The VECRO hypothesis

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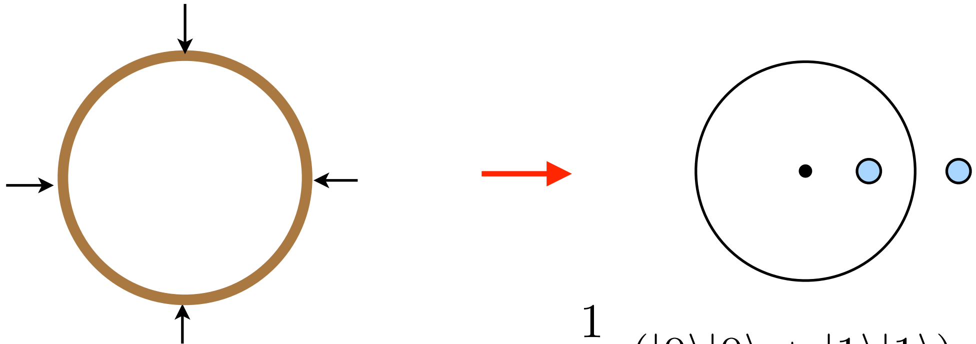
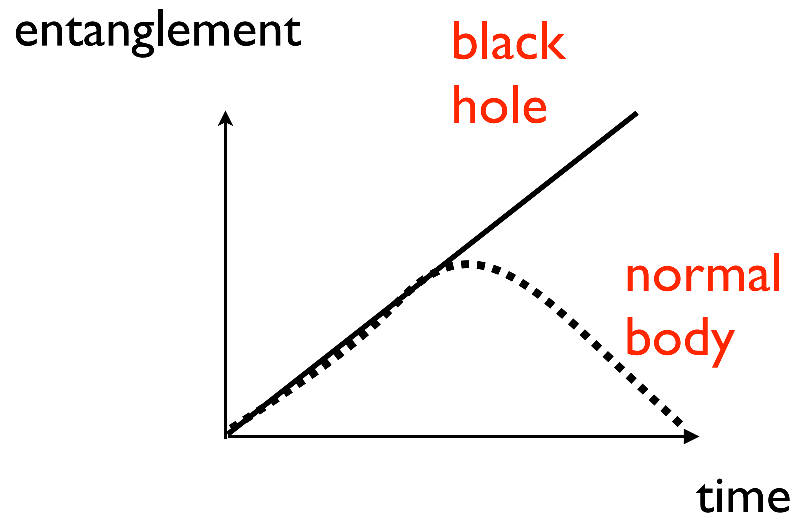
Thanks to everyone for making possible this wonderful conference in these difficult circumstances

(arxiv: 1703.03042,1705.06407, 1812.11641, 1905.12004, 2001.11057)

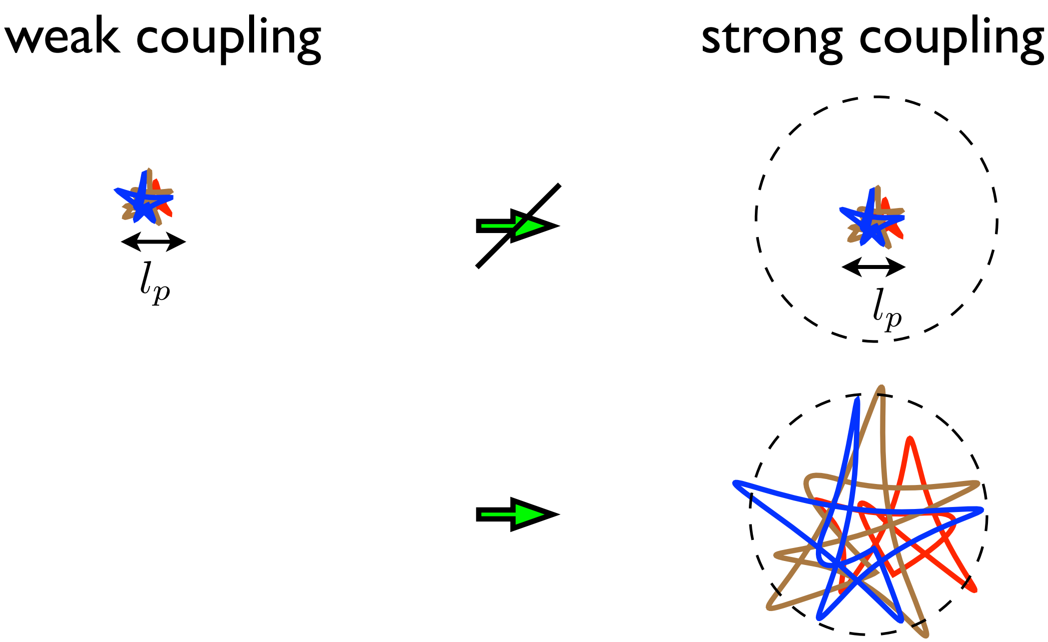
The black hole information paradox



$$\frac{1}{\sqrt{2}}(|0\rangle|0\rangle + |1\rangle|1\rangle) + O(\epsilon)$$



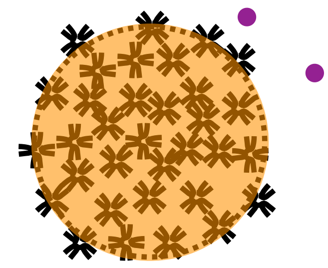
Fuzzballs: Consider bound states of branes in string theory:



The size of the bound state grows with the number of branes, and a horizon never forms

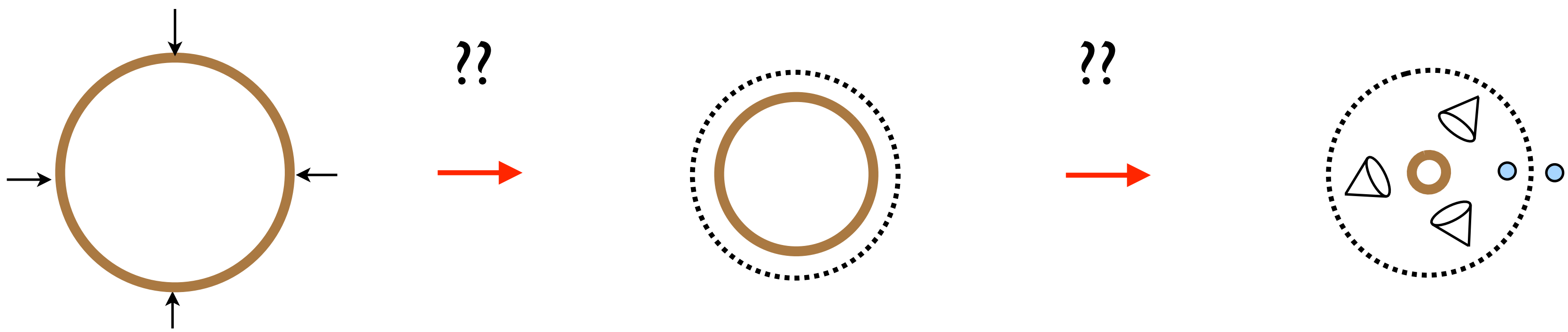
→ *fuzzball*

In the fuzzball paradigm, black hole microstates do not have a horizon; they radiate like normal objects from their surface

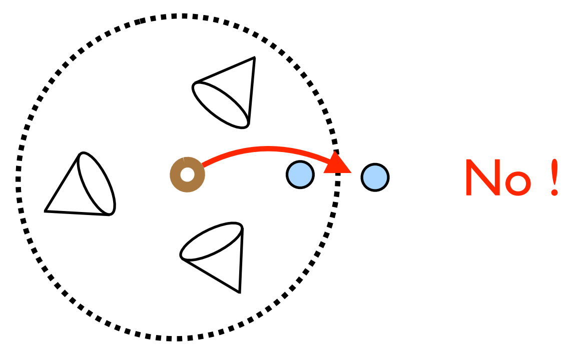


Thus we do not have any information puzzle

But we will learn a lot by asking a more refined question: Where and why does the semiclassical approximation break down ?



We will assume that there are no large violations of causality in our gravity theory



Then, how does the semiclassical collapse get replaced by fuzzball formation ?

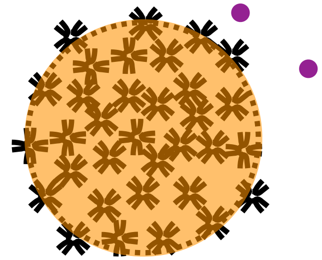
This is the central aspect of the paradox from the viewpoint of a relativist. (This is a qualitative question, so our discussion will also be qualitative)

We will argue for a picture of the quantum gravity vacuum which will resolve this puzzle

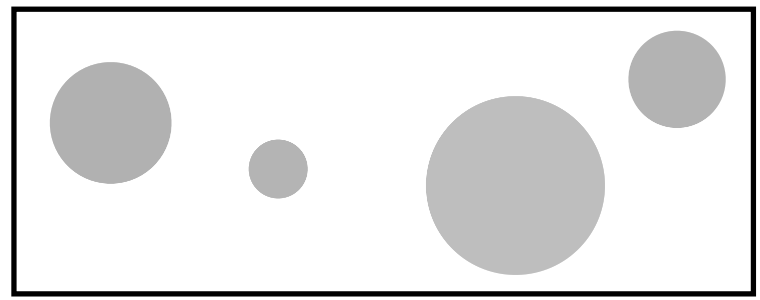
We call this picture the VECRO hypothesis

VECRO: Virtual Extended Compression-Resistant Objects

(a) On shell microstates are Extended objects (fuzzballs) with size $R \sim 2GM + l_p$



(b) Thus the quantum gravity vacuum must contain Virtual fluctuations corresponding to these objects

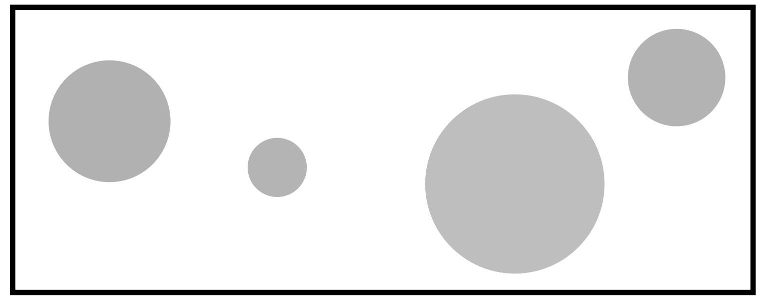


(c) The fluctuations to a fuzzball type configuration with $R \gg l_p$ will be highly suppressed, but there are $Exp[S_{bek}(R)]$ fuzzball states of this size, so there will be a large phase space of such configurations.

We assume that the largeness of this phase space will offset the suppression, so that these vecro fluctuations are an important component of the quantum gravity vacuum

The VECRO hypothesis: The quantum gravity vacuum contains an important component consisting of virtual fuzzball type configurations.

This component plays a crucial role in situations where a horizon is predicted by the semiclassical theory, and modifies the dynamics to resolve the puzzles that arise



(a) Explains how a collapsing shell turns into fuzzballs while maintaining causality of the underlying theory

(b) Gives a resolution of the bags of gold problem

(c) Are the Rindler, Black hole, Cosmological horizons similar? (No, differ in vecro flictuations)

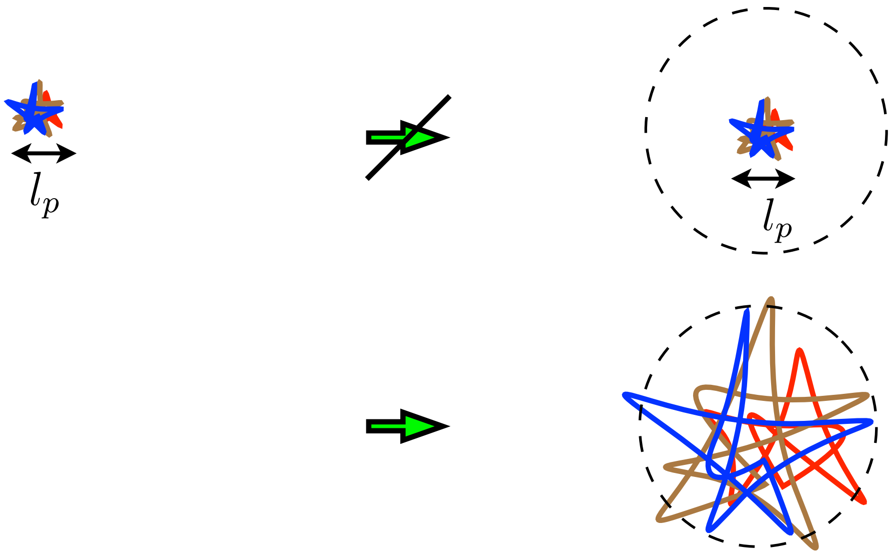
(d) Can impact cosmological issues like inflation, cosmological constant, bubble nucleation

Fuzzballs

Avery, Balasubramanian, Bena, Bobev, Bossard, Carson, Ceplak, Chowdhury, de Boer, Gimon, Giusto, Guo, Hampton, Heidmann, Jejjala, Katmadas, Kanitscheider, Keski-Vakkuri, Kraus, Levi, Lunin, Madden, Maldacena, Maoz, Martinec, Mayerson, Niehoff, Park, Peet, Potvin, Puhm, Ross, Ruef, Rychkov, Saxena, Shigemori, Simon, Skenderis, Srivastava, Taylor, Titchner, Turton, Vasilakis, Wang, Warner ... and many others

Consider the bound states of D1, D5, P charges.

weak coupling   strong coupling



The size of the bound state grows with the number of branes, and a horizon never forms

→ *fuzzball*

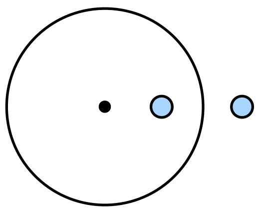
$$D \sim \left[\frac{\sqrt{n_1 n_5 n_p}\, g^2\, \alpha'^4}{V\, L}\right]^{\frac{1}{3}} \sim R_H$$

(SDM hep-th/9706151)

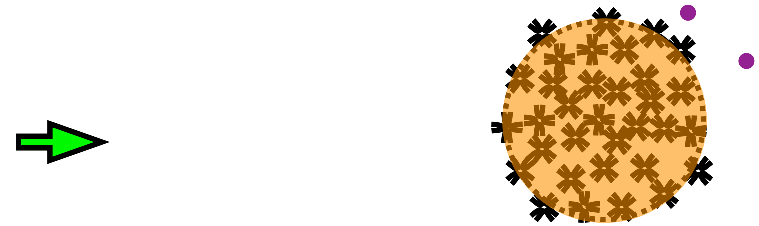
Many examples of string solutions have been constructed, and in each case we have found that the solution has no horizon (Large program by Bena, Warner et al)

(All 2 charge extremal states, many families of 3 and 4 charge extremal, some families of nonextremal, radiation from near extremal matches expectations exactly …)

Fuzzball conjecture: No microstate in string theory will have a traditional horizon which has a vacuum region in its vicinity



$$\frac{1}{\sqrt{2}}(|0\rangle|0\rangle + |1\rangle|1\rangle) + O(\epsilon)$$



state of radiated quantum depends on details at the surface

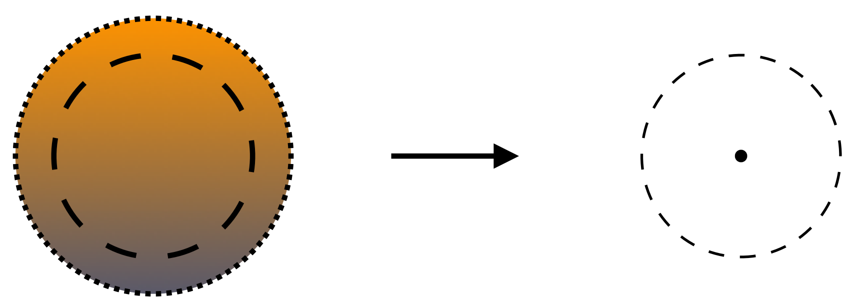
How did we bypass the various no-hair theorems?

There are special features of a theory like string theory which has extra dimensions/ extended objects/Chern-Simmons terms etc.

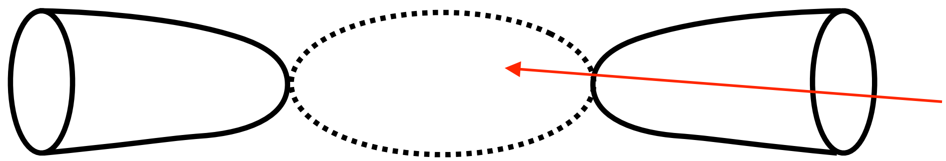
(Gibbons+Warner 13)

What about Buchdahl theorem? Fluid sphere with pressure decreasing outwards must collapse if

$$R < \frac{9}{4} M$$



Toy model: Euclidean Schwarzschild plus time ('neutral fuzzball')



$$ds^2 = -dt^2 + (1-\frac{r_0}{r})d\tau^2 + \frac{dr^2}{1-\frac{r_0}{r}} + r^2(d\theta^2 + \sin^2\theta d\phi^2) \ , \qquad 0 \le \tau < 4\pi r_0$$

We can reduce on the direction τ to get a scalar field in 3+1 gravity.

The stress tensor is the standard one for a scalar field $T_{\mu\nu} = \Phi_{,\mu}\Phi_{,\nu} - \frac{1}{2}g^E_{\mu\nu}\Phi_{,\lambda}\Phi^{,\lambda}$

Why does this shell of scalar field not collapse inwards ?

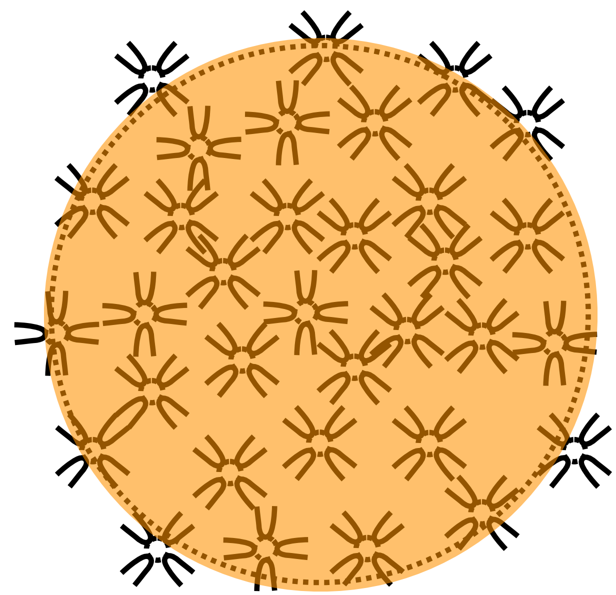
$$T^{\mu}{}_{\nu} = \mathrm{diag}\{-\rho, p_r, p_\theta, p_\phi\} = \mathrm{diag}\{-f, f, -f, -f\} \ , \qquad f = \frac{3r_0^2}{8r^4(1-\frac{r_0}{r})^{\frac{3}{2}}}$$

Pressure diverges at tip of cigar so a Buchdahl type analysis would call this a singularity

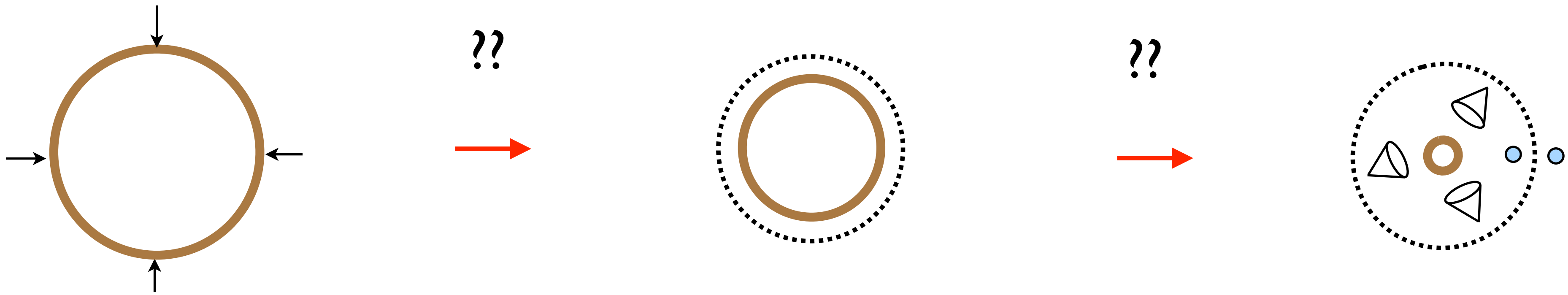
But the 4+1 dimensional solution is completely regular
(g_{tt} never changes sign, so there is no horizon)

In general constructing a fuzzball needs all the details of string theory: extra dimensions, strings, branes, fluxes, …

But for our present purposes we can keep in mind a heuristic picture of the fuzzball where we have many the holes (bubbles) in space that are linked together in a way that they support each other …



The causality puzzle

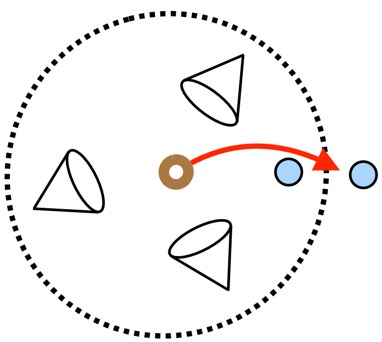


Collapsing shell

Shell passes through horizon with all curvatures low

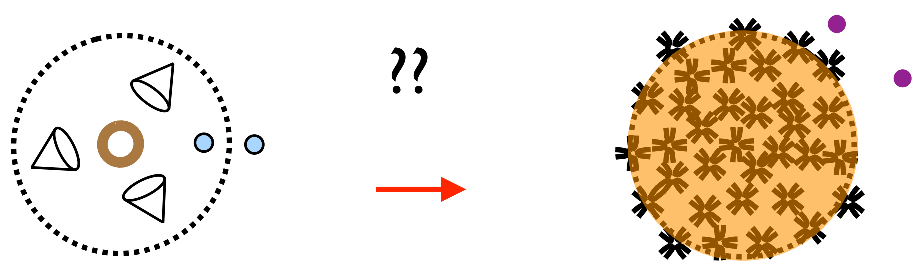
Light cones point inwards inside horizon

We will assume: If curvatures are low throughout a spacetime region, then causality holds to leading order. Here causality means that signals do not propagate outside the light cone, and that there are no nonlocal interactions between points that are spacelike separated.

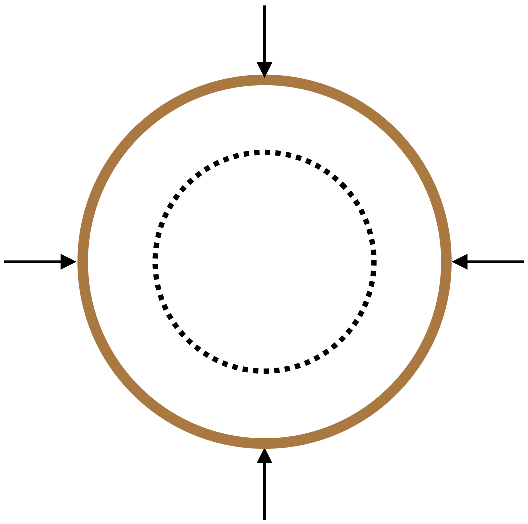


No large effects

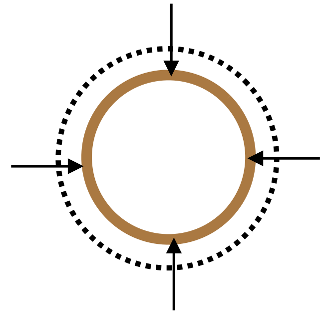
How do we form the fuzzball?



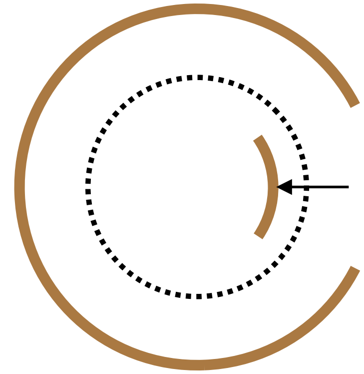
A strong constraint comes from considering *partial shells*



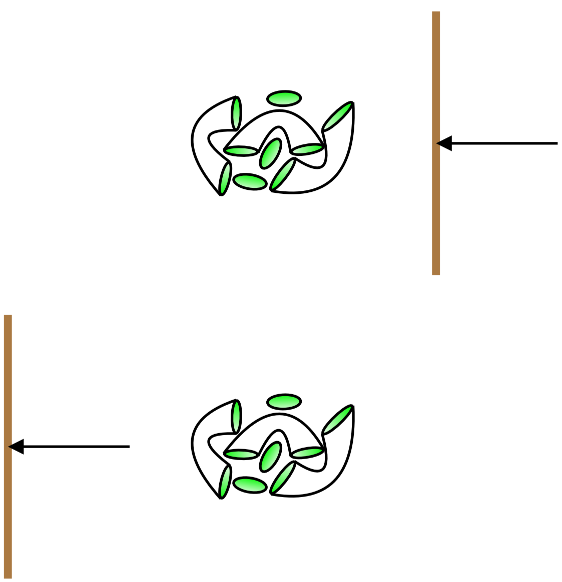
Shell collapsing
at speed of light



(a) black hole
formation

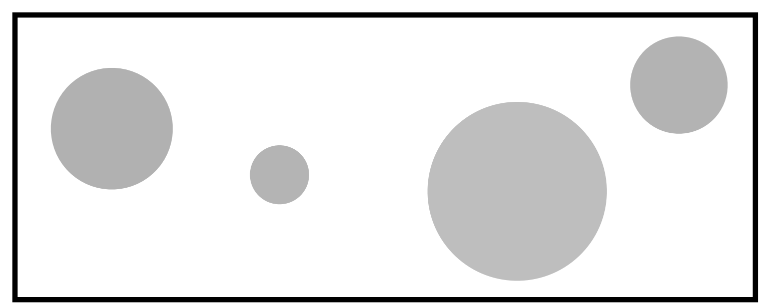


(b) Partial shell continues in; rest
stops; expect no black hole formation



Aichelburg-Sexl shock wave; vacuum
fluctuations return to original form
after wave

If we only consider small scale vacuum fluctuations
we will be trapped by the causality problem



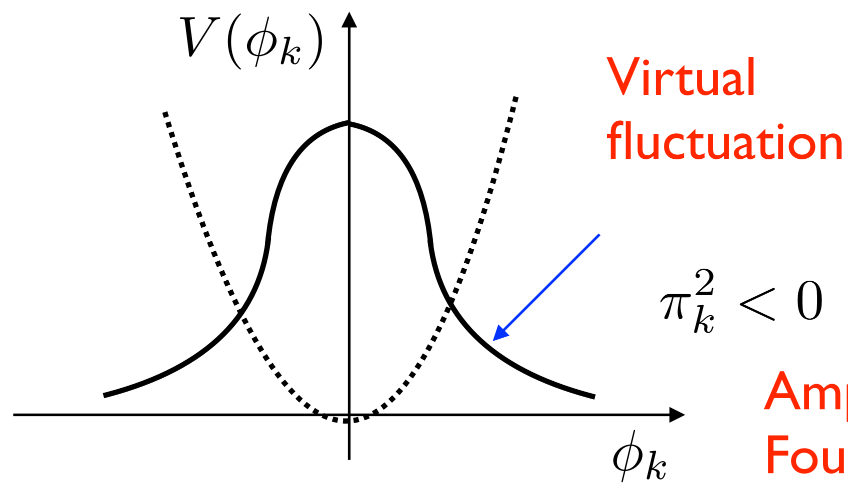
Virtual fuzzballs of radius $\sim R_h$ can 'feel
around' the scale of the collapsing shell
and know when a hole should form

Resolution of the causality puzzle under the VECRO hypothesis

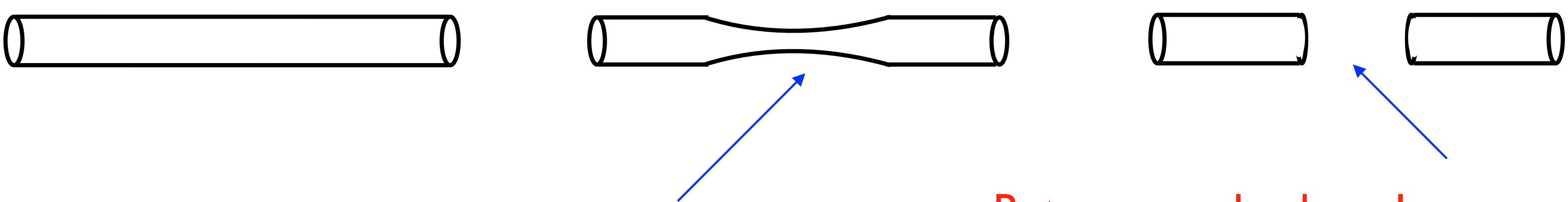
VECRO: Virtual Extended Compression-Resistant Objects

(A) What is a virtual fluctuation ?

For a free scalar field, 'Virtual fluctuations' are just the part of the vacuum wavefunctional that are 'under the potential barrier'

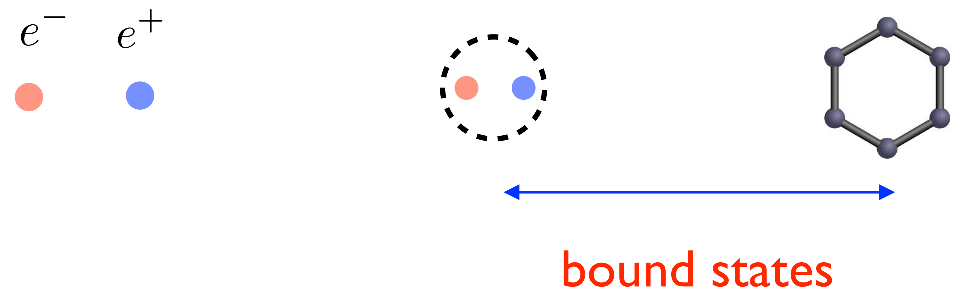


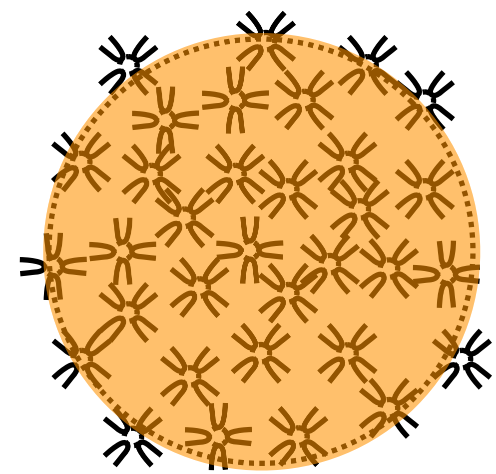
(B) Suppose this scalar arises as the size of a compact circle



(C) Let us think of fuzzball type configurations are bound states of such local structures

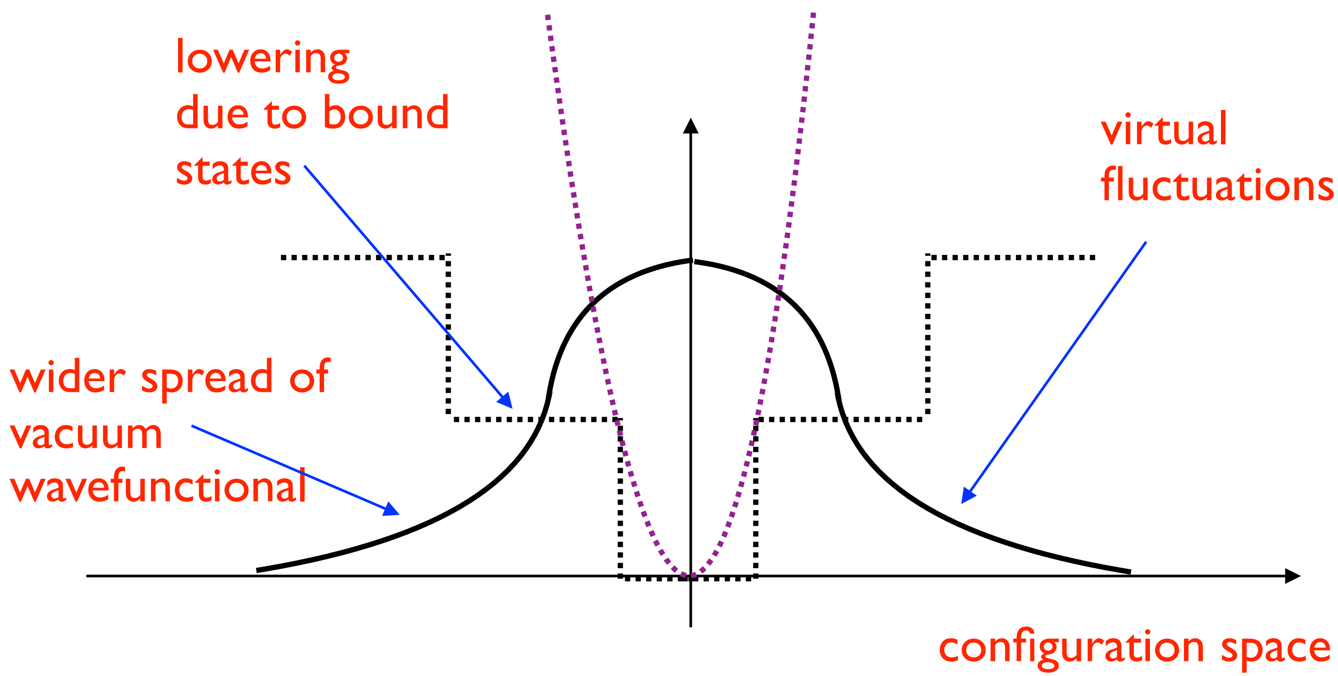
How do bound states of the theory show up in the potential?





(An on-shell positronium state is orthogonal to the vacuum)

Bound states are manifested as a lowering of the potential over appropriate regions of configuration space



(D) The fluctuation to any large fuzzball configuration is highly suppressed:

$$P \sim e^{-S} \sim e^{-ET}$$

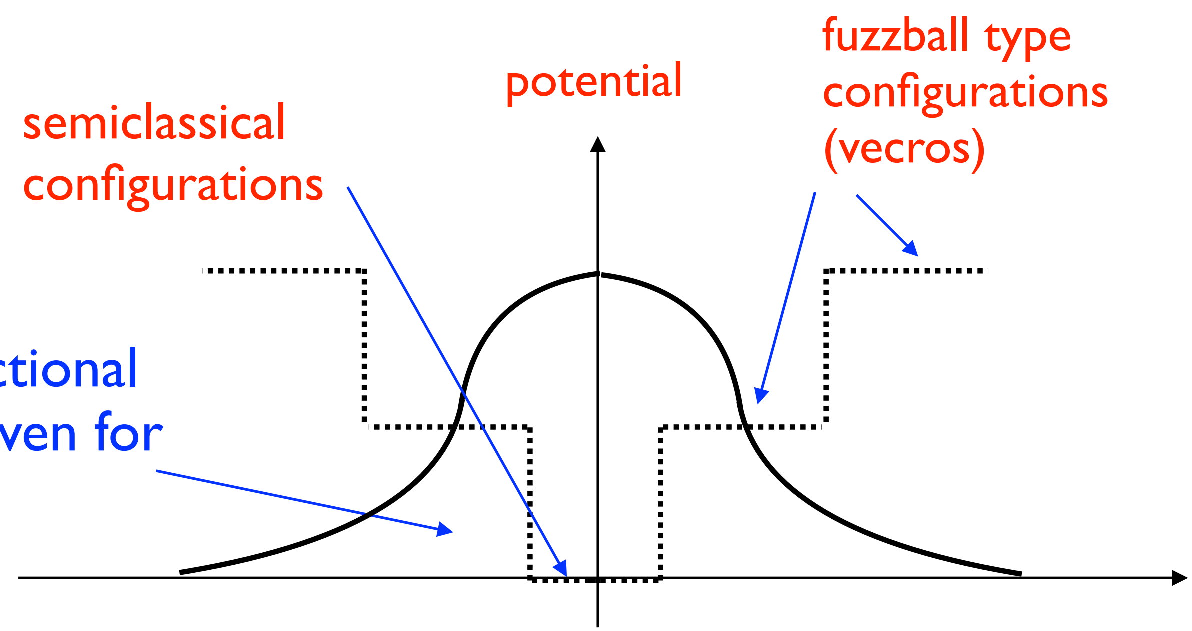
$$E \sim M \sim \frac{R^{d-2}}{l_p^{d-1}}, \quad T \sim R \quad \longrightarrow \quad S \sim \left(\frac{R}{l_p}\right)^{d-1}$$

But there are a very large number of fuzzballs:

$$\mathcal{N} \sim e^{S_{bek}}, \qquad S_{bek} \sim \frac{A}{G} \sim \left(\frac{R}{l_p}\right)^{d-1}$$

Thus we can have $P\mathcal{N} \sim 1$; i.e., the suppression is offset by the large degeneracy

The part of the vacuum wavefunctional 'under the barrier' is significant even for large vecros

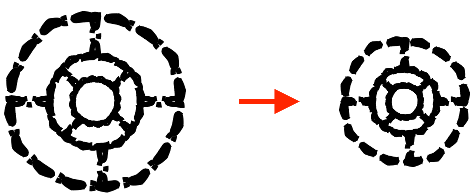


(E) Compression-Resistance: Fuzzball configurations are resistant to compression

Equation of state $p = \rho$ is stiffest allowed by causality

(Sasakura 99, Banks+Fischler 01, Veneziano 03, SDM+Masoumi 14, Quintin, Brandenberger, Gasperini, Veneziano 18)

Compressing a vecro of radius R_v by a factor of order unity gives $\Delta E \sim M(R_v)$
i.e. the energy goes up by order the black hole mass for radius R_v



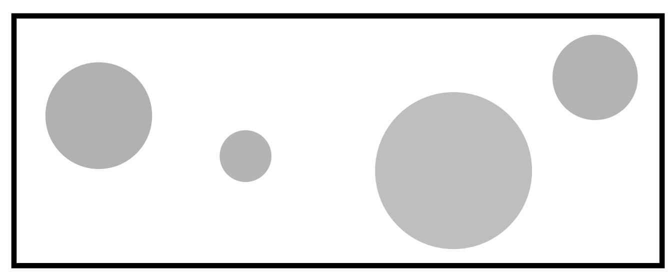
R_v $\quad$ $(1-\delta)R_v$

Heuristic model:

$$U(R_v, \delta) = \beta \frac{R_v^{d-2}}{G} \sin^2\left(\frac{\pi}{2}\frac{\delta}{\delta_c}\right), \qquad -\delta_c < \delta < \delta_c$$

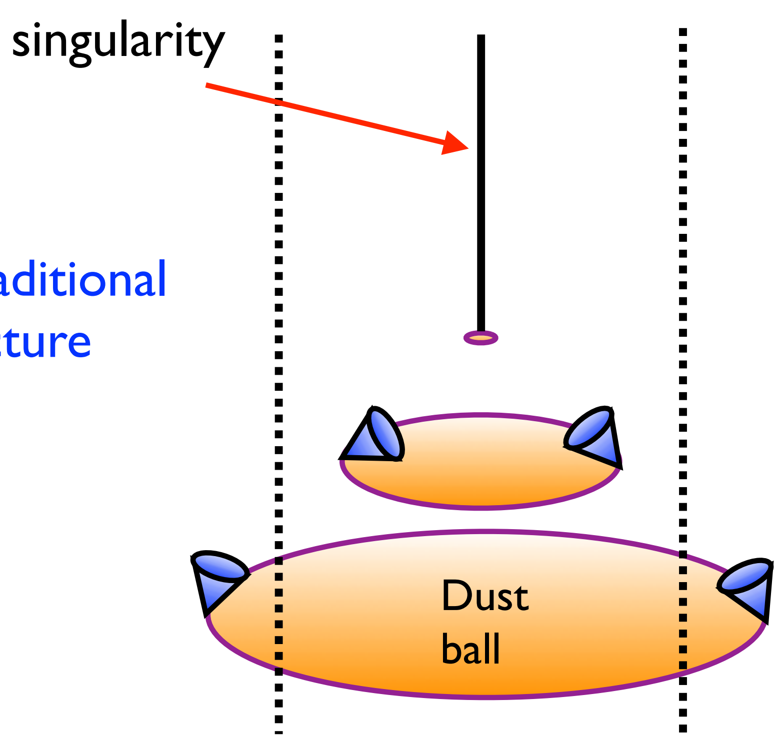
$$\beta \sim 1, \qquad \delta_c \sim 1$$

Thus we have arrived at a qualitative picture for the behavior of these vecro fluctuations



A star has a weak gravitational pull, so the vecro compresses slightly and stabilizes. This distortion of the wavefunctional is included in the Einstein action dynamics

Traditional picture

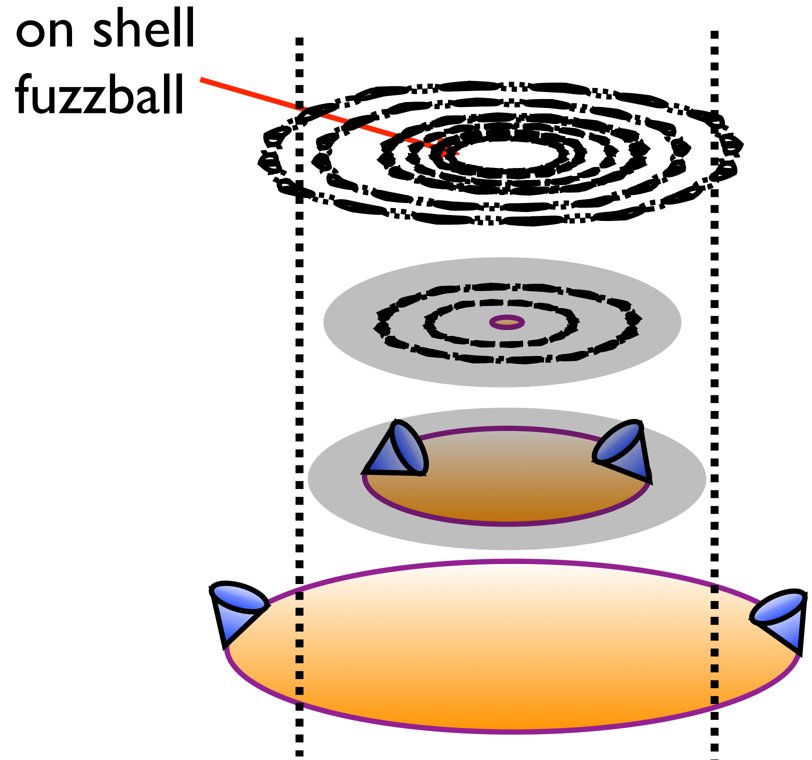


But now we have to consider what the vecro fluctuations are doing

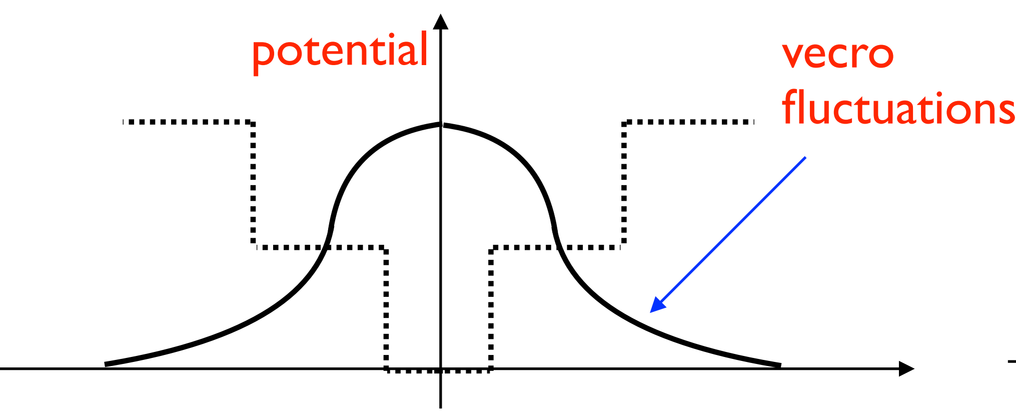
Inside the horizon, the light cones point inwards, so a vecro must keep on compressing (i.e., it cannot stabilize)

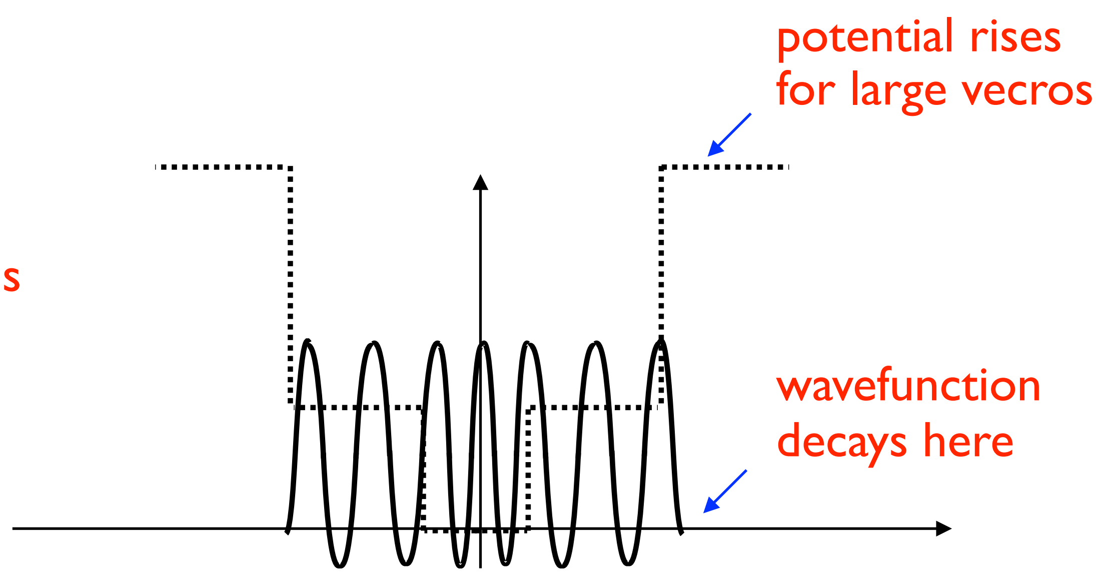
An order unity compression of the vecro distorts the wavefunctional to the point where vecros turn into onshell fuzzballs

The picture of collapse under the Vecro hypothesis



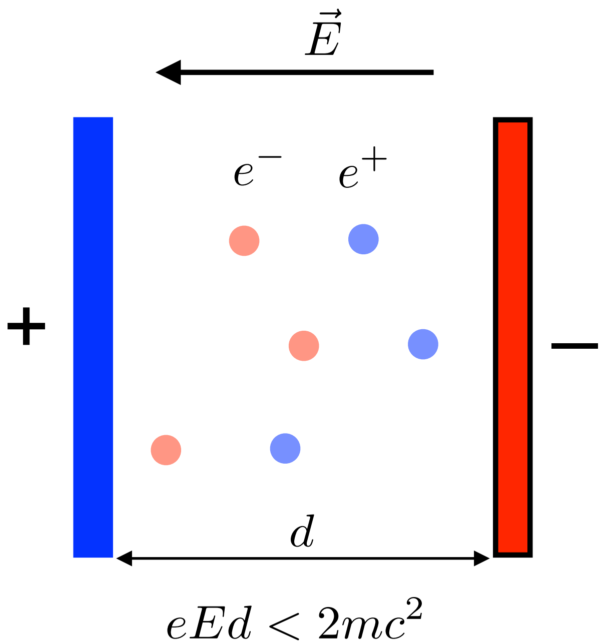
In terms of potential graphs:

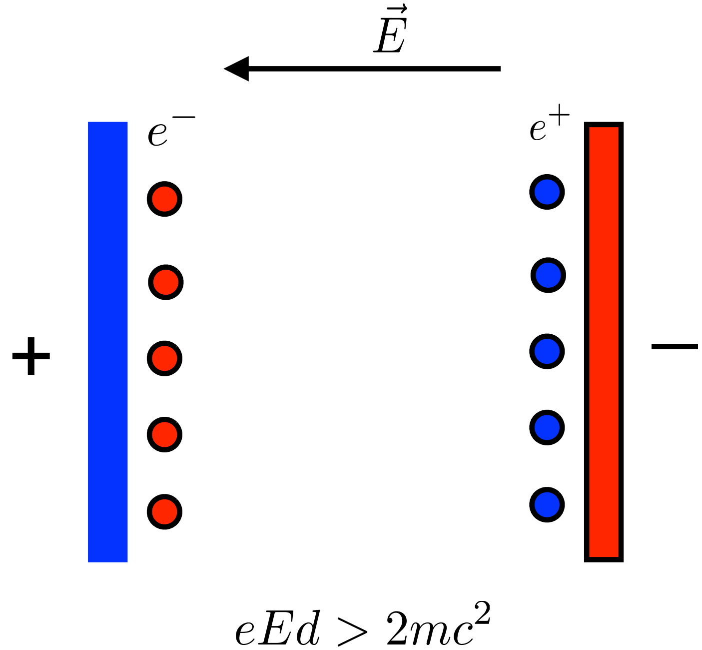




The wavefunctional becomes oscillatory ($\pi^2 > 0$) instead of decaying ($\pi^2 < 0$) over vecro configurations of energy $E \sim M$, signalling the transition to on-shell fuzzballs

Illustrative model: The Schwinger effect

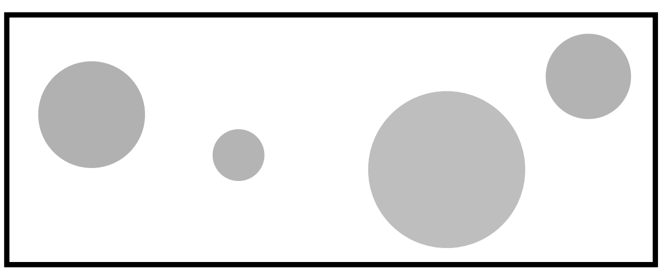




Let there be $N \gg 1$ flavors of charged particles.

The vacuum is highly polarized for plate separations $d < \dfrac{2mc^2}{eE}$

A person ignoring this polarizations will be surprised at the cascade of on-shell particles for $d > \dfrac{2mc^2}{eE}$

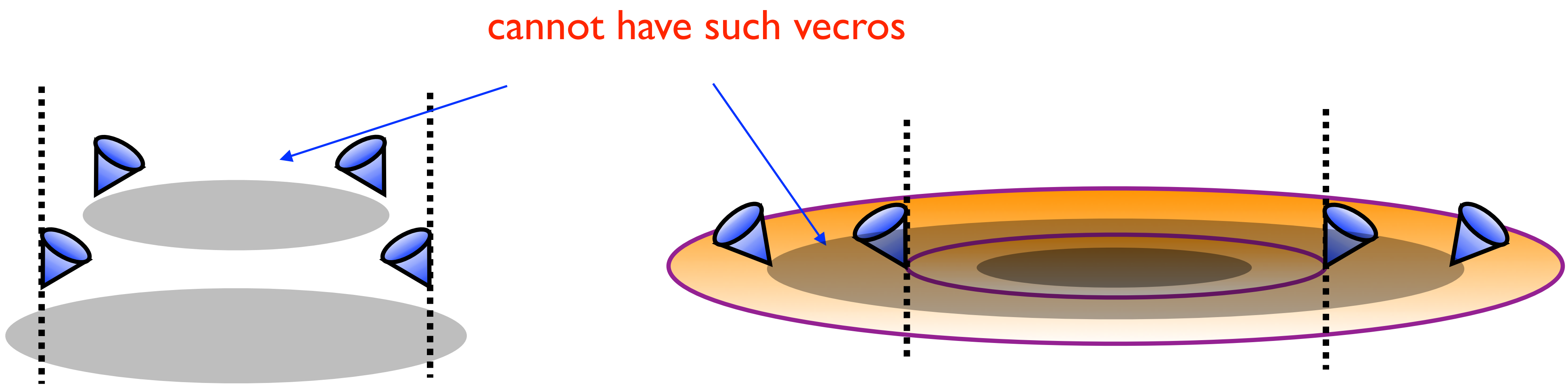


Large degeneracy of possible vecro fluctuations

Cascade to on-shell fuzzballs upon unbounded compression in a closed trapped surface

Cosmology

The black hole has a closed trapped surface. An expanding cosmology has anti-trapped surfaces

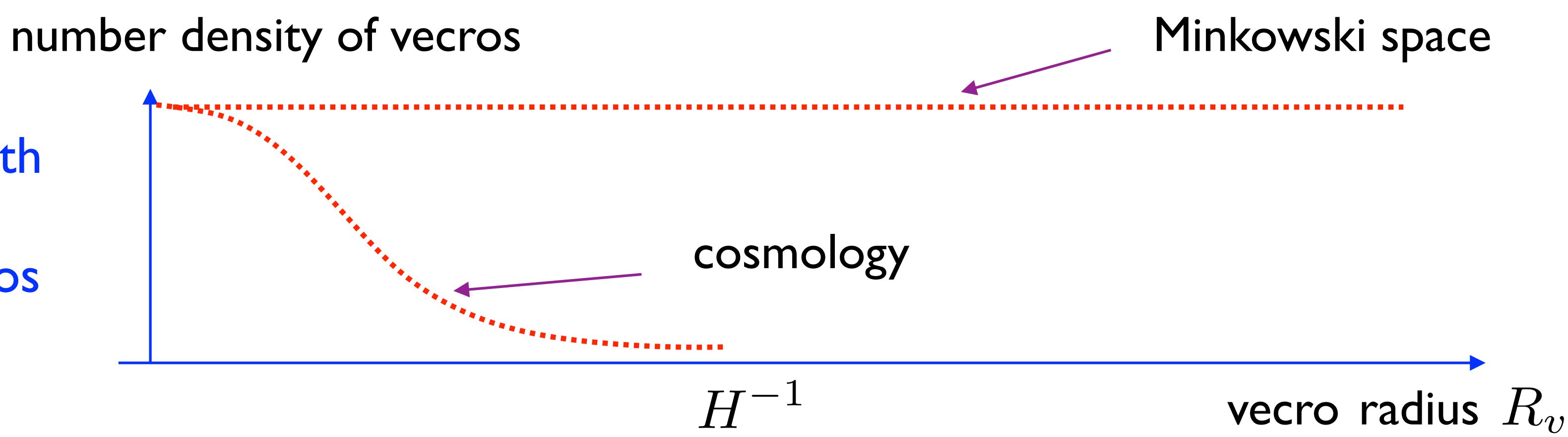


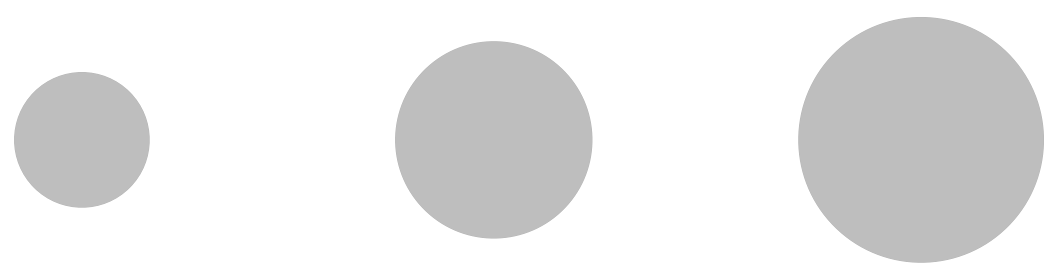
Flat space has vecros with

$0 < R_v < \infty$

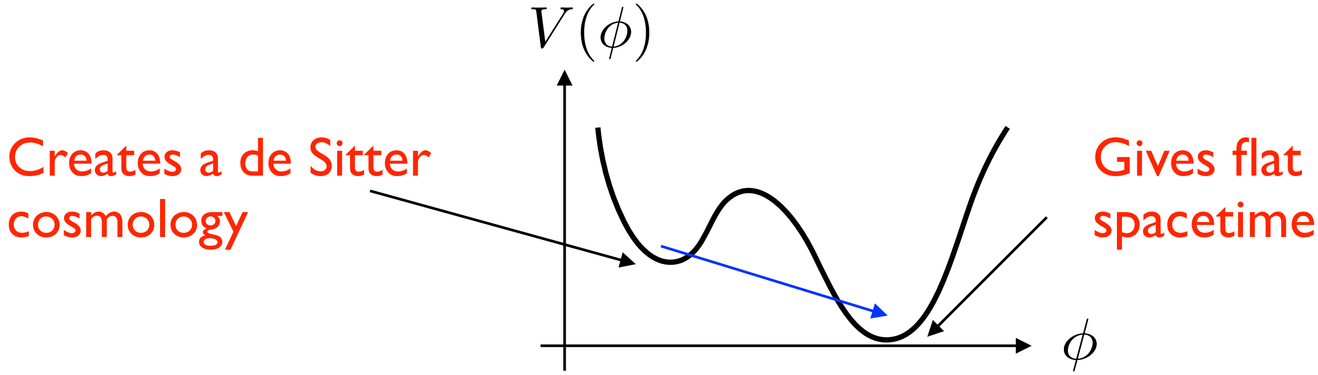
but cosmology has vecros only with

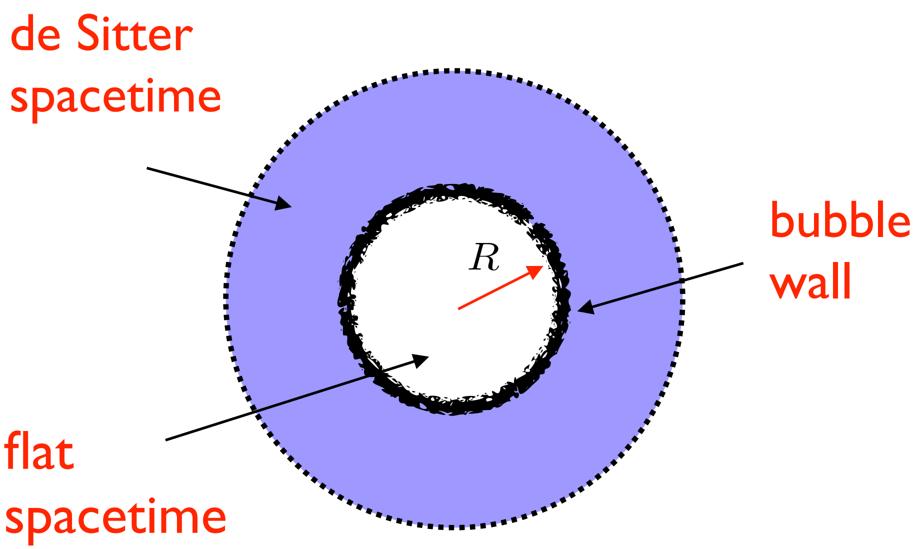
$0 < R_v \lesssim H^{-1}$





Bubble nucleation:





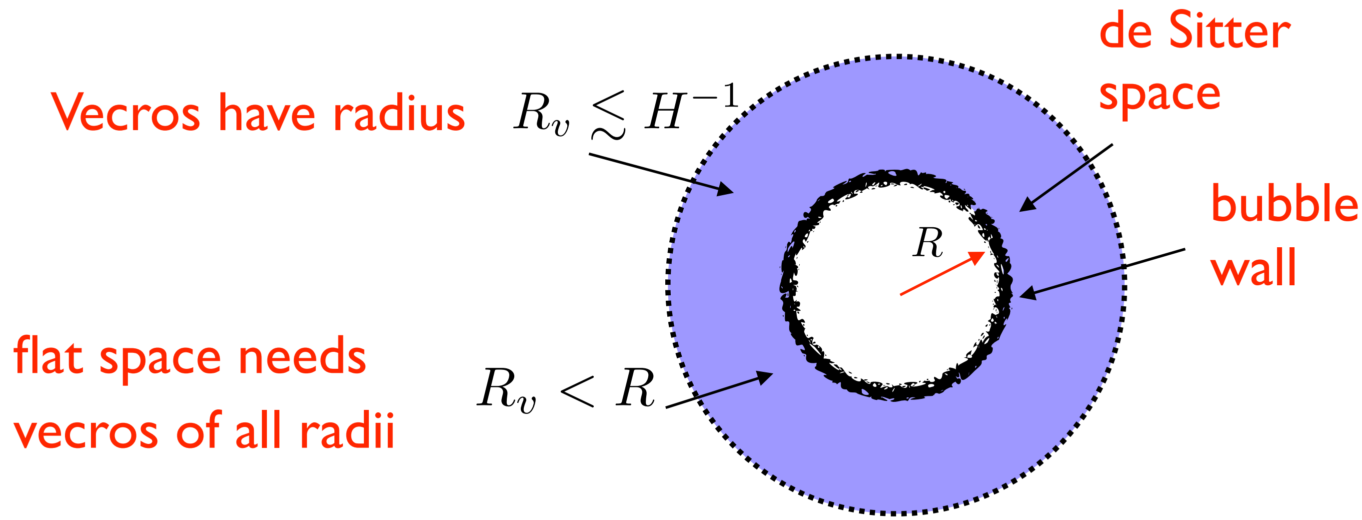
The speed of the bubble wall approaches the speed of light for $R \to \infty$

Energy from potential drop is proportional to volume, while energy of bubble wall is proportional to area

$$V_0 R^3 \sim \sigma R^2 \gamma$$

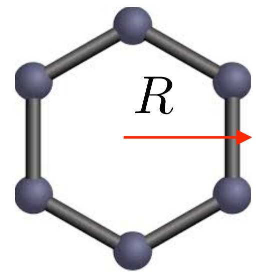
For $R \to \infty$ we get $\gamma \to \infty, \Rightarrow v \to 1$

But now we must ask about the vecro fluctuations …



But to make a vecro of radius R needs a time $t \gtrsim 2R$

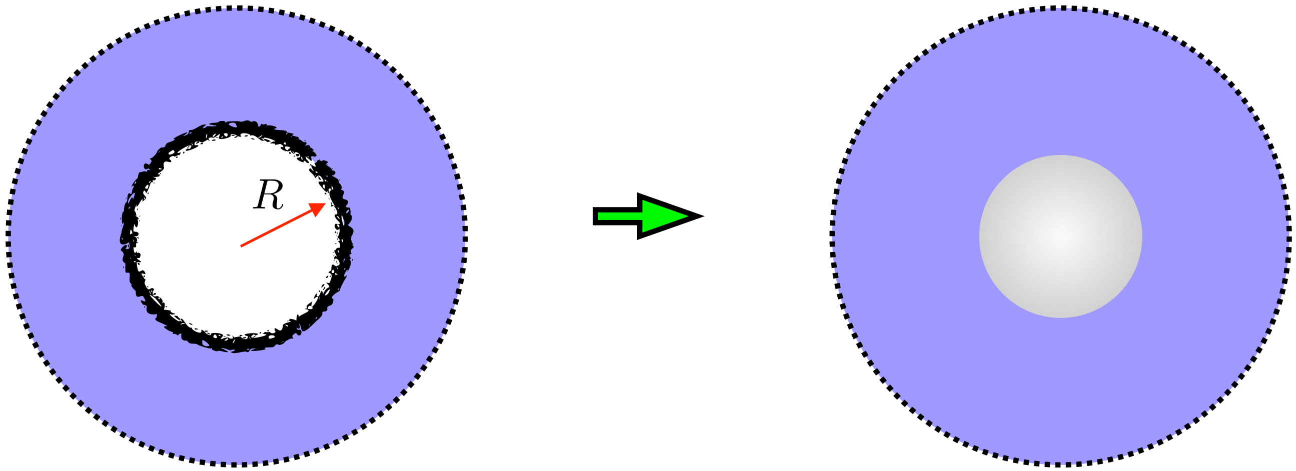
$t \gtrsim$ Light crossing time $\sim 2R$



Thus the flat space region can only expand with $v \lesssim \frac{1}{2}$. This implies $\gamma \sim 1$

Thus we cannot get the energy balance $V_0 R^3 \sim \sigma R^2 \gamma$ where all the energy of the bubble is in the bubble wall

Energy distributes throughout the bubble instead of staying in the wall



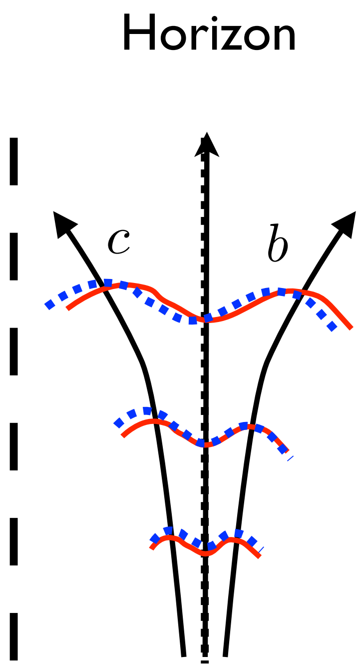
One difficulties with early studies of bubble nucleation was that energy stayed in bubble walls; so the vecro effects may change the dynamics in a way that is relevant to cosmology …

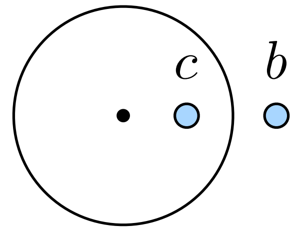
SUMMARY

The small corrections theorem: This inequality makes the information puzzle precise

Suppose we make two assumptions:

(a)





$$\frac{1}{\sqrt{2}}(|0\rangle_b|0\rangle_c + |1\rangle_b|1\rangle_c) \longrightarrow$$

$$\frac{1}{\sqrt{2}}(|0\rangle_b|0\rangle_c + |1\rangle_b|1\rangle_c) + \epsilon_k \frac{1}{\sqrt{2}}(|0\rangle_b|0\rangle_c - |1\rangle_b|1\rangle_c)$$

$$(\,|\epsilon_k| < \epsilon \ll 1\,)$$

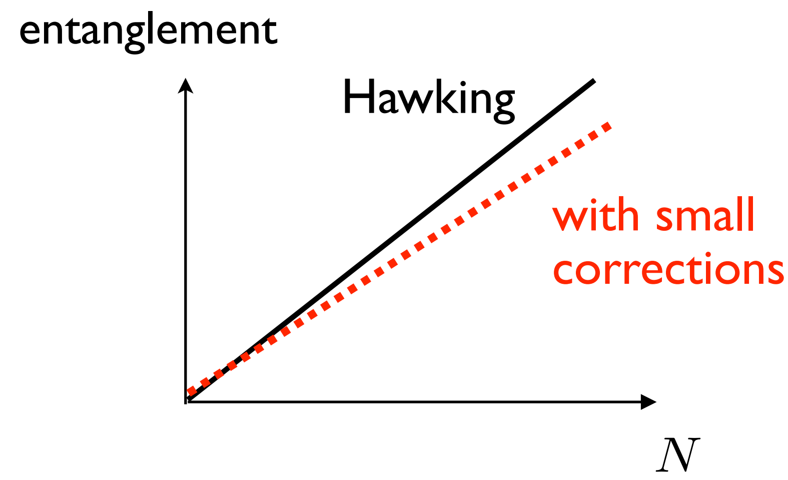
(b) Assume radiated quanta are not modified once they are far from the hole

No further modification
(this is what happens for burning paper)

Then the entanglement will keep growing

$$S_{N+1} > S_N + \ln 2 - 2\epsilon$$

(SDM 0909.1038)



Why is this worth proving?

Overall state after two emissions

$$\frac{1}{2}\Big(|0\rangle_{b_1}|0\rangle_{c_1}[(1+\epsilon_1)|0\rangle_{b_2}|0\rangle_{c_2}+(1-\epsilon_1)|1\rangle_{b_2}|1\rangle_{c_2}]$$
$$+|1\rangle_{b_1}|1\rangle_{c_1}[(1+\epsilon_1')|0\rangle_{b_2}|0\rangle_{c_2}+(1-\epsilon_1')|1\rangle_{b_2}|1\rangle_{c_2}]\Big)$$

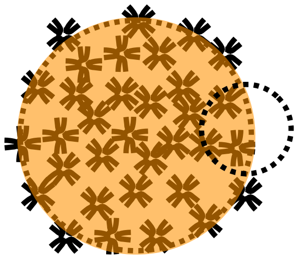
After N steps of emission, there are $\sim 2^N$ correction terms

Since $N \gg 1$, maybe even with a small ϵ the corrections cumulate to modify Hawking's leading order result and encode 'subtle' changes in the radiation that resolve the problem?

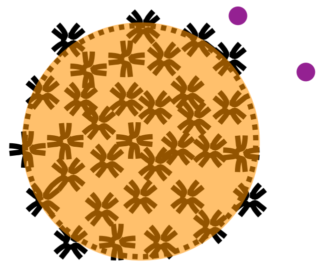
▶ No, this is not possible; one needs order unity corrections to evade the problem

Leaves two sharply different possibilities: 'Fuzzball paradigm' and 'Wormhole paradigm'

(A) Fuzzball:



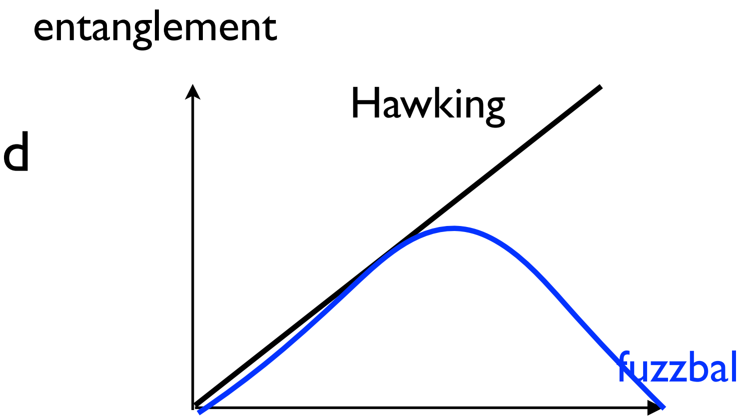
$\langle 0|\psi\rangle = \epsilon$



$$\frac{1}{\sqrt{2}}(|0\rangle|0\rangle + |1\rangle|1\rangle) + O(\epsilon)$$

(Evaporates like burning paper, radiated quanta not modified at $r \gg M$)

Use string theory to construct fuzzball states and see how no-hair arguments are bypassed

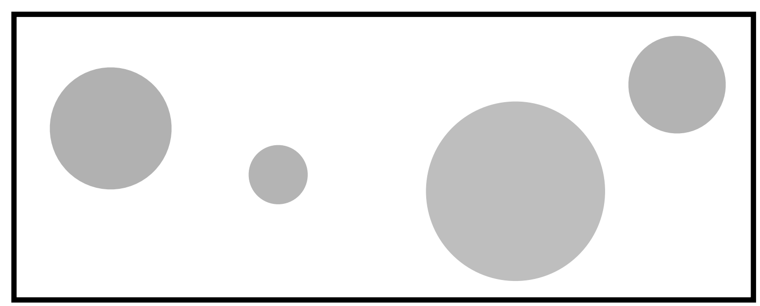


Vecro hypothesis: Resolves puzzles while maintaining causality and locality of the underlying theory

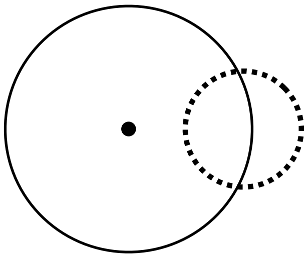
(a) Causality puzzle in gravitational collapse

(b) Bags of gold problem

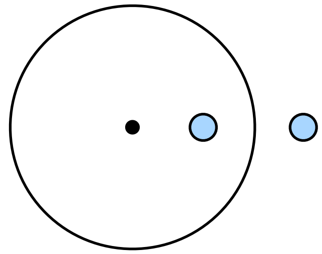
(c) May affect many issues in cosmology



(B) ‘Wormhole’: Horizon is a ‘normal’ place to leading order

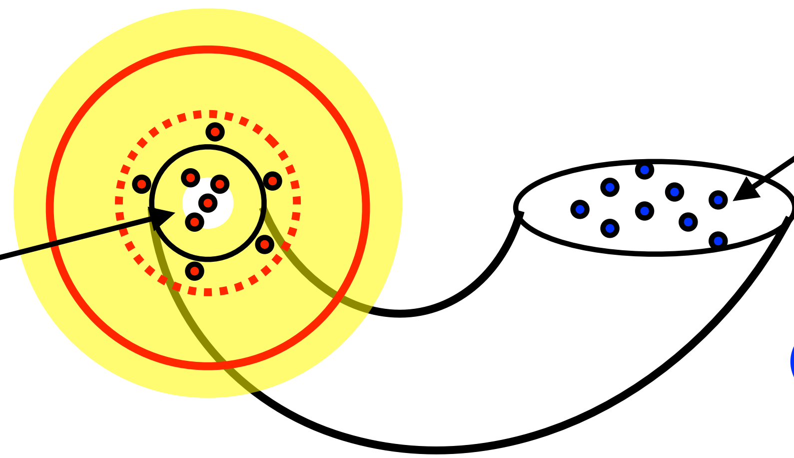


$$\langle 0|\psi\rangle = 1-\epsilon$$



$$\frac{1}{\sqrt{2}}(|0\rangle|0\rangle + |1\rangle|1\rangle) + O(\epsilon)$$

‘Inside’ of horizon not like inside of coal (island)



Complicated operations on radiation quanta at $r \gtrsim M^3$ can extract data from the island

(Not like radiation from coal)

Entangled quanta in Island form a remnant which can pinch off into a baby universe

Traversible wormhole transport information out of hole

Multi-universe dynamics, topology change in Minkowski dynamics, ensemble dynamics ..

(Pennington, Almheiri, Maldacena +.. Saad +… Engelhart +…Marolf +…… …)

Nonlocalities all the way from hole to infinity (Hawking-Perry-Strominger, Raju …)

THANK YOU !!