The String Theory Landscape: Prospects for Predictivity

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Leuven

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Outline

Falsifiability

Is string theory falsifiable?

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Yes.

A caricatural example

LHC measures a tower of massive scalars with $m^2 = N\, m_*^2$, $m_* = 124\,\mathrm{GeV}$, and (among further supporting evidence) degeneracies $d(N)$ which perfectly fit

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But what can we *really* hope for?

Low energy predictions from string theory in four easy steps

1. Construct/enumerate all vacua meeting rough observational constraints (4 huge dim, no massless scalars, $t_{\mathrm{decay}} > 10\,\mathrm{Gyr}$, ...).

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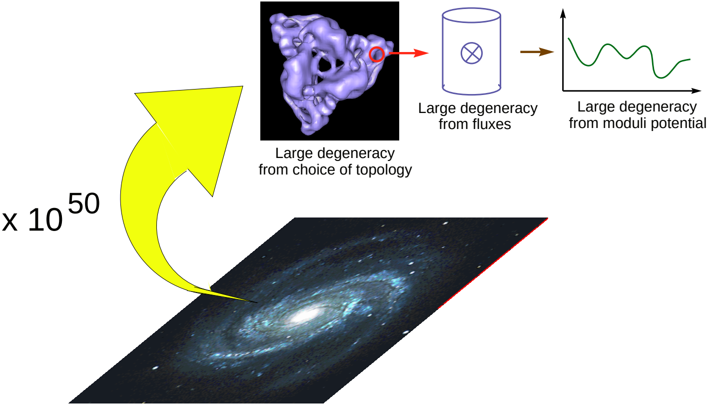

Vacua labeled by discrete microscopic data $\vec{m}$: topology, flux, critical points.

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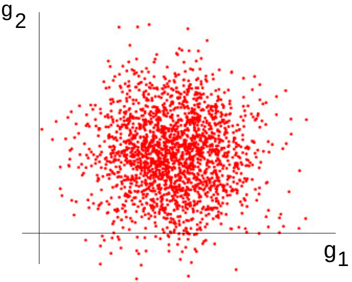

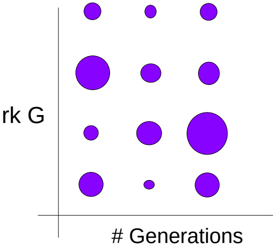

$=$ computing map $\vec{m} \mapsto \Phi(\vec{m})$.

Low energy predictions from string theory in four easy steps

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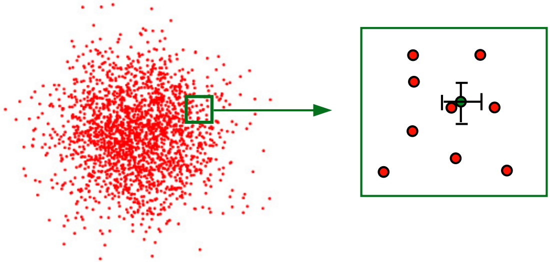

$=$ find $\vec{m}$ such that $\Phi(\vec{m}) = \Phi_{\rm exp}(\vec{m})$.

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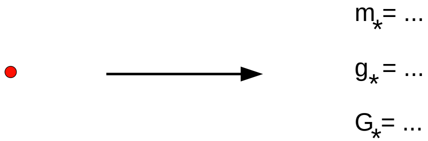

$=$ compute $\tilde{\Phi}_{\text{everything}}(\vec{m})$.

Central question

Is this a tractable problem *in principle*?

Constructability

Examples of controlled constructions which satisfy some rough observational constraints

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- IIB CY_3 O3/O7 + flux + inst., of suitable topological type [Kachru-Kallosh-Linde-Trivedi, FD-Douglas-Florea-Grassi-Kachru,Lüst-Reffert-Scheidegger-Schulgin-Stieberger].

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  1. need basis of rigid divisors $\rightsquigarrow$ resolved orbifold models.
  2. $\log(m_{3/2}) \sim V_4 \sim C_{ab} V_2^a V_2^b \Rightarrow (V_2)_{\min} \sim (\log m_{3/2})/|C|$ small if $|C| \gg 1$

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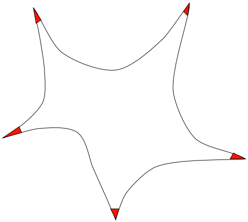

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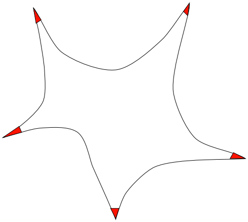

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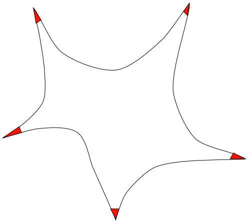

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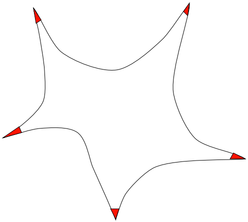

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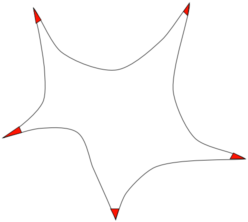

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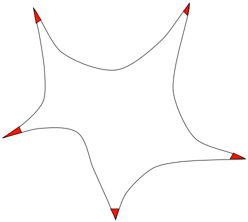

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$\rightsquigarrow$ Metastability?

$$\text{decay rate} \sim \sum e^{-c/g^2}$$

$\rightsquigarrow$ only suff. small g can lead to suff. metastable vacua?

Enumerability

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  $\Rightarrow$ E.g. potentially infinite number of CY manifolds does not matter to finiteness of quasi-realistic vacua.

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- Note: number densities in measurable parameter space matter more than total numbers.

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$\rightsquigarrow$ not very practical; need some more structure + approx.

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$\Rightarrow$ $V'_N(z)$ and $V''_N(z)$ can be expressed in terms of $W \equiv W_N(z)$, $F_A \equiv D_A W_N(z)$, $M_{AB} \equiv D_A D_B W_N(z)$, $Y_{ABC} \equiv D_A D_B D_C W_N(z)$.

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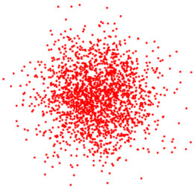

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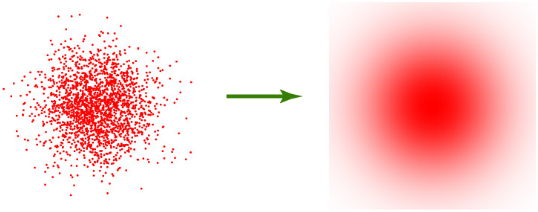

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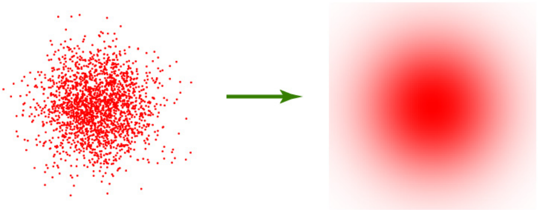

$$\Rightarrow \rho(z) = \int d\mu_0[W, F, M, Y]_z \, f(W, F, M, Y)_z$$

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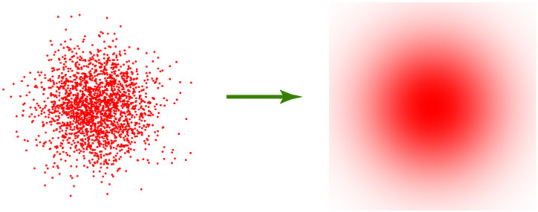
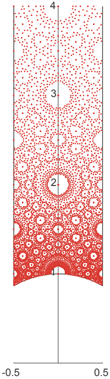


$\Rightarrow \rho(z) = \int d\mu_0[W, F, M, Y]_z \, f(W, F, M, Y)_z \rightarrow$ finite dim. int!

Toy example

Type IIB on rigid CY ($\Rightarrow$ only dilaton-axion τ).



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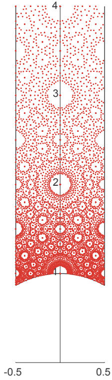

$$
\begin{aligned}
\mathcal{N}_{vac}(\mathcal{R}) &= \int_{\mathcal{R}} \frac{d^2\tau}{(\mathrm{Im}\,\tau)^2} \int_{|W|^2-|F|^2 \leq L_*} d^2W\, d^2F\, \delta^2(F)|W|^2 \\
&= \frac{\pi L_*^2}{2} \int_{\mathcal{R}} \frac{d^2\tau}{(\mathrm{Im}\,\tau)^2}
\end{aligned}
$$

General distributions of susy IIB flux vacua

- Number of flux vacua in region $\mathcal{S}$ of moduli space

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$\rightarrow$ low breaking scale "disfavored" (but much less than naive guess dF^{2n})

Statistics of gauge groups, particle spectra, ...

Statistics of intersecting brane models [Gmeiner-Blumenhagen-Honecker-Lüst-Weigand,Gmeiner,Dijkstra-Huiszoon-Schellekens,Dienes]:

- Finite number of intersecting brane models in given background.
- No significant correlations between gauge groups, matter representations, number of generations etc.
- Number of "standard models": about one in a billion.

Lessons: are quasi-realistic string vacua enumerable?

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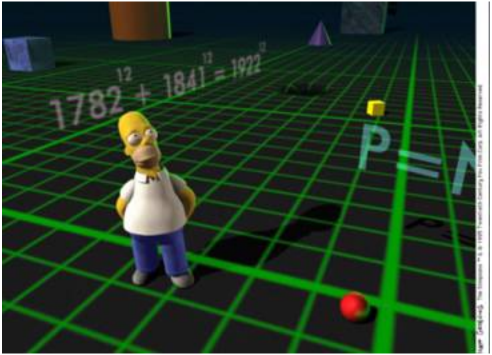
We don't know, but there is no evidence against it. Nontrivial finiteness results indicate yes, in principle.

Complexity

2026: string theory under full control!

Imagine that we have a systematic classification of all vacua, and that we can compute for each vacuum every low energy quantity to very high accuracy.



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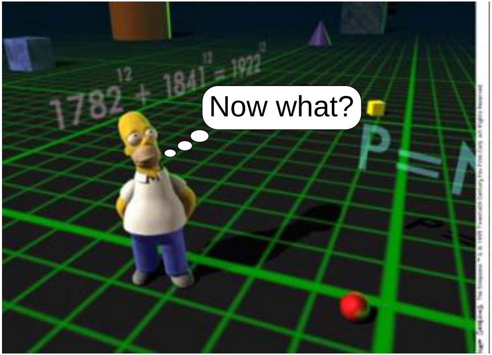
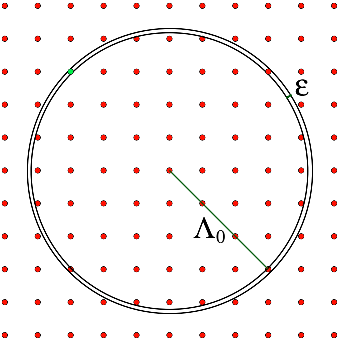


Simple model for matching observable data with discrete microscopic data



E.g. cosmological constant in Bousso-Polchinski model:

$$\Lambda(N) = -\Lambda_0 + \sum_{ij} g_{ij} N^i N^j$$

with flux $N \in \mathbb{Z}^K$.

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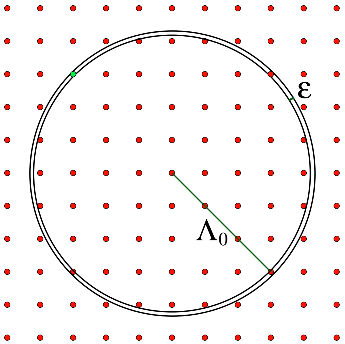

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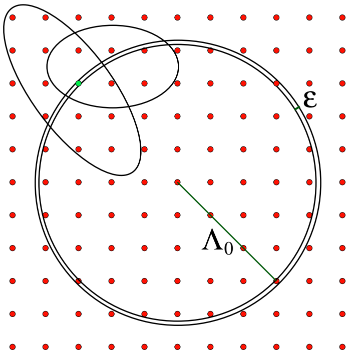

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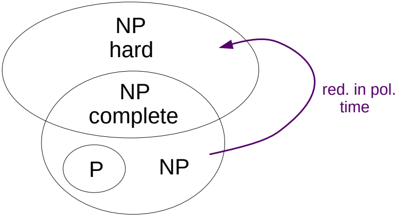
Can be extended to more complicated models, other parameters, ...

Is this a tractable problem?

- Tractable = can we solve it before the sun burns out?
- Such questions are addressed in computational complexity theory.

Basic complexity classes



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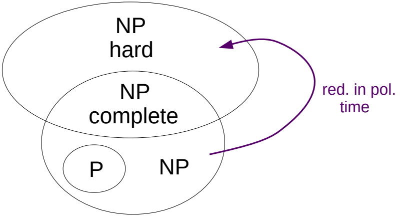

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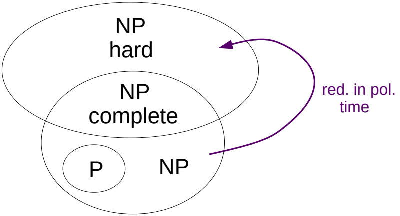

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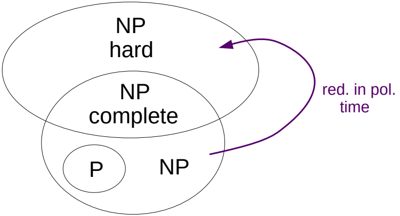

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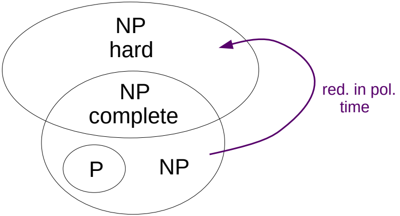

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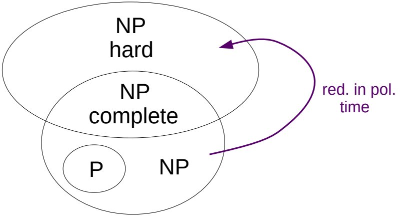

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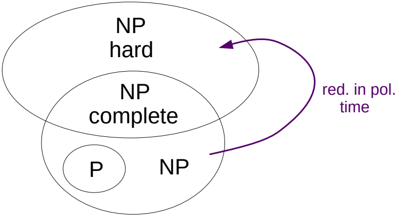

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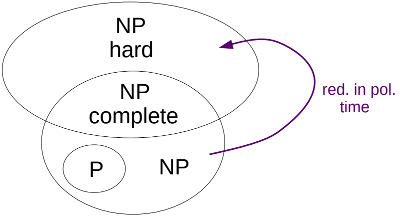

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Therefore: expect no P algorithms for NP-complete problems.

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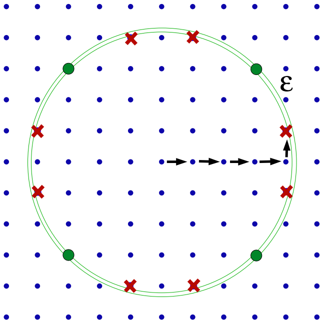
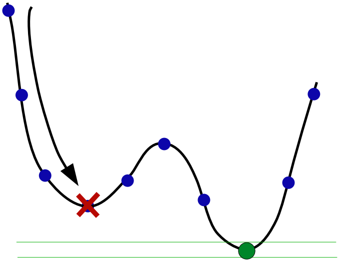
- (Hard part is to show that promise version of subset sum is still NP-complete.)

Physical intuition





Exponentially many local minima for local relaxation process of $|\Lambda - \epsilon/2|$ with steps $\Delta N_i = \pm\delta_{ki}$, say for $g_{ij} \equiv g_i \delta_{ij}$:

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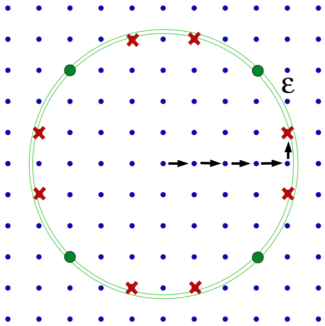

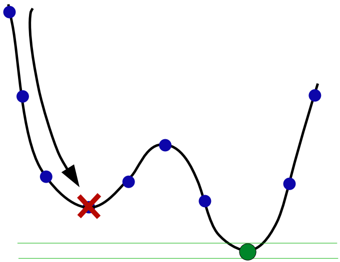

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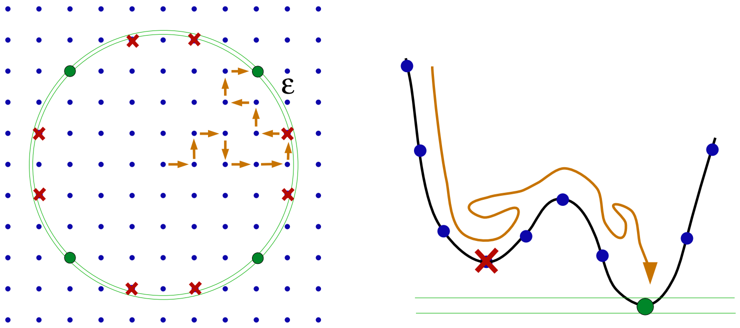
$\Rightarrow$ any $|\Lambda - \epsilon/2| < \min_k g_k/2$ is local minimum, but if $\epsilon \ll \min_k g_k$, one generically gets stuck far from target range.

Simulated annealing



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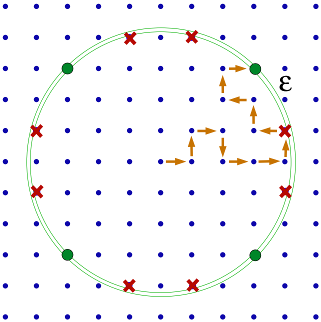

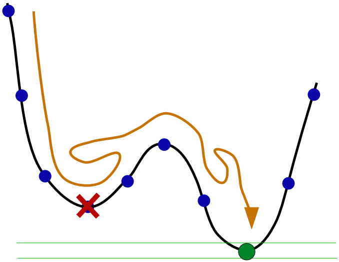

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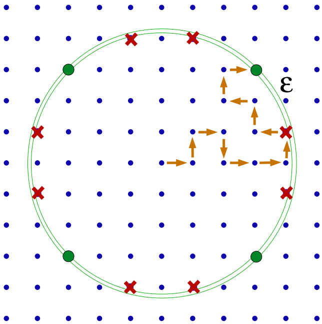

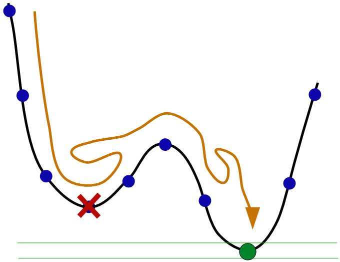

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- E.g. metropolis algorithm $\rightsquigarrow$ converges to Boltzman distribution, so will always find target range, but only guaranteed in time exponential in problem size.

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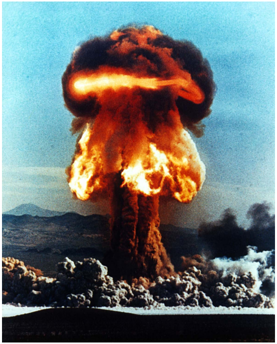
- String theory may have much more (as yet hidden) structure and underlying simplicity than current landscape models suggest.
- Number distributions together with experimental input could lead to exclusion of certain future measurable properties without need to determine our vacuum.

Flattening the landscape?



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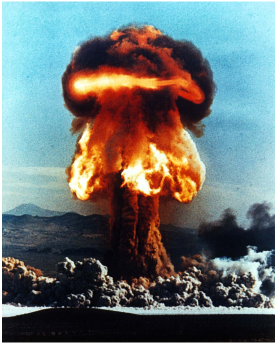

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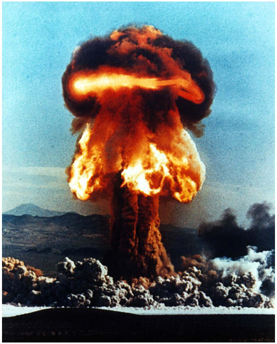

- Controlled constructions of string vacua are tricky and explicit examples sparse $\rightsquigarrow$ maybe overestimate size?
- Relatively unexplored stability issues: large number of potential decay channels [Kachru-Pearson-Verlinde, Frey-Lipper-Williams, Ceresole-Dall'Agata-Giryavets-Kallosh-Linde]

Example: thin wall bubble nucleation

Bubble nucleation rate per unit spacetime volume for a bubble with tension T, cosmological constant Λ_o outside and cosmological constant Λ_i inside [Brown-Teitelboim,Coleman-De Luccia] ($M_p \equiv 1$):

$$\Gamma \sim e^{-12\pi^2 B}$$

$$B = \frac{T\rho^3}{6} - \frac{1 - \sigma_i(1 - \frac{\Lambda_i \rho^2}{3})^{3/2}}{\Lambda_i} + \frac{1 - \sigma_o(1 - \frac{\Lambda_o \rho^2}{3})^{3/2}}{\Lambda_o}$$

$\sigma_{i,o} = \text{sign}\left[\pm 3\, T^2 + 4(\Lambda_o - \Lambda_i)\right]$, $\rho =$ bubble radius, evaluated at stationary point of $B(\rho)$:

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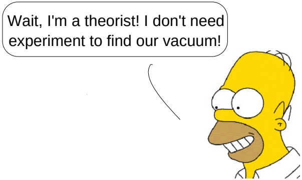
Generically $\Gamma \sim e^{-cV^2}$, but if just one out of 10^{500} or so decay channels is accidentally not suppressed, vacuum is not metastable...

Probability

Computing vacuum from cosmological selection principles?



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- Example: (unrealistic) Hartle-Hawking measure selects smallest positive Λ with overwhelming probability. $\Rightarrow$ No need to match data, just find the one with smallest Λ!
- Problem: finding minimal $\Lambda(N)$ in BP is even harder than NP-complete!

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  - not derived from first principles, so still ambiguous.
  - highly model-dependent distributions.

Conclusions

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