TESTING GR WITH HORIZON-SCALE IMAGING

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Event Horizon Telescope

KISS, 09-17-2019

ROADMAP

- **Review of theoretical prejudice**
  - Hair, Kerr, and logic
  - Deviations, why and when
  - Information paradox
  - The physics (semantics) of horizons
  - Advocating empiricism
- **Imaging horizons and GR tests**
  - Mass estimates and circularlity
  - Extracting photon rings
  - Dynamical features 1-2-3
  - Evidence for horizons
  - Messages from the edge

IN THEORY

BLACK HOLE HAIRSTYLES IN GR

If

- Vacuum
- Stationary
- Non-pathological
- Asymptotically flat

then Kerr.

Black holes fully defined by

1. Mass
2. Angular momentum
3. ~~Electric charge~~

Simple, unambiguous, testable.

PRACTICAL PROBLEMS WITH MOVING BEYOND GR

1. If a BH is Kerr, not necessarily GR.

- Brans-Dicke theory (GR + scalar) has Kerr BHs
- Lots of theories have Kerr as a solution (e.g., $f(R)$)
- Solutions are very difficult to come by!

2. If a BH is not Kerr, not necessarily not GR.

- Light bosons? (BUT, would be mass dependent.)
- Astrophysics …

GENERAL STATEMENTS ON SCALE: EFFECTIVE FIELD THEORY

GR as low energy limit

$R^2, R^{\mu\nu}R_{\mu\nu}, R^{\alpha\beta\mu\nu}R_{\alpha\beta\mu\nu}$, etc.

$$S = \frac{1}{16\pi G}\int d^4x\sqrt{-g}\,(R + \lambda_2 R^2 + \lambda_3 R^3 + \cdots)$$

Einstein-Hilbert action

High-energy deviations

"Big" deviations typical when $R \sim 1/\lambda_2$
(natural scale for $\lambda_2 \sim \ell_P^{-2}$!!)

<u>BUT</u> for BHs $R \sim \frac{GM}{r^3} \sim M^{-2}$

INFORMATION PARADOX (Mathur, AMPS)

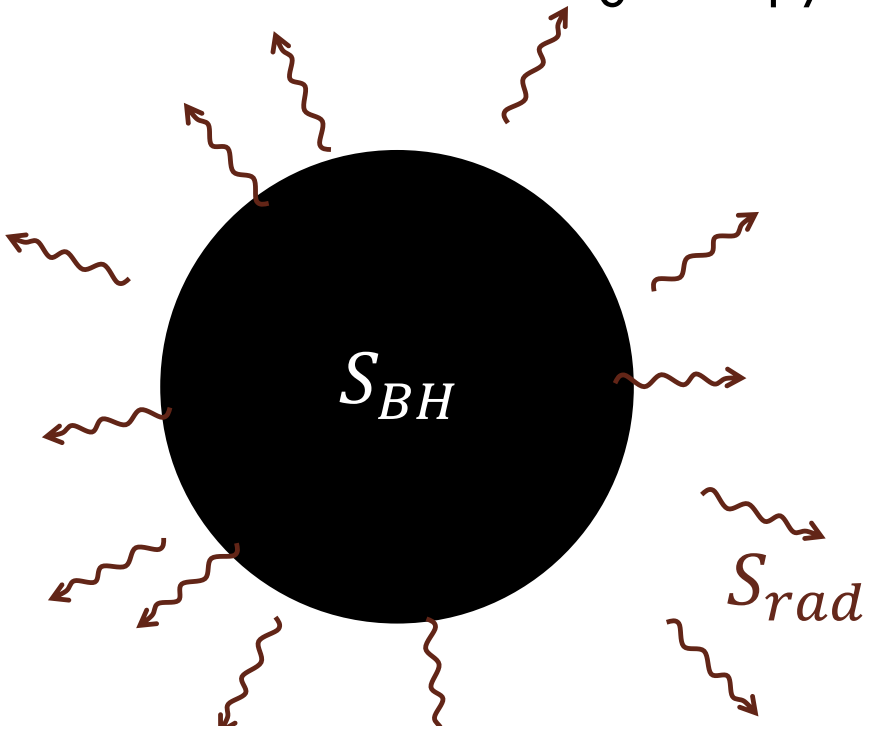
$$S = \frac{k_B A}{4\ell_P^2} \propto M^2$$

Bekenstein-Hawking entropy

Hawking radiation
entangled with BH!

When $M \to M/2$, S_{BH} to small!

Quantum gravity
enters on horizon scales!



WHAT IS A "HORIZON"?

What theorists care about

- Event horizon

  The surface that divides the region from which null geodesics escape to null infinity from that in which they do not.

  Teleological, mathematically powerful, hard to prove.

- Apparent horizon

  The surface separating outward directed null geodesics that move outward and inward.

  Local, easy to define, less mathematically useful.

How theorists hide from data

THEORETICAL PREJUDICE VS EMPIRICISM

- Any deviation would be seen in small black holes first.
- Unless you have an event horizon, which you cannot prove.
- And deviations should be on the Planck scale anyway.

- Nothing unexpected was ever found by looking for it.
  → "Test" GR via precision verifications wherever possible

IN PRACTICE

THE MASS OF M87

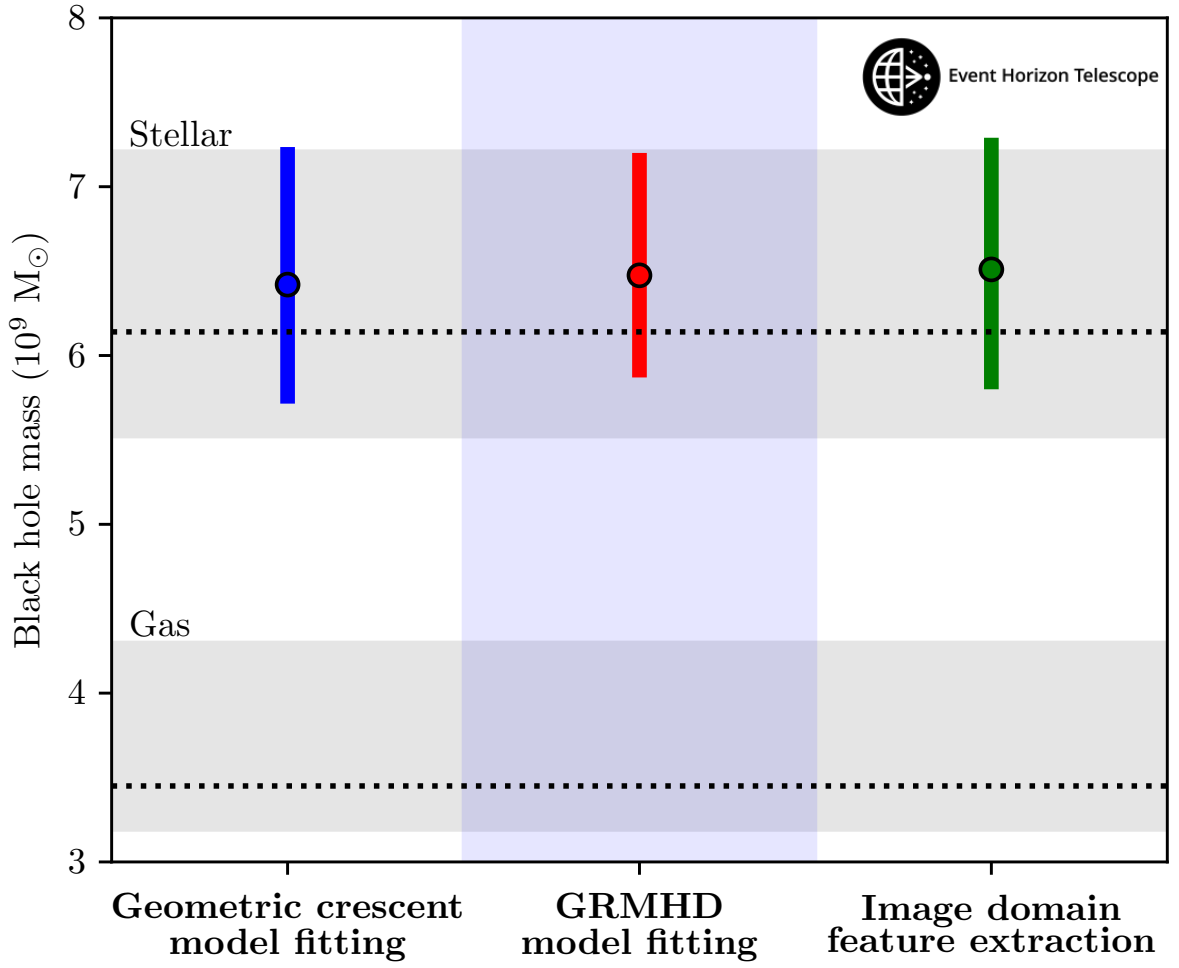
Assumes 16.8 ± 0.7 Mpc

Dominated by systematic errors in calibration.

Exquisite agreement!

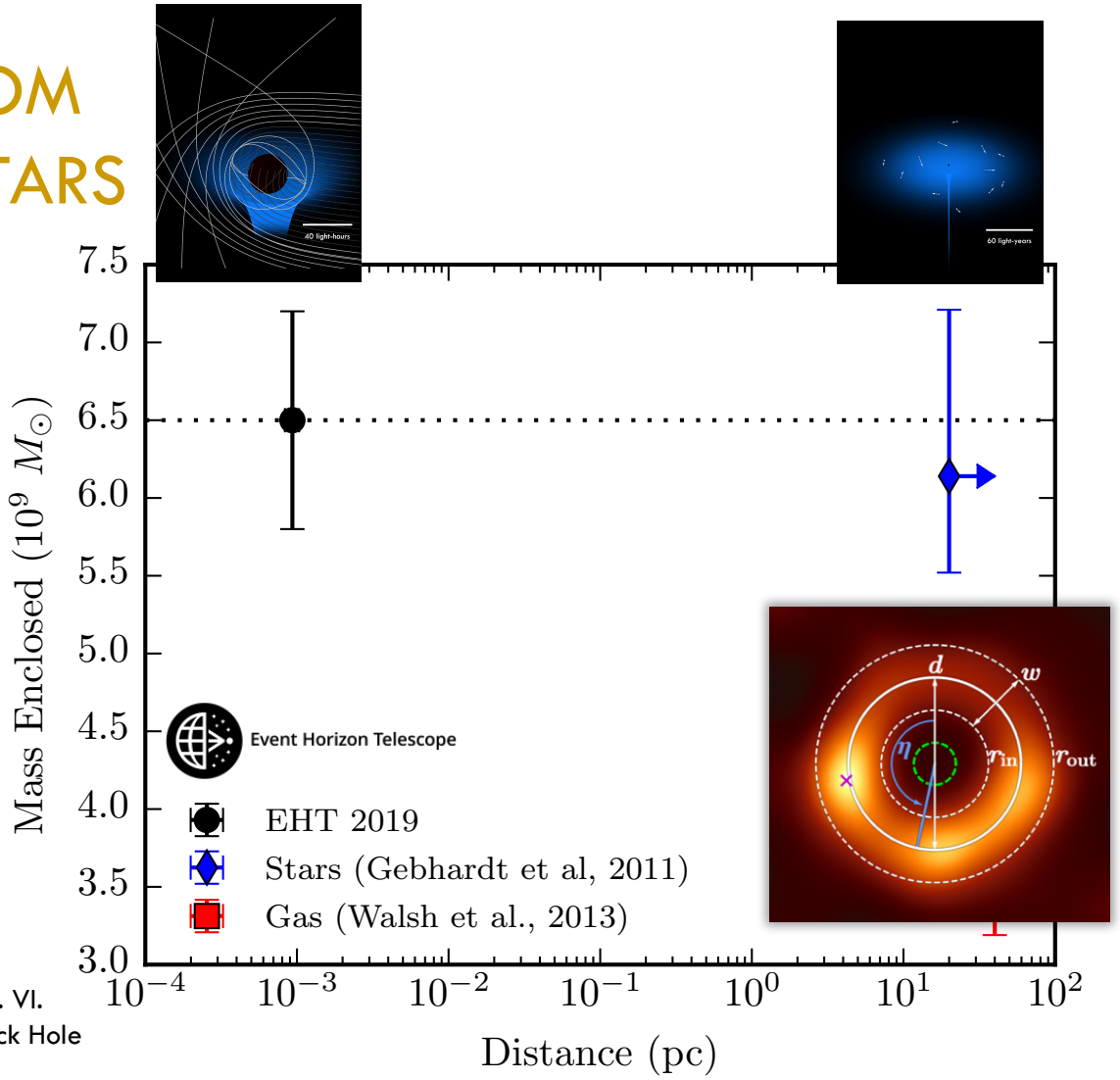
First major science result of the EHT

First M87 Event Horizon Telescope Results. VI. The Shadow and Mass of the Central Black Hole EHTC+ 2019



GENERAL RELATIVITY FROM THE HORIZON TO THE STARS

- Stellar dynamics mass!
- Needs modest changes to the **inclination** and/or **dynamical state** of the gas.
- **Dynamics** of both matter and light matches predictions of GR over 4 orders of magnitude.



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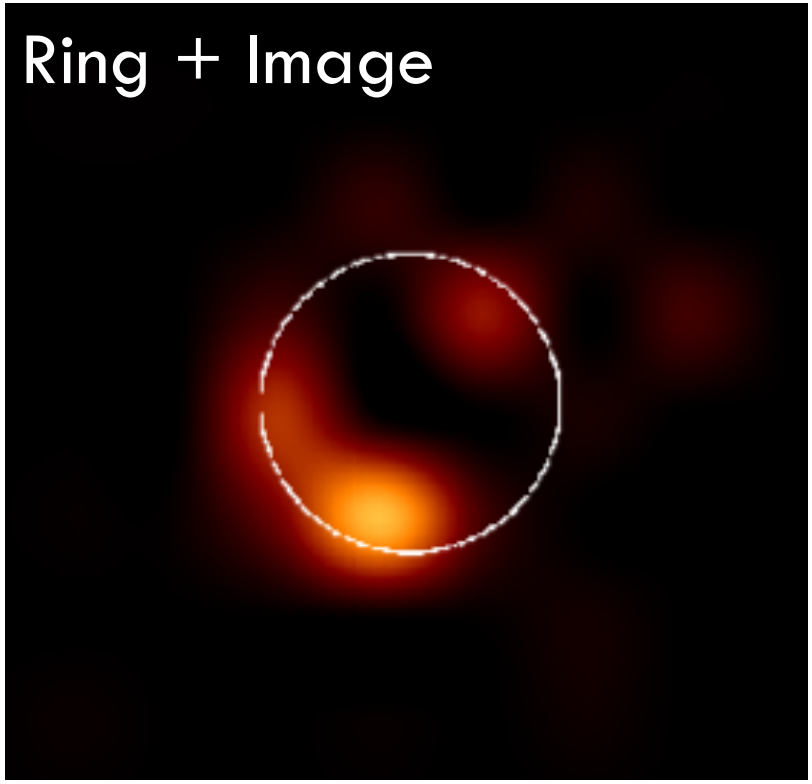
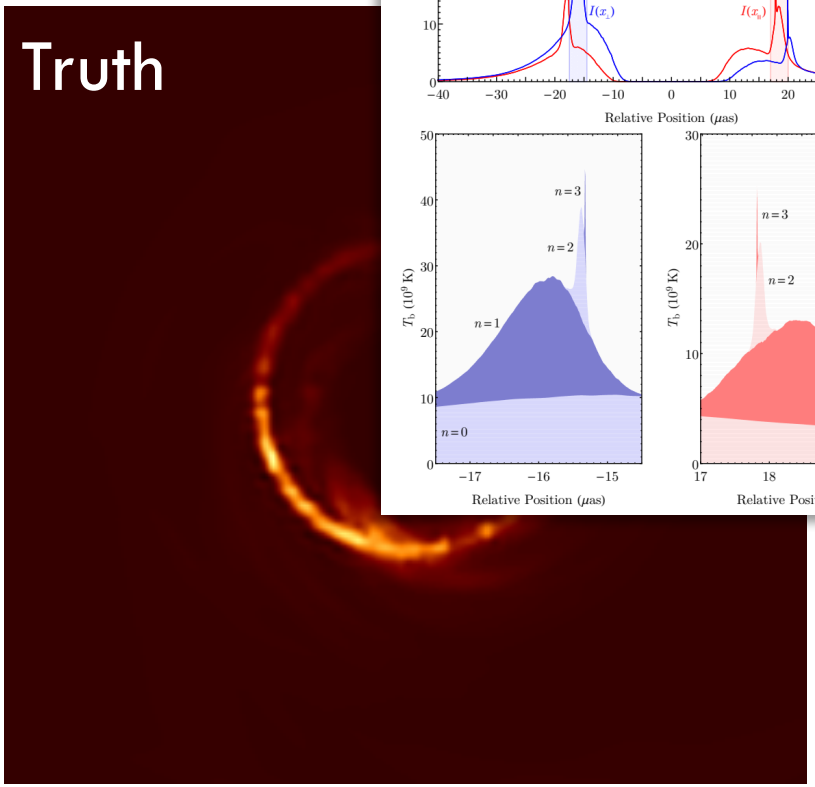
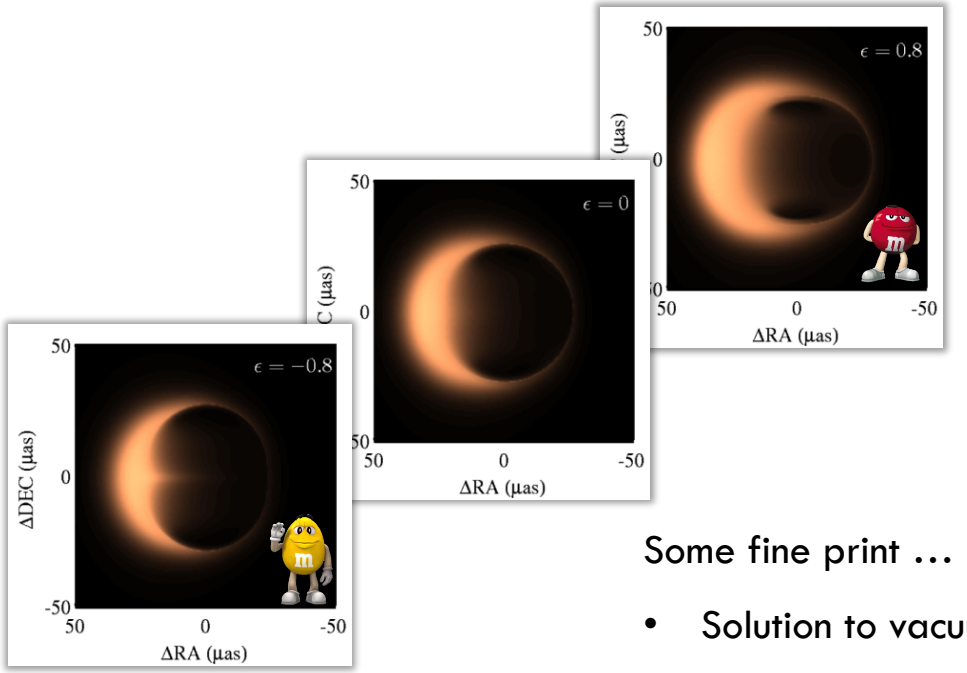
HYBRID MODELING/IMAGING RECONSTRUCTING THE PHOTON RING





DYNAMICS 1: QUADRUPOLAR DEVIATIONS



Quasi-Kerr Metric: Parameterized Deviation

$$g_{\mu\nu} = g^{K}_{\mu\nu} + \epsilon h_{\mu\nu}$$

$$M = M, \qquad J = aM,$$

$$Q = -a^2 M - \epsilon M^3$$

Some fine print …

- Solution to vacuum Einstein equations when $|a| \ll M$
- Adds quadrupolar perturbation
  (based on Hartle-Thorne metric for slowly spinning neutron stars!)
- No-hair theorems → Quasi-Kerr metric must be sick! It is inside $2M$.

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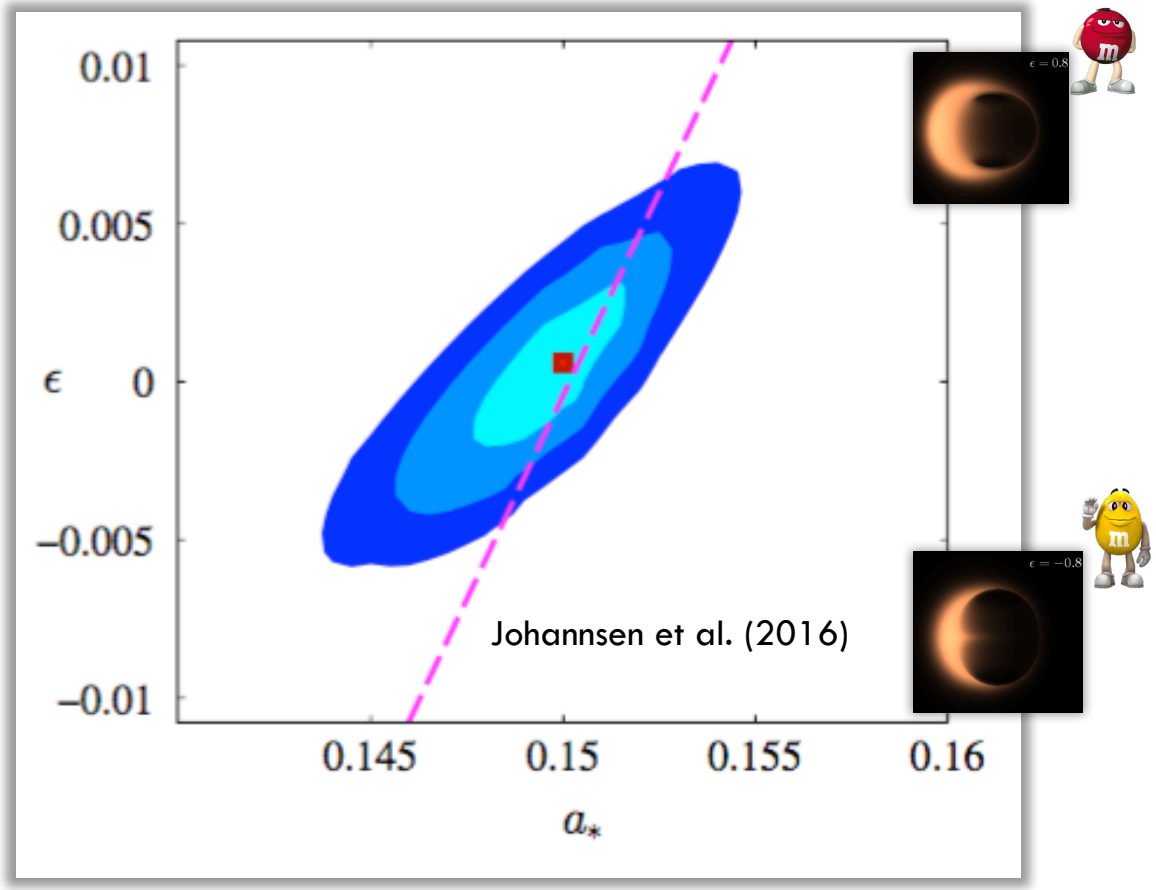
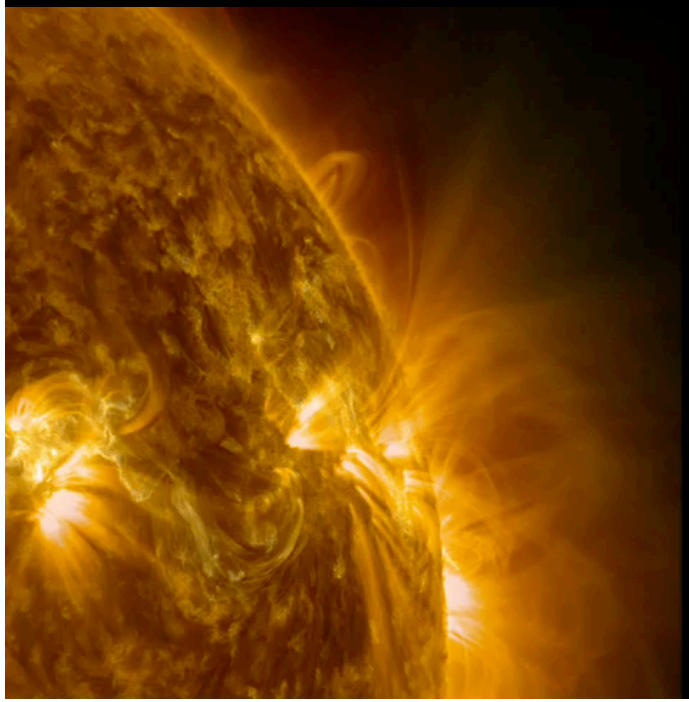
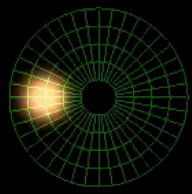
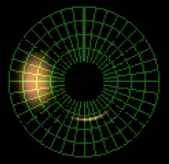


DYNAMICS 2: TOMOGRAPHY



a=0, r=6M





F_{LP}

F_{tot}

Broderick & Loeb, 2006, MNRAS, 367

GRAVITY collaboration (2018)

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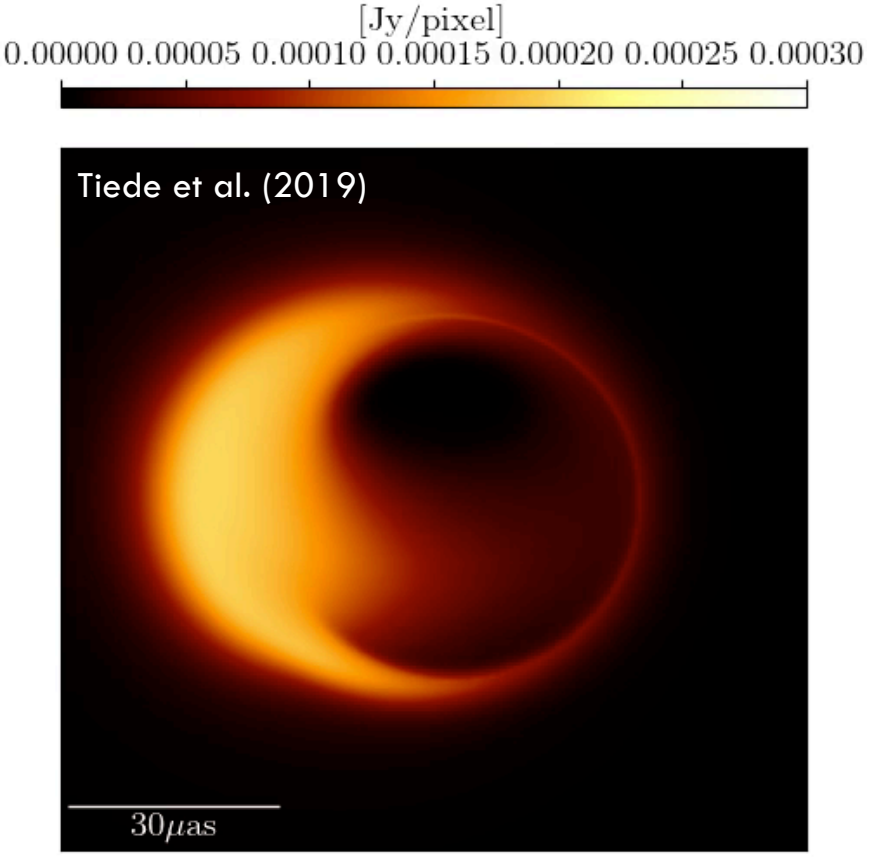
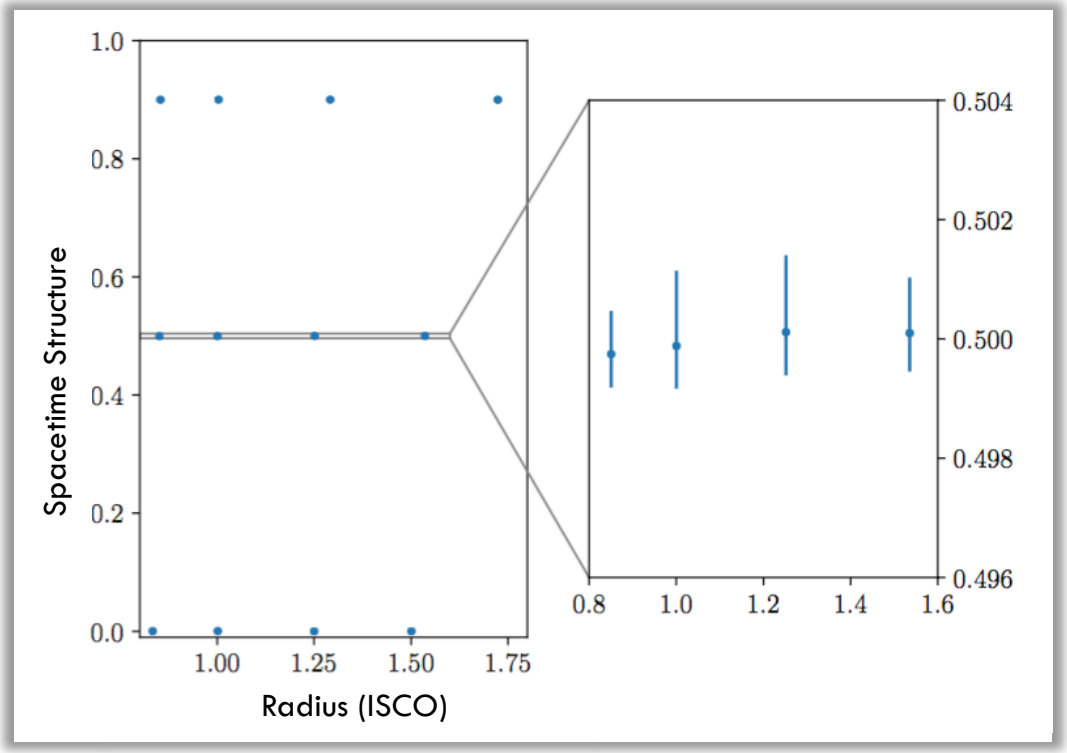
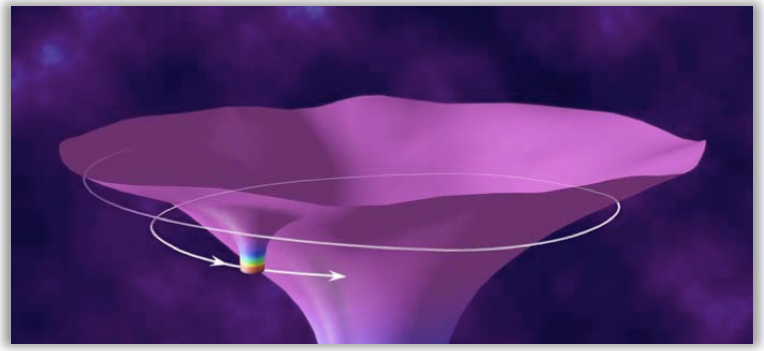
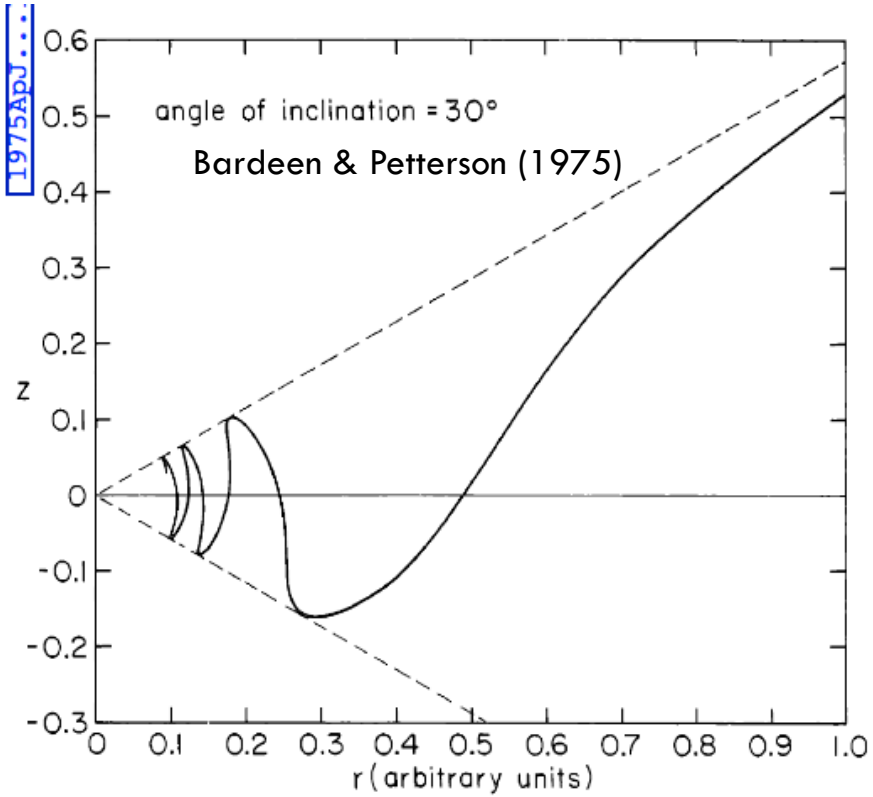
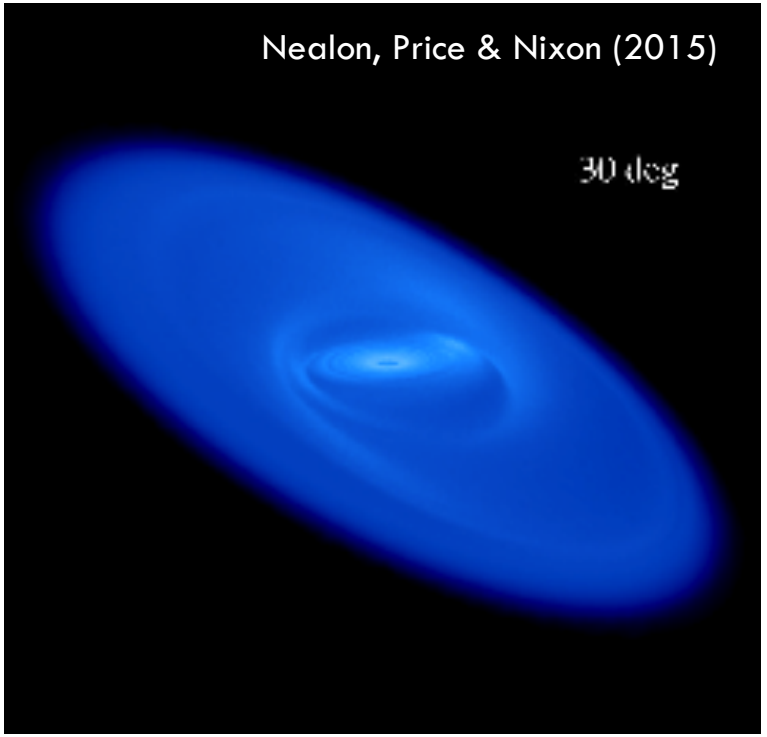






DYNAMICS 3: LENSE-THIRRING





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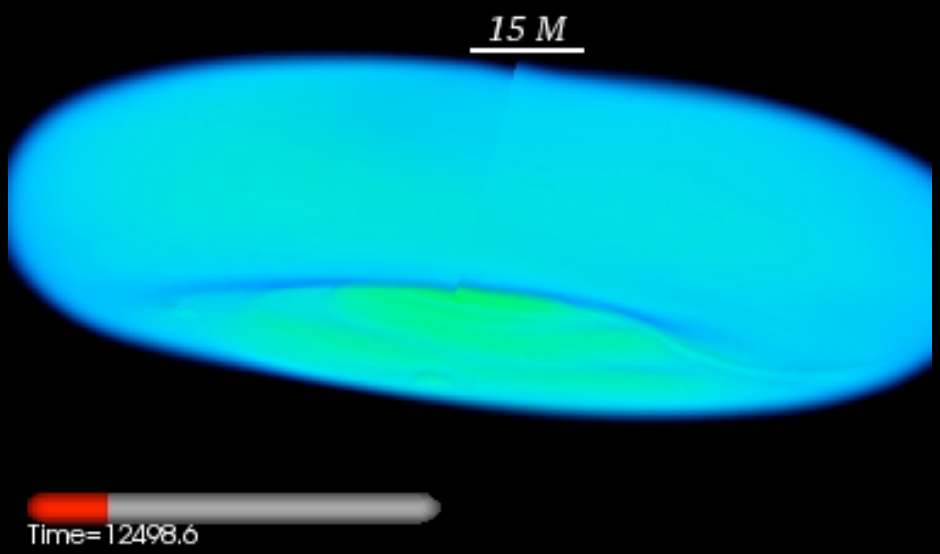
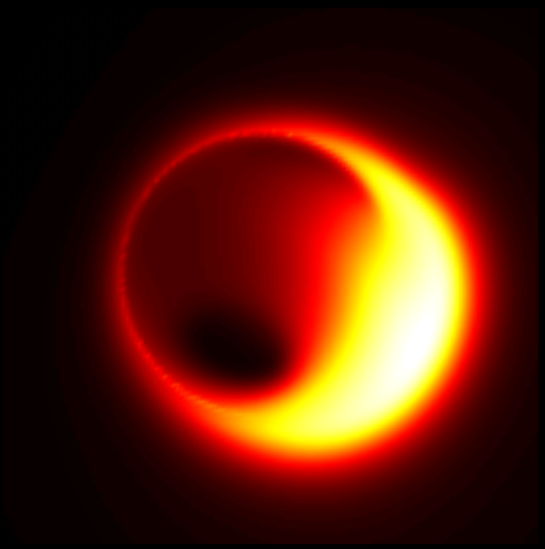
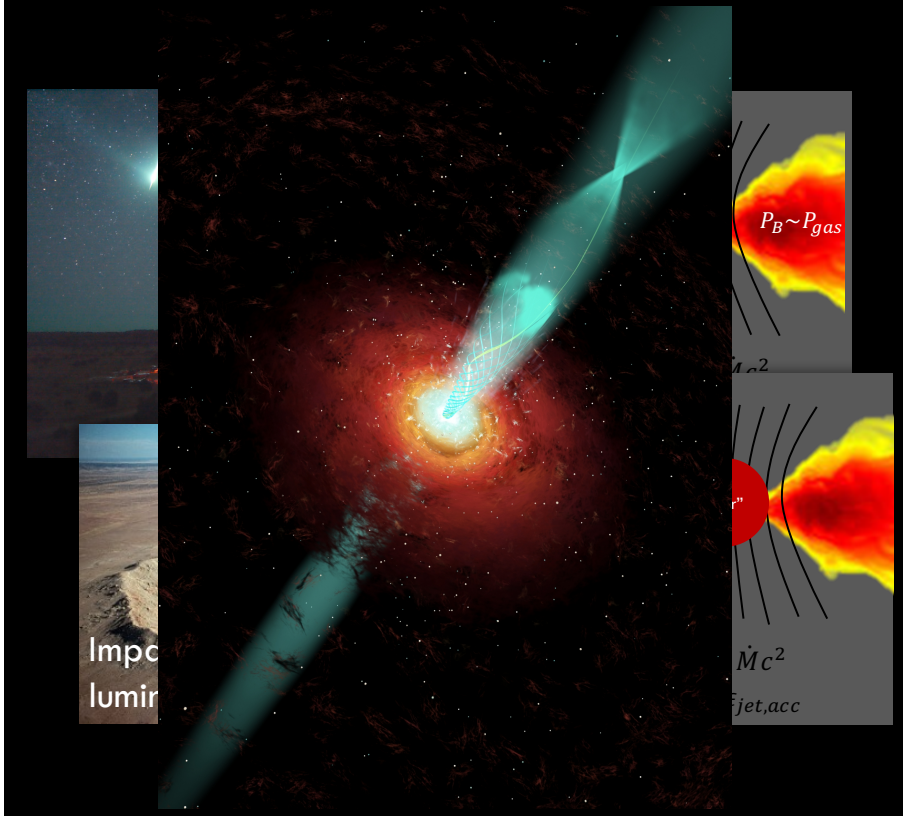
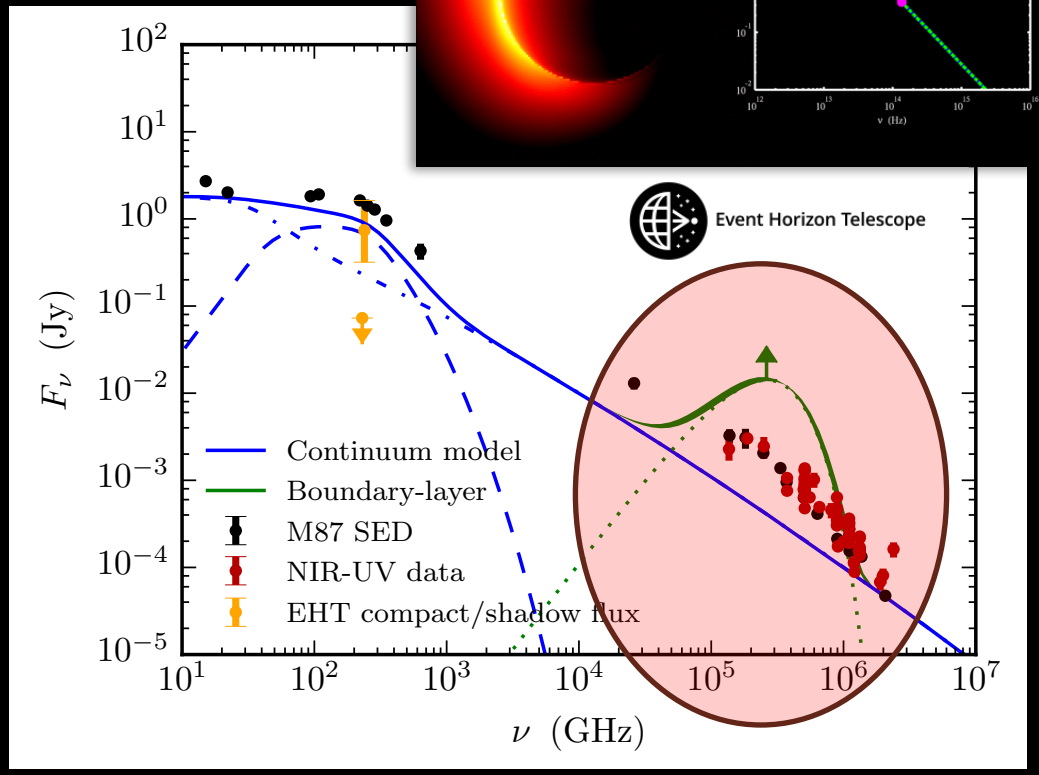




$$T_{prec} \sim \frac{L_{disk}}{\tau_{LT}} \sim \frac{2}{a \sin\Theta} \left(\frac{r_o}{10^3}\right)^{5/2} \text{yr}$$

DO HORIZONS EXIST?





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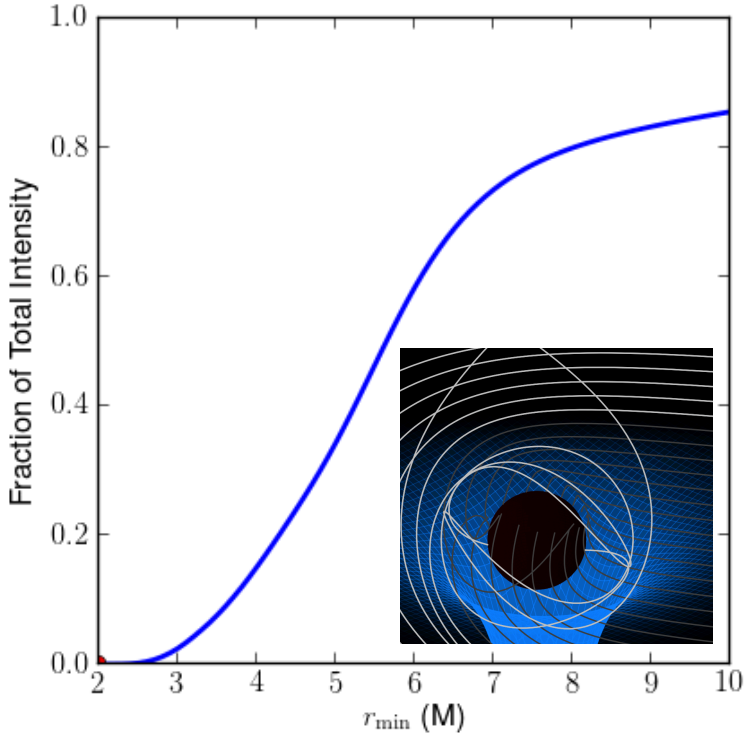
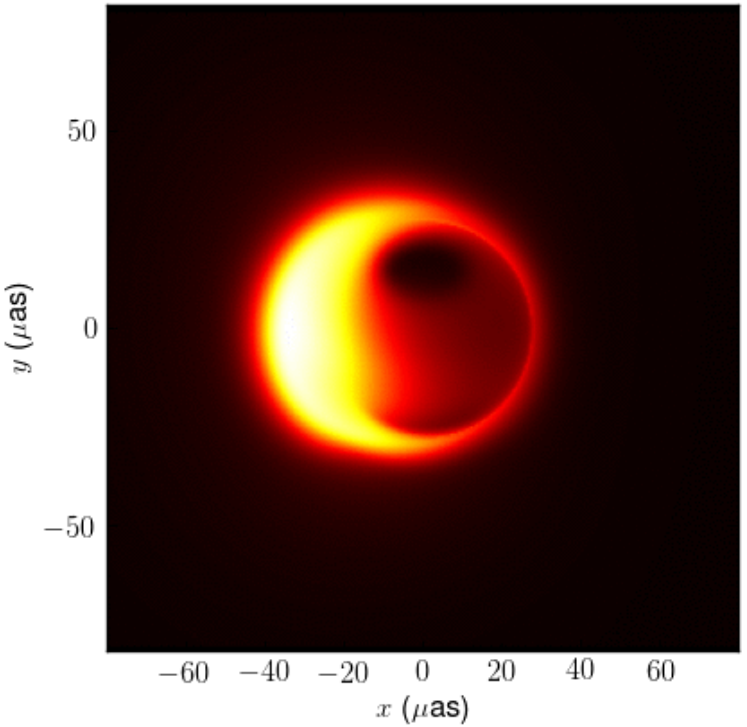
INSIDE THE PHOTON ORBIT





H.-Y. Pu & AEB (2018)

OTHER …

- Achromatic nature of lensing features
- Very-short timescale variability about quantum BHs
- Modeling images in specific BH foils
  (Boson stars, naked singularities, etc.)
- Galactic center pulsars
- SMBH binaries, the final parsec problem and PTAs

DISCUSSION STARTERS

- What constitutes a “Test of GR”?
- What kinds of theoretical foils are necessary?
- Optimizing between sensitivity, coverage, and resolution?
- Monitoring duty cycles? Monitoring array size?
- Project lifetimes and long term plans?
- Multimessenger leverage over the next decade?