

Beyond the Standard Model

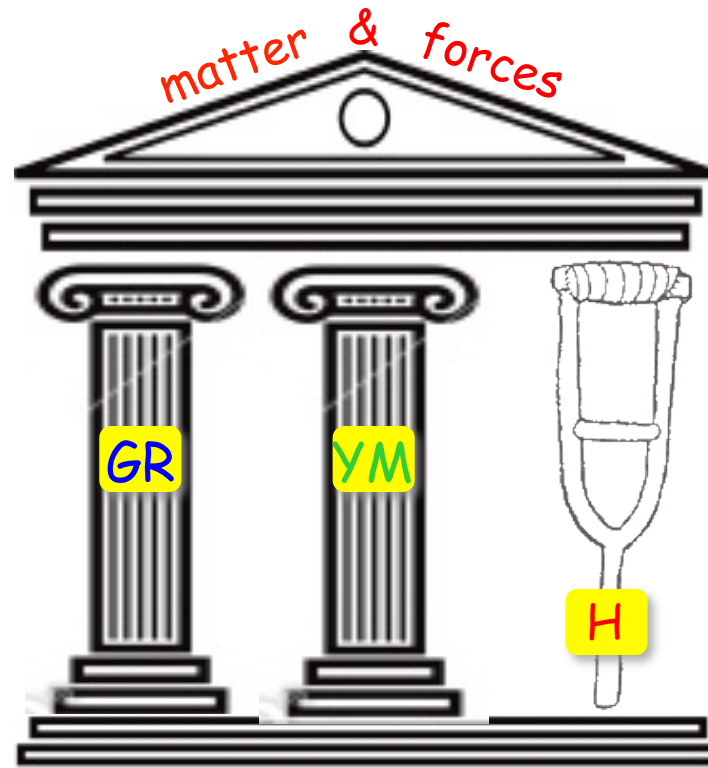
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Lecture 2

CERN Summer Student
Programme 2013

The Standard Model is an extraordinary conceptual success



- GR & YM are elegant structures dictated by symmetry, have few free parameters, and fare marvelously with exp. data
- The Higgs sector looks like a provisional structure

→ the LHC may find surprises

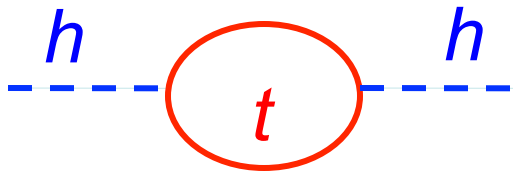


Courtesy of C. Grojean & A. Weiler₃

Most physicists believe that the Higgs cannot be the end of the story

- The structure is not determined by pure symmetry principles
- The mechanism is unable to predict the values of quark and lepton masses
- The field value is very sensitive to quantum fluctuations

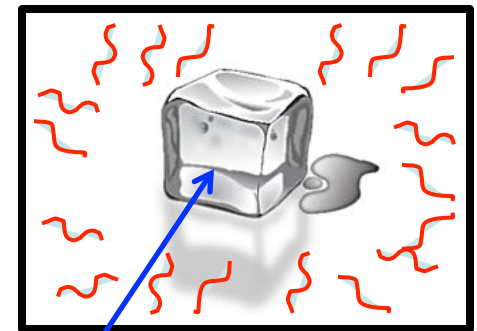
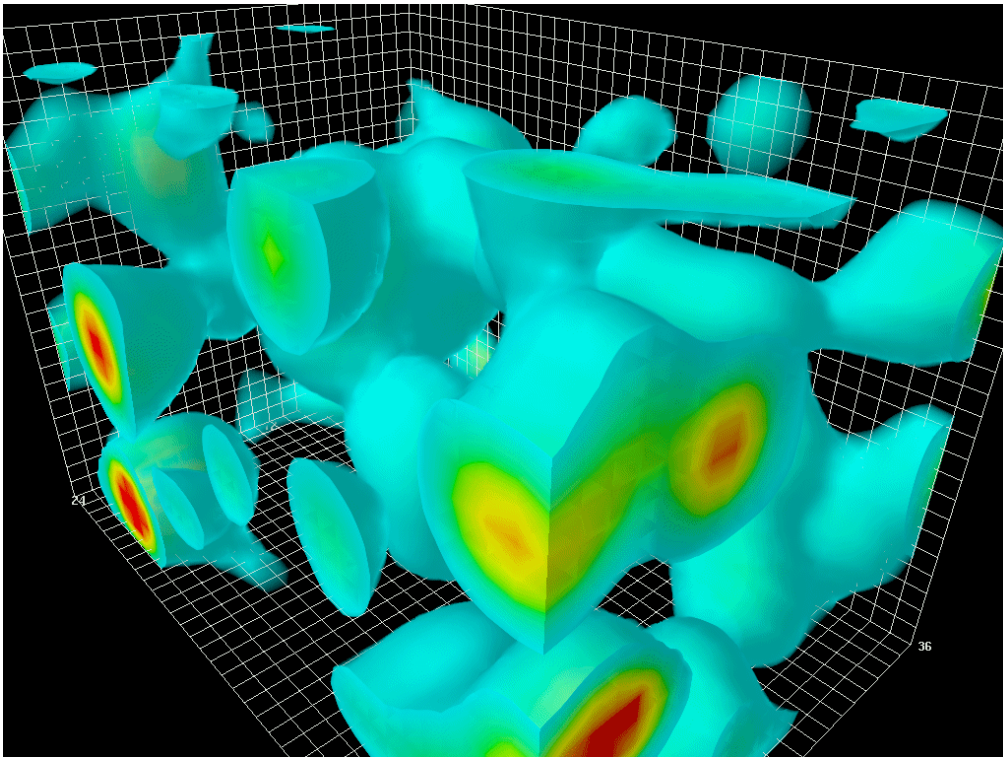
Sensitivity to quantum fluctuations



$$M_h^2 \propto \frac{y_t^2 \Lambda^2}{16\pi^2}$$

No separation of scales:

why $M_Z \ll M_{Pl}$
($G_N \ll G_F$)?

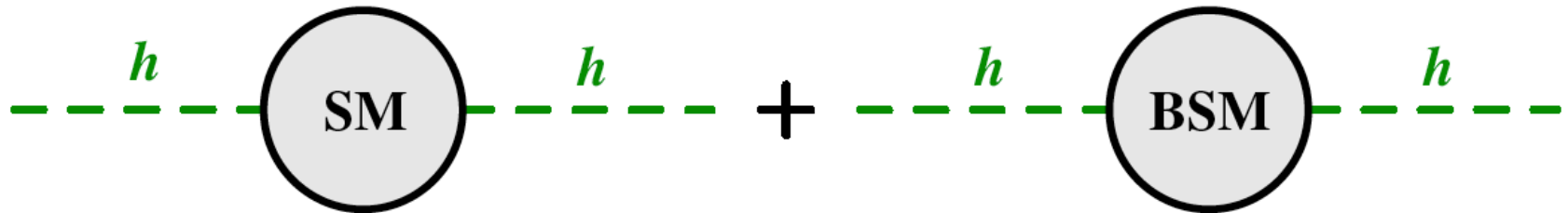


Higgs

Having $M_Z \ll M_{Pl}$ requires tuning up to 34th digit !

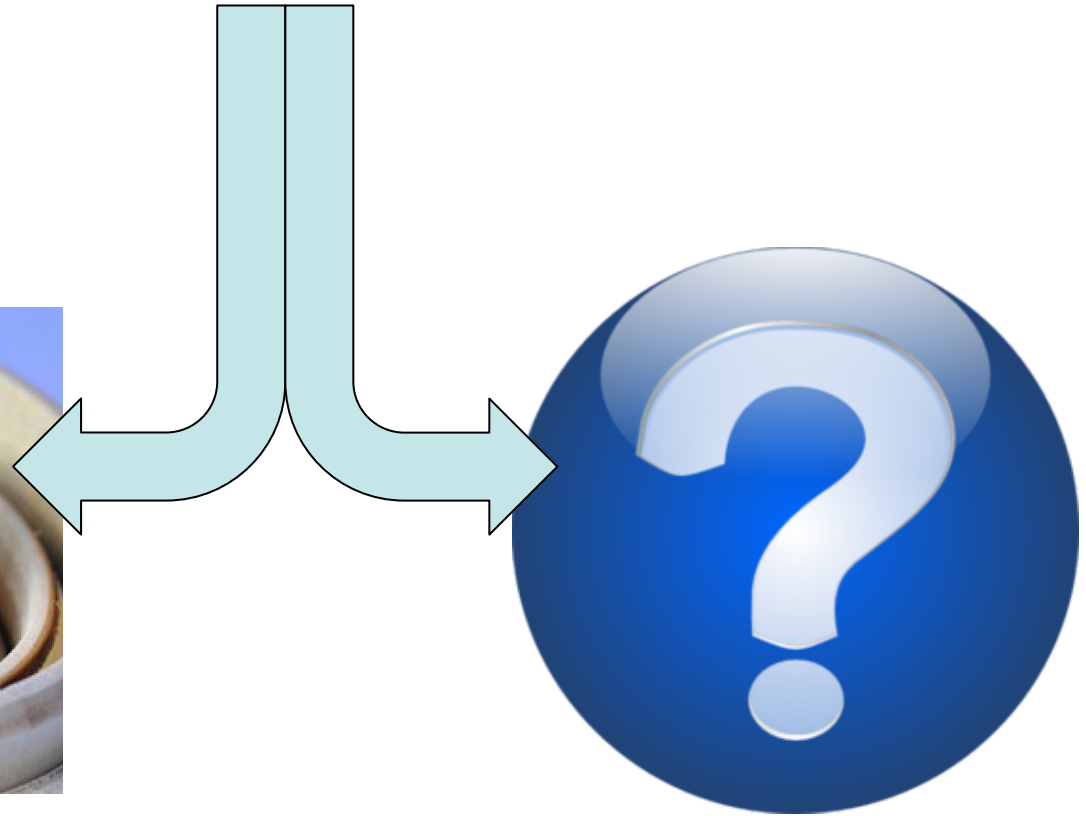
The “stability” of the hierarchy M_Z / M_{Pl} requires an explanation

Higgs is “screened” at energies larger than TeV \Rightarrow
new forces and new particles within LHC energy range

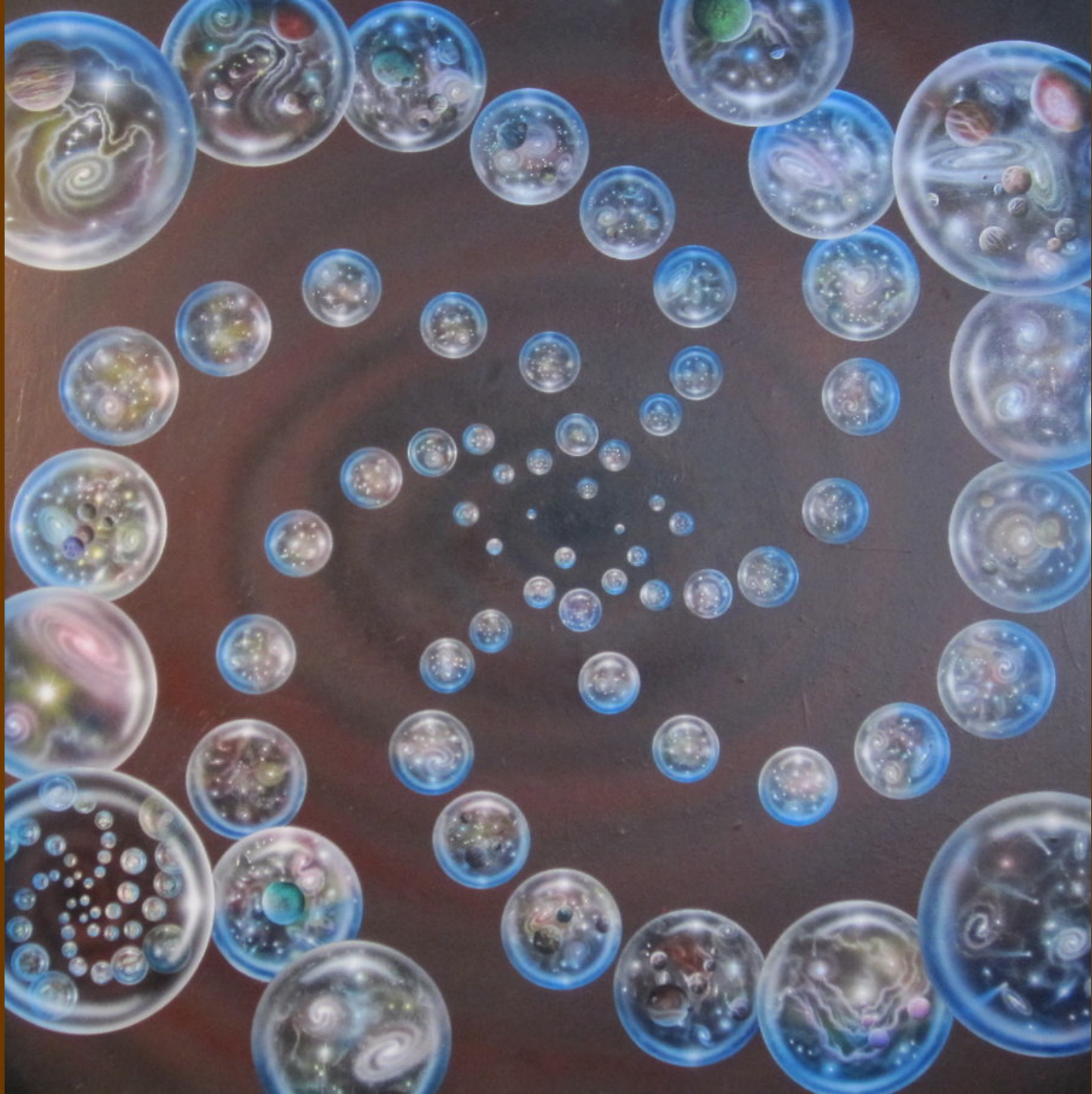


What is the new phenomenon? Enter pure speculation...
These speculations created remarkable conceptual discoveries

Does the Higgs respect the naturalness principle ?



Largely an experimental question

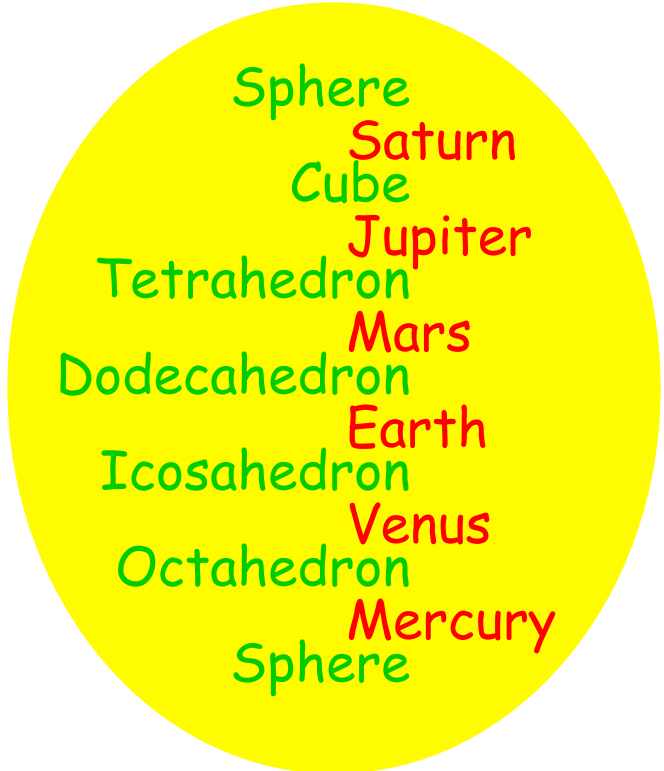
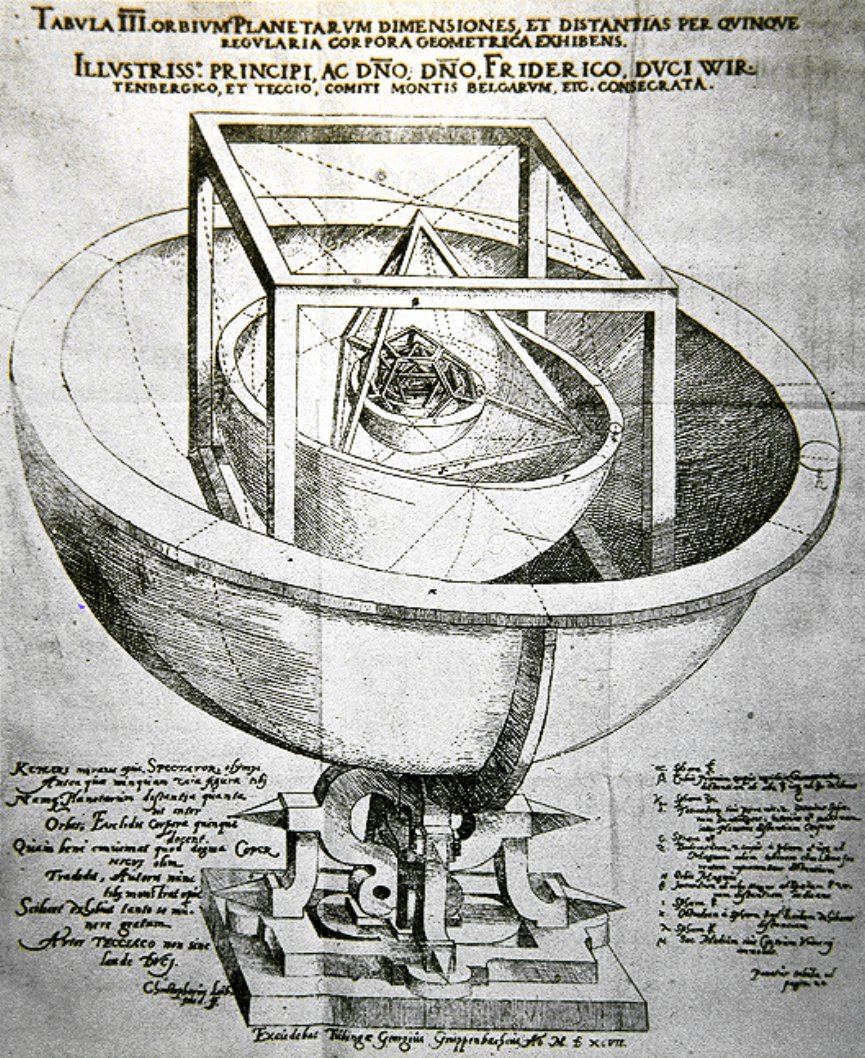




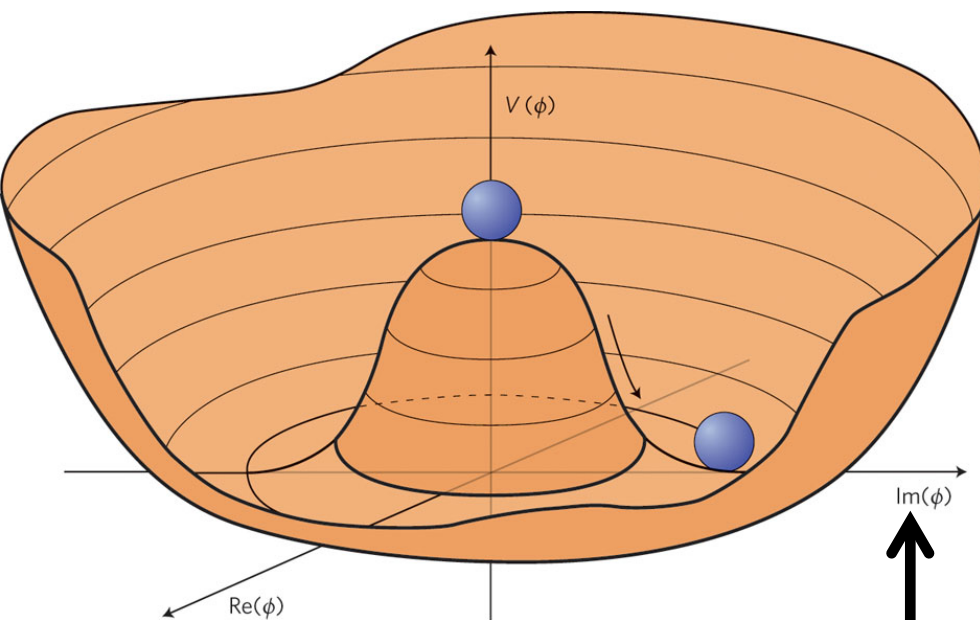
In 1595 Kepler asked the question
“Why are there 6 planets?” It
seems a proper scientific question
(“Why are there 3 quark families?”)

“Mysterium Cosmographicum” gives a geometrical explanation

Planetary orbits lie within the only 5 Platonic solids that can be both circumscribed and inscribed within a sphere. It well matched planetary distances known at that time.



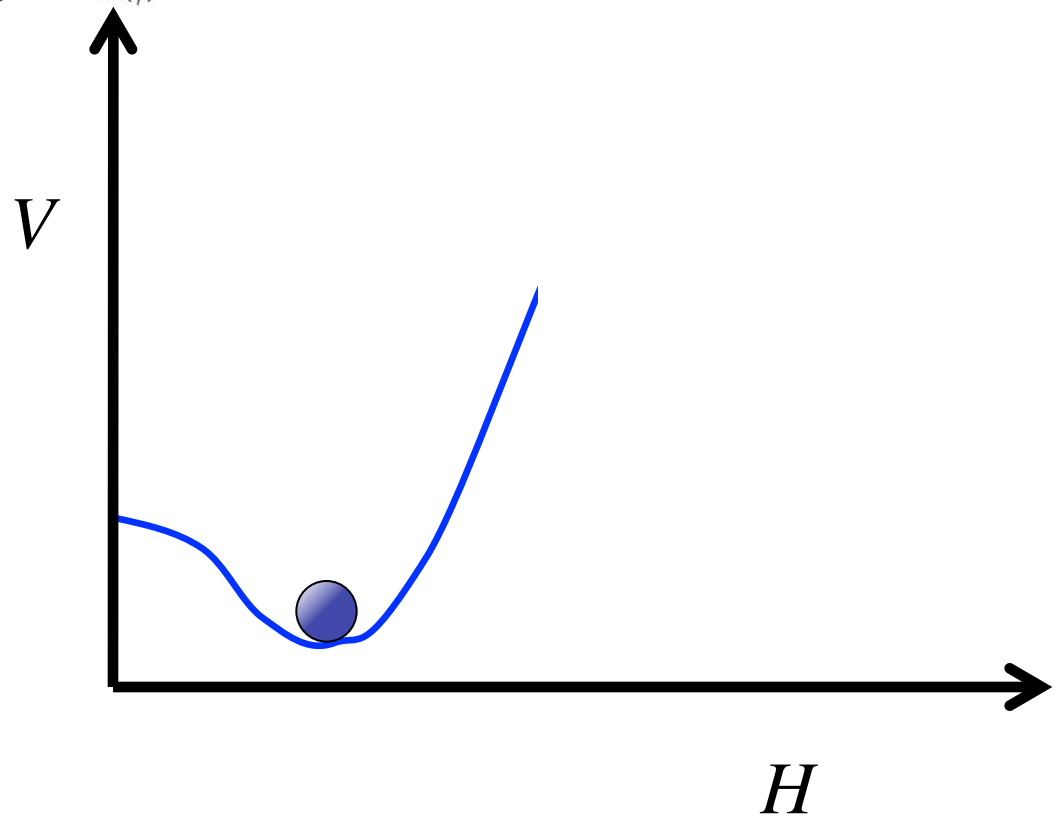
$$V(H) = -\mu_H^2 |H|^2 + \lambda |H|^4$$

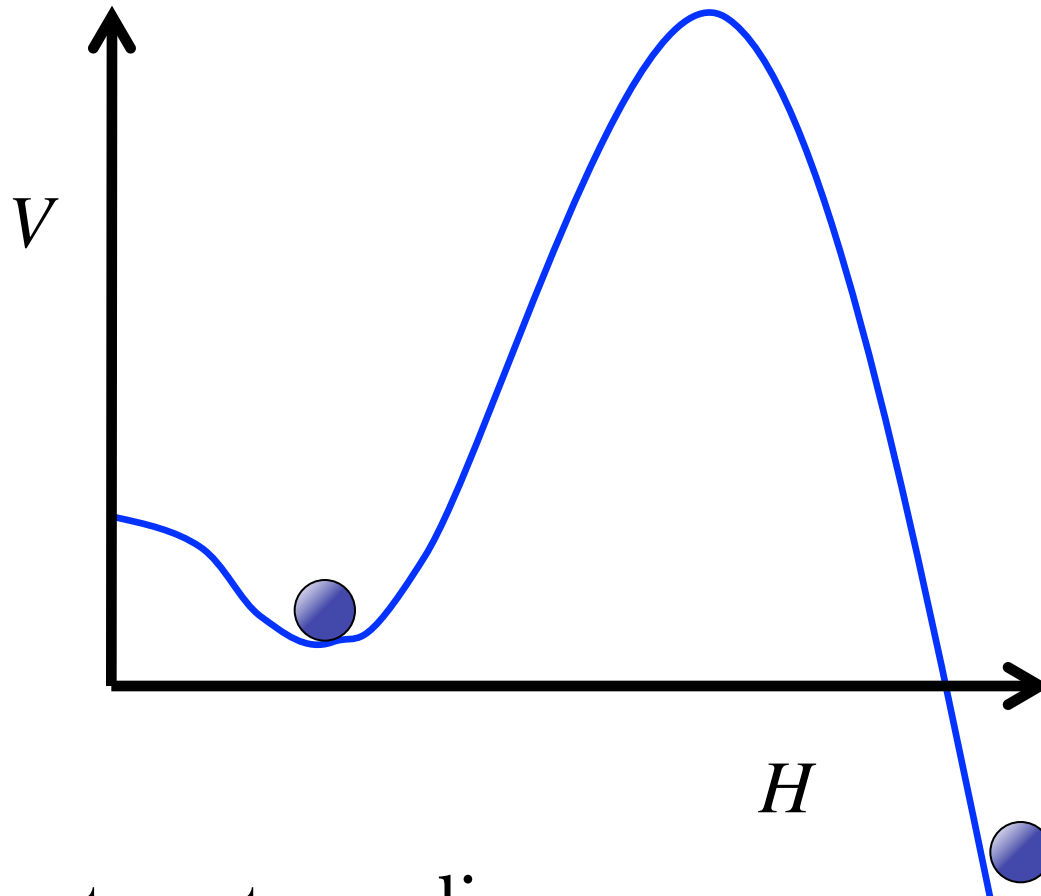


Extrapolate the SM up to very high energies

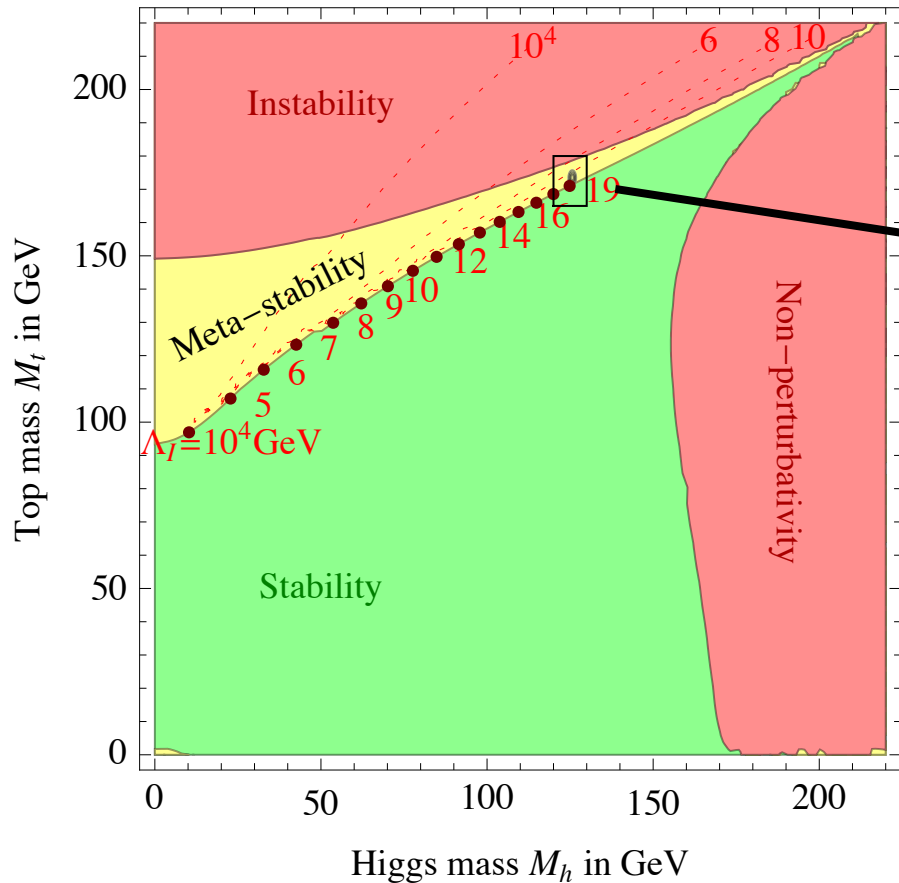
↑ Higgs mass

↓ Top quark mass

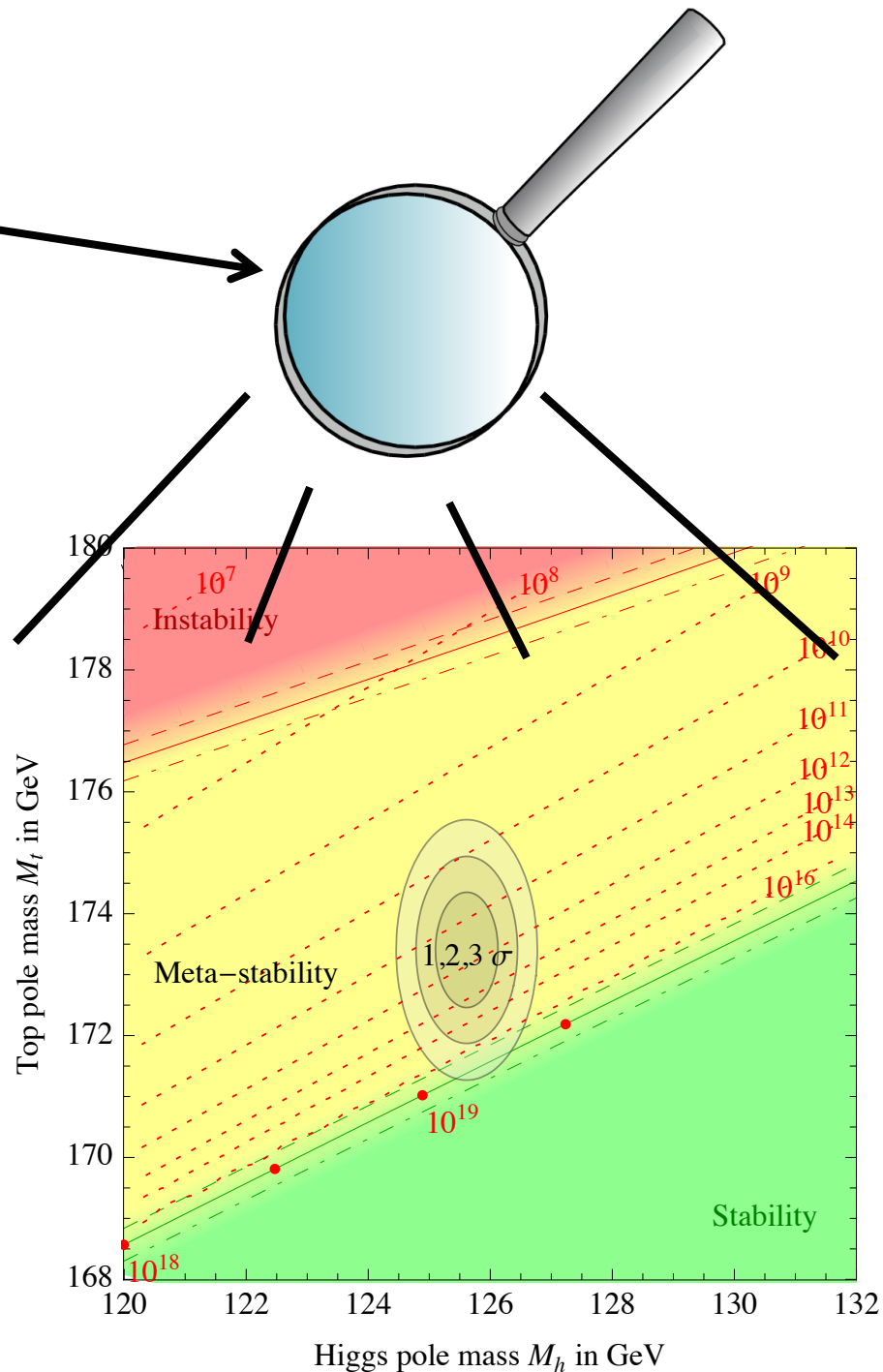




- Quantum tunneling
- Thermal tunneling

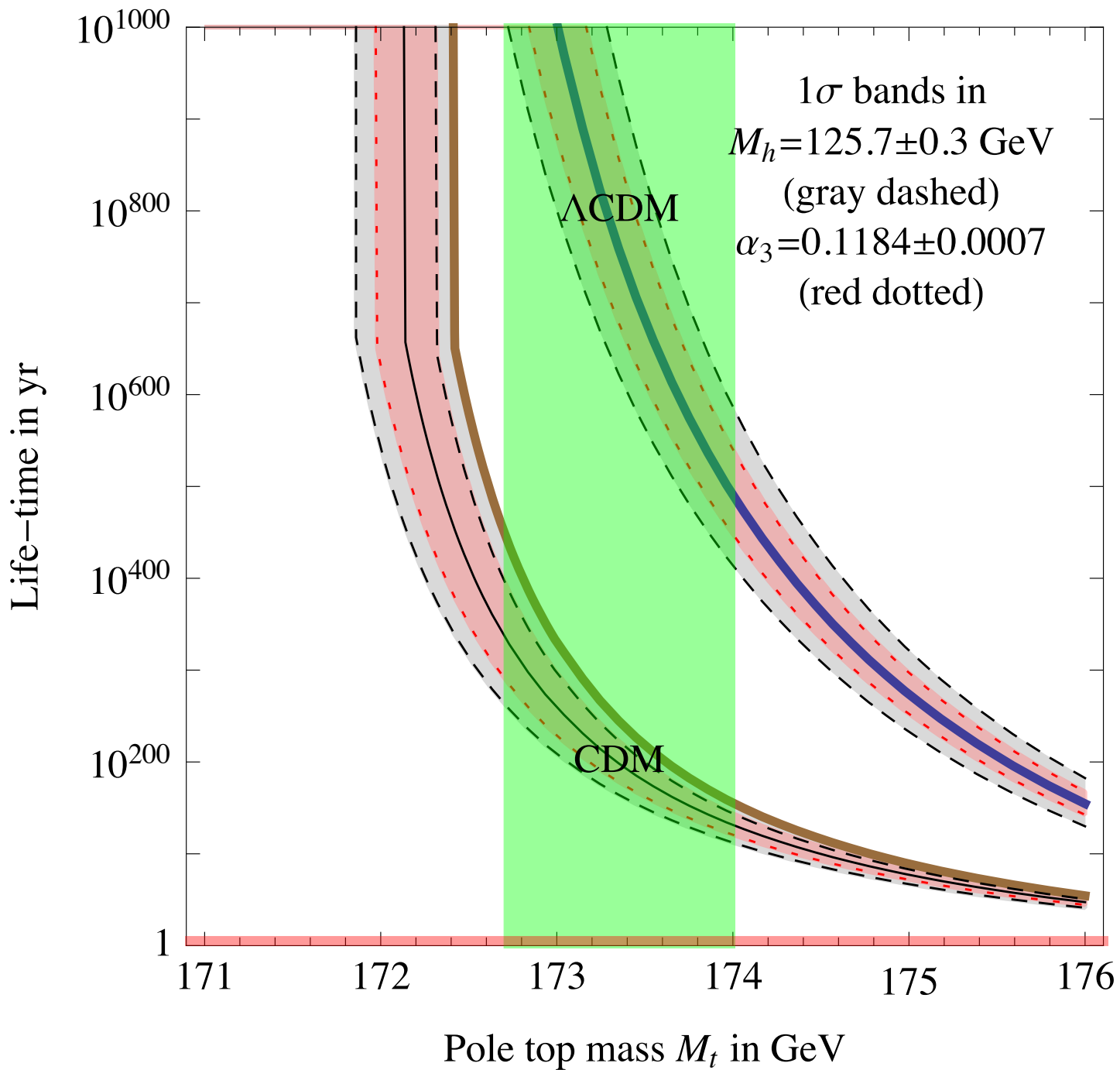


Higgs mass just right to keep the universe at the edge of vacuum stability

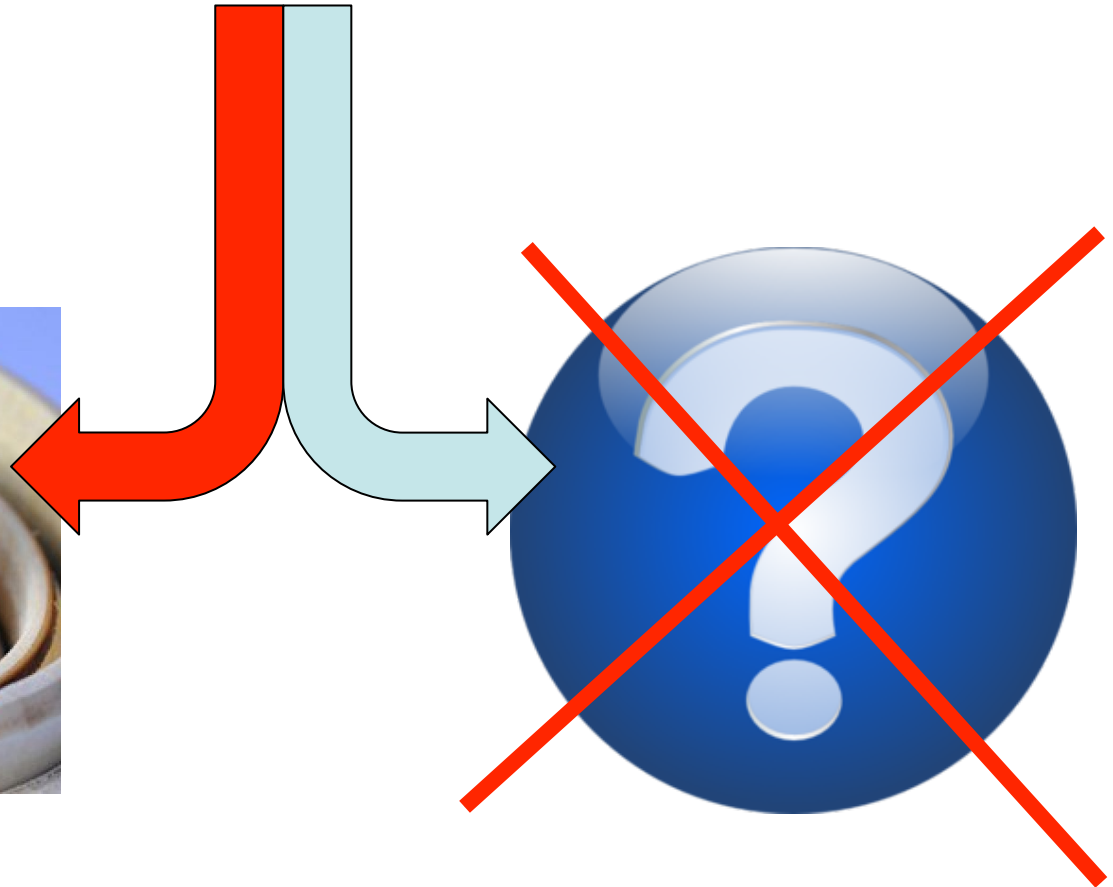


Why is the Higgs mass just right to keep the universe on the verge of a cosmic catastrophe?





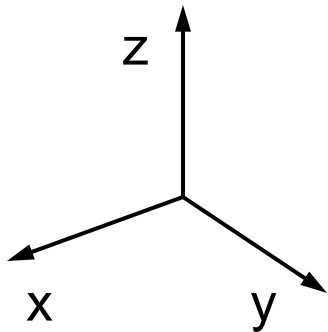
Does the Higgs respect the naturalness principle ?



Largely an experimental question

Some of the new ideas about naturalness and EW breaking revolutionize our concepts of space-time, matter and forces

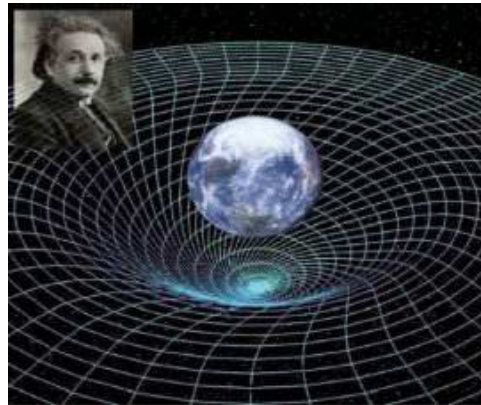
Supersymmetry emerges from the search for new space-time symmetries



3-d space

translations/rotations

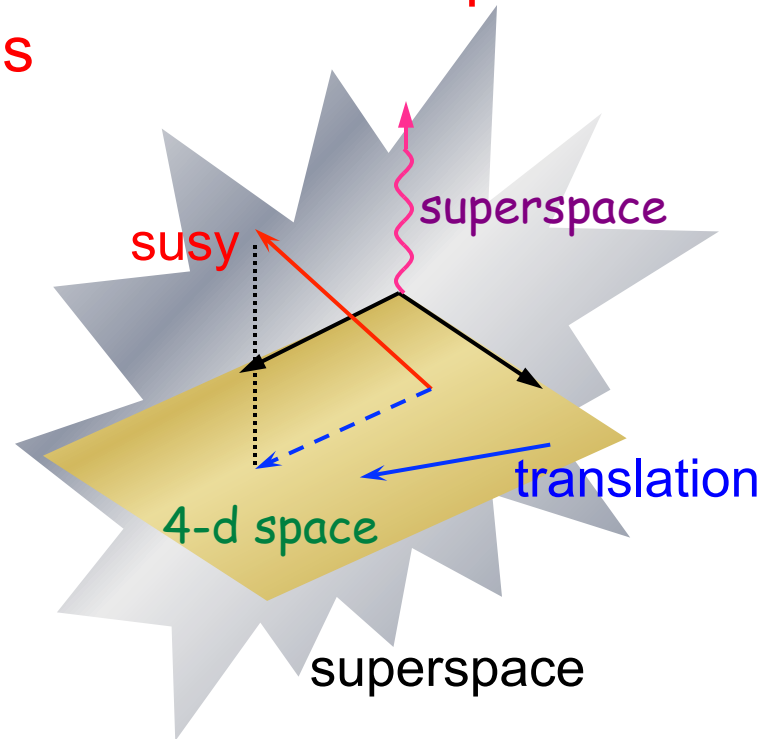
$$P = (x,y,z)$$



4-d space-time

Poincaré

$$P = (t,x,y,z)$$

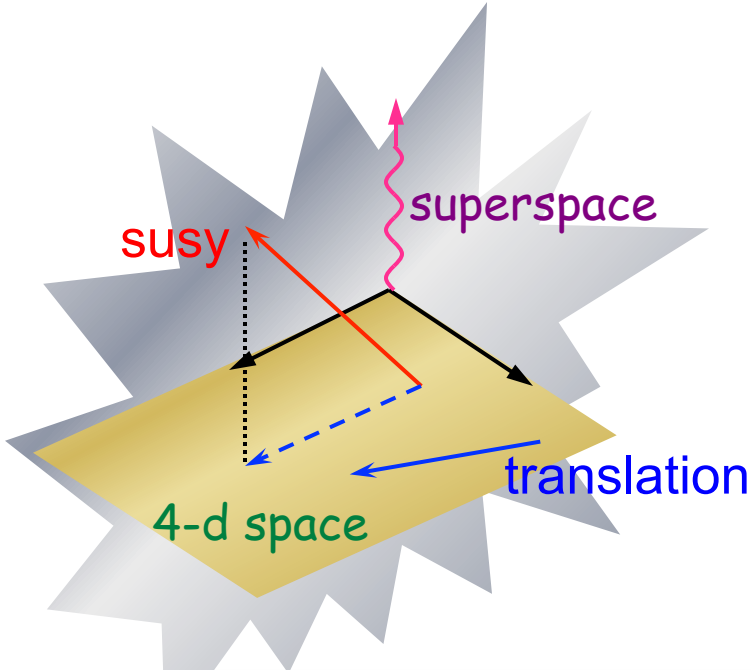


superspace

supersymmetry

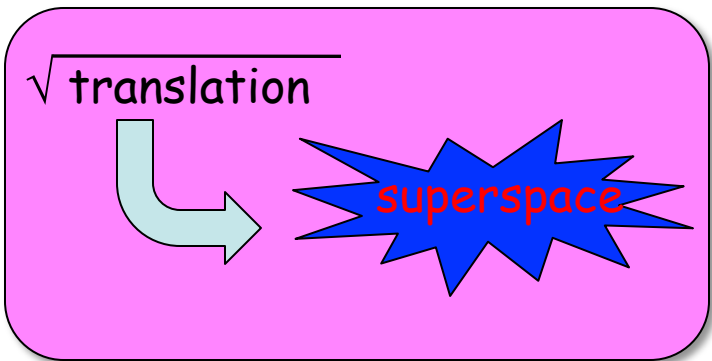
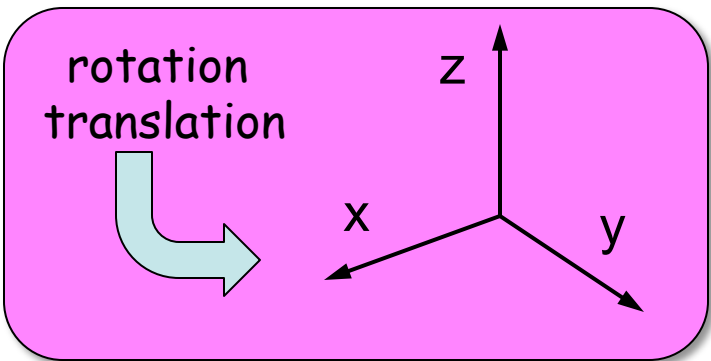
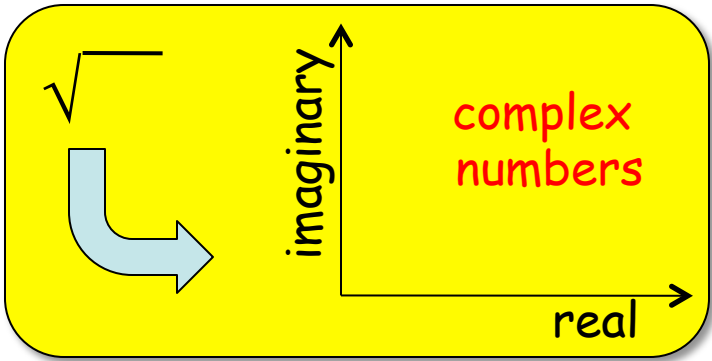
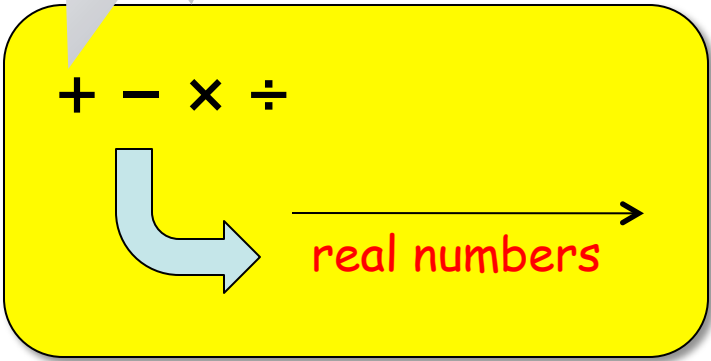
$$P = (t,x,y,z,\bar{\theta},\theta)$$

The new coordinates have a quantum character and cannot be described by ordinary numbers



$$\theta \times \eta = -\eta \times \theta \implies \theta^2 = 0$$

SUSY × SUSY = Translation



This new space has unfamiliar geometric properties
(but it is mathematically consistent)

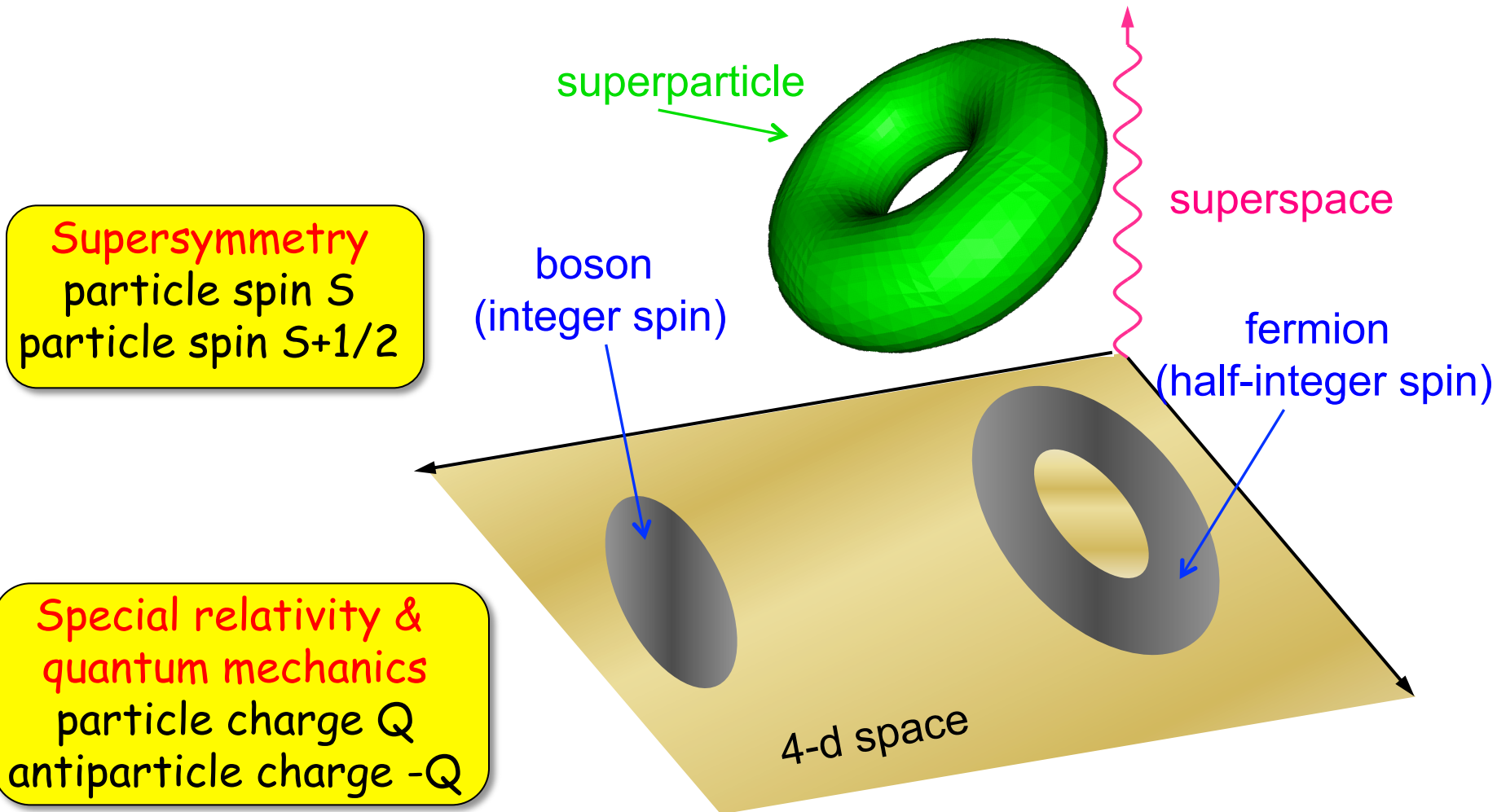
What is the physical meaning of superspace?

Fields: $\psi(x) \rightarrow$ particles

Taylor expansion of superfields:

$$\varphi(x, \theta) = \sum_n \varphi_n(x) \theta^n = \varphi_0(x) + \varphi_1(x) \theta$$

What happens to particles propagating in superspace? **Superparticle!**



Why is supersymmetry interesting?

- supersymmetry relates particles with different spin → must involve space-time transformations → (super)gravity
- supersymmetry necessary ingredient for string theory?
- supersymmetry may be the answer to the naturalness problem