Here be Dragons

[fairy] tales from Beyond the Standard Model

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Cornell Society of Physics Students
25 April 2013

Image: Trogdor, from *Homestar Runner*

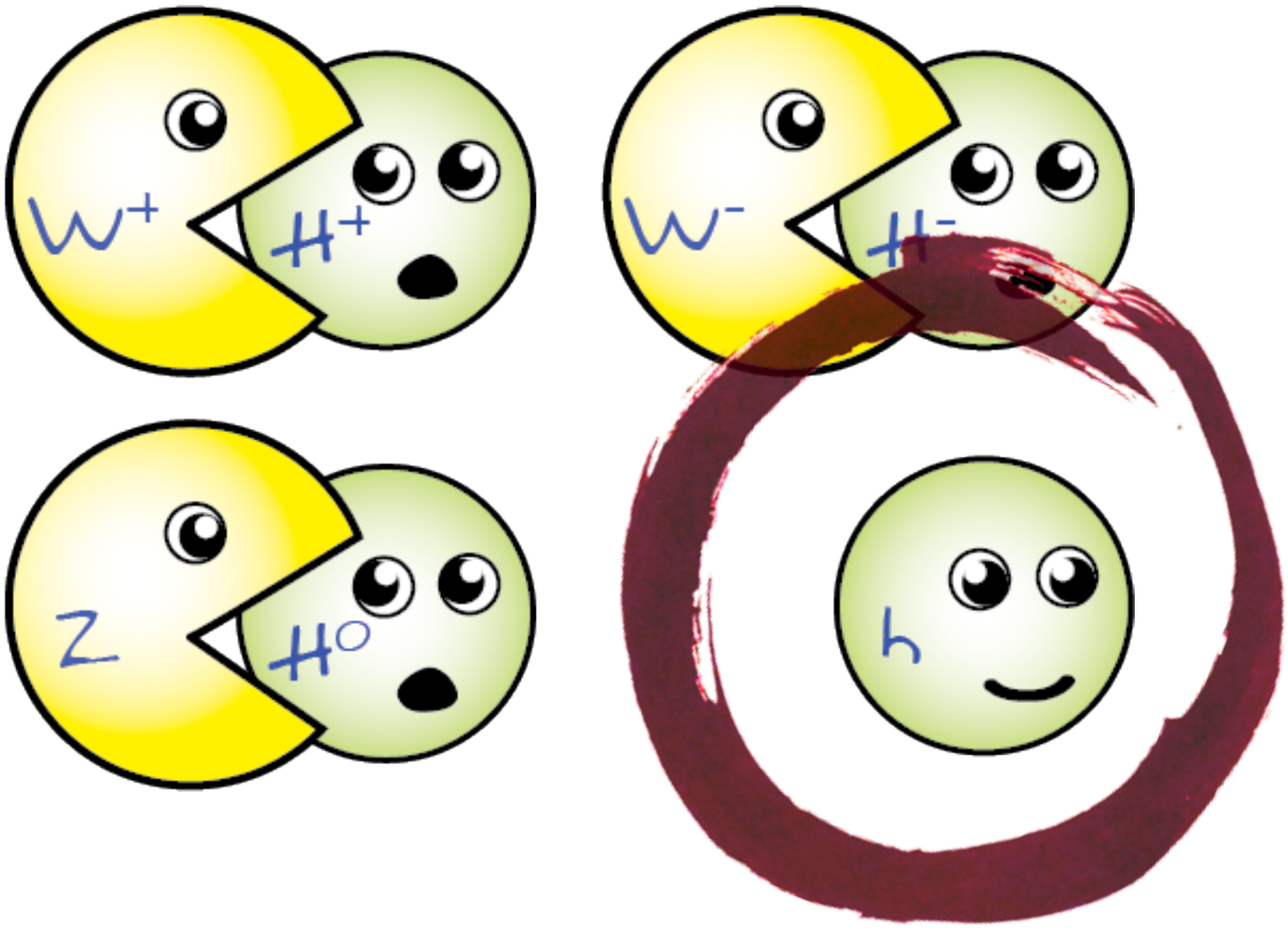
Cornell
Particle Theory

“The LHC might make dragons that might eat us up”

Nima Arkani-Hamed

Image: http://seamonstr.se/2010/09/here-be-dragons-preview/
Quote: “Asking a Judge to Save the World, and Maybe a Whole Lot More,” Dennis Overbye, *New York Times,* 29 March 2008

We will not talk about



Nor will we talk about

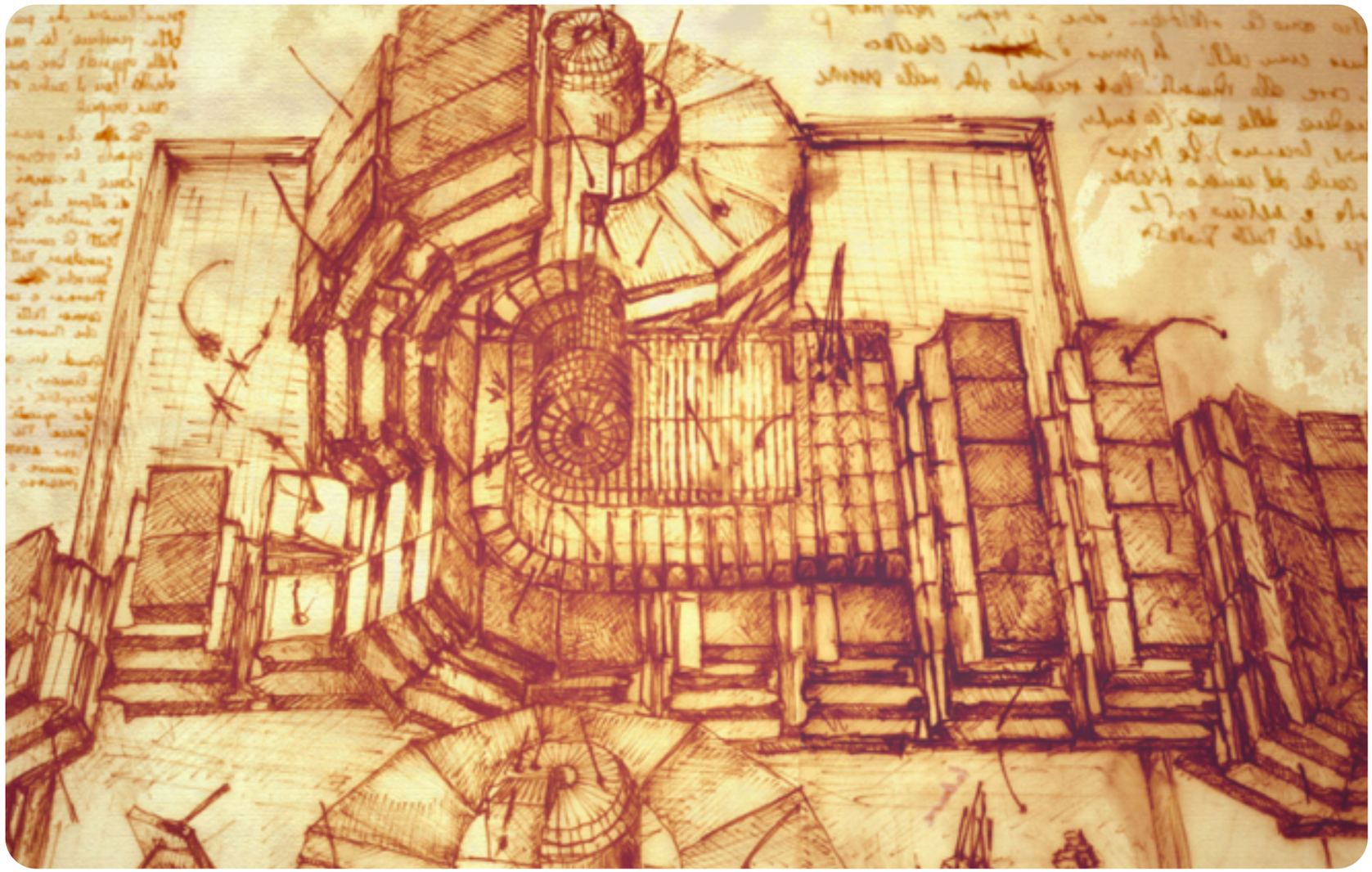


Image: Sergio Cittolin, e.g. http://www.symmetrymagazine.org/article/may-2009/gallery-sergio-cittolin

“The LHC might make dragons that might eat us up”

Nima Arkani-Hamed

this talk: hypotheticals

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Overview

Size of colored box ~ proportion of US effort
Caveat: just a personal opinion!

why new physics?

Focus on: hierarchy, origin of matter
Briefly: other reasons for optimism

collider physics

implications of experiments, clever ways to test models

extra dimensions

Focus on: holographic principle
Briefly: particle implications

supersymmetry

Focus on: recent sobering results
Briefly: promising theoretical directions

dark matter

Focus on: astroparticle physics
Briefly: recent hints in direct detection

formal theory

Focus on: duality, scattering amplitudes
Briefly: strings as a theory of other things

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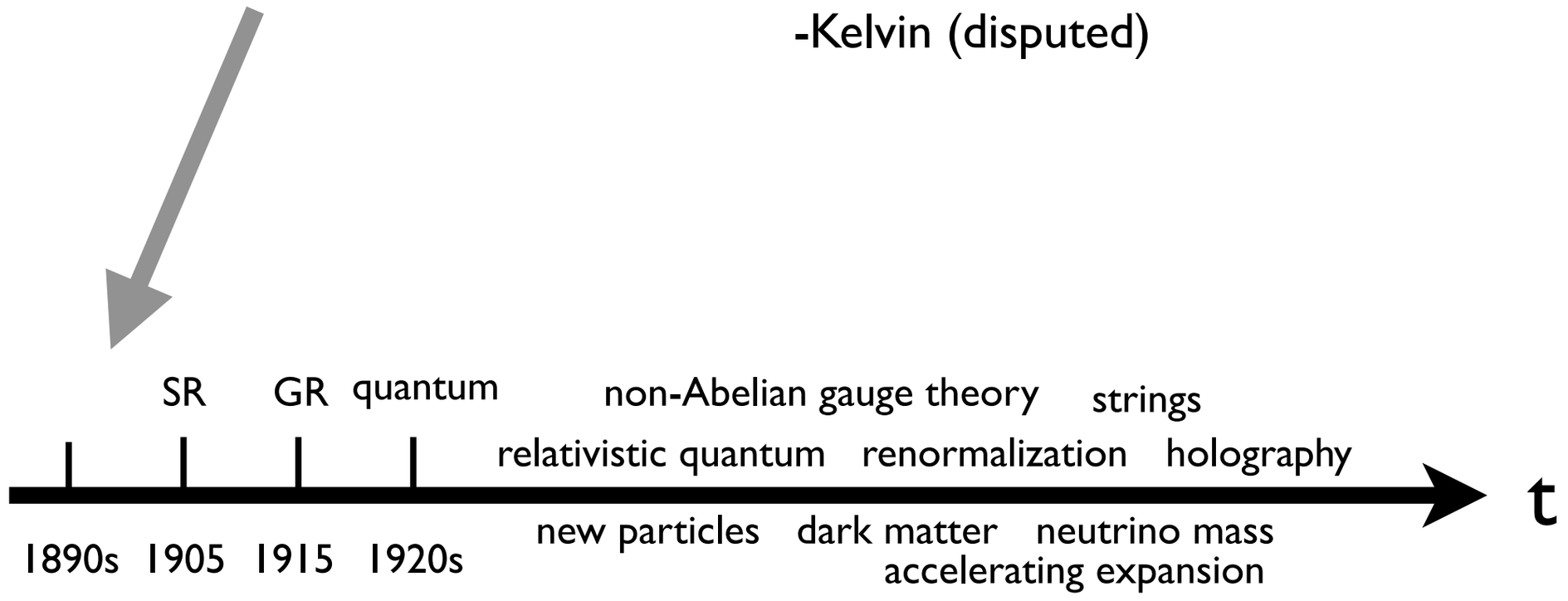
"There is nothing new to be discovered in physics now. All that remains is more and more precise measurement"

-Kelvin (disputed)



Hierarchy problem

classical

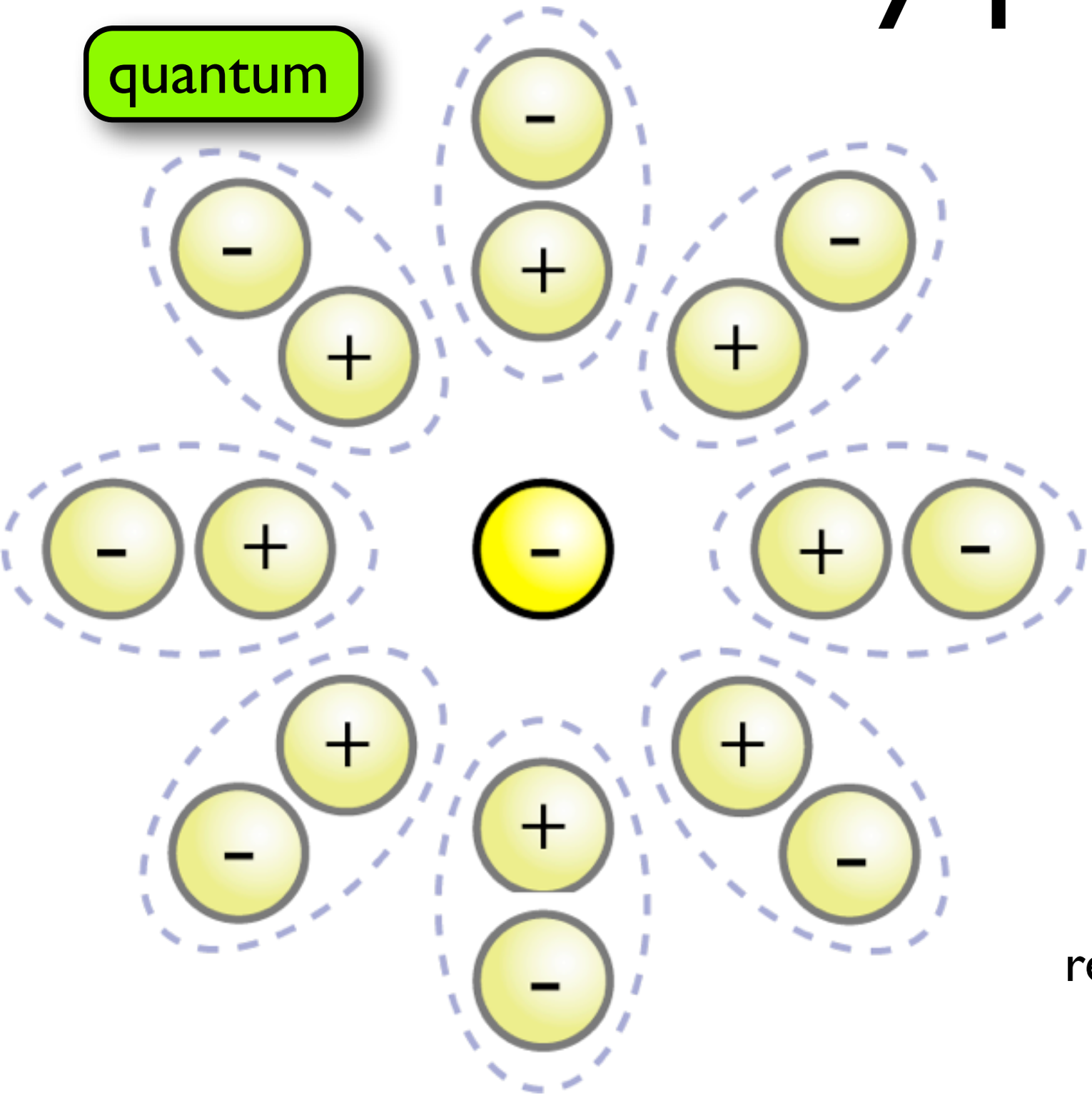
analog:

$$V \sim \frac{\alpha}{r}$$

What happens at the origin?

pro tip: singularity → something new

Hierarchy problem



analog:

$$V \sim \frac{\alpha}{r}$$

vacuum polarization
(virtual particles)

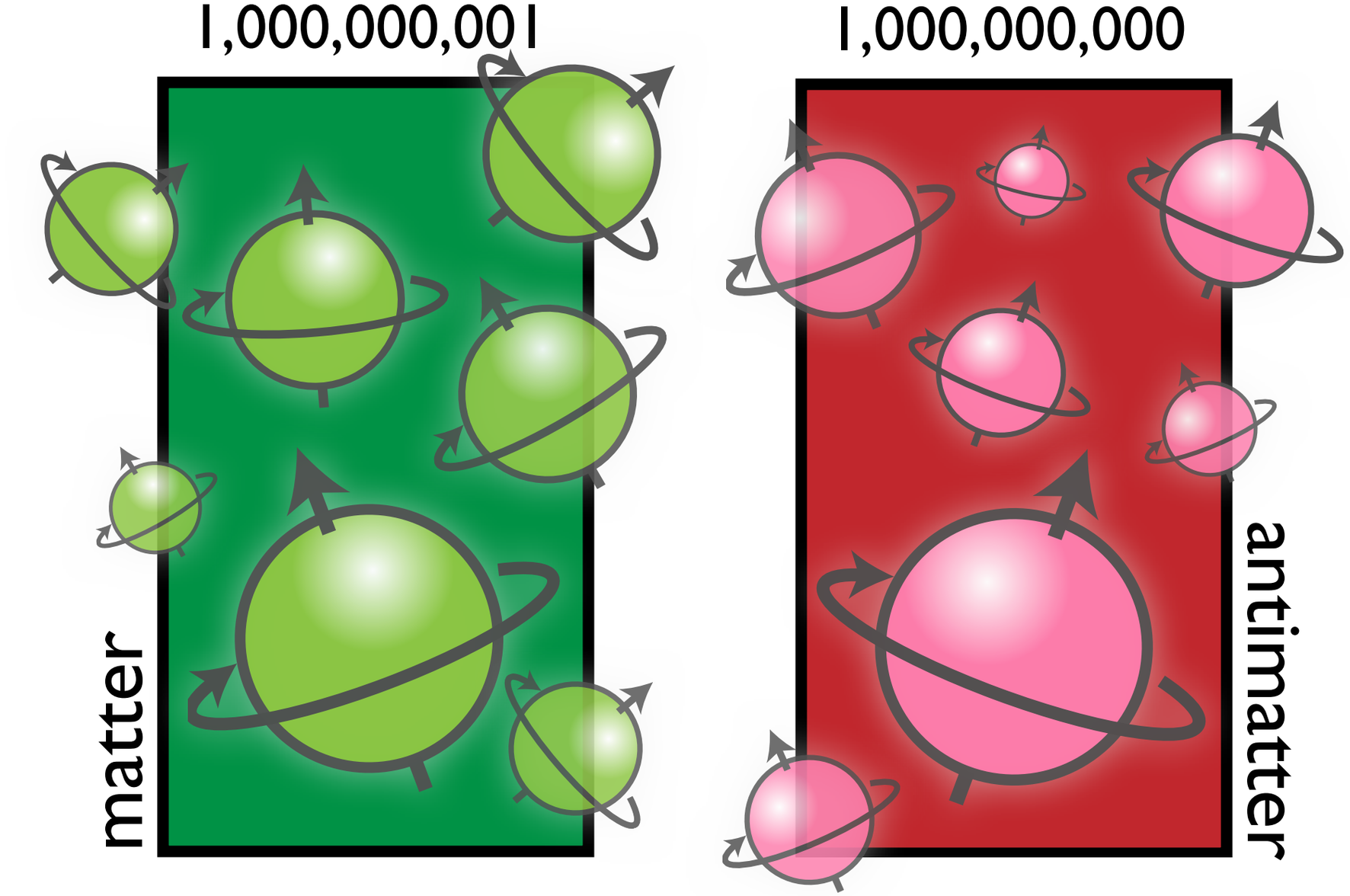
behavior at origin is finite
reason for finiteness is edifying

A snowball's chance in hell

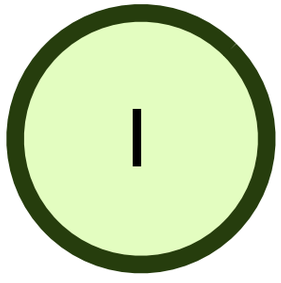
Virtual particles contribute to the Higgs mass... expect Planck scale mass

problem: why is the Higgs light?

matter vs. antimatter



matter vs. antimatter



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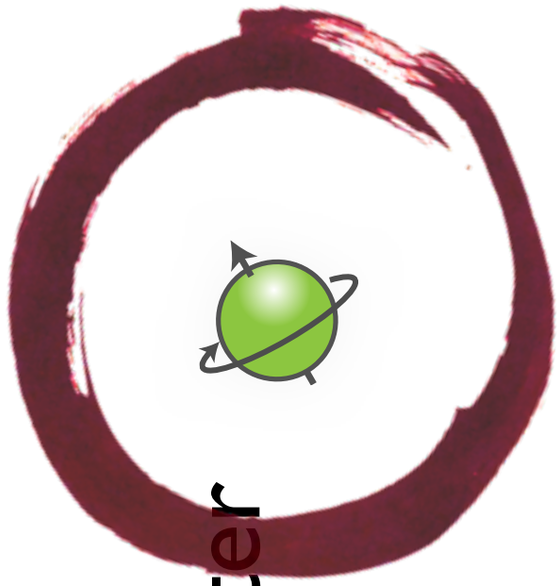
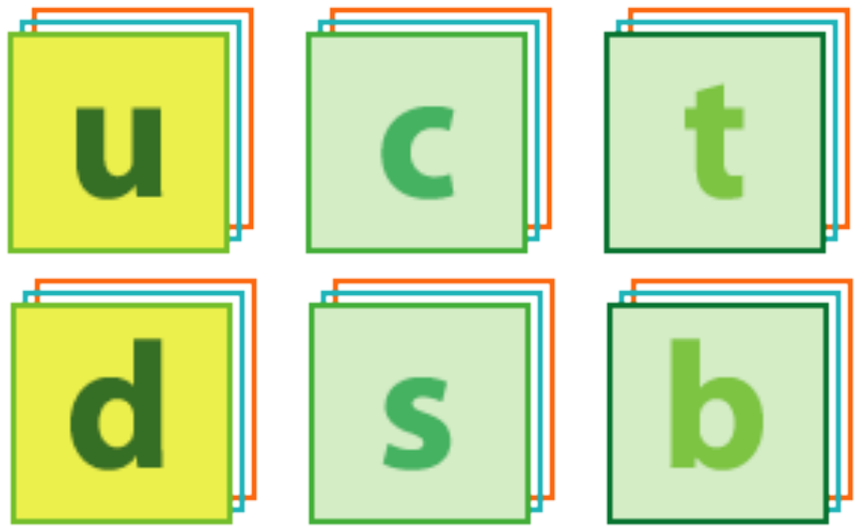


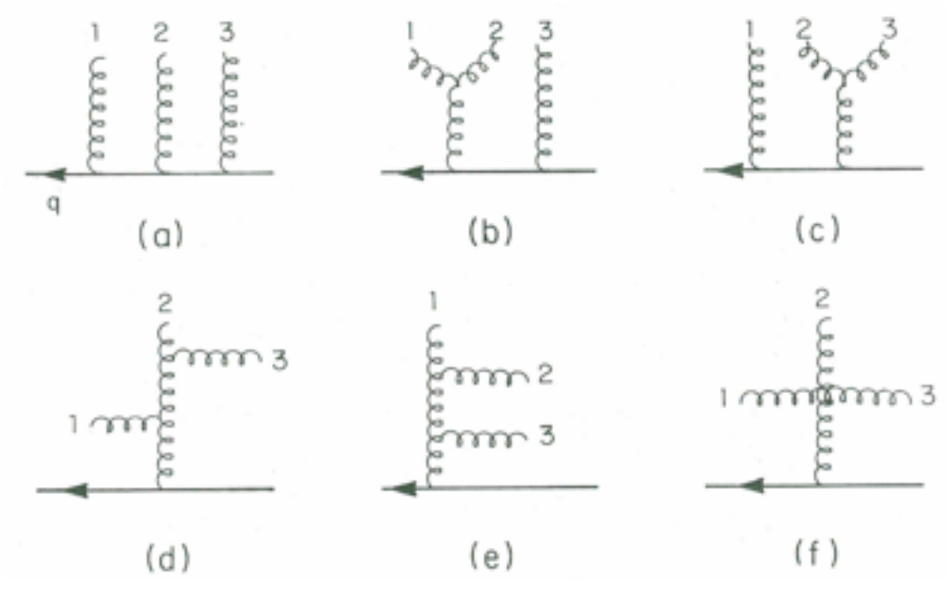
this is us

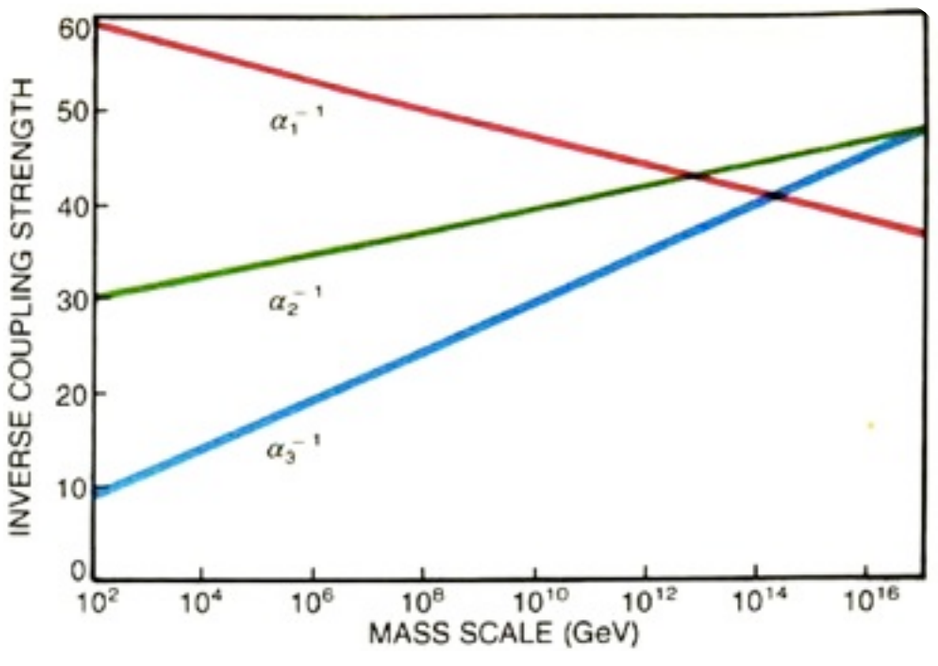
matter

antimatter

Other reasons for BSM







Images: Bullet Cluster, astronomy picture of the day. http://apod.nasa.gov/apod/ap060824.html
From: "Unification of Couplings" by Wilczek et al., *Physics Today*, October 1991
From: Mangano and Parke, "Multi-parton amplitudes in gauge theories" (hep-th/0509223)

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collider physics

implications of experiments, clever ways to test models

extra dimensions

Focus on: holographic principle
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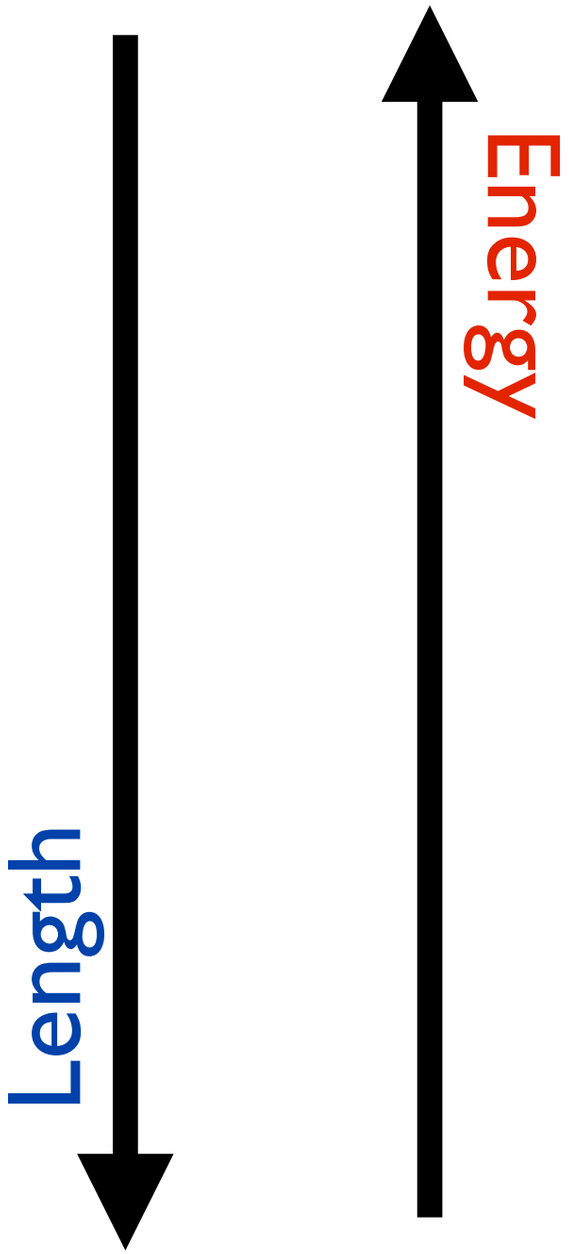
Fundamental physics



Nature at short distances?
Need to go to high energy.

$$\Delta x \, \Delta p \sim \hbar$$

Experimental solution:

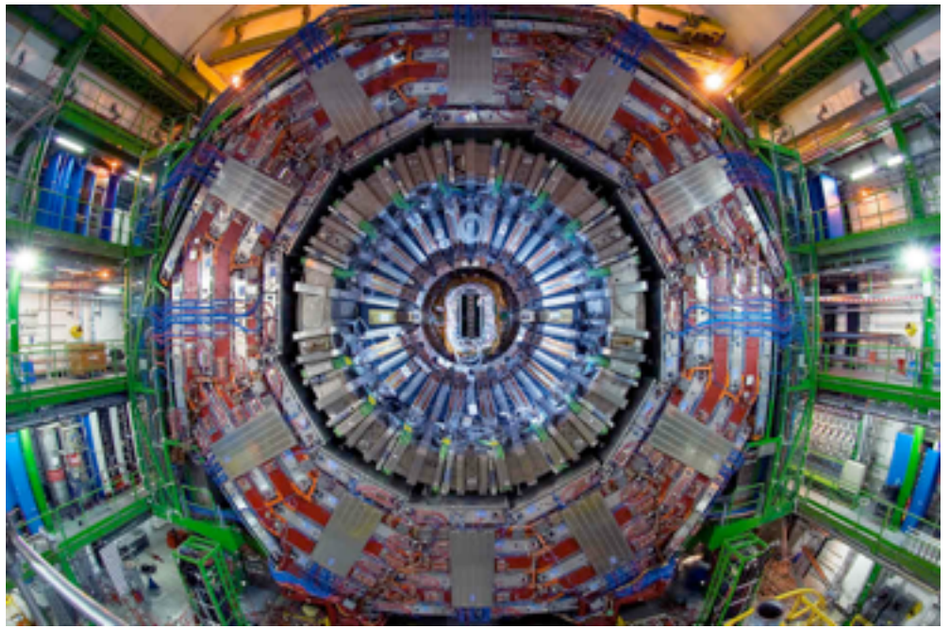
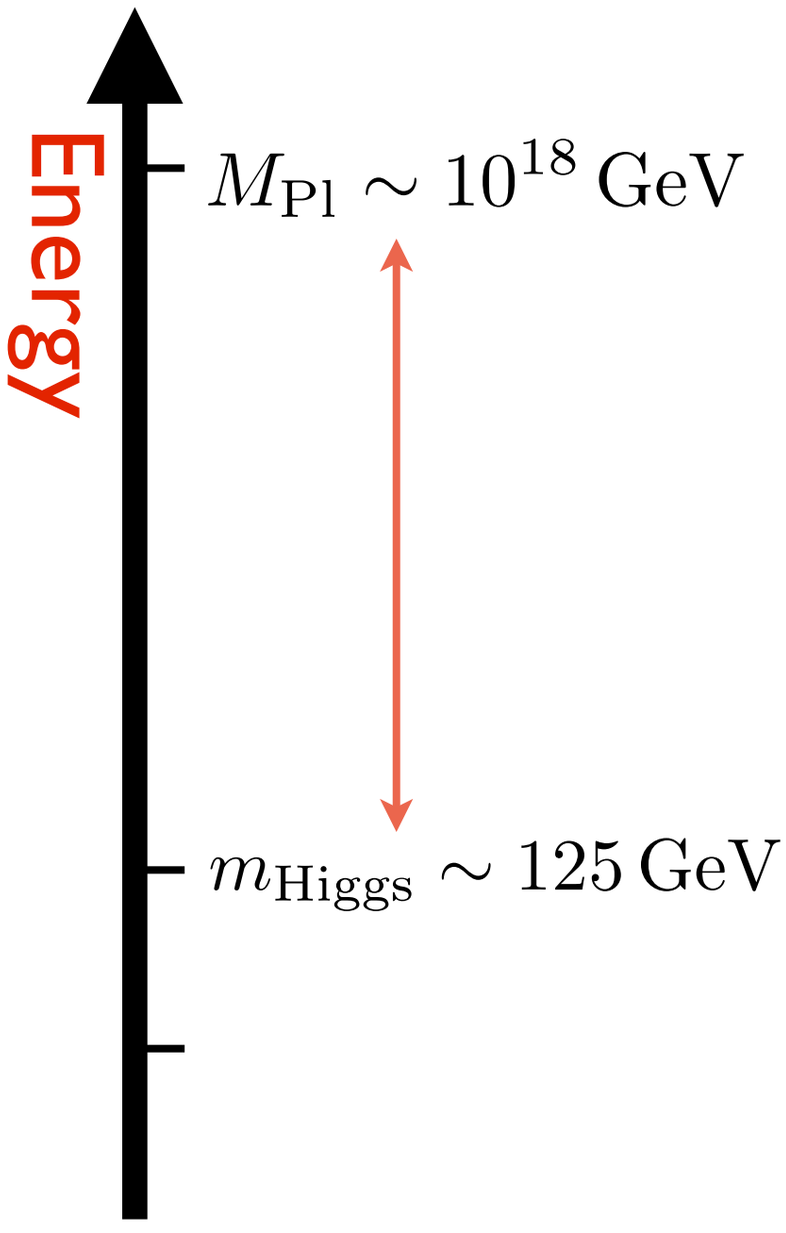


Image: CMS via AP and npr.org

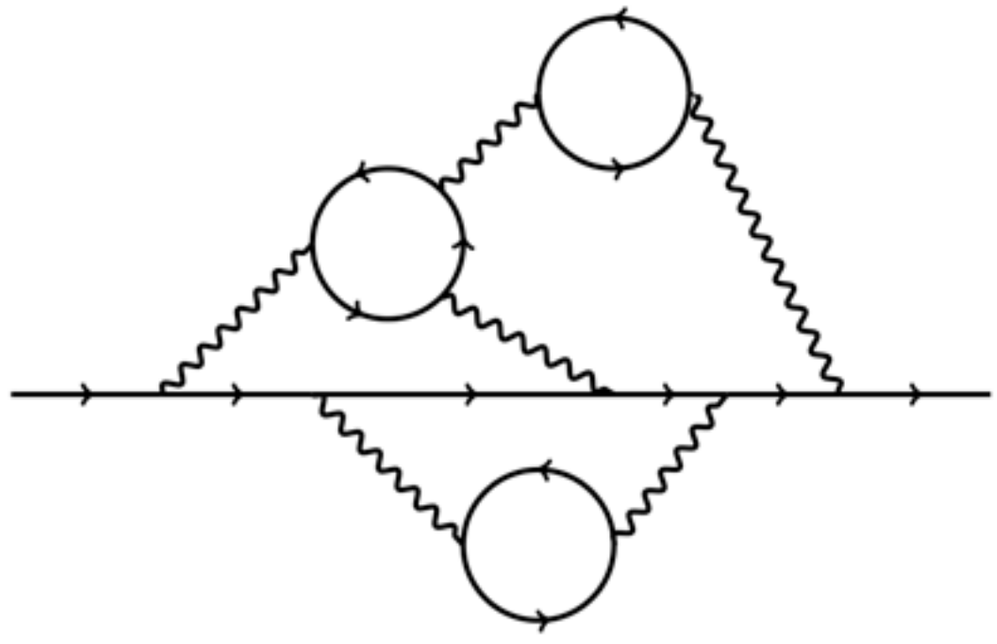
Fundamental physics



Theoretical issues:

Origin of apparent hierarchy?

Strong coupling: hard to calculate.



Better way to calculate?

Holographic Principle

Image: Lawrence Migdale / Mira Images (Mira.com, 0209A406.jpg) @ the Exploratorium museum

Holographic Principle

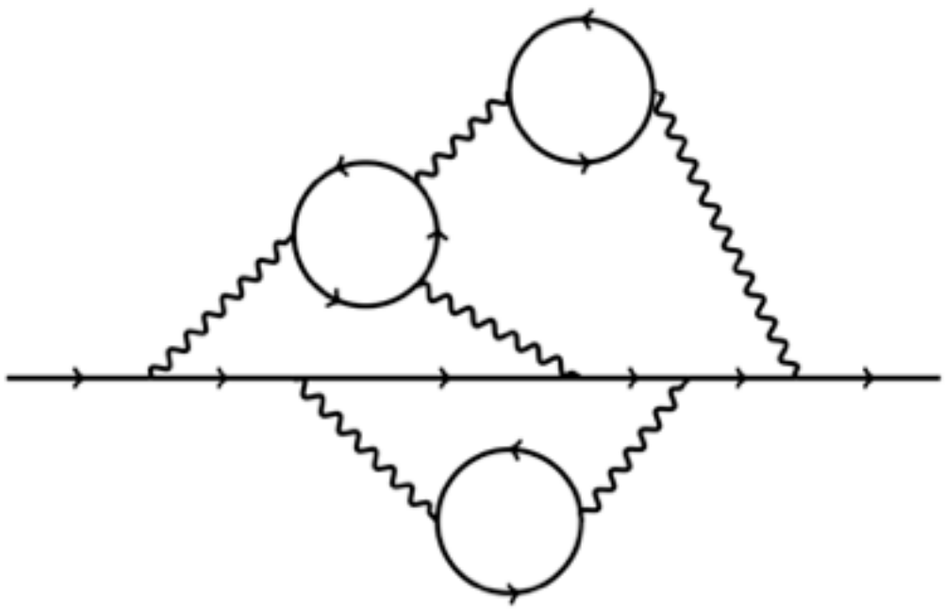
Things that appear large on a 2D projection are either:

large or close

Are things at the smallest length scales the same as things that are far away in an extra dimension?

Holographic Principle

Instead of a very quantum theory in 4D



In particular: strongly coupled, hard to calculate!

Use a gravitational theory in 5D

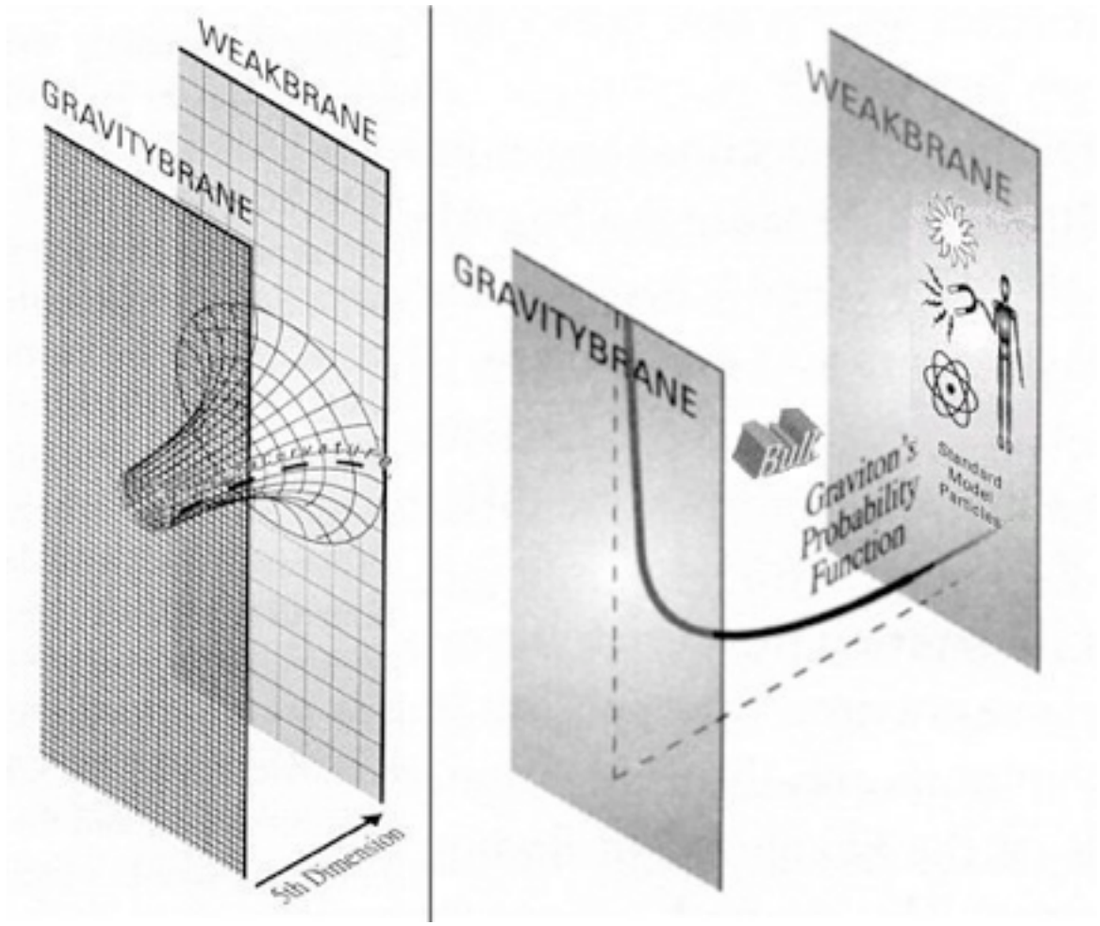
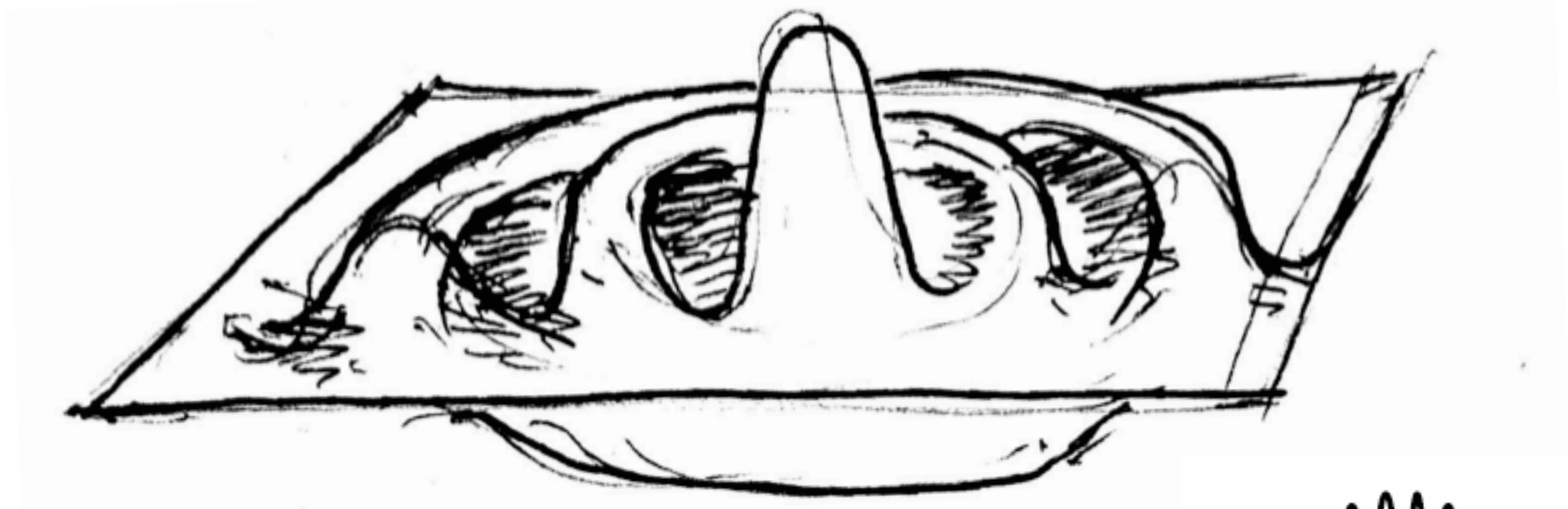


Image: Cetin BAL via http://scienceblogs.com/startswithabang/2012/09/19/the-greatest-unsolved-problem-in-theoretical-physics/

Quantum fields

Ripples in probability amplitude



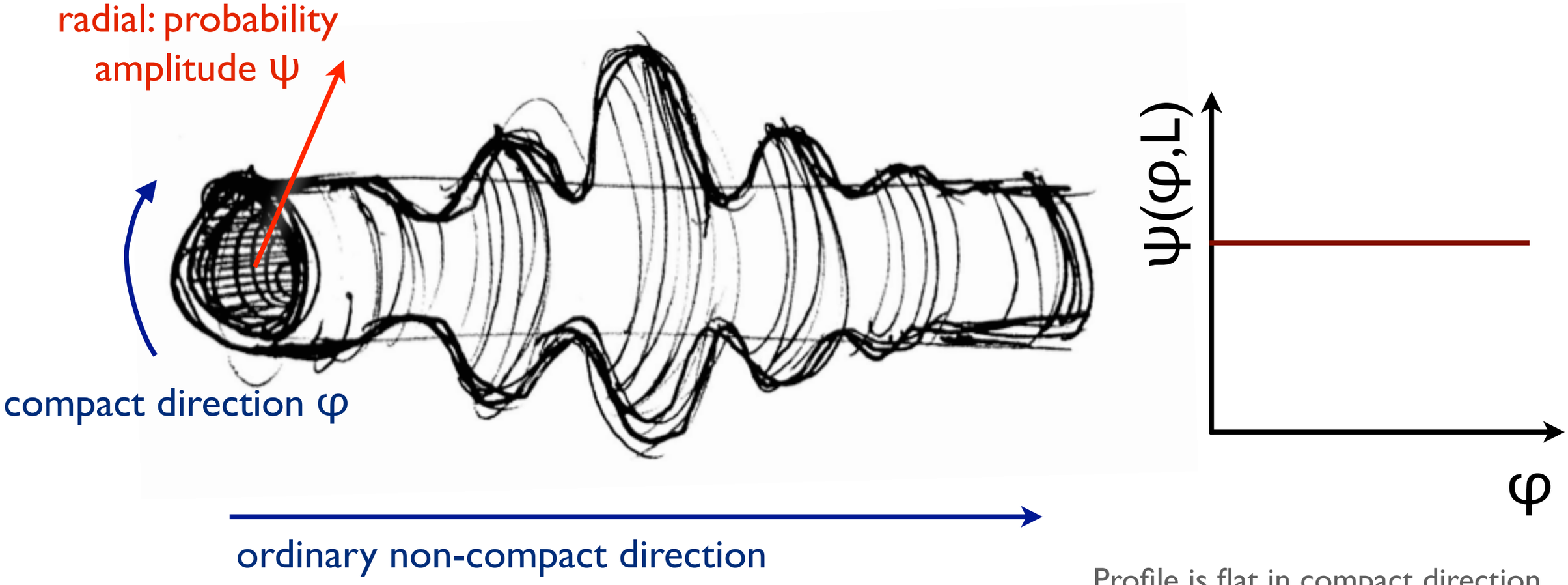
More wiggly ~ more energetic (heavier)
Think about Schrodinger equation!

Wave Packet
one dimensional version

Particle as a quantum field

Image: http://en.wikibooks.org/wiki/Communication_Systems/Fiber_Optic_Systems

Quantum fields in XD

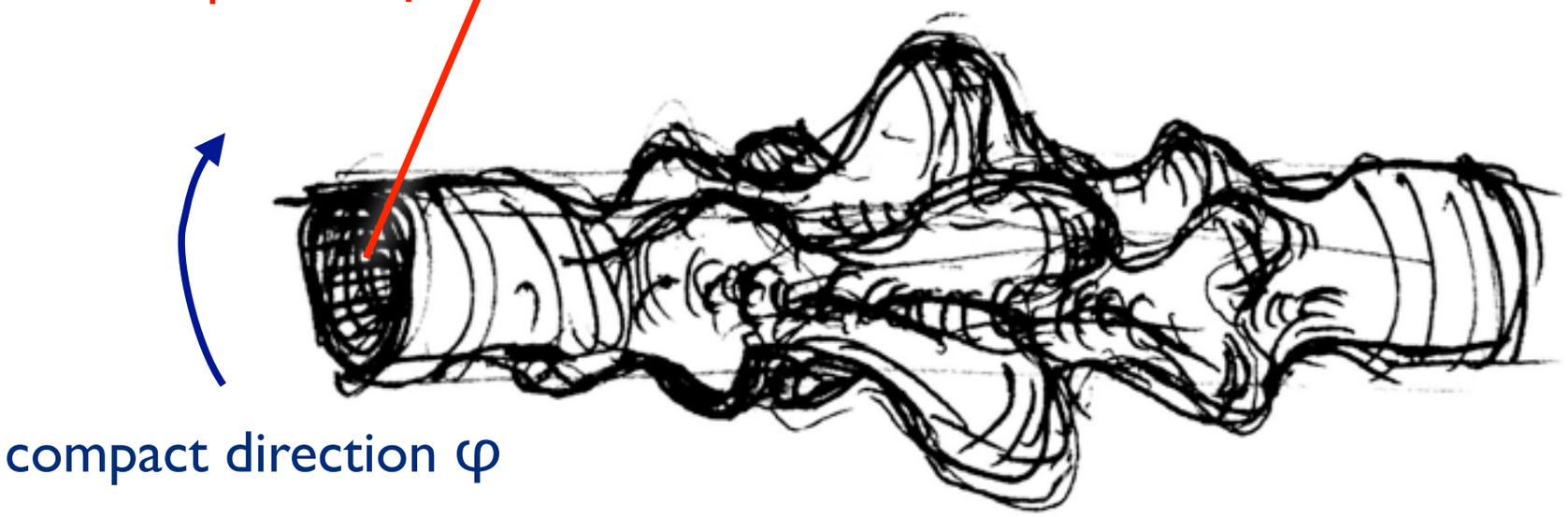


Profile is flat in compact direction
'Wiggles' are all in non-compact direction
... looks like ordinary one dimensional field

"Zero mode" in a compact extra dimension

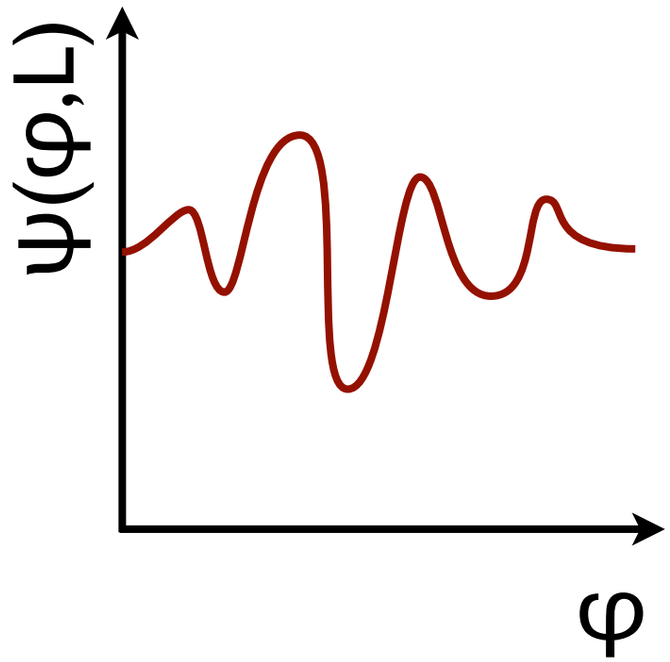
Quantum fields in XD

radial: probability amplitude ψ



compact direction φ

ordinary non-compact direction



More wiggles per [long direction]
Looks like a more energetic (heavier) copy of the previous particle!

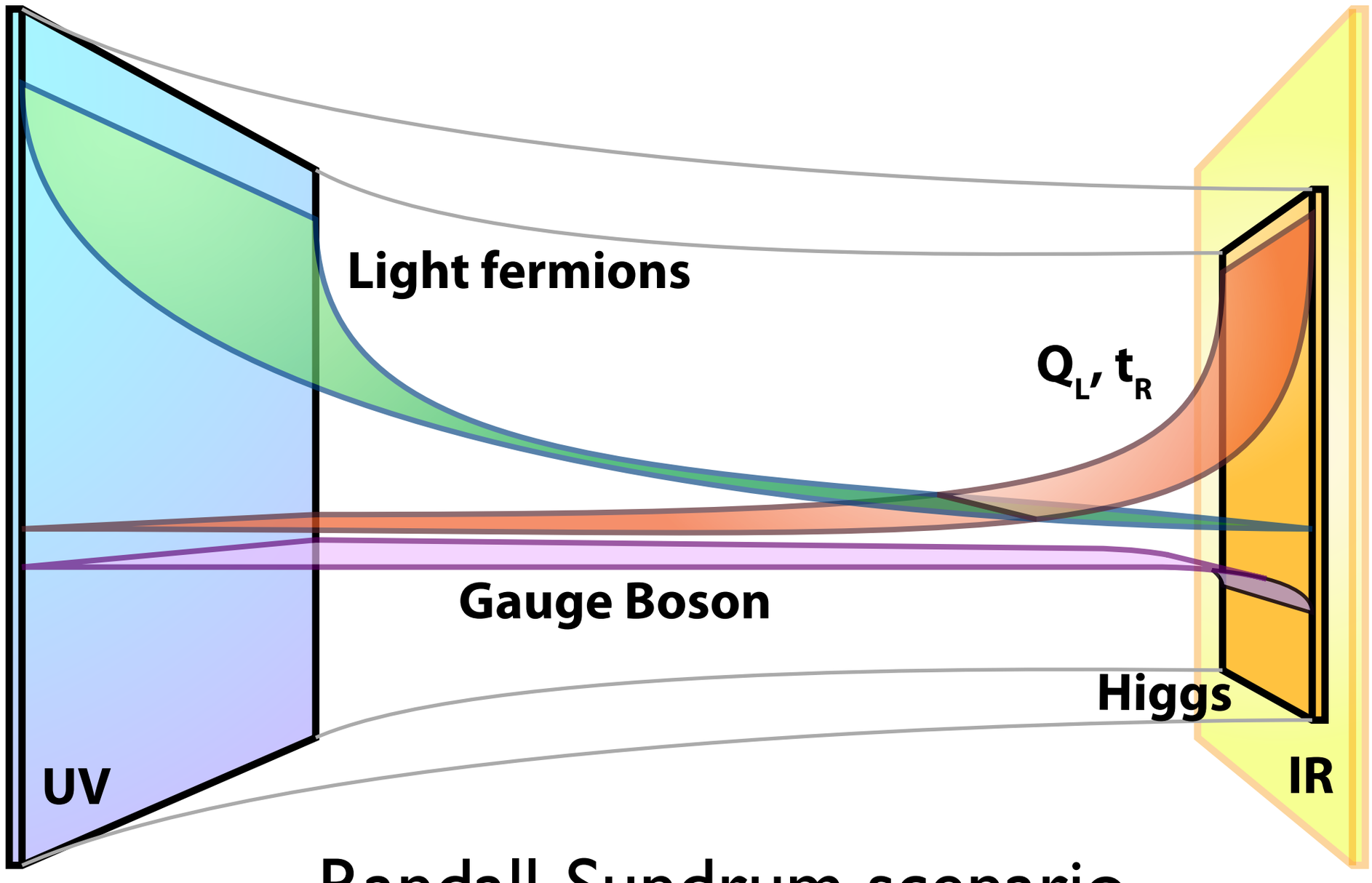
"KK mode" in a compact extra dimension

Remark: when λ < R (radius), particles can 'see' the extra dimension
e.g. they can move around each other

What does it buy us?

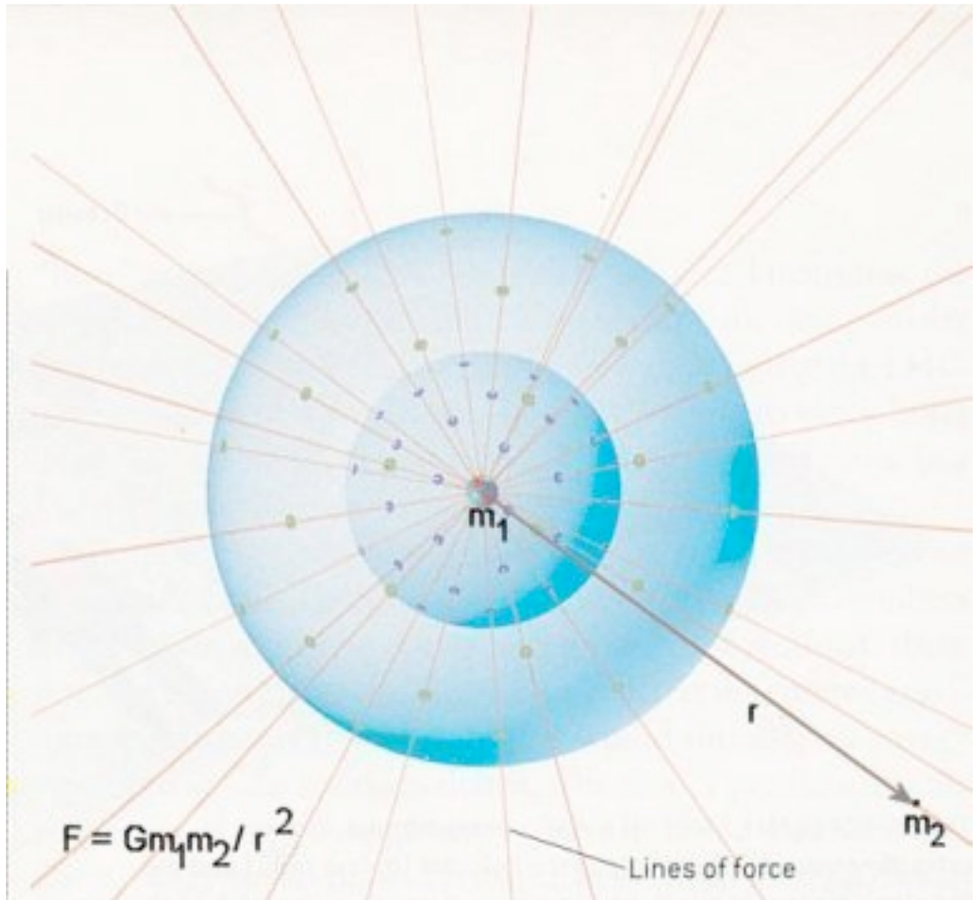
- Can calculate in the strong coupling limit!
  The very quantum regime where our usual Feynman diagram expansion fails
- Warped dimension: can explain hierarchies
  Interval extra dimension with “black holes” that redshift particles
- Application: observed mass spectrum
- Application: why gravity is weak
- Prediction: resonances of known particles
  None observed! Implies constraints on warping or radius of extra dimension.

Extra Dimensions



Randall-Sundrum scenario

Gravity in XD



GRAVITATIONAL LINES OF FORCE spread out from the earth in three dimensions. As distance from the earth increases, the force becomes diluted by being spread across a larger surface area (*spheres*). The surface area of each sphere increases as the square of its radius, so gravity falls as the inverse square of distance in three dimensions.

Image: http://universe-review.ca/R15-16-manyfoldu.htm (but I'm pretty sure they stole it from a magazine)

Report card: XD

Hierarchy problem	A-
Dark matter candidates	C
Unification of couplings	C
Family replication	B+
Matter vs antimatter	D
Dark energy	C
Formal theory	A

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"The story was an imaginary tale which told the final story of the Silver Age Superman and his long history."
(Wikipedia article for "Whatever Happened to the Man of Tomorrow?")

Supersymmetry: whatever happened to the theory of tomorrow?

Golden age (1970-80s): a miracle theory!

Silver age (1990s-00s): supersymmetric particles "right around the corner"

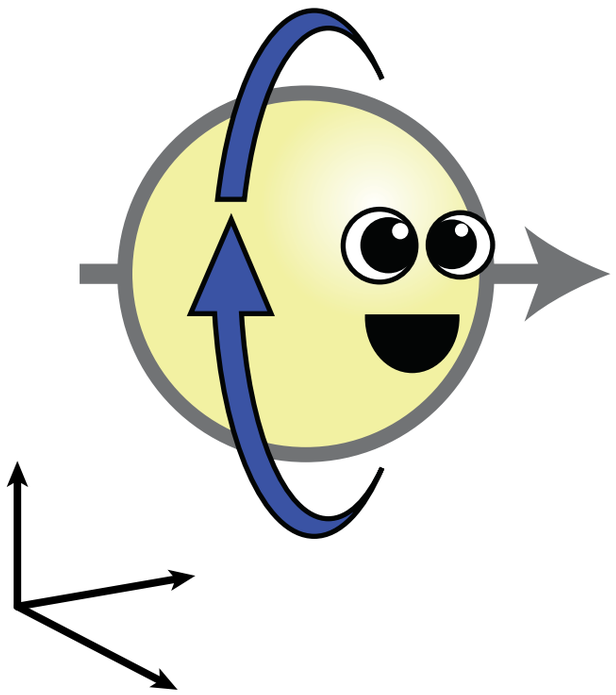
Modern age (00s-??): where's the party?

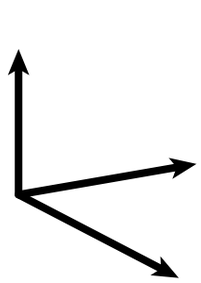
my opinion

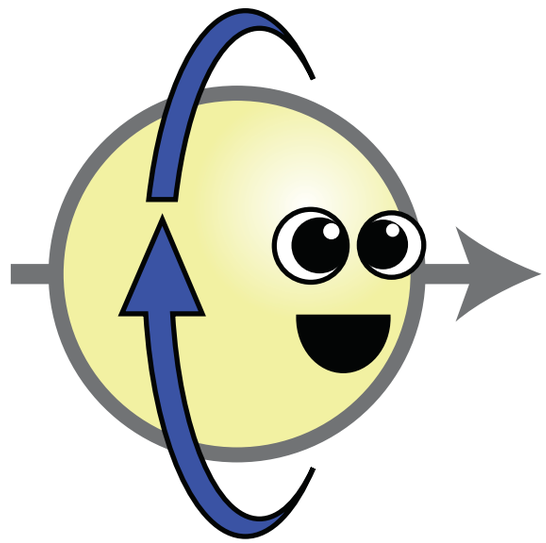
SUSY remains the favorite theory of new physics despite **zero** experimental evidence.

Alan Moore, Curt Swan, et al. DC Comics. *Superman: Whatever Happened to the Man of Tomorrow?* (1987, 1997 reprint)

Usual symmetries





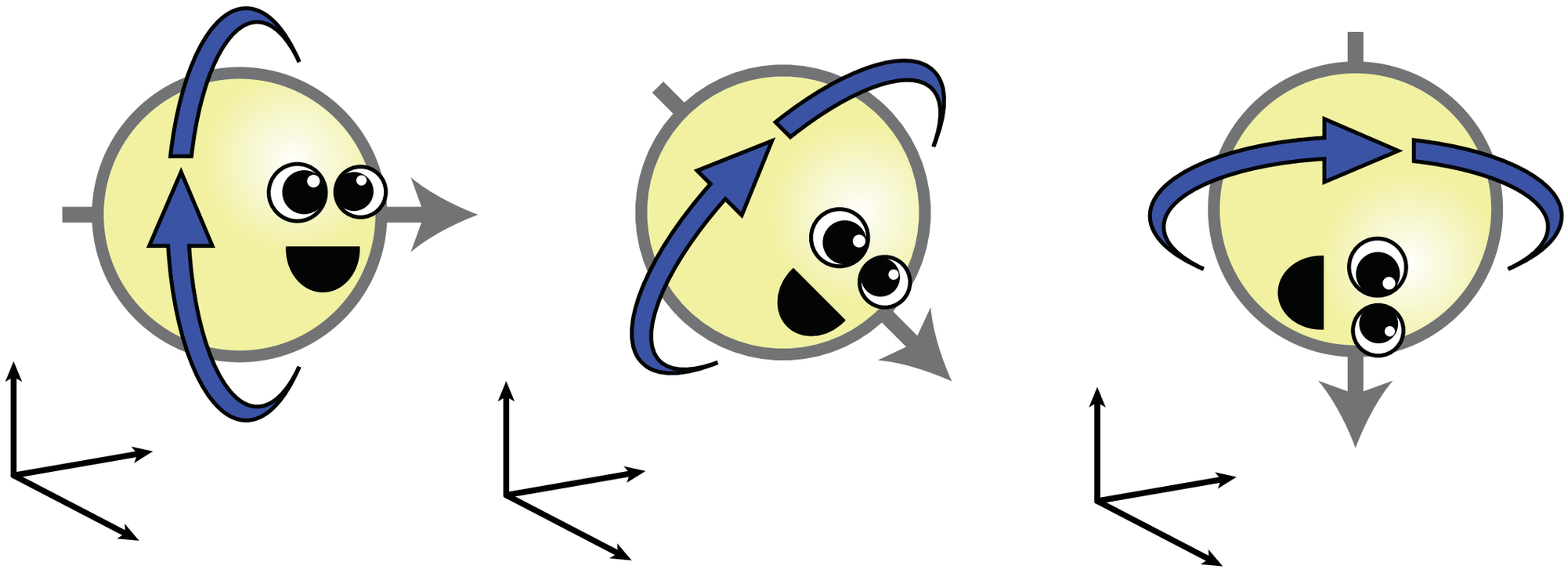


same particle, just moved over

Translation

(including time evolution)

Usual symmetries



same particle, just turned around

Rotation
(including boosts)

Symmetry → Spacetime

$$\text{Space} = \frac{\text{Symmetry}}{\text{Rotations}}$$

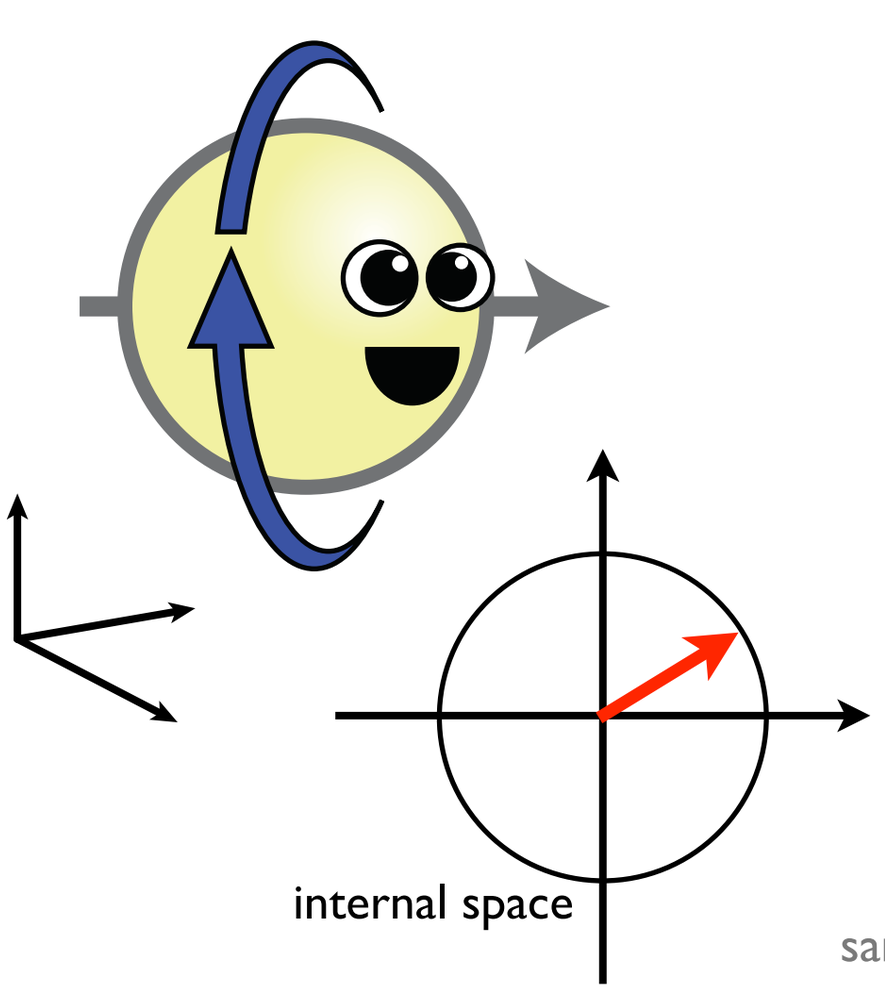
identify rotated states

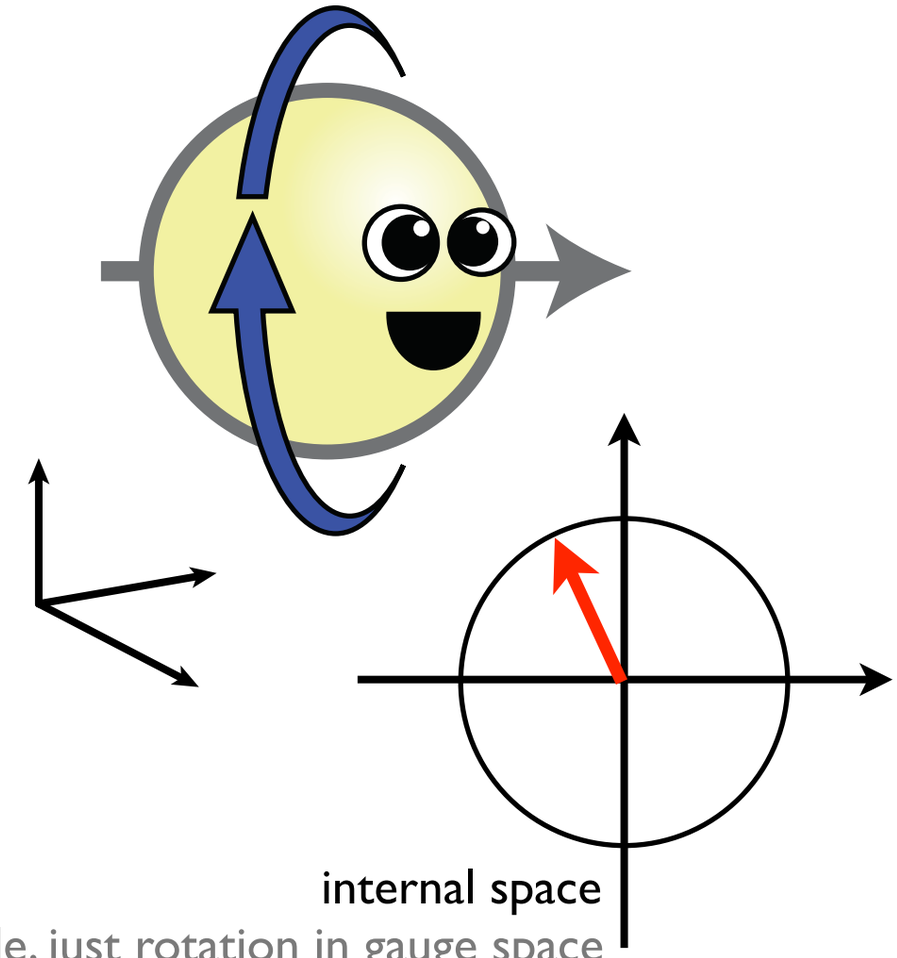
$$\simeq \text{Translations}$$

Particles: defined with respect to the symmetry

Rotations: 'internal' quantum numbers (e.g. spin)

Internal symmetries





same particle, just rotation in gauge space

Electromagnetism

(generalizes to Yang-Mills theory)

Symmetry → Spacetime

$$\text{Space} = \frac{\text{Symmetry}}{\text{Internal}}$$

$$\simeq \text{Translations}$$

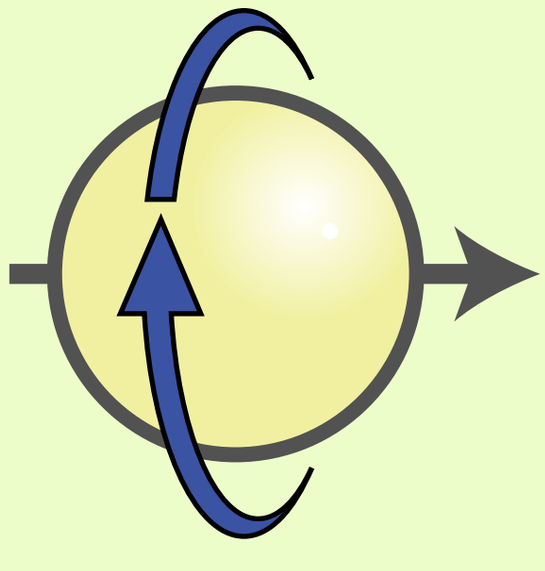
Particles: defined with respect to the symmetry

Internal: 'internal' quantum numbers (e.g. spin)

... also electric charge

Supersymmetry

Matter particle
spin 1/2

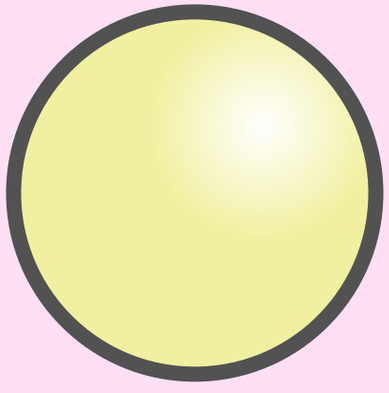


Fermion

SUSY is related to spin

discrete symmetry space

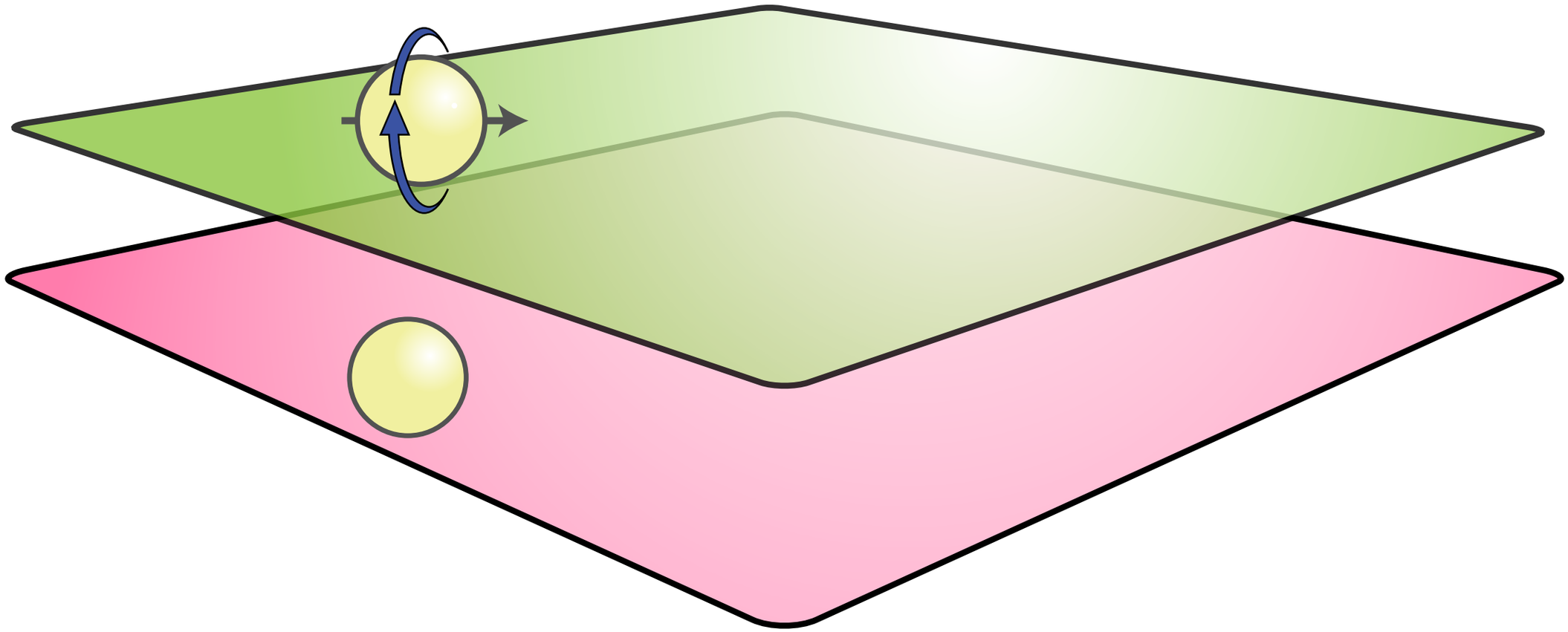
Force particle
spin 0 or 1



Boson

Superspace

SUSY is a quantum extra dimension



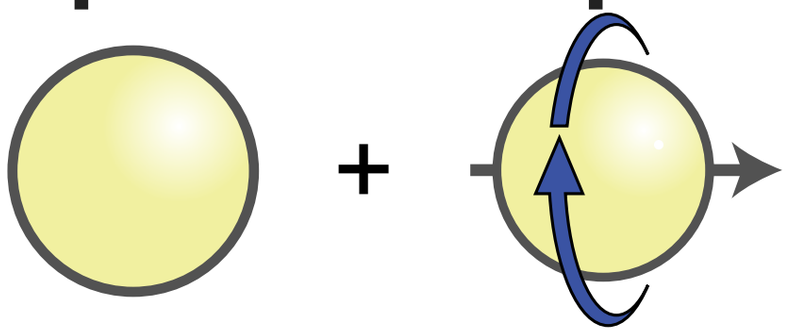
Symmetry → Spacetime

$$\text{Superspace} = \frac{\text{Symmetry}}{\text{Internal}}$$

SUSY, translations, rotations, gauge

rotations
gauge rotations

Particles come in supermultiplets



same superparticle, just rotation in superspace

Mathematical Interlude

$$\text{Space} = \frac{\text{Symmetry}}{\text{Internal}}$$

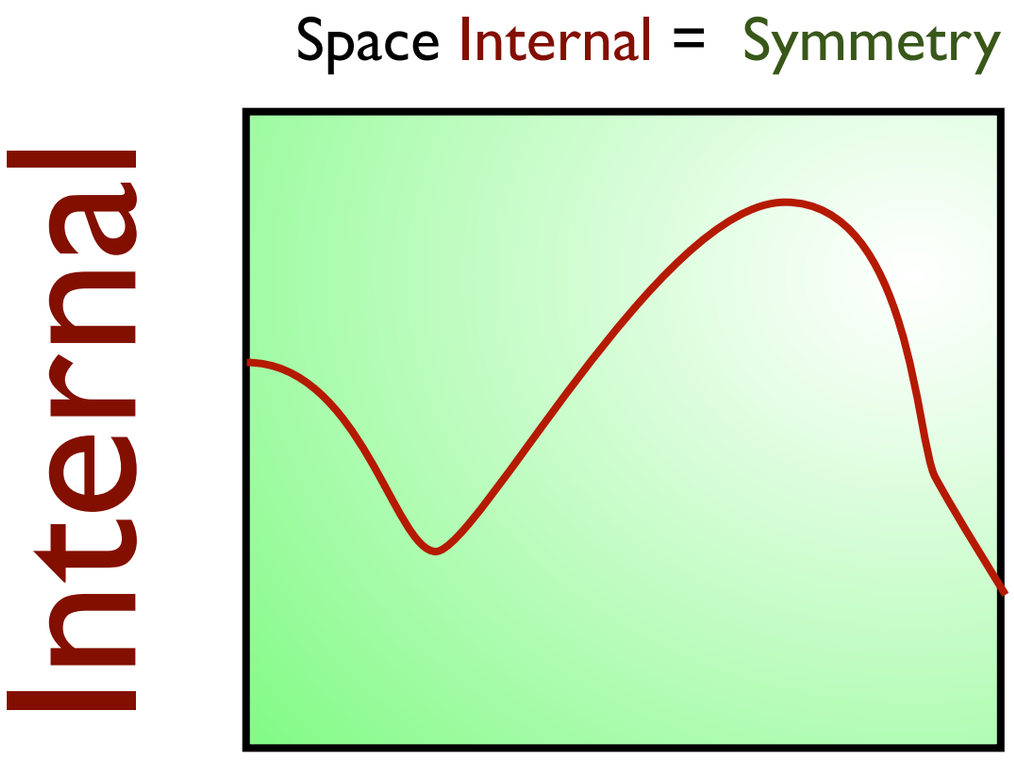
$$\text{Space} \quad \underbrace{\text{Internal}} \quad = \quad \text{Symmetry}$$

"Fiber bundle"

Mathematical construct described by differential geometry. In my opinion, this is the natural language of physics.

Relates calculus, topology, group theory, ...

Mathematical Interlude



Particles are functions on the fiber bundle

Internal: contains all the quantum numbers you would put into a ket.

Forces come from the geometry of the bundle

in the same way that general relativity is geometry

What does it buy us?

- Gives a reason for the Higgs to be light
  But 125 GeV Higgs is a little heavier than the most natural models
- Right particle content for unification!
  Automatically from supersymmetrizing the Standard Model... but may have to sacrifice
- R-Parity automatically gives Dark Matter ?
  But: non-observation of SUSY at the LHC suggests sacrificing this
- Inherits the power of complex analysis
  Theoretical control gives new handles on dualities and new approaches to field theory
- Prediction: different-spin partner particles
  None observed! Implies weird spectrum or high SUSY breaking scale.

SUSY is broken

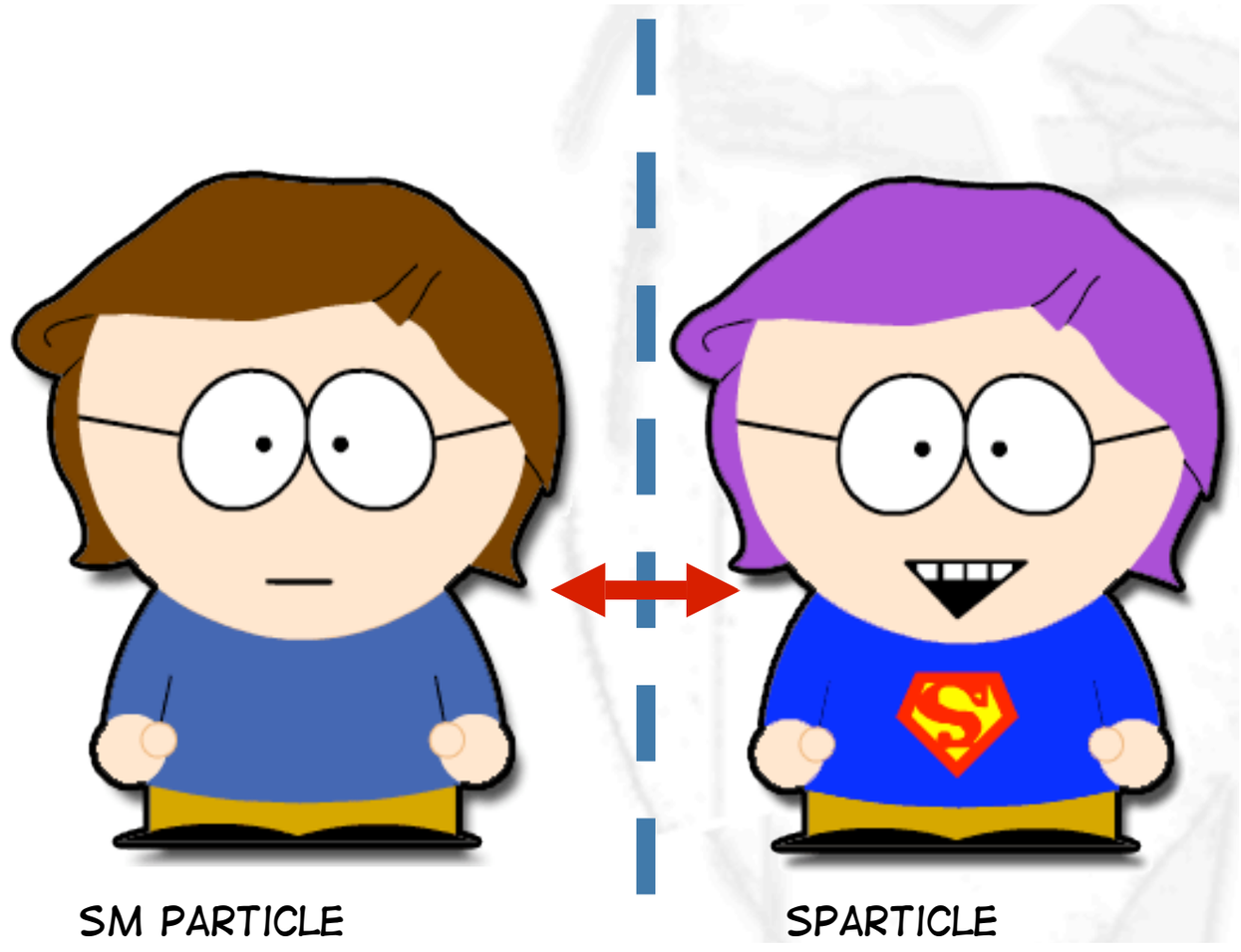
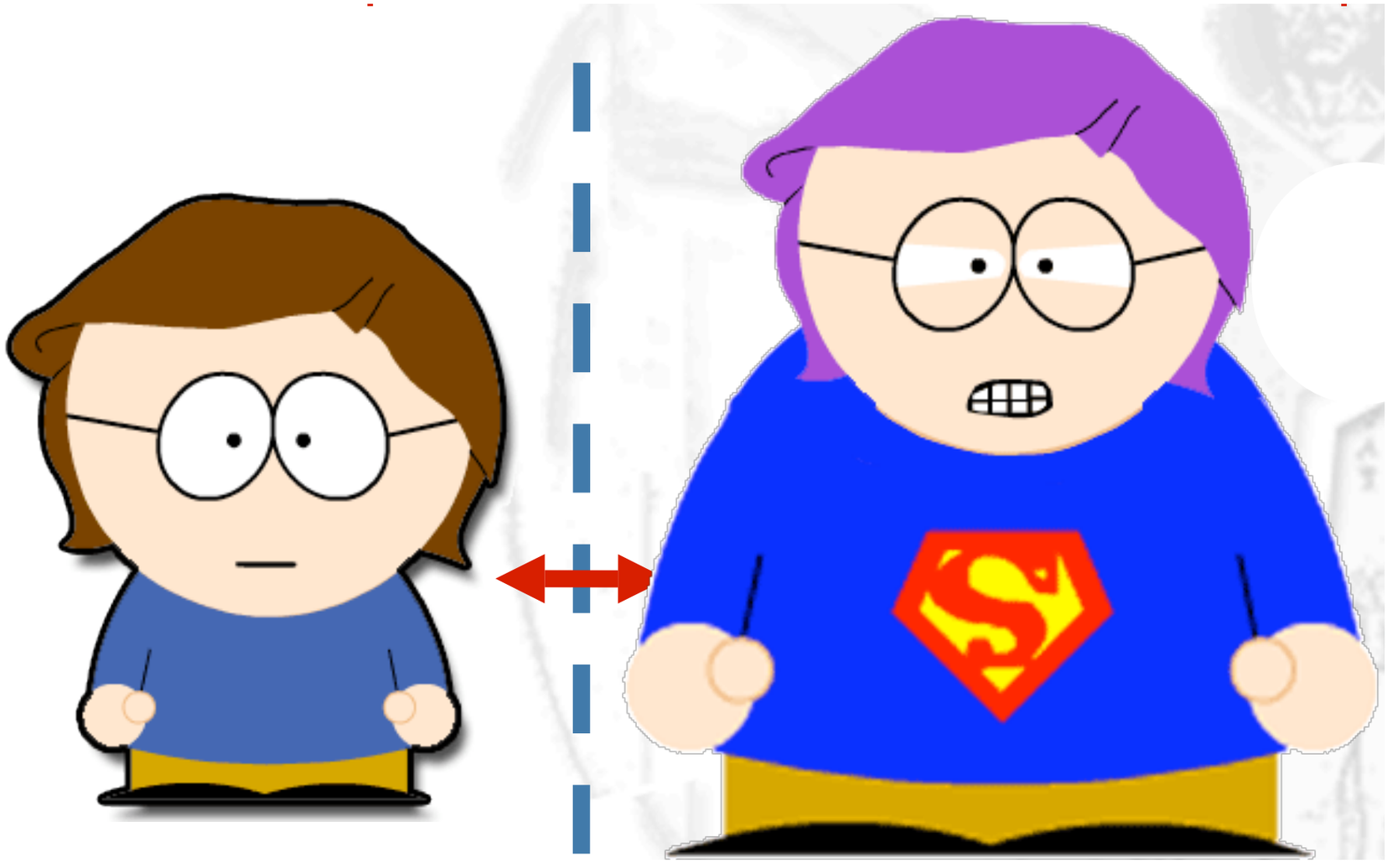


Image: from an old version of the *South Park* character creator, via an old talk I gave

SUSY is broken



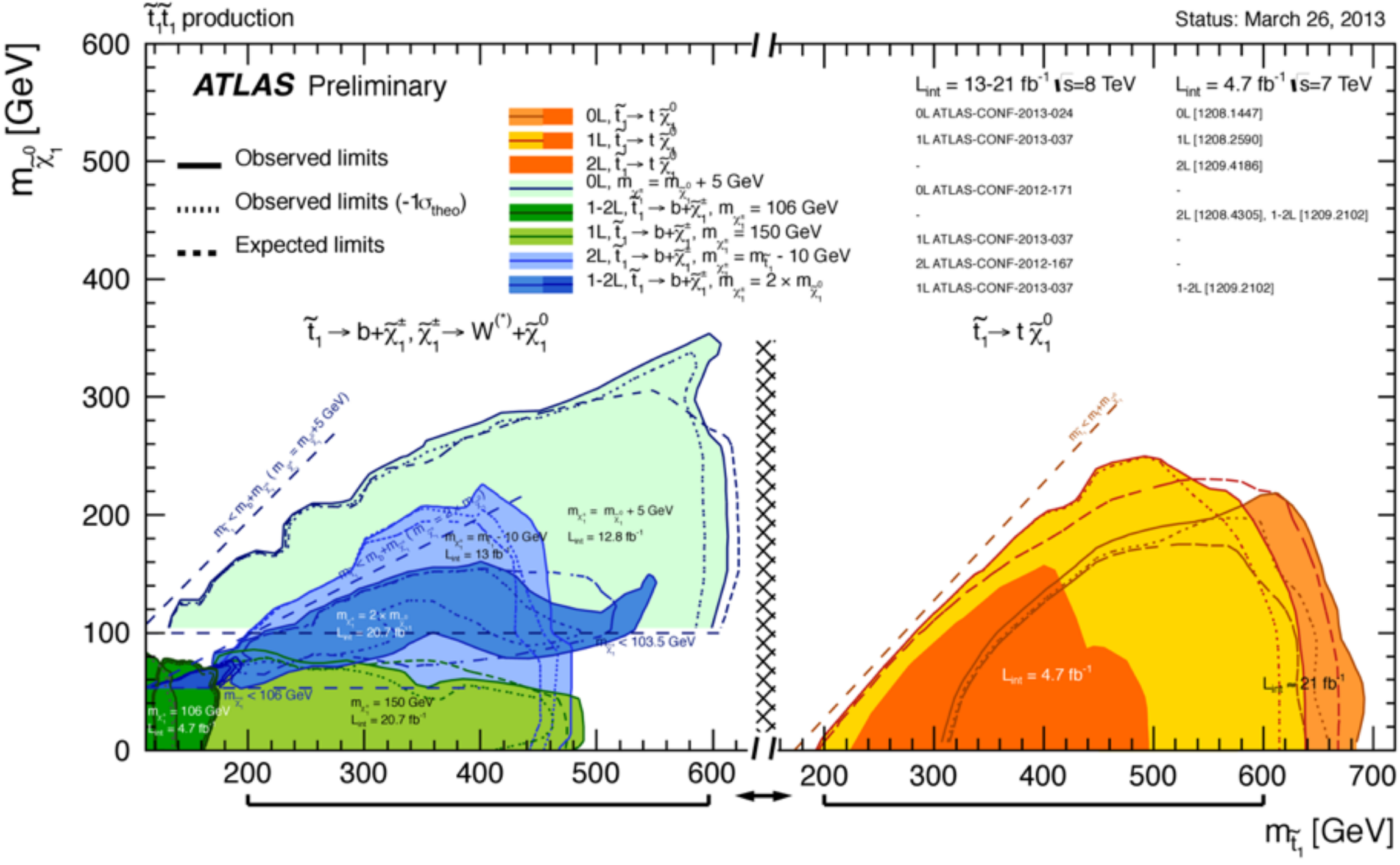
SM particle

Heavy Sparticle

Too light: would have found it by now
Too heavy: doesn't explain lightness of Higgs

Image: from an old version of the *South Park* character creator, via an old talk I gave

SUSY is hiding



Status of SUSY vs LHC

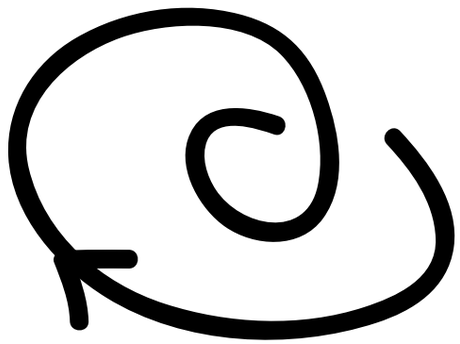
- Nicest models of the 1990s do not survive
- May have to give up on simplicity, unification, dark matter, naturalness?
- Clever ideas wanted!
- ... meanwhile, still many interesting theoretical directions independent of LHC

SUSY Dualities

When is a particle not a particle?

SUSY dualities provide complementary descriptions of a theory; analogous to the holographic principle.

When one theory is difficult to calculate, dual theories can be easy to calculate.



In such dualities, new particles can describe composite objects. This is a realization of electromagnetic duality.

Some particles reappear as vortices or monopoles!

Report card: SUSY

		2013
Hierarchy problem	A+	B
Dark matter candidates	A+	B+
Unification of couplings	A+	A-
Family replication	D	
Matter vs antimatter	B	
Dark energy	C+	
Formal theory	A+	

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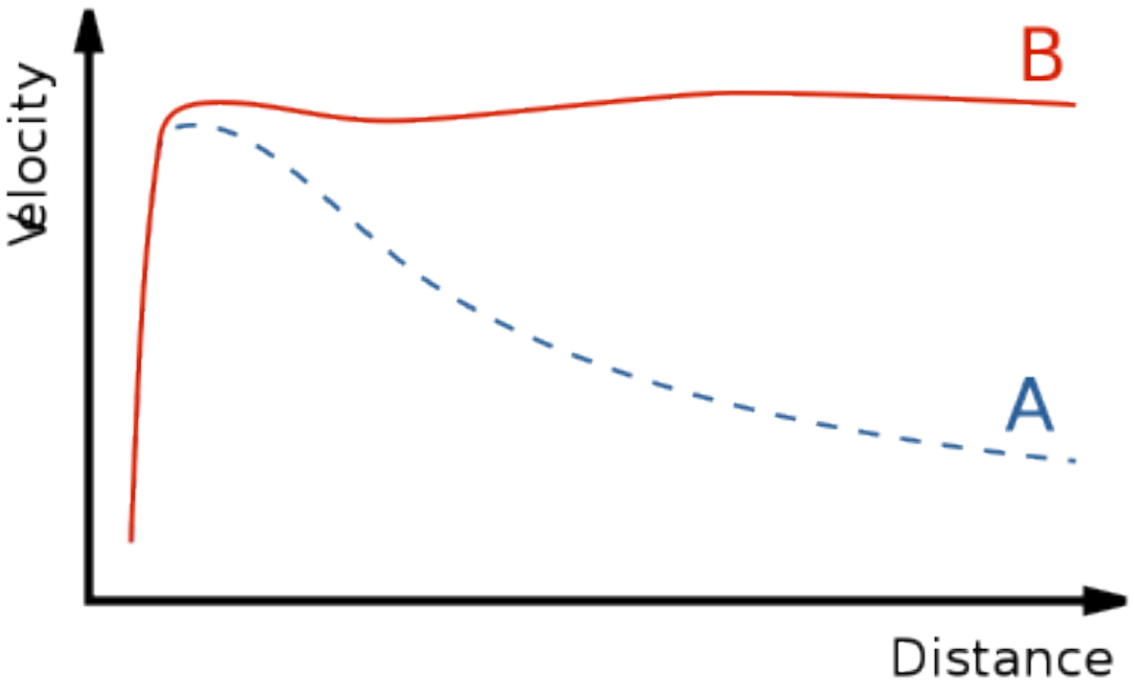
Evidence



Purely phenomenological: data looking for a theory

Can any of our models of new physics explain DM?

Images: http://nazaroo.blogspot.com/2012/07/disproving-both-newtonian-gravity-and.html
Bullet Cluster, astronomy picture of the day. http://apod.nasa.gov/apod/ap060824.html

Sobering?

CDMS

This week

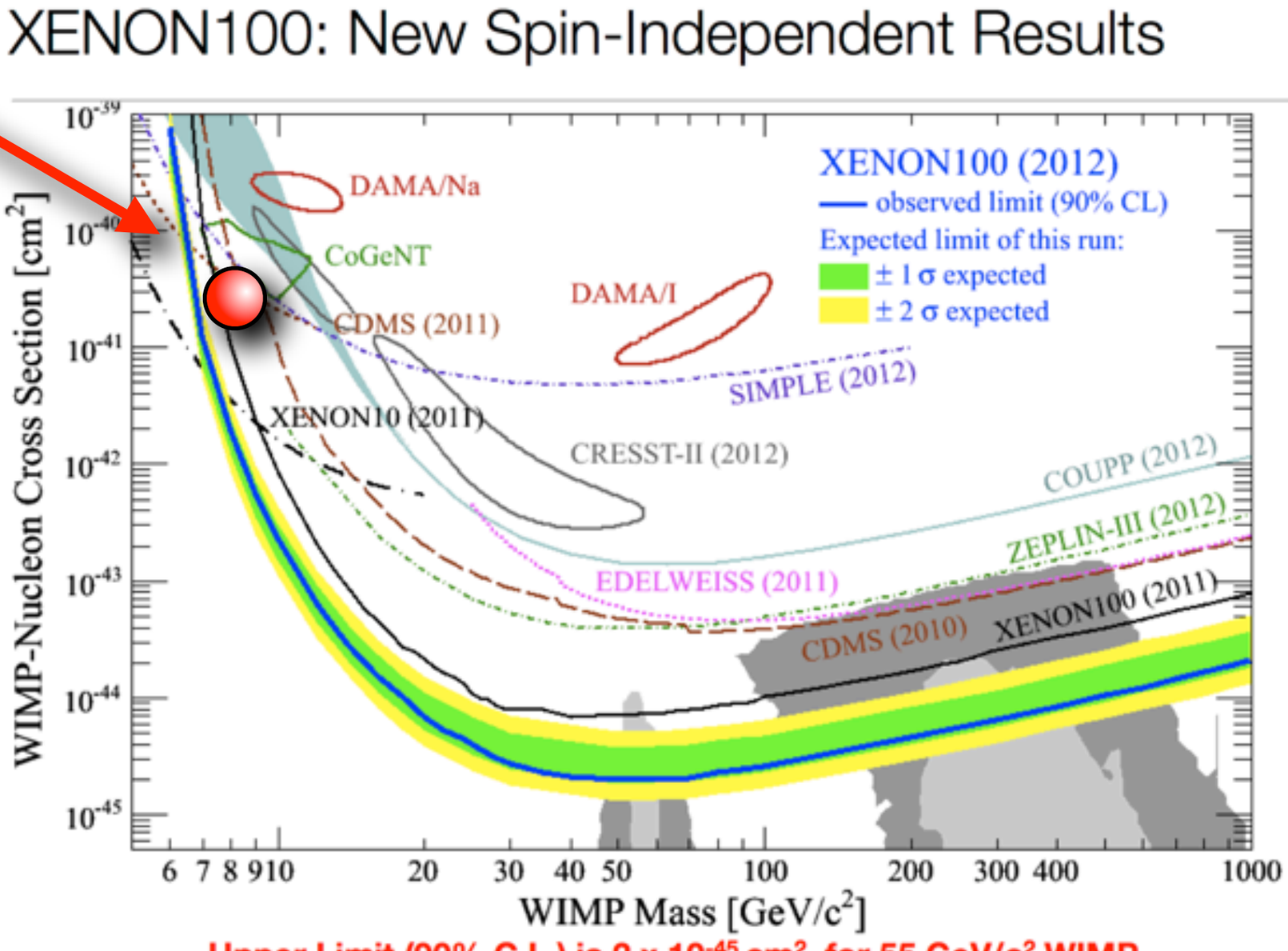
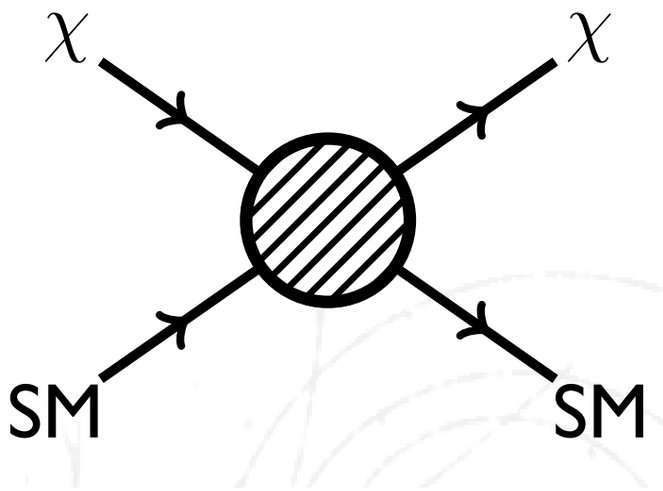


Image: from http://scienceblogs.com/startswithabang/2013/04/03/itll-take-a-lot-more-than-ams-to-find-dark-matter/

Dark Matter Searches

Read from left to right

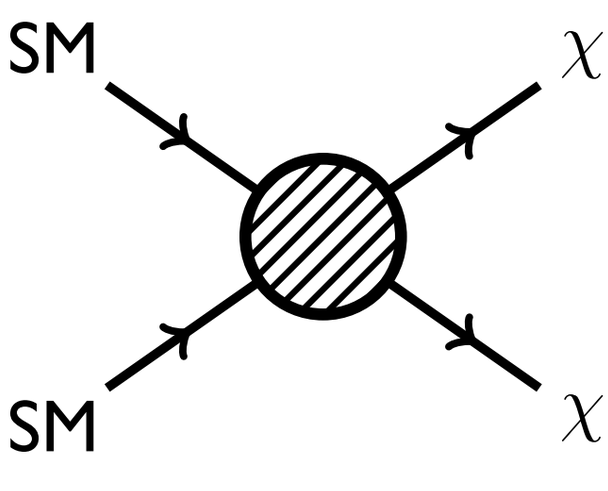


underground

direct detection
e.g. CDMS, XENON

DM in the solar system bounces off of a heavy nucleon. Measure the recoil energy, determine mass.

nothing conclusive

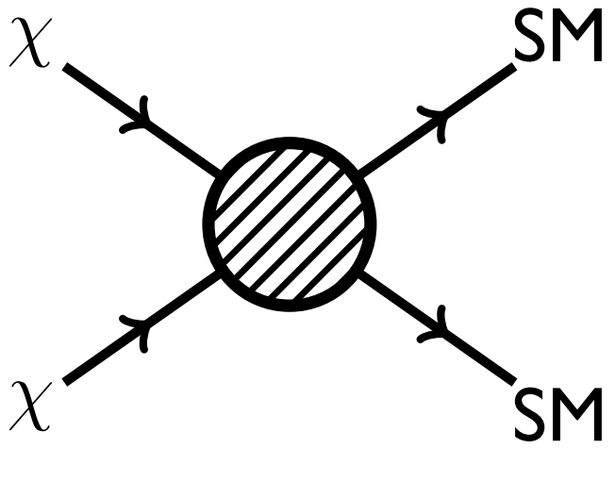


@ high energy

direct production
e.g. LHC

Collide protons, hope to produce dark matter particles which fly off undetected: missing energy

nothing (yet?)



in the sky

indirect detection
e.g. FERMI, AMS

DM in the galaxy annihilates, try to observe the remnants in cosmic data (photons, cosmic rays)

hints... large background?

Positron excess

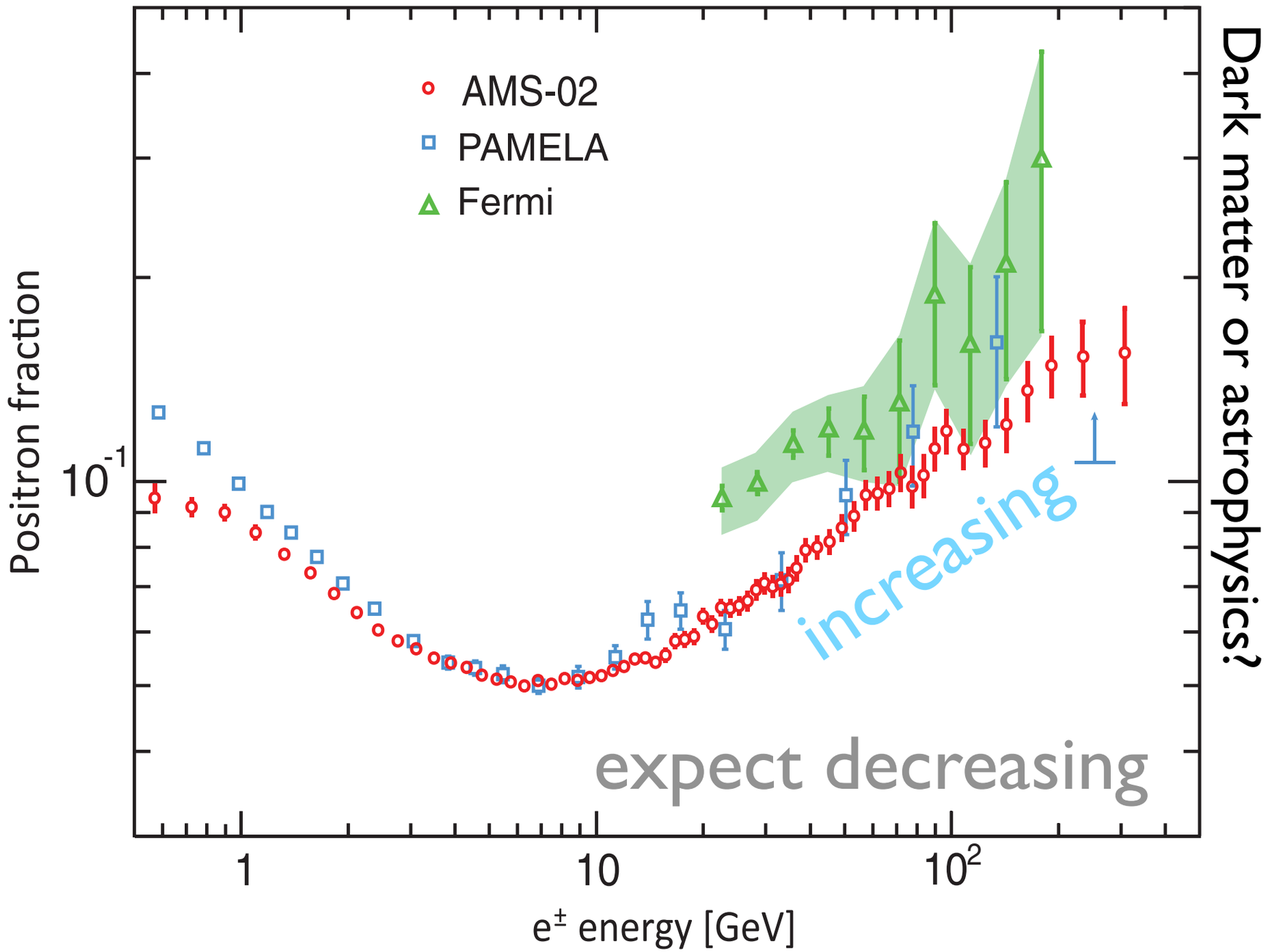


Image: PRL 110, 141102 (2013)

A 130 GeV Line?

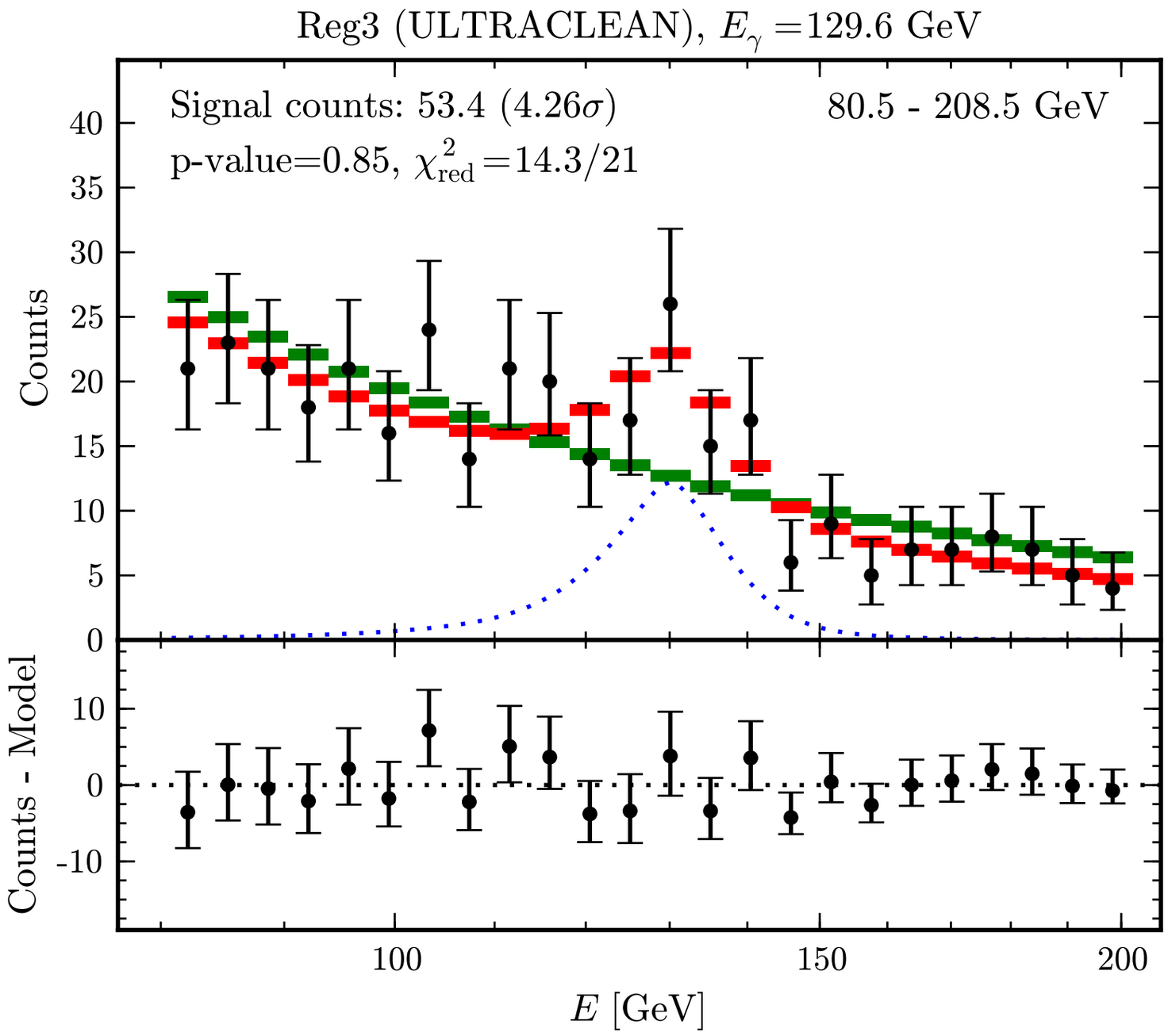


Image: 1204.2797

Status

- Rise of astroparticle physics: particle models being tested in the galaxy
- Hard to determine DM vs background
- Still one of the best hopes for new physics
- Models are still Baroque

Report card: DM

Hierarchy problem	C
Dark matter candidates	A (auto)
Unification of couplings	D+
Family replication	D
Matter vs antimatter	B+
Dark energy	dropped
Formal theory	dropped

why new physics?

Focus on: hierarchy, origin of matter

Briefly: other reasons for optimism

collider physics

implications of experiments, clever ways to test models

extra dimensions

Briefly: particle implications

supersymmetry

Focus on: recent sobering results

Briefly: promising theoretical directions

dark matter

Focus on: astroparticle physics

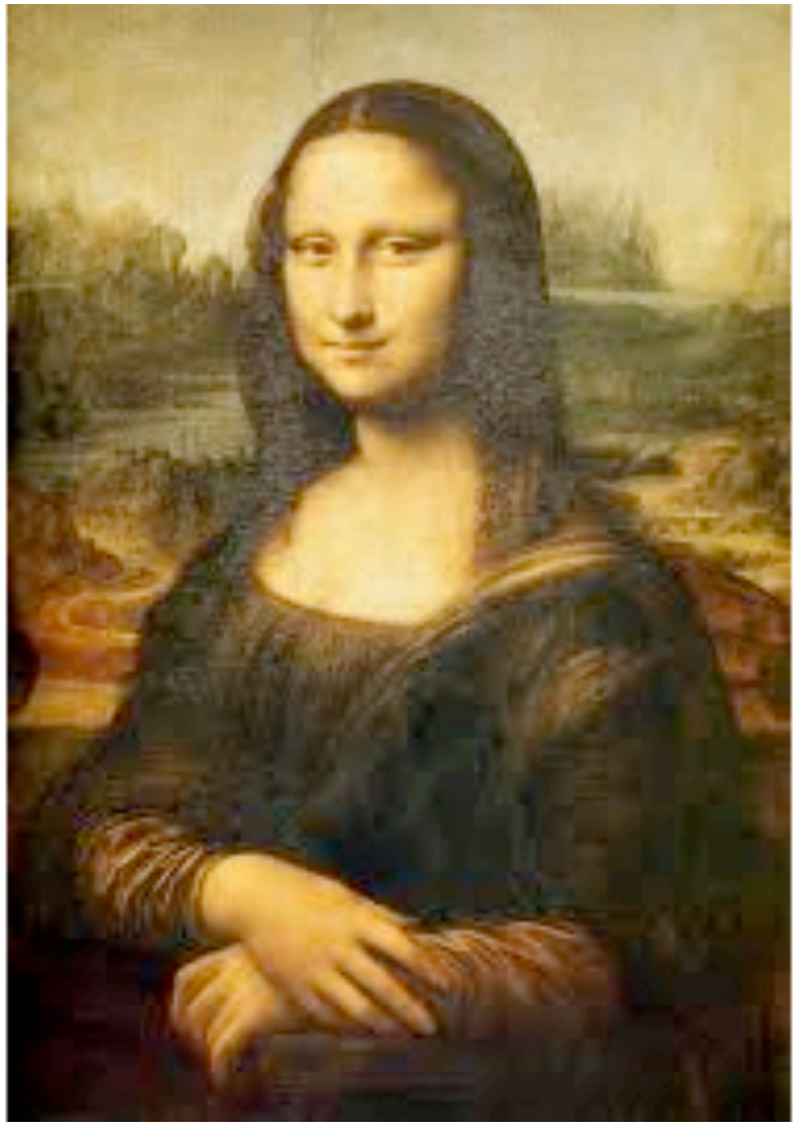
Briefly: recent hints in direct detection

formal theory

Focus on: duality, scattering amplitudes

Briefly: strings as a theory of other things, cosmo

Effective theories



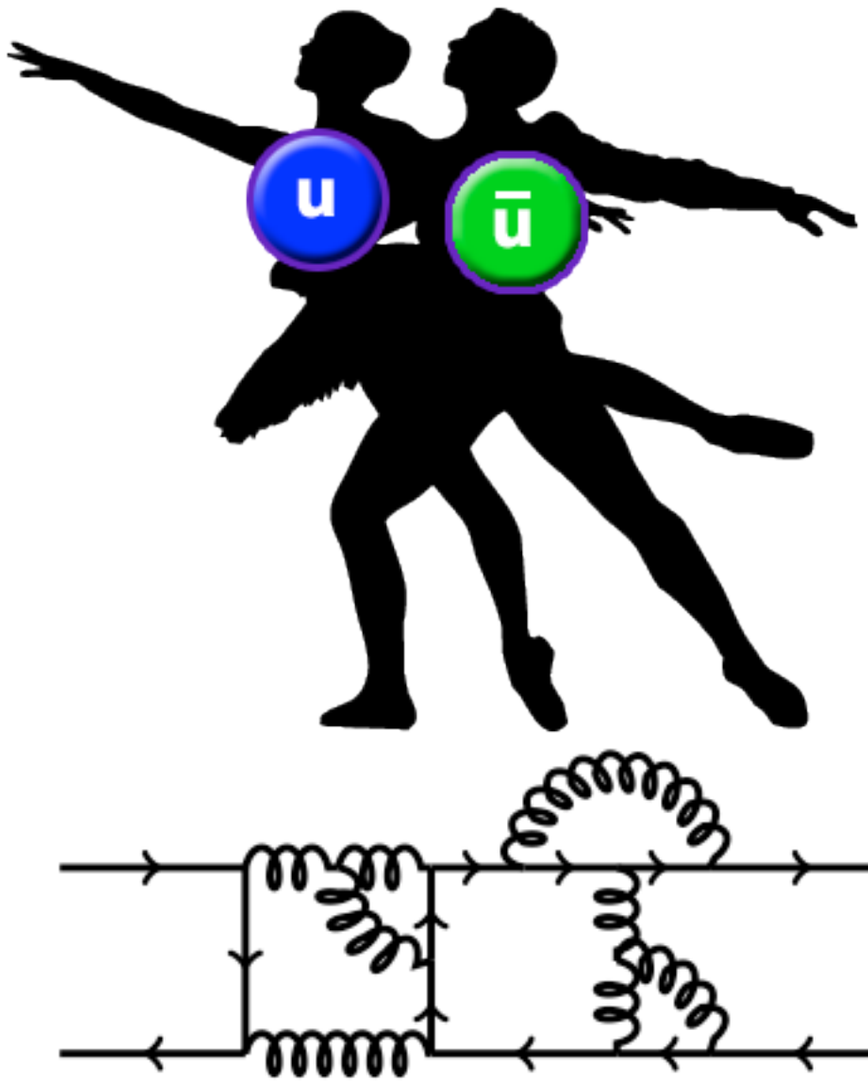
complete theory

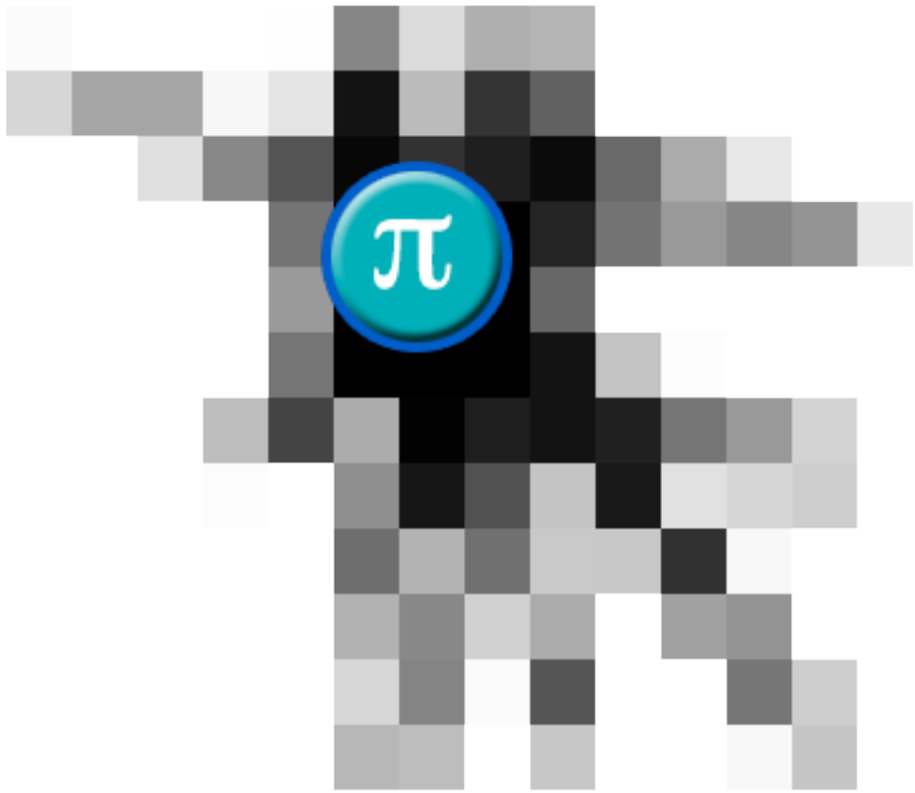
Contains full information for many questions, but very complicated. May not be possible to construct from available low energy data.

effective theory

Contains only low energy information, but very simple! Many ways to construct. Easy to construct from low energy data. Usually easy to calculate.

Effective theories





quark-antiquark pair

pion

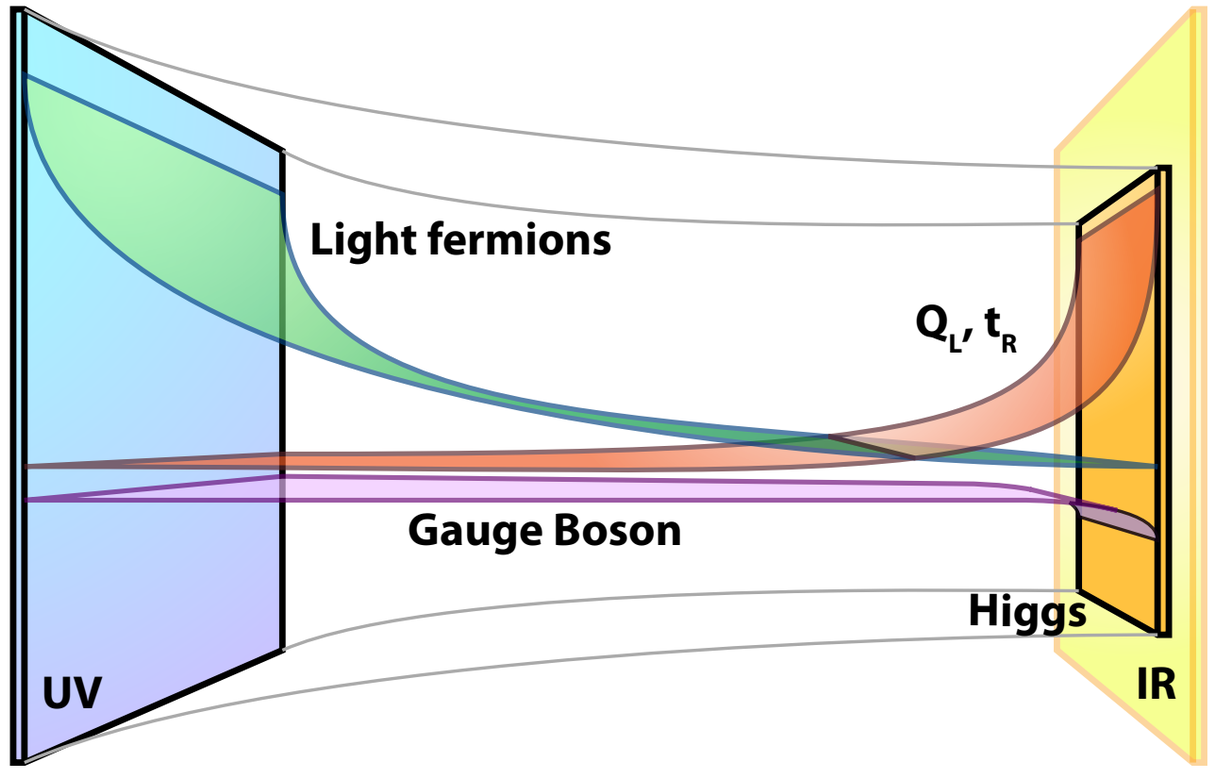
Einstein Simplified

an effective theory isn't always trivialized

Image: Sidney Harris, via the web, e.g. http://www.jokelibrary.net/yyDrawings/Physics3.html

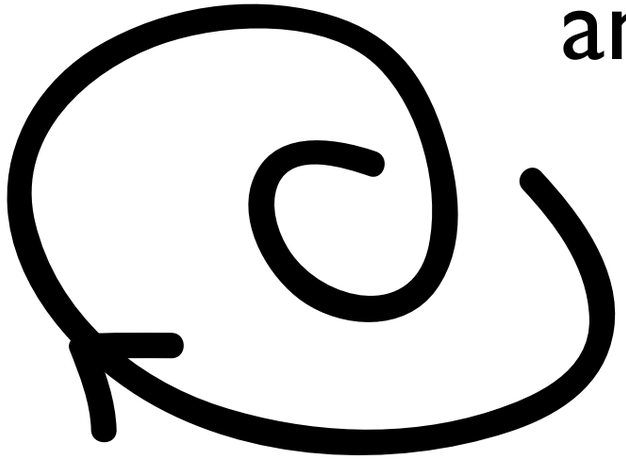
effective ≠ trivialized

SUSY dualities between
particles and extended objects



Holographic principle

both of these can be realized
and understood in string theory



String Cosmology

"Until recently, string cosmology was the marriage of a field with no predictions and one with no data."

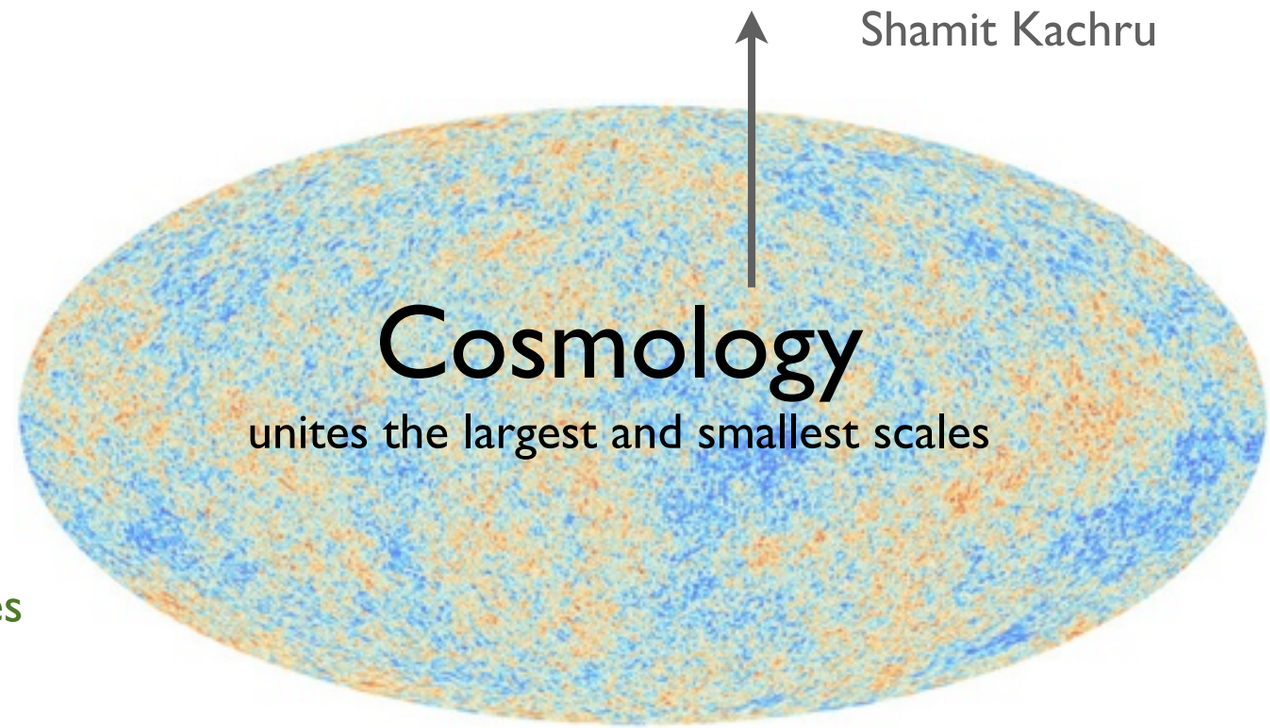
Shamit Kachru

String theory

Theory of everything or theory of anything?

unique vacuum?

framework for new dualities

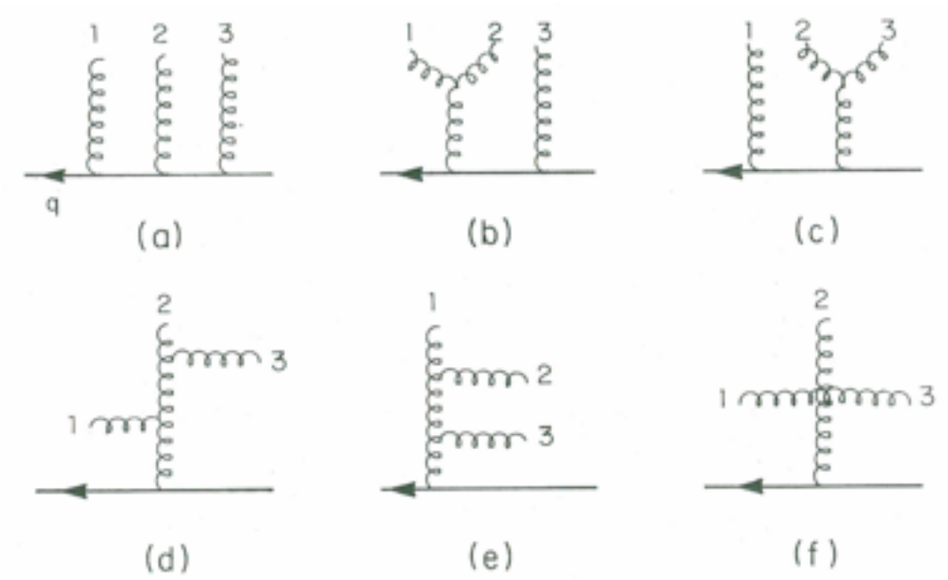


Cosmology

unites the largest and smallest scales

Scattering Amplitudes

$$\langle \text{out} \mid \text{in} \rangle$$



+ permutations of 1,2,3

annoying:
lots of redundancy

... coming from
gauge invariance!

6 gluons: 220 diagrams, tens of thousands of terms
+ many more quantum corrections

Image: hep-th/0509223

Scattering Amplitudes

features

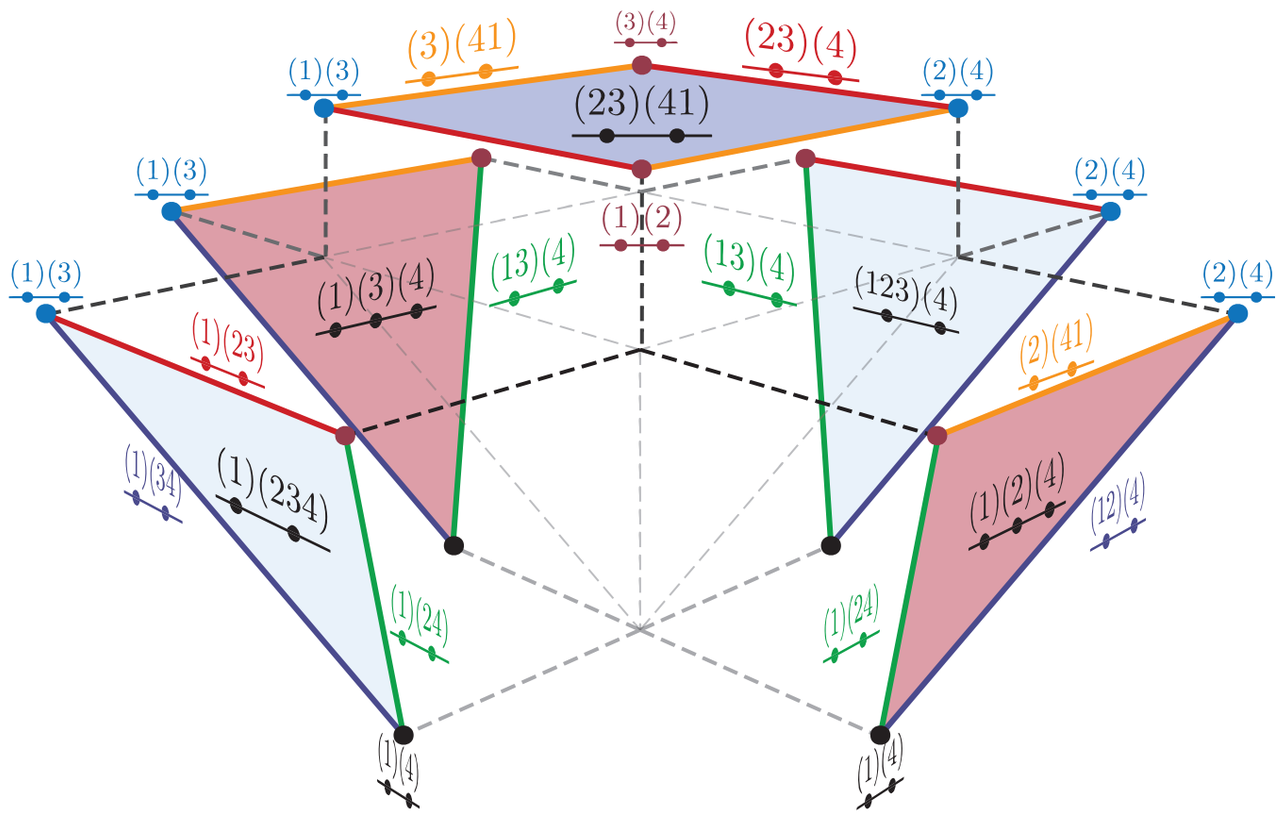
Manifestly gauge invariant
... hides unitarity (Probability cons.)
... hides locality

but maybe this is the point?
Problem of quantizing gravity boils down to one of finding good observables, issues with locality keep popping up.

analog?

Classical → quantum mechanics
Least action principle hides causality, but it pops out again. On the other hand, it gave a bridge to develop quantum mechanics!

The positive Grassmannian



new way of looking at scattering
as slices of polytopes in a complex space

Images: hep-th/0509223, 1212.5605

Report card: formal theory

Hierarchy problem	incomplete
Includes Standard Model	incomplete
Quantum gravity	incomplete
Unique theory	dropped
Applications	A
New directions	B+

Summary

why new physics?

hierarchy problem, (dark) matter

Size of colored box ~ proportion of US effort

Caveat: just a personal opinion!

collider physics

implications of experiments, clever ways to test models

extra dimensions

classical description of very quantum physics

supersymmetry

hasn't been found!

interesting dualities

dark matter

really requires new physics!

development of astroparticle physics... hints in the sky?

formal theory

dualities & scattering amplitudes