UNIVERSITY OF TORONTO

Not Quite a Black Hole

--- A novel horizonless 2-2-hole in Quadratic Gravity

Jing Ren

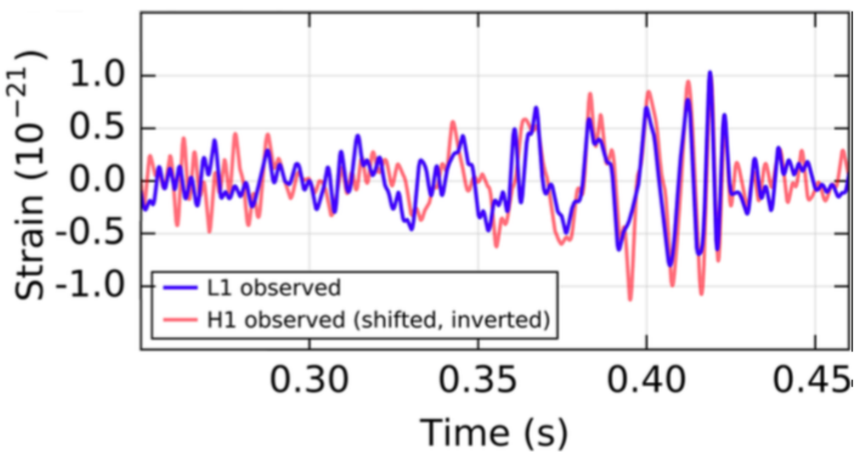
VIA lecture

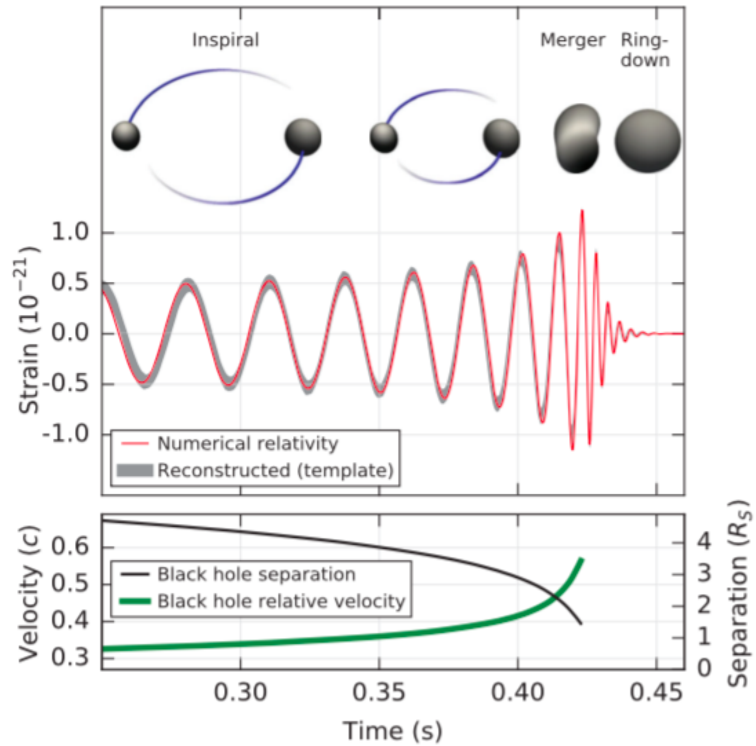
February 17, 2017

Based on Holdom, Ren, arXiv: 1512.05305, 1605.05006, 1612.04889

First direct detection of gravitational wave

GW150914

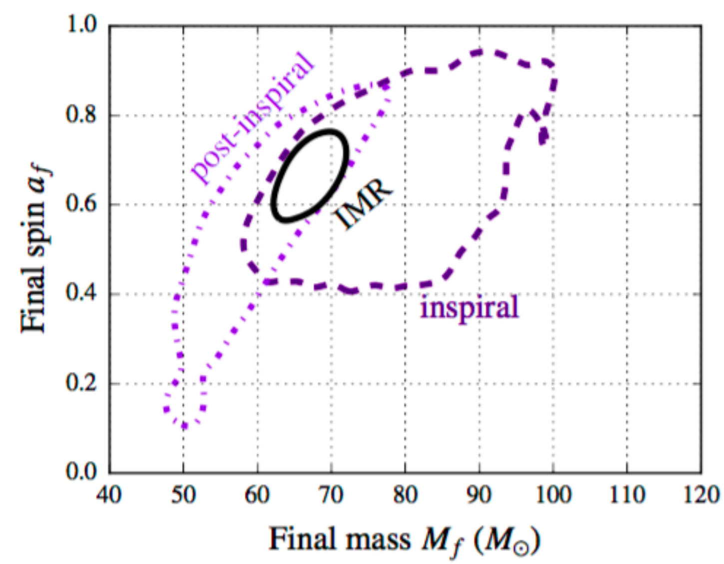




Nice agreement with GR prediction for a binary black hole

- Inspiral: large mass and high compactness
- Merger: numerical relativity
- Ringdown: dominant quasinormal mode

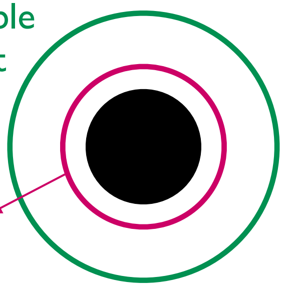
B. P. Abbott et al. [LIGO Scientific and Virgo Collaborations], PRL 116, no. 6, 061102 (2016); PRL 116, no. 22, 221101 (2016)



Does the event horizon exist?

Observation evidence?

- ISCO: accretion disk, inspiral phase terminates
- Light ring: image of light ring, GW ringdown mode



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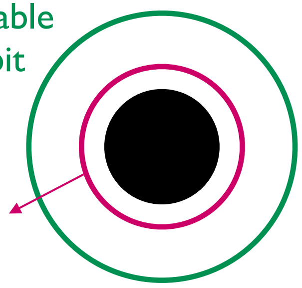
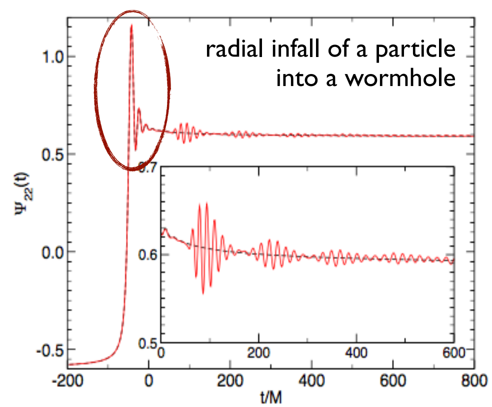
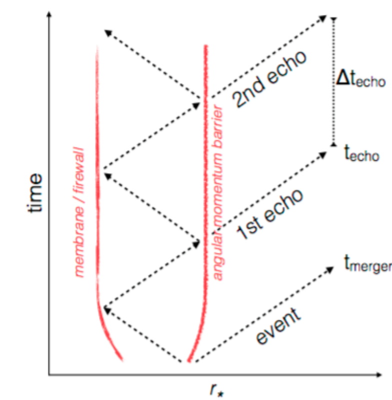
  (resemble the BH spacetime down to the light ring)



- Display a ringdown stage at early time similar to a black hole, although quite different QNMs
- The initial ringdown can be reflected back after some time delay, e.g. echoes (modulation, distortion)
- Initial attempt to find echoes in aLIGO data

  Abedi, Dykaar, Afshordi, arXiv:1612.00266 [gr-qc].





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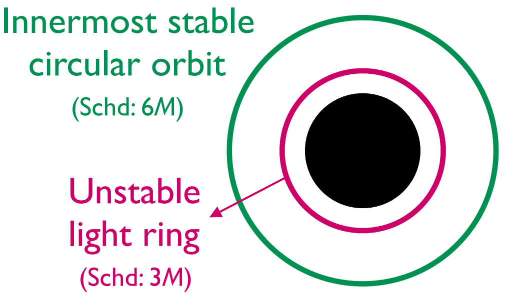

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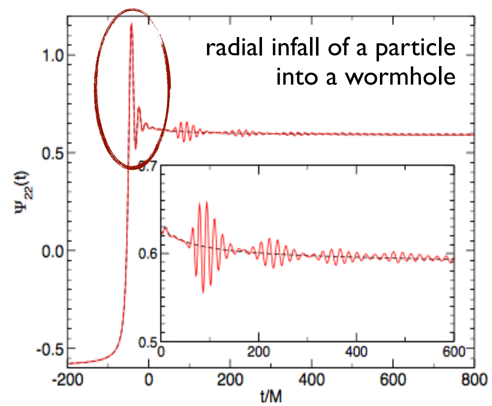
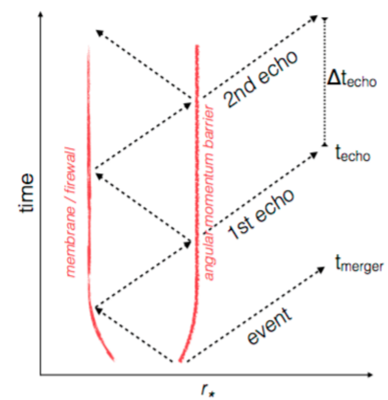




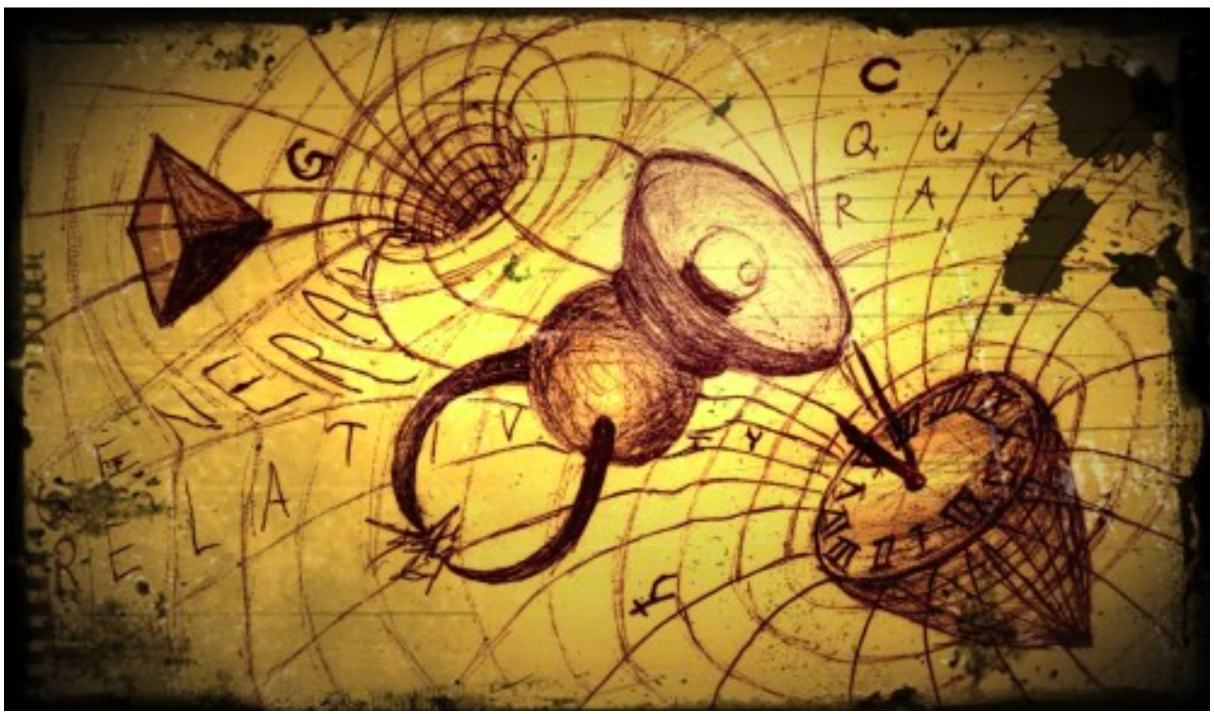
Information paradox?

- Drastic modification close to horizon in the effective theory: firewall, …
- Maybe no event horizon formed: quantum gravity (fuzzball), quantum phase transition (gravastar), time-dependent dynamical effect (blackstar) …
- Unrealistic or fine-tuned properties? Still need better candidates…

Outline

- Asymptotically free quadratic gravity
  - *A new perspective on quadratic gravity*
  - *Finding solutions in a classical theory that captures its main features*
- A novel horizonless 2-2-hole
  - *Generic solutions in quadratic gravity as sourced by dense matter*
  - *Exterior is the Schwarzschild (Schd) metric down to would-be horizon*
  - *An interior with a tiny proper volume, a seemingly innocuous timelike curvature singularity and a deep gravitational potential*
  - *Interesting implications: time delay, entropy…*
- Summary

Asymptotically free quadratic gravity



An old candidate: Quadratic Gravity

Generalization with all quadratic curvature terms

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

- Quadratic gravity is renormalizable and asymptotically free

Flat spacetime: $g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$, $1/k^4$ propagator softens UV divergence Stelle, PRD 16, 953 (1977)

$$\frac{df_2^2}{dt} = -\left(\frac{133}{10} + a_m\right) f_2^4, \quad \frac{1}{f_2^2}\frac{dw^2}{dt} = -\left[\frac{5}{12} + w\left(5 + \frac{133}{10} + a_m\right) + \frac{10}{3}w^2\right] \qquad w = f_2^2/f_0^2 \quad a_m > 0$$

[Fradkin, Tseytlin, NPB 201, 469 (1982); Avramidi, Barvinsky, PLB 159, 269 (1985)]

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- Standard picture: running couplings remain weak at the mass scale $\sim |f_i\mathcal{M}|$

  But the perturbative spectrum suffers "the ghost problem"

Spin-2 sector
$h_{\mu\nu}$ propagator

$$\frac{-i}{k^2(k^2 - M_2^2)} = \frac{1}{M_2^2}\left(\frac{i}{k^2} - \frac{i}{k^2 - M_2^2}\right) \Longrightarrow \begin{cases} \text{Vacuum instability} \\ \text{Probability interpretation and unitarity problem} \end{cases}$$

$$M_2^2 = \frac{1}{2} f_2^2 \mathcal{M}^2$$

HOWEVER, note one caveat

The ghost problem (based on tree-level propagator) is linked to the assumption of weak couplings, i.e. the perturbative analysis reflects the true physical spectrum for any relevant physical process.

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BUT when $\mathcal{M}$ is small, f_i^2 get strong at some scale $\Lambda_{\mathrm{QQG}} > \mathcal{M}$.
Perturbative poles fall into the nonperturbative region.

The theory may not have "the ghost problem" in the strong phase?

- Holdom, Ren, arXiv: 1512.05305, 1605.05006
- Donoghue, arXiv:1609.03523, 1609.03524

A QCD analogy for Quadratic Gravity

Holdom, Ren, arXiv: 1512.05305, 1605.05006

	QCD	QQG $(\mathcal{M} \lesssim \Lambda_{\rm QQG})$
UV behavior	perturbative renormalizable, asymptotically free	
Strong scale	gauge coupling strong at $\Lambda_{\rm QCD}$	gravitational couplings strong at $\Lambda_{\rm QQG}$
Nonperturbative effects * *conjecture*	the transverse 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, $m_{\rm Pl} \sim \Lambda_{\rm QQG}$

* Conjecture led by an analogy between the full gluon propagator (lattice) and full graviton propagator, assuming the similarity of nonperturbative effects

Asymptotically free Quadratic Gravity

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What nontrivial curved background solution can we have?

As an approximation, find solutions in the Classical Quadratic Gravity that has the same limits in small and large curvatures

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

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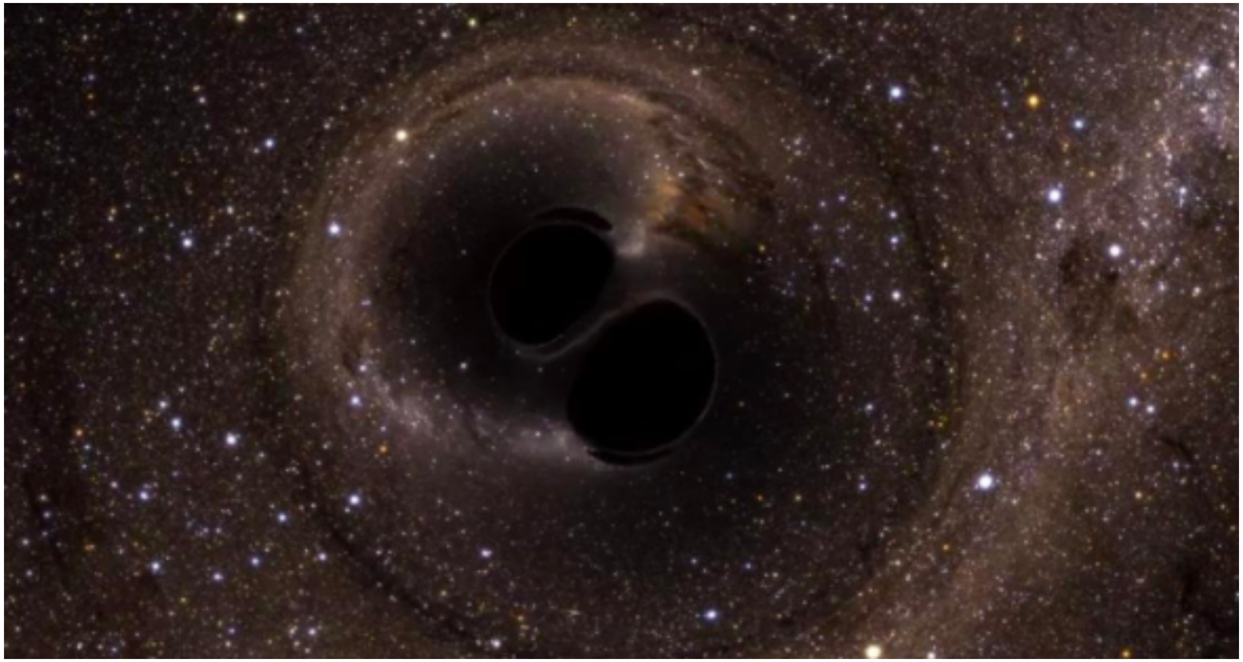
- Previous works treated this as a truncation and had problems with higher order terms when describing solutions with arbitrarily large curvatures.
- A macroscopic large 2-2-hole, its exterior has small curvature (IR), while the majority of its interior has super-Planckian curvature (UV).

The Novel Horizonless 2-2-holes

Holdom, Ren, arXiv: 1612.04889 [gr-qc]



Static spherically symmetric solutions

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

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- Series expansion around the origin [Stelle, Gen. Rel. Grav. 9, 353 (1978); Holdom, Phys. Rev. D 66, 084010 (2002)]

$$A(r) = a_s r^s + a_{s+1} r^{s+1} + \ldots, \; B(r) = b_t (r^t + b_{t+1} r^{t+1} + \ldots) .$$

(s,t)	behavior at $r=0$	GR	generic CQG
$(0,0)$	non-singular	none	a_2, b_2
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- (2,2) is a brand new family
- Five free parameters: the most generic solutions, rich structure
- Mild effects from smooth matter
- Similarity of the subclass $(2,2)_E$ and the (0,0) family

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- Linear approximation at large r (asymptotically-flatness) $m_2^2 = m_{\rm Pl}^2/2\alpha,\ m_0^2 = m_{\rm Pl}^2/6\beta$

$$B(r) = 1 - \frac{2M}{r} + C_0 \frac{e^{-m_0 r}}{r} + C_2 \frac{e^{-m_2 r}}{r}, \quad A(r) = 1 + \frac{2M}{r} + C_0 \frac{e^{-m_0 r}}{r}(1 + m_0 r) - \frac{1}{2} C_2 \frac{e^{-m_2 r}}{r}(1 + m_2 r).$$

- Exponentially small corrections to the Schd metric (essentially invisible for $m_i \sim m_{\rm Pl}$)
- Generally nonzero for different matter sources Lu, Perkins, Pope, Stelle, Phys. Rev. D 92, no. 12, 124019 (2015)

Question: which families of solution are actually realized as a response to matter distributions in the fully nonlinear theory?

Search for asymptotically-flat solutions that couple to a thin-shell (M, ℓ)

- Easy to isolate the shell effects on metric functions
- Study (0,0) family and $(2,2)_E$ family (both with two free parameters)
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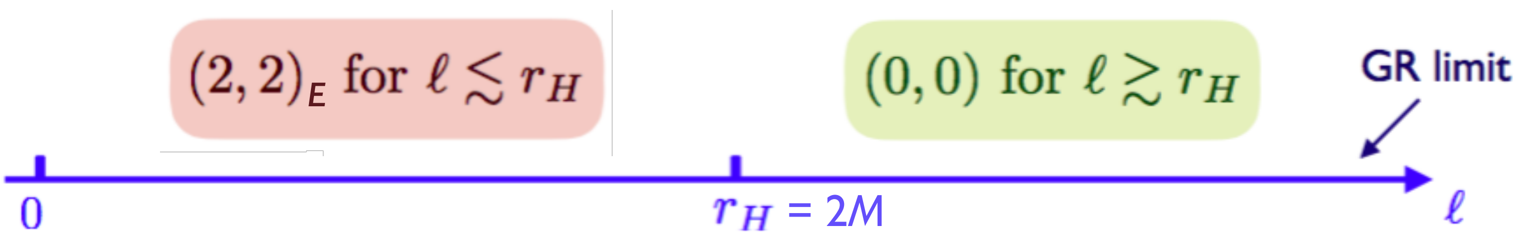


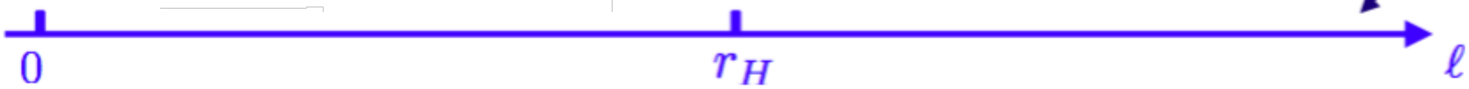
- When $\ell \gg r_H$, the regular (0,0) solutions approach the GR limit
- When $\ell \sim r_H$, (0,0) solutions can differ substantially from GR solutions
- When $\ell \lesssim r_H$, $(2,2)_E$ solutions take over. They remain ***horizonless*** and closely match the exterior Schd solutions (as dictated by the dynamics of gravity)

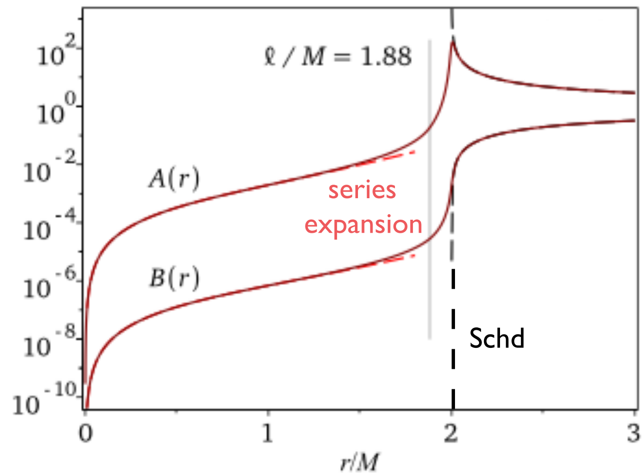
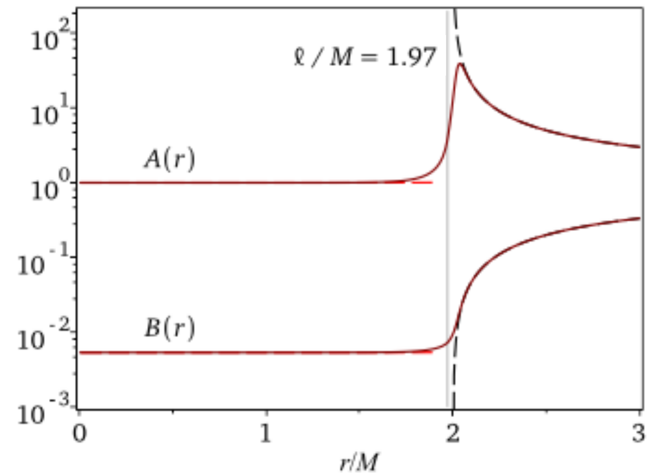
$M = 10$
$m_{0,2} = 1$

$(2,2)_E$ for $\ell \lesssim r_H$

$(0,0)$ for $\ell \gtrsim r_H$

GR limit



Metric functions		

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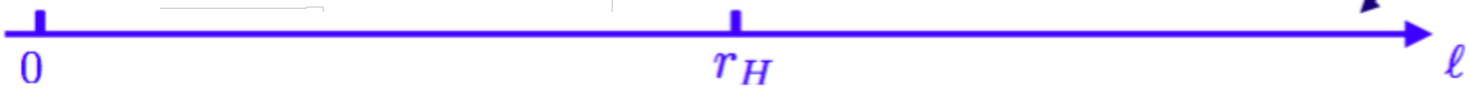

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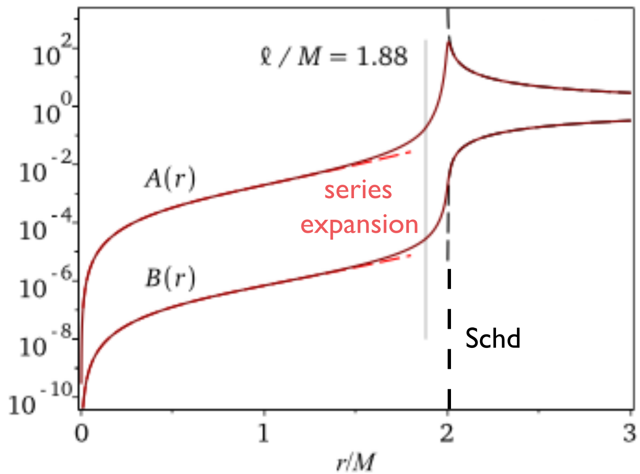

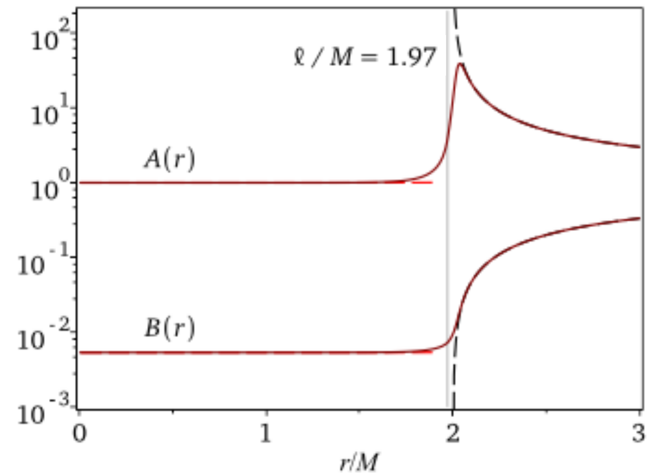

$r = 0$ expansion

$R \propto r^0$, $(R_{\mu\nu\rho\sigma})^2 \propto 1/r^8$, $(C_{\mu\nu\rho\sigma})^2 \propto 1/r^4$

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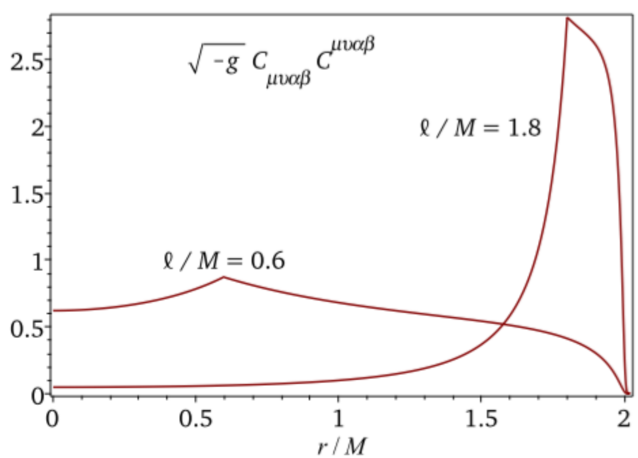
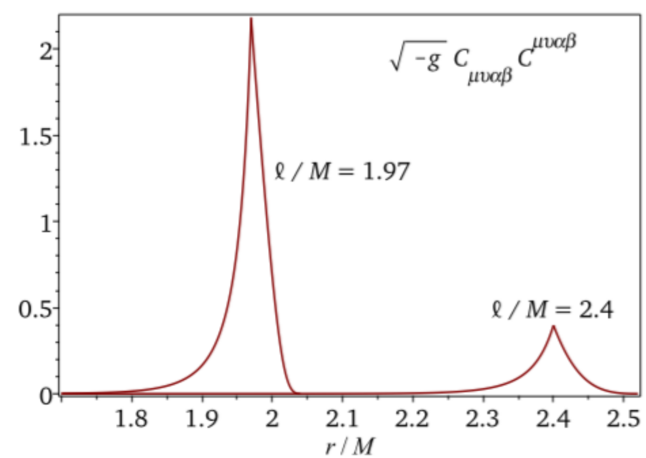
Curvature invariant





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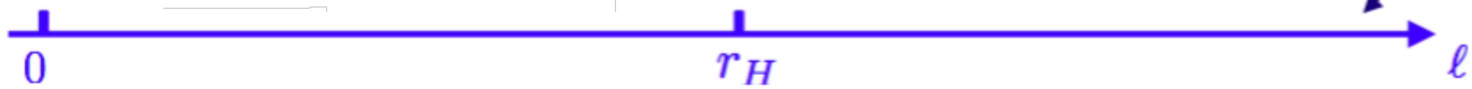
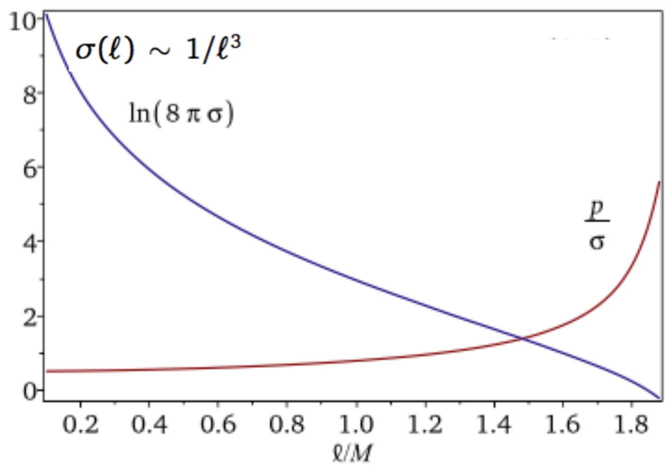
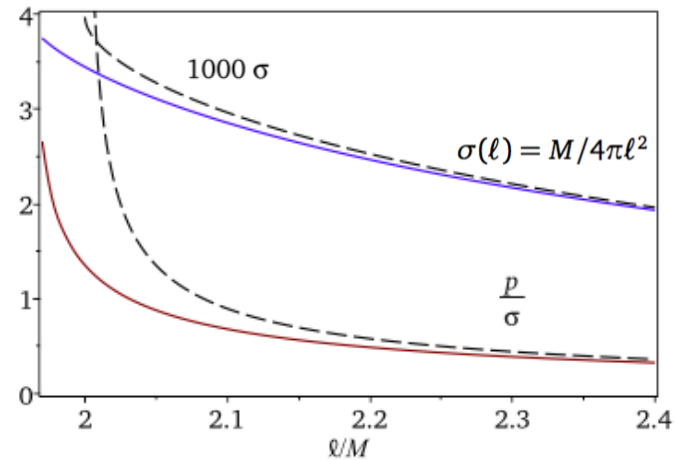


Shell energy density and pressure		

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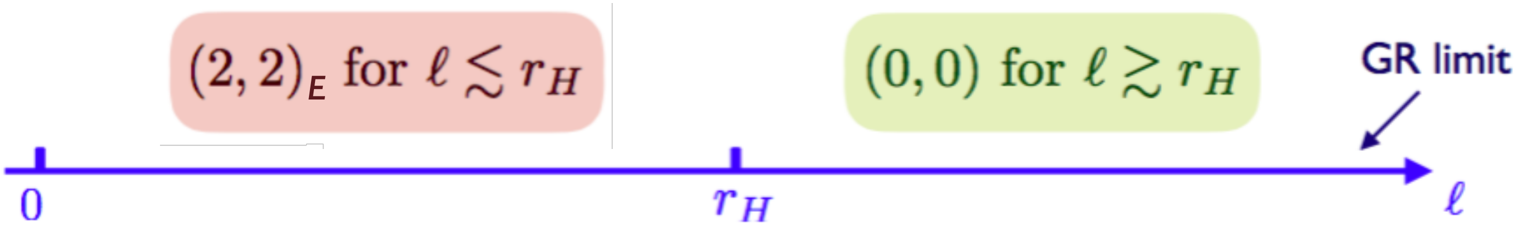
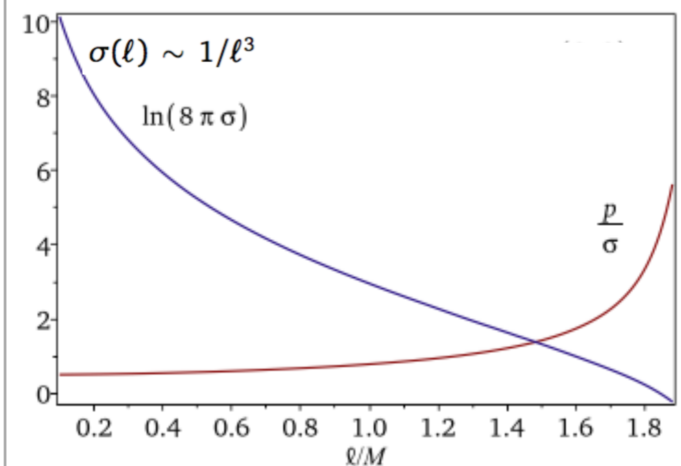
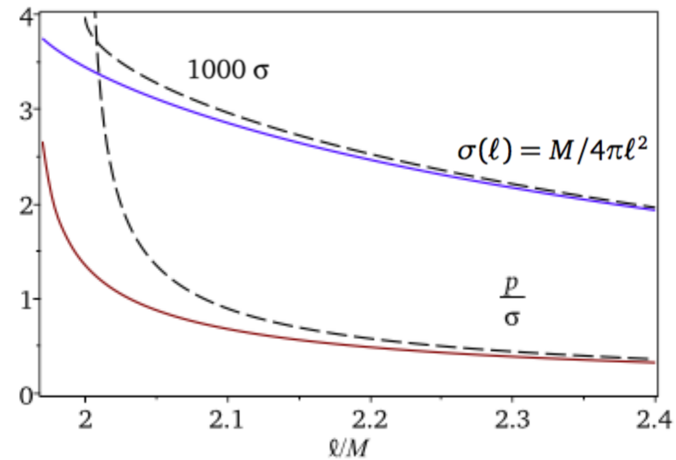
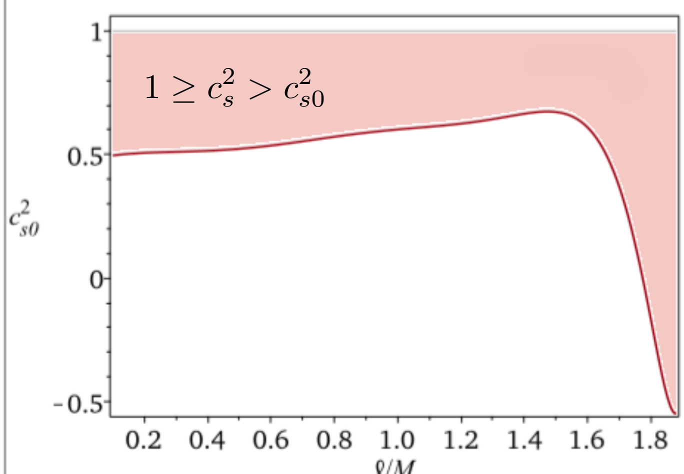
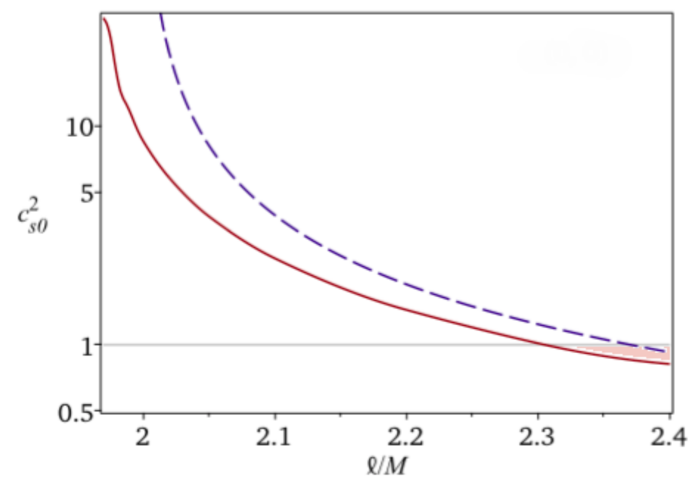


Shell energy density and pressure		
Radial stability $\delta^2 M > 0$		

Novel scaling for 2-2-holes interior

General features of the 2-2-holes with large mass $M_\odot \sim 10^{38} m_{\rm Pl}$?

The 2-2-holes interior $r \lesssim r_H$ is governed by a novel scaling wrt to its *M*.

For a given ℓ/M, the interior solutions for M and ϱM are related as below

	Novel scaling	Schd scaling	
metric function	$A_M(r) = \varrho^2 A_{\varrho M}(r\varrho)$ $B_M(r) = \varrho^2 B_{\varrho M}(r\varrho)$	$A_M(r) = A_{\varrho M}(r\varrho)$ $B_M(r) = B_{\varrho M}(r\varrho)$	
curvature invariant	$I_M(r) = I_{\varrho M}(r\varrho)$	$I_M(r) = \varrho^{2n} I_{\varrho M}(r\varrho)$	$\dim I(r) = 2n$

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- Interesting features: $S_{\rm CQG} \sim TM$; shell quantities (σ, p) and radial proper distance independent of *M* (proper distance for $r/M \in [0, 1.8]$ is about $\ell_{\rm Pl}$)
- Given the ℓ dependent solutions at one *M*, we know the 2-2-hole interior for all *M*.

Novel scaling for 2-2-holes interior

General features of the 2-2-holes with large mass $M_\odot \sim 10^{38} m_{\rm Pl}$?

The 2-2-holes interior $r \lesssim r_H$ is governed by a novel scaling wrt to its *M*.

For a given ℓ/M, the interior solutions for M and ϱM are related as below

	Novel scaling	Schd scaling	
metric function	$A_M(r) = \varrho^2 A_{\varrho M}(r\varrho)$ $B_M(r) = \varrho^2 B_{\varrho M}(r\varrho)$	$A_M(r) = A_{\varrho M}(r\varrho)$ $B_M(r) = B_{\varrho M}(r\varrho)$	
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- Given the ℓ dependent solutions at one *M*, we know the 2-2-hole interior for all *M*.

A 2-2-hole = large curvature interior (novel scaling) + transition (numerical) + small curvature exterior (Schd scaling)

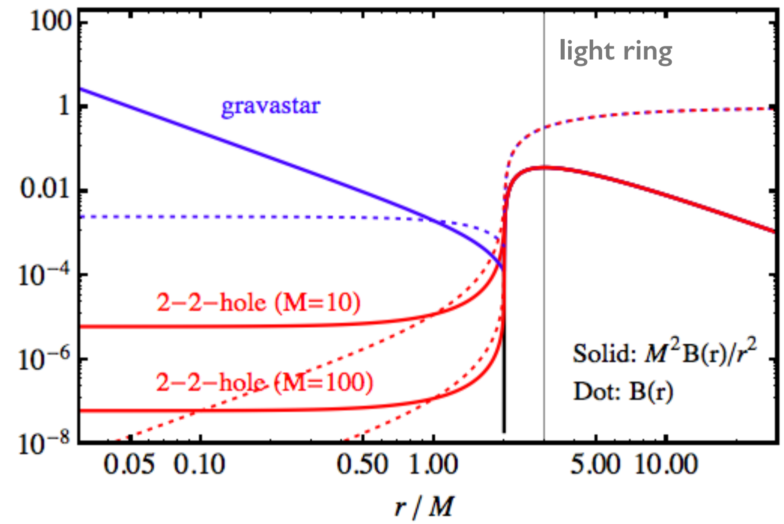
Point particles motion and trapping

Geodesics equations (equatorial plane):

$$\frac{dt}{d\zeta} = \frac{E}{B(r)}, \quad \frac{d\phi}{d\zeta} = \frac{L}{r^2}.$$

$$A(r)B(r)\left(\frac{dr}{d\zeta}\right)^2 + \left[\frac{B(r)}{r^2}L^2 + B(r)\vartheta\right] = E^2$$

$\vartheta = 1$ (0) for massive (massless) particles



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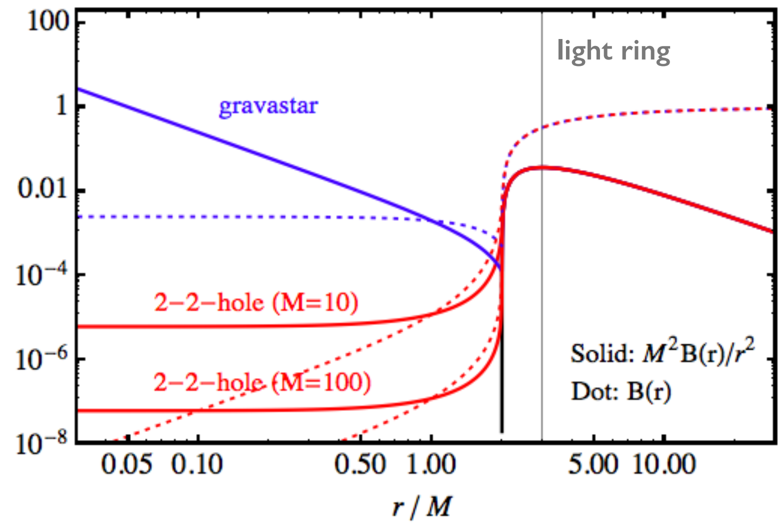

- Extremely deep gravitational potential for astrophysical 2-2-holes (novel scaling)
- The absence of the centrifugal potential and any other light rings

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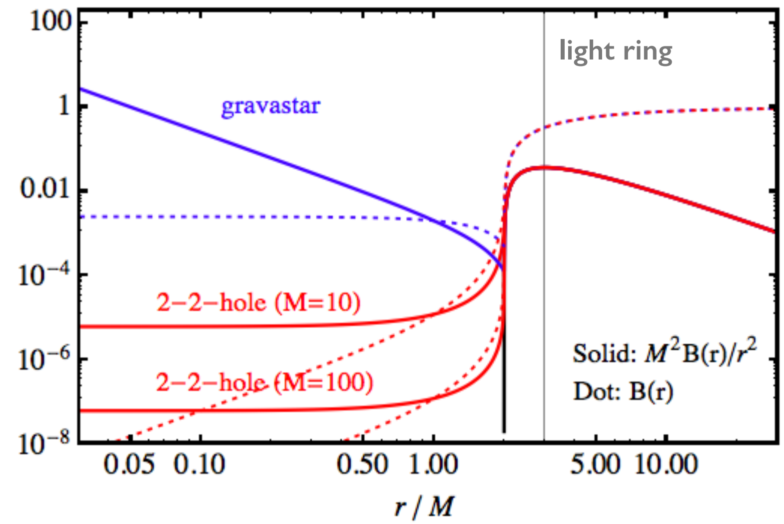


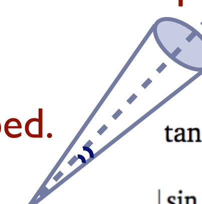
- Extremely deep gravitational potential for astrophysical 2-2-holes (novel scaling)
- The absence of the centrifugal potential and any other light rings
- Ultra-high energy particle collider: super-Planckian $\mathbb{E}_{\mathrm{cm}}^2$ for generic kinematics

  e.g. $\mathbb{E}_{\mathrm{cm}}^2 \approx 4\mathbb{E}_1\mathbb{E}_2/B(r)$ for radial head-on collisions

- **Trapping**: internal collisions produce particles with large *L/E* out of the escape cone

  A large trapped phase space is populated, with escape fraction ~ $1/M^2$

  Extremely small luminosity; accretion of matter may get efficiently absorbed.



$$\tan\chi = \sqrt{\frac{L^2B(r)/E^2r^2}{1 - L^2B(r)/E^2r^2}}$$

$$|\sin\chi| < 3\sqrt{3B(r)}M/r$$

Timelike curvature singularity?

Geodesic incompleteness? (problem for point particle probes)

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The 2-2-singularity appears regular as probed by finite energy wave-packets

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

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- The initial value problem of the wave equation is well-posed if "a boundary condition can be uniquely imposed", i.e. $\mathbb{A}$ has a unique positive self-adjoint extension

R. M. Wald, J. Math. Phys. **21**, 2802 (1980); Ishibashi, Wald, Class. Quant. Grav. **20**, 3815 (2003); Horowitz, Marolf, PRD **52**, 5670 (1995)

- For finite energy wave-packets, no ambiguity of the dynamics if only one solution has finite Sobolev norm around the origin Ishibashi, Hosoya, PRD **60**, 104028 (1999)

$$||f||^2 = \frac{1}{2}\int_\Sigma d\Sigma B^{-1/2} f^* f + \frac{1}{2}\int_\Sigma d\Sigma B^{1/2} h^{ij} D_i f^* D_j f$$

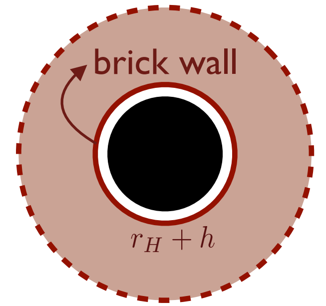
- Near origin behaviors: the 2-2-singularity appears very mild; all the waves behave like the s-wave on a nonsingular spacetime. A Neumann boundary condition is imposed at the origin.

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

"A brick wall" and Entropy

The brick wall model: attribute the black hole entropy to the 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)

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



$T(r) \equiv T_\infty/\sqrt{B(r)}$

- Artificial UV cutoff? Why d.o.f. localized outside the horizon?
- Back-reaction from large local energy density? Mukohyama, Israel, PRD 58, 104005 (1998)

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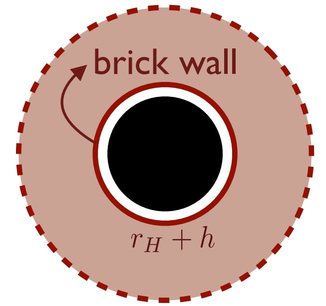

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Directly generalized to the 2-2-hole with now the brick wall replaced by the origin (with a Newnman boundary condition)

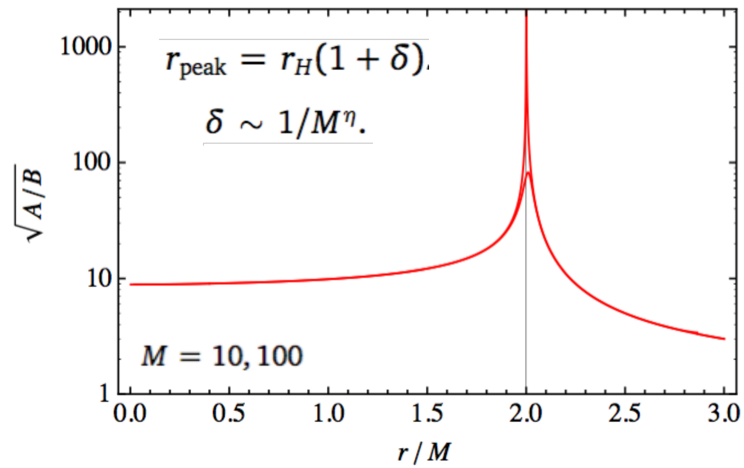
$$S = \frac{(2\pi)^3}{45}\int_0^L T(r)^3 A(r)^{1/2} r^2 dr, \quad U = \frac{3}{4} T_\infty S.$$

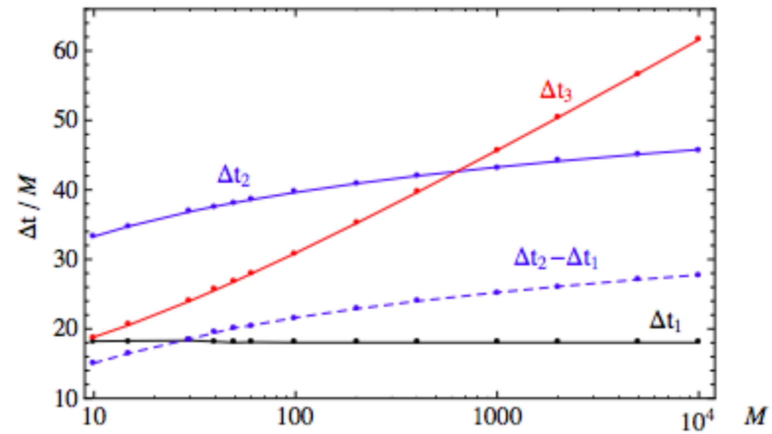
- Consider the case that the back-reaction is negligible, $T_\infty \propto T_{\rm Hawking}$
- Both *S* and *U* are finite, and dominated by the interior contribution. Again the area law is recovered due to the novel scaling, with $S \sim S_{\rm BH}$.
- The timelike singularity is covered by its own fireball

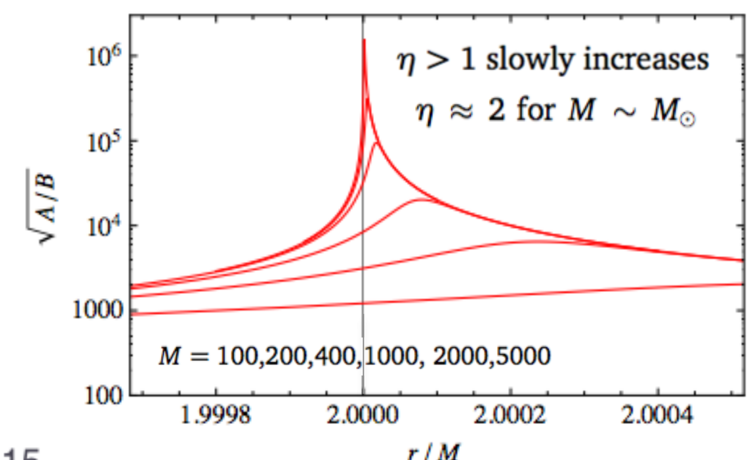
The time delay to probe internal structure

Time spacing
between echoes of
the initial ringdown

$$\Delta t = 2\int_0^{3M}\sqrt{\frac{A(r)}{B(r)}}dr = \Delta t_1 + \Delta t_2 + \Delta t_3 \quad [0,M], [M, r_{\text{peak}}], [r_{\text{peak}}, 3M]$$







Extrapolation to astrophysical objects

- Interior: $\Delta t_1/M \sim 2\sqrt{a_2/b_2}$
- Inner peak: $\Delta t_2 - \Delta t_1$ grows slower than Δt_3
- Outer peak (dominant): $\Delta t_3/M \sim 4\eta \ln M$

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

For $M \sim 30M_\odot$ Δt is in the 100-125 ms range.

(similar time delay used in arXiv:1612.00266 [gr-qc].)

Summary

- With the new perspective on quadratic gravity, we find that sufficiently dense matter produces a novel horizonless 2-2-hole that closely matches the exterior Schd solution. As a generic static solution, it may then be the nearly black endpoint of gravitational collapse.
- The large curvature 2-2-hole interior has interesting features: a tiny volume, a novel scaling, a large trapped phase space, area law for the thermal entropy, a singularity covered by a fireball…
- The 2-2-hole provides motivation for further study of the strong phase of quadratic gravity. It may also serve as a benchmark to search for effects of large curvatures in gravitational wave signal.
- Open questions…
  - Quasinormal modes and the relation to echoes? Metric perturbations?
  - Rotating 2-2-holes, ergoregion instability?
  - Solutions with time dependence, endpoint of gravitational collapse?

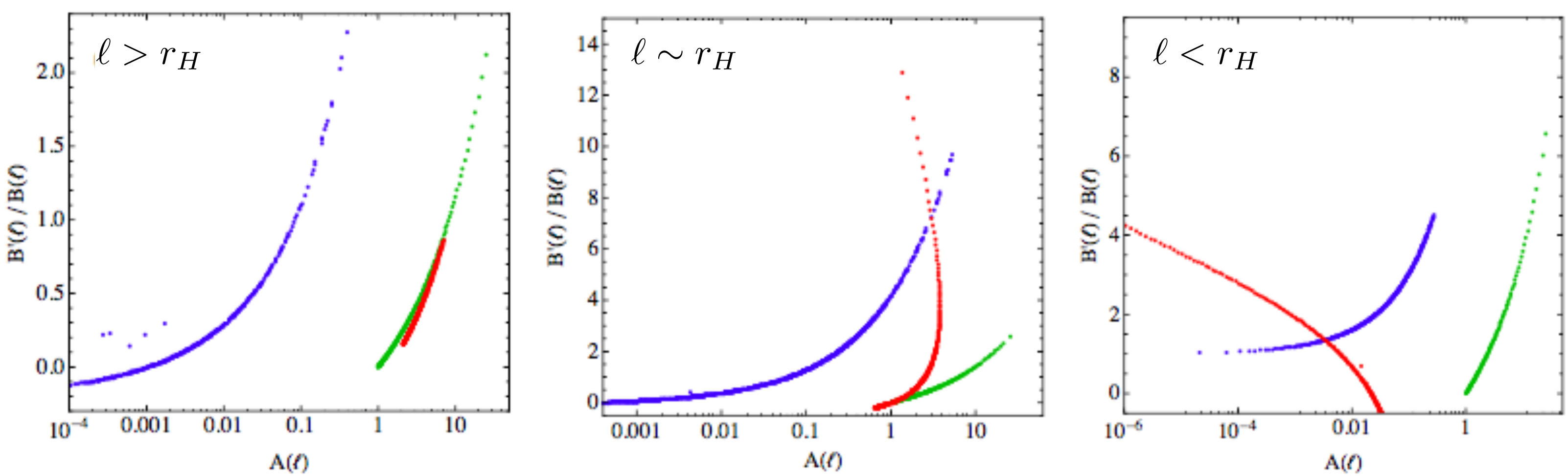
Thank You!

Shooting and matching method

Search for asymptotically-flat solutions that couple to a thin-shell (M, ℓ)

- The shell energy density implies that A'' has a jump of at the shell radius
- Find *A(r)*, *B(r)* for a pair of (M, ℓ) by matching at $r = \ell$ for $A, A', B'/B, B''/B$ (4)
- Shooting from the outside with small deviations from Schd metric (2)
- Shooting from the inside using series expansions in $(2,2)_E$ family or (0,0) family (2)

$\beta = 0$ CQG (half of the initial conditions and free parameters)



Parameters counting not enough to determine the correct interior behaviors

Potential in scalar field equation

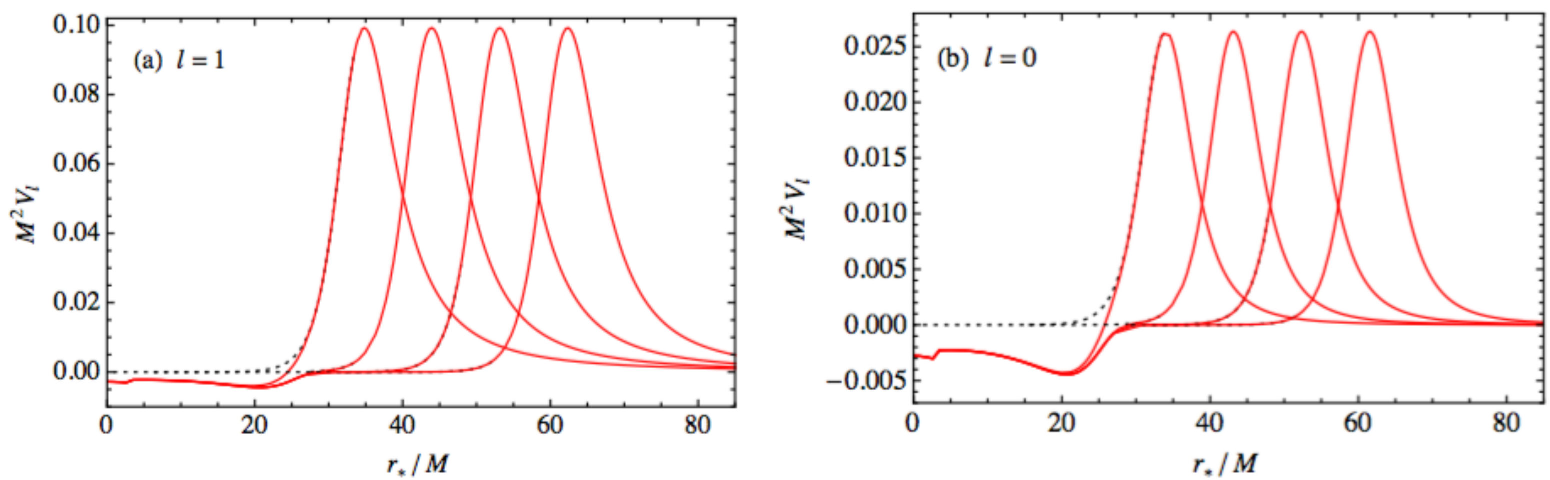
Scalar wave equation in tortoise coordinate $dr_*/dr = \sqrt{A/B}$: $\psi_l(r,t) = e^{-i\omega t}\Psi_l(r)/r$

$$(\partial_{r_*}^2 + \omega^2 - V_l(r))\Psi_l = 0, \quad V_l(r) = B(r)\frac{l(l+1)}{r^2} + \frac{1}{2r}\frac{B(r)}{A(r)}\left(\frac{B'(r)}{B(r)} - \frac{A'(r)}{A(r)}\right). \quad r_*(0) = 0$$

$\beta = 0$ CQG

$M = 10, 100, 1000, 10^4$

(left to right)



- Large radius dominant by light ring peak $M^2 V_l(r) \approx l^2/27$ (shift of the peak from Δt_3)
- Small radius (interior): potential dominant by the *l*-independent term, i.e. S-wave
- A small negative potential with the depth and width independent of *M* (from the scaling behavior). Interestingly it is barely small enough so that there is no instability.

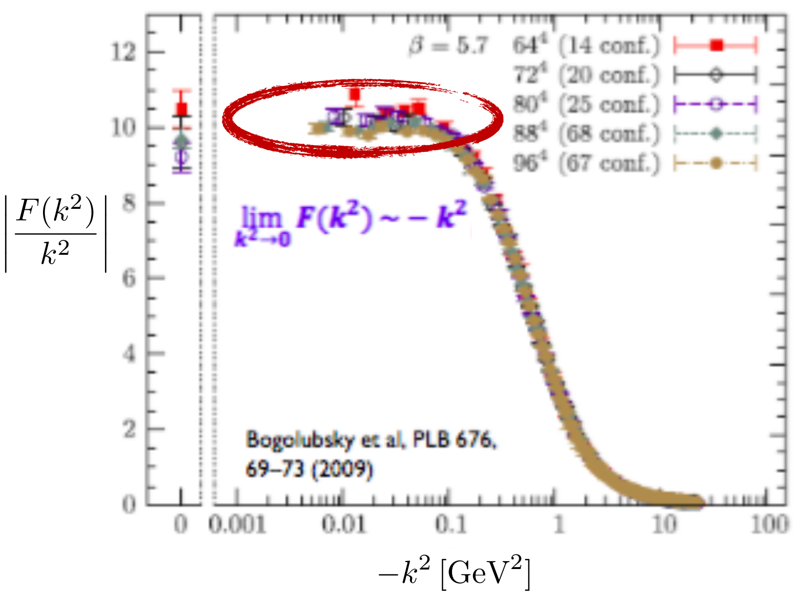
Analogy based on full propagators $(\mathcal{M}=0)$

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

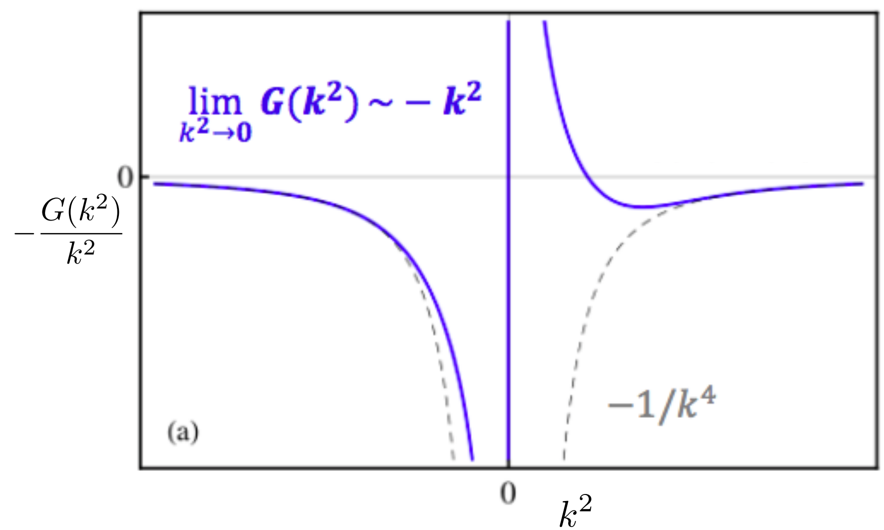
Graviton: $-G(k^2)/k^4$ × (tensor factor) × (perturbative correction)

the existence and the 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)



Lattice data in Landau gauge



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

$m_{\rm Pl}^2/8\pi = -1/G'(0) \sim \Lambda_{\rm QQG}^2$