String Theory and Inflation

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Trieste Observatory April 2010

String Theory

- **‘Noumenology’**

- **‘Phenomenology’** 

E. Kant: Noumenon~thing in itself

Phenomenon~thing as it manifests

20 Century ‘Fundamental’ Physics

- **Standard Theory: QFT & GR**

  Few predictions: antiparticles, CPT, running couplings, identical particles

- **Standard Model of Particle Physics**

  3+1 Dimensions

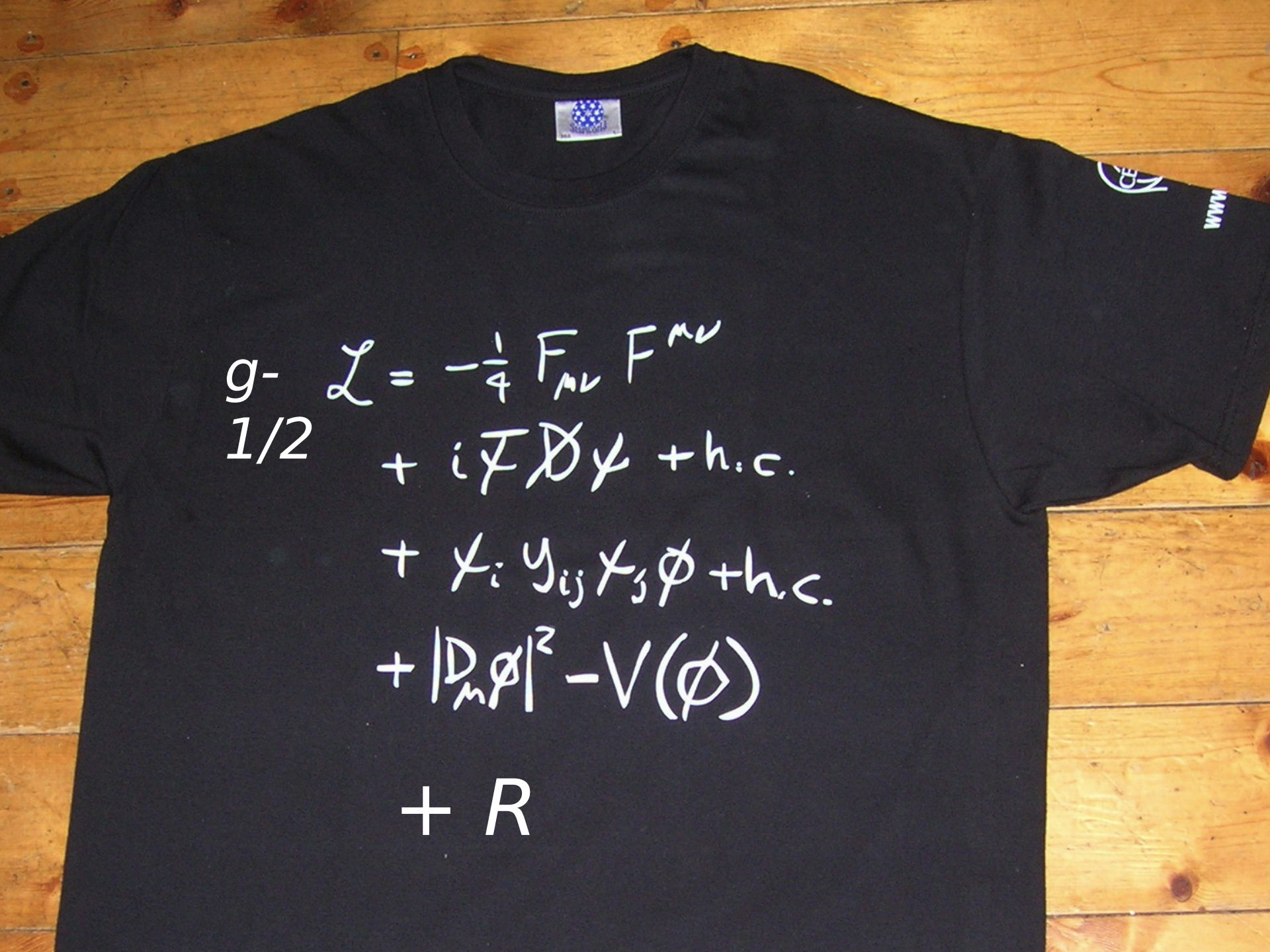
  3+1 Interactions

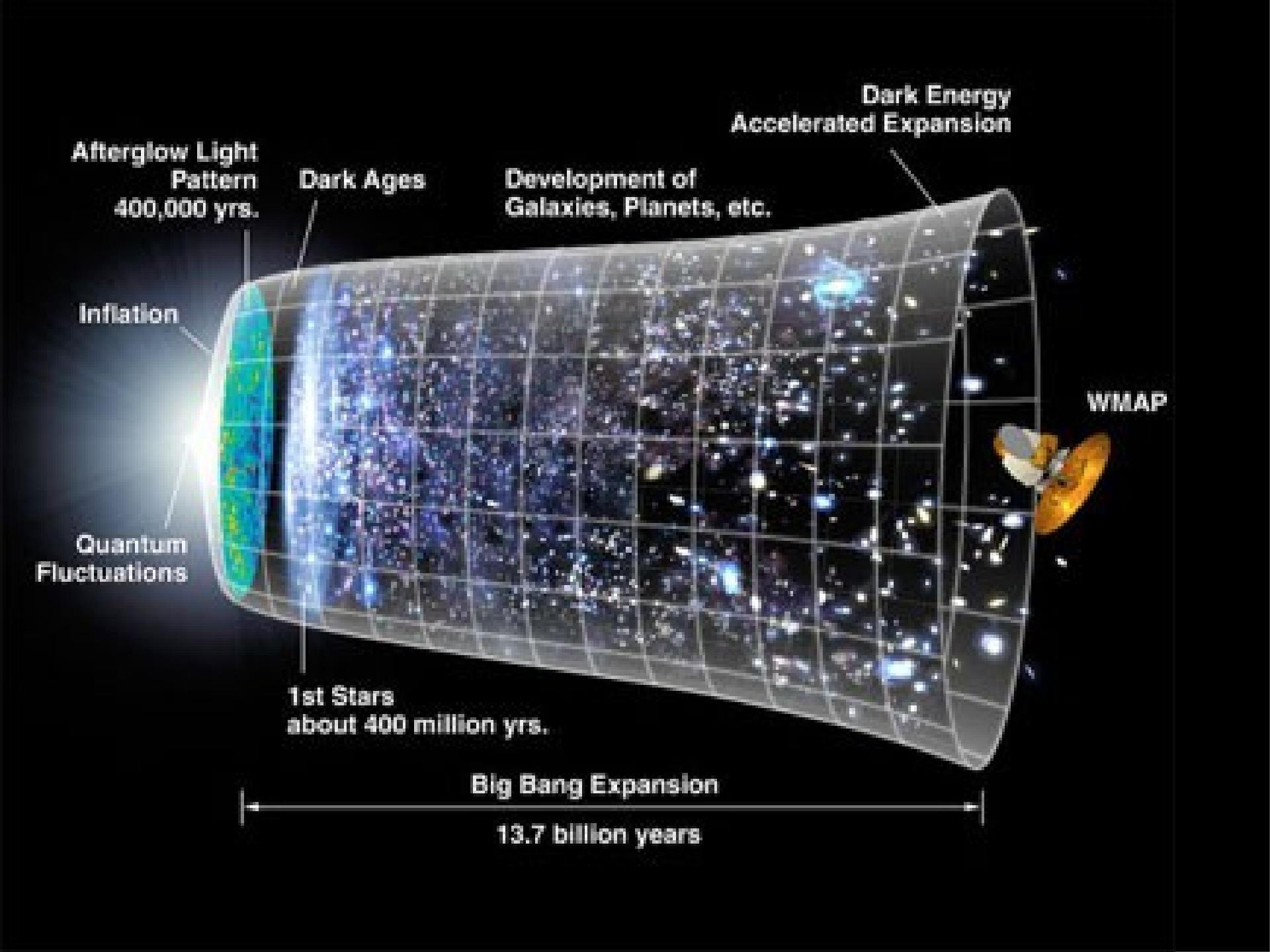
  3+1 Families

- **Standard Model of Cosmology**

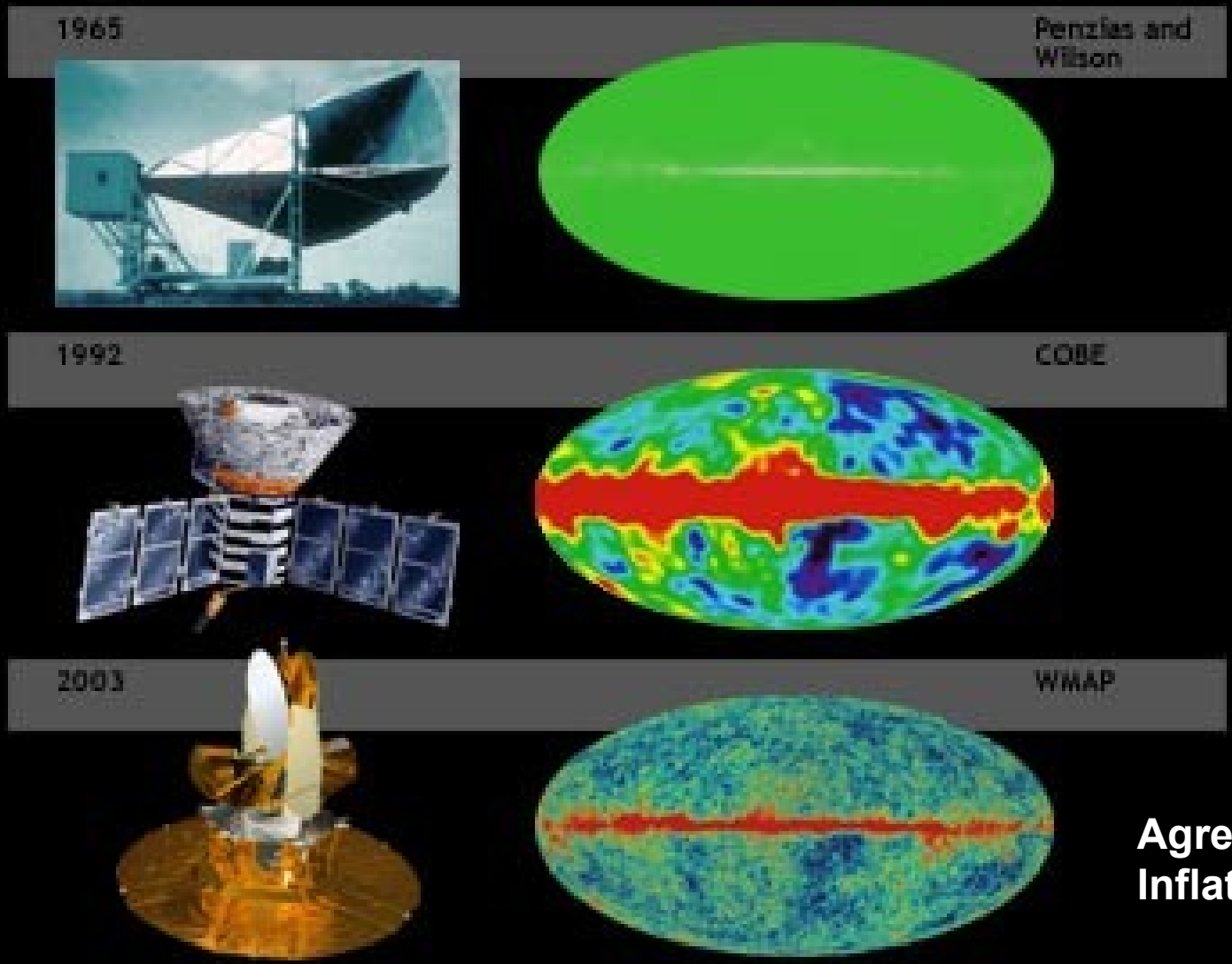
  Big-Bang Model (FRW) +

  Standard Model of PP + Thermodynamics


g-
1/2
$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$
$+ i \not{\psi} \not{D} \psi + h.c.$
$+ \chi_i y_{ij} \chi_j \phi + h.c.$
$+ |D_\mu \phi|^2 - V(\phi)$
$+ R$


Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
400,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
WMAP
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.7 billion years

Cosmic Microwave Background



Agree with Inflation! !!!

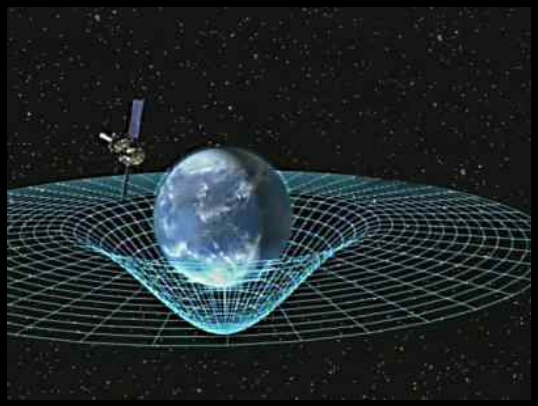
Outstanding Questions

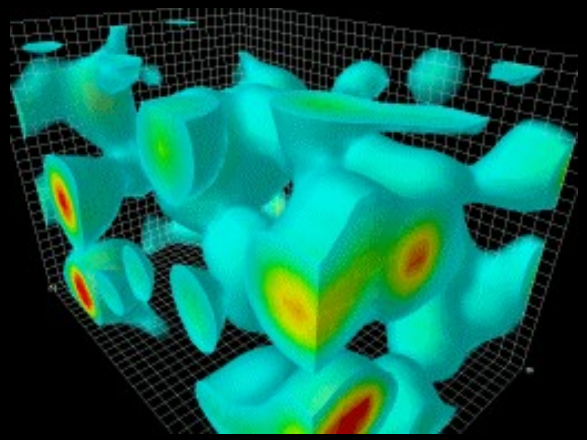
- **Quantisation of Gravity**

  Hierarchies : M /M =M /M =10

FUNDAMENTAL PROBLEM

Quantum Gravity





$$h/2\pi = \hbar = 1.0546\times10^{-34}\ \text{kg m}^2\ \text{sec}^{-1}$$

$$G_N = 6.672\times10^{-11}\ \text{m}^3\ \text{kg}^{-1}\ \text{sec}^{-2}$$

$$c = 2.99792458\times10^{8}\ \text{m/sec}$$

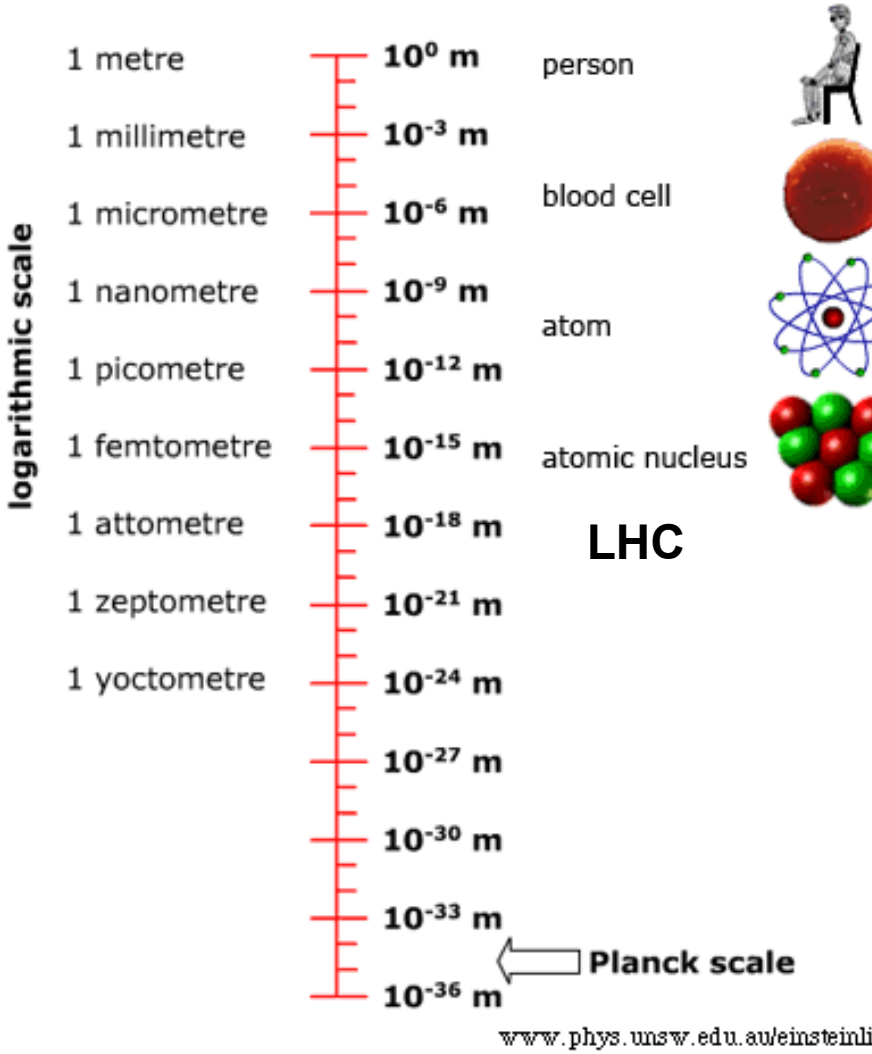
Planck Units

$$L_{\text{Planck}} = \sqrt{\frac{\hbar\, G_N}{c^3}} = 1.616\times10^{-33}\ \text{cm}$$

$$M_{\text{Planck}} = \sqrt{\frac{\hbar c}{G_N}} = 21.8\ \mu\text{g}$$

$$T_{\text{Planck}} = \sqrt{\frac{\hbar\, G_N}{c^5}} = 5.39\times10^{-44}\ \text{sec}$$

$$m_p = \sqrt{\frac{\hbar c}{G}}$$

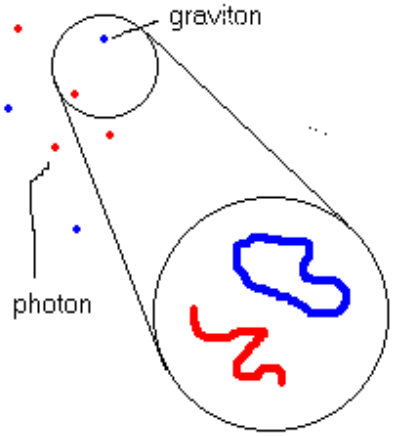


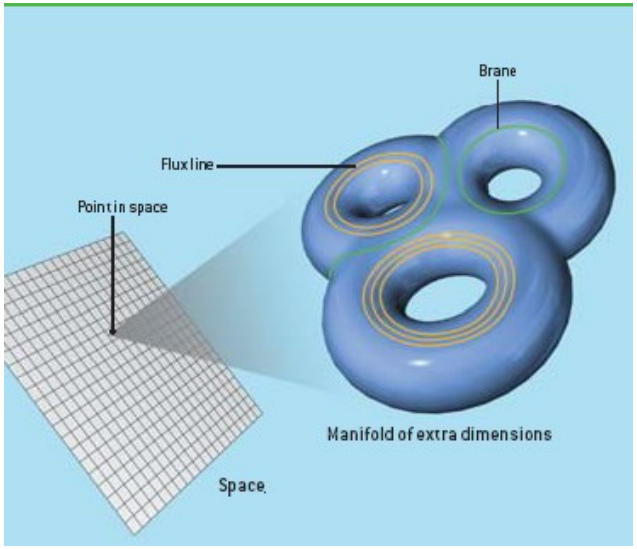
www.phys.unsw.edu.au/einsteinli

String Theory

String Theory

- Particles ‘look like’ strings
- (Super) Gravity is included
- Can unify all particles and interactions (Einstein’s dream)
- Universe lives in 10 (11) dimensions !!!
- For our universe 10d = 4d+6d (6d very small?)
- Dimensionful scale: Ms.
- Many couplings: Moduli (1/g =T)





General ‘Predictions’ of String Theory

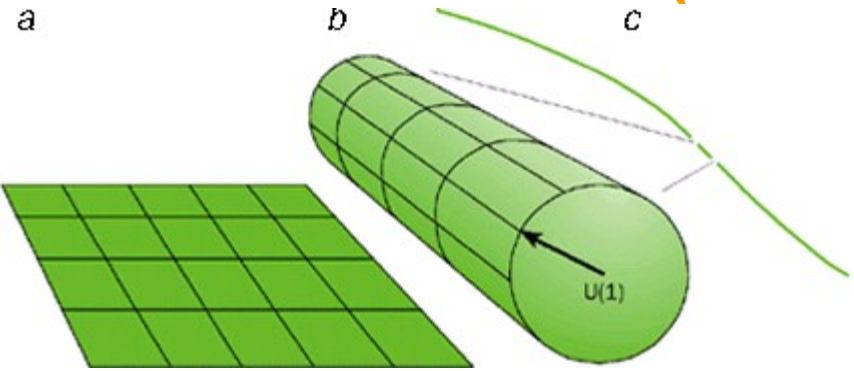
Gravity + other interactions + matter + … exist!

MASSLESS SPECTRUM OF STRING THEORIES				
THEORY	DIMENSION	SUPERCHARGES	BOSONIC SPECTRUM	
Heterotic $E_8 \times E_8$	10	16	$g_{\mu\nu}, B_{\mu\nu}, \phi$ A_μ^{ij} in adjoint representation	
Heterotic $SO(32)$	10	16	$g_{\mu\nu}, B_{\mu\nu}, \phi$ A_μ^{ij} in adjoint representation	
Type I $SO(32)$	10	16	NS-NS	$g_{\mu\nu}, \phi$
			A_μ^{ij} in adjoint representation	
			R-R	$C_{(2)}$
Type IIB	10	32	NS-NS	$g_{\mu\nu}, B_{\mu\nu}, \phi$
			R-R	$C_{(0)}, C_{(2)}, C_{(4)}$
Type IIA	10	32	NS-NS	$g_{\mu\nu}, B_{\mu\nu}, \phi$
			R-R	$C_{(1)}, C_{(3)}$

Extra Bosonic Dimensions

Extra 'bosonic' Dimensions

(Kaluza-Klein)



$$\varphi(x^\mu, y) = \sum_{n=-\infty}^{\infty} \varphi_n(x^\mu) \exp\left(\frac{iny}{r}\right)$$

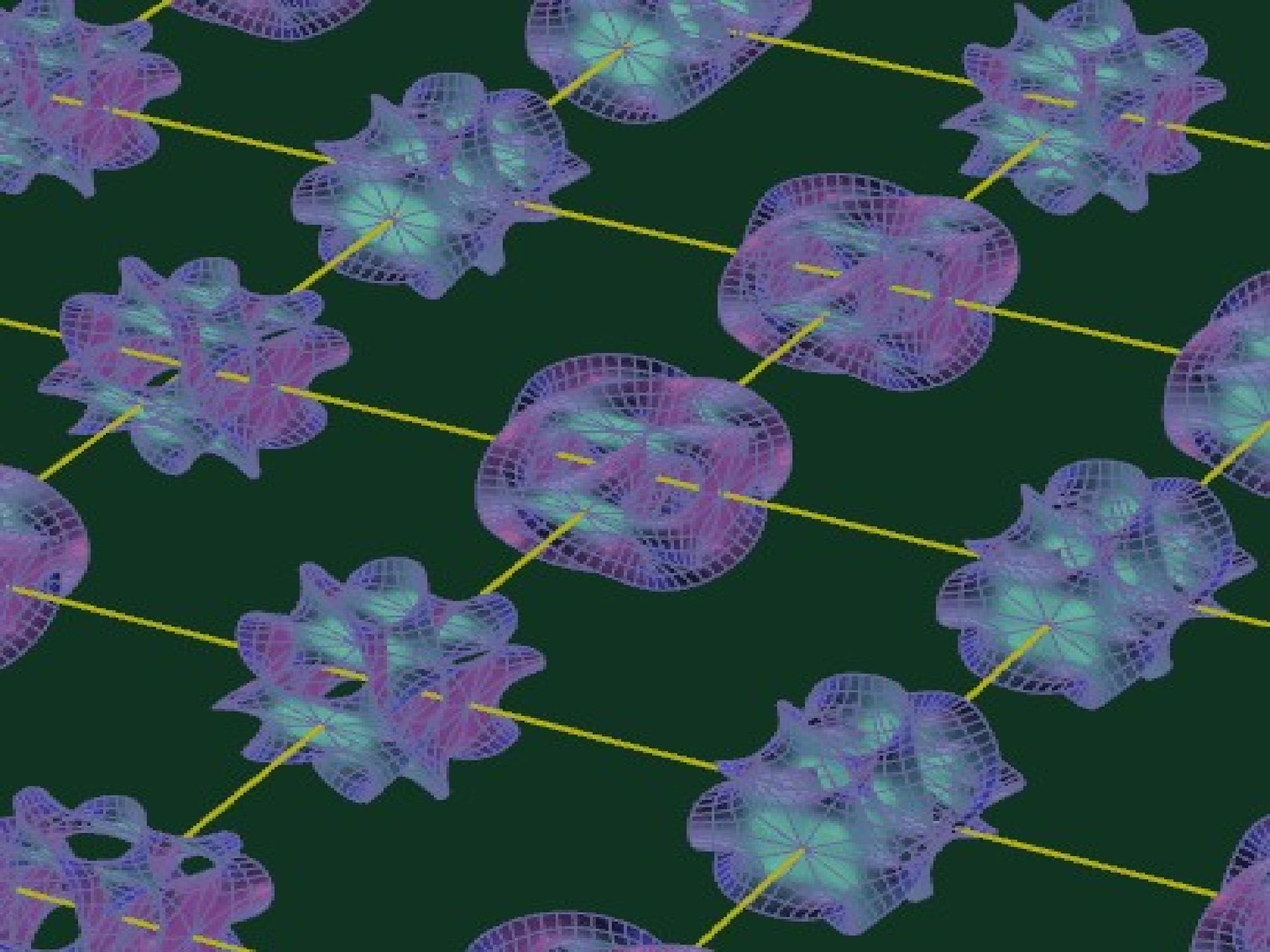
Fourier expansion

One massless particle in 5D

$$\partial^M \partial_M \varphi = 0 \implies \sum_{n=-\infty}^{\infty} \left(\partial^\mu \partial_\mu - \frac{n^2}{r^2}\right) \varphi_n(x^\mu) \exp\left(\frac{iny}{r}\right) = 0$$

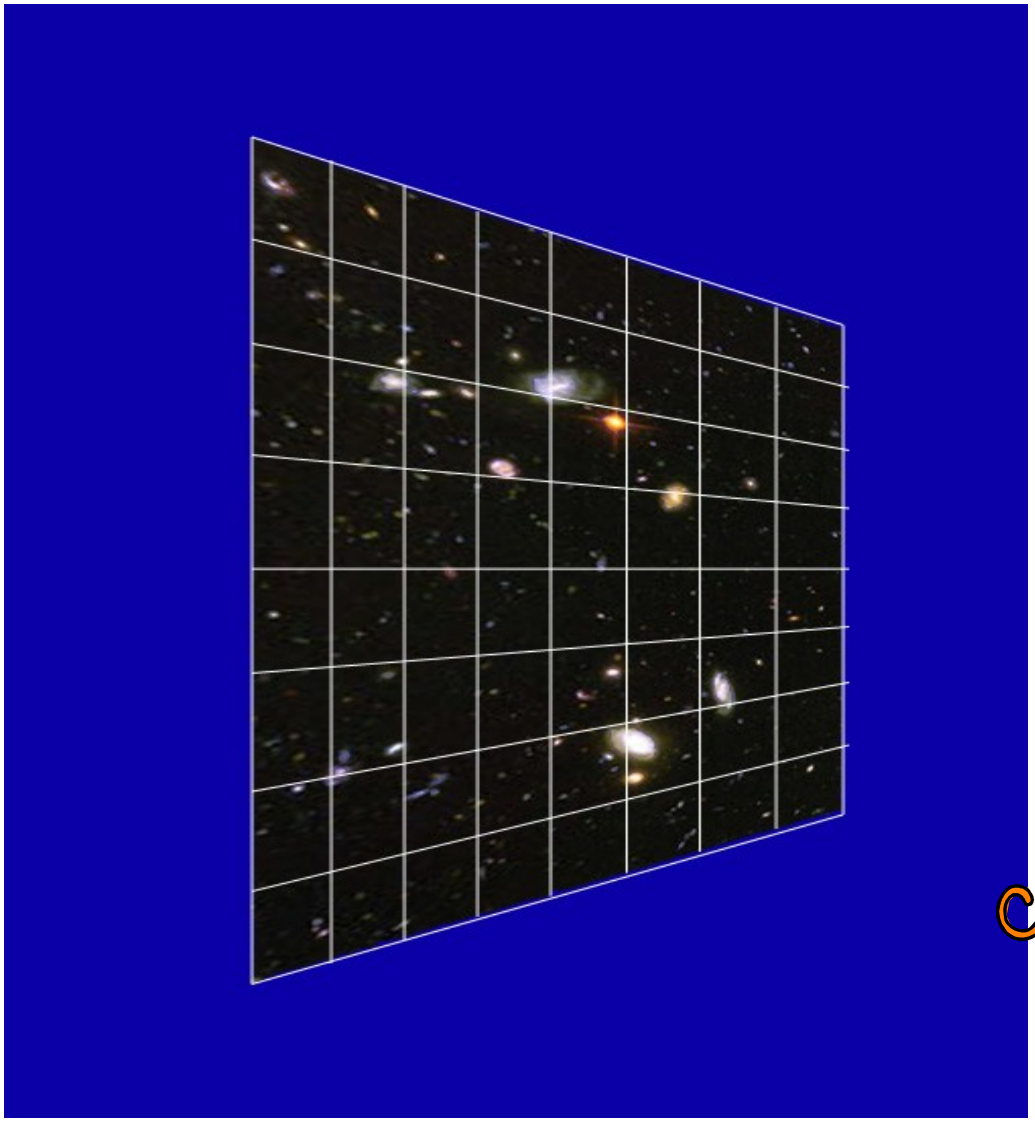
$$\implies \partial^\mu \partial_\mu \varphi_n(x^\mu) - \frac{n^2}{r^2} \varphi_n(x^\mu) = 0 \,.$$

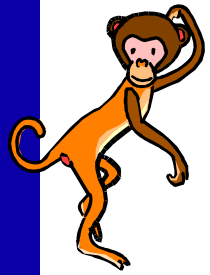
Infinite massive particles in 4D!!!
MKK~1/r



The Brane World

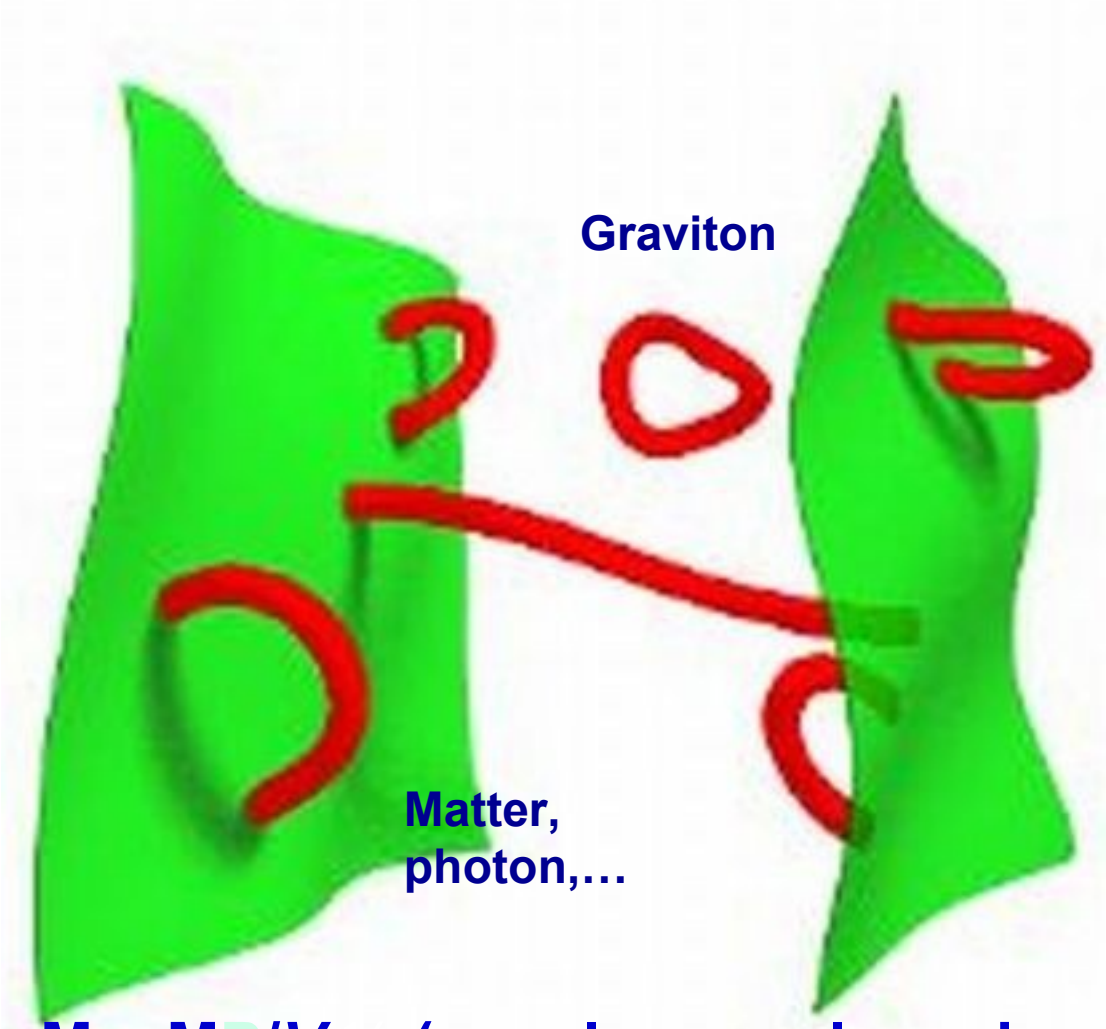
Is the Universe a Brane ?





Large extra dimensions may obviate hierarchy problem!

Brane world in string theory



tring scale Ms=MP/*V* (very large volume implies strings
elevant at scalesmuch smaller than Planck!!!!)

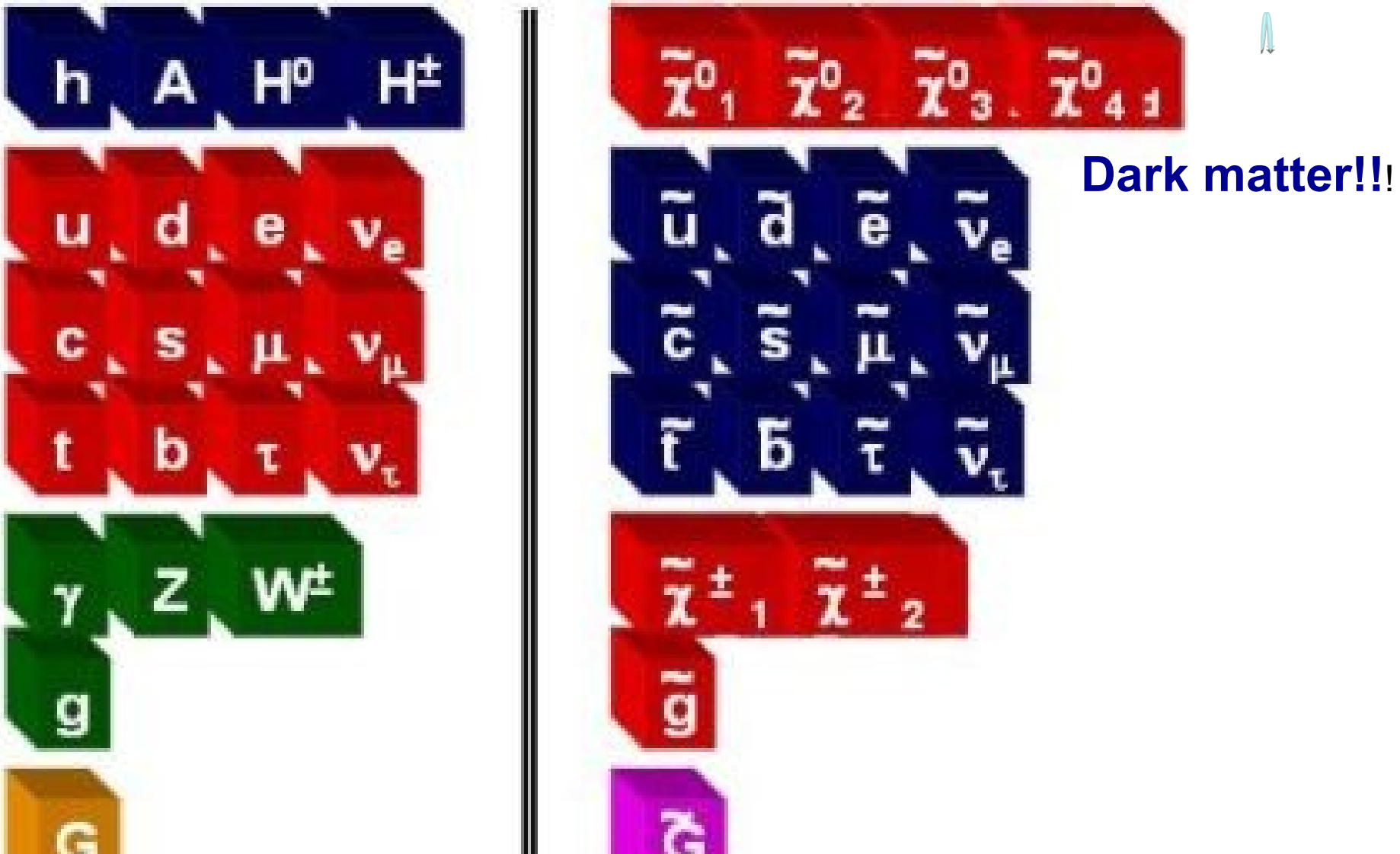
Extra Fermionic Dimensions

(Supersymmetry (SUSY))

Boson → Fermion → Boson

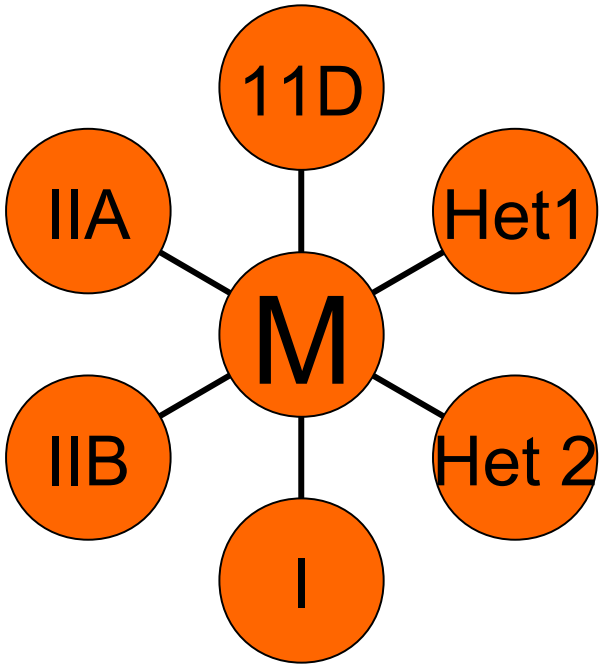
SUPERSYMMETRY

If SUSY particles mass 1TeV can solve hierarchy problem!!!



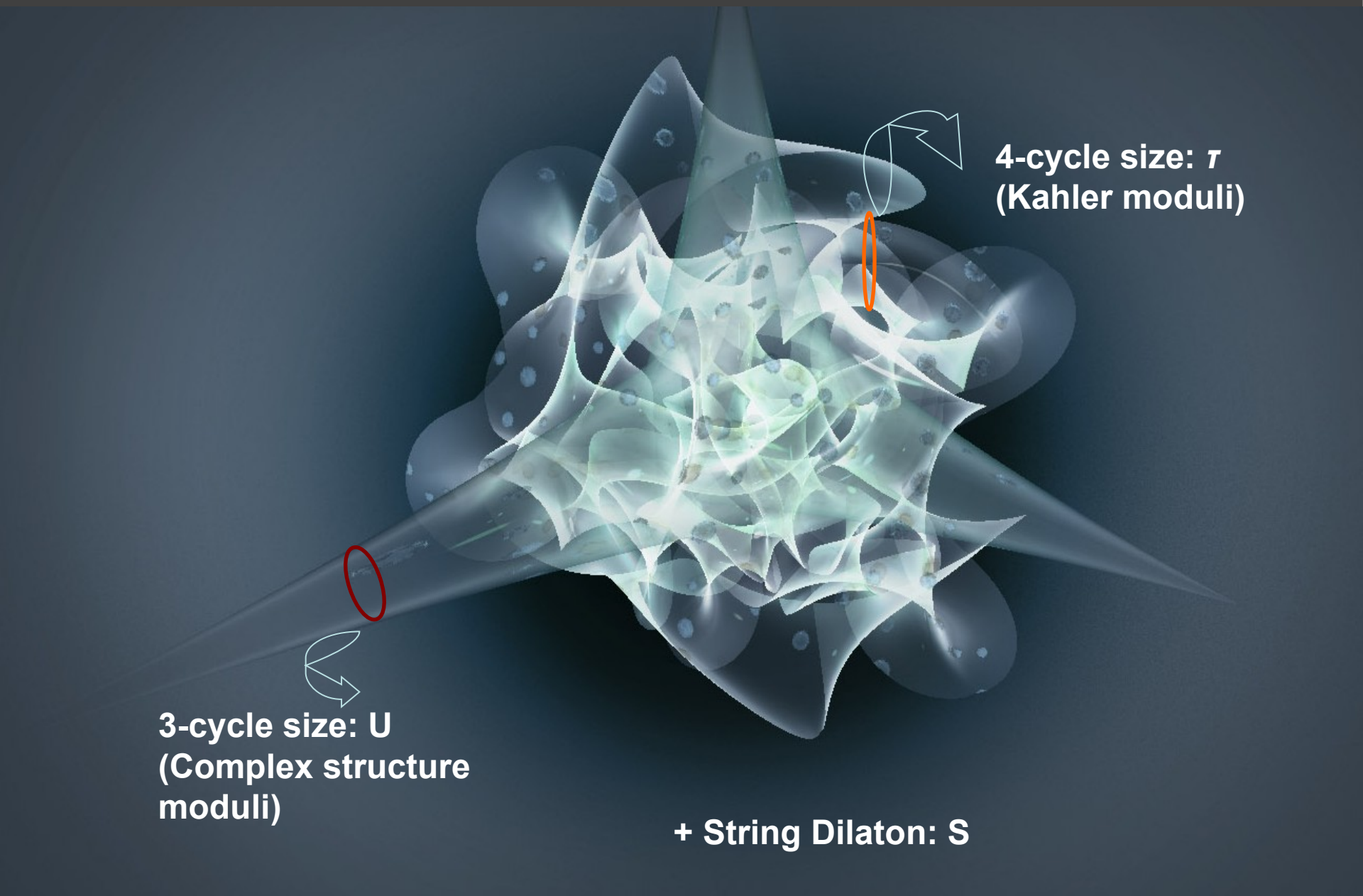
Dark matter!!!

4 The Theory is Unique

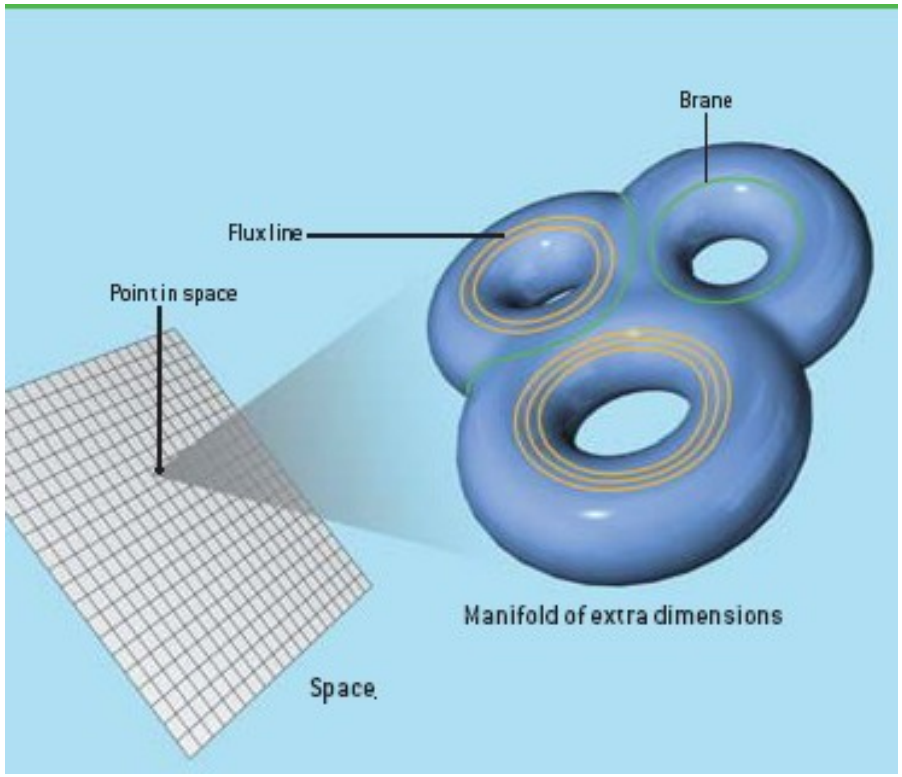


But many possible solutions or 'vacua'
Each solution a different universe!!!

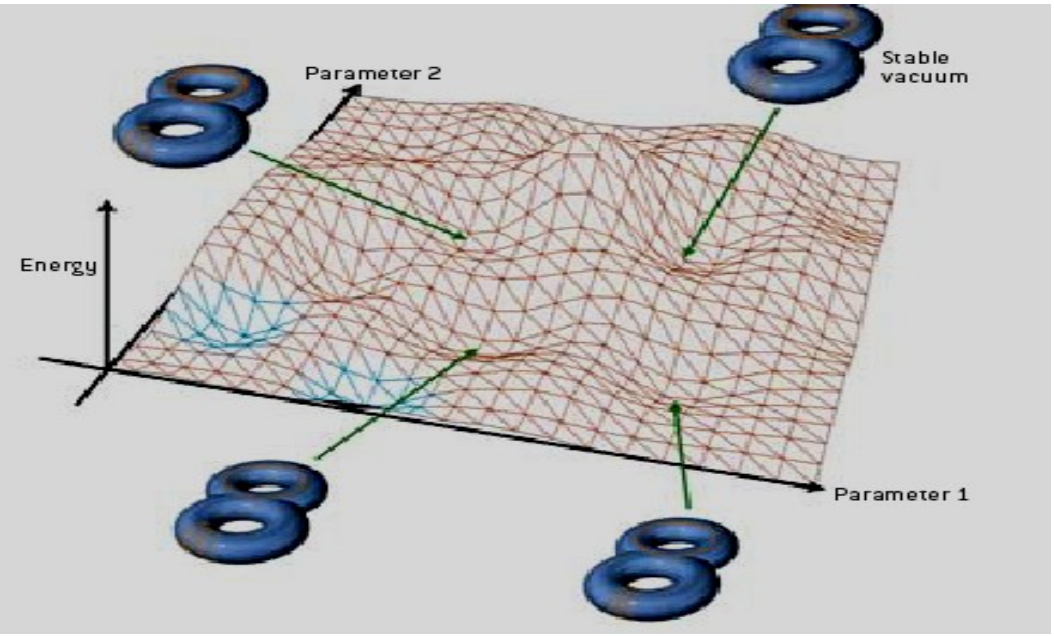
Size and Shape of Extra Dimensions



- **'Most' vacua have unfixed moduli** 
  ruled out by experiment!!!(5th force)
- **Physically interesting: moduli fixed by fluxes and non perturbative effects**

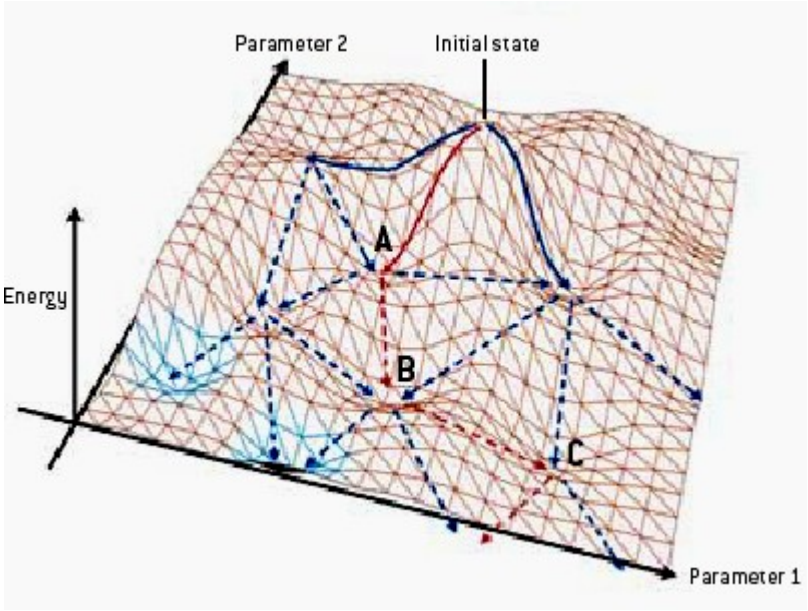


The Landscape

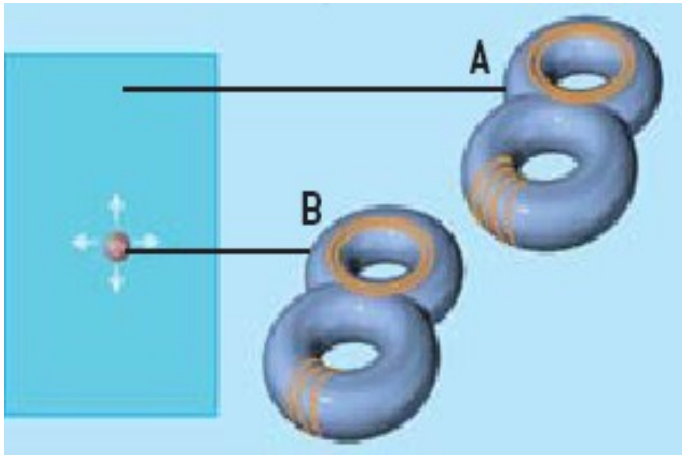


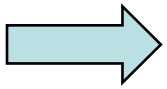
Classical Solutions

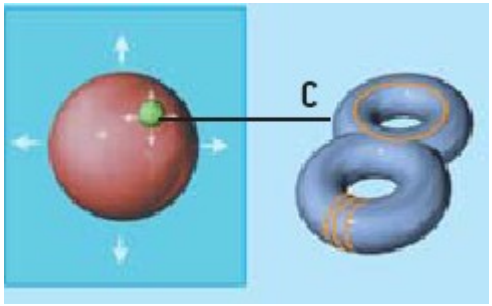
Quantum Decay (tunnel effect)



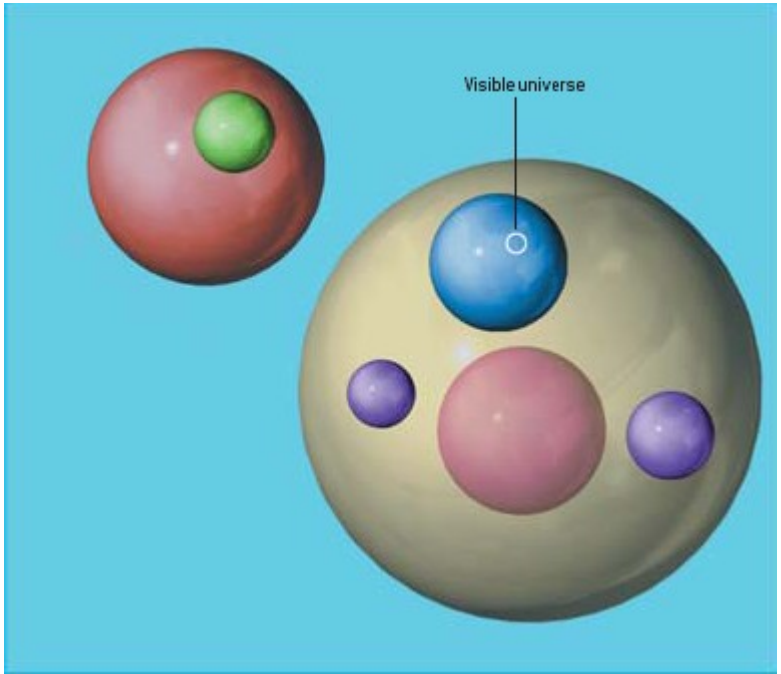
Multiverse







Anthropic ‘explanation’ of dark energy??



Few general predictions * + Many solutions (universes!)

Consider particular (classes of) models

(Compare with QFT)

*Add: Cosmological moduli problem, low-dimension group representations

LARGE Volume Scenario

Exponentially Large Extra Dimensions

BBCQ, CQS (2005)

Example : $\mathbb{P}^4_{[1,1,1,6,9]}$,

Perturbative (alpha') corrections to K

$$\mathcal{K} = -2\ln\left(\frac{1}{9\sqrt{2}}\left(\tau_b^{3/2} - \tau_s^{3/2}\right) + \frac{\xi}{2g_s^{3/2}}\right)$$

Volume

$$W = W_0 + A_s e^{-a_s T_s}.$$

Fluxes

Nonperturbative corrections to W

$$V = \sum_{\Phi=S,U} \frac{\hat{K}^{\Phi\bar{\Phi}} D_\Phi W \bar{D}_{\bar{\Phi}} \bar{W}}{\mathcal{V}^2} + \frac{\lambda (a_s A_s)^2 \sqrt{\tau_s} e^{-2a_s\tau_s}}{\mathcal{V}} - \frac{\mu W_0 a_s A_s \tau_s e^{-a_s\tau_s}}{\mathcal{V}^2} + \frac{\nu\xi|W_0|^2}{g_s^{3/2}\mathcal{V}^3}$$

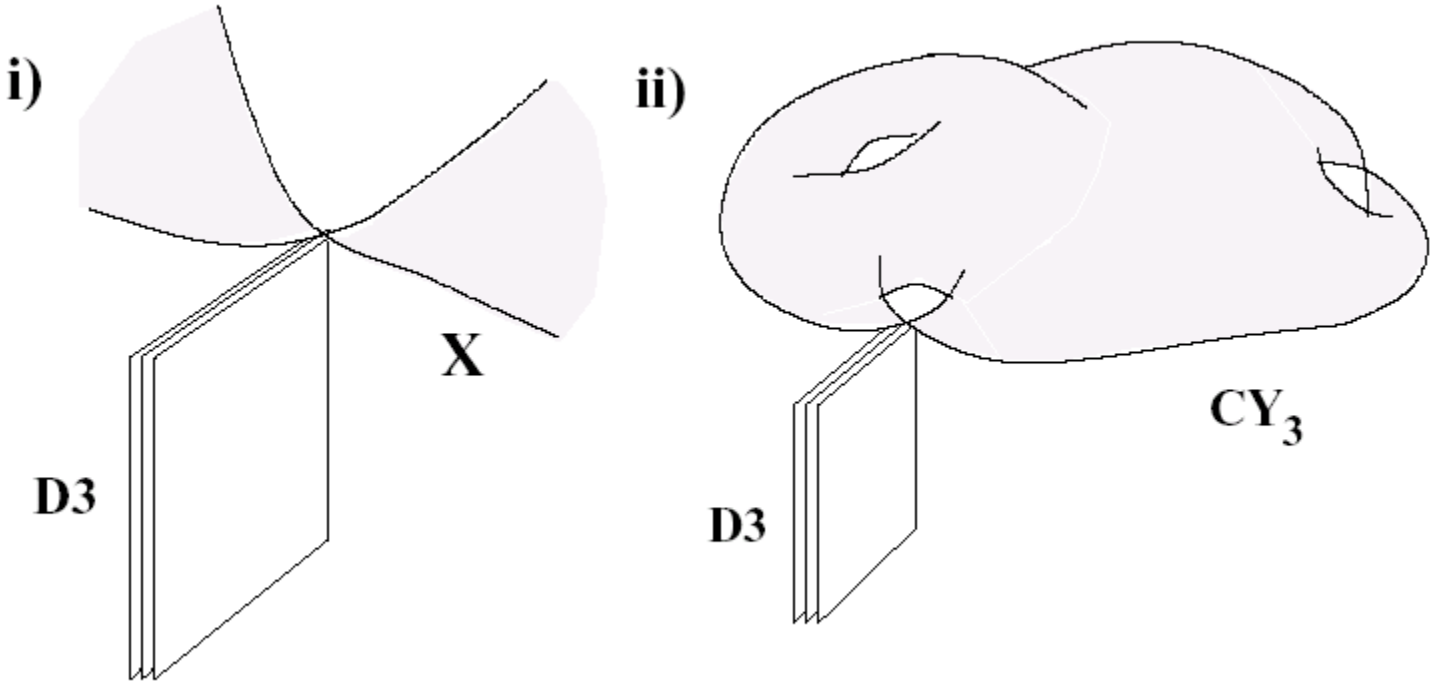
$$\mathcal{V} \sim e^{a_s\tau_s} \gg 1 \text{ with } \tau_s \sim \frac{\xi^{2/3}}{g_s}.$$

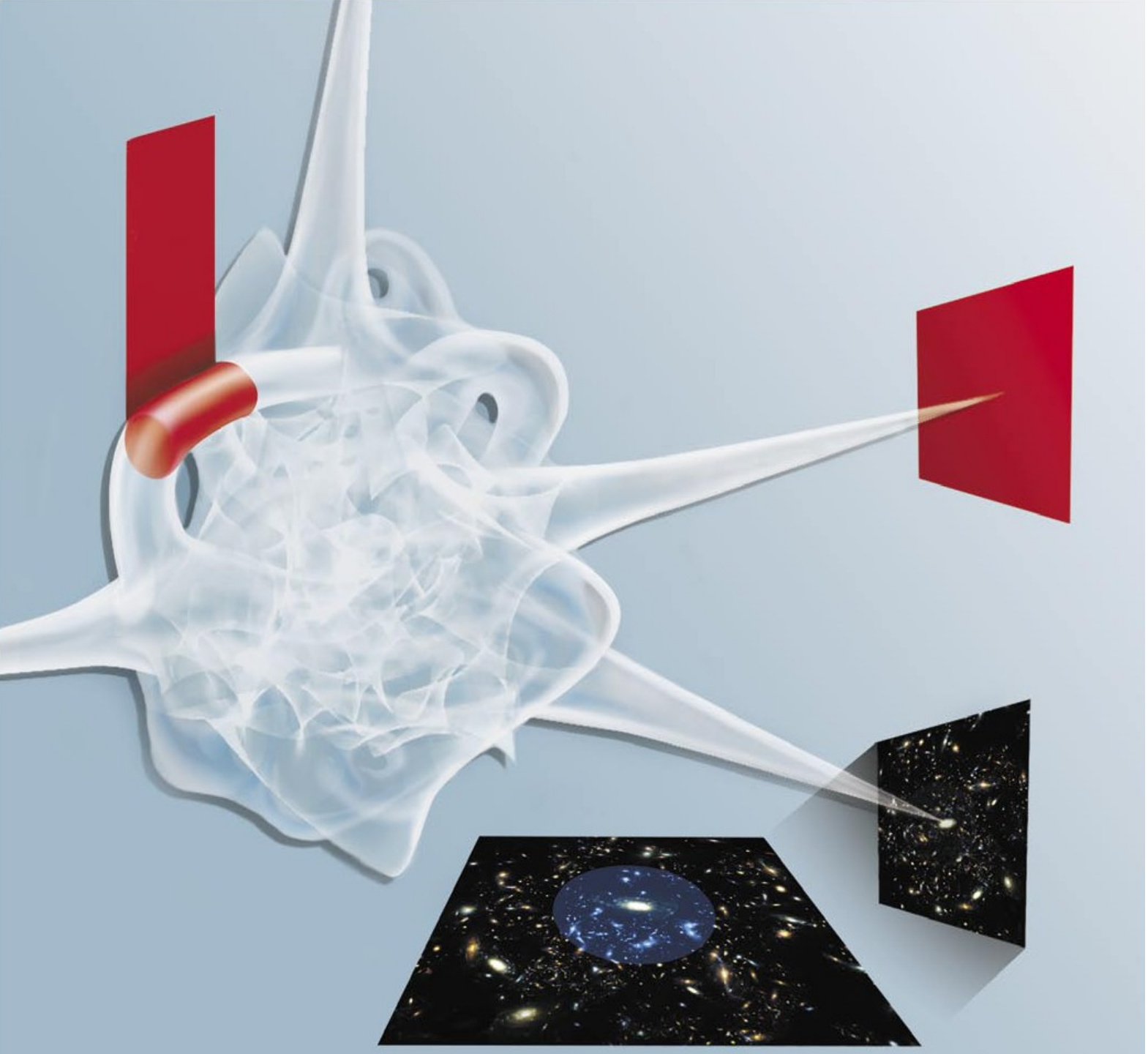
Exponentially large volumen + Broken SUSY!!!

LARGE Volume Implies

Standard Model is localised !

(SM D7 cannot wrap the exponentially large cycle since g =1/*V*)





Universe

D3 Brane

or

D7 Brane

(F-Theory)

Cosmological Inflation

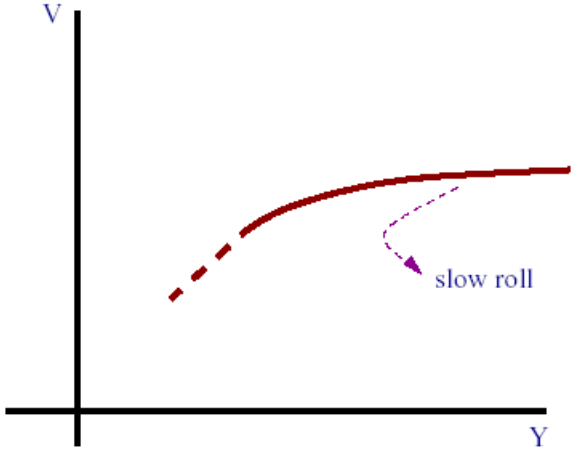
String Inflation Motivation

- Inflation: very successful but is only ad-hoc scenario in search of a theory
- String theory: fundamental theory but lacks experimental tests.
- Is it possible to ‘derive’ inflation from string theory?

Need to compute scalar potential from String theory satisfying slow-roll conditions:

$$\epsilon \equiv \frac{M_{Planck}^2}{2}\left(\frac{V'}{V}\right)^2 \ll 1\,,$$

$$\eta \equiv M_{Planck}^2\,\frac{V''}{V} \ll 1\,.$$



Number of e-folds N>50

$$N(t) \equiv \int_{t_{init}}^{t_{end}} H(t')dt' = \int_{\psi_{init}}^{\psi_{end}} \frac{H}{\dot{\psi}}d\psi = \frac{1}{M_{Planck}^2}\int_{\psi_{end}}^{\psi_{init}} \frac{V}{V'}d\psi\,.$$

Density perturbations

$$\delta_H = \frac{2}{5}\mathcal{P}_{\mathcal{R}}^{1/2} = \frac{1}{5\pi\sqrt{3}}\,\frac{V^{3/2}}{M_p^3\,V'} = 1.91\times 10^{-5}\,,$$

$$n-1 = \frac{\partial \ln \mathcal{P}_{\mathcal{R}}}{\partial \ln k} \simeq 2\eta - 6\epsilon\,, \qquad \frac{dn}{d\ln k} \simeq 24\epsilon^2 - 16\epsilon\eta + 2\xi^2\,.$$

$$n_{grav} = \frac{d\ln \mathcal{P}_{grav}(k)}{d\ln k} = -2\epsilon\,. \qquad (r=16\,\epsilon\,)$$

Two General Classes of String Inflation

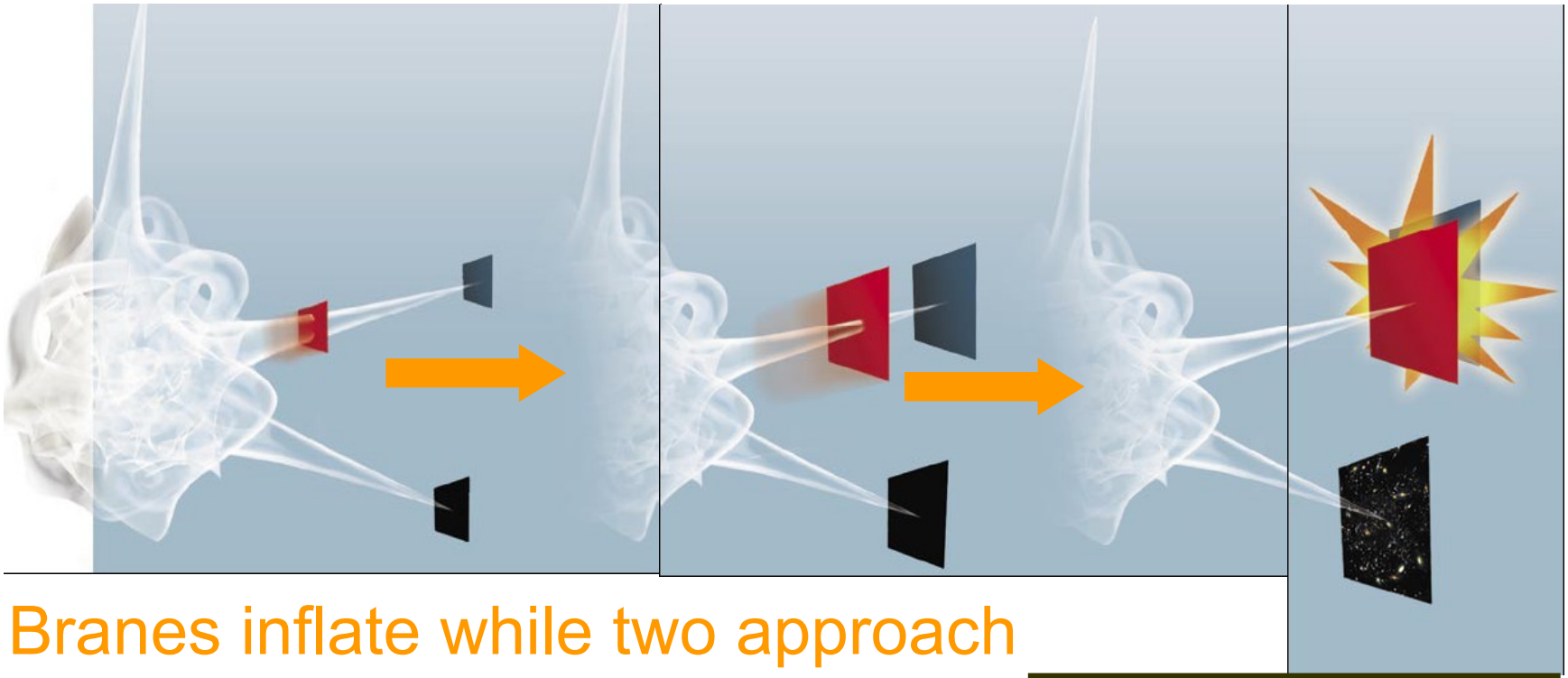
- **Open String Inflaton**
- **Closed String Inflaton**

OPEN STRING INFLATON

Dvali+Tye

Burgess et al.

Dvali et al.



Branes inflate while two approach

Also D3/D7, Wilson-line

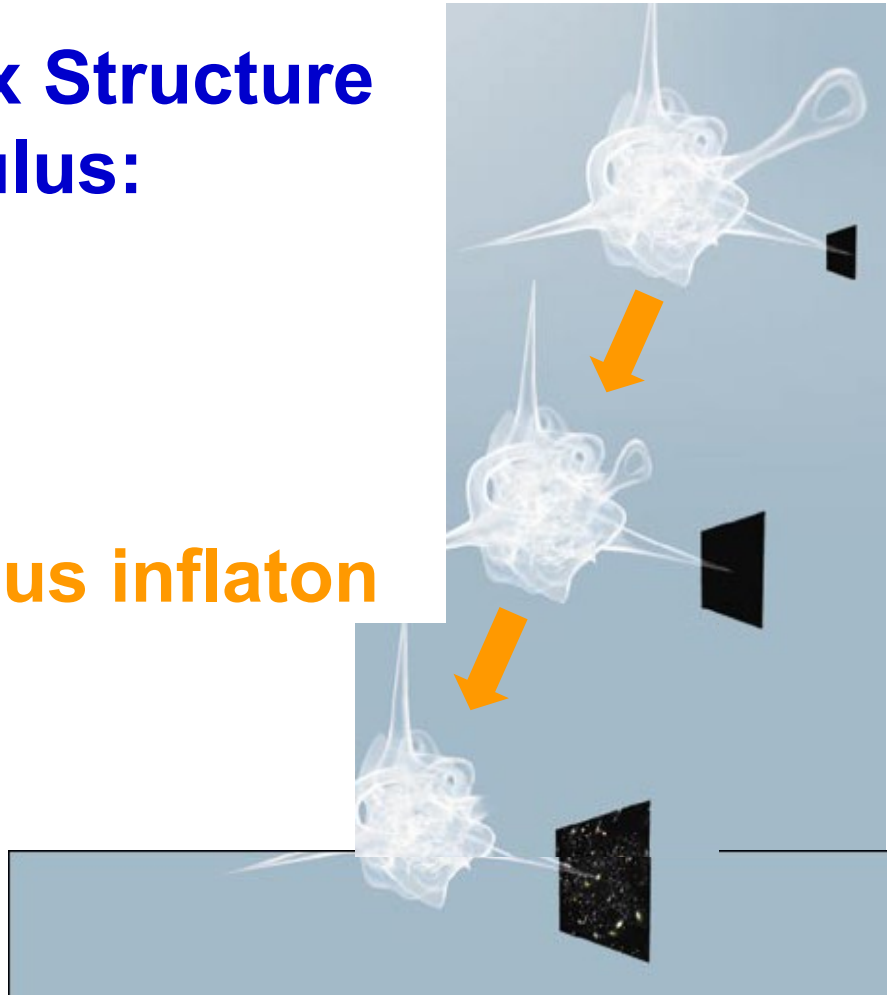
Slow-roll or DBI (need tuning but tunable, r~0)

Tachyon condensation: cosmic strings,…

CLOSED STRING INFLATON

Dilaton, Complex Structure or Kahler Modulus:

- **Axion Inflaton**
- **Blow-up modulus inflaton**
- **Fibre inflaton**
- **Volume**



Kähler Moduli Inflation (Blow-up)

$$V = \sum_i \frac{8(a_i A_i)^2 \sqrt{\tau_i}}{3\mathcal{V}\lambda_i \alpha} e^{-2a_i\tau_i} - \sum_i 4\frac{a_i A_i}{\mathcal{V}^2} W_0 \tau_i e^{-a_i\tau_i} + \frac{3\xi W_0^2}{4\mathcal{V}^3}.$$

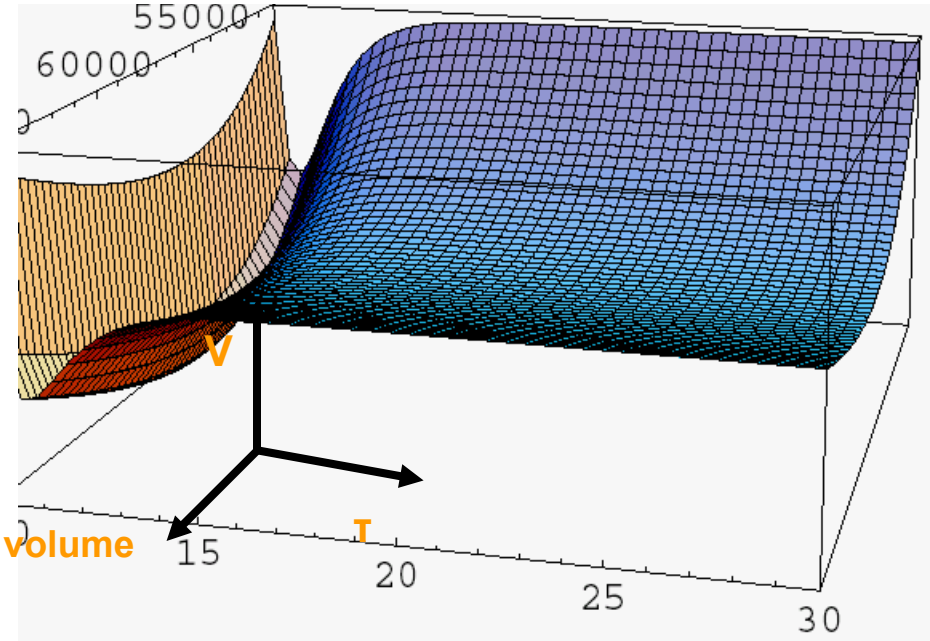
Conlon-FQ

Bond et al.

…

$$V \cong V_0 - \frac{4W_0 a_n A_n}{\mathcal{V}^2}\left(\frac{3\mathcal{V}}{4\lambda}\right)^{2/3}(\tau_n^c)^{4/3}\exp\left[-a_n\left(\frac{3\mathcal{V}}{4\lambda}\right)^{2/3}(\tau_n^c)^{4/3}\right].$$

Calabi-Yau: $h_{21} > h_{11} > 2$



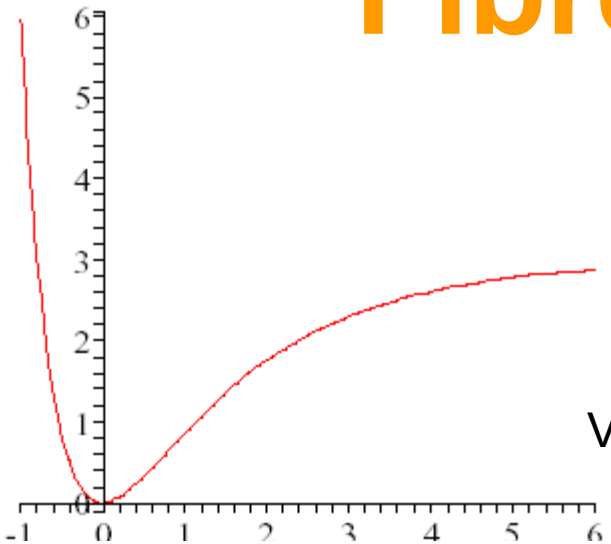
small field inflation (r<<<1)

no fine-tuning!!

0.960<n<0.967

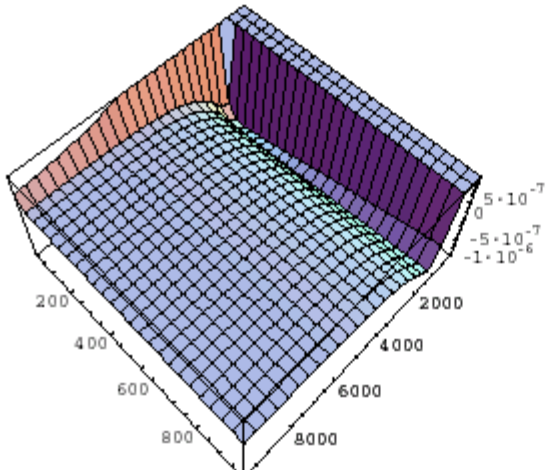
loop corrections??

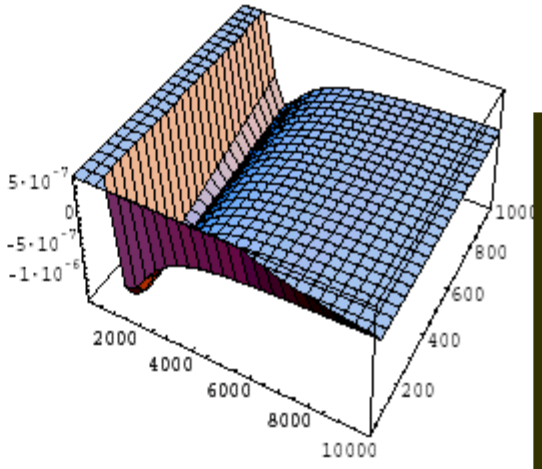
Fibre Inflatons



$$\mathcal{V} = \alpha\left[\sqrt{\tau_1}(\tau_2 - \beta\tau_1) - \gamma\tau_3^{3/2}\right],$$

$$V = \frac{m_\varphi^2}{4}\left(3 - 4\,e^{-\kappa\hat{\varphi}/2} + e^{-2\kappa\hat{\varphi}}\right) \qquad \kappa = \frac{2}{\sqrt{3}}.$$

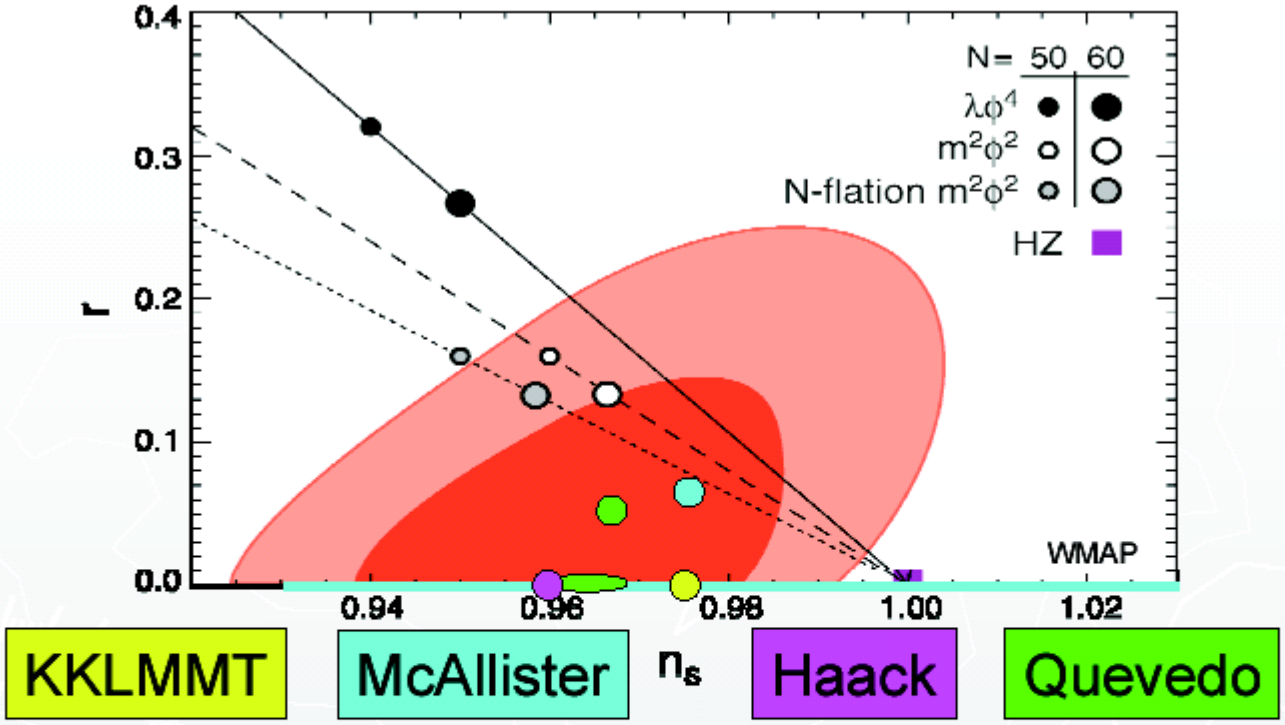




$$n_s \simeq 0.970, \qquad r \simeq 4.6 \cdot 10^{-3},$$

Observable gravity waves !

(can be ruled out by Planck if they observe them and CMBpol… if they do not observe them)



Expect dramatic improvements in these limits in next 5-10 years: Planck launch 2009, SPIDER, Clover, QUIET, BICEP, EBEX, PolarBEAR, ...
+ possible additional observables: nongaussianities, cosmic strings, … (hints at $<2\sigma$).

Polchinski, ICHEP 2008

CONCLUSIONS

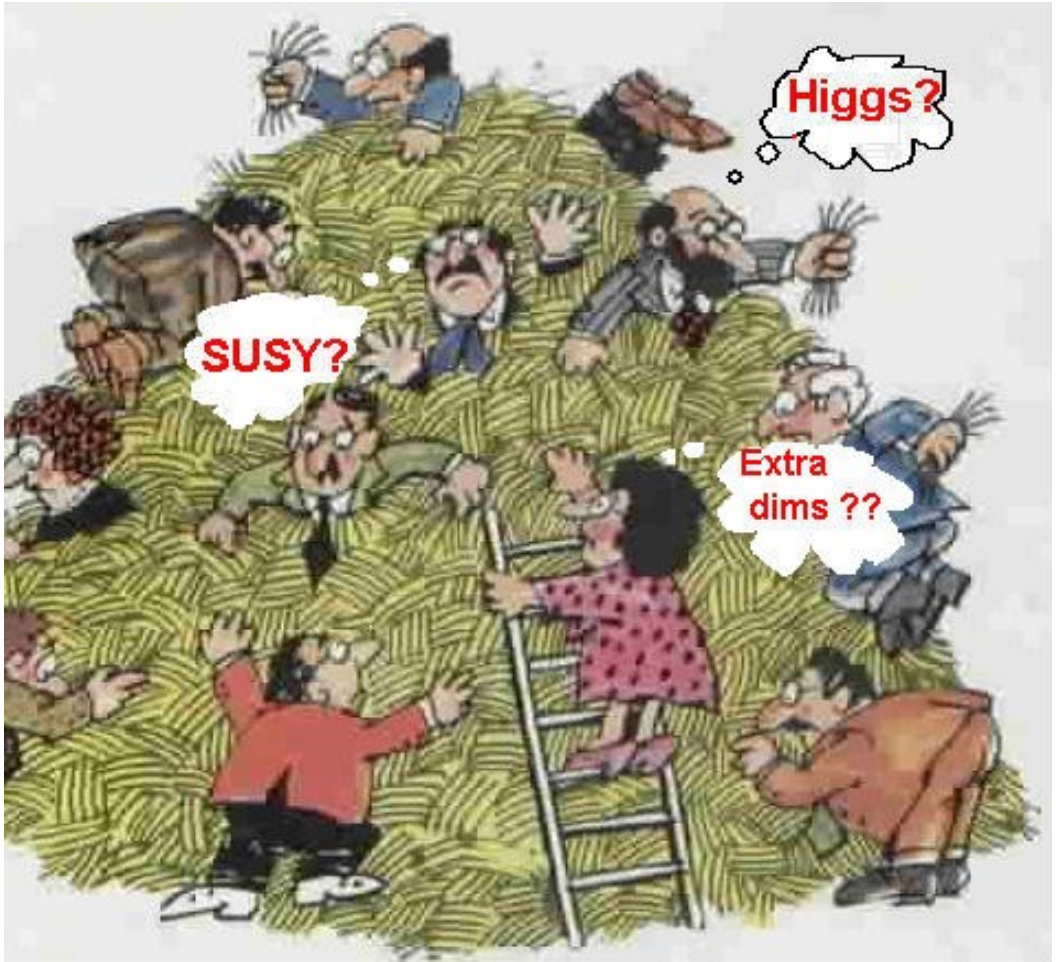
- Exciting times!!! **'Decade of Applied String Theory'**
- Warping and large extra dimensions!
- Calculable models of inflation
- Simple principles, complicated solutions, (but SM is ugly!)
- Many open questions

(A fully realistic model?

Testable model independent predictions?

Non-gaussianities?...)

In the meantime: LHC + …

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