When black holes collide: Probing the interior composition by the emitted gravitational waves

Ram Brustein

אוניברסיטת בן-גוריון

RB, Medved, Yagi
1704.05789
1701.07444
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RB, Medved
1607.03721
1602.07706
1505.07131

- Q:What’s inside a large BH?
- A: Special form of exotic matter

- Q:How can we tell?
- A: By the emitted GW when two BH’s collide

State of the interior : Possible distribution of matter

- Classical GR, empty, surrounding a classically singular center
- Concentrated near horizon in a highly exited state (~"firewall"), interior does not exist (also fuzzballs),
- **Distributed throughout the interior region**
- Other proposals: gravstars, classical wormholes, boson stars
  - Do not have a horizon
  - Violate some basic principles, negative energy, unstable matter, ...

State of the interior:
Black holes cannot be empty

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1505.07131
RB, Medved, Zigdon,
To appear

- BH “purifier” of radiation → Interior non-classical
- Interior *cannot* be described by a semiclassical metric
- BH is a highly excited state, highly degenerate →

density of states >> density of states of “normal” bound states in known QFT’s, known matter

Initial state (almost) pure: solar mass BH $S_{ini} \sim 10^{57}$, $S_{BH} \sim 10^{77}$

State of the interior:
Black holes cannot be full ??!!

- Known form of matter cannot support such Schwarzschild-sized objects without collapsing,
- All known interactions of standard matter are weaker than gravity

General Relativistic Fluid Spheres

H. A. BUCHDAHL*
Institute for Advanced Study, Princeton, New Jersey
(Received June 16, 1959)

system (see Appendix I)—the ratio of the total mass M to the (coordinate) radius R of the sphere cannot have a value greater than 4/9, or 5/18 if the trace of the energy-momentum tensor is postulated to be non-negative. In other words, although the quantity

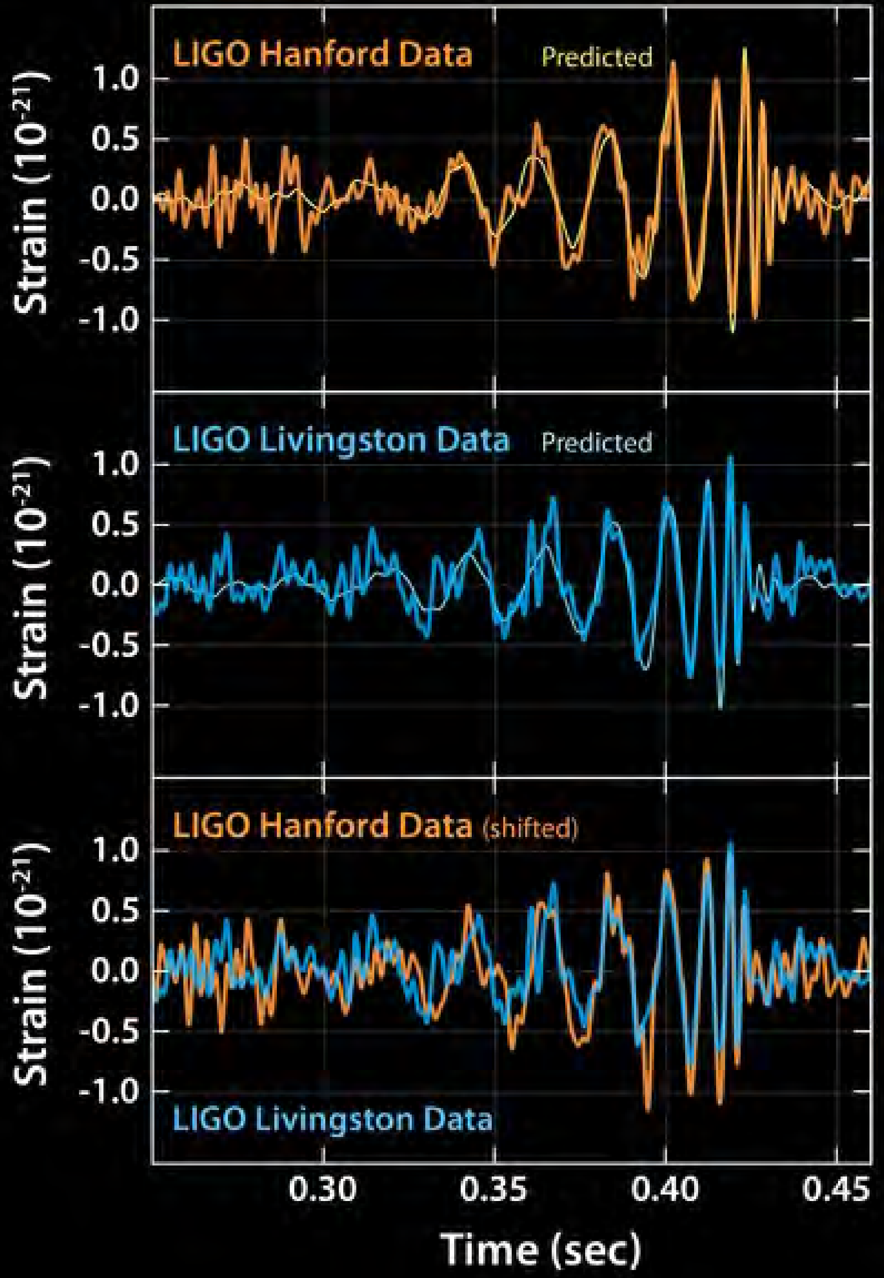
$$\Delta = 1 - 2M/R \geq 1/9 \quad (1.1)$$

No longer purely theoretical & abstract questions !

LIGO Detected Gravitational Waves from Black Holes

On September 14, 2015 at 5:51 a.m. EDT, LIGO measured gravitational waves – arriving at the Earth from a cataclysmic event in the distant universe.

Since then 2 ~ 3 additional events, rate ~ months



- What “is” a BH ?

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

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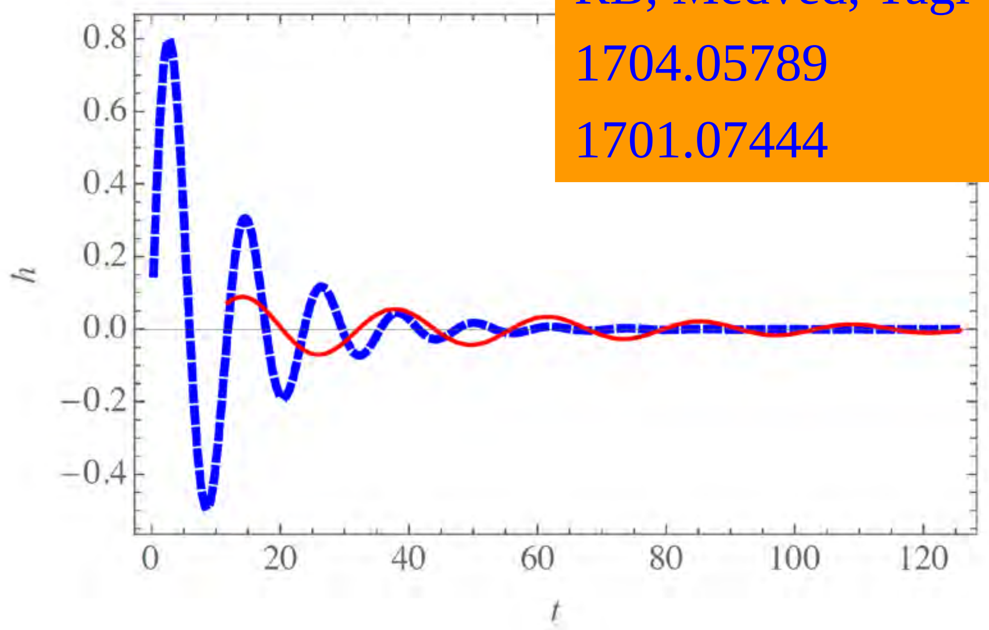
- What happens when two BH’s collide ?

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



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Plan

- BH as a bound state of highly excited strings:
  “quantum star” , “string ball”, “collapsed polymer”
- New “quantum hair”, “supersized” Hawking radiation
- Estimate of additional GW emission from quantum BH’s
- Current and future bounds with GW observations

BH as a bound state of highly excited strings

Highly excited (Hagedorn) phase of strings

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

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

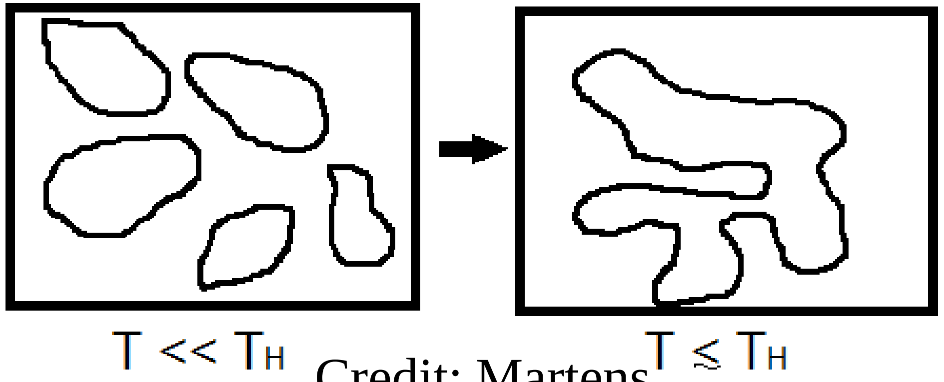
Hagedorn divergence $T_{Hag} = \frac{1}{4\pi\alpha'^{1/2}}$

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

Long string: Energy, Entropy ~ Length

$T < T_{Hag}$, Energy dominates

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

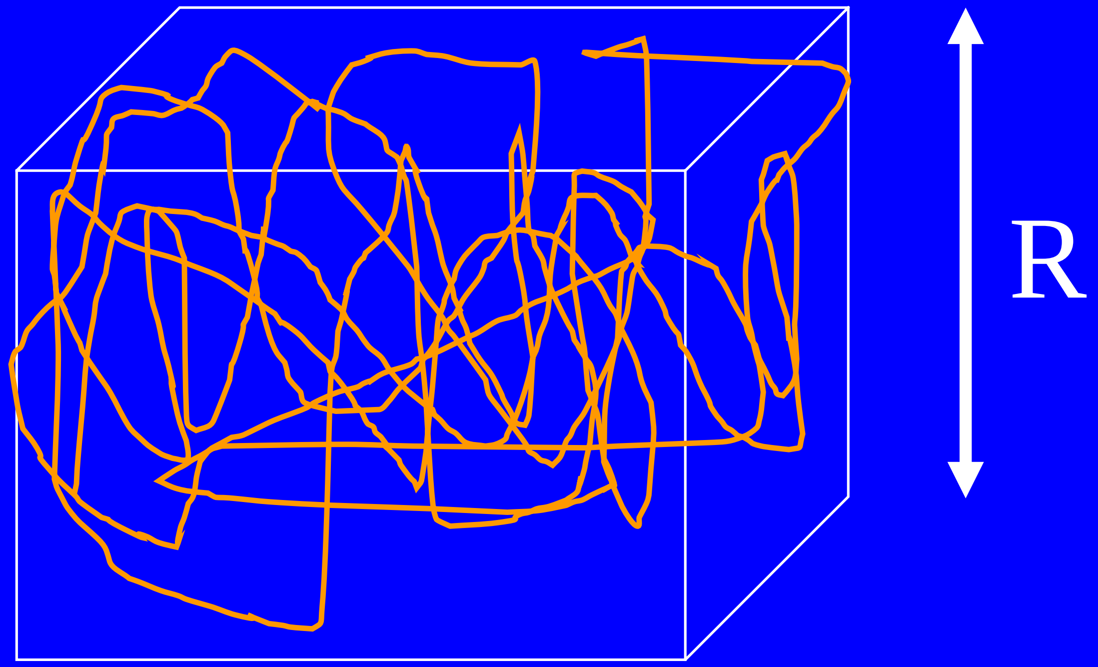


Credit: Martens

Dominated by long string(s) : entropically favourable

Free long string ←→ Random walk

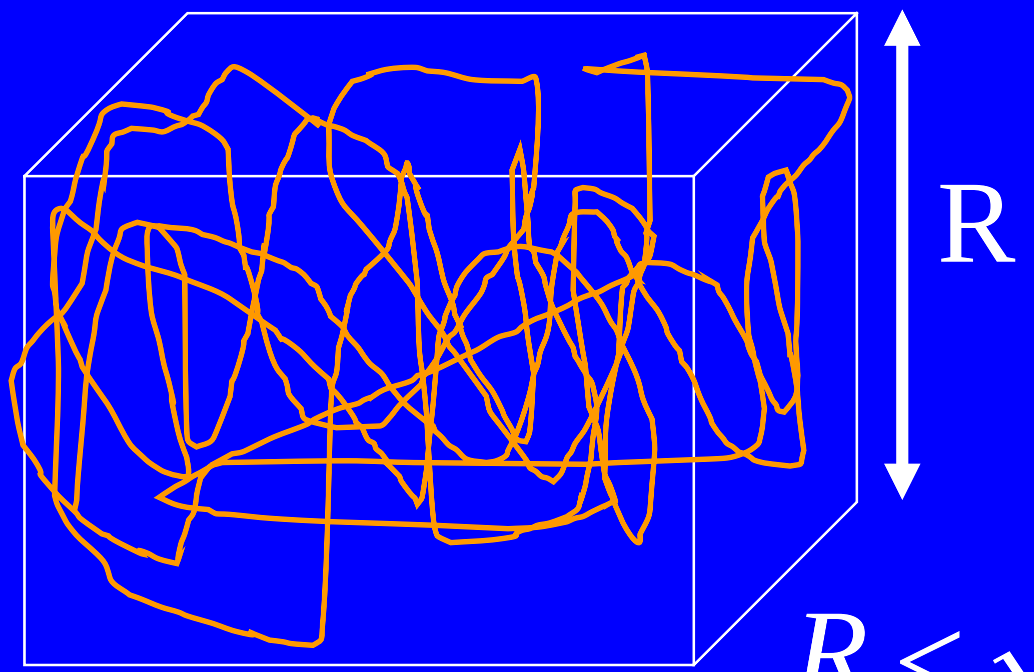
$$R = \sqrt{L}$$



Highly excited strings in a bounded region

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

Closed strings
Total length L



$R < \sqrt{L}$

Dominated by long strings

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

$$\ell \sim L$$

$$\nu = 1/(d-1)$$

Area law

Flory-Huggins theory of polymers

Bound state of highly excited strings:

quadratic free energy (a “collapsed polymer”)

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

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

$$V \sim R^d$$

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

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

$$c = \epsilon / g_s^2$$

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

$$c = N/V$$

Extremely complicated in terms of asymptotic fields

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

BH as a bound state of highly excited strings

$$R_S = \frac{l_s}{\epsilon} \qquad T_{Haw} = \epsilon \qquad g_s^2 = (l_P/l_s)^{d-1}$$

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

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

Lattice Gauge Theory model

Test in progress: Long Wilson loops in SU(N) lattice gauge theory slightly above the deconfinement temperature

Hanada, Maltz, Susskind, 1405.1732

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

$$\hat{H} = N\lambda_{YM} \sum_{\substack{\vec{x},\mu \\ \alpha=1,\dots,N^2}} \frac{1}{2}(E^{\alpha}_{\mu,\vec{x}})^2$$
$$- \frac{N}{\lambda_{YM}} \sum_{\vec{x},\mu,\nu} \frac{1}{2}\left(N - \mathrm{Tr}\left(U_\mu(\vec{x})U_\nu(\vec{x}+\hat{\mu})U^\dagger_\mu(\vec{x}+\hat{\nu})U^\dagger_\nu(\vec{x})\right)\right)$$

$$\lambda_{YM} \to \infty$$

$$\hat{K} = N \sum_{\substack{I \\ \alpha=1,\dots,N^2}} \frac{1}{2}(E^{\alpha}_{I})^2$$

After a field redefinition

$$\left[\hat{K}, W_{C_1,L_1}W_{C_2,L_2}\right]|0\rangle = \frac{1}{2}(L_1+L_2)W_{C_1,L_1}W_{C_2,L_2}|0\rangle$$
$$+ \frac{1}{2N}\sum_{I}\sum_{\substack{i=1,\dots,L_1 \\ j=1,\dots,L_2}} \delta_{I,J_i}\delta_{I,J_j} W_{C_1+C_2,L_1+L_2}|0\rangle + \cdots,$$

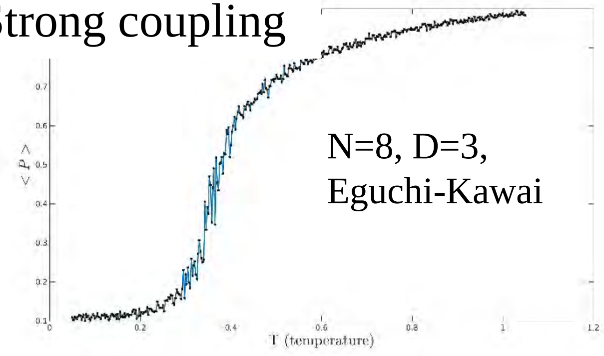
Lattice Gauge Theory model

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

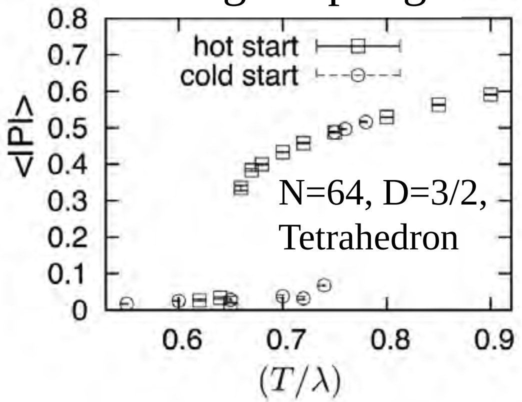
$$\frac{F_{YM}}{T_{Hag}} = -N^2 \frac{T - T_{Hag}}{T_{Hag}} + \frac{N^4}{N T_{Hag}^d V_{YM}} + \cdots ,$$

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

Strong coupling



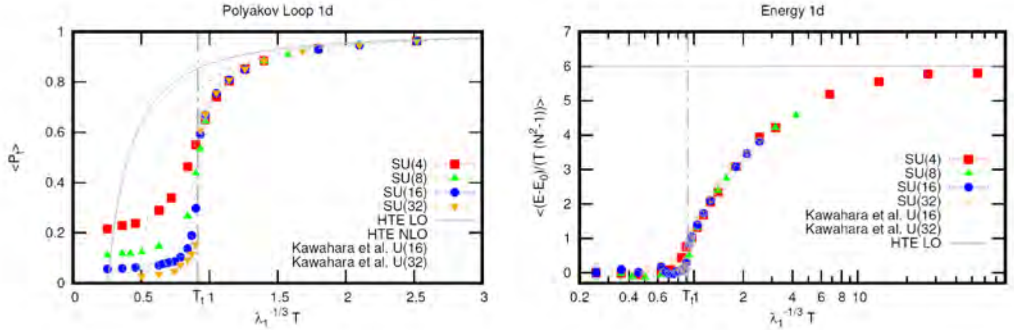
Strong coupling



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

Hanada, Maltz, Susskind, 1405.1732

Weak coupling

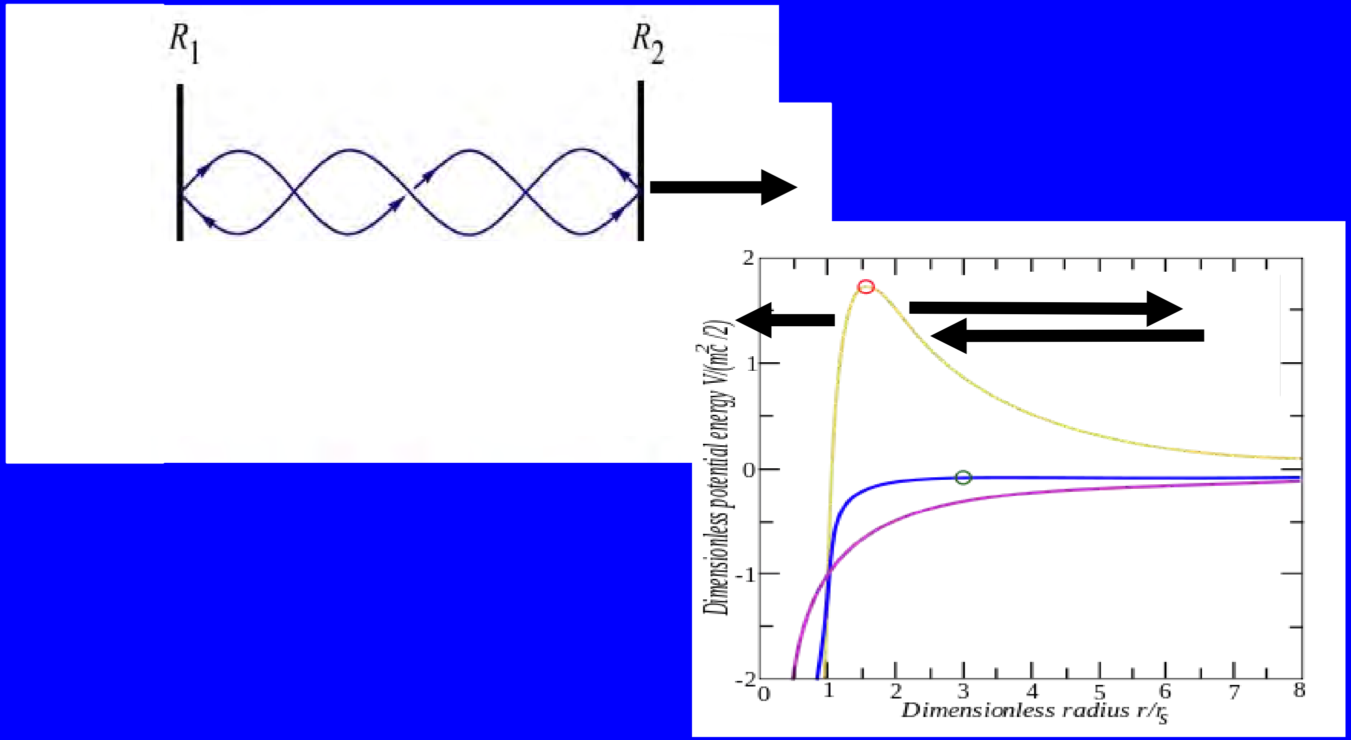


Hanada & Romatschke 1612.06395

Quantum hair out of equilibrium
“supersized” Hawking radiation

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



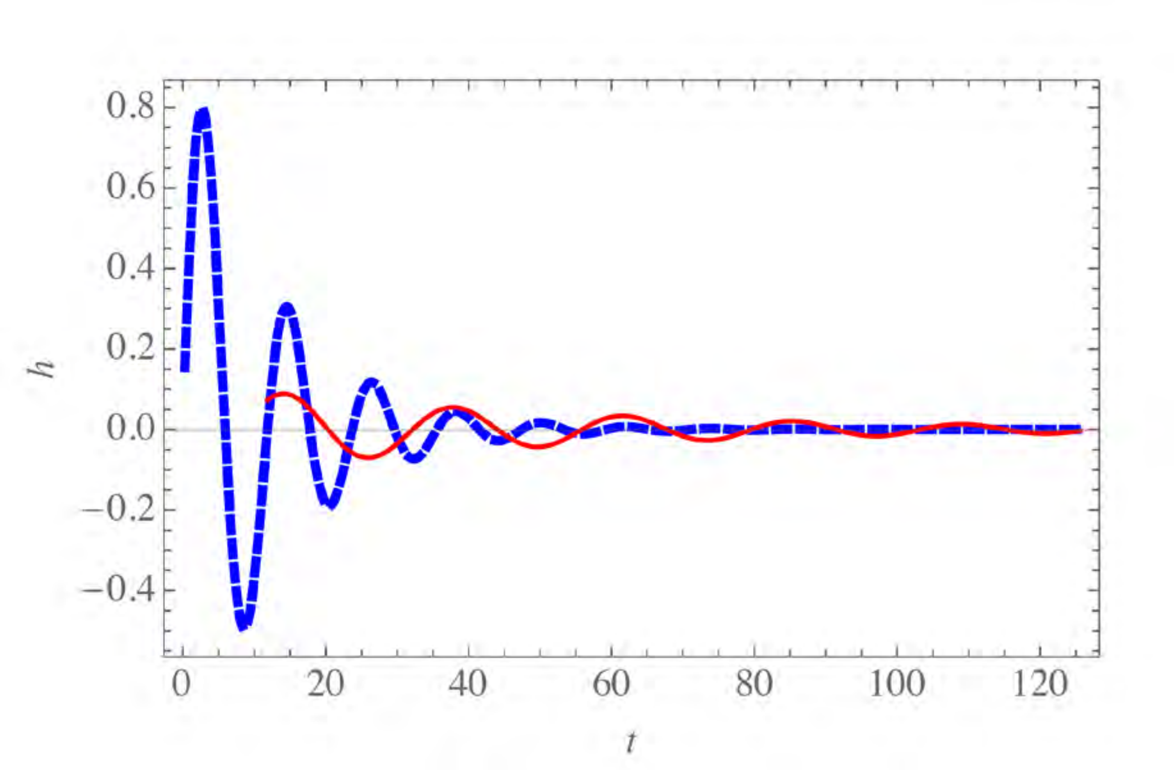
<u>Intrinsic dissipation</u>
Only matter that saturates KSS-like bound can support waves!

Standard QNM's – Fluid modes

- As for ultra-compact relativistic stars, the real part of the frequency is determined by the speed of sound v_{sound}
- For any BH-like object, the spatial scale of the interior is Rs
- ➔ $v_{sound} \leq c/R_S$

$$\omega_R \leq c/R_S$$

- + a time delay



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 !

$$v_{sound}^2 = p/\rho$$

$$\Delta p = -\Delta(F/V)$$

Non-relativistic "fracture modes"

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

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

$$F \sim \epsilon N + g_s^2 \epsilon N + \cdots$$

$$v_{sound}^2 = \Delta F/E = g_s^2$$

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

New QNM's – Fluid modes

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

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

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

$$v_{sound} < 1$$

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

- Paremetrically smaller frequencies
- Parematerically longer damping times

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

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

- Intrinsic dissipation

QNM's can survive *only* if KSS bound saturated !

$$\frac{1}{\tilde{\tau}} = (\ell-1)(2\ell+1)\int_0^{R_S} dr\, r^{2\ell}\eta\left(\int_0^{R_S} dr\,\rho r^{2\ell+2}\right)^{-1}$$

$$\frac{1}{\tilde{\tau}} = \frac{25}{16\pi}\frac{v_{sound}^2}{c^2}\frac{c}{R_S}$$

$$\rho = 1/(g_s^2 r^2) \qquad \eta = s/(4\pi) = 1/(4\pi g_s^2 r)$$

$$\frac{1}{\tilde{\tau}} = (\ell-1)(2\ell+1)\int_0^{R_S} dr\frac{1}{4\pi}r^{2\ell-1}\left(\int_0^{R_S} dr r^{2\ell}\right)^{-1} = \frac{1}{4\pi}\frac{(\ell-1)(2\ell+1)^2}{2\ell}\frac{c}{R_S}$$

$$\tilde{\tau} = 2\frac{1}{g_s^2}\frac{R_S}{c} \simeq 2\tau_{damp}$$

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

$$\frac{1}{\tilde{\tau}} = \frac{25}{16\pi}\frac{c}{R_S}$$

See also Yunes, Yagi, Pretorius 1603.08955

$$\bar{\eta}_{\rm eff} \sim 4\times 10^{28}\frac{\rm g}{\rm cm\cdot s}\left(\frac{m}{65M_\odot}\right)\left(\frac{370{\rm km}}{R}\right)\left(\frac{4{\rm ms}}{\tau_{\bar{\eta}}}\right) \qquad \bar{\eta} = \frac{1}{(\ell-1)(2\ell+1)}\frac{\rho R^2}{\tau_{\bar{\eta}}}$$

$$\bar{\zeta}_{\rm eff} \sim 3\times 10^{30}\frac{\rm g}{\rm cm\cdot s}\left(\frac{m}{65M_\odot}\right)\left(\frac{370{\rm km}}{R}\right)\left(\frac{4{\rm ms}}{\tau_{\bar{\zeta}}}\right) \qquad \bar{\zeta} = \left(\frac{5}{3}\right)^4\frac{2(2\ell+3)}{\ell^3}\frac{\rho R^2}{\tau_{\bar{\zeta}}}$$

Estimate of gravitational-wave emission

Strength of the coupling of the fluid modes to the emitted GWs estimated using the quadrupole formula

$$h \sim \frac{M}{r}\frac{d^2Q}{dt^2}$$

Two perspectives on the strength of the quadrupole lead to the same estimate

Interior

$$\frac{E_{frac}}{E_{st}} \sim g_s^2$$

Exterior

$$E_{frac} \sim E_{st}T_{hor} \sim E_{st}g_s^2$$

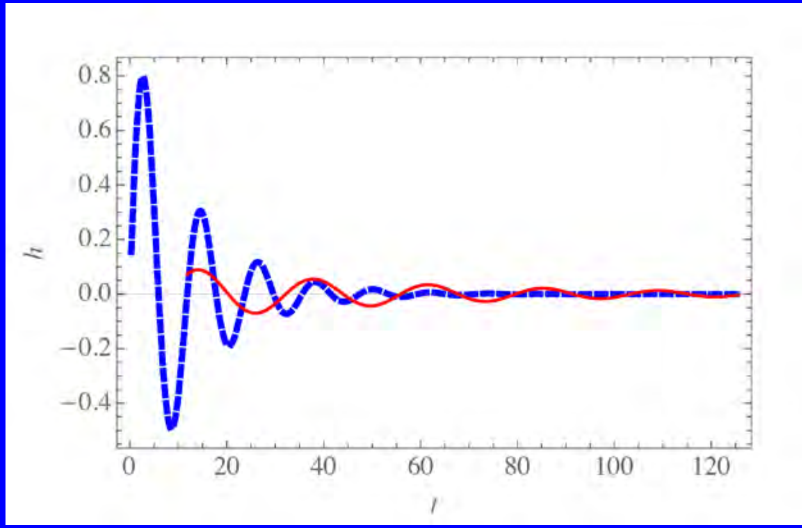
$$\omega_{frac}^2/\omega_{st}^2 \simeq g_s^2$$

$$\frac{h_{frac}}{h_{st}} \simeq \frac{E_{frac}}{E_{st}}\frac{\omega_{frac}^2}{\omega_{st}^2} \simeq (g_s^2)^2$$

Summary of results:

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

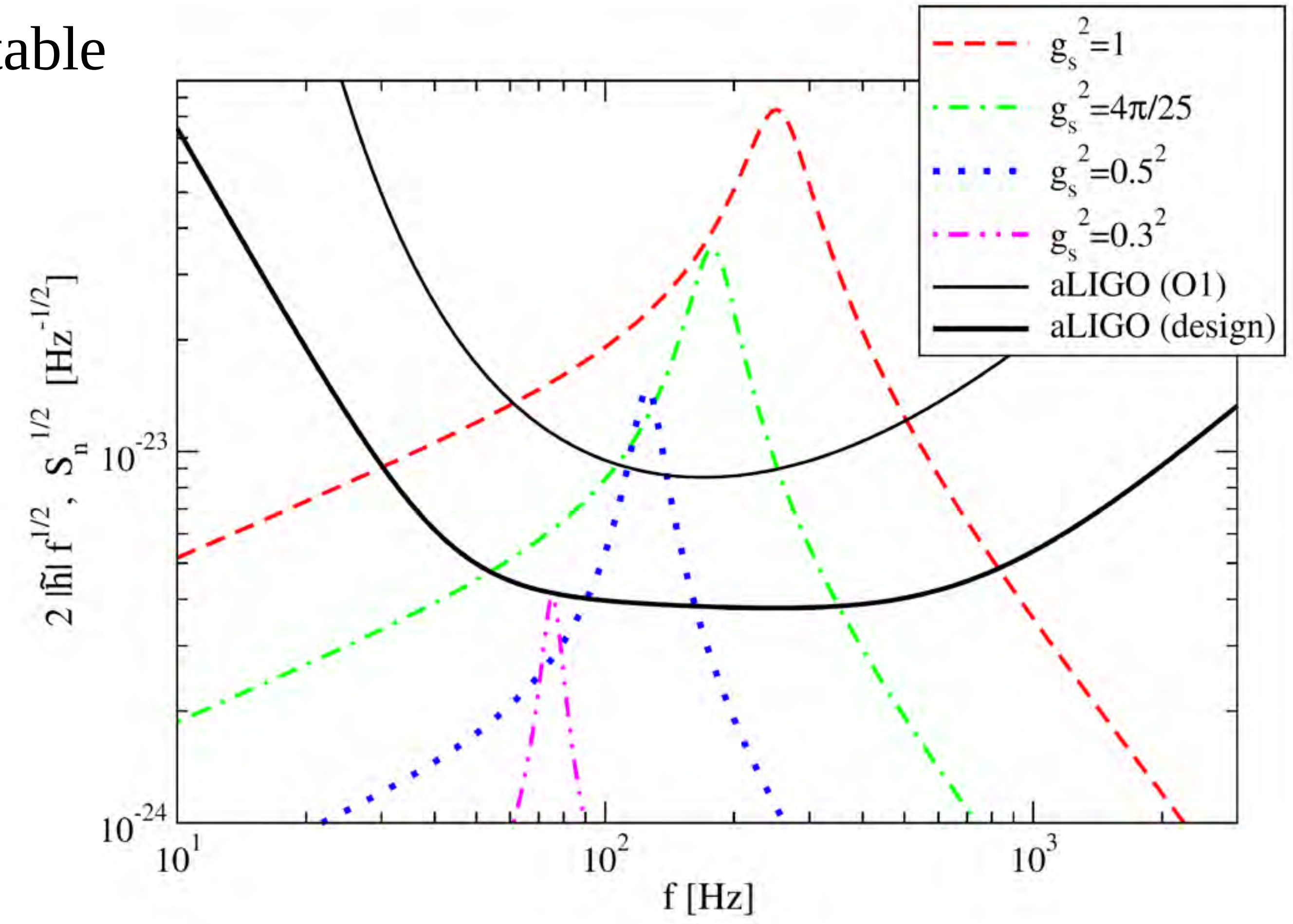
Reasonable estimate　　Very reliable　　Reliable

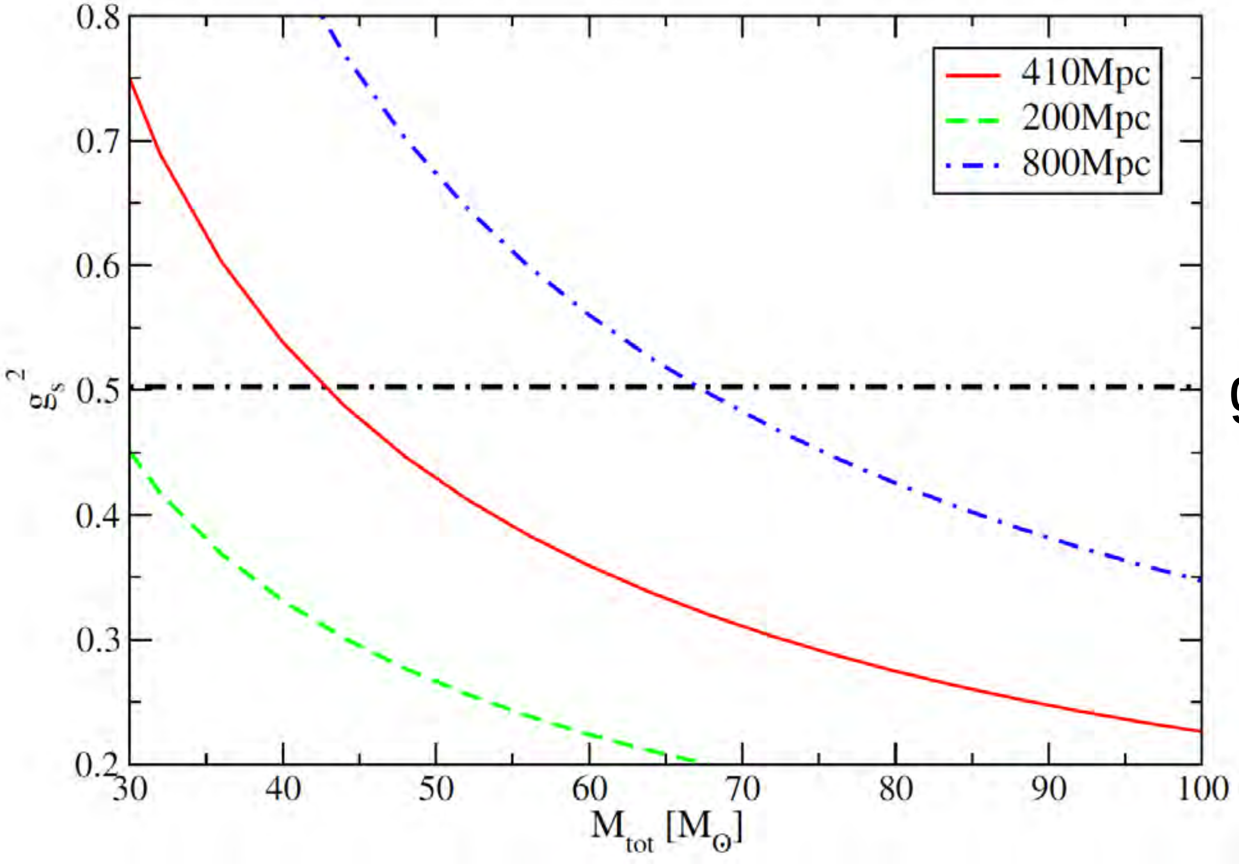


Bounds from GW observations for GW150914

Ratio signal/noise ~ SNR. The spectrum is detectable if SNR> 5.

For $g_s^2= 1$, amplitude, frequency and damping time for the polymer modes are the same as those of a classical BH.





$g^2 = 4\pi/25$

Projected upper bound on g^2 as a function of the total mass of an equal-mass BH binary at various distances using aLIGO's design sensitivity.
The upper bound on g^2 scales with $r^{2/3}$.

Summary & Conclusions

RB+ Medved
1602.07706
1607.03721

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