The Hiccupping Universe

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A. Strumia and D. Teresi, *Cosmological constant: relaxation vs multiverse*, arXiv:1904.07876 [gr-qc]

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Why putting a flat scalar field in the sky?

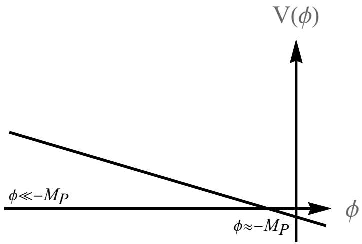
- Standard Model and ΛCDM very (too much) successful
- usual list of unexplained facts: dark matter, baryon asymmetry, isotropy. . .
- . . . plus the old **naturalness problems**:
  - why is the Universe big? (i.e. gravity is way way way way weaker than quantum mechanics would suggest)
  - why does the Universe have a non-boring history? (i.e. the **CC** is way way way way **smaller** than quantum mechanics would suggest)
- now unfashionable, but not having found the solution doesn't mean that a problem has disappeared
- classical approaches based on symmetries
- more recently: **approaches** based on **dynamics** in the Early Universe (paradigmatic example: relaxion [Graham, Kaplan, Rajendran, '15])
- also for the CC!

  [Abbott '85; Alberte, Creminelli, Khmelnitsky, Pirtskhalava, Trincherini '16; Graham, Kaplan, Rajendran, '19]
- typically involve a **scalar field** with a **bottom-less quasi-flat potential**

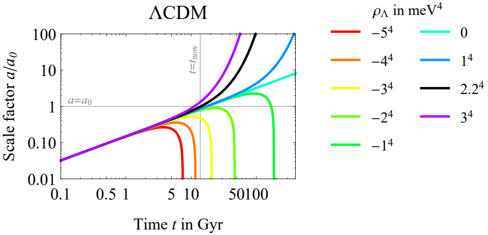
Cosmology with a bottom-less scalar

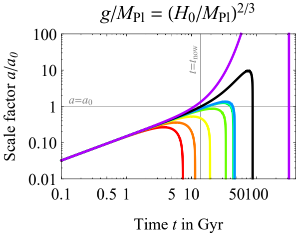
- scalar field with $\mathcal{L} = \frac{1}{2}(\partial\phi)^2 - V(\phi)$ with $V(\phi) \simeq -g^3\phi$ g tiny
- for large $-\phi \ggg M_P \longrightarrow$ inflation with $H^2 = \frac{8\pi}{3M_P^2}\left(\frac{\dot\phi^2}{2} + V(\phi)\right)$
- quantum $\delta\phi \sim H/2\pi$ and classical slow-roll $\dot\phi \simeq -V'/3H$
- classical slow roll from $\phi \gtrsim \phi_{\rm class} = -M_P^2/g$ to $-\phi \sim M_P$
- then $V(\phi)$ quickly becomes negative and compensates $\dot\phi^2$:

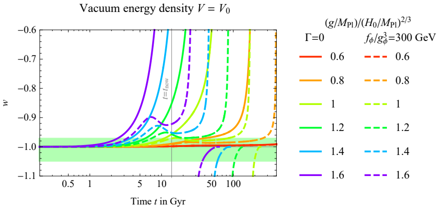
  expansion $\to$ **contraction**

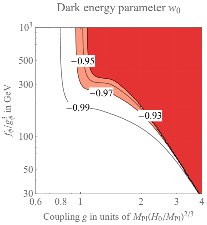


Is this compatible with what we see?









- recollapse **compatible** with **observed positive** cosmological constant!

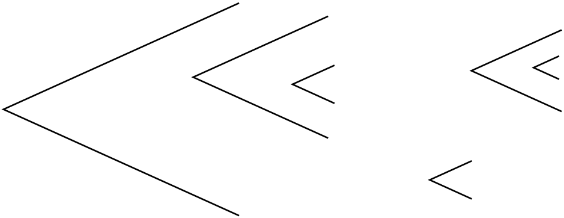
Bouncing: relaxation of the cosmological constant

- slow-roll ends at $\phi \sim -M_P$, turning point at $\phi \sim M_P$
- **special point** of dynamics, with **small CC**: $V_{\text{end}} \sim -g^3 M_P$
- cosmological constant has **relaxed** from $V_{\text{in}} \sim g^3 \phi_{in}$ to $V_{\text{end}} \lll V_{\text{in}}$
  [Graham, Kaplan, Rajendran, '19]
- at this stage Universe is collapsing; anti-de Sitter vacua “terminal”?
- resolution of singularity not known $\rightarrow$ it makes sense to assume the possibility of a **rebounce** mechanism (e.g. [Graham, Kaplan, Rajendran, '17])
- assumption: during the rebounce V is changed by **small** V_{rebounce}
- if $|V_{\text{end}}| \lesssim V_{\text{rebounce}} \approx$ CC: $O(1)$ probability to have observed Universe
- GKR want to avoid eternal inflation $\leftrightarrow$ spatial multiverse
  $\phi_{\text{in}} > \phi_{\text{class}} \Longrightarrow V_{\text{in}} \lesssim g^2 M_P^2 \approx$ MeV

. . . but the story goes on . . .

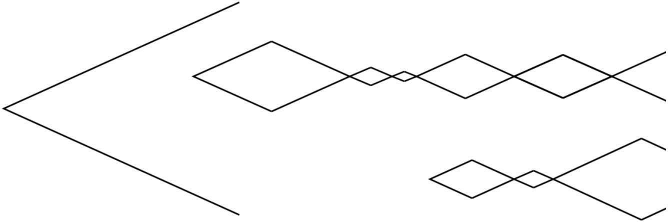
- ϕ keeps rolling down...
- we found that the recollapse happens unavoidably (unless the assumptions fail)
- **again**, at $V \simeq V_{\text{end}} = -g^3 M_P$ recollapse, re-heating, bounce, expansion, . . .
- if $V_{\text{rebounce}} > V_{\text{class}}$:
  - quantum evolution now dominates $\longrightarrow$ eternal inflation
  - tunnelling/quantum fluctuations bring locally a patch to $V < V_{\text{class}}$
  - this patch relaxes, collapses, bounces and back to $V_{\text{rebounce}} > V_{\text{class}}$
  - qualitatively similar to standard spatial multiverse (and to [Garriga, Vilenkin, '12])
- if $V_{\text{rebounce}} < V_{\text{class}}$ (the Universe “hiccups”):
  - the **whole** Universe (or the starting patch) follows classical evolution
  - it undergoes, as a whole, **cycles of finite life-time**
  - formally an infinite number of cycles, each with different $V \sim V_{\text{rebounce}} \longleftrightarrow$ CC
  - a **“hiccupping” temporal multiverse** is generated!

The hiccupping multiverse



- Universes with **finite** (not exponentially long!) life-time regardless of **sign** of CC
- no “monsters” inside the hiccupping multiverse:
  - exponentially long de Sitter (like in ΛCDM) would make **Boltzmann brains** more probable than us $\longrightarrow$ **killed** by the **finite lifetime**
  - similarly for the youngness paradox (although avoided by some meaasures already in the spatial multiverse)
- more “probable” to get observed small CC through this dynamics, rather than directly from spatial multiverse

The hiccupping multiverse



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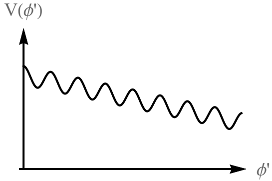
Hiccupping

- **disordered landscape** (like from string theory) could exist or not; the bounce shouldn't trigger it (e.g. $T_{\rm bounce} \ll M_P$)
- the mechanism needs an **ordered landscape**: **minima close-by** in field space have **similar energy** [Abbott '85; Graham, Kaplan, Rajendran '15; Arvanitaki, Dimopoulos, Gorbenko, Huang, Van Tilburg, '16; Cline, Espinosa '18; Geller, Hochberg, Kuflik '18; Cheung, Saraswat '18; Hook, '19]
- example: Abbott's model $V_{\phi'} = -g_{\phi'}^3 \phi' - \Lambda^4 \cos \frac{\phi'}{f_{\phi'}}$ (ϕ' could be ϕ)
- at each contraction/bounce/expansion a phase where **fluctuations dominate** and ϕ' **diffuses** (upwards and downwards)
- combined with average drift downwards $\rightarrow$ asymmetric hiccup
- symmetric hiccupp possible?

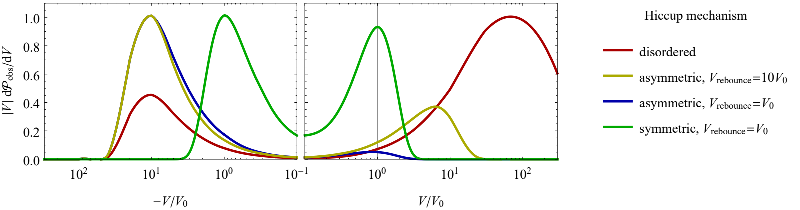


“““““““““Probabilities”””””””””

- disclaimer: “probabilities” for 1 observer (us), affected by infinities...
- **probability** for a given CC V as **measured** by an **observer**:

$$\mathcal{P}_{\rm obs}(V) = \mathcal{P}(V)\,\mathcal{P}_{\rm ant}(V) \qquad \text{(Bayes' theorem)}$$

- anthropic $\mathcal{P}_{\rm ant}$ affected by infinities (measure problem): $\mathcal{P}_{\rm ant}(V) \propto \int dt\, \mathcal{V}_{\rm reg} \frac{d^2 n}{dt d\mathcal{V}}(V)$
- anthropic factor $\mathcal{P}_{\rm ant}(V)$ favours $V \approx 100\,$CC ($\Longrightarrow$ anthropics not enough?)
  [Weinberg ’87, ’00; Garriga, Vilenkin ’99]
- a-priori distribution $\mathcal{P}(V)$ given by **hiccupping dynamics**
- **dynamics** gives $V \simeq 0$ as **special point**, $\mathcal{P}(V)$ can **peak** there



The End