Title: Effects of black hole radiation: horizon avoidance

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Abstract: Event horizons are the defining feature of classical black holes. They are the key ingredient of the information loss paradox which, as paradoxes in quantum foundations, is built on a combination of predictions of quantum theory and counterfactual classical features. Within the semi-classical theory we investigate the possibility that black hole radiation still does not allow for a finite time crossing of the Schwarzschild radius of collapsing matter as seen by distant observers. The exact form of the pre-Hawking radiation is not yet settled, and we make only minimal assumptions about its nature.

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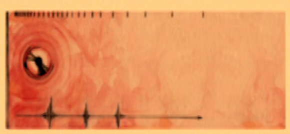
Effects of black hole radiation: horizon avoidance?

Valentina Baccetti

QUANTUM BLACK HOLES IN THE SKY?



8-10 November 2017

PERIMETER INSTITUTE

Collaborators

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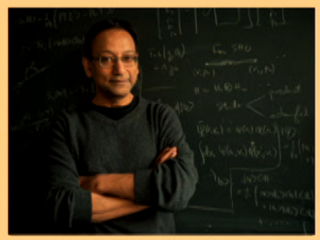
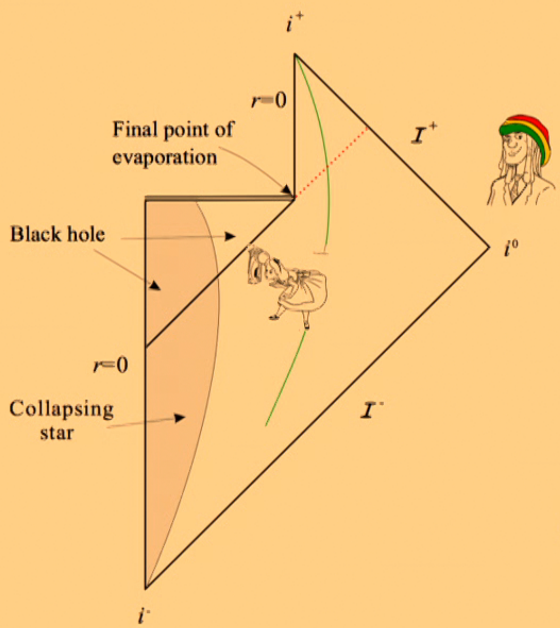


Viqar Husain

Unaware contributors:

- Unknown PRL referees
- Bill Unruh
- Pisin Chen
- Et al.

Information loss paradox?



Ingredients

GR: horizon, mass-area relation

QFT: radiation

Why is it a paradox?

GR: deterministic

[spherically-symmetric

collapse on a asymptotically flat background:

Hamiltonian evolution]

Unruh, Phys. Rev. D **14**, 870 (1976).

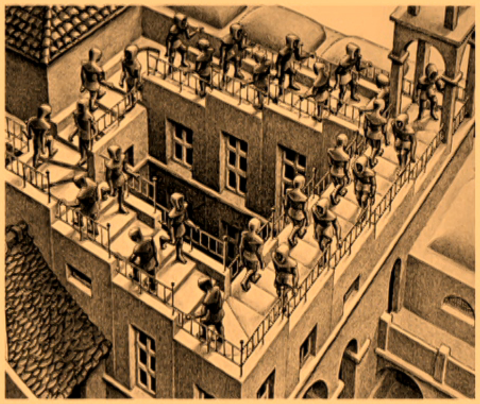
VH and DRT, Phys. Rev. D **81**, 044039 (2010)

QM▸*QFT*: unitary

Additional causality issue:

- Collapse (i.e. event horizon crossing) takes an infinite amount of time
- Radiation (that needs a horizon?) evaporates a BH in finite amount of time

Foundationally speaking
Paradoxes of quantum mechanics



Ingredients:

1. Classical ideas/assumptions/results
2. Quantum features/results
3. Combine and try to obtain

probability distributions that satisfy all of (1) & (2)

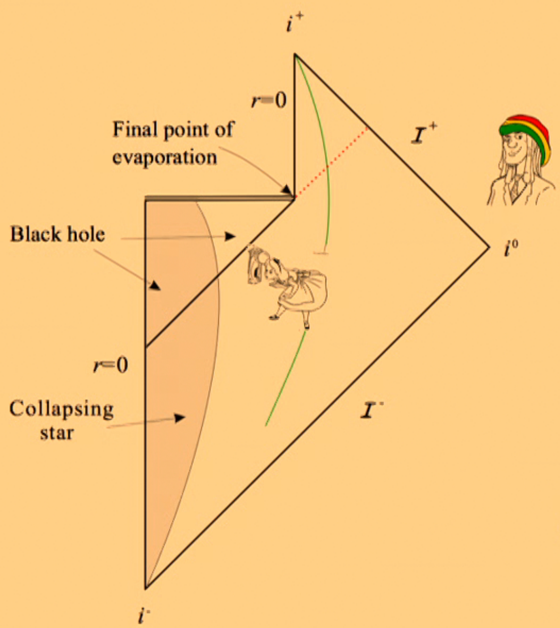
Outcome

- Contradiction
  (before all QM results are used)

Examples:

- EPR: Bell-CHSH;
- Kochen-Specker paradox
- Information loss?

Information loss paradox?



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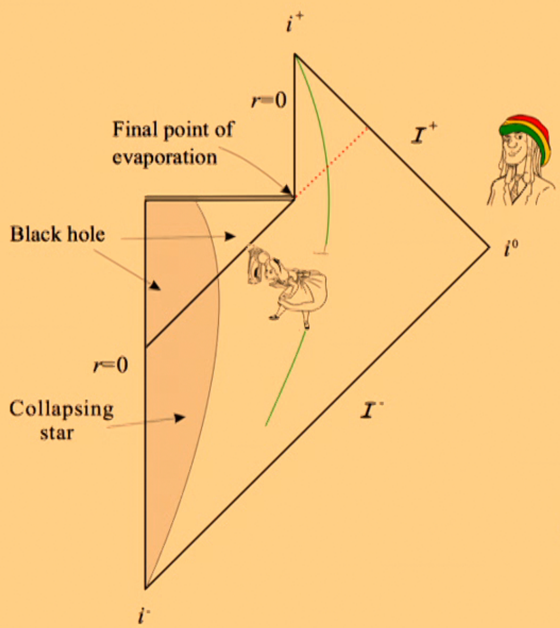
Information loss paradox?



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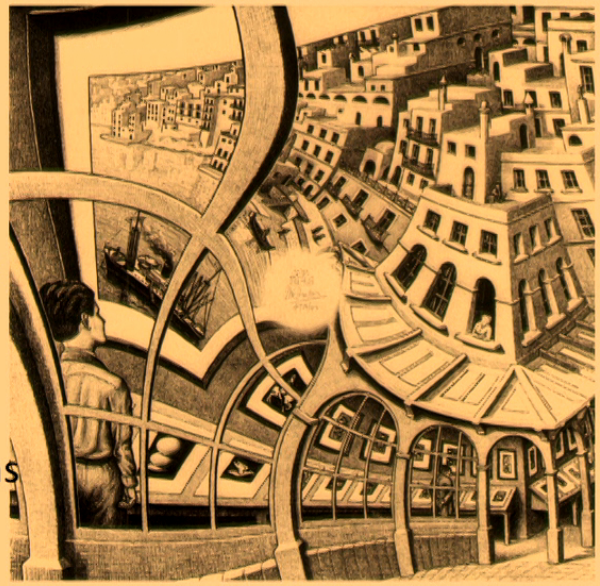
Logic of the Analysis

Hierarchy of models

- Quantum field theory on a curved background
- Semiclassical gravity
- Semiclassical stochastic gravity
- Effecive field theories of matter-gravity systems
- Full theory of quantum gravity



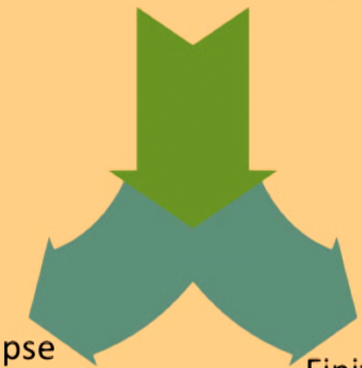
Logic of causality

Causality issues

Collapse takes infinite Bob's time

Collapse takes finite Alice's time

Evaporation takes finite Bob's time



(*) A case for existance of pre-Hawking radiaton

- Gerlach, PRD **14**, 1479 (1976).
- Alberghi, Casadio, Vacca, Venturi,PRD **64**, 104012 (2001).
- Barcelo, Liberati, Sonego, Visser, CQG **23**, 5341 (2006)
- Vachaspati, Stojkovic, Kraus, PRD **76**, 024005 (2007).

Four assumptions

1. The classical spacetime structure is still meaningful and is described by a metric $g_{\mu\nu}$.

2. Classical concepts, such as trajectories, event horizon and singularity can be used.

3. The collapse leads to pre-Hawking radiation.

4. The metric is modified by quantum effect. The resulting curvature satisfies the semiclassical equation:

$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} = 8\pi \langle \widehat{T}_{\mu\nu} \rangle \qquad \langle \widehat{T}_{\mu\nu} \rangle = \frac{2}{\sqrt{-g}} \frac{\delta W}{\delta g^{\mu\nu}}$$

❖ Paranjape and Padmanabhan, Phys. Rev. D **80**, 044011 (2009)

Goals and tools

Self-consistency of the semiclassical theory

- possibility of the horizon avoidance (no finite proper time crossing)?

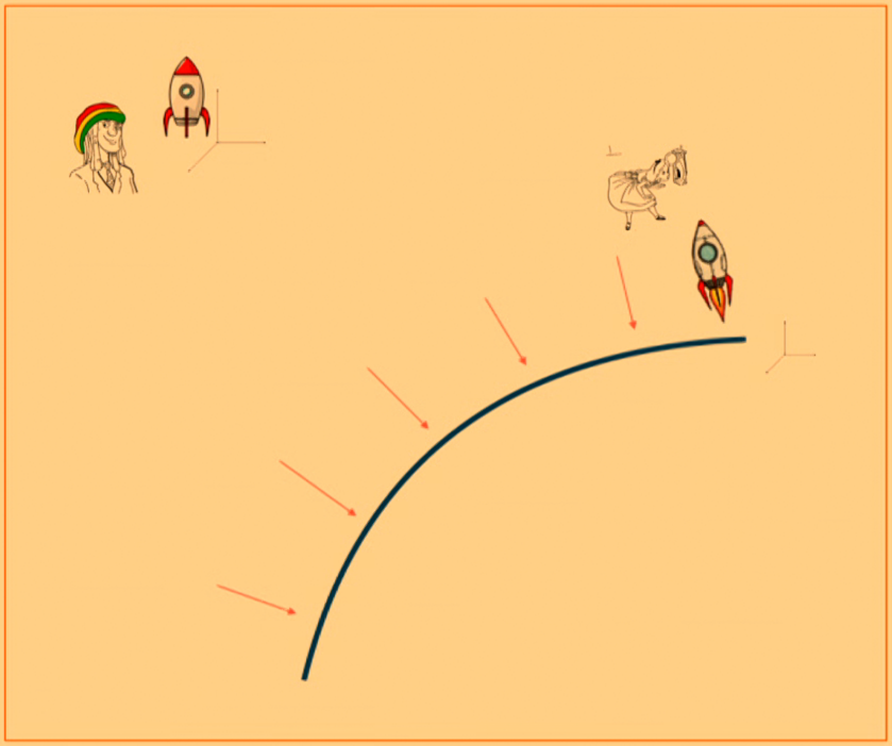
Classical horizon obtains its physical status because of the finite proper time crossing(co-moving/in-fallingAlice).

Quantum-affected horizon should be tested in the same way

- massive shells, etc.

Collapse of a massive thin shell

The big picture



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9

Collapse of a massive thin shell

Structure

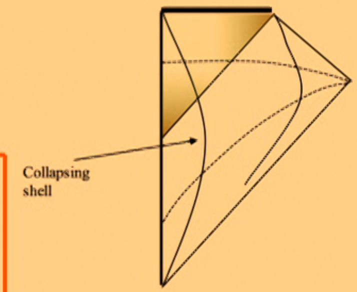
(+) Eddigton-Finkelstein/Schwarzschild

$$ds_+^2 = -f(r,u)du^2 - 2du dr + r^2 d\Omega^2$$

$$ds_+^2 = -\tilde{f}(r,u)dt^2 + \tilde{f}(t,r)^{-1}dr^2 + r^2 d\Omega^2$$

$(U(\tau), R(\tau))$

$(T(\tau), R(\tau))$



Minkowski inside, Schwarzschild outside

(-) Minkowski

$$ds_-^2 = -dt_-^2 + dr_-^2 + r_-^2 d\Omega^2$$

Junction conditions:

(1) $g_{\mu\nu}|_{\Sigma+} \to h_{ab} \leftarrow g_{\mu\nu}|_{\Sigma-}$ $\qquad r_- = r_+ \equiv r$

(2) $S_{ab} = -\frac{1}{8\pi}([K_{ab}] - K[h_{ab}])$ $\qquad [K_{ab}] = K_{ab}^+ - K_{ab}^+$ $\qquad$ EoM

Thin shell

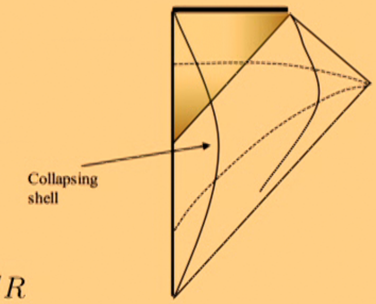
Vaidya metric

(+) $$ds_+^2 = -f(r,u)du^2 - 2dudr + r^2 d\Omega^2$$

$$f(u,r) = 1 - C(u)/r$$

$$\Sigma : F = 1 - C(U)/R$$

$$r_g(u) \equiv C(u, r_g(u))$$



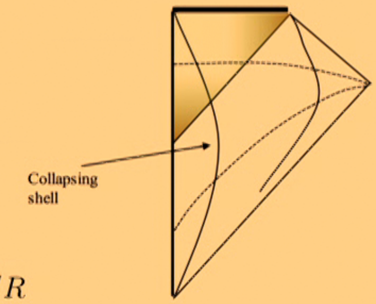
EoM

$$\begin{cases} \mathcal{D}(R) - F_U \dot{U} \left(\frac{\dot{R}}{2F\sqrt{F+\dot{R}^2}} - \frac{1}{2F} \right) = 0 \\ \dot{U}_+ = \frac{-\dot{R} + \sqrt{F+\dot{R}^2}}{F} \end{cases}$$

Thin shell

Vaidya metric

(+) $ds_+^2 = -f(r,u)du^2 - 2dudr + r^2 d\Omega^2$



$f(u,r) = 1 - C(u)/r$

$\Sigma: \ F = 1 - C(U)/R$

$r_g(u) \equiv C(u, r_g(u))$

EoM

Non evaporating collapse

$$\mathcal{D}(R) := \frac{2\ddot{R} + F'}{2\sqrt{F + \dot{R}^2}} - \frac{\ddot{R}}{\sqrt{1 + \dot{R}^2}} + \frac{\sqrt{F + \dot{R}^2} - \sqrt{1 + \dot{R}^2}}{R}$$

Thin shell

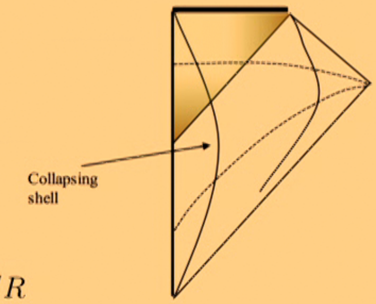
Vaidya metric

(+) $$ds_+^2 = -f(r,u)du^2 - 2dudr + r^2 d\Omega^2$$

$$f(u,r) = 1 - C(u)/r$$

$$r_g(u) \equiv C(u, r_g(u))$$

$$\Sigma : \; F = 1 - C(U)/R$$

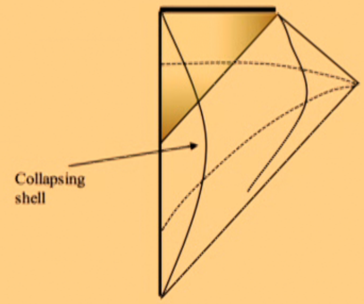


EoM
$$\begin{cases} \mathcal{D}(R) - F_U \dot{U} \left(\frac{\dot{R}}{2F\sqrt{F + \dot{R}^2}} - \frac{1}{2F} \right) = 0 \\ \dot{U}_+ = \frac{-\dot{R} + \sqrt{F + \dot{R}^2}}{F} \end{cases}$$

Thin shell

Vaidya metric

The gap to monitor $x(\tau) := R(\tau) - r_g(U(\tau))$



EoM
$$\begin{cases} \dot{U} \approx -2\dot{R}/F \approx -2\dot{R}C/x \\ \ddot{R} \approx 4\dot{R}^4 \dfrac{C}{x^2}\dfrac{dC}{dU} \end{cases}$$

- Shell's rate of approach to r_g

$$\dot{x} = \dot{R}\left(1 - \frac{2C}{x}\left|\frac{dC}{dU}\right|\right) = |\dot{R}|\left(\frac{\epsilon_*(\tau)}{x} - 1\right)$$

$$\epsilon_* := 2C\left|\frac{dC}{dU}\right|$$

Collapse accelerates

Shell is stuck at ϵ_* from reciding r_g

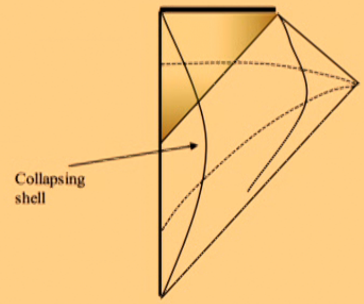
❖ P. Chen, W. G. Unruh, C-H. Wu, and D-H. Yeom, arXiv:1710.01533

Thin shell

Vaidya metric

EoM
$$\begin{cases} \dot{U} \approx -2\dot{R}/F \approx -2\dot{R}C/x \\ \ddot{R} \approx 4\dot{R}^4 \dfrac{C}{x^2}\dfrac{dC}{dU} \end{cases}$$

$$\dot{R}(\tau_0) = -\infty$$



❑ Shell becomes (and stays) null in a finite proper time

➢ Shell's rate of approach to r_g:

$$\lambda = -R \qquad x_\lambda = R_\lambda - dr_g/d\lambda = -1 + \frac{2r_g}{x}\left|\frac{dC}{dU}\right|$$

$$x_\lambda = -(1 - \epsilon_*/x(\lambda))$$

$$\epsilon_* := 2C\left|\frac{dC}{dU}\right|$$

Dilemma:

➢ Horizon avoidance?

➢ Suppression of radiation?

❖ H. Kawai, Y. Matsuo, and Y. Yokokura, Int. J. Mod. Phys. A 28, 1350050 (2013)
❖ R. B. Mann, I. Nagle, and D. R. Terno, in preparation

Thin shell

Retarded Schwarzschil metric

(+) $$ds_+^2 = -\tilde{f}(r,u)dt^2 + \tilde{f}(t,r)^{-1}dr^2 + r^2 d\Omega^2$$

$$\tilde{f}(t,r) = 1 - C(\tilde{t})/r \equiv f(\tilde{t}, r)$$

$$\frac{dr}{dt} = 1 - C(\tilde{t}/r)$$

Similar to
Lienard - Wiechert potential

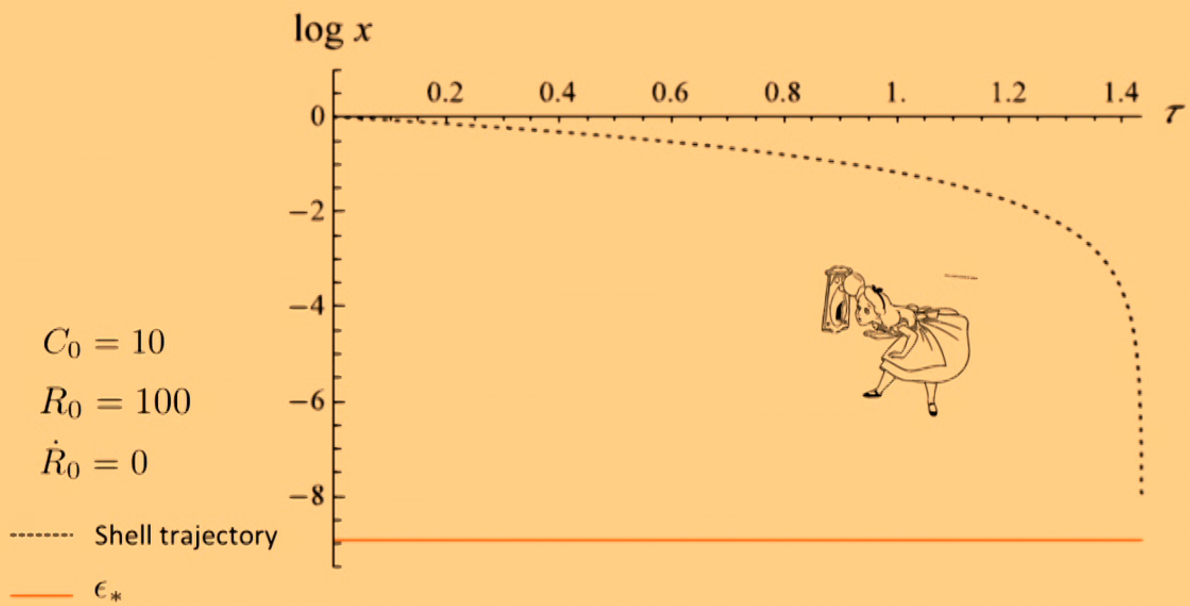
EoM:
$$\begin{cases} \mathcal{D}(R) - \dfrac{F_T \dot{R}}{F^2} = 0 \\ \dfrac{dC}{dt} = \dfrac{8 \times 8}{15,360\pi} \dfrac{1}{C^2} \end{cases} \Rightarrow \quad \ddot{R} \approx -\frac{\dot{R}^4}{3\kappa C x^2}, \quad \dot{C} \approx -\frac{\dot{R}}{3\kappa C x}$$

Thin shell

Retarded Schwarzschil metric

(+

Ec



Thin shell

Retarded Schwarzschil metric

(+

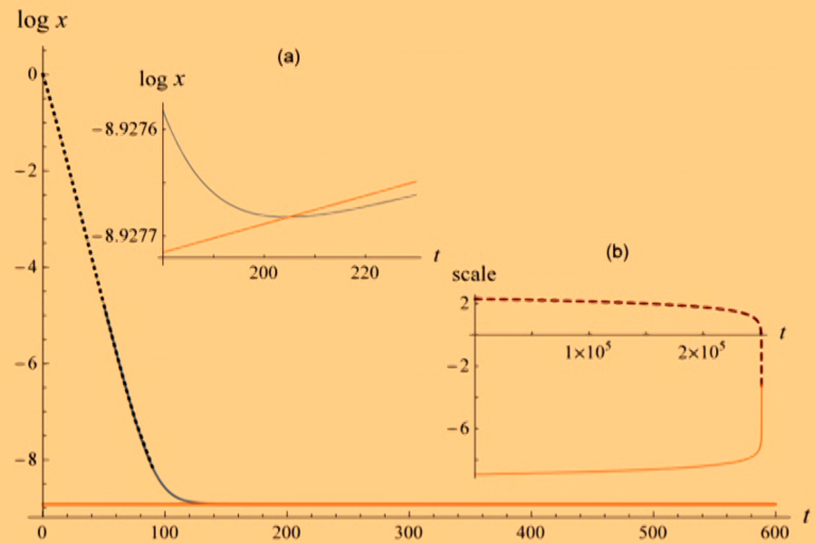
$$\frac{dx}{dt} = -\frac{x}{C} + \frac{1}{3\kappa C^2}$$

Ec

$C_0 = 10$

$R_0 = 100$

$\dot{R}_0 = 0$



-------- Shell trajectory

—— ϵ_*

Summarize:
Known and known unknows

Known

- ❑ Thin massive shell:
  - ➢ collapse and evaporation without horizon
  - ➢ collapse and suppression of radiation

Generic spherically-symmetric metric
Arbitrary dimension D > 3+1
Works for shell collapsing on a core
Thin massive rotating dust shell

Known unknowns

- ❑ What happens to Alice?
- ❑ Is the horizon avoidance generic?
- ❑ Which stress-energy tensor to use?
- ❑ Can we have the exceptional metric?
- ❑ Trapped surfaces?
- ❑ What happens at the next level [semiclassical stochastic gravity]?

Summarize: Context

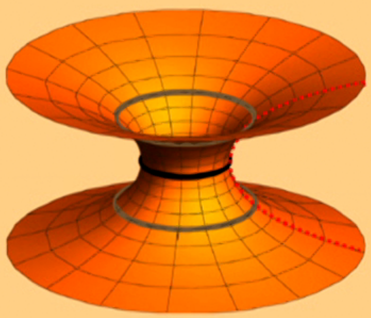
- Absence of the event horizon is consistent with arguments that quantum effects destroy it.

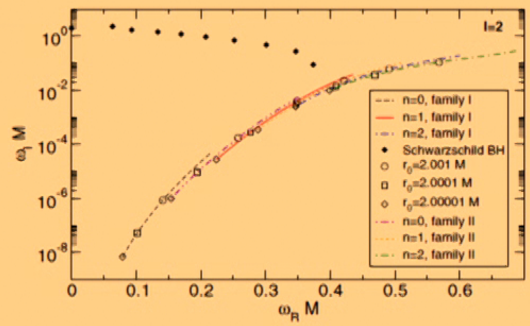
  †Brustein, Fortschr. Phys. **62**, 255 (2014)

- No info loss in semiclassical theory: it is consistent.

  The paradox seems to go the way of the paradoxes of QM.

- Observability? May be…





❖ Cardoso, Franzin, and Pani,Phys. Rev. Let. **116**, 171101 (2016)

Summarize: Unknown unknows

- How quantum correlations get distributed between the tripartite system of gravity/early modes/late modes.

- Bekestein-Hawing black hole entropy is $S_{BH} = A/4$
  If event horizons do not correspond to asymptotically reachable states of collapsing matter, what are the thermodynamics propertiers of the resulting ultra-compact object

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Thank you

- VB, RBM, DRT, *Do event horizons exist?* Int.J.Mod.Phys D26 (2017) 743008
- VB, RBM, DRT, *Horizon avoidance in spherically-symmetric collapse*, arXiv: 1703.09369 (2017).
- VB, RBM, DRT, *Effects of evaporation on gravitational collapse*, arXiv: 1610.07839 (2016).
- VB, VH, DRT, *The information recovery problem*, Entropy **19**,17 (2017).