



# SPLIT SUPERSYMMETRY

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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 ANTHROPIIC PRINCIPLES

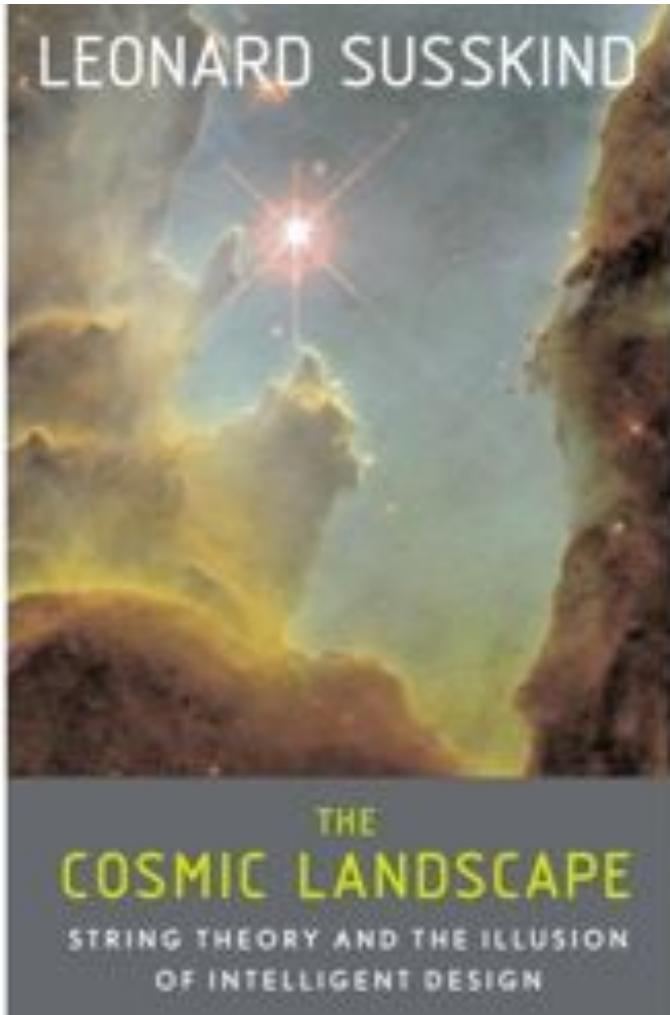
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**The Weak Anthropic Principle:** Isn't it great that humans have evolved to a point where they can make a living in universities?

**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]

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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)

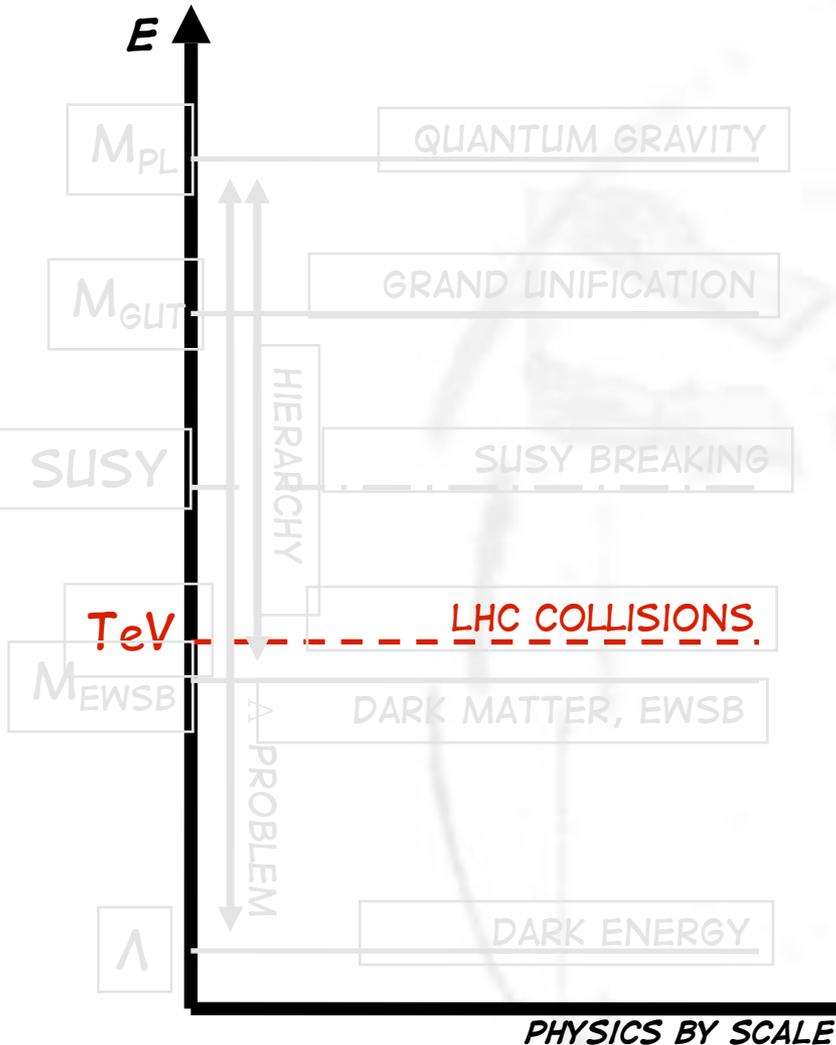


# OUTLINE

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

# THE IMPORTANCE OF SCALES

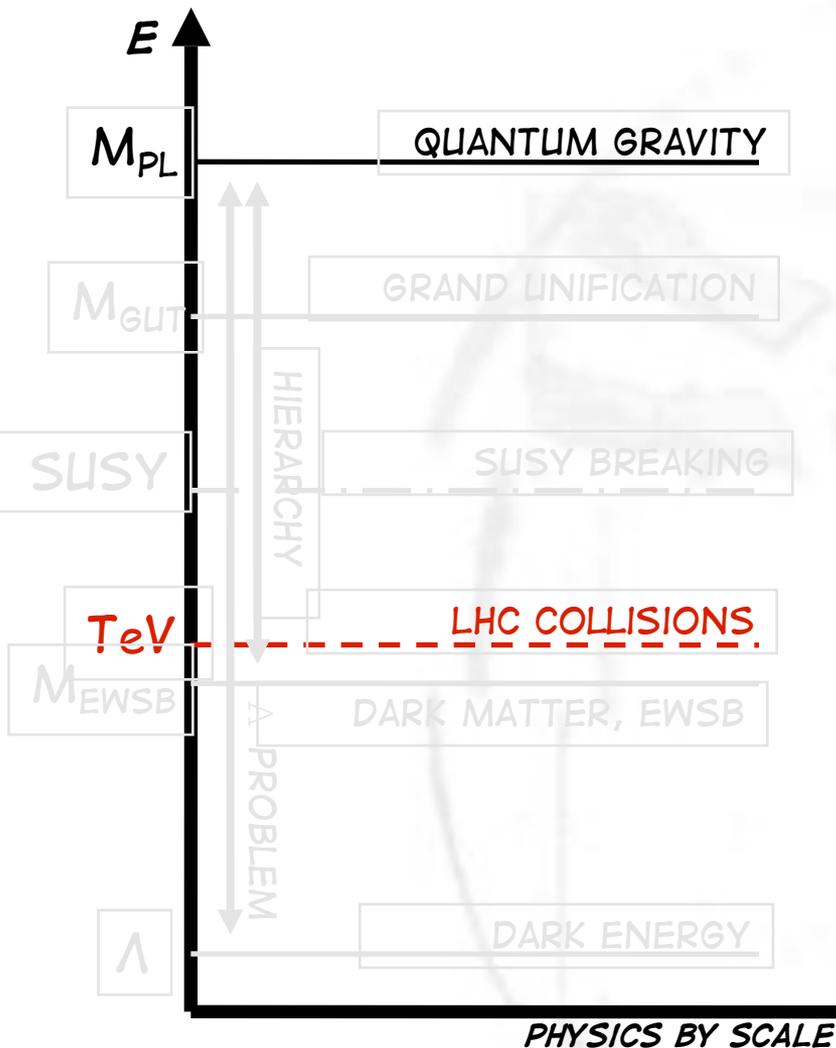


- Physics at very different scales **decouple**.  
RG FLOW NEAR UV FIXED POINT

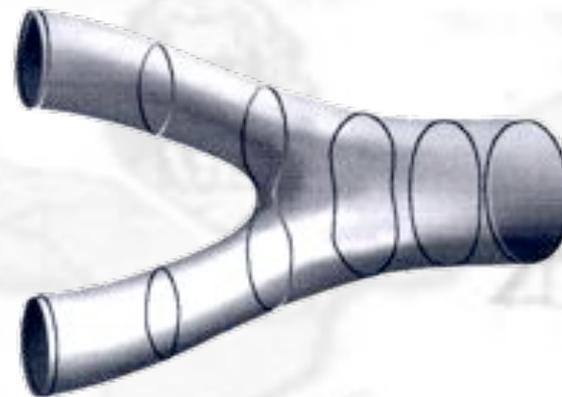
"A CHEF DOES NOT NEED TO KNOW GAUGE THEORY"  
-S. DIMOPOULOS

- **Naturalness** ("GOOD")  
PARAMETERS ARE  $O(1)$   $(\Lambda_{UV})^{4-D}$
- **vs. fine-tuning**  
"BAD" DEPENDENCE OF PHYSICS ON DECIMAL POINTS

# 5 BIG IDEAS AND 5 IMPORTANT SCALES

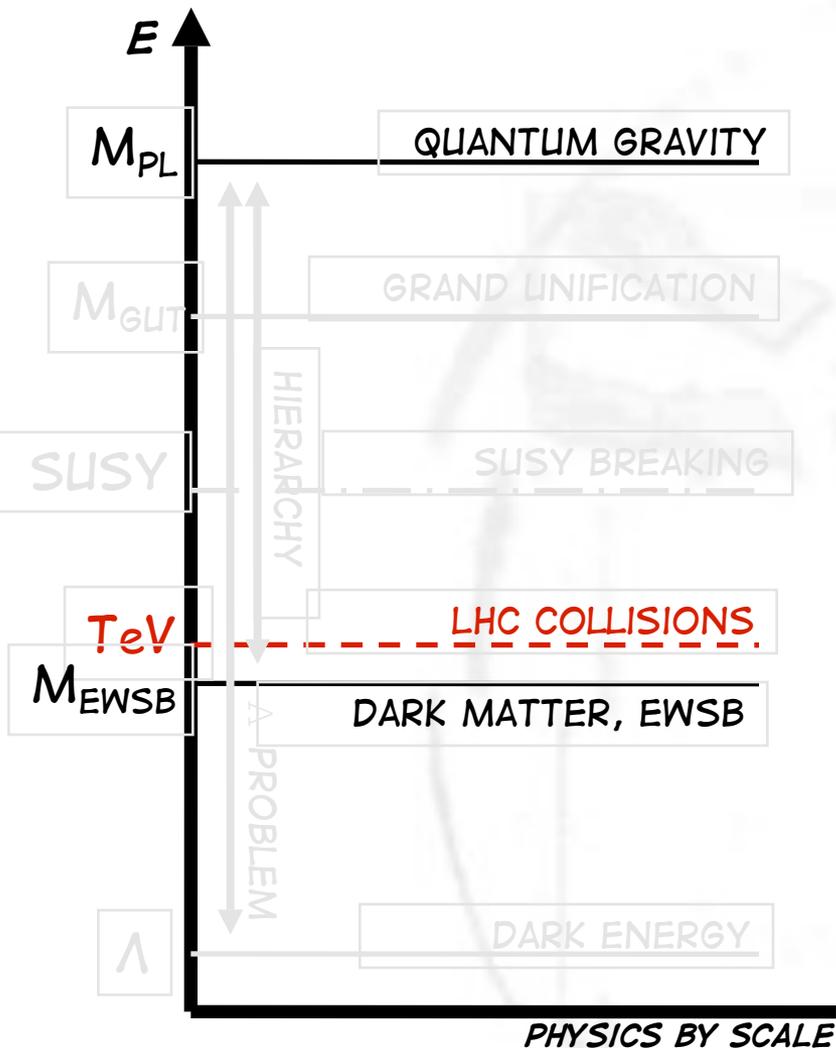


## 1. Quantum Gravity



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

# 5 BIG IDEAS AND 5 IMPORTANT SCALES

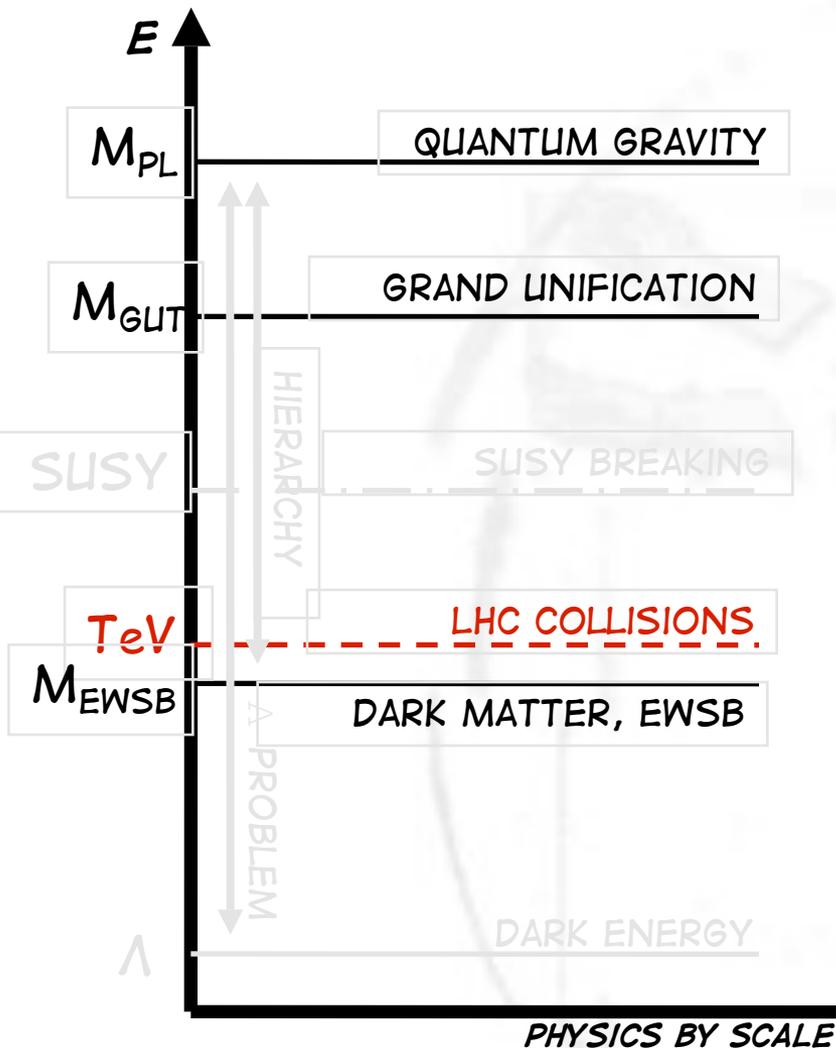


## 2. Dark Matter

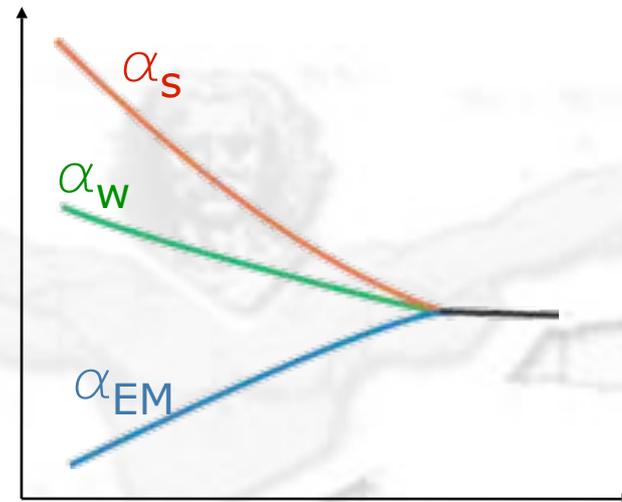


- $\sim 200$  GeV
- WIMP particle?
- EWSB mechanism?

# 5 BIG IDEAS AND 5 IMPORTANT SCALES

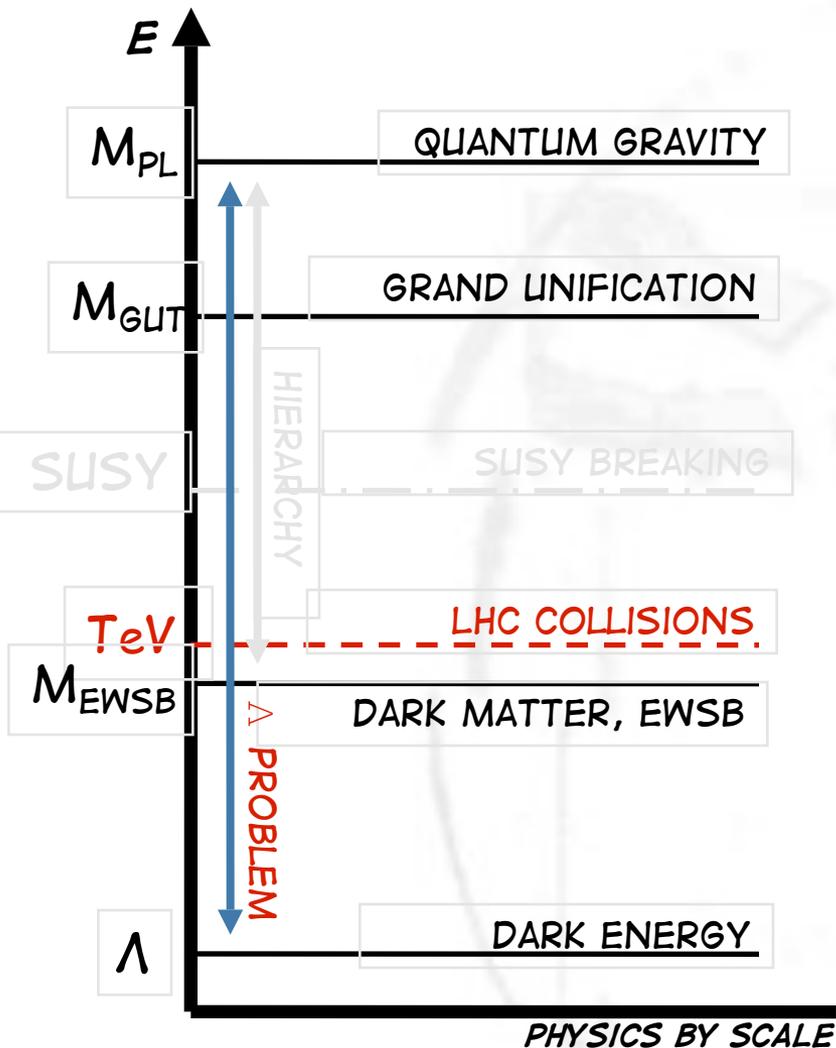


## 3. Grand Unification

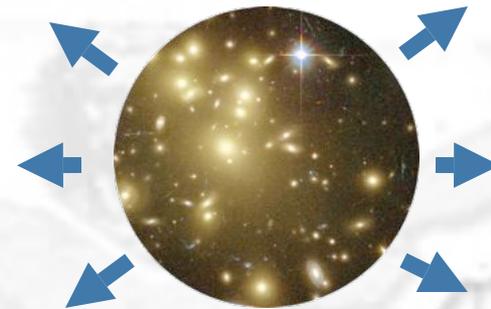


- $SU(3) \times SU(2) \times U(1) \subset SU(5)$
- FCNC,  $P^+$  DECAY
- LEP: SUSY?
- NEUTRINO SEE-SAW

# 5 BIG IDEAS AND 5 IMPORTANT SCALES

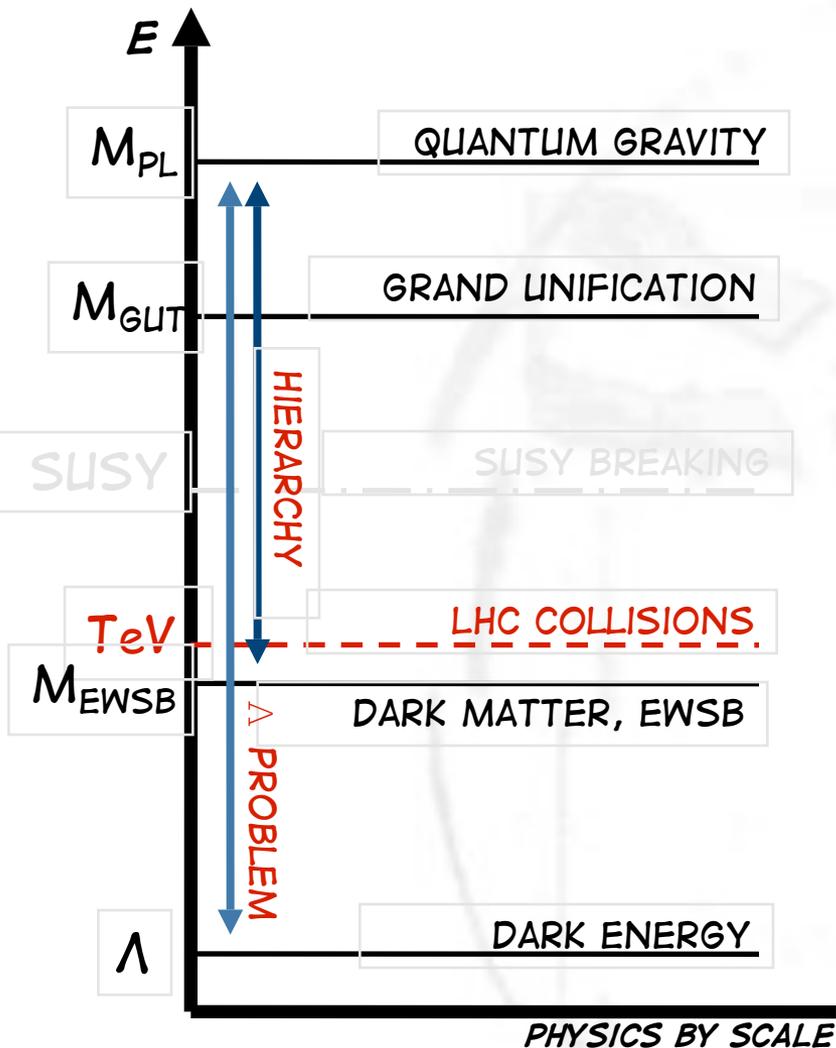


## 4. $\Lambda$ Problem



- 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

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

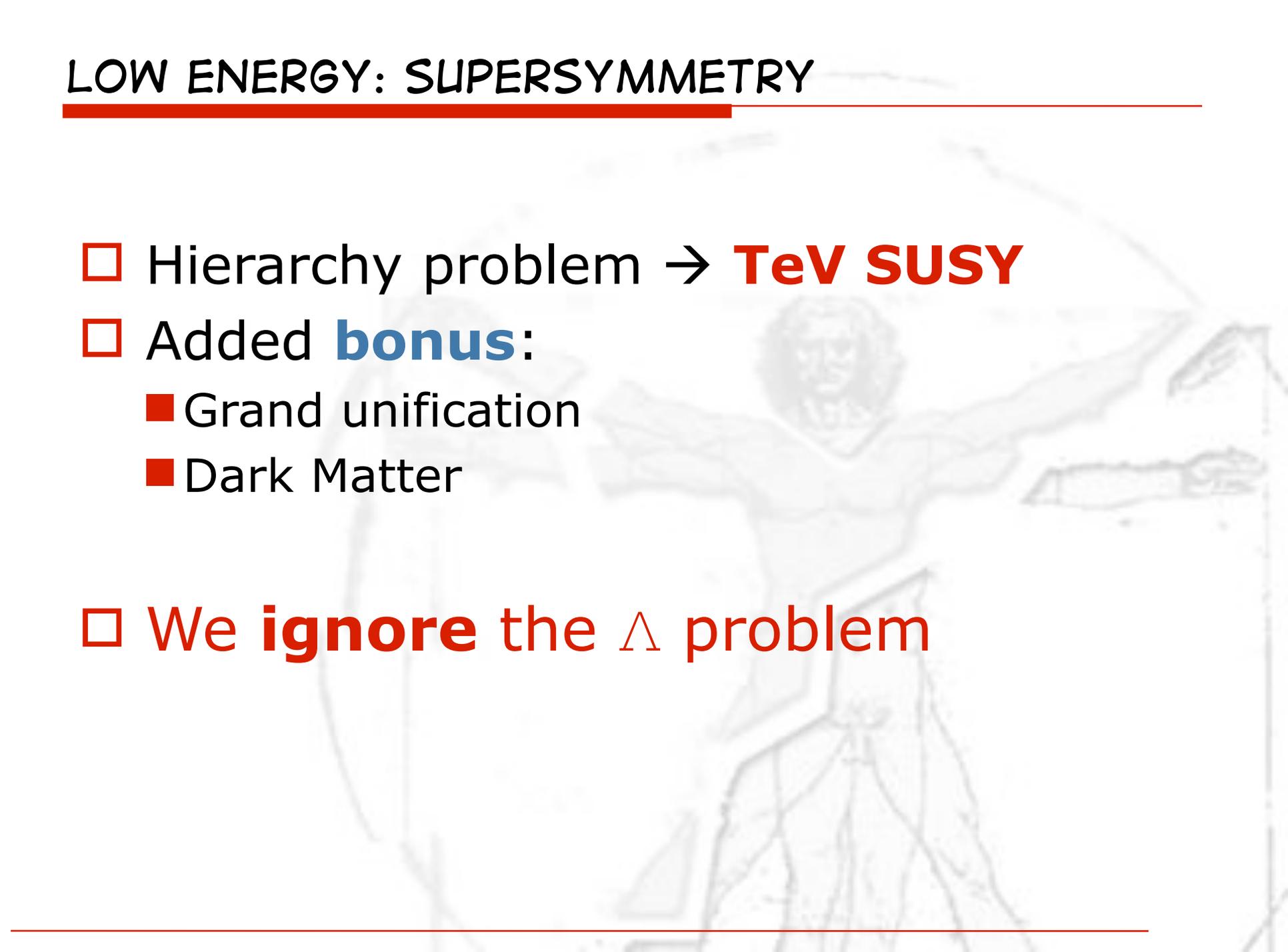
- $M_{\text{scalar}}$  not protected
- $M_{EWSB}/M_{PL} = 10^{-17}$ 
  - Fine tuning?
  - or  $M_H \sim M_{BSM}$ ?

# SUPERSYMMETRY

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I'M *SUPER*, THANKS FOR ASKING.  
-SOUTH PARK

# LOW ENERGY: SUPERSYMMETRY



- Hierarchy problem → **TeV SUSY**
  - Added **bonus**:
    - Grand unification
    - Dark Matter
  
  - We **ignore** the  $\Delta$  problem
-

# LOW ENERGY: SUPERSYMMETRY

FERMIONS  $\leftrightarrow$  BOSONS

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

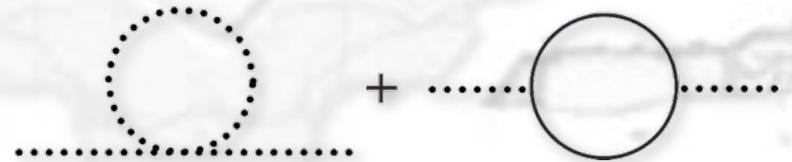
- SPACETIME SYMMETRY
- ONLY EXTENSION WITHIN COLEMAN-MANDULA
- CANCELS  $M_H$  DIVERGENCE



SM PARTICLE



SPARTICLE

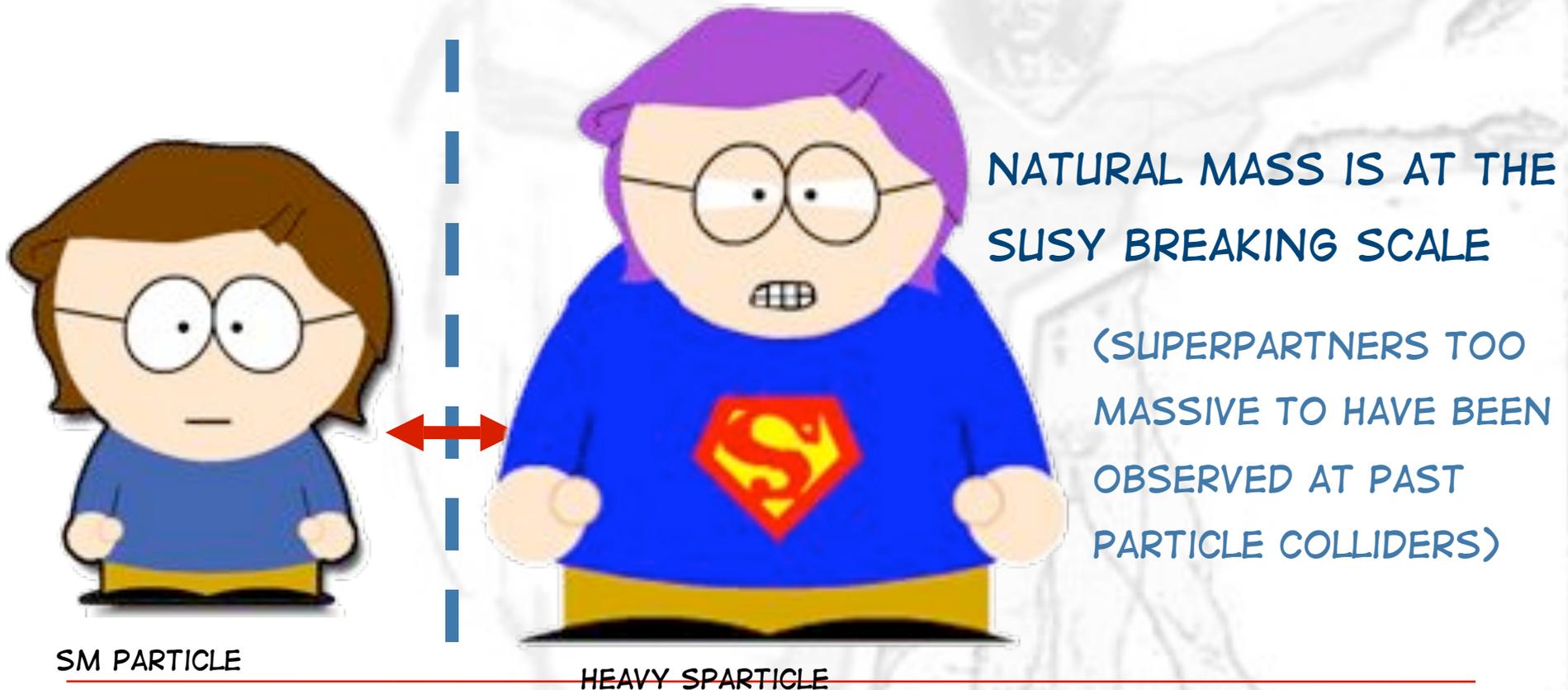


■ To date, no SUSY particles detected

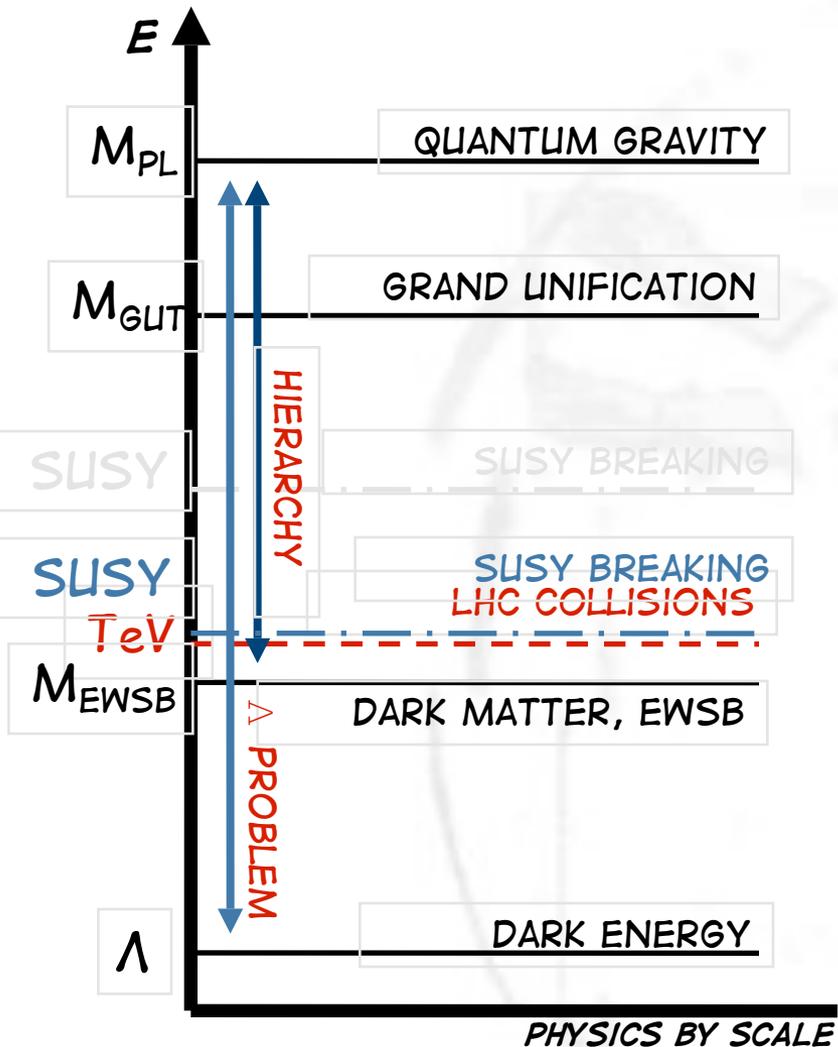
# LOW ENERGY: SUSY BREAKING

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



# SUSY: SCORECARD (IMPORTANT!)



## 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)
- We still have  $\Lambda \sim 10^{60} M_{SUSY}^4$

## Poop list: things we didn't want

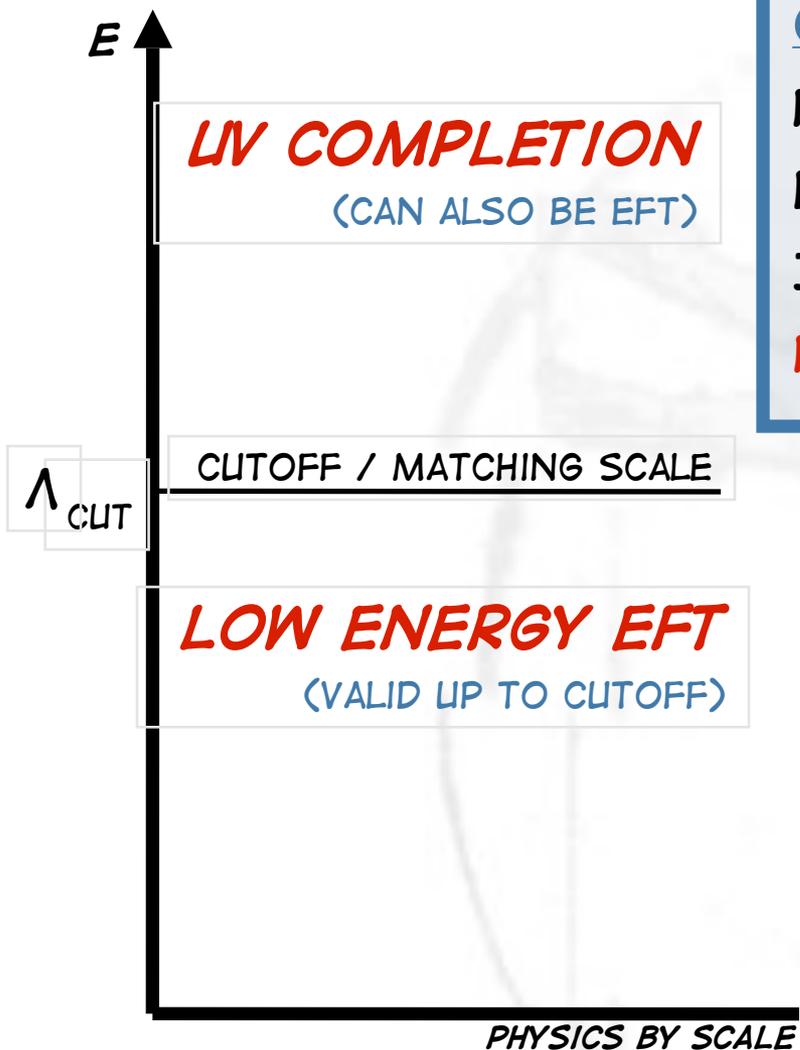
- Flavor changing neutral currents
  - $(B-L)$  violation and  $p^+$  decay
  - Electric dipole moment, etc.
- All mediated by scalar superpartners!*
- 'little hierarchy' problem
  - $\mu$  problem

# NATURALNESS

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A MODEL IS *FINE-TUNED* IF A PLOT OF THE ALLOWED PARAMETER SPACE MAKES YOU WANNA PUKE. -D.E. KAPLAN

# WILSONIAN PHILOSOPHY



**Q: HOW DOES EFT DEPEND ON LVT?**

FINITE TERMS:

INSENSITIVE

DIMENSIONLESS:

$$\text{LOG } \Lambda_{\text{CUT}}$$

IRRELEVANT OP:

$$1/\Lambda_{\text{CUT}}^{(+)}$$

RELEVANT OP:

$$\Lambda_{\text{CUT}}^{(+)}$$



**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:**

$$M \ll \Lambda_{\text{CUT}}, \text{ SYM RESTORED IF } M=0$$

E.G. FERMION MASSES

**SUPERNATURAL:**

$$\text{LVT SETS } M=M^* \text{ AT } \Lambda_{\text{CUT}}$$

E.G. TECHNICOLOUR, GARDEN-VARIETY SUSY

**UNNATURAL:**

$$\text{FINE TUNED, } M \ll \Lambda_{\text{CUT}}$$

SENSITIVE TO RADIATIVE CORRECTIONS

WE'VE TAKEN NATURALNESS AS MOTIVATION FOR NEW PHYSICS... WHAT IF NATURE IS UNNATURAL? WHAT KIND OF LVT WOULD DO THIS?

FINE TUNING VIA SONIC SCREWDRIVER?

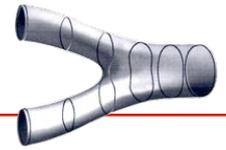


# THE STRING LANDSCAPE

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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?



PHYSICAL REVIEW D **68**, 046005 (2003)

### de Sitter vacua in string theory

Shamit Kachru,<sup>1,2</sup> Renata Kallosh,<sup>1</sup> Andrei Linde,<sup>1</sup> and Sandip P. Trivedi<sup>3</sup>

<sup>1</sup>*Department of Physics, Stanford University, Stanford, California 94305-4060, USA*

<sup>2</sup>*SLAC, Stanford University, Stanford, California 94309, USA*

<sup>3</sup>*TIFR, Homi Bhabha Road, Mumbai 400 005, India*

(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

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Different points in the landscape are different possible universes.



# THE LANDSCAPE OF METASTABLE VACUA

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Is there a **vacuum selection principle**?

ANALOGY: LOCATION OF THEORY VS. EXPERIMENT GRAD OFFICES

**BASEMENT**

EXPERIMENT

**TOP FLOOR**

THEORY



"Crystal Hills, Hoheems, Austria"

© Peter Mathis, Hoheems, Austria

THIS IS AN ENTROPICALLY UNLIKELY CONFIGURATION...  
BUT THERE'S AN UNDERLYING SELECTION PRINCIPLE.

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# THE ANTHROPIC/ENTROPIC PRINCIPLE

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SU-ITP 02-11  
hep-th/0204027

## The Anthropic Landscape of String Theory

*L. Susskind*

Department of Physics  
Stanford University  
Stanford, CA 94305-4060

### Abstract

In this lecture I make some educated guesses, about the landscape of string theory vacua. Based on the recent work of a number of authors, it seems plausible that the landscape is unimaginably large and diverse. Whether we like it or not, this is the kind of behavior that gives credence to the Anthropic Principle. I discuss the theoretical and conceptual issues that arise in developing a cosmology based on the diversity of environments implicit in string theory.

## Actually...

- ❑ Atomic Principle
- ❑ Galactic Principle
- ❑ Etc.



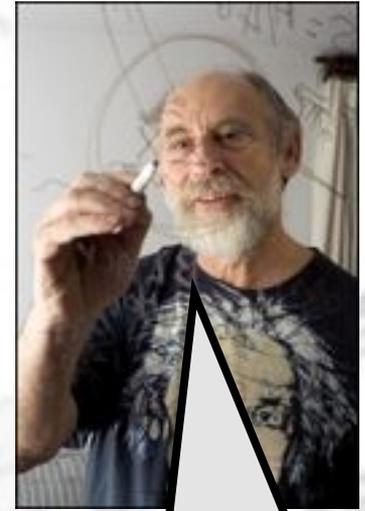
Maybe: **vacuum state chosen randomly!** We're only here because this is where we can be.

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# A BRIEF HISTORY OF ANTHROPISM IN PHYSICS



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



VOLUME 59, NUMBER 22

PHYSICAL REVIEW LETTERS

30 NOVEMBER 1987

## Anthropic Bound on the Cosmological Constant

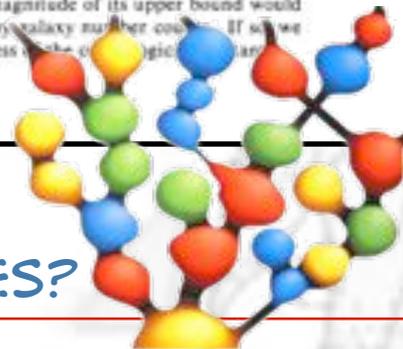
Steven Weinberg

*Theory Group, Department of Physics, University of Texas, Austin, Texas 78712  
(Received 5 August 1987)*

In recent cosmological models, there is an "anthropic" upper bound on the cosmological constant  $\Lambda$ . It is argued here that in universes that do not recollapse, the only such bound on  $\Lambda$  is that it should not be so large as to prevent the formation of gravitationally bound states. It turns out that the bound is quite large. A cosmological constant that is within 1 or 2 orders of magnitude of its upper bound would help with the missing-mass and age problems, but may be ruled out by galaxy number counts. If so, we may conclude that anthropic considerations do not explain the smallness of the cosmological constant.

PACS numbers: 98.80.Dv, 04.20.Cv

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



WEST COAST HIPPIES?



# ASKING THE RIGHT QUESTIONS...

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- 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

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LIVING WITH FINE TUNING...

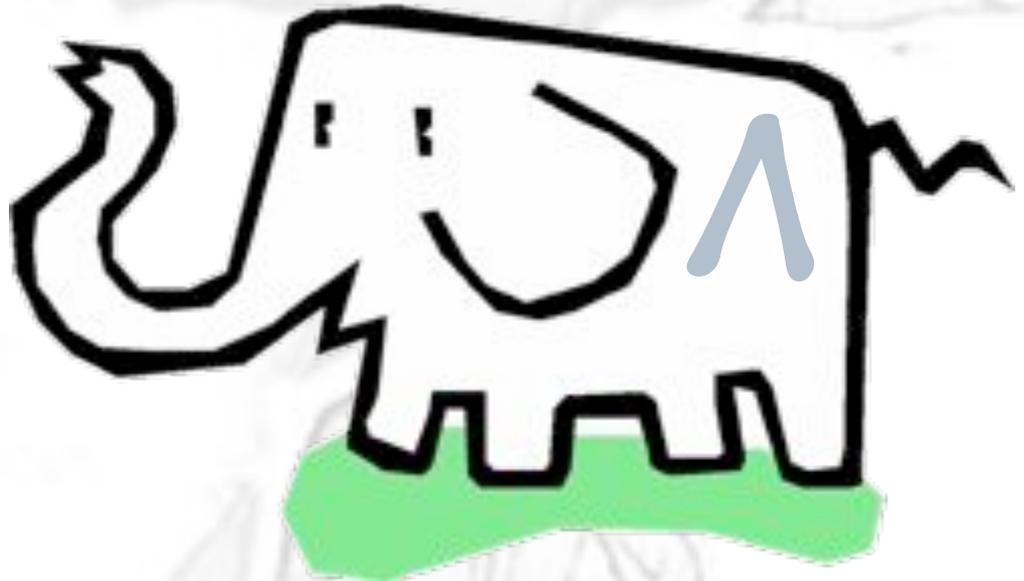
"OUR PAPER DIDN'T BECOME TOP-CITED UNTIL SOMEONE CAME UP WITH A CATCHY NAME."  
-S. DIMOPOULOS (PARAPHRASED)

# 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  $\Delta$  problems **aren't problems at all!**



HOLY MOLY, IT'S  
AN ELEPHANT!!  
... **BUT WHAT ABOUT  
SUPERSYMMETRY?**



# SPLIT SUPERSYMMETRY

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- **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”

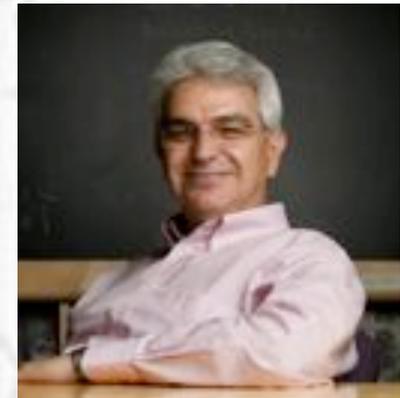


Supersymmetric Unification  
Without Low Energy Supersymmetry  
And Signatures for Fine-Tuning at the LHC

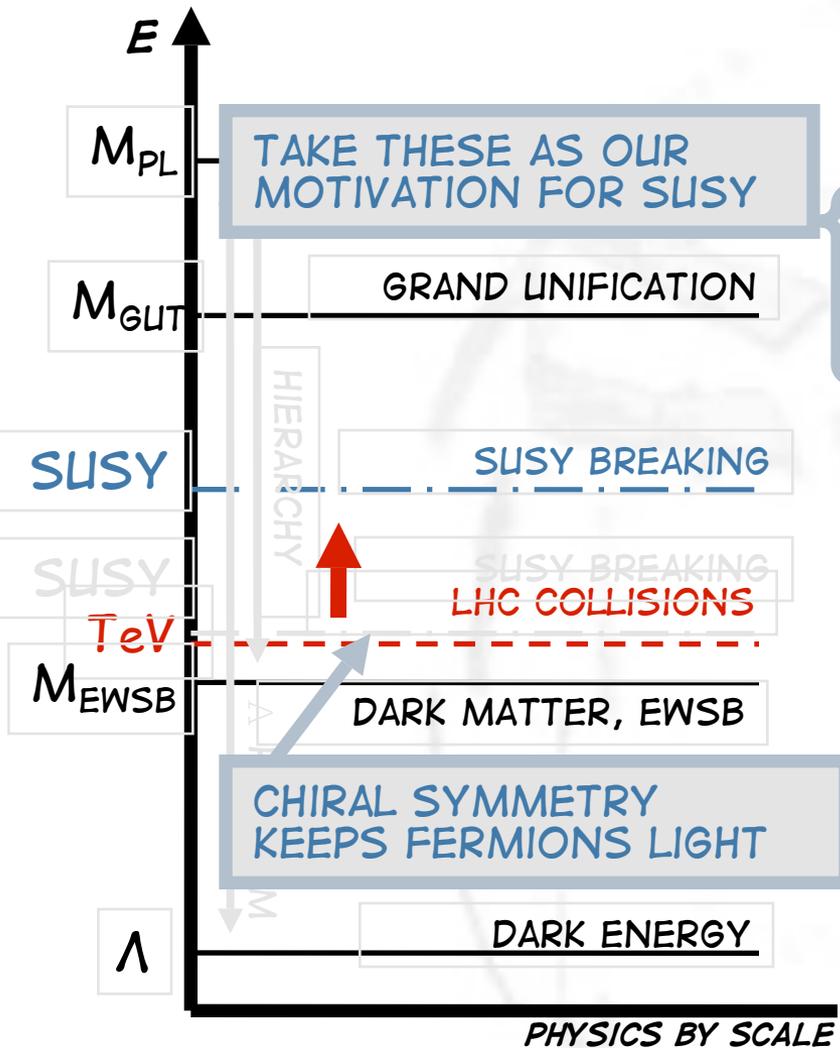
Nima Arkani-Hamed<sup>a</sup> and Savas Dimopoulos<sup>b</sup>

<sup>a</sup>Jefferson Laboratory of Physics, Harvard University  
Cambridge, Massachusetts 02138

<sup>b</sup>Physics Department, Stanford University  
Stanford, California, 94305



# REASSESSING SUSY, FINELY-TUNED VERSION



## Checklist: things we want

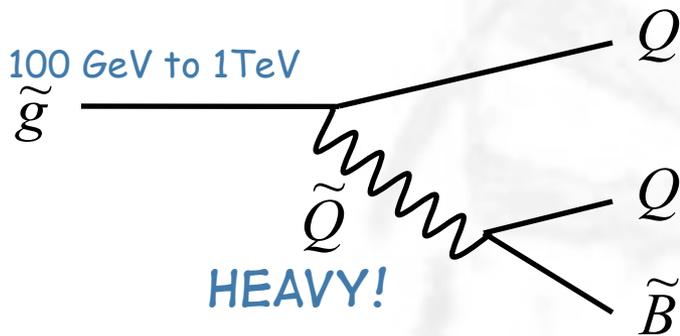
- Hierarchy:  $m_H$  naturally light
- LSP Dark Matter (R-parity)
- Grand Unification (LEP)
- Can generate Higgs potential
- $\Delta$  problem (ignore at low energy)

## Poop list: things we didn't want

- Flavor changing neutral currents
  - $(B-L)$  violation and  $p^+$  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!**



## Smoking gun:

- Displaced vertex
- Stopped gluinos

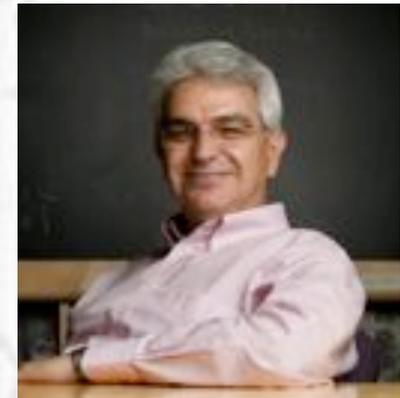


### Supersymmetric Unification Without Low Energy Supersymmetry And Signatures for Fine-Tuning at the LHC

Nima Arkani-Hamed<sup>a</sup> and Savas Dimopoulos<sup>b</sup>

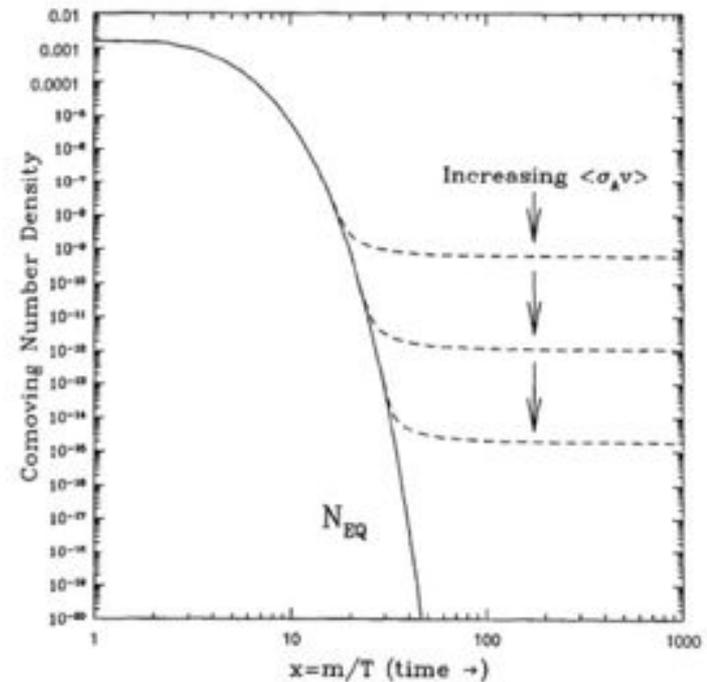
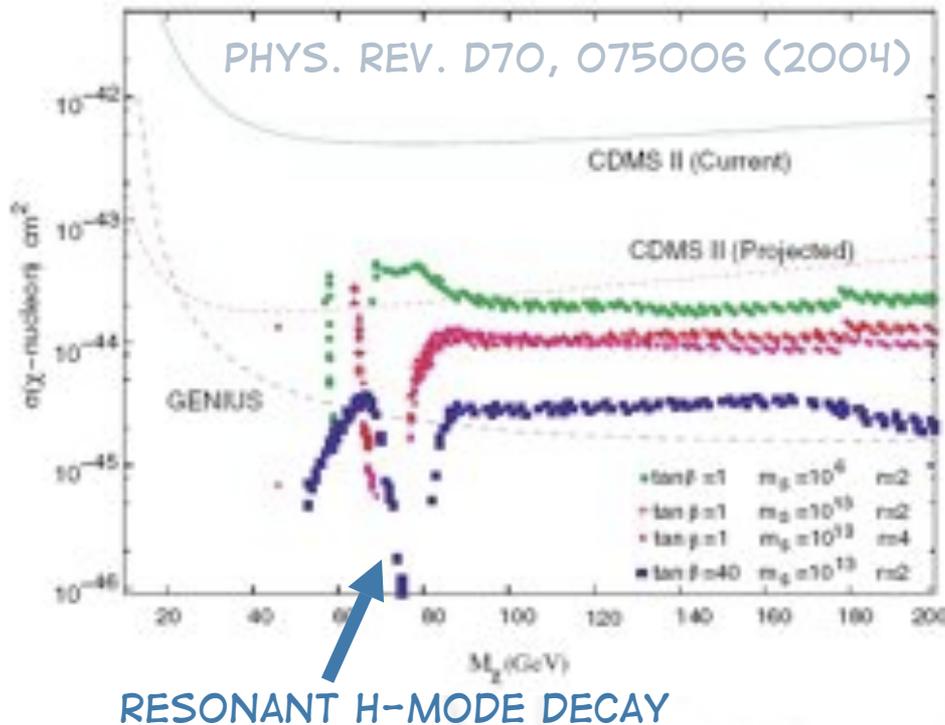
<sup>a</sup>Jefferson Laboratory of Physics, Harvard University  
Cambridge, Massachusetts 02138

<sup>b</sup>Physics Department, Stanford University  
Stanford, California, 94305



# SPLIT SUSY PHENOMENOLOGY: E.G. BINO DM

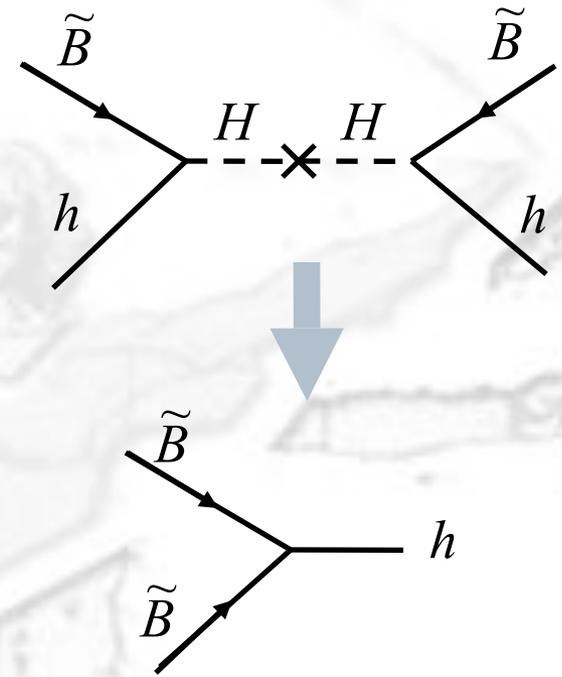
- MSSM parameters  $\rightarrow$  LSP decay cross section
- Boltzmann equation  $\rightarrow$  DM Relic Density



- **Constrained** by astro/cosmo observations

# SPLIT SUSY PHENOMENOLOGY: MORE DETAIL

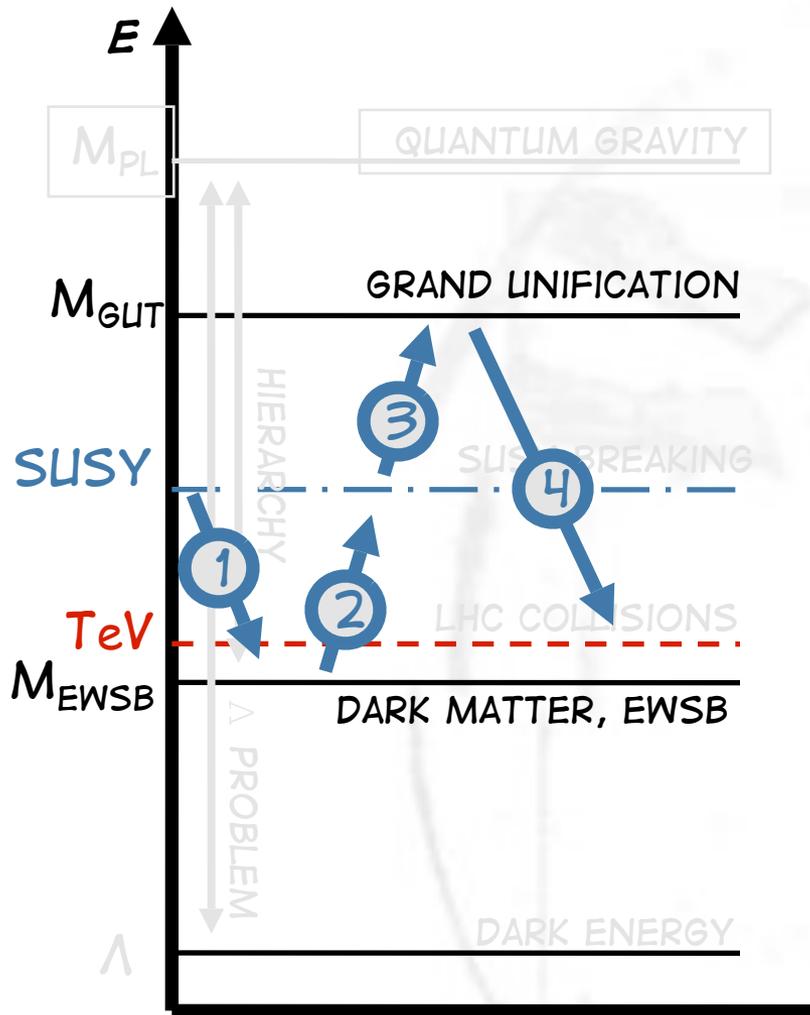
$$\begin{aligned}
 L_{eff} = & L_{SM} + M_{\tilde{B}}\tilde{B}\tilde{B} + M_{\tilde{g}}\tilde{g}\tilde{g} + \mu H_u H_d \\
 & + \sqrt{2}\kappa_u h^\dagger \tilde{W} H_u + \sqrt{2}\kappa_d h^\dagger \tilde{W} H_d \\
 & + \frac{\sqrt{2}}{2}\kappa'_u h^\dagger \tilde{B} H_u + \frac{\sqrt{2}}{2}\kappa'_d h^\dagger \tilde{B} H_d \\
 & - m^2 h^\dagger h - \frac{\lambda}{2} (h^\dagger h)^2 + \text{h.c.}
 \end{aligned}$$



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

$$g_{eff} = -2i \frac{v\kappa'_u \kappa'_d}{\mu}$$

# SPLIT SUSY PHENOMENOLOGY: MORE DETAIL



1. DETERMINE EFFECTIVE COUPLINGS FROM SUSY LAGRANGIAN, CONSTRAIN USING  $\Omega_{\text{DM}}$
2. MATCH TO  $M_{\text{SUSY}}$  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~~

# SPLIT SUSY PHENOMENOLOGY: MORE DETAIL

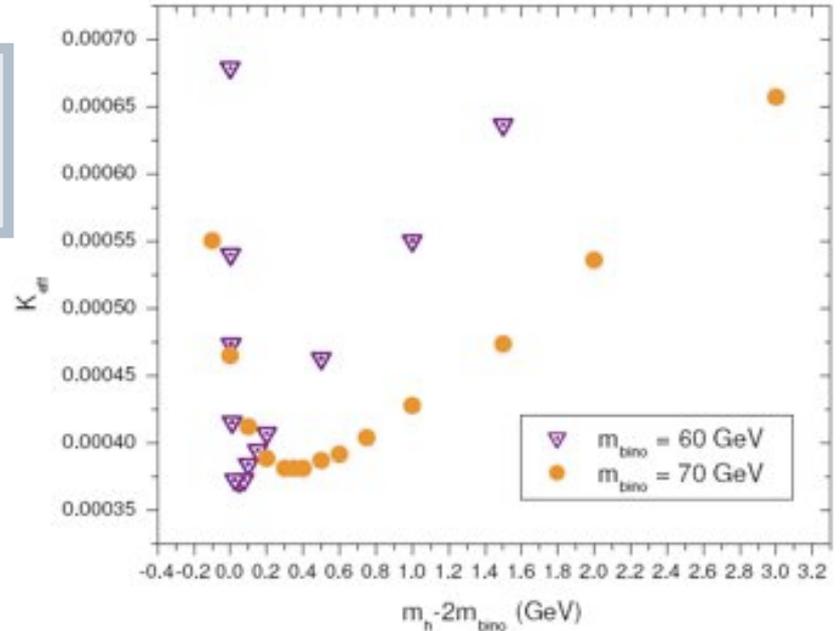
Sample point in parameter space:

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

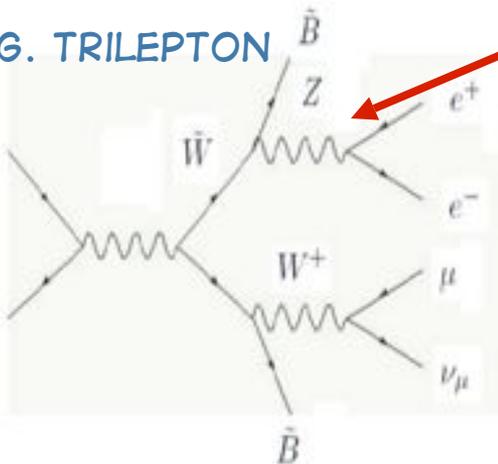
UNITS: GEV WHERE APPROPRIATE

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)



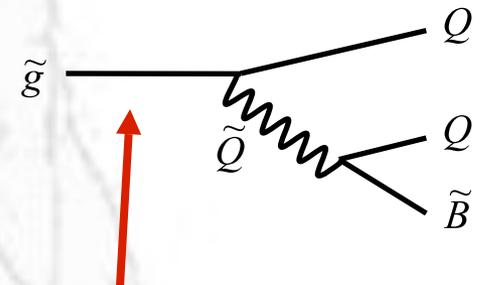
E.G. TRILEPTON



VIRTUAL Z, INVARIANT MASS HAS KINEMATIC EDGE

$$m_{\tilde{B}} + m_Z > m_{\tilde{W}}$$

$$(p_{e^+} + p_{e^-}) \leq (m_{\tilde{B}} - m_{\tilde{W}})$$



LONG LIVED GLUINO IS STILL THE SMOKING GUN

# CONCLUSION

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- Maybe nature is finely tuned (high scale)
  - Forget about **hierarchy** and  **$\Delta$  problems**
  - Low scale physics should focus on GUT, DM, etc.
- **Split Supersymmetry**
  - Fine tuning: send  $M_{\text{SUSY}}$  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

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SPECIAL THANKS TO  
***DAN WOHN'S***  
FOR VOLUNTEERING ME FOR THIS TALK



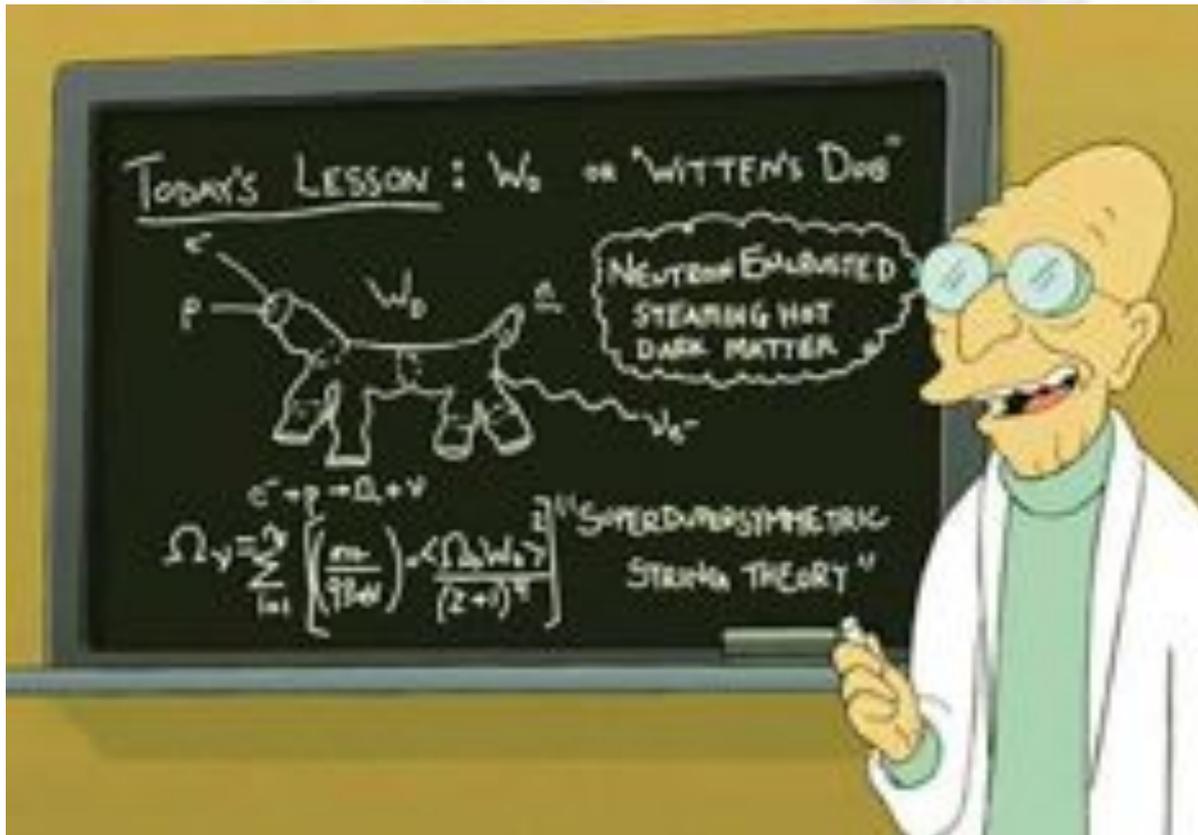
2001: A SPACE ODYSSEY

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Aw man, is this guy still talking?

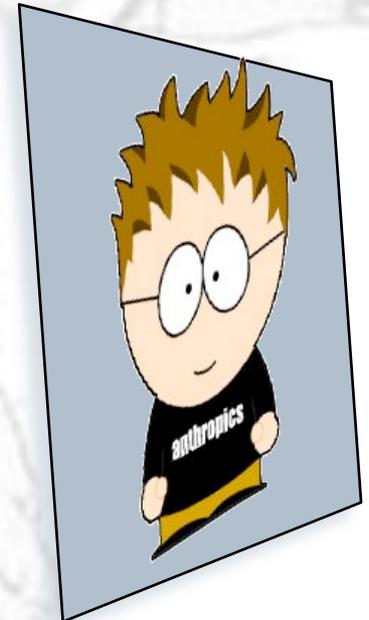
# EXTRA SLIDES

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# ANOTHER WAY OUT OF THE HIERARCHY

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



ADD Phys.Lett. B429 (1998) 263

Randall-Sundrum Phys.Rev.Lett. 83 (1999) 3370

# "TEACH THE CONTROVERSY"

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## Is anthropic reasoning reasonable?

SLAC-PUB-11795, hep-ph/0604027

### A Universe Without Weak Interactions

Roni Harnik<sup>1</sup>, Graham D. Kribs<sup>2</sup>, and Gilad Perez<sup>3</sup>

<sup>1</sup>*Stanford Linear Accelerator Center, Stanford University, Stanford, CA 94309 and  
Physics Department, Stanford University, Stanford, CA 94305*

<sup>2</sup>*Department of Physics and Institute of Theoretical Science  
University of Oregon, Eugene, OR 97403*

<sup>3</sup>*Theoretical Physics Group, Ernest Orlando Lawrence Berkeley National Laboratory,  
University of California, Berkeley, CA 94720*

roni@slac.stanford.edu, kribs@uoregon.edu, gperez@lbl.gov

### QUANTUM HORIZONS OF THE STANDARD MODEL LANDSCAPE

Nima Arkani-Hamed<sup>a</sup>, Sergei Dubovsky<sup>a,b</sup>,  
Alberto Nicolis<sup>a</sup> and Giovanni Villadoro<sup>a</sup>

<sup>a</sup> *Jefferson Physical Laboratory,  
Harvard University, Cambridge, MA 02138, USA*

<sup>b</sup> *Institute for Nuclear Research of the Russian Academy of Sciences,  
60th October Anniversary Prospect, 7a, 117312 Moscow, Russia*

# PHYSICS HUMOUR...

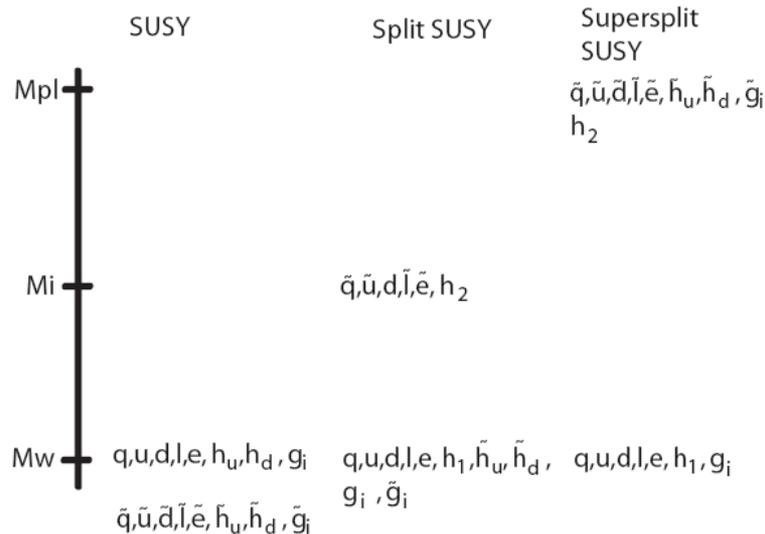
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HEP-TH/0503249

## ***SUPERSPLIT SUPERSYMMETRY***

P. FOX, D.E. KAPLAN, E. KATZ, E. POPPITZ, V. SANZ, M. SCHMALTZ, M. SCHWARTS, N. WEINER

POSTED TO ARXIV: 1 APRIL 2005



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

**(I.E. NO PREDICTIONS.)**

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

# Recommended reading

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- 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. pirs.org/07080007 (Perimeter summer school lecture on low-energy SUSY)
  
- Burgess, Moore. *The Standard Model: A Primer*.
  - 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

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  - Carroll. The Cosmological Constant. *Living Rev. Relativity* **4**, (2001), 1. URL (cited on 13 March 2007): <http://www.livingreviews.org/lrr-2001-1>
  
  - Kumar. A Review of Distributions on the String Landscape. *Int.J.Mod.Phys.* A21 (2006) 3441-3472
  - M. Douglas, "The statistics of string / M theory vacua", *JHEP* 0305, 46 (2003).
  - A. Maloney, E. Silverstein and A. Strominger, hep-th/0205316
  - R. Bousso and J. Polchinski, "Quantization of four-form fluxes and dynamical neutralization of the cosmological constant", *JHEP* **06**, 006 (2000).
  
  - Giudice and Romanino. "Split Supersymmetry", *Nucl.Phys.* B699 (2004) 65-89
  - Arkani-Hamed, Dimopoulos, Giudice, Romanino. "Aspects of Split Supersymmetry", *Nucl.Phys.* B709 (2005) 3-46
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