Title: Where in the String Landscape is Quintessence.

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Abstract: I will make the case that the Bousso-Polchinski landscape may contain quintessential corners.


N. Kaloper, UC Davis & L. Sor


Landscape is Quintessence
N. Kaloper, UC Davis & L. Sorbo, UMass Amherst

Where in the String Landscape is Quintessence

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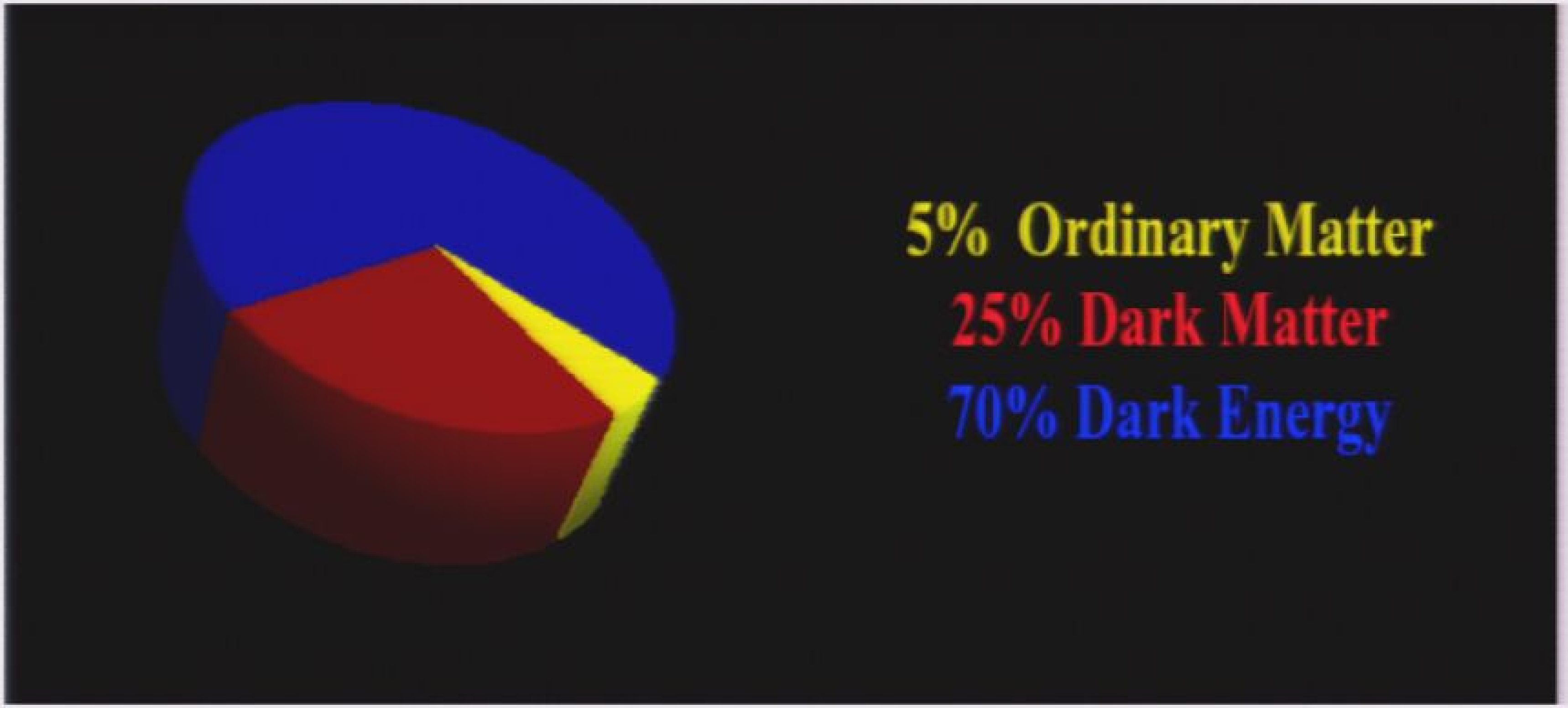
OVERVIEW

- Weird universe: Dark Energy!
- Landscape & its String Theory incarnation
- Quintessential corners in the Landscape
- Summary

Splitting the cosmic pie



Weird Universe:

- What is Dark Matter?
- What is Dark Energy?
- Why do we see them NOW?

Dark Energy Model Building...

"The time has come," the Walrus said,
"To talk of many things:
Of shoes–and ships–and sealing-wax–
Of cabbages–and kings–
And why the sea is boiling hot–
And whether pigs have wings."

(Lewis Carroll)

Thermodynamics of Λ

- Classical Λ problem is very similar to something we know in thermodynamics:

  Third Law of Thermodynamics (Nernst's thm): "the entropy of a pure substance approaches zero as the absolute temperature approaches zero"
- To prove this we need to know the microscopic properties of materials, otherwise this is only a postulate.
- ... microscopics is lacking ... (regardless of why!)
- Can we at least desensitize the `missing postulate' (whatever it may be) from quantum effects?

Anthropics: you live where is nice

Assumption of `equal opportunity': i.e. uniform distribution of vacua and access to all.

How does the Landscape work?

- Cosmological constant is really a sum of classical and quantum pieces!

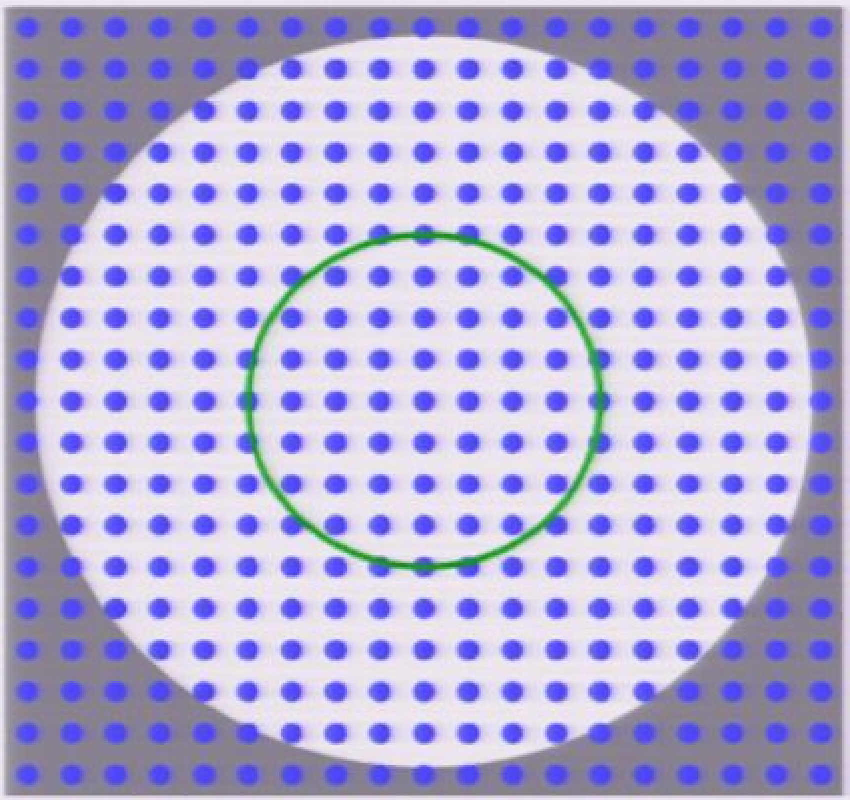
$$\Lambda_{total} = \Lambda_{classical} + \Lambda_{quantum}$$

- To set it (close) to zero, must cancel quantum against classical.
- If the classical variable is really a random variable, there may be cancellations
- `Randomization': 4-form and inflation (Linde, Brown & Teitelboim, Bousso & Polchinski): 4-form is locally like classical integration constant, which varies form place to place by membrane emission and inflation makes a lot of space with different number of emitted membranes.

Discretuum

- Take many forms. Make q's slightly misaligned. Cancel cosmological constant by random walk:

$$\Lambda_{eff} = \frac{1}{2}\sum q_i^2 - \Lambda_{bare}$$



Interesting questions

- How do we fix the measure of probability?
- Lots of DIFFERENT arguments
- Aposteriori measures - anthropics (Weinberg, Linde, Vilenkin, Bousso)
- Nonetheless: STRONG CLAIMS: observed dark energy IS CC, w=-1 - forget all other models! (e.g. Bousso, TASI07)

I have failed to describe the recent discovery in tones of wonder and stupefaction, as a "mysterious dark energy", a nonclustering fluid, with equation of state $w = p_{\rm DE}/\rho_{\rm DE}$ close to -1, which currently makes up 75% of the energy density of the universe. Why obfuscate? If a poet sees something that walks like a duck and swims like a duck and quacks like a duck, we will forgive him for entertaining more fanciful possibilities. It could be a unicorn in a duck suit—who's to say! But we know that more likely, it's a duck.

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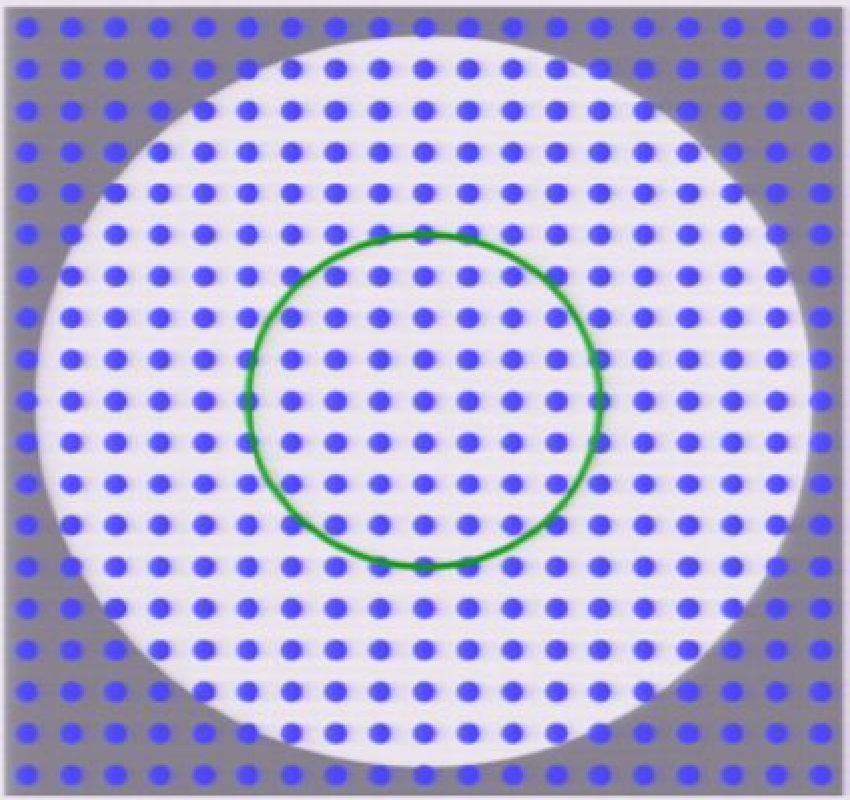

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Enter axion-4-form mixing...

- Consider a simple theory

$$\mathcal{S}_{bulk} = \int d^4x\sqrt{g}\Big(\frac{M_{Pl}^2}{2}R - \frac{1}{2}(\nabla\phi)^2 - \frac{1}{48}F^2_{\mu\nu\lambda\sigma} + \frac{\mu\phi}{24}\frac{\epsilon^{\mu\nu\lambda\sigma}}{\sqrt{g}}F_{\mu\nu\lambda\sigma} + \ldots\Big)$$

$$\mathcal{S}_{brane} \ni \frac{e}{6}\int d^3\xi\sqrt{\gamma}e^{abc}\partial_a x^\mu\partial_b x^\nu\partial_c x^\lambda A_{\mu\nu\lambda}$$

Dvali & Vilenkin

- Add `Gibbons-Hawking' terms

$$\int d^4x\sqrt{g}\ \tfrac{1}{6}\ \nabla_\mu(F^{\mu\nu\lambda\sigma}A_{\nu\lambda\sigma})$$ Duncan & Jensen

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What are eqs of motion?

- Direct variation of bulk action:

$$\nabla^2 \phi = \frac{\mu}{24} \frac{\epsilon^{\mu\nu\lambda\sigma}}{\sqrt{g}} F_{\mu\nu\lambda\sigma}$$

$$\nabla^2 F_{\mu\nu\lambda\sigma} = \mu^2 F_{\mu\nu\lambda\sigma}$$

- Substituting,

$$\nabla_\mu \Big(\nabla^2 \phi - \mu^2 \phi) = 0$$

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Mass

- Therefore: we have a mass term!

$$\frac{\mu\phi}{24}\frac{\epsilon^{\mu\nu\lambda\sigma}}{\sqrt{g}}F_{\mu\nu\lambda\sigma}$$

- What is UNUSUAL: this RETAINS the shift symmetry

$$\phi \longrightarrow \phi + \phi_0$$

- The lagrangian changes only by a total derivative:

$$\Delta\mathcal{L} = \frac{\mu\phi_0}{24}e^{\mu\nu\lambda\sigma}F_{\mu\nu\lambda\sigma}$$

- The symmetry is broken spontaneously after a solution is picked!

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Making symmetry manifest

- First order formalism: enforce F = dA with a constraint

$$\mathcal{S}_q = \int d^4x \, \frac{q}{24} \epsilon^{\mu\nu\lambda\sigma} \Big(F_{\mu\nu\lambda\sigma} - 4\partial_\mu A_{\nu\lambda\sigma} \Big)$$

- Then change variables NK, 1994

$$\tilde{F}_{\mu\nu\lambda\sigma} = F_{\mu\nu\lambda\sigma} - \sqrt{g}\epsilon_{\mu\nu\lambda\sigma}(q + \mu\phi)$$

- This completes the square; integrate F out. What remains:

$$\mathcal{S}_{eff} = \int d^4x \sqrt{g} \Big(\frac{M_{Pl}^2}{2} R - \frac{1}{2}(\nabla\phi)^2 - \frac{1}{2}(q + \mu\phi)^2 + \frac{1}{6} \frac{\epsilon^{\mu\nu\lambda\sigma}}{\sqrt{g}} A_{\nu\lambda\sigma} \partial_\mu q \Big)$$

- The membrane term enforces jump on q (ie *F):

$$\Delta q|_{\vec{n}} = e$$

Mass & symmetries manifest!

- Mass term

$$V = \frac{1}{2}\left(q + \mu\phi\right)^2$$

- Shift symmetry

$$\phi \rightarrow \phi + \phi_0 \qquad q \rightarrow q - \phi_0/\mu$$

- Mass is radiatively stable; symmetry is broken spontaneously once background q is picked, as a boundary condition.
- Value of q can still change, by membrane emission

$$\Delta q|_{\vec{n}} = e$$

Quantization

- Classically q is continuous
- Quantum consistency requires that it be QUANTIZED! (Bousso, Polchinski)
- Example: 11D SUGRA

$$e_3 \int F_{\mu_1 \ldots \mu_4} = 2\pi n \qquad e_6 \int {}^*F_{\mu_1 \ldots \mu_7} = 2\pi n$$

- After compactification:

$$q_i = n_i \frac{2\pi M_{11}^3}{\sqrt{Z_i}} \qquad Z_e = \frac{M_{Pl}^2}{2} \qquad Z_m = \frac{M_{Pl}^2}{2 M_{11}^3 V_3^2}$$

- Numerically q is NEVER smaller than $(10^{-16} eV)^2$

Discretuum, deja vu

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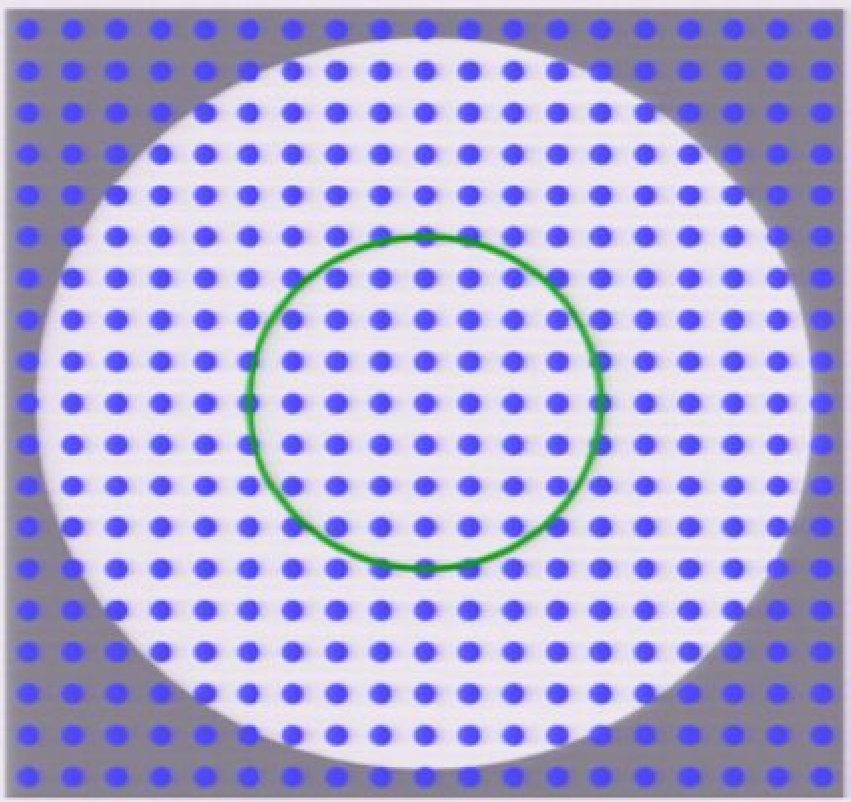

Mass as charge

- 11D SUGRA (assume volume moduli stabilized as BP)

$$S_{11D\ forms} = M_{11}^9 \int *F \wedge F + M_{11}^9 \int A \wedge F \wedge F$$

- Truncate on $M_4 \times T^3 \times T^4$

$$A_{\mu\nu\lambda}(x^\mu) \qquad \phi = A_{abc}(x^\mu) \qquad A_{ijk}(y^i)$$

- This yields QUANTIZED MASS!

$$S_{4D forms} = -\int d^4x\sqrt{g}\Big(\frac{1}{2}(\partial\phi)^2 + \frac{1}{48}\sum_a (F^a_{\mu\nu\lambda\sigma})^2 + \frac{\mu\phi}{24}\frac{e^{\mu\nu\lambda\sigma}}{\sqrt{g}}F_{\mu\nu\lambda\sigma}\Big)$$

$$\mu = n\mu_0 \qquad \mu_0 = 2\pi V_3 M_{11}^3 \Big(\frac{M_{11}}{M_{Pl}}\Big)^2 M_{11}$$

Numerology

- As before, μ cannot be smaller than 10^{-16} eV
- For quintessence, the mass must be below 10^{-33} eV
- Is this incompatible?
- Well: this is qualitatively the SAME problem as BP: the individual steps are too large; but if there is many different directions, the sequence of steps can yield small misalignments in the off-axis directions
- We can seek the same thing for Q: with many forms and many fields (all already present in the landscape and invoked by BP) we can get MIXING matrices and seek ultrasmall eigenvalues!

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Multifield setups

- Couplings

$$S_{couplings} = \int d^4x \sum_{a,b} \mu_{ab}\, \epsilon^{\mu\nu\lambda\sigma}\, F^a_{\mu\nu\lambda\sigma}\phi^b$$

- Effective action

$$S_{eff} = \int d^4x \sqrt{g}\Big(\frac{M_{Pl}^2}{2}R - \frac{1}{2}\sum_b(\nabla\phi^b)^2 - \frac{1}{2}\sum_a(q^a + \sum_b \mu_{ab}\phi^b)^2 + \frac{1}{6}\frac{\epsilon^{\mu\nu\lambda\sigma}}{\sqrt{g}}\sum_a A^a_{\nu\lambda\sigma}\,\partial_\mu q$$

- Mass matrix

$$M_{bc} = \sum_a \mu_{ab}\mu_{ac}$$

- If mass matrix depends on many independent random fluxes it will have tiny eigenvalues

Explicit example

- Type IIB string theory (assume all volume moduli fixed)

$$S_{IIB} = \frac{1}{2\kappa_{10}^2}\int d^{10}x\sqrt{g}\Big(R - \frac{1}{12}g_s^{-1}H_3^2 - \frac{1}{12}g_s F_3^2 - \frac{1}{240}\tilde{F}_5^2\Big) + \frac{1}{4\kappa_{10}^2}\int F_5 \wedge B_2 \wedge$$

- Truncate to 4D:

$$F^1_{\mu\nu\lambda\sigma} = \frac{M_{Pl}}{\sqrt{2}}\tilde{F}_{\mu\nu\lambda\sigma 5}\,, \qquad F^2_{\mu\nu\lambda\sigma} = \frac{M_{Pl}}{\sqrt{2}}\tilde{F}_{\mu\nu\lambda\sigma 6}\,, \qquad F^3_{\mu\nu\lambda\sigma} = \frac{M_{Pl}}{\sqrt{2}}\tilde{F}_{\mu\nu\lambda\sigma}$$

$$\phi_1 = \frac{M_{Pl}}{\sqrt{6g_s}}B_{47}\,, \qquad \phi_2 = \frac{M_{Pl}}{\sqrt{6g_s}}B_{48}\,, \qquad \phi_3 = \frac{M_{Pl}}{\sqrt{6g_s}}B_{49}\,,$$

$$F_{ijk} = (2\pi)^2\alpha'\frac{n_{ijk}}{L_i L_j L_k}$$

$$\{(5,6,8),(5,6,9),(5,7,8),(5,7,9),(5,8,9),(6,7,8),(6,7,9),(6,8,9)\}$$

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Mixing and mass matrices

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- Mixing matrix

$$\left(\mu_{ab}\right) = \begin{pmatrix} \varepsilon^2 & n\varepsilon & (n+1)\varepsilon \\ \varepsilon^2 & (n-1)\varepsilon & n\varepsilon \\ 0 & n\varepsilon & (n-1)\varepsilon \end{pmatrix}\mu_0$$

$$\varepsilon = \sqrt{2\pi\alpha'}/L \qquad \mu_0 = \sqrt{\frac{3\pi g_s}{2\alpha'}}$$

- Mass matrix secular eq for n »1 » ε

$$P_3(\lambda) = \lambda^3 - 6n^2\varepsilon^2\lambda^2 + 8n^2\varepsilon^4\lambda - \varepsilon^8$$

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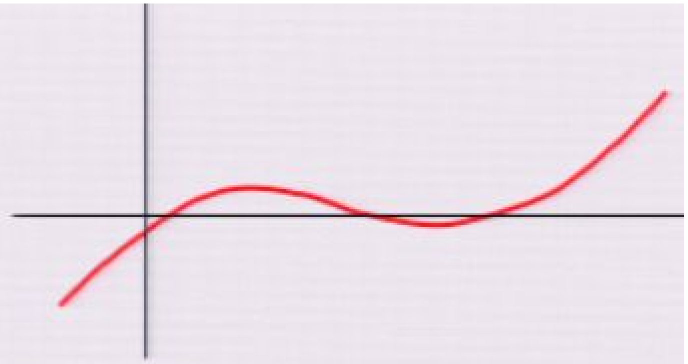
Eigenvalues



- Solve graphically:

$$P_3(\lambda) = \lambda^3 - 6n^2\varepsilon^2\lambda^2 + 8n^2\varepsilon^4\lambda - \varepsilon^8$$

$$m^2_{min} \simeq \frac{\varepsilon^4}{8n^2}\mu_0^2 \simeq \frac{3\pi^3 g_s \alpha'}{4L^4}\frac{1}{n^2}$$

- Consistency checks:

$$g_s F_3^2 \lesssim \frac{1}{2\pi\alpha'} \to n^2 \lesssim \frac{L^2}{48\pi^3\alpha' g_s} \qquad L^2 = 16\pi^5 M_{Pl}^2 \alpha'^2$$

- This implies

$$m^2_{min} \simeq \frac{3g_s}{2^{10}\pi^7 M_{Pl}^4 \alpha'^3}\frac{1}{n^2} \gtrsim \frac{9g_s^2}{2^{10}\pi^9 M_{Pl}^6 \alpha'^4}$$

$$g_{s\,*} = \frac{32}{3}\pi^{9/2} M_{Pl}^3 \alpha'^2 H_0 \simeq 10^{-2}\left(\frac{\text{eV}}{M_s}\right)^2\left(\frac{M_{Pl}}{M_s}\right)^2$$

Numerics

- Gauss law formula: $L < 0.1$ mm, $M_s >$ few X 10 TeV
- Coupling $g_s \sim 0.001$
- 10D Planck mass $M_{10} \sim M_s/g_s >$ few X 10^4 TeV

$$m_{min} \lesssim 10^{-33} eV$$

- This is a proof of existence: if one accepts landscape, one WILL find in there corners where quintessence exists
- Why would our world reside there? Well, we don't really know apriori probabilities, so will not try to answer that question, leaving it to experiments… but…

Protecting Q from strongly coupled GT

- So far we have argued that the mass is radiatively stable - perturbatively. What if Q couples to some gauge theory?
- Instanton effects generate an extra potential:

$$V_{eff} \sim \sum {\lambda_n}^4 \cos(\frac{2n\phi}{f_\phi})$$

- Usually one tries to use this potential to drive cosmic acceleration and get axion to be Q
- That requires $f_\phi > M_{Pl}$ which appears hard to get in string theory (Dine; Banks et al; Arkani-Hamed et al)
- If $f_\phi < M_{Pl}$ when axion is transplanckian the higher harmonics steepen the potential and obstruct acceleration

Avoiding instanton V

- We get small mass directly from the random fluxes somewhere in the landscape. The instanton potential is not necessary.
- So let $f_\phi < M_{Pl}$ but make sure that the instanton potential curvature is systematically smaller than the curvature of the 4-form term

$$\lambda^4 < m_{min}^2 f_\phi^2$$

- Pick an axion which does not couple to a theory that goes strong at too high a scale, so λ remains small for a given f; then the instantons merely yield small bumps...
- Similar suppression for gravitational instantons.

After acceleration...

- So: suppose we are in a corner where axion is quintessence

$$V_{lightest} = \frac{1}{2}m_{min}^2(\phi + q_{eff}/m_{min})^2 \qquad \phi + q_{eff}/m_{min} \gtrsim M_P$$

- Eventually axion rolls to the minimum, where V=0. But:

$$q_{eff}^2 \gg M_{Pl}^2 H_0^2$$

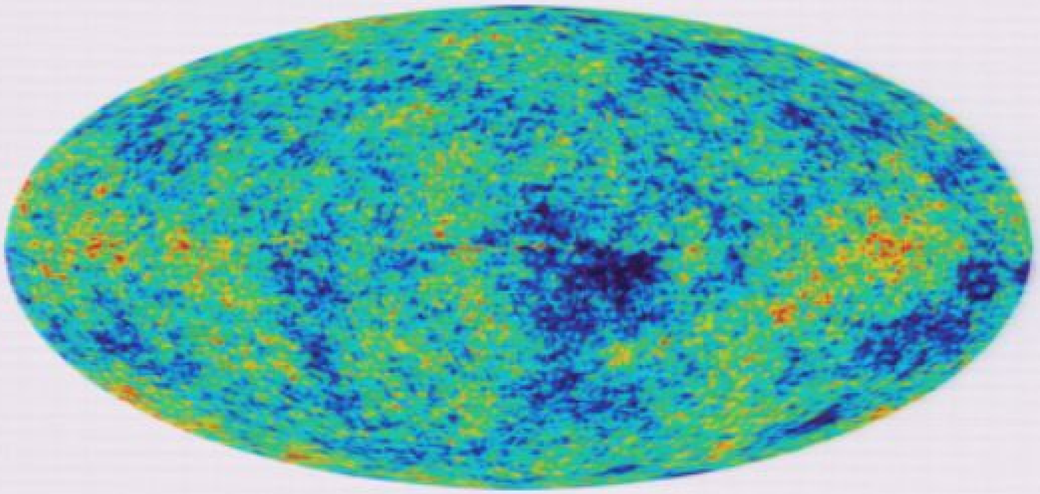
- So when the axion rolls into the minimum it will overcompensate the cosmological constant, leaving a negative leftover! Such a universe will quickly recollapse; there are interesting tests for observers (Garriga, Linde & Vilenkin)

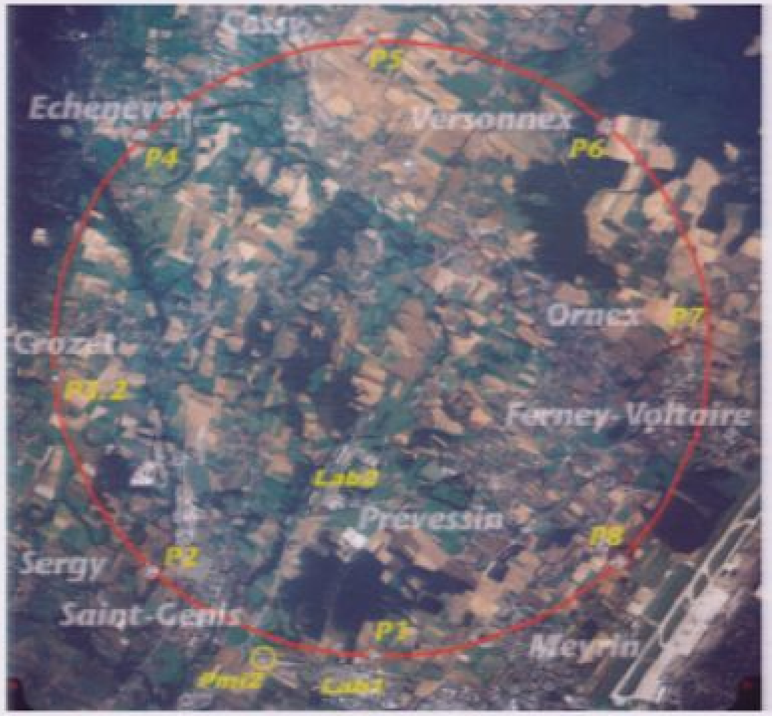
Summary

- Landscape: key argument for cancelling the cosmological constant is the presence of a classical random variable induced by 4-form
- This requires many different 4-forms in 4D to obtain a small number for residual cosmological term
- They may come from dimensional reductions of 11D SUGRA; but then there may be many boroughs with massive scalars, and somewhere scalars will be light
- **The mass cancellation is 4-form misalignment around large background flux - see/saw formula.**
- How likely is this?...

Bottomline

- Maybe the best strategy is to keep an open mind and LOOK!





- We are NOW in a UNIQUE SITUATION: LHC turns on THIS YEAR! And the picture of the universe, as can be captured by CMB, LSS etc may be the best it will ever be! (Planck, CMB-pol, LSST, JDEM, ...)

"The game is afoot, my dear Watson...