Utrecht University

CERN 22nd European School
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Theory Outlook

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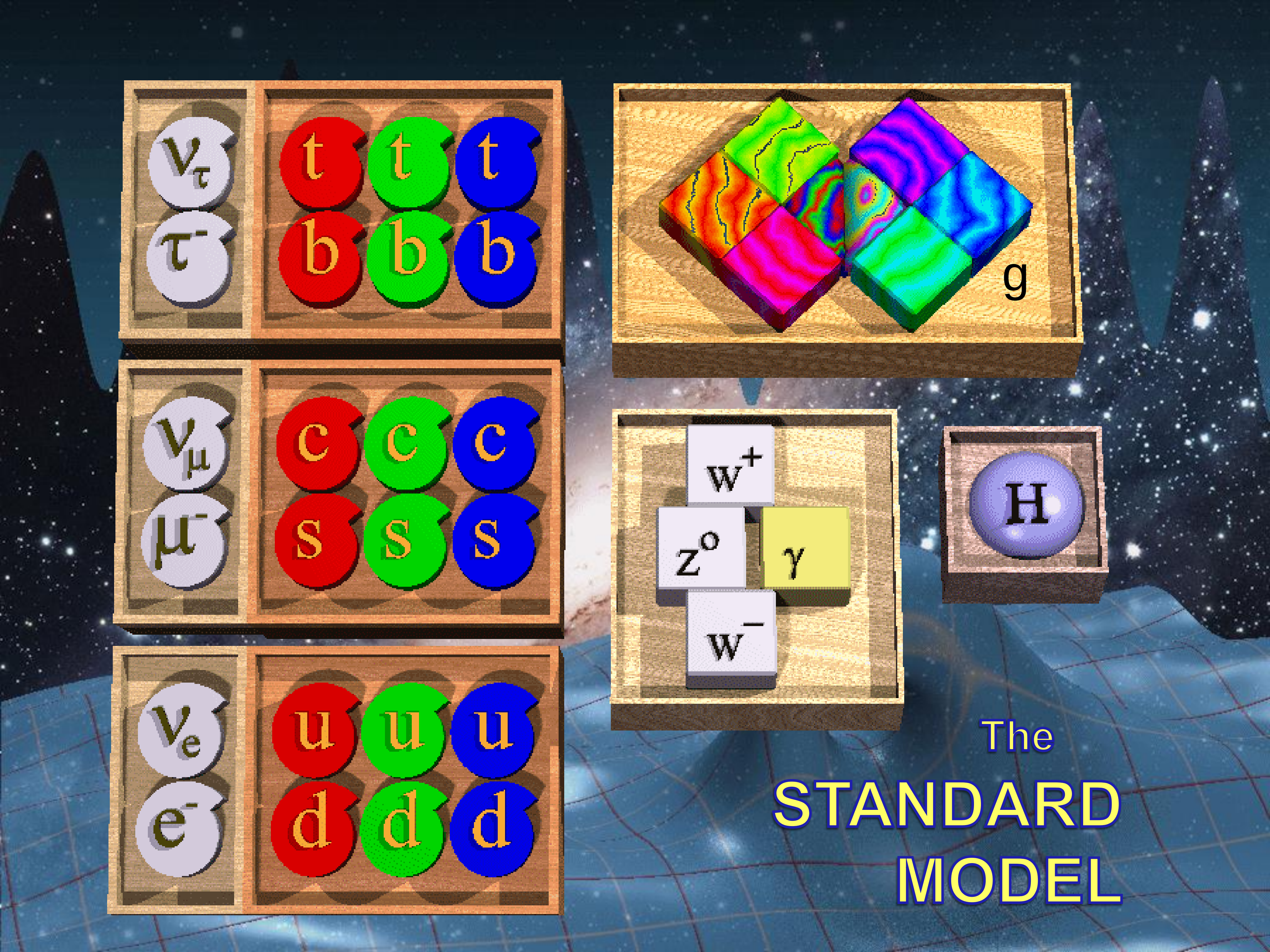
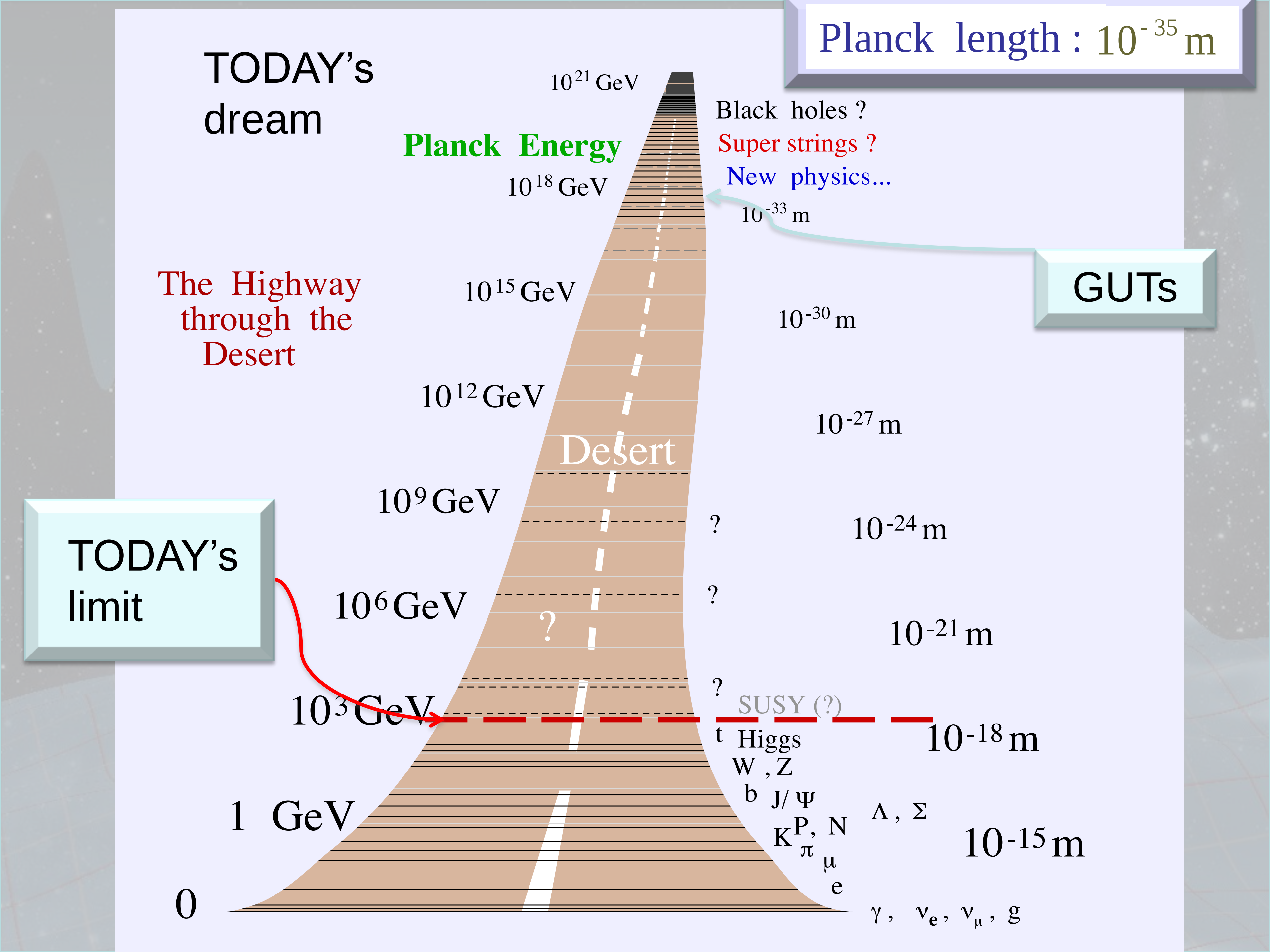


ν_τ
τ^-
t t t
b b b
ν_μ
μ^-
c c c
s s s
ν_e
e^-
u u u
d d d
g
W^+
Z^0
γ
W^-
H
The
STANDARD
MODEL



Planck length : 10^{-35} m
TODAY's dream
Planck Energy
10^{21} GeV
10^{18} GeV
10^{15} GeV
10^{12} GeV
10^{9} GeV
10^{6} GeV
10^{3} GeV
1 GeV
0
Black holes ?
Super strings ?
New physics...
10^{-33} m
GUTs
10^{-30} m
10^{-27} m
10^{-24} m
10^{-21} m
10^{-18} m
10^{-15} m
The Highway through the Desert
Desert
?
TODAY's limit
SUSY (?)
t Higgs
W , Z
b J/ Ψ
Λ , Σ
K P, N
π
μ
e
γ , ν_e , ν_μ , g

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

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

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

The Planck Units:

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

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

$$E_{\text{Planck}} = M_{\text{Planck}} c^2 = \sqrt{\frac{\hbar c^5}{G_N}} = 1.20 \times 10^{28}\,\mathrm{eV}$$

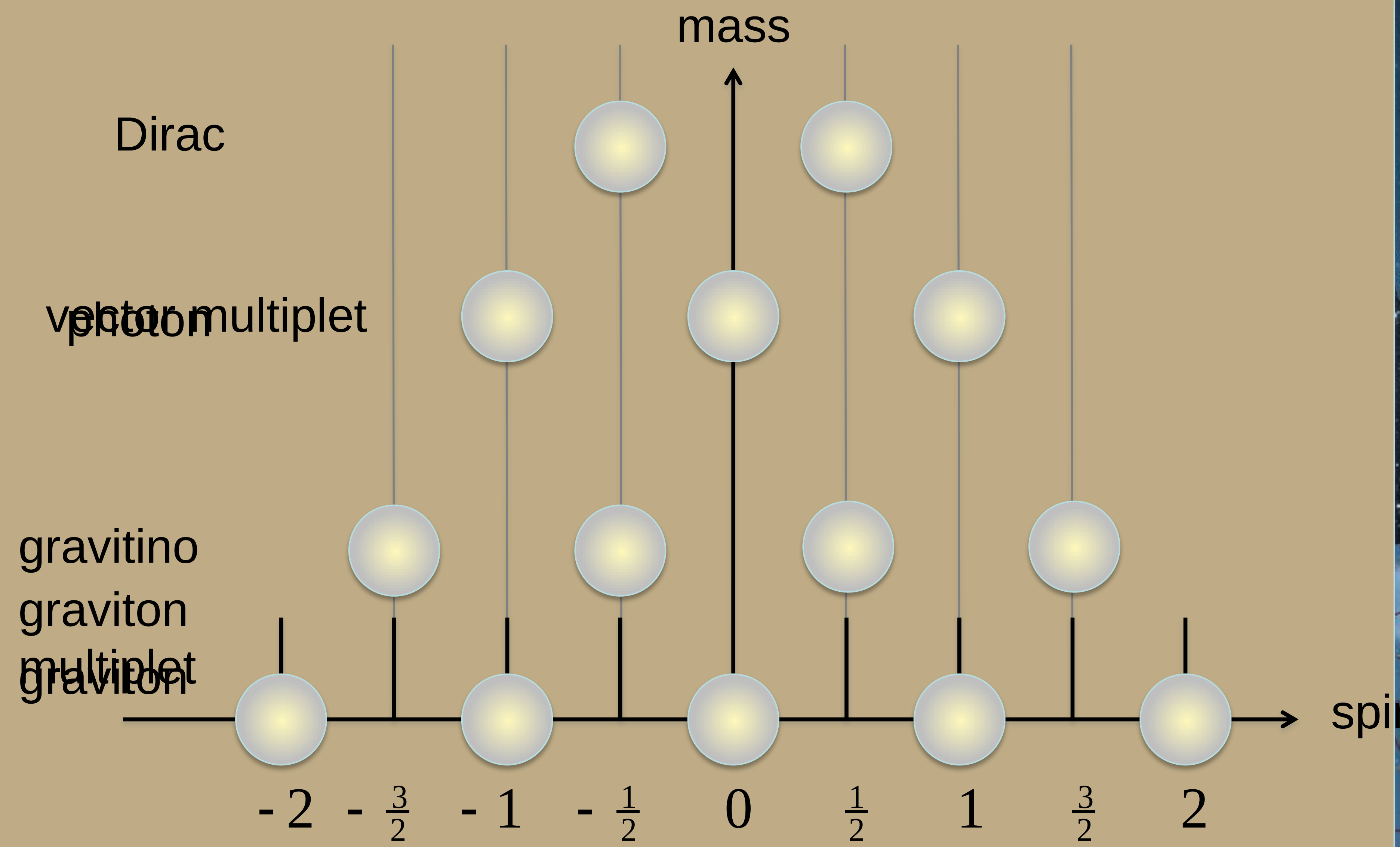
Essential clues needed:

What's the first thing beyond today's limit ?

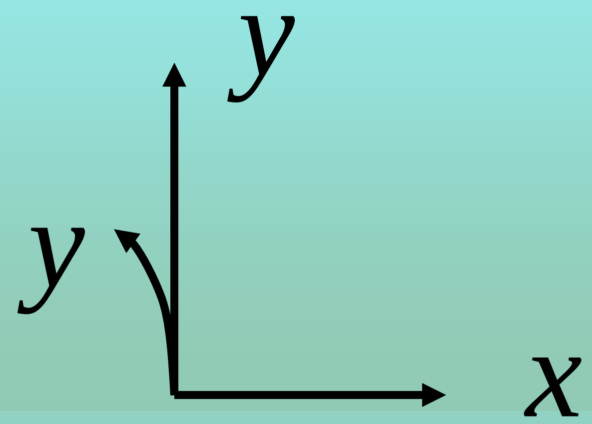
- Is there supersymmetry ?
- Extra dimensions ?
- Nothing ??

phenomenology | basic theory

Supersymmetry: a promising new view on space and time since Einstein 1916



Extra Dimensions

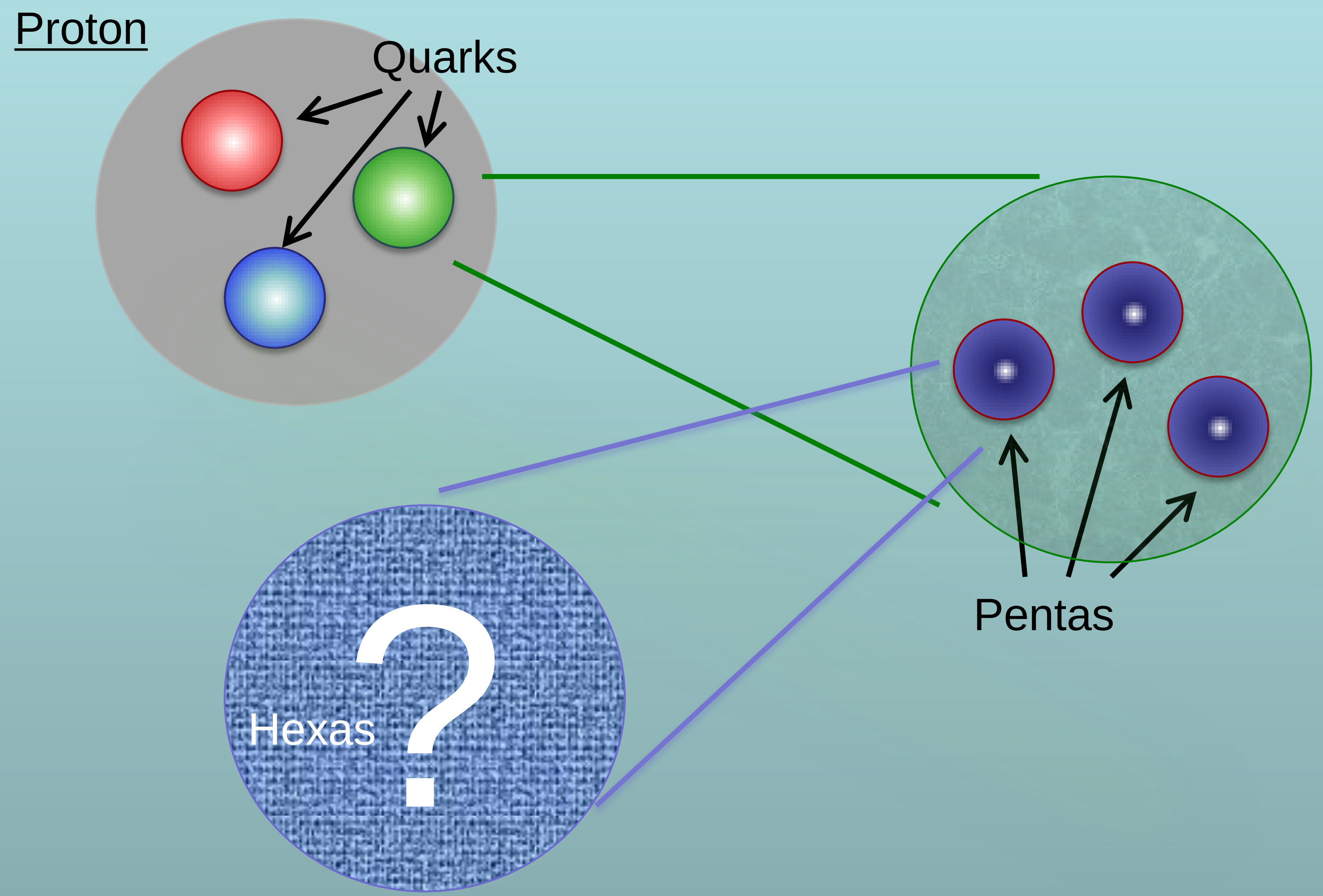


Extra dimensions: $x \longrightarrow x + L\,e^5 \qquad e^{ip^5 L} \equiv \mathbb{I}$

$$E = \sqrt{\vec{p}^{\,2} + (p^5)^2 + m^2}$$

Kaluza Klein towers: $p^5 = 2\pi\, n / L \;;\quad M_n = \sqrt{m^2 + (2\pi n/L)^2} \rightarrow \dfrac{2\pi n}{L}$

Compositeness



Problem with the compositeness idea:

Quarks and leptons are *light*; but their constituents must be *very pointlike* (invisible below a TeV).

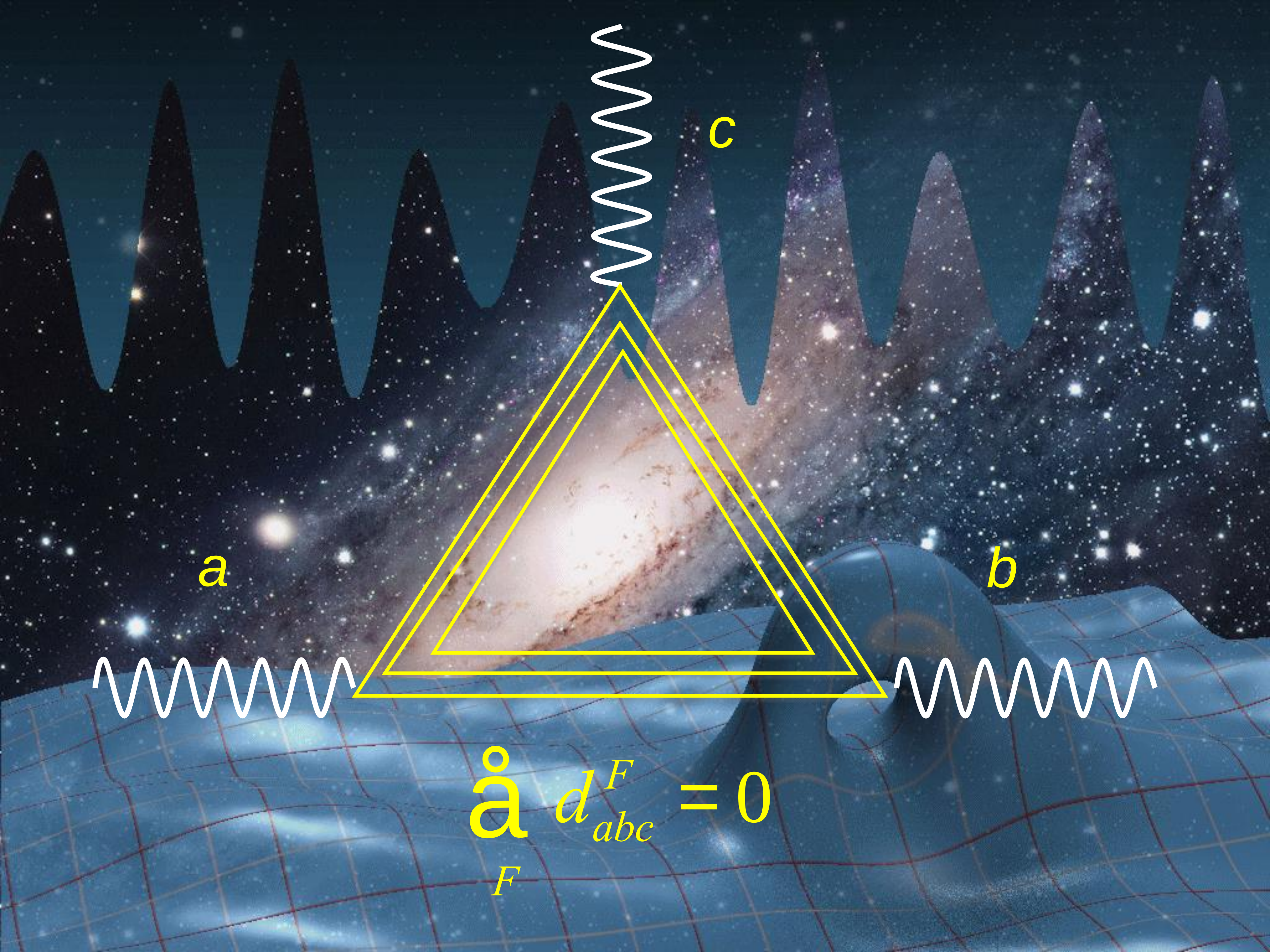
Compare: pions are light, yet quarks are pointlike.

Pions are *protected* by the conservation of the chiral current (PCAC). We need such a protection mechanism for the pentas.

Chiral currents can be conserved only if they are not broken by anomalies. They must contribute to the anomalies exactly as the chiral currents that protect the leptons and the quarks themselves ...

Anomaly matching conditions

These conditions tell you how many light fermions you can build out of pointlike constituents, and usually those numbers seem to emerge as *fractional.*


c
a
b
å $d_{abc}^{F} = 0$
F

To better guess about what's out there, investigate the *other end* of the highway through the desert:

The end point is *quantum gravity*

Amazingly, we have no comprehensive theoretical models telling us how to do this right:

- what happens *to space and time*? Do they become *discrete*?
- how should the *complete spectrum* of physical states be described?
- how does the spectrum of ***black holes*** relate to the spectrum of the elementary field quanta?

What is Nature's book keeping system?

Superstring Theory comes closest to such a theory, but it has too many ill understood features

superstring theory cannot be the entire truth regarding physics at the Planck scale

Quantum gravity must be the *end point*:

At the Planck scale: - gravitational interactions become strong
- space-time curvature becomes unbounded

Holographic principle: - limit to density of quantum states per unit of surface
- this is the scale where black holes behave as particles, and particles behave as black holes.

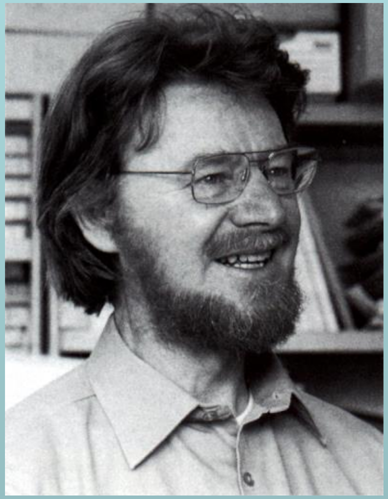
Most investigators take it for granted that the smallest pieces of information are **qubits**.

But it's quantum mechanics that is one of the causes of our problems there: basic operators such as displacement p_μ in space and time, become ambiguous due to curvature.

Proposal: the elementary unit of information could be classical: a single boolean **bit**.

The idea that there are ordinary bits & bytes underlying quantum mechanics is very old …

and most often categorically dismissed:
Bell's theorem and CHSH inequality.



John S. Bell

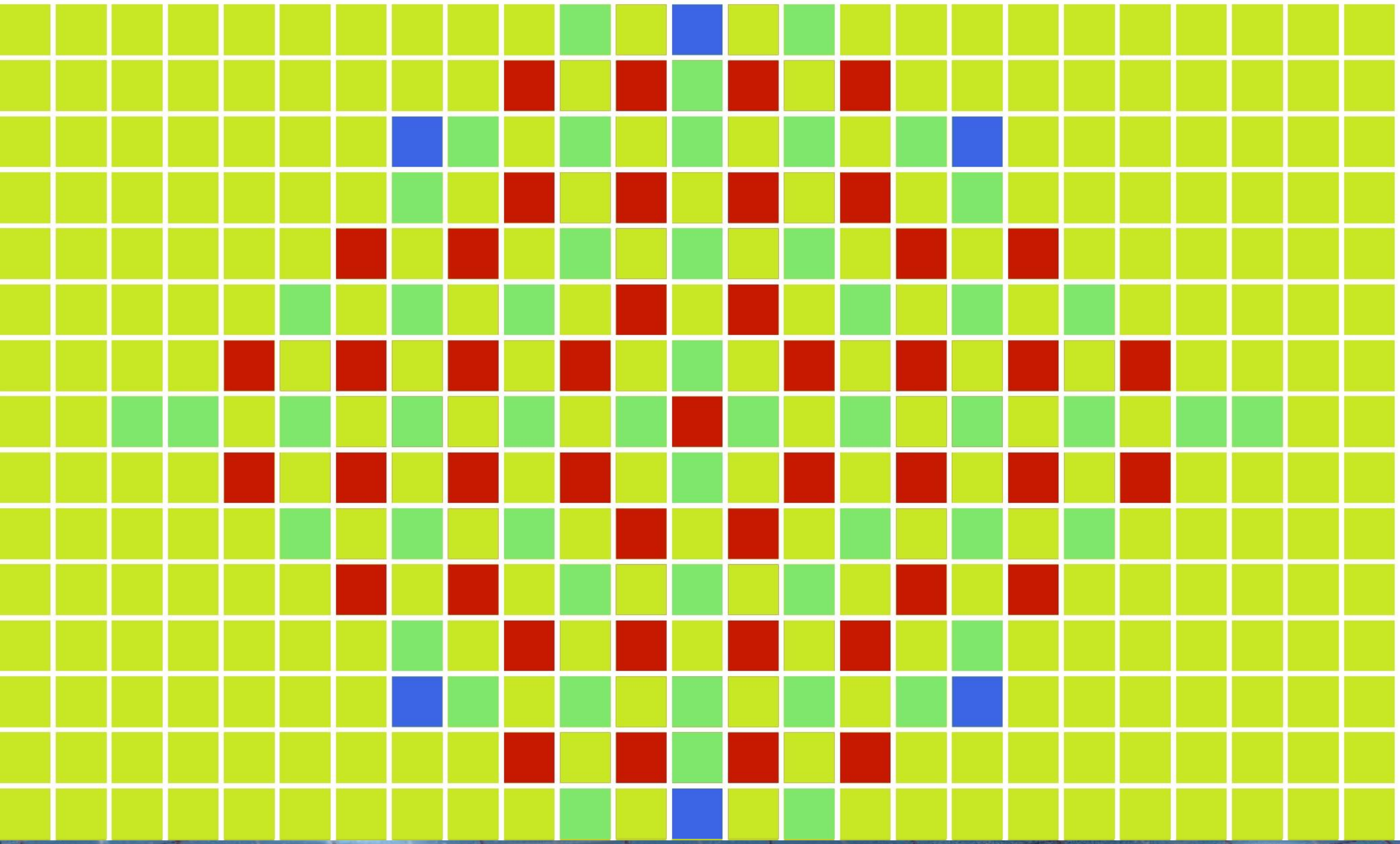
J.F. Clauser,
M.A. Horne,
A. Shimony,
R.A. Holt.

But what they prove, is not quite that. Rather:

You can't have local counterfactual realism

The Cellular Automaton Interpretation of Quantum Mechanics (CAI)

Compulsory or impossible ?



At the Planck scale, nature is just an
information processing machine

(Perhaps fundamentally quantum mechanical, but possibly simply classical)

Can we link this to LHC physics or other directly observable features?

Probably not. But maybe we can shed some light on

THE SCALAR SECTOR

- The Higgs particle and its mass
- Quadratic divergences and naturalness in QFT
- The tachyon in string theories
- Conformal symmetries in gravity

Scale transformations cover some 20 orders of magnitude from the Higgs to the Planck scale.

Now assume this symmetry to be only very weakly broken (as concluded from the very special value found for the Higgs mass)

Scale symmetry --➔ Conformal symmetry

Could conformal symmetry, rather than supersymmetry, be used to restore naturalness?

The Hierarchy problem:

Why is the universe so **big** ?

Can any “simple” theory explain our gigantically complex universe?

Sizes in the Universe

Size of Universe itself:	$5 \times 10^{26}\ m$
Size of stars and planets:	$10^{7} - 10^{10}\ m$
Size of humans:	$1\ m$
Size of Atoms:	$10^{-10}\ m$
…	
…	
Planck size:	$10^{-35}\ m$

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Many other constants make *dimensionless combinations*:

Fine structure constant:

$$\alpha = e^2 / 4\pi\hbar c = \frac{1}{137.036}$$

$\dfrac{\text{proton mass}}{\text{Planck units}}$:

$$\kappa = m_P \sqrt{G/\hbar c} = 7.685 \times 10^{-20}$$

$\dfrac{\text{proton mass}}{\text{electron mass}}$:

$$\frac{m_P}{m_e} = 1836.1527$$

$\dfrac{\text{Cosmological Constant}}{\text{Planck units}}$:

$$\frac{\Lambda \hbar G}{c^5} = 3 \times 10^{-122}$$

Size atomic nucleus: $$10\frac{\hbar}{m_P\,c} \approx 2\times 10^{-15}\,m$$

Size of atoms : $$\frac{\hbar}{\alpha\, m_e\, c} \approx 0.5\times 10^{-10}\,m$$

Density of rock: $$\approx m_P\left(\frac{\alpha\, m_e c}{\hbar}\right)^3 \approx 11\,g\,/\,cm^3$$

Mass of planet (chemical):

$$\sqrt{\frac{\alpha^3 c^3 \hbar^3}{m_P^4\, G^3}} \approx 384\ M_{\mathrm{Earth}}$$

Mass of planet (chemical): $$\sqrt{\frac{\alpha^3 c^3 \hbar^3}{m_P^4 G^3}} \approx 384\ M_{\text{Earth}}$$

$$\frac{\text{mass of star (nuclear)}}{\text{mass of planet (chemical)}} :$$

$$\left(\frac{m_P}{m_e\ \alpha^2}\right)^{3/4} \approx 450\,000$$

$$\frac{\text{“ Size of the universe”}}{\text{Planck length}} : \quad \sqrt{\frac{c^5}{\Lambda\ \hbar\, G}} = 10^{61}$$

The anthropic argument:

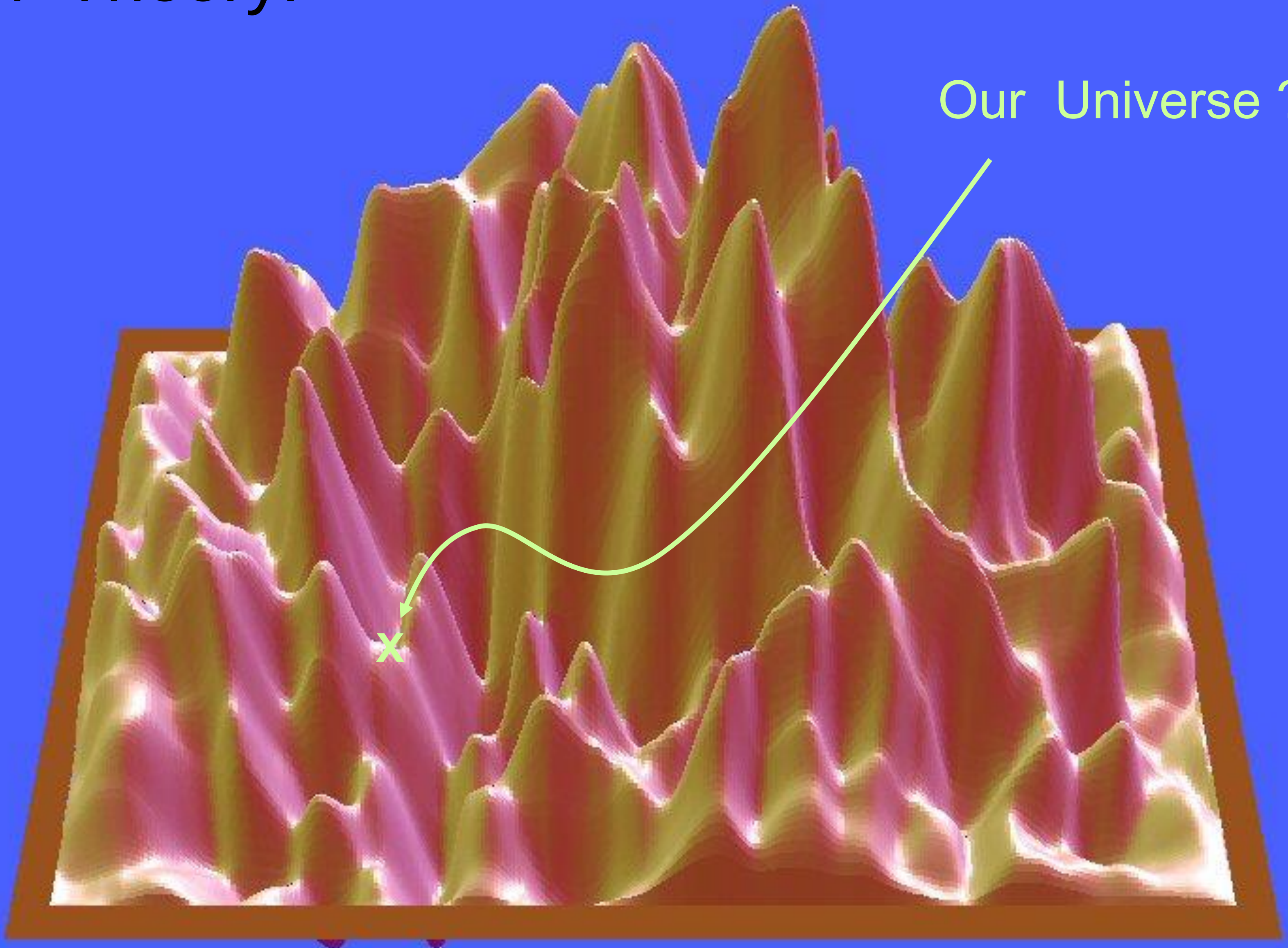
"Constants of Nature are what they are (very big or very small) because if they weren't, we wouldn't be here to observe them ..."

Other universes, with different constants, exist but are not inhabited ...

One version of this anthropic argument is obviously true:

M Theory:

The Landschape



Alternative approach to the hierarchy problem:

Large and small mathematical numbers can arise very quickly in theories with only modest complexity

Or: can we find a natural theory that generates a quantum world where masses and interaction constants take values that range over scales up to more than 120 orders of magnitude?

Possible strategy:
First: find a theory that leads to non-interacting, massless quantum fields.
Next: introduce a very tiny interaction or disturbance of the scale invariance.
This might generate tiny masses (at the Planck scale) and tiny running couplings (very tiny beta functions)

But it is not known how to carry out such a program

≈

This is where new ideas are needed.