Class 21 :
Event Horizon Telescope

ASTR350 Black Holes (Spring 2022)
Cole Miller

RECAP

- **The course so far!**

- Part I : Background physics of black holes
  - Newton’s and Einstein’s theories of gravity
  - General Relativistic description of black holes
- Part II : Stellar mass black holes
  - Life and death of massive stars
  - Neutron stars, pulsars and stellar mass black holes
  - Accretion disks; X-ray binaries
- Part III : Supermassive black holes
  - Discovery of quasars and AGN
  - Properties of AGN; properties of jets
  - AGN feedback on galaxy evolution/formation

This class

- Start on the final phase of the course… black holes as laboratories for *fundamental* physics
- TODAY
  - What do we mean by fundamental physics, and why is it interesting to study?
  - Direct (or are they?) observations of event horizon physics with the Event Horizon Telescope
  - Start on our discussion of gravitational waves… what are GWs?

I : Fundamental Physics

- Physics seeks to explain and describe the most basic aspects of the Universe
  - **Fundamental Physics** is the study of basic properties, materials, and forces in our Universe.

- Let's think a bit
  - What kinds of things do we mean by "the most basic aspects"?
  - Why is it important to keep pushing our understanding?
    - why do we keep 'testing' GR?
    - why do we 'need' confirmation that the objects are the 'black holes' predicted by GR ?

I : Fundamental Physics

- A bit of history
  - Discoveries in the last century+ in fundamental physics have overturned our assumptions about the world around us.
    - General relativity reshaped our picture of space and time, and quantum mechanics replaced the march of cause and effect with a dance of probabilities. Recently the discoveries of **dark matter and dark energy** show that they account for most of the contents of the Universe.
    - This century is likely to produce more surprises.
      - Physicists are opening windows into the deep structure of reality.

https://breakthroughprize.org/Prize/1

I : Fundamental Physics

- GR and quantum mechanics have both been tested in their relevant scales and so far they pass all tests
- General relativity, accounts for gravity and all of the things it dominates: orbiting planets, colliding galaxies, the dynamics of the expanding universe as a whole. **That's big.**
- Quantum mechanics, describes the other three forces – electromagnetism and the two nuclear forces. Quantum theory describes what happens at the atomic and sub-atomic level, or physics of light. **That's small.**

BUT

I : Fundamental Physics

They do not work together well

The division between the relativity and quantum systems as "smooth" versus "chunky".

- In general relativity, events are continuous and deterministic, meaning that every cause matches up to a specific, local effect.
- In quantum mechanics, events happen in jumps with probabilistic outcomes. Quantum mechanics allow processes forbidden by classical physics.

https://www.theguardian.com/news/2015/nov/04/relativity-quantum-mechanics-universe-physicists

I : Fundamental Physics

- Relativity gives nonsensical answers when scaled to quantum sizes
- Quantum mechanics runs into serious trouble on cosmic scales.

- We may revisit these questions at the end of the class

Some Basic Principles of GR Testable with the Event Horizon Telescope Data

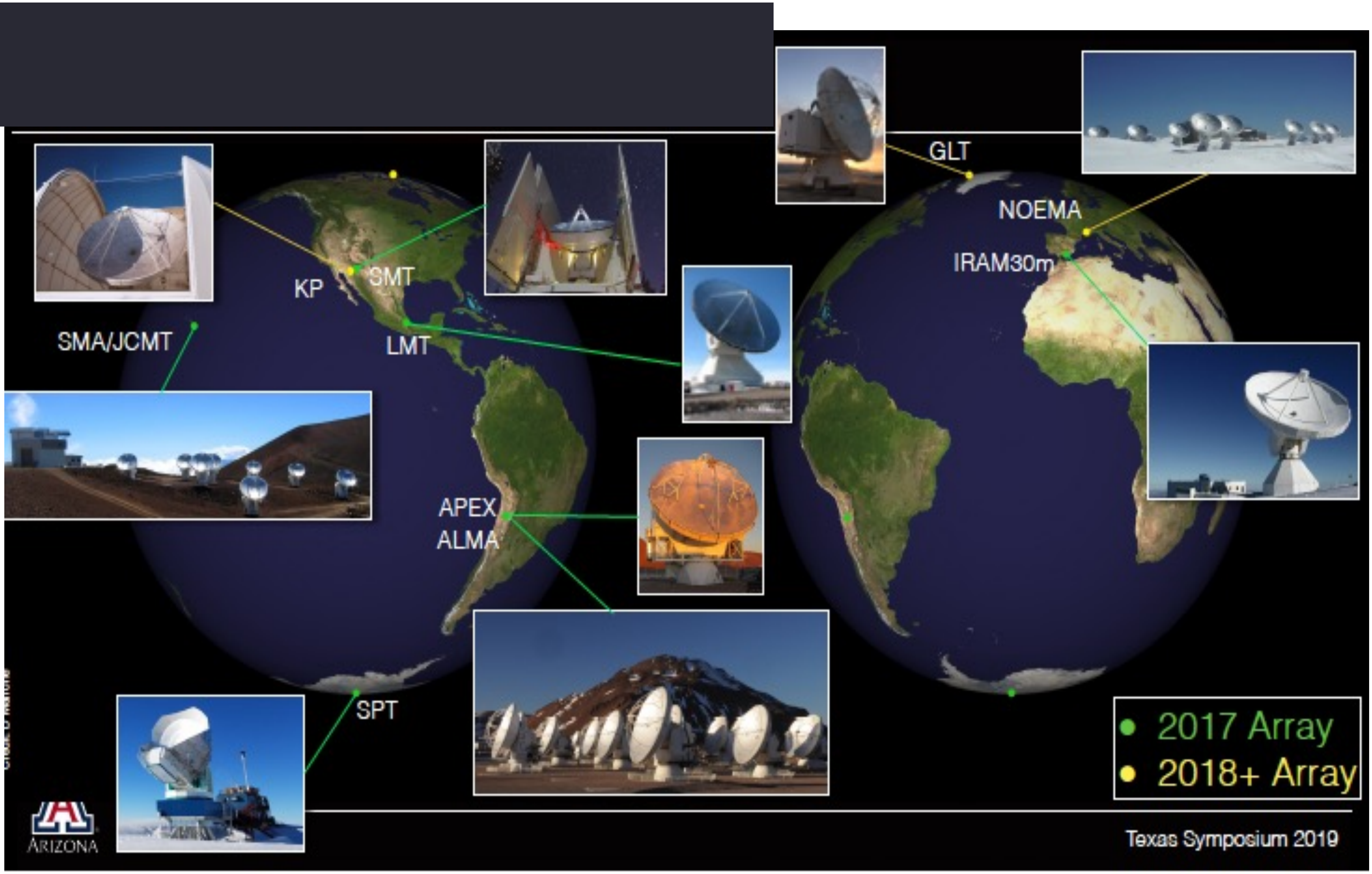
- Existence of an event horizon (EH)-The diameter of the shadow is proportional to the mass of the black hole.
- Are SMBHs described by the Kerr metric?

- Physics associated with this 'place'
- EH size and 'shape'
- Measurements of luminous matter ("hotspots") orbiting near the event horizon, can map the space time metric near the black hole and constrain the black hole spin.

- Test of the "no hair" theorem - General relativity predicts that the shadow of a black hole should be circular, but a black hole that violates the no-hair theorem could have a prolate or oblate shadow.

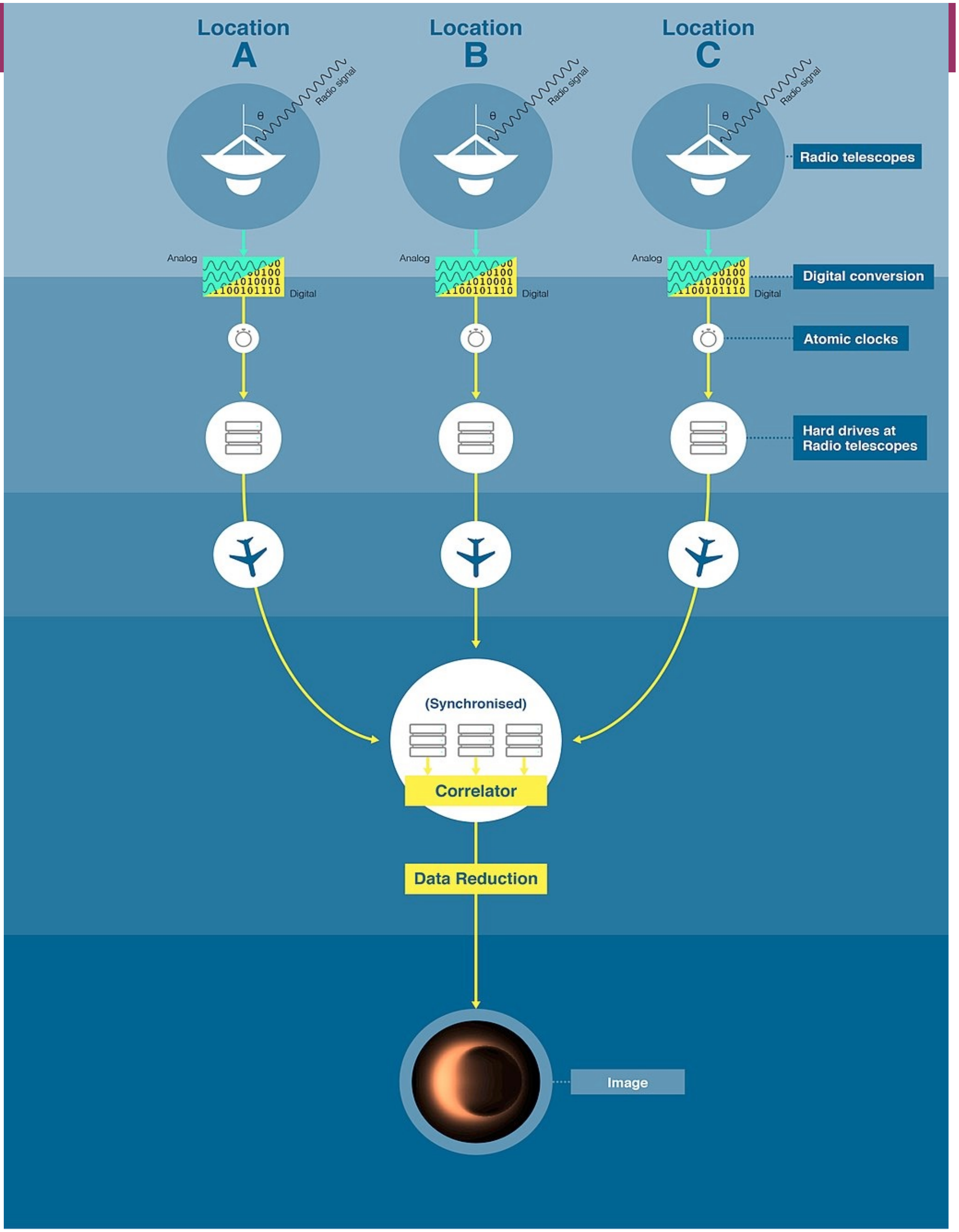
EHT-World's "Largest" Telescope-

Need long baselines and lots of collecting area



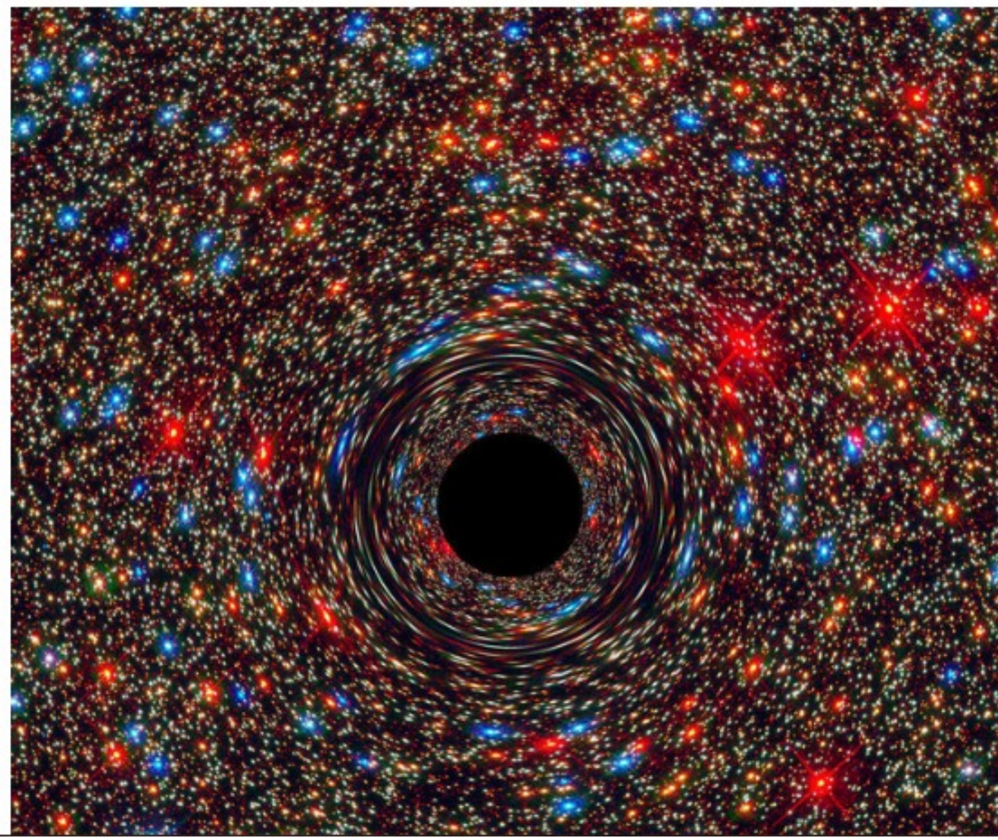
How it works

Synthesize a very large telescope by combing many smaller ones spread out across the earth
Collect the data, synchronize it, send it via largest data pipeline (hard disks via airplane!!!)



Photographing a Black Hole: Historic Campaign Now Underway

By Mike Wall, Space.com Senior Writer | April 5, 2017 03:30pm ET

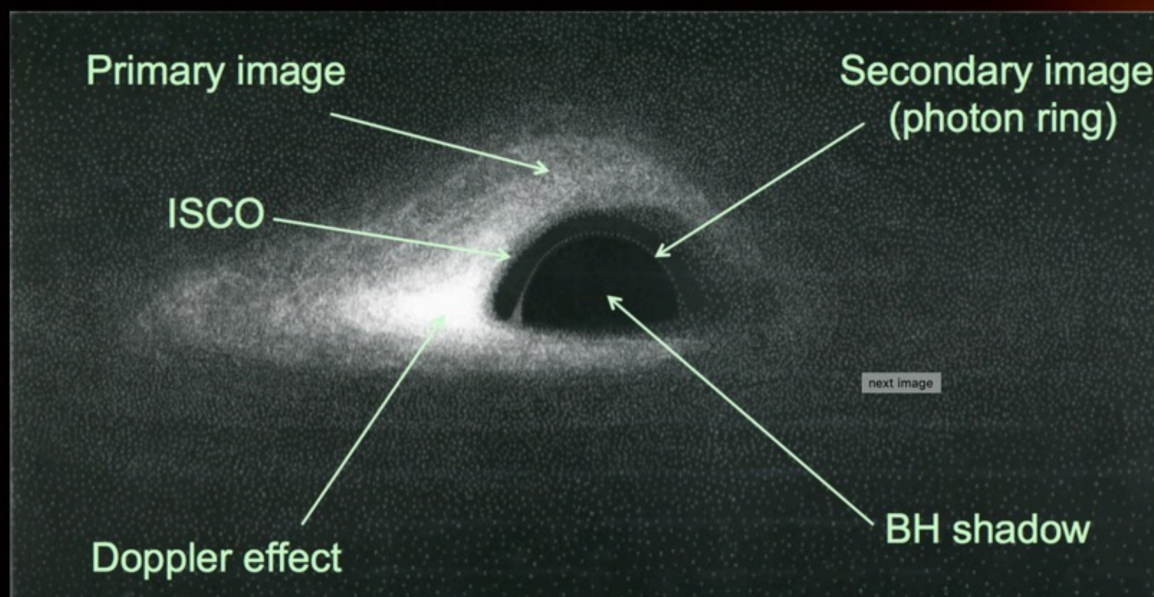


Shadow of A Black Hole

- "To a distant observer, the event horizon casts a “shadow” whose diameter is ~10 gravitational radii" (Bardeen 1973) –

more exact solution - a dark circular region in the center — a shadow — is always present. The outer edge of the shadow is located at the photon ring radius $r_{ph} \equiv \sqrt{27} r_g$, where $r_g = GM/c^2$

The shadow phenomenon is caused by gravitational light deflection – gravitational lensing – by the black hole



J-P Luminet; Bardeen 1973; Luminet 1979

Shadow of A Black Hole

- This shadow is potentially observable for a SMALL number of objects given our present technology (limited by size of earth, the known mass of nearby black holes and their distance)*.
- Detection of a shadow signals the existence of a black hole,.. the precise form of the shadow can discriminate between different candidate black hole solutions.

- * if one could put the appropriate radio telescope into space there would be more targets...***but*** telescopes in space have to be smaller (why?), so the sensitivity would be worse

Shadow of A Black Hole

- The best way to observe the shadow is at mm wavelengths for several reasons
  - the very high angular resolution possible with intercontinental VLBI at high frequencies
  - the likelihood that at mm wavelengths the emission was optically thin synchrotron radiation – makes physical modeling tractable
  - the emission is bright enough to detect

The 'size' of the event horizon is

$[1 + \mathrm{sqrt}\,(1 - a^2_*)]\, R_g$, where $R_g \equiv GM/c^2$,

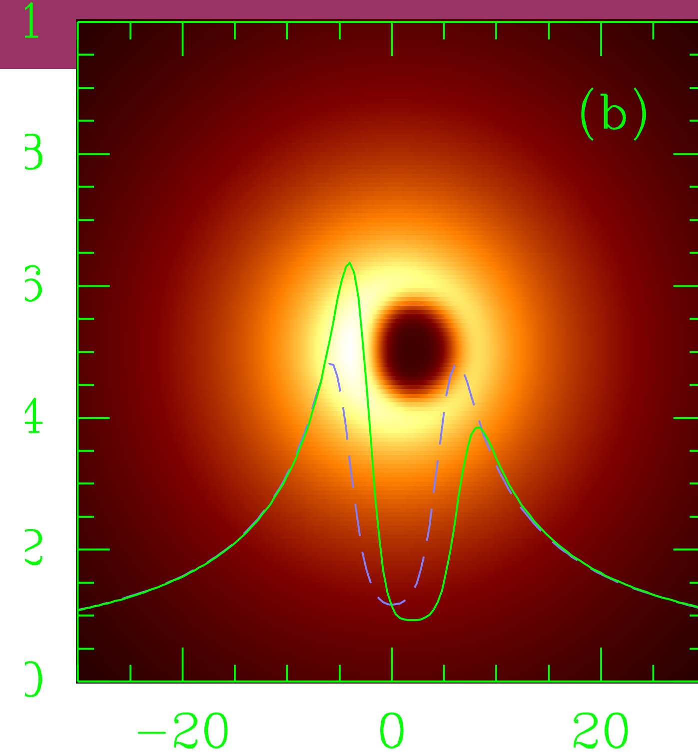
– the shadow is ~5x larger

M mass of the black hole, $a_* \equiv Jc/(GM^2)$ is the dimensionless **spin** of the black hole in the range 0 to 1, and J is the angular momentum of the black hole.

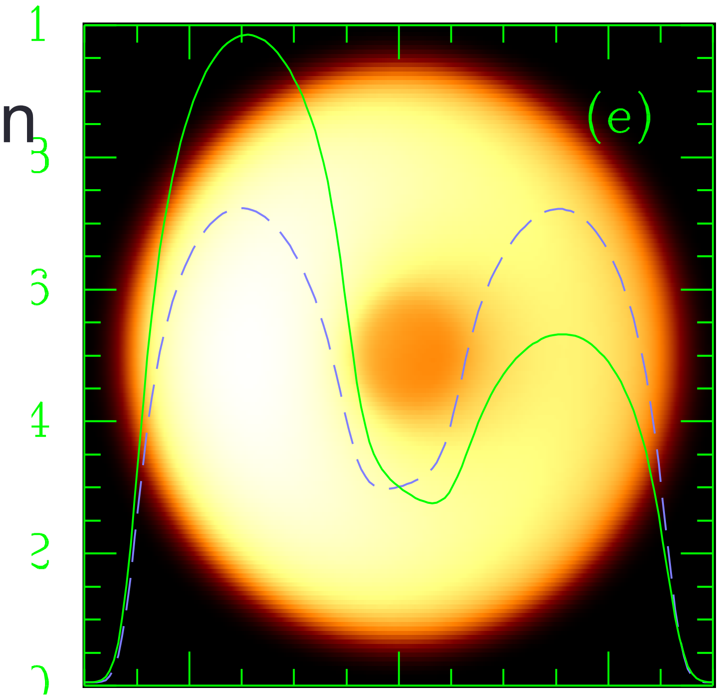
Simulations

The size and shape of the shadow depends slightly on the spin of the BH and more on how the material is accreted and radiates

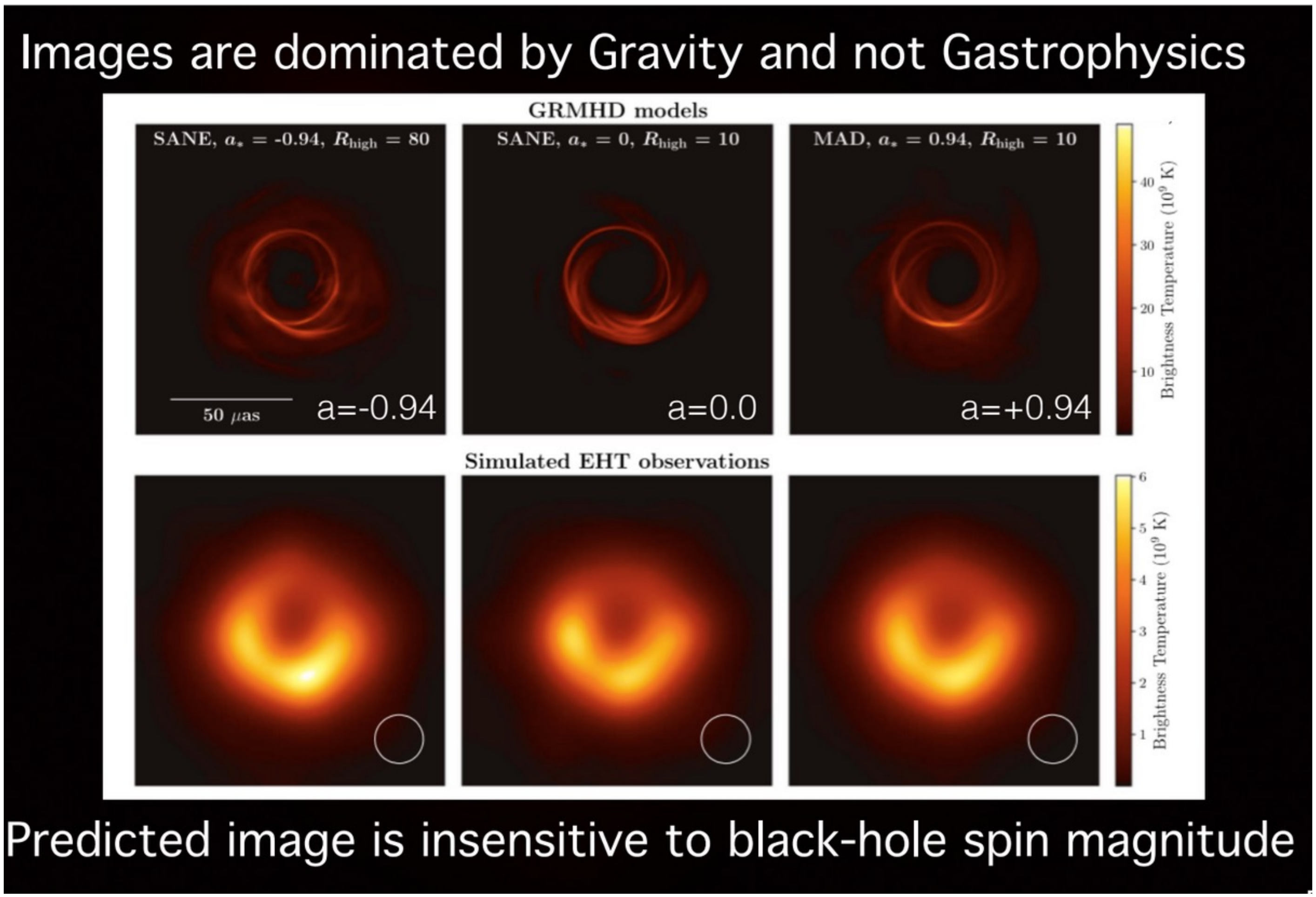
a=0.998
spherical
accretion



a=0
Disk accretion



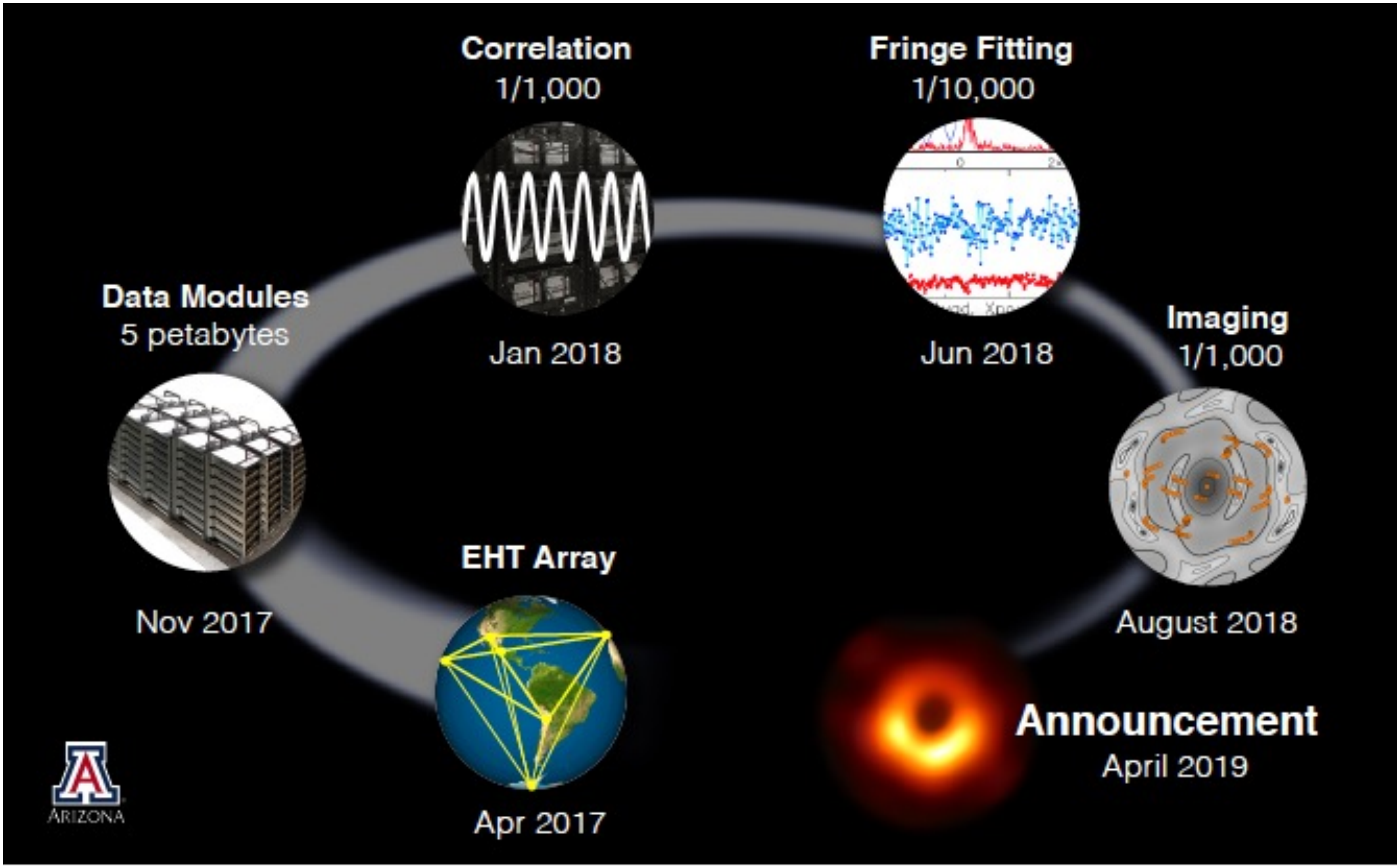
- The Kerr case has radially free-falling gas while in the Schwarzschild case the gas is on Keplerian orbits.
  - This is responsible for more of the variation than the spin.



EHT Paper V, 2019
D.Psaltis

To see the Shadow

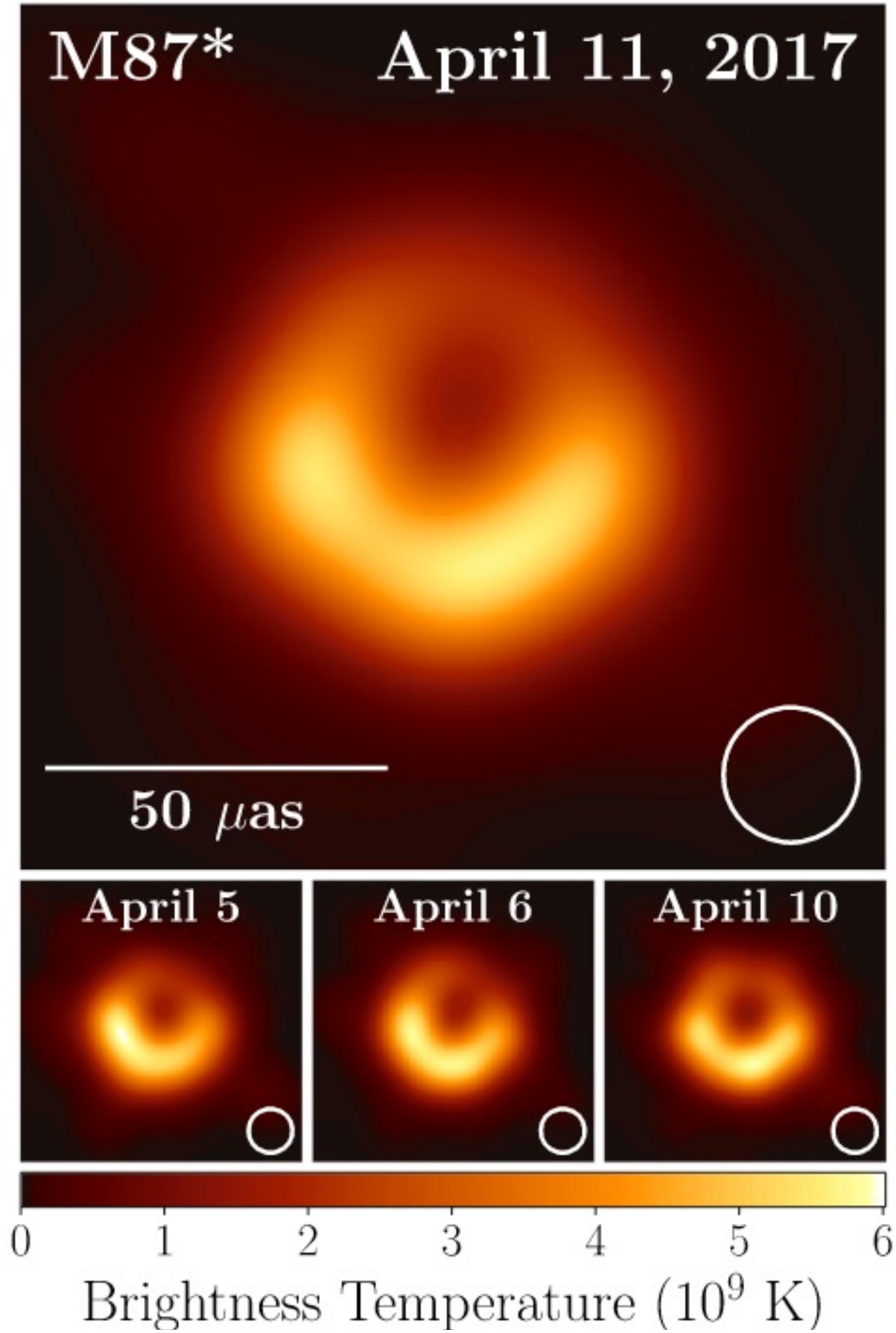
- Huge job of data analysis- need world's 'largest' telescope and serious computers



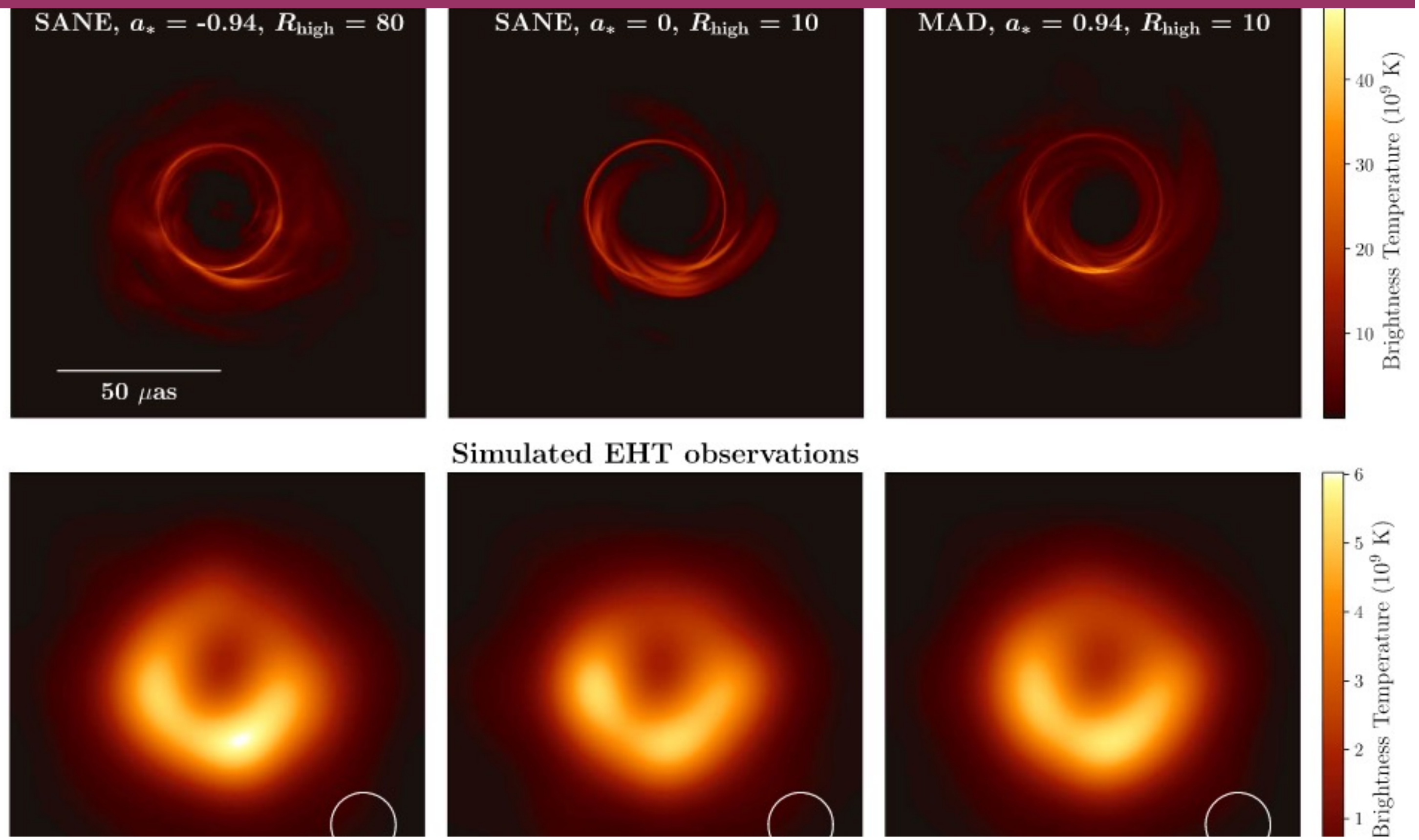
The Result for M87

- the simulations predict a shadow and an asymmetric emission ring.
- The ring is **not** the innermost stable circular orbit, or ISCO, but is instead related to the lensed photon ring.
- Angular resolution of EHT ~20μas~1.5x10^{-3}pc

~$6GM/c^2$ for $M=6x10^9M_{\odot}$



Simulations of the shadow with different physical models- top row bottom row what the EHT would see



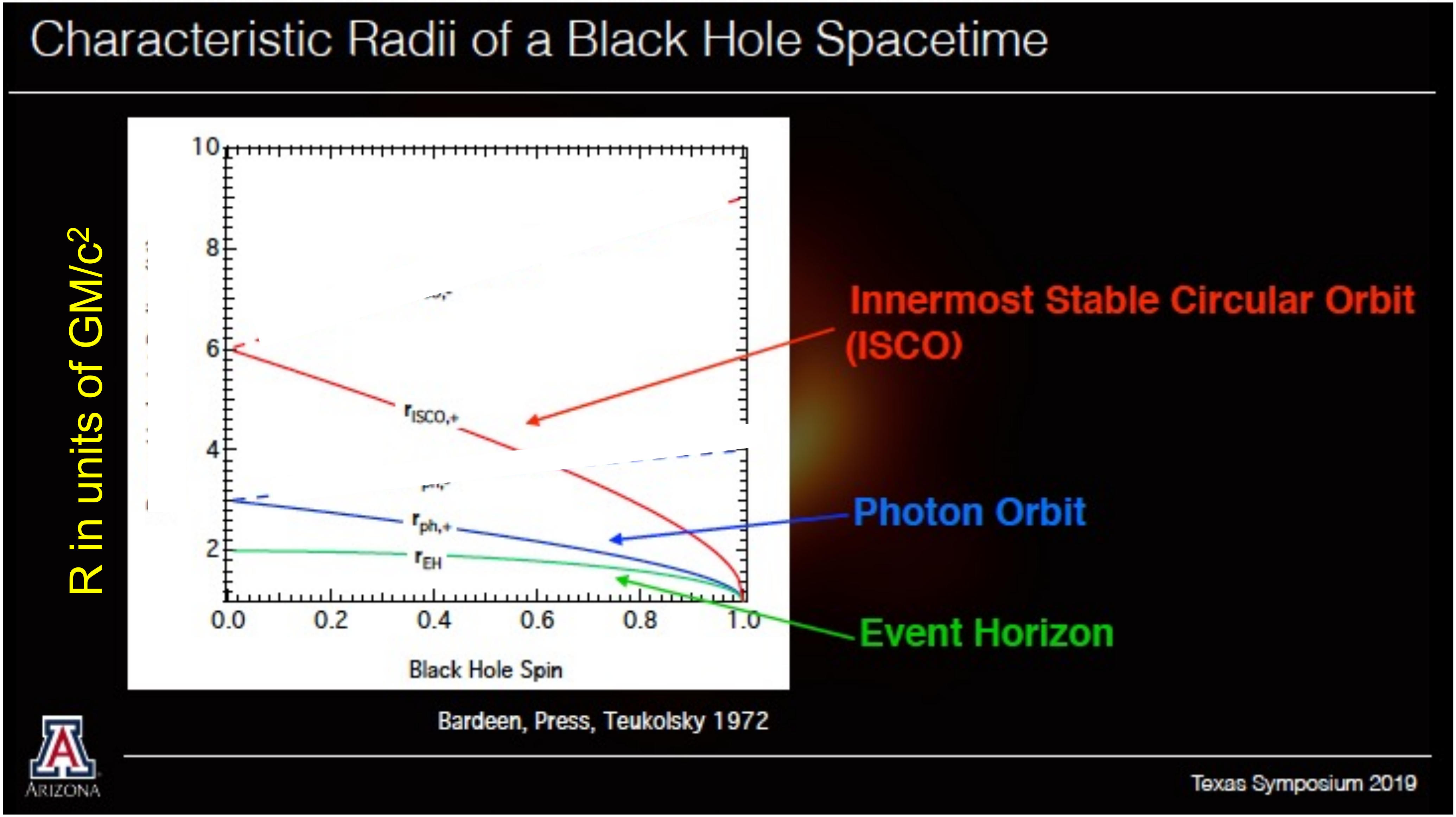
$$\theta_{\rm size} = (4.8 - 5.2)\frac{GM}{Dc^2}$$

=3.8 ± 0.4 μas

crescent angular diameter d_{in} terms of the gravitational radius and distance, $\theta_{size} = GM/c^2D$,

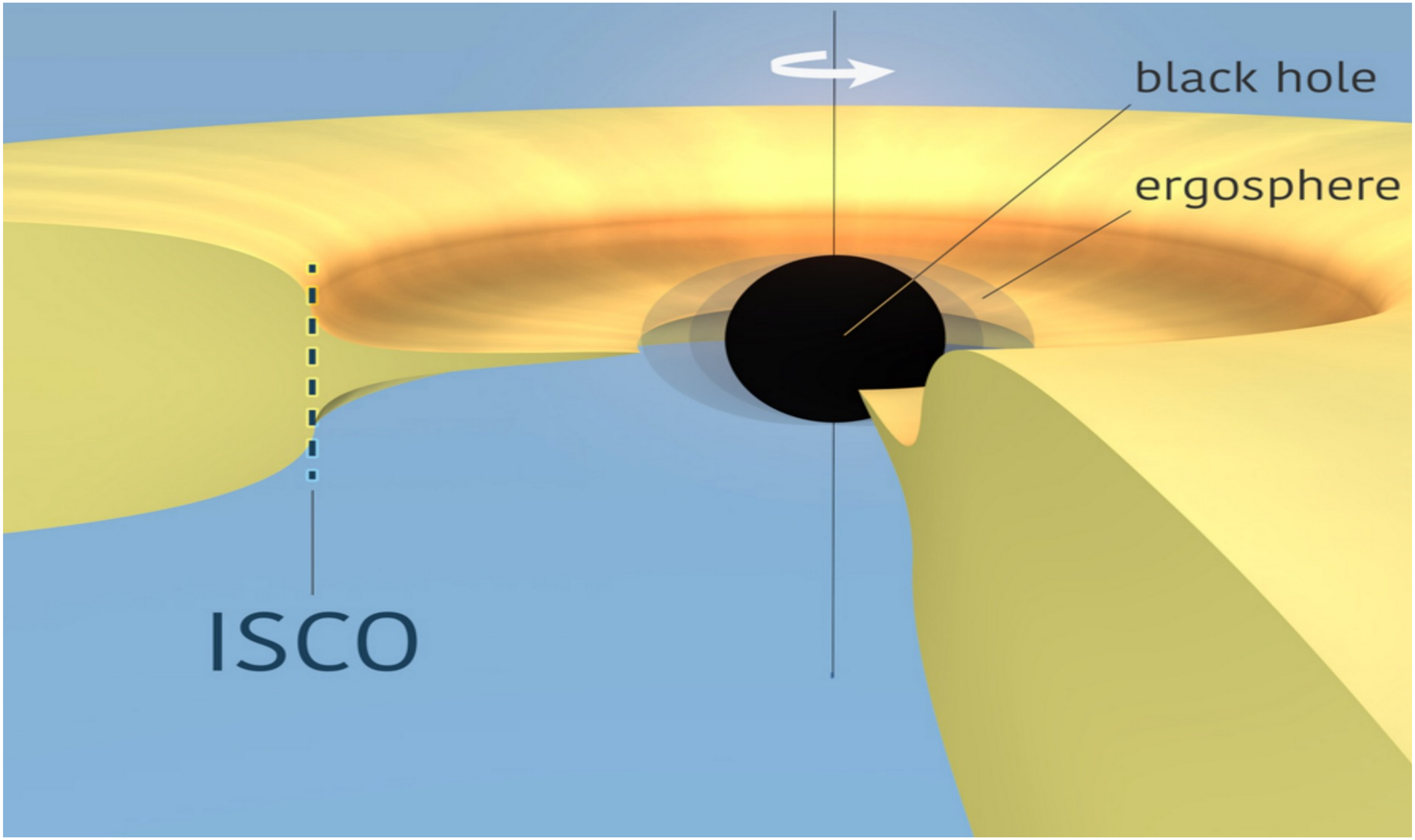
d□=□$\alpha\theta_{size}$,where α is a function of spin, inclination, and R ▪

How Things Change with Spin

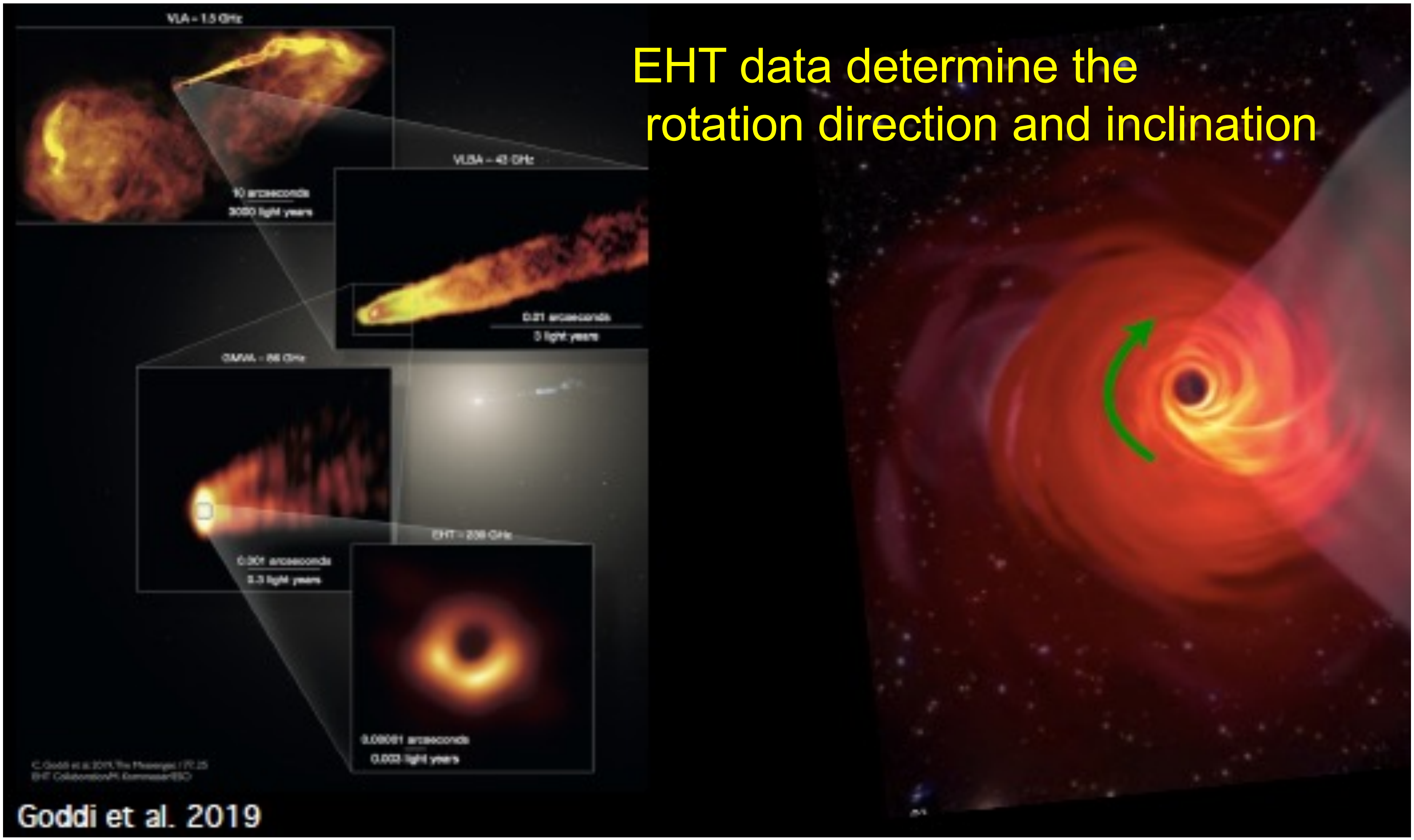


Psaltis 2019

A Reminder of Where Things Are



How EHT Results fit in with jet structure for M87



Main Results from EHT for M87

- $M_{BH}=6.5x10^9M_\odot$
  - Prior mass from stars=$6.2x10^9M_\odot$, from gas velocities=$3.5x10^9M_\odot$
- The asymmetric ring is consistent with strong gravitational lensing of synchrotron emission from a hot plasma orbiting near the black hole event horizon. The ring radius and ring asymmetry depend on black hole mass and spin
  - The asymmetry in the image is produced primarily by Doppler beaming

Main Results

- The central flux depression is the so-called black hole "shadow"(Falcke et al.2000)
  - The "ring" corresponds to lines of sight that pass close to (unstable) photon orbits, linger near the photon orbit, and therefore have a long path length through the emitting plasma

- For a non-spinning black hole the ring has a radius
  - $R=5.2GM/c^2D=18.8(M/6.2x10^9M_\odot)(D/16.9Mpc)\mu as$

  where 16.9 Mpc is the distance to M87

Other BH "Stuff" Testable with the Event Horizon Telescope Data

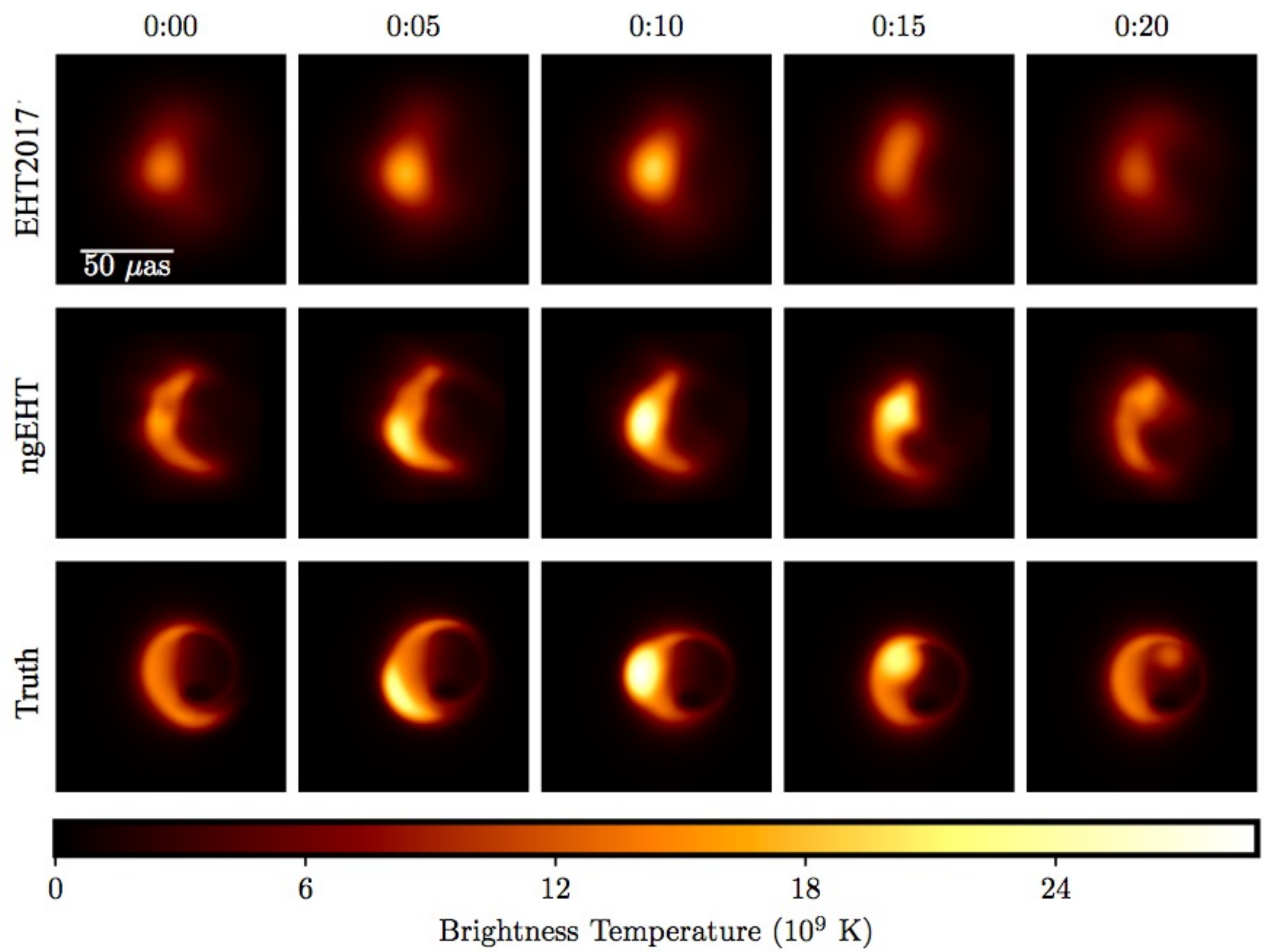
- Tracing magnetic field geometry
- What is the role of the SMBH in forming, collimating & powering a relativistic jet?
- Physics of accretion in low accretion rate objects
  - only 2 objects which can be studied with the EHT (M87 and SgrA*) have very low Eddington ratios
- What drives accretion onto a SMBH and triggers flaring events?

Future Goals

- Making the first real-time movies of supermassive black holes (SMBH) and their jets

- Testing strong-field gravity features predicted by general relativity
- Details of active accretion and relativistic jet launching that drive galaxy evolution

It is expected that M87 and SgrA* will be changing on their orbital timescales (down to ~20 seconds for SgrA* and ~1 day for M87)



Caveats

- The "image" is wonderful! It would have been on my wall as a poster when I first learned about BHs...
- But what have we learned that we didn't know before?
- Mass of M87 BH? No, known from stellar orbits
- Tests of GR? No, it turns out that tests for lower-mass black holes (such as with LIGO; next lectures) are vastly more constraining
- Plasma physics or other astrophysics near BH? No, the EHT team was admirably honest about this: from EHT data alone, can't really say anything
- Maybe eventually learn about the magnetic field structure in the disk, but even that isn't clear