EHT Observations, Theoretical Models, and Results

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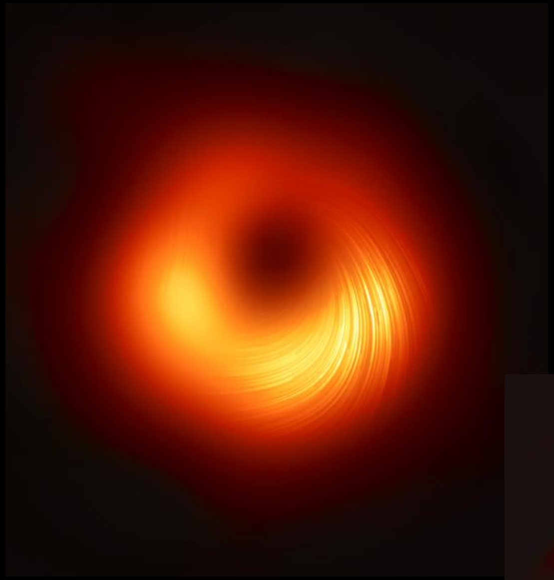
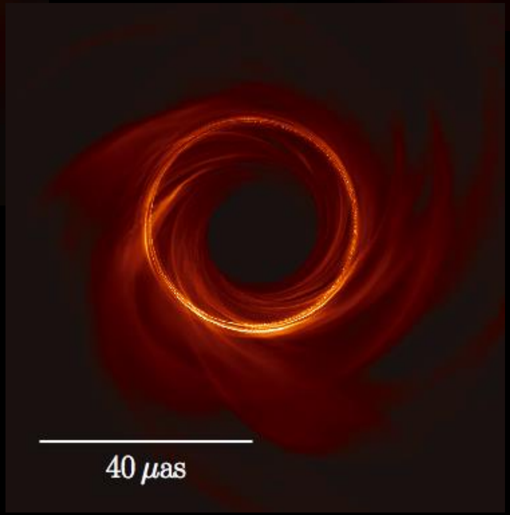
2/7/2023

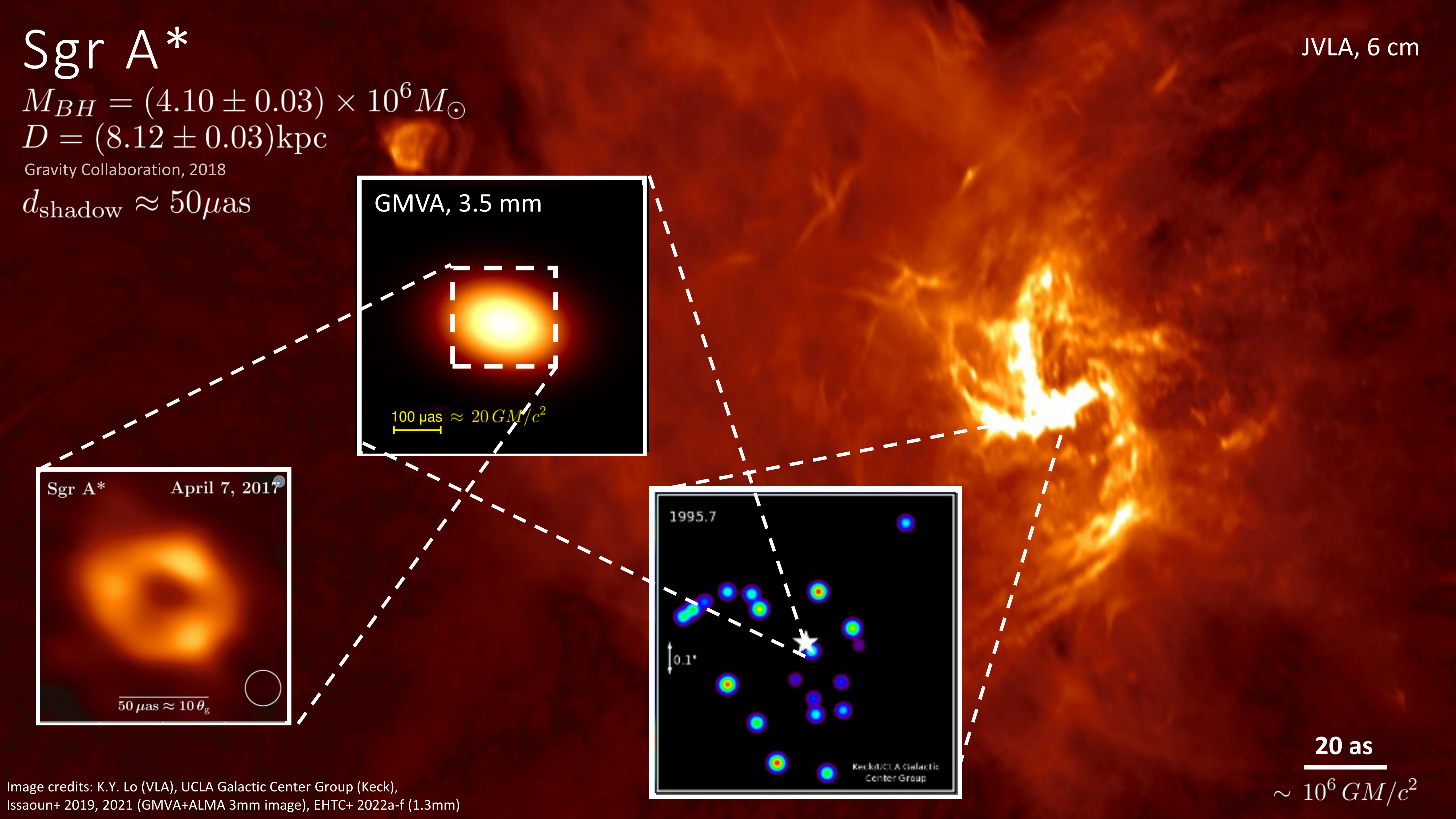




PRINCETON CENTER FOR THEORETICAL SCIENCE

Princeton gravity Initiative

Event Horizon Telescope



Sgr A*
$M_{BH} = (4.10 \pm 0.03) \times 10^6 M_\odot$
$D = (8.12 \pm 0.03)\mathrm{kpc}$
Gravity Collaboration, 2018
$d_{\rm shadow} \approx 50\mu\mathrm{as}$
JVLA, 6 cm
GMVA, 3.5 mm
100 µas $\approx 20\, GM/c^2$
Sgr A*
April 7, 2017
$50\,\mu\mathrm{as} \approx 10\,\theta_g$
1995.7
0.1"
Keck/UCLA Galactic Center Group
20 as
$\sim 10^6\, GM/c^2$
Image credits: K.Y. Lo (VLA), UCLA Galactic Center Group (Keck), Issaoun+ 2019, 2021 (GMVA+ALMA 3mm image), EHTC+ 2022a-f (1.3mm)

The Event Horizon Telescope

2017 Observations

ARIZONA

EHT Multi-wavelength partners

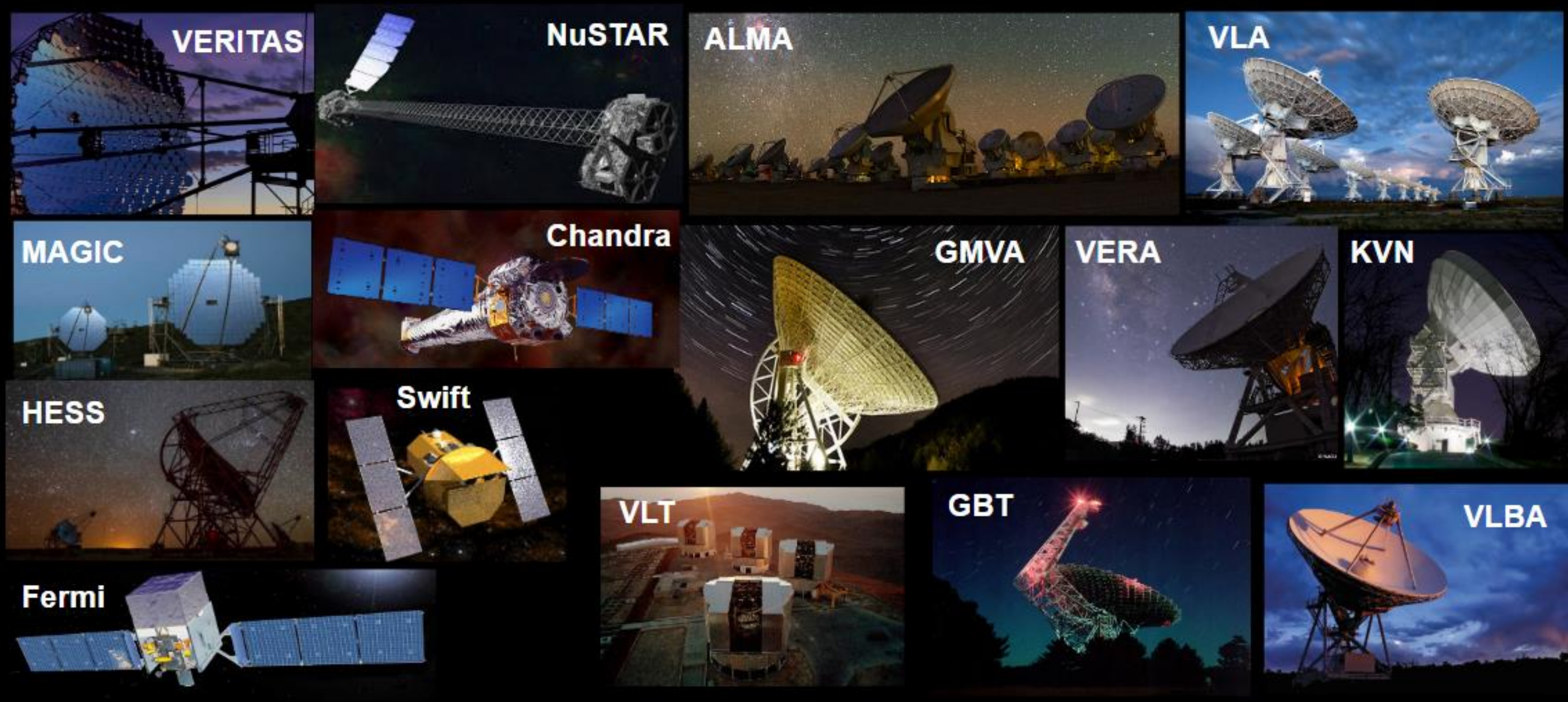
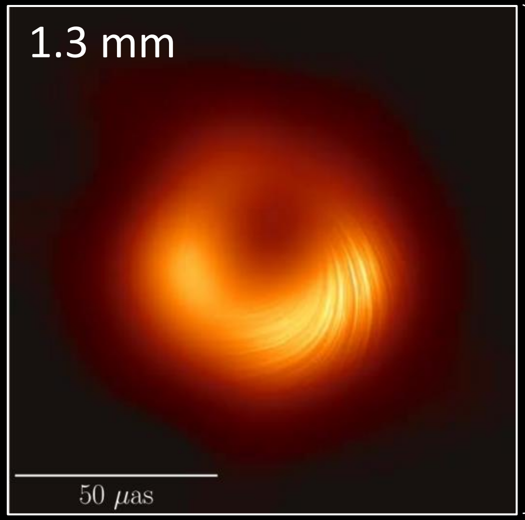


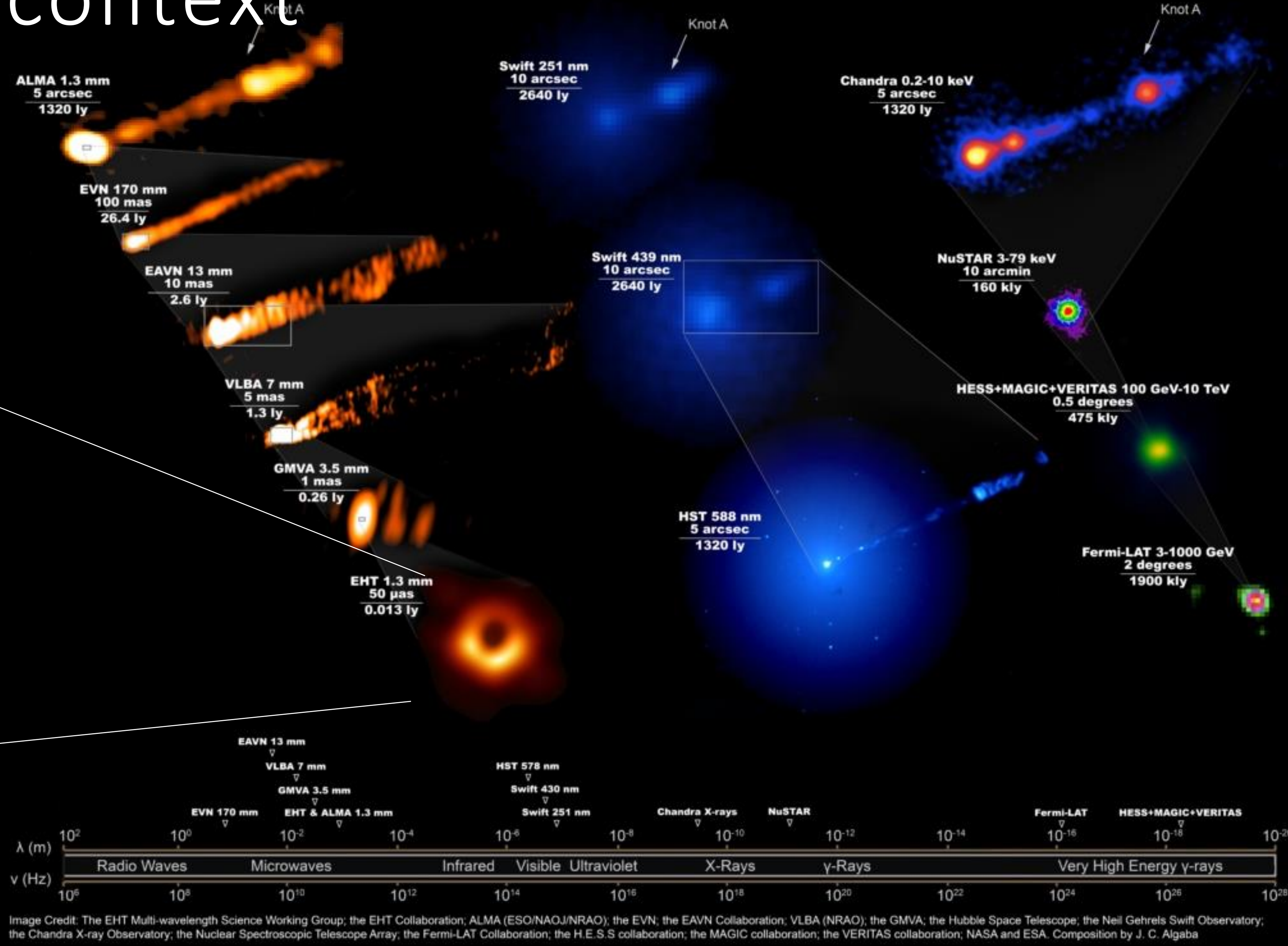
Image credits: NSF/VERITAS, Juan Cortina, Vikas Chander, NASA, NASA/JPL-Caltech, NASA/CXC/SAO, NASA, ESO, P. Kranzler & A. Phelps, NRAO/AUI/NSF, HyeRyung, NAOJ, MPIfR/N. Tacken

Slide credit: Sara Issaoun

EHT images in context

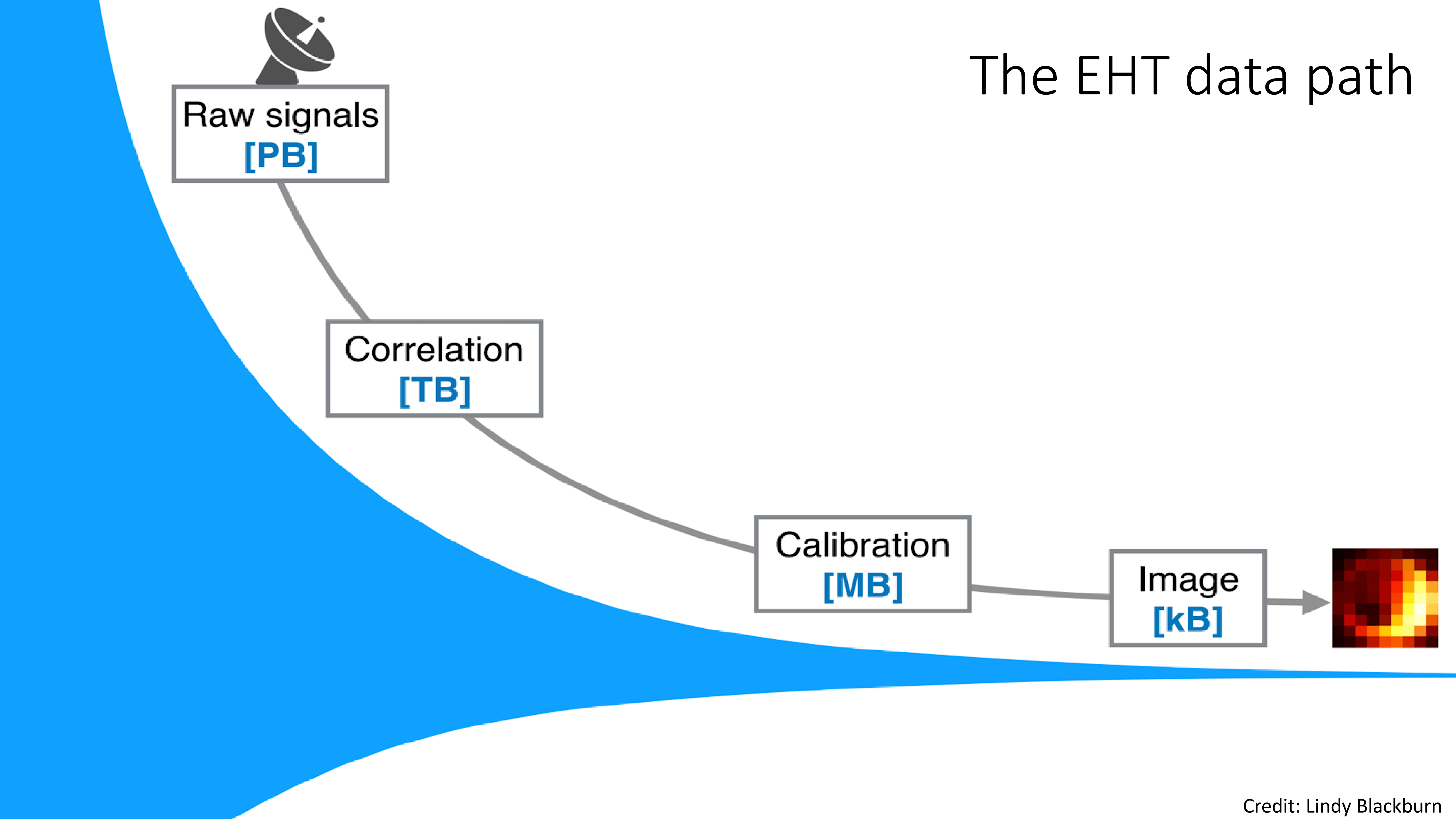
$$M_{BH} = (6.5 \pm 0.7) \times 10^9 M_\odot$$
$$D = (16.8 \pm 0.8)\mathrm{Mpc}$$





Credit: EHTC, NASA/Swift; NASA/Fermi; Caltech-NuSTAR; CXC; CfA-VERITAS; MAGIC; HESS: arXiv 2104.06855

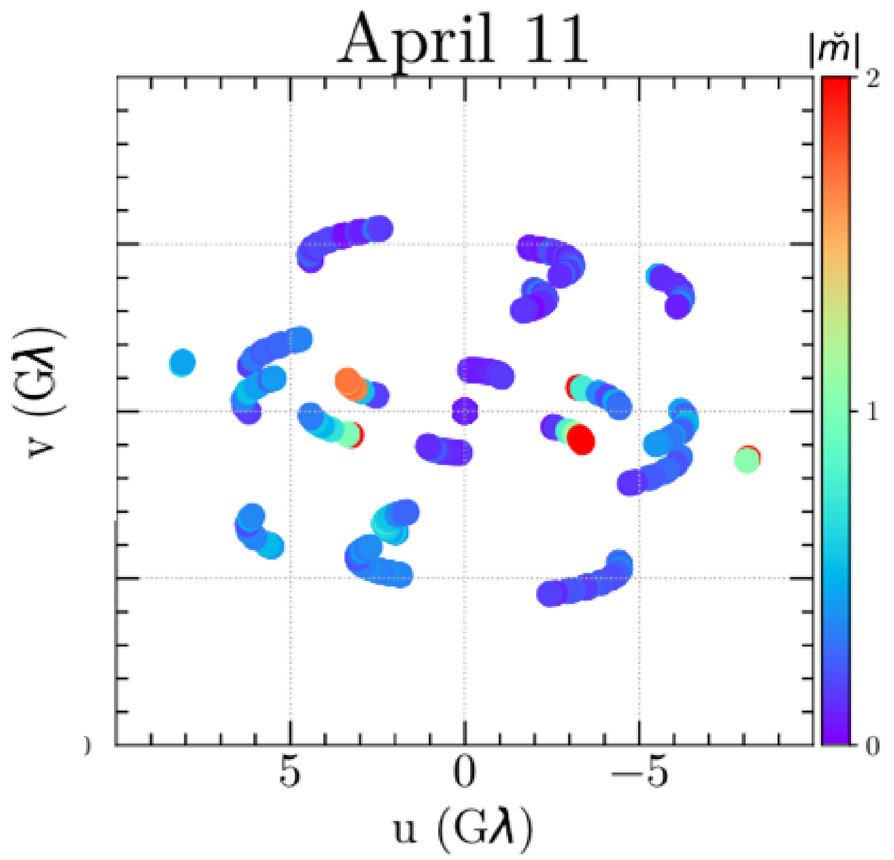
The EHT data path



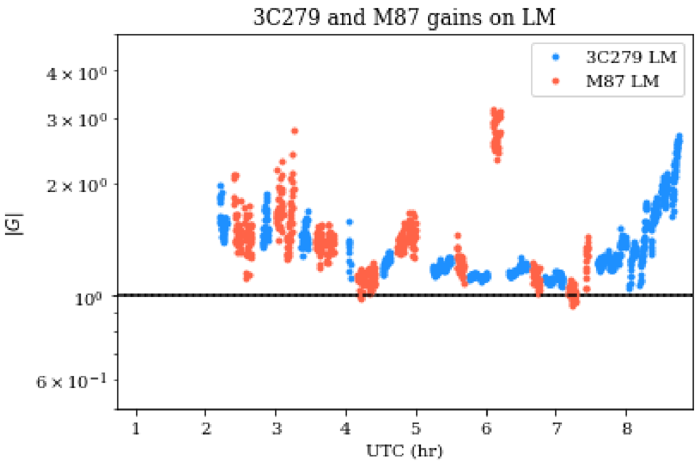
Credit: Lindy Blackburn

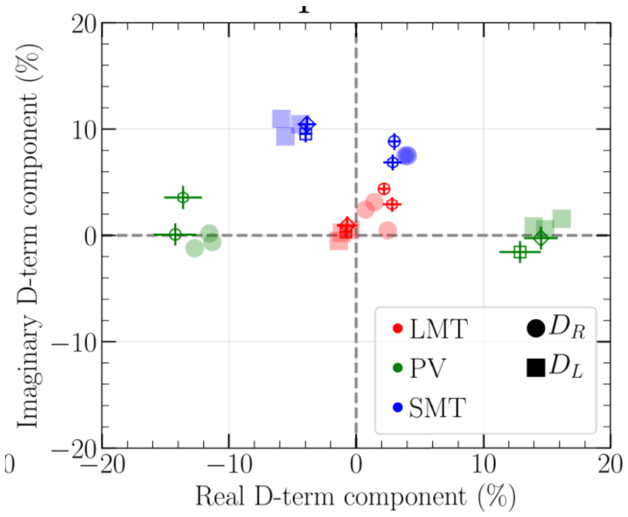
Challenges of EHT imaging/modeling

1. EHT coverage is **sparse**: inversion of image from the data is highly unconstrained



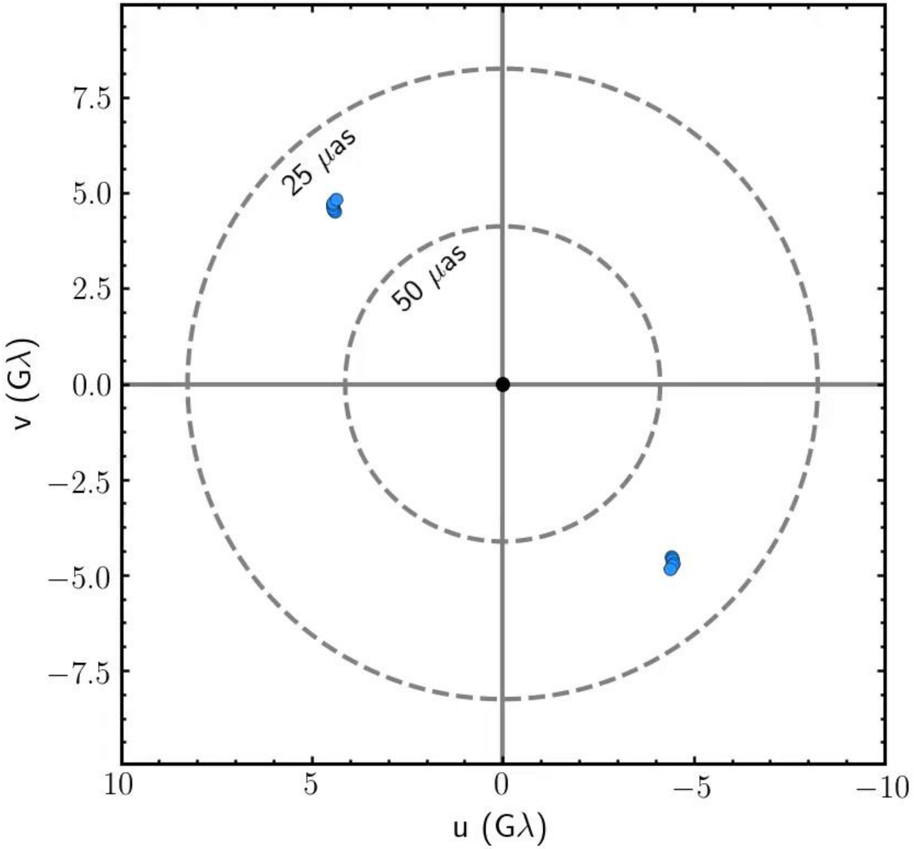
Data at each station are corrupted by unknown **complex gains** and polarimetric **leakage**





EHTC 2019 IV, 2021 VII

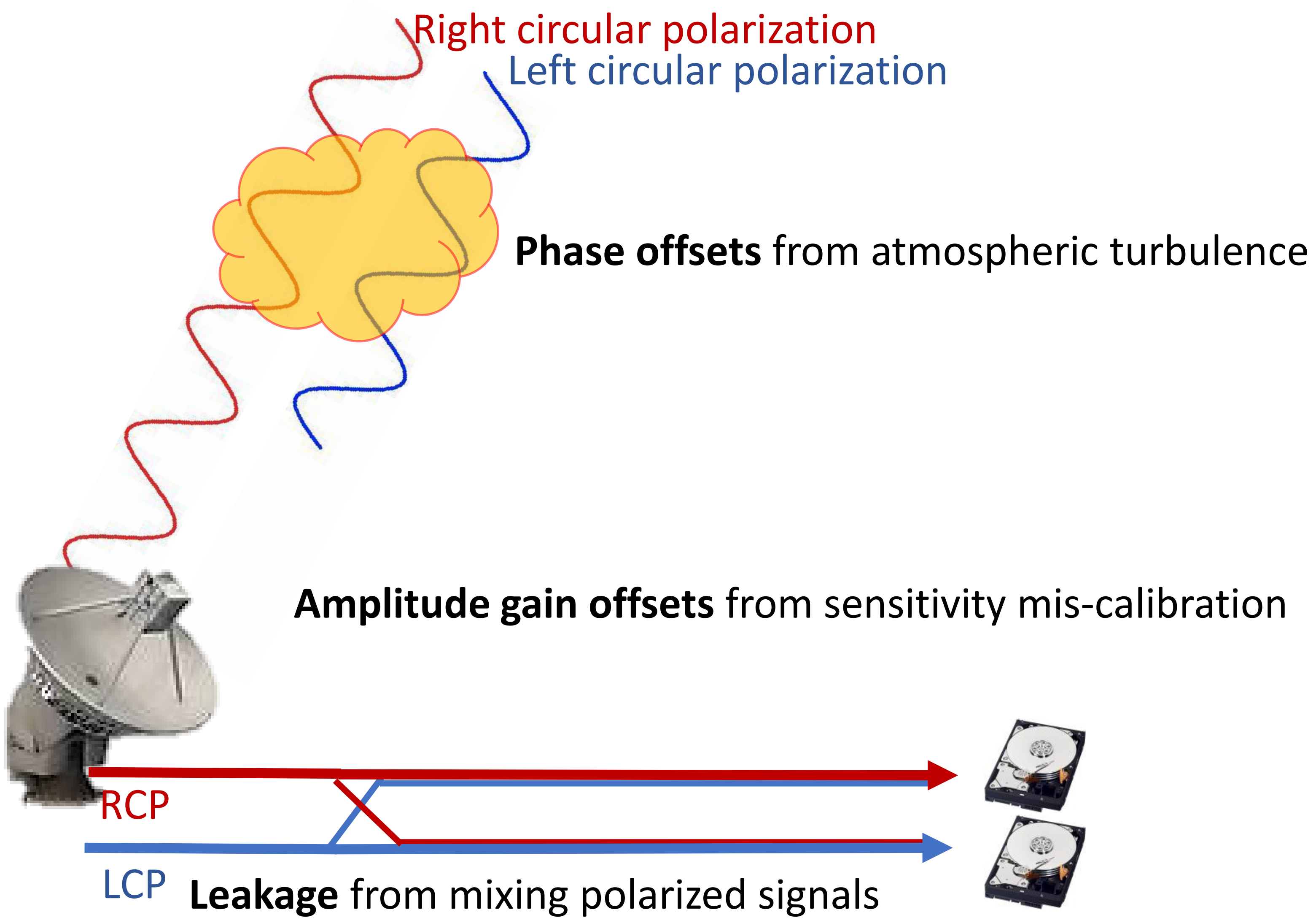
Very Long Baseline Interferometry (VLBI)



EHT coverage is **sparse**: inversion of image from the data is highly unconstrained

slide credit: Katie Bouman, Daniel Palumbo

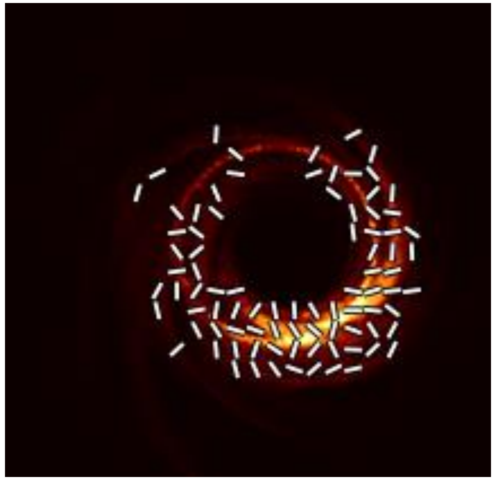
Corrupting effects at EHT stations



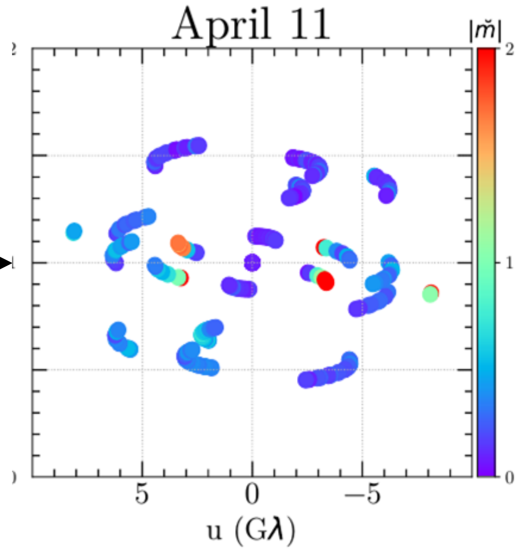
Data at each station are corrupted by unknown **complex gains** and polarimetric **leakage**

Solving for the Image

True Image

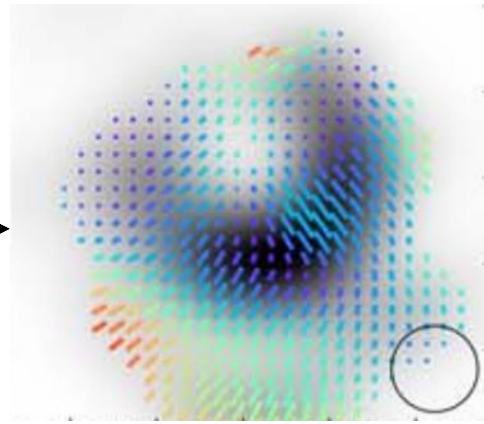


Sparse/ Corrupted Measurements



RECONSTRUCTION ALGORITHM

Reconstruction

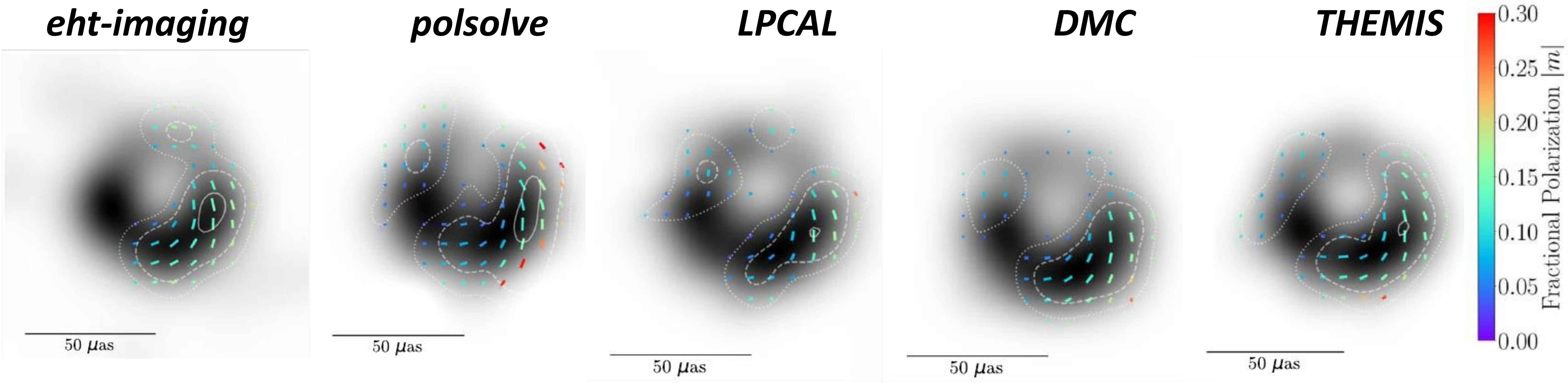


Different types of reconstruction algorithms:

- **CLEAN-based**: standard and efficient, but can have difficulties on very sparse data
  - LPCAL/GPCAL (Park+ 2021) and polsolve (Marti-Vidal+ 21)
- **Regularized Maximum Likelihood / Gradient Descent**: fast and flexible, but lots of hyperparameters
  - eht-imaging (Chael+ 2016, 2018)
- **Bayesian MCMC posterior exploration:** fully characterizes uncertainty, but expensive
  - Themis (Broderick+ 21), DMC (Pesce+ 21)

Slide credit: Katie Bouman, Andrew Chael, EHTC 2021, VII

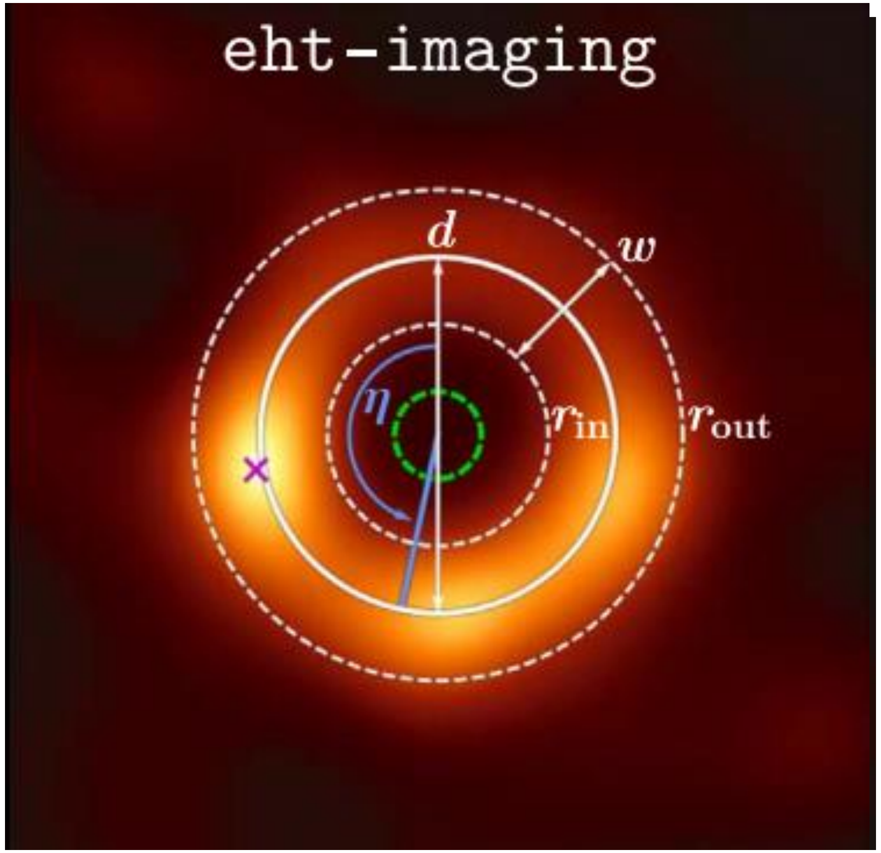
Validation: consistent features from different methods

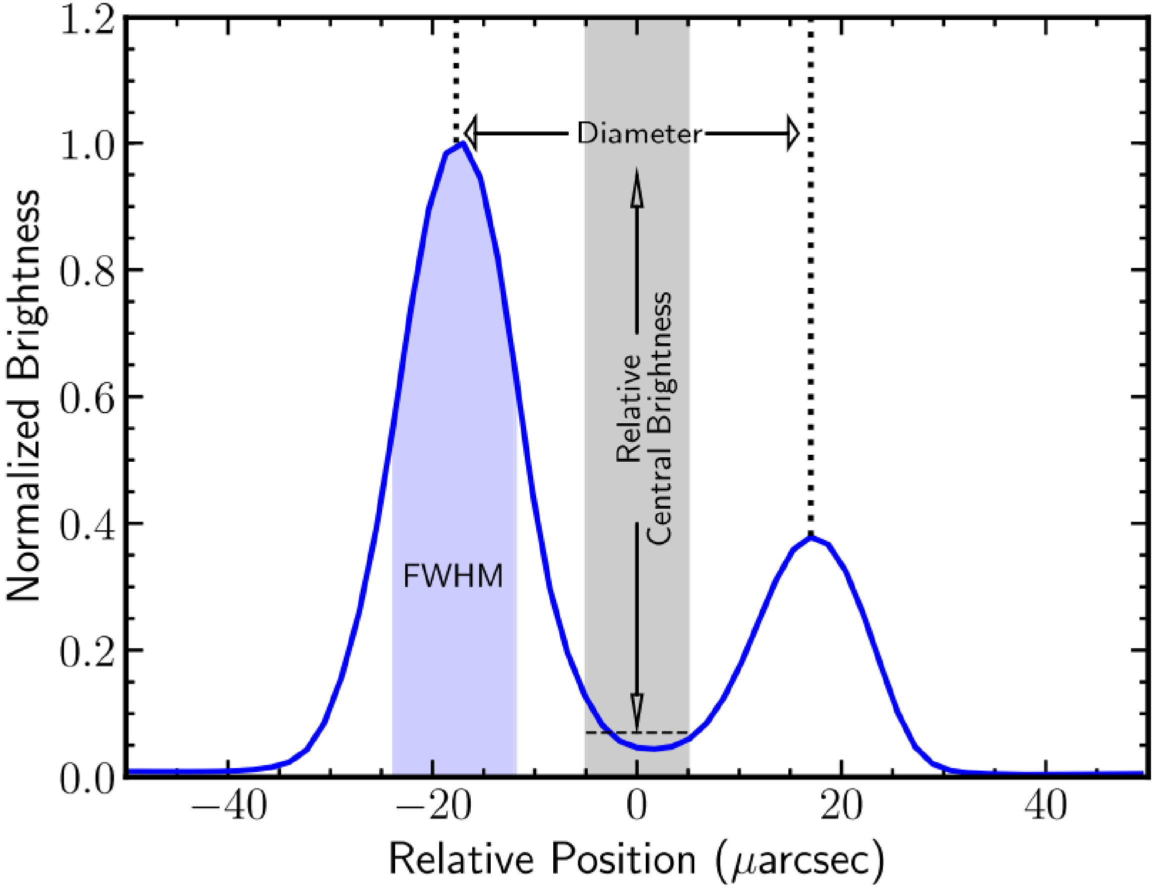


How do we compare results **across methods**?
compare **to simulation models**?

Credit: EHT 2021 Paper VII

Summarizing an image: Total Intensity





EHT Paper VI, 2019

Summarizing an image: Polarization

Unresolved
polarization fractions

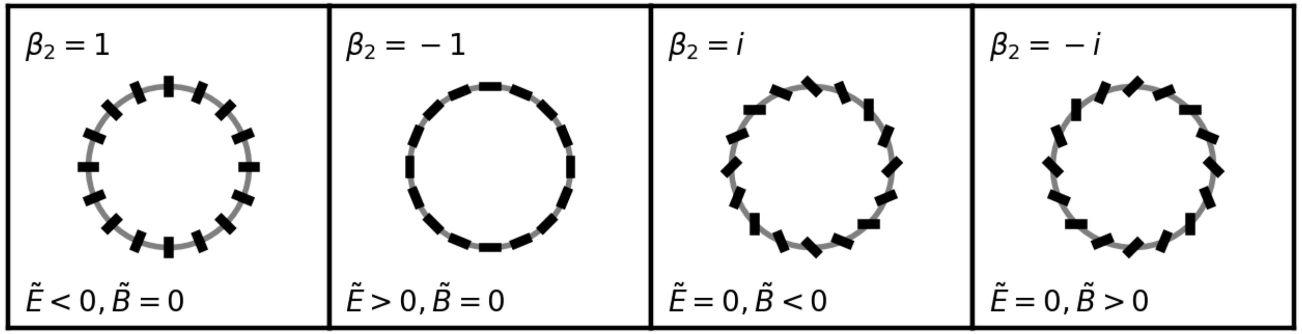
$|m|_{\mathrm{net}}$ $|v|_{\mathrm{net}}$

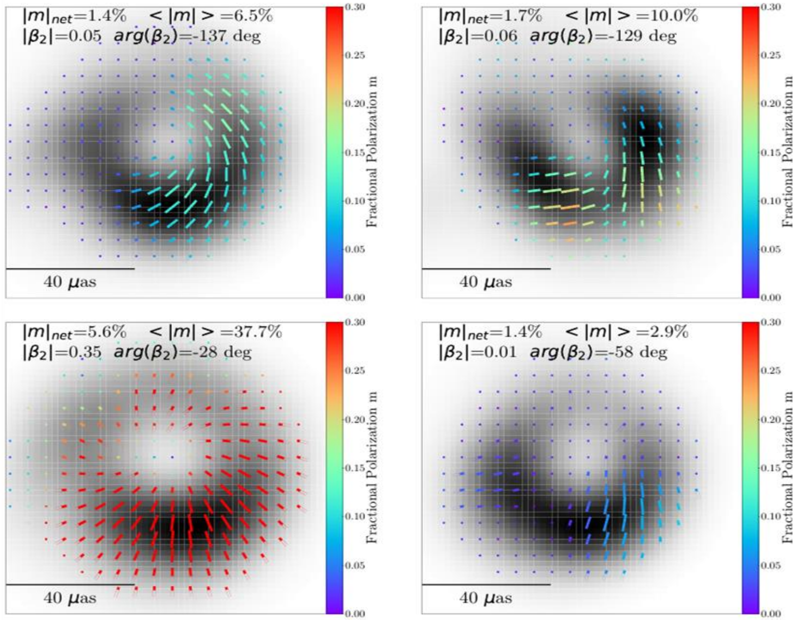
Average Resolved
linear polarization fraction

$\langle |m| \rangle$

Azimuthal structure
2nd Fourier mode

$$\beta_2 = \frac{1}{I_{\mathrm{ring}}} \int_{\rho_{\min}}^{\rho_{\max}} \int_{0}^{2\pi} P(\rho, \varphi)\, e^{-2i\varphi}\, \rho\, d\varphi\, d\rho$$



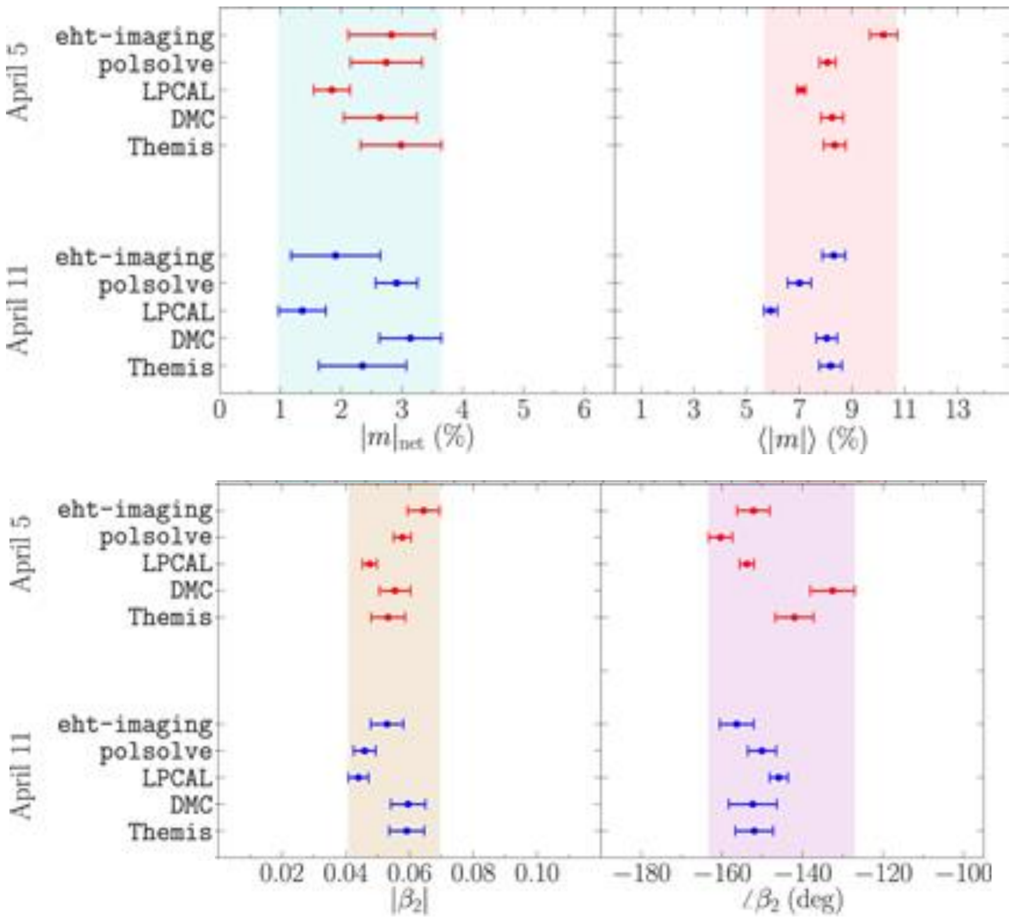


GRMHD images can be **strongly** or **weakly** polarized:
with **patterns** that are radial/toroidal/helical

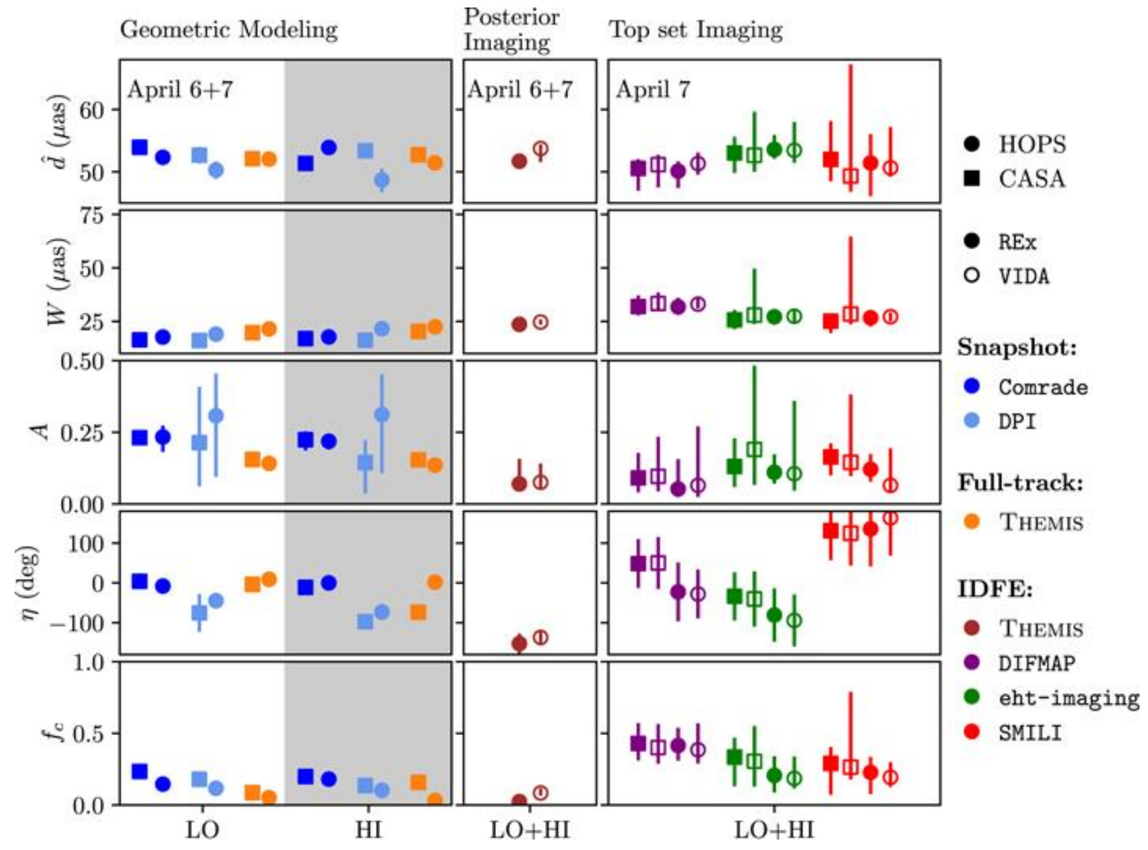
EHTC+ VII, VIII 2021

Summarizing an image: comparing methods

M87 Linear polarimetric metrics: Paper VII



Sgr A* Linear polarimetric metrics: Paper IV



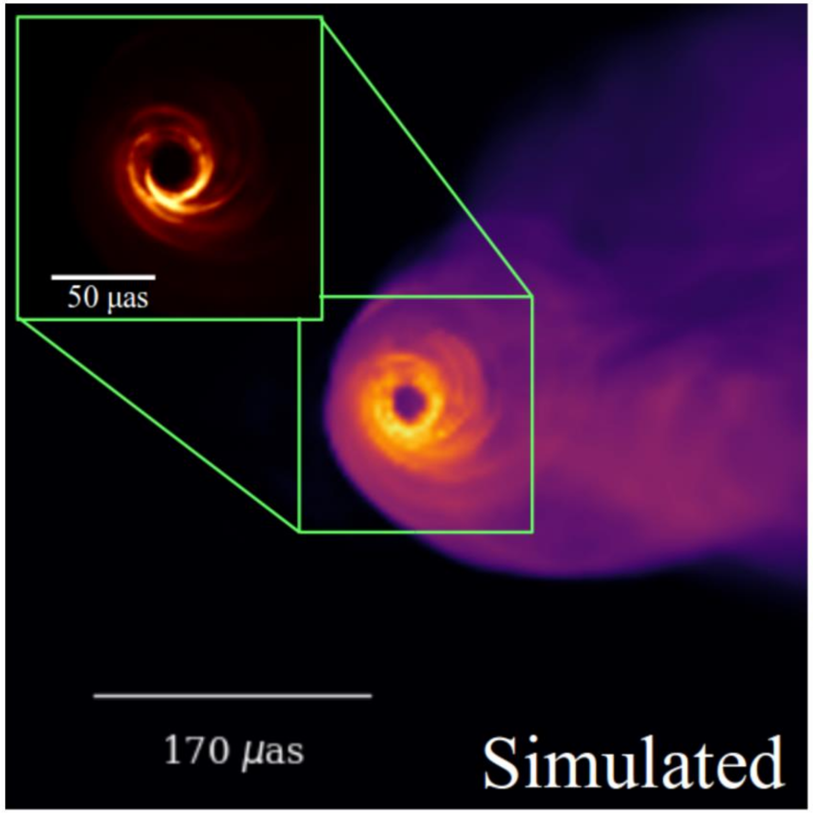
summary statistics defined in EHT papers represent quantities we confidence in measuring provide a **natural point of comparison for new theoretical models** to existing

EHTC 2021, Paper VII
EHTC 2022, Paper IV

Future EHT observations: dynamic range

- Increased (u,v) filling from new telescope sites in EHT can enhance image **dynamic range** from ~10 to ~1000.

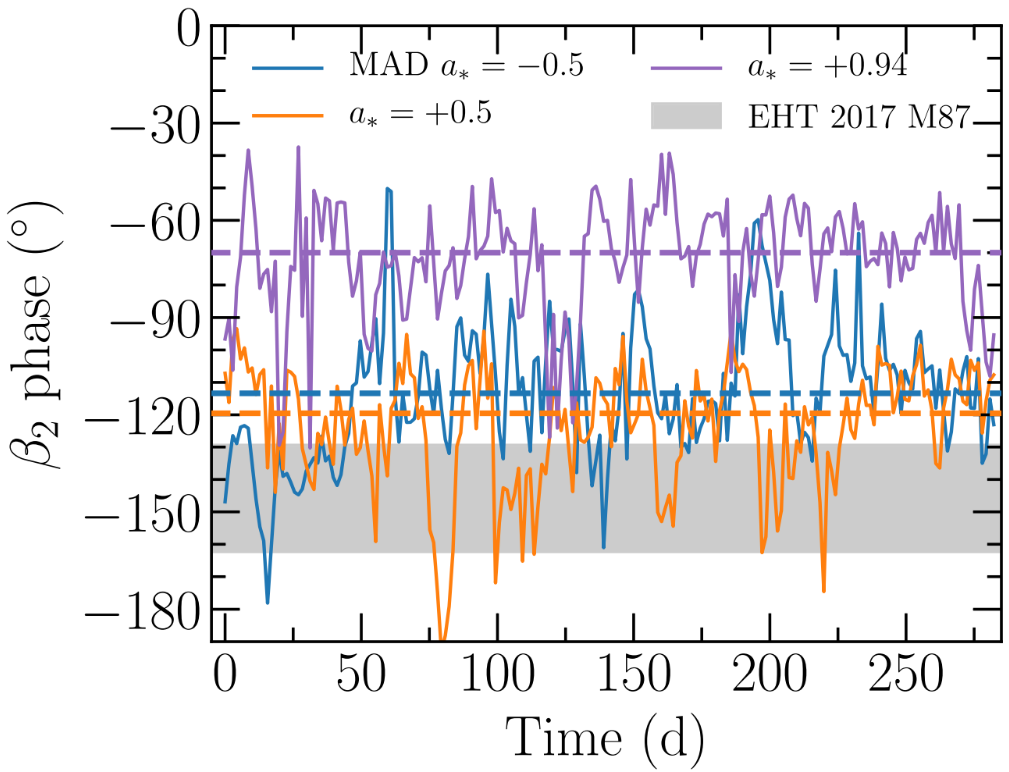
- High dynamic range images will illuminate the **BH-jet connection**



See EHT Ground Astro2020 APC White Paper
(Blackburn, Doeleman+; arXiv:1909.01411)
Simulation credit: Chael+ 2019

Future EHT observations: dynamics

- Future EHT observations should see **strong variability** on **week-month timescales in M87**
- More measurements should further tighten our constraints, and may require us to expand our space of models
- Variability on **minute-hour timescales in Sgr A*** already poses a **strong challenge to GRMHD** models

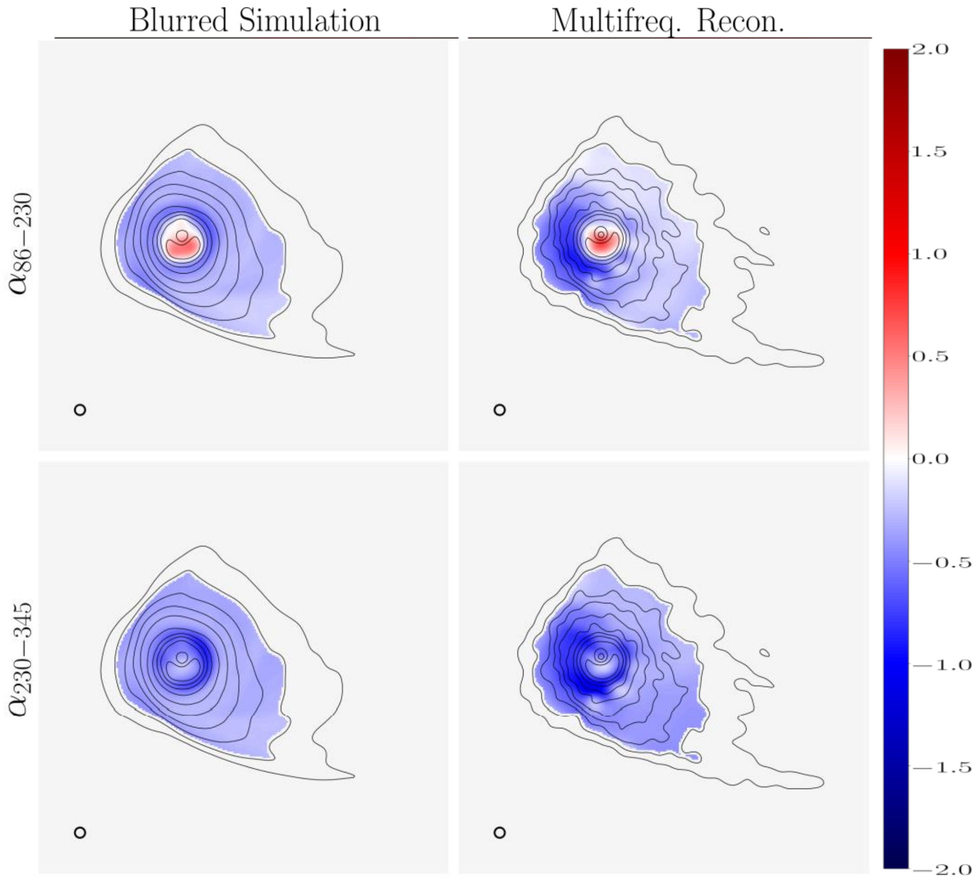


EHTC 2021, Paper VIII

Future EHT observations: multi-frequency

- Future EHT observations will observe **simultaneously at 230 and 345 GHz**
    - and simultaneous GMVA observations at **86 GHz**

- Spectral index and rotation measure measurements from 86-345 GHz can help constrain magnetic fields and particle distribution functions



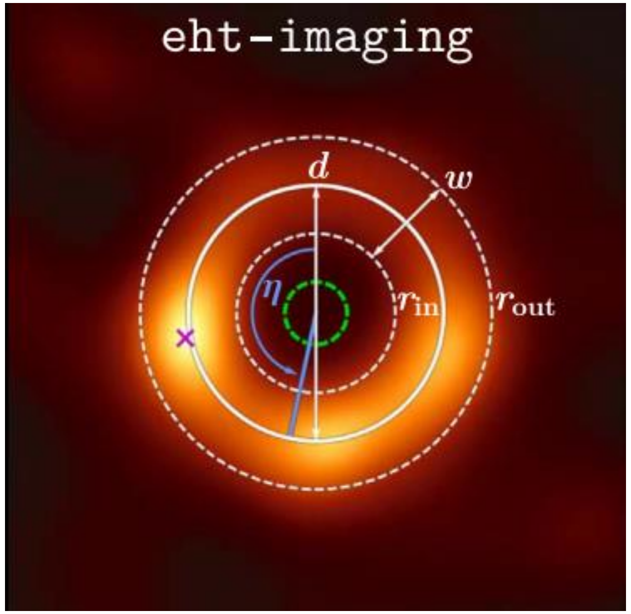
Chael+ 2022, arxiv 2210.12226

EHT observations: Summary

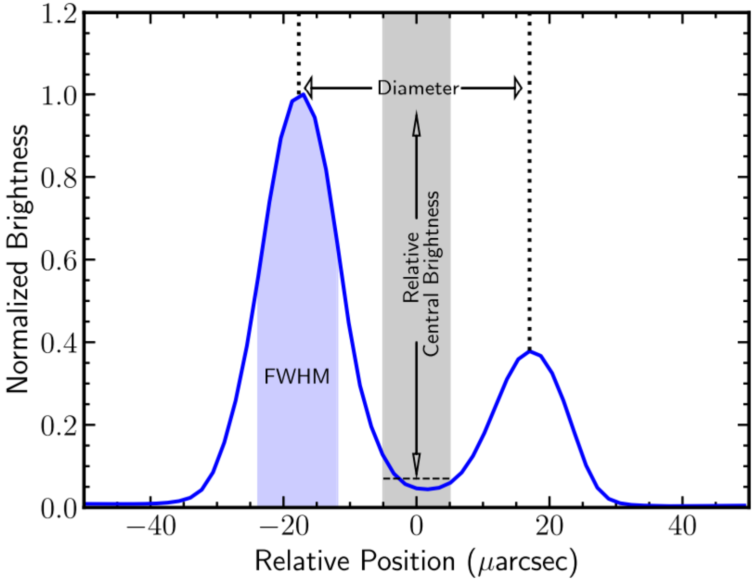
- Inverting EHT data to get an image of the source is highly non-trivial
  - we must deal with data **sparsity and corruption**
  - a hands on, slow process requiring extensive validation (so far)
- Before comparing to theory, we summarize EHT images with metrics
  - e.g. ring diameter / polarization Fourier modes
  - these are a good choice for comparing to new simulations!
- Future observations will have enhanced dynamic range, spatial-, time- and spectral resolution
- Multi-wavelength data is a big part of EHT analyses to date and will be even more important in the future!

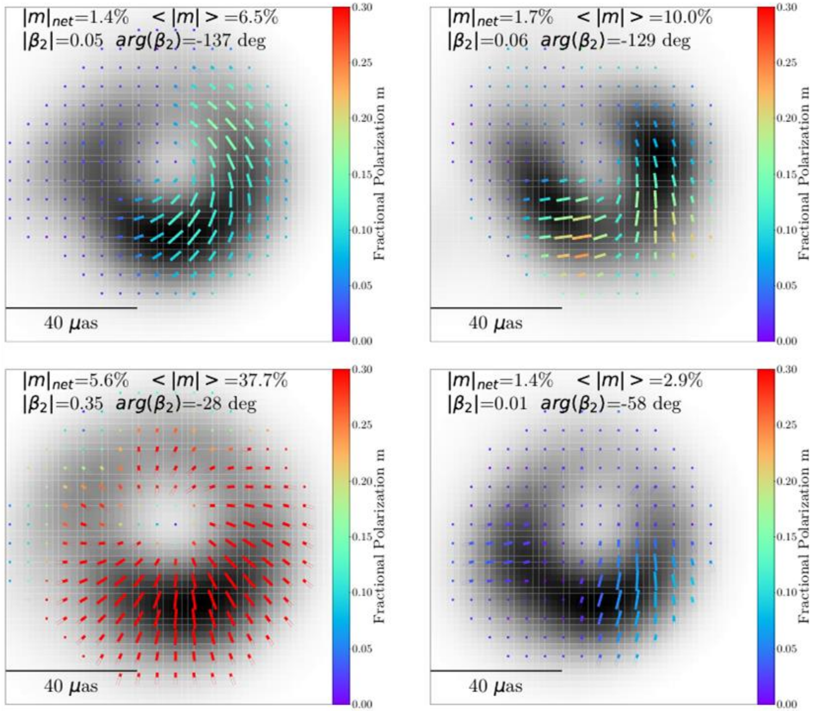
How do we Model?

What do we hope to learn from the observations?



EHT M87 Paper VI, 2019

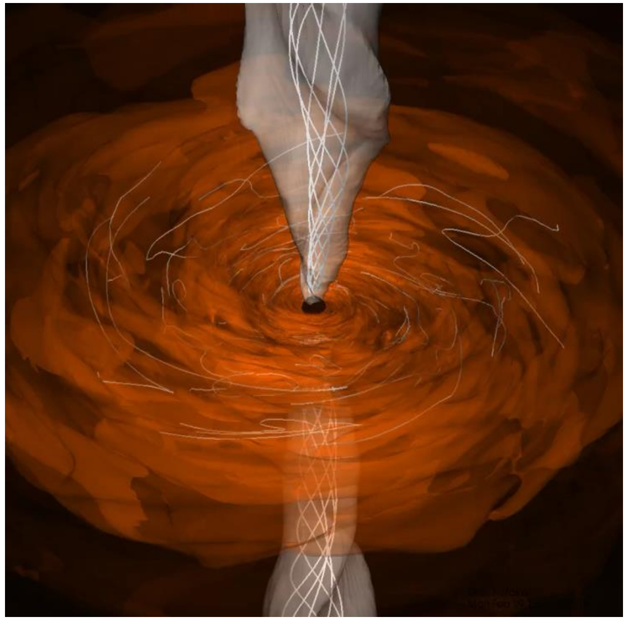




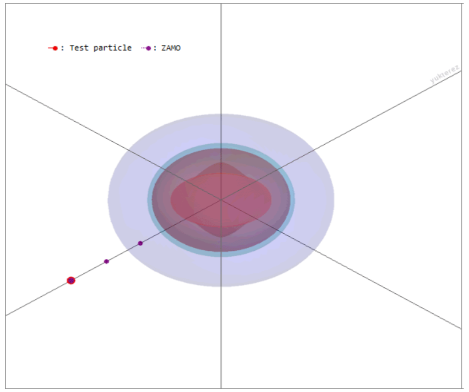
EHT M87 Paper VIII, 2021

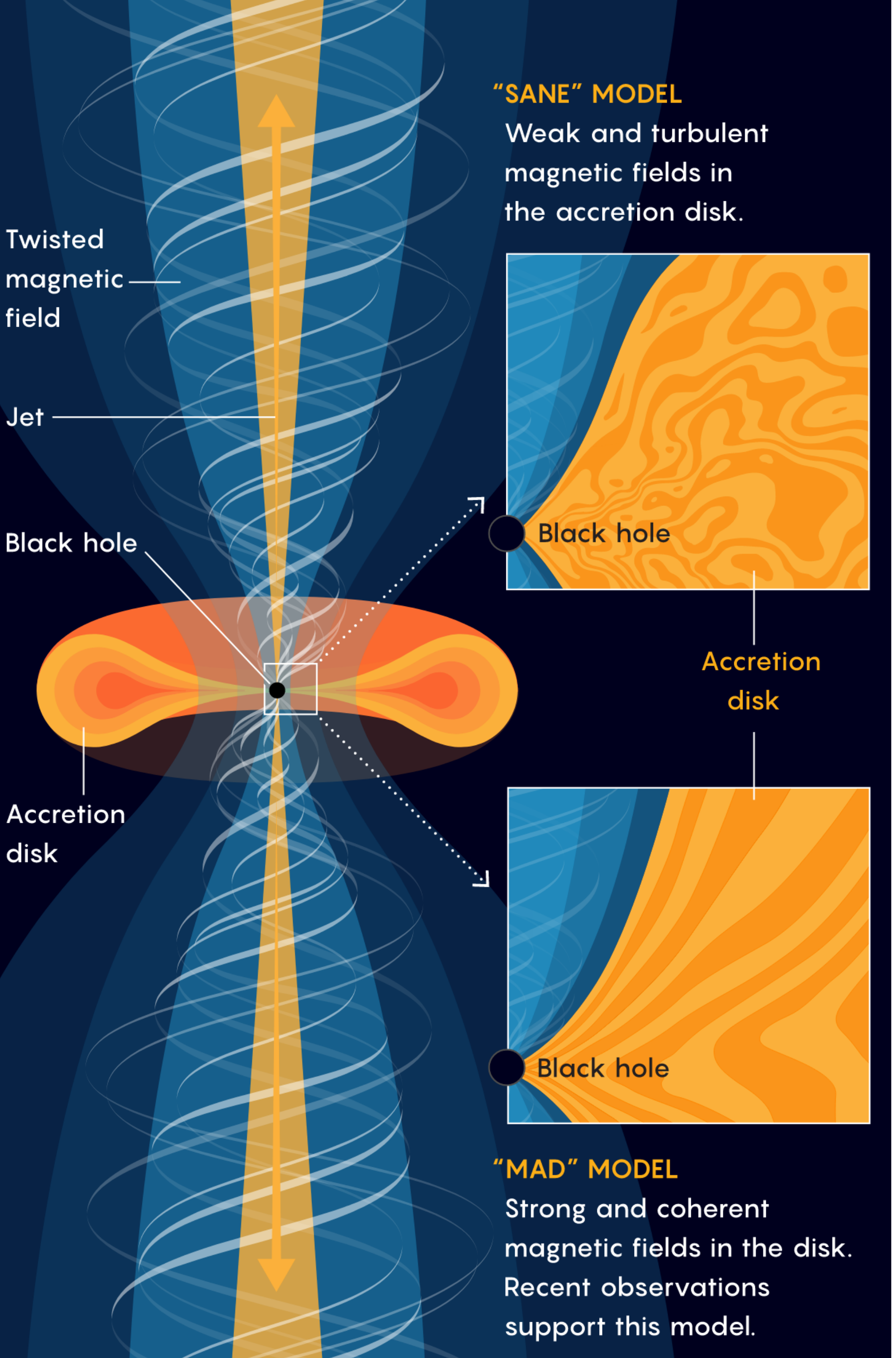
What do we hope to learn from the observations?

- What are the (characteristic) parameters of the system?
  - black hole mass
  - black hole angular momentum
  - boundary conditions (source of plasma)
  - mass accretion rate
  - temperature of ions/electrons
  - magnetic field strength & structure



- What is the relationship between the black hole, the accretion, and the jet?
  - dynamical influence of spinning black hole
  - source of jet power (for M87)
  - origin and composition of jet mass





Magnetic field structure and effect

Magnetic fields are weak and turbulent

Standard and Normal Evolution

Strong, coherent magnetic fields build up on the horizon

Magnetically Arrested Evolution

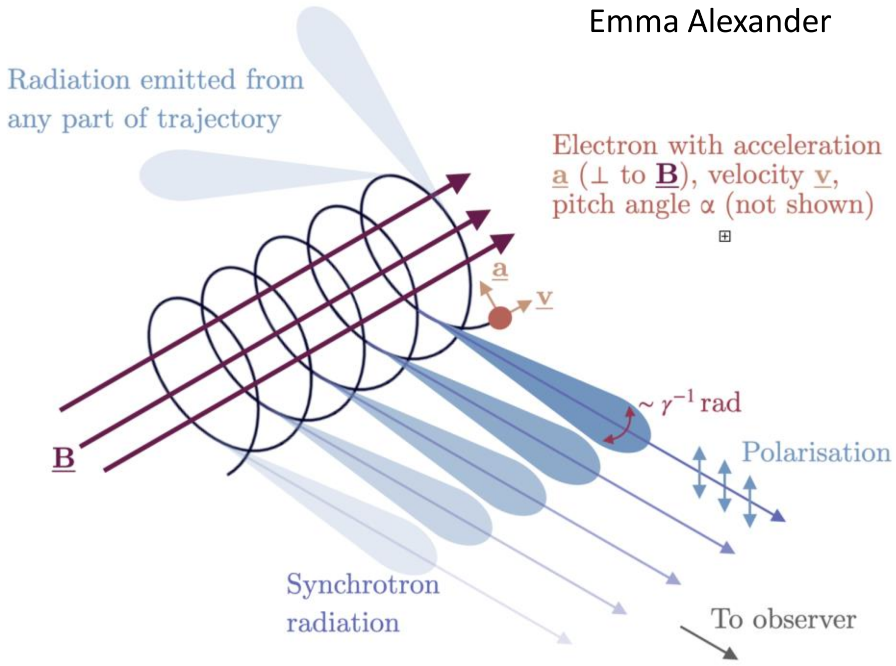
strong fields = 10-100 G at the horizon for M87

Igumenschchev 1977, Narayan+2003, Tchekhovskoy+2011, Narayan+ 2012

Image credit: O'Riordan+ 2017, Quanta Magazine

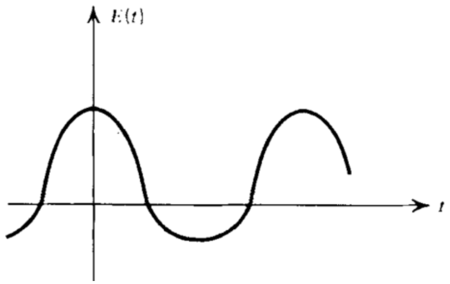
Simple estimates from a simple model

Emma Alexander



EHT observations are of synchrotron radiation at 230 GHz
Constraints:

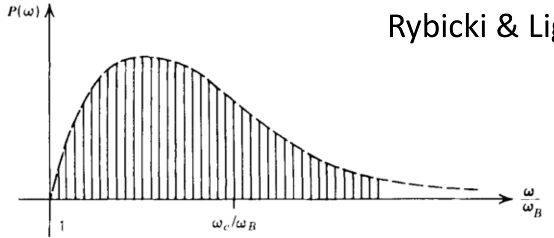
- black hole mass
- source size on sky
- total flux density
- peak brightness temperature (a.k.a. peak intensity)
- rotation measure (from linear polarization)



example values for Galactic Center (Sgr A*)

$$r_g \equiv GM/c^2 \simeq 6.1 \times 10^{11}\,\mathrm{cm}, \quad t_g \equiv GM/c^3 \simeq 20.4\,\mathrm{s},$$

$$\Theta_e \equiv k_B T_e/(m_e c^2) \sim 10$$
$$n_e \simeq 1.0 \times 10^6\,\mathrm{cm}^{-3}$$
$$B \simeq 29\,\mathrm{G}.$$



Rybicki & Lightman

Simple estimates from a simple model

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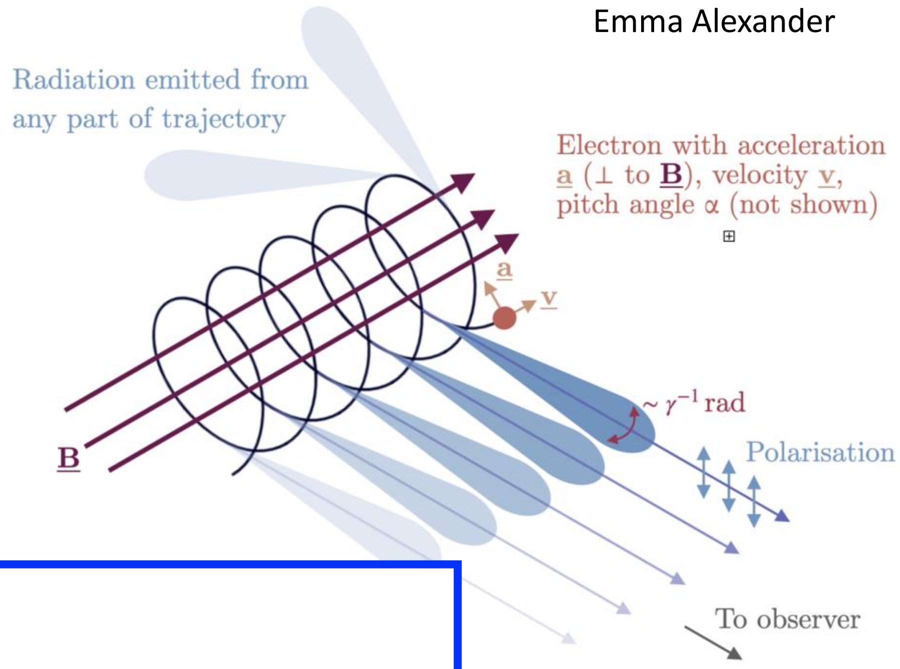


EHT observations are of synchrotron radiation at 230 GHz
Constraints:

- black hole mass
- source size on sky
- total flux density
- peak brightness temperature (a.k.a. peak intensity)
- rotation meas

exam

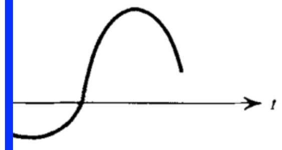
$$r_g \equiv GM/c^2 \simeq 6$$

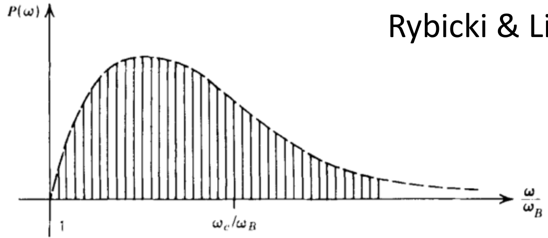
$$t_g \equiv GM/c^3 \simeq 20.4\,\mathrm{s},$$

$$B \simeq 29\ \mathrm{G}.$$

but …

- ➢ geometric features in resolved image
- ➢ want to explain observed source variability





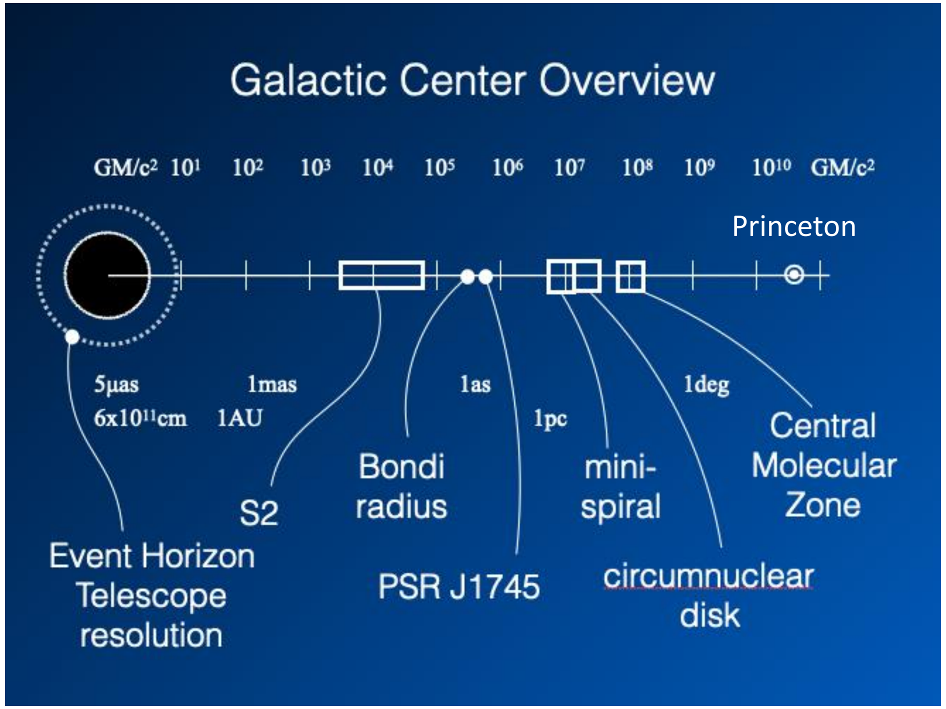
Rybicki & Lightman

Toward complexity

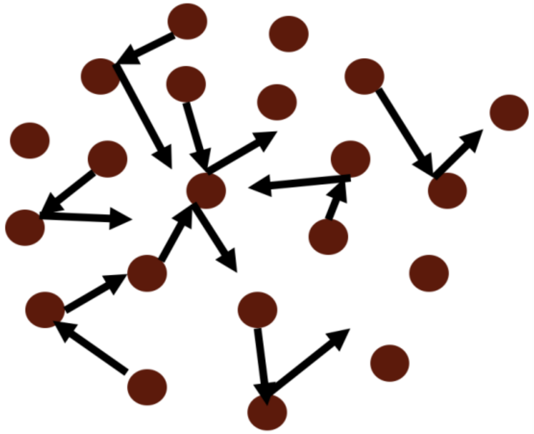
Why not simulate everything?

"Particle-in-cell" methods track large number of electrons, ions, positrons, photons … and solve kinetic equations!

Problem: Expensive! Separation of scales!



system size: 10^{10} m
Coulomb mean free path: 10^{15} m
electron gyroradius: 100 m
ω_{pl} : 10^7 rad/s
dynamical time: 100 s
m_i / m_e: 2000



$$\frac{\partial f_s(\vec{x},\vec{v},t)}{\partial t} + \vec{v}\cdot\nabla_x f_s + \frac{q_s}{m_s}\left(\vec{E} + \frac{\vec{v}}{c}\times\vec{B}\right)\cdot\nabla_v f_s = \mathrm{C}[\mathrm{f_s}]$$

Simulating complexity

GRMHD simulation

+ black hole spin
+ magnetic field
+ boundary conditions

fluid description

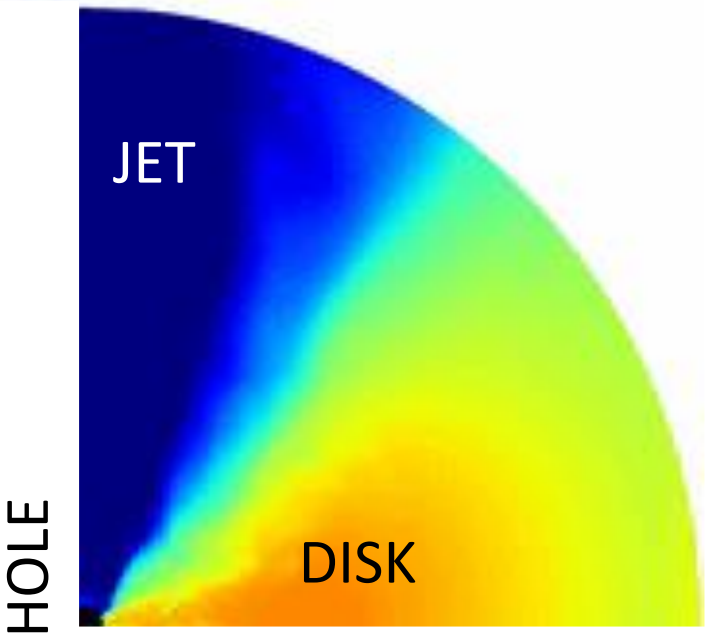
density, internal energy, velocity, magnetic field

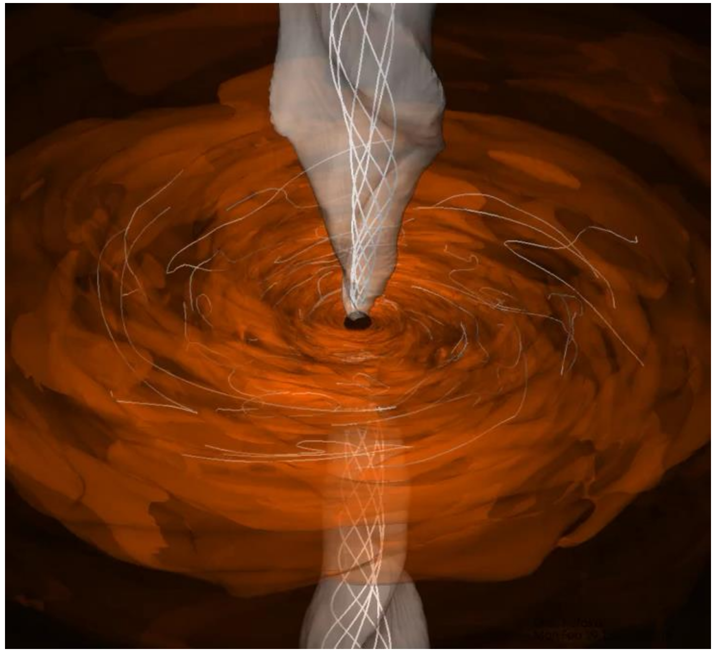
Radiative transfer

+ inclination / orientation
+ thermodynamics

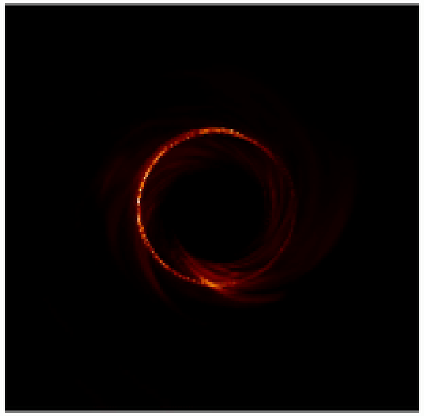
observables

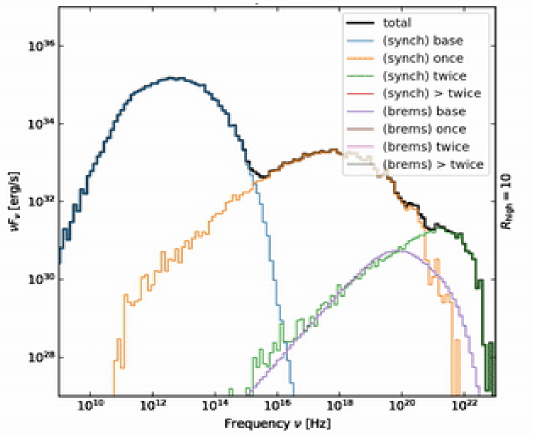
polarimetric movies & spectra





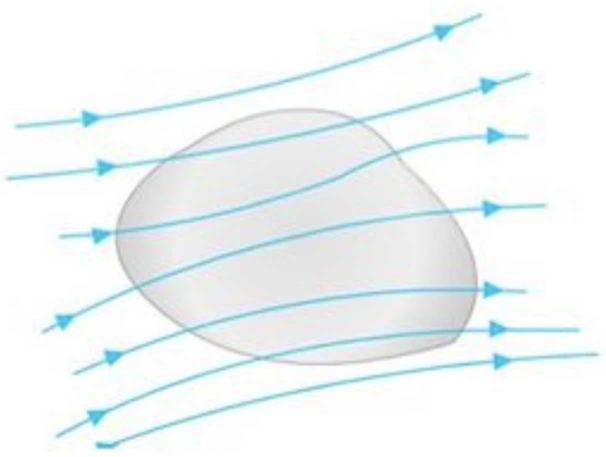
credit: H. Shiokawa





Fluid modeling in a nutshell

finite volume
(conservative) method



$$\frac{\partial}{\partial t}\int_V U\,\mathrm{d}V = -\oint_{\partial V} \vec{F}\cdot \mathrm{d}\vec{S} + \int_V Q\,\mathrm{d}V$$

governing equations

conservation laws
Maxwell's equations

$$\nabla_\mu N^\mu = 0,$$
$$\nabla_\mu T^{\mu\nu} = 0.$$

$$\nabla_\nu \star F^{\mu\nu} = 0,$$
$$\nabla_\nu F^{\mu\nu} = 4\pi j^\mu,$$

$$T^{\mu\nu} = T^{\mu\nu}_{\mathrm{EM}} + T^{\mu\nu}_{\mathrm{fluid}} + T^{\mu\nu}_{\mathrm{rad}}$$

EM / fluid / radiation sectors
coupled to each other

$$\nabla_\mu T^{\mu\nu}_{\mathrm{EM}} = j_\mu F^{\mu\nu},$$
$$\nabla_\mu T^{\mu\nu}_{\mathrm{fluid}} = -j_\mu F^{\mu\nu} + G^\nu,$$
$$\nabla_\mu T^{\mu\nu}_{\mathrm{rad}} = -G^\nu.$$

Fluid modeling in a nutshell

$$h^{\mu\nu} \equiv g^{\mu\nu} + u^\mu u^\nu$$

Fluid sector can be decomposed into **ideal** and **dissipative** components.

- **heat conduction**
- **viscosity**

$$T^{\mu\nu} = e u^\mu u^\nu + P h^{\mu\nu} + q^\mu u^\nu + q^\nu u^\mu + \pi^{\mu\nu},$$

$$T^{\mu\nu} = (\rho + u)\, u^\mu u^\nu + P h^{\mu\nu}$$
$$= (\rho + u + P)\, u^\mu u^\nu + P g^{\mu\nu}$$

$$T^{(a)(b)} = \begin{pmatrix} \rho + u & 0 & 0 & 0 \\ 0 & P & 0 & 0 \\ 0 & 0 & P & 0 \\ 0 & 0 & 0 & P \end{pmatrix}$$

$$T^{\mu\nu} = T^{\mu\nu}_{\rm ideal} + T^{\mu\nu}_{\rm cond} + T^{\mu\nu}_{\rm visc}$$

$$T^{\mu\nu}_{\rm ideal} = (\rho + u)\, u^\mu u^\nu + (P - \Pi)\, h^{\mu\nu},$$
$$T^{\mu\nu}_{\rm cond} = q^\mu u^\nu + q^\nu u^\mu,$$
$$T^{\mu\nu}_{\rm visc} = \Pi h^{\mu\nu} + \pi^{\mu\nu}.$$

canonical EHT models:

- neglect kinetic effects
- track one internal energy
- neglect dissipative effects
  - viscosity
  - heat conduction
  - resistivity

Radiative transfer model

The electron (+ positron) distribution function(s)

Must translate **fluid internal energy** from simulation into **distribution function** to model emission, absorption, and rotation

1. how much energy ends up in electrons?

parametric “r high” model:

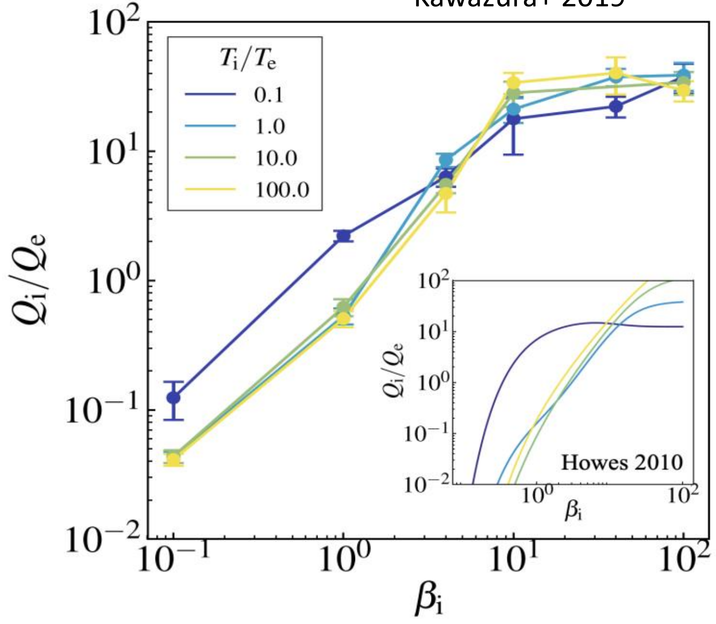
$$R \equiv T_i/T_e = r_{\rm low}\frac{1}{1+\tilde{\beta}^2} + r_{\rm high}\frac{\tilde{\beta}^2}{1+\tilde{\beta}^2},$$

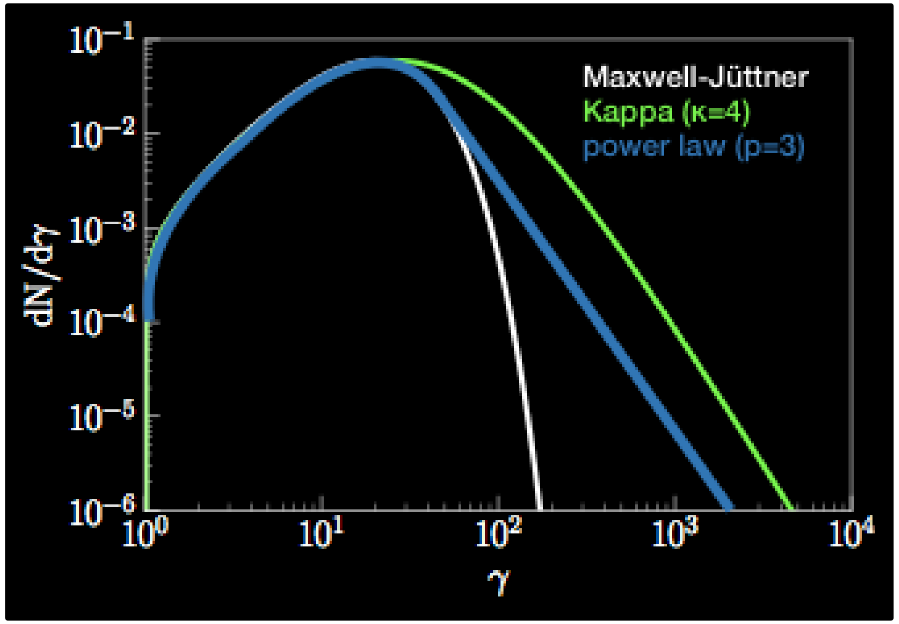
$$\tilde{\beta} \equiv \beta/\beta_{\rm crit}$$

2. what is distribution function of electrons?

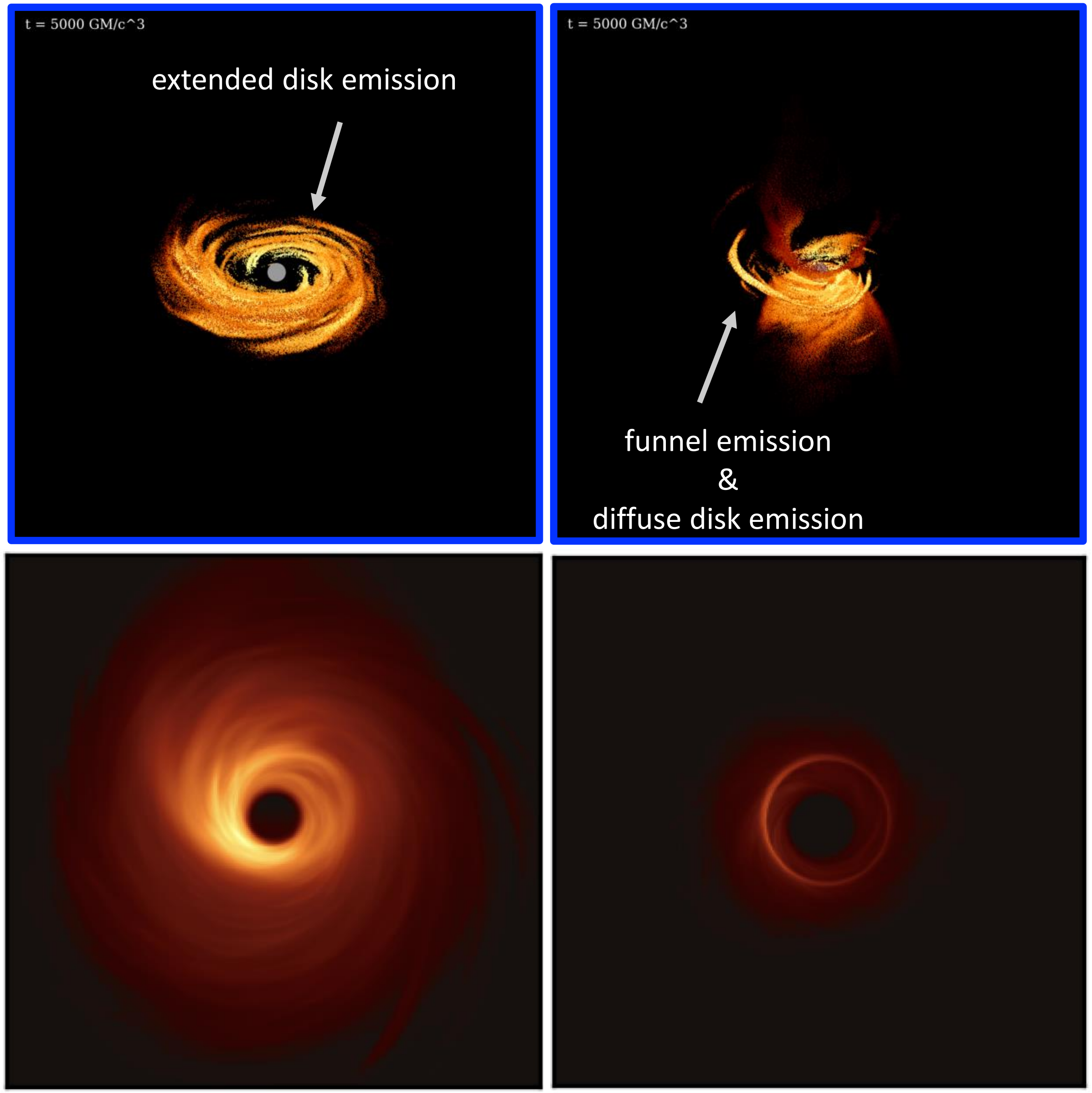
parametric models for thermal core + power law “non-thermal” tail:

Kawazura+ 2019



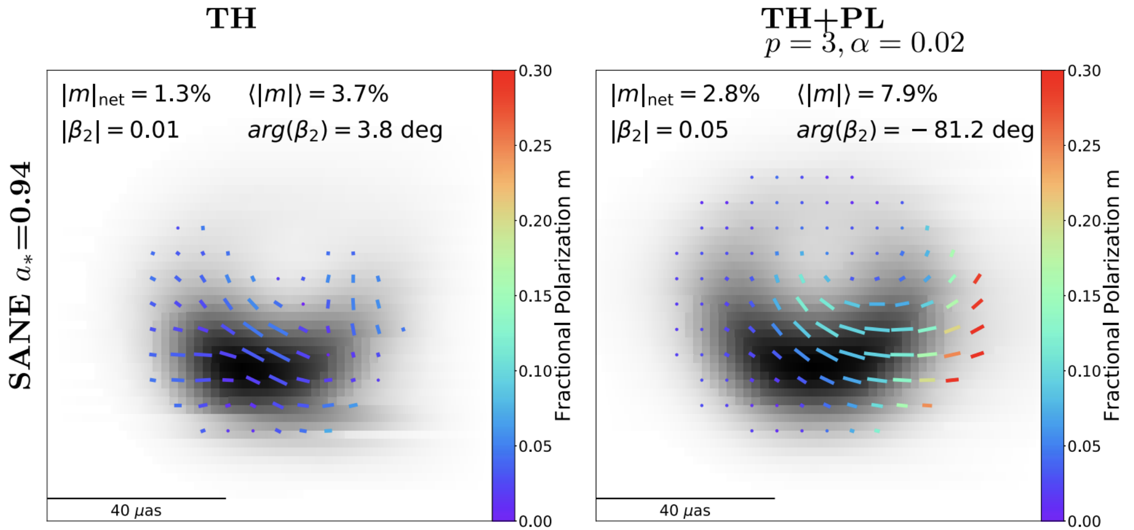


Radiative transfer model

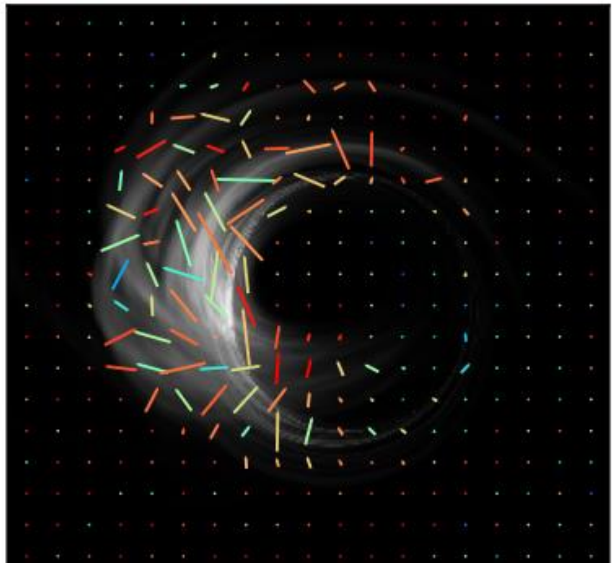


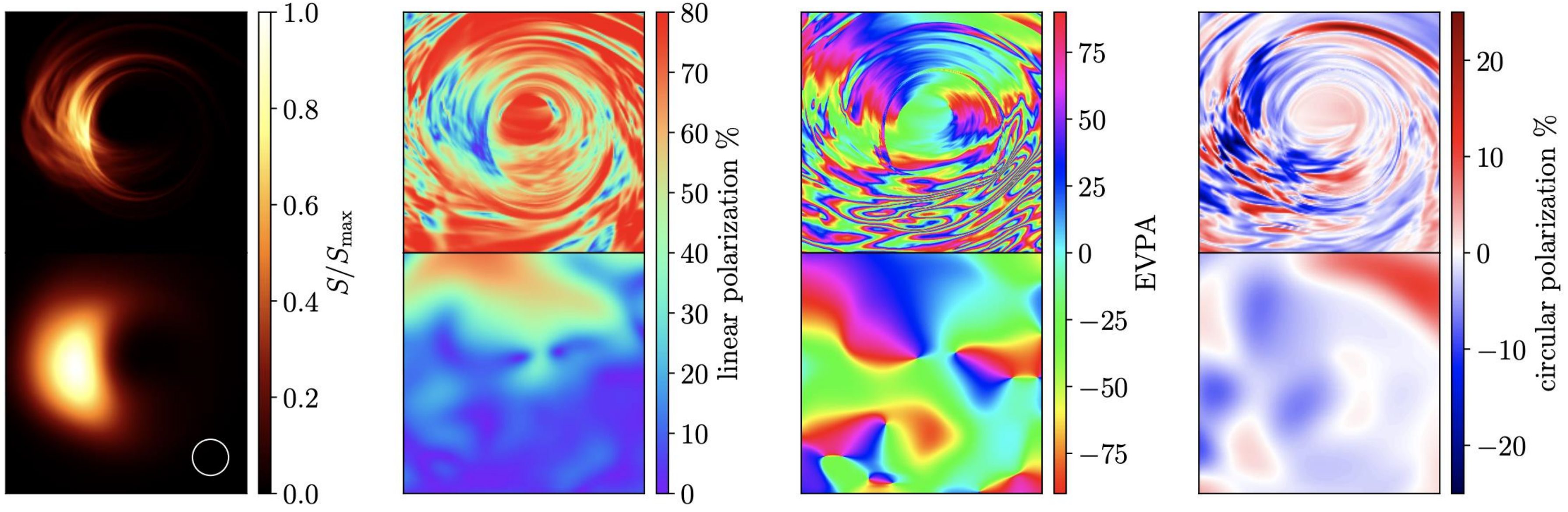
changing electron thermodynamics

changing electron distribution function

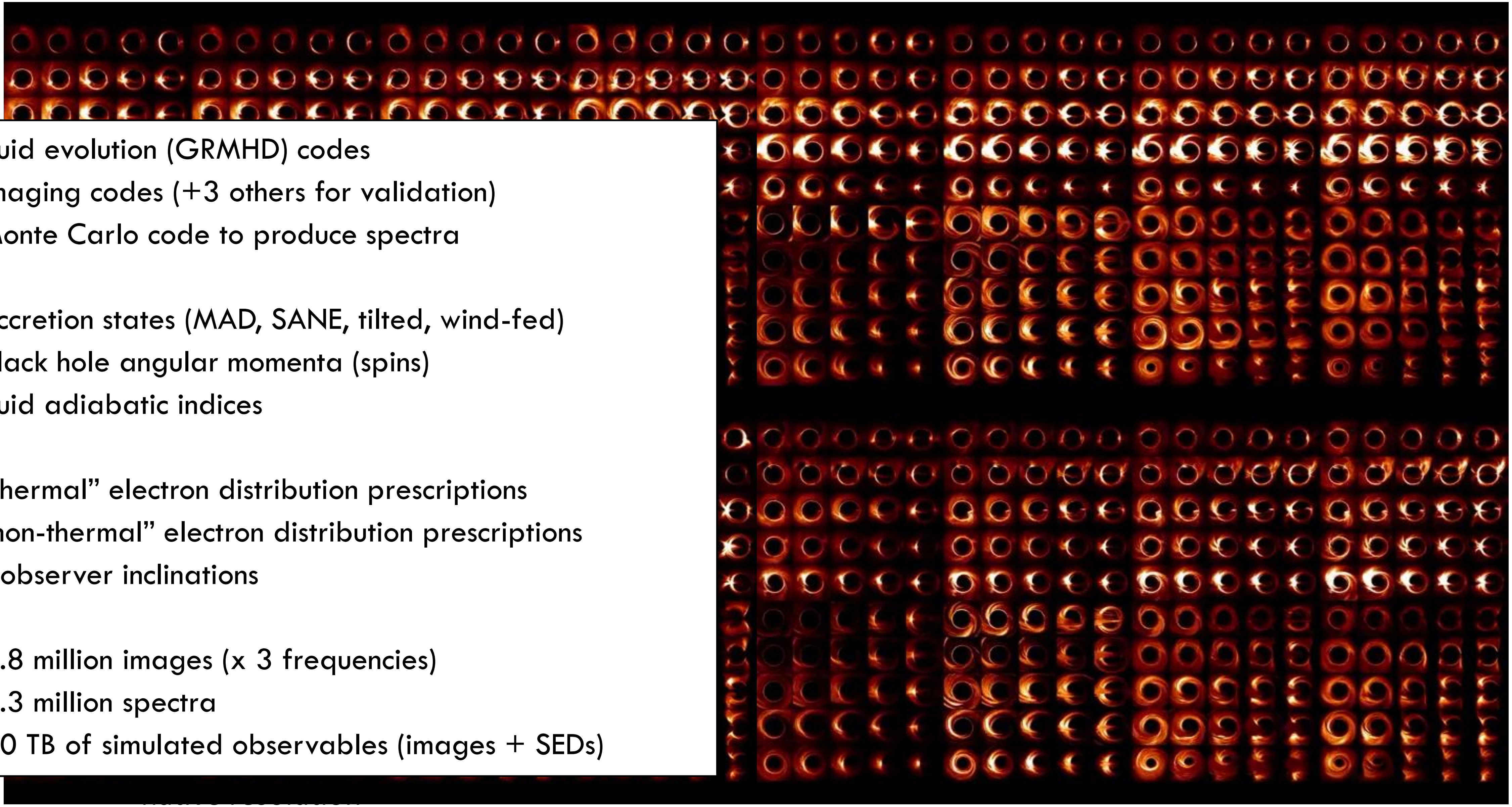


Example output from radiative transfer code





Covering parameter space



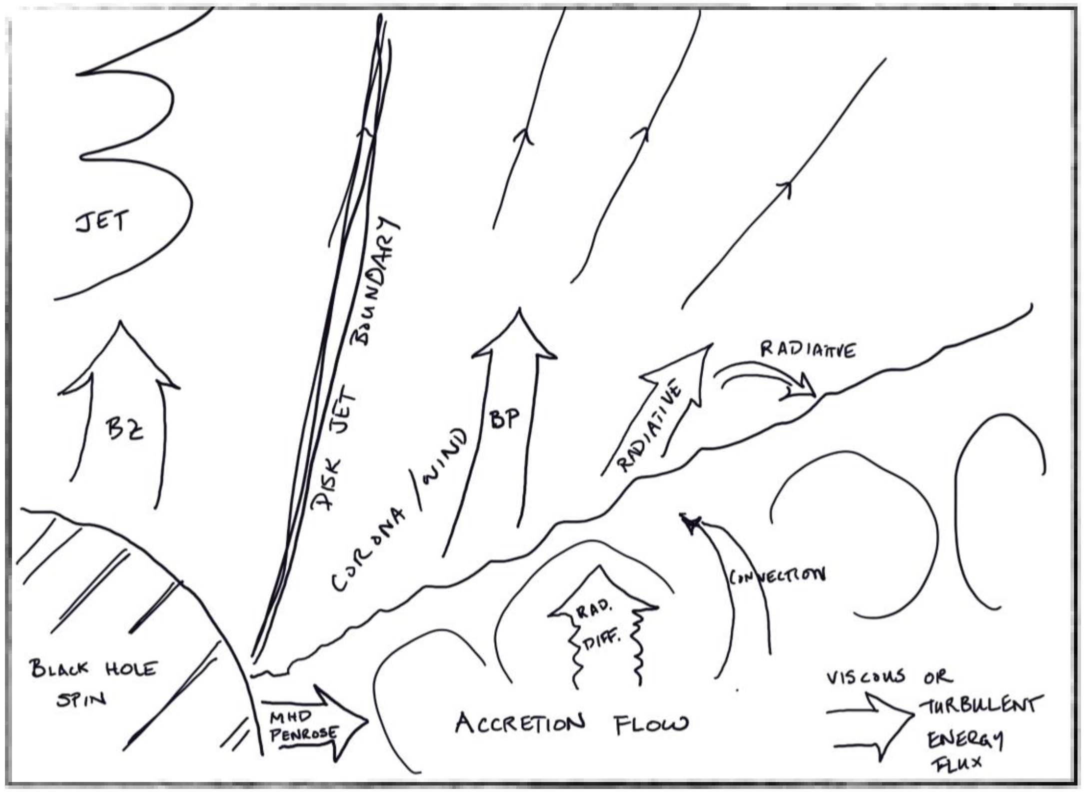
6 fluid evolution (GRMHD) codes
2 imaging codes (+3 others for validation)
1 Monte Carlo code to produce spectra

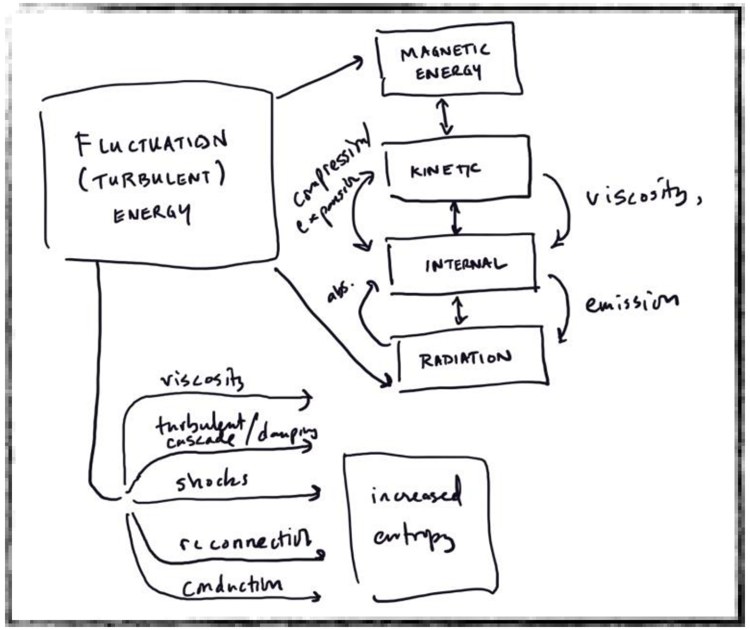
4 accretion states (MAD, SANE, tilted, wind-fed)
9 black hole angular momenta (spins)
3 fluid adiabatic indices

7 “thermal” electron distribution prescriptions
6 “non-thermal” electron distribution prescriptions
9 observer inclinations

~ 1.8 million images (x 3 frequencies)
~ 1.3 million spectra
~ 50 TB of simulated observables (images + SEDs)

The state of EHT modeling





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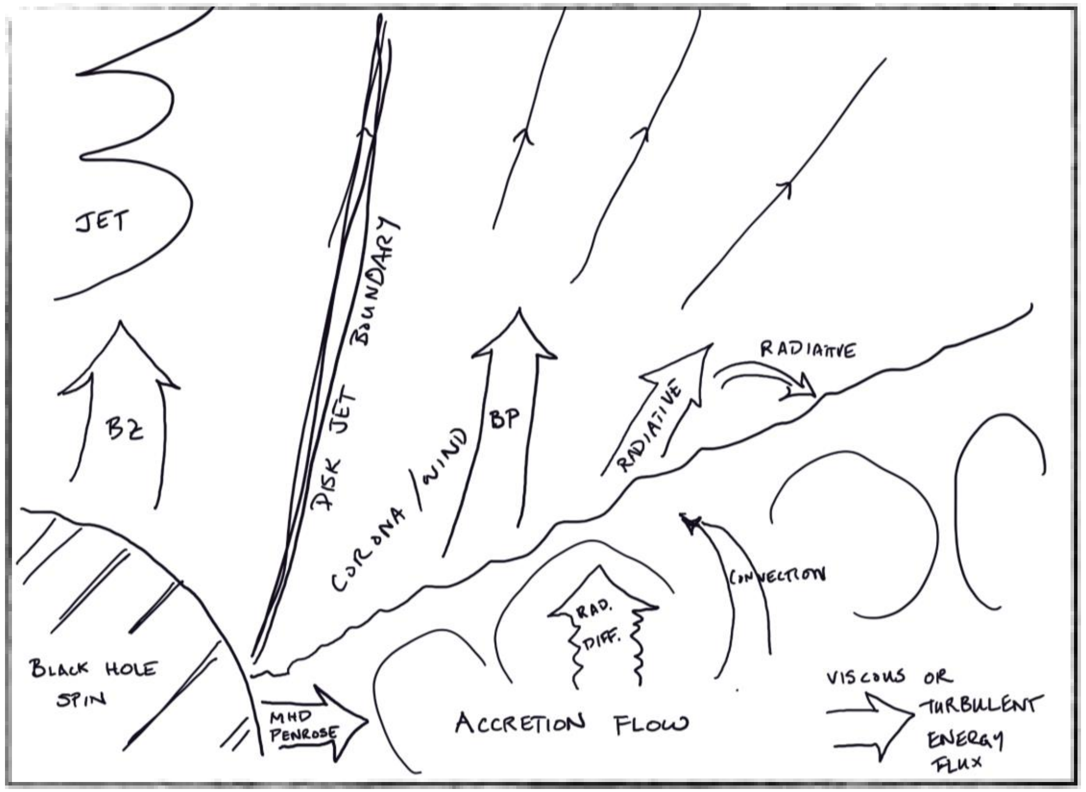
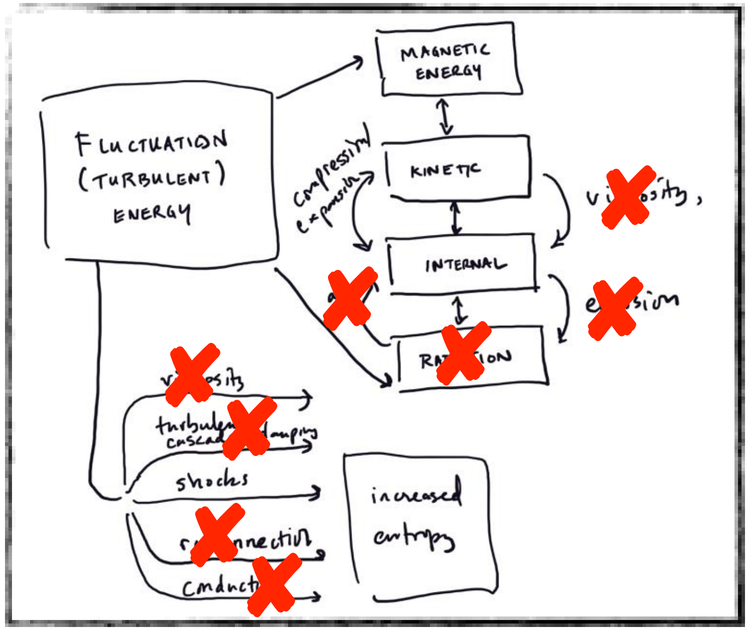


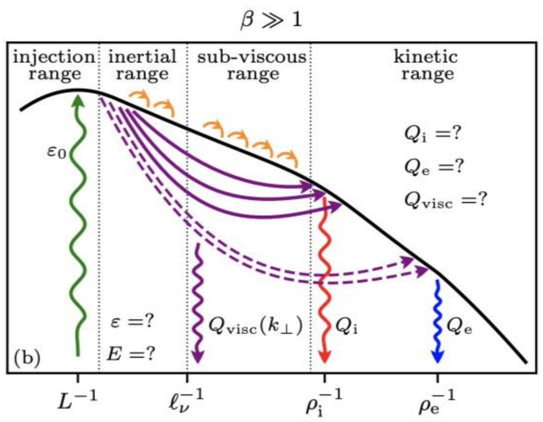


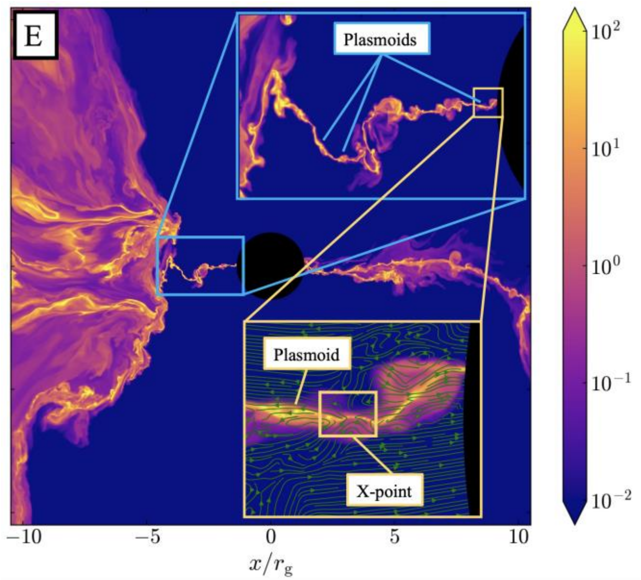
Ongoing efforts …

What are we still missing?

What physics is essential?

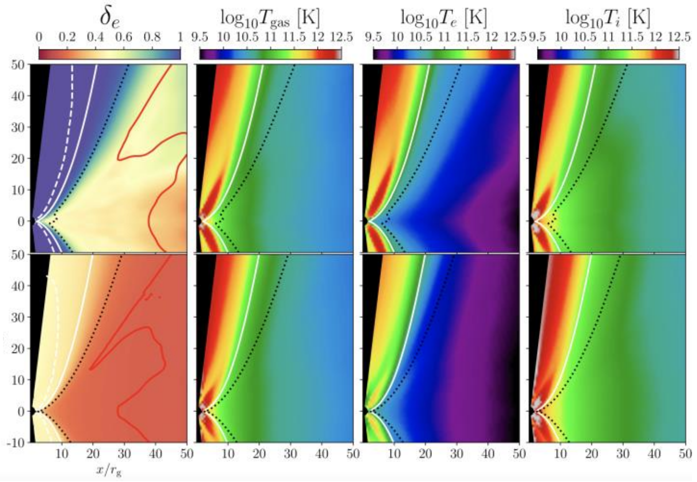
When is it "worth" the cost of adding an extra dimension to the parameter space?

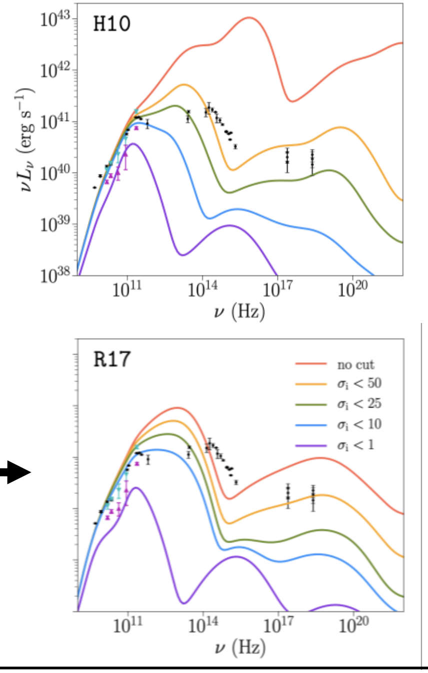




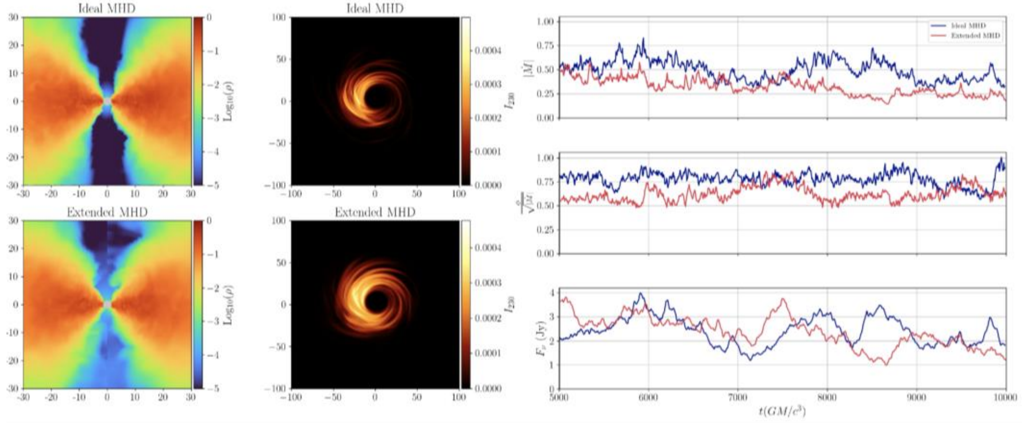
resistivity (Ripperda+ 2022)

radiation + e- thermodynamics (Chael+ 2019)





viscosity & heat conduction (Dhruv+ 2023)



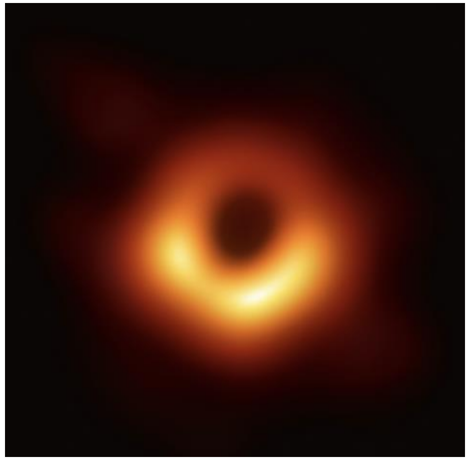
What do we Learn?

I will summarize the main results of the following papers:

M87 total intensity theory results

EHT 2019e

First M87 Event Horizon Telescope Results. V. Physical Origin of the Asymmetric Ring



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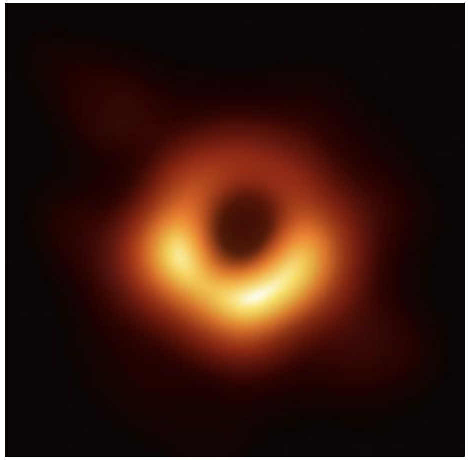
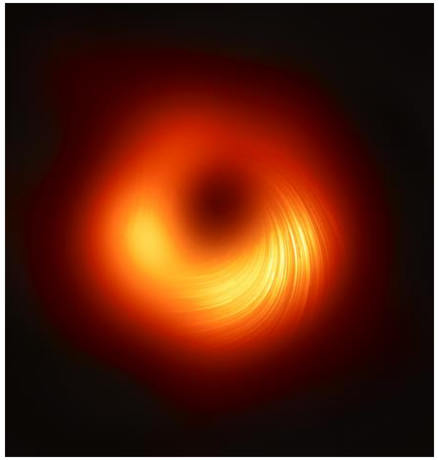


M87 polarization theory results

EHT 2021b

First M87 Event Horizon Telescope Results. VIII. Magnetic Field Structure near The Event Horizon



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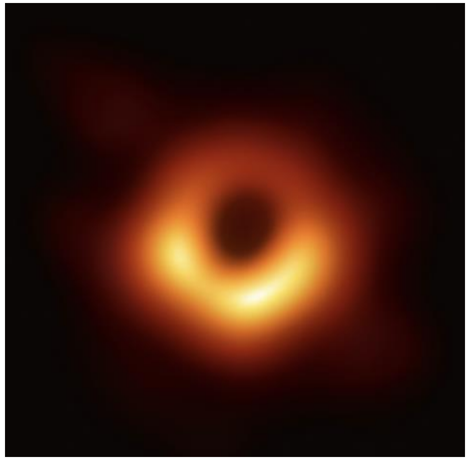

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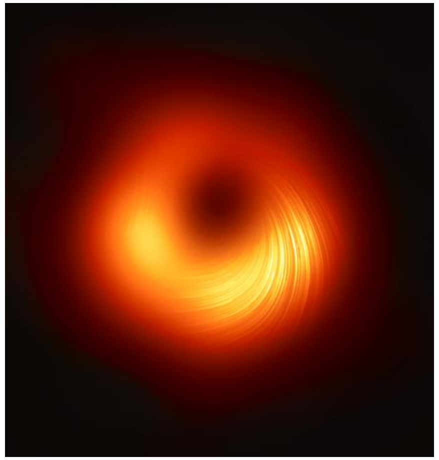
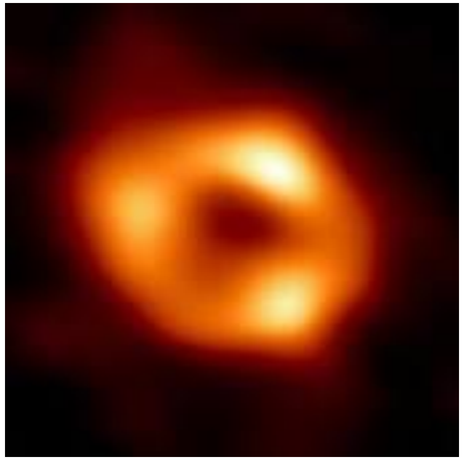


Sgr A* total intensity theory results

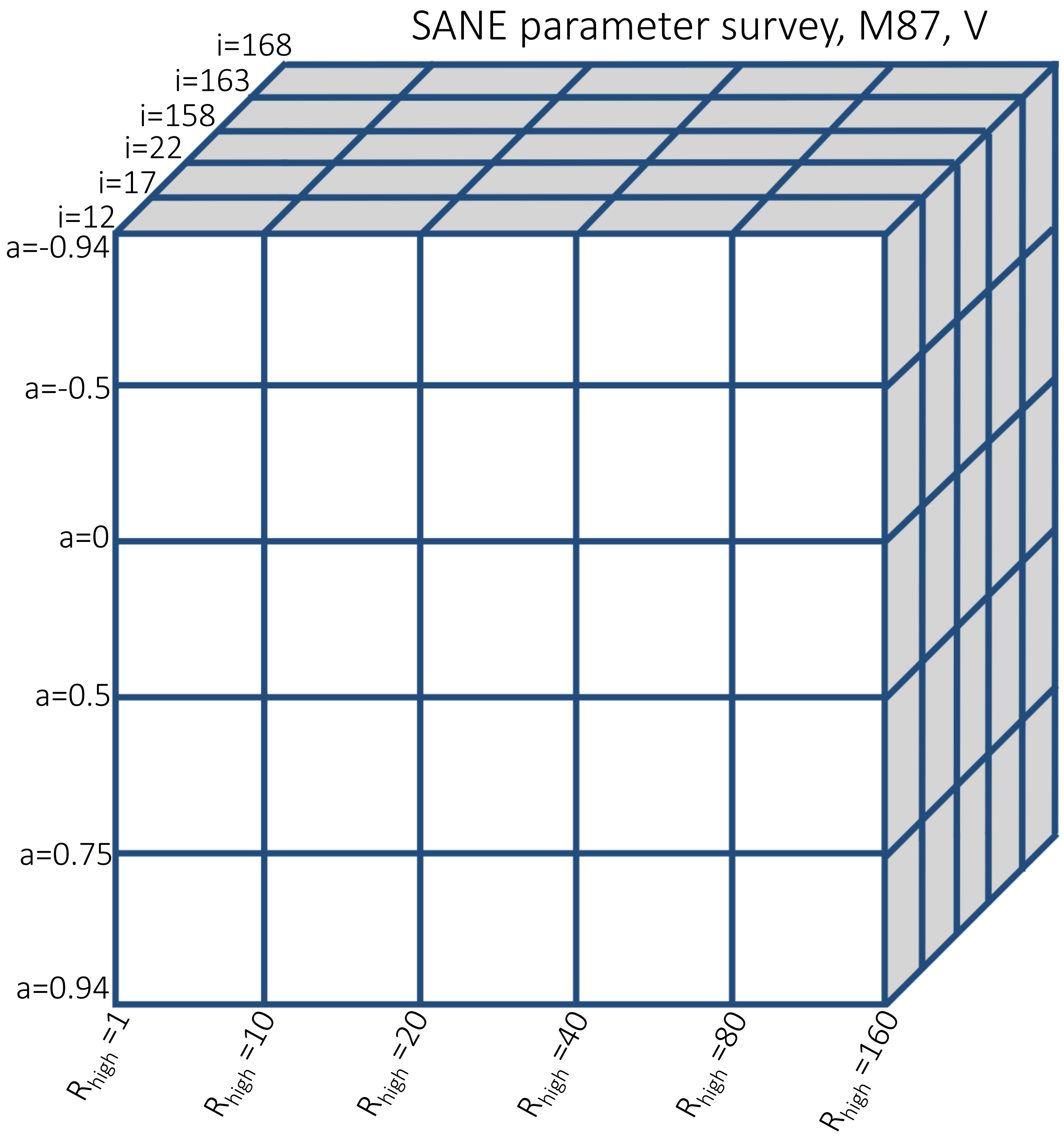
EHT 2022e

First Sagittarius A* Event Horizon Telescope Results. V. Testing Astrophysical Models of the Galactic Center Black Hole



In all three papers we compare data to a simulation library that spans a broad range of parameters

However, due to the expense of simulations, the grid of model parameters is still sparse



* We also explore additional models, recall George's talk

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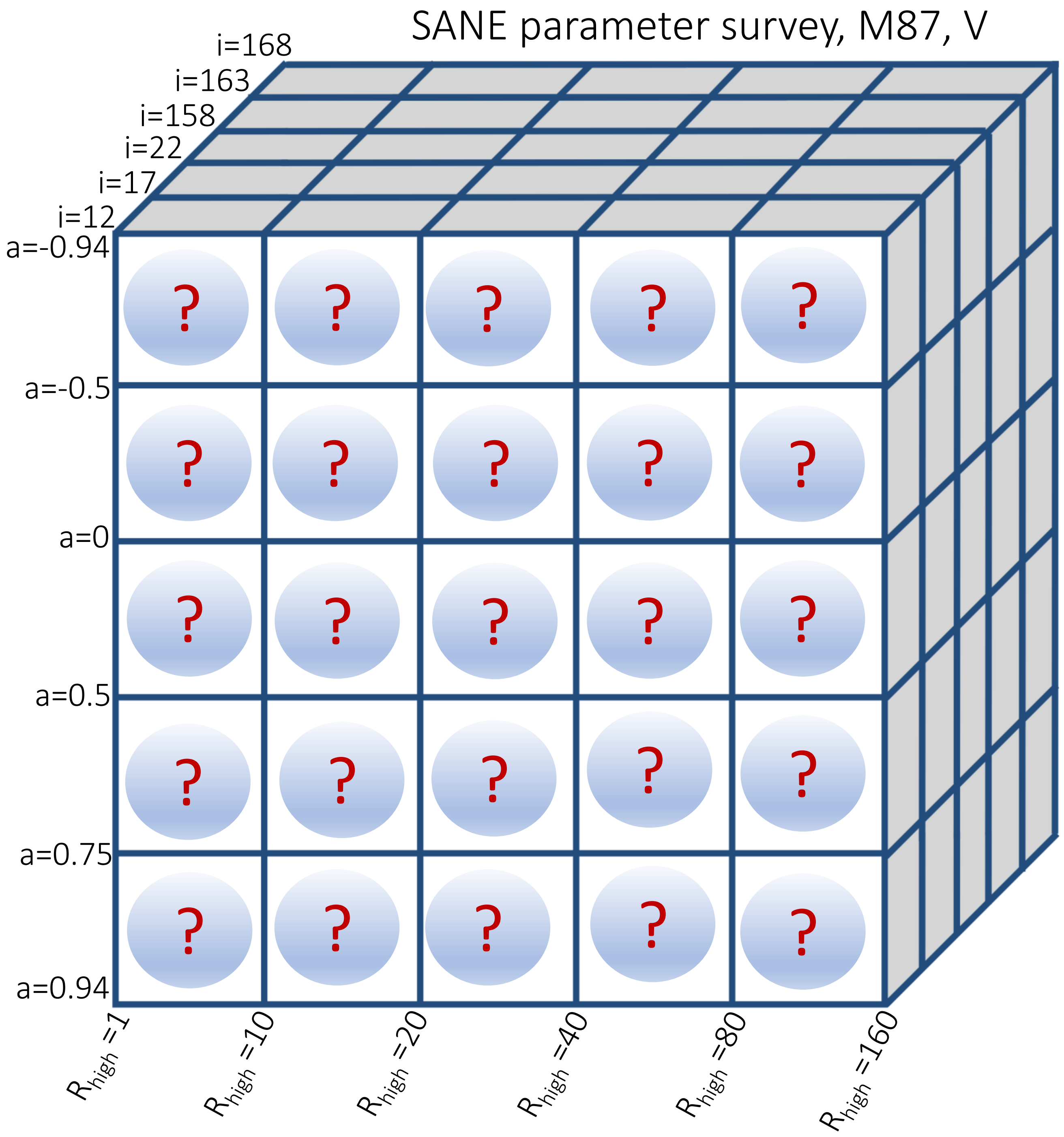

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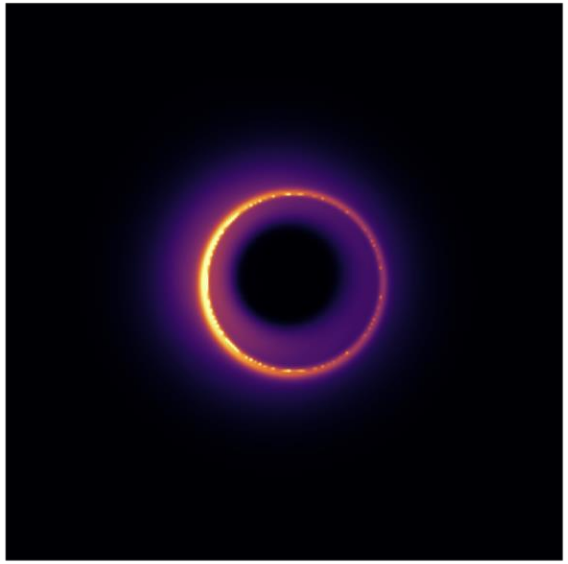
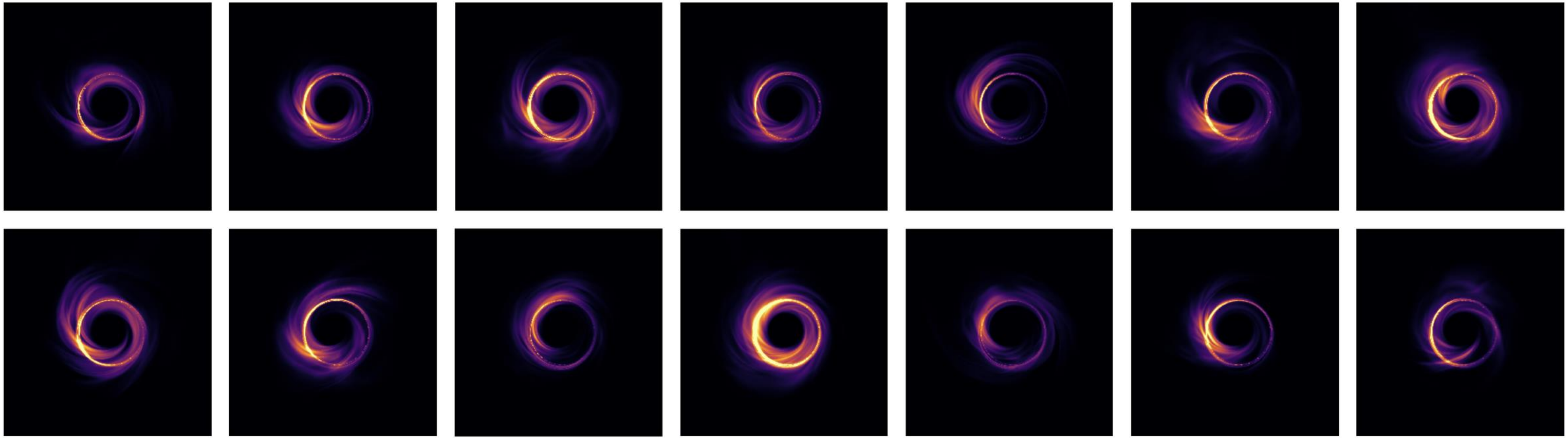
Comparing simulations to data is challenging



Snapshots from a simulation do not necessarily resemble the average image of that simulation.

Observations are essentially probing one snapshot, so comparing observations to the average image is not ideal.



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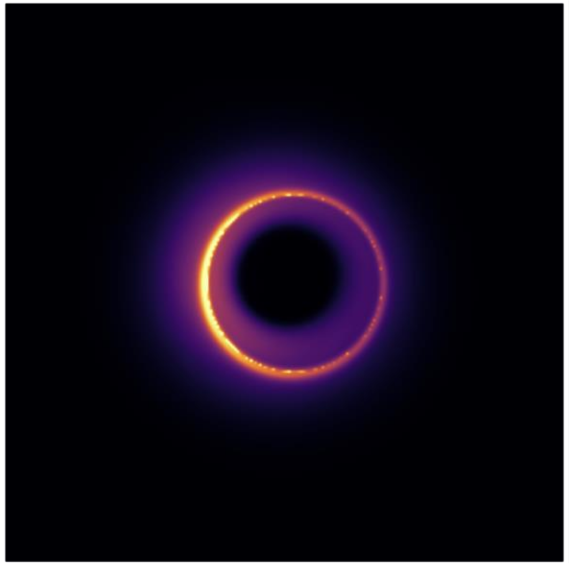

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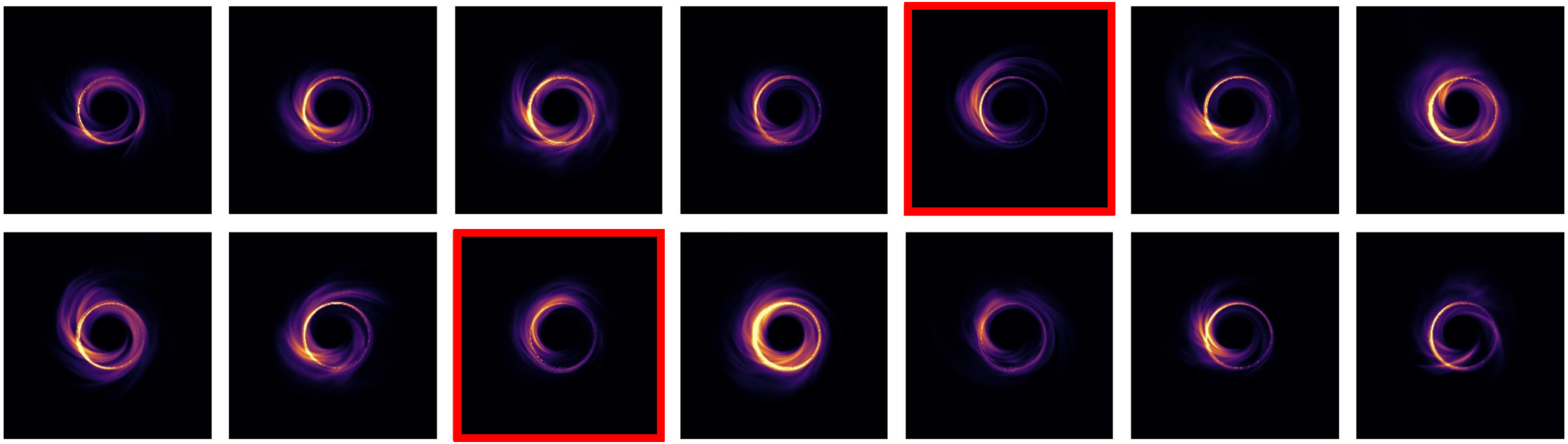
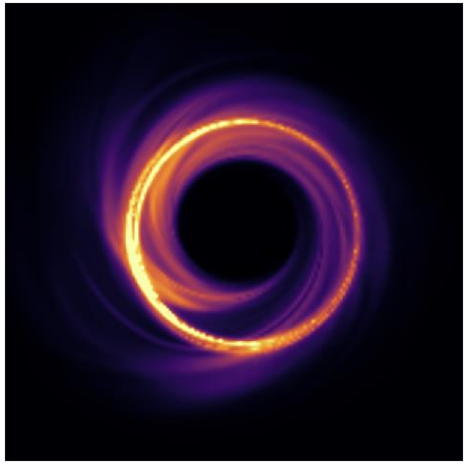


Constraints employed: derived from EHT

M87 total intensity theory results

Calculate error by comparing each snapshot directly to the data

vary M/D and PA



M87 polarization theory results

Sgr A* total intensity theory results

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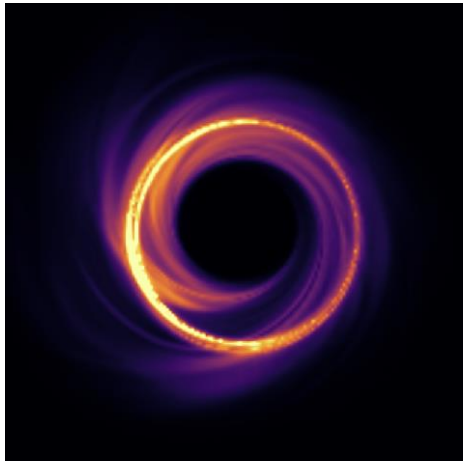
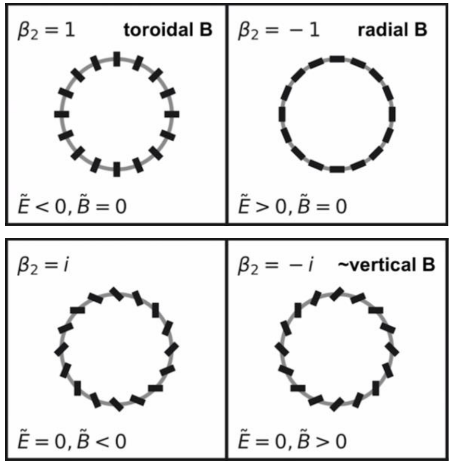


M87 polarization theory results

- Image-integrated net linear polarization
- Image-averaged linear polarization
- **Amplitude and phase of the complex β_2 coefficient (EVPA pattern)**



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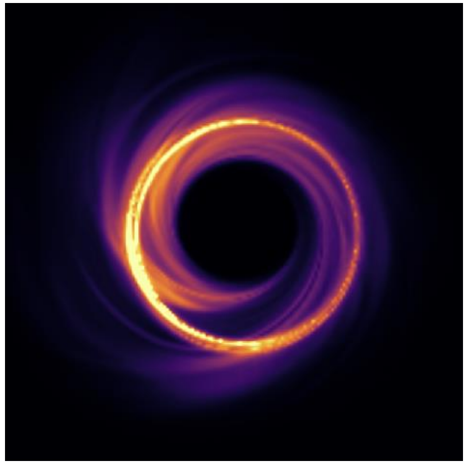

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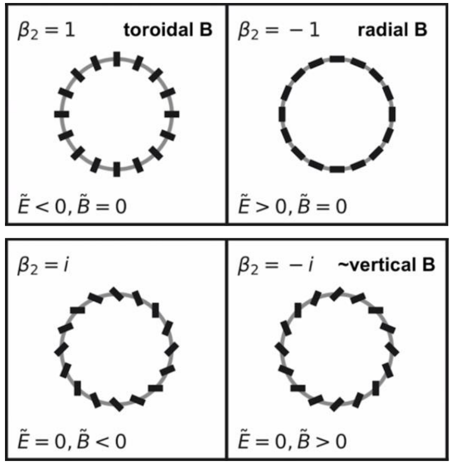
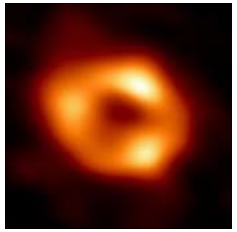


Sgr A* total intensity theory results

- 230 GHz image size
- VA morphology
- geometric model* diameter, **width,** and asymmetry
- 4 G lambda variability

Variability



* m-ring

Constraints employed: **not** derived from EHT

M87 total intensity theory results

- Radiative self consistency (is radiative cooling important?)
- Maximum X-ray luminosity
- **Minimum jet power**

M87 polarization theory results

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M87 polarization theory results

- Image-integrated net circular polarization (ALMA-only)*
- Include also constraints from M87 total intensity theory results

* Coming soon circular EHT constraints?

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Sgr A* total intensity theory results

- 86 GHz flux
- 86 GHz image size
- 2.2 micron flux
- X-ray flux
- **lightcurve variability** } Variability

* Coming soon circular EHT constraints?

Main results

M87 total intensity theory results

- **Spin axis points away from us**
- GRMHD simulations consistent with data, hard to rule out models
- EHT only: Reject MAD, retrograde, high-spin models
- all constraints: Reject most SANE, and all non-spinning
- Jet powered by Blandford-Znajek process

M87 polarization theory results

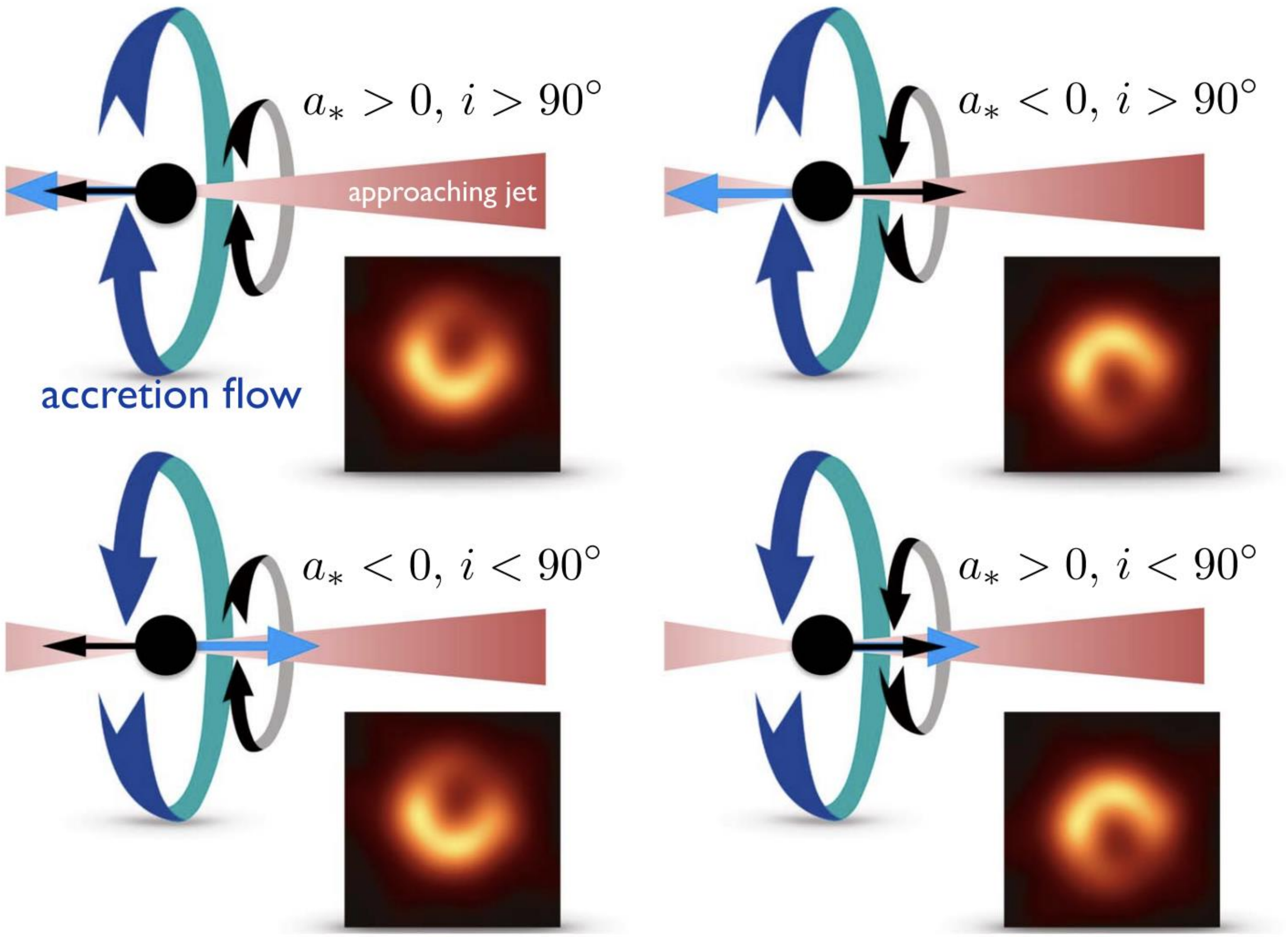
Sgr A* total intensity theory results

M87 total intensity theory results

Spin axis points away from us

Emitting material rotates with the black hole

Image asymmetry determines direction of spin



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M87 polarization theory results

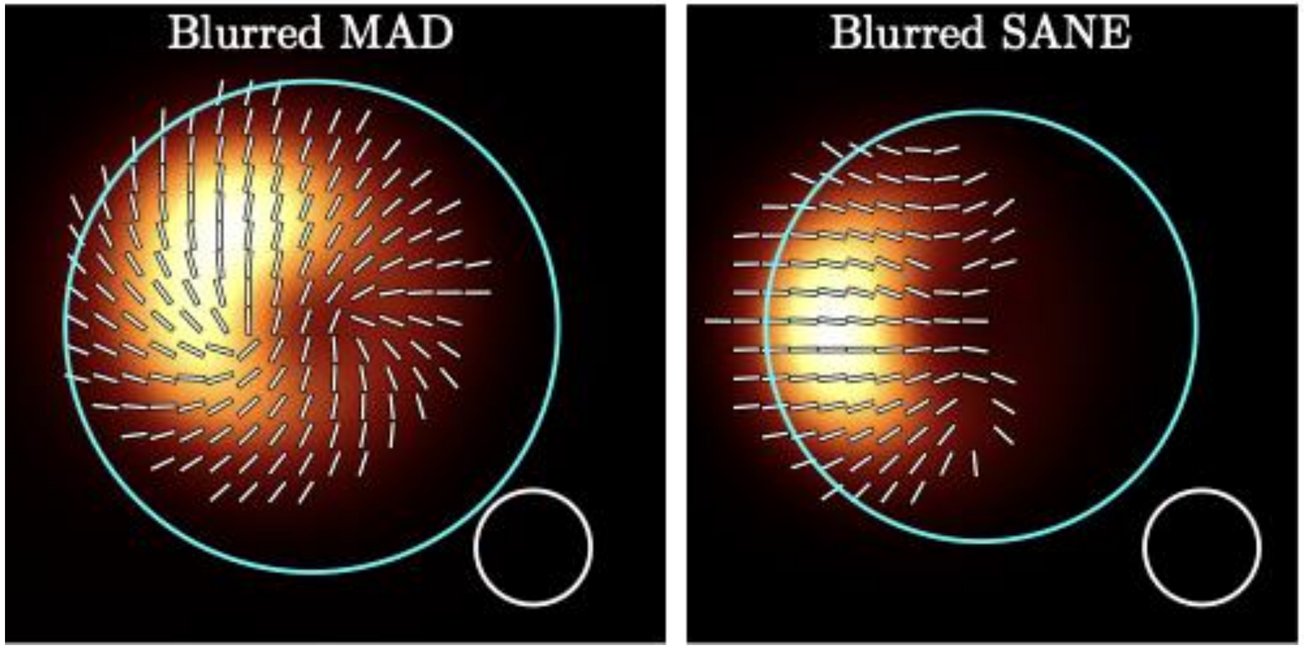
- **Strong, ordered magnetic fields- MAD**
- Polarization constraints disfavor most models
- Estimates for
  - $B{\sim}1-30\mathrm{G}$
  - $\mathrm{T_e}{\sim}1-40\times10^{10}\mathrm{K}$
  - $n_e{\sim}10^{4-7}\mathrm{cm}^{-3}$
  - $\dot{\boldsymbol{M}} = 3-20 \times 10^{-4}$ solar masses/year

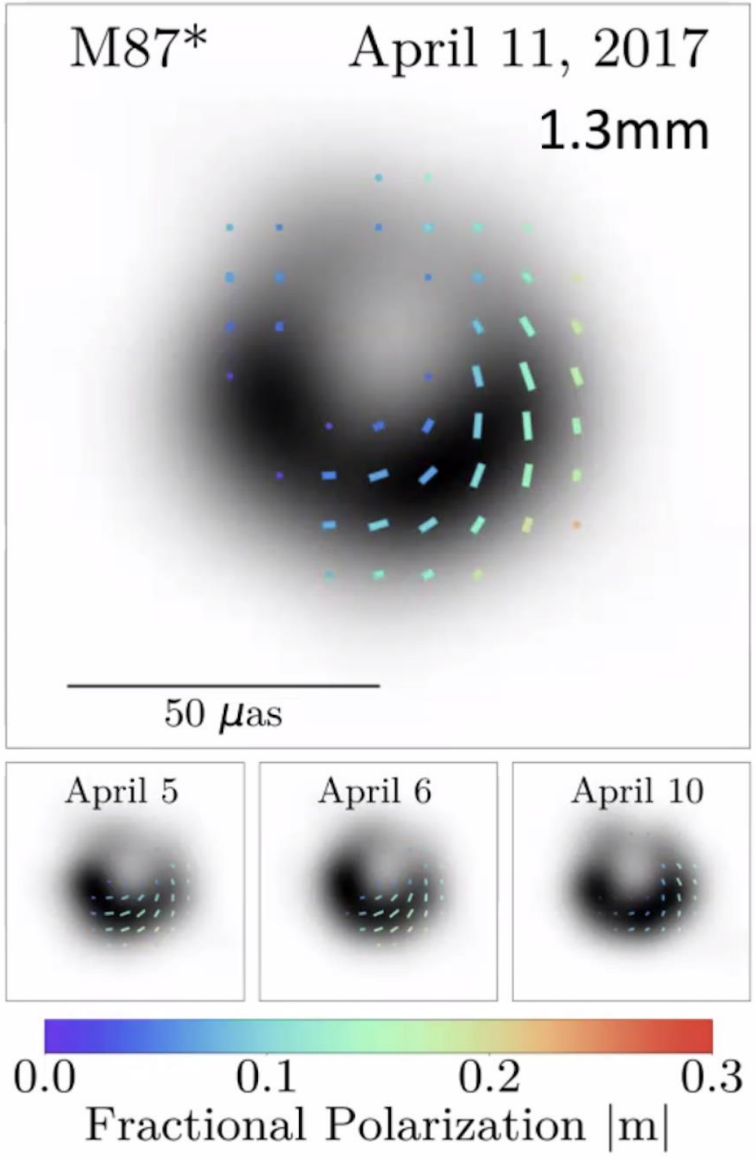
Sgr A* total intensity theory results

M87 polarization results

Strong, ordered magnetic fields - MAD

Twisty pattern implies coherent magnetic field structure and dynamically important B-fields





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Sgr A* total intensity theory results

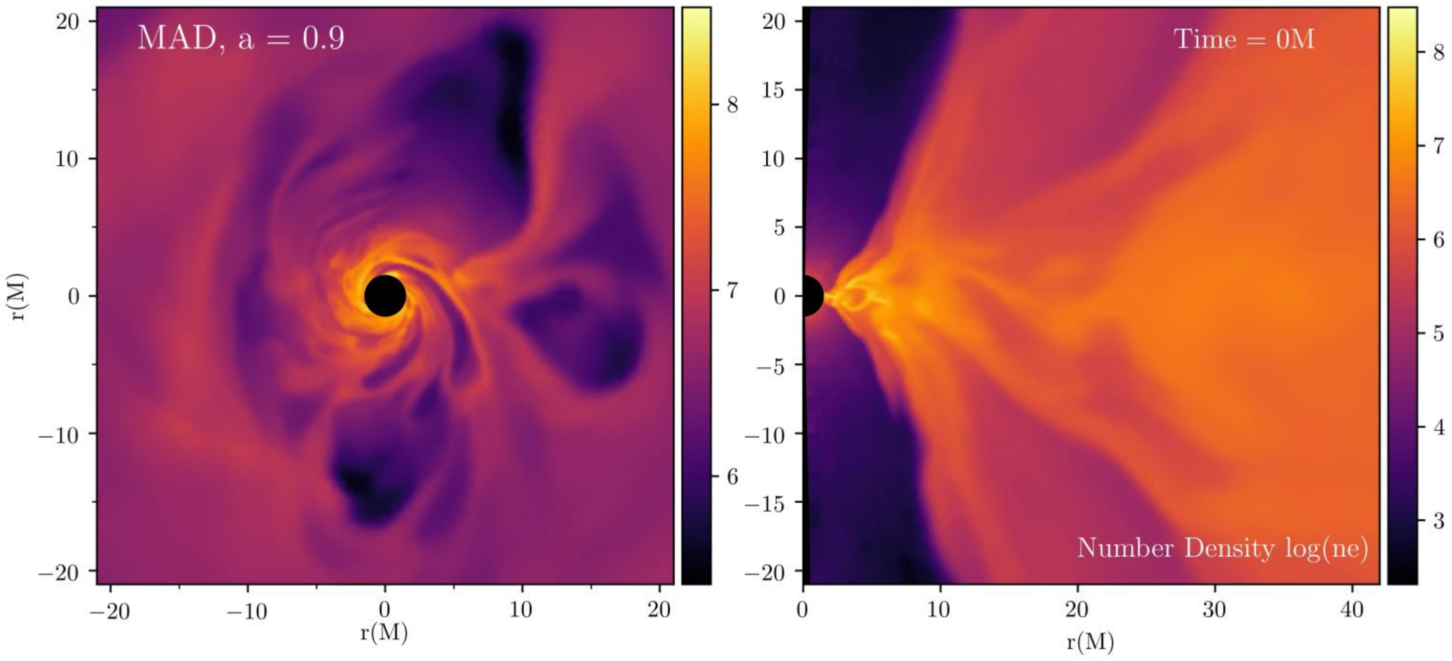
- **Simulations are more variable than the data**
- All models ruled out if all constraints used
- All models with $i > 70$ or $T_e = T_i$ fail at least two constraints
- EHT only: $a \geq 0, i \neq 90,$ and $T_e \neq T_i$

Sgr A* total intensity results

Simulations are more variable than the data

Possible explanations*:

- Simulation grid too sparse
- extended slowly varying structure that is resolved out by the EHT
- Collisionless/dissipative effects (e.g., viscosity or conductivity)
- sophisticated thermodynamics including cooling
- Different B-field polarity or geometry



* Definitely not an exhaustive list

Throughout the workshop this week we would love to discuss your ideas for explaining the variability crisis and how we can use the EHT to learn more about plasma physics.