Crunching away the CC Problem

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Outline

- Introduction - the different faces of the CC problem and attempts at solving
- The idea
- The crunching sector
- The calculation of the bubble nucleation rate
- Constraints and predictions
- The scanning and inflationary sector
- Summary

The many faces of the CC problem

- Current observed CC very small

$$\Lambda_{obs} \sim (10^{-3}\ \mathrm{eV})^4 \ll M_{Pl}^4$$

- Hardest question actually $\Lambda_{obs} \ll \Lambda_{QCD}^4$

- Why is it so small compared to any naive estimate?

- The CC problem

The many faces of the CC problem

- Even more puzzling $\Omega_{\Lambda,0} \sim \Omega_{m,0}$

- This ratio changes constantly in standard picture, and could have been many orders of magnitude off.

- ``Why now” problem - coincidence problem

Possible approaches to the CC problem

- A UV softly broken symmetry sets the CC to zero

- SUSY - expect $\Lambda \propto M_{SUSY}^4$

- SUSY breaking scale at least 10 - 100 TeV (for example in gauge mediation) - reduces CC problem

- Could try to use conformal symmetry, typically

$$\Lambda \propto \epsilon M_{UV}^4$$

- ϵ is anomalous dimension, not a very big suppression generically

Possible approaches to the CC problem

- Dynamically relax the CC (adjustment mechanism)

- Too bad there aren't any - Weinberg no-go

- No coupled scalar-gravity theory will have its ground state at 0 CC without tuning

- Of course has assumptions: solution exactly Minkowski, no t or T dependence allowed - perhaps there are ways out?

Possible approaches to the CC problem

- Anthropic approach

- Many Universes (``Multiverse”) with different CC’s (CC ``scanned”)

- We should live in Universe where structure can form $$\Lambda < (\mathrm{few} \cdot 10^{-3}\ \mathrm{eV})^4$$

- Need to populate multiverse - eternal inflation?

- Need theory providing landscape - string theory?

Problems with these approaches

- No known symmetry that works all the way

- No known adjustment mechanism (+ no go)

- Anthropics - no experimental predictions

- Eternal inflation (seems to be necessary for anthropics) has measure problem - does not seem to have predictive power either

- We are proposing a different approach - some elements similar to anthropics but dynamical selection, will have predictions and no measure problem

Our idea

- Have an in-between solution that has some elements from anthropic approach, some dynamics

- Circumvent Weinberg no-go by starting with a multiverse with many patches with different CC's

- Rather than do statistics and anthropic considerations have patches with large CC dynamically crunch in short time $H_\Lambda^{-1} \sim \left(\Lambda^2/\sqrt{3}M_{\rm Pl}\right)^{-1}$

Our idea

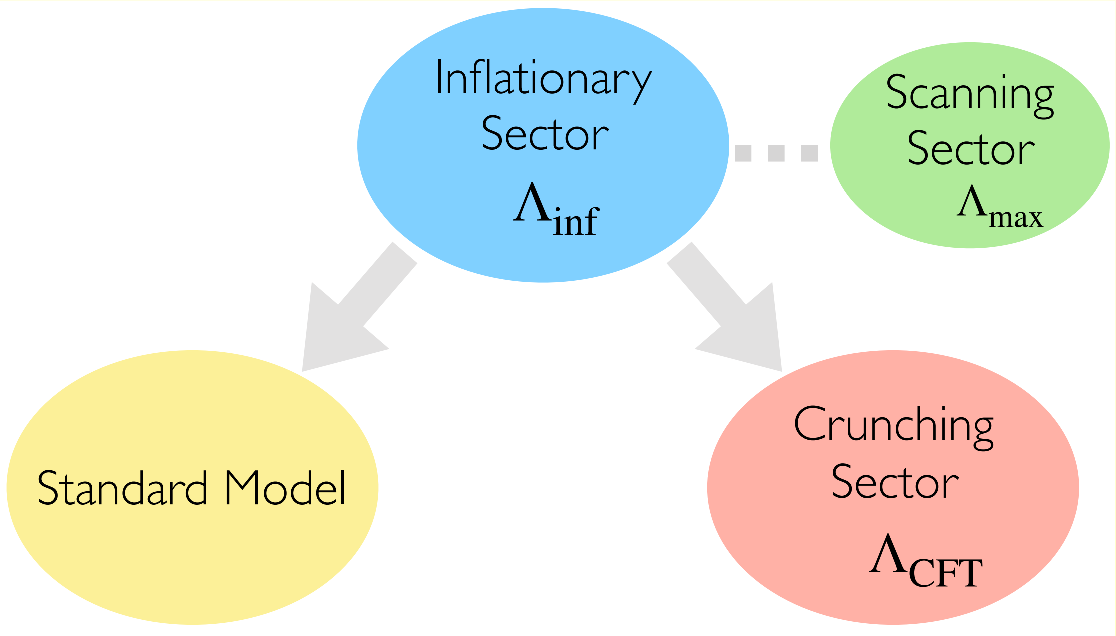
- Have 3 sectors
  - Inflationary sector - drives inflation and then reheating with scale Λ_{inf} - finite relatively short period of inflation (will see how much N ~ 200)

  - Scanning sector - will populate the different vacua, scale Λ_{max}. Like Bousso- Polchinsky

  - Crunching sector - will be responsible for crunching, scale Λ_{CFT}

- Need hierarchy of scales $\Lambda_{max} < \Lambda_{CFT} < \Lambda_{inf}$

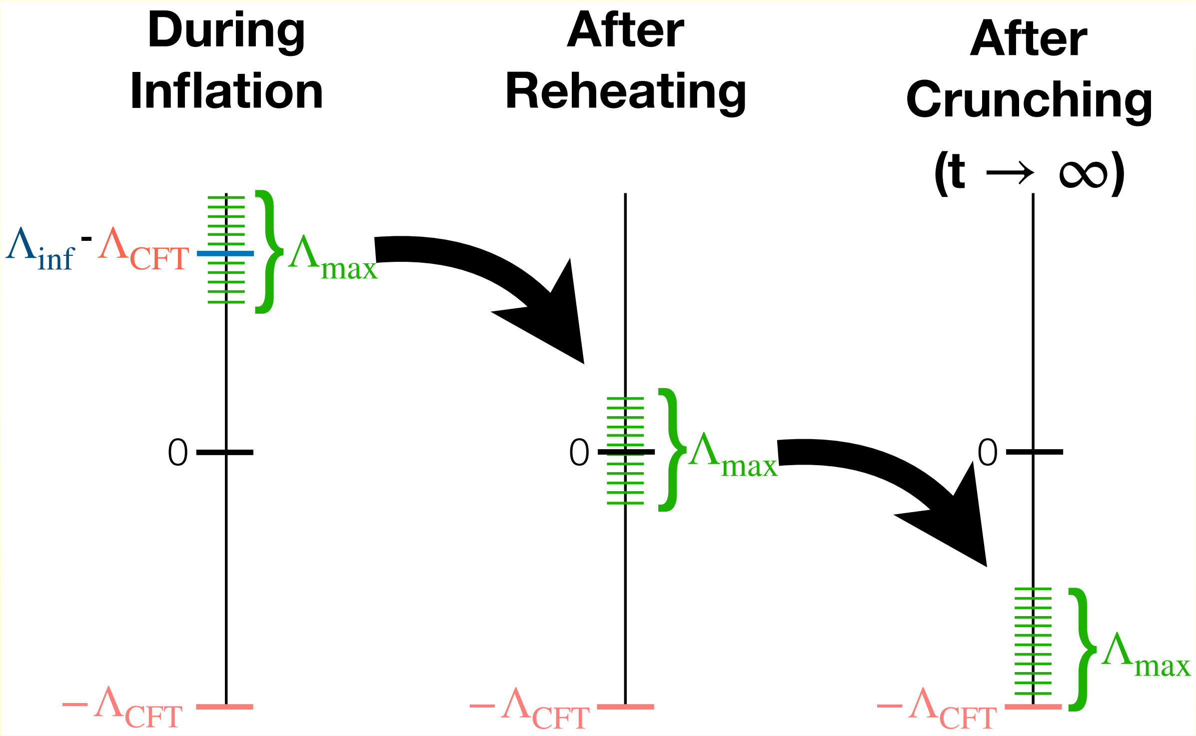
Our idea



- During inflation different Hubble patches will give rise to different CC's due to scanning dynamics (but inflation does not have to last long)

- Assume there is a maximal value $\Lambda_{\rm max} < \Lambda_{\rm inf}$

Our idea



- After inflation Universe reheated to $T > \Lambda_{inf}$

- Patches with highest Λ will re-enter inflation first and trigger phase transition in the CFT. If $\Lambda_{CFT} > \Lambda_{max}$ patch will crunch first. Patches with small Λ will live long

The crunching sector should be special

- Should turn large positive CC into large negative CC

- Should not have happened for our Universe yet, so meV scales should not have crunched

- meV scale should be metastable and energy differences should be much larger than the actual T and E now

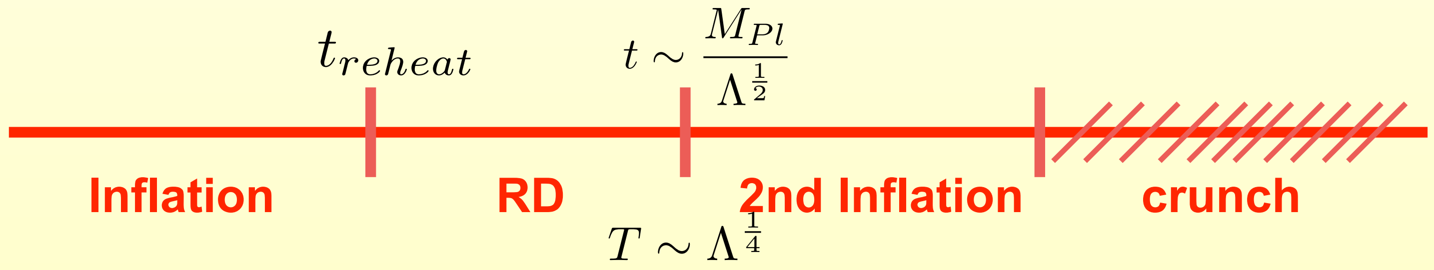
- Phase transition has to be strongly supercooled

- Actual transition should happen much below the critical T

Cosmic history

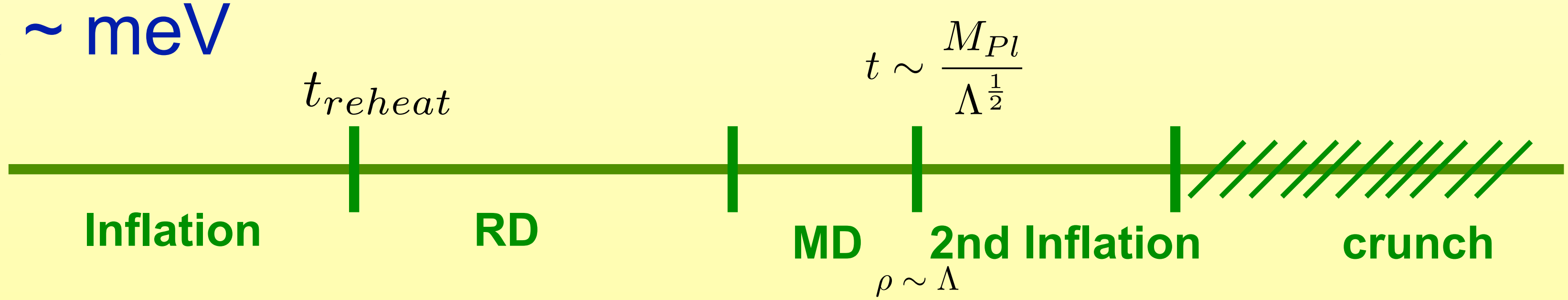
- For large CC patches

$\Lambda \sim 100$ GeV



- For our patch

$\Lambda \sim$ meV



The cosmic history

- After reheating every patch radiation dominated (that's why we need Λ_{max})

- A patch will crunch after few inverse Hubble times

$$t_H \sim H_\Lambda^{-1} \sim \frac{M_{Pl}}{\Lambda^{\frac{1}{2}}}$$

- Regions with small Λ will be long lived

- Avoids measure problem - will only only need relatively short finite period of inflation

- Solves ``Why now" - we are close to critical point about to undergo catastrophic PT

The crunching sector

- This is the essential new ingredient of our model

- Requirements: undergoes phase transition at low T which will trigger the crunch of the patch

- PT for T < T_0 such that we have not crunched yet, but jump in vacuum energy should be large

$$\Lambda_{CFT} > \mathrm{TeV}^4 \gg T_0^4 \sim \mathrm{meV}^4$$

- To be able to trigger crunch. Need strongly super cooled PT

- Spontaneously broken CFT's feature exactly such super cooled PT (at least for large N)

The crunching sector

- CC in unbroken phase (high T) vanishes

- CC in broken phase (zero T) could be large negative

- PT via bubble nucleation

- Tunneling probability has to remain negligible down to $T < T_0$ but soon after should jump to be high

- Randall-Sundrum large N dual of broken CFT has all these properties automatically

- Only issue tunneling probability only mildly T-dependent - will need to go much below meV for PT

The crunching sector

- Will see from explicit calculation $\Lambda_{max} \sim \sqrt{\tilde{T}_{CFT} M_{Pl}}$ where $\tilde{T}_{CFT}$ is T where PT actually happens

- We want $\tilde{T}_{CFT} \sim T_0$ to have maximize CC that can be canceled

- In that case we get an actual prediction

$$\Lambda_{max} \sim \sqrt{\mathrm{meV}\, M_{Pl}} \sim \mathcal{O}(\mathrm{TeV})$$

- A dynamical realization of the numerical relation prediction the weak scale

- To achieve $\tilde{T}_{CFT} \sim T_0$ will have to add a hidden QCD' sector to RS (will see details soon)

The model

- Two phases of RS. Low temperature phase: RS - Goldberger Wise model
- Slice of AdS_5 with metric $ds^2 = \frac{R^2}{z^2}(dx^2 - dz^2)$
- z=R UV brane, z=R' IR brane
- Location of IR brane: radion/dilaton $\chi = \frac{1}{R'}$
- Original RS: χ is a flat direction (no potential at all)
- With GW stabilization potential V(χ)

$$V_{eff}(\chi) = \lambda\chi^4 + \frac{\lambda_1}{M^{\epsilon_1}}\chi^{4+\epsilon_1} - \frac{\lambda_2}{M^{-\epsilon_2}}\chi^{4-\epsilon_2}$$

CFT interpretation

- CFT interpretation: χ is Goldstone boson of broken scale transformation (dilaton). χ^4 potential scale invariant and allowed (does not have to be derivative)

- $4+\epsilon_{1,2}$ terms (small) explicit breaking terms

- ϵ_1 term usual GW stabilization

- Coefficient of ϵ_2 term very small $\lambda_2 << 1$ - will be due to additional bulk dynamics (needed to generate right properties of bubble nucleation rate)

The model

- Minimum of potential (third term negligible)

$$\chi_{\min} \simeq M \left(-\frac{4\lambda}{(4+\epsilon_1)\lambda_1} \right)^{1/\epsilon_1}$$

- For very small χ the behavior of potential changes due to third term $V_{eff}(\chi)/\chi^4 \sim \mathcal{O}(1)$ for

$$\chi_* \equiv \lambda_2^{1/\epsilon_2} M \ll \chi_{\min}$$

- Will be crucial for drop in bounce action

- Aside on generating the third term

Effect of extra bulk group

- A simple way to generate third term in the potential: add an additional bulk gauge group that confines (idea of von Harling and Servant)

- Running of coupling:

$$\frac{1}{g^2(Q,\chi)} = \frac{\log\frac{k}{\chi}}{kg_5^2} - \frac{b_{UV}}{8\pi^2}\log\frac{k}{Q} - \frac{b_{IR}}{8\pi^2}\log\frac{\chi}{Q} + \tau_{UV} + \tau_{IR}$$

- Get χ dependent confinement scale:

$$\Lambda(\chi) = \left(k^{b_{UV}}\chi^{b_{IR}}e^{-8\pi^2\tau}\left(\frac{\chi}{k}\right)^{-b_{CFT}}\right)^{\frac{1}{b_{UV}+b_{IR}}} = \Lambda_0\left(\frac{\chi}{\chi_{min}}\right)^n$$

- Where $n = \dfrac{b_{IR} - b_{CFT}}{b_{UV} + b_{IR}}$

Effect of extra bulk group

- The expected contribution to the potential of this confining group:

$$V_G = -\alpha \Lambda_G^4(\chi) \;\; = -\alpha \Lambda_0^4 \left(\frac{\chi}{\chi_{min}} \right)^{4n} \equiv -\kappa \chi_*^4 \left(\frac{\chi}{\chi_*} \right)^{4n}$$

- Where $\chi_* = \Lambda_0 \left(\frac{\Lambda_0}{\chi_{min}} \right)^{\frac{n}{1-n}}$

- $\chi_* \sim \mathcal{O}(10^{-3}\mathrm{eV})$ is the value at which this term becomes large

The high T phase

- At high T model on 5D side described by AdS-Schwarzschild

$$ds^2 = \left(\frac{R^2}{z^2} - \frac{z^2 R^2}{z_H^4}\right) dt^2 + \frac{R^2}{z^2}\sum_i dx_i^2 + \frac{\frac{R^4}{z^4}}{\frac{R^2}{z^2} - \frac{z^2 R^2}{z_H^4}} dz^2$$

- z_H is location of the horizon. For $z_H \rightarrow \infty$ reproduce AdS metric. z_H also sets the Hawking temperature of the BH:

$$T_H = \frac{1}{\pi z_H}$$

- Which also has to coincide with the periodicity of the time coordinate

$$\beta^{-1} = T = T_H$$

The phase transition

- Hawking-Page PT - easiest to describe on CFT side

- There simply going from unbroken CFT at high T to broken CFT

- Critical temp. from equality of free energies:

$$F_{broken}(\chi, T) \approx V(\chi) \qquad F_{min} = -\frac{\epsilon_1 \lambda}{4}\chi^4_{min}$$

- In hot phase just black body radiation $N = 4\pi(MR)^{\frac{3}{2}}$

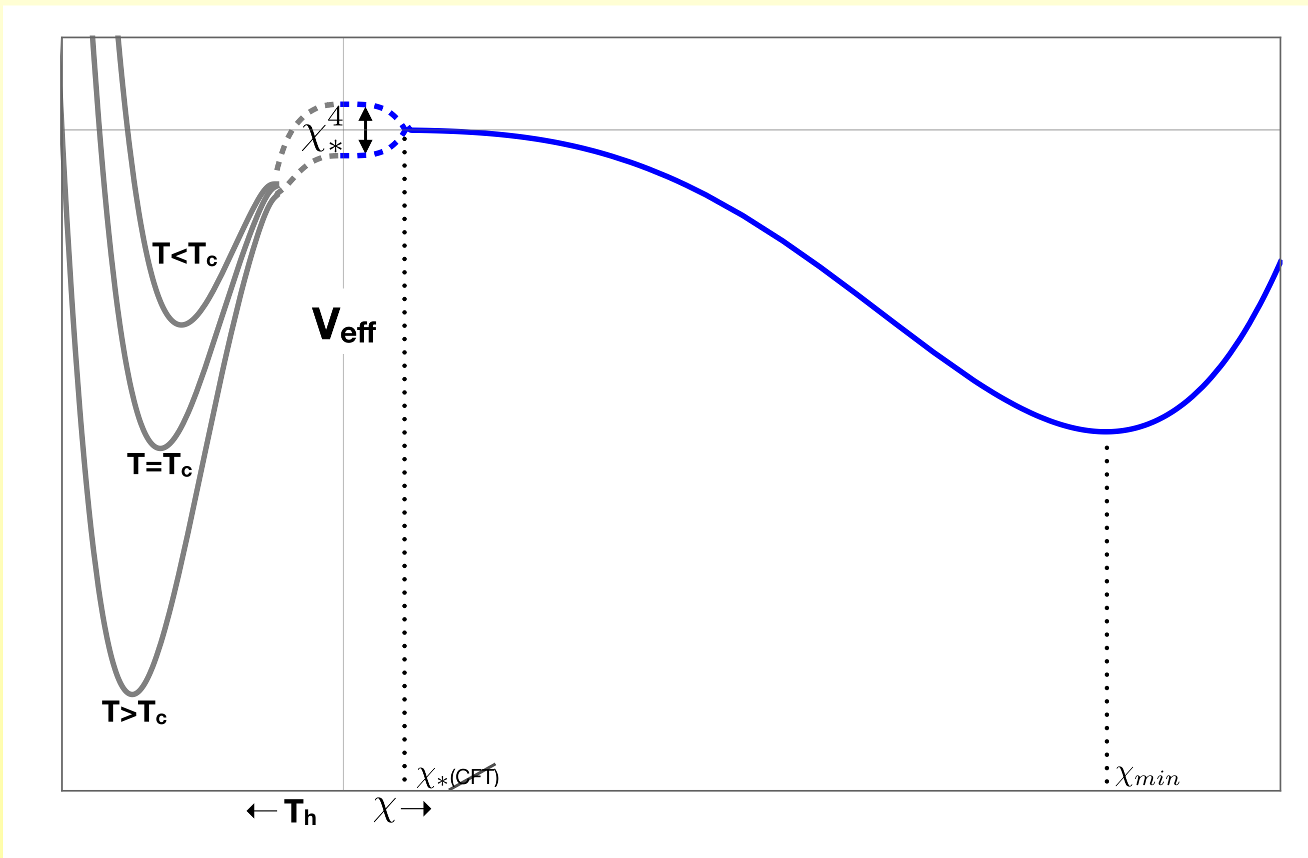
$$F_{\rm conformal} = -\frac{\pi^2}{8}N^2T^4$$

- The critical temperature

$$T_c = \chi_{min}\left(\frac{2\lambda}{\pi^2 N^2}\right)^{1/4}$$

The full potential of the two phases

• Simplified sketch of full potential: glue together dilaton potential and BH potential at point where the IR brane is moved to infinity to the point where the BH horizon is moved to infinity (Creminelli et al 2001)

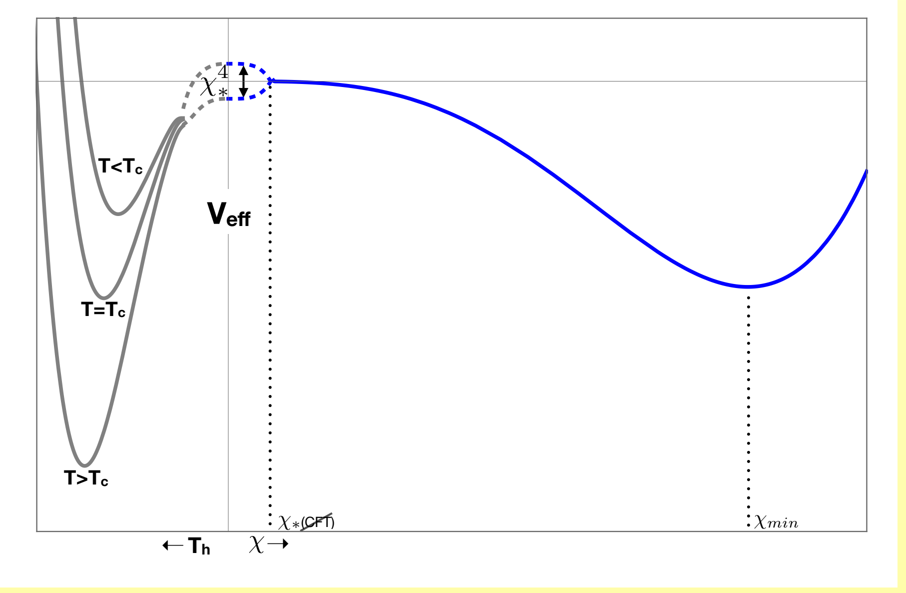


The full potential of the two phases

- Note at small $\chi < \chi_*$ explicit breaking will be large.

In CFT language we expect to flow to a different CFT. Characteristic scale will be χ_* rather than T in uncalculable region $\chi < \chi_*$

- Other uncalculable region: χ<T - finite T corrections sizeable, local Planck scale below T.



The crunching phase transition

- Hawking-Page transition from metastable high T phase of CFT (described by AdS-S) to spontaneously broken phase (described by RS-GW)

- Usually two contributions O(3) and O(4) invariant

- At T >> χ_* usually O(3) symmetric solution dominates

- Bubble nucleation probablility

$$\Gamma(T)/V = \Gamma_0 \cdot T^4 \left(\frac{S_3(T)}{2\pi T}\right)^{3/2} e^{-S_3(T)/T}$$

- S_3 is the O(3) invariant bounce action

The crunching phase transition

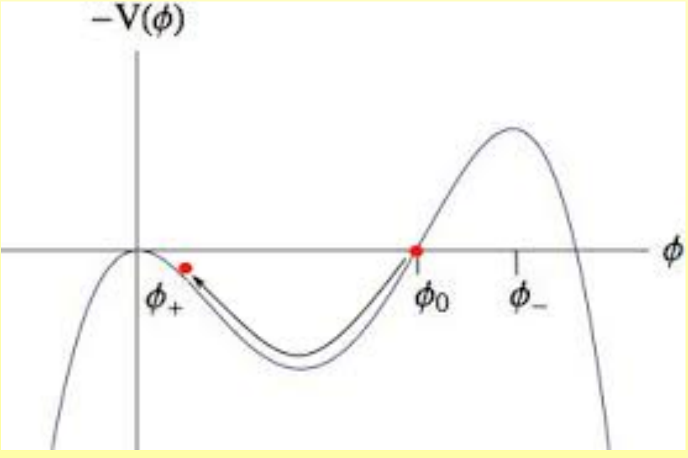
- For $T \lesssim \chi_*$ we expect S$_4$ will become important.
  Will have characteristic scale χ_* setting Γ_0

$$\Gamma/V \propto \chi_*^4 (S_4/2\pi)^2 e^{-S_4}$$

- We will focus on S$_3$

- Need to solve Euclidean EOM for bounce

$$\phi'' + \frac{2}{r}\phi' - V'(\phi) = 0\,.$$

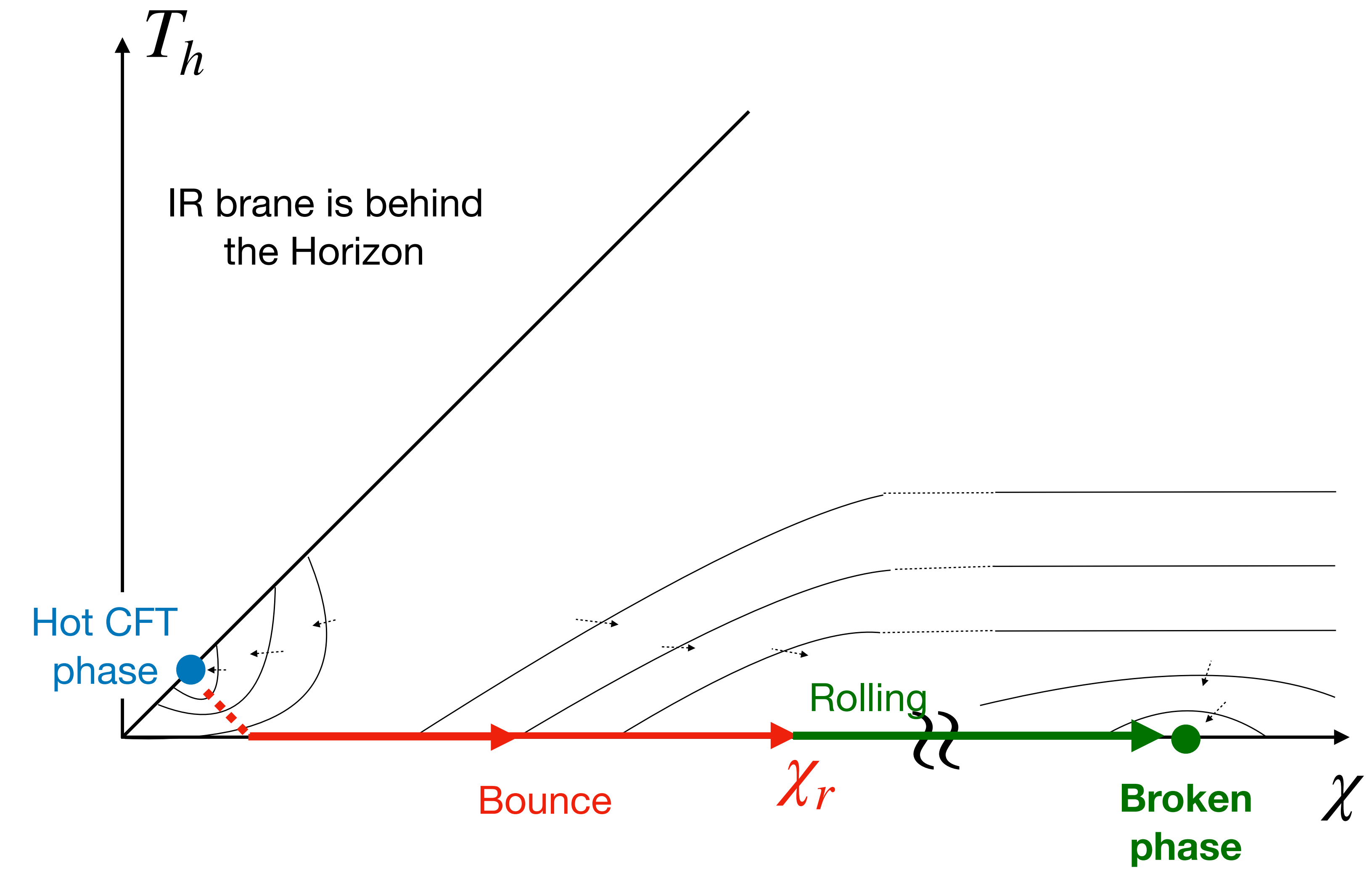


$$S_3 = 4\pi \int_0^\infty dr \cdot r^2 \left(\frac{\bar{\phi}'^2}{2} + V(\bar{\phi}) - V_{\rm CFT} \right)$$

The potential for tunneling

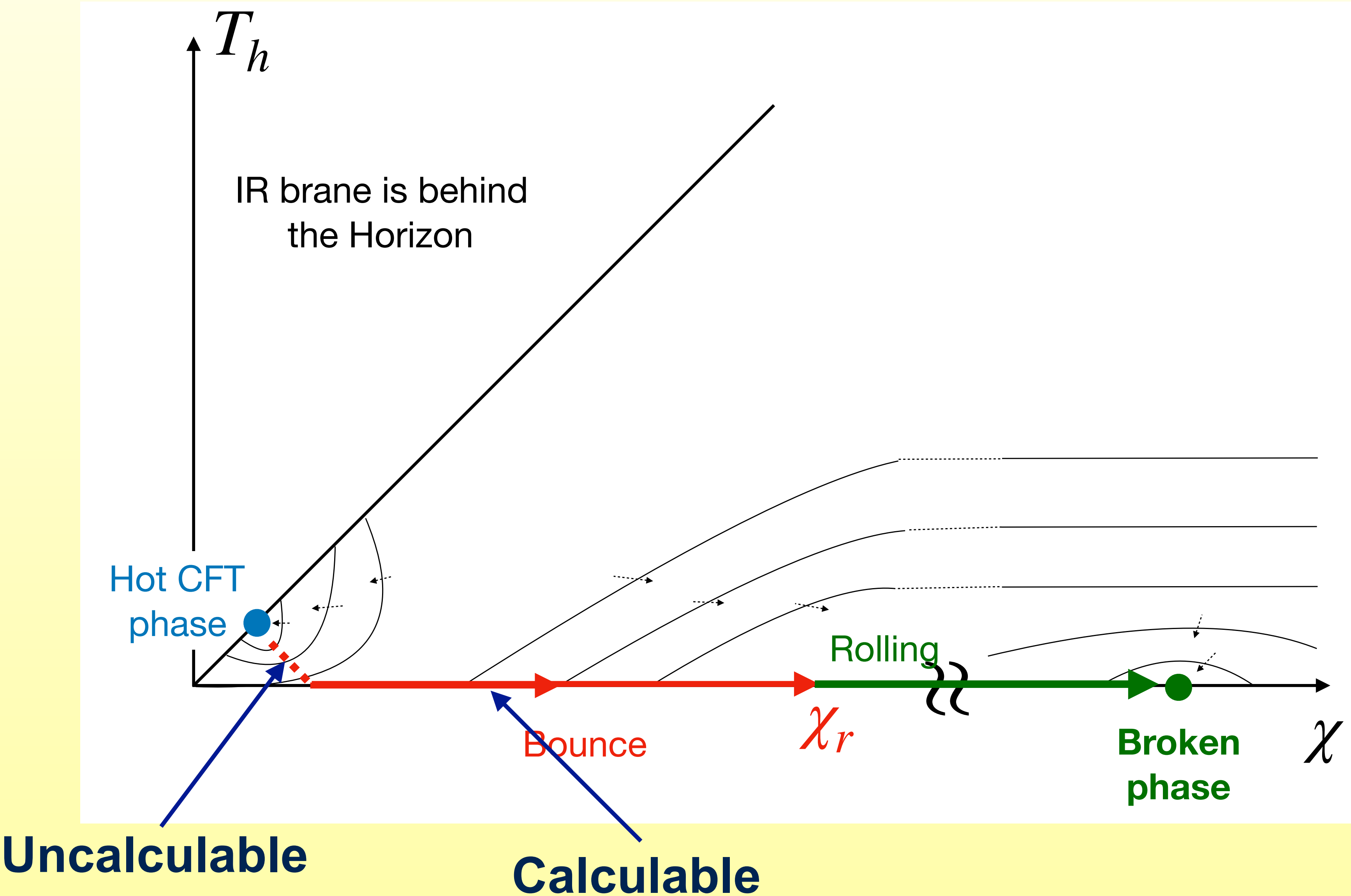
- What is the field to use in bounce?
- For $\chi \gtrsim T$: clear - just the dilaton
- For $\chi \lesssim T$ potential breaks down, more DOF's may be needed….
- For hot CFT phase no small parameter, not clear what the right DOF's are…
- Nevertheless…

The potential for tunneling



The potential for tunneling

$$S_3(T) = S_3^{\text{calc}}(T) + S_3^{\text{non-calc}}(T)$$



Estimate for the bounce action

- Simple estimate for calculable part

- The region where bounce is will be dominated by the ϵ_2 term. Characteristic length scale ~ bubble radius

$$R_{\rm bubble} \sim [V''_{\rm eff}(\chi_r)]^{-1/2} \sim \left(\frac{M^{\epsilon_2}}{\lambda_2}\right)^{1/2} \chi_r^{-1-\epsilon_2/2} .$$

- Release point should be such that we barely make it up to the false vacuum $\chi_r^2/R^2_{\rm bubble} \sim V_{CFT}$

$$\chi_r \sim N T^2 R_{\rm bubble}$$

$$\chi_r \sim N^{\frac{1}{2(1+\epsilon_2/4)}} \lambda_2^{-\frac{1}{4(1+\epsilon_2/4)}} M^{\frac{\epsilon_2/4}{1+\epsilon_2/4}} T^{\frac{1}{1+\epsilon_2/4}}$$

Estimate for the bounce action

- Expression for bubble action $S_3 \sim R_{\text{bubble}} \chi_r^2$

$$\frac{S_3(T)}{T} \sim \left[\frac{N^{2-\epsilon_2}}{\lambda_2^3} \left(\frac{M}{T} \right)^{3\epsilon_2} \right]^{\frac{1}{4(1+\epsilon_2/4)}}$$

- For small ϵ_2 very mild T dependence - will not have sudden jump in tunneling probability

- Need ϵ_2 to be large - can do with the explicit breaking from extra bulk confining group (in that language n small)

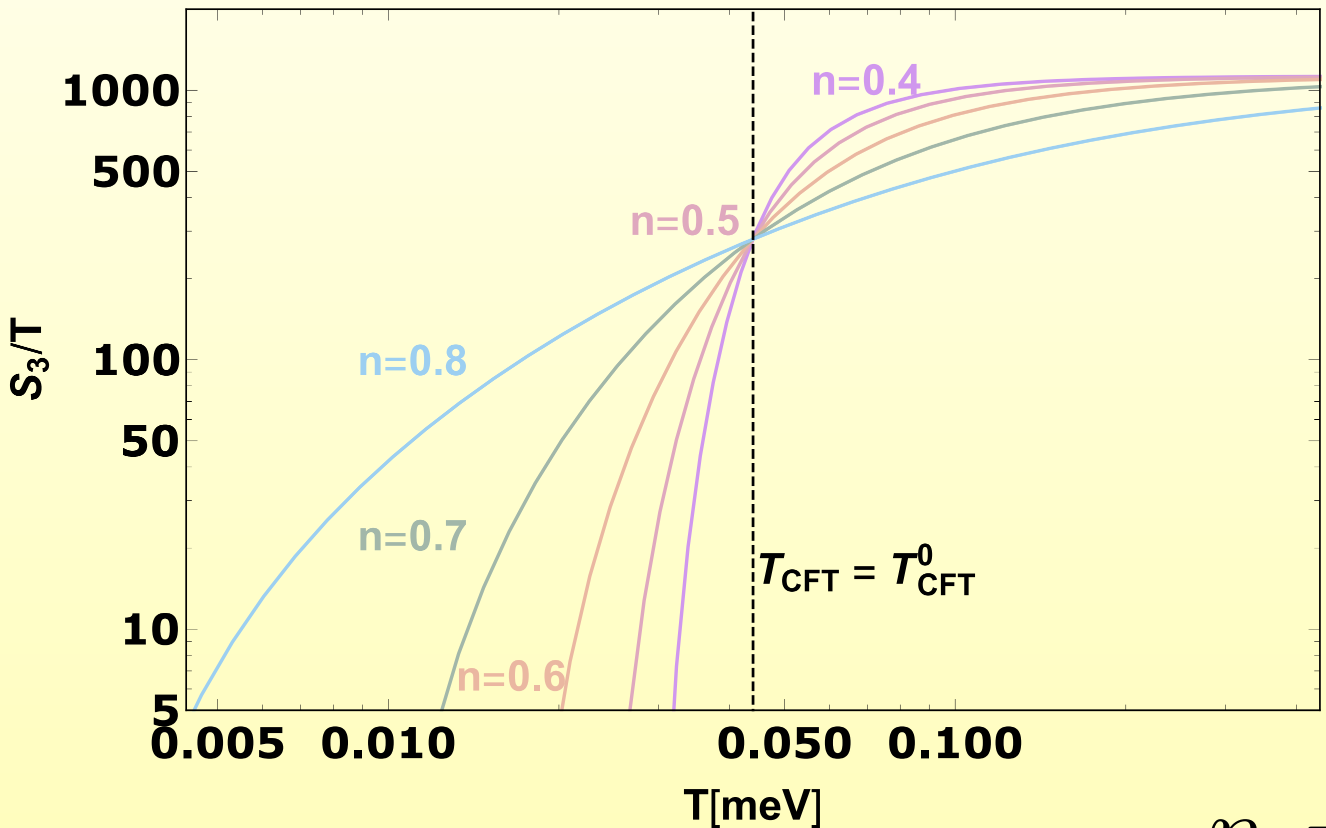
Estimate for the bounce action

- From expression of release value

$$\chi_r \sim N^{\frac{1}{2(1+\epsilon_2/4)}} \lambda_2^{-\frac{1}{4(1+\epsilon_2/4)}} M^{\frac{\epsilon_2/4}{1+\epsilon_2/4}} T^{\frac{1}{1+\epsilon_2/4}}$$

- We see for low T $\chi_r \to 0$ so at some point we will lose any calculability

Numerical evaluation of the bounce action



$$n = \frac{\epsilon_2 - 4}{4}$$

- $\lambda = 2.5 \times 10^{-3}$ fixed here
- Verifies expectation from estimate $S_3(T) \propto T^{3/n-2}$

Region of validity of potential

- Three conditions have to be satisfied for dilaton potential to be valid
- $1.\ \chi \gtrsim T$ 5D description breaks down if T larger than local Planck mass
- $2.\ \chi > \chi_*$ Ensures that the effect of the QCD' is still small
- $3.\ T < \Lambda_{\mathrm{QCD}'}(\chi)$ makes sure that QCD' is actually in a confining phase
- Each require minimal χ - turns out $\chi \gtrsim T$ most stringent

Contribution of incalculable region

- For $\chi < \chi(r_{\mathrm{max}})$ dilaton potential description breaks down - entering incalculable regime
- Will happen for low T - expect S_4 to dominate there
- No small parameters, scale dominated by χ^*
- Action can be estimated as

$$S_4^{min} \sim \frac{9N^4}{32\pi^2} \sim 7\left(\frac{N}{4}\right)^4$$

- Will limit the maximal value of CC that can be canceled

The release value

- Since we have an uncalculable region we can not use usual shooting method for estimating the release value

- Need to use different method (Euclidean energy)

- $$E_{\mathrm{E}}(r) = \frac{1}{2}\phi'(r)^2 - V(\phi(r))$$
- From EOM $\dfrac{dE_{\mathrm{E}}}{dr} = -\dfrac{2\phi'^2}{r}$

- $E_{\mathrm{E}}(r_{\mathrm{max}})$ calculable and can estimate

$$E_{\mathrm{E}}(r_{\mathrm{max}}) = -V_{\mathrm{CFT}}(T) + \alpha(T) \cdot \frac{T^3}{r_{\mathrm{max}}}$$

Cosmological dynamics - constraints

- Our patch should not have crunched yet

$$\Gamma/V|_{T=T_0} < H_0^4$$

- Gives lower bound on bounce action

$$S_3/T|_{T=T_0} \gtrsim 280$$

Cosmological dynamics - constraints

- We have a hot hidden CFT - will give aditional DOF's

$$\rho_{\rm CFT} < \rho_{N_{\rm eff}}$$

- Will translate into bound

$$T_{\rm CFT,0} < \left(\frac{N}{4.4}\right)^{-1/2} \cdot \left(\frac{\delta N_{\rm eff}}{0.56}\right)^{1/4} \cdot 0.044 \text{ meV}$$

- Exp'l bound from Planck $N_{eff} \leq 0.56$

- Lower bound on N from NDA $N \geq 4.4$

Cosmological dynamics - constraints

- No eternal inflation $\max_{T_{\rm CFT}>H} \frac{\Gamma}{VH^4}[T_{\rm CFT}] > 1$

- Every patch has a temperature where nucleation rate overcomes Hubble expansion (will crunch)

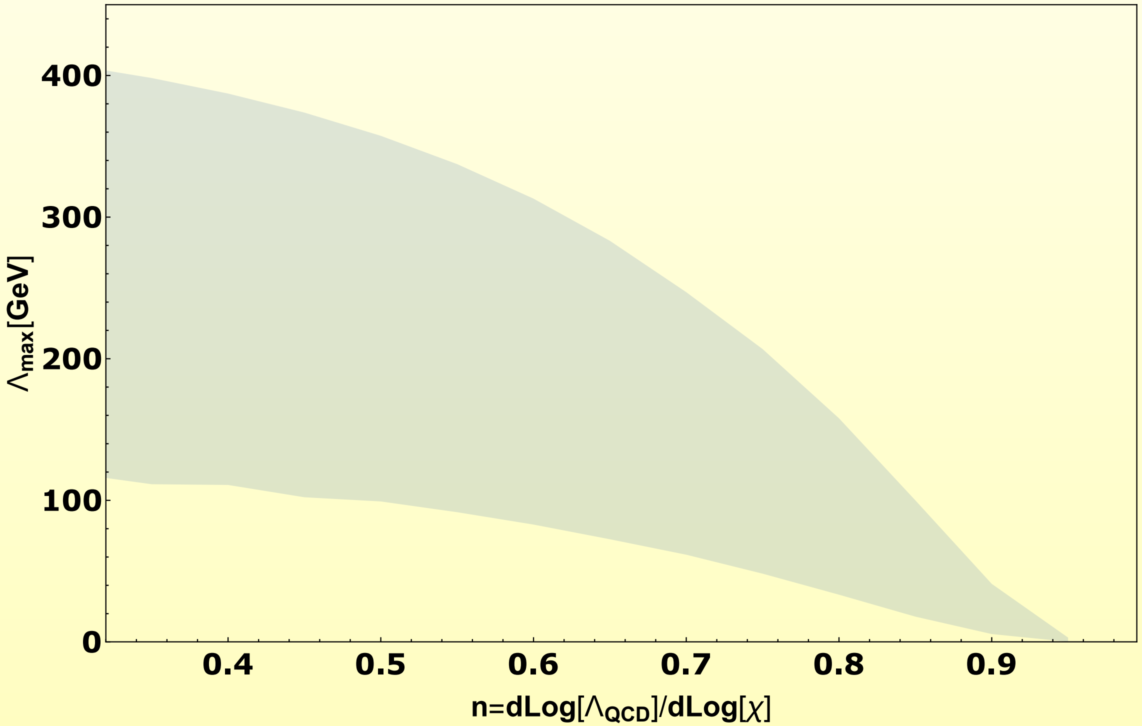
- Additional requirement is that this happens before it could eternally inflate preventing hopping to the top of the potential

- Can be translated into bound on Λ_{max}

$$\Lambda_{\rm max} = \left(\frac{3}{8\pi}\right)^{1/4} \cdot \left(M_{\rm Pl}^4 \cdot \max_{T_{\rm CFT}} \frac{\Gamma}{V}[T_{\rm CFT}]\right)^{1/8}$$

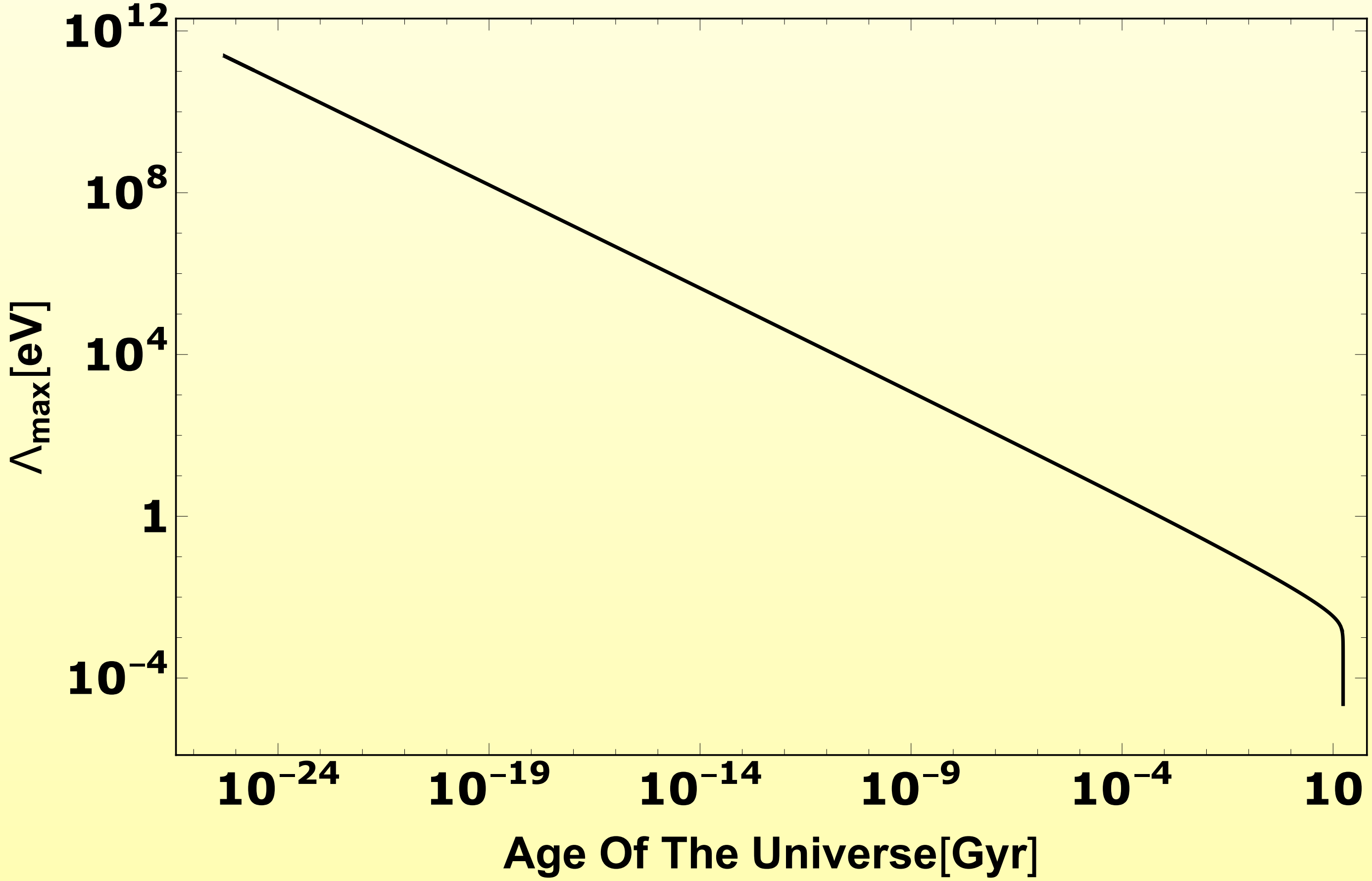
$$\Lambda_{\rm max} \sim \sqrt{T_{\rm CFT}^0 \cdot M_{\rm Pl}} \sim \mathcal{O}(100 \text{ GeV})$$

The bound on Λ_{max}



- Band of uncertainty due to uncalculable part of action
- Can get up to few 100 GeV, but not to 1 TeV

Age of the Universe vs. Λ_{max}



Experimental predictions

- Measurable N_{eff}

$$\Lambda_{max} \sim 300 \text{ GeV} \left(\frac{\delta N_{eff}}{0.6}\right)^{\frac{1}{8}}$$

- The tighter the N_{eff} bound will be the less effective our mechanism is (but only 1/8th power…)

- There should be new physics (around the weak scale!) to cancel contributions above Λ_{max}

$$\Lambda_{\rm max} \sim \sqrt{T^0_{\rm CFT} \cdot M_{\rm Pl}} \sim \mathcal{O}(100 \text{ GeV})$$

- Our Universe is about to crunch

The scanning and inflationary sectors

- Still need to show can populate vacua (``scan") without eternal inflation
- Assume collection of vacua with fixed tunneling rate
- How many e-folding do we need to populate vacua?
- Assume $N_{e-folds}$ and start with Hubble patch of size $1/H_{inf}$

$$N_{populated} \sim N_{patches} P(decay) \sim e^{3N_{e-folds}} \frac{\Gamma_{landscape}}{V} \frac{N_{e-folds}}{H_{inf}^4} < e^{3N_{e-folds}} N_{e-folds} \frac{H_0^4}{H_{inf}^4}$$

- Where we used that our patch is stable

$$\frac{\Gamma_{landscape}}{V} < H_0^4$$

The scanning and inflationary sectors

- To have a fine enough scanning need number of vacua

$$N_{populated} > \frac{\Lambda_{max}^4}{\Lambda_{cc}^4} \sim 10^{60}$$

- The needed number of e-folds:

$$e^{3N_{e-folds}} N_{e-folds} \frac{H_0^4}{H_{inf}^4} > 10^{60}$$

- Assuming GUT scale inflation all these will be satisfied for $N_{e-folds} \gtrsim 200$

Summary

- New approach to the CC problem
- Patches with highest CC will crunch first
- Regions with small CC will be long lived
- Dynamics via hidden hot CFT that undergoes PT
- Nucleation rate can be (partly) calculated
- Concrete experimental predictions
- Novel argument for appearance of weak scale
- Solves the measure problem