String Theory and Particle Physics

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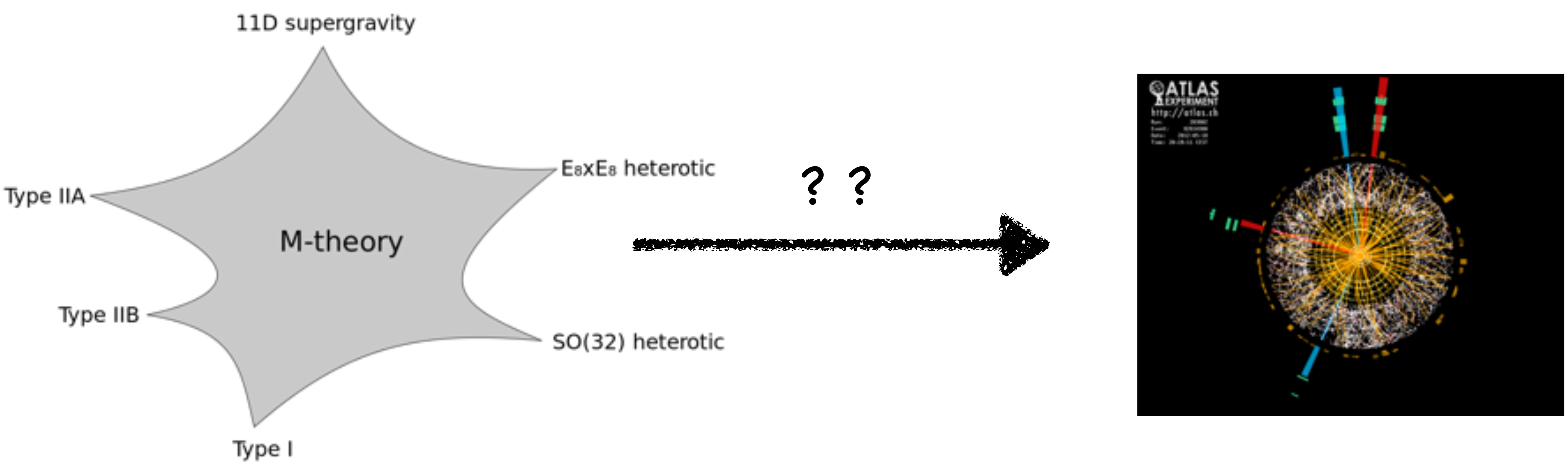
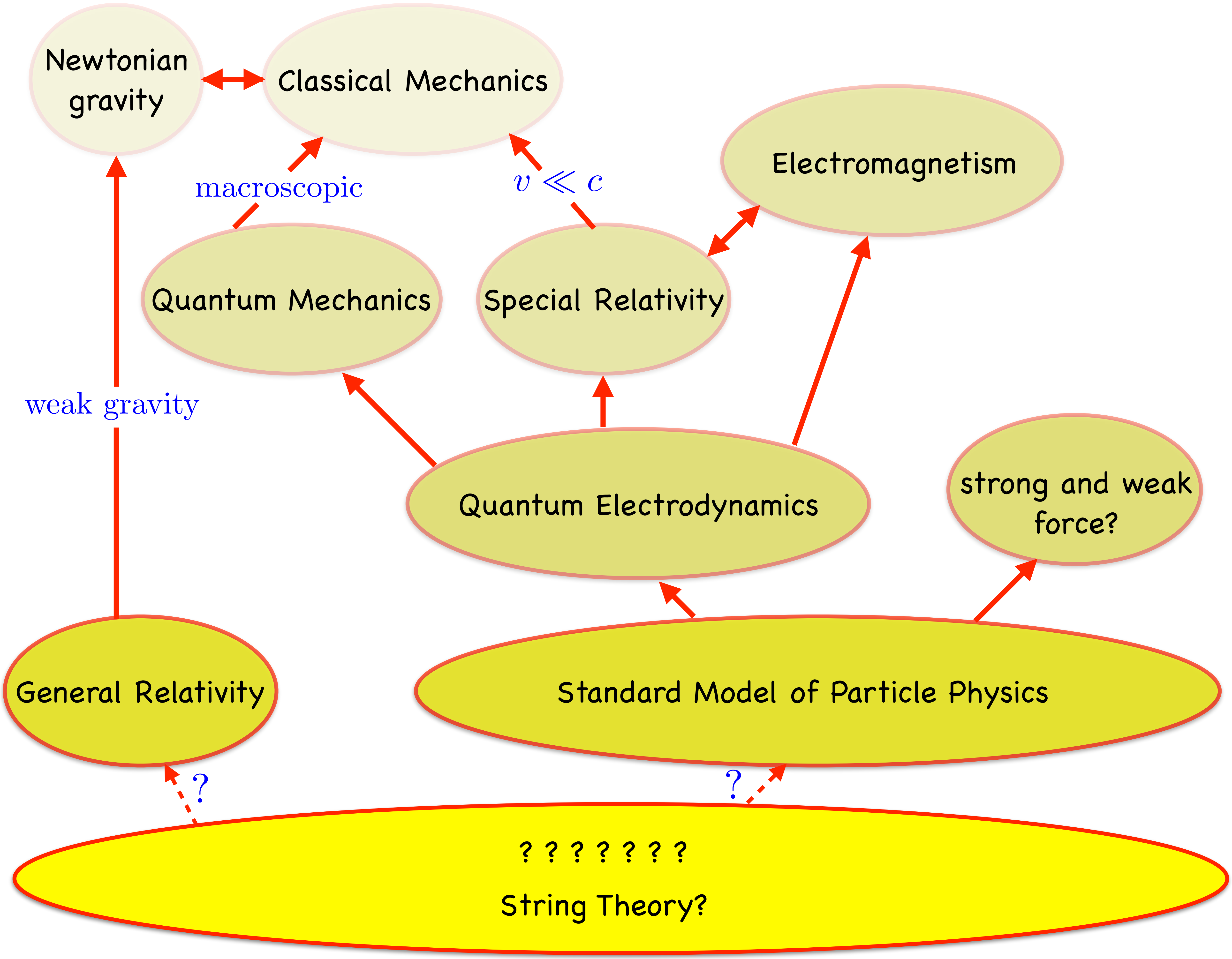


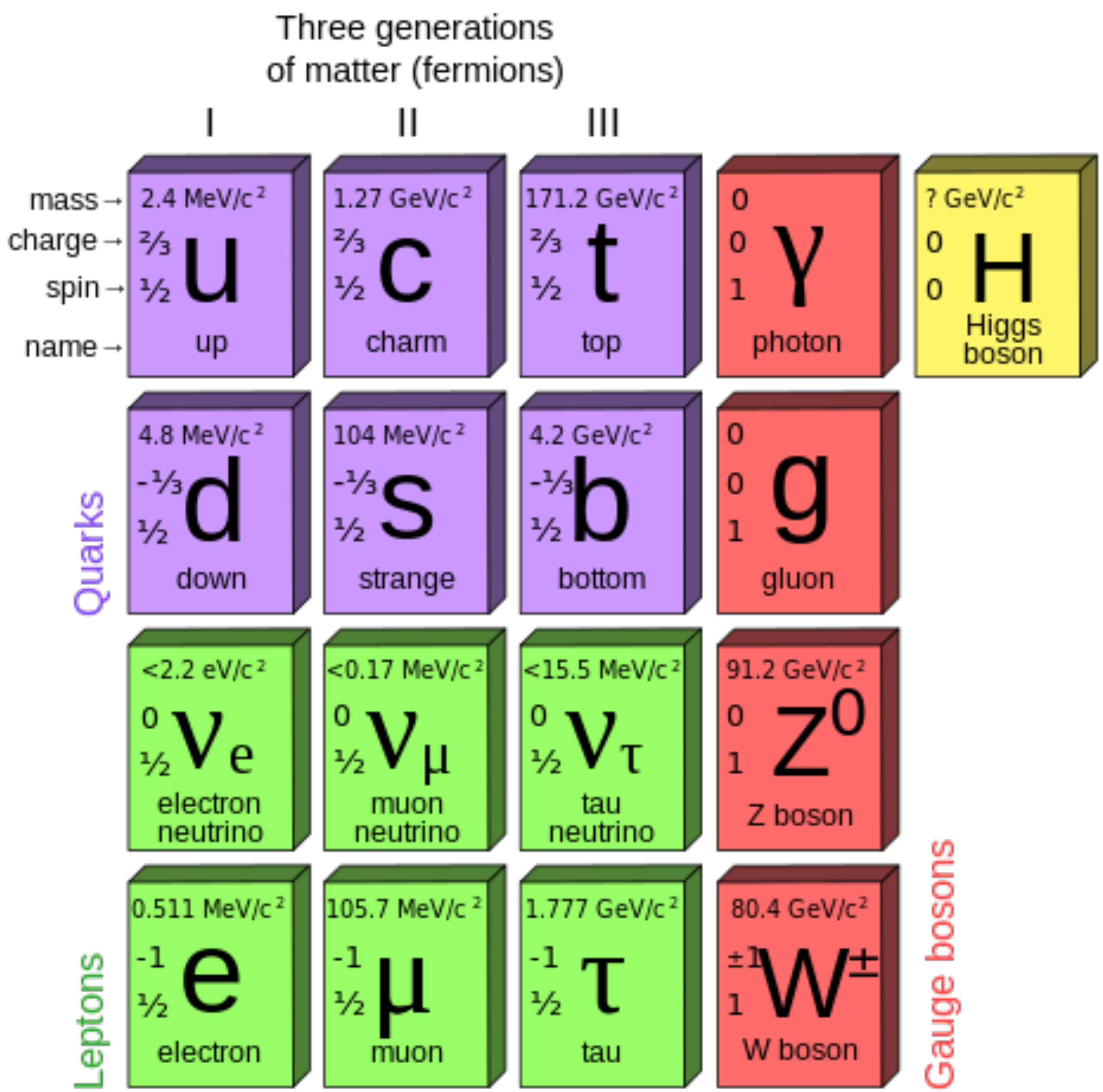
Outline

- Introduction: modern fundamental physics
- Why go on?
- String theory
- String theory and particle physics
- Conclusion

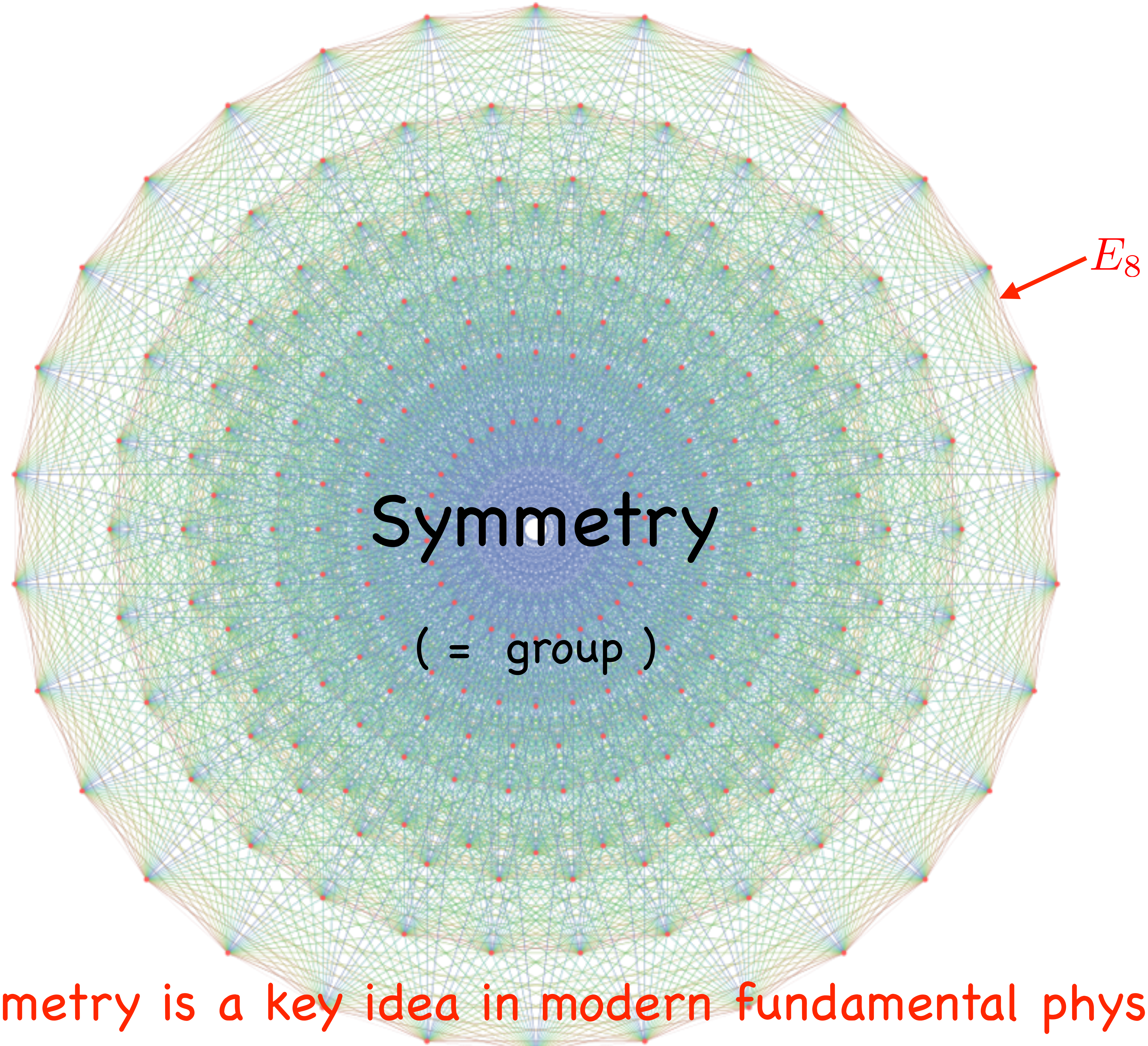
Introduction: modern fundamental physics


Newtonian gravity
Classical Mechanics
Electromagnetism
macroscopic
$v \ll c$
Quantum Mechanics
Special Relativity
weak gravity
Quantum Electrodynamics
strong and weak force?
General Relativity
Standard Model of Particle Physics
?
?
? ? ? ? ? ? ?
String Theory?

The standard model of particle physics



This picture hides the most important structural feature:



Symmetry is a key idea in modern fundamental physics!

Symmetry of the standard model:

strong force — electro-weak force — gravity

$$SU(3) \times SU(2) \times U(1) \times$$ Lorentz symmetry, gen. coord. transformations

U_3 — U_2 — $U_1 = e^{i\phi}$

What is $U(n)$?

Unitary nxn matrices: $U^\dagger U = \mathbf{1}$

transform n-dim. vectors $\mathbf{v} \to U\mathbf{v}$

What is $SU(n)$?

Special unitary nxn matrices: $U^\dagger U = \mathbf{1}$, $\det(U) = 1$

Matter in the standard model:

1. family:

$$\begin{array}{ccc} & \leftarrow \; U_3 \; \rightarrow & \\ \begin{array}{c}\uparrow\\ U_2\\ \downarrow\end{array} & \begin{pmatrix} u_L & u_L & u_L \\ d_L & d_L & d_L \end{pmatrix} & \end{array} \qquad \begin{pmatrix} \nu_e \\ e_L \end{pmatrix} \begin{array}{c}\uparrow\\ U_2\\ \downarrow\end{array}$$

$$\begin{array}{c} \leftarrow \; \bar{U}_3 \; \rightarrow \\ (d_R \; d_R \; d_R) \end{array} \qquad (e_R)$$

$$\begin{array}{c} \leftarrow \; \bar{U}_3 \; \rightarrow \\ (u_R \; u_R \; u_R) \end{array} \qquad (N_e) \; ?$$

$$(\mathbf{3},\mathbf{2})_{-1/3} \quad (\bar{\mathbf{3}},\mathbf{1})_{2/3} \quad (\bar{\mathbf{3}},\mathbf{1})_{-4/3} \quad (\mathbf{1},\mathbf{2})_{-1} \quad (\mathbf{1},\mathbf{1})_{2} \quad (\mathbf{1},\mathbf{1})_{0}$$

Similar for 2. and 3. family.

What does the standard model actually look like?

$$S = S_{SM} + S_{GR}$$

matter fields and their interactions with force carriers

force carriers, E&M

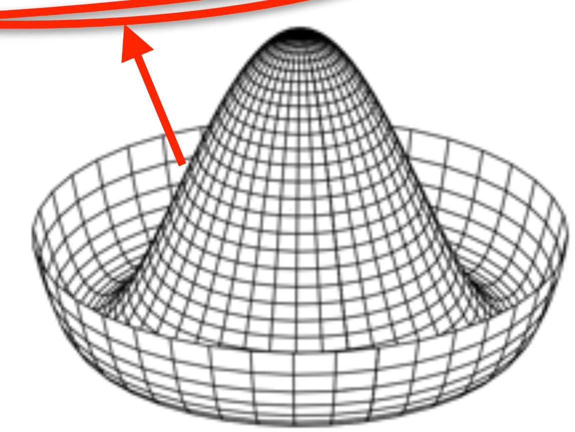
$$S_{SM} = \int \sqrt{-g}\left[\sum_\psi i\bar{\psi}\gamma^\mu D_\mu\psi - \frac{1}{4}\mathrm{tr}\left(F_{\mu\nu}F^{\mu\nu}\right) + \right.$$

matter field masses

$$\lambda_{ij}^{(e)}\bar{L}^i H e_R^j + \lambda_{ij}^{(u)}\bar{Q}^i\tilde{H}u_R^j + \lambda_{ij}^{(d)}\bar{Q}^i H d_R^j +$$

Higgs field

$$\left.(D_\mu H)^\dagger (D^\mu H) - \mu^2 H^\dagger H + \lambda\left(H^\dagger H\right)^2\right]$$



$$S_{\mathrm{GR}} = \frac{1}{16\pi G}\int \sqrt{-g}\,R$$

Einstein eq.

Why go on?

Consistency and beauty....

Gravity

Standard Model is a quantum theory -

General Relativity is classical.

$$M_{\mathrm{SM}} \sim M_{\mathrm{Higgs}} \sim 10^2\mathrm{GeV} \qquad\qquad M_{\mathrm{Pl}} = \sqrt{\frac{\hbar c}{G_{\mathrm{N}}}} \sim 10^{19}\mathrm{GeV}$$

Attempts to quantise GR by conventional methods have failed.

How can the Standard Model and GR be combined
in a quantum theory?

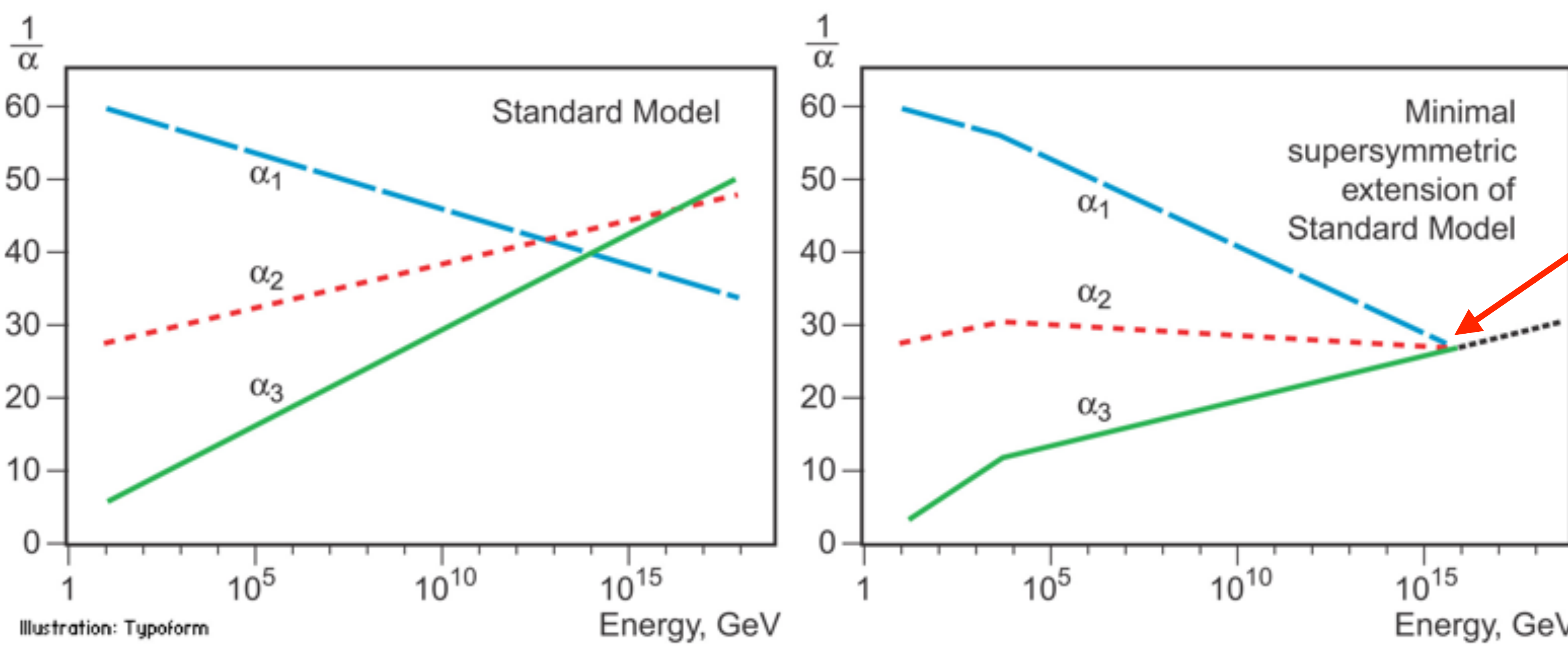
Symmetry

Standard Model symmetry:

$$\overset{\alpha_3}{SU(3)} \times \overset{\alpha_2}{SU(2)} \times \overset{\alpha_1}{U(1)} \quad \subset \quad \overset{\alpha_5}{SU(5)}$$

$$U_3 \qquad U_2 \qquad U_1 = e^{i\phi} \longrightarrow U_5 = \begin{pmatrix} e^{2i\phi}U_3 & 0 \\ 0 & e^{-3i\phi}U_2 \end{pmatrix} \in SU(5)$$

Coupling constant unification:



$M_{\mathrm{U}} \sim 10^{16}\mathrm{GeV}$

Can we find suitable theories with SU(5) symmetry?

Matter content

1. family : (d_R) $\quad L_e = \begin{pmatrix} \nu_e \\ e_L \end{pmatrix}$ $\quad Q_u = \begin{pmatrix} u_L \\ d_L \end{pmatrix}$ $\quad (u_R)$ $\quad (e_R)$

$SU(3) \times SU(2) \times U(1)$: $\quad (\bar{\mathbf{3}}, \mathbf{1})_{2/3} \quad (\mathbf{1}, \mathbf{2})_{-1} \quad (\mathbf{3}, \mathbf{2})_{-1/3} \quad (\bar{\mathbf{3}}, \mathbf{1})_{-4/3} \quad (\mathbf{1}, \mathbf{1})_{2}$

$\cup$

$SU(5)$: $\quad \bar{\mathbf{5}} \qquad \mathbf{10}$

right-handed neutrino

$\cup$

$SO(10)$: $\quad \mathbf{16}$

$\cup$

E_6, E_7, E_8

In a theory with SU(5), SO(10), . . . symmetry families have a much more natural description.

Families

Even if we understand the structure of each family,
why are there three?

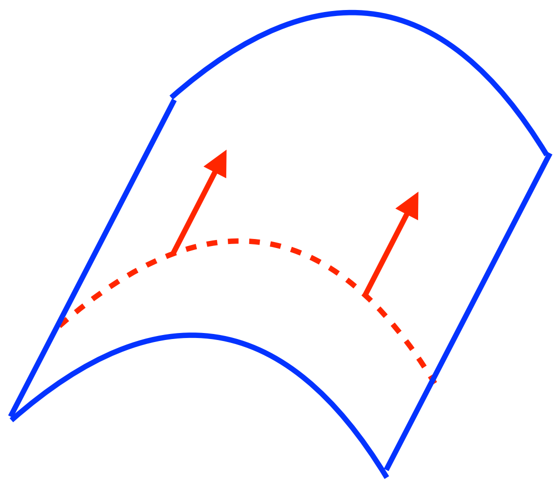
Is there a theory where family replication can be explained?

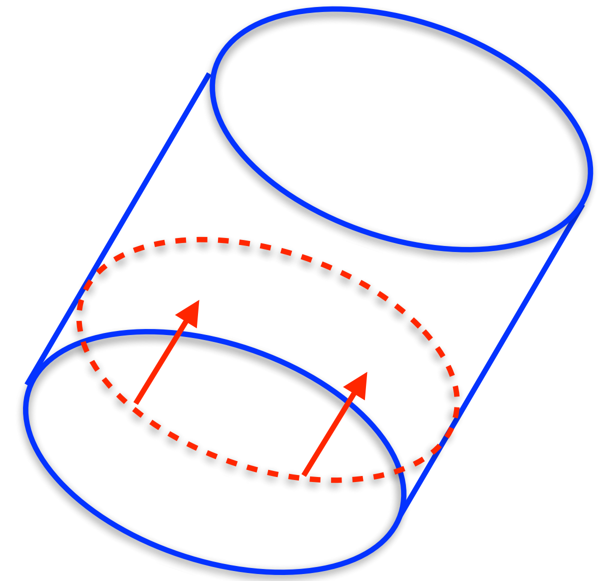
One attempt to address these and related questions is

String Theory

String theory recap

- open string   closed string





- One free constant: string tension $T = \dfrac{1}{2\pi\alpha'}$

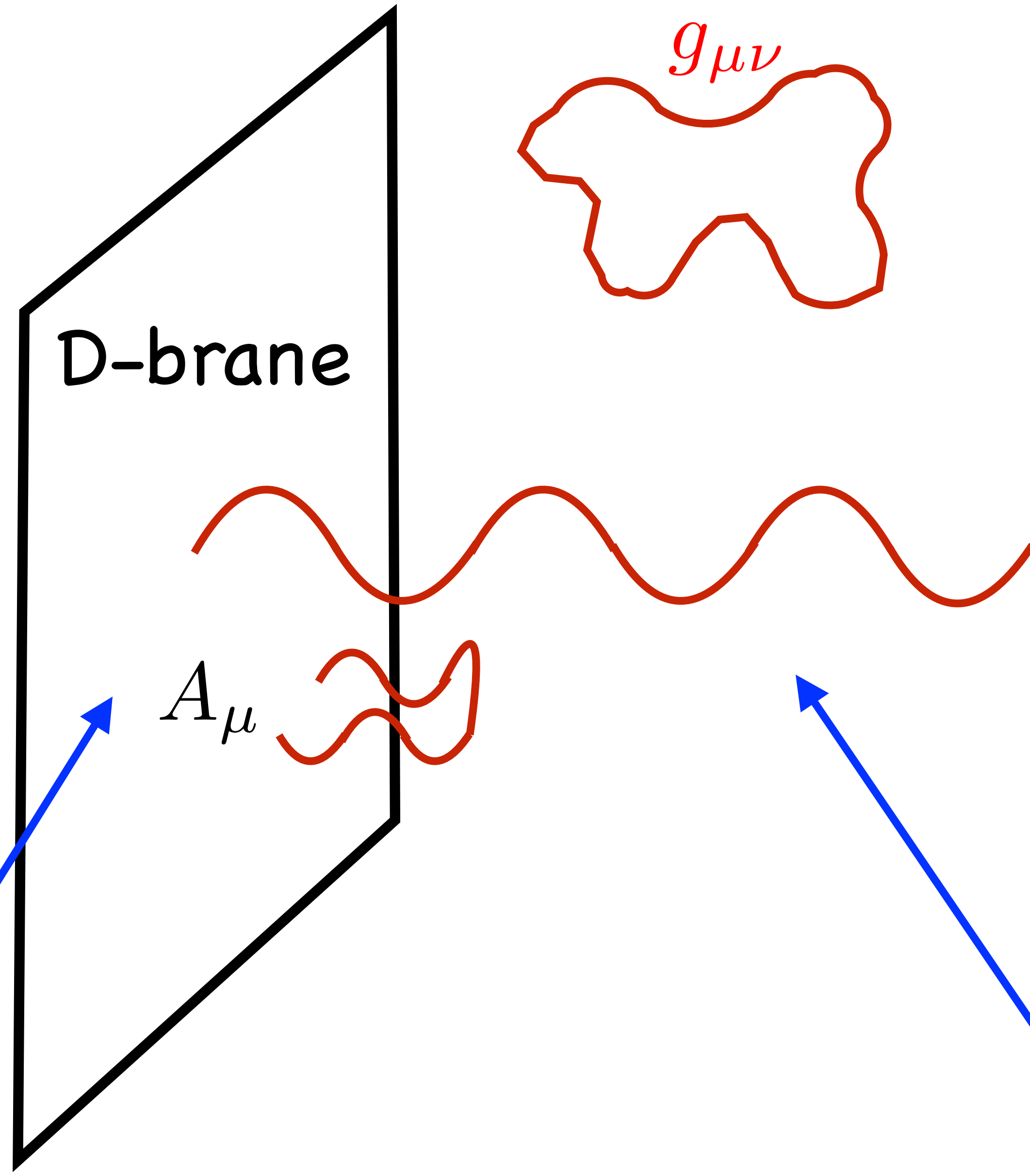
- Consistent in 10 (or 11) space-time dimensions

- spectrum: $\alpha' m^2 = n \in \mathbb{N}$ $\begin{cases} n = 0 & \rightarrow \quad \text{observed particles} \\ n > 0 & \rightarrow \quad \text{superheavy} \end{cases}$

massless $(n = 0)$ modes contain: graviton (closed string)
gauge fields (open string)

$$M_s = \frac{1}{\sqrt{\alpha'}} \sim M_{Pl} \sim 10^{19}\text{GeV} > M_U \sim 10^{16}\text{GeV}$$

• branes



AdS/CFT correspondence (A. Starinets)

gauge and matter field on brane

gravity in 10/11 dimensions

String Theory and Particle Physics

?

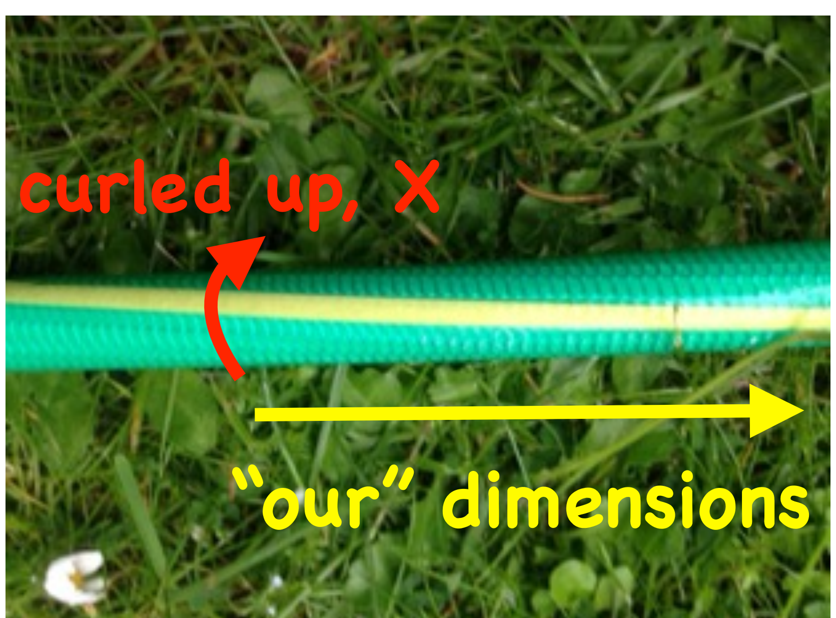
Dimensions

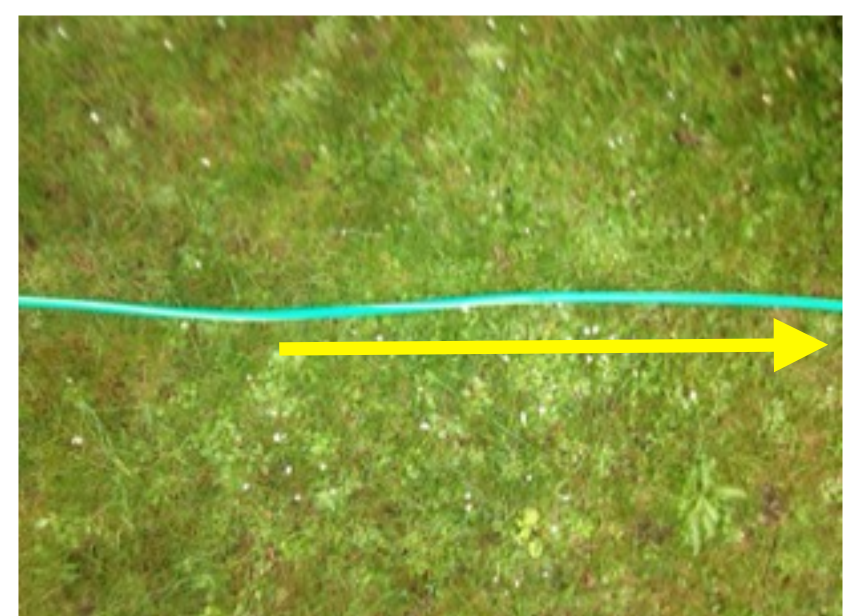
We need to ``curl up" six (or seven) of the dimensions to make contact with physics -> compactification

D=10/11
string/M–theory

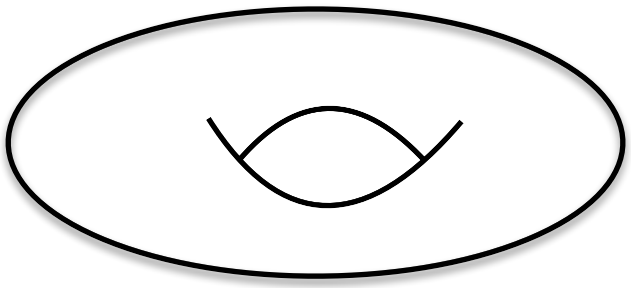
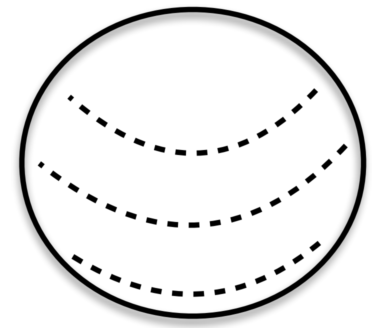
$\downarrow$ on d=6/7 – dim. space X

D=4 theory

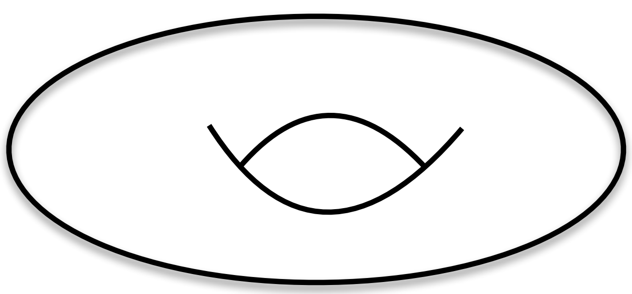
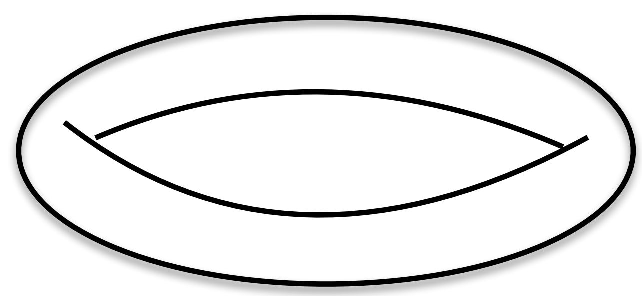




How does the 4d theory depend on the ``curling-up"?

topology :  or  ?

-> determines structure of 4d theory: forces, matter content, . . .
(Maths: Algebraic Geometry)

shape :  or  ?

-> determines couplings/particle masses in 4d theory
(Maths: Differential Geometry)

Gravity

String theory always contains gravity from closed strings.
It can also contain the other force carriers from open strings.

Within string theory, gravity is a quantum theory as are all the other forces!

Symmetry

String theory contains all the right symmetries,

$$SU(5), SO(10), E_6, E_7, E_8$$

and has a natural way of reducing them to

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

String theory can provide the standard model symmetry and supports unification of coupling constants!

Matter content

String theory can provide the right multiplets, for example for

$$SU(5) \quad \subset E_8$$

it can lead to

$$\bar{\mathbf{5}} \oplus \mathbf{10} \quad \subset \mathbf{248}_{E_8}$$

= one family of quarks and leptons.

String Theory is consistent with the multiplet structure of the Standard Model.

Families

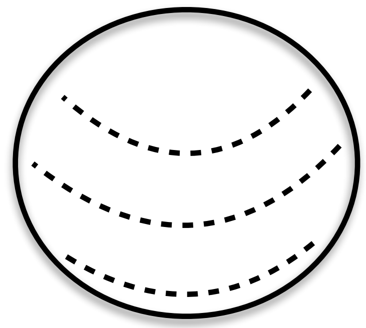
Recall: topology of curling-up -> particle content in 4d

Number of families is given by a topological number!

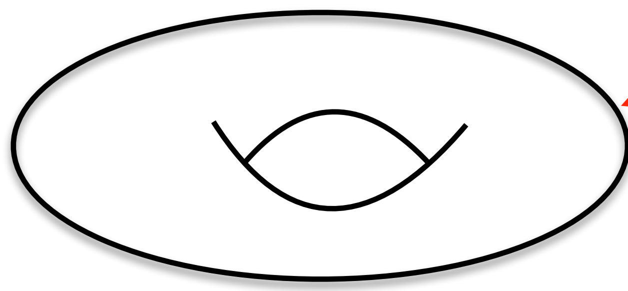
Family replication is natural in string theory (although it doesn't necessarily lead to three families).

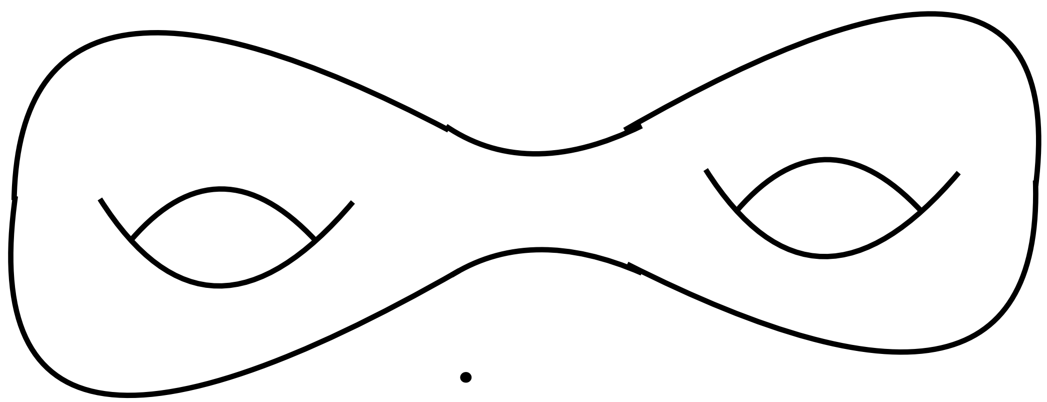
Sounds great – what's the catch?

Topologies for curling up, e.g in 2d:

sphere:  $g = 0$

only consistent choice for 2d curling-up

torus:  $g = 1$

 $g = 2$

$\vdots$

In 2d topology is classified by the genus g = ``number of holes".

What about in 6d? - Calabi-Yau manifolds:

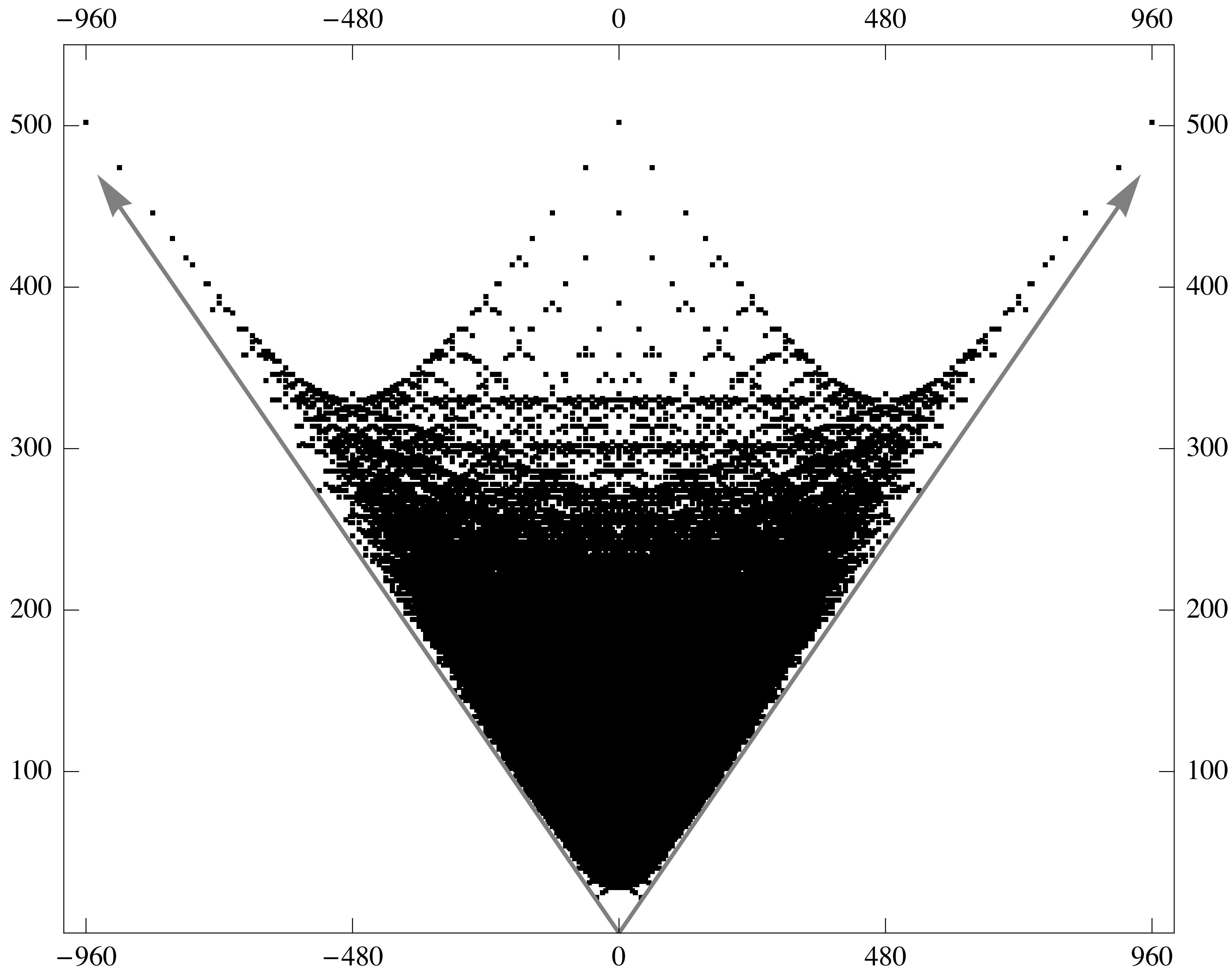
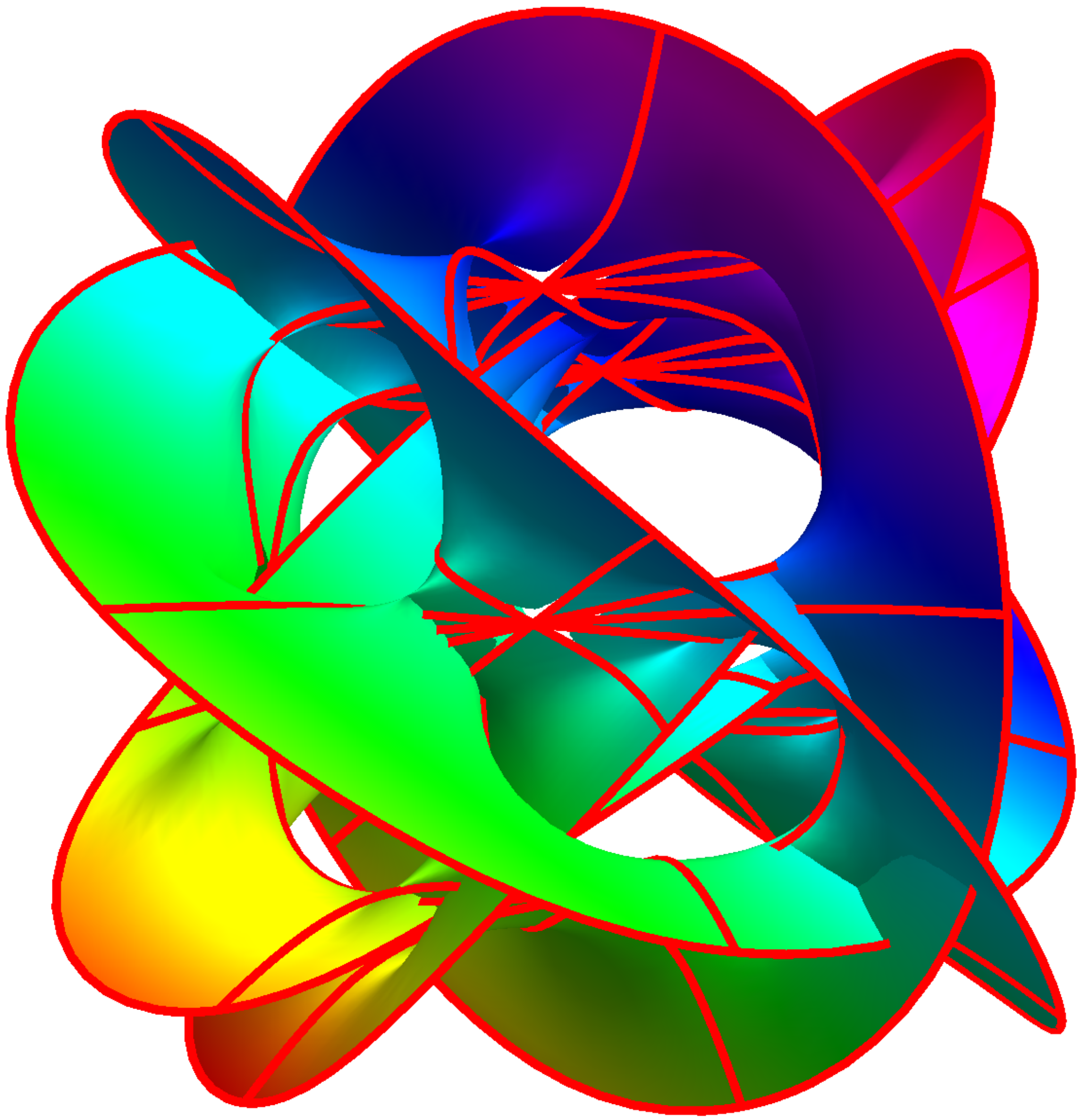


Figure 1: A plot of the Hodge numbers of the Kreuzer–Skarke list. $\chi = 2(h^{11} - h^{21})$ is plotted horizontally and $h^{11} + h^{21}$ is plotted vertically. The oblique axes bound the region $h^{11} \geq 0$, $h^{21} \geq 0$.

Billions of possible topologies!



String Theory does not (currently) tell us which choice of topology to make!

Every choice leads to a different 4d theory, with different forces and matter content.

Currently, we can only explore the choices and find the ones which lead to promising physics.

How far has this progressed?

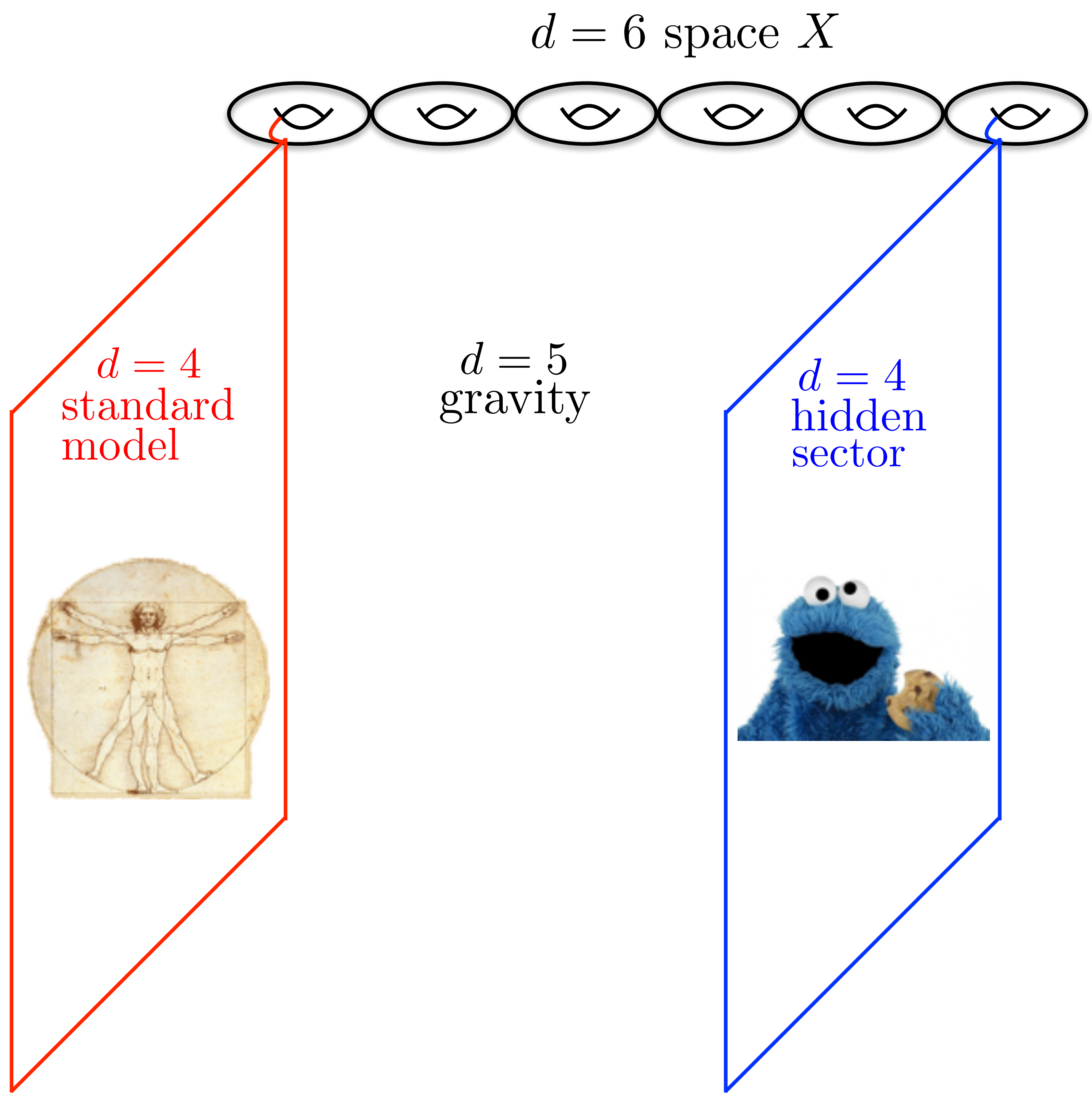
We know how to find (many) examples with the symmetry and matter content of the standard model.

We are beginning to work out particle masses and coupling strengths but a lot remains to be understood...

Paradoxically, despite all the choice not a single model which gives the exact standard model has been found yet.

The medium-term hope is to find such a model - feasible but very challenging...

What does space-time for such a model look like?



How might it manifest itself in observations?

- Supersymmetry (?)
- very light, very weakly coupled bosons (axions)
- additional, exotic and heavy ``photons”
- additional families of matter

Conclusion

- String theory has all generic ingredients to account for observed particle physics.

- Detailed model building now allows construction of models with the correct particle content.

- Finer details, such as the values of particle masses, are within reach but a fully realistic model has yet to be found.

- Possible string physics beyond the standard model includes supersymmetry, additional U(1) symmetries, axions, new matter fields, . . . Details depend on model.

- Many conceptual and technical problems remain...

Is the choice of topology arbitrary or will string theory provide a mechanism to select a specific topology?

Thanks