Supersymmetry and how it helps us understand our world

Séminaire Commun LAL/LPT

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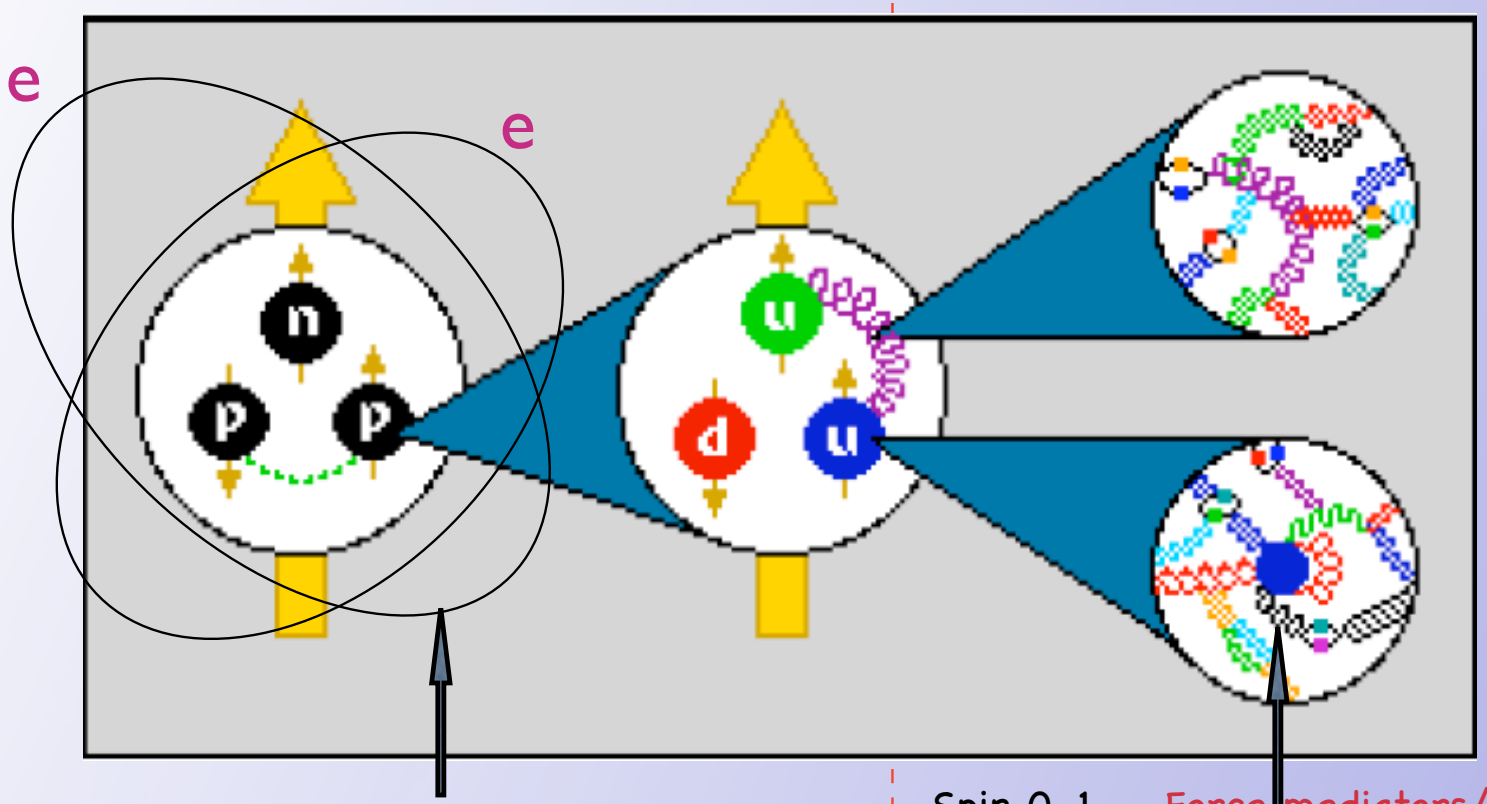
What is supersymmetry (SUSY)?

Fermions

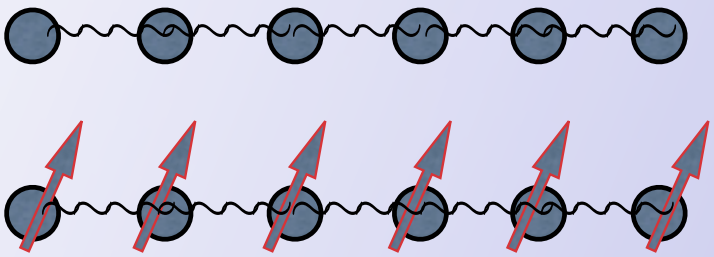
Bosons



Spin 1/2, 3/2, ... Building blocks of matter ...
Absolute individualists:
Fermi's Exclusion Principle

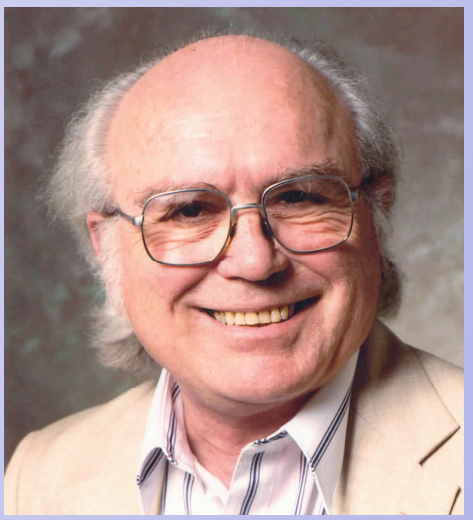
Spin 0, 1, ... Force mediators/helpers in delicate issues... Love to congregate and mimic each other:
Huge ensembles -> Classical

Matter				Force	
Leptons		Quarks		Bosons	
Electron 0.0005	Electron neutrino < 2 x 10^{-9}	Up 0.003	Down 0.006	Photon 0	(Electromagnetic force)
Muon 0.106	Muon neutrino < 2 x 10^{-9}	Charm 1.3	Strange 0.1	W, Z, Higgs 80.4/91.2	(Weak force)
Tau 1.777	Tau neutrino < 2 x 10^{-9}	Top 175	Bottom 4.3	Gluons 0	(Strong force)



Can there be ANY symmetry between bosons and fermions?

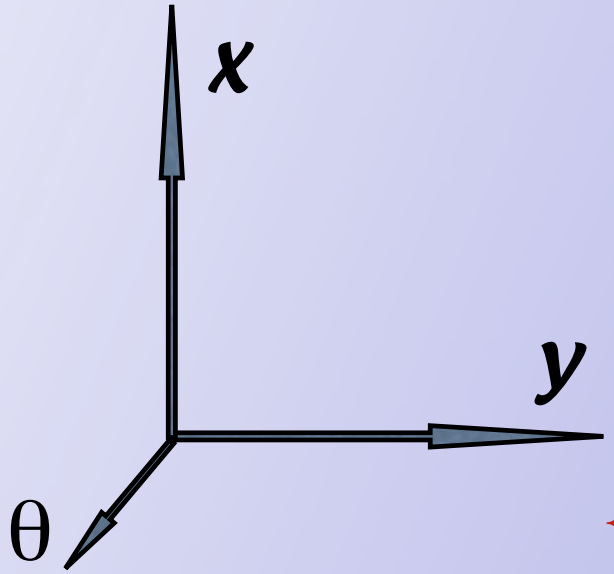
1970's: YES!



Golfand & Likhtman, 71

Wess & Zumino, 73

$$\theta^2 = 0$$



"fermion" direction of the superspace $\longrightarrow$

In 1+3 dimensions

$$\{t, x, y, z\} \longrightarrow \{t, x, y, z;\ \theta^i_\alpha\}$$

E. Witten:

Supersymmetry, if it holds in nature, is part of the quantum structure of space and time. In everyday life, we measure space and time by numbers, "It is three o'clock, the elevation is ten meters," and so on. Numbers are classical concepts, known to humans since long before quantum mechanics we developed in the early 20-th century. The discovery of quantum mechanics changed our understanding of almost everything in physics, but our basic way of thinking about space and time has not yet been affected.

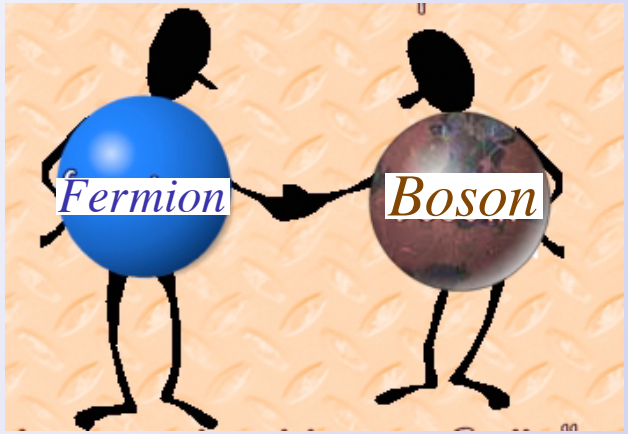
Showing that nature is supersymmetric would change that, by revealing a quantum dimension of space and time, not measurable by ordinary numbers. This quantum dimension would be manifested in the existence of new elementary particles, which would be produced in accelerators and whose behavior would be governed by supersymmetric laws.

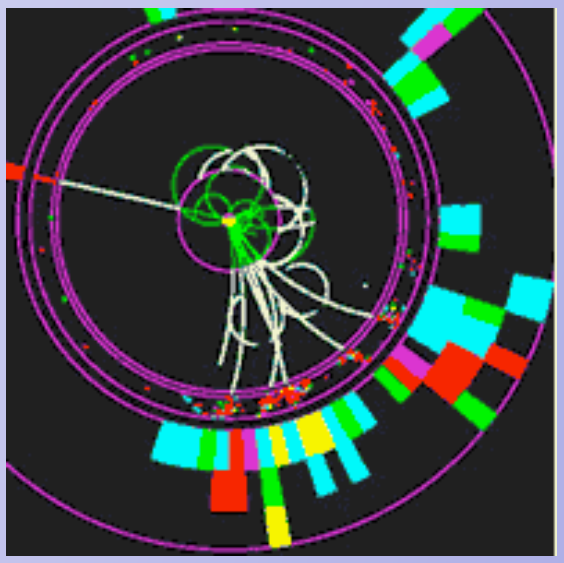
$$E = mc^2$$

Cultural icon of the 20th century

$$\{\bar{Q}_{\dot{\alpha}}, Q_{\beta}\} = 2\sigma^{\mu}_{\dot{\alpha}\beta} P_{\mu}$$ ⟵ Of the 21st ?

Supersymmetry entails that for every particle that has been found there are mirror particles that are identical in all respects except for their spin. Bosons of spin 1 — the photon, W, Z, and gluon — have spin 1/2 partners called the photino, wino, and gluino. Fermions of spin 1/2 — leptons and quarks — have spin 0 partners called the sleptons and squarks.





This is a simulation of the production and decay of supersymmetric particles in a proposed linear collider detector. The straight line is a lepton, the tracks are two overlapping jets of particles, and several invisible particles are inferred by conservation of energy and momentum.

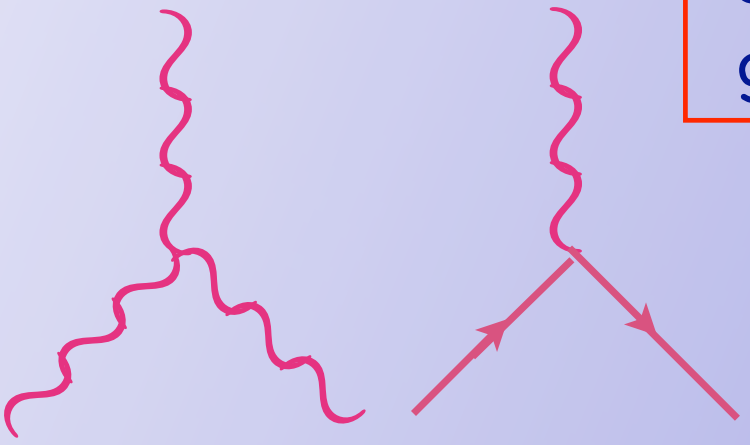
$$\mathcal{L} = -\frac{1}{4g^2} G^a_{\mu\nu} G^{\mu\nu\, a} + \frac{i}{2} \bar{\lambda} \not{D} \lambda$$

gluon

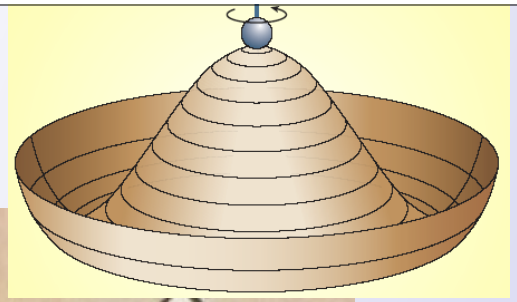
gluino

SUSY Yang-Mills

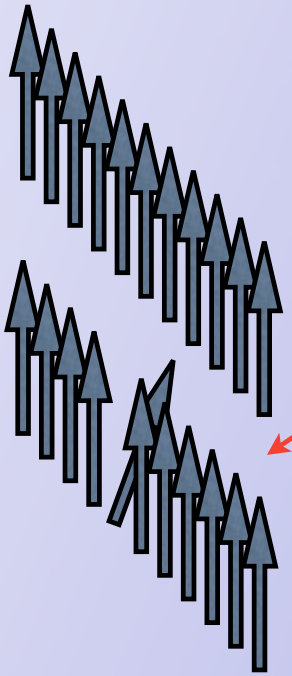
supersymmetric gluodynamics



SUSY must be broken ! → Usually spontaneously



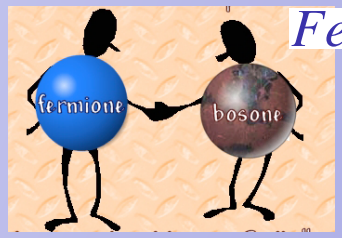
Spontaneous symmetry breaking



magnon

=gapless excitation

Goldstone boson → Goldstino



Fermion

gravitino goldstino gravitino goldstino

= massive gravitino

✶✶✶ Why do we need SUSY at all? ✶✶✶

Supersymmetric model-building

Hierarchy problem: $M_{part} \approx$ 1-100 GeV

while $M_{Planck} \approx 10^{19}$ GeV

$\mathcal{E}_{vac} = 0$

More efficient decoupling of high energies: Comes at a price

▲▲▲▲▲▲▲▲▲

Lots of problems +

SUSY partners to be discovered

A tool for solving otherwise unsolvable problems of strong coupling dynamics

Costs nothing;

Enormous progress since mid-1990's!

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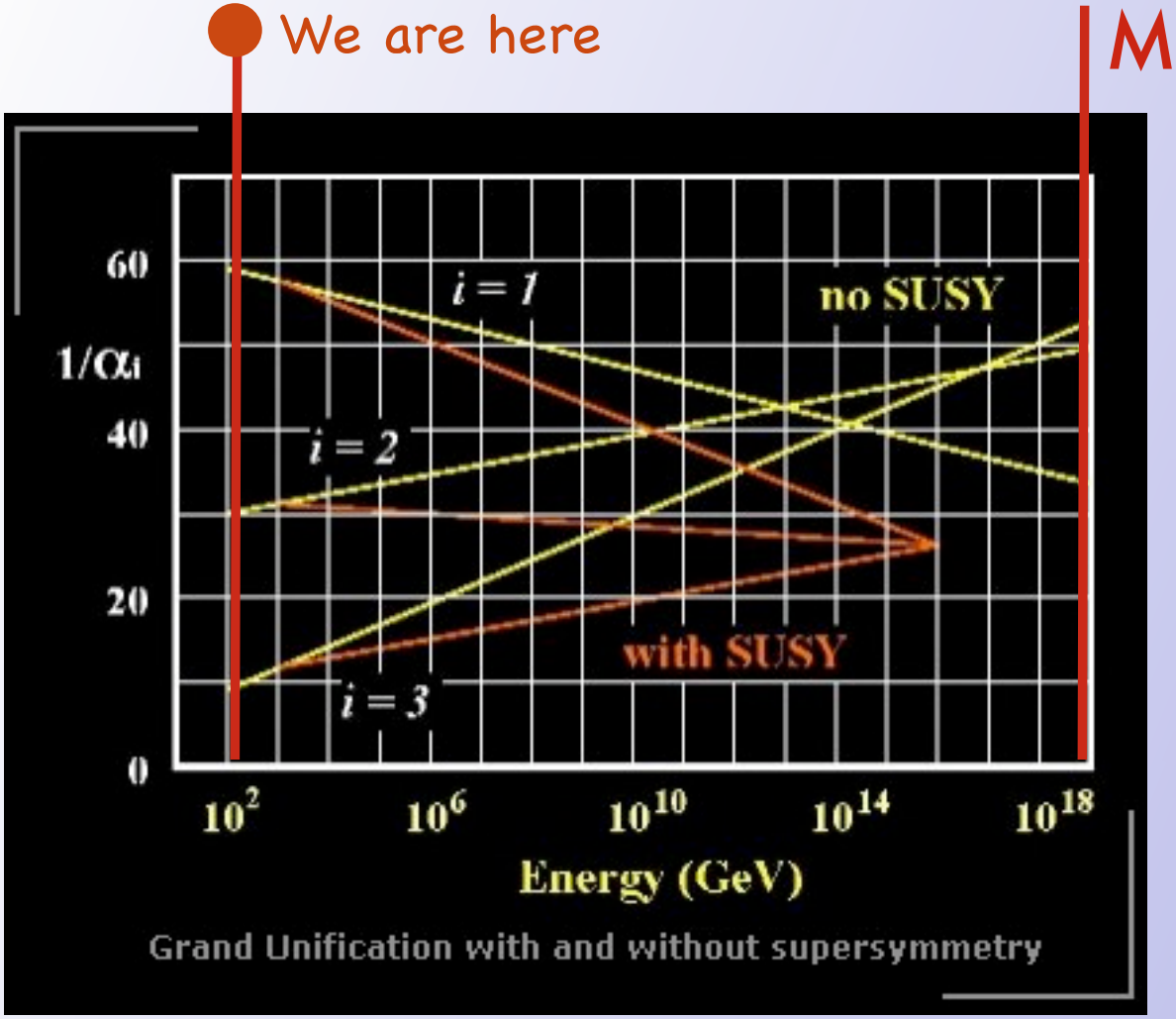
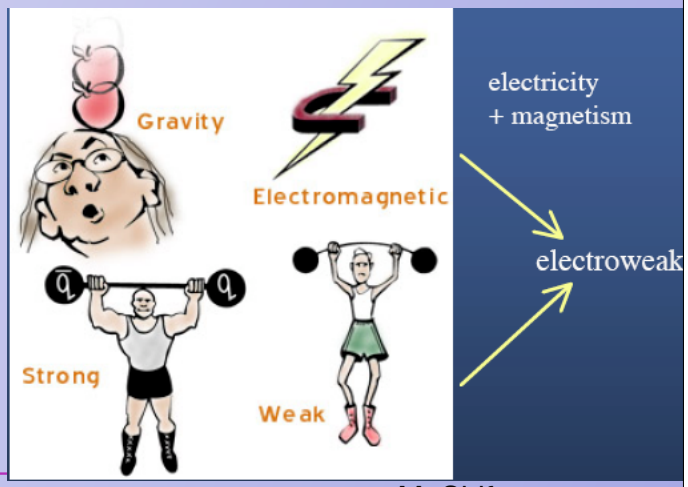
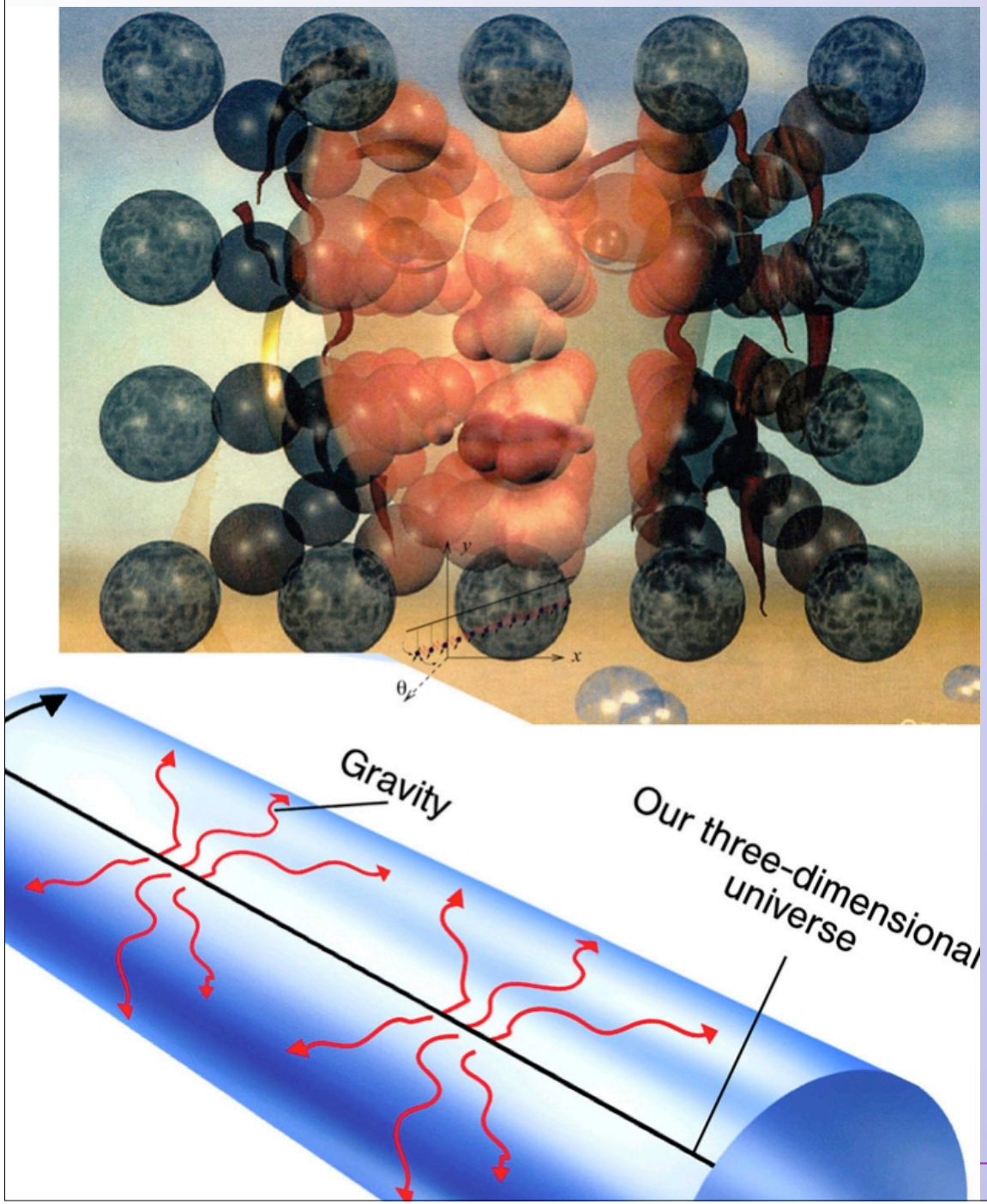
A success of SUSY: gauge coupling unification







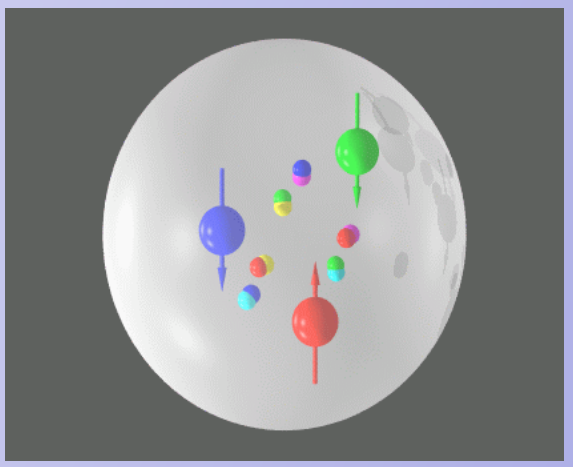
Supersymmetric model-building gave birth to large extra dimensions paradigm !

Quantum Chromodynamics (QCD):

- Quantum Field Theory of **Strong Interactions** of quarks and gluons,
- Interaction mediated by exchange of gluons
- Gluons carry color charges;

Special Properties of QCD:

- "Asymptotic Freedom,"
- **Color Confinement**: Hadrons are always "white,"
- Linear potential between quarks.



Unlike models whose relevance to nature is ? QCD will stay with us

QCD is extremely rich:

- ★ Nuclear Physics
  - ★ Regge behavior
    - ★ QGM: high-T/high μ (neutron stars)
      - ★ Richness of the hadronic world:

- ★ chiral;
- ★ light & heavy quarkonia;
- ★ glueballs & exotics;
- ★ exclusive & inclusive phenomena;
- ★ interplay between strong forces & weak interactions...

That's why I do not expect **FULL** analytic solution to QCD to be found

Give us 1973

Give us 1979

Give us.... 1985

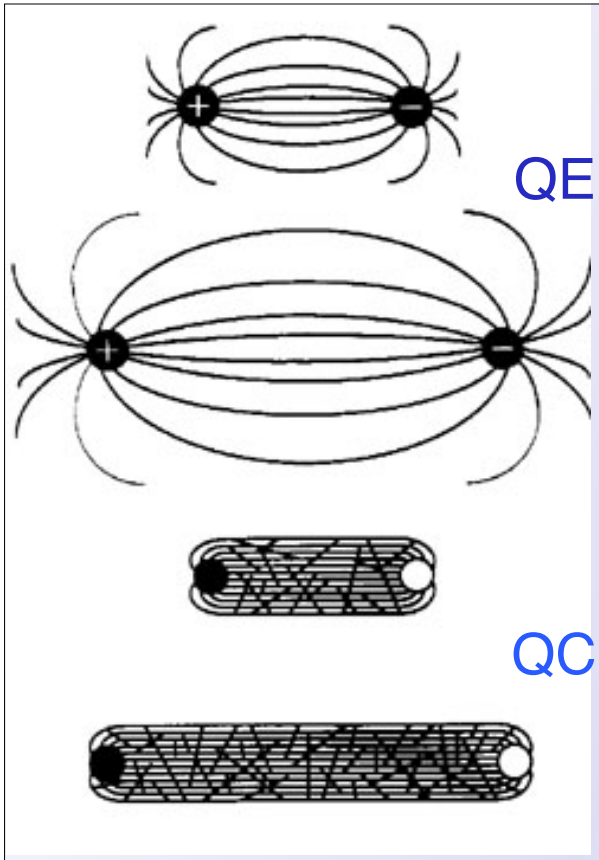
please... 1991

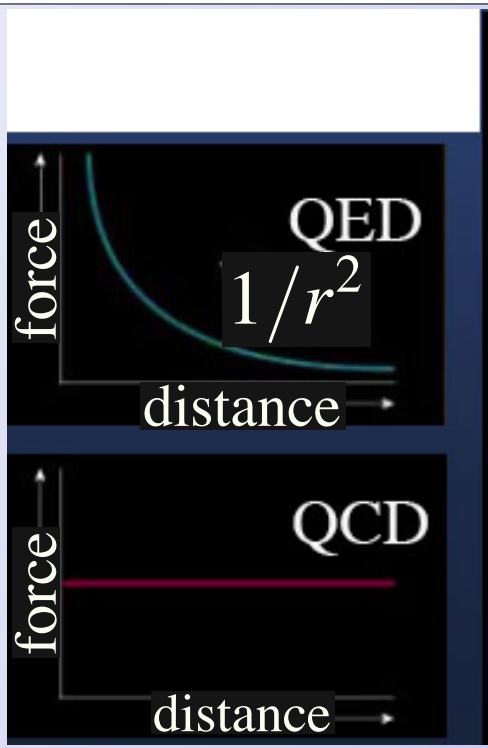
We beg 2001

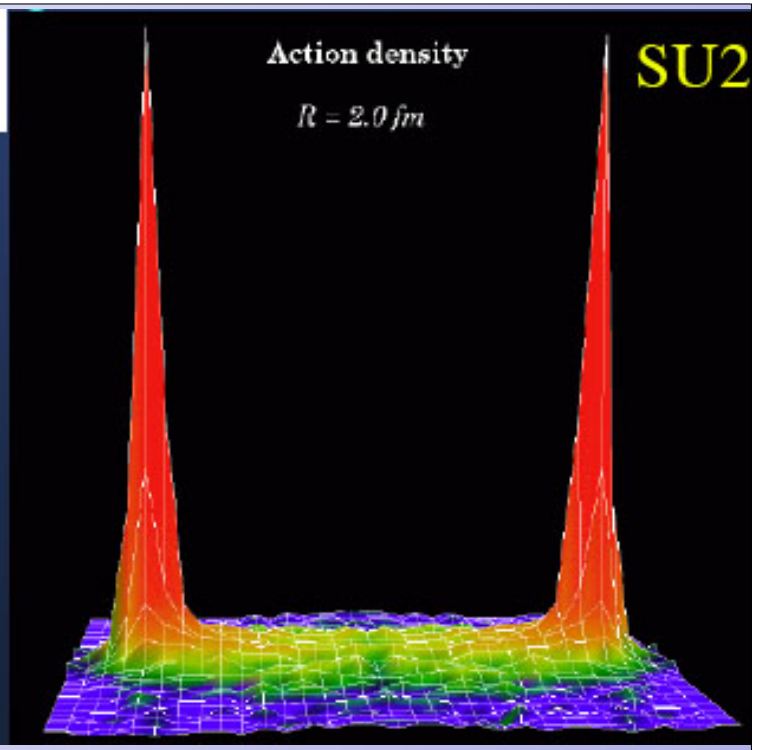
for a WEAK parameter

Take What's available !!!

SUSY







- ✭ Dual Meissner effect for confinement conjectured
- ✷ Triumph of SUSY-based methods for QCD cousins (e.g. $\mathcal{N}=2$);
- ✷ Strings ↔ QCD, e.g. SYM "D-branes";
- ✷ Seiberg's dualities in gauge theories.
- ✷ Seiberg'-Witten demonstration of the dual Meissner effect
- ✷ Planar equivalence between SYM and orbi "1-flavor QCD"

The idea of orientifolding comes from string theory

Parent theory: SUSY gluodynamics

$$\mathcal{L} = -\frac{1}{4g^2} G^a_{\mu\nu} G^a_{\mu\nu} + \frac{i}{g^2} \lambda^{a\alpha} \mathcal{D}_{\alpha\dot{\beta}} \bar{\lambda}^{\alpha\dot{\beta}} \,,$$

Daughter theory: non-SUSY

$$\boldsymbol{\lambda}^i_j \longrightarrow \boldsymbol{\eta}_{[ij]} + \boldsymbol{\xi}^{[ij]} \longrightarrow \boldsymbol{\Psi}^{[ij]}$$

't Hooft limit: $g^2 N \ \ fixed, \ N \to \infty$ <= Planar limit

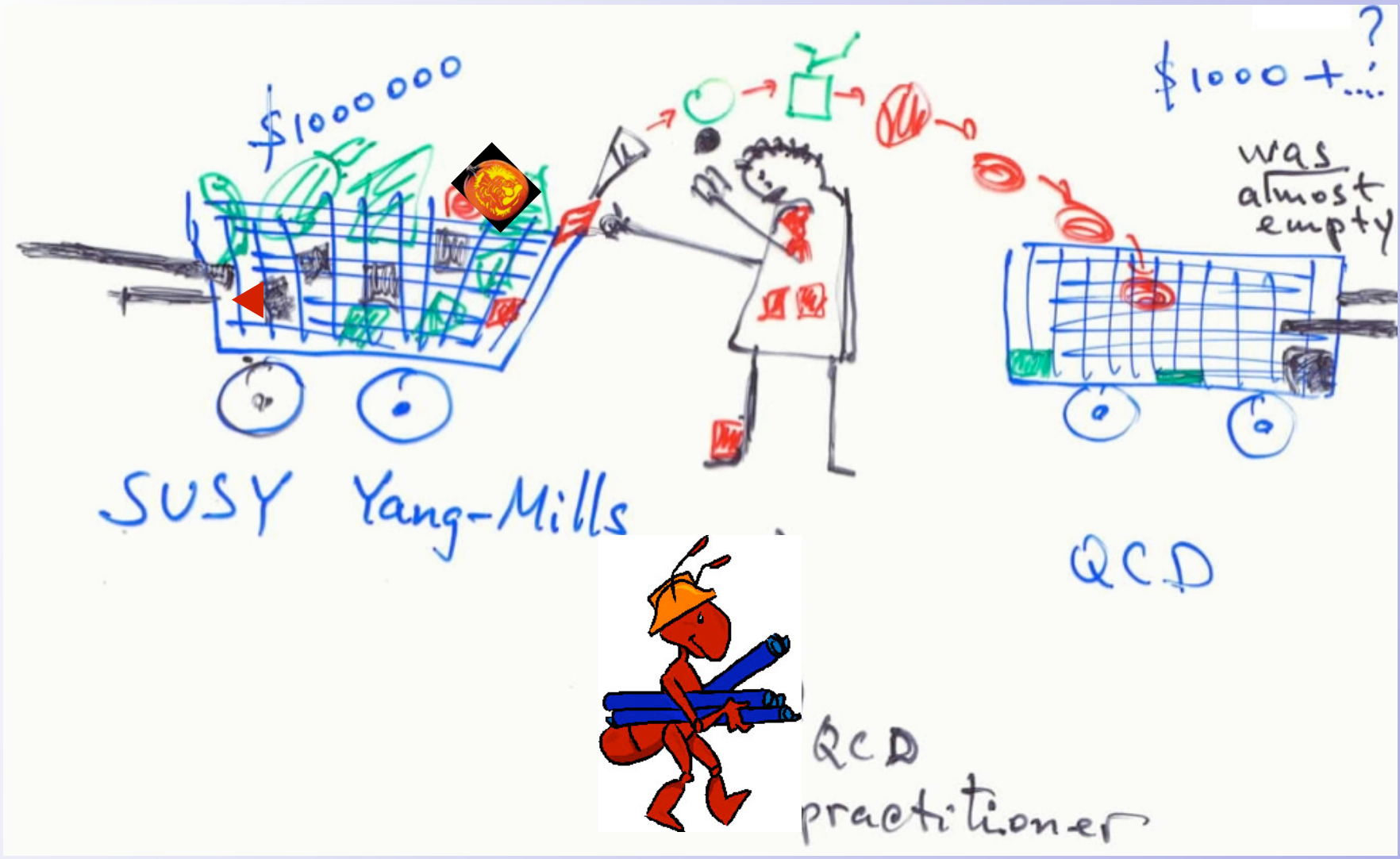
Composite fermion masses: m~O(1) parent; m~O(N) daughter.

Consequences in the common sector:

- ☆ Infinite number of degeneracies, e.g. 0+ & 0-, 1- & 0+, ...
- ☆ Light σ, $m_\sigma^2/m_{\eta'}^2 = 1 + O(1/N)$
- ☆ "BPS" domain walls with known tension
- ☆ Orienti A = one flavor QCD!
- ☆ Quark condensate

$$\langle \bar{\Psi}_L \Psi_R \rangle = -6(N-2)\Lambda^3(1+O(1/N))$$

- ☆ New "orientifold" large *N* expansion (supplements 't Hooft)



Gauge coupling and other parameters get complexified; dependences on these parameters are holomorphic ! ◀

Predictions (indirectly depend on external factors, e.g. LHC):

SUSY-based methods will proliferate

- Closer relatives of QCD
- Aspects of QCD per se
  - Other str-coupl. theories/cond.matter

Gap between strings and "realistic" gauge theories will narrow from both sides

Combination of SUSY and 1/N (or g_{st}) will become a quantitative tool

A "hydrogen atom" of nonperturbative QCD will be found along these lines

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