



The Emerging Connections Between String Theory, Cosmology and Particle Physics

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Theme of Talk

- New connections are emerging between string theory, cosmology and particle physics.
- As the data in cosmology and particle physics improves, and as String Theory matures, we will learn more about these connections.

Outline of Talk

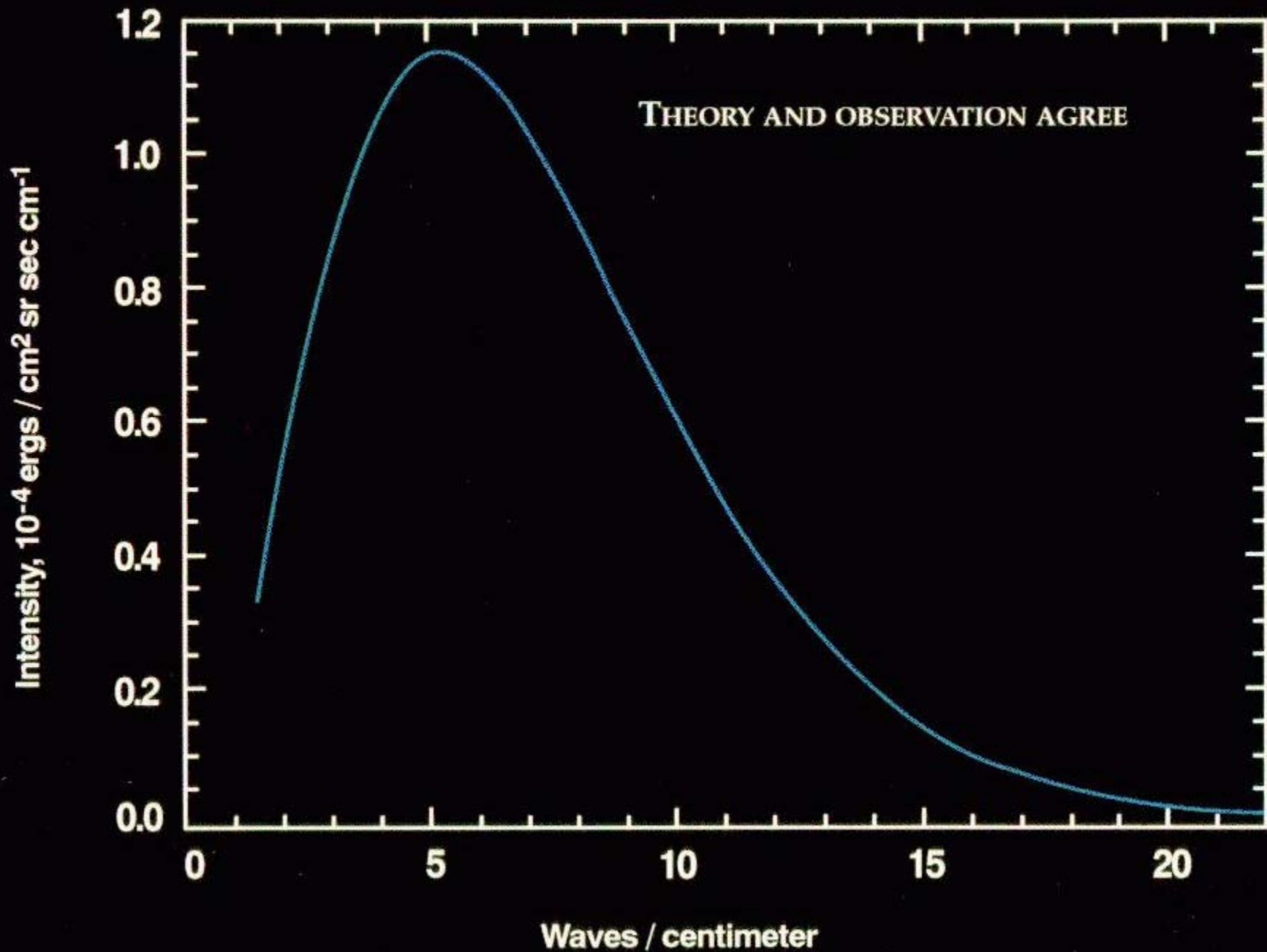
- Recent Advances in Cosmology
- Related Progress in String Theory:
 - i) The Cosmological Constant
 - ii) Inflation
- Connections to Particle Physics: New ways to break supersymmetry .
- Landscape: Challenges and Promises
- Conclusions

Advances in Cosmology

Impressive Progress in Observational Cosmology:

- 1) Cosmic Microwave Background
- 2) Super Novae
- 3) Large Scale Sky Surveys
- 4) Hubble Space Telescope

COSMIC MICROWAVE BACKGROUND SPECTRUM FROM COBE



Cosmic Microwave Background Radiation

- COBE:

$$T = 2.728 \pm 0.004 K$$

Confidence level of fit better than
any terrestrial experiment!

CMB space mission : WMAP

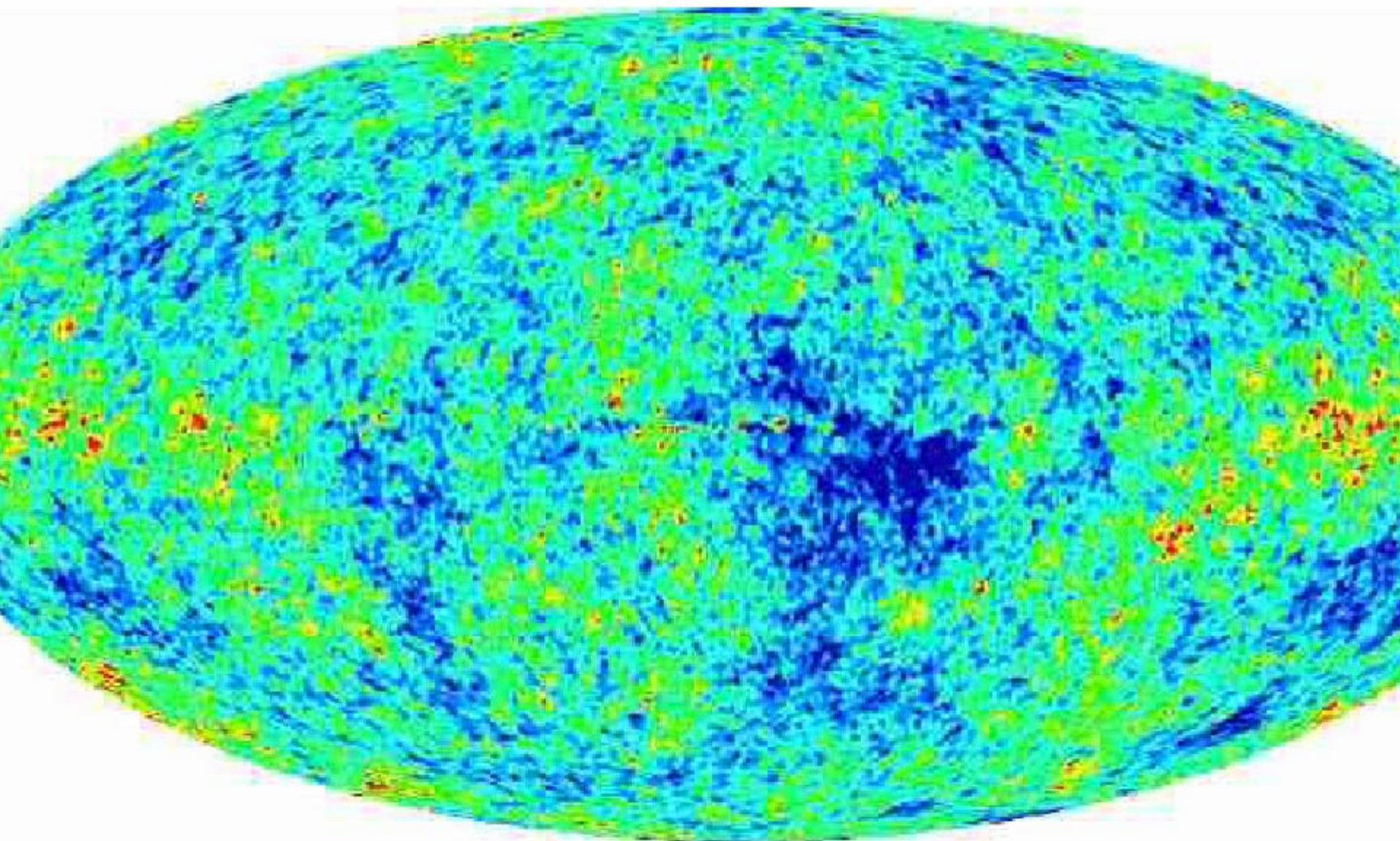
Wilkinson Microwave Anisotropy Probe

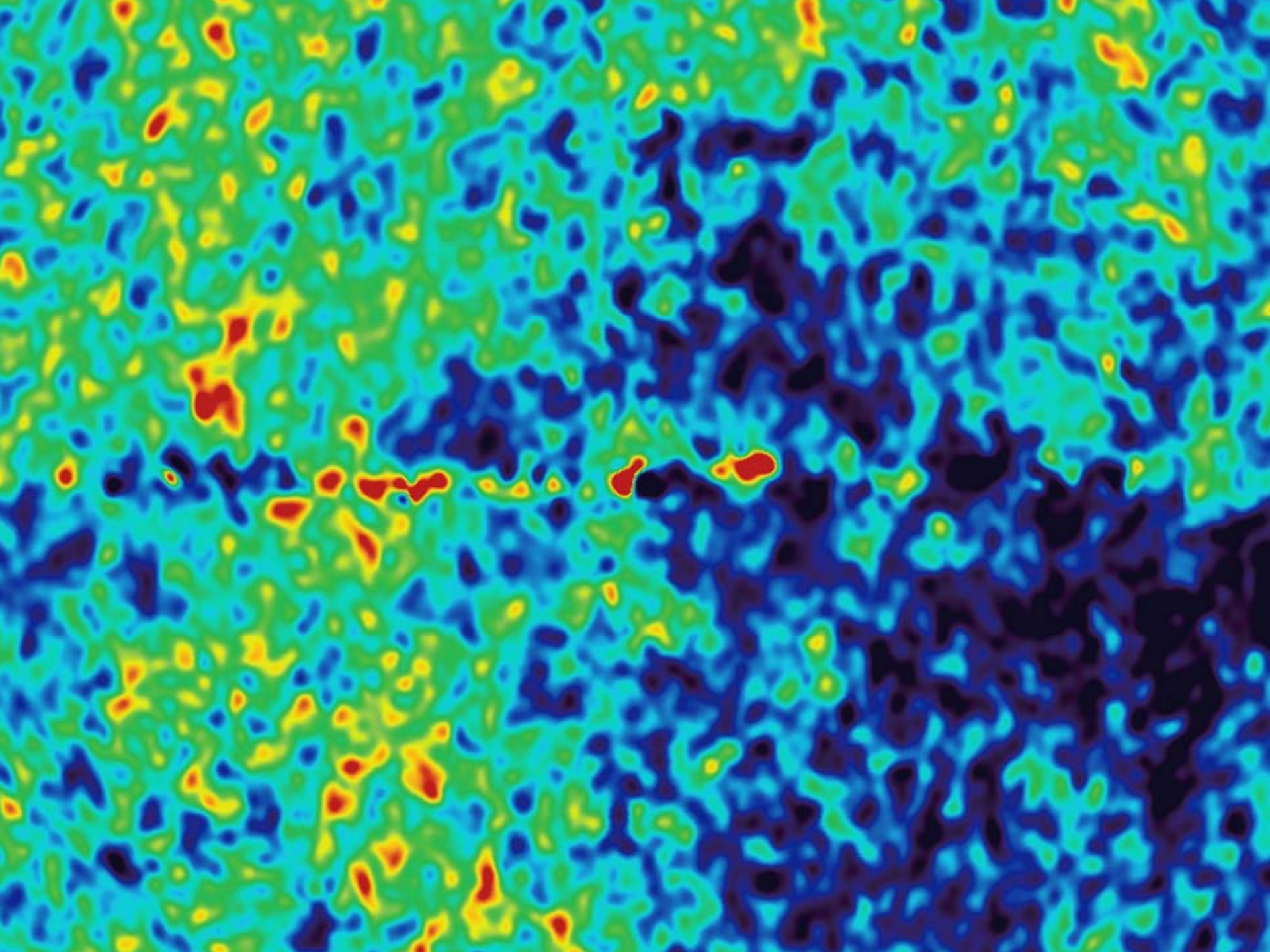
NASA Launched July 2001

**WMAP: First
year results
announced on
Feb. 11, 2003 !**

NASA/WMAP science team







• Temperature Anisotropy:

Small differences in the temperature of the Cosmic Microwave Background coming to us from different directions in sky have been measured, with a precision:

$$\frac{\Delta T}{T} \sim 10^{-5} - 10^{-6}$$

New Discovery

What have we learnt from these experiments?

- The Universe is Accelerating.
- The Rate at which Galaxies are flying apart is increasing with time.

The Accelerating Universe

- The Acceleration is surprising.
- Gravity is universally attractive.
- A mysterious form of matter-energy must be dominating the universe causing gravity to repel.

Dark Energy and Dark Matter

Most of the Universe is made up of unknown forms of matter and energy:

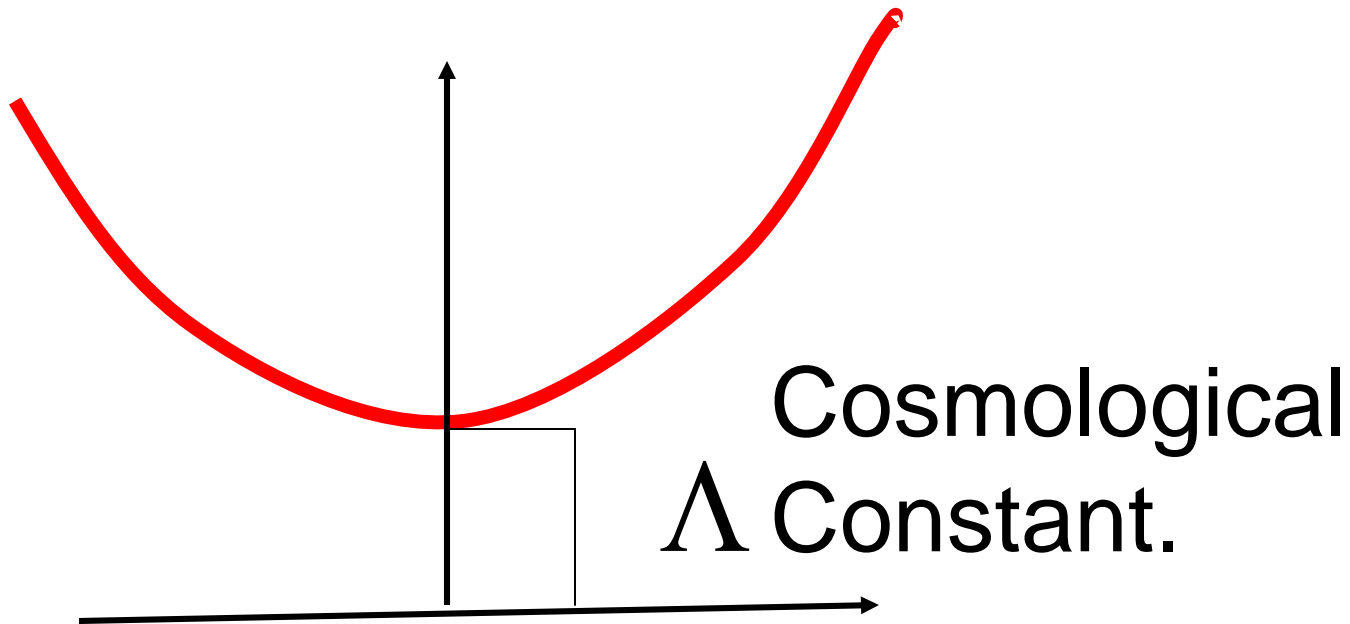
- 67% : Dark Energy – completely unfamiliar. Must have negative pressure!
- 29% Dark Matter (will be tested at the LHC experiment that gets underway soon)
- 4% Familiar Baryonic Matter.

Accelerating Universe & String Theory

- What is Dark Energy?
- Most promising Explanation:
Cosmological Constant.
- A Positive Cosmological Constant
Gives Rise to Acceleration.

The Cosmological Constant

The cosmological constant is the ground state energy. If this energy is positive it gives rise to acceleration.



Ground State Energy

Example: Harmonic oscillator

$$E = E_0 + \frac{1}{2}\hbar\omega$$

- Nothing depends on the constant E_0 (except for gravity).
- Quantum Mechanics is essential to calculate the answer.

The Cosmological Constant and Gravity

To calculate the cosmological constant from first principles we need a theory of gravity consistent with the rules of quantum mechanics.

Enter String Theory!

The Accelerating Universe and String Theory

Question:

Can String Theory Give rise to a positive cosmological constant?

The Accelerating Universe and String Theory

- Preliminary Attempts:
Unsuccessful.
- No-go Theorems Formulated
- We showed that a positive cosmological constant can arise in string theory.

Kachru, Kallosh, Linde, S. P. T., PRD 68:046005

The Accelerating Universe and String Theory

- Thus String Theory passes another difficult test.
- We are more confident that a positive cosmological constant makes sense.

Advances in String Theory

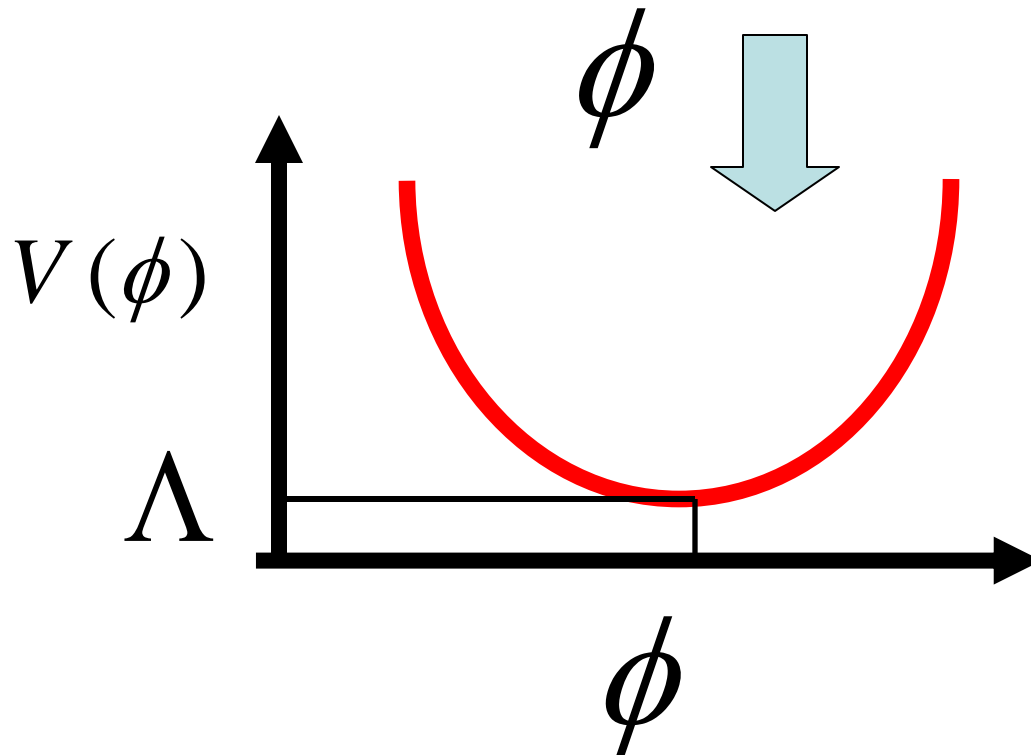
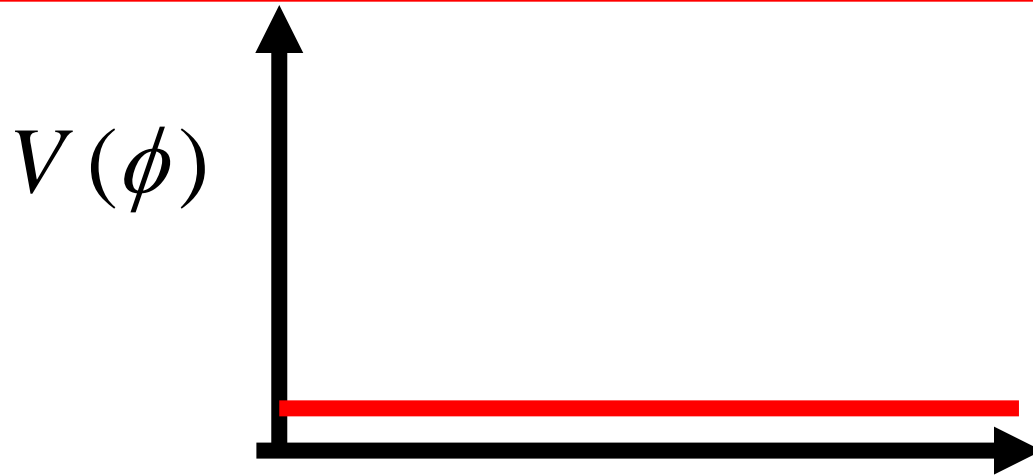
Two related advances in String Theory were required:

- Understanding the Breaking of Supersymmetry.

A positive cosmological constant can only arise after supersymmetry is broken.

- Solving the Moduli stabilisation problem.

Moduli Stabilisation and Susy Breaking



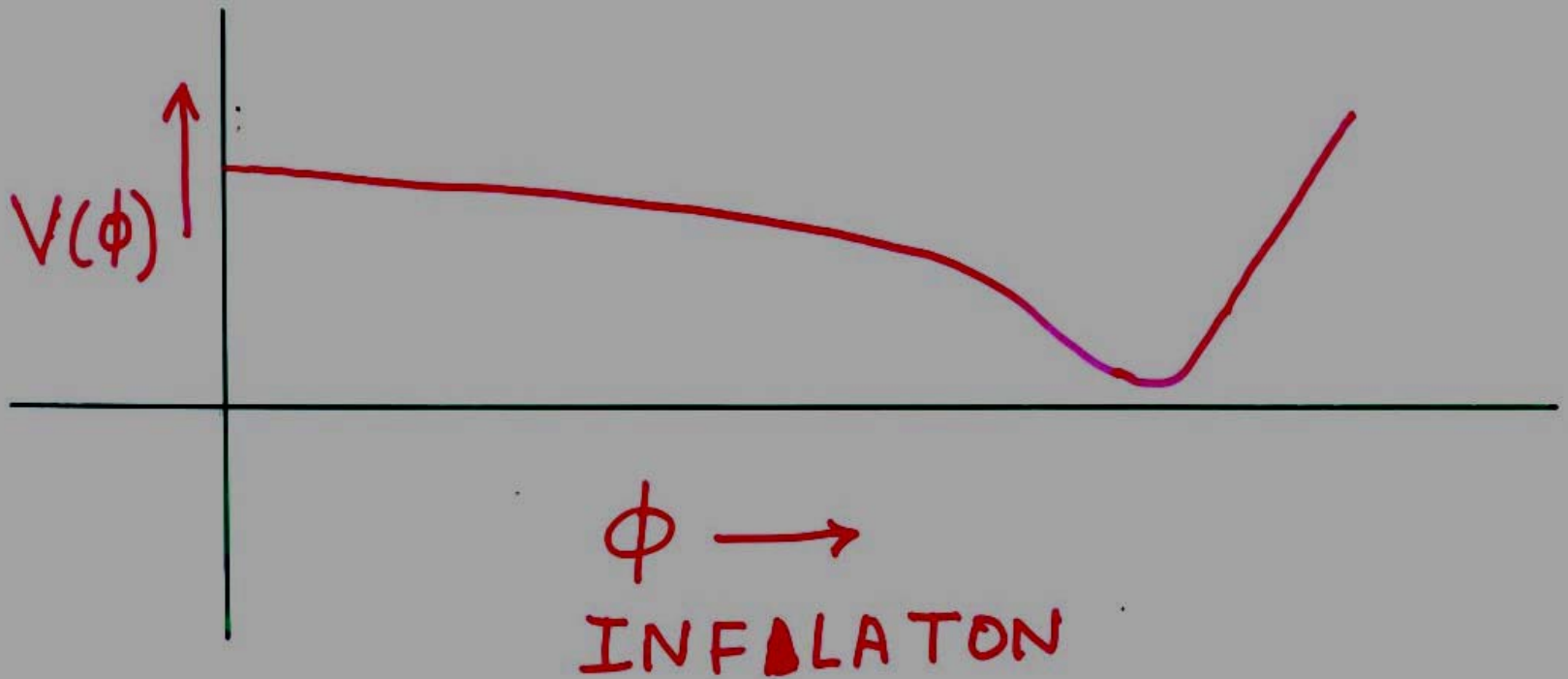
Inflation

- Cosmological data also supports

- Inflation:

- A period of rapid expansion early in the history of the universe.
- Can explain the near isotropy of CMBR.
- And generate a nearly scale invariant spectrum of density perturbations.

SLOW-ROLL INFLATION.



Inflation and String Theory

Using the recent advances models of inflation in string theory have been constructed.

Inflaton: A Brane modulus.

1. Dvali and Tye, Phys. Let., B450:72.
2. Kachru, Kallosh, Linde, Maldacena, McAllister and Trivedi, JCAP 0310:013
3. Iizuka, Trivedi, Phys. Rev D70, 04319.

Inflation and String Theory

The string models have one robust generic feature:

- No appreciable gravity waves are produced during inflation.
- Thus the Planck experiment and others should not see any B mode polarisation if these models are correct.

Inflation and String Theory

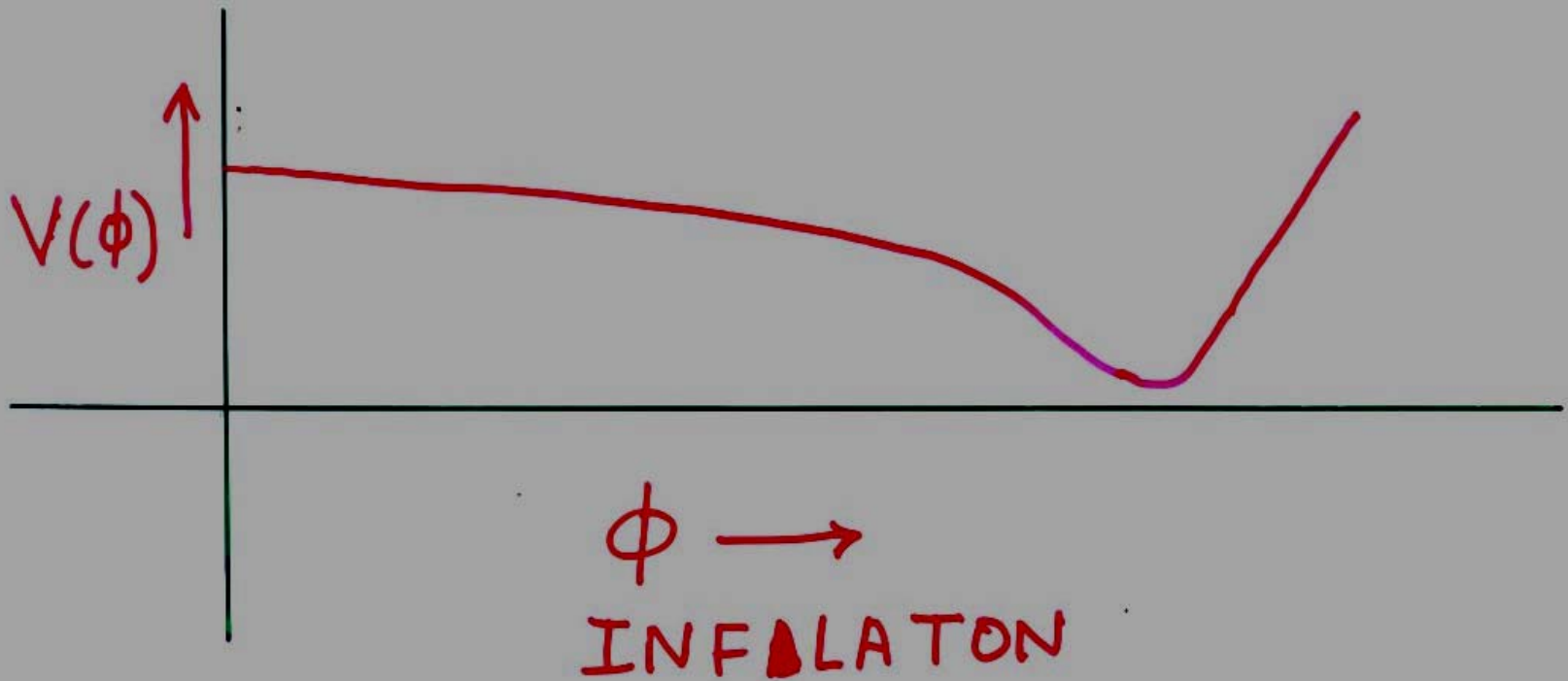
- This feature arises because the inflaton varies over a small range during inflation:

$$\frac{\Delta\Phi}{M_{Pl}} \leq 1$$

Recap of Talk so far:

- Progress in Cosmology has thrown up important challenges for string theory.
- These have led to advances in string theory which in turn has consequences for cosmology.
- Next, we turn to connections with particle physics.

SLOW-ROLL INFLATION.



New Models for Supersymmetry Breaking:

- Supersymmetry : attractive idea for new physics beyond the standard model.
- Must be spontaneously broken.

Supersymmetry Breaking

Supersymmetry
Breaking
Sector



Mediator

Supersymmetric
Standard Model

e, γ, \dots

$\tilde{e}, \tilde{\gamma}, \dots$

Mediator: e.g., gravity, gauge fields, etc

Soft masses and phenomenology
depend in crucial ways on the mediator.

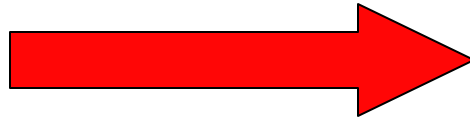
Susy Breaking and String Theory

- Recent advances in string theory lead to novel ways in mediating supersymmetry breaking:
- Anomaly mediation
- Moduli mediation.
- In the KKLT –like constructions both novel methods of mediation occur and with comparable strength.
- Leading to a distinct phenomenology.

Anomaly Mediation

Randall,
Sundrum

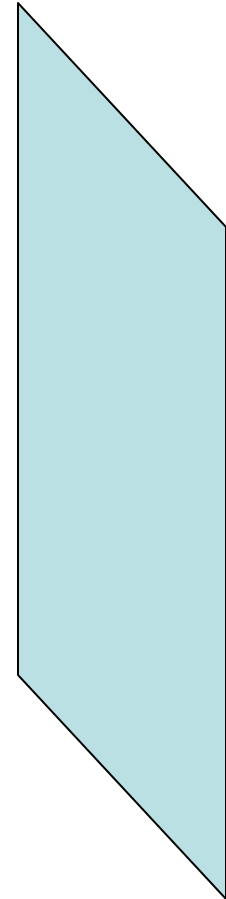
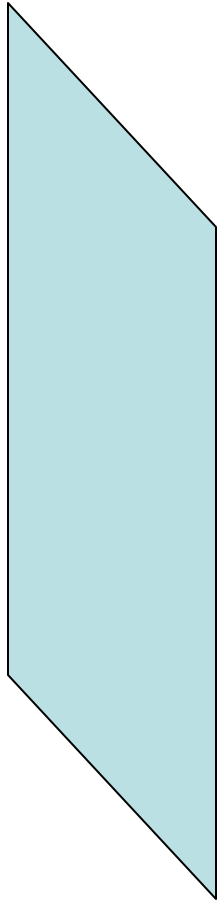
Extra Dimension



(No direct contact)

Supersymmetry
Breaking sector

Standard Model Brane



Mixed Anomaly Moduli Mediation

- Resulting Gaugino masses at 1TeV

$$M_1 : M_2 : M_3 \simeq 1.66 : 2.2 : 4.2$$

(I have taken $\alpha = 1$)

- Contrast this with Gravity Mediation:

$$M_1 : M_2 : M_3 \simeq 1 : 2 : 6$$

Based on work by:

Choi, Falkowski, Nilles, Olechowski, Pokorski,
JHEP 0411, 076

Choi, Falkowski, Nilles, Olechowski, Nucl. Phys.
B712, 113.

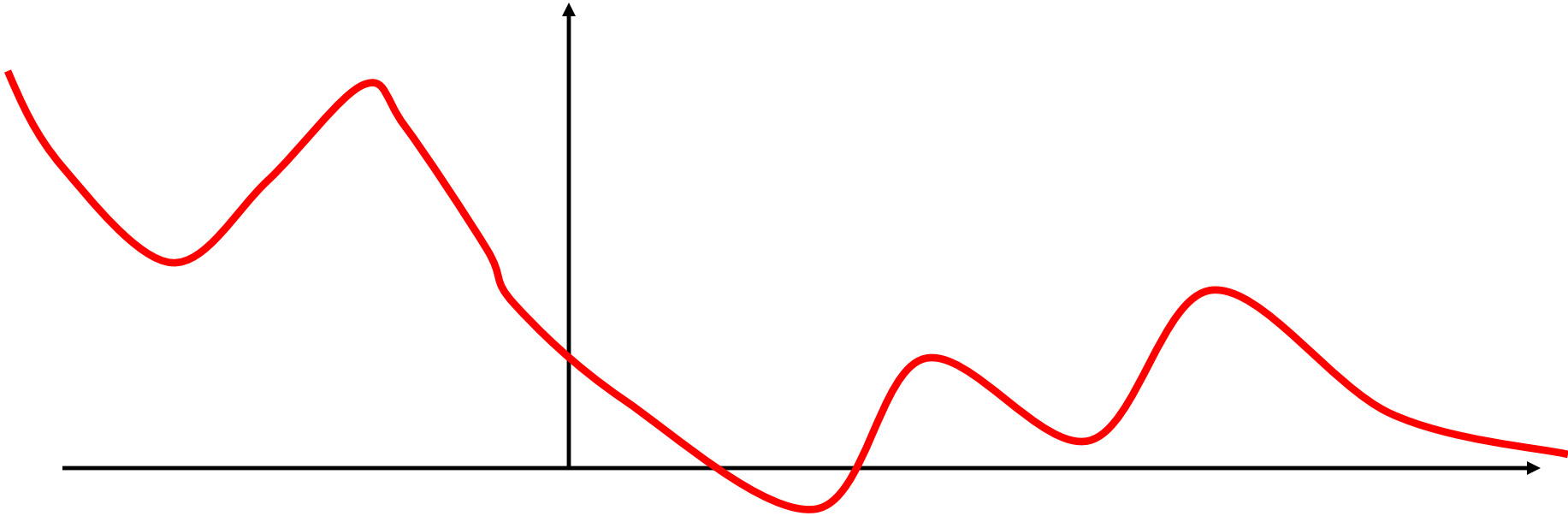
H. Baer, E. K. Park, X. Tata and T. T. Wang,
JHEP 0608,041

Etc.

Mixed Anomaly and Moduli Mediation

- The string theory inspired models are useful if only as foils to the more conventional models like gravity mediation or gauge mediation.
- Experimentally one will be able to tell them apart.

Landscape



- Many Many Vacua
- Many directions

Bousso Polchinski

Susskind

Landscape

- ~ 100 Directions.
- ~ 10^{500} different vacua.
- Varying cosmological constants.
- Transitions among vacua possible.

Implications of the Landscape

- Who ordered the extra vacua?
- In what sense is String Theory predictive?
- Is there a new way to think about Naturalness ?
- Do we have to resort to the Anthropic Principle?

The Landscape and the Cosmological Constant

- With so many vacua some will have a Small enough cosmological constant.

$$N(\Lambda) = N_{Total} \left(\frac{\Lambda}{M_{Pl}^4} \right)$$

$$N \simeq 10^{500-120} = 10^{380}$$

- But how do we choose amongst these?

Personal View:

- String Theory is a general Framework.
- Broad enough to include quantum mechanics and gravity; chiral matter closely resembling that of the standard model; a positive cosmological constant and inflation.
- Challenge is to find vacua that resemble the standard model and make predictions. This might well be possible.

- The very generality of the framework opens up new possibilities for connections between string theory, particle physics, and cosmology.
- For example it is widely believed now that many gauge theories in some limits can be usefully thought of as string theories. (E.g: The Maldacena conjecture).
- This means string theory might be useful where ever gauge theories are important.

- Example: String theory and Technicolor
- Old Idea: Solve the Hierarchy problem by taking the Higgs to be a composite at TeV scale.
- However a workable model was difficult to construct.
- More recently Randall and Sundrum and subsequently, Agashe, Sundrum and collaborators, have constructed models which seem to avoid these problems.

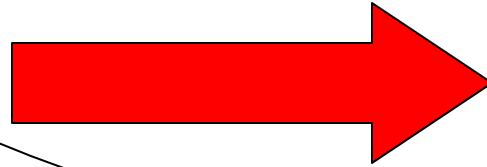
Some References :

- Randall, Sundrum, PRL 83, 3370
- Agashe, Delgade, May, Sundrum, JHEP 0308.
- Agashe, Contino and Pomarol, hep-ph/0412089

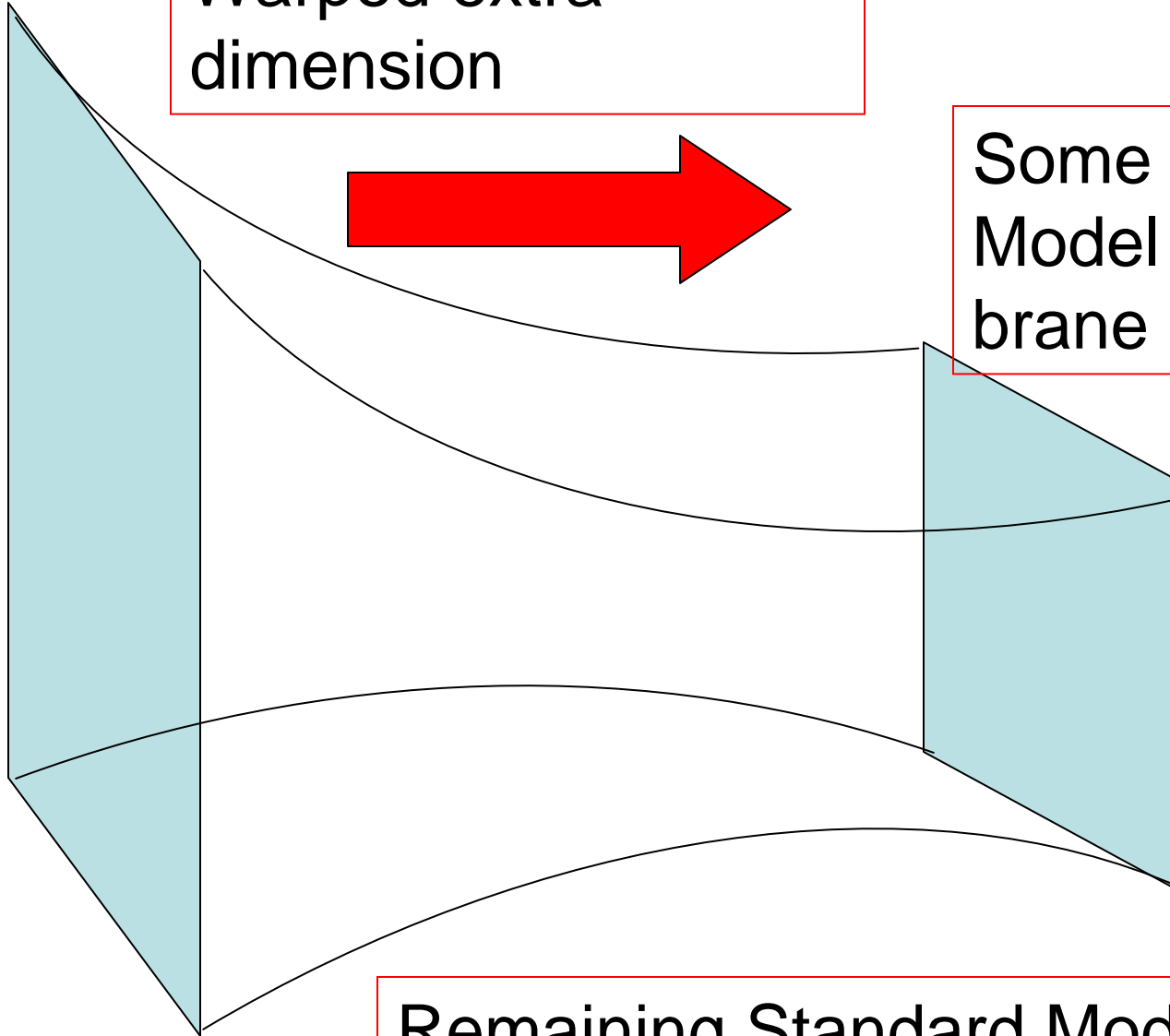
Randall Sundrum Models

- They have used an alternate description, inspired by string theory, to analyse these models.
- In this description there is an extra dimension which is warped.
- The Higgs lives on a brane in the Infra-red. Other standard fields live in the bulk.
- A Custodial $SU(2)$ symmetry allows precision electroweak constraints to be met.

Warped extra
dimension



Some Standard
Model fields on a
brane



Remaining Standard Model
fields in Bulk

Randall Sundrum Models

- The 4+1 dimensional description is an alternative to a more conventional 3+1 dim field theory description. But this dual description proves more convenient for some purposes.
- It suggests some distinct signals – based on spin two higher excitations of the graviton- which can be looked at at the LHC.

Randall Sundrum Models

- If Technicolor/Higgs compositeness does turn out to be the correct theory beyond the standard model then we can perhaps use string theory to understand some features of it.

Conclusions:

- Recent progress in Cosmology has thrown up new challenges for string theory.
- These have been met. String Theory can give rise to a positive cosmological constant and to inflation.
- The resulting string inflation models have some robust features.

Conclusions:

- The string constructions suggest new ways in which supersymmetry might be broken with distinct signatures that can be observed at the LHC. .

Conclusions

- These developments reveal that there is a Landscape of many different vacua.
- This poses a big challenge for string theory: how do we extract predictions from it?
- But it offers also some promise

Conclusions

- Contact with experiment might come in ways unforeseen originally.
- E.g: in the understanding of a strongly coupled gauge theory :
 - i) Of relevance to beyond standard model physics
 - ii) Or QCD in some limits.

Conclusions:

As string theory matures, and the data gets better in cosmology, and particle physics, the connections between these subjects are likely to get deeper, leading to a better understanding of all of them.

