Acceleration, then and now

Inflation and Dark Energy after Planck

Cliff Burgess
w Ross Diener, Richard Holman, Leo van Nierop, Matt Williams

Accelerations

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

Accelerations

Inflationary paradigm in trouble after Planck2013

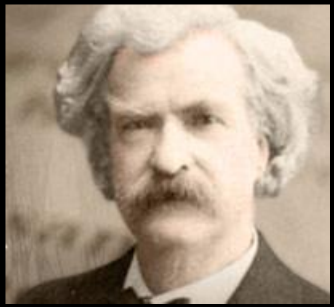
Planck 2013

Accelerations

Inflationary paradigm in trouble after Planck2013

Mark Twain -

"The report of my death was an exaggeration."



Accelerations

Planck2013 results support the simplest cyclic models

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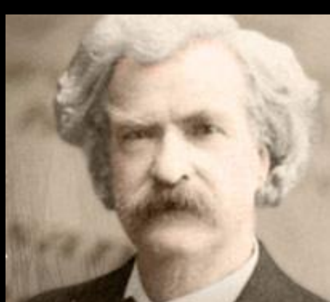
Planck2013 results support the simplest cyclic models

Mark Twain -

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



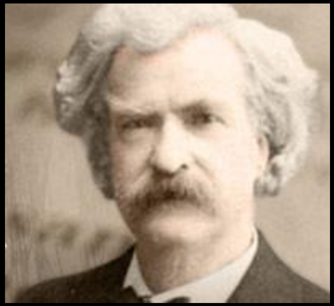
Accelerations

- Then (inflation)
  - Occam vs Wilson
  - String inflation: a scorecard
- Now (dark energy)
  - What if there were a solution to the cc problem: *a natural system with cc* $\ll m^4$
  - Fast *vs* slow response

Accelerations

Mark Twain -

"Get your facts first. Then you can distort them as much as you please."



Then

Then (inflation)

- Occam vs Wilson

- A scorecard

Then (inflation)

- Oc
- A

- Occam:
- Wilson:

Then (inflation)

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

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- Wilson: *Low energy limit is often messy. What is generic and stable?*

Then (inflation)

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Why embed into UV theory? *initial conds; reheating; control of approx; large fields,...*

Then (inflation)

- Occam vs Wilson

- A scorecard

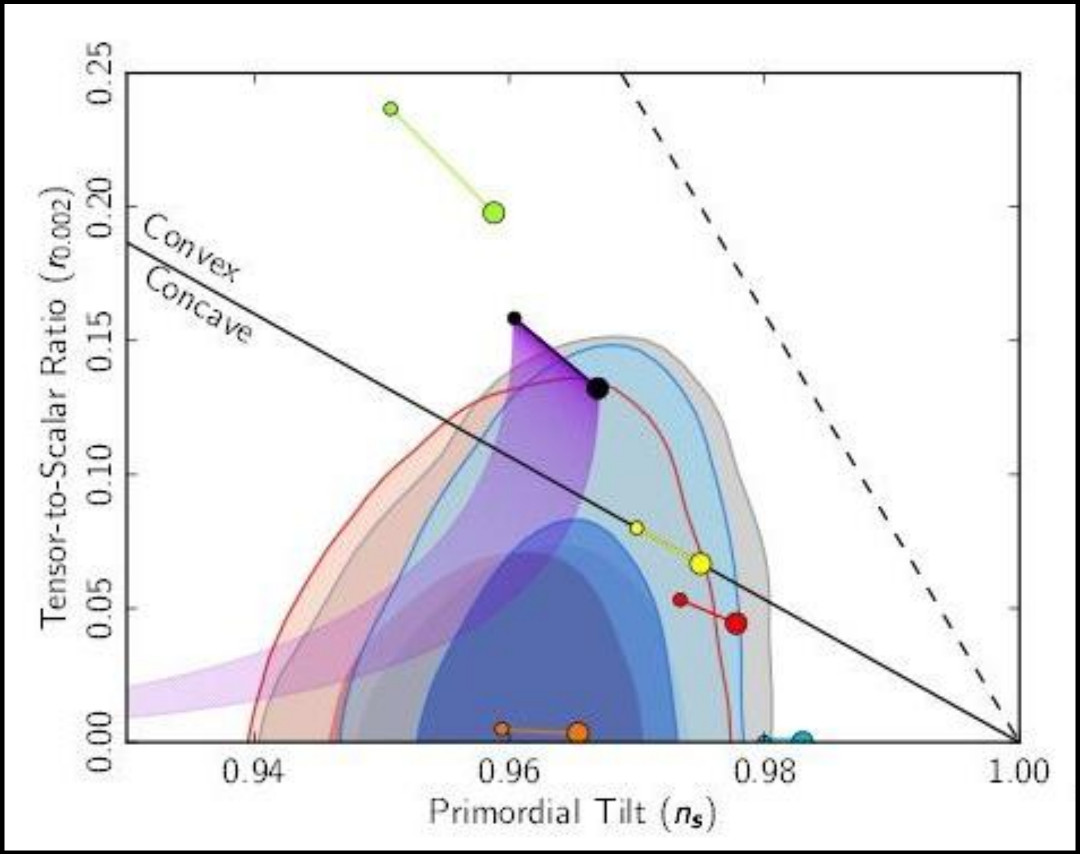
Then (inflation)

Planck 2013

- Oc

- A

- n_s *vs* r

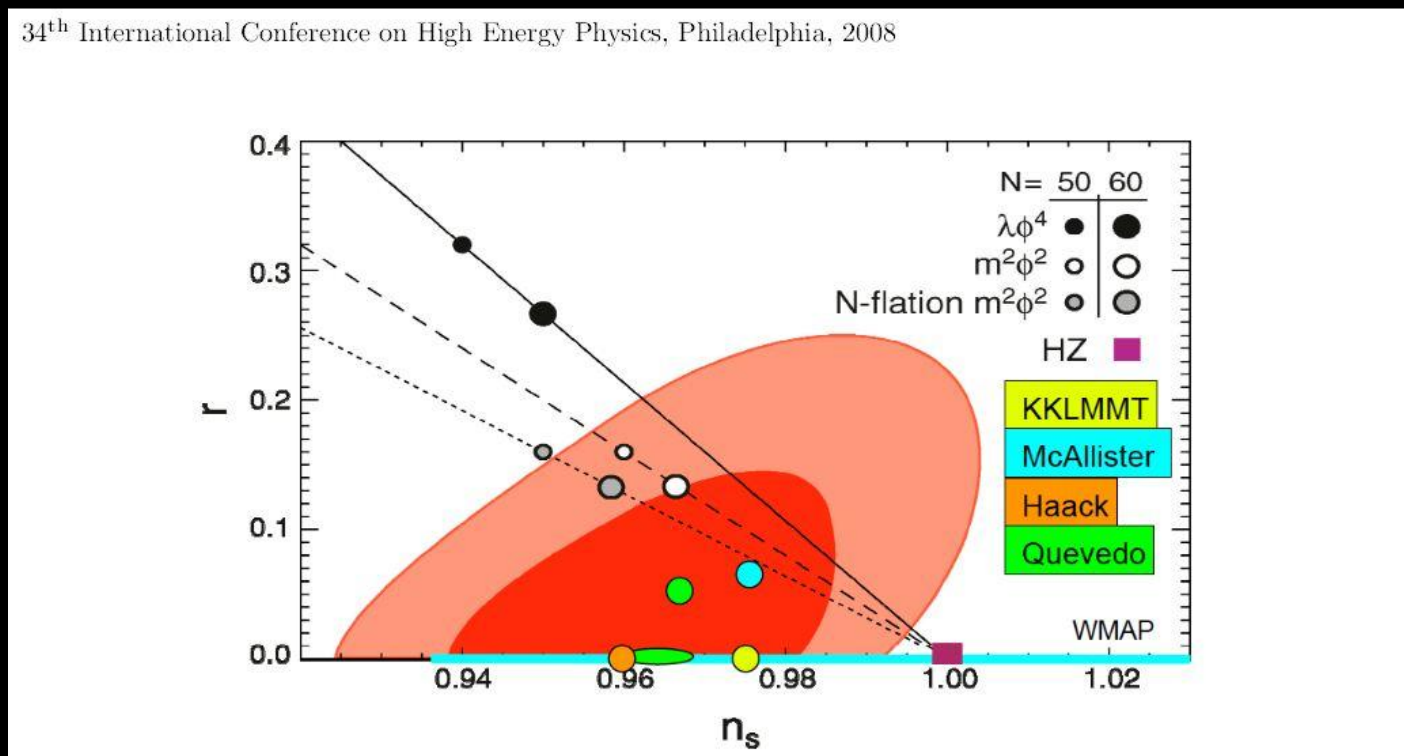


Planck 2013

Then (inflation)

- Oc
- A

- *J. Polchinski ICHEP 08 summary talk*



Planck 2013

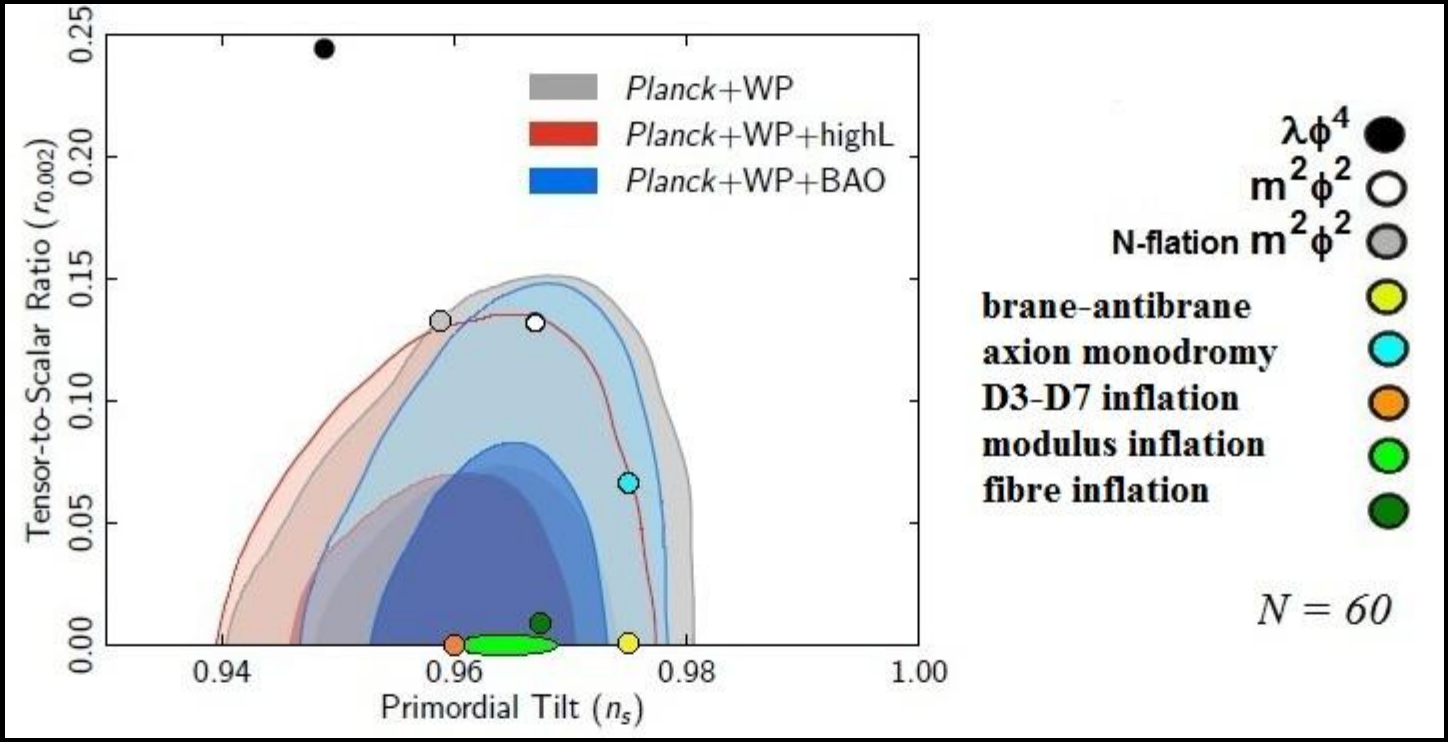
Then (inflation)

Lyth

- Oc

- A

- *String models like small r (Lyth bound)*



Planck 2013

Then (inflation)

Planck 2013

- Oc
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Nongaussianity: Planck (WMAP9)

f_{NL} = *2.7 +- 5.8 (37.2 +- 19.9) local*

f_{NL} = *-42 +- 75 (51 +- 136) equilat*

f_{NL} = *-25 +- 39 (-245 +- 100) orthog*

Then (inflation)

CB, Cicoli, Quevedo, Tasinato, & Zavala

- Oc
- A

Nongaussianity: predictions

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

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

Then (inflation)

- O(
- A

Summary:

String inflation nails the $n_s - r$ plane because models prefer small r, due to difficulty producing trans-Planckian roll (Lyth)

Generically gaussian, but some brane-inflation cases largely excluded (like DBI)

Planck 2013

Now

Now (dark energy)

- The cosmological constant

- The 4D perspective

Now (dark energy)

- Th
- Th

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

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

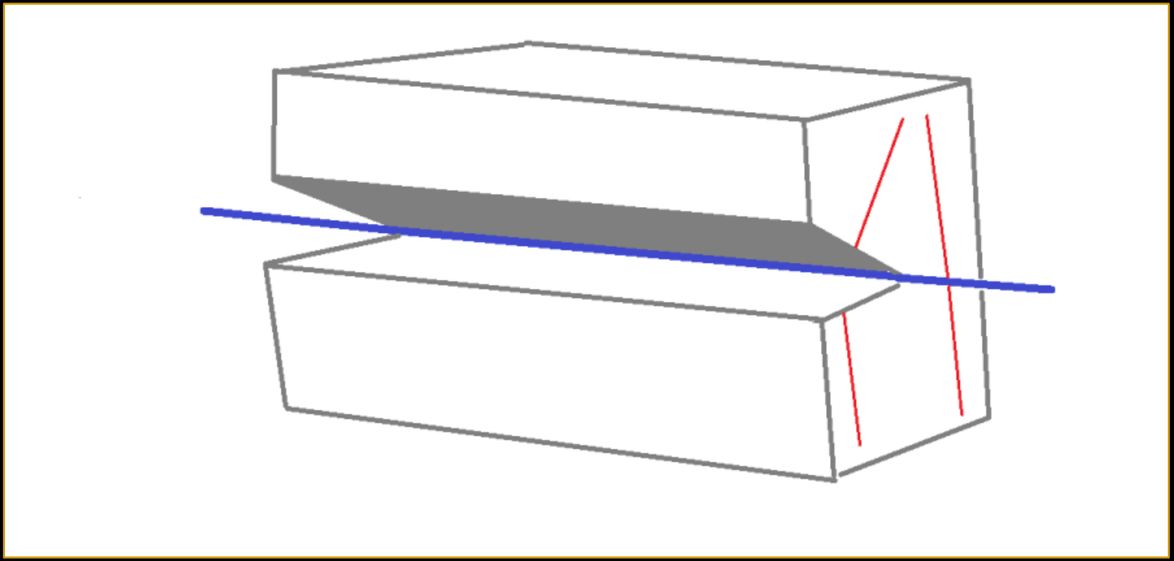
which in Einstein's equations obstructs having the small curvature we measure

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)

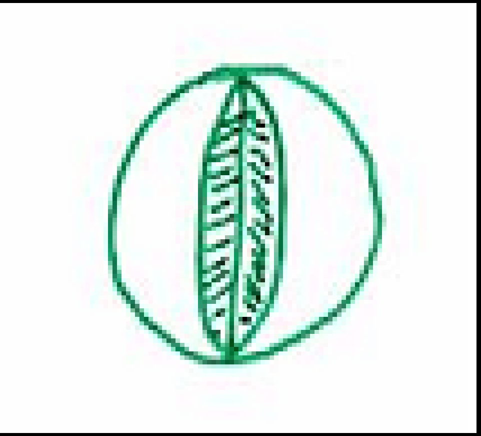
Chen, Luty & Ponton
Carroll & Guica
Aghababaie et al

- 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)

Aghababaie, CB, Parameswaran & Quevedo
CB & van Nierop

- Th
- Th

- 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*
  - *There exist supersymmetric bulks for which cc ~ KK scale << scale m on branes*

SLED with brane-localized fluxes

Now (dark energy)

S Weinberg

- Th
- Th

- 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 $(1/r)^4 > cc$?

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Now (dark energy)

- The cosmological constant

- The 4D perspective

Now (dark energy)

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- Dynamical behaviour: *bulk back-reaction modifies low-energy dynamics, but only for processes* slow enough *and* large enough *that the bulk reacts adiabatically.*

Small and/or fast

$$L_{he} = L_{vis}(\psi, g, X) + L_{Bulk}(g, X)$$

Large and slow

$$L_{le} = L_{vis}\big(\psi, g, X(g)\big) + L_{Bulk}\big(g, X(g)\big)$$

Now (dark energy)

- Th
- Th

- If faster or smaller than KK (0.01 eV):
  SM plus missing energy in bulk

- If slower *and* larger than KK (0.01 eV):

$$L_{le} = \tilde{L}_{vis}(\psi, g) + L_g(g)$$

$$\tilde{L}_{vis} = L_{vis} - \frac{1}{2} g^{\mu\nu} \frac{\partial L_{vis}}{\partial g_{\mu\nu}}$$

Now (dark energy)

- Th
- Th

- If slower and larger than KK (0.01 eV):

Vacuum energy cancels

Masses smaller than KK scale also cancel

Radiation unchanged

Masses larger than the KK scale change:

$$m \rightarrow 3m/4$$

Planck 2013

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Now (dark energy)

- Ol
- W

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

A. Conan Doyle

Summary

Summary

- Then (inflation)
  - Data prefers simplicity
  - String models in great shape
  - Many conceptual issues to sort out
- Now (dark energy)
  - Dark Energy can be natural and related to hierarchy
  - Points in a very different direction: no MSSM but *very* supersymmetric gravity sector

Opportunities & Concerns

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Fin