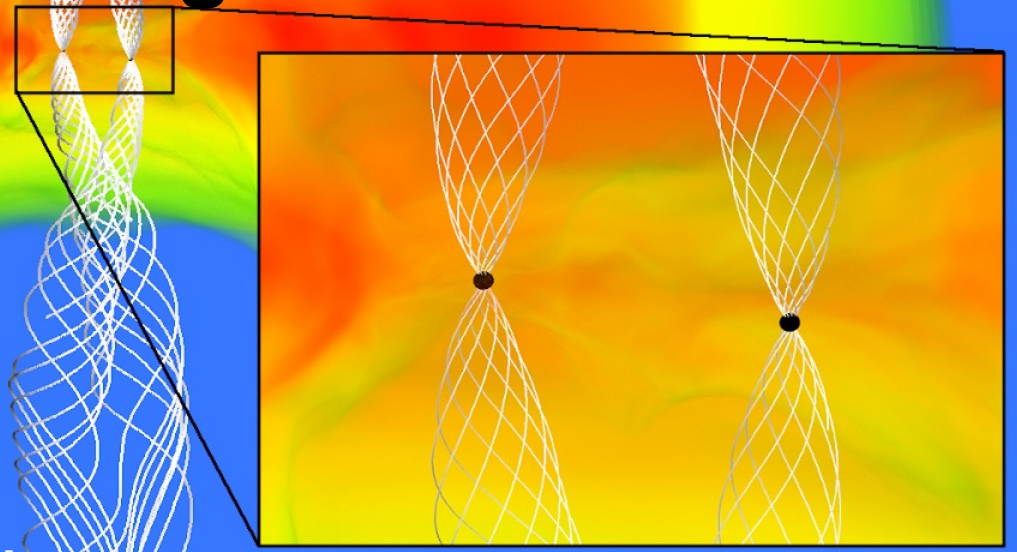
t/M = 3026

Gravitational Wave-driven binary supermassive black holes as VLBI targets

Speaker: Roman Gold

SDU UNIVERSITY OF SOUTHERN DENMARK

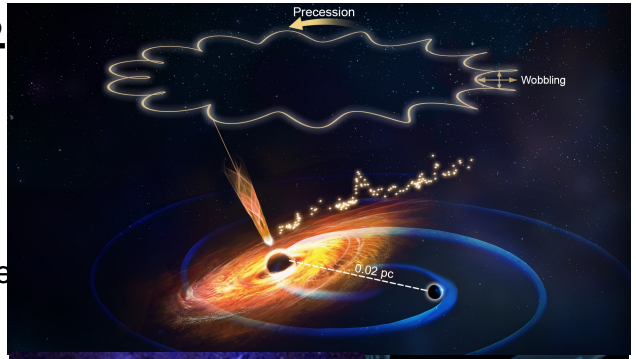
CP3

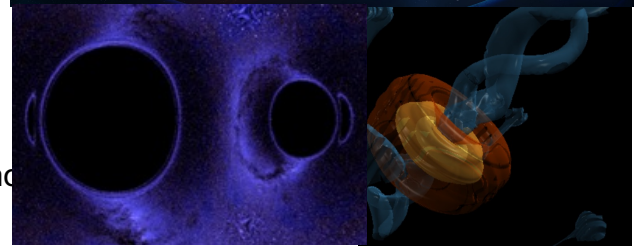


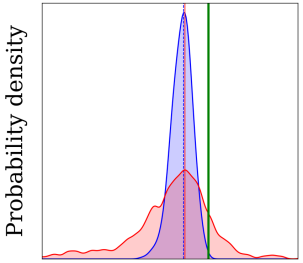
Simulation from: [Paschalidis, Bright, Ruiz, RG 2021]

Outline

- **Introducing the physics of accreting SMBHB**
- **Observational Challenges:**
  - Need good & many candidate sources
  - Poorly understood sources, expect great variety in physical regime
  - see one recent example M81 [Wu et al 2023a,2023b]
- **Modeling Challenges:**
  - Modeling must capture essential physics , variety needed! Be agno
  - Product of LIGO/VIRGO/KAGRA and EHT parameter space!
  - Full chain from model prediction to data as taken by imperfect instrument
- **Analysis Challenges:**
  - mitigate anything else in the data
  - Model fitting / parameter estimation must address systematics

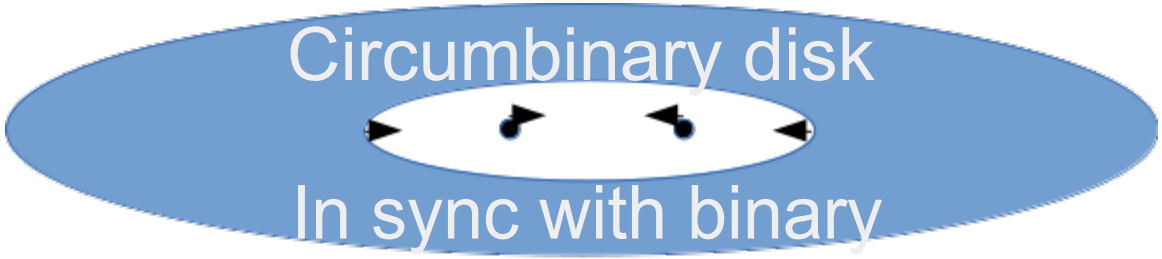






Introducing the physics of accreting SMBHB

pre-decoupling regime:
viscous time (disk) « inspiral time scale
(more sources expected,
ngEHT regime?!)



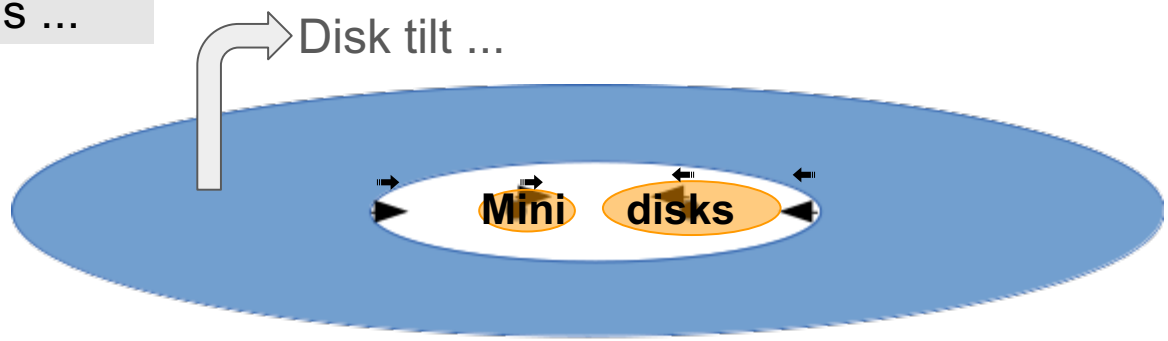
post-decoupling regime:
viscous time in disk long compared to inspiral time scale:
Binary inspiral runs away from disk
Disk cannot keep up and is left behind

Merger aftermath, rebrightening:
BH mass and spin change rapidly
Disk can respond

Introducing the physics of accreting SMBHB

Still many idealizations ...

pre-decoupling regime:
viscous time (disk) « inspiral time scale
(more sources expected,
ngEHT regime?!)



Not necessarily a cavity ...

post-decoupling regime:
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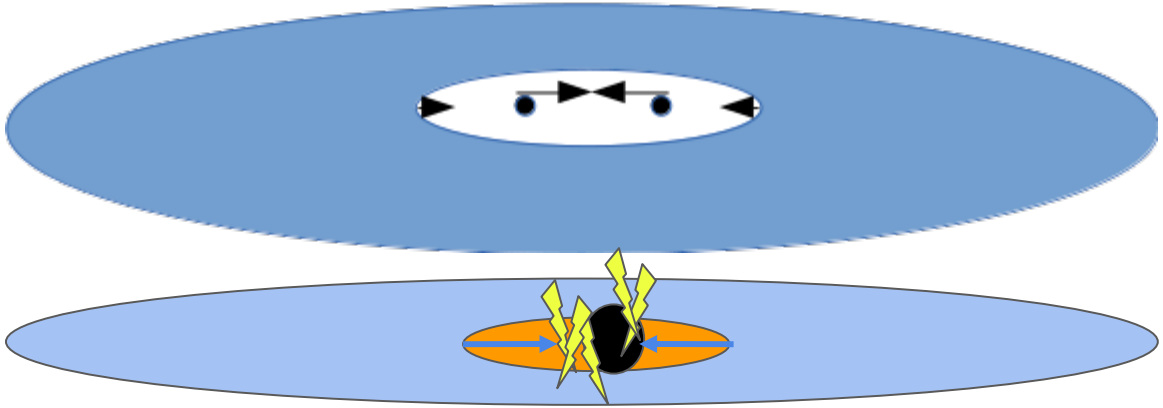

Introducing the physics of accreting SMBHB

pre-decoupling regime:
viscous time (disk) « inspiral time scale
(more sources expected,
ngEHT regime?!)

Realism: Circumbinary disk, tilt, mini disks, inner cavity, turbulent structure, variability, jet emission, spacetime: GR, BH spin, Gravitational Waves

post-decoupling regime:
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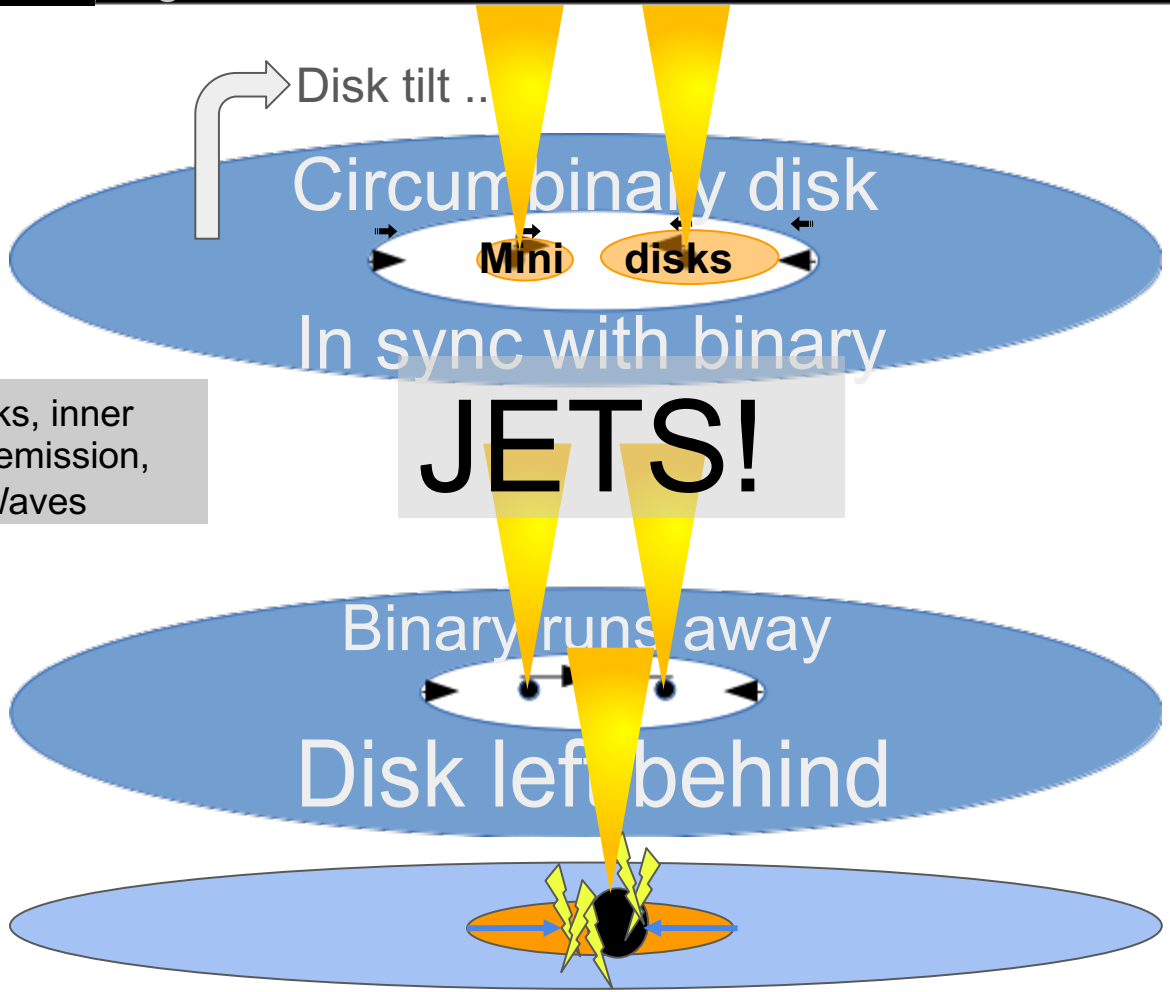
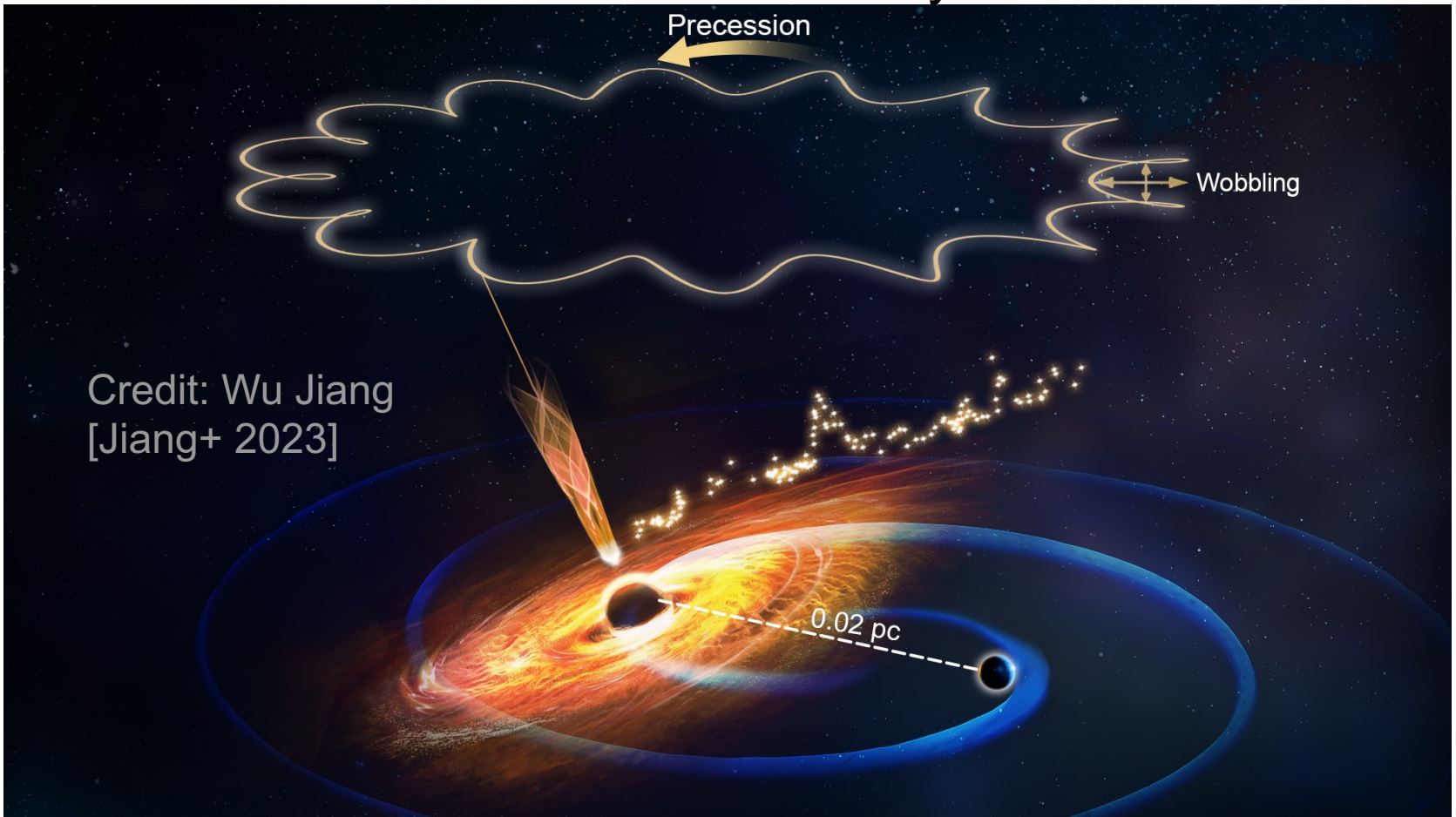
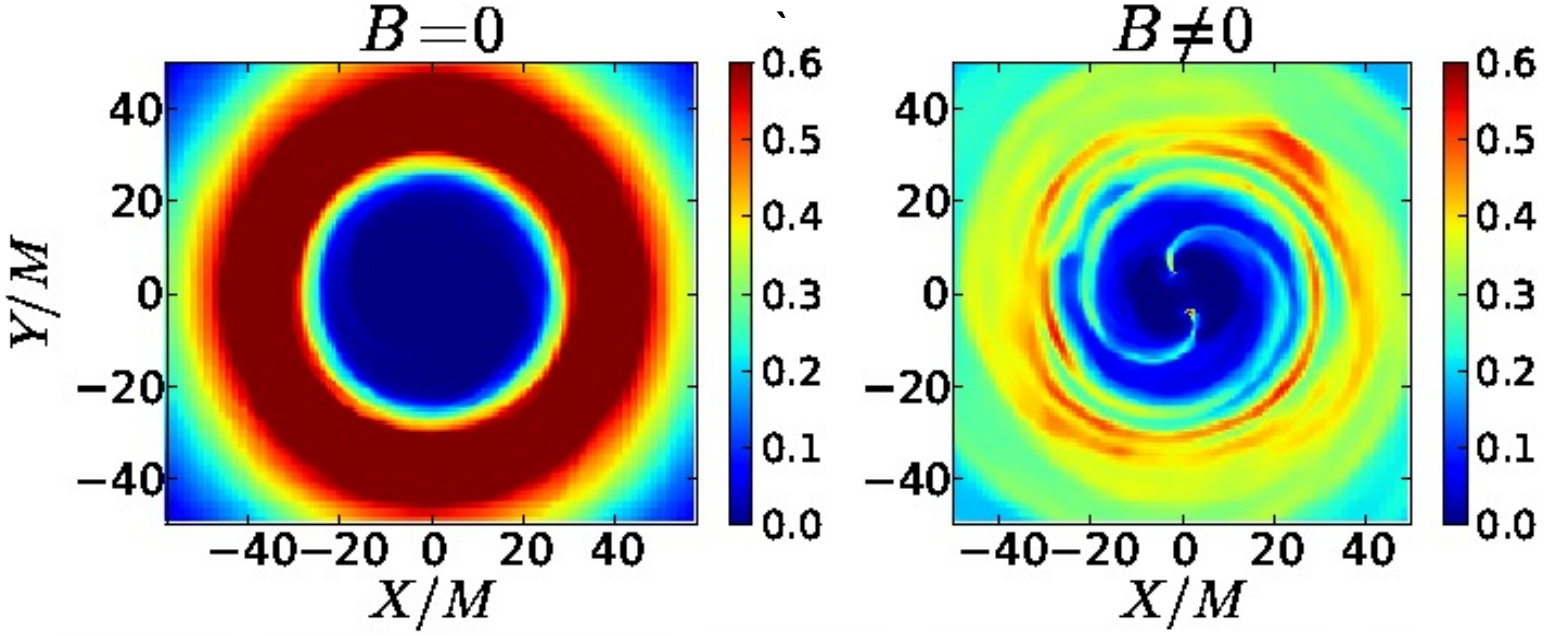


M81: A candidate for nearby SMBHB



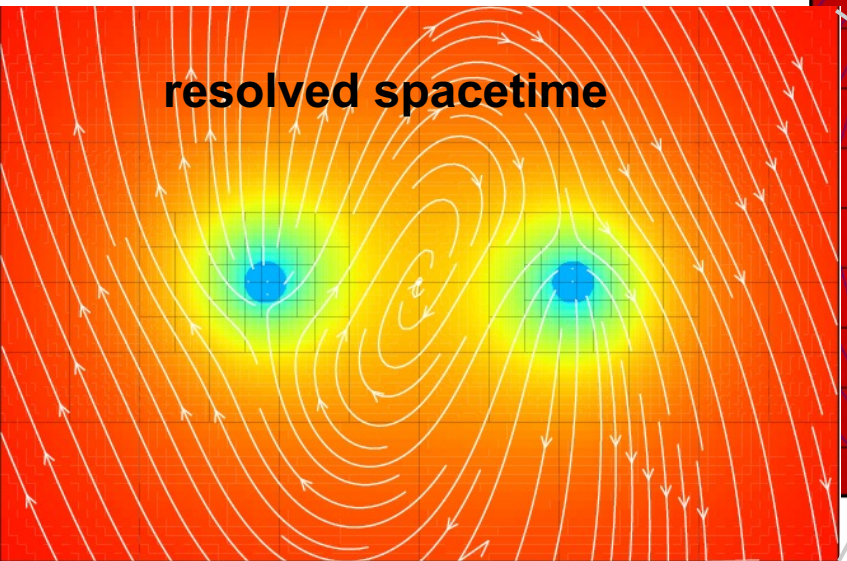
- Intrinsic dynamics of accreting binaries are messy and complicated
  - EHT models for single BHs: GR**M**HD in curved (but stationary) spacetime
  - EHT models for binary BHs must address the same regime but in dynamical spacetime
    We inherit LIGOs parameter space!

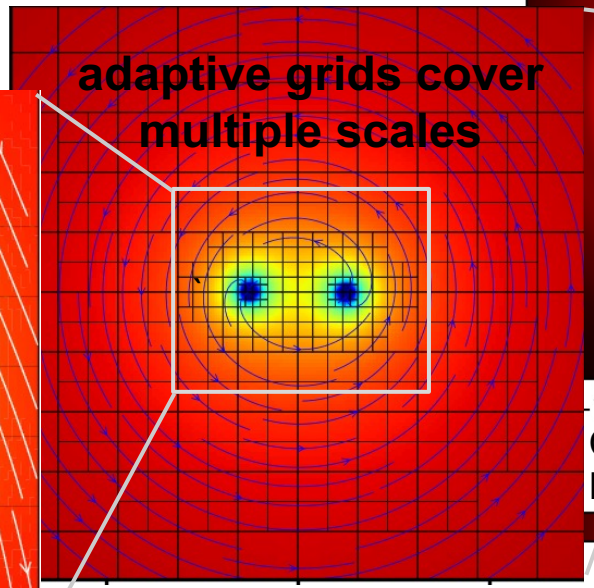


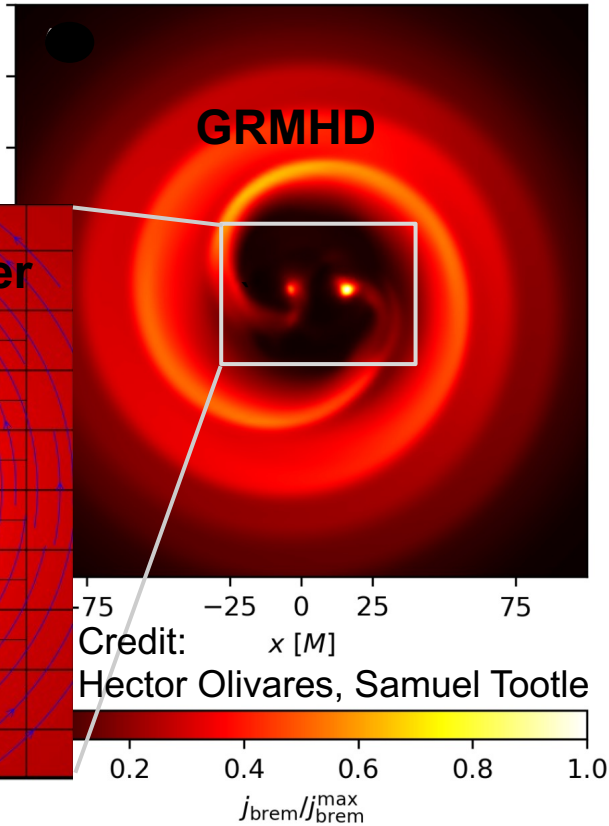
Gold et al [2013/2014], Gold et al [2014]

GRMHD simulations of accreting binaries with BHAC code

- Simulate ***binary*** spacetimes with ***stationary*** spacetime code BHAC
- As accurate and ~affordable as accreting single BH simulations
- Already interfaced with radiative transfer codes
- BHOSS [Younsi] handles binary spacetime



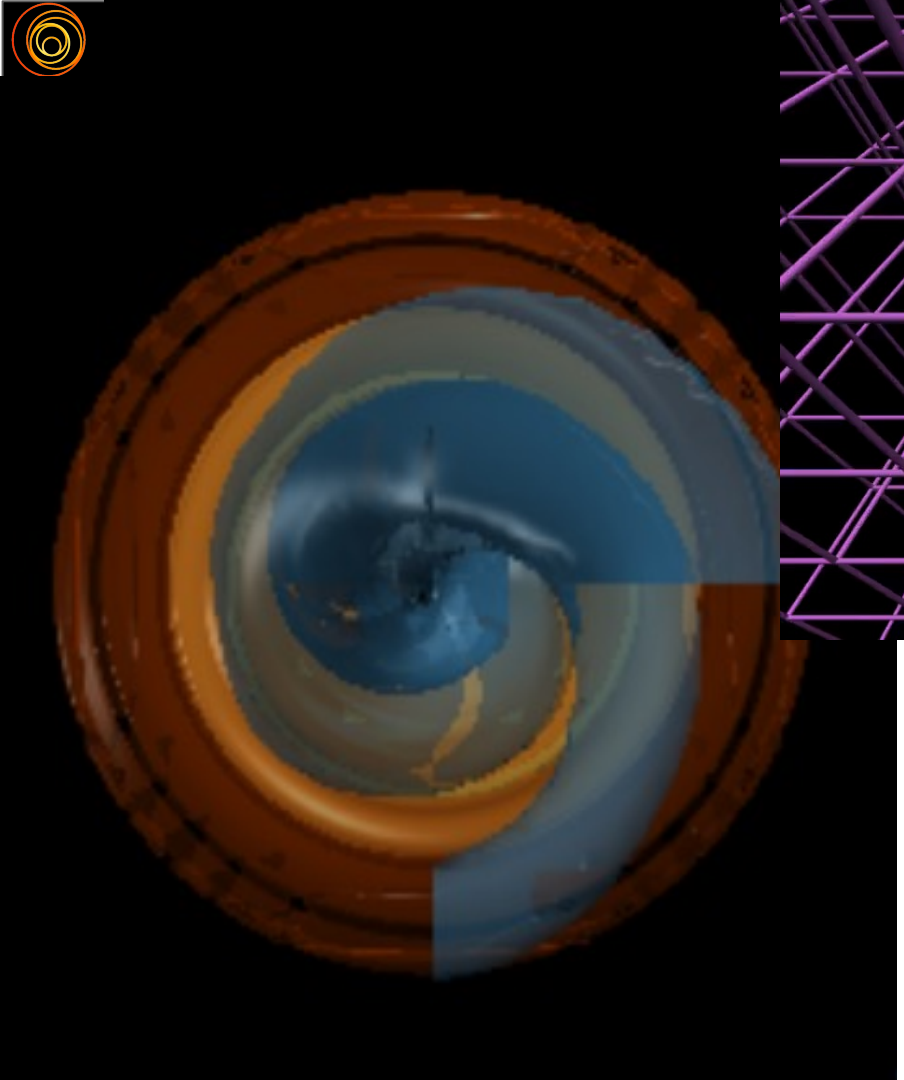


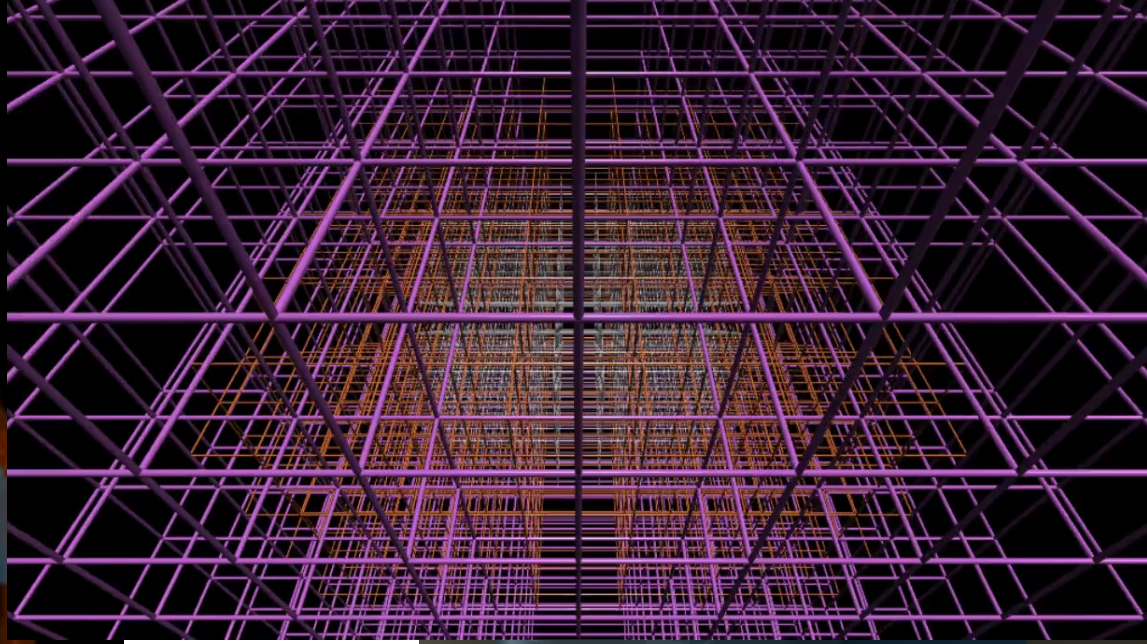


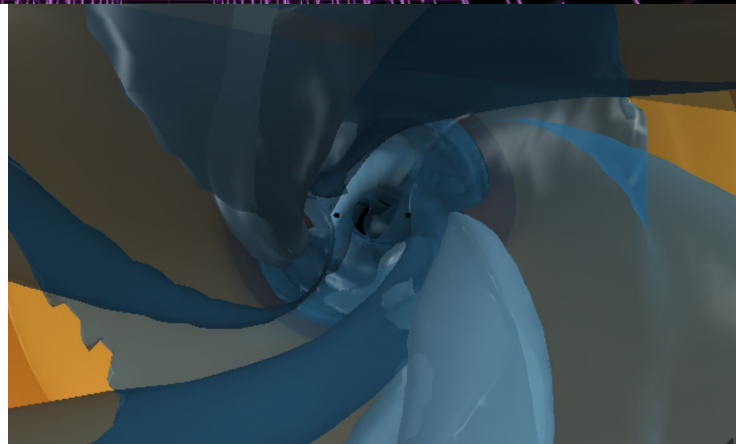
BHAC code reference

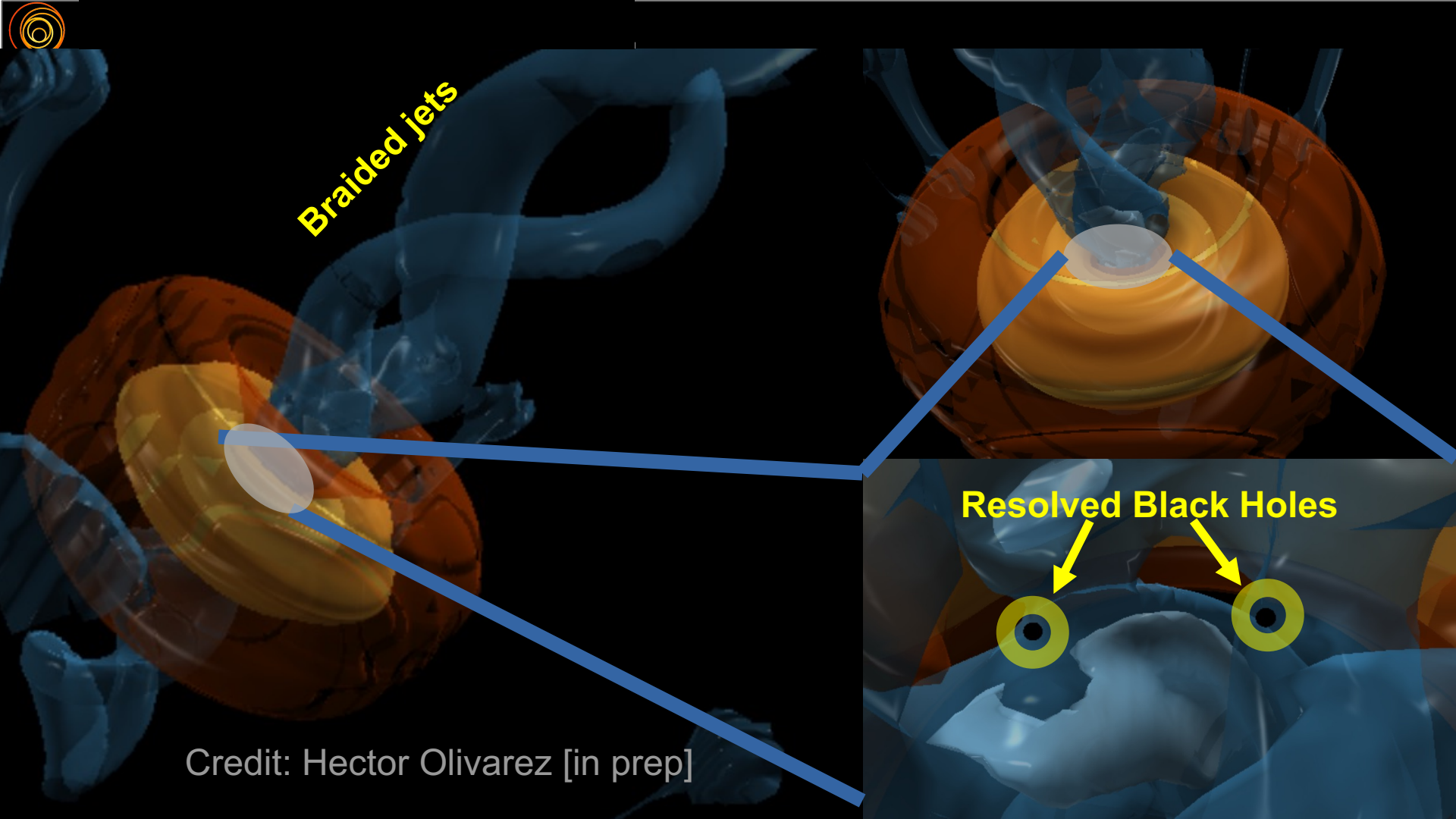
Advantages of computational set up

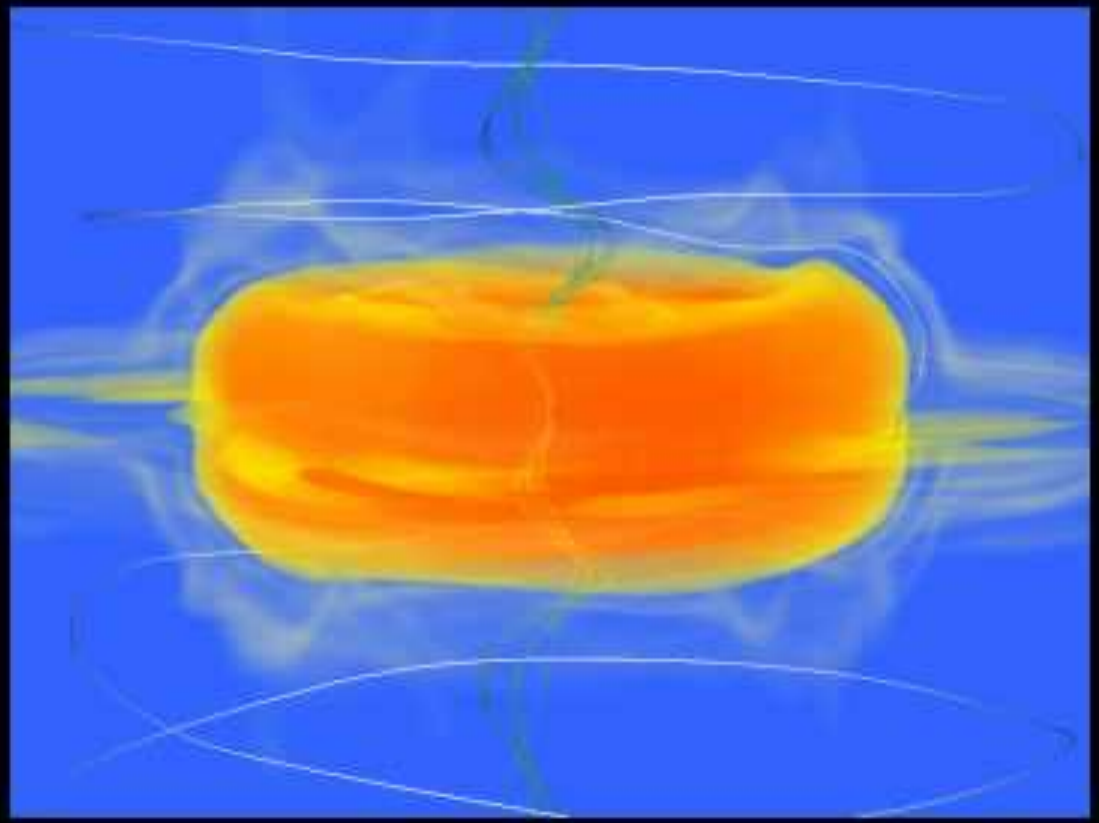
- Spectrally accurate space time metric and its derivative
- Much better scaling of stationary GRMHD code compared to numerical relativity codes
- BHAC code already used/**tested [Porth+ 2019]** and interfaced with (ng)EHT








Braided jets
Resolved Black Holes
Credit: Hector Olivarez [in prep]



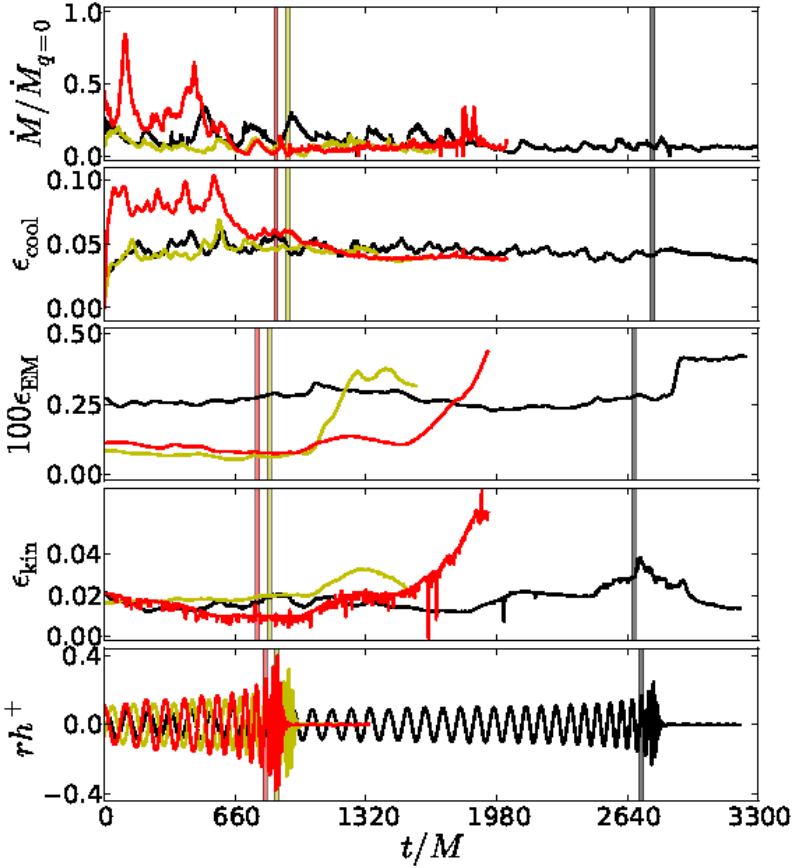
Accreting black hole binaries carry the same complexities as accreting single black holes *PLUS* additional complications

The images in general will not just be a simple double source with a sinusoidal light curve.

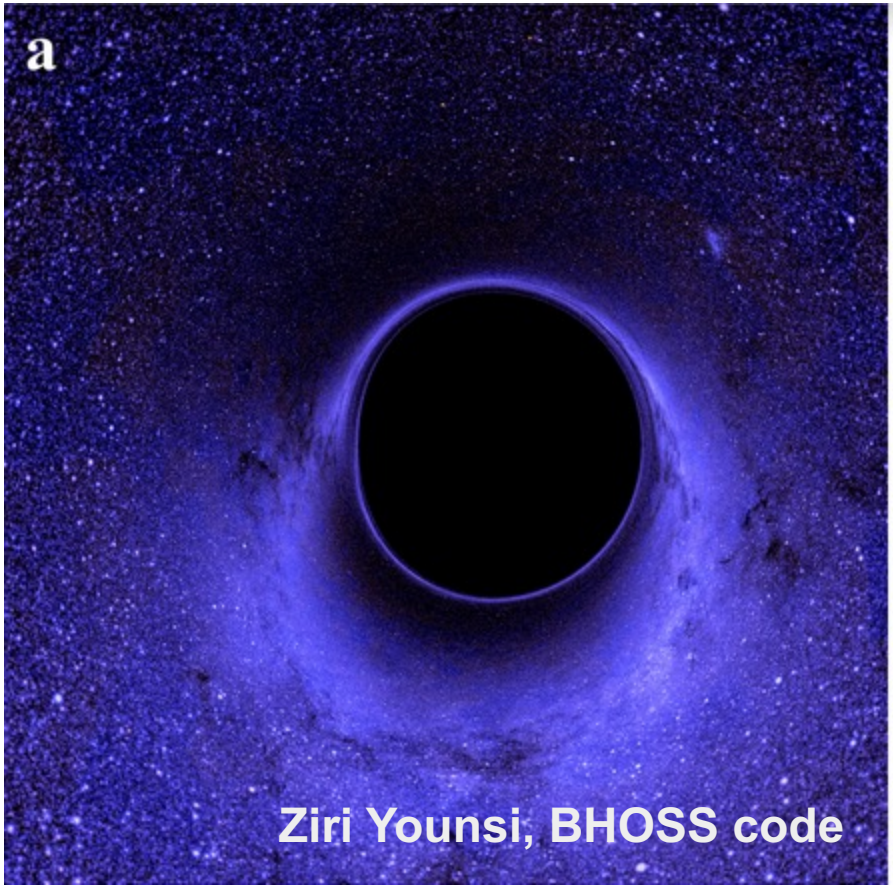
Simple models will not capture this, so we shall proceed with at least mitigating astrophysical realities

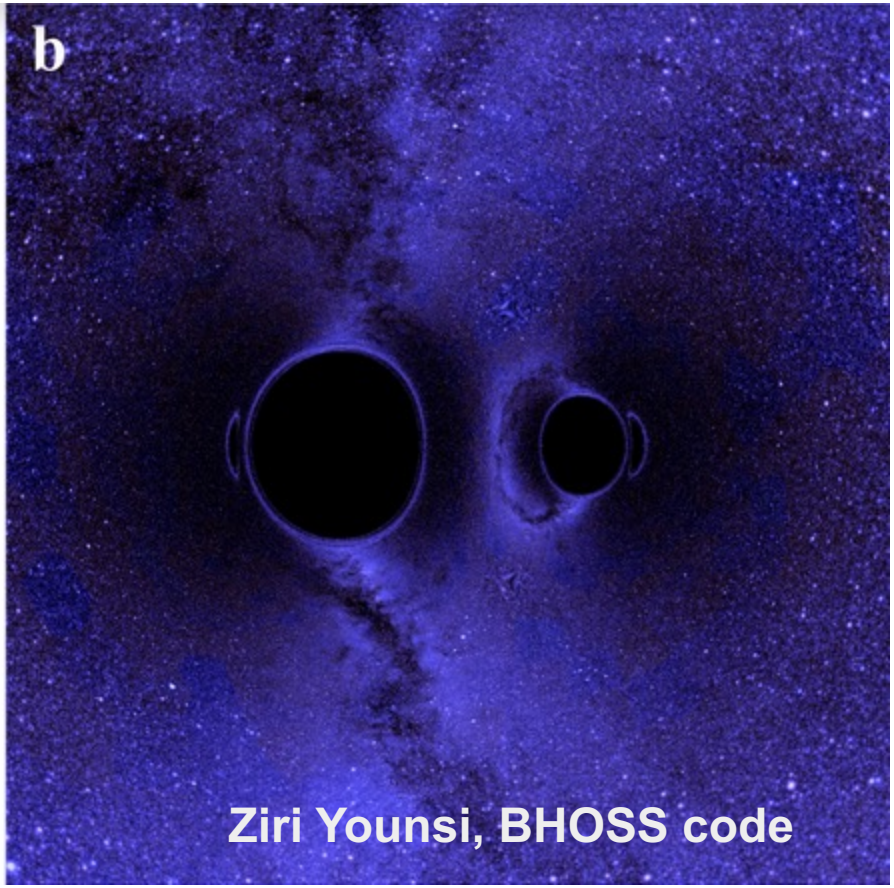
Simulation:
Gold+ 2014

- Even in predecoupling stage where disk follows binary complicated dynamics
- Not necessarily much drop in radiative cooling losses (from shock heating) in early stages of inspiral
- Increase in Poynting luminosity
- GW signal well understood



BHOSS ray-tracing in binary spacetimes, binary RIAFs coming

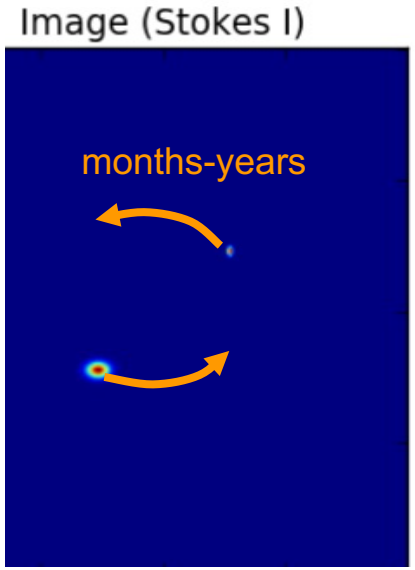


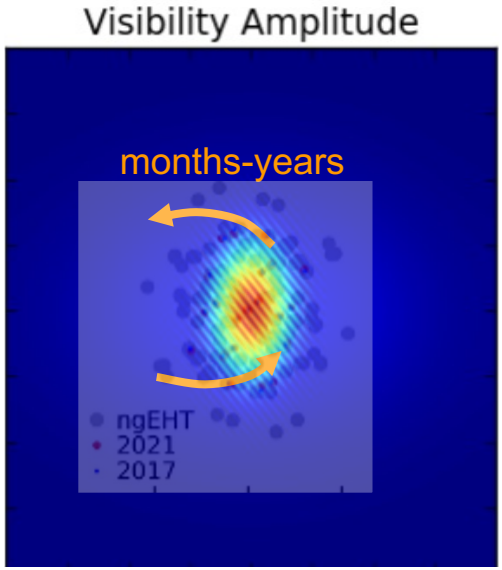


Modeling: 2 main routes:

1. **Simplified but effective:**
   - "Orbiting blobs"
   - As simple as possible *and no simpler*:
     Hybrid modeling + image reconstruction
     "Model what we know - image the rest"

2. **Challenging but more physical:**
   - GRMHD simulations models
   - Binary semi-analytic RIAFs
     (with Ziri Younsi, Samuel Tootle)
     + radiative transfer



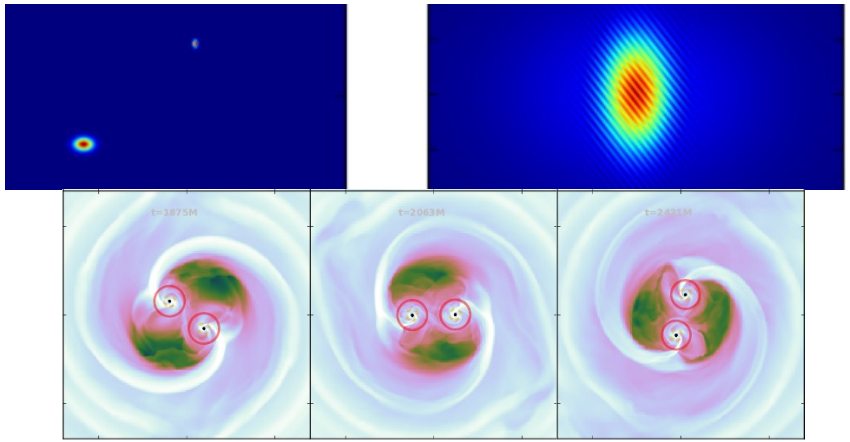


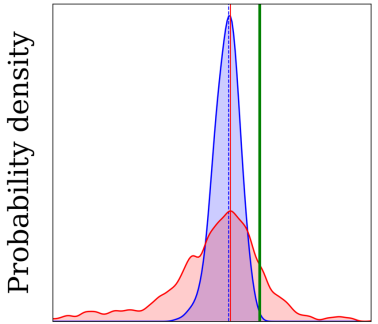
Most classes implemented in **Bayesian parameter estimation** package THEMIS [Broderick et al 2020] designed for EHT and ngEHT applications

- (ng)EHT can **spatially resolve and track binary orbital motion** of SMBHB [**ngEHT 2023**]
- direct/**unambiguous inference of binary nature** than periodicity searches or spectral evidence

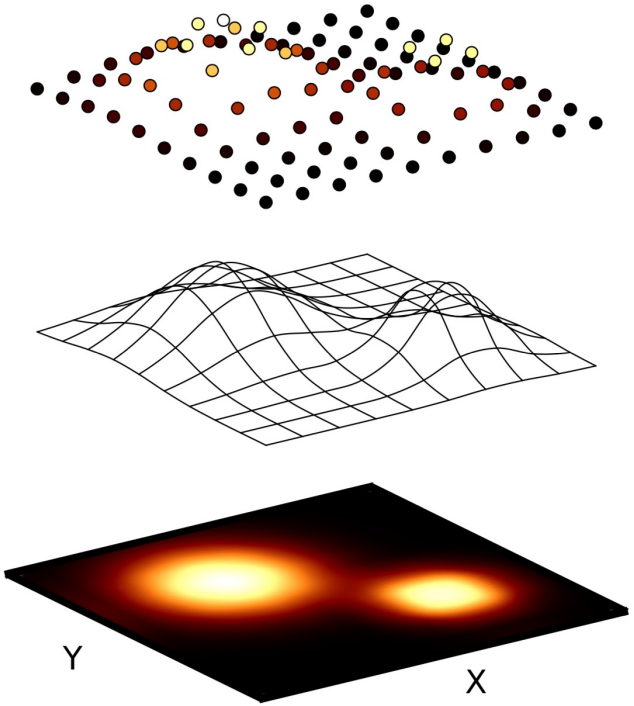
Infering orbital properties in gastrophysical messiness

- The VLBI signature two point source or two Gaussian blobs is very simple
- **BUT**: Real binaries are very messy!
- Ignoring this messiness may prevent detections or bias infered parameters and their uncertainties
- How do we deal with this?





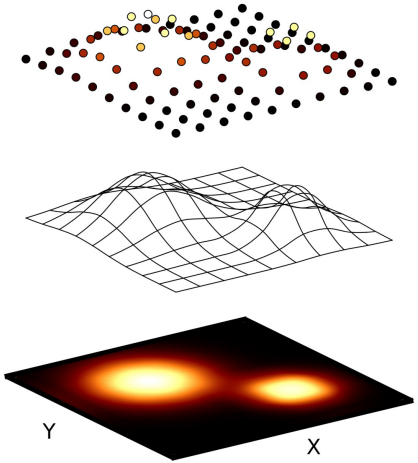
Themaging -- Merging modeling and imaging



- “Non-parametric” models
  - Choose a complete basis
  - Recast coefficients as params.
  - Enforce positivity (image!)
  - Interpolate to all points.
- Do all the modeling stuff:
  - Explore multimodal solutions
  - Construct posteriors
  - Select among “models”

With Avery Broderick, Dom Pesce, Paul Tiede, Hung-Yi Pu

Modeling and Imaging: Extracting Mass (and Spin)



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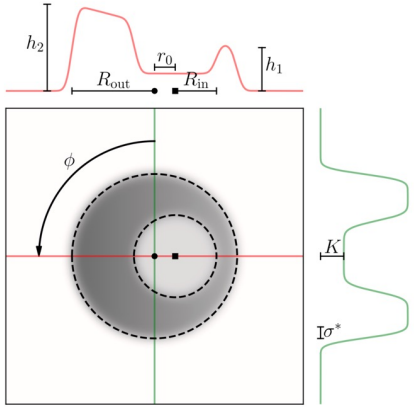


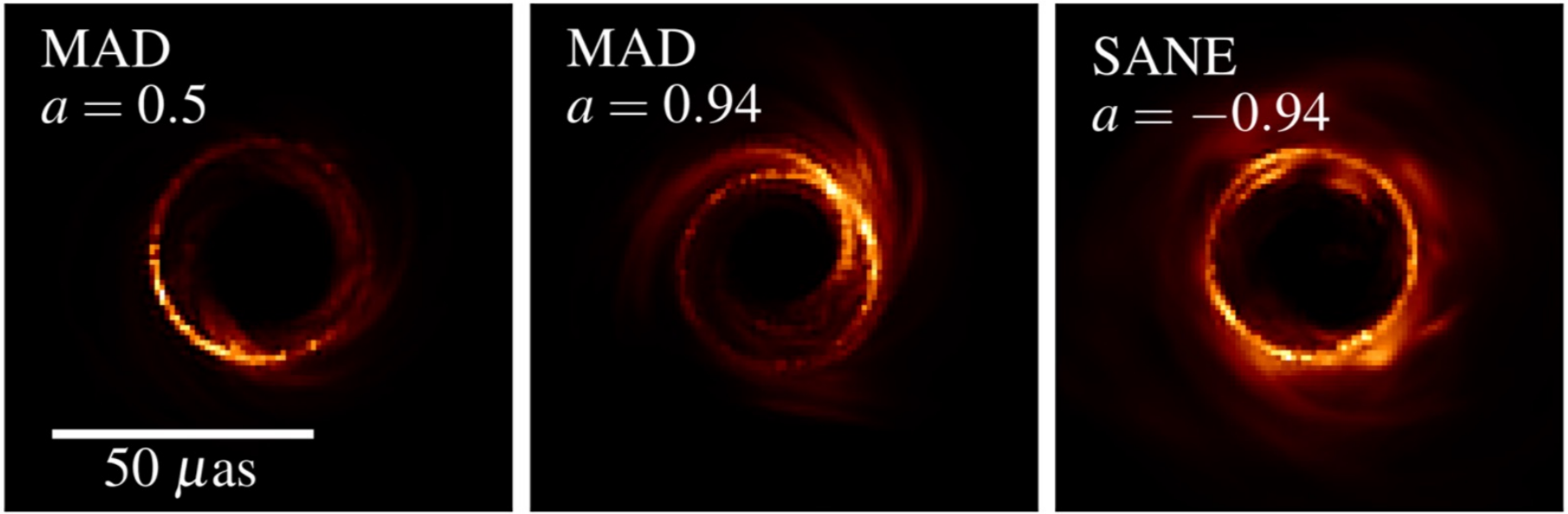
Themage
(Astrophysics!)

Ring / Orbit / etc
(Gravity!)

- Restrictions:
  - Narrow
- Permitted:
  - Large range of positions/shifts
  - Large range of diameters
  - Large range of fluxes (incl. 0)
  - Flux asymmetry (slash & orientation)
  - Ellipticity
- Complications:
  - Variability

With Avery Broderick, Dom Pesce, Paul Tiede, Hung-Yi Pu

Example: Imaging + Ring fitting



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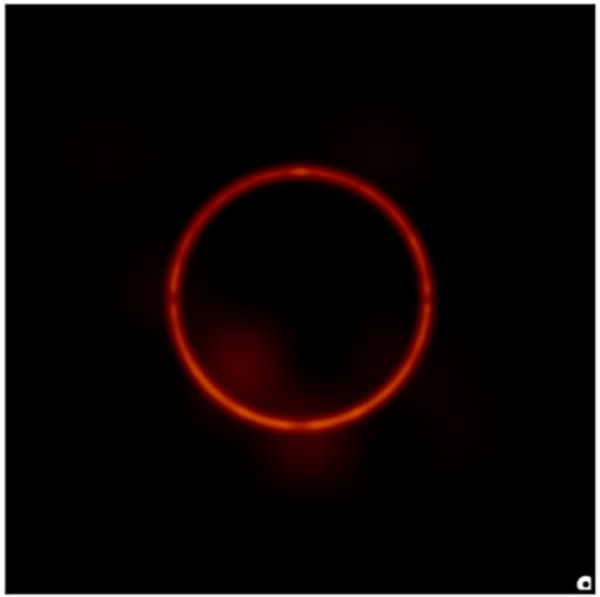
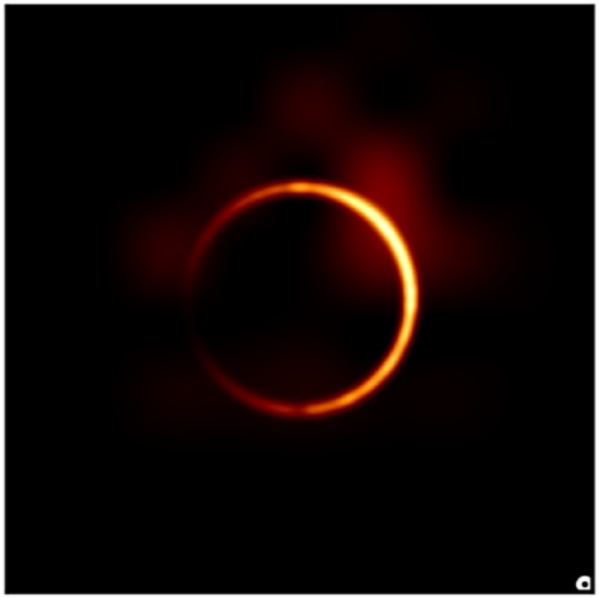
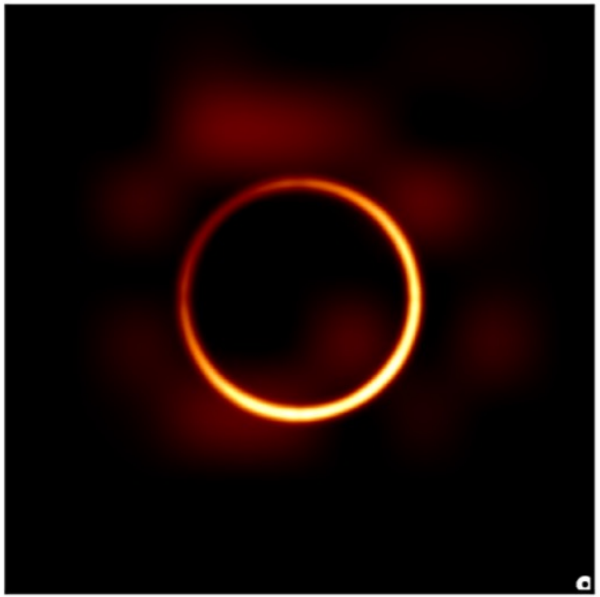

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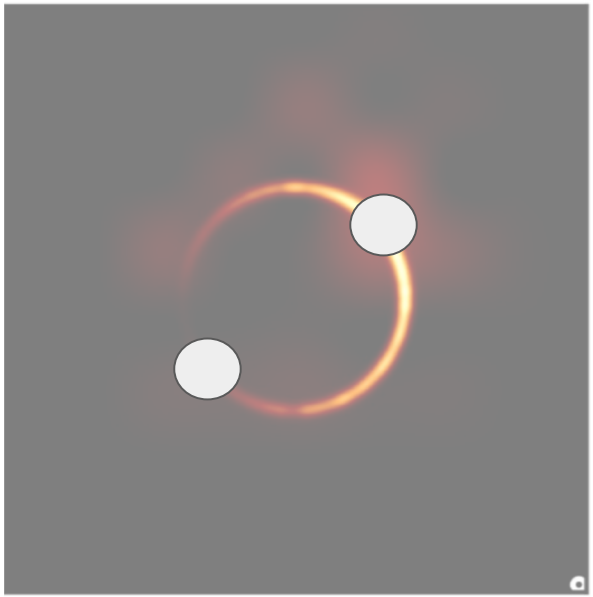
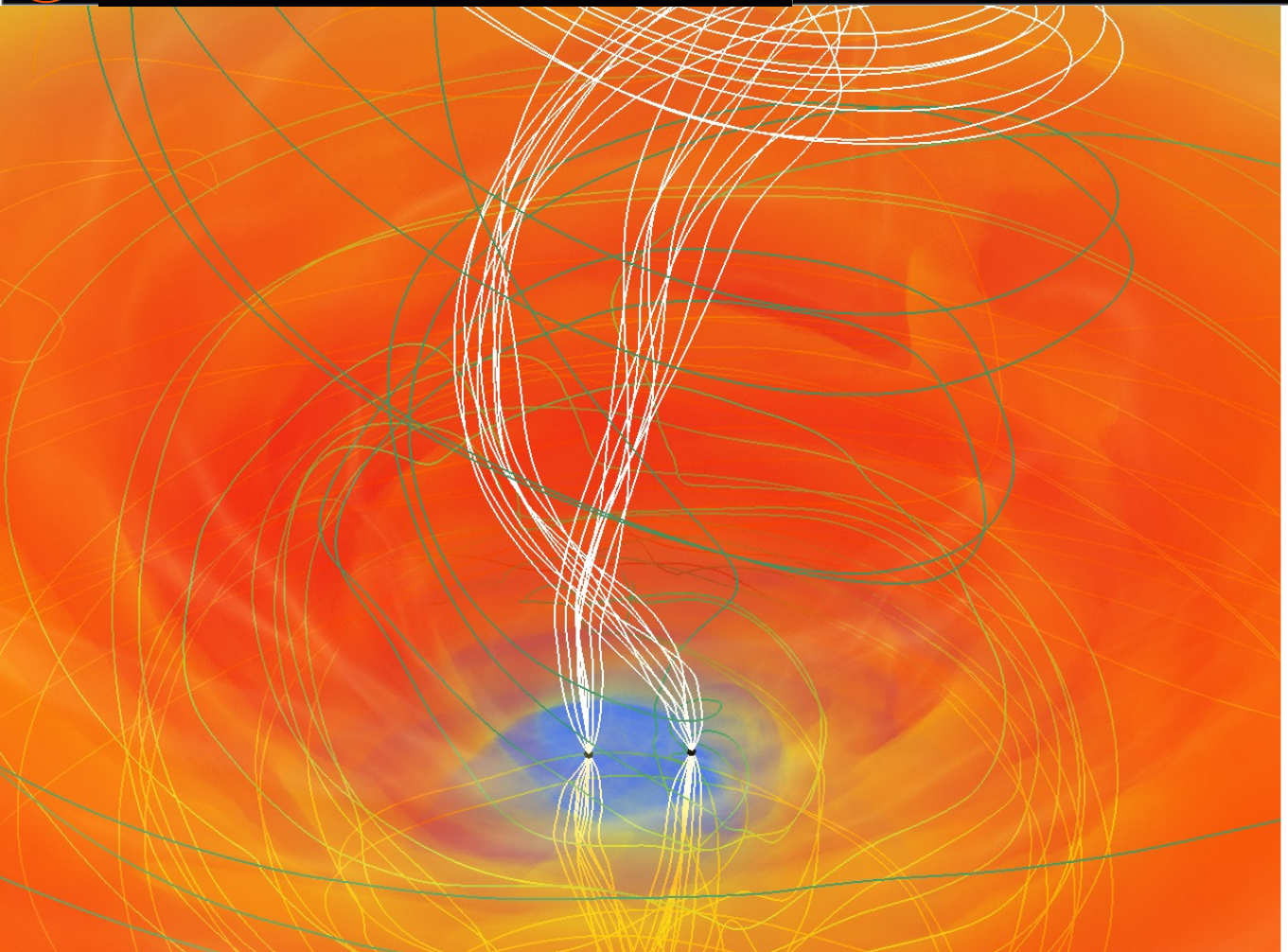
Example: Imaging + Binary



How should we best use these models to guide our efforts?

- Generate a model prediction
- Simulate VLBI dataset (eht-imaging [Chael]) for different array configurations
- Perform analysis
- Assess fit quality, inference bias etc
- determine how large an array and how long monitoring we'll need
- Assess importance of
  coverage, sensitivity, resolution, observing frequency, etc



Accreting BH binary =
accreting single BH
+ a lot more!

Simple models (orbiting blobs on Kepler orbits, Doppler boosting, …) will not capture every case

Need for variety of (incl physical) models and mitigating astrophysical realities

Simulation:
Farris, RG+ 2012
Gold+ 2013/14,2014
Paschalidis 2021

Literature

- Yun Fang, Huan Yang: http://arxiv.org/abs/2111.00368
- d'Orazio & Loeb https://arxiv.org/pdf/1712.02362.pdf
- Infrared VLBI: Dexter et al https://arxiv.org/abs/2010.09735
- Coauthored:
- Hybrid themaging: https://doi.org/10.3847/1538-4357/ab9c1f

Accreting Black Hole Binaries in Dynamical Spacetime with my involvement:

Paschalidis et al [2021]
Gold [2019], Gold et al [2014], Gold et al [2014],
Farris et al [2012]