A first evidence of the CMSSM is appearing soon

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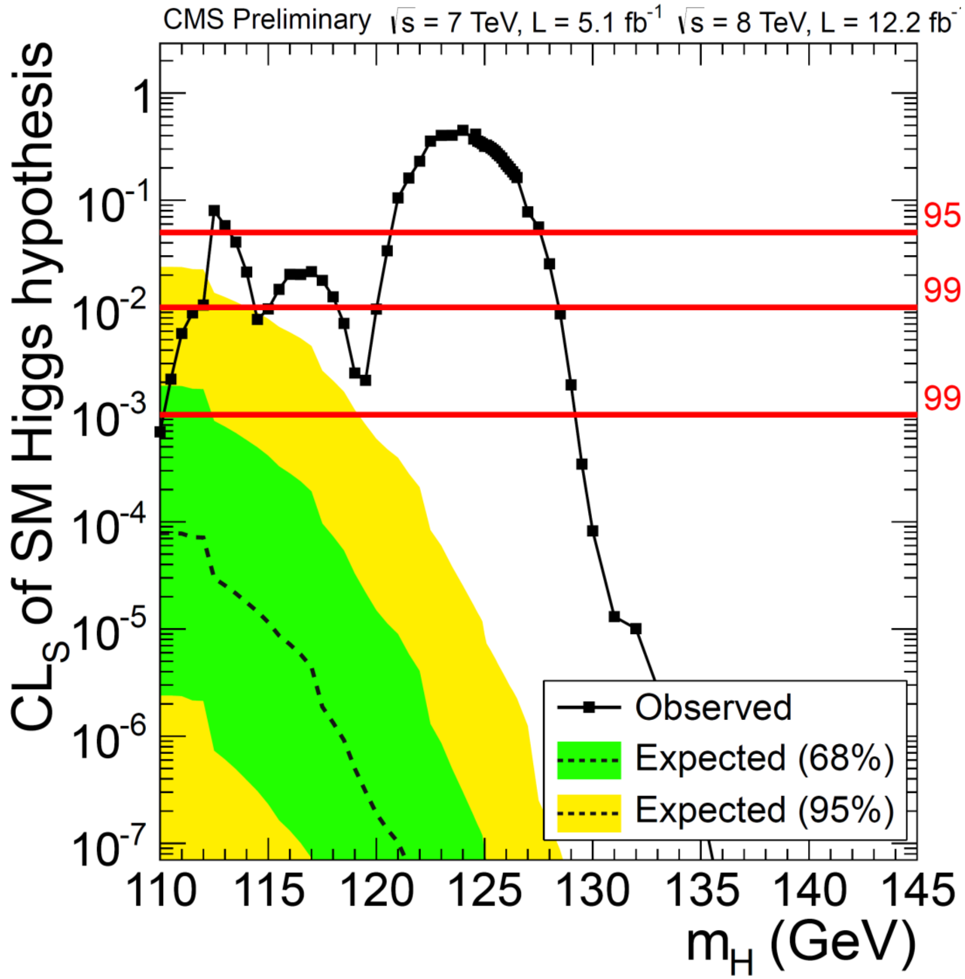
arXiv:1309.2067

Tuesday, December 3, 2013,IPMU

Introduction

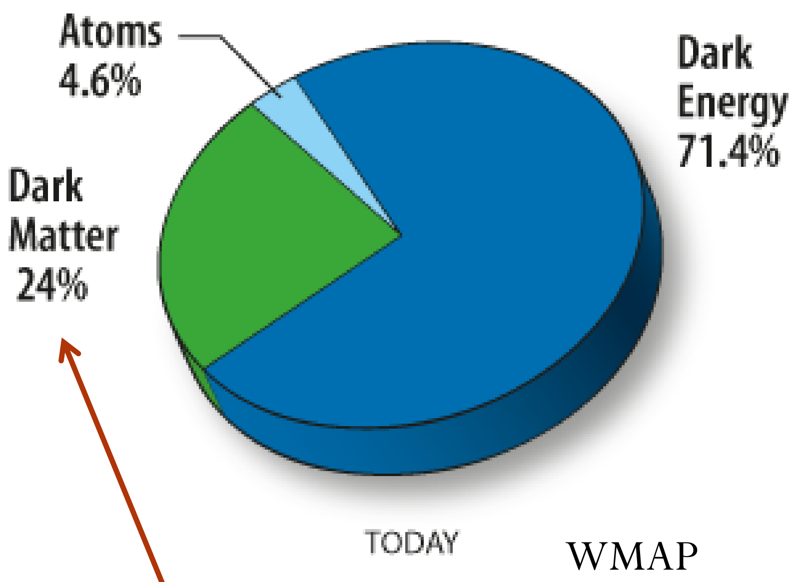
Higgs Mass

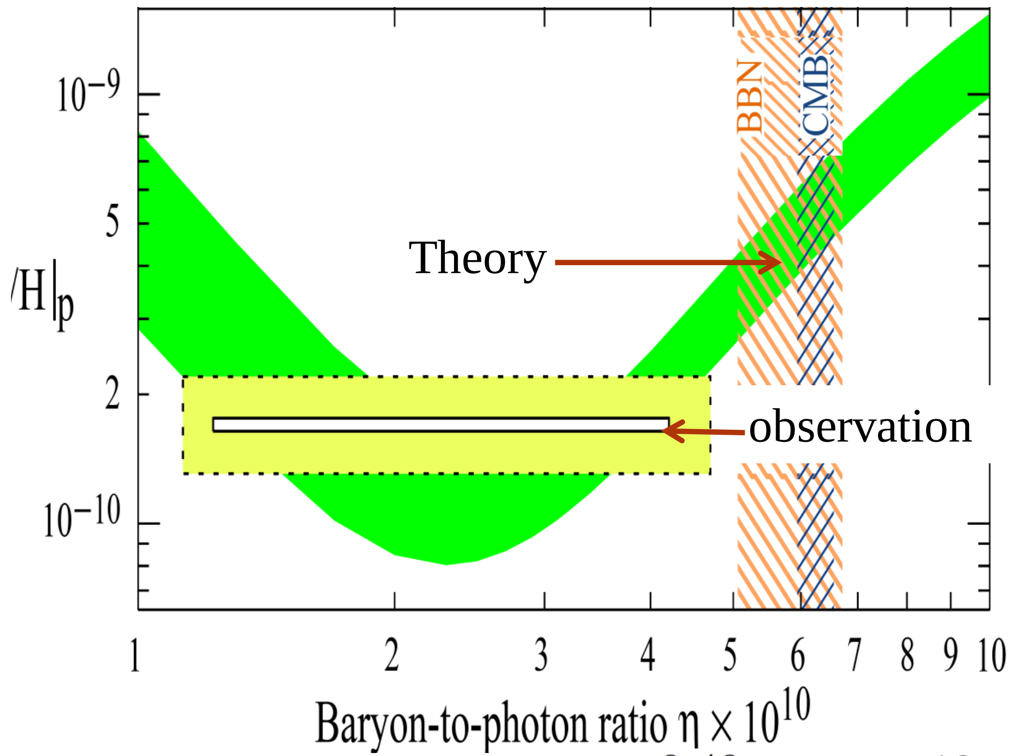


$$m_h = 125.8 \pm 0.4(\text{stat}) \pm 0.4(\text{syst}) \quad [\text{GeV}]$$

CMS-PAS-HIG-12-045

Dark Matter & Li problem





What's the identity??

Theoretical value: $(4.15^{+0.49}_{-0.45}) \times 10^{-10}$

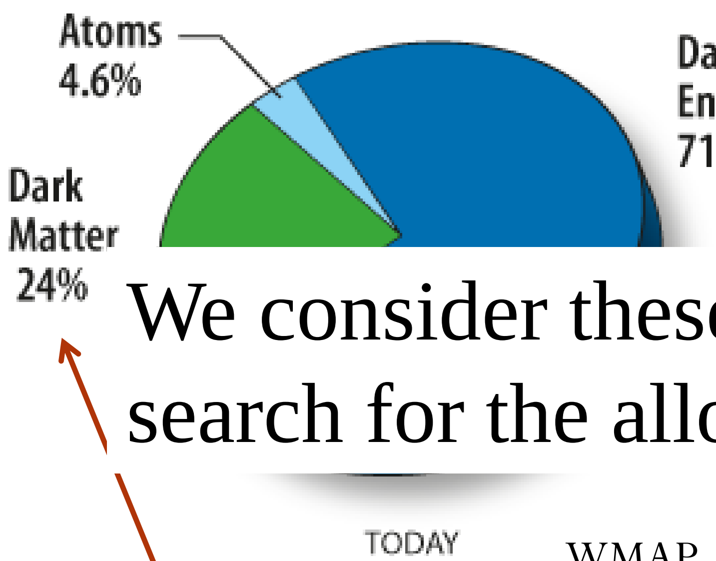
A.Coc, et al., astrophys. J. 600,544(2004)

Inconsistency! $\vee$

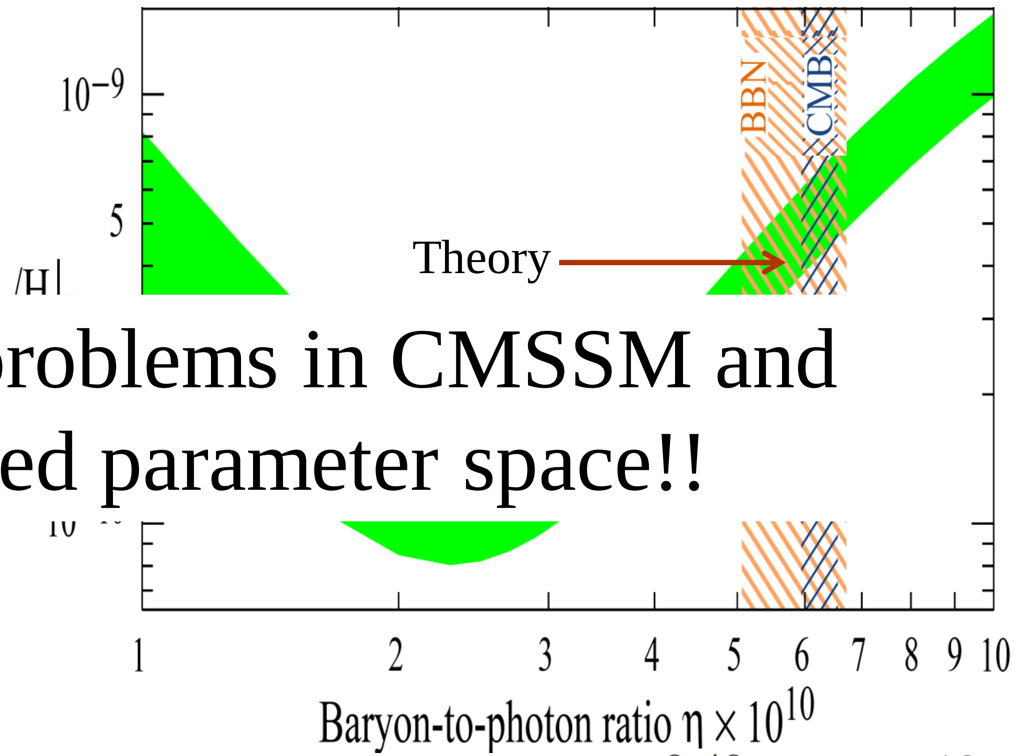
Observed value: $(1.26^{+0.29}_{-0.24}) \times 10^{-10}$

P.Bonifacio, et al., astro-ph/0610245

Dark Matter & Li problem



WMAP



We consider these problems in CMSSM and search for the allowed parameter space!!

What's the identity??

Theoretical value: $(4.15^{+0.49}_{-0.45}) \times 10^{-10}$

A.Coc, et al., astrophys. J. 600,544(2004)

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Model & Constraints

Model

- CMSSM+ R-parity

free parameter : m_0, $M_{1/2}$, A_0, tan β, sign(μ)

- LSP : Bino-like Neutralino ($\tilde{\chi}$) ←neutral & stable
- NLSP : Stau ($\tilde{\tau}$)

→ Coannihilation Mechanism : The neutralino accounts for the DM abundance.

$\tilde{\tau}\tilde{\chi}^0 \leftrightarrow \text{SM particles}$

Requirement of
Coannihilation Mechanism

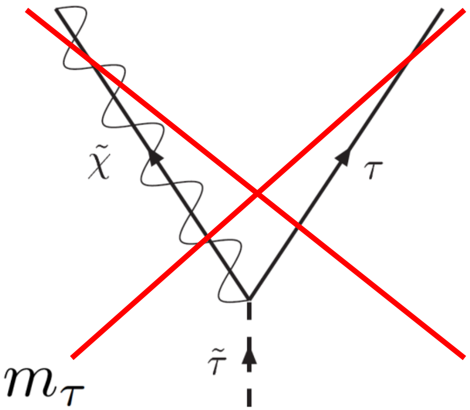
$$\frac{\delta m \equiv m_{\tilde{\tau}} - m_{\tilde{\chi}^0}}{m_{\tilde{\chi}^0}} \sim \text{a few}\%$$

The stau becomes long lived!!

K. Griest and D. Seckel, Phys. Rev. D **43** (1991) 3191.

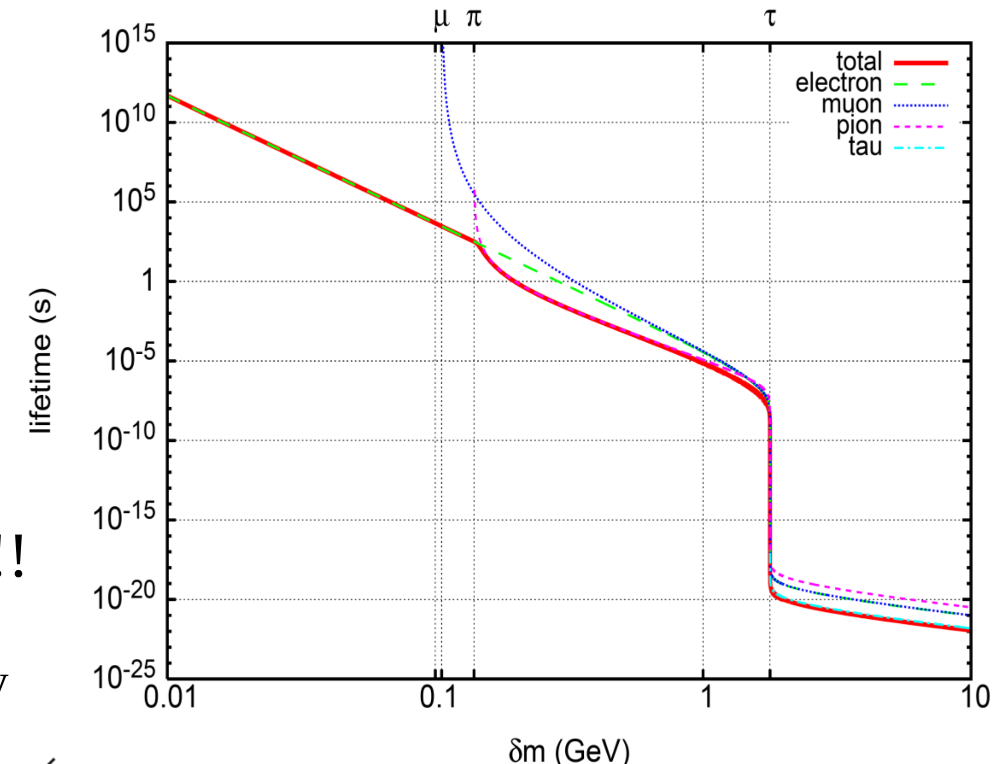
Long lived stau

2 body decay

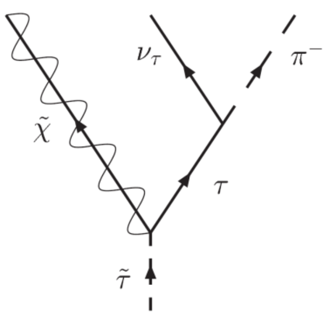


$\delta m < m_\tau$

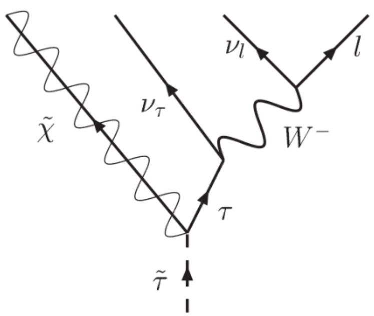
➡ kinematically forbidden!!



3 body decay



4 body decay

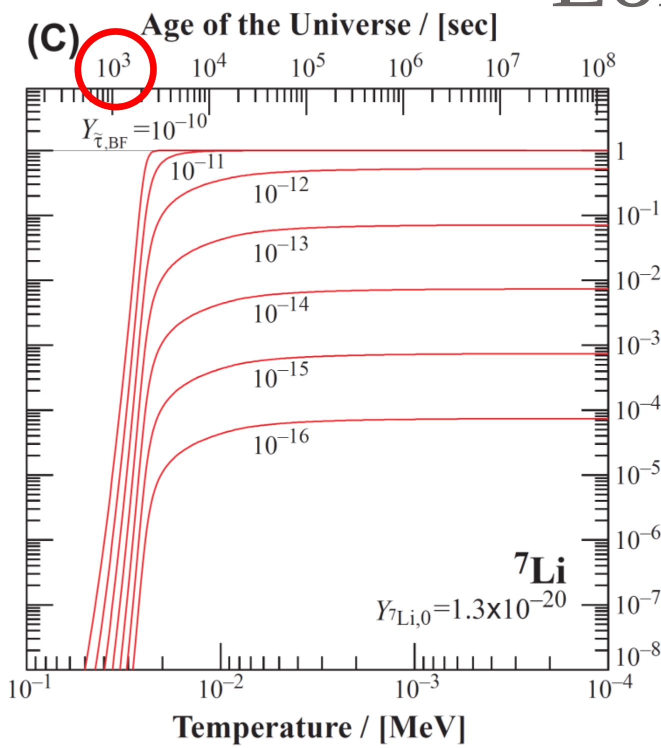


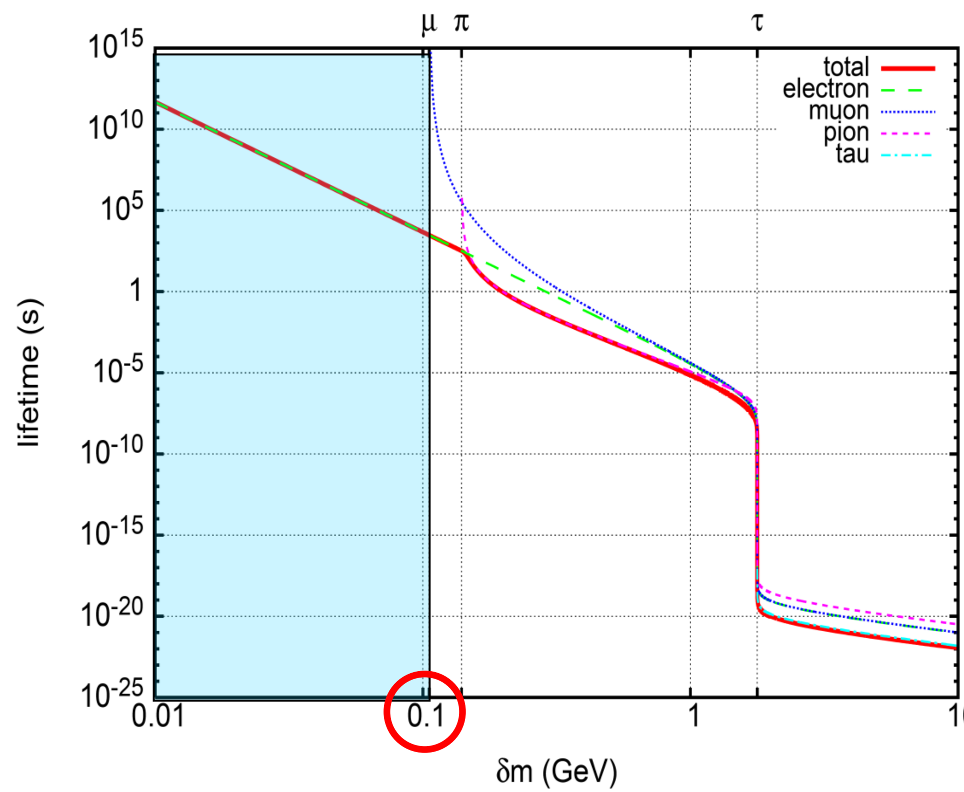
Phase space suppression

→The stau becomes long lived!

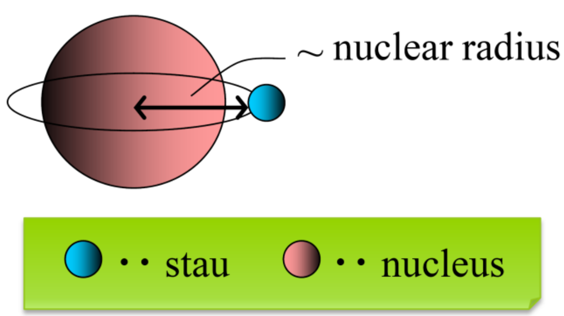
T. Jittoh *et al*, Phys. Rev. D **73** (2006) 055009 [arXiv:hep-ph/0512197]

Long lived stau





Bound state



If the stau sufficiently long lived,
the stau forms bound state with nuclei.

→**The stau causes exotic nuclear reactions through the bound state!!**

Exotic nuclear reaction

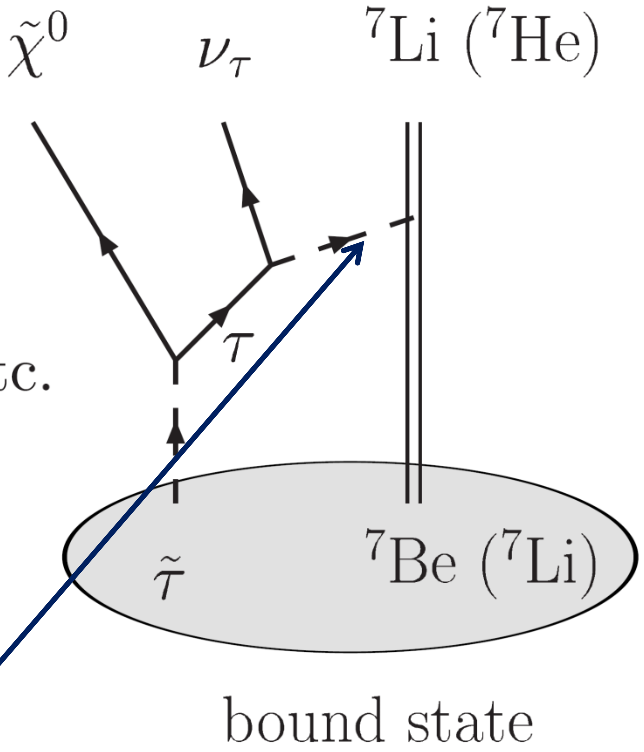
Internal conversion

$$(\tilde{\tau}\,{}^7\mathrm{Be}) \to \tilde{\chi}^0 + \nu_\tau + {}^7\mathrm{Li},$$

$$(\tilde{\tau}\,{}^7\mathrm{Li}) \to \tilde{\chi}^0 + \nu_\tau + {}^7\mathrm{He},$$

$${}^7\mathrm{He} \to {}^6\mathrm{He} + \mathrm{n}$$

$${}^6\mathrm{He} + \text{background particles} \to {}^3\mathrm{He}, {}^4\mathrm{He}, \text{etc.}$$



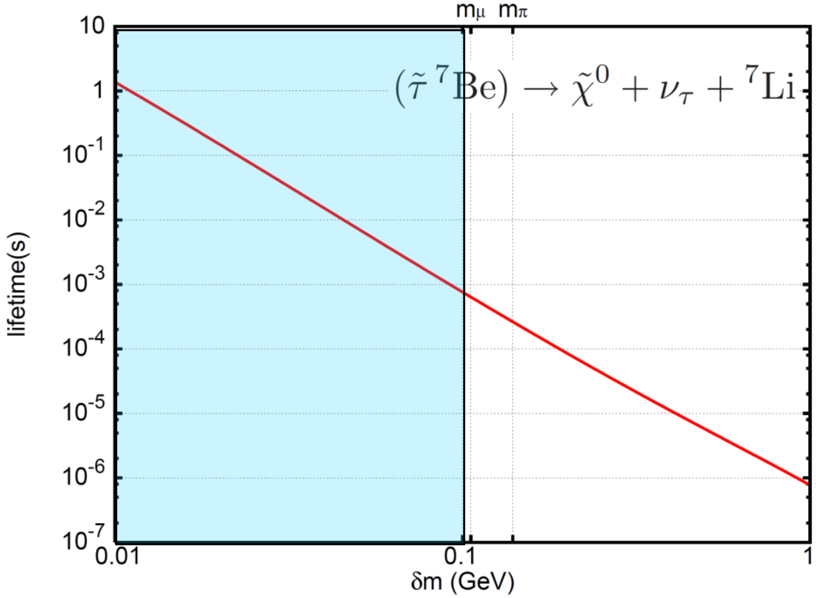
Enhancement of the reaction rate due to

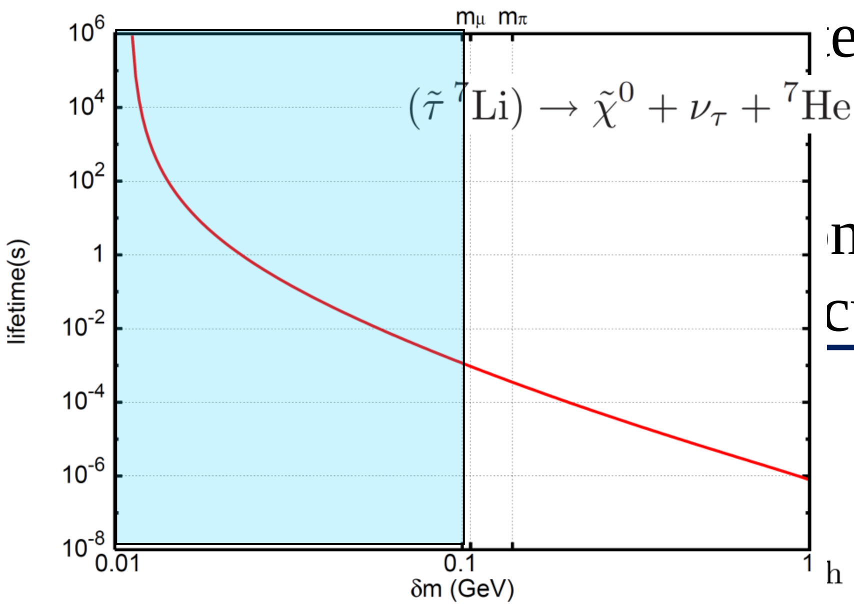
- Overlap of the wave frunction
- Interaction rate of hadronic current

The stau changes the abundance of the ^{7}Li from the theoretical value of the SBBN.

T. Jittoh *et al*, Phys. Rev. D **76** (2007) 125023 [arXiv:0704.2914 [hep-ph]]

clear reaction





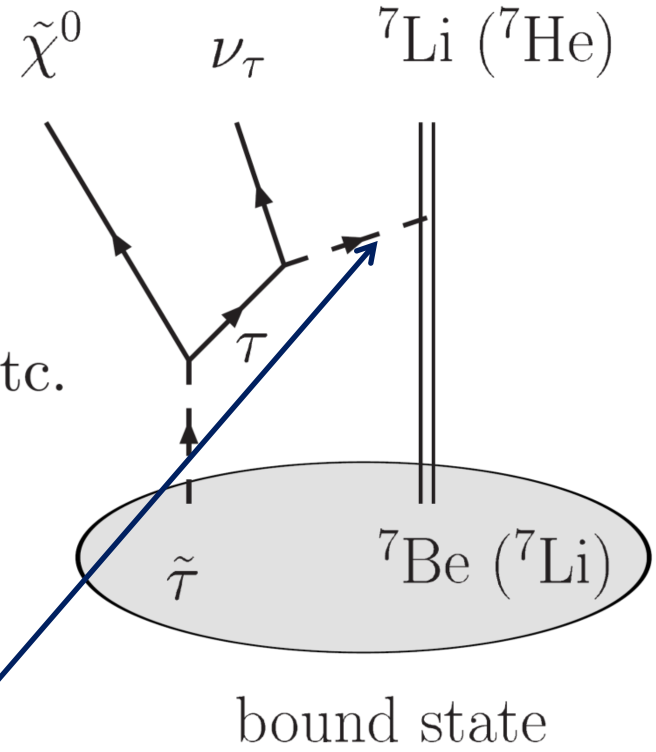
^{6}H

He, ^{4}He, etc.

e

n

current

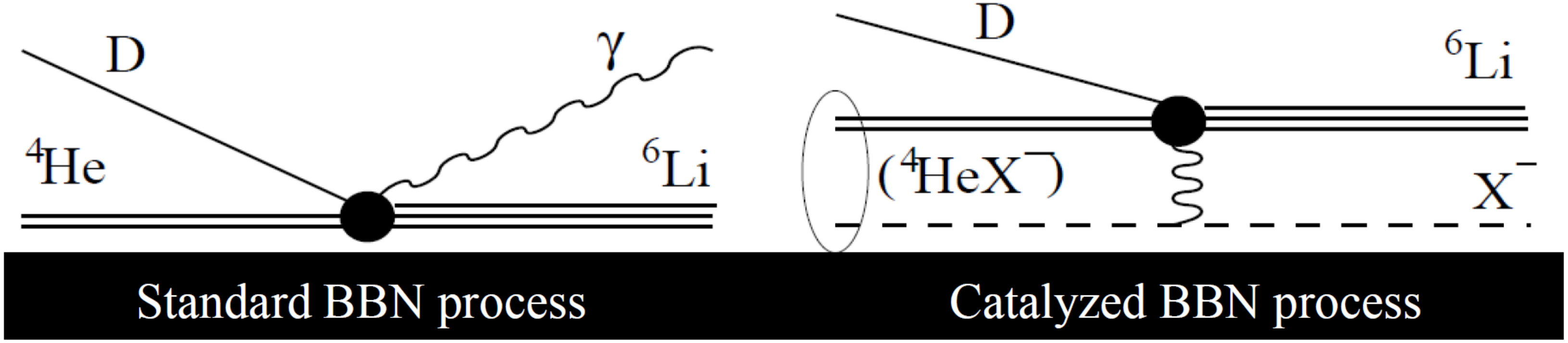


The stau changes the abundance of the ^{7}Li from the theoretical value of the SBBN.

h *et al*, Phys. Rev. D **76** (2007) 125023 [arXiv:0704.2914 [hep-ph]]

Exotic nuclear reaction

Stau catalyzed fusion



$^4\mathrm{He} + \mathrm{d} \rightarrow ^6\mathrm{Li} + \gamma$

$(^4\mathrm{He}\ \tilde{\tau}^-) + \mathrm{d} \rightarrow ^6\mathrm{Li} + \tilde{\tau}^-$

$$\Gamma_{\mathrm{SBBN}} \ll \Gamma_{\mathrm{CBBN}}$$

The stau can causes over production of ^{6}Li

Upper bound for lifetime(δm) not to produce much ^{6}Li

[M. Pospelov, PRL. 98 (2007)]

Exotic nuclear reaction

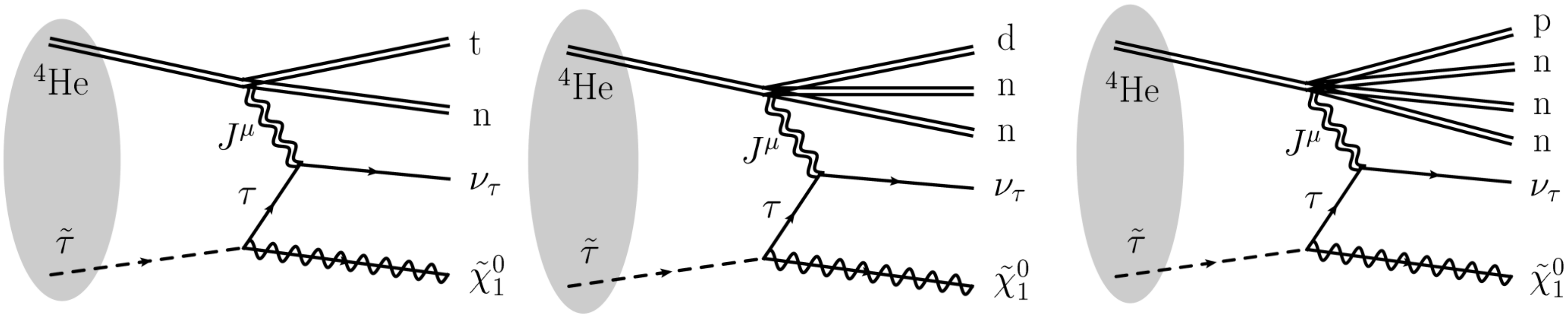
^{4}He Spallation Processes

$$(\tilde{\tau}\,^4\mathrm{He}) \to \tilde{\chi}_1^0 + \nu_\tau + \mathrm{t} + \mathrm{n},$$
$$(\tilde{\tau}\,^4\mathrm{He}) \to \tilde{\chi}_1^0 + \nu_\tau + \mathrm{d} + \mathrm{n} + \mathrm{n},$$
$$(\tilde{\tau}\,^4\mathrm{He}) \to \tilde{\chi}_1^0 + \nu_\tau + \mathrm{p} + \mathrm{n} + \mathrm{n} + \mathrm{n},$$

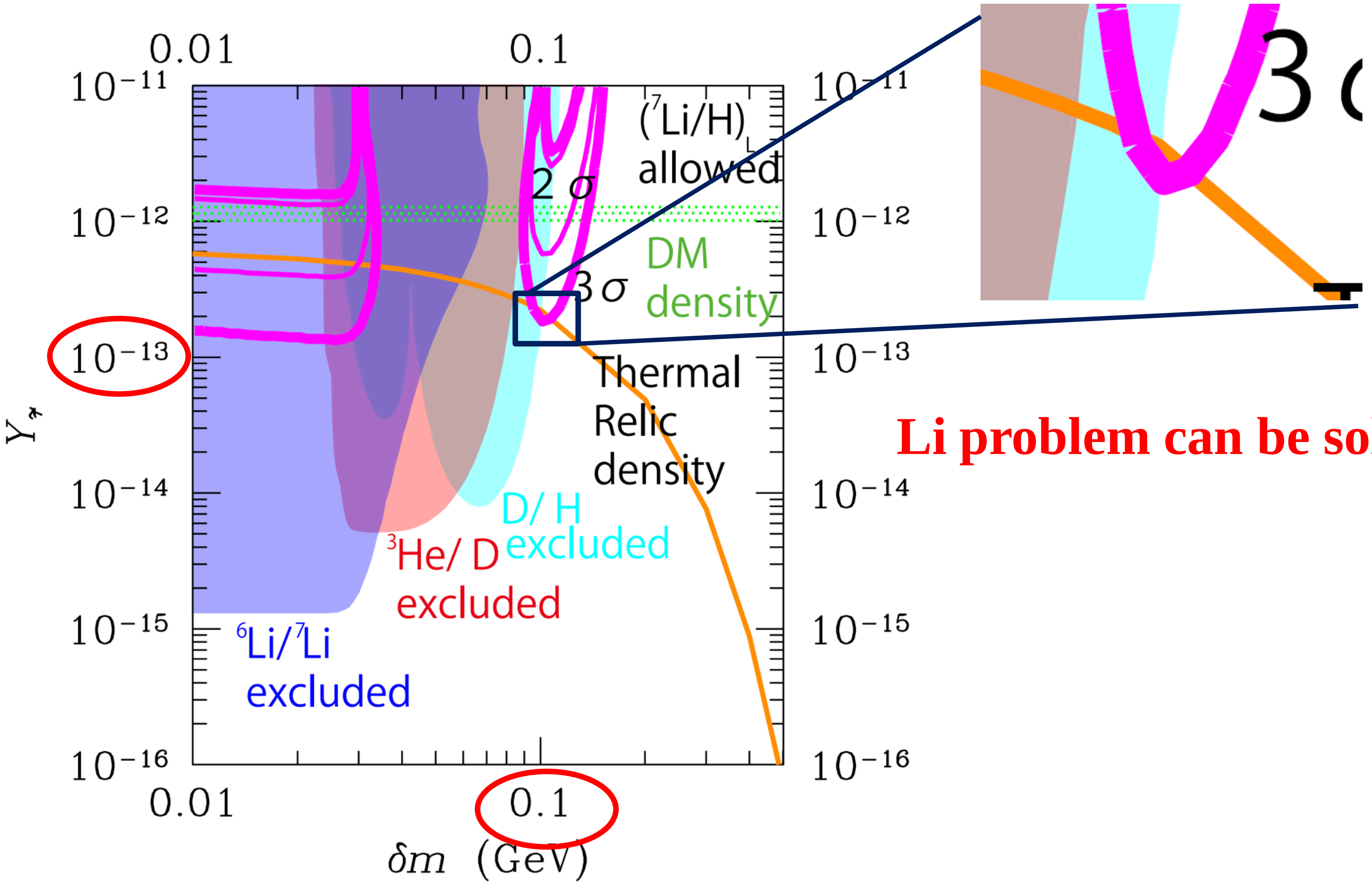
Enhancement of the reaction rate due to

- Overlap of the wave function
- Interaction of hadronic current

Upper bound for lifetime(δm) not to produce much d/t

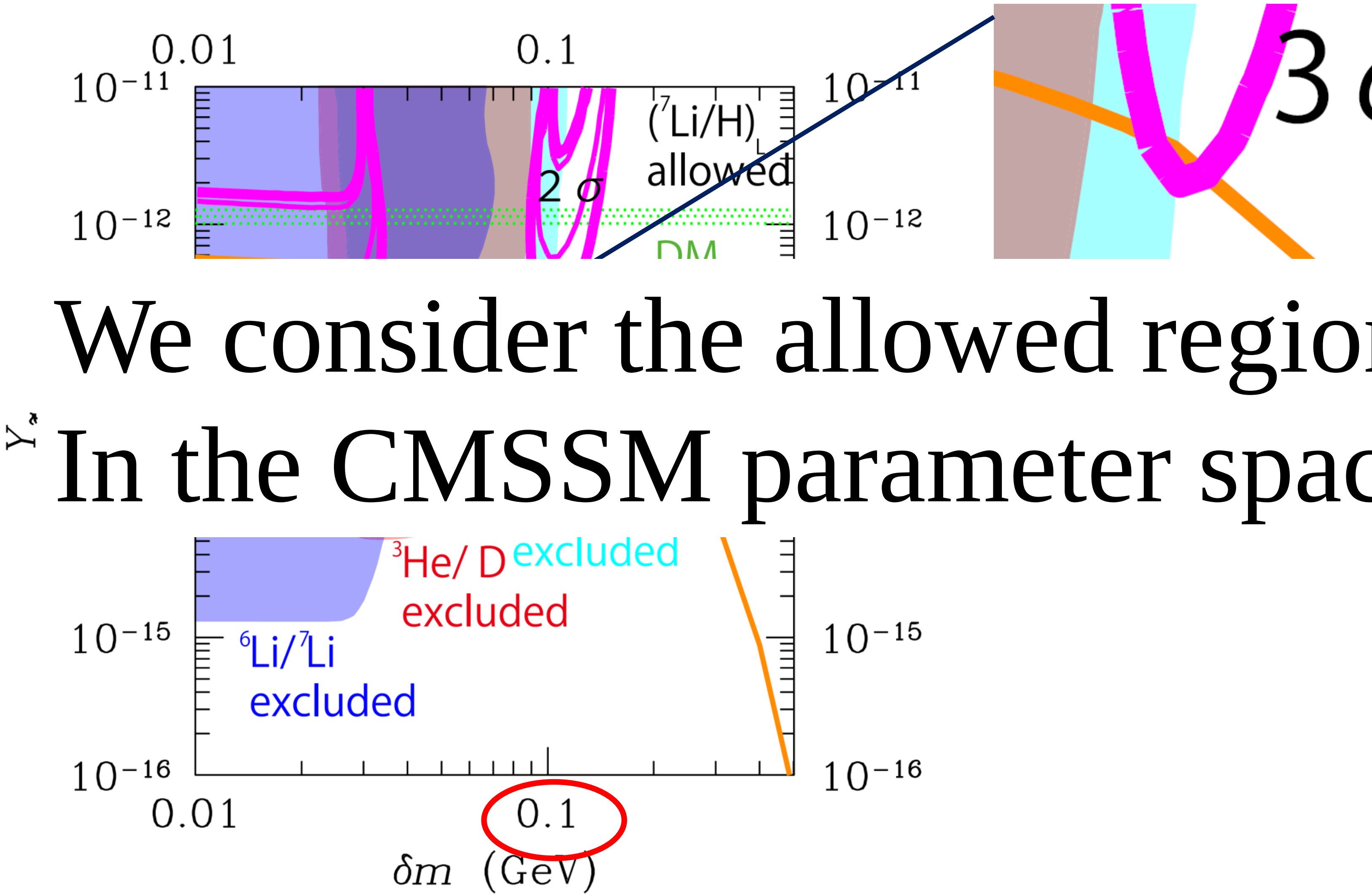


Allowed region in "MSSM"



Li problem can be solved!

Allowed region in "MSSM"



We consider the allowed region
In the CMSSM parameter space!!

Constraint ~DM & Light Elements abundance~

- Constraint from DM & light elements abundance

  Calculation of the DM relic abundance (MicrOmegas2.4.5)

  constraint: $0.089 \leq \Omega_{DM}h^2 \leq 0.136(3\sigma)$

  WMAP G. Hinshaw *et al.* arXiv:1212.5226 [astro-ph.CO]

Calculation of SUSY mass spectrum(SPheno3.2.3)

$$\delta m \equiv m_{\tilde{\tau}} - m_{\tilde{\chi}} \leq 0.1(1.0)[\mathrm{GeV}]$$

Constraint from the stau lifetime.

Uncertainty of Public code ~ 2GeV

Constraint ~DM & Light Elements abundance~

- Constraint on the stau mass

$$339\ [\mathrm{GeV}] < m_{\tilde{\tau}} < 450\ [\mathrm{GeV}]$$

LHC bound

- Requirement of the sufficient number density of the stau

$$Y_{\tilde{\tau}} \geq 1.0 \times 10^{-13}$$

Sufficient bound state
= Enough stau@BBN

- Relation between number density of the stau and neutralino.

$$n_{\mathrm{DM}} = 2s_0(1 + e^{\delta m/T_{\mathrm{f}}})Y_{\tilde{\tau}}$$

Strongly correlated with number density of the DM

- Upper bound for the DM relic abundance

$$\Omega_{\mathrm{DM}}h^2 = \frac{2s_0(1 + e^{\delta m/T_f})Y_{\tilde{\tau}}m_{\tilde{\chi}_1^0}h^2}{\rho_c} \leq 0.136$$

DM abundance(fixed)
= number density × mass

$$m_{\tilde{\chi}_1^0} \leq \frac{\rho_c}{2s_0h^2(1 + e^{\delta m/T_f})}\frac{0.136}{1.0 \times 10^{-13}}$$

Constraint ~Higgs mass~

- Experimental Value

$$m_h = 125.8 \pm 0.4(\mathrm{stat}) \pm 0.4(\mathrm{syst}) \quad [\mathrm{GeV}]$$

CMS-PAS-HIG-12-045

$$m_h = 125.2 \pm 0.3(\mathrm{stat}) \pm 0.6(\mathrm{syst}) \quad [\mathrm{GeV}]$$

ATLAS-CONF-2012-170

- Constraint

  Calculation of the Higgs mass spectrum (FeynHiggs)

Constraint: $m_h = 125.0 \pm 3.0 [\mathrm{GeV}]$

We take into account the uncertainty of input parameters.

Constraints

- Higgs mass: $m_h = 125.0 \pm 3.0[\text{GeV}]$
- DM abundance: $0.089 \leq \Omega_{DM} h^2 \leq 0.136 (3\sigma)$
- Mass difference: $\delta m \equiv m_{\tilde{\tau}} - m_{\tilde{\chi}} \leq 0.1(1.0)[\text{GeV}]$
- Stau mass: $339 \ [\text{GeV}] < m_{\tilde{\tau}} < 450 \ [\text{GeV}]$

We put these 4 constraints on the calculated value,
and obtain the allowed parameter space in the CMSSM!!

Then we give predictions to

- the mass spectra of the SUSY particles,
- the direct detection of the neutralino dark matter,
- the number of SUSY particles produced in a 14TeV run at the LHC experiment.

Results

$A_0 - m_0$ plane

Almost in a line

$$m_0 = \begin{cases} (-5.5 \times 10^{-3} A_0 + 5.15) \tan\beta + 67.67 \\ \text{for lower line,} \\ (-5.5 \times 10^{-3} A_0 + 4.65) \tan\beta + 140.67 \\ \text{for upper line,} \end{cases}$$

- Small δm relate $M_{1/2}$ and (m_0, A_0)
- With fixed $m_{\tilde{\chi}_1^0} \simeq 0.43 M_{1/2}$ increasing m_0 means increasing $m_{\tilde{\tau}_1}$

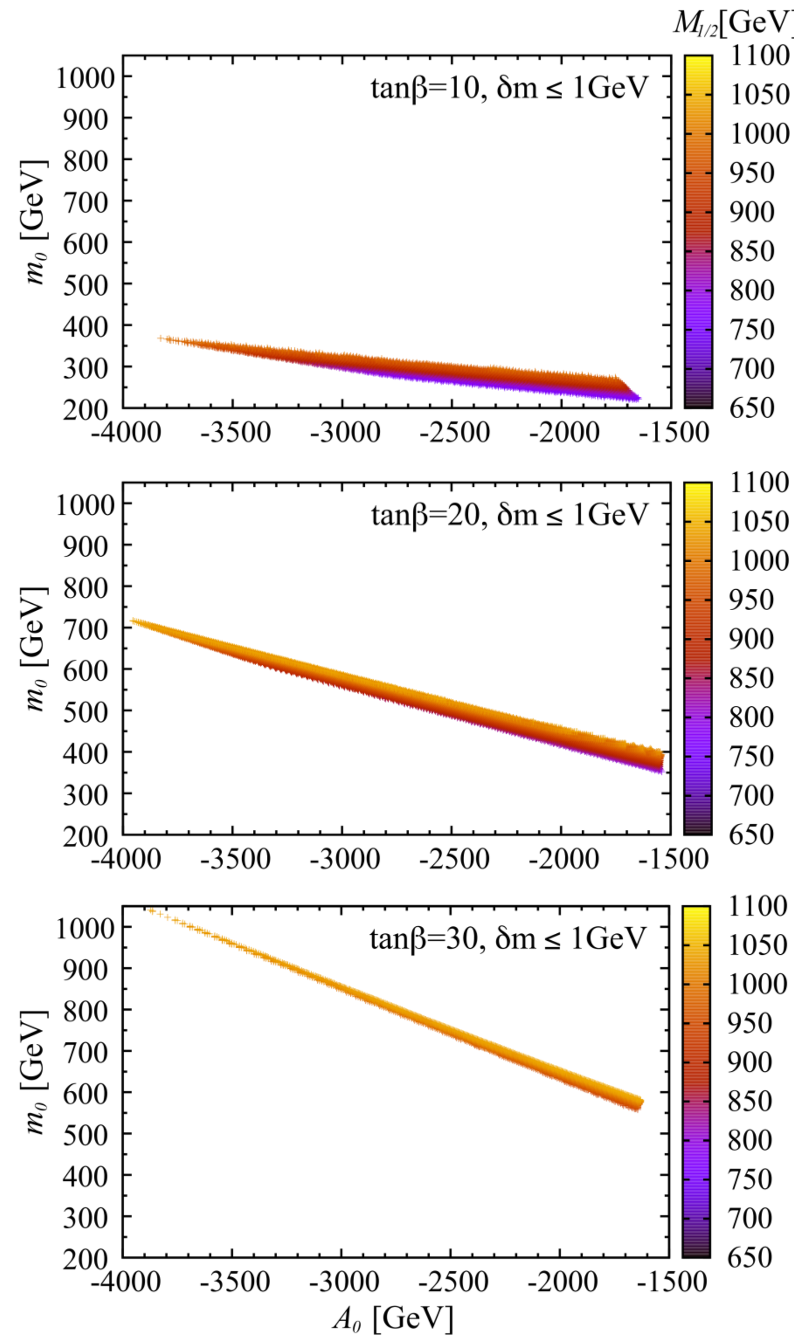
↓

- Need to increase $|A_0|$ to decrease $m_{\tilde{\tau}_1}$ by raising off-diagonal element of stau mass matrix.

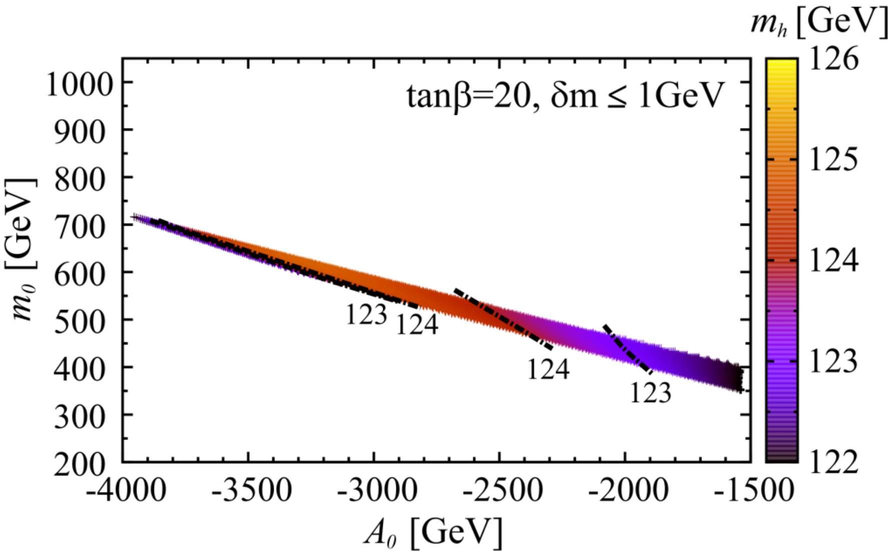
Upper & Lower edge

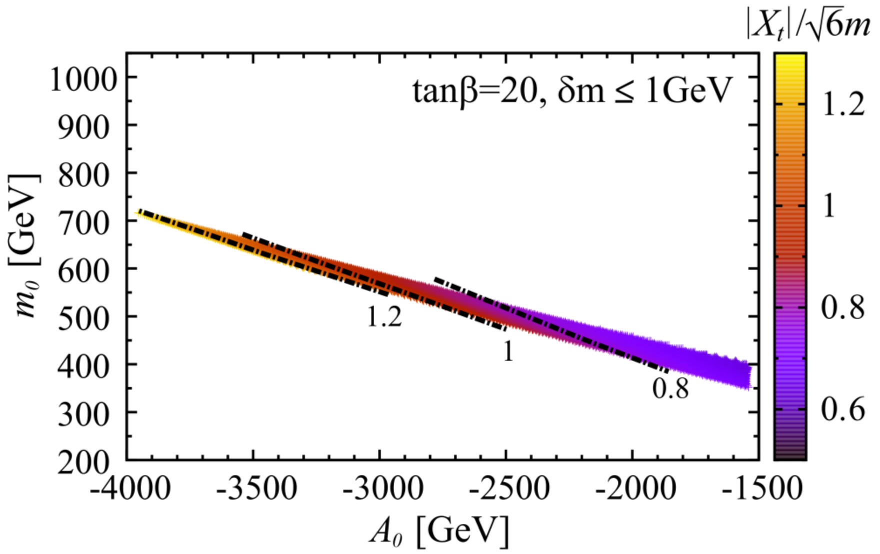
- $339\ [\text{GeV}] < m_{\tilde{\tau}} < 450\ [\text{GeV}]$
- Large RGE effect for large tan β

→ • Large m_0 for large tan β



$A_0 - m_0$ plane





Left & Right edge

- Lower constraint on m_h : $122.0\ [\mathrm{GeV}] \leq m_h$

$$m_h^2 = m_Z^2 \cos^2 2\beta + \frac{3m_t^4}{16\pi^2 v^2}\left[\log\left(\frac{m_{\tilde{t}}^2}{m_t^2}\right) + \frac{X_t^2}{m_s^2}\left(1 - \frac{X_t^2}{12m_{\tilde{t}}^2}\right)\right]$$

$$(X_t = A_t - \mu\cot\beta, \quad m_{\tilde{t}} = \sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}})$$

Maximum @ $|X_t| = \sqrt{6}m_{\tilde{t}}$

$|X_t| < \sqrt{6}m_{\tilde{t}}$

$|X_t| > \sqrt{6}m_{\tilde{t}}$

Too small correction to m_h.

From right to left, $|X_t|/\sqrt{6}m_{\tilde{t}}$ increases

Higgs boson mass first increases, then decreases.

$m_0 - M_{12}$ plane

Upper edge

- $m_{\tilde{\chi}_1^0} \simeq 0.43 M_{1/2}$
- $339\ [\mathrm{GeV}] < m_{\tilde{\tau}} < 450\ [\mathrm{GeV}]$

→ $M_{1/2} \leq 1050\ [\mathrm{GeV}]$

Left & Right edge

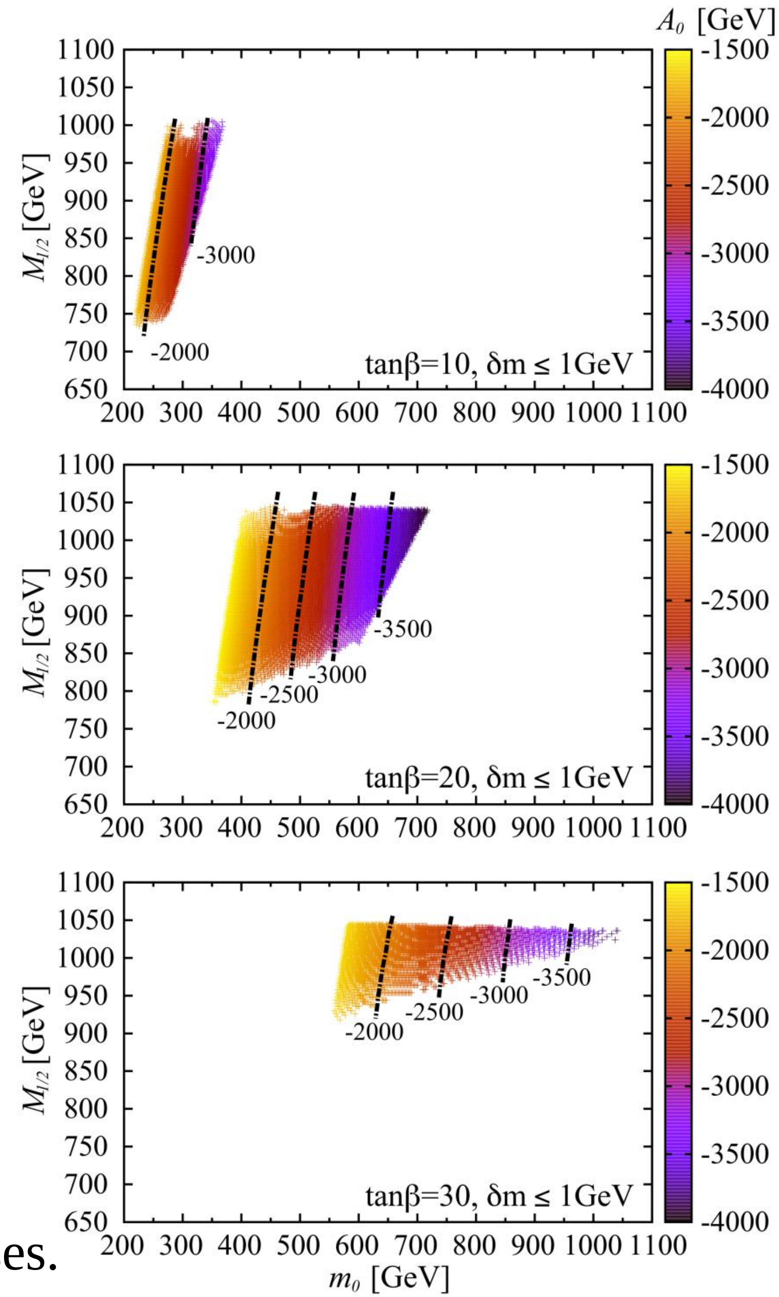
- Lower constraint : $122.0\ [\mathrm{GeV}] \leq m_h$
- With fixed $m_{\tilde{\chi}_1^0} \simeq 0.43 M_{1/2}$ increasing m_0 means increasing $m_{\tilde{\tau}_1}$

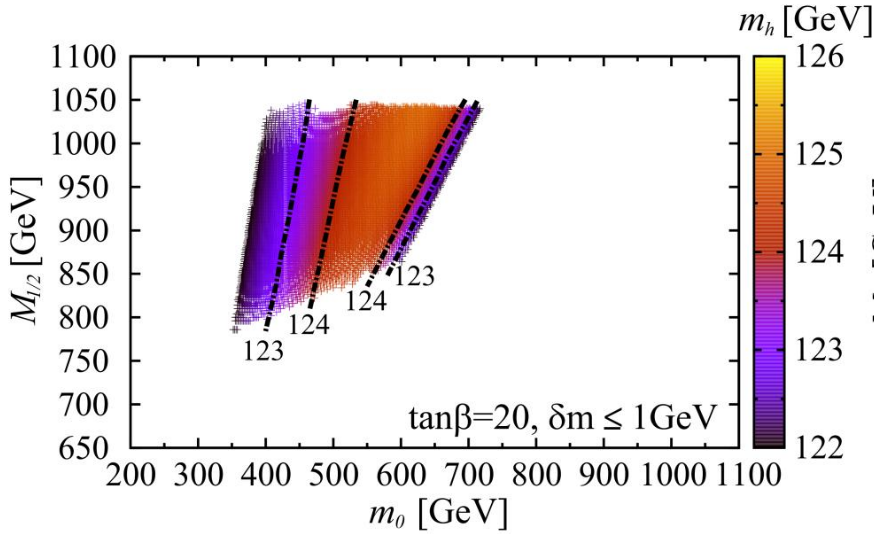
↓

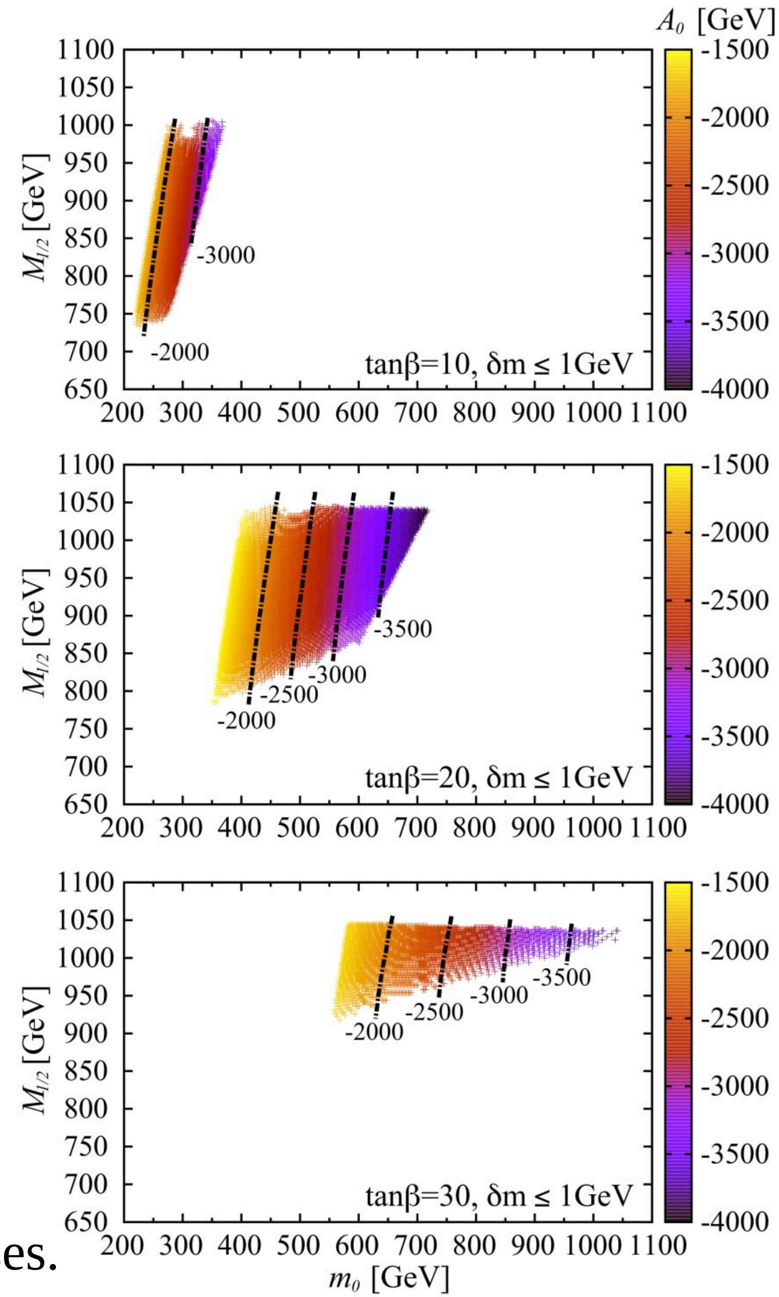
- Need to increase $|A_0|$ to decrease $m_{\tilde{\tau}_1}$ by raising off-diagonal element of stau mass matrix.

↓

From left to right, $|X_t|/\sqrt{6} m_{\tilde{\tau}}$ increases
Higgs boson mass first increases, then decreases.







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⇓

- Need to increase $|A_0|$ to decrease $m_{\tilde{\tau}_1}$ by raising off-diagonal element of stau mass matrix.

⇓

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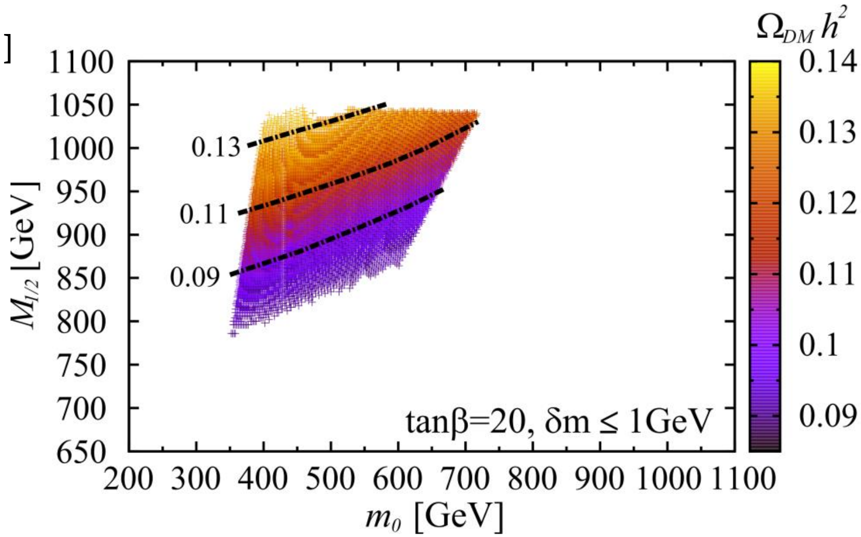


Lower edge

- Lower bound on the DM abundance

$$0.089 \leq \Omega_{\mathrm{DM}} h^2$$

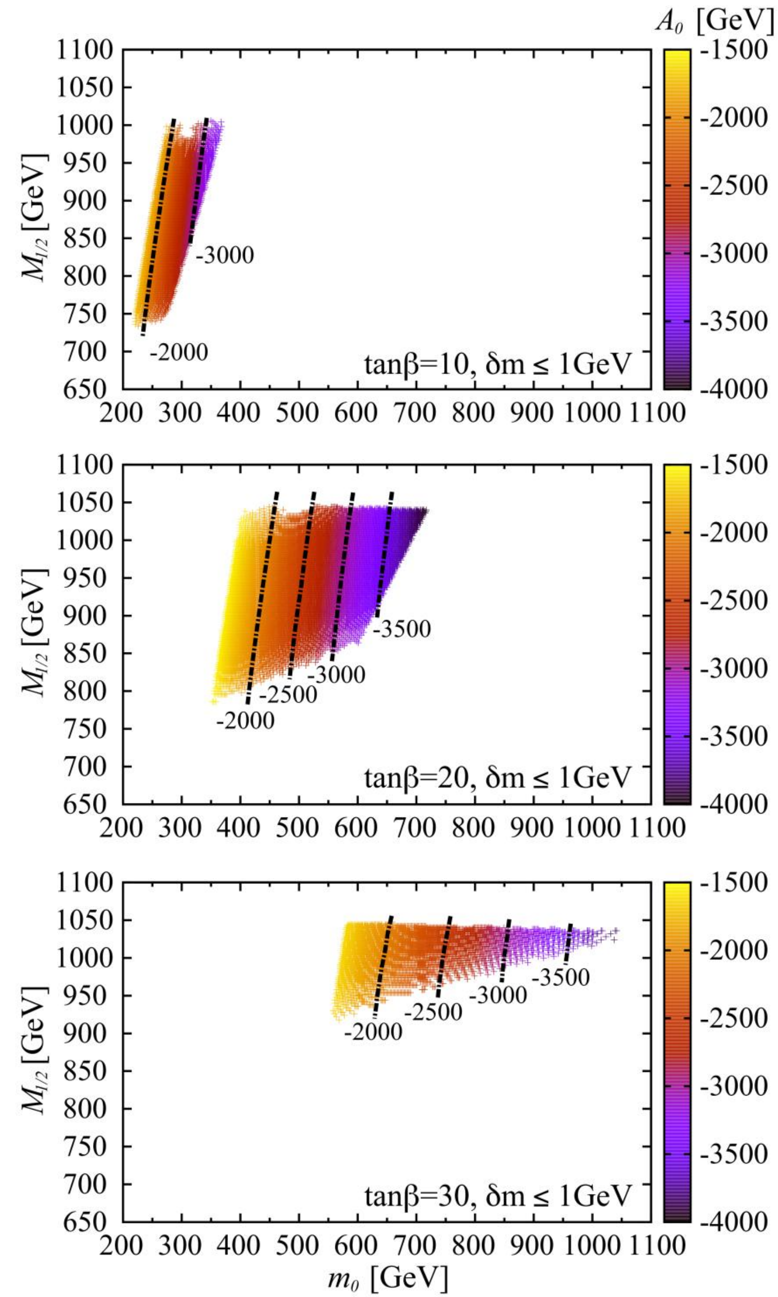
- Increasing $\tan\beta$ means increasing stau-tau-higgsino coupling

⬇

- Increasing coannihilation rate

⬇

- Increasing DM mass



Mass spectrum

Gauginos

$$M_3 : M_2 : M_1 \simeq 6 : 2 : 1$$

$$M_1 \simeq m_{\tilde{\chi}_1^0} \simeq 0.43 M_{1/2}$$

M_2: 2nd neutralino

M_3: gluino

1st,2nd generation scalars

$$m_{\tilde{q}_L}^2 \simeq m_0^2 + 4.7 M_{1/2}^2$$

$$m_{\tilde{q}_R}^2 \simeq m_0^2 + 4.3 M_{1/2}^2$$

$$m_{\tilde{e}_L}^2 \simeq m_0^2 + 0.5 M_{1/2}^2$$

$$m_{\tilde{e}_R}^2 \simeq m_0^2 + 0.1 M_{1/2}^2$$

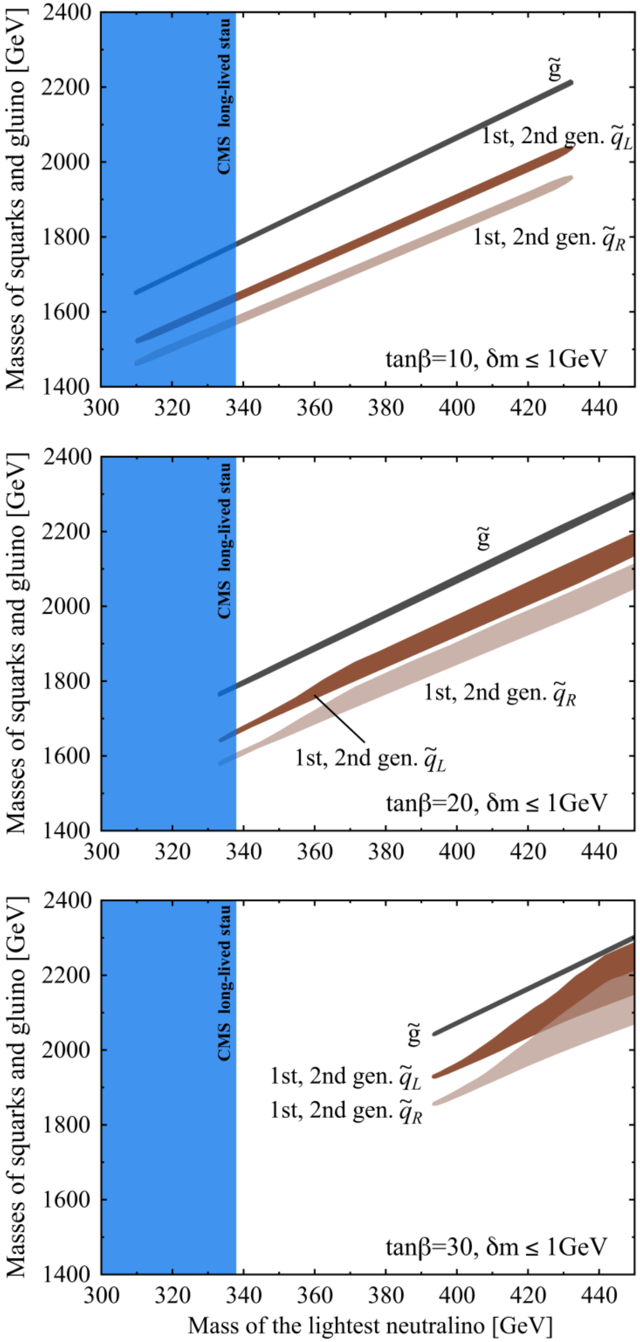
Due to small yukawas

In our parameter region

$$m_{\tilde{q}_L} \simeq 2.2 M_{1/2}$$

$$m_{\tilde{q}_R} \simeq 2.1 M_{1/2}$$

5 times larger than DM



Mass spectrum

stau vs. 1st,2nd generation sleptons

- small tan β

small tau-yukawa and similar RG effect

↓

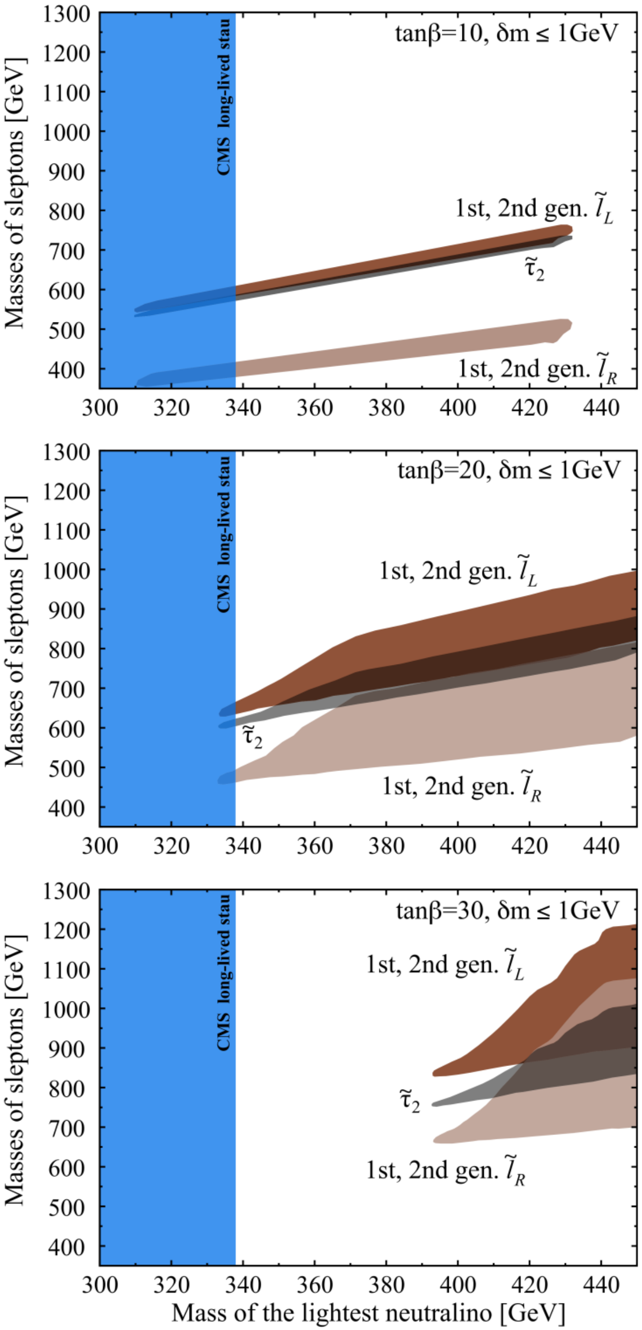
Similar mass spectrum

- large tan β

large tau-yukawa and different RG effect
large A-term contribution

↓

stau becomes lighter than other slepton



Mass spectrum

Higgsinos, heavy Higgs

Electroweak Sym. Br.

$$|\mu|^2 = \frac{1}{2}\left[\tan 2\beta\left(M_{H_u}^2 \tan\beta - M_{H_d}^2 \cot\beta\right) - m_Z^2\right]$$

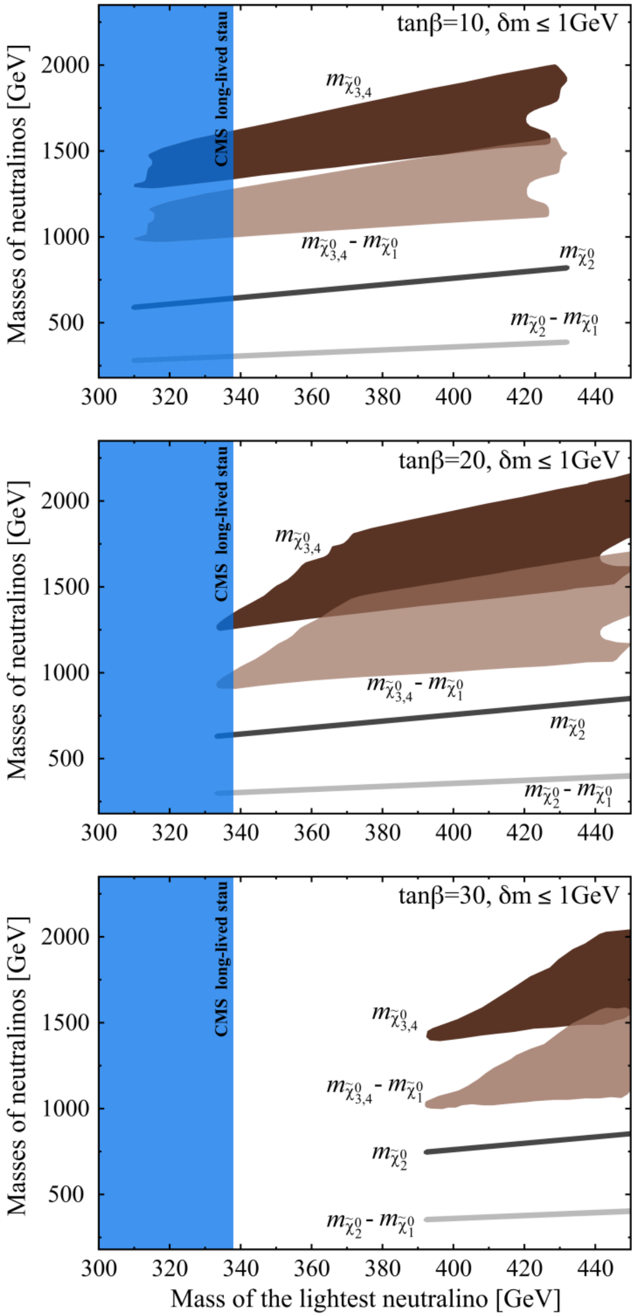
For $\tan\beta \gg 1 \qquad |\mu|^2 \simeq -M_{H_u}^2$

Numerically,

$$m_{H_u}^2 \simeq -3.5\times 10^3 \cot^2\beta m_0'^2 + 87\cot\beta M_{1/2} m_0' - 2.8 M_{1/2}^2$$

$$m_0' \equiv m_0 - b$$

$$b \simeq \begin{cases} 5.15\tan\beta + 67.67 & \text{for lower line,} \\ 4.65\tan\beta + 140.67 & \text{for upper line.} \end{cases}$$



Mass spectrum

3^{rd} generation squarks

stop

$$m^2_{\tilde{t}_1,\tilde{t}_2} \simeq \frac{1}{2}\left(m^2_{Q_3}+m^2_{U_3}\right) \mp \frac{1}{2}\sqrt{(m^2_{Q_3}-m^2_{U_3})^2+4(m^2_{\tilde{t}_{LR}})^2},$$

$$m^2_{\tilde{t}_{LR}} = m_t(A_t-\mu\cot\beta),$$

Large A term and Large RGE effect
→Lighter stop generally pretty light
though still above LHC constraint

sbottom

- small tan β

  small bottom-yukawa and similar RG effect

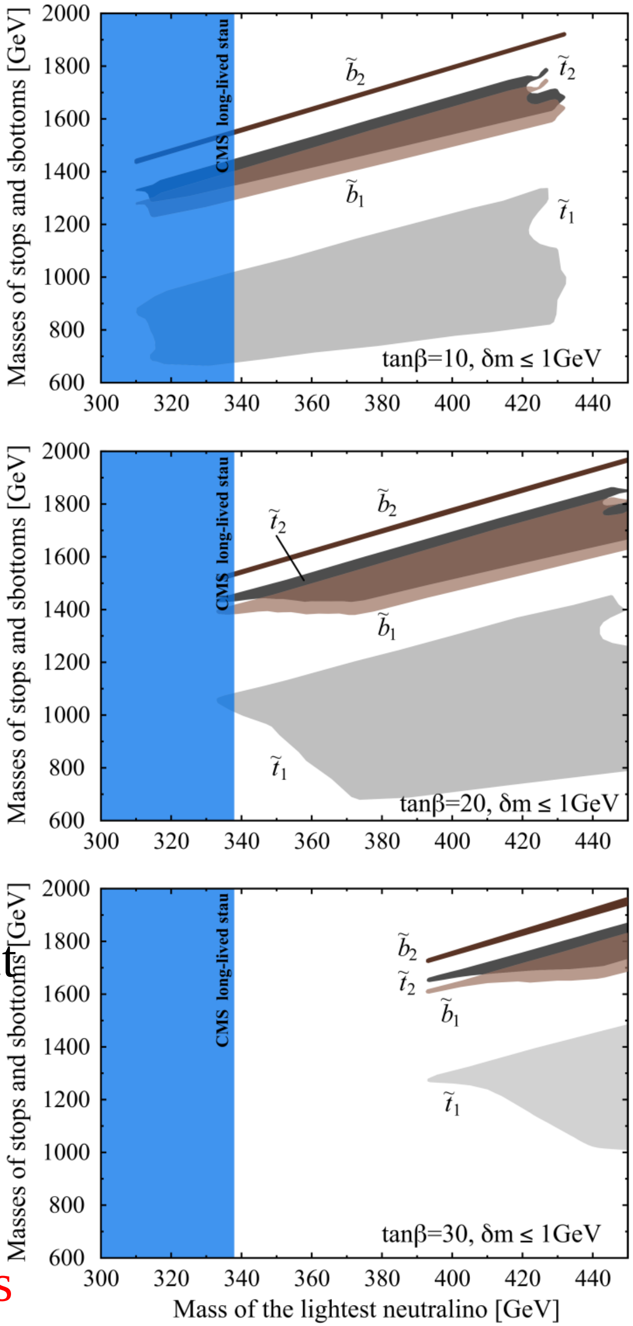
  ⟶ Similar sbottom mass spectrum

- large tan β

  large tau-yukawa and different RG effect

  large A-term contribution

  ⟶ sbottom is lighter than other squarks



Features for spectrum summarized

- All masses are strongly related with $m_{\tilde{\tau}} (\simeq m_{\tilde{\chi}_1^0})$
- Mass of the Squarks, gluino,2nd neutralino, and sleptons is proportional to $m_{\tilde{\tau}} (\simeq m_{\tilde{\chi}_1^0})$
- Our 4 requirements automatically, naturally predicted that the LHC could not observe any signal for SUSY.

Higgs mass, DM relic abundance,
BBN(mass diffenrence & mass range)

Direct detection of DM

- Cross section

$$\sigma_{\rm SI} = \frac{4}{\pi}\left(\frac{m_{\tilde{\chi}_1^0} m_T}{m_{\tilde{\chi}_1^0} + m_T}\right)^2 (n_p f_p + n_n f_n)^2$$

$$f_p = \sum_q f_q \langle p|\bar{q}q|p\rangle = \sum_{q=u,d,s} \frac{f_q}{m_q} m_p f_{T_q}^{(p)} + \frac{2}{27} f_{T_G} \sum_{q=c,b,t} \frac{f_q}{m_q} m_p$$

$$f_q = m_q \frac{g_2^2}{4m_W}\left(\frac{C_{h\tilde{\chi}_1^0\tilde{\chi}_1^0} C_{hqq}}{m_h^2} + \frac{C_{H\tilde{\chi}_1^0\tilde{\chi}_1^0} C_{Hqq}}{m_H^2}\right)$$

- Correlation between $m_H \sim \mu$ and $\sigma_{\rm SI}$

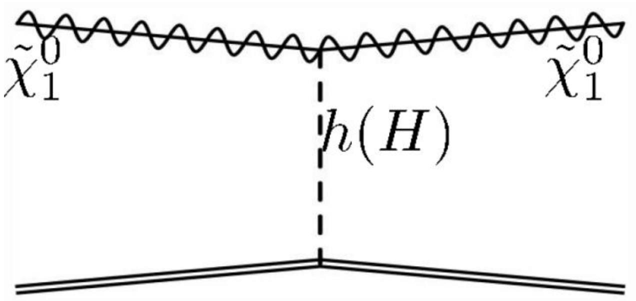
Heavy Higgs contribution is negligible

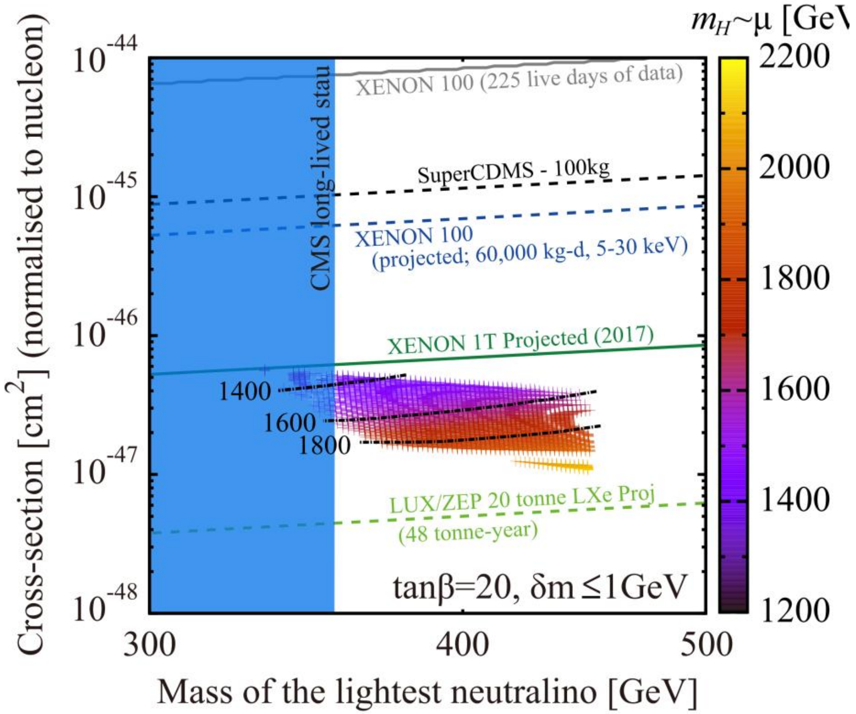
$$C_{h\tilde{\chi}_1^0\tilde{\chi}_1^0} \simeq \frac{m_Z \sin\theta_W \tan\theta_W}{M_1^2 - \mu^2}[M_1 \sin\beta + \mu\cos\beta]$$

Smaller μ , larger coupling for $h\tilde{\chi}_1^0\tilde{\chi}_1^0$

Within the reach in the near future!

Most important channel





LHC in near Future

- Testable with 100 fb^{-1}
- 10 % efficiency?

Signals

- Stau track penetrating detector
- Missing energy as same as the stau mass
- Many lighter stop

- Center of mass energy 14TeV
- Luminosity 100fb^{-1}

Input Parameters	Point 1 [GeV]	Point 2 [GeV]	Point 3 [GeV]
$M_{1/2}$	818.6	932.8	1038.0
m_0	452.0	557.7	639.7
A_0	-2264.7	-2918.4	-3397.0
Particle			
h	123.8	124.6	124.9
$\tilde{g}$	1822.4	2057.8	2272.6
$\tilde{\chi}_1^0$	349.3	400.9	448.5
$\tilde{\tau}_1$	350.3	401.0	449.1
$\tilde{u}_L$	1710.9	1942.2	2149.7
$\tilde{t}_1$	945.8	968.6	1016.3
Cross Section	Point1 [fb]	Point2 [fb]	Point3 [fb]
$\sigma(\tilde{u}_L, \tilde{u}_L)$	2.915	1.277	0.614
$\sigma(\tilde{u}_L, \tilde{u}_R)$	1.672	0.668	0.296
$\sigma(\tilde{u}_R, \tilde{u}_R)$	2.970	1.327	0.652
$\sigma(\tilde{u}_L, \tilde{d}_L)$	3.243	1.335	0.608
$\sigma(\tilde{u}_R, \tilde{d}_R)$	2.680	1.124	0.522
$\sigma(\tilde{g}, \tilde{u}_L)$	2.735	0.899	0.330
$\sigma(\tilde{g}, \tilde{u}_R)$	3.156	1.041	0.391
$\sigma(\tilde{t}_1, \tilde{t}_1^*)$	4.399	3.662	2.655
$\sigma(\tilde{\chi}_1^+, \tilde{\chi}_1^-)$	2.459	1.274	0.711
$\sigma(\tilde{\chi}_1^+, \tilde{\chi}_2^0)$	3.514	1.858	1.075
$\sigma(\tilde{\chi}_1^-, \tilde{\chi}_2^0)$	1.232	0.616	0.341
σ(all SUSY)	39.798	18.387	8.681
Number of produced			
$N(\tilde{\tau}_1)$	1802	756	345
$N(\tilde{\tau}_1^*)$	2469	1091	450
$N(\tilde{\chi}_1^0)$	3687	1829	940

Summary

Summary

- Constrained minimal SUSY standard model(CMSSM)

with 4 requirement

1. Dark matter relic abundance
2. Higgs boson mass
3. Stau – DM mass degeneracy
4. $339\ [\mathrm{GeV}] < m_{\tilde{\tau}} < 450\ [\mathrm{GeV}]$

- Very constrained Predictions

  Lower and upper limit for mass of SUSY particles

  - It is matter of course that the LHC has not observed yet, next LHC must observe SUSY signals!
  - Very strong correlation among SUSY particles
  - DM direct detection in near future must observe DM signal.