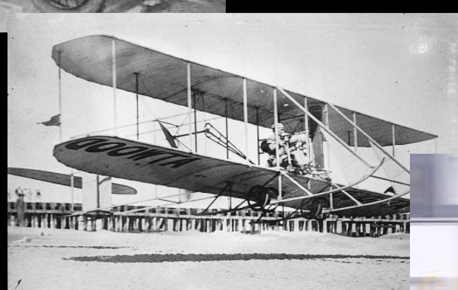
Acceleration, Then & Now

Inflation & Dark Energy after Planck






Cliff Burgess

Context: naturalness principles

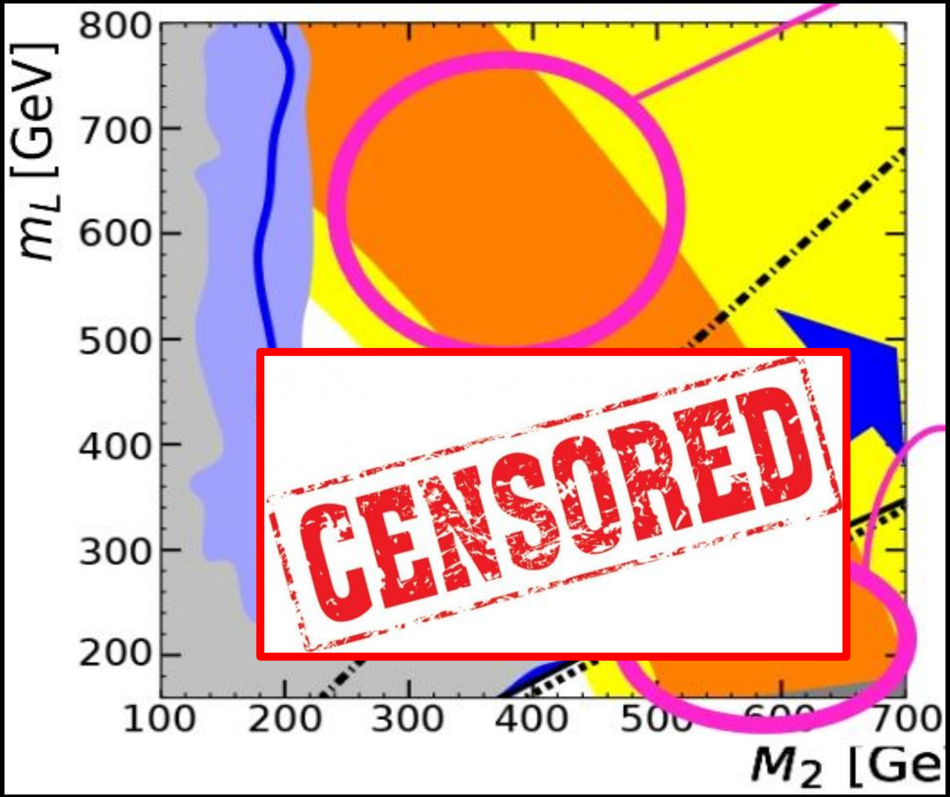
- Light scalars are unnatural
  - The LHC will see lots of new SUSY particles
  - Inflation will be complex

Patron Saint of All Things Natural

Context: naturalness

- SUSY exclusion plot

Sho Iwamoto
@ SUSY 2013



Context: naturalness

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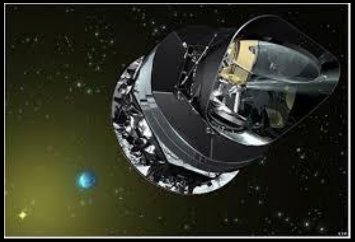
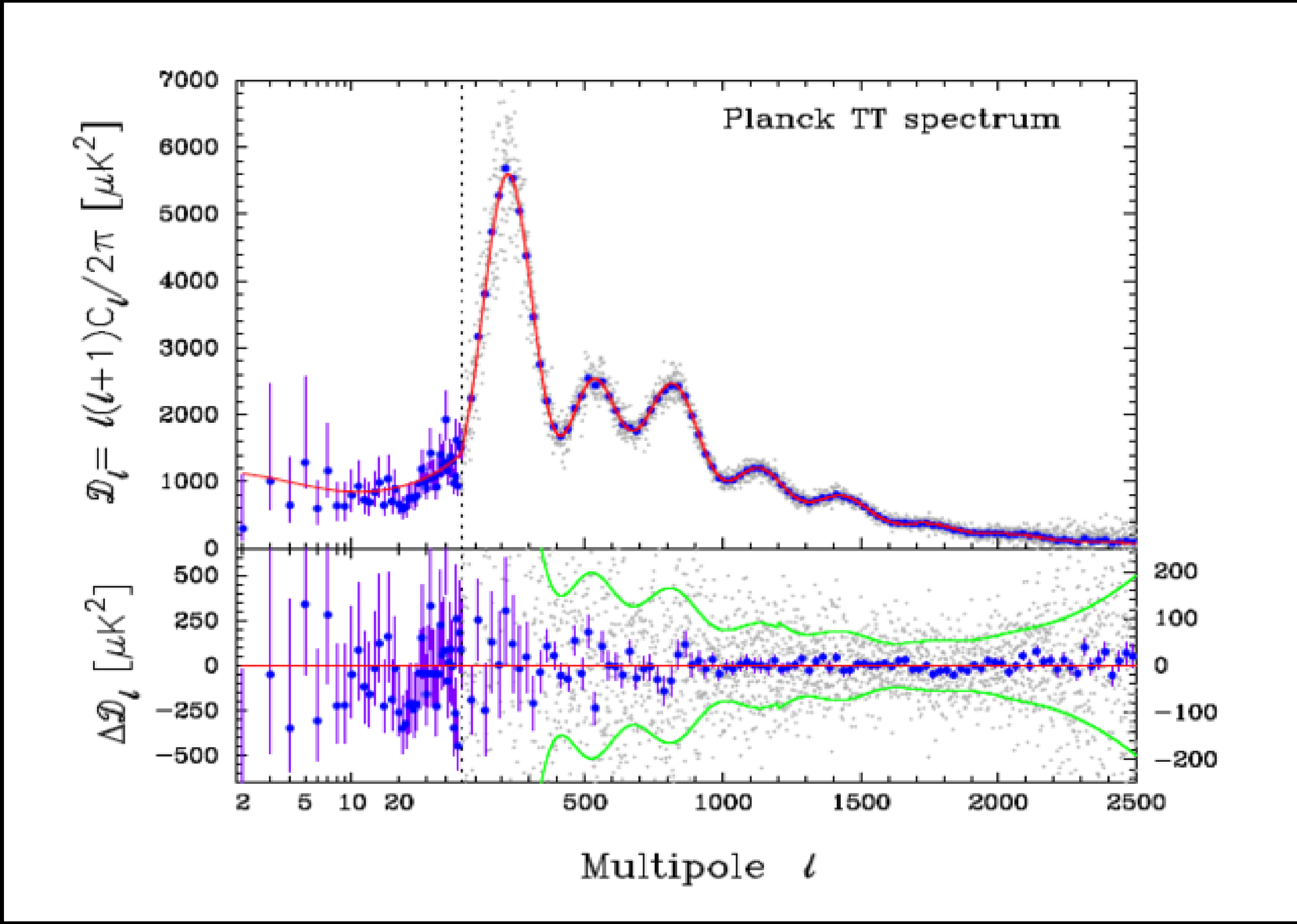
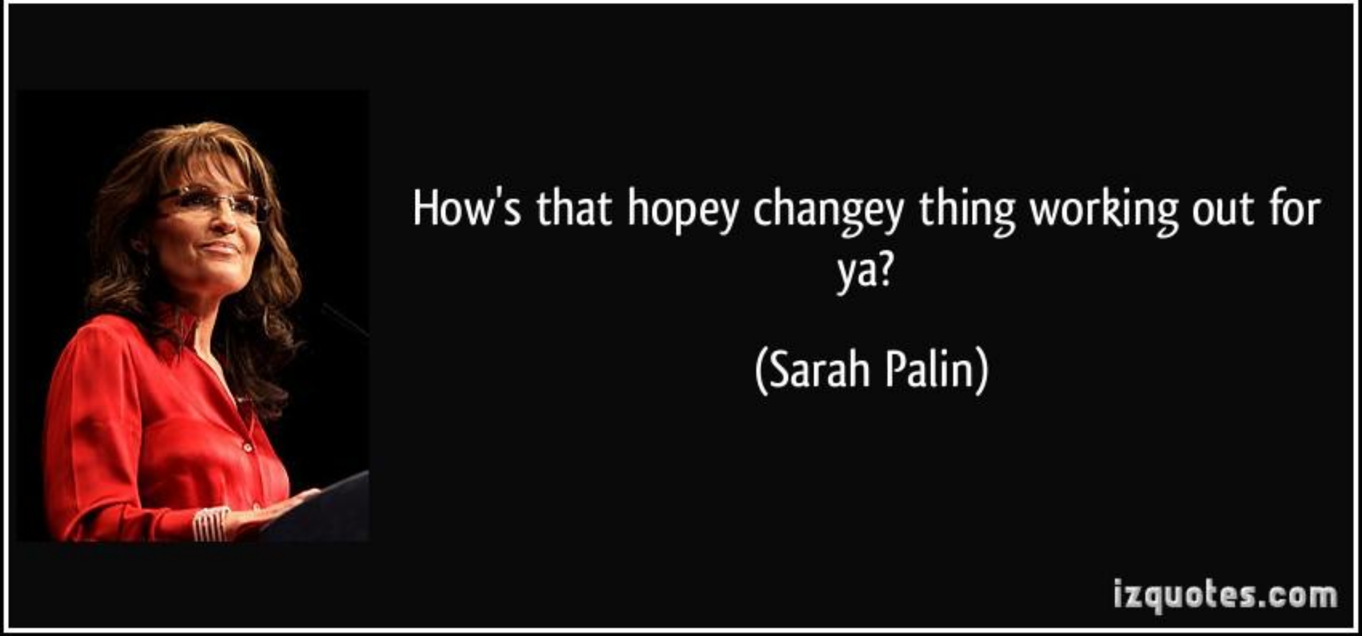




The Cosmological Constant?

Context: naturalness?

- Is Naturalness Dead?



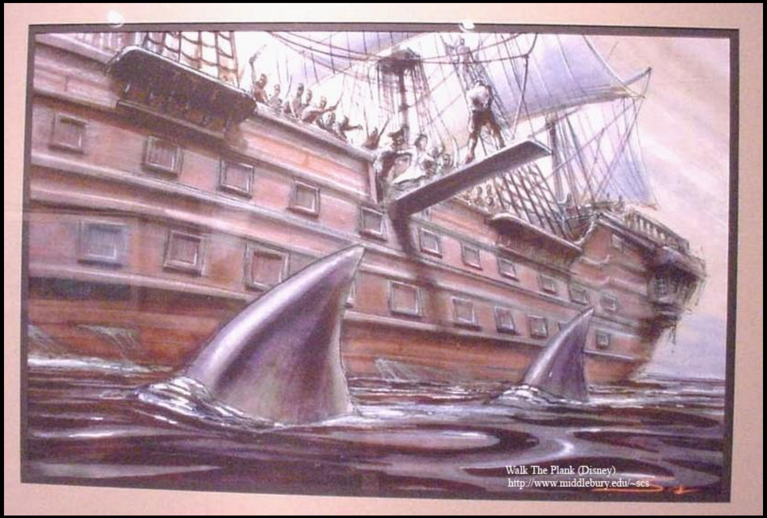
Context: naturalness!

- Is Naturalness Dead?

- Long Live Naturalness!

Outline

- Acceleration Then (inflation) *(1306.3512)*
  - Occam vs Wilson



Outline

- Acceleration Then (inflation) *(1306.3512)*
  - Occam vs Wilson
  - String inflation: a scorecard

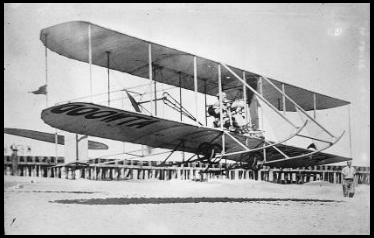
Outline

- Acceleration Then (inflation) *(1306.3512)*
  - Occam vs Wilson
  - String inflation: a scorecard
- Acceleration Now (dark energy) *(1309.4133)*
  - Novel form of SUSY breaking

Then

with M. Cicoli & F. Quevedo

arXiv:1306.3512



Acceleration Then

- Occam vs Wilson
- A scorecard

Acceleration Then

- Occam vs V
- A scorecar

Divided by a common language

Acceleration Then

- Oc
- A

- Occam:
- Wilson:

Acceleration Then

- Oc
- A

- Occam: *What is the simplest possible model that the data requires?*
- Wilson:

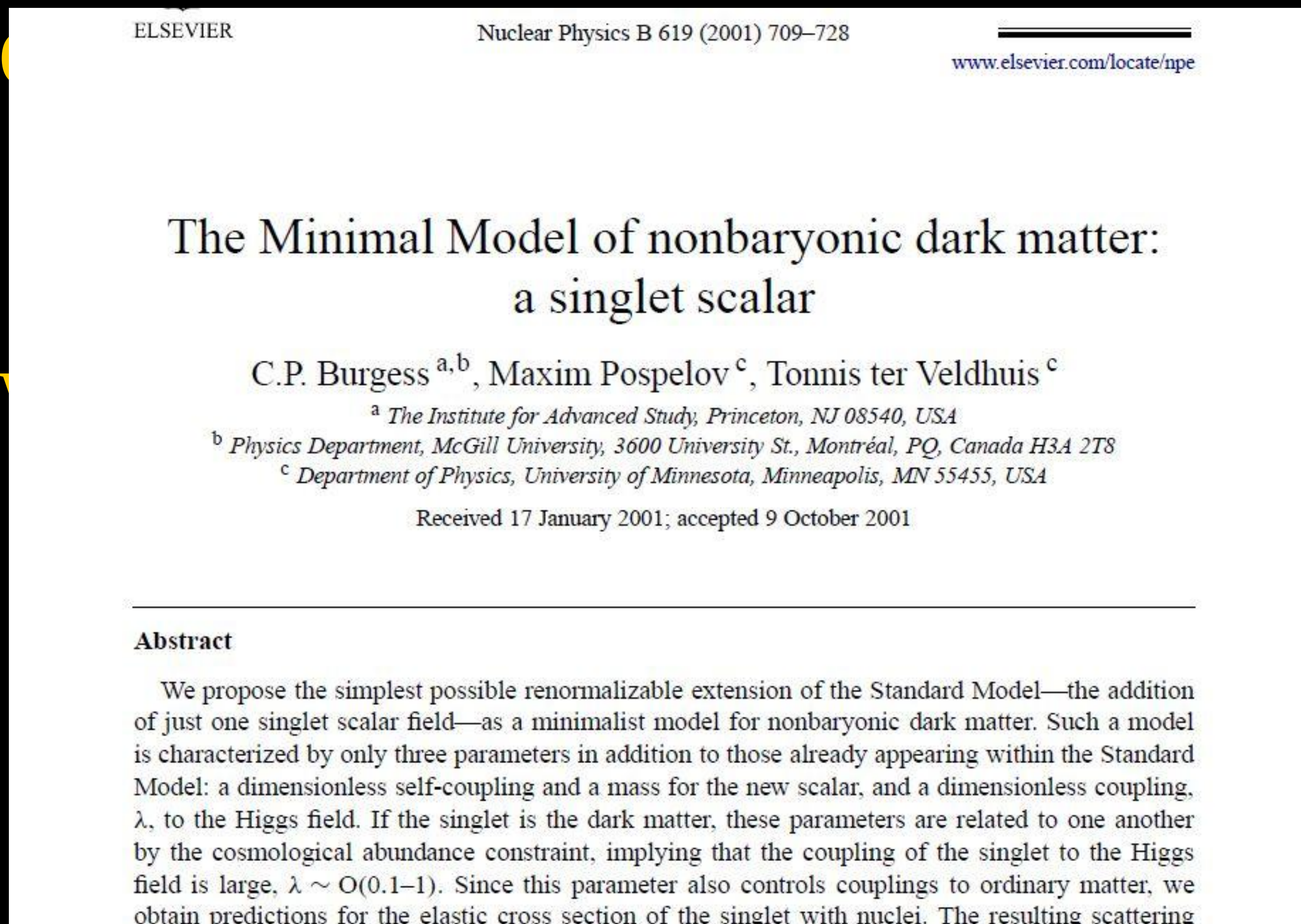
Acceleration Then

- Oc
- A

- Occam: *What is the simplest possible model that the data requires?*
- Wilson: *Low energy limit is often messy. What is generic and stable?*

  eg SUSY vs simple dark matter model

Acceleration Then



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Nuclear Physics B 619 (2001) 709–728

www.elsevier.com/locate/npe

The Minimal Model of nonbaryonic dark matter: a singlet scalar

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Received 17 January 2001; accepted 9 October 2001

Abstract

We propose the simplest possible renormalizable extension of the Standard Model—the addition of just one singlet scalar field—as a minimalist model for nonbaryonic dark matter. Such a model is characterized by only three parameters in addition to those already appearing within the Standard Model: a dimensionless self-coupling and a mass for the new scalar, and a dimensionless coupling, λ, to the Higgs field. If the singlet is the dark matter, these parameters are related to one another by the cosmological abundance constraint, implying that the coupling of the singlet to the Higgs field is large, $\lambda \sim O(0.1\text{–}1)$. Since this parameter also controls couplings to ordinary matter, we obtain predictions for the elastic cross section of the singlet with nuclei. The resulting scattering

Acceleration Then

- Oc
- A

- Occam: *What is the simplest possible model that the data requires?*
- Wilson: *Low energy limit is often messy. What is generic and stable?*

Why embed into UV theory? *Is inflation a good theory of primordial fluctuations? Are there others?....*

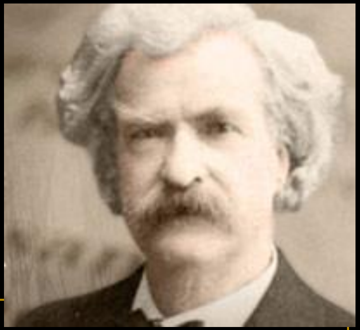
Acceleration Then

- O
- A

Inflationary paradigm in trouble after Planck2013

Planck2013 results support the simplest cyclic models

Acceleration Then



- Oc

Inflationary paradigm in trouble after Planck2013

Mark Twain -

"The report of my death was an exaggeration."

Planck2013 results support the simplest cyclic models

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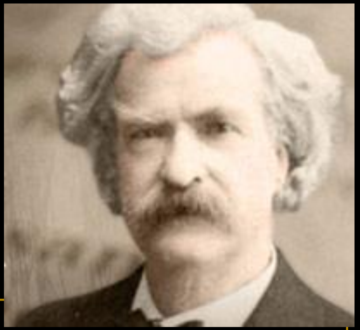
Acceleration Then



- Oc
- A

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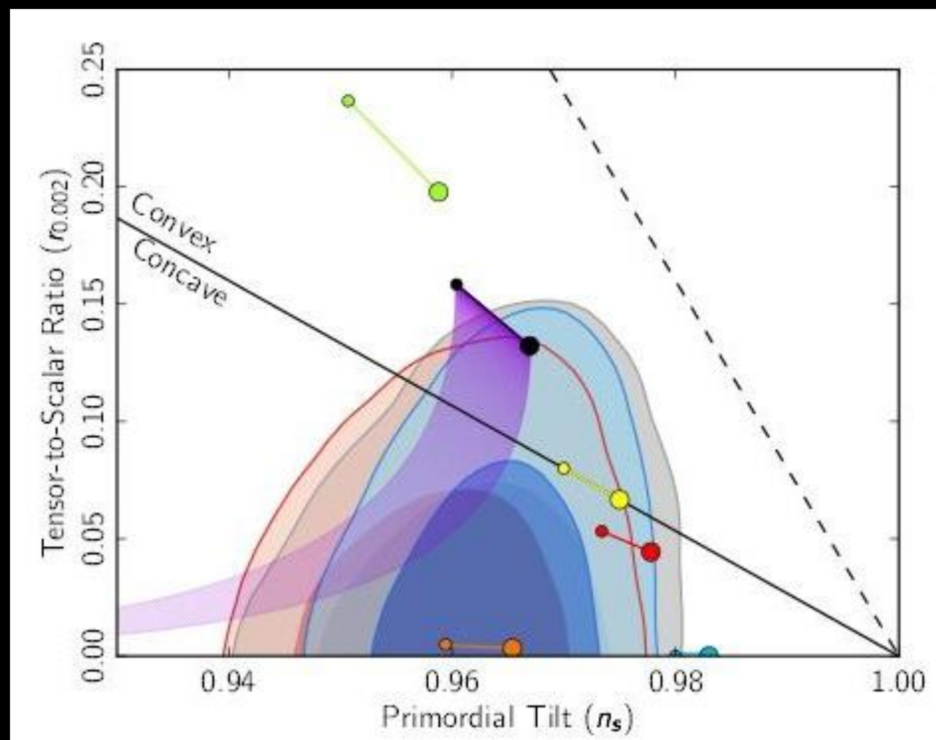
Planck2013 results support the simplest cyclic models

"I didn't attend the funeral, but sent a nice letter saying that I approved of it."

Acceleration Then

- Oc

Inflationary paradigm in trouble after Planck2013



- A

Acceleration Then

- Oc

- A

Inflationary paradigm in trouble after Planck2013

Problems with inflation

Often requires special initial conditions

Requires scalar not just light, but lighter than H

Can fields roll over trans-Planckian distances?

Reheating? Trans-Planckian intrusions?

Eternal inflation?

….and so on

Acceleration Then

- O
- A

Planck2013 results support the simplest cyclic models

Problems with cyclic models

How to control all approximations through the required bounce

Acceleration Then

- Occam vs Wilson
- A scorecard

Acceleration Then

- Oc
- A

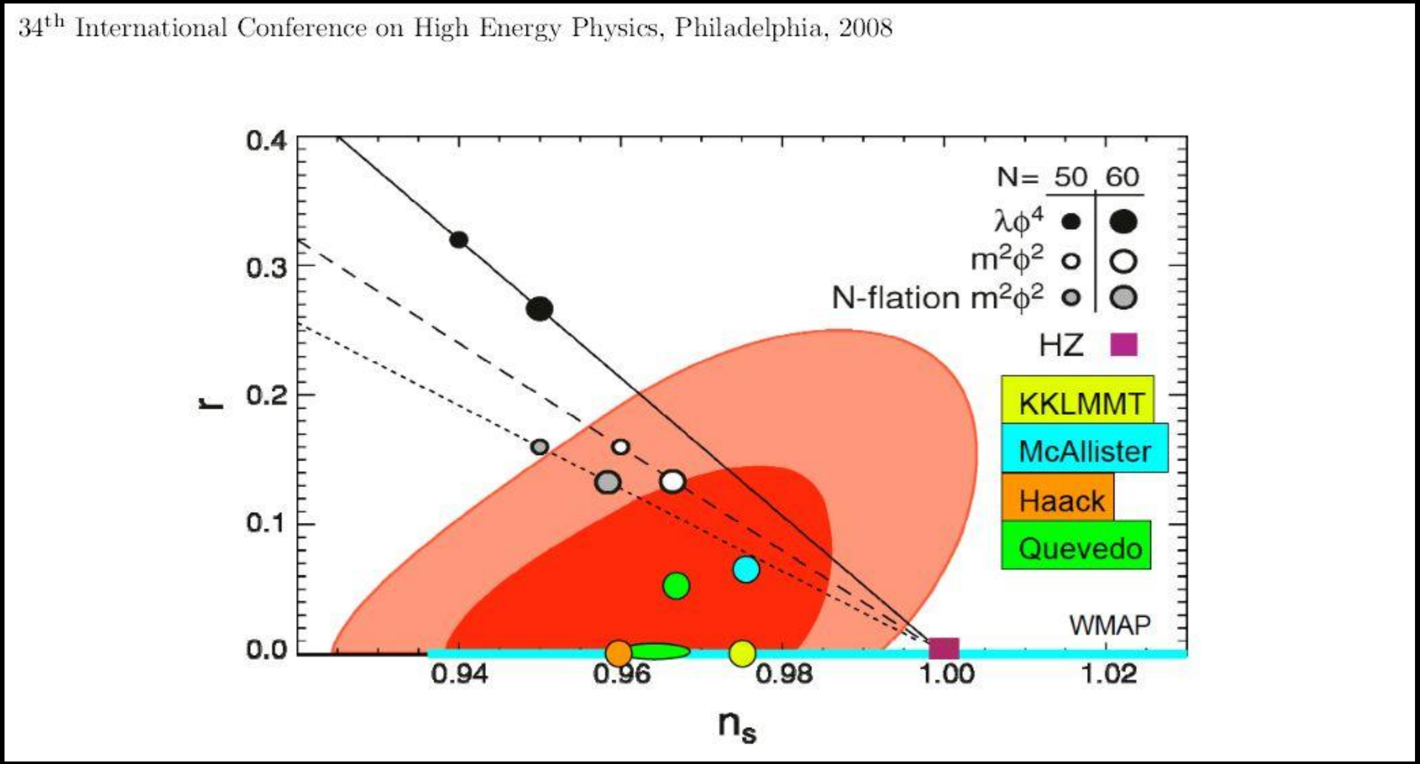
- *That's all very nice, but it is not predictive: you can get *anything* from string theory.*

Acceleration Then

- Oc

- A

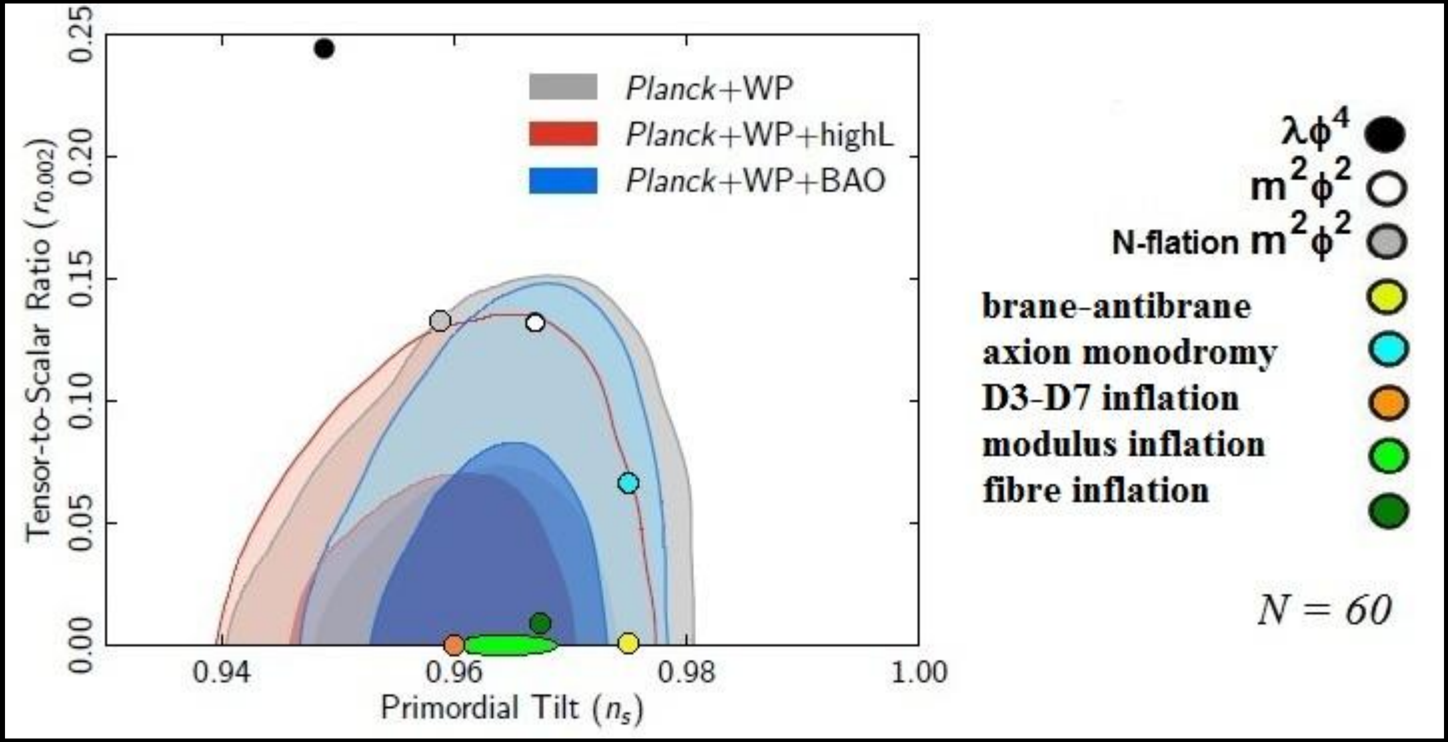
- *J. Polchinski ICHEP 08 summary talk*



Acceleration Then

- Oc
- A

- *String models like small r and $n_s < 0$*



Acceleration Then

- Oc
- A

- *What* n_s *and* r *are telling us:*
  - *Large r is hard to get*

Acceleration Then

- Oc
  - *What* n_s
    - *Large r*
- A

Usually large r corresponds to large excursions in field space

$$\Delta\phi > M_p \; (r/4\pi)^{1/2} \quad \text{(Lyth)}$$

These turn out to require things like branes rolling further than the extra dimensions are large.

Acceleration Then

- Oc
- A

- *What n_s and r are telling us:*
  - *Large r is hard to get*
  - *Exponential potentials are very attractive*

Acceleration Then

- Oc
  - *What*
    - *Larg*
    - *Exp*
- A

Starobinsky inflation with action

$$L = M_p^2 R + \zeta R^2$$

is equivalent to inflation with an exponential potential

$$L = M_p^2 R + (d\,\phi)^2 + V$$
$$V = V_0 \,(1 - A\, e^{-a\,\phi})^2$$

Acceleration Then

- Oc
- A

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Why aren't R^3 and R^4 important?

Acceleration Then

CB, Martineau, Quevedo, et al 2001
Conlon & Quevedo 2005
Cicoli, CB & Quevedo 2008

- Oc
- A

- *More generally, exponential potentials arise generically when inflaton is a geometrical modulus (eg fibre inflation)* $e^{\varphi} = r/\ell_s$

$$V(\varphi) = V_0\left(1 - \frac{1}{r^p} + \cdots\right)$$

$$= V_0\left(1 - e^{-k\,\varphi} + \cdots\right) \textit{ since } L = \frac{(\partial r)^2}{r^2}$$

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Progress on slow roll problem: slow roll if φ *is large, but* φ *is large whenever* $r \gg \ell_s$

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Progress on slow roll problem: slow roll if φ *is large, but* φ *is large whenever* $r \gg \ell_s$

Predictive! $\epsilon \sim k\,\eta^2$ *and so* $r \sim (n_s - 1)^2$

Acceleration Then

Silverstein & Tong
CB, Cicoli, Quevedo, Tasinato & Zavala

- Oc
- A

Nongaussianity: predictions

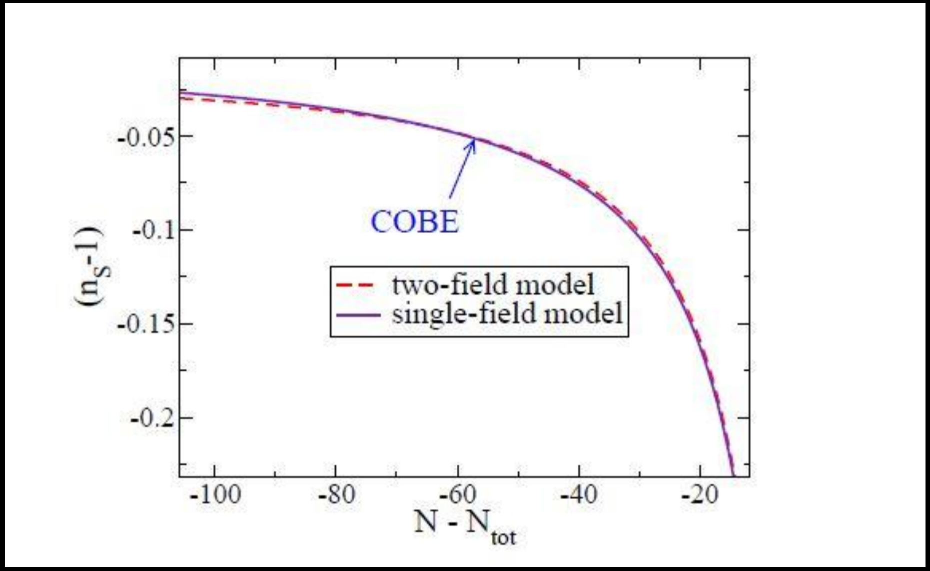
Brane inflation: *generically gaussian unless moving in strongly warped region (DBI)*

$$\mathcal{L}_{\rm DBI} = -f(\phi)^{-1}\sqrt{1 - 2f(\phi)g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi} + f(\phi)^{-1} - V(\phi)$$

Multiple fields: *generically effectively single field (so gaussian) though local mechanisms (curvaton, modulation) can be implemented.*

Acceleration Then

- Although usually complicated multi-field models, these are also usually nonetheless well-described by an effective single-field model



- Oc

- A

Acceleration Then

- Oc
- A

Summary: *UV complete inflation prefers small r, and this agrees well with the data*

Moduli as inflaton naturally gives 'no-scale' 'Starobinsky type' exponential potential

Generically gaussian, but some strongly constrained (like DBI in strong warping)

Now

with L. van Nierop & M. Williams
and S. Parameswaran & A. Salvio,

Now (dark energy)

- The cosmological constant

- Update

Now (dark energy)

- Th
- Th

- The problem: *particle of mass m generates Lorentz-invariant vacuum stress-energy:*

$$T_{\mu\nu} \sim m^4 \; g_{\mu\nu}$$

which in Einstein's equations obstructs having the small curvature we measure

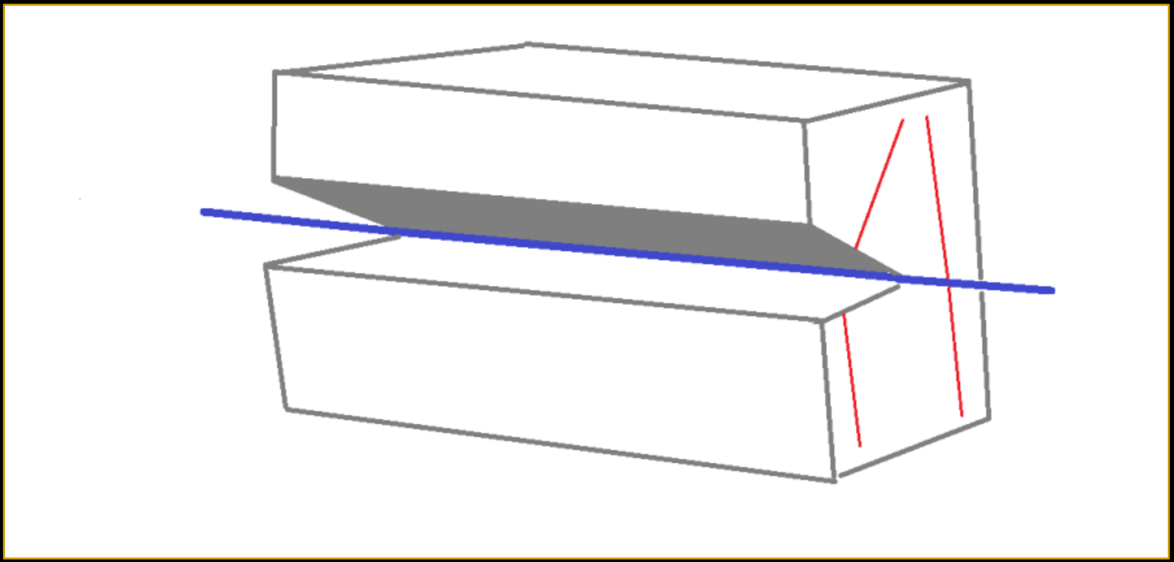
$$G_{\mu\nu} = \kappa^2 \; T_{\mu\nu}$$

Now (dark energy)

Vilenkin

- Th
- Th

- Towards a solution: *higher dimensions can break this link between vacuum energy and curvature (eg cosmic string)*



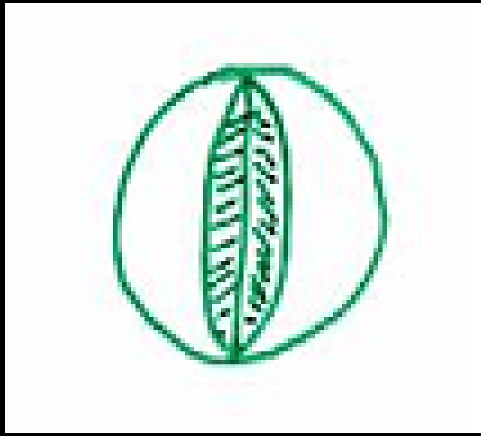
Now (dark energy)

Chen, Luty & Ponton
Carroll & Guica
Aghababaie et al

- Th
- Th

- A higher-dimensional analog:
  - Similar *(classical)* examples also with a 4D brane in two extra dimensions: *e.g. the rugby ball*

$$R = -2\kappa^2 \sum T_i \ \delta^2(x_i)$$



$$4\text{D cc} = \sum T_i + \frac{1}{2\kappa^2}\int d^2x\, R$$
$$= 0 \ \text{ for all } T_i$$

Back-reaction is crucial

Now (dark energy)

CB, van Nierop, Williams

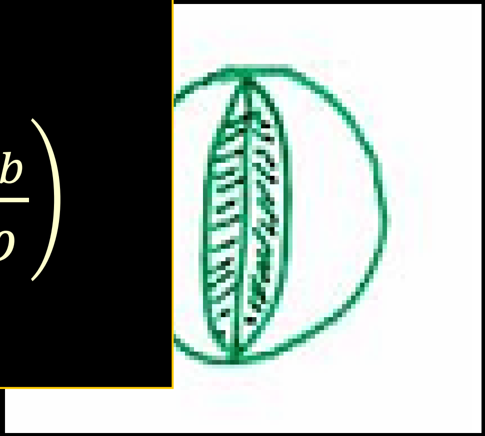
- Th
- Th

- A higher-dimensional analog:
  - Similar *(classical)* examples also with a 4D brane in two extra dimensions: *e.g. the rugby ball*

$R = -2$

4D cc =

$$\lim_{r\to 0}\left(r\frac{\partial\varphi}{\partial r}\right) = \kappa^2\left(\frac{\delta S_b}{\delta\varphi}\right)$$



$= 0$ for all T_i

Back-reaction is crucial

Now (dark energy)

Aghababaie, CB,
Parameswaran & Quevedo
CB & van Nierop

- Th

- Must re-ask the cc problem:
  - *Stabilize extra dimensions (with fluxes)*
  - *What choices ensure flat branes?*
  - *Are these choices stable against UV loops?*

- Th

Now (dark energy)

Aghababaie, CB,
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- Must re-ask the cc problem:
  - *Stabilize extra dimensions (with fluxes)*
  - *What choices ensure flat branes?*
  - *Are these choices stable against UV loops?*
- *Upshot:*
  - *Generically: NO*
  - *BUT, with supersymmetric bulk can have cc ~ KK scale << scale m on branes*

Now (dark energy)

- The cosmological constant

- Update

Now (dark energy)

CB, van Nierop, Parameswaran, Salvio & Williams

- Th
- U

- Why are quantum corrections so small?
  - *1. Accidental SUSY*
  - *2. SUSY only breaks nonlocally*
  - *Predict* $cc \sim k / (4 \pi r)^4$

Now (dark energy)

Williams, CB, van Nierop & Salvio

- Th
- Up

- Why are quantum corrections so small?
  - *1. Acc*
  - *2. SUS*
  - *Predic*

- Accidental SUSY
  - *Branes can have tension and magnetic charge*

$$L_b = T_b + A_b \quad {}^*F$$

  - *SUSY requires BPS-like condition* $T_b = A_b e^{\varphi_b}$

Now (dark energy)

Williams, CB, van Nierop & Salvio

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Flat direction of bulk, evaluated at b

SUSY requires BPS-like condition $T_b = A_b e^{\varphi_b}$

Now (dark energy)

Williams, CB,
van Nierop & Salvio

- Th
  - Why are quantum corrections so small?
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- SUSY Broken Nonlocally
  - *Normalization of flat direction fixed by flux quantization, which fixes φ_b at all branes*
  - *Resulting φ_b can, but need not, simultaneously preserve SUSY at all branes.*

Now (dark energy)

S Weinberg

- Th
- U

- If you claim to solve the cosmological constant problem, aren't you crazy?
  - Weinberg's no-go theorem?
  - Didn't we see this all before in 5D?
  - What about Nima's argument against x dims
  - What stops proton decay?
  - How is inflation possible?
  - Other effects seen in 4D cosmology?
  - Don't constraints already force $(1/r)^4 > cc$?

Now (dark energy)

- Th
- U

- If true, many striking implications:
  - Micron deviations from inverse square law
  - *Missing energy at the LHC and in astrophysics: requires M_g > 10 TeV*
  - *Probably a vanilla SM Higgs*
  - Excited string states (or QG) *below* 10 TeV
  - *Low energy SUSY without the MSSM*
  - Modified macroscopic physics & cosmology
  - *Sterile neutrinos from the bulk?*

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- The cosmological constant problem is telling us that there must be two micron-sized dimensions (plus possibly more smaller ones)

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- These dimensions must be supersymmetric (but need *NOT* require the MSSM)

"...when you have eliminated the impossible, whatever remains, however improbable, must be the truth."

A. Conan Doyle

The message:

- The cosmological constant problem is telling us that there must be two micron-sized dimensions (plus possibly more smaller ones)
- These dimensions must be supersymmetric (but need *NOT* require the MSSM)
- *More generally: back-reaction for higher codimension objects is a very promising, but largely unexplored area*

Summary

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- Inflation @ Planck
  - Data prefers simplicity
  - String models in great shape
  - Many conceptual issues to sort out

Summary

- Inflation @ Planck
  - Data prefers simplicity
  - String models in great shape
  - Many conceptual issues to sort out
- Now (dark energy)
  - Dark Energy may be telling us to *double down*
  - Points in a very different direction: no MSSM but *very* supersymmetric gravity sector

Opportunities & Concerns

- If true, many striking implications:
  - Micron deviations from inverse square law
  - Missing energy at the LHC and in astrophysics: requires Mg > 10 TeV
  - Probably a vanilla SM Higgs
  - Excited string states (or QG) below 10 TeV
  - Low energy SUSY without the MSSM
  - Modified cosmology
  - Sterile neutrinos from the bulk?
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Fin