RECENT TRIUMPHS OF GR – THE FIRST IMAGE OF BH

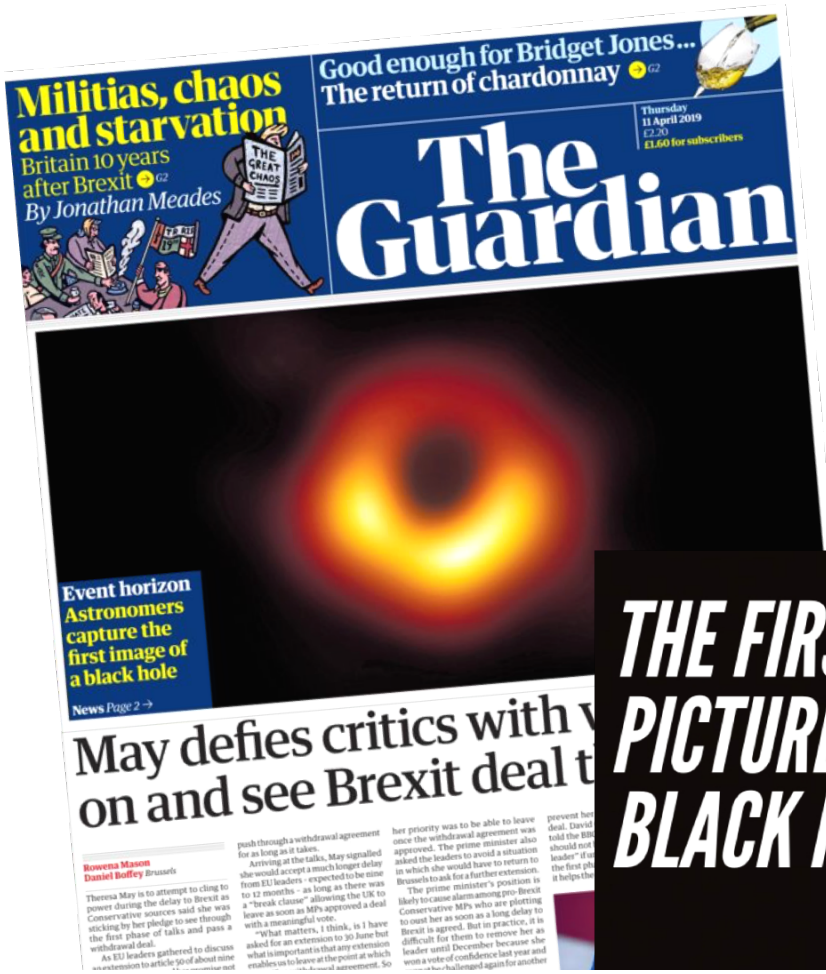
Lecture 14, Introduction ot Black Hole Astrophysics

NTHU, 6/1/2021

THROUGHOUT THE SERIES…

- Lecture 01 (4/13)： A brief history of BHs / 黑洞簡史
- Lecture 02 (4/20)： BHs in Einstein's theory of general relativity / 廣義相對論中的黑洞
- Lecture 03 (4/27)： Observational discovery of BHs / 黑洞的觀測證據
- Lecture 04 (5/4)： BH accretion disks / 黑洞吸積盤
- Lecture 05 (5/11)： Supermassive BHs and Active Galactic Nuclei (AGN) / 超大質量黑洞與活躍星系核
- Lecture 06 (5/18)： The SMBH at our Galactic center / 銀河系中心的超大質量黑洞
- Lecture 07 (5/25)： Relativistic jets from BHs / 黑洞噴射流
- Lecture 08 (6/1)： AGN feedback on galaxies / 黑洞對星系的反饋效應
- Lecture 09 (6/8)： Origin of SMBHs / 超大質量黑洞的形成機制
- Lecture 10 (6/15)： Recent triumphs of GR – gravitational waves & the first image of BH / 廣義相對論的最新驗證--重力波和首張黑洞影像

April 10, 2019



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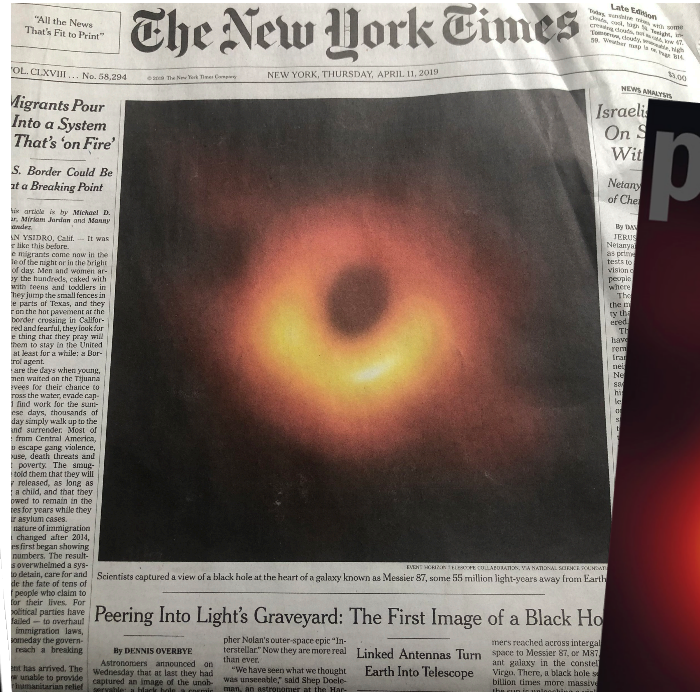

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Late Edition

VOL. CLXVIII ... No. 58,294 — NEW YORK, THURSDAY, APRIL 11, 2019 — $3.00

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Scientists captured a view of a black hole at the heart of a galaxy known as Messier 87, some 55 million light-years away from Earth.

Peering Into Light's Graveyard: The First Image of a Black Ho

By DENNIS OVERBYE

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NEWS ANALYSIS

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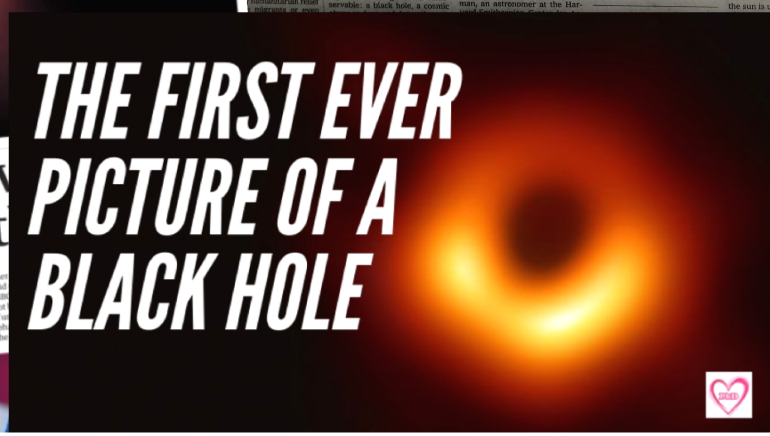
Volume 32 No 5 May 2019

SEEING THE UNSEEABLE Historic first image of a black hole



The New York Times

Late Edition

Today, some sunshine giving way to times of clouds, cold, high 28. Tonight, a flurry or heavier squall late, low 15. Tomorrow, windy, frigid, high 21. Weather map, Page A19.

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NEW YORK, FRIDAY, FEBRUARY 12, 2016

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WITH FAINT CHIRP, SCIENTISTS PR… EINSTEIN COR…

A RIPPLE IN SPACE…

An Echo of Black Holes Colliding a Billion Light-Years Away

By DENNIS OVERBYE

A team of scientists announced on Thursday that they had heard and recorded the sound of two black holes colliding a billion…

Feb 11, 2016

重力波 世界初観測

山陰新聞

2016年2月12日

2月12日 金曜日

米大チーム

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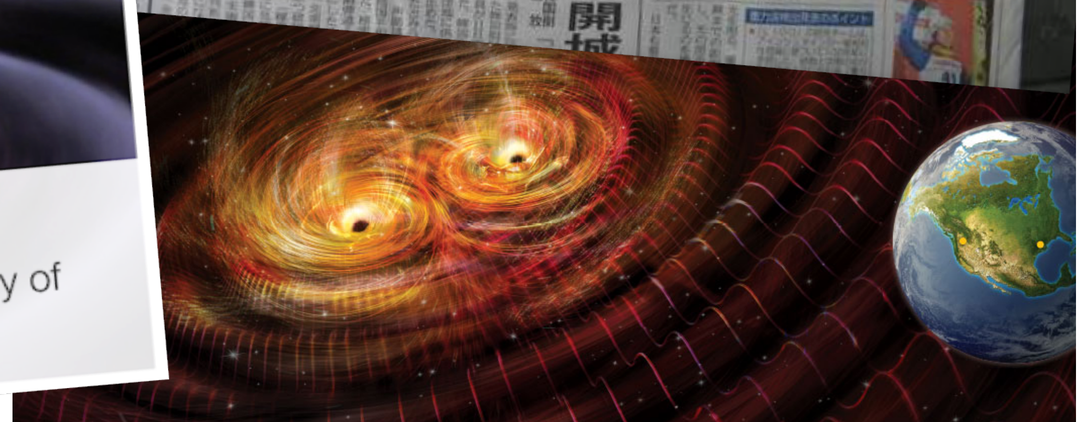
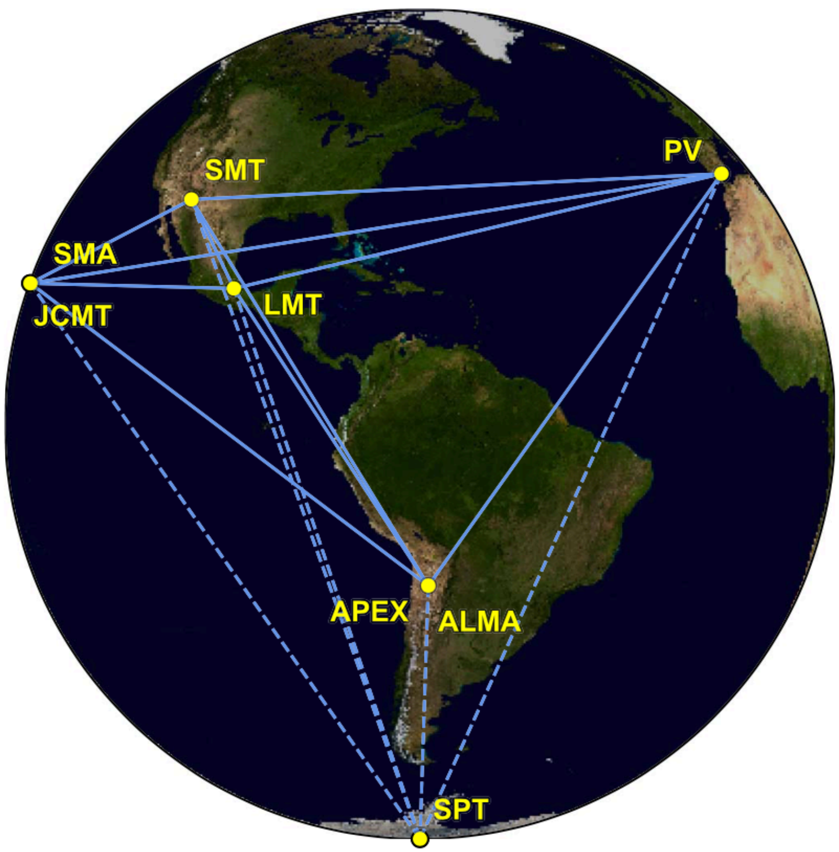
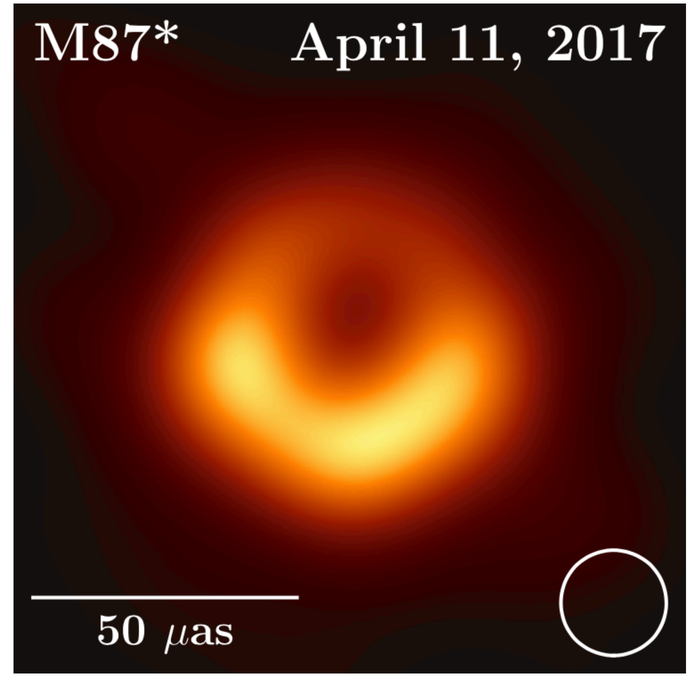


THIS LECTURE

- First image of BH
  - The image of the M87 BH observed by EHT
  - BH shadows
  - What to expect in the future
- Gravitational waves (GWs)
  - Properties of GWs
  - Indirect detection of GWs
  - First GW detection by LIGO
  - First detection of NS-NS merger
  - Current status and future prospects

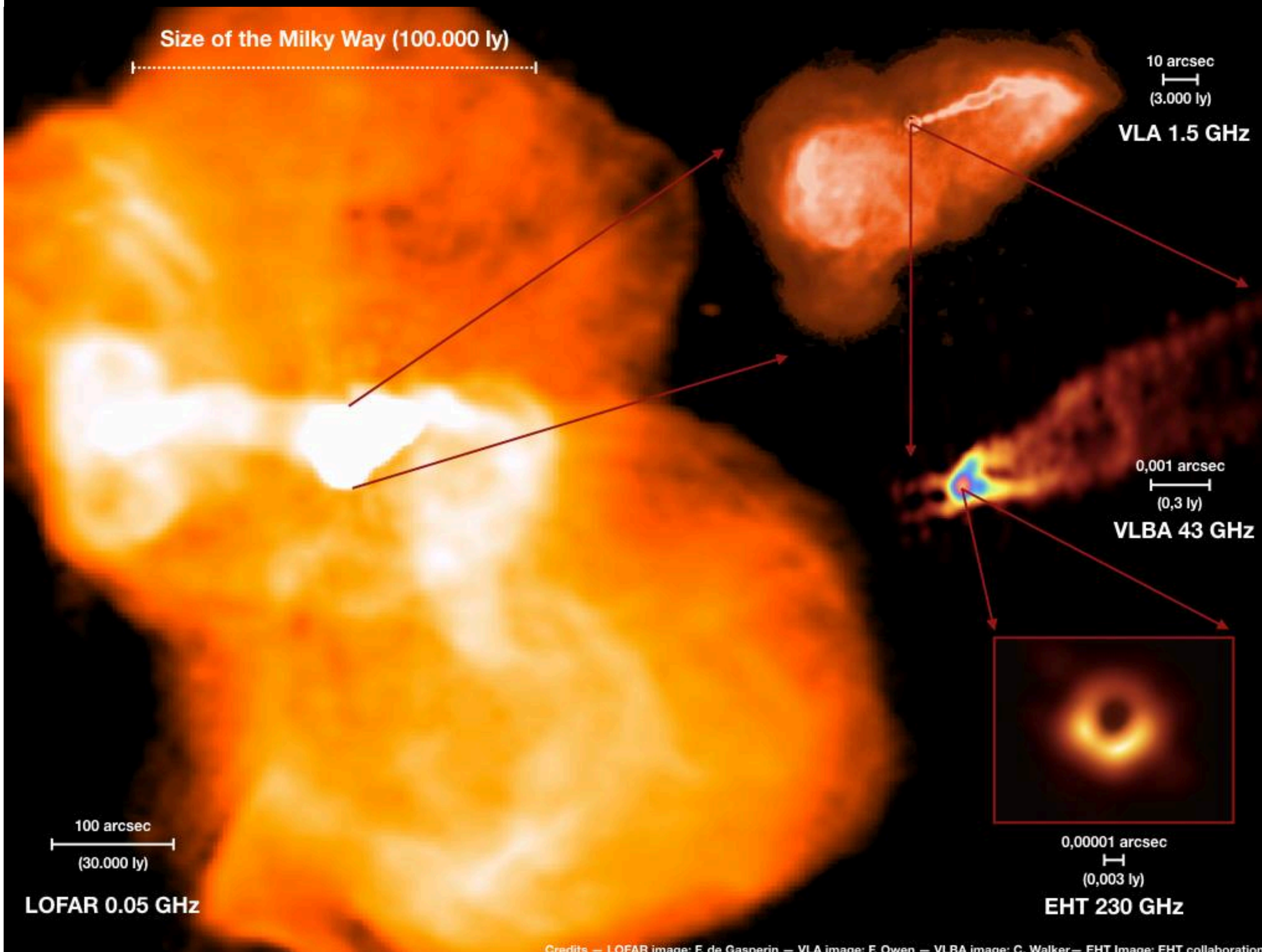
THE FIRST BH IMAGE – M87





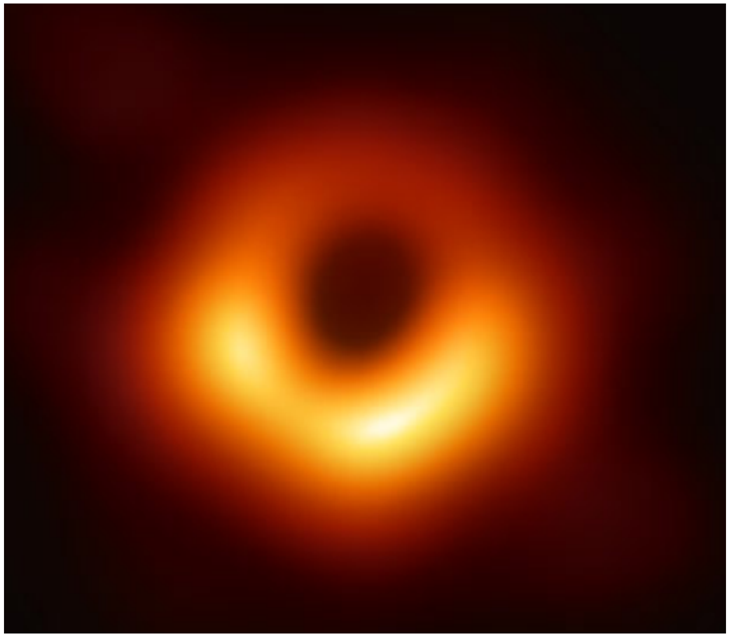
- Taken by the Event Horizon Telescope (EHT), which included 8 radio observatories across 4 continents observing on and off for 10 days in April 2017
- Diffraction limit of telescopes: $\theta \propto \lambda/D$
- Extraordinary resolution ~ 25 microarcsec!

THE M87 SMBH



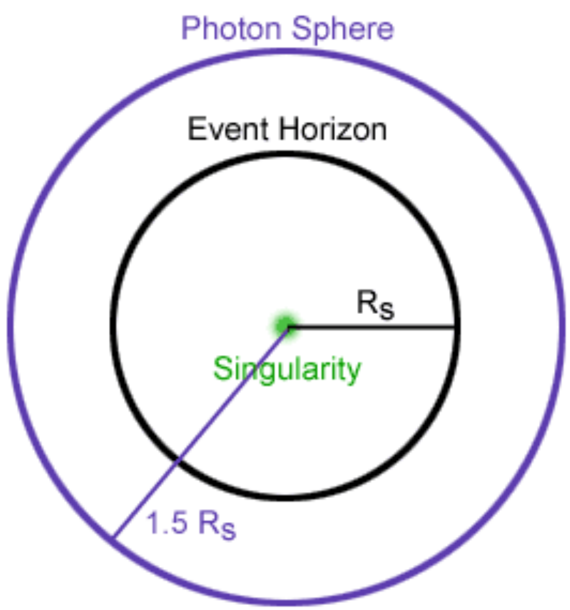
- M_{BH}~6.5×10^9 M_{sun} within M87 galaxy in Virgo cluster
- Distance~55 million light years
- Radiatively inefficient thick accretion flows
- Relativistic jets and lobes extending to 10^5 light years

WHAT ARE WE SEEING?



- BH "***shadow***" – dark region due to light rays captured by the BH
- Bright ring – synchrotron emission from the thick accretion flow
- Asymmetry – because of ***relativistic beaming***
- Properties well described by ***GR***!
- Shadow diameter ~ 42 microarcsec
  - M_{BH} ~ 6.5 x 10^9 M_{sun}
  - R_s ~ 0.002 light years ~ 7.6 microarcsec
  - Shadow size does NOT correspond to the event horizon!

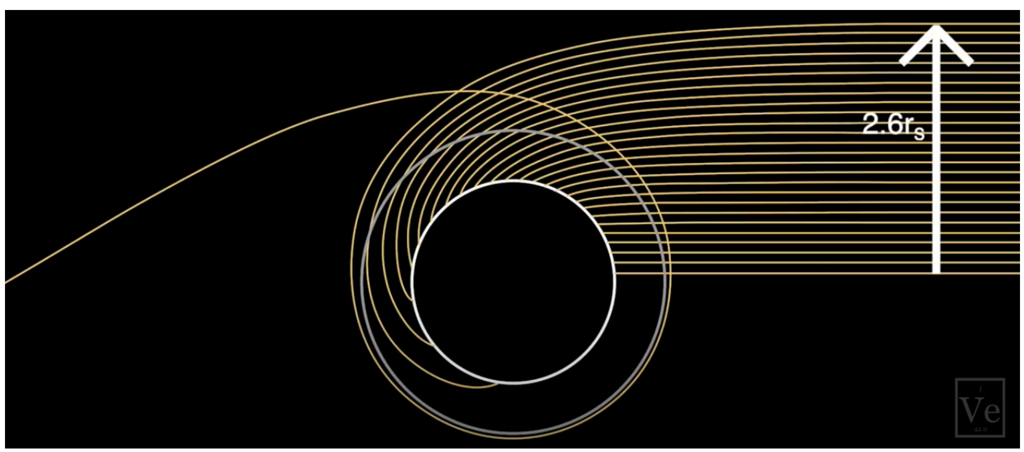
RECALL THE STRUCTURE OF BH



- For a Schwarzschild BH, the event horizon is at $R_s = 2GM/c^2$
- Innermost stable circular orbit (ISCO) for ***particles*** is at $R_{ISCO} = 3\ R_s$
- ***Photon sphere at $R_{ph} = 1.5\ R_s$***
  - The radius ***photons*** can maintain a circular orbit
  - But unstable -> so photons would either go in or out given any perturbations
- But the shadow size does NOT correspond to the radius of photon sphere either!?

WHAT IS THE SHADOW?

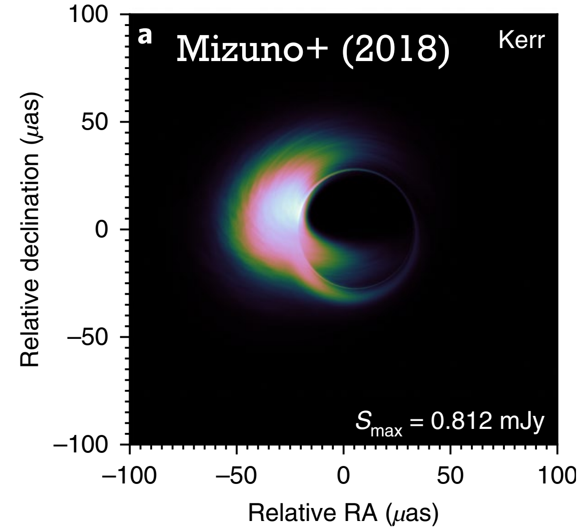
- Light rays are strongly bent due to curved spacetime near the BH -> ***gravitational lensing***
- Light rays would be captured within the ***photon capture radius $R_c = 2.6\ R_s$*** -> this times 2 is the size of the shadow!
- The shadow size is mainly dependent on M_{BH}, though the exact shadow radius and shape would be slightly modified by resolution, spin, inclination, etc., which can be calibrated using simulations



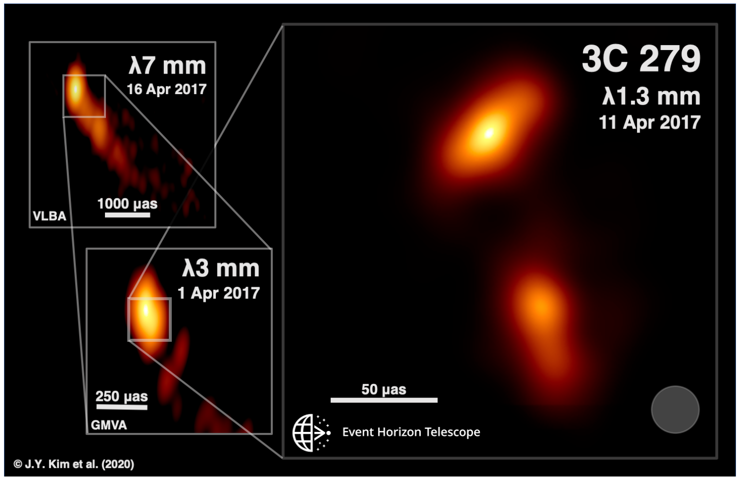
WHAT TO EXPECT NEXT?

- The image of Sgr A*!
  - Shadow size comparable to M87
  - Variability timescale < 1 hour
- Jets from BHs like the one recently discovered for quasar 3C 279
  - Images taken at different times could constrain, e.g., jet speed
- Next-generation EHT will focus on sharpening the images and variability of the sources

Simulated image of Sgr A*



EHT image of jets from quasar 3C 279



SUMMARY

- The theory of ***GR*** remains valid after the two recent observational breakthroughs, i.e., gravitational waves, and the first BH image
- ***The first BH image*** of the M87 SMBH by EHT
  - Requires extraordinary resolution ~ 25 microarcsec
  - The observed image is fully consistent with GR prediction
  - The bright ring comes from emission of gas within the thick accretion flows
  - The BH shadow is caused by ***gravitational lensing*** of light rays close to BH, shadow size ~ $2R_c \sim 5.2\ R_s$

RECENT TRIUMPHS OF GR – THE FIRST IMAGE OF BH (UPDATES)

Lecture 14, Introduction of Black Hole Astrophysics

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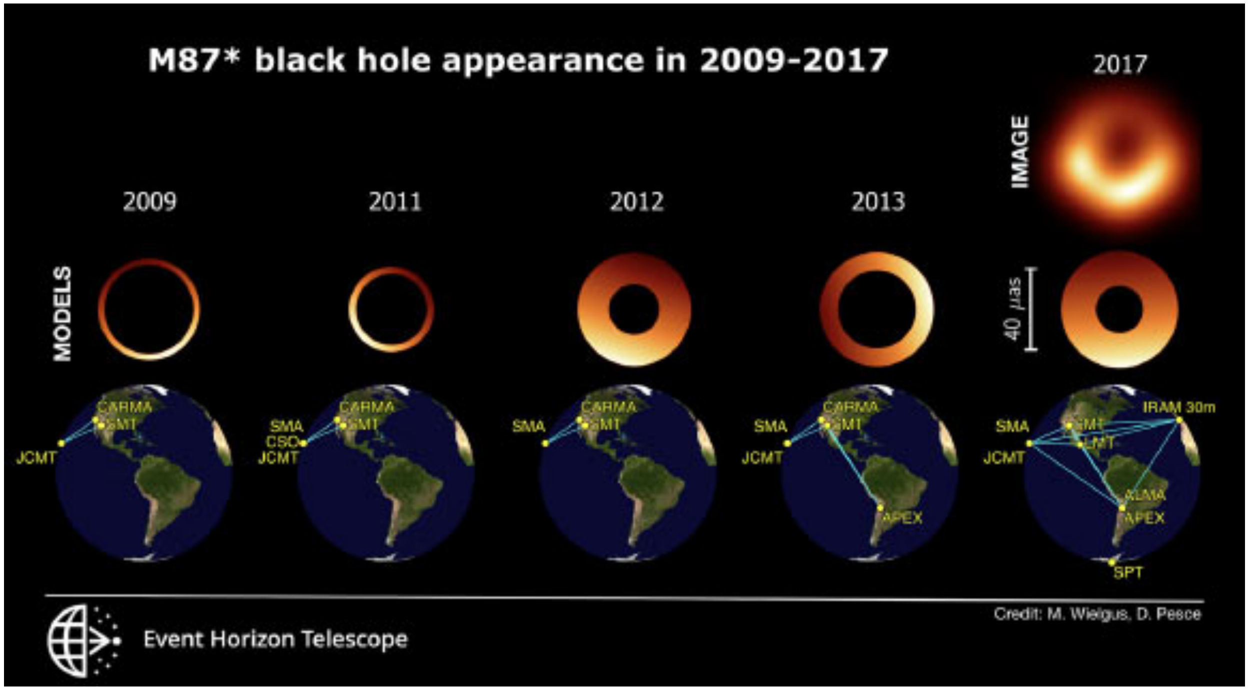
WHAT CAN EHT DO?

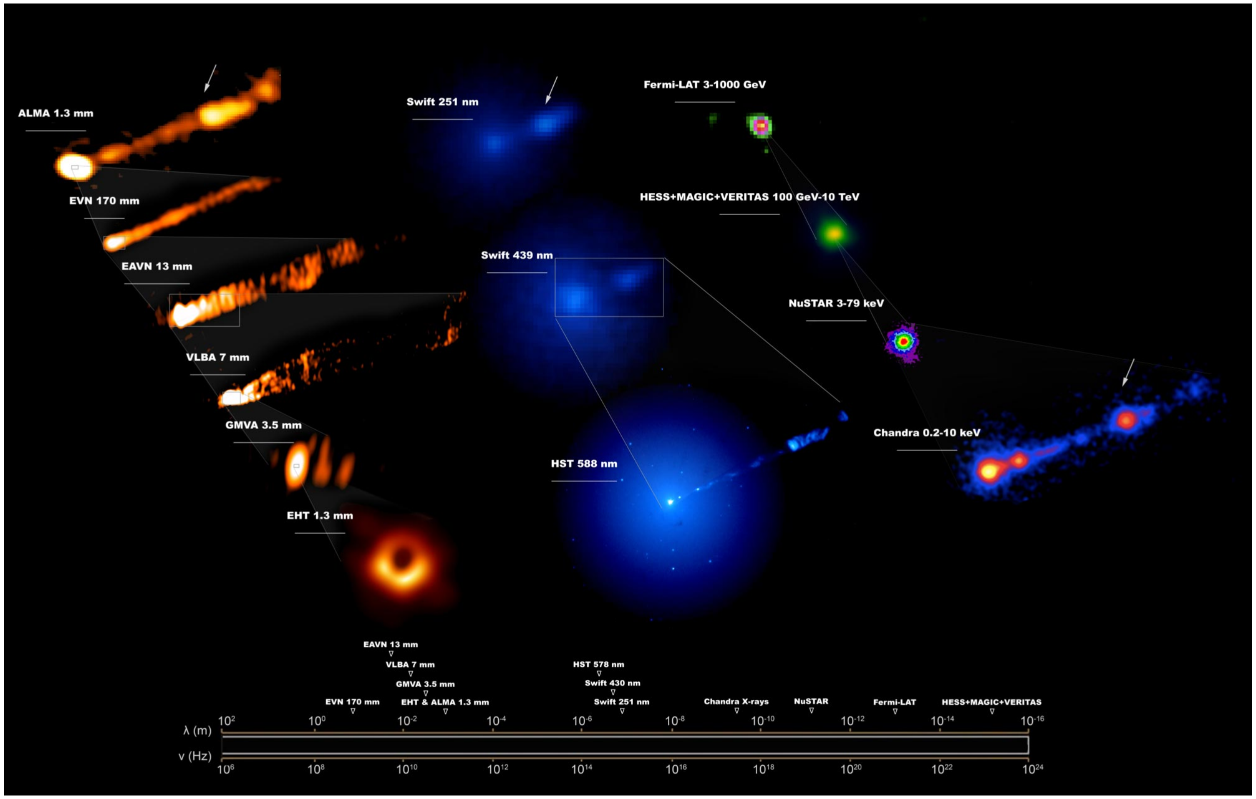
(1) Study the ***variability*** of the ring (see the news [here])

- The ring is persistent, but the bright part wobbles on timescale of years, possibly due to turbulence within the accretion flow



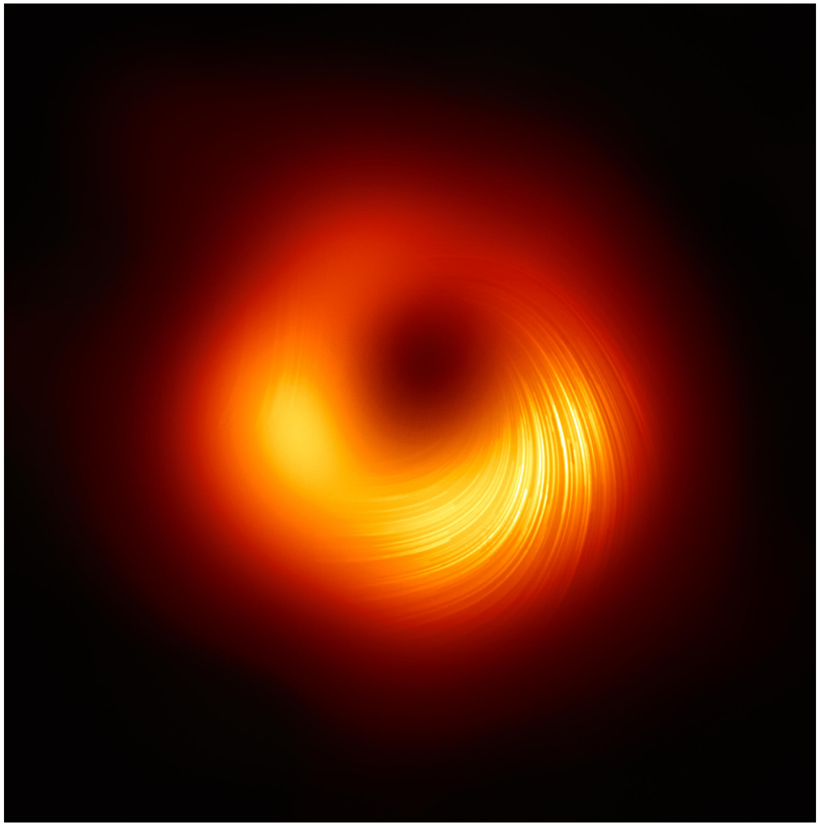
WHAT CAN EHT DO?

(2) Combine observations across different scales and different ***wavelengths*** (see the news **here**) -- This allows us to learn about the emission mechanisms and launching conditions of jets



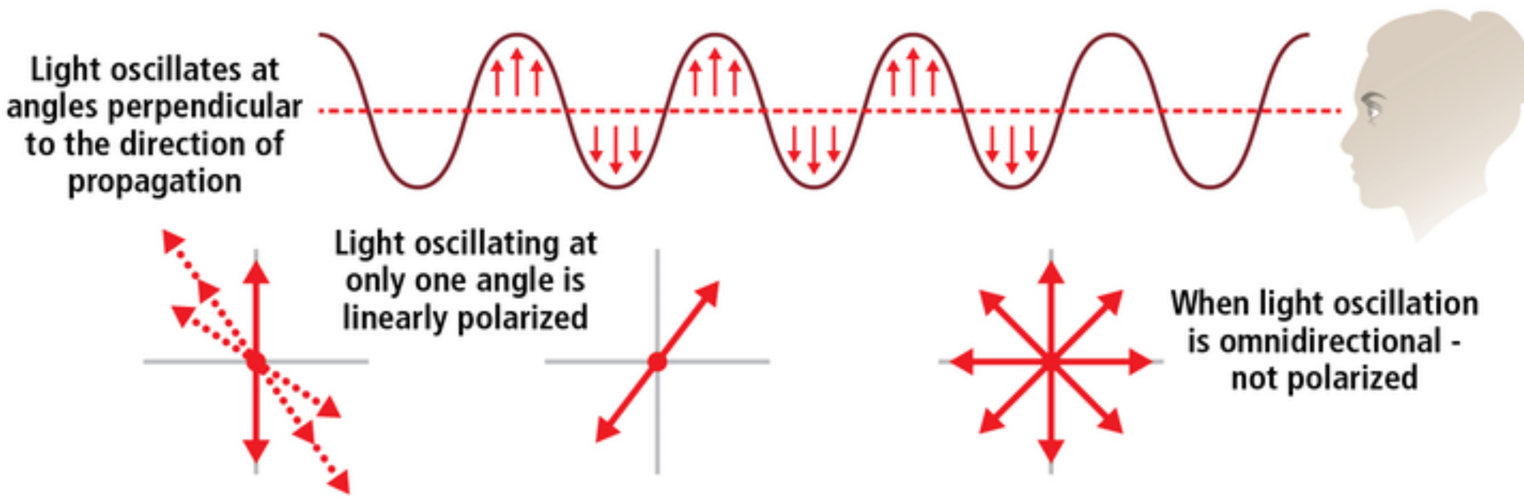
WHAT CAN EHT DO?

(3) ***Polarization*** allows constraints on the strengths and structures of B field



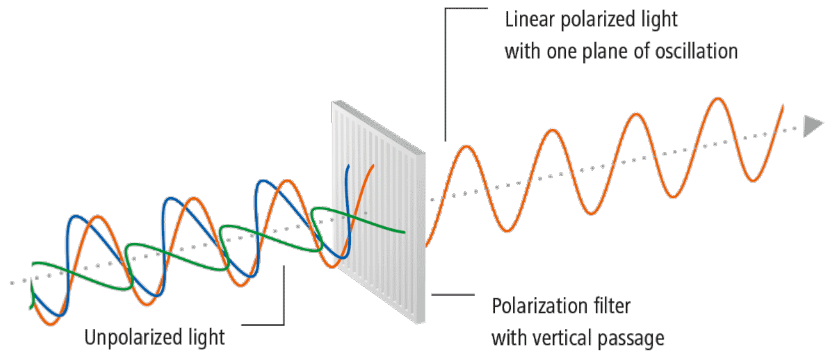
POLARIZATION OF LIGHT

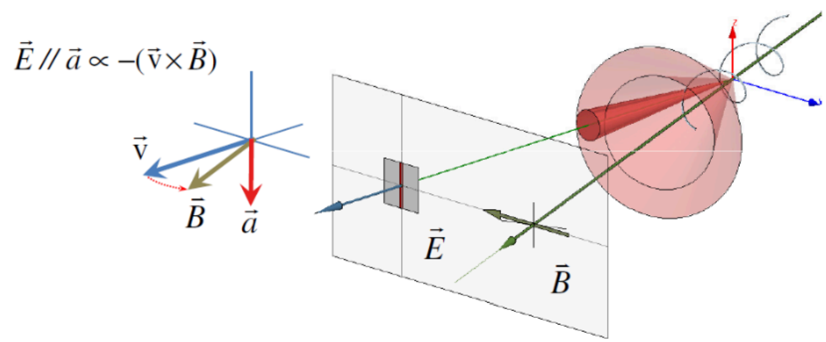
- Light is an electromagnetic wave, consisting of oscillating electric (E) and magnetic (B) fields, which are perpendicular to each other and both are perpendicular to the direction of propagation
- ***Polarization*** refers to the direction of the ***E field*** as seen by an observer



POLARIZATION OF LIGHT

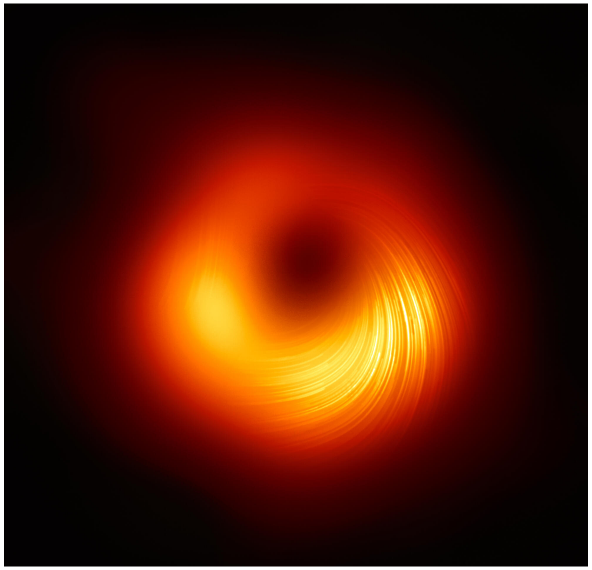
- Unpolarized light gets polarized when it passes through a polarizer, which allows waves of only one polarization to pass through, e.g., sunglasses with a polarized filter, or a magnetized medium
- ***Synchrotron radiation is polarized*** too
  - Due to relativistic beaming, synchrotron emission is confined in a cone
  - Averaged synchrotron emission is ***polarized*** on the plane of sky perpendicular to B

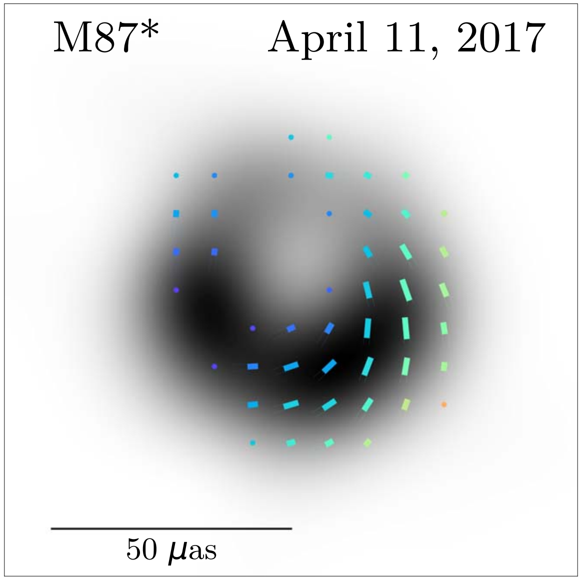




WHAT ARE WE SEEING?

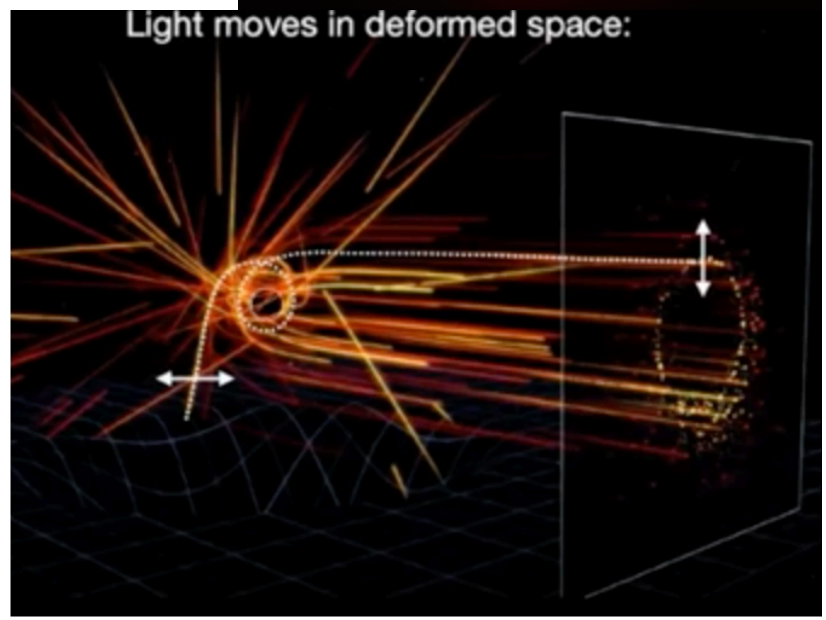
- This pretty image is an artistic representation to blend the ***total intensity*** image with the ***polarization angle***
  - Note that the lines do NOT represent B field directions
- Lower right figure shows the actual polarization fraction and direction
- Robust detection of polarized emission in the southwest direction of the image
- Polarization fraction is ~5-10%

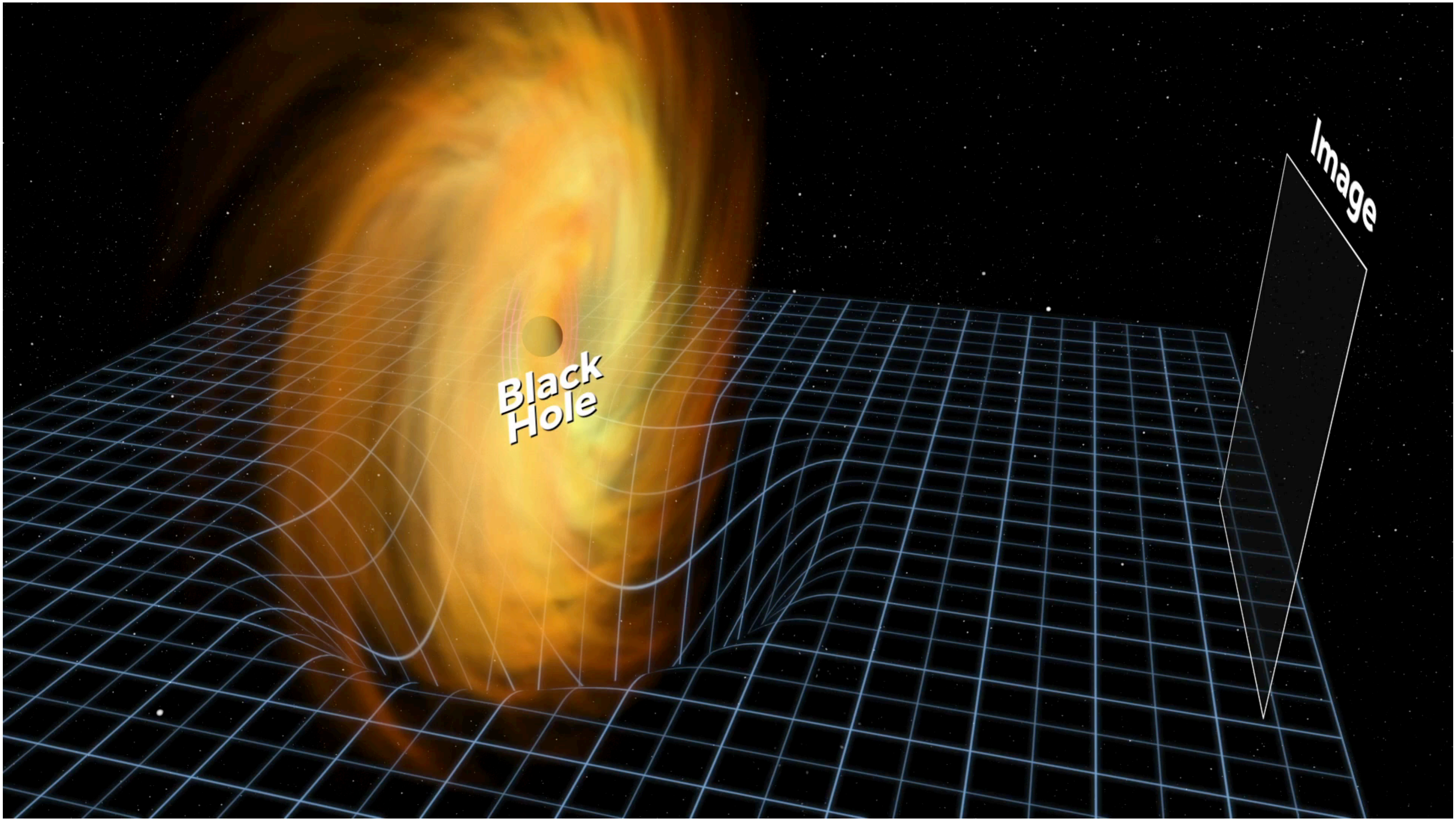




WHAT ARE WE SEEING?

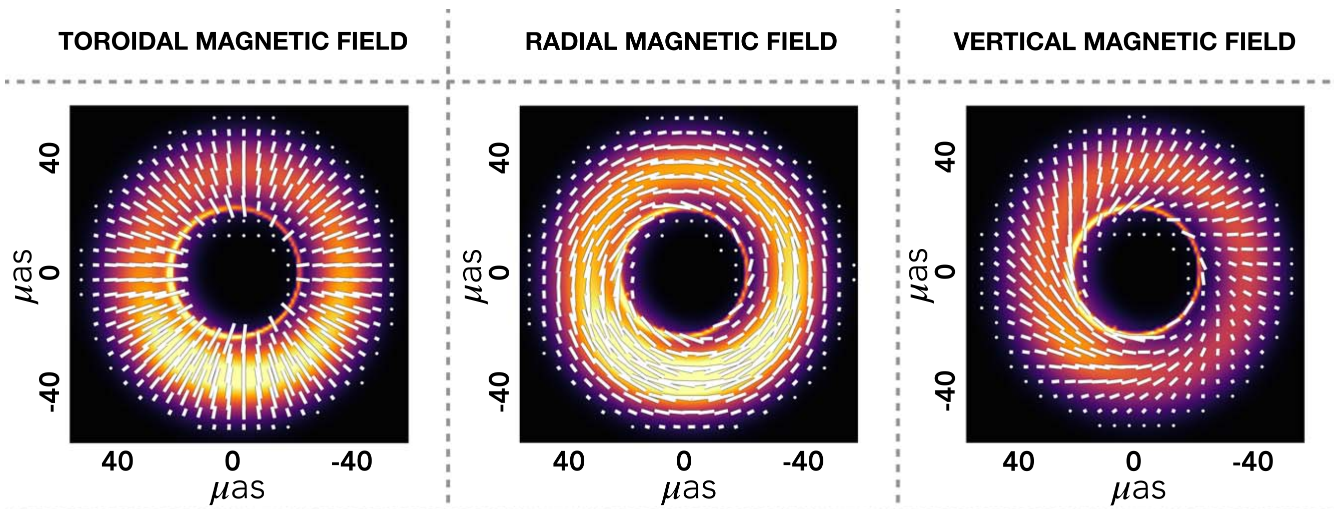
- Do the lines represent perpendicular directions of the B field within the accretion flow?
- Not necessarily, because
  - The image we are seeing includes all the photons traveling towards us from the photon sphere, even including photons behind the BH due to ***gravitational lensing***
  - Lensing changes the polarization angle too
- To infer the true B field structure, the EHT used GRMHD simulations with various parameters to find the best-fit parameters (not an easy task!)




Black Hole
Image

WHAT HAVE WE LEARNED?

- The ***wrapping*** geometry of the M87 polarization image is best described by a ***relatively strong B field*** with |B|~ 1-30 G
- This B field means that magnetic field is dynamically important within the accretion flow
  - This has narrowed down the parameter space and allowed better constraints on, e.g., BH accretion rates and jet power
- The B field configuration is likely to be ***poloidal*** (i.e., with substantial vertical component)



SUMMARY

- In the future, EHT will continue to probe the accretion properties of BHs, especially studying their ***variability***, ***multi-wavelength observations***, and ***polarization***
- The M87 polarization image has allowed us to learn about the B field properties near the M87 SMBH
  - Complex due to ***lensing*** -> B field inferred using numerical simulations
  - Wrapping of the polarization angle -> dynamically important field of $|B| \sim 1\text{-}30$ G
  - B field likely to be poloidal
  - Narrowed the parameter space compared to only having the total intensity image

PRESENTATIONS 6/1

- A supermassive black hole on the move by Yu-Xuan Fan 范宇軒

https://qrgo.page.link/iwAL5

- New study suggests supermassive black holes could form from dark matter by Zheng-Xian Xu 許正憲

https://qrgo.page.link/erLTX

- Is there a black hole in our backyard? By Jun-Ting Li 李俊霆

https://qrgo.page.link/T22hW