Title: Whatâ€™s inside a BH?

Date: Nov 10, 2017 10:50 AM

URL: http://pirsa.org/17110096

Abstract: We propose that a large Schwarzschild black hole (BH) is a bound state of highly excited, long, closed strings just above the Hagedorn temperature. The effective free-energy density is expressed as a function of its entropy density and contains only linear and quadratic terms, in analogy with that of collapsed living polymers.   Classically, the horizon of such BHâ€™s is completely opaque, hiding any clues about the state and very existence of its interior. Quantum mechanically and in equilibrium, the situation is not much different: Hawking radiation will now be emitted, but it carries a minimal amount of information. The situation is significantly different when such a quantum BH is out of equilibrium. The BH can then emit ``supersized" Hawking radiation with a much larger amplitude than that emitted in equilibrium. The result is a new type of quantum hair that can reveal the state and composition of the BH interior to an external observer.

What’s inside a black hole ?
Probing the interior of black holes with gravity waves

Ram Brustein

אוניברסיטת בן-גוריון

RB, Medved, Yagi

1704.05789

1701.07444

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RB, Medved

1709. 03566

1607.03721

1602.07706

1505.07131

RB, Medved, Zigdon

1707.08427

- Q:What’s inside a large astrophysical BH?
- A1: We’ll never know – it’s inside the horizon
- A2: Specific form of exotic matter
- Q: How can we tell? (Yagi’s talk, Wednesday)
- A: By the emitted GW when two BH’s collide (EM? ν ?)

What’s inside a black hole ? Probing the interior of black holes with gravity waves

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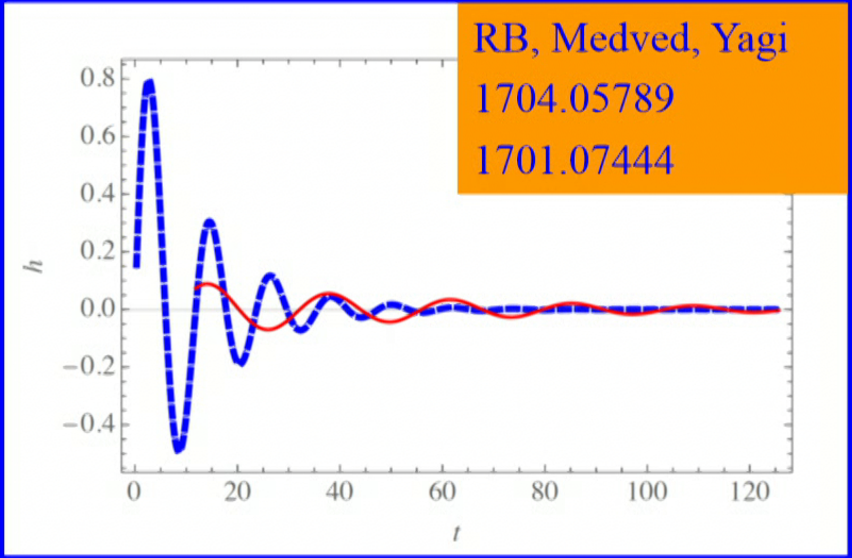
- What “is” a BH ?

A large BH “is” a bound state of highly excited, interacting, long, closed strings just above the Hagedorn temperature (“collapsed polymer”)

RB+ Medved
1602.07706
1607.03721

- What happens when two BH’s collide ?

New “quantum hair”, “supersized” Hawking radiation ➔ Additional GW, @ lower frequencies, longer decay time & lower amplitude than the leading signal.



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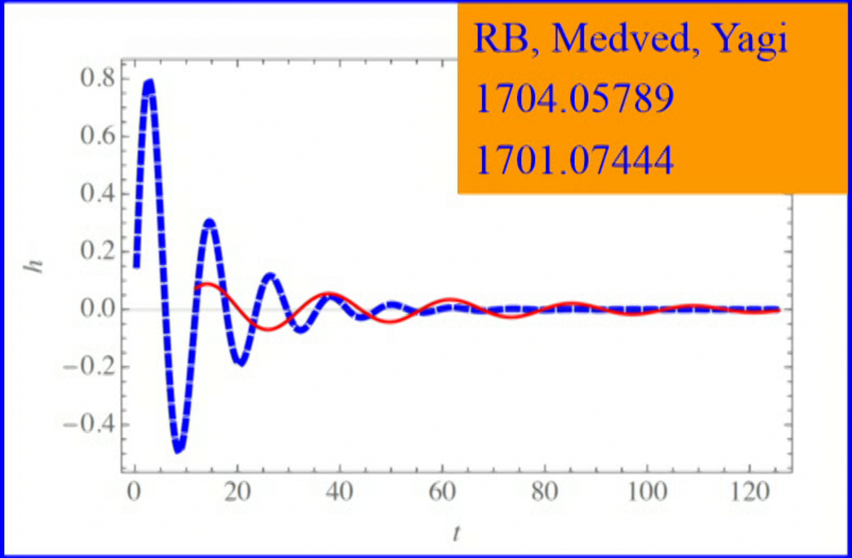

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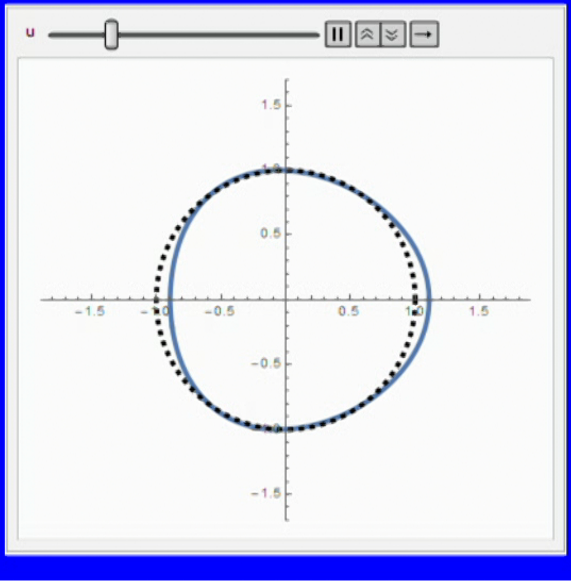
1709.03566

Quantum mechanically

-ive null energy → horizon shrinks

☺ causality (Mathur '17, Maldacena + …'17)



Classically: horizon tidal deformation

(**Hartle '73**, O'Sullivan & Hughes '14)

+ive null energy ←→ horizon grows

☺ causality

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1709.03566

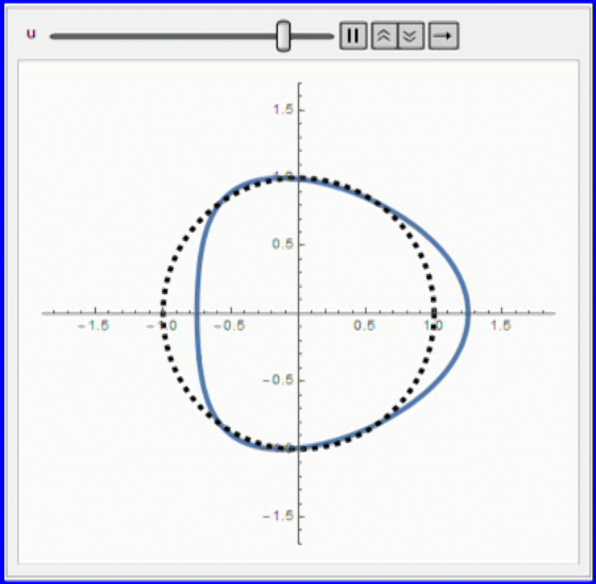
- Standard Hawking radiation

Need to wait a Page time to "read the interior"

- "Supersized" Hawking radiation:

Faster, stronger coherent emission
➔ large # of
"equivalent Hawking modes",
"early Page time"

- Amount of information that can be "read" determined by the degree of excitation ΔE/E



Plan

- BH as a bound state of highly excited strings:
  "quantum star" , "string ball", "collapsed polymer"
- New "quantum hair", "supersized" Hawking radiation when the BH is driven out of equilibrium
- ============ Yagi's talk – Wednesday =========
- Estimate of additional GW emission from quantum BH's
- Current and future bounds with GW observations

Highly excited (Hagedorn) phase of strings

$$Z = \mathrm{Tr}\, e^{-\beta H} \sim \int_0^\infty dm\, \exp(4\pi m \alpha'^{1/2}) \exp(-m/T)$$

$$n(m) \approx \exp(4\pi m \alpha'^{1/2})$$

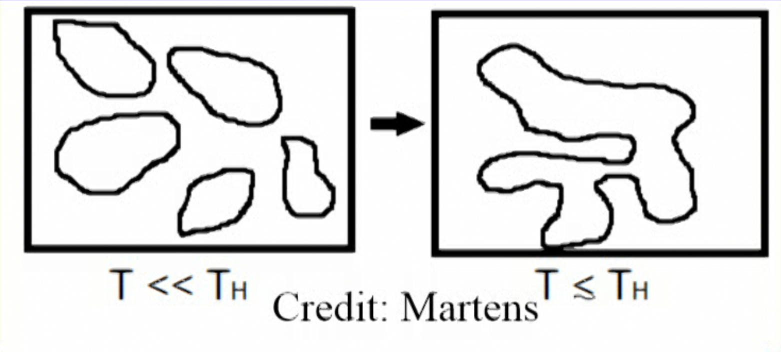
Hagedorn divergence $T_{Hag} = \frac{1}{4\pi \alpha'^{1/2}}$

$$\omega(\varepsilon) \approx \frac{V \exp(\beta_H \varepsilon)}{\varepsilon^{D/2+1}}$$

Long string: Energy, Entropy ~ Length

$T < T_{\mathrm{Hag}}$, Energy dominates

$T \sim T_{\mathrm{Hag}}$, Entropy dominates (strong coupling)



Credit: Martens

Dominated by long string(s) : entropically favourable

Highly excited strings in a bounded region

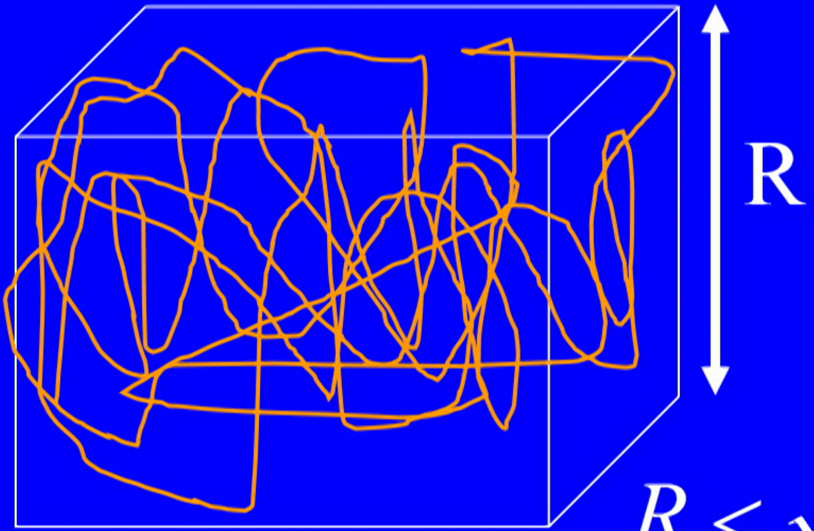
Salomonson & Skagerstan ‘86
Low+Thorlacius ’94
==================
Horowitz+Polchinski ’98
Damour + Veneziano ‘00

Closed strings
- Total length L
- Entropy N

$N = L/\ell_s$

Dominated by long strings

$\ell \sim L$



$R < \sqrt{L}$

Area law

Flory-Huggins theory of polymers

$$N \sim (R/l_s)^{1/\nu}$$
$$\nu = 1/(d-1)$$

Bound state of highly excited strings:

quadratic free energy (a "collapsed polymer")

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$$-\left(\frac{F}{T_{Hag}}\right)_{strings} = \epsilon N - \frac{1}{2}\frac{g_s^2}{V}N^2$$

$$\epsilon = (T - T_{Hag})/T_{Hag}$$

$$V \sim R^d$$

$$-\left(\frac{F}{V\,T_{Hag}}\right) = \varepsilon c - \tfrac{1}{2} g_s{}^2 c^2$$

$$\frac{\partial F}{\partial c} = 0 \Rightarrow$$

$$\boxed{c = \epsilon/g_s^2}$$

$$\boxed{\varepsilon = g_s{}^2 \frac{N}{V}}$$

$$c = N/V$$

Extremely complicated in
terms of asymptotic fields
Solution "non-perturbative"
not valid as $g_s \to 0$

BH as a bound state of highly excited strings

$$g_s^2 \frac{N^2}{V} = G_N \frac{E^2}{R}$$

Gravitational energy dominates

$$\xRightarrow{} \quad \epsilon = 1/R$$

$$G_N = l_P^2 = g_s^2 l_s^2 = g_s^2$$

$$\boxed{\varepsilon = g_s{}^2 \frac{N}{V}}$$

$$R_S = \frac{l_s}{\epsilon}$$

$$T_{Haw} = \epsilon$$

$$g_s^2 = (l_P/l_s)^{d-1}$$

$$S_{BH} = N = V \frac{\epsilon}{g_s^2} = \left(\frac{R_S}{l_p}\right)^{d-1}$$

$$E_{bound} = V \frac{\epsilon^2}{g_s^2} = \frac{1}{l_P} \left(\frac{R_S}{l_P}\right)^{d-2} = M_{BH}$$

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Solution “non-perturbative” not valid as $g_s \rightarrow 0$

Emergent horizon, Hawking radiation

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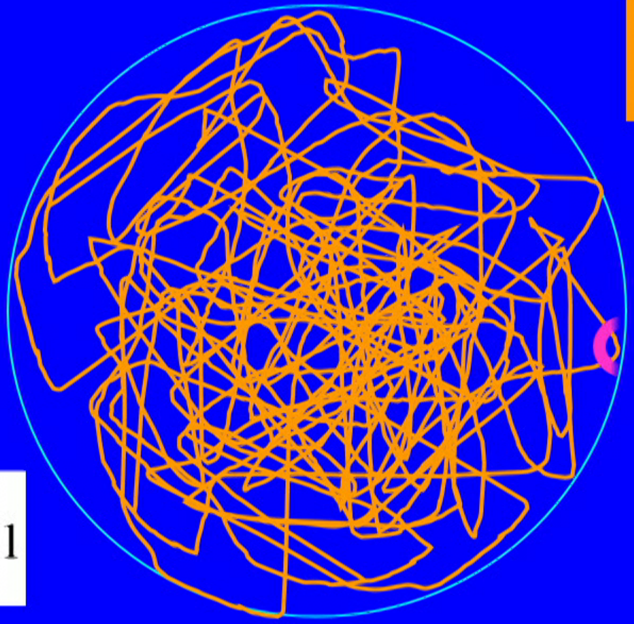
$$\frac{\Delta V^2}{V^2} = \frac{g_s{}^2}{V\varepsilon} = 1/S_{BH}$$

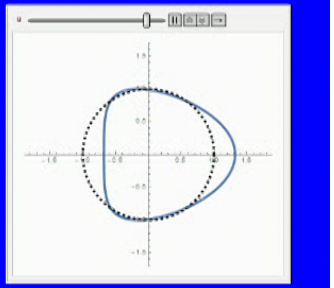
$$\frac{\Delta A^2}{A^2}, \frac{\Delta R^2}{R^2} = 1/S_{BH}$$

In 4D, $\Delta R \sim l_P$

Rate of escape ~

$$\frac{g_s{}^2}{V}\frac{N}{\ell} = \varepsilon = 1/R_S \text{ for a loop of length } \ell = 1$$





From an external perspective: Horizon absorbs negative null energy & becomes a little smaller

BH as a bound state of highly excited strings – "collapsed polymer"

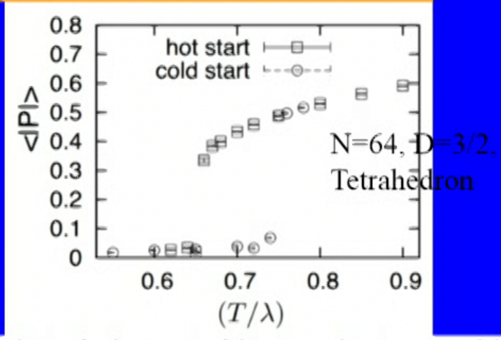
- From the outside, in equilibrium, looks exactly like a BH
    - Mass and entropy scale correctly
    - Does not collapse – entropy dominated/random walk
    - Extremely sharp horizon
    - Correct rate of Hawking radiation

Large-N Lattice Gauge Theory model

$$\frac{F_{YM}}{T_{Hag}} = -N^2\frac{T-T_{Hag}}{T_{Hag}} + \frac{N^4}{NT_{Hag}^d V_{YM}} + \cdots ,$$

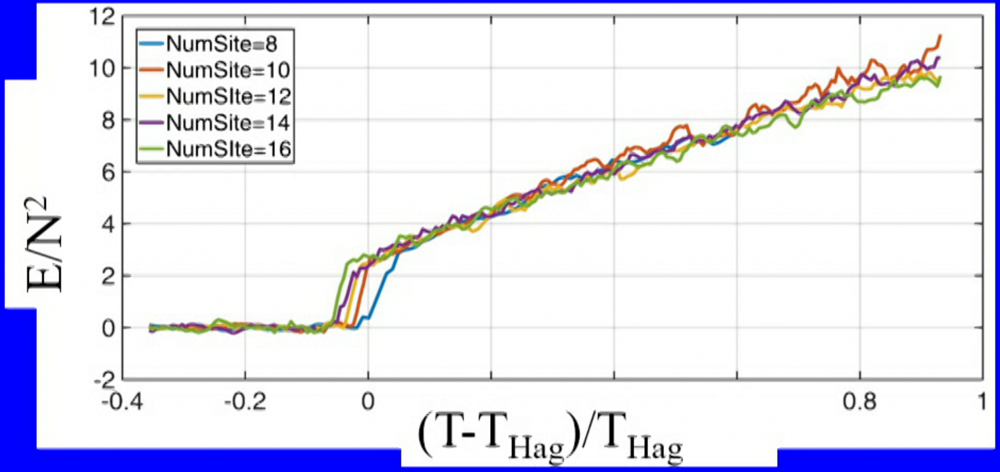
$$F_{YM} = -L\epsilon + \frac{L^2}{NV_{YM}} + \cdots$$

Hanada, Maltz, Susskind, 1405.1732



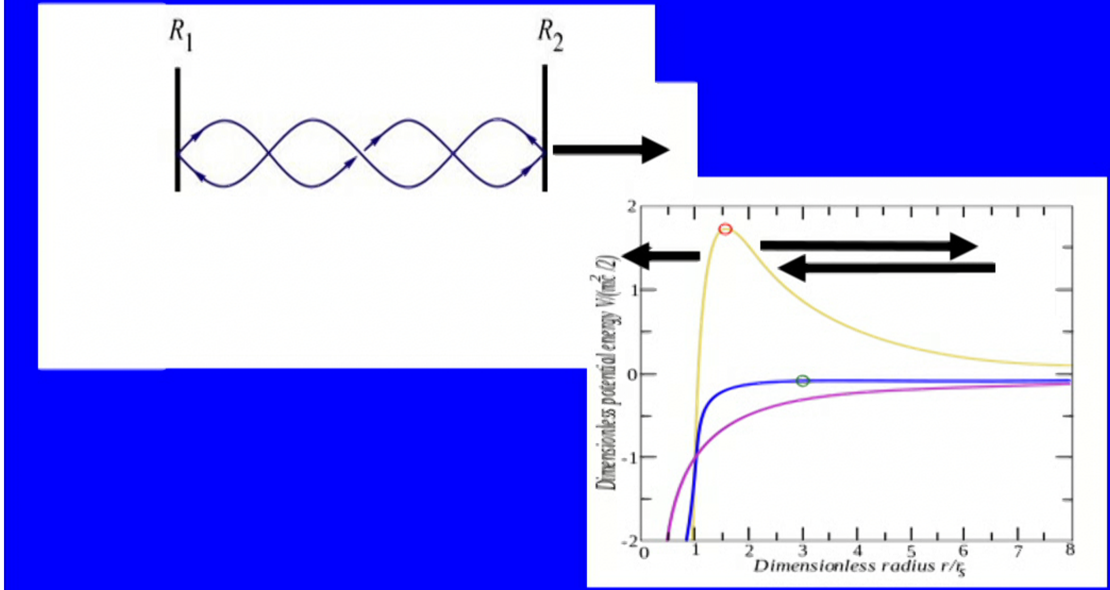
$$(T_c/\lambda) = 1/(2\log(2D-1))$$

RB, Cotler, Hanada, Medved, Wolfson – In progress



New “quantum hair”– Fluid modes

- The matter inside the BH supports QNM’s
- Classically, perfectly opaque horizon ➔ fluid modes decouple
- Quantum mechanically, “horizon transparency” ➔ emission

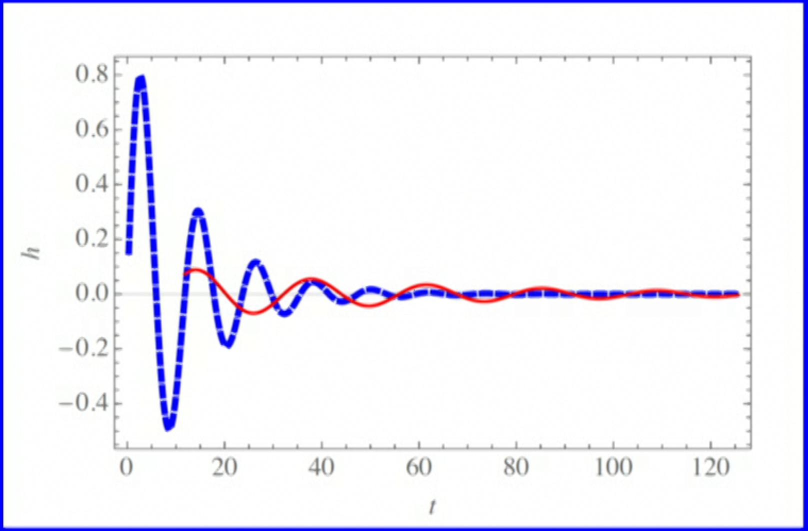


Intrinsic dissipation

Only matter that saturates KSS-like bound can support waves!

Standard QNM's – Fluid modes: Interior perspective

- As for ultra-compact relativistic stars, the real part of the frequency determined by the speed of sound v_{sound}
- Spatial scale of the interior is R_S
- ➔ $v_{sound} \leq c/R_S$ $\boxed{\omega_R \leq c/R_S}$ + a time delay



Exterior perspective

- Extent of excitation ➔ horizon deformation
- Horizon deformation ➔ ω redshift

$$\boxed{\omega_R \leq c/R_S}$$

Sound velocities in the “collapsed polymer”

$$n(\vec{r}) = c/v_{sound}(\vec{r})$$

$$\omega_m = \frac{m\pi}{2R_S\, n} - \frac{i}{2R_S\, n}\ln\left(\frac{n+1}{n-1}\right)$$

Relativistic modes suppressed !
External perspective – no redshift!

Non-relativistic “fracture modes”

$$\boxed{v_{sound}^2 = g_s^2 c^2}$$

- New QNM’s – Fluid modes

$$v^2_{sound} = g_s^2 c^2$$

$$n(\vec{r}) = c/v_{sound}(\vec{r})$$

$$v^2_{sound} = g_s^2 c^2$$

$$v_{sound} < 1$$

$$\omega_m = \frac{m\pi}{2R_S\, n} - i\left[\frac{1}{R_S\, n^2} + \mathcal{O}\left(\frac{1}{n^4}\right)\right]$$

- Paremetrically smaller frequencies
- Parematerically longer damping time

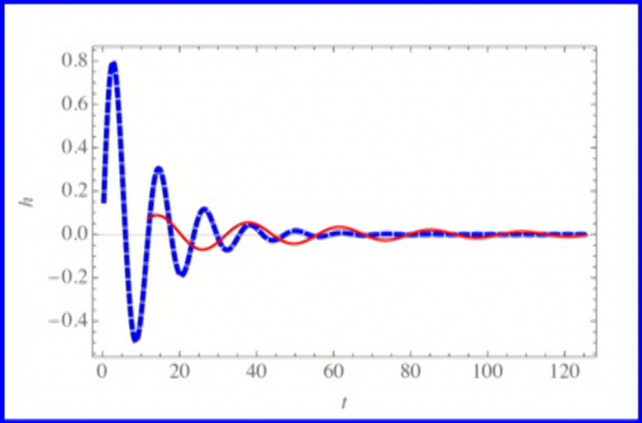
$$\omega_R \sim v_{sound}/R_S \sim g_s\, c/R_S$$

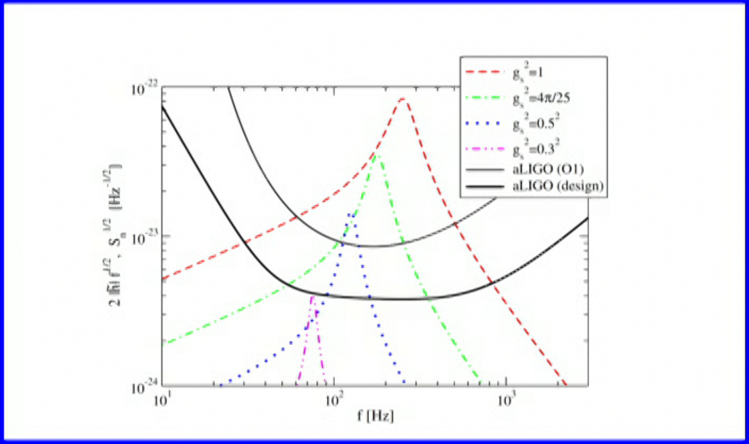
$$\tau_{damp} \sim (1/g_s^2)\,(R_S/c)$$

Summary of results (Yagi's talk):

$$A_p \sim g_s^4 A_{\rm BH}\ ,\ \ f_p \sim g_s f_{\rm BH}\ ,\ \ \tau_p \sim \tau_{\rm BH}/g_s^2$$

Reasonable estimate   Very reliable   Reliable

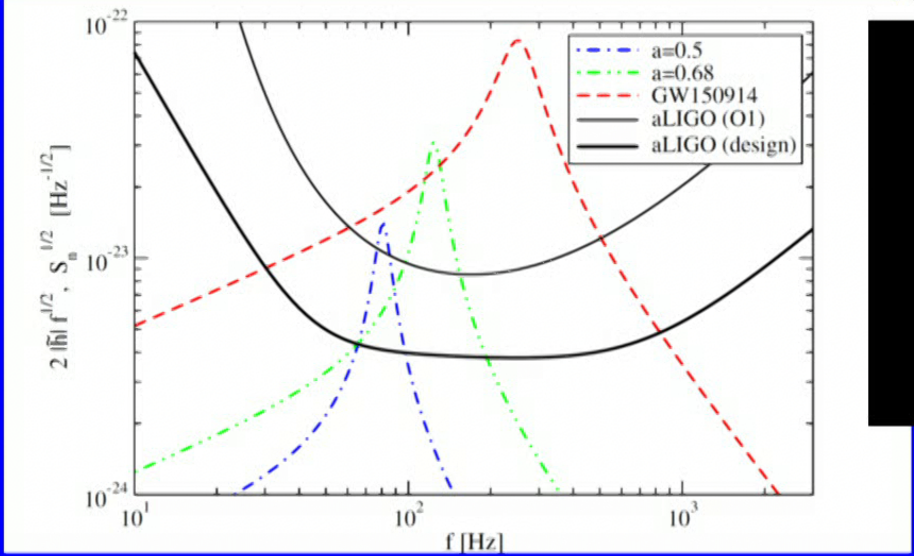




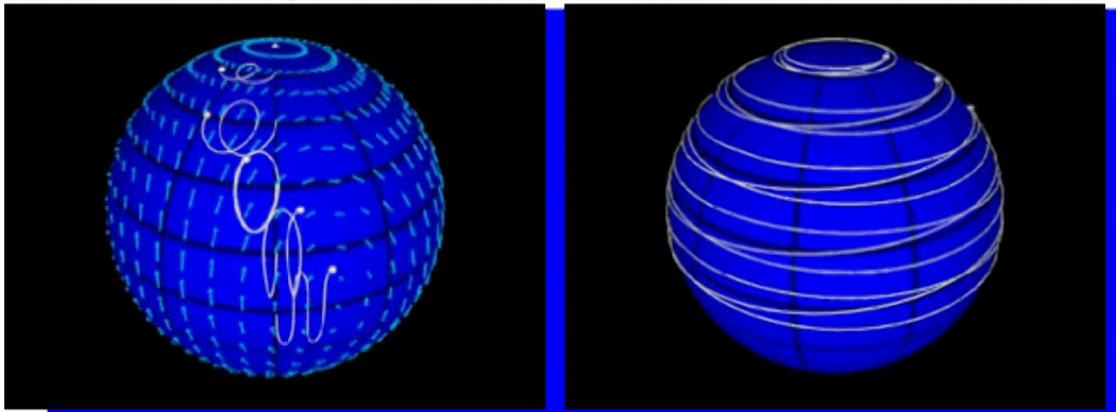
- What happens when two BH's collide ?

RB, Medved, Yagi
1701.07444 (revised version)

In addition to the standard, spacetime modes, additional matter modes result in **additional GW** emitted at **lower frequencies, longer decay time** and **lower amplitude** than the leading signal.



Rotating BH r-modes



r-Mode Oscillations of Rotating Magnetic Neutron Stars
Frederick K. Lamb, Luciano Rezzolla, Stuart L. Shapiro
University of Illinois at Urbana-Champaign

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1607.03721

Summary & Conclusions

- What “is” a black hole (BH) ?

A large Schwarzschild BH is a bound state of highly excited, long, closed strings just above the Hagedorn temperature. (“collapsed polymer”)

$$-\left(\frac{F}{T_{Hag}}\right)_{strings} = \epsilon N - \frac{1}{2}\frac{g_s^2}{V}N^2$$

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