Title: Classical Spacetime and Quantum Black Holes

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Abstract: A quantum system behaves classically when quantum probabilities are high for coarse-grained histories correlated in time by deterministic laws. That is as true for the flight of a tennis ball as for the behavior of spacetime geometry in gravitational collapse. Classical spacetime may be available only in patches of configuration space with quantum transitions between them. Global structures of general relativity. such as event horizons may not be available.

We consider the quantum dynamics of gravitational collapse in a model in which classical spacetime breaks down because the wave function spreads over a large ensemble of classical end states as envisioned in the fuzzball proposal. Probabilities of coarse-grained observables are highly peaked around the classical black hole values. By contrast, probabilities for finer-grained observables probing the near horizon region are broadly distributed, and no notion of `averaging' applies. This means that the formation of fuzzballs may result significant observational features including a novel type of gravitational wave burst associated with tunneling between classical solutions.

Classical Spacetime and Quantum Black Holes

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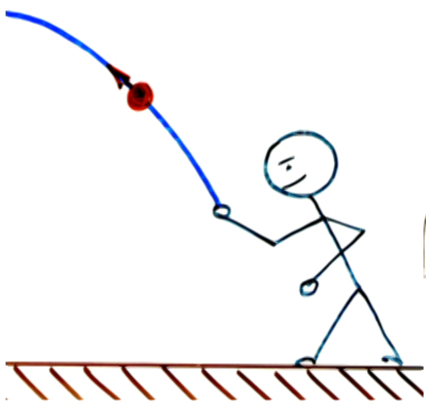
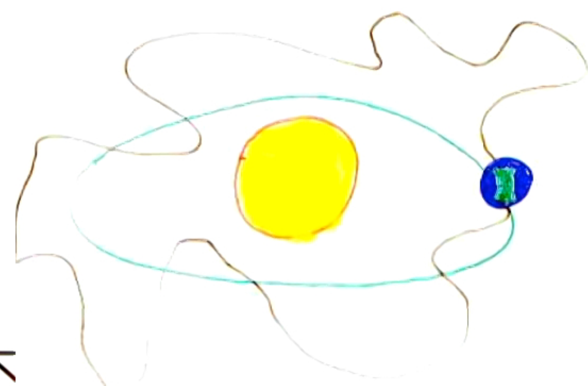
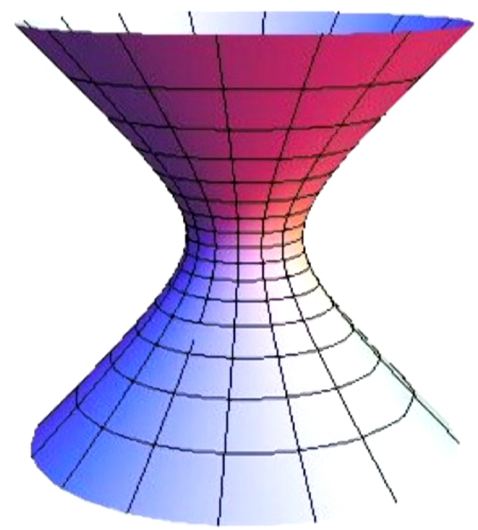
Quantum Black Holes in the Sky
Perimeter Institute, Nov. 8, 2017

A quantum system behaves classically when its state and Hamiltonian predict high probabilities for histories with correlations in time governed by deterministic laws.





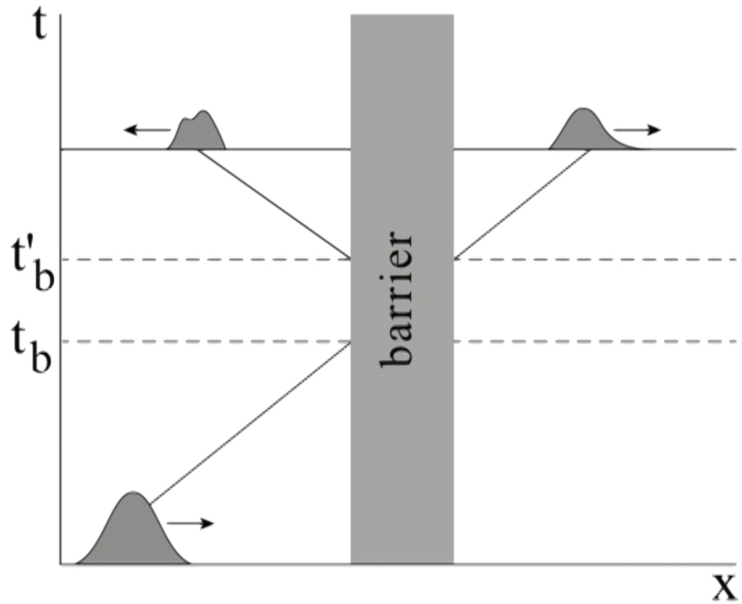


Classical Spacetime

- Classical histories of geometry and field are generally available only in limited patches of configuration space.
- In a given patch quantum states generally do not predict one classical spacetime but an ensemble of possible ones with probabilities for them.
- In between patches classical evolution can be replaced by quantum evolution. One history branches into many histories.
- Classical evolution based on quantum probabilities can break down on scales much larger than the Planck scale with no breakdown in the classical equations of motion.

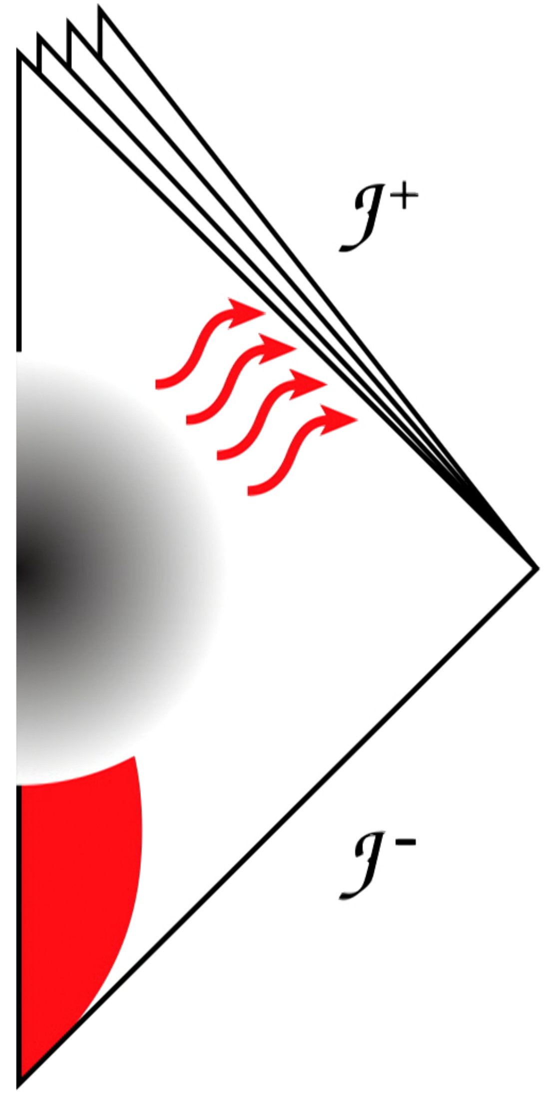
Barrier Penetration I

- A wave packed peaked narrowly about definite position and momentum scatters off of a potential barrier.
- Classical evolution is predicted before the collision and afterwards but not during the transition across the barrier.
- Quantum evolution connects the two classical regimes.



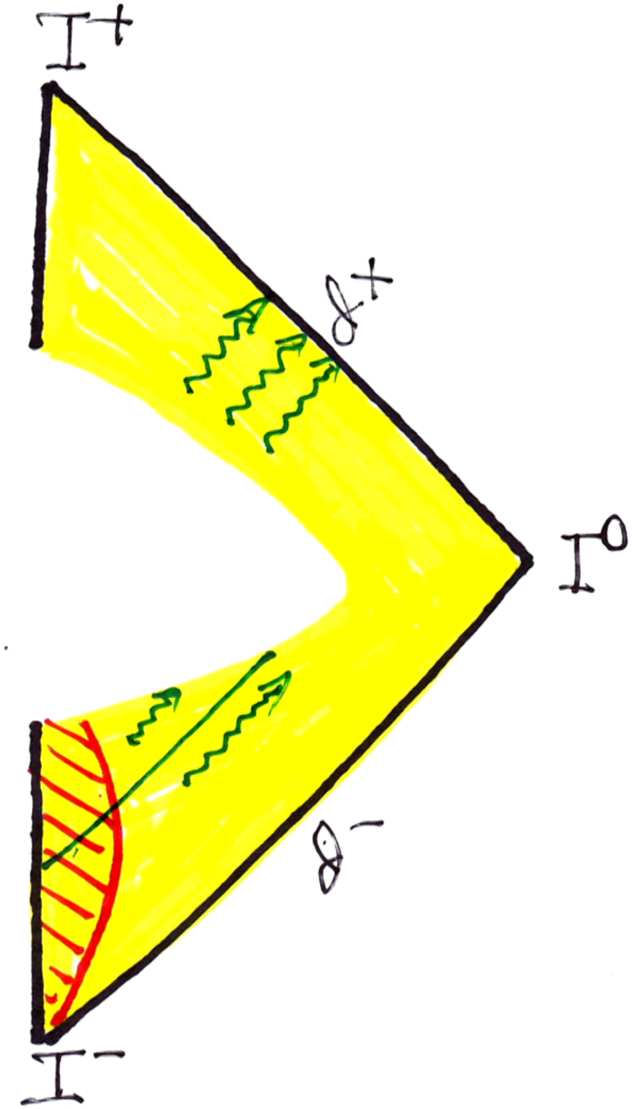
Black Holes

- We expect classical spacetimes in asymptotic patches.
- The region of breakdown could be larger than the realm of Planck scale fields near the singularity.
- Many final asymptotic class. spacetimes for each initial one.
- WdW supplies an `S-matrix' between these.
- The quantum state remains pure.



Maybe No Horizon

Not one spacetime but many, and maybe not all of them have horizon defined as the boundary of the past of $\mathcal{I}^+$, because there is not enough classical spacetime to define it.



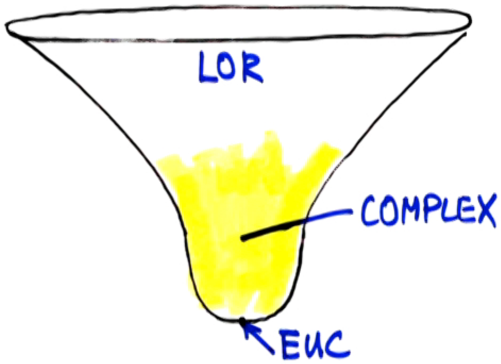
Minisuperspace Model

- **Geometry:** homogeneous, isotropic, closed.

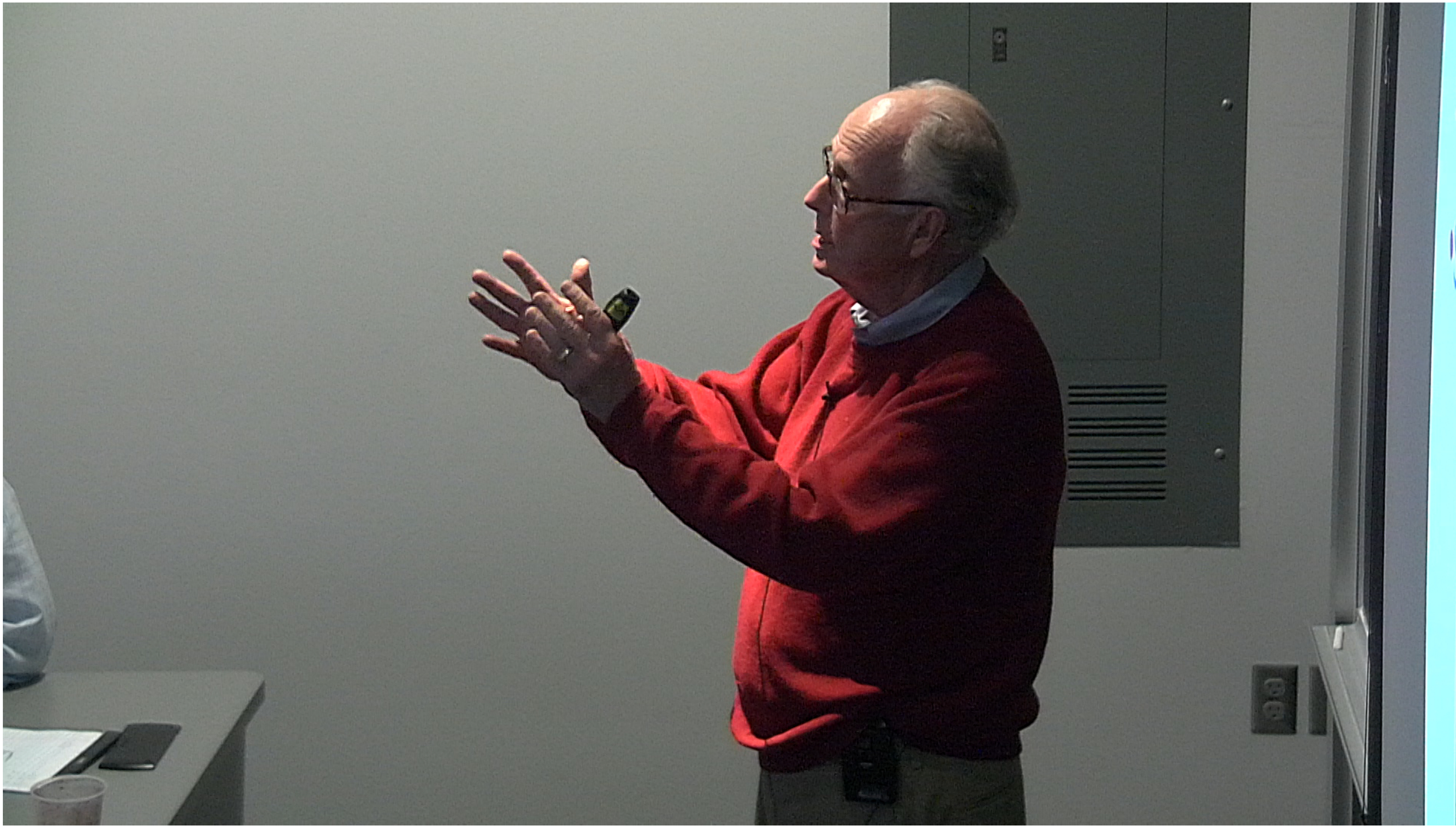
$$ds^2 = dt^2 + b(t)^2 d\Omega_3^2$$

- **Matter:** single homogeneous scalar, $\chi(t)$ moving in a quadratic potential plus Λ.
- **Action:** Einstein action plus action for scalar and Λ .
- **State:** No Boundary Wave Fn.

(b,χ)



$$\Psi = \Psi(b, \chi).$$



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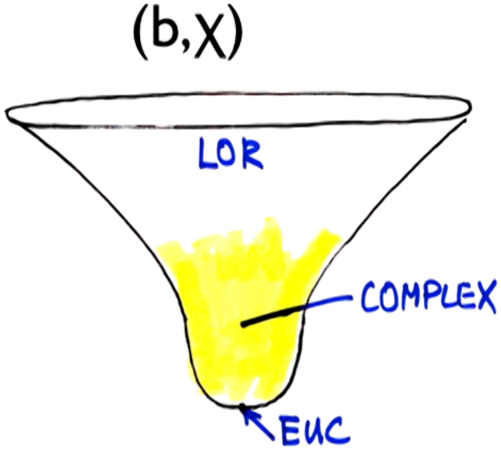


$$\Psi = \Psi(b, \chi).$$

Breakdown of Classicality at a Bounce

$$\Psi(b,\chi) \approx \exp\{[-I_R(b,\chi) + iS(b,\chi)]/\hbar\}$$

This semiclassical form will predict classical Lorentian histories that are the integral curves of S, ie the solutions to: $p_A = \nabla_A S$ with probabilities

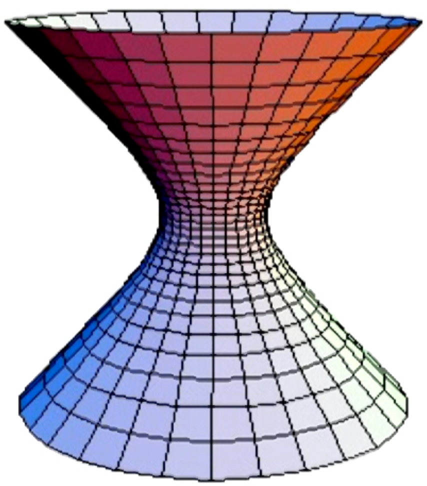
$$p(\text{class. hist.}) \propto \exp(-2I_R/\hbar)$$

in regions of (b, χ) where the classicality constraint is satisfied.

$$(\nabla I_R)^2 \ll (\nabla S)^2.$$

This won't be satisfied at a bounce where

$$\partial S/\partial t \approx 0$$

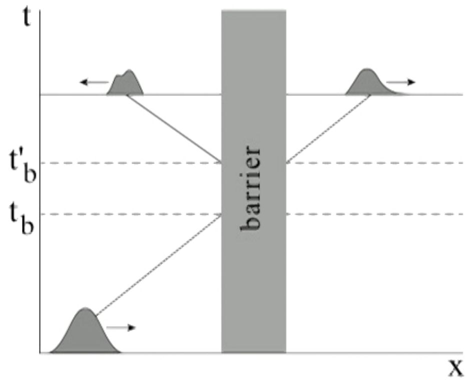


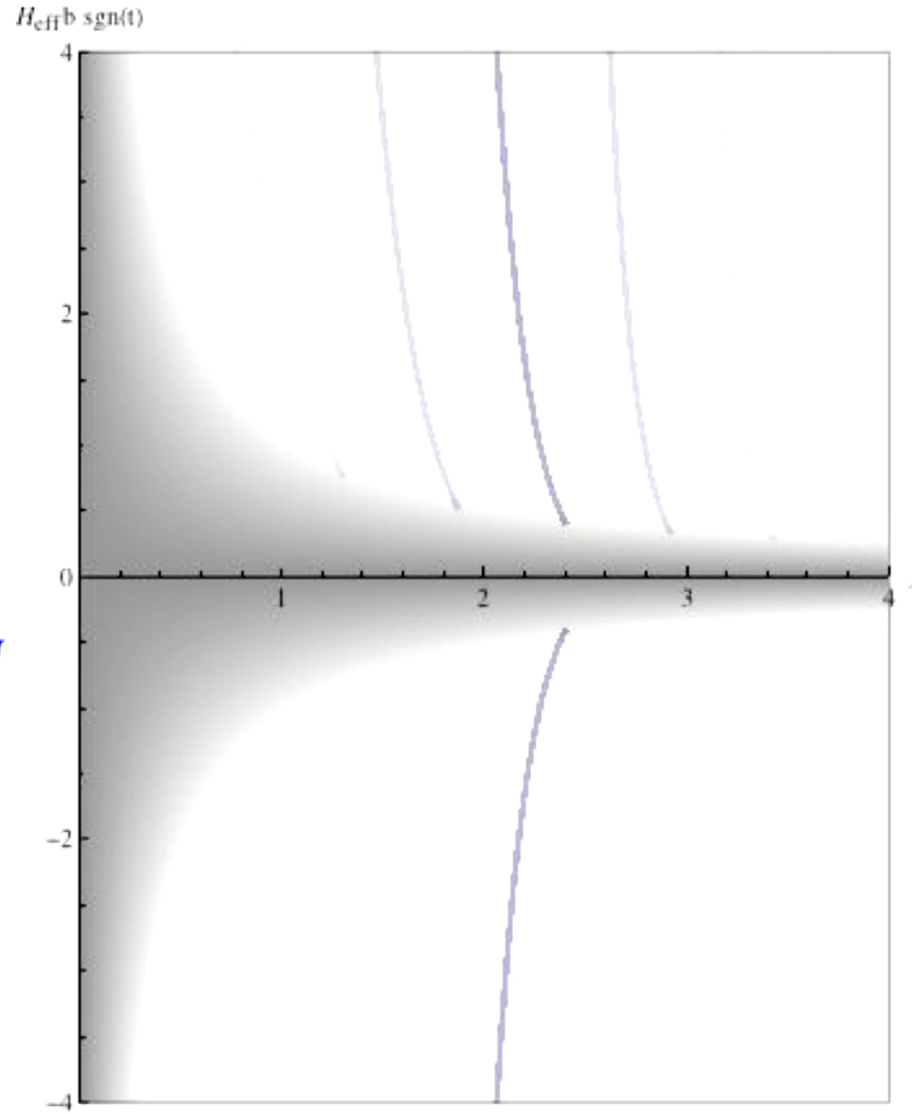
Quantum Trans. Thru a Bounce

Parametrized time t.

$$\Psi = \Psi(\chi, b, t)$$

$$i\hbar\frac{\partial\Psi}{\partial t} = H_{WDW}\Psi$$





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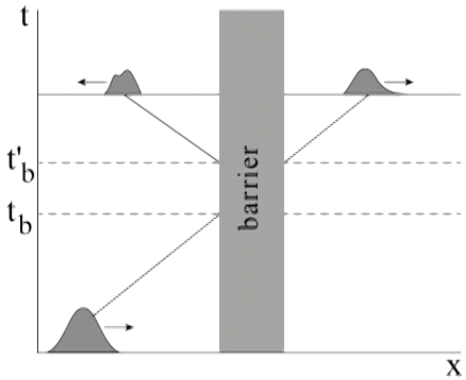
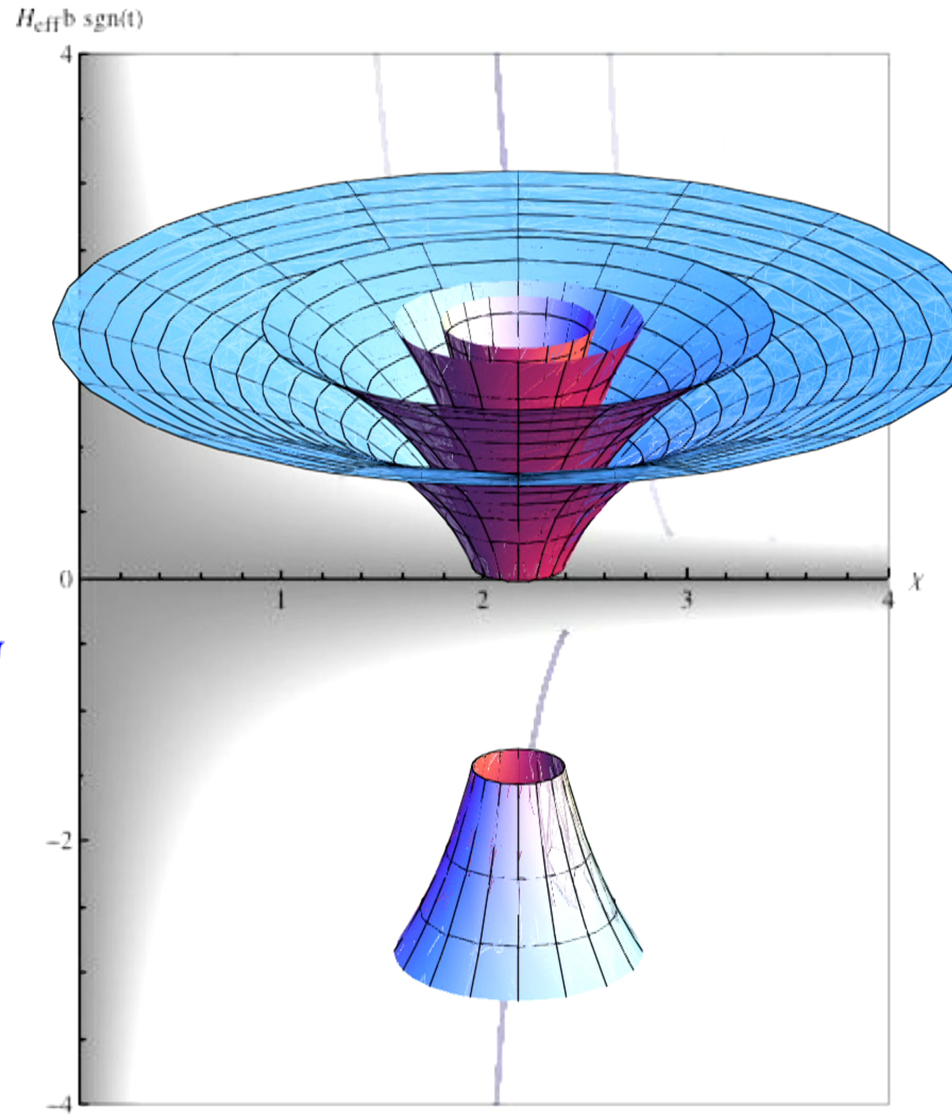
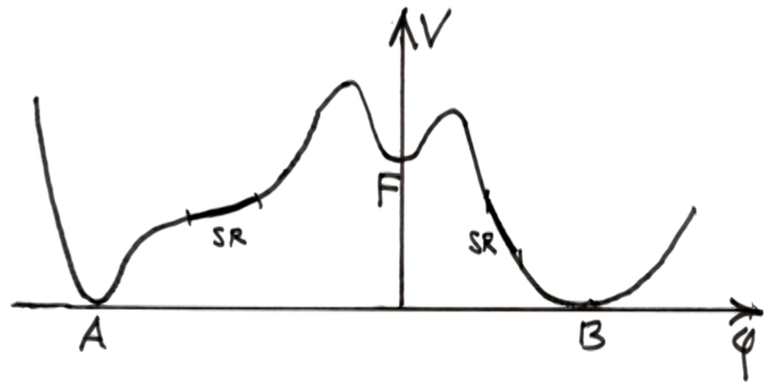




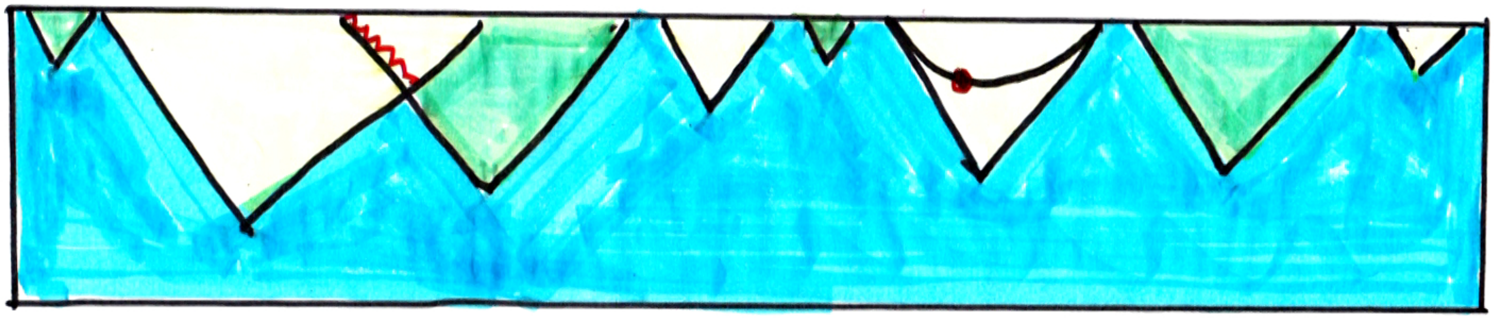
A Model of False Vacuum EI

- (H) Einstein gravity coupled to a single scalar field.
- (Ψ) A quantum state.



- One false vacuum F and two true vacua A and B.
- Nucleation of true vacuum bubbles A or B are the dominant exit channels from F.
- Different slow roll regimes leading to different predictions for the CMB in A or B.

Eternal Inflation



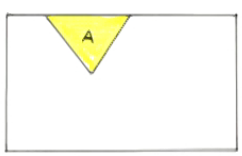
Fine-Grained Descriptions

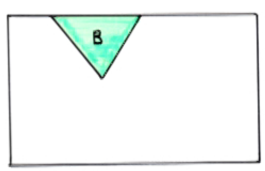
- Our Hubble volume is but one of an infinite number of Hubble volumes on a reheating surface in one bubble.
- That is but one of an infinite number of bubbles in a universe that is very large.

Coarse Graining for Local Obs.

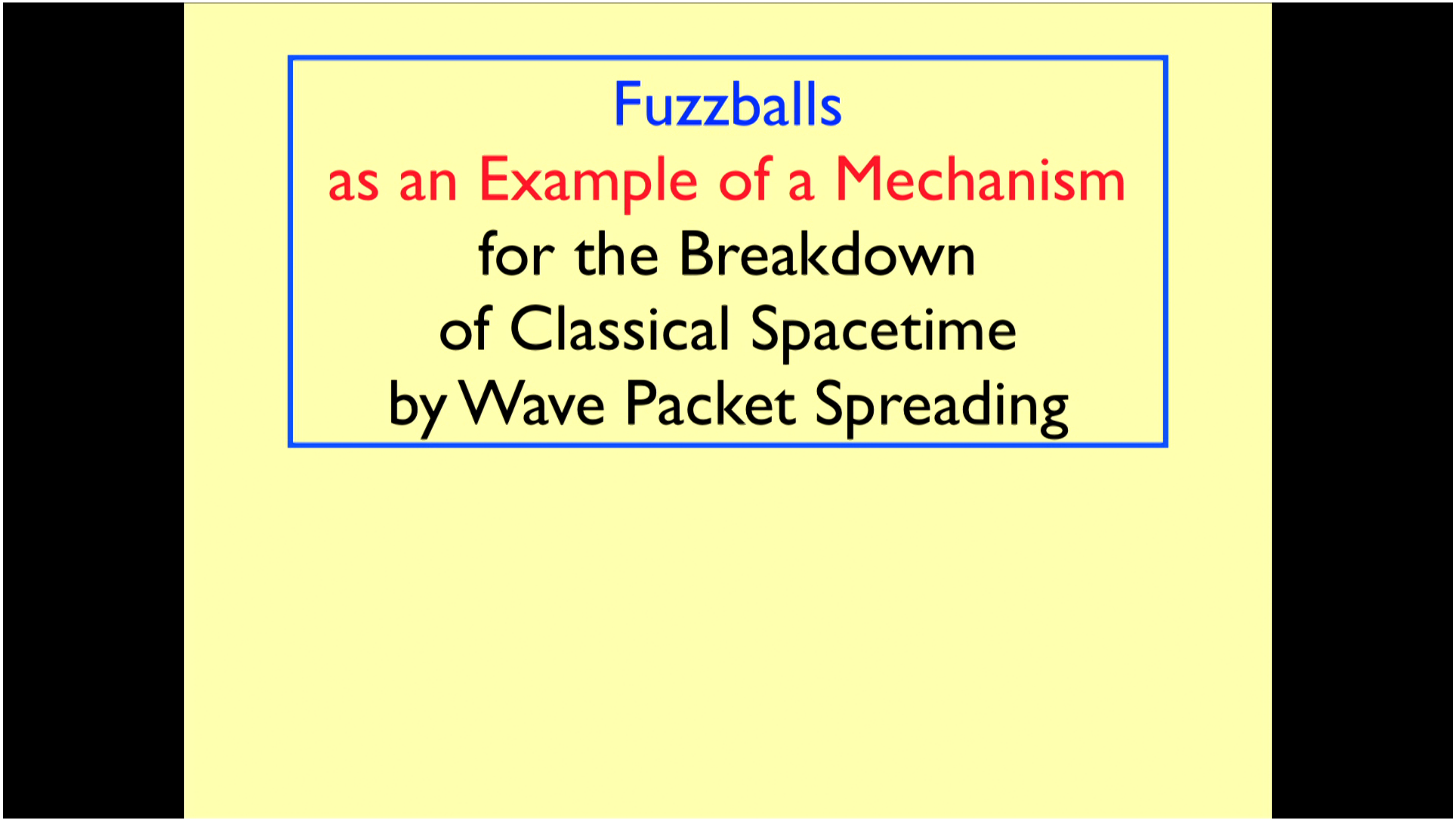
Our observations are restricted to one Hubble volume.

- Coarse grain of everything outside our bubble. Not by summing fine-grained probabilities over everything outside, but by summing amplitudes.
- Then there are only two histories. One in which our bubble nucleated somewhere, sometime, in true vacuum A and the other in true vacuum B.
- From the symmetries of deSitter these are the same as the probabilities that A or B nucleated in a particular place in spacetime.





For more see Hawking and Hertog 1707.07702


Fuzzballs
as an Example of a Mechanism
for the Breakdown
of Classical Spacetime
by Wave Packet Spreading

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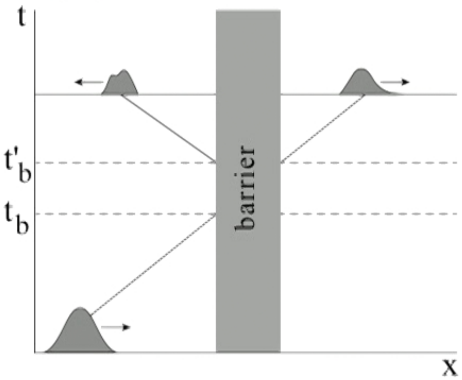
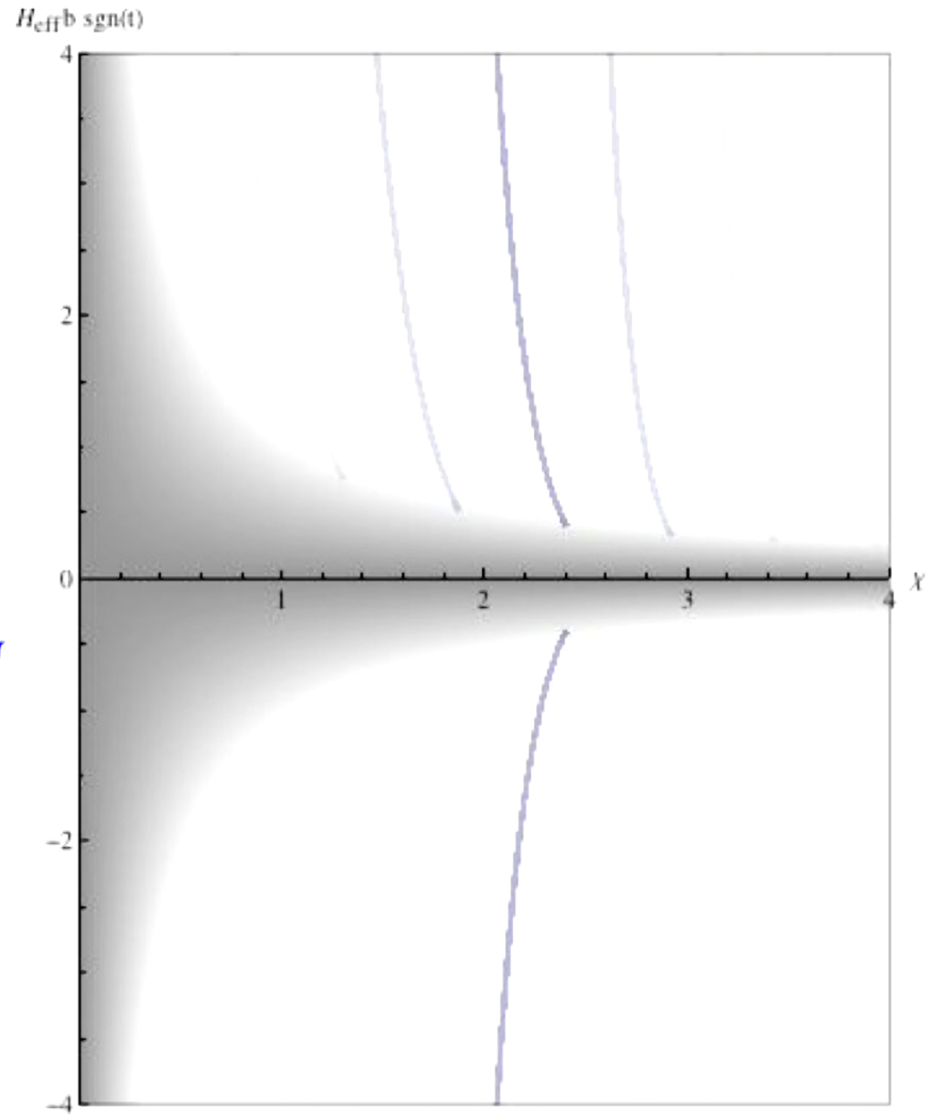
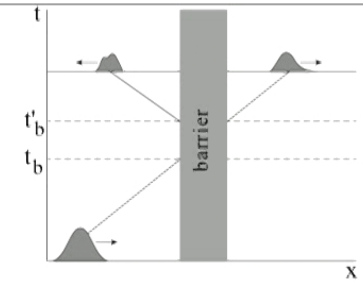


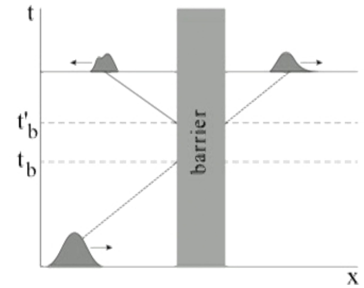


Gravitational Collapse in the Fuzzball Picture



- Initially a wave packet peaked around a classical collapse solution for a spherical shell of mass M and angular momentum J.
- $R \sim M$ the wave function spreads by quantum tunneling over different FB solutions with the same M and J but with possibly different Q. The tunneling rate is small but that is compensated for by the large number of solutions to tunnel into.
- Most of the subsequent results depend just on this spreading, not on the string theory, the details of the microstates, etc,

Observations



- Coarse Grained Observations: far out by light rays, EMRI's and observers falling in give results indistinguishable from a classical black hole spacetime.
- Fine-grained observations that probe further in might measure the value of Q, not as an average over the ensemble of possible values but as one or the other of them. These could distinguish FB from BH.
- Fine-grained observations of many different collapses could verify the probabilities if the initial M and J were understood.

Gravitational Radiation

If the quadrupole moment Q changes in the course of tunneling between one FB state an another in a time T then we expect gravitational radiation to be emitted.

$$L_{GW} = \frac{1}{5}\frac{G}{c^5}(\dddot{Q}_{ij}\dddot{Q}^{ij}) \qquad E_{GW} \sim \frac{G}{c^5}\left(\frac{\Delta Q}{T^3}\right)^2 T$$

$$\Delta Q = \eta_Q M R^2 \qquad T = \eta_T R/c$$

$$T \sim R/c \qquad R \sim M$$

$$E_{GW} \sim \left(\frac{\eta_Q}{\eta_T^5}\right) M c^2$$

It's often asked: Why and where does classical spacetime break down?

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The answer is in the quantum state Ψ.