

**An
Unoriented
Trip
to the Edge of
String Theory**

Bert Schellekens
NIKHEF

**String
Theory**

**Super
Symmetry**

**Modular
Invariance**

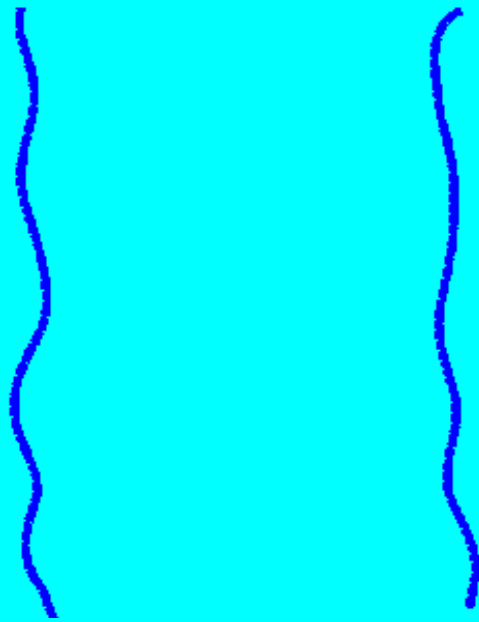


**String
Theory**

**Super
Symmetry**

**Modular
Invariance**

String Theory is a Theory of Gravity

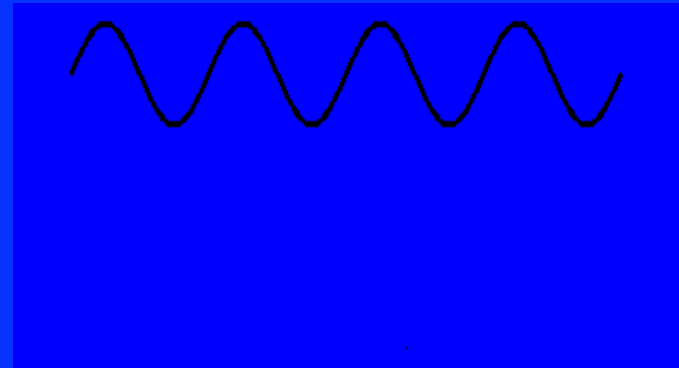
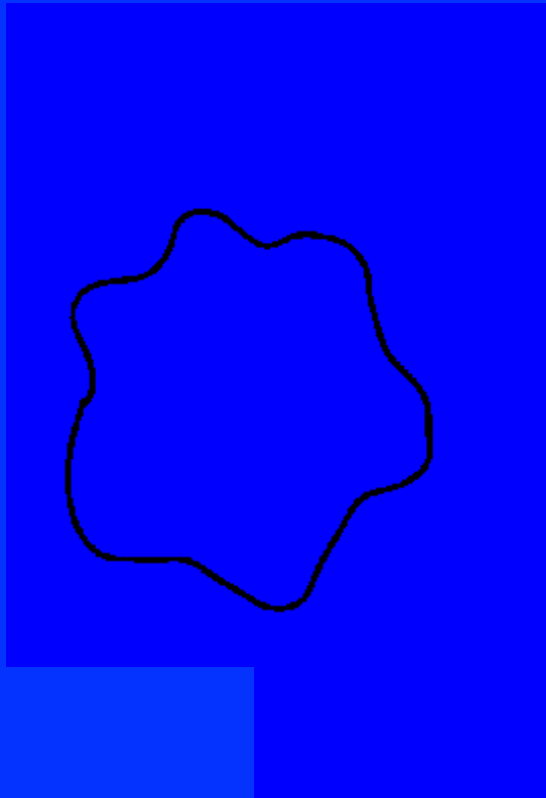


The Crux of the Matter

- General Relativity couples to any Matter
- String Gravity only couples to String Matter

→ Everything must be made of strings!

The String Spectrum



Quantized oscillations must produce all particles

String tension determines:

- Strength of gravity
- Mass of excitations

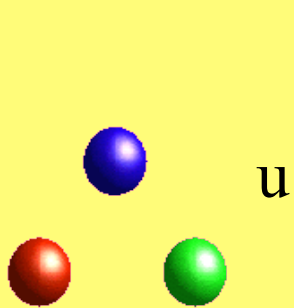
Dimensional analysis:

Excitations separated by $\approx \Delta m = \sqrt{\frac{\hbar c}{G_N}}$

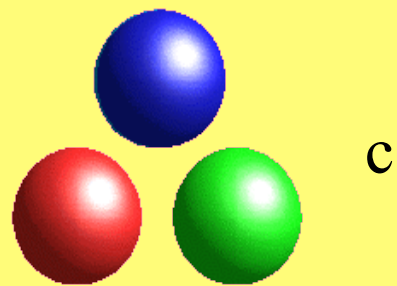
\equiv The Planck mass: 1.22×10^{19} GeV

The Spectrum

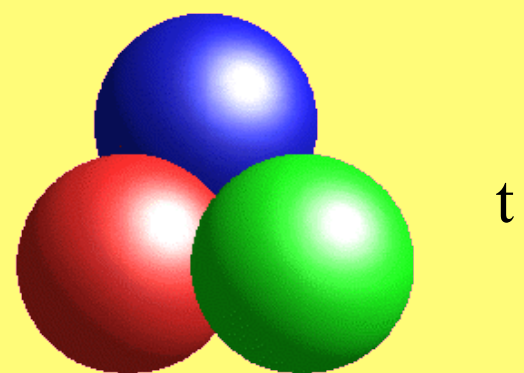
- An infinite number of massive excitations (unobservable)
- All observable particles are “massless” modes
- Degeneracy due to “extra dimensions”



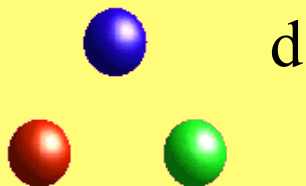
u



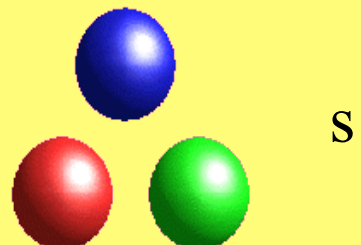
c



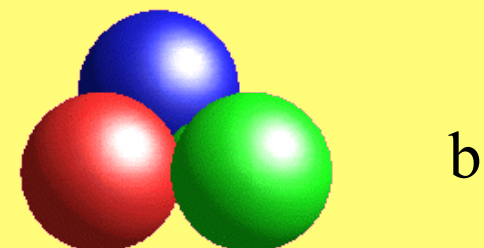
t



d



s



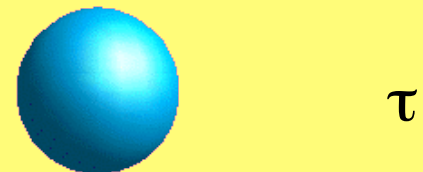
b



e



μ



τ



ν_e



ν_μ



ν_τ

Bosons

- Photon
- W^+ , W^- , Z
- Gluons



Vector Bosons
(\rightarrow interactions)

- Higgs

Scalar boson
(\rightarrow particle masses)

	Standard Model		
Consistency			
Experiment			
Naturalness			
Beauty			

	Standard Model		
Consistency	✓		
Experiment	✓		
Naturalness	✗		
Beauty	✗		

	Standard Model	Quantum Gravity	
Consistency	✓	✗	
Experiment	✓	✓	
Naturalness	✗	✗	
Beauty	✗	✓	

The background of the slide is a Cosmic Microwave Background (CMB) fluctuation map. It shows a complex pattern of temperature variations across the sky, represented by a color scale from blue (cooler) to red (warmer). The map is filled with small-scale fluctuations and larger-scale structures, with some prominent features like the 'CMB dipole' and 'quadrupole' visible. The text is overlaid on this map.

Message from the Cosmos:

- **Dark Mass (up to 90%)**
- **Dark Energy**

	Standard Model	Quantum Gravity	Cosmology
Consistency	✓	✗	
Experiment	✓	✓	✗
Naturalness	✗	✗	
Beauty	✗	✓	

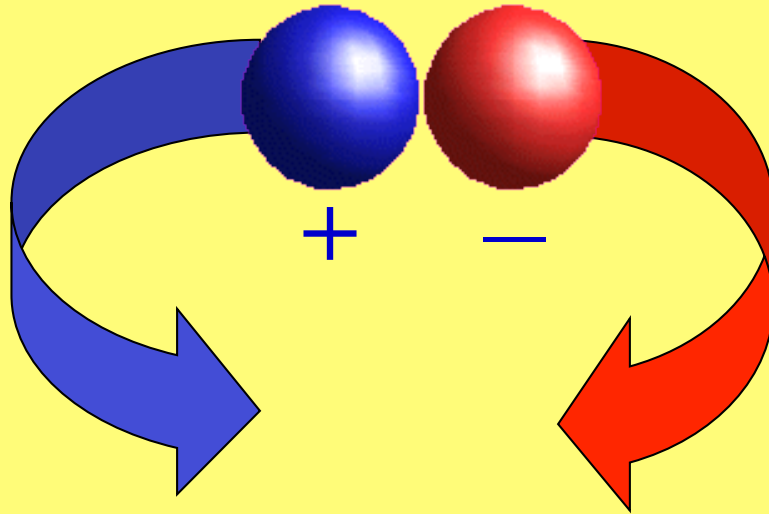
String Score Card

- Quantum Gravity ✓ ?
- Gauge Symmetry ✓
- Family Replication ✓
- Family Structure ✓ ?
- Dark Matter ✓ ?
- Dark Energy ✗ ?
- Supersymmetry Breaking ✗ ?
- Higgs Mechanism ✗ ?
- Particle Masses ?
- Naturalness ✗
- Beauty ✓ ✓ ?

Problems of Quantum Gravity

- Non-renormalizable
- Black hole information
- Matters of principle

Renormalizability



Leads to "divergent" integrals:

$$\int \frac{d^4p}{(p^2+m^2)^2}$$

Renormalizability (2)

Infinite number of infinities



Infinite number of parameters

Renormalizable:

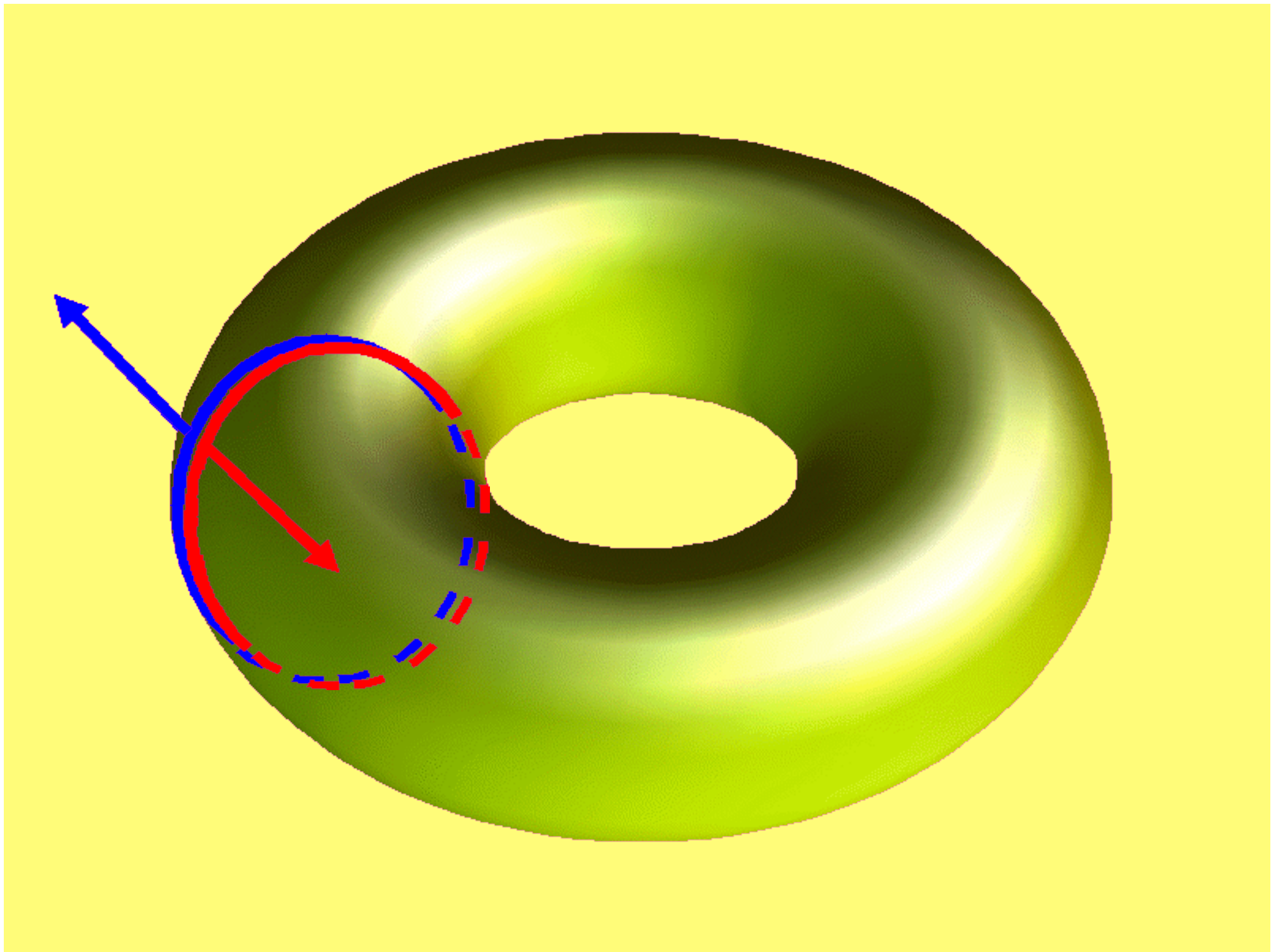
FINITE number of linear combinations

String Theory:
Infinite number of particles

Expect triple infinity:

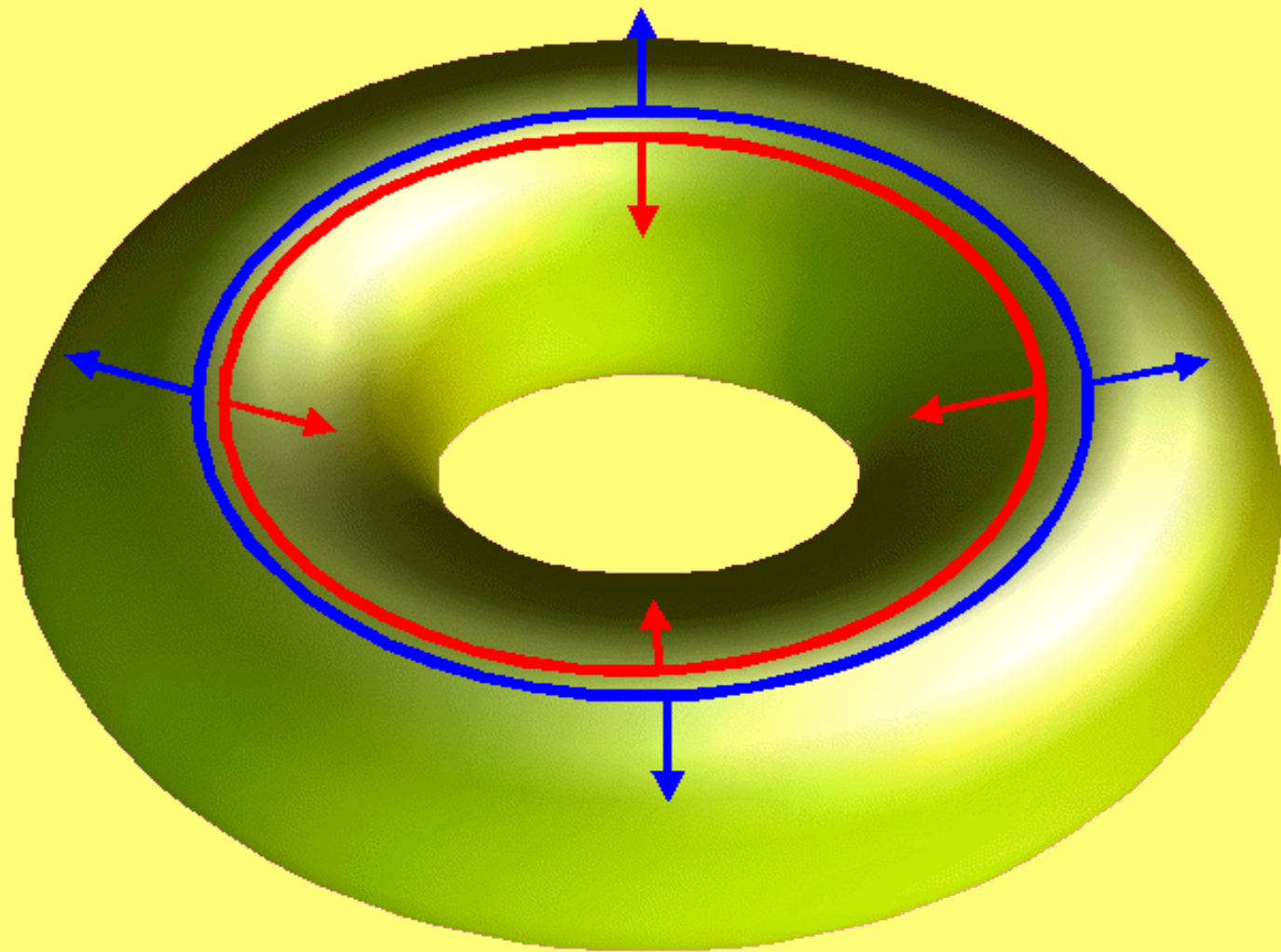
- Number of amplitudes
- Momentum integrals
- Number of particle types

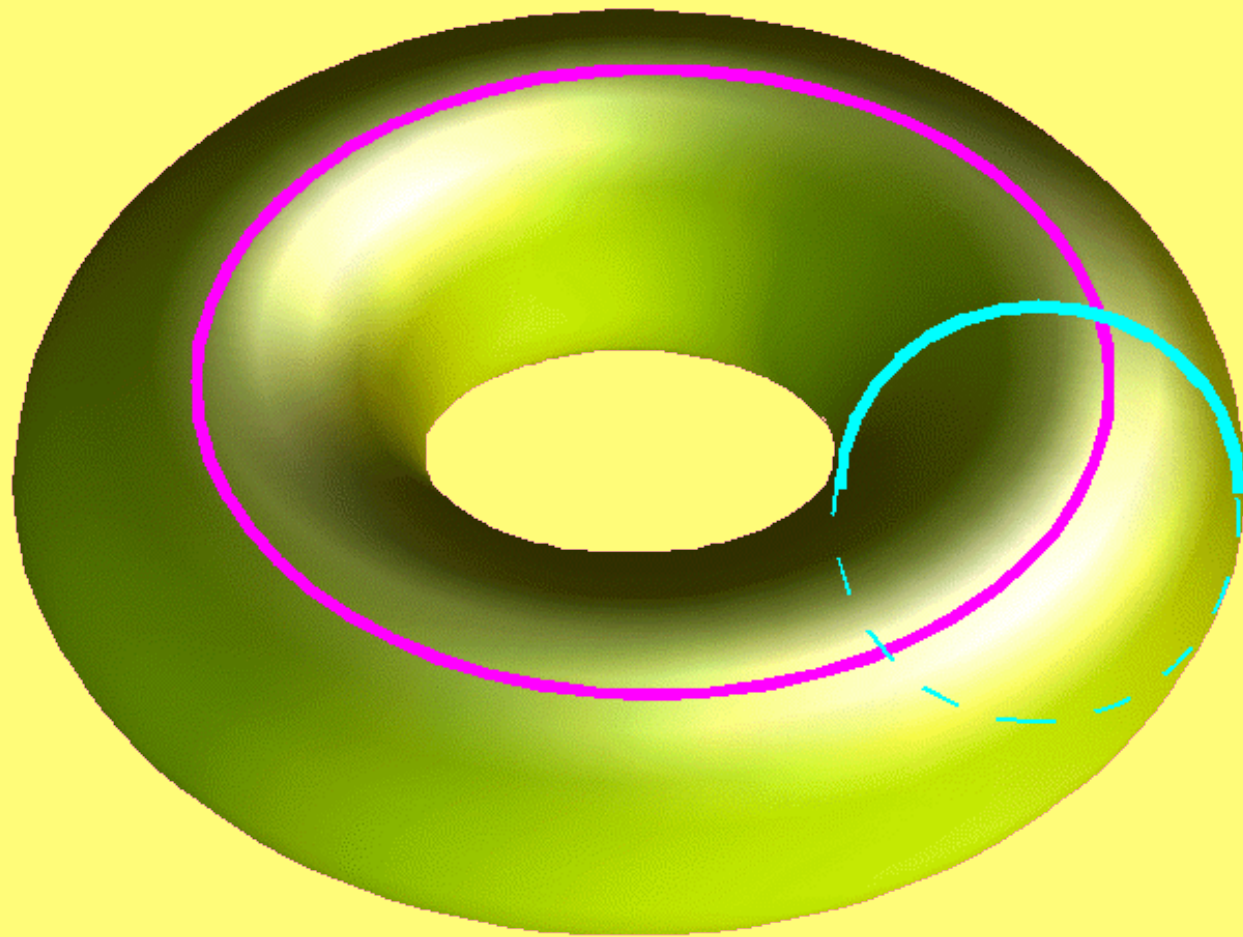
But: the result is finite and calculable

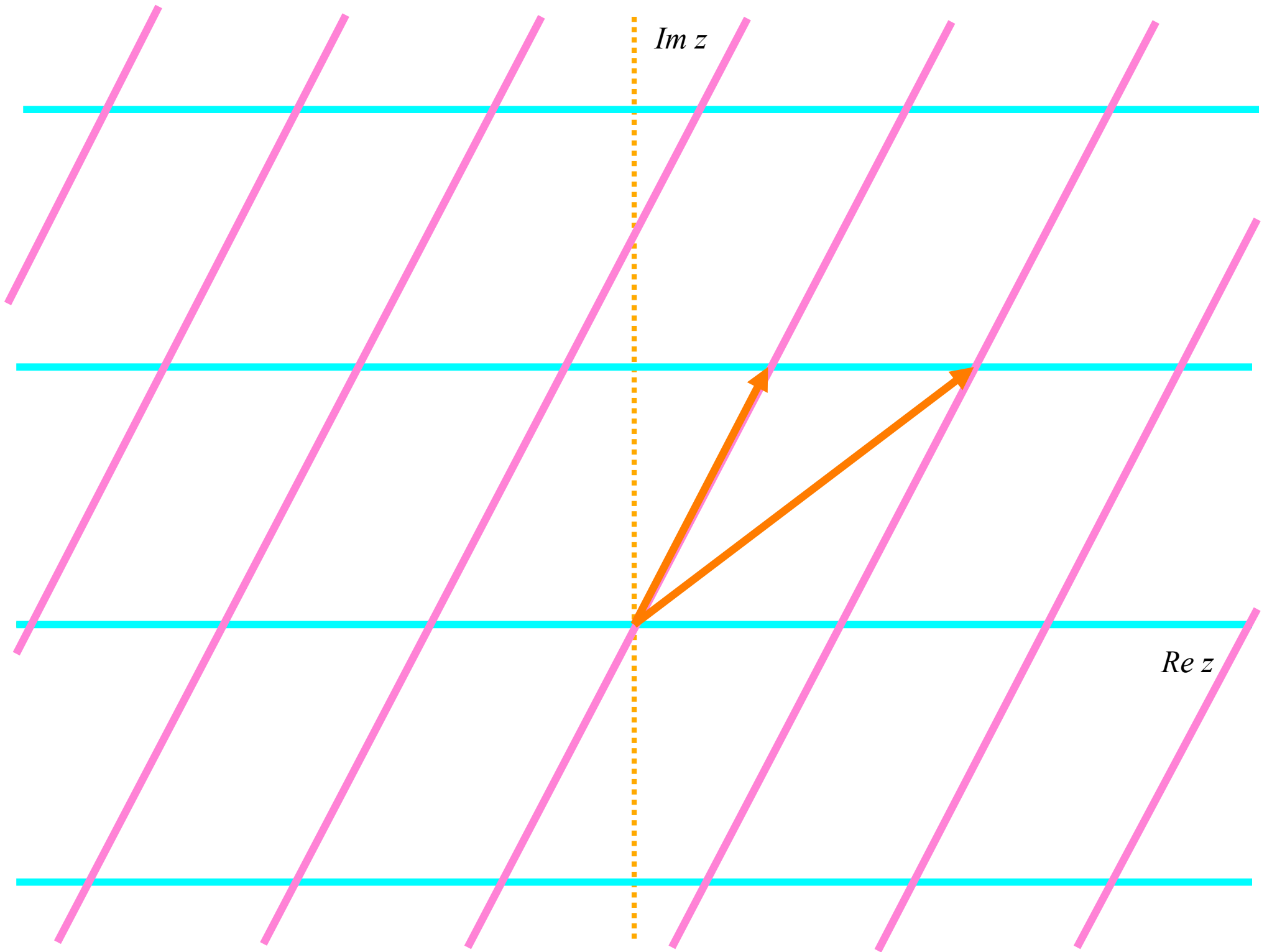


A World Sheet



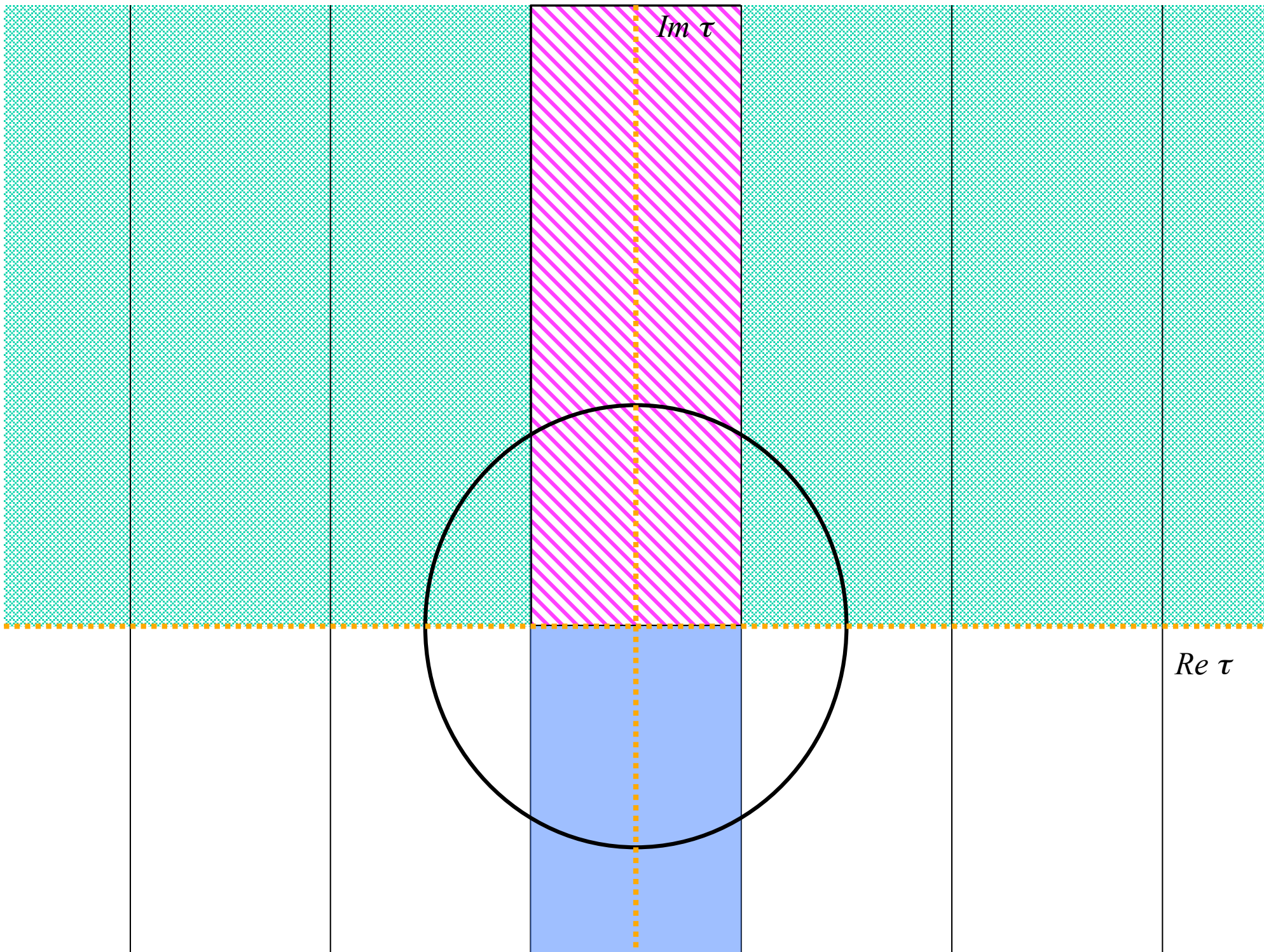






$Im \tau$

$Re \tau$

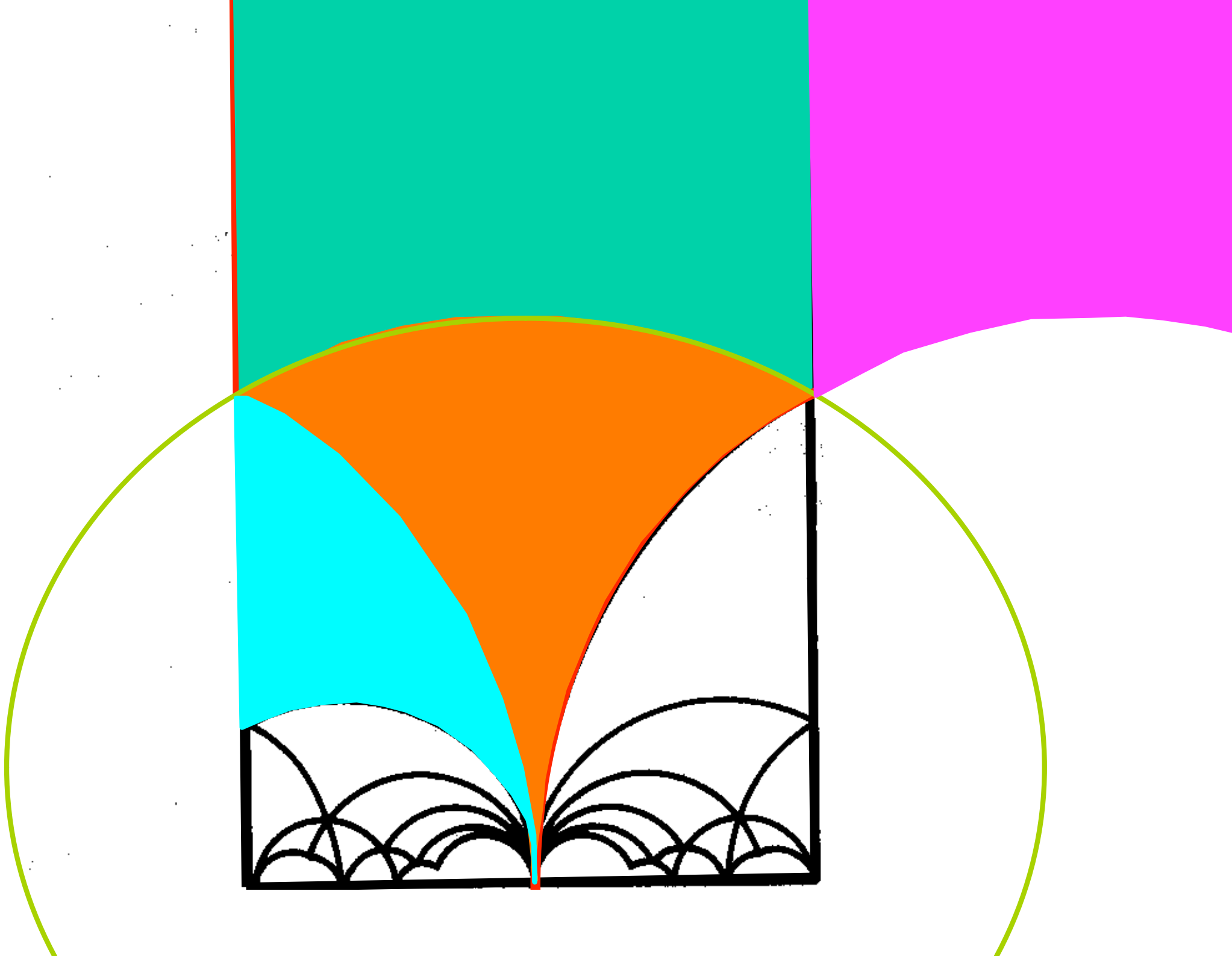


The Integral

(Re τ ignored)

$$\int \frac{d^2\tau}{(\text{Im } \tau)^{D/2+1}} \text{Tr } e^{-\text{Im } \tau H}$$

Diverges for $\text{Im}\tau \rightarrow 0$





Footnote



Supersymmetry still needed for

- Absence of tachyons
- Absence of tadpoles

Modular Invariance

Partition Function

$$\text{Tr } e^{[-\text{Im } \tau H]} \quad (\dots)$$

Must be invariant under:

$$\left. \begin{array}{l} \tau \rightarrow -\frac{1}{\tau} \\ \tau \rightarrow \tau + 1 \end{array} \right\}$$

$$\tau \rightarrow \frac{a\tau + b}{c\tau + d}$$

$$(a, b, c, d \in \mathbb{Z}; \quad ad - bc = 1)$$

Modular Invariance

→ restricts the spectrum

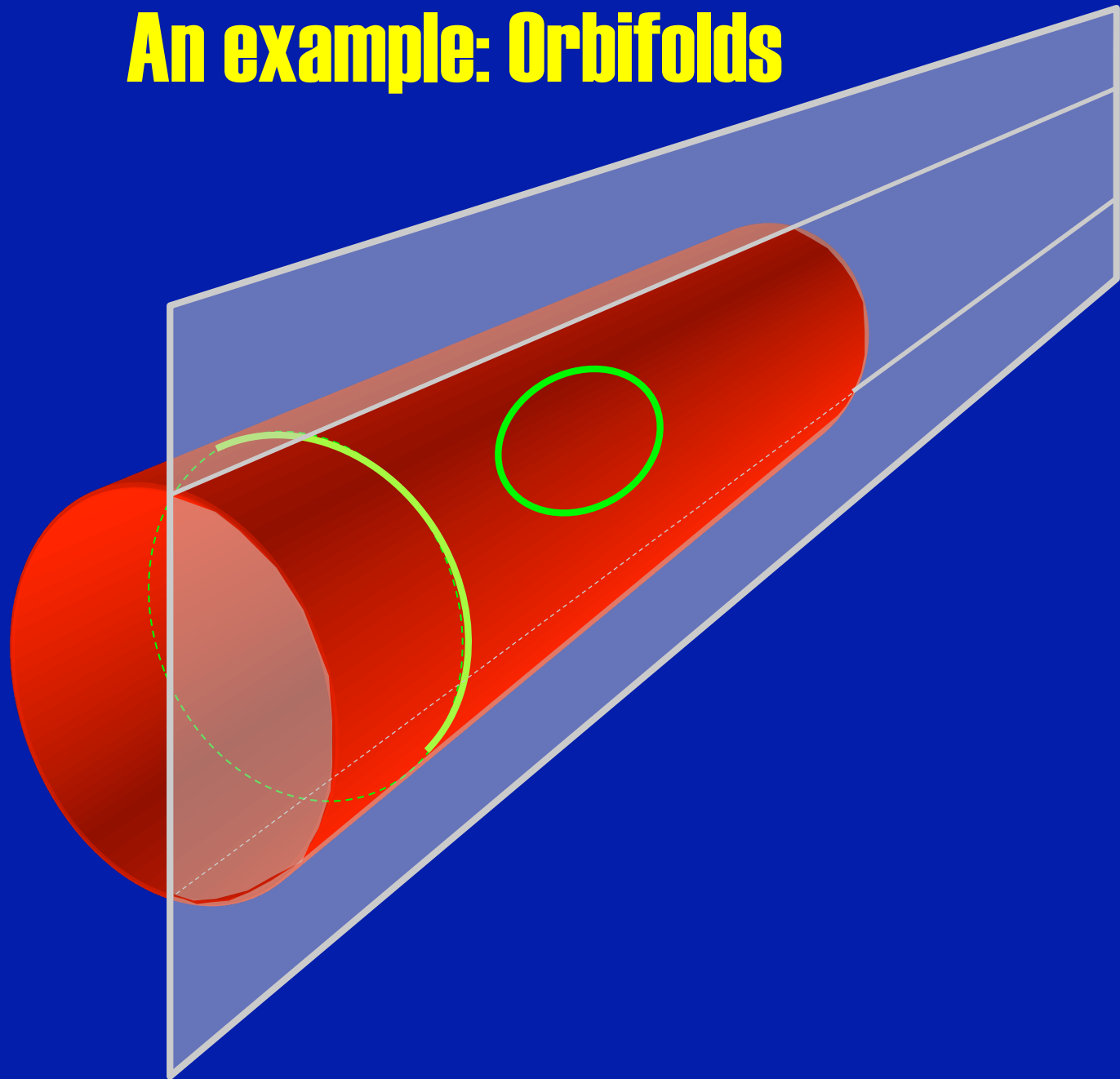
- Check
(if you know what you are doing)
- Constraint
(if you don't know what you are doing)

Modular Invariance

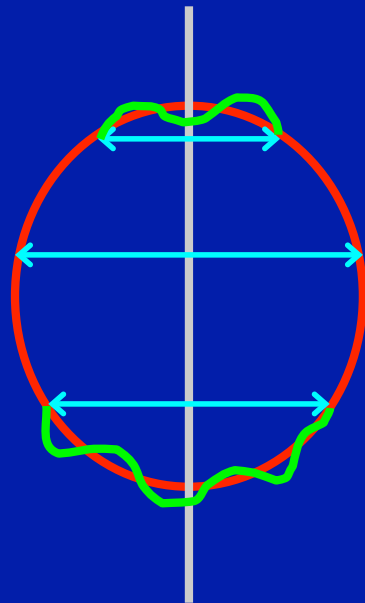
Restrictions on the spectrum:

- Nothing can be removed
- Nothing can be added
- But states can be replaced by others

An example: Orbifolds



An example: Orbifolds

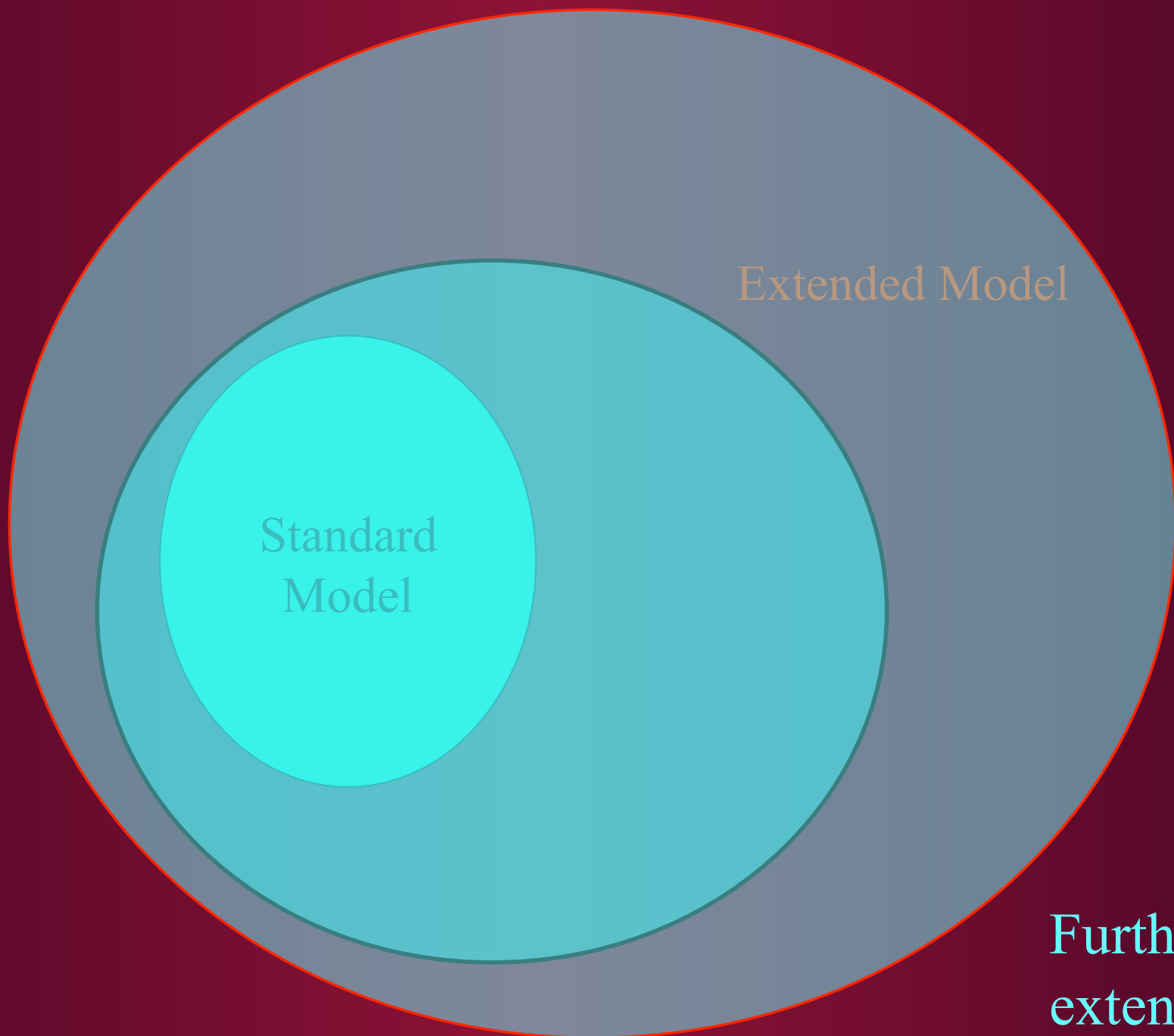


Even modes

~~Odd modes~~

Identification

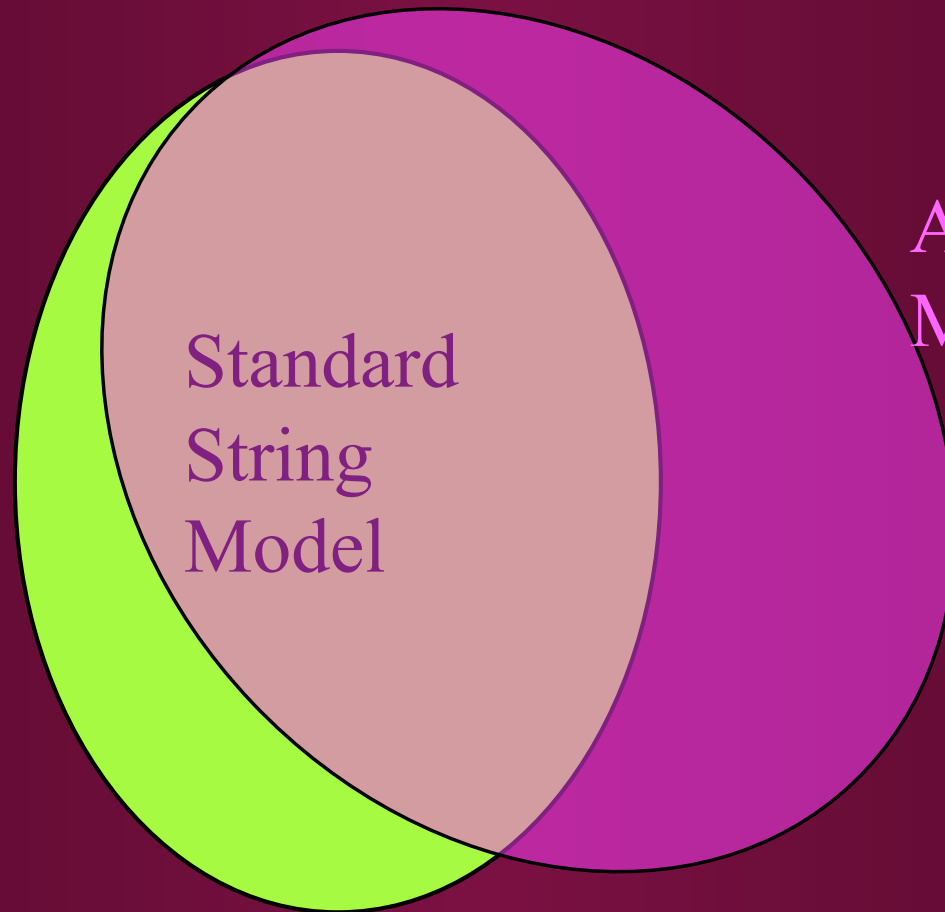
Instead of odd modes:
“Twisted states”



Standard
Model

Extended Model

Further
extension



Standard
String
Model

Alternative
Model

Another example: Charge Quantization

All free particles have integral charges

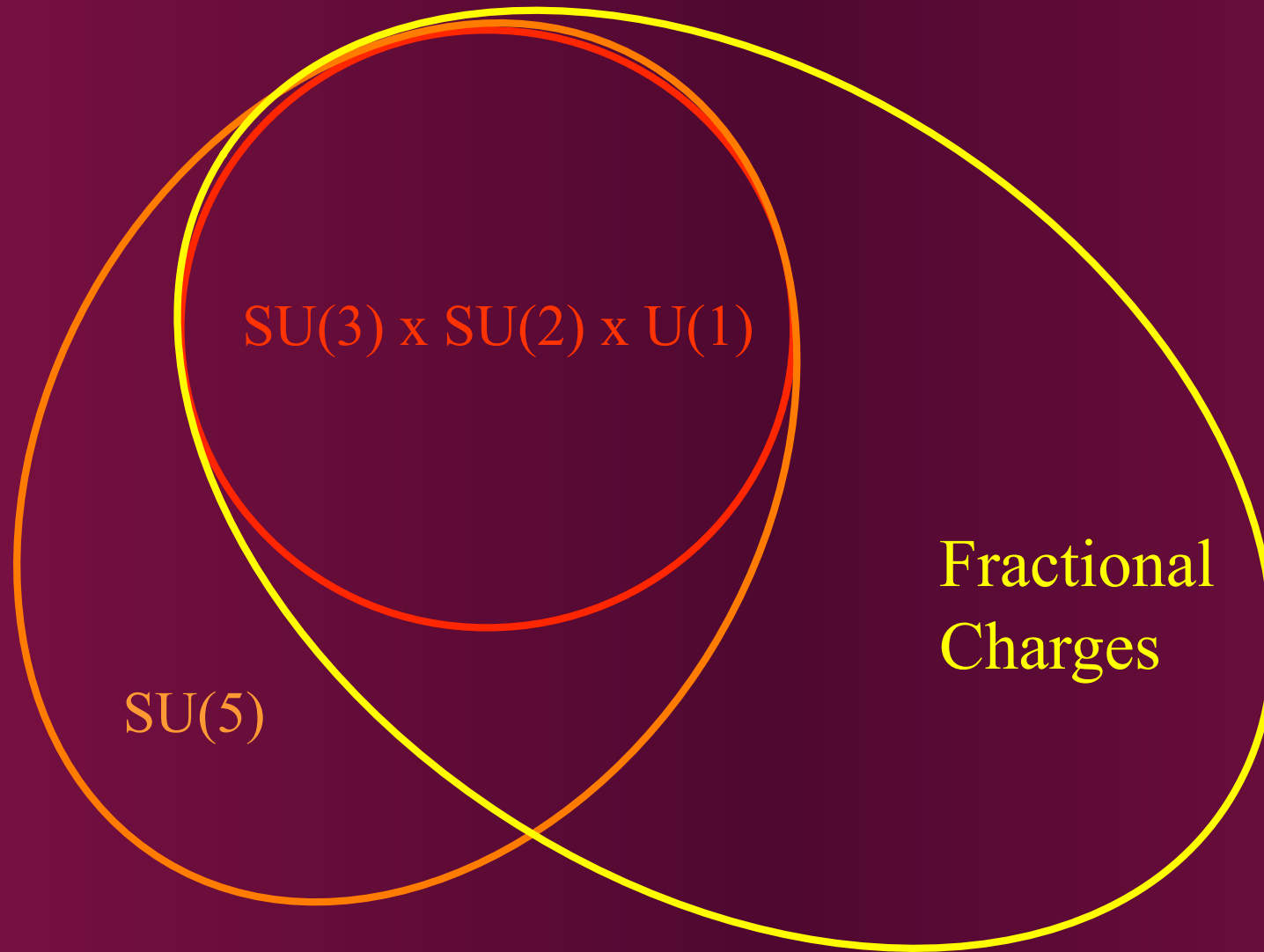
(in units of electron charge)

Standard model gives no explanation

But an extension of the standard model would explain it
("Grand Unification")

$$SU(3) \times SU(2) \times U(1) \subset SU(5)$$

Another example: Charge Quantization



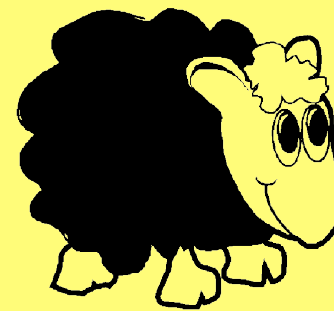
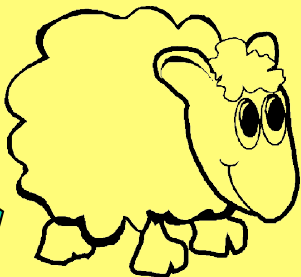
String Zoology

U-Duality used in Dualities Strings

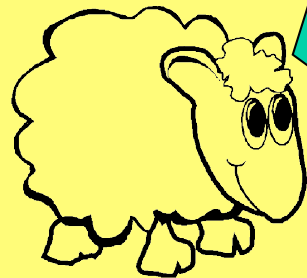
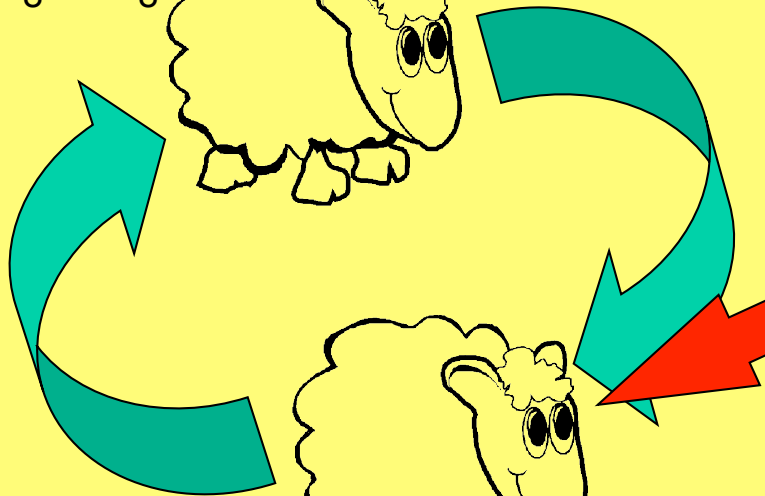


D=11
Supergravity
("M-theory")

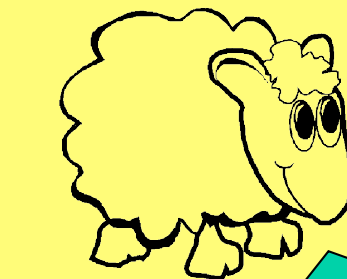
Heterotic
 $E_8 \times E_8$



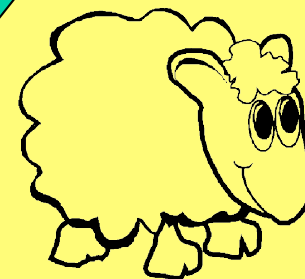
Type I



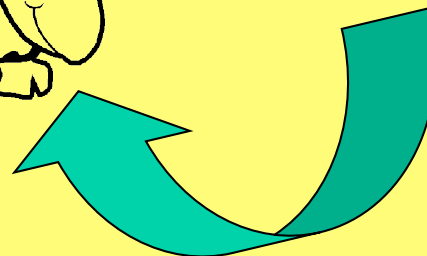
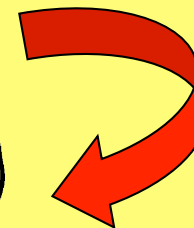
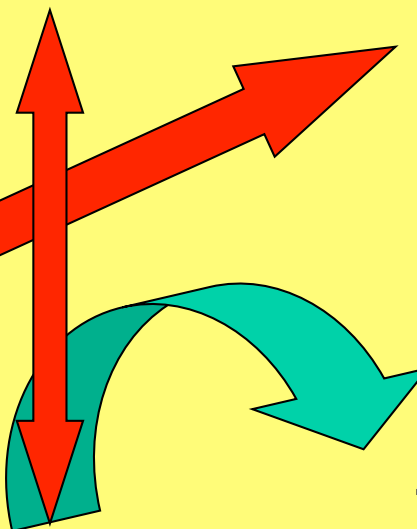
Heterotic
SO(32)



Type IIA



Type IIB

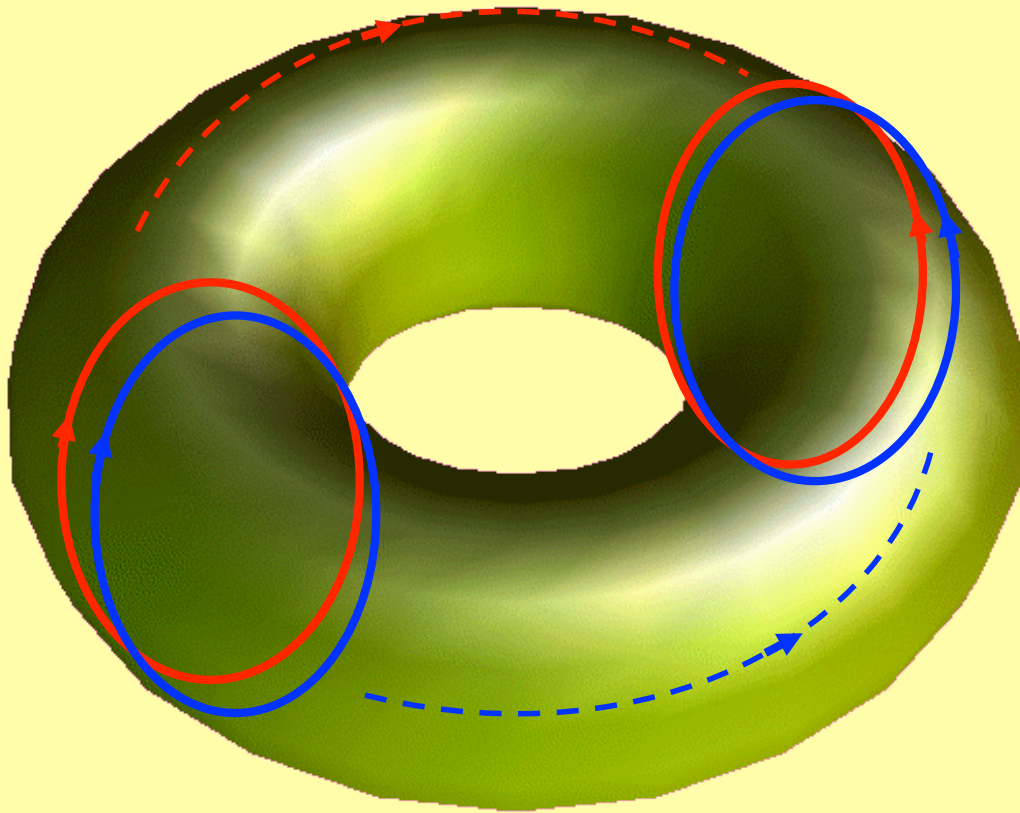


Good News and Bad News

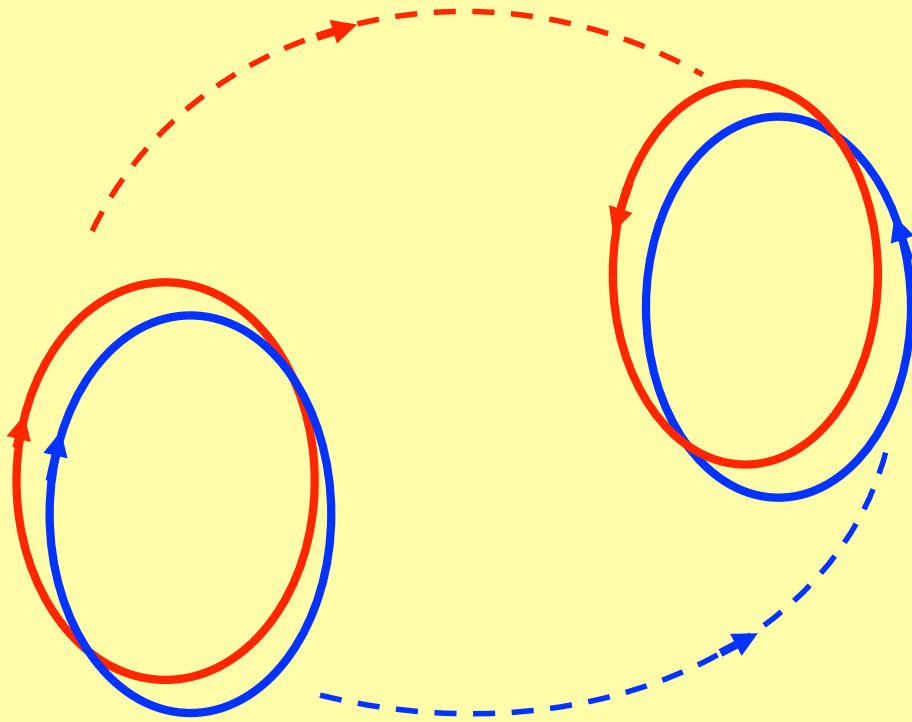
- String Theory is Unique
(but ground state is not)
- String Theory is Dead
(as a fundamental principle of nature)

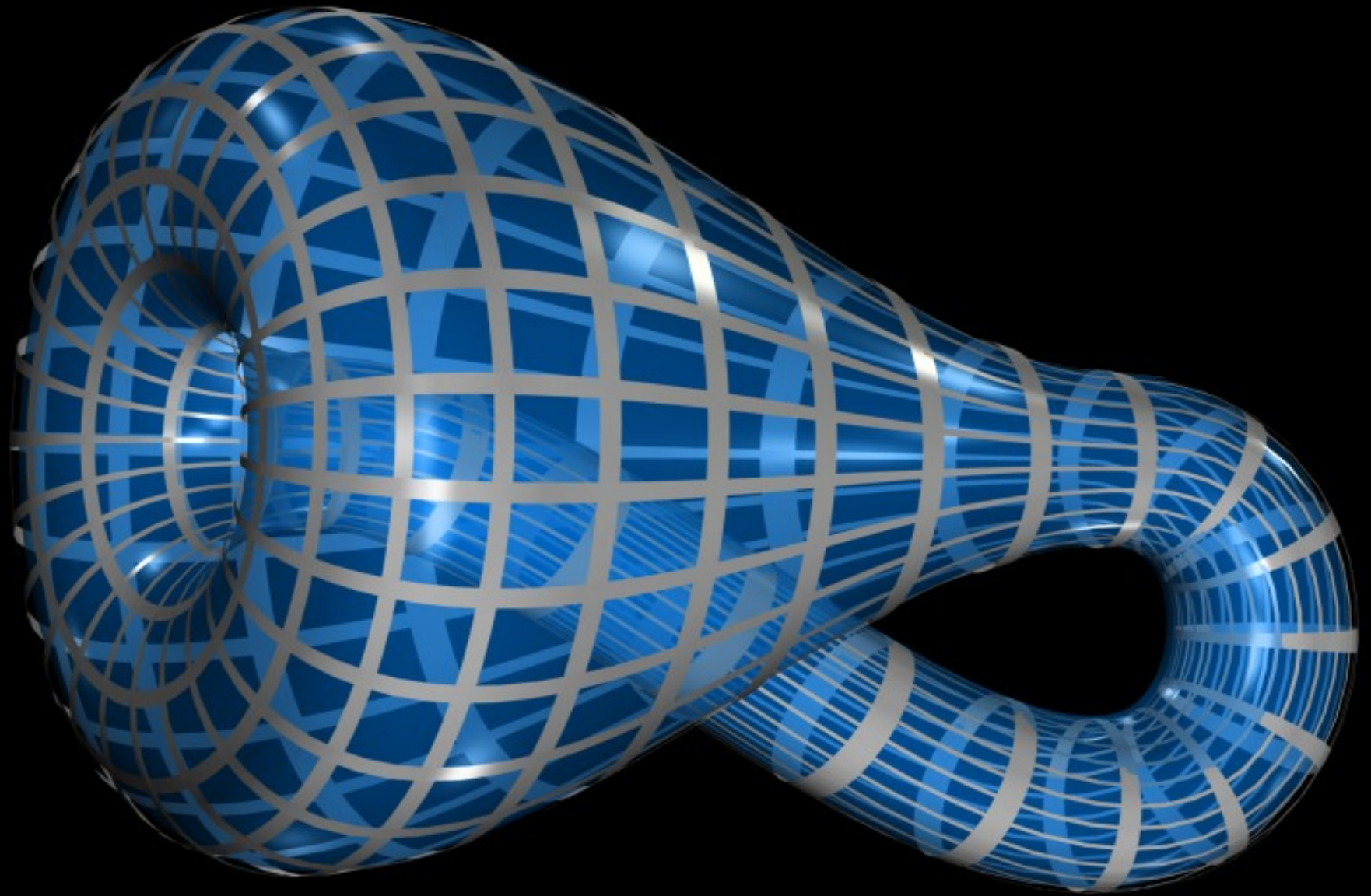


Oriented Strings

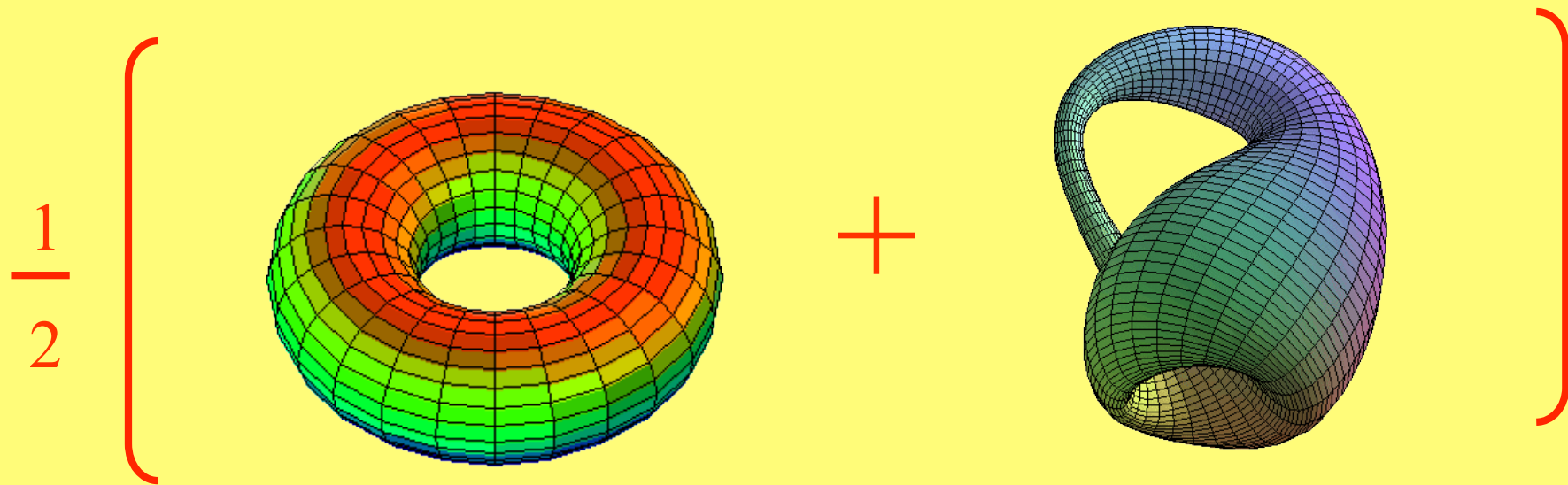


Unoriented Strings



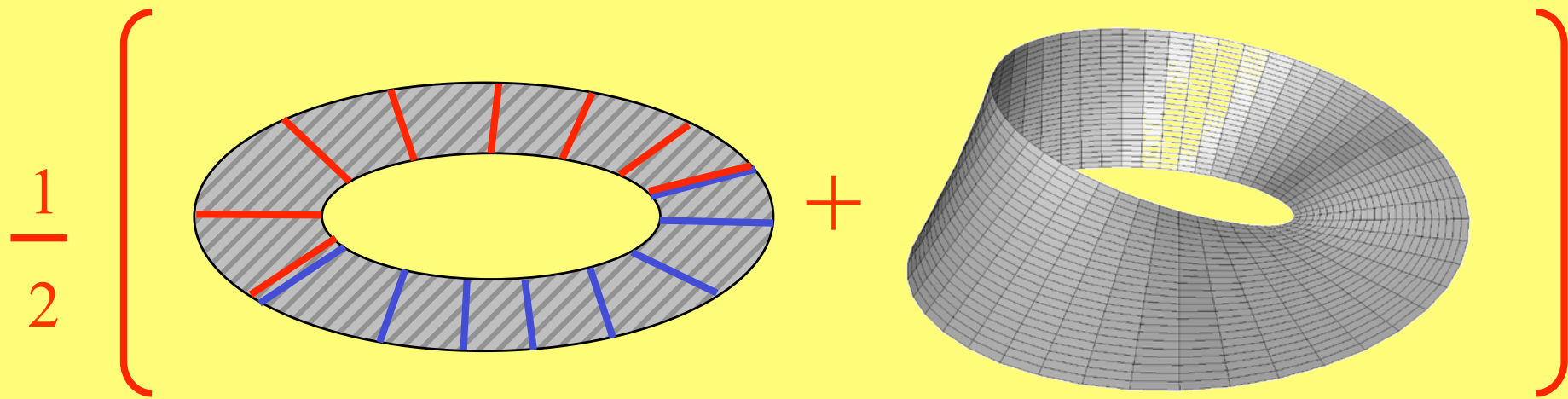


Closed String Partition Function



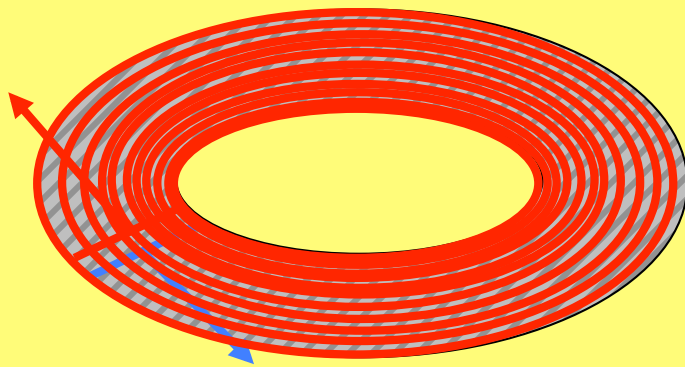
Destructive interference: spectrum truncated

Open String Partition Function

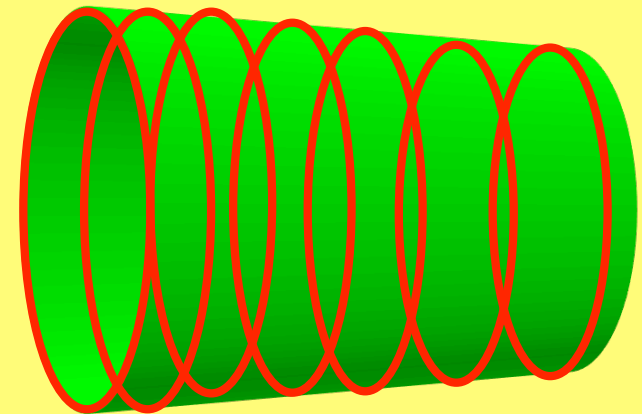


Finiteness ?

Direct Channel



Transverse Channel

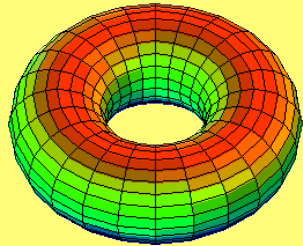


Two distinct process: no double counting

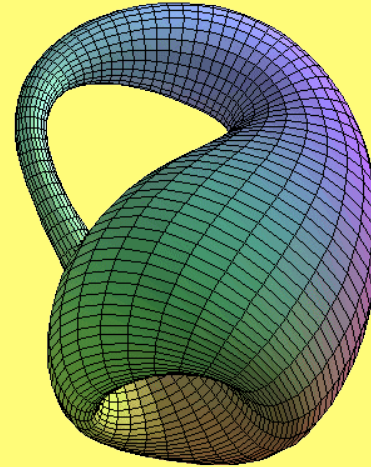
→ Field theory divergence not removed!

**A German topologist named Klein
Thought the Moebius Loop was divine
Said he, "If you glue
The edges of two
You get a weird bottle like mine."**

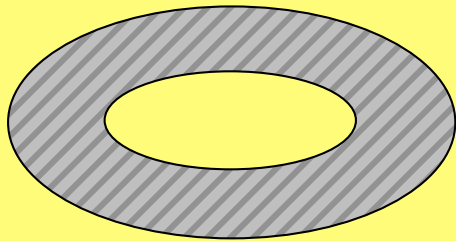
Tadpole Cancellation



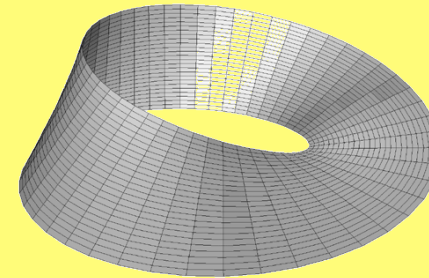
+



+ N^2



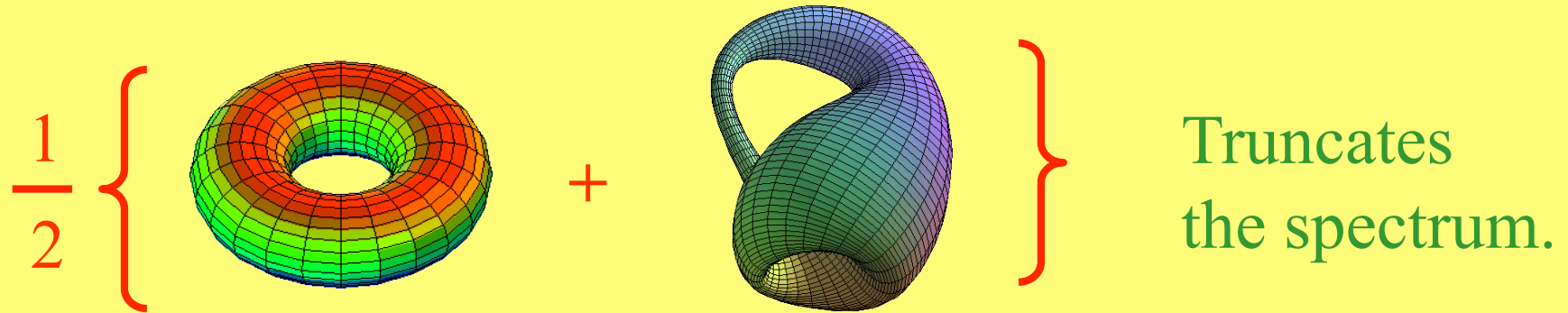
+ N



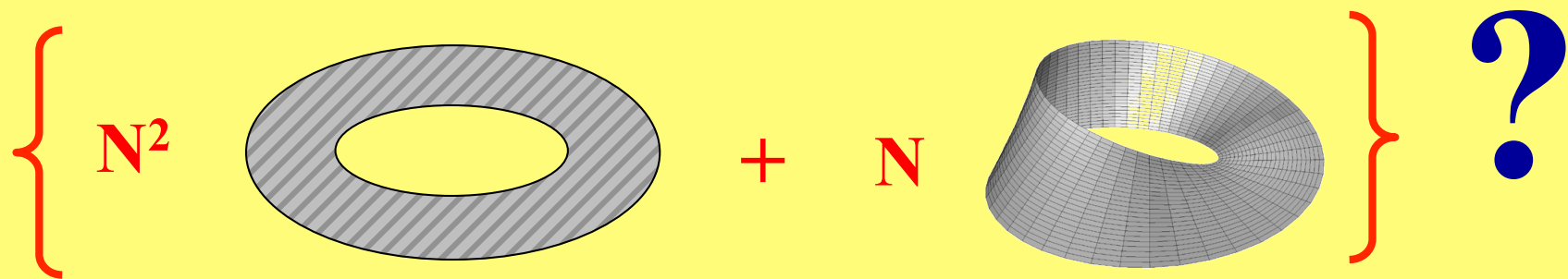
= **FINITE**

→ Equation for N (linear)

Completeness ?



“Twisted states”



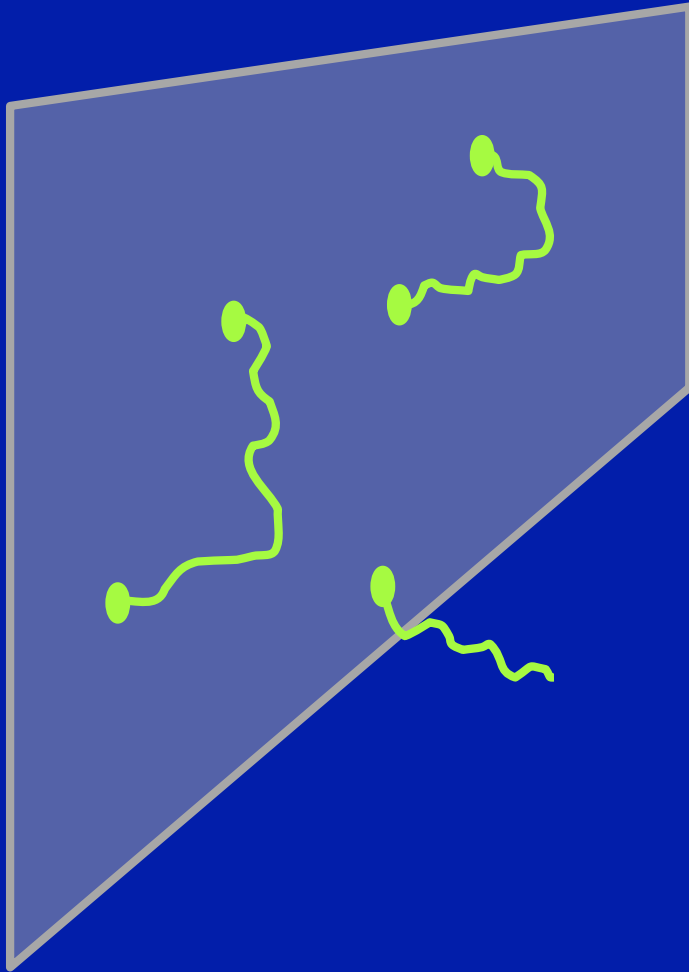
NO !

There are examples with $N=0$

But, there's more....

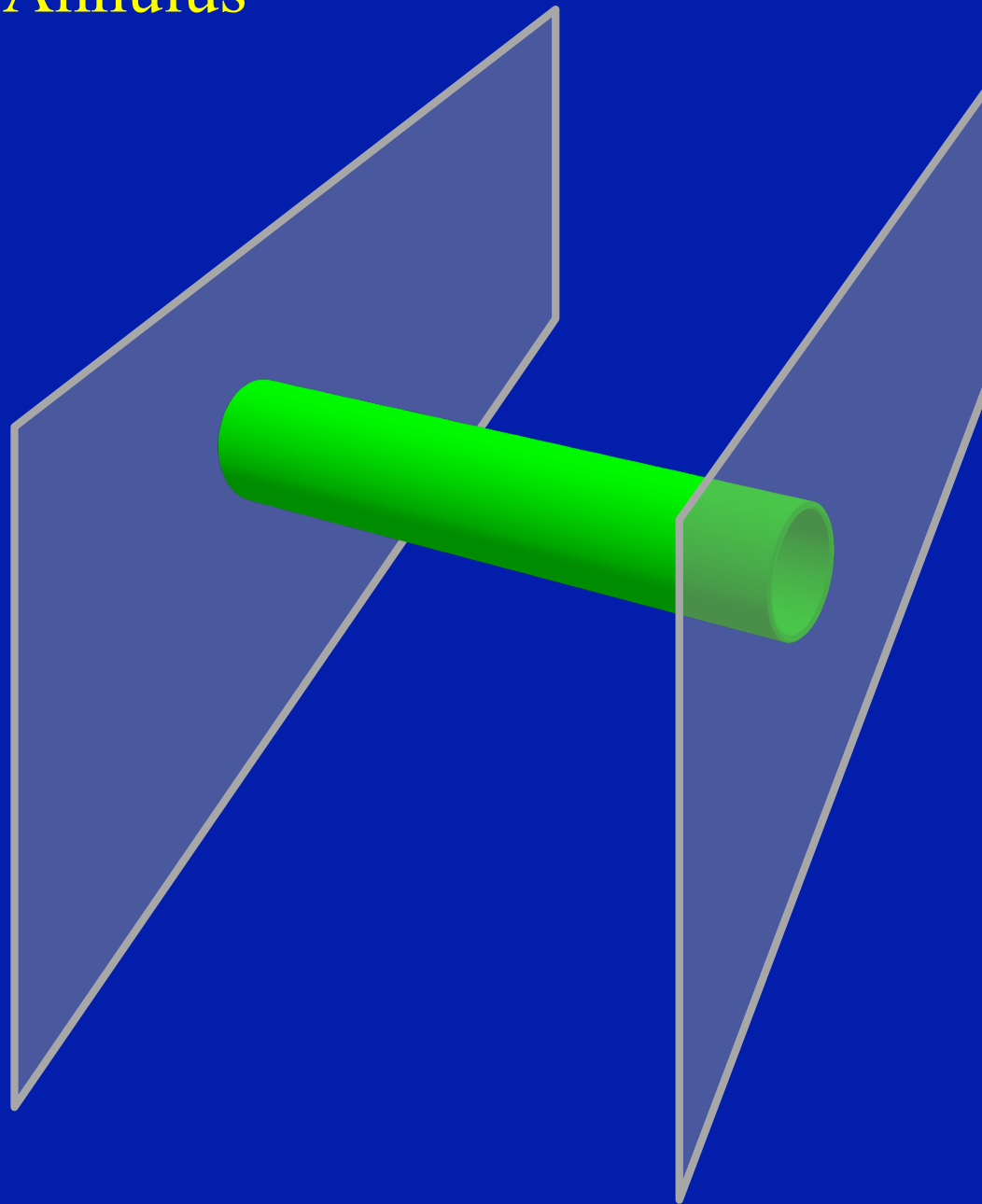
D-Branes

Open strings ending on lower-dimensional plane

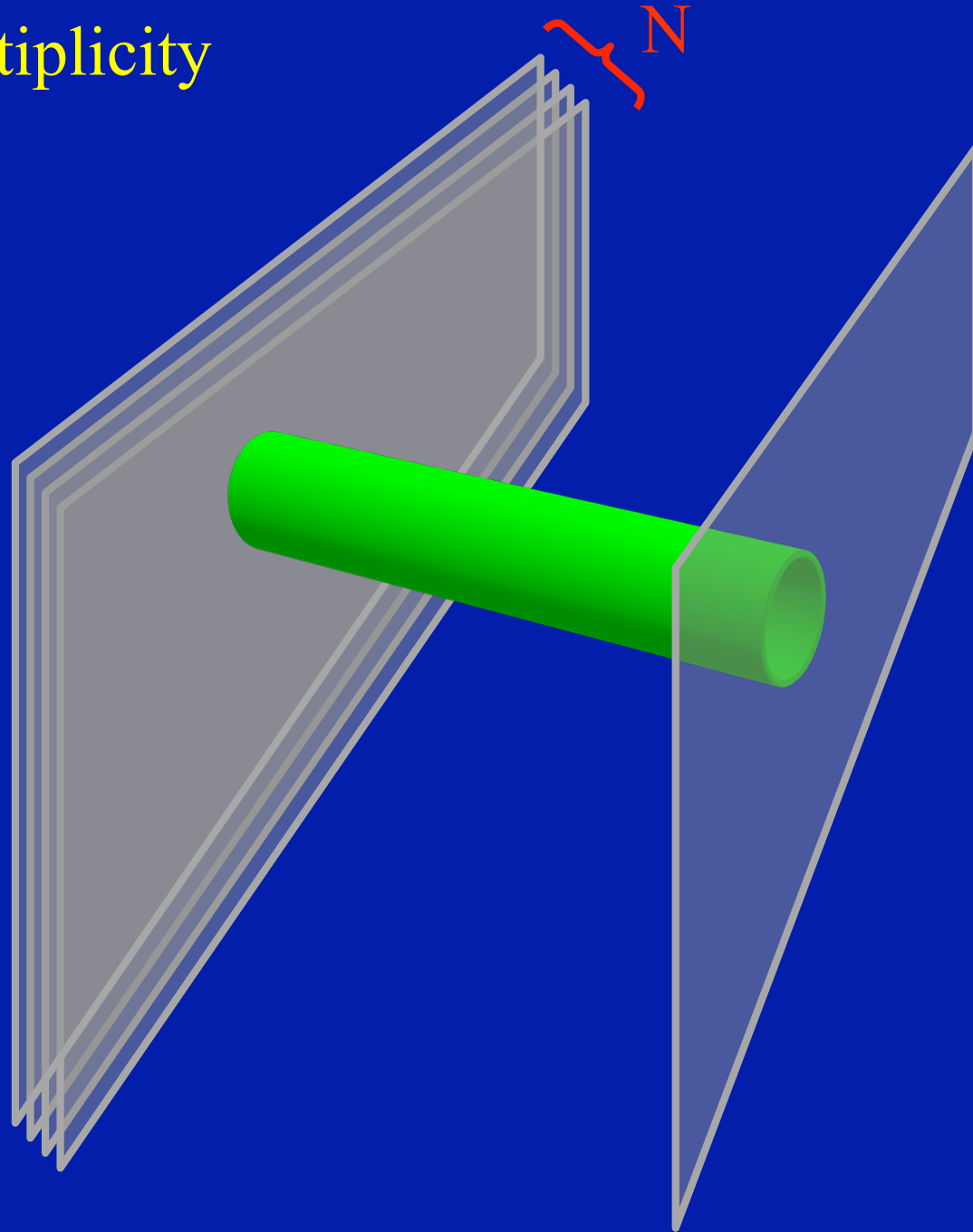


- Physical object of dimension p
- “Open strings”: $p=D-1$
(space-time filling)

Transverse Annulus

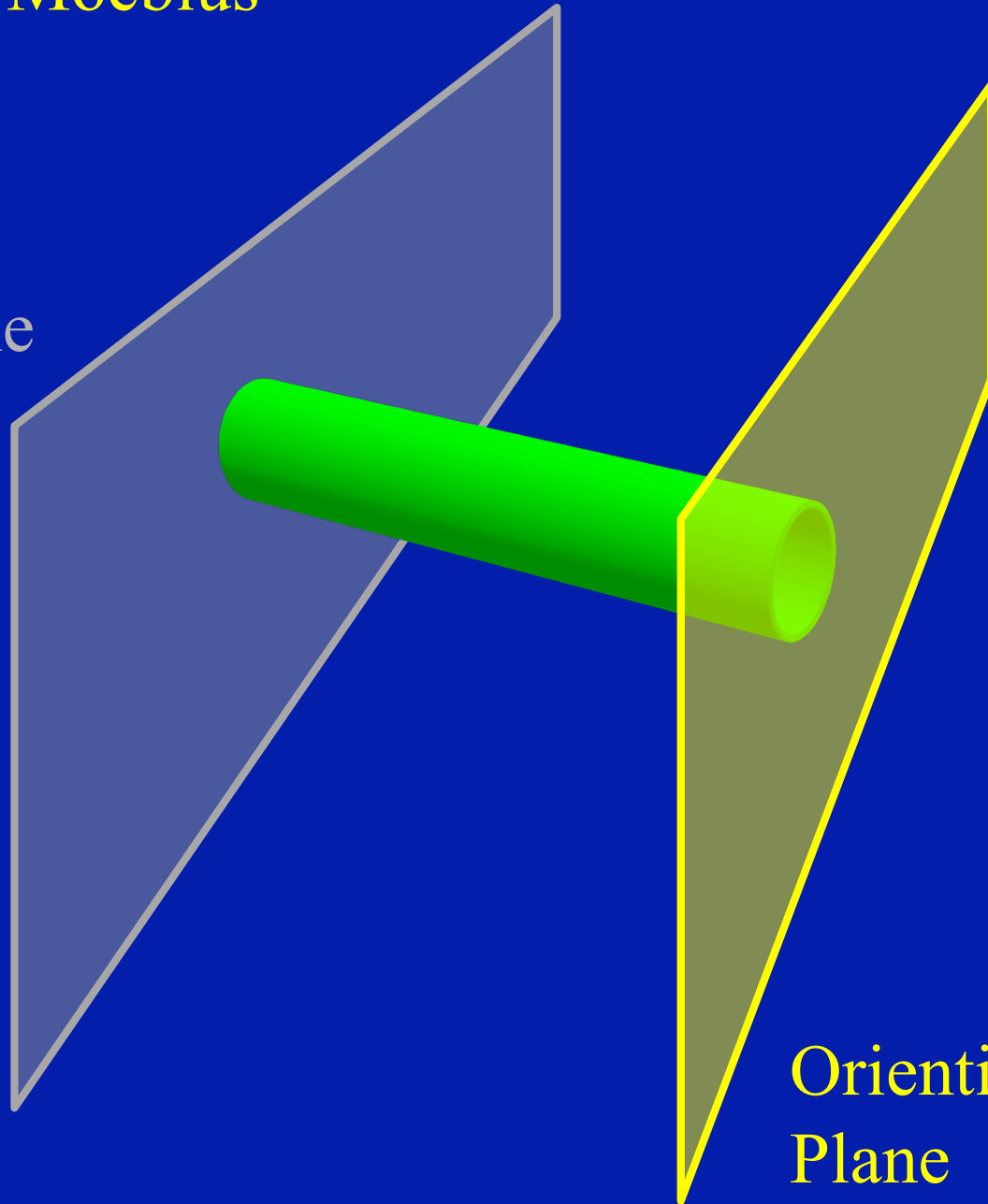


Brane multiplicity



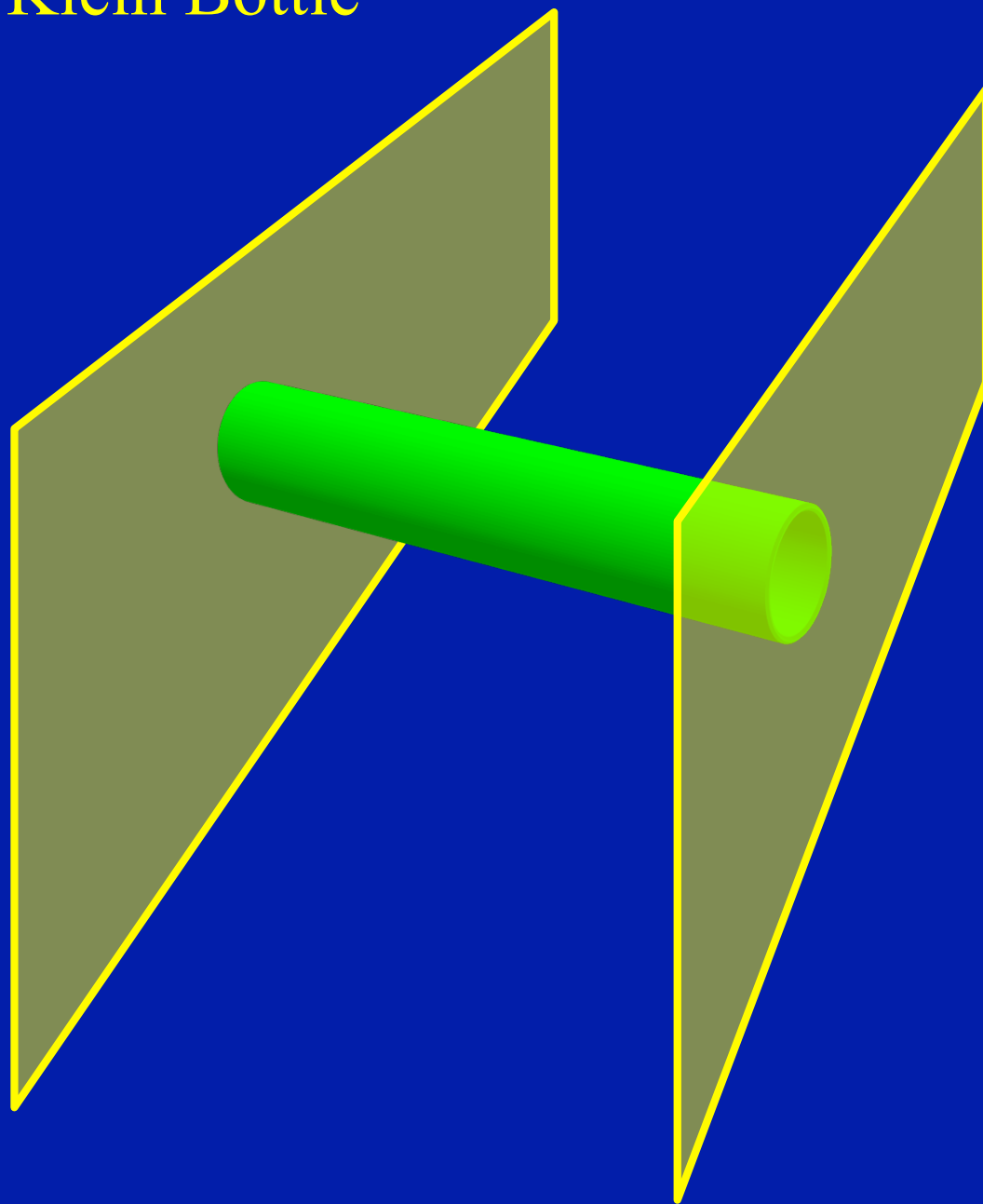
Transverse Moebius

D-brane



Orientifold
Plane

Transverse Klein Bottle



Completeness of Boundaries

Branes (boundaries) carry an additional label, a

→ Many different branes, each with multiplicity N_a

Tadpole Cancellation:

$$\sum_a N_a B_{ai} = 2^{D/2} \Gamma_i$$

Only affects space-time filling branes

This selects special boundaries, but the others
may
still appear as non-space-time filling branes

Completeness of Boundaries (2)

Conjecture: (Pradisi, Sagnotti, Stanev)*

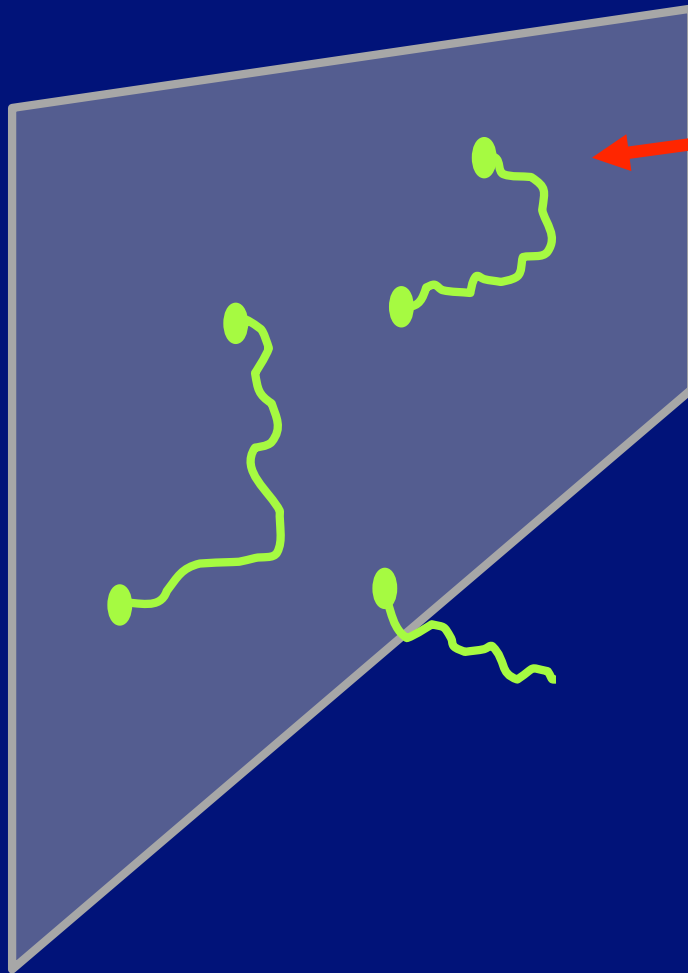
Boundaries form a “complete set”

Completeness for particle spectrum plus branes ?

*) Verified for a large class of string theories:

Huiszoon, Fuchs, Schellekens, Schweigert, Walcher

Brane Worlds



We could be here!

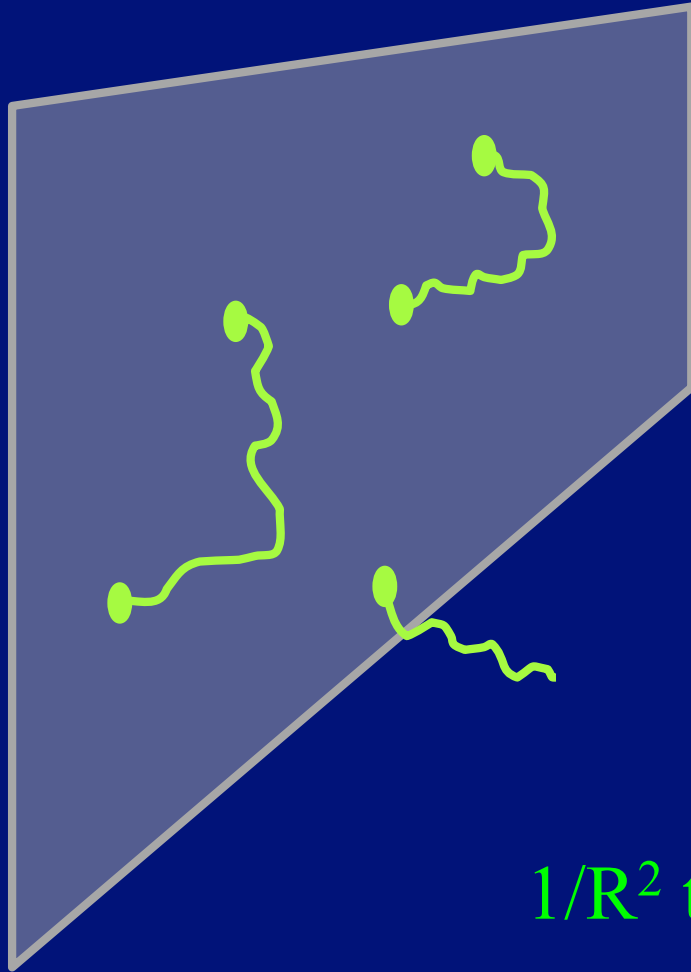


Open string ends induce
Charged particles and
Vector bosons on the plane



Standard model

Brane Worlds (2)



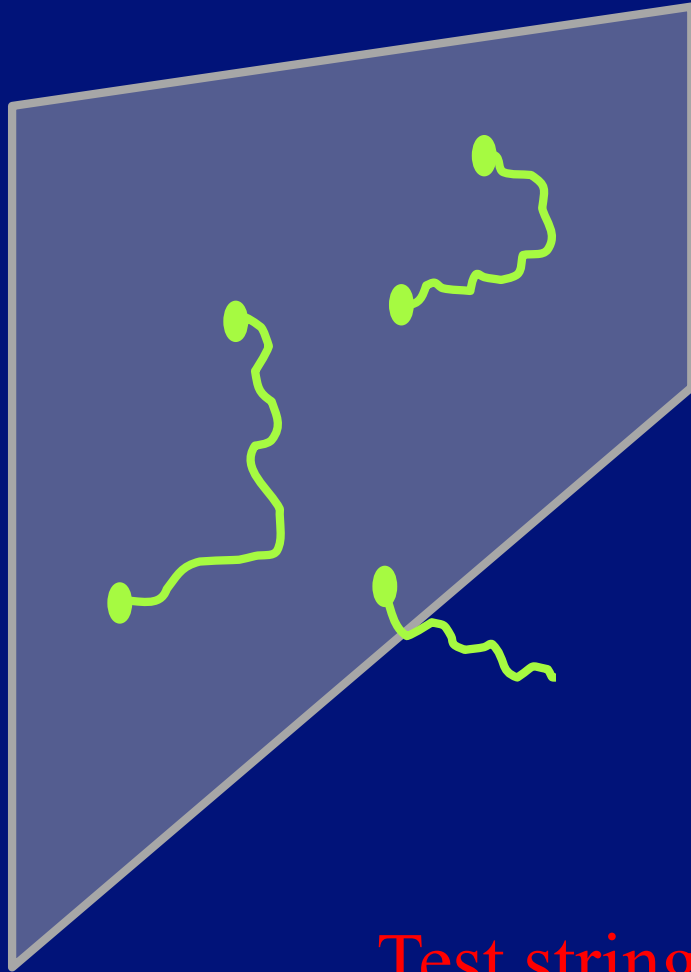
But gravity lives in
the “bulk”

$$F = G_N \frac{m_1 m_2}{R^{(D-2)}}$$

$1/R^2$ tested to ≈ 1 mm.

(Arkani-Hamed, Dimopoulos, Dvali)

Brane Worlds (3)



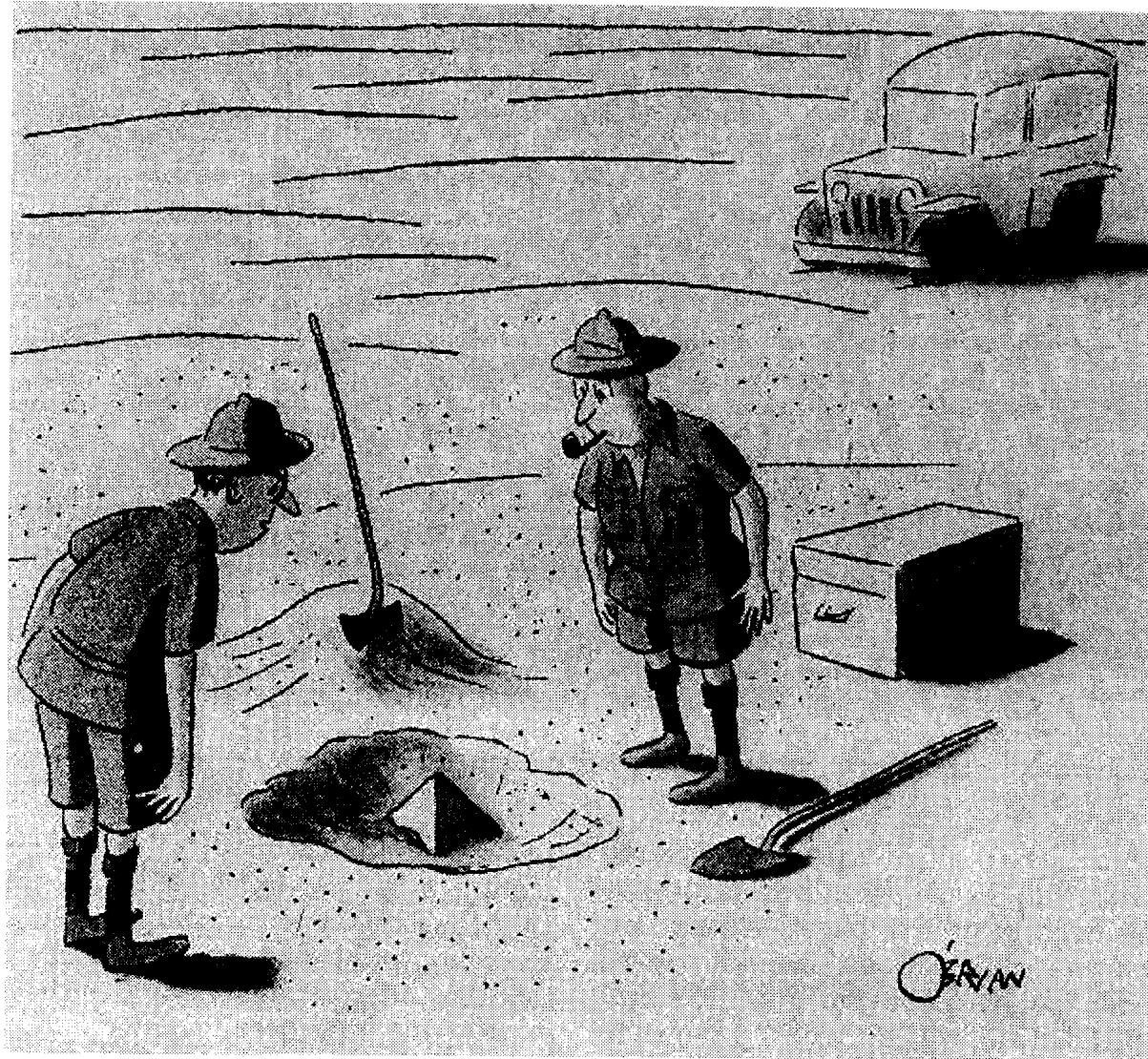
Consequence:

“Planck mass”
can be ≈ 1 TeV

Test string theory at LHC ?

Conclusions

- String theory is a candidate theory for quantum gravity and “everything else”
- But what is “String Theory ?”
 - Underlying Principle ?
 - Derivable?
 - Completeness ?
 - SUSY?
 - Space-time?
 - Quantum mechanics?
- Phenomenological Desorientation:
 - Calabi-Yau compactification
 - 4-D strings
 - M-theory compactifications
 - Open string compactifications
 - Brane Worlds
 -



"This could be the discovery of the century. Depending, of course, on how far down it goes."

Conclusions (2)

Where will Copernicus stop?

- Earth?
- Solar System?
- Galaxy?
- Our Matter?
- Our Universe?
- The Standard Model?
- String Theory?