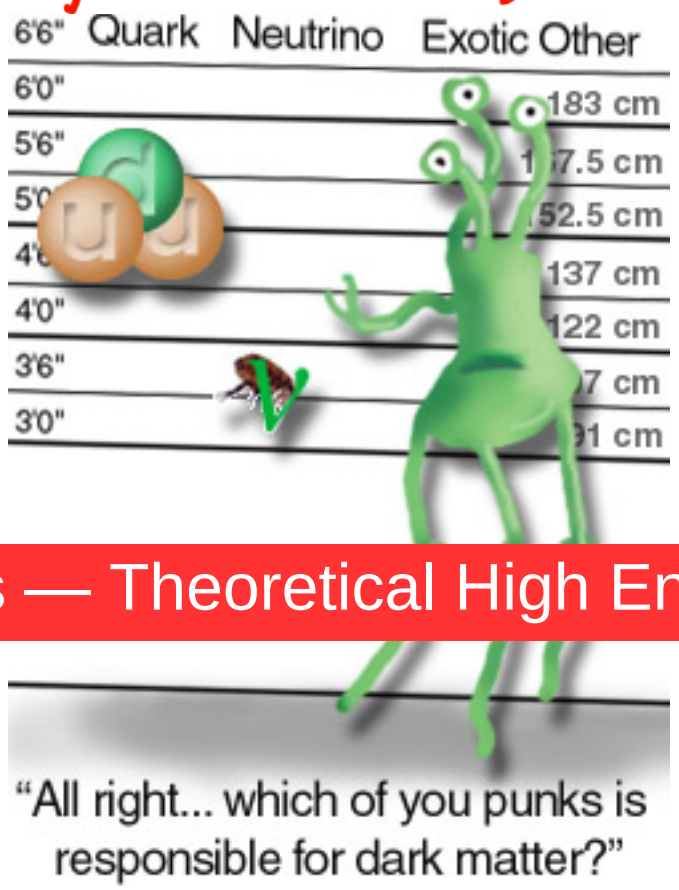
New Physics at the TeV Scale?

A Supersymmetric and Extra-dimensional talk

which maybe → string theory ?

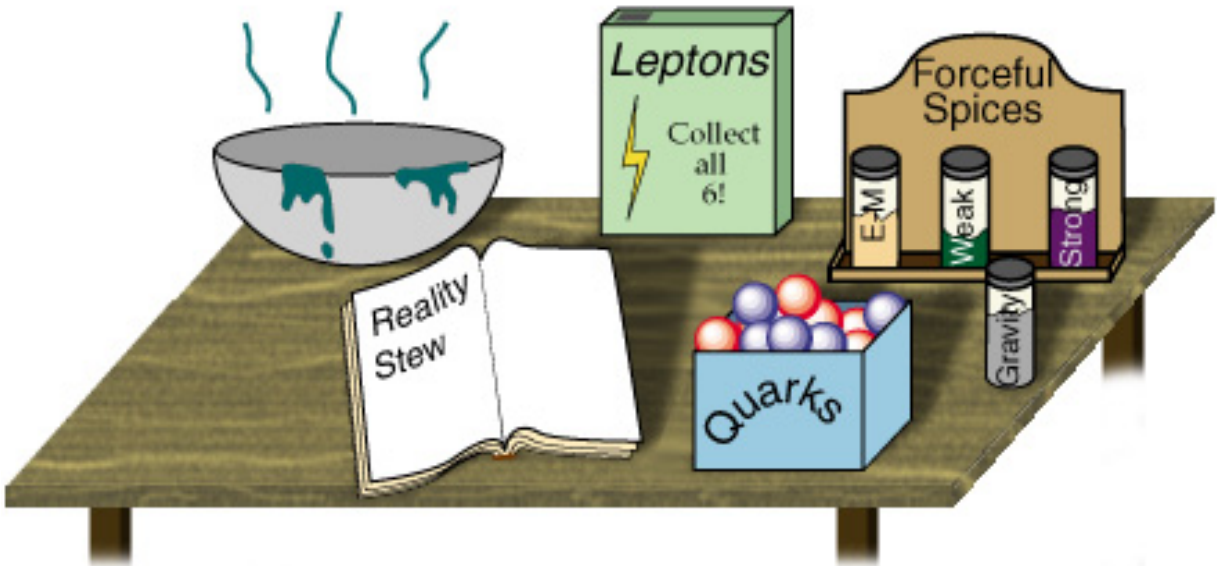


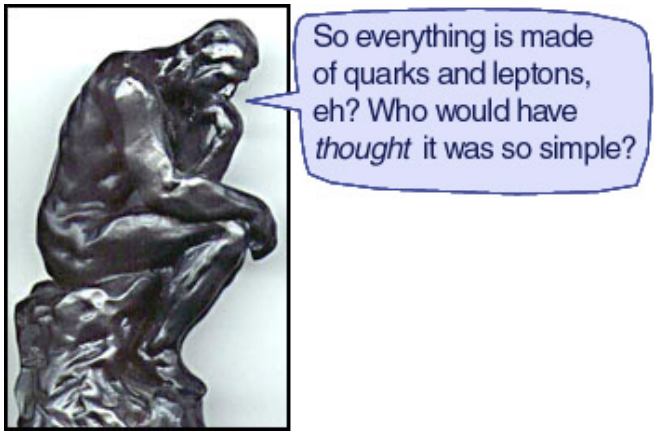
Peter Skands — Theoretical High Energy Physics

New Physics at the TeV Scale?

1. The story so far.
2. Why go beyond it?
3. The Standard Model: year 2020.
4. The not-so-Standard Model: year 2020.

The Standard Model of Particle Physics





matter: 6 leptons + 6 quarks S=$\frac{1}{2}$

force: photon + $W^{\pm}$ and Z^0 + gluon S=1

mass: Higgs S=0

The Standard Model of Particle Physics

Facts about the Standard Model

- Has been tested in a *LARGE* multitude of ways, to precisions up to $\mathcal{O}(10^{-12})$!
- Nothing seems to be wrong with it!!

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EXCEPT:

- A few experiments (incl. last year's nobel)
- Some mathematics (inconsistencies?)
- Aestheticism (doctrine that beauty alone is fundamental)

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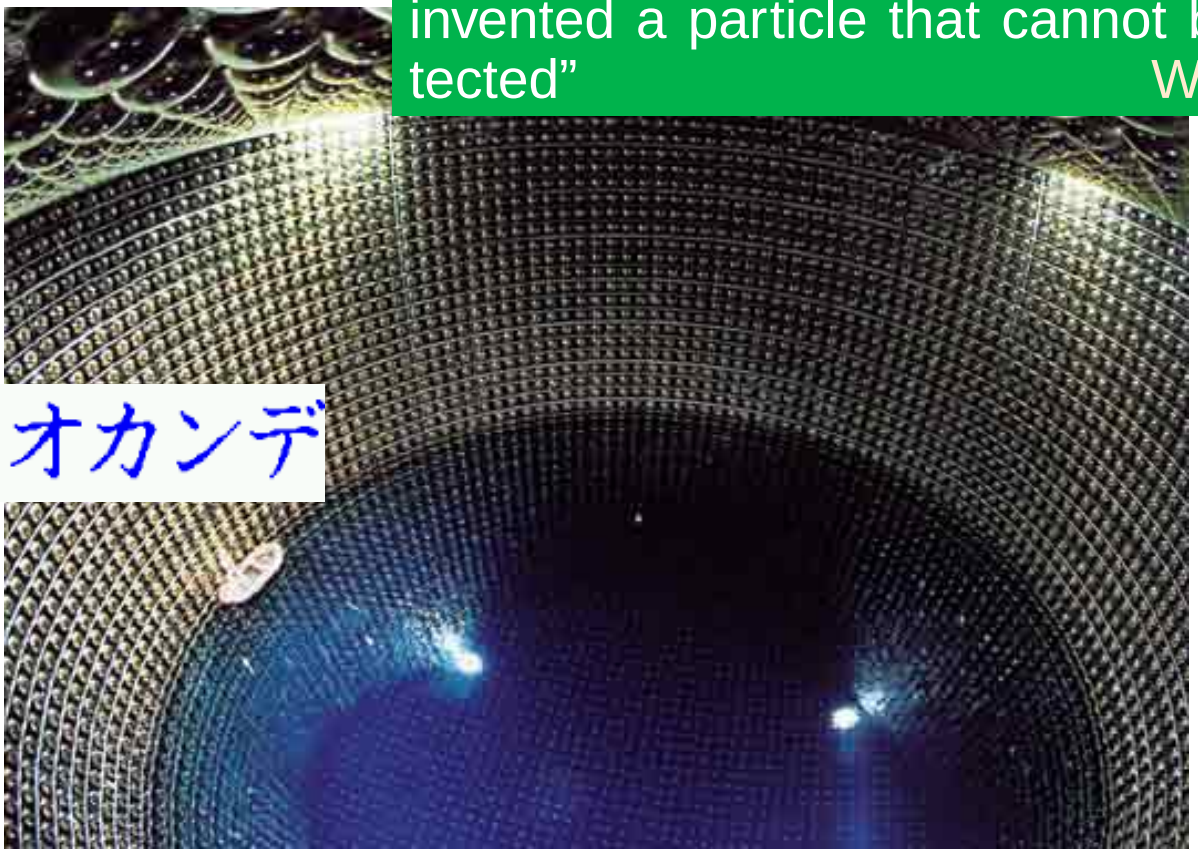
Why go beyond it?

A few experiments:

“I have done a terrible thing, I have invented a particle that cannot be detected” W. Pauli

スーパーカミオカンデ



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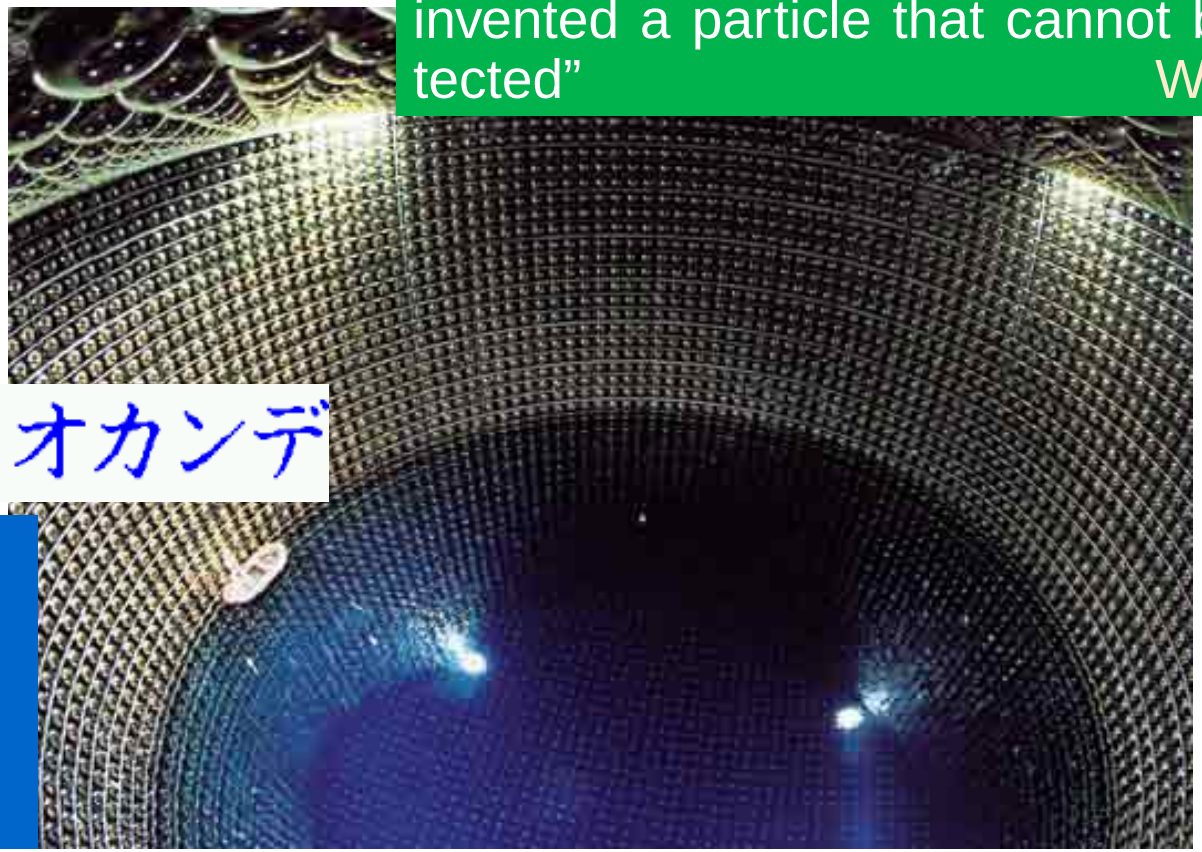


スーパーカミオカンデ

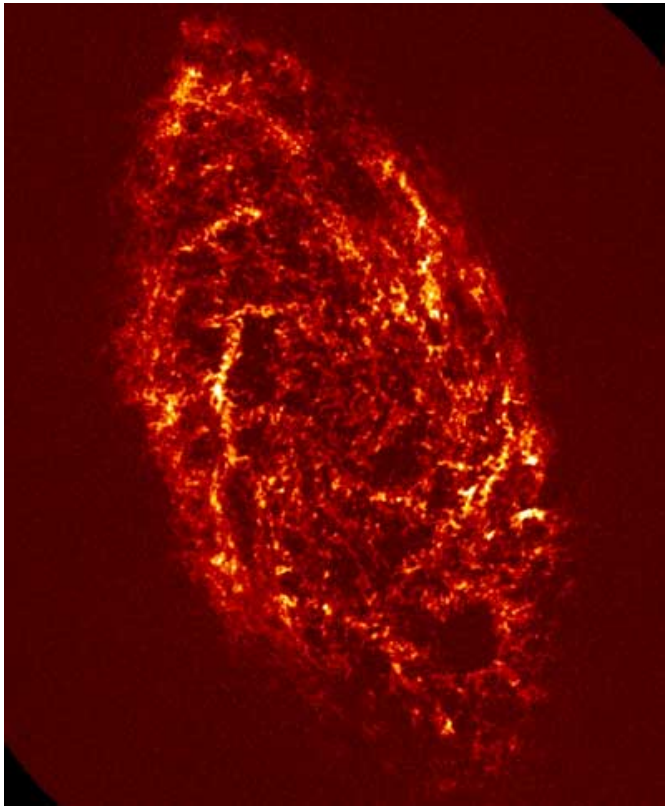
Masatoshi Koshiba

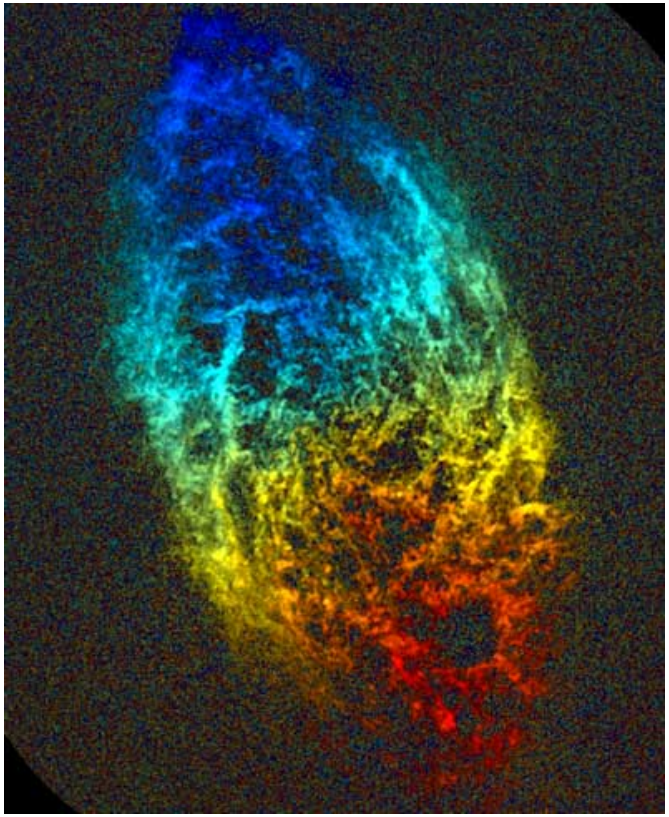
Raymond Davis Jr.

Nobel prize 2002: Neutrinos have mass!

Why go beyond it?

A few experiments:





Doppler shifts $\rightarrow$ Rotation profiles of galaxies

Why go beyond it?

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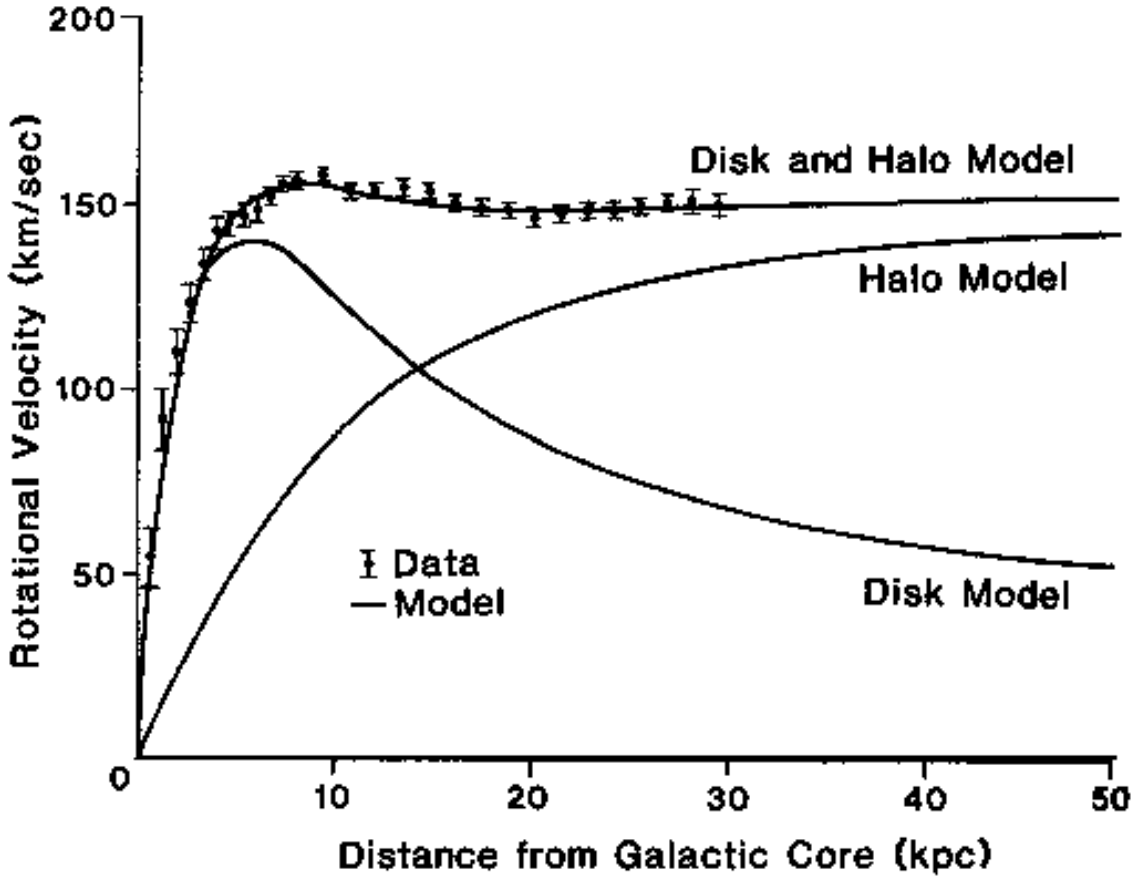

"It's a dark matter in cosmology... but then again, in that field most things are..." [A. Khodjamirian]

Why go beyond it?

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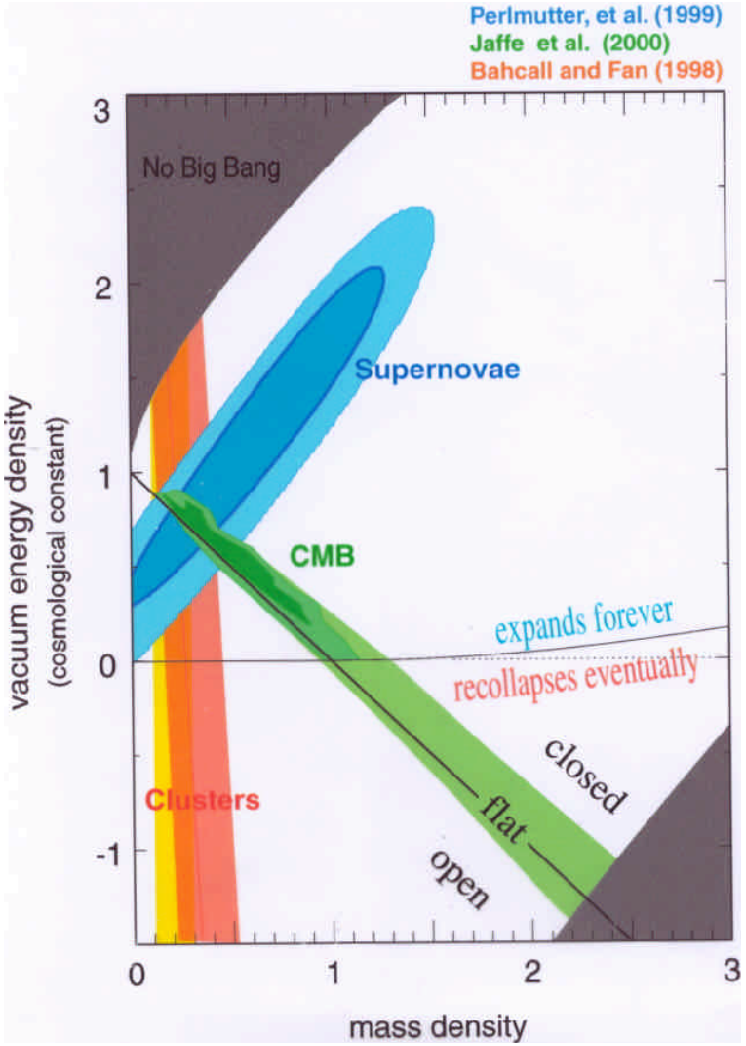

- Looks like Universe will expand forever.
- 30% matter (incl. the dark kind)
- 70% vacuum energy density (cosmological constant)

What is Λ?

Why go beyond it?

Some mathematics:

- The Standard Model isn't natural!
  - The Higgs is special. It's the only scalar.
  - Its mass gets *huge* quantum corrections from higher energies, $m^2 = m_0^2 + \Delta m^2$, with $\Delta m \sim 10^{19}\ \frac{\mathrm{GeV}}{c^2}$.

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The Standard Model has no explanation for this phenomenon, known as the *hierarchy problem*.

Why go beyond it?

Some mathematics:

- Gravity does not fit in the Standard Model
  - The graviton is special.
  - General Relativity: gravity is described by a tensor field: the metric $g_{\mu\nu}$, describing the curvature of space–time.
  - $\rightarrow$ a mixture of $\ell = 0$, $\ell = 1$, and $\ell = 2$ fields.

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  - $\rightarrow$ a mixture of $\ell = 0$, $\ell = 1$, and $\ell = 2$ fields.
  - Spin-2 fields are non–renormalizable in quantum field theory (basically, they don't make sense).
- Gravity appears to be incompatible with Quantum Field Theory.

Why go beyond it?

Some aesthetics:

- What's the origin of mass?

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- Are the true fundamental objects in Nature really point-like, or are they strings, or even membranes?
- Could there be *one* fundamental theory of everything?

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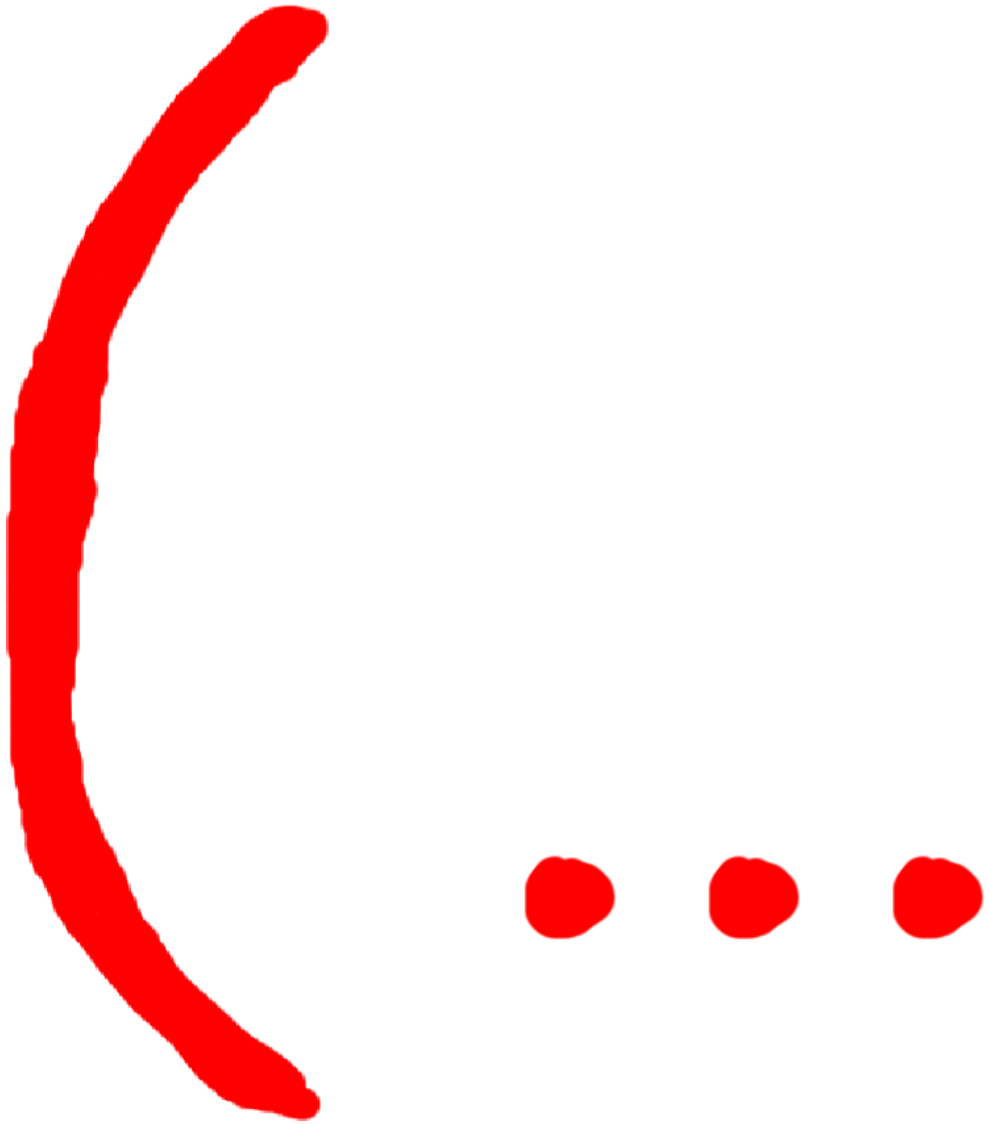
The Standard Model: year 2020.

What do we think might be discovered:

- at the Large Hadron Collider?
  LHC (CERN, Geneva): first run April 2007.
- at the next electron–positron Linear Collider?
  TESLA (DESY, Hamburg?): first run 2014?
- at future neutrino experiments?
  IceCUBE (South Pole): first run 2010?
- at future satellite–based experiments?
  Planck surveyor: launch and first light 2007.

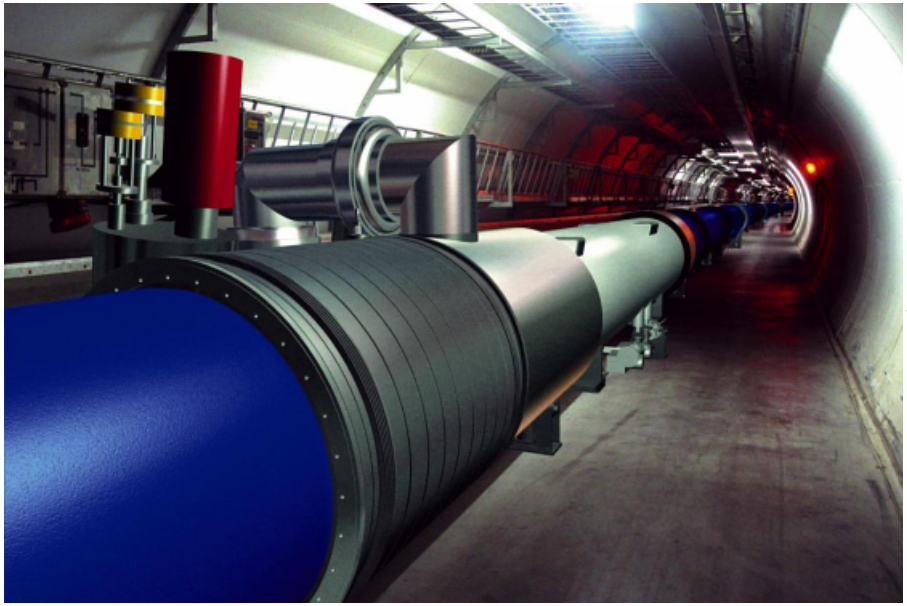
Now a small digression...

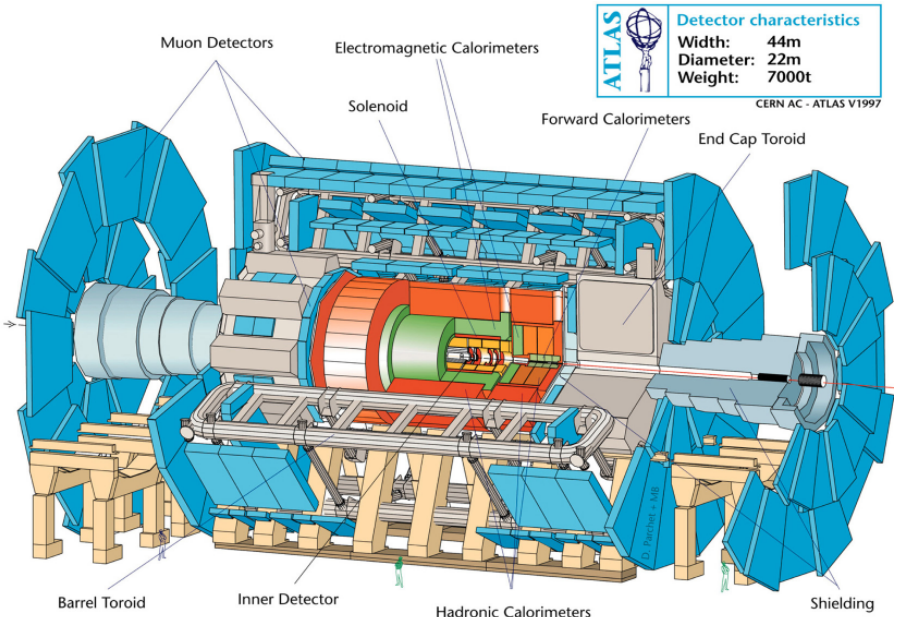


The future experiments

The Large Hadron Collider (LHC)

- Collisions of protons on protons at 14 TeV CM Energy.
- Task: to determine the origin of mass and explore the TeV scale.



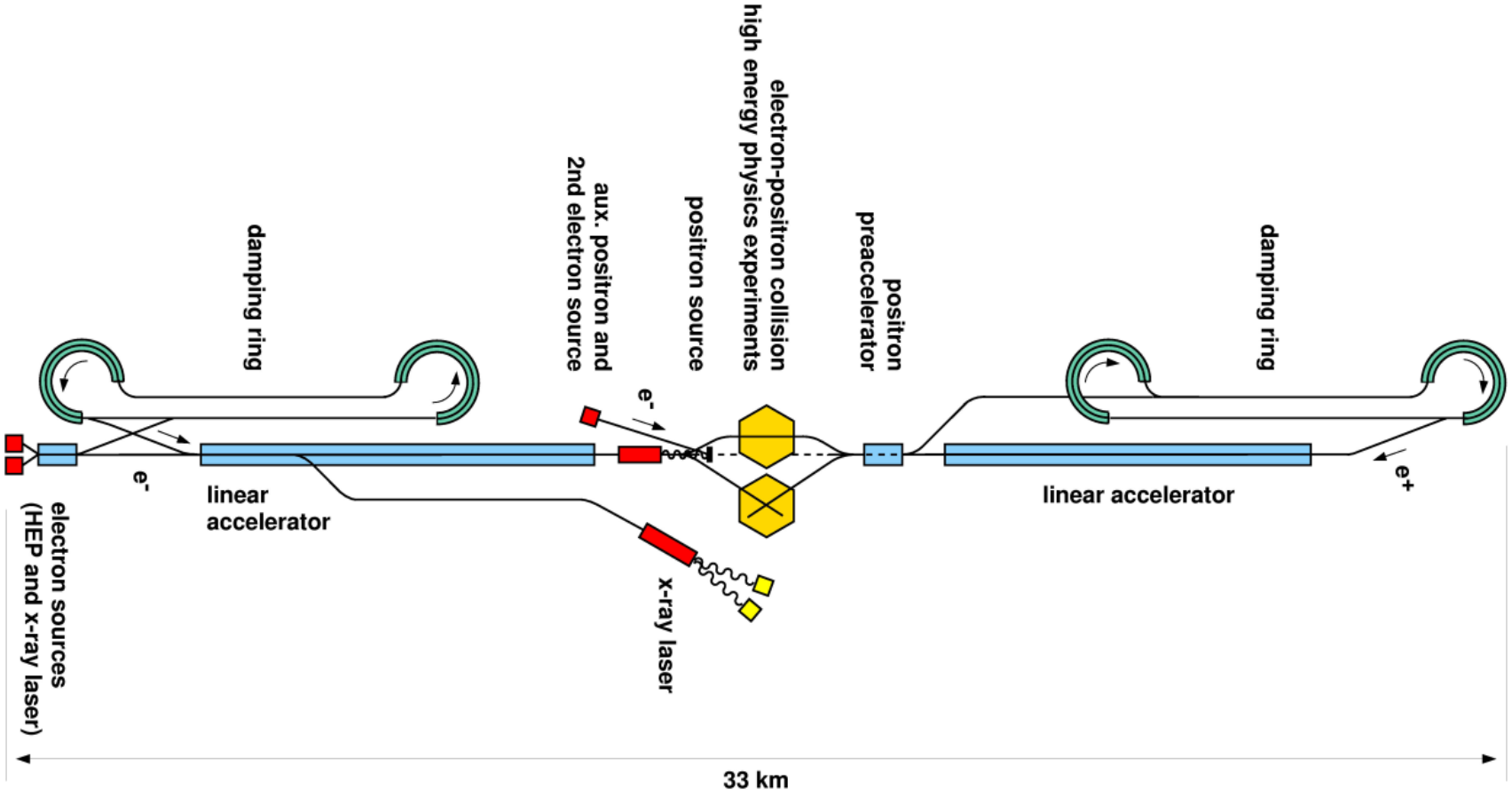


- Lund University is part of the ATLAS collaboration.

The future experiments

The Next Linear Collider (NLC)

- Collisions of electrons on positrons at 0.5 — 3(5?) TeV CM Energy. For e^+e^-, that's *a lot*!



Ice-fishing for neutrinos

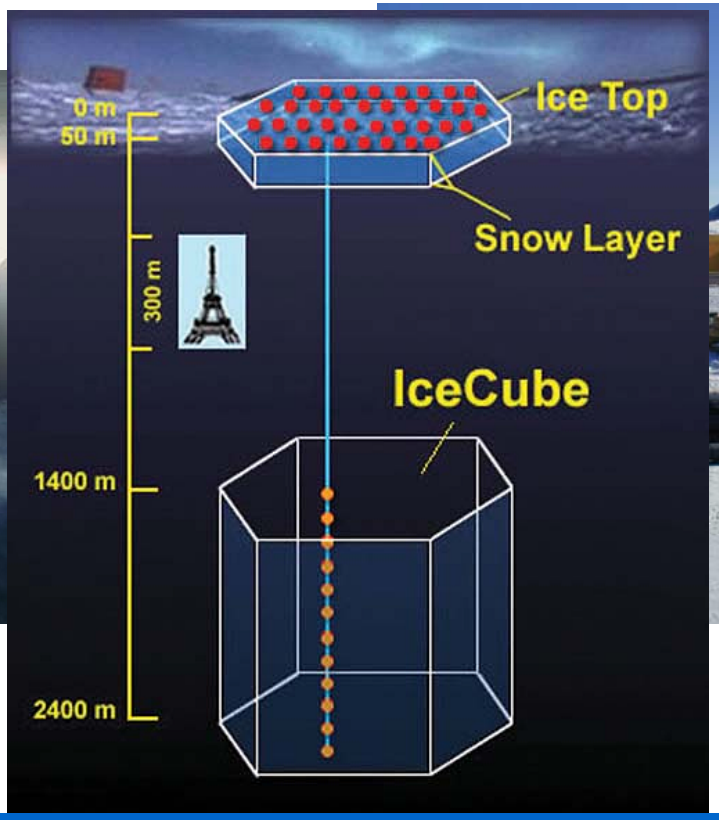
IceCUBE

Is it a dark matter detector too?

Ice-fishing for neutrinos

IceCUBE

- A BIG Neutrino Detector (1 km^3) at the South Pole $\rightarrow$ a neutrino telescope.



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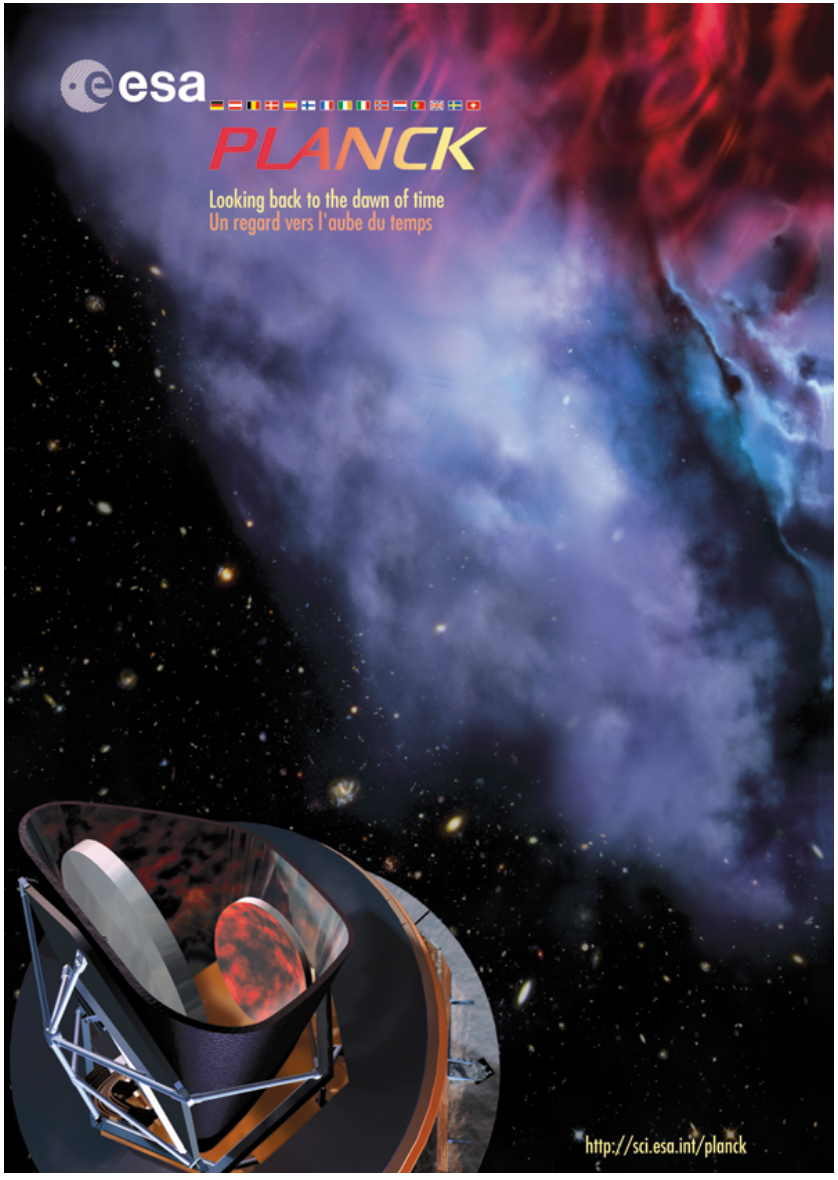
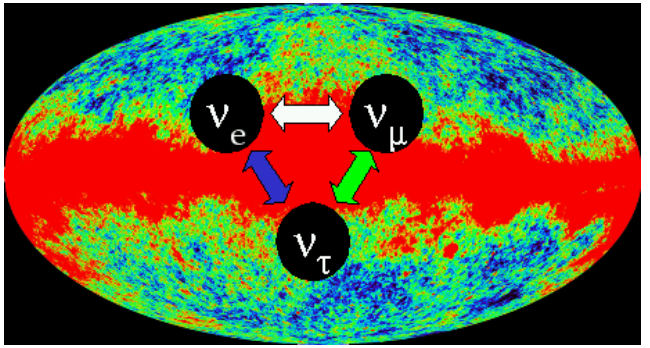
Neutrinos in Space



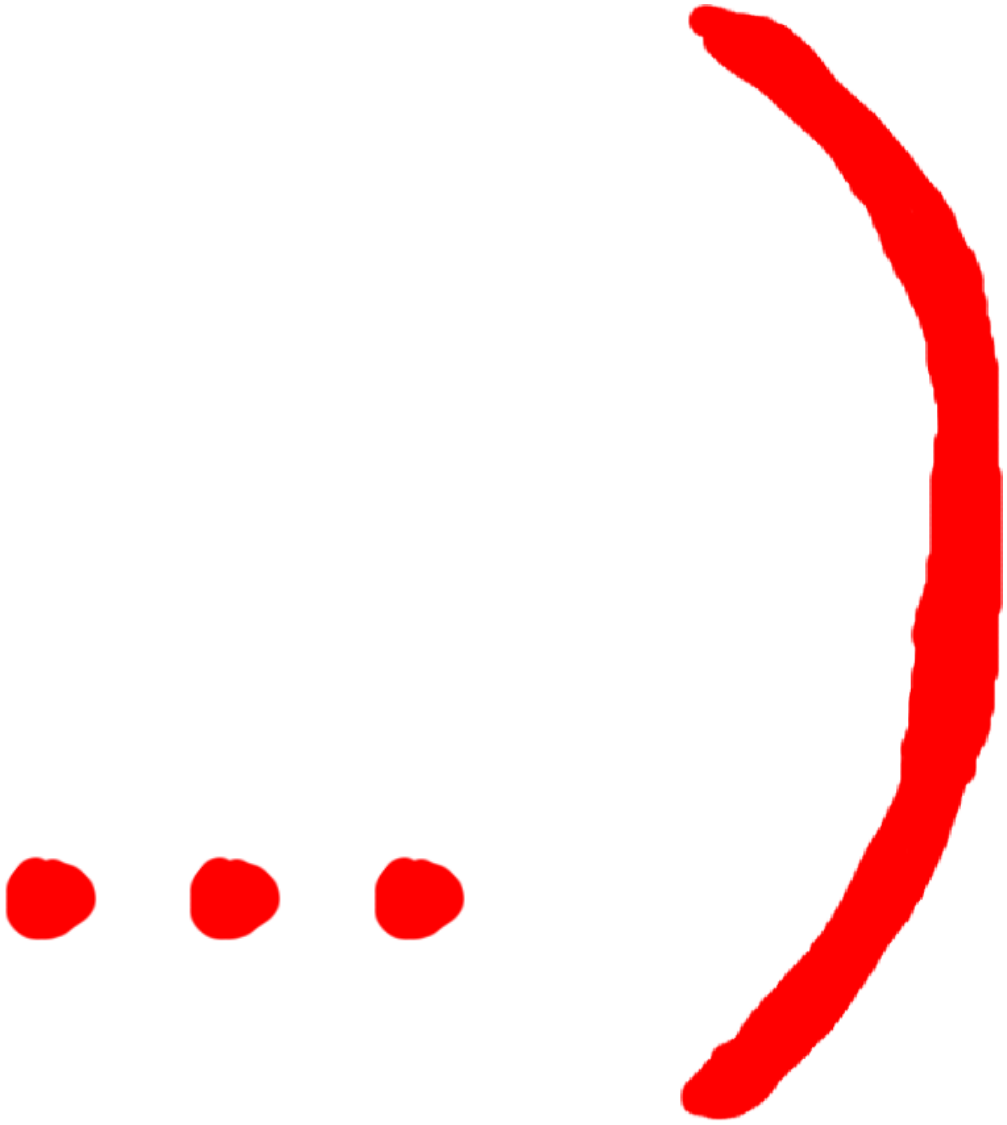
Planck Surveyor

- Mission: to measure fluctuations in the CMBR.



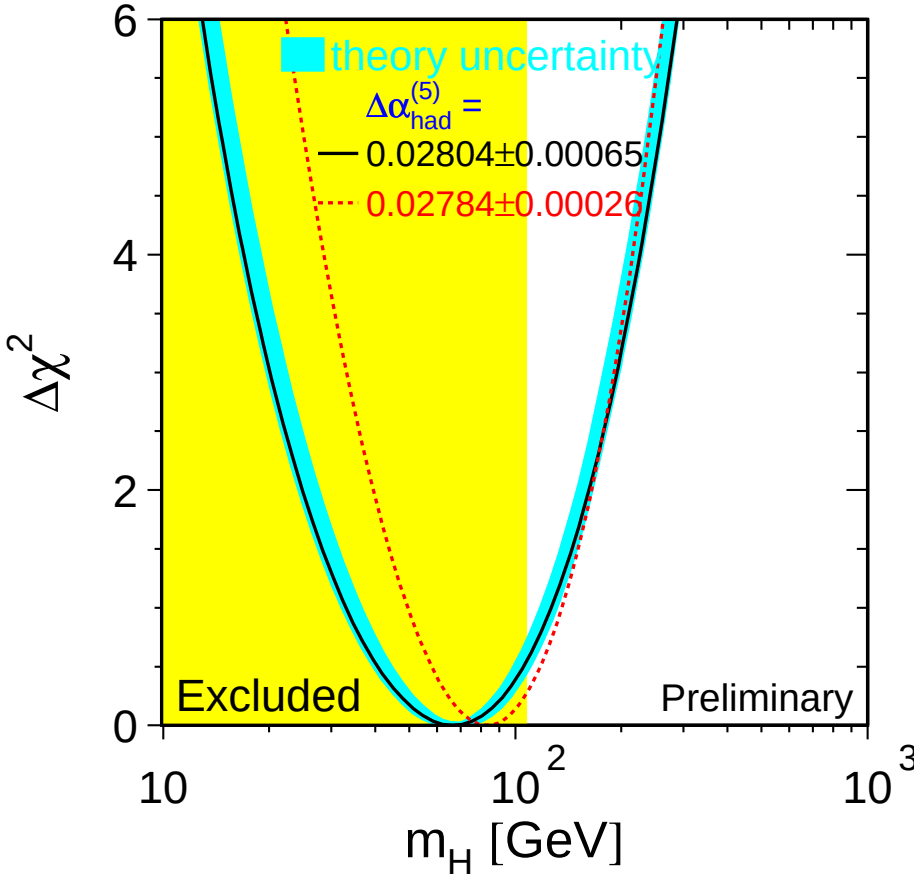
- $\rightarrow$ measure neutrino masses too?

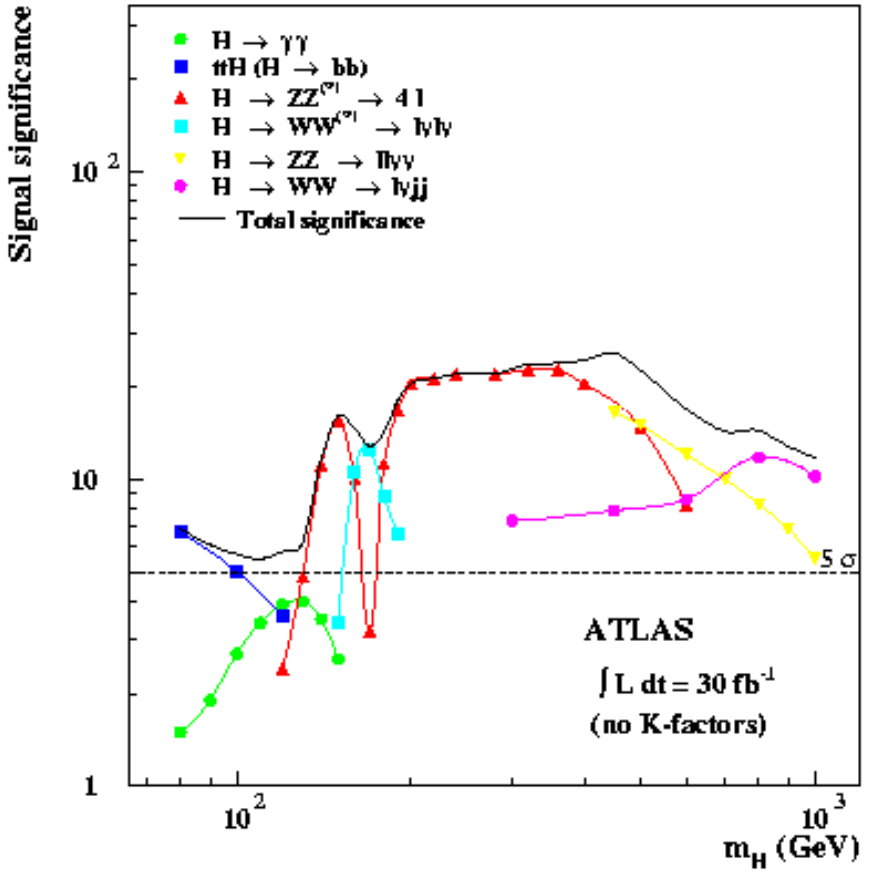
And now: back to the Higgs and beyond



#1: the Higgs boson

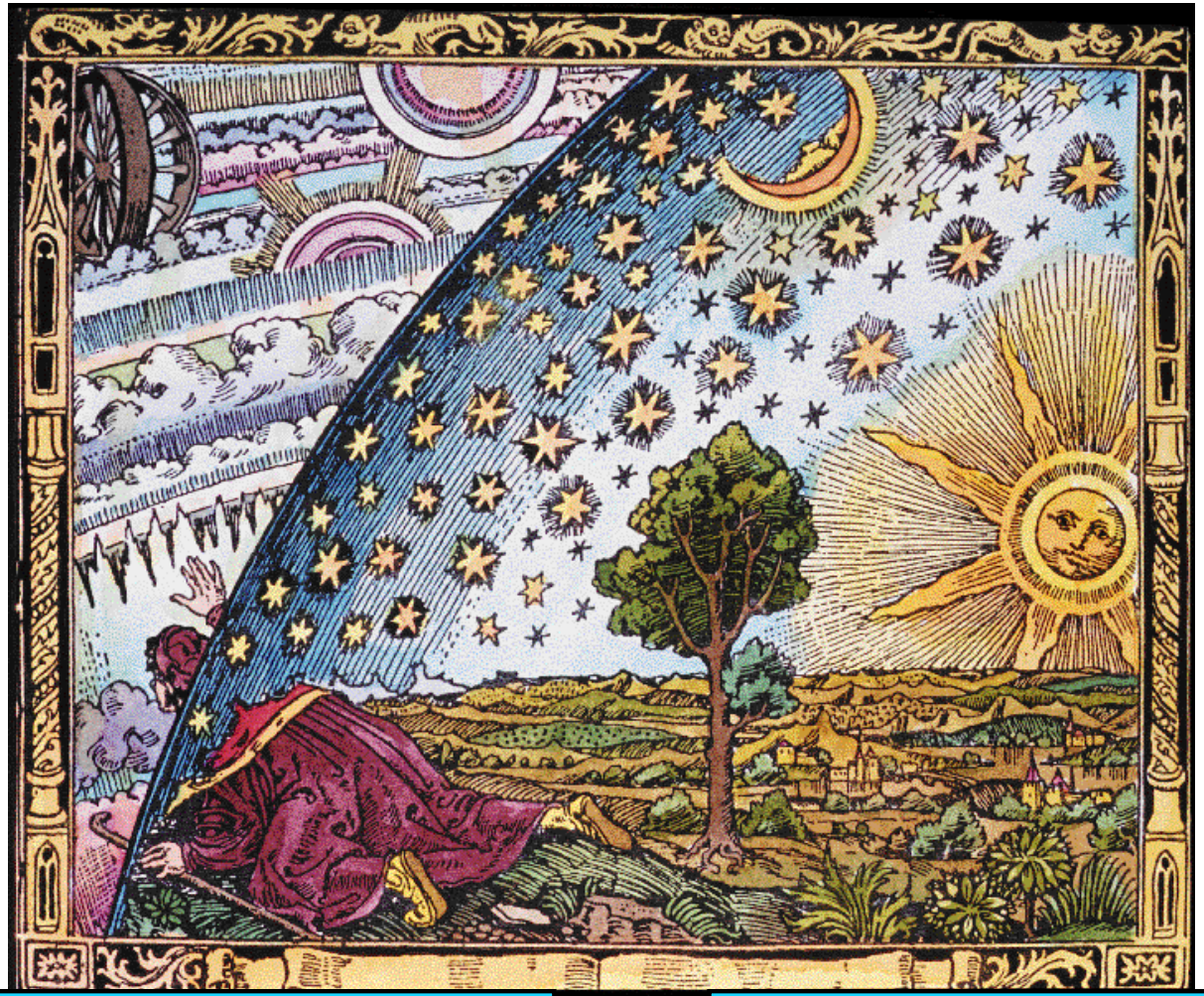
- Indirect evidence → Higgs can't be too heavy!





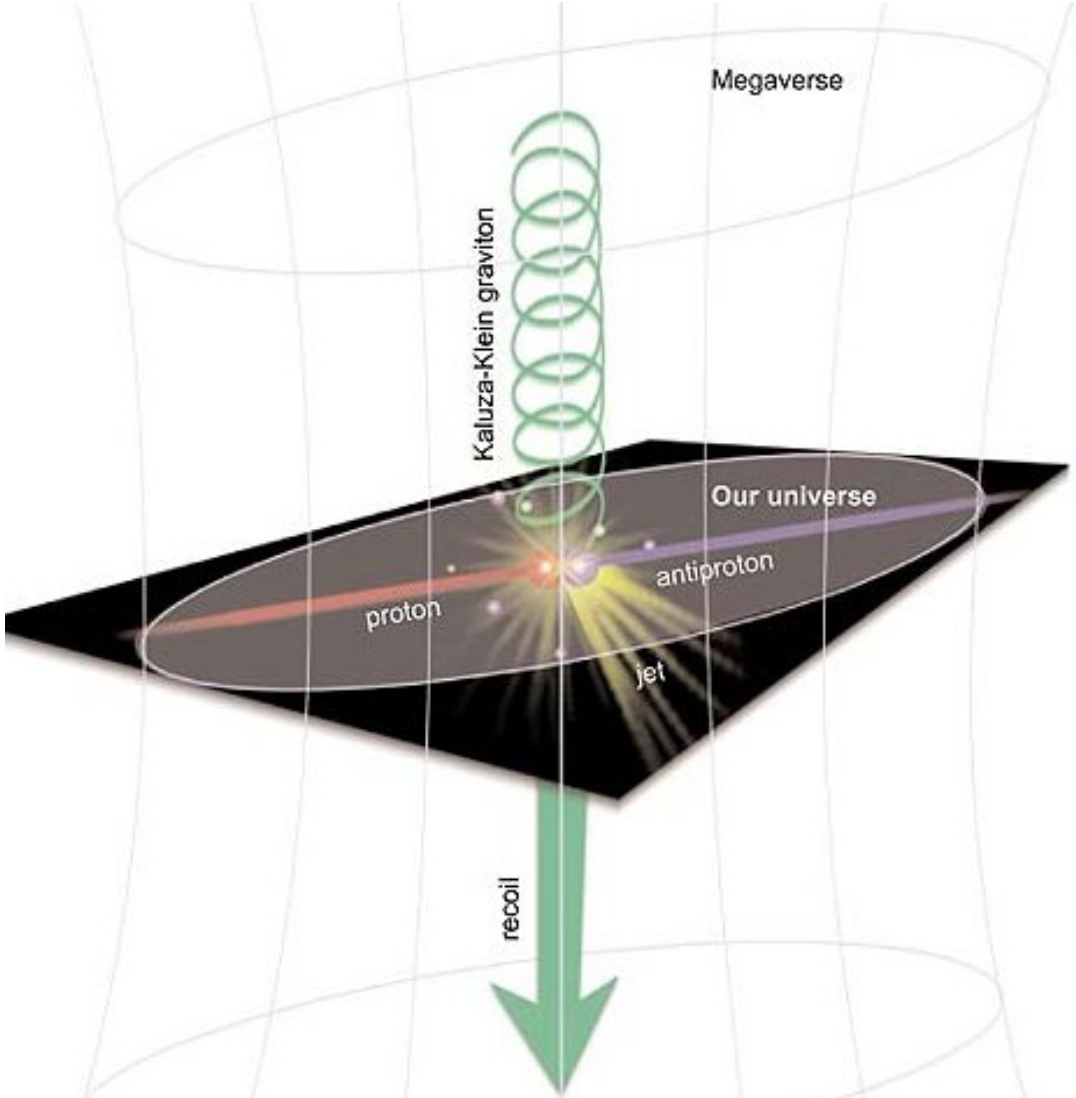
- Discovered at the LHC in 2009? (but still just SM...)

Beyond the Standard Model



Extra Dimensions and Supersymmetry

Extra Dimensions



- Is space–time more than 4 dimensional?
- Could extra dimensions be discovered at the TeV scale?

Extra Dimensions

- An old idea, resurrected in 1998: there may exist extra, compactified dimensions which so far have eluded discovery. Two basic variants:

LARGE

and

small

Extra Dimensions

1. Extra Dimensions à la ADD — LARGE EXTRA DIMENSIONS
"The Hierarchy Problem and New Dimensions at a Millimeter",Phys.Lett.B429(1998)

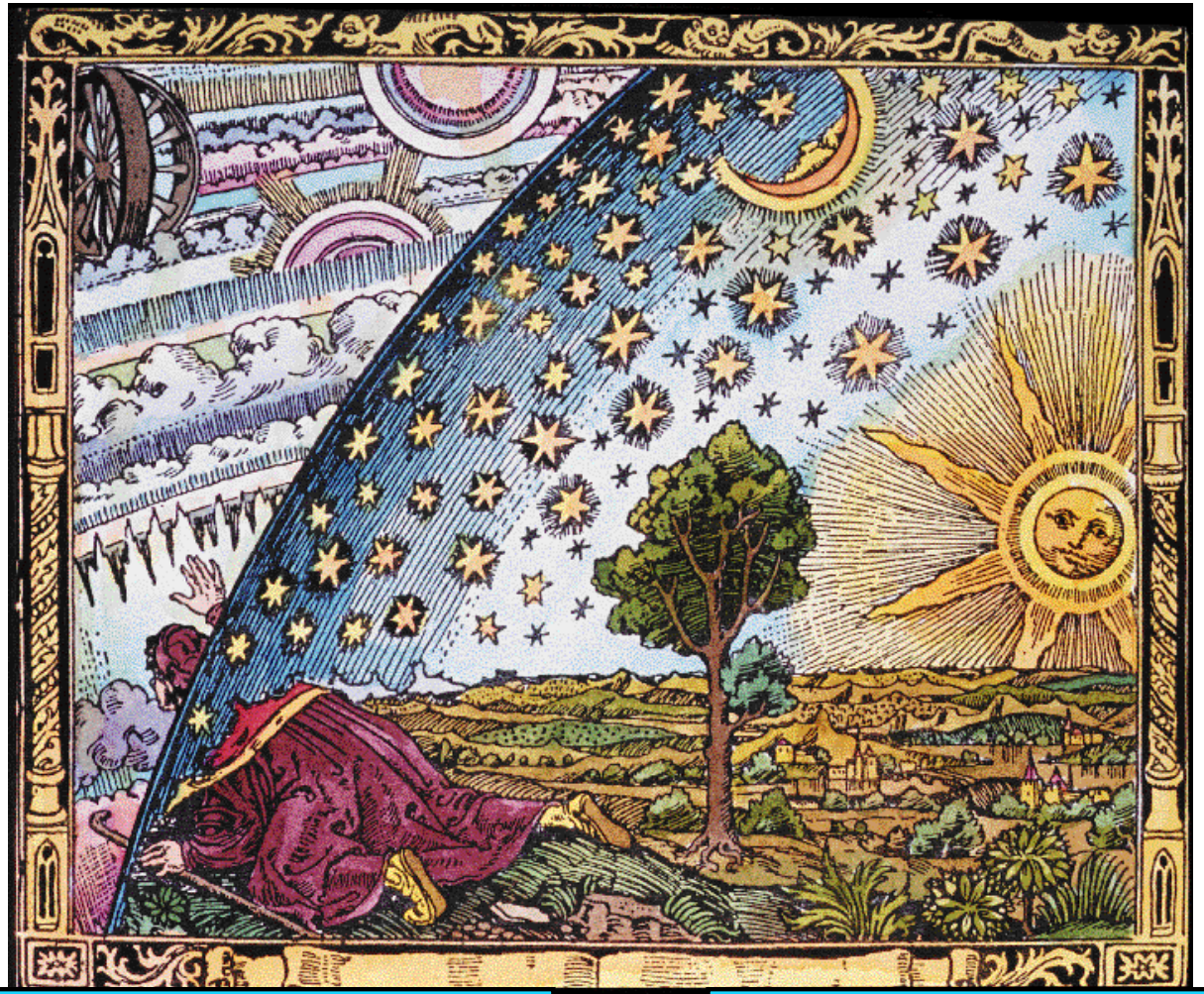
- up to millimeter size extra dimensions where (usually) only gravitons can propagate.
- $m_{\text{planck}} = \sqrt{\hbar c/G}$ could be as low as 1 TeV.
- Deviations from Newtonian gravity at small length scales: $V(r) \propto \frac{m_1 m_2}{r} \rightarrow \frac{m_1 m_2}{r^{1+n}}$.
- $n = 1$ basically excluded, since astronomocally large. $n \geq 2$ gives $L \leq 1$ mm.
- A pseudo-continuum of Kaluza-Klein graviton excitations above 1 TeV.
- Trans-planckian collisions at small impact parameter $\rightarrow$ Black Holes at accelerators !!

Extra Dimensions

2. Extra Dimensions à la RS — WARPED EXTRA DIMENSIONS
"A Large Mass Hierarchy from a Small Extra Dimension",Phys.Rev.Lett.83(1999)

- One small extra dimension with two end-of-the-world 3-branes.
- The two fundamental scales (one on each 3-brane) are related by *geometry*.
- The extradimensional geometry contains a *warp factor*, so that physical masses on the visible 3-brane are $m = m_0 \exp(-kr_c\pi)$.
- No (observable) deviation from Newtonian gravity.
- Signal: distinct towers of Kaluza-Klein excitations above 1 TeV.

Beyond the Standard Model



Extra Dimensions and Supersymmetry

Supersymmetry.

- Could there be more space–time symmetries?

  The Symmetries of Space and Time:
  - Lorentz invariance, Translational invariance, Rotational invariance – is that all?

- Coleman-Mandula Theorem

  "All possible symmetries of the S matrix",Phys.Rev.159:1251(1967)

  → YOU CAN'T DO IT... it's too boring.

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- Haag-Lopuszanski-Sohnius Theorem:
  "All possible generators of supersymmetries of the S matrix",Nucl.Phys.B88:257(1975)

  → WITH SUPERSYMMETRIES it's not boring at all...

So what is Supersymmetry?

- Could bosons and fermions be related?

  The generators of a supersymmetry, Q (and $Q^\dagger$), *anti*-commute:

$$\{Q, Q\} = \{Q^\dagger, Q^\dagger\} = 0$$

  i.e. they are fermionic and relate particles of different spin:

$$Q|\,\text{boson}\,\rangle = |\,\text{fermion}\,\rangle \quad \text{and} \quad Q|\,\text{fermion}\,\rangle = |\,\text{boson}\,\rangle$$

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- If Nature incorporates supersymmetry, bosons and fermions should thus be intimately related.

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SUPERSYMMETRY

For every boson, there is a fermion

For every fermion, there is a boson

6 leptons + 6 quarks S=$\frac{1}{2}$

photon + $W^{\pm}$ and Z^{0} + gluon S=1

Higgs S=0

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SUPERSYMMETRY

For every boson, there is a fermion
For every fermion, there is a boson

6 leptons + 6 quarks		$S=\frac{1}{2}$
2×6 sleptons + 2×6 squarks		$S=0$
photon + $W^{\pm}$ and Z^0 + gluon		$S=1$
photino + Winos and Zino + gluino		$S=\frac{1}{2}$
Higgs		$S=0$
Higgsino		$S=\frac{1}{2}$

Supersymmetry.

- But what's the point?
  - Why should Nature respect this weird symmetry?
  - Instead of reducing the mess, we've *doubled* the spectrum of physical states!
- It makes sense because:
  - SUSY gives the largest possible space–time symmetry.

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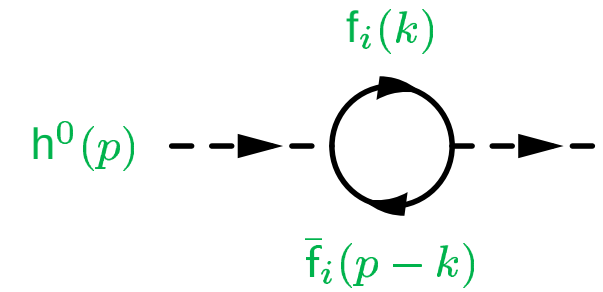
SUSY can solve the Hierarchy Problem

Quantum corrections to the Higgs mass due to fermions:

$$\Delta m^2_{\mathsf{h}^0} = \sum_i$$



$$= -2\frac{|\lambda_{\mathsf{hff}}|^2}{16\pi^2}\Lambda^2_{\text{cutoff}}$$

$$m^2_{\mathsf{h}^0} = (m^0_{\mathsf{h}^0})^2 + \Delta m^2_{\mathsf{h}^0} \Longrightarrow 10^4\,\mathsf{GeV}^2 \sim X - 10^{36}\,\mathsf{GeV}^2$$

EXTREMELY finetuned! (with $\Lambda \to m_{\mathsf{planck}}$)

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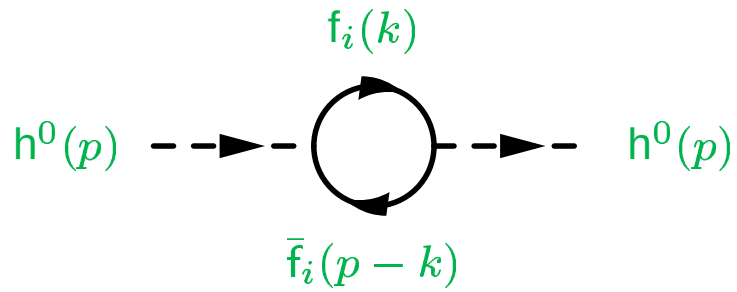
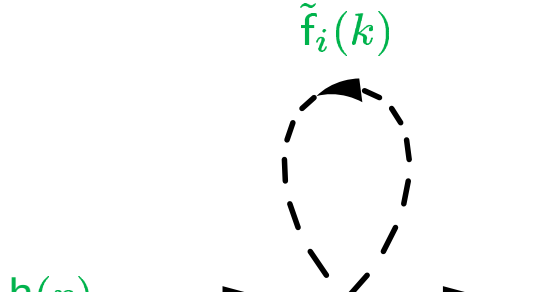


$$+ \sum_i$$



$= 0$

$$m^2_{\mathsf{h}^0} = (m^0_{\mathsf{h}^0})^2$$

NOT finetuned! (even with $\Lambda \to m_{\mathsf{planck}}$)

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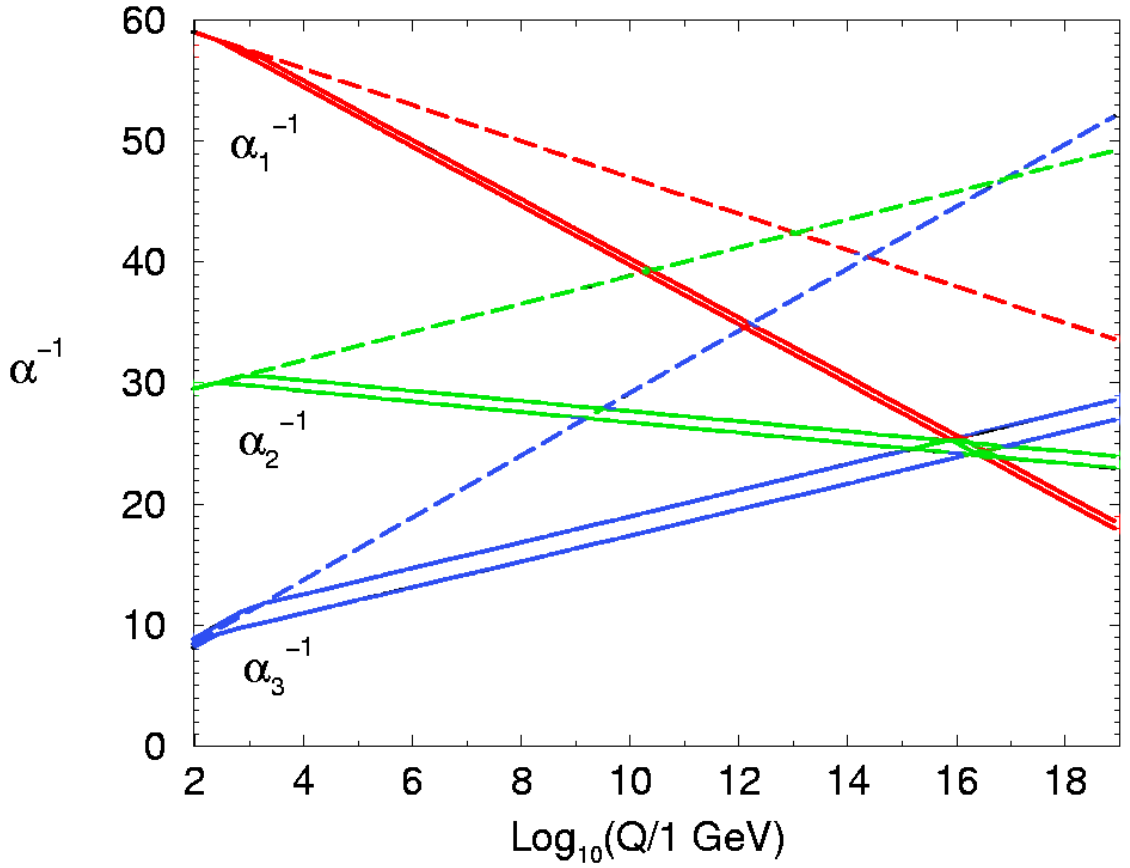
  - SUSY leads to Grand Unification.

SUSY Leads to Grand Unification

- GUT's with only SM as underlying theory are ruled out, essentially from measurements of the weak mixing angle.
- GUT's with SUSY can do wonderful things:



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  - SUSY can solve the dark matter problem.
  - SUSY leads to Grand Unification.
  - SUSY is the "super" in superstring theory.

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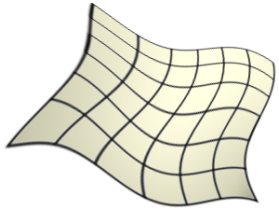
String Theory

Basic postulate: "Elementary" particles are different modes of vibration of fundamental strings.

Basis of string theory: wave equations on the 2d (σ, τ) world-sheets traced out by the strings.



On the string sheet: the 4d space-time coordinates, x_μ, are $x_\mu(\sigma, \tau)$, i.e. they are like fields in a 2d field theory defined on the sheet.

Basics of String Theory

Solutions of 1+1d wave equations can always be written as a sum of waves travelling in opposite directions.

$$x^\mu(\sigma,\tau) = x^\mu_R(\tau-\sigma) + x^\mu_L(\tau+\sigma) \qquad (0)$$

called “left-movers” and “right-movers”.

An open string also has boundary conditions at its two end points, Dirichlet ($\dot{x}=0$) or Neumann ($x'=0$).

Dimensions of String Theory

Bosonic string theory (x^μ without superpartners): $d > 26$ gives states with negative norm. $d \neq 26$ gives anomalies (breakdown of gravitational/gauge invariance at the quantum level).

Superstring theory (x^μ with superpartners ψ^μ): $d \neq 10$ gives anomalies.

NB: Bosonic string theories not realistic since no fermions (+ tachyons) $\Longrightarrow$ string theory suggests we live in $d = 10$.

The Story So Far

We got:

- Strings living in 9+1 dimensions
- 10 supermultiplets (x^μ and superpartners ψ^μ) living on the string worldsheets, satisfying 2d wave equations with boundary/periodicity conditions.
- Bonus: geometry is determined dynamically $\Longrightarrow$ quantum theory of gravity!
- Bonus: just one finite diagram at each order of perturbation theory!

Status after 1st superstring revolution (1985)

1 universe to explain... 5 consistent string theories.

SO(32) heterotic
N=1 SUSY
Closed $\leftrightarrow$ strings

$E_8 \times E_8$ heterotic
N=1 SUSY
Closed $\leftrightarrow$ strings

Type II B
N=2 SUSY
(same chirality)
Closed $\leftrightarrow$ strings

Type I (SO (32))
N=1 SUSY
Open+Closed
$\leftarrow$ or $\rightarrow$ strings

Type II A
N=2 SUSY
(opposite chirality)
Closed $\leftrightarrow$ strings

Why *those* 5 ?

Again... Because everything else contains ANOMALIES:

Type IIA is non-chiral (parity conserving) $\Longrightarrow$ no anomalies.

Type IIB has 3 chiral fields contributing to many gravitational anomalies, but sum = 0!

Type I coupled to SYM has both gauge and gravitational anomalies, but not if gauge group is SO(32)!

"Heterotic" means $d = 26$ bosonic strings for the left-movers, and $d = 10$ superstrings for the right-movers. Again, SO(32) is anomaly free, but $E_8 \times E_8$ also works.

STRING THEORY PHENOMENOLOGY

How does OUR universe come out of this?

How does *our* universe come out of this?

Our universe:
4d, $N = 0$ or $N = 1$ SUSY, $SU(3) \times SU(2) \times U(1)$

Example: Type I superstring theory.

- $N = 1$ in 10d.
- How many SUSY charge d.o.f.? $N \times \frac{1}{2_M 2_W} \times 2^{d/2} = 8$.
- In 4d, a SUSY charge has $\frac{1}{2} \times 2^{4/2} = 2$ d.o.f.
- So we need *4 4d charges* to accommodate *1 10d one*.
- $\Longrightarrow$ from 4d perspective we have $N = 4$ SUSY.

We need to get rid of six dimensions, three 4d supersymmetries, and get the right force and particle content... how hard can that be?

All good things...

- First try: the extra 6 dimensions are compactified on something simple: circles or tori.
- But then all SUSY remains $\rightarrow$ no cigar.
- Second try: the extra 6 dimensions are compactified on a Calabi-Yau 3-manifold, CY_3.
- OK. SUSY broken to $N = 1$ in 4d, but more than 100 different CY_3's to choose between, and all horribly complicated.
- $\rightarrow$ still no cigar for phenomenology.

Mucking up String Theory

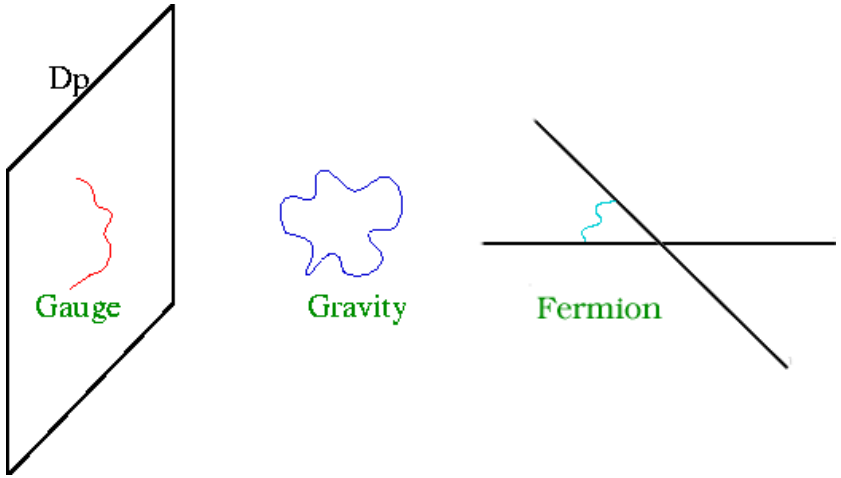
From a the simple string theory viewpoint, our universe thus looks like it's rather complicated.

What is effectively done to do phenomenology is:

- Do the compactification on a simple manifold ($S^n \times T^{6-n}$ or similar)
- But first muck up this simple manifold in a way that makes it *look* like a CY_3.
- This is orbifolding.
- E.g. a toroidal orbifold is the closest we can get to a torus while reducing SUSY from $\mathcal{N} = 4$ to $\mathcal{N} = 1$.

String Theory in Action

- Observation:



Open strings $\leftrightarrow$ Gauge interactions

Closed strings $\leftrightarrow$ Gravity

Strings at intersections $\leftrightarrow$ Fermions

- Open strings that begin and end on a *stack* of N_i branes generate the gauge bosons of $U(N_i)$.
- Fermions arise at *intersections* of such stacks! e.g. $(3, \bar{2})$ quarks at a $U(3) - U(2)$ intersection etc.

Way beyond the Standard Model

So, the Universe might really look like...

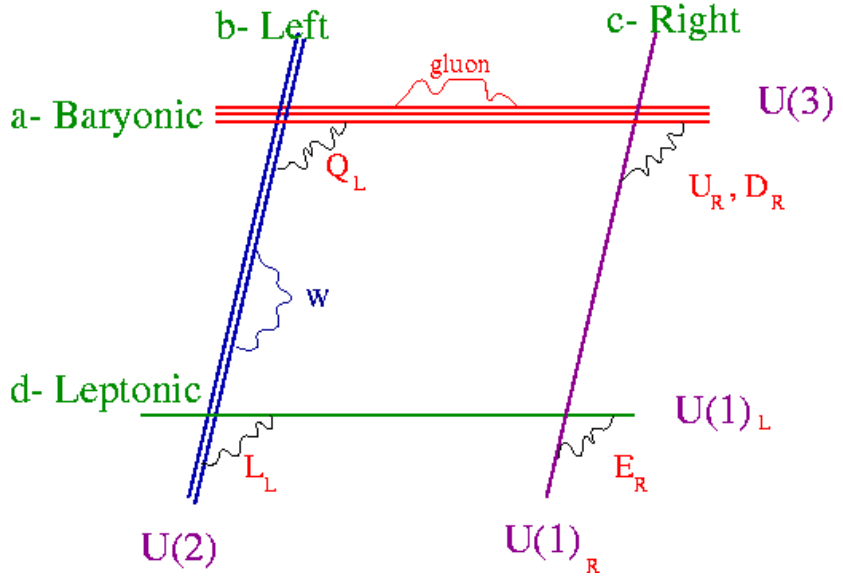
Way beyond the Standard Model

So, the Universe might really look like...

A 3-stack, a 2-stack, and 2 single branes!

$$U(3) \times U(2) \times U(1)^n = SU(3) \times SU(2) \times U(1)^{n+2}$$

stack a	$N_a = 3$	$SU(3) \times U(1)_a$	Baryonic brane
stack b	$N_b = 2$	$SU(2) \times U(1)_b$	Left brane
stack c	$N_c = 1$	$U(1)_c$	Right brane
stack d	$N_d = 1$	$U(1)_d$	Leptonic brane



The End

"An indispensable hypothesis, even though still far from being a guarantee of success, is however the pursuit of a specific aim, whose lighted beacon, even by initial failures, is not betrayed"

[M. Planck]

The End