Institute of High Energy Physics
Chinese Academy of Sciences

Not quite a black hole

— from quadratic gravity to gravitational wave echoes

Jing Ren (任婧)

Theoretical Physics Division, IHEP

ICTS Seminar, UCST

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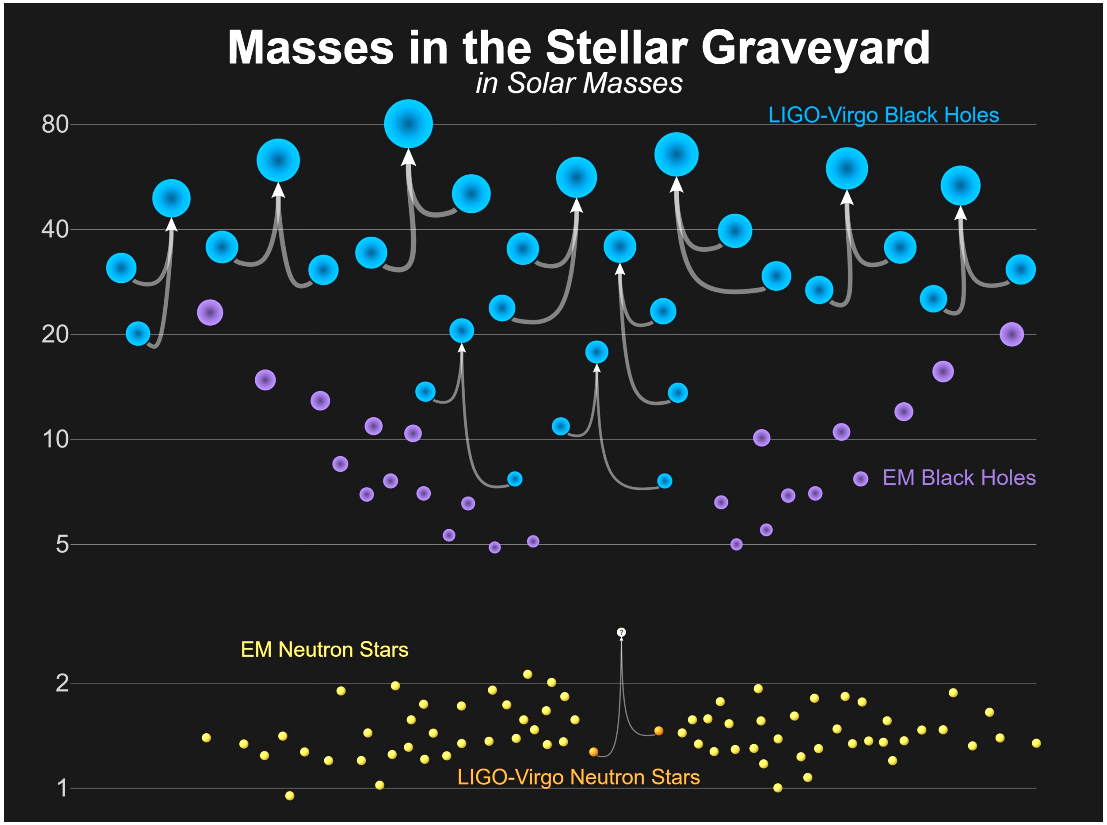
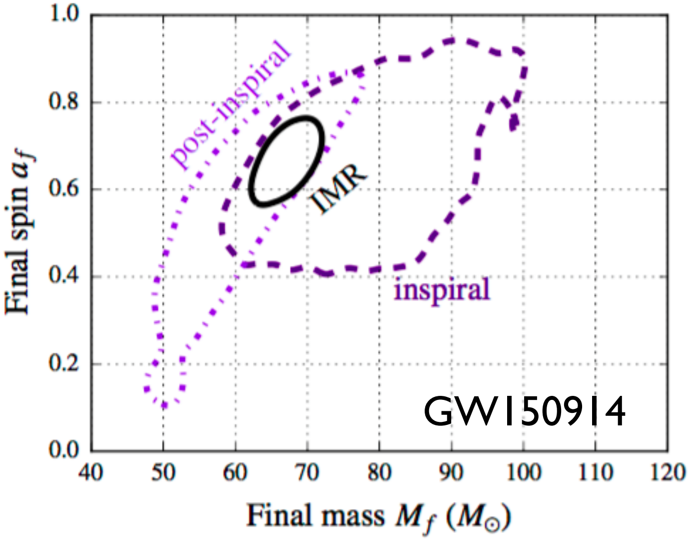
collaboration with Bob Holdom, arXiv: 1512.05305, 1605.05006, 1612.04889, ongoing…
collaboration with Randy Conklin and Bob Holdom, 1712.06517

LIGO/Virgo detection of gravitational wave from compact binary coalescence



Nice agreement with GR prediction for binary black holes

- *Inspiral*: large mass and high compactness
- *Merger*: numerical relativity
- *Ringdown*: least-damping quasinormal mode



Q: Do astrophysical black holes have event horizons?

A: Maybe not if they are *horizonless ultracompact objects (UCOs)*, which resemble *BHs* closely from the exterior…

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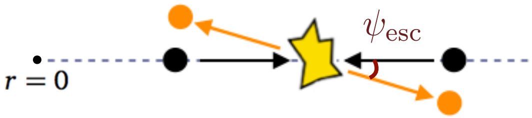
Electromagnetic radiation: efficient trapping (appear black)

Geodesic motion (short wavelength)



Escape cone for outgoing particles, very small in the high redshift region

$$\sin\psi_{\rm esc} = 3M\sqrt{3f_0}/r_0$$

$$f_0 = 1 - 2M/r_0 .$$

In the high redshift region, the internal collisions produce particles with large *L/E* out of the escape cone. A large trapped phase space is populated, with the escape fraction. The luminosity is extremely small!

Cardoso and Pani, arXiv:1707.03021 [gr-qc]

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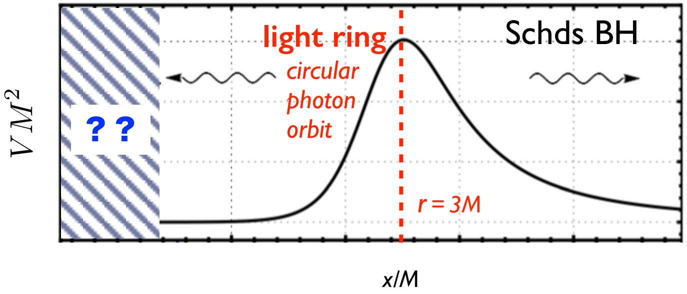
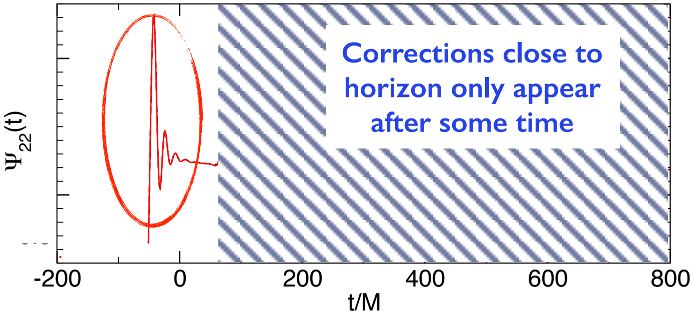
Gravitational waves: similar ringdown at early time

$$\left(\partial_x^2 + \omega^2 - V(x)\right) \psi_\omega(x) = S(x, \omega)$$

tortoise coordinate effective potential source



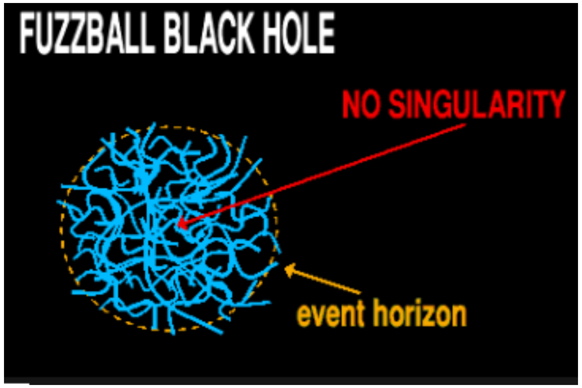


The dominant ringdown mode, $M\omega_{\rm RD} \approx 0.37 - i0.089$, is directly associated with the light ring potential barrier instead of the ingoing boundary condition at horizon. Need multiple QNMs to establish the existence of the black hole horizon.

Cardoso and Pani, arXiv:1707.03021 [gr-qc]

Theoretical motivation for *UCOs*

- *The black hole information loss paradox?* Drastic modification close to the horizon expected. Maybe the event horizon is never formed, and *UCOs* provide a natural way out.



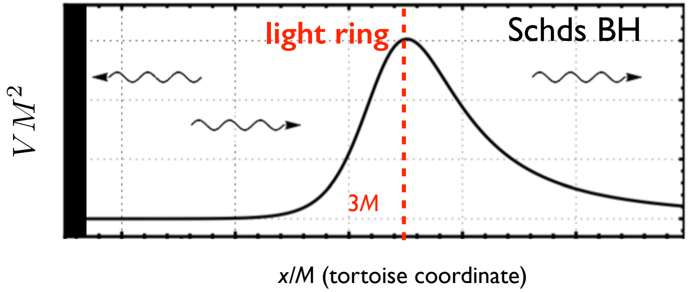
Mathur, Fortsch. Phys. 53, 793 (2005)

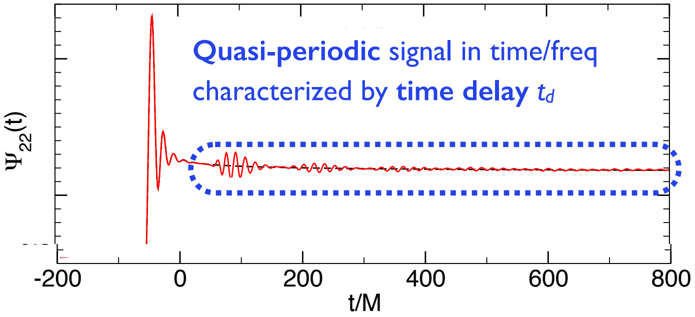
Mazur and Mottola, gr-qc/0109035

- *Fundamental connection with quantum gravity?* Given the big hierarchy between the cutoff $m_{\rm Pl}$ and curvature scale at horizon of macroscopic black holes $m_{\rm Pl}^2/M$, how *UCOs associated with quantum gravity effects* can be naturally produce (e.g. not clear in Fuzzball proposal)?

New observation for *UCOs*

- ***Gravitational wave echoes?*** After initial black hole ringdown, gravitational waves can be reflected out by the interior, and then impinge back on the potential barrier after some *time delay*, with some transmitted to the outside and some reflected back in. This process repeats and generates a distinct set of **echoes**.





- ***Echoes search in LIGO data?*** The matched filtering method suffers from great theoretical uncertainties for template construction. Need new method to extract generic features of echoes buried in the noise.

Outline

- Asymptotically free quadratic gravity
  - *A plausible UV completion of GR*
  - *A new perspective on quadratic gravity*

- A novel horizonless 2-2-hole
  - *Horizonless UCOs sourced by dense matter*
  - *Planckian deviation around would-be horizon*

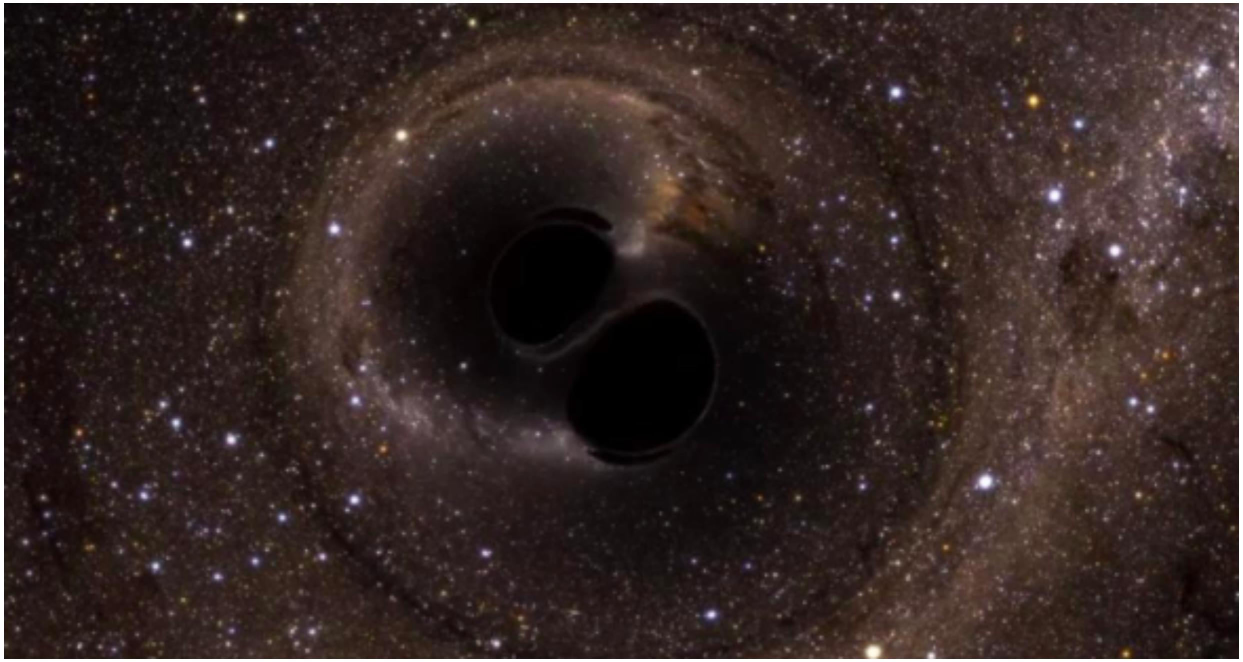
- Gravitational wave echoes through new windows
  - *Extract generic properties of echoes with window functions*
  - *Tentative signals from the LIGO data search*

- Summary and outlook

Asymptotically free quadratic gravity

Holdom, Ren, arXiv: 1512.05305, 1605.05006

(Gravity Research Foundation 2016 essay competition, 4th prize)



Asymptotically free extension of GR

GR is non-renormalizable: graviton loops create more powers of derivatives

$$S_{\rm GR} = \int d^4x\sqrt{-g}\left[M_{\rm Pl}^2\left(-\Lambda + \frac{1}{2}R\right) + c_1R^2 + c_2R_{\mu\nu}R^{\mu\nu} + \ldots\right]$$

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$$

($1/M_{\rm Pl}^2k^2$ propagator)

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Quantum Quadratic Gravity: an old candidate of quantum gravity, generalize GR with all quadratic curvature terms

$$S_{\mathrm{QQG}} = \int d^4x\,\sqrt{-g}\left(\frac{1}{2}\mathcal{M}^2R-\frac{1}{2f_2^2}C_{\mu\nu\alpha\beta}C^{\mu\nu\alpha\beta}+\frac{1}{3f_0^2}R^2\right)$$

- Perturbatively renormalizable Stelle, PRD 16, 953 (1977)

  Power counting changes behaviors: $1/k^4$ propagator softens UV divergence

- Asymptotically free Fradkin, Tseytlin, NPB 201, 469 (1982); Avramidi, Barvinsky, PLB 159, 269 (1985)

$$\frac{df_2^2}{dt} = -\left(\frac{133}{10}+a_m\right)f_2^4,\quad \frac{1}{f_2^2}\frac{dw^2}{dt} = -\left[\frac{5}{12}+w\left(5+\frac{133}{10}+a_m\right)+\frac{10}{3}w^2\right]$$

$w = f_2^2/f_0^2$

$a_m > 0$

Wait … "the ghost problem" ?

$$S_{\rm QQG} = \int d^4x\,\sqrt{-g}\left(\frac{1}{2}\mathcal{M}^2 R - \frac{1}{2f_2^2}C_{\mu\nu\alpha\beta}C^{\mu\nu\alpha\beta} + \frac{1}{3f_0^2}R^2\right)$$

Standard picture: running couplings remain weak at the mass scale $\sim |f_i\mathcal{M}|$, the perturbative spectrum has a *massive, spin-2 ghost* (different from the Faddeev-Popov ghost)

$$\frac{-i}{k^2(k^2-M_2^2)} = \frac{1}{M_2^2}\left(\frac{i}{k^2} - \frac{i}{k^2-M_2^2}\right) \qquad M_2^2 = \tfrac{1}{2}f_2^2\mathcal{M}^2$$

Negative energy *(vacuum instability)* or negative norm *(unitarity problem)??*

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Ongoing effort to resolve the ghost problem in the perturbative theory

- Lee-Wick theory: *Lee, Wick (1969, 1970); Cutkoski, Landshoff, Olive and Polkinghorne (1969); Tomboulis (1980); Boulware, Gross (1984)…*
- Lee-Wick theory (continue): *Grinstein, O'Connell, Wise (2009); Anselmi, Piva (2017); Donoghue (2018)…*
- PT symmetry and non-Hermitian theory: *Bender, Mannheim (2008)…*
- Modify quantum interpretation: *Salvio, Strumia (2016)…*
- …

CERN workshop: https://indico.cern.ch/event/740038/timetable/#all

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A new perspective: away from the perturbative regime!

If $\mathcal{M}$ is small and f_i^2 gets strong at some higher scale $\Lambda_{\mathrm{QQG}} > \mathcal{M}$, perturbative poles could be drastically modified by strong interactions. Taking into account non-perturbative effects, **the theory in the strong phase could be well-defined!**

Holdom, Ren, PRD 93, no. 12, 124030 (2016); IJMPD 25, no. 12, 1643004 (2016)

A QCD analogy for quadratic gravity

	QCD	QQG $(\mathcal{M} \lesssim \Lambda_{\rm QQG})$
UV behavior	perturbatively renormalizable, asymptotically free	
Strong scale	gauge coupling strong at $\Lambda_{\rm QCD}$	gravitational couplings strong at $\Lambda_{\rm QQG}$
Nonperturbative effects	the perturbative gluon removed from the physical spectrum and a mass gap developed as controlled by $\Lambda_{\rm QCD}$	

Analogy based on full propagators $(\mathcal{M} = 0)$

Gluon: $F(k^2)/k^2$ × (tensor factor) × (perturbative correction)

Graviton: $-G(k^2)/k^4$ × (tensor factor) × (perturbative correction)

the existence and the
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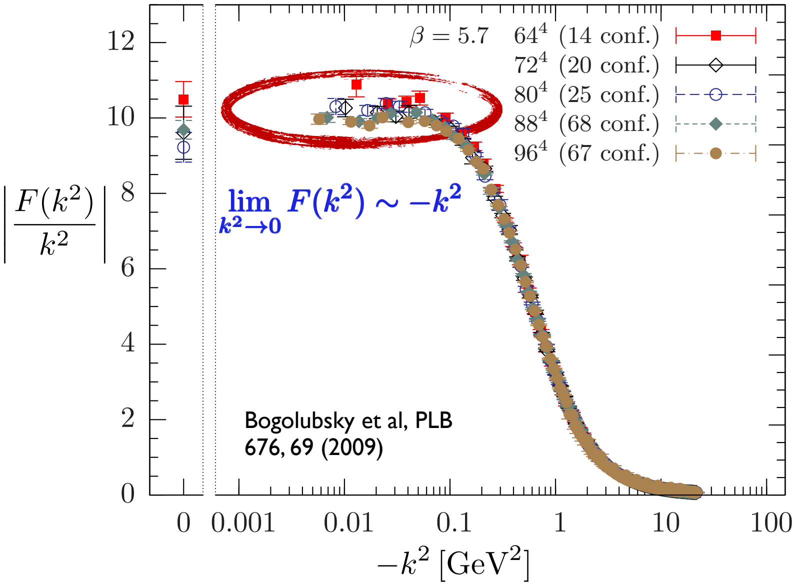

Bogolubsky et al, PLB 676, 69 (2009)

Lattice data in Landau gauge

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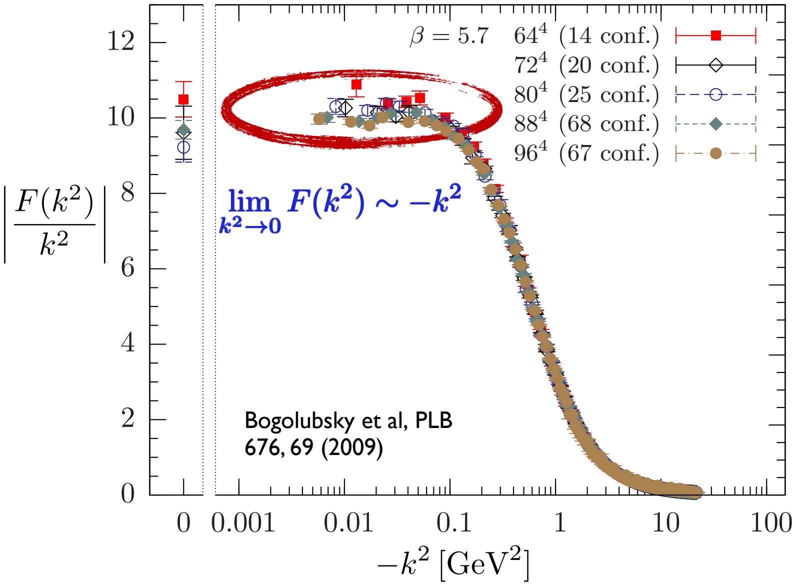
the existence and the position of the poles are gauge independent

Assume the nonperturbative effects in quadratic gravity operate in a way similar to QCD ($G(k^2)$ takes the same form of $F(k^2)$ as found from lattice QCD)



$\lim_{k^2\to 0} F(k^2) \sim -k^2$

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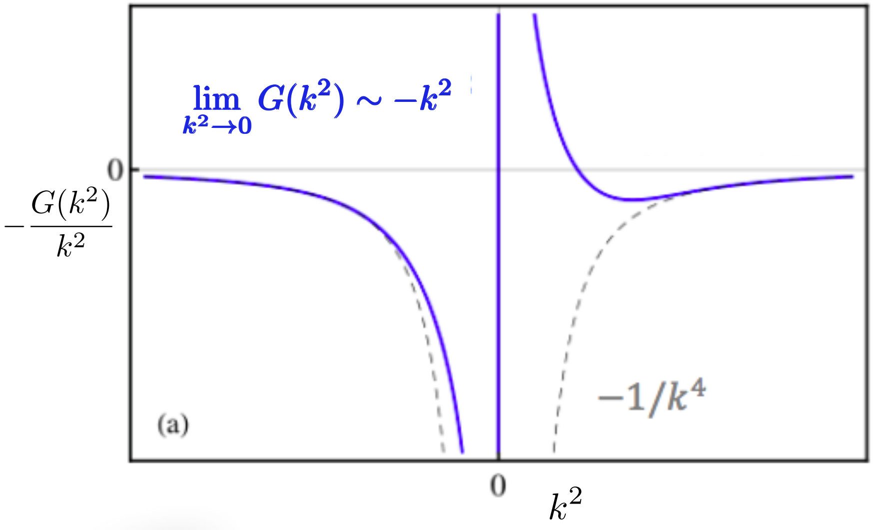

$\lim_{k^2\to 0} G(k^2) \sim -k^2$

$-1/k^4$ softened to a $1/k^2$ pole (positive sign), i.e. the on-shell massless graviton

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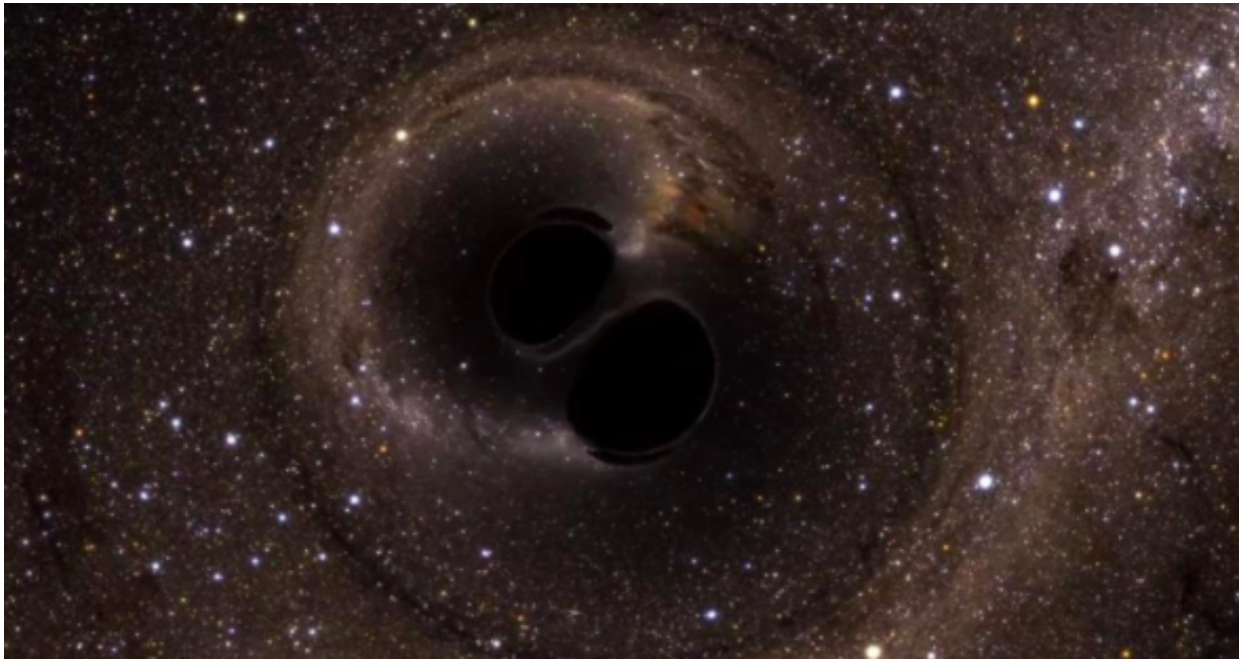
Strong scale	gauge coupling strong at $\Lambda_{\rm QCD}$	gravitational couplings strong at $\Lambda_{\rm QQG}$
Nonperturbative effects	the perturbative gluon removed from the physical spectrum and a mass gap developed as controlled by $\Lambda_{\rm QCD}$	$\mathcal{M} \neq 0$: all perturbative poles removed from the physical spectrum and a mass gap now controlled by $\mathcal{M}$
		$\mathcal{M} = 0$: the massless graviton pole emerges as the only light state in the physical spectrum
IR effective description	color singlet states described by Chiral Lagrangian	massless graviton described by GR with the derivative expansion, $m_{\rm Pl} \sim \Lambda_{\rm QQG}$

GR emerges as the low energy effective theory!

A novel horizonless 2-2-hole

Holdom, Ren, arXiv: 1612.04889, ongoing…



A new picture for gravity

(IR) Perturbative General relativity + corrections

Strong region $O(M_{Pl})$

Perturbative quadratic gravity (UV)

energy curvature

Large corrections to black holes?

Find solutions in *Classical Quadratic Gravity*, a theory with the same limits for small and large curvatures (but it interpolates between the two in its own way)

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

Previous works treated this as a truncation and had problems with higher order terms when describing solutions with arbitrarily large curvatures.

Our new perspective allows exploration of solutions containing both sub-Planckian and super-Planckian curvature regions.

New solutions for dense matter sources

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

Static, spherically symmetric, asymptotically-flat solution: no Birkhoff's theorem.
Numerical solutions sourced by matter distributions with larger compactness.

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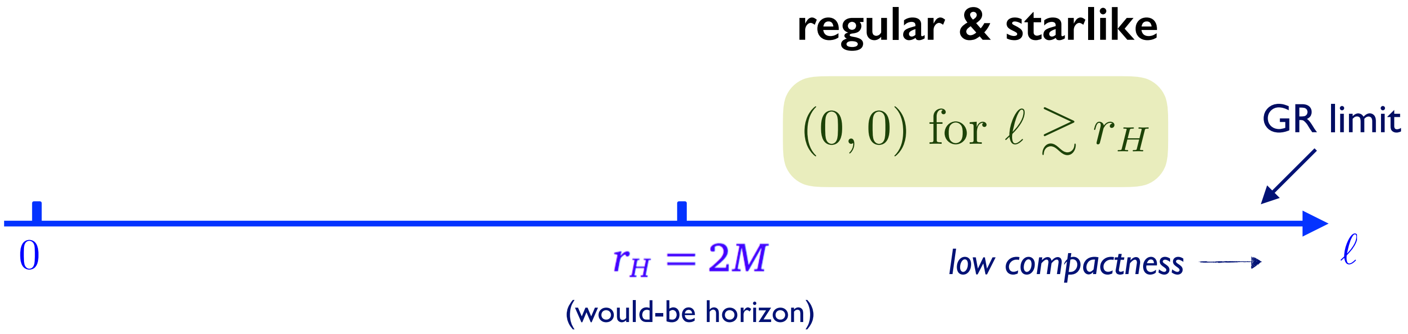
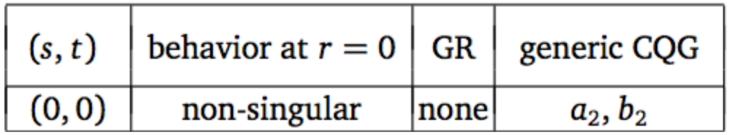
A spherical thin-shell model (M, ℓ)



$(m_{\rm Pl} = 1)$

Series expansion around the origin



(s,t)	behavior at $r=0$	GR	generic CQG
$(0,0)$	non-singular	none	a_2, b_2

$$A(r) = a_s r^s + a_{s+1} r^{s+1} + \ldots$$

$$B(r) = b_t (r^t + b_{t+1} r^{t+1} + \ldots)\,.$$

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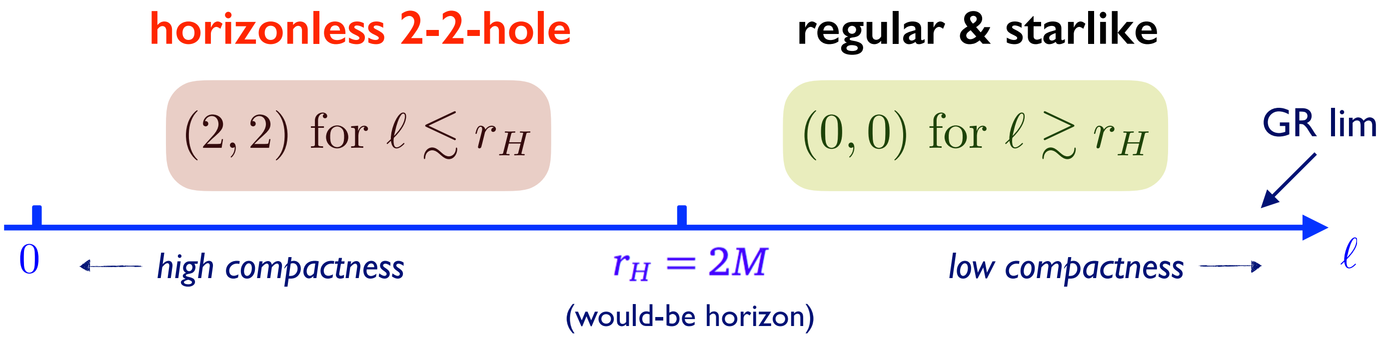
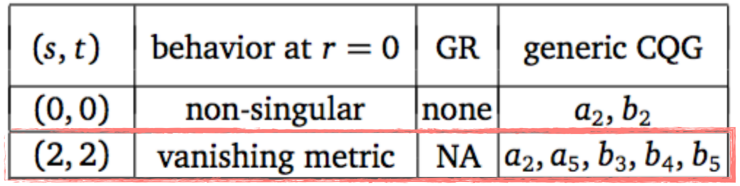
No need to form horizon!



$(m_{\rm Pl} = 1)$

Series expansion around the origin

A brand new family, the *most generic solutions*



(s,t)	behavior at $r=0$	GR	generic CQG
$(0,0)$	non-singular	none	a_2, b_2
$(2,2)$	vanishing metric	NA	a_2, a_5, b_3, b_4, b_5

$$A(r) = a_s r^s + a_{s+1} r^{s+1} + \ldots$$

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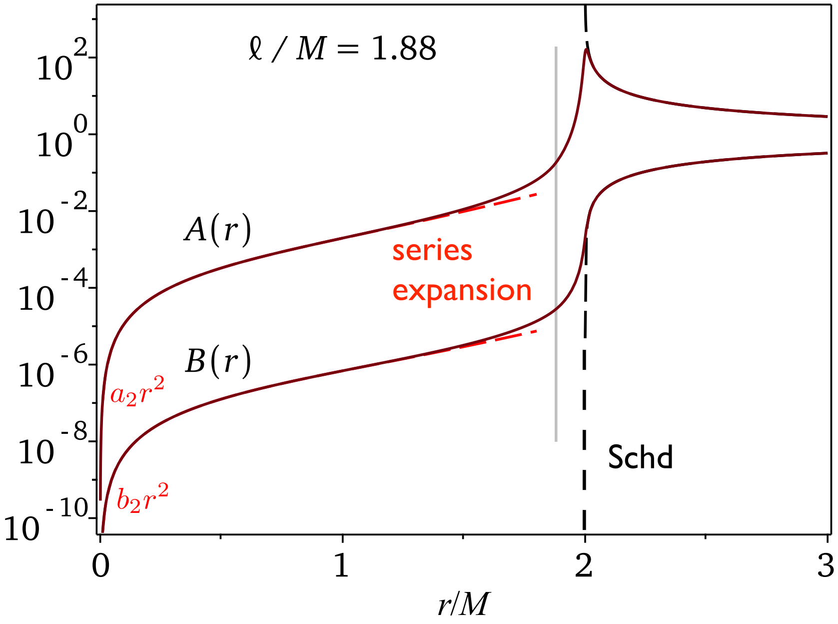
2-2-hole = Super-Planckian curvature interior + transition region + Sub-Planckian curvature exterior



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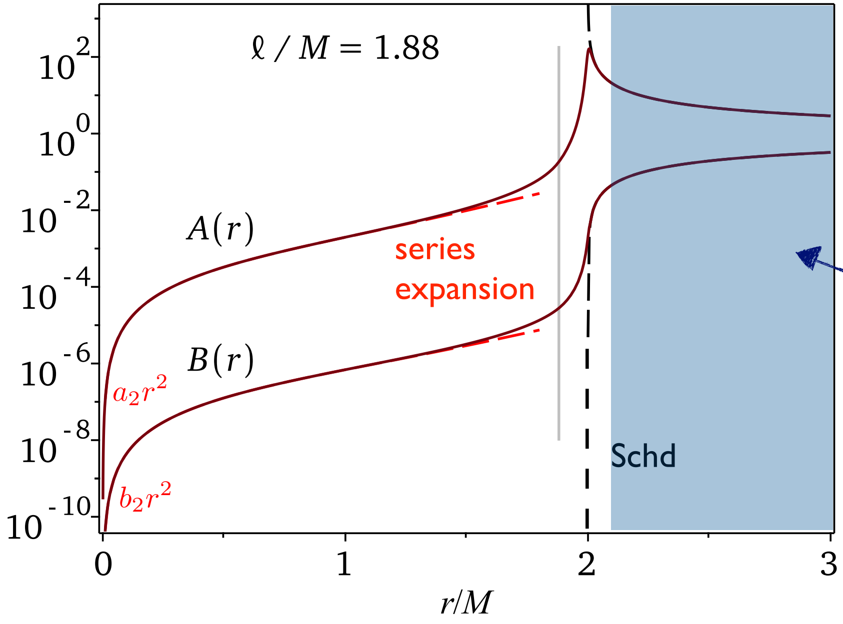

Schd scaling

- Exponentially small corrections to Schd solution
- Curvatures highly suppressed for large objects

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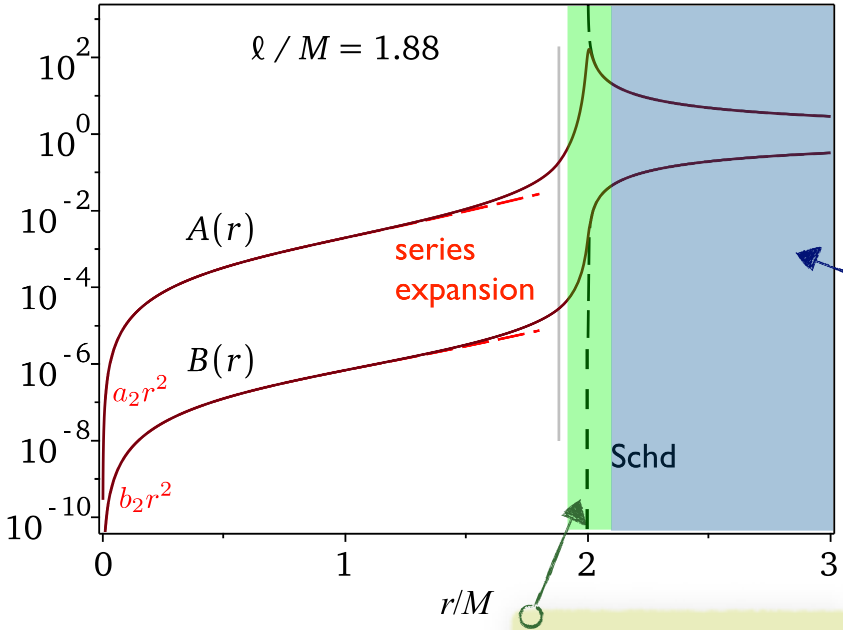

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Deviation at Planck distance

(determined by dynamics, applied for all $M \gg m_{\mathrm{Pl}}$)

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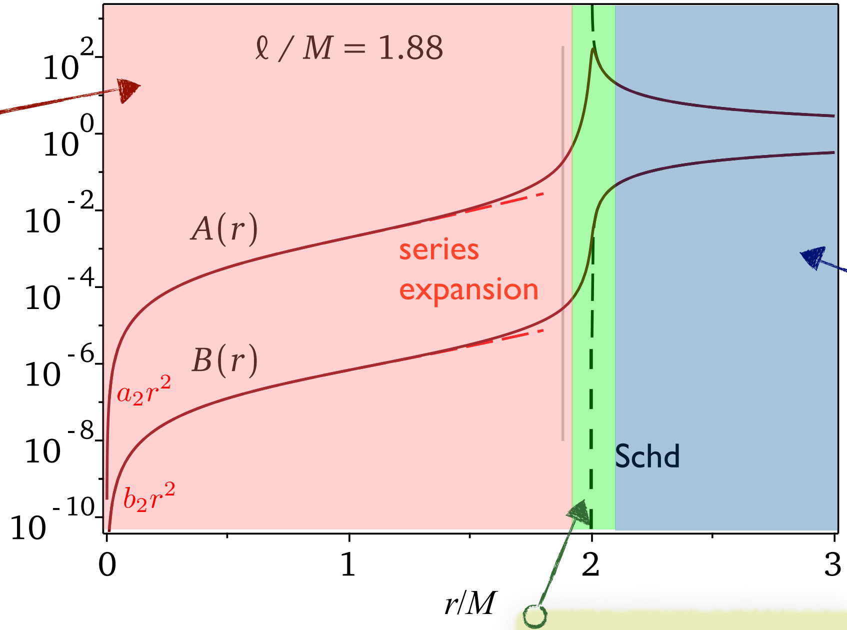

Novel scaling

- Small *B(r)*: very large gravitational redshift (deep potential)
- Small *A(r)*: shrinking radial size (~Planck proper length)

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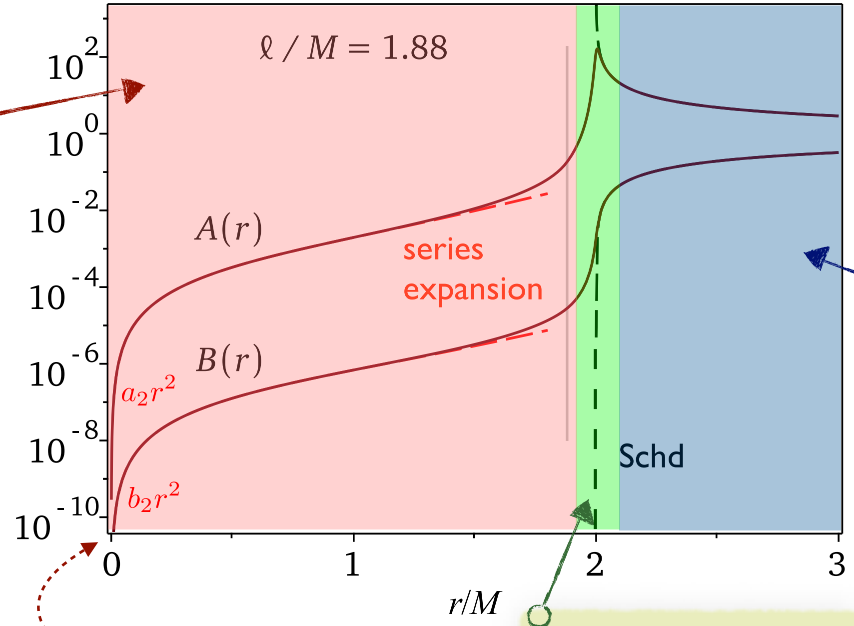

Naked (curvature) singularity

$$(R_{\mu\nu\rho\sigma})^2 \propto 1/r^8, \ \ (C_{\mu\nu\rho\sigma})^2 \propto 1/r^4$$

Geodesic-incompleteness?! ***Regular*** as probed by finite energy wave-packets

reflecting Dirichlet boundary condition

Deviation at Planck distance

(determined by dynamics, applied for all $M \gg m_{\rm Pl}$)

Schd scaling

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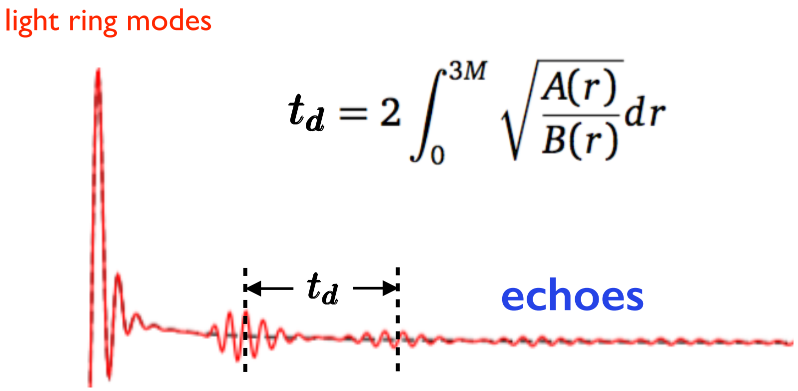
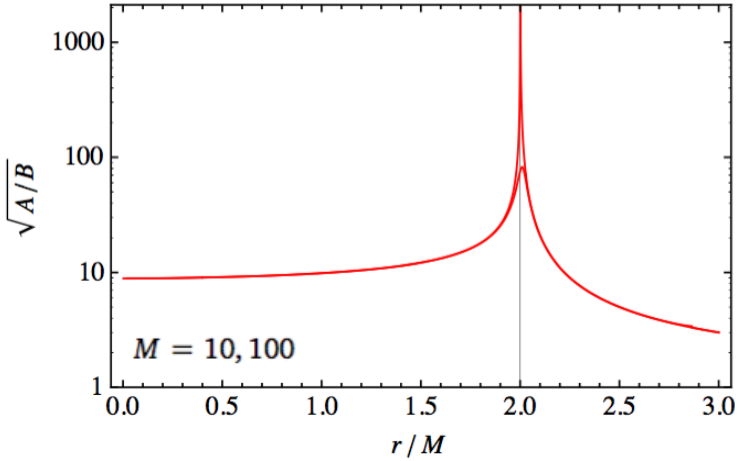
Time delay for astrophysical 2-2-hole

$$t_d = 2\int_0^{3M}\sqrt{\frac{A(r)}{B(r)}}dr$$



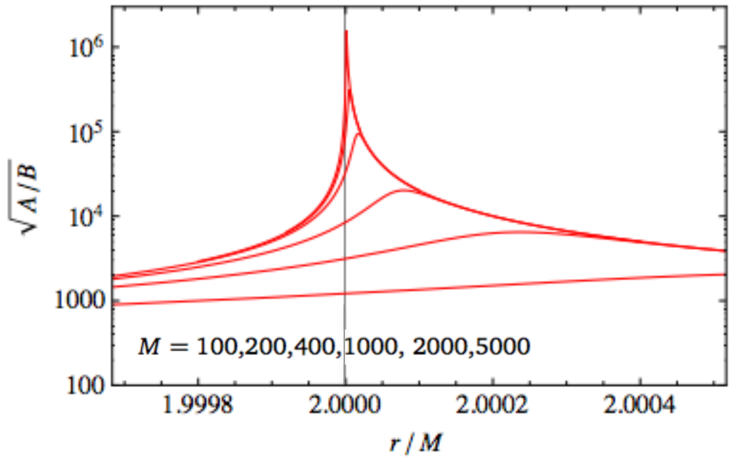


A new time scale for quantum gravity:

contribution mainly from exterior, with only log(M/m_{Pl}) dependence on the mass hierarchy

$$700 + 7\ln\frac{M}{30M_\odot} \lesssim \frac{t_d}{M} \lesssim 860 + 9\ln\frac{M}{30M_\odot}$$

For $M \sim 30M_\odot$, t_d is about *0.1s*, i.e. longer than the damping time of BH dominant ringdown *O(1ms)* and shorter than the duration of stable strain data *O(10s)*.



More properties of 2-2-hole

For 2-2-holes, αC^2 term essential, while βR^2 is optional

Einstein-Weyl gravity ($\beta = 0$): two scales (m_2, m_{Pl}), $R = 0$ (traceless matter)

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New results: 2-2-holes sourced by relativistic thermal gas ($\varrho = 3p$)

- Expected form of in-falling particles in the high curvature interior after they interact for long time (thermal equilibrium: $T(r) = T_\infty/\sqrt{B}$)
- One-parameter family solution with $m_2 r_H \gtrsim 1$ (lower bound for minimum 2-2-hole)
- Novel scaling behavior for 2-2-hole interior: large and small mass limit

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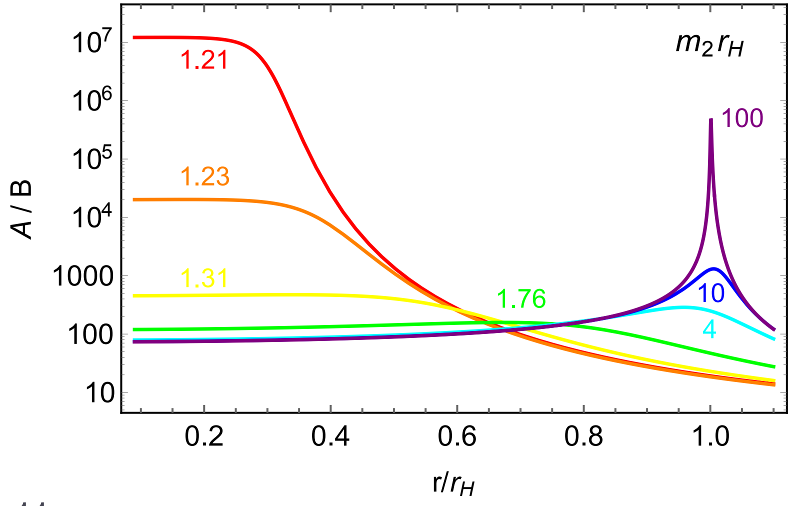
- One-parameter family solution with $m_2 r_H \gtrsim 1$ (lower bound for minimum 2-2-hole)
- Novel scaling behavior for 2-2-hole interior: large and small mass limit

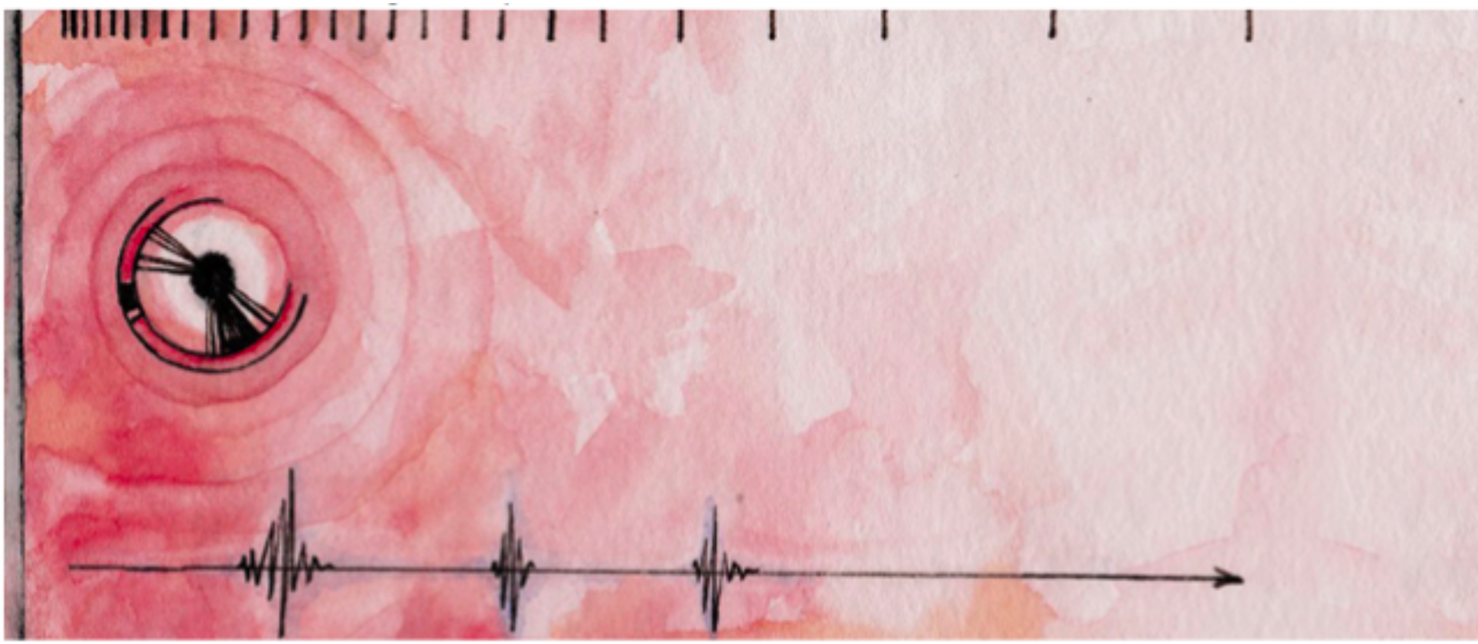


Interior behavior	Curvature	$\ell_{\rm in}$	$S_{\rm in}$	
(large mass) $m_2 r_H \gg 1$	$I(r)m_2^{-2n}$	$\frac{1}{m_2}$	$\frac{r_H^2}{\ell_{\rm Pl}^2}\sqrt{\frac{m_2}{m_{\rm Pl}}}$	**area law (finite)**
(small mass) $m_2 r_H \gtrsim 1$	$I(r)r_a^{2n}$	r_a	$\left(\frac{r_a^2}{\ell_{\rm Pl}^2}\right)^{3/4}$	

$r_a \equiv 1/\sqrt{a_2}$ drop dramatically in small mass limit

Gravitational wave echoes through new windows

Conklin, Holdom, Ren, arXiv: 1712.06517

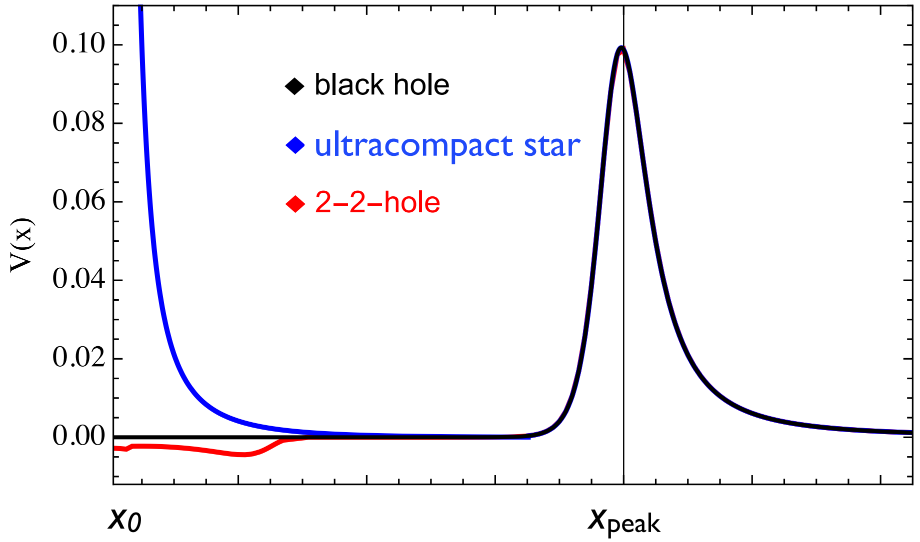


Kaća Bradonjić

Challenge for the template method?

Precise waveforms of echoes suffer huge theoretical uncertainties, e.g. the effective potential in perturbation wave equations depends on the background spacetime (*UCOs*)

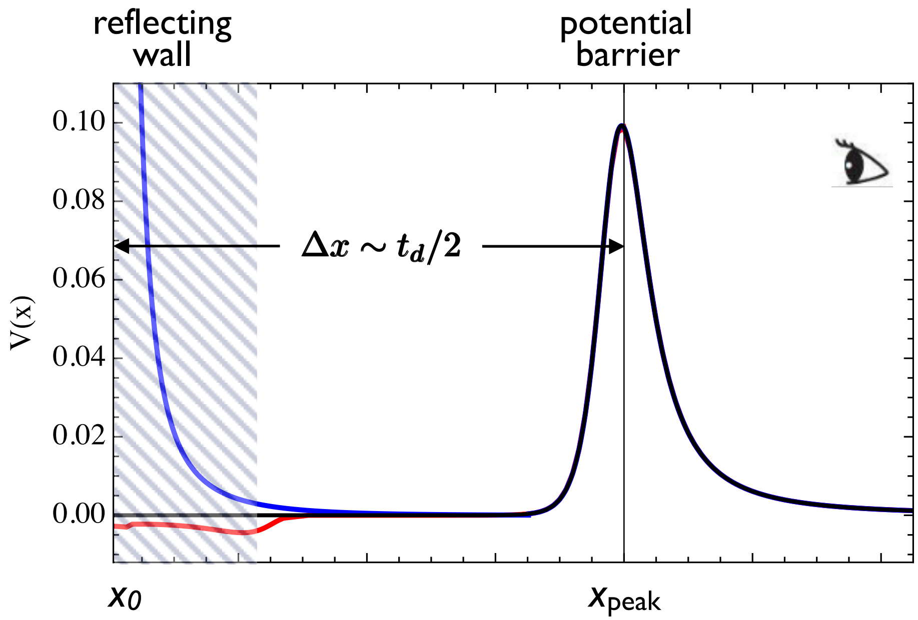
$$\left(\partial_x^2 + \omega^2 - V(x)\right) \psi_\omega(x) = S(x, \omega)$$



- **Truncated black hole:** reflecting wall at some x_0
- **Ultracompact stars:** potential blows up at origin x_0
- **2-2-holes:** potential deviates by a small negative step
- …

Challenge for the template method?

UCOs as leaky cavities: echoes result from the initial trapped waves gradually leaking out through barrier. Current LIGO observation of a clear BH ringdown constrains the potential barrier shape and puts a lower bound on the cavity size, i.e. $\Delta x/M \gg 10$



New method: extract the ***time delay*** t_d **of echoes**, while being less sensitive to more model-dependent variations close to the would-be horizon

Echoes in the frequency domain

Green function:

$$\frac{d^2 G_\omega(x,x')}{dx^2} + (\omega^2 - V(x))G_\omega(x,x') = \delta(x-x').$$

$$G_\omega(x,x') = \frac{\psi_{\text{left}}(\min(x,x'))\psi_{\text{right}}(\max(x,x'))}{W(\psi_{\text{left}},\psi_{\text{right}})}. \qquad W(\omega) = \psi_{\text{left}}\psi'_{\text{right}} - \psi'_{\text{left}}\psi_{\text{right}}$$

Observation at spatial infinity

$$\psi_\omega = e^{i\omega x} \cdot \underline{\overset{1/W(\omega)}{\overset{\shortparallel}{\mathcal{K}(\omega)}}} \cdot \underline{\int_{-\infty}^{\infty} dx' \psi_{\text{left}}(x') S(x',\omega)}$$

transfer function *UCOs*

source frequency content

Echoes in the frequency domain

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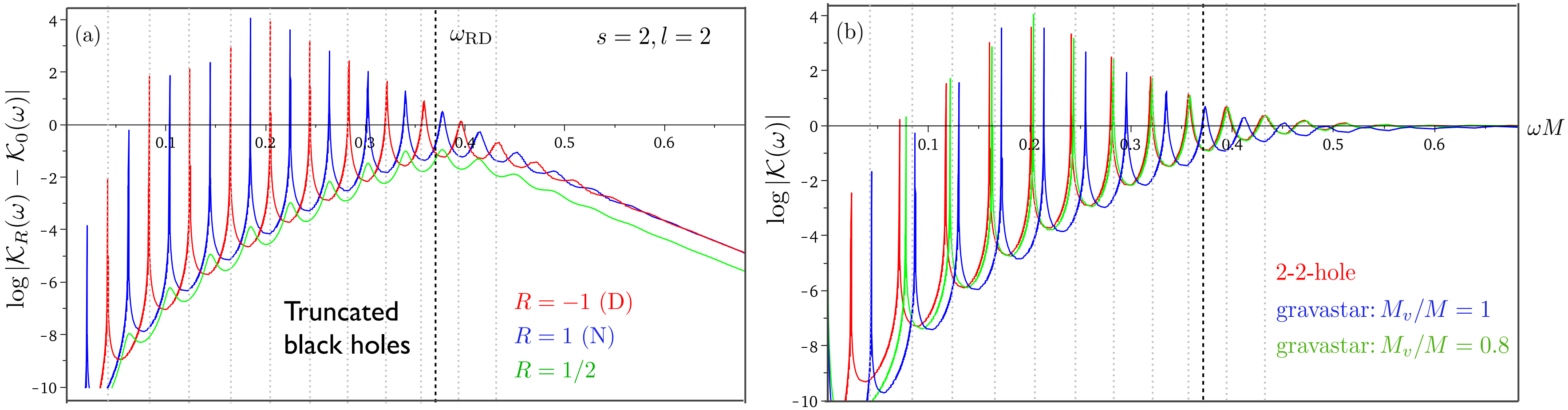
transfer function *UCOs* source frequency content

Absolute value of transfer function: different spinless *UCOs*



Similarities: nearly evenly spaced resonances $(1/t_d)$ up to ω_{RD}, narrower at lower frequency

Differences: an overall shift; resonances spacing at lower frequency

Echoes in the frequency domain

Green function:

$$\frac{d^2G_\omega(x,x')}{dx^2}+(\omega^2-V(x))G_\omega(x,x')=\delta(x-x').$$

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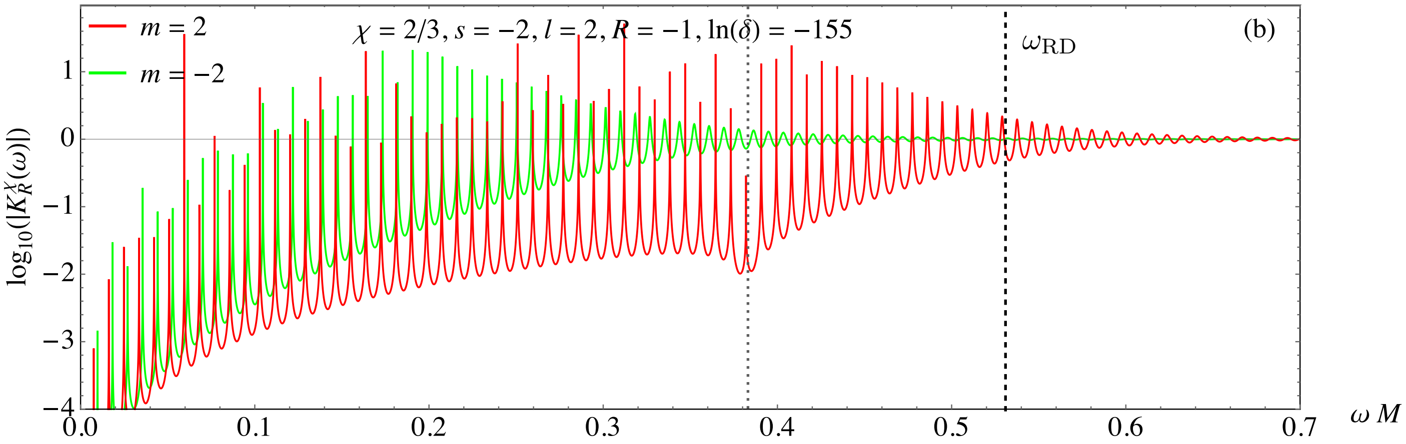
transfer function *UCOs* source frequency content



Truncated Kerr black holes

UCOs' spin adds interesting structure to the shape of the resonance pattern, e.g. a wider range of narrow resonances with comparable height

Echoes in the frequency domain

Green function:

$$\frac{d^2G_\omega(x,x')}{dx^2}+(\omega^2-V(x))G_\omega(x,x')=\delta(x-x').$$

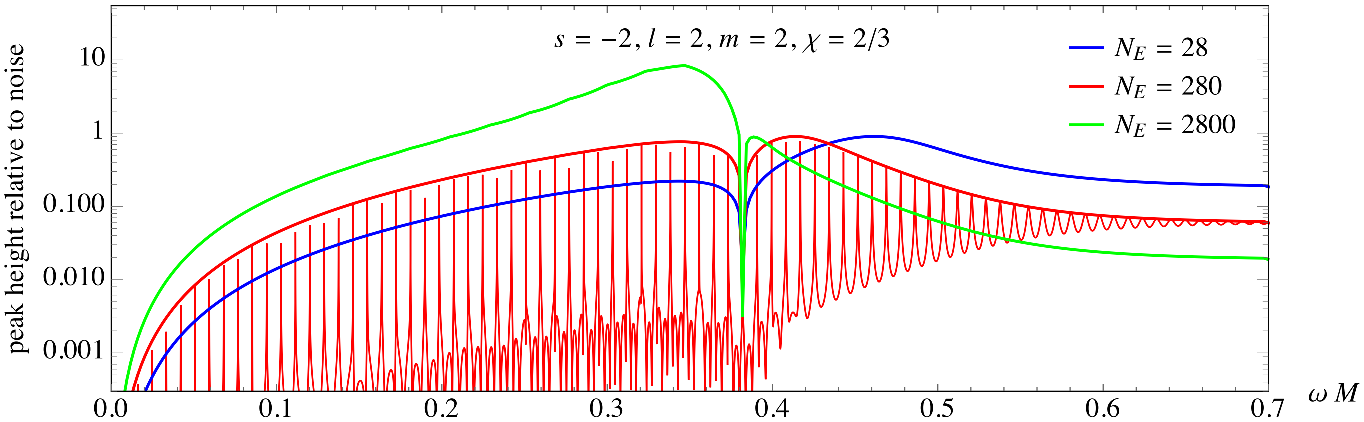
$$G_\omega(x,x')=\frac{\psi_{\mathrm{left}}(\min(x,x'))\psi_{\mathrm{right}}(\max(x,x'))}{W(\psi_{\mathrm{left}},\psi_{\mathrm{right}})}. \qquad W(\omega)=\psi_{\mathrm{left}}\psi'_{\mathrm{right}}-\psi'_{\mathrm{left}}\psi_{\mathrm{right}}$$

Observation at spatial infinity

$$\psi_\omega = e^{i\omega x}\cdot \underline{\overset{1/W(\omega)}{\overset{/\!/}{\mathcal{K}(\omega)}}}\cdot \underline{\int_{-\infty}^{\infty} dx'\psi_{\mathrm{left}}(x')S(x',\omega)}$$

transfer function *UCOs* source frequency content

Reconstructed resonance pattern *(N_E echoes in the time domain)*



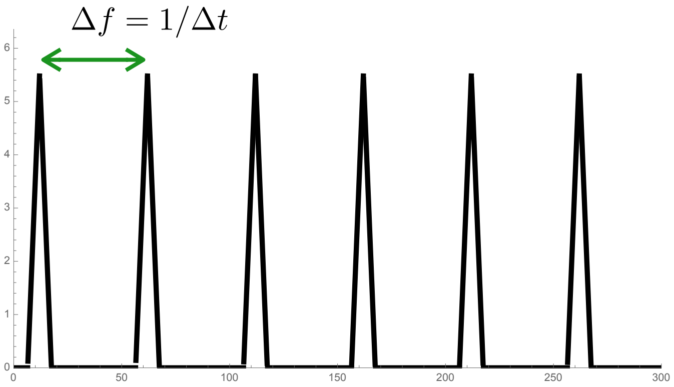
Search target: nearly evenly spaced resonances pattern ***within an intermediate frequency range*** around or below ω_{RD} (reduce model dependence on source and *UCOs*)

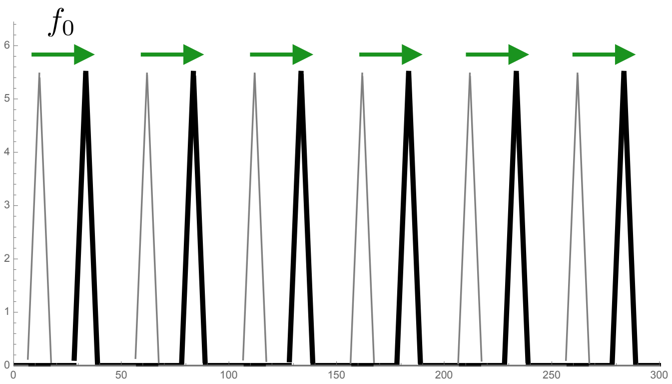
Reduce noise with window functions

To extract resonance pattern, multiply a quasi-periodic window function onto data to reduce noise *(in between matched-filtering method and unmodelled search)*

1) For each LIGO detector, take absolute value of the Fourier transform of whitened strain data after merger; high frequency resolution $\delta f = 1/T$ needed to resolve more narrow resonances

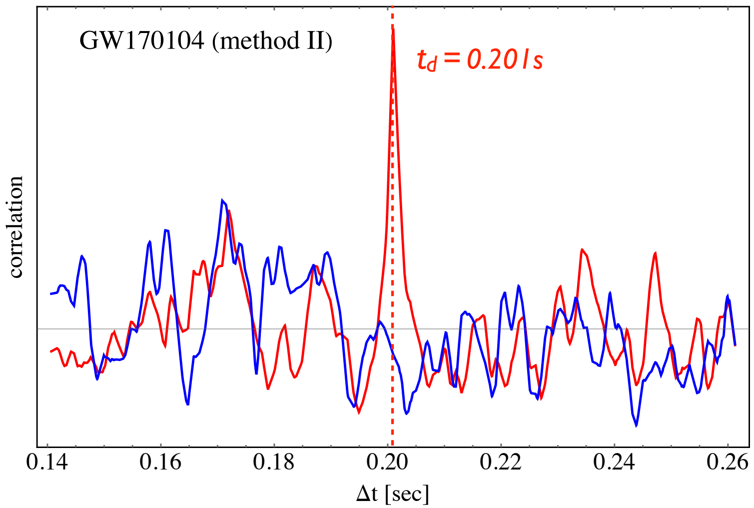
2) Apply a frequency window function (defined by spacing, shift, bandpass) to data sets from two detectors; find the amplitude of windowed data

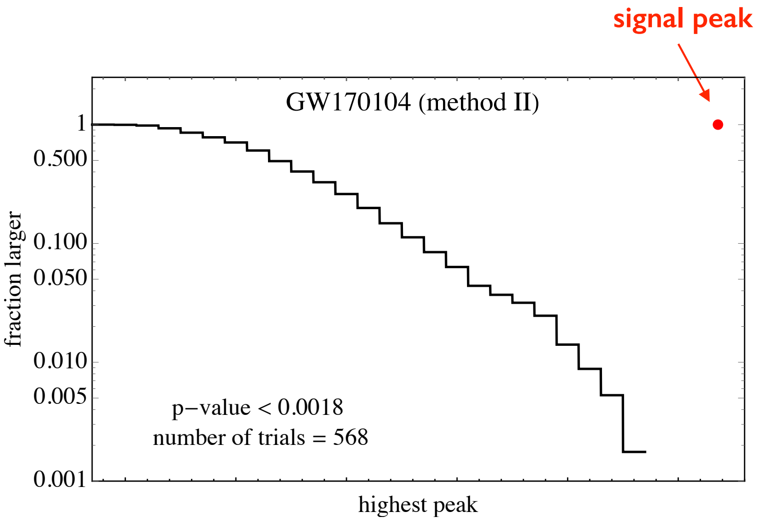




3) Maximize correlation of two amplitudes with respect to window parameters, (average over a range of echoes number N_E); obtain the best-fit $\Delta t = t_d$

Tentative echoes signals in LIGO data





- ***Signal search:*** time delay range ± 30% from the central peak; applying the same procedure to data before merger (one background search)

- ***Initial p-value estimation:*** the probability of finding a highest peak of equal or greater height by applying the same procedure to LIGO data away from the event

Tentative signals for multiple events

Event (method)	Best-fit t_d (sec)	p-value (%)	Bandpass $(f_{\rm min}, f_{\rm max})t_d$	Window parameters for average
GW151226 (I)	0.0786	< 0.13 [a]	$(34, 62)$	$N_E = (1\text{-}29), (5\text{-}29), (9\text{-}29)$ [b]
GW151226 (II)	0.0791	0.76	$(12, 58)$	$N_E = (260, 270)$
GW170104 (II)	0.201	< 0.18	$(16, 62)$	$N_E = (100, 125, 150, 175, 200)$
GW170608 (II)	0.0756	< 0.4	$(14, 60)$	$N_E = (140, 200, 260)$
GW170814 (II)	0.231	4.1	$(12, 58)$	$N_E = (170, 190)$ [c]
GW170814 (III)	0.228	0.77	$(30, 80)$	$N_E = 10\text{-}17,\ t_w = 40, 80$ [d]
GW170817 (II)	0.00719	0.33	$(9, 50)$	$N_E = (200, 220, 240, 260)$

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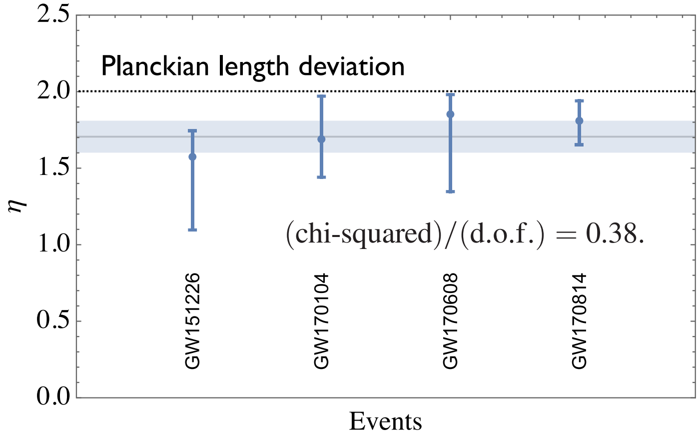
Consistency of best-fit time delay

Assuming a truncated Kerr black hole with a universal deviation for boundary at r_0

$$\delta = (r_0 - r_H)/r_H \equiv (r_H/\ell_{\rm Pl})^{-\boxed{\eta}}$$

$$t_d = \boxed{\eta}\, r_H \ln(r_H/\ell_{\rm Pl})(1 + 1/\sqrt{1-\chi^2})(1+z)$$

doing fit with final objects properties (mass M, spin χ, redshift z) reported by LIGO



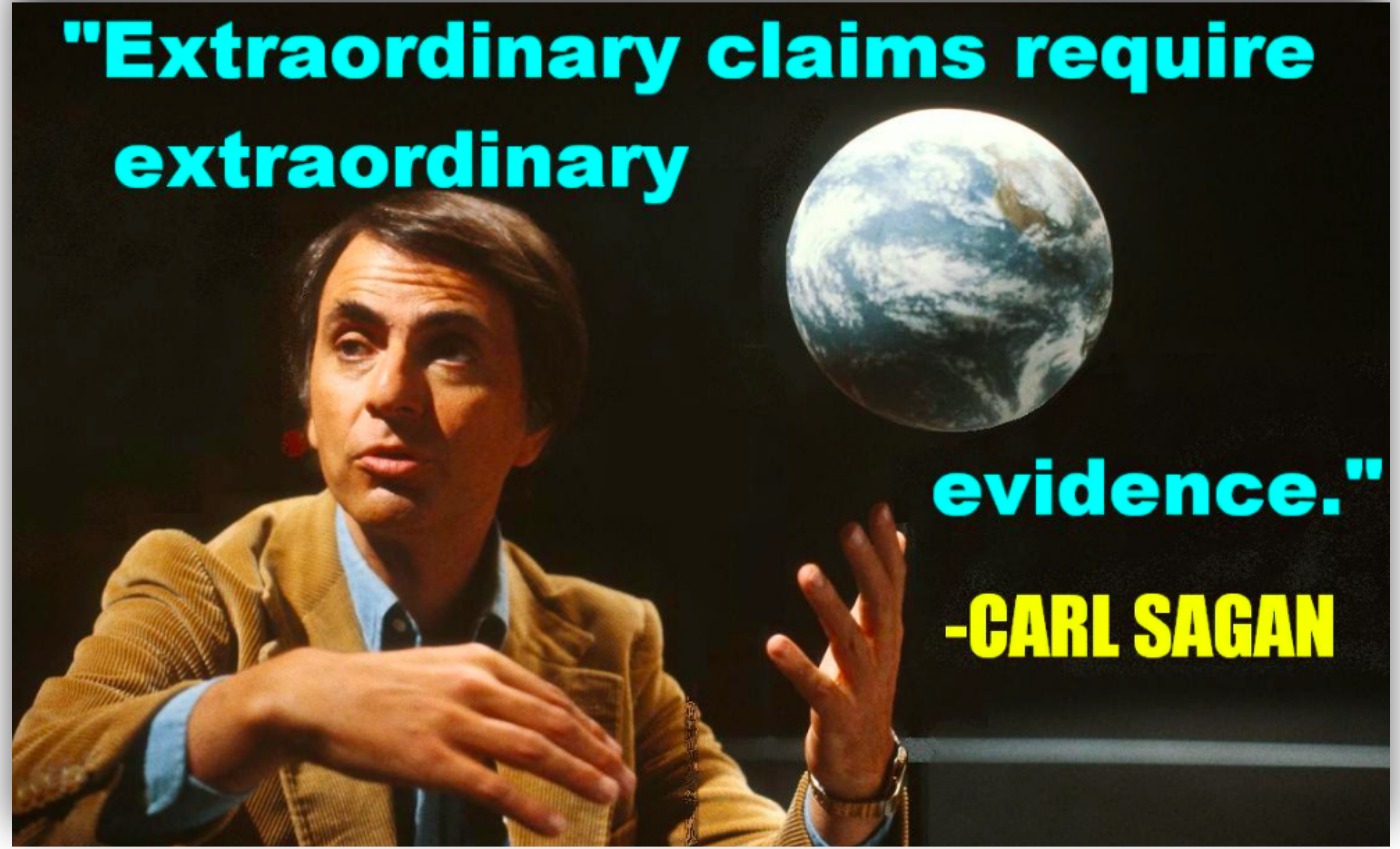
$\eta = 1.7 \pm 0.1$

Summary and outlook

- With the new perspective on quadratic gravity, sufficiently dense matter are found to produce ***novel horizonless 2-2-holes.*** Planckian deviation around the would-be horizon naturally occurs for all $M \gg m_{\rm Pl}$

- Gravitational wave echoes provide a smoking-gun for near-horizon new physics. We suggest to use the windowing methods to extract the preferred time delay of echoes for various *UCOs*. Tentative signals are found for multiple LIGO BBH events.

- Open questions
  - Quadratic gravity: test "the idea" by toy models on lattice
  - 2-2-holes: rotation (ergoregion instability), gravitational collapse (transition from regular solutions to 2-2-holes), absorption of GW (boundary condition for echoes)…
  - Echoes search: more systematic study of the methods, more rigorous background estimation, signal detection efficiency…



Yes, but the data provide great opportunities…

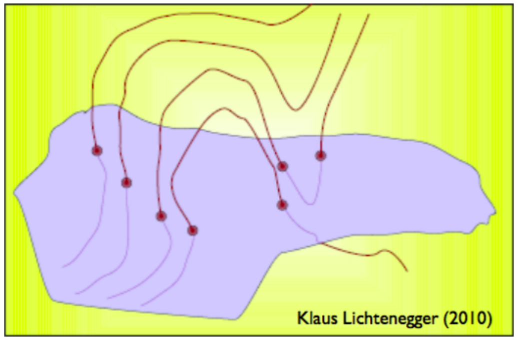
Thank You!

Analogy in view of Gribov copies

Use path integral as a nonperturbative definition of the quantum theory

- For a gauge theory path integral is defined in the space of gauge orbits. With gauge-fixing Faddeev-Popov trick extends the path integral to the full configuration space.

- There are Gribov copies in sensible gauges. Need to construct nontrivial measure. Gribov, Nucl.Phys.B139 (1978) 1; Singer, Commun.Math.Phys. 60, 7 (1978).



QCD: $$Z = \int \mathcal{D}A \, \frac{1}{1+N_F(A)} \delta(F(A^U)) \left|\det M_F(A)\right| \, e^{iS(A)}$$

Number of copies

Counting copies to determine the full gluon propagator $F(k^2)$

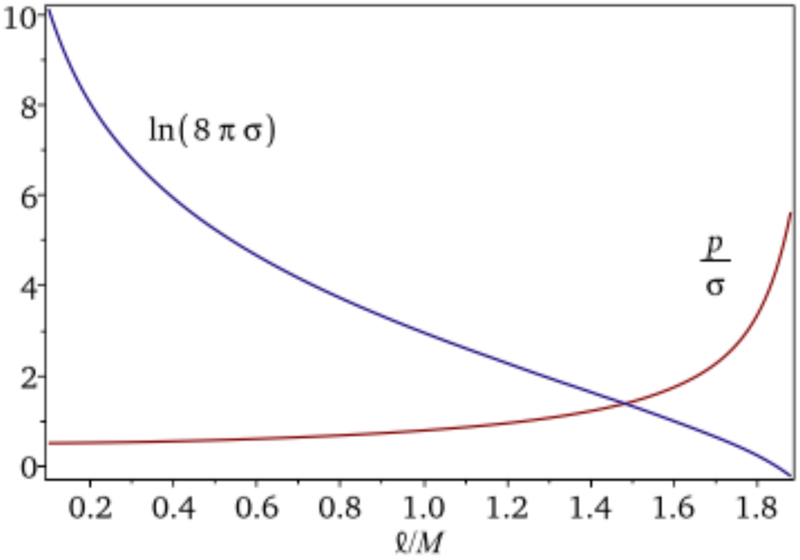
[Holdom, PRD 79, 085013 (2009)]

Gravity: $$Z = \int \mathcal{D}h \, \frac{1}{1+N_F(h)} \delta(F(h)) \left|\det M_F(h)\right| \, e^{iS_{QG}(g)}$$

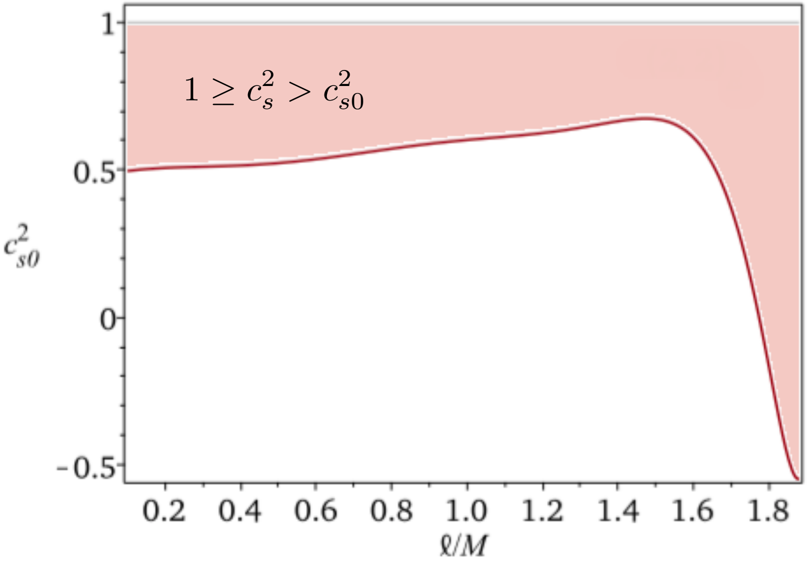
- Infinitesimal version: find similar Gribov horizon as in QCD
- The nontrivial measures set the similarity between gravity and gauge theory, which may cure problems of the tree-level action

Matter properties and stability of 2-2-holes

Shell energy density and pressure



Radial stability $\delta^2 M > 0$

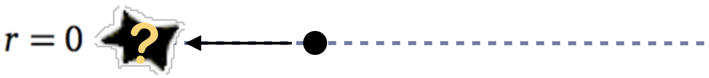


Energy conservation: $\sigma(\ell) \sim 1/\ell^3$

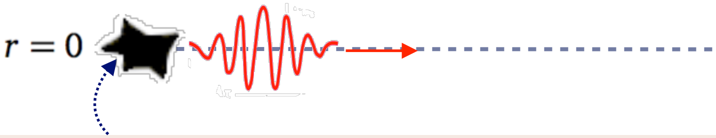
$$c_{s0}^2 = \left.\frac{\partial p}{\partial \sigma}\right|_M = \frac{dp/d\ell}{d\sigma/d\ell} = \frac{p}{\sigma} + \frac{\sigma}{d\sigma/d\ell}\frac{d}{d\ell}\left(\frac{p}{\sigma}\right)$$

Timelike curvature singularity?!

Geodesic
incompleteness?



May appear regular as
probed by finite energy
wave-packets?



A Neumann boundary condition is imposed

- The initial value problem of the wave equation is well-posed if $\mathbb{A}$ has a **unique** positive self-adjoint extension

Wald, JMP. **21**, 2802 (1980); Ishibashi, Wald, CQG. **20**, 3815 (2003);
Horowitz, Marolf, PRD **52**, 5670 (1995) Ishibashi, Hosoya, PRD **60**, 104028 (1999)

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

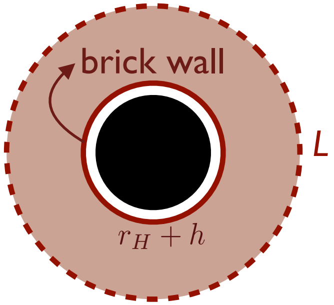
- Near the 2-2-singularity, all waves behave like the s-wave on a nonsingular spacetime. Only one solution has finite energy.

Spacetime	$A(r)$	$B(r)$	$\psi_{l1}(r,t)$	$\psi_{l2}(r,t)$
2-2-hole	r^2	r^2	1	r^{-1}
star	r^0	r^0	r^l	$r^{-(l+1)}$

“A brick wall” and 2-2-hole entropy

The brick wall model: attribute black hole entropy to ordinary entropy of its thermal atmosphere located just outside the horizon. If $T_\infty = 1/8\pi M$, recover the area law for $h \sim \ell_{\rm Pl}$ (proper length).

QUE: need artificial UV cutoff? why d.o.f. localized outside the horizon?



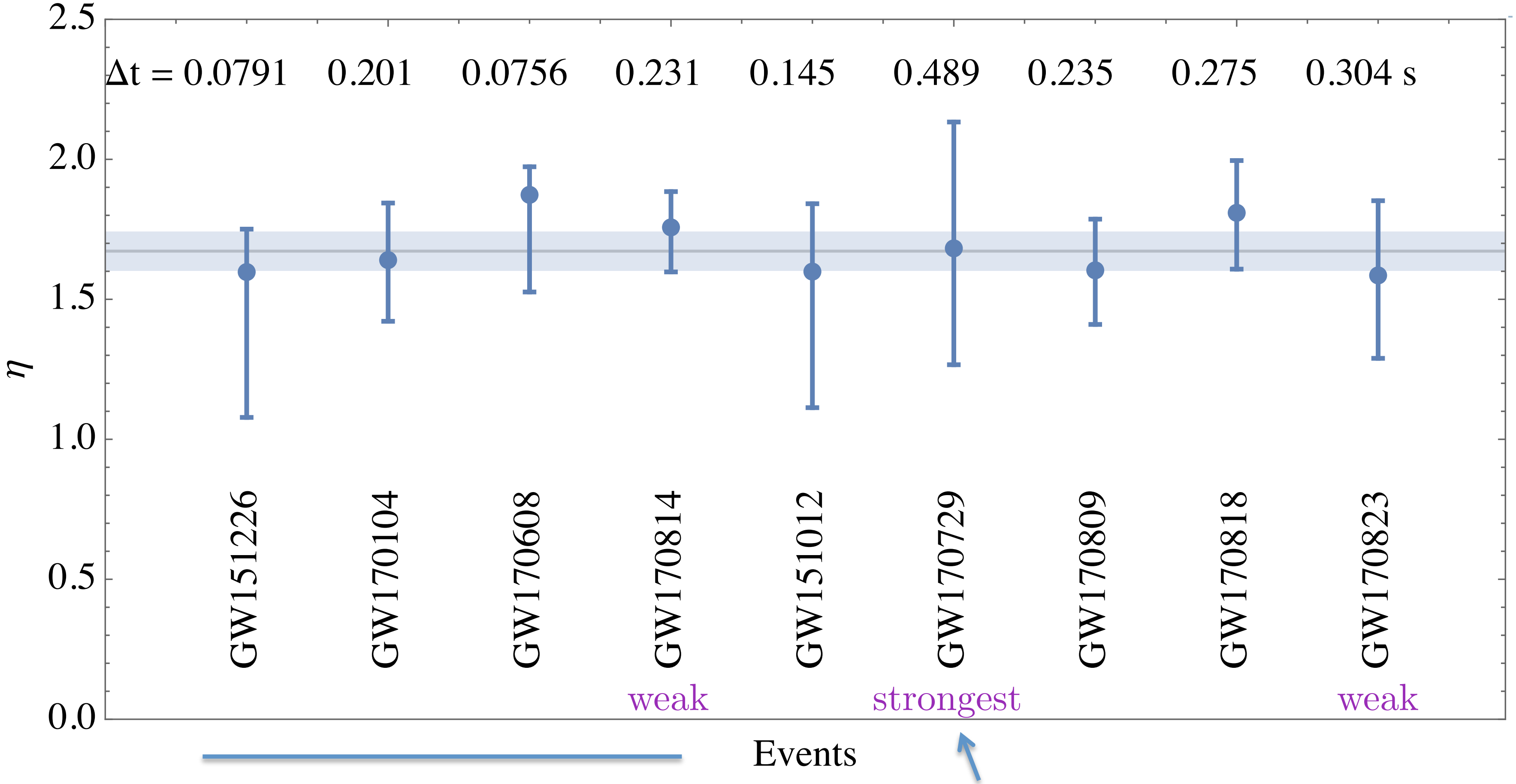
['t Hooft, NPB 256, 727 (1985)]

Entropy well defined for 2-2-holes sourced by relativistic thermal gas, i.e. the brick wall is replaced by the origin with a reflecting boundary condition

$$S = \frac{(2\pi)^3}{45}\int_0^L T(r)^3 A(r)^{1/2} r^2 dr, \quad U = \frac{3}{4} T_\infty S.$$

- Both S and U are finite, and dominated by the interior contribution. The area law recovered due to the novel scaling in the large mass limit
- For number of species N>1 (m_2 not too small), S>S_{BH}, i.e. 2-2-hole favored than BH
- The timelike singularity is covered by its own fireball (T becomes infinite at origin)

Update of echoes search (new BBH events)



weak

strongest

weak

previously reported

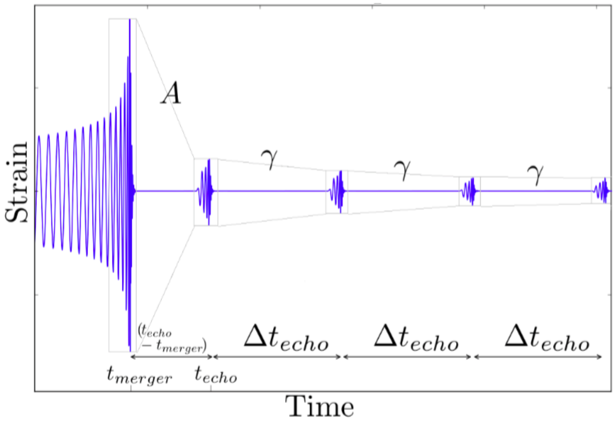
event with largest final mass and spin

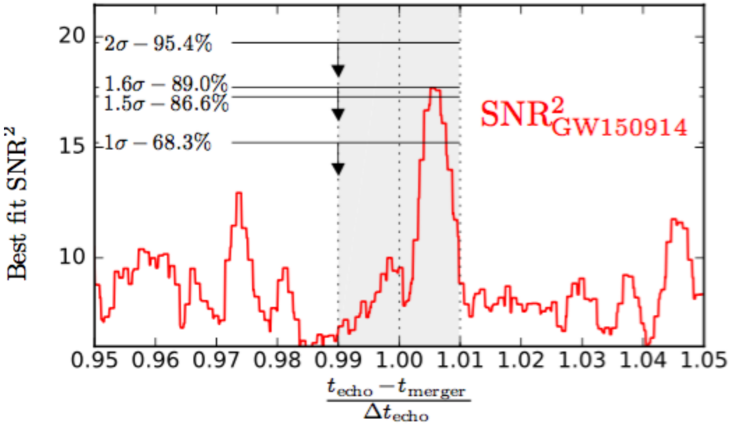
* weakest and strongest echo signals are indicated (nothing to do with error bars)

Echoes search from other groups

Tentative evidence by using *matched filtering method* with a toy model template (the time delay is fixed by Planck distance deviation)

*Abedi, Dykaar, Afshordi, PRD **96**, no. 8, 082004 (2017)*





One LIGO team reexamined the analysis, concluded *no observational evidence for or against echoes*: found some problems with prior range and background estimation and lower significance by analyzing the same data

Westerweck, Nielsen, Fischer-Birnholtz et al., PRD 97, no. 12, 124037 (2018)

Quite model independent search for GW170817 by using the lowest QNM

Abedi, Afshordi, arXiv:1803.10454