dS self-organized criticality for the weak scale

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2107.02801 with TaeHun Kim, and another with Jiwoo Park

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Overview

Take-home message:

"dS may have a built-in mechanism that can explain why our Universe lies near critical points."

1. Near-criticality of our Universe.
2. dS self-organized criticality: New beauty?
3. What quantum critical points for the Higgs mass?
4. dS entropy bound vs. eternal inflation !

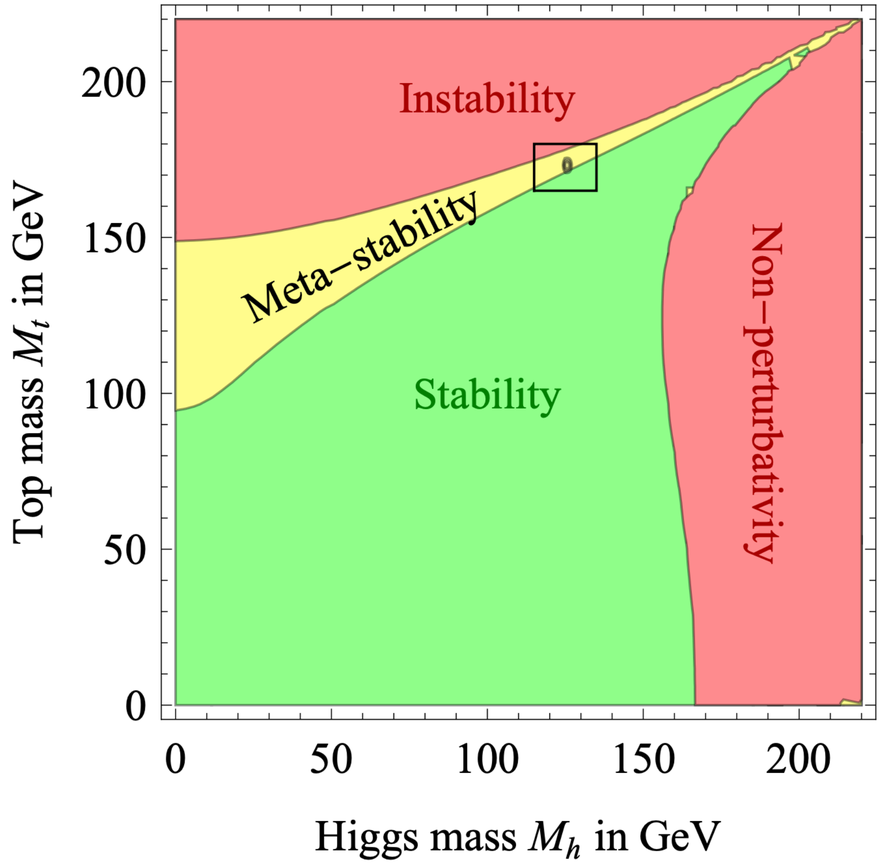
   (the part that I would like to consult experts here.)

Near-criticality of our Universe

Two well-known evidences:

Higgs mass and c.c.

One surprising implication of the Higgs discovery:



Degrassi et al. (12,13)

Why curious?

Sentimental: Why are we living dangerously?

Coincidence? Or any physical or compelling reasons?:
No known particle mechanism for fixing a theory near critical points.

New beauty for naturalness?!:
The Higgs mass and c.c. turned out to be extremely un-natural in QFT.

Giudice (08)

Self-organized criticality

Examples in nature:

Sand piling,

1/f noise seems to be a result of a SOC,

Self-similar, fractal…

In a sense, statistical phenomenon in a system with large # of dofs.

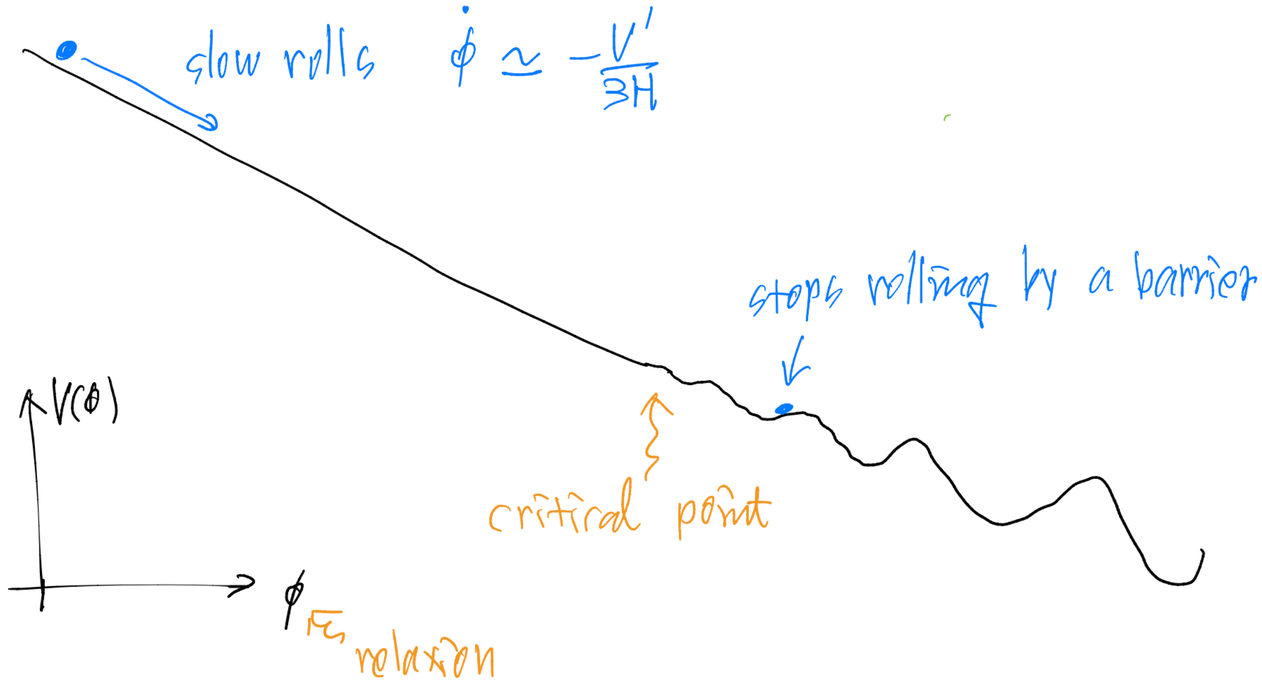
So can really be a new beauty, replacing the symmetry paradigm?!

Prototype (classical) mechanism - relaxion

During inflation, a theory inevitably evolves toward a critical point, independent of initial conditions.

The relaxion, determining the parameter value slow rolls until reaching the critical point, where a barrier starts to grow.

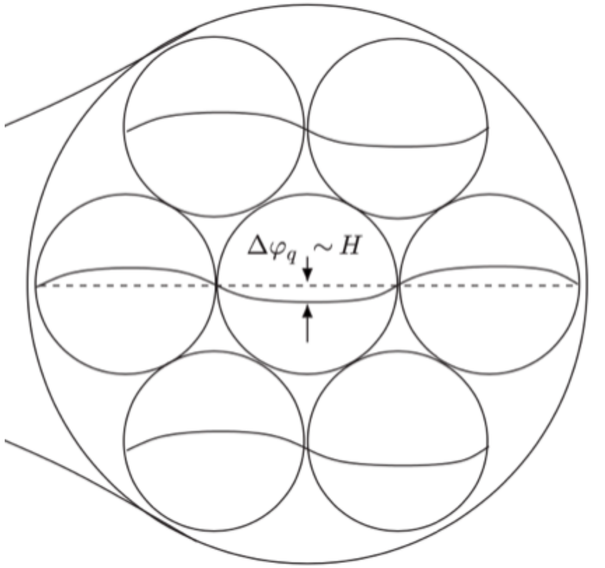
The parameter is fixed afterwards, explaining its near criticality today.



P.W.Graham, D.Kaplan, S.Rajendran (15)

Quantum self-organization : Ensemble

Stronger and sharper selection possible.
Contents: Ensemble, evolution, volume bias, criticality.



Ensemble consists of Hubble patches (universes),
each causally disconnected w/ indep parameter value.

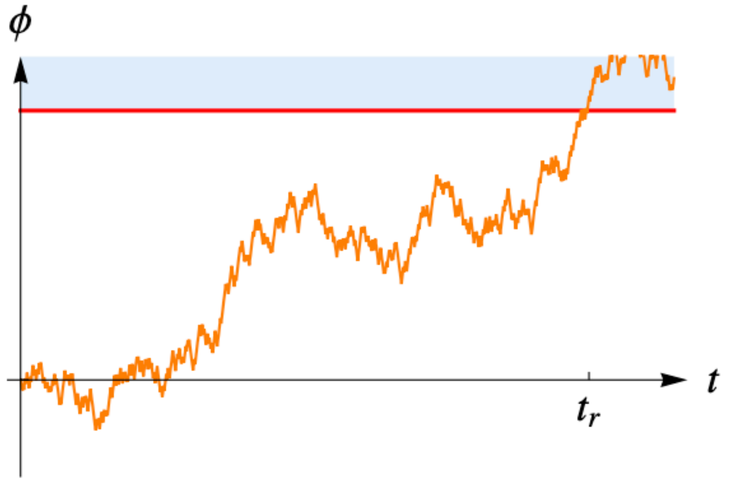
Think of the prob distribution of the parameter.

It evolves, as Hubble expansion reproduces new Hubble patches with the field value slightly evolved,
via classical rolling + quantum fluctuations.

Quantum self-organization : Basic evolution

During inflation, scalar field value is subject to

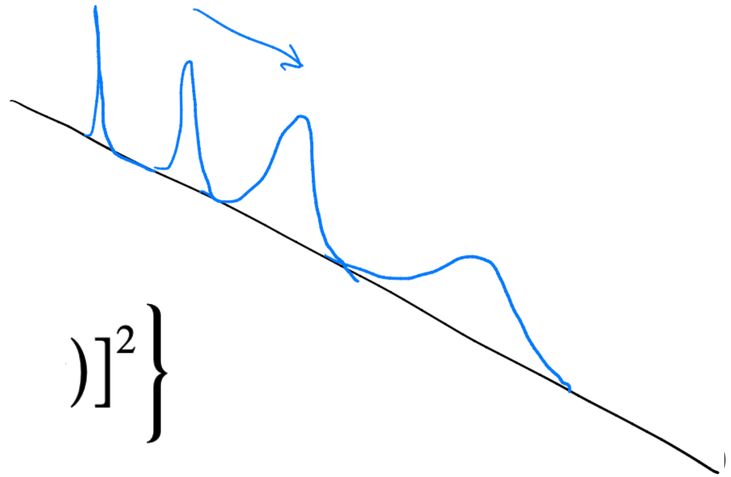
(1) classical rolling ~ -V'/3H : always downward
(2) random walk ~ H/2pi : symmetric up or down



In each patch, field value always rolls down on average.
But different patches differently.

Prob distribution: peak follows classical,
width broadens with sym quantum diffusion.

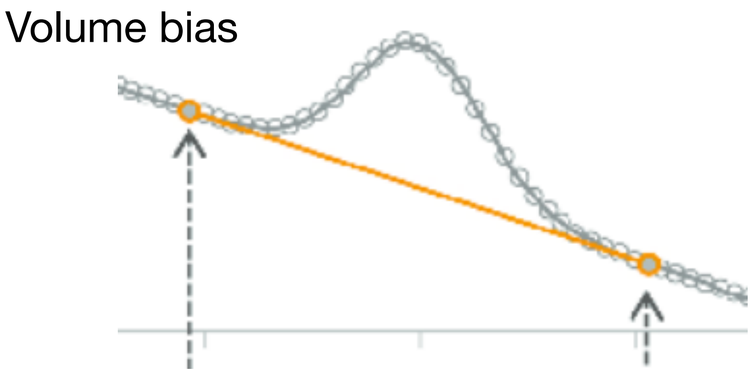
$$\rho(\phi,t) \propto \exp\left\{\frac{-1}{2\sigma_\phi^2(t)}\left[\phi-\left(\phi_0+\dot{\phi}_c t\right.\right.\right. \qquad \left.\left.\left.\right)\right]^2\right\}$$



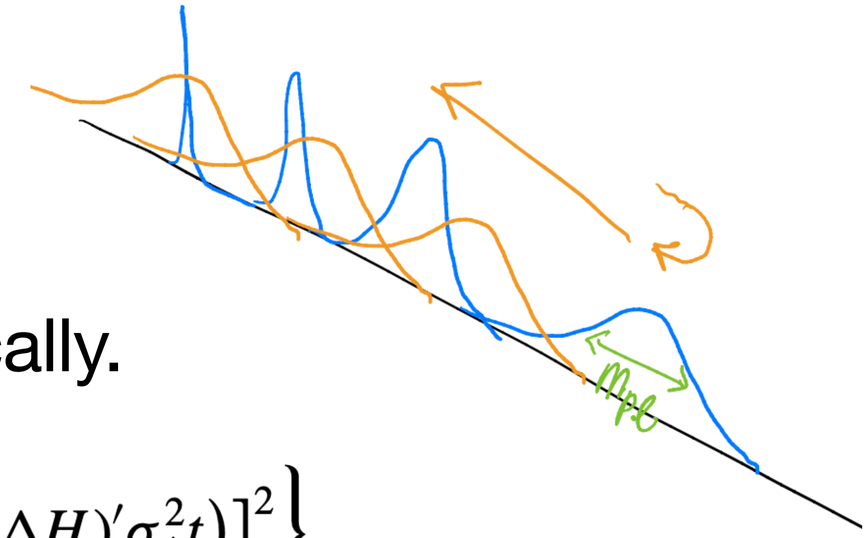
Quantum self-organization : Volume bias

The patch at higher-potential has a larger H, reproducing more rapidly.

Thus, the prob distribution can actually climb up !



Volume bias upward > slow-roll downward,
when distribution becomes broad ~Mpl,
to make large difference within it.



It's a quantum phenomenon, impossible classically.
(Mpl reflects it.)

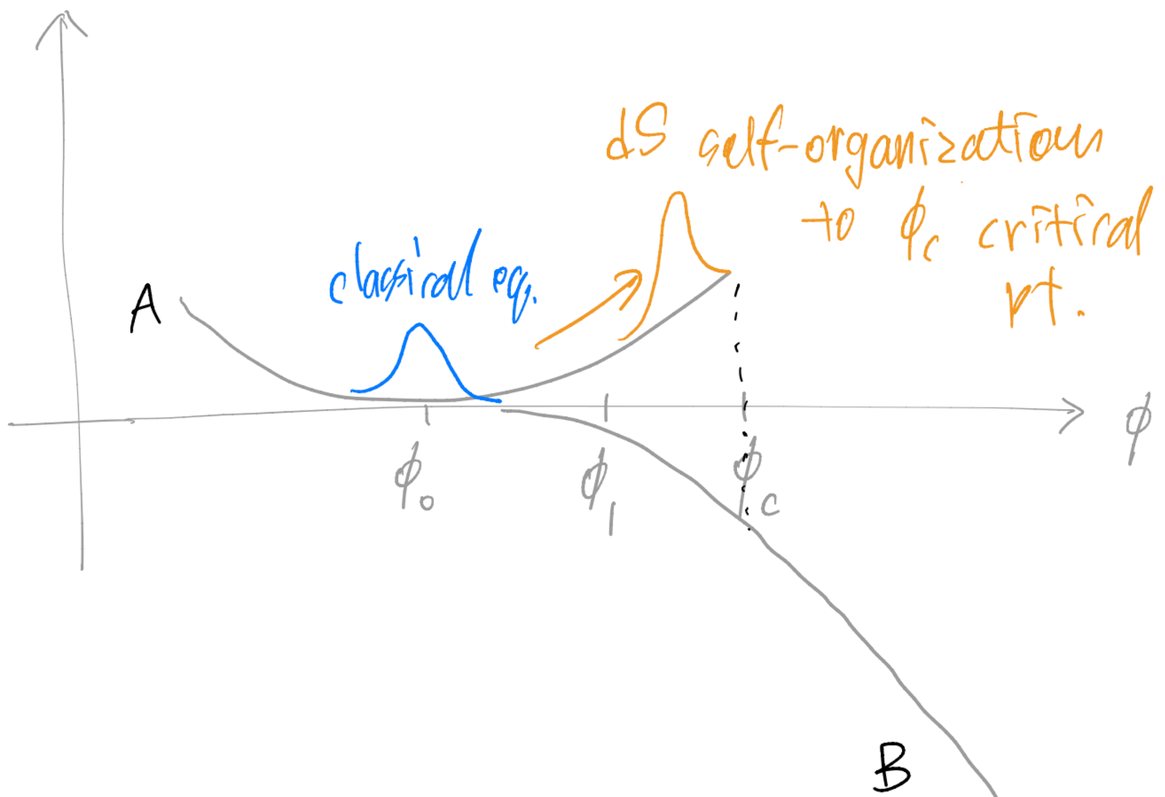
$$\rho(\phi,t) \propto \exp\left\{\frac{-1}{2\sigma_\phi^2(t)}\left[\phi-\left(\phi_0+\dot{\phi}_c t+\tfrac{3}{2}(\Delta H)'\sigma_\phi^2 t\right)\right]^2\right\}$$

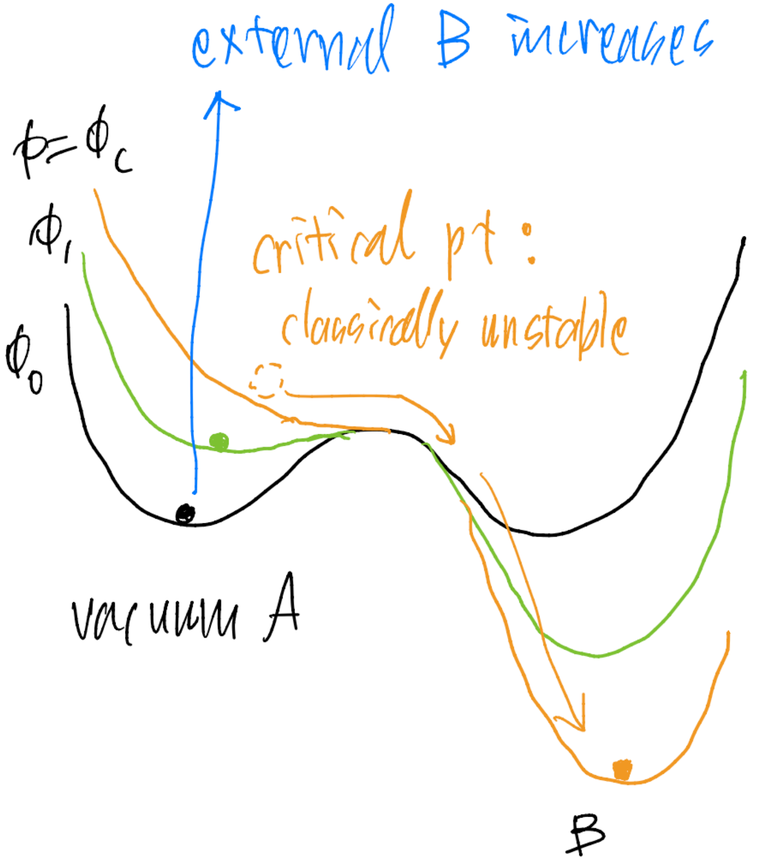
Quantum self-organization : Criticality

Equilibrium near the highest point of the potential.

The 1st-order critical point is a great candidate.

Such provides a *sharp* localization/selection rule.

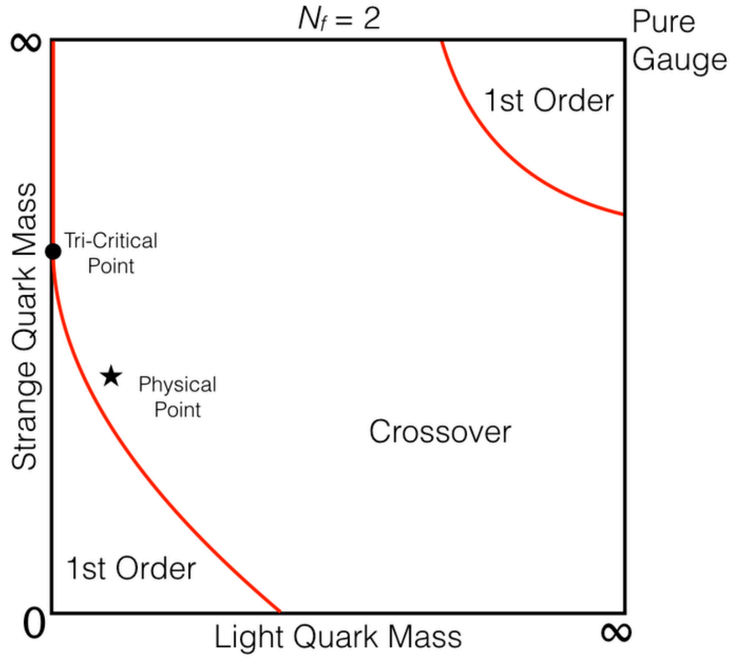


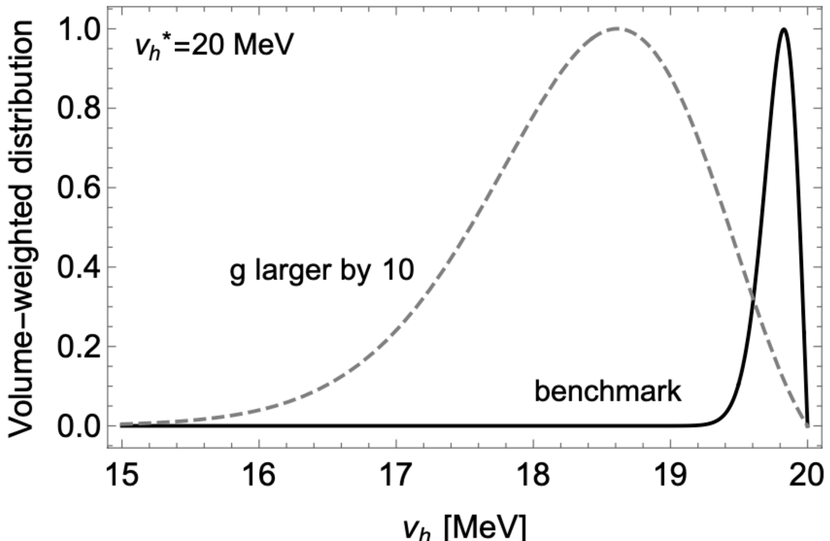


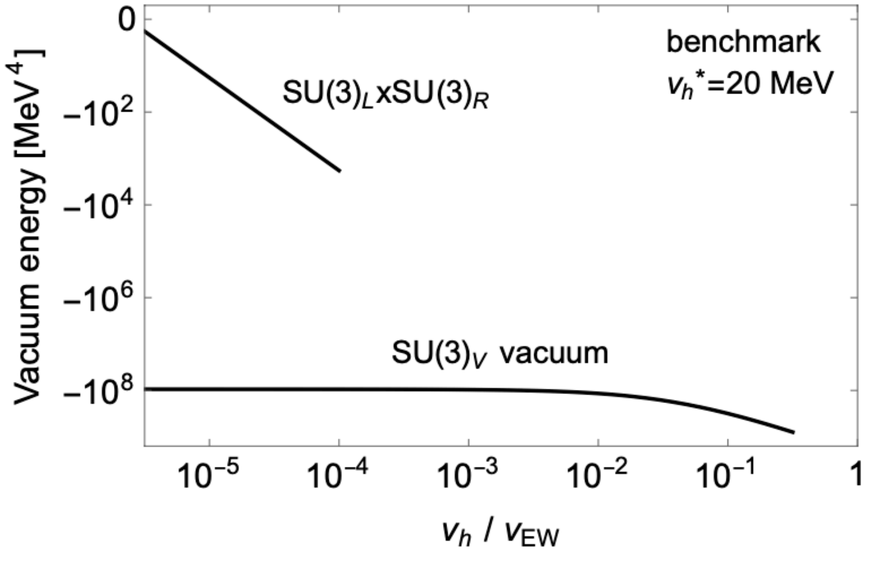
Giudice et al. (21)

1st-order quantum critical points for the Higgs mass?

- Coexisting Electroweak & Planck minimum :
  Critical Higgs mass ~ 10^12 GeV too far away.
- QCD chiral symmetry breaking :
  Has been unknown. (maybe never motivated)
  ~ L_QCD. (interesting connection)
  Needs verification with lattice, holography.







SJ, T.Kim (2107.02801 PRR letter)

dS self-organized criticality

dS entropy bound

dS spacetime has a horizon ~1/H,
thus its entropy is bounded by Bekenstein-Hawking area law.

$$S_{dS} = \frac{A}{4G} = \frac{\pi}{4GM^2} \simeq \frac{M_{pl}^2}{H^2}$$

But dS spacetime can be indefinitely large (even can be infinite).
In particular, the length of inflation is just a free parameter of a model.

Long enough inflation for self-organization

The time for Planckian width ~ dS entropy bound.

$$\therefore N = Ht \simeq \frac{M_{pl}^2}{H^2}$$

$$S_{dS} = \frac{A}{4G} = \frac{\pi}{4GH^2} \simeq \frac{M_{pl}^2}{H^2}$$

Self-organization violates dS entropy bound.

$$-\dot{\phi}_c = 3\langle\Delta H\rangle' \sigma_\phi^2$$

$$\Leftrightarrow \frac{V'}{3H} = \frac{V'}{2M_{pl}^2 H_0}\cdot \sigma_\phi^2$$

$$\therefore \sigma_\phi^2 = \frac{2}{3}M_{pl}^2 = \left(\frac{H}{2\pi}\right)^2 Ht$$

$$\therefore N = Ht \simeq \frac{M_{pl}^2}{H^2}$$

Questions for the remaining today

The time for Planckian width ~ dS entropy bound.

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Self-organization violates dS entropy bound.

What is the physical origin of dS entropy and its bound?!

Self-organization?
Fundamental phy?

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Self-organization violates dS entropy bound.

What is the physical origin of dS entropy and its bound?!

Self-organization? ==> dS complementarity means eternal inflation?
Fundamental phy? ==> dS islands recover Page curve?

dS complementarity?

Problems arise only when one tries to describe what cannot be accessible to him. The global view of dS may not make sense.

Operational meaning of the dS entropy could be:

An asymptotic observer in the Minkowski (after dS stage) can observe early dS dofs as curvature fluctuations; superhorizon modes re-enter.

Then what happens when the total modes that re-entered exceed the dS area law?

dS complementarity and eternal inflation

It's exactly when the inflation becomes eternal;
quantum flucts to the inflaton field value exceeds classical rolling.

It's exactly when the curvature perturbation exceeds 1;
spacetime geometry becomes singular or trapped, so no future.

It's also the Page time, where BH EFT breaks down. (see next)

$$S = \pi H^{-2}/G. \qquad \dot{H} = -(4\pi G)\,\dot{\phi}^2 \qquad \frac{dS}{dN} = \frac{8\pi^2\dot{\phi}^2}{H^4} \sim \left(\frac{\delta\rho}{\rho}\right)^{-2}$$

$$N_{\rm tot} \lesssim \left(\frac{\delta\rho}{\rho}\right)^2 \cdot S_{\rm end}$$

t ~ N/H ~ S/H ~ Page time

Arkani-Hamed et al. (07)
Bousso et al. (06)

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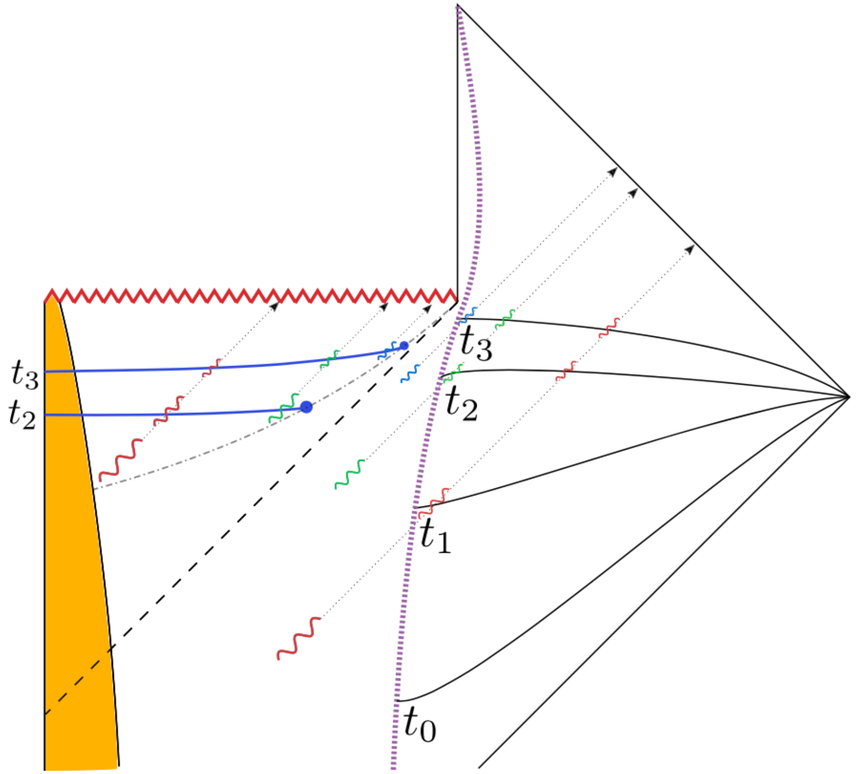
$$N_{\rm tot} \lesssim \left(\frac{\delta\rho}{\rho}\right)^2 \cdot S_{\rm end}$$

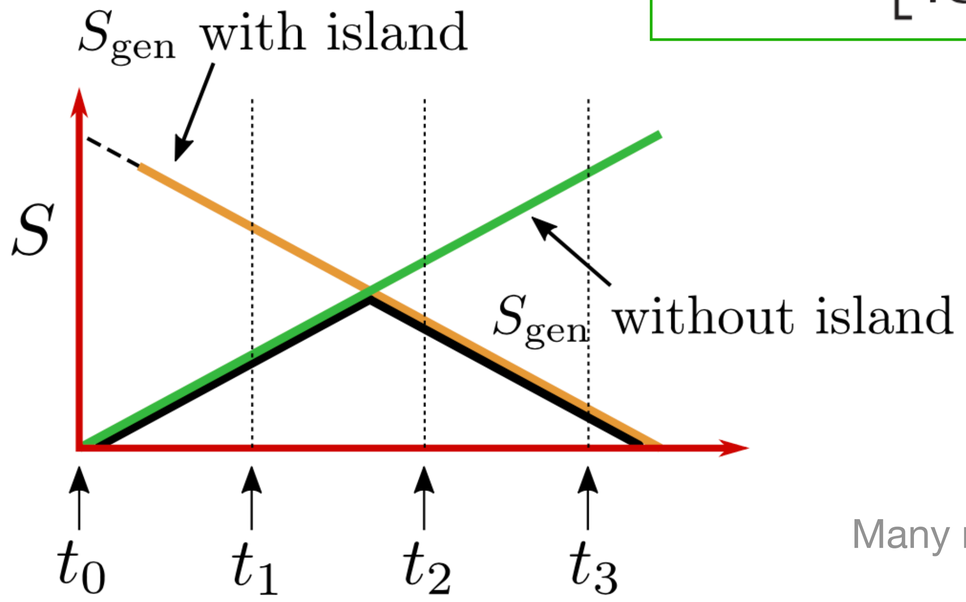
But this is a bit probabilistic and coincidental.

Islands

Recently, black hole entropy was greatly advanced with an aid of islands; non-local entanglement btwn inside and outside of a BH.



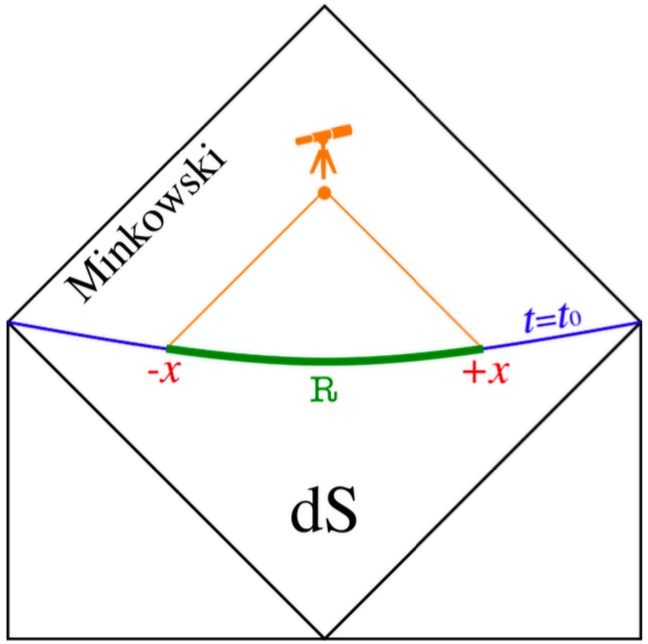
$$S \sim \min\left[\frac{\text{area}}{4G_N} + S_{\text{outside}}\right]$$

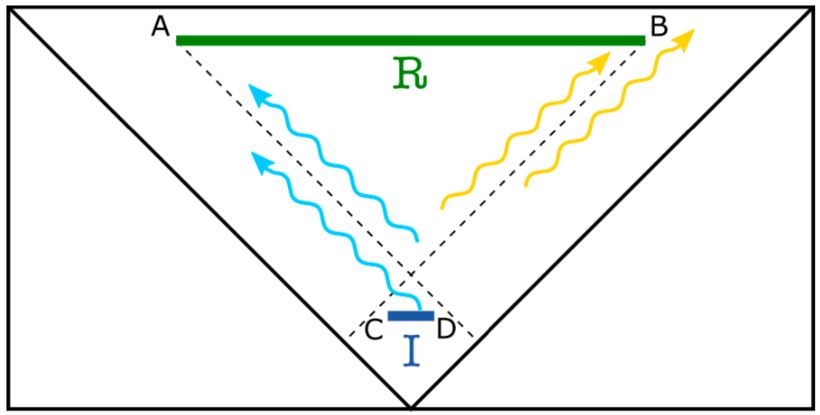


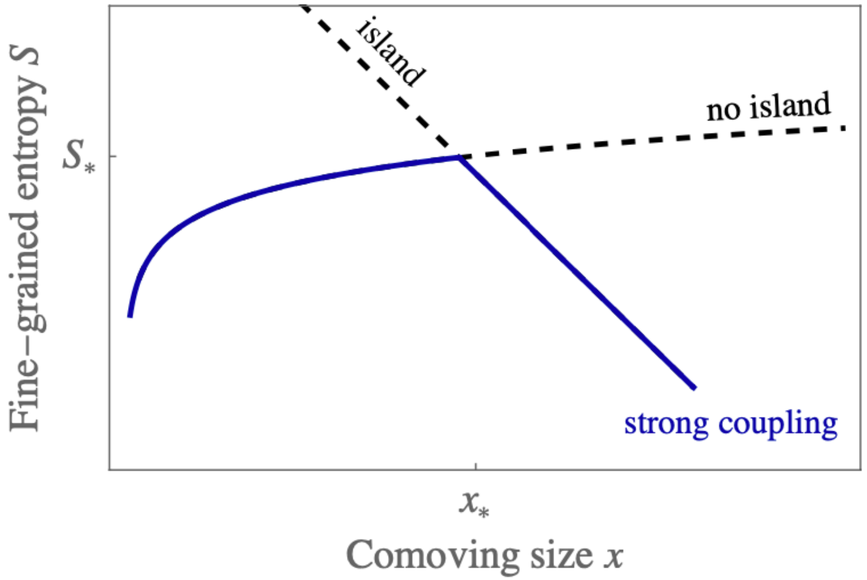
Many recent works…

dS islands?

Under dispute.
Exist claims that 2D dS (JT+CFT) has islands and Page curve.







Teresi (22), Gorbenko et al. (21)

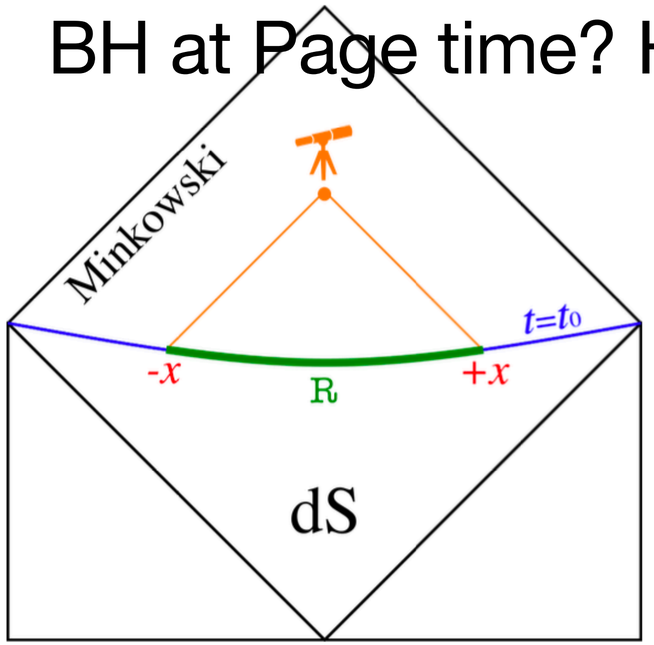
dS islands?

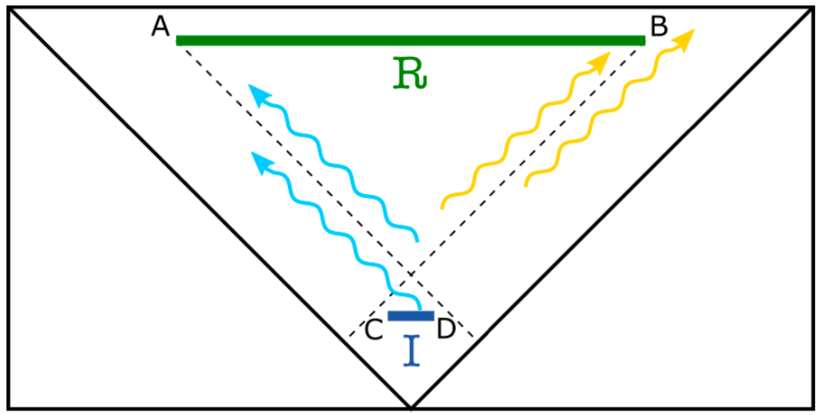
Which saddles, in principle? Maximax or minimax? Separated Cauchy?

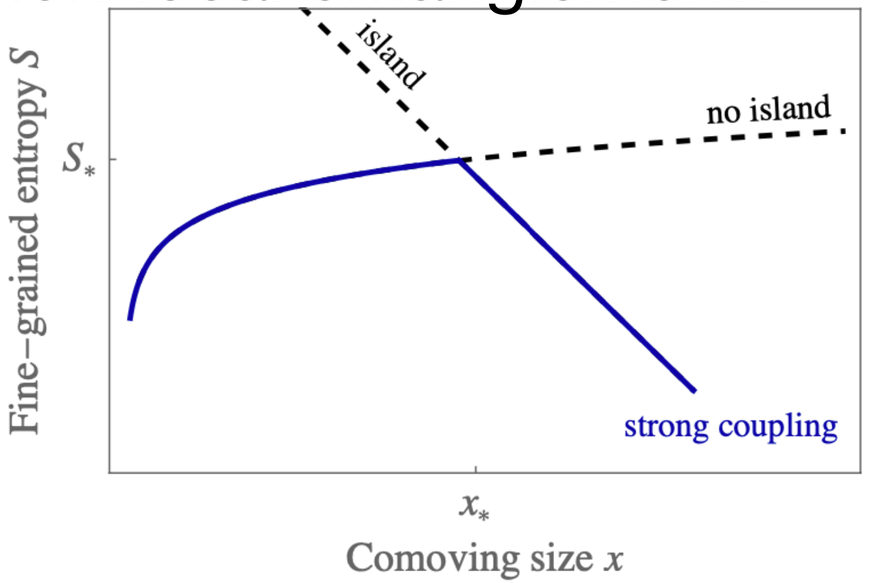
Setup? No boundary, no holography? dS + asym Minkowski, or + aux?

Where's the singularity? No entropy bound on the length of inflation?

BH at Page time? How does geometry knows non-local entanglement?







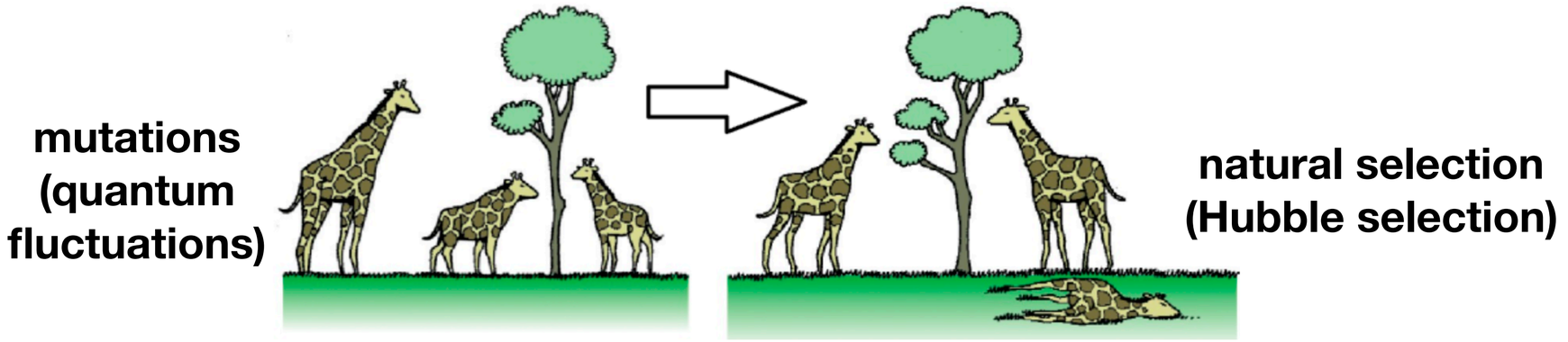
Summary

dS self-organized criticality : dS quantum effects can drive universes toward a 1st-order quantum critical point, indep on initial conditions

Apparent fine-tunings can indeed be due to SOC.

SOC requires long inflation, probably eternal if dS complementarity.

dS entropy, complementarity, islands… Non-intuitive and coincidental.



Complexity and Poincare recurrence?

What is actually changing even after thermal equilibrium?

Page time ~ evaporation time ~ minimal time measurable ~ S R

>> Planckian

<< recurrent time ~ exp S