Classical Spacetimes of Bouncing Universes and Evaporating Black Holes

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Classical Behavior of Quantum Systems

- A quantum system behaves classically when the probability is high for histories that exhibit correlations in time governed by classical deterministic laws.
- Probabilities for histories arise from the system's theory of dynamics and its quantum state Ψ.
- This applies to the flight of a tennis ball, the orbit of the moon around the Earth, and the classical spacetime of our quantum universe.

Bouncing Universes

Bouncing Universes of the No-Boundary Quantum State

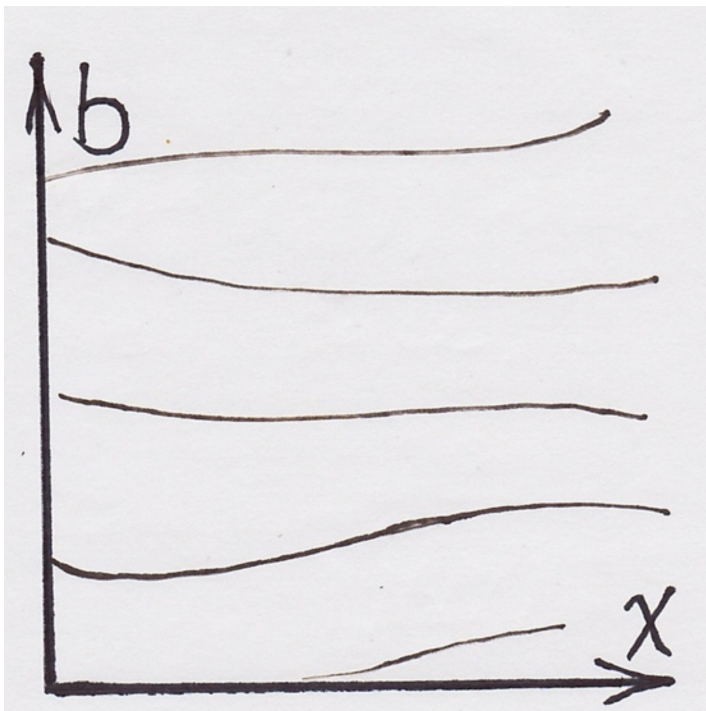
A state of the universe Ψ lives on a configuration apace of three-geometries and matter field configurations

$$V(\phi) = (1/2)m\phi^2 + \Lambda$$

Minisuperspace of homo-iso geometries and fields.

$$ds^2 = b^2 d\Omega_3^2 \qquad \phi \equiv \chi$$

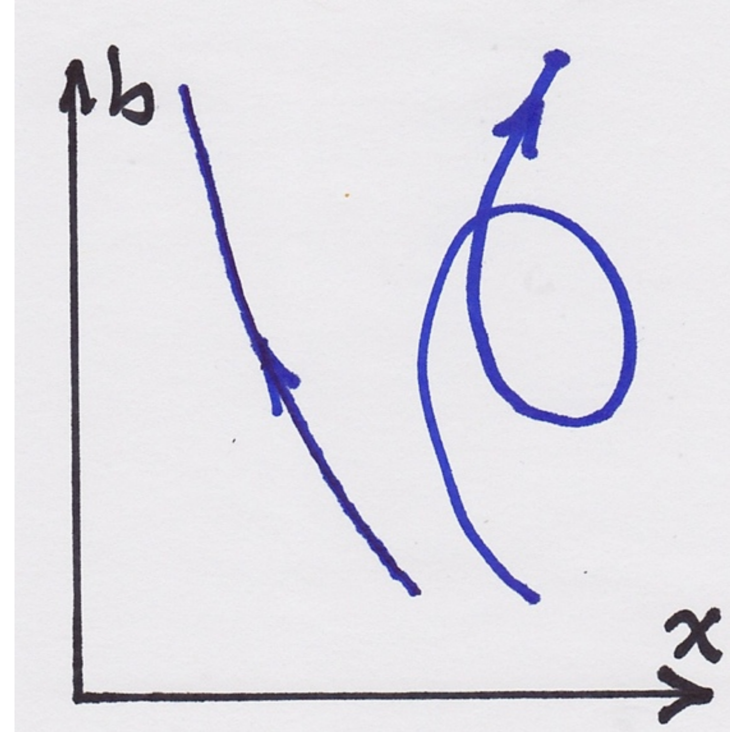
$$\Psi = \Psi(b, \chi)$$



$H\Psi = 0$ is the Wheeler-DeWitt eqn which evolves Ψ in superspace.

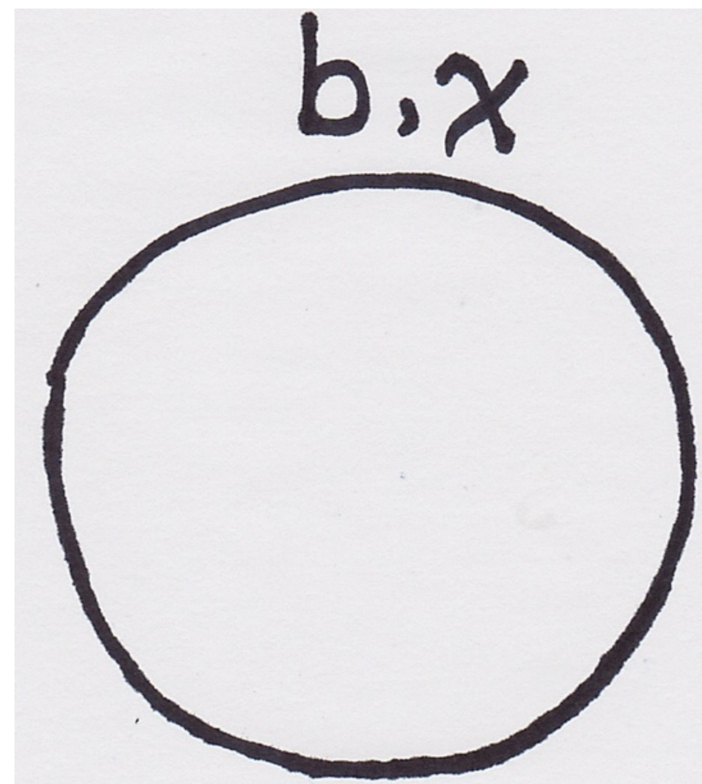
Histories

Histories are curves in config. space. A classical history is a curve satisfying the Einstein eq.



The NBWF is a model quantum state which semiclassically has the form

$$\Psi(b,\chi) \propto \exp[-I(b,\chi)/\hbar]$$



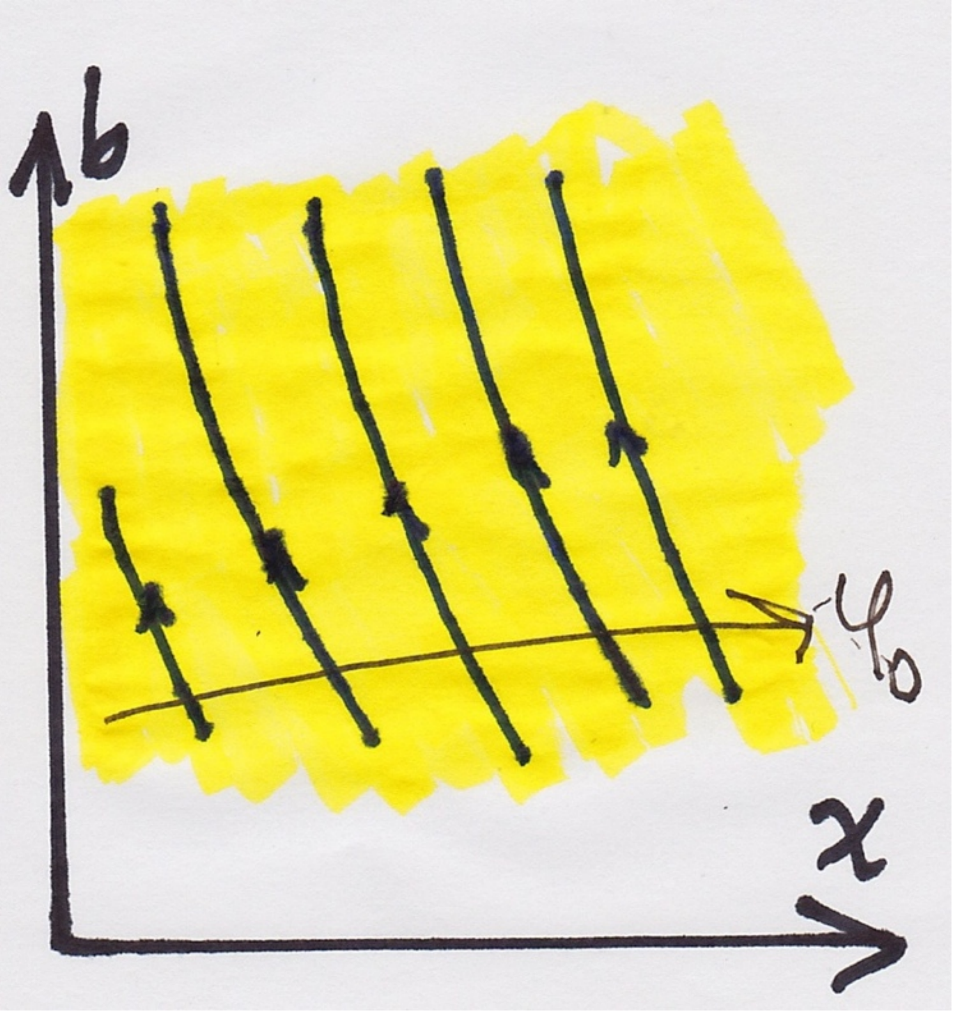
$I(b,\chi)$ is the action of a complex saddle point regular on a 4-disk with one boundary matching (b,χ)

Ensemble of Classical Spacetimes

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

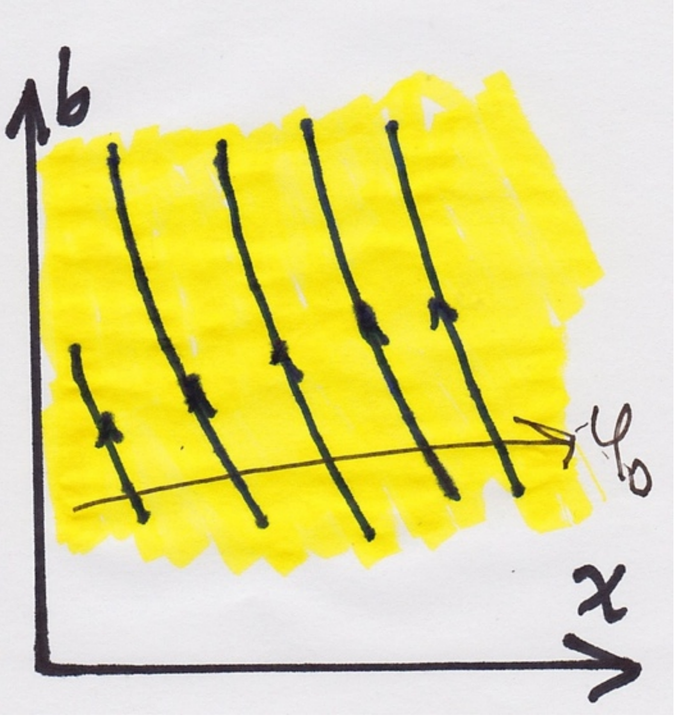
WKB: When S varies rapidly compared to I_R, we predict an ensemble of possible classical spacetimes that are the integral curves of S, $\pi = \nabla S$

This defines a one parameter family of classical histories labeled by φ_0.



Classical Extrapolation

- The WKB approximation breaks down for small b because $\nabla S \gg \nabla I_R$ doesn't hold.



- Extrapolating with classical equations anyway gives universes that bounce at a radius much larger than the Planck scale --- no breakdown in the eqns or solutions.

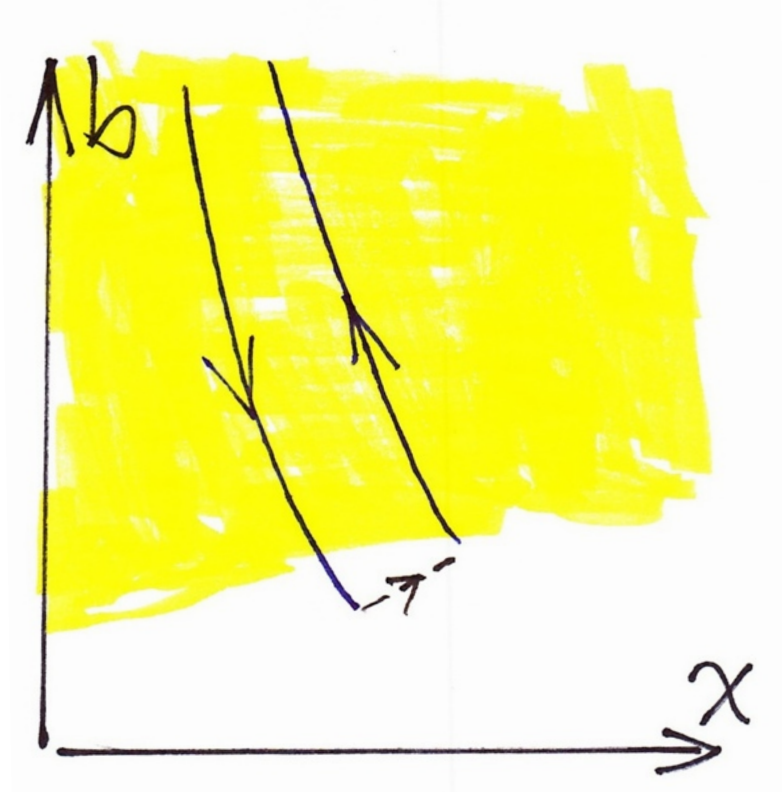
- But the results are inconsistent with the time-reversal invariance of the NBWF.

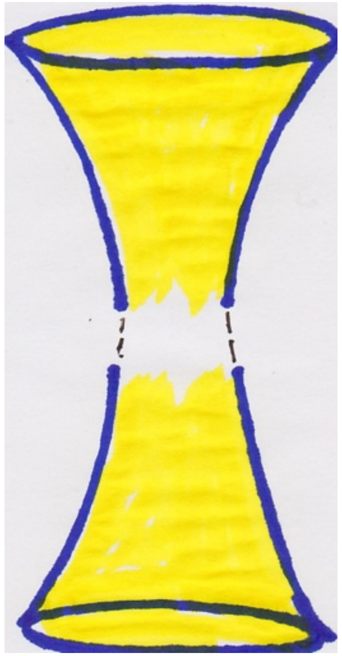
Quantum Extrapolation

- There is a quantum amplitude to go through the bounce from one classical history to any other that can be calculated from WdW.

- These are consistent with time reversal invariance of NBWF.

A WdW `S-matrix'





Lessons of Bouncing U's

- There may be no global spacetime. Classicality may only hold in patches of configuration space.
- In each patch there is generally not one, but an ensemble of possible classical spacetimes.
- Quantum transitions between classical patches can be calculated by WdW evolution.
- Classical spacetime can break down at energy densities well below the Planck scale.

Evaporating Black Holes

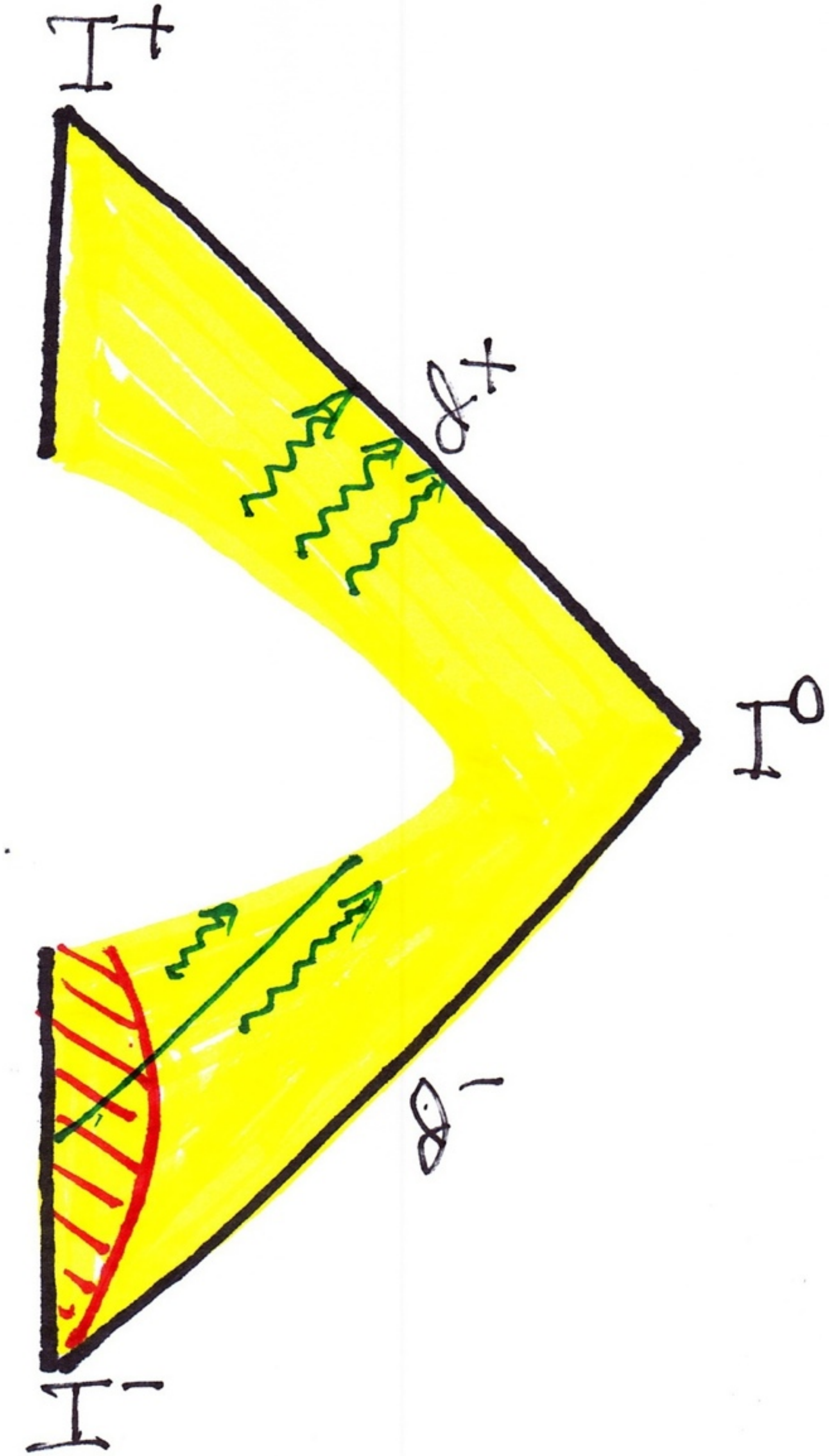
WdW for Evaporating Black Holes

$$\Psi = \Psi[h_{ij}(x), \chi(x), t)$$

- WdW evolution is not field theory in curved spacetime. There is generally no fixed background spacetime.
- WdW evolution is formally unitary.
- The WdW equation is neither local or non-local, neither causal or a-causal.

Classical Patches

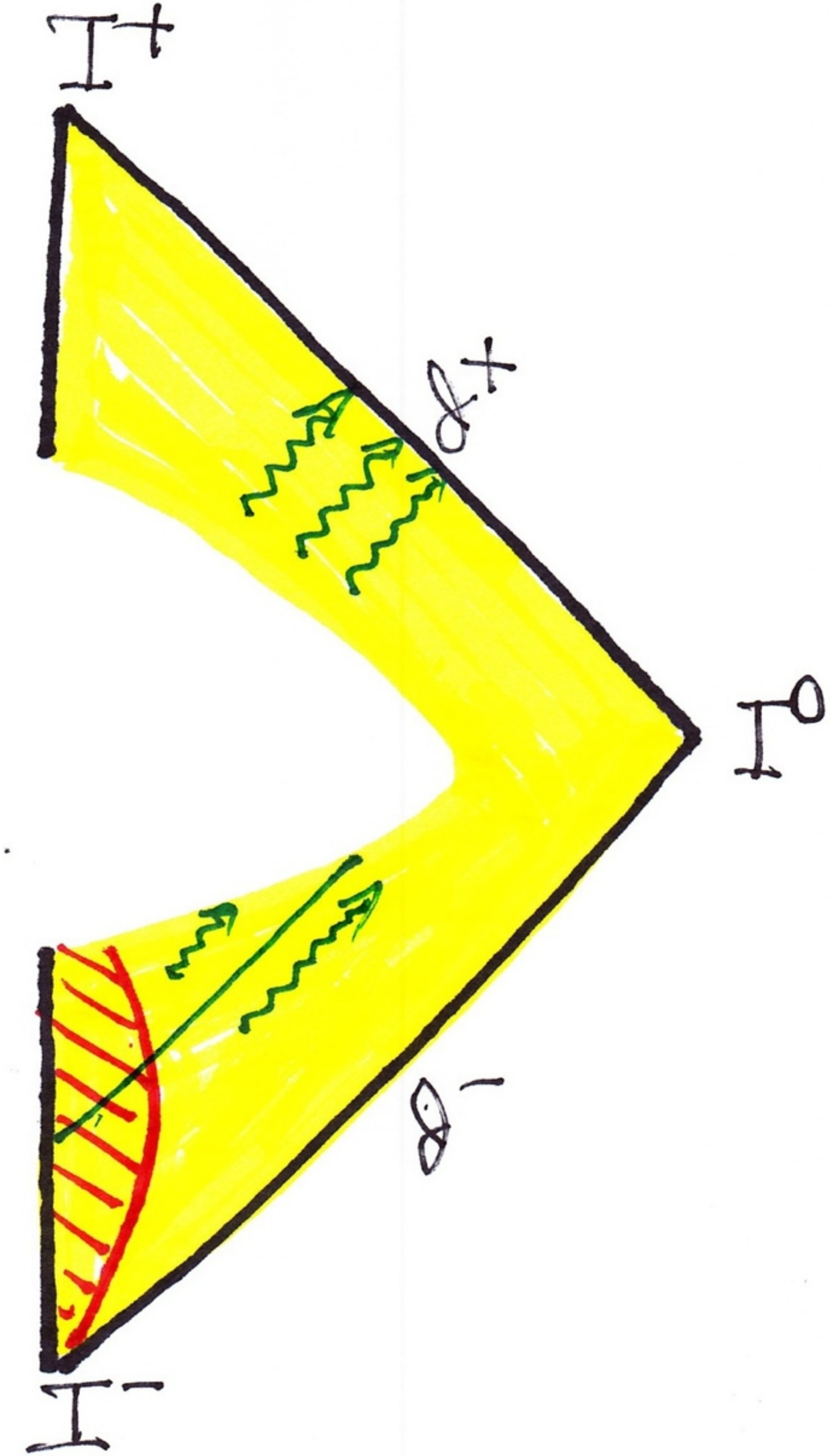
- We expect classical spacetimes only in asymptotic patches. (Certainly not near the classical singularity.)
- Many final asymptotic class. spacetimes for each initial one.
- WdW supplies an `S-matrix' between these.
- The quantum state remains pure.



No Horizon

There is no horizon defined as the boundary of the past of $\mathcal{I}^+$, because there is no global classical spacetime to define it.

There will be apparent horizons that are defined locally in a patch

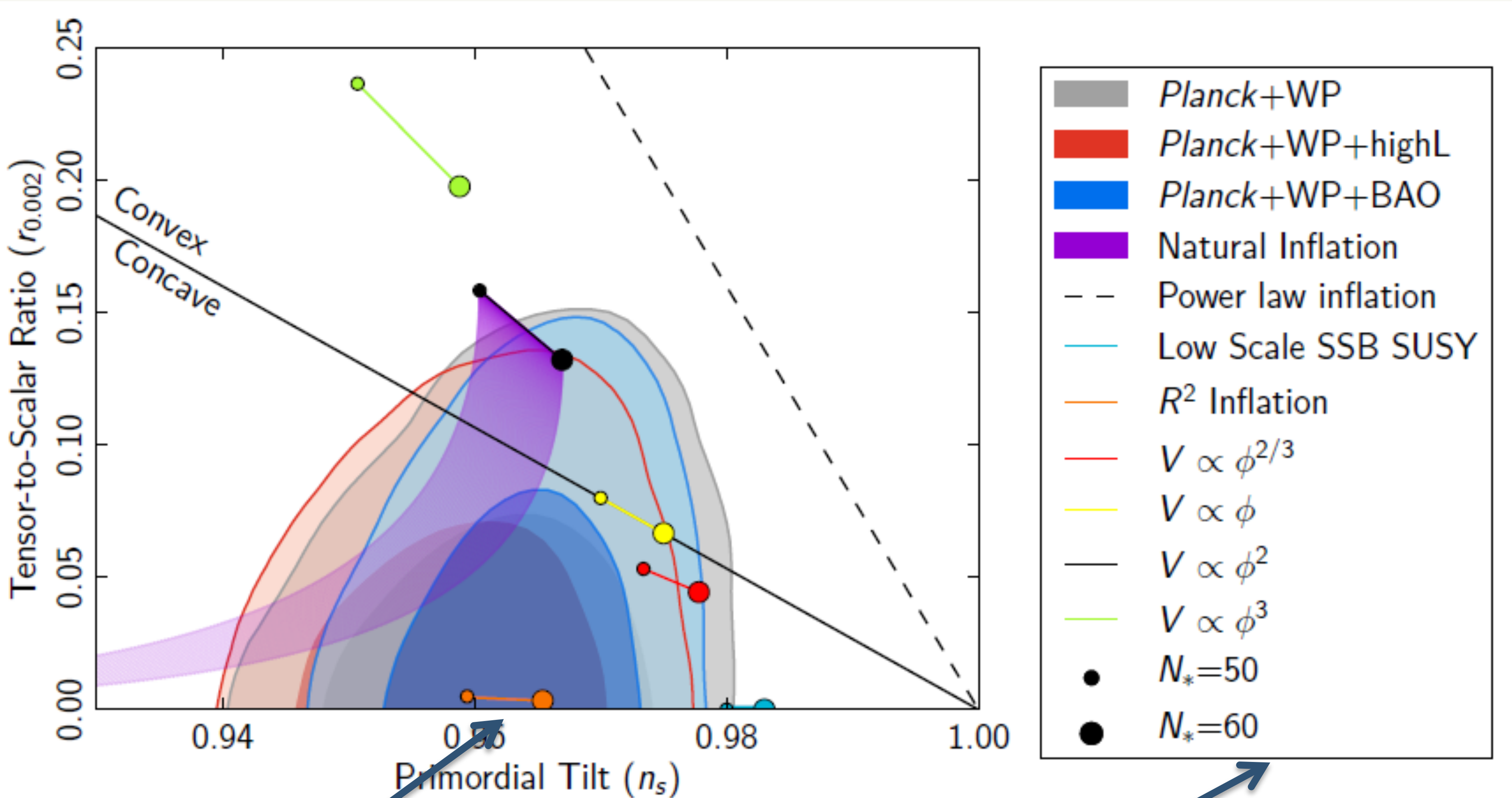


Its often asked: Why and where does classical spacetime break down?

In quantum mechanics the question is: Why and where do we have classical spacetime at all?

A Prior for Planck

Hertog



$$\Psi_{HH} \propto e^{-I_E}$$

Landscape

Classical spacetime exists only where quantum mechanics permits it to.