SPLIT SUPERSYMMETRY

or...

“How I learned to stop worrying and love fine-tuning.”

WHO?
CSABA’S NEW STUDENT.

FLIP TANEDO, 18 JULY 2008

Student Theory Seminar
LEPP, CORNELL UNIVERSITY
ON THE WEAK AND STRONG ANTHROPIC PRINCIPLES

The Weak Anthropic Principle: Isn’t it great that humans have evolved to a point where they can make a living in universities?

The Strong Anthropic Principle: On the contrary, the whole point of the universe is that humans should not only work in universities, but write books for with words like ‘cosmic’ and ‘chaos’ in the title.

Terry Pratchett, Hogfather (1996) [paraphrased]
It makes no more sense than saying that the reason the eye evolved is so that someone can exist to read this book. But it is really shorthand for a much richer set of concepts.

-Leonard Susskind

(Cornell Alumnus)
OUTLINE

- 5 big ideas, 5 important scales in physics
- **Low scale:** supersymmetry
- **Intermission:** naturalness
- **High scale:** string landscape
- **Split supersymmetry**
The Importance of Scales

Physics at very different scales decouple. RG flow near UV fixed point

"A CHEF DOES NOT NEED TO KNOW GAUGE THEORY"
-S. DIMOPOULOS

Naturalness ("GOOD")
Parameters are $O(1)$ $(\Lambda_{UV})^{4-D}$

vs. fine-tuning
"BAD" dependence of physics on decimal points

Physics by Scale

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5 BIG IDEAS AND 5 IMPORTANT SCALES

1. Quantum Gravity

- $M_{\text{Pl}} \sim 10^{19}$ GeV
- String theory?
2. Dark Matter

- ~ 200 GeV
- WIMP particle?
- EWSB mechanism?
5 BIG IDEAS AND 5 IMPORTANT SCALES

3. Grand Unification

- QUANTUM GRAVITY
- GRAND UNIFICATION
- LHC COLLISIONS
- DARK MATTER, EWSB
- PHYSICS BY SCALE

- SU(3) × SU(2) × U(1) ⊂ SU(5)
- FCNC, P+ DECAY
- LEP: SUSY?
- NEUTRINO SEE-SAW
5 BIG IDEAS AND 5 IMPORTANT SCALES

4. Δ Problem

- Non-zero…but tiny
- $\Lambda \sim 10^{-120} M_{Pl}^4$
- Why is $L_{Hub} \gg L_{Pl}$?
5 BIG IDEAS AND 5 IMPORTANT SCALES

5. Hierarchy Problem

\[
\frac{i}{(2\pi)^4} \int \frac{d^4 k}{k^2 - m_H^2}
\]

- M_{scalar} not protected
- \(M_{EWSB}/M_{PL} = 10^{-17}\)
- Fine tuning?
- or \(M_H \sim M_{BSM}\)?
SUPERSYMMETRY

I’M SUPER, THANKS FOR ASKING.
-SOUTH PARK
LOW ENERGY: SUPERSYMMETRY

- Hierarchy problem $\rightarrow$ TeV SUSY
- Added bonus:
  - Grand unification
  - Dark Matter

- We **ignore** the $\Delta$ problem
LOW ENERGY: SUPERSYMMETRY

FERMIONS $\leftrightarrow$ BOSONS

$$\{Q_\alpha, \bar{Q}_\beta\} = 2\sigma^{\mu}_{\alpha\beta} P_\mu$$

- SPACETIME SYMMETRY
- ONLY EXTENSION WITHIN COLEMAN-MANDULA
- CANCELS $m_H$ DIVERGENCE

To date, no SUSY particles detected
LOW ENERGY: SUSY BREAKING

- SUSY must be broken!
- **Naturalness**: broken at TeV scale
  - Higgs mass naturally light, non-zero
  - Explains non-observation of SUSY partners

Natural mass is at the SUSY breaking scale
(Superpartners too massive to have been observed at past particle colliders)
SUSY: SCORECARD (IMPORTANT!)
A model is **FINE-TUNED** if a plot of the allowed parameter space makes you wanna puke. –D.E. Kaplan
Wilsonian Philosophy

UV Completion
(Can also be EFT)

Cutoff / Matching Scale

Low Energy EFT
(Valid up to cutoff)

Physics by Scale

Q: How does EFT depend on UVT?

Finite Terms:
Insensitive

Dimensionless:
Log \( \Lambda_{\text{cut}} \)

Irrelevant Op:
\( 1/\Lambda_{\text{cut}}^{(+) \text{cut}} \)

Relevant Op:
\( \Lambda_{\text{cut}}^{(+) \text{cut}} \)

Ken Wilson
1982 Nobel Prize
UV-SENSITIVE PARAMETERS, $M$ ...

**NATURAL**: $M \sim \Lambda_{\text{cut}}$

E.G. XD (ADD, RS), LITTLE HIERARCHY PROBLEM

**SYM. NATURAL**: $M \ll \Lambda_{\text{cut}}$, SYM RESTORED IF $M=0$

E.G. FERMION MASSES

**SUPERNATURAL**: UV T SETS $M=M^*$ AT $\Lambda_{\text{cut}}$

E.G. TECHNICOLOUR, GARDEN-variety SUSY

**UNNATURAL**: FINE TUNED, $M \ll \Lambda_{\text{cut}}$

SENSITIVE TO RADIATIVE CORRECTIONS

WE’VE TAKEN NATURALNESS AS MOTIVATION FOR NEW PHYSICS... WHAT IF NATURE IS UNNATURAL? WHAT KIND OF UV T WOULD DO THIS?

FINE TUNING VIA SONIC SCREWDRIVER?
THE STRING LANDSCAPE

THAT’S NOT A THEORY OF EVERYTHING, THAT’S A THEORY OF ANYTHING.
–L. KRAUSS
HIGH ENERGY: STRING THEORY

Why are there no stringy LHC predictions?

- **Decoupling/RG flow**: pass through many (not understood) energy scales
- Even trickier: inherently **non-predictive**?

**KKLT**: $10^{500}$ metastable vacua?

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**Physical Review D 68, 046005 (2003)**

**de Sitter vacua in string theory**

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(Received 10 February 2003; published 7 August 2003)

We outline the construction of metastable de Sitter vacua of type IIB string theory. Our starting point is highly warped IIB compactifications with nontrivial NS and RR three-form fluxes. By incorporating known corrections to the superpotential from Euclidean D-brane instantons or gaugino condensation, one can make models with all moduli fixed, yielding a supersymmetric AdS vacuum. Inclusion of a small number of D3-branes in the resulting warped geometry allows one to uplift the AdS minimum and make it a metastable de Sitter ground state. The lifetime of our metastable de Sitter vacua is much greater than the cosmological time scale of $10^{10}$ yr. We also prove, under certain conditions, that the lifetime of dS space in string theory will always be shorter than the recurrence time.

DOI: 10.1103/PhysRevD.68.046005

PACS number(s): 11.25.Yb, 98.80.-k
THE LANDSCAPE OF METASTABLE VACUA

Different points in the landscape are different possible universes.
THE LANDSCAPE OF METASTABLE VACUA

Is there a **vacuum selection principle**?

ANALOGY: LOCATION OF THEORY VS. EXPERIMENT GRAD OFFICES

**BASEMENT**

**TOP FLOOR**

EXPERIMENT

THEORY

THIS IS AN ENTROPICALLY UNLIKELY CONFIGURATION...

BUT THERE'S AN UNDERLYING SELECTION PRINCIPLE.
THE ANTHROPIC/ENTROPIC PRINCIPLE

Actually...
- Atomic Principle
- Galactic Principle
- Etc.

Maybe: vacuum state chosen randomly! We’re only here because this is where we can be.
A BRIEF HISTORY OF ANTHROPISM IN PHYSICS

**MAN** IS NOT AT THE CENTRE OF THE UNIVERSE!

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**THE UNIVERSE IS NOT AT THE CENTRE OF THE UNIVERSE!**

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WEST COAST HIPPIES?
ASKING THE RIGHT QUESTIONS...

- Why are the angular areas of the sun and moon equal?
- What determines the radii of planetary orbits?
  - Circular orbits → Platonic solids
  - Elliptic orbits → Newton’s Gravity
  - There is a landscape of orbital radii in other solar systems
  - Fitting circular orbits: wrong question!
SPLIT SUSY

LIVING WITH FINE TUNING...

“OUR PAPER DIDN’T BECOME TOP-CITED UNTIL SOMEONE CAME UP WITH A CATCHY NAME.”
-S. DIMOPOULOS (PARAPHRASED)
**SO WHAT? (LOW ENERGY SCALE?)**

- Low energy phenomenologists focus on the hierarchy problem and ignore the **white elephant** in the room.
- Maybe the hierarchy and $\Lambda$ problems *aren’t problems at all!*

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HOLY MOLY, IT’S AN ELEPHANT!!
... BUT WHAT ABOUT SUPERSYMMETRY?
Split Supersymmetry

- **Forget hierarchy:** nature is *finely tuned*
  - SUSY is *still* important for GUT and DM
- Freedom to choose **high scale** SUSY breaking
  - (s)fermions can stay light (eg. LSP dark matter)
  - scalar(ino)s live at the heavy scale (no protection)
- Keeps good features, drops problems
  - Cost: “paradigm shift”

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Supersymmetric Unification
Without Low Energy Supersymmetry
And Signatures for Fine-Tuning at the LHC

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Reassessing SUSY, Finely-Tuned Version

Checklist: things we want
- Hierarchy: $m_H$ naturally light
- LSP Dark Matter (R-parity)
- Grand Unification (LEP)
- Can generate Higgs potential
- $\Lambda$ problem (ignore at low energy)

Poop list: things we didn’t want
- Flavor changing neutral currents
- $(B-L)$ violation and $\mu^+$ decay
- Electric dipole moment, etc

Scalars are now decoupled!!
- ‘little hierarchy’ problem
- $\mu$ problem, more fine-tuning?
**Split Supersymmetry: LHC Signature?!**

- **Spectrum:** decoupled scalars, \( \sim \) TeV fermions
- **Experimental signature:** long lived gluino!

### 100 GeV to 1 TeV

\[ g \quad \tilde{g} \quad Q \quad \tilde{Q} \quad \tilde{B} \]

**Smoking gun:**
- Displaced vertex
- Stopped gluinos

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**Supersymmetric Unification**

*Without Low Energy Supersymmetry And Signatures for Fine-Tuning at the LHC*

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SPLIT SUSY PHENOMENOLOGY: E.G. BINO DM

- MSSM parameters $\rightarrow$ LSP decay cross section
- Boltzmann equation $\rightarrow$ DM Relic Density

- Constrained by astro/cosmo observations
\[ L_{\text{eff}} = L_{\text{SM}} + M_{\tilde{B}} \tilde{B} \tilde{B} + M_{\tilde{g}} \tilde{g} \tilde{g} + \mu H_u H_d \]
\[ + \sqrt{2} \kappa_u h^\dagger \tilde{W} H_u + \sqrt{2} \kappa_d h^\dagger \tilde{W} H_d \]
\[ + \frac{\sqrt{2}}{2} \kappa'_u h^\dagger \tilde{B} H_u + \frac{\sqrt{2}}{2} \kappa'_d h^\dagger \tilde{B} H_d \]
\[ - m^2 h^\dagger h - \frac{\lambda}{2} (h^\dagger h)^2 + \text{h.c.} \]

- E.g. bino dark matter near the higgs resonance region
- Read off vertex for higgs-channel decay

\[ g_{\text{eff}} = -2i \frac{\nu \kappa'_u \kappa'_d}{\mu} \]
1. **Determine effective couplings from SUSY lagrangian**, constrain using $\Omega_{DM}$

2. **Match to $M_{SUSY}$ where SUSY is unbroken** (constraint)

3. **Match couplings to GUT couplings** (constraint)

4. **Flow back to TeV scale** to check consistency, compare to LHC physics

**Note:** $\beta$ functions are different at different scales! SUSY vs $SUSY$
Sample point in parameter space:

\[(m_h, m_b, m_{\text{SUSY}}, \tan \beta) = (146, 70, 10^6, 5)\]

**Units: GeV where appropriate**

- charginos \(\sim 116\) GeV
- wino \(\sim 116\) GeV
- bino (DM) \(\sim 70\) GeV
- gluino \(\sim 989\) GeV
- higgsino \(\sim 3970\) GeV

(poor choice of parameters)

**E.G. TRILEPTON**

Virtual Z, invariant mass has kinematic edge

\[m_{\tilde{\chi}} + m_Z > m_{\tilde{W}}\]

\[\left(p_{e^+} + p_{e^-}\right) \leq \left(m_{\tilde{\chi}} - m_{\tilde{W}}\right)\]

Long lived gluino is still the smoking gun
CONCLUSION

- Maybe nature is finely tuned (high scale)
  - Forget about hierarchy and $\Lambda$ problems
  - Low scale physics should focus on GUT, DM, etc.

- **Split Supersymmetry**
  - Fine tuning: send $M_{SUSY}$ to a high scale
  - Scalar partners no longer problematic
  - Experimental signature: long lived gluinos

- Philosophy?
  - No need to mention anthropics
  - ... but a signal of Split SUSY might force us to reconsider naturalness
CONCLUSION

SPECIAL THANKS TO

DAN WOHNS

FOR VOLUNTEERING ME FOR THIS TALK

2001: A SPACE ODYSSEY
Aw man, is this guy still talking?

**EXTRA SLIDES**

Today's lesson: $W_0$ or "Witten's Dog"

- Neutron Enlarged Steaming Hot Dark Matter
- Superdoublesymmetric String Theory

\[ \Omega = \frac{\Omega_{DM}}{\Omega_{M}} \left( \frac{\Omega_{DM}}{\Omega_{M}} + \Omega_{\Lambda} \right) \]

\[ e^\gamma = \frac{e^\lambda}{e^\alpha} \]
ANOTHER WAY OUT OF THE HIERARCHY

- **Extra dimensions**: fundamental Planck scale can be low (~TeV)
- **Effective** 4D Planck scale much higher
- Also string-motivated model
- Does not **solve** Hierarchy, just reparameterizes it as...
  - Radius of compactification
  - Warp factor

"TEACH THE CONTROVERSY"

Is anthropic reasoning reasonable?

A Universe Without Weak Interactions

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Quantum Horizons of the Standard Model Landscape

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**SUPER_SPLIT SUPERSYMMETRY**


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**FIG. 1:** Mass scales in the MSSM, Split SUSY and Supersplit SUSY.

**ALL SUSY PARTICLES DECOUPLED AT PLANCK SCALE, LEAVING ONLY STANDARD MODEL AT THE LOW SCALE.**

*(i.e. no predictions.)*
Recommended reading

- Arkani-Hamed, Dimopoulos. hep-th/0405159 (first paper)
- Bousso. arXiv:0708.4231 (TASI lectures on the cosmological constant)
- Lykken. eConf C040802 (SLAC SSI lecture on naturalness, video.)
- Arkani-Hamed. pirsa.org/07080007 (Perimeter summer school lecture on low-energy SUSY)

  - Ch. 11: Open questions, proposed solutions

- Dine. *Supersymmetry and String Theory.*
  - Ch. 11.3: Why is one Higgs mass negative?

- Tim Hollowood. “Cutoffs and Continuum Limits: a Wilsonian Approach to Field Theory.” The most accessible explanation of the renormalisation group at a `deep’ level.
References not mentioned


- A. Maloney, E. Silverstein and A. Strominger, hep-th/0205316