Observing Black Holes

Britt Jeter
Postdoctoral Fellow
ASIAA

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What is a Black Hole?

- Take Newton seriously: if light is "corpuscular", then it should be affected by gravity
- What if the escape velocity > speed of light (John Mitchel, 1784)
- A star 500x the size of our sun could have a large enough escape velocity…
- "Dark Stars" would only be detected by their gravitational influence on neighboring stars (took a while, see El-Badry et al. 2022)
- *An Astrophysical Object*!

What is a Black Hole?

- Solutions (vacuum) to Einstein's Field Equations (Schwarzschild 1915)

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- Metric Tensor = Rulers and Clocks
- Stress Energy Tensor = Stuff and Things: Matter, Light, Fields, etc.
- In Vacuum, T = 0, so Einstein's equations reduce to:

$$R_{\mu\nu} = 0 \qquad\qquad \text{Much Simpler!}$$

What is a Black Hole?

- Schwarzschild solution was not immediately recognized as a "Black Hole", but rather a funny region in space where the metric became singular
- Some work in the 1920s-1930s on these peculiar solutions to the field equations, but not much progress
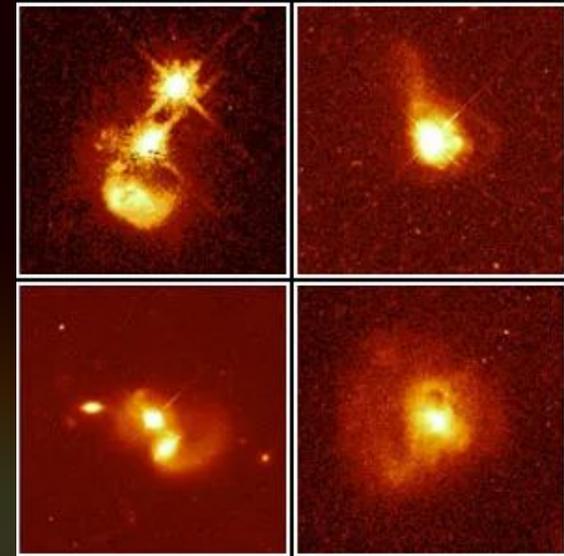
$$r_s = \frac{2GM}{c^2}$$

$$ds = \left(1 - \frac{r_s}{r}\right) c^2 dt^2 - \left(1 - \frac{r_s}{r}\right)^{-1} dr^2 - r^2 d\Omega^2$$

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- Kerr '63 developed a generalized metric that included angular momentum (spin), and Newman added electric charge in '67
- No-Hair Theorem was developed: any stationary black hole solution to Einstein's equations can only be described Mass, Spin, and Charge

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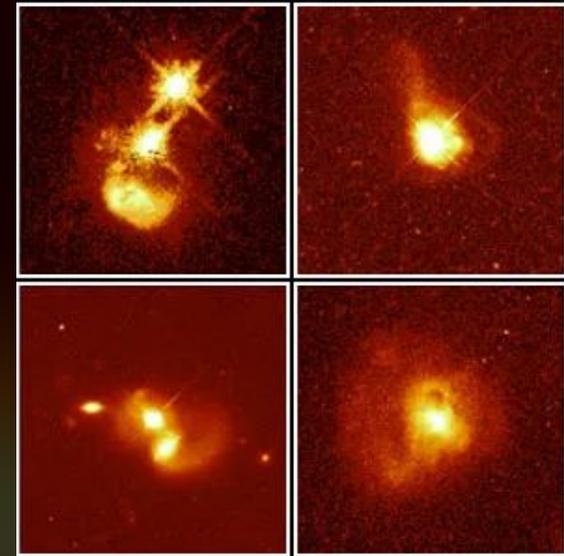
Quasars?

- In 1950s started detecting bright radio sources with no visible counterpart or very blue star-like objects (quasi-stellar objects…)
- Occultations and masking revealed diffuse background, and both the "quasi-star" and the nebula (galaxy) had very broad emission lines in very strange places

WFPC2

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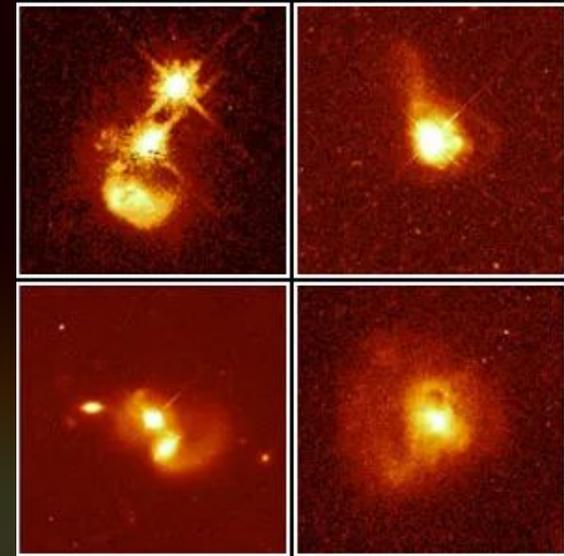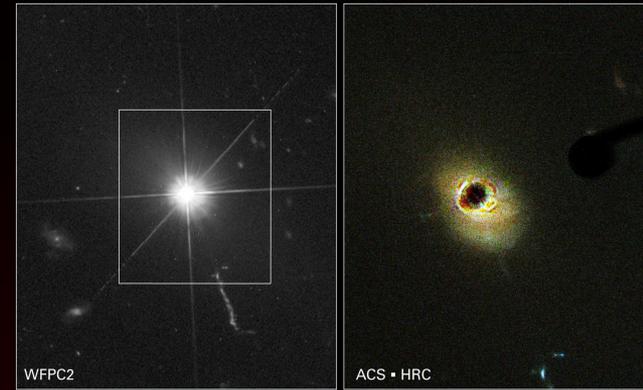
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- Occultations and masking revealed diffuse background, and both the "quasi-star" and the nebula (galaxy) had very broad emission lines in very strange places
- Emission lines are actually very strongly redshifted, implying cosmological distances
- And they vary! 3C273 varies on yearly timescales, so the emission region must be smaller than 1 ly?!?!
- Salpeter and Zeldovich '64 suggested accretion onto supermassive black holes could produce sufficient power

WFPC2

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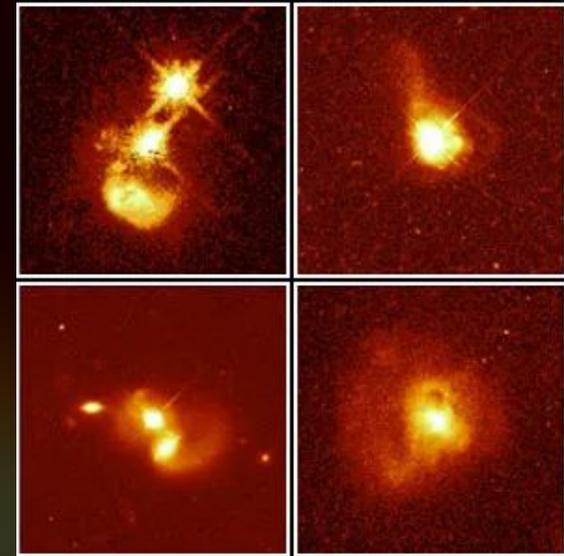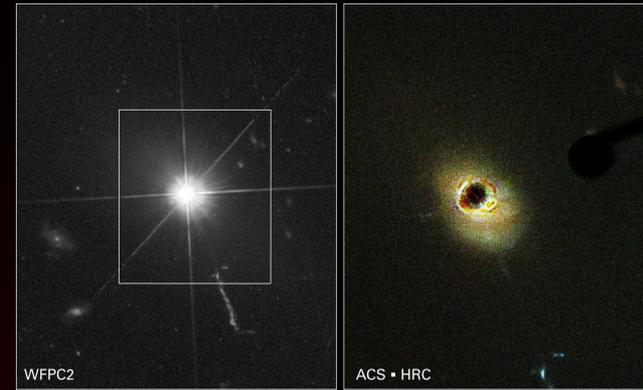
What are Black Holes?

- Supermassive black holes seem to live at the centers of every galaxy, and somehow can produce tremendous amounts of energy
- How can we study them? What should we try to measure?
- No-Hair Theorem says they only have Mass, Spin, and Charge…
- Universe is neutral, so probably no charge, lets measure Mass and Spin!
- Mass is easy! Use velocity of orbiting stars or gas and Kepler's laws:

$$v^2 \approx \frac{GM}{r}$$

What are Black Holes doing?

- SMBH mass *strongly* correlates with galaxy velocity dispersion, luminosity, halo mass, stellar mass, … etc. *But why?*
- SMBHs are "small": R_s can be measured in AU, and the direct sphere of influence is usually <100 pc…
- Some SMBH regions are brighter (active), and some produce large jets
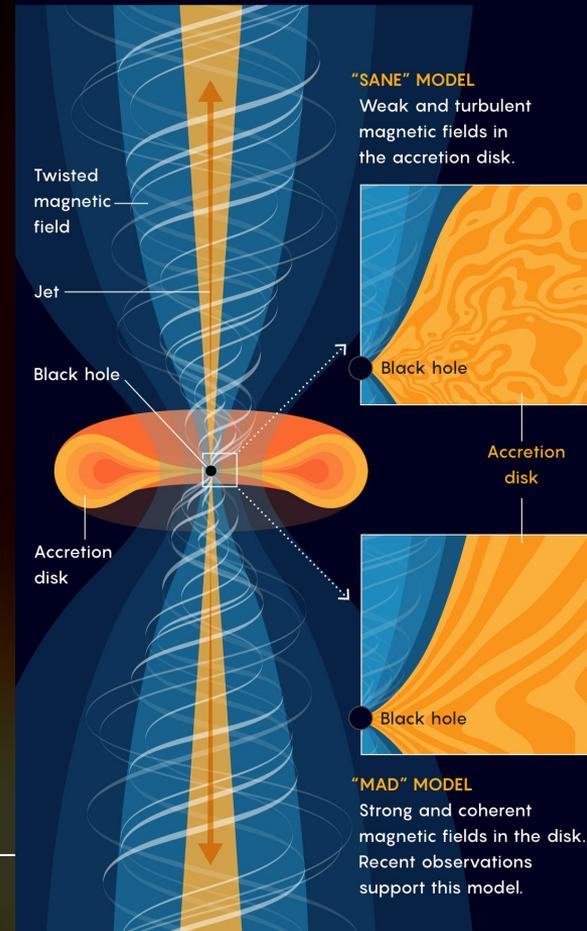- Maybe AGN and jets interact with the galaxy too?
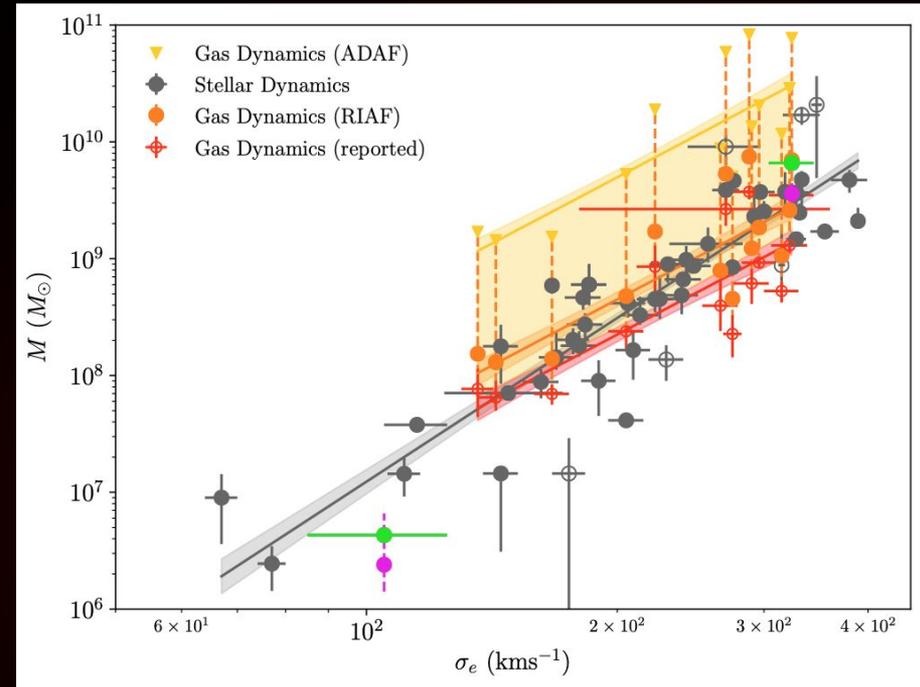
How do Black Holes Make Jets?
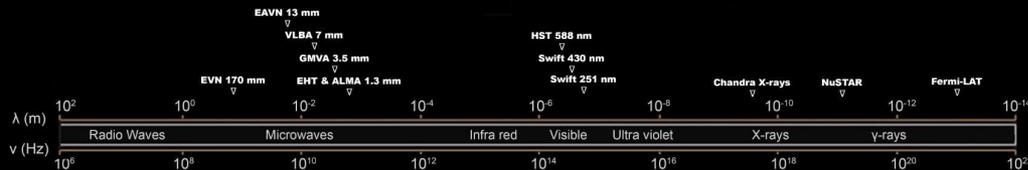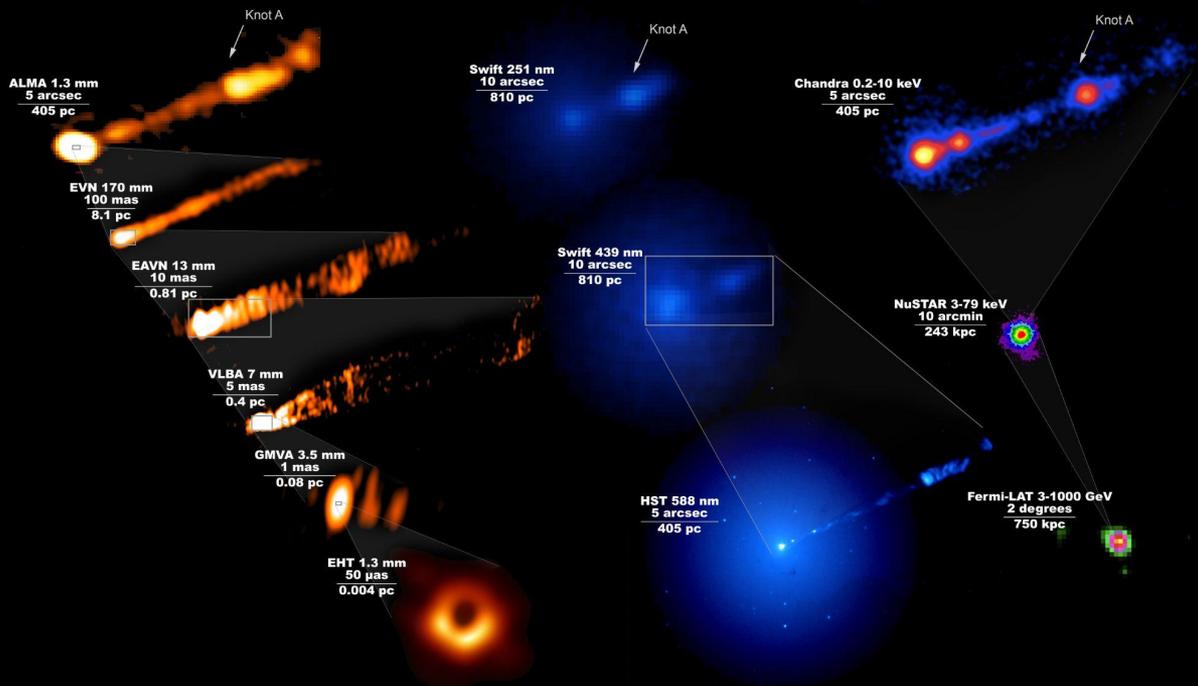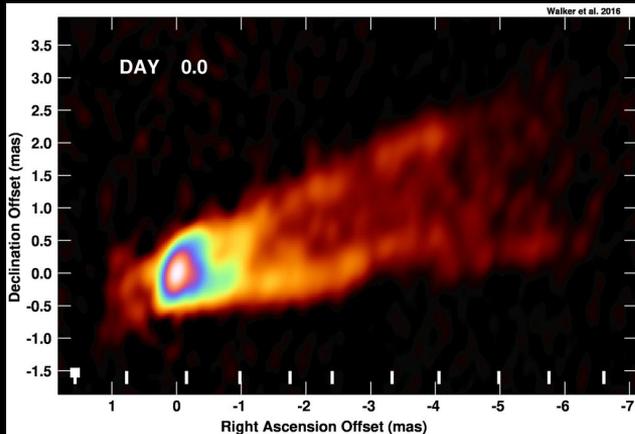
Black Hole Jets

- Supermassive Black Holes are surrounded a hot accretion disk filled with plasma
- Magnetic fields should thread the accretion disk and black hole, and particles and energy will flow out along the field lines

Inside a Black Hole's Jet Engine

As a spinning black hole pulls in matter, it creates a rotating "accretion disk" of charged particles. The motion generates twisted magnetic fields that accelerate particles into two thin jets.
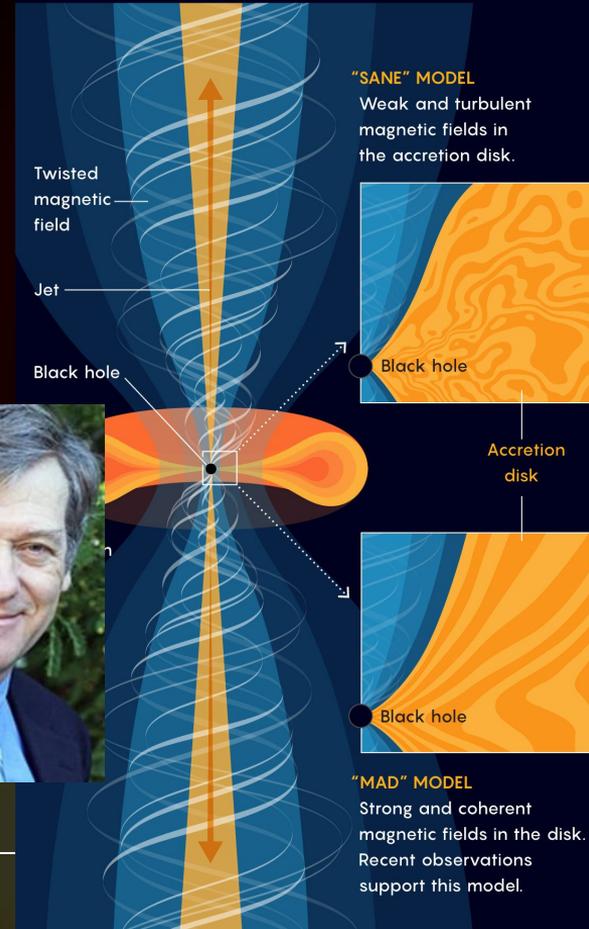
Twisted magnetic field

Jet

Black hole

Accretion disk

"SANE" MODEL
Weak and turbulent magnetic fields in the accretion disk.

Black hole

Accretion disk

Black hole

"MAD" MODEL
Strong and coherent magnetic fields in the disk. Recent observations support this model.

Black Hole Jets

- Supermassive Black Holes are surrounded a hot accretion disk filled with plasma
- Magnetic fields should thread the accretion disk and black hole, and particles and energy will flow out along the field lines
- Two ways to power jets: Leverage the BH rotation (spin) (Blandford and Znajek '77) or the accretion disk rotation (Blandford and Payne '82)
- Jet power depends on the magnetic flux and spin: high flux leads to coherent fields and strong jets, low flux leads to turbulent fields and weak jets

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Observing Black Holes

- We can roughly measure BH masses, and we can see that lots of AGN have large jets

- Can we see a Black Hole directly? It could help us measure spin, and figure out which Blandford model is correct …

- But BH are "small": Sgr A* is 4.2e6 Solar masses, and 8kpc away… so θ_g = GM/Dc^2 ~ 5 µas…

Observing Black Holes

- Telescope resolution Θ ~ λ/D, so we need a big telescope and a short wavelength …

- What do we think a black hole would even look like?

- The Black Hole itself is obviously dark, but the material around it will be hot and bright

- At the right wavelength, the material should also be optically thin, and we should see through the bulk of the accretion disk right down the event horizon

Black Hole Shadows

- Light propagates along geodesics: straight lines in curved space
- Around a Black Hole, light gets deflected around the event horizon, and can even orbit multiple times!
- For distant observers, some rays will fall into the horizon and be lost
- The missing photons produce a dark region, or "shadow"
- The shadow diameter is typically $\sim 10*GM/Dc^2$
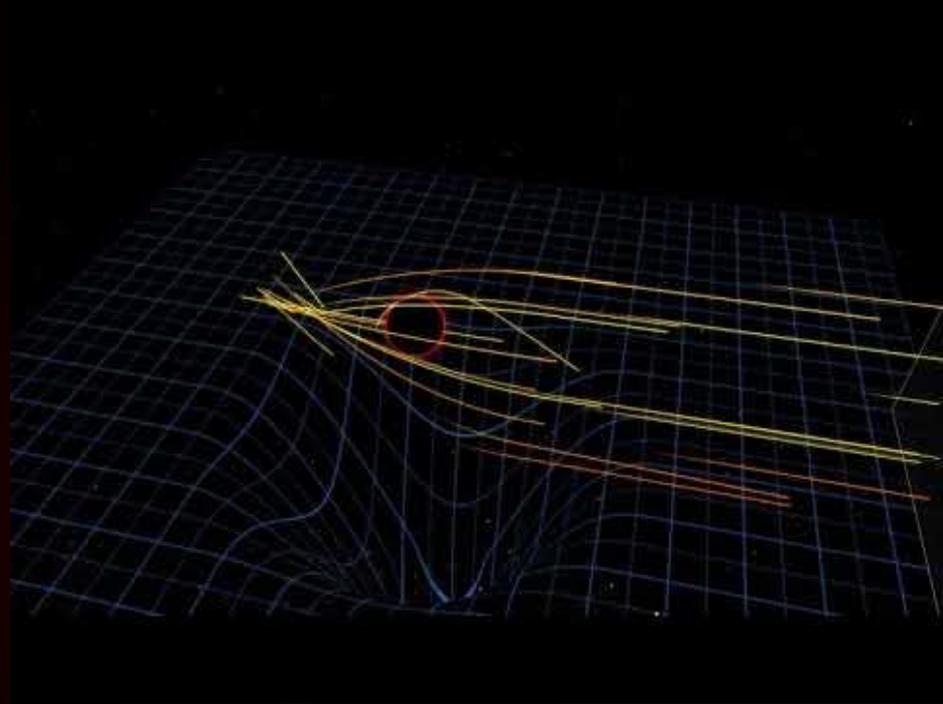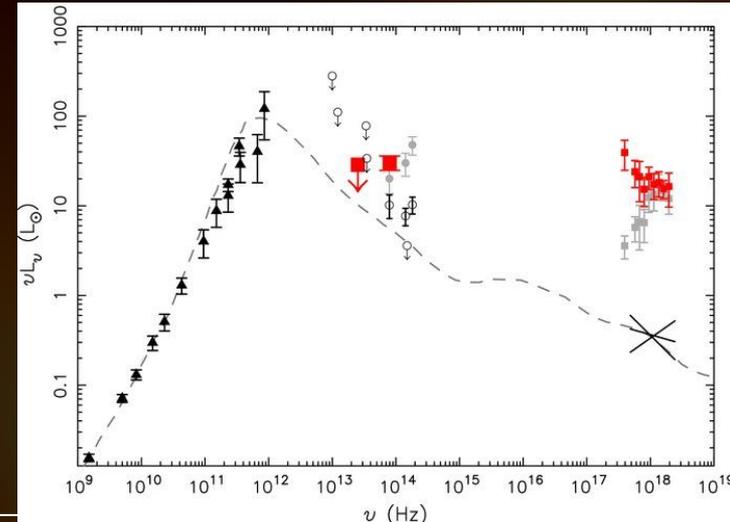
Seeing Black Hole Shadows

- Need to find Black Holes with optically thin accretion flows
- Some AGN have very low radiative power ($L_{BH} \ll L_{Edd}$), so the plasma cannot lose energy efficiently: the disk gets very hot and very puffy and low density
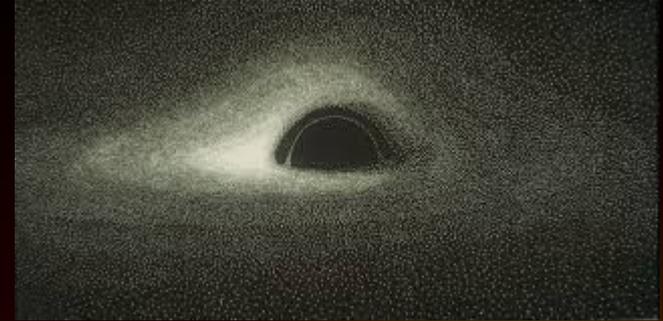
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- Need to find Black Holes with optically thin accretion flows
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- These Low Luminosity AGN are optically thin at high radio frequencies
- Also need the source to be bright, and large enough (High Mass or Nearby)
- Sgr A* and the SMBH at the center of M87 seem like good targets

Dodds-Eden et al. 2009

Seeing Black Hole Shadows

- Using Very Long Baseline Interferometry, the effective angular resolution of a network of radio telescopes depends on the distance between dishes instead of the size of the individual dishes
- Let's collaborate with radio telescopes all over the Earth to try to see a Black Hole!

Event Horizon Telescope (EHT)
A Global Network of Radio Telescopes

2017 OBSERVATIONS

ALMA	Atacama Large Millimeter/ submillimeter Array	CHAJNANTOR PLATEAU, CHILE
APEX	Atacama Pathfinder EXperiment	CHAJNANTOR PLATEAU, CHILE
30-M	IRAM 30-M Telescope	PICO VELETA, SPAIN
JCMT	James Clerk Maxwell Telescope	MAUNAKEA, HAWAII
LMT	Large Millimeter Telescope	SIERRA NEGRA, MEXICO
SMA	Submillimeter Array	MAUNAKEA, HAWAII
SMT	Submillimeter Telescope	MOUNT GRAHAM, ARIZONA
SPT	South Pole Telescope	SOUTH POLE STATION

Seeing Black Hole Shadows with the EHT

- The Event Horizon Telescope Collaboration operates 12 telescopes at 10 locations (circa 2024) to observe Black Hole shadows and AGN
- When operating at 230 GHz (1.3 mm), it can achieve an effective resolution of ~20 μas
- ASIAA participates mainly through the Greenland Telescope (GLT) and the JCMT, but we also provide lots of support to the SMA and ALMA
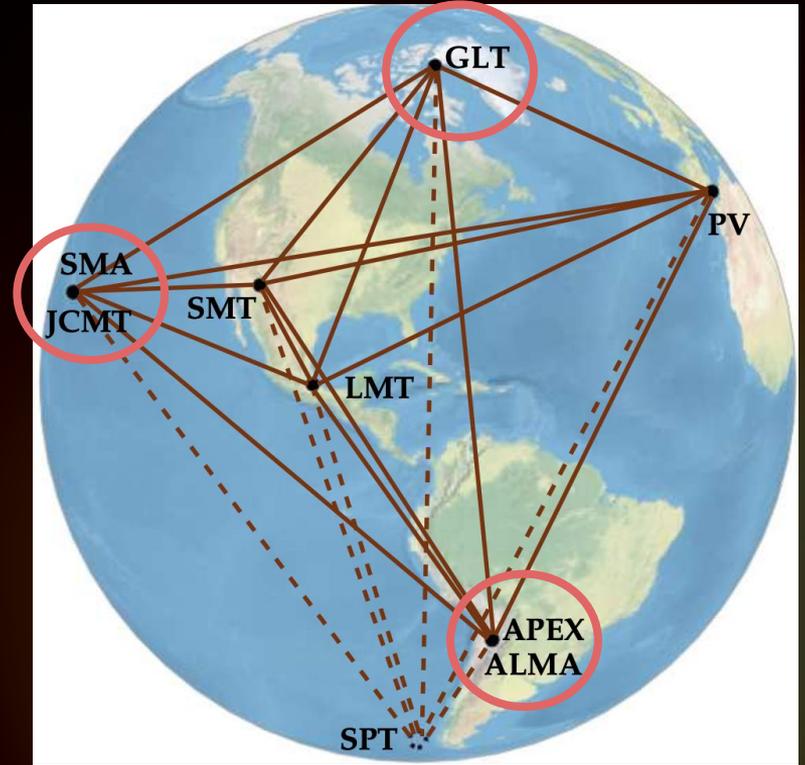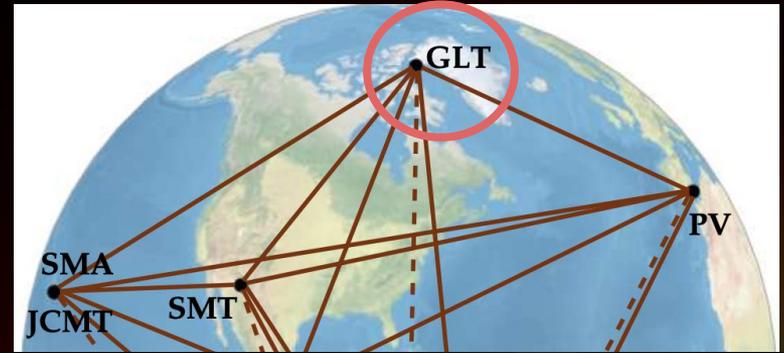
Seeing Black Hole Shadows with the GLT

- What does it take to make an EHT observation? Lets tour the GLT!
- Atmosphere is usually transparent to radio, except at high frequencies: need sites to be "high and dry"
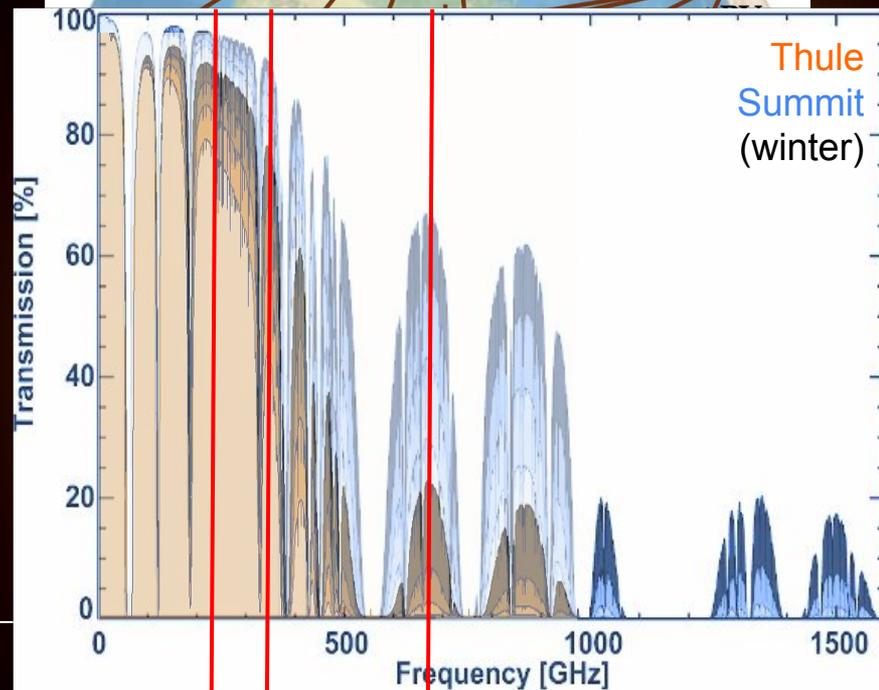
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- Try to optimize observation for best weather at all sites, in the Northern and Southern Hemisphere (tough…)
- March-April seems best…still cold in the North, getting cold in the South
- Still, spring/fall weather can be annoying…

Prepping for Observations

- GLT crew starts preparing for Spring observations in Aug-Sept the previous year
- Engineers make sure the telescope is "physically" ready: preventative and proactive maintenance, install new equipment, adjust the surface

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- VLBI scientists start to travel around Nov-Dec to make sure the telescope is "mentally" ready: Check the computers, instruments, operational computer scripts, pointing model
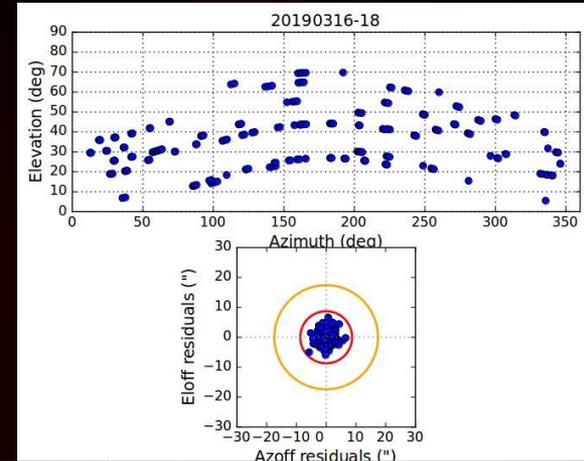
Telescope Operation

- Science season starts in January with Dress Rehearsals: short run with multiple telescopes to check recorders, backends, and observing procedures, usually remote
- 2-4 Telescope operators travel to GLT 1-2 weeks before official campaign, and usually stay for ~1 month
- 2-4+ Extra operators are on standby for each day for Remote Observing from ASIAA
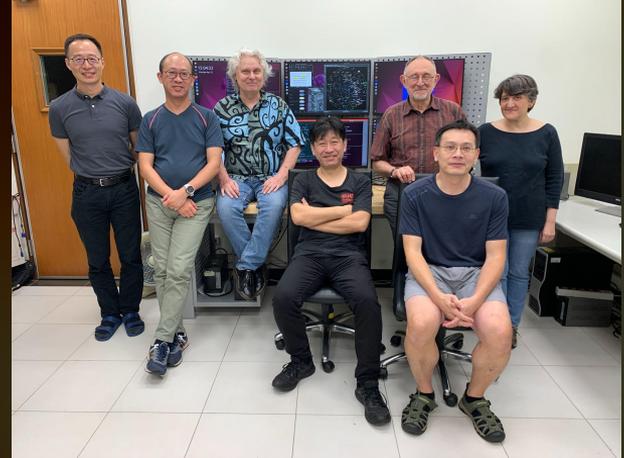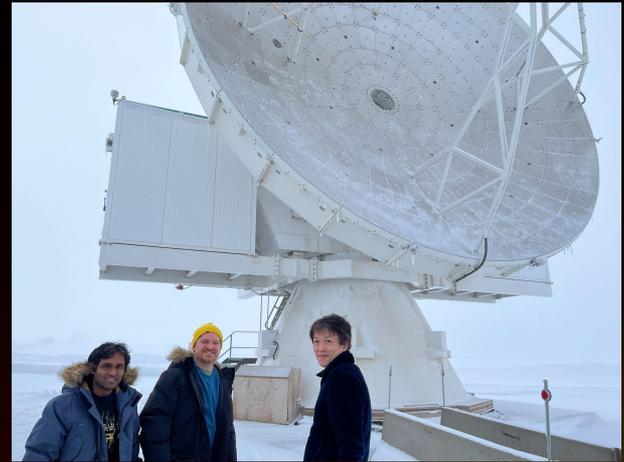
Telescope Operation

- In VLBI, the goal is to capture the full information of the wave front: this means very rapid data collection
- To keep track of the wave front phase, we use a hydrogen maser clock to set a very precise reference signal
- The receivers record onto specialized hard drive modules at 64 Gbps
- Scans are usually a few minutes long, alternating between main targets and calibrators for the connected element arrays (SMA, ALMA, NOEMA)
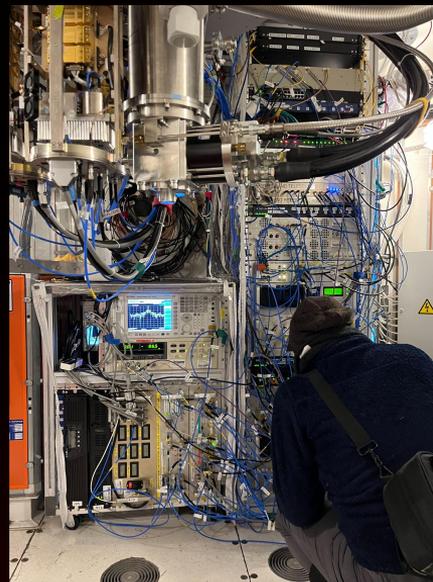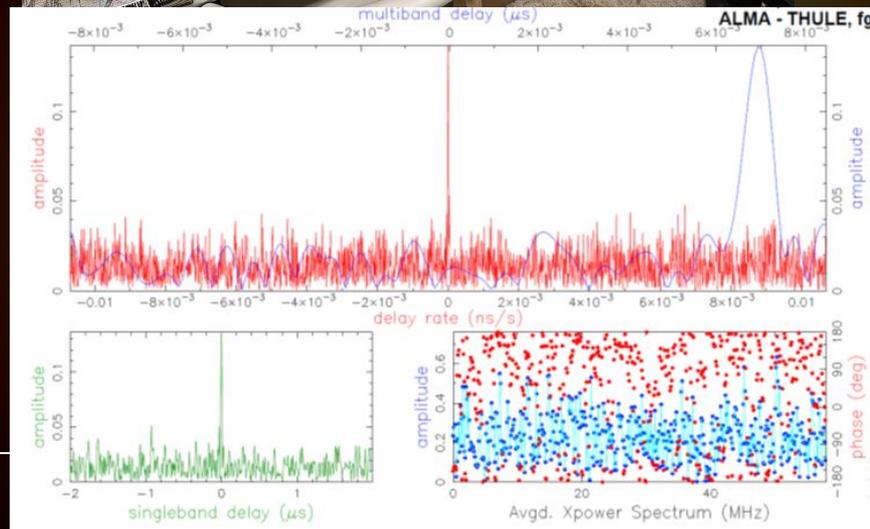
Data Processing

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- The correlated data is then post-processed to eliminate residual clock errors
- Then we convert the data to a unified circular polarimetric basis (because ALMA observes in a different basis from everyone else)

Data Processing

- Instruments are not perfect, so we need to find the best fringes in the delay/rate space before we average down
- We can use our existing knowledge of our telescopes, and leverage our most sensitive telescopes to help us find higher SNR fringes without coherence losses
- Now we can average the data, usually to 10s. Now only MBs!
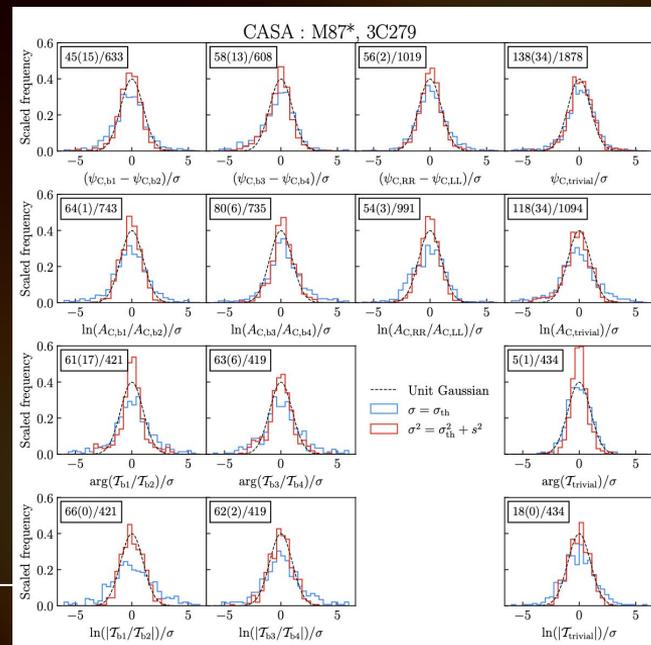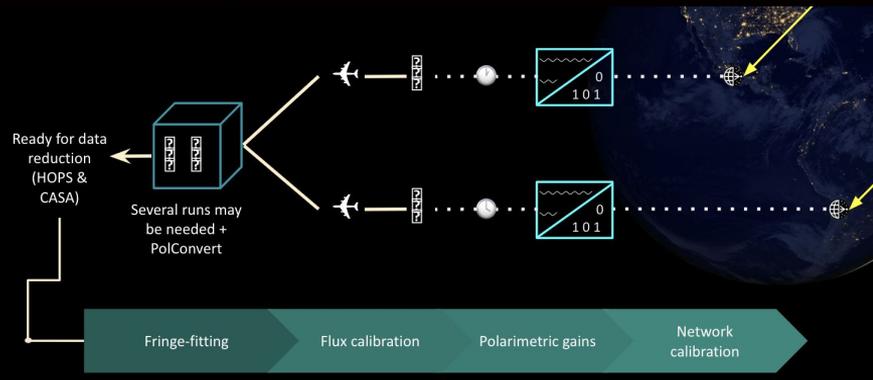
Data Analysis

- With calibrated data, we can start to reconstruct images!
- Reconstruct? Our data are Visibilities, not pixels

M87* band 3   2018 April 21
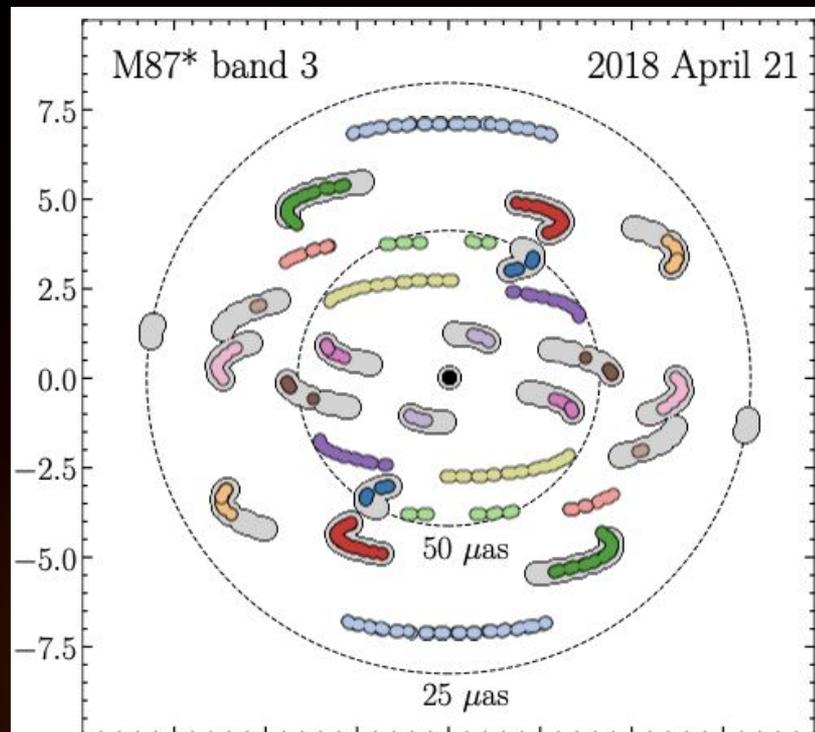
$$\mathcal{V}(u, v) = \iint e^{-2\pi i (ux+vy)} I(x, y) dx\, dy.$$

Data Analysis

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- Reconstruct? Our data are Visibilities, not pixels
- VLBI (or any interferometer) measures the Spatial Fourier Transform of the on-sky brightness distribution
- But sparse coverage means the inversion process is ill-defined
- Need to apply physical priors to find reasonable images
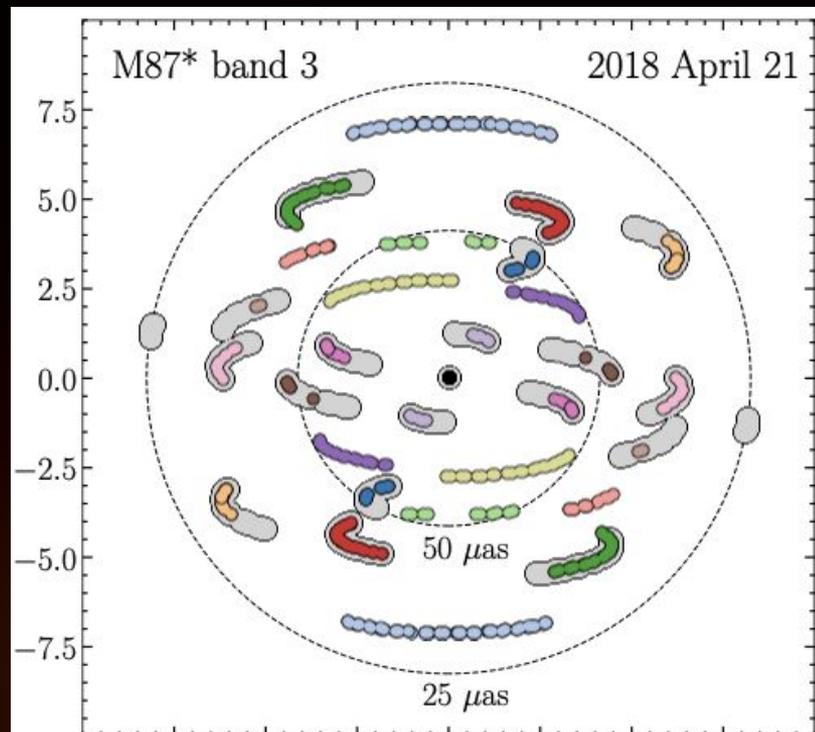
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Closure Quantities

$$\mathbf{V}_{i,j} = \mathbf{J}^i \mathcal{V}_{i,j} \left(\mathbf{J}^j\right)^\dagger + \mathbf{N}_{i,j}$$

$$\boldsymbol{J} = \boldsymbol{GD}\Phi = \begin{pmatrix} G_R & 0 \\ 0 & G_L \end{pmatrix} \begin{pmatrix} 1 & D_R \\ D_L & 1 \end{pmatrix} \begin{pmatrix} e^{-i\phi} & 0 \\ 0 & e^{i\phi} \end{pmatrix}.$$

- Calibration still hasn't gotten rid of all data issues: instrument gains and thermal noise still affect the Visibilities
- One can construct special combinations of Visibilities to cancel out gain effects: Closure quantities

Closure Quantities

- Calibration still hasn't gotten rid of all data issues: instrument gains and thermal noise still affect the Visibilities
- One can construct special combinations of Visibilities to cancel out gain effects: Closure quantities
- Closures tell you exactly what the source is doing, but can be hard to interpret
- If using closures, also lose absolute flux information: only relative fluxes are preserved
- Can still fit Complex Visibilities and Amplitudes, but have to model or optimize for the telescope gains and leakages

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$$\psi_{\mathrm{C},ijk} = \psi_{ij} + \psi_{jk} + \psi_{ki} = \Psi_{ij} + \Psi_{jk} + \Psi_{ki},$$

$$A_{\mathrm{C},ijk\ell} = \frac{A_{ij}A_{k\ell}}{A_{ik}A_{j\ell}} = \frac{\mathcal{A}_{ij}\mathcal{A}_{k\ell}}{\mathcal{A}_{ik}\mathcal{A}_{j\ell}},$$

$$Tr_{i,j,k,l} = \frac{1}{2}\mathrm{trace}\left(\mathbf{V}_{i,j}\mathbf{V}_{k,j}^{-1}\mathbf{V}_{k,l}\mathbf{V}_{i,l}^{-1}\right)$$
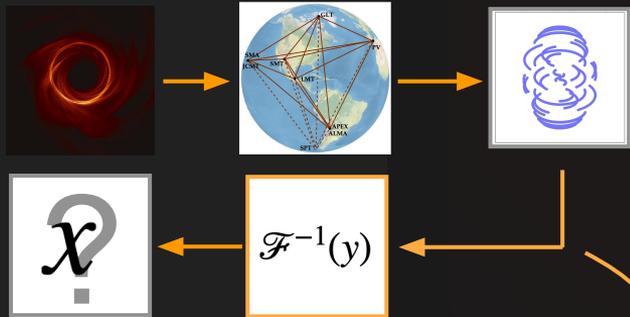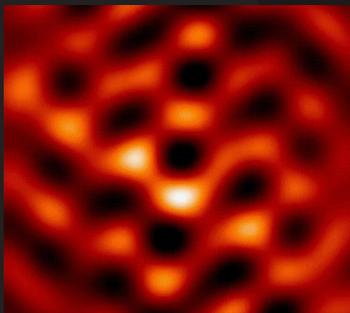
$$CT_{i,j,k,l} = [Tr_{i,j,k,l}, Tr_{i,j,l,k}, Tr_{i,k,j,l}, Tr_{i,k,l,j}, Tr_{i,l,j,k}, Tr_{i,l,k,j}]$$
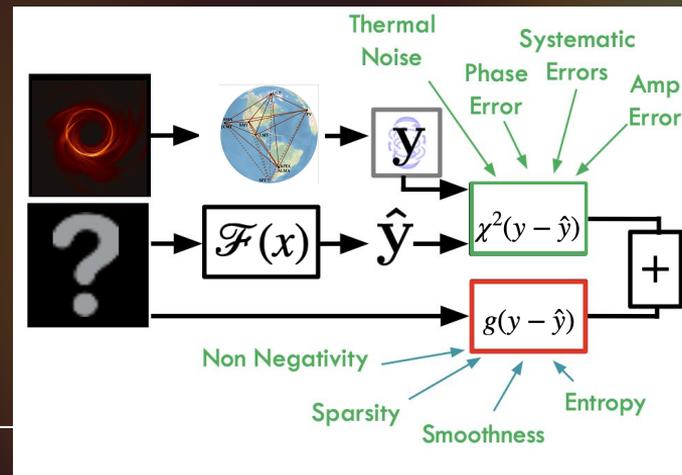
CLEAN Imaging vs RML Imaging

Inverse Approach | CLEAN Imaging (Difmap)

Forward Approach | RML Imaging (ehtim, smili)

$\mathscr{F}^{-1}(y)$

x?

Solve for gains that best match the image

Thermal Noise
Systematic Errors
Phase Error
Amp Error

$\mathbf{y}$

$\mathscr{F}(x)$ → $\hat{\mathbf{y}}$

$\chi^2(y - \hat{y})$

$+$

$g(y - \hat{y})$

Non Negativity
Sparsity
Smoothness
Entropy

CLEAN+ self calibration

Bayesian Imaging

- Sample data|model likelihood using posterior sampling techniques (MCMC, etc.)
- Forward modeling like RML methods, but also returns uncertainties on every model parameter
- Instrument effects can be model parameters too! So we can "self-calibrate" at every step

$y =$ observed data

$x =$ model

$$P(x|y) \sim \mathscr{L}(y|x) \times P(x)$$
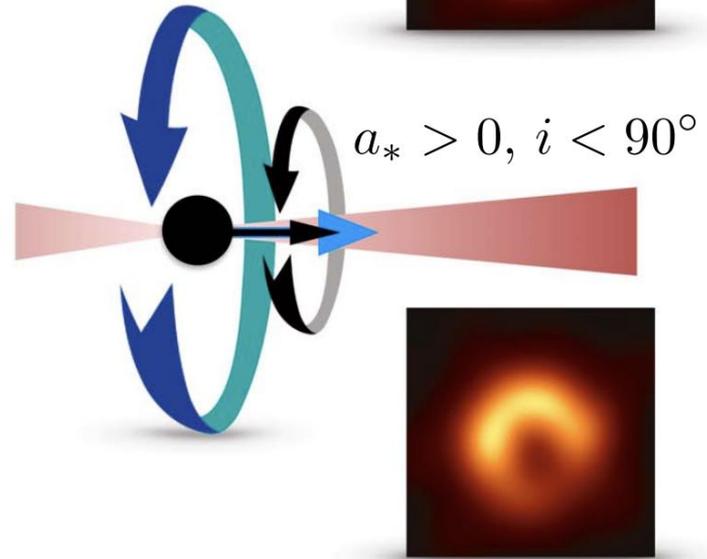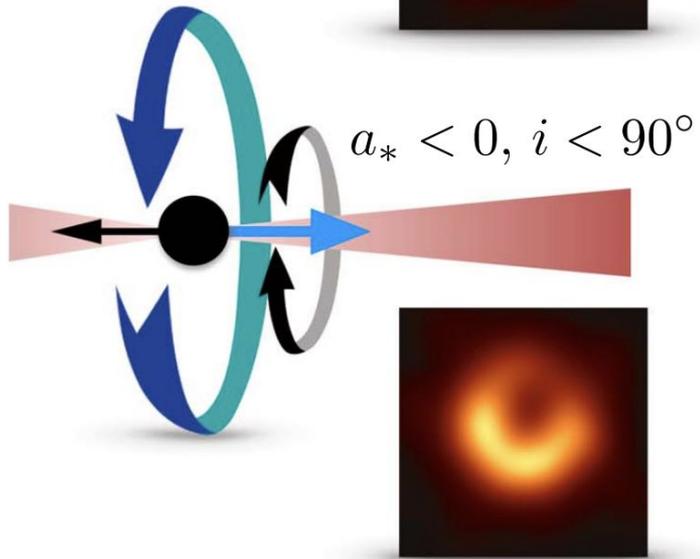
Posterior

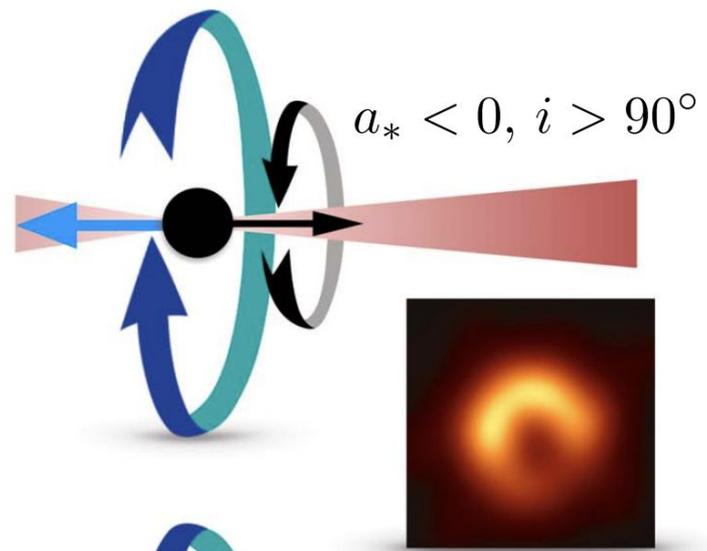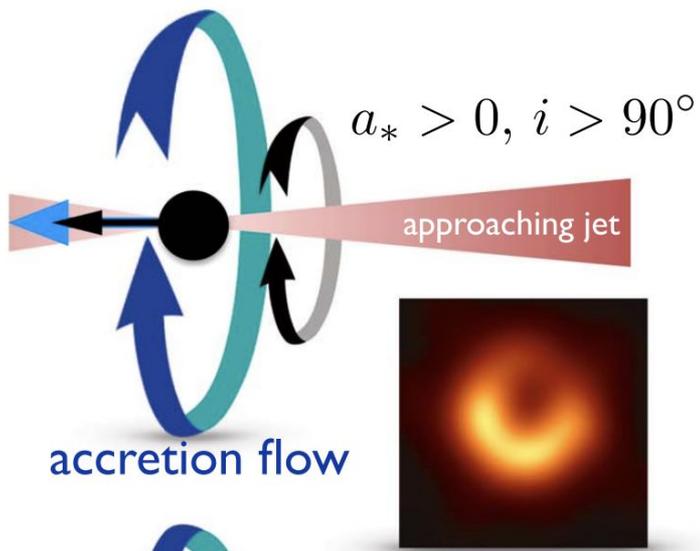Likelihood

Prior
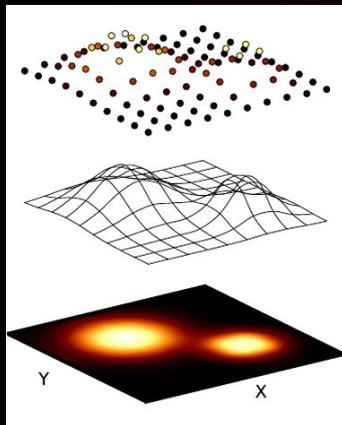
raster
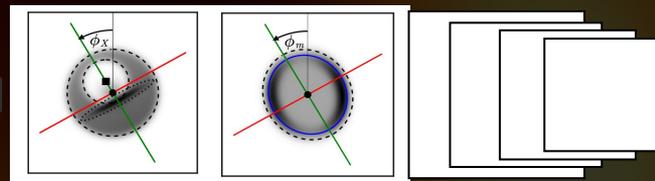
Geometric Modelling

Black Hole Images: M87* and Sgr A*
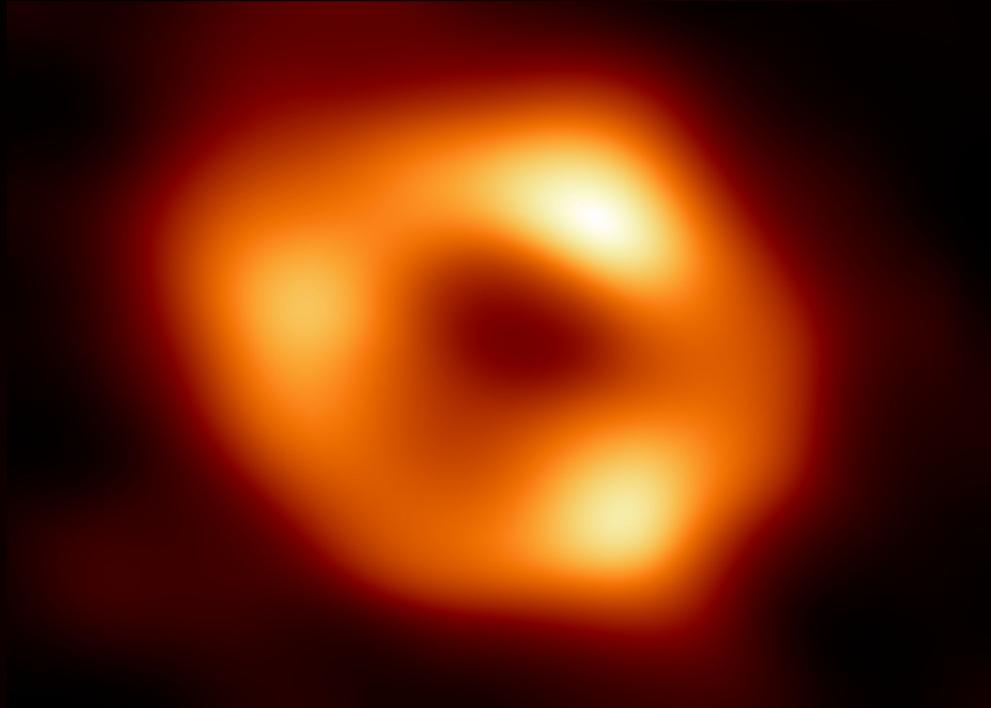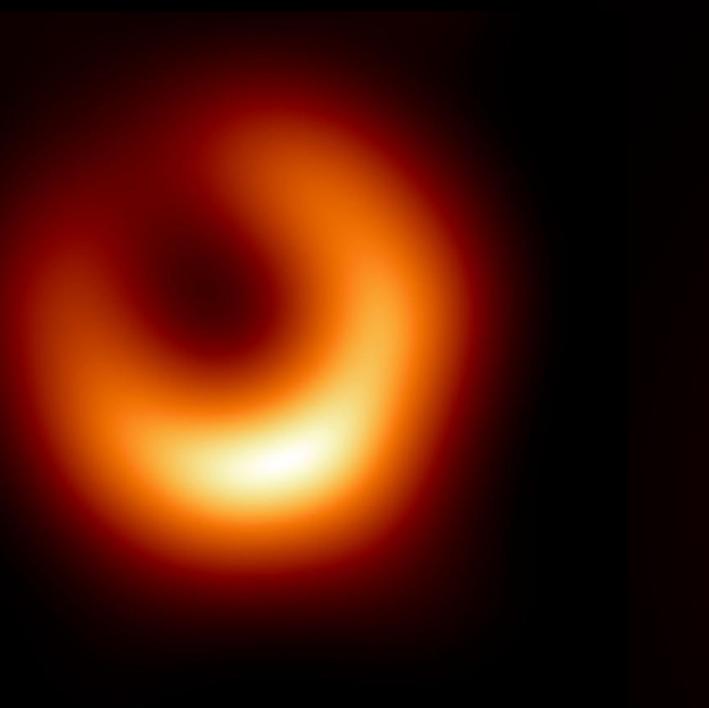
What do these mean?

- We see the shadow! A dark region surrounded by bright emission

- For M87*, the ring asymmetry gives us a good idea about the direction of the Black Hole Spin. It points away from Earth!
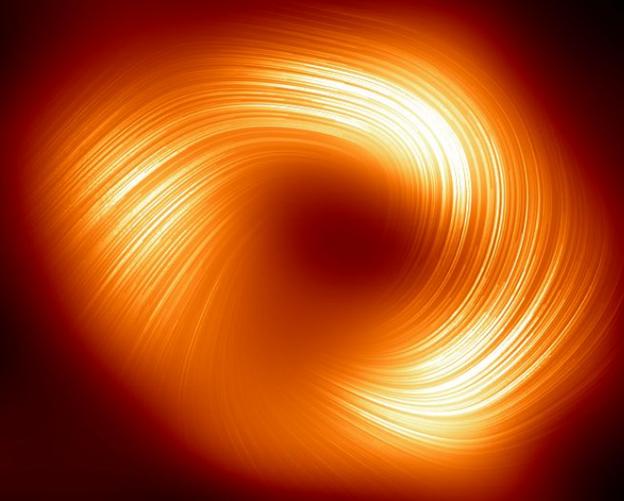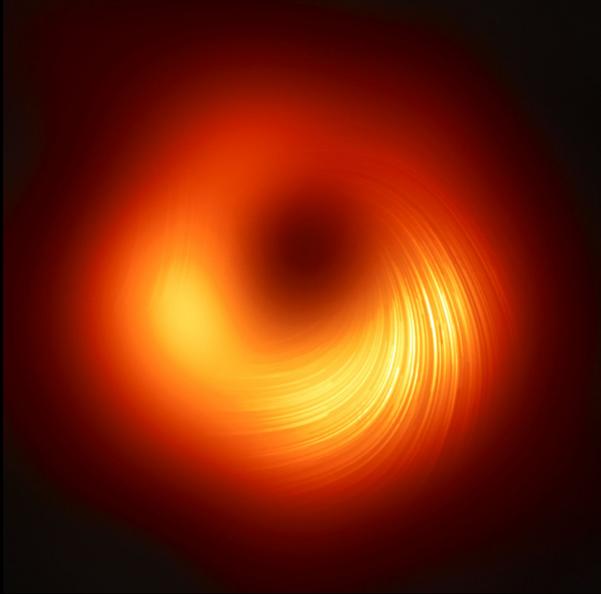
$a_* > 0, i > 90°$

approaching jet

accretion flow

$a_* < 0, i > 90°$

$a_* < 0, i < 90°$

$a_* > 0, i < 90°$

What do these mean?

- The diameter of the shadows are also important: For M87*, we measure d ~ 43 μas, and Sgr A* has d ~ 52 μas

- Remember, d_{sh}~5*R_s = 10 G/Dc^2 * M, and the distance to M87* is 17 Mpc, and the distance to Sgr A* is 8 Kpc.

- This means the Mass of M87* is ~ 6e9 solar masses, and Sgr A* is ~ 4e6 solar masses
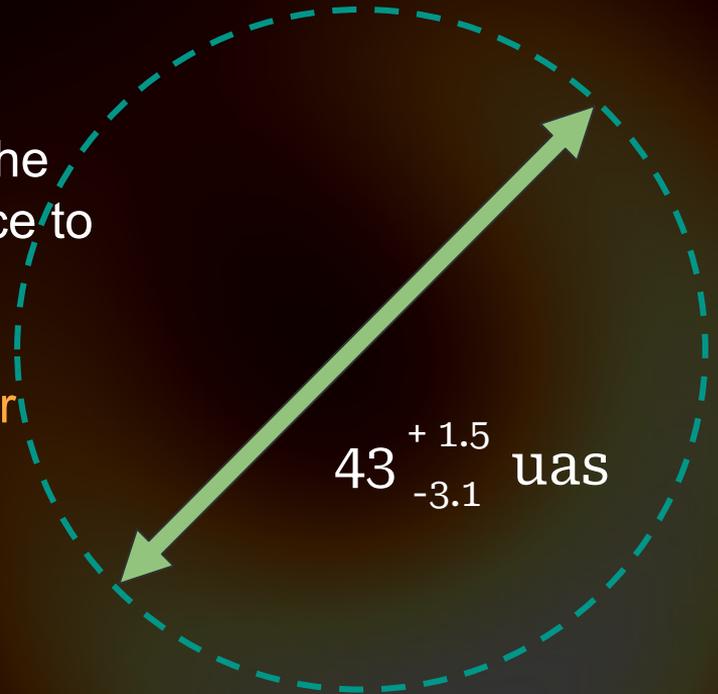
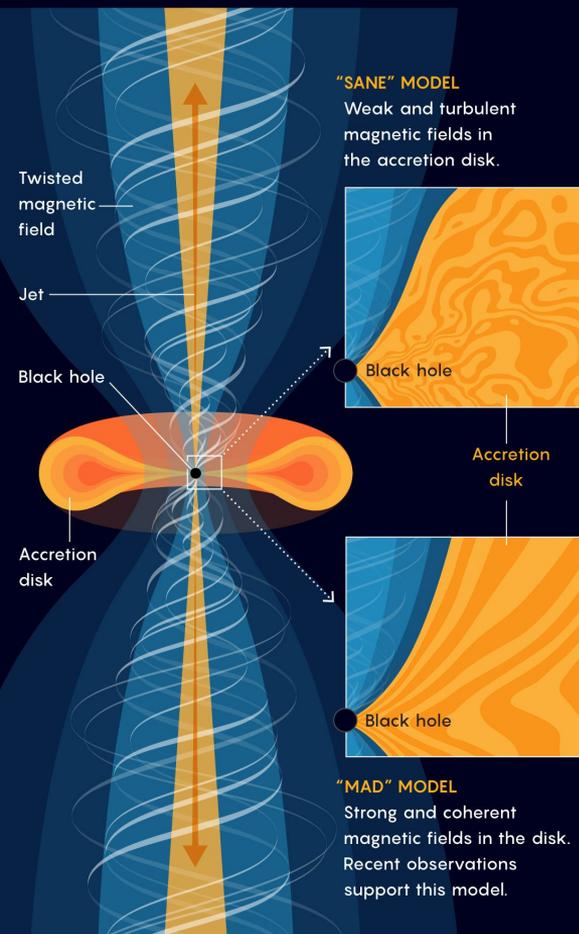$43^{+1.5}_{-3.1}$ uas

Polarized Imaging

As a spinning black hole pulls in matter, it creates a rotating "accretion disk" of charged particles. The motion generates twisted magnetic fields that accelerate particles into two thin jets.

Twisted magnetic field

Jet

Black hole

Accretion disk

"SANE" MODEL
Weak and turbulent magnetic fields in the accretion disk.

Black hole

Accretion disk

Black hole

"MAD" MODEL
Strong and coherent magnetic fields in the disk. Recent observations support this model.

Polarization is more informative

Emission (near peak)

$$J_I \propto n_e B^2$$

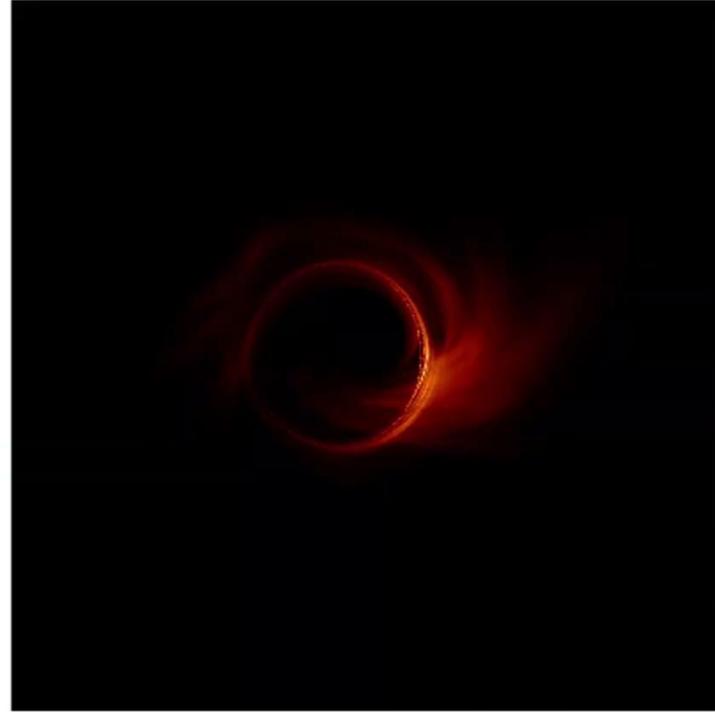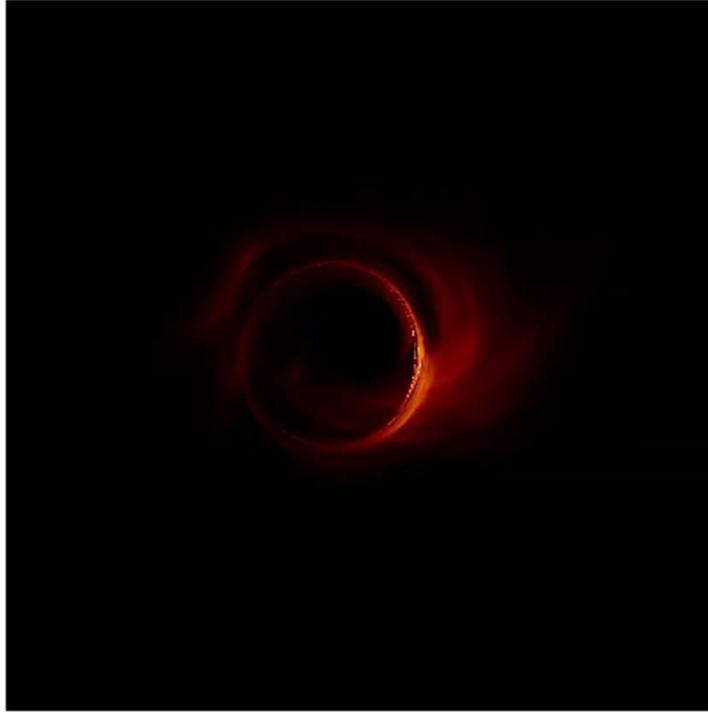Models with weaker fields compensate with higher n_e.

Faraday rotation
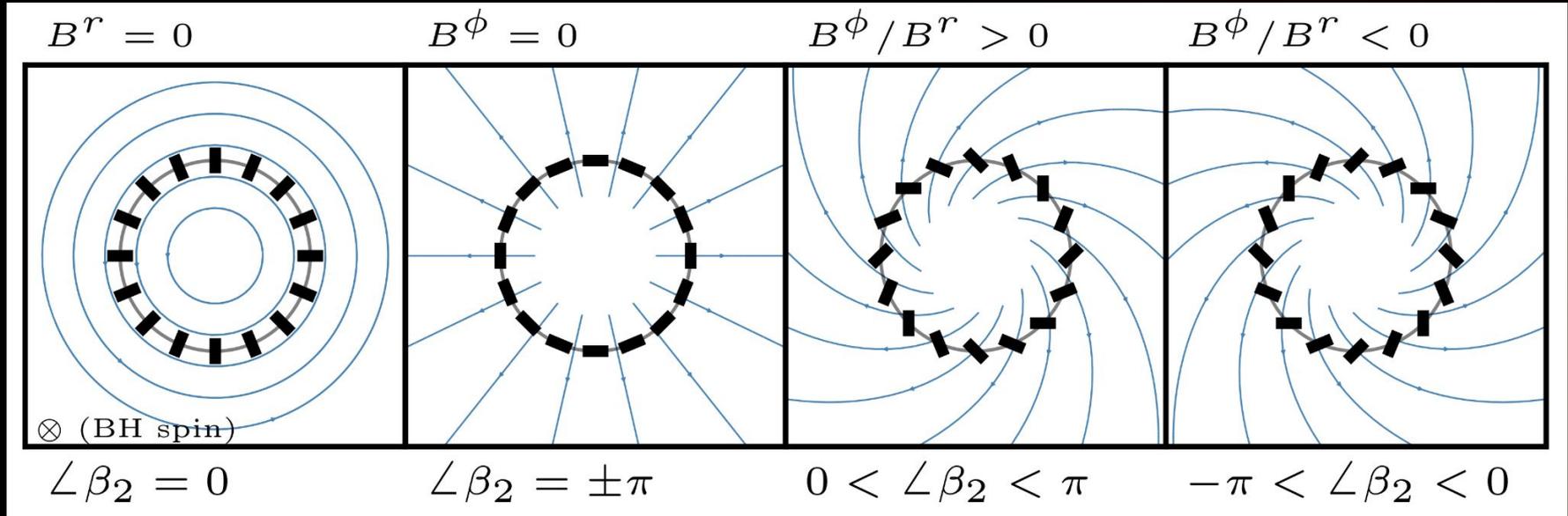
$$\rho_V \propto n_e B$$

Models with higher n_e will be more Faraday depolarized!

One of the reasons we prefer models with strong magnetic fields is that their lower accretion rates tend to cause less depolarization.

Summer Student Lecture

Comparison to Simulations

Quantifying the "Twistyness"

$B^r = 0$ $B^\phi = 0$ $B^\phi / B^r > 0$ $B^\phi / B^r < 0$

$\otimes$ (BH spin)

$\angle \beta_2 = 0$ $\angle \beta_2 = \pm\pi$ $0 < \angle \beta_2 < \pi$ $-\pi < \angle \beta_2 < 0$

Cartoon picture:
- face on fields, no Faraday rotation, no optical depth, no relativistic parallel transport/abberation
- The BH spin is axis **into the screen** (EHT Paper V, 2019)

$$\angle \beta_2 \approx 2 \arctan\left(\frac{B^r}{r B^\phi}\right) \quad \text{(observer at } \theta_o = \pi)$$

Which Simulations Work?

- We know the GRMHD are missing physics, but are there some models that get close enough to the real data?
- Yes!* Models with strong, coherent magnetic fields tend to look more like M87* and Sgr A* than other models

All Polarimetric Constraints

All Polarimetric Constraints
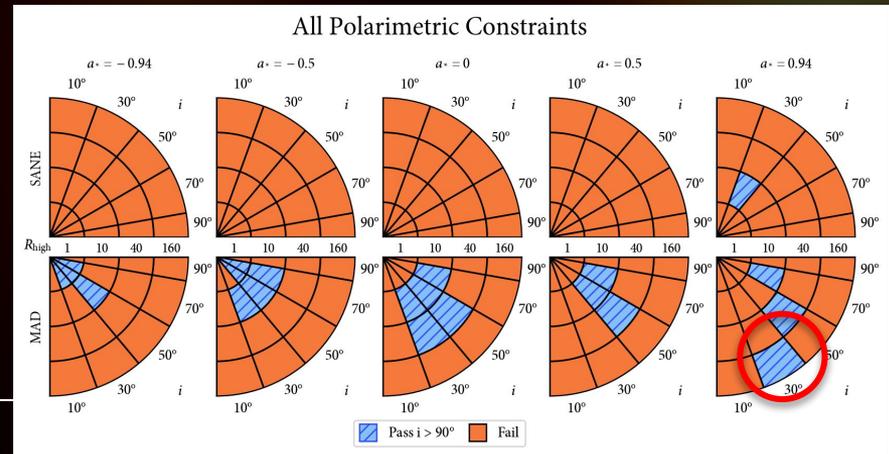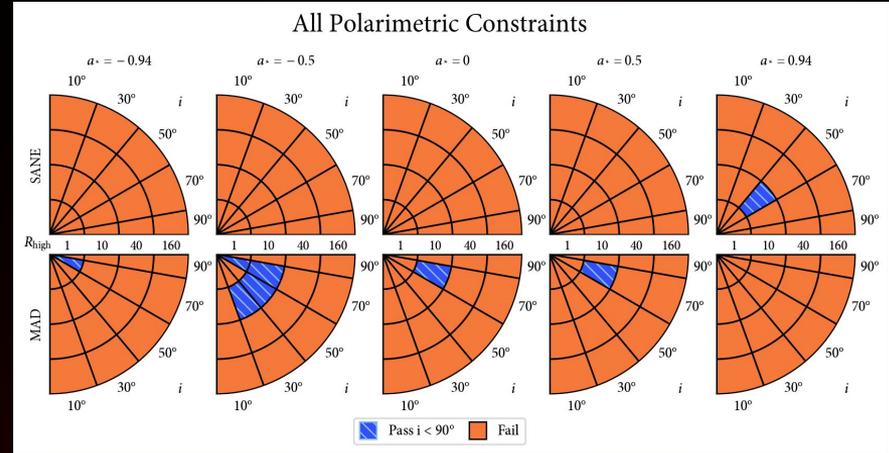
Which Simulations Work?

- We know the GRMHD are missing physics, but are there some models that get close enough to the real data?
- Yes!* Models with strong, coherent magnetic fields tend to look more like M87* and Sgr A* than other models
- *Except nearly all models are too variable…The best-bet model for Sgr A* doesn't recover the relatively calm variability we in the data!
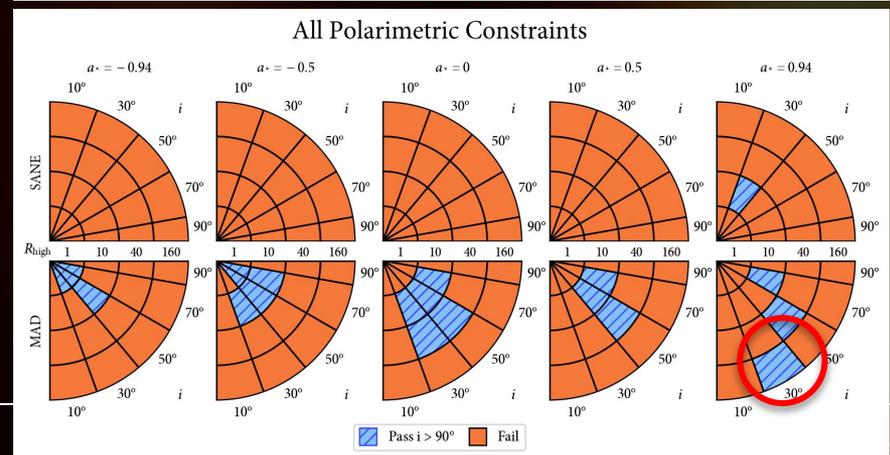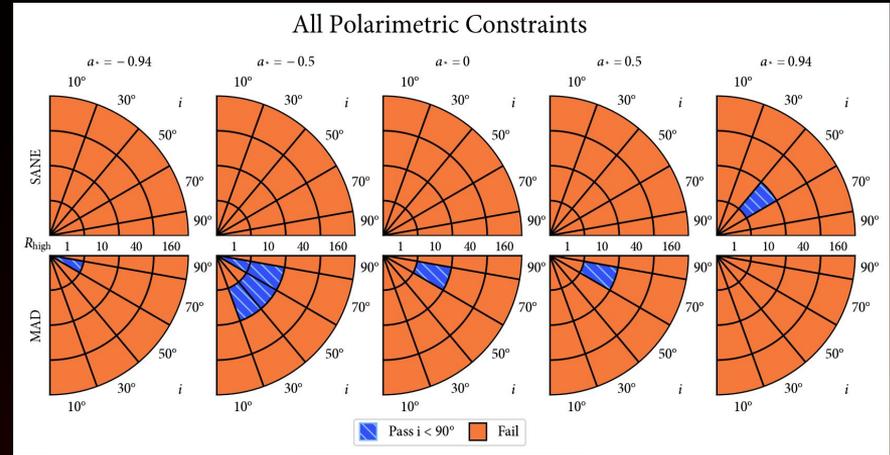
What did we discover?

- High frequency Global VLBI works as expected!

- Black holes look like bright rings of emission: the shadow is real!

- The sizes we measure are consistent with our predictions from GR: there is no evidence for deviations from Kerr

- We can learn about spin! A little…we can know about the spin direction in M87*, but the magnitude is harder to pin down

- Still haven't seen the jet: no baselines probe the jet scales, so no data means no constraints

What did we learn? What is next?

- Simulations with strong, ordered magnetic fields look more like the real thing than other models, and have jets that are definitely launched by the BZ mechanism, but…

- Our simulations are too variable! We need to come up with some way to calm them down. They also do not include physics *we know* should be present (non-thermal $e^{-/+}$, cooling, small-scale plasma physics).

- Future observations with more telescopes (deeper images) and special monitoring campaigns (black hole movies!) will help us pick out the connection between the jet and BH, and tell us much more about the accretion flow dynamics and particle content