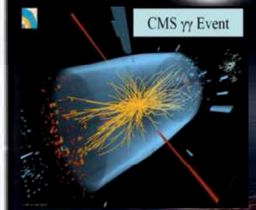


Particles and Universe

Lecture 13 Beyond SM

Maria Krawczyk, Aleksander F. Żarnecki

Faculty of Physics UW

I. Standard Model - problems

II. Beyond SM

Standard Model very successful- however they are problems:

- Many parameters (masses)~20 *more in other models*
- Why 3 fermion families? *no answer in other models*
- Why matter=fermions and forces=bosons
- Hierarchy problem -

$$M_H(\sim 100 \text{ GeV}) \ll M_{\text{Planck}} \ (10^{19} \text{ GeV})$$

often formulated as difference of the EW (~ 1 TeV) and Planck scales

- Gravitation (gravity)?
- Describes 4 % of Universe - no candidate for Dark Matter, no explanation for Dark Energy

Standard Model very successful- however they are problems:

- Why lepton and barion numbers conserved?
- Nonzero mass of neutrinos
- Barion asymmetry in the universe -

  require CP violation much stronger than in SM
- What is the mechanism of the

  EW symmetry breaking?

Deviation from the SM? Higgs boson as in SM ?

Non-zero neutrino mass

⇒ ograniczenie na masę neutrina elektronowego:

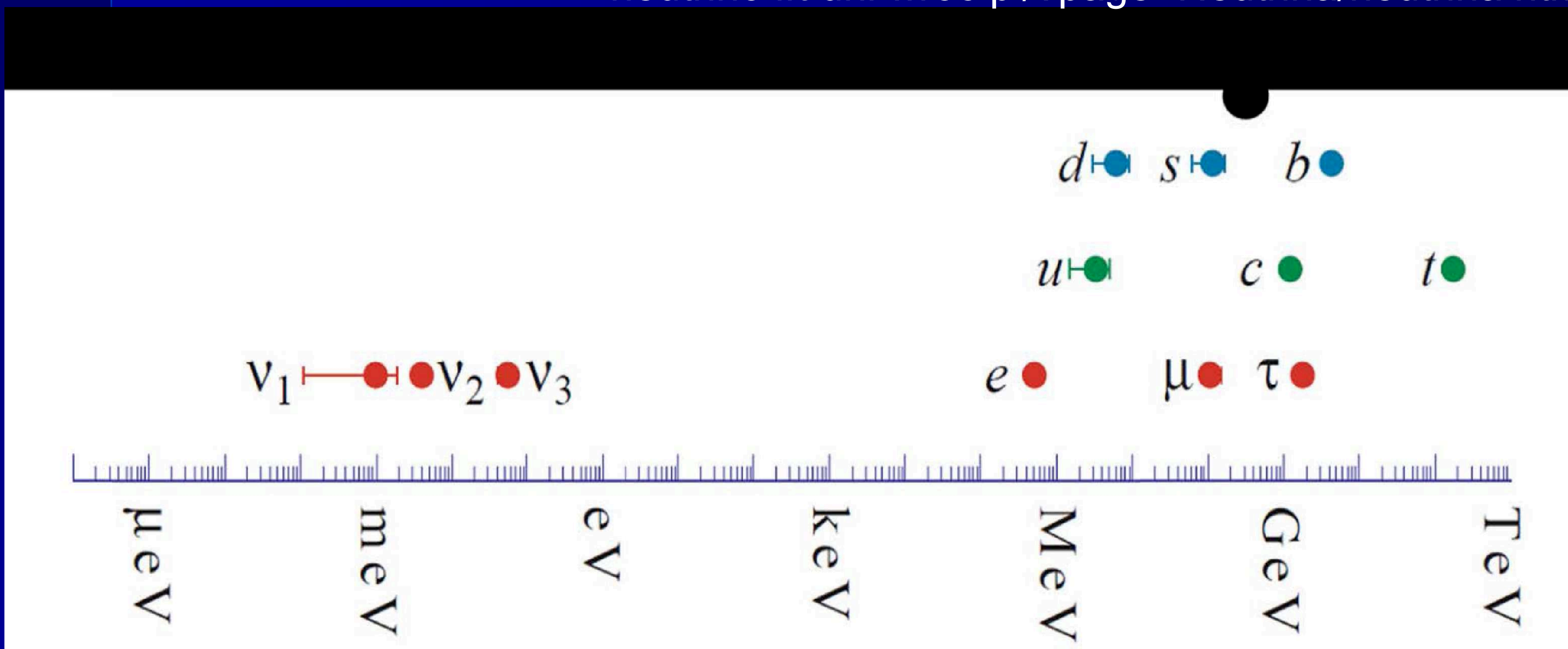
$m_\nu < 2.2\,eV$ (95% CL)

- In the SM (neutrino mass ZERO)
  - only left neutrinos and right antineutrinos
- However from ~ 2001 we know that neutrinos have masses → extra neutrino/ antineutrino states
- For sure weak interaction of these extra states very, very weak (experiments)

- SM extension in the EW sector – with extra SU(2) symmetry for left and right states, and suppression mechanism explaining very small masses of neutrinos (seesaw ..)

Masses of fermions

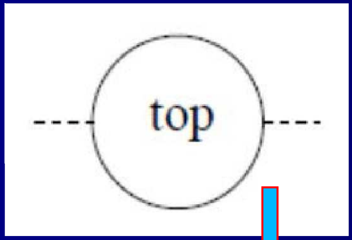
neutrino.ift.uni.wroc.pl/?page=Neutrina/neutrina.html

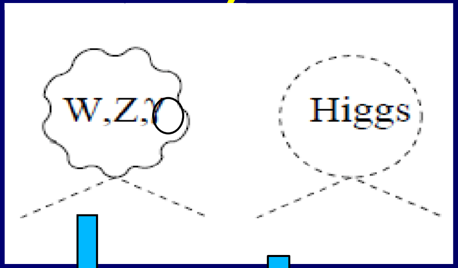


Hierarchy problem in the SM

- SM works at present energies – up to which energy (Λ) can we apply it?
- Quantum corrections to the Higgs mass - loops with arbitrary large energies.
- If we include contributions only up to energy Λ (cut –off)
- Corrections to the Higgs mass (squared)

~ {couplings²} x Λ^2





For Λ = 10 TeV

and mass ~ 200 GeV

$$m_h^2 = m_{tree}^2 - [100 - 10 - 5]\,(200GeV)^2$$

Fine-tuning for SM

- 10 TeV

$$m_h^2 = m_{tree}^2 - [100 - 10 - 5]\,(200GeV)^2$$

1/100 fine tuning

$$-\frac{3}{8\pi^2}\lambda_t^2\Lambda^2 \sim -(2\,TeV)^2$$

from the top loop,

$$\frac{1}{16\pi^2}g^2\Lambda^2 \sim (700\,GeV)^2$$

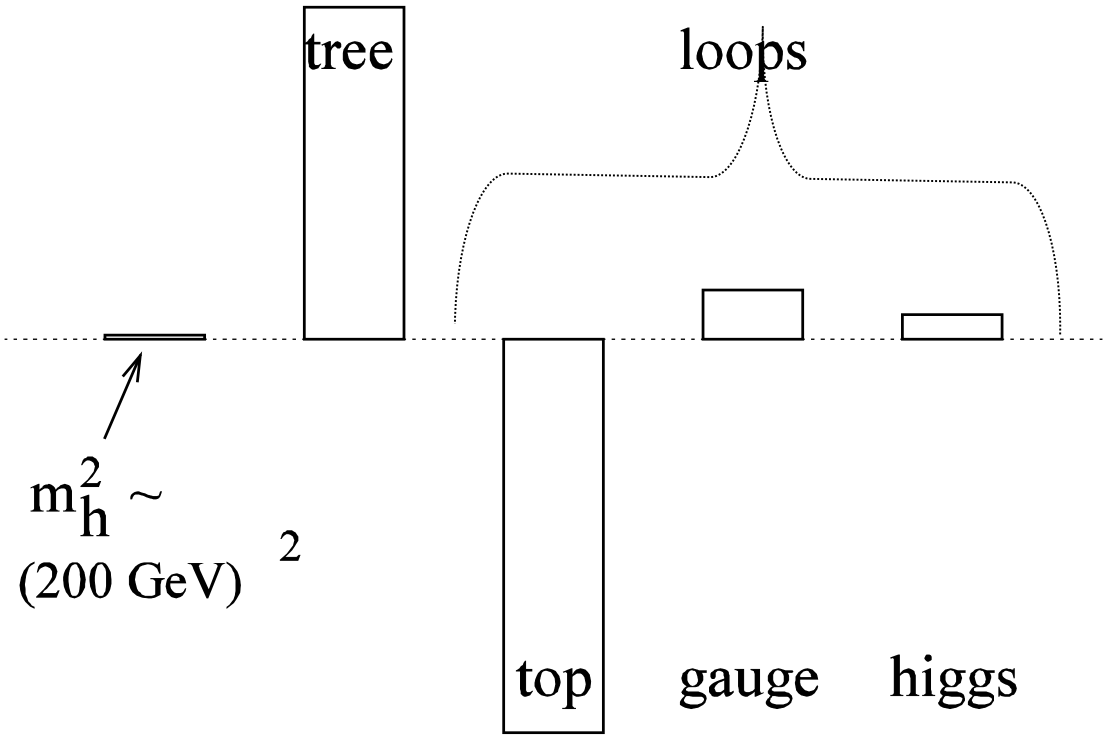
from the gauge loop, and

$$\frac{1}{16\pi^2}\lambda^2\Lambda^2 \sim (500\,GeV)^2$$

from the Higgs loop. Thus

- Λ =1 TeV no fine tuning (SM natural)

Fine tuning for Λ = 10 TeV



Schmaltz'
2000

Fine tuning in the SM → new physics

In LHC energy ~ 10 TeV (Λ)

fine tuning 1/100

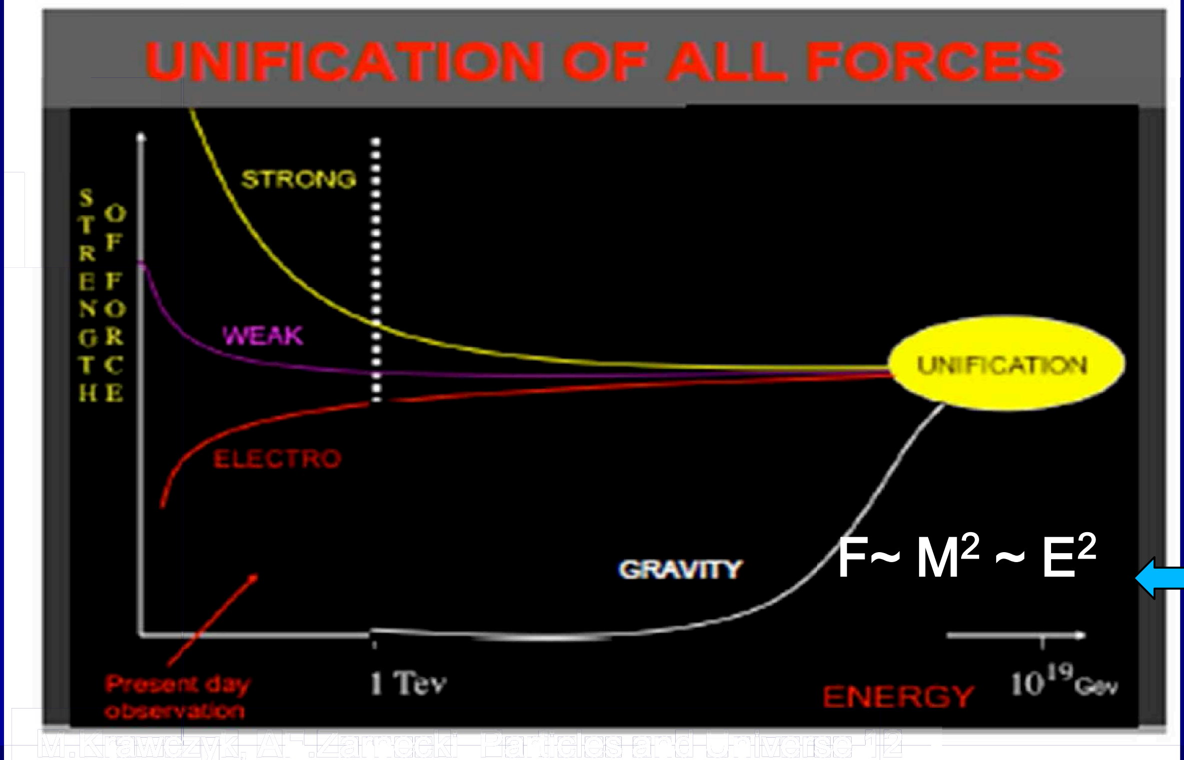
→ new physics expected:

new particles and/or new interactions

Gravitation

- New physics - gravitation?
- Gravitation- very weak for small energies.
  It is strong at very large energies

→ „strength" equal to other couplings for Planck energy



Newton law

David Gross: The Coming Revolutions
in Theoretical Physics

http://www.youtube.com/watch?v=AM7SnUlw-DU&feature=channel

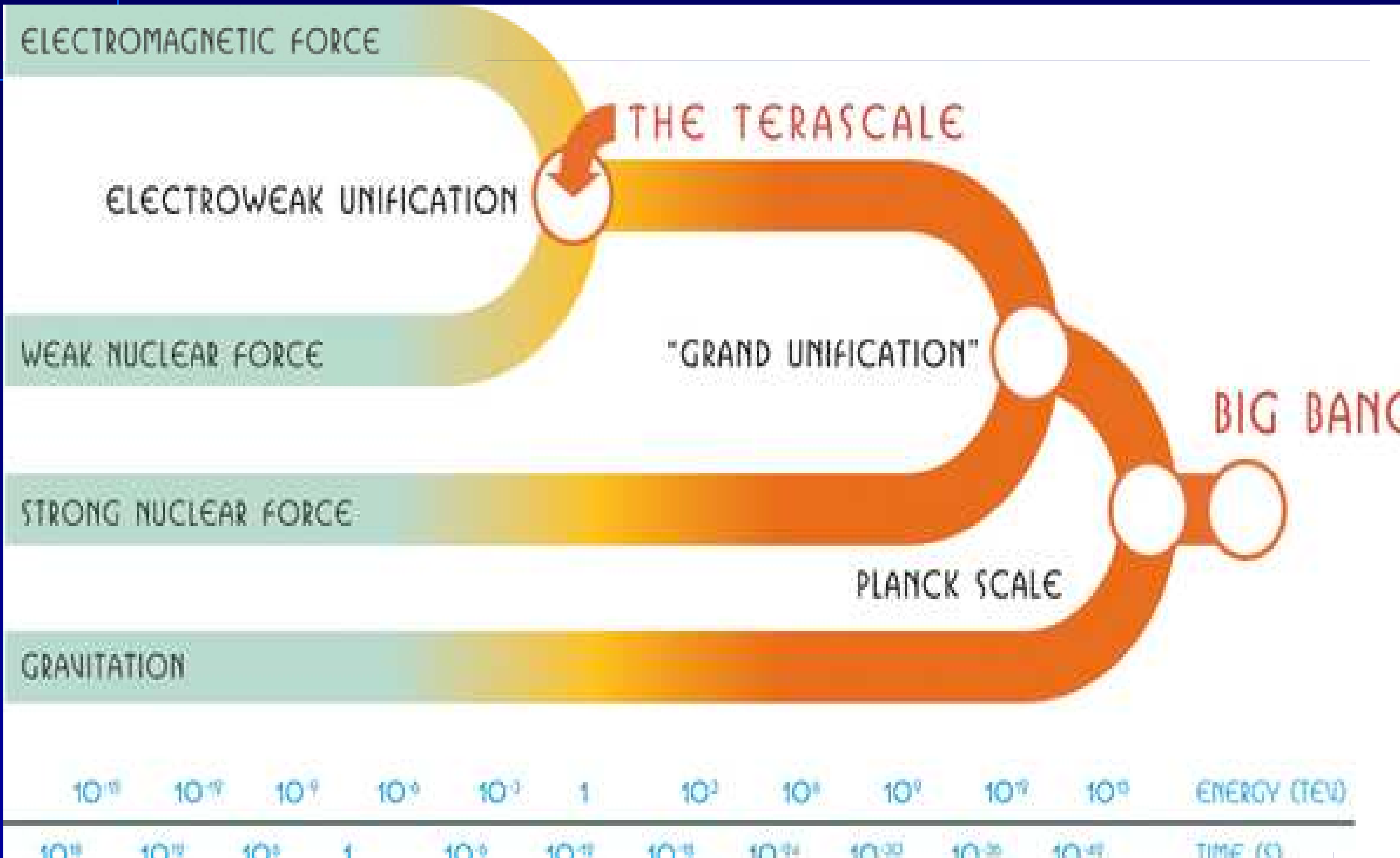
Beyond SM → towards unification

- Standard Model: gauge symmetry $\underline{SU(2)xU(1)}xSU(3)_c$
  EW: $\underline{SU(2)xU(1)}$ → partial unification of weak and e-m interactions
- Grand Unified Theory – GUT (various models)
  → unification of EW and strong interaction.
  Gauge symmetry GUT acts at energies above $10^{15\text{-}16}$ GeV.
- In fundamental description of gravity → Planck scales:
  Planck mass 1.2×10^{19} GeV
  Planck lenght 1.6×10^{-35} m
- Theory of Everything - full unification of interactions (together with gravity)

J. Lukierski: Od Modelu Standardowego do teorii M: Teorie Wszystkiego

http://postepy.fuw.edu.pl/zjazdy/Gdansk2003/PF404Lukierski.pdf

UNIFICATION WITH GRAVITATION AND EARLY UNIVERSE



Beyond the Standard Model

1/ Extension of symmetry

→ supersymmetry

2/ Extension of space-time

→ extra space dimensions

3/ Extension of size of particles

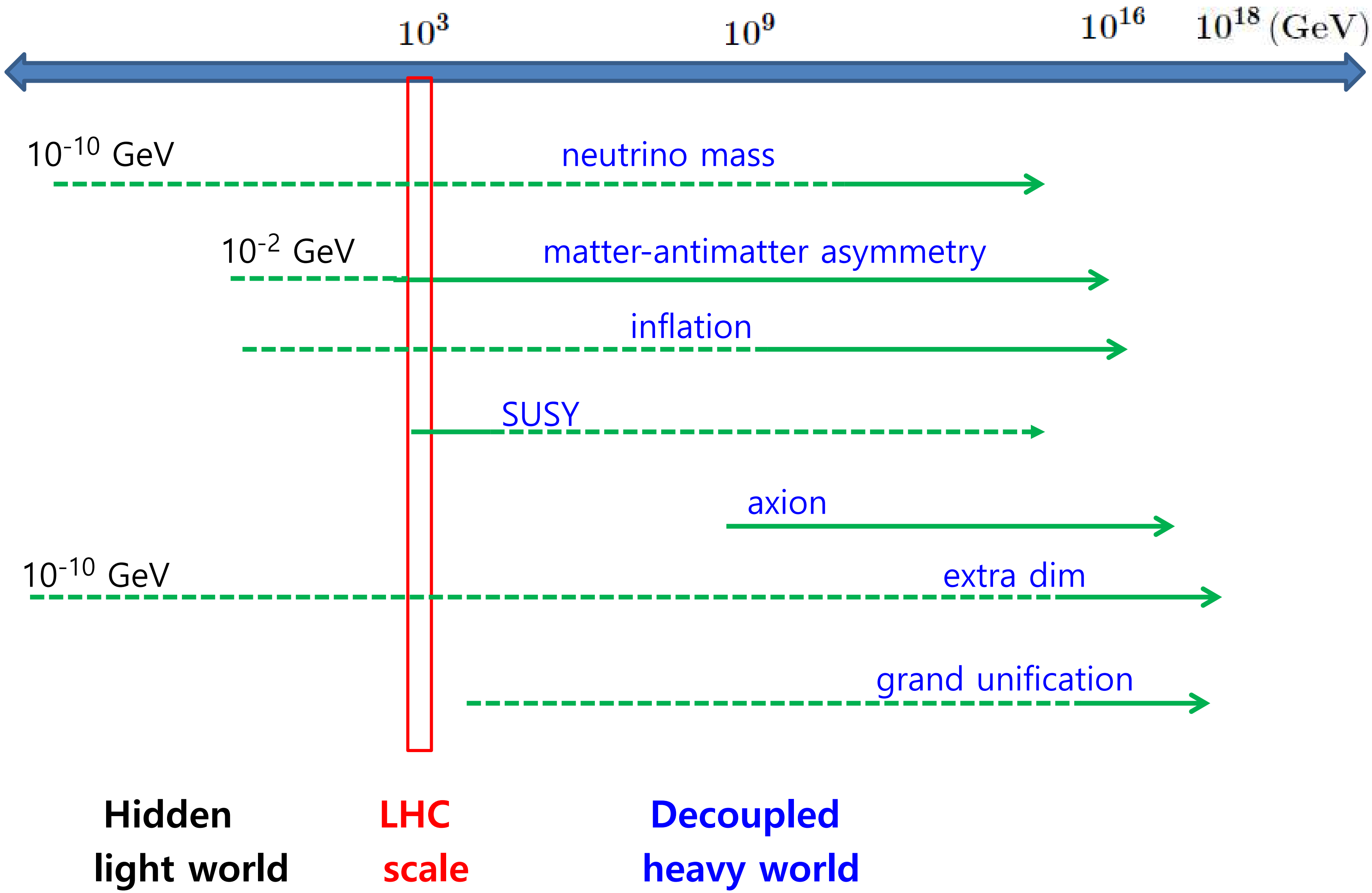
→ extended fundamental particles

(strings, membrans and p-brans)

Towards the Theory of Everything (TOE)

(almost no works on substructure...)

Scales of new physics



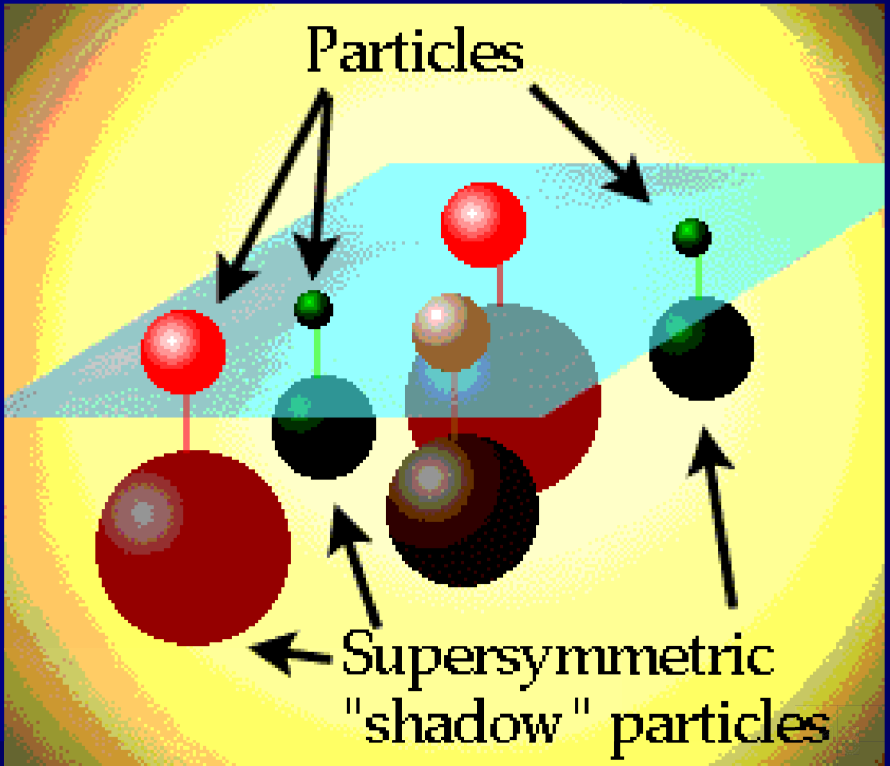
SUPERSYMMETRY

- In Nature only two types of particles: fermions and bosons
- In Supersymmetry there is a symmetry fermion↔boson, so doubling of fundamental particles is assumed
- Supersymmetric partners of all known SM fundamental particles = SUSY particles

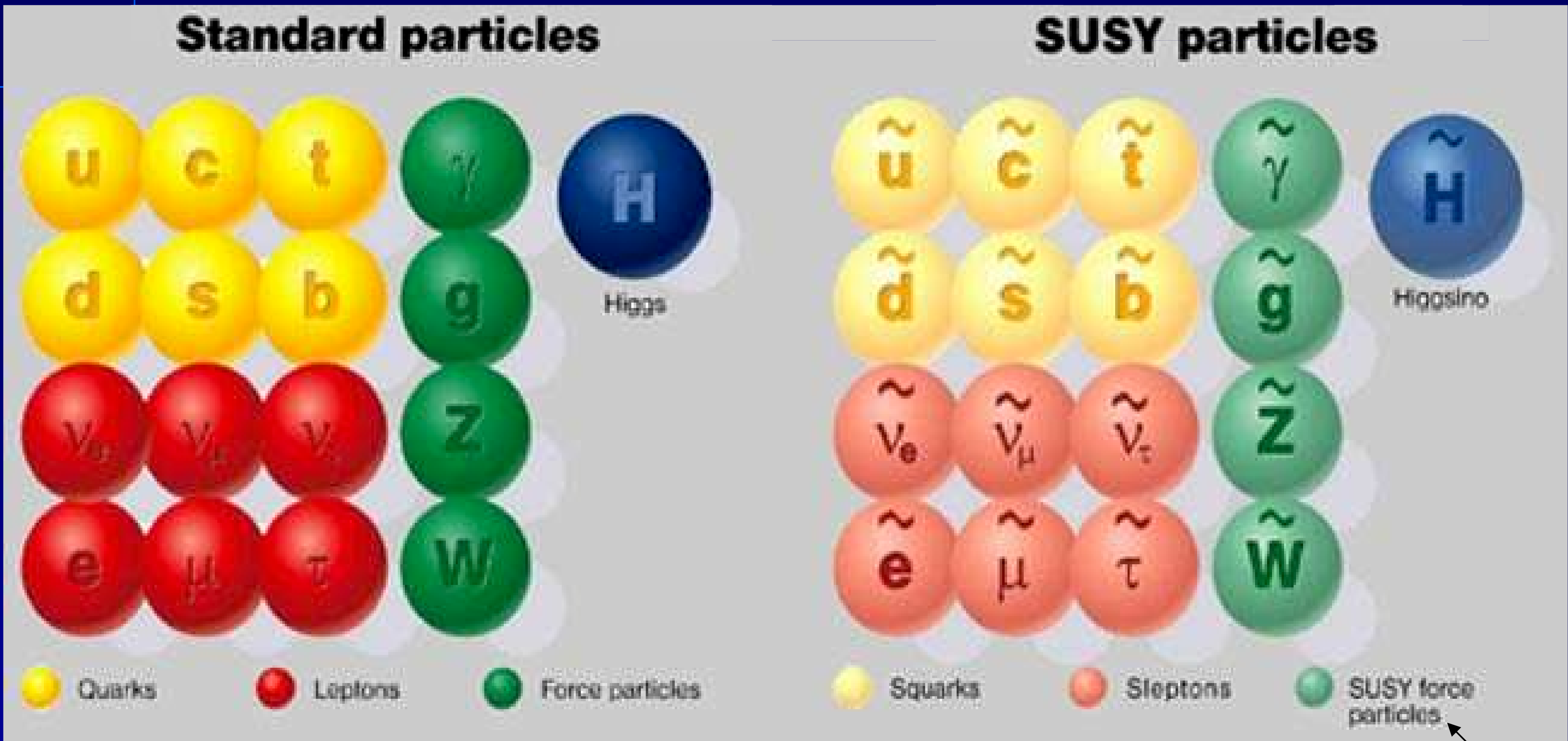
However SUSY particles have to be very massive- we do not see them

(even at LHC) !

Supersymmetry must be violated !



SUSY particles



skwarki, sleptony, gaugina,higgsino
spin 0 spin 1/2

Masses ~ 1 TeV?

Two spin 0 doublets Φ_1 and Φ_2

Supersymetria

Widmo cząstek

	spin 0	spin $\frac{1}{2}$	spin 1
(s)leptony	$\begin{pmatrix} \tilde{e}_L \\ \tilde{\nu}_e \end{pmatrix}$ $\tilde{e}_R$	$\begin{pmatrix} e_L \\ \nu_{e_L} \end{pmatrix}$ e_R	
(s)kwarki	$\begin{pmatrix} \tilde{u}_L \\ \tilde{d}_L \end{pmatrix}$ $\tilde{u}_R$ $\tilde{d}_R$	$\begin{pmatrix} u_L \\ d_L \end{pmatrix}$ u_R d_R	
bozony i gaugina		gluina $\tilde{g}$ fotino $\tilde{\gamma}$ zino $\tilde{Z}$ wina $\tilde{W}^{\pm}$	gluony g foton γ Z° $W^{\pm}$
Higgs(ina)	h°, H°, A° $H^{\pm}$	$\tilde{H}_1^{\circ}$, $\tilde{H}_2^{\circ}$ $\tilde{H}^{\pm}$	

Supersymmetry is super

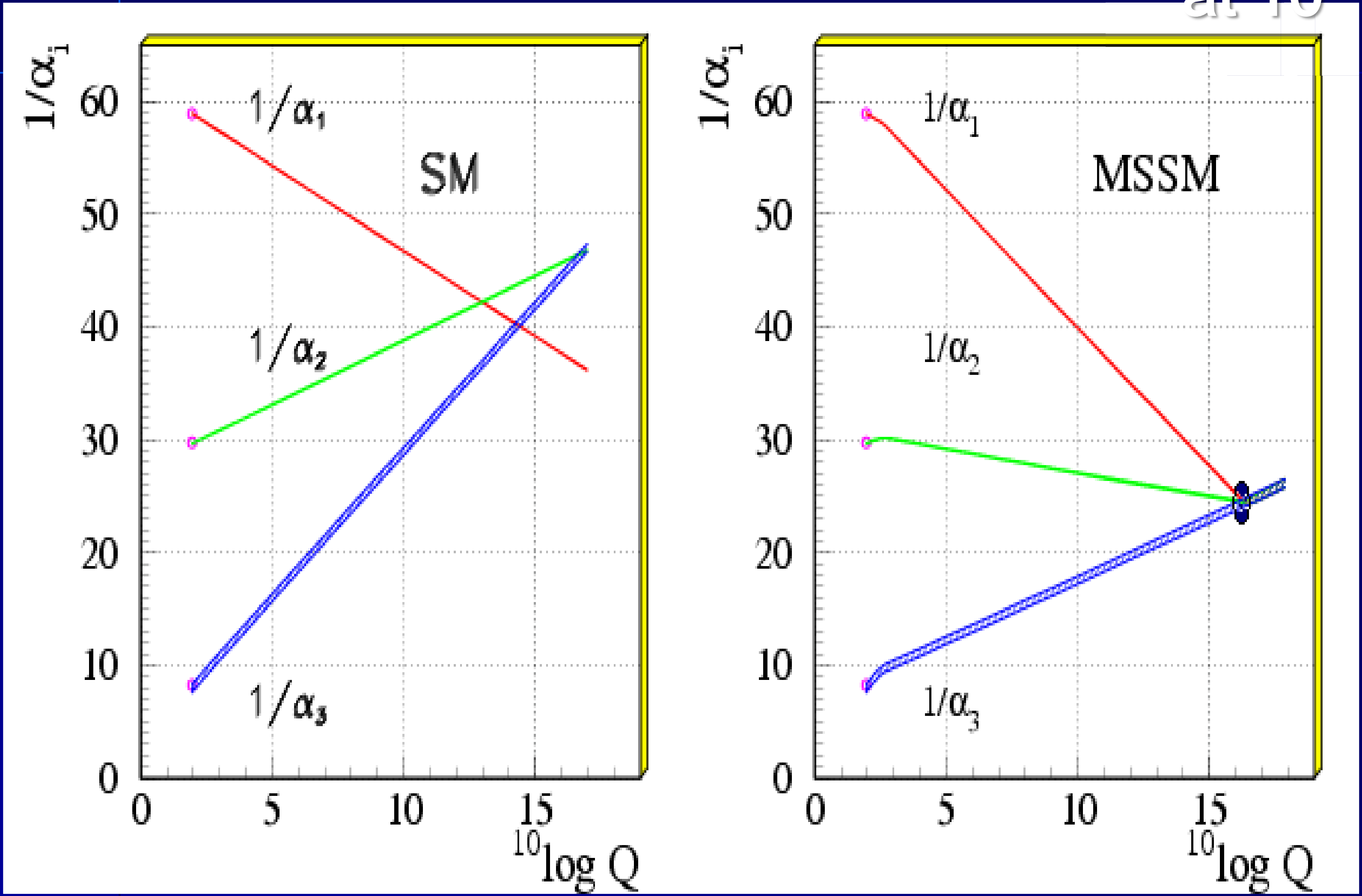
- Hierarchy ?– no problem here (almost), since cancelation of fermionic and bosonic loops

- Unification of interaction(GUT): better than in SM
- Prediction: SM-like Higgs particle with mass below 135 GeV
- Additional assumption: R symmetry

(and conservation of additive quantum number R for SUSY particles), then the lightest neutral SUSY particle is stable → dark matter candidate

Unification of forces(couplings) in SM and MSSM (Minimal Supersymmetric Standard Model)

at 10^16 GeV



axis y: from top $1/\alpha$ U(1) , $1/\alpha_W$ SU(2) , $1/\alpha_s$ SU(3) ; axis *x:* log of energy Q/GeV

MSSM – Higgs sector

- Two doublets with spin-0 fields to generate masses of fundamental particles

- Prediction: existence of 5 Higgs particles(spin 0)

  h, H, A (neutral) i $H^{\pm}$ (charged)

  Note - h has properties as the SM Higgs particle,

  that why LHC does not exclude MSSM !

  But no SUSY particle seen….

- Higgsino - spin ½

  Gauginos (spin ½: *photino, gluino, wino, zino*) mix with higgsino→

  neutralinos (neutral) and charginos (charged)

  →DM particle

SUPERSYMMETRY

D. Gross

Discovery of supersymmetry -
discovery of quantum dimension of space-time

(in addition to normal coordinates there are non-commuting ones)

Natural and unique extension of relativistic symmetries of nature

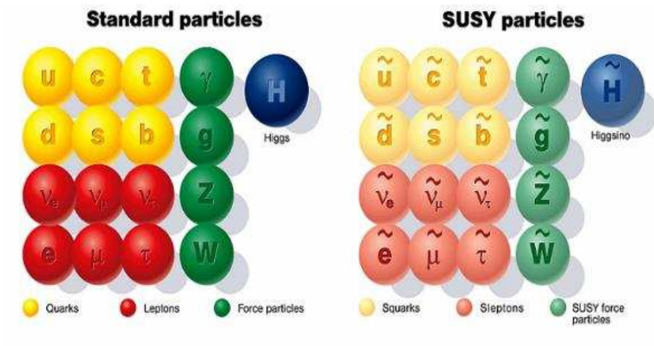
LHC - two main directions of searches:

Higgs and SUSY particles

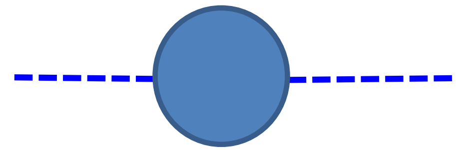
No signal of SUSY yet...

SUSY

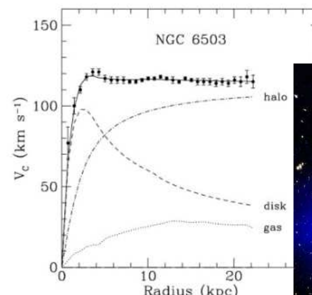
SUSY has been the prime candidate for BSM physics near the TeV scale.

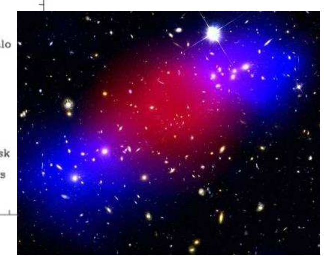


Hierarchy problem

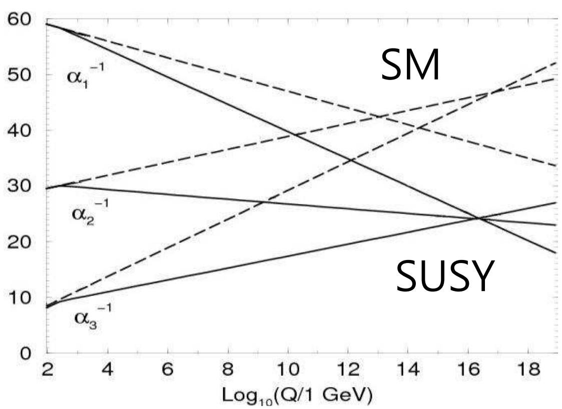


$$\delta m_H^2 \sim M_{\rm Planck}^2 \Rightarrow m_{\rm SUSY}^2$$

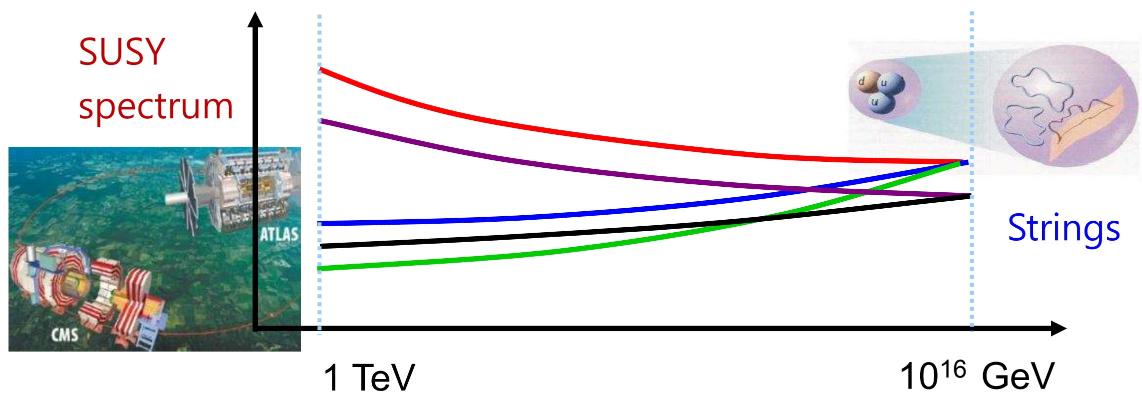




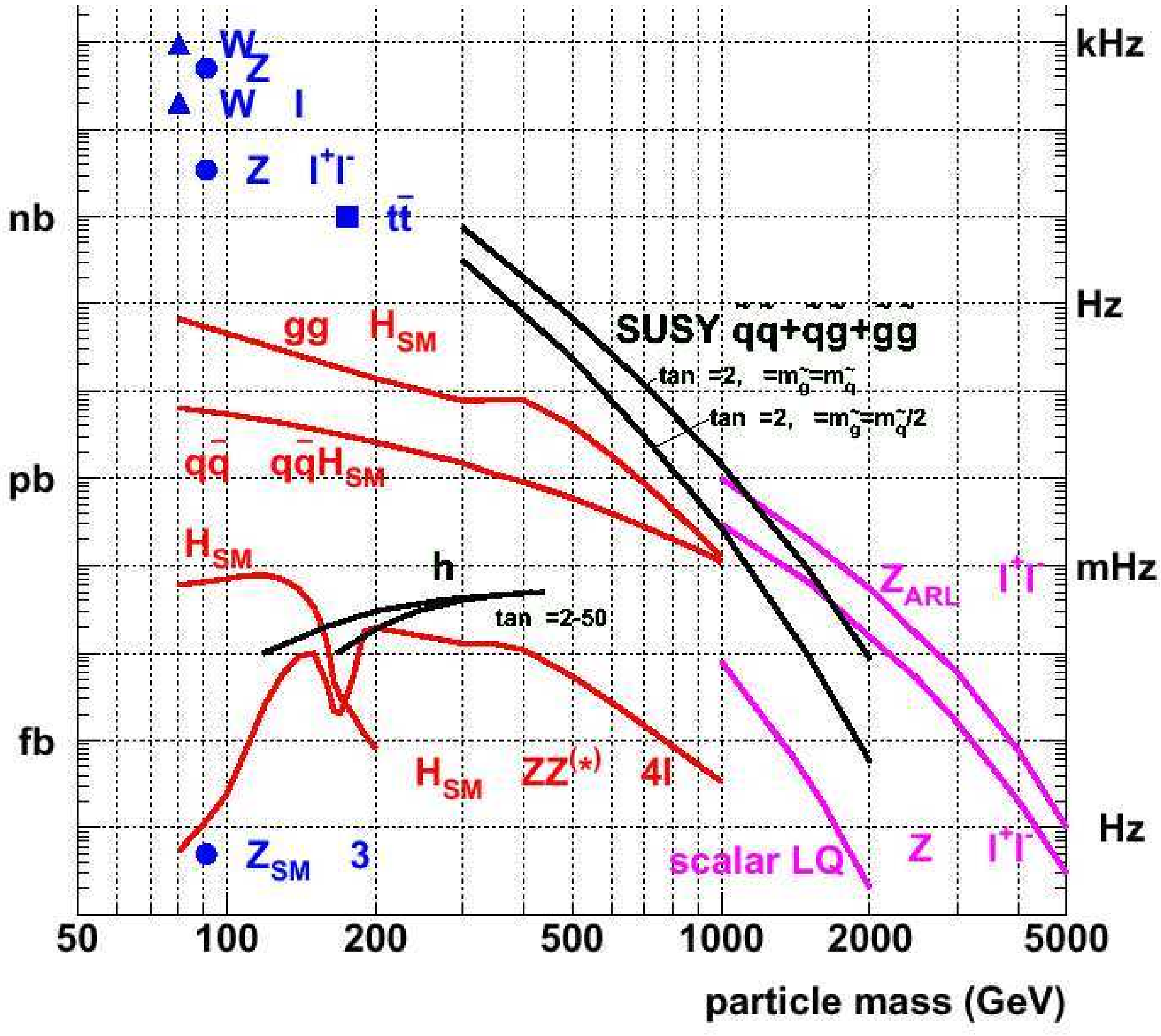
Dark matter



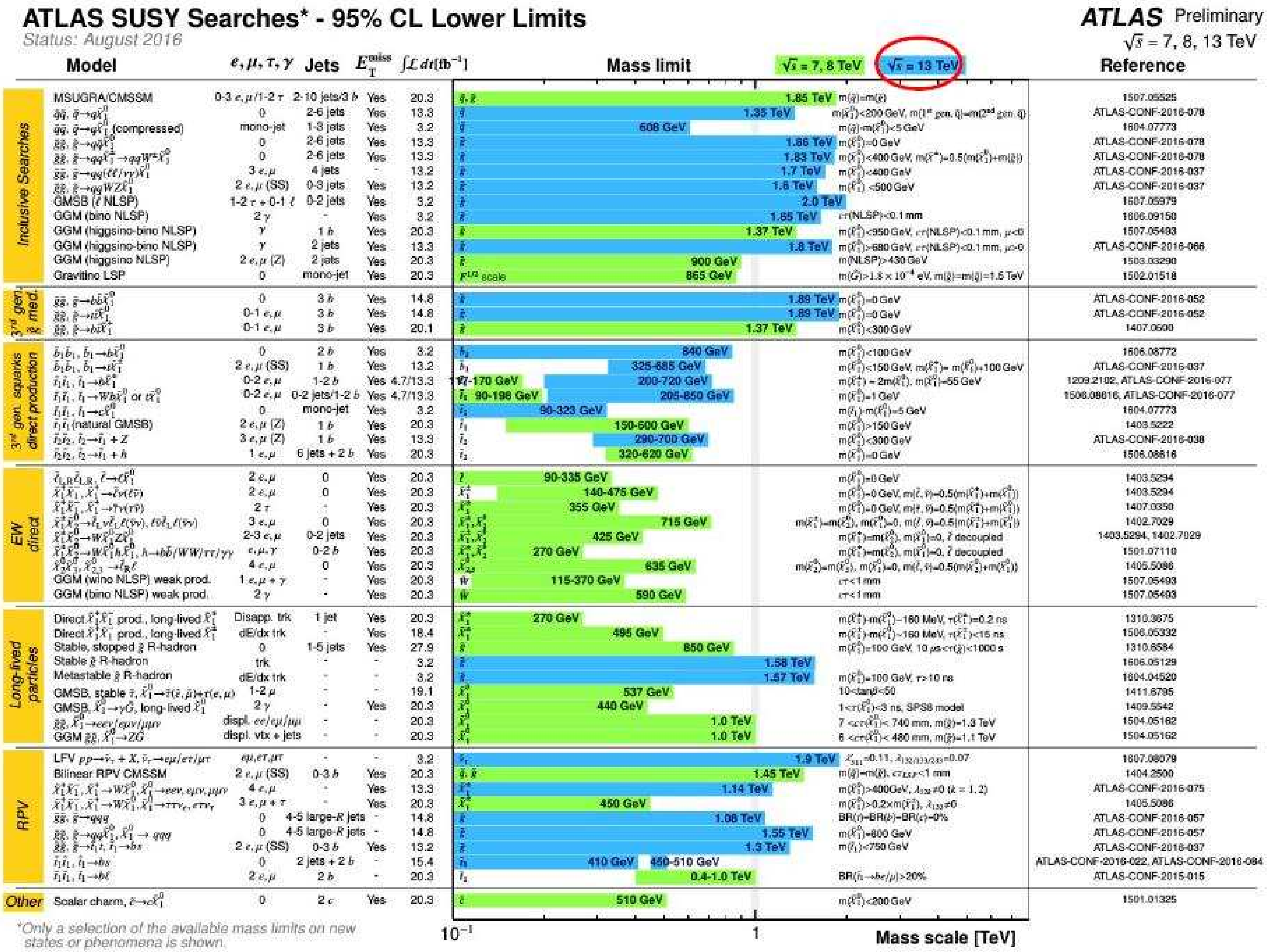
Gauge coupling unification



If Supersymmetry (SUSY) is there, it should be clearly visible at LHC !



Theorists are ready well to interpret any SUSY signature at LHC, but there is no sign of SUSY yet!



First Theory of Grand Unification :SU(5)

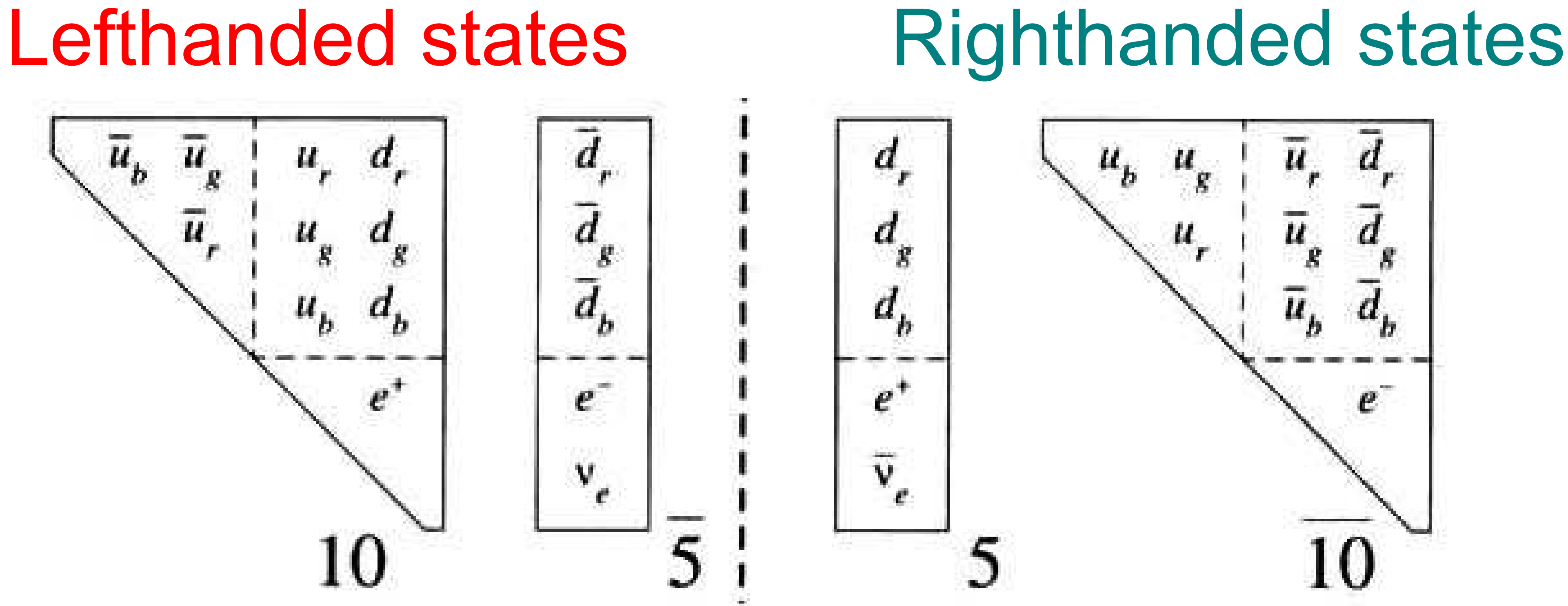
- Gauge symmetry SU(5) - it contains SM symmetry SU(2)xU(1)xSU(3) – idea in 1974 by Glashow, Georgi
- In multiplets of SU(5) they are both quarks and leptons so they can transform to each other ! (nonconservation of baryonic B and leptonic quantum number L!)
- 12 color gauge bosons (leptoquarks):

  X (el. -1/3) i Y(- 4/3)

  plus gluons, photon, W/Z – in total 24 gauge bosons
- 3 families of fermions(15 states) eg. for right states 5-plet=(d_R,d_G,d_B, e^+, $\bar{\nu}_e$), there are also 10-plets (u)
- In this model quantisation of el.charge.:

  charge of electron = - charge of proton

Multiplets of SU(5)



SU(2) dublets and SU(3) triplets are combined to form SU(5) 5- and 10-plets

New interactions

Higher symmetry group require additional bosons,
to allow transitions within multiplet members:

Final state particle (b):

Diagram for emited boson V
in vertex

a -> b + V

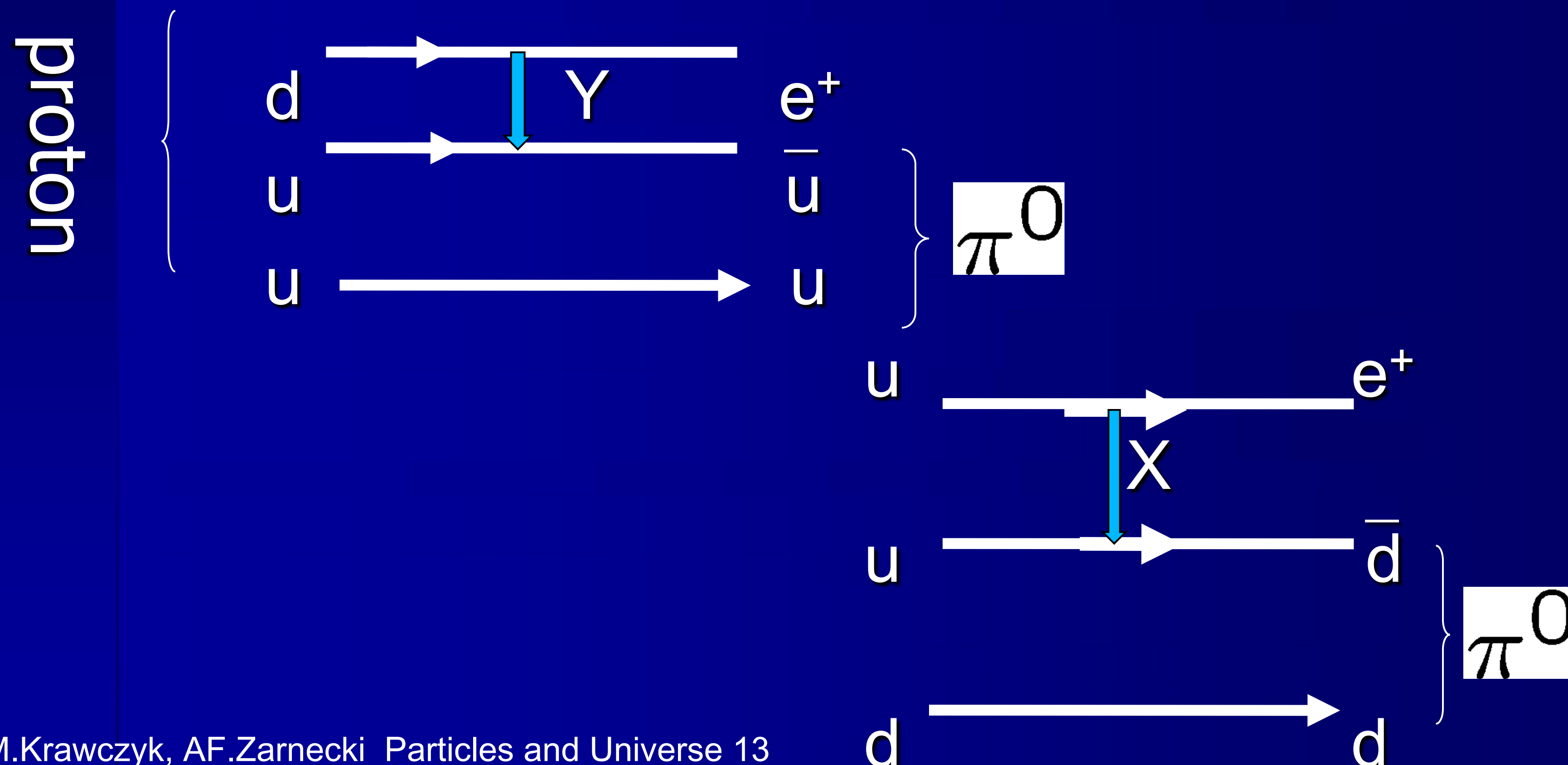
Initial state particle (a):

	d_R^{red}	d_R^{green}	d_R^{blue}	e_R^+	$\bar{\nu}_e$
d_R^{red}	g^0, γ, Z^0	$g^{r \cdot g}$	$g^{r \cdot b}$	$X^{red}_{-\frac{4}{3}}$	$X^{red}_{-\frac{1}{3}}$
d_R^{green}	$g^{g \cdot r}$	g^0, γ, Z^0	$g^{g \cdot b}$	$X^{green}_{-\frac{4}{3}}$	$X^{green}_{-\frac{1}{3}}$
d_R^{blue}	$g^{b \cdot r}$	$g^{b \cdot g}$	g, γ, Z^0	$X^{blue}_{-\frac{4}{3}}$	$X^{blue}_{-\frac{1}{3}}$
e_R^+	$X^{red}_{\frac{4}{3}}$	$X^{green}_{\frac{4}{3}}$	$X^{blue}_{\frac{4}{3}}$	γ, Z^0	W^+
$\bar{\nu}_e$	$X^{red}_{\frac{1}{3}}$	$X^{green}_{\frac{1}{3}}$	$X^{blue}_{\frac{1}{3}}$	W^-	Z^0

Proton decay p→ $e^+ \pi^0$ in SU(5)

Proton decays with exchange of X/Y bosons too fast →
life time of proton 10^{30-31} y , however experiment >10^{31-33} y
- that why this model has been rejected

Example of processes with exchange of X/Y



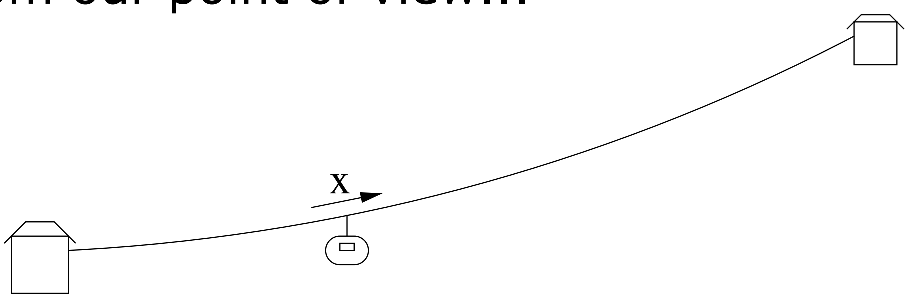
Extra dimensions

How well do we know the properties of space ?
Can we be sure that there are only three spatial dimensions ?!

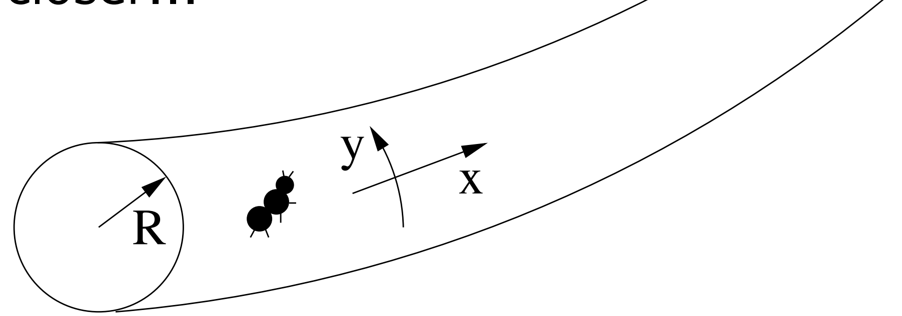
YES - if we consider only infinite dimensions, but what if there are finite ones ?...

Let us imagine an ant on the cable car line:

The line has only one dimension from our point of view...



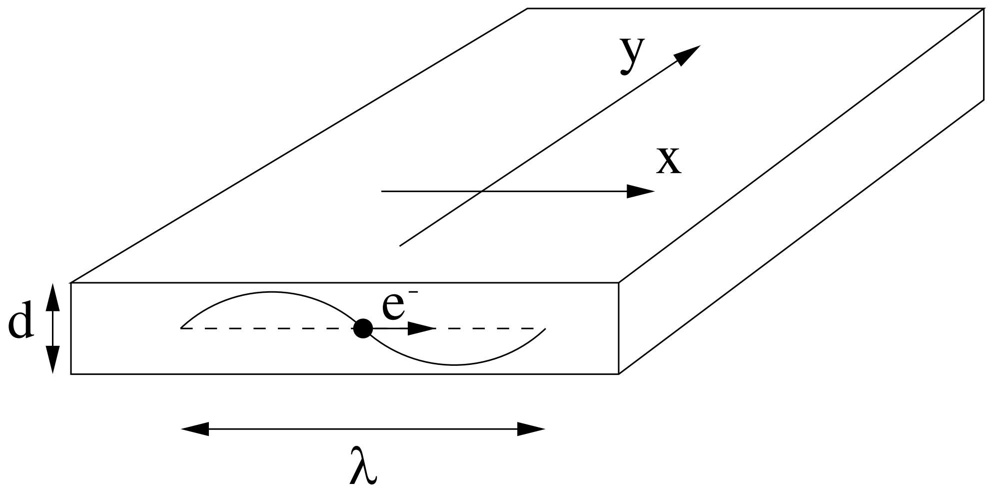
But it has clearly two dimensions for an ant, which looks much closer...



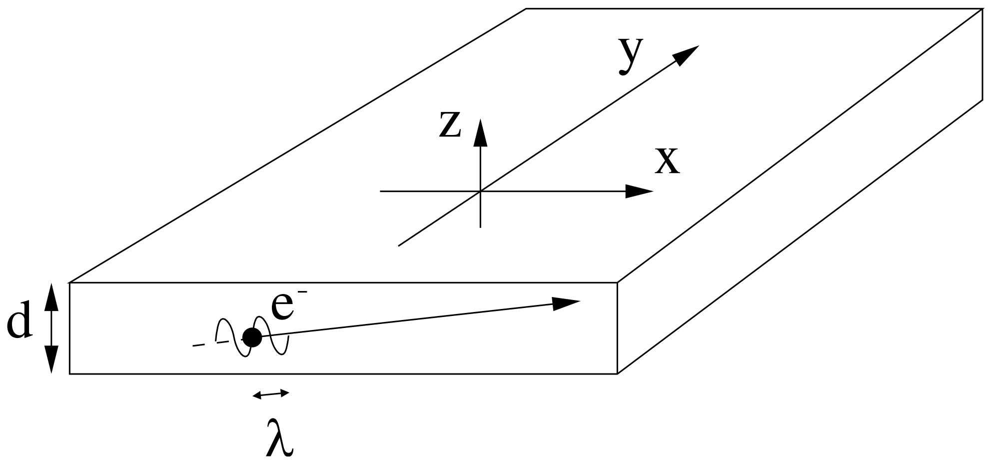
y coordinate is a compact (curled) dimension

Extra dimensions

We already measure this kind of phenomena eg. in material science:



low energy electron trapped in a thin conductor layer (thinner than the electron wavelength) moves only in two dimensions (quantum Hall effect - Nobel 1985)



However, if the electron energy is higher (its wavelength shorter), it starts to "feel" the third dimension

KALUZA-KLEIN THEORY

First theory with extra dimensions (compact) ; unification of gravity and electromagnetism

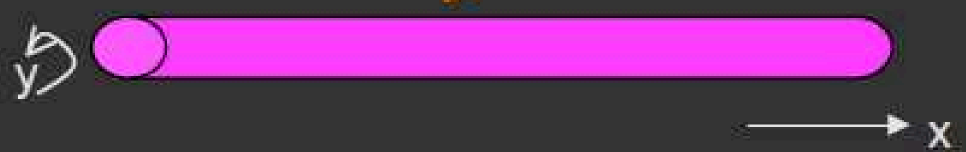
(1919-21) If space-time is dynamical there might exist new, curled up, spatial dimensions.

Klein 1926 (quantum)

In April 1919 Kaluza noticed that when he solved Einstein's equations for general relativity using five dimensions, then Maxwelli equations for electromagnetism emerged ..

Einstein was fascinated by this idea and came back to it over and over again---for over 30 years.

Can explain E&M as an effect of gravity in 5 dimensions



New idea – 1998 Arkani-Hamed, Dimopulos, Dvali
large extra dimensions

Assumption: Gravity and EW interaction may have similar strength already for energy ~1- 10TeV !

Since gravity was studied (tested) up to distance of 1 cm (what about 1 cm down to 10^{-33} cm ???)

Newton law can be modified, eg.

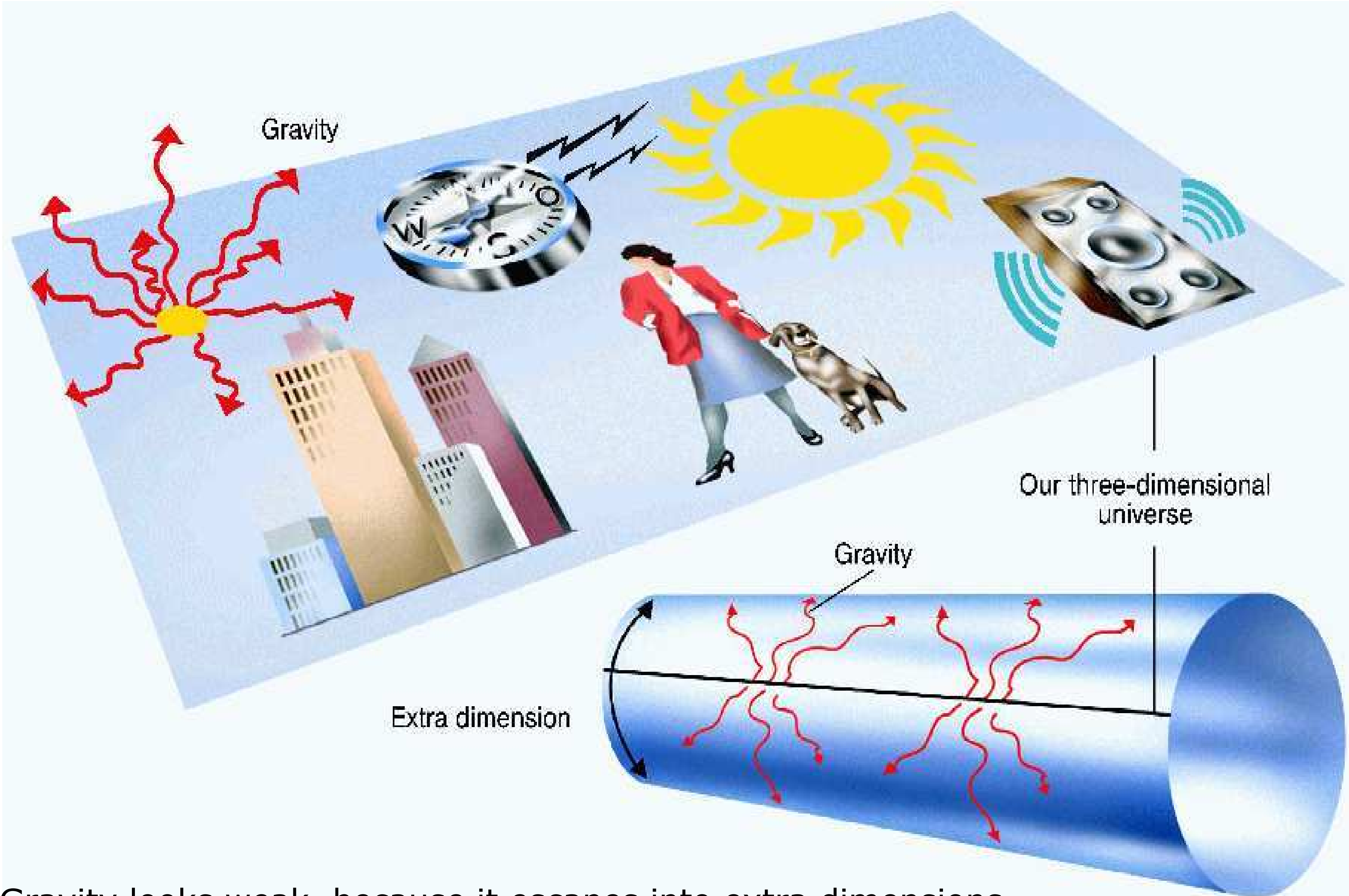
$$1/r^2 \rightarrow 1/r^4$$

> the weak scale, which we take as the only fundamental short distance scale in nature. The observed weakness of gravity on distances $\gtrsim$ 1 mm is due to the existence of $n \geq 2$ new compact spatial dimensions large compared to the weak scale. The Planck scale $M_{Pl} \sim G_N^{-1/2}$ is not a fundamental scale; its enormity is simply a consequence of the large size of the new dimensions. While gravitons can freely propa-

with two extra curled (compact) space dimensions

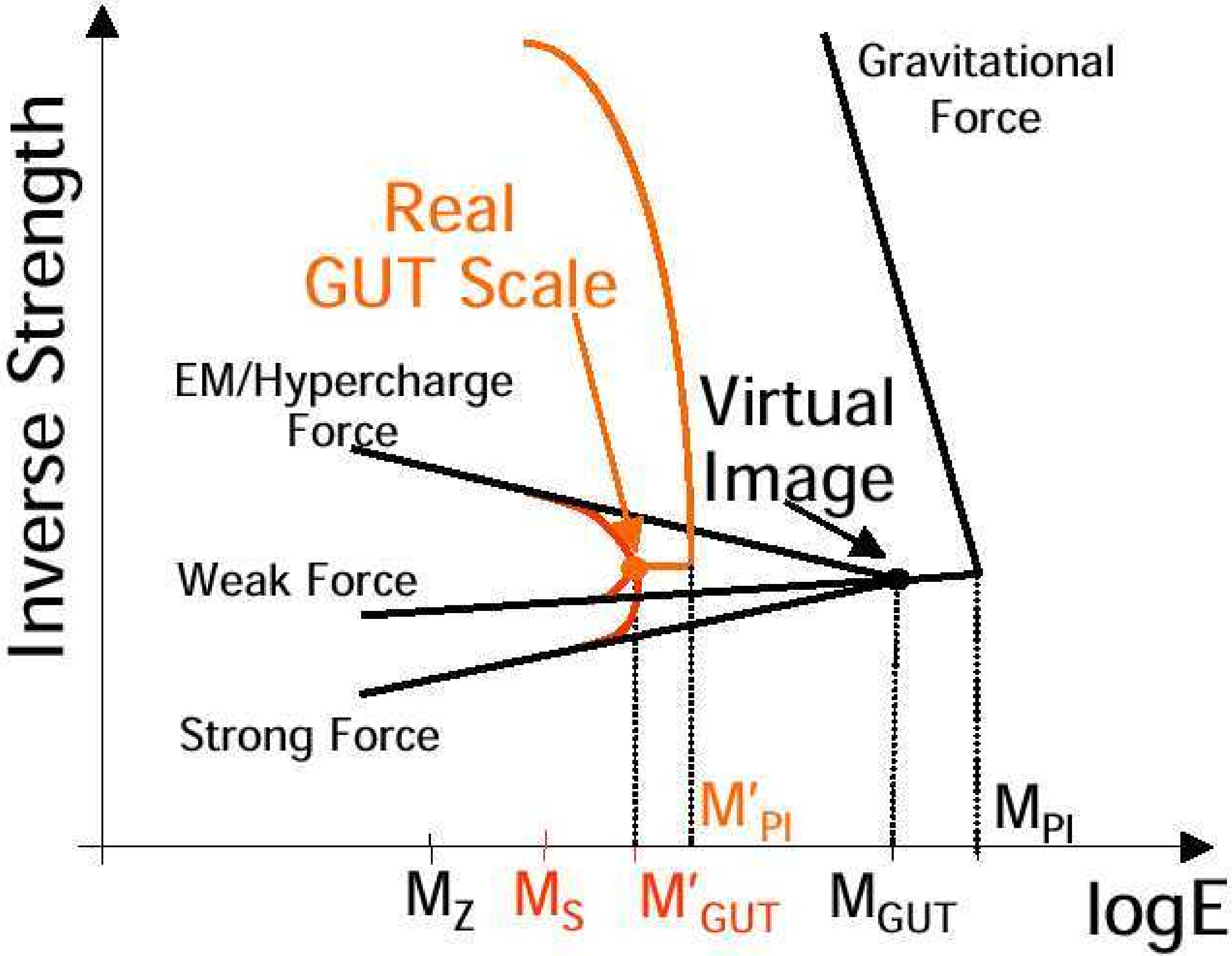
Idea: particles of SM live in 4 dimensions (3+1), while graviton in extra dimensions

M. Shifman http://arxiv.org/pdf/0907.3074v2.pdf



Gravity looks weak, because it escapes into extra dimensions...

If there are more spacial dimensions at large energy scales, gravity can unify with other forces much earlier !...



Problem running RHIC collider at BNL

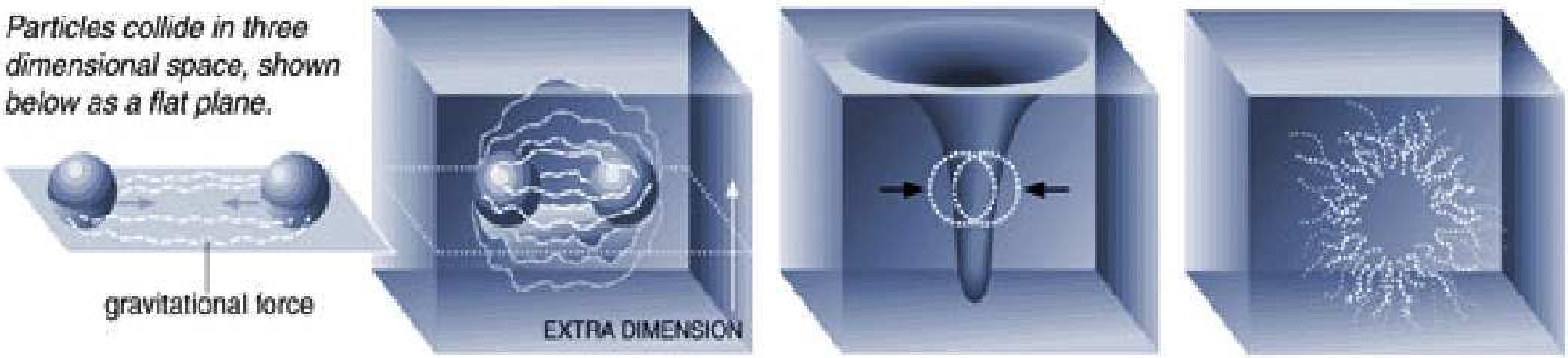
Black Holes on Demand

NYT, September 11, 2001

The New York Times ON THE WEB

Scientists are exploring the possibility of producing miniature black holes on demand by smashing particles together. Their plans hinge on the theory that the universe contains more than the three dimensions of everyday life. Here's the idea:

Particles collide in three dimensional space, shown below as a flat plane.



As the particles approach in a particle accelerator, their gravitational attraction increases steadily.

When the particles are extremely close, they may enter space with more dimensions, shown above as a cube.

The extra dimensions would allow gravity to increase more rapidly so a black hole can form.

Such a black hole would immediately evaporate, sending out a unique pattern of radiation.

Superstrings

- Theory of Everything TOE - all interactiion including gravity

  In quantum field theory – interactions are pointlike, this leads to infinities
- Superstrings – example of TOE. Pointlike particles are replaced by strings with finite length.
- Planck scales are relevant l_{Pl}=1.6 10^{-35} m, M_{Pl}=1.2 10^{19} GeV
- Various excitation of strings → different fundamental particles (open and closed strings)
- Superstrings – renormalized theory in 10 (or 26 for nonsupersymmetric strings) dimensions
- Parameter described strings α' - the same as for hadronic strings (*see below*)
- Superstrings – no clear predictions and many versions

THE ACHIEVEMENTS OF STRING THEORY

- A Consistent, Logical Extension of the Conceptual Framework of Physics

REVOLUTIONS IN PHYSICS

Relativity	c	Velocity of light
Quantum Mechanics	h	Quantum of action
String Theory	G	Planck length

- A Consistent and Finite Quantum Theory of Gravity

- A Rich Structure That Could Yield a Unique and Comprehensive Description of the Real World (a T.O.E)

D.Gross 2005

There are other opinions as well

M. Veltman (Facts and Mysteries in Elementary Particle Physics, 2003):

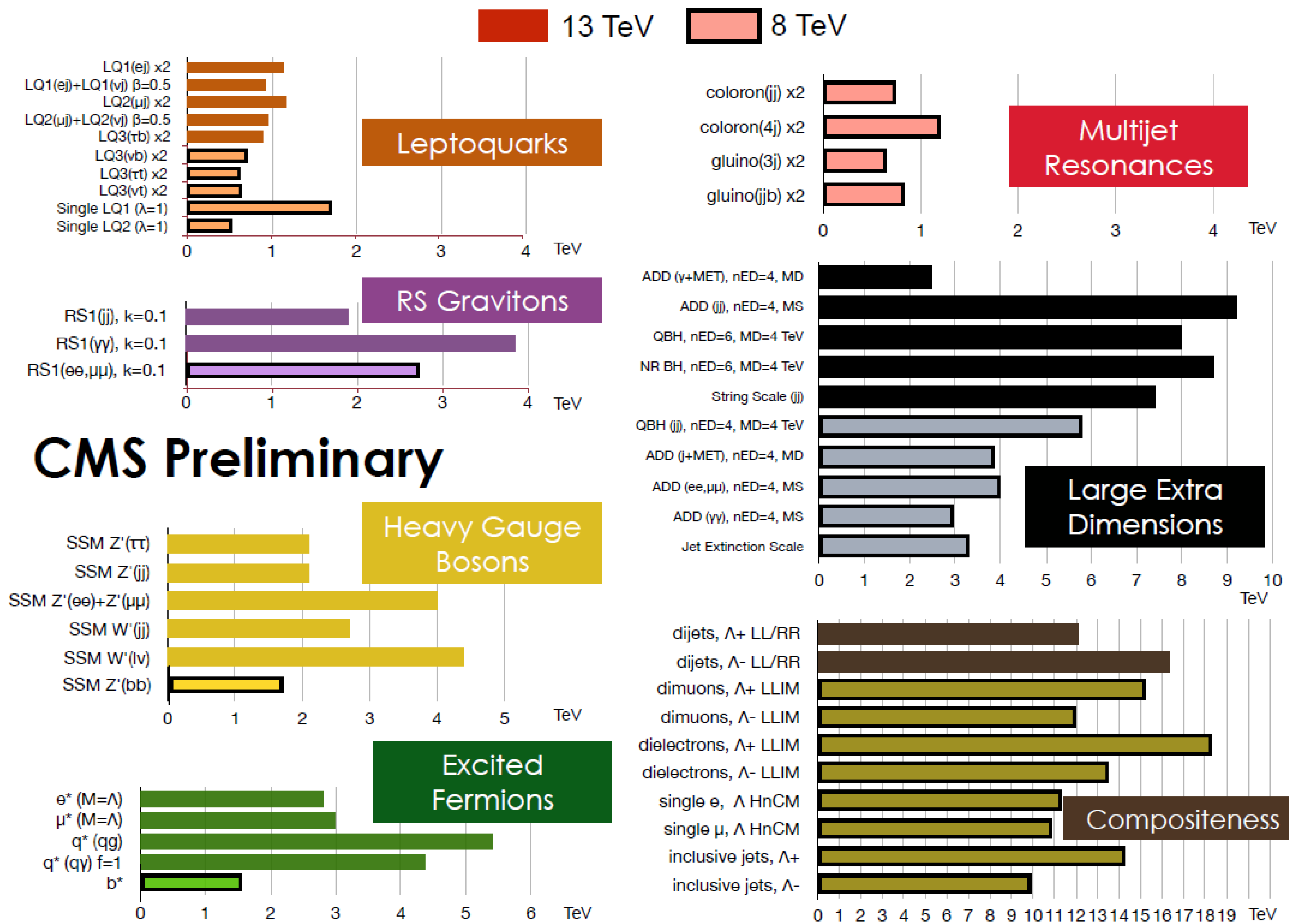
..this book is about a physics, and this implies that the theoretical ideas discussed must be supported by experimatal facts. Neither supersymmetry nor string theory satisfy this criterion. They are figments of the theoretical mind.

To quote Pauli: „They are not even wrong."

They have no place here.

No sign of other BSM also!

Excluding Dark Matter and Long Lived particles searches



CMS Exotica Physics Group Summary – ICHEP, 2016

We have a long list of possible BSM physics, but we don’t know **where they are.**

After the discovery of the Higgs boson, we don’t have anymore a convincing argument to pinpoint the next scale.

Questions to lecture 13

- Write 3 problems of the SM
- What is a meaning of GUT?
- GUT – is this a common (unified) description of all fundamental interaction including gravity?
- What is energy of GUT?
- Has supersymmetry been discovered ?
- How many Higgs particles is predicted in the MSSM?
- Is life time of the proton predicted in the SU(5) in agreement with experiment?
- Is the baryonic number conserved in SU(5) ?
- Do exist models with more than 4 space-time dimentions?
- What is main idea of superstring theory?
- Does the superstring theory include gravity?
- What is the parameter of the superstring theory existing in the hadronic interactions?