Strong moduli stabilization: motivations and phenomenology

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1. **Motivations:**

2. **Strong moduli stabilization and uplift**

3. **Phenomenology**

4. **Conclusions**

1. Motivations:

1) A framework providing flexibility to describe observational data in the context of supergravity/string theory motivated models

2) Solving the cosmological moduli problem, the gravitino problem, and the problem of the cosmological vacuum destabilization in string theory.

3) Supersymmetry breaking patterns in models with strongly stabilized moduli, leading to mini-split SUSY spectra.
4) Compatible with large-field inflation.

- Cosmological moduli problem

Typically the moduli fields in the early universe take values which are different from their equilibrium values after inflation. During their evolution to their present minimum, they oscillate, and eventually decay.

If they are superheavy, they decay early, but if they are light, they do not decay. In this case, the universe would be dark matter dominated. If they decay very late, they may destroy the products of the nucleosynthesis.

For the moduli in the TeV mass scale, this may contradict observational data by many orders of magnitude.

This problem arises for Polonyi fields and for volume modulus in the KKLT model, since the KKLT volume modulus is only 1-2 orders of magnitude heavier than $m_{3/2}$

- Gravitino problem

- Gravitinos are produced, in particular, by particle collisions after reheating.

- To avoid the gravitino problem for gravitinos around TeV mass scale, one should have reheating temperature below 10^8 GeV.

- One may avoid this problem if gravitinos are much heavier and decay fast, or if gravitinos are super-light.

- If large-field (chaotic) inflation realized in nature

(talks L.Heurtier, C. Wieck)

- Then $H \sim 10^{14}\ GeV$, $m_{inf.} \sim 10^{13}\ GeV$

- Moduli should be heavy enough $M_{moduli} > H$

- SUSY breaking scale below inflaton mass
  $m_{3/2} < m_{inf.}$ (Buchmuller, E.D.,Heurtier,Wieck)

⇨ Strong moduli stabilization seems then necessary.

2. Strong moduli stabilization and uplift

We will attempt to **STRONGLY** stabilize all string theory specific moduli, such as volume modulus, as well as hidden sector moduli, such as Polonyi fields.

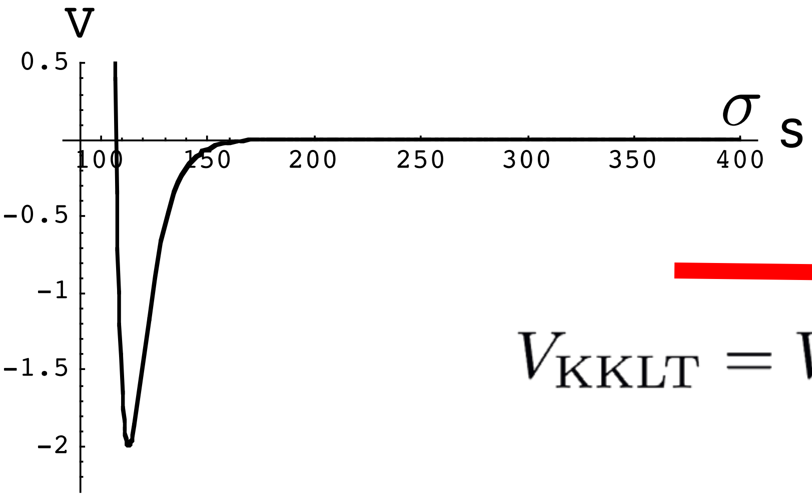
Consequences:

Split supersymmetry with $M_{moduli} >> m_{3/2} >> m_{gaugino}$
Solves the vacuum destabilization problem, the cosmological moduli and the gravitino problems, and admits Higgs with m ~ 125 GeV for $m_{3/2} \sim 10^2$ TeV. Wide range of inflationary models in supergravity, which can fit observational data with **any** values of n_s and r.

Vacuum stability and SUSY breaking in KKLT

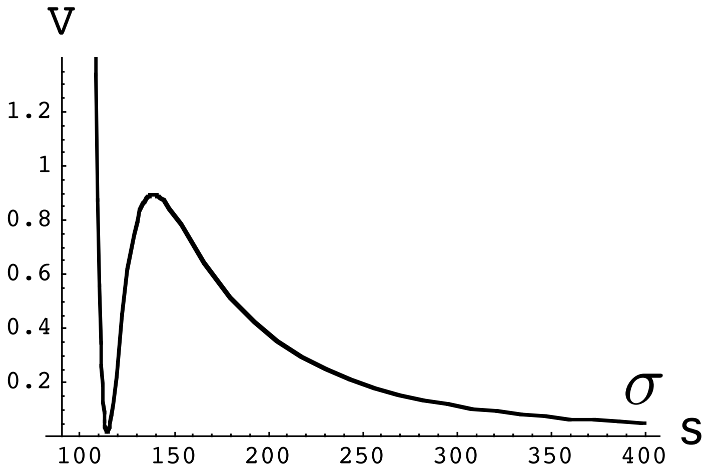
$$W = W_0 + Ae^{-a\rho} \qquad \mathcal{K} = -3\ln[(\rho+\bar{\rho})]$$

$$\rho = \sigma + i\alpha$$



Stabilization in a supersymmetric AdS minimum

$$V_{\text{KKLT}} = V_{\text{AdS}} + \frac{D}{\sigma^2}$$



Uplifting to dS breaks SUSY

$$m_{3/2}^2 = |V_{\text{AdS}}/3|$$

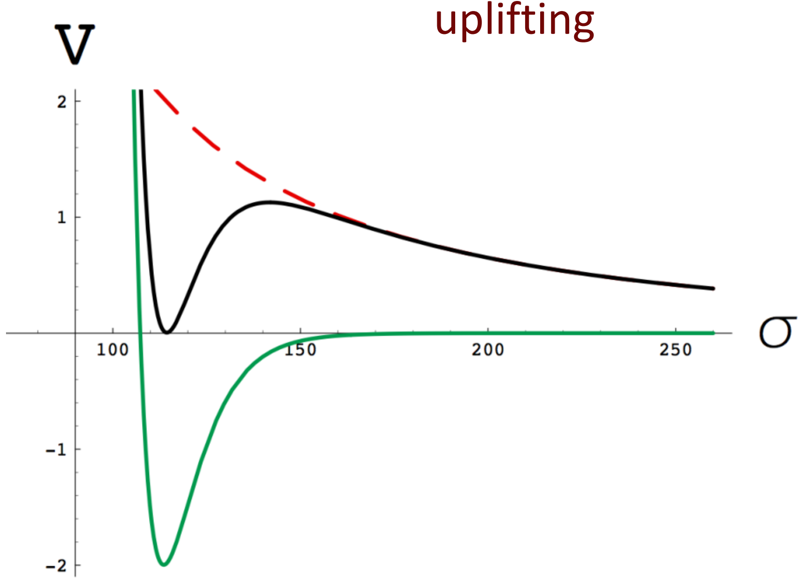
$$D_\rho W = \frac{3\sqrt{2}}{a\sqrt{\sigma_0}}\, m_{3/2}$$

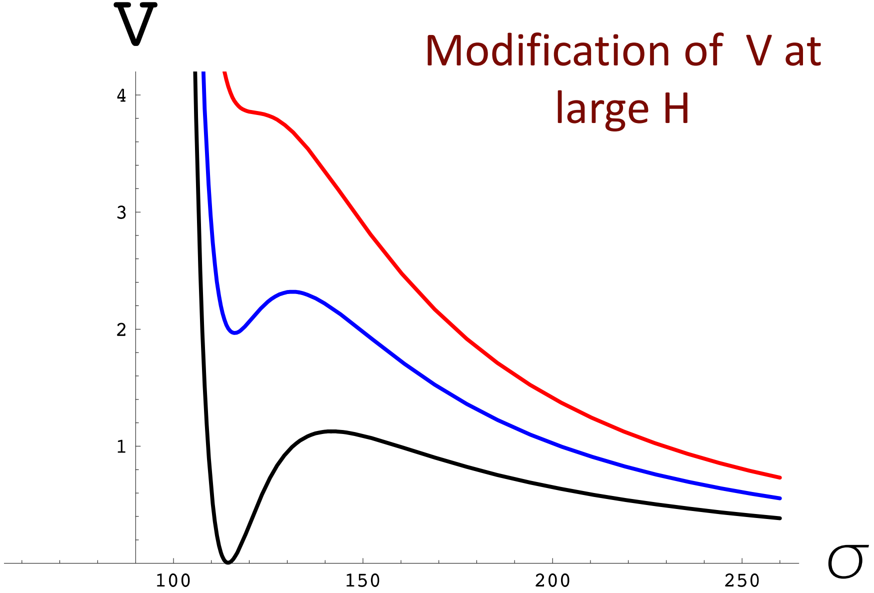
Modulus SUSY breaking of order $m_{3/2}$

Vacuum destabilization during inflation

Kallosh, Linde 2004

The height of the KKLT barrier is smaller than $|V_{AdS}| = 3m^2_{3/2}$. The inflationary potential V_{infl} cannot be much higher than the height of the barrier. Inflationary Hubble constant is $H^2 = V_{infl}/3 < |V_{AdS}/3| \sim m^2_{3/2}$.


uplifting


Modification of V at large H

Constraint on the Hubble constant in this class of models:

$$H < m_{3/2}$$

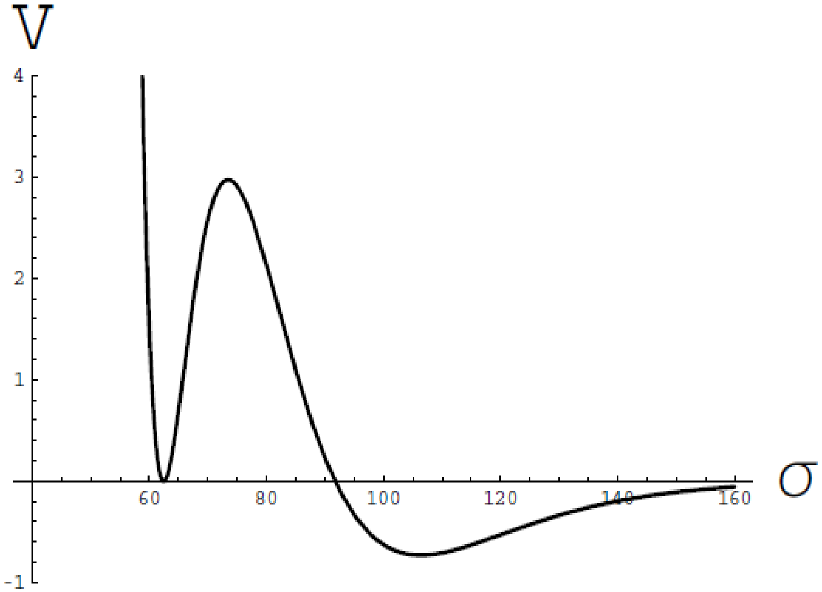
- Strong moduli stabilisation prototype: KL

Kallosh, Linde 2004

$$\mathcal{K} = -3\ln[(\rho + \bar{\rho})]$$

$$W = W_0 + Ae^{-a\rho} - Be^{-b\rho}$$

$$W_0 = -A\left(\frac{a\,A}{b\,B}\right)^{\frac{a}{b-a}} + B\left(\frac{a\,A}{b\,B}\right)^{\frac{b}{b-a}} \quad +\Delta$$



It has a supersymmetric Minkowski vacuum for $\Delta = 0$, with a high barrier.

Δ makes it a supersymmetric AdS.

Uplifting breaks SUSY

$$m_{3/2} \sim \Delta$$

Thus one can have a high barrier and a tiny gravitino mass

H can be arbitrarily large

More on uplift

Simplest uplift picture:

- F-term by a DSB or O’R sector, fields S, with a dynamical scale M.
- The uplift sector breaks SUSY in the rigid limit.
- It is coupled only by gravity to KL and MSSM sectors.

$$\begin{aligned} W &= W_{\mathrm{KL}}(\rho) + W_F(S) + W_{MSSM}(\rho, \Phi^i) \\ K &= -3\ln(\rho+\bar{\rho}) + K(S,\bar{S}) + K_{MSSM}(\rho,\bar{\rho},\Phi^i,\bar{\Phi}^i) \end{aligned}$$

Provided KL modulus mass and uplift sector masses >> $m_{3/2}$, SUGRA interactions change the original KL and uplift sector dynamics in a very tiny way.

Simplest examples of uplifts: O'KL and ISS.

Ex: O'KL

$$\begin{aligned} W_F(S) &= M^2 S \\ K(S,\bar{S}) &= S\bar{S} - \frac{(S\bar{S})^2}{\Lambda^2} \end{aligned}$$

(Kallosh-Linde, Dine et al.)

M=dynamical scale; Λ is an effective scale from integrating out heavy states.

In this case we get :

$$M^4 = 3\Delta^2 = 24\sigma_0^3 m_{3/2}^2 \quad , \quad \langle S \rangle = \frac{\sqrt{3}\Lambda^2}{6}$$ << 1

$$m_S^2 = \frac{3\Delta^2}{2\sigma_0^3\Lambda^2} = \frac{12 m_{3/2}^2}{\Lambda^2} \gg m_{3/2}^2$$ and

$$D_S W \sim \sigma_0^{3/2} m_{3/2} \quad , \quad D_\rho W \sim \frac{m_{3/2}^2}{m_\sigma}$$ is negligible.

- It is often said that in string/SUGRA, there is at least one light modulus since

$$M^2_{min} = m^2_{3/2}(2 \; + \; |r|)$$

$$\text{where} \quad r = \frac{1}{3} R_{i\bar{j}k\bar{l}} G^i G^{\bar{j}} G^k G^{\bar{l}}$$

But in SMS $\quad r \sim \dfrac{M_P^2}{\Lambda^2} \gg 1$

- Since both moduli and uplift fields are very heavy

$$m_\sigma \;, \; m_S \; \gg \; m_{3/2}$$

there are no cosmological (Polony) moduli problems.

- Cosmological gravitino problem is also solved for

$$m_{3/2} \; \geq \; 30 \; TeV$$

3. Phenomenology (DLMMO)

- Soft terms:

Soft terms for MSSM fields are given by supergravity interactions

In our models with :
- strong moduli stabilization
- decoupling between uplift and matter fields

we find to a high accuracy $m_0^2 = m_{3/2}^2$,

which fixes the universal scalar masses.

SUGRA contributions to A-terms and gaugino masses are very small, since $D_\rho W \ll m_{3/2}\ ,\ \langle S\rangle \ll 1$

$$A \sim max\ (m_{3/2}\Lambda^2, \frac{m_{3/2}^2}{m_\sigma})$$

$$m_{1/2} \sim \frac{m_{3/2}^2}{m_\sigma}$$

The main contributions come from anomaly mediation:

$$m^a_{1/2} = \frac{b_a g_a^2}{16\pi^2}\frac{F^C}{C_0} \quad , \quad A_{ijk} = -\frac{\gamma_i+\gamma_j+\gamma_k}{16\pi^2}\frac{F^C}{C_0}$$

where $$\frac{F^C}{C_0} = -\frac{1}{3}e^{K/2}K^{\alpha\bar\beta}K_\alpha \bar D_{\bar\beta}\bar W + m_{3/2} \simeq m_{3/2}$$

For the Higgs sector, we get

$$\mu = \mu_0 + m_{3/2} K_{12} \quad , \quad B\mu = (A_0 - m_{3/2})\mu_0 + 2m_{3/2}^2 K_{12}$$

where $\mu_0 = e^{K/2} W_{12}$ is the mu-term

and $m_{3/2} K_{12}$ is a Giudice-Masiero contribution

Soft Higgs masses are $m_1^2 = m_2^2 = m_{3/2}^2$

However, usually in string theory Higgses have a different origin compared to quarks/leptons. If they couple directly to the uplift field S ⇒ non-universal Higgs masses.

- Phenomenology similar to that of mini-split models (Arkani-Hamed,Dimopoulos) and « pure gravity mediation » Ibe,Yanagida (2011).

Remarks:

-The word decoupling here means that coeff. of operators like

$$\begin{aligned} \Delta K &= \frac{1}{(\rho+\bar{\rho})^n} S\bar{S} + S\bar{S}\,\Phi^i\bar{\Phi}_i \ , \\ \delta f &= S\, W^\alpha W_\alpha \end{aligned}$$

are small. Can be realized in IIB strings with D7/D3 branes. Some results do not change significantly by relaxing this hypothesis.

- Uplifting with antibranes unrealistic: pure anomaly mediation.
  - Suppressing moduli contribution to SUSY breaking welcome for flavor issues.

Low-energy phenomenology

- LEP chargino mass limit $m_{\chi^+} > 104\ GeV$

  implies $m_{3/2} \geq 31\ TeV$

- The Higgs mass at this value of $m_{3/2}$ is 125.3 GeV (slight dependence on $\tan\beta$).

- For $30\ TeV \leq m_{3/2} \leq 10^3\ TeV$ and reasonable values of the other parameters we find

$$125\ GeV \leq m_h \leq 130\ GeV$$

- Only light superpartners are gauginos , bino and gluinos.

- The LSP is the neutral wino (anomaly-mediation)

parameter	1	2	3	4	5
$m_{3/2}$ [TeV]	32	50	100	500	1000
$m_{\tilde{g}}$ [TeV]	1.0	1.5	2.7	11.1	20.8
$m_{\tilde{\chi}1}$ [GeV]	107	168	338	1705	3423
$m_{\tilde{\chi}2}$ [GeV]	314	495	1000	5130	10400
$m_{\tilde{\chi}3}$ [TeV]	22.0	34.9	70.7	367	745
$m_{\tilde{\chi}4}$ [TeV]	22.0	34.9	70.7	367	745
$m_{\chi_1^+}$ [GeV]	107	168	338	1705	3420
$m_{\chi_2^+}$ [TeV]	22.0	34.9	70.7	367	745
$m_{\tilde{t}_1}$ [TeV]	24.2	38.0	77.2	397	803
$m_{\tilde{t}_2}$ [TeV]	26.8	42.1	84.6	428	860
$m_{\tilde{b}_1}$ [TeV]	26.9	42.1	84.7	428	860
$m_{\tilde{b}_2}$ [TeV]	30.6	47.9	96.0	483	969
$m_{\tilde{q}_L}$ [TeV]	31.4	49.2	98.5	494	990
$m_{\tilde{u}_R}$ [TeV]	31.5	49.3	98.7	495	990
$m_{\tilde{d}_R}$ [TeV]	31.6	49.4	98.9	496	992
$m_{\tilde{\tau}_1}$ [TeV]	29.6	46.2	92.3	459	917
$m_{\tilde{\tau}_2}$ [TeV]	31.2	48.7	97.5	488	978
$m_{\tilde{\nu}_\tau}$ [TeV]	31.2	48.7	97.5	488	978
$m_{\tilde{e}_L}$ [TeV]	31.9	49.8	99.6	498	996
$m_{\tilde{e}_R}$ [TeV]	32.0	50.0	100	500	1000
$m_{\tilde{\nu}_L}$ [TeV]	31.9	49.8	99.6	498	996
m_h [GeV]	125	127	128	132	133
μ [TeV]	20.4	32.3	65.0	333	673
m_A [TeV]	19.5	30.6	58.4	262	494
$\Omega_{\tilde{\chi}} h^2$	0.0003	0.0008	0.0030	0.067	0.26
$\sigma^{SI}(\chi_1 p) \times 10^{14}$ [pb]	4.74	1.81	0.44	0.02	0.003
$\sigma^{SD}(\chi_1 p) \times 10^{12}$ [pb]	6.78	0.94	0.04	0.0008	0.001

Dark matter relic density is generically too small. One can invoke three standard possibilities:

i) Non-thermal LSP's creation via gravitino decays (see also Evans,Garcia,Olive). Thermal density comes out to be

$$\Omega_\chi h^2 = \frac{m_\chi}{m_{3/2}} \Omega_{3/2} h^2 = 0.4 (\frac{m_\chi}{\mathrm{TeV}})(\frac{T_R}{10^{10}\mathrm{GeV}}) \, .$$

Ex. that saturates PLANCK

$$m_\chi \sim 100 \; GeV \;\; , \;\; T_R \sim 3 \times 10^{10} \; GeV$$

ii) Increase gravitino mass. Ex:

$$m_{3/2} \simeq 650 \; TeV \;\; \Rightarrow \;\; \Omega_\chi h^2 \simeq 0.11$$

In this case higgs mass is a bit large, 128.5 GeV.

iii) Dark matter is something else (axion ?)

Conclusions

Strong moduli stabilization addresses cosmological questions like :

- destabilization of internal space during inflation
- Polony moduli and gravitino cosmological problems
- Compatibility with large-field inflation, which requires $M_{moduli} > H$ and $m_{3/2} < m_{inf}.$

- Our main hypothesis is decoupling of uplift sector.

- LEP constraints on chargino mass and DM relic density $\Longrightarrow$ $30\ TeV \leq m_{3/2} \leq 650\ TeV$,

implying $125\ GeV \leq m_h \leq 128.5\ GeV$

- Low-energy spectrum: particular version of mini-split SUSY: gaugino masses and A-terms given by anomaly mediation, heavy higgsinos.

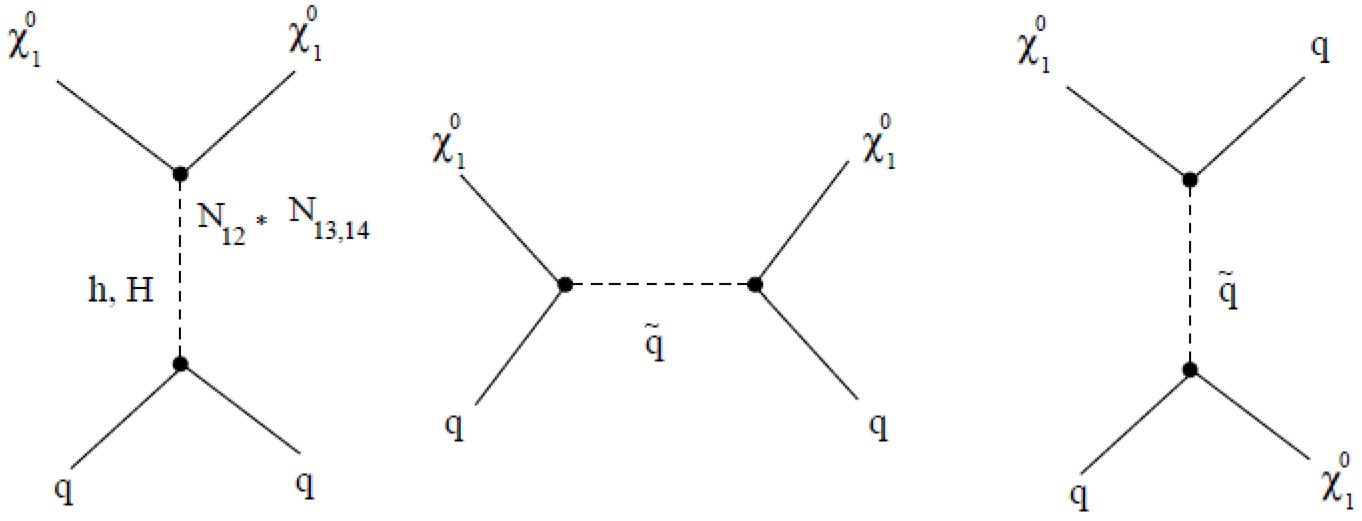
- LHC signatures of SMS are difficult :

- no sizeable displaced vertices from gluinos decays
- small mass difference between chargino and LSP wino leads to very soft pions in the decay

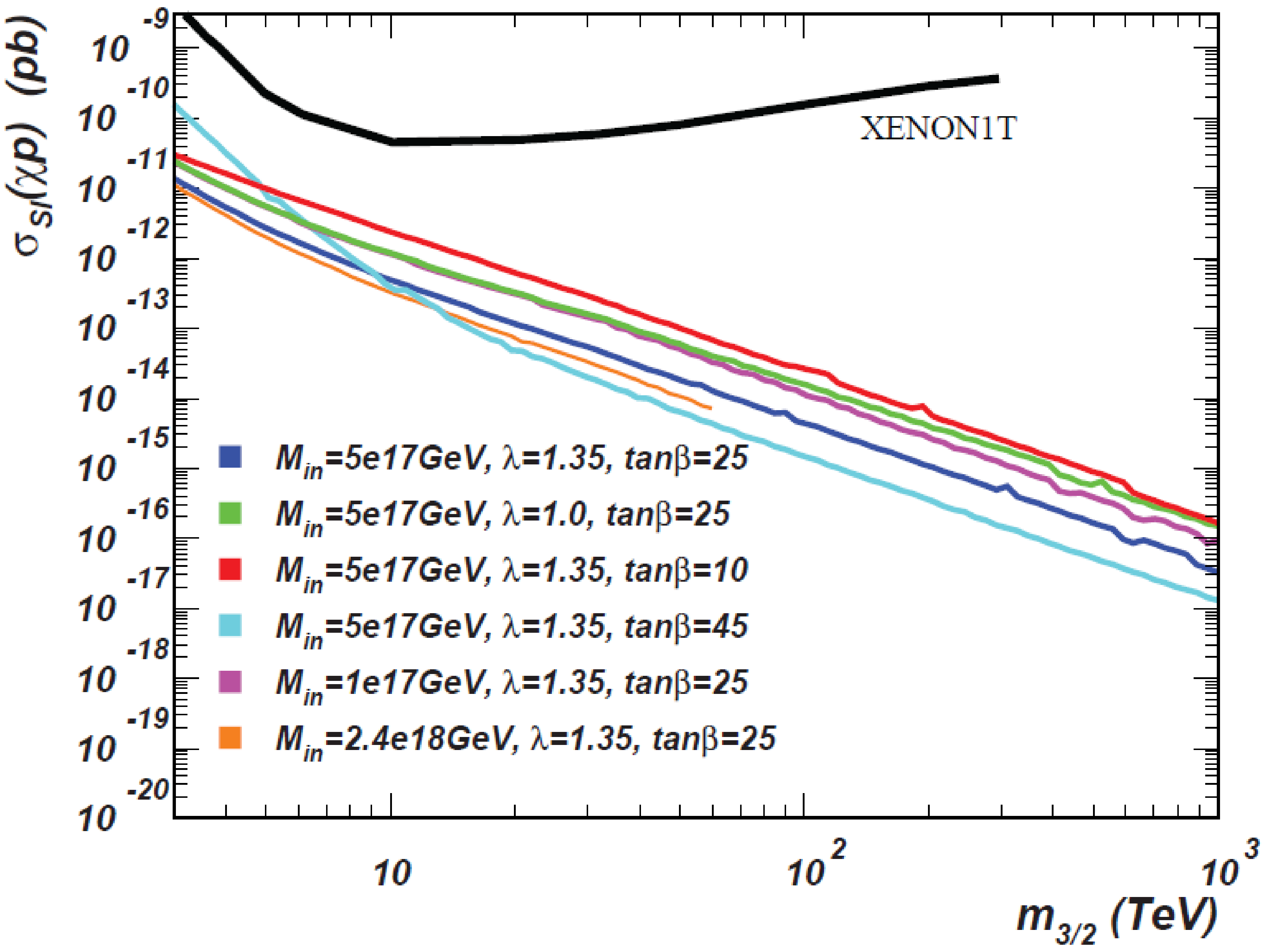
$$\tilde{\chi}_1^{\pm} \rightarrow \tilde{\chi}^0 + \pi^+$$

which were argued to lead to observable charged track stubs.

Backup slides



$\sigma^{SI}_{\chi p}$


$\sigma_{SI}(\chi p)$ (pb)
10^{-9}
10^{-10}
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XENON1T
🟦 M_{in}=5e17GeV, λ=1.35, tanβ=25
🟩 M_{in}=5e17GeV, λ=1.0, tanβ=25
🟥 M_{in}=5e17GeV, λ=1.35, tanβ=10
🟦 M_{in}=5e17GeV, λ=1.35, tanβ=45
🟪 M_{in}=1e17GeV, λ=1.35, tanβ=25
🟧 M_{in}=2.4e18GeV, λ=1.35, tanβ=25
10
10^{2}
10^{3}
$m_{3/2}$ (TeV)