…But What Does String Theory Predict?

Michele Cicoli

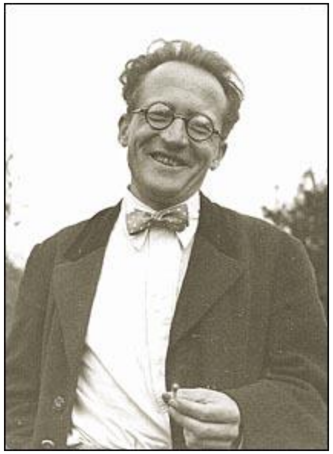
Bologna Univ., INFN and ICTP

Naples, 20 November 2015

Two Pillars of 20th Century Physics

- ***Special Relativity*** describes the physics of objects moving at speeds close to the speed of light as a maximum speed
- ***General Relativity*** is the extension of this theory to include gravity

- ***Quantum Mechanics*** is the framework for studying the physics of very short distances

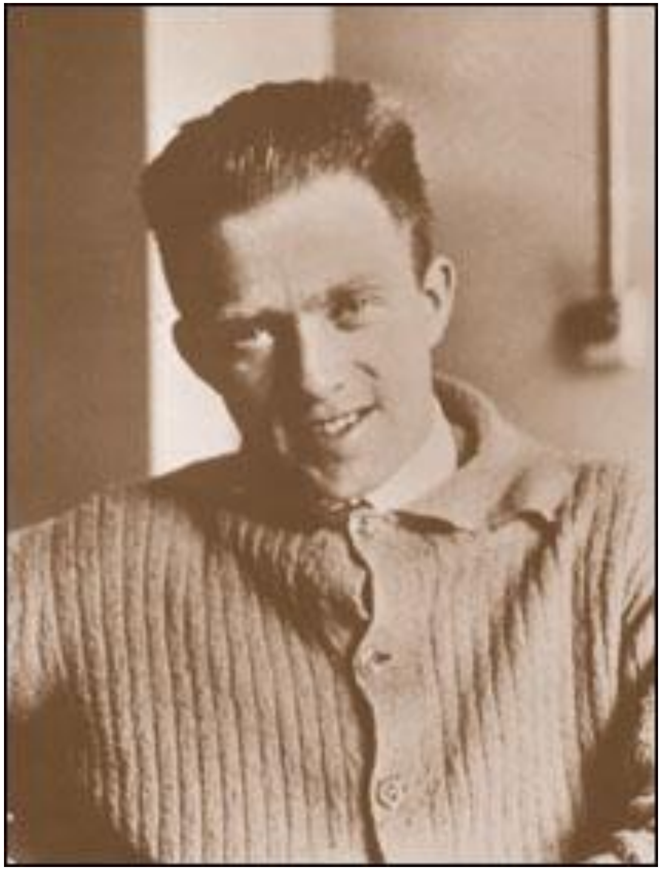


Almost inconsistent with each other!

Quantum Physics comes into the game

The Uncertainty Principle

The more precisely the position is determined, the less precisely the momentum is known in this instant and viceversa



$$\boxed{\Delta x \Delta p_x \geq \frac{\hbar}{2}}$$

General Relativity

- Gravity is the curvature of spacetime
- Equivalence Principle: Free-falling observes do not see locally any gravitational field
- They are equivalent to inertial observers
- Spacetime is locally flat
- Difficult conflict with the Uncertainty Principle!

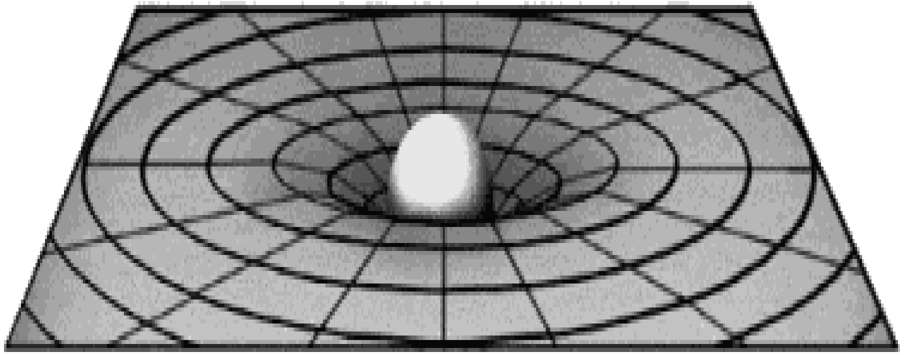
Need a theory of Quantum Gravity!

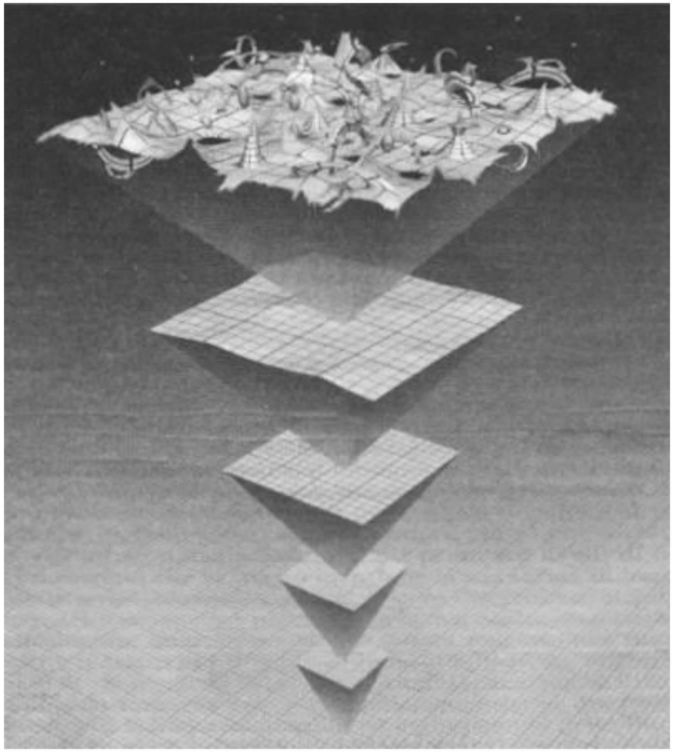
- But Gravity is very weak
- Can still make a lot of progress

E.g.: Standard Model of Particle Physics!

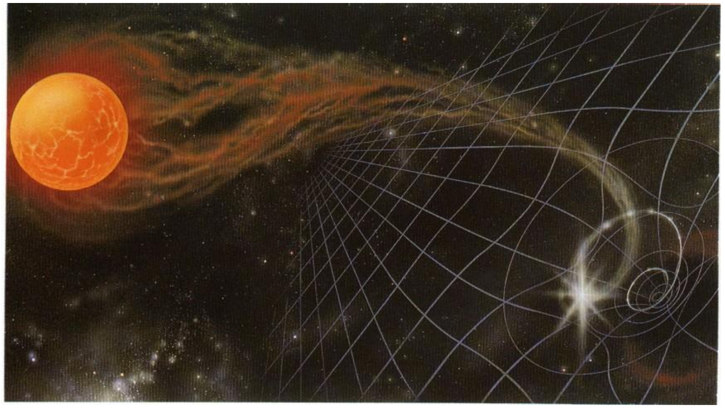
- But Gravity becomes strong at high energies of order $M_P \sim 10^{18}$ GeV or short distances $\ell_p \sim 1/ M_P \sim 10^{-35}$ m

Quantum Gravity cannot be neglected!





Most important problem: Quantum Gravity



Black Holes?

Big Bang?

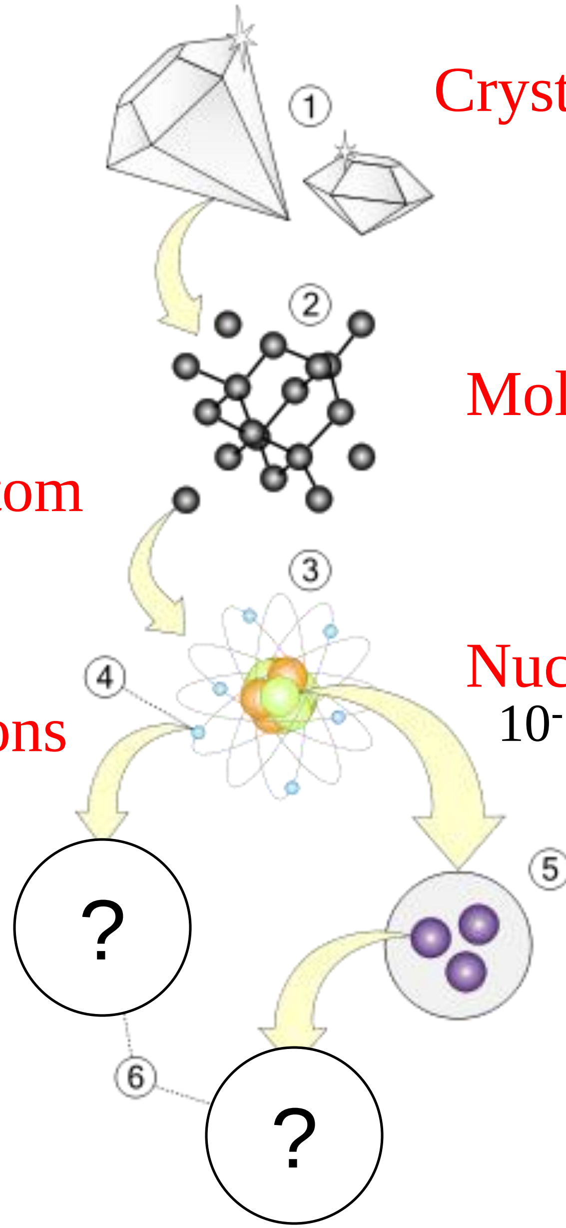
Dark Energy?

Unification of all fundamental forces?

Fondamental theory at the base of our Universe?

The answer to all these questions requires a theory of quantum gravity!

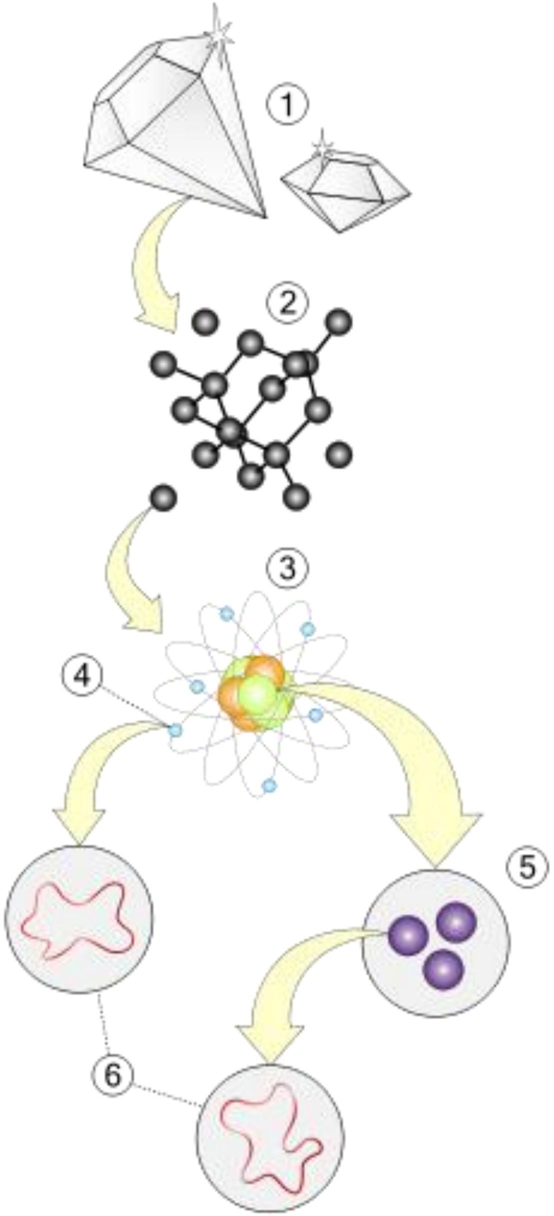
Subnuclear Physics



String Theory: the idea

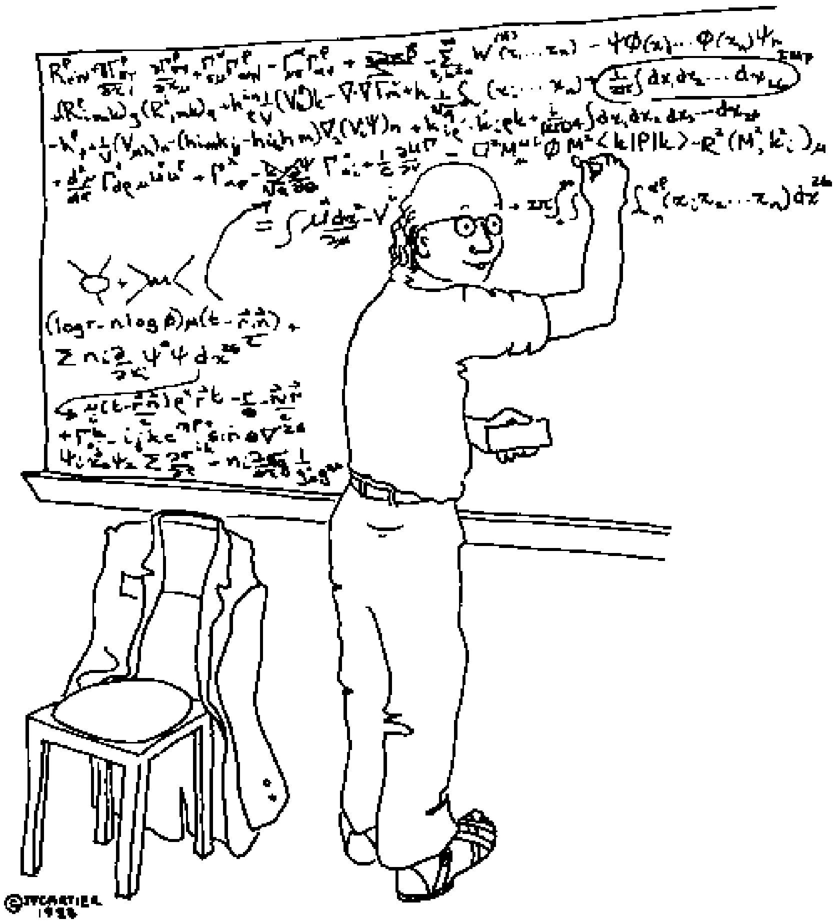
Need to change point of view completely:
substitute point-like particles
with one-dimensional objects!

1) All kinds of particles are simply different vibration modes of the same string
2) Unification of matter and interactions!
3) Consistently includes quantum gravity!
4) There is just one parameter, the string length ℓ_s, from which everything can be derived!
5) At low energies contains General Relativity and known particle theories!



Theory of Everything!

Extra Dimensions



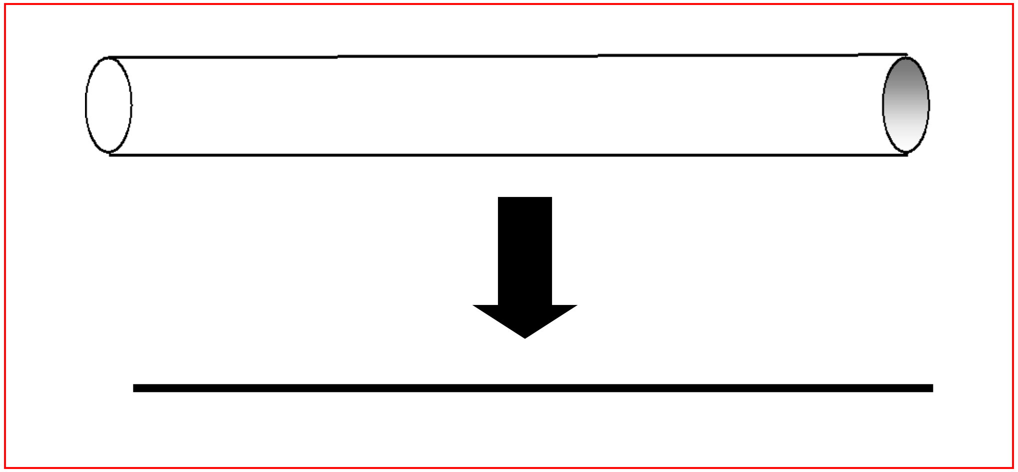
"At this point we notice that this equation is beautifully simplified if we assume that space–time has 92 dimensions."

- String Theory predicts that our Universe has 9 spatial dimensions and 1 time
- Experimental update: the observed number of (large) dimensions is 3 spatial and 1 time
- Falsifiable or false?

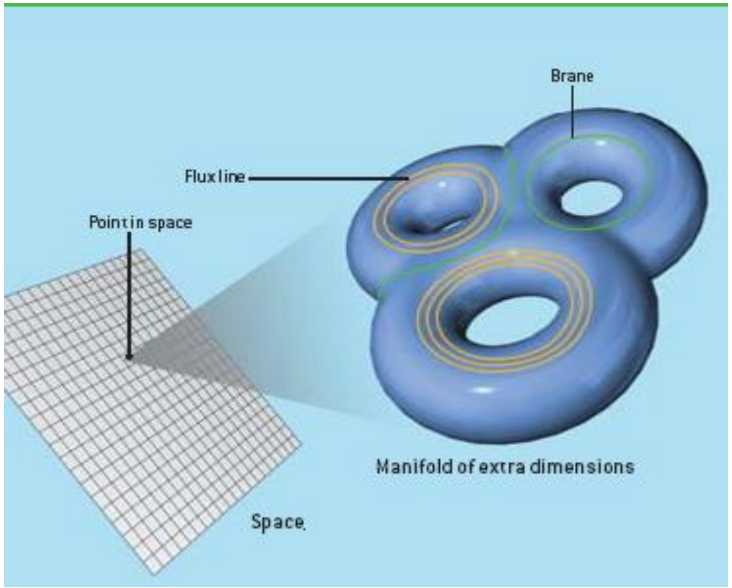
How would we know?

Our Universe: 10D = 4D large + 6D very small

$$d < 10^{-18}\ \mathrm{m}$$



It is crucial to *predict* the size of all dimensions!



D-Branes

- String Theory is much bigger

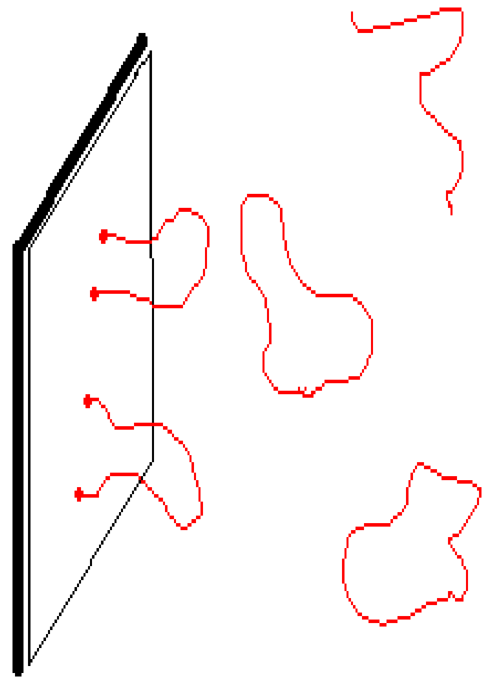
  1) Normally, the ends of open strings move freely at the speed of light

  2) Strings can also exist whose ends are attached to surfaces

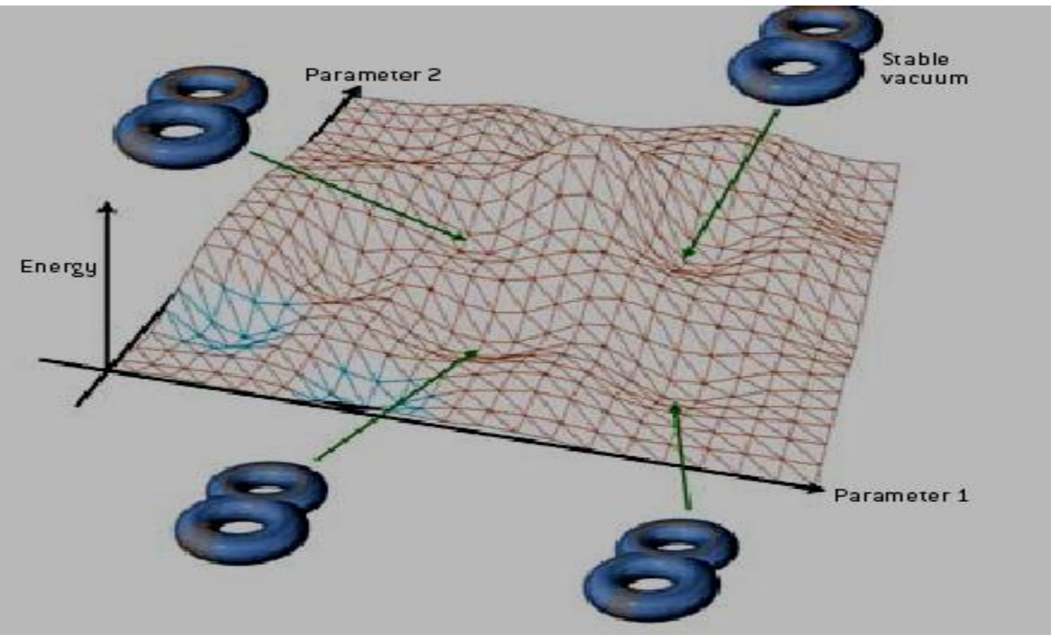
- These surfaces are interpreted as large massive objects, called D-branes, in spacetime
- Allow to discover web of dualities

→ Unique theory in 11D but….

a plethora of 4D solutions!

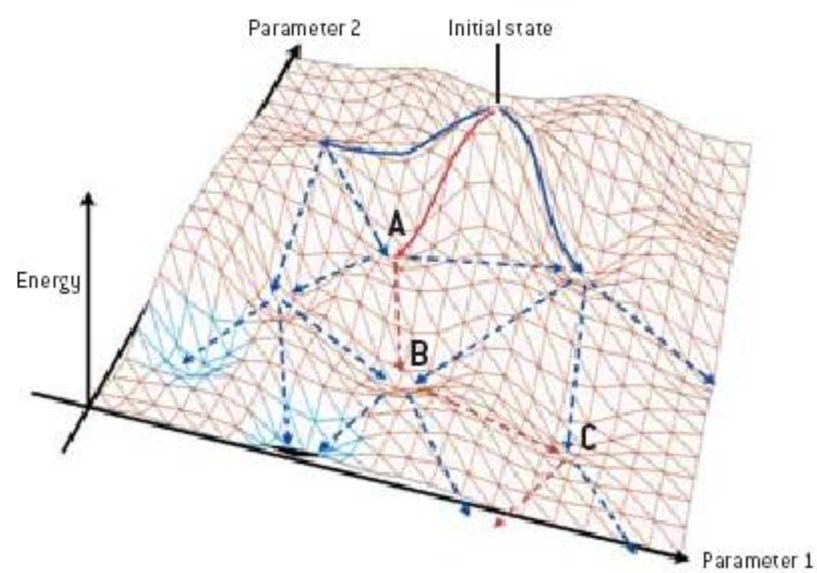


String Landscape

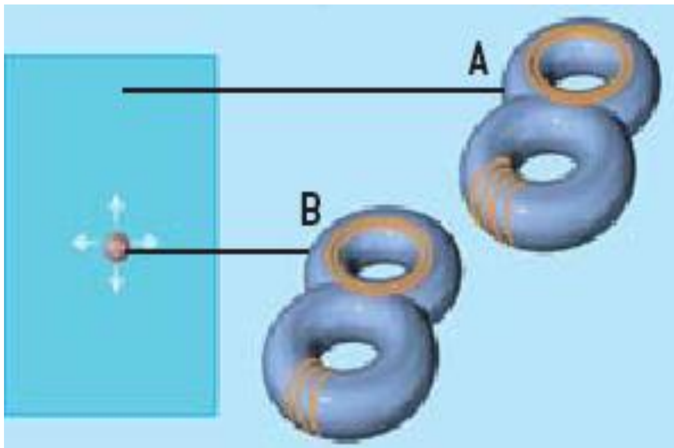


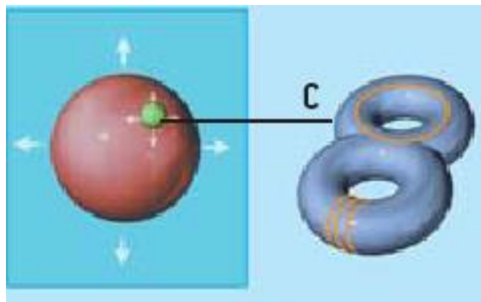
Classical Solutions

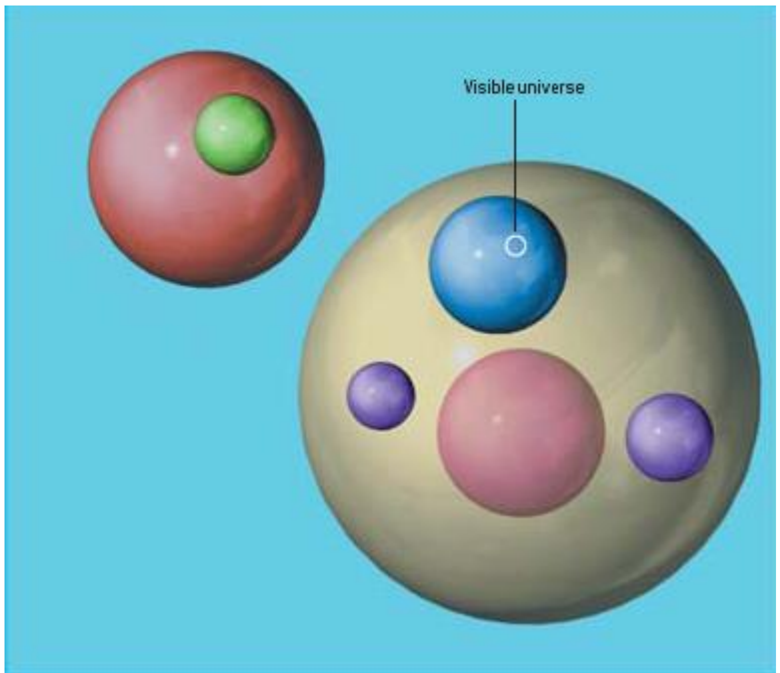
Quantum transitions
(tunneling effect
or inflation)



Multiverse







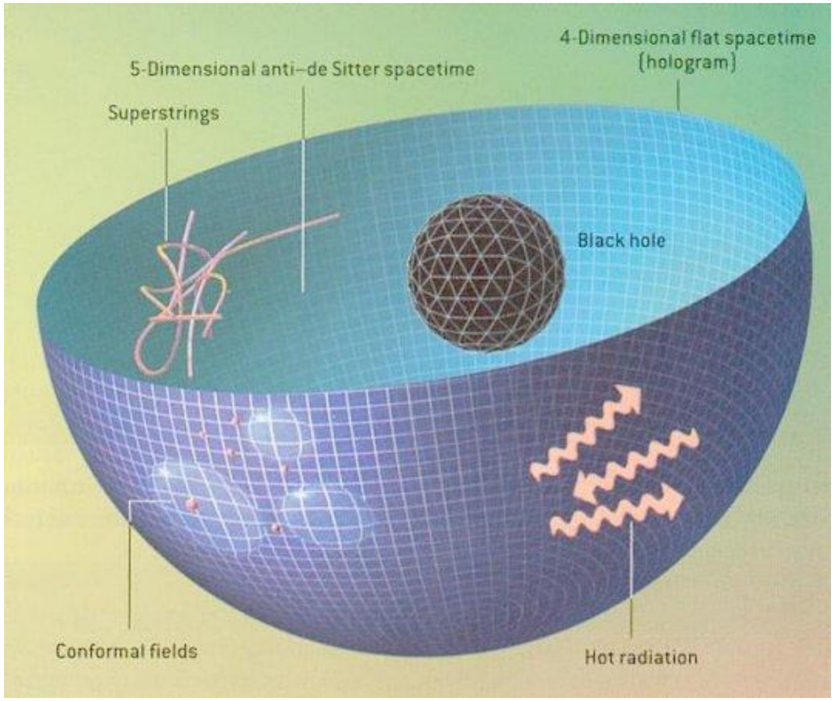
Anthropic Principle

- Many different configurations
  → $\sim 10^{500}$ solutions !!!
- Each solution = one Universe
- Get several values of cosmological constant Λ
- Anthropic Principle 'solves' the cosmological constant problem:

$$\Lambda \sim 10^{-120} M_P^{\,4}$$

- Is it a solution?
- Statistics …

Duality between particles and strings



Holography: Certain elementary particle theories can be seen as particular string theories and viceversa!

A new concept of spacetime?

- In some cases the physics at distances smaller than the string scale ℓ_s is the same as the physics at distances larger than ℓ_s

  → Notion of distance could just be approximate, being valid only for distances $R \gg \ell_s$

$$\boxed{R \Leftrightarrow \ell_s^2 / R}$$

- Possibility to avoid initial singularity of Big Bang theory

…but what does String Theory predict?

Different approaches

1) Clear prediction: existence of strings but to see them need to go to very high energies close to M_P

→ No implications for low-energy physics

→ Cannot check real prediction of String Theory!

2) We do not know the theory well enough to make trustable predictions!

3) String Theory predicts nothing since it predicts everything!

→ String Landscape

Probably there is some truth in each of these considerations BUT…

Strategy

- Not everything seems to come out of string theory!

- Interested in two kinds of predictions:

  i) Predictions which are hard to get from string theory
  (inflation with large gravity waves and low-scale SUSY,
  large local non-Gaussianities, N_{eff}=3…)

  ii) Predictions which look generic from string theory and unlikely from 4D
  (many light fields, non-standard cosmology with matter domination,
  axionic dark radiation, non-thermal dark matter, extra U(1)s,
  millicharged particles, hidden photons…)

If (i) is found $\longrightarrow$ rule out most of the string landscape

If (ii) is found $\longrightarrow$ hint in favour of strings

String Phenomenology

- String phenomenology: attempt to test string theory

  i) Directly: detection of strings in colliders for very low M_s
  ii) Indirectly: low-energy implications for ordinary 4D physics

  → depend on properties of extra dimensions
  → study string compactifications

- Long term plan: String theory scenario that satisfies all particle physics and cosmological observations and leads to measurable predictions

- The Lament of a string phenomenologist:

Formal string theorists:

"Not real string theory"

Low-energy phenomenologists:

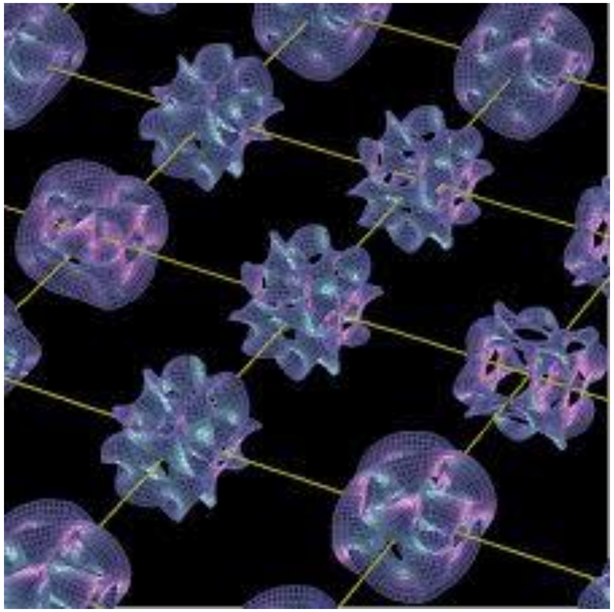
"Not real physics"

Rest of the world:

"Not even wrong"

String Moduli

- 10D = 4D large + 6D very small
- 6D space is Calabi-Yau Y
- Y can be deformed in size and shape
- 4D theory for $d >> \mathrm{Vol}(Y)^{1/6}$



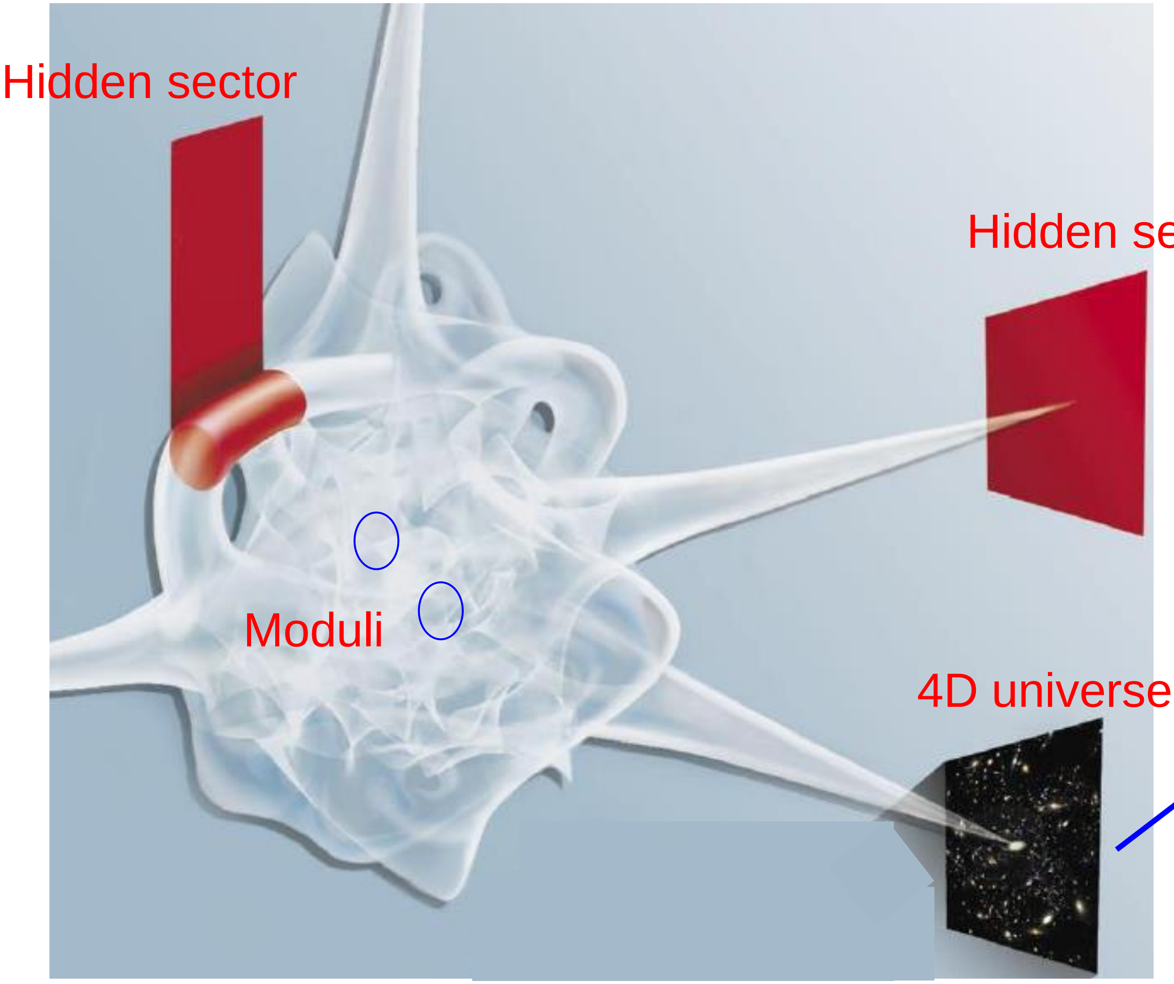
- Deformations become new spin=0 particles, called moduli, with only gravitational couplings to matter

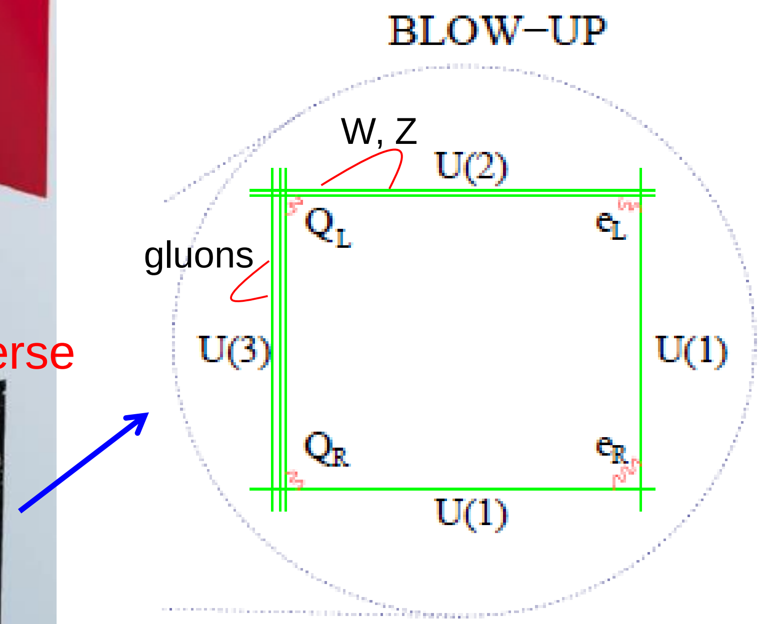
- Moduli must be massive otherwise they mediate unobserved long-range fifth forces
  $\Longrightarrow$ m > 1 meV (m > 50 TeV to avoid cosmological problems!)

- All properties (kind of interactions, mass spectrum, couplings….) of 4D theory depend on moduli
  $\Longrightarrow$ Need to know their values to make predictions!

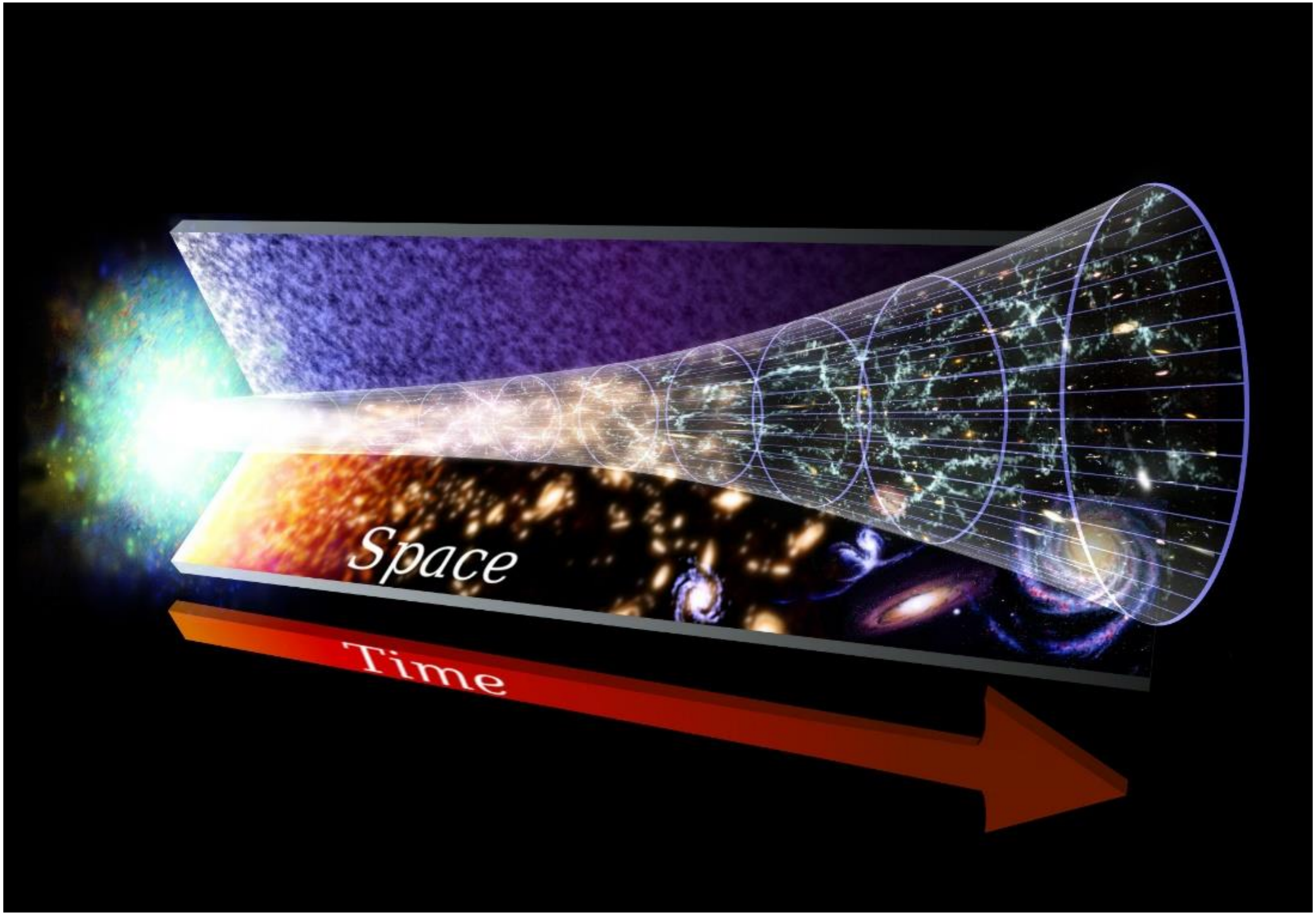
Where is the Standard Model?

- Ordinary particles are open strings living on branes
- Branes provide interactions and particles with features typical of the Standard Model!
- Standard Model localised on branes
- Closed string moduli live in the bulk of the extra dimensions





Cosmic Inflation



Why string inflation?

- Inflation involves energies higher than those reached by any experiment on earth

  → promising to probe string-related physics

- Inflation is very sensitive to quantum gravity effects that can spoil it!

  → Need to control quantum gravity interactions

  → String theory

- String theory has many non-trivial constraints to inflationary model building

  → It is not obvious that you can get everything out of it!

  Hard to get large gravity waves, large local non-gaussianites, N_{eff}=3,….

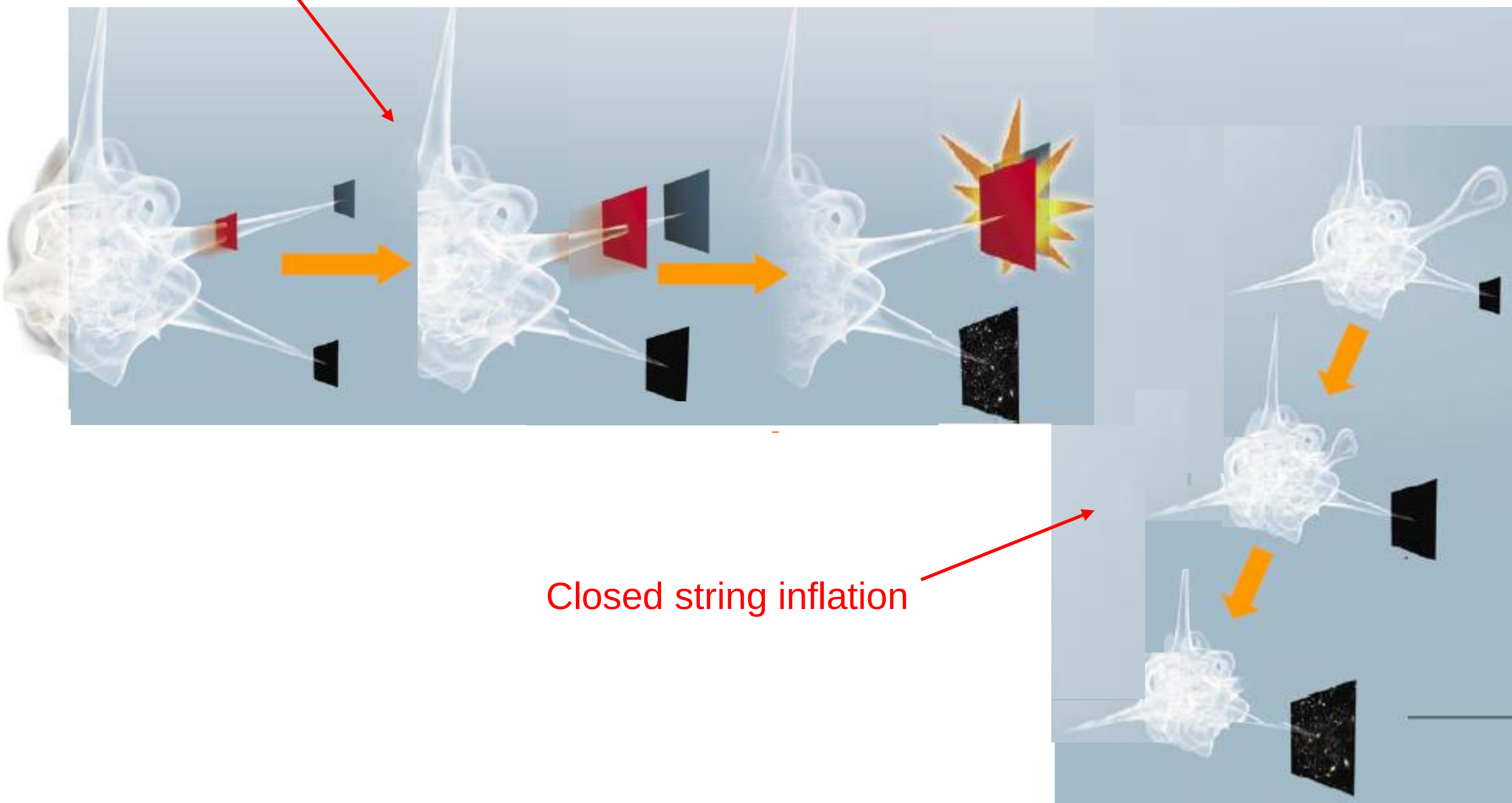
- Sensible embedding into string theory restricts the number of viable 4D models

- New data coming soon: Planck, EPIC, Spider, CMBPol, LiteBIRD, Euclid

String inflationary scenarios

- String theory provides for free many scalars which can drive inflation!

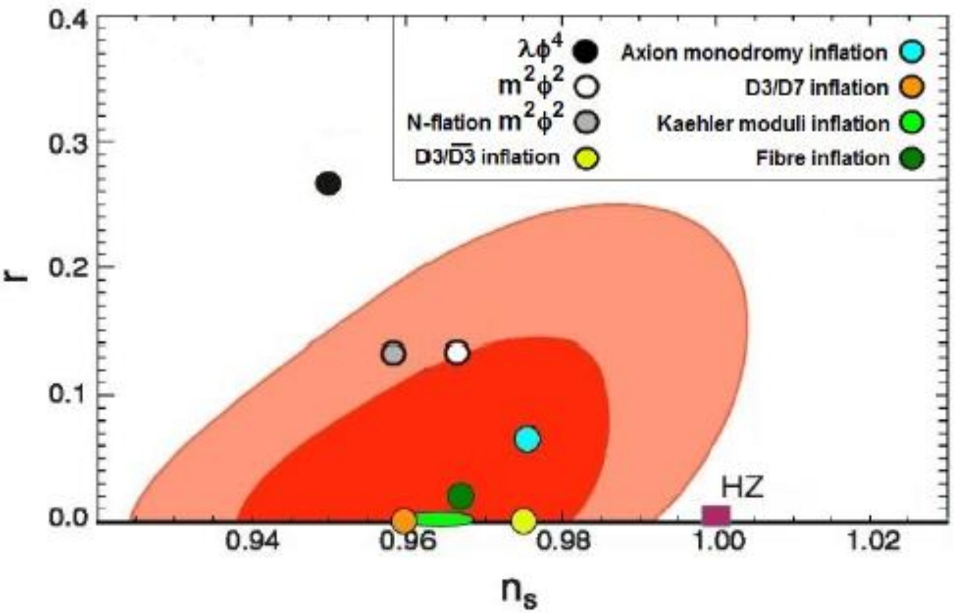
Open string inflation



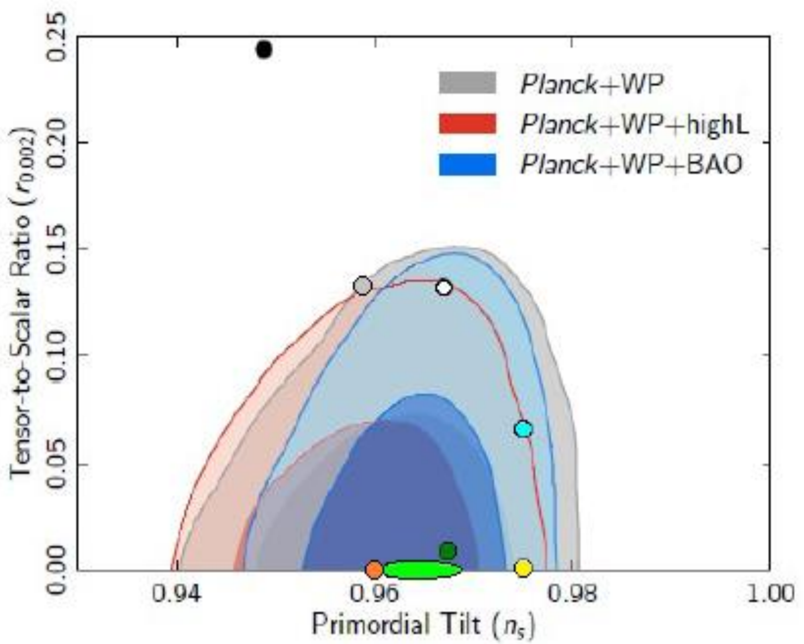
Closed string inflation

Cosmological predictions

2008



2013



- Almost unanimous prediction of undetectable gravity waves
  → expect r not larger than 0.01

- Well agreement with observations!

- Is there a deep quantum gravity reason for this agreement (large r needs trans-Planckian field ranges)?

Multi-field dynamics

- Most models of string inflation are single-field
- Why? For simplicity (hard to get inflation)
- Solutions are known based on symmetries

→ work out predictions for cosmological observables n_s,r, f_{NL},….

- Non-Gaussianities are negligible (very weak inflaton self interaction)
- But is this the generic case from string theory? NO
- A generic compactification has many moduli
- Light fields get large quantum fluctuations

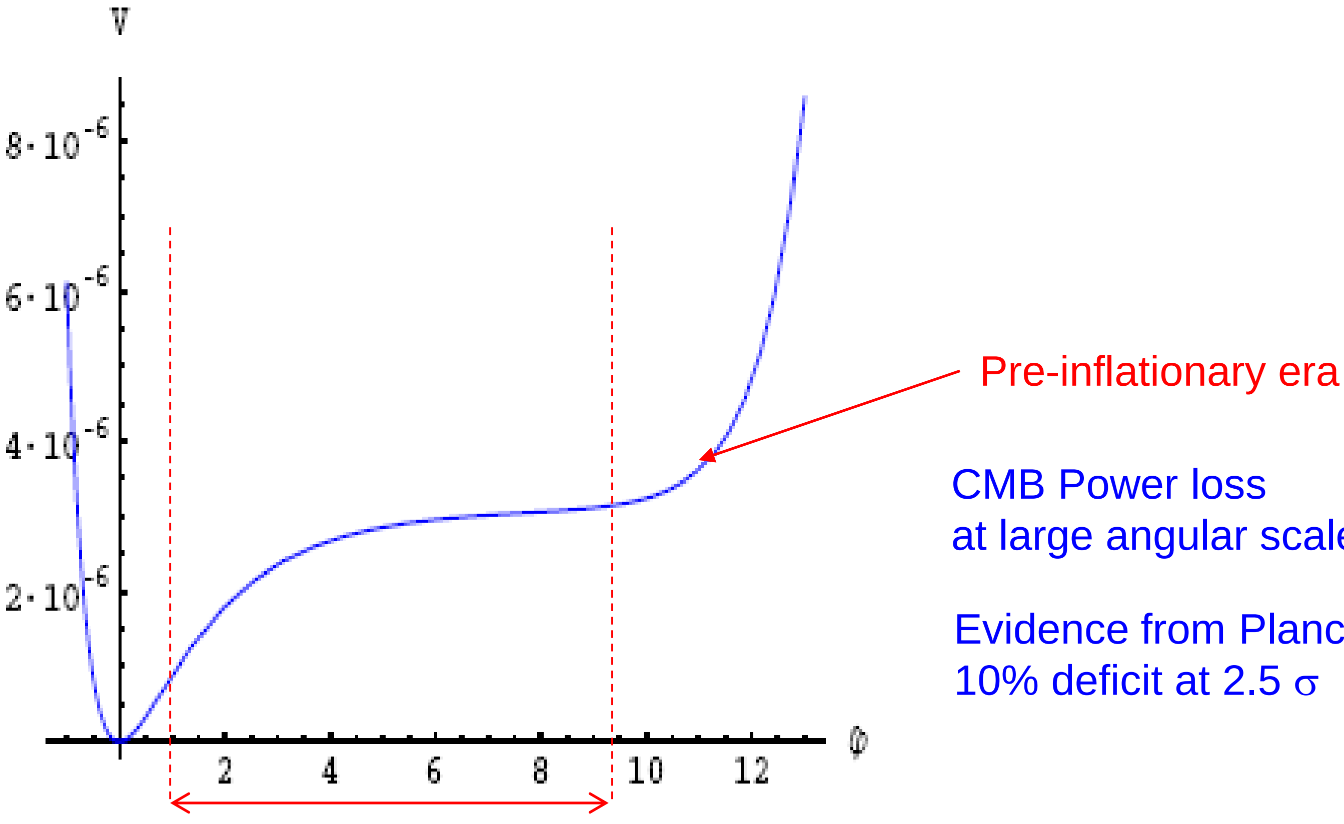
→ Potentially large non-Gaussianities!

BUT in most cases multi-field models do NOT generate large non-Gaussianities due to an effective single-field dynamics

→ partial explanation of why string inflation models describe the data so well

CMB power loss at large scales

- Typical behaviour of some string inflation models



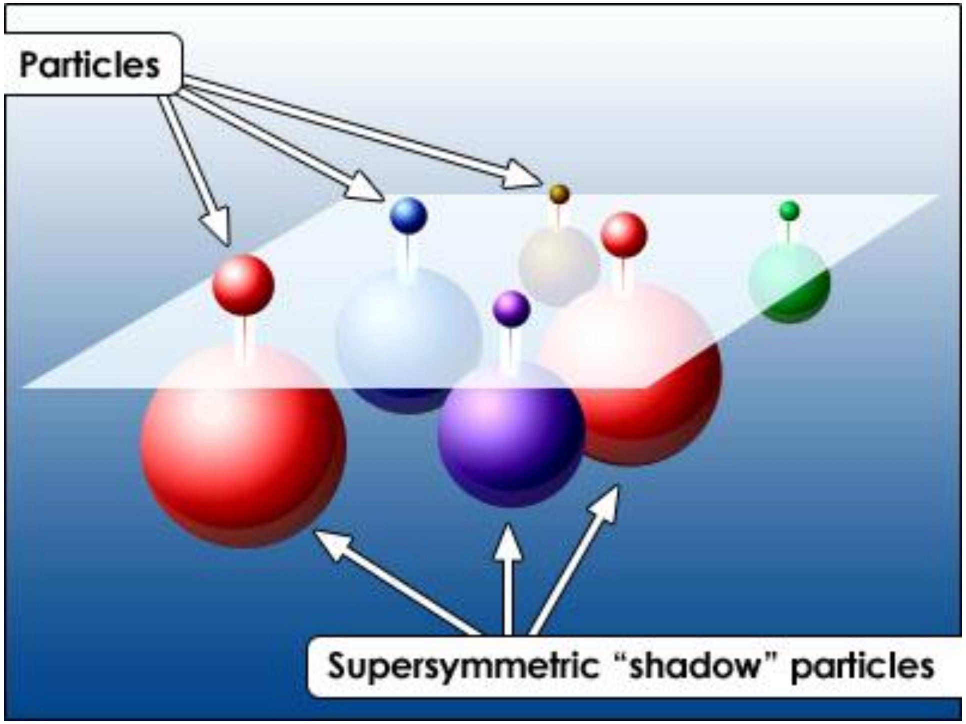
CMB Power loss
at large angular scales!

Evidence from Planck data!
10% deficit at 2.5 σ

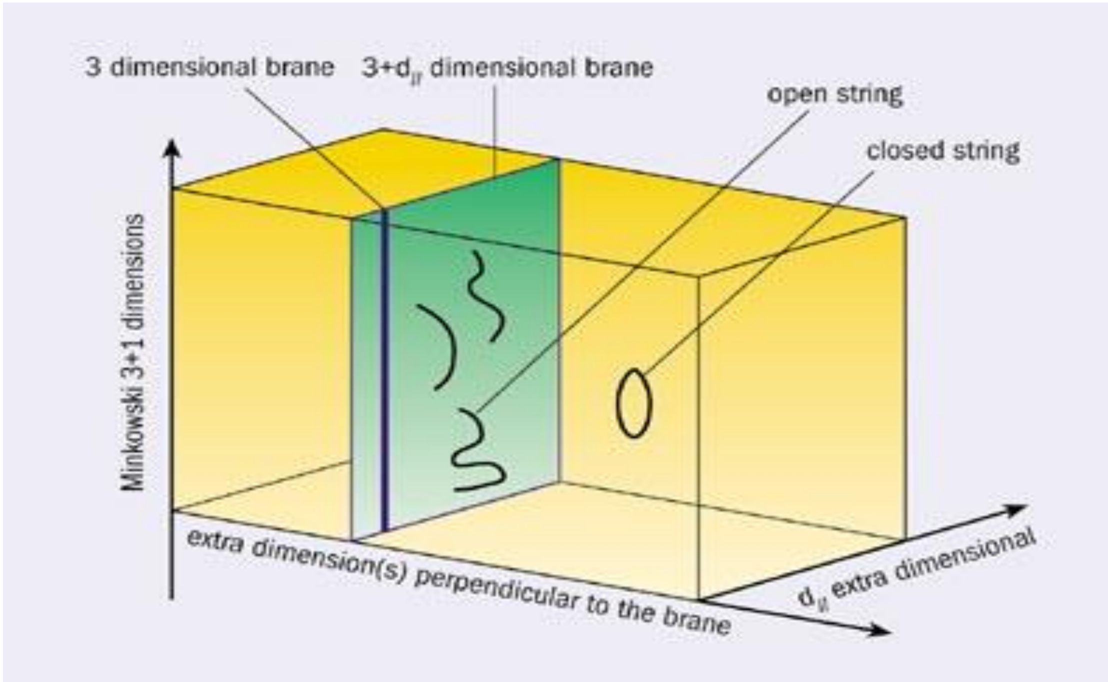
Supersymmetry and its breaking

- Supersymmetry naturally present in String theory for consistency
- Each particle as a superpartner with same mass but different spin
- Symmetry not seen in Nature → must be broken
- Supersymmetry can explain:
  i) Higgs mass around 125 GeV
  ii) Unification of non-gravitational forces
  iii) Dark matter
- Moduli dynamics breaks supersymmetry!
- Generate mass of superpartners
  via gravity interactions

→ Can make predictions for LHC!



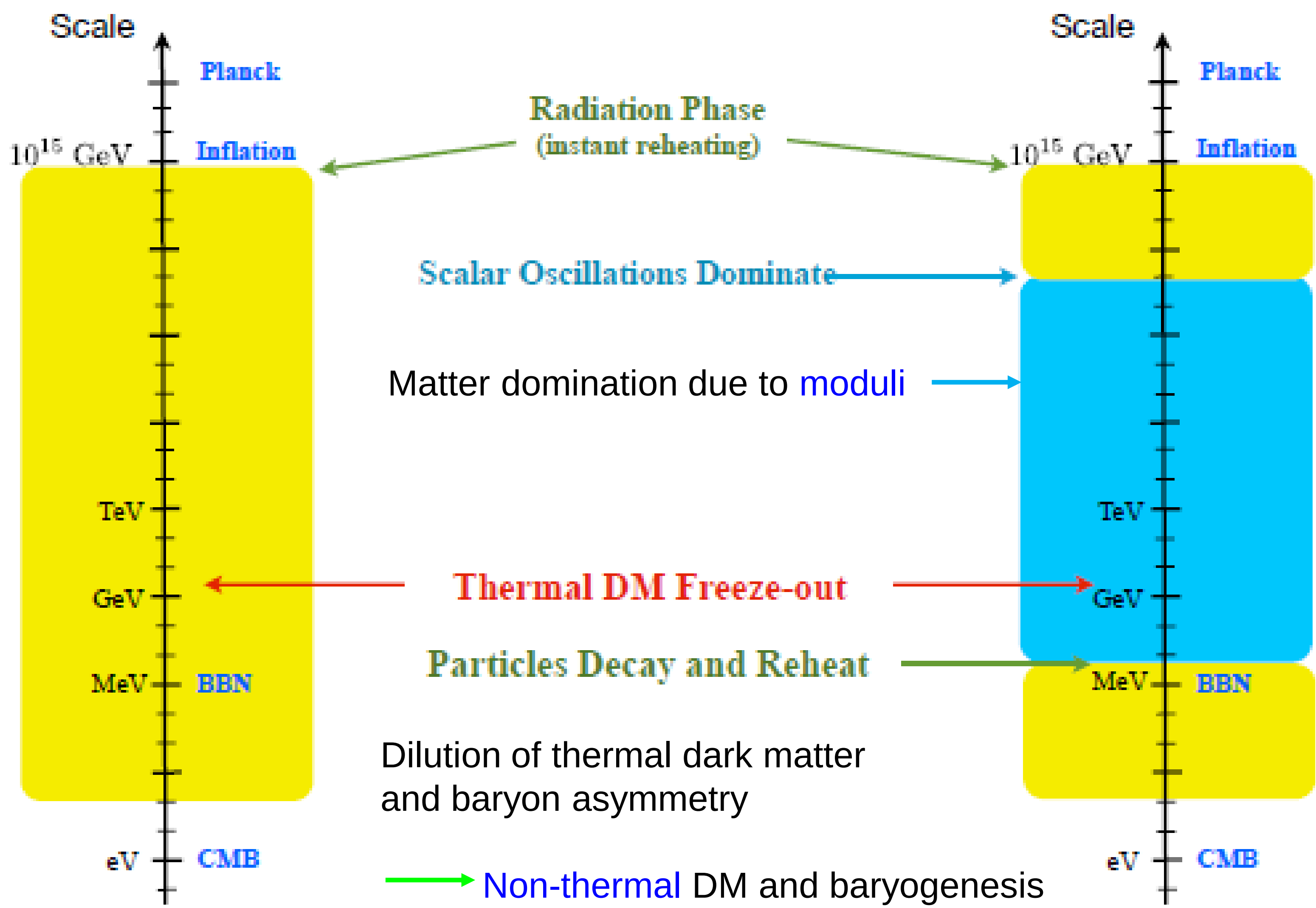
LARGE extra dimensions



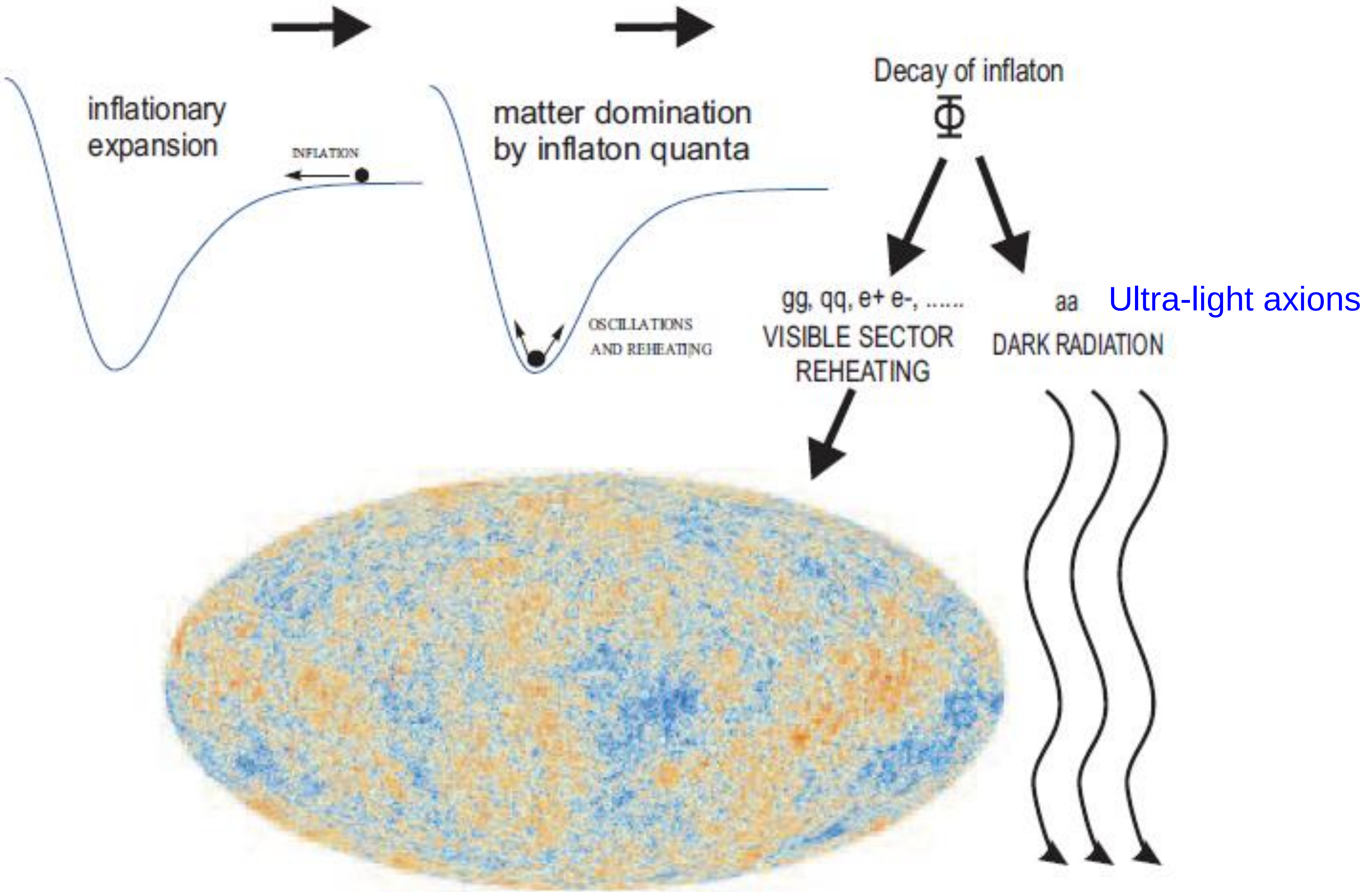
- Open strings trapped on branes whereas closed string move freely through spacetime
- All particles and fundamental interactions (except for gravity) confined on branes
- Moduli dynamics can give LARGE extra dimensions detectable via modifications of Newton's Law at micron size for 2 large EDs!
- Stringy effects might soon be detectable at the LHC due to TeV-scale strings!

Non-standard cosmology from strings

Thermal History | Alternative History



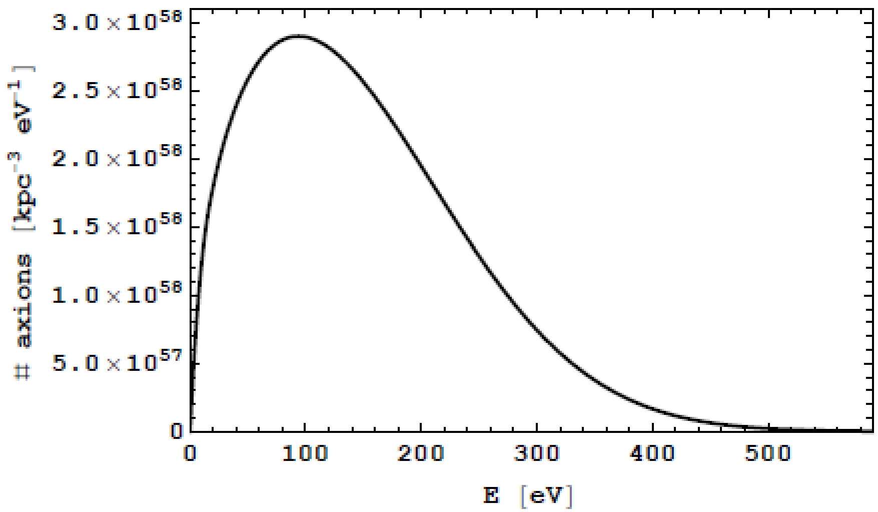
Axionic dark radiation production



Prediction: $N_{eff} > 3$

Cosmic Axion Background

PREDICTION: Cosmic Axion Background



- Energy tied to TeV-scale SUSY!
- How to discover it?
- Via axion - photon conversion in magnetic field of galaxy clusters!
- Soft X-ray excess in galaxy clusters observed since 1996 by several missions (EUVE, ROSAT, XMM-Newton, Suzaku, Chandra)
- No good astrophysical explanation
- Sign of stringy physics in the sky for 20 years?!?!

Conclusions

- String theory is a beautiful framework for quantum gravity and unification
- Hard to make a clear trustable and testable prediction
- But there is no time limit as long as progress is made
- Connection between string theory and 4D physics $\longrightarrow$ string compactifications
- Extra dimensions $\longrightarrow$ Moduli ϕ: new scalars with gravitational couplings
- Hard to get inflation with large gravity waves, large local non-Gaussianities, inflation and TeV-scale SUSY, N_{eff} =3….
- Moduli can break SUSY and generate masses of SUSY particles testable at the LHC
- Can have LARGE EDs, modifications of Newton's Law at micron size and TeV-scale strings
- Typical features of string compactifications: light moduli, Non-standard cosmology: CMB power loss at large scales, Non-thermal dark matter, axionic dark radiation, Cosmic axion background detectable via axion-photon conversion in B, soft X-ray excess in galaxy clusters
- Other stringy features: Extra Z', hidden photons, millicharged particles…….

Hopefully in the future we will reach our Goal!