Title: Echoes and Quadratic Gravity

Speakers: Bob Holdom

Collection: Echoes in Southern Ontario

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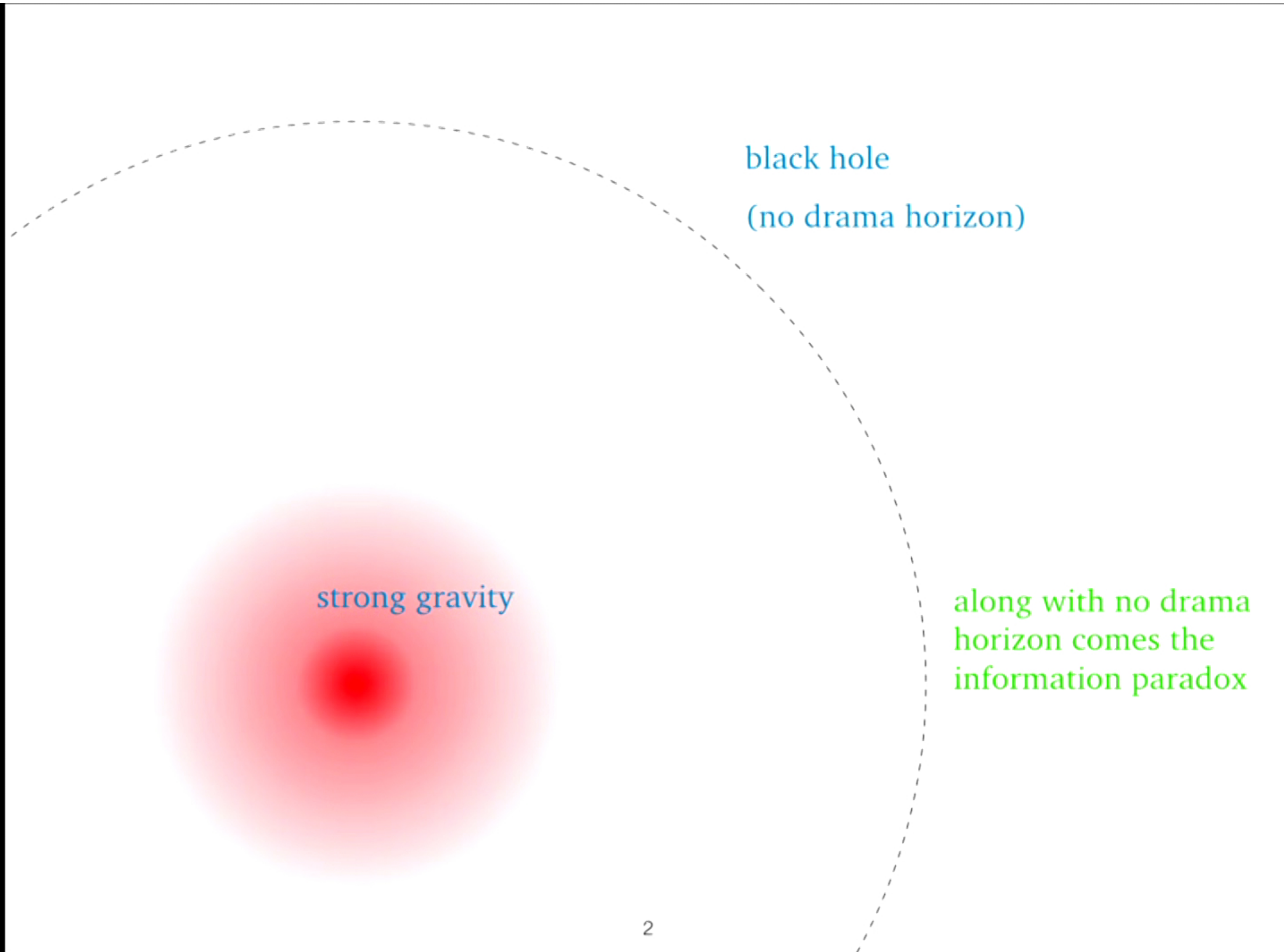
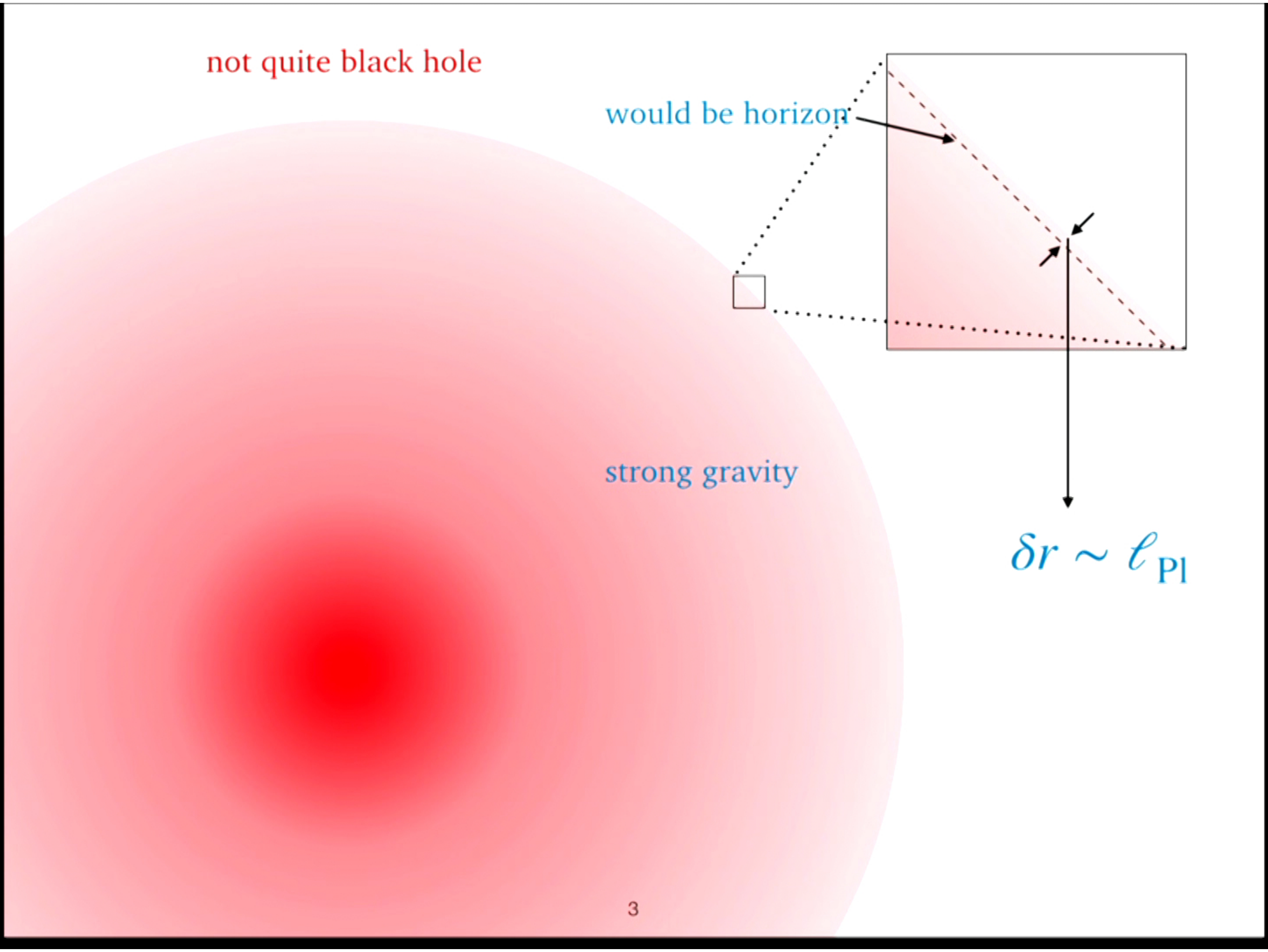

black hole
(no drama horizon)
strong gravity
along with no drama horizon comes the information paradox
2


not quite black hole
would be horizon
strong gravity
$\delta r \sim \ell_{\mathrm{Pl}}$
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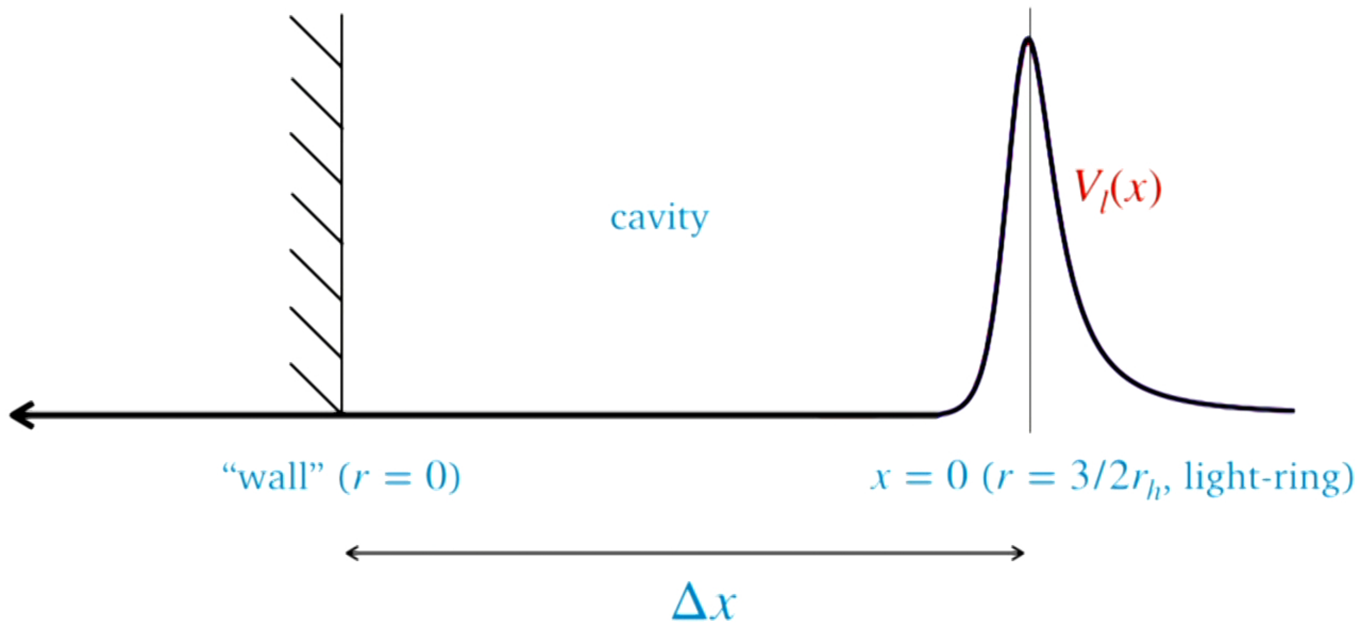
basic echo picture

- start with scalar wave equation in Schd background using tortoise coordinate x

$$(\partial_x^2 + \omega^2 - V_l(x))\Psi_l = 0$$

- black hole:

- for not quite black holes, waves have a finite travel time to the origin
- implies a boundary at a finite tortoise coordinate



- round trip travel time in cavity is $\Delta t = 2\Delta x$

my path to LIGO data

- consider quantum gravity as a QFT, in analogy with QCD
  - adapt an old proposal for a UV completion of gravity, quadratic gravity

- reconsider ghost in this 'QCD-like' theory
  - naive perturbative states and physical spectrum are different
  - naive ghost → unstable state with slight acausality

- study the "not quite black hole" solutions

Lucky break 1: Cardoso and Pani point out connection between ECOs and echoes

- our solutions are natural ECOs with echo time delay Δt roughly predicted

Lucky break 2: LIGO releases public data

- join Afshordi & Co and other outsiders looking for echoes, but with our own strategy

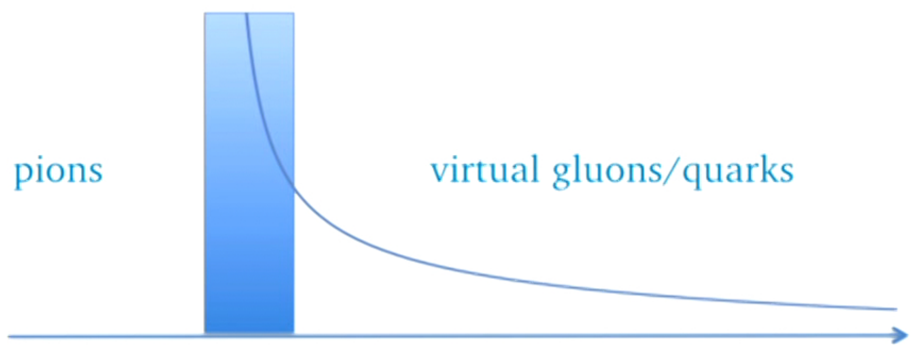
Lucky break 3: LIGO does not take over the echo search themselves

- can gradually figure out what we are doing
  - recently obtained p-values for signals in 10 BH merger events

collaborators

- my former postdoc Jing Ren has been involved from the beginning
  - now on the IHEP faculty in Beijing
- my student Randy Conklin has been involved with echoes
- the echo search that I am reporting on is being done on my own

how does nature generate a mass scale?



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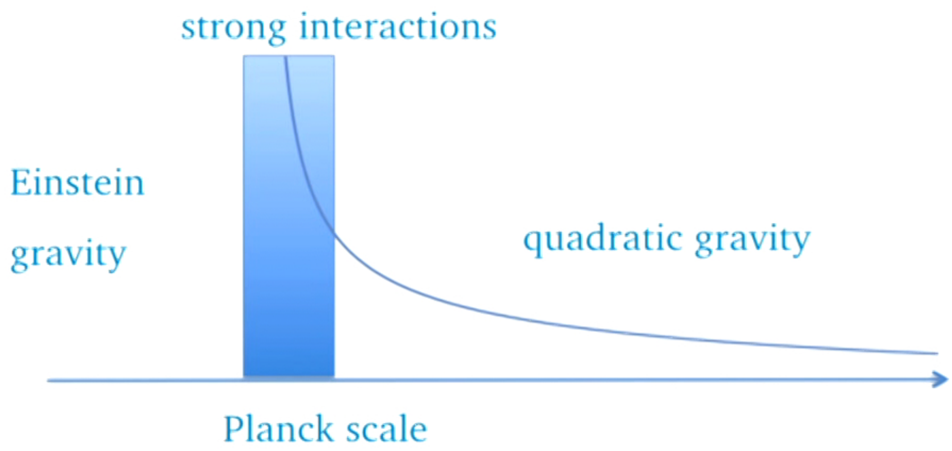
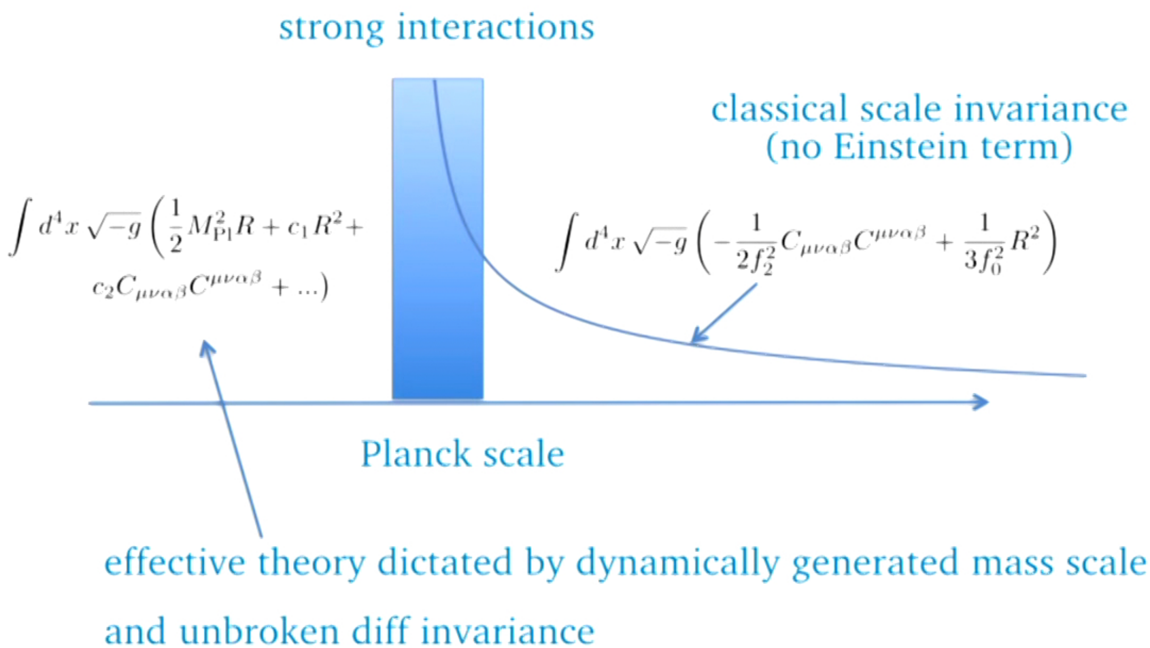
can the same work for the Planck mass?




strong interactions
classical scale invariance
(no Einstein term)
$\int d^4x\,\sqrt{-g}\left(\frac{1}{2}M_{\rm Pl}^2 R + c_1 R^2 + c_2 C_{\mu\nu\alpha\beta}C^{\mu\nu\alpha\beta} + \ldots\right)$
$\int d^4x\,\sqrt{-g}\left(-\frac{1}{2f_2^2}C_{\mu\nu\alpha\beta}C^{\mu\nu\alpha\beta} + \frac{1}{3f_0^2}R^2\right)$
Planck scale
effective theory dictated by dynamically generated mass scale
and unbroken diff invariance

no black holes in nature?

- UV complete theory allows for a different endpoint of gravitational collapse
- "not quite black hole" solutions have a low curvature exterior region where the Einstein term dominates and a high curvature interior region where the quadratic terms dominate
  - thus the interior structure probes the UV completion

- solutions obtained by replacing quantum theory by a classical approximation

$$S_{\rm CQG} = \frac{1}{16\pi}\int d^4x\,\sqrt{-g}\,\left(M_{\rm Pl}^2 R - \alpha C_{\mu\nu\alpha\beta}C^{\mu\nu\alpha\beta} + \beta R^2\right)$$

- this action has high and low curvature limits similar to the quantum theory

$$ds^2 = -B(r)dt^2 + A(r)dr^2 + r^2 d\theta^2 + r^2 \sin^2\theta d\phi^2$$

$$A(r) \sim r^2 + \mathcal{O}(r^4)$$

$$B(r) \sim r^2 + \mathcal{O}(r^4)$$

$\rightarrow$ "2-2-hole"

$g_{\mu\nu} \rightarrow 0$ at $r = 0$

- naked time-like singularity

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wave equation is nonsingular

- $\Box\varphi = 0$ with $\varphi = \sum_{lm} \psi_l(r,t) Y_{lm}(\theta,\phi)$

$$\partial_t^2 \psi_l = \frac{B}{A}\partial_r^2 \psi_l + \frac{B}{A}\left(\frac{2}{r} + \frac{B'}{2B} - \frac{A'}{2A}\right)\partial_r \psi_l - B\frac{l(l+1)}{r^2}\psi_l$$

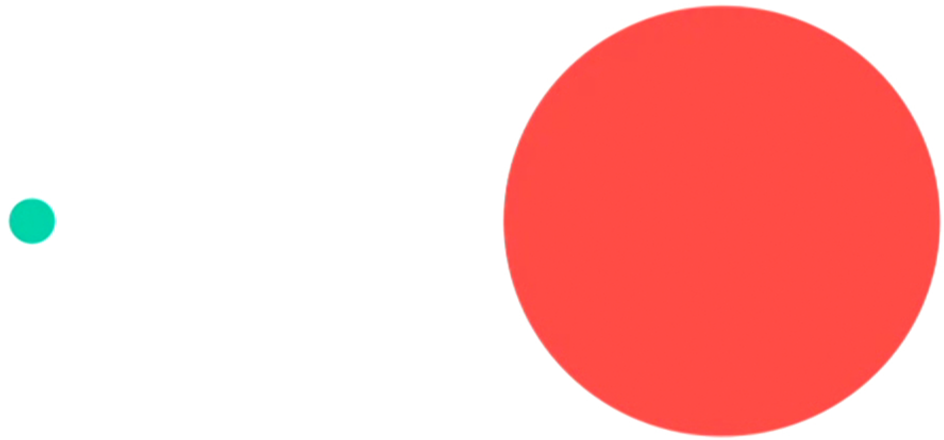
this term is now finite

- no centrifugal barrier term
- all waves behave as $l = 0$ waves (s-waves) near the origin

- and as usual there is only one finite energy solution
- thus singularity introduces no ambiguity or ill-defined time evolution

- boundary condition at the origin is determined

- 2-2-holes come in two types:

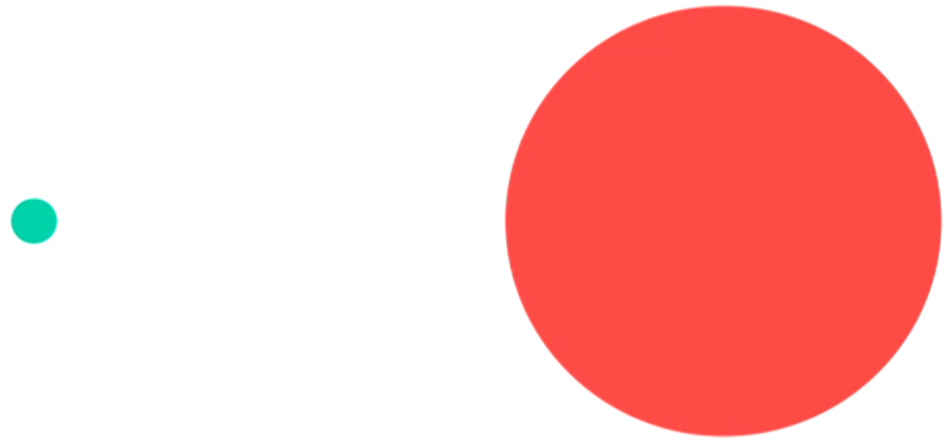


smallest ones with Planck size

large ones with no upper limit on size

- inner structure of the two types is quite different
- different size large ones have interiors related by a scaling relation

- not unlike QCD:



hadrons with fixed size

variable size quark matter states
that extend up to neutron star size

- in both cases we have macroscopically large objects
- interiors have suppressed chiral condensate (QCD) or volume element (gravity)

- αC^2 term in action is essential for 2-2-hole solutions
- solutions were found by using a thin shell as matter source

- then solutions were found sourced by relativistic gas ($\rho = 3p$)
- local temperature is $T(r) = T_\infty B(r)^{-1/2}$ (hydrostatic equilibrium)

- well-defined and easy to calculate entropy — linked to ordinary hot gas
- gives an area law for entropy

- thermodynamics and geometry are explicitly linked
- thermodynamics and particle content of the universe are linked

- field equations determine $A(r)$, $B(r)$ and $\tilde{N}T_\infty^4$
- $\tilde{N} = N/(2\alpha)$ and $N =$ species number

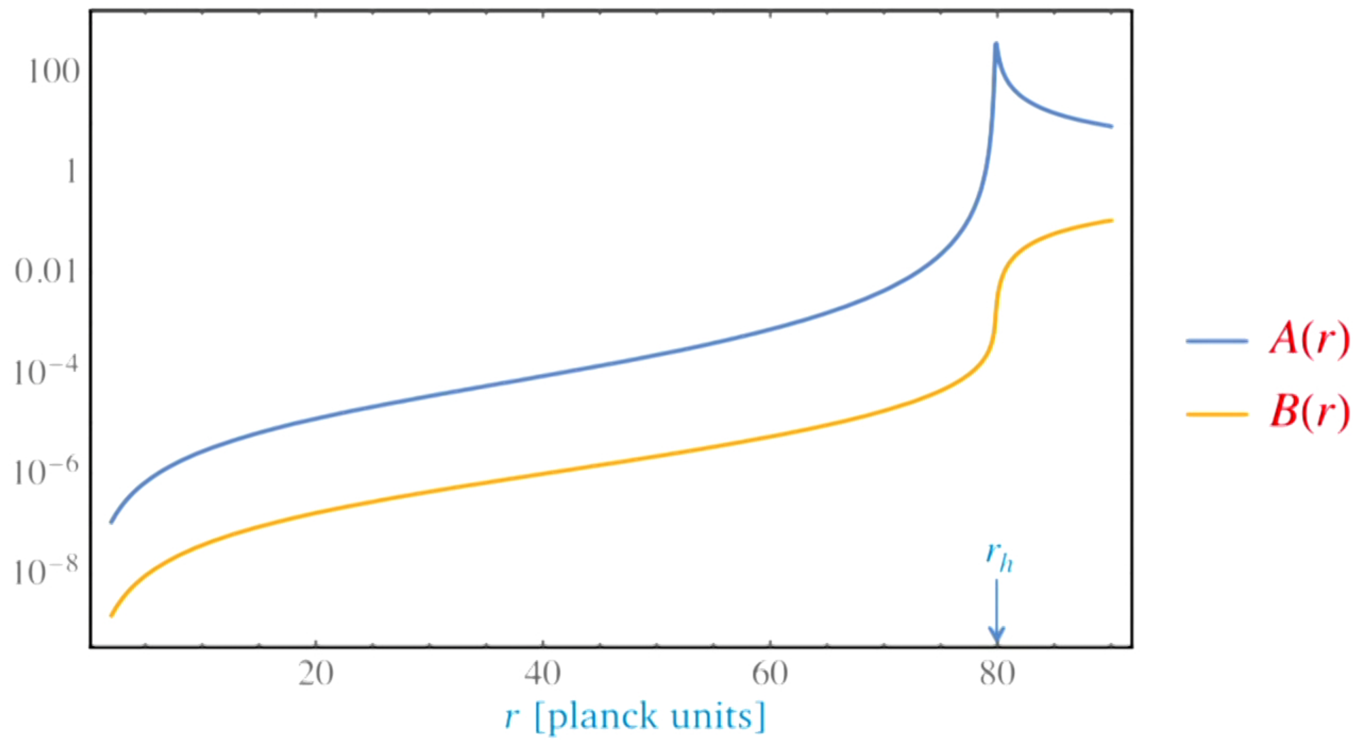
$$T_\infty \approx 1.33\tilde{N}^{-1/4}T_{\mathrm{Hawking}}$$

$$S = \frac{(2\pi)^3}{45}N\int_0^L T(r)^3 A(r)^{1/2} r^2 dr \approx 0.75\tilde{N}^{1/4}\frac{\mathrm{Area}}{4\ell_{\mathrm{Pl}}^2}$$

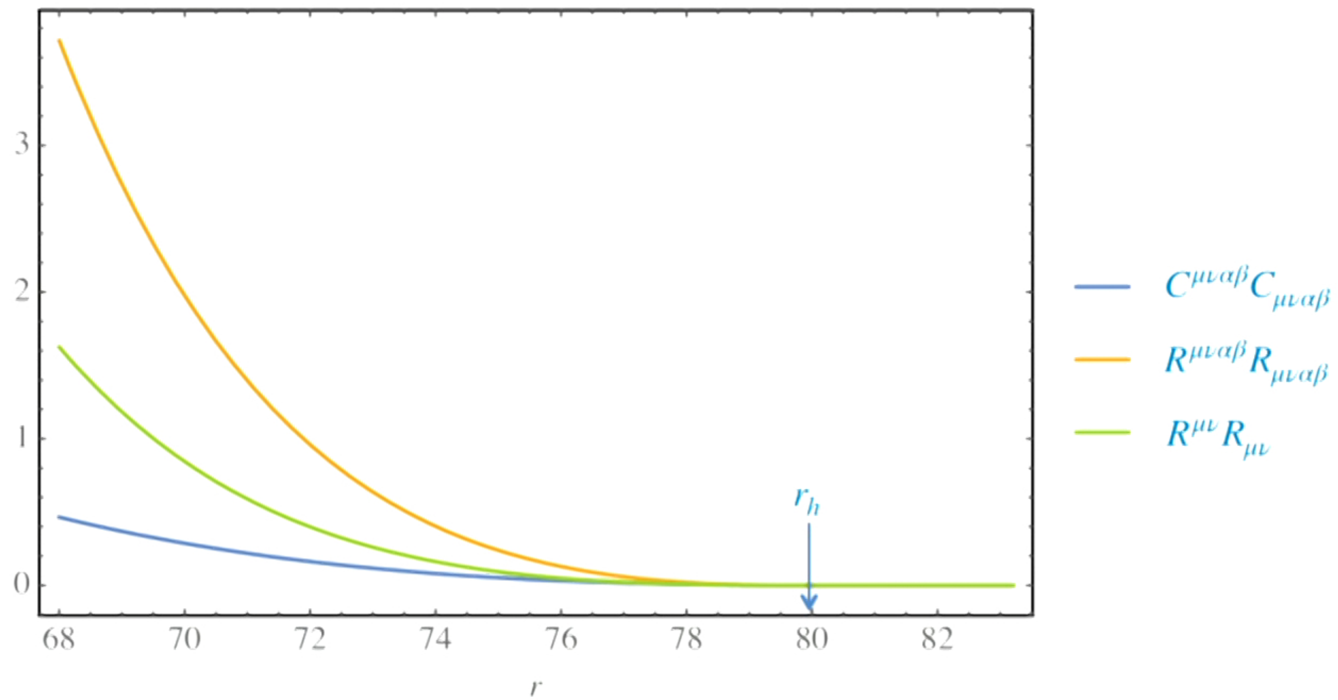
$$T_\infty S = \frac{M}{2}$$

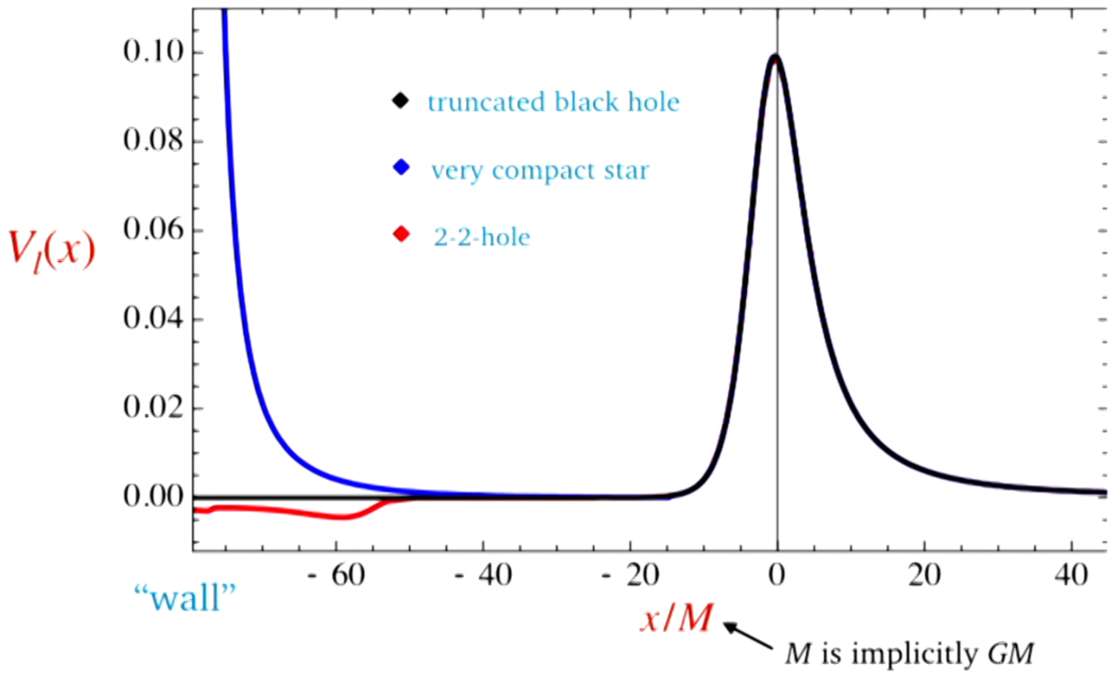
$$U = \frac{3}{4}T_\infty S = \frac{3}{8}M$$

- since $0.75\tilde{N}^{\frac{1}{4}} > 1$, entropy of 2-2-hole is larger than same size black hole
- thus gravitational collapse to 2-2-hole can be favored over BH


100
1
0.01
10^{-4}
10^{-6}
10^{-8}
20
40
60
80
r_h
r [planck units]
$A(r)$
$B(r)$

- curvature invariants turn on smoothly below $r = r_h$





- a 2-2-hole, like a star, has an origin ($r = 0$), not an artificial wall
- but a truncated black hole (artificial wall just outside the horizon) is not bad approximation to a 2-2-hole
- this approximation is all we have when there is spin

the cavity structure

- the effective radial description of low frequency waves is that of a 1D cavity with one end that slightly leaks
- pulse moving back and forth in the cavity produces echoes

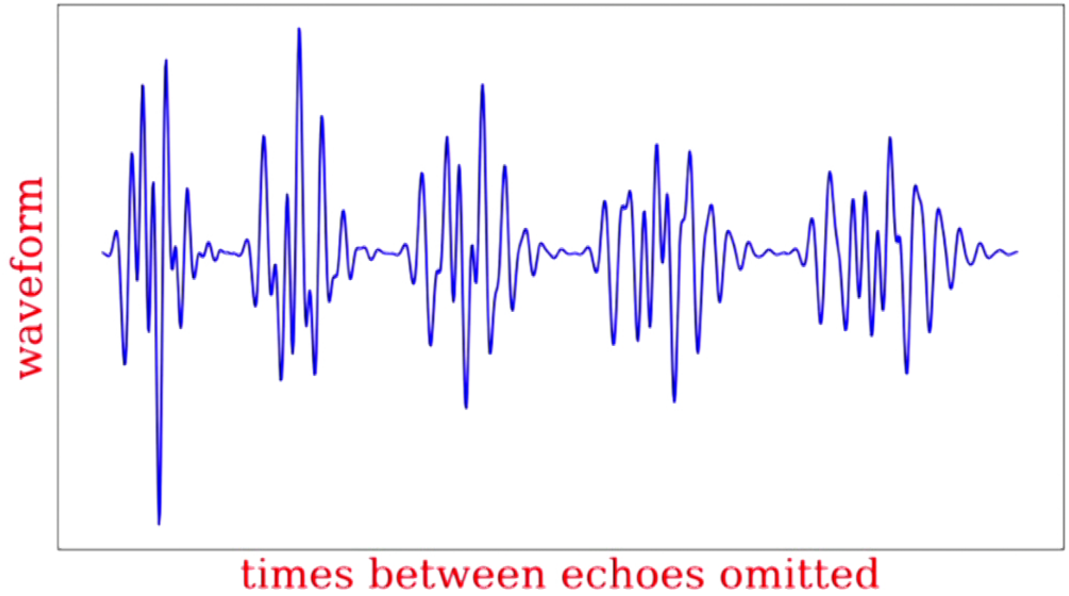
- but what if the perturbed state of a newly formed not quite BH is more complicated, resulting not in a simple pulse moving back and forth?
    - there might not be a simple echo structure

- a 1D cavity has a more general feature: an evenly spaced resonance spectrum

$$\Delta f = \frac{1}{2\Delta x} = \frac{1}{\Delta t}$$

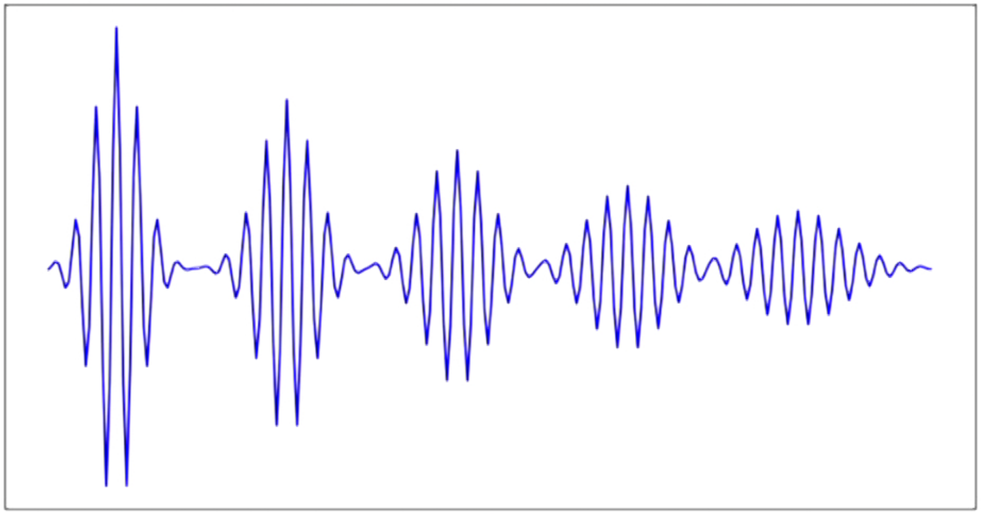
- LIGO should be thinking of a resonance search!

- even one pulse moving back and forth gives a nontrivial waveform
- first 5 echoes, with inactive time between echoes removed

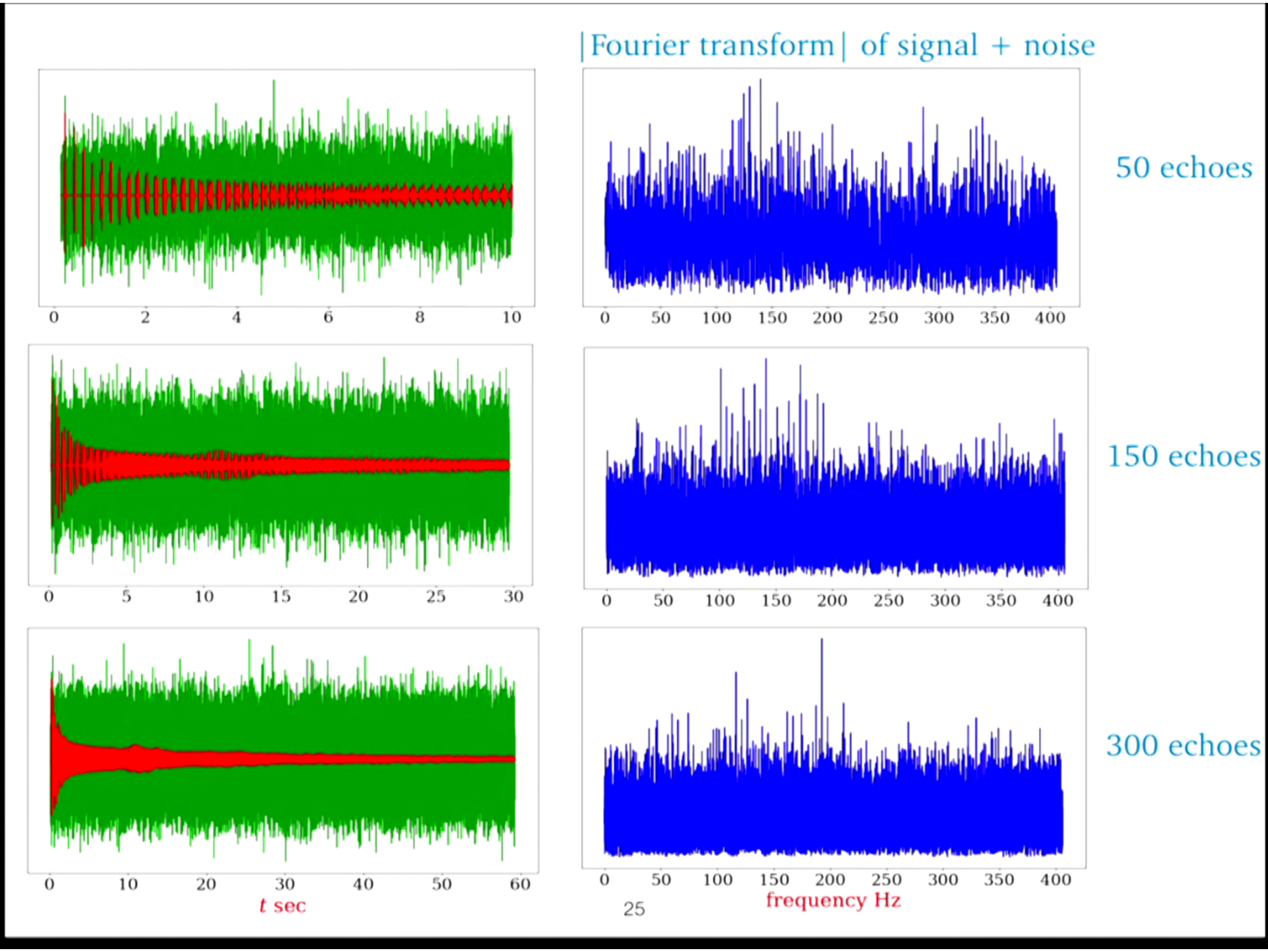


- rather more difficult to model than the merger waveform

- a LIGO echo search (Tsang et. al., 1906.11168)
- templates are generalized sine-Gaussians, each with 9 parameters



- a superposition of N such waveforms was used: needs $9N$ parameters
- sensitivity then goes like $\sim 1/\sqrt{9N}$


|Fourier transform| of signal + noise
50 echoes
150 echoes
300 echoes
0 2 4 6 8 10
0 5 10 15 20 25 30
0 10 20 30 40 50 60
t sec
0 50 100 150 200 250 300 350 400
frequency Hz
25