A first evidence of the CMSSM is appearing soon

SATO, Joe (Saitama University)

- based mainly on arXiv:1309.2067

Y. Konishi, S. Ohta, J.S., T. Shimomura K. Sugai, M. Yamanaka

- Also, PRD 73 (2006) 055009, 76 (2007) 125023, 78 (2008) 055007, 82 (2010) 115030, 84 (2011) 035008, D 86 (2012) 095024

1. Introduction

At this moment

- ☑ Higgs Doublet was found
- ☑ No New Physics @ LHC
- ☑ No New (Quark) Flavor Violation

SM works quite well

Go beyond SM

- ☑ Dark Matter candidate
- ☑ Baryon Asymmetry
- ☑ Lepton Flavor Violation among Neutrino
- ☑ Lithium Problem in Big-Bang Nucleosynthesis

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Go beyond SM

Constrained minimal SUSY standard model (CMSSM) can solve them!?
Keeping the good feature of SM

Which parameter region ?

～DM abundance and LHC result

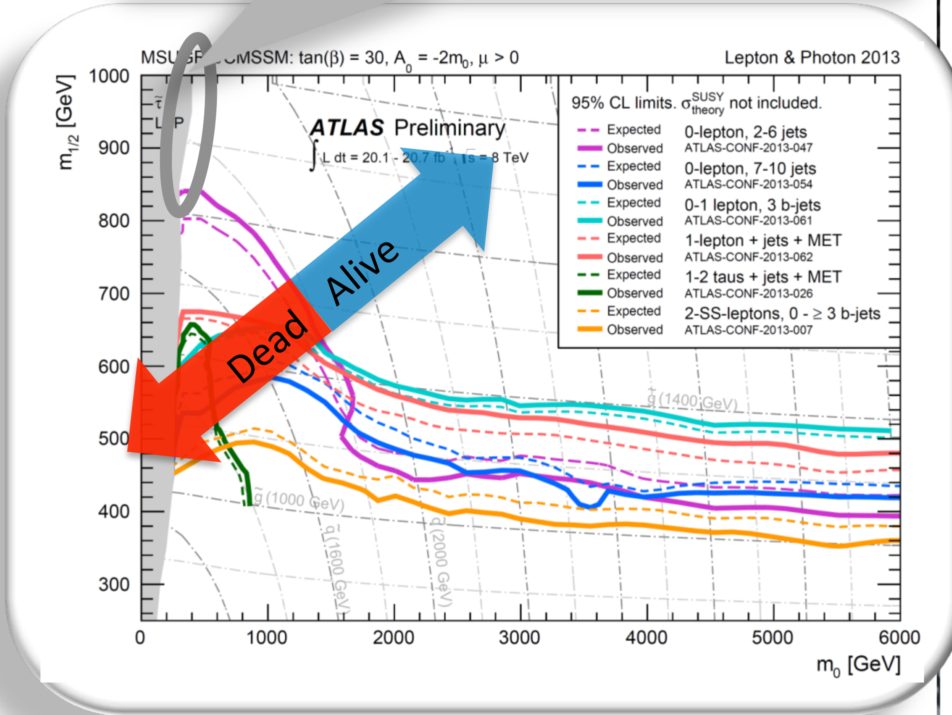
☑ Coannihilation region Griest,Seckel

DM and Stau : degenerate in mass

DM and Stau pair-annihilate at decoupling from thermal history to give appropriate abundance

DM abundance can be explained

Coannihilation region



☑ Imposing 125GeV Higgs, muon g-2 etc, tight degenerasy,

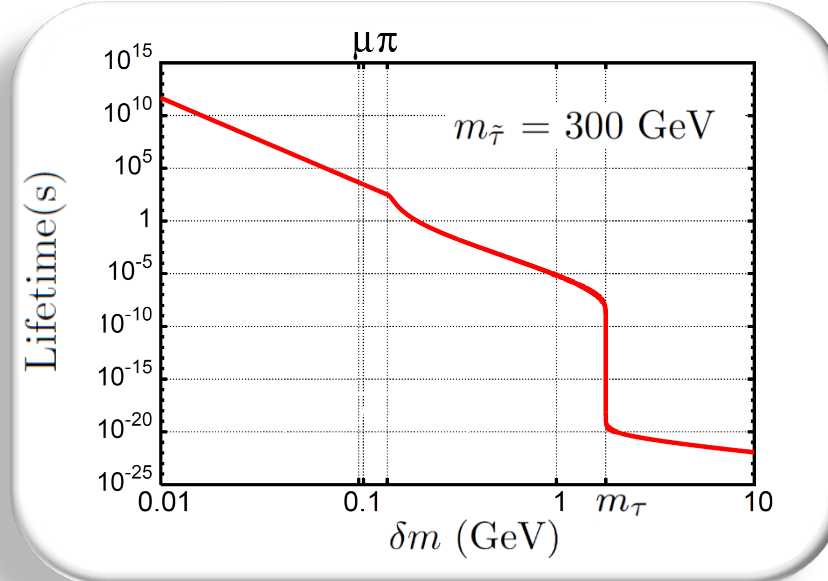
$$\delta m \equiv m_{\tilde{\tau}} - m_{\tilde{\chi}} < m_{\tau}$$

[L. Aparicio, D. Cerdeno, L. Ibanez, JHEP(2012)]

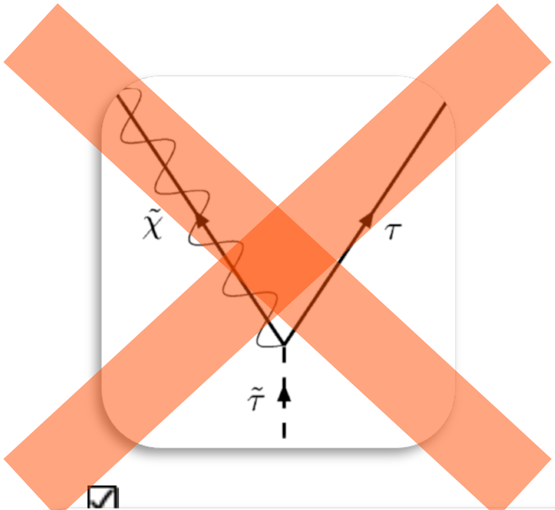
[M. Citron,J. Ellis, F.Luo ,et al, PRD87(2013)]

Very fortunately

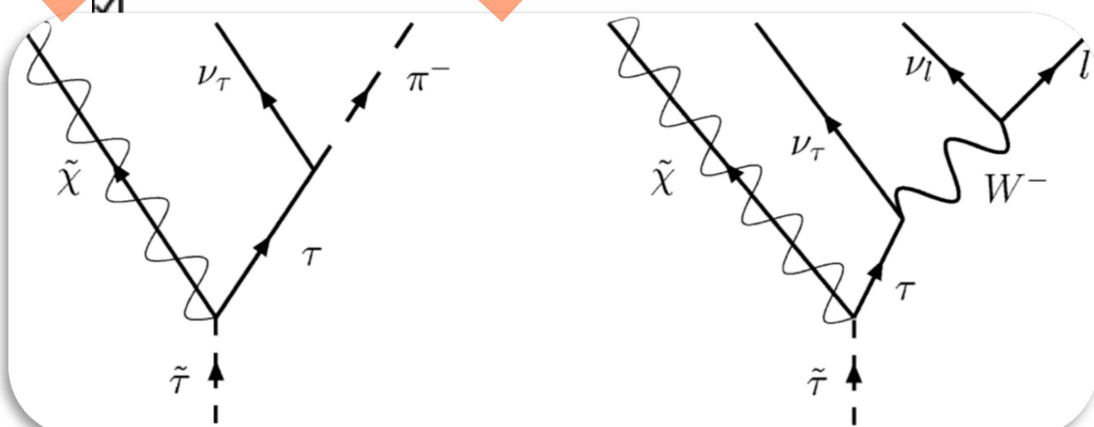
Stau is long-lived at $\delta m < m_\tau$ since 2-body decay is kinematically prohibited



[T. Jittoh, J. S T. Shimomura, M.Yamanaka, PRD73 (2006)]



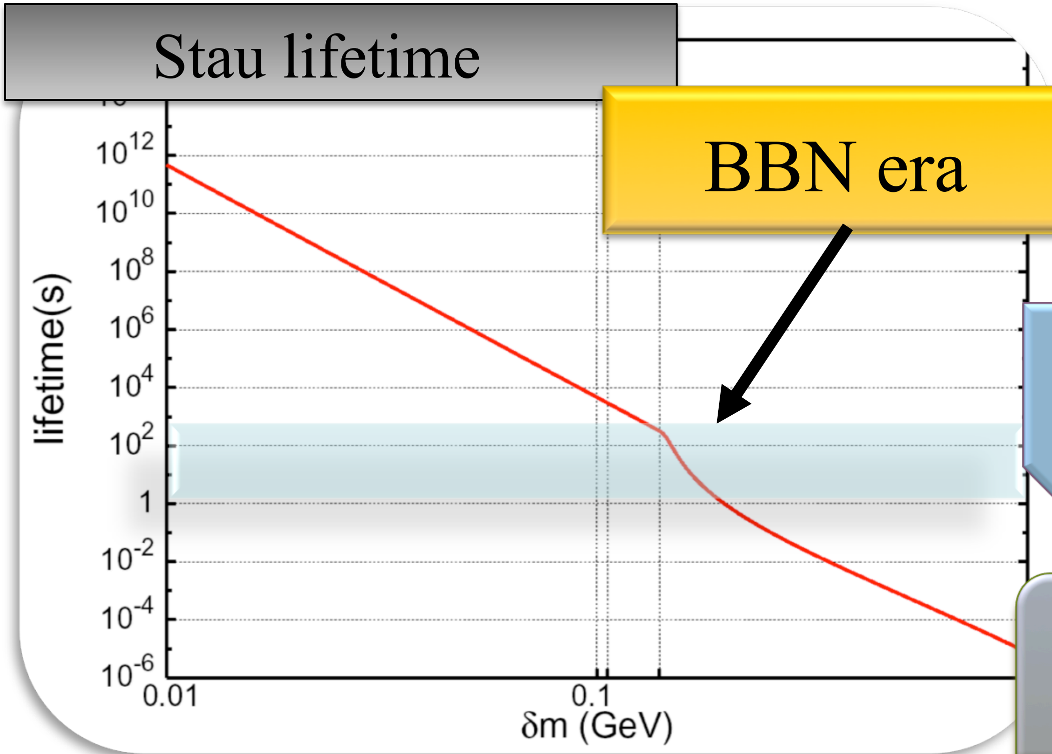
Can not decay into two body



Phase space suppression

→ Long-lived particle

long-lived stau in the coannihilation scenario

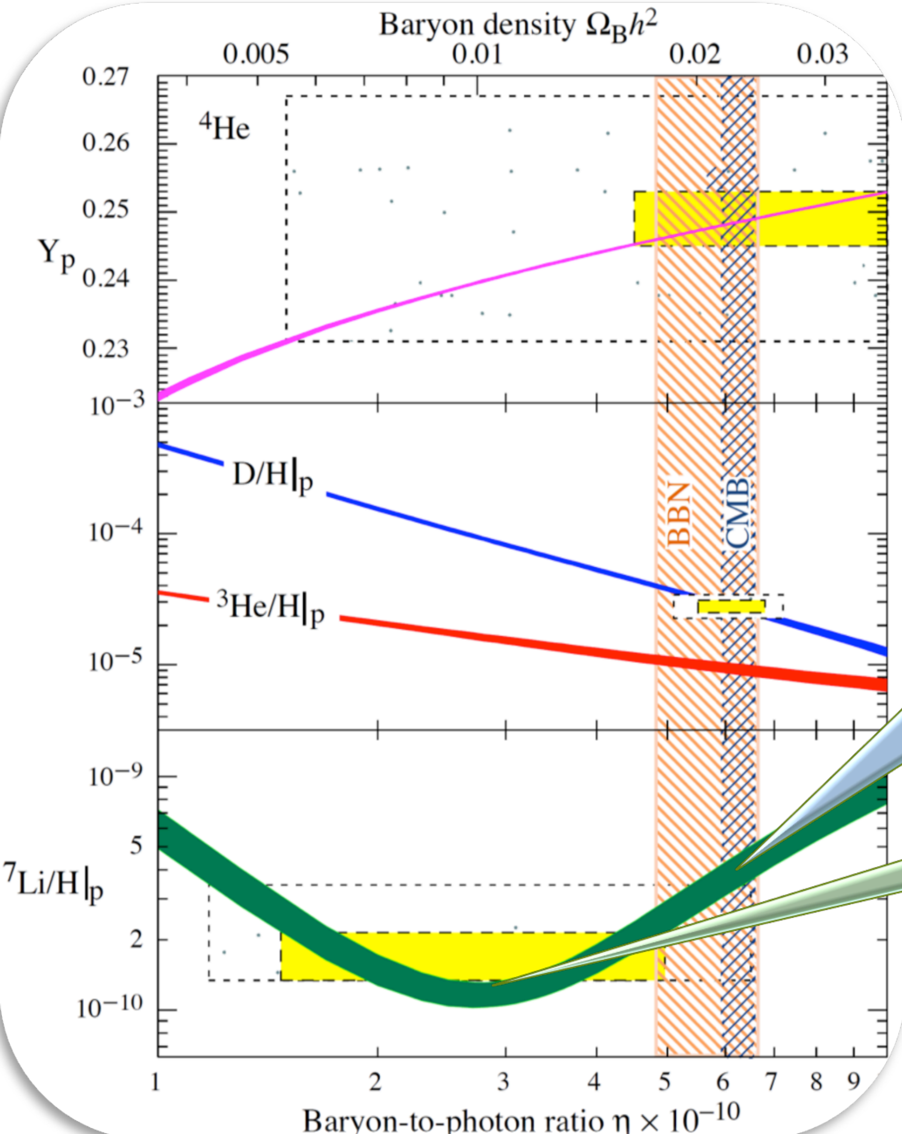


Surviving until the BBN era !!

Stau can affect
Big-Bang Nuclepsynthesis !

Lithium Problem can be solved

2.Li problem and a solution by long-lived stau



Theoretical prediction

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

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

Observation

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

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

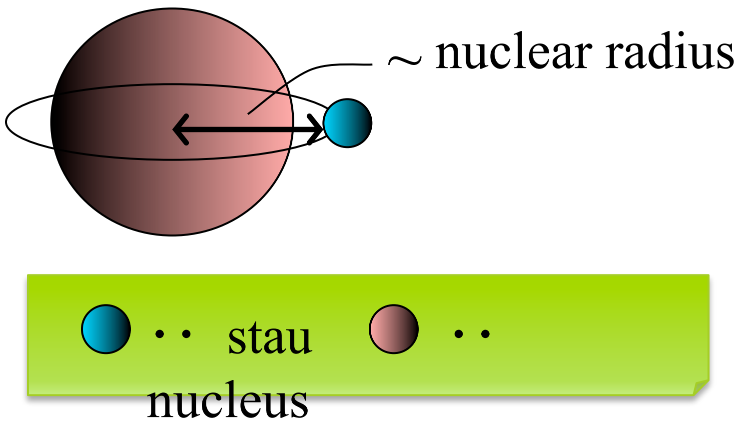
Predicted ^{7}Li abundance
$\neq$ observed ^{7}Li abundance

→ ^{7}Li problem

Solving the Li problem with stau

Key ingredient for solving the ^{7}Li problem

Negative-charged stau can form a bound state with nuclei

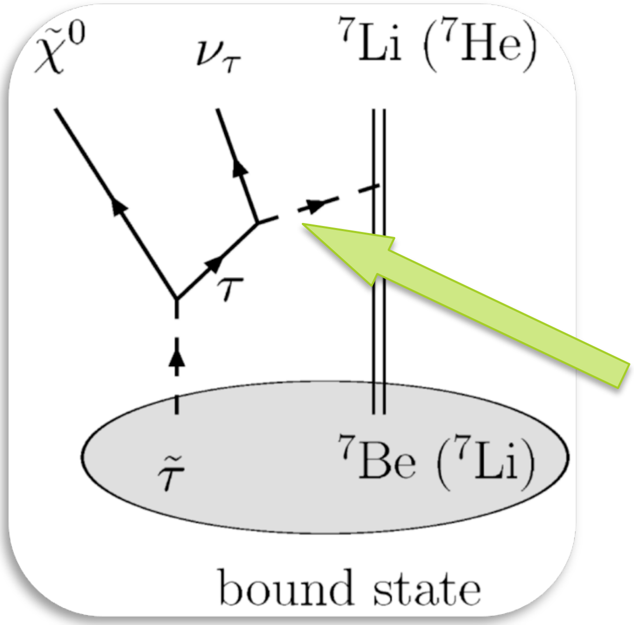


Formation rate

→ Solving the Boltzmann Eq.

New processes

- Internal conversion in the bound state
- Stau catalyzed fusion
- Spallation process of nucleus in the bound state



Internal conversion

PRD76,78

Hadronic current

- Closeness between stau and nucleus

→ Overlap of the wave function : **UP**

Interaction rate of hadronic current : **UP**

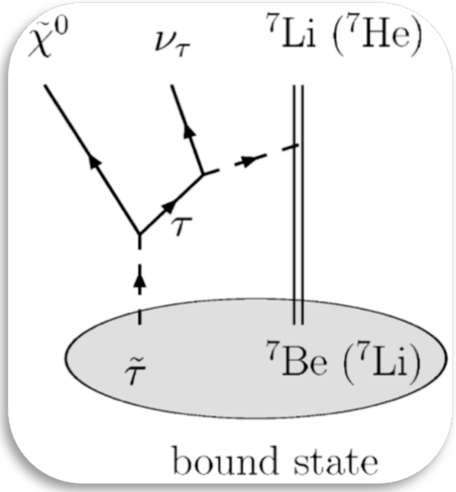
- $\tilde{\tau}^+$ does not form a bound state

→ No cancellation processes

Internal conversion rate

The lifetime of the stau-nucleus bound state

$$\tau_{\rm IC} = \frac{1}{|\psi|^2 \cdot (\sigma v)}$$



◇ Wave function of the bound state

$$|\psi|^2 = \frac{1}{\pi a_{\rm nucl}^3}$$

(nuclear radius

$$a_{\rm nucl} = (1.2 \times A^{1/3})$$
)

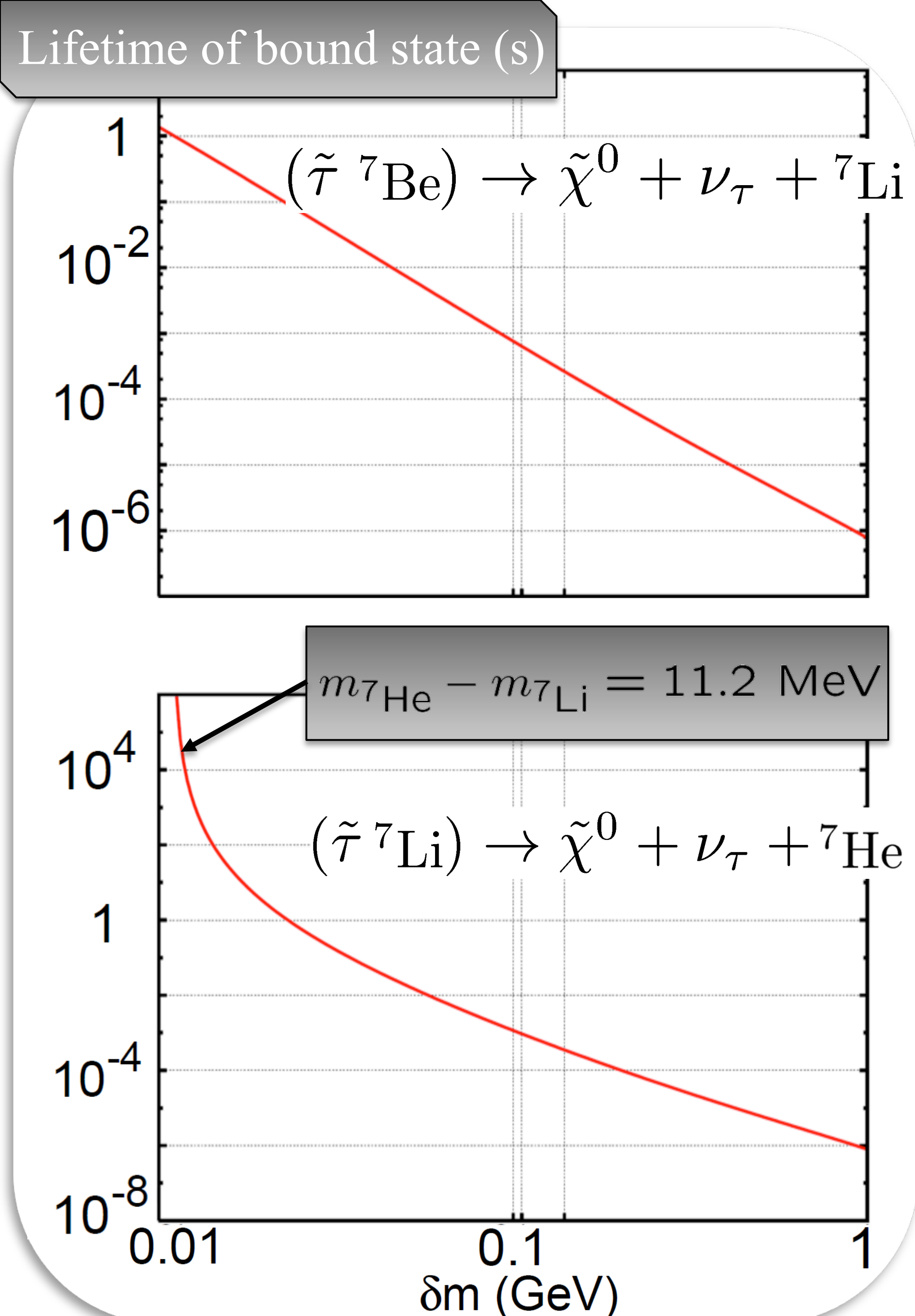
◇ (σv) is evaluated by using *ft*-value

$$(\sigma v) \propto (ft\text{-}value)^{-1}$$

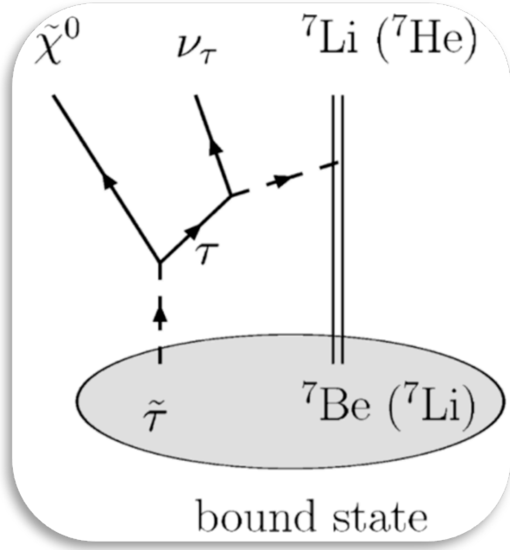
ft-value of each processes

^{7}Be → ^{7}Li ・・・ $ft = 10^{3.3}$ sec (experimental value)

^{7}Li → ^{7}He ・・・ similar to ^{7}Be → ^{7}Li (no experimental value)



Interaction rate of internal conversion

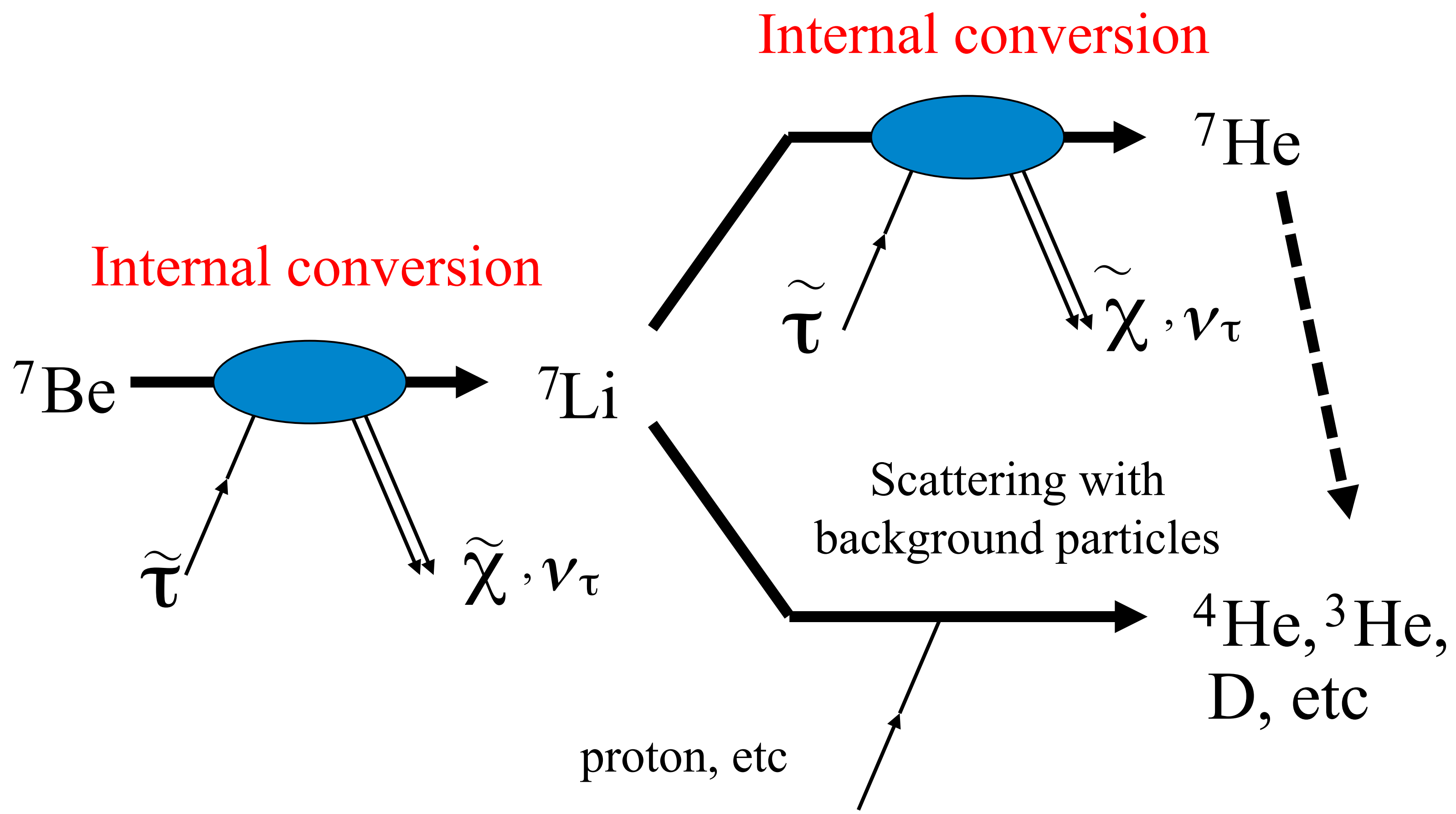


Very short lifetime

↓

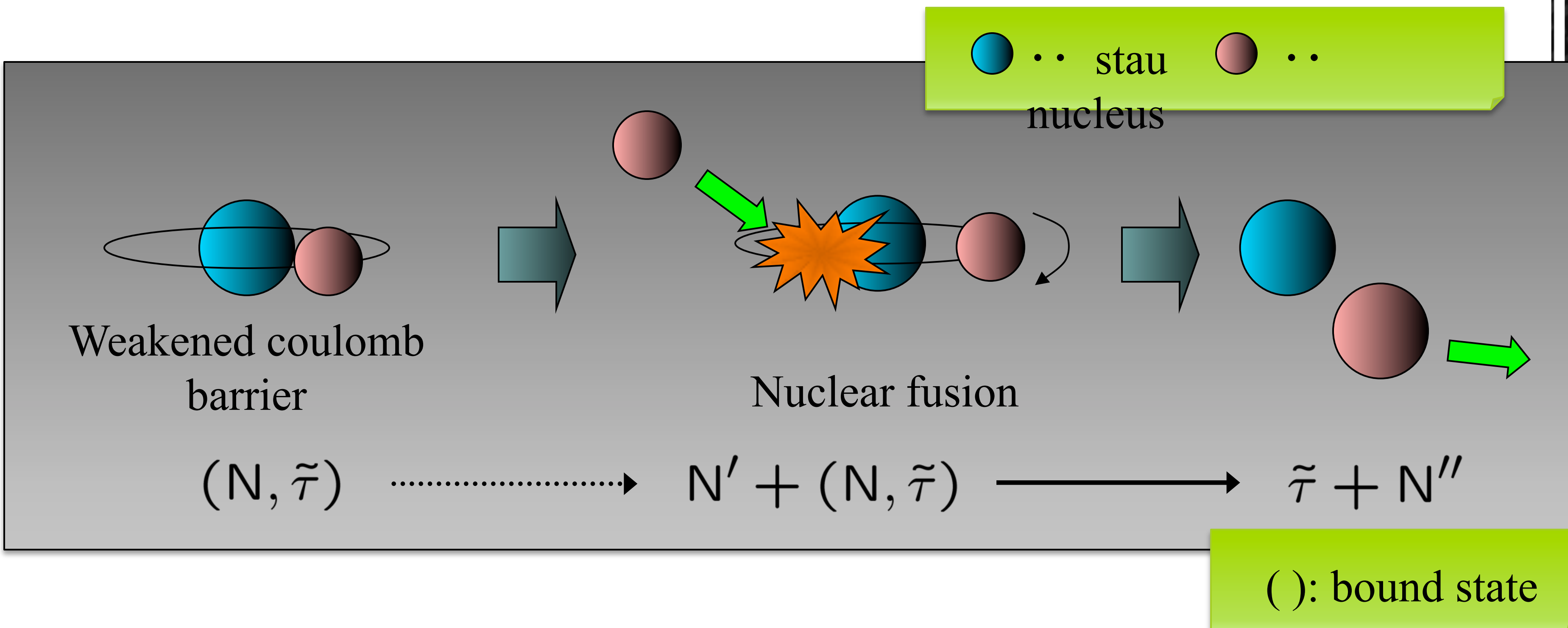
Significant process
for reducing ${}^7\mathrm{Li}$ abundance

Li destruction chain with internal conversion



Stau catalyzed fusion

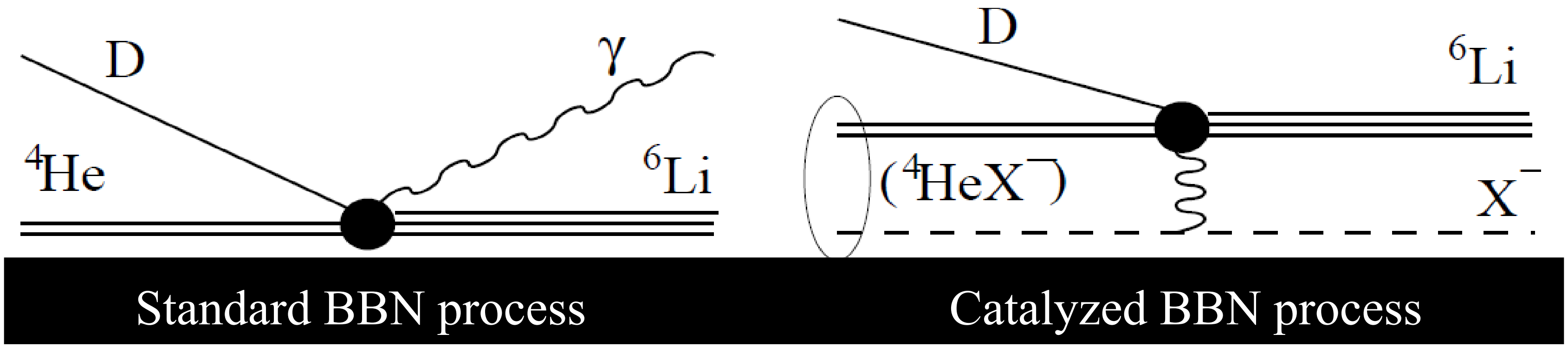
[M. Pospelov, PRL. 98 (2007)]

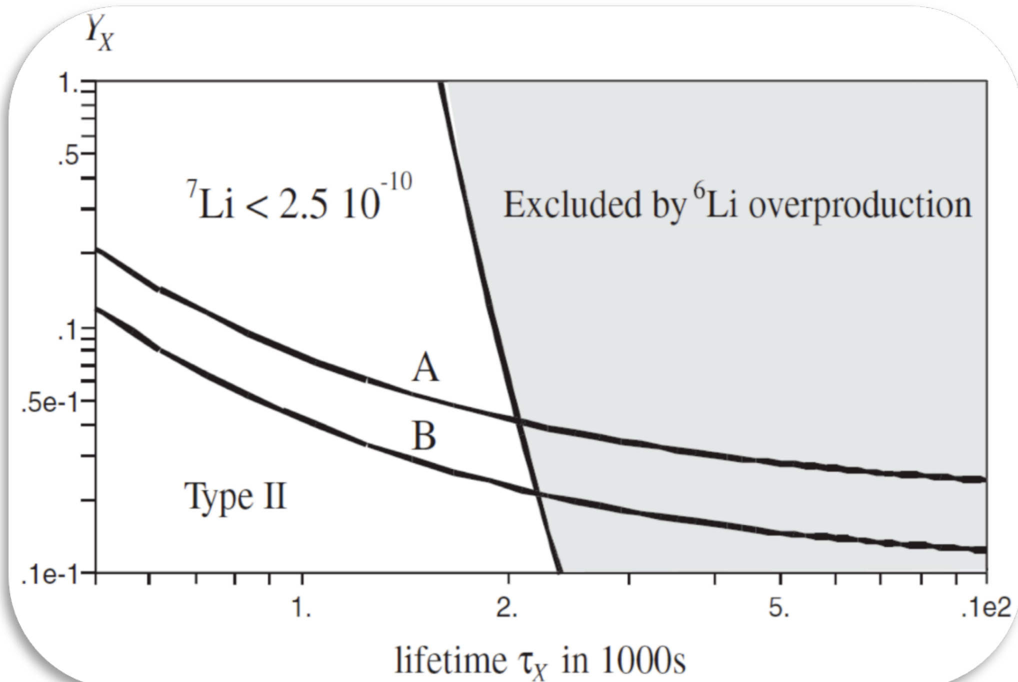


Ineffective for reducing ^{7}Li and ^{7}Be

∵ stau can not weaken the barrieres of Li^{3+} and Be^{4+} sufficiently

Stau catalyzed fusion





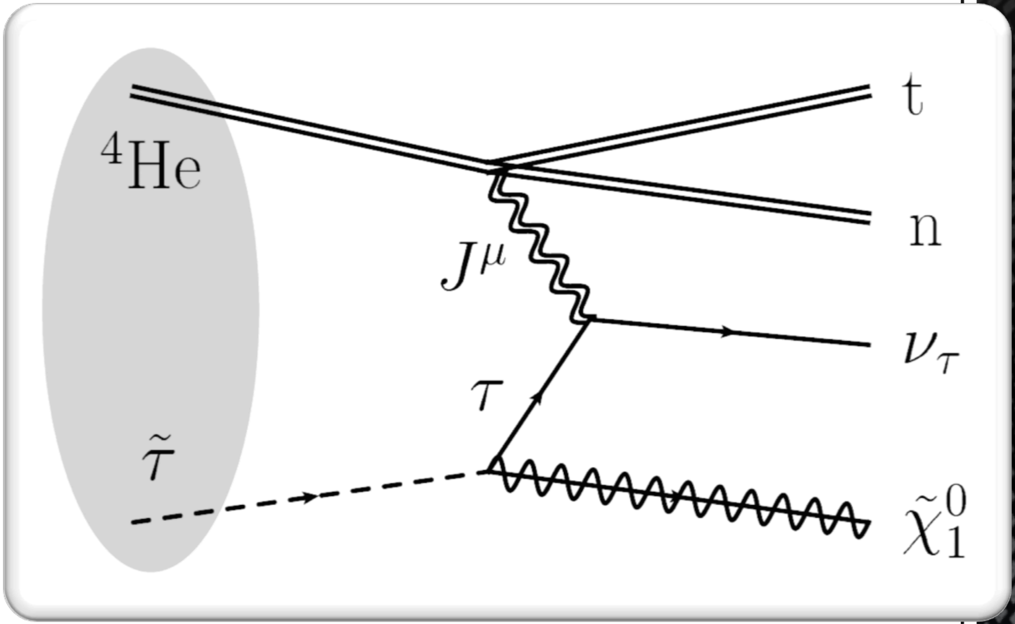
Catalyzed BBN cause over production of ^{6}Li

Constraint on stau life time

^{4}He spallation process PRD 84

Bound state formation via EM int.

$$\tilde{\tau} + {}^4\mathrm{He} \rightarrow (\tilde{\tau}\,{}^4\mathrm{He})$$



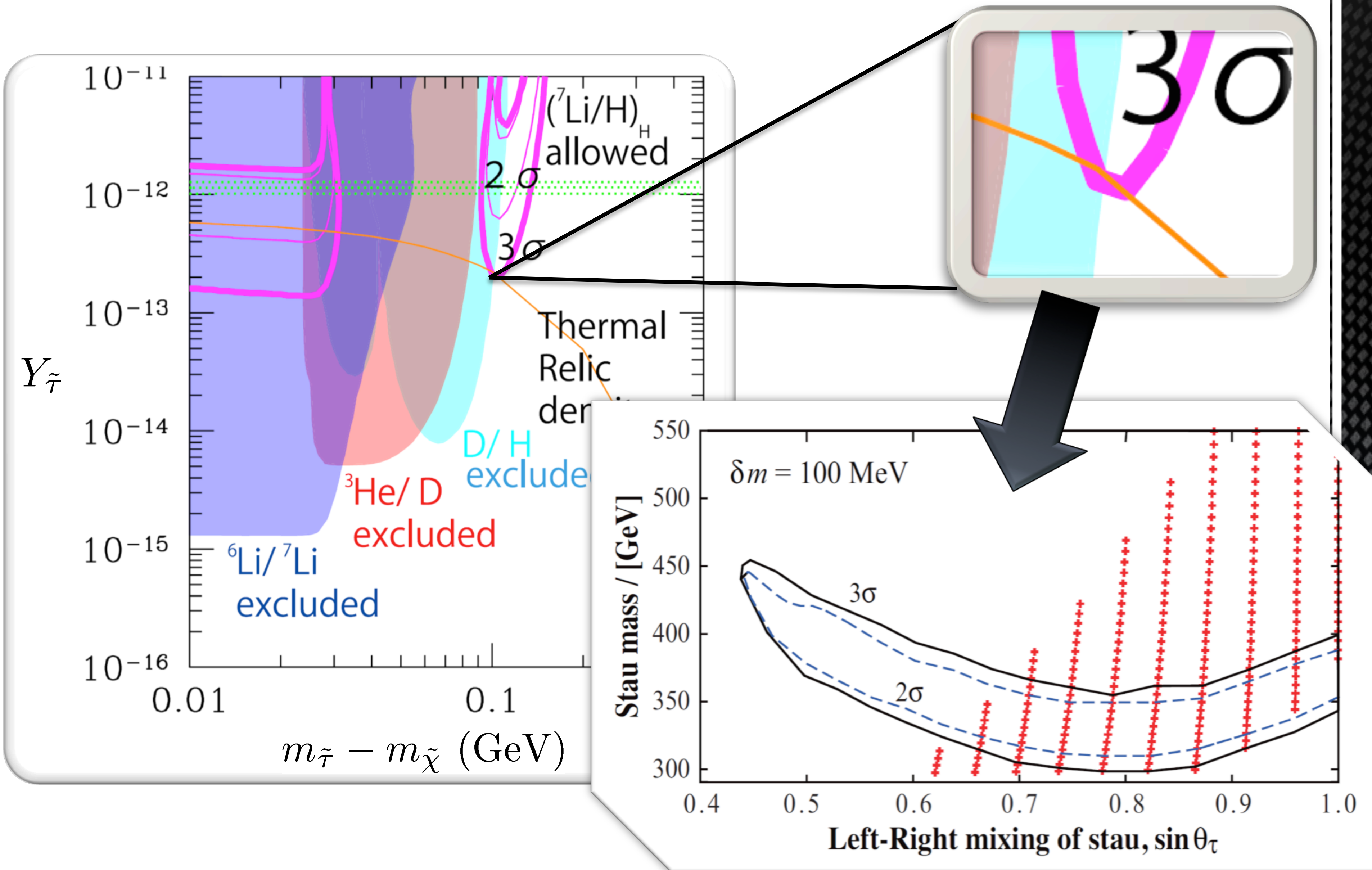
Spallation process

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

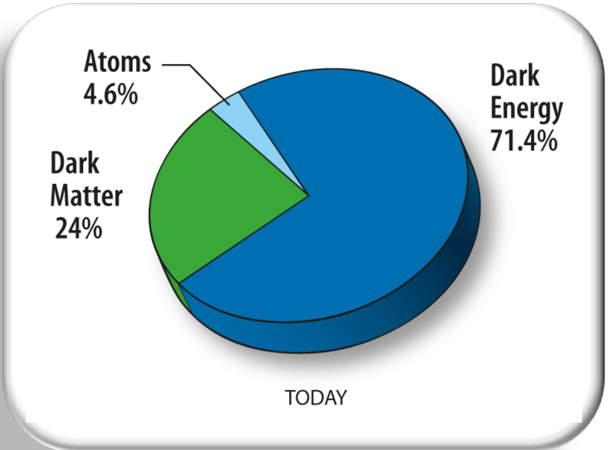
Reaction rate $\Gamma\big((\tilde{\tau}\,{}^4\mathrm{He}) \rightarrow \tilde{\chi}^0_1 \nu_\tau \mathrm{tn}\big) = |\psi|^2 \cdot \sigma \mathrm{v}_{\mathrm{tn}}$

Upper bound for lifetime from not to produce much t/d

Favored parameter space in MSSM

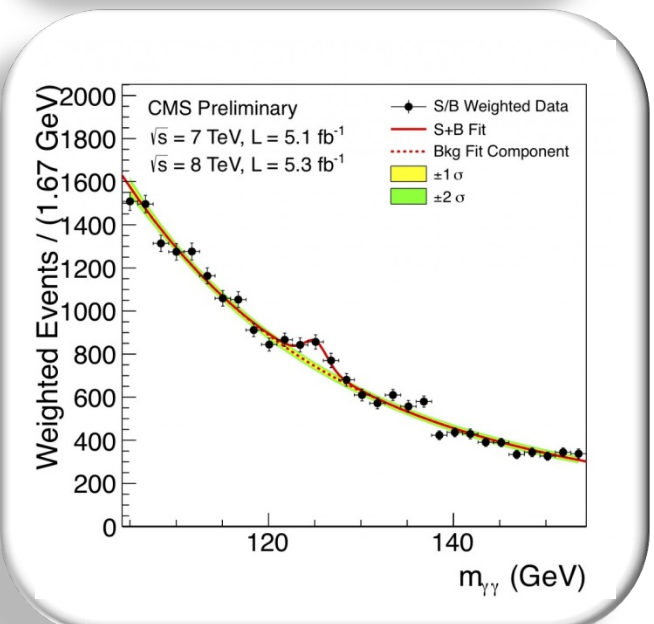


3.Requirement for Parameter Search



☑ Req 1 : DM Abundance

$$0.089 \leq \Omega_{\rm DM} h^2 \leq 0.136$$ [WMAP 9-year]



☑ Req.2 : Higgs Mass

$$m_h = 125.0 \pm 3.0 \ [\rm GeV]$$

- Current Observation

$$m_h = 125.8 \pm 0.4({\rm stat}) \pm 0.4({\rm sys}) \ [\rm GeV]$$ [CMS]

$$m_h = 125.2 \pm 0.3({\rm stat}) \pm 0.6({\rm sys}) \ [\rm GeV]$$ [ATLAS]

- Uncertainty of Public Code

  ～ 2GeV

☑ Req3 : mass difference

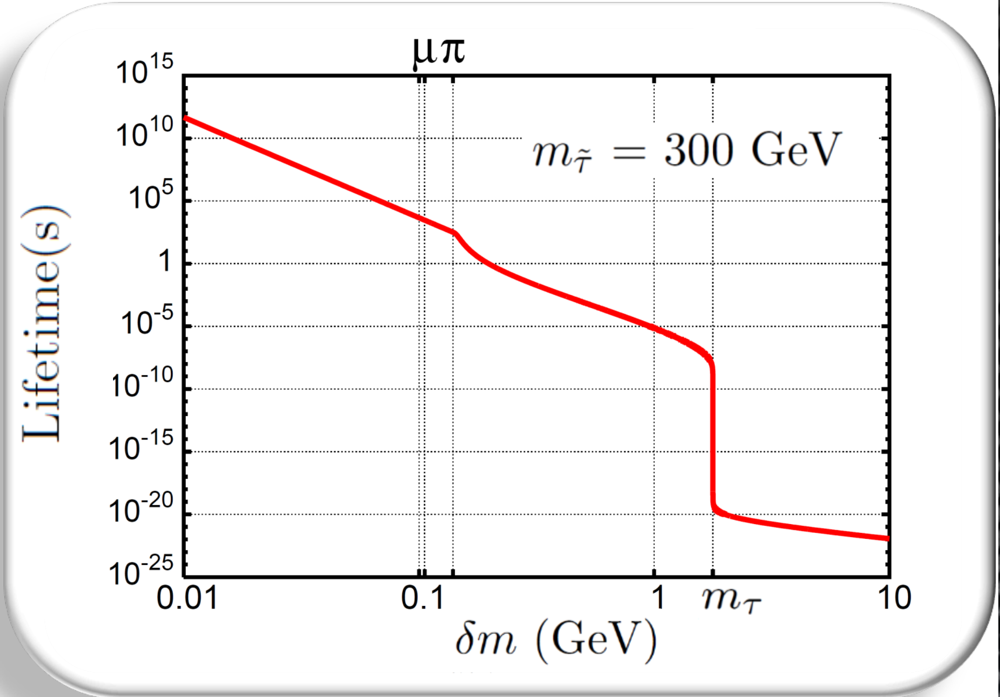
$$\delta m = m_{\tilde{\tau}} - m_{\tilde{\chi}} \leq 1[\mathrm{GeV}]$$

- To form a bound state with Lithium

$$\delta m \leq \ 0.1[\mathrm{GeV}]$$

- Uncertainty of Public Code

  ～ 2GeV



We have calculated the case <0.1GeV but there is no qualitative difference

☑ req4 : Stau (and DM(Lightest Neutralino)) mass

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

LHC bound

$$Y^{\mathrm{BBN}}_{\tilde{\tau}_1} \gtrsim 1.0 \times 10^{-13} \quad Y_{\tilde{\tau}_1} = n_{\tilde{\tau}_1}/s$$

We need many staus to destroy Be/Li

$$Y^{\mathrm{BBN}}_{\tilde{\tau}_1} = \frac{Y^{\mathrm{relic}}_{\tilde{\chi}^0_1}}{2(1+e^{\delta m/T_f})}$$

Exchange process stau<->DM after coanihillation

- Sufficient bound states = Enough Stau at BBN

Strongly correlated with Number density of DM

DM abundance (fixed) = number density × mass

$$\Omega_{\mathrm{DM}} h^2 \equiv \frac{Y^{\mathrm{relic}}_{\tilde{\chi}^0_1} s_0 m_{\mathrm{DM}} h^2}{\rho_c} \leq 0.136$$

Upper bound of DM abundance

$$m_{\tilde{\chi}^0_1} \lesssim \frac{\rho_c}{2 s_0 h^2 (1+e^{\delta m/T_f})} \frac{0.136}{1.0 \times 10^{-13}}$$

- Direct measurement at LHC

4. Result

☑ Numerical Analysis

DM abundance : microOMEGA with SPheno

Higgs mass : FyenHiggs

CMSSM spectrum : SPheno

All other outputs : SPheno

4. Result

4.1. A_0 - m_0 plane

☑ Almost in a line

$$m_0 = -5.5 \times 10^{-3} A_0 \tan\beta + b$$

$$165[\text{GeV}] \lesssim b \lesssim 228[\text{GeV}] \quad \text{for } \tan\beta = 20$$

due to small mass difference

☑ Negative Slope

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 $m_{\tilde{\tau}_1}$

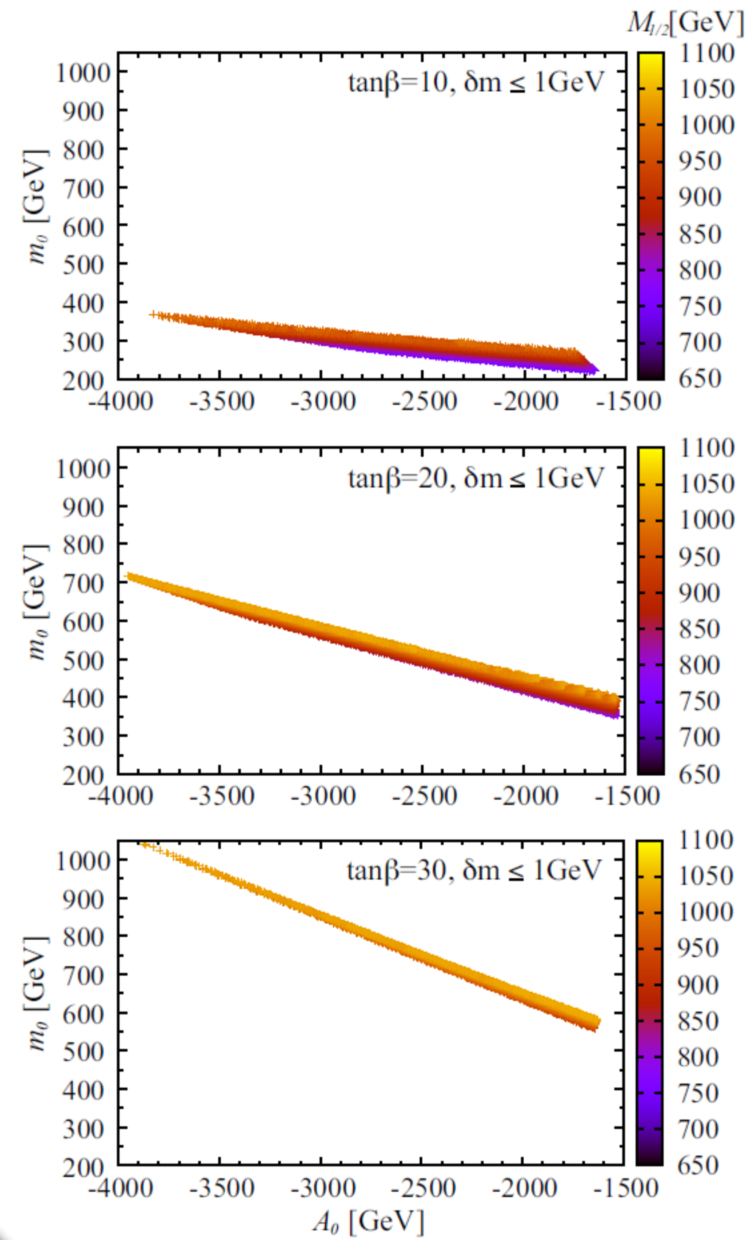
by raising off-diagonal element of stau mass matrix

☑ Upper & Lower edge

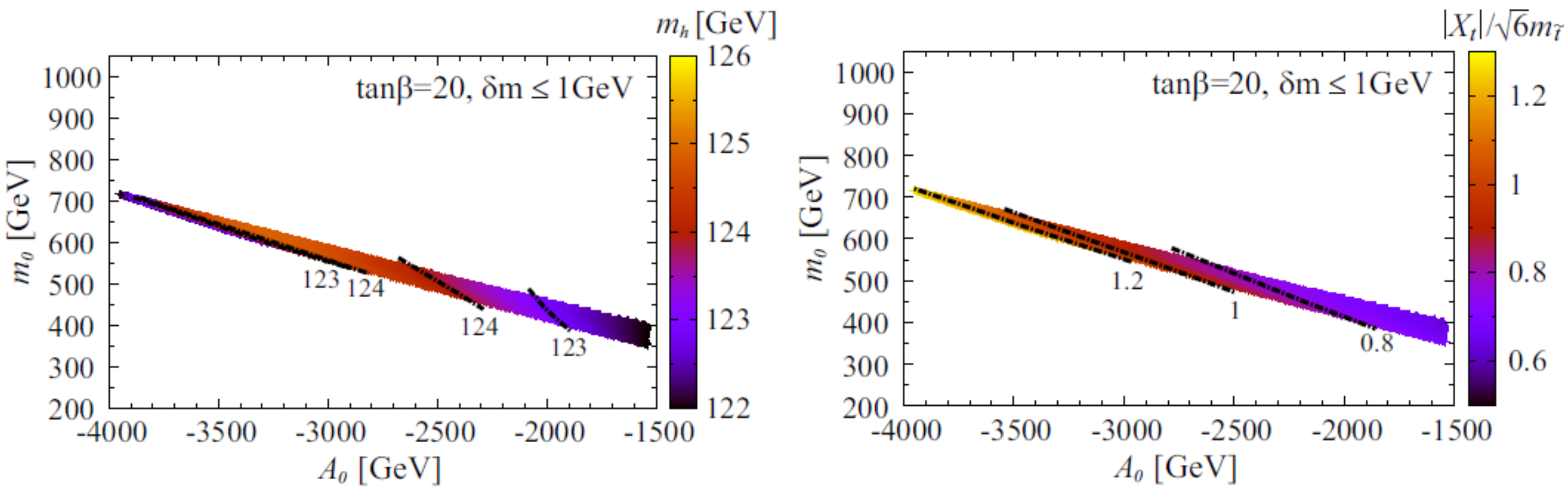
{ Large RGE effect for large $\tan\beta$

Req. 4 $339[\text{GeV}] \leq m_{\tilde{\tau}} \leq 450[\text{GeV}]$

Larger m_0 for lager $\tan\beta$



☑ Left-Right edges are determined by the higgs mass



Higgs mass : strong dependence on $|X_t|/\sqrt{6}m_{\tilde{t}}$, max at 1

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

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

From right to left, $|A_0|$ becomes large more rapidly than m_0

Higgs mass first increases , then decreases,
at maximum 126 GeV

4.2. m_0-$M_{1/2}$ plane

☑ Upper edge

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

Req. 4 $339[\mathrm{GeV}] \leq m_{\tilde{\tau}} \leq 450[\mathrm{GeV}]$

→ $M_{1/2}$ < 1050 GeV

☑ Left-Right edges are determined by the higgs mass

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

increasing m_0 means increasing $m_{\tilde{\tau}_1}$

→

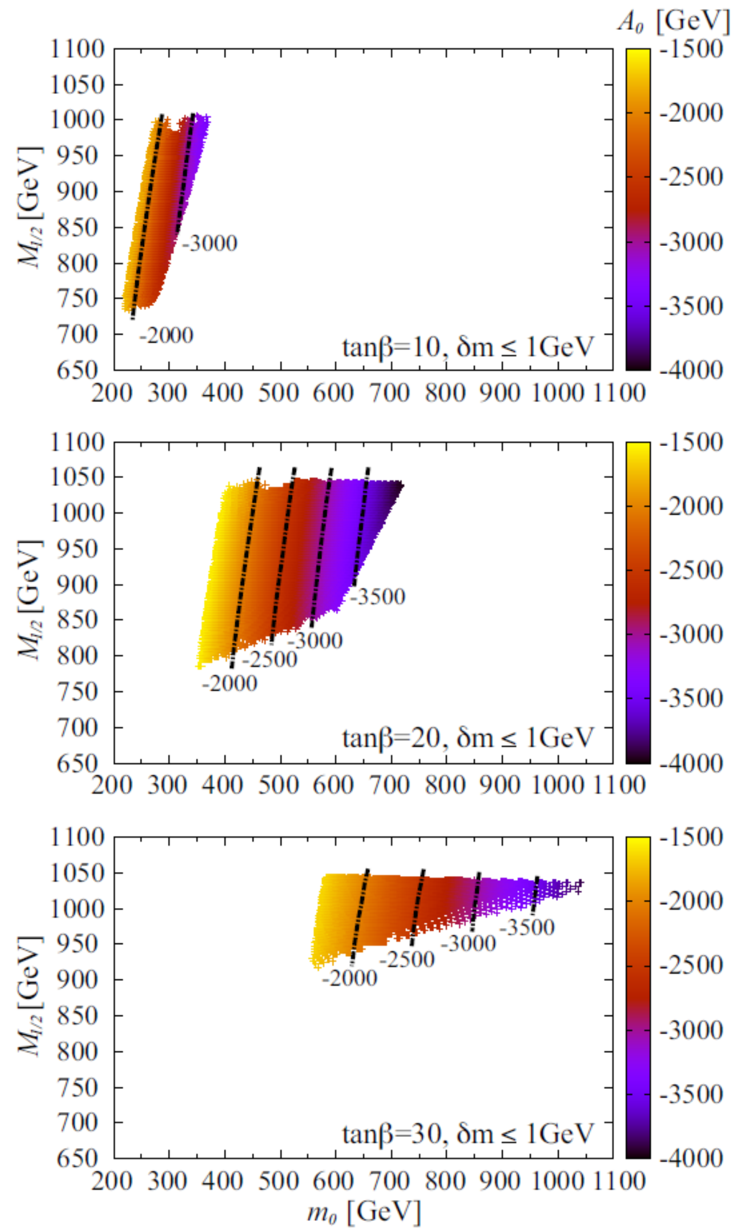
Need to increase | A_0 | to decrease $m_{\tilde{\tau}_1}$

by raising off-diagonal element of stau mass matrix

→

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

Higgs mass first increases , then decreases

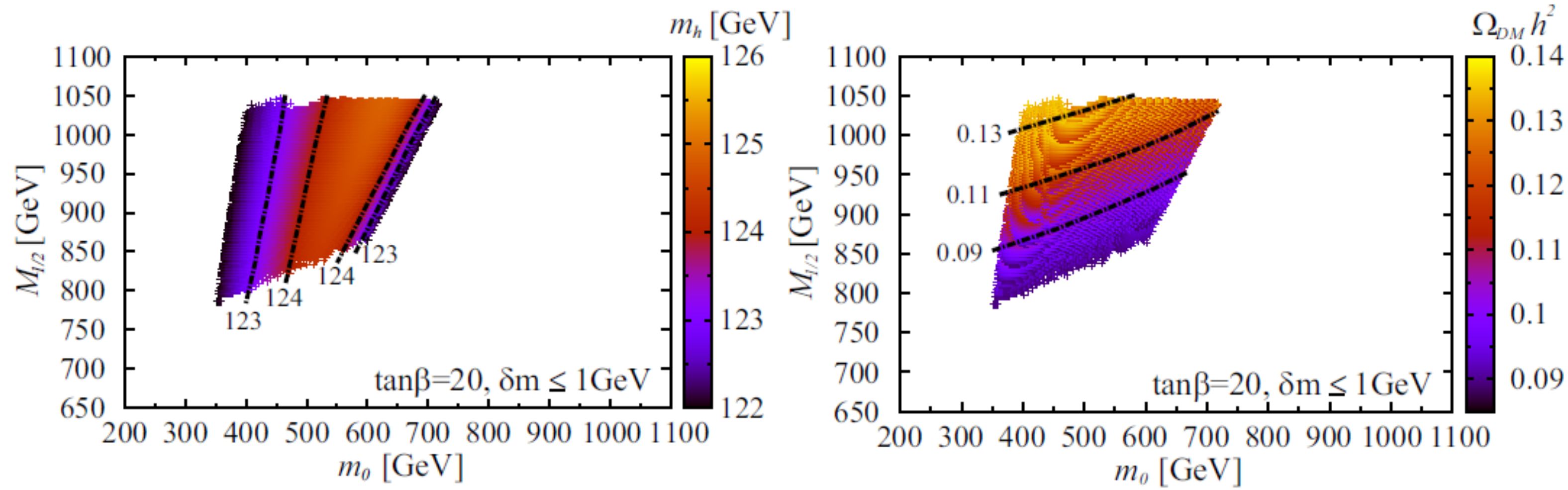


4.2 m_0-$M_{1/2}$ plane

☑

{

☑ L
b



Wit

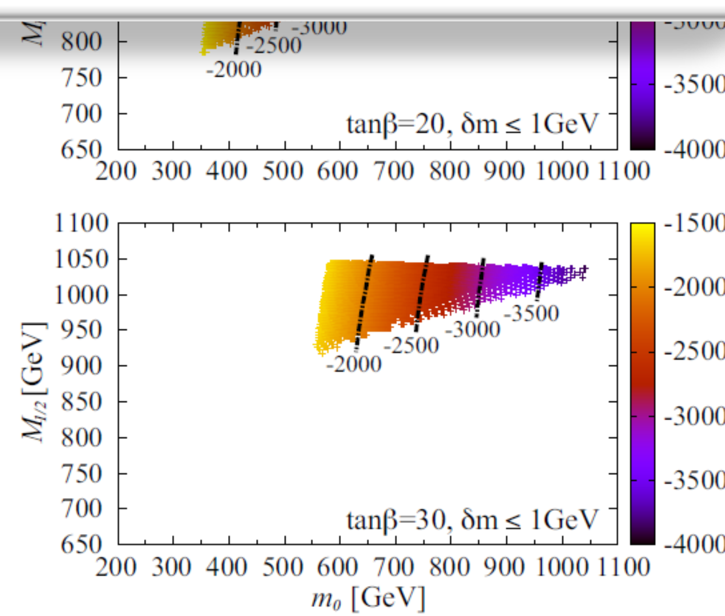
increasing m_0 means increasing $m_{\tilde{\tau}_1}$

Need to increase $|A_0|$ to decrease $m_{\tilde{\tau}_1}$

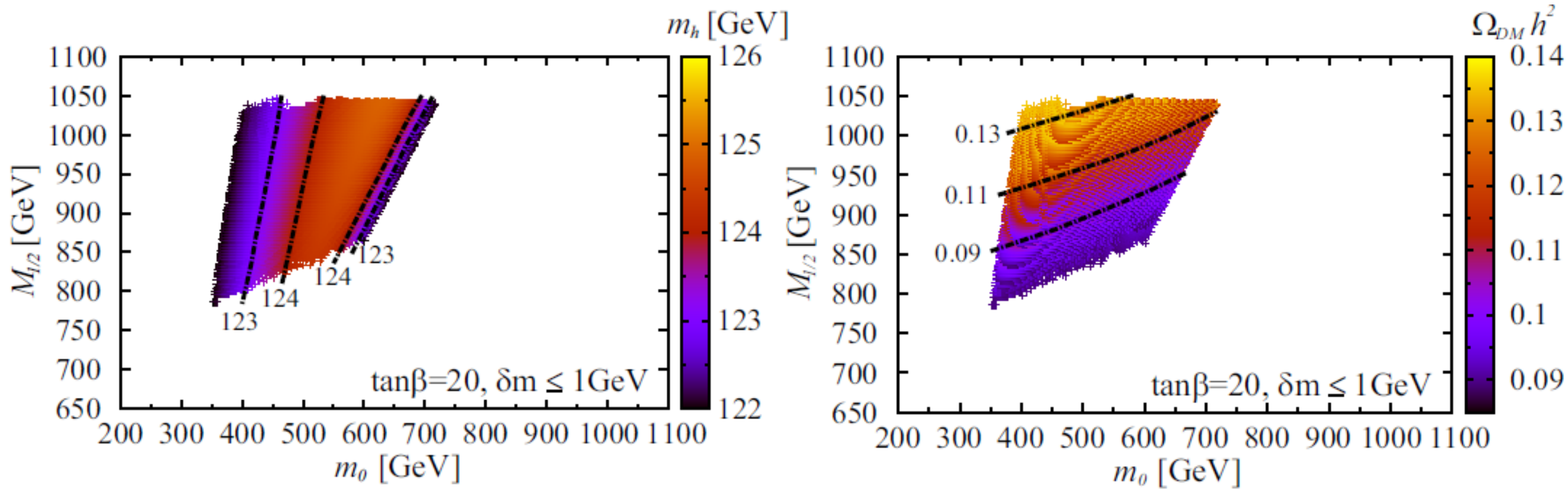
by raising off-diagonal element of stau mass matrix

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

Higgs mass first increases , then decreases



☑ Lower bound is deterbimed by DM aboundance



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

Increasing coanihhilation rate

Increasing DM mass

4.3. Mass spectrum

☑ Well know relations

- 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 : secnd neutralino

M_3 : gluino mass

- 1st & 2nd generation scalars

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

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

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

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

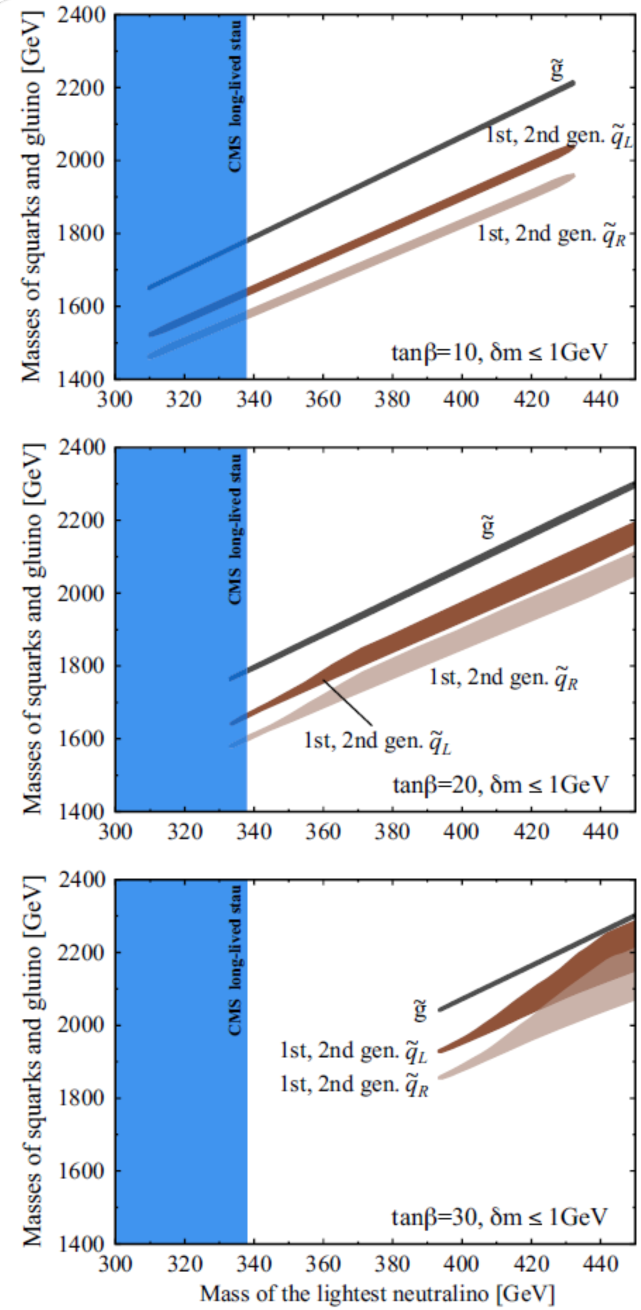
due to small yukawas

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



4.3. Mass spectrum

☑ Well know relations

- stau vs. 1st & 2nd generation sleptons

small $\tan\beta$:

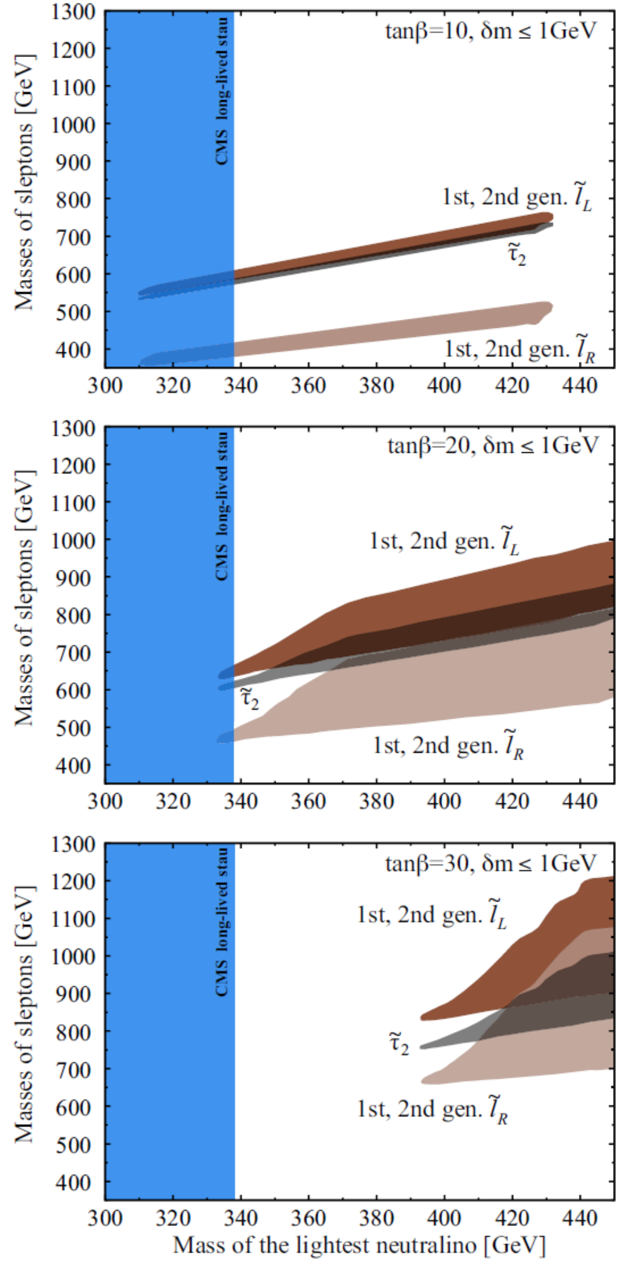
Small tau-yukawa and similar RG effect

➡ Similar mass spectrum

large $\tan\beta$:

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

➡ Stau is lighter than other sleptons.



☑ Well know relations cont'd

- Higgsinos, heavy higgses

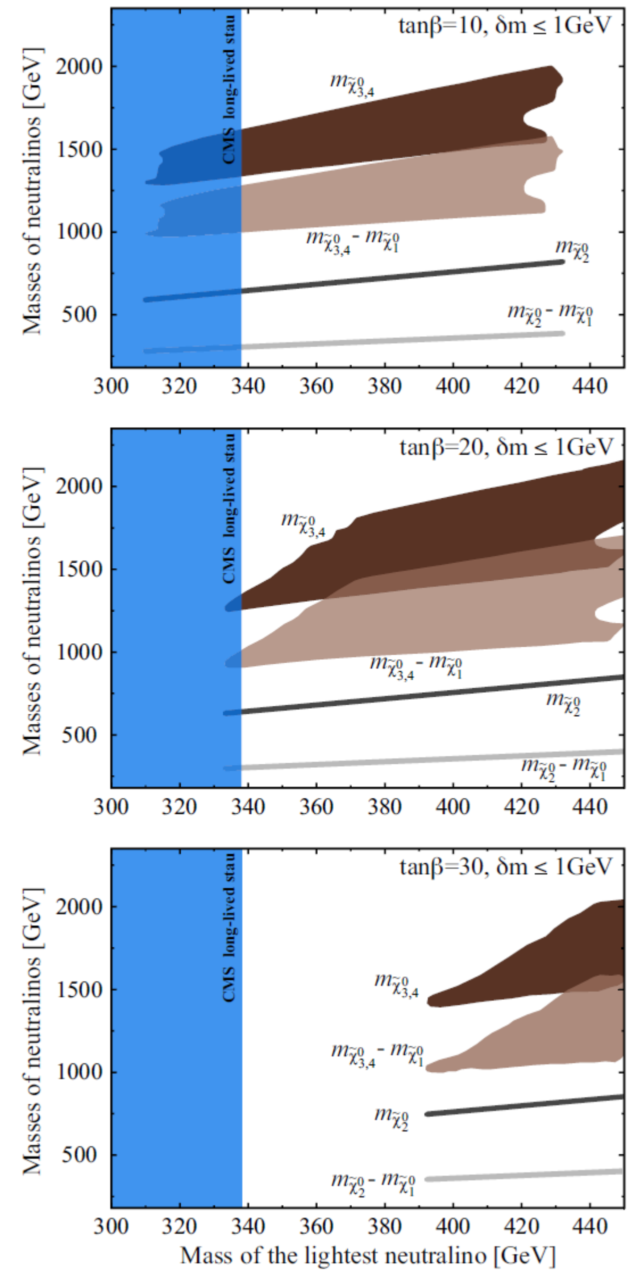
Electroweak Sym Br.

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

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

Numerically,

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



☑ Well know relations cont'd

- 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 is generally pretty light
though still above LHC constraint

sbottom

small $\tan\beta$:

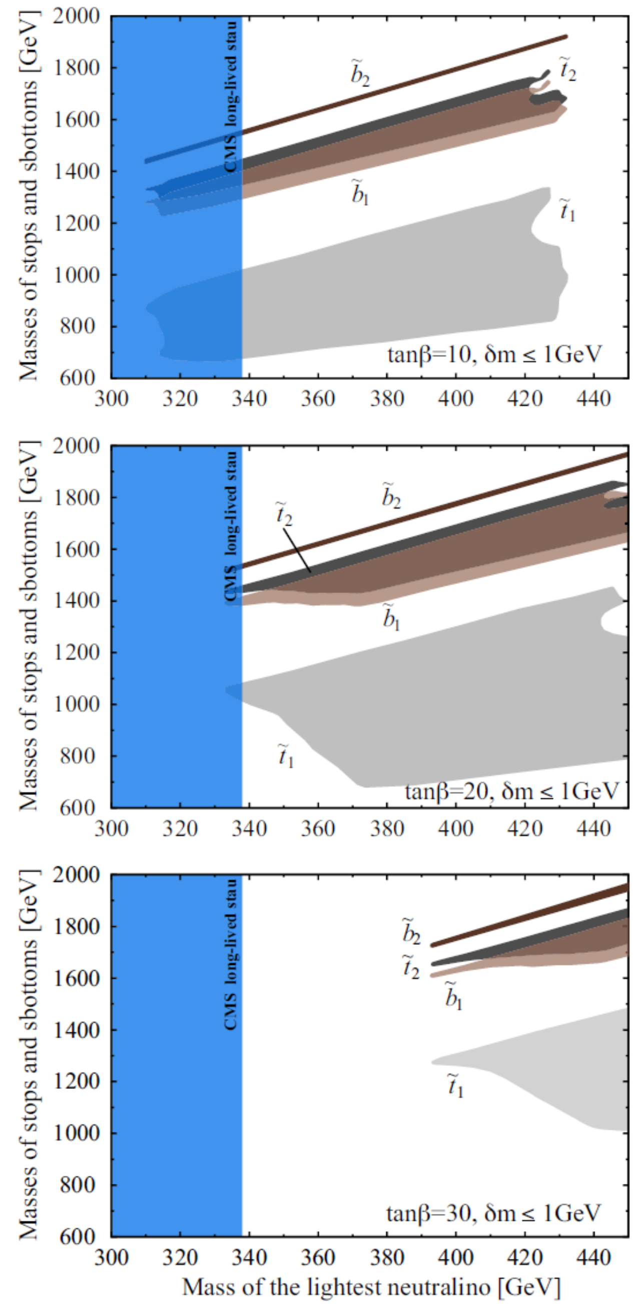
Small bottom-yukawa and similar RG effect

Similar sbottom mass spectrum

large $\tan\beta$:

{ large bottom-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 (predicted by) $m_{\tilde{\tau}}(=m_{\tilde{\chi}_1^0})$
- ☑ Squarks, gluinos, 2nd neutralino, and sleptons are proportional to

$$m_{\tilde{\tau}}(=m_{\tilde{\chi}_1^0})$$

- ☑ Our 4 requirements automatically, naturally predicted that LHC could not observe any signal for SUSY

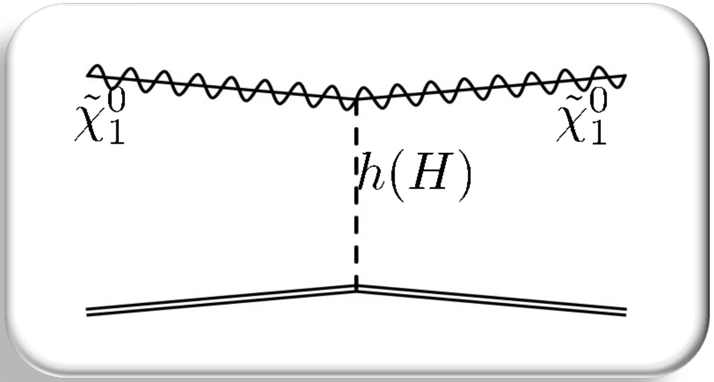
DM Higgs mass, BBN (mass difference & massrange

4.4 other constraints

- ☑ g-2 becomes within 3 sigma
- ☑ Tiny effects on B physics

4.5 Direct ditection of DM

- ☑ Most important channel



- ☑ Cross section

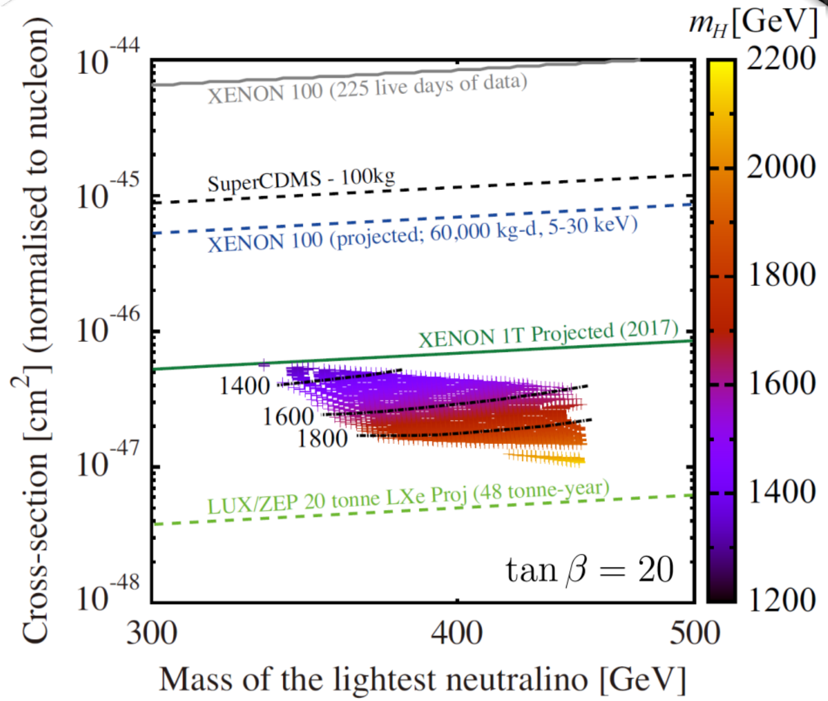
$$\sigma_{SI} = \frac{4}{\pi}\left(\frac{m_{\tilde{\chi}_1^0} m_T}{m_{\tilde{\chi}_1^0} + m_T}\right)^2 (n_p f_p + n_n f_n)^2$$

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

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

- ☑ Correlation between $m_H \simeq \mu$ and σ_{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 $\tilde{\chi}_1^0\tilde{\chi}_1^0 h$



Within the reach in the near future

4.6 LHC in near future

- ☑ Testable with $100\mathrm{fb}^{-1}$

  20% efficiency ?

- ☑ Signals
  - Stau track penetrating detector
  - Missing energy event as same as stau
  - Many light stop

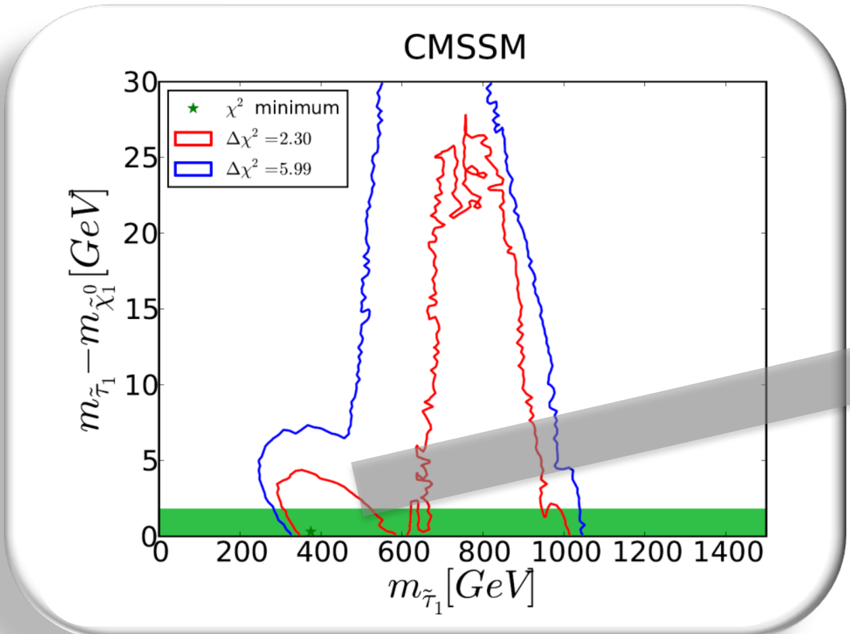
Input	Point 1[GeV]	Point 2[GeV]	Point 3[GeV]
$M_{1/2}$	818.6	932.8	1038.0
m_0	452.0	657.7	639.7
A_0	-2264.7	-2918.4	-3397.0
Particle			
h	123.8	124.6	124.9
$\tilde{g}$	1822.4	2057.8	2272.6
$\tilde{\chi}_1^0$	349.3	400.9	448.5
$\tilde{\tau}_1$	350.3	401.0	449.1
$\tilde{u}_L$	1710.9	1942.2	2149.7
$\tilde{t}_1$	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
$\sigma(\tilde{\chi}_1^+, \tilde{\chi}_1^-)$	1.229	0.629	0.355
$\sigma(\tilde{\chi}_1^+, \tilde{\chi}_2^0)$	3.514	1.858	1.075
$\sigma(\tilde{\chi}_1^-, \tilde{\chi}_2^0)$	1.232	0.616	0.341
σ(All SUSY)	37.730	17.277	8.456
Produced number			
$N_{\tilde{\tau}_1}$	1595	774	303
$N_{\tilde{\tau}_1^*}$	2270	989	409
$N_{\tilde{\chi}}$	3679	1692	978

5.Summary

- ☑ Constrained minimal SUSY standard model (CMSSM) with 4 requirement
- ☑ 4 requirement
  - Dark matter relic abundance
  - Higgs mass
  - Stau – DM mass degeneracy
  - $339[\mathrm{GeV}] \leq m_{\tilde{\tau}} \leq 450[\mathrm{GeV}]$
- ☑ Very constrained Predictions

  Lower limit and lower limit for mass of SUSY particle
  - It is matter of cource that 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

どこのパラメーター領域に注目すべきか？



[J. Ellis, et al, PRD87 (2013)]

☑ 125GeV Higgs、muon g-2 なども含めると尤もらしい領域は？

$$\delta m < m_\tau$$

$$\delta m = m_{\tilde{\tau}_R} - m_{\tilde{\chi}}$$

暗黒物質とスタウの質量差

リチウム7問題

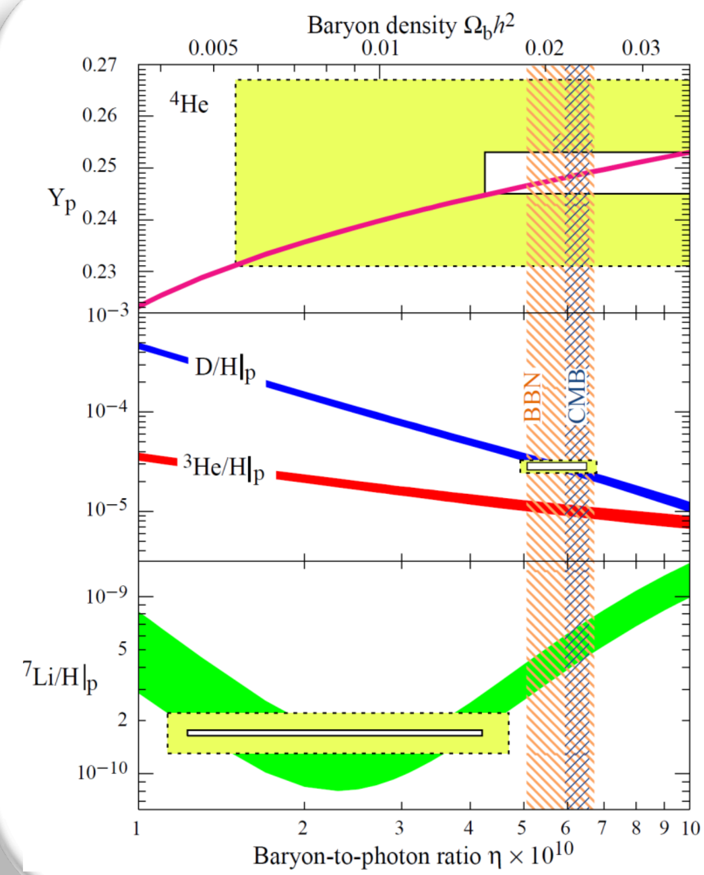
- ☑ Prediction
  $^7\mathrm{Li/H} = (4.15^{+0.49}_{-0.45}) \times 10^{-10}$

- ☑ Observation
  $^7\mathrm{Li/H} = (1.26^{+0.29}_{-0.24}) \times 10^{-10}$

- ☑ Discrepancy: ^{7}Li problem

- ☑ No solutions by modifying nucleus reaction rates

- ☑ Find mechanism to reduce both ^{7}Li and ^{7}Be at the BBN epoch



☑ req4 : Stau (and DM(Lightest Neutralino)) mass

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

LHC bound

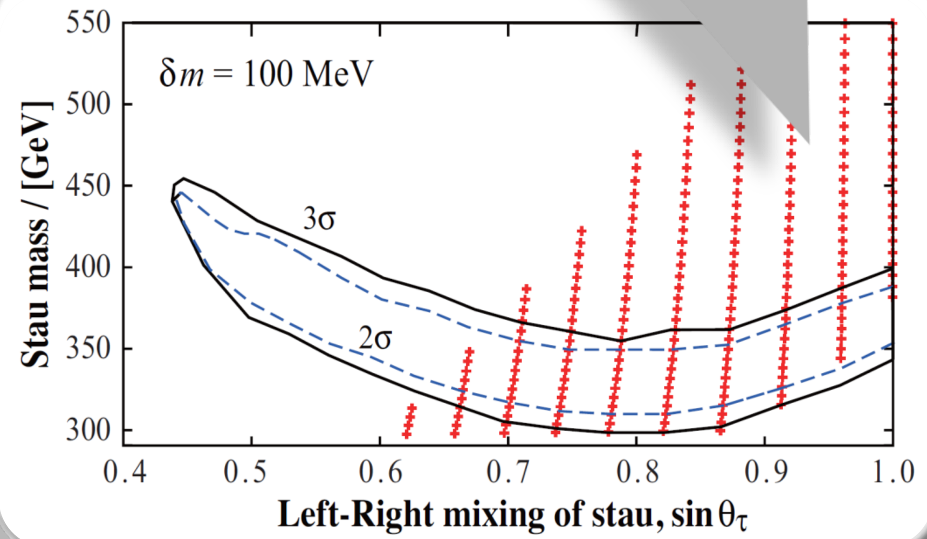
- Sufficient bound states
  = Enough Stau at BBN

  Strongly correlated with
  Number density of DM

  DM abundance (fixed)
  = number density × mass

- Direct measurement at LHC

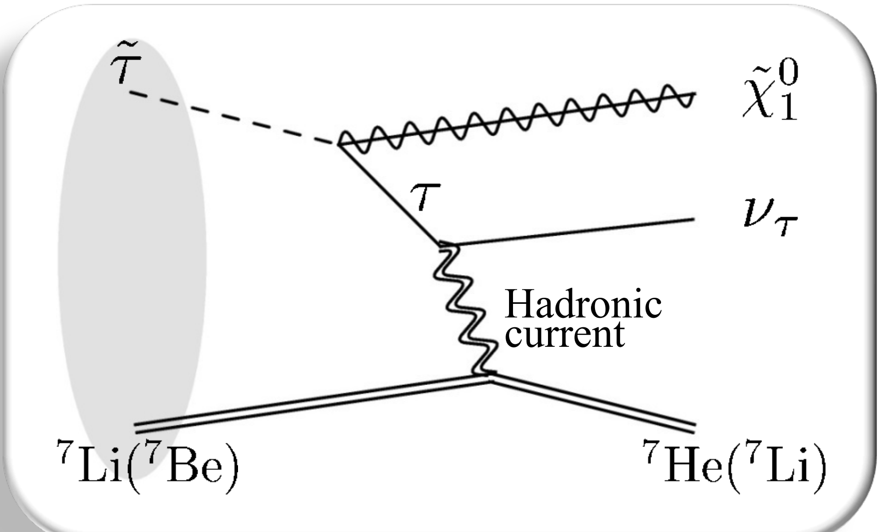
Red Point : BBN
"Islands" :DM Abundance

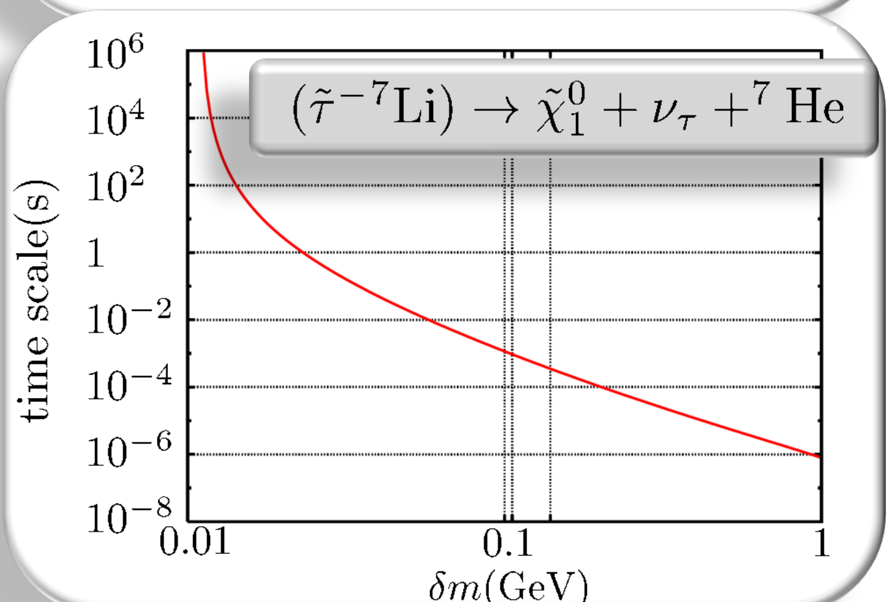


[T. Jittoh, K. Kohri, M. Koike, J. S, T. Shimomura, M.Yamanaka, PRD82(2010)]

Internal conversion for solving the lithium7 problem

[T. Jittoh, K. Kohri, M. Koike, J. Sato, T. Shimomura, MY, PRD76 (2007)]





- ☑ Mechanism to reduce both ^{7}Li and ^{7}Be

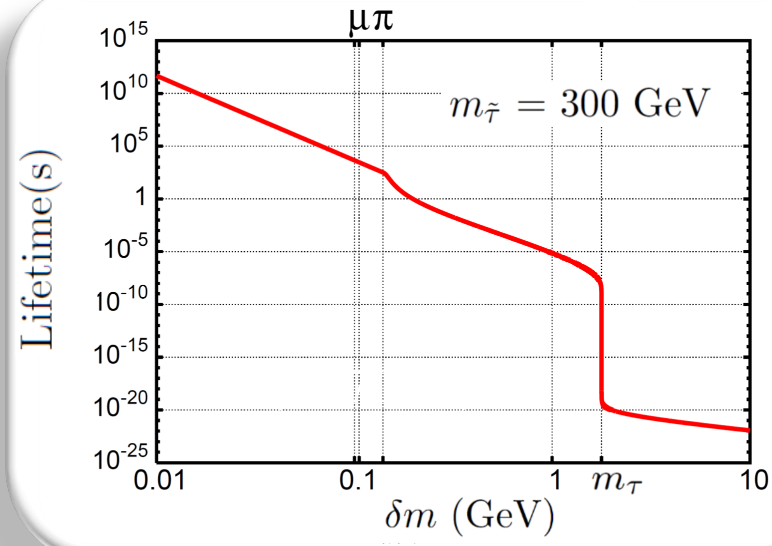
- ☑ Nuclear transformation by the bound state $(\tilde{\tau}^{-7}\mathrm{Li})$ and $(\tilde{\tau}^{-7}\mathrm{Be})$

  (cf. electron capture)

- ☑ ^{7}Li is immediately destroyed once forming the bound state

Very fortunately

- ☑ Stau is long-lived at $\delta m < m_\tau$ since 2-body decay is kinematically prohibited



[T. Jittoh, J. Sato, T. Shimomura, MY, PRD73 (2006)]

- ☑ $\delta m > m_\tau$ のCMSSMを調べるだけでは見落とす現象や制限あり

- ☑ CMSSMの確立に向け、実現可能性大の領域を丁寧に洗い直すべき

研究目的：新たな現象、それに伴う特典・制限を含め、現実的CMSSMの検証可能性を真摯に解析