Title: Fuzzball Shadows: Emergent Horizons from Microstructure

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Series: Quantum Gravity

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Abstract: The advent of black hole imaging has opened a new window into probing the horizon scale of black holes. An important question is whether string theory results for black hole physics can predict interesting and observable features that current and future experiments can probe.

I will discuss the physical properties of four-dimensional, string-theoretical, horizonless "fuzzball" geometries by means of imaging their shadows. Their microstructure traps light rays straying near the would-be horizon on long-lived, highly redshifted chaotic orbits. In fuzzballs sufficiently near the scaling

limit this creates a shadow much like that of a black hole, while avoiding the paradoxes associated with an event horizon.

Finally, I will consider comparing such fuzzball images to their black hole counterparts. In particular, detailed measurements of higher order photon rings have the potential to discriminate between fuzzballs and black holes in future observations.

Fuzzball Shadows: Emergent Horizons from Microstructure

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- ***Fuzzball Shadows: 2103.12075*** *(PRL)*
  with Fabio Bacchini, Bart Ripperda, Jordy Davelaar, Hector Olivares, Thomas Hertog, Bert Vercnocke
- *Fuzzballs & Observations: 2010.09736 (review)*

Outline

- Introduction: Fuzzballs
- Introduction: EHT

- Fuzzball Shadows: Emergent Horizons
- Distinguishing Fuzzballs

- What next?

Introduction: Fuzzballs (1)

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

« Exotic compact object » (ECO):

[Maggio, Pani, Raposo 2105.06410; Cardoso, Pani 1904.05363]

- Scale $r_0 = r_h(1+\epsilon)$ with $\epsilon \ll 1$ (Buchdahl $\epsilon \geq 1/8$)
- Boson stars, wormholes, ... $\rightarrow$ motivation??

- Fuzzballs:
  - *top-down, quantum gravity (string theory)*
  - *horizon-scale microstructure*
  - $\rightarrow$ observable signals???

Introduction: Fuzzballs (2)

- Information paradox:
  - Information trapped in BH
  - Hawking radiation thermal, no information
  - What happens with information in BH?

Introduction: Fuzzballs (2)

- 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***

Introduction: Fuzzballs (3)

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

Introduction: Fuzzballs (4)

Limitations of microstate geometries:

- Mostly SUSY! (also: not asympt. flat; D>4)
  - 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?

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Structure/mechanism of microstate geometries:

- BH « redshift throat » but:

~~horizon~~ $\longrightarrow$ microstructure « cap »

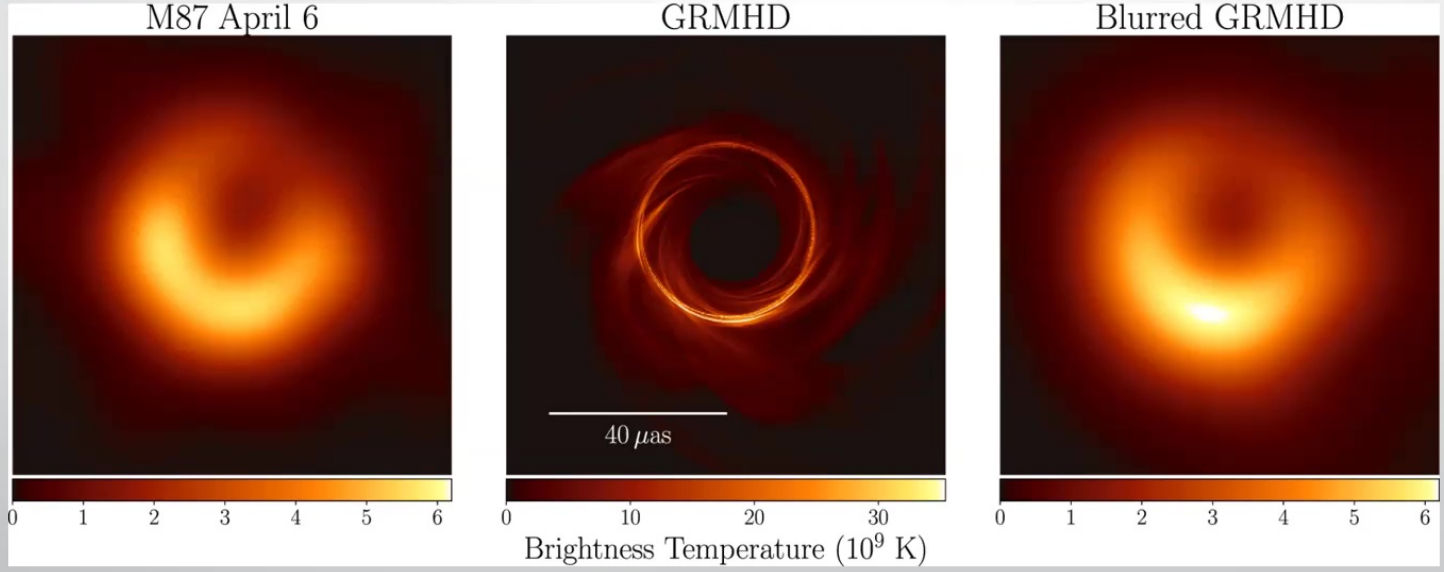
- Cap prevented from collapse by non-trivial topology

Introduction: Fuzzballs (5)

- « Fuzzball phenomenology »
  - Fuzzballs top-down, quantum gravity motivated
  - Explicit solutions to study in SUGRA: microstate geometries
  - Robust features – e.g. topology as only mechanism for solitons without horizons
  - « Toy models »; Identify universal properties (cfr. philosophy holo QCD etc)
- Two-step process:
  - Direct phenomenological study of geometries
  - Model general string theory inspired phenomenological effects
- New field; many insights waiting for harvesting!

Introduction: EHT

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



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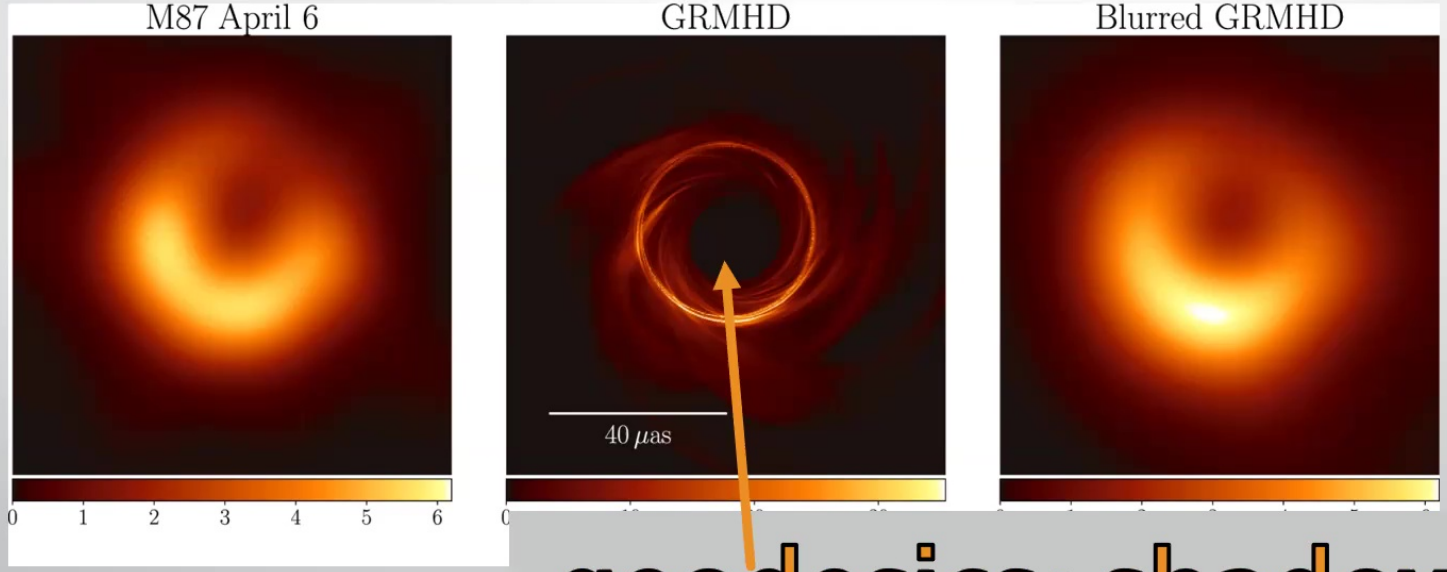


- Effects of microstructure??

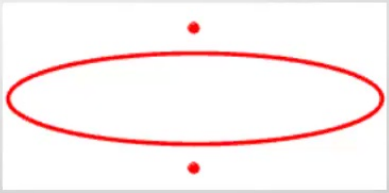
geodesics; shadows

Fuzzball Shadows: Emergent Horizons (1)

- Based on [Bacchini, Mayerson, Ripperda, Davelaar, Olivares, Hertog, Vercnocke 2103.12075];
  Earlier work (e.g. geodesic trapping) [Bianchi, Consoli, Morales: +Grillo 1811.02397; 1711.10287; Eperon, Reall, Santos 1607.06828; Keir 1609.01733; Eperon 1702.03975]

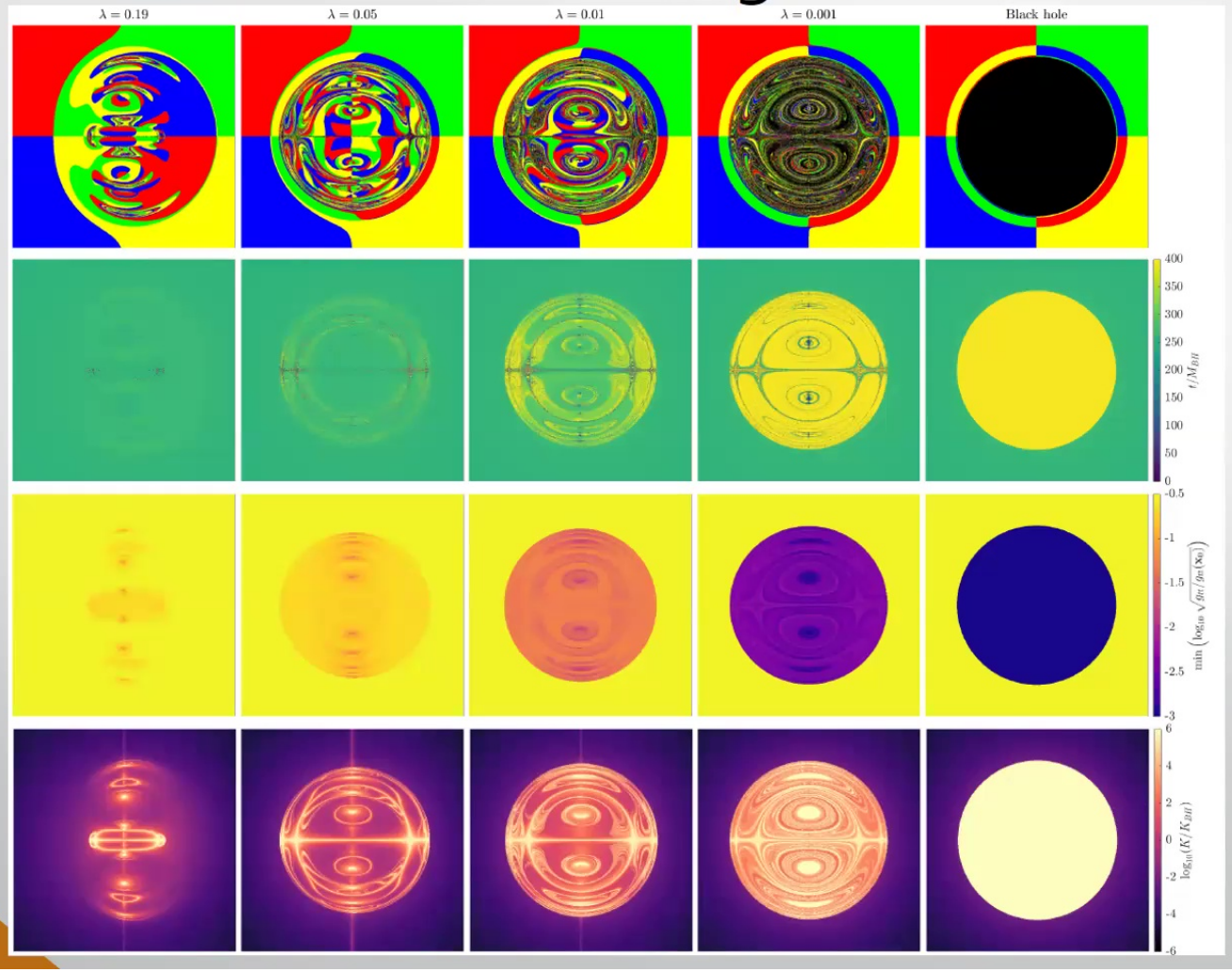
- How does fuzzball achieve BH « blackness »?
- Can we distinguish BH vs. fuzzball shadows/images (cfr. EHT etc)?

- Setup: SUSY « multicentered » geometry in 4D



- « Four-color screen »:

Fuzzball Shadows: Emergent Horizons (2)



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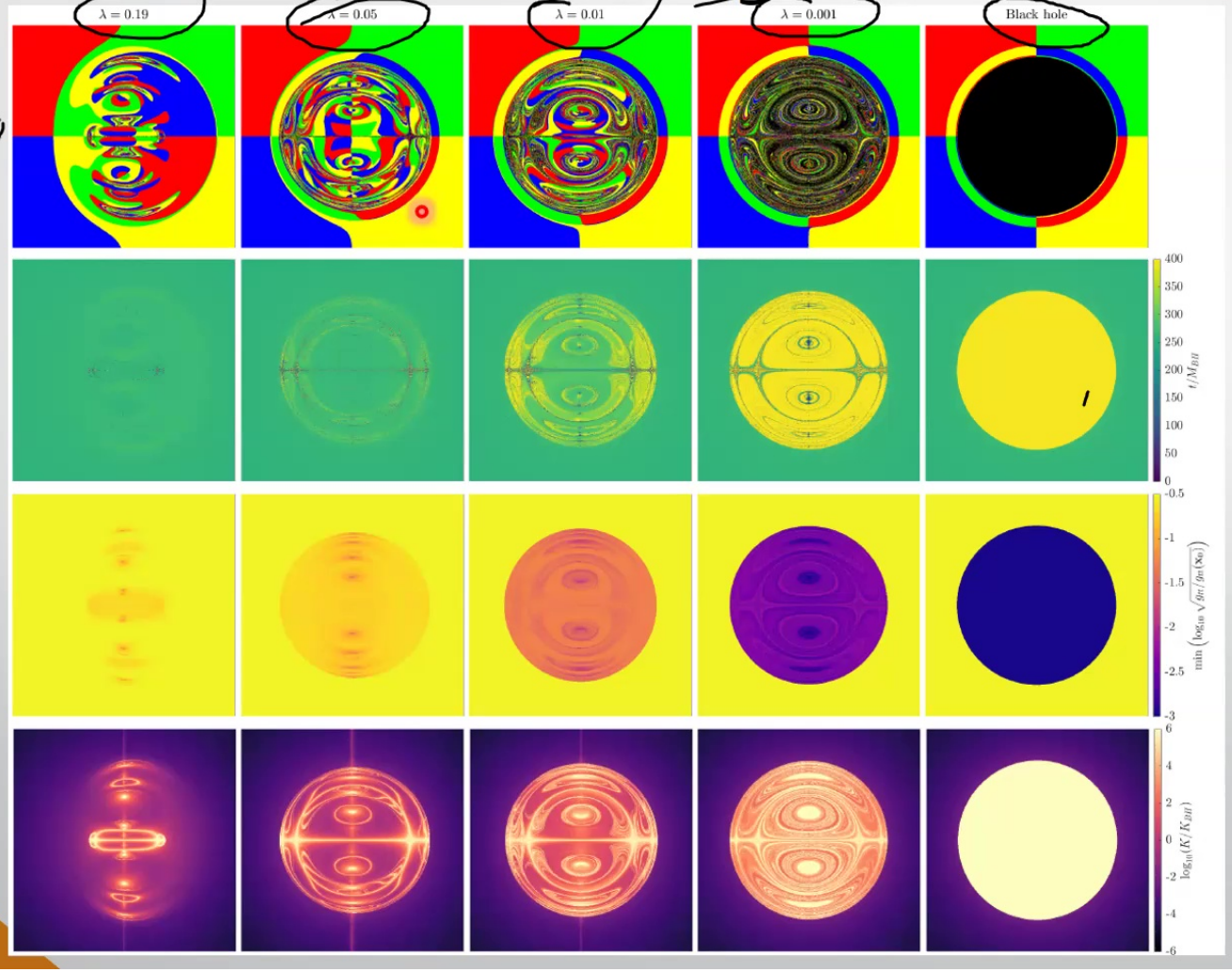

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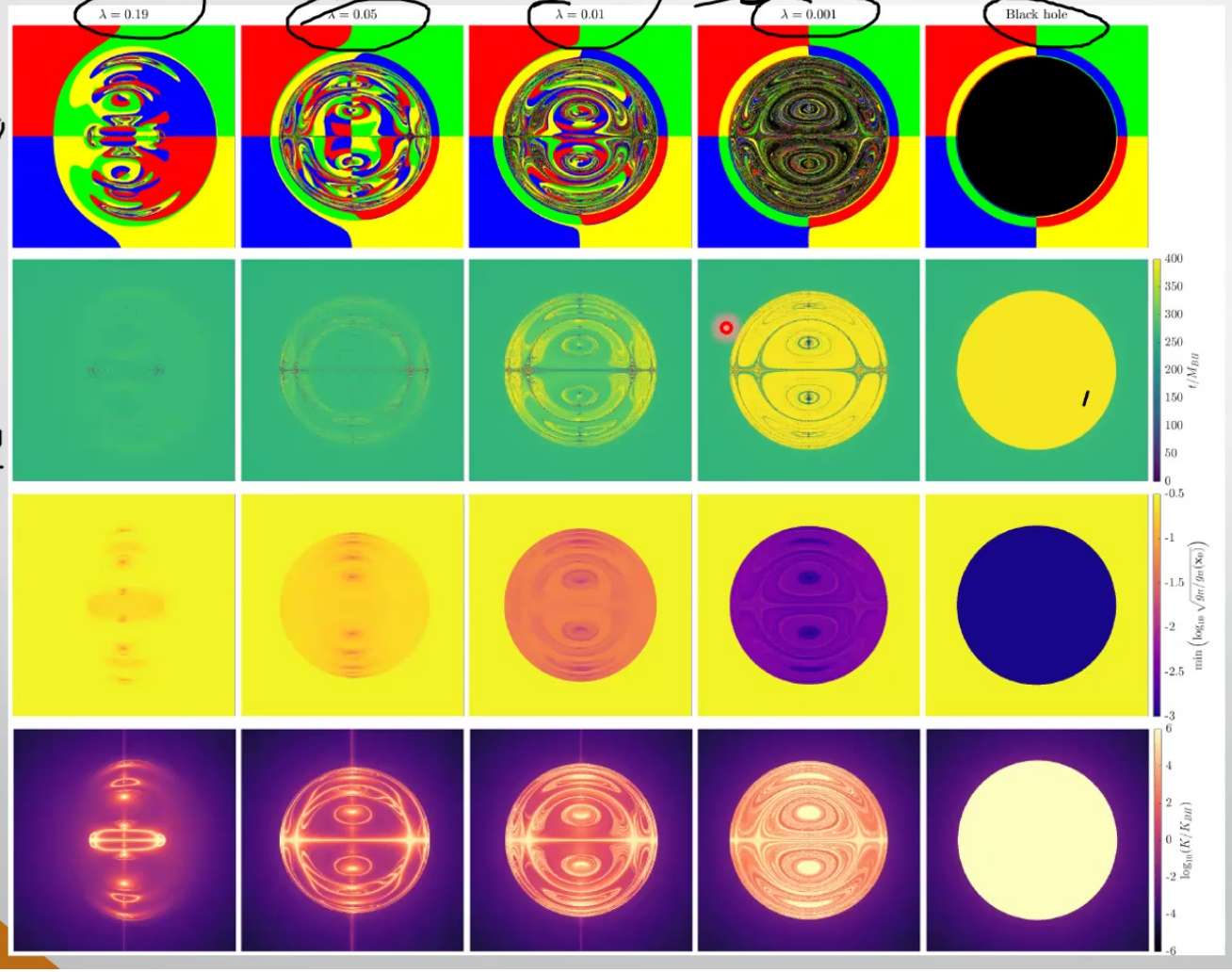

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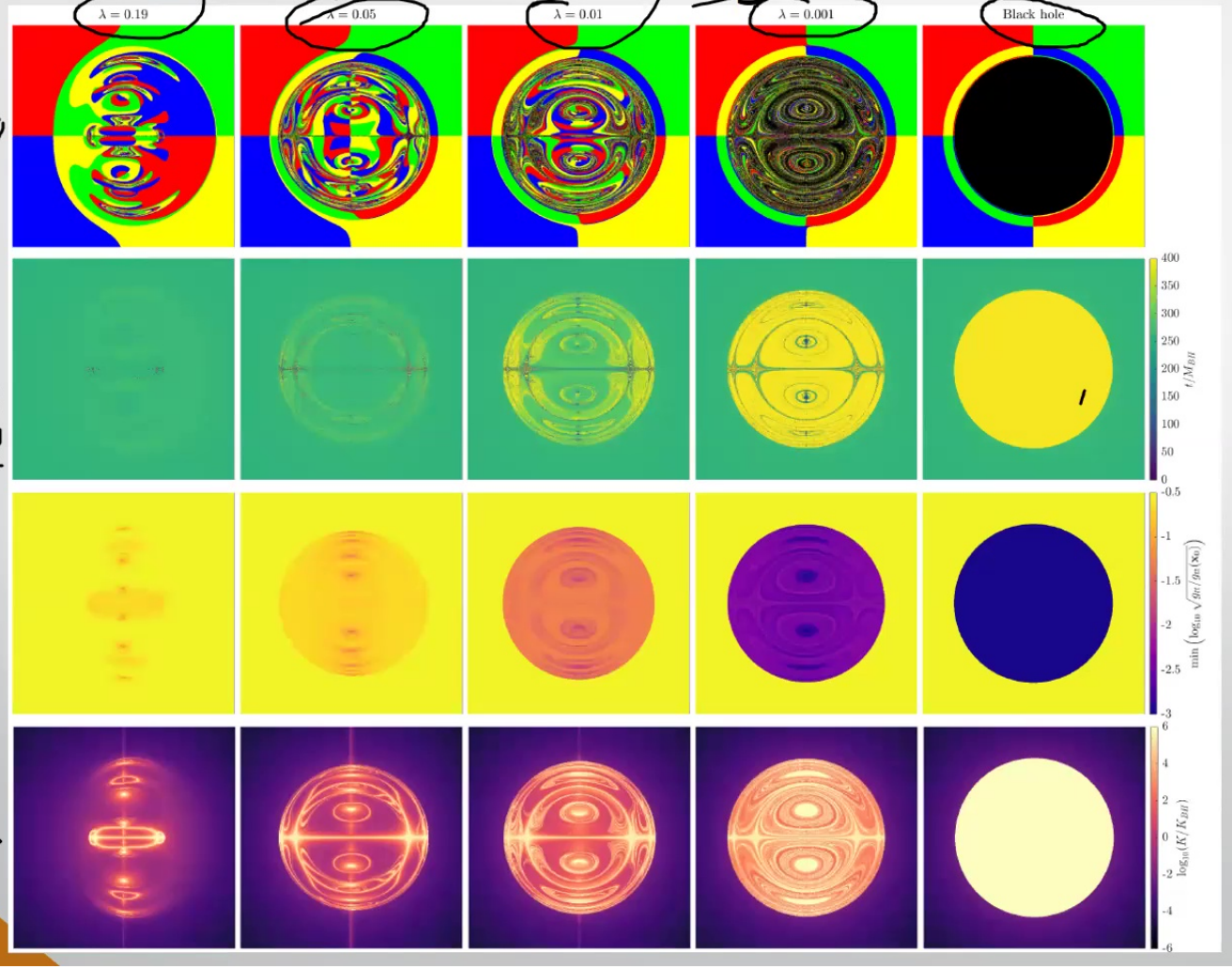
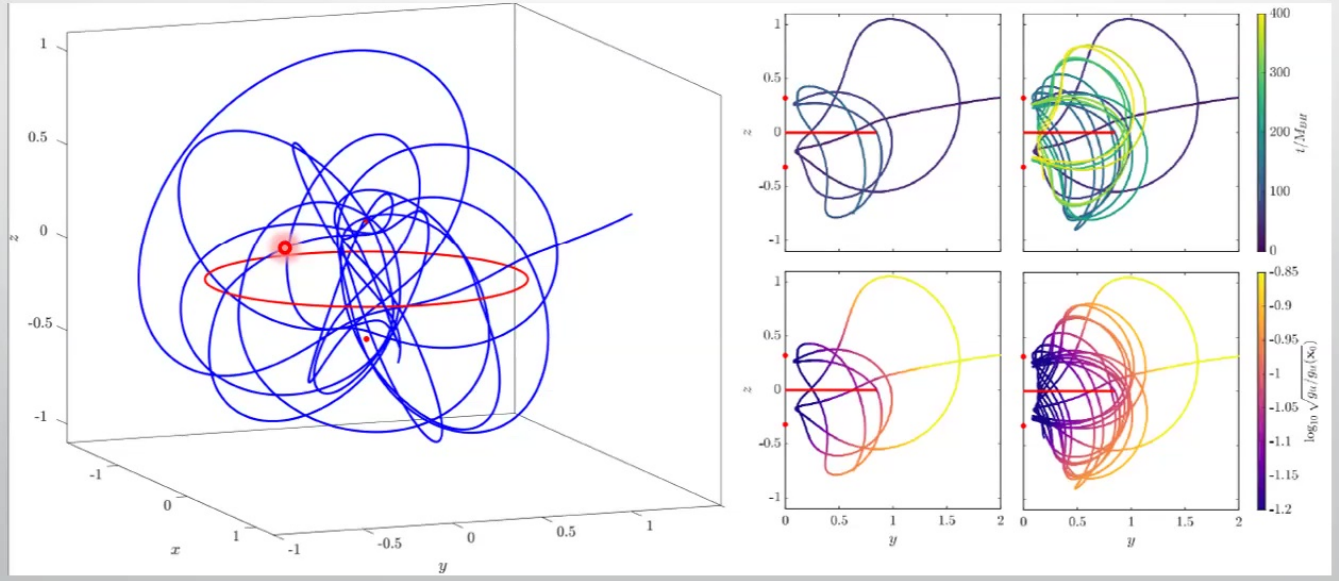


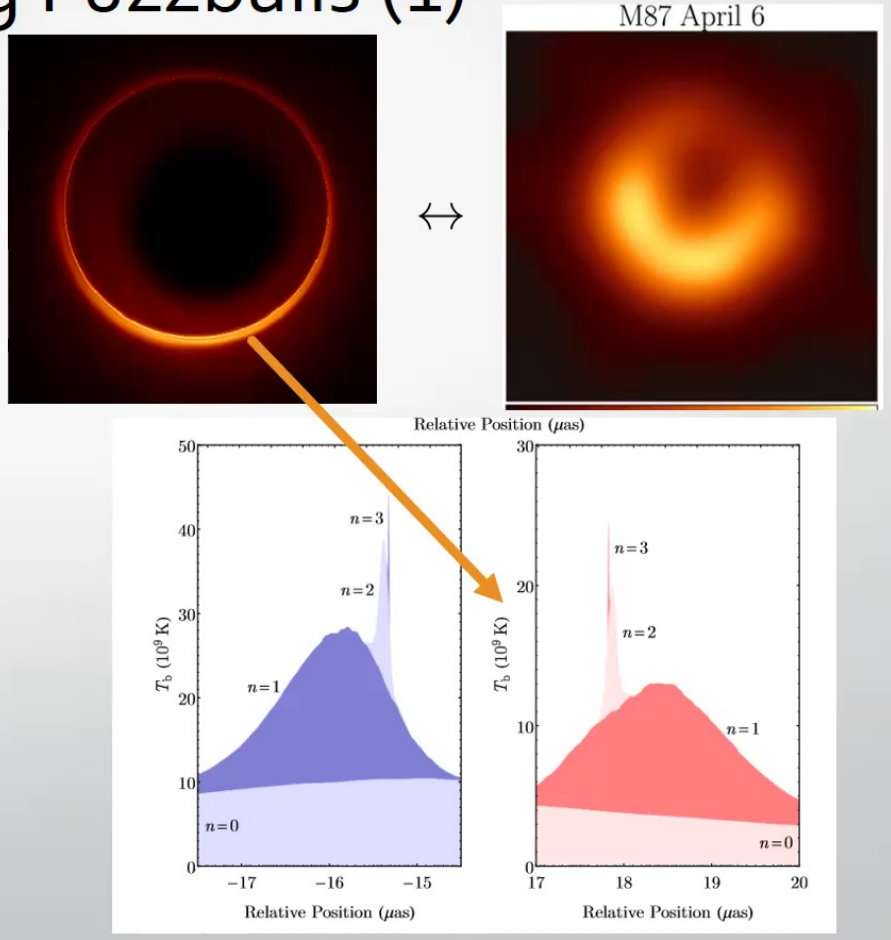
Fuzzball Shadows: Emergent Horizons (3)

- « Effective blackness »: Chaotic orbits that:
  - (i) are long lived
  - (ii) encounter high redshift and
  - (iii) high curvature/tidal forces



Distinguishing Fuzzballs (1)

- Actual detection/distinctions?
- Uncertainty in plasma physics $\leftrightarrow$ hard to probe geometry
- Idea: $n > 1$ photon rings
  [Johnson, Lupsasca, Strominger, et al. 1907.04329]
  - Photons which travel around BH near photon ring n times
  - $n \gg 1$ not (as) sensitive to plasma
  - Higher resolution/frequency $\rightarrow$ ngEHT & space based VLBI



Outlook

- Fuzzballs:
  - Can mimic BHs arbitrarily well $\longrightarrow$ « emerging » horizons
  - Restrict parameter range by observations
  - $n \gg 1$ photon rings exciting possibility for real distinction
- « Fuzzball phenomenology »
  - Fuzzballs top-down, quantum gravity motivated ECOs
  - Microstate geometries explicit solutions to study
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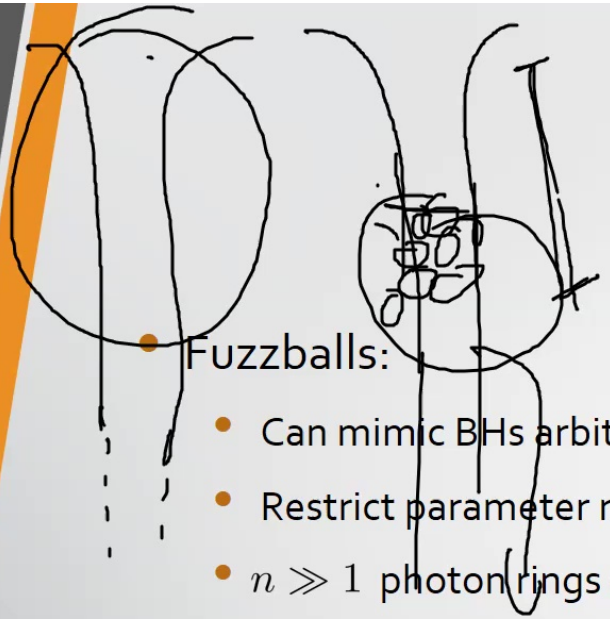

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