Detecting Equatorial Symmetry Breaking

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"New horizons for (no-)horizon physics:
From gauge to gravity and back"
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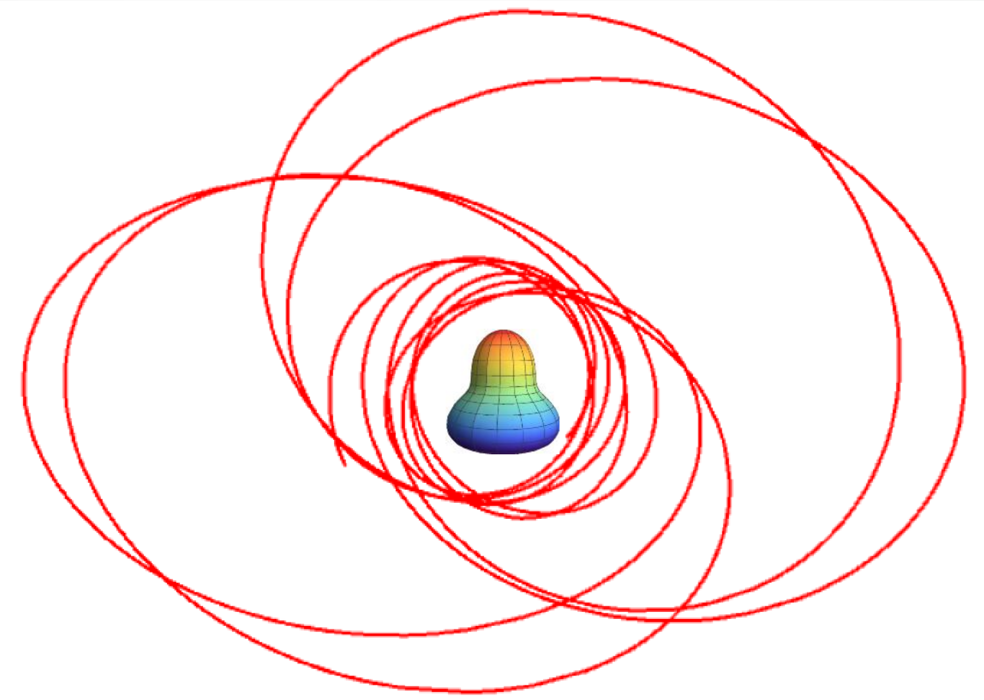


- ***[2201.03569]*** *with Kwinten Fransen*
  (EMRIs at LISA)
- ***[22xx.xxxxx]*** *with Pablo Cano, Bogdan Ganchev, Alejandro Ruiperez Vicente*
  *(**Higher derivative corrections, BH multipoles**)*
- ***[22xx.xxxxx]*** *with Fabio Bacchini, Bart Ripperda, Seppe Staelens*
  *(**Imaging asymmetric objects**)*

Outline

- Introduction

- Analytic kludge for EMRIs
- Measuring equatorial symmetry breaking
- Application: Constraining (2) models

GWs (LISA EMRIs)

- Image and shadow asymmetry

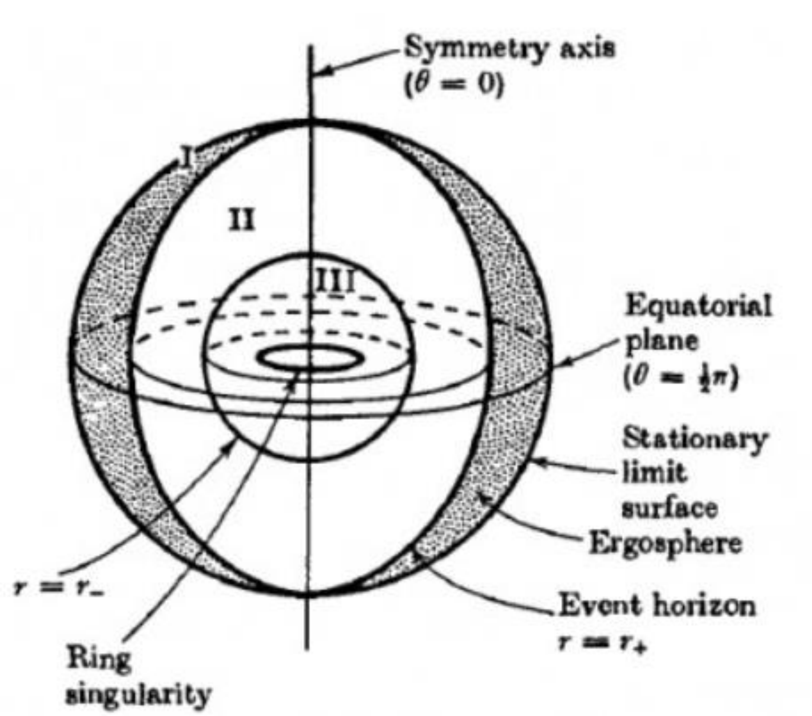
BH imaging (EHT+)

- (Longer) Outlook

Introduction (1)

- Equatorial symmetry ($z \leftrightarrow -z$) as « accidental » symmetry of Kerr
  - Unlike axisymmetry!
  - Generically broken
- Nevertheless often overlooked
  - Symmetry usually assumed
  - ~~Some work specific to dCS~~
- *What effect does it have to break this* $\mathbb{Z}_2$ *?*
- Constrain/observe symmetry breaking?
- → 1) LISA EMRIs: probe larger objects over many cycles

→ 2) Imaging asymmetric objects

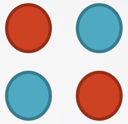


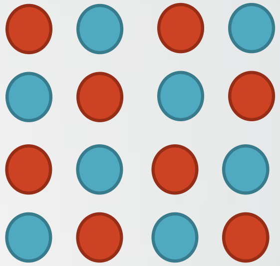
[Hawking, Ellis]

Introduction (2)

- Parametrize odd parity using *multipoles* S_2, M_3
- Cfr. Electrodynamics:

$$V = \sum_{l\geq 0} \frac{1}{r^{l+1}} M_l P_l(\cos\theta) = \frac{M_0}{r} + \frac{M_1}{r^2}\cos\theta + \frac{M_2}{r^3}P_2(\cos\theta) + \frac{M_3}{r^4}P_3(\cos\theta) + \ldots$$





- GR: mass $g_{tt} \sim \sum_l \frac{M_l}{r^{l+1}}$ and current $g_{t\phi} \sim r \sum_l \frac{S_l}{r^{l+1}}$
- Kerr: $M_{2n} = M(-a^2)^n, \qquad S_{2n+1} = Ma(-a^2)^n$

Analytic kludge for EMRIs (1)

« Analytic kludge » for EMRIs [Barack-Cutler gr-qc/0310125]

Orbit evolution → Waveform → Fisher analysis

- Newtonian/Keplerian orbit of small object
  - + PN effects of dissipation (energy, angular momentum) to 3.5PN (lowest +1)
  - + Central spin S leading perturbation effects (Newtonian precession + dissipation/radiation)
  - Evolve backwards from approx. last stable orbit radius (~1yr)

Analytic kludge for EMRIs (2)

« Analytic kludge » for EMRIs [Barack-Cutler gr-qc/0310125]

Orbit evolution → Waveform → Fisher analysis

- Orbit → approx. « detected » waveform
  - Quadrupole approx.
  - LISA motion (Doppler shift) + noise curve
  - SNR = 30 (normalize distance)

Analytic kludge for EMRIs (3)

« Analytic kludge » for EMRIs [Barack-Cutler gr-qc/0310125]

Orbit evolution → Waveform → Fisher analysis

- Fisher information matrix for all variable EMRI parameters (BH masses, eccentricity, orbit inclination, central BH spin, …)
- $\longrightarrow$ estimate for accuracy of measurement parameters

- Analytic kludge: fast, but (only) order of magnitude estimate!
- Important EMRI parameters very accurate! E.g. $\Delta(S_1/M^2) \sim 10^{-4}$ [Barack-Cutler gr-qc/0310125]

Analytic kludge for EMRIs (4)

« Analytic kludge » for EMRIs [Barack-Cutler gr-qc/0310125]


Orbit evolution → Waveform → Fisher analysis

- **Application:** deviations of Kerr quadrupole [Barack-Cutler gr-qc/0612029]
- \+ parameter: mass quadrupole M_2 precession, dissipation effects
  - Deviations from Kerr quadrupole $M_2/M^3 = -S^2/M^4$ measurable within $10^{-2} - 10^{-4}$

Analytic kludge for EMRIs (5)

« Analytic kludge » for EMRIs [Barack-Cutler gr-qc/0310125]

Orbit evolution → Waveform → Fisher analysis

- **Our application:** measuring equatorial symmetry breaking
- + odd parity: S_2, M_3 [Fransen, **Mayerson** 2201.03569]
  - Corrected (Barack-Cutler) M_2 evolution
  - + precession/dissipation effects of S_2, M_3
    - Interesting effects e.g. « repulsion » from equatorial orbit

- Focus on « symmetry breaking parameter » $\tilde{M}_1 = S_2/M^3 = M_3/M^4$
- *How do different EMRI orbit parameters affect detectability* $\Delta\tilde{M}_1$ *?*

Measuring equatorial symmetry breaking (1)

- Measuring $\Delta\tilde{M}_1$ (compare to $\Delta\tilde{M}_2$)
[Fransen, **Mayerson** 2201.03569]

$$\tilde{M}_1 = S_2/M^3 = M_3/M^4$$

$$\tilde{M}_2 = M_2/M^3$$

$$\tilde{S}_1 = S_1/M^2$$

- Representative measurement for $M = 10^6 M_\odot,\ \mu = M_\odot,\ \tilde{S}_1 = 0.25,\ e_{LSO} = 0.1$

$SNR = 30$

inclination

$\Delta(\ln\mu)$	$\Delta(e_0)$	$\Delta(\cos\lambda)$	$\Delta\tilde{\gamma}_0$
7.4×10^{-4}	3.9×10^{-4}	9.04×10^{-3}	2.4×10^{-1}

argument of periapsis

$\Delta(\ln M)$	$\Delta\tilde{S}_1$	$\Delta\tilde{M}_2$	$\boldsymbol{\Delta\tilde{M}_1}$
8.2×10^{-4}	7.0×10^{-4}	4.4×10^{-3}	$\mathbf{1.8\times10^{-2}}$

Measuring equatorial symmetry breaking (2)

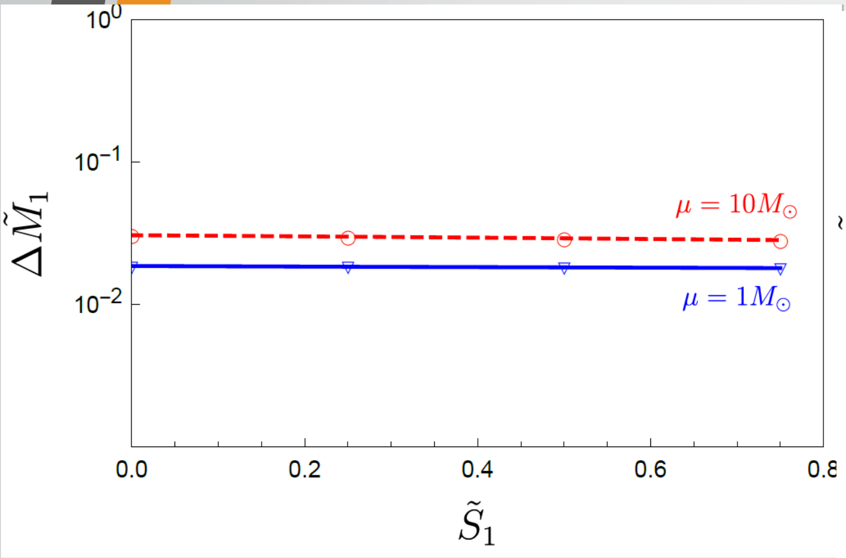
- Measuring $\Delta\tilde{M}_1$ (compare to $\Delta\tilde{M}_2$)

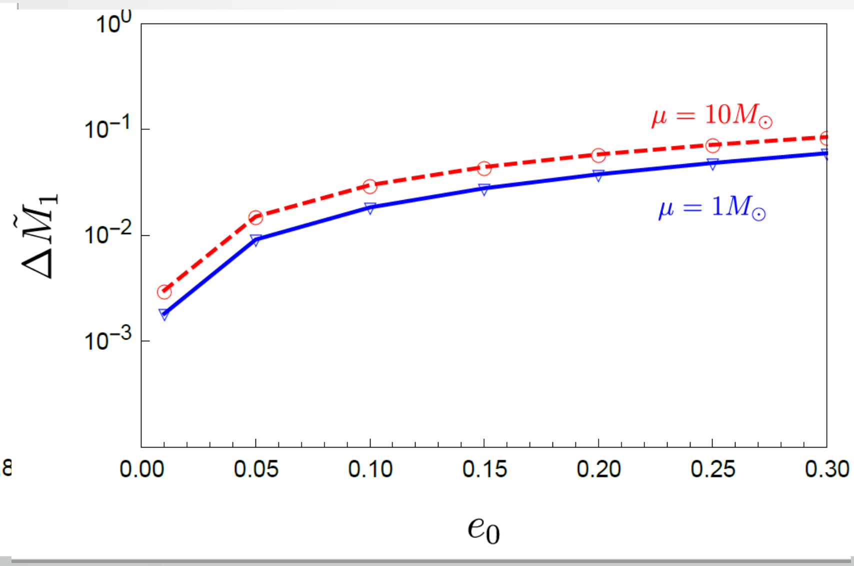
$$\tilde{M}_1 = S_2/M^3 = M_3/M^4$$

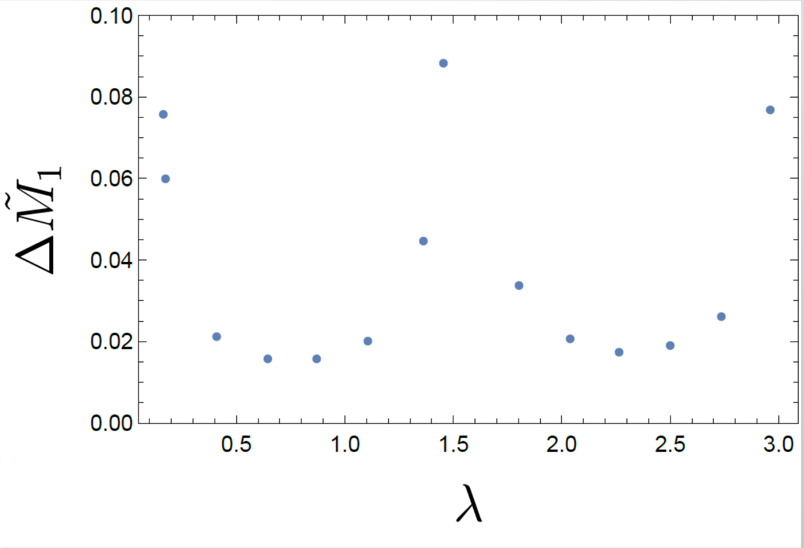
$$\tilde{M}_2 = M_2/M^3$$

$$\tilde{S}_1 = S_1/M^2$$

- Measurements rather independent of parameters:







Application: Constraining models (0)

- 1) « Scale set by solution »: almost-BPS black holes

- 2) « Scale set externally »: higher-derivative corrections

Application: Constraining models (1)

1) « Scale set by solution »

- Use M_2, S_2 to constrain models with tuneable parameters
- « Almost-BPS » BHs in string theory [Bah, Bena, Heidmann, Li, **Mayerson** 2104.10686]
- Tuneable parameter h :

$$M_2^{(\mathrm{aBPS})} = -M\left(\frac{S_1}{M}\right)^2\left(\frac{1-h^2}{h^2}\right), \qquad S_2^{(\mathrm{aBPS})} = \mp 2S_1\left(\frac{S_1}{M}\right)\left(\frac{1-h^2}{h^2}\right)^{1/2}$$

- $h^{-1} = \sqrt{2}$ to match M_2
- then measurement $\Delta\tilde{S}_2 \sim 10^{-2}$ would rule out model if $S_1/M^2 \geq 0.1$
- $\longrightarrow$ *Pretty good constraints on model(s)!*

Application: Constraining models (2a)

2) « Scale set externally »

- Generic higher-derivative corrections to GR:
  - New length scale ℓ
  - Set by quantum gravity?
    $\ell \sim \ell_{\text{Planck}}$

$$S = \frac{1}{16\pi G}\int d^4x\sqrt{|g|}\left\{R + \ell^4\mathcal{L}_{(6)} + \ell^6\mathcal{L}_{(8)} + \ldots\right\} ,$$

$$\mathcal{L}_{(6)} = \lambda_{\text{ev}} R_{\mu\nu}{}^{\rho\sigma} R_{\rho\sigma}{}^{\delta\gamma} R_{\delta\gamma}{}^{\mu\nu} + \lambda_{\text{odd}} R_{\mu\nu}{}^{\rho\sigma} R_{\rho\sigma}{}^{\delta\gamma} \tilde{R}_{\delta\gamma}{}^{\mu\nu} ,$$

$$\mathcal{L}_{(8)} = \epsilon_1 \mathcal{C}^2 + \epsilon_2 \tilde{\mathcal{C}}^2 + \epsilon_3 \mathcal{C}\tilde{\mathcal{C}} ,$$

$$\mathcal{C} = R_{\mu\nu\rho\sigma}R^{\mu\nu\rho\sigma} , \quad \tilde{\mathcal{C}} = R_{\mu\nu\rho\sigma}\tilde{R}^{\mu\nu\rho\sigma} .$$

- HD effects:
  - BH metric (~finite size effects)
    - Multipoles $\delta M_2, \delta S_2 \sim O(1)\ell^4/M$
      [Cano, Ganchev, **Mayerson**, Ruipérez 22xx.xxxxx]
  - Effective coupling to radiation $Q_{ij} \to Q_{ij}(1 + (cte)\ell^4 M^2/r^6)$
    [Endlich, Gorbenko, Huang, Senatore 1704.01590]

$\longrightarrow$ subleading at large distance

Application: Constraining models (2b)

2) « Scale set externally »

- Generic higher-derivative corrections to GR: New length scale ℓ
  - Set by quantum gravity? $\ell \sim \ell_{\text{Planck}}$

$$S = \frac{1}{16\pi G}\int d^4x\sqrt{|g|}\left\{R + \ell^4\mathcal{L}_{(6)} + \ell^6\mathcal{L}_{(8)} + \ldots\right\},$$

- Leading HD effects: BH multipoles $\delta M_2, \delta S_2 \sim O(1)\ell^4/M$
  [Cano, Ganchev, **Mayerson**, Ruipérez 22xx.xxxxx]
- *Actually very inefficient constraint!* Suppressed by supermassive BH M

$$\Delta(M_2/M^3) \sim 10^{-4} \quad \rightarrow \quad \Delta\ell \sim 10^{-1}M \sim 10^4\,km$$

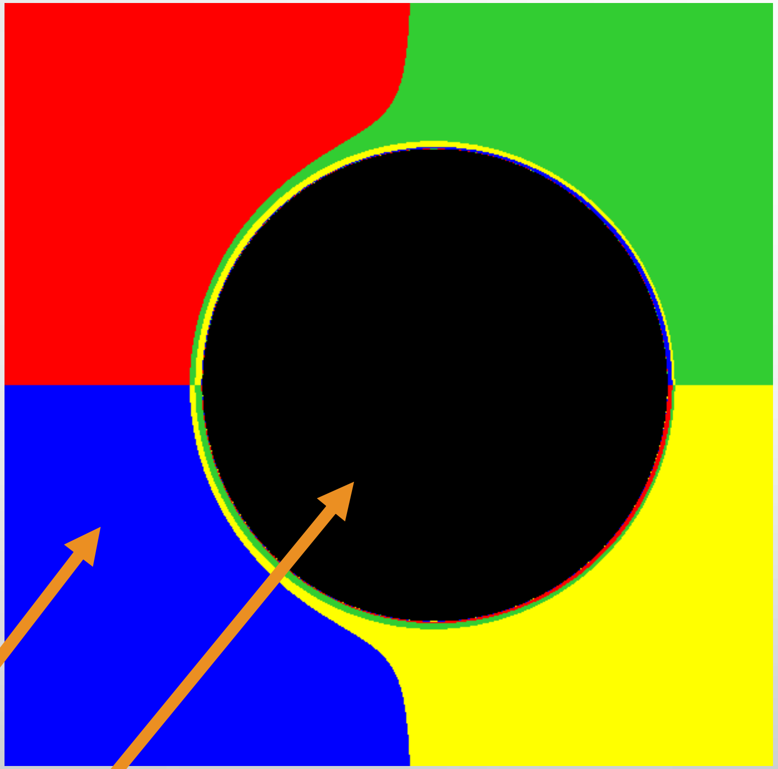
- Much better constraints with ground-based detectors
  e.g. ET: $\Delta\ell \sim 10 - 100\,m$

Image and Shadow Asymmetry (1)

[Bacchini, **Mayerson**, Ripperda, Staelens 22xx.xxxxx]

- *Can we see breaking of equatorial symmetry in BH images?*

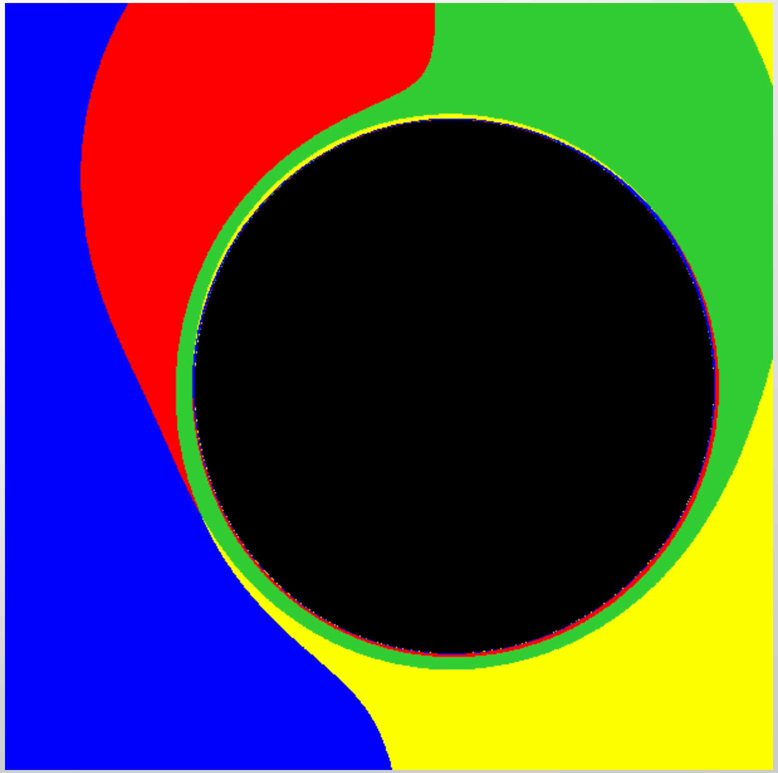
Four-color screen



Image

Shadow

Kerr 90°

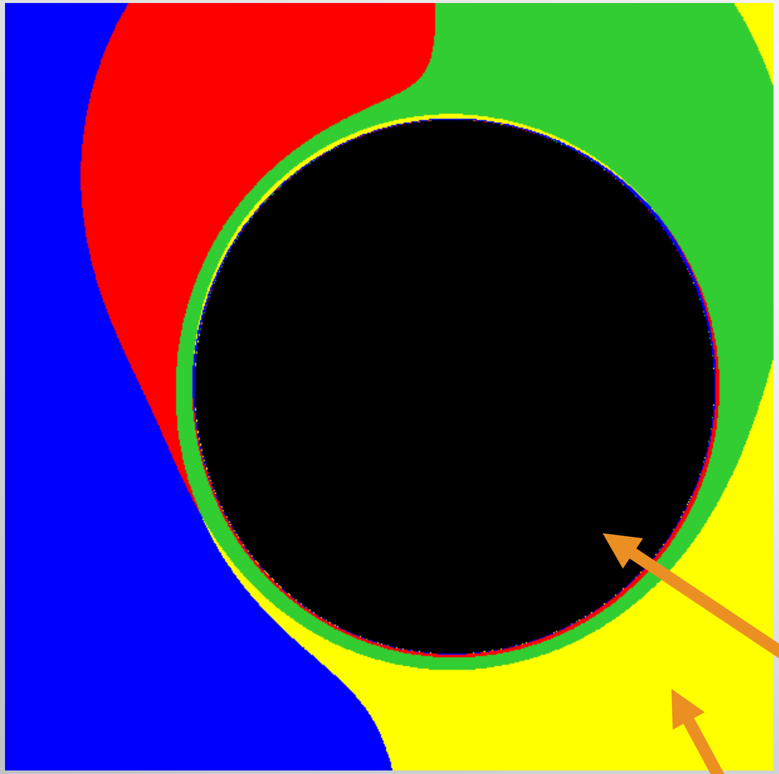


Kerr 60°

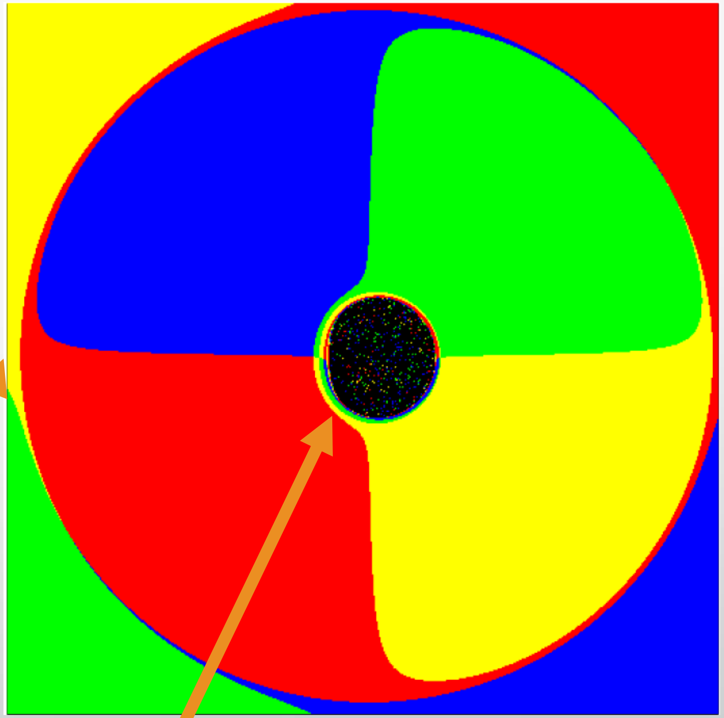
Image and Shadow Asymmetry (2)

[Bacchini, **Mayerson**, Ripperda, Staelens 22xx.xxxxx]

- *Can we see breaking of equatorial symmetry in BH images?*



Kerr 60°



Rasheed-Larsen 90°

Image asymmetry

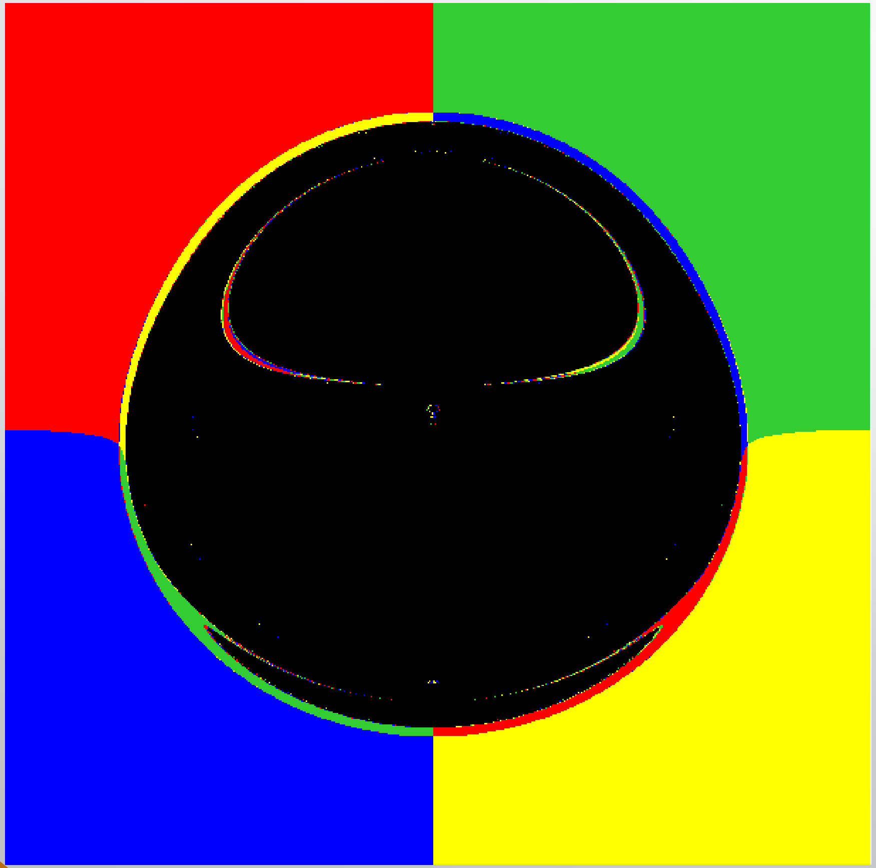
Shadow still symmetric $\longrightarrow$ from integrability!

[Cunha, Herdeiro, Radu 1808.06692]

Image and Shadow Asymmetry (3)

[Bacchini, **Mayerson**, Ripperda, Staelens 22xx.xxxxx]

- *Can we see breaking of equatorial symmetry in BH images?*
  - Asymmetric shadow: need to **break equatorial symmetry** + **break integrability**



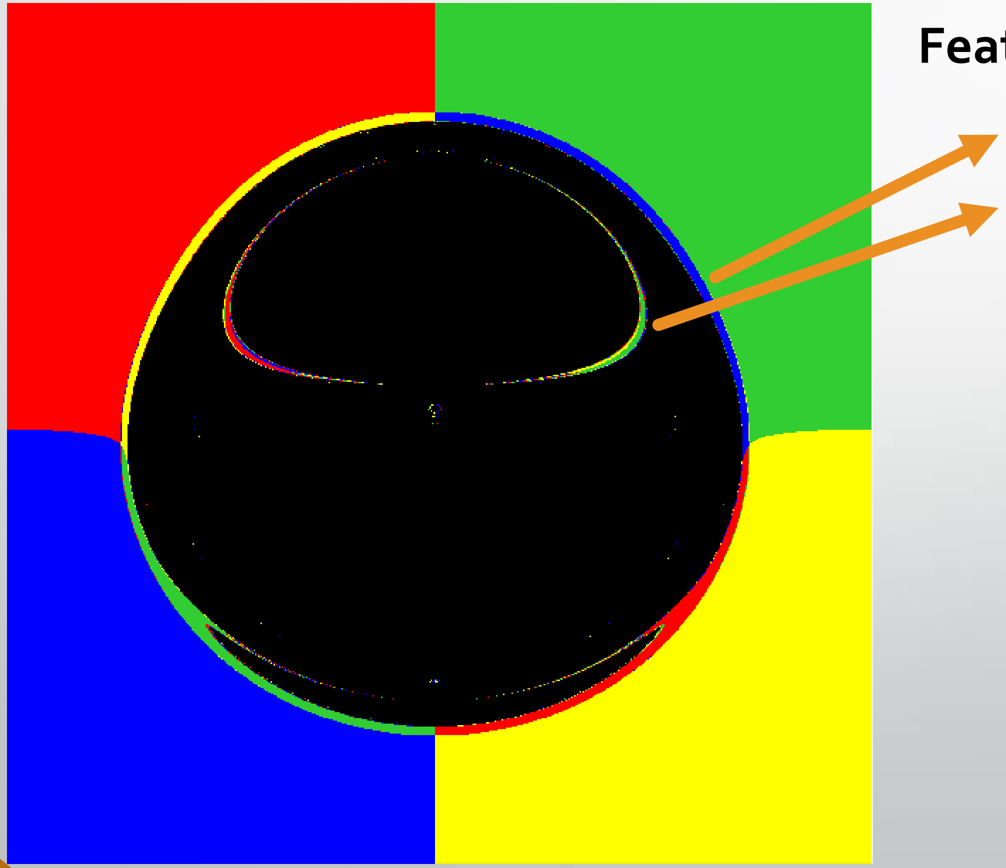
Manko-Novikov metric:

- « Schwarzschild +M_3 bump »
- Mildly singular on equator
- Breaks equatorial symmetry
- Breaks geodesic integrability

Image and Shadow Asymmetry (4)

[Bacchini, **Mayerson**, Ripperda, Staelens 22xx.xxxxx]

- *Can we see breaking of equatorial symmetry in BH images?*
  - Asymmetric shadow: need to **break equatorial symmetry** + **break integrability**



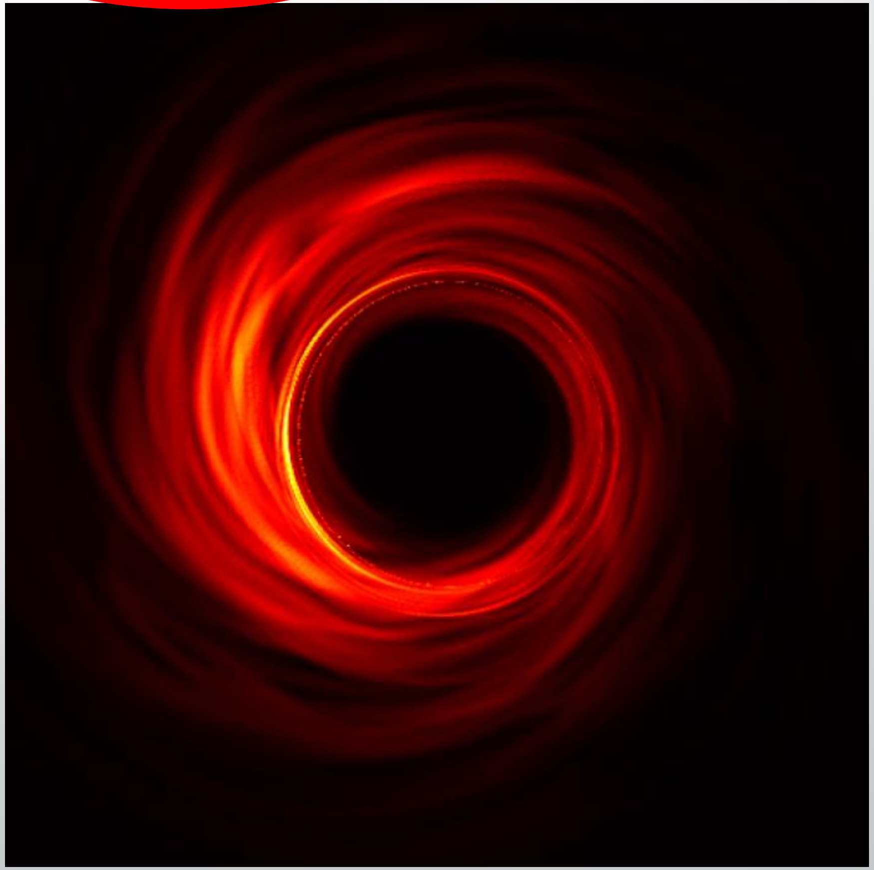
Features:

- Asymmetric image AND shadow!
- Break integrability
  ⟶ chaos
  ⟶ « holes » in shadow
  (generic feature)
- (to be continued…)

Image and Shadow Asymmetry (5)

[Kuchler, Ripperda, Davelaar, Bacchini, **Mayerson** 22xx.xxxxx]

- *Can we see breaking of equatorial symmetry* ***in OBSERVED*** *BH images?*
- Shadow is not really « observable »
- Plasma asymmetry ↔ image asymmetry?
  - Jet power, direct image, …: too much plasma « noise »!
- *(to be continued…)*
- → real observable: photon rings!

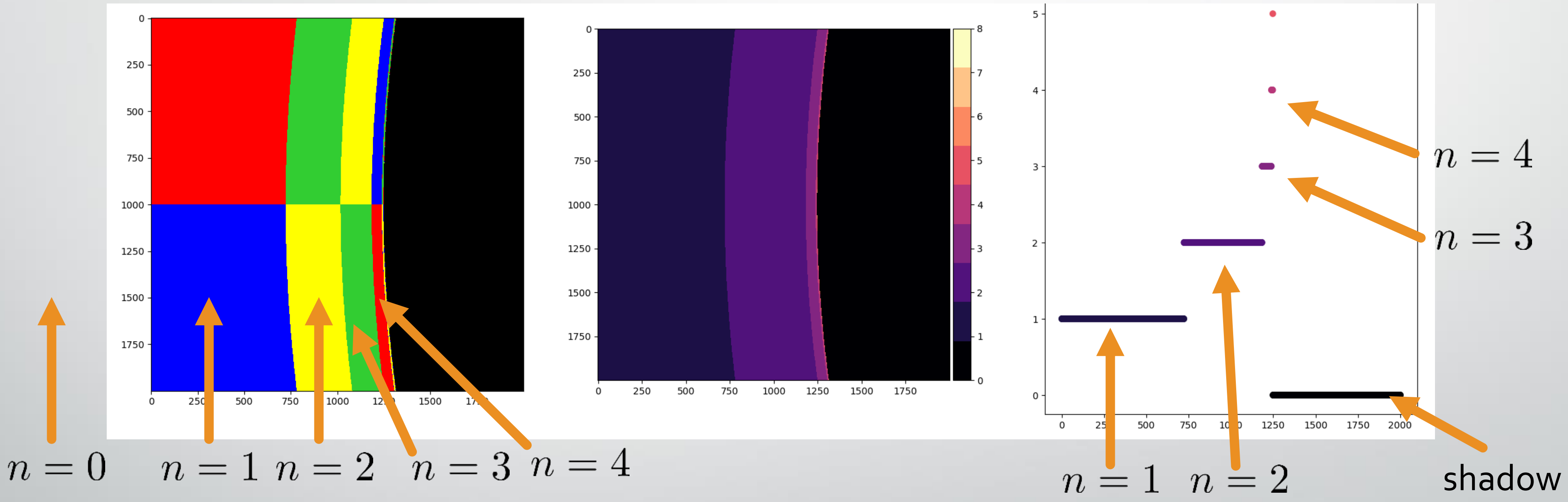


Rasheed-Larsen BH image with GRMHD

Image and Shadow Asymmetry (6)

[Bacchini, **Mayerson**, Ripperda, Staelens 22xx.xxxxx]

- **Photon rings**: probably the only real precision observable in BH imaging!
  [Johnson, Lupsasca, Strominger, Wong, Hadar 1907.04329; Gralla, Lupsasca, Marrone 2008.03879]

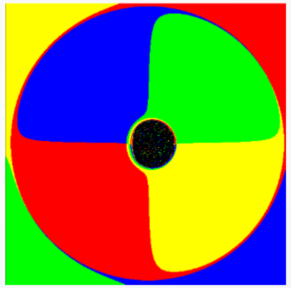


- **n-th photon ring**: photons that have travelled around the BH n half-circles
  - Width each successive ring exponentially suppressed $\sim e^{-\gamma}$
  - *Widths and shape carry details of BH geometry*

(Longer) Outlook (1):

« Black holes and revelations – our hopes and expectations » ? [Muse]

- This talk: « **breaking equatorial symmetry** » as **smoking gun** of beyond-GR
  - From observing it in RL and generalizing it



- What are other **<u>smoking gun, quantum gravity</u>** signatures?
- → Two insights from fuzzballs/string theory

(Longer) Outlook (2):

« Black holes and revelations – our hopes and expectations » ? [Muse]

Two insights from fuzzballs/string theory:

- *Quantum effects at merger?*
  - Hint #1: Papadodimas-Raju, non-local effects « near horizon », « islands », …
  - Hint #2: Tunneling effects (in fuzzballs [Kraus, Mathur; Bena, **Mayerson**, Puhm, Vercnocke]) « near horizon »
  - Hint #3: Kerr scattering minimizes entanglement entropy [Aoude et al. 2007.09486]
  - How do we model/capture/see this?
- *Stringy tidal forces:* massless particles $\longrightarrow$ massive; happens « way before » microstructure is reached [Martinec, Warner; Bena, Houppe, Warner]
  - Model: position-dependent mass?

Summary

- Breaking equatorial symmetry largely unexplored in grav. pheno.
- « Smoking gun » of beyond-GR/Kerr
- *How observable is it?*
  - $\longrightarrow$ *Surprisingly well!*
- Analytic kludge: $\Delta\tilde{M}_1 \sim 10^{-2}$
  - Can give good or bad model constraints
- Imaging: shadow asymmetry if also break integrability,
  ...but not clear if distinguishable in observations