Tests of nature of Black Holes
From WG Perspective

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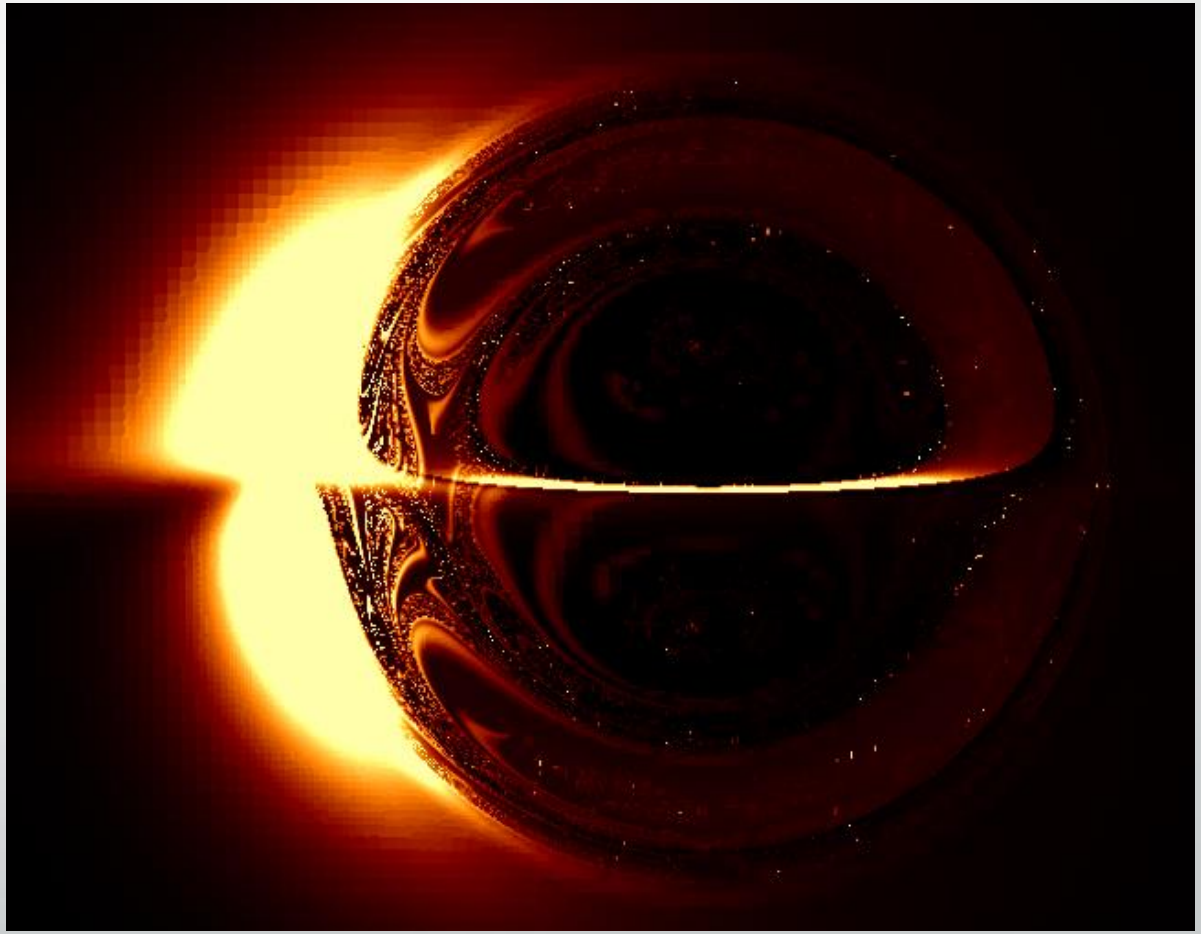
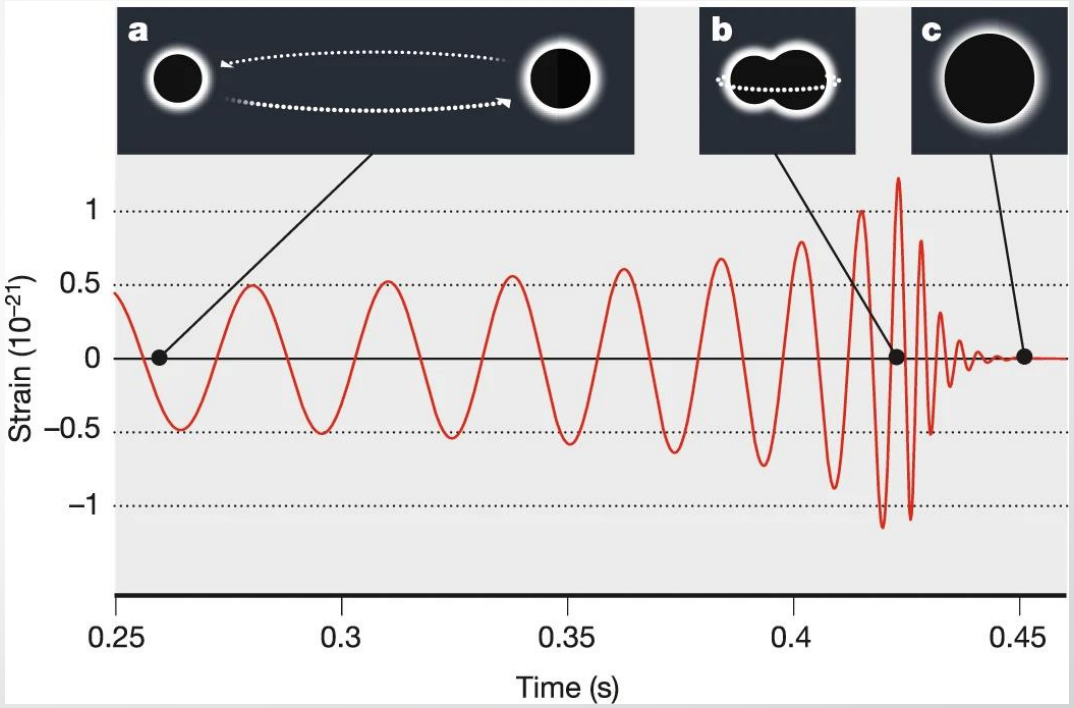


Introduction: LISA Observations of Black Holes

- Ground-based detectors:
  - 1-100 $M_\odot$, ~equal mass
  - Short signals, « late » inspiral

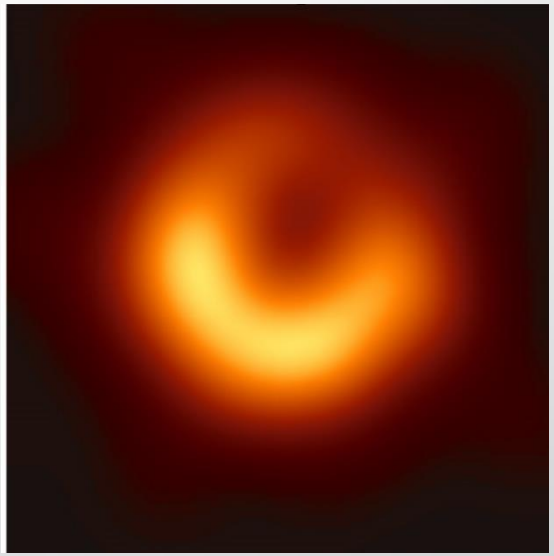
- LISA:
  - SMBH mergers
  - EMRIs (SMBH + $M_\odot$ BH)
  - Long signals, years of inspiral
  - However: SMBH curvature scales weak



Observables/tests per phase: inspiral – merger - ringdown

Introduction: Going Beyond Kerr (1)

- Strong claim in GR: Kerr is unique <u>vacuum, stationary, flat</u> BH
  - Collapse, mergers, stellar mass to SMBH
- Single supermassive BH $S \sim 10^{91}$
  vs. Entropy observable universe w/o BHs $S \sim 10^{88}$
- GR gives incredibly strong "Kerr hypothesis"



- However:
  - GR is not quantum theory – what changes?
  - Many unknown factors (eg DM)
- Hard to build "BH mimicker" (cfr. Buchdahl's theorem)!
  Also ultracompact ECO ~ stable LR ~ instability ~ to what?
  [Cunha, Herdeiro, Radu, Sanchis-Gual 2207.13713]

Introduction: Going Beyond Kerr (2)

- Two separate questions/motivations of "nature of BHs":
- 1) **Are there other objects beside (vacuum) BHs (and NSs?)**
  - Dark, undetected (e.g. DM surroundings)
  - Could be « large »
- 2) **Is Kerr quantum corrected?**
  - Resolve singularity, information paradox
  - Need quantum corrections at horizon scale [Mathur 0909.1038, ...]
    (cfr. fuzzballs, firewalls; non-locality)
  - So: yes! But: visible??
  - Cfr. « testing GR »

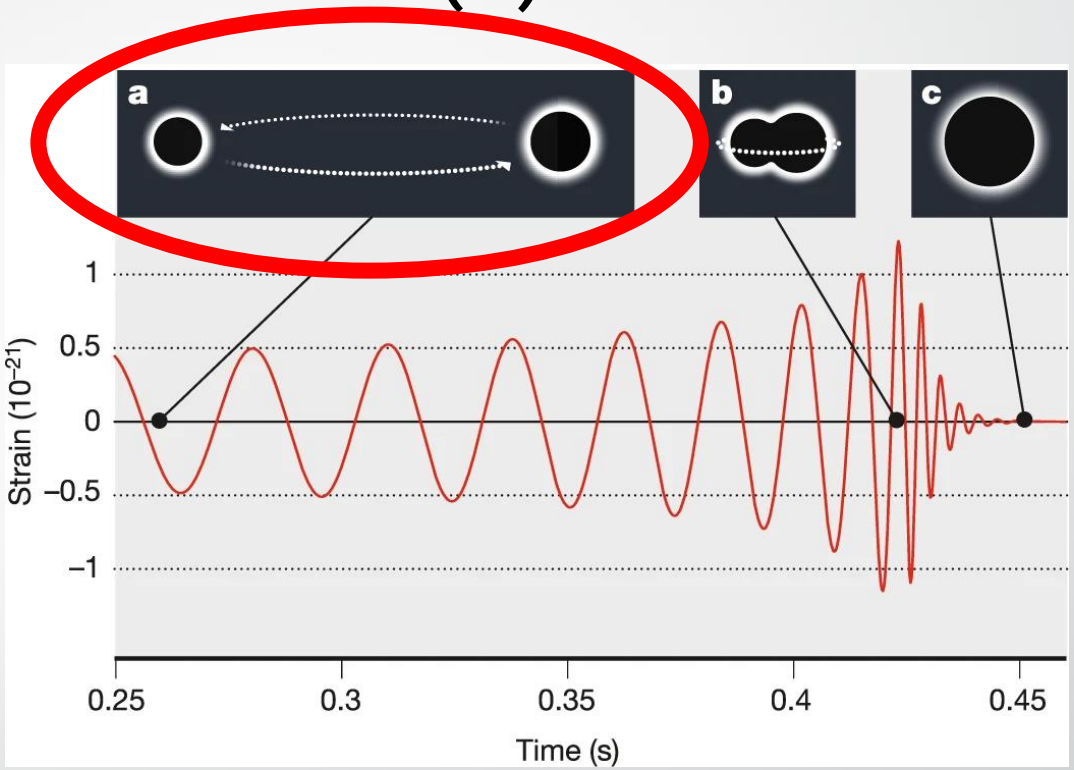
Observables Per Phase (1)

Inspiral:

- **Multipoles** (non-trivial structure)
  - Kerr gives precise prediction
  - Can signify breaking symmetries (axisymmetry, equatorial symmetry) [Fransen, **DRM** 2201.03569, Loutrel, Brito, Maselli, Pani 2203.01725]
  - Deviations expected depend on "spin-induced" or not [Raposo, Pani, Emparan 1812.07615]

$$\delta M_\ell, S_\ell \sim a_\ell \chi^\ell \log|\epsilon| + b_\ell\, \epsilon$$

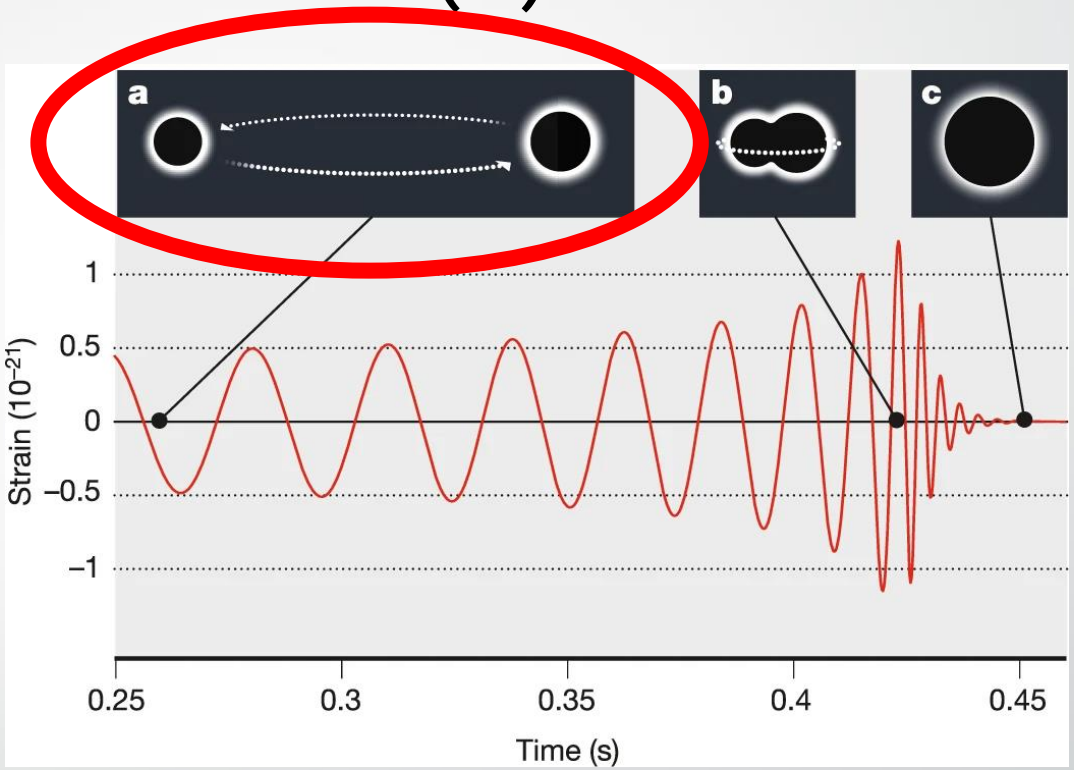
$$\epsilon = r_0/(2M) - 1$$



Observables Per Phase (2)

Inspiral:

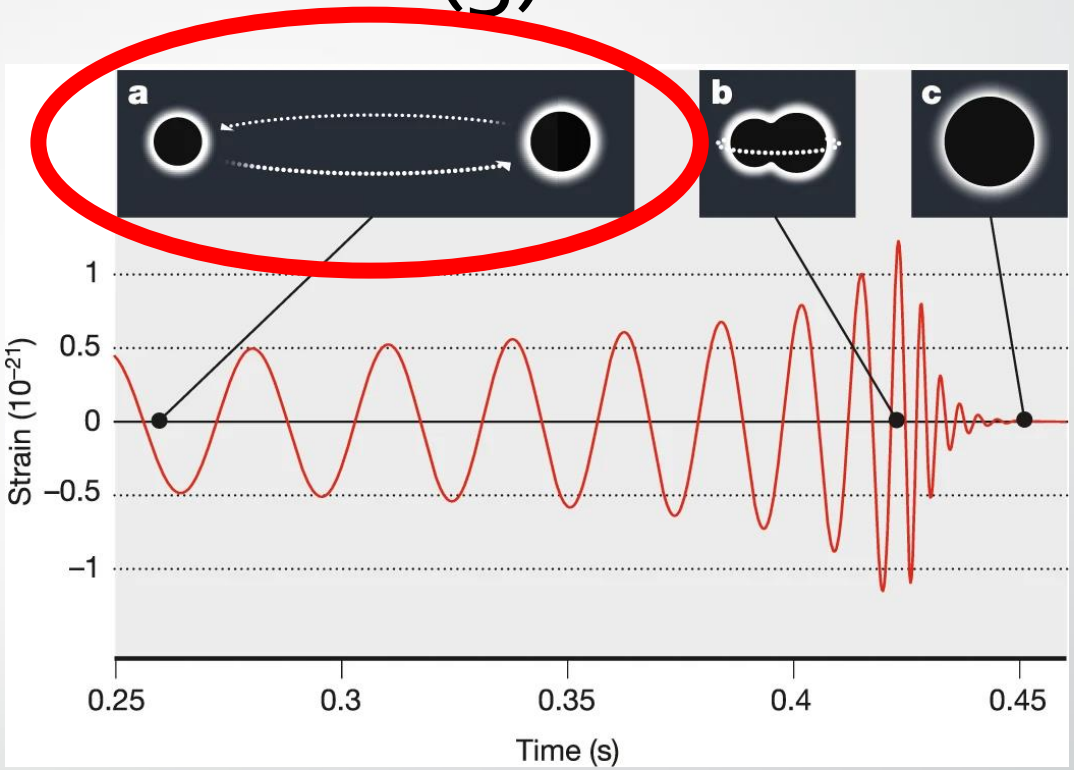
- **Tidal deformability**:
  - Kerr TLN vanish ("Love symmetries")
  - Some ECOs $k \sim \log|r_0/(2M) - 1|$
    [Cardoso, Franzin, Maselli, Pani, Raposo 1701.01116]
    Even Planck-scale $k \sim \mathcal{O}(10^{-3})$
    Enter in waveform $\sim k\,(r_0/(2M))^5$
  - Quantum BH: TLN $k \sim \Delta E/M$
    [Brustein, Sherf 2104.06013]
- **Tidal heating**: [Datta, Brito, Bose, Pani, Hughes 1910.07841]
  - Backreaction (absorption) of GW on objects
  - ECO: (partial) reflection?



Observables Per Phase (3)

Inspiral:

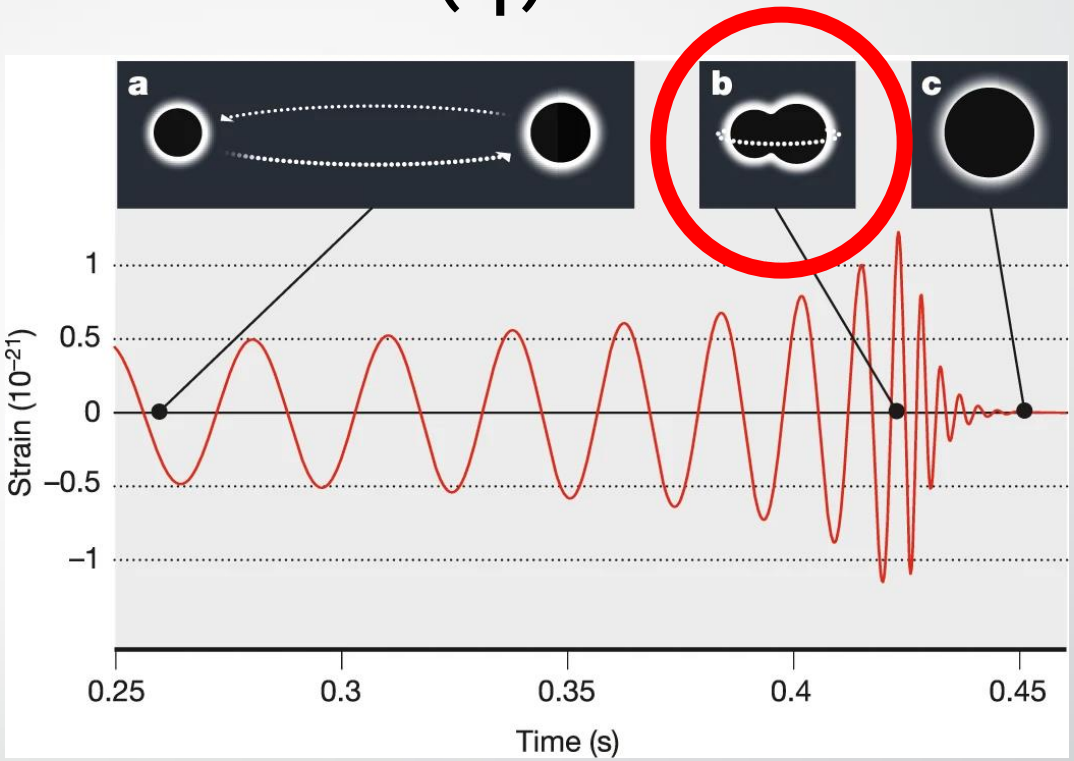
- **Chaos / resonances:**
- Kerr geodesics integrable vs non-Kerr chaotic
- Resonate w/ ECO internal structure
- Beyond perturbative/adiabatic analysis – "**glitches**"
- Quantum BH [Avitan, Brustein, Sherf 2306.00173] [Chen, Chiang, Patel 2306.08356]
  BS resonant orbits [Destounis, Angeloni, Vaglio, Pani 2305.05691];
  "glitches" [Destounis, Huez, Kokkotas 2301.11483]



Observables Per Phase (4)

Merger?

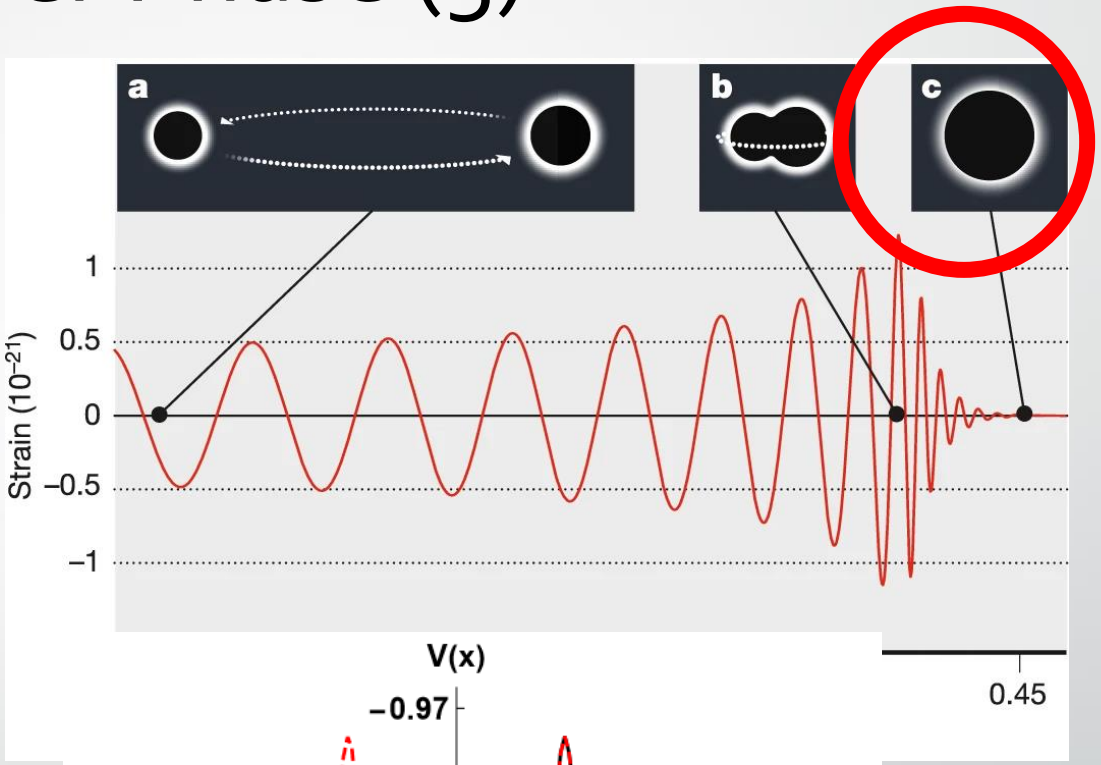
- Some NR simulations – mostly BS
  [Bezares, Bona, Cardoso, Di Giovanni, Font, Herdeiro, Lehner, Liebling, Palenzuela, Pani, Radu, Sanchis-Gual, …]
- Universal signatures or methods?

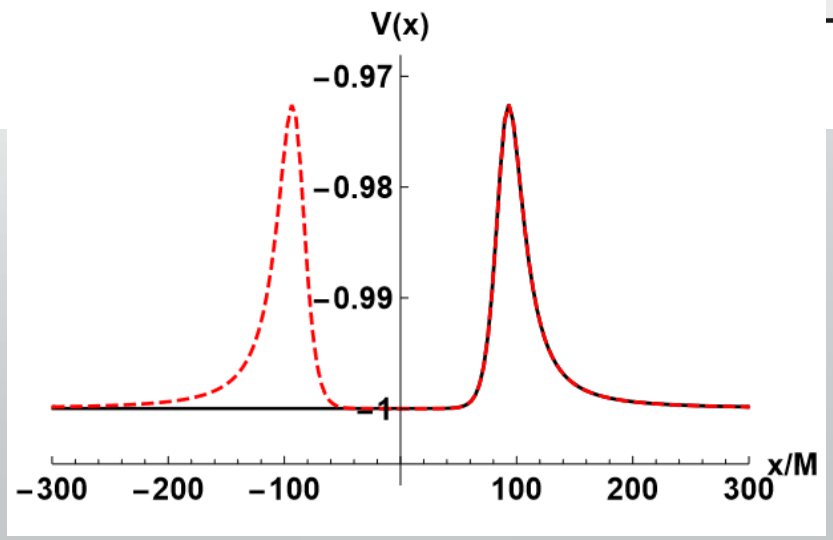


Observables Per Phase (5)

Ringdown:

- **QNM frequencies of ringdown**
- "Global": small change geometry ~ big change QNM
  Cavity $\sim L \quad (L \sim \log|r/(2M) - 1|)$
  $\omega_R \sim 1/L; \quad \omega_I \sim \omega_R^{2\ell+3}$
  [Cardoso, Pani 1904.05363]
- Initial ringdown dominated by "light-ring" modes, ~universal for ultracompact ECO
  [Cardoso, Franzin, Pani 1602.07309]
- Axial/polar QNM difference in ECOs
  [Maggio, Buoninfante, Mazumdar, Pani 2006.14628]





Observables Per Phase (6)

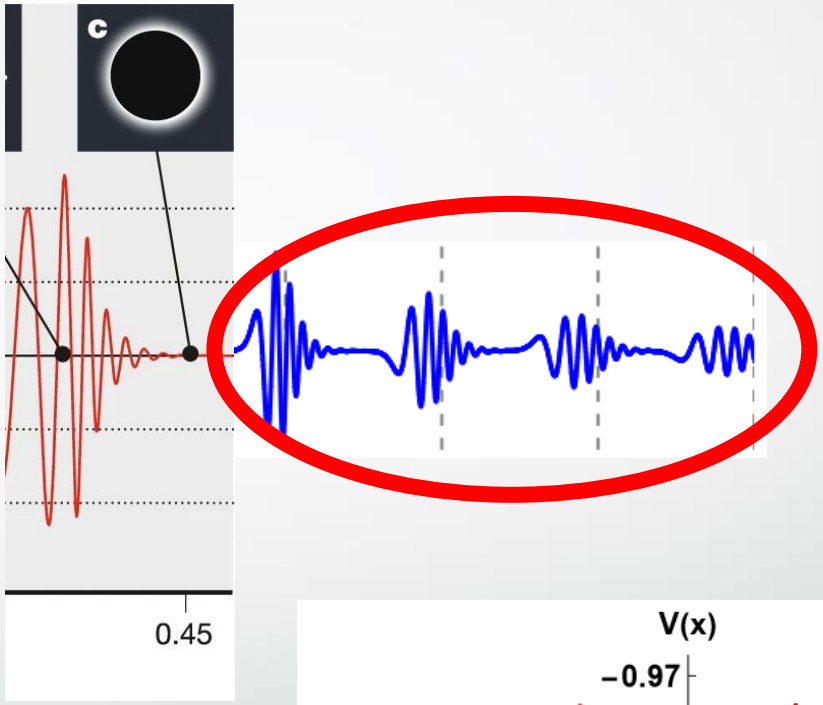
Ringdown:

- **Echoes – late ringdown**
- ECO has "cavity" where wave can be trapped and slowly leak out

  [Cardoso, Pani 1904.05363]

  - echo timescale

    $\sim L \quad (L \sim \log|r/(2M) - 1|)$

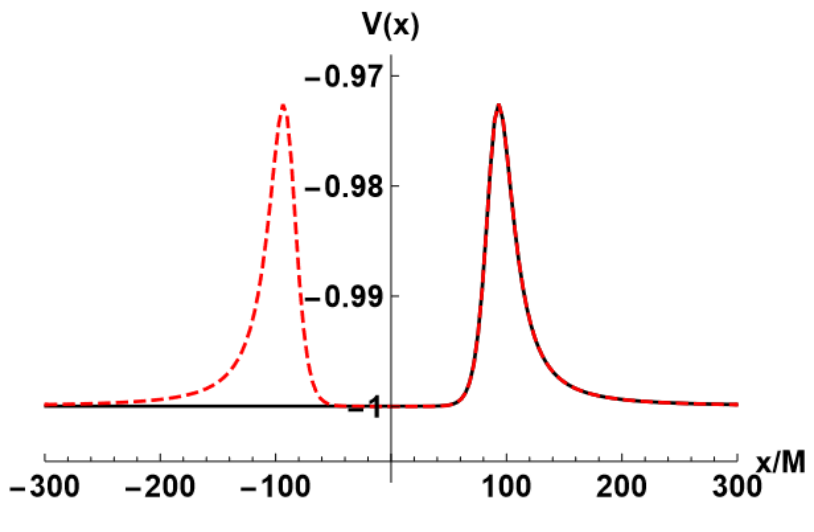


- Also "Quantum resonance"

  [Conklin, Afshordi 2201.00027; Oshita, Tsuna, Afshordi 2001.11642]]

- (Partial) reflectivity

  vs. More realistic absorption / reemission?



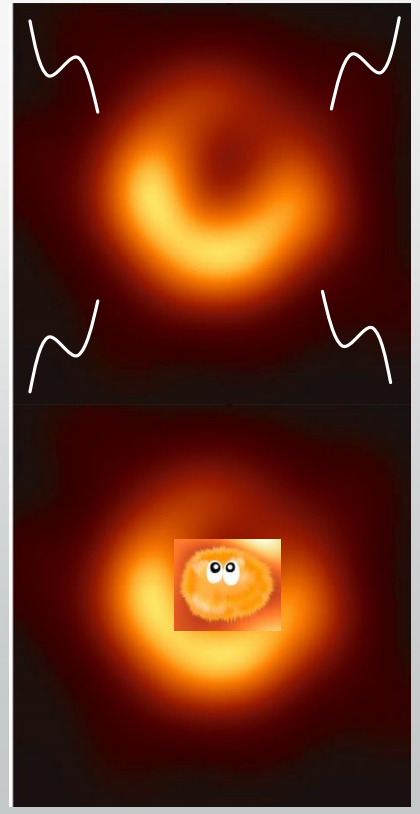
(Some) Models Beyond Kerr (1)

Recall: Two separate questions/motivations of "nature of BHs":

- **Are there other objects beside (vacuum) BHs (and NSs?)**
- **Is Kerr quantum corrected?**

Roughly two possibilities:

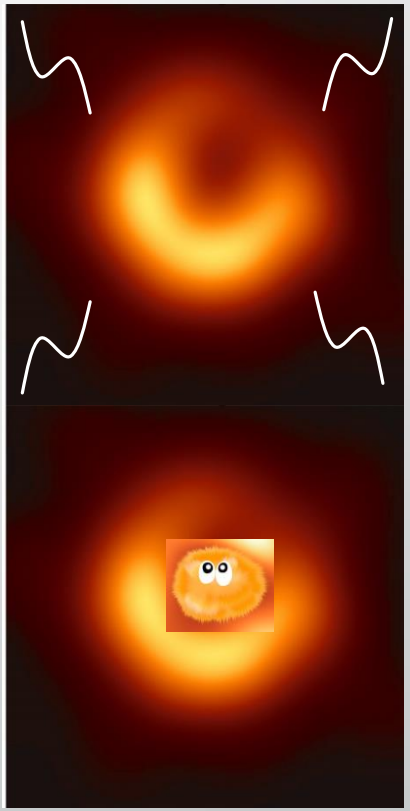
- **Alter BH**
  - Introduce non-vacuum / dark surroundings
    "Hairy BHs" (cfr. Detecting DM)
  - (Quantum) change of physics at horizon (non-locality)
- **Replace BH**
  - "Exotic compact object"



(Some) Models Beyond Kerr (2)

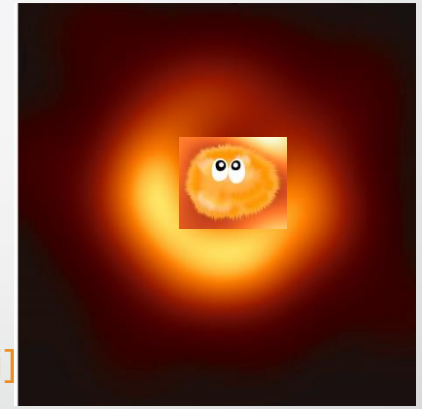
Models can be distinguished/classified by:

- **(Observable) properties**
  - e.g. Compactness (bound photon orbits?)
  - Multipole moments, TLNs, QNMs, …
- **Theoretical handle**
  - Ad hoc
  - Dynamics known in principle
  - Dynamics simulatable / formation known (avoid horizons?)



(Some) Models Beyond Kerr (3)

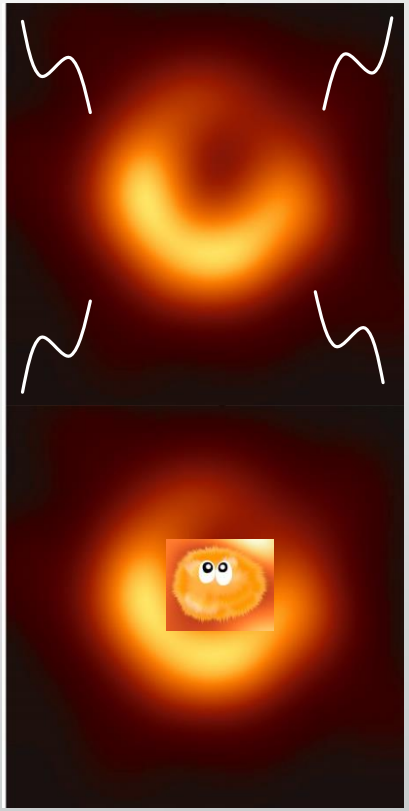
- **Boson(ic) stars:**
  [Cardoso, Franzin, Maselli, Pani, Raposo 1701.01116; …; Vaglio, Pacilio, Maselli, Pani 2203.07442]
  - Solution to Einstein + scalar (but: motivation(?)
  - Dynamics can be simulated
  - Typically "Large" vs BH
  - Multipoles ✓ TLN ✓ QNM, echoes ✓ formation ✓



- **Fuzzballs:** [Bah, Bena, Heidmann, Li, **DRM**; Bianchi, Consoli, Grillo, Ikeda, Morales, Pani]
  - Solutions to SUGRA but usually unrealistic (extremal, charges, SUSY, …)
    Crucial ingredient: extra dim
  - Dynamics in SUGRA in principle but hard
    (also: quantum dynamics?? Crucial for formation/merger)
  - Arbitrarily compact
    QG "replacement" for BH but also prototype "large" ECO
  - Multipoles ✓ TLN (✓ ✗) QNM, echoes (✓ ✗) formation ✗

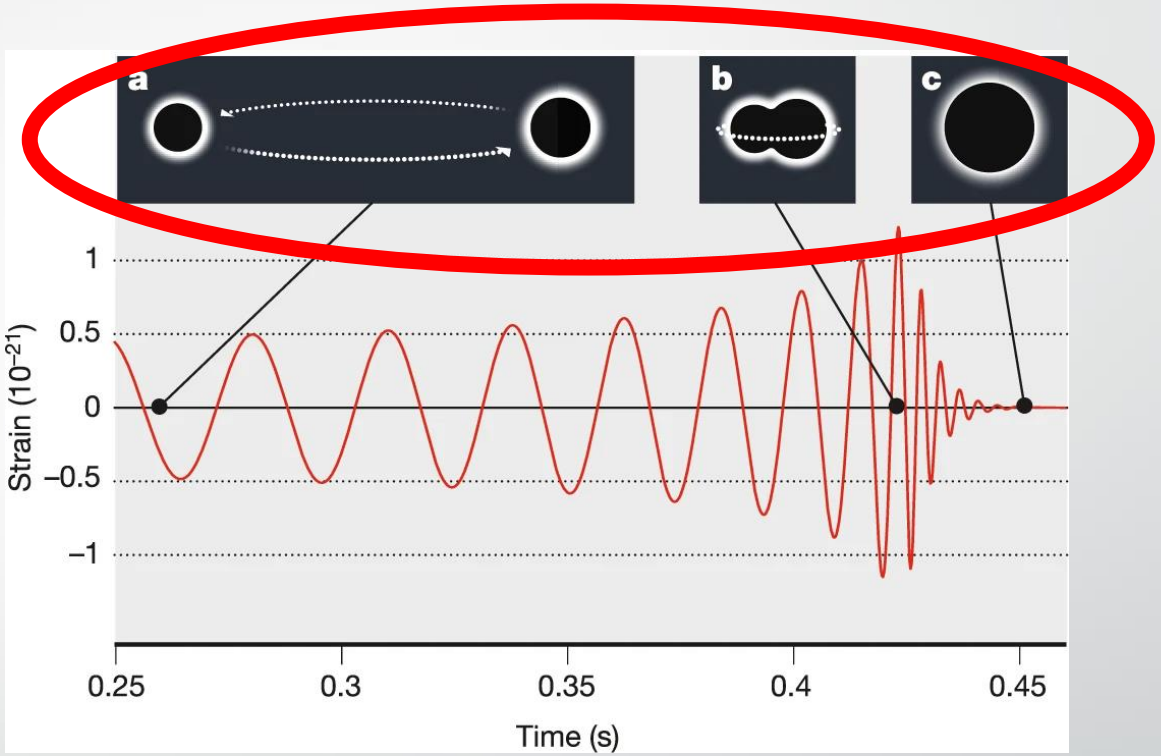
(Some) Models Beyond Kerr (4)

- **Wormholes:** [e.g. Cardoso, Franzin, Maselli, Pani, Raposo 1701.01116]
  - Ad hoc alteration to BH
  - Arbitrarily compact
  - Multipoles ✓ TLN ✓ ✗ QNM, echoes ✓ ✗ formation ✗
- **Other models e.g.**
  - Gravastar [Mazur, Mottola, …]
  - Long string / "collapsed polymer" model [Brustein, Sherf, …]



Issues/Questions (1): Holistic Observables?

- Parametrizing individual deviations
  - Degenerate
  - Confusion / less SNR
  - Universal parametrizations
- Holistic model deviations
  - Parametrize all deviations at once
  - Much stronger test/detection
  - Very specific test



Issues/Questions (2): Detection strategy?

- Individual deviations can be indication, but holistic waveform needed for clear detections
- Pipeline? First test individual/universal params, then (if deviation) test holistic models?

- Detecting chaos / resonances / “glitches”?
- Merger phase deviations?!