String Cosmology

Liam McAllister
Cornell

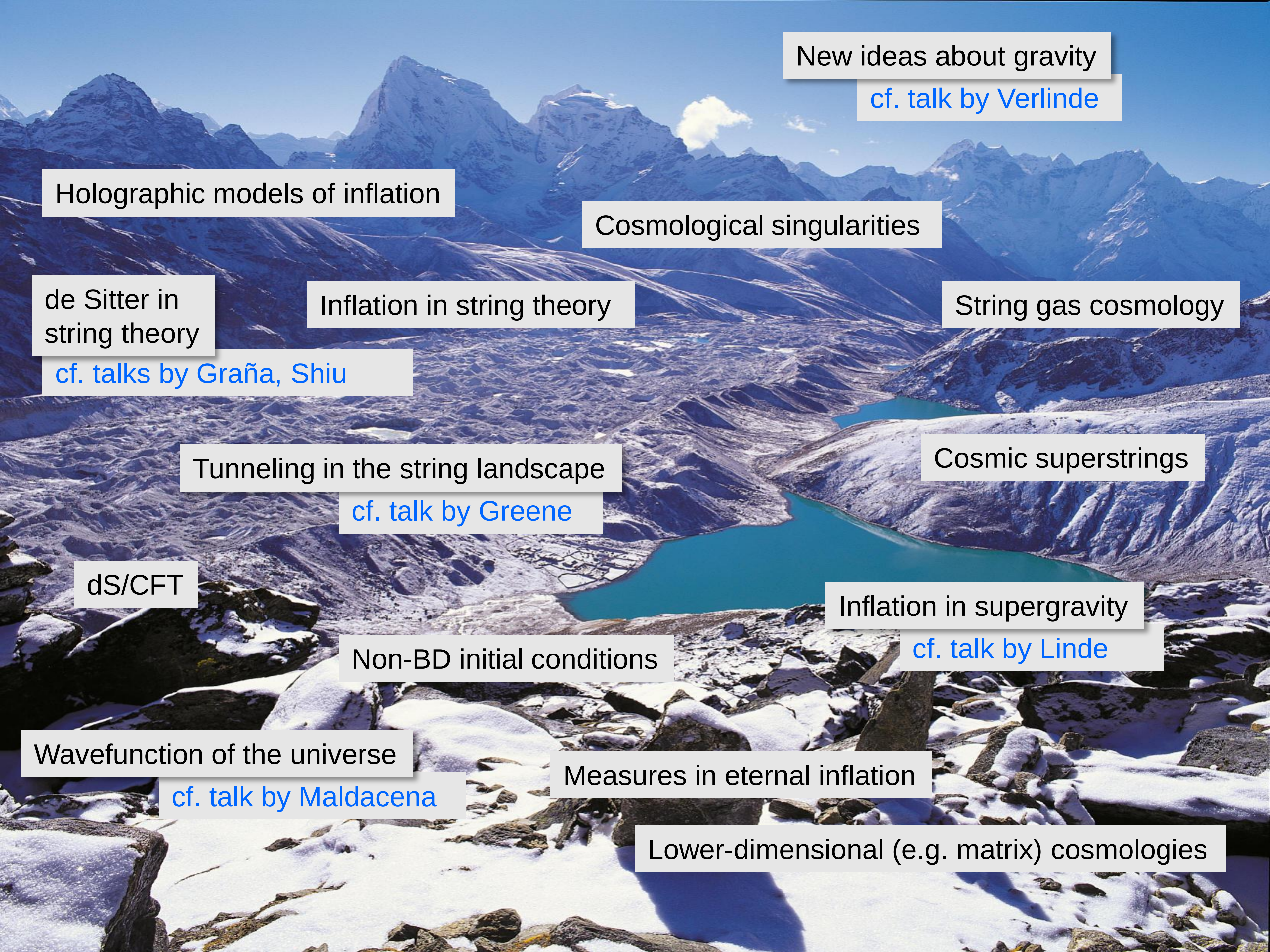
Strings 2011, Uppsala

July 1, 2011

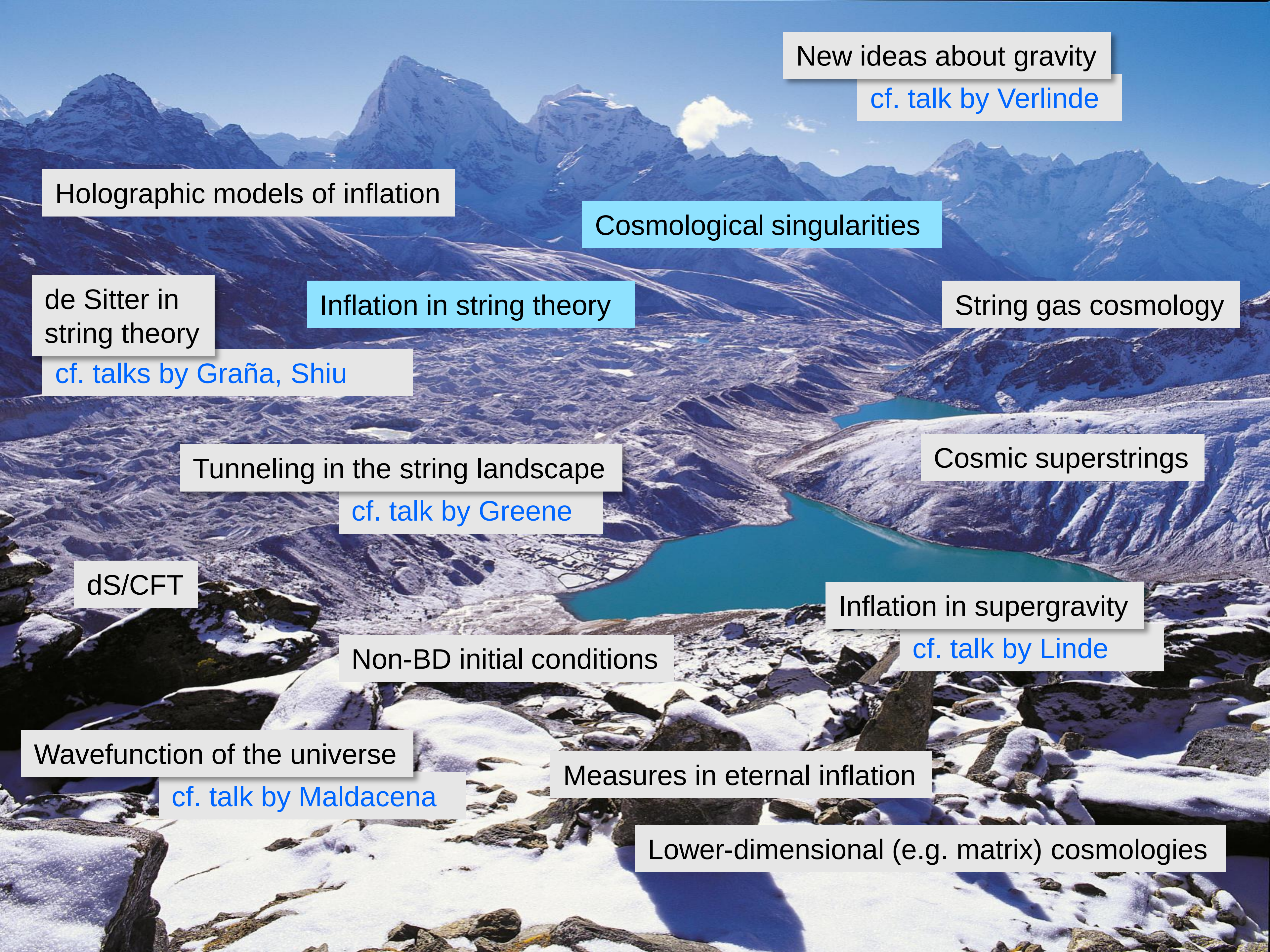
Subject of this talk

Mandate from the organizers:

- “one hour review talk on string cosmology”
- “should be an overview of the whole activity!”



New ideas about gravity
cf. talk by Verlinde
Holographic models of inflation
Cosmological singularities
de Sitter in string theory
cf. talks by Graña, Shiu
Inflation in string theory
String gas cosmology
Tunneling in the string landscape
cf. talk by Greene
Cosmic superstrings
dS/CFT
Inflation in supergravity
cf. talk by Linde
Non-BD initial conditions
Wavefunction of the universe
cf. talk by Maldacena
Measures in eternal inflation
Lower-dimensional (e.g. matrix) cosmologies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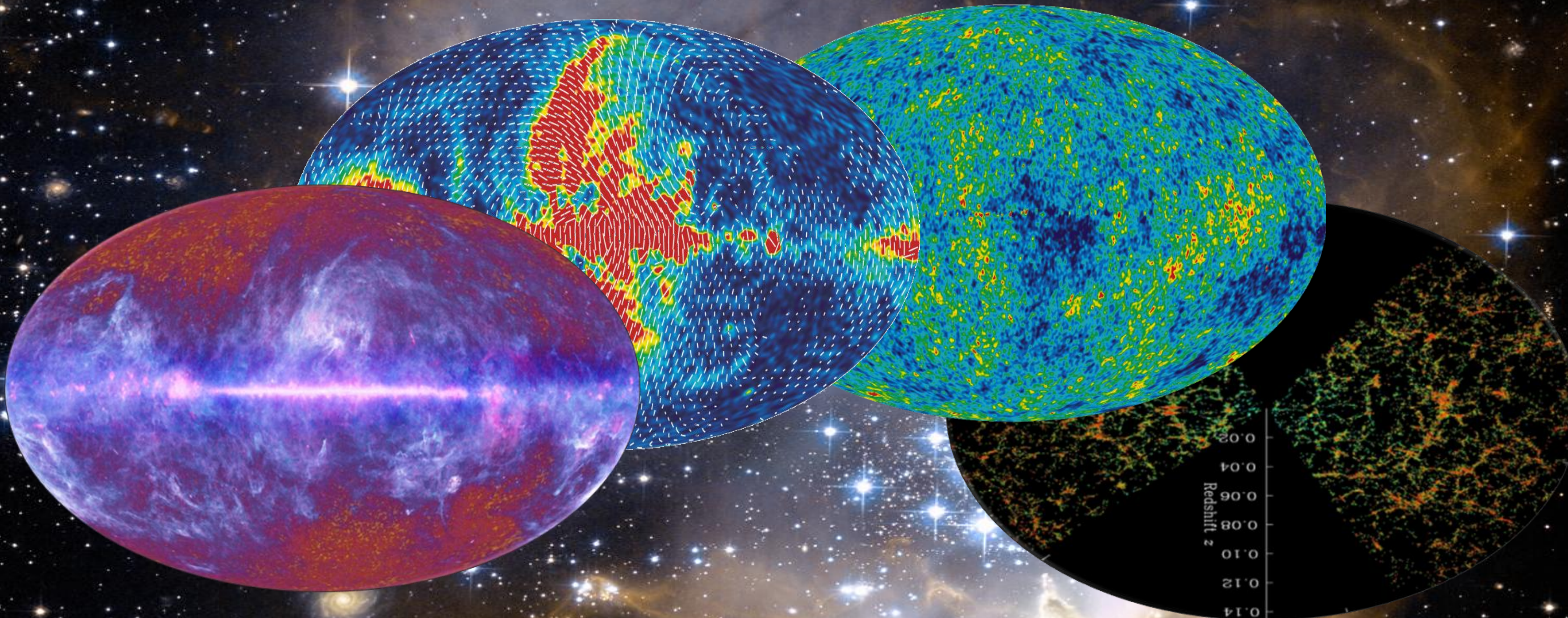
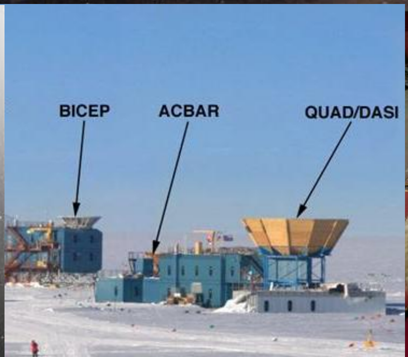
Plan

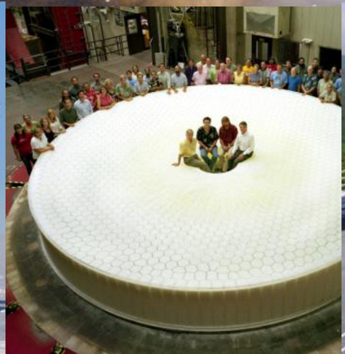
I. Cosmology in 2011
II. Why use string theory in cosmology?
III. Inflation in string theory
    i. D3-brane inflation
    ii. Axion inflation
IV. The initial singularity
V. Alternative cosmologies
VI. Outlook

A golden age of cosmology

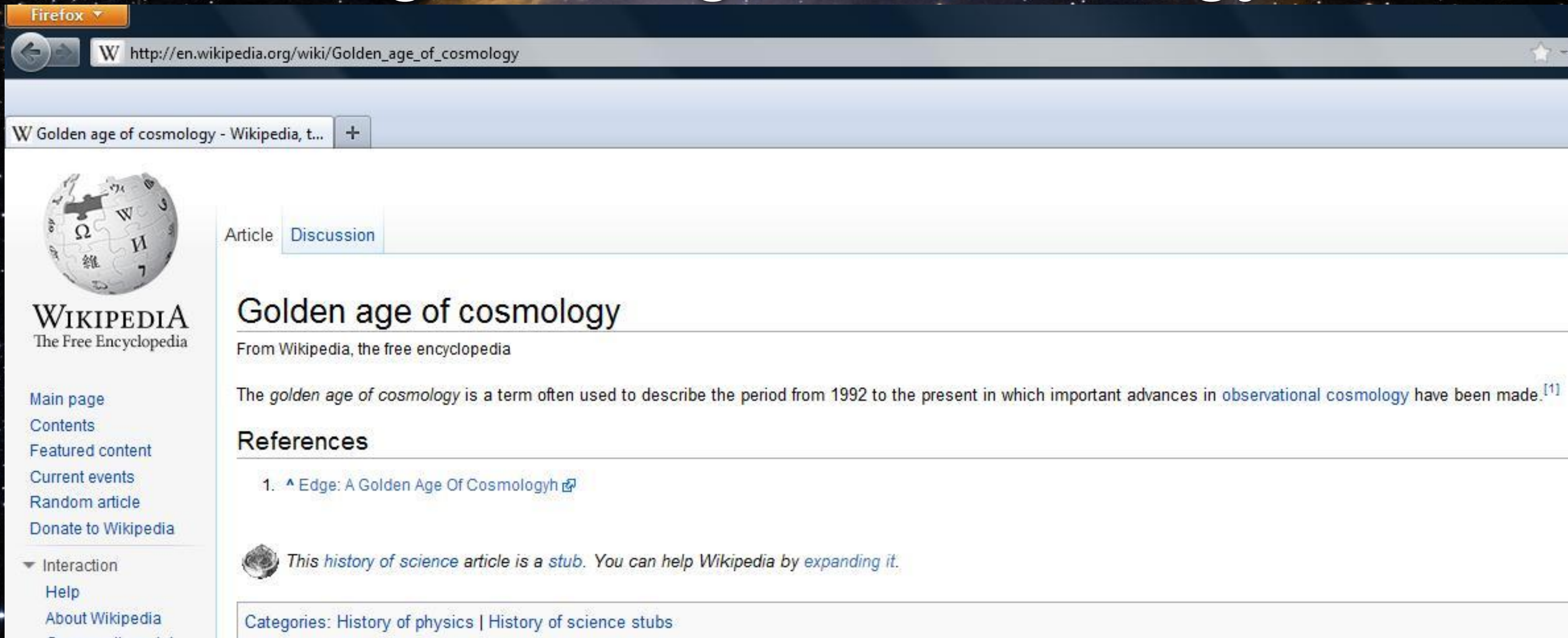


Planck; WMAP; SDSS





A golden age of cosmology



Firefox

http://en.wikipedia.org/wiki/Golden_age_of_cosmology

Golden age of cosmology - Wikipedia, t...

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Article | Discussion

Golden age of cosmology

From Wikipedia, the free encyclopedia

The *golden age of cosmology* is a term often used to describe the period from 1992 to the present in which important advances in observational cosmology have been made.[1]

References

1. ^ Edge: A Golden Age Of Cosmologyh

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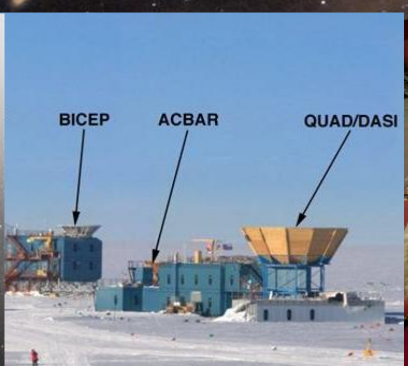
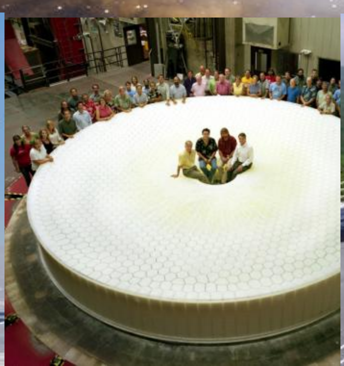
Categories: History of physics | History of science stubs

Planck; WMAP; SDSS





Cosmology in 2011

- Vigorous, diverse experimental effort
  - CMB (Planck; balloon-based and ground-based missions)
  - Large-scale structure (multiple surveys)
  - Dark energy (supernovae; probes of structure formation)
  - Dark matter (direct and indirect)
- Theoretical status: compelling phenomenological description using QFT+GR, but:
  - Late universe: dark energy presents a severe failure of naturalness.
  - Early universe: inflation is an impressive paradigm with multiple successful predictions, but:
    - Inflation is sensitive to Planck-scale physics, and is therefore best described in a theory of quantum gravity.
    - Diversification of inflationary models (multiple fields, non-slow roll, non-standard kinetic terms,…) requires a coherent understanding.
    - Alternatives to inflation are overshadowed by microphysical questions (e.g., singular bounces)

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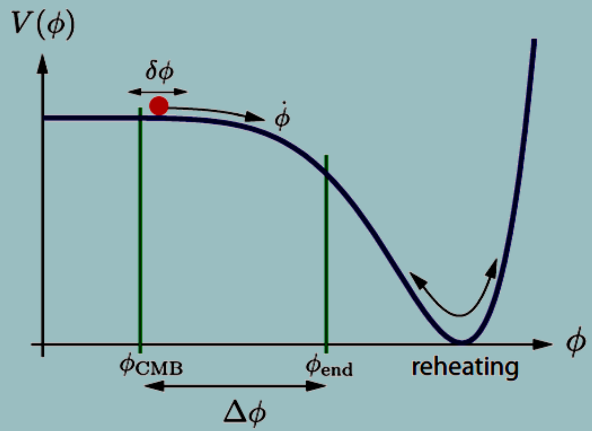
Physics of inflation: background

Guth 81; Linde 82; Albrecht, Steinhardt 82

- Simplest case: single scalar field with a potential,

$$\mathcal{L} = \frac{1}{2}\left(\partial\phi\right)^2 - V(\phi)$$



- Potential drives acceleration.

$$ds^2 = -dt^2 + a(t)^2 d\vec{x}^2$$

$$a(t) = a(0)e^{Ht}$$
$$H \approx const.$$

- Acceleration is prolonged if V is flat in Planck units,

$$\epsilon \equiv \frac{M_p^2}{2}\left(\frac{V'}{V}\right)^2 \ll 1 \qquad \eta \equiv M_p^2 \frac{V''}{V} \ll 1$$

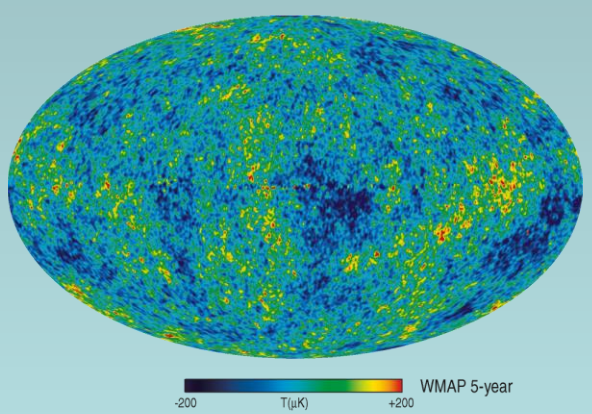
- Readily generalized to multiple fields with nontrivial kinetic terms.

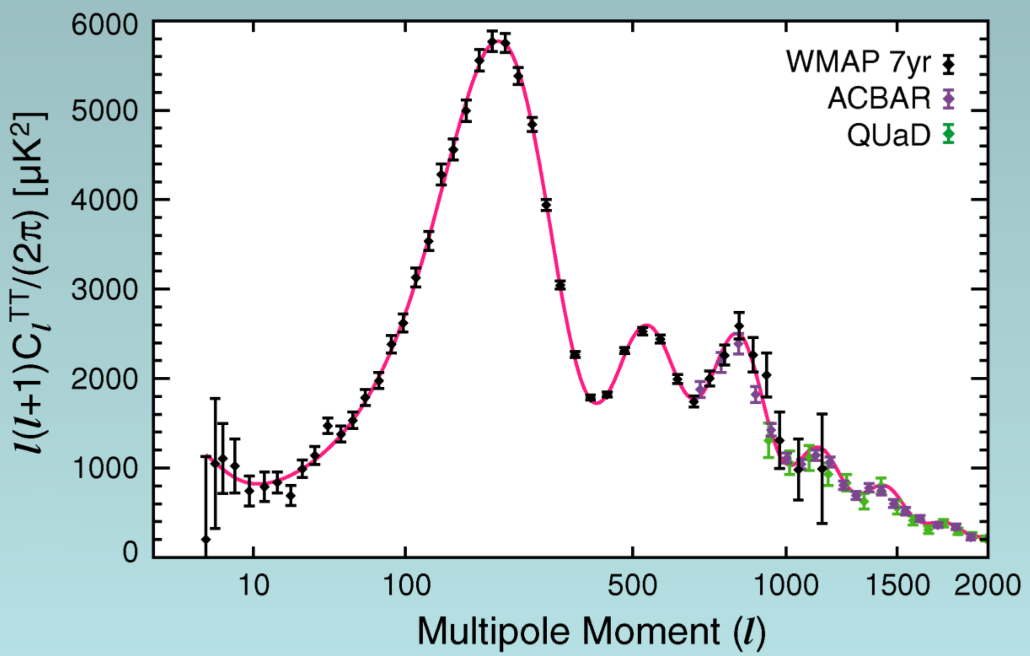
Scalar perturbations from inflation

$$g_{ij} = a^2(t)[1 + 2\zeta]\delta_{ij}$$

$$\langle \zeta_{\mathbf{k}} \zeta_{\mathbf{k}'} \rangle = (2\pi)^3\, \delta(\mathbf{k} + \mathbf{k}')\, \frac{2\pi^2}{k^3} P_s(k)$$

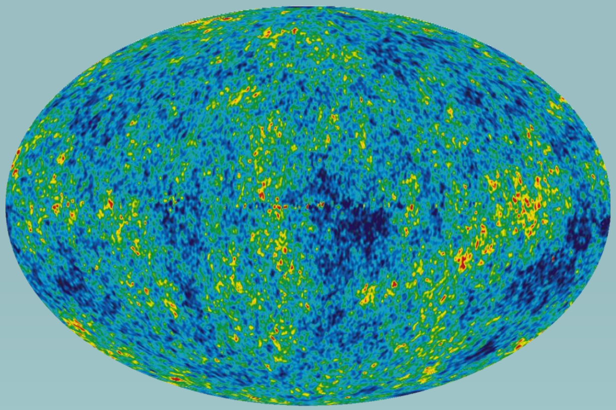
$$P_s(k) = A_s(k_\star) \left(\frac{k}{k_\star} \right)^{n_s(k_\star)-1}$$

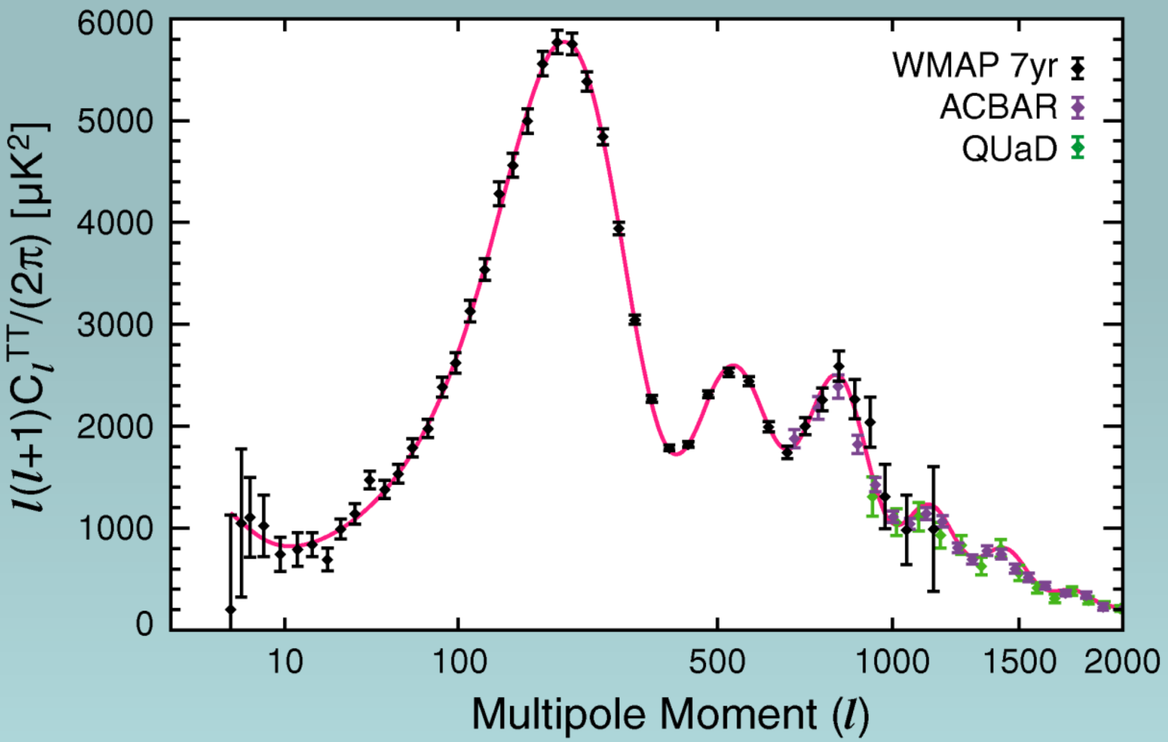




Inflation predicts:

Universe on large scales is homogeneous, isotropic, and flat





Perturbations are:

Nearly Gaussian
Adiabatic
Nearly scale-invariant
Correlated on super-horizon scales

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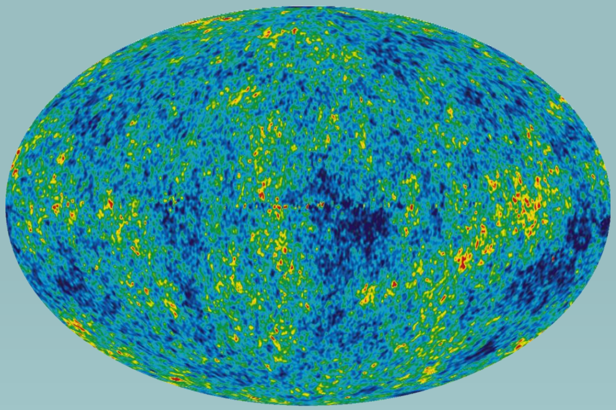

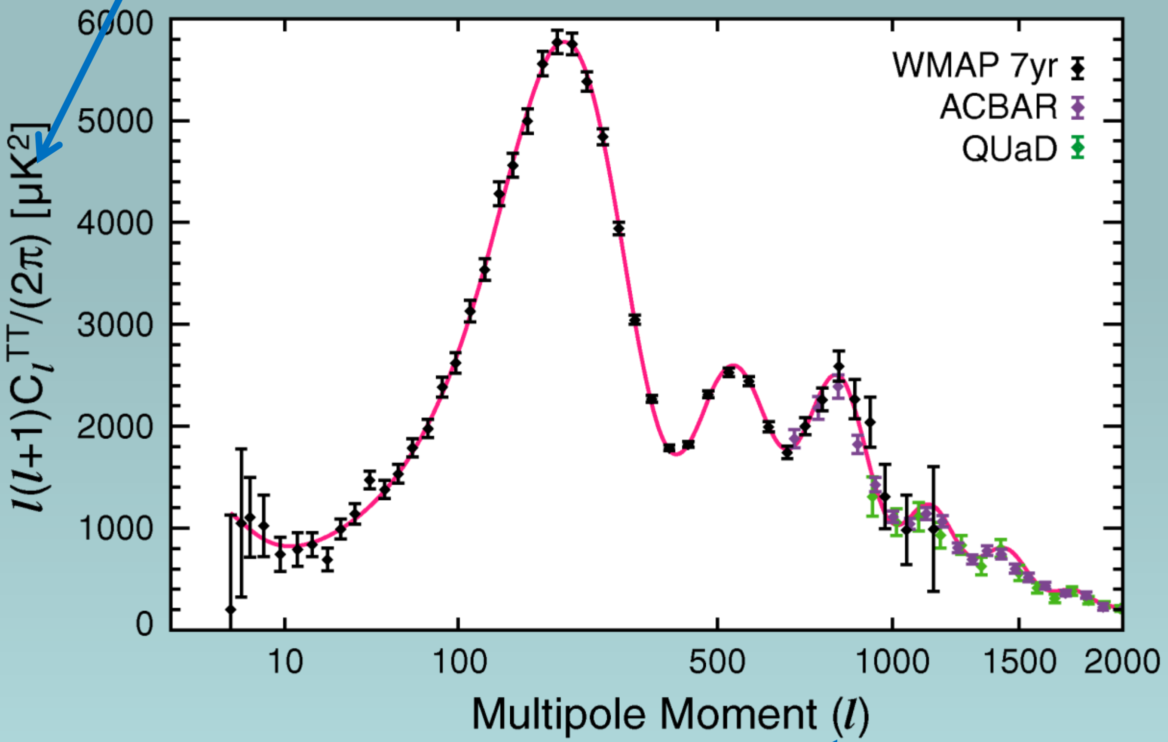

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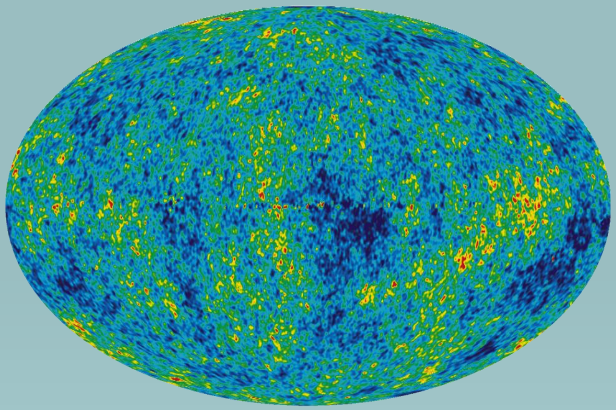

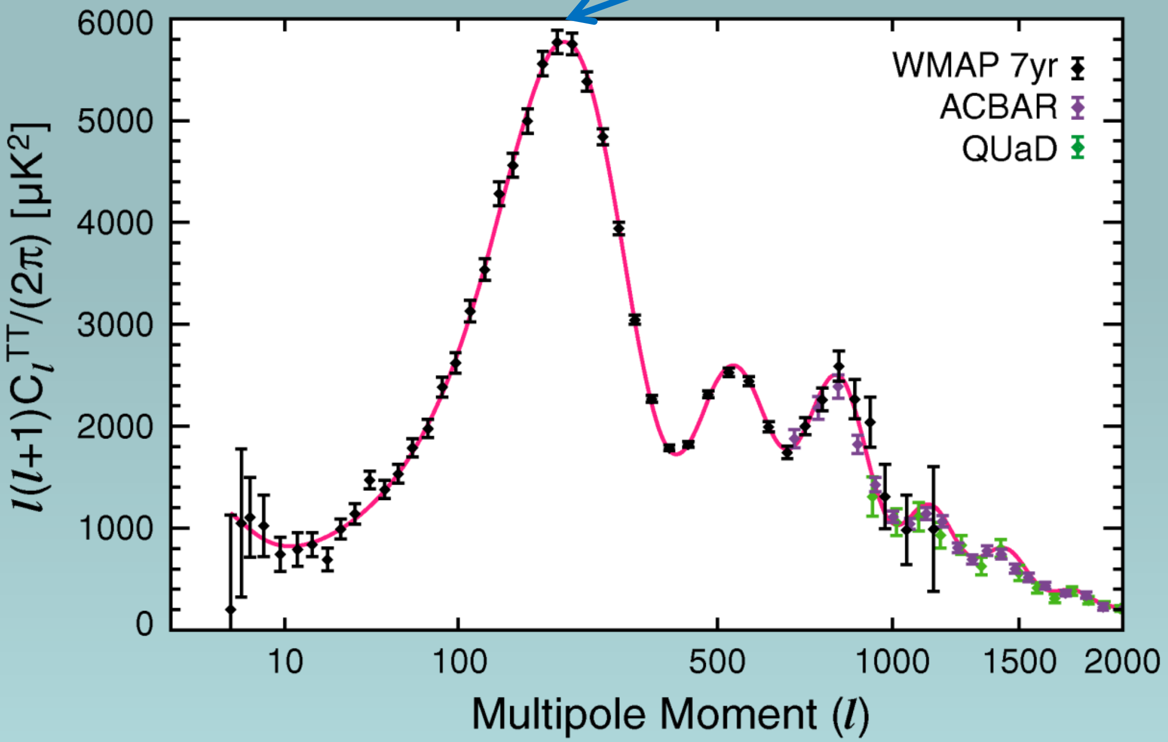

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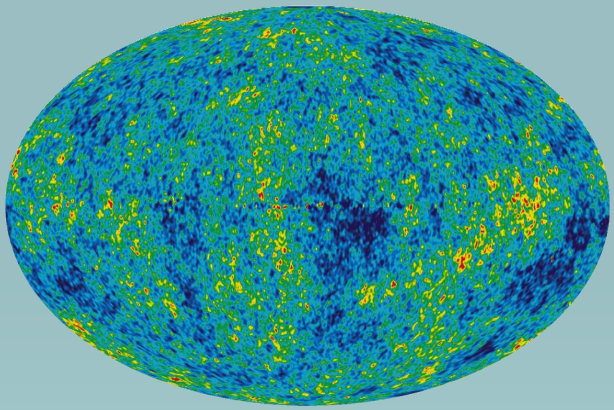

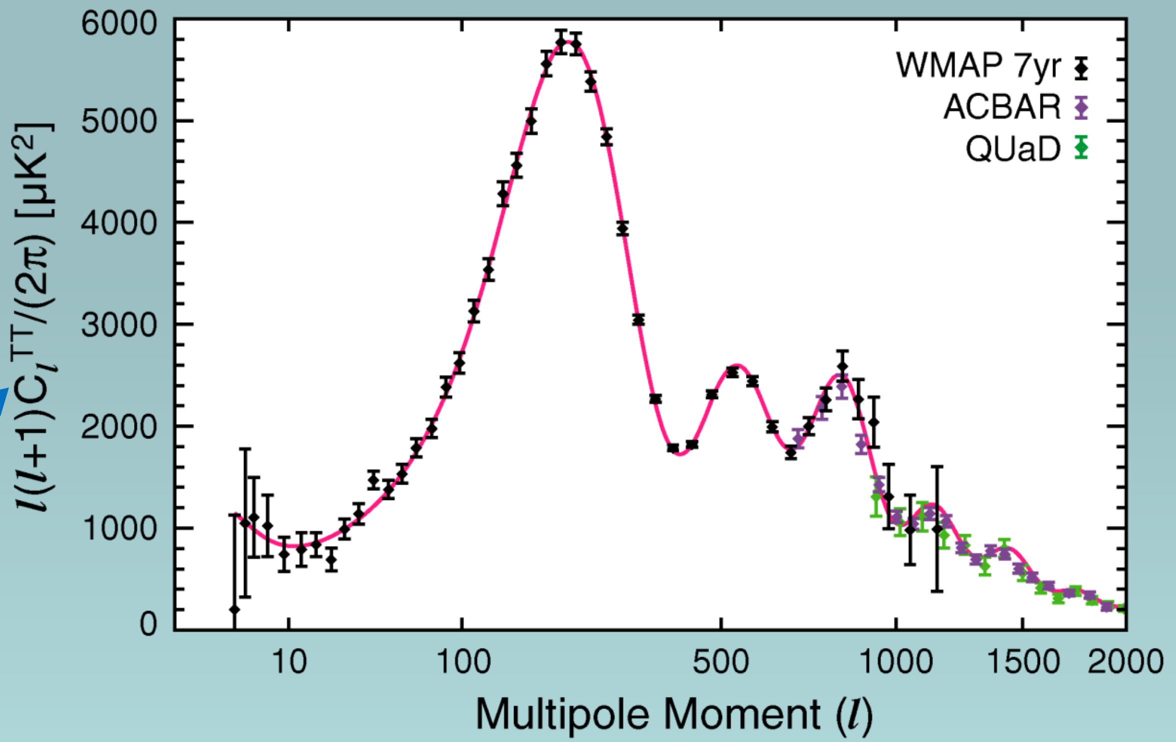

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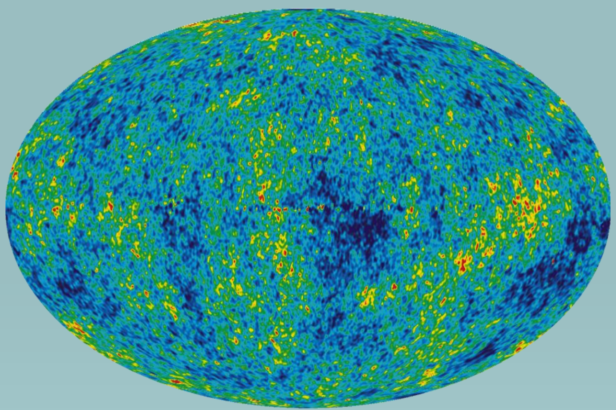

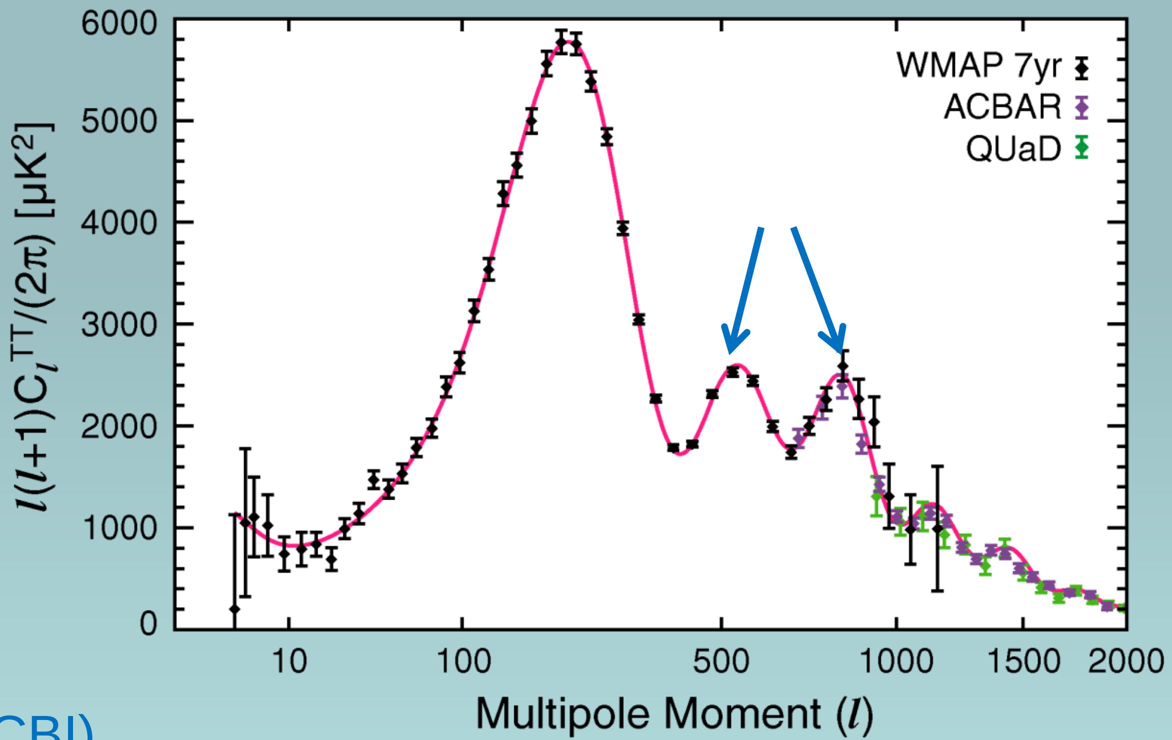

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cf. talk by Wilczek

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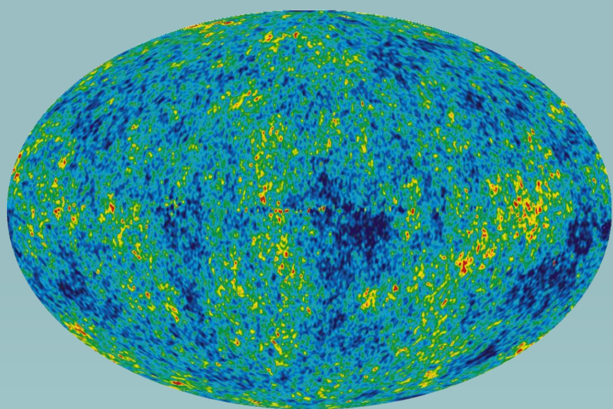

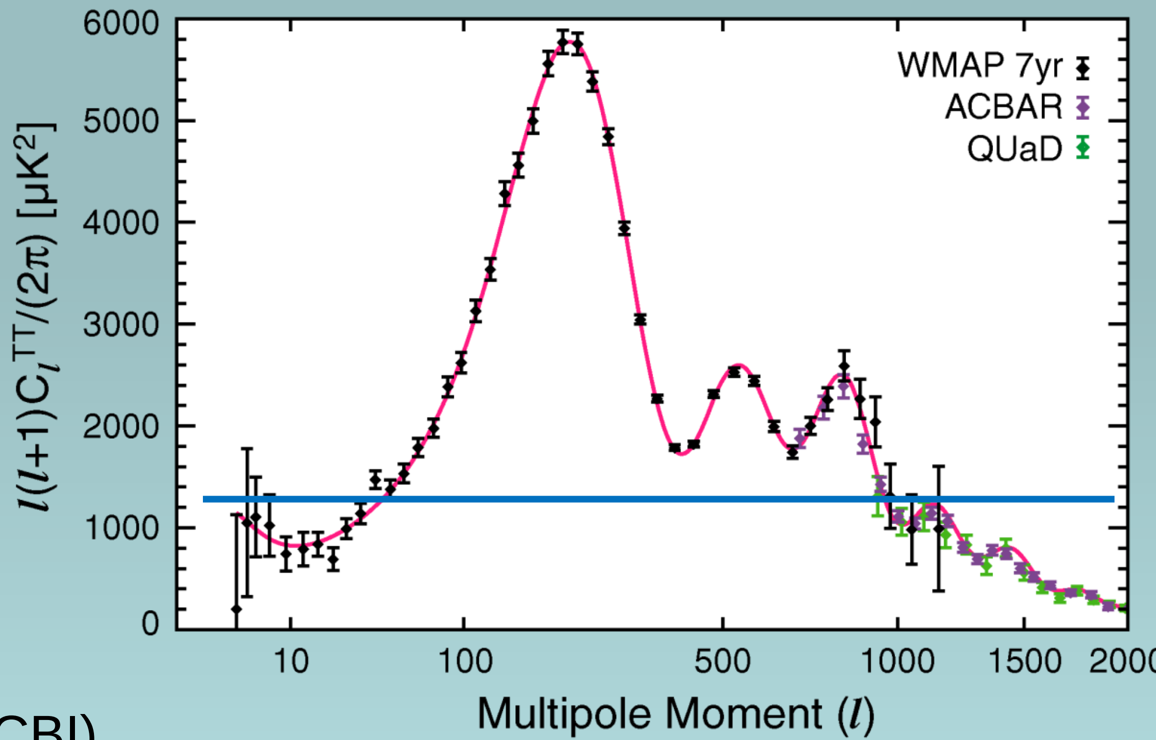

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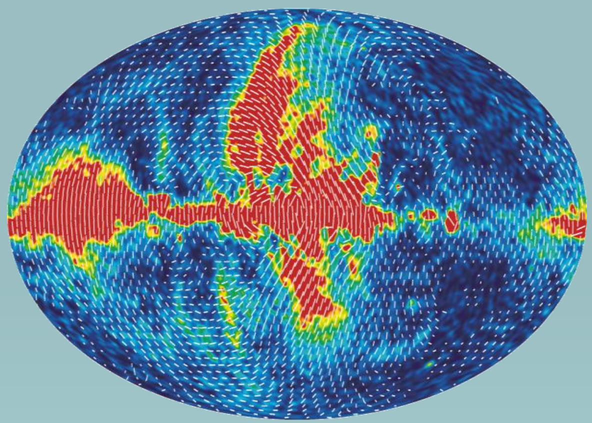

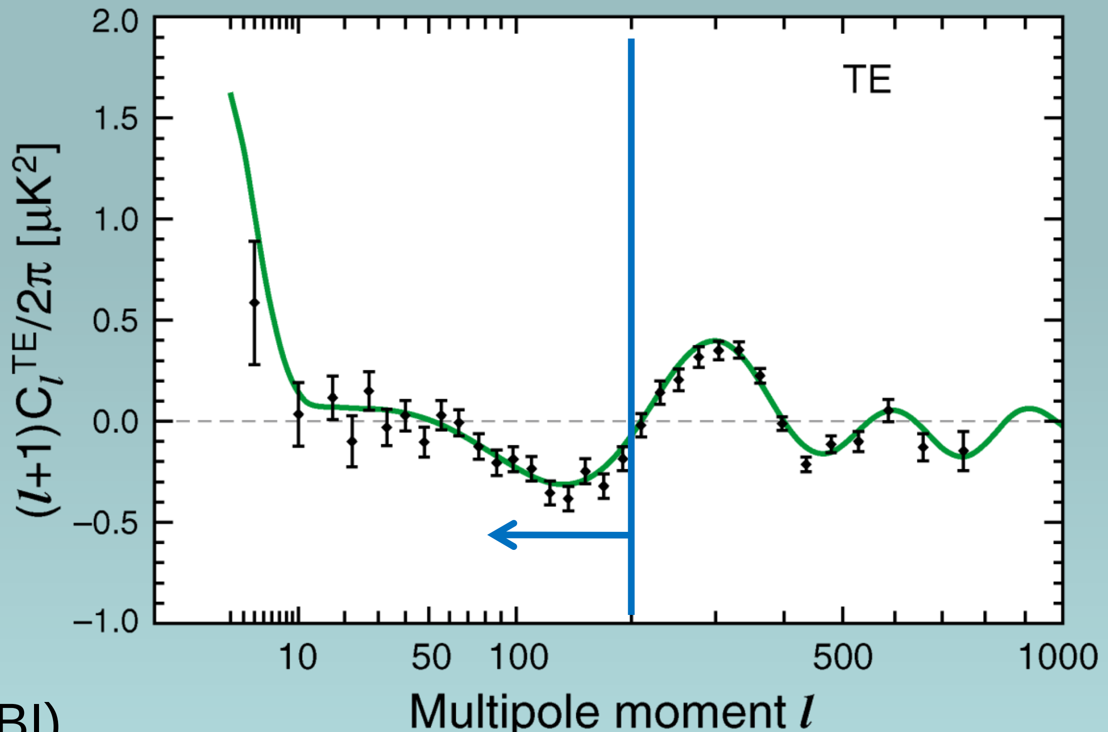

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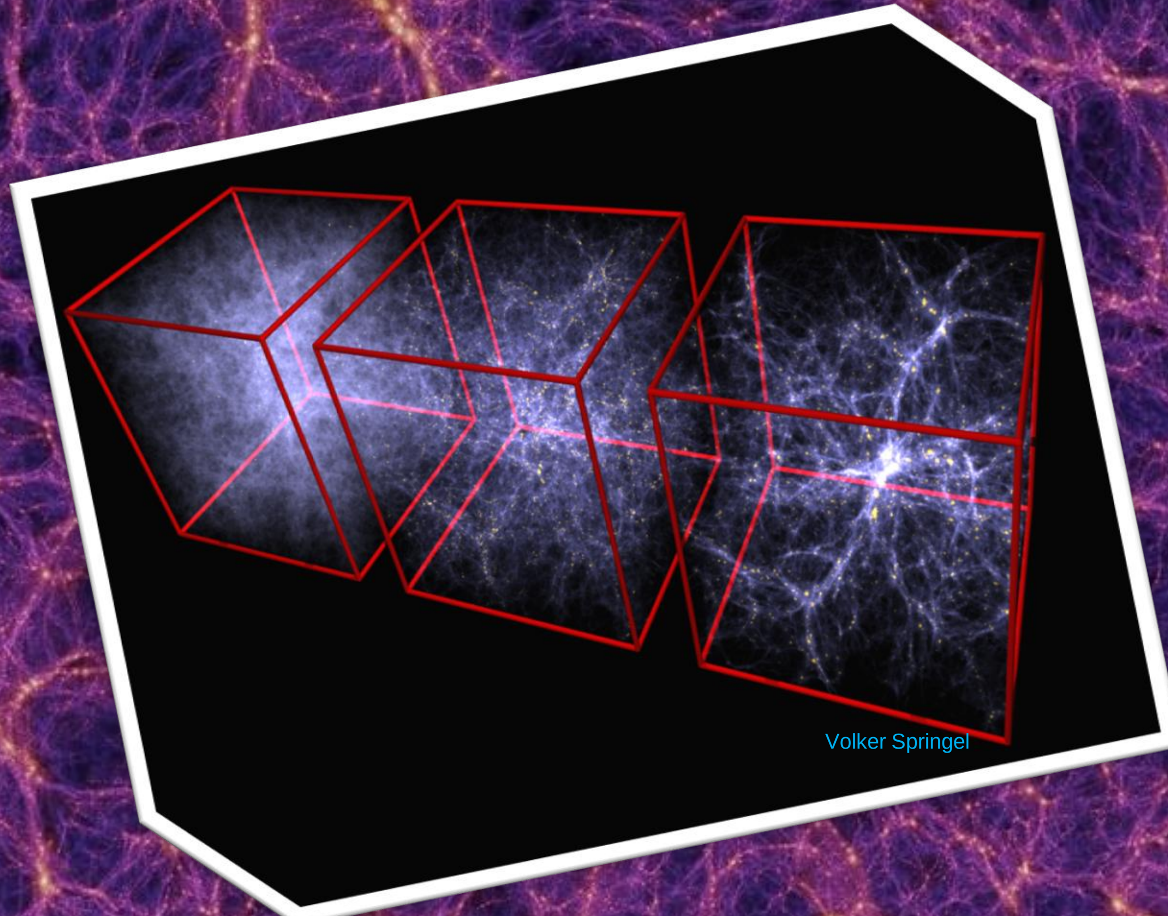


Scalar perturbations are well-tested as the seeds for structure formation.

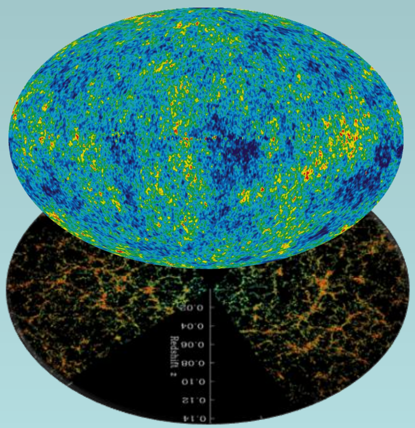
Windows on the physics of inflation

All observations are consistent with scalar perturbations that are Gaussian and adiabatic, and vanishing tensor perturbations.

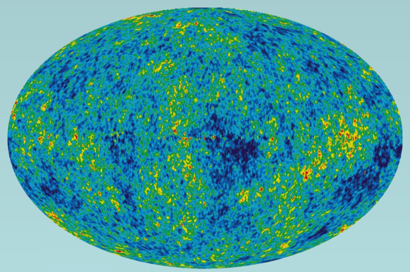
$-10 < f_{NL}^{local} < 74$

$r < 0.20$

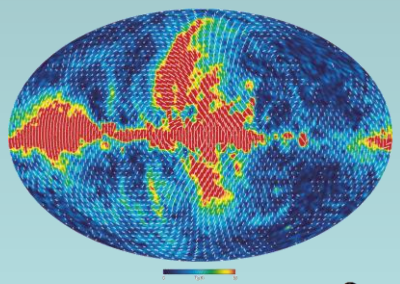
Gaussian for a free field; non-Gaussianity probes interactions



Adiabatic when there is a single clock (field); non-adiabaticity would prove that multiple fields were light during inflation

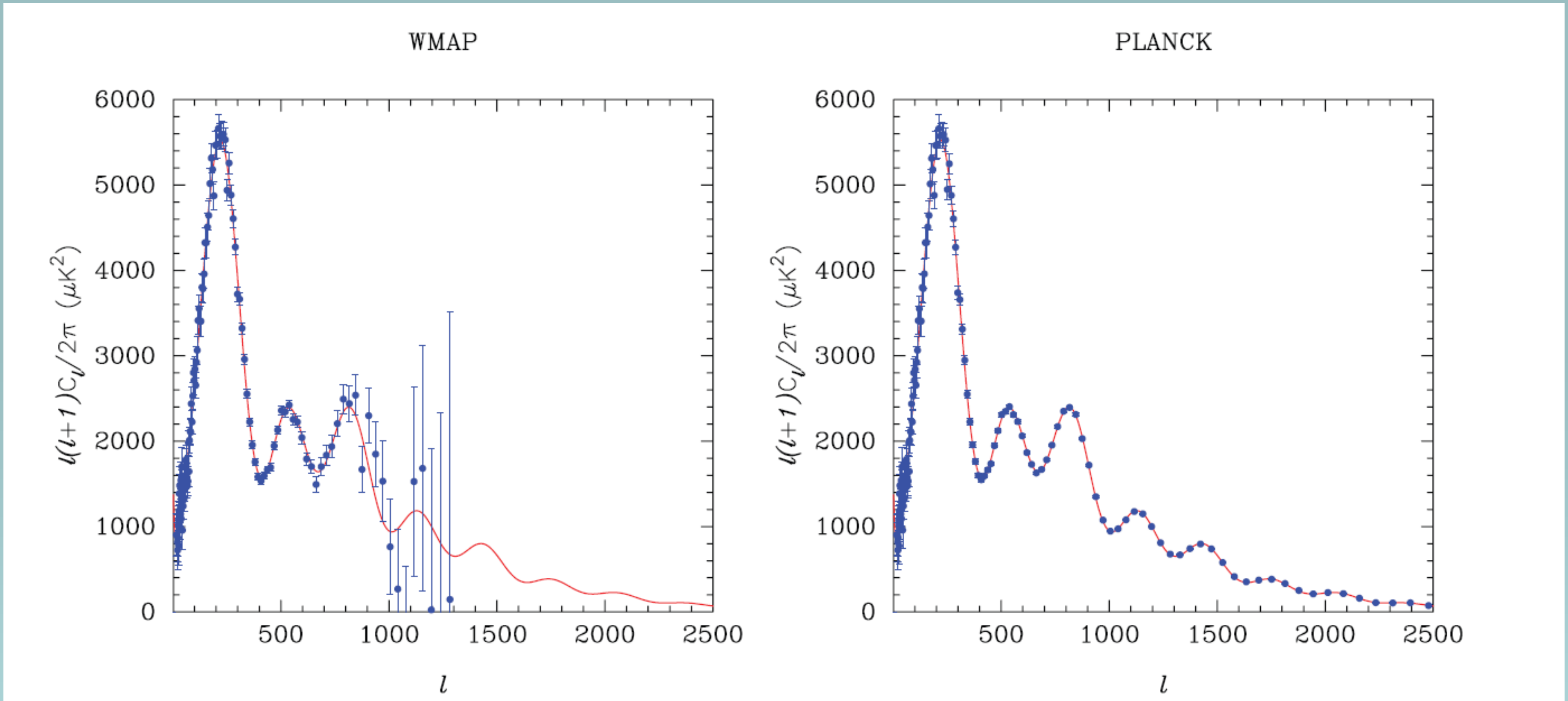


Amplitude directly reveals energy scale of inflation; detectable only in GUT-scale models with super-Planckian inflaton displacements **Lyth 96**



$$r < 0.01 \left(\frac{\Delta\phi}{M_p}\right)^2$$

Near-term prospects



Planck blue book forecast

II.
Why use string theory in cosmology?

Inflation is sensitive to Planck-scale physics.

- Inflationary dynamics is generically controlled by non-renormalizable contributions to the effective Lagrangian.
  - We expect contributions from integrating out massive degrees of freedom, with mass Λ, to which the inflaton couples.
  - The ultraviolet completion of gravity should furnish new d.o.f. with Λ at or below the Planck scale.
  - With $\Lambda = M_p$ and $\mathcal{O}(1)$ couplings, a class of operators with dimension $\Delta \leq 6$ make critical corrections to the dynamics.
  - Thus, Planck-scale physics does not decouple from inflation.
- In this sense, inflation is sensitive to the ultraviolet completion of gravity.
  - This presents a remarkable opportunity!

Planck-sensitivity of inflation

$$\mathcal{L} = \frac{1}{2}(\partial\phi)^2 - V_0(\phi)$$

$$\eta \equiv M_p^2 \frac{V''}{V} \ll 1$$

$$\Delta V \equiv \mathcal{O}_\Delta = V_0 \left(\frac{\phi}{\Lambda}\right)^{\Delta-4} \Longrightarrow \delta\eta \sim \left(\frac{M_p}{\phi}\right)^2 \left(\frac{\phi}{\Lambda}\right)^{\Delta-4}$$

$$\Delta = 6: \quad \delta\eta \sim \left(\frac{M_p}{\Lambda}\right)^2 \gtrsim 1$$

For small inflaton displacements, $\Delta\phi \lesssim M_{pl}$, one must control corrections $\mathcal{O}_\Delta$ with $\Delta \lesssim 6$.

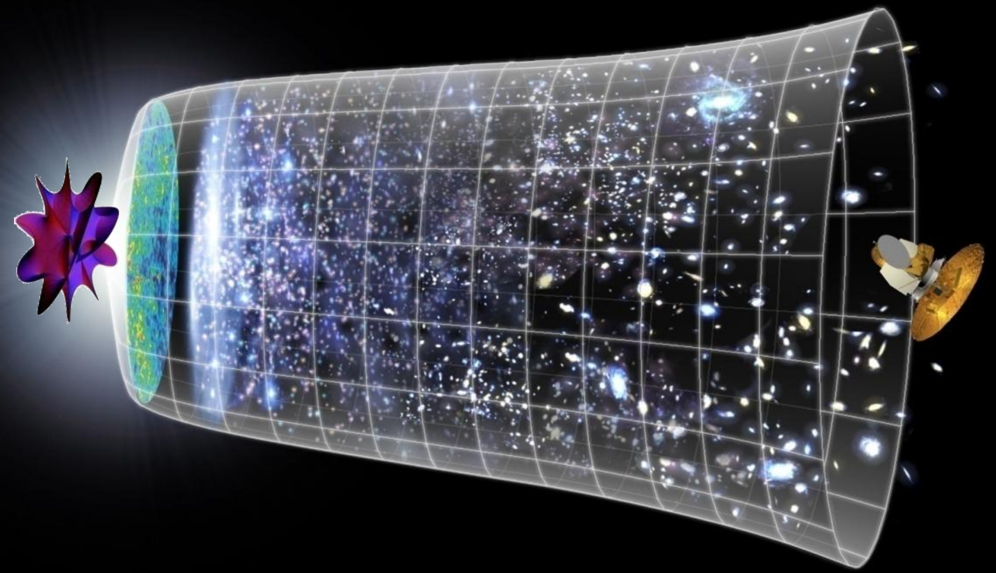
For large inflaton displacements, $\Delta\phi \gg M_{pl}$, one must control an infinite series of corrections, with arbitrarily large Δ.
(These large-field models we can identify unambiguously by detecting primordial tensors.)

cf. talk by Linde

Naturalness and the inflaton mass

- Without a symmetry, inflaton mass can run up to the cutoff Λ, and $\Lambda > H$.
- Even low-scale models with small inflaton displacements are affected.
- For models with large inflaton excursions, one must further understand why the inflaton enjoys a symmetry that suppresses its couplings to the massive d.o.f so that its potential can remain flat over a super-Planckian range.
- It is not difficult to write down low-energy theories that inflate, even over super-Planckian distances. The questions are whether these theories are natural, and whether they can be UV completed.
- Task: understand contributions to inflaton action from integrating out massive fields that are part of the ultraviolet completion of gravity.
- In string theory, these massive fields include stabilized compactification moduli. So we need a detailed understanding of moduli stabilization.
- Very general lesson: proper embedding in string theory enforces naturalness, i.e. all possible contributions appear with $\mathcal{O}(1)$ coeffs.

III.
Inflation in string theory



NASA/WMAP Science Team

The moduli problem

- Zeroth-order problem: in the best-understood compactifications, we have light moduli. These are generally fatal for cosmology. (decompactification instability; photo-dissociation; overclosure;…)
- A key development of the past decade: emergence of methods for moduli stabilization.
- Tasks:
  1. find a string compactification with stabilized moduli. For inflation or dark energy, this should be a compactification to (quasi-) de Sitter space.
  2. understand the effective theory of this stabilized compactification.

de Sitter vacua

- We need to identify compactifications of string theory to dS_4 in which all moduli are stabilized. cf. talks by Graña, Shiu
- Common approach: find a stabilized AdS_4 vacuum, which may or may not be SUSY, and 'uplift' to dS_4.

KKLT 03; Balasubramanian, Berglund, Conlon, Quevedo 05; Conlon, Quevedo, Suruliz 05; Bobkov, Braun, Kumar, Raby 10

- Critical ingredients:
  1. a mechanism fixing all the moduli
  2. a mechanism producing controllably small, metastable SUSY breaking in string theory (not in global SUSY)

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I will not review (1). The evidence appears strong (at least for AdS in IIA, IIB).

Derendinger et al.; DeWolfe,Giryavets,Kachru,Taylor 05; Villadoro, Zwirner 05; Silverstein 07; Danielsson, Haque, Koerber,Shiu, Van Riet, Wrase 11

In type IIB, anti-D3-branes in a Klebanov-Strassler throat region provide (2), cf. talk by Graña. **Bena, Graña, Halmagyi 09; BGH+Giecold 10; BGGH+Massai 11; Dymarsky 11**

In other string theories, no compelling solution for (2). Some claimed solutions are global mechanisms in disguise, but coupling to gravity promotes control parameters to dynamical fields, with corresponding runaways. cf. also **Komargodski, Seiberg 10**

A realistic task for the model-builder

- For the basic question of embedding inflation in string theory, one needs to achieve the following:
  - ❑ Construct a compactification with stabilized moduli;
  - ❑ Select an inflaton candidate;
  - ❑ Compute the inflaton action, including the significant Planck-suppressed contributions (finitely many iff inflaton displacement is sub-Planckian);
  - ❑ Determine a controllable regime in which inflation occurs and ends.
- One hopes for more, e.g.:
  - ❑ Distinctive signatures;
  - ❑ Understanding of initial conditions;
  - ❑ Natural mechanism protecting the inflaton potential (e.g., shift symmetry).
- Compact models with broken supersymmetry and stabilized moduli are messy systems!
  - – Many approximations (long wavelength, weak coupling, probe, noncompact…) required, and their domain of overlapping validity can be slender.

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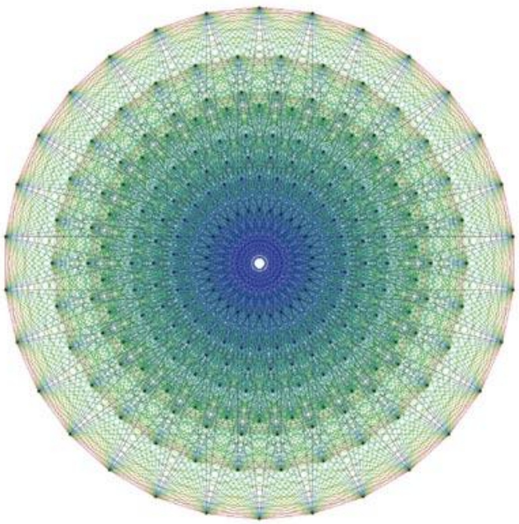
Selected attempts to realize inflation in string theory

Dvali, Tye 98; Dvali,Shafi,Solganik 01; Burgess,Majumdar,Nolte,Quevedo,Rajesh,Zhang 01;
Garcia-Bellido, Rabadan, Zamora 01; Blumenhagen, Körs, Lüst,Ott 02;
Kachru, Kallosh, Linde, Maldacena, L.M., Trivedi 03;
Silverstein, Tong 03;
DeWolfe, Kachru, H. Verlinde 04;
Blanco-Pillado et al. 04;
Kallosh, Hsu, Prokushkin 04; Haack, Kallosh, Krause, Linde, Lüst, Zagermann 08;
Becker, Becker, Krause 05;
Conlon, Quevedo 05;
Dimopoulos, Kachru, McGreevy, Wacker 05; Grimm 07;
Kecskemeti, Maiden, Shiu, Underwood 06; Pajer 08;
Baumann, Dymarsky, Kachru, Klebanov, L.M. 07; Krause, Pajer 07;
Cicoli, Burgess, Quevedo 08;
L.M., Silverstein, Westphal 08; Berg, Pajer, Sjörs 09;
Silverstein, Westphal 08;
Ashoorioon, Firouzjahi, Sheikh-Jabbari 09, 11;
Hebecker, Kraus, Lüst, Steinfurt, Weigand 11.

Given the difficulty in finding controllable de Sitter vacua outside of type IIB flux compactifications, the presently best-developed models are set in KKLT or Large Volume Scenario compactifications of type IIB string theory.

Two approaches



Enumerate
all significant contributions
in a computable example

Identify a robust symmetry,
in a UV completion,
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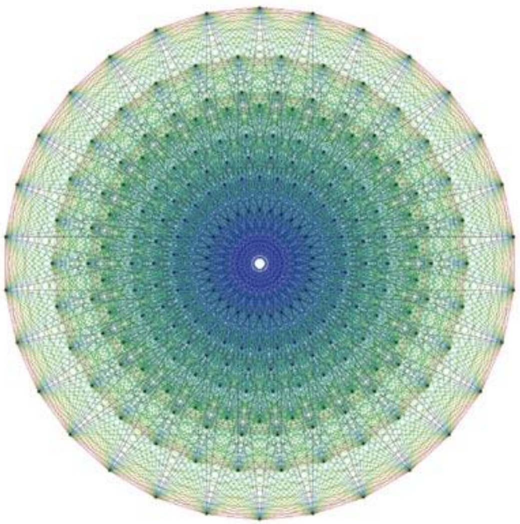
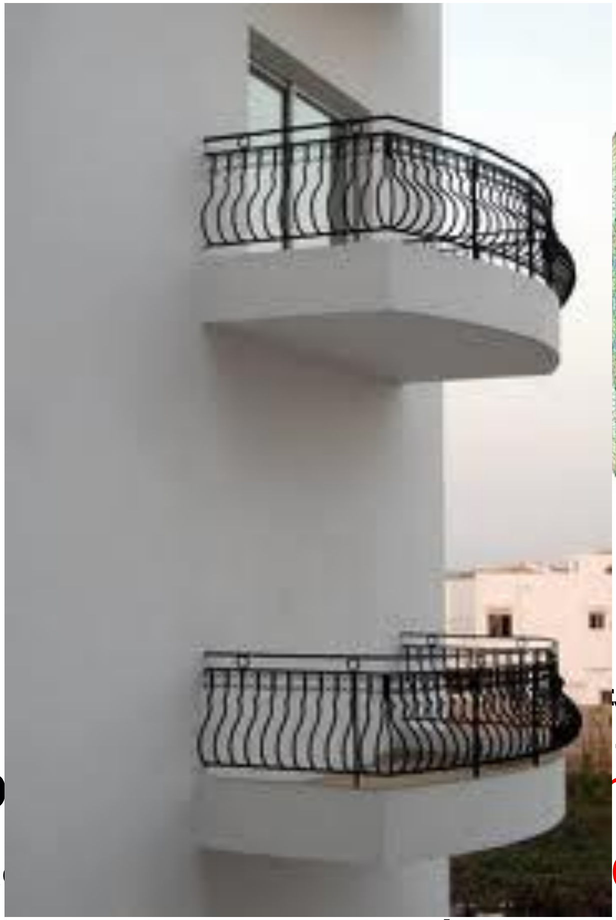
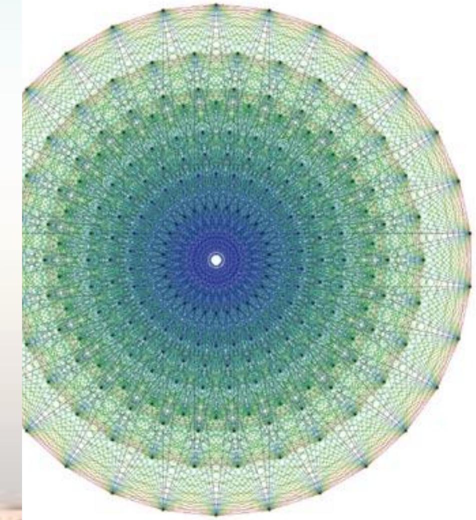


Enumerate
some significant contributions
in a computable example

Identify a symmetry,
broken by the UV
completion, that would
have protected the inflaton

Two approaches





Enumerate
some significant co
in a computable ex

y a symmetry,
n by the UV
etion, that would
have protected the inflaton

Example 1:
Warped D3-brane inflation

Kachru, Kallosh, Linde, Maldacena, L.M., Trivedi 03

Choosing a lamppost

- In principle we'd like to choose a compact model with explicitly stabilized moduli, and *directly* compute the effective theory up to (say) $\Delta=8$ contributions.
- This has not been achieved at present.
- Idea: study the effective theory of a local region of a stabilized compactification, and use 10d locality to simplify the calculation.
- Key simplification: in type IIB string theory, the best-understood methods of moduli stabilization yield 10d solutions that can be formulated in systematic expansion around conformally Calabi-Yau backgrounds.

Conformally Calabi-Yau (CCY) background

$$
\begin{aligned}
&\mathrm{d}s^2 = e^{2A(y)} g_{\mu\nu} \mathrm{d}x^\mu \mathrm{d}x^\nu + e^{-2A(y)} g_{mn} \mathrm{d}y^m \mathrm{d}y^n \,, \\
&\tilde{F}_5 = (1 + \star_{10})\, \mathrm{d}\alpha(y) \wedge \sqrt{-\det g_{\mu\nu}}\, \mathrm{d}x^0 \wedge \mathrm{d}x^1 \wedge \mathrm{d}x^2 \wedge \mathrm{d}x^3 \,, \\
&G_{mnl} = G_{mnl}(y) \,, \quad m, n, l = 4, \ldots 9 \,, \\
&G_{\mu NL} = 0 \,, \quad \mu = 0, \ldots 3 \,, \quad N, L = 0, \ldots 9 \,, \\
&\tau = \tau(y) \,,
\end{aligned}
$$

$$
\begin{aligned}
G_\pm &\equiv (\star_6 \pm i) G_3 \,, \\
\Phi_\pm &\equiv e^{4A} \pm \alpha \,,
\end{aligned}
$$

$$
\begin{aligned}
G_- &= 0 \,, \\
\Phi_- &= 0 \,, \\
\nabla \tau &= 0 \,.
\end{aligned}
$$

Perturbation expansion for stabilized vacua

- CCY spaces provide some of the best-studied type IIB flux compactifications, but yield ‘no-scale’ models in which the complex structure moduli and dilaton are stabilized, but the Kähler moduli are massless at leading order. **Giddings, Kachru, Polchinski 01**
- Flat directions in Kähler moduli space lifted by:
  - Euclidean D3-branes, or gaugino condensation on N_c D7-branes, wrapping suitable four-cycles.
  - α' and g_s corrections

KKLT 03; Balasubramanian, Berglund, Conlon, Quevedo 05; Conlon, Quevedo, Suruliz; Bobkov, Braun, Kumar, Raby

- These effects are typically treated in 4d, but can be described in 10d. The stabilized geometry is no longer CCY.

cf. my talk at Strings 2010

Koerber, Martucci 07;
Baumann, Dymarsky, Kachru, Klebanov, L.M. 09, 10;
Heidenreich, L.M., Torroba 10; Dymarsky, Martucci 10

- The moduli potential is small in string units, so deviations from the CCY background are small, and can be treated perturbatively.
- Expanding to any order n, one finds a remarkable simplification: the EOM are triangular, and hence can be solved iteratively. (SUSY not required.)

Gandhi, L.M., Sjörs 11

Triangularized EOM: a toy model

$$\frac{\mathrm{d}}{\mathrm{dr}}\varphi_A^{(n)} = N_A{}^B \varphi_B^{(n)} + \mathcal{S}_A$$

$N_A{}^B$ depends on $\varphi_C^{(0)}(r)$

$\mathcal{S}_A$ depends on $\varphi_C^{(m)}(r)$, $m < n$

Triangularized EOM: a toy model

$$\frac{\mathrm{d}}{\mathrm{dr}}\varphi_A^{(n)} = N_A{}^B \varphi_B^{(n)} + \mathcal{S}_A$$

$$N_A{}^B \text{ depends on } \varphi_C^{(0)}(r)$$
$$\mathcal{S}_A \text{ depends on } \varphi_C^{(m)}(r),\ m < n$$

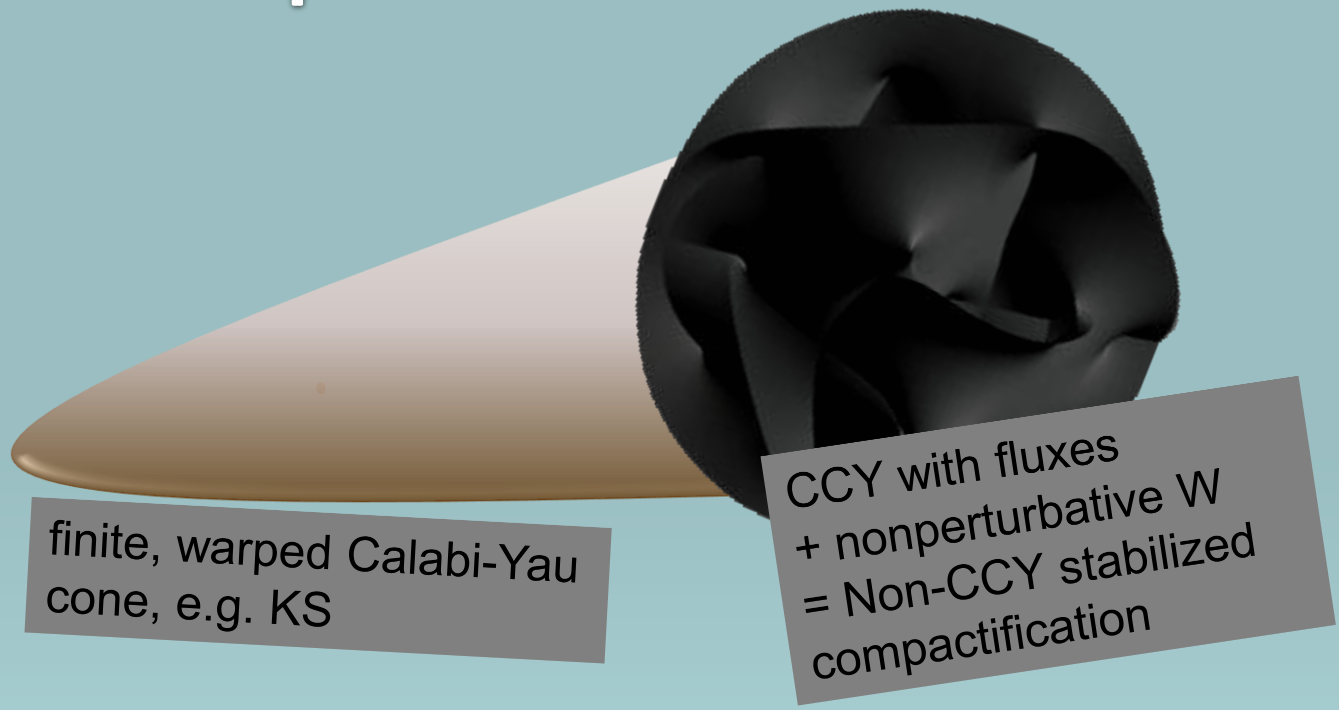
$$N_A{}^B = 0 \text{ for A} < \text{B}$$

We find that the type IIB EOM, expanded to any order n around a CCY background, are triangular. **Gandhi, L.M., Sjörs 11**

cf. Borokhov, Gubser 02 for singlet modes in KS
cf. talk by Graña

To perform actual calculations in IIB supergravity, we will need to use a local approximation.

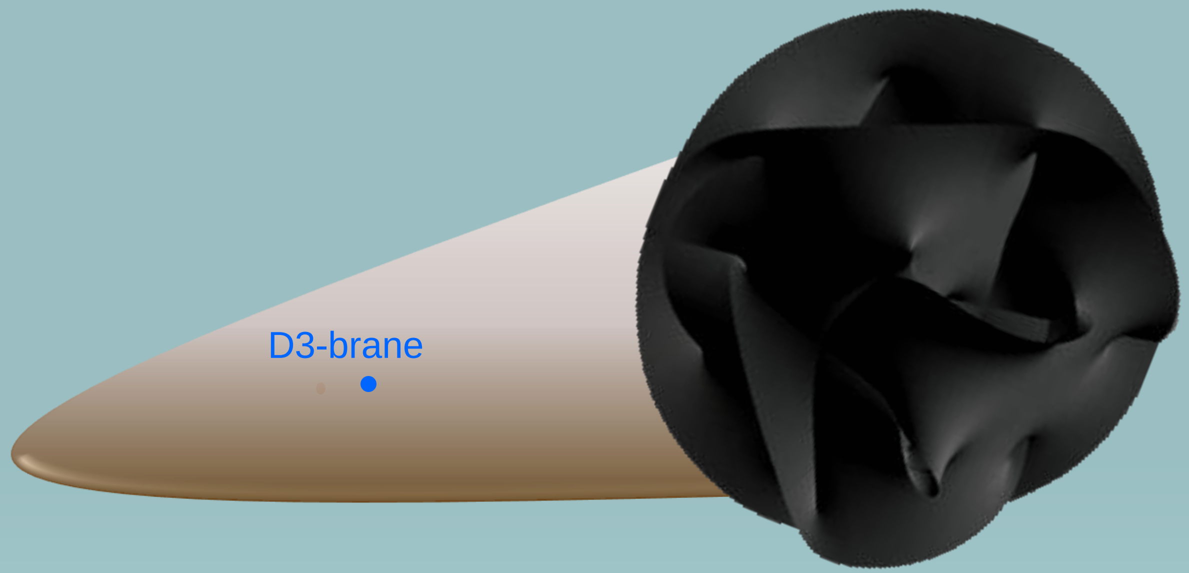
The local geometry of a stabilized compactification



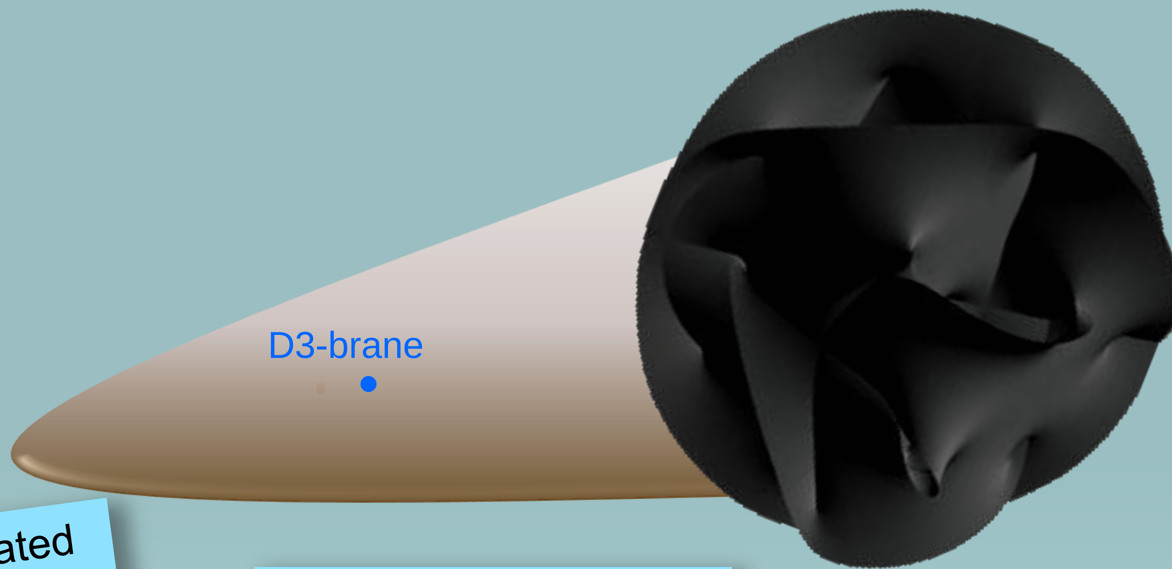
Using the perturbative tools just described, we can find a general solution in the throat region sourced by arbitrary effects in the bulk. cf. my talk at Strings 2010

This is our lamppost: such a solution specifies the potential felt by a D3-brane in a throat region of a stabilized compactification.

Warped D-brane inflation



Warped D-brane inflation



Wilson coefficients dictated by details of bulk sources

Operator dimensions fixed by local geometry

$$V(r,\Psi) = \sum_i c_i r^{\Delta_i} h_i(\Psi)$$

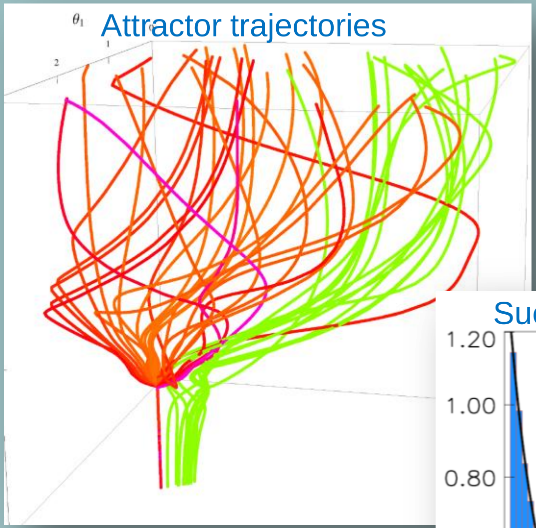
$$\Delta = 1, \tfrac{3}{2}, 2, \sqrt{28}-3, \tfrac{5}{2}, \sqrt{28}-\tfrac{5}{2}, \ldots$$

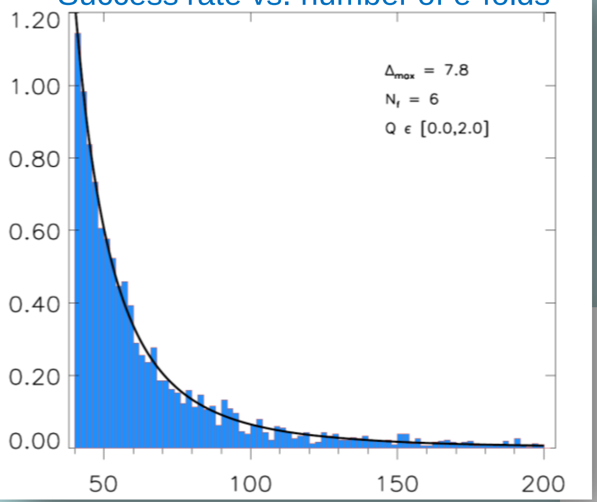
Ceresole, Dall'Agata, D'Auria, Ferrara 99
Baumann, Dymarsky, Kachru, Klebanov, L.M. 08, 09, 10
Gandhi, L.M., Sjörs, 11

Statistics of D-brane inflation

Agarwal, Bean, L.M., Xu 11

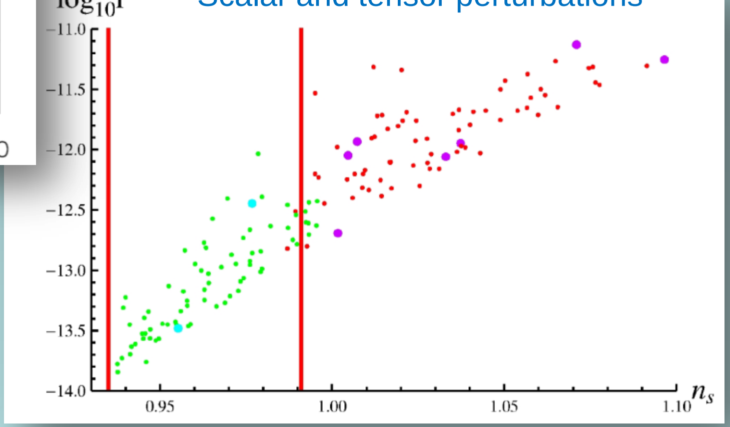
$$V(r,\Psi) = \sum_i c_i r^{\Delta_i} h_i(\Psi)$$


Attractor trajectories



Success rate vs. number of e-folds

We kept the 333 terms with $\Delta<7.8$, and created an ensemble of 7×10^7 realizations of the system, drawing the Wilson coefficients from statistical distributions.



Scalar and tensor perturbations

We then identified phenomenological properties that are demonstrably independent of the distribution, and hence are statistically insensitive to ultraviolet physics.

Status summary for D3-brane inflation

Motivations:

- local geometry makes computations possible.
- signatures include cosmic superstrings. **Sarangi, Tye 02; Copeland, Myers, Polchinski 03**
- if DBI kinetic term is important, striking ‘equilateral’ non-Gaussianity. **Silverstein, Tong 03; Alishahiha, Silverstein, Tong 04**

This model is not protected by a symmetry.

- inflation occurs by chance, at an inflection point that is small in Planck units.

We can compute the ‘structure’ of the inflaton potential.

- incorporates effects of moduli stabilization, to any desired order.
- we cannot presently compute the Wilson coefficients.

The phenomenology is statistically insensitive to ultraviolet physics.

Example 2:
Axion inflation

Kim, Nilles, Peloso 04
Dimopoulos, Kachru, McGreevy, Wacker 05
Grimm 07
L.M., Silverstein, Westphal 08
Flauger, L.M., Pajer, Westphal, Xu 09
Berg, Pajer, Sjörs 09

cf. Silverstein, Westphal 08

Symmetries and large field inflation

Large-field inflation is interesting and important, because it is particularly sensitive to ultraviolet physics.

Approach: identify a robust symmetry in a UV completion that protects the inflaton over a super-Planckian range.

In axion inflation models, a PQ symmetry is supposed to protect the inflaton potential over super-Planckian distances.

Freese, Frieman, Olinto 90

To address questions of the UV completion, we will try to embed these models in string theory. Burning question: will the moduli potential respect the candidate shift symmetry?

Promising candidate: an axion

- Axions are numerous, descending from $\int_{\Sigma_p} C_p$ and $\int_{\Sigma_2} B_2$
- Typically enjoy all-orders shift symmetry

Wen, Witten 86
Dine, Seiberg 86

- Nonperturbative effects break the continuous shift symmetry, generating a periodic potential:

$$V = \Lambda^4 \cos(a) = \Lambda^4 \cos\left(\frac{\phi}{f}\right) \qquad \frac{1}{2} f^2 (\partial a)^2 \equiv \frac{1}{2}(\partial\phi)^2$$

- The field range, i.e. the periodicity, is 2πf.

cf. talk by Wilczek

Idea: “Natural Inflation”

Q: Can we use $V = \Lambda^4 \cos(a) = \Lambda^4 \cos\left(\frac{\phi}{f}\right)$ to drive inflation? This requires $f \gg M_p$.

Freese, Frieman, Olinto 90

A: Not possible in presently computable limits of string theory.

Banks, Dine, Fox, Gorbatov 03

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Banks, Dine, Fox, Gorbatov 03

Since the individual decay constants are too small, we can:

- Take the inflaton to be a collective excitation of many axions (N-flation)

  Dimopoulos, Kachru, McGreevy, Wacker 05; Easther, L.M 05; Grimm 07
  cf. M-flation Ashoorioon, Firouzjahi, Sheikh-Jabbari 09

- Traverse many periods of one axion (axion monodromy)

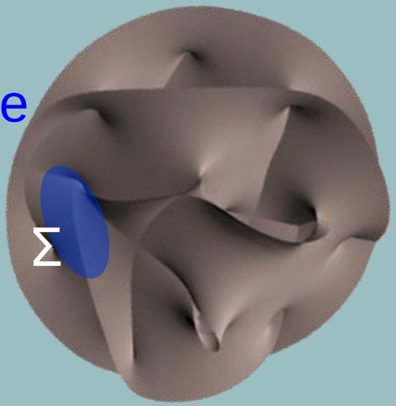
L.M., Silverstein, Westphal 08

cf. first monodromy model (D-brane monodromy) Silverstein, Westphal 08

Axion monodromy from wrapped fivebranes

D5-brane

$\int_{\Sigma} B_2 \equiv b$



$$V_{DBI} = \int_{\Sigma_2} \frac{d^2\xi \, e^{2A-\Phi}}{(2\pi)^5 \alpha'^3} \sqrt{\det(G+B)}$$

Axion monodromy from wrapped fivebranes

D5-brane

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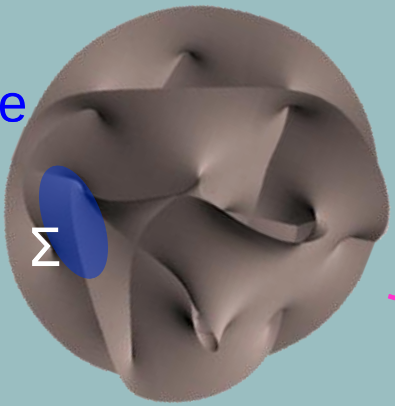

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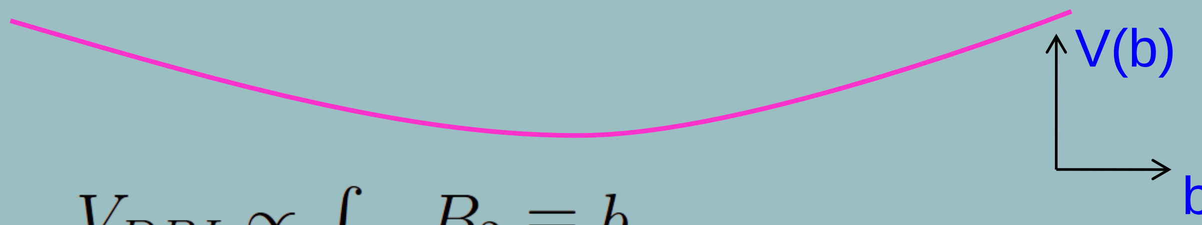


For large b, $$V_{DBI} \propto \int_{\Sigma_2} B_2 \equiv b$$

so we can define $$\boxed{V_{DBI} \approx \mu^3 b f \equiv \mu^3 \phi}$$

Fivebrane contribution not periodic: as axion shifts by a period, potential undergoes a monodromy that unwraps the axion circle.
Result: asymptotically linear potential over an *a priori* unlimited field range.

L.M., Silverstein, Westphal 08

For $\mathcal{O}(10^2)$ circuits one can obtain $$\boxed{\Delta\phi = 11 M_p}$$

Compactification and stabilization

- For tadpole cancellation, take fivebrane and anti-fivebrane wrapped on homologous curves, metastabilized by a larger representative in between. **cf. Aganagic, Beem, Seo,Vafa**

Attach to KKLT compactification.

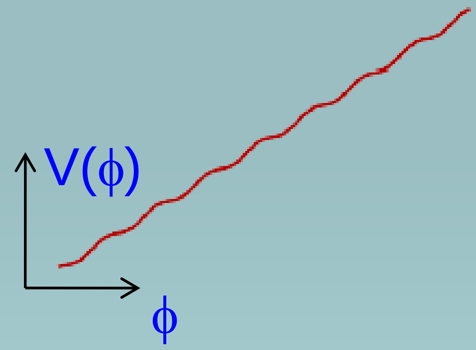
- Moduli potential gives a fatal Δ=6 contribution to the potential for b, but not for c. This is the axionic shift symmetry in action!
- Thus, take NS5-brane pair, and take c to be the inflaton. The leading c-dependence in the effective action comes from the NS5-brane tension. $V(\phi) = \mu^3\phi$

Nonperturbative corrections

Continuous shift symmetry is also broken by nonperturbative effects (e.g., Euclidean D1-branes).

This introduces periodic modulations of the previously-linear inflaton potential.

$$V(\phi) = \mu^3\phi + \Lambda^4 \cos\left(\frac{\phi}{f}\right)$$

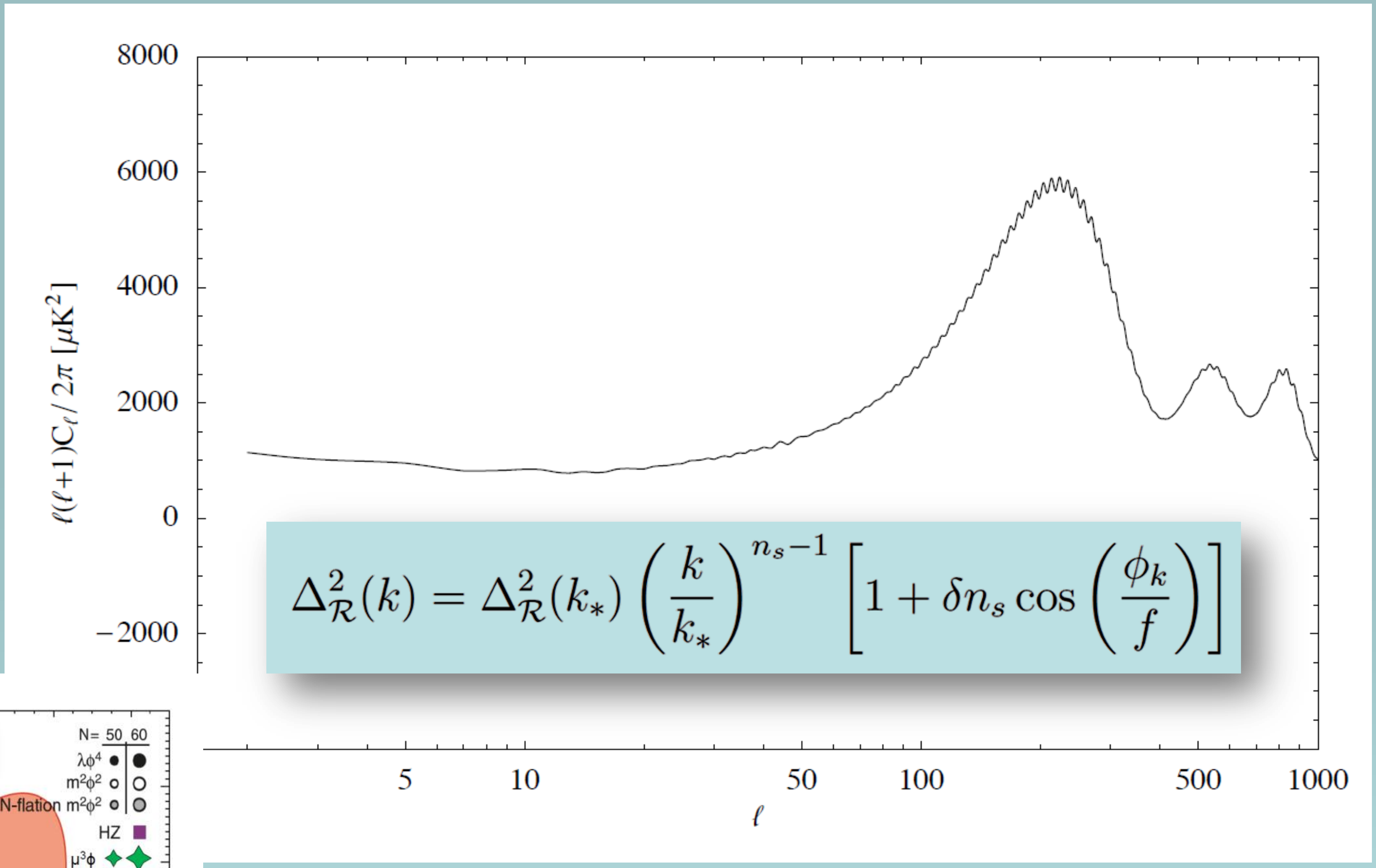


The modulations produce a driving force that resonates with the oscillations of modes inside the horizon.

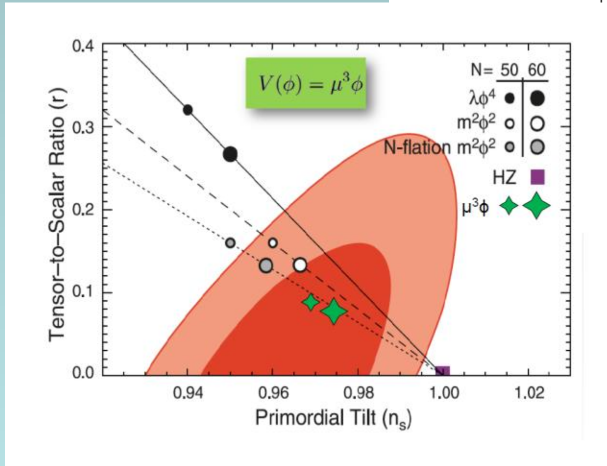
Result: resonant perturbations of the spectrum and bispectrum.

Flauger, L.M., Pajer, Westphal, Xu 09

Modulated scalar power spectrum



$$\Delta^2_{\mathcal{R}}(k) = \Delta^2_{\mathcal{R}}(k_*)\left(\frac{k}{k_*}\right)^{n_s-1}\left[1+\delta n_s \cos\left(\frac{\phi_k}{f}\right)\right]$$



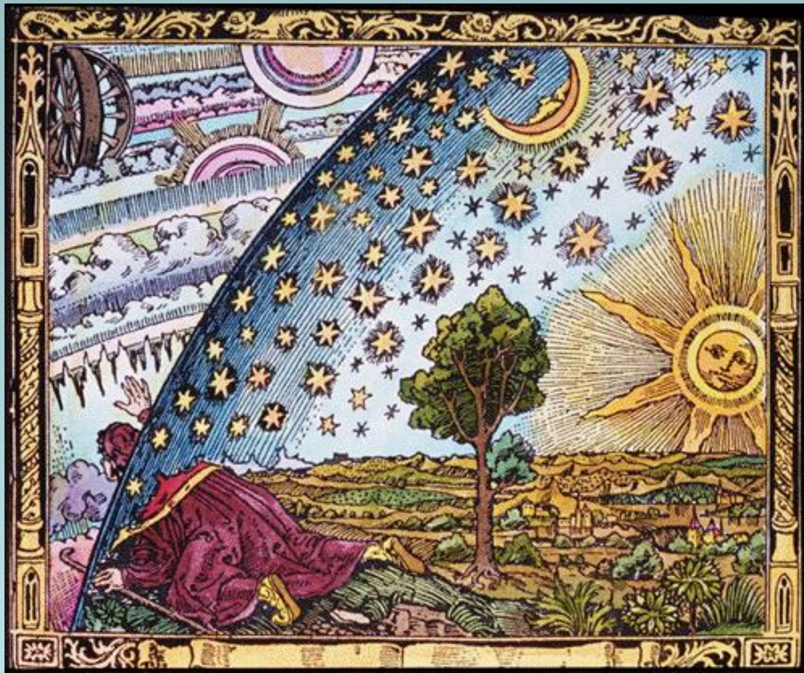
Key effect: resonance between oscillations inside the horizon and driving force from modulations.

Eternal inflation in a landscape of vacua

- Eternal inflation remains one of the most pressing conceptual issues in theoretical cosmology.
- So far, string theory has interacted with this problem in two primary ways:
  - by providing a toy landscape for false vacuum eternal inflation
  - through holographic duals of eternal inflation

Freivogel, Hubeny, Maloney, Myers, Rangamani, Shenker 05
Freivogel, Sekino, Susskind, Yeh 06
Lowe, Roy 10

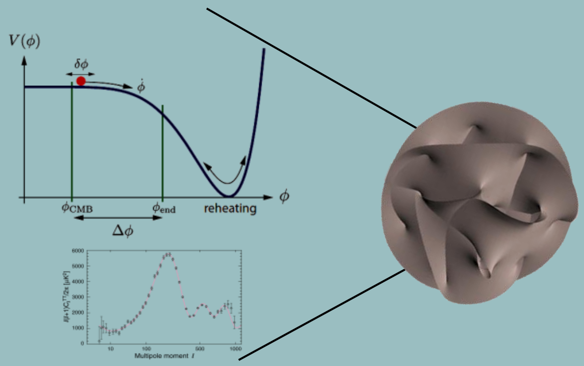
The tools are interesting, but it is not yet clear that the urgent questions (e.g., how to define the measure) have been resolved.



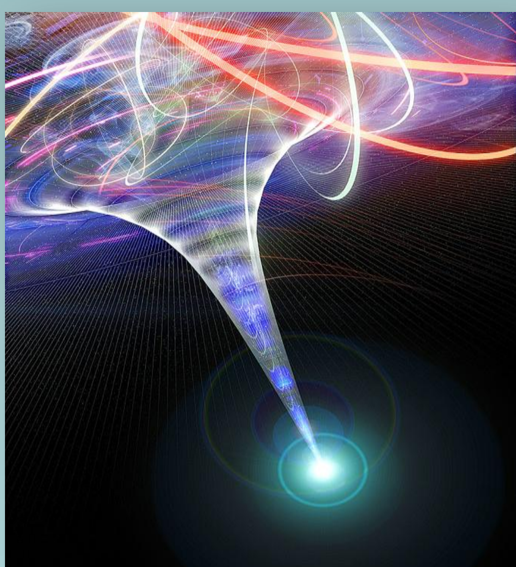
IV.
The initial singularity,
and
alternative cosmologies

Inflation and the initial singularity

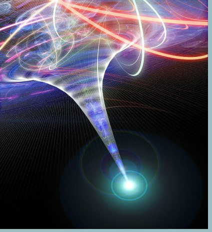
Two broad approaches to describing the early universe in string theory:



Embed inflation in a string compactification.
Study the dynamics in effective field theory. String theory contributes information about Planck-suppressed contributions in the EFT, and can also suggest novel mechanisms.



Study the Big Bang singularity.
Use string theory to develop a computable resolution of the singularity, e.g. a nonsingular bounce, or to understand basic properties of the singularity. Bouncing models are often presented as alternatives to inflation.



The initial singularity

Further choice:

- Toy models of the initial singularity, in string theory.

  Study particularly computable singularities in string theory (e.g. null singularities in Lorentzian orbifolds, in plane waves, or in AdS/CFT) and gradually approach the harder problem of the spacelike singularity in FRW. These toy models have highly unrealistic cosmology, but can be firmly grounded in string theory.

- Avoiding the initial singularity, in ‘toy models of string theory’.

  Try to replace the singularity with a nonsingular bounce. When long-wavelength gravity description fails, appeal to string theory.

  These bouncing models are typically presented as alternatives to inflation, with correspondingly realistic cosmologies. The connection to string theory requires further work!

Toy models of the initial singularity in string theory

Plan: identify a comparatively tractable singularity that is a toy model for the spacelike singularity in FRW, e.g.

1. Null singularity in a Lorentzian orbifold

Horowitz, Steif 91; Balasubramanian, Hassan, Keski-Vakkuri, Naqvi 02; Cornalba, Costa 02; Liu, Moore, Seiberg 02; Lawrence 02; Fabinger, McGreevy 02; Berkooz, Pioline, Rozali

2. Null singularity in an exact plane wave

Horowitz, Steif, Papadopoulos, Russo, Tseytlin, Craps, de Roo, Evnin 08; cf. Madhu, Narayan 09

3. Null/spacelike singularity in AdS

Hertog, Horowitz 04; Das, Michelson, Narayan, Trivedi 06; Craps, Hertog, Turok 07

4. Singularity removed by a winding tachyon

McGreevy, Silverstein

In many cases, there is a singular crunch upon adding even one particle or string.

Horowitz , Polchinski 02; Hertog, Horowitz 04; Craps, de Roo, Evnin 08

Gauge theory suggests null AdS case may be smooth. **Das, Michelson, Narayan, Trivedi 06**

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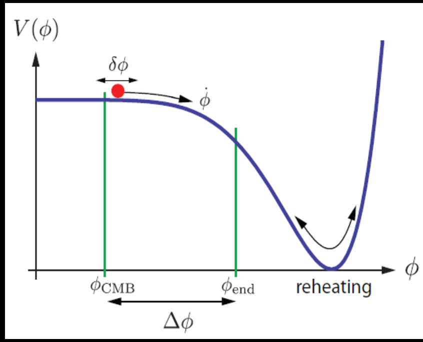
In many cases, th ... or string.

Ho

Gau ... y be smooth. **Das, Michelson, Narayan, Trivedi 06**

Impressive tools, but much work required to connect to the observed universe

V.
Slightly Alternative Cosmologies



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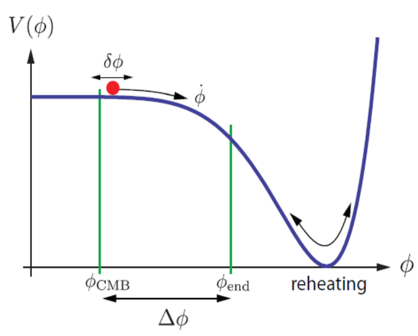

Push the boundaries of QFT+GR

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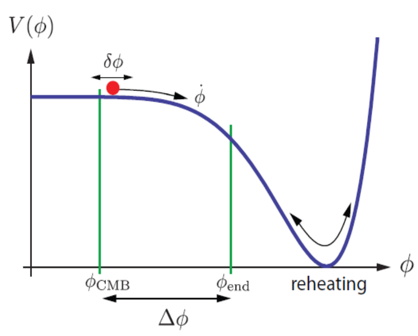

Push the boundaries of QFT+GR

Reformulate QFT+GR

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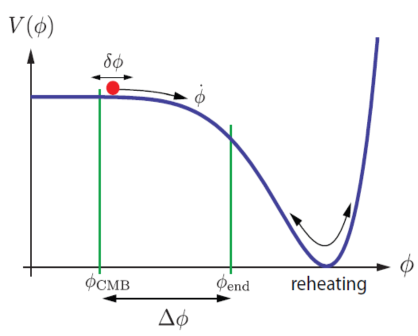

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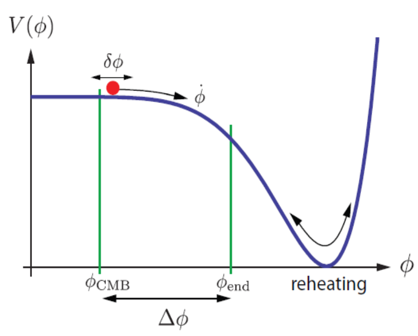

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Toward bouncing cosmologies

Veneziano 91; Gasperini, Veneziano 92; Khoury, Ovrut, Steinhardt, Turok 01, Steinhardt, Turok 01; Buchbinder, Khoury, Ovrut 07

Idea: replace the Big Bang singularity with a transition to a prior contracting phase.

When low-energy Einstein equations apply, for FRW we have

$$\left(\frac{\dot{a}}{a}\right)^2 + \frac{k}{a^2} = \frac{8\pi G}{3}\rho \quad \text{and} \quad \frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3p)$$

Then for k=0 or k=-1, a bounce requires violation of the null energy condition! This generically leads to instabilities – tachyons or ghosts.

Toward bouncing cosmologies

Proposal: ghost condensate [**Arkani-Hamed, Cheng, Luty, Mukohyama 03**] could support a nonsingular bounce. **Creminelli, Luty, Nicolis, Senatore 06**

UV completion of ghost condensate highly questionable,

Adams, Arkani-Hamed, Dubovsky, Nicolis, Rattazzi 06

Arkani-Hamed, Dubovsky, Nicolis, Trincherini, Villadoro 07

Kallosh, Kang, Linde, Mukhanov 07

and there is no hint that this could be realized in string theory.

Even if we allow a ghost condensate, quantum fluctuations generate anisotropies that lead to an anisotropic crunch. **Steinhardt, Xue 11**

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No evidence for a controllable bounce in a UV-completable effective theory

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Then for k=0 or k=-1, a bounce requires violation of the null energy condition! This generically leads to instabilities – tachyons or ghosts.

What about bounces at high curvatures, beyond effective (super)gravity?

Bouncing models beyond effective supergravity

One sees claims that string theory produces bouncing alternatives to inflation. These models are “string inspired”:

- They write down potentials for ekpyrotic, dark energy, and ghost condensate phases without explaining how these arise in string theory;
- Moduli stabilization is typically ignored;
- At the critical juncture, when a bounce that is singular in supergravity arises, string theory is appealed to, but reliable computations yielding a smooth bounce are not available.

Models of inflation in string theory may seem involved, but at least one can stabilize the moduli, compute the inflaton potential, and describe everything in a consistent effective field theory.

Alternatives to inflation – at present – are rarely subjected to the same requirements.

Bouncing models beyond effective supergravity

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- Moduli stabilization is typically ignored;
- At th

Bouncing models provide interesting alternative mechanisms to produce primordial perturbations. At present, they are not compelling, and the connection to string theory is overstated:

- No evidence that the background evolution arises in a string construction.
- The perturbations depend on the details of a singular bounce, so any claim of predictivity deserves skepticism.

ive field theory.

Alternatives to inflation – at present – are rarely subjected to the same requirements.

String gas cosmology

- Initial idea: ask why we see three large dimensions, and propose that intercommutation of a gas of strings on T^9 would dynamically select this.
- Further developments: extensive attempts to move beyond heuristic thermodynamic arguments.

Brandenberger, Vafa 89
Tseytlin, Vafa 91
Alexander, Brandenberger, Easson 00
Easther, Greene, Jackson 02
Easther, Greene, Jackson, Kabat 04
Watson, Brandenberger 03
Battefeld, Watson 05
Kaloper, Kofman, Linde, Mukhanov 06

String gas cosmology

- Initial idea: ask why we see three large dimensions, and propose that intercommutation of a gas of strings on T^9 would dynamically select this.
- Further developments: extensive attempts to move beyond heuristic thermodynamic arguments.
- Many difficulties, but the most serious is the absence of adequate quantitative tools for describing the Hagedorn phase:

The equations that govern the background of string gas cosmology are not known.

Brandenberger 11

- That is, all predictions presently made for the CMB anisotropies involve perturbations around a background whose equations of motion are not yet specified.

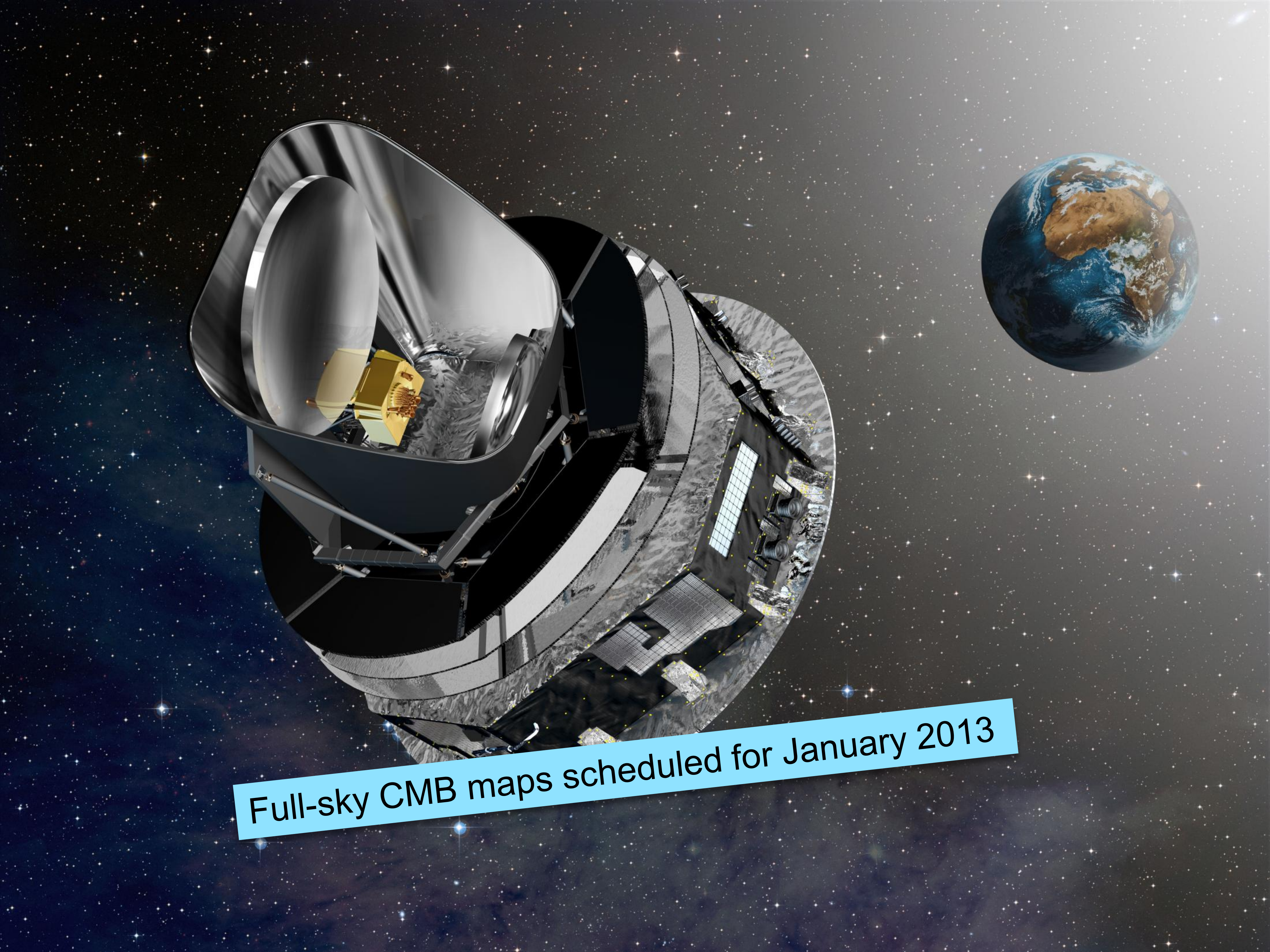
Conclusions

Why string cosmology?

- QFT+GR models of the early universe are sensitive to Planck-scale physics
- String theory may illuminate or resolve the initial singularity
- Tools like AdS/CFT could help us understand (eternal) inflation
- String theory can inspire novel cosmological scenarios
- These connections might turn observational cosmology into a window on string theory.

Conclusions

- The essential requirement for any model of the early or late universe in string theory is a clear understanding of the dynamics of moduli.
- Stabilizing the moduli remains challenging. Given a stabilized vacuum, obtaining Planck-suppressed contributions to the effective action is also challenging.
- String theory realizations of inflation have suggested novel mechanisms and signatures. A few scenarios are now realistic enough to be falsifiable.
- Alternatives to inflation are often inspired by string theory, but have not been realized in string theory. Making these models quantitative and predictive is an open challenge.
- Much work remains before we can understand what sort of cosmological dynamics is generic in string theory.


Full-sky CMB maps scheduled for January 2013