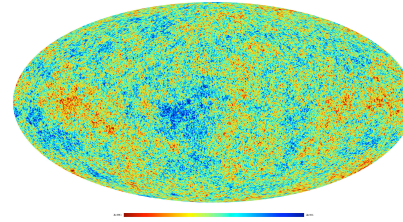


String Theory and Physics?

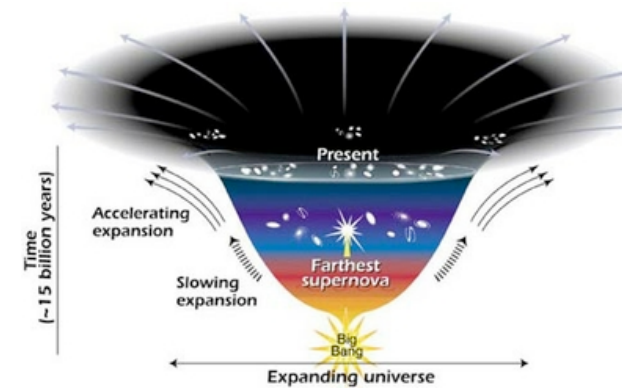
Fernando Quevedo
ICTP (Trieste), DAMTP (Cambridge)
Bologna, November 2014

Greatest Recent Discoveries

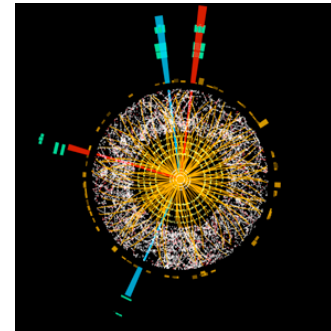
- **Fluctuations of Cosmic Microwave Background (1992) (Nobel Prize 2006)**



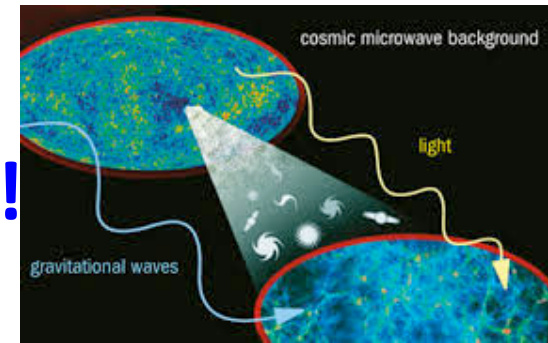
- **Dark Energy (1998) (Nobel Prize 2011)**



- **Higgs Discovery (2012) (Nobel Prize 2013)**



- **'Cosmic gravitational waves' (2014! (Nobel Prize ?) ??)**





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4th July 2012
Celebration !!!
CERN ('Higgsdependence day')



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IAEA
International Atomic Energy Agency





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IAEA
International Atomic Energy Agency

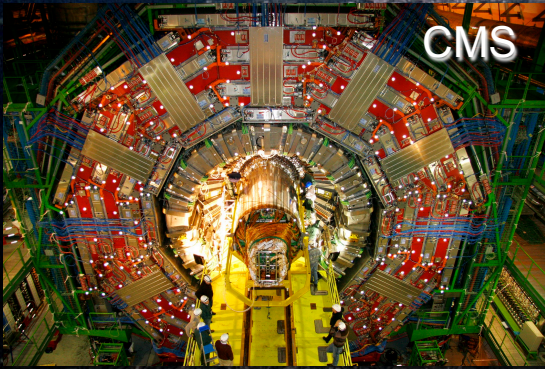




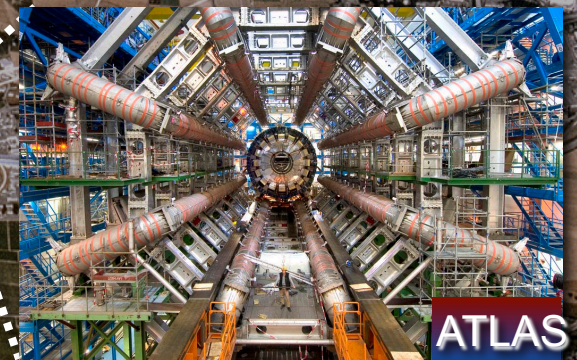
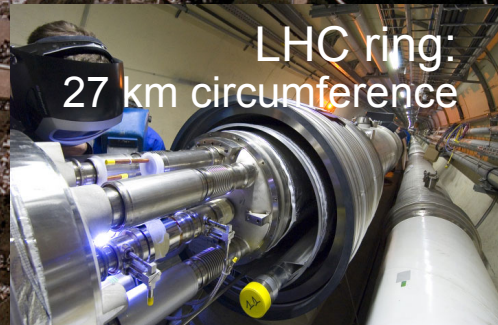
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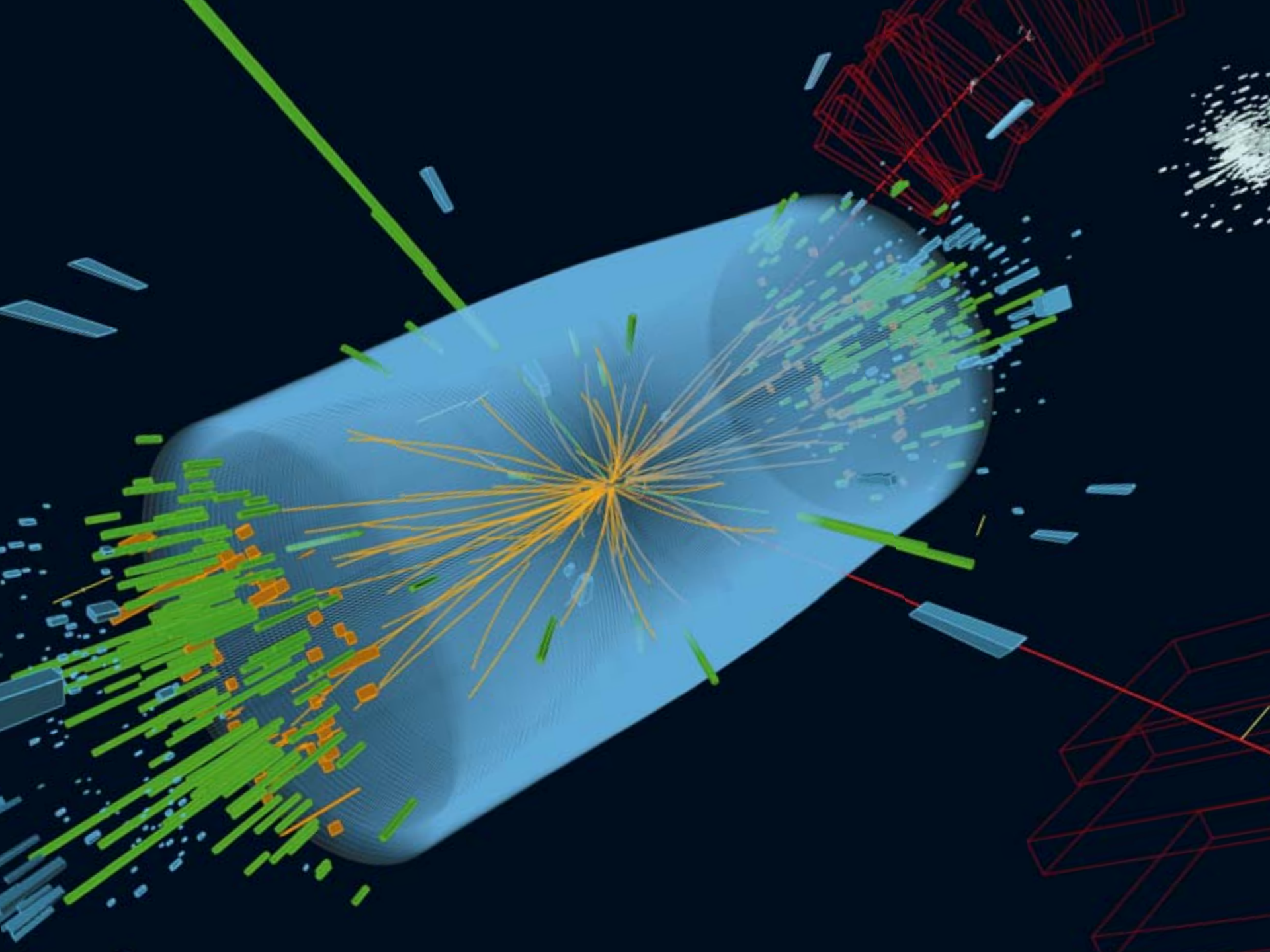
LHC (Large Hadron Collider)



Biggest Experiment in History!!!









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Why is the Higgs discovery so important?



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Composition of Visible Matter

FERMIONS

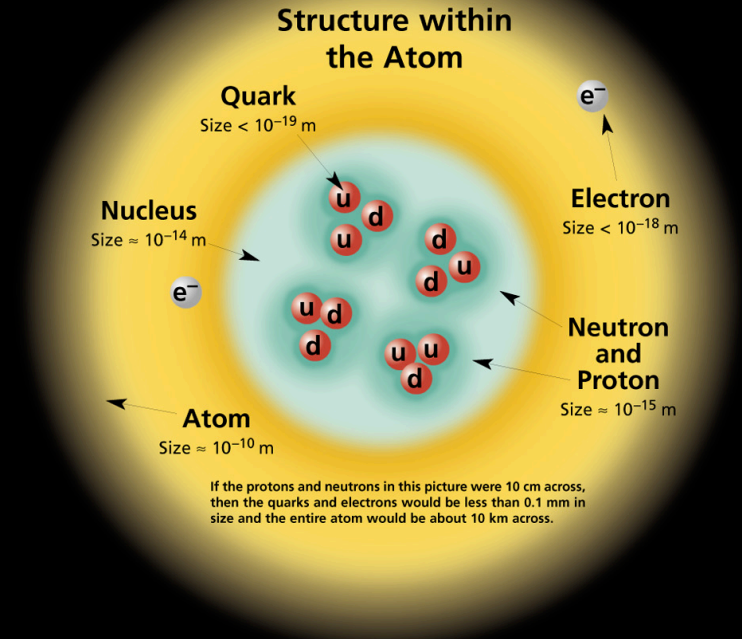
matter constituents
spin = 1/2, 3/2, 5/2, ...

Leptons spin = 1/2

Flavor	Mass GeV/c ²	Electric charge
ν_e electron neutrino	$<1 \times 10^{-8}$	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



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 spin=0
- Graviton, charge=Mass=0
spin=2

Glashow, Weinberg, Salam

Higgs Mechanism explains electro-weak interactions
(Nobel Prize 1979)

Mass to W^+ , W^- , Z and quarks+leptons!!!!
(W^+ , W^- , Z discovered in 1982)



An Equation is worth a thousand Pictures!!!

$$\begin{aligned}\mathcal{L} = & \sqrt{g} \left\{ R - \frac{1}{4} F^{\mu\nu} F_{\mu\nu} + \theta F^{\mu\nu} \tilde{F}_{\mu\nu} \right. \\ & + i \bar{\Psi} \not{D} \Psi + Y_{ij} H \Psi_i \Psi_j + \text{h.c.} \\ & \left. + |D_\mu H|^2 - V(H) \right\} \\ \cong & \text{Our Universe... so far}\end{aligned}$$

Higgs Potential Energy

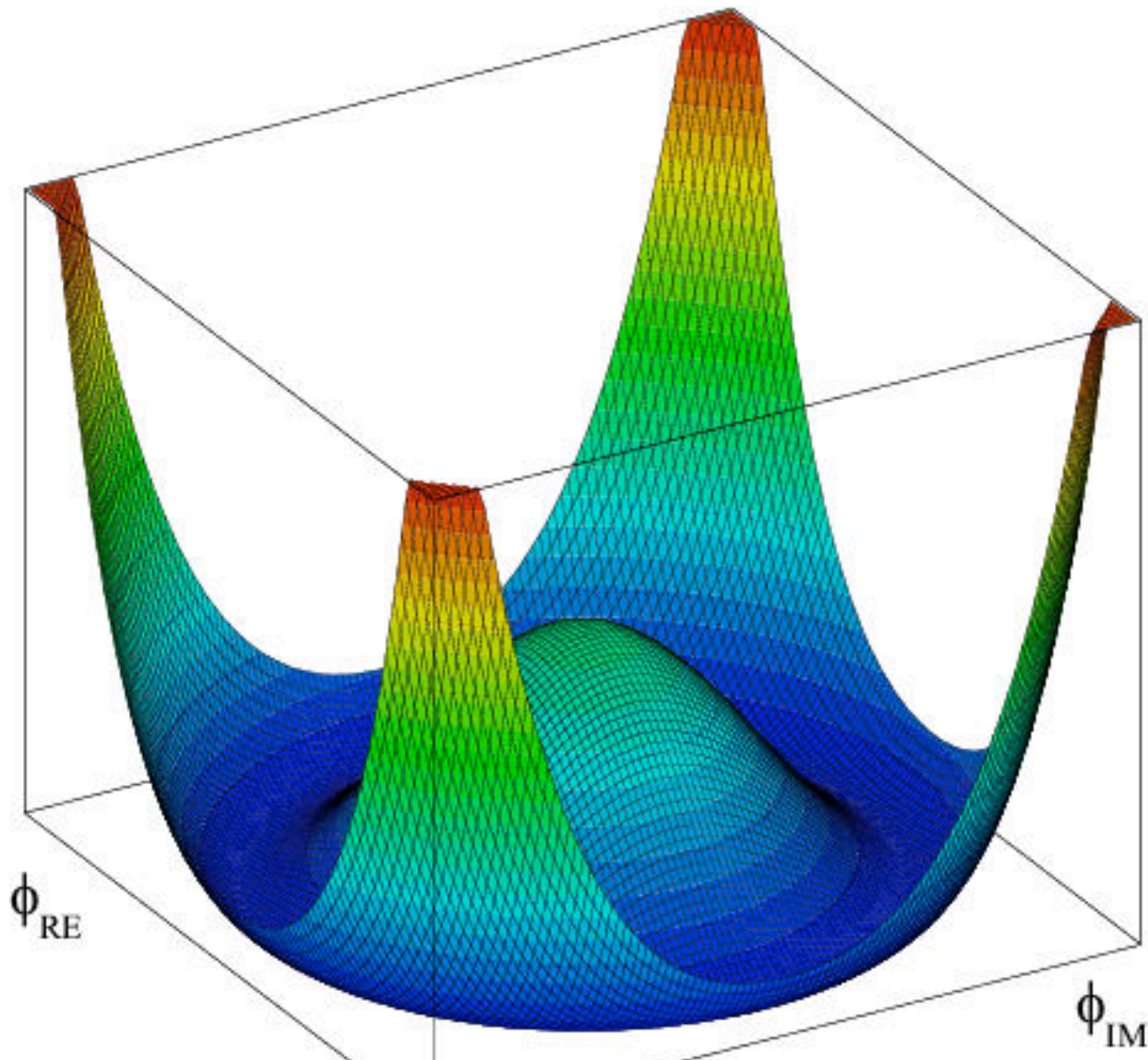
$$V(H) = \Lambda - m^2 |H|^2 + \lambda |H|^4$$

Λ : ~cosmological constant(Einstein)

m : ~‘mass’

λ : quartic coupling

Higgs Potential Energy $V(H)$



Higgs and Origin of Mass



- Zero mass object



- Light object



- Heavy object

Not everybody is celebrating!

Hawking pays \$100 to Gordy Kane



He Didn't Believe in the Boson!
(NO HIGGS)

Martinus Veltman (Nobel prize 1999)





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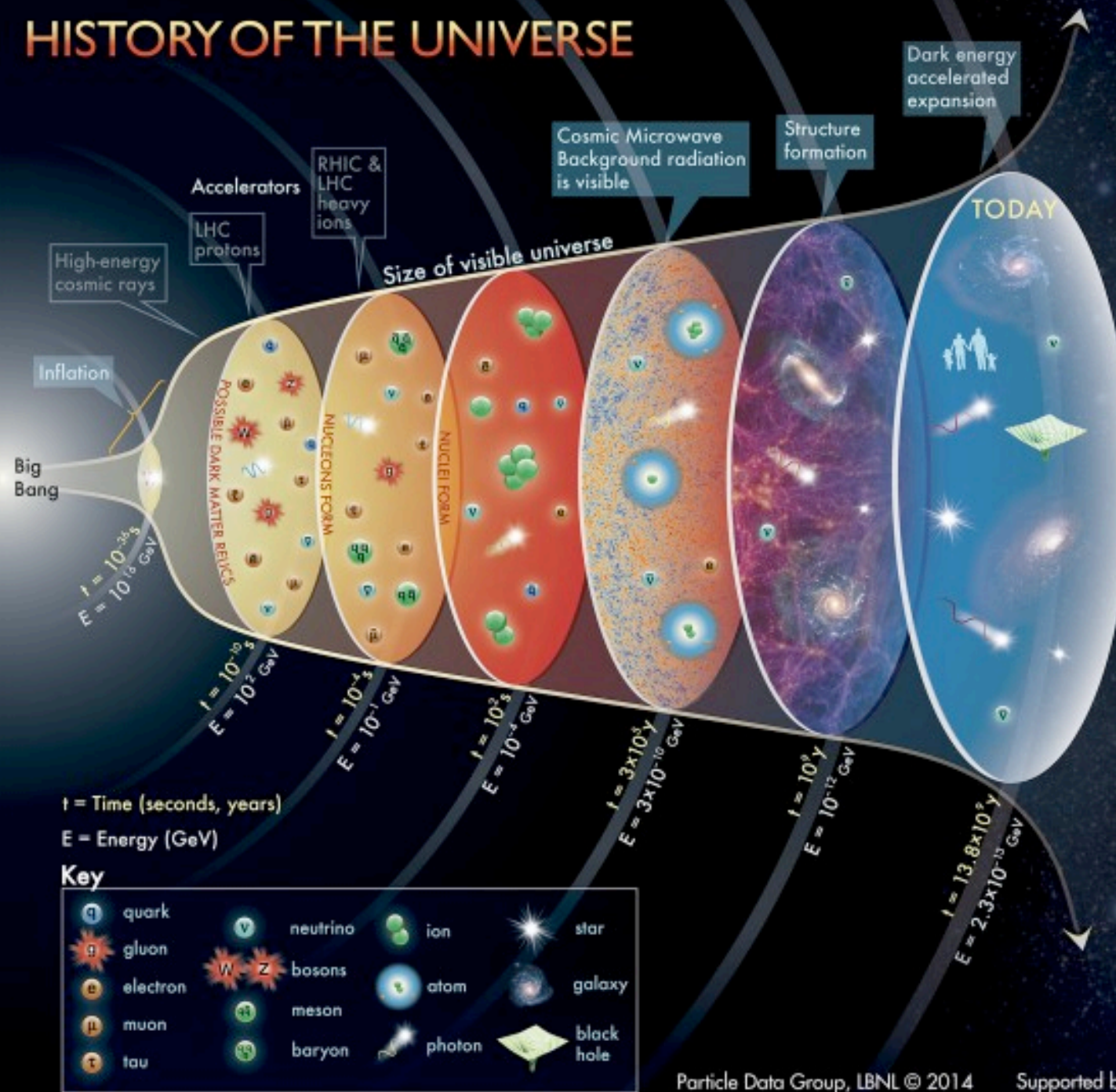
Implications for this Discovery

Implications

- **First fundamental scalar particle !** (inflation, susy, strings?)
- **Origin of masses**
- **Completes the Standard Model!**
- **Hints at essentially unlimited symmetries!**
- **SM+Gravity=infinite universes!?** (Standard Model Landscape)
- **Hierarchy problem ($m=125.6$ GeV)!**
- **Instability ($\lambda=0.13$)?**
- **Cosmological constant ($\Lambda \sim 10^{-120}$) (dark energy)**

Particle Physics and our Universe

HISTORY OF THE UNIVERSE



Cosmic Microwave Background

1965



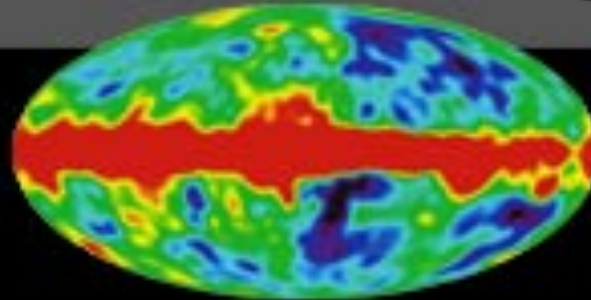
Penzias and
Wilson



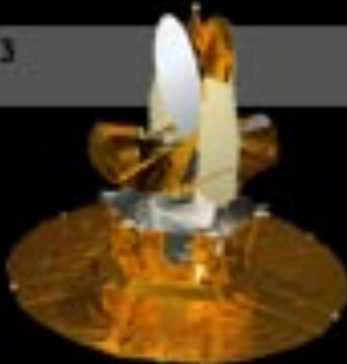
1992



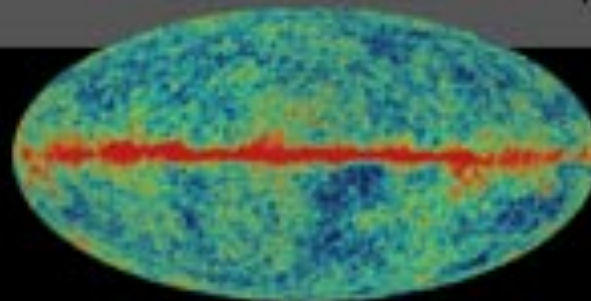
COBE



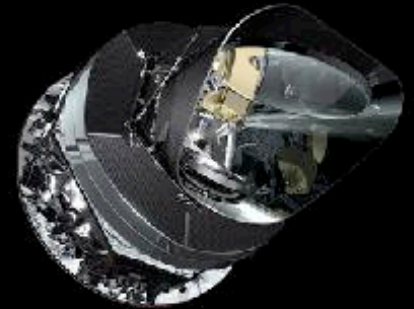
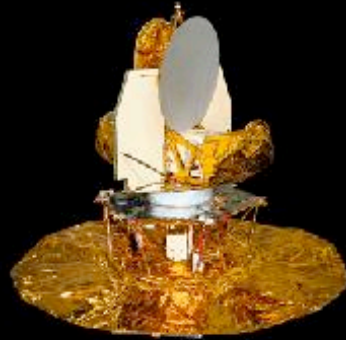
2003



WMAP

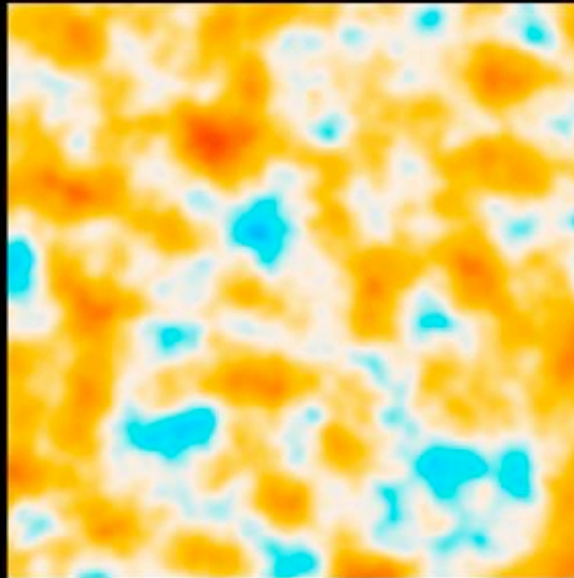


**Agree with
Inflation! !!!**



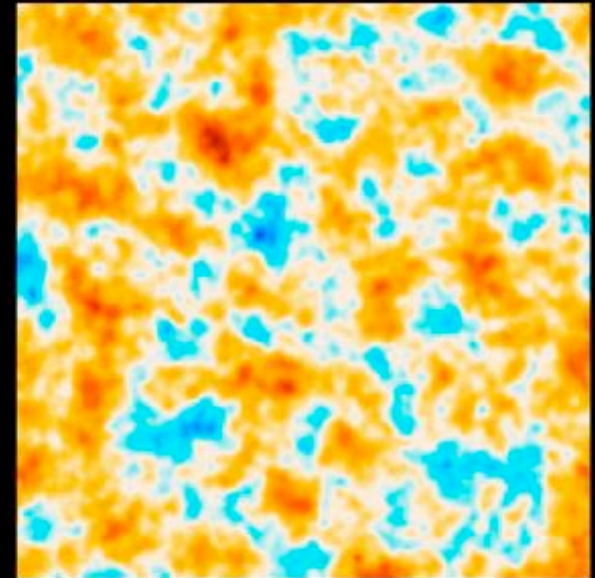
COBE

1992



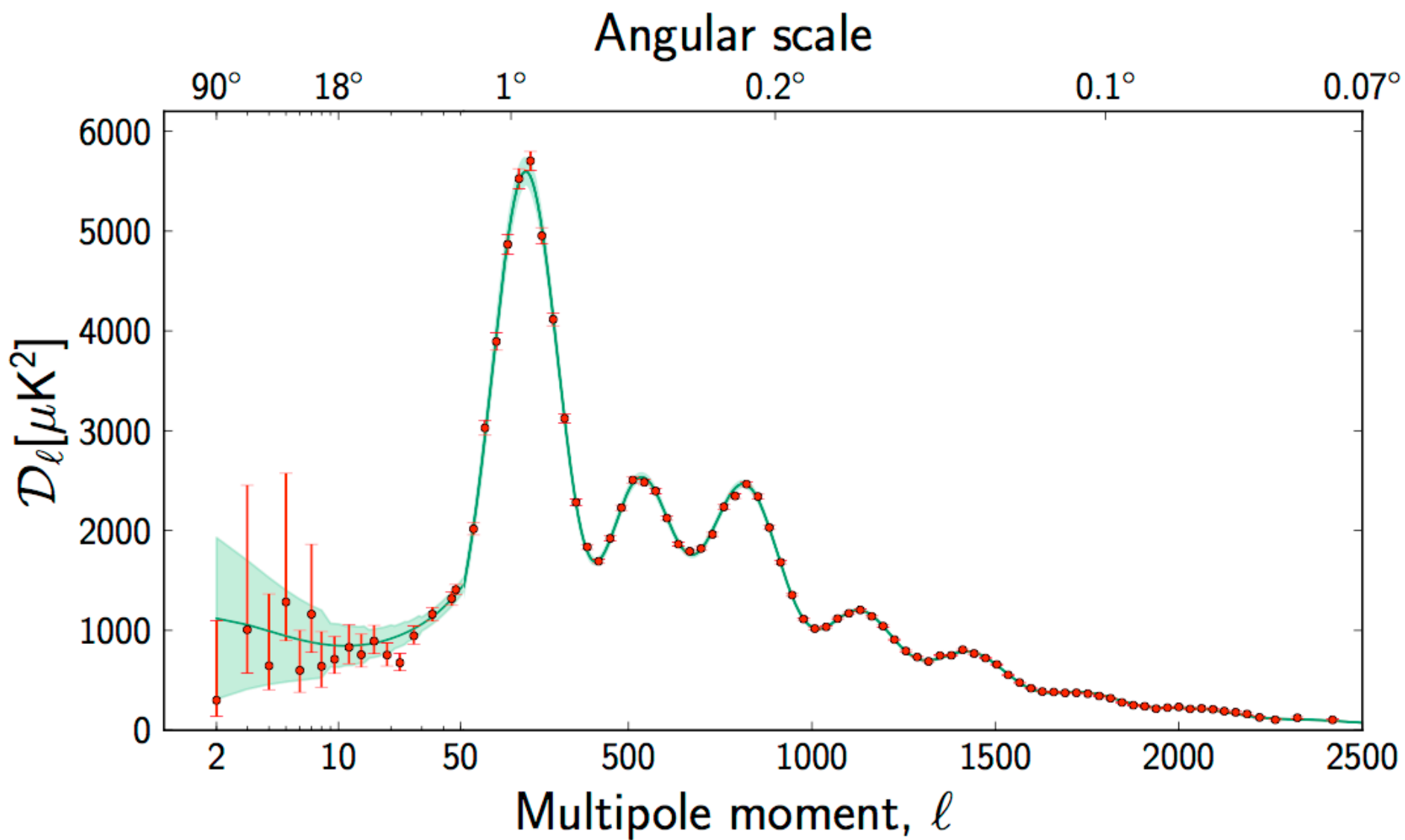
WMAP

2003

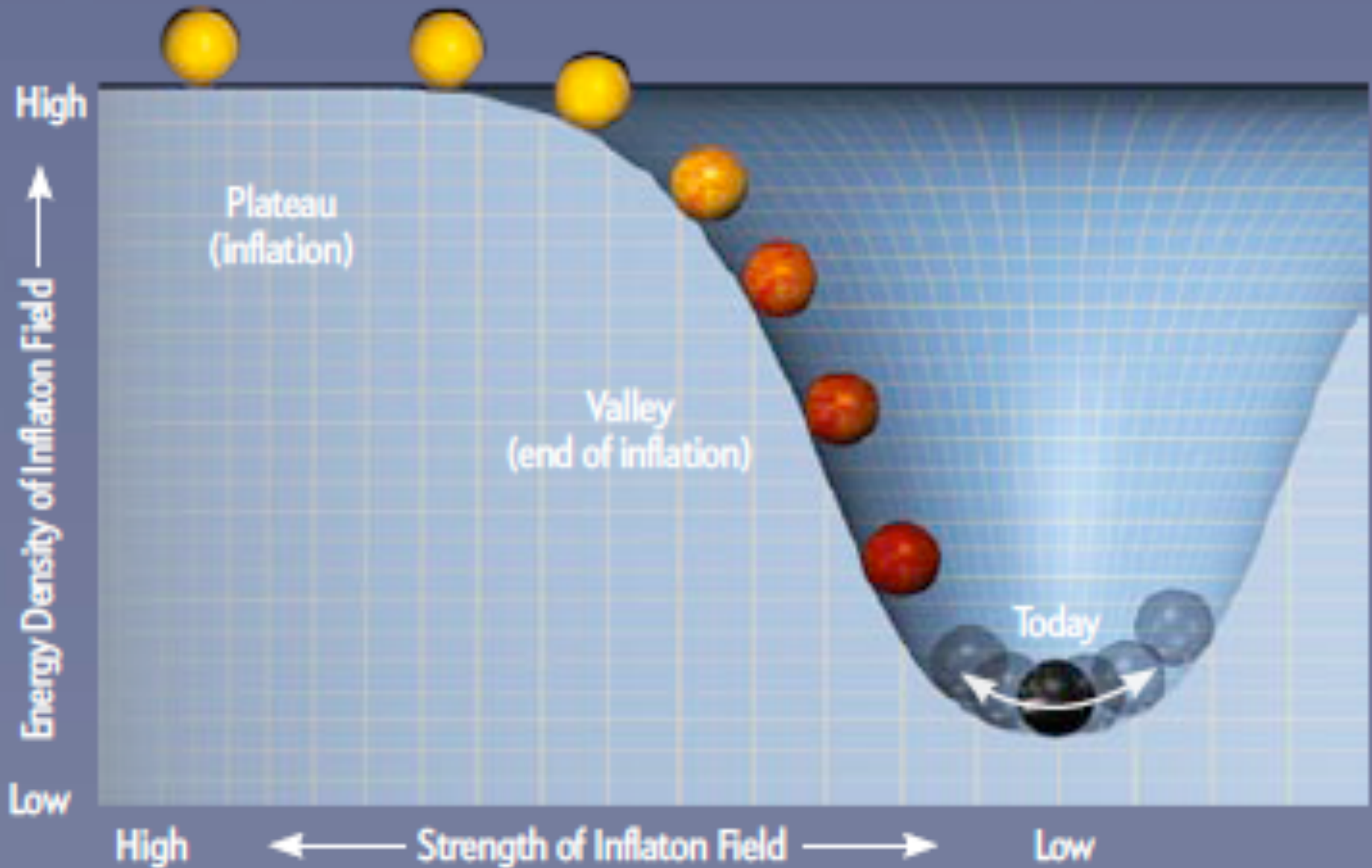


Planck

2013



Slow-roll Inflation





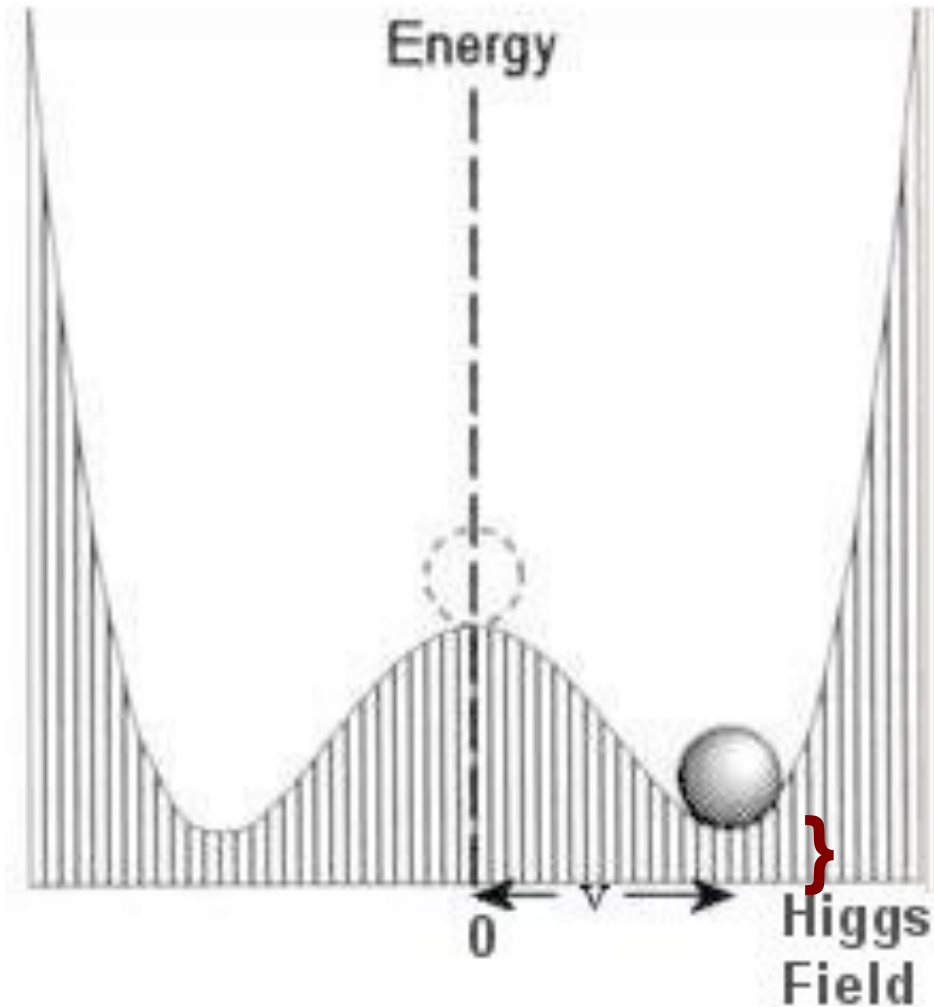
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OPEN PROBLEMS

(CHALLENGES FOR YOUNG GENERATION)

Problem 1: Cosmological constant



Cosmological constant =

[illegible]

$$\hbar / 2\pi = \hbar = 1.0546 \times 10^{-34} \text{ kg m}^2 \text{ sec}^{-1}$$

$$G_N = 6.672 \times 10^{-11} \text{ m}^3 \text{ kg}^{-1} \text{ sec}^{-2}$$

$$c = 2.99792458 \times 10^8 \text{ m/sec}$$

Planck Units

$$L_{\text{Planck}} = \sqrt{\frac{\hbar G_N}{c^3}} = 1.616 \times 10^{-33} \text{ cm}$$

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

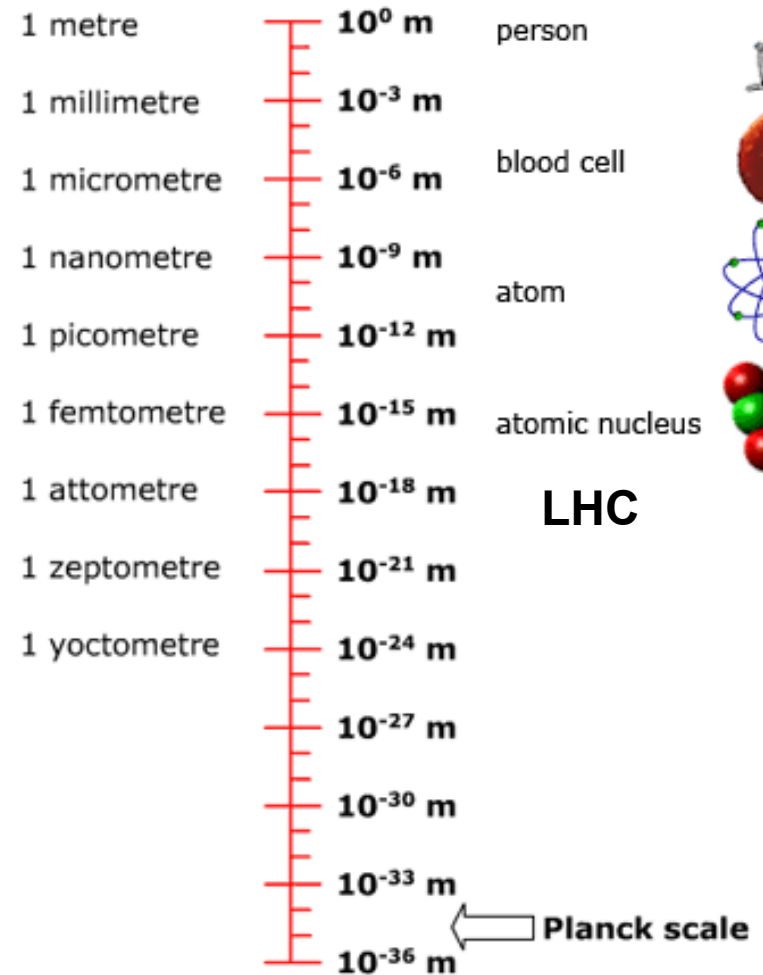
$$T_{\text{Planck}} = \sqrt{\frac{\hbar G_N}{c^5}} = 5.39 \times 10^{-44} \text{ sec}$$



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

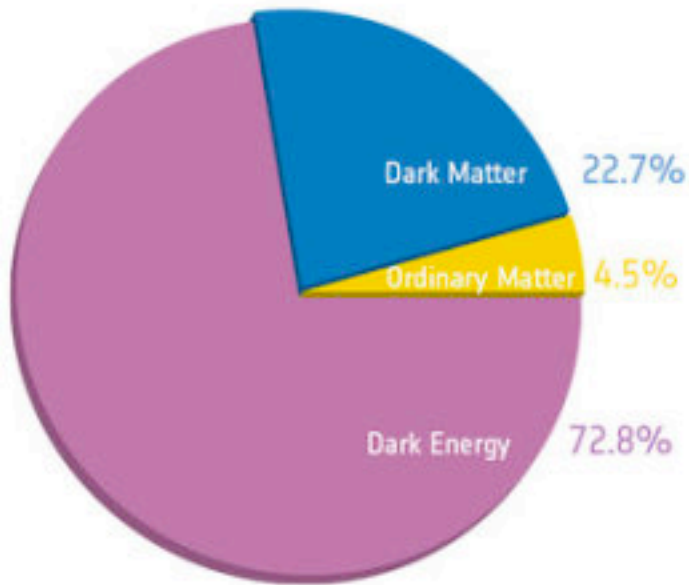
$$= 10^{19} \text{ GeV}$$

logarithmic scale

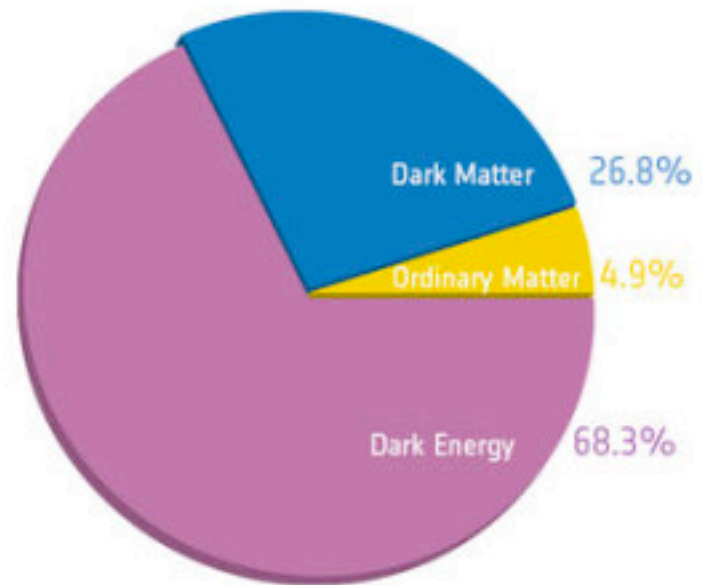


www.phys.unsw.edu.au/einsteinli

Dark Energy and Dark Matter



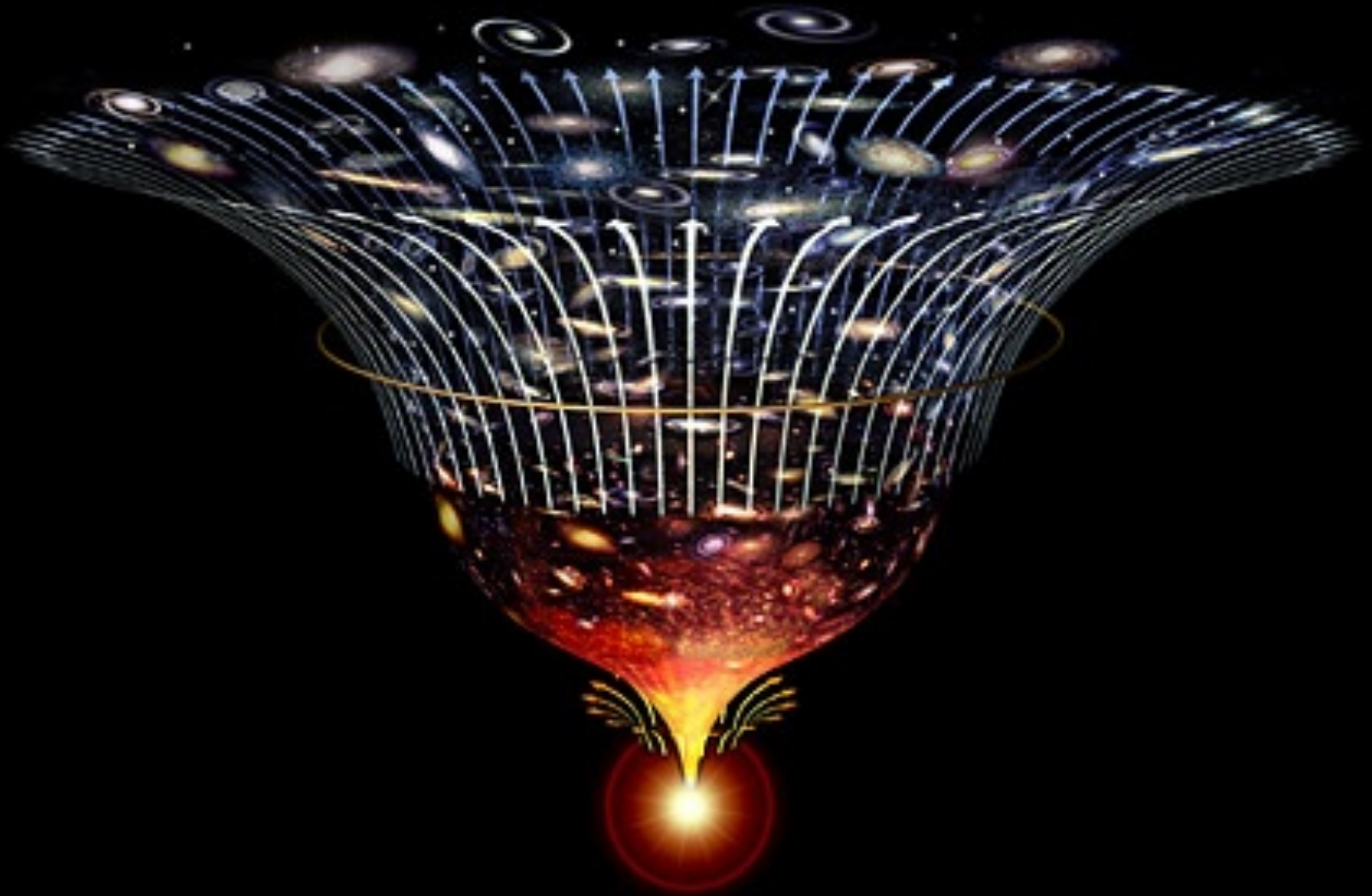
Before Planck



After Planck

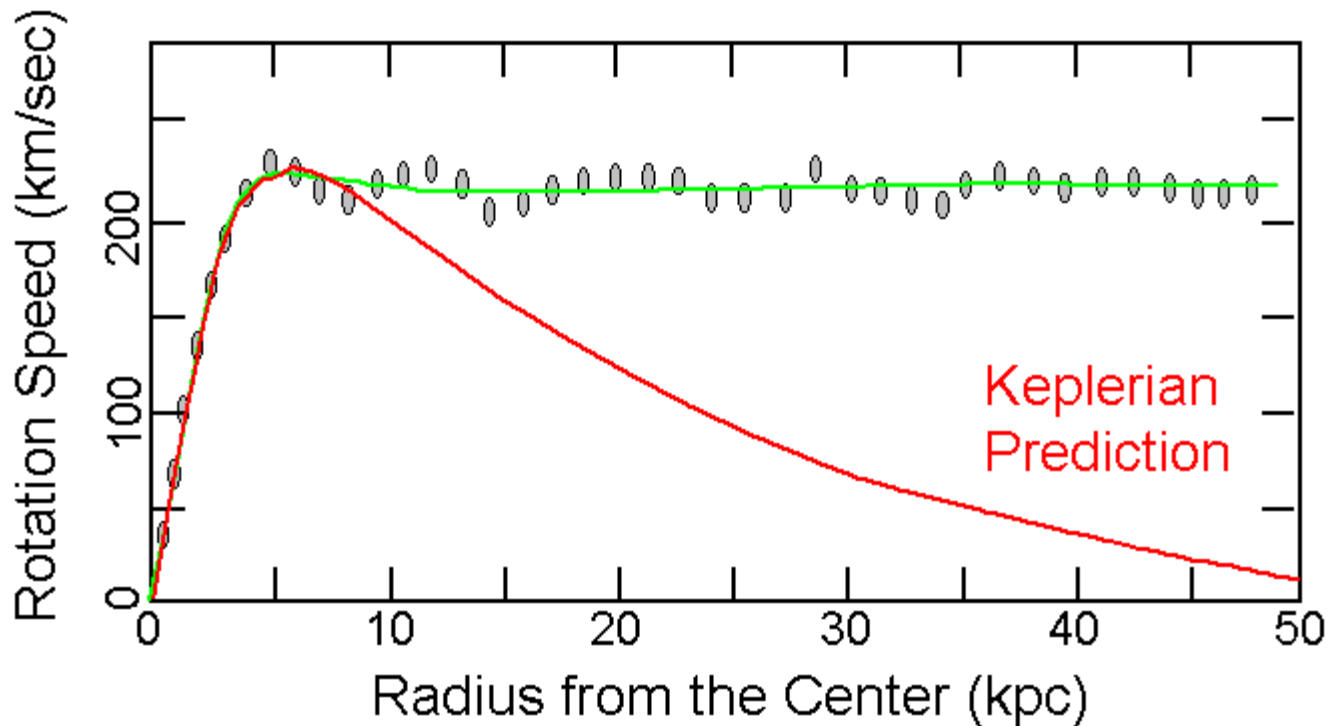
Dark Energy (Accelerating Universe 1998)

$$\Lambda > 0?$$



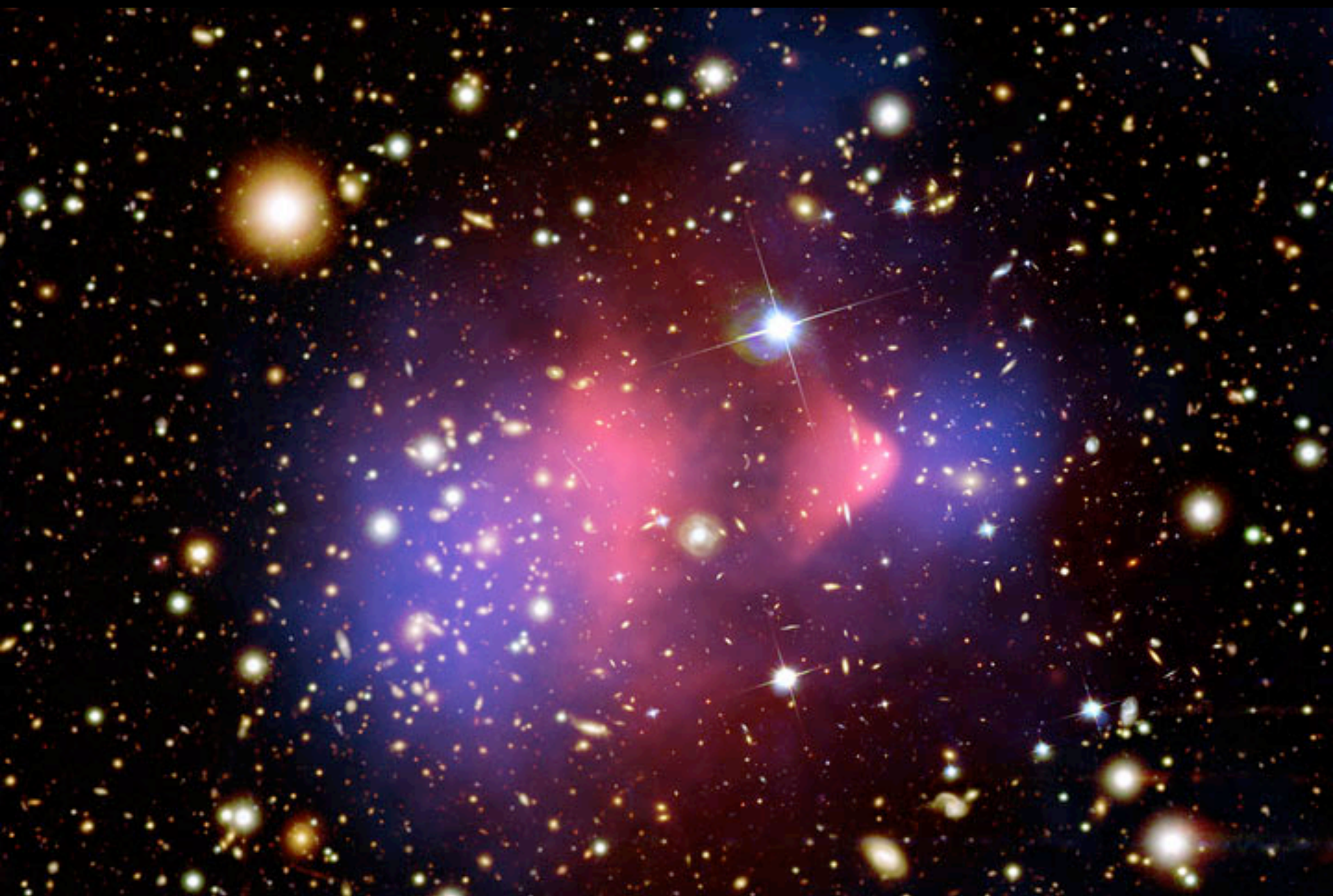
Dark Matter

Observed vs. Predicted Keplerian



Bullet cluster

(red X ray gas, blue dark matter, collision of two superclusters)



Problem 2: Hierarchy

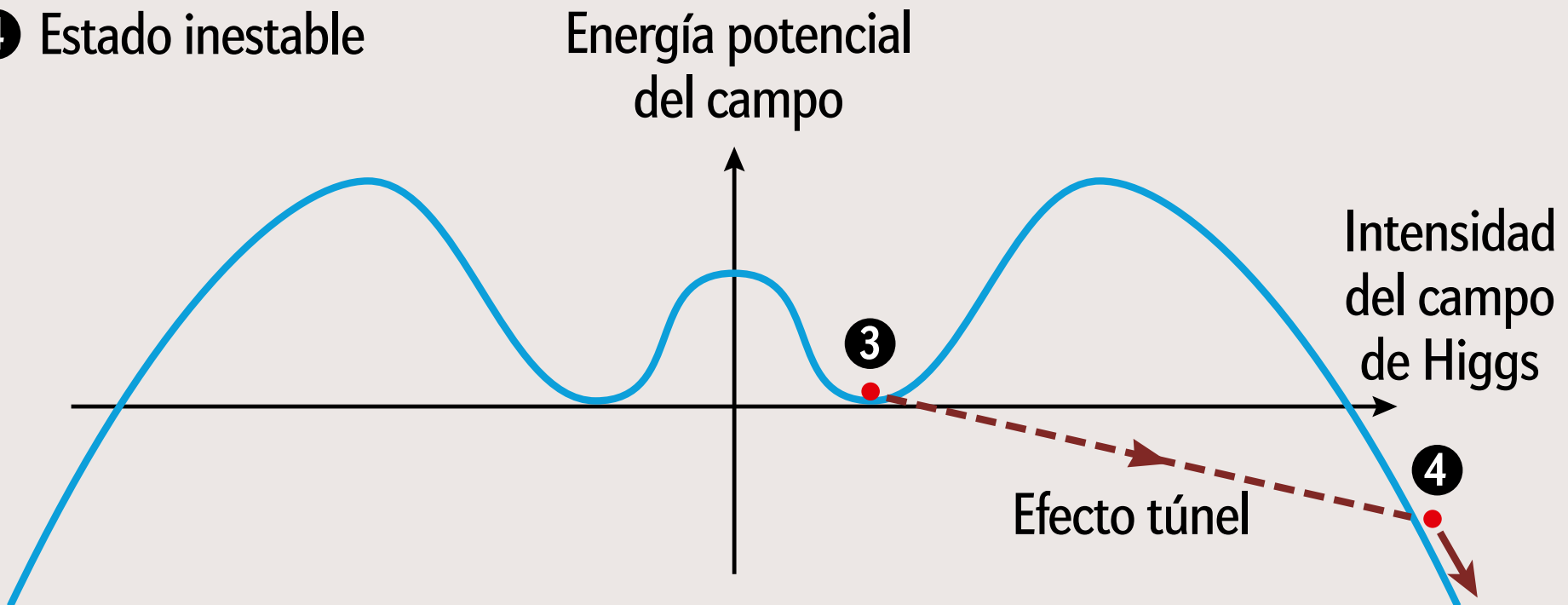
Couplings to other particles increases Higgs mass enormously: (up to 1,000,000,000,000,000 times!!!)
 $125\text{GeV} \rightarrow \sim 1,000,000,000,000,000,000\text{ GeV} = 10^{18}\text{GeV} = M_{\text{Planck}}$
 $\rightarrow$ Extreme fine tuning of Higgs mass (1 part in 10^{15}) ???



Problem 3: Instability?

③ Solución metaestable

④ Estado inestable



Summary of Outstanding Questions

- Quantisation of Gravity (**big-bang, black holes**)
- Hierarchies : $M_{\text{Higgs}}/M_{\text{Planck}} = M_{\Lambda}/M_{\text{Higgs}} = 10^{-15} ???$
- **Why?** (3+1 dimensions, forces, families; masses, couplings (20 free parameters), quark confinement)
- **Cosmology :**

Big-Bang singularity

Flatness, Horizon,...



Inflation?

Dark Energy (cosmological constant?)

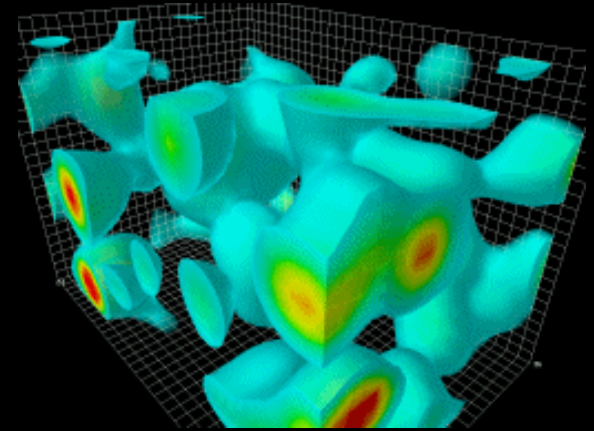
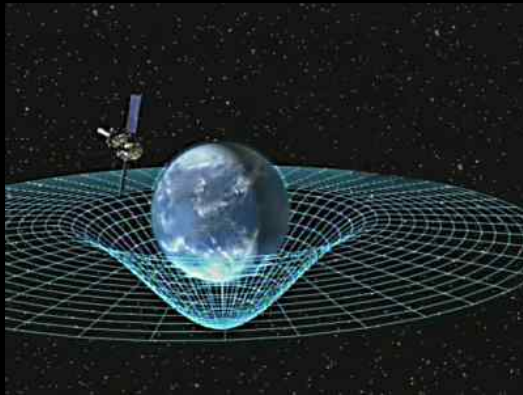
Dark Matter

Dark Radiation ($N_{\text{eff}} > 3.04?$)

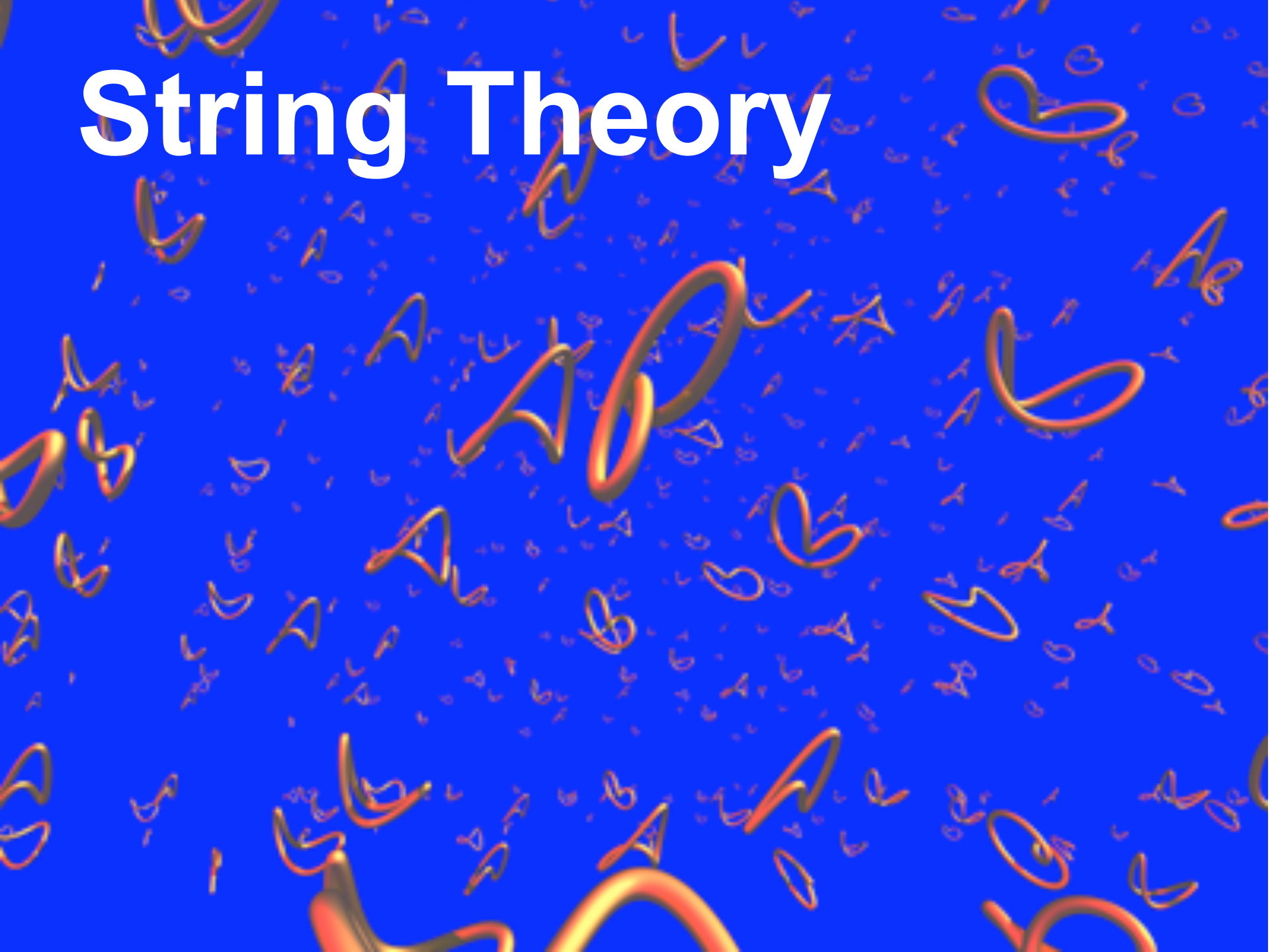
Baryogenesis...

FUNDAMENTAL PROBLEM

Quantum Gravity

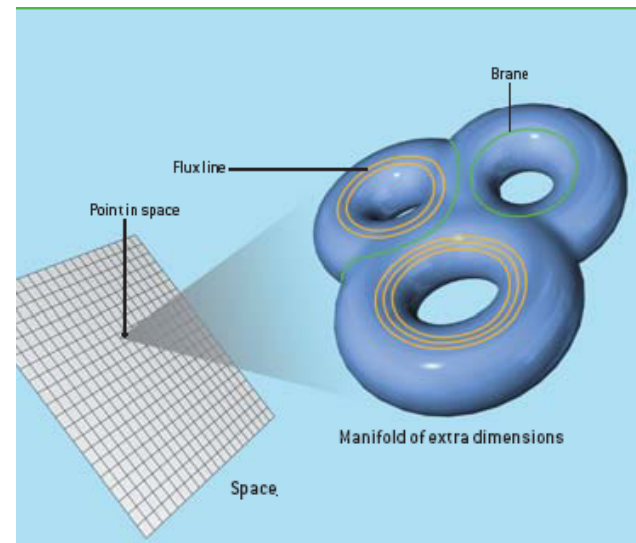
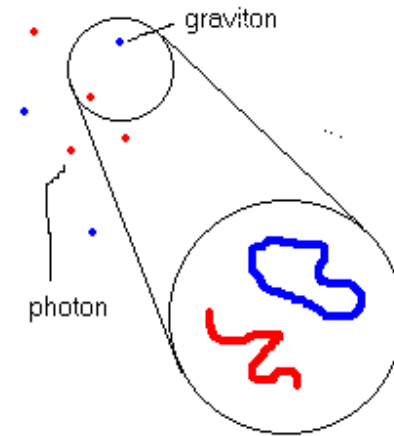


String Theory



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 ($1/g^2 = T$)



General ‘Predictions’ of String Theory

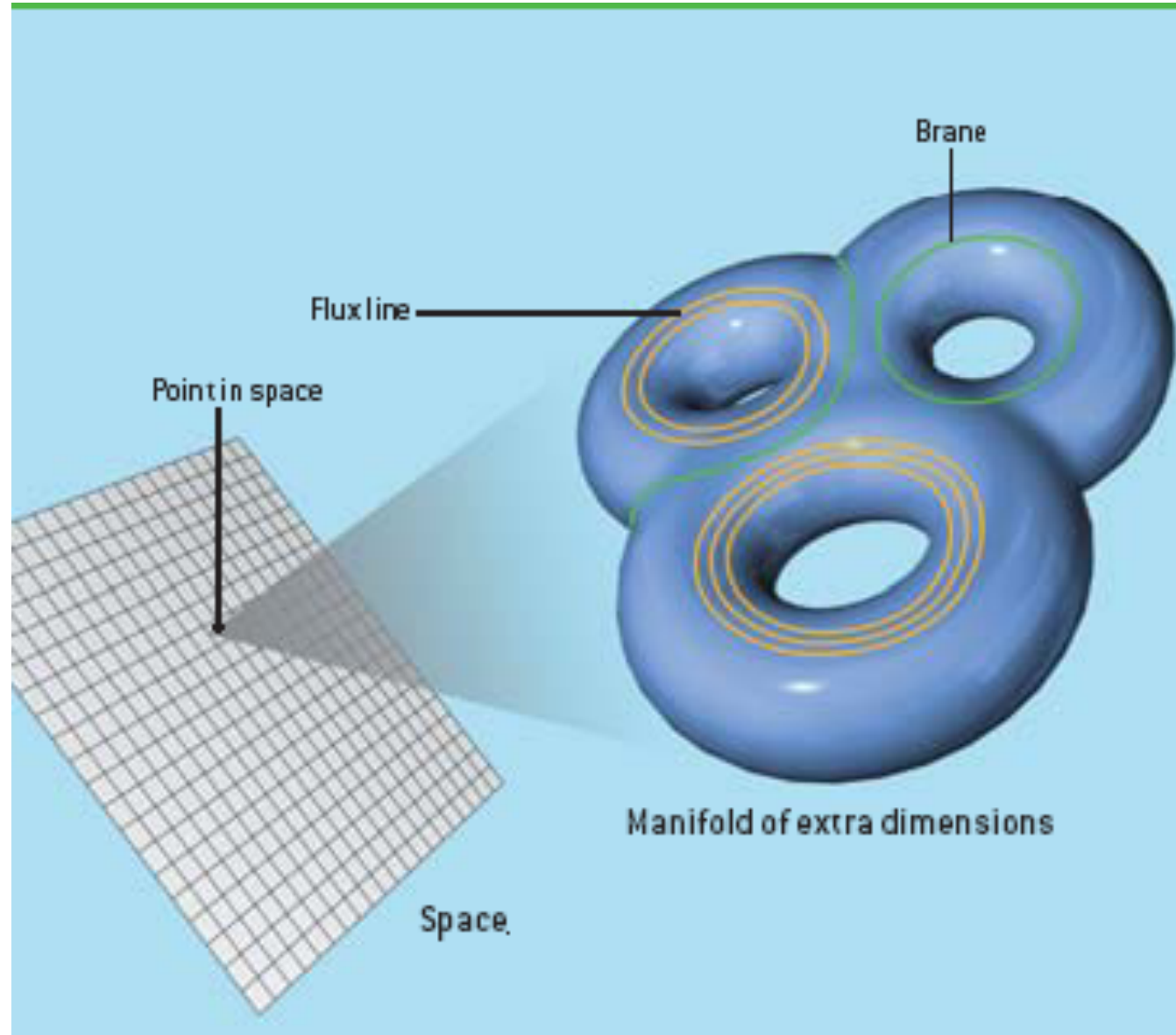
0

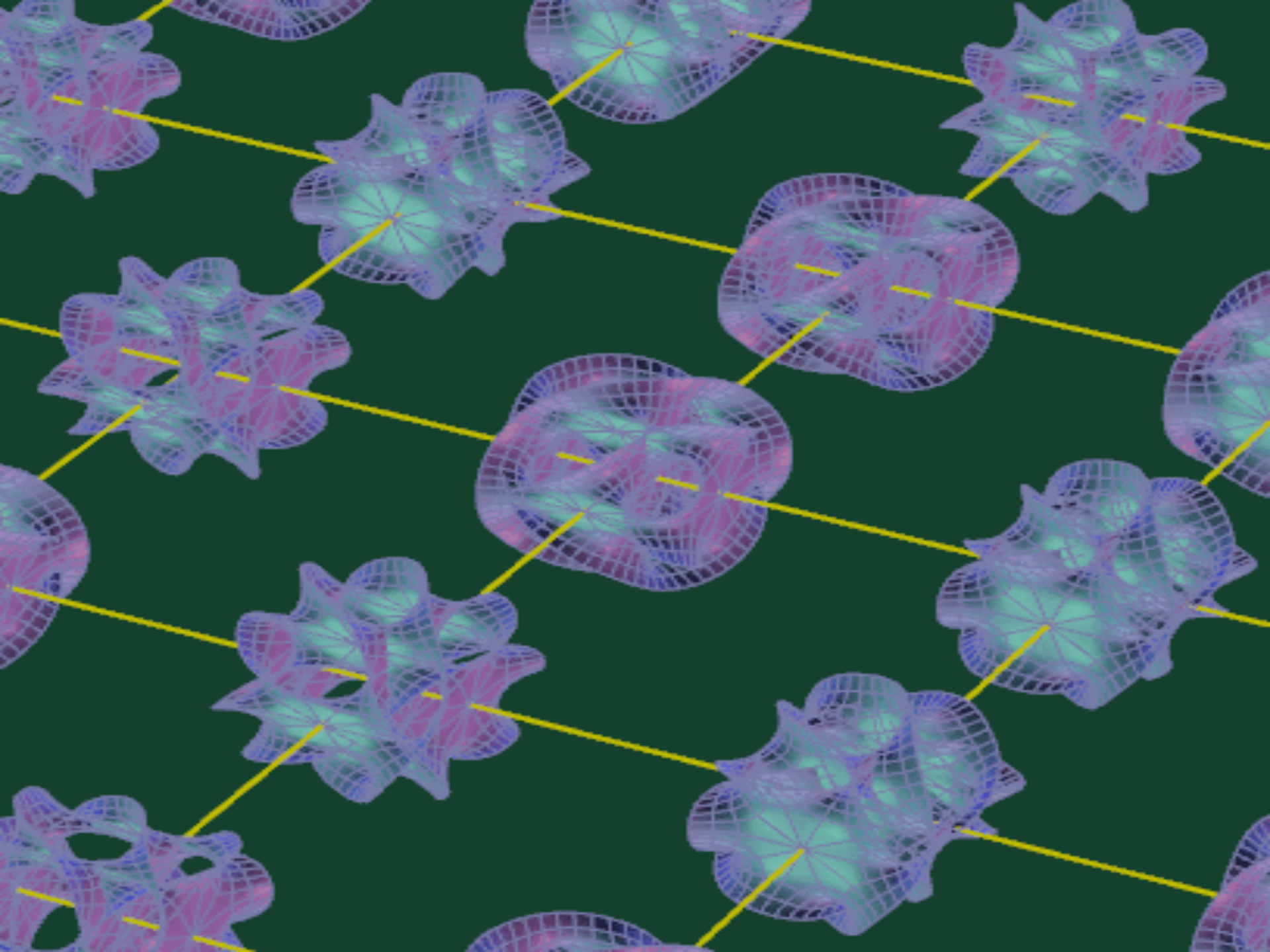
Gravity + other interactions + matter + ... exist!

MASSLESS SPECTRUM OF STRING THEORIES				
THEORY	DIMENSION	SUPERCHARGES	BOSONIC SPECTRUM	
Heterotic $E_8 \times E_8$	10	16	$g_{\mu\nu}, B_{\mu\nu}, \phi$ $A_\mu^{i\bar{j}}$ in adjoint representation	
Heterotic $SO(32)$	10	16	$g_{\mu\nu}, B_{\mu\nu}, \phi$ $A_\mu^{i\bar{j}}$ in adjoint representation	
Type I $SO(32)$	10	16	NS-NS	$g_{\mu\nu}, \phi$
			$A_\mu^{i\bar{j}}$ 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

1

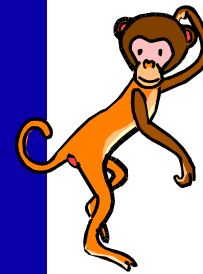
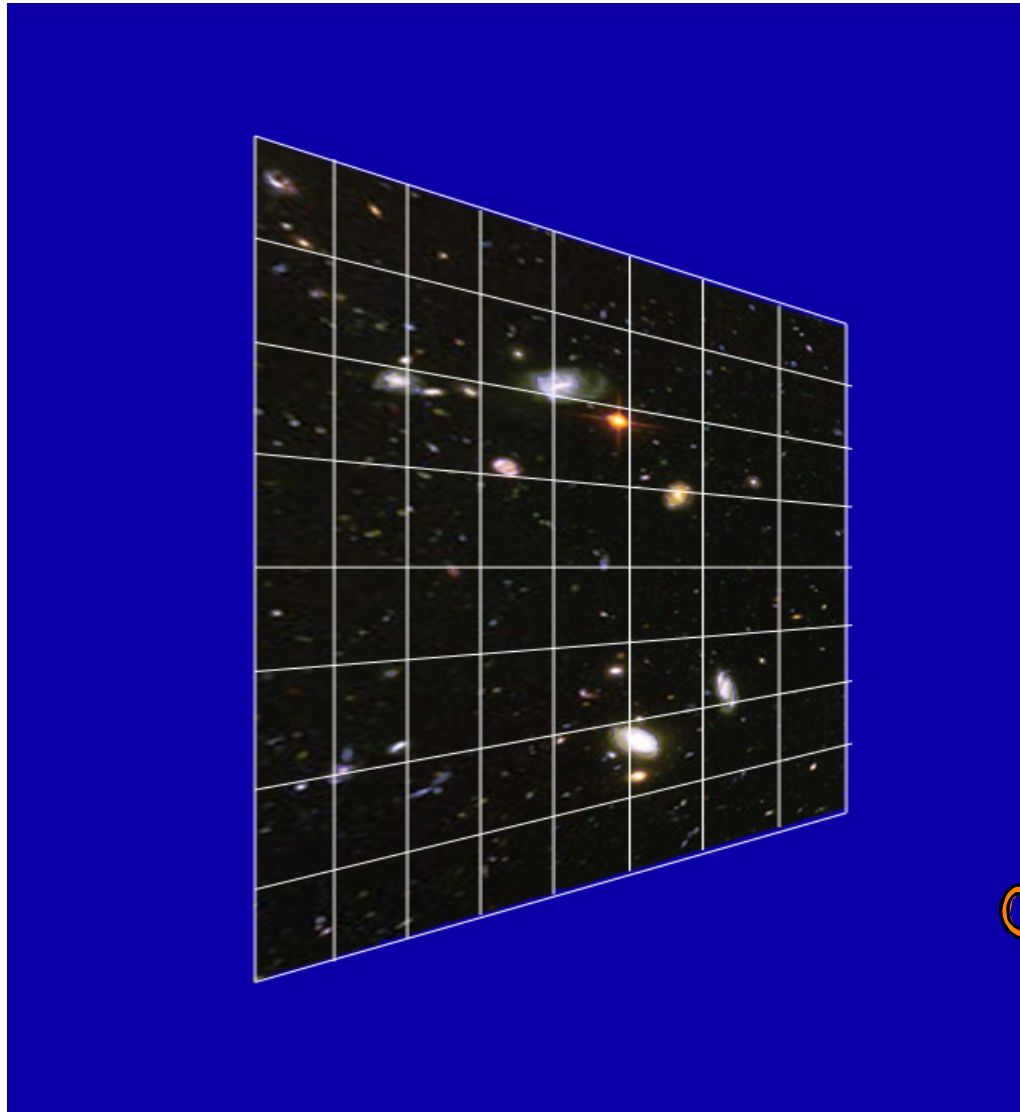




2

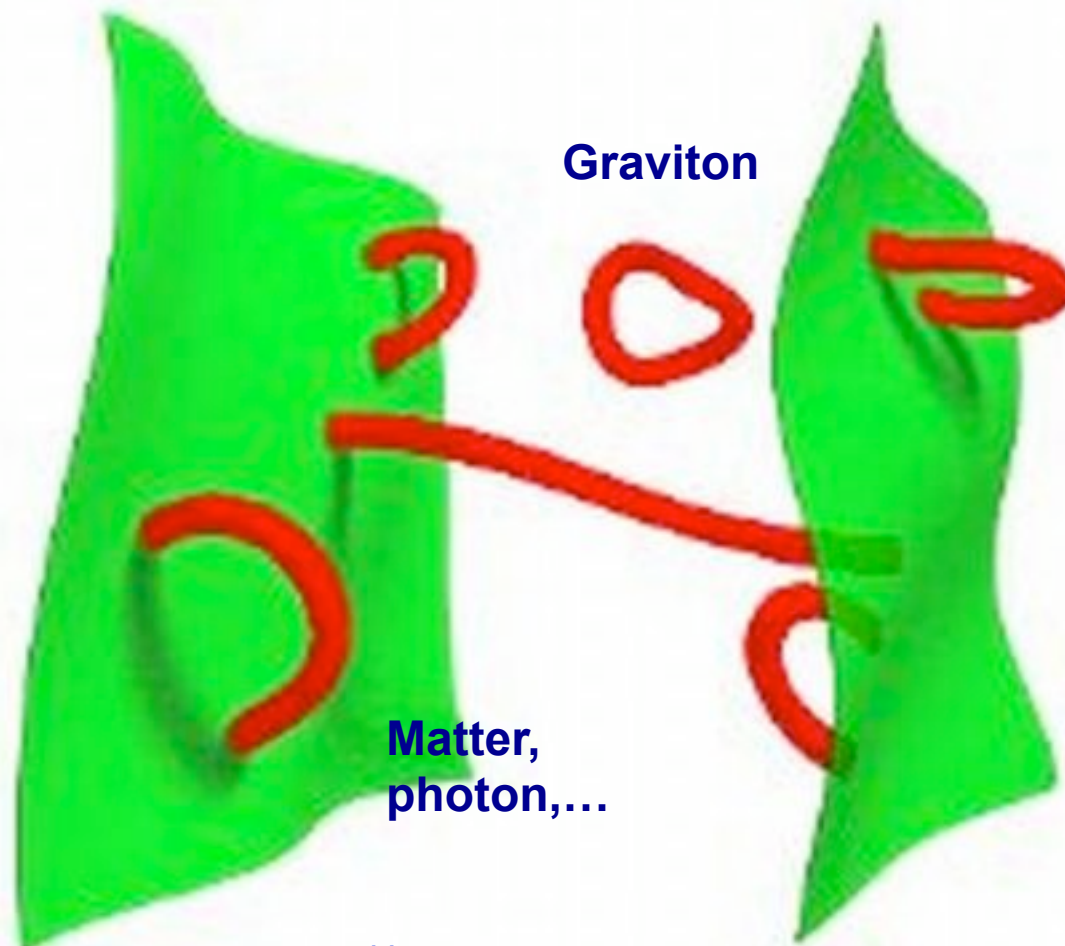
The Brane World

Is the Universe a Brane ?



Large extra dimensions may obviate hierarchy problem!

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!!!!)

3

Extra Fermionic Dimensions

(Supersymmetry (SUSY))

Boson → Fermion → Boson

Supersymmetry (SUSY)

(Extra fermionic dimensions)

Boson  **Fermion**  **Boson**

SUPERSYMMETRY !



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

h A H^0 $H^\pm$

u d e ν_e
 c s μ ν_μ
 t b τ ν_τ

γ Z $W^\pm$
 g

G

$\tilde{\chi}^0_1$ $\tilde{\chi}^0_2$ $\tilde{\chi}^0_3$ $\tilde{\chi}^0_4$

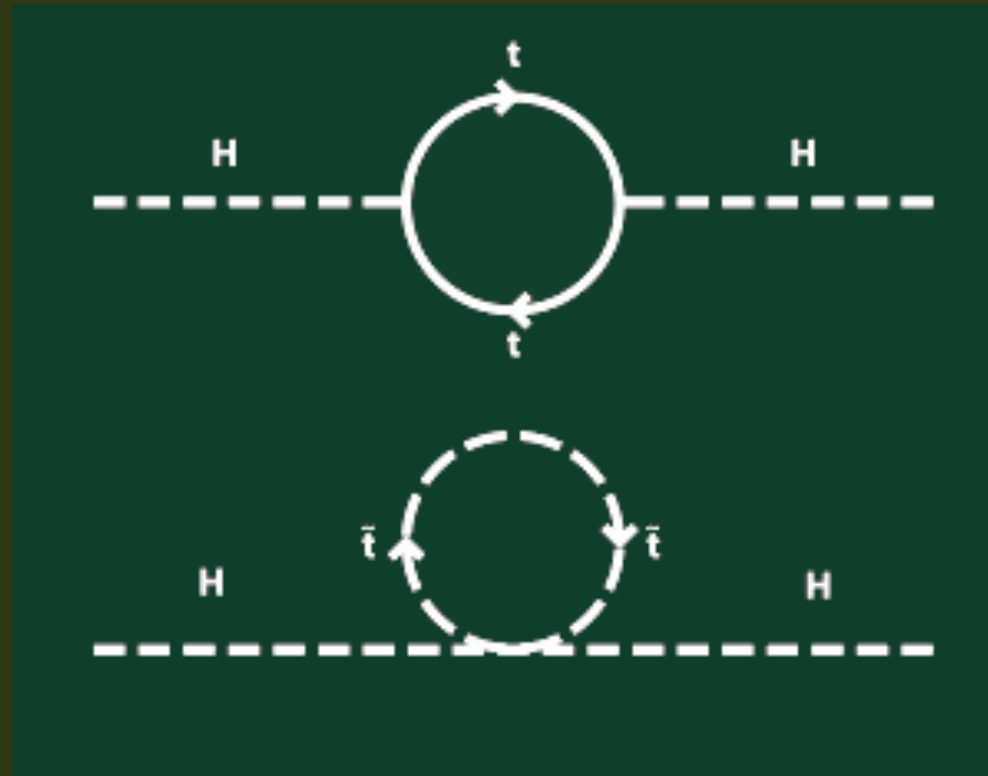
$\tilde{u}$ $\tilde{d}$ $\tilde{e}$ $\tilde{\nu}_e$
 $\tilde{c}$ $\tilde{s}$ $\tilde{\mu}$ $\tilde{\nu}_\mu$
 $\tilde{t}$ $\tilde{b}$ $\tilde{\tau}$ $\tilde{\nu}_\tau$

$\tilde{\chi}^\pm_1$ $\tilde{\chi}^\pm_2$
 $\tilde{g}$

$\tilde{G}$

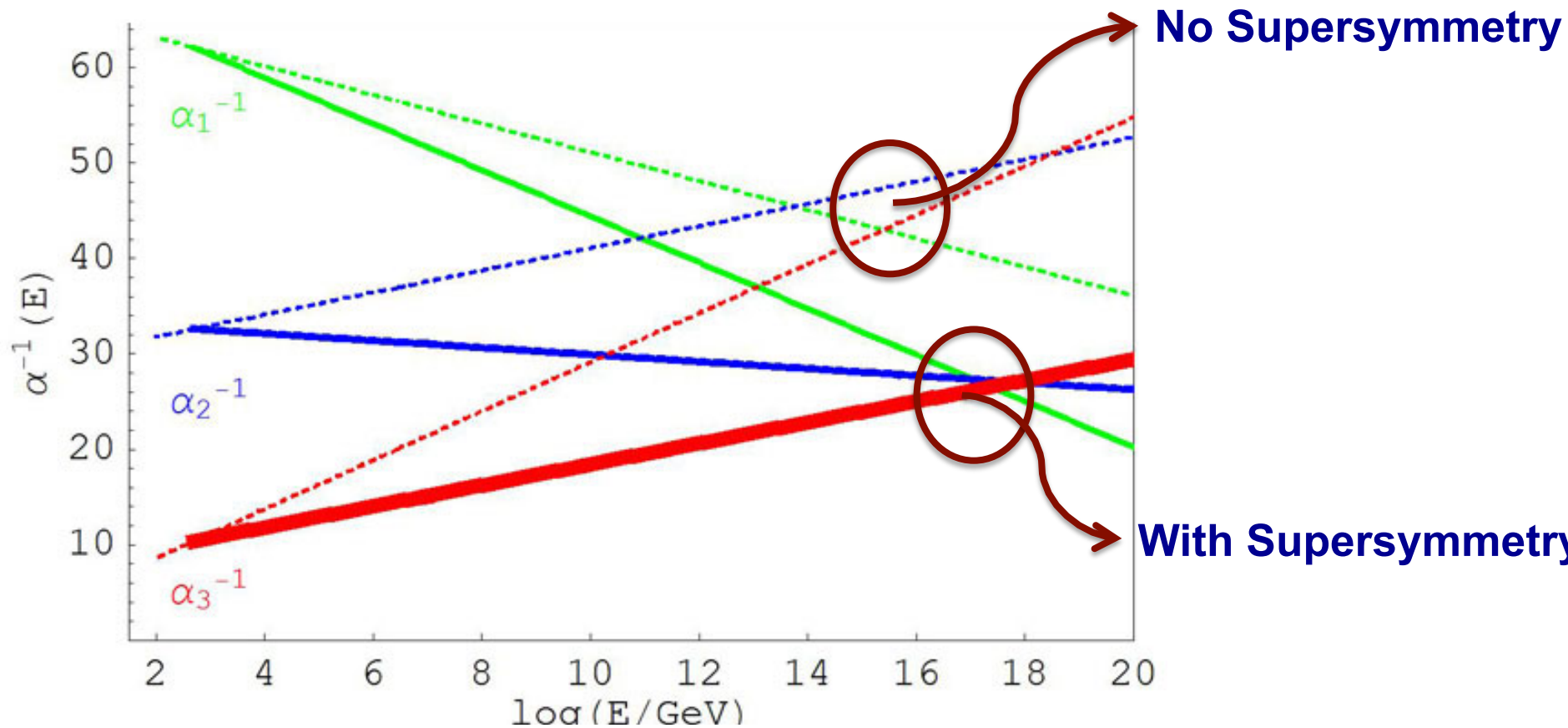
Dark matter!!!

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 $\sim 10^3$ GeV

Unification



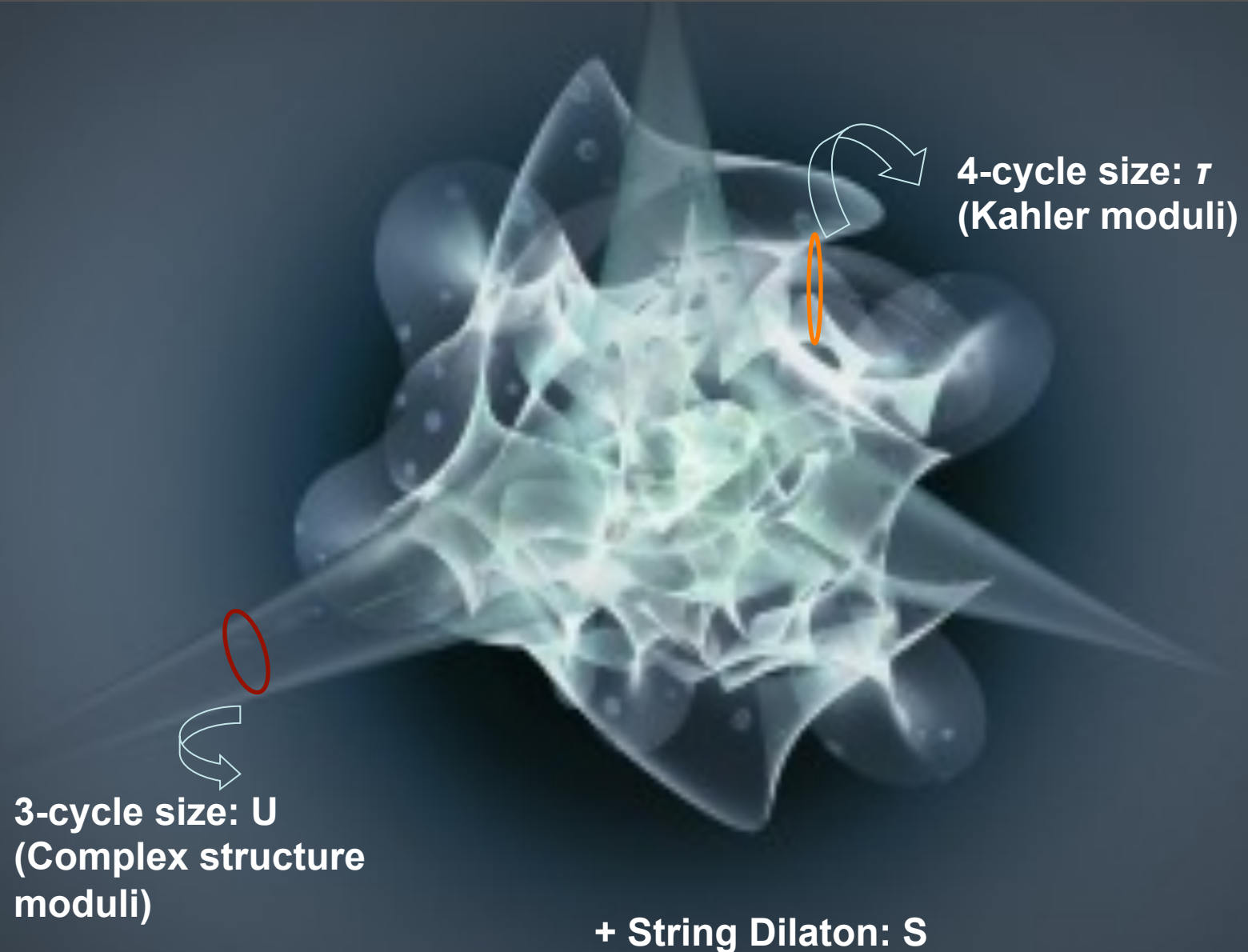
Supersymmetry

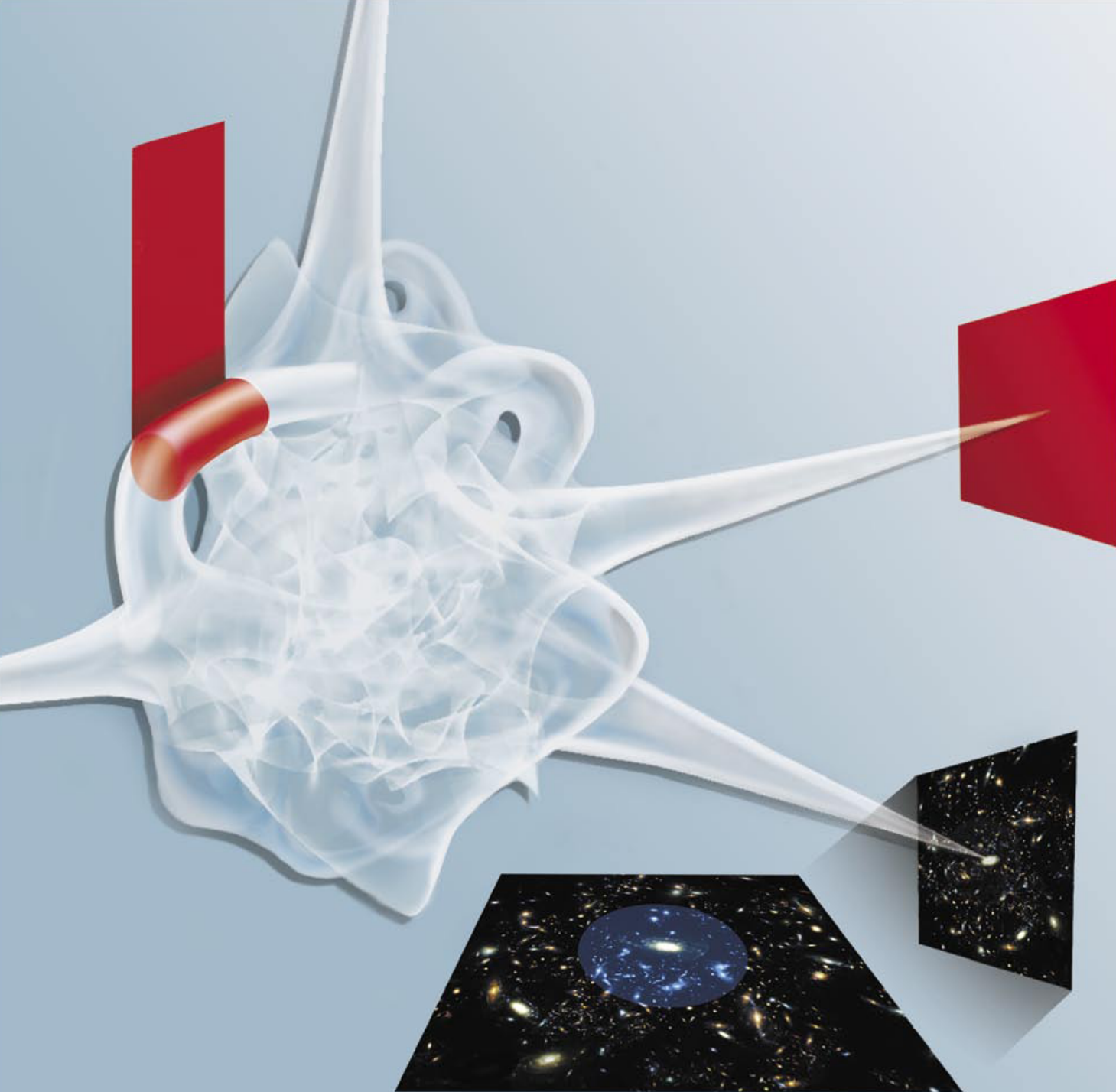
- Hierarchy ✓
- Unification ✓
- Dark Matter ✓
- Instability ✓
- Cosmological Constant ✗
- Experimental Evidence?? (fine tuning again?) ✗
- (Super) Strings ? (SUSY needed but scale?)

4

String Landscape

Size and Shape of Extra Dimensions





Universe

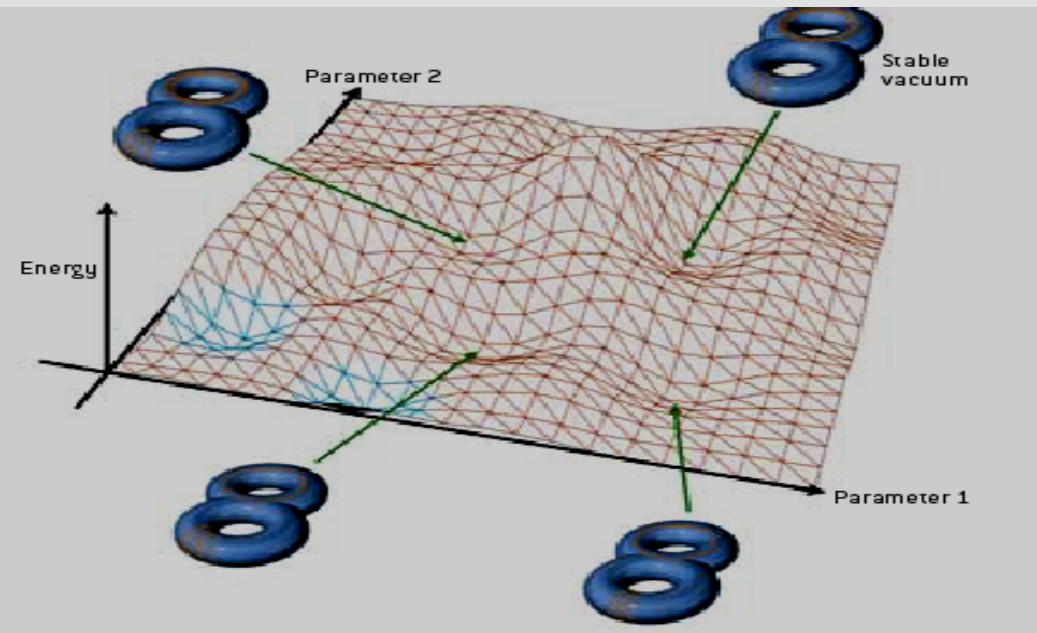
D3 Brane

or

D7 Brane

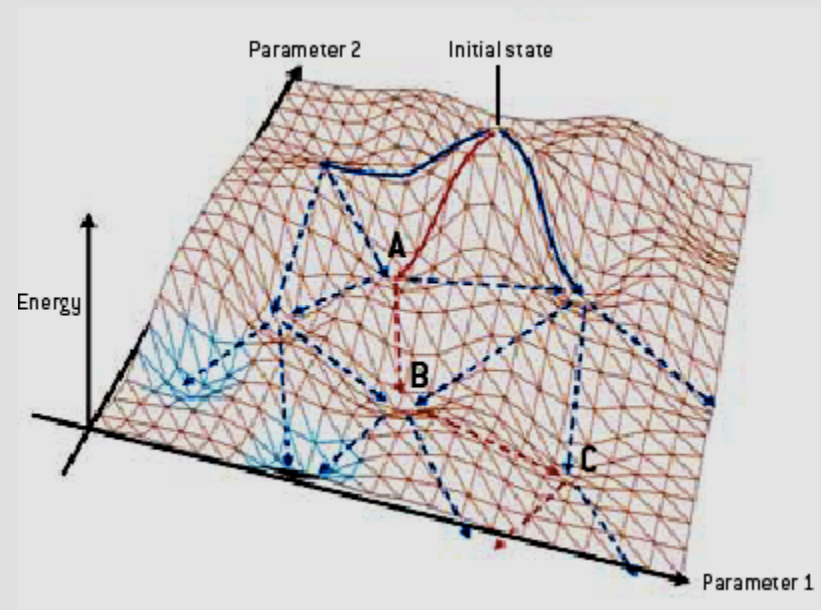
(F-Theory)

The String Landscape

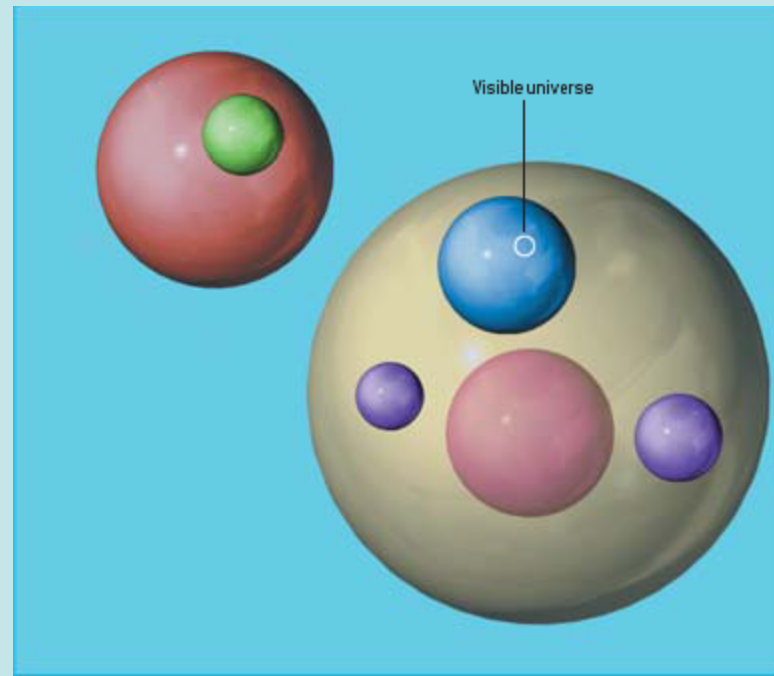
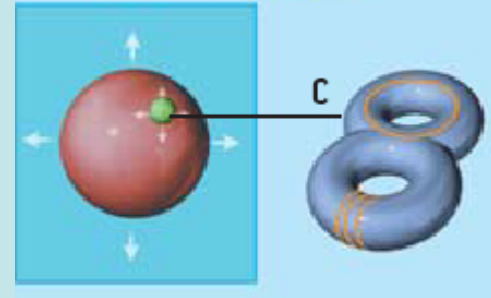
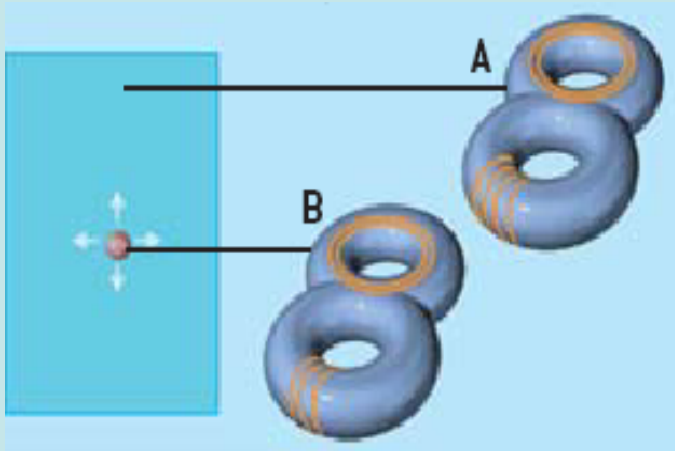


← **Classical Solutions**

**Quantum Decay
(tunnel effect)** →



Multiverse



**Anthropic 'explanation'
of dark energy!!?????**

5

Holography

Holography !

(e.g.
 $\text{AdS}_5 \times \text{S}^5 = \text{CFT}_4$)

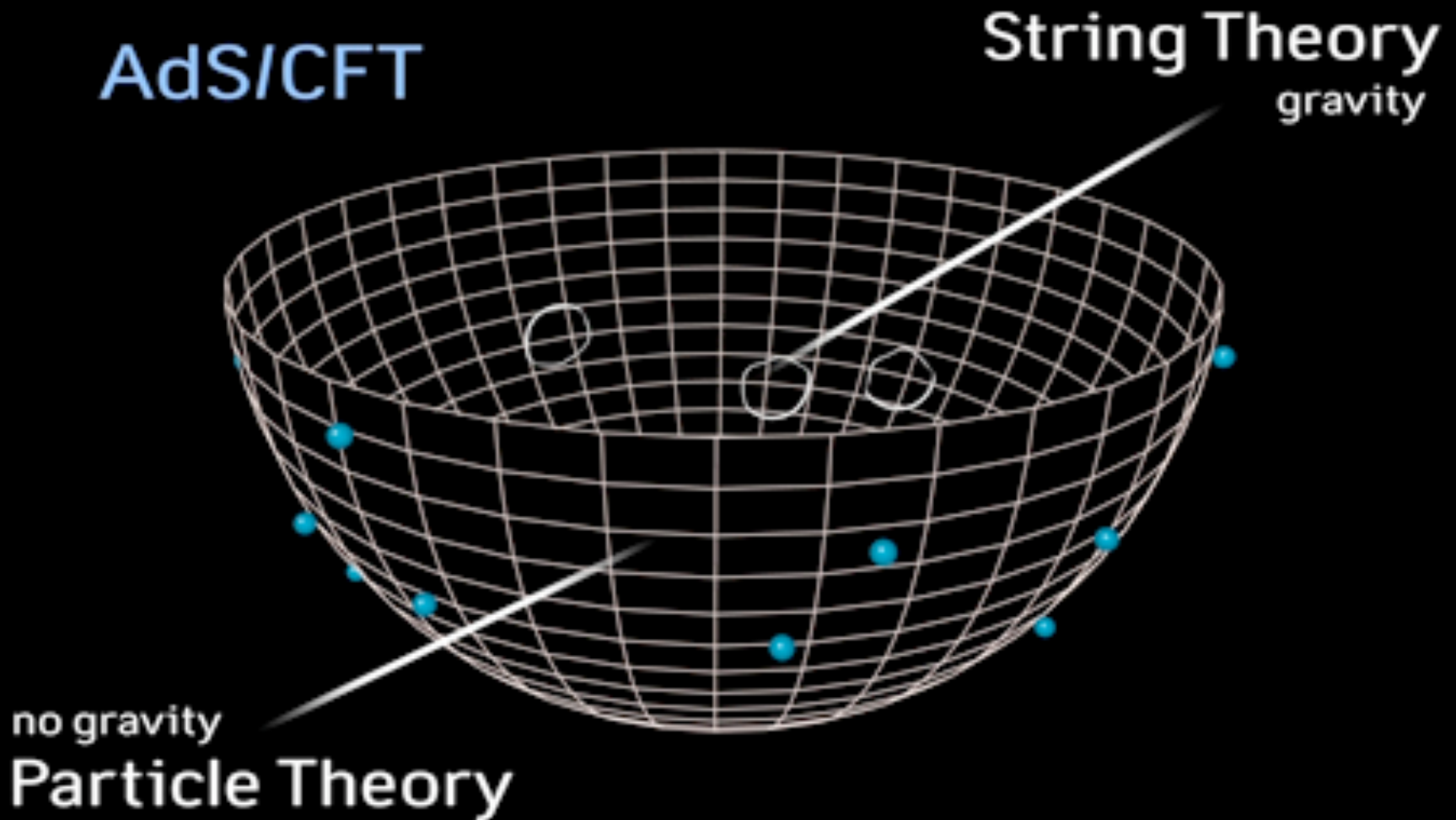


anti-de Sitter space

conformal
boundary

time

Gravity/No-Gravity correspondence!



Some Implications of Holography

- Proper definition of quantum gravity theory!
- Black hole entropy/area! $S_{\text{BH}} = (kc^3/4G\hbar) A$
- 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????

Other 4D String Implications

- **No Continuous spin representations!**
- **No global symmetries (all local)**
- **Axion-like particles**
- **Cosmological moduli problem (if TeV SUSY)**
- **Several quasi-realistic scenarios that can be confronted with experiments (like QFT!).**
Open question: fully realistic string model.

Short Term Future?

- **Nightmare Scenario: LHC discovers only the Higgs (worst than no discovery at all?)!!!!**
- **Supersymmetry (?) (or anthropic/tuning?)**
- **Extra Dimensions (???)**
- **Unexpected !!!!**
- **Strings???** (Probably long term since $M_{\text{planck}} \gg \gg \text{LHC scales}$ but may get lucky and/or accumulate several low energy successes)

Future Experiments?

- **LHC 2015...**(twice energy 10 times more data!!!)
- **ILC, CLIC, TLEP,...?**
- **Muon colliders, etc.?**
- **100Km/100TeV expansion of LHC!!?? (or China?)**
- **Cosmological observations (Dark matter searches, Planck, LISA, axions, spectrum gamma, X,..rays.)**



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Thank You