Title: To Split or Not to Split

Date: Apr 02, 2013 01:00 PM

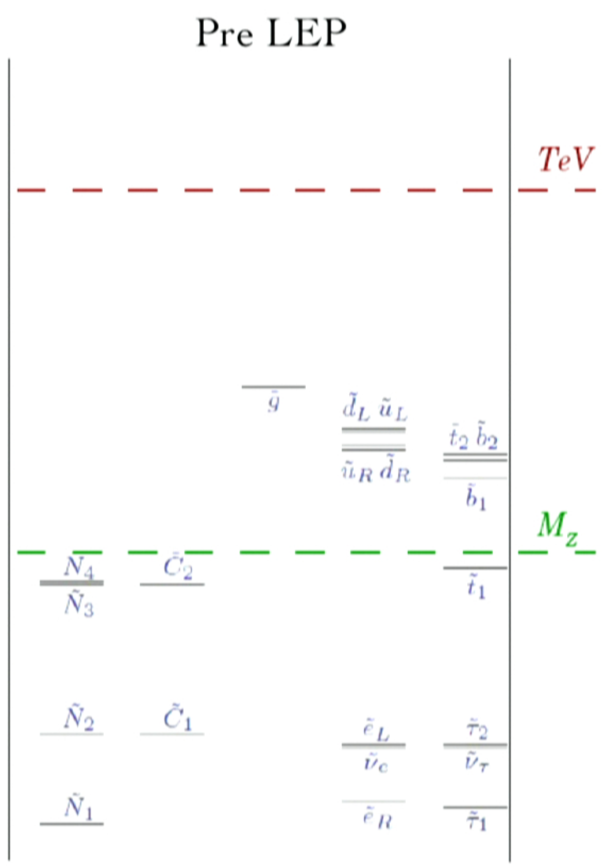
URL: http://pirsa.org/13040115

Abstract: Physics
is at a crossroad that leads either to Naturalness or the Multiverse. While the confirmation of gauge coupling unification in the early 90s gave a tremendous boost to naturalness and to low energy SUSY, the lack of evidence for new physics beyond the standard model at the LHC points to a paucity of new particles near the weak scale. This suggests that the weak scale is tuned and that supersymmetry, if present at all, is realized at higher energies. This points to Split SUSY, a framework motivated by the String Landscape. Fine-tuning electroweak symmetry breaking and the renormalization group evolution of the scalar masses constrains Split model building and I review the expectations at the LHC for the different possible Split SUSY particle spectra.

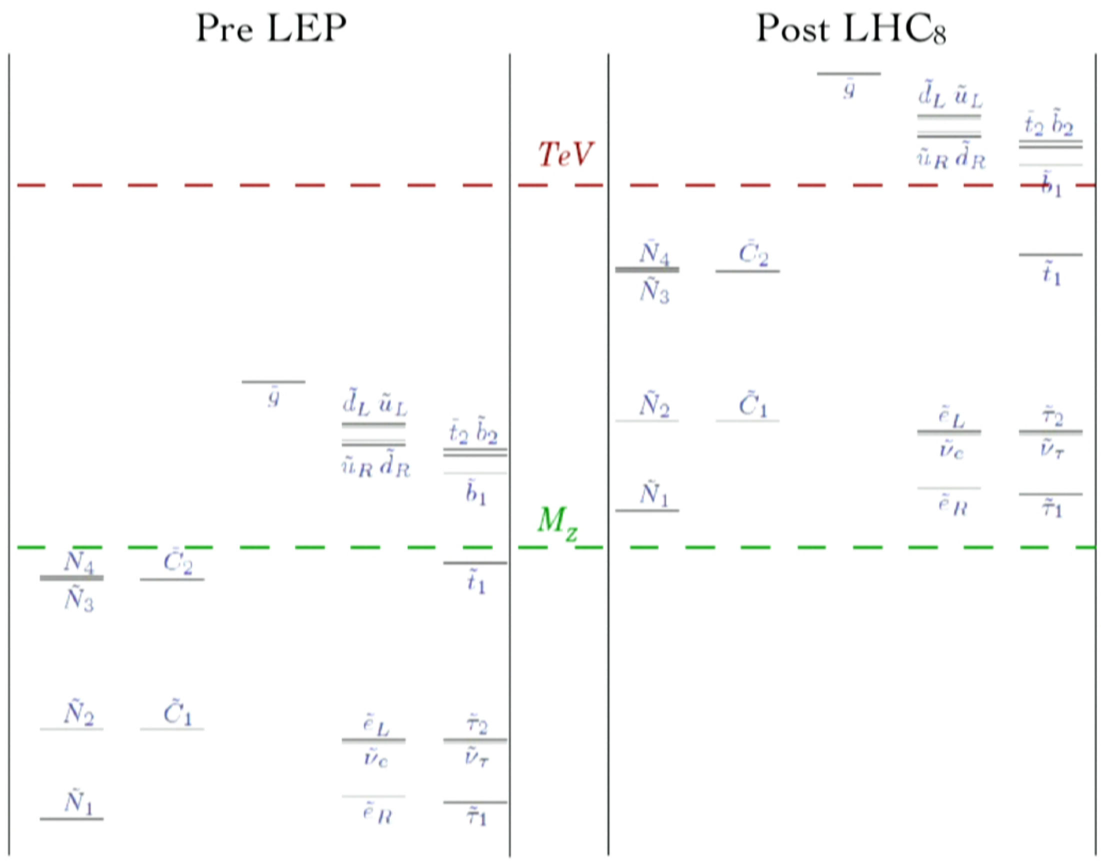
To Split Or Not To Split

Asimina Arvanitaki
Stanford University

The Hard Facts

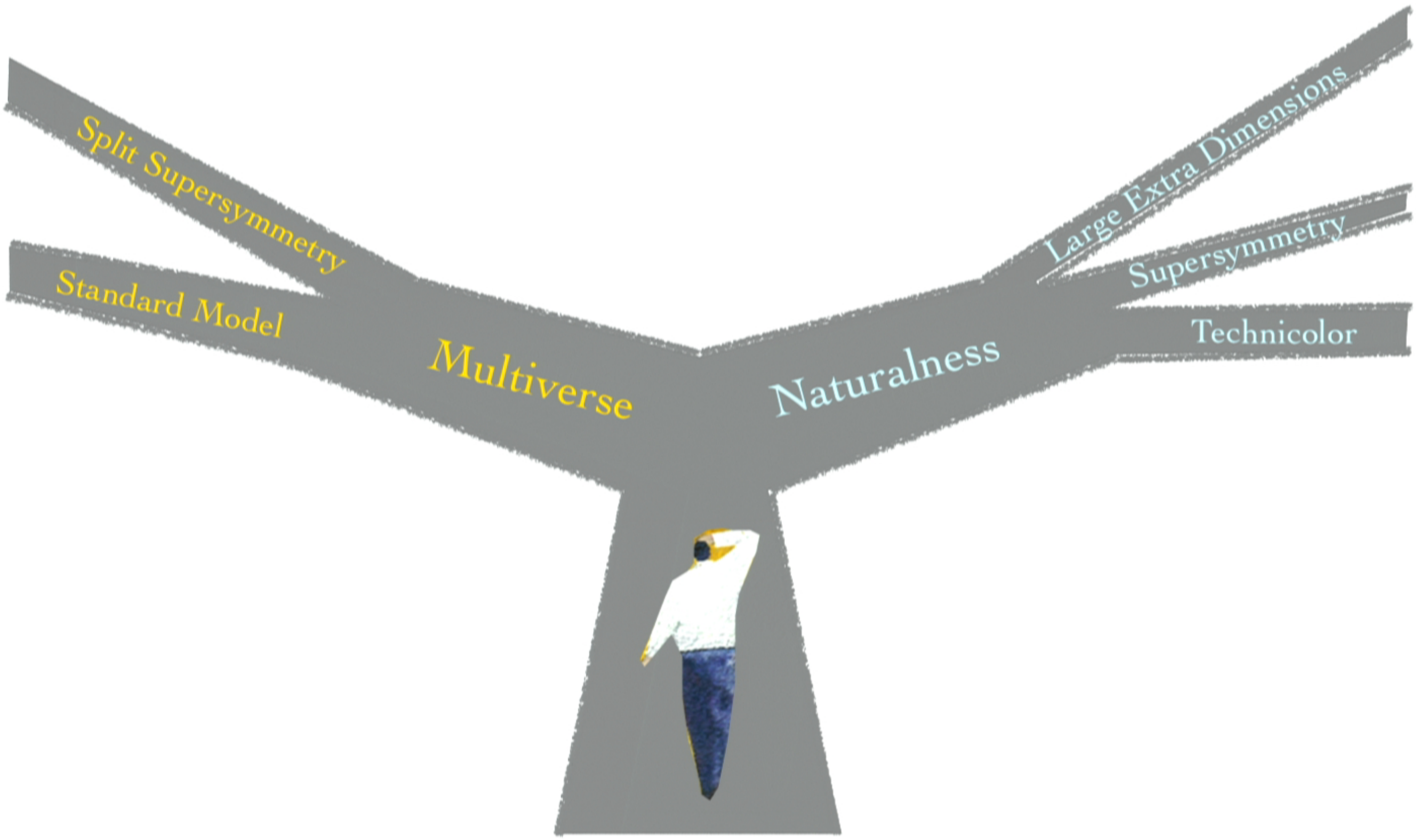


The Hard Facts



The connection with the hierarchy problem is diminished

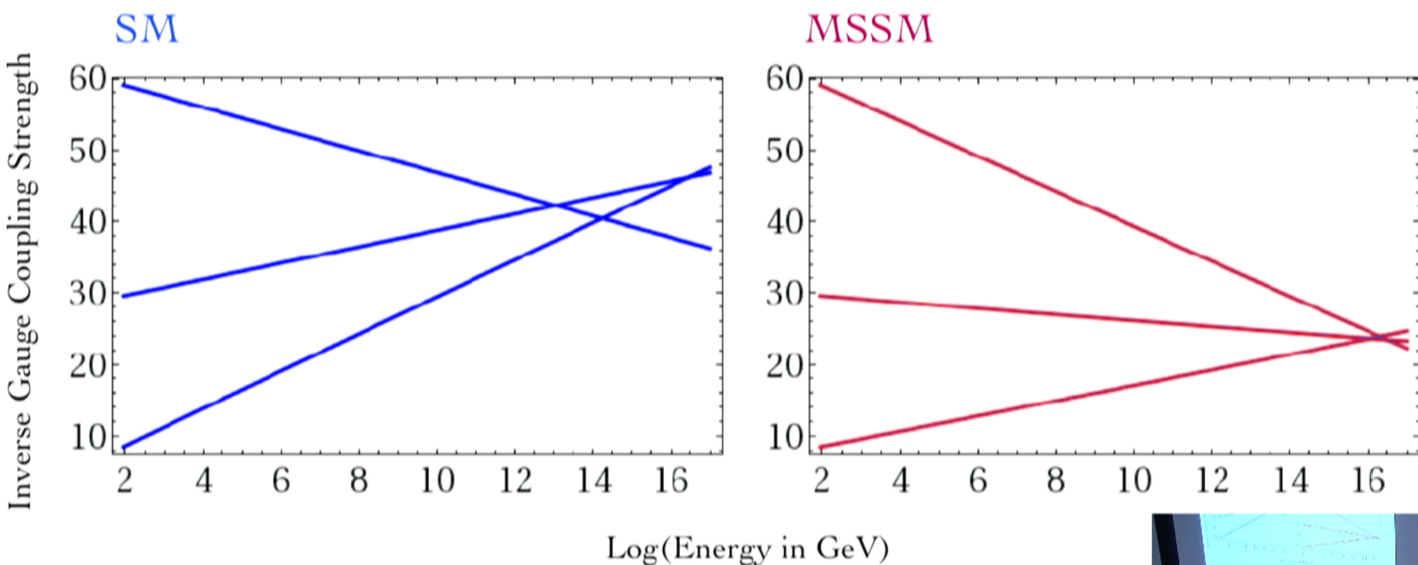
At the Crossroads



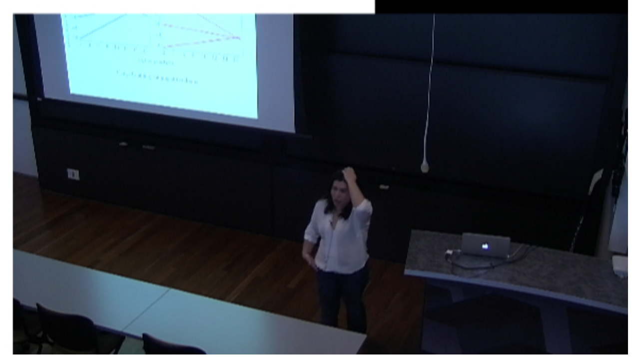
Outline

- Low Energy Supersymmetry
- Split Supersymmetry
    - Models of Mini-Split
    - Phenomenology of Mini-Split
- What will the Higgs tell us?

Why Supersymmetry?



Gauge Coupling running at two loops

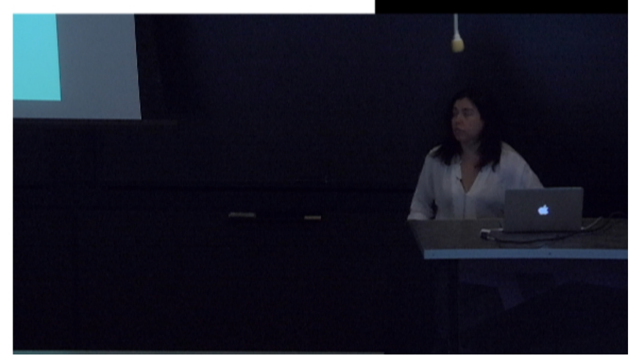


SSM and the Higgs at 125 GeV

- If minimal particle content

$$m_h^2 \leq m_Z^2$$

1. Need stops heavier than several TeV - tuned



SSM and the Higgs at 125 GeV

- If minimal particle content

$$m_h^2 \leq m_Z^2$$

1. Need stops heavier than several TeV - tuned
2. Increase tree level higgs mass with increased quartic

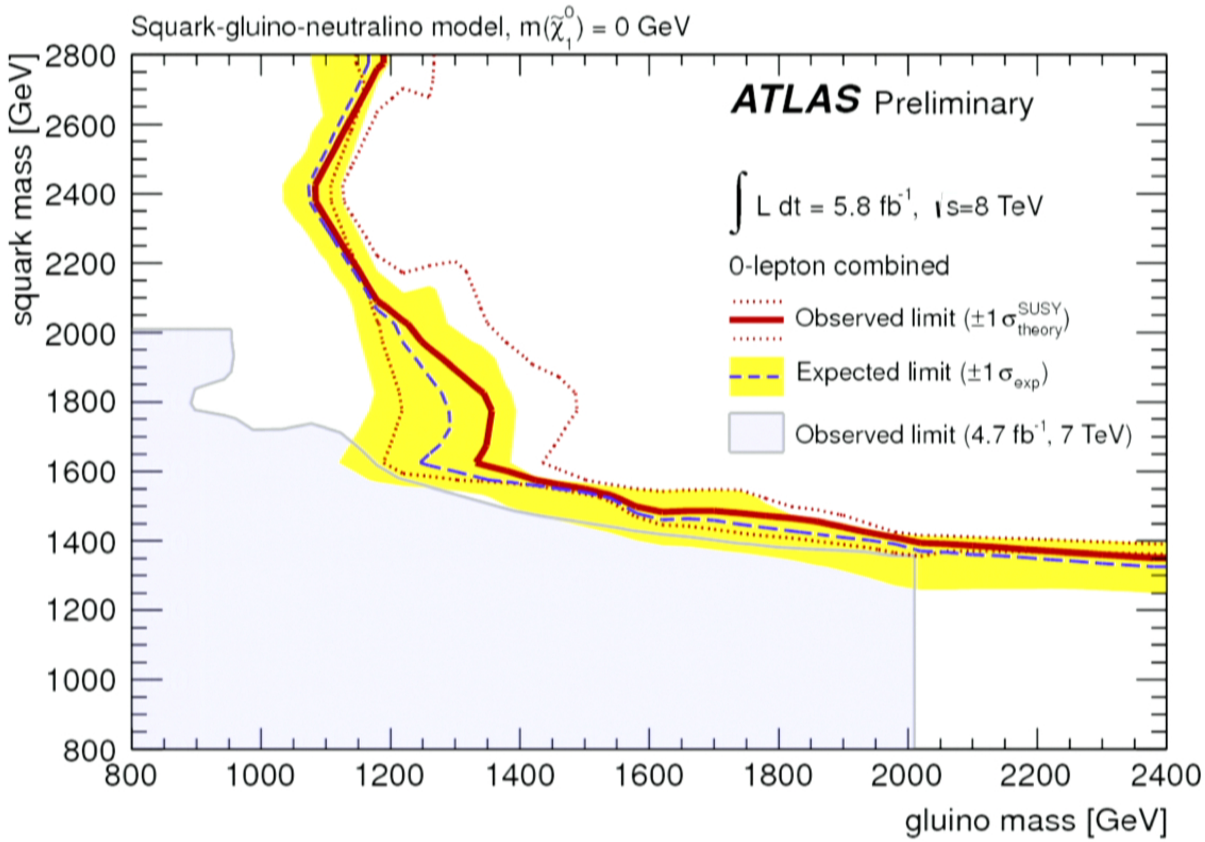
- New singlet - NMSSM

or

- New U(1)$'$ at the TeV scale

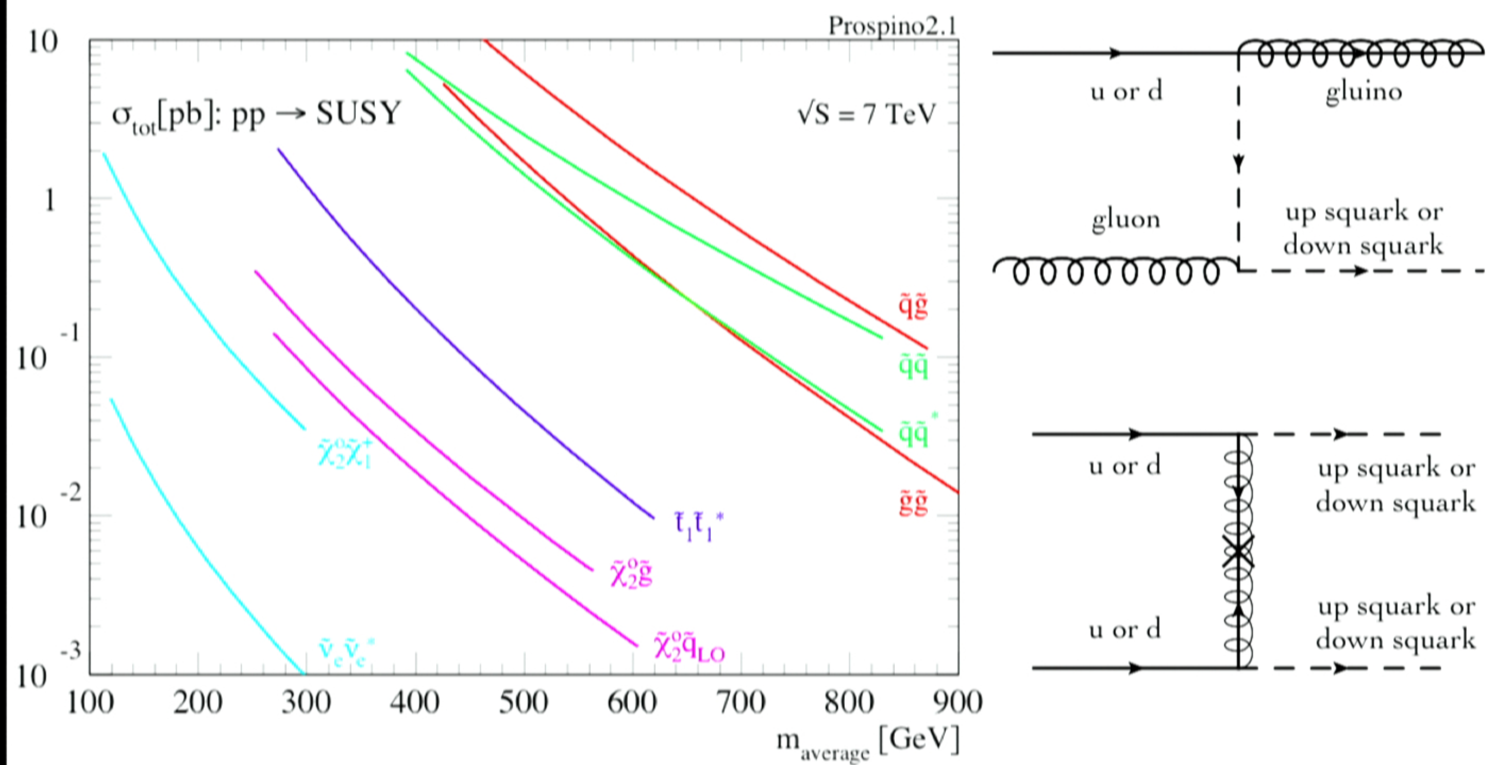
$$m_{h-tree}^2 \leq \left(m_Z^2 + g'^2 v^2\right)$$

The Missing Superpartner Problem



Squark and Gluino Production at the LHC

The importance of the valence quarks



A Way out for Supersymmetry

Dimopoulos, Giudice (1995)

Hierarchy Problem

Favors
light sparticles

LHC bounds

Favors
heavy sparticles

A Way out for Supersymmetry

Dimopoulos, Giudice (1995)

Unnecessary tension:
Depend on Different Sparticles

Hierarchy Problem

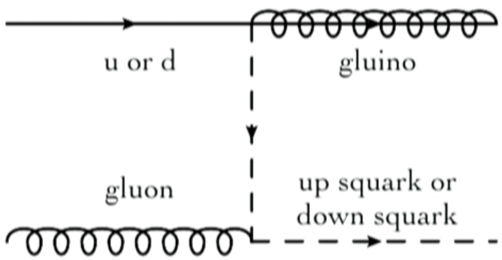
Favors
light sparticles

Stops

LHC bounds

Favors
heavy sparticles

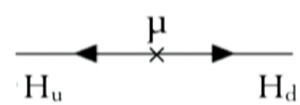
1st family squarks



Natural SUSY or Split Families

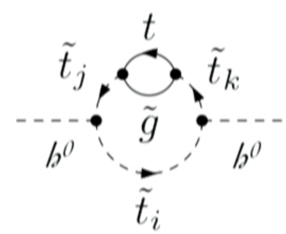
Bare minimum light spectrum:

- For less than 10% tuning:
    - At tree-level: Higgsinos < 250 GeV

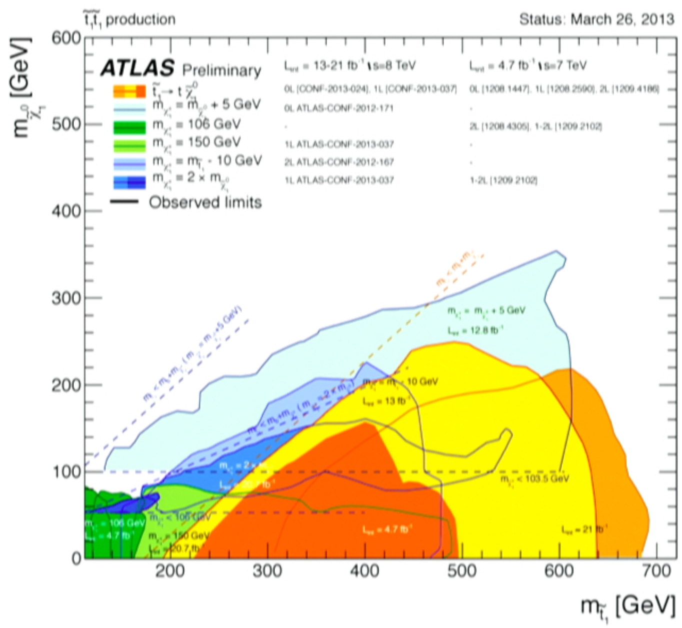


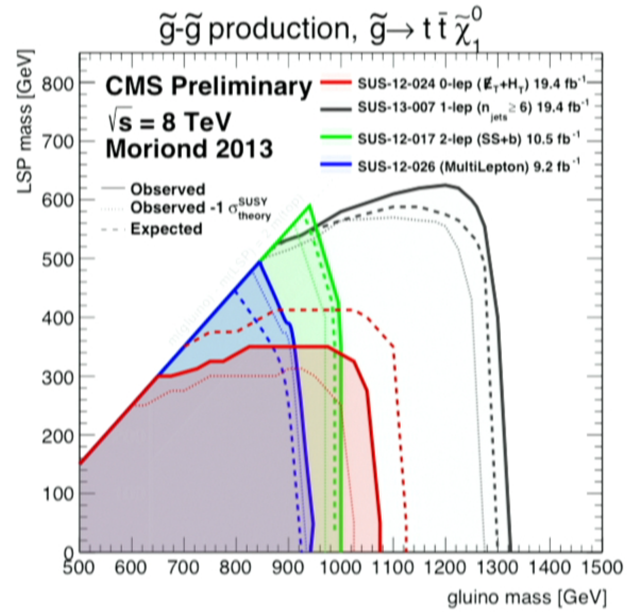
    - At one loop: Stops < 600 GeV

    - At two loops: Gluino < 1.4 TeV



Bounds on Split Families



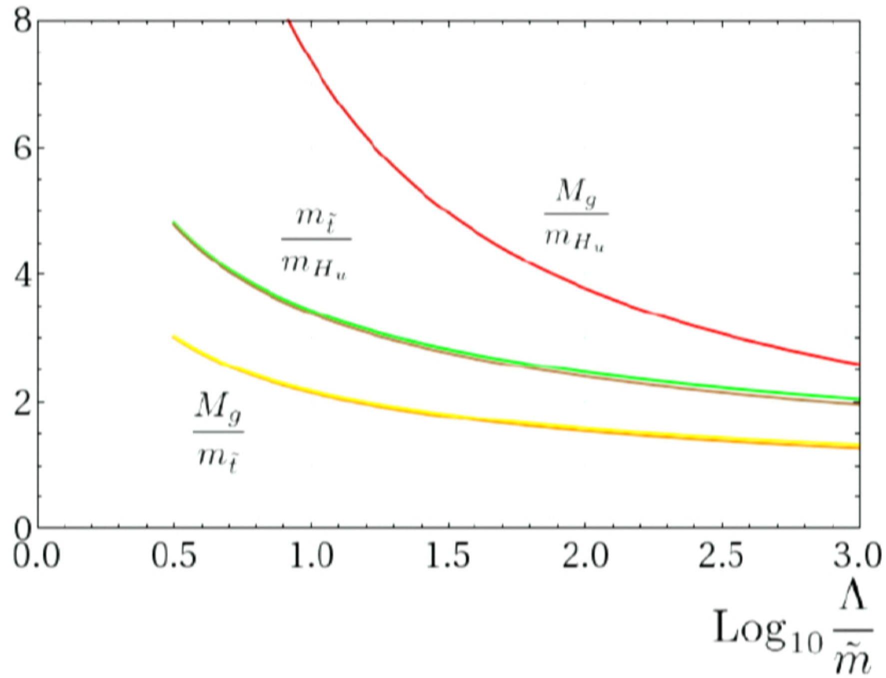


- Stop up to ~ 700 GeV

- Gluino up to ~ 1.3 TeV

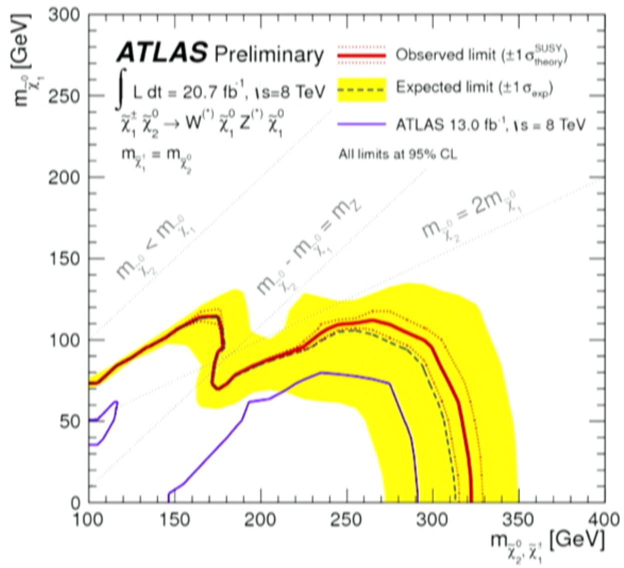
The Gluino Sucks

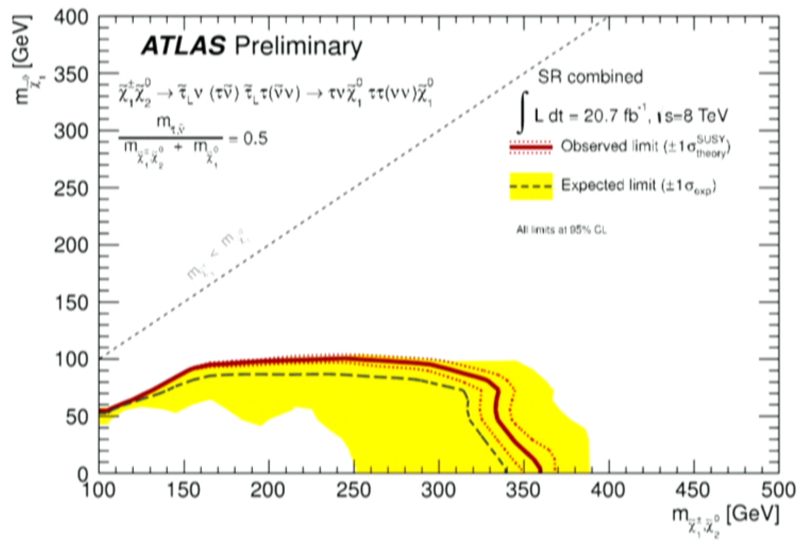
with N. Craig, S. Dimopoulos, G. Villadoro



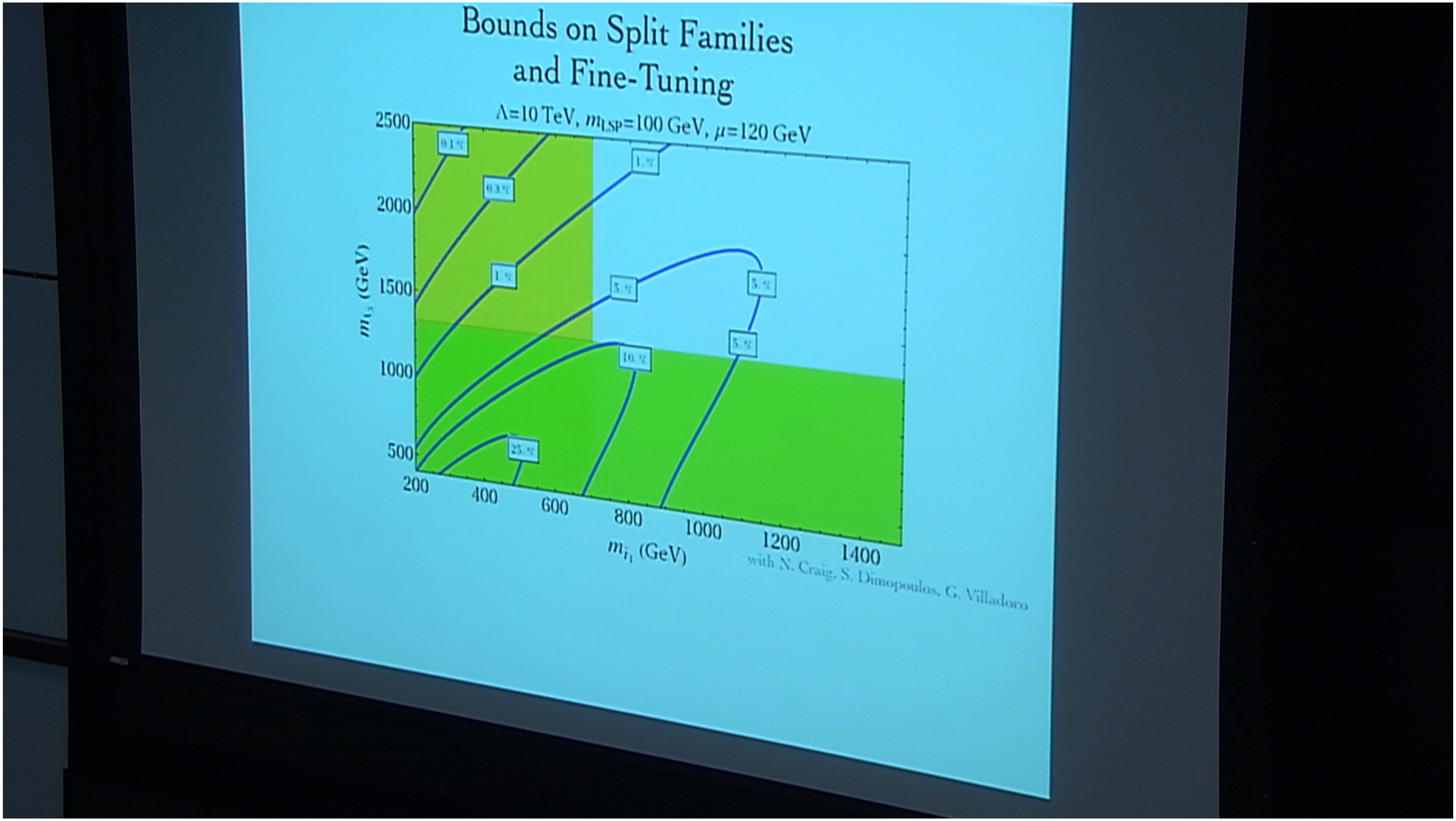
Gluino Bounds constrain all Low Energy Supersymmetry scenarios

Electroweakino Bounds



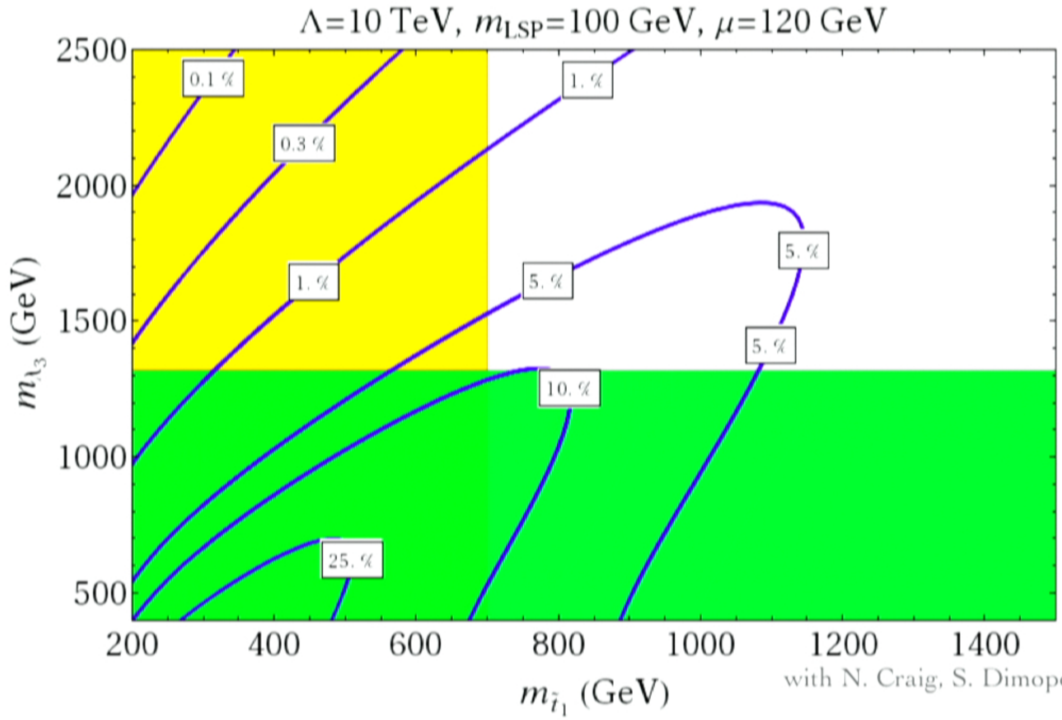


- Naive bound on the Higgsinos: 350 GeV
- Tree-level tuning introduced



Bounds on Split Families
and Fine-Tuning
Λ=10 TeV, m_{LSP}=100 GeV, μ=120 GeV
m_{t_3} (GeV)
$m_{\tilde{t}_1}$ (GeV)
2500
2000
1500
1000
500
200
400
600
800
1000
1200
1400
0.1 %
0.3 %
1 %
1 %
5 %
5 %
5 %
10 %
25 %
with N. Craig, S. Dimopoulos, G. Villadoro

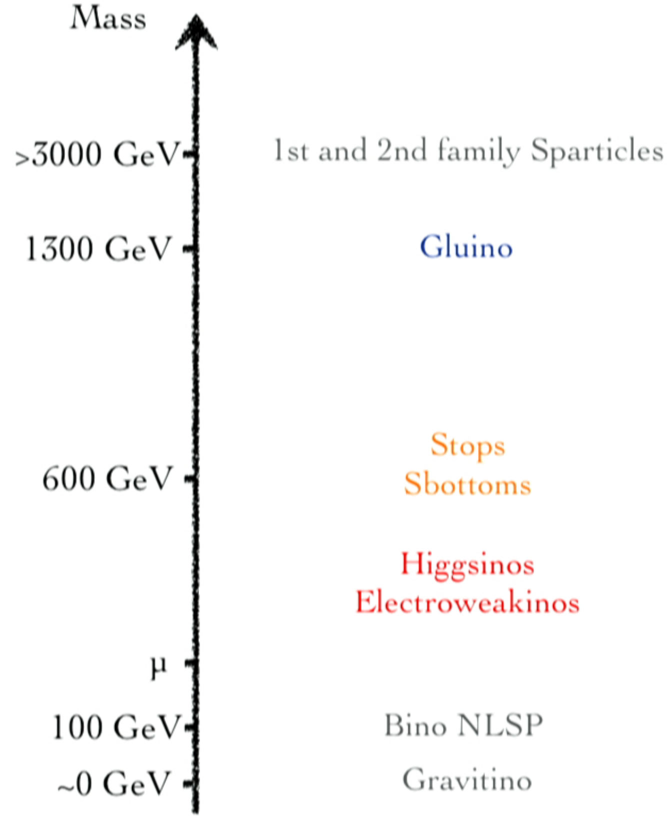
Bounds on Split Families and Fine-Tuning



with N. Craig, S. Dimopoulos, G. Villadoro

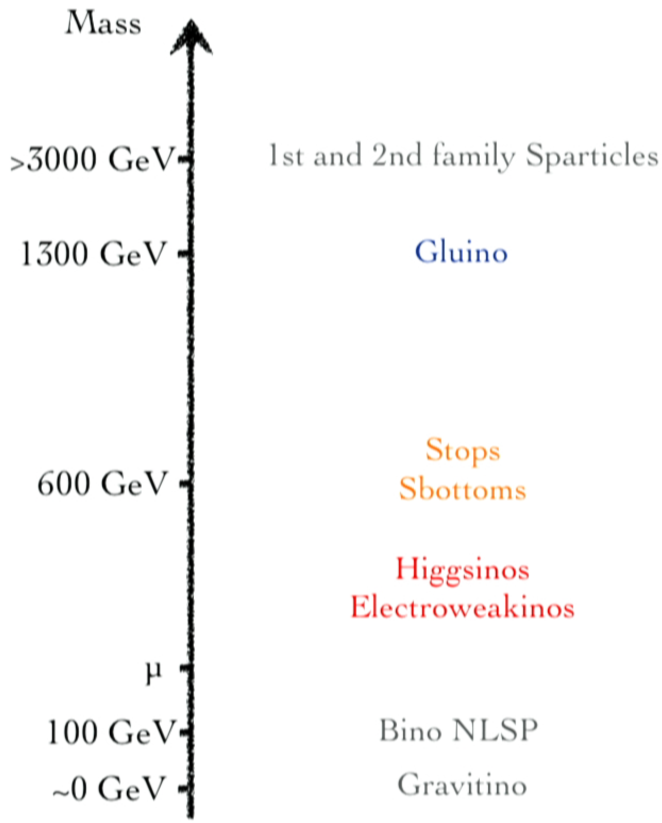
- Gluino bounds imply more than 10% tuning (ignoring higgs mass)
- Tuning increases with higher cutoff and higher higgsino mass

A Split Families Spectrum



A Split Families Spectrum

- Involves one additional singlet for the Higgs mass
- Requires breaking gaugino universality to have large hierarchy between bino and gluino



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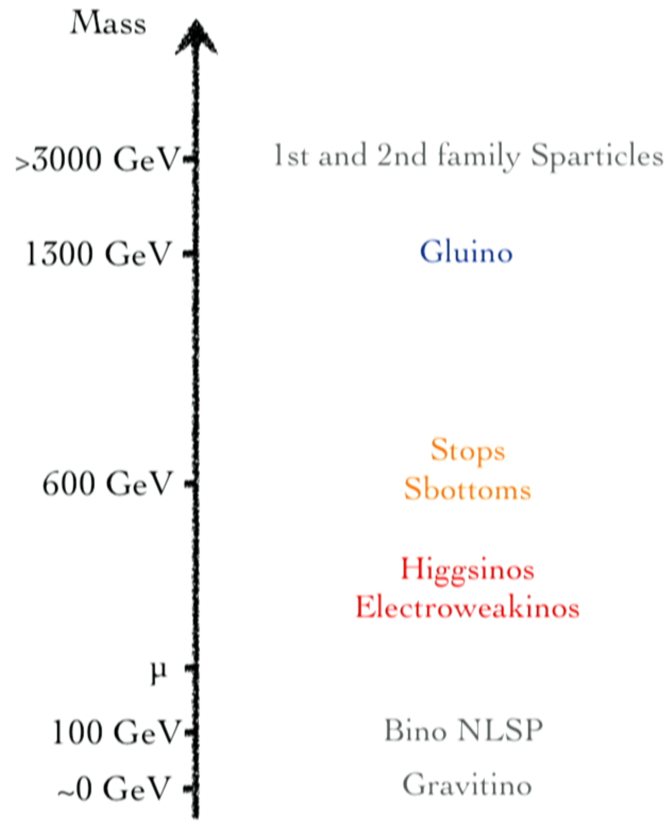

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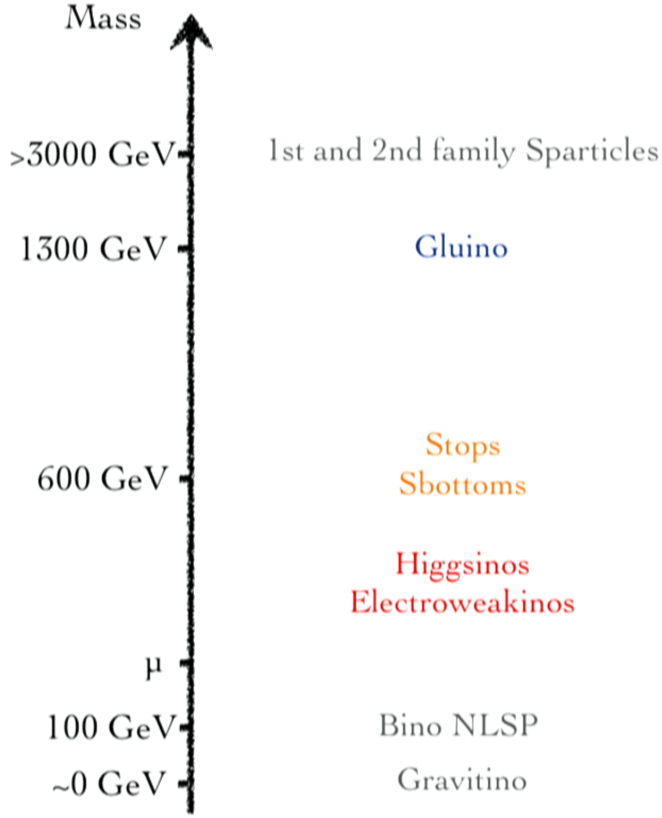

A Split Families Spectrum

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- Requires l… to minimiz…
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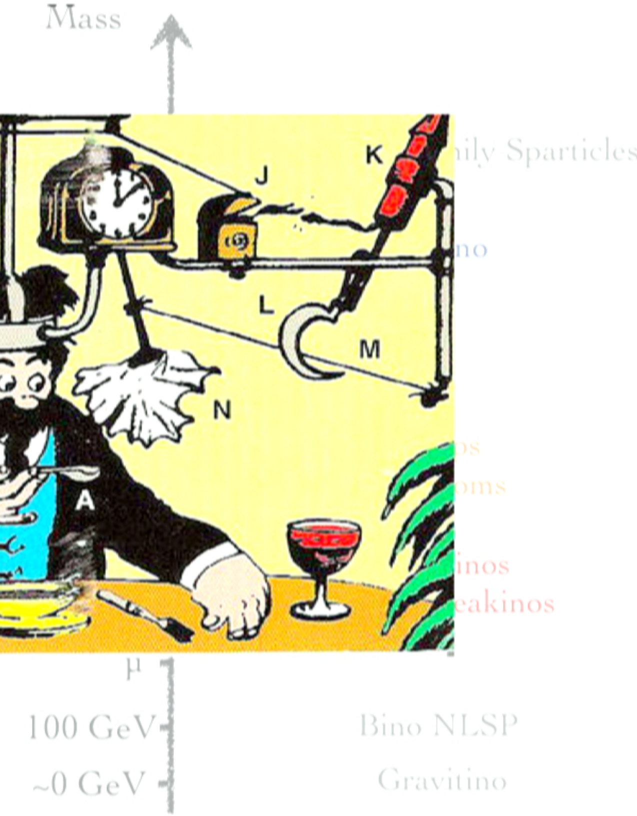
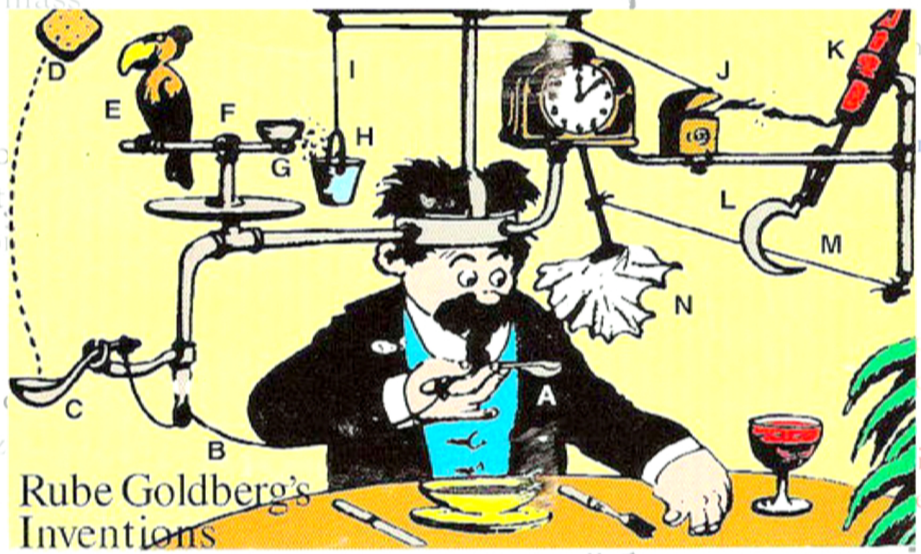
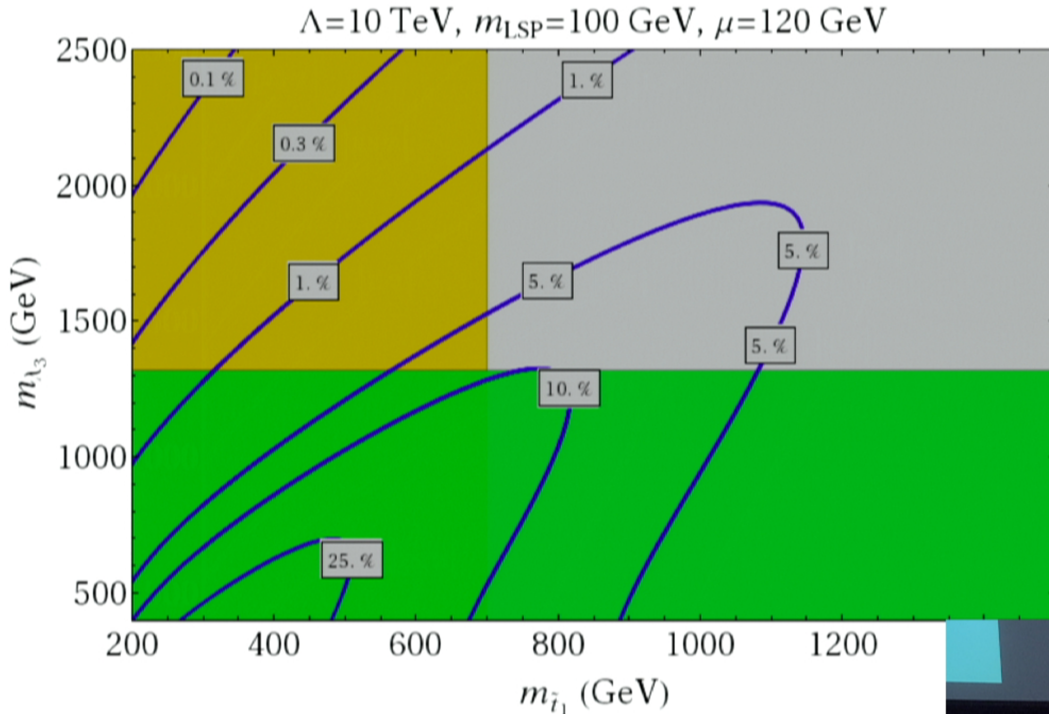




Bounds on Split Families and Fine-Tuning



- Expected LHC-14 reach for the gluino: 2.5-3 TeV
- Still have to wait for a few years...

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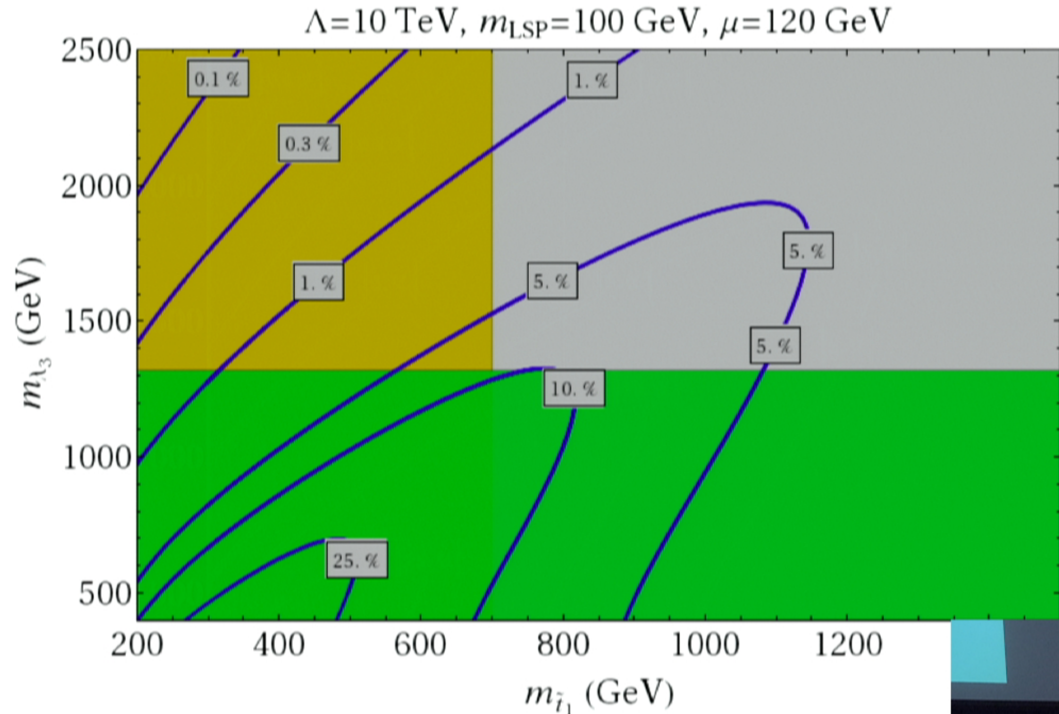

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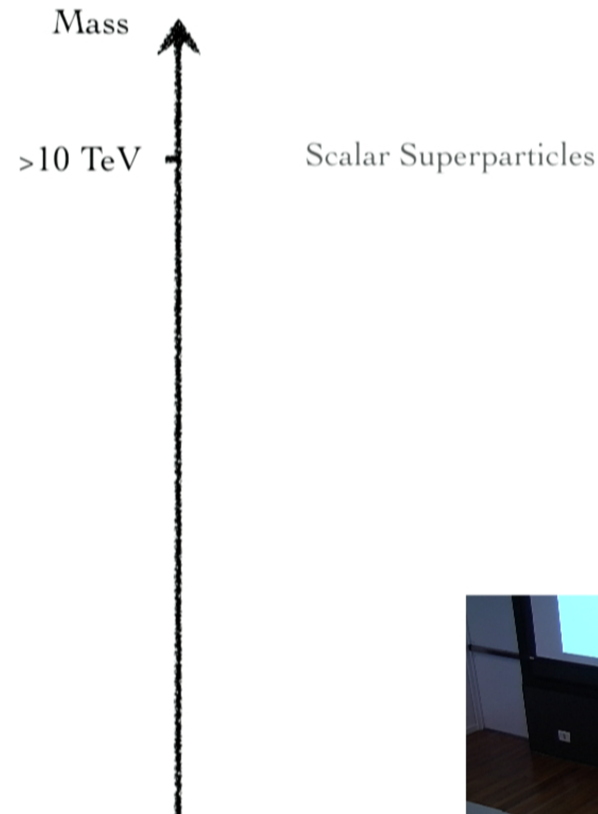
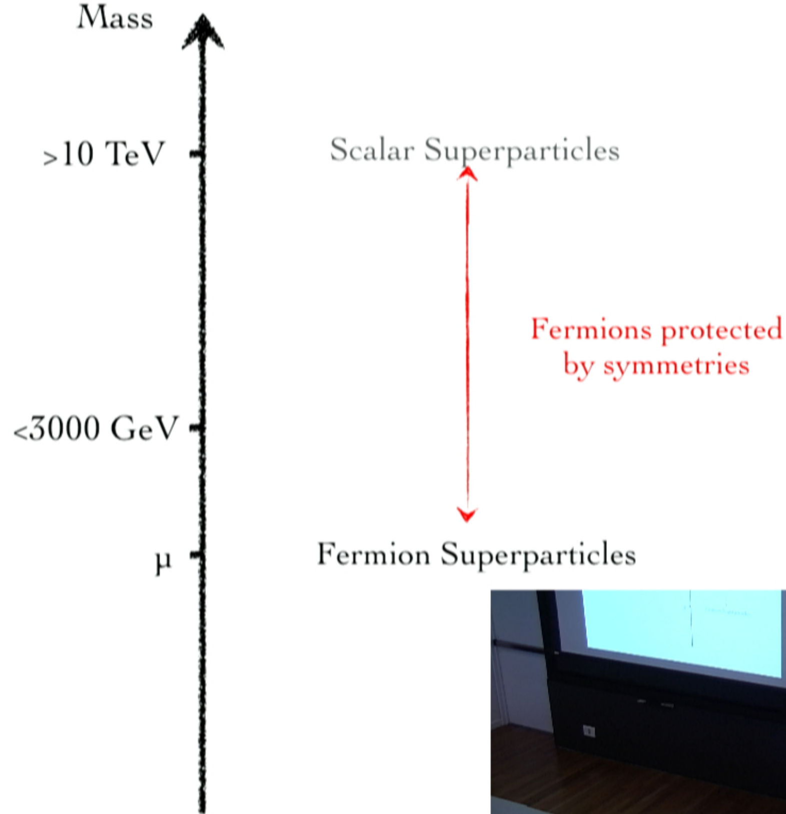
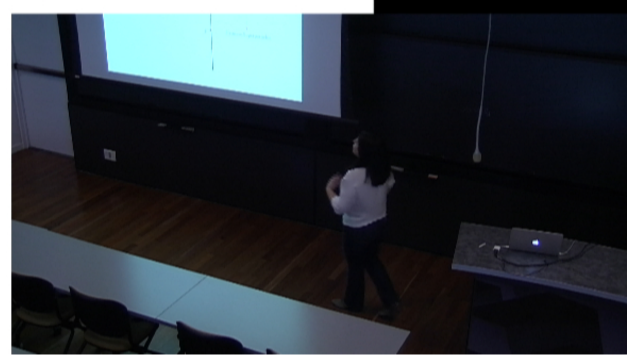
Split Supersymmetry



Split Supersymmetry



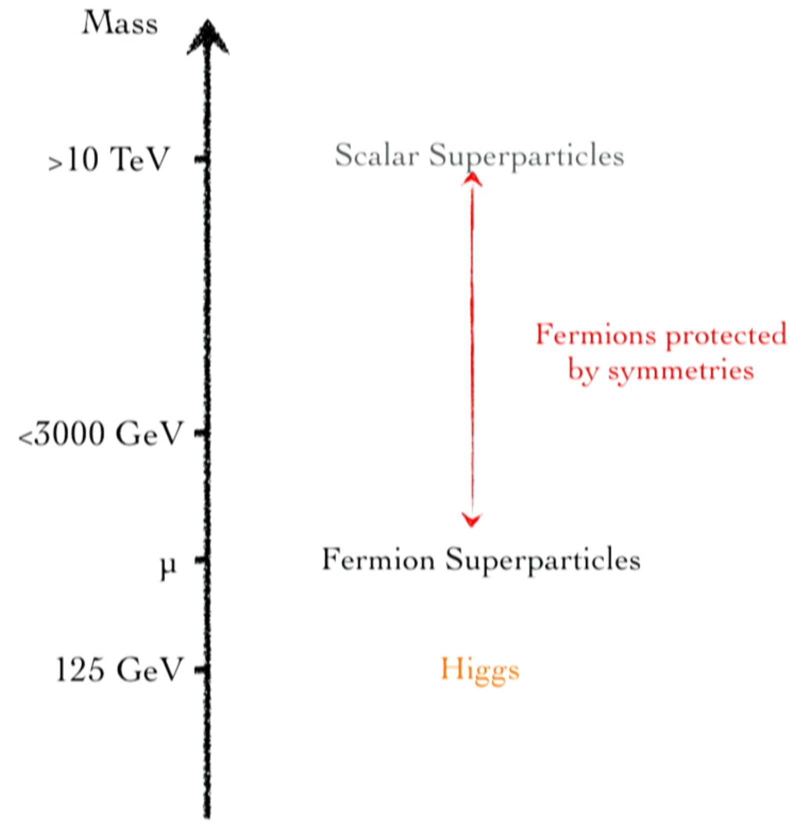
- Preserves successes of Dark Matter and gauge coupling unification



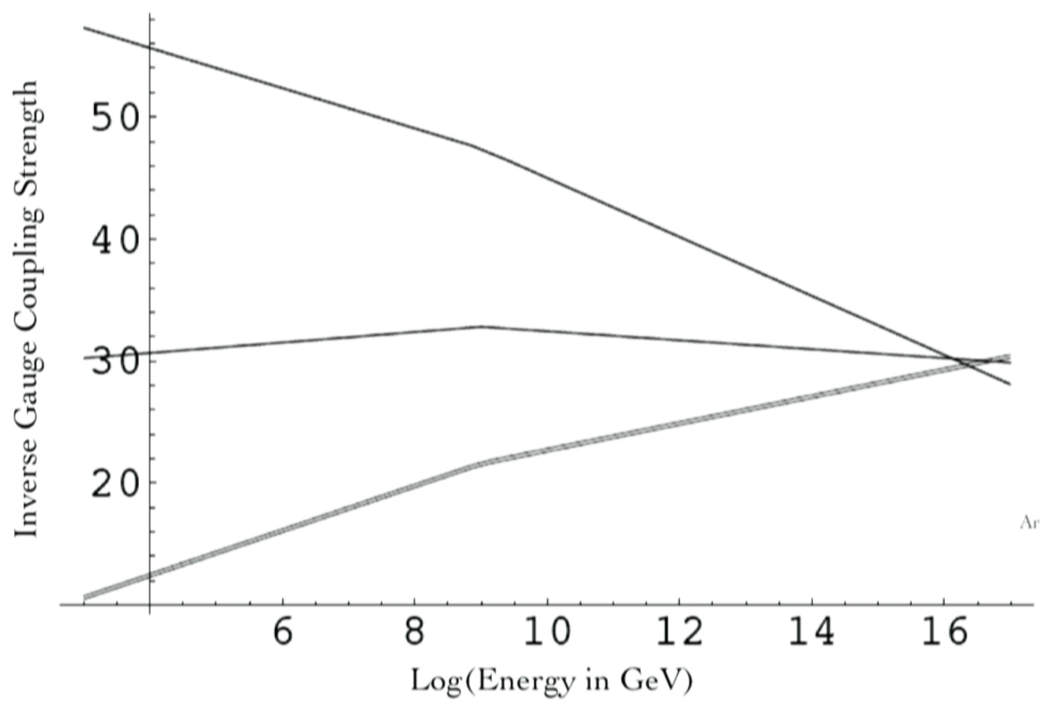
Split Supersymmetry

- Preserves successes of Dark Matter and gauge coupling unification

- Atomic Principle: One tuned light higgs



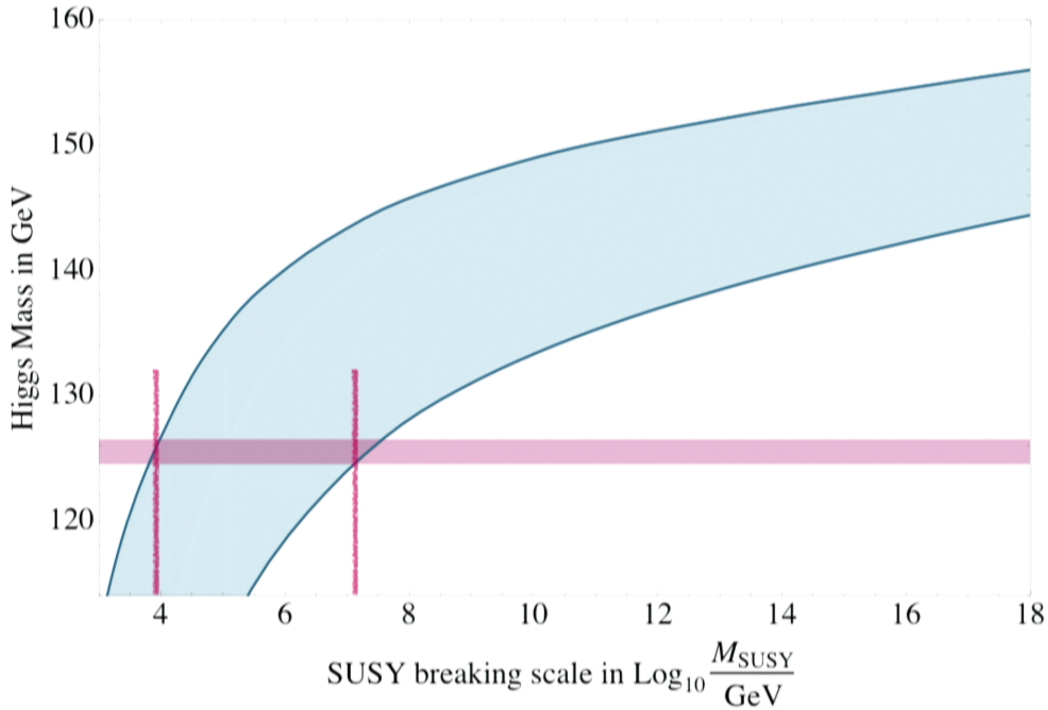
Unification in Split Supersymmetry



Arkani-Hamed, Dimopoulos (2004)

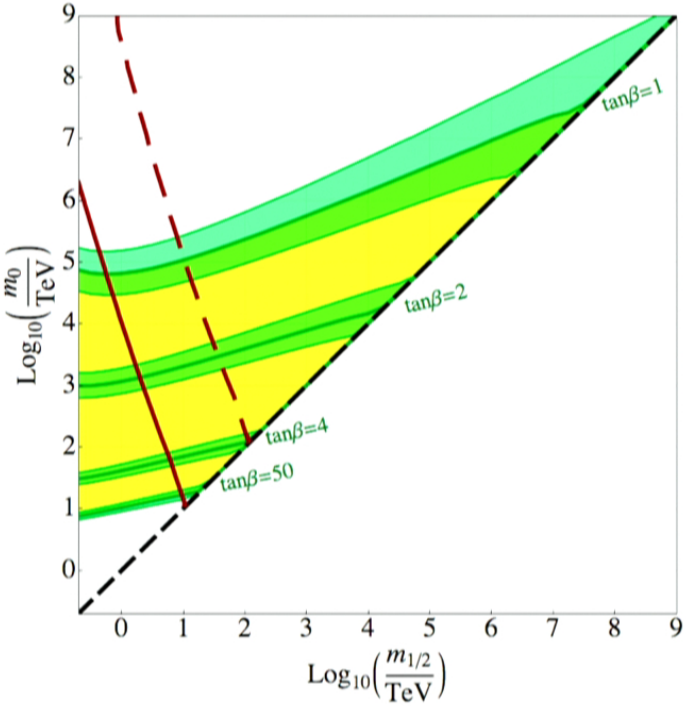
Works as well as ordinary Supersymmetry

125 GeV Higgs in Split Supersymmetry



- Favors scalars between 10-10^5 TeV: Mini-Split
- One- or two-loop separation from the gauginos

The 125 GeV Higgs and Unification in Mini-Split



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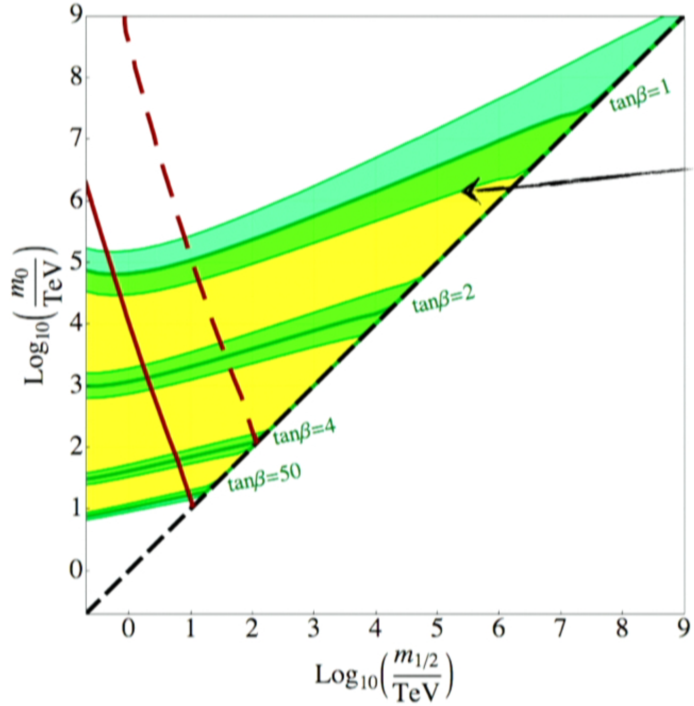
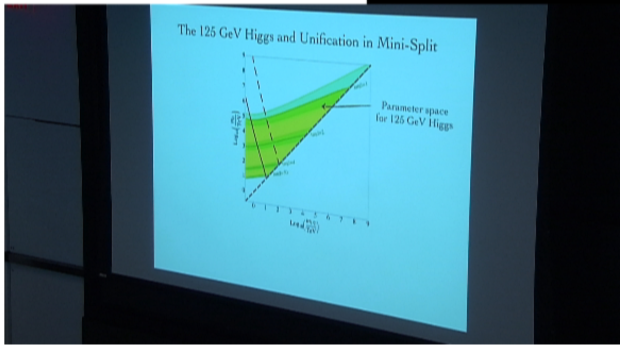
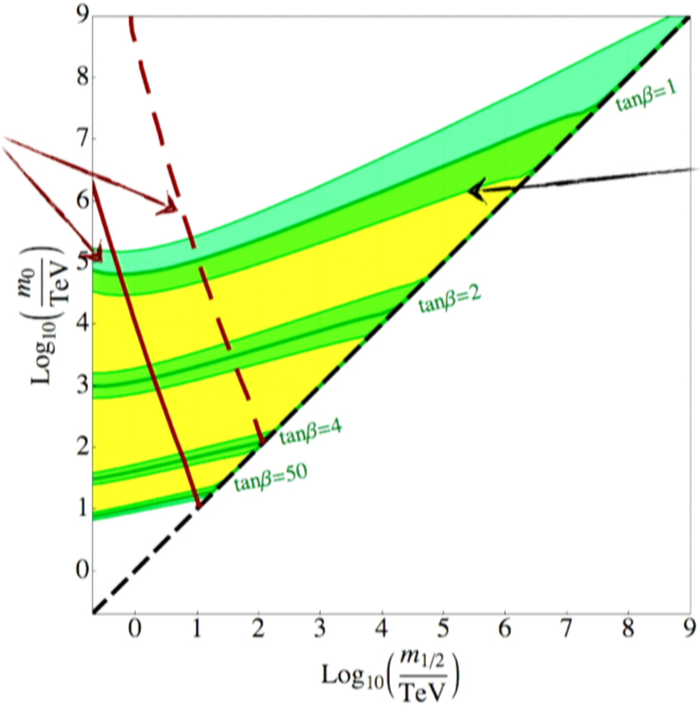


Parameter space
for 125 GeV Higgs



The 125 GeV Higgs and Unification in Mini-Split

1σ and 2σ contours for unification



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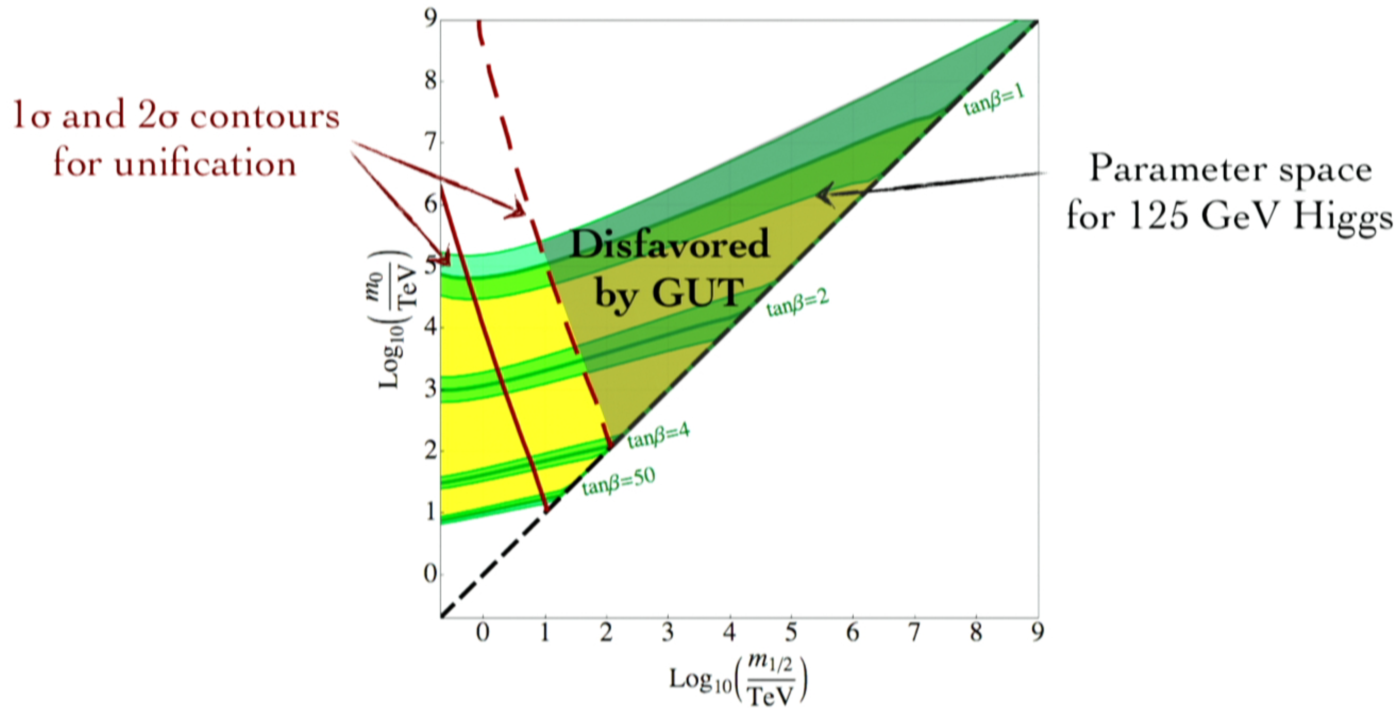
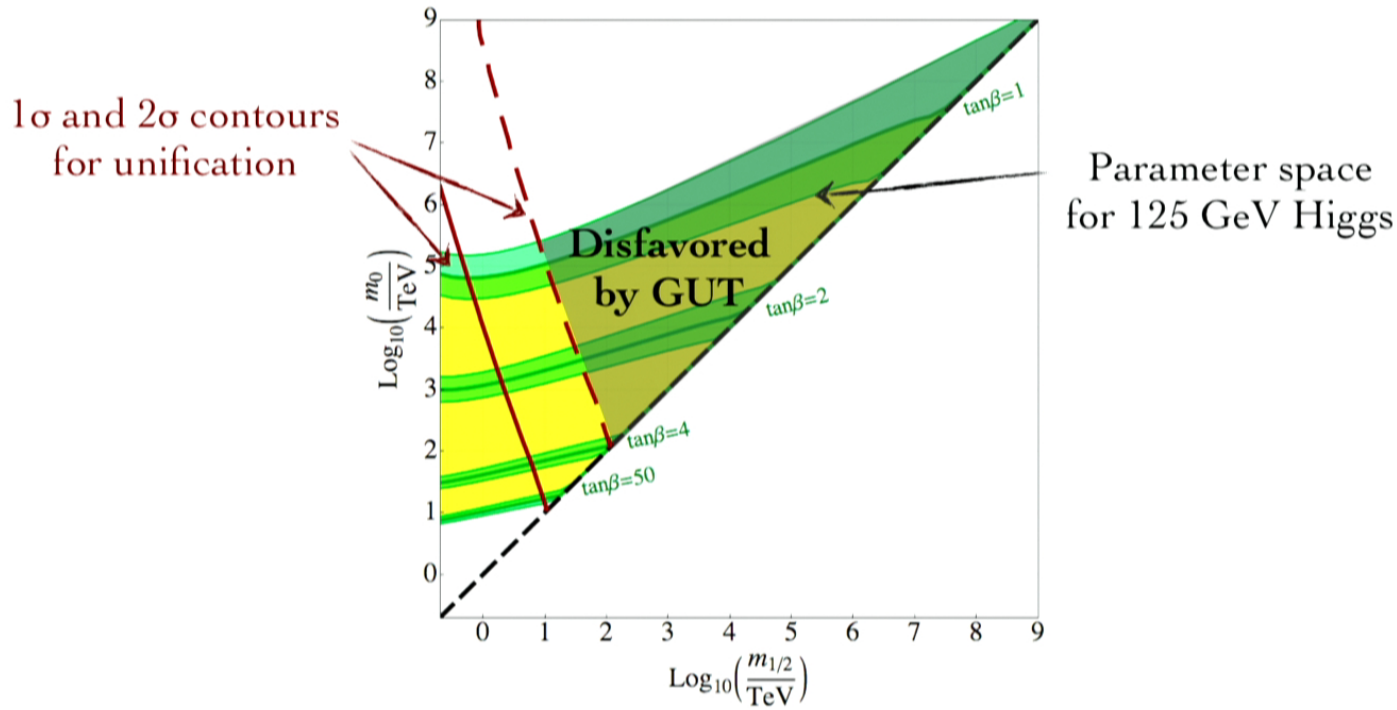


- Higgsinos have to be lighter than 100 TeV for Unification
- Scalars below 100 TeV when tanβ > few
- Flavor bounds constrain scalars to be (naively) above 1000 TeV

The 125 GeV Higgs and Unification in Mini-Split



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A Guide to Tuning the Weak Scale

$$\det \begin{pmatrix} |\mu|^2 + m_{H_u}^2 & -B_\mu \\ -B_\mu^* & |\mu|^2 + m_{H_d}^2 \end{pmatrix} \approx 0$$

- $m_{H_u}^2 < 0$:
  - Higgsinos have to be heavy

$$|m_{H_u}^2| \lesssim |\mu^2|$$

- $m_{H_u}^2 > 0$:
  - B_μ term has to be heavy

$$|B_\mu| \approx \sqrt{m_{H_u}^2 m_{H_d}^2}$$

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Tachyonic Masses from RG Running

$$\frac{dm_i^2}{dt} = c_i X_t \equiv c_i \frac{|y_t|^2}{8\pi^2}(m_{H_u}^2 + m_{\tilde{t}_L}^2 + m_{\tilde{t}_R}^2) \quad + \text{~~gaugino contribution~~}$$

$$\{c_{\tilde{t}_L},\ c_{\tilde{t}_R},\ c_{H_u}\} = \{1,\ 2,\ 3\}$$

- IR fixed point at $X_t = 0$:
  - Either the up-type higgs or one of the stops runs tachyonic
- UV fixed point at $m_{H_u}^2 = 3m_{\tilde{t}_L}^2$ and $m_{\tilde{t}_R}^2 = 2m_{\tilde{t}_L}^2$:
  - Appearance of tachyons delayed depending on proximity to the UV fixed point

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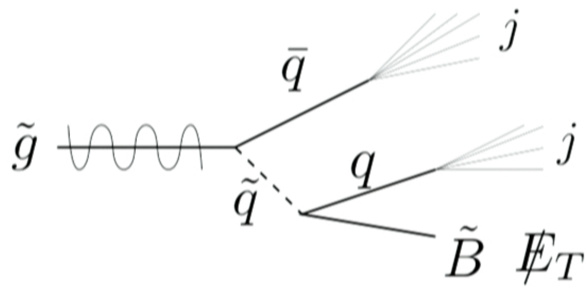
Model Building in Mini Split

Requirements:

- Avoid tachyonic stops
- Successful electroweak symmetry breaking
- Scalars between 10 and 10^5 TeV while Higgsinos lighter than 100 TeV
- Satisfy flavor bounds

Long-lived Gluinos

Gluino decay through the heavy scalars

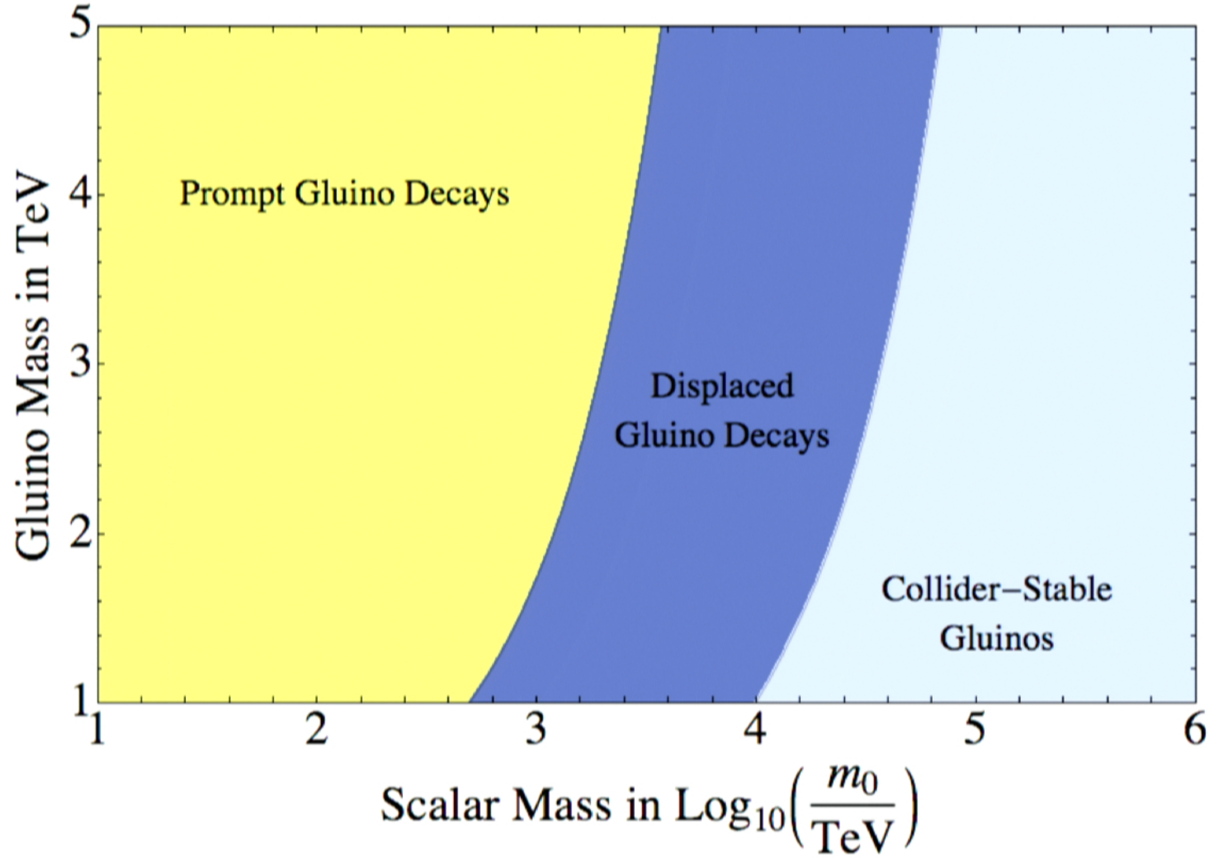


Signature:
2 jets and missing energy

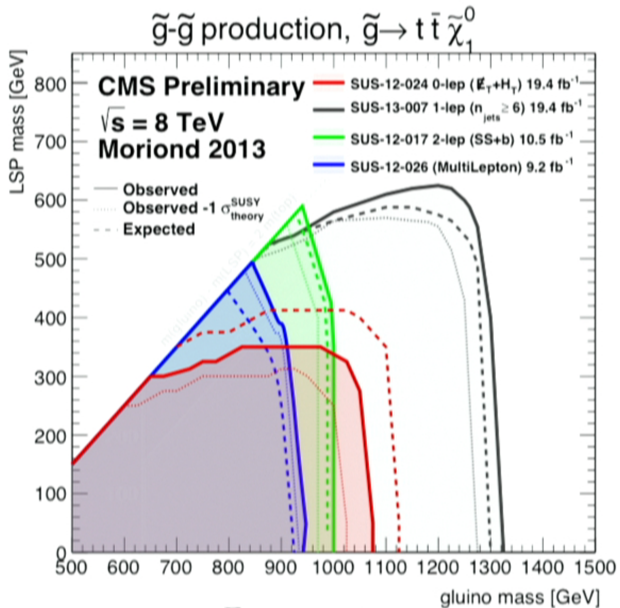
Lifetime:

$$c\tau_{\tilde{g}} \simeq 3 \times 10^{-2}\ \mathrm{m} \left(\frac{1\ \mathrm{TeV}}{m_{\tilde{g}}}\right)^5 \left(\frac{M_{\mathrm{Susy}}}{10^4\ \mathrm{TeV}}\right)^4$$

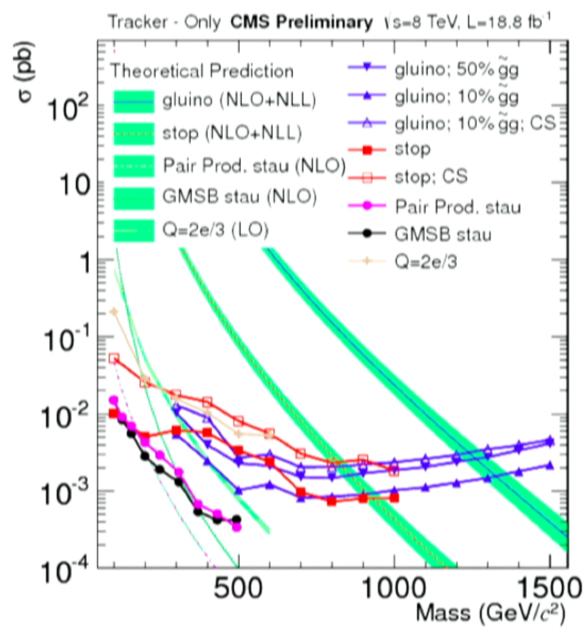
Long-lived Gluinos at the LHC



Gluino Bounds from the LHC



For prompt or slightly displaced gluinos



For collider "stable" gluinos

M_{gluino} > 1.3 TeV for split gluino

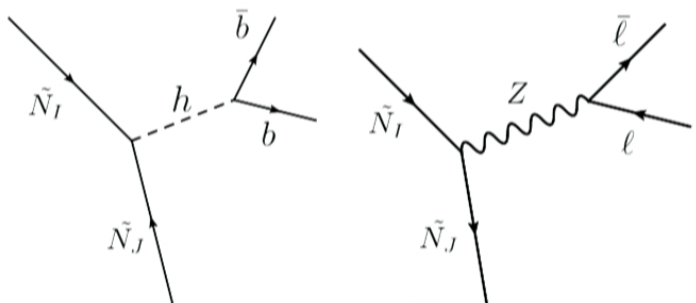
2.5 TeV to 3 TeV ultimate reach for split gluino

Split Signatures beyond the Gluino: Electroweakinos and Higgsinos

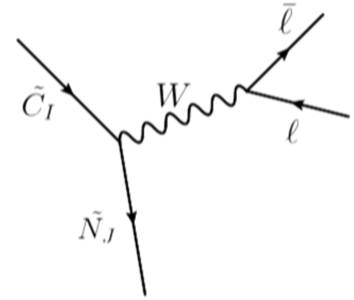
- Light Higgsinos
  - Electroweakino and Higgsino Yukawa Coupling Unification
- Heavy Higgsinos
  - Displaced Winos at the LHC
- The Minimal Model: Two Higgsino Doublets at the LHC
  - Displaced Higgsinos at the LHC

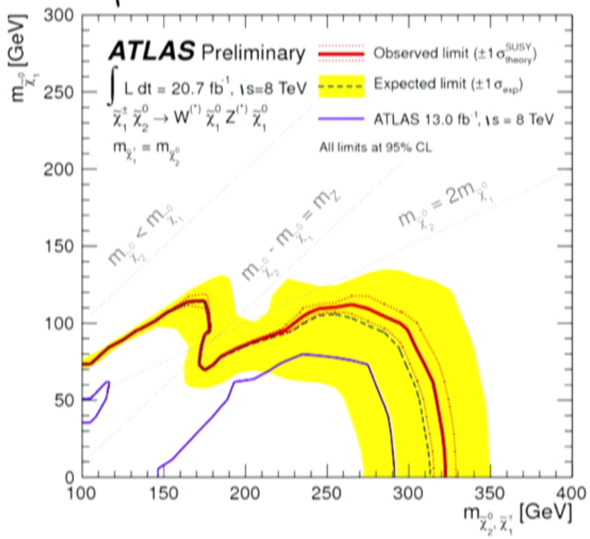
Electroweakinos and Higgsinos at the LHC

Neutralino decays



Chargino decays





Electroweakinos and Higgsinos at the LHC

Neutralino decays

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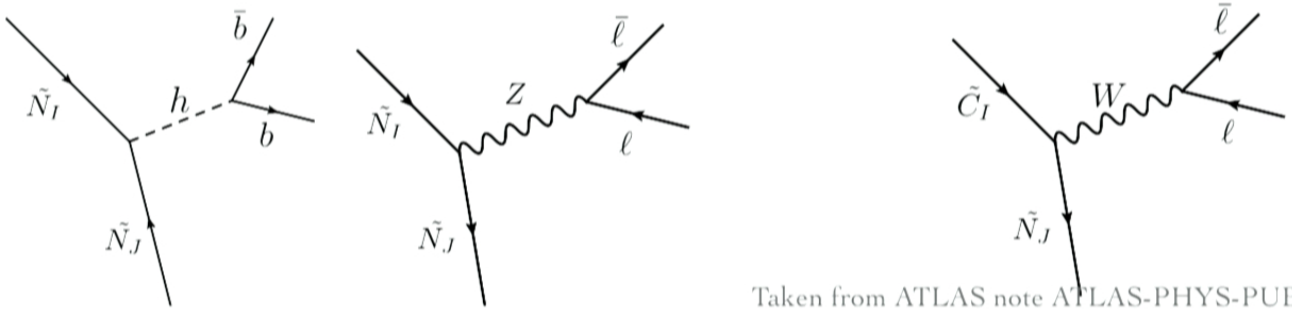
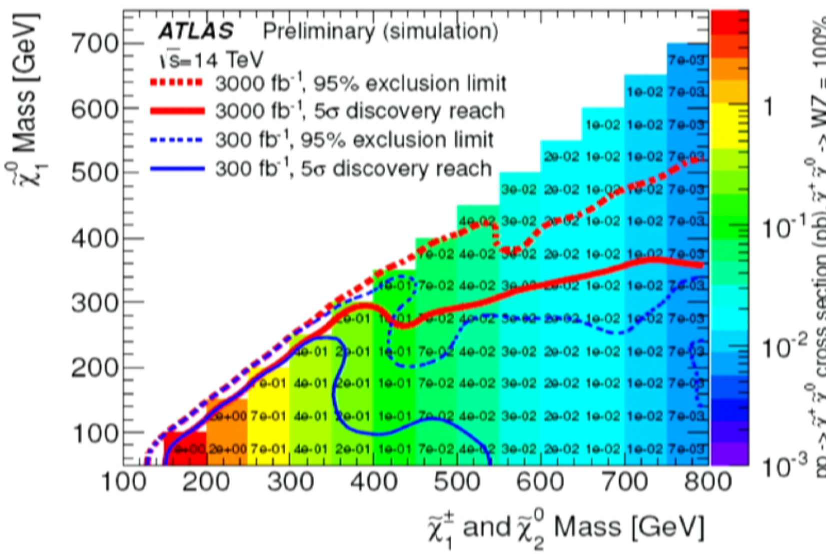
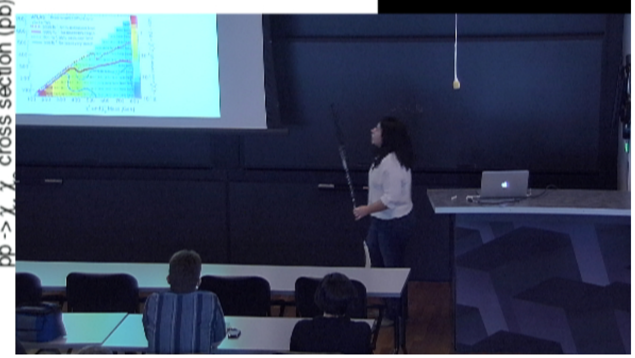


Taken from ATLAS note ATLAS-PHYS-PUB-2013-002





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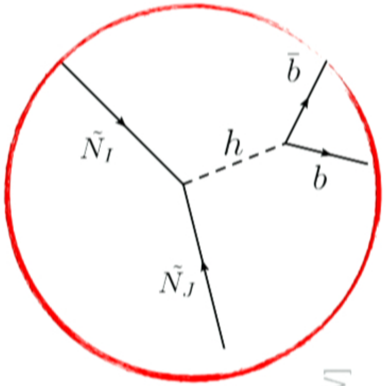

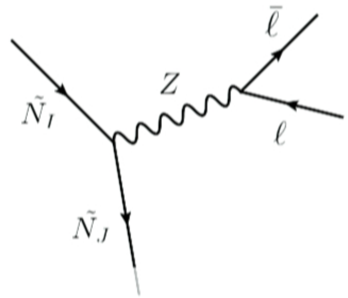

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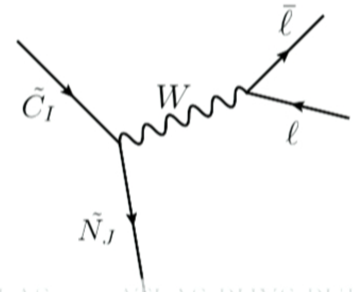

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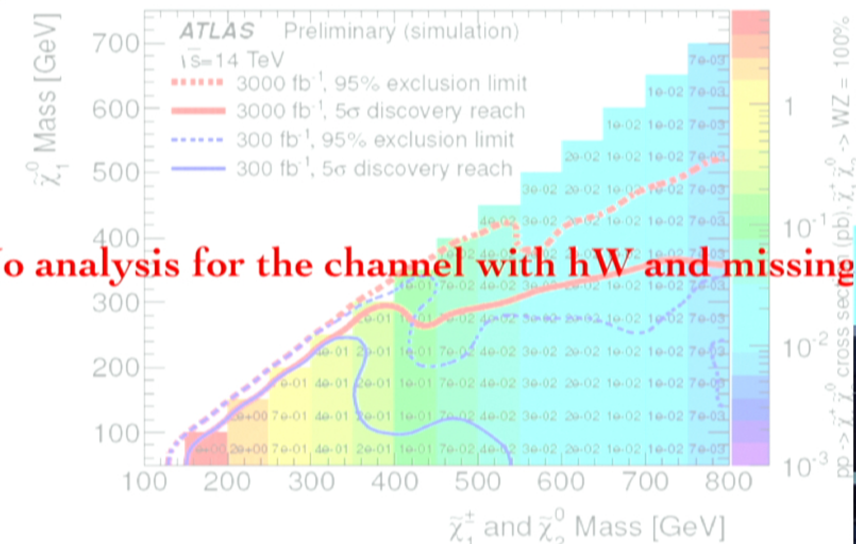
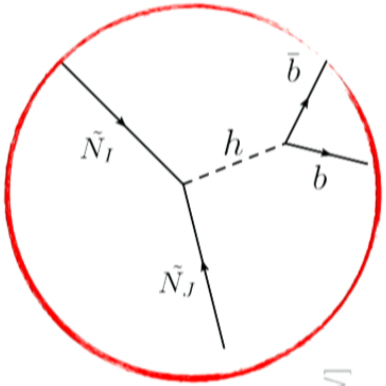
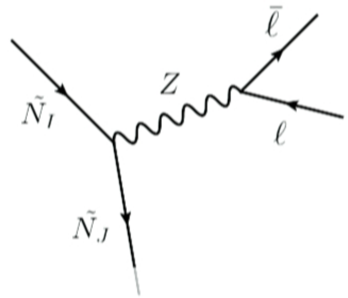


No analysis for the channel with hW and missing

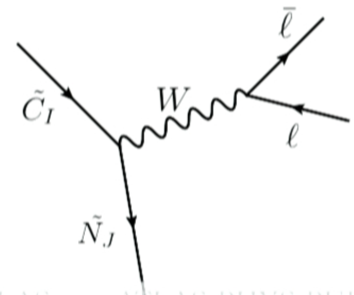
Electroweakinos and Higgsinos at the LHC

Neutralino decays

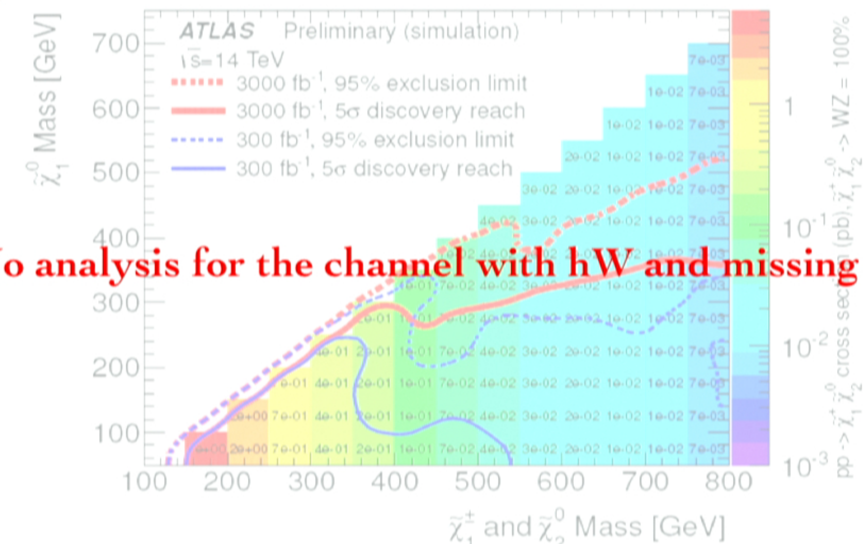




Chargino decays



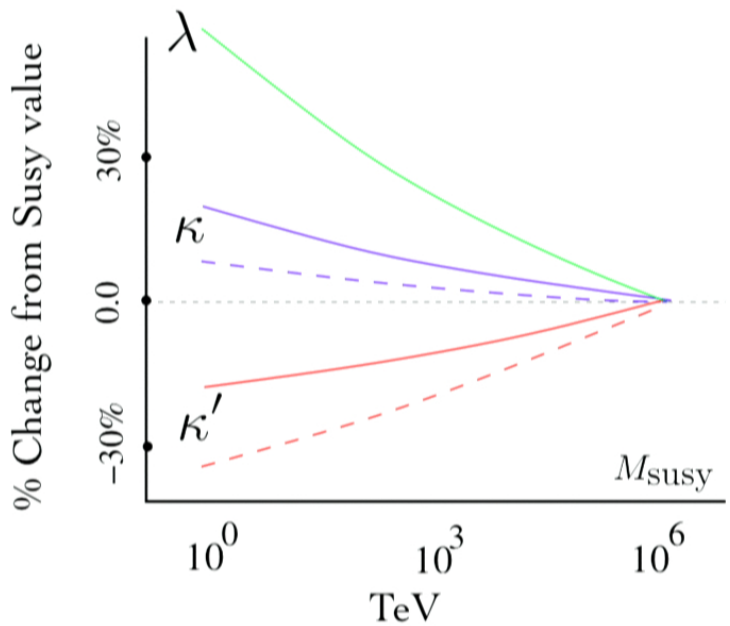
Taken from ATLAS note ATLAS-PHYS-PUB-2013-002



No analysis for the channel with hW and missing energy

Electroweakinos and Higgsinos at the LHC

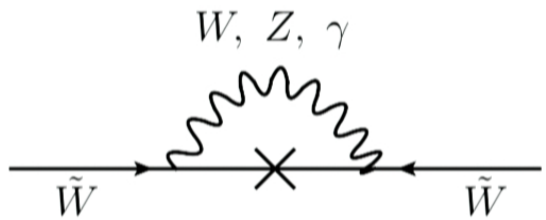
Gaugino and Higgsino Yukawa Coupling Unification



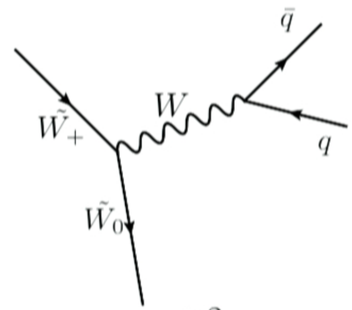
$$\kappa_u H \widetilde{H}_u \widetilde{W} + \kappa_d H^\dagger \widetilde{H}_d \widetilde{W} \qquad \kappa'_u H \widetilde{H}_u \widetilde{B} + \kappa'_d H^\dagger \widetilde{H}_d \widetilde{B}$$

λ: Higgs Quartic

Wino LSP with Heavy Higgsinos

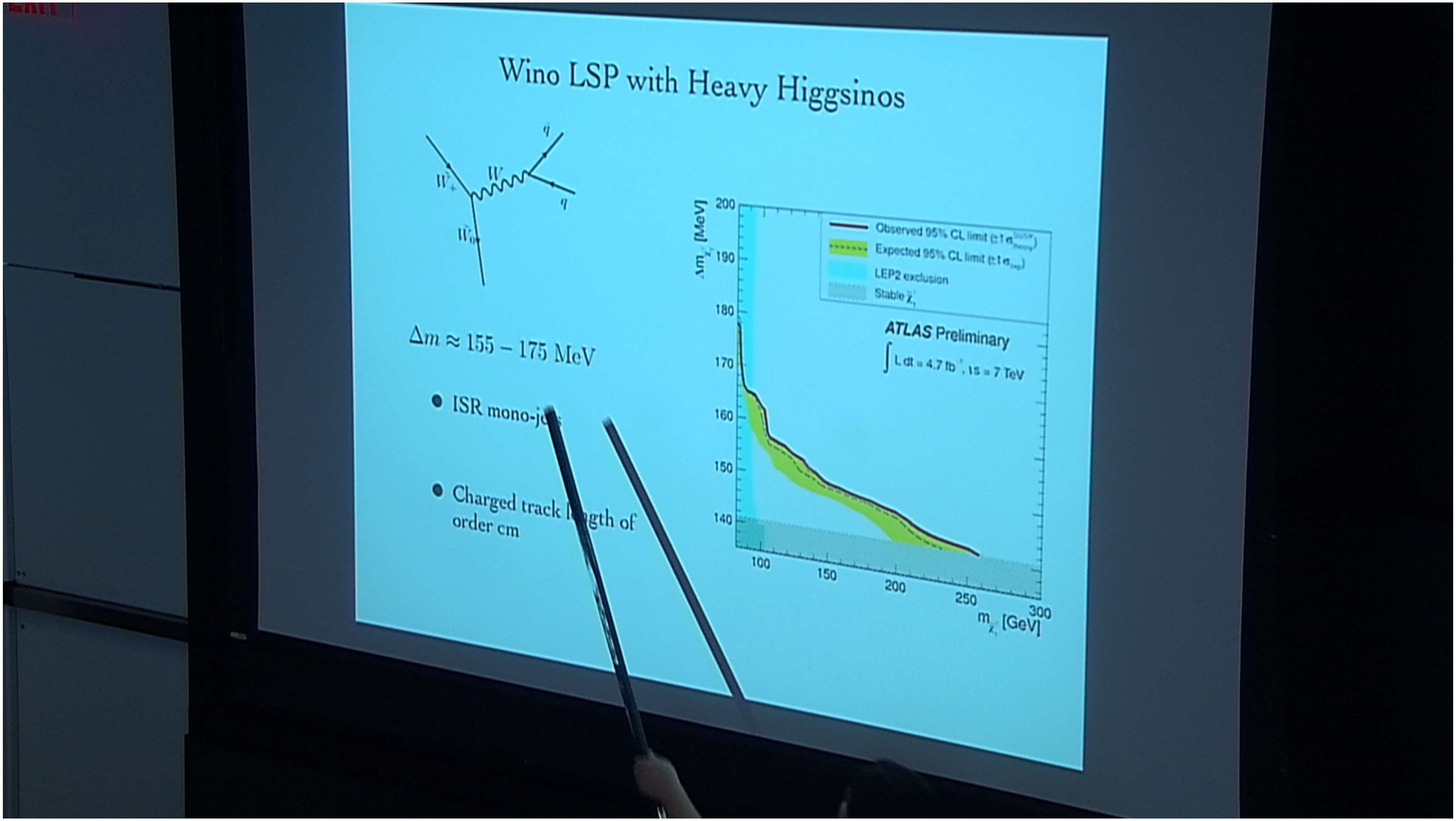


$$\Delta m \sim \frac{\alpha}{4\pi} M_Z \approx 155 - 175 \text{ MeV}$$



$$\Gamma \sim \frac{G_F^2}{4\pi} f_\pi^2 \Delta m^3$$

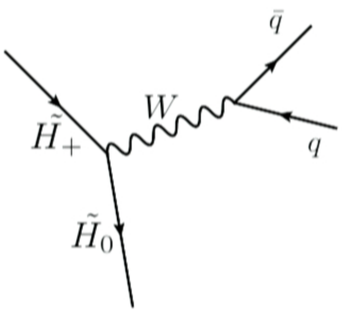
- Charged wino heavier than Neutral Wino
- cm size tracks with soft pions


Wino LSP with Heavy Higgsinos
Δm ≈ 155 – 175 MeV
ISR mono-je
Charged track
gth of
order cm
Observed 95% CL limit
Expected 95% CL limit
LEP2 exclusion
Stable
ATLAS Preliminary
L dt = 4.7 fb⁻¹, √s = 7 TeV
Δm [MeV]
m [GeV]

Higgsino LSP:
The Minimal Model for Unification

Arkani-Hamed, Dimopoulos, Kachru (2005)

- Only light Higgsinos in the Spectrum



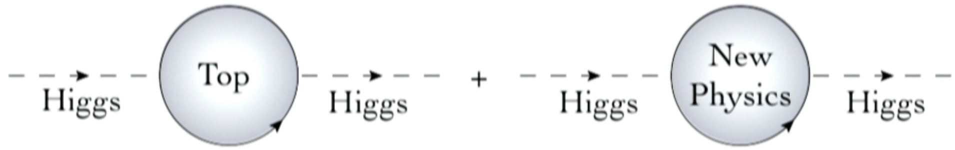
- Mass splitting ~355 MeV
- Soft pions with sub-cm charged tracks
- No LHC bounds
  - No working search strategy yet

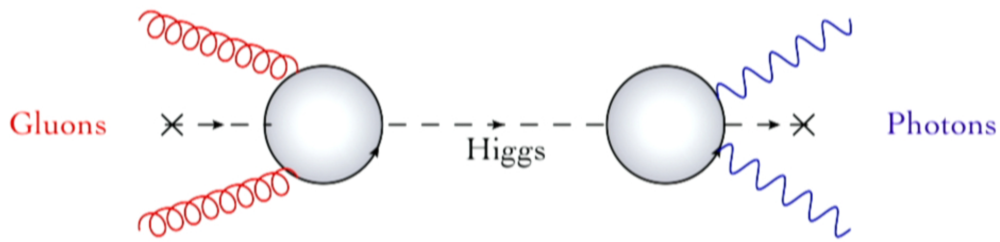
Mini-Split Phenomenology

- Displaced Gluinos at the LHC
- Yukawa Coupling Unification
- Displaced Winos and Higgsinos at the LHC

Naturalness and Higgs Properties

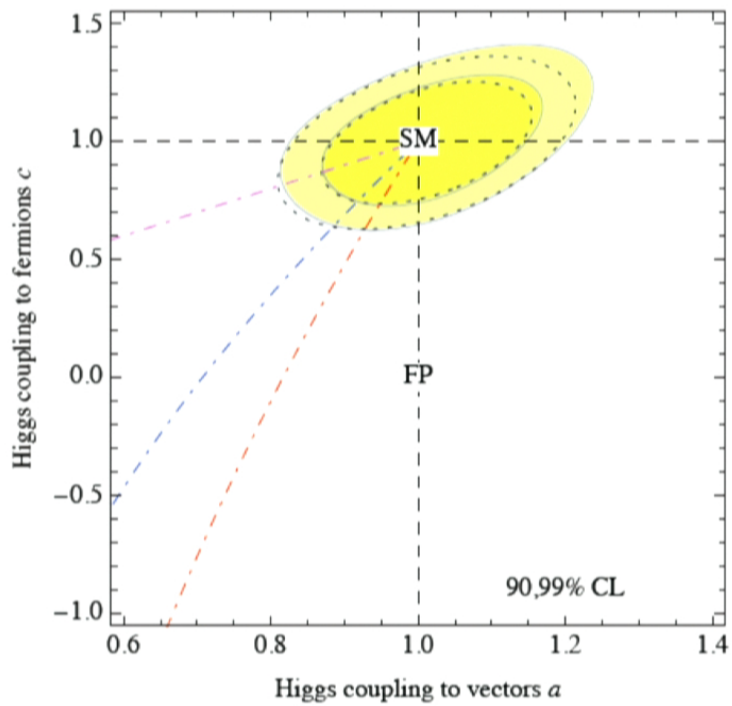
with G. Villadoro





A Natural Higgs is not the SM Higgs

The hints for a SM-like 125 GeV Higgs



Higgs couplings agree with SM within 20%

The SUSY Higgs with Light Stops

Proportional to the β-function

$$\frac{\sigma(gg \to h)}{\sigma_{SM}(gg \to h)} \approx \left[1 + \frac{1}{4}\left(\frac{m_t^2}{m_{\tilde{t}_1}^2} + \frac{m_t^2}{m_{\tilde{t}_2}^2} - \frac{m_t^2 A_t^2}{m_{\tilde{t}_1}^2 m_{\tilde{t}_2}^2}\right)\right]^2$$

SUSY Higgs production at the LHC enhanced (suppressed)
with small (large) stop mixing

Current bounds allow only ~10% deviations

The SUSY Higgs with Light Charginos

$$\frac{\Gamma_{h\to\gamma\gamma}}{\Gamma^{SM}_{h\to\gamma\gamma}} \simeq 1 + \frac{12}{17}\frac{m_W^2 \sin 2\beta}{\mu\, m_{\lambda_2} - m_W^2 \sin 2\beta}$$

- Requires large mixing and small $\tan\beta$
- Enhanced (suppressed) when $m_{\lambda 2}\,\mu$ positive (negative)

Maximum increase in $h\to\gamma\gamma \sim 20\%$

What if...

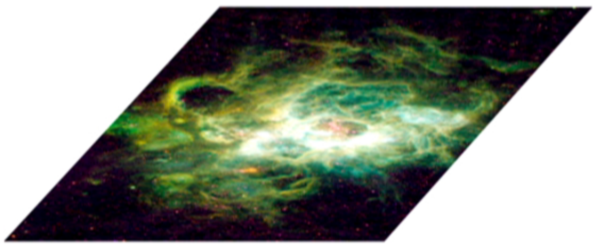
...the LHC discovers slightly displaced gluinos

- We learn:
    - The SUSY breaking scale: Build a higher energy collider (if we can)
    - Possibility of Yukawa coupling unification: The ILC (if the gauginos and higgsinos are accessible)
    - The SM is tuned

Single Universe

The existence of Galaxies

$$\rho_{\text{vacuum}} \leq 10^{-120} M_{\text{Planck}}^4$$

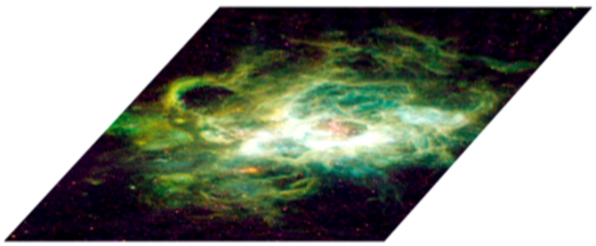


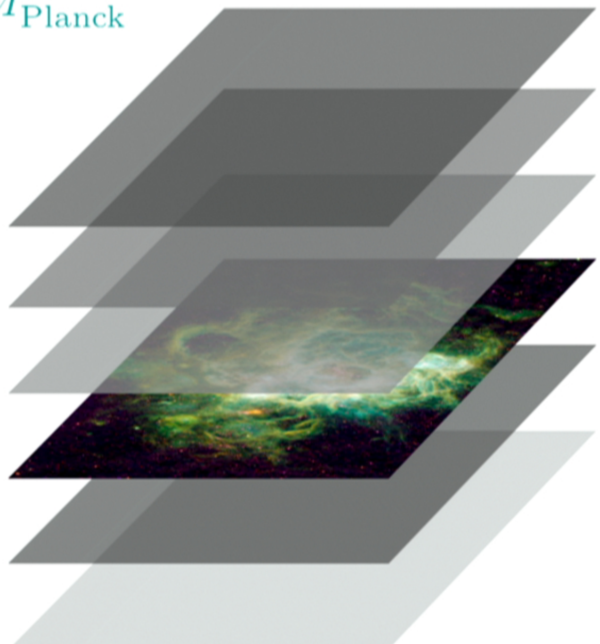
Single Universe

Many Universes

The existence of Galaxies

$$\rho_{\text{vacuum}} \leq 10^{-120} M_{\text{Planck}}^4$$



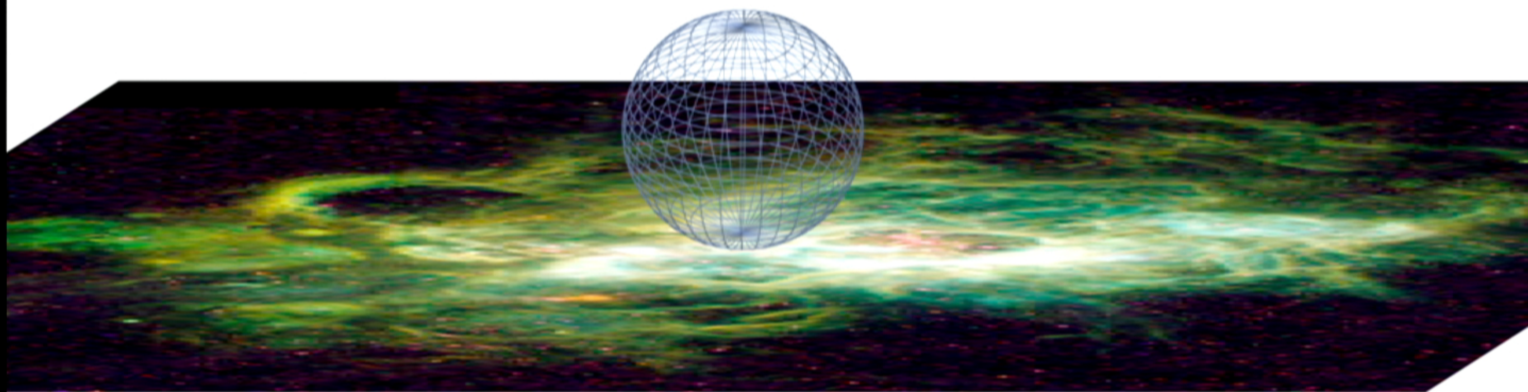


"Divine" Intervention

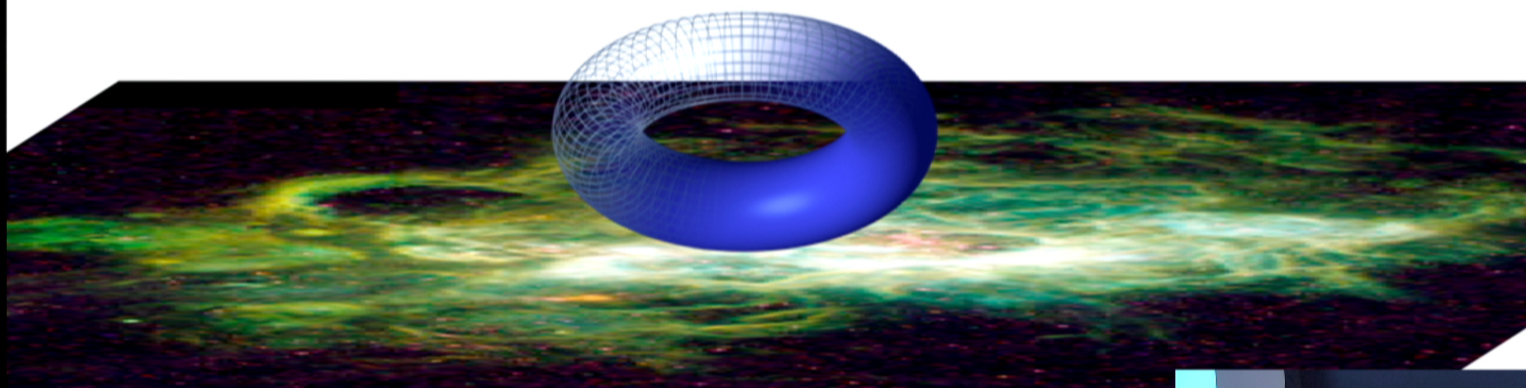
Environmental Selection

Linde, Banks, Weinberg

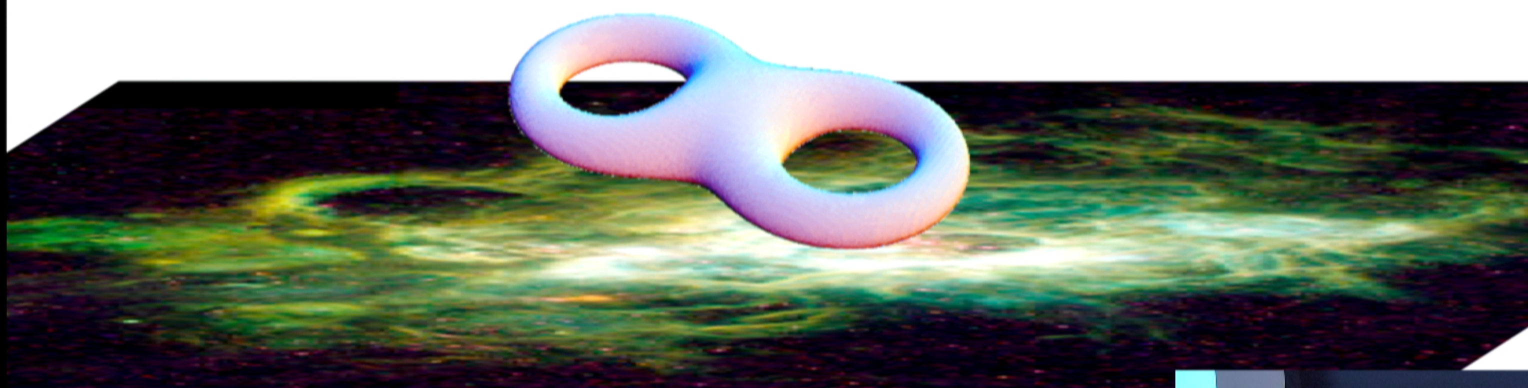
The Many Universes of String Theory



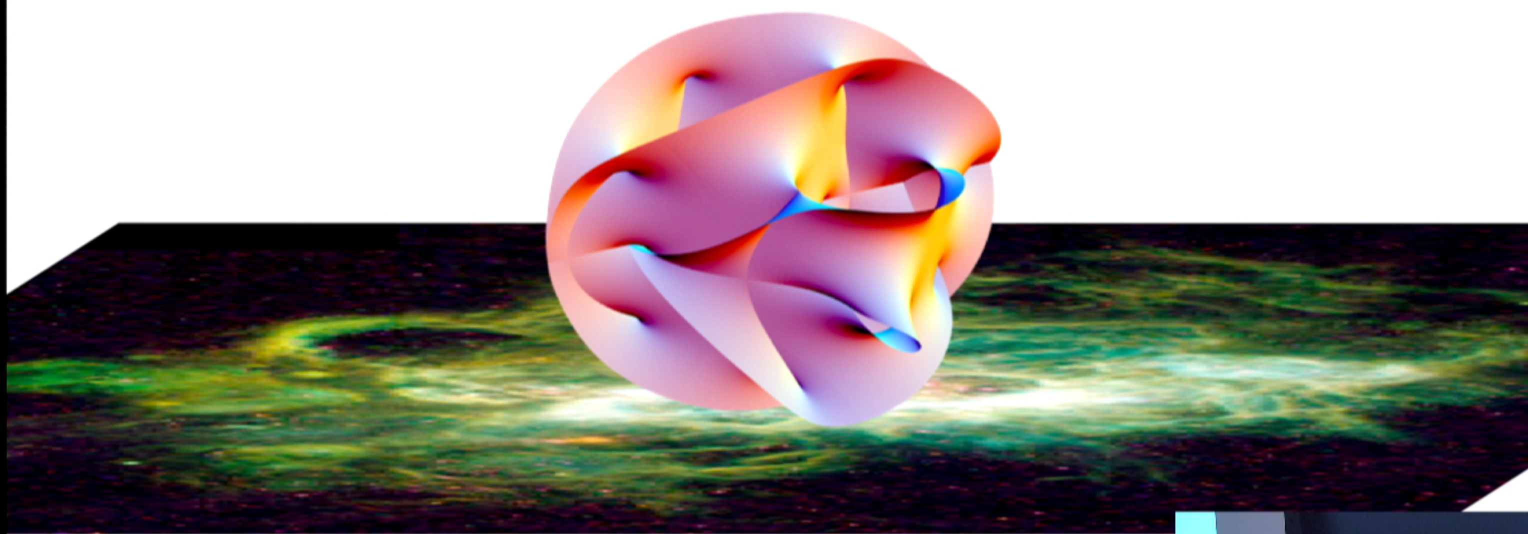
The Many Universes of String Theory



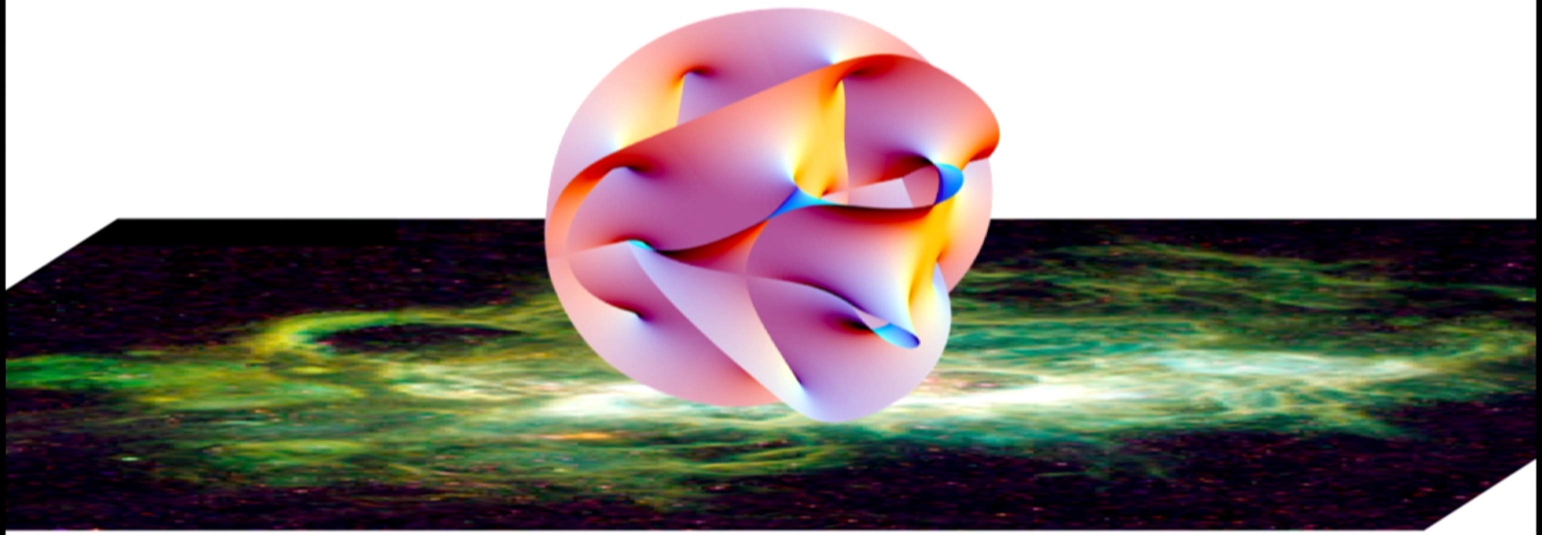
The Many Universes of String Theory



The Many Universes of String Theory



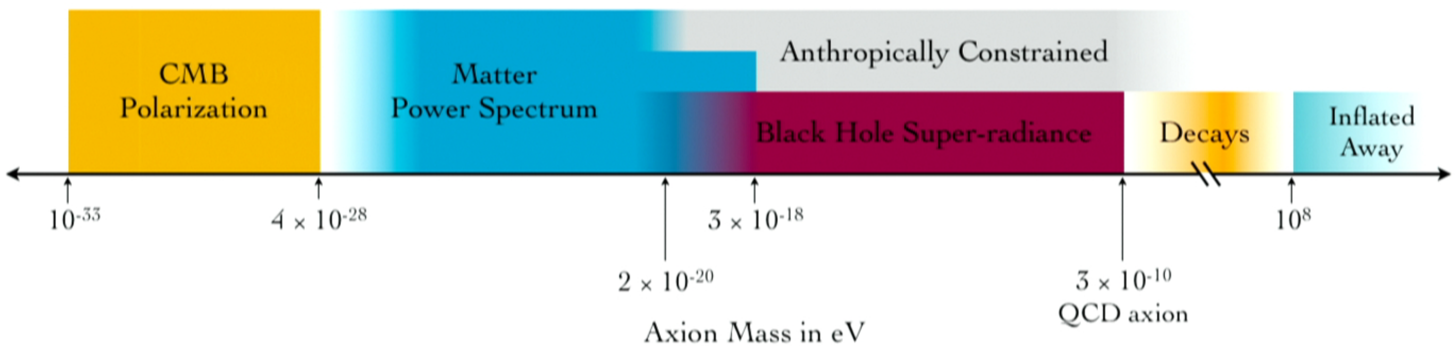
The Many Universes of String Theory



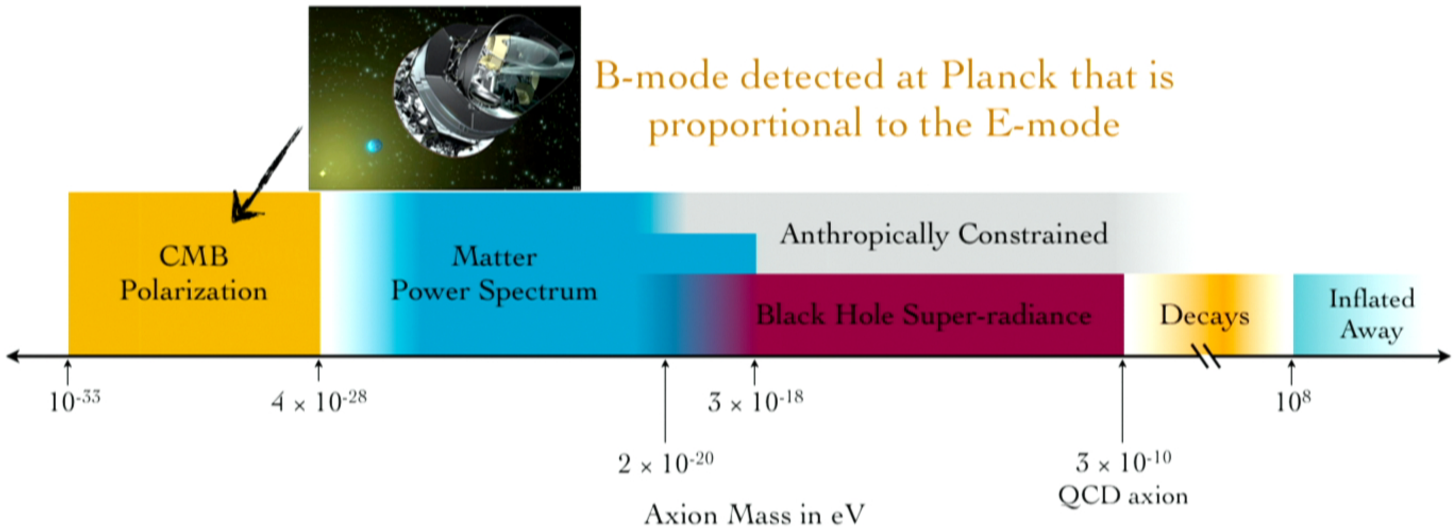
Extra dimensions of String Theory imply a Plenitude of Universes

Laws of Nature depend on the shape of the extra dimensions

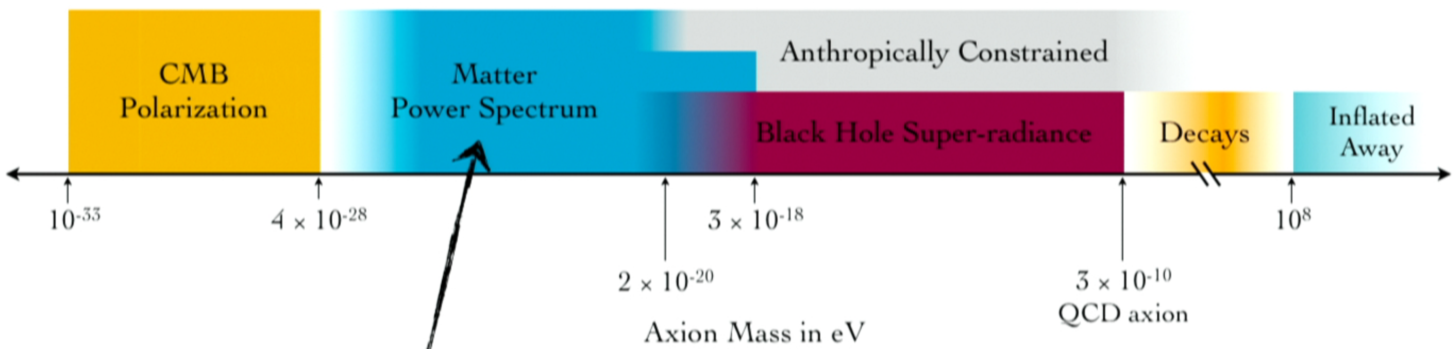
The String Axiverse

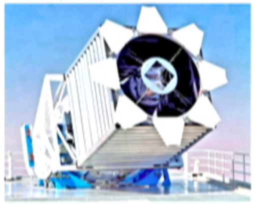


The String Axiverse



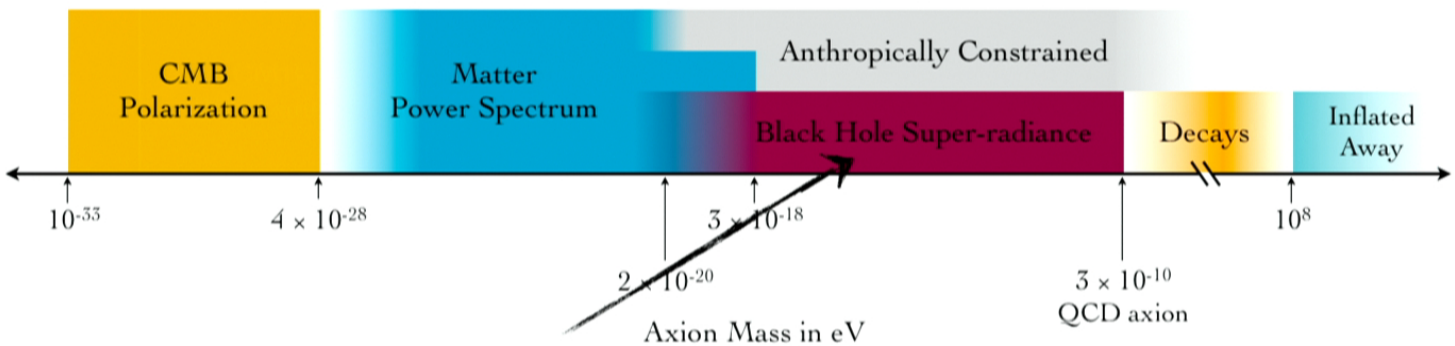
The String Axiverse

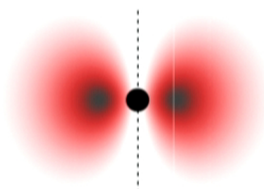




BOSS and 21-cm line experiments
detect suppression of small scale structure

The String Axiverse

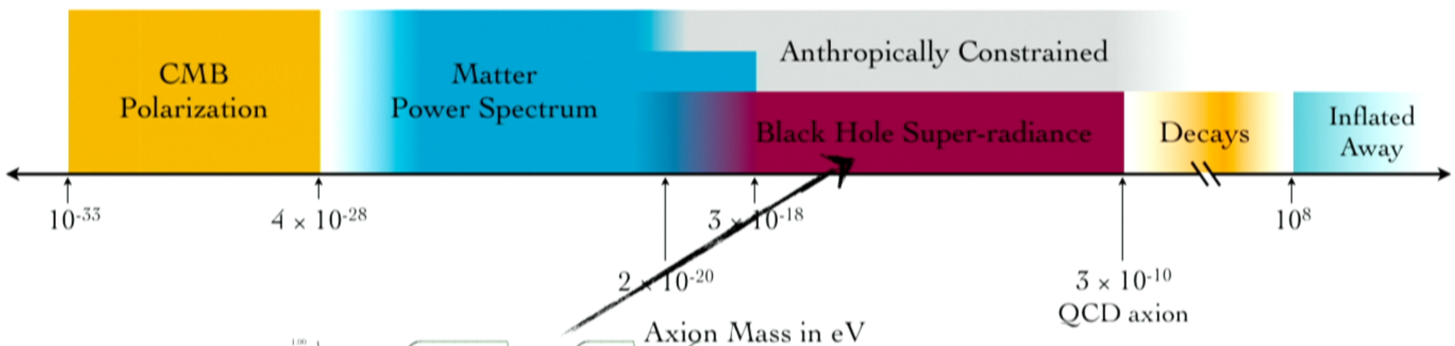


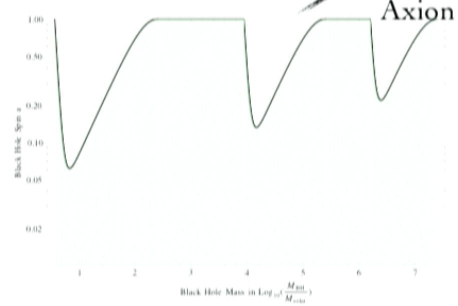


Axions spin down astrophysical black holes

with S. Dubovsky

The String Axiverse

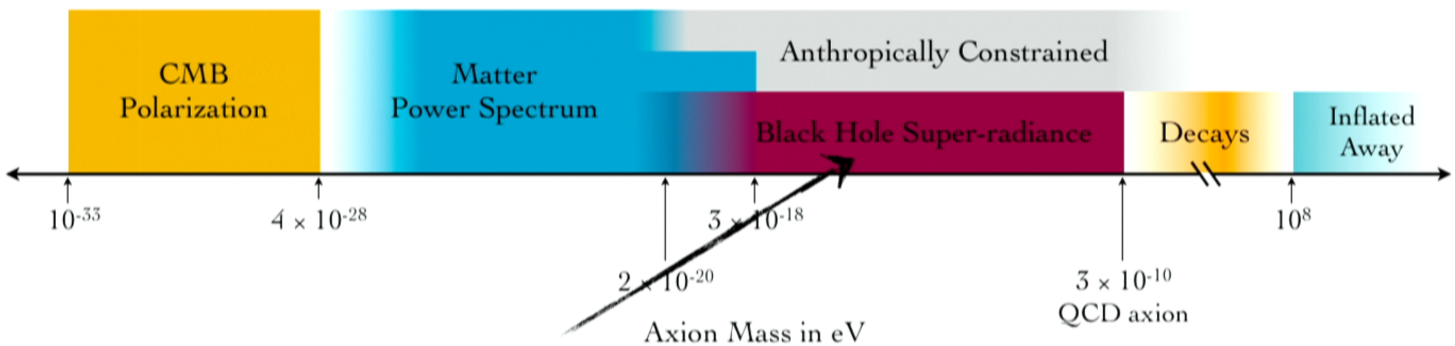




Gaps in the mass vs spin plot

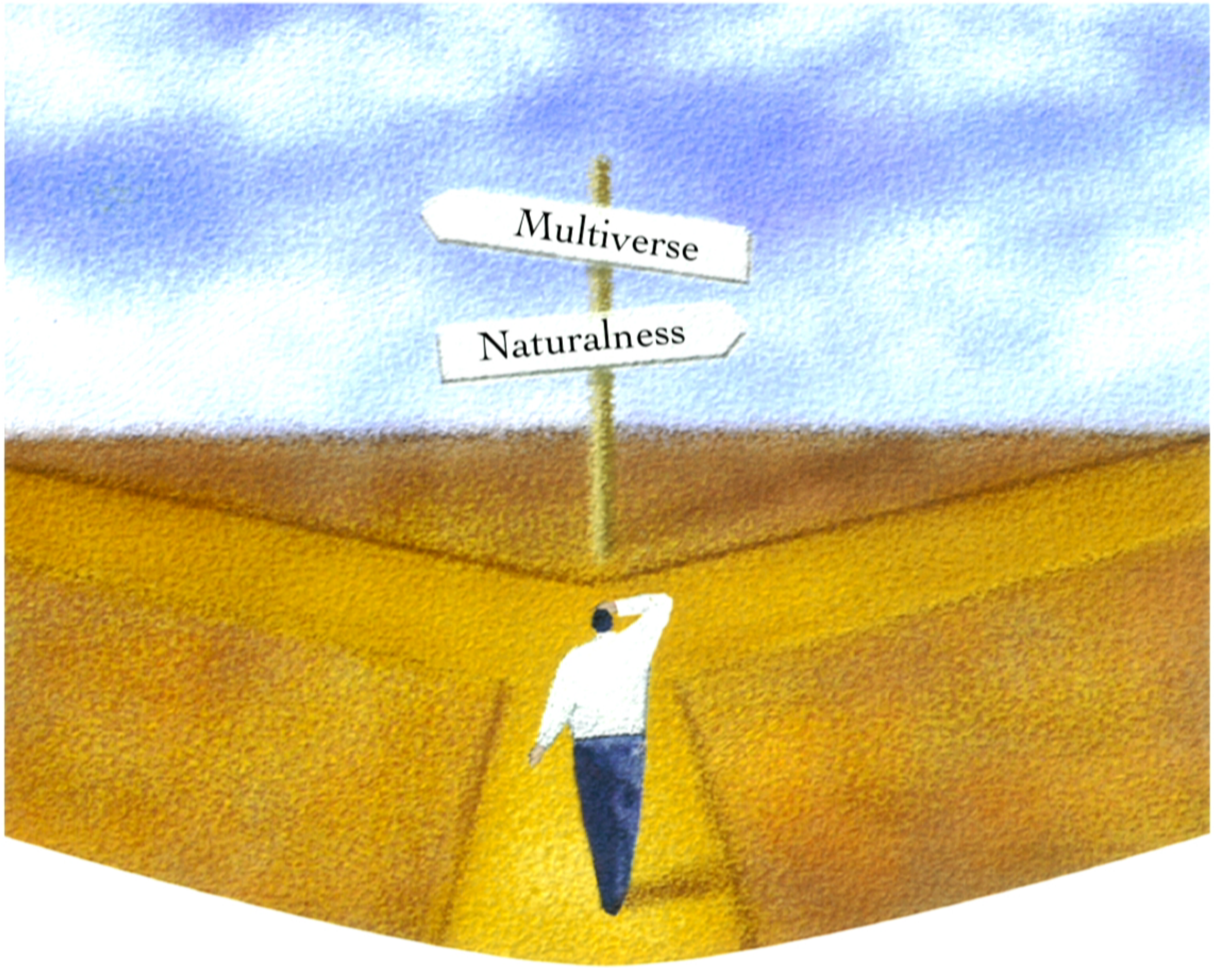
with S. Dubovsky

The String Axiverse



Monochromatic gravitational waves
detected in advanced LIGO

with S. Dubovsky



The Large Hadron Collider will tell us!

$\sin^2\theta_W$
α_s
$\lambda S H_u H_d$