Big-bang nucleosynthesis with a long-lived CHAMP including ^{4}He spallation process

Masato Yamanaka (KEK)

Based on PRD84, 035008 (2011)

Long-lived charged massive particle

- Predicted in many models of beyond SM
- Various hunting
  (collider experiments, neutrino telescope, etc.)
- Cosmological constraints on its property
  (Big-Bang Nucleosynthesis(BBN), large scale structure, etc.)

One of the interesting objects for particle physics, astrophysics, and nuclear physics

Longevity of charged massive particle

Origin of longevity of charged massive particle (CHAMP)

- ☑ Suppression of small phase space
  - NLSP stau (neutralino LSP scenario)
  - NLSP chargino (anomaly-mediated scenario)

and so on

- ☑ Suppression of super-weakly interaction
  - NLSP stau (gravitino LSP scenario)
  - NLKP KK lepton (graviton LKP scenario in UED)

and so on

- ☑ etc.

Longevity of charged massive particle

☑ Suppression of small phase space

- NLSP stau (neutralino LSP scenario)

☑ Suppression of super-weakly interaction

- NLSP stau (gravitino LSP scenario)

To clear and simplify discussion, this talk focuses on the NLSP stau as a long-lived CHAMP

Notice!

Results for the NLSP stau are applicable to other CHAMP

Long-lived stau and BBN

Modifications to light elements abundances are induced by Long-lived stau depending on property of the stau

☑ Destruction of light elements by its decay products

☑ Catalyzed fusion after forming bound state with nuclei

☑ etc.

Big-bang nucleosynthesis (BBN) is one of the best stage for studying long-lived stau

Important point and aim of work

Important for understanding stau property and each scenario

(1) To identify what exotic reactions are induced by each type of long-lived stau

(2) To understand what light elements are over-produced or over-destructed by each type of reactions

Important point and aim of work

Important for understanding stau property and each scenario

(1) To identify what exotic reactions are induced by each type of long-lived stau

(2) To understand what light elements are over-produced or over-destructed by each type of reactions

☑ Proposing a new process(^{4}He spallation process)

☑ Constraining the property of long-lived stau including this new process

Exotic nuclear reactions with long-lived stau

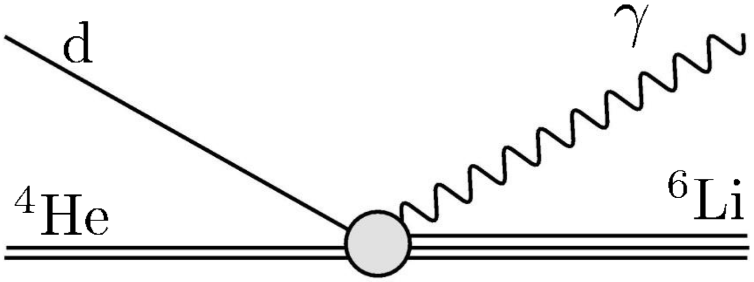
Catalyzed fusion

[M. Pospelov, PRL98]

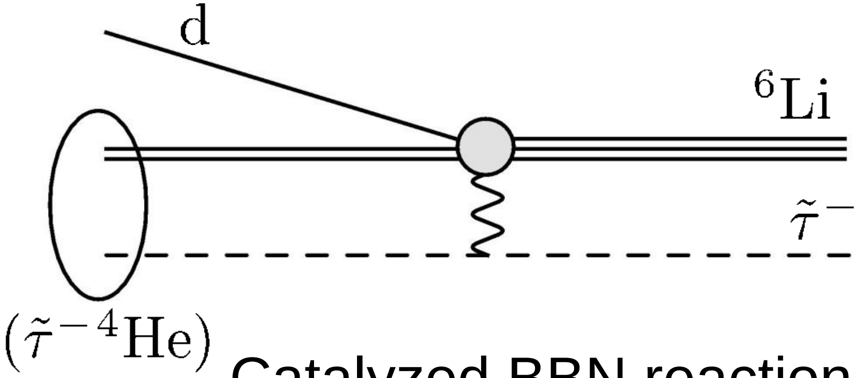
Bound state formation via EM int. $\tilde{\tau} + {}^4\mathrm{He} \to (\tilde{\tau}^- \, {}^4\mathrm{He})$

Catalyzed fusion $(\tilde{\tau}^- \, {}^4\mathrm{He}) + \mathrm{d} \to {}^6\mathrm{Li} + \tilde{\tau}^-$

^{6}Li is over-produced via catalyzed fusion

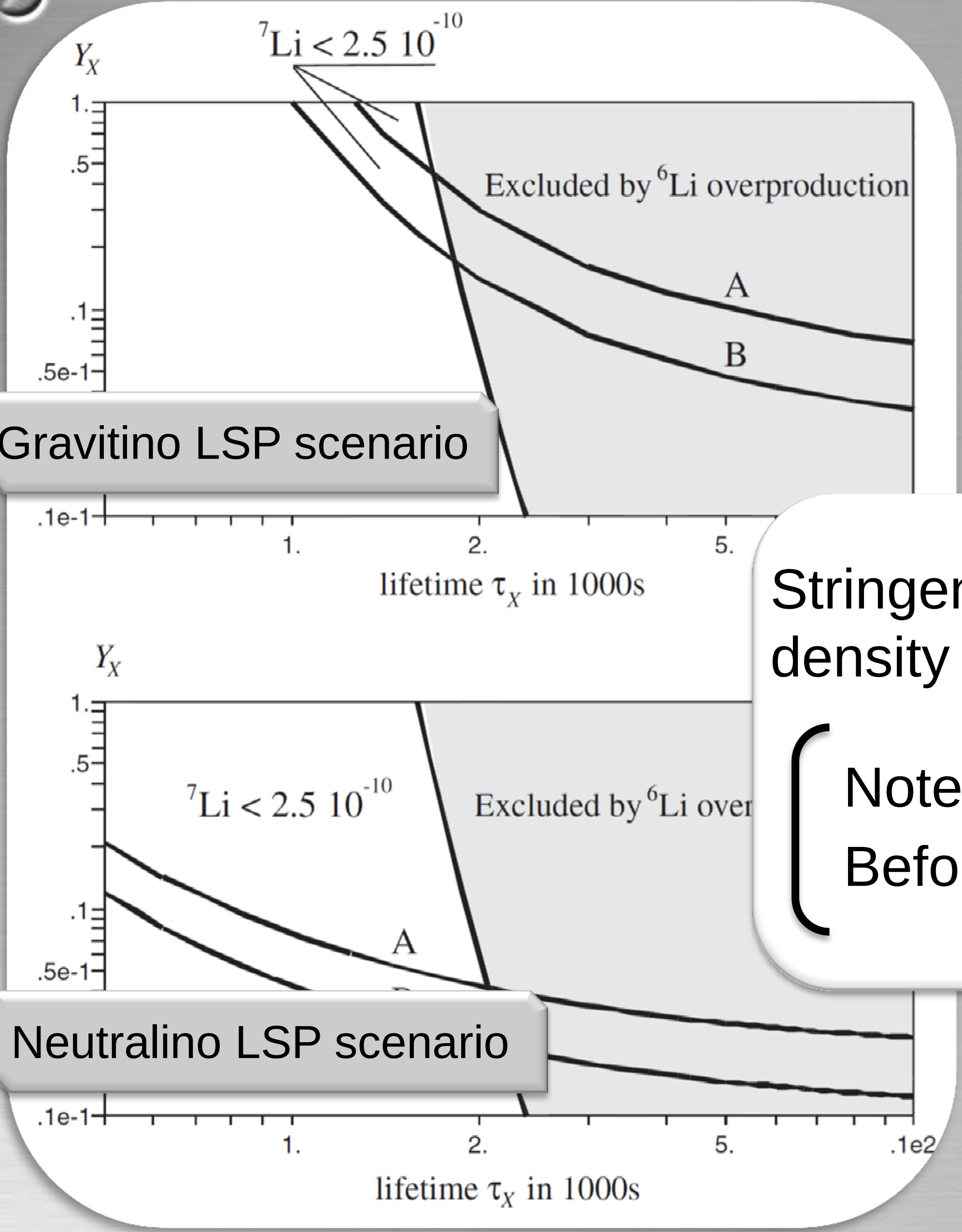


Standard BBN reaction



Catalyzed BBN reaction

Catalyzed fusion



Gravitino LSP scenario

Neutralino LSP scenario

Stringent constraint on stau lifetime and density to evade ^{6}Li overproduction

Note!!
Before including spallation process

[C. Bird, K. Koopmans and M. Pospelov, PRD78]

^{4}He spallation process

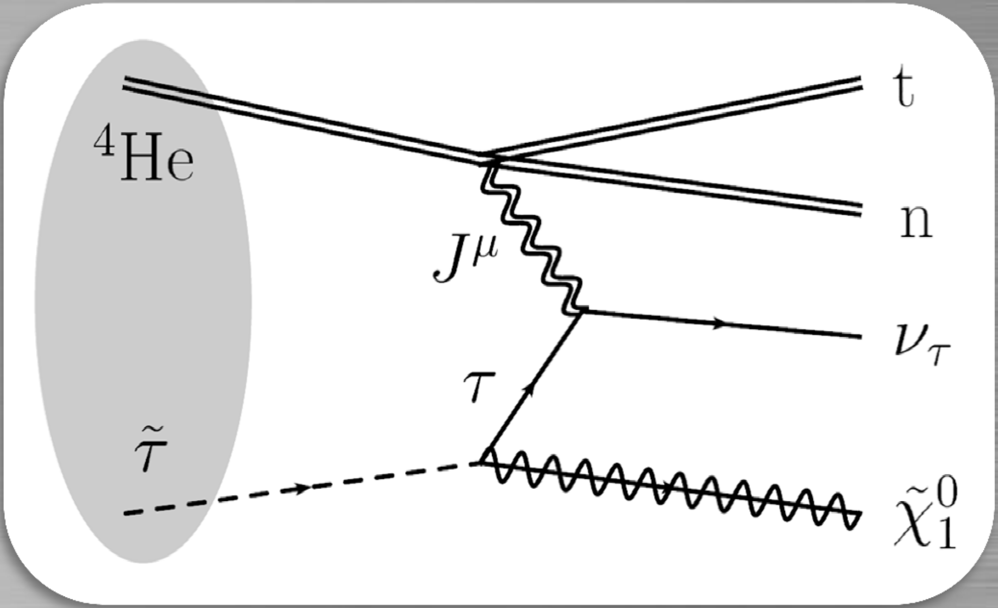
[T. Jittoh, K. Kohri, M. Koike, J. Sato, K. Sugai, K. Yazaki, and MY, PRD84]

Bound state formation via EM int.

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

Spallation process

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



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

^{4}He spallation process

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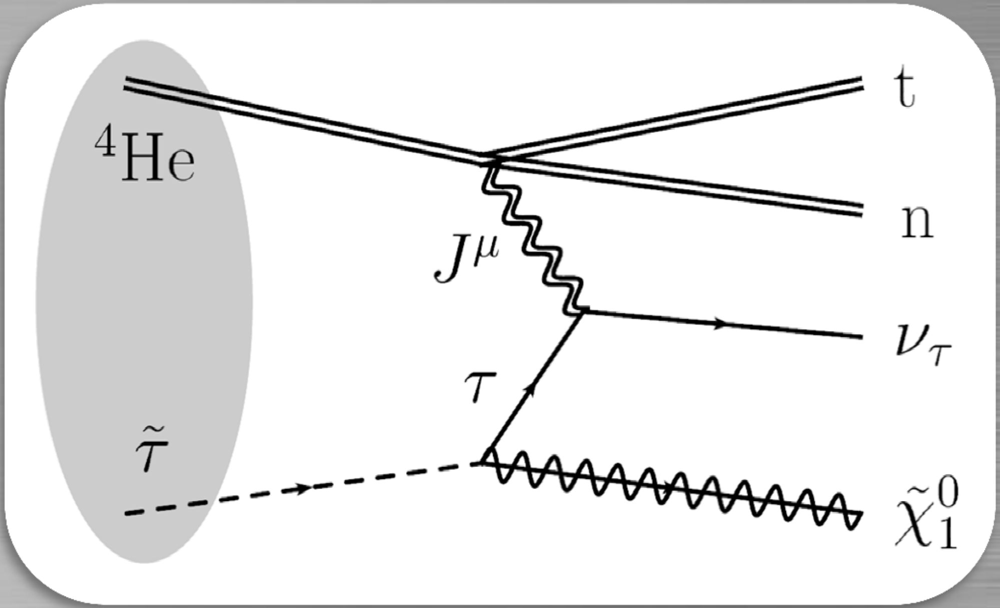


Reaction rate $\Gamma((\tilde{\tau}\,{}^4\mathrm{He}) \to \tilde{\chi}_1^0 \nu_\tau \mathrm{tn}) = |\psi|^2 \sigma \mathrm{v}_{\mathrm{tn}}$

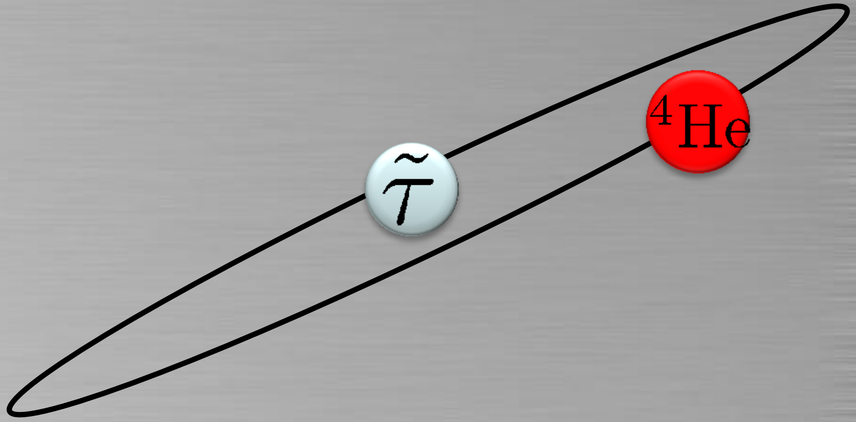
Overlap of initial state wave functions

Overlap of wave functions

Approximation

Localization of $\tilde{\tau}$ at center position in $(\tilde{\tau}\,^4\mathrm{He})$ $\left[\because\ m_{\mathrm{He}} \ll m_{\tilde{\tau}}\right]$

→ Overlap = ^{4}He wave function at the center position



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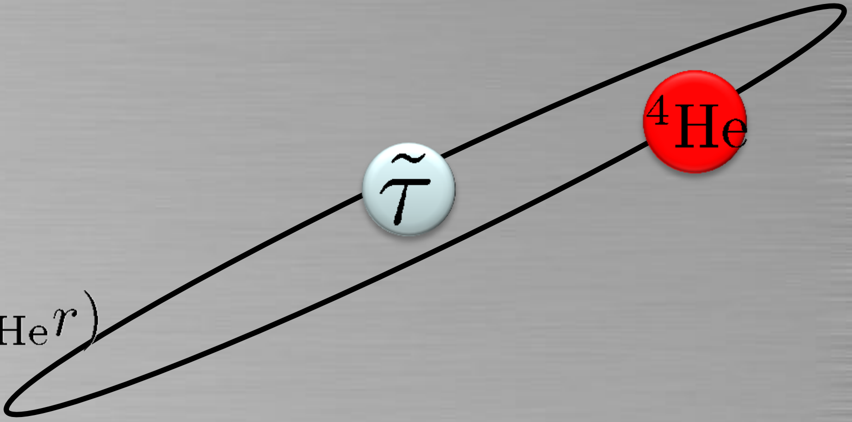


Wave function of ^{4}He

$$\psi_{1\mathrm{S}}^{(\mathrm{He})}(r;Z) = \frac{(Z\alpha m_{\mathrm{He}})^{3/2}}{\sqrt{\pi}} \exp(-Z\alpha m_{\mathrm{He}} r)$$

Overlap of wave functions $$|\psi|^2 = |\psi_{1\mathrm{S}}^{(\mathrm{He})}(0;2)|^2 = \frac{(2\alpha m_{\mathrm{He}})^3}{\pi}$$

^{4}He spallation process

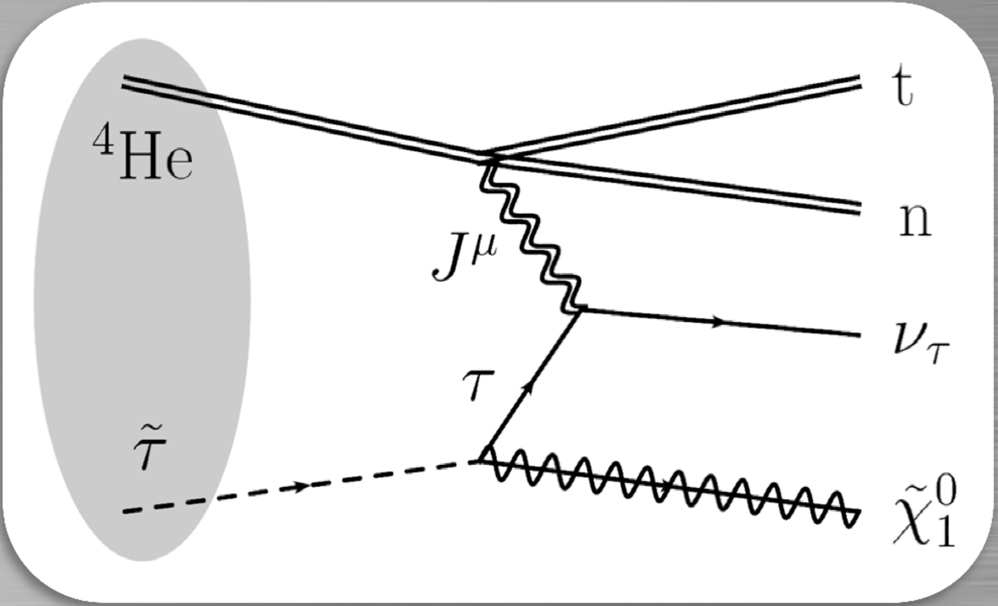
Bound state formation via EM int.

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

↓

Spallation process

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



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

Cross section of elemental reaction

Cross section

Cross section of elemental reaction

$$\sigma v_{\mathrm{tn}} = \frac{1}{2E_{\tilde{\tau}}} \int \frac{d^3\boldsymbol{p}_\nu}{(2\pi)^3 2E_\nu} \frac{d^3\boldsymbol{p}_{\tilde{\chi}}}{(2\pi)^3 2E_{\tilde{\chi}}} \frac{d^3\boldsymbol{q}_{\mathrm{n}}}{(2\pi)^3} \frac{d^3\boldsymbol{q}_{\mathrm{t}}}{(2\pi)^3}$$

$$\times \left|\mathcal{M}\big((\tilde{\tau}\,{}^4\mathrm{He}) \to \tilde{\chi}_1^0 \nu_\tau \mathrm{tn}\big)\right|^2 (2\pi)^4 \delta^{(4)}(p_{\tilde{\tau}} + p_{\mathrm{He}} - p_\nu - q_{\mathrm{t}} - q_{\mathrm{n}})$$

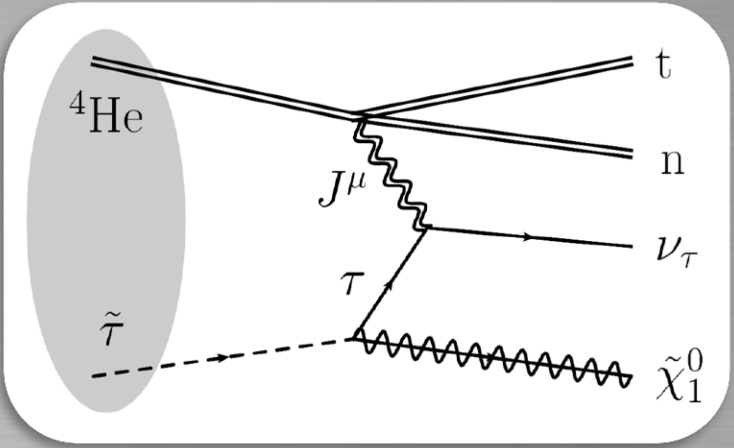
Amplitude

$$\mathcal{M}\big((\tilde{\tau}\,{}^4\mathrm{He}) \to \tilde{\chi}_1^0 \nu_\tau \mathrm{tn}\big)$$

$$= \langle \mathrm{t\,n}\,\tilde{\chi}_1^0\,\nu_\tau | \mathcal{L}_{\mathrm{int}} | {}^4\mathrm{He}\,\tilde{\tau}\rangle$$

$$= \langle \mathrm{t\,n} | J^\mu | {}^4\mathrm{He}\rangle\ \langle \tilde{\chi}_1^0\,\nu_\tau | j_\mu | \tilde{\tau}\rangle$$

Leptonic part; calculated straightforwardly



Hadronic matrix element

☑ Building up wave functions of ^{4}He, t, d, and n

Requirement: anti-symmetric under the exchange of two nucleons

spin, isospin part
(anti-symmetric)

$$\left|{}^4\mathrm{He}\right\rangle = \frac{1}{2\sqrt{6}}\Big[|\mathrm{pnpn}\rangle\big(|{\uparrow\uparrow\downarrow\downarrow}\rangle + |{\downarrow\downarrow\uparrow\uparrow}\rangle - |{\uparrow\downarrow\downarrow\uparrow}\rangle - |{\downarrow\uparrow\uparrow\downarrow}\rangle\big)$$

$$+ \,\ldots\ldots\, + |\mathrm{nnpp}\rangle\big(-|{\uparrow\downarrow\uparrow\downarrow}\rangle + |{\uparrow\downarrow\downarrow\uparrow}\rangle + |{\downarrow\uparrow\uparrow\downarrow}\rangle - |{\downarrow\uparrow\downarrow\uparrow}\rangle\big)\Big]$$

spatial part
(symmetric)

$$\psi_{\mathrm{He}}(\boldsymbol{r}_1, \boldsymbol{r}_2, \boldsymbol{r}_3, \boldsymbol{r}_4) = \left(2\frac{a_{\mathrm{He}}^3}{\pi^3}\right)^{3/4}$$

$$\times \exp\left\{-a_{\mathrm{He}}\left[\boldsymbol{r}_1^2 + \boldsymbol{r}_2^2 + \boldsymbol{r}_3^2 + \boldsymbol{r}_4^2 - \frac{1}{4}(\boldsymbol{r}_1 + \boldsymbol{r}_2 + \boldsymbol{r}_3 + \boldsymbol{r}_4)^2\right]\right\}$$

$$a_{\mathrm{He}} = \frac{9}{16}\frac{1}{(R_{\mathrm{m}})_{\mathrm{He}}^2}, \;\; a_{\mathrm{t}} = \frac{1}{2}\frac{1}{(R_{\mathrm{m}})_{\mathrm{t}}^2} \qquad (R_{\mathrm{m}} : \mathrm{matter\ radius})$$

Hadronic matrix element

☑ Explicit form of the hadronic current

In non-relativistic limit $$J_\mu = V_\mu + g_A A_\mu \to (V_0,\ g_A A_i)$$

V^0 : Time component in vector current

A^i : Spatial components in axial vector current

g_A : axial vector coupling

Taking operators as a sum of a single-nucleon operators $$V^0 = \sum_{a=1}^{4} \tau_a^- \mathrm{e}^{\mathrm{i}\boldsymbol{q}\cdot\boldsymbol{r}_a}\,, \quad A^i = \sum_{a=1}^{4} \tau_a^- \sigma_a^i \mathrm{e}^{\mathrm{i}\boldsymbol{q}\cdot\boldsymbol{r}_a}$$

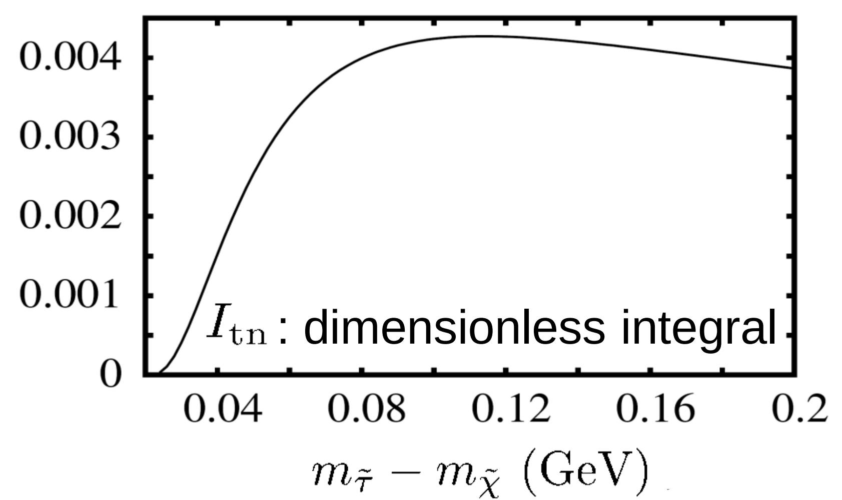
τ_a^-: isospin ladder operator of a-th nucleon

σ_a^i: spin operator of a-th nucleon

Calculated result of cross section

Cross section of elemental reaction

$$\sigma v_{\mathrm{tn}} = \frac{8}{\pi^2}\left(\frac{32}{3\pi}\right)^{3/2} g^2 \tan^2\theta_W \sin^2\theta_\tau (1+3g_A^2) G_F^2 \times \Delta_{\mathrm{tn}}^4 \, \frac{m_{\mathrm{t}} m_{\mathrm{n}}}{m_{\tilde{\tau}} m_\tau^2} \, \frac{a_{\mathrm{He}}^{3/2} a_{\mathrm{t}}^3}{(a_{\mathrm{He}}+a_{\mathrm{t}})^5} \, I_{\mathrm{tn}}$$



I_{tn} : dimensionless integral

$$\Delta_{\mathrm{tn}} \equiv m_{\tilde{\tau}} - m_{\tilde{\chi}} + \Delta_{\mathrm{He}} - \Delta_{\mathrm{t}} - \Delta_{\mathrm{n}} - E_{\mathrm{b}}$$

$$\Delta_{\mathrm{He}} = m_{\mathrm{He}} - 4A,$$
$$\Delta_{\mathrm{t}} = m_{\mathrm{t}} - 3A,$$
$$\Delta_{\mathrm{n}} = m_{\mathrm{n}} - A$$

A : Unified atomic mass unit

Evolution of stau-^{4}He bound state

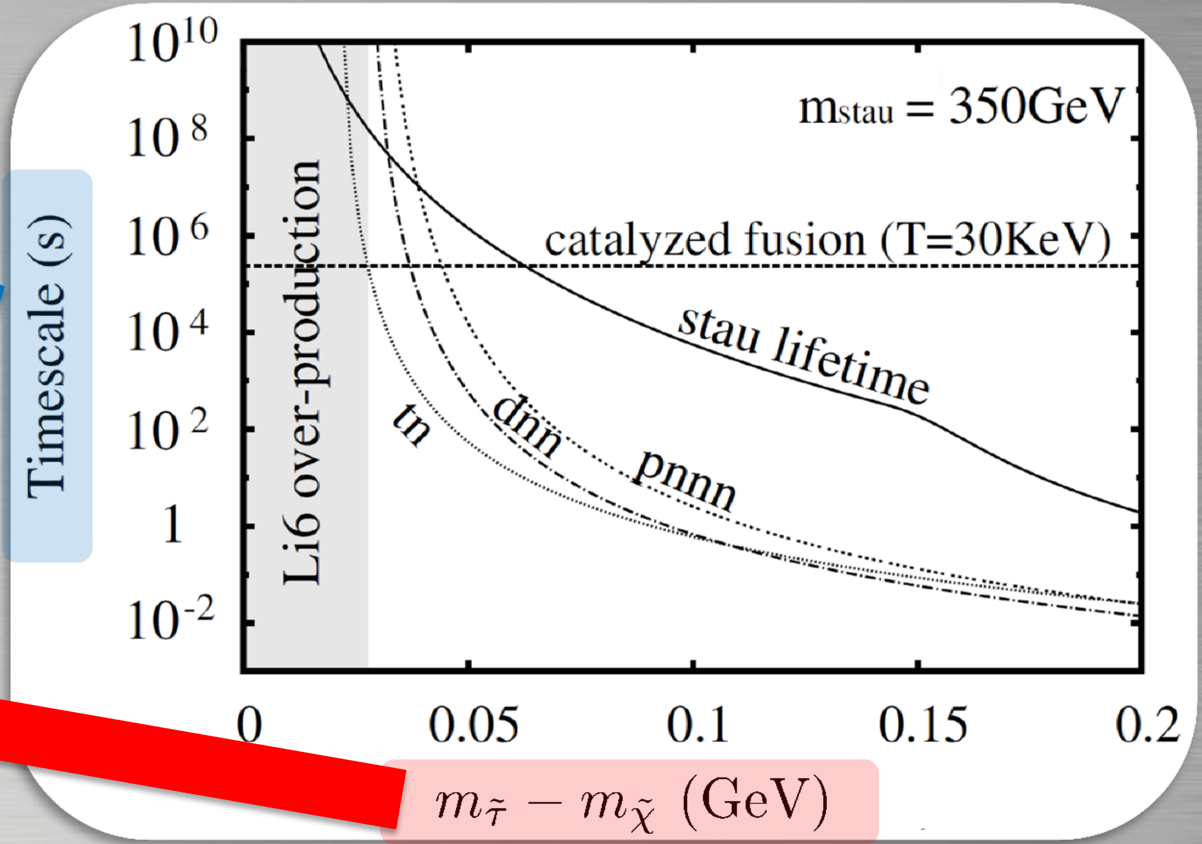
- ☑ Catalyzed fusion → ^{6}Li over-production
- ☑ Spallation process → d and t over-production
- ☑ Standard particle decay → Free from BBN constraint

Important

Which is dominant process?

Evolution of stau-^{4}He bound state

- ☑ Catalyzed fusion → ^{6}Li over-production
- ☑ Spallation process → d and t over-production
- ☑ Standard particle decay → Free from BBN constraint



Time scale of each process

Mass difference of NLSP stau and LSP neutralino

Evolution of stau-^{4}He bound state

- ☑ Catalyzed fusion → ^{6}Li over-production
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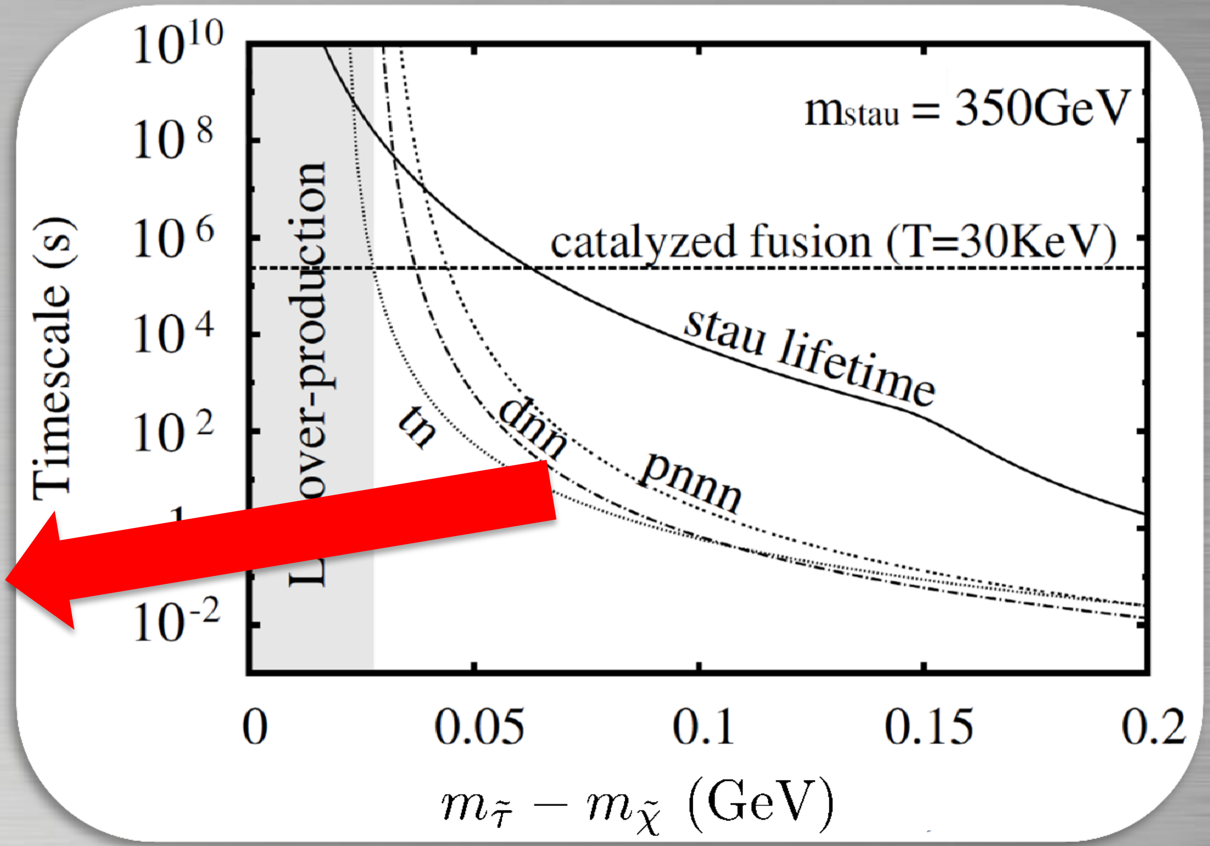
- ☑ Standard particle decay → Free from BBN constraint

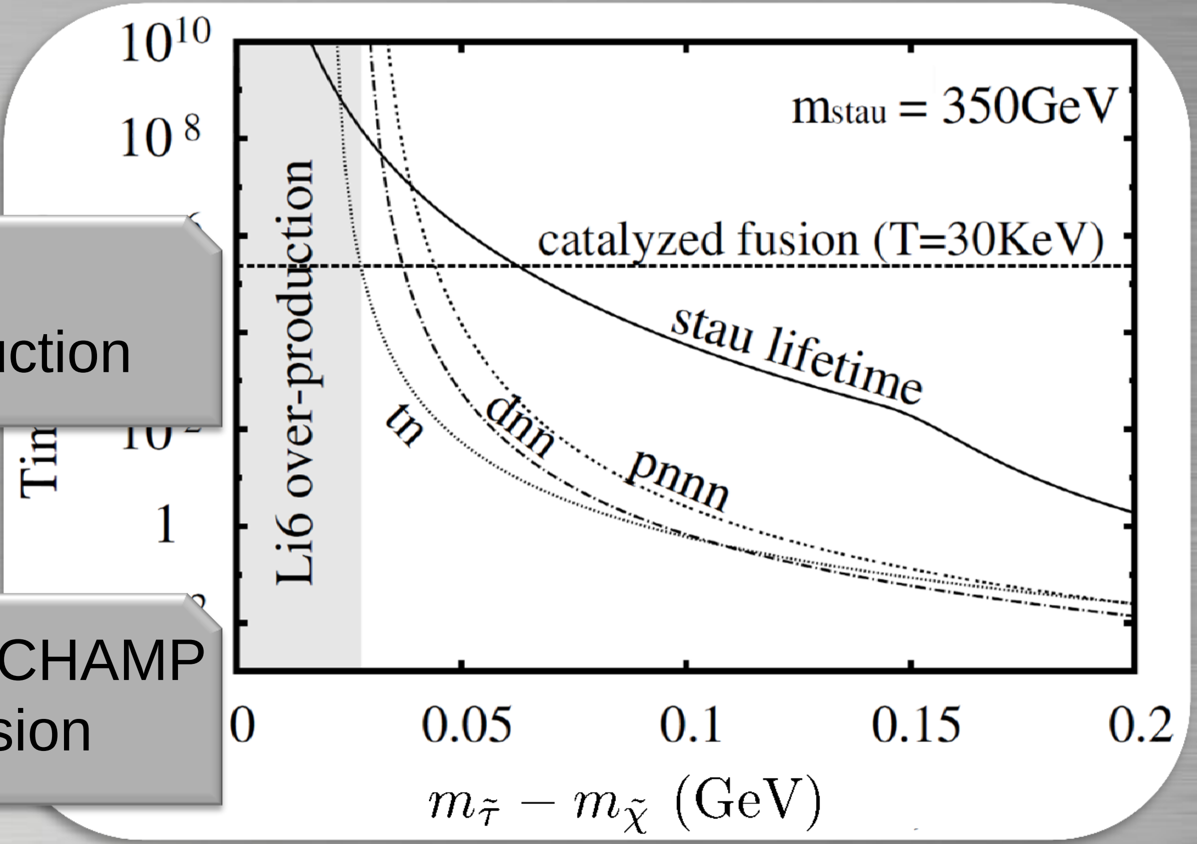


^{4}He spallation processes

Evolution of stau-^{4}He bound state

Why are spallation processes dominant?

- Large overlap of initial state wave functions
- Without external deuteron



Most stringent constraint
due to d and t over-production

For also other long-lived CHAMP
by phase space suppression

Summary

☑ It is important for understanding the property of long-lived charged massive particle

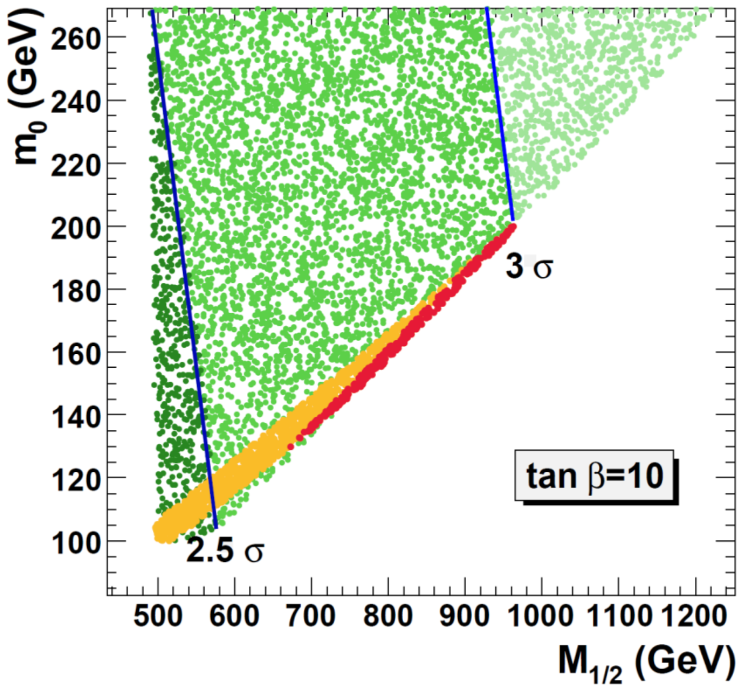
→ To identify what exotic reactions are induced

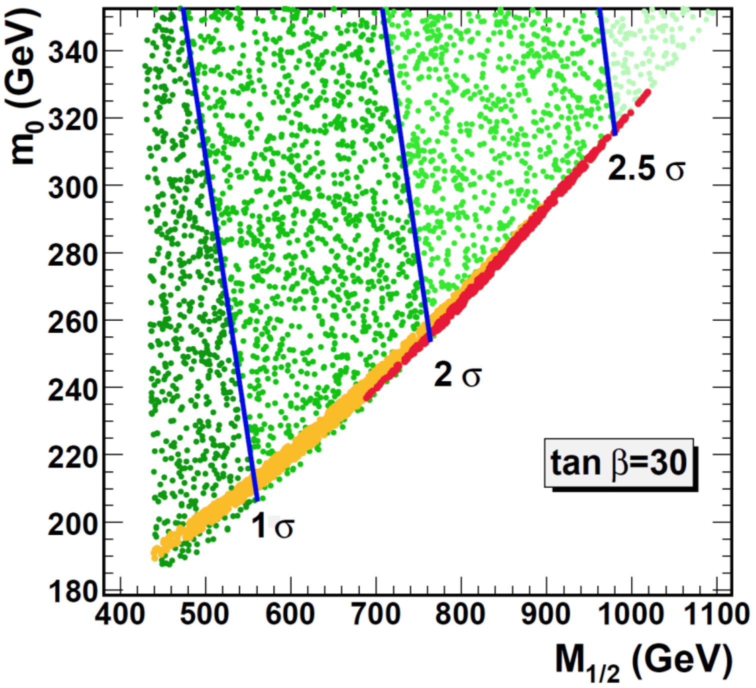
→ To understand what nuclei are over-produced(-destructed)

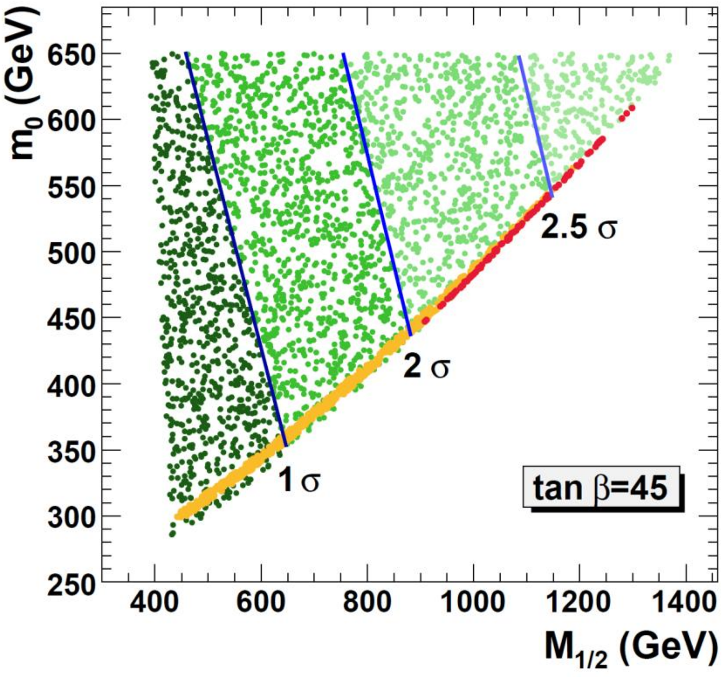
☑ This work proposed new exotic reaction: ^{4}He spallation process

☑ Most stringent bound on Long-lived CHAMP comes from ^{4}He spallation process, if the longevity is guaranteed by phase space suppression.

Back-up slides





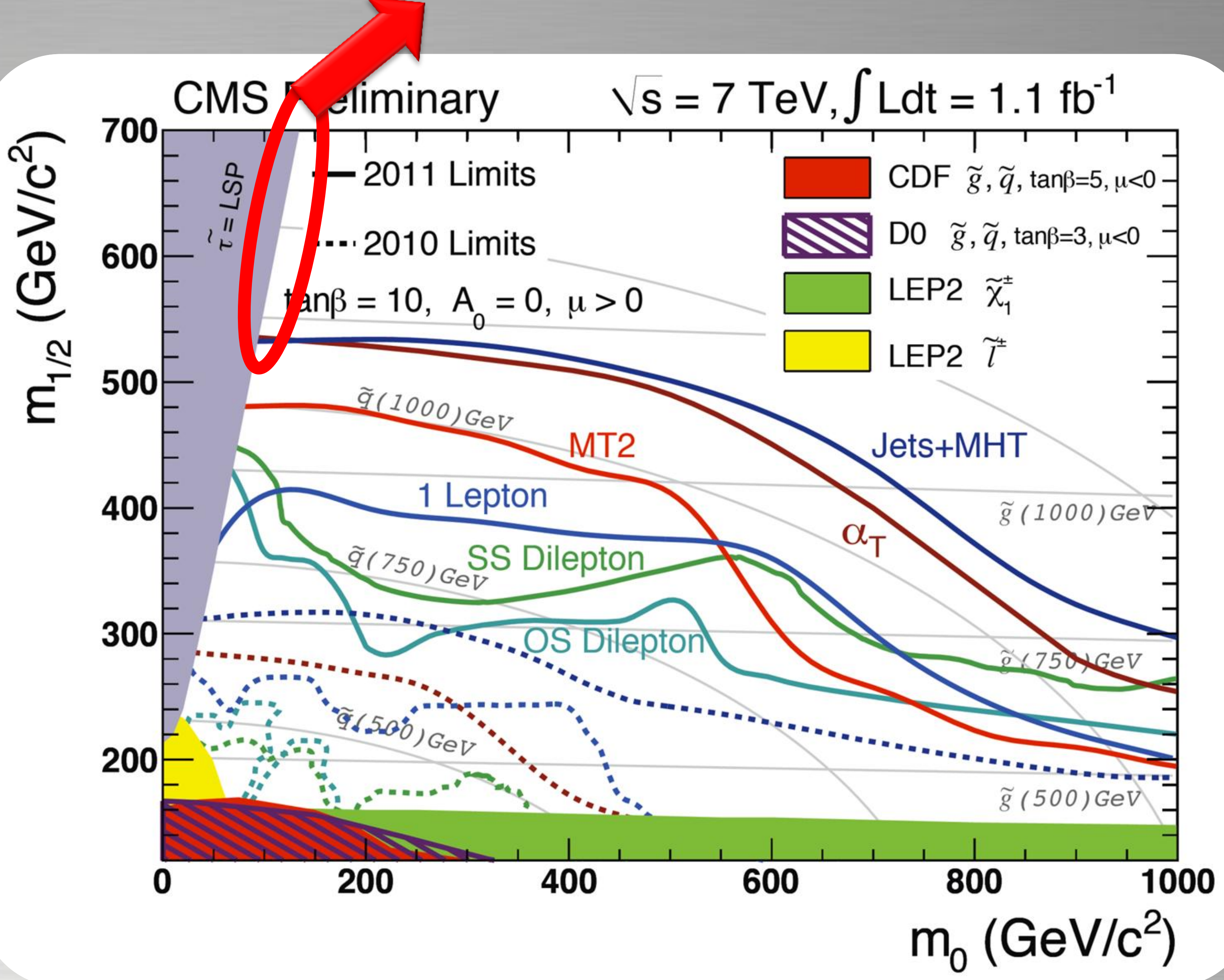


Red band: consistent with DM abundance with $\delta m < m_\tau$

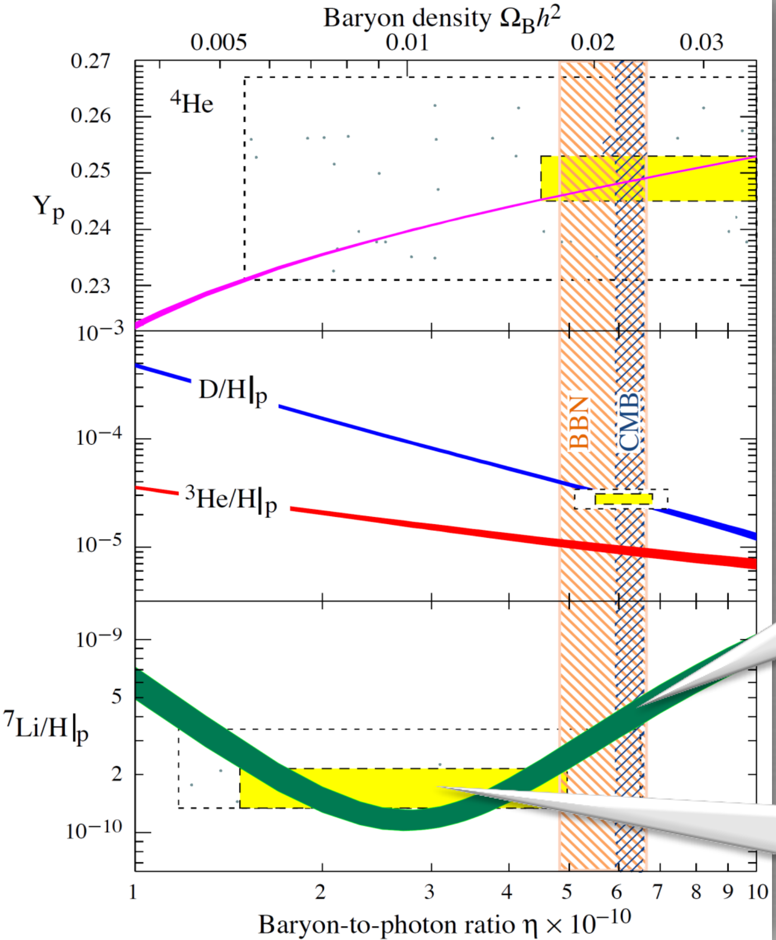
Green band: consistent with DM abundance with $\delta m > m_\tau$

White region: stau LSP

Consistent with relic abundance of neutralino dark matter



^{7}Li problem



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

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

Discrepancy between them

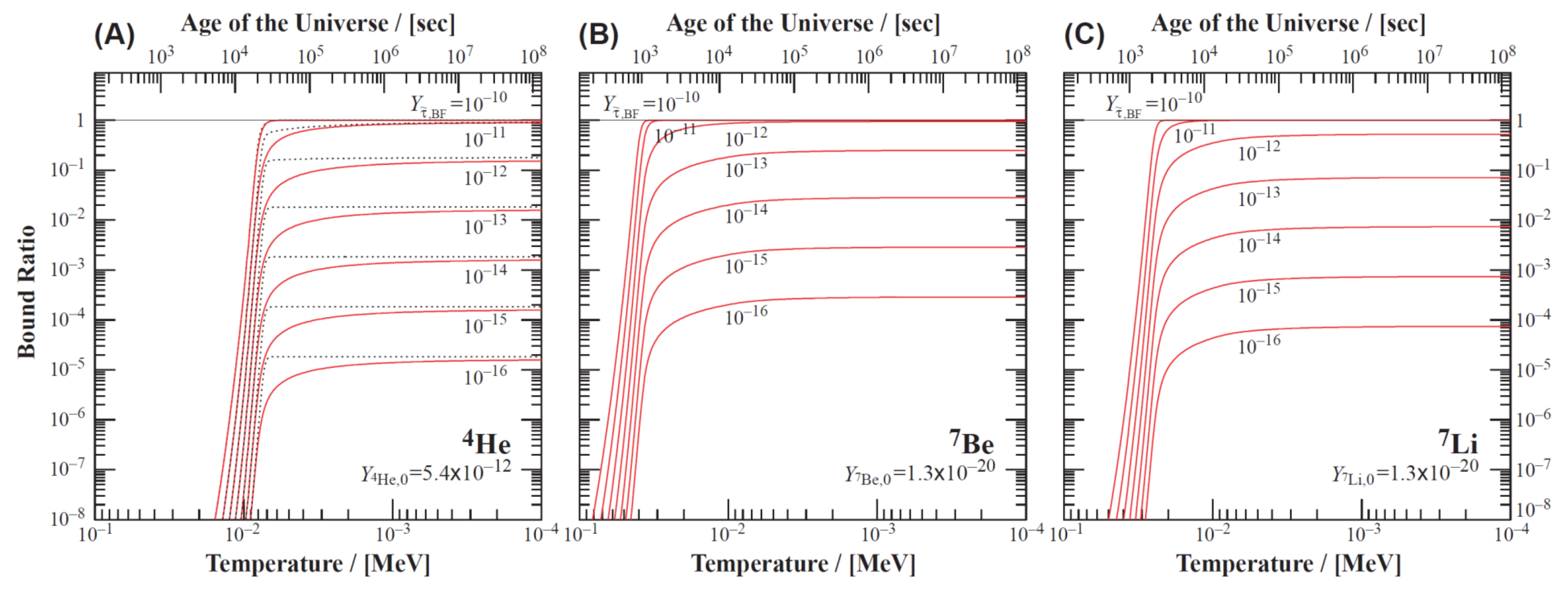
^{7}Li problem

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

P. Bonifacio, et al., Astronomy and Astrophysics, 462 (2007)

Solving the problem ⇔ Reducing ^{7}Li and ^{7}Be abundances

Formation rate of bound state



Internal conversion

[T. Jittoh, K. Kohri, M. Koike, J. Sato, T. Shimomura and MY, PRD76 (2007)]
[C. Bird, K. Koopmans and M. Pospelov, PRD78 (2008)]

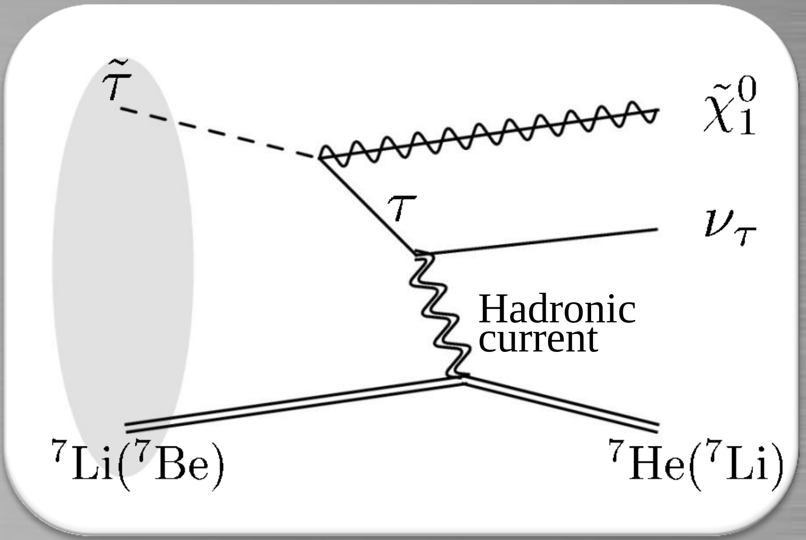
Bound state formation

$$\tilde{\tau}^- + {}^7\mathrm{Li}({}^7\mathrm{Be}) \rightarrow (\tilde{\tau}^- \, {}^7\mathrm{Li}({}^7\mathrm{Be}))$$

Internal conversion

$$(\tilde{\tau}^- \, {}^7\mathrm{Li}) \rightarrow \tilde{\chi}_1^0 + \nu_\tau + {}^7\mathrm{He}$$

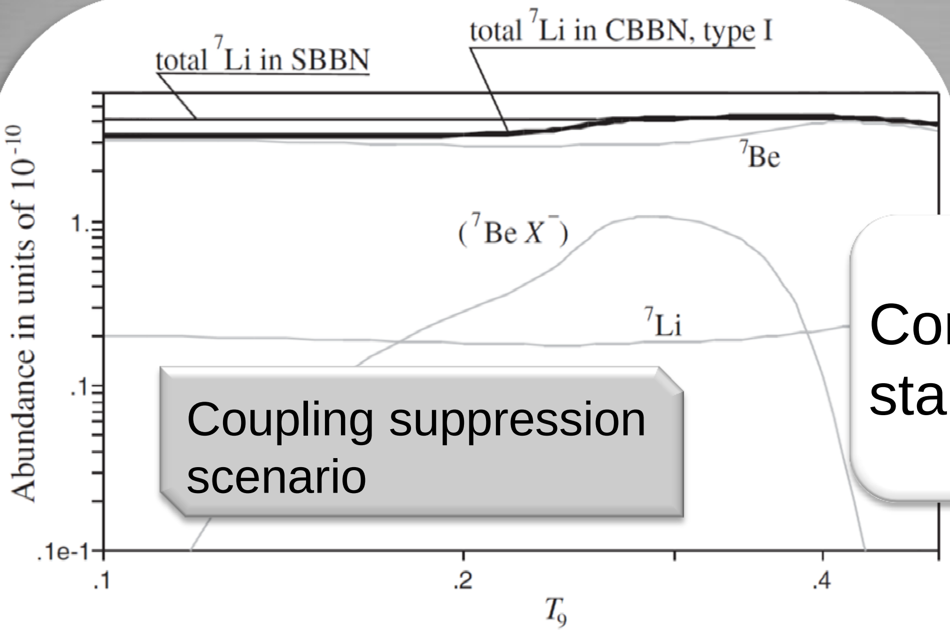
$$(\tilde{\tau}^- \, {}^7\mathrm{Be}) \rightarrow \tilde{\chi}_1^0 + \nu_\tau + {}^7\mathrm{Li}$$



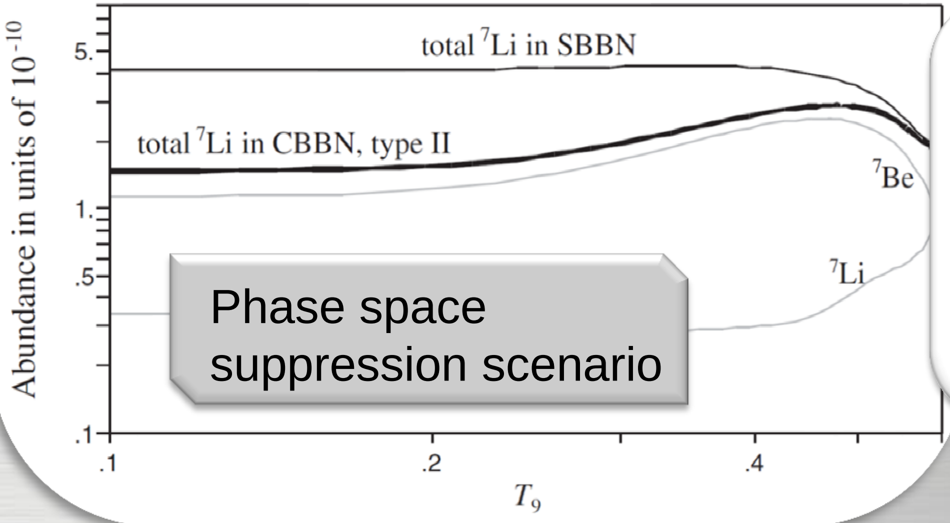
$$\frac{\text{Timescale of internal conversion}}{\text{Timescale of BBN era }(\sim 1\text{sec})} \ll 1$$

(∵ Overlap of initial state
wave functions
(c.f. electron capture))

Internal conversion



Coupling suppression scenario



Phase space suppression scenario

Constraint on the property of long-lived stau by evading over-destruction of ^{7}Li

Reducing ^{7}Li abundance compared with standard BBN

→ Solving the ^{7}Li problem

(In phase space suppression scenario)

[C. Bird, K. Koopmans and M. Pospelov, PRD78 (2008)]

Cosmologically Favored parameter space in MSSM

How to constrain the property of long-lived stau

Requirement in light of BBN

- Evading overproduction of d and t (^{4}He spallation process)
- Evading overproduction of ^{6}Li (catalyzed fusion)
- Solving the ^{7}Li problem (internal conversion)

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

Discrepancy between them

^{7}Li problem

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

How to constrain the property of long-lived stau

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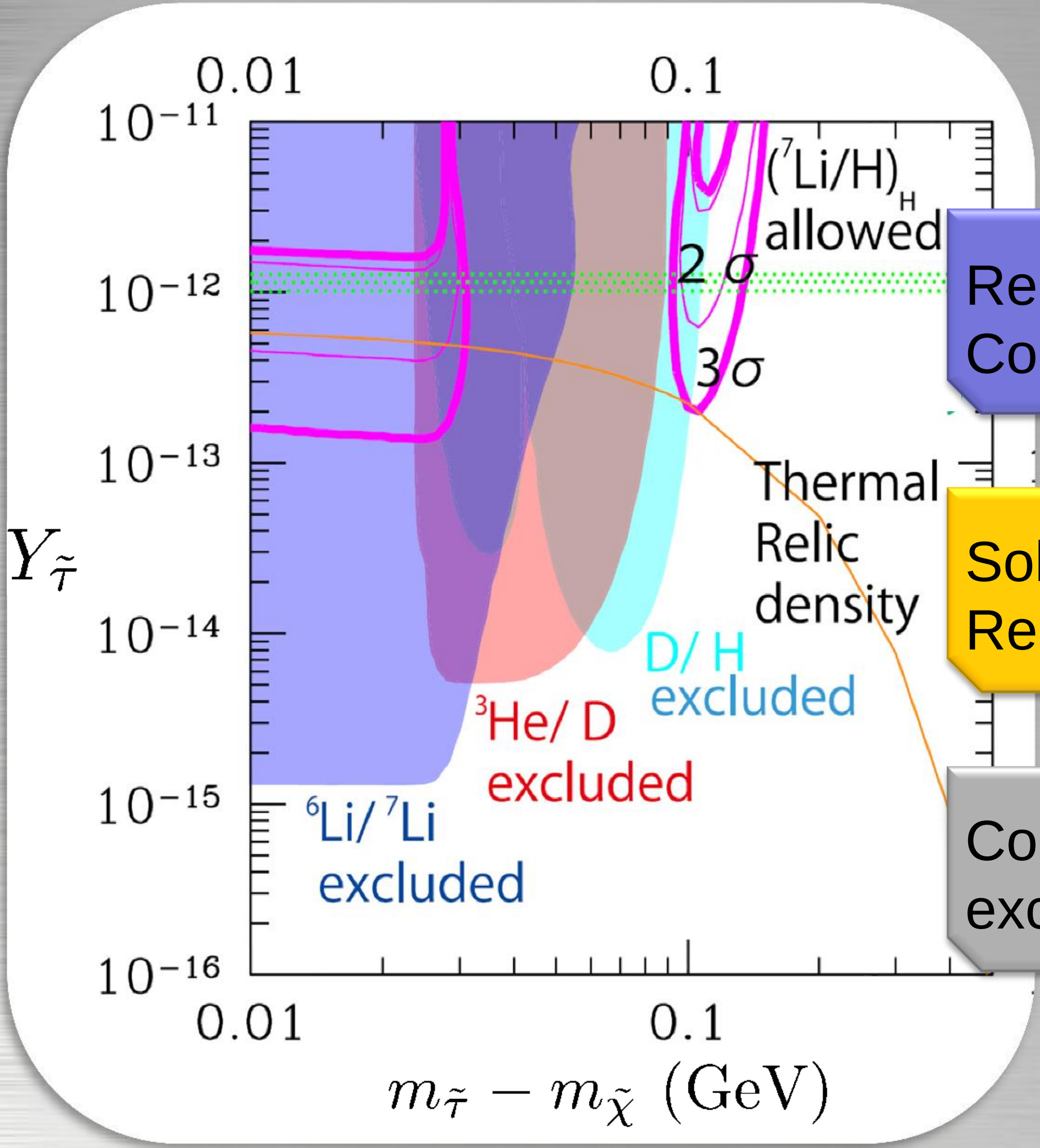
- Solving the ^{7}Li problem (internal conversion)

Requirement in light of dark matter

- Reproducing observed relic abundance of neutralino

Favored parameter space in MSSM

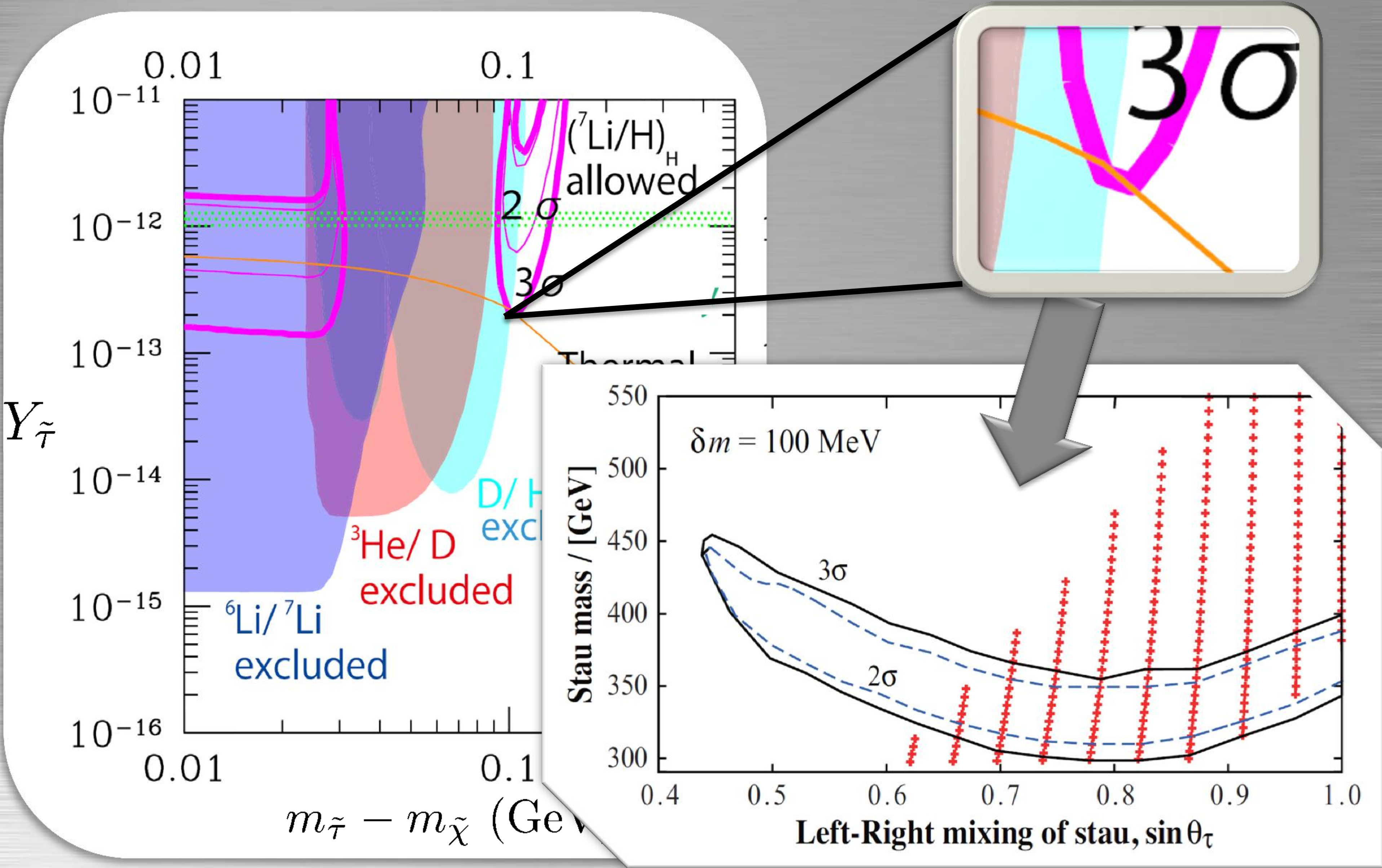


Region surrounded by purple line:
Consistent with observed ^{7}Li

Solid line (orange line):
Relic density of long-lived stau

Colored region:
excluded by over-production

Favored parameter space in MSSM

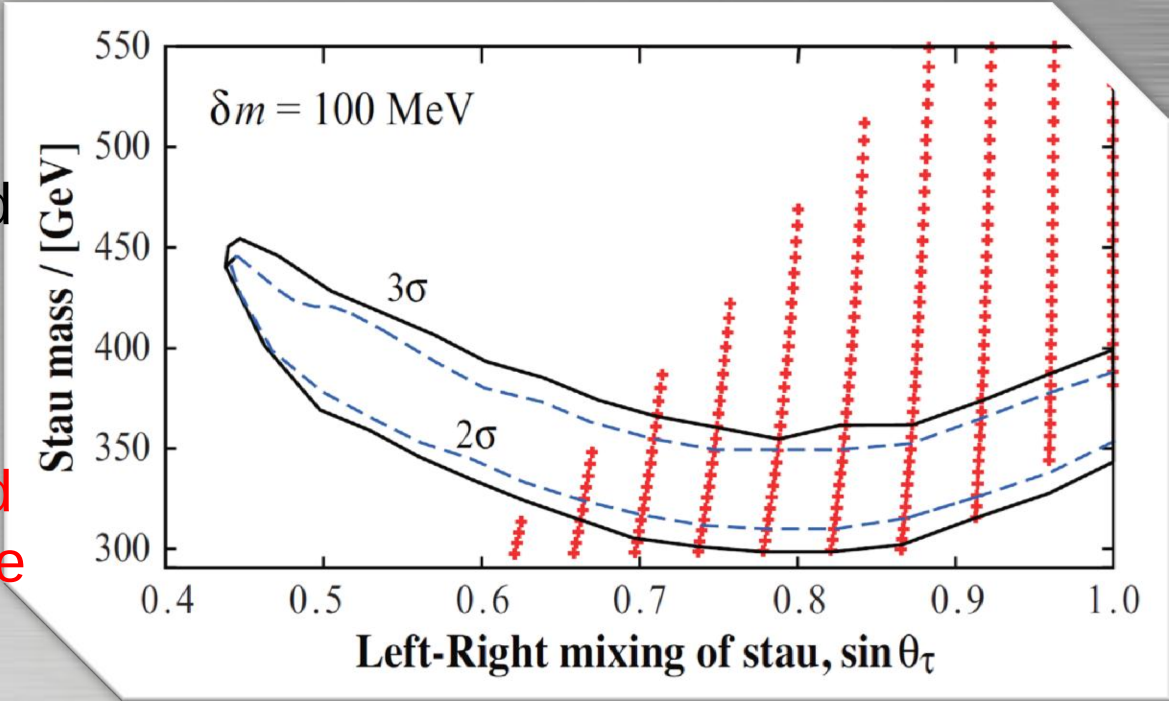


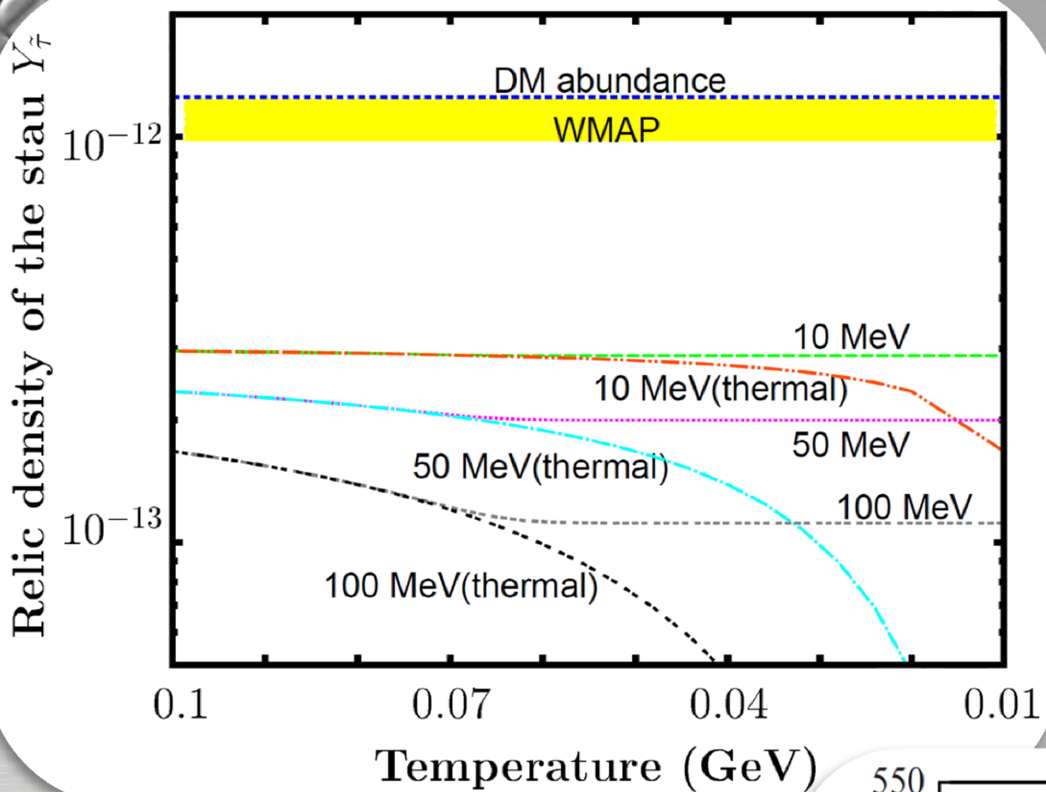
Prediction to observable from the physics of BBN and dark matter

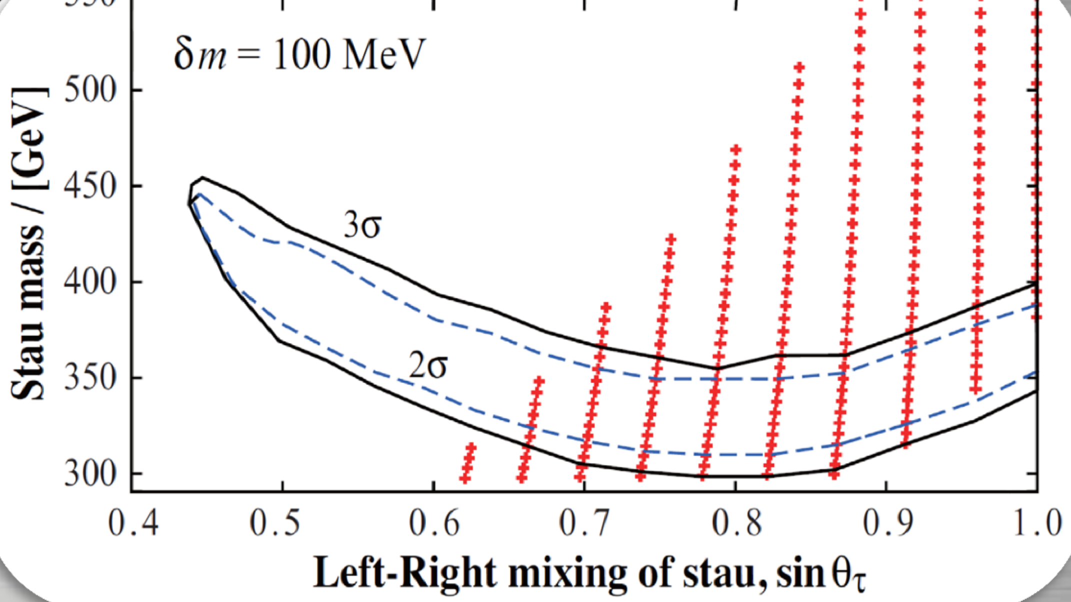
→ Complementary information for the test of MSSM in terrestrial experiments

Region in solid line:
Consistent with observed dark matter abundance

Red cross points:
Consistent with observed light elements abundance




Relic density of the stau $Y_{\tilde{\tau}}$
DM abundance
WMAP
10^{-12}
10^{-13}
10 MeV
10 MeV(thermal)
50 MeV
50 MeV(thermal)
100 MeV
100 MeV(thermal)
0.1
0.07
0.04
0.01
Temperature (GeV)


δm = 100 MeV
Stau mass / [GeV]
550
500
450
400
350
300
3σ
2σ
0.4
0.5
0.6
0.7
0.8
0.9
1.0
Left-Right mixing of stau, sin θ_τ

Candidate of long-lived CHAMP: NLSP stau in SUSY models

NLSP: Next Lightest SUSY particle

Scenarios predicting long-lived stau

- neutralino LSP scenario (phase space suppression)

  [S. Profumo, K. Sigurdson, P. Ullio and M. Kamionkowski, PRD71 (2005)]

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

- gravitino LSP scenario (Planck suppressed coupling)

  [W. Buchmuller, K. Hamaguchi, M. Ratz and T. Yanagida, PLB588 (2004)]

  [J. L. Feng, S. Su and F. Takayama, PRD70 (2004)]

- axino LSP scenario (loop suppression)

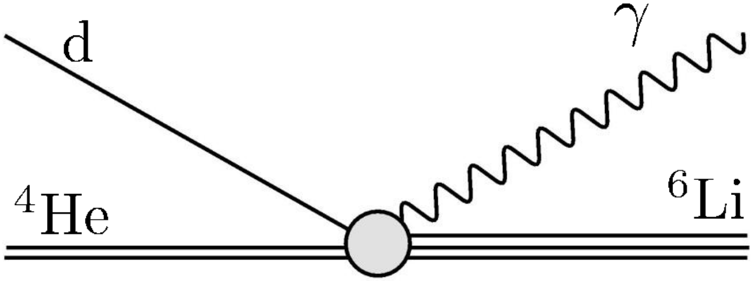
  [A. Freitas, F. D. Steffen, N. Tajuddin and D. Wyler, arXiv:1105.1113]

Catalyzed fusion

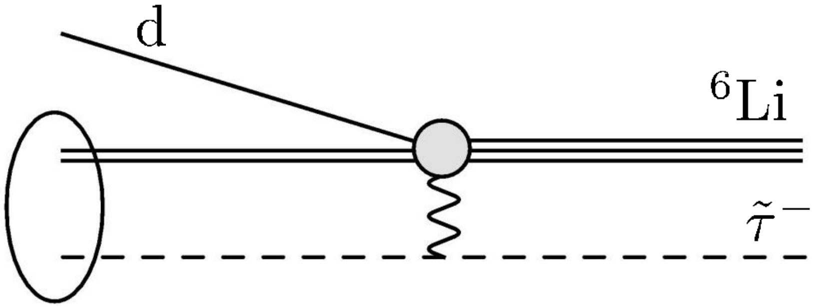
[M. Pospelov, PRL98]

Bound state formation via EM int. $\tilde{\tau} + {}^4\mathrm{He} \to (\tilde{\tau}^- \, {}^4\mathrm{He})$

Catalyzed fusion $(\tilde{\tau}^- \, {}^4\mathrm{He}) + \mathrm{d} \to {}^6\mathrm{Li} + \tilde{\tau}^-$



Standard BBN reaction



Catalyzed BBN reaction

$$\frac{\langle \sigma v \rangle_{\mathrm{catalyzed}}}{\langle \sigma v \rangle_{\mathrm{standard}}} \simeq 10^7$$

$\because$ Standard: forbidden E1 transition

Catalyzed: α transfer reaction