Hidden Sectors and Associated Physics:
- Supersymmetry Breaking,
- De Sitter Vacuum,
- Dark matter
also, The inflaton for G_2

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IN PHYSICS, G_2 MANIFOLDS ARE VERY IMPORTANT AND THEY DO NOT COME ALONE

- They arise in compactifications, particularly 11D M-theory to 4D
- Compactifications allow obtaining comprehensive theory including quantum theory of gravity and Standard Model forces
- They are generically accompanied by many "hidden sectors" – we live on one of the "hidden sectors", called the visible sector

Hidden sectors lead to major physics results, especially:

- ❑ Supersymmetry is a visible sector broken symmetry - the breaking cannot occur in the visible sector – can occur in a hidden sector – transmitted to visible sector
- ❑ Hidden sector matter leads to De Sitter vacuum
- ❑ Probably hidden sectors necessary generically for mathematical consistency, and more
- ❑ Hidden sectors do provide candidates for the dark matter

SO STUDY HIDDEN SECTORS ALONG WITH G_2 MANIFOLDS

- **Hidden sector particles don’t have any Standard Model charges, such as electromagnetic, weak, QCD, so they don’t couple at tree level to SM stuff**

- **Visible sector – underwent inflation, so three large space dimensions**

- **Think of this as what can be done assuming appropriate “manifolds” exist**

•Historical goal of physics– understand the world we perceive

•What are the basic particles we are made of? – quarks and electrons – chiral fermions

•What forces act to give the world we see? – strong force, electroweak (electroweak=electromagnetic and weak) force, gravity

•These particles plus these forces = Standard Model

•What are the rules to calculate what happens – relativistic quantum field theory (modern version of F=ma) – works for any forces, particles

Want all forces in comprehensive package, so quantum theory of gravity plus Standard Model in 3 space dimensions – not "local"

Since mid-1980s expect 9 or 10 space dimensions for theory with quantum gravity – Michael Green and John Schwarz, anomaly free

Compactified string/M-theory seems like very good path to have full "UV complete" theory for our world

→ We live in the ground state of a compactified string/M-theory, the vacuum – write the potential energy, minimize it

FOCUS ON M-THEORY

Witten, 1995

Then compactifying M-theory on a singular 7D "manifold" X with G_2 holonomy preserves N=1 supersymmetry – 4D theory is supersymmetric relativistic quantum field theory Papadopoulos, Townsend, hep-th/9506150 → the "rules"

•**Non-Abelian gauge fields are localized on three-dimensional submanifolds $Q \in X$ along which there is an orbifold singularity. Acharya: hep-th/9812205, hep-th/0011089, Acharya-Gukov: hep-th/0409191**
→the forces, Yang-Mills gauge theories

•Chiral fermions are localized at point-like conical singularities $p \in X$ – Atiyah-Witten. hep-th/0107177, Acharya-Witten. hep-th/0109152

→ the particles, quarks and electrons

To write a supersymmetric relativistic 4D quantum field theory of forces and particles, need to specify three functions:

- **Superpotential**
- **Kahler potential**
- **Gauge kinetic function**

MODULI, SUPERPOTENTIAL

- **In M theory on G_2 manifolds the only t_i moduli one has are $z_i=s_i+it_i$. They are the zero modes of the metric whose bosonic superpartners are s_i -- the zero modes of the three-form, i.e. the axions**

- **The axionic shift symmetry can only be broken by the non-perturbative effects. Thus the entire moduli superpotential is non-perturbative**

- **All moduli must be stabilized – observables are functions of moduli, so they must get fixed vacuum values, "vacuum expectation values", "vevs"**

Since 2005, series of dozen papers, Bobby Acharya and/or GK, and collaborators

- **An M theory Solution to the Hierarchy Problem, hep-th/0606262**
- **Explaining the Electroweak Scale and Stabilizing Moduli in M Theory, hep-th/0701034**
- **Stabilized all moduli**
- **Calculated supersymmetry breaking Lagrangian**
- **Higgs mechanism generic, predict M_{higgs}/M_Z**
- **Predict some superpartner masses in TeV region**
- **Axions, solve strong CP problem**
- **Electric dipole moments small**
- **Inflaton is linear combination of moduli, approximately the overall volume modulus (recent, GK and Martin Winkler, arXiv:1902.02365)**

Moduli Stabilization for G_2

- In order to generate the hierarchy we choose to work in a sector with zero background fluxes (Acharya) – important choice, with good motivation

- The non-perturbative superpotential is assumed to be generated by the strong gauge dynamics in the hidden sectors – gaugino condensation (generic):

$$W = \sum_{k=1}^{M} A_k e^{i b_k f_k}$$

where the gauge kinetic function $f_k = \sum_{i=1}^{N} N_i^k z_i$ is an integer linear combination of the moduli. Lukas, Morris. hep-th/0305078

• **For simplicity we choose two hidden sectors for semi-analytic work, i.e.**

$$W = A_1 e^{ib_1 f_1} + A_2 e^{ib_2 f_2}$$

The A_k **are moduli independent normalization constants,**

$b_k = \frac{2\pi}{c_k}$ **where** c_k **are dual Coxeter numbers, N for SU(N)**

•**Also for examples use well-motivated** $f_1 = f_2$

•**An N-parameter family of Kahler potentials consistent with G_2 holonomy and known to describe accurately some explicit G_2 moduli dynamics is given by:**

$$K = -3\ln(4\pi^{1/3}V_7)$$

where the 7-dim volume $V_7 = \prod_{i=1}^{N} s_i^{a_i}$

and the positive rational parameters a_i **satisfy** $\sum_{i=1}^{N} a_i = \frac{7}{3}$

Beasley-Witten: hep-th/0203061, Acharya, Denef, Valandro. hep-th/0502060

Including Charged Matter in the Hidden Sector

- **Include massless quark states** Q **and** $\tilde{\mathrm{Q}}$ **transforming as** N_c **and** $\bar{N}_c$ **under** $SU(N_c)$ **and as singlets under** $SU(Q)$

- **The non-perturbative superpotential in the first hidden sector with** $SU(N_c)$ **gauge group becomes** **Seiberg: hep-th/9402044, hep-th/9309335**

$$W = A_1 e^{i\frac{2\pi}{N_c - N_f}\sum_{i=1}^{N} N_i s_i} \det\left(\mathrm{Q}\tilde{\mathrm{Q}}\right)^{-\frac{1}{N_c - N_f}}$$

- **First consider** $N_f = 1$**, check** $N_f > 1$ **later**

\

$$\phi \equiv \left(\mathrm{Q}\tilde{\mathrm{Q}}\right)^{\frac{1}{2}} = \phi_0 e^{i\theta}$$

$$W = A_1 \phi^a e^{i b_1 f} + A_2 e^{i b_2 f}$$

$$b_1 = \frac{2\pi}{P} \qquad b_2 = \frac{2\pi}{Q} \qquad a \equiv -\frac{2}{P} \qquad P \equiv N_c - 1$$

Note

- The N=1 supergravity scalar potential is given by

$$V=\frac{e^{\phi_0^2}}{48\pi V_7^3}\Bigg[\Bigg(b_1^2A_1^2\phi_0^{2a}e^{-2b_1\vec{v}\cdot\vec{a}}+b_2^2A_2^2e^{-2b_2\vec{v}\cdot\vec{a}}+2b_1b_2A_1A_2\phi_0^a e^{-(b_1+b_1)\vec{v}\cdot\vec{a}}\cos\left(\left(b_1-b_2\right)\vec{N}\cdot\vec{t}+a\theta\right)\Bigg)$$

$$\times\sum_{i=1}^{N}a_i\nu_i^2+3\left(\vec{v}\cdot\vec{a}\right)\Bigg(b_1A_1^2\phi_0^{2a}e^{-2b_1\vec{v}\cdot\vec{a}}+b_2A_2^2e^{-2b_2\vec{v}\cdot\vec{a}}+\left(b_1+b_2\right)A_1A_2\phi_0^a e^{-\left(b_1+b_2\right)\vec{v}\cdot\vec{a}}$$

$$\times\cos\left(\left(b_1-b_2\right)\vec{N}\cdot\vec{t}+a\theta\right)\Bigg)+3\Bigg(A_1^2\phi_0^{2a}e^{-2b_1\vec{v}\cdot\vec{a}}+A_2^2e^{-2b_2\vec{v}\cdot\vec{a}}+2A_1A_2\phi_0^a e^{-\left(b_1+b_1\right)\vec{v}\cdot\vec{a}}$$

$$\times\cos\left(\left(b_1-b_2\right)\vec{N}\cdot\vec{t}+a\theta\right)\Bigg)+\frac{3}{4}\phi_0^2\Bigg(A_1^2\phi_0^{2a}\left(\frac{a}{\phi_0^2}+1\right)^2e^{-2b_1\vec{v}\cdot\vec{a}}+A_2^2e^{-2b_2\vec{v}\cdot\vec{a}}$$

$$+2A_1A_2\phi_0^a\left(\frac{a}{\phi_0^2}+1\right)e^{-(b_1+b_1)\vec{v}\cdot\vec{a}}\cos\left(\left(b_1-b_2\right)\vec{N}\cdot\vec{t}+a\theta\right)\Bigg)\Bigg]$$

The hierarchy problem(s) are the central problems of particle physics today

Basically, two scales, the Planck scale formed from the fundamental constants (G_N , c, h)

- **$M_{planck} \approx 10^{19}$ GeV**

and

- **$M_{electroweak} \approx 10^2$ GeV, Higgs boson or EW scale**

1. **Such a huge separation would not be stable in a quantum field theory**
2. **What are the origins of the two scales**

- **We can set the tree level CC to zero by requiring**

$$P\ln\left(\frac{A_1 Q}{A_2 P}\right)=\frac{28(Q-P)}{3(Q-P)-8}$$

- **We check that the superpartner masses are not sensitive to the tuning of the CC**

- **Get a surprising result for the hierarchy:**

$m_{3/2}$ ~ 50 TeV

Don't need to separately set CC~ 0 and gravitino mass tens of TeV!

- **HIERARCHY PROBLEM(s) SOLVED**

Results that don't depend on knowing details of manifolds:

- Gravity mediation of supersymmetry breaking
- Stabilization of all moduli
- Presence of generic electroweak symmetry breaking; prediction of M_{higgs}/M_Z; higgs boson decay branching ratios
- EDMs surprisingly small
- Inflation
- Lightest superpartner will decay to hidden sector matter
- Gravitino mass ~ 40 TeV
- Gauginos light, average mass ~ TeV; scalars heavy, ~ gravitino mass

1. Dark matter **(Acharya et al; Halverson, Nelson et al; Acharya, Kane, Perry,Nelson et al)**

- **Some hidden sectors have stable matter**
- **Can compute it’s relic density**
- **Could be the dark matter**

2. DE SITTER VACUUM (Acharya and GK et al, 2007)

(~ 600 papers in past two years)

- Scalar potential

$$V=F^2_{moduli} + F^2_{HSmatter} - 3W^2 > 0$$

where $F_i = \partial W/\partial\phi_i$

but $F^2_{moduli} - 3W^2 < 0$ so if only consider moduli do not find De Sitter vacuum

3. SUPERSUMMETRY BREAKING

- Supersymmetry says boson and fermion masses equal – but is can be a broken symmetry, e.g. by scalar partners of electrons being heavy

Can write sum rule

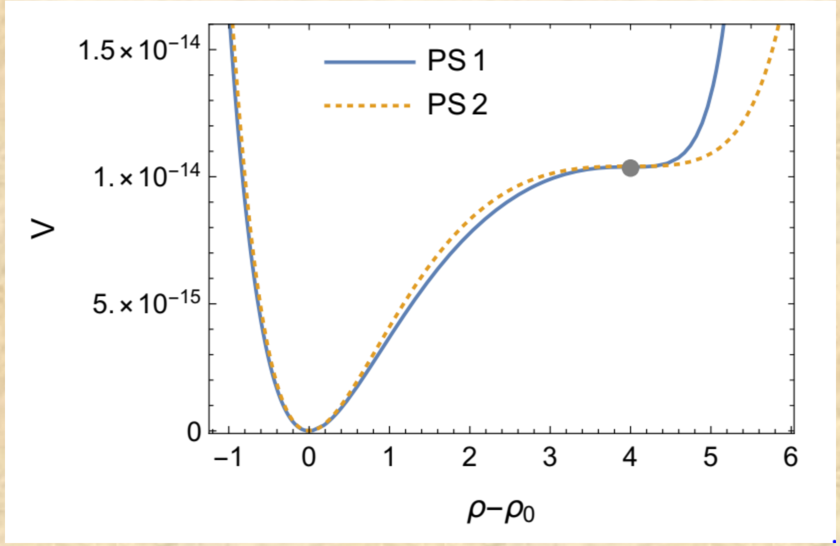
$$STr\, M^2_e = M^2_{electron\text{-}squarkL} + M^2_{electron\text{-}squarkR} - 2M^2_e = 0$$

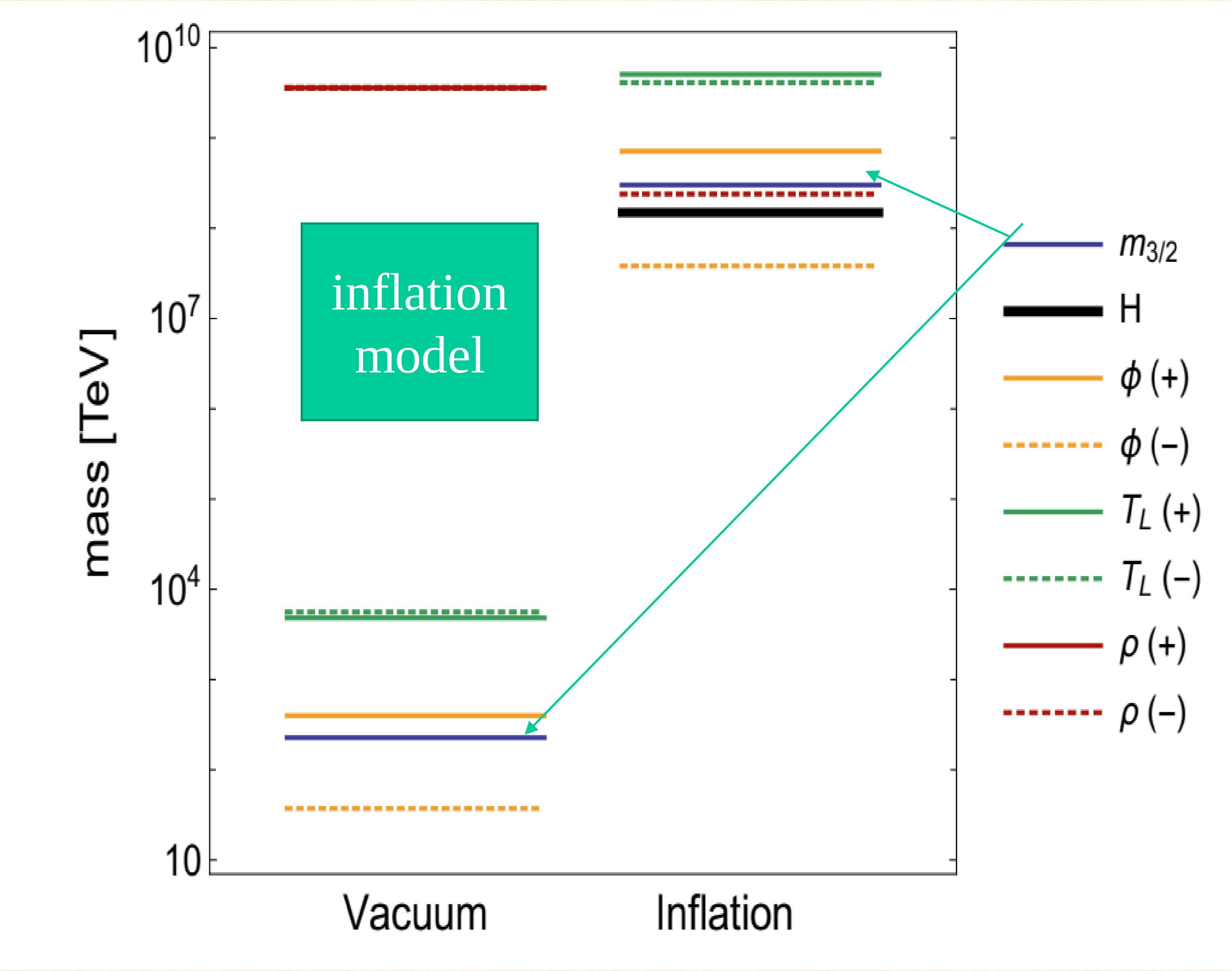
But squarks not seen, presumably heavy, never could satisfy this

Can break supersymmetry in hidden sector with sum rules satisfied, and transmit breaking by gravitational interactions

Inflation - Compactifying M-theory on a manifold of G2 holomany gives a UV complete 4D theory. The theory also contains a successful inflaton, which is a linear combination of moduli closely aligned with the overall volume modulus of the compactified G2 manifold. The result does not depend on ad hoc assumptions, but follows from an effective quantum gravity theory. (GK and Martin Winkler)

Inflation
arxiv:1902.02365





10^{10}
10^7
10^4
10
mass [TeV]
inflation model
Vacuum
Inflation
$m_{3/2}$
H
ϕ (+)
ϕ (−)
T_L (+)
T_L (−)
ρ (+)
ρ (−)

Planck scale input – no other dimensionful parameters

No free parameters – generic W, K, f

$V^{1/4}_{inflation} \sim 10^{15}$ GeV, $r \sim 10^{-6}$

Gauginos ~ ½-few TeV

$M_{higgs} \approx 125$ GeV

DON’T IGNORE HIDDEN SECTORS