On sliding, hiccupping and the multiverse

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A. Strumia and D. Teresi, *Cosmological constant: relaxation vs multiverse*, Phys.Lett. B797 (2019) 134901. arXiv:1904.07876 [gr-qc]

P. Ghorbani, A. Strumia and D. Teresi, *A landscape for the cosmological constant and the Higgs mass,* JHEP ???. arXiv:1911.01441 [hep-th].

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…not a drunk talk

Post-naturalness

- 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 cosmological constant is way way way way smaller than quantum mechanics would suggest)
- now getting unfashionable, but not having found the solution doesn't mean that a problem has disappeared
- classical approaches to naturalness based on symmetries: quantum corrections cancelled because of symmetry. However, symmetric partners of known particles have not been found (yet?)
- post-naturalness: the problem is still there, but qualitatively new paradigms, e.g.
  - unnatural values special points of cosmological dynamics (first part of the talk)
  - environmental solutions: huge number of vacua, including unnatural ones (2nd part)

Part I

The Hiccupping Universe

Why putting a flat scalar field in the sky?

- classical approaches to naturalness based on symmetries
- more recently: approaches based on **dynamics** in the Early Universe (paradigmatic example for the Higgs mass: relaxion [Graham, Kaplan, Rajendran, '15])
- ingredients:
  - some dynamics in the early Universe
  - different values of parameters (Higgs mass, CC, . . .) are scanned
  - unnatural values special points of dynamics
  - there a back-reaction is triggered, that stops dynamics
- 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

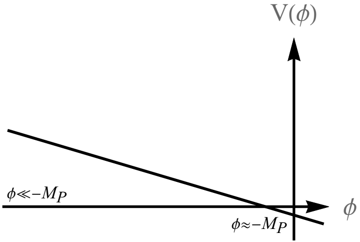
- scalar field with $\mathcal{L} = \frac{1}{2}(\partial\phi)^2 - V(\phi)$ with $V(\phi) \simeq -g^3\phi$ g tiny
- for large $-\phi \ggg M_P \longrightarrow$ inflation with

$$H^2 = \frac{8\pi}{3M_P^2}\left(\frac{\dot{\phi}^2}{2} + V(\phi)\right)$$

- classical slow roll up to $-\phi \sim M_P$
- then $V(\phi)$ quickly becomes negative and compensates $\dot{\phi}^2$:

  expansion $\rightarrow$ **contraction**

- slow-roll ends at $\phi \sim -M_P$, turning point at $\phi \sim M_P$



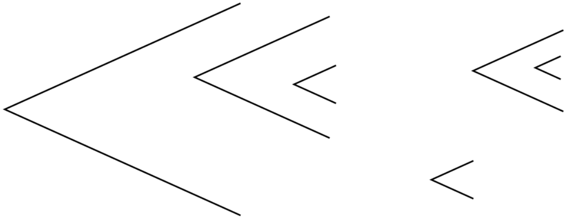
Relaxation of the cosmological constant [Graham, Kaplan, Rajendran, '19]

- cosmological constant has **relaxed** from $V_{\rm in} \sim g^3 \phi_{in}$ to $V_{\rm end} \sim -g^3 M_P$, with $|V_{\rm end}| \lll V_{\rm in}$
- Universe is now collapsing, but **small CC** has become a **special point** of dynamics
- anti-de Sitter vacua "terminal"?
- resolution of singularity not known $\to$ 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** $V_{\rm rebounce}$
- if $|V_{\rm end}| \lesssim V_{\rm rebounce} \approx$ CC: $O(1)$ probability to have observed Universe
- GKR want to avoid eternal inflation $\leftrightarrow$ spatial multiverse
  $\phi_{\rm in} > \phi_{\rm class} \implies V_{\rm in} \lesssim g^2 M_P^2 \approx$ MeV

. . . but the story goes on . . . [Strumia, Teresi, '19]

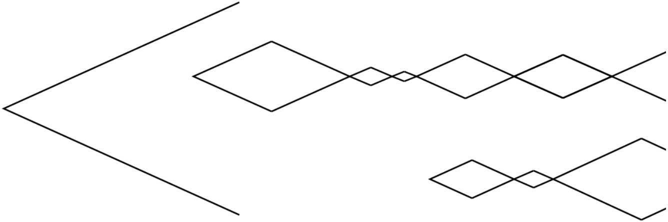
- ϕ keeps rolling down...
- we found that the recollapse happens unavoidably (unless the assumptions fail)
- **again**, at $V \simeq V_{\rm end} = -g^3 M_P$ recollapse, re-heating, bounce, expansion, . . .
- if $V_{\rm rebounce} > V_{\rm class}$:
  - quantum evolution now dominates $\longrightarrow$ eternal inflation
  - tunnelling/quantum fluctuations bring locally a patch to $V < V_{\rm class}$
  - this patch relaxes, collapses, bounces and back to $V_{\rm rebounce} > V_{\rm class}$
  - qualitatively similar to standard spatial multiverse (and to [Garriga, Vilenkin, '12])
- if $V_{\rm rebounce} < V_{\rm class}$ (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 $V \sim V_{\rm rebounce} \longleftrightarrow$ 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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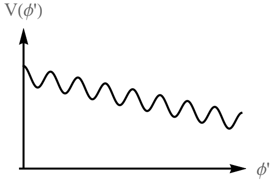
Hiccupping

- hiccupping $\longleftrightarrow$ V doesn't change much at each bounce
- **disordered landscape** (like from string theory) could exist or not; the bounce shouldn't trigger it (e.g. $T_{\text{bounce}} \ll M_P$)
- 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 $V_{\phi'} = -g^3_{\phi'}\phi' - \Lambda^4 \cos\dfrac{\phi'}{f_{\phi'}}$ (ϕ' could be ϕ)
- at each contraction/bounce/expansion a phase where fluctuations dominate and ϕ' diffuses (upwards and downwards)
- at each cycle V changes a little, the Universe "hiccups"



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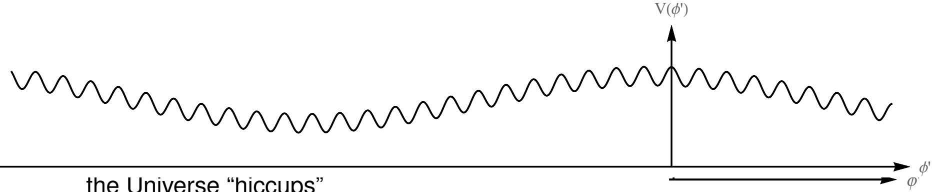

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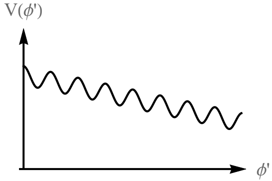
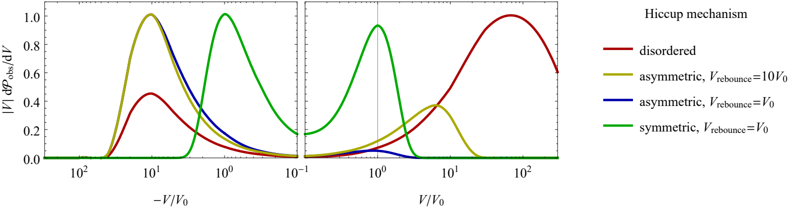


"""""""""Probabilities"""""""""

- 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 probl.): $\mathcal{P}_{\rm ant}(V) \propto \int dt\, \mathcal{V}_{\rm reg} \frac{d^2 n}{dt d\mathcal{V}}(V)$
- 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



Part II

QFT Landscape

Environmental solutions to naturalness

- the scalar potential has a huge ($\gtrsim 10^{160}$) number of minima
- they form a **landscape**, i.e. the cosmological constant V and the Higgs vev v scan on super-horizon bubbles
- typical scale of the potential $M \approx M_{\rm Pl}$ but the scan includes $V \approx \mathrm{meV} \simeq 0$ and $v \approx \mathrm{TeV} \simeq 0$ for "statistical" and structural reasons $\Longrightarrow$ successful landscape
- a selector mechanism "chooses" the unnatural Universe
  - anthropics: galaxies form only if $V \lesssim \mathcal{O}(100) V_{\rm obs}$ [Weinberg '89, ...], elements spread [D'Amico, Strumia, Urbano, '19] only if $v \sim \mathrm{TeV}$.

    "Anthropics is a serious thing" (A. Strumia)
  - hiccupping dynamics [Strumia, Teresi, '19]
  - other dynamics [... Giudice, Kehagias, Riotto, '19]
- string-theory compactifications can give $\mathcal{O}(100)$ fluxes $\Longrightarrow \gtrsim 10^{160}$ different minima. A successful landscape? Difficult to calculate...
- QFT with $\mathcal{O}(100)$ scalars can give $\gtrsim 10^{160}$ different minima. Calculate?

QFT landscape

- assume QFT is valid (e.g. SUSY at Planck scale limits sensitivity to UV)
- finding if a generic potential has many minima $\longrightarrow$ no general solution
- **calculable** possibility $\longrightarrow$ non-interacting scalars: [Arkani-Hamed, Dimopoulos, Kachru '05]

$$V = \sum_{i=1}^{N} V_i(\phi_i) \qquad \text{with} \qquad V_i = V_i^0 - \frac{\mu_i^2}{2}\phi_i^2 - \frac{A_i}{3}\phi_i^3 + \frac{\lambda_i}{4}\phi_i^4$$

- all dimensionful quantities at the high scale M
- structure technically natural
- QFT $\Longrightarrow$ each scalar has two minima $V_{\rm av}^i \pm V_{\rm diff}^i$
- summing $N \gg 1$ scalars: 2^N vacua, scanning the cosmological constant V (successfully? back on this later)
- no landscape for masses: to scan the Higgs mass H should be introduced as a special field with large interactions with many ϕ_i (rather ad hoc...)

A fragile landscape

- large generic interactions destroy the landscape: each stationary point has probability $\mathcal{P} \sim 1/2^N$ to be a minimum $\longrightarrow$ most are saddle points
- actually worse than this:
  Random Matrix Theory $\Longrightarrow$ eigenvalues repel, $\mathcal{P} \sim e^{-N^2/4}$ [Aazami, Easther, '05]
- landscape destroyed for $\lambda_{\text{cross}} \sim 1/(N\sqrt{\log N})$
- mass scanning: $\delta m^2 \sim \sqrt{N}\lambda_{\text{cross}} v^2 \sim v^2/\sqrt{N \log N}$
- light field with probability $\mathcal{P} \sim 2^N e^{-\frac{1}{2}\left(\frac{\mu^2}{\delta m^2}\right)^2} \sim 2^N e^{-N\log N} \to 0$
- is it possible to have a **landscape with large cross-interactions**?
  ($\Longrightarrow$ masses are scanned, including the Higgs one)

Bi-quadratic landscape

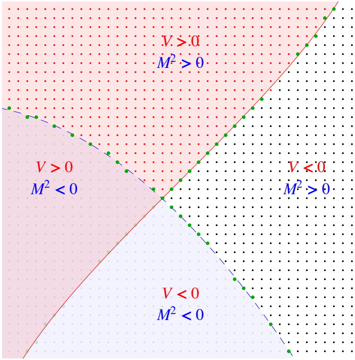
- we find that an approximately **bi-quadratic landscape** works
  [Ghorbani, Strumia, Teresi, '19]
- rather than from non-interacting scalars, start from unperturbed $\mathbb{Z}_2^N$-symmetric:

$$V = V_0 - \frac{1}{2}\sum_{i=1}^{N}\mu_i^2\phi_i^2 + \frac{1}{4}\sum_{i,j=1}^{N}\lambda_{ij}\phi_i^2\phi_j^2$$

- calculable: minima by linear equation $\lambda_{ij}v_j^2 = \mu_i^2$
- mass matrix $\dfrac{\partial^2 V}{\partial\phi_i\partial\phi_j} = 2\lambda_{ij}v_iv_j$
- λ_{ij} is positive semi-definite (stability) $\Longrightarrow$ all masses are positive
  $\Longrightarrow$ all stationary points are **minima**!
- cross-couplings can be large $\lambda_{ij} = R^T \cdot \text{diag}(\lambda_i) \cdot R$, $\quad R$ with large angles $\sim \theta$

Perturbations

- all minima have the same height and same mass matrix
- to obtain a landscape, add **perturbations**, e.g.
    - cubics $-\frac{1}{3}A\phi^3$ with $A = 2\mu\sqrt{\lambda}\,\epsilon$
    - linear $-B\,\phi$ with $B = 2\mu^3\epsilon/\sqrt{\lambda}$
    - general quartics $\propto \epsilon$
- by increasing $\epsilon \lesssim \theta$, at some point some masses become negative
  $\Longrightarrow$ light scalar at boundary
  $\Longrightarrow$ Higgs



Scanning

- scalar masses are scanned $\delta m^2 \approx \sqrt{N}\mu^2\theta\,\epsilon$
- δm^2 grows with $N \Longrightarrow$ **many light scalars** in the landscape
- for the cosmological constant same as in [Arkani-Hamed, Dimopoulos, Kachru '05]: it depends on unknown overall scale of potential
- take for instance $V \sim NV_{\rm av} \sim N\,\dfrac{\mu^4}{\lambda}$
- scanning of cosmological constant $\delta V \sim \sqrt{N} V_{\rm diff} \sim \sqrt{N}\,\dfrac{\mu^4\epsilon}{\lambda}$
- probability of small cosmological constant: $\mathcal{P} \sim 2^N e^{-\frac{1}{2}\left(\frac{V}{\delta V}\right)^2} \sim 2^N e^{-\mathcal{O}(1)N}$
- however, choice of $\mathcal{O}(1)$ factors essentially arbitrary

  $\Longrightarrow$ **success is possible**, but not guaranteed

A successful landscape

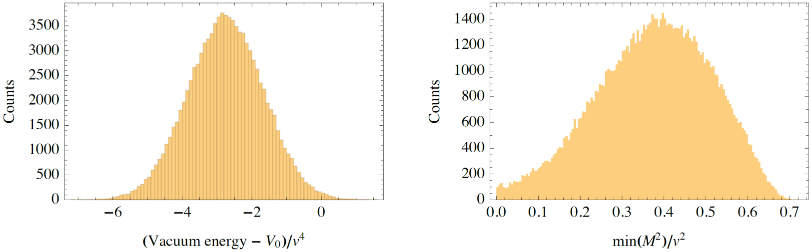
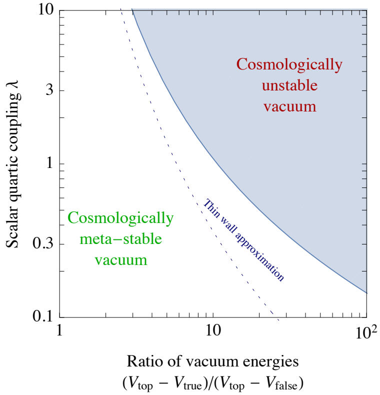


Figure 2: *We consider* $N = 100$ *scalars with the bi-quadratic potential of eq. (7) for quartics* λ_{ij} *as in eq. (10), with comparable diagonal eigenvalues* $\lambda_i \approx 1$ *extracted from a Gaussian, mixing angles* $\theta \sim 0.1$*, vacuum expectation values* $v_i = v$*. We add cubic terms* $V_{\rm odd} = \mathcal{O}(0.1) v \phi_i^3$*. We compute* 10^5 *random local minima and show their distribution of the vacuum energy (left plot) and of the lightest scalar squared mass (right panel).*

Vacuum decay

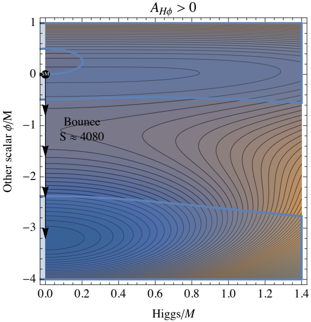
- are the "good" vacua sufficiently stable?
- [Arkani-Hamed, Dimopoulos, Kachru '05] estimate $S_{\text{bounce}} \sim 27\pi^2/\lambda \Longrightarrow \lambda \lesssim 0.5$ in tension with sufficient scanning of CC
- for $\approx$ independent fields we find:

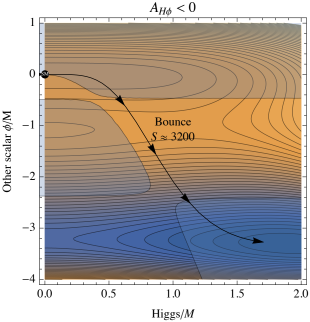


- vacuum decay by single-field bounce $\Longrightarrow \sim N$ bounces, not 2^N
- sufficient scanning of CC $\longrightarrow$ Ratio $\gtrsim 2$
- **compatible with stability**

Vacuum decay with a light scalar

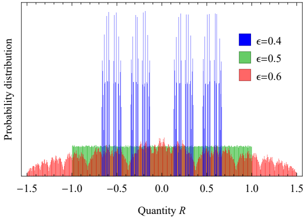
- does the presence of a light scalar ($\longrightarrow$ Higgs) make vacuum decay fast?
- by studying 2-field toy examples we find that:
  - yes for vacua that start from $\phi \approx \mu$ in $\mathbb{Z}_2$ limit (not the Higgs): perturbations that reduce m^2 also reduce the barrier
  - not for vacua that start in symmetric phase $h = 0$ if large cubics are not present (like the Higgs, because of gauge): a barrier $\lambda |H|^4$ protects the minimum

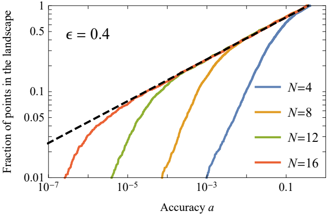




Non-Gaussian landscape?

- are distributions **necessarily** so **featureless** as Gaussians?
- consider a quantity R such that $R = \sum_{i=1}^{N} s_n\, r_n$ with $s_n = \pm 1$
- if all r_n at the same scale $f(R) \to$ Gaussian
- if hierarchies in $r_n \implies$ central-limit theorem not valid or with slow convergence
- toy example: $r_n = \epsilon^n$, with $0 < \epsilon \leq 1$





- hope for some predictivity?

Conclusions

- no new physics at LHC, Planck, . . .
- naturalness issues have gotten worse, not better

Two roads diverged in a wood, and I-
I took the one less traveled by,
And that has made all the difference.
(R. Frost)

- the beaten road: find a symmetry that cancels contributions that create un-naturalness, predict symmetry-partners of SM, not (yet?) find them
- the less beaten road: Standard Model is un-natural, but un-naturalness because of some dynamical mechanism
  - dynamics in the early Universe?
  - observer bias?
  - a combination of both?
  - . . .
- the un-beatable road (in my opinion): deny the problem

Well, now I realise that my chance is today. As a scientist, I have the privilege to live in a new era of krisis. Ideas thrive in the periods of krisis dominated by uncertainty and confusion [...] A new paradigm change seems to be necessary. (G.F. Giudice, The Dawn of the Post-Naturalness Era, 2017)

The End