Fuzzballs and Observations

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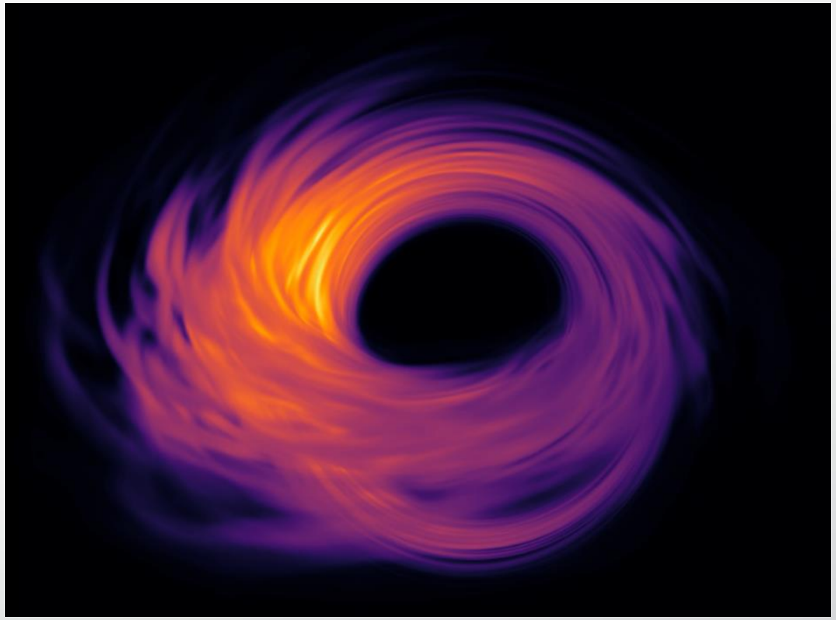


- ***Review: 2010.09736***

- ***Multipoles*** *(w/ Iosif Bena): 2006.10750 (short) & 2007.09152 (long)*
- ***Echoes etc.*** *(w/ Vasil Dimitrov, Tom Lemmens, Vincent Min, Bert Vercnocke): 2007.01879*
- *Lots of work in progress…*

Outline

- Introduction
- The Observations: GWs and EHT
- Fuzzballs & Microstate Geometries
- Observable Topics:
  - Echoes & quasinormal modes
  - Multipoles & tidal Love numbers
  - Geodesics (trapping/instabilities, tidal forces, chaos)
- What Next?

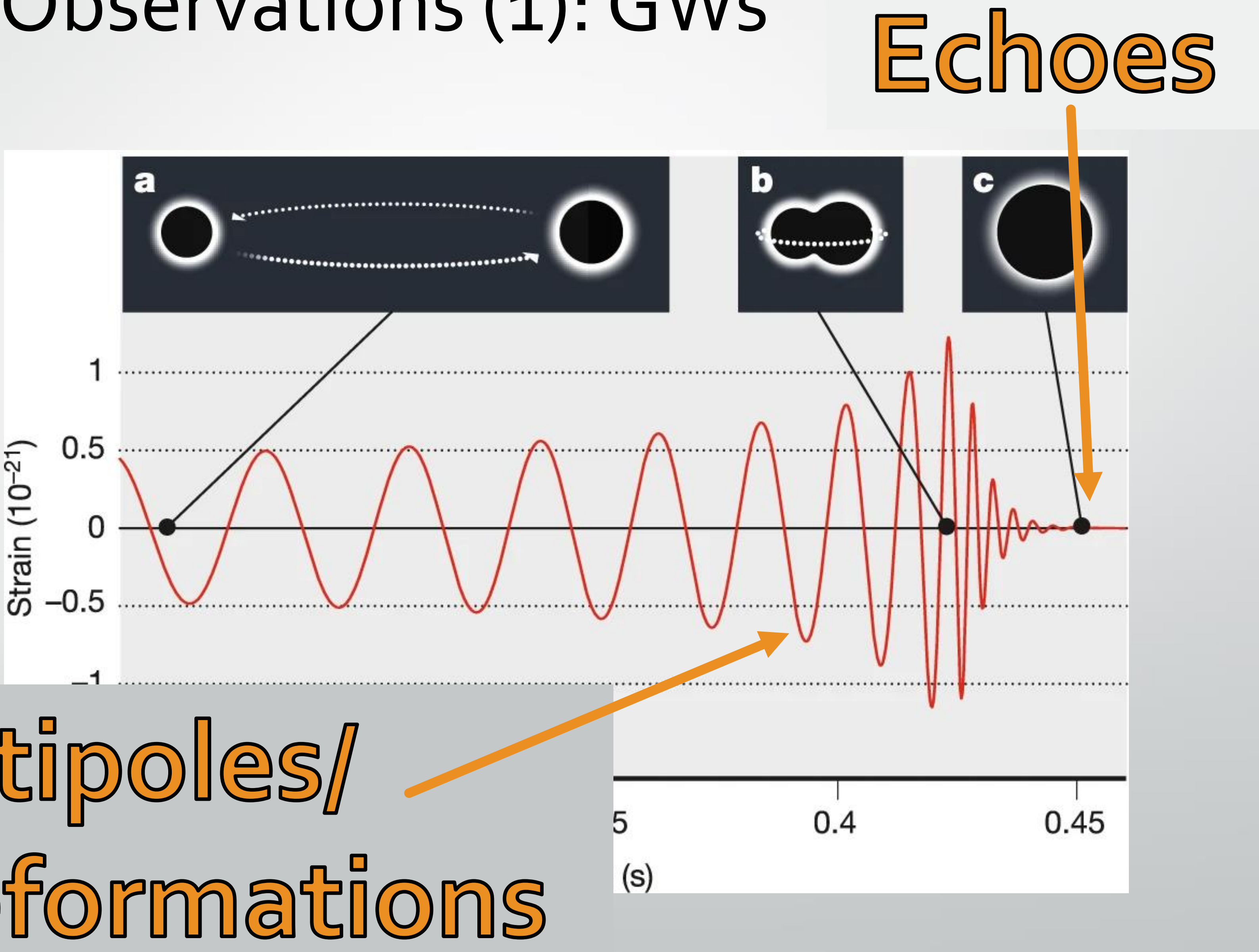
Introduction

- GR $\longrightarrow$ black hole
- Quantum gravity $\longrightarrow$???

- « Exotic compact object » (ECO):
  - Scale $r_0 = r_h(1+\epsilon)$ with $\epsilon \ll 1$ (Buchdahl $\epsilon \geq 1/8$)
  - Boson stars, gravastars, wormholes, … $\longrightarrow$ motivation??
- Fuzzballs:
  - *top-down, quantum gravity (string theory)*
  - *horizon-scale microstructure*
  - $\longrightarrow$ observable signals???

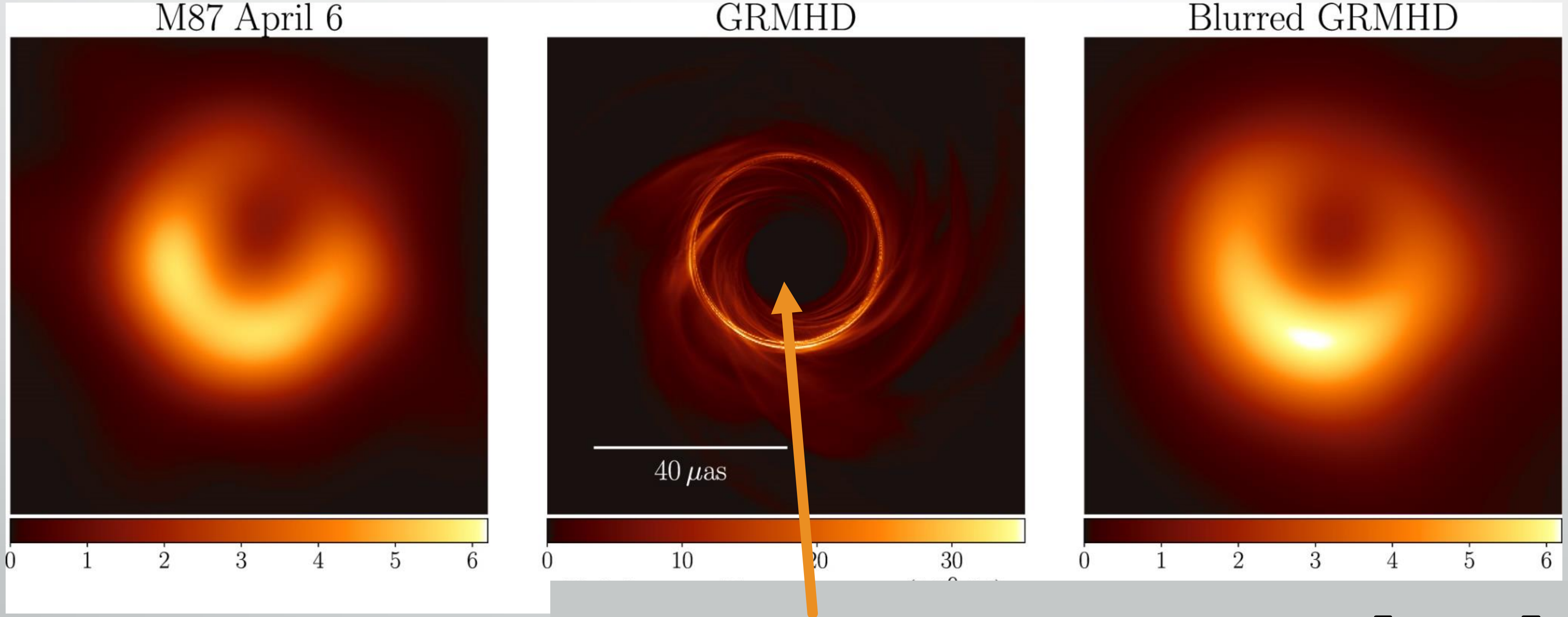
The Observations (1): GWs

- BH + BH $\longrightarrow$ BH
- (a) Inspiral:
  - Pert. GR
- (b) Merger
  - Numerical GR
- (c) Ringdown
  - Pert. of single BH



The Observations (2): EHT

- Single BH: snapshot or movie
  - Complex interactions gravity + plasma $\longrightarrow$ much uncertainty in physics!



  - Effects of microstructure??

"Step 0": geodesics

Fuzzballs & Microstate Geometries (1)

- Information paradox:
  - Information trapped in BH
  - Hawking radiation thermal, no information
  - What happens with information in BH?
- Mathur: « small corrections at horizon not enough »
- Three ways out:
  - Remnants (firewalls)
  - Non-local effects (Papadodimas-Raju, Giddings' non-violent non-locality)
  - Large corrections = *new physics at horizon scale* $\longrightarrow$ ***fuzzball paradigm***

Fuzzballs & Microstate Geometries (2)

Fuzzballs vs microstate geometries

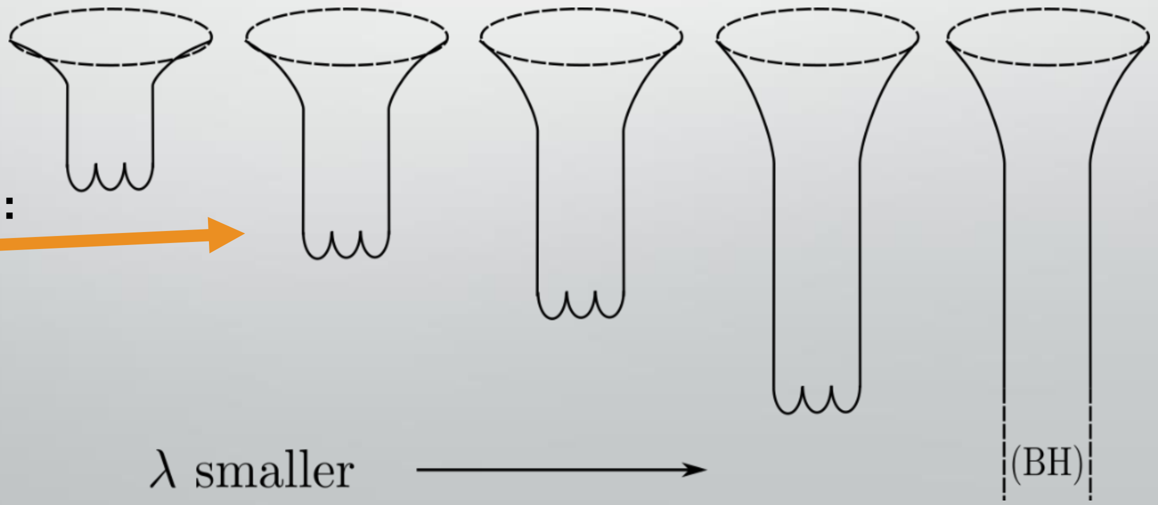
Fuzzball	Microstate geometry
Microstate of BH	
Looks like BH far away (charges etc)	
Horizonless	
Quantum, stringy	Coherent (semi-)classical geometry
???	Smooth
Only with generic arguments	Explicit solution in SUGRA

Fuzzballs & Microstate Geometries (3)

Families of microstate geometries:

- Multicentered bubbling geometries:
  - Microstates of: **4D** (SUSY, static) BH OR **5D** (SUSY, rot. BMPV) BH
  - N « centers » and S^2 « bubbles » between them
  - « bubble equations » for center positions
  - « Scaling solutions» approaching BH at « scaling point » $\lambda = 0$

Redshift « throat » gets « deeper » (BH: infinite)

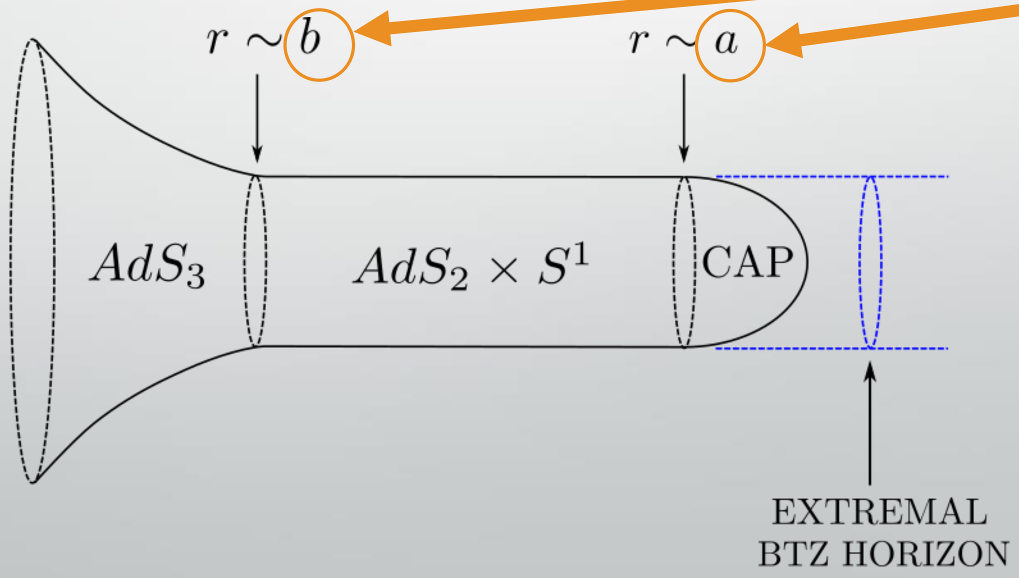


Fuzzballs & Microstate Geometries (4)

Families of microstate geometries:

- Superstrata:
  - Microstates of: **5D** (SUSY, rot. BMPV) BH (with BTZ near-horizon region)
  - Two centers, so one S^2 , but has charge density profile
  - Ends in smooth « cap » instead of horizon

Redshift « throat » with « length » $\sim b^2/a^2$



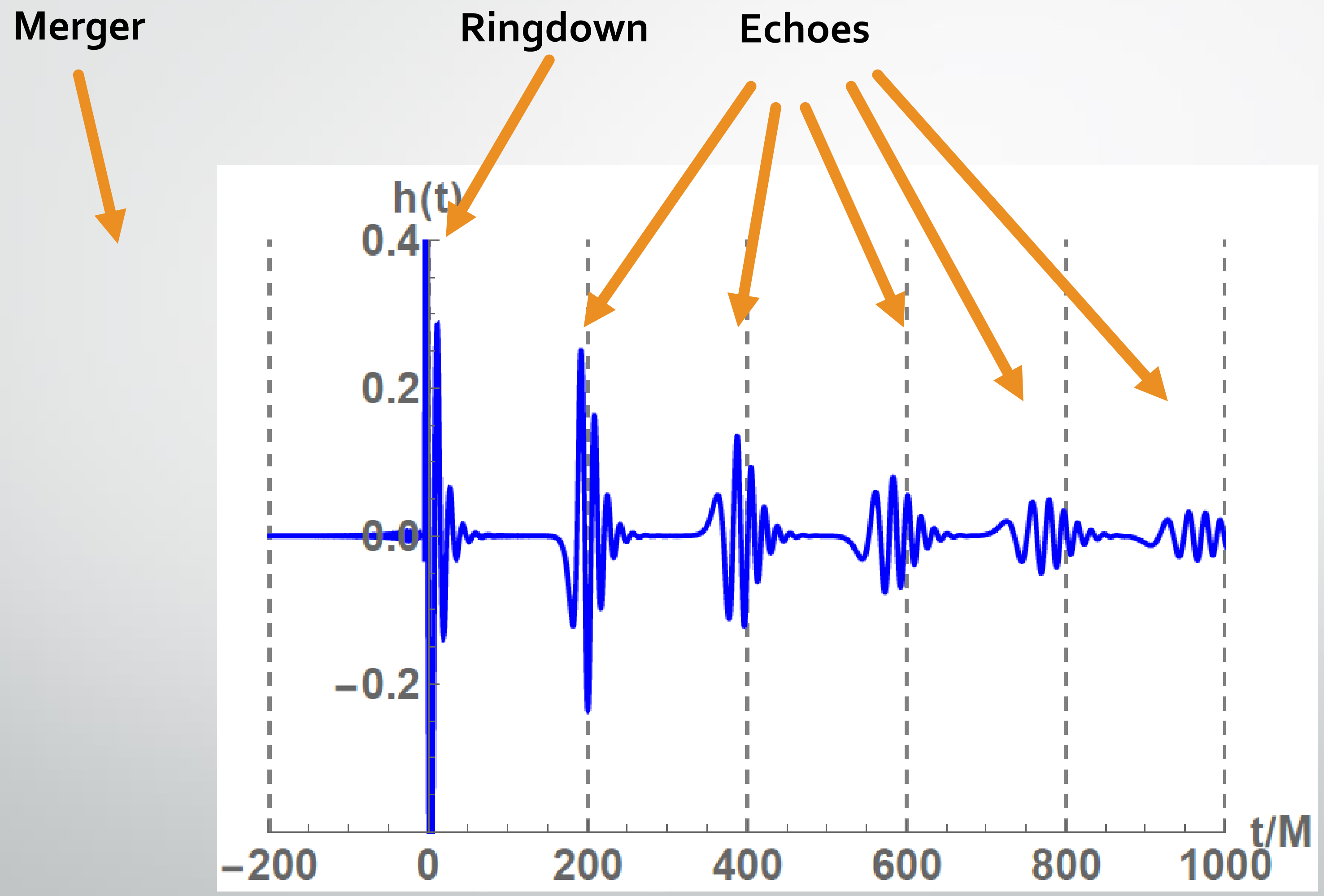
Fuzzballs & Microstate Geometries (5)

Limitations:

- Other microstate geometries?
  - Hard to construct non-SUSY (but some exist)
  - No microstate geometries for realistic BHs
- Formation/evolution?
- Typicality
  - MGs coherent, semi-classical
  - Very different from « typical » fuzzball?

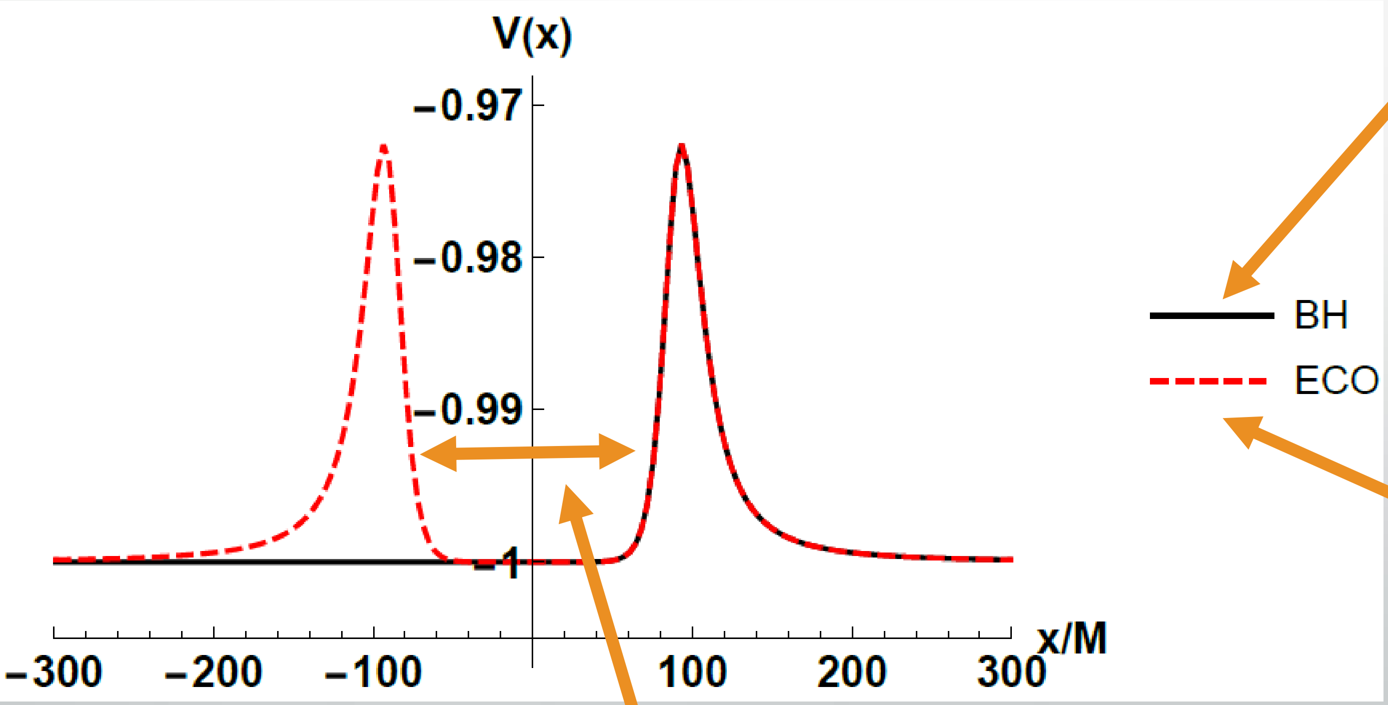
« Toy models »; Identify universal properties, <u>qualitatively</u> point to observables

Echoes & Quasinormal Modes (1)



Echoes & Quasinormal Modes (2)

Why echoes in ECOs?



Pert. absorbed

Pert. « trapped », slow periodic leakage (=echoes)

Cavity size $\sim L$

Echo period $\sim 2L$

Echoes & Quasinormal Modes (3)

Echoes in fuzzballs?

- Superstrata analysis (free scalar): [Bena, Heidmann, Monten, Warner 1905.05194; Bena, Eperon, Heidmann, Warner 2005.11323]
  - $\tau_{\text{echo}} \sim b^2/a^2 \sim N_1 N_5$ (= depth of throat)
  - $\tau_{\text{interm}} \sim b/a \sim \sqrt{N_1 N_5}$ where response (signal after pert) differs from BH

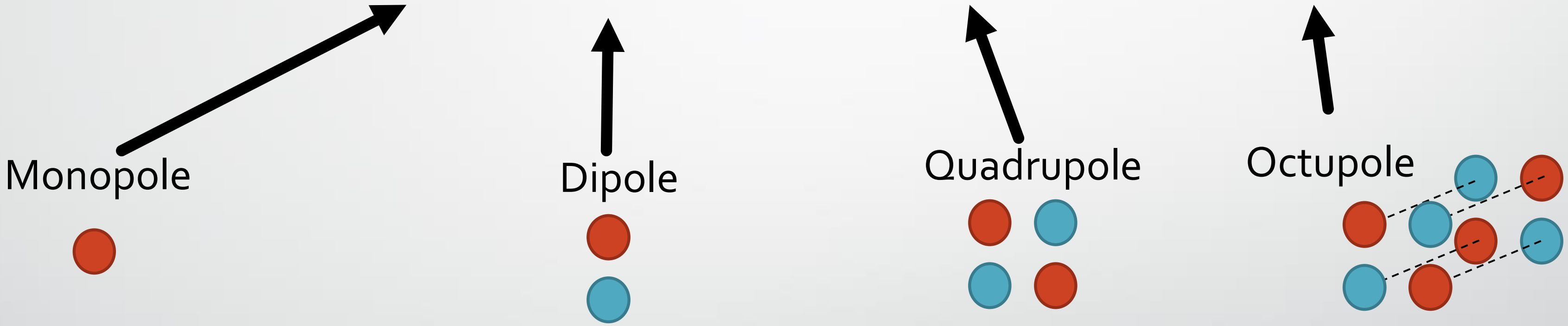
- **String** probe in superstrata [Martinec, Warner 2009.07847]
  - Tidal forces stretch string $\longrightarrow$ dampen kinetic energy, successive bounces
  - Less sharp echoes, still periodic

- Remark: echoes in typical state??
  - Superposition may destroy echoes… [Dimitrov, Lemmens, **Mayerson**, Min, Vercnocke 2007.01879]

Multipoles & Tidal Love Numbers (1)

- Multipoles in electrodynamics

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



- Problem in GR: coordinate transformations $\leftrightarrow$ multipoles not well-defined?
- Solution: Geroch-Hansen, Thorne formalism

Multipoles & Tidal Love Numbers (2)

- Mass multipoles M_l , current multipoles S_l

$$g_{tt} \sim \sum_l \frac{M_l}{r^{l+1}} \qquad g_{t\phi} \sim r \sum_l \frac{S_l}{r^{l+1}}$$

(axisymmetry)

  - Mass $M = M_0$ angular momentum $J = S_1$

- Basic example: Kerr (M, a)
- Multipoles: $M_{2n} = M(-a^2)^n, \qquad S_{2n+1} = Ma(-a^2)^n$

$$M_{2n+1} = S_{2n} = 0$$

Multipoles & Tidal Love Numbers (3)

- Kerr: $M_{2n} = M(-a^2)^n, \qquad S_{2n+1} = Ma(-a^2)^n \qquad M_{2n+1} = S_{2n} = 0$

[Bena, **Mayerson** 2006.10750 & 2007.09152]

- Undefined multipole ratios: e.g. $\mathcal{R} \equiv \frac{M_2 S_2}{M_3 S_1}$

Vanish for Kerr ⟷ ratio undefined

- Deform Kerr to more general string theory BH
- Now $\mathcal{R}$ is well-defined!
- Take limit back:

$$\lim_{(\text{def. BH}) \to (\text{Kerr})} \mathcal{R} := \mathcal{R}_{\text{Kerr}}$$

Analogy: $\frac{\sin 0}{0} = ?$

vs

$$\lim_{x \to 0} \frac{\sin x}{x} = 1$$

- Examples:

$$\mathcal{R} \equiv \frac{M_2 S_2}{M_3 S_1} = 1 \qquad \frac{M_{l+2} S_l}{M_l S_{l+2}} = 1 - \frac{4}{3 + (-1)^l (2l+1)}$$

Multipoles & Tidal Love Numbers (4)

- **String theory prediction** for small deviations from Kerr
  - Constrains all perturbative deviations away from Kerr! $\delta(\mathrm{Kerr}) \sim \epsilon$

$$S_{2n} = -nM(-a^2)^n\epsilon \qquad M_{2n+1} = nMa(-a^2)^n\epsilon$$

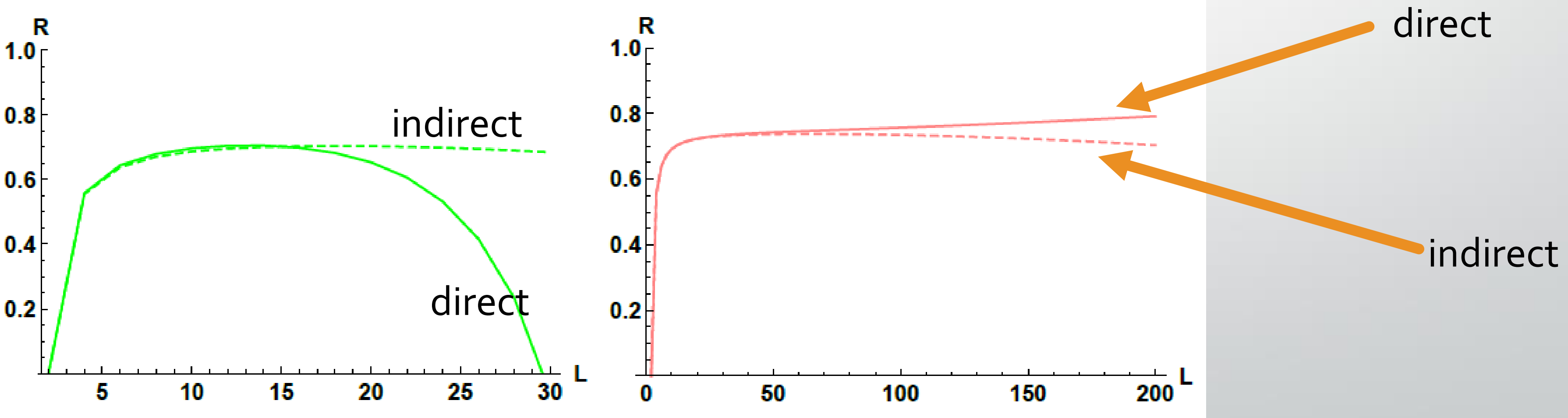
$$\delta M_{2n} = -n^2M(-a^2)^n\left(\frac{2n-3}{4n}\right)\epsilon^2 \qquad \delta S_{2n+1} = -n^2(-a^2)^nMa\left(\frac{2n+1}{4n}\right)\epsilon^2$$

  - Constrains models of (small) deviations of Kerr!
- Observability?
  - Late-time relaxation after BH formation; how different multipole rad. dies out
    - Relation to quasinormal modes?

Multipoles & Tidal Love Numbers (5)

- Multipole ratios in scaling multicentered solutions: « **direct** »
- Remarkable agreement between **indirect** and **direct** for some BHs

$$\lim_{(\text{def. BH})\to(\text{SUSY})} \mathcal{R} := \mathcal{R}_{\text{SUSY}} \qquad \mathcal{R}_{(\text{microstate})} := \mathcal{R}_{\text{SUSY}}$$



(b) $R_2^{(M)}(L, \delta = 1/2)$ as a function of L for geometry A

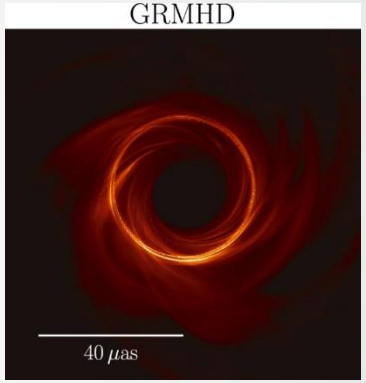
(c) $R_2^{(M)}(L, \delta = 1/2)$ as a function of L for geometry B

Other work on microstate multipoles: [Bianchi, Consoli, Grillo, Morales, Pani, Raposo 2007.01743 & 2008.01445]

Multipoles & Tidal Love Numbers (6)

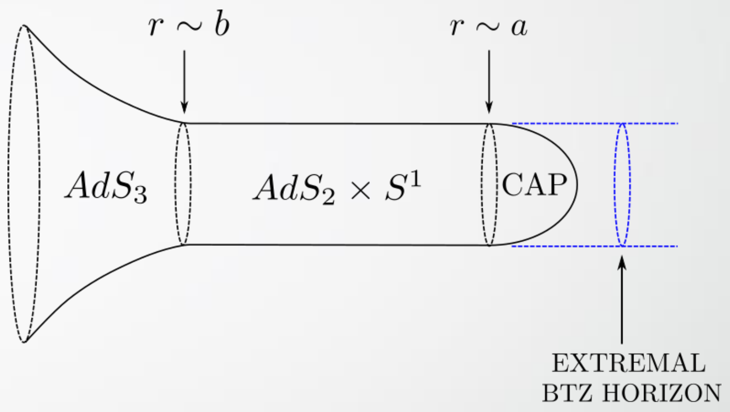
- **Multipoles:** object is alone
- **Tidal Love numbers**: deformation of multipole from tidal stress other object
  - Imprint on gravitational waveform (late inspiral)
  - Hard to calculate (pert. of EOMs)
  - TLN of Schwarzschild $= 0$
  - TLN of static BHs (Einstein-Maxwell) $= 0$
  - TLN Kerr?
  - TLN in modified/higher derivative gravity $\neq 0$

Geodesics (1): Trapping



- No « images » yet made of microstate geometries vs BHs
- « BH features » in microstates: geodesic trapping
  [Bianchi, Consoli, Morales: +Grillo 1811.02397; 1711.10287; Eperon, Reall, Santos 1607.06828; Keir 1609.01733; Eperon 1702.03975]
  - BH absorbs impact param below critical
  - MG absorbs 1 particular impact param. $\longrightarrow$ « Blackness » as collective feature??
  - Instabilities $\longrightarrow$ evolution to more typical state?

Geodesics (2): Tidal Forces



- Geodesic deviation in MGs
  [Bena, Houppe, Martinec, Tyukov, Walker, Warner]
  - Superstrata: long before reaching the « cap »!

    $$\tau_{\text{echo}} \sim b^2/a^2 \sim N_1 N_5$$
    $$\tau_{\text{tidal}} \sim \tau_{\text{interm}} \sim b/a \sim \sqrt{N_1 N_5}$$
  - Similar analysis in multicentered geometries

- **String** probe in superstrata [Martinec, Warner 2009.07847]
  - Tidal forces stretch string
  - Kinetic energy $\longrightarrow$ effective mass
  - Photons at horizon $\leftrightarrow$ stringy? $\longrightarrow$ *Deviations from null geodesic images??*

Geodesics (3): Chaos

- Signal of chaos:

$$C(t) \sim \left| \langle [\mathcal{O}_1(0), \mathcal{O}_2(t)]^2 \rangle \right| \sim e^{\lambda_L t}$$

- Lyapunov exponent λ_L and scrambling time τ_s (at which $C(t) \sim \mathcal{O}(1)$)
  - After: evolution according to QNMs (also related to λ_L $\longrightarrow$ ringdown signal?)
- $C(t) \sim$ OTOCs $\sim$ geodesic instabilities
- $(\lambda_L)_\mathrm{MG} < (\lambda_L)_\mathrm{BH}$ for superstrata [Bianchi, Grillo, Morales 2002.05574]
- $\tau_\mathrm{s} \ll \tau_\mathrm{tidal}$ for superstrata [Craps, De Clerck, Hacker, Nguyen, Rabideau 2009.08518]

What Next? (1)

- Other observables
  - Resonance effects in inspiral (tidal forces); interaction with accretion discs; tidal heating; …
- Same observables
  - Echoes: more general superstrata (multi-mode)
  - Tidal Love numbers?
  - Images of MGs
  - …
- Generic fuzzball arguments (not using MGs)
  - GW burst from quantum transitions in formation process? [Hertog, Hartle 1704.02123]
  - …

What Next? (2)

- Experimental sensitivities
  - Echoes perfectly reflecting ECO: LIGO/VIRGO at 5σ
  - Multipoles: eLISA $\delta M_2/M^3 < 10^{-4}$
  - Love numbers: eLISA 1% accuracy for $\epsilon \geq 2/3$ and $M/M_\odot \sim 10^4 - 10^6$
  - EHT images: unclear if very sensitive… (uncertainty in disc plasma physics)

- « Fuzzball phenomenology »
  - Fuzzballs top-down, quantum gravity motivated
  - Microstate geometries explicit solutions to study
  - New field; many insights waiting for harvesting!