New physics @ horizon

Mind the Cap !

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with

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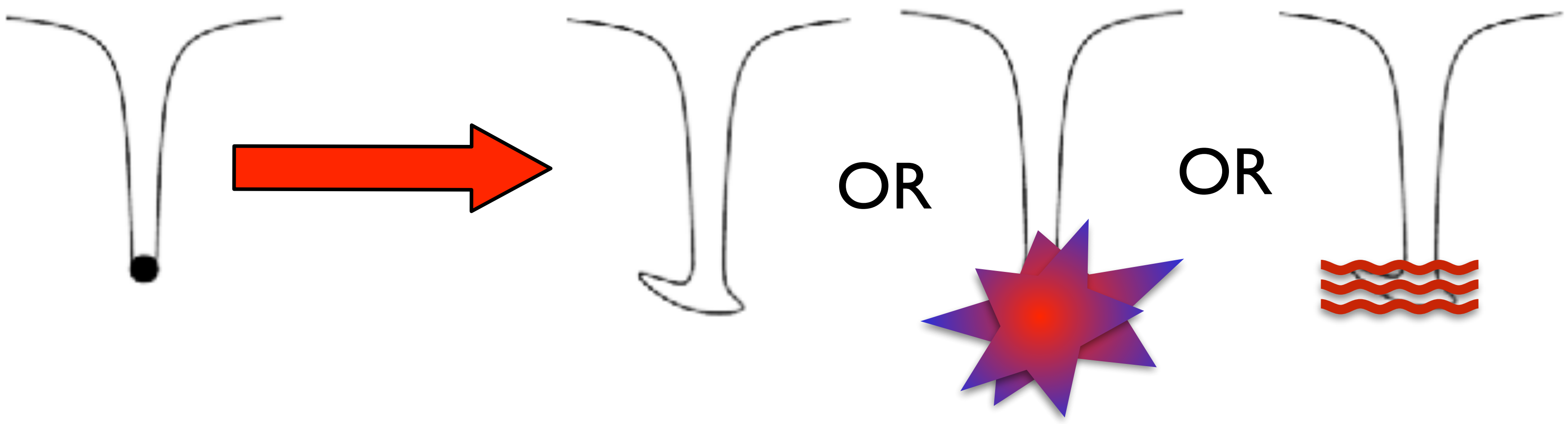
BLACK HOLES: CONFLICT between General Relativity and Quantum Mechanics

There must exist STRUCTURE @ horizon scale

Mathur 2009, Almheiri, Marolf, Polchinski, Sully 2012

Fuzzball / Firewall / etc.



How does STRUCTURE @ horizon look like ?

our work over the past 15 years

Analogy with ideal gas

Thermodynamics

(Air = ideal fluid)

$$P V = n R T$$

$$dE = T\,dS + P\,dV$$

→

Statistical Physics

(Air -- molecules)

e^S microstates

typical

atypical

Thermodynamics

Black Hole Solution

→

Statistical Physics

Microstate geometries

Long distance physics

Gravitational lensing

Physics at horizon

Information loss

Gravity waves ?

Word of caution

- Everybody&their brother - replace classical BH by BH-sized object
  - Gravastar, quark-star, boson-star
  - Infinite density firewall hovering just above horizon
  - Gas of wormholes
  - Bose-Einstein condensate of gravitons
  - LQG configuration…

3 very stringent tests:

1. Same growth with G_N !!!

Horowitz

BH size grows with G_N ; "normal objects" shrink

- BH microstate geometries pass this test
- Highly nontrivial mechanism: $G_N = g_s^2$
- D-branes = solitons, tension ~ $1/g_s$ → lighter as G_N increases

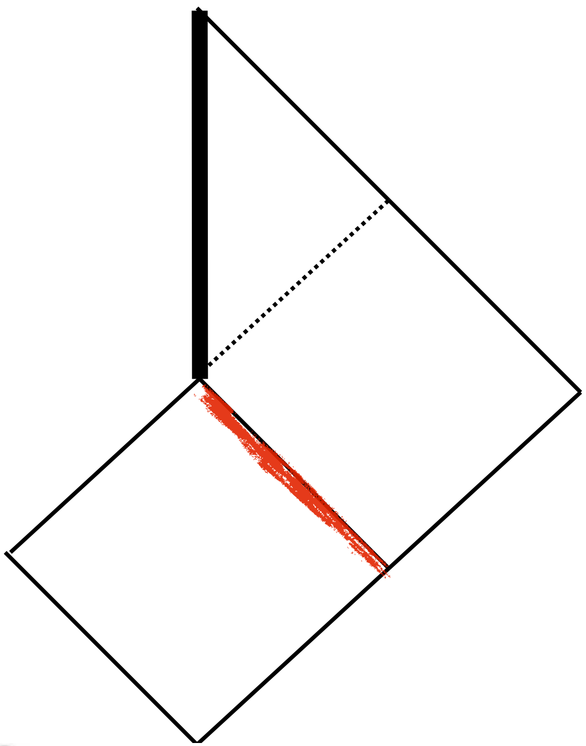
To build structure@horizon, non-perturbative degrees of freedom you must use !

2. Mechanism not to fall into BH

Very difficult !!!

GR Dogma:

Thou shalt not put anything at the horizon !!!



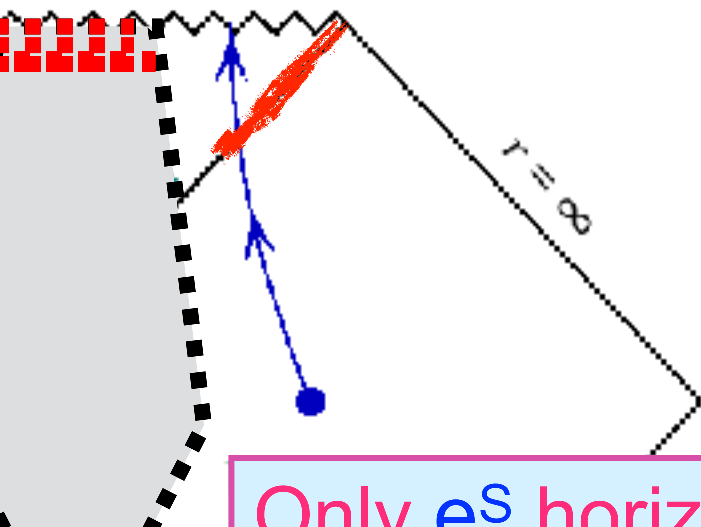
- Null ➞ speed of light.
- If massive: ∞ boost ➞ ∞ energy
- If massless: dilutes with time

- Nothing can live there ! (or carry degrees of freedom)
- No membrane, no spins, no "quantum stuff"
- No (fire)wall

If support mechanism have you not, b.s. you are doing

3. Avoid forming a horizon

– Collapsing shell forms horizon — Oppenheimer and Snyder (1939)
– If curvature is low, no reason not to trust classical GR
– By the time shell becomes curved-enough for quantum effects to become important, horizon in causal past (60 hours for NGC 4889 BH)



Backwards in time - illegal !

BH has e^S microstates with no horizon
Small tunneling probability = e^{-S}
Will tunnel with probability **ONE** !!!
Kraus, Mathur; Bena, Mayerson, Puhm, Vercnocke

Only e^S horizon-sized microstates can do it !

Black hole entropy the structure must have

Microstates geometries

- Where is the BH charge ?

$$L = q\, A_0$$

magnetic

$$L = \ldots + A_0\, F_{12}\, F_{34} + \ldots$$

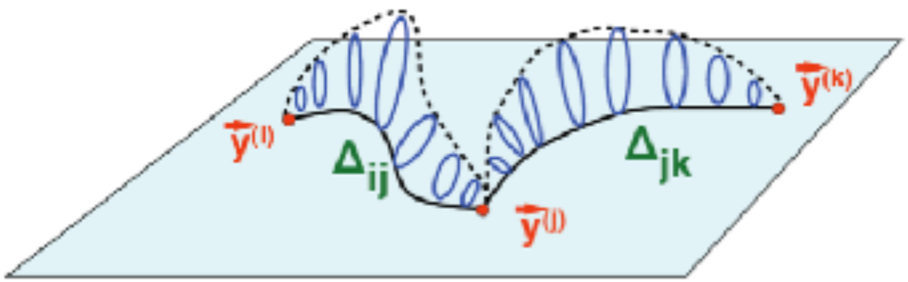
- Where is the BH mass ?

$$E = \ldots + F_{12}\, F^{12} + \ldots$$

- BH angular momentum

$$J = E \times B = \ldots + F_{01}\, F_{12} + \ldots$$

2-cycles + magnetic flux



Bubbling Geometries

The charge is dissolved in magnetic fluxes. No singular sources.

Largest family of solutions known to mankind

Arbitrary functions of two variables: ∞ X ∞ parameters

Bena, Giusto, Russo, Shigemori, Warner

$$ds_{10}^2 = \frac{1}{\sqrt{\alpha}}\, ds_6^2 + \sqrt{\frac{Z_1}{Z_2}}\, d\hat{s}_4^2\,,$$

$$ds_6^2 = -\frac{2}{\sqrt{\mathcal{P}}}(dv+\beta)\left[du+\omega+\frac{\mathcal{F}}{2}(dv+\beta)\right] + \sqrt{\mathcal{P}}\, ds_4^2\,,$$

$$e^{2\phi} = \frac{Z_1^2}{\mathcal{P}}\,,$$

$$B = -\frac{Z_4}{\mathcal{P}}(du+\omega)\wedge(dv+\beta) + a_4\wedge(dv+\beta) + \delta_2\,,$$

$$C_0 = \frac{Z_4}{Z_1}\,,$$

$$C_2 = -\frac{Z_2}{\mathcal{P}}(du+\omega)\wedge(dv+\beta) + a_1\wedge(dv+\beta) + \gamma_2\,,$$

$$C_4 = \frac{Z_4}{Z_2}\,\widehat{\mathrm{vol}}_4 - \frac{Z_4}{\mathcal{P}}\gamma_2\wedge(du+\omega)\wedge(dv+\beta) + x_3\wedge(dv+\beta) + \mathcal{C}\,,$$

$$C_6 = \widehat{\mathrm{vol}}_4 \wedge \left[-\frac{Z_1}{\mathcal{P}}(du+\omega)\wedge(dv+\beta) + a_2\wedge(dv+\beta) + \gamma_1\right] - \frac{Z_4}{\mathcal{P}}\mathcal{C}\wedge(du+\omega)\wedge(dv+\beta)\,,$$

$$\alpha \equiv \frac{Z_1 Z_2}{Z_1 Z_2 - Z_4^2}\,, \qquad \mathcal{P} \equiv Z_1 Z_2 - Z_4^2\,.$$

$$= -\frac{R\,r}{\sqrt{2}\,k_2(m_1^2-1)}\,\frac{m_1(k_2+m_1+1)\Delta_{k_2+m_1-1,m_1-1} + (k_2+m_1-1)\Delta_{k_2+m_1 \ldots}}{(r^2+a^2)^2}$$

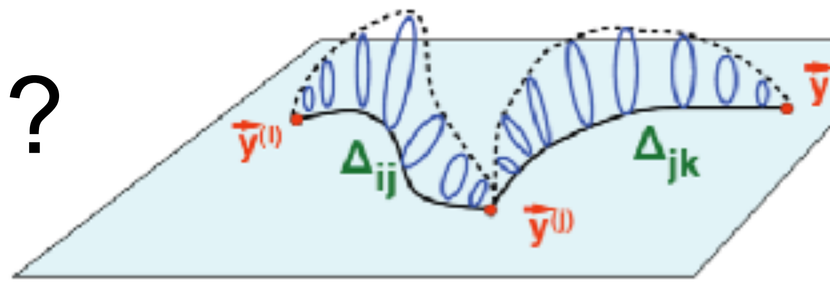
$$= \frac{R}{\sqrt{2}\,k_2(m_1^2-1)a^2\sin\theta\cos\theta}\Big[2(m_1-1)\Delta_{k_2+m_1-3,m_1-1}$$
$$+ (m_1-1)(m_1-2)\Delta_{k_2+m_1-1,m_1-1} + m_1(k_2-2)\Delta_{k_2+m_1-1,m_1+1}$$
$$- m_1(m_1-1)\Delta_{k_2+m_1+1,m_1-1} + (m_1^2(k_2-1)+1)\Delta_{k_2+m_1+1,m_1+1}\Big]\,,$$

$$= -\frac{R}{\sqrt{2}}\frac{\Delta_{k_2+m_1+1,m_1+1}}{\Sigma}\sin^2\theta - \frac{R}{\sqrt{2}\,k_2(m_1^2-1)a^2}\Big[2(m_1-1)\Delta_{k_2+m_1-3,m_1-1}$$
$$+ (m_1^2-2m_1+k_2-1)\Delta_{k_2+m_1-1,m_1-1} + m_1(k_2-2)\Delta_{k_2+m_1-1,m_1+1}$$
$$+ m_1(k_2-m_1-1)\Delta_{k_2+m_1+1,m_1-1} + (k_2(m_1^2+m_1-1)-m_1(m_1+1))\Delta_{k_2 \ldots}$$

$$= -\frac{R}{\sqrt{2}}\frac{\Delta_{k_2+m_1+1,m_1+1}}{\Sigma}\cos^2\theta - \frac{R}{\sqrt{2}\,k_2(m_1^2-1)a^2}\Big[(k_2-1)(m_1-1)\Delta_{k_2+m_1 \ldots}$$
$$- 2(m_1-1)\Delta_{k_2+m_1-3,m_1-1} - (m_1-1)(m_1-2)\Delta_{k_2+m_1-1,m_1-1}$$
$$- (m_1-1)(k_2-3)\Delta_{k_2+m_1-1,m_1+1} + m_1(m_1-1)\Delta_{k_2+m_1+1,m_1-1}$$
$$- (m_1-1)(m_1(k_2-1)+1)\Delta_{k_2+m_1+1,m_1+1}\Big]\,.$$

Habemus Superstratum !!!

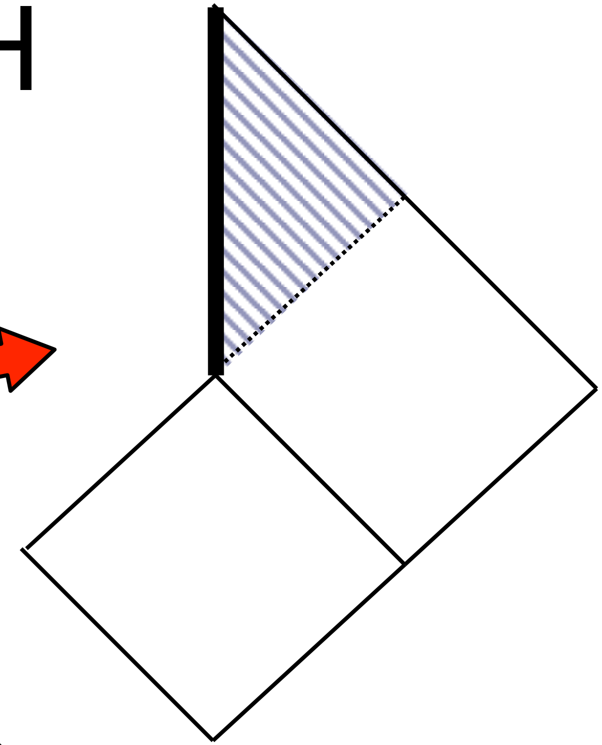
Why not collapsing ?

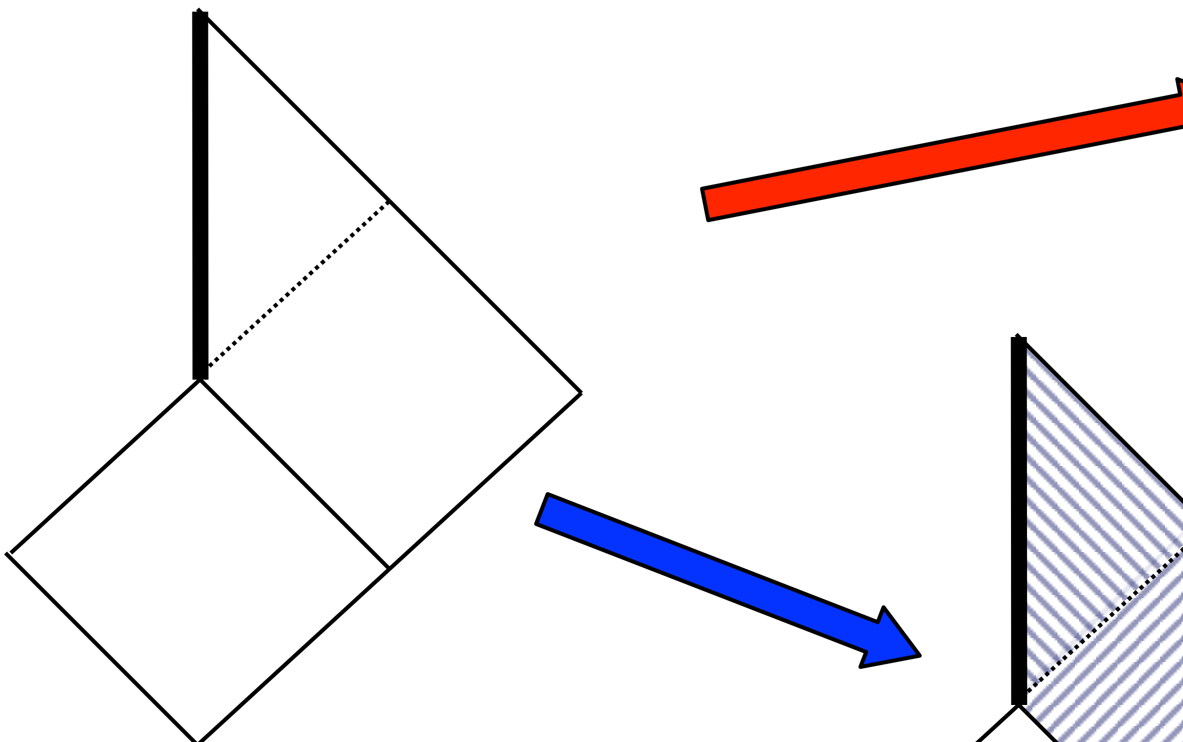


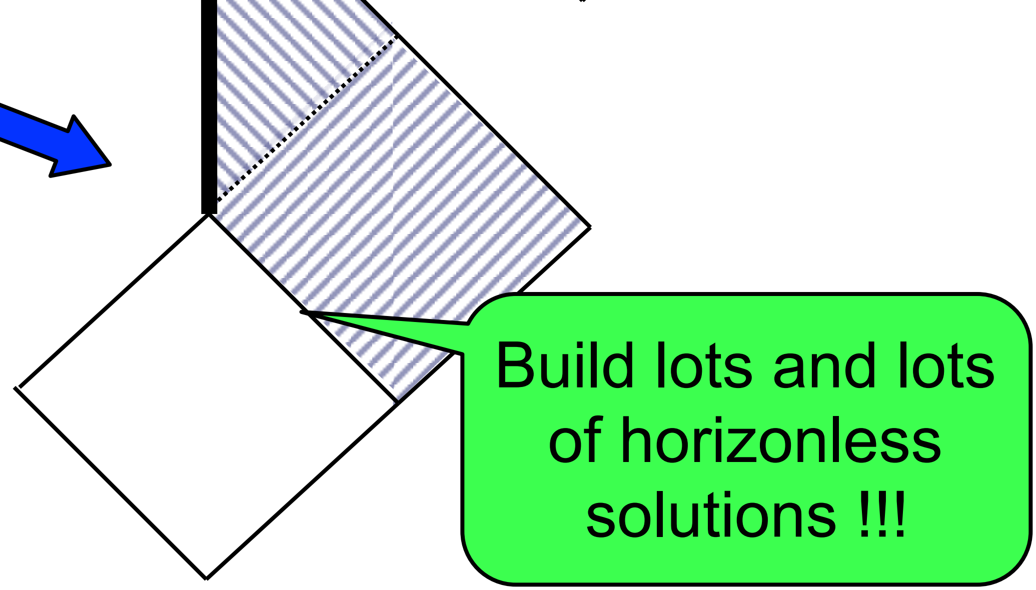
- 5(+6)d : smooth solutions + quantized magnetic flux on topologically-nontrivial 2-cycles
  - cycles smaller $\longrightarrow$ increases energy
  - bubbling = only mechanism to avoid collapse in semiclassical limit Gibbons, Warner
  - If any state in the **e^S-dimensional** BH Hilbert space has a semiclassical limit, it **must** be a microstate geometry !
- 4(+6)d : multicenter solutions Denef
  - smooth GH centers with negative charge $\longrightarrow$ centers with negative D6 charge and negative mass
  - common in String Theory (e.g. orientifolds); nowhere else
  - **Highly unusual** matter from a 4d perspective
  - Usual matter does not hang around, just falls in BH

Q = M : extremal BH

Need non-extremal







Very few known. Extremely hard to build...

– Coupled nonlinear 2'nd order PDE's do not factorize

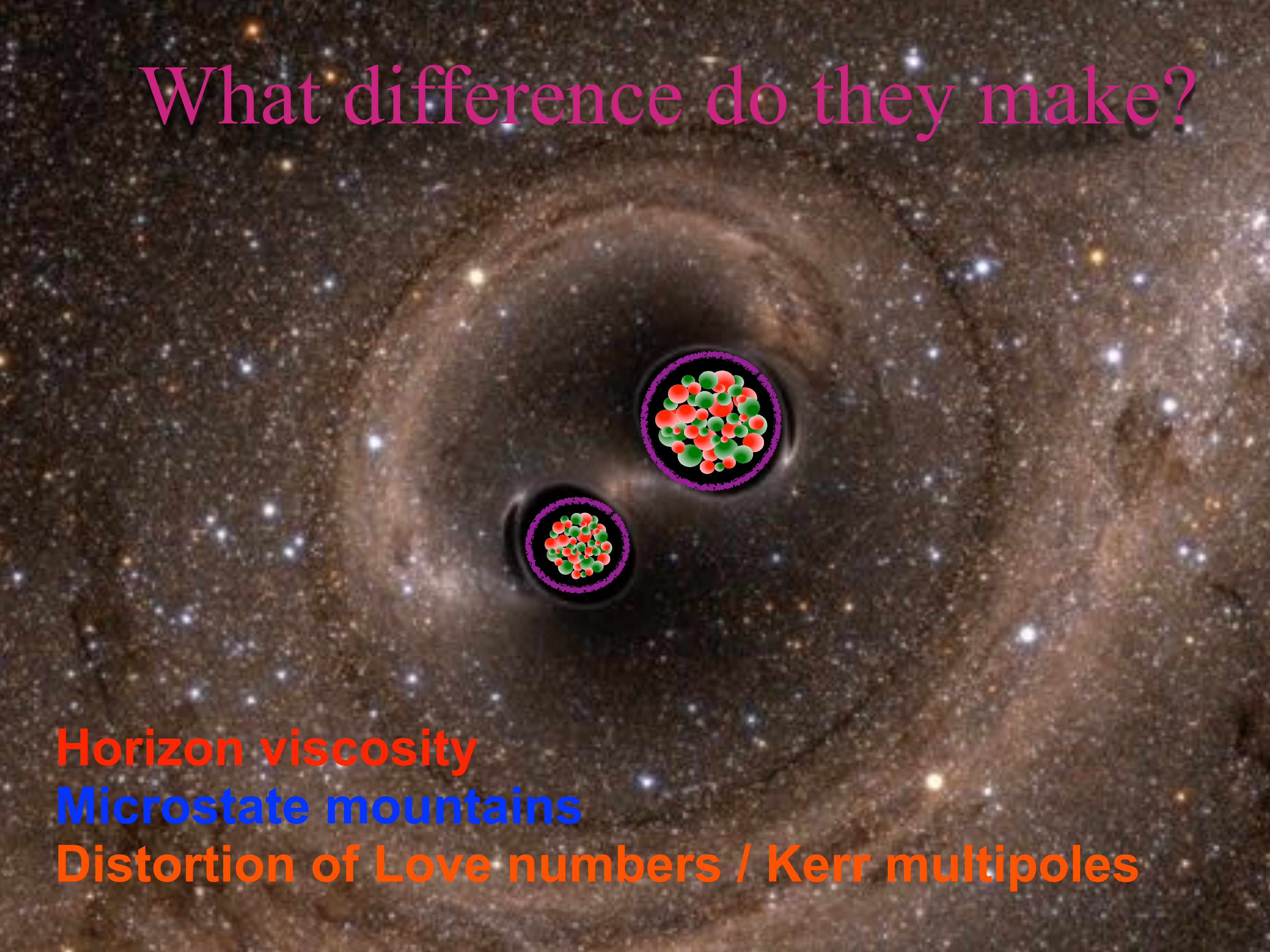
- Near-extremal Bena, Puhm, Vercnocke
- A few solutions far from extremality with large angular momenta Bena, Bossard, Katmadas, Turton
- Extremal Kerr (NHEK) Heidmann (upcoming paper)

Universal feature:

Yuge™ amount of new degrees of freedom @ horizon

- Effect on gravity waves ?
- Supermassive BH formation easier ?

What difference do they make?



Horizon viscosity

Microstate mountains

Distortion of Love numbers / Kerr multipoles

Horizon viscosity

more d.o.f - more dissipative effects (electron moving parallel to a conducting plate)

reflection

lots of d.o.f. - expect complete absorption (no reflection Ashfordi & friends)

😈 Already taken into account by GR BH ?

Microstate mountains

microstates non-spherical (mountains on neutron stars). Jitters on infalling stuff

😈 Typical microstates may be very spherical ? Planck-size bumps ?

Distortion of Kerr multipole moments :

spinning ball of dust or liquid
spinning solid shell
spinning BH with vacuum at horizon
spinning STRUCTURE @ horizon scale

effect on collisions with non-aligned spins

Love numbers : response to tidal stress Cardoso&al
similar story

😈 Fuzzball complementarity: unusual matter forming STRUCTURE @ horizon gives “classical horizon experience” to infalling observer. Same as vacuum.