Compressed Supersymmetry from the High Scale

Martin W. Winkler

JHEP 1303, Phys. Rev. D88 *with M. Badziak, S. Krippendorf, H.P. Nilles, M. Ratz*

arXiv:1404.2275 *with W. Buchmüller, C. Wieck*

Mitchell Workshop on Collider and Dark Matter Physics,
College Station

May 15 2014

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$$\Delta M_{H_u}\big|_{\text{gluino}} \propto -y_t^2\, \alpha_s\, m_{\tilde{g}}^2 \log^2\left(\frac{\Lambda}{\text{TeV}}\right)$$

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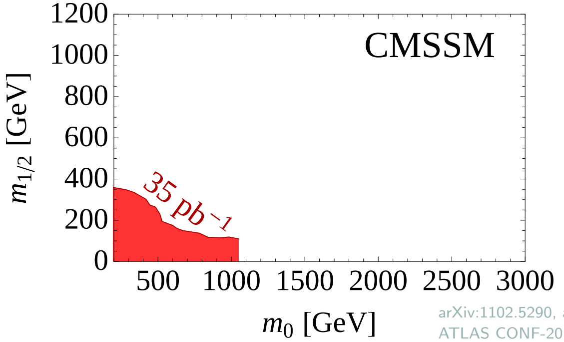

arXiv:1102.5290, arXiv:1109.6572
ATLAS CONF-2013-047

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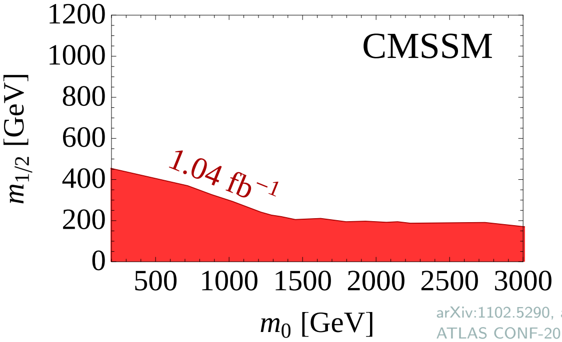

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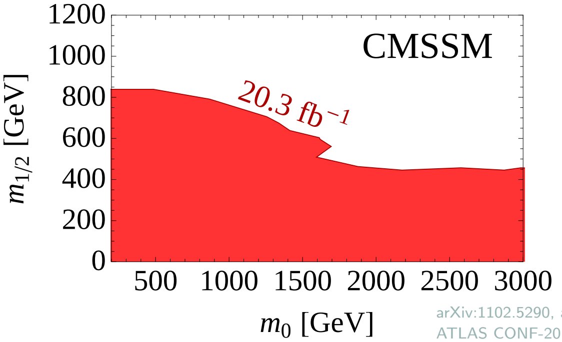

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- Conserved R-parity $\hookrightarrow$ dark matter candidate
- thermal production

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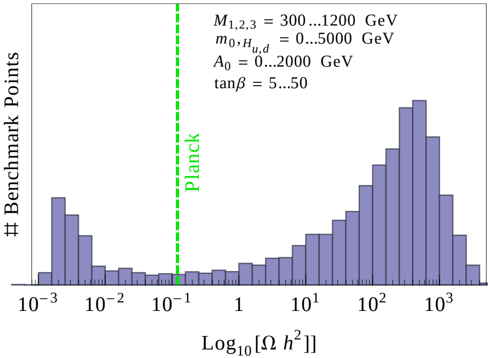
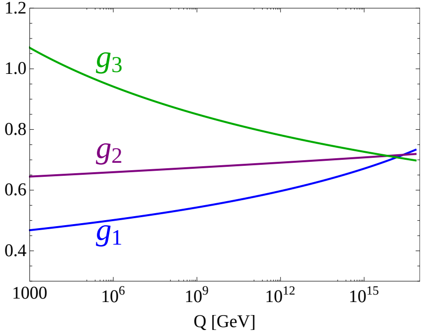


Gauge coupling unification

- gauge coupling unification strong motivation for Supersymmetry
- running gauge couplings in the MSSM



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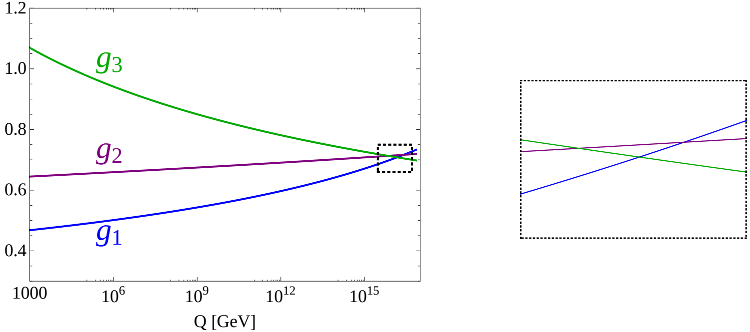
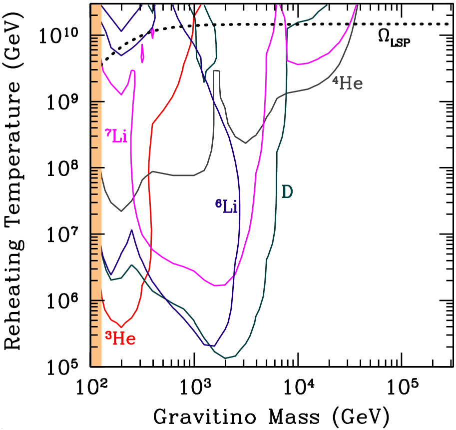


- BUT: g_i miss by a few per cent in minimal models

Gravitino Problem

- gravitino production
  $\Omega_{3/2} \propto T_R$
  Bolz et al. , Nucl. Phys. **B606** (2001)
- late gravitino decay
  $\Gamma_{3/2} \sim m_{3/2}^3 / M_P^2$
  Weinberg, Phys. Rev. Lett. **48** (1982)
  ☹ nucleosynthesis



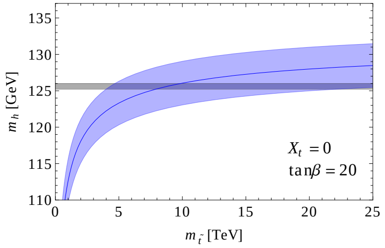
Kawasaki et al., Phys. Rev. **D78** (2008)

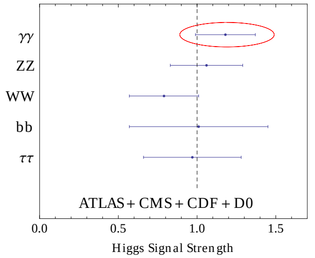
Solutions:

- very low reheating temperature?
- heavy gravitino?

The Higgs Discovery

- discovery of the Higgs boson with $m_h = 126$ GeV
  ATLAS, CMS, Phys. Lett. **B716** (2012)





extracted from Ellis et al., JHEP **1306** (2013)

- heavy stops?

- decay pattern SM-like
- decoupling of SUSY effects

Outline

A string-inspired mediation scheme

- occurs in various string constructions

  KKLT: Choi et al., Nucl. Phys. **B718** (2005), Choi et al. JHEP **0509** (2005), Falkowski et al. JHEP **0511** (2005)
  heterotic string: Lowen et al., Phys. Rev. **D77** (2005), Krippendorf et al., Phys. Lett. **B712** (2012)

- all moduli stabilized at a high energy scale except one light modulus: dilaton S in heterotic string, Kahler modulus T in Type IIb

- light modulus stabilized by gaugino condensate + uplifting sector

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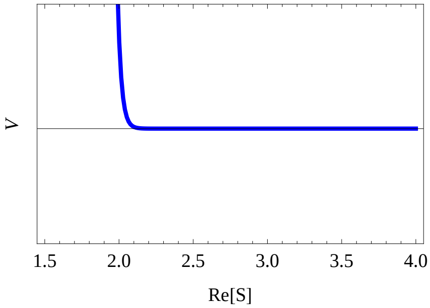

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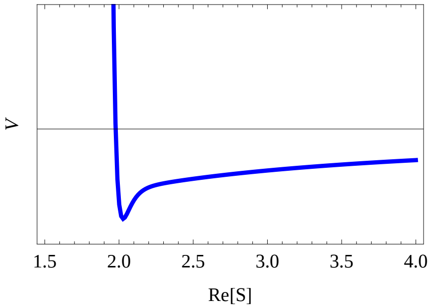

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Brümmer et al., JHEP **1004** (2010)

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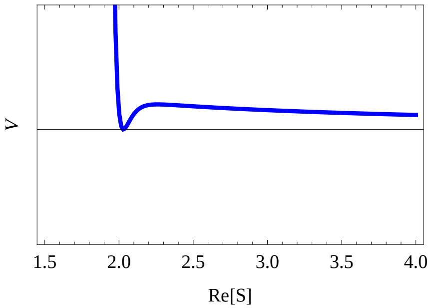

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Brümmer et al., JHEP **1004** (2010)

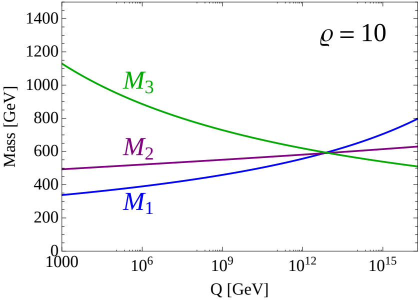
Lebedev et al., Phys. Lett. **B636** (2006)

SUSY breaking

- SUSY breaking pattern fixed by modulus stabilization
- subdominant modulus contribution to SUSY breaking

$$F_S \simeq \frac{F_X}{b} \qquad \text{with} \qquad b \sim \log \frac{M_P}{m_{3/2}}$$

- gravity mediated gaugino masses suppressed (due to $f_a \sim S$)



mirage mediation:
mixed gravity / anomaly mediation

$$M_i = \frac{m_{3/2}}{16\,\pi^2}\,(\varrho + b_i\,g^2)$$

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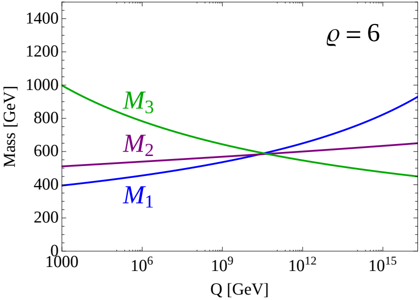

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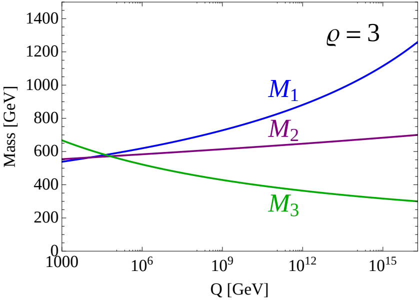

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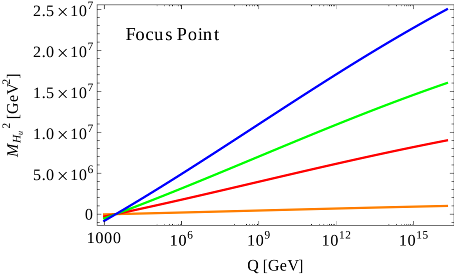
Scalars

- unless for sequestering, scalars $m_0 \sim m_{3/2} \gg m_{1/2}$
  - ☺ Higgs mass easily explained
  - ☺ no gravitino problem
  - ☹ naturalness?
- attractive possibility: universal scalar masses



- multi-TeV scalars not unnatural due to focus point

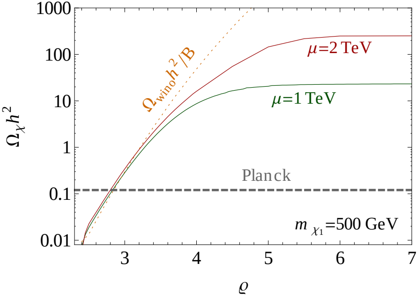
  Feng et al., Phys. Rev. Lett. **84** (1999)

Dark Matter Relic Density

- relic neutralino density

$$\frac{\Omega_\chi}{\Omega_{\mathrm{DM}}} \simeq \frac{\mathrm{pb}}{\langle \sigma v \rangle} \qquad \langle \sigma v \rangle_{\mathrm{bino}} \ll \mathrm{pb} \ll \langle \sigma v \rangle_{\mathrm{wino}} \quad ☹$$

- mirage mediation allows for compressed gaugino spectrum



- bino LSP, wino coannihilations
- Boltzmann suppressed contribution

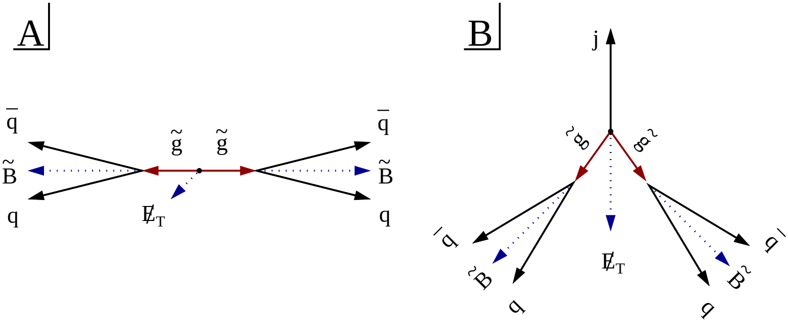
$$\langle \sigma v \rangle_{\mathrm{bino}} \supset B \times \langle \sigma v \rangle_{\mathrm{wino}}$$

$$B \simeq e^{-2\,\Delta m / T_F}$$

Compressed gauginos at the LHC

- Small mass splitting $\Delta m = m_{\widetilde{g}} - m_{\widetilde{\chi}_1}$
- difficult to detect: soft jets, low $\not{E}_T$

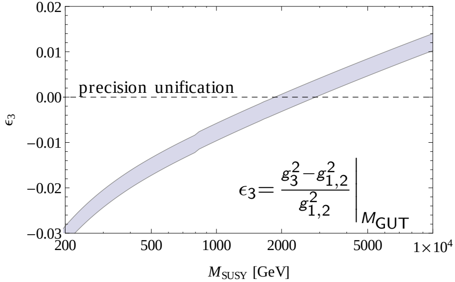
LeCompte et al., Phys. Rev. **D84** (2011), Dreiner et al., Europhys. Lett. **99** (2012)



Alwall et al., Phys. Lett. **B666** (2008)

- initial state radiation required

Gauge coupling unification without GUT thresholds



- assume universal superpartner mass $M_{\rm SUSY}$

$$\frac{1}{g_{i,\rm Thr}^2} = \frac{b_i - b_i^{\rm SM}}{8\pi^2} \ln\left(\frac{M_{\rm SUSY}}{M_Z}\right)$$

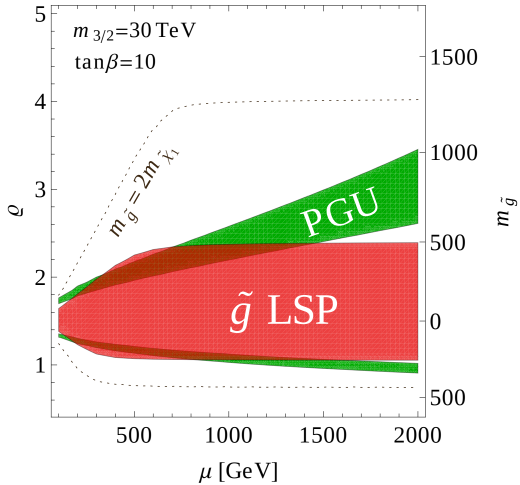
- PGU for $M_{\rm SUSY} \sim 2$ TeV

- general case: define effective threshold scale

$$M_{\rm SUSY} \simeq \frac{m_{\widetilde{W}}^{32/19}\, m_{\tilde{h}}^{12/19}\, m_H^{3/19}}{m_{\tilde{g}}^{28/19}}$$

- PGU requires $\mu \sim 10$ TeV in models with universal $m_{1/2}$

- searching regions with precision unification

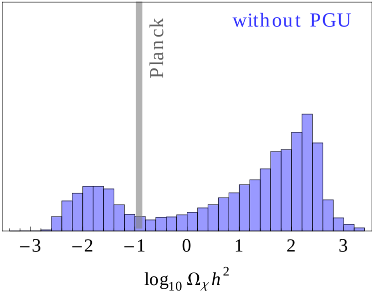


- precision unification with small μ
- **compressed spectrum**

$$m_{\tilde{g}} < 2\, m_{\tilde{\chi}_1}$$

PGU, Dark Matter and LHC

- relic density in mirage mediation
- with / without requiring PGU



benchmark sample: $\varrho = 0.5 - 30$, $m_{1/2}^{\text{grav}} = 0.25 - 1.25$ TeV, $\mu = 0.1 - 2$ TeV, $\tan\beta = 10 - 50$

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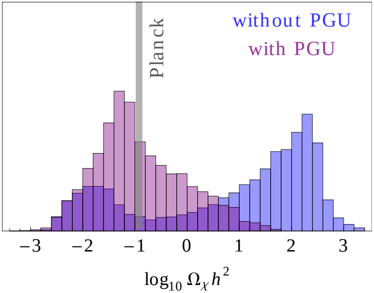

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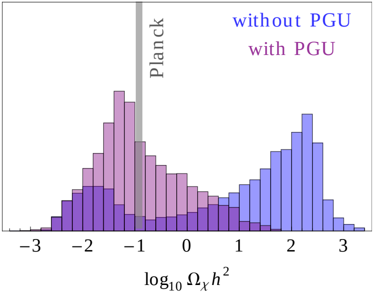
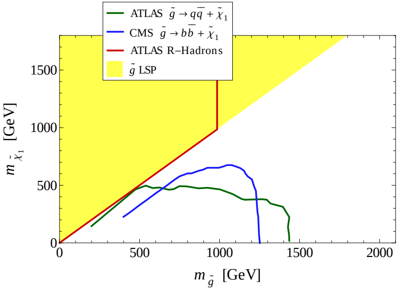


- LHC: use simplified models

  ATLAS CONF-2013-047, CMS-PAS-SUS-13-007

- benchmark points with PGU



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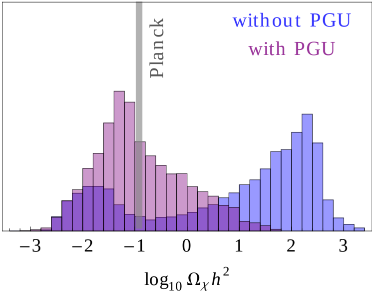

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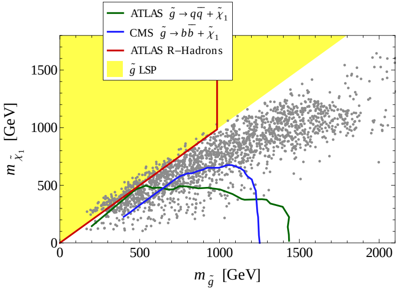

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The Inflationary Challenge

- BICEP2 observation of B-modes from inflation (?)
  Ade et al. arXiv:**1403.3985** (2014)

$$r = 0.16^{+0.06}_{-0.05}$$

- fixes energy scale of inflation

$$V* \simeq M_{\mathrm{GUT}}^4$$

- consider modulus with Kahler potential $K = -n \log(\rho + \bar{\rho})$ and generic F-term inflation

$$V \sim \frac{V_0}{\sigma^n} + m_\rho^2 (\sigma - \sigma_0)^2 + \ldots , \quad \sigma = \mathrm{Re}(\rho)$$

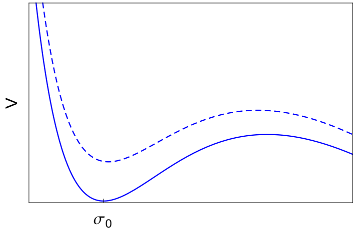
- modulus gets displaced during inflation
- backreaction on the inflaton potential

The Heavy Modulus Case

- all moduli stabilized supersymmetrically with $m > H \gg m_{3/2}$
- example: KL model

  Kallosh, Linde, JHEP **0412** (2004)

$$W = A\, e^{-a\rho} + B\, e^{-b\rho} + C$$



- modulus can be integrated out
- corrections to the inflaton potential arise as power series in H/m_ρ

  Buchmuller et al. arXiv:**1404.2275** (2014)

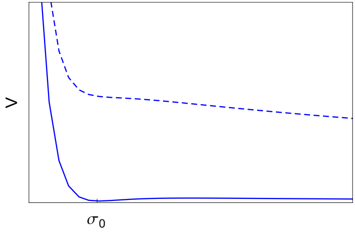
- example: chaotic inflation + modulus

$$V(\varphi) = V_0(\varphi)\left(1 - 3\frac{V_0(\varphi)}{m_\rho^2} + \ldots\right), \qquad V_0(\varphi) = \frac{m^2}{2}\,\varphi^2$$

- interesting corrections to CMB observables

A light Modulus

- in mirage mediation $m_\rho \sim m_{3/2} \ll H$
- modulus participates in the dynamics of inflation



- in generic F-term inflation modulus minimum disappears
- problem: modulus destabilization

- possible solution: stronger moduli stabilization during inflation
- large superpotential during inflation, stabilizing modulus-inflaton coupling

Kachru et al. **1006** (2010), Antusch et al. JHEP **1203** (2012)

Conclusion

- Supersymmetry faces several challenges: non-observation of superpartners, dark matter, cosmology
- mirage mediation can lead to a compressed gaugino spectrum with many attractive features
  - ☺ relaxed LHC constraints on the gluino mass
  - ☺ bino with correct relic density from wino coannihilations
  - ☺ precision unification of gauge couplings
  - ☺ large Higgs mass explained by heavy scalars
  - ☺ no gravitino problem
- connection to high scale inflation has to be further explored