Quest for Supersymmetry and Unification

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March 25, 2014

The Greatest Equations Ever?

Survery by Physics World (2004)

$$e^{i\pi} + 1 = 0$$

(Euler's Equation)

"The most powerful mathematical statement ever written!"

"What could be more mystical than an imaginary number interacting with real numbers to produce nothing?"

Tied for 1st place:

$$\partial_\mu F^{\mu\nu} = J^\nu$$
$$\partial_\mu {}^*F^{\mu\nu} = 0$$

(Maxwell's Equations)

$$\begin{aligned} \nabla \cdot \mathbf{E} &= 4\pi\rho \\ \nabla \times \mathbf{B} &= 4\pi\mathbf{J} + \frac{\partial \mathbf{E}}{\partial t} \\ \nabla \cdot \mathbf{B} &= 0 \\ \nabla \times \mathbf{E} &= -\frac{\partial \mathbf{B}}{\partial t} \end{aligned}$$

Top Finishers

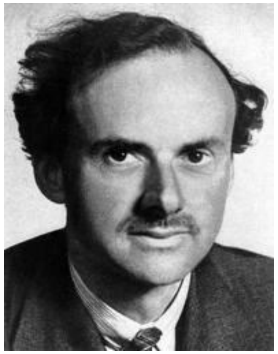
$$
\begin{aligned}
\mathbf{F} &= m\mathbf{a} \\
a^2 &= b^2 + c^2 \\
H\Psi &= E\Psi \\
E &= m\,c^2 \\
S &= k\,\mathrm{lnW} \\
1 + 1 &= 2 \\
\delta S &= 0 \\
p &= h/\lambda \\
G_{\mu\nu} &= 8\,\pi\,G\,T_{\mu\nu} \\
C &= 2\pi r \\
i\gamma \cdot \partial\Psi &= m\,\Psi
\end{aligned}
$$

Quantum Mechanics & Relativity

$$i\hbar\frac{\partial}{\partial t}|\psi,t\rangle = H|\psi,t\rangle$$

Schrodinger equation not Lorentz covariant

Dirac's Equation (1927)



$$H = c\boldsymbol{\alpha}\cdot\mathbf{P} + \boldsymbol{m}\boldsymbol{c}^{\mathbf{2}}\,\boldsymbol{\beta}$$

$\boldsymbol{\alpha}$, $\boldsymbol{\beta}$ anticommutning 4×4 matrices

Results in 4 states with energy $\{E,\, E,\, -E,\, -E\}$

$$E^2 = \mathbf{p}^2c^2 + m^2c^4$$

(Nobel Prize 1933, Schrodinger & Dirac)

Antiparticles

Dirac identified negative energy solutions as antiparticle

Predicted the existence of positron

Positron discovered by C. Anderson in 1933

(Nobel Prize 1936)

Every particle has an antiparticle with same mass, but with opposite charge

Clear mathematical understanding of antiparticles given by Stueckelberg & Feynman

Quantum Electrodynamics

Relativistic quantum theory of electrons, positrons and photons

$$\mathcal{L}_{\mathrm{QED}} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \overline{\psi}_e(iD_\mu\gamma^\mu - m)\psi_e$$

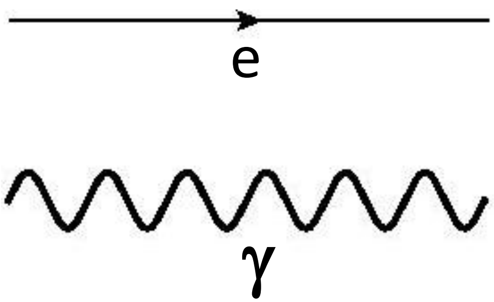
$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu, \qquad D_\mu = \partial_\mu - ieA_\mu$$

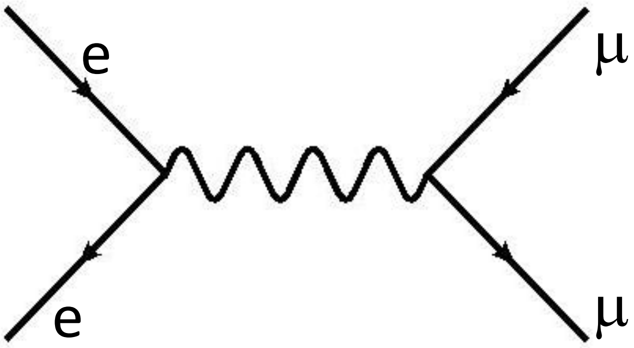
Lagrangian has the symmetry under space–time dependent phase rotations:

$$\psi_e \to e^{i\alpha(x)}\psi_e \qquad\qquad A_\mu \to A_\mu + \frac{1}{e}\partial_\mu\,\alpha$$

This gauge invariance keeps photon massless

Great Success of Quantum Electrodynamics





$e^+e^-\rightarrow\mu^+\mu^-$

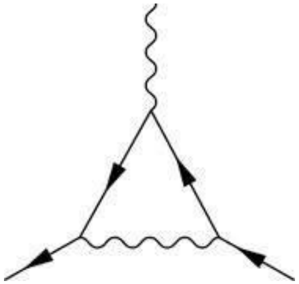
Calculable theory of physical observables

Feynman, Schwinger, Tomonaga, Dyson – Nobel Prize 1965




Example

Anomalous magnetic moment of the electron:



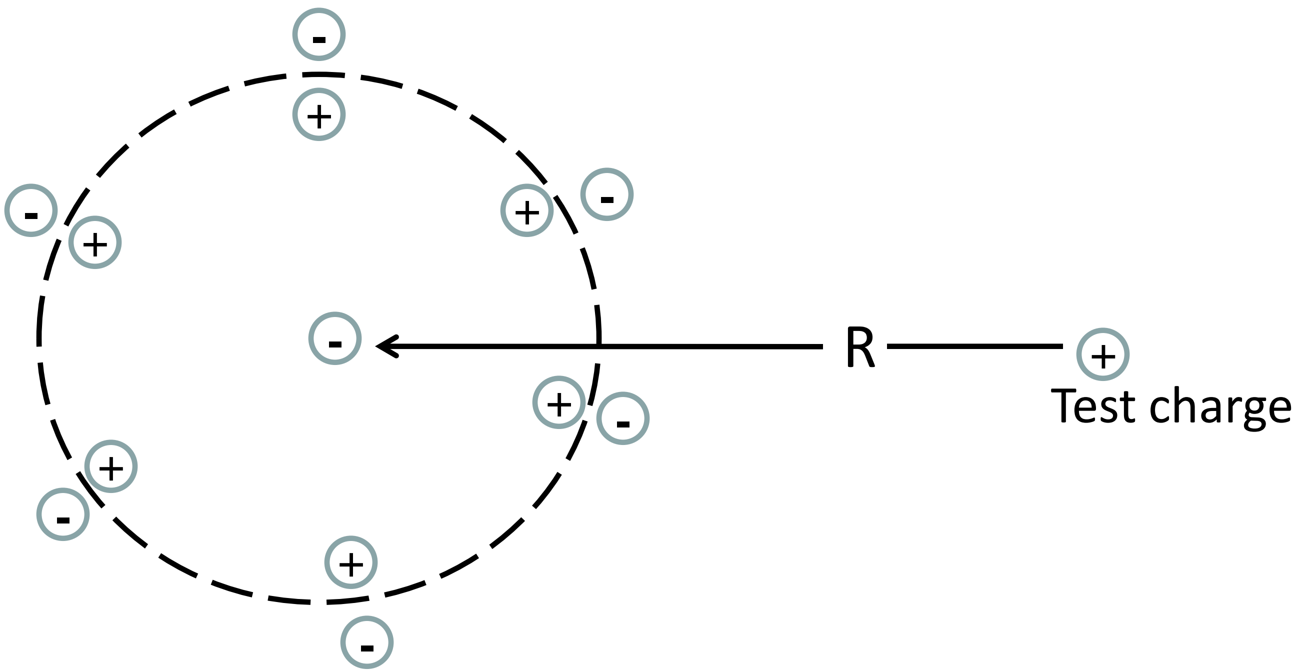
$$a_e^{\text{exp}} = 0.00115965218073 \pm 0.00000000000028$$

$$a_e^{\text{exp}} - a_e^{\text{theory}} = -2.06(7.72) \times 10^{-12}$$

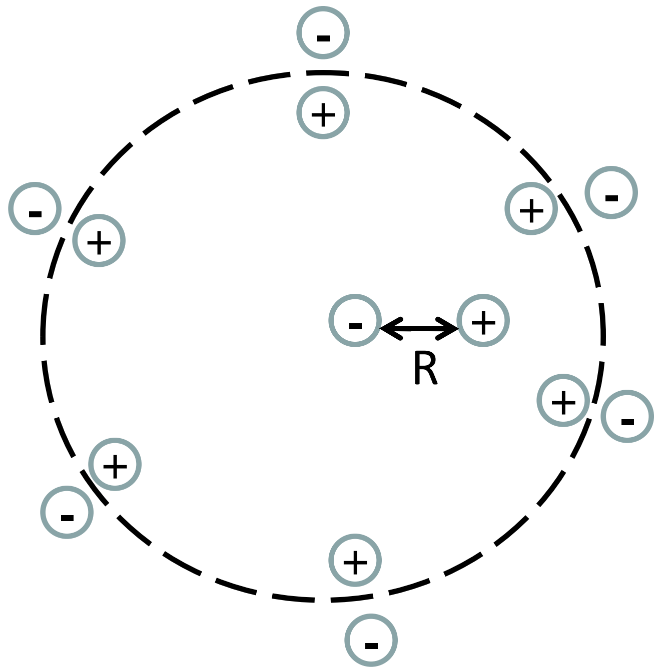
Best measurement of fine structure constant α

$$\alpha^{-1} = 137.035999085(12)(37)(33) \ [0.37\text{ppb}]$$

Charge Screening in QED



With low energy positively charged probe, electron-positron cloud effectively reduces the measured charge



With high energy test charge, screening effect is reduced

Agrees with experiments

$$\alpha^{-1}(\mu = 91 \text{ GeV}) = 127.916 \pm 0.015$$

(LEP experiments at CERN, SLD at SLAC)

Strong Interactions

Unlike electromagnetism, strong force is short range $\sim$ Fermi

Yet, strong force has essentially the same structure as QED

Lagrangian for strong interactions:

$$\mathcal{L}_{\mathrm{QCD}} = \bar{q}(iD_\mu \gamma^\mu - m)q - \frac{1}{4} G^a_{\mu\nu} G^{\mu\nu}_a$$

$$D_\mu = \partial_\mu - igT^a G^a_\mu \ , \quad G^a_{\mu\nu} = \partial_\mu G^a_\nu - \partial_\nu G^a_\mu - g f_{abc} G^b_\mu G^c_\nu$$

G^a_μ are the gluon – analogs of photon in strong interactions

$a = 1 - 8$ is the internal symmetry – called color

3 quarks and 8 gluons form $SU(3)$ symmetry

QCD Lagrangian invariant under $SU(3)$ gauge transformations:

$$q(x) \rightarrow e^{i\alpha_a(x)T^a} q(x), \qquad G^a_\mu \rightarrow G^a_\mu - \frac{1}{g}\partial_\mu \alpha_a - f_{abc}\alpha_b G^c_\mu$$

Generators of $SU(3)$ transformations:

$$[T_a, T_b] = i f_{abc} T^c$$

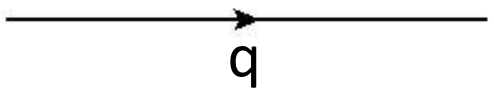
T_a: Gell–Mann matrices, generalize Pauli matrices to 3D

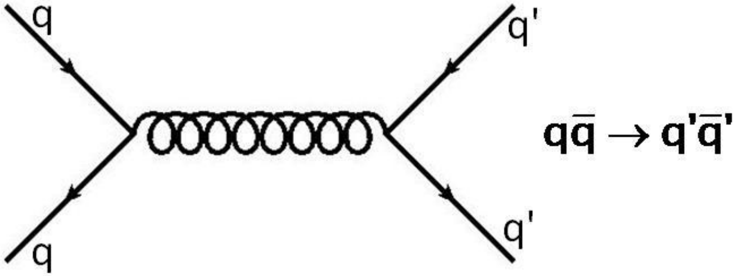
Matrix structure of QCD interactions $\Rightarrow$

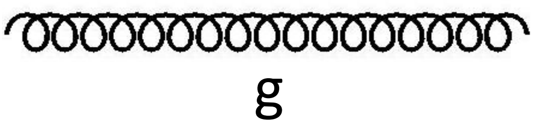
Gluons carry color – unlike photons, which are charge neutral

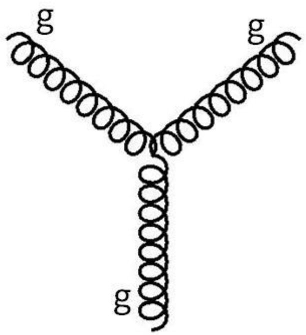
This feature makes QCD force short–range and *asymptocially free*

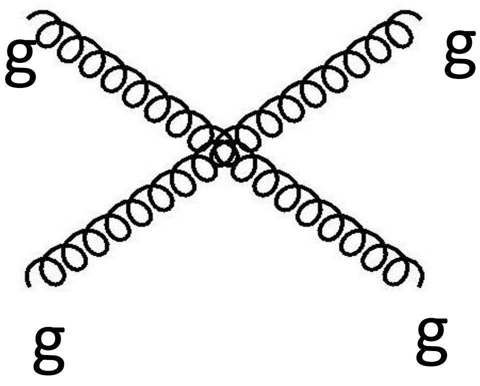
QCD Interactions



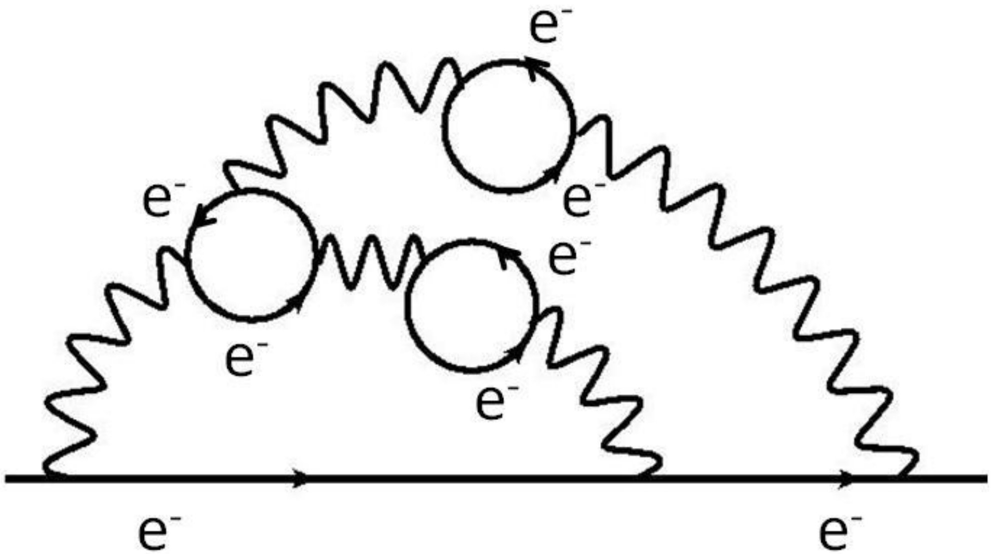






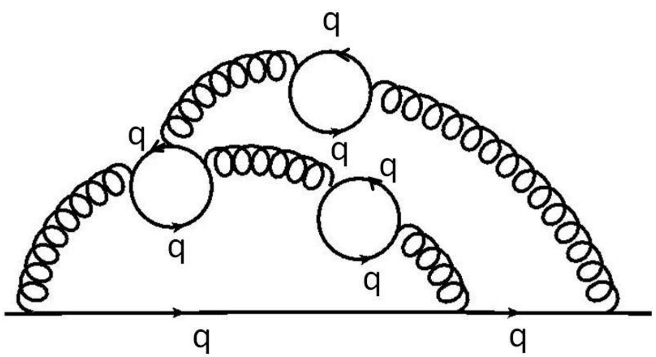


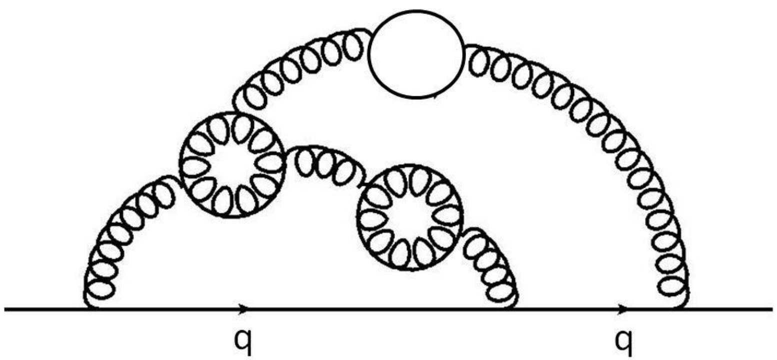
Effective charge of electron in QED



Causes charge screening

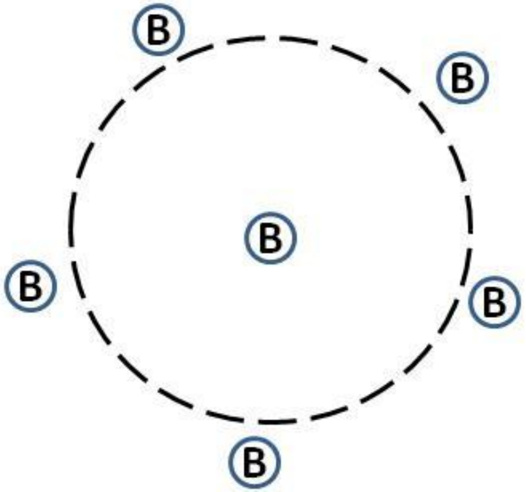
Effective color charge of quark in QCD





Causes color charge anti-screening

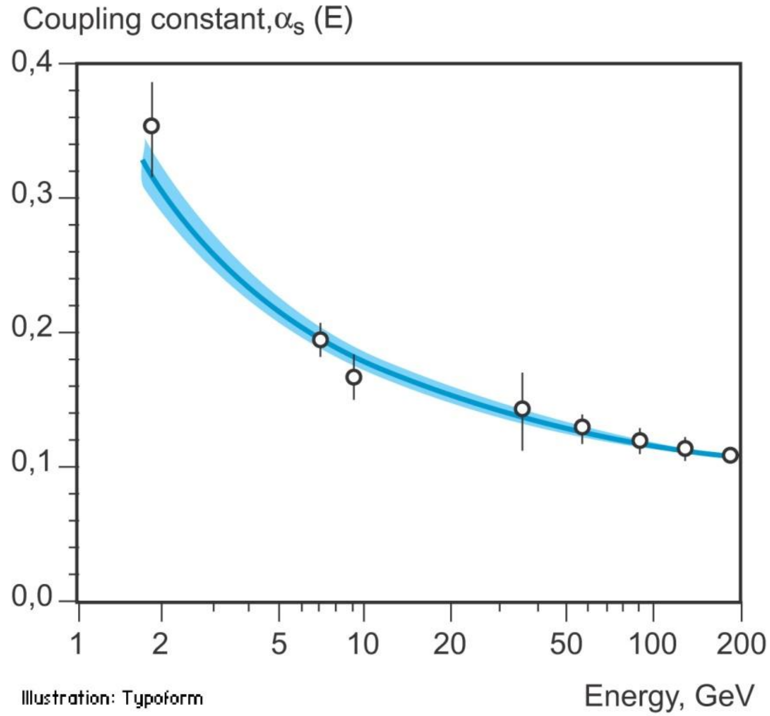
Color charge anti–screening



Quarks cannnot be separated from a hadron

Confinemet of quarks & short range of strong force

Effective color charge in QCD decreases with energy



Asymptotic freedom

Gross, Wilczek, Politzer
Nobel Prize, 2004

Weak Force

Similar structure as QCD, but based on $SU(2)$ internal symmetry

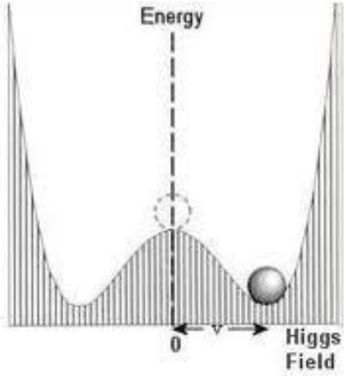
$$\mathcal{L}_{\text{weak}} = \overline{\psi}(iD_\mu\gamma^\mu - m)\psi - \frac{1}{4}W^a_{\mu\nu}W^{\mu\nu}_a$$

$$\psi(x) \rightarrow e^{i\alpha_a(x)\tau^a}\psi(x), \quad W^a_\mu \rightarrow W^a_\mu - \frac{1}{g_w}\partial_\mu\alpha_a - \epsilon_{abc}\alpha_b W^c_\mu, \quad [\tau_a, \tau_b] = i\epsilon_{abc}\tau^c$$

Weak force is short–range due to spontaneous symmetry breaking

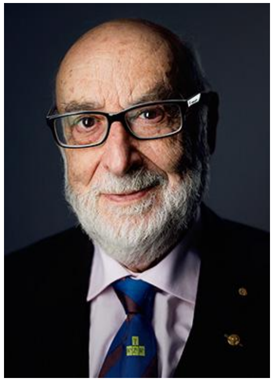
Force carriers, $W^\pm$, Z^0 become massive via Higgs mechanism

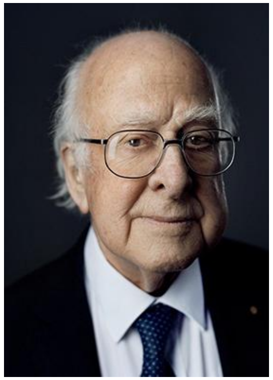
$$V(\phi) = -\mu^2|\phi|^2 + \lambda|\phi|^4$$



At the minimum of potential $\langle\phi^0\rangle \neq 0$

Predicts a spin zero particle – the Higgs boson





Englert, Higgs
Nobel Prize, 2013

Different phases of the same theory?

Electromagnetism, Strong and Weak forces described by very similar mathematics

Electromagnetism: Coulomb phase: $\boldsymbol{U(1)}$

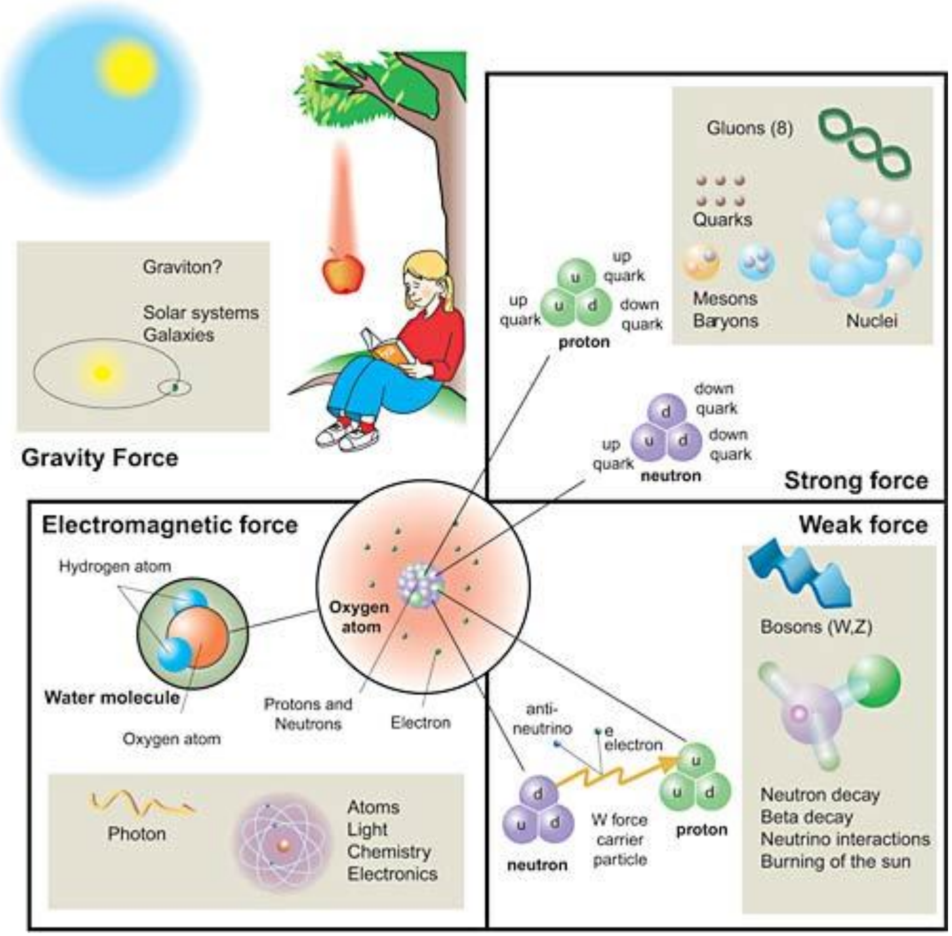
Strong Force: Confining phase: $\boldsymbol{SU(3)}$

Weak Force: Higgs phase: $\boldsymbol{SU(2)}$

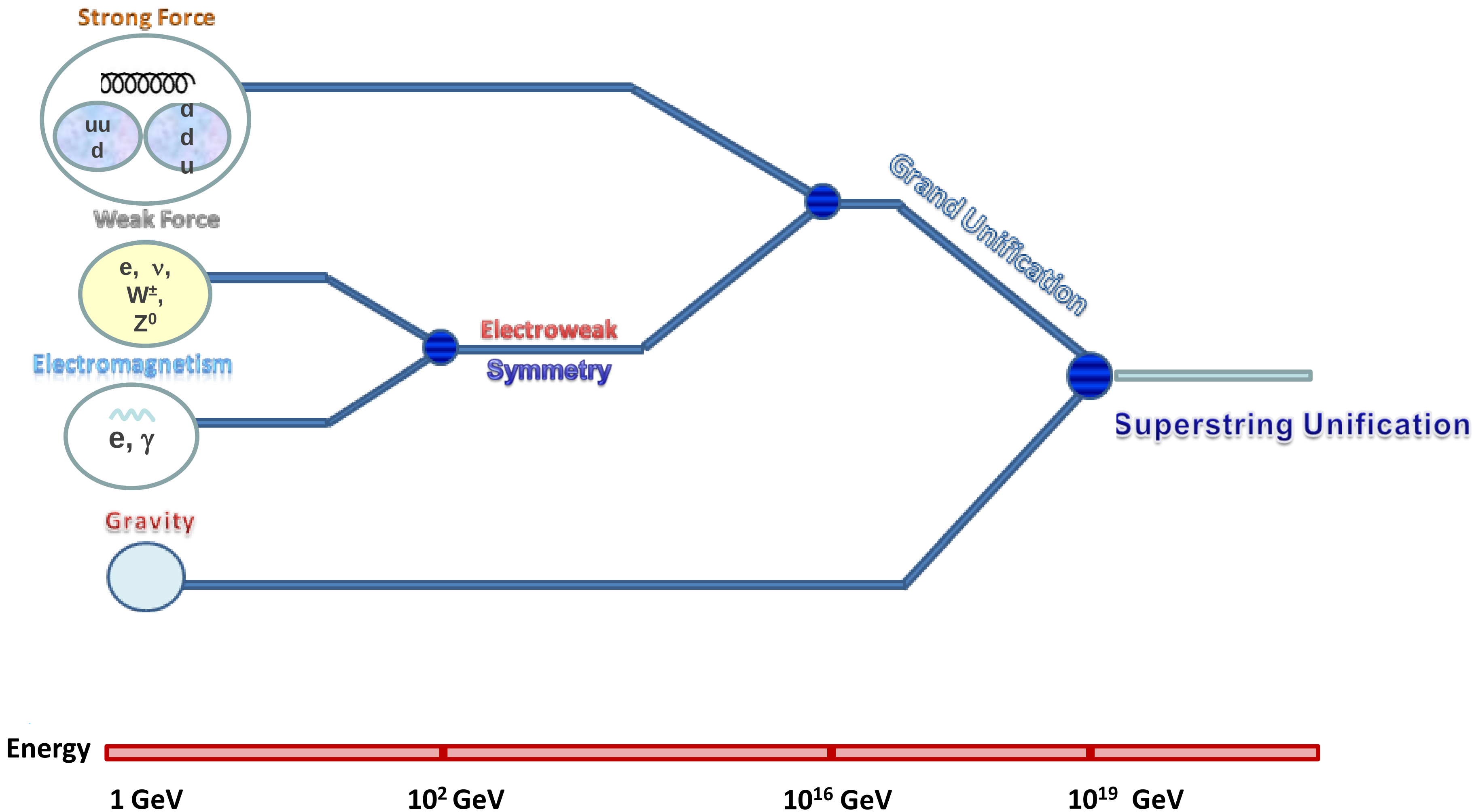
Possible to embed all three symmetry groups into a single symmetry

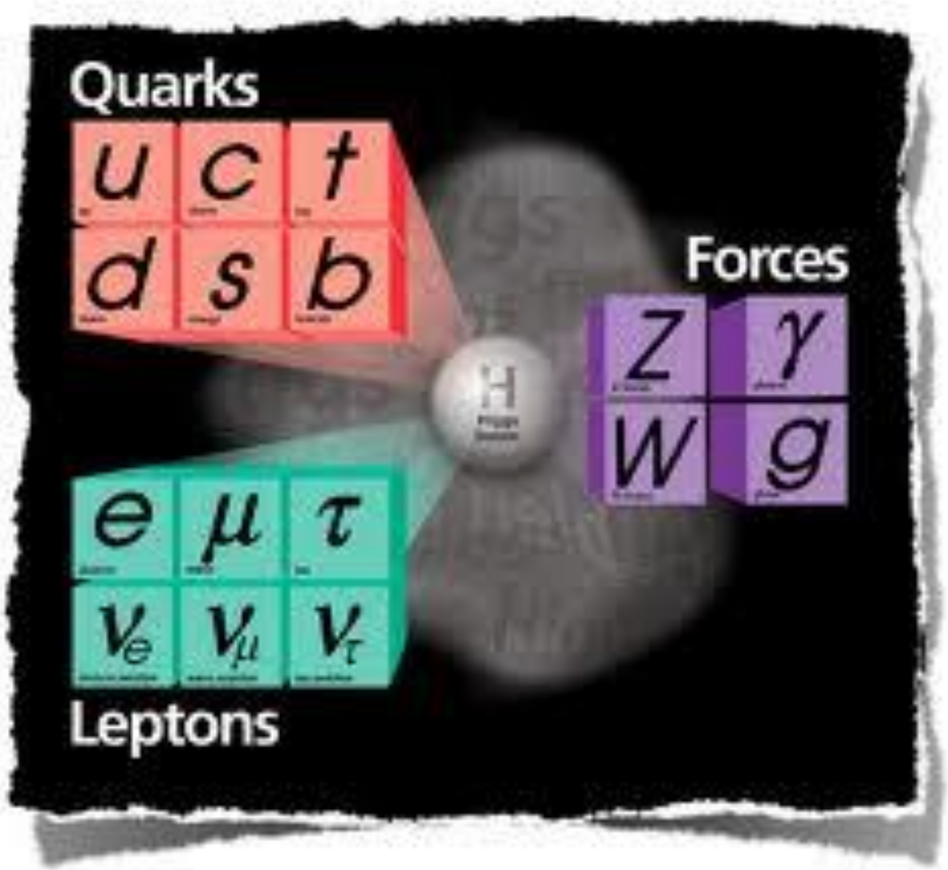
Grand Unified Symmetry: $\boldsymbol{SU(5)}$ and $\boldsymbol{SO(10)}$, ..

Unifcation of Forces?

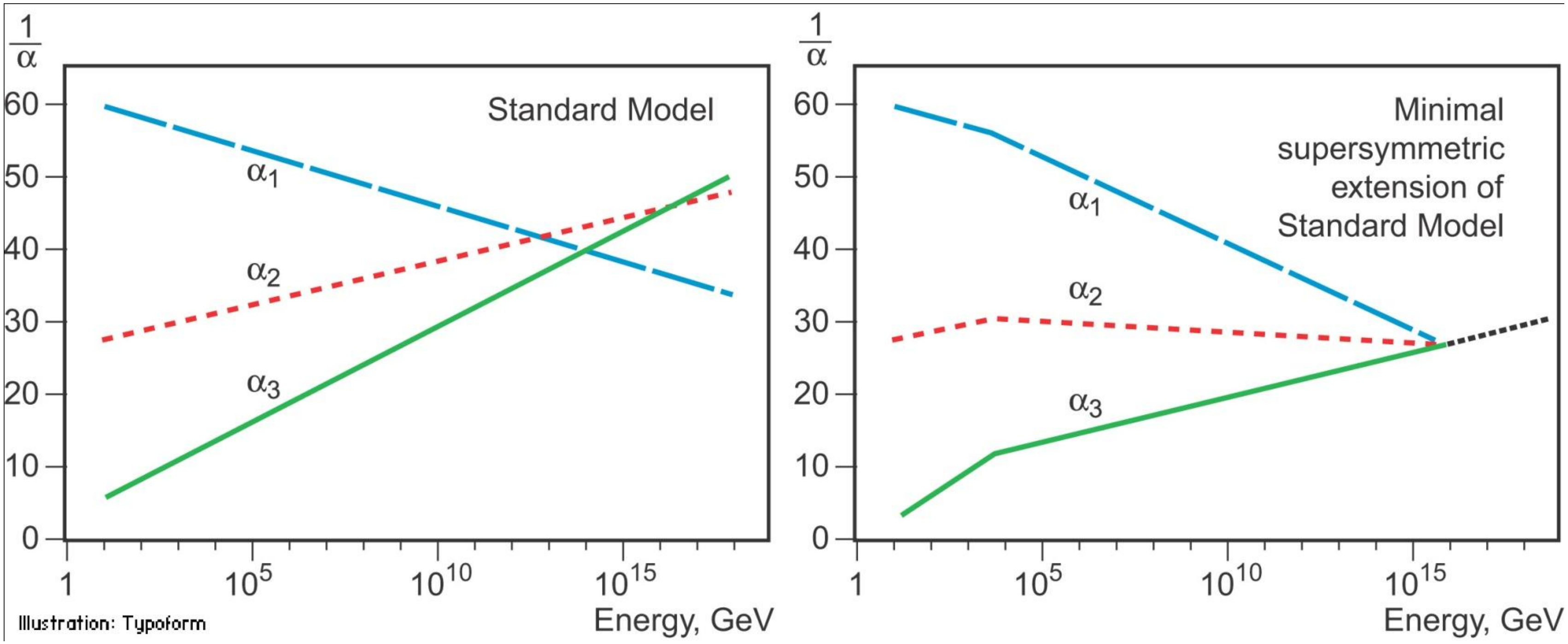


Strong, weak and elctromagnetic forces may be unified!

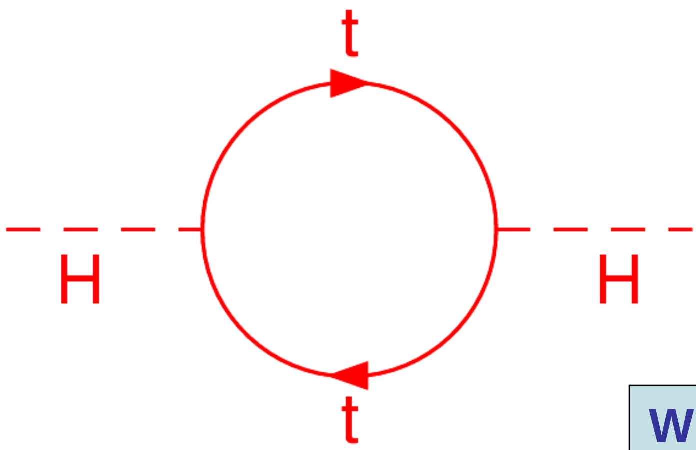

Strong Force
uu
d
d
d
u
Weak Force
e, ν,
W±,
Z0
Electromagnetism
e, γ
Gravity
Electroweak
Symmetry
Grand Unification
Superstring Unification
Energy
1 GeV
10^2 GeV
10^16 GeV
10^19 GeV


Quarks
u c t
d s b
Forces
Z γ
W g
H
e μ τ
ν_e ν_μ ν_τ
Leptons

Evolution of couplings with energy

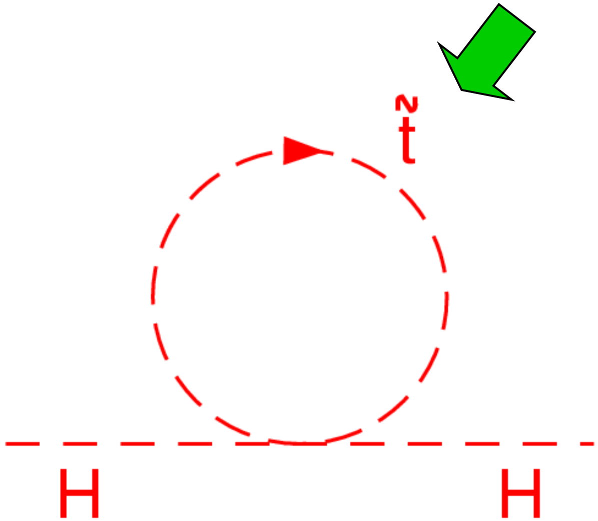


Stability of Higgs mass



$$\Delta m_H^2 = -\frac{\lambda_t^2}{8\pi^2}\Lambda^2$$

With SUSY, Quadratic Divergence Cancels



$$\Delta m_H^2 = +\frac{\lambda_t^2}{8\pi^2}\Lambda^2$$

$$m_{\tilde{t}}^2 - m_t^2 \lesssim (\text{TeV})^2$$

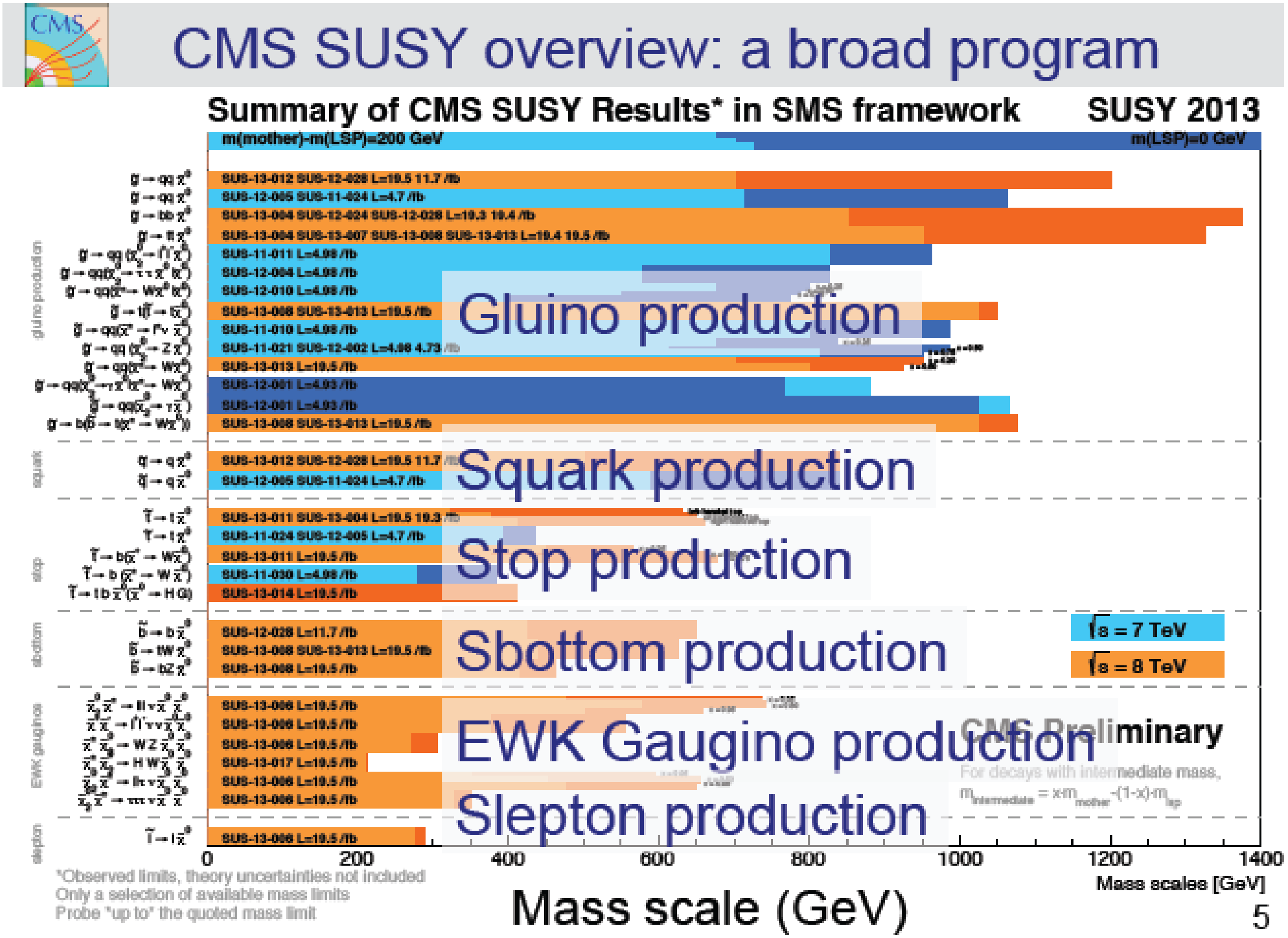
Supersymmetric standard model

SM Particles		SUSY Partners	
	Q	$\tilde{Q}$	
	u^c	$\tilde{u}^c$	
Spin = 1/2	d^c	$\tilde{d}^c$	Spin = 0
	L	$\tilde{L}$	
	e^c	$\tilde{e}^c$	
Spin = 0	H_u	$\tilde{H}_u$	Spin = 1/2
	H_d	$\tilde{H}_d$	
	g	$\tilde{g}$	
Spin = 1	W	$\tilde{W}$	Spin = 1/2
	B	$\tilde{B}$	

$$R = (-1)^{3B+L+2S}$$

SUSY Dark Matter

Supersymmetry Under Siege?



Making SUSY Natural

A symmetry makes first two families of SUSY particles degenerate. Eg: S_3 Permutation Symmetry

Third family squarks have different masses

Impose unification constraints

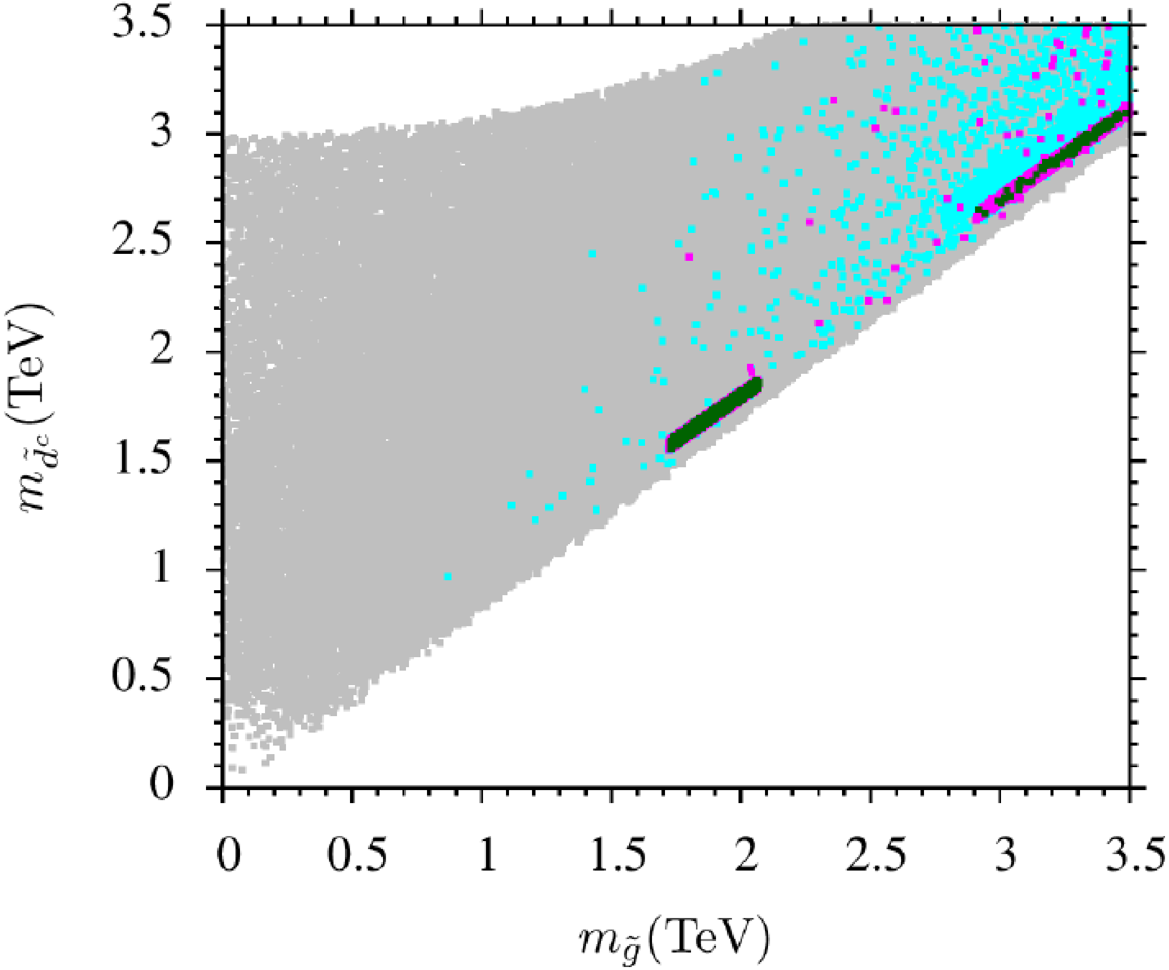
Phenomenology consistent with LHC data

Testable at LHC at the next run

Ad hoc assumption of universality is given up

Gogoladze, Raza, Shafi, KSB (2014)

SUSY Spectrum



Gluino mass versus squark mass

Color Codes

Grey: REWSB & Neutralino LSP

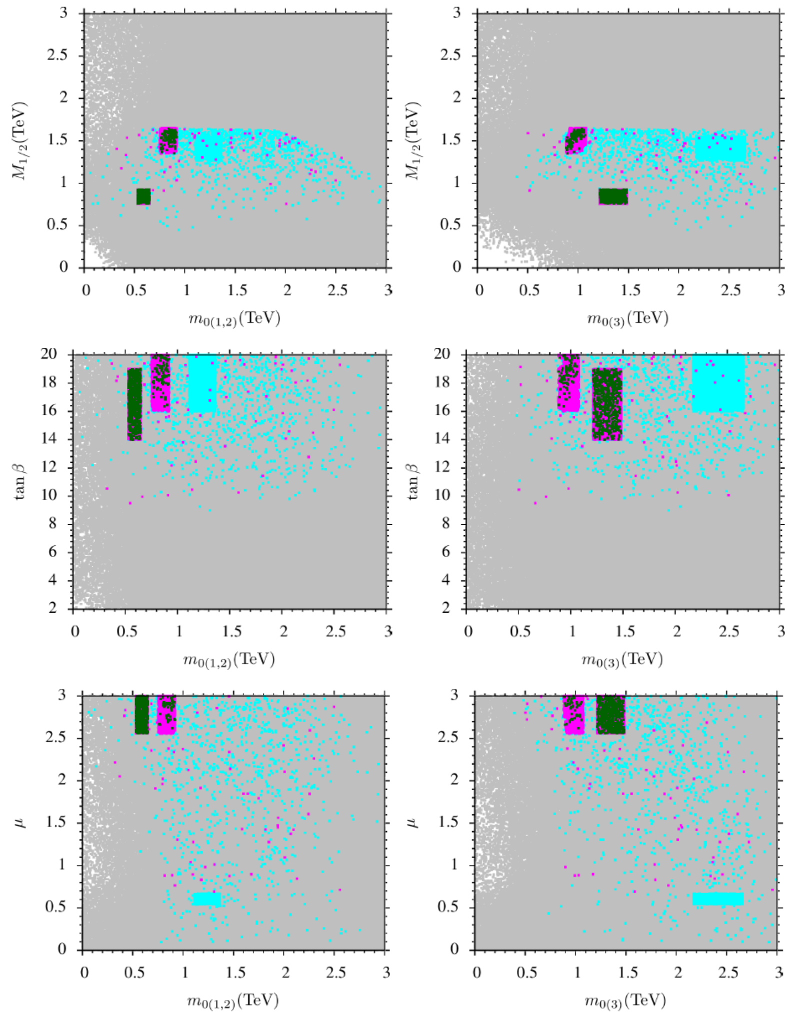
Aqua: Mass bounds for squarks and gluino: (1-3.5) TeV,
Stop > 0.7 TeV, Higgs mass $=$ 124-126 GeV, B physics OK

Magenta: Also obeys $\Omega h^2 < 1$ for dark matter abundance

Green: $\Omega h^2 = 0.1088 - 0.1277$ (WMAP 3 sigma range)

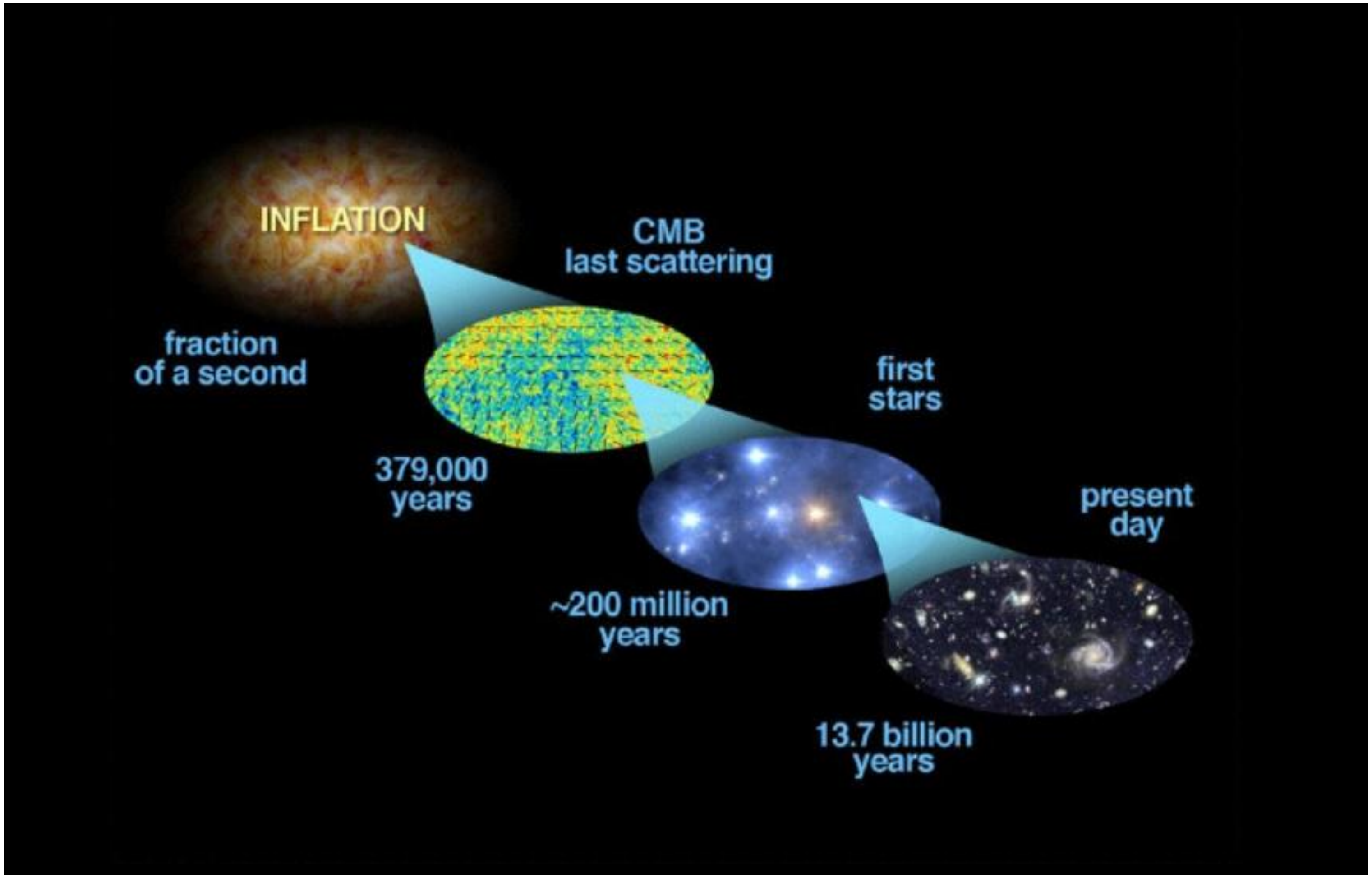
Gogoladze, Raza, Shafi, KSB (2014)

More Detailed SUSY Spectrum

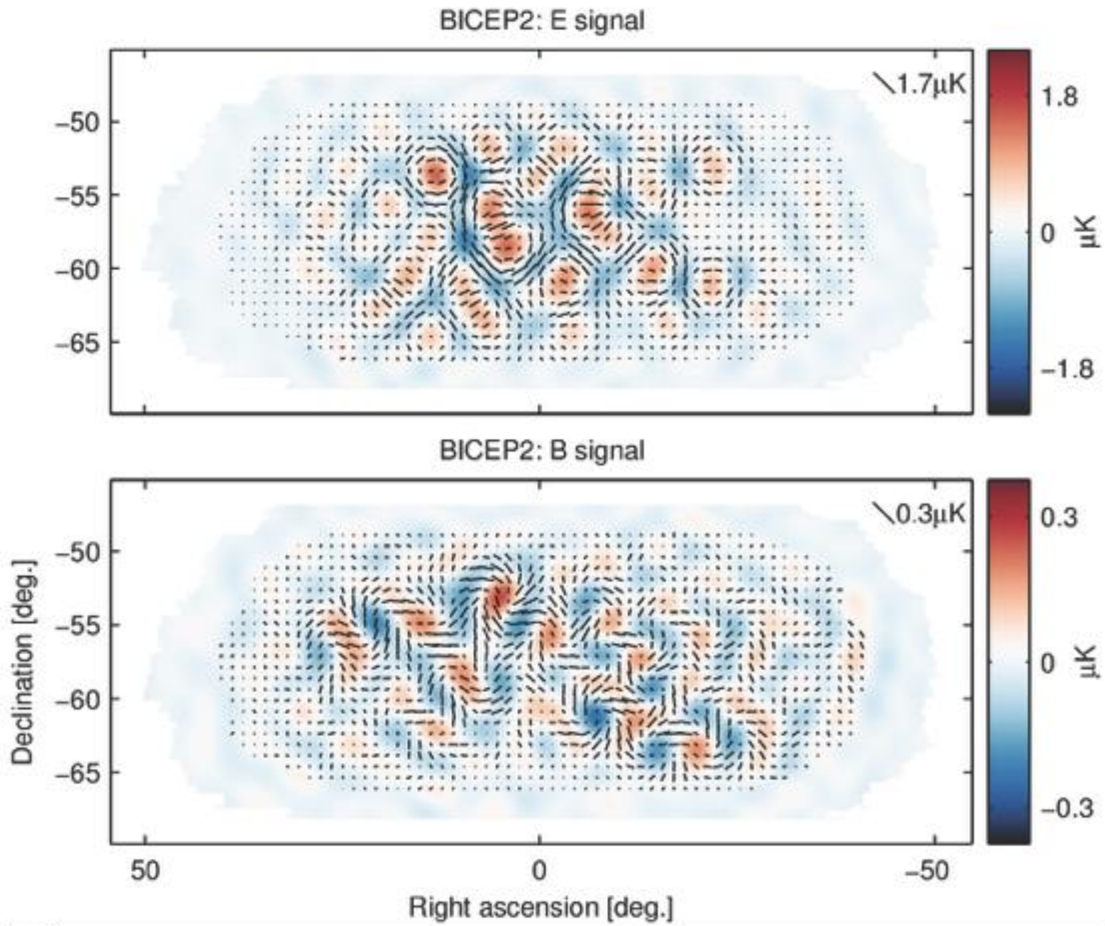


Slices of parameter space

Recent BICEP2 Data and SUSY Unification

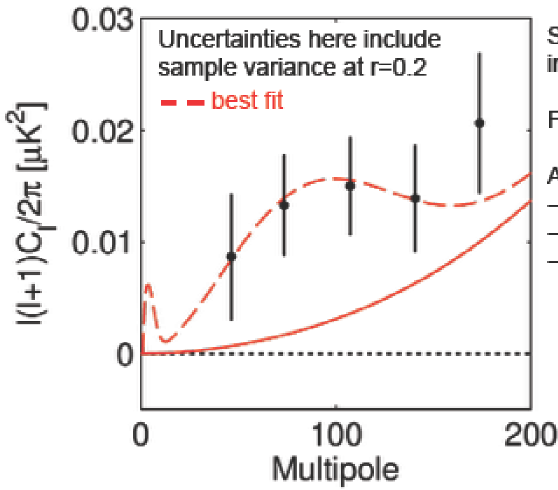


BICEP2 E- and B-mode Maps



The Bicep2 Collaboration

Constraint on Tensor-to-scalar Ratio r



Substantial excess power in the region where the inflationary gravitational wave signal is expected to peak

Find the most likely value of the tensor-to-scalar ratio r

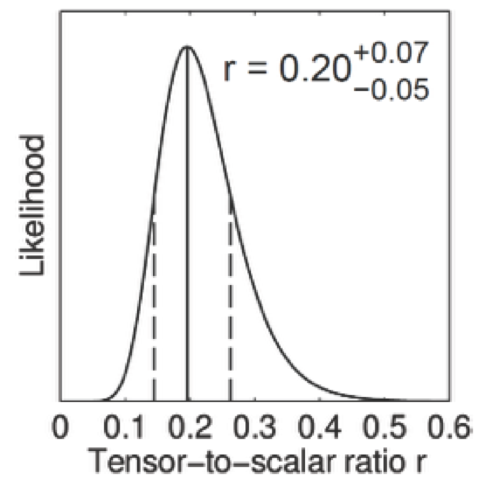
Apply "direct likelihood" method, uses:
→ lensed-ΛCDM + noise simulations
→ weighted version of the 5 bandpowers
→ B-mode sims scaled to various levels of r (n_T=(

Within this simplistic model we find:

r = 0.2 with uncertainties dominated by sample variance

PTE of fit to data: 0.9
→ model is perfectly acceptable fit to the data

r = 0 ruled out at 7.0σ



The Bicep2 Collaboration

Vacuum energy during inflation obeys $V^{1/4} = 2 \times 10^{16}$ GeV

Tantalizingly close to the SUSY unification scale

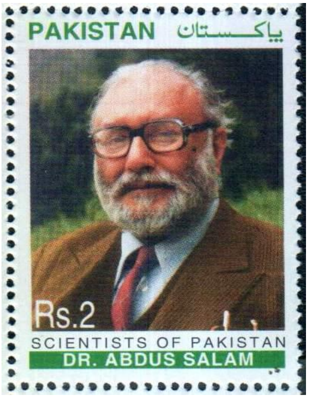
Higgs that breaks GUT symmetry may be the inflaton!

More Hints in favor of GUTs

- Electric charge quantization
  - $Q_p = -Q_e$ to better than 1 part in 10^{21}
- Miraculous cancellation of anomalies
- Quantum numbers of quarks and leptons
- Existence of ν_R and thus neutrino mass
- Unification of gauge couplings with low energy SUSY
- $b - \tau$ unification
- Baryon asymmetry of the universe

Unifying Forces and Matter

First successful attempt by Pati and Salam (1973)



Based on $SU(4)_c \times SU(2)_L \times SU(2)_R$ gauge symmetry

$$\psi_L = \begin{pmatrix} u_1 & u_2 & u_3 & e \\ d_1 & d_2 & d_3 & \nu \end{pmatrix}_L , \quad \psi_R = \begin{pmatrix} u_1 & u_2 & u_3 & e \\ d_1 & d_2 & d_3 & \nu \end{pmatrix}_R$$

Lepton number identified as fourth color

Unification in SU(5)

Almost complete unification of forces and matter discovered in SU(5) by Georgi and Glashow (1974)


$$\mathbf{10}: \begin{pmatrix} 0 & u_3^c & -u_2^c & u_1 & d_1 \\ -u_3^c & 0 & u_1^c & u_2 & d_2 \\ u_2^c & -u_1^c & 0 & u_3 & d_3 \\ -u_1 & -u_2 & -u_3 & 0 & e^c \\ -d_1 & -d_2 & -d_3 & -e^c & 0 \end{pmatrix} \qquad \bar{\mathbf{5}}: (d_1^c, d_2^c, d_3^c, e, -\nu_e)$$

Particles unify with antiparticles

Quarks and leptons are unified

Structure of Matter Multiplets

SO(10)

$u_r: \{-++\ +-\}$	$d_r: \{-++\ -+\}$	$u_r^c: \{+--\ ++\}$	$d_r^c: \{+--\ --\}$
$u_b: \{+-+\ +-\}$	$d_b: \{+-+\ -+\}$	$u_b^c: \{-+-\ ++\}$	$d_b^c: \{-+-\ --\}$
$u_g: \{++-\ +-\}$	$d_g: \{++-\ -+\}$	$u_g^c: \{--+\ ++\}$	$d_g^c: \{--+\ --\}$
$\nu: \{---\ +-\}$	$e: \{---\ -+\}$	$\nu^c: \{+++\ ++\}$	$e^c: \{+++\ --\}$

Frist 3 spins refer to color, last 2 are weak spins

$$Y = \tfrac{1}{3}\Sigma(C) - \tfrac{1}{2}\Sigma(W)$$

Standard Model

$$\boldsymbol{Q} = \begin{pmatrix} u_1 & u_2 & u_3 \\ d_1 & d_2 & d_3 \end{pmatrix} \sim (3, 2, \frac{1}{6})$$

$$\boldsymbol{u^c} = (u_1^c \quad u_2^c \quad u_3^c) \sim (\bar{3}, 1, -\frac{2}{3})$$

$$\boldsymbol{d^c} = (d_1^c \quad d_2^c \quad d_3^c) \sim (\bar{3}, 1, \frac{1}{3})$$

$$\boldsymbol{L} = \begin{pmatrix} \nu \\ e^- \end{pmatrix} \sim (1, 2, -\frac{1}{2})$$

$$\boldsymbol{e^c} \sim (1, 1, +1)$$

$$\boldsymbol{\nu^c} \sim (1, 1, 0)$$

Stability of Matter

Electron is believed to be absolutely stable

$$e \longrightarrow \nu\gamma$$

Forbidden by charge conservation

$\tau > 2.1 \times 10^{24}$ yrs. Aharonov et. al. (1995)

1.1 kg of Ge source, looks for 255 keV γ ray

$$e \longrightarrow \pi^{-}\gamma$$

Forbidden by energy conservation

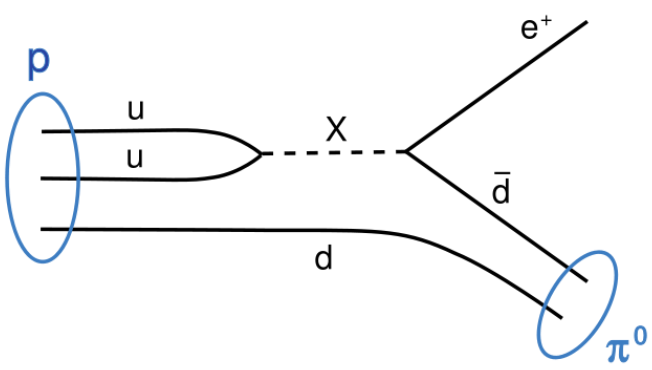
$$e \longrightarrow \gamma\gamma$$

Forbidden by angular momentum conservation

Stability of Matter (cont.)

In contrast, proton stability is not guaranteed by any fundamental symmetry

$$p \longrightarrow e^{+}\pi^{0}$$

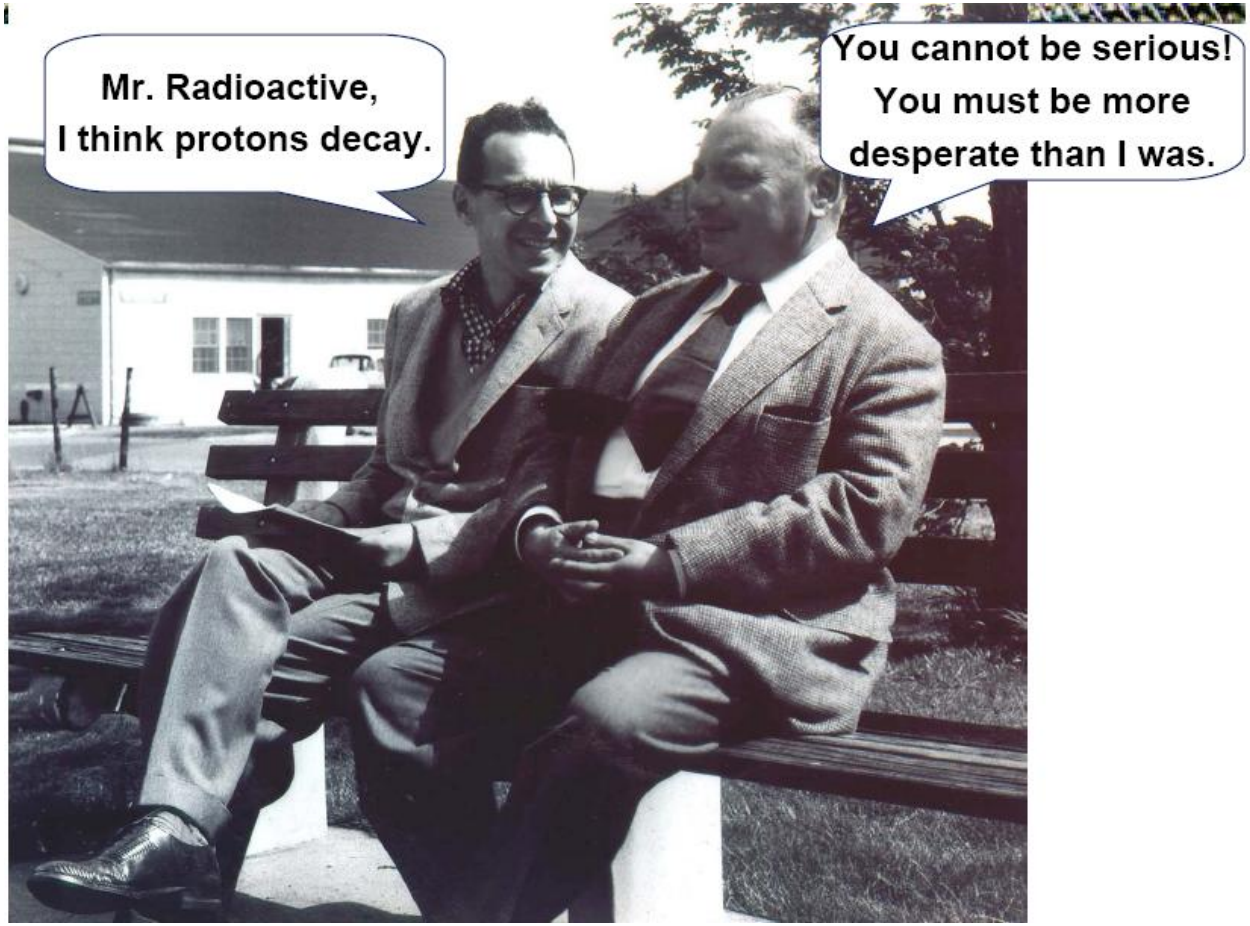


Hermann Weyl postulated Baryon Number symmetry

Intensely studied by many experiments

$\tau(p \rightarrow e^{+}\pi^{0}) > 1.3 \times 10^{34}$ yrs SuperKamiokande

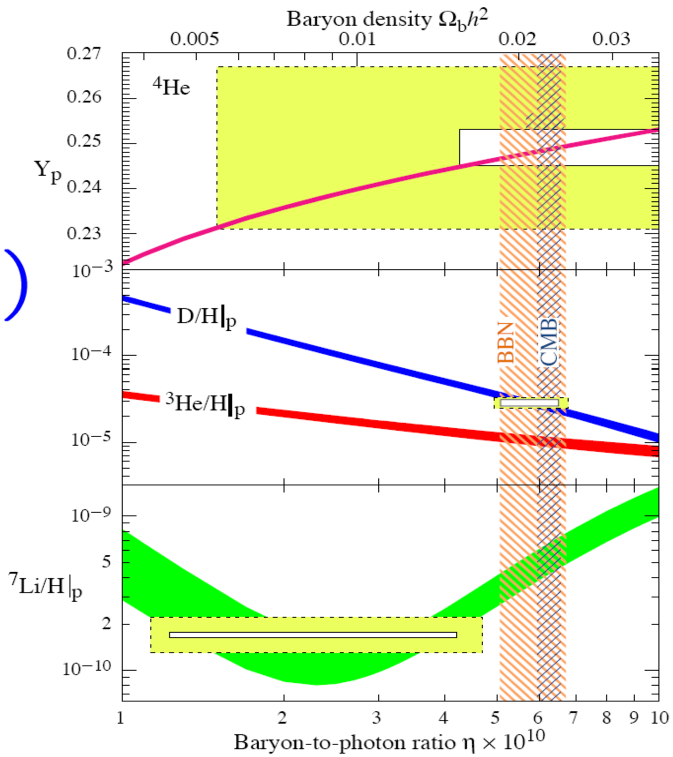
M. Goldhaber and W. Pauli



Goldhaber, Reines, Cowan (1954) initiated proton decay searches

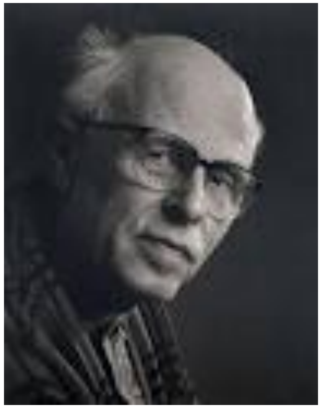
Baryon asymmetry of the universe

$$\eta_B = \frac{n_B}{n_\gamma} = 6.1^{+0.3}_{-0.2} \times 10^{-10}$$



Sakharov conditions (1967)

- Baryon number violation
- C and CP violation
- Out of equilibrium processes



Unified theories can generate η_B dynamically

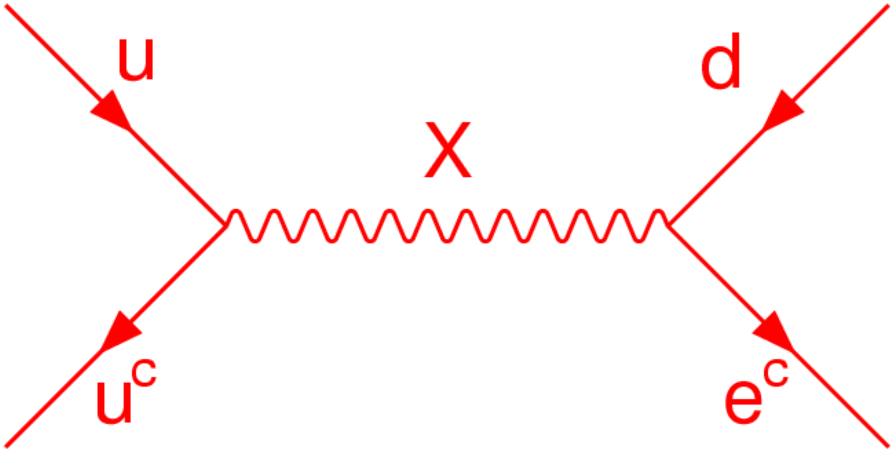
Initial condition unlikely

10,000,000,000 quarks and 10,000,000,001 antiquarks

Proton decay in Grand Unified Theories (GUT)

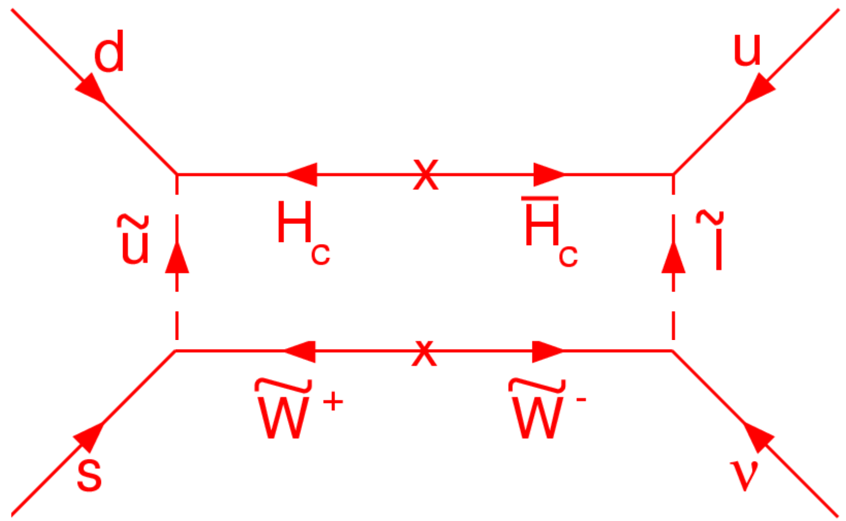
Superheavy gauge bosons mediate proton decay

$p \longrightarrow e^+\pi^0$



$$\tau_p^{-1} \approx \left[\frac{g^2}{M_X^2}\right]^2 m_p^5 \approx [10^{35\pm1} yr]^{-1}$$

Supersymmetric mode



Sakai, Yanagida (1982)

Weinberg (1982)

$$p \to \bar{\nu} K^{+}$$

$$\tau_p^{-1} \approx [\frac{f^2}{M_{H_c} M_{SUSY}}]^2 (\frac{\alpha}{4\pi})^2 m_p^5 \approx [10^{28} - 10^{32} yr]^{-1}$$

Proton Decay in Supersymmetric SO(10)

Babu, Pati, Wilczek (2000)
Babu, Pati, Tavartkiladze (2010)

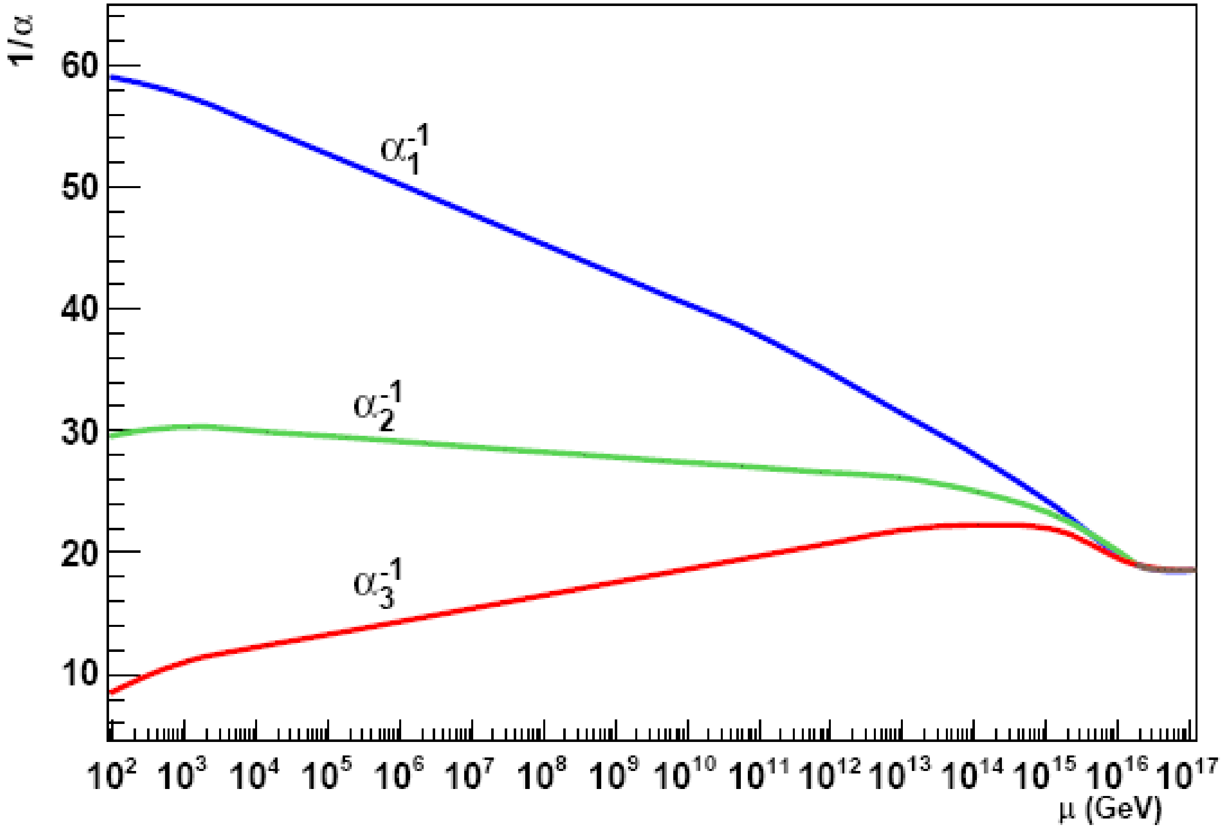
$$W_{D-T} = \lambda(\mathbf{10}_H \mathbf{45}_H \mathbf{10}'_H) + M' \mathbf{10}'_H \mathbf{10}'_H$$

$$\langle 45_H \rangle = \begin{pmatrix} a & 0 & 0 & 0 & 0 \\ 0 & a & 0 & 0 & 0 \\ 0 & 0 & a & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{pmatrix} \otimes i\tau_2 \quad \propto B - L$$

Avoids fine-tuning to make Higgs of Standard Model light

(Dimopoulos-Wilczek mechanism)

Dimopoulos, Wilczek (1981)
Babu, Barr (1993)
Barr, Raby (2000)

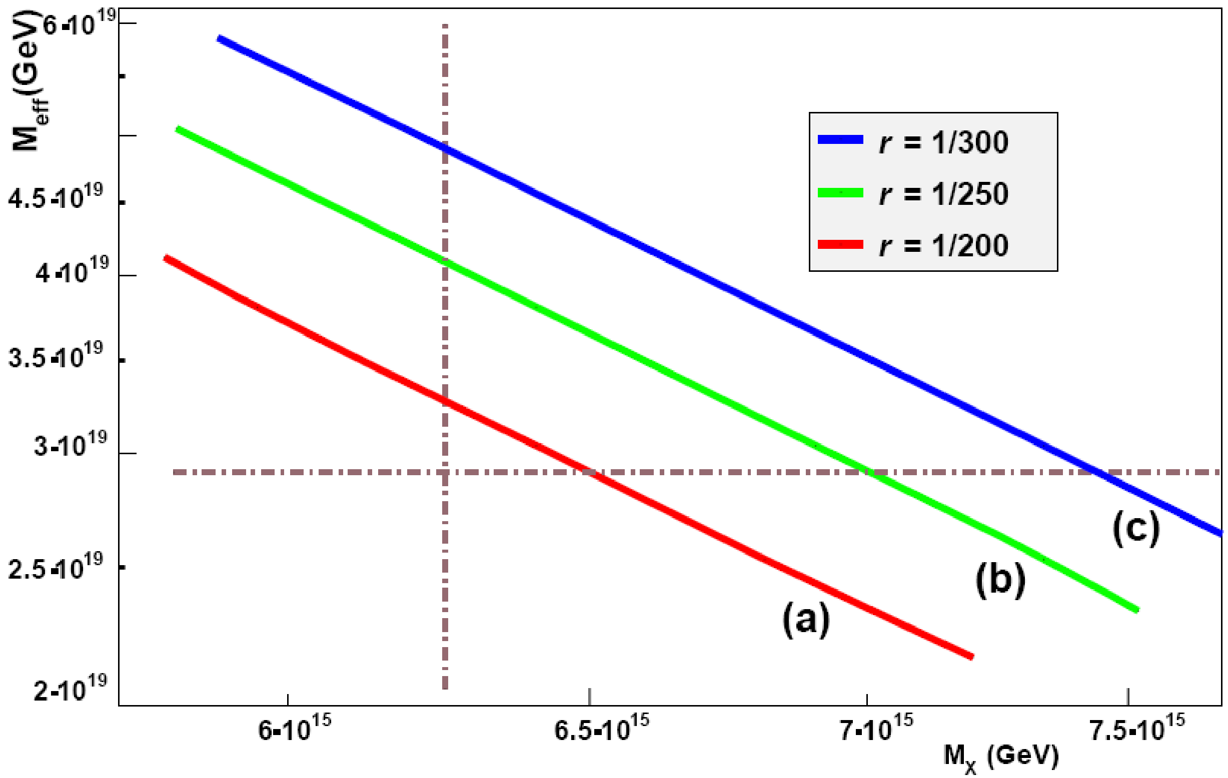


Gauge coupling evolution in explicit SO(10) model

K.S. Babu, J.C. Pati, and Z. Tavartkiladze, JHEP 1006: 084, 2010

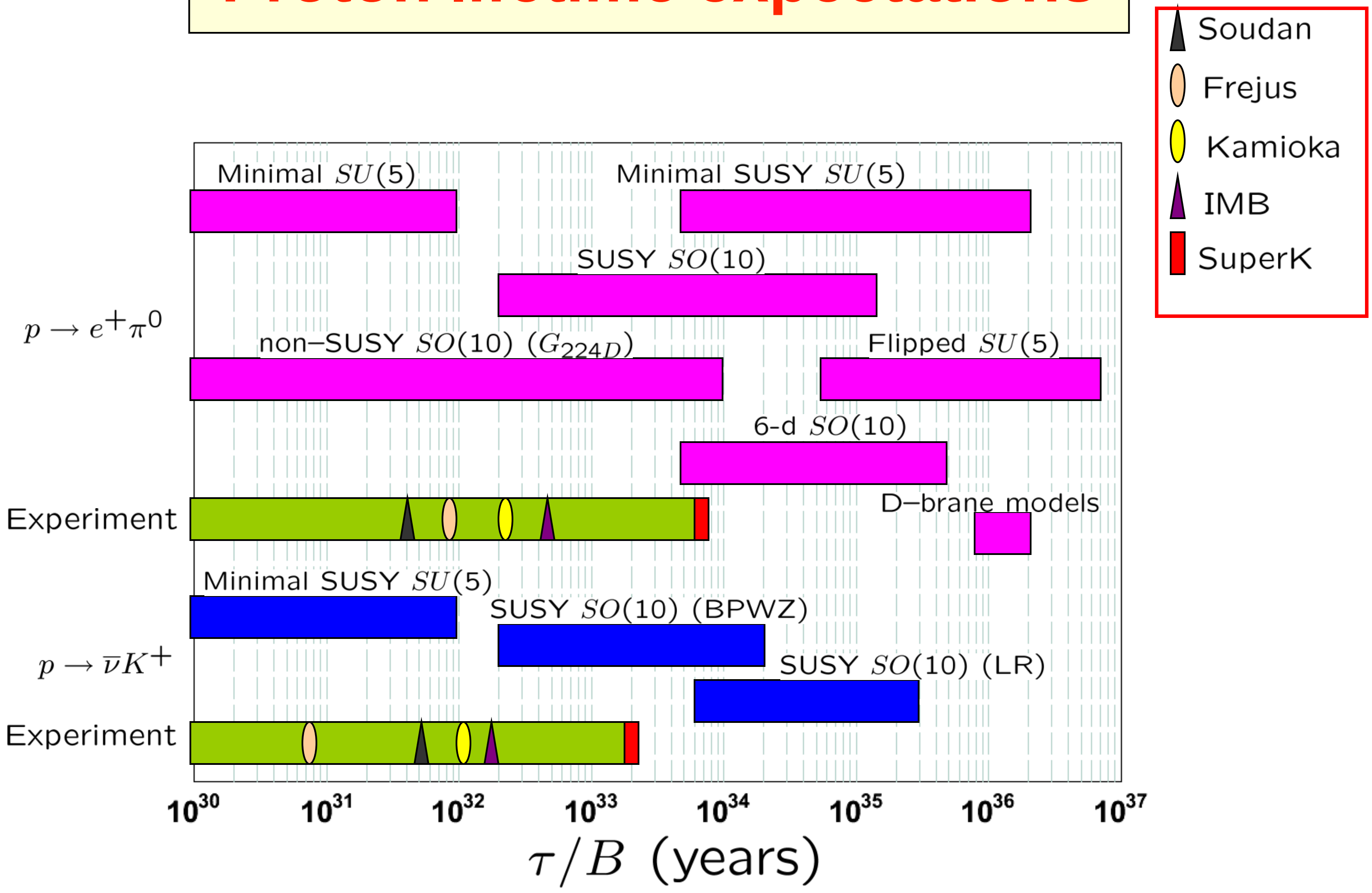
Correlation between two modes of proton decay

$$M_{\rm eff} \simeq 10^{19}{\rm GeV}\cdot\left(\frac{10^{16}{\rm GeV}}{M_X}\right)^3\left(\frac{3}{\tan\beta}\right)\left(\frac{1/100}{r}\right)\frac{\exp[2\pi(\Delta^{(2)}_{2,w}-\Delta^{(2)}_{3,w}-\delta\alpha_3^{-1})]}{2.54\cdot 10^{-2}}\,.$$



$p \to e^+\pi^0$ and $p \to \overline{\nu}K^+$ within reach of next generation experiments: $\tau_p < 5\times 10^{34}$ yrs.

Proton lifetime expectations



Neutrino Masses Probe the Scale of Unification of all Forces

Small neutrino mass arises from

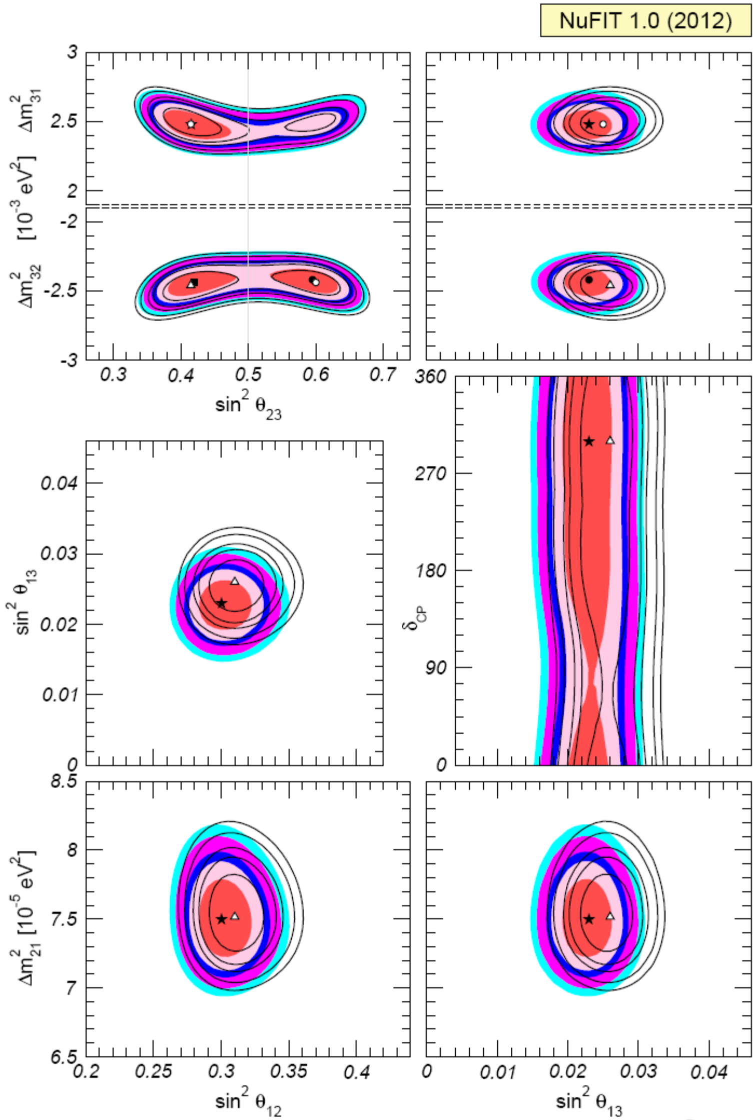
$$\mathcal{L} = \frac{LLHH}{M}$$

Using $m_\nu = v^2/M \simeq$ 0..05 eV $\Rightarrow$

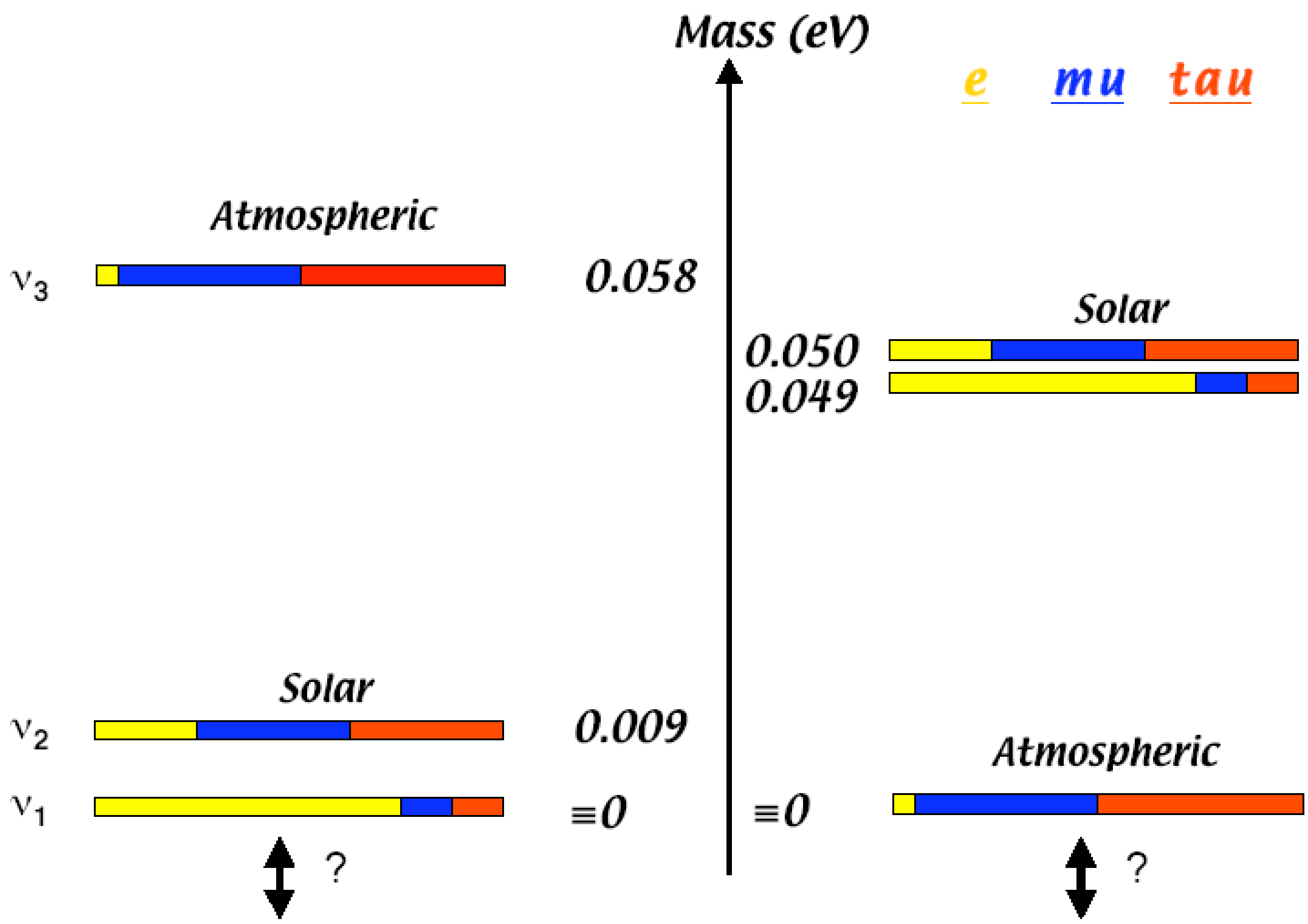
$$M \sim 10^{15} \text{ GeV}$$

Close to unification scale!

Global Fit to 3-Neutrino Oscilaltions



Schwetz et. al., 2012


Mass (eV)
e
mu
tau
Atmospheric
ν_3
0.058
Solar
0.050
0.049
Solar
ν_2
0.009
Atmospheric
ν_1
≡0
≡0
?
?

Seesaw Mechanism for Neutrino Mass

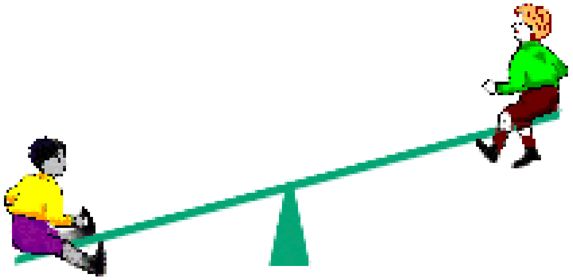
$(\nu,\ \nu^c)$ Mass Matrix:

Minkowski (1977)
Yanagida (1979)
Gell-Mann, Ramond, Slansky (1979)
Mohapatra, Senjanovic (1980)

$$M_\nu = \begin{pmatrix} 0 & m_D \\ m_D^T & M_R \end{pmatrix}$$

m_D breaks $SU(2)_L \times U(1)_Y$ symmetry $\Rightarrow m_D \leq$ 200 GeV

M_R not protected by any symmetry and can be large, $M_R \sim 10^{14}$ GeV



$$m_\nu(\text{light}) \approx \frac{m_D^2}{M_R} \sim 10^{-2}\ \text{eV}$$

$$m_\nu(\text{heavy}) \approx M_R \sim 10^{14}\ \text{GeV}$$

Neutrino mixing versus quark mixing

Leptons

$$U_\ell = \begin{pmatrix} 0.85 & -0.52 & 0.15 \\ 0.33 & 0.62 & -0.72 \\ -0.40 & -0.59 & -0.70 \end{pmatrix}$$

Quarks

$$V_q = \begin{pmatrix} 0.976 & 0.22 & 0.003 \\ -0.22 & 0.98 & 0.04 \\ 0.007 & -0.04 & 1 \end{pmatrix}$$

Disparity a challenge for Quark-Lepton unified theories.

Finding order in fermion mass spectrum

Fermion masses in units of m_t

$$
\begin{aligned}
m_t &= 1.0 & m_b &= 1.67 \times 10^{-2} \\
m_c &= 3.6 \times 10^{-3} & m_s &= 3.1 \times 10^{-4} \\
m_u &= 1.3 \times 10^{-5} & m_d &= 2.3 \times 10^{-5}
\end{aligned}
$$

$$
\begin{aligned}
m_\tau &= 1.0 \times 10^{-2} & m_3 &= 2.9 \times 10^{-13} \\
m_\mu &= 6.2 \times 10^{-4} & m_2 &= 5.2 \times 10^{-14} \\
m_e &= 3.0 \times 10^{-6} & m_1 &= < m_2
\end{aligned}
$$

$$
V_q = \begin{pmatrix} 0.976 & 0.22 & 0.004 \\ -0.22 & 0.98 & 0.04 \\ 0.007 & -0.04 & 1 \end{pmatrix} \qquad U_\ell = \begin{pmatrix} 0.85 & -0.54 & < 0.2 \\ 0.33 & 0.62 & -0.72 \\ -0.40 & -0.59 & -0.70 \end{pmatrix}
$$

$$
\mathrm{Im}\left(\frac{V_{ub}V_{cs}}{V_{us}V_{cb}}\right) = 0.34
$$

Minimal SO(10) Model

$$\mathcal{L}_{\text{Yukawa}} = f_{ij}\mathbf{16}_i\mathbf{16}_j\mathbf{10}_H + h_{ij}16_i16_j\overline{126}_H$$

Two Yukawa matrices determine all fermion masses and mixings, including the neutrinos

$$M_u = A + B, \quad M_{\nu D} = A - 3B$$
$$M_d = \alpha A + \beta B, \quad M_\ell = \alpha A - 3\beta B$$
$$M_{\nu^c} = cB$$

Model has only 11 real parameters plus 7 phases

Babu, Mohapatra (1993)
Fukuyama, Okada (2002)
Bajc, Melfo, Senjanovic, Vissani (2004)
Fukuyama, Ilakovac, Kikuchi, Meljanac, Okada (2004)
Aulakh et al (2004)

Bertolini, Frigerio, Malinsky (2004)
Babu, Macesanu (2005)
Bertolini, Malinsky, Schwetz (2006)
Dutta, Mimura, Mohapatra (2007)
Bajc, Dorsner, Nemevsek (2009)

Specific Example for Quark & Lepton masses

Fit

Input at GUT scale

$$\tan\beta = 55$$

$$m_u = 0.85 \ MeV \qquad m_d = 1.08 \ \text{MeV}$$
$$m_c = 222.3 \ MeV \qquad m_s = 34.3 \ \text{MeV}$$
$$m_t = 85.5 \ GeV \qquad m_b = 1.549 \ \text{GeV}$$
$$\delta_{CKM} = 1.508$$
$$V_{us} = 0.22 \quad V_{ub} = 0.0027 \quad V_{cb} = 0.036$$

Output: Type II Seesaw

$$\sin^2 2\theta_\odot = 0.635$$
$$\sin^2 2\theta_{e3} = 0.08$$
$$\sin^2 2\theta_{atm} = 0.892$$
$$\frac{\Delta m^2_{atm}}{\Delta m^2_\odot} = 15.2$$

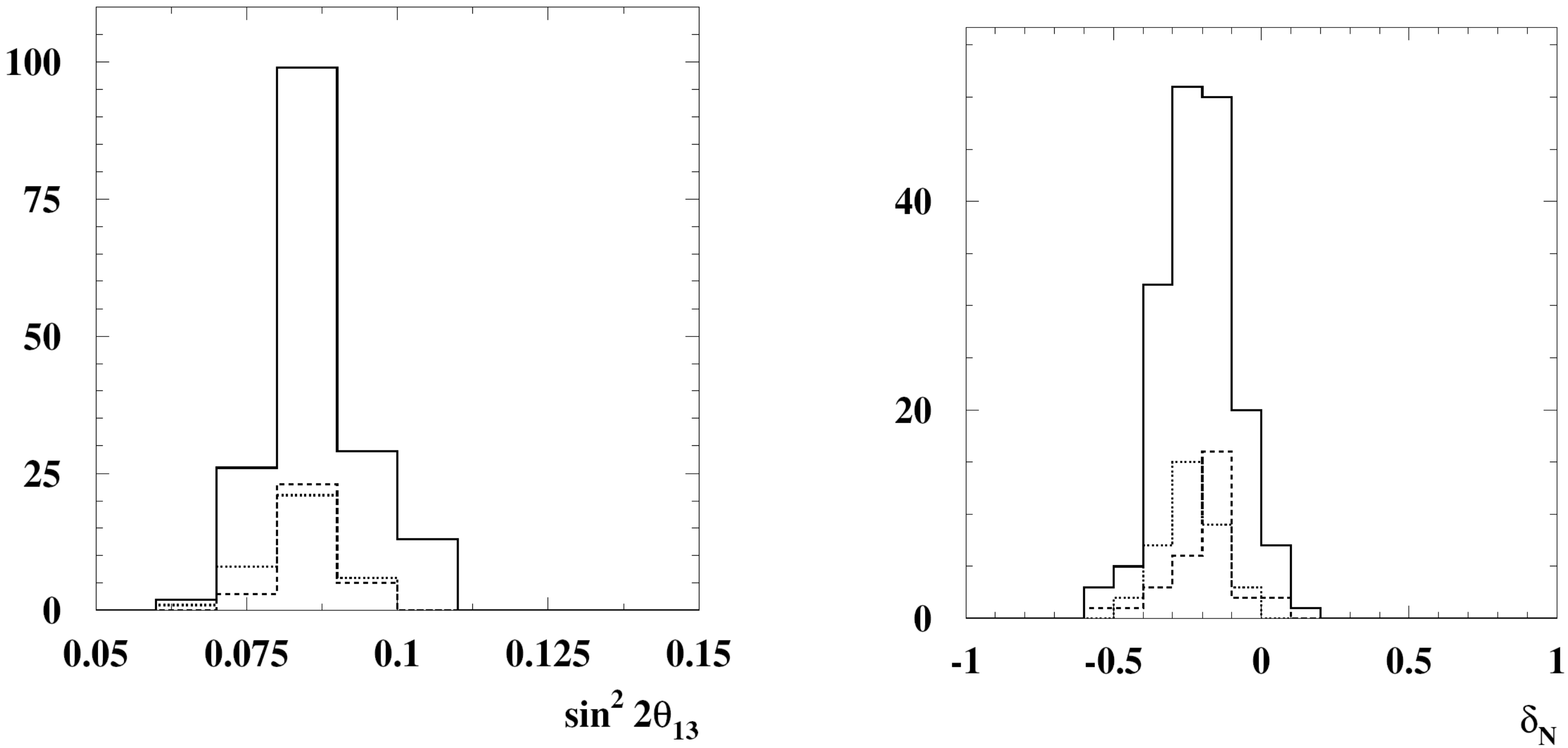
Babu, Macesanu (2005)

$\sin^2 2\theta_{13}$ prediction in nice agreement with Daya Bay results

$$\sin^2 2\theta_{13} = 0.092 \pm 0.016 \pm 0.005$$

5.2σ effect

Theta(13) in Minimal SO(10)



$\sin^2 2\theta_{13}$ and CP violating phase δ_N

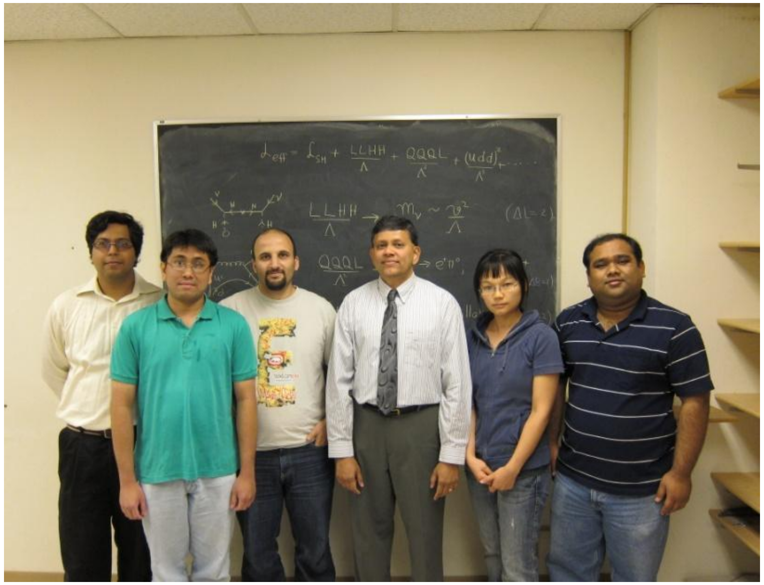
K.S. Babu and C. Macesanu (2005)

$\sin^2 2\theta_{13} = 0.092 \pm 0.016 \pm 0.005$ 5.2σ effect

Summary and Conclusions

- Grand Unification idea appears to be very promising
- Supersymmetry an essential ingredient, which should show up at LHC when it resumes
- Proton decay may be within reach of next generation experiments
- Both $p \to e^+\pi^0$ and $p \to \overline{\nu}K^+$ may be observable
- Light gauginos and heavy scalars preferred for LHC
- Minimal $SO(10)$ model predicts "correct" neutrino mixing angle

Acknowledgments



Support: DOE, DOE EPSCoR

Collaborators on Grand Unification

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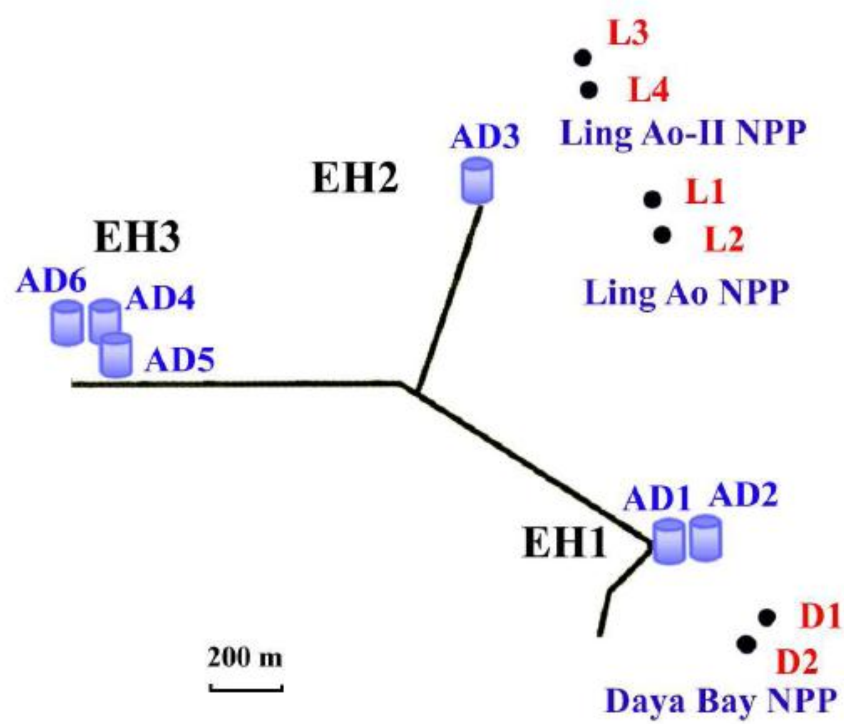
Pran Nath (Northeastern)
Frank Wilczek (MIT)

OSU High Energy Physics Group

	Point 1	Point 2	Point 3
$M_{1/2}$	922	915	1419
$m_{0(1,2)}$	621	551	771
$m_{0(3)}$	1256	1437	896
$\tan\beta$	16.98	15.45	18.15
A_0	-4255	-4246	-4189
μ	3112	2656	2662
m_A	804.8	798.6	545.8
$sign(\mu)$	+	+	+
m_h	124.5	124	125
m_H	809	803	549
$m_{H^\pm}$	814	808	555
$m_{\tilde{\chi}^0_{1,2}}$	400, 763	396, 755	620, 1168
$m_{\tilde{\chi}^0_{3,4}}$	3087, 3087	2635, 2636	2644,2645
$m_{\tilde{\chi}^\pm_{1,2}}$	766, 3087	758, 2639	1172, 2649
$m_{\tilde{g}}$	2058	2040	3041
$m_{\tilde{u}_{L,R}}$	1946, 1912	1906, 1893	2853, 2796
$m_{\tilde{t}_{1,2}}$	1358, 1910	1141, 1872	1545, 2366
$m_{\tilde{d}_{L,R}}$	1948, 1860	1908, 1817	2854, 2717
$m_{\tilde{b}_{1,2}}$	1863,2089	1843, 2179	2338, 2640
$m_{\tilde{\nu}_1}$	9184	889	1282
$m_{\tilde{\nu}_3}$	9184	889	1812
$m_{\tilde{e}_{L,R}}$	925 , 585	897, 413	1288,718
$m_{\tilde{\tau}_{1,2}}$	1122, 1388	1291, 1563	623, 1298
σ_{SI}(pb)	4.54×10^{-12}	6.76×10^{-12}	2.31×10^{-11}
σ_{SD}(pb)	2.45×10^{-9}	1.25×10^{-9}	2.26×10^{-10}
$\Omega_{CDM}h^2$	0.11	0.108	0.121

Daya Bay Reactor Neutrino Experiment



$$P_{\rm sur} \approx 1 - \sin^2 2\theta_{13} \sin^2(1.267 \Delta m^2_{31} L/E)$$

$$R = 0.940 \pm 0.011(\text{stat}) \pm 0.004(\text{syst})$$

$$\sin^2 2\theta_{13} = 0.092 \pm 0.016(\text{stat}) \pm 0.005(\text{syst})$$