



What's So Small to
You is So Large to Me
High Energies and Small Distances

Lisa Randall Harvard

Exciting Time for Physics

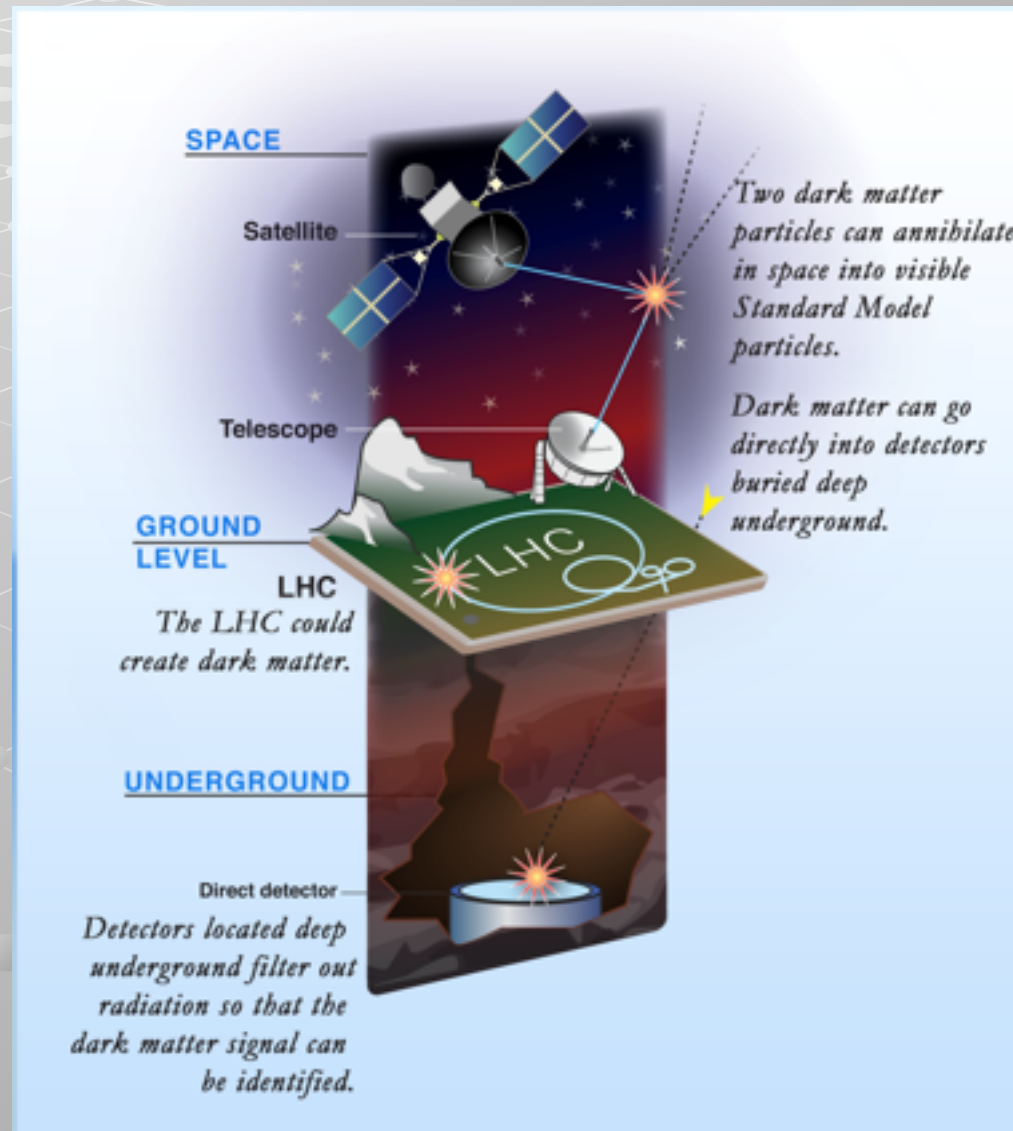
- **Physicists are exploring the universe at larger and smaller scales than ever before**
 - **Astrophysical probes let us see out into the Universe**
 - **Particle experiments are about to look at smaller distances and higher energies than ever before**
- **We could be at the verge of revolutionary discoveries**

Large Hadron Collider

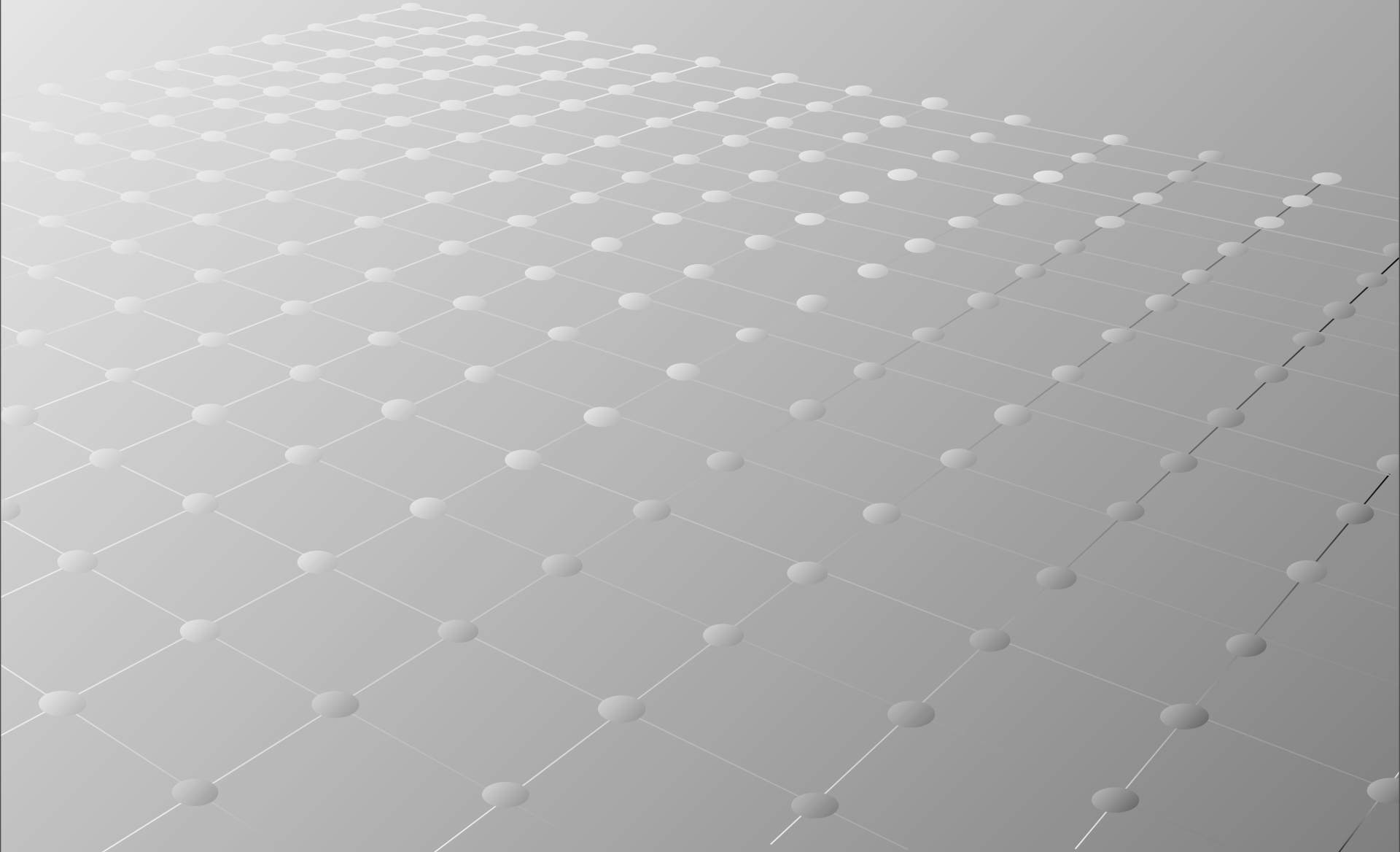
Protons accelerated to high energies, collide



Dark Matter Searches: Three-pronged approach

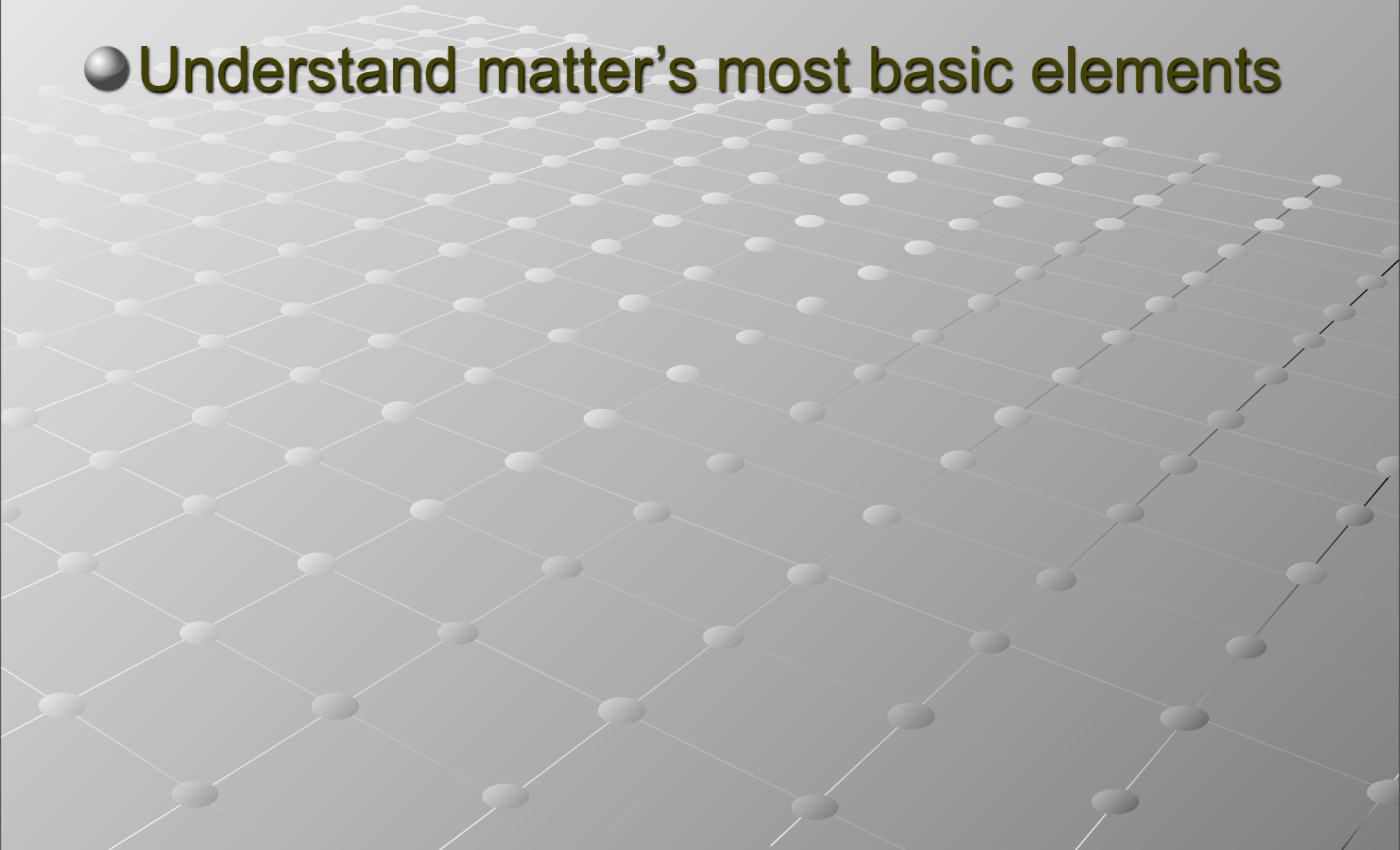


Goals



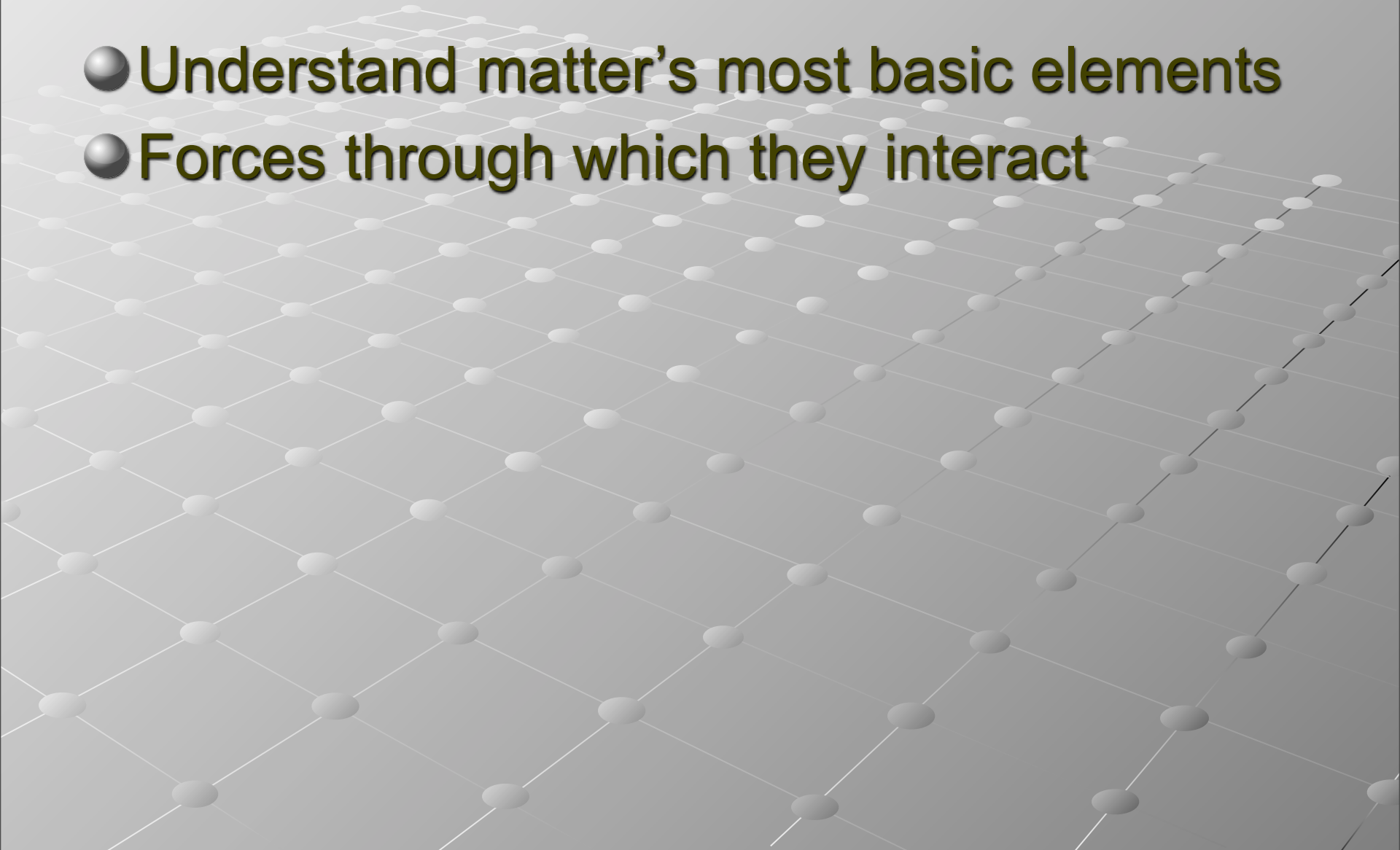
Goals

- Understand matter's most basic elements



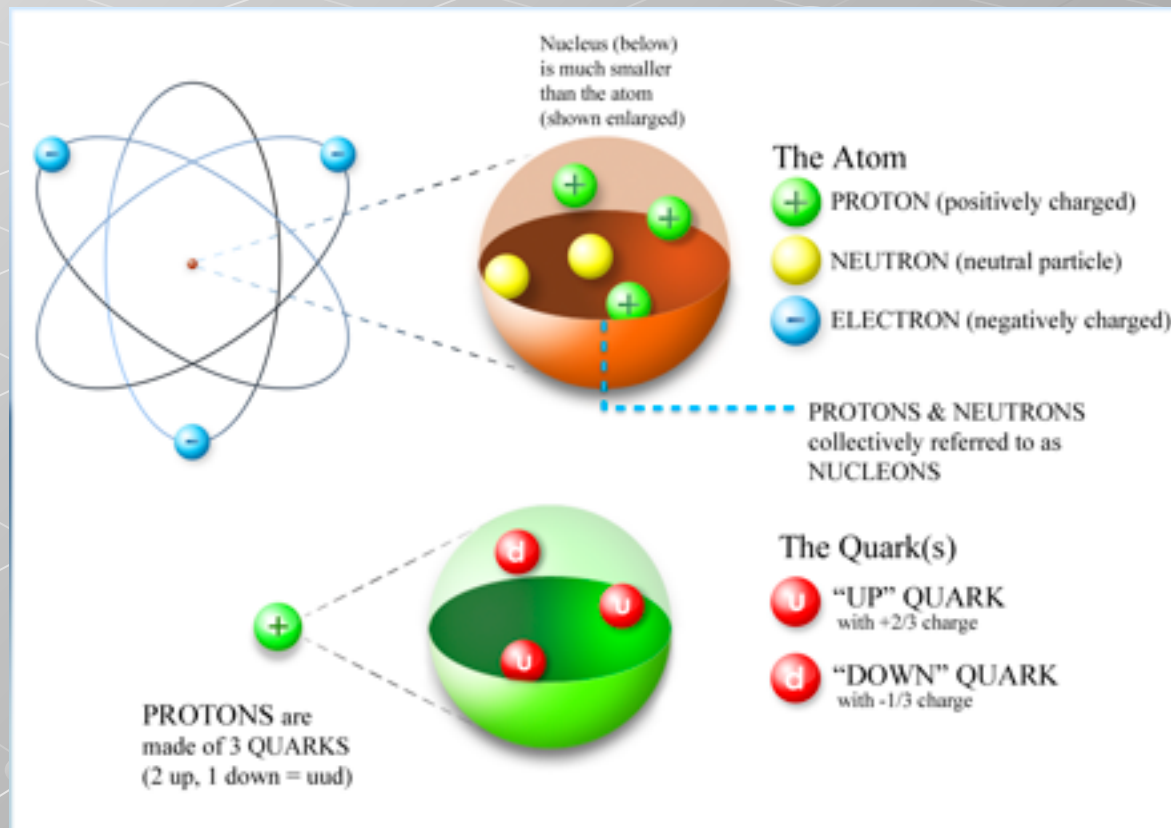
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 - String theory
 - Deeper understanding of spacetime?

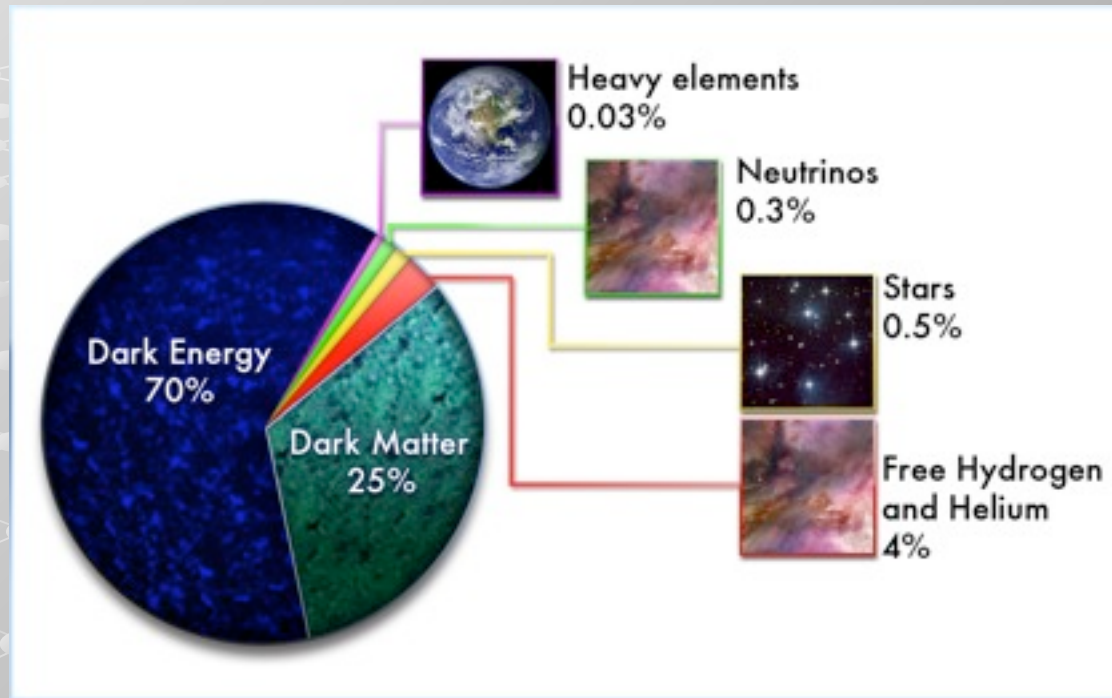
Goals

- Understand matter's most basic elements
- Forces through which they interact
- Connections to underlying theoretical frameworks
 - String theory
 - Deeper understanding of spacetime?
- Develop connections to cosmology

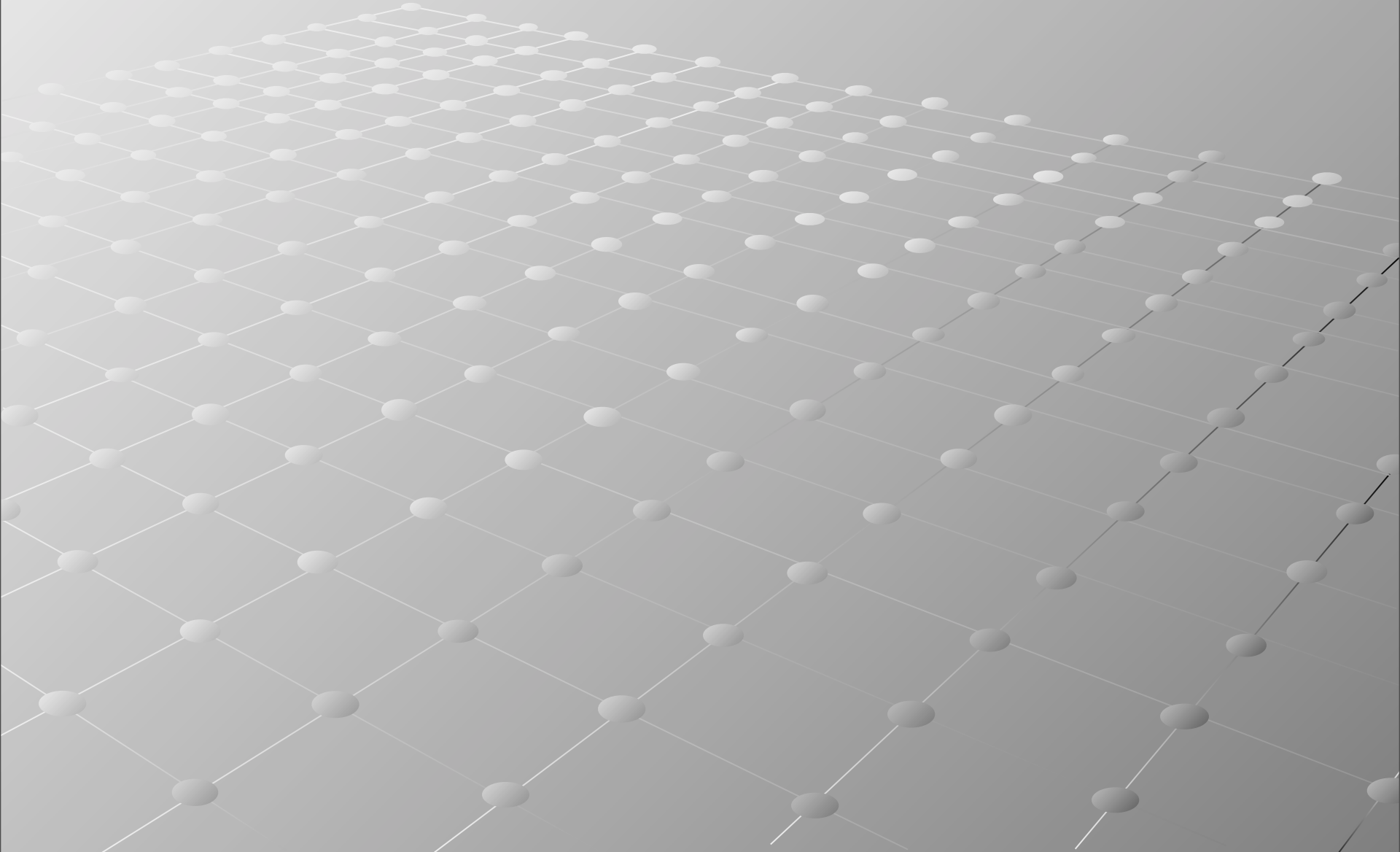
Goals

- **Develop connections to cosmology**

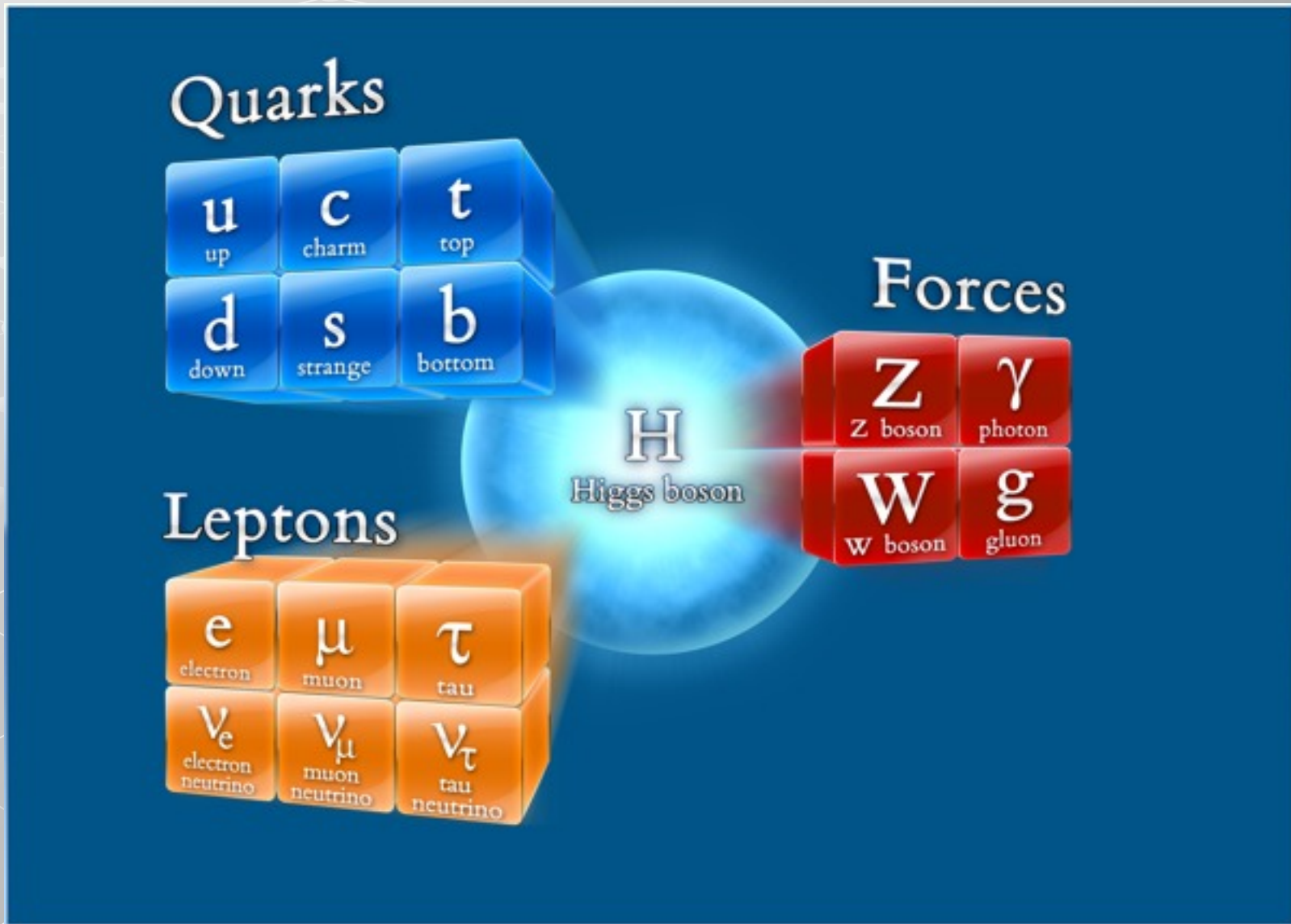
Goals



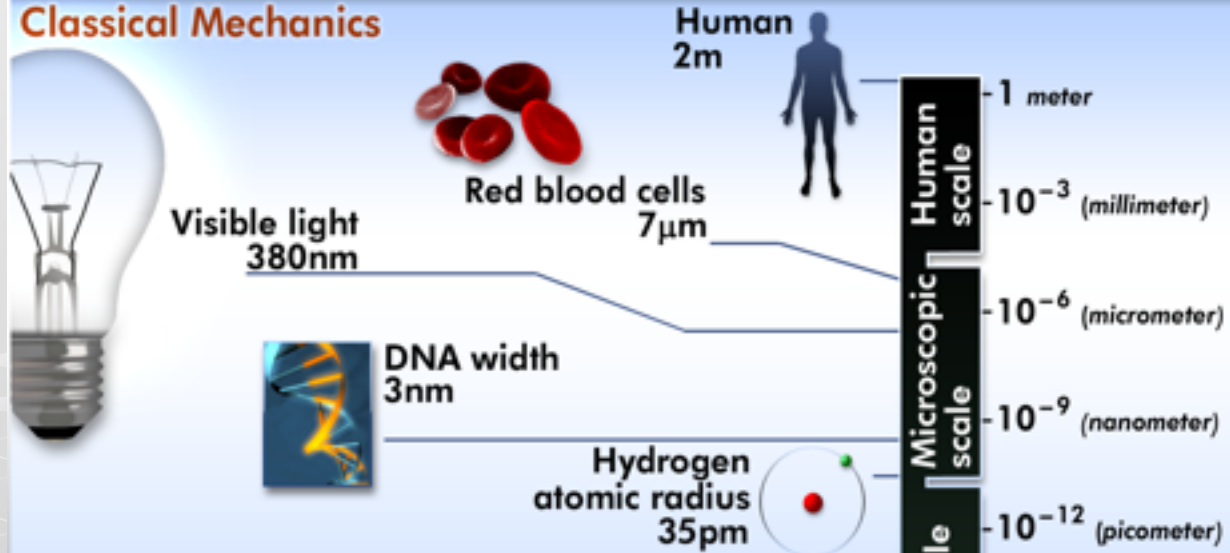
Goals



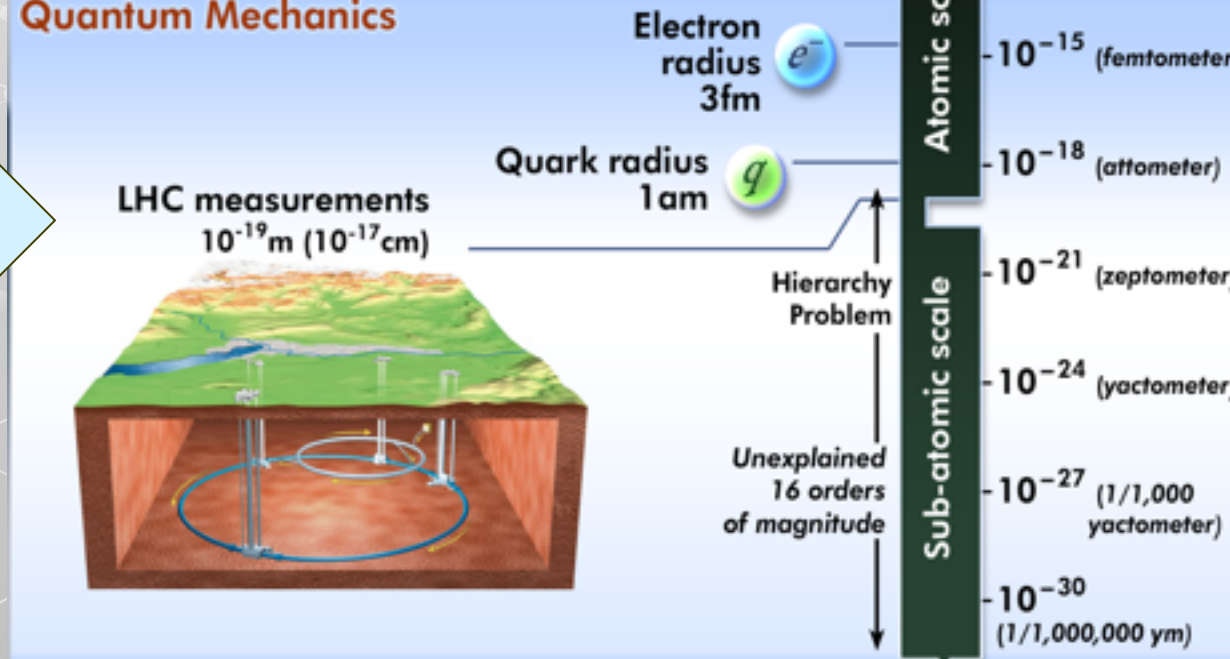
Standard Model of Particle Physics



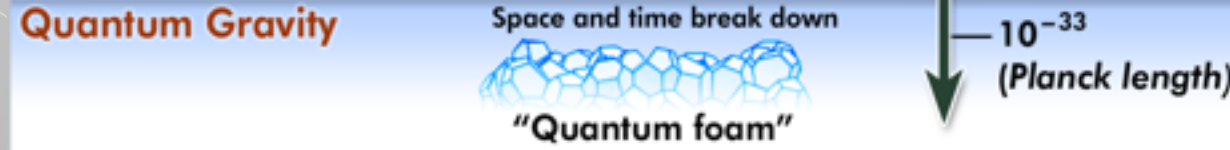
Classical Mechanics



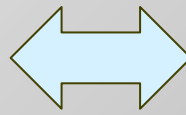
Quantum Mechanics



Quantum Gravity



Go down in scale

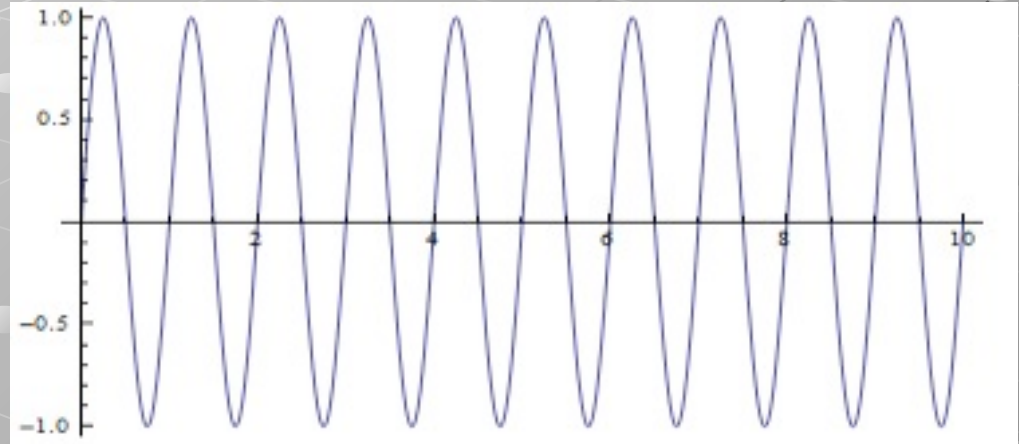


High energy

Short distance

$$\Delta p \Delta x \geq \frac{1}{2} \hbar$$

$$\Delta E \Delta t \geq \frac{1}{2} \hbar$$



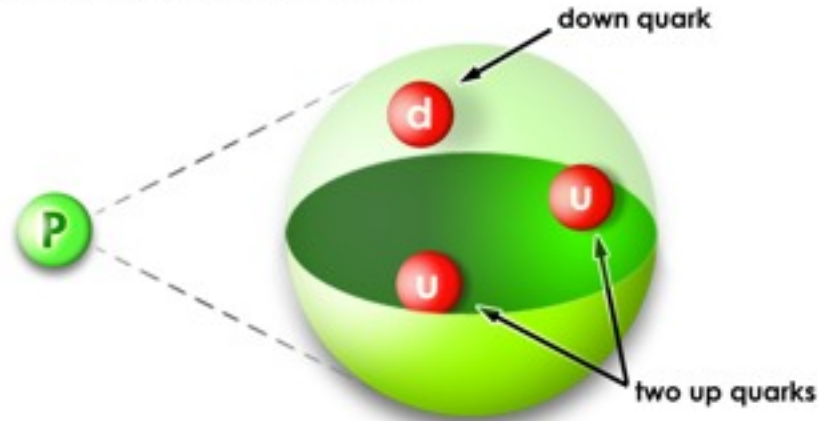
LHC Reaches Extremes

- Highest Energy (7 times highest before)
- Luminosity (100 times bigger)
- Coldest (1.9 degrees above absolute zero)
- Biggest most effective vacuum (ten trillionth of an atmosphere)
- Strongest magnets in production
- Magnetic field energy equivalent of a couple of tons of TNT

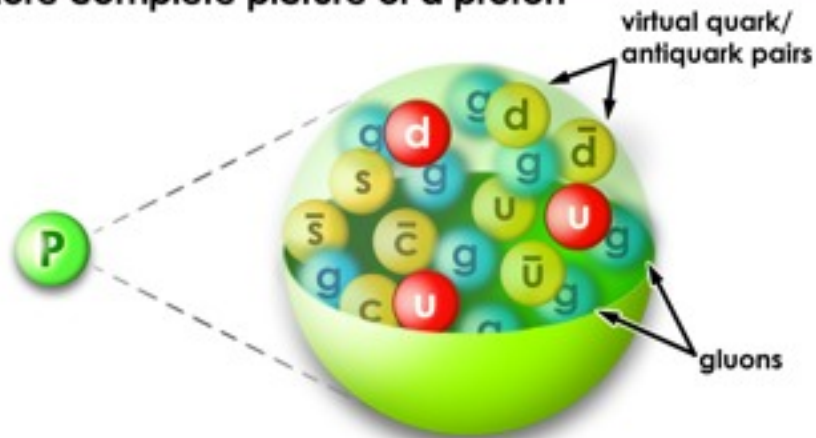
Collide protons

● Protons rich and complicated objects

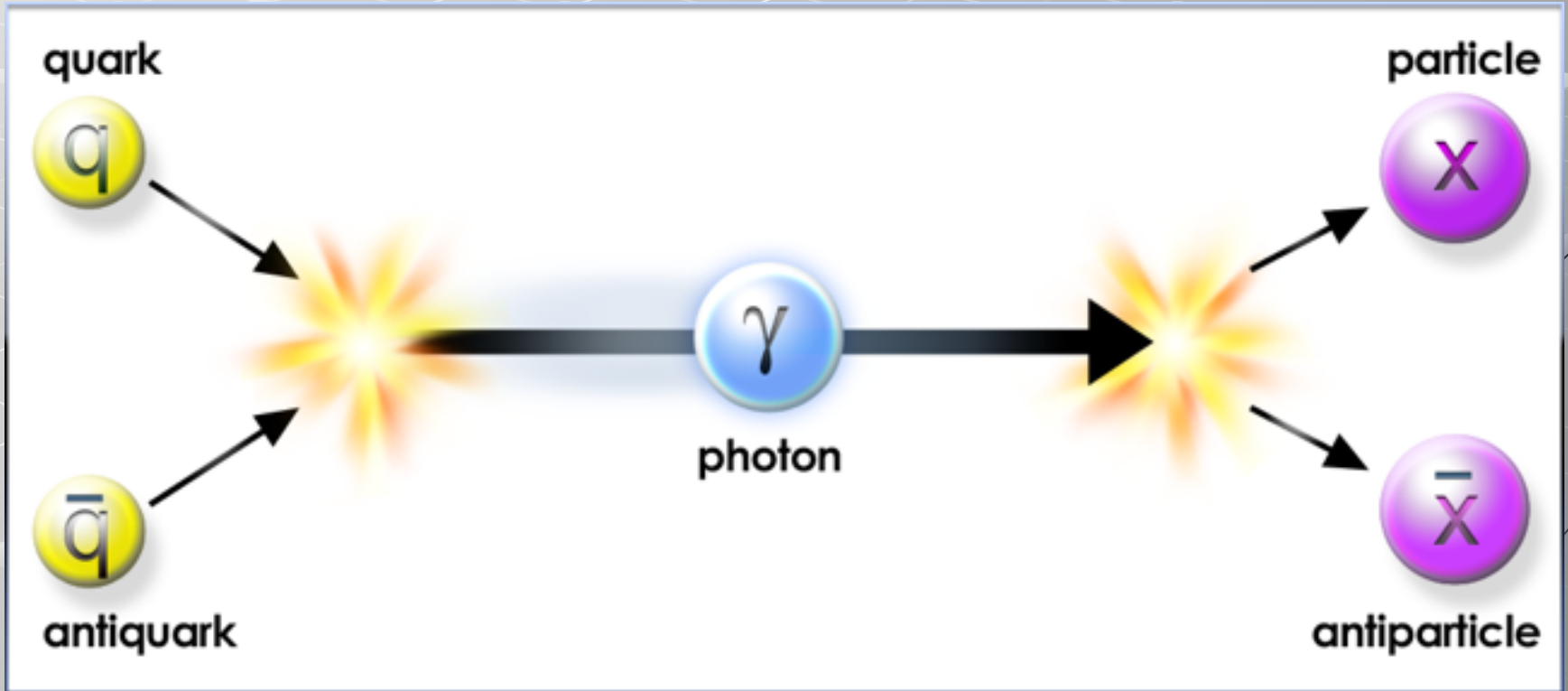
Primary quarks in a proton



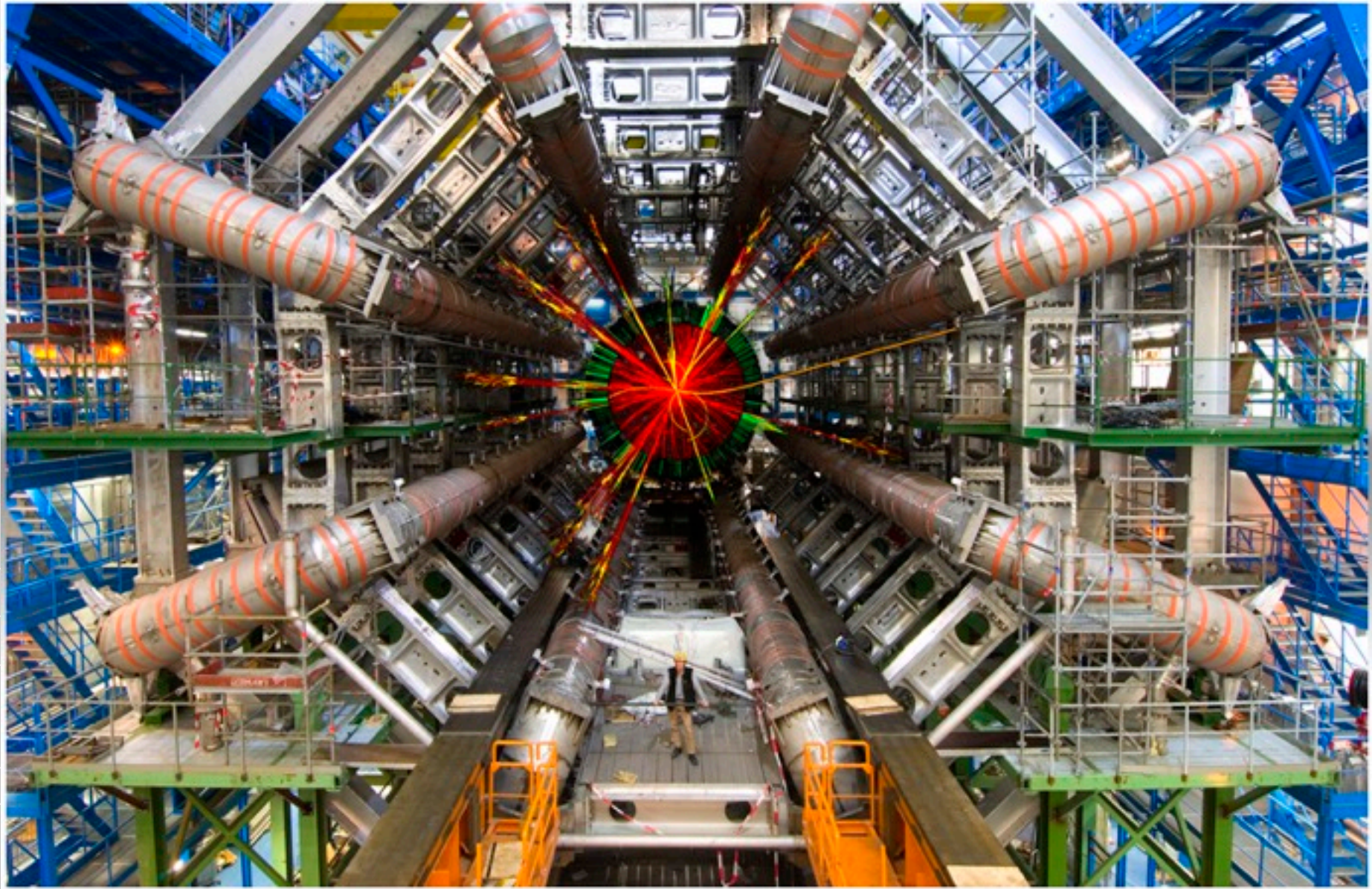
More complete picture of a proton



Proton Proton->New Matter

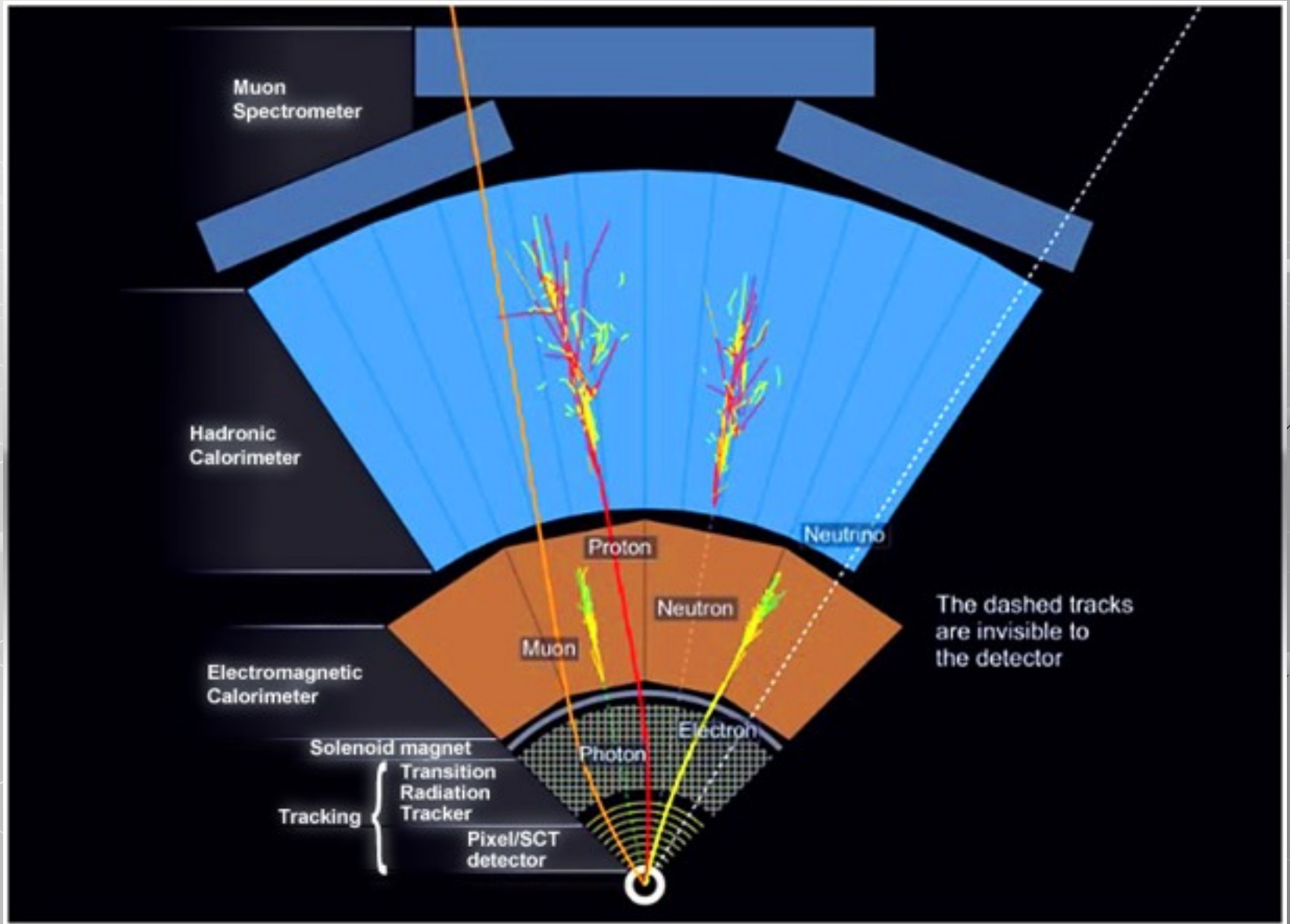


ATLAS "event"



Tuesday, April 26, 2011

Different layers distinguish SM



I was there...

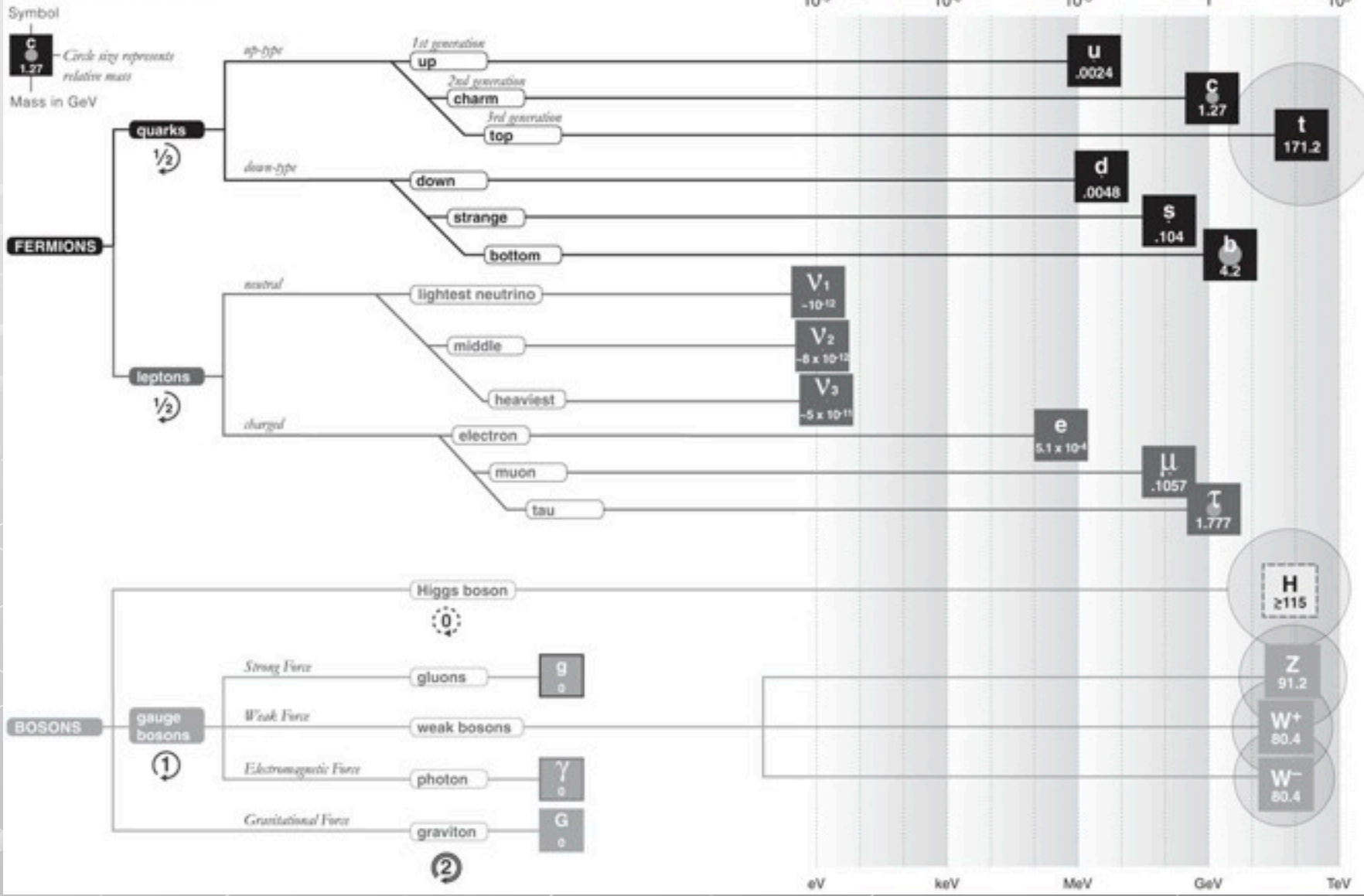


Tuesday, April 26, 2011

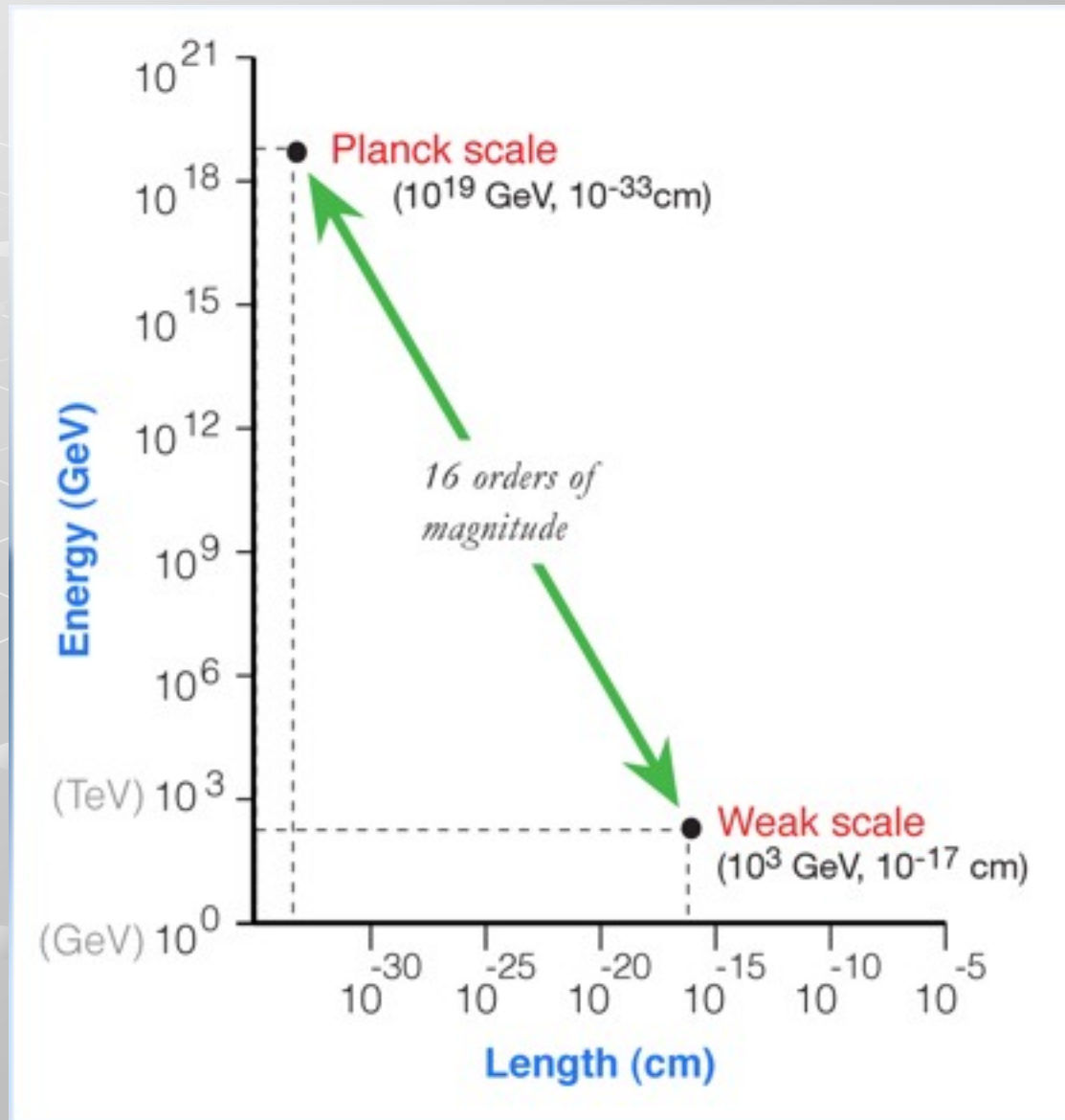
Left to Understand: Weak Scale and Particle masses:

- Particles don't obviously have nonzero masses
- Symmetries of Standard Model don't seem to permit them
- Need a mechanism to explain them

FUNDAMENTAL PARTICLES



Question still remains: Hierarchy Problem



- Question remains—why is Higgs mass what it is?
- Related to question of why any particle mass is what it is
- Quantum mechanics tells you Higgs mass should be much bigger—Planck scale!
- Need something new and interesting to get hierarchies necessary for physical theories
- Fine-tuning or something new and profound

Restate Hierarchy Problem:

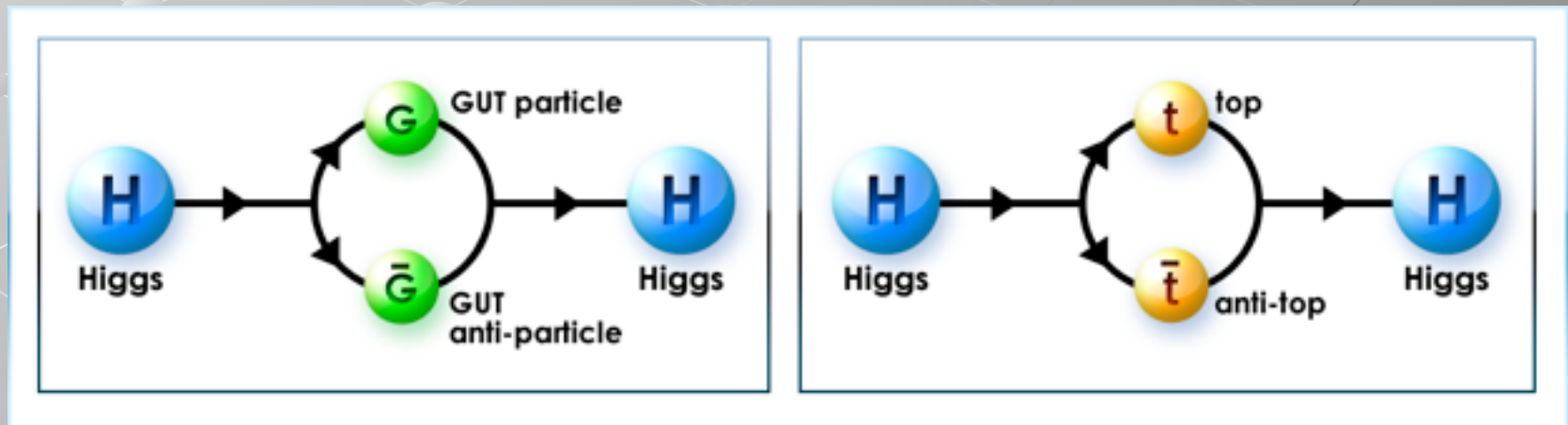
- **Why is gravity so weak compared to the other elementary forces?**
- **Suggests gravity solution**

Might not seem weak but magnet can take on the entire Earth

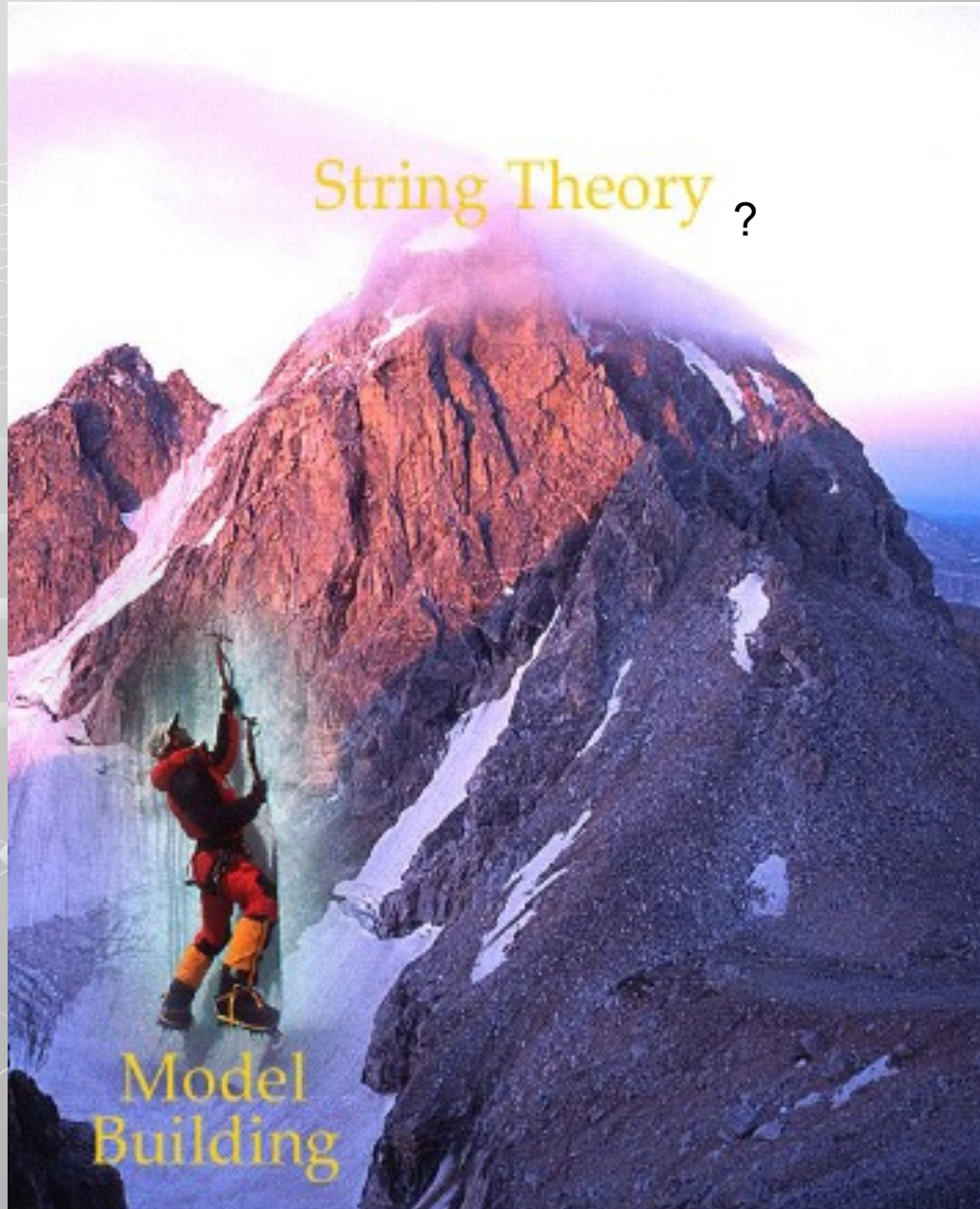


Hierarchy Problem

- Worse than it seems
- Quantum mechanics and general relativity tell you without a fine-tuning, nothing works



The best route to answering?




Model Building:
adventure travel
through world of
ideas ?

We don't yet know the answers


State of the Field: Duel 1

Lisa Randall




Supersymmetry


Landscape



Dark Matter



Extra Dimensions

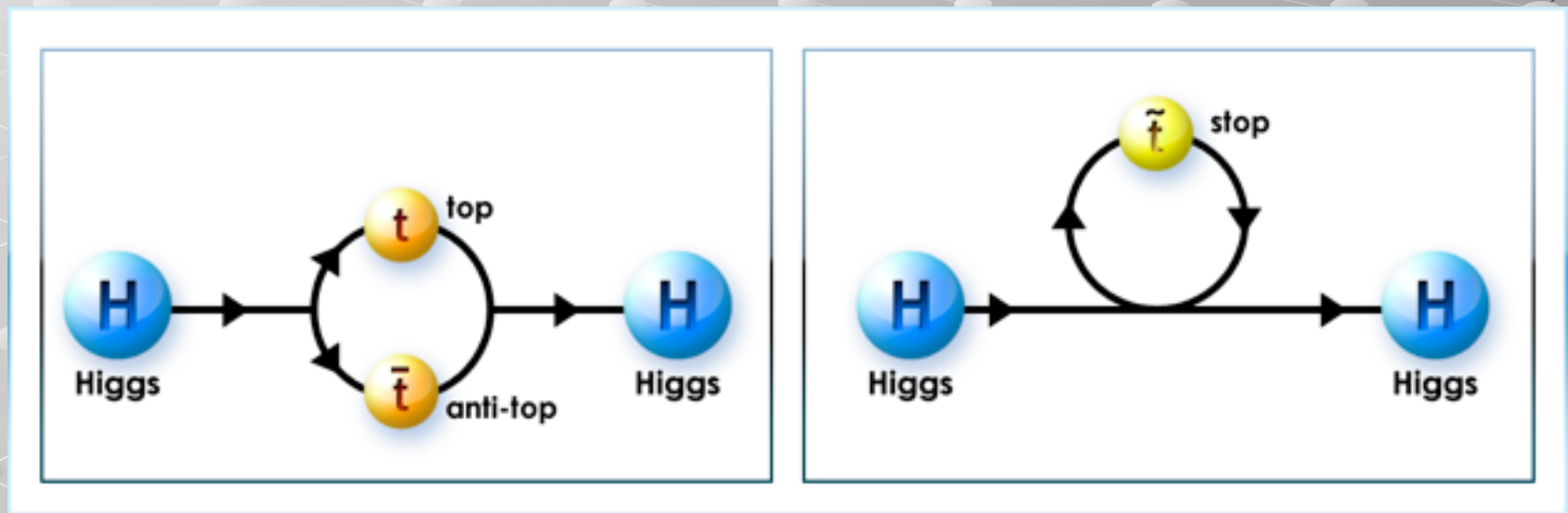


Supersymmetry one possible answer

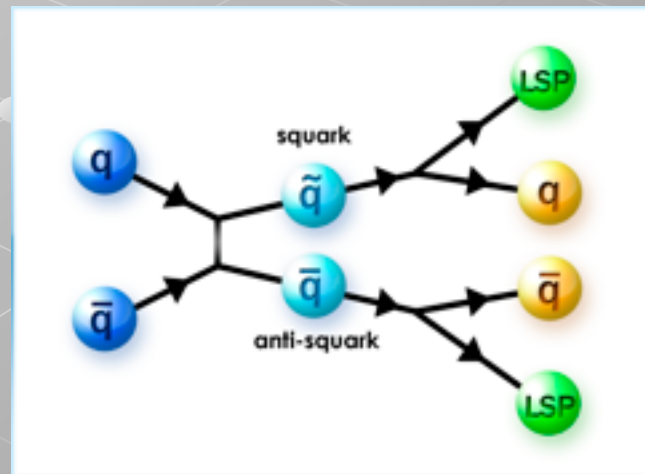
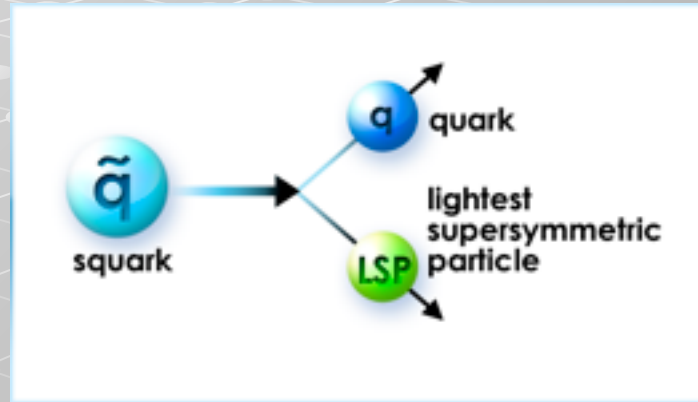
Standard Model Particles				Supersymmetric Partners			
Quarks		Leptons		Squarks		Sleptons	
u up	d down	ν_1 lightest neutrino	e electron	\tilde{u} sup	\tilde{d} sdown	$\tilde{\nu}_1$ sneutrino	\tilde{e} selectron
c charm	s strange	ν_2 middle neutrino	μ muon	\tilde{c} scharm	\tilde{s} sstrange	$\tilde{\nu}_2$ sneutrino	$\tilde{\mu}$ smuon
t top	b bottom	ν_3 heaviest neutrino	τ tau	\tilde{t} stop	\tilde{b} sbottom	$\tilde{\nu}_3$ sneutrino	$\tilde{\tau}$ stau
Electroweak Gauge Bosons				Winos, Higgsinos, Charginos			
W^+ W^- Z γ				$\tilde{\chi}_1^+$ $\tilde{\chi}_1^-$ $\tilde{\chi}_2^+$ $\tilde{\chi}_2^-$			
Higgs Bosons				Higgsinos, Neutralinos			
H A H^0 H^\pm				$\tilde{\chi}_1^0$ $\tilde{\chi}_2^0$ $\tilde{\chi}_3^0$ $\tilde{\chi}_4^0$			
Gluons				Gluinos			
g				\tilde{g}			

Addresses quantum effects:

Supersymmetric contributions cancel SM ones



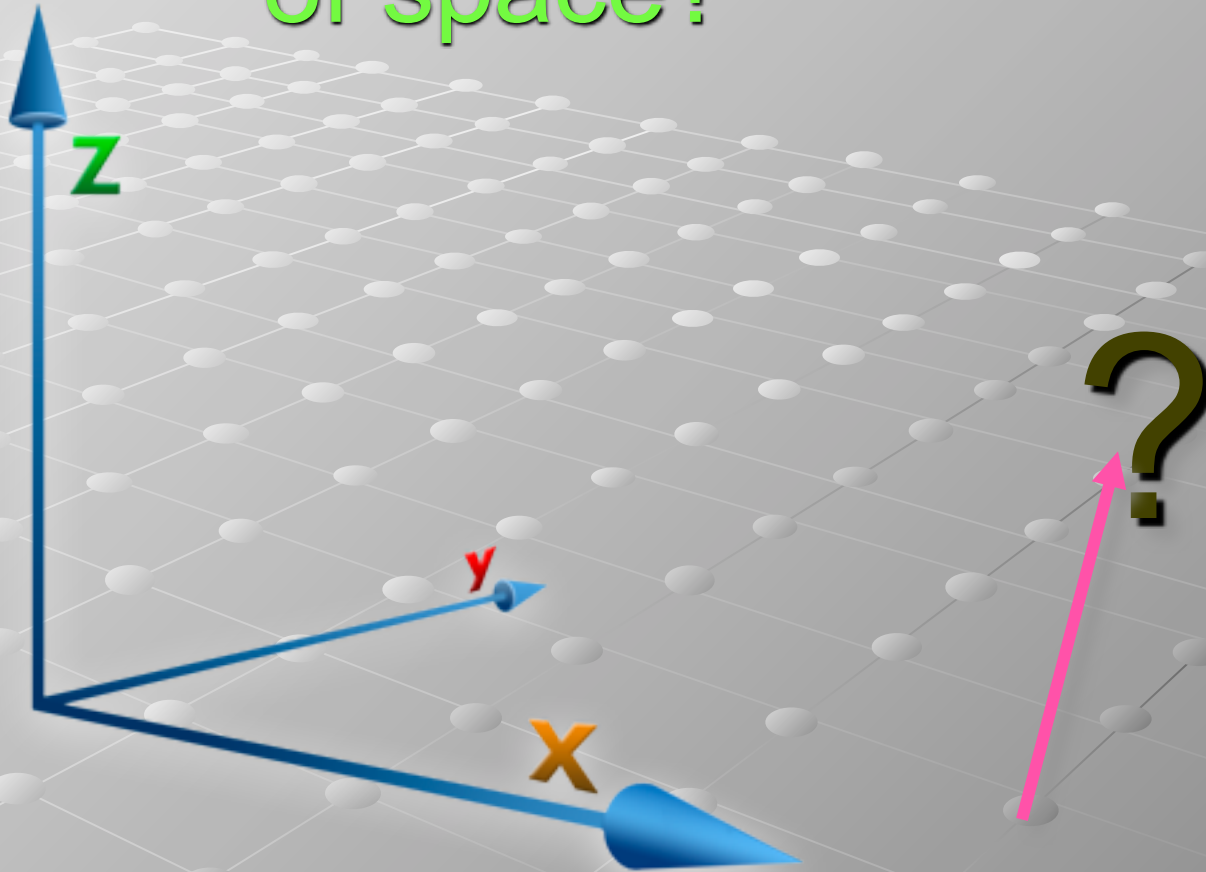
Experimental consequences



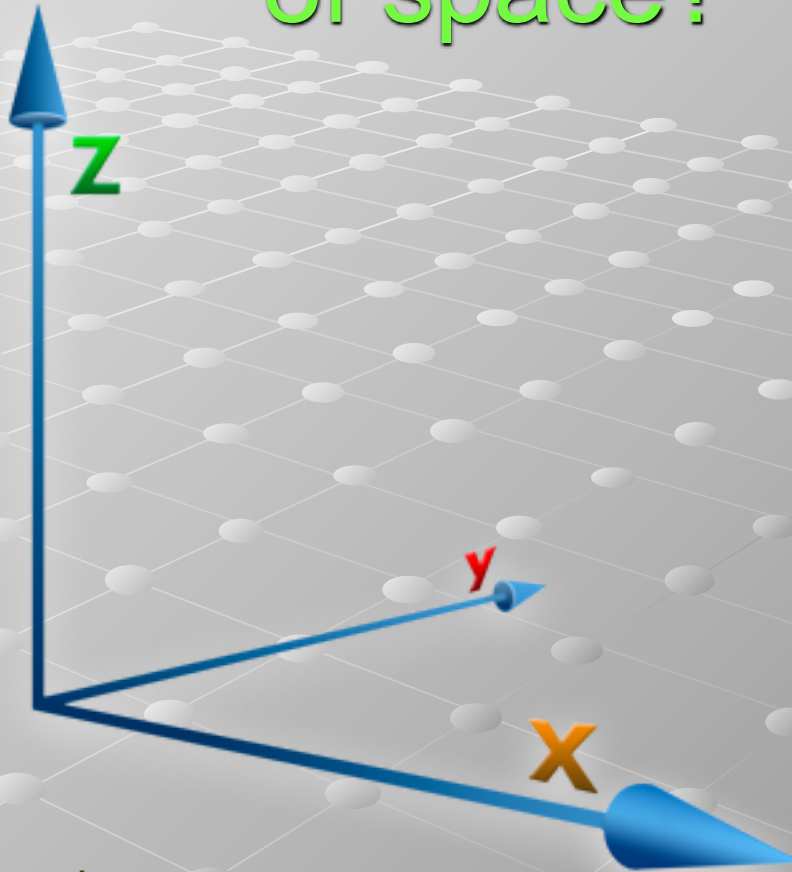
Supersymmetry

- **Jury still out**
- **Waiting for experimental answers**
- **Meanwhile...think about alternatives**

Another possibility: Extra dimensions of space?



Another possibility: Extra dimensions of space?

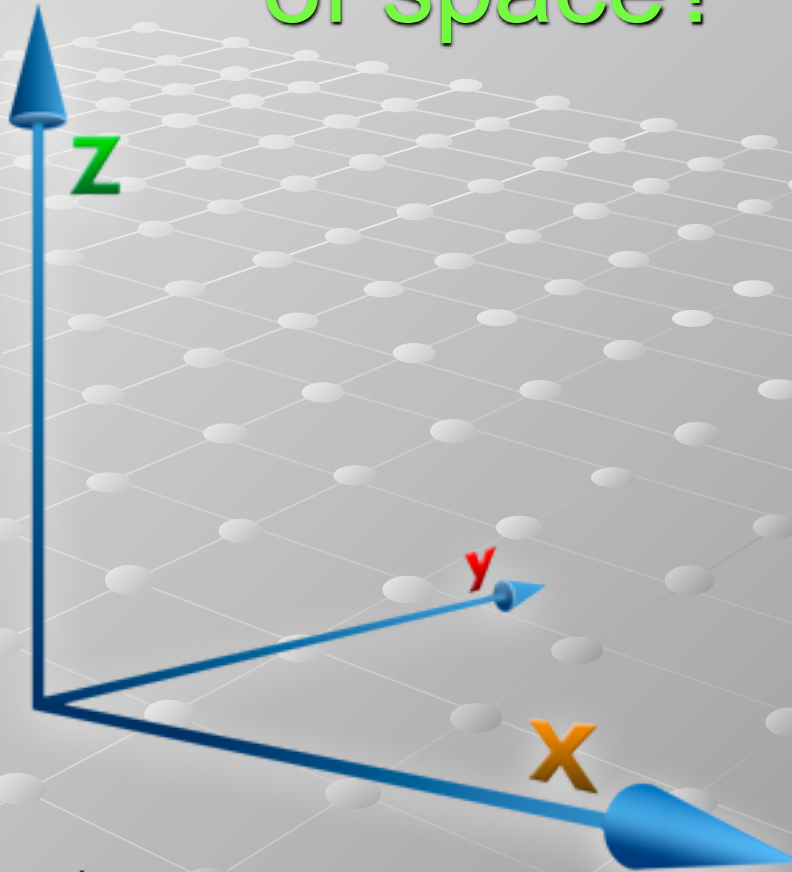


?



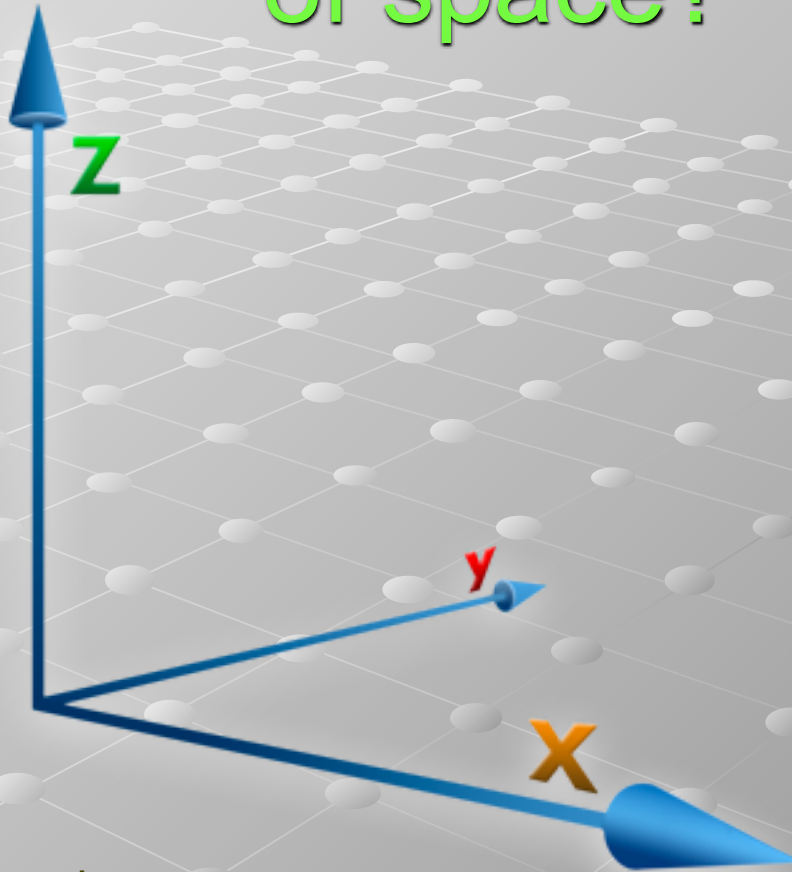
•Spatial dimensions:

Another possibility: Extra dimensions of space?



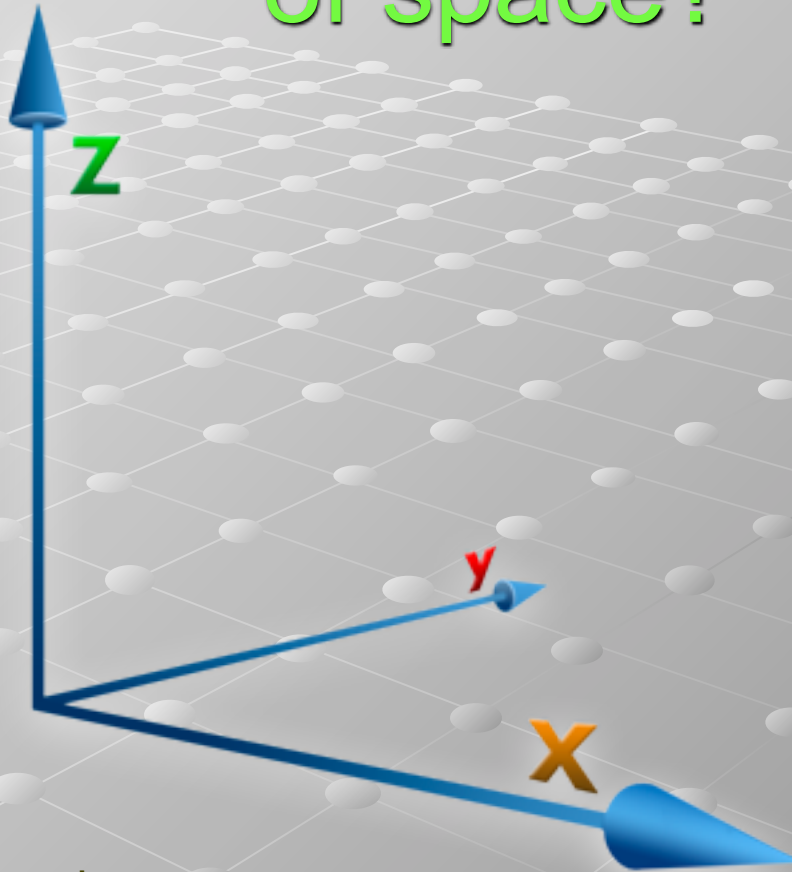
- Spatial dimensions:
- We are familiar with three dimensions:

Another possibility: Extra dimensions of space?



- Spatial dimensions:
- We are familiar with three dimensions:
 - x,y,z (up-down, forward-backward, left-right)

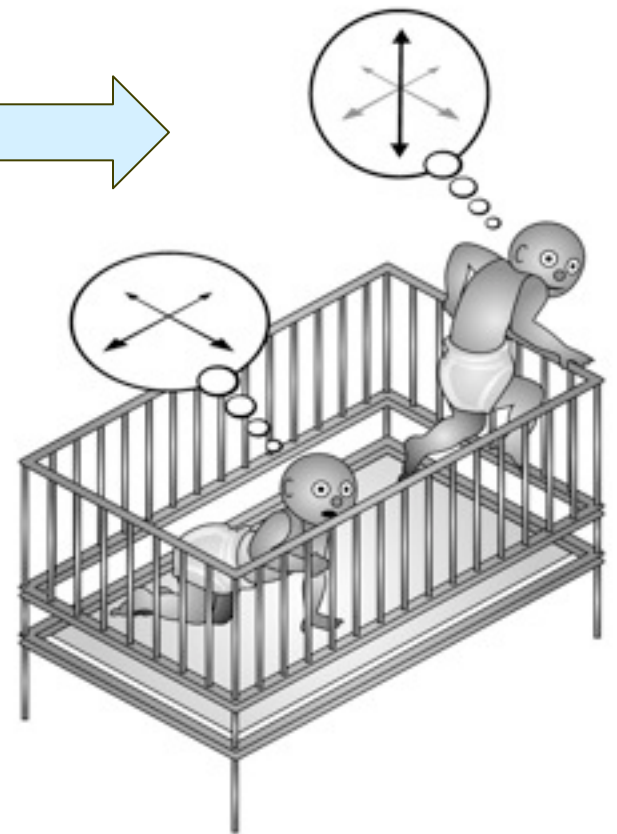
Another possibility: Extra dimensions of space?



- Spatial dimensions:
- We are familiar with three dimensions:
 - x,y,z (up-down, forward-backward, left-right)
 - However, there may be more we don't see!

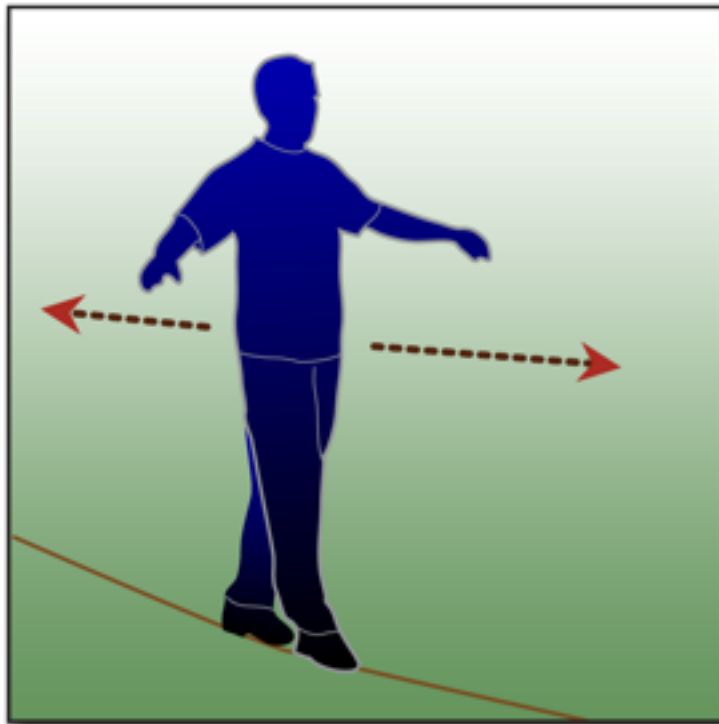
Why: extra dimensions?

- **String theory**
- **Spirit of inquiry: We don't know why there appear to be four spacetime dimensions**
 - **No physics laws mandate that**
- **Explain connections among physical parameters in our universe**

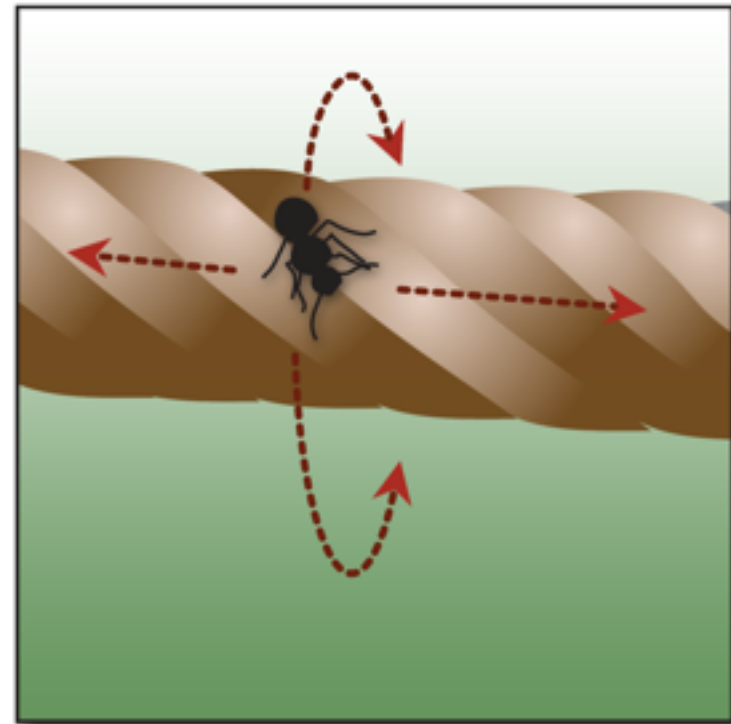


Hidden (rolled up or small?) dimensions

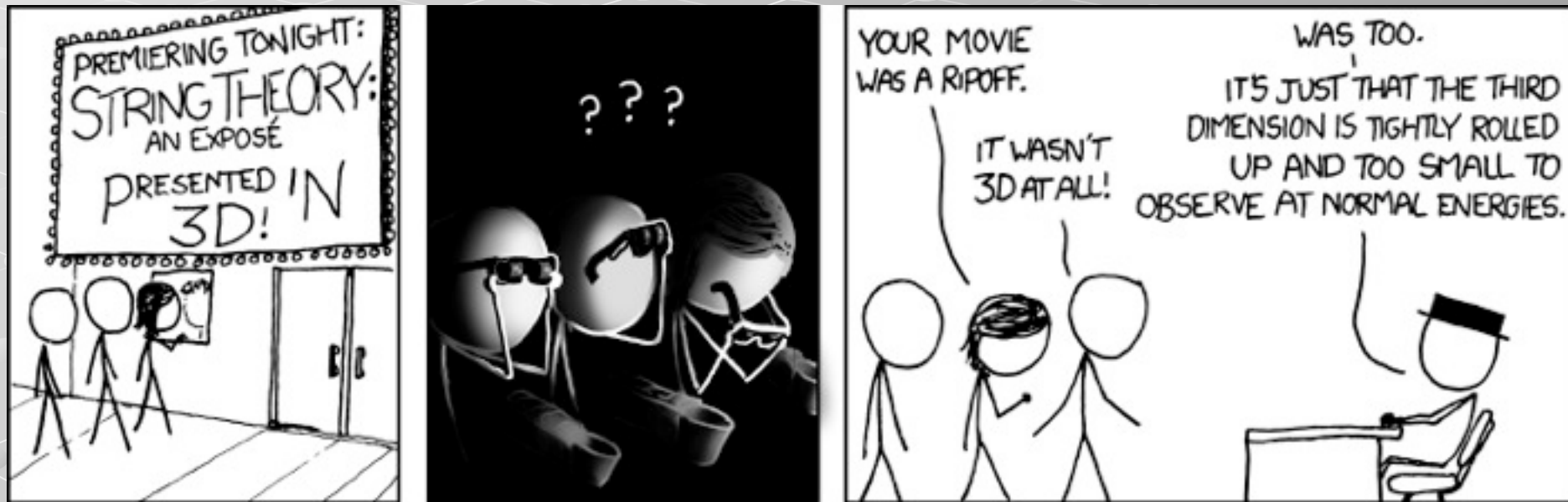
Man on tightrope



Ant on tightrope



We clearly don't see them



BraneWorld: one way to hide dimensions:

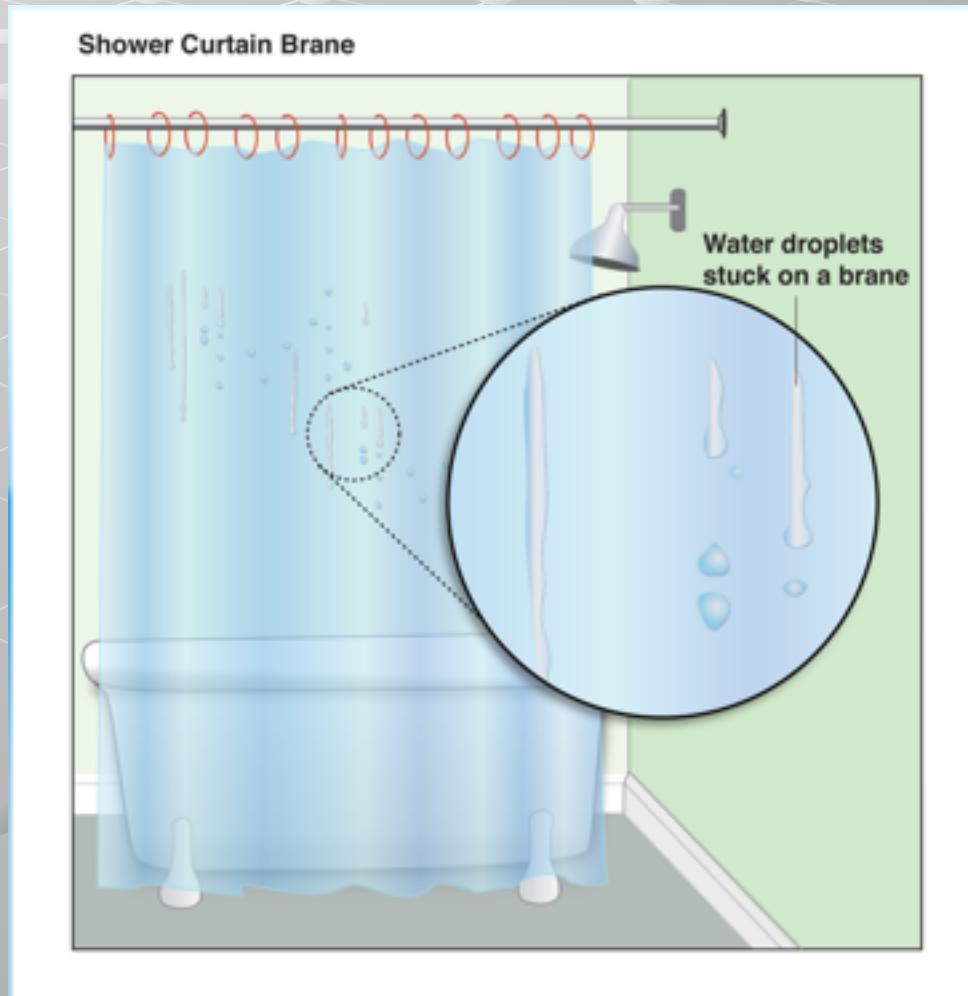
Higher-dimensional world in which particles and matter are stuck on a brane



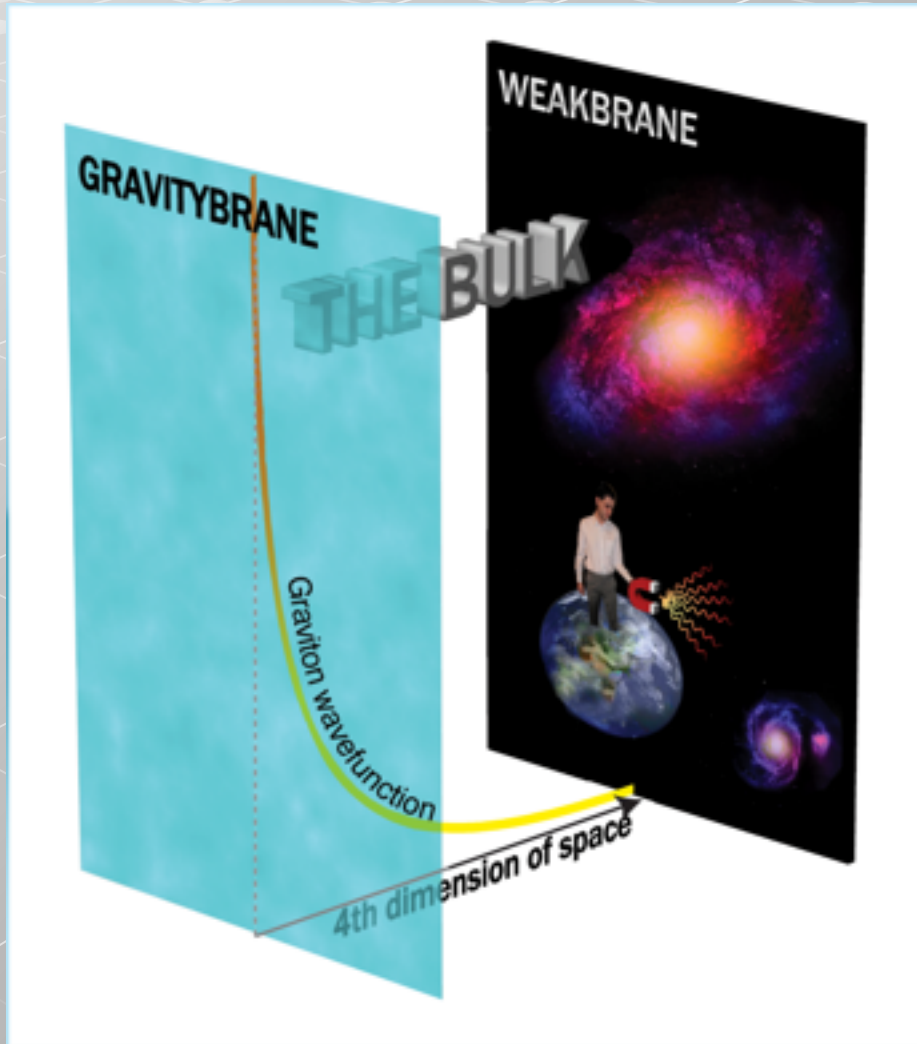
Drawn as
2D

Really 3D
And really
infinite

Matter and our world can be stuck on a brane—



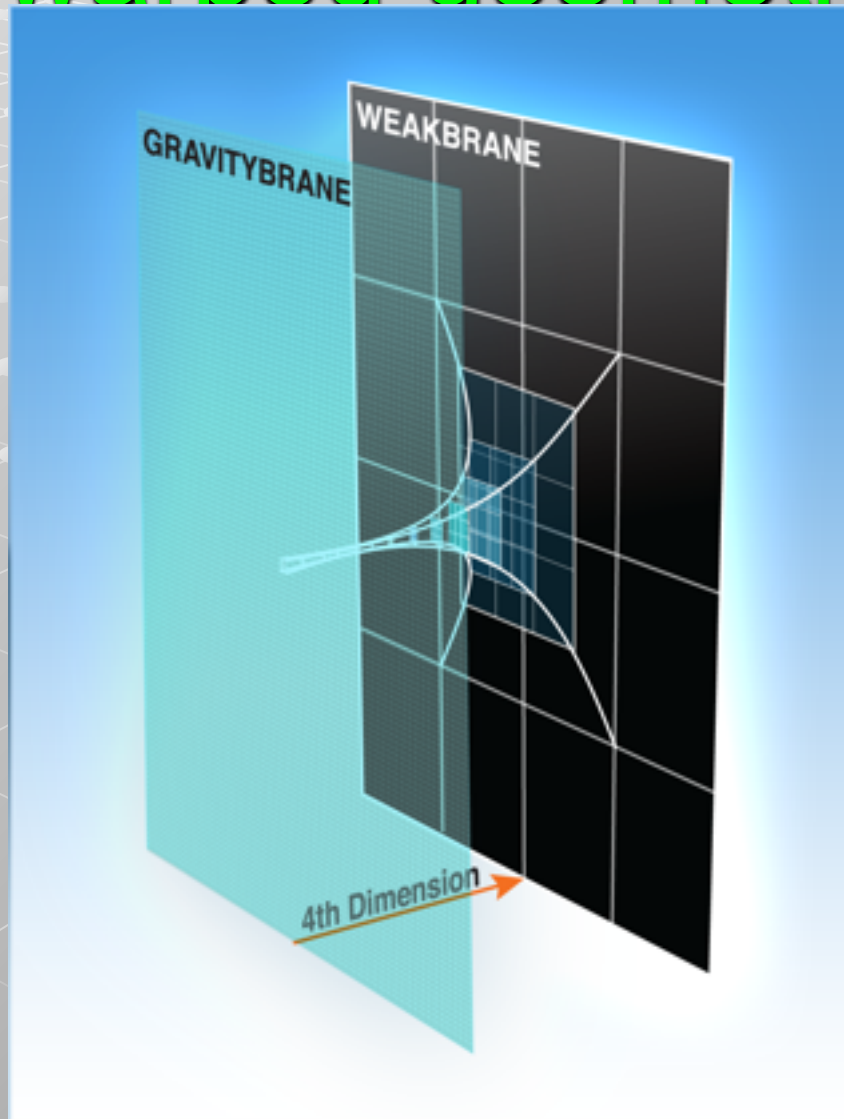
Warped Spacetime Geometry: Can Solve Hierarchy Problem



Gravity strong in our universe; weak elsewhere

Can explain hierarchy by graviton wavefunction

Can also understand from warped geometry

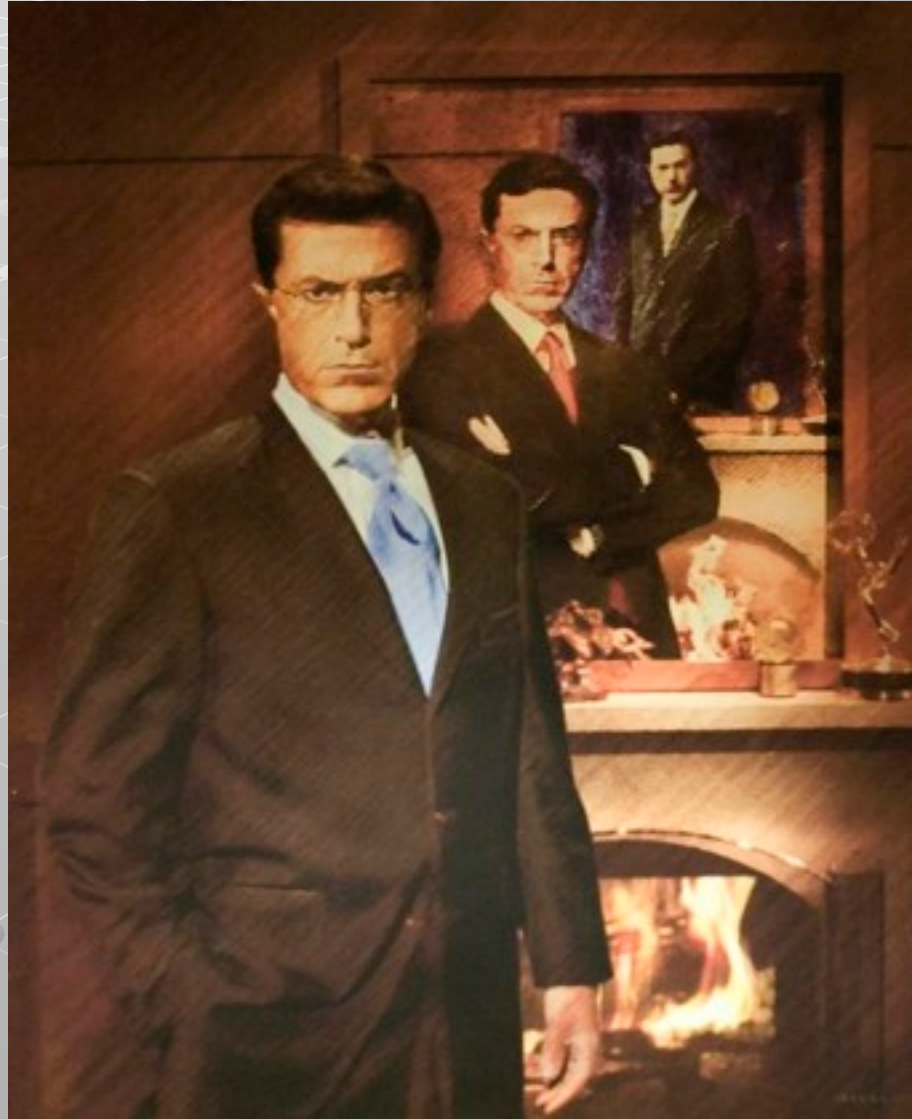


Space, time

Matter,
energy

All
Exponential
Recalled

Really Different Universes!



Experimental Signal: Can search for extra dimensions!

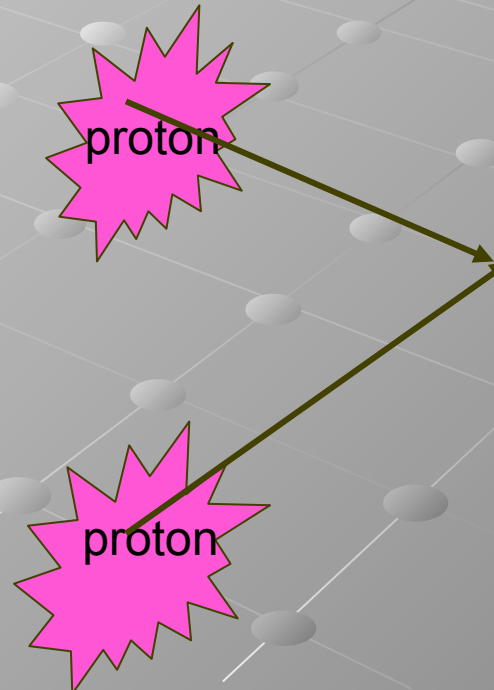
- **Protons collide**
- **Produce a particle that travels in extra dimensions**
- **Decay in detector**

LHC Collision

Experimental Signal: Can search for extra dimensions!

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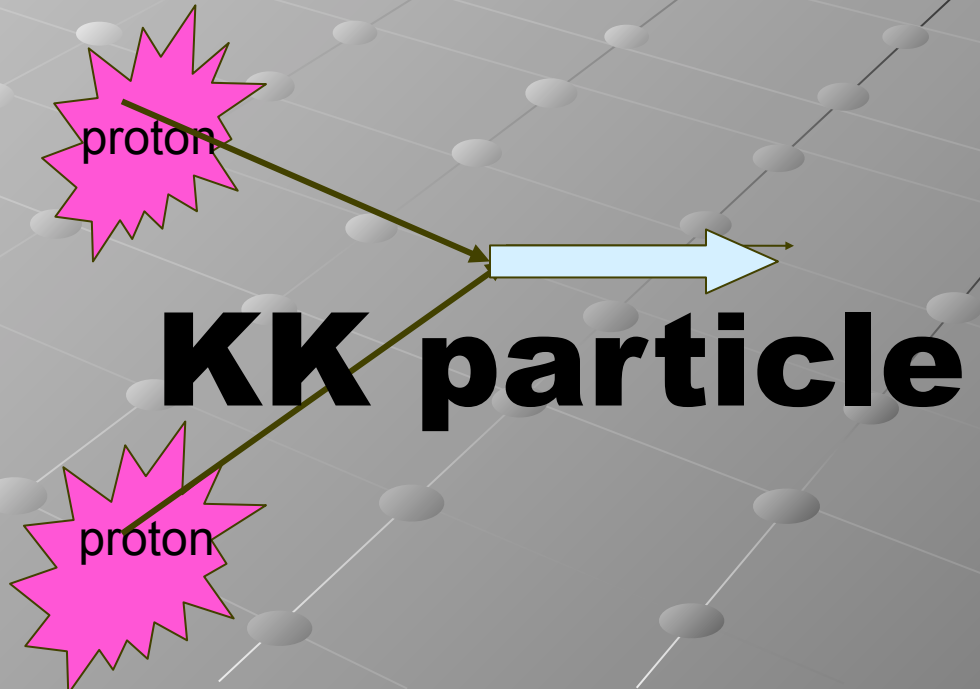
LHC Collision



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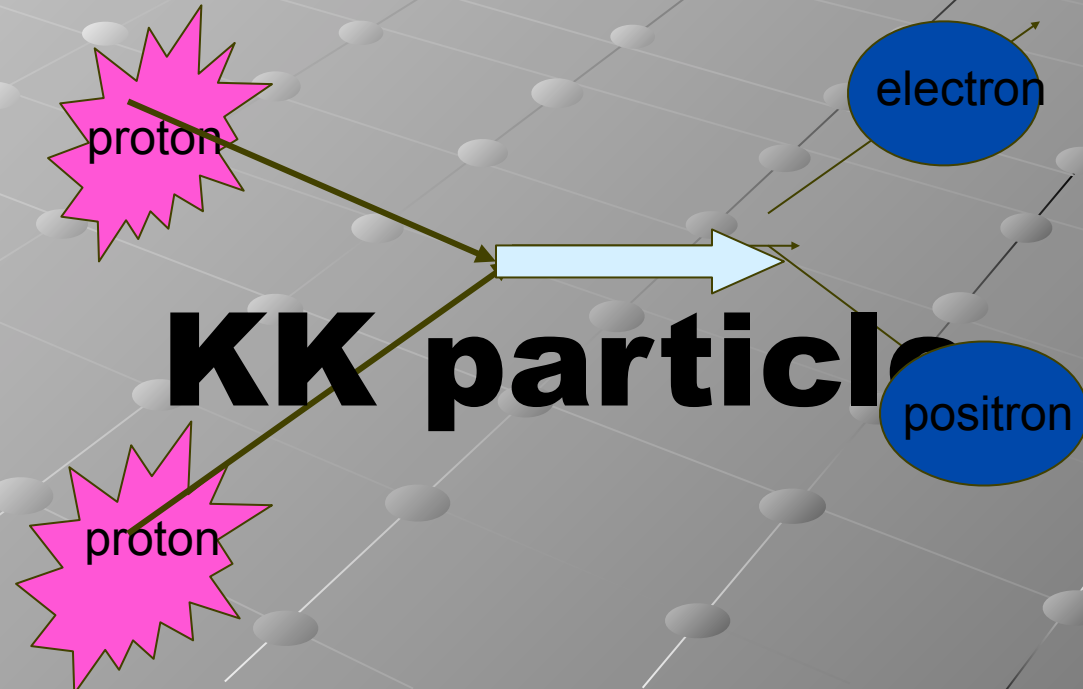
LHC Collision



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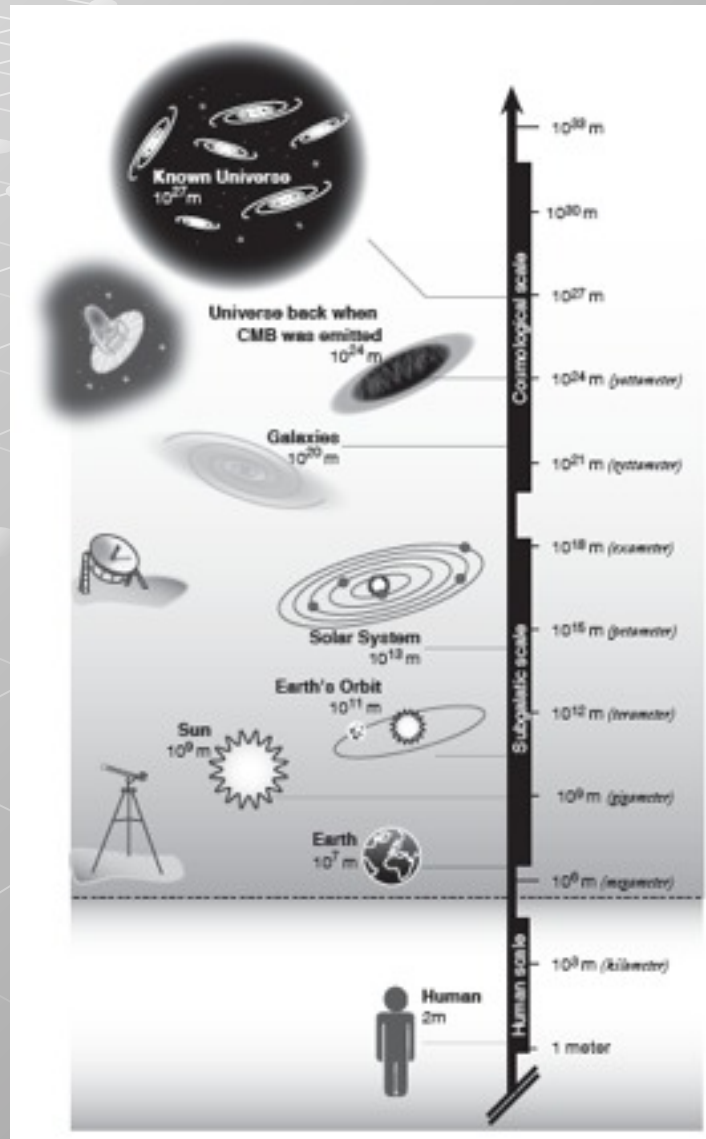
LHC Collision



Waiting for Results

- What will LHC reveal?
 - Warped xtra dimension?
 - Supersymmetry?
 - Dark matter?
 - Something entirely unforeseen?
- Waiting for higher intensity beams
- Higher energy protons
- Hopefully we will know

Exploring large Scales too

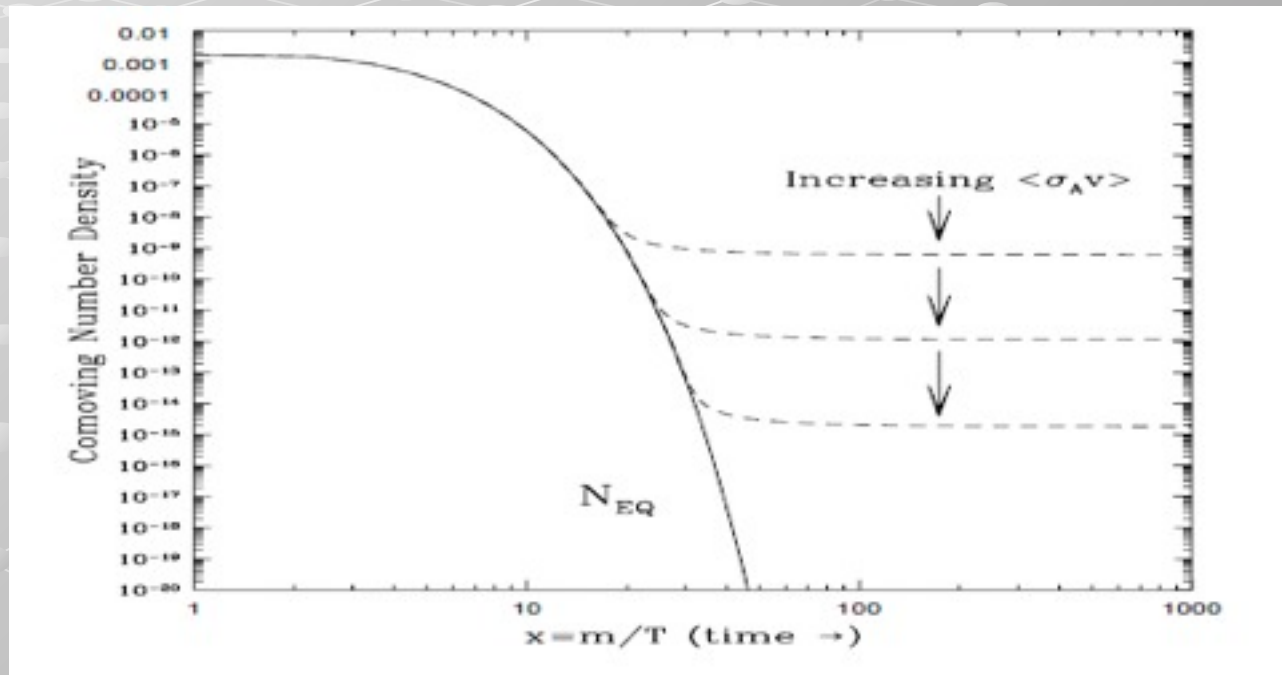


Mysteries of Dark Stuff

- **Dark energy: most mysterious**
 - Energy not carried by matter
 - Doesn't clump, doesn't dilute as universe expands
- **Dark Matter: what is it?**
 - And why are the matter densities and dark matter densities so close?



WIMP "Miracle"



$$\Omega_\chi h^2 = \frac{m_\chi n_\chi}{\rho_c} \simeq 0.1 \left(\frac{3 \times 10^{-26} \text{ cm}^3 \text{ sec}^{-1}}{\langle \sigma_A v \rangle} \right)$$

$$\sigma_{\text{weak}} \simeq \frac{\alpha^2}{m_{\text{weak}}^2}$$

Is WIMP the right Miracle?

- $\rho_X \sim 5\rho_B$
- Why should dark matter and ordinary matter energy densities be at all comparable?
- Could just be independently generated—baryogenesis somehow and weak miracle
- Could be related: Asymmetric Dark Matter
 - $n_B \sim 5n_X$
- Could be more generally related; naturalness not quite so inflexible
 - Weak scale dark matter still natural
 - Thermal suppression
 - Bleeding excess number density through in eqm lepton violation below sphaleron scale

Idea

- Asymmetry in dark matter
- Transfer asymmetry to normal matter
- Here we assume dark matter asymmetry produced in early universe
- Question is when we have operators violating B or L and X simultaneously will we get correct matter density
- Question is whether number densities work out for a given mass

Light Dark Matter: “Relativistic Solution”

- Chemical equilibrium between B or L and X

$$\mu_X / \mu_B = \mathcal{O}(1)$$

- Net asymmetry

$$n_i = g_i f(m_i/T) T^2 R(T)^3 \mu_i$$

- Ratio chemical potential ~ ratio number density ~ ratio energy density

$$\mu_X / \mu_B \sim \mathcal{O}(1)$$

$$m_X / m_{\text{proton}} \sim \Omega_{DM} / \Omega_B$$

Weak Scale (or Heavy) Dark Matter “Nonrelativistic Solution”

● More generally

$$n_i = g_i f(m_i/T) T^2 R(T)^3 \mu_i$$

Number density suppressed for $m \gg T$

$$f(x) = \frac{1}{4\pi^2} \int_0^\infty \frac{y^2 dy}{\cosh^2\left(\frac{1}{2} \sqrt{y^2 + x^2}\right)}$$

Xogenesis New Class of Models

● New “miracle”-New models

- Transfer asymmetry from dark matter to matter
- Create both at same time
 - Can be weak scale
 - Can be light

● Different bounds

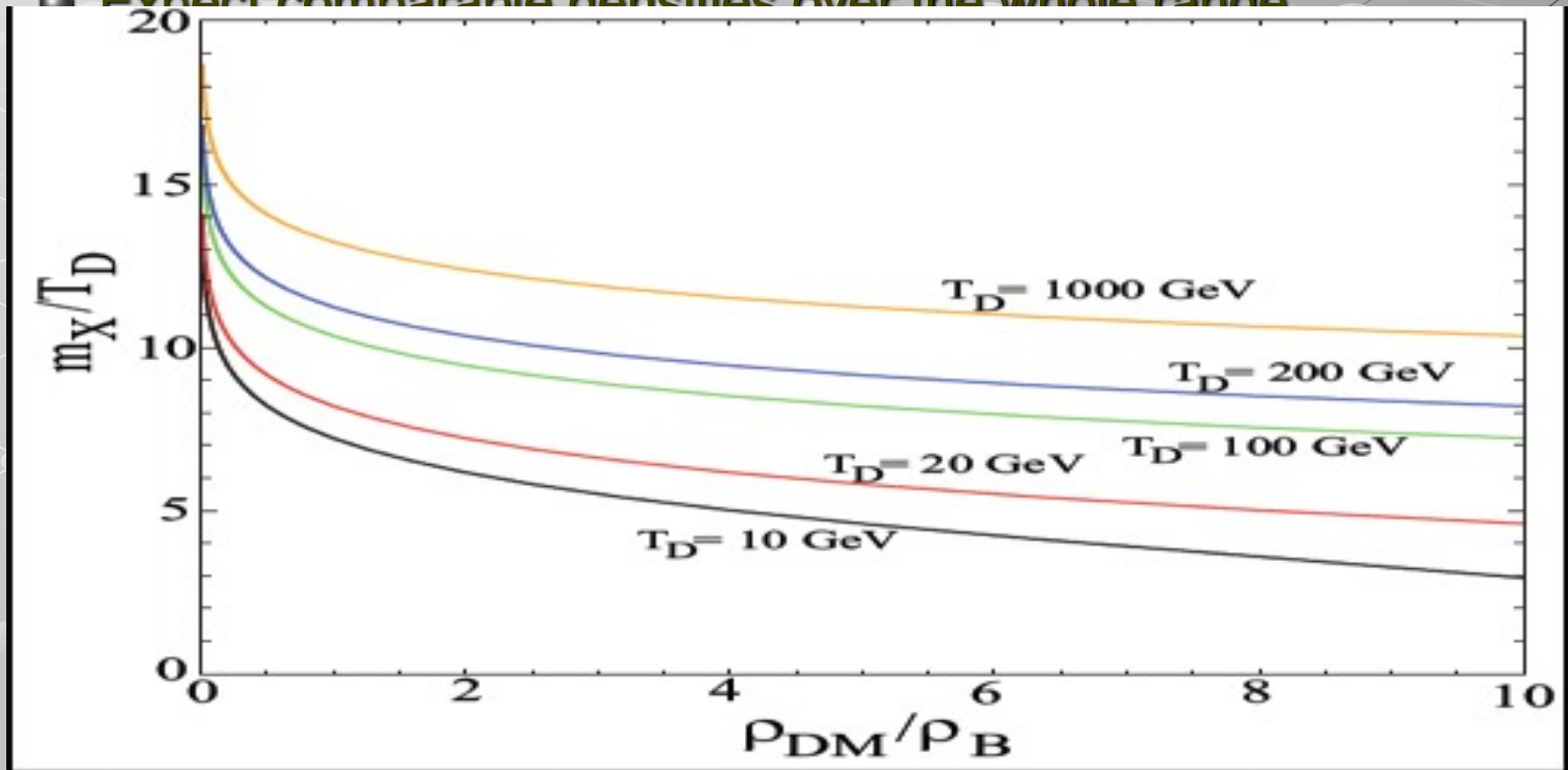
● Different tests

● Lighter more accessible

● Challenges for future-

Naturalness allows hierarchy of order 10

- Right ratio of densities found for wide range of m/T
- Usually need $m/T \sim 10$, which is quite reasonable
- Expect comparable densities over the whole range



Entering a new era in physics

- **Every time we've explored smaller or larger length scales, we've found new phenomena, new connections**
- **Many exciting new ideas for what we might discover**
- **More connections are there—we just have to find them**
- **Secrets of the universe are about to unravel**

Hidden riches in the universe

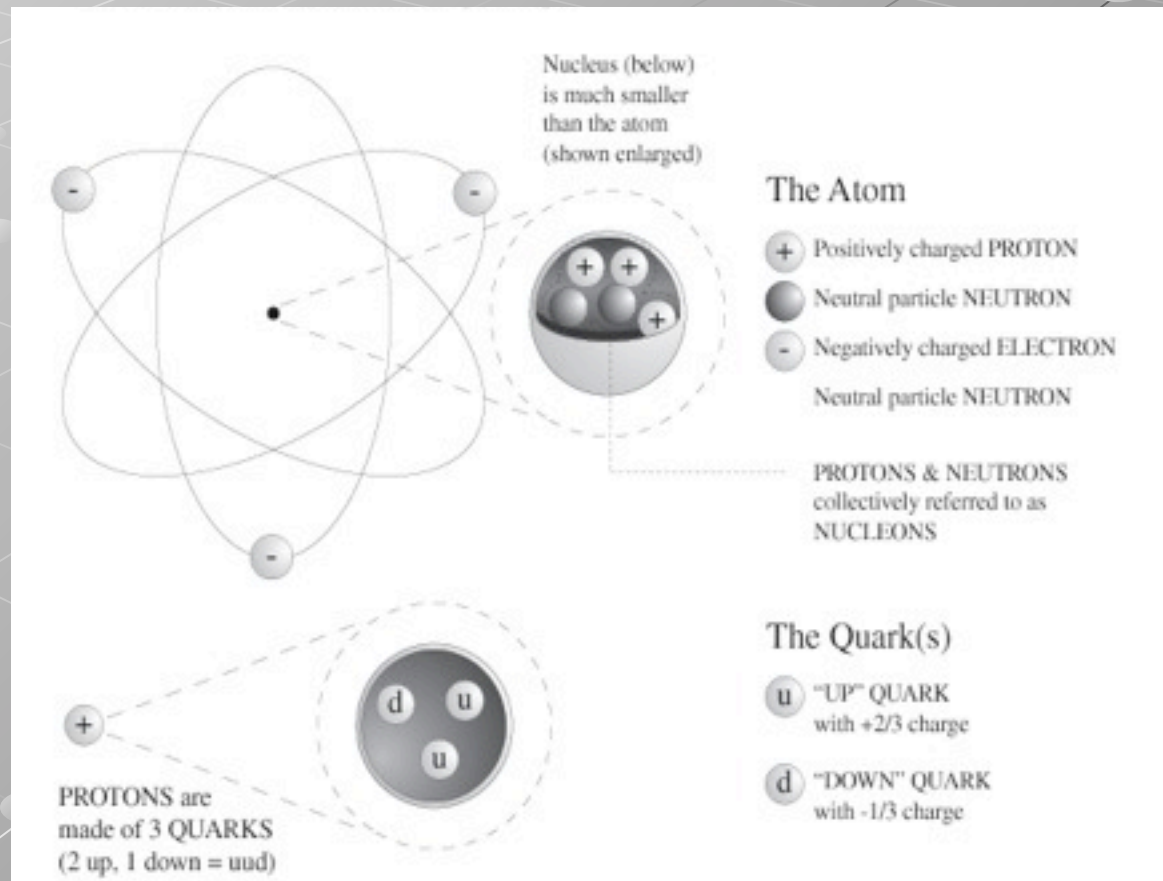


What do we explore at small scales?



What do we explore at small scales?

● Interior of matter

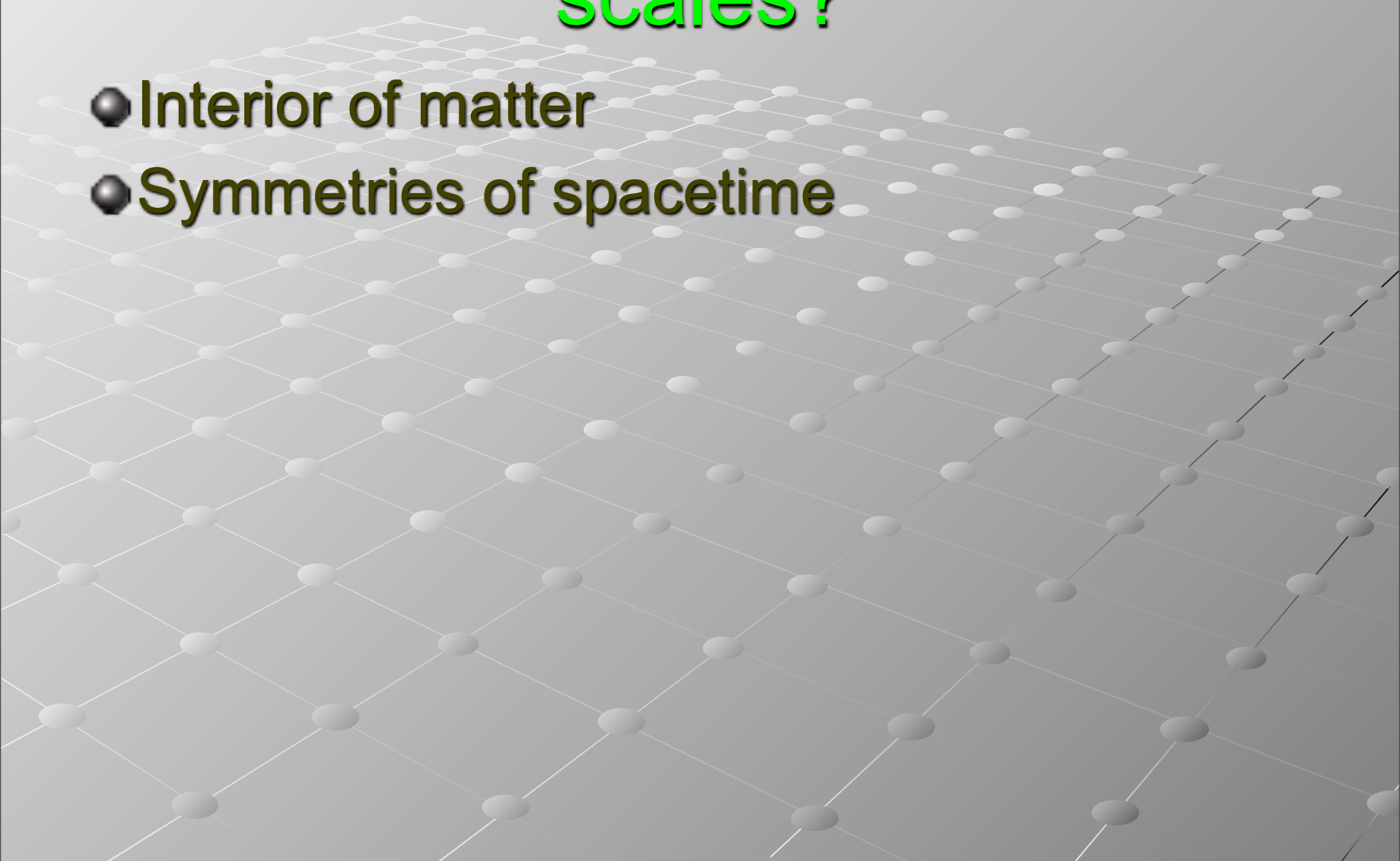


What do we explore at small scales?



What do we explore at small scales?

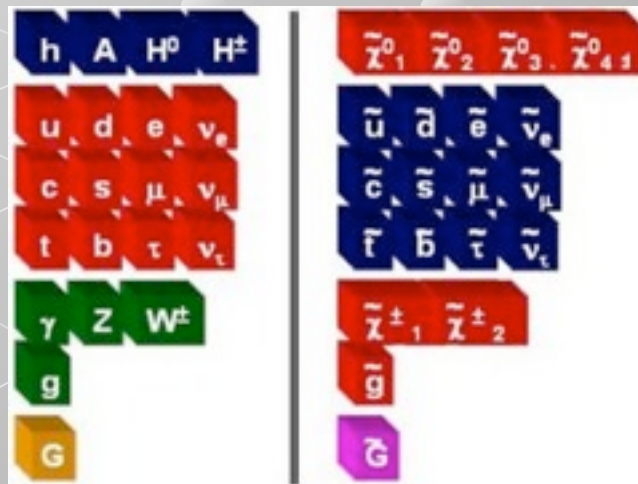
- Interior of matter
- Symmetries of spacetime



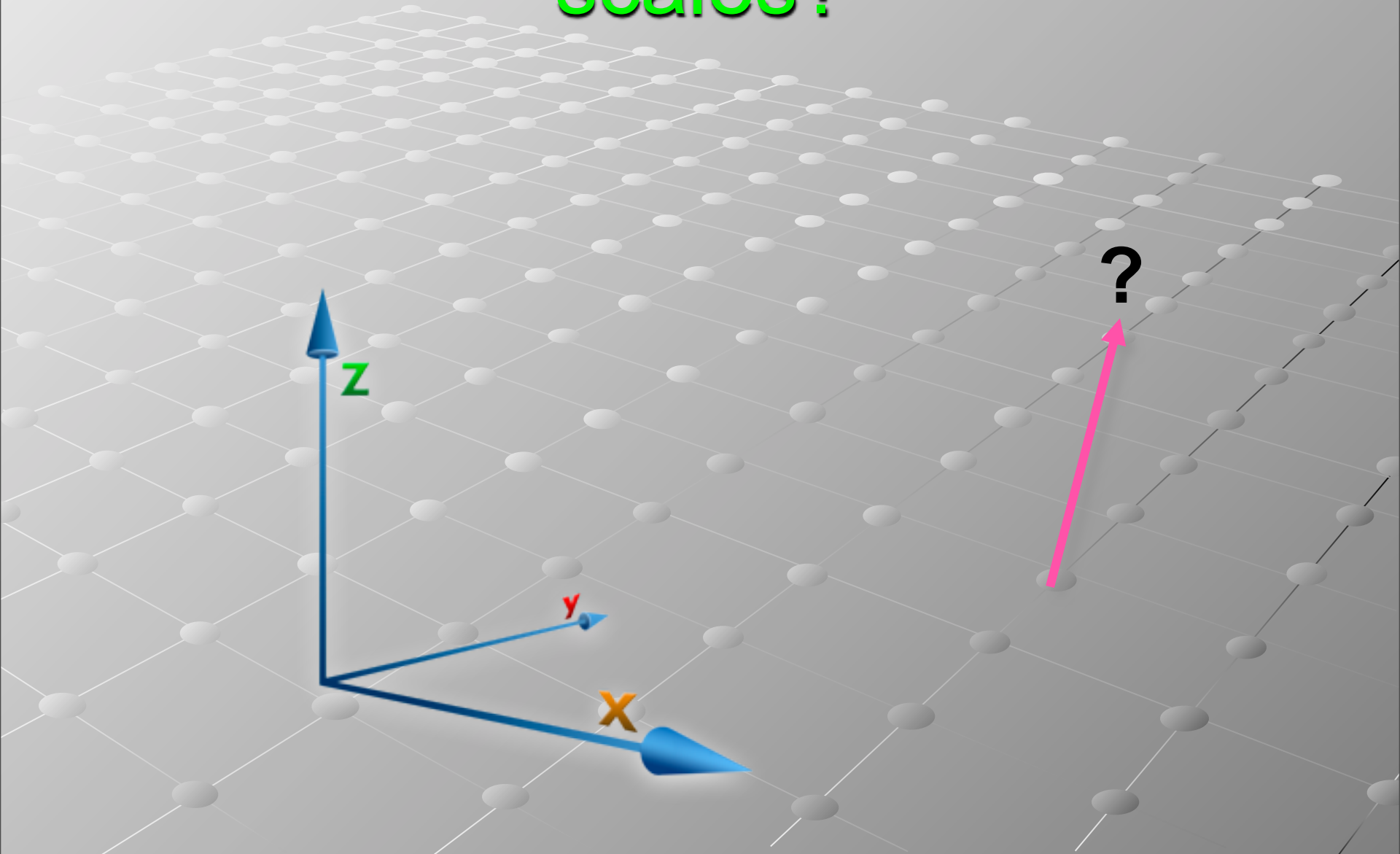
What do we explore at small scales?

- Interior of matter
- Symmetries of spacetime
- Space itself

What do we explore at small scales?

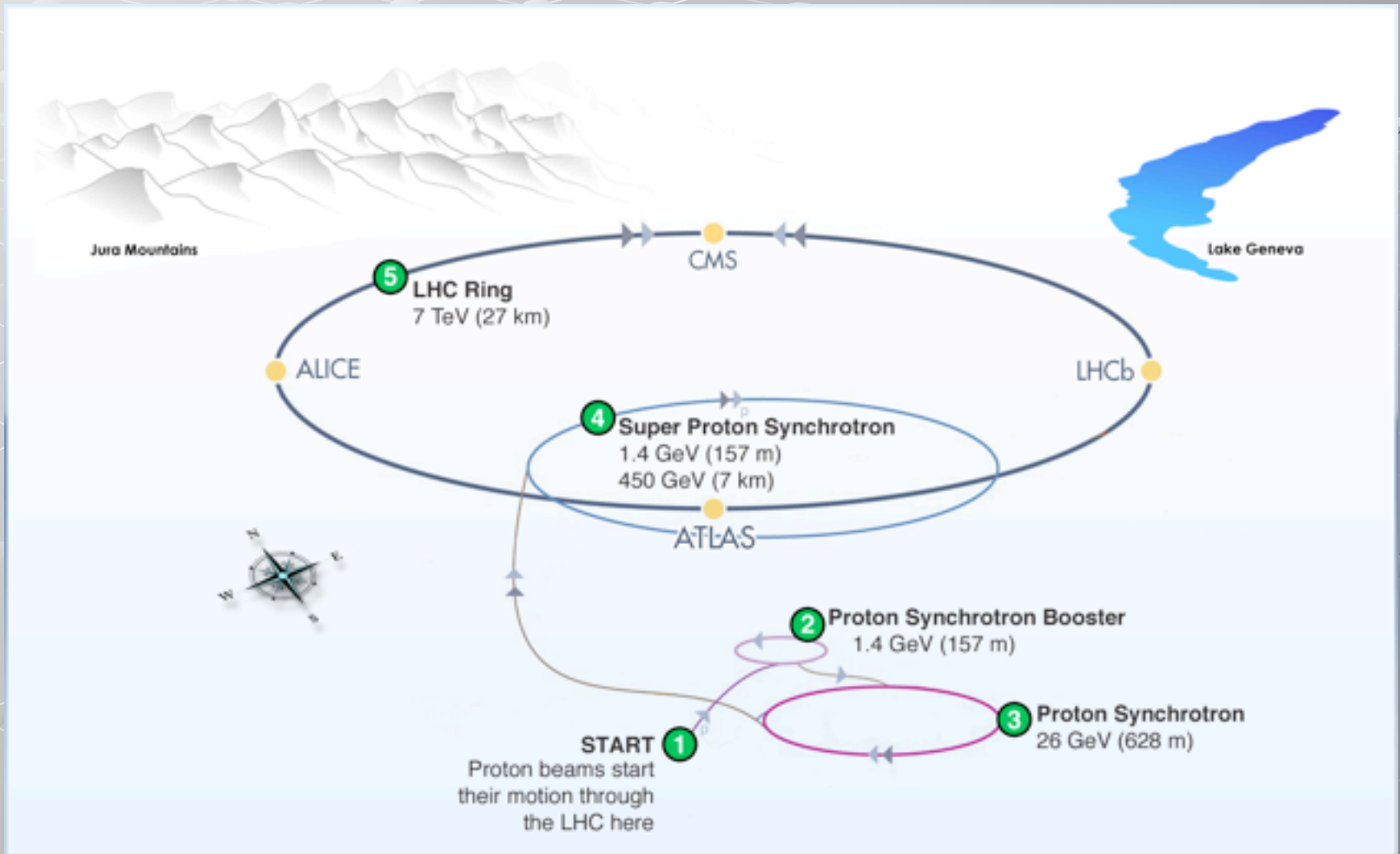


What do we explore at small scales?



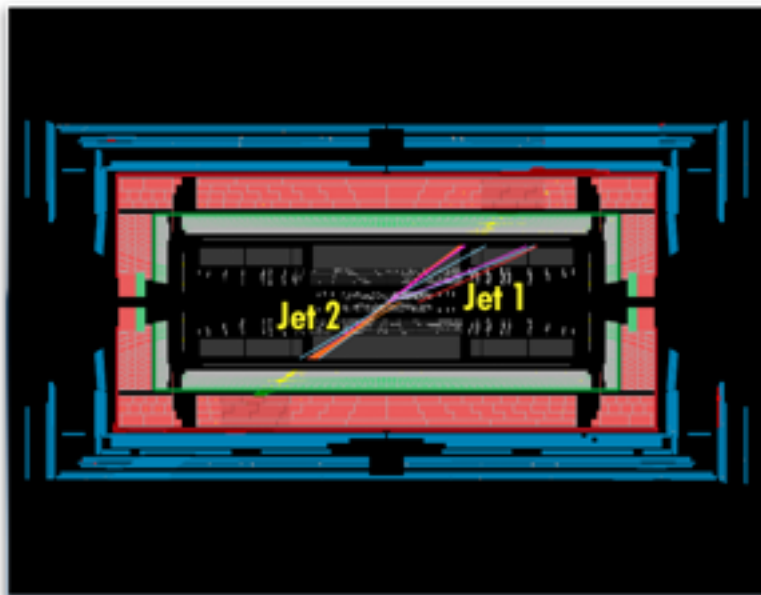
LHC Machine

Series of accelerations
Circular accelerator means you can give successive kicks
A number in succession



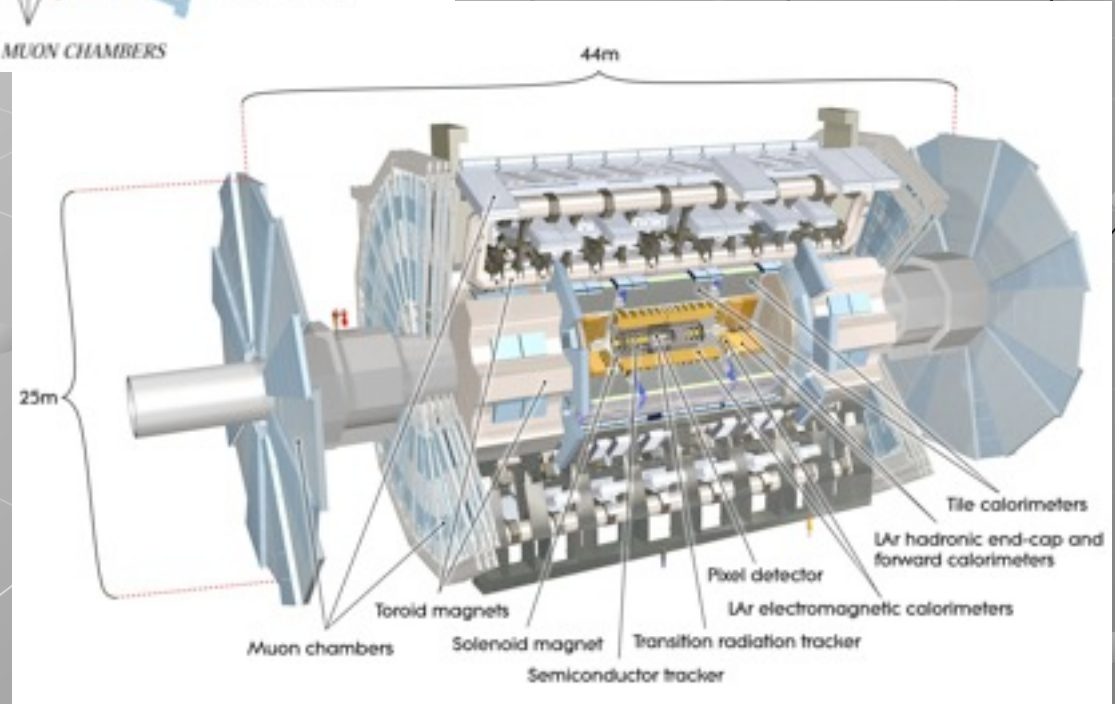
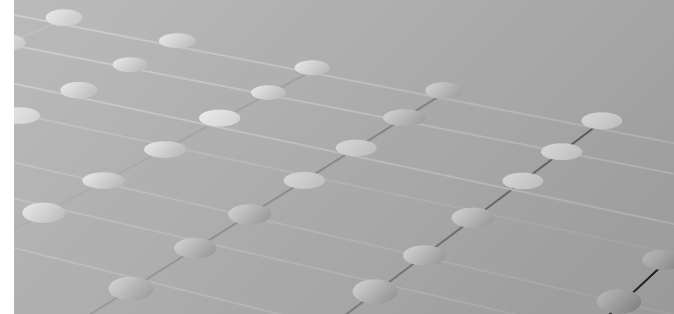
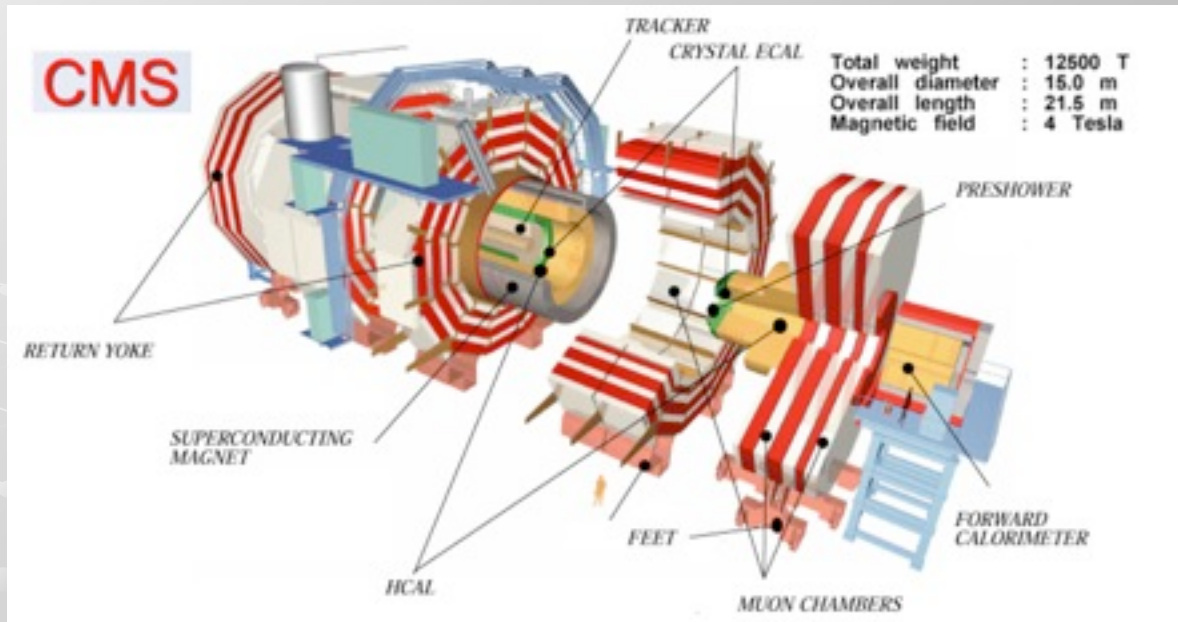


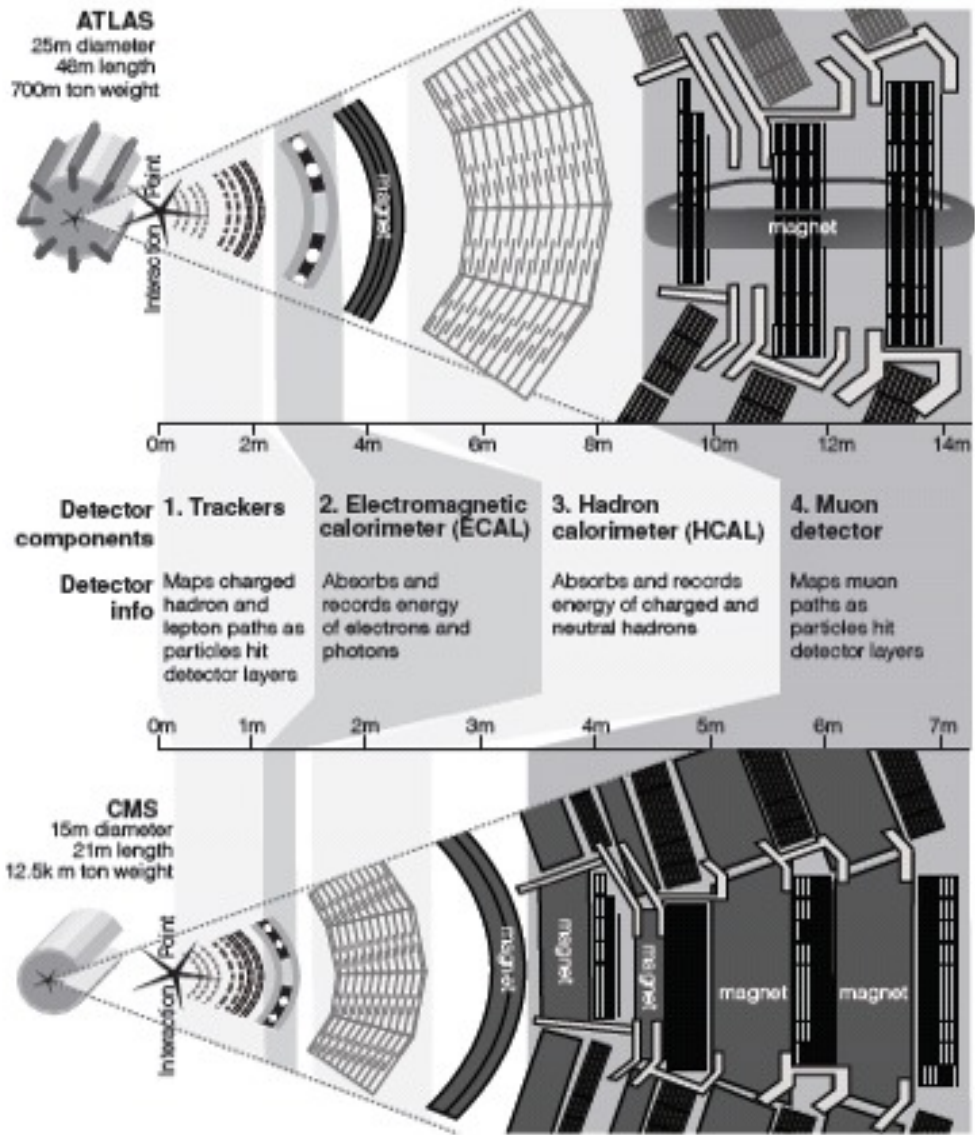
cross section view



side view

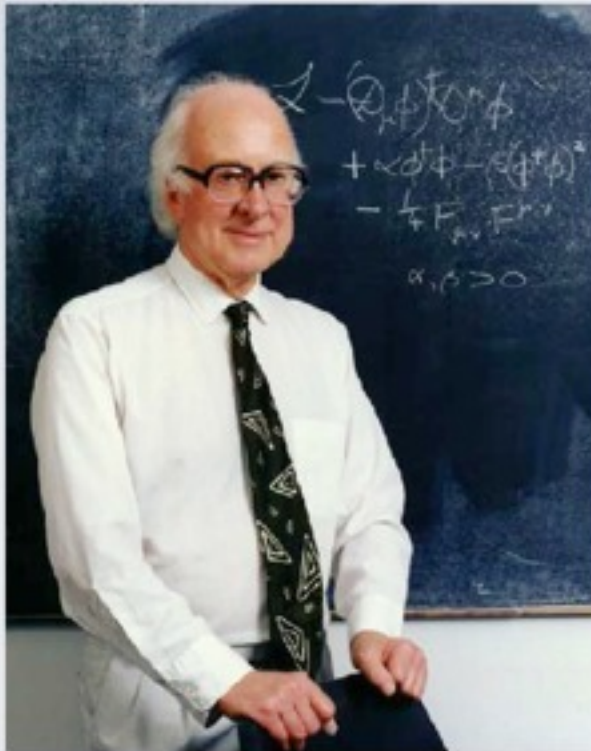
Experiments: find "fingerprints"





Higgs

Higgs: the man, the mechanism and the particle



The man



The other men
(Kibble, Guralnik, Hagen,
Englert, Brout)

Thanks to Paddy Fox

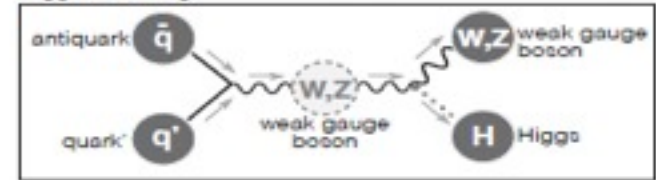
Higgs Mechanism

- Higgs field spreads throughout space
- If it has zero value, elementary particles don't have mass
- If it has nonzero value, particles get mass
- How big their mass is depends on how much they interact with Higgs field
- Heavier particles have biggest interaction

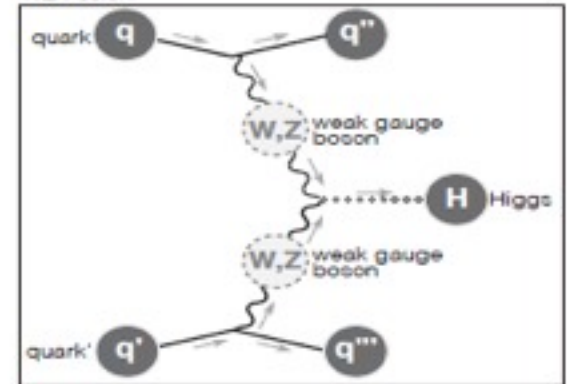
(Future) experimental evidence: Higgs Particle!

**Higgs search tricky
Because connected to
mass, interacts most
with heavy particles
But protons don't
contain heavy particles!
Need to rely on virtual
(quantum) effects**

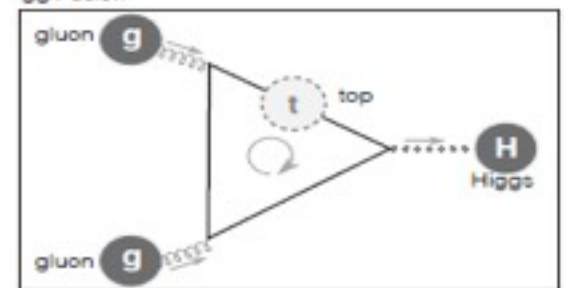
Higgs-Strahlung



WZ Fusion



gg Fusion



Higgs Decays

