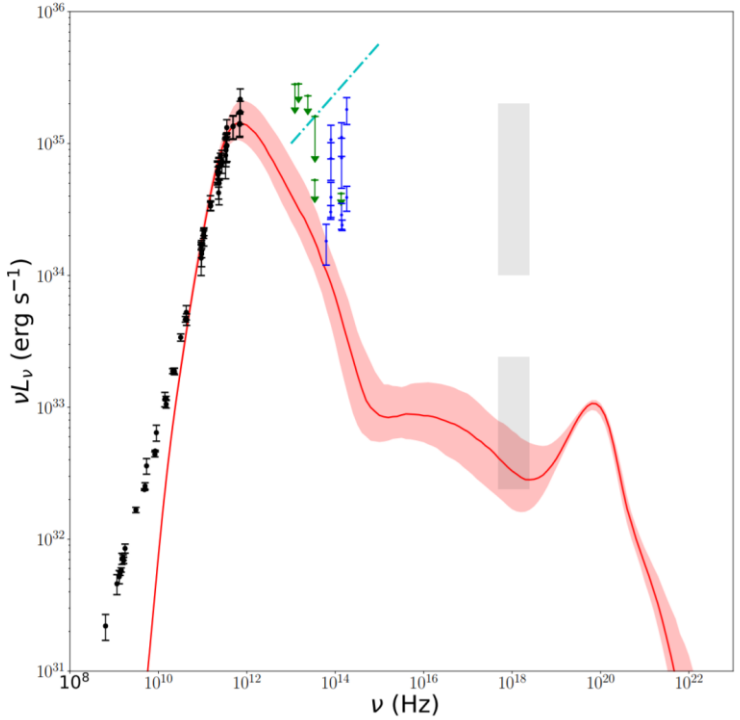
Simulations of Sgr A*



Chael 2018

Simulations of Sgr A*





Chael 2018

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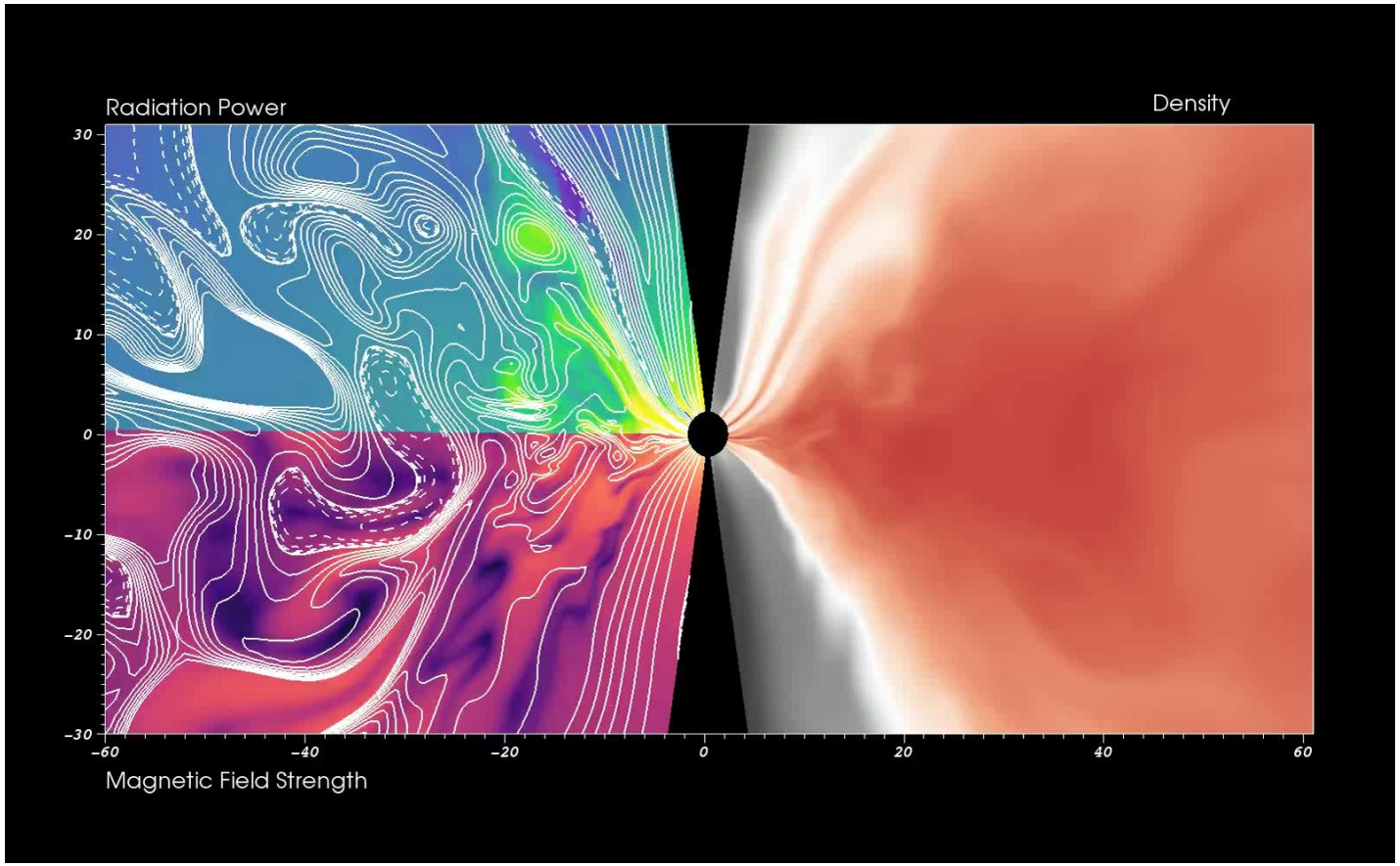
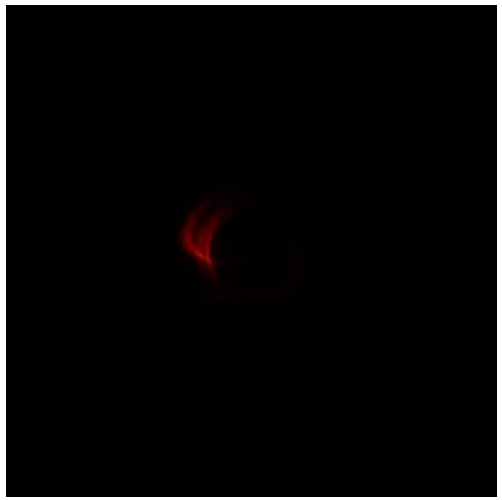
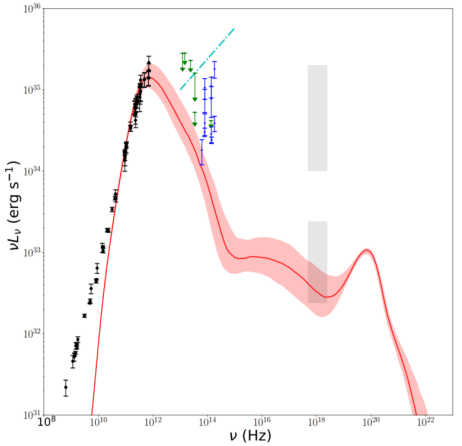






Chael 2018

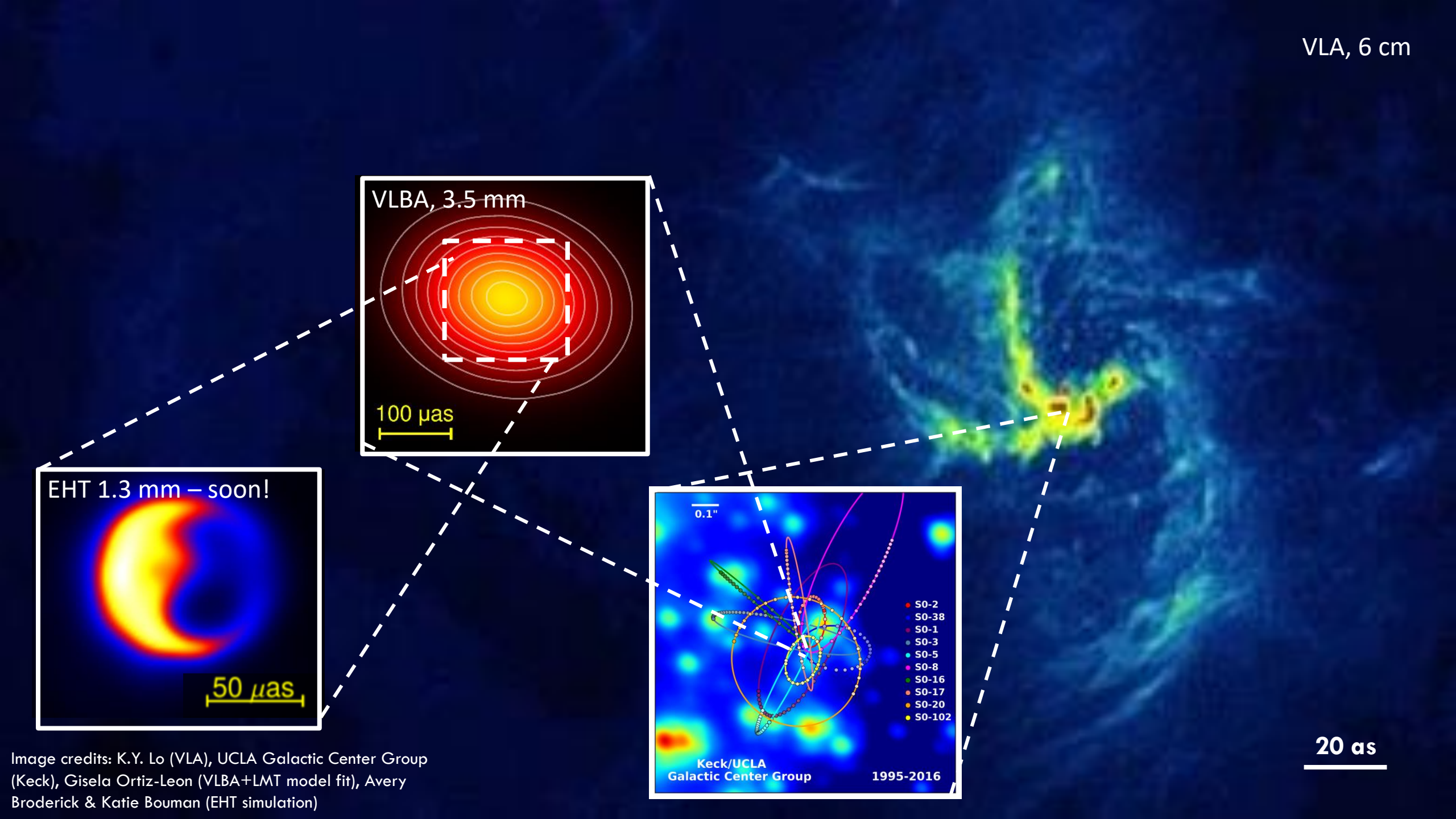
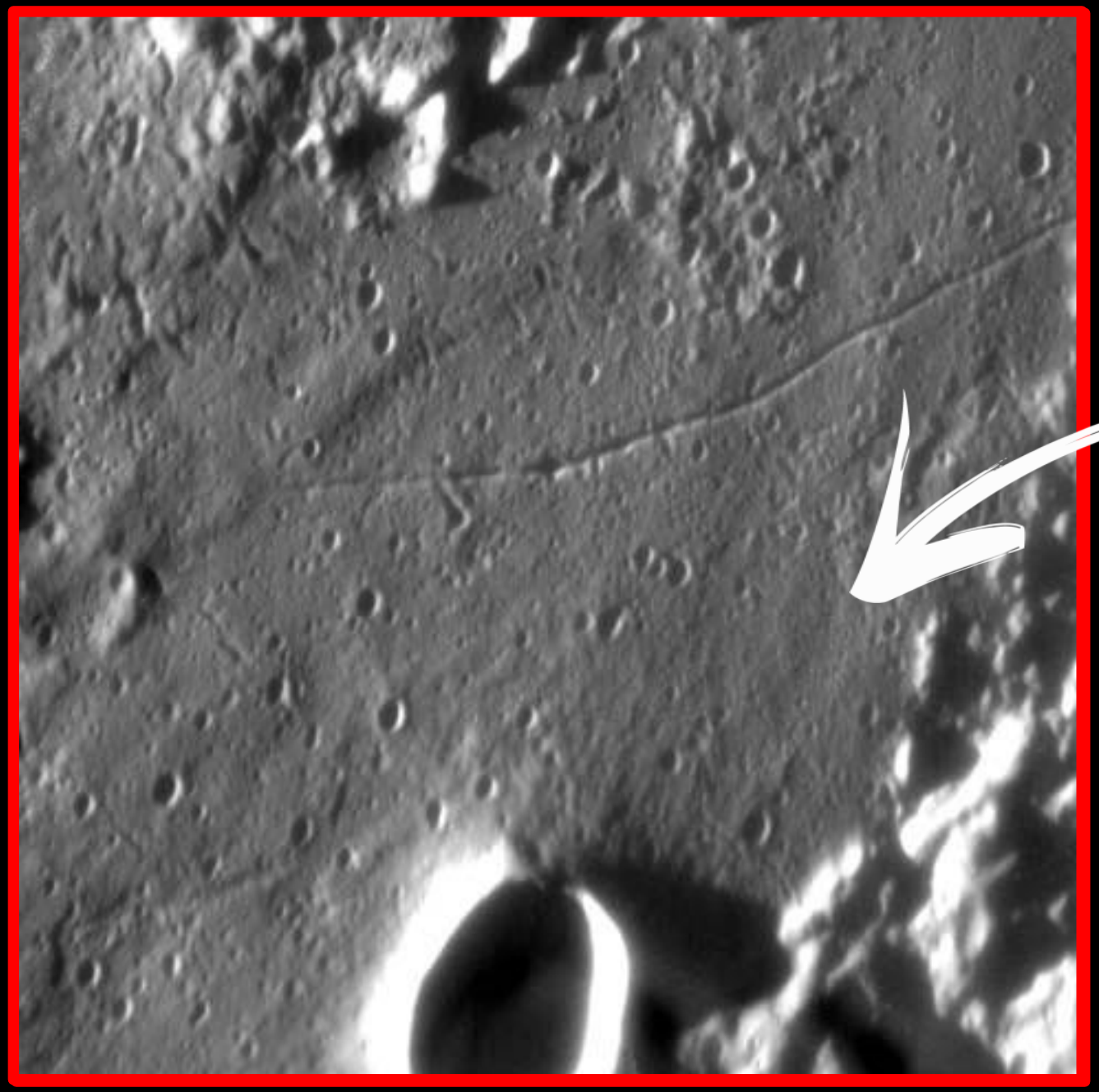


Image credits: K.Y. Lo (VLA), UCLA Galactic Center Group (Keck), Gisela Ortiz-Leon (VLBA+LMT model fit), Avery Broderick & Katie Bouman (EHT simulation)

Imaging a Black Hole

Simulation of a Black Hole

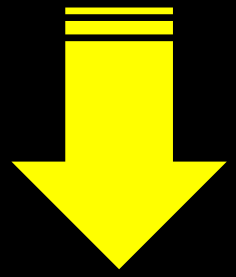
Video courtesy of Hotaka Shiokawa



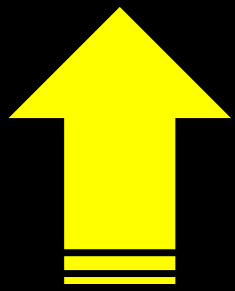
Each Pixel is 1.5 Million ’s

Yepun telescope, Paranal Observatory in Chile / George Tarsoudis

Diffraction Limit

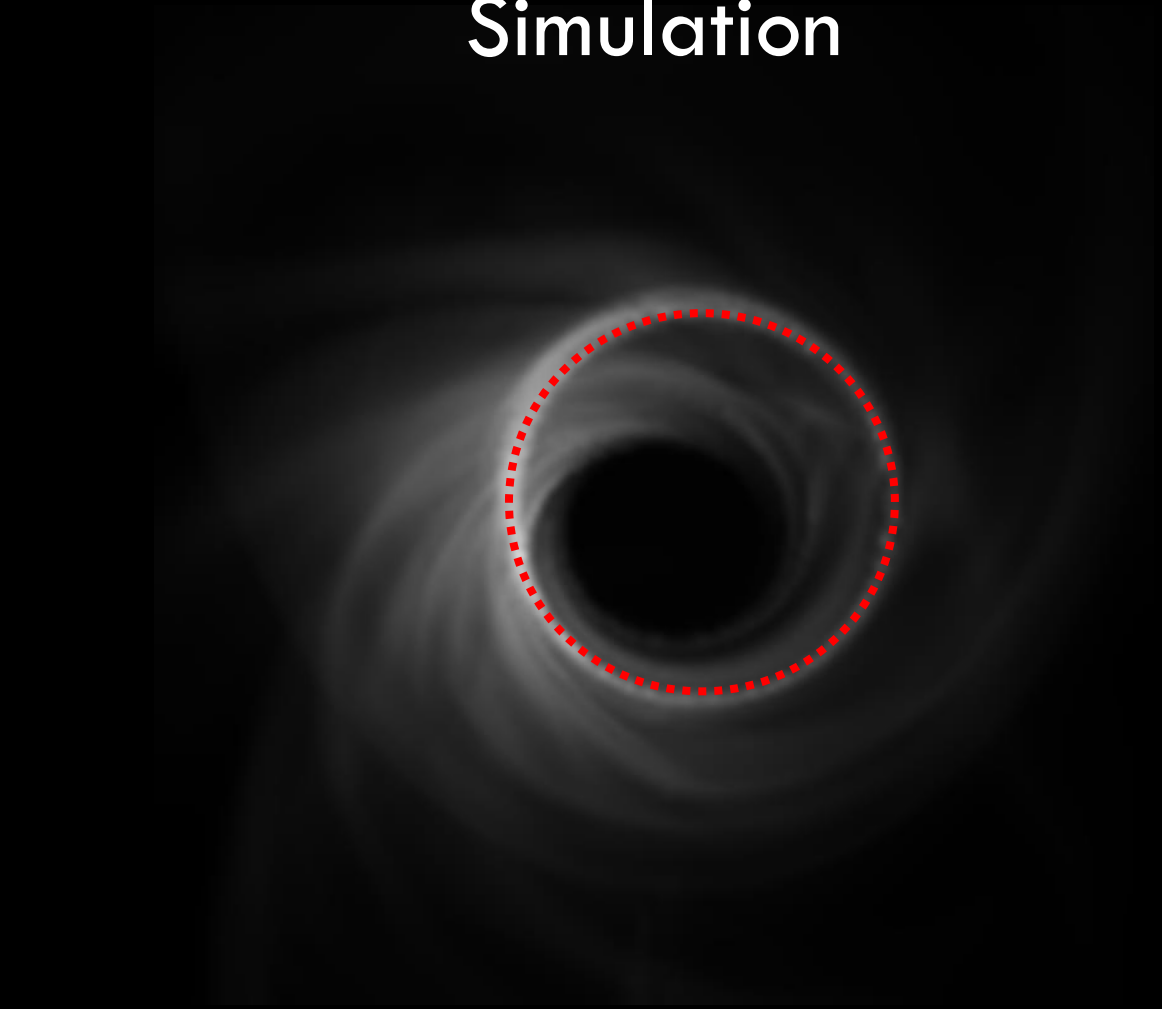


Angular Resolution $\propto$ $\frac{\text{Wavelength}}{\text{Telescope Size}}$

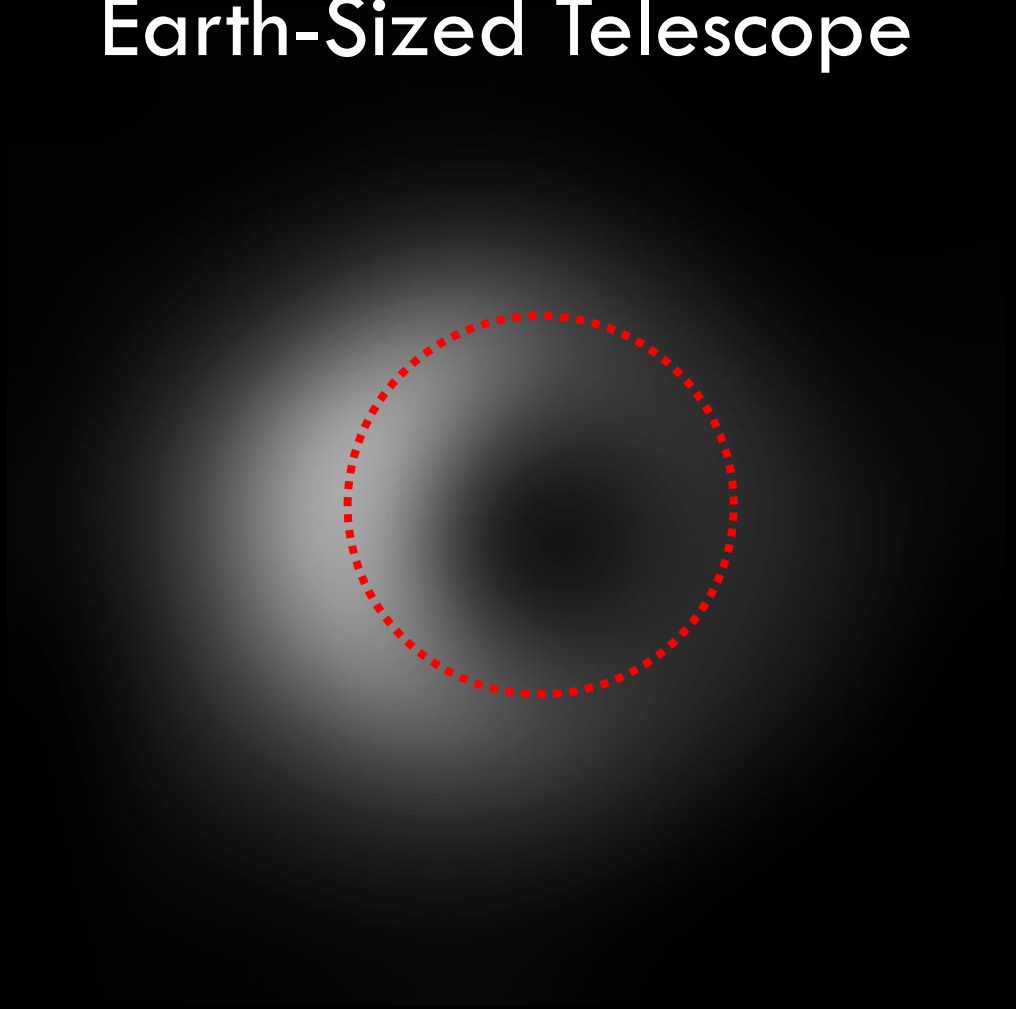



We Need an
Earth-Sized
Telescope!

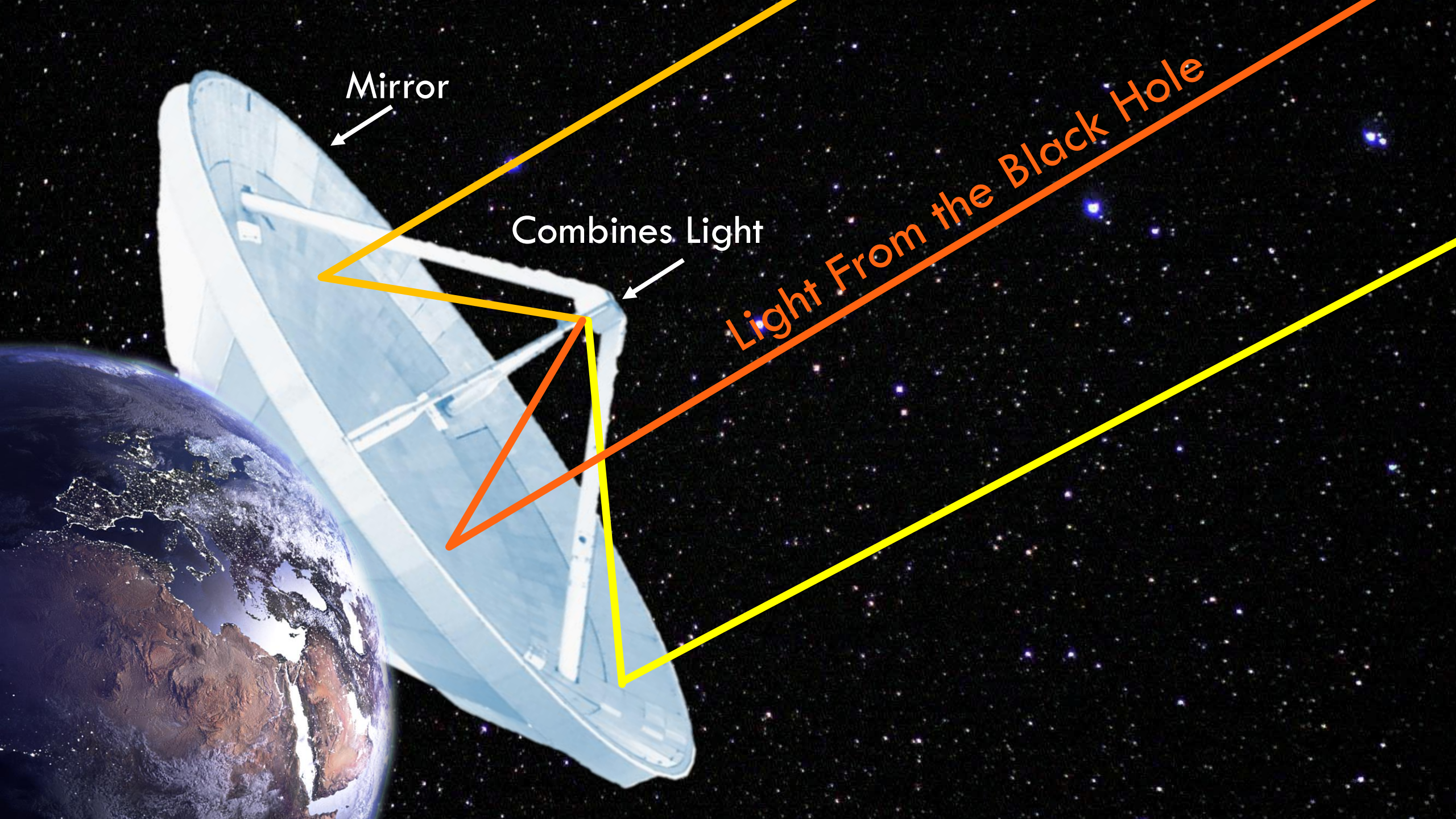
Original Black Hole Simulation

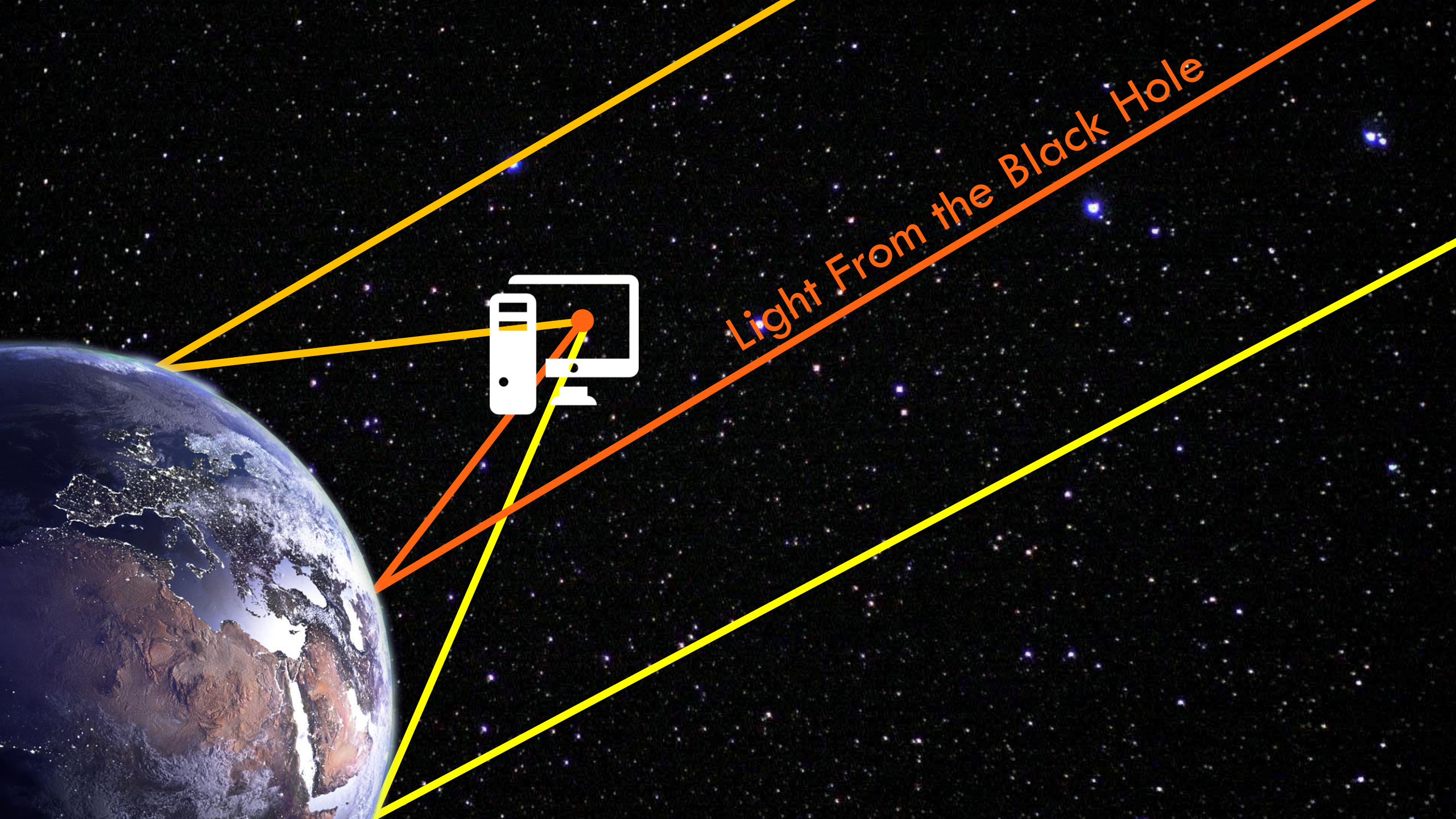


Picture if We Had an Earth-Sized Telescope

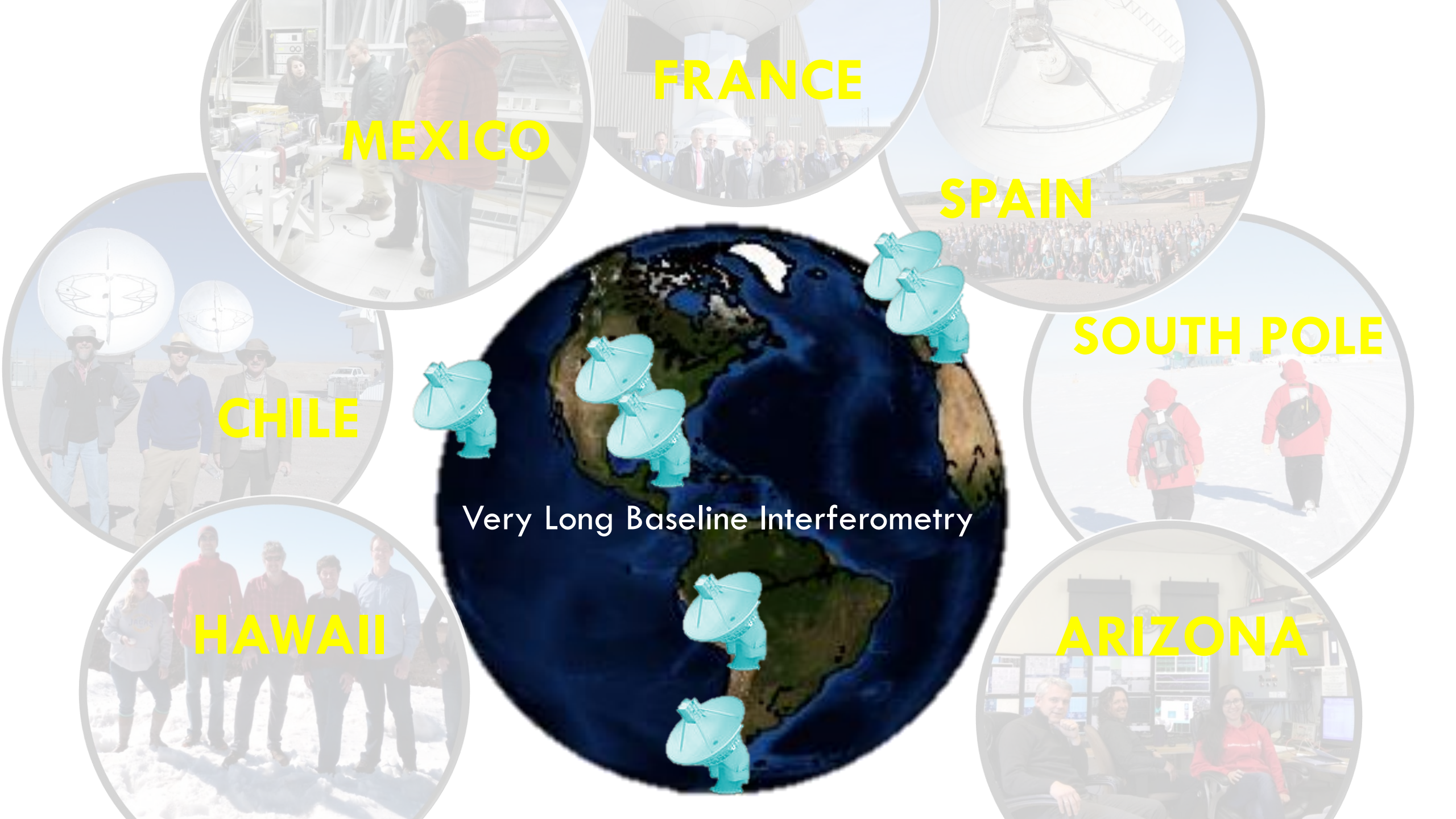


Original Image courtesy of Jason Dexter, Monika Moscibrodzka, Hotaka Shiokawa


Mirror
Combines Light
Light From the Black Hole

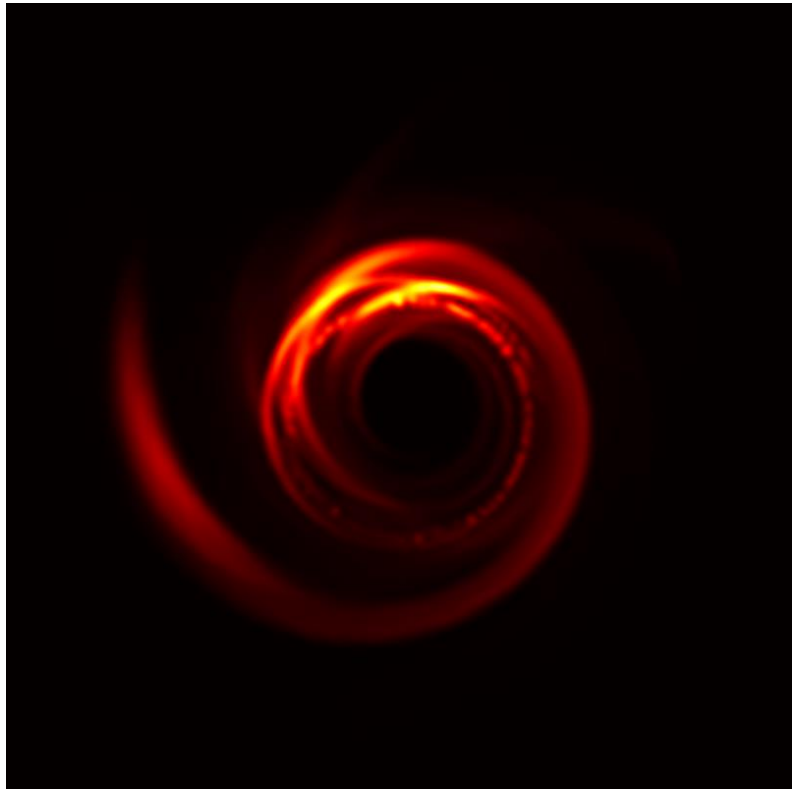

Light From the Black Hole

The Event Horizon Telescope


FRANCE
MEXICO
SPAIN
CHILE
SOUTH POLE
Very Long Baseline Interferometry
HAWAII
ARIZONA

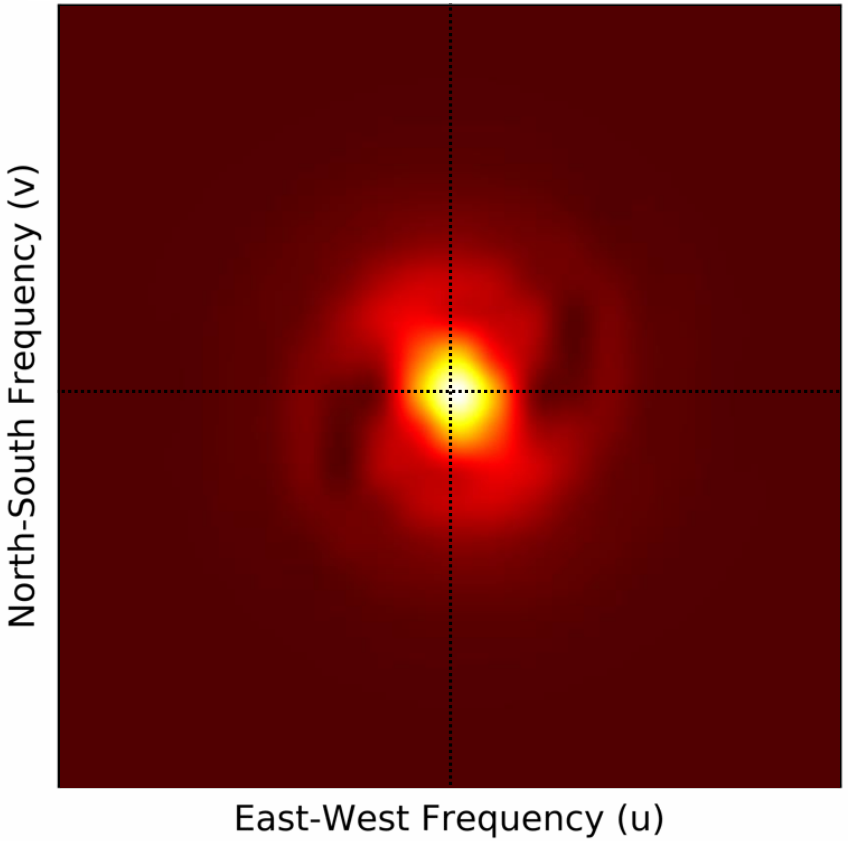
Very Long Baseline Interferometry (VLBI)

Black Hole Image

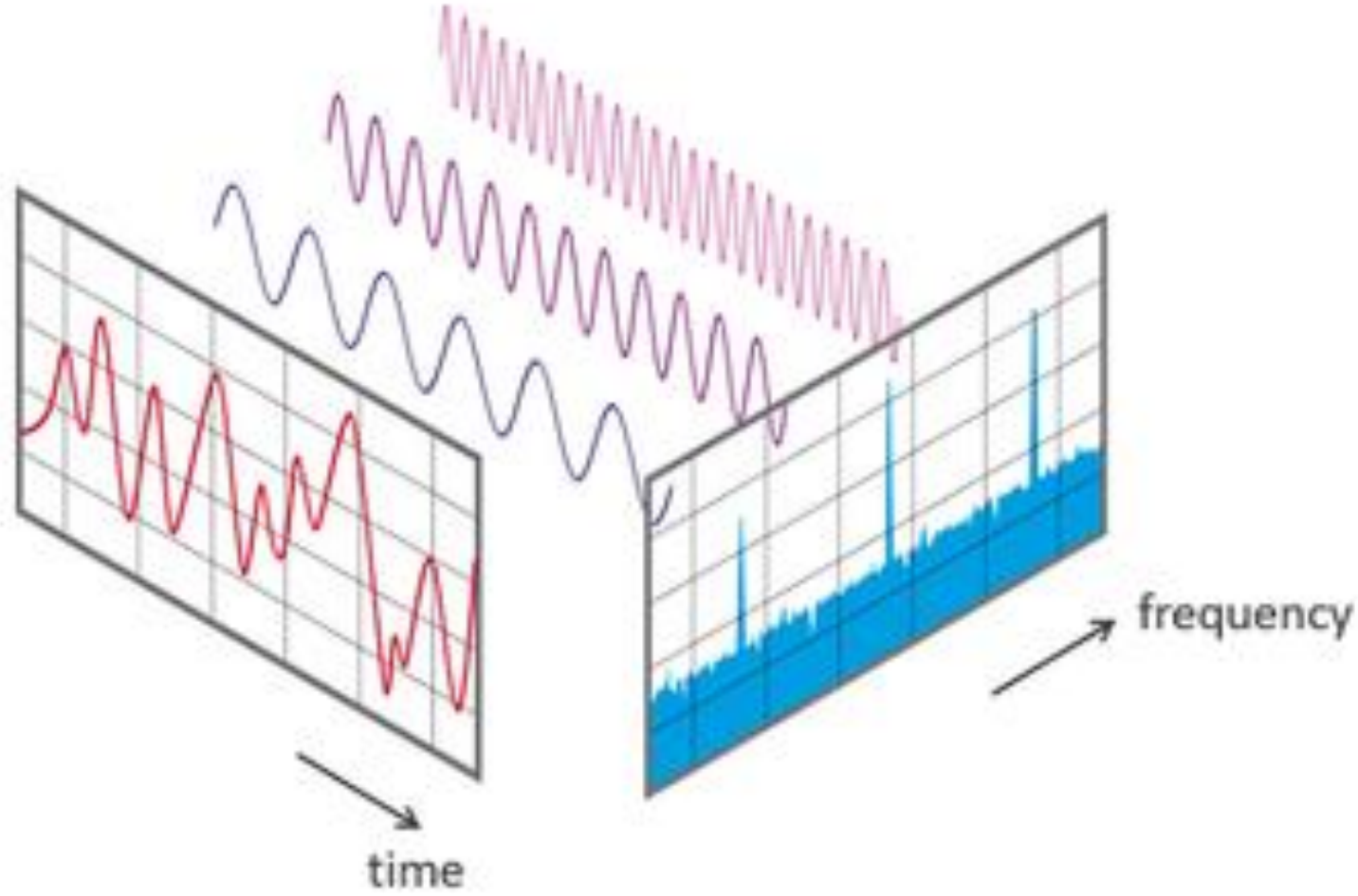


Fourier Transform

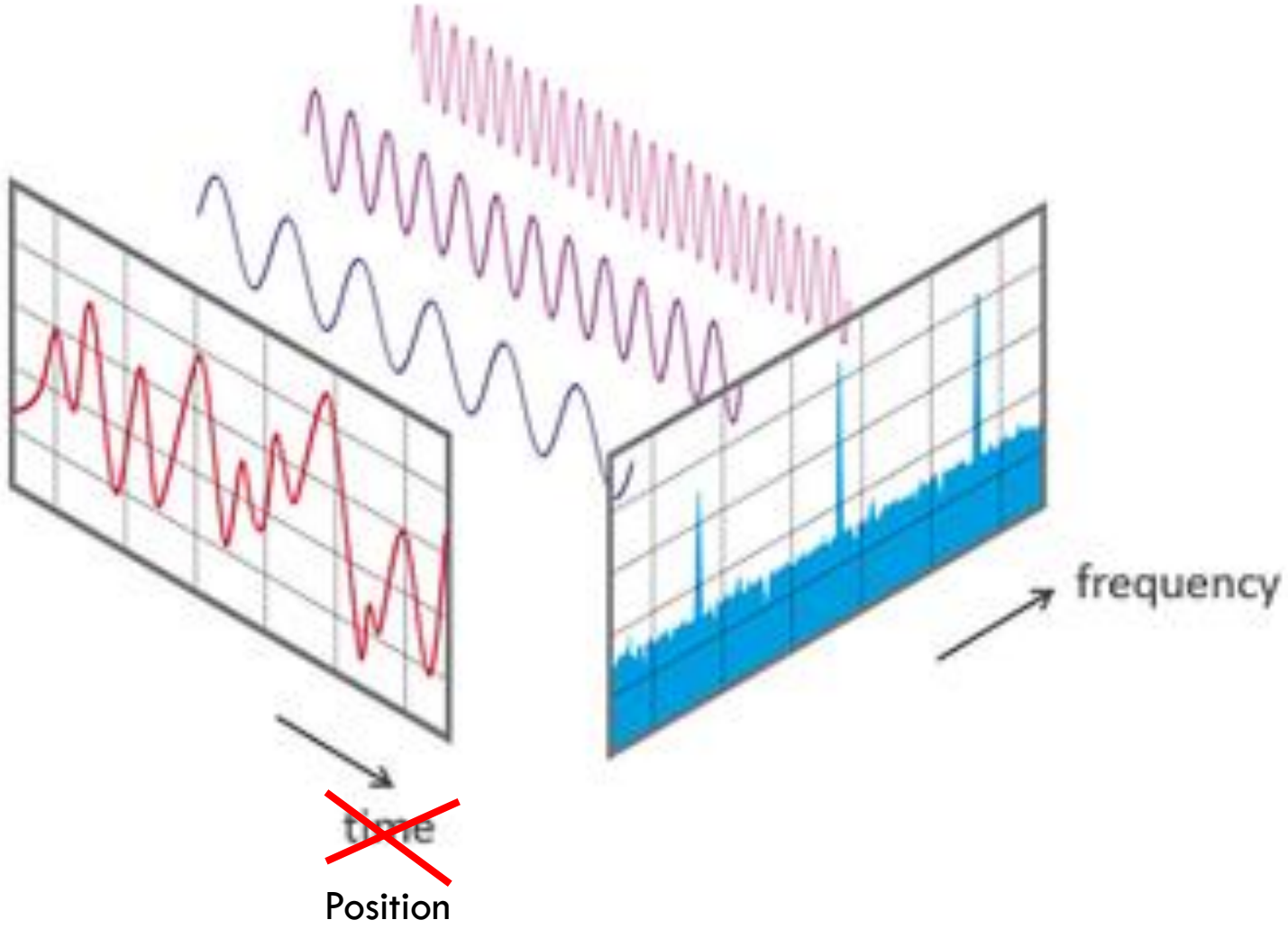
Frequency Measurements



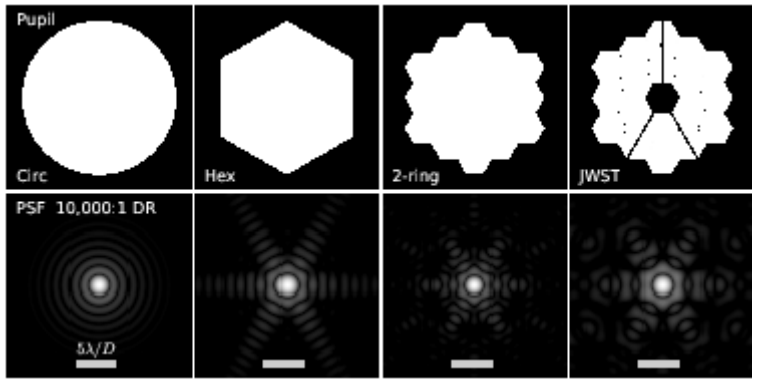
Fourier Transform



Fourier Transform



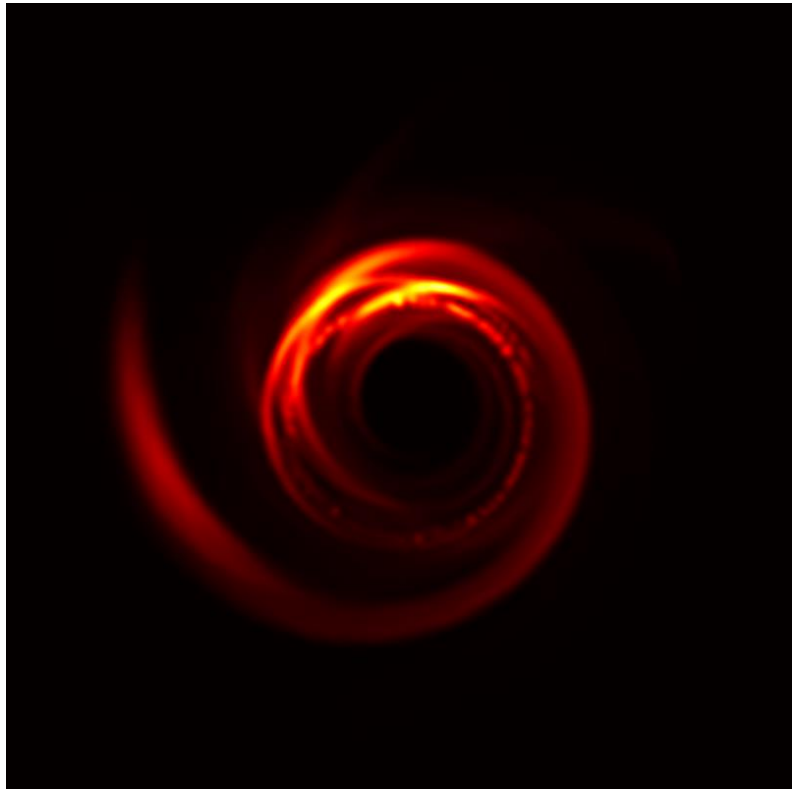
In a telescope, the Point Spread Function is the Fourier Transform of the aperture



K.E. Ford

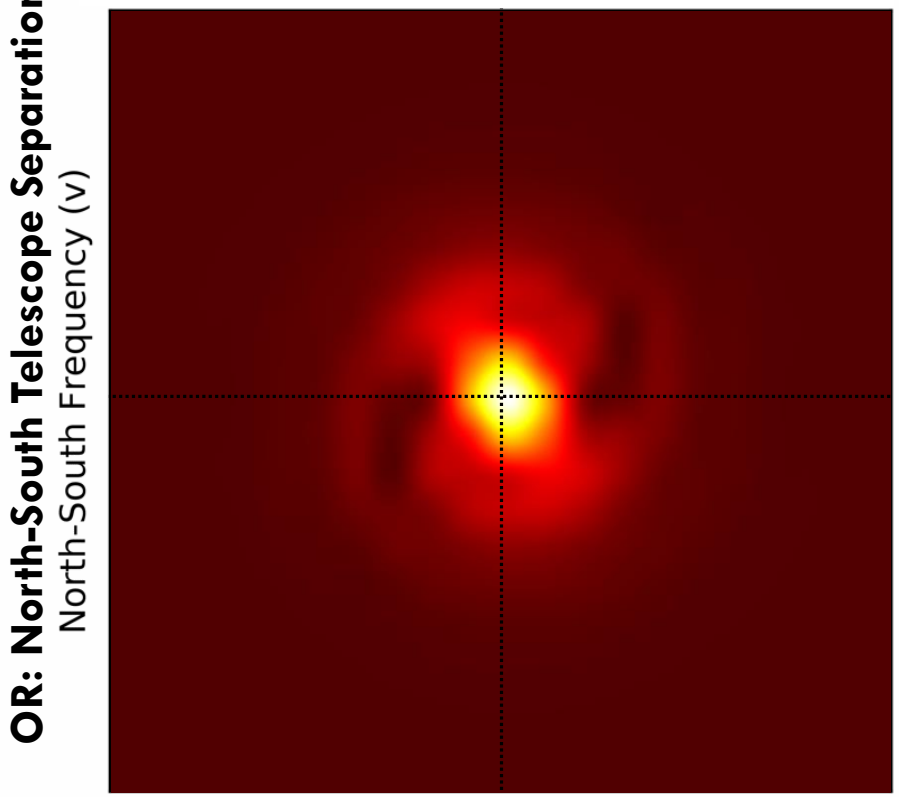
Very Long Baseline Interferometry (VLBI)

Black Hole Image

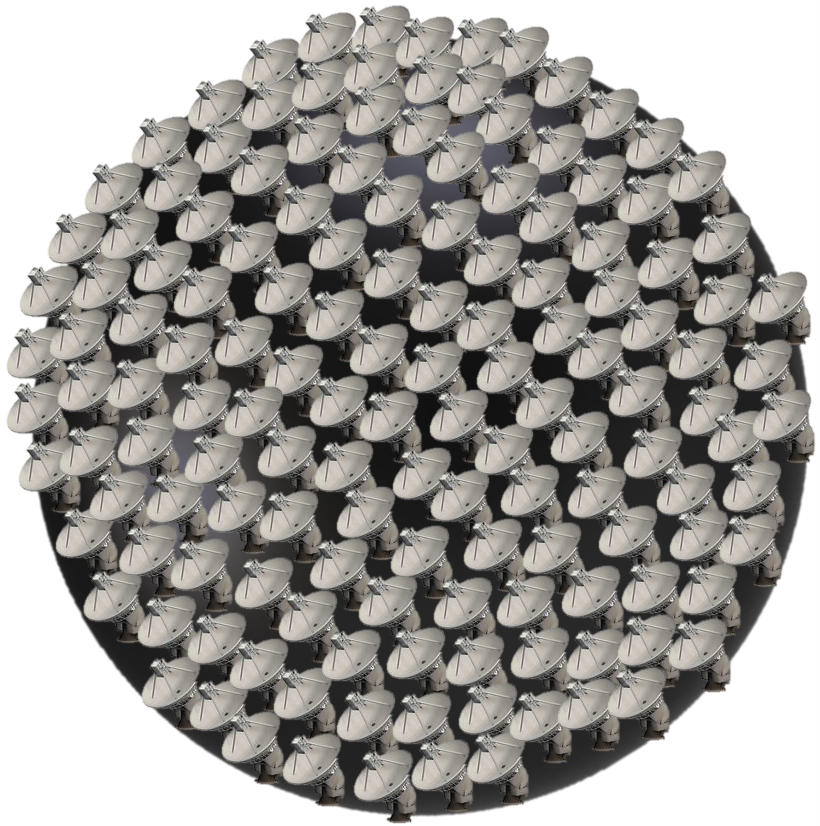


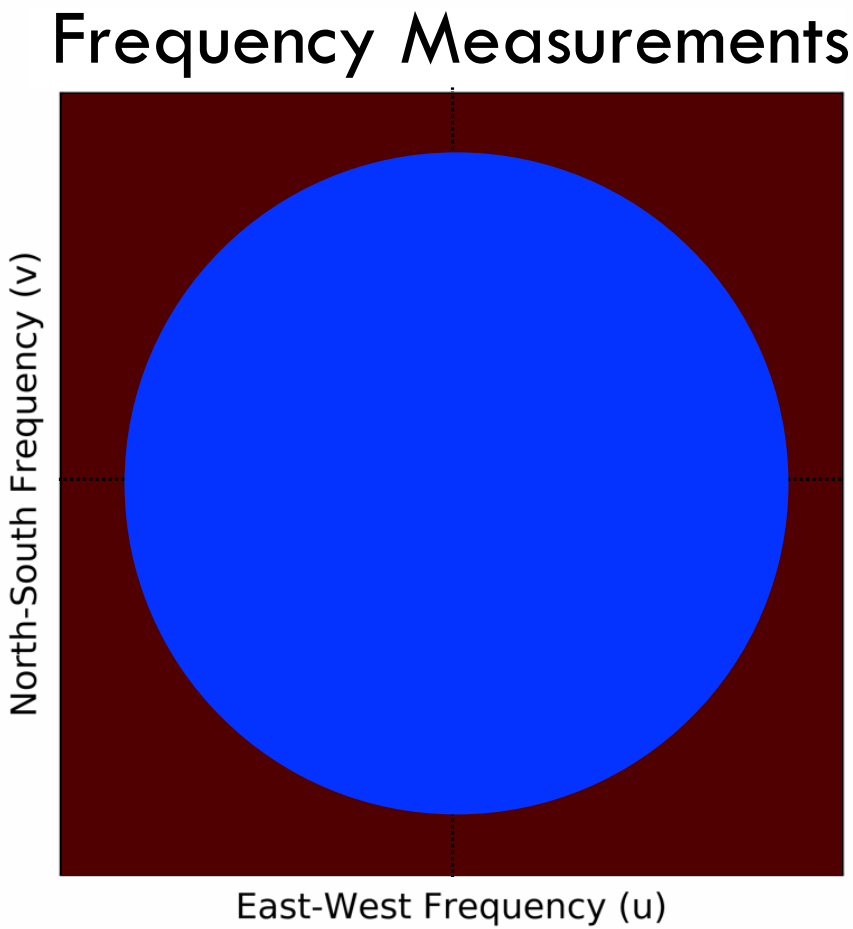
Fourier Transform

Frequency Measurements

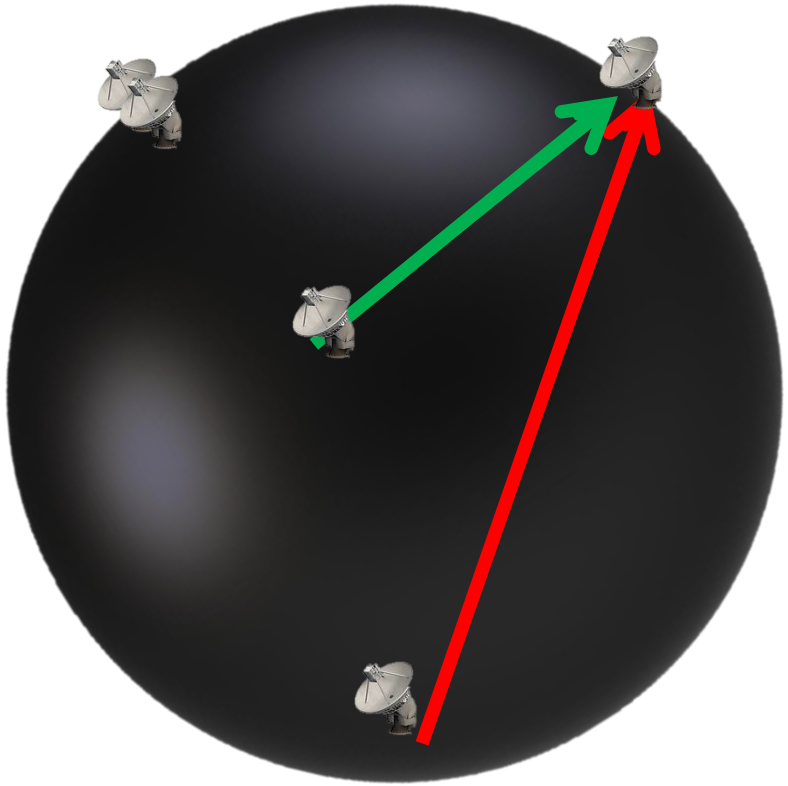


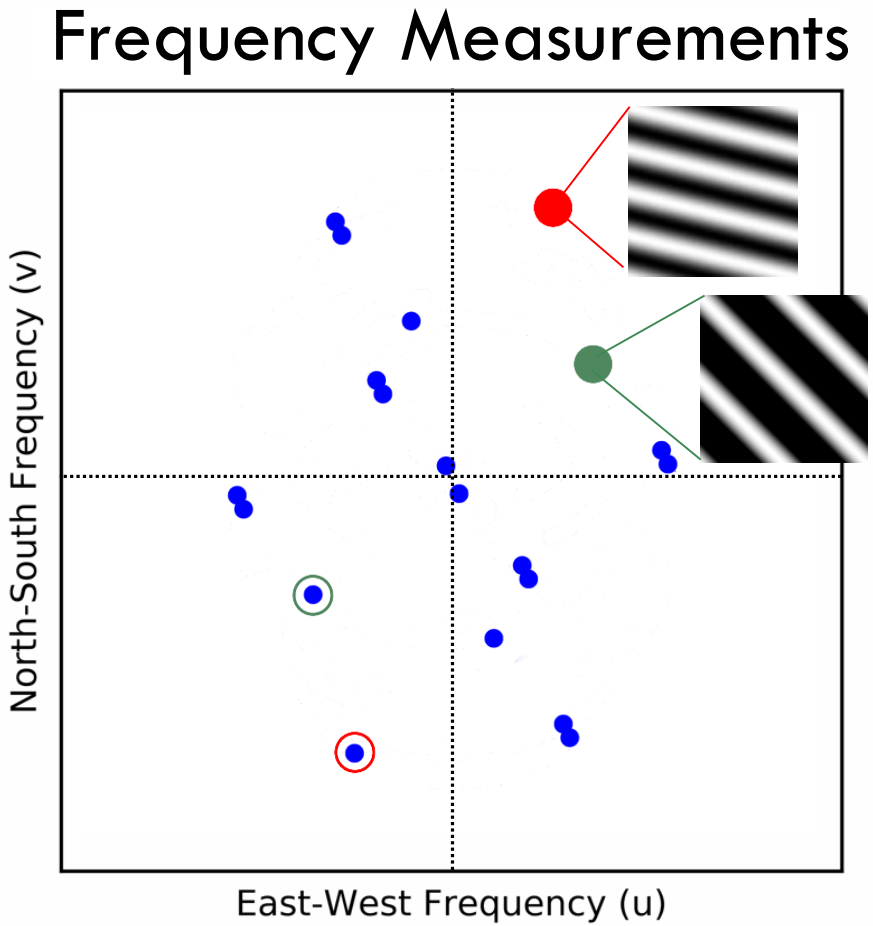
Very Long Baseline Interferometry (VLBI)



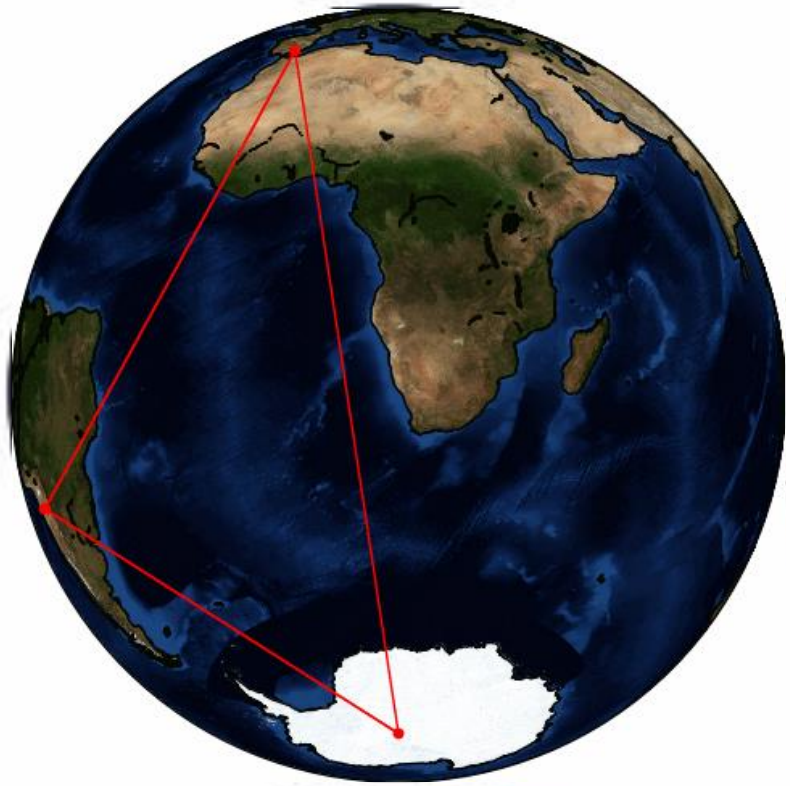


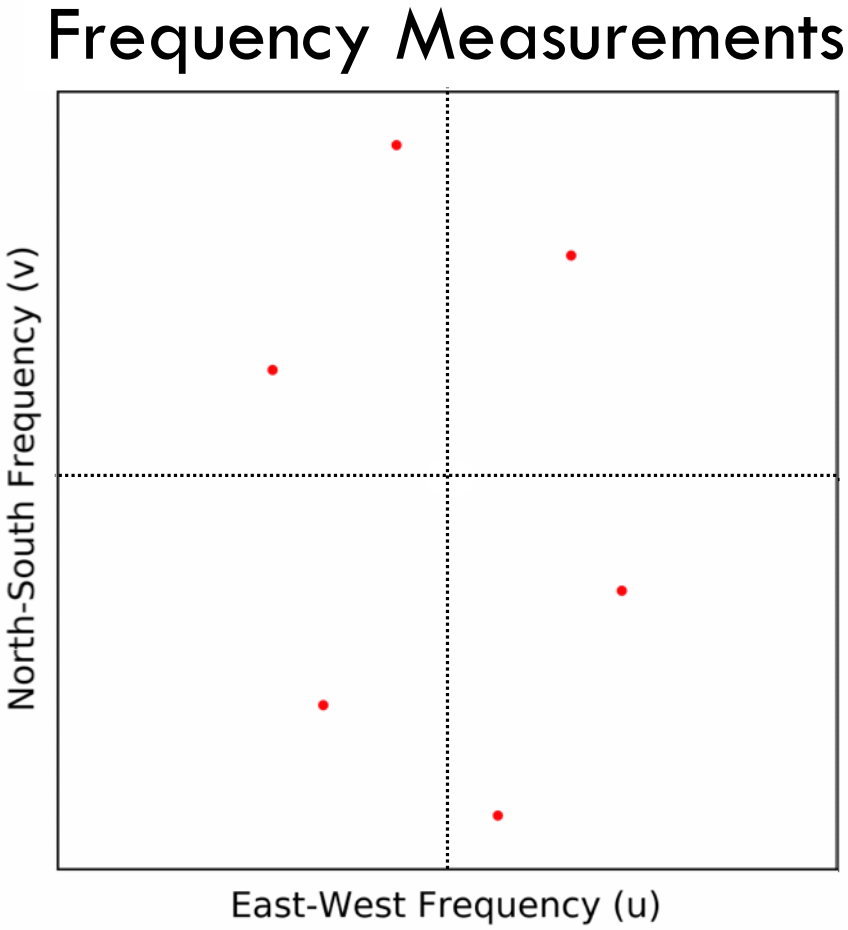
Very Long Baseline Interferometry (VLBI)



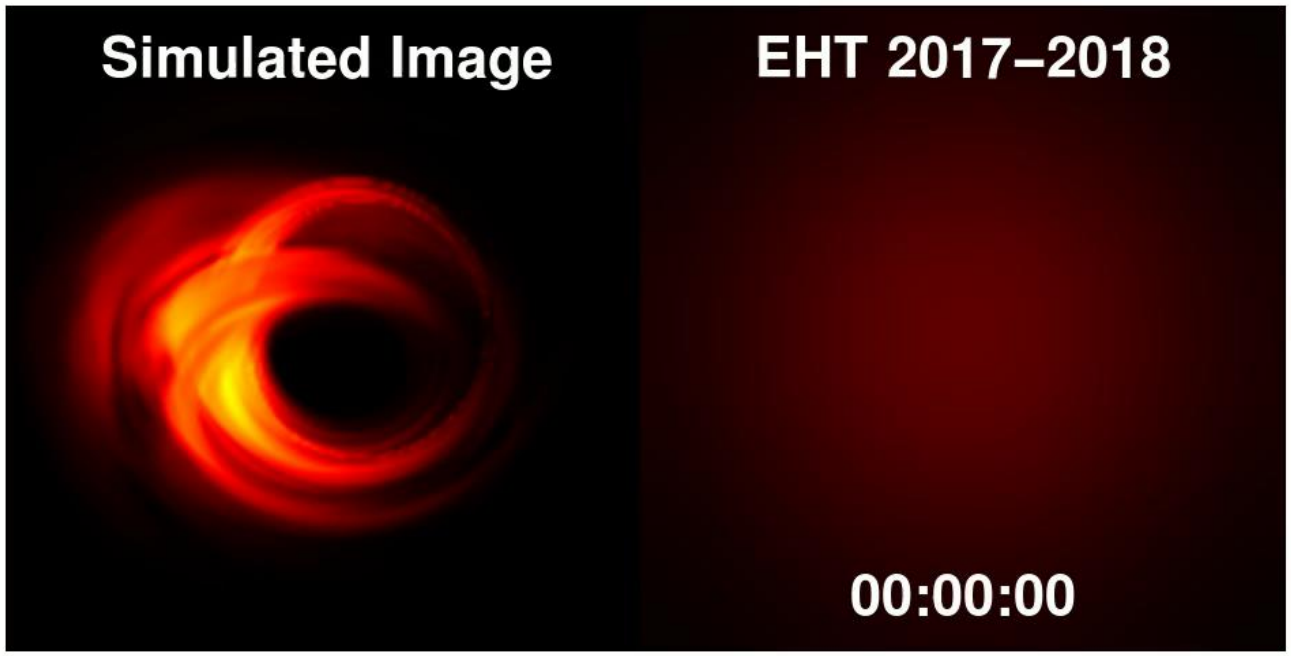


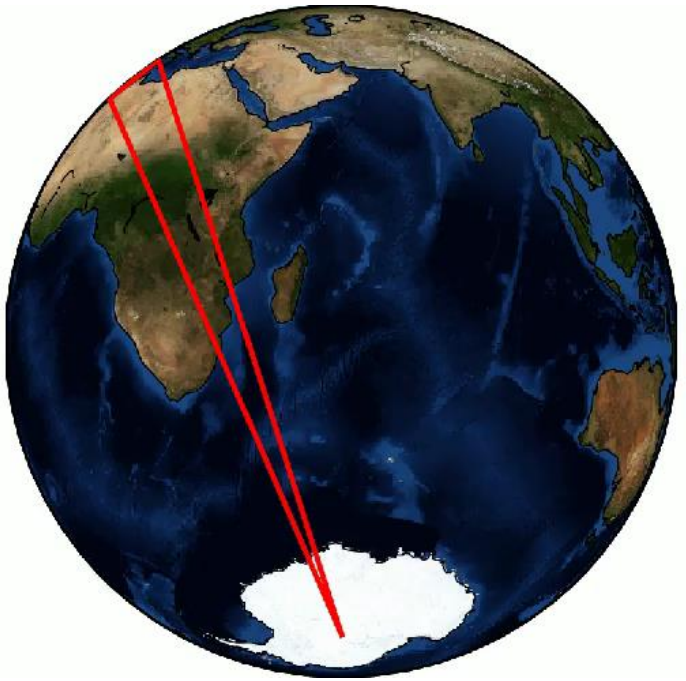
Very Long Baseline Interferometry (VLBI)



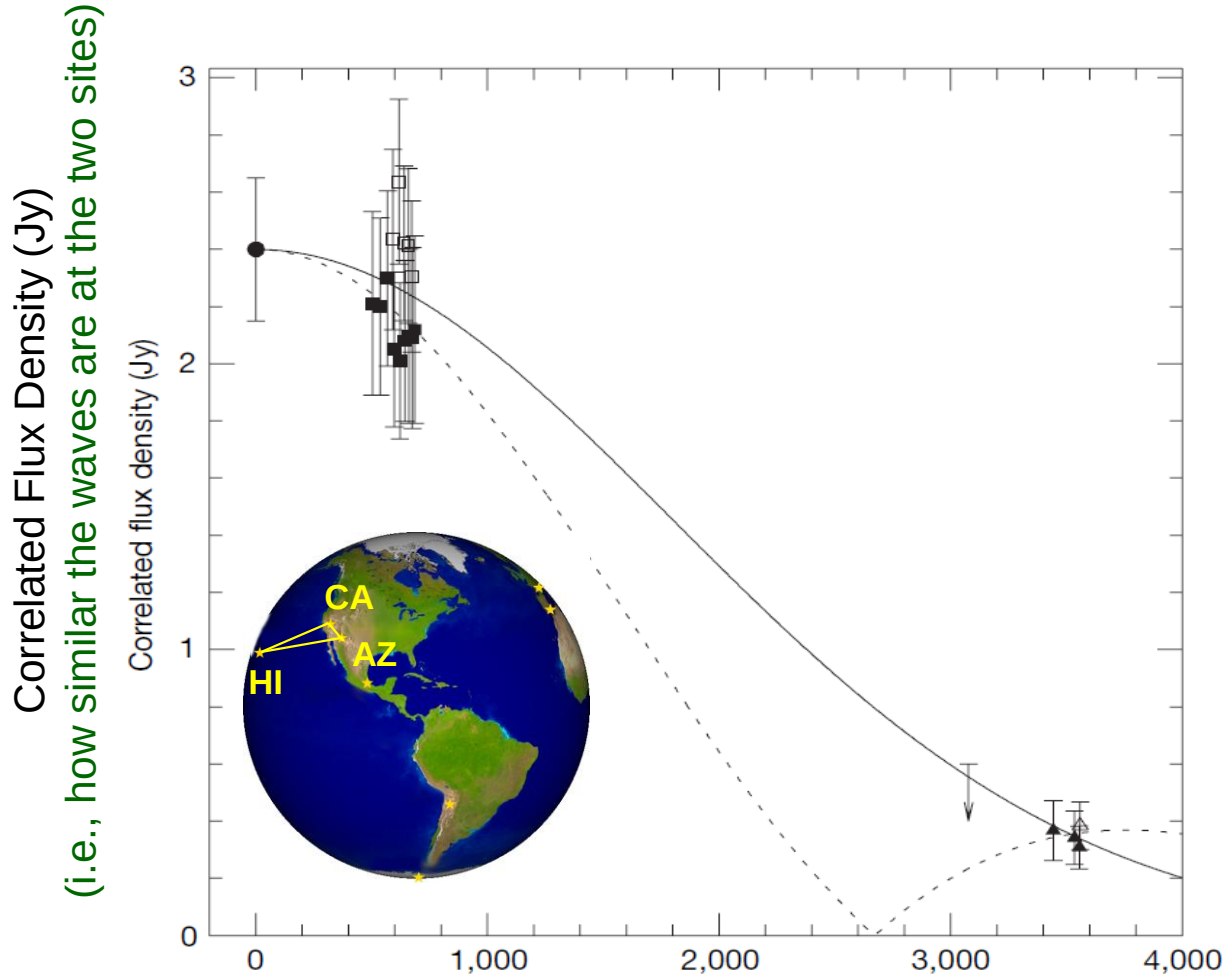


Very Long Baseline Interferometry (VLBI)



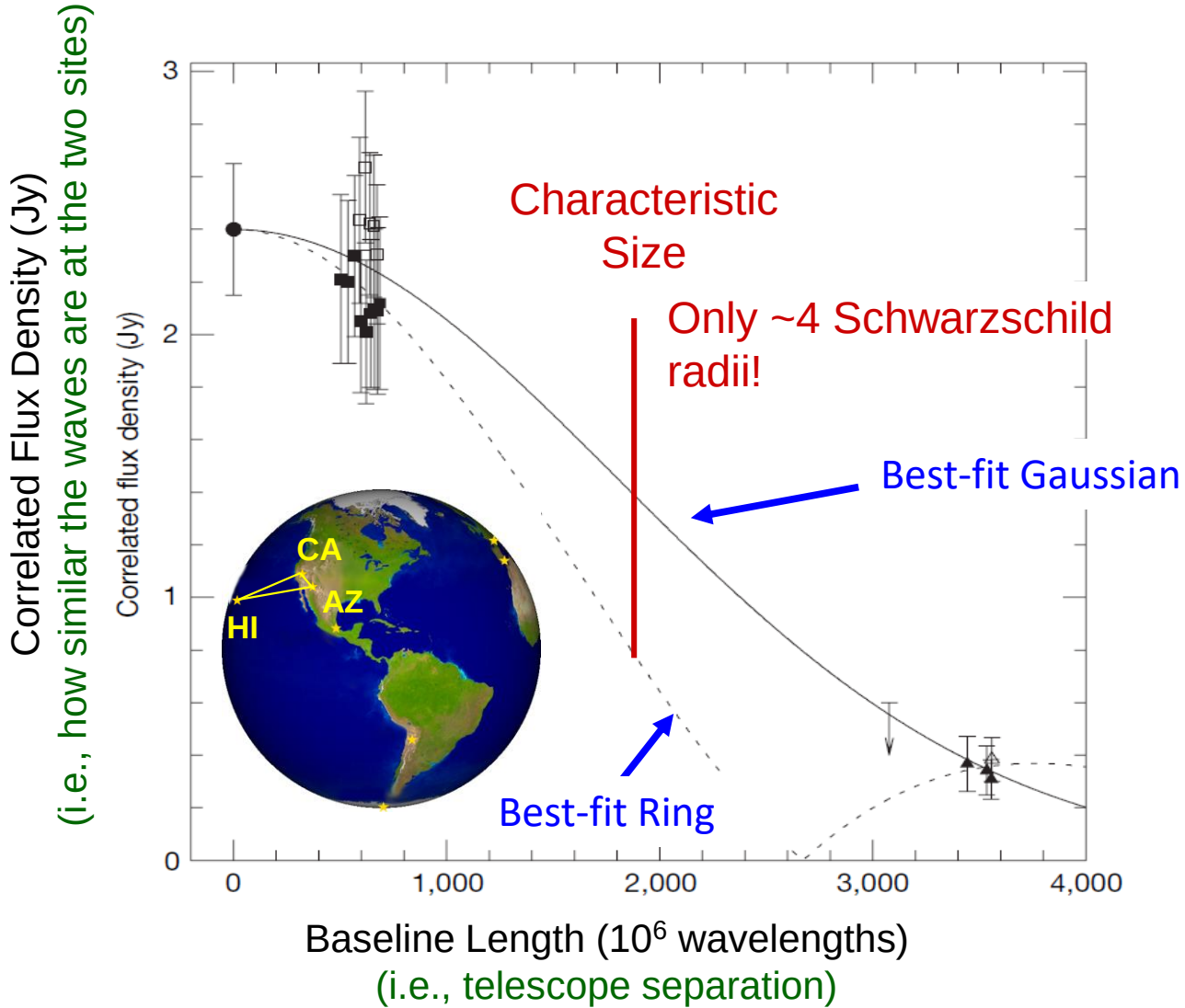


Sgr A* with the EHT



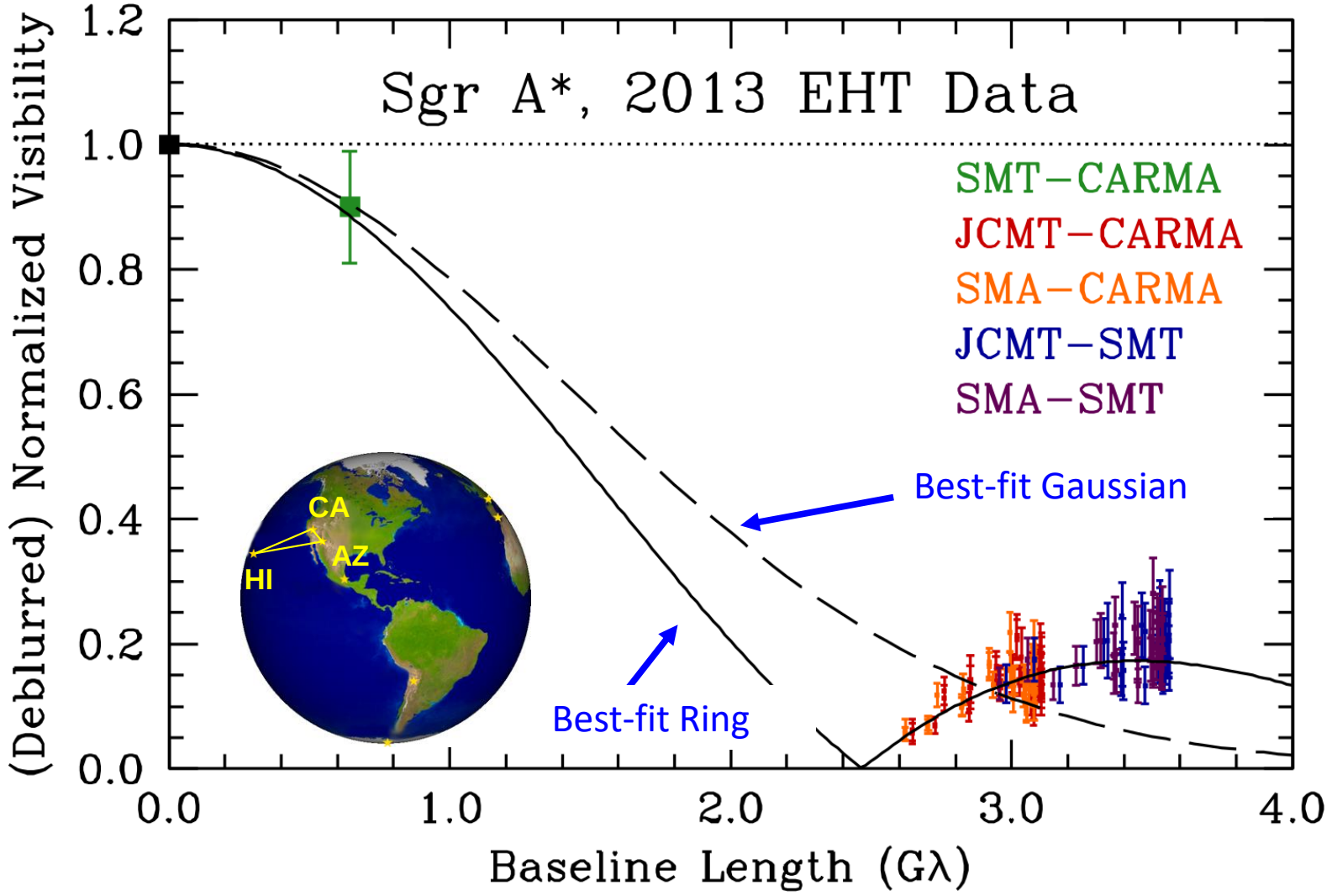
Doeleman et al. (2009)
Fish et al. (2011)

Sgr A* with the EHT



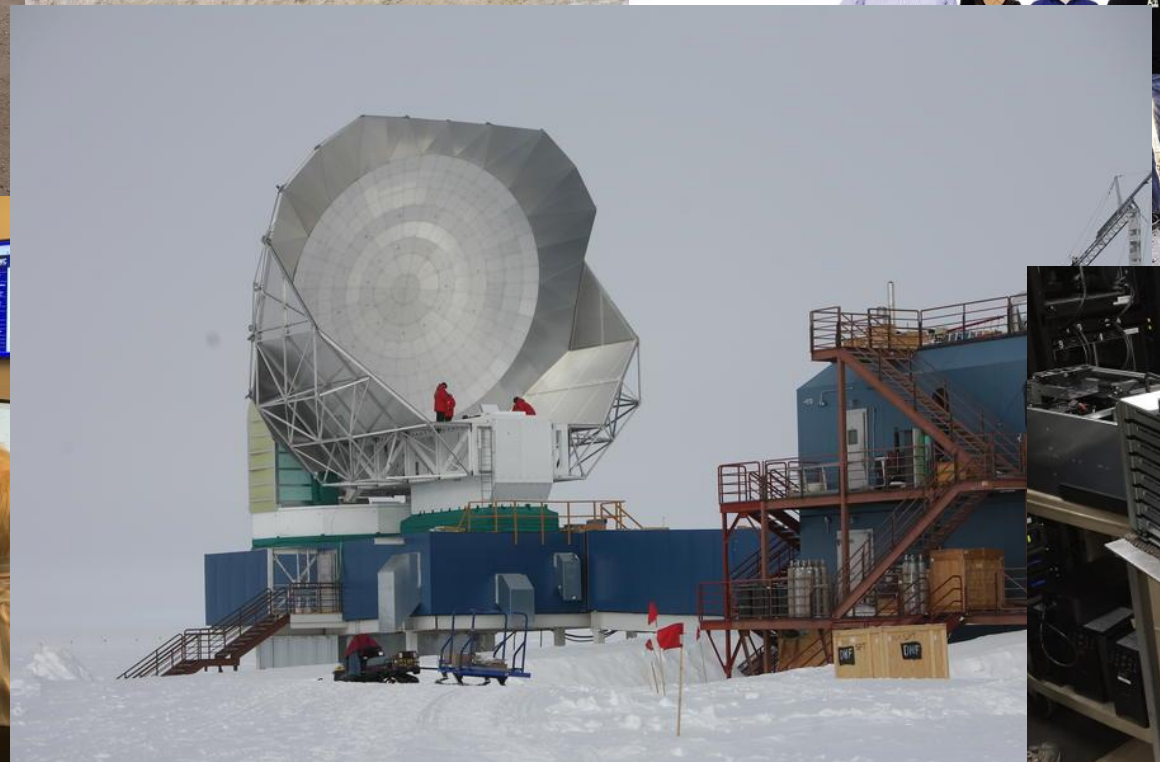
Doeleman et al. (2009)
Fish et al. (2011)

Sgr A* with the EHT



Doeleman et al. (2009)
Fish et al. (2011)

2017 EHT Observations



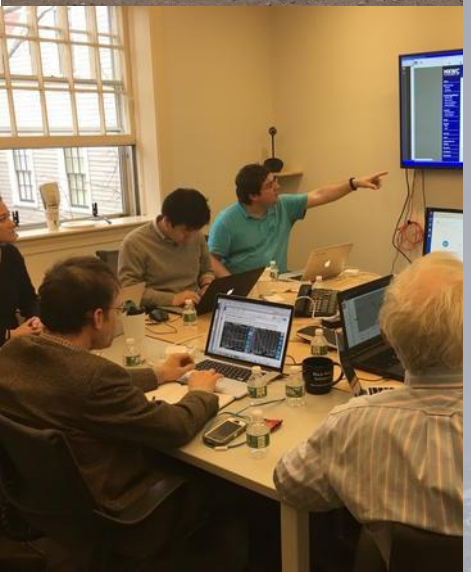
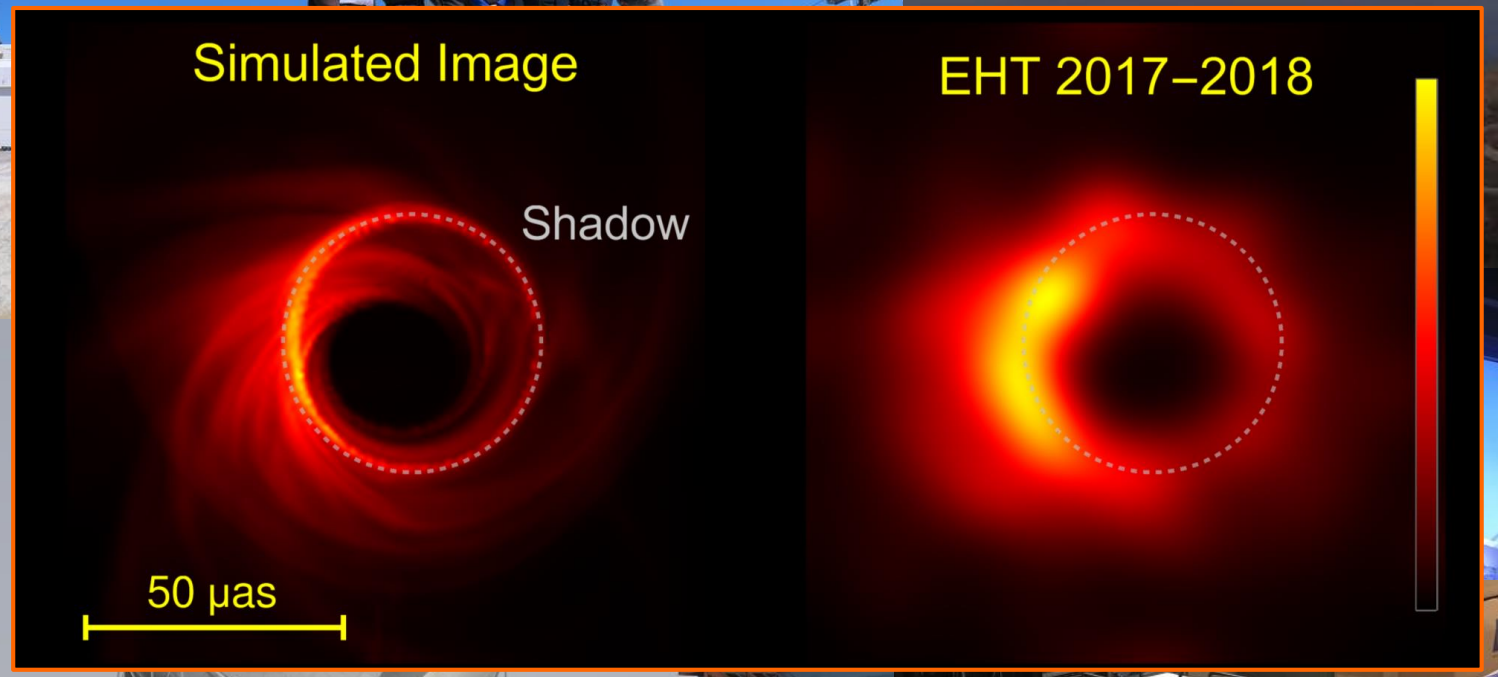
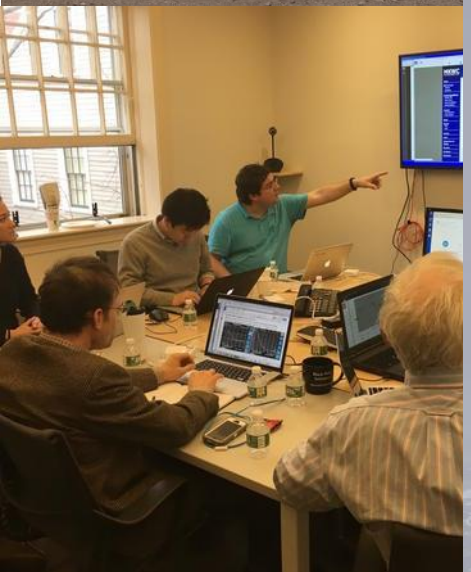


Image credits: David Michalik,Atish Kamble, Ju
Salvaor Sanchez, Helge Rottman , Katie Boum
Haystack Observatory

2017 EHT Observations





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Thank You!