Is String Phenomenology an Oxymoron?

Fernando Quevedo
ICTP/Cambridge
Northeastern
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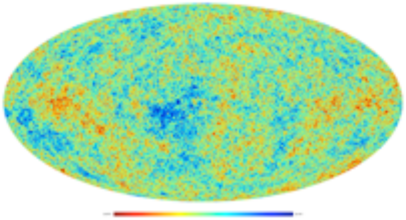
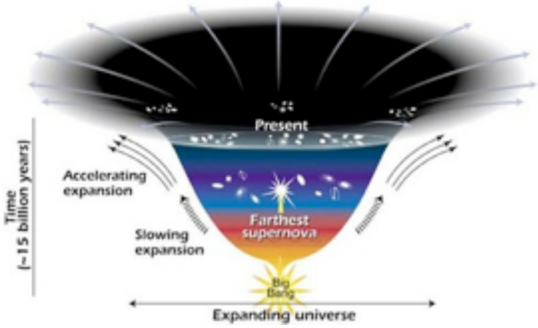
FQ, arXiv:1612.01569 (CUP to appear)

Greatest `Recent' Discoveries

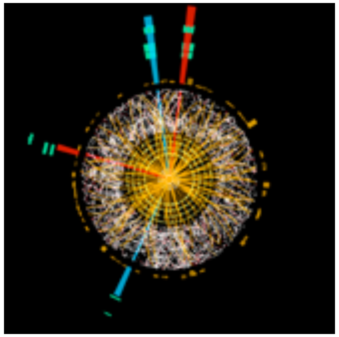
- Fluctuations of Cosmic Microwave Background (1992) (Nobel Prize 2006)



- Dark Energy (1998) (Nobel Prize 2011)



- Higgs Discovery (2012) (Nobel Prize 2013)



- Gravitational waves (2016) (Nobel Prize 2017)

Fundamental Theories:

Special Relativity and Quantum Mechanics

Poincaré Group: (SR and QM)

Wigner 1939

Massive particles: (Little group SO(3)) $p = (m, 0, 0, 0)$

$$|m, J; p_\mu, s\rangle \text{ with } s = -J, -J+1, \cdots, J \text{ and } p^2 = m^2$$

Tachyons?

Massless particles: (Little group E2) $p = (E, 0, 0, E)$

→ **∞-dimensional representations (CSR): not observed ??**

Restricted Little group: O(2) in E2: $|p_\mu, \lambda\rangle$ with $\lambda = 0, \pm 1/2, \pm 1, \cdots$.

Theories for spins 0,1/2,1: Quantum Field Theories (QFT)

Massless spins 3/2,2: (super) gravity: Effective Field Theories (EFT)

"Generic Predictions" of QFT

- Identical particles
- Antiparticles
- CPT
- Spin-statistics
- 'Decoupling' (physics organised by scales, EFTs)

The Standard Model

(A particular QFT)

FERMIONS
matter constituents
spin = 1/2, 3/2, 5/2, ...

Leptons spin = 1/2		
Flavor	Mass GeV/c^2	Electric charge
ν_e electron neutrino	$<1\times10^{-8}$	0
e electron	0.000511	−1
ν_μ muon neutrino	<0.0002	0
μ muon	0.106	−1
ν_τ tau neutrino	<0.02	0
τ tau	1.7771	−1

Quarks spin = 1/2		
Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.003	2/3
d down	0.006	−1/3
c charm	1.3	2/3
s strange	0.1	−1/3
t top	175	2/3
b bottom	4.3	−1/3

SU(3)xSU(2)xU(1) + Gravity
3 Families + Higgs
3+1 Dimensions

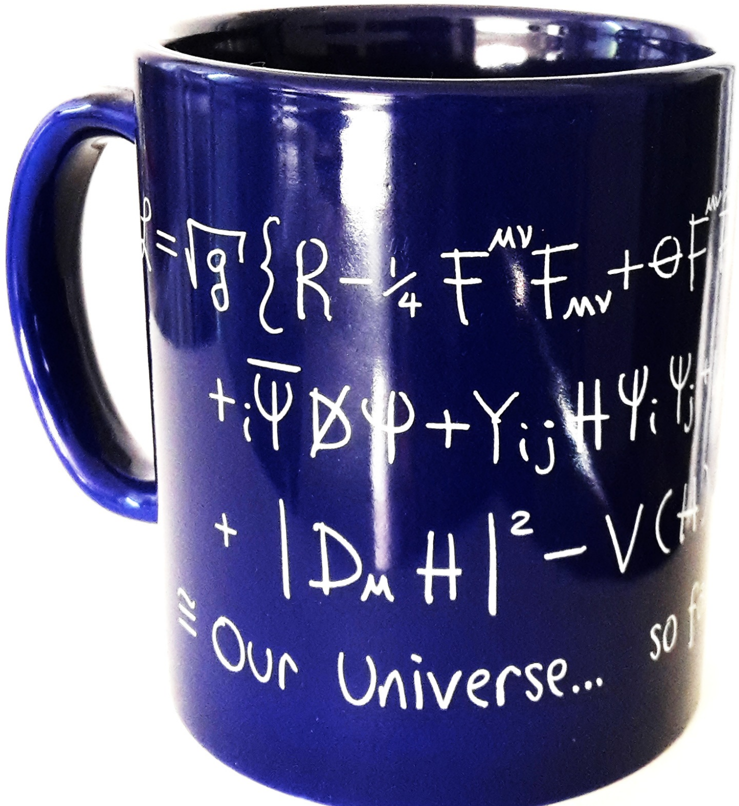
BOSONS
force carriers
spin = 0, 1, 2, ...

Unified Electroweak spin = 1		
Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.4	−1
W^+	80.4	+1
Z^0	91.187	0

Strong (color) spin = 1		
Name	Mass GeV/c^2	Electric charge
g gluon	0	0

- Higgs H spin=0
- Graviton G spin=2 (Classical!?)

Standard Model + Gravity



Some Properties of the SM

- Arguably greatest theoretical achievement in past 75 years.
- It is renormalisable but also an EFT (large cutoff)
- It is simple (not the simplest)
- Matter in bi-fundamental representations
- Illustrates several phases of gauge theories
- It is ‘ugly’ (elegant principles but many free parameters)
- SM+gravity + neutrino mass could imply a SM `landscape’
- Not complete (baryogenesis, dark matter, gravity)

Open Problems

(Challenges for young generation)

Open Questions

- Why? (3+1 (dimensions, families, interactions);
  + some 20 parameters (masses, couplings))

- Naturalness (hierarchy, cc, strong CP)

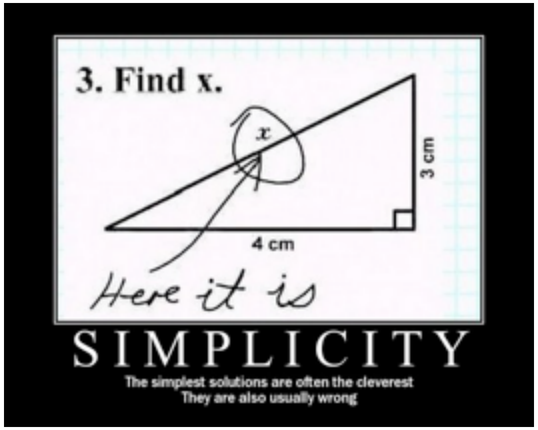
- 'Technical' (confinement,...)

- Cosmology (dark matter, baryogenesis, density perturbations of CMB, origin/alternatives to inflation,..., big-bang)

- Consistency (gravity)

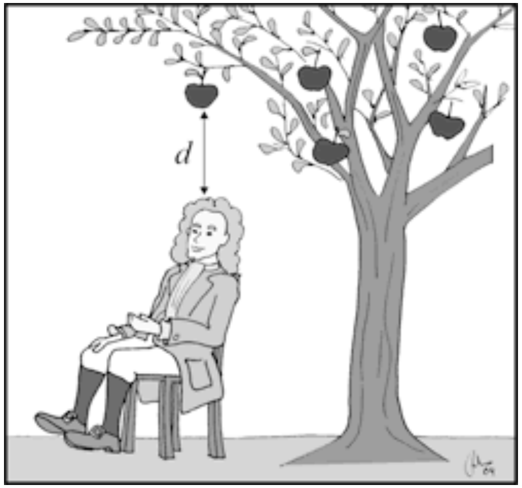
Approaches to BSM

Approaches to BSM



Simplicity

Follow your nose

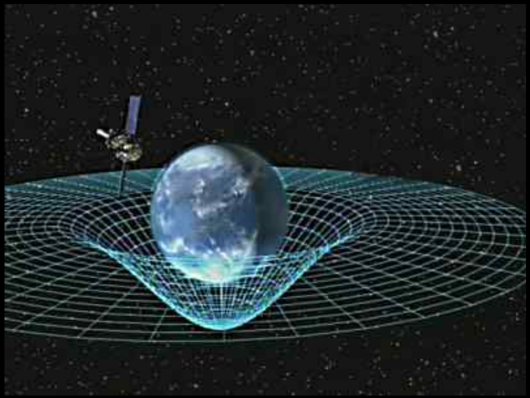


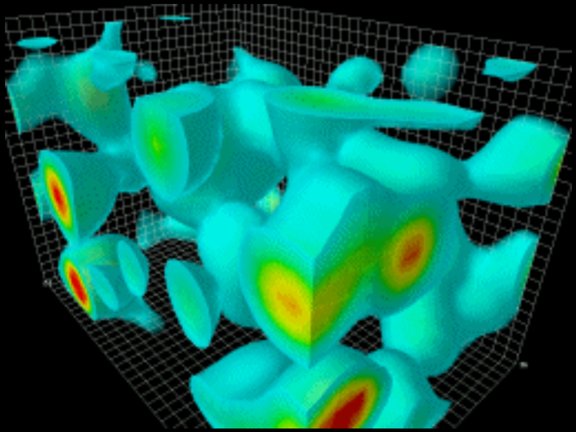
Top-down

Bottom-up

FUNDAMENTAL PROBLEM

Quantum Gravity





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

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

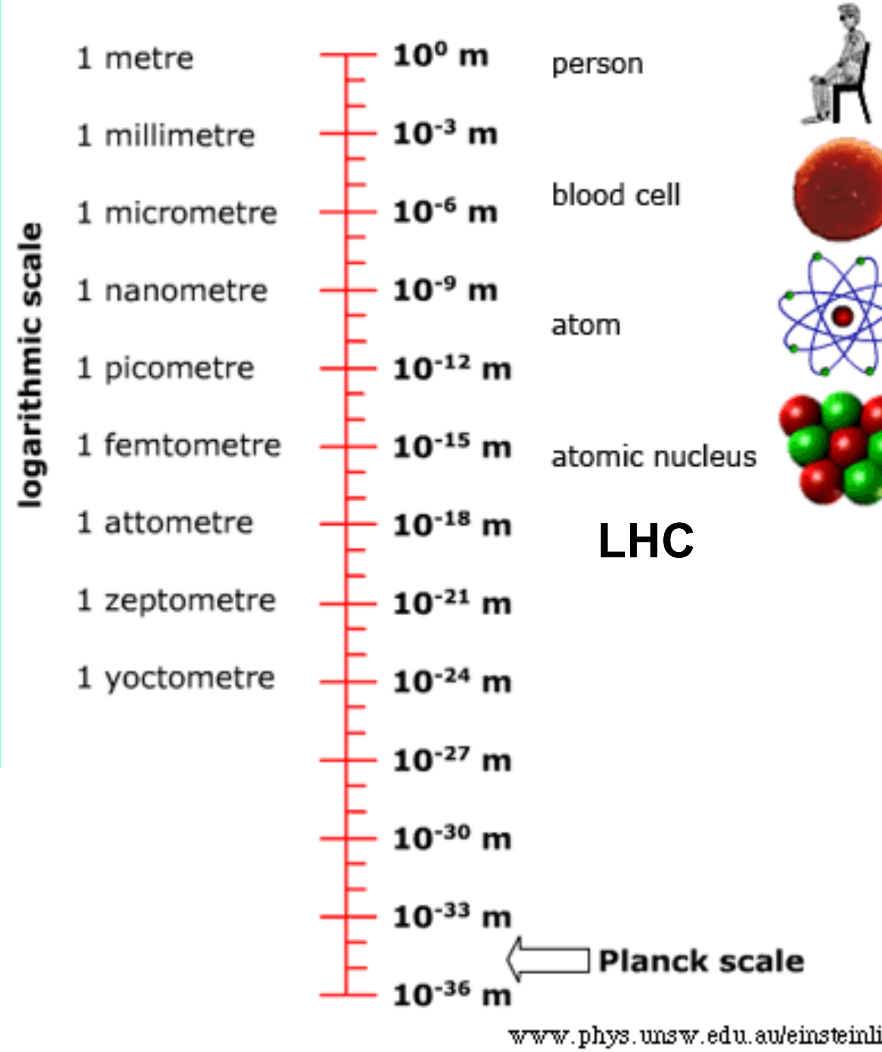
$$c = 2.99792458\times10^{8}\ \text{m}/\text{sec}$$

Planck Units

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

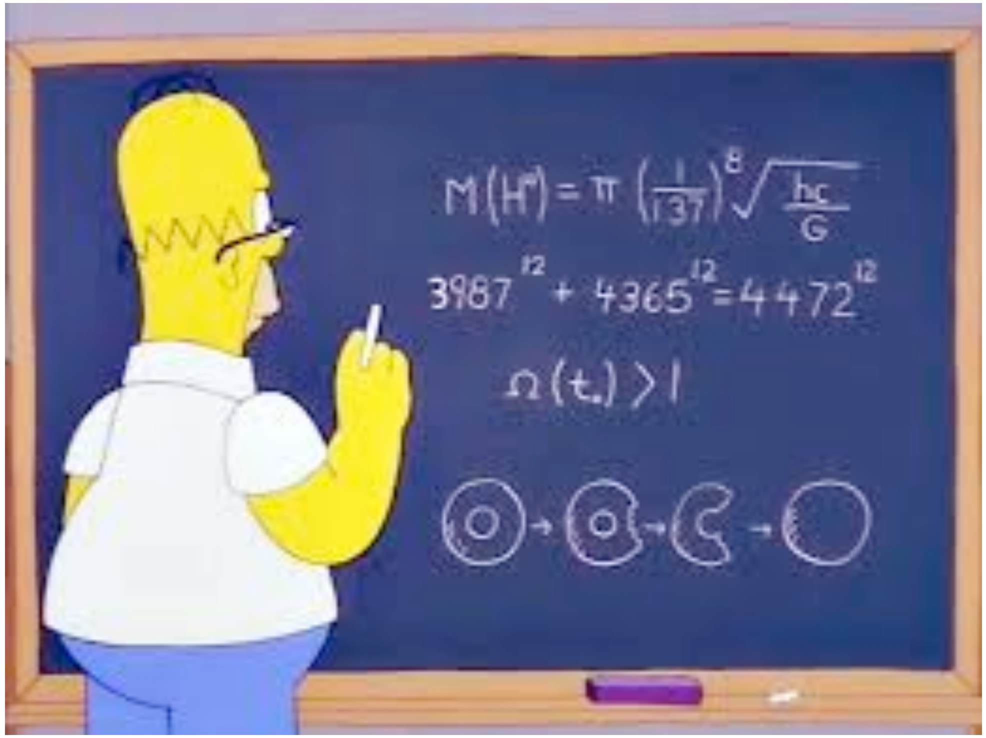
$$M_{\text{Planck}} = \sqrt{\frac{\hbar c}{G_N}} = 21.8\ \mu\text{g}$$

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



$$m_p = \sqrt{\frac{\hbar c}{G}} = 10^{19}\ \text{GeV}$$

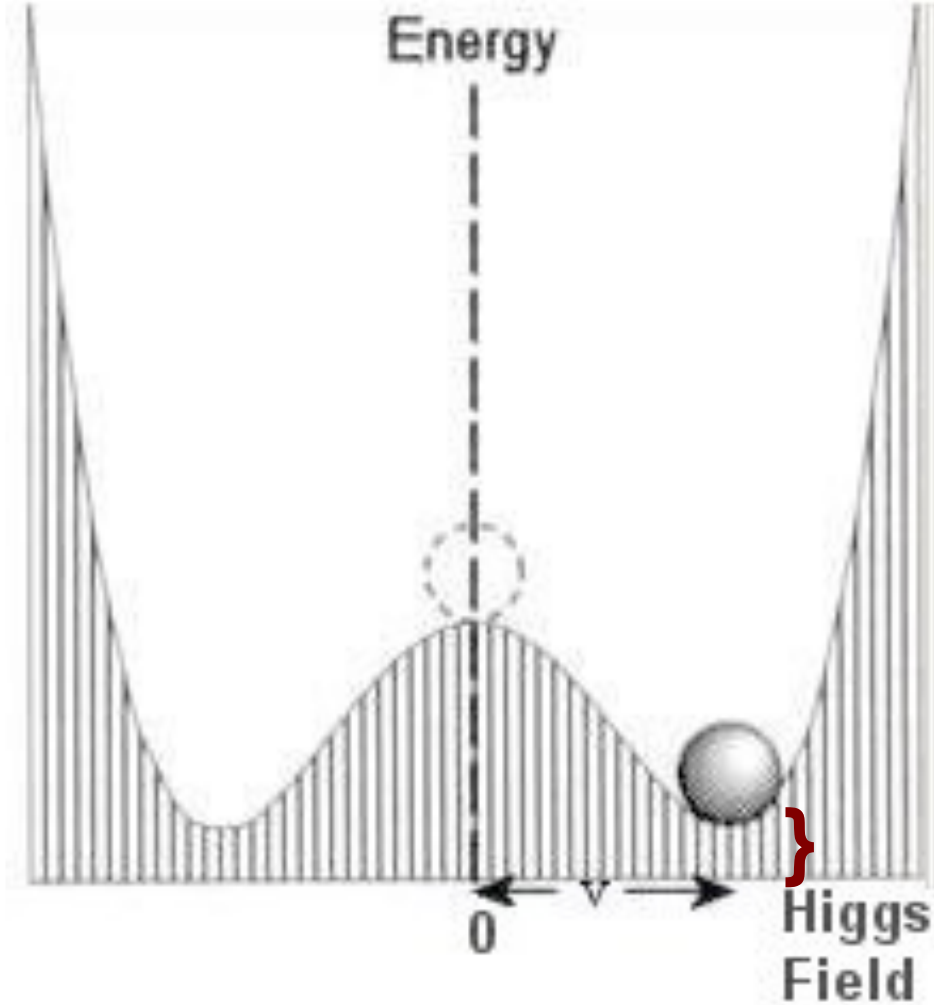
Hierarchy Problem



HS 1997

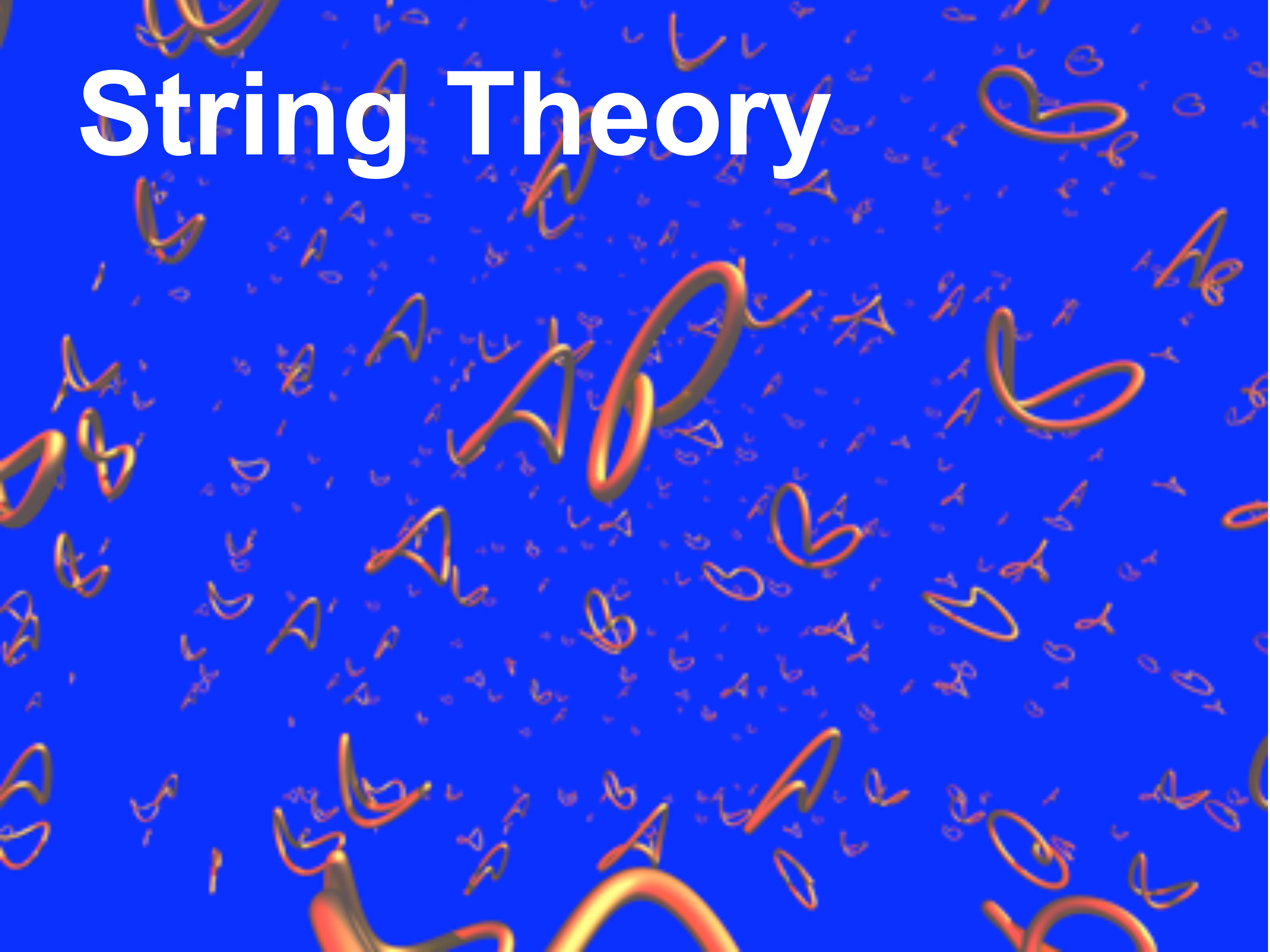
Quantum corrections?

Cosmological constant

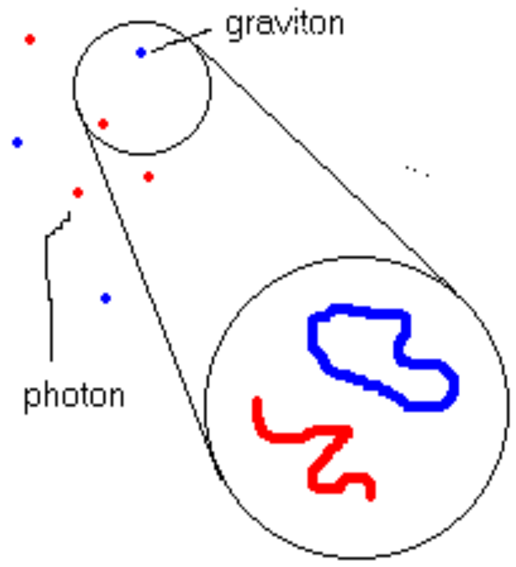


Cosmological constant =
0.0000000000000000000000000000000000000000000000000000000000000000
00000000000000000000000000000000000000000000000000000001 M_{Planck}^4 ????

String Theory



General ‘Predictions’ of (Super) String Theory



0

Gravity + other interactions + matter + … exist!

Theory	Dimensions	Supercharges	Bosonic Spectrum	
Heterotic $E_8 \times E_8$	10	16		g_{MN}, B_{MN}, ϕ A_M^{ij}
Heterotic $SO(32)$	10	16		g_{MN}, B_{MN}, ϕ A_M^{ij}
Type I $SO(32)$	10	16	NS-NS R-R	g_{MN}, ϕ, A_M^{ij} C_{MN}
Type IIA	10	32	NS-NS R-R	g_{MN}, B_{MN}, ϕ C_M, C_{MNP}
Type IIB	10	32	NS-NS R-R	g_{MN}, B_{MN}, ϕ C, C_{MN}, C_{MNPQ}
11D Supergravity	11	32		g_{MN}, C_{MNP}

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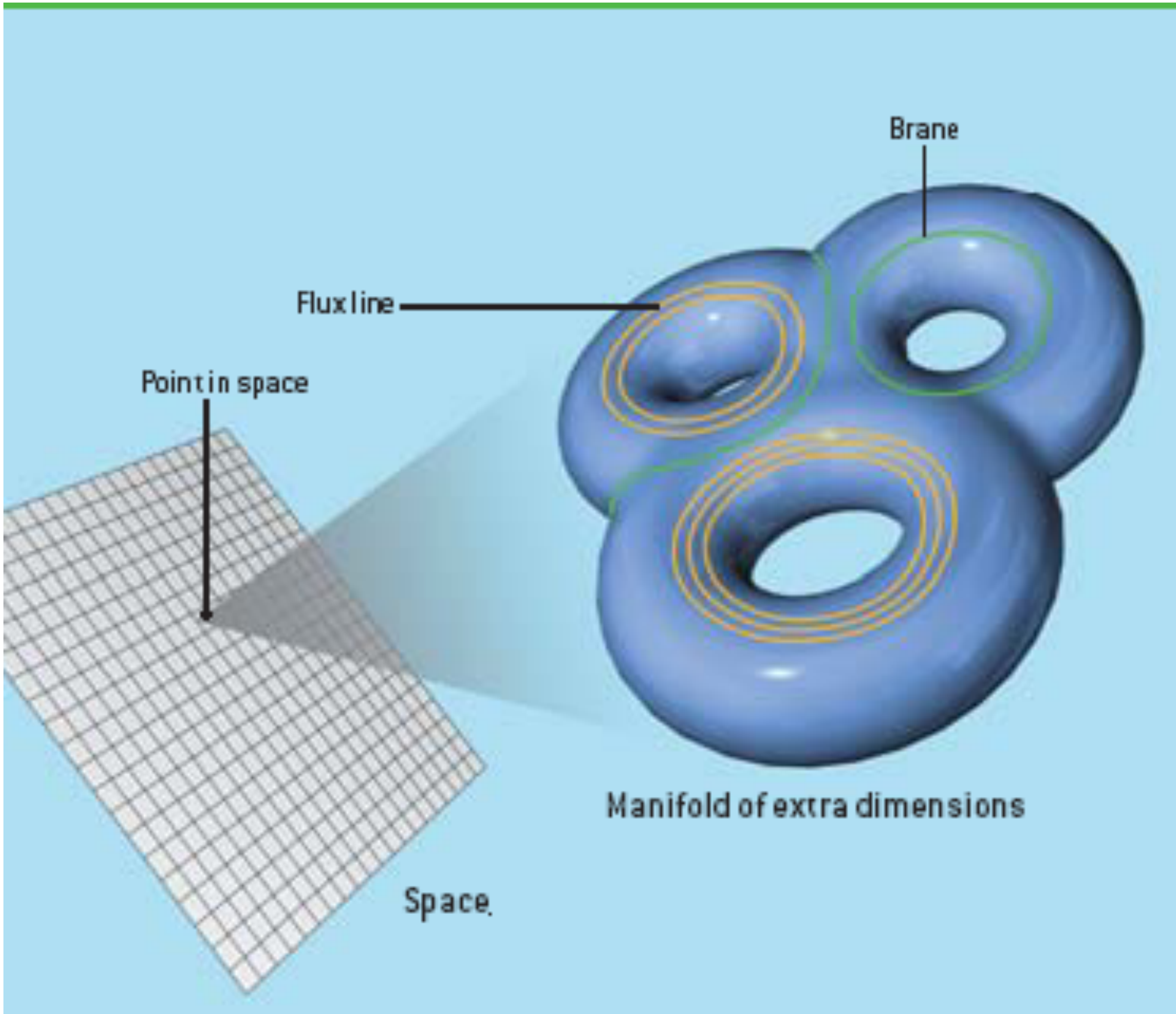
- **No tachyons**

- **No CSR (continuous spin representations)**

*** Both in principle allowed by Special relativity+quantum mechanics + QFT (?) but not on perturbative (super) strings.**

Extra Bosonic Dimensions

2



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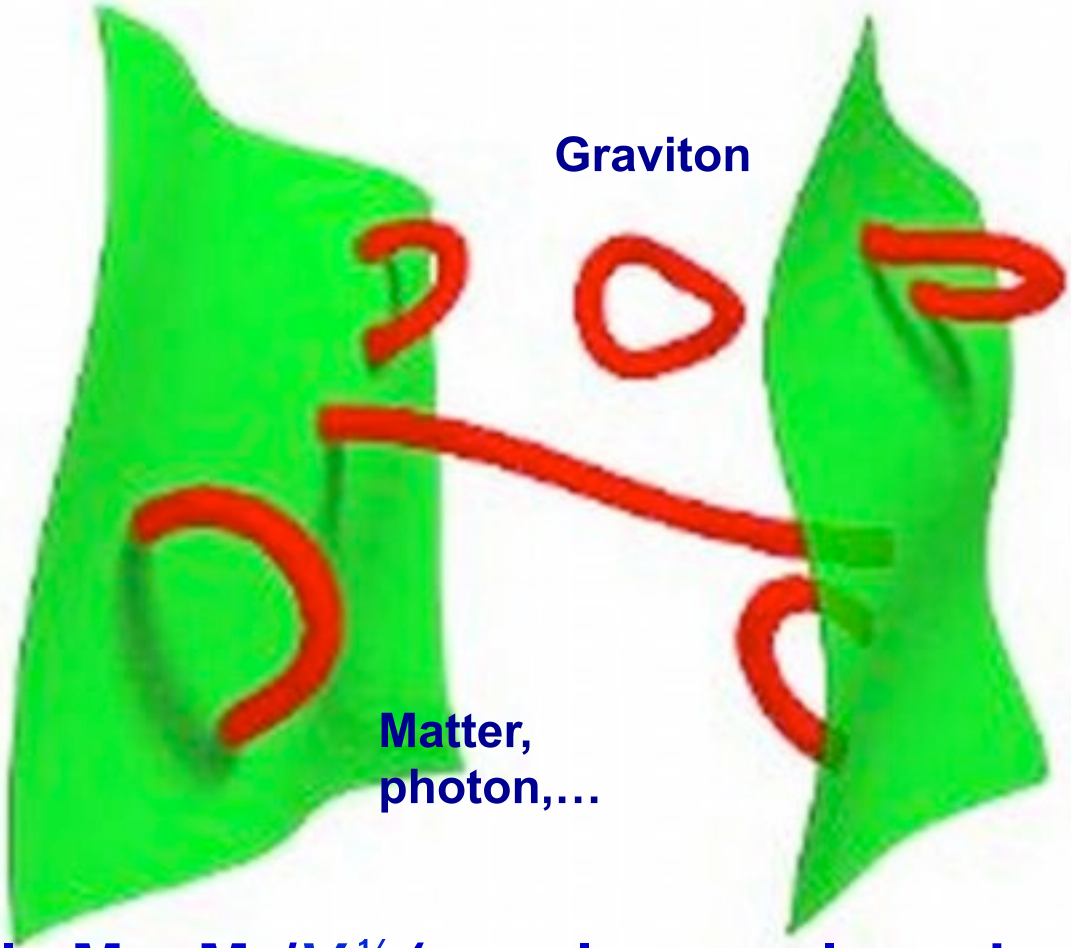
The Brane World

Brane world in string theory



String scale $M_s = M_P / V^{1/2}$ (very large volume implies strings relevant at scales much smaller than Planck!!!!)

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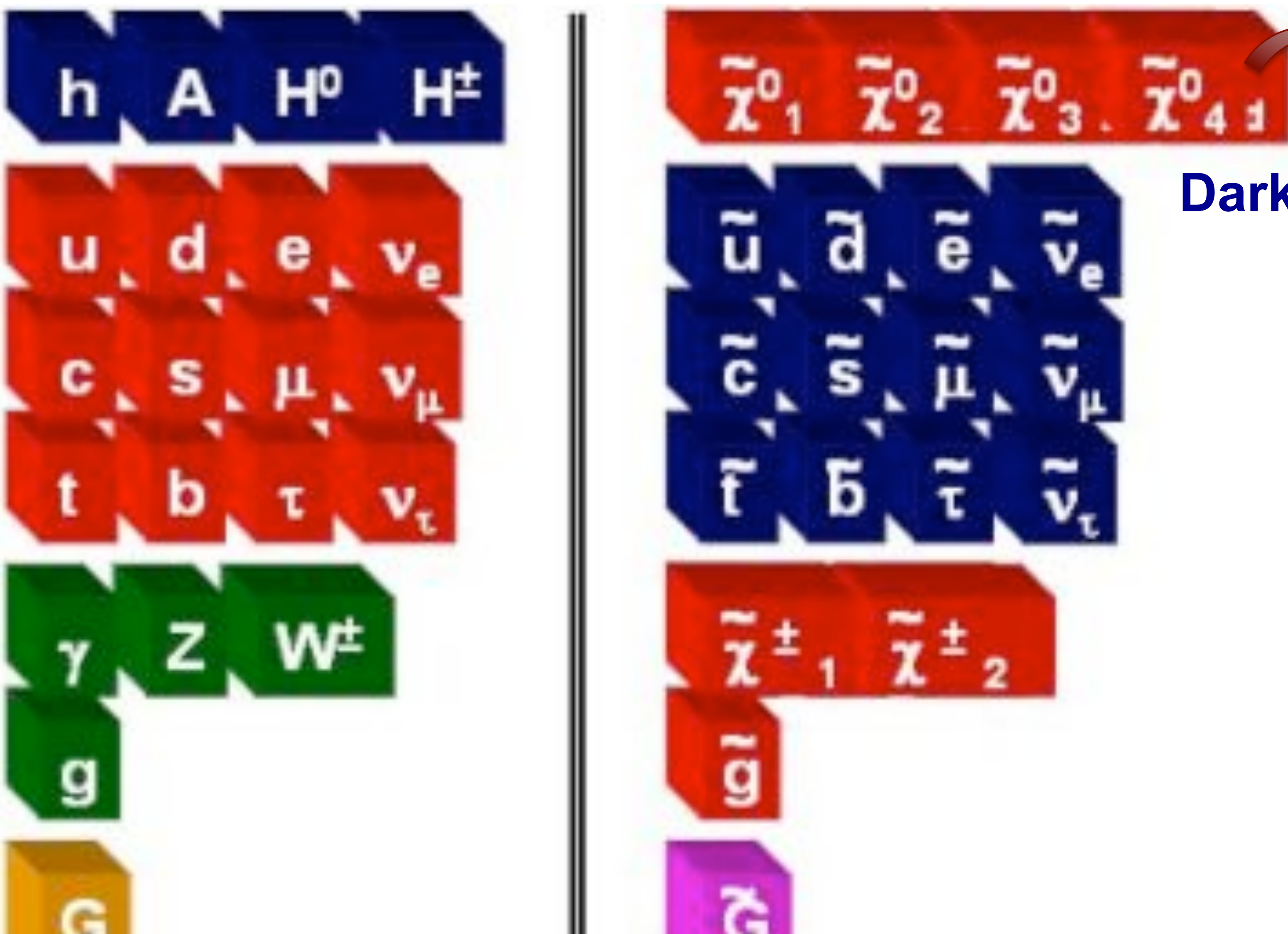
Extra Fermionic Dimensions

(Supersymmetry (SUSY))

Boson → Fermion → Boson

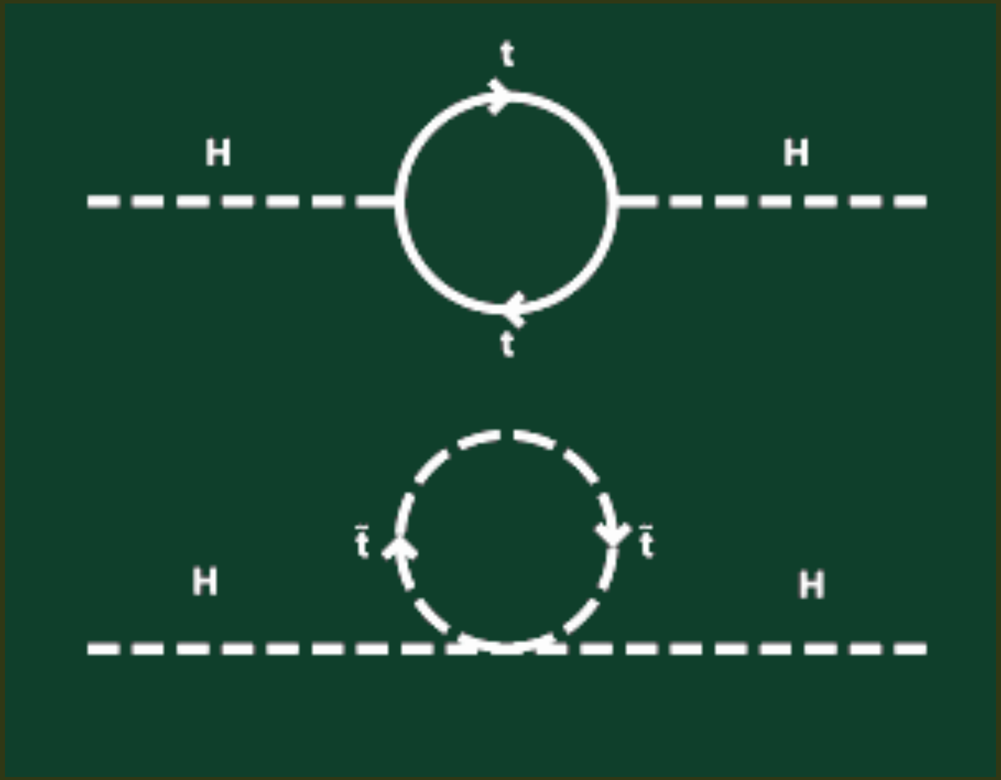
SUPERSYMMETRY !

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



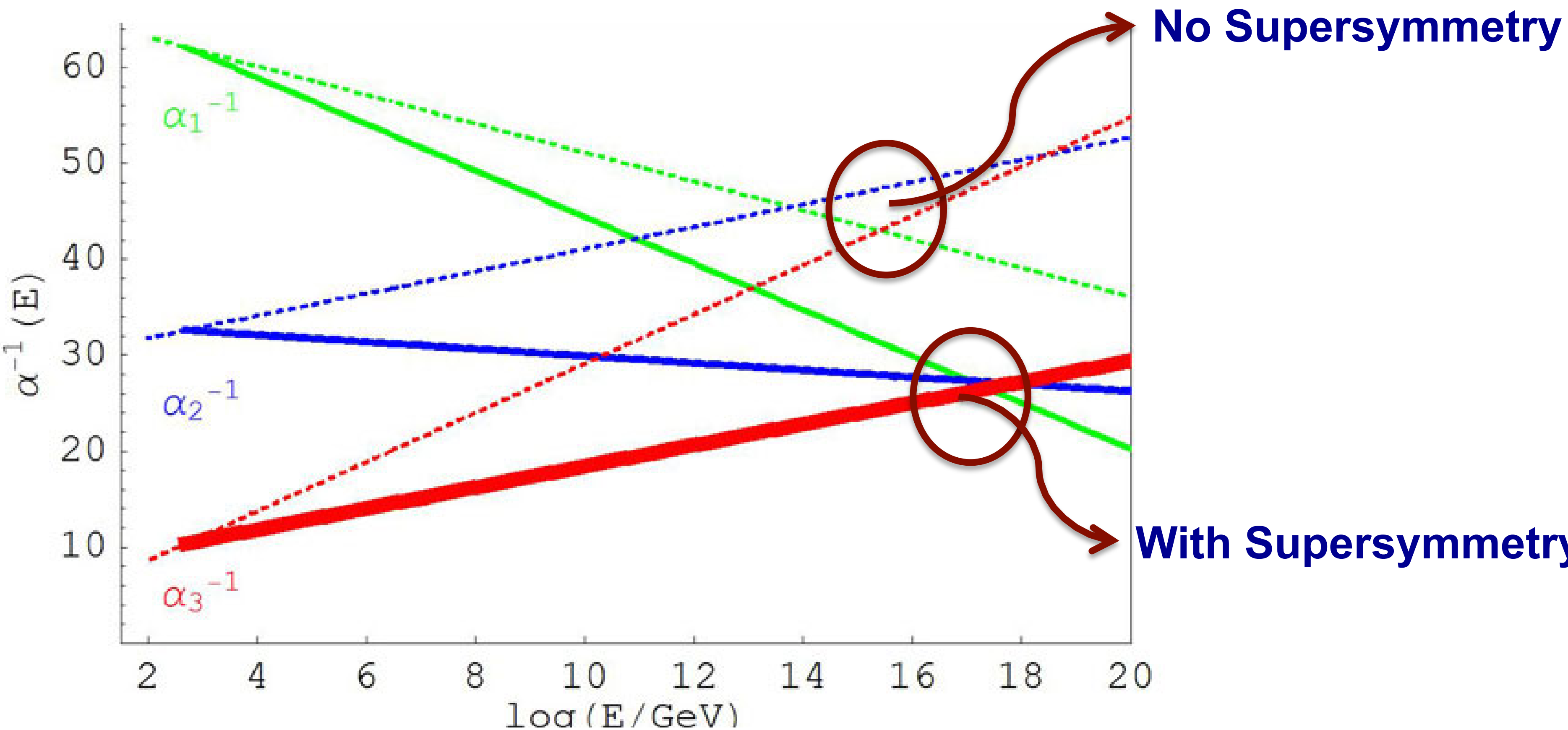
Dark matter!!?

Supersymmetry and Hierarchy



Supersymmetric particles contribute to the mass of the Higgs with opposite signs as SM particles and solves the hierarchy if their own mass is ~ 10^3 GeV

SUSY + Unification



Supersymmetry

- Hierarchy ✓
- Unification ✓
- Dark Matter ✓
- Instability ✓
- Cosmological Constant ✗
- Experimental Evidence?? (fine tuning again?) ✗
- (Super) Strings ? (SUSY needed but scale?)

Why SUSY?

- SUSY does not solve the cc problem
- SUSY may not solve the hierarchy problem
- SUSY B,L + flavour problem
- SUSY complicates cosmology (cosmological moduli problem, gravitino problem)
- Best dark matter candidates not neutralino
- Unification: other options
- Stability of Higgs potential? No tachyons? String Theory?

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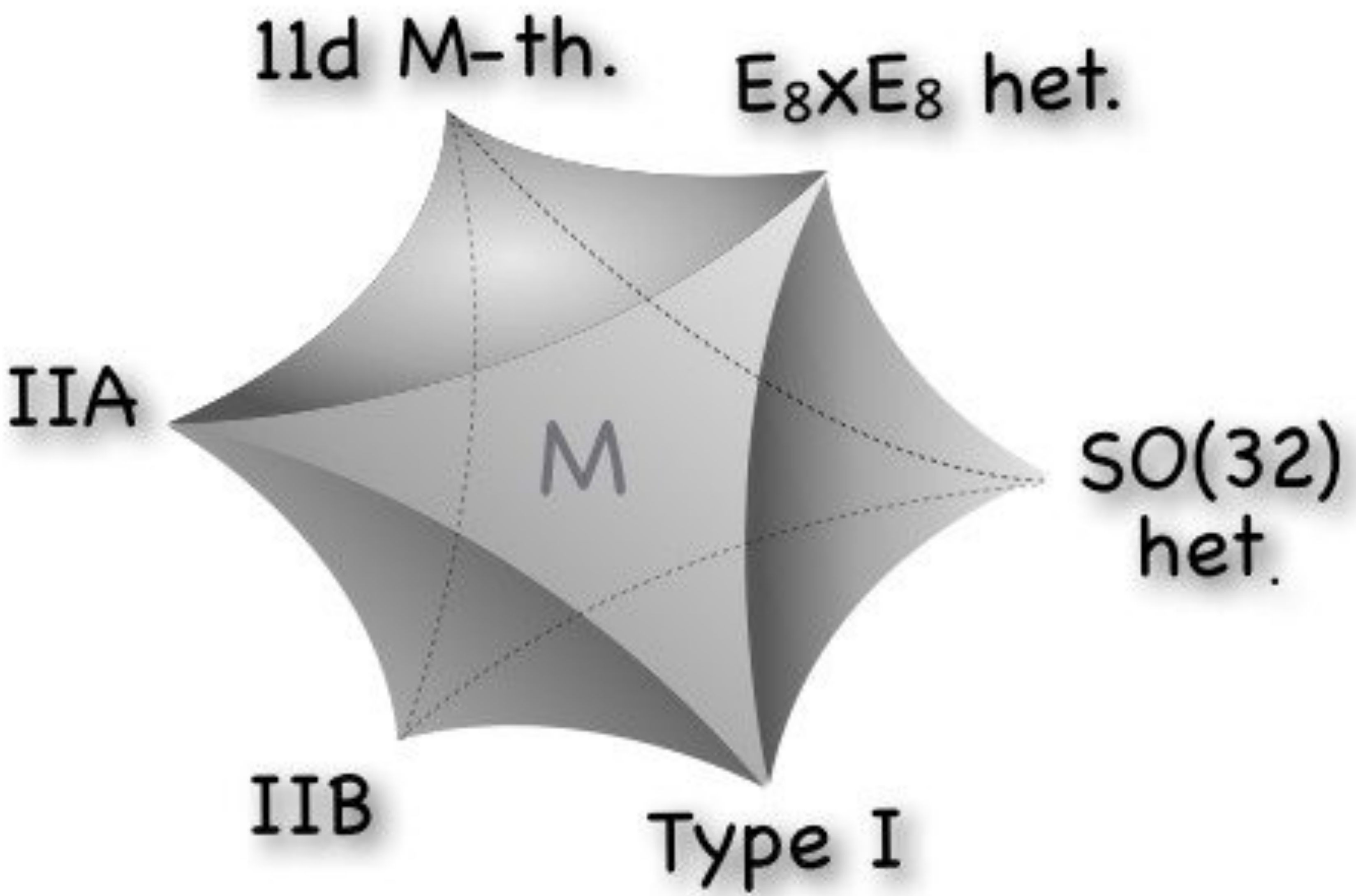
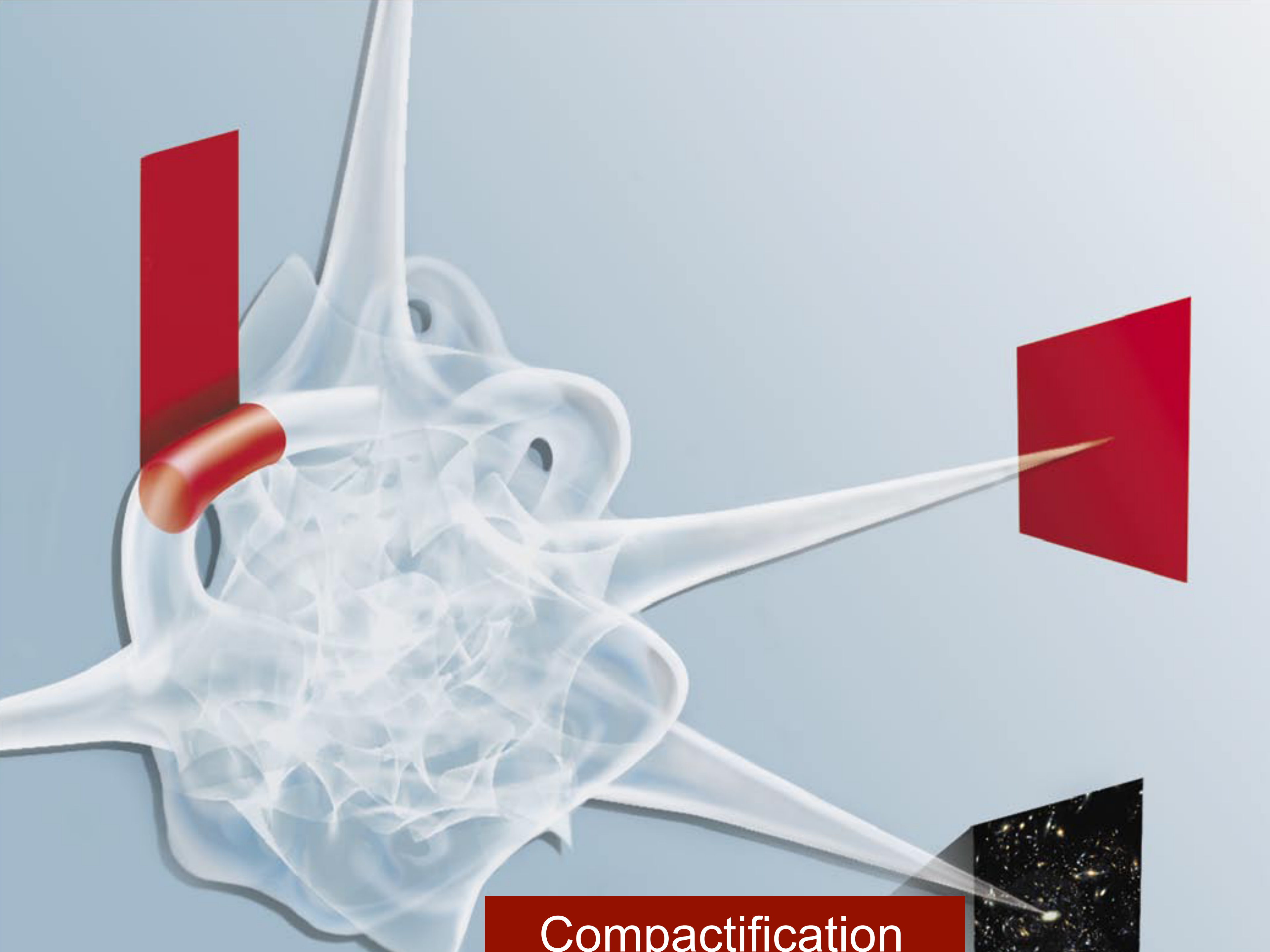
One Theory Many Solutions

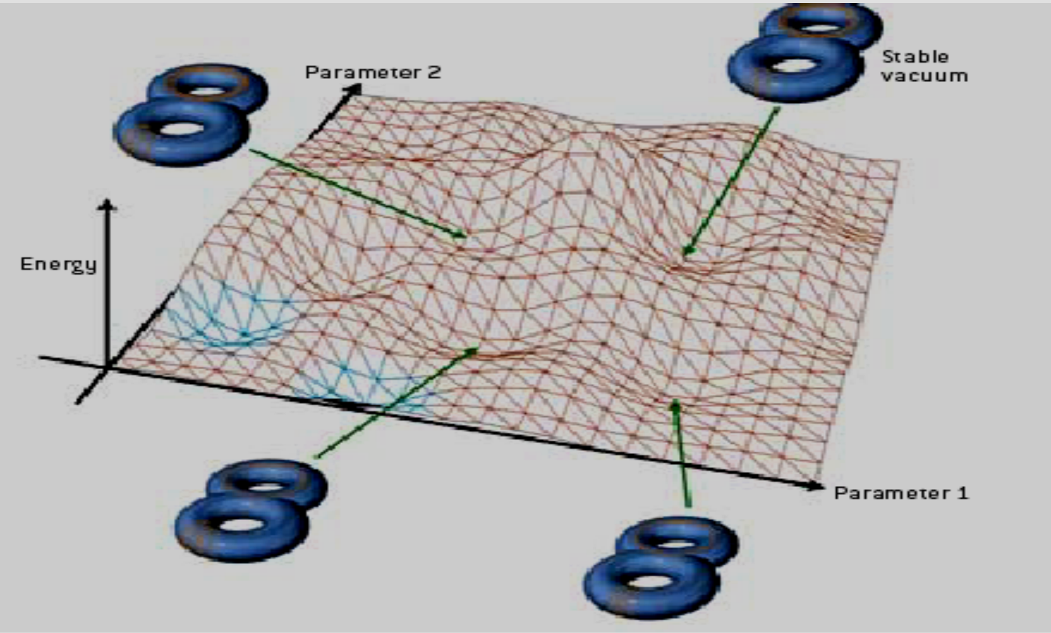
One single theory (+ no free parameters) but MANY solutions





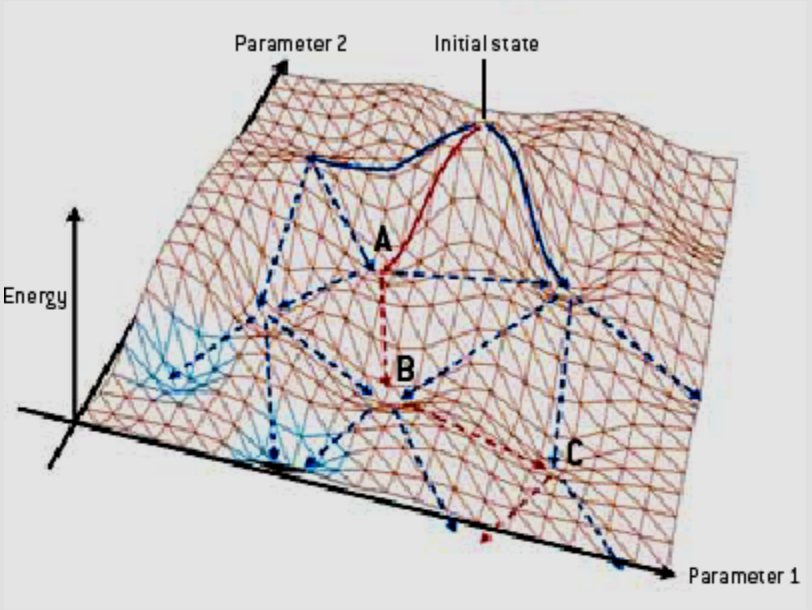
Compactification

The String Landscape

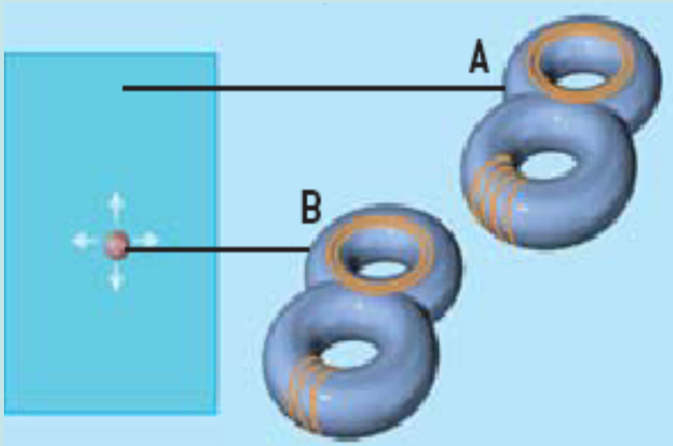


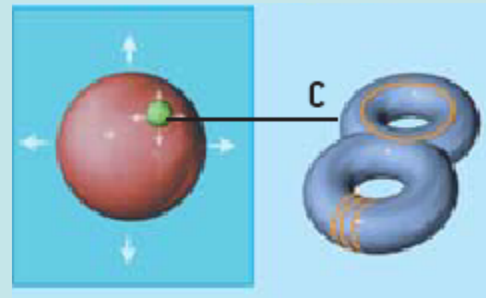
Classical Solutions

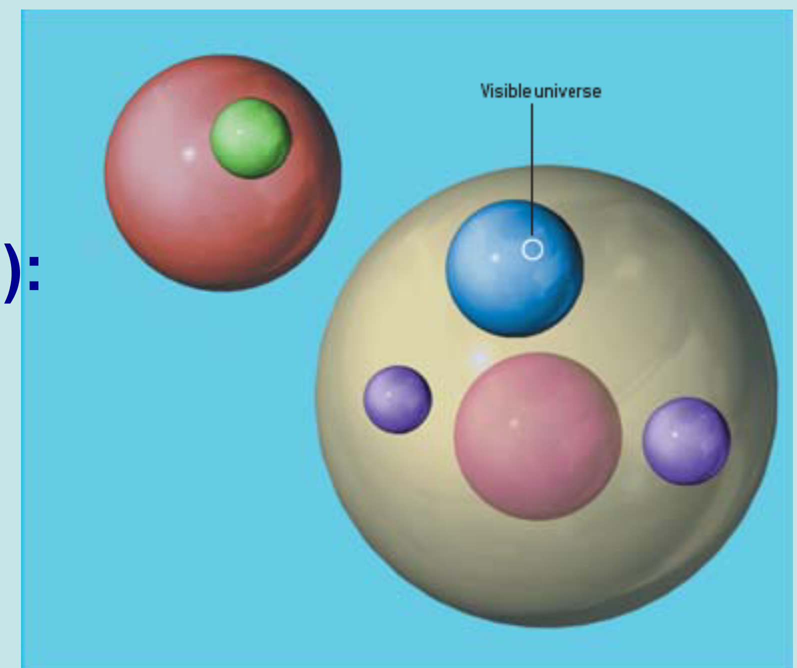
Quantum Decay (tunnel effect)



Multiverse







MANY solutions ($>10^{100000}$!): Anthropic ‘explanation’ of dark energy!!?????

The Landscape

- **Good:** A `solution' of dark energy and allows for the first time to trust calculations for low-energy SUSY breaking.

- **Bad:** missed opportunity to have new physics at low energies from small Λ.

- **Ugly:** It may also be used to `solve' other problems (Split SUSY, High-energy SUSY) in unnatural ways.

Very few predictions (~QFT)

To make progress:

- Construct concrete ‘realistic’ models?

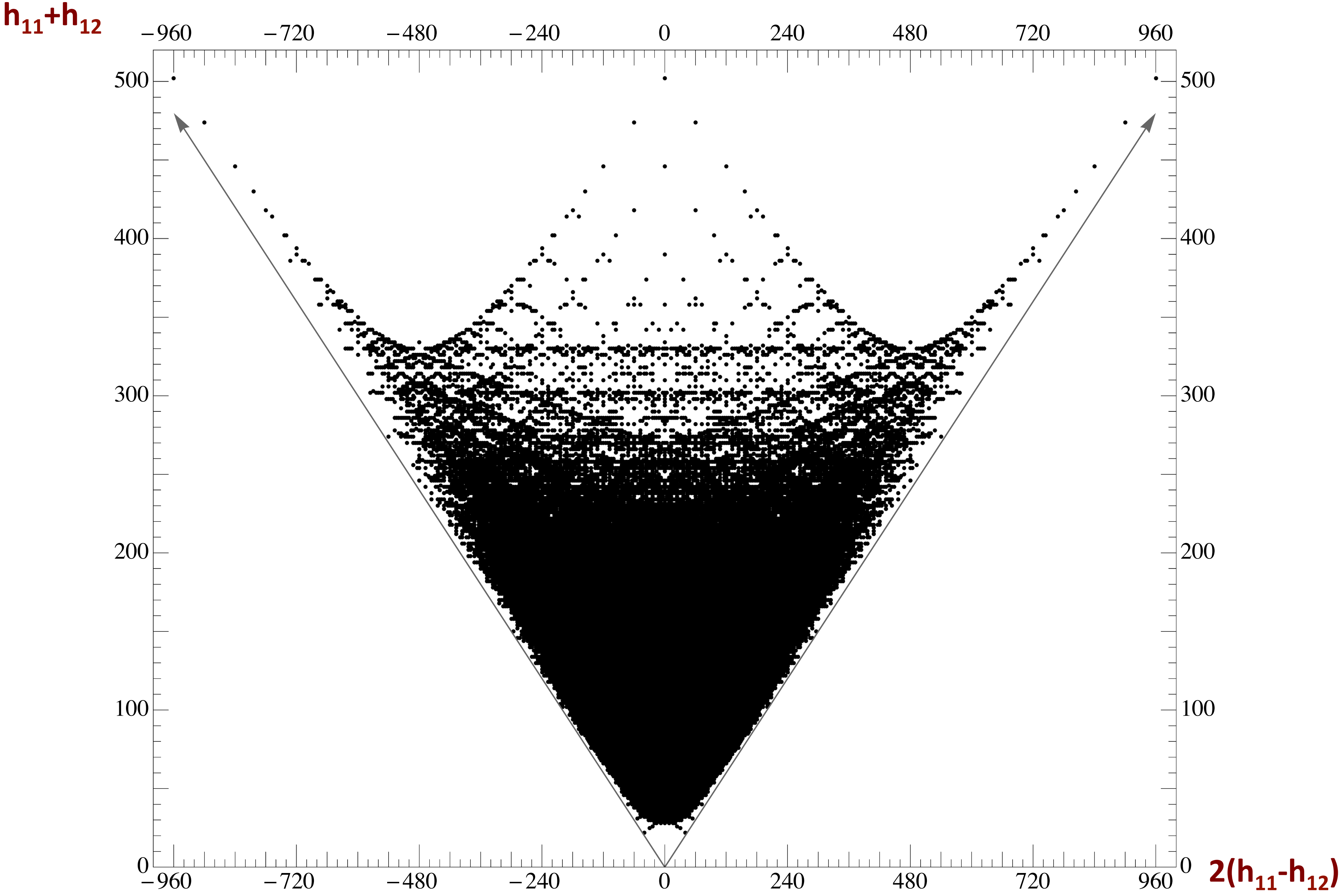
- Extract properties of classes of models (`big data’?)

- General ‘scenarios’ (global vs local issues)

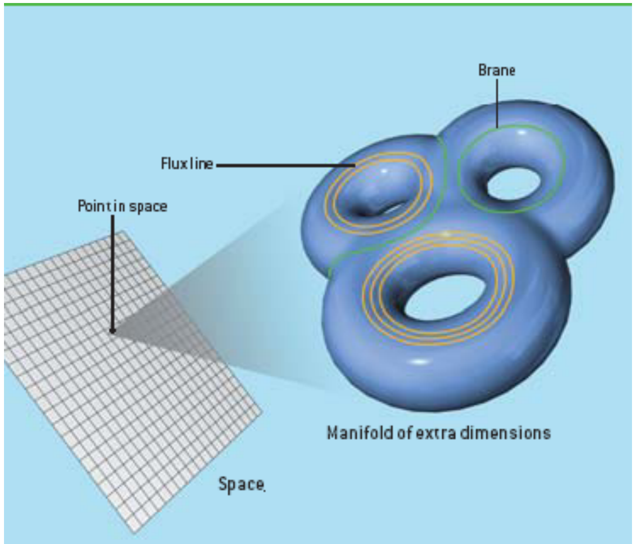
- General questions (SUSY breaking and moduli stabilisation)

‘Predictions’ of Classes of String Models

Mirror Symmetry



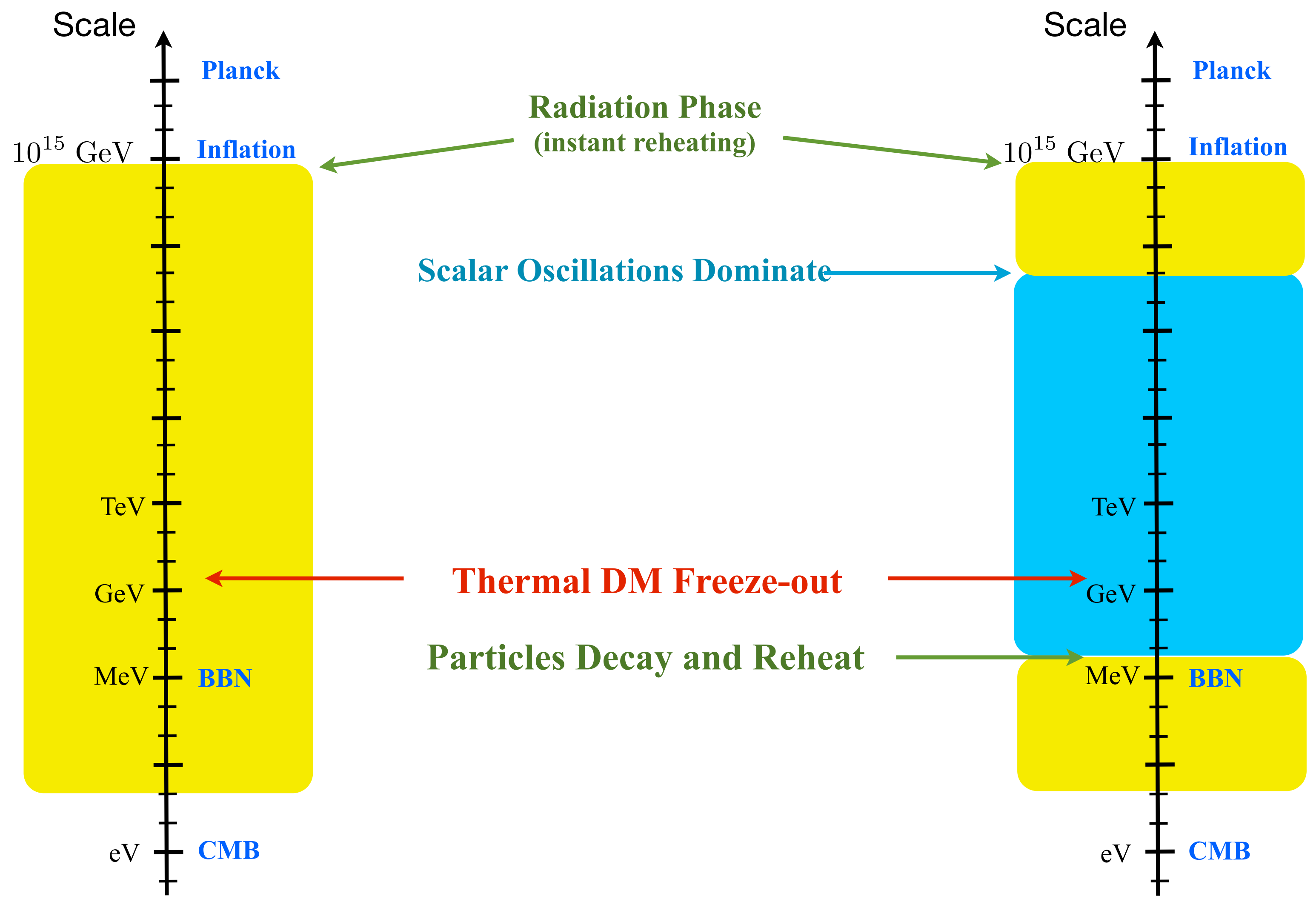
Generic 4D String Predictions



- Moduli (~thousands)
- Axions (many)
- No global symmetries
- Small irreps (fundamental, bifundamental, symmetric, antisymmetric, adjoint)
- If 4D N=1 SUSY: Cosmological Moduli 'Problem'! (unless M_{moduli}>30 TeV)

Thermal History

Alternative History



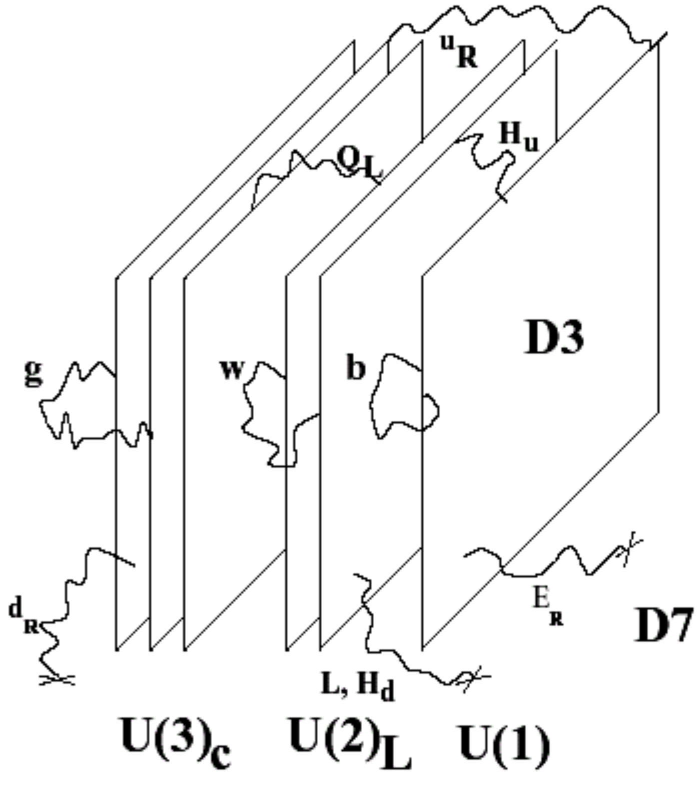
From S. Watson, SUSY 2013

Challenges for String Models

- Gauge and matter structure of SM
- Hierarchy of scales + masses (including neutrinos)
- Flavor CKM, PMNS mixing, CP no FCNC
- Hierarchy of gauge couplings (unification?)
- 'Stable' proton + baryogenesis
- Inflation or alternative for CMB fluctuations
- Dark matter (+ avoid overclosing)
- Dark radiation (N_{eff}~3.04)
- Dark energy

N.B. If ONE of them does not work, rule out the model!!!

e.g. Standard Model on D3/D7 Branes



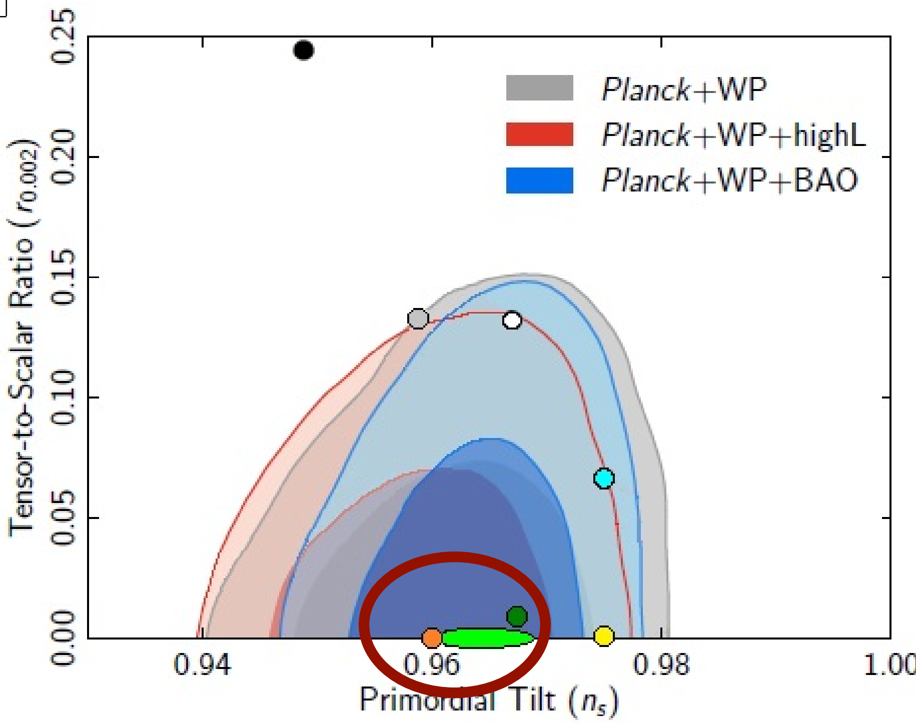
e.g.: Models close to SM: 3 families, hierarchy of quark masses, etc.

String Scenario	n_s	r
$D3/\overline{D3}$ Inflation	$0.966 \leq n_s \leq 0.972$	$r \leq 10^{-5}$
Inflection Point Inflation	$0.92 \leq n_s \leq 0.93$	$r \leq 10^{-6}$
DBI Inflation	$0.93 \leq n_s \leq 0.93$	$r \leq 10^{-7}$
Wilson Line Inflation	$0.96 \leq n_s \leq 0.97$	$r \leq 10^{-10}$
D3/D7 Inflation	$0.95 \leq n_s \leq 0.97$	$10^{-12} \leq r \leq 10^{-5}$
Racetrack Inflation	$0.95 \leq n_s \leq 0.96$	$r \leq 10^{-8}$
N − flation	$0.93 \leq n_s \leq 0.95$	$r \leq 10^{-3}$
Axion Monodromy	$0.97 \leq n_s \leq 0.98$	$0.04 \leq r \leq 0.07$
Kahler Moduli Inflation	$0.96 \leq n_s \leq 0.967$	$r \leq 10^{-10}$
Fibre Inflation	$0.965 \leq n_s \leq 0.97$	$0.0057 \leq r \leq 0.007$
Poly − instanton Inflation	$0.95 \leq n_s \leq 0.97$	$r \leq 10^{-5}$

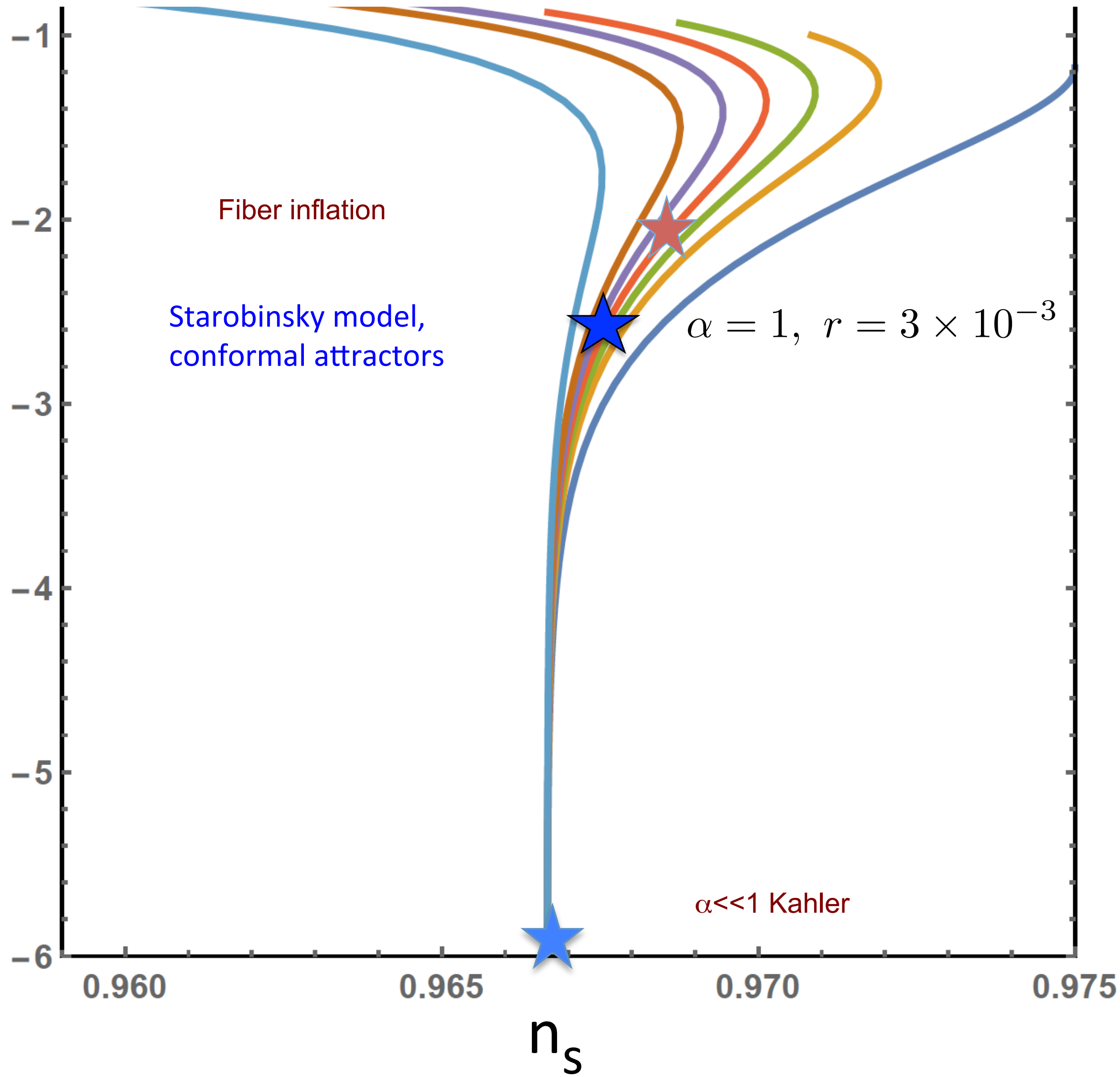
e.g. String Inflation models

In excellent shape after Planck 2013-2015,

(but most would have been RULED OUT if bicep2 were OK !)



e.g. Moduli inflation



e.g. SUSY Breaking

- Split Supersymmetry $m_0 \sim 50\ M_{1/2}$

  $m_0 \sim 1000\ M_{1/2}$

$M_{1/2} \sim 1$ TeV

(Concrete realisation of split susy in a framework including landscape, relative scales fixed, matching well with experiments...)

- High energy SUSY $m_0 \sim M_{1/2} \sim 10^{11}$ GeV

General Progress

- **Field is broad:** **Mathematics, cosmology, phenomenology, computer,...**
- **After the Higgs it is one of the main guides to BSM physics because UV completion.**
- **`String inspired' phenomenology (large extra dimensions, Randall-Sundrum, axiverse, split supersymmetry, anomalous U(1)'s...)**
- **Continuous 'cumulative' progress**
- **The 'Swampland'? (WGC, non SUSY AdS,...?)**
- **Correlations? (inflation vs SUSY, etc.)**

Concrete Achievements

- **Realistic Model Building:** **Many quasi-realistic models (local and global) but not fully realistic yet.**

- **SUSY Breaking and Moduli Stabilisation:** **A handful of 'scenarios' (generically scalars much heavier than gauginos)**

- **Inflation and postinflation cosmology:** **(Few scenarios with concrete predictions).**

Future?

- **Experimentally driven? (LHC, axion search, post-Planck/ experiments)**

  (SUSY? Z'? non-gaussianities?, DR settled? tensor modes!?)

- **Accelerators: ILC, 100Km/100TeV hadron collider!?**

- **Evidence for String (GUT) scale physics??**

  (proton decay, cosmic strings, tensor modes, bubble collisions?,...)

String Models

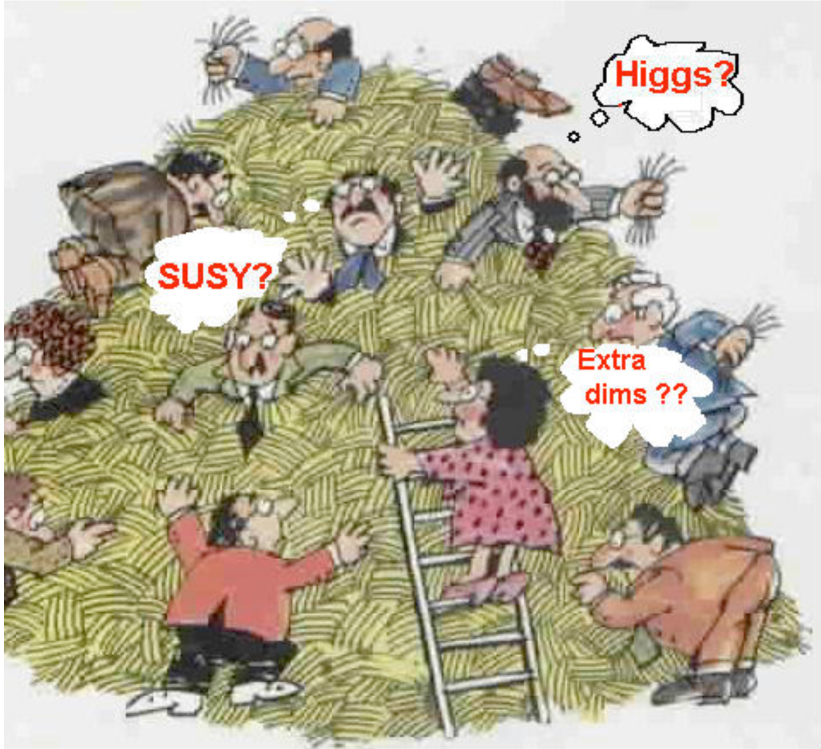
- **Too many string models?**

  (Heterotic, IIA, I, IIB, Landscape,...)

- **Or too 'few' models?**

  (Not fully Realistic model yet!!!)

Machine learning?



Optimistic Perspective

- **Typical statement: "We do not understand well enough string theory to try to extract its physics implications"**

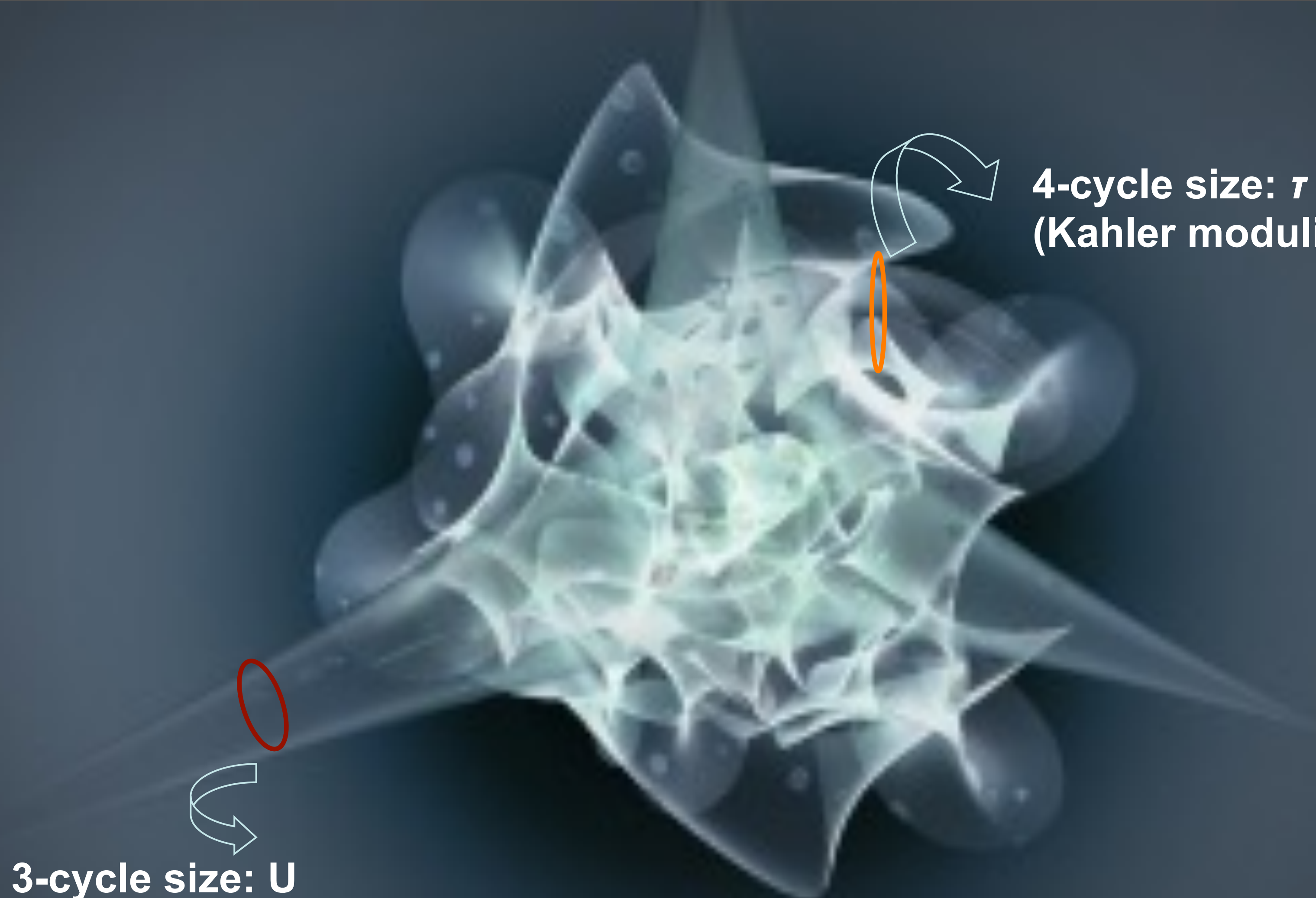
- **Bold answer: "We may understand the theory better than we think (at low energies and weak couplings) using all foreseeable ingredients: geometry, branes, fluxes, perturbative, nonperturbative effects, etc."**

'...our mistake is not that we take our theories too seriously, but that we do not take them seriously enough. It is always hard to realise that these numbers and equations we play with at our desks have something to do with the real world.'

Steven Weinberg

THANK YOU !

Size and Shape of Extra Dimensions



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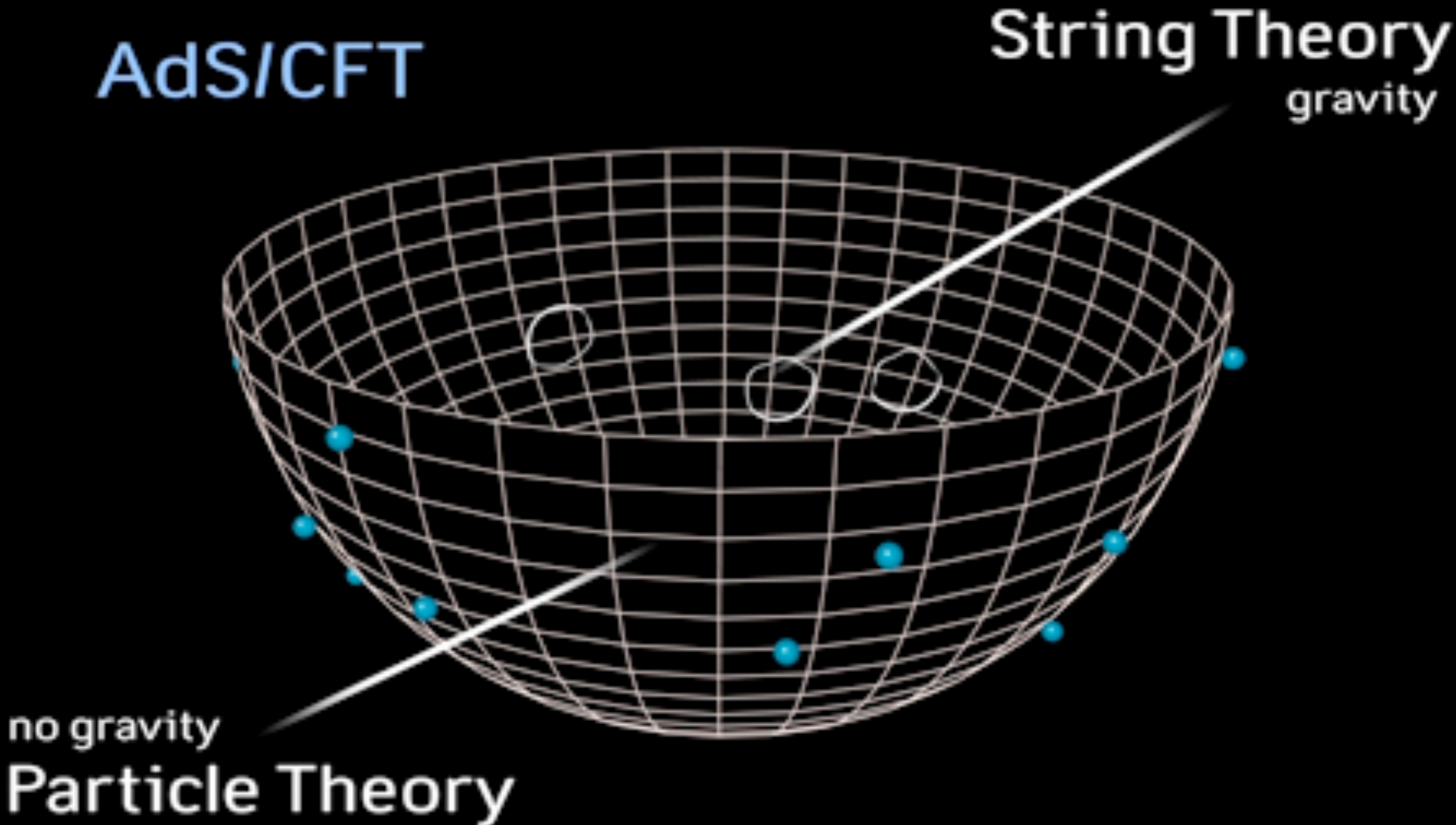
Holography

Gravity/No-Gravity correspondence!



Some Implications of Holography

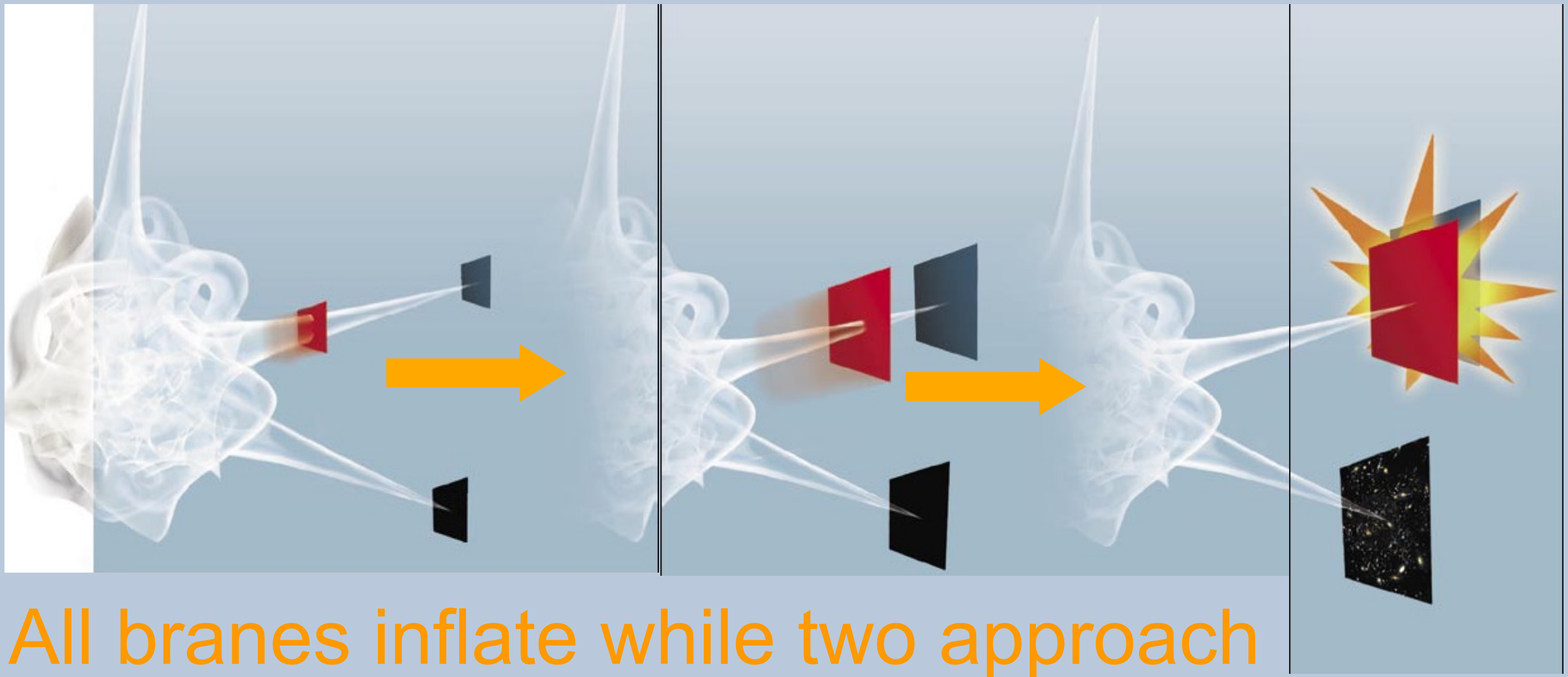
- Proper definition of quantum gravity theory!
- Black hole entropy/area! $S_{BH} = (kc^3/4G\hbar)\,A$
- Information loss paradox ‘solved’!?
- Potential applications to ‘strong coupling systems’ (quark-gluon plasma, condensed matter physics, turbulence,...)
- Technique compute non gaussianities of CMB!
- Cosmological singularity/ acceleration????

e.g. SUSY Breaking

	KKLT	**LVS**
Soft term	D3	D3
$M_{1/2}$	$\pm\left(\frac{3}{2a\mathcal{V}^{2/3}}\right)\ m_{3/2}$	$\pm\left(\frac{3s^{3/2}\xi}{4\mathcal{V}}\right)\ m_{3/2}$
m_0^2	$\left(\frac{s^{3/2}\xi}{4\mathcal{V}}\right)m_{3/2}^2$	$\left(\frac{5s^{3/2}\xi}{8\mathcal{V}}\right)\ m_{3/2}^2$
A_{ijk}	$-(1-s\partial_s\log Y_{ijk})\,M_{1/2}$	$-(1-s\partial_s\log Y_{ijk})\,M_{1/2}$

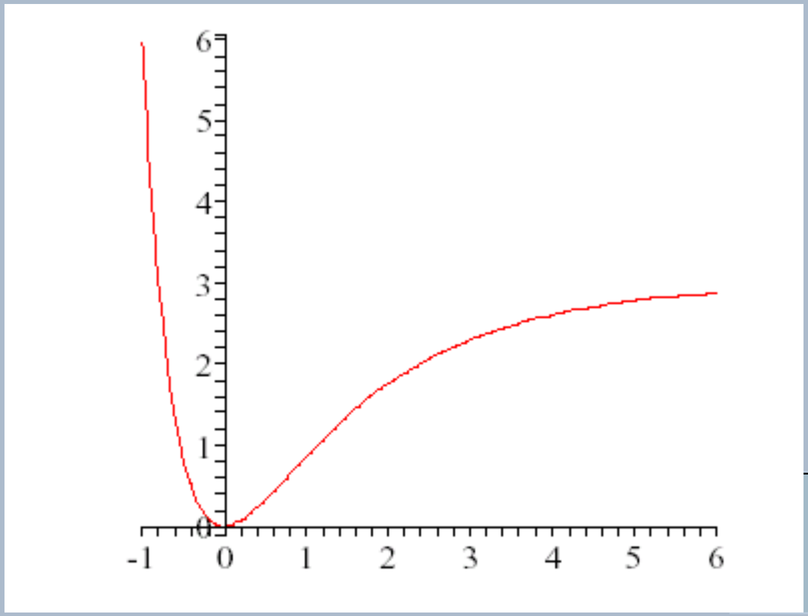
	KKLT	**LVS**
Soft term	D7	D7
$M_{1/2}$	$\pm\left(\frac{1}{a\mathcal{V}^{2/3}}\right)m_{3/2}$	$\pm\left(\frac{3}{4a\tau_s}\right)m_{3/2}$
m_0^2	$(1-3\omega)\,m_{3/2}^2$	$\left(\frac{9(1-\lambda)}{16a^2\tau_s^2}\right)\ m_{3/2}^2$
A_{ijk}	$\frac{3}{2}(2\lambda-1-s\partial_s\log Y_{ijk})\,M_{1/2}$	$-3(1-\lambda)\,M_{1/2}$

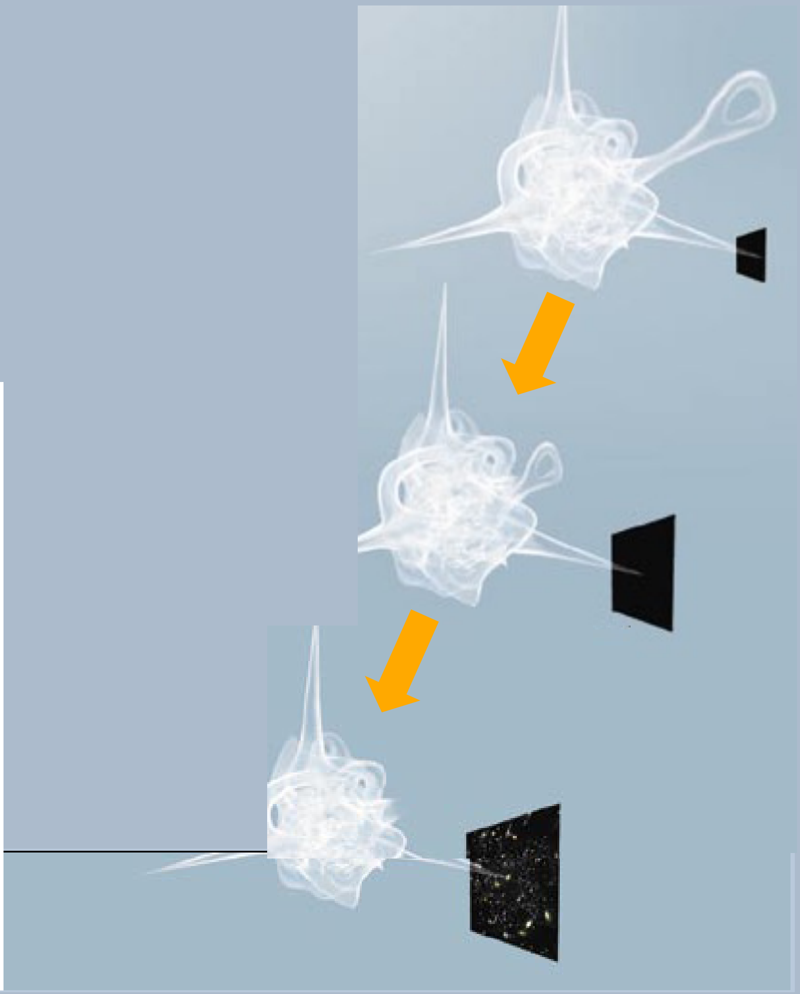
e.g. BRANE - ANTIBRANE INFLATION



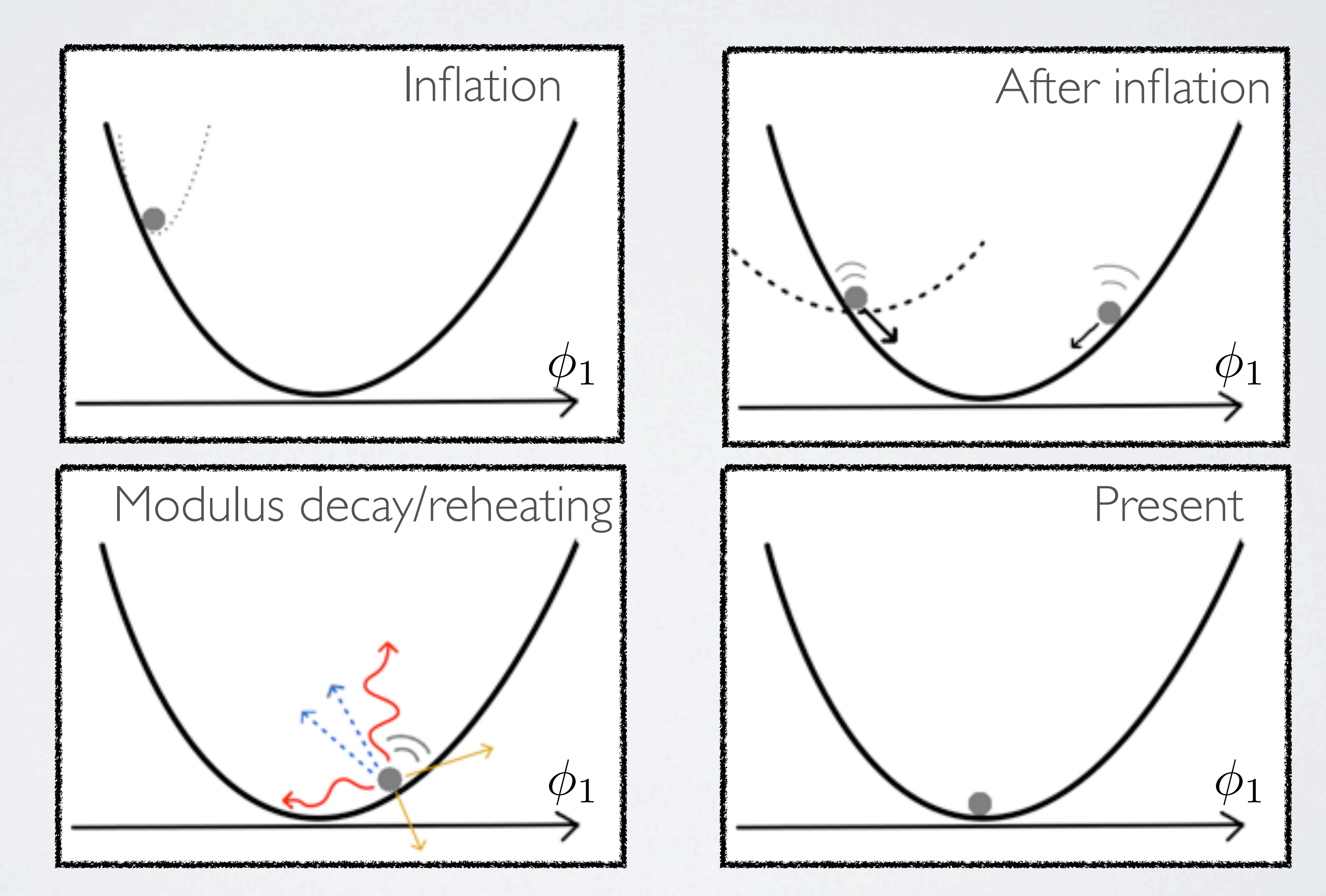
All branes inflate while two approach

e.g. MODULI INFLATION





Cosmological Moduli Domination



$$\Gamma_\phi \sim \frac{1}{8\pi}\frac{m_\phi^3}{M_{\rm Pl}^2}$$

T > O(1 MeV), so $m_\phi \gtrsim 3 \cdot 10^4$ GeV

String Phenomenology*:

Long Term Plan:

String theory scenario that satisfies all particle physics and cosmological observations and hopefully lead to measurable predictions

***In contrast to "String Noumenology"**