Long-lived CHAMPs

Masato Yamanaka

Long-lived charged massive particle

- ☑ Long-lived CHAMPs in many models beyond SM
- ☑ Various hunting
  (collider, neutrino telescope observations, etc)
- ☑ Cosmological constraints on its property
  (big-bang nucleosynthesis, large scale structure., etc)

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

Long-lived stau

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

NLSP: Next lightest SUSY particle

- ☑ Illustrative example in this talk

  (same phenomenology also for other long-lived CHAMPs)

- ☑ Three scenarios of long-lived stau
  - Gravitino dark matter scenario (coupling suppression)
  - Neutralino dark matter scenario (phase space suppression)
  - Axino dark matter scenario (loop suppression)

Long-lived stau

☑ Similar but different in appearance

	Neutralino scenario	Gravitino scenario
Why long-lived?	Phase space suppression	Coupling suppression
Typical signals	Missing E_T + heavy charged track	Heavy charged track ($\longrightarrow$ missing E_T + hard tau)
Signal with flavor violation	Variations of lifetime and lepton p distribution	Energetic e (or μ) with small BR
Cosmological effects	・Solving Li6 (Li7) problem ・Over-production of D	・Solving Li6 problem ・gravitino problem

Long-lived stau

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Cosmological effects	・Solving Li6 ・Over-produ	

Necessary to have correct pictures of these signals and effects in each case for precise understanding of the stau

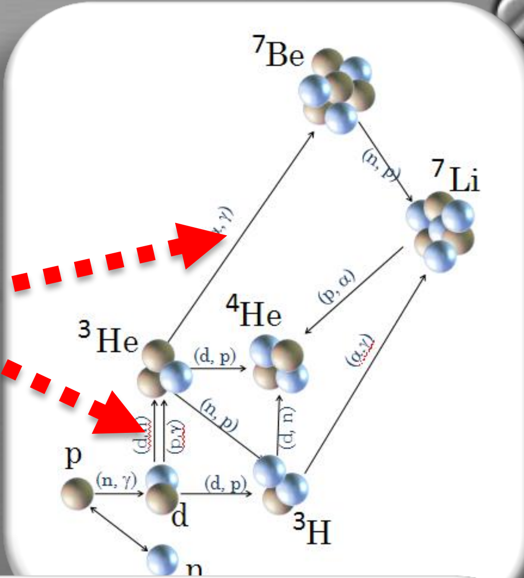
Outline

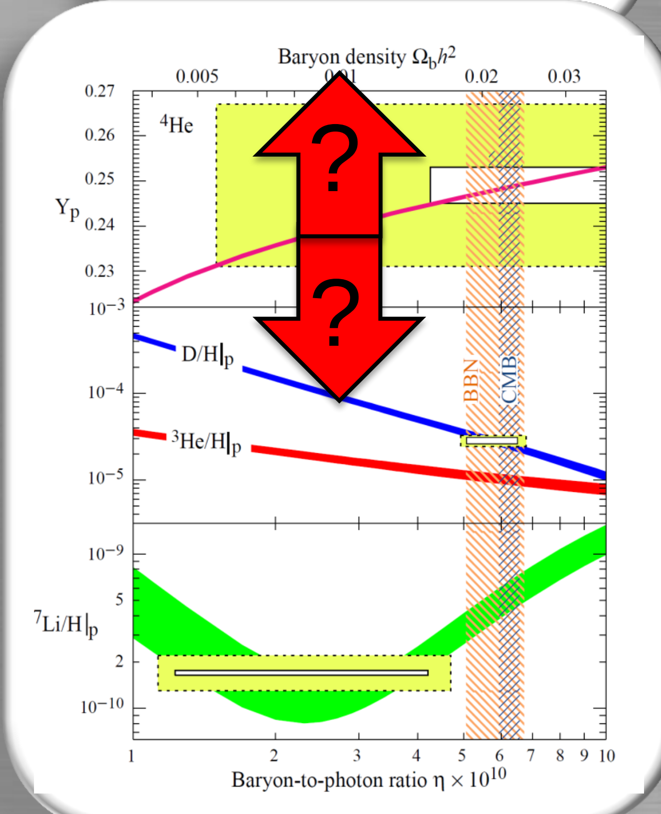
- Long-lived CHAMP in BBN
  - Energetic decay
  - Exotic nuclear reaction by bound state
- Long-lived CHAMP at collider
  - Flavor conserved stau
  - Flavor violating stau
- Summary

Long-lived CHAMP in big-bang nucleosynthesis (BBN)

Various effects on BBN

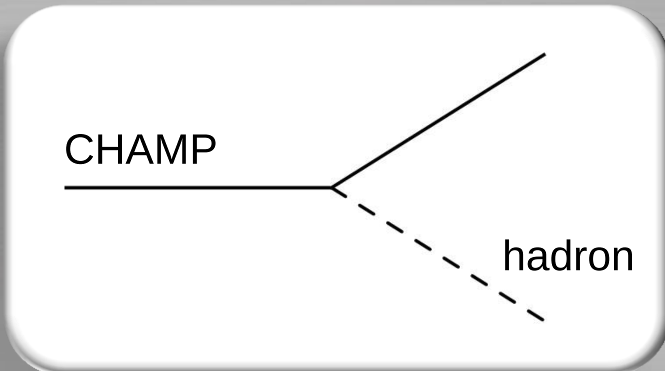
Exotic interactions

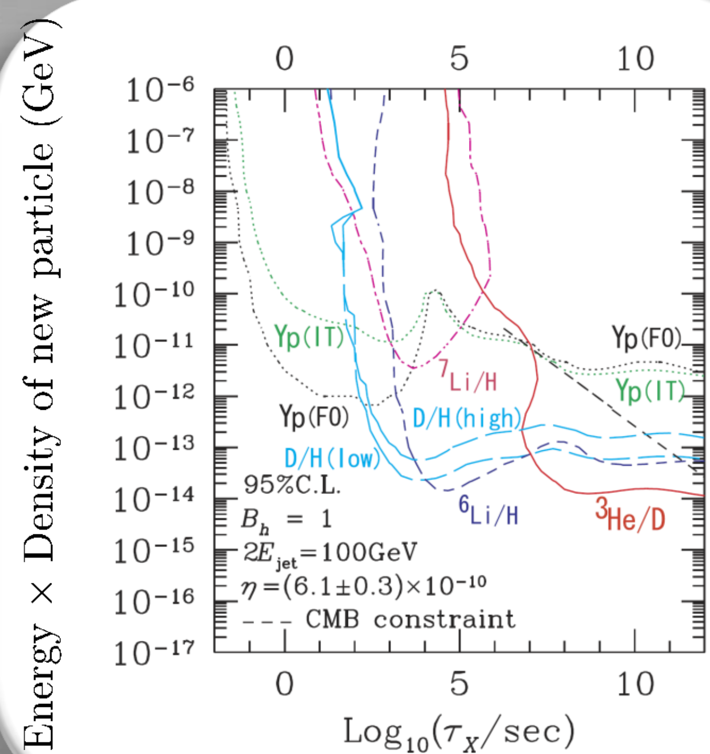




- ☑ Over-production (-destruction) of light elements by long-lived CHAMPs
- ☑ Good accuracy of observations and calculations of light elements densities
- ☑ BBN is good prove to long-lived CHAMPs

Ex. 1: hadronic energy injection





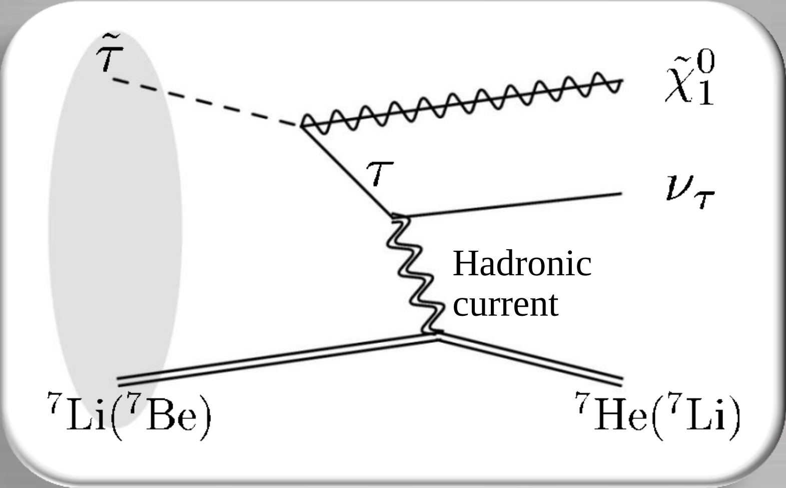
☑ Over-production (-destruction) of light elements by decay products

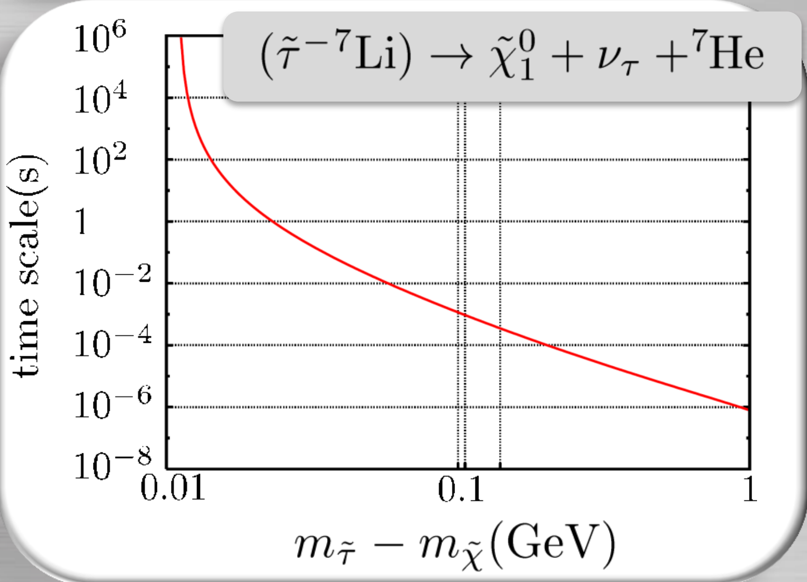
☑ Lifetime of hadronic decay and hadronic energy are constrained

[M. Kawasaki, K. Kohri and T. Moroi (2005)]

Ex. 2: internal conversion process

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





- ☑ Bound state formation of nucleus and negative charged stau
- ☑ Nuclear transformation in the bound state of nucleus and stau
  (cf. muon capture)
- ☑ Solving the ^{7}Li problem by rapid reduction of ^{7}Li and ^{7}Be

Discrepancy between calc. and obs.

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

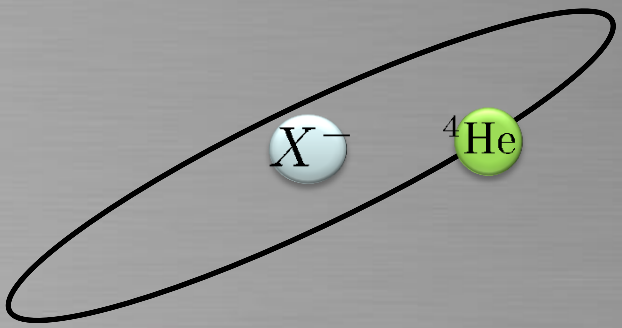
Obs. $^7\mathrm{Li/H} = (1.26^{+0.29}_{-0.24}) \times 10^{-10}$

Ex. 3: catalyzed fusion process

[M. Pospelov, PRL98]

- Catalyzed fusion by the bound state of CHAMP (X^-) and ^{4}He

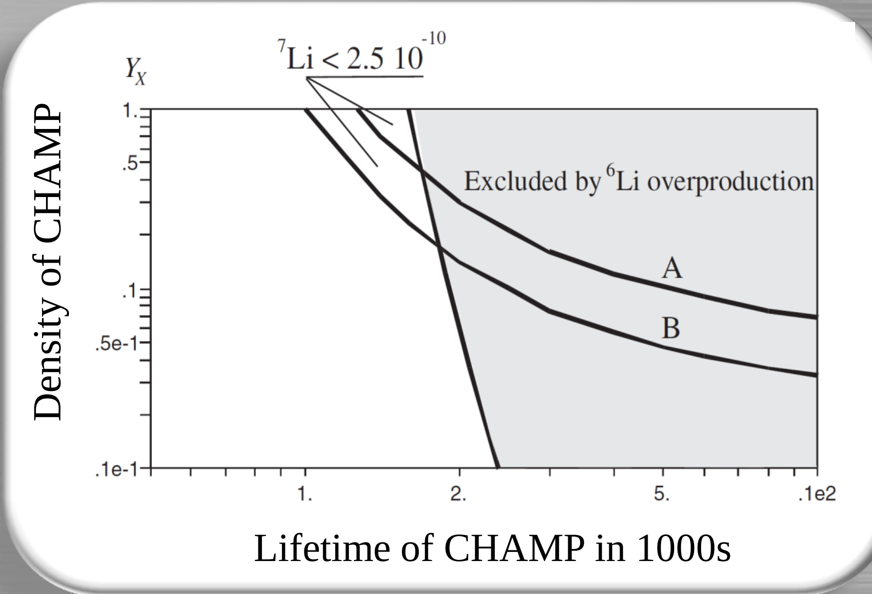
$$(^4\mathrm{He}\,\mathrm{X}^-) + \mathrm{d} \to {}^6\mathrm{Li} + \mathrm{X}^-$$



- Solving the ^{6}Li problem by enhancements of ^{6}Li production

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

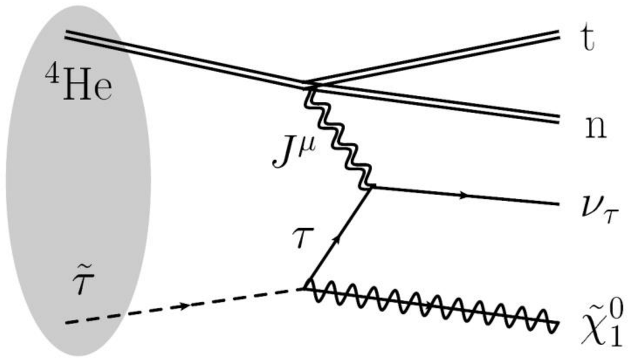
- Note: valid constraint only on gravitino dark matter scenario



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

Ex. 4: spallation process

[T. Jittoh, K. Kohri, M. Koike, J. Sato, K. Sugai, MY, and K. Yazaki (2011)]

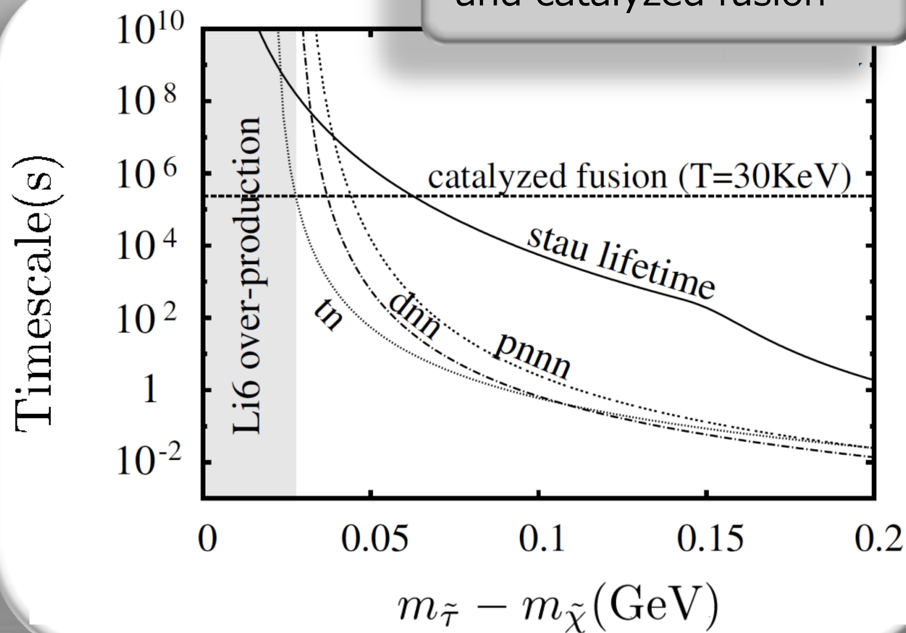


- ☑ Spallation of He nucleus in the bound state, producing triton, deutron, and neutron

- ☑ Larger reaction rate than catalyzed fusion

- ☑ More stringent constraint to avoid over-production of deuteron

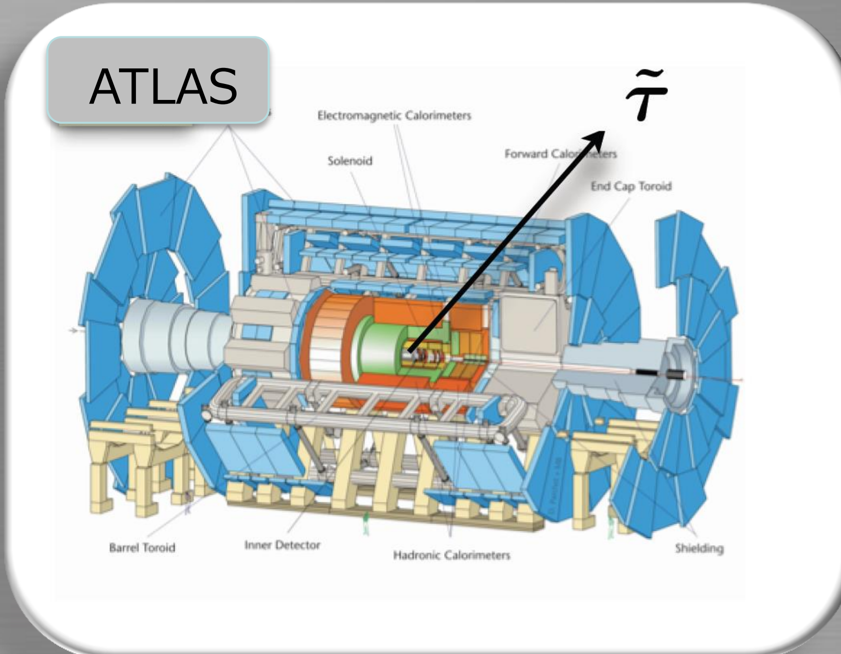
Timescale of spallation and catalyzed fusion

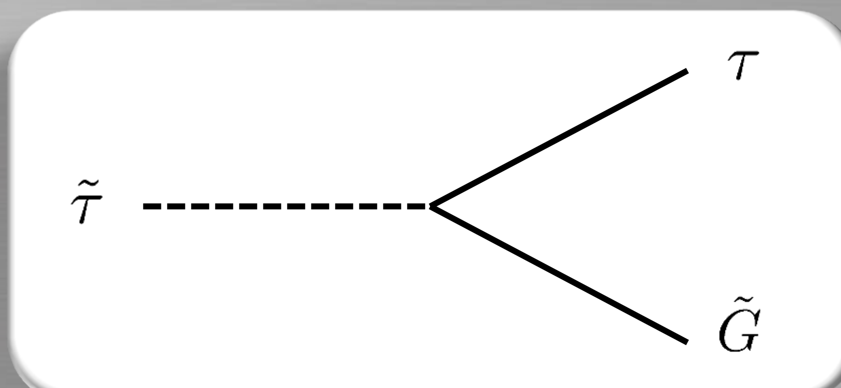


Long-lived CHAMP at collider

Signal in gravitino DM scenario

- ☑ Signal
  - Heavy charged track
  - (Energetic tau + missing energy)
- ☑ Information from signals
  - Stau mass
  - SUSY breaking scale
- ☑ With flavor violation
  - No variation of stau lifetime
  - (Energetic e (or μ) with small BR)





Signal in neutralino DM scenario

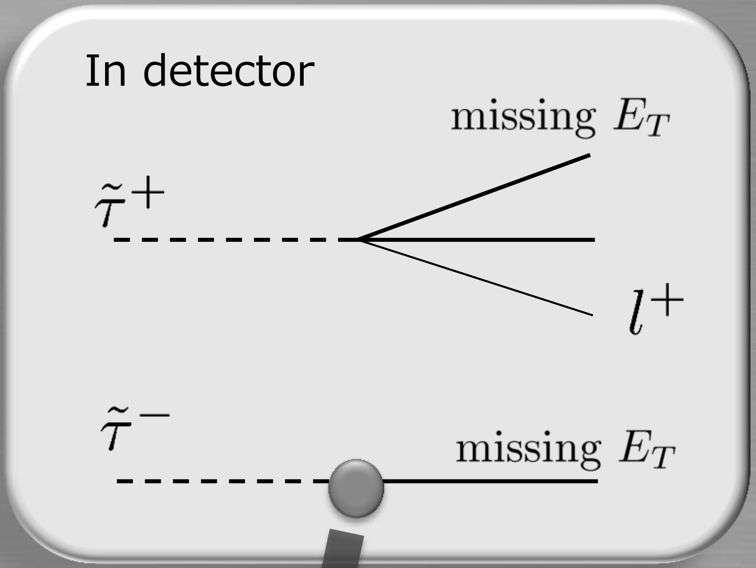
(flavor consrving)

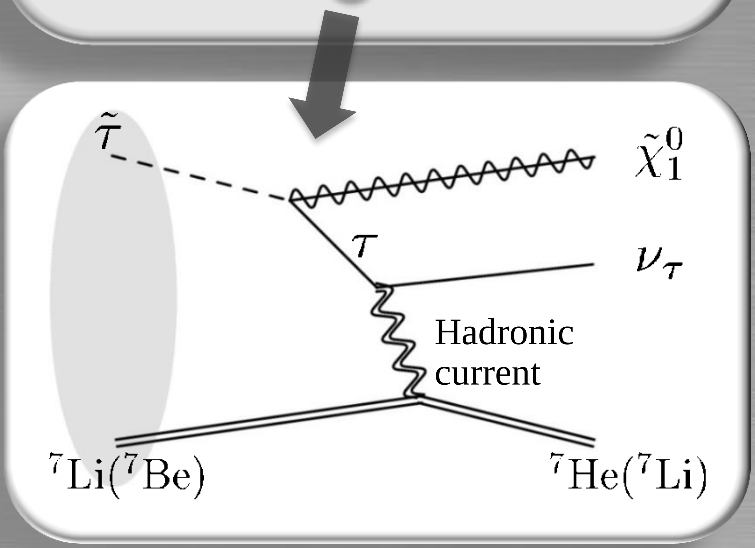
- ☑ Bound state formation of negative charged stau and material in detector
- ☑ Internal conversion before particle decay

  [cf. muon capture process]
- ☑ Signal: missing E_T + positive track

  No negative charged track!
- ☑ Necessary to carefully search the signal to avoid misidentification

  [Now preparing to submit]





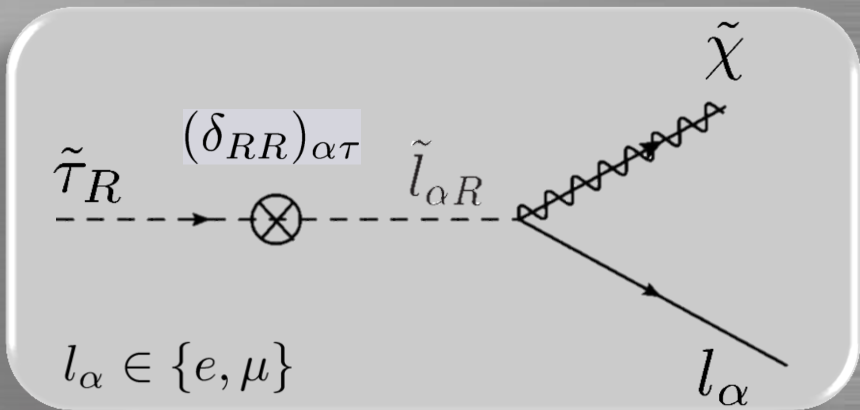
Signal in neutralino DM scenario

(flavor violating)

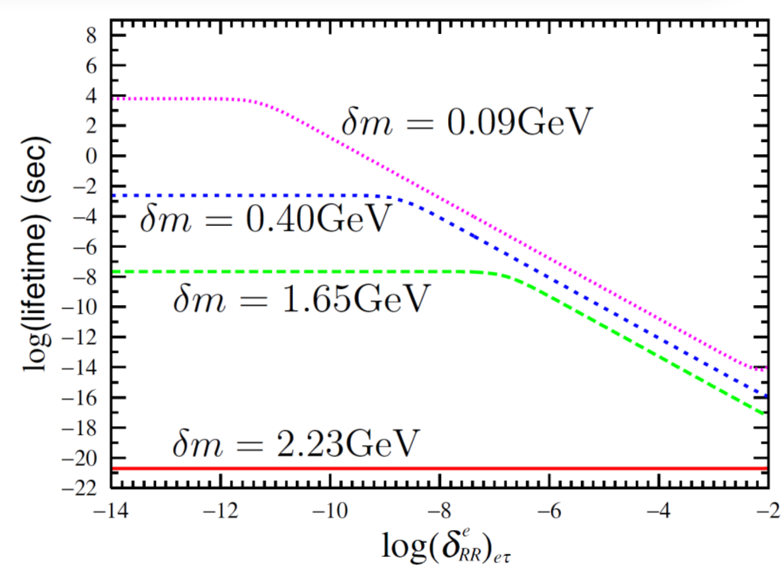
$\tilde{\tau} \to \tilde{\chi}\tau$

$\tilde{\tau} \to \tilde{\chi}\mu$

$\tilde{\tau} \to \tilde{\chi}e$



- ☑ New 2-body decay channel via flavor violation
- ☑ Determination of flavor violating para. as a function of stau lifetime
- ☑ More sensitive to tiny violation than rare decay search experiments



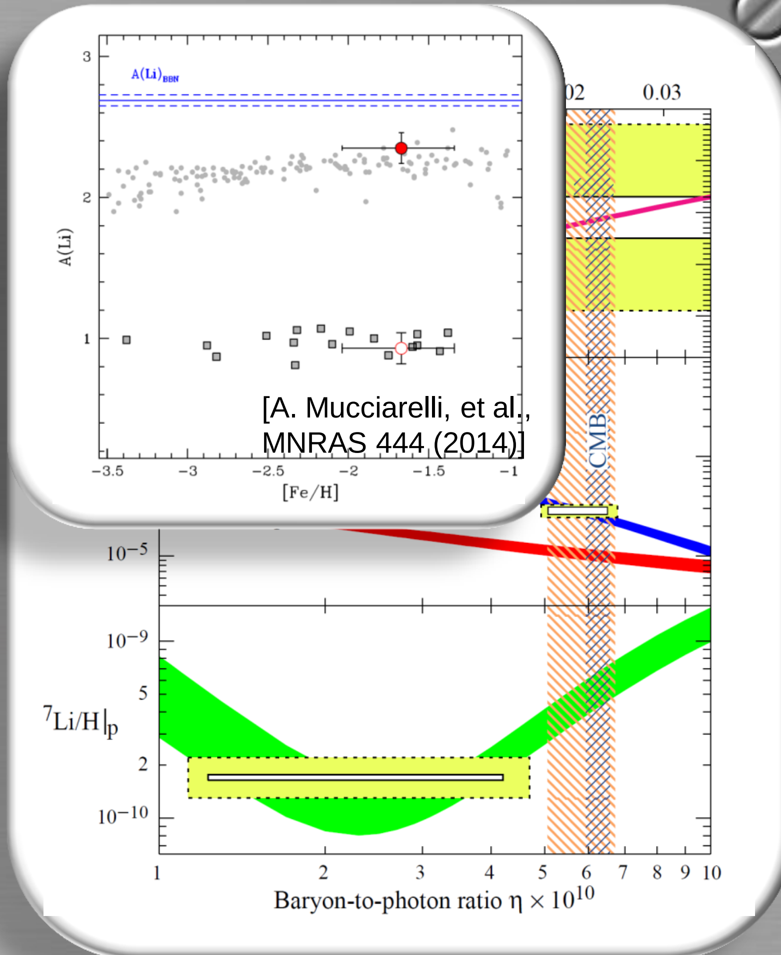
[S. Kaneko, J. Sato, T. Shimomura, O. Vives, MY (2008)]

Summary

- ☑ Long-lived charged massive particles in many models beyond SM
- ☑ Important for comprehension of long-lived CHAMPs and each model
  - to identify what exotic reactions are induced by each type of CHAMP
  - to understand what light elements are over-produced (-destructed) by each type of reactions
- ☑ Necessary for detecting CHAMP signal at collider to arrange depending on
  - the reason of longevity
  - the flavor is conserving or violating

Backup slides

^{7}Li problem



- ☑ Prediction

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

- ☑ Observation

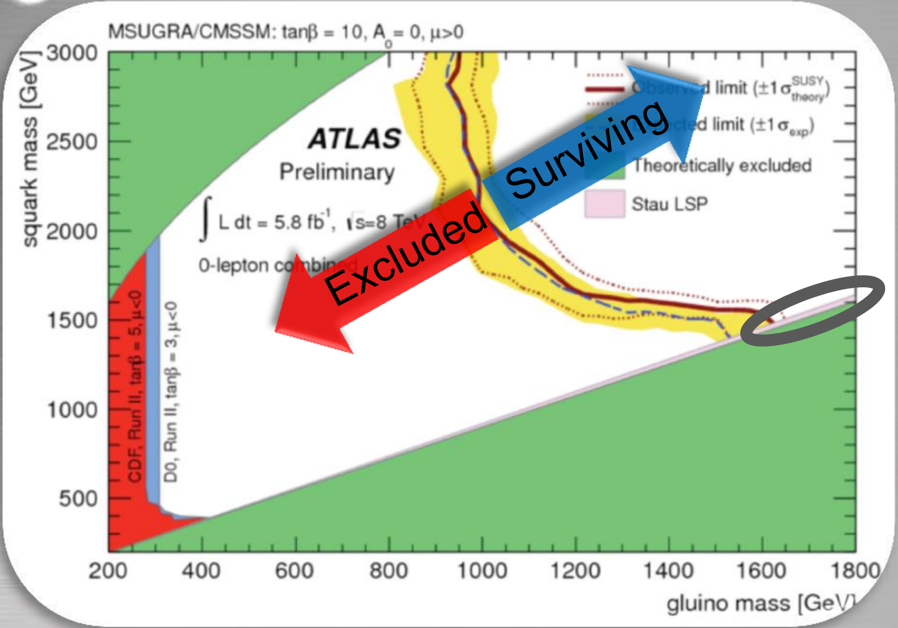
$$^7\mathrm{Li/H} = (1.26^{+0.29}_{-0.24}) \times 10^{-10}$$

- ☑ 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

Long-lived stau in CMSSM

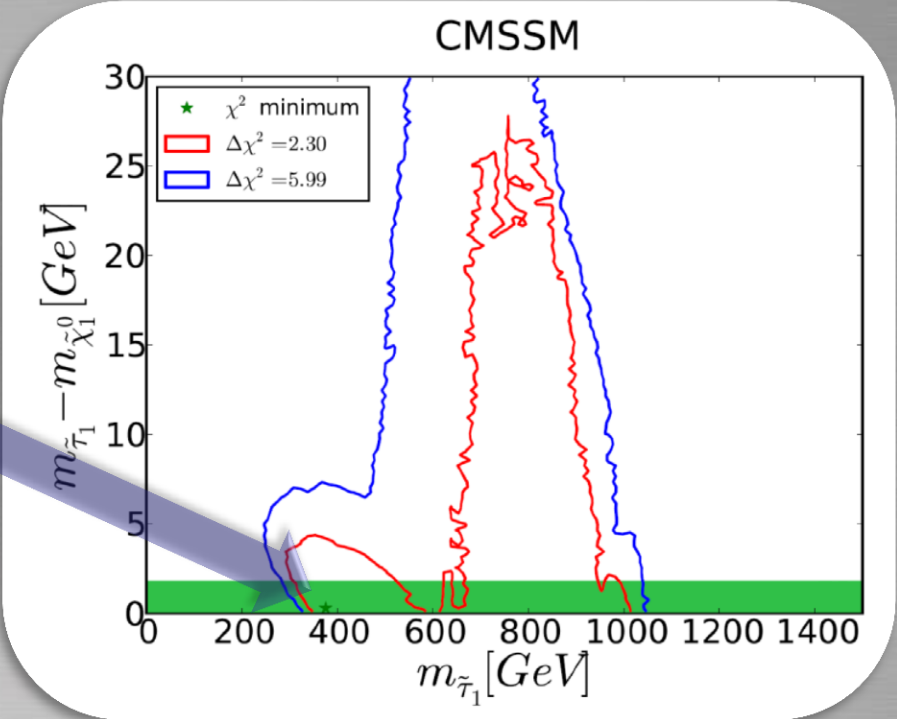


☑ Consistent with DM abundance

☑ DM and stau are degenerated

☑ Point favored from Higgs mass, DM physics, and so on

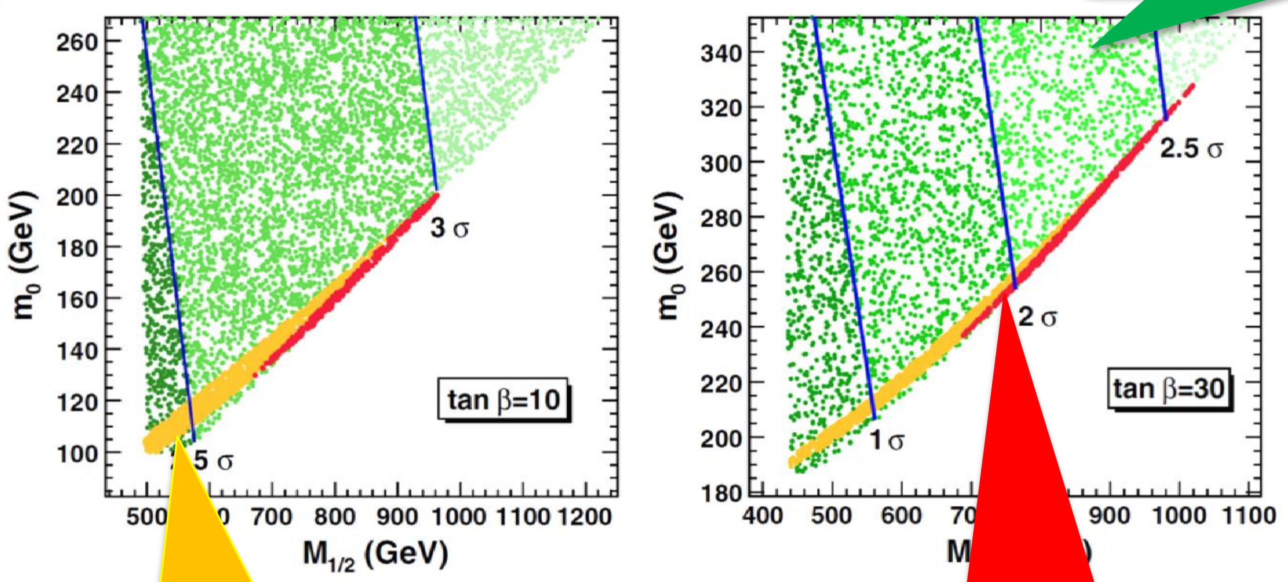
☑ Requirement: $\delta m < m_\tau$



[M. Citron, J. Ellis, F. Luo, J. Marrouche, K. Olive and K. de Vries (2013)]

Coannihilation region

暗黒物質残存量の
観測値出せず



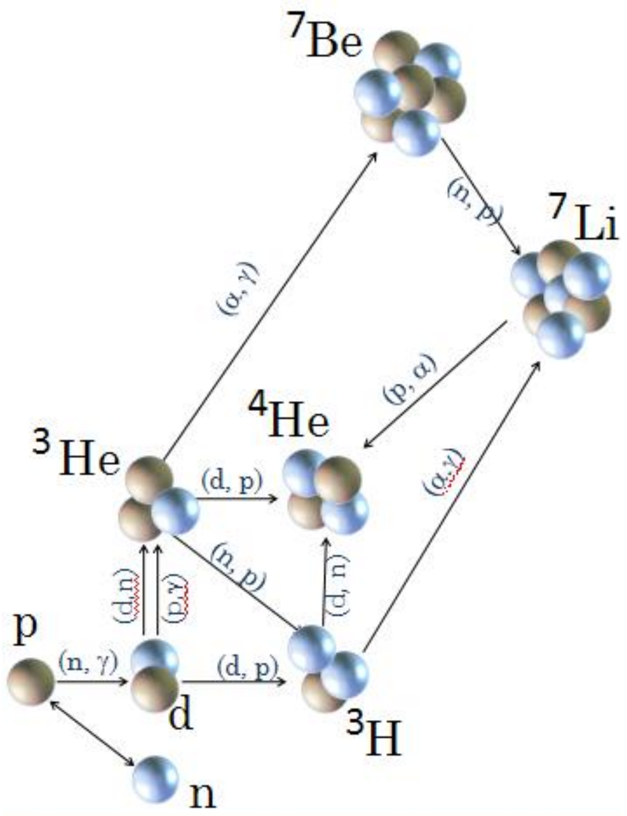
- ☑ Coannihilation region をズームアップ
- ☑ ポイントをランダムに振ってチェック
- ☑ 許容領域の大部分で $\delta m < m_\tau$

- ☑ 暗黒物質残存量OK
- ☑ $\delta r \ > m_\tau$

- ☑ 暗黒物質残存量OK
- ☑ $\delta m < m_\tau$

$\delta m = m_{\tilde{\tau}_R} - m_{\tilde{\chi}}$: ダークマターとスタウの質量差

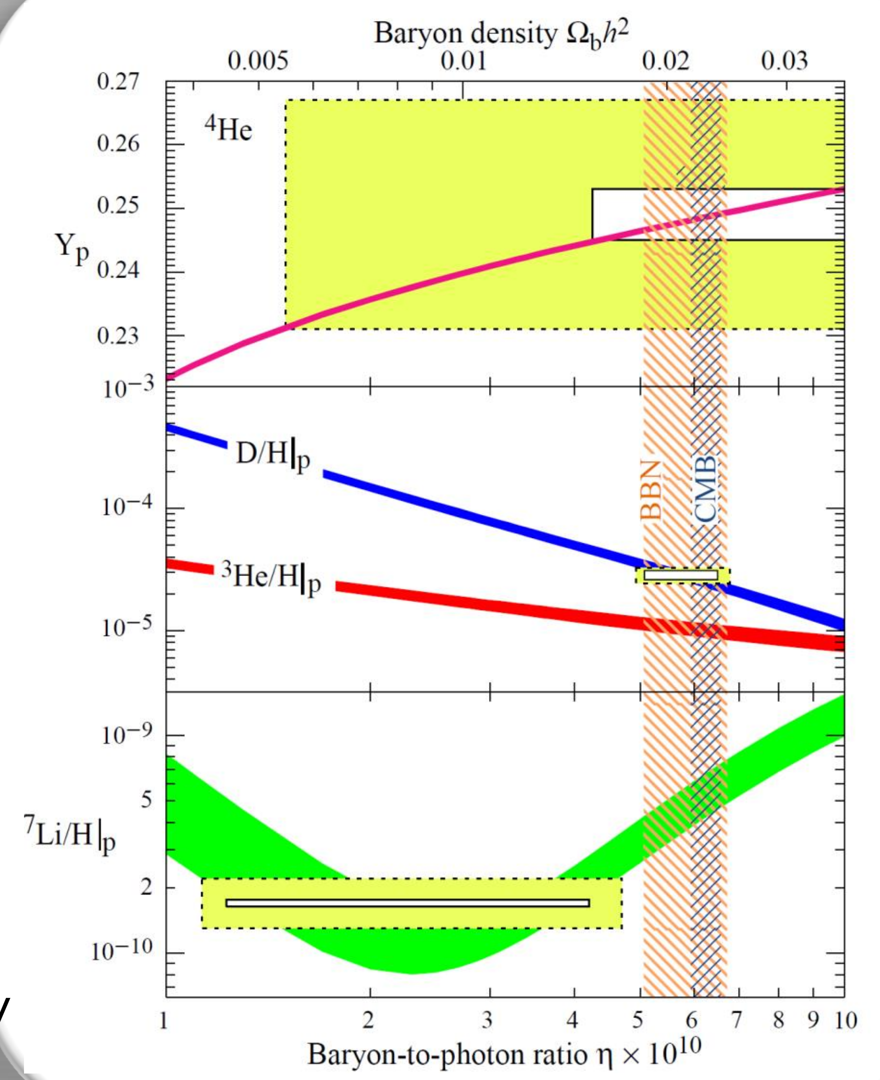
Big-bang nucleosynthesis (BBN)



- ☑ Production of light elements
- ☑ Era: 1sec - 3min
- ☑ Parameter: baryon density
  - Densities of p and n
  - Ratio of p and n
- ☑ Input: reaction rates of nuclei

Big-bang nucleosynthesis (BBN)

- ☑ Light elements densities are predicted for a baryon density
- ☑ Evidence for the success of the big-bang theory



Curve: theoretical prediction

Box: observation

Vertical band: observed baryon density

[PDG2012]

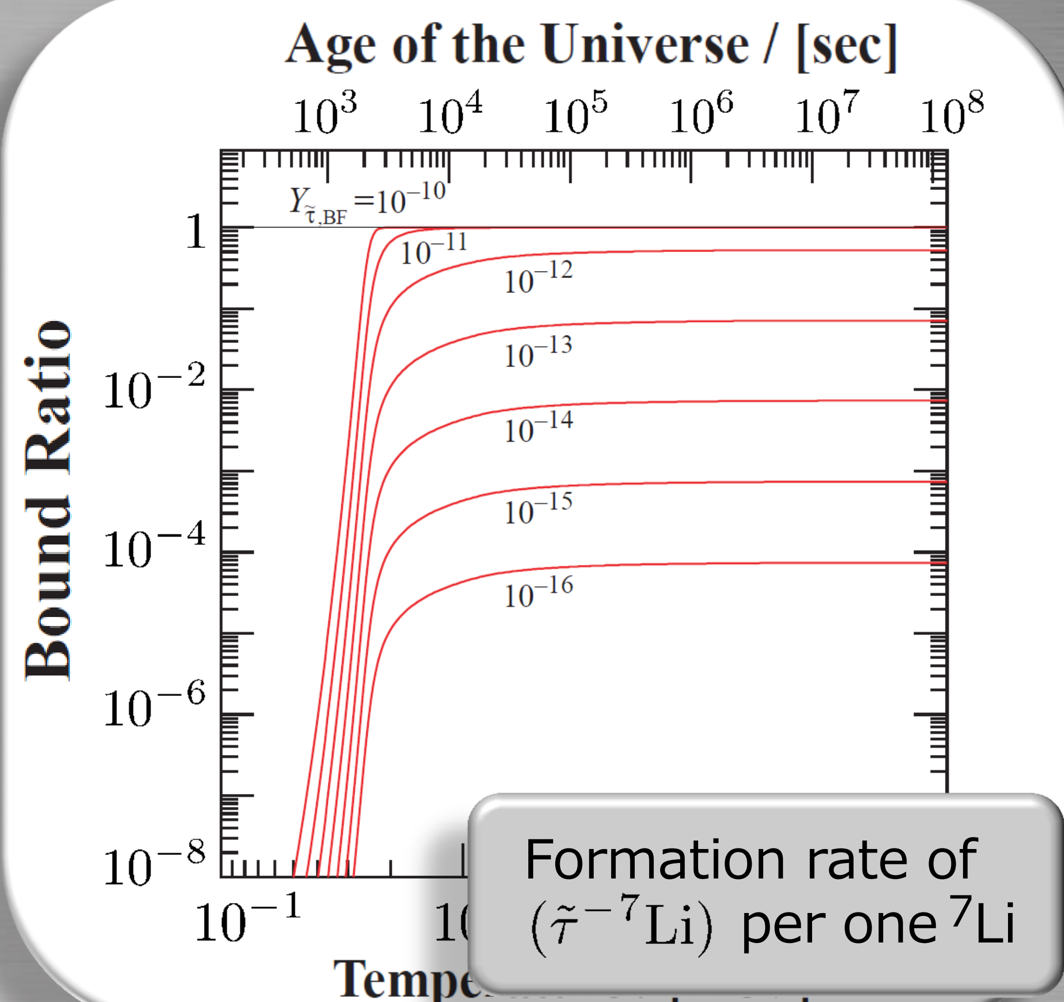
Required lifetime and density

- ☑ Required lifetime to form the bound state?

$$\text{Lifetime} \gtrsim 1000(\text{s})$$

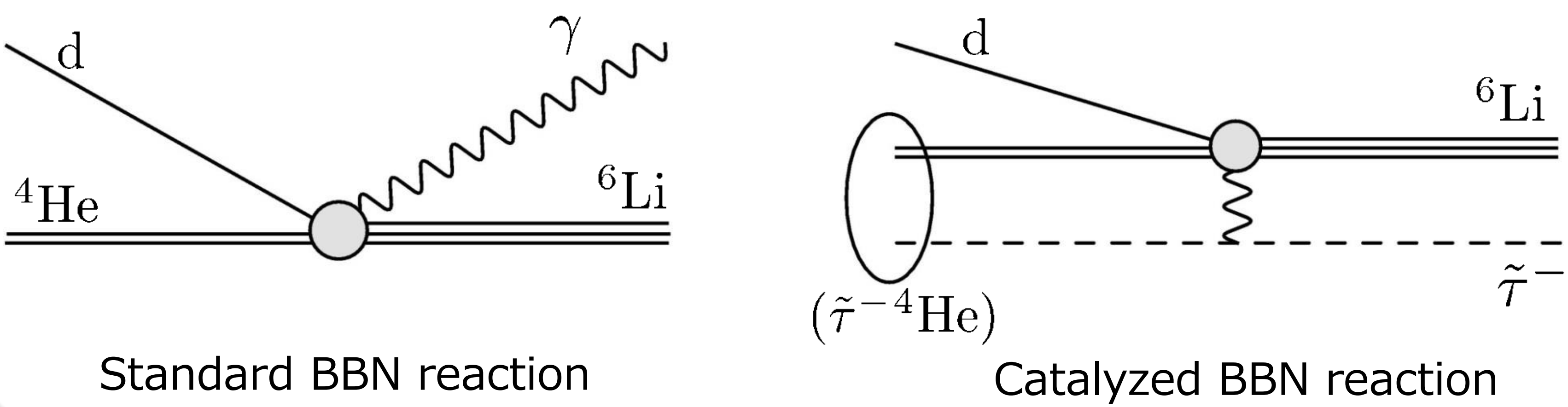
- ☑ Required density is to sufficiently reduce ^{7}Li?

$$Y_{\tilde{\tau}} \gtrsim 2 \times 10^{-12}$$



Formation rate of $(\tilde{\tau}^{-7}\mathrm{Li})$ per one ^{7}Li

Catalyzed fusion



- ☑ Exotic reaction induced by the bound state $(\tilde{\tau}^{-\,4}\mathrm{He})$
- ☑ ^{6}Li over-production

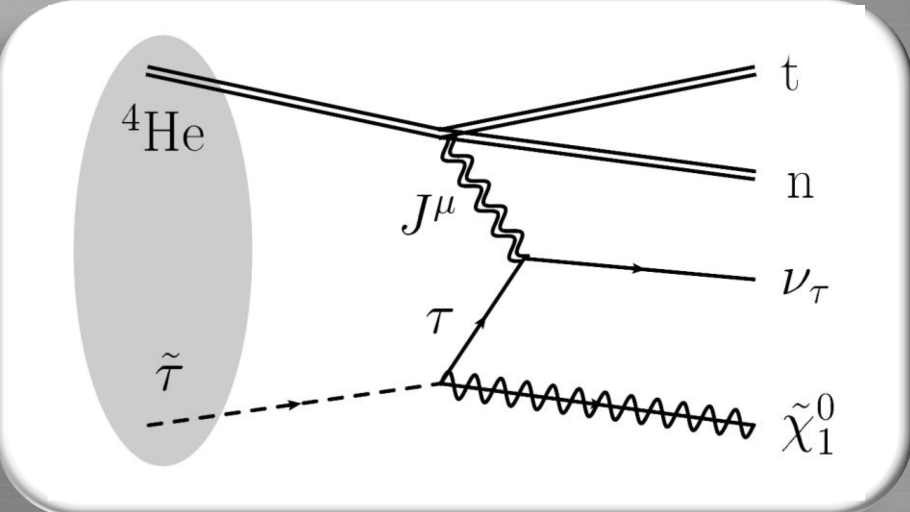
$$\frac{\langle \sigma v \rangle_{\mathrm{catalyzed}}}{\langle \sigma v \rangle_{\mathrm{standard}}} \simeq 10^7$$

(∵ Standard: forbidden E1 transition
Catalyzed: α transfer reaction)

Spallation process

[T. Jittoh, K. Kohri, M. Koike, J. Sato, K. Sugai, K. Yazaki, and MY, PRD84 (2011)]

- ☑ Origin of stau's longevity: phase space suppression
- ☑ Spallation process after forming a bound state



Overlap of initial state wave function

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

Cross section of elemental reaction

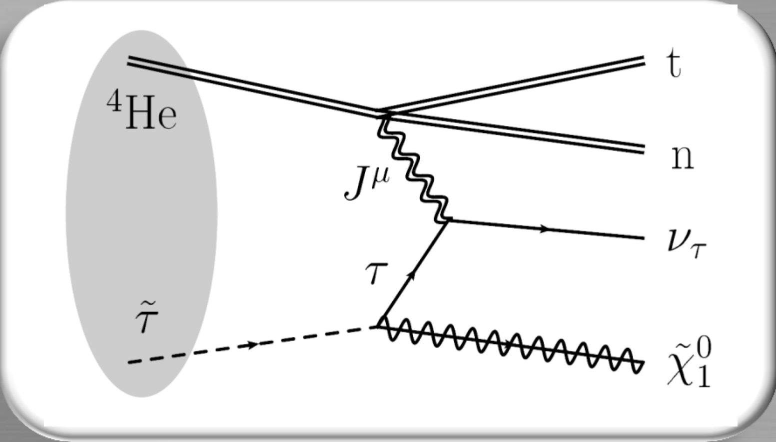
Cross section of elemental reaction

- ☑ Cross section of elemental reaction

$$\sigma v_{\rm tn} = \frac{1}{2E_{\tilde\tau}} \int \frac{d^3\boldsymbol{p}_\nu}{(2\pi)^3 2E_\nu} \frac{d^3\boldsymbol{p}_{\tilde\chi}}{(2\pi)^3 2E_{\tilde\chi}} \frac{d^3\boldsymbol{q}_{\rm n}}{(2\pi)^3} \frac{d^3\boldsymbol{q}_{\rm t}}{(2\pi)^3}$$
$$\times \left|\mathcal{M}\left((\tilde\tau^4{\rm He}) \to \tilde\chi_1^0 \nu_\tau {\rm tn}\right)\right|^2 (2\pi)^4 \delta^{(4)}(p_{\tilde\tau} + p_{\rm He} - p_\nu - q_{\rm t} - q_{\rm n})$$

- ☑ Amplitude

$$\mathcal{M}\left((\tilde\tau^4{\rm He}) \to \tilde\chi_1^0 \nu_\tau {\rm tn}\right)$$
$$= \langle {\rm t\,n}\,\tilde\chi_1^0\,\nu_\tau|\mathcal{L}_{\rm int}|^4{\rm He}\,\tilde\tau\rangle$$
$$= \langle {\rm t\,n}|J^\mu|^4{\rm He}\rangle\ \langle\tilde\chi_1^0\,\nu_\tau|j_\mu|\tilde\tau\rangle$$



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)

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

spatial part
(symmetric)

$$\psi_{\mathrm{He}}(\boldsymbol{r}_1,\boldsymbol{r}_2,\boldsymbol{r}_3,\boldsymbol{r}_4) = \left(2\frac{a_{\mathrm{He}}^3}{\pi^3}\right)^{3/4}$$
$$\times \exp\left\{-a_{\mathrm{He}}\left[\boldsymbol{r}_1^2+\boldsymbol{r}_2^2+\boldsymbol{r}_3^2+\boldsymbol{r}_4^2-\frac{1}{4}(\boldsymbol{r}_1+\boldsymbol{r}_2+\boldsymbol{r}_3+\boldsymbol{r}_4)^2\right]\right\}$$

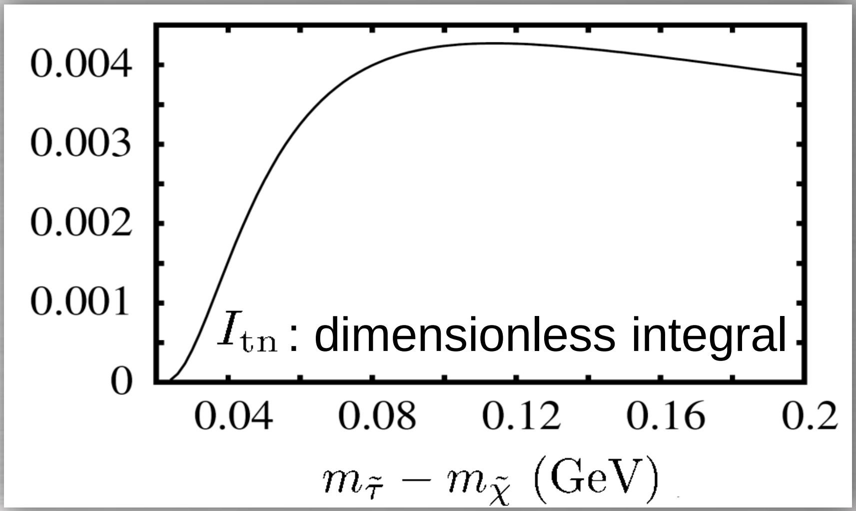
$$a_{\mathrm{He}} = \frac{9}{16}\frac{1}{(R_{\mathrm{m}})^2_{\mathrm{He}}},\ a_{\mathrm{t}} = \frac{1}{2}\frac{1}{(R_{\mathrm{m}})^2_{\mathrm{t}}} \quad (R_{\mathrm{m}}:\text{matter radius})$$

Cross section

Cross section of elemental reaction

$$\sigma v_{\mathrm{tn}} = \frac{8}{\pi^2}\left(\frac{32}{3\pi}\right)^{3/2} g^2 \tan^2\theta_W \sin^2\theta_\tau (1+3g_A^2) G_F^2$$

$$\times\, \Delta_{\mathrm{tn}}^4\, \frac{m_{\mathrm{t}} m_{\mathrm{n}}}{m_{\tilde{\tau}} m_\tau^2}\, \frac{a_{\mathrm{He}}^{3/2} a_{\mathrm{t}}^3}{(a_{\mathrm{He}}+a_{\mathrm{t}})^5}\, I_{\mathrm{tn}}$$



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

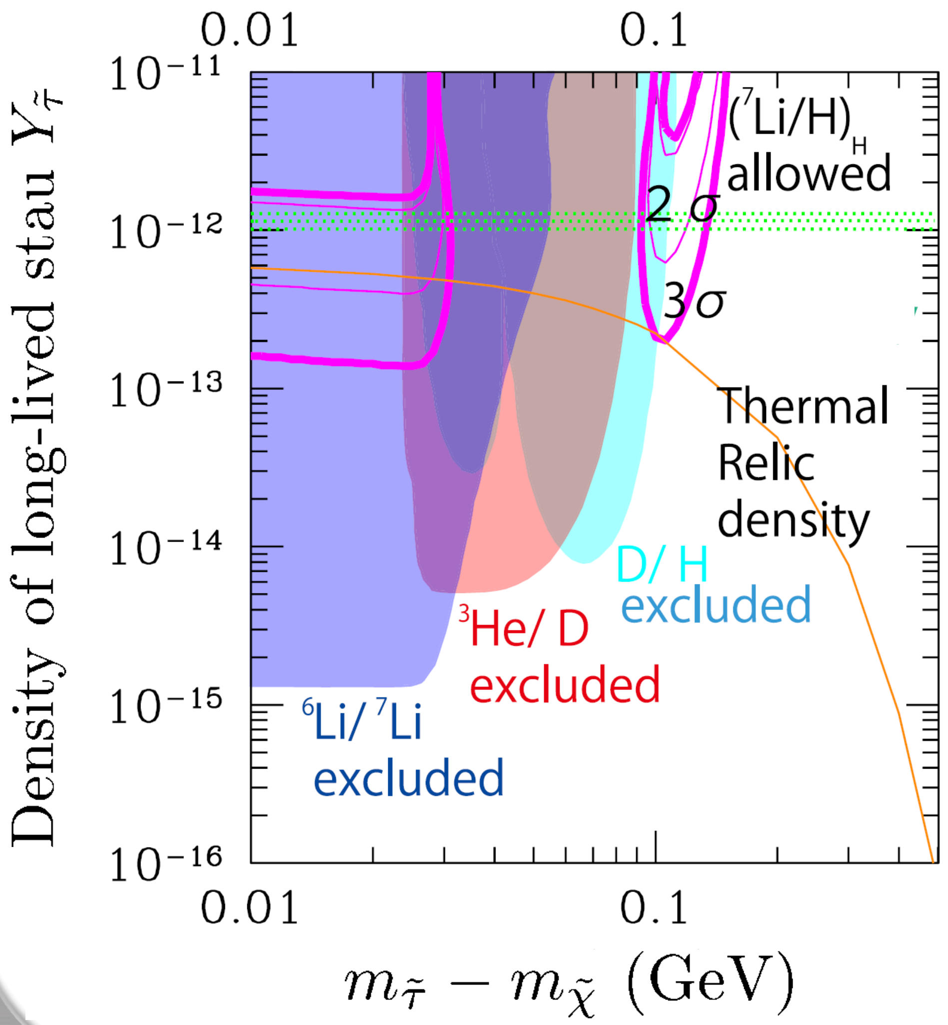
$$\Delta_{\mathrm{He}} = m_{\mathrm{He}} - 4A,$$

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

$$\Delta_{\mathrm{n}} = m_{\mathrm{n}} - A$$

A : Unified atomic mass unit

Prediction of property of the stau

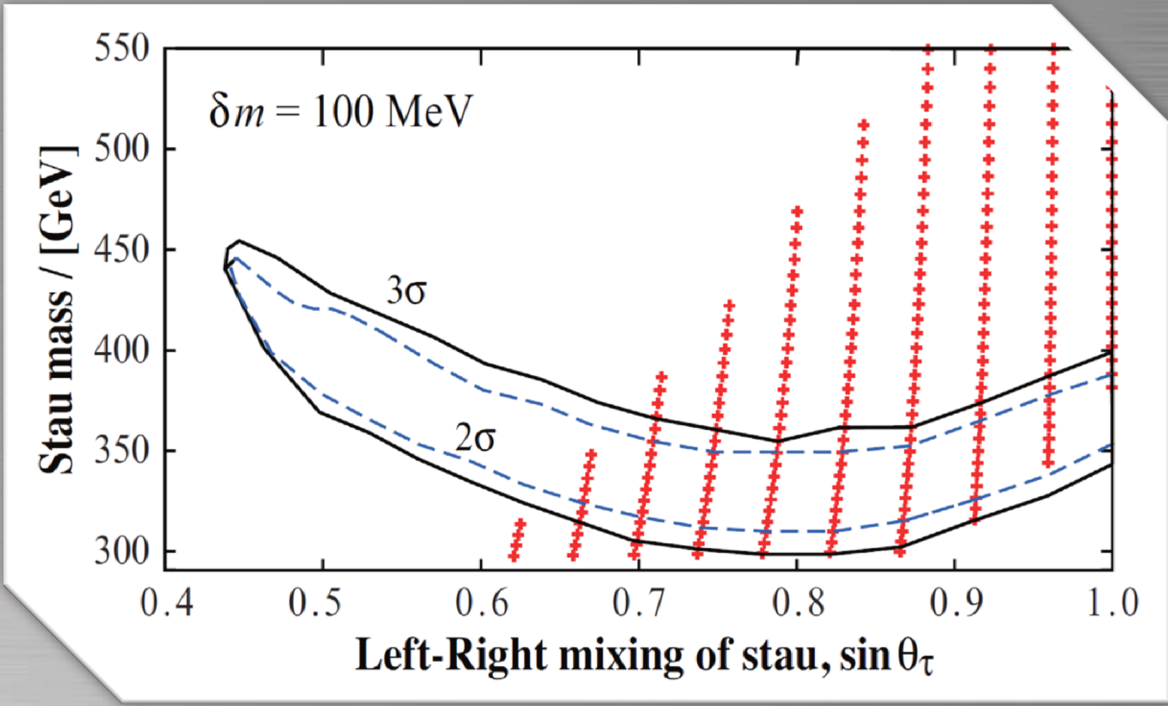


Region surrounded by purple line:
Consistent with observed ^7Li

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

Colored region:
excluded by over-production

Prediction on the long-lived stau

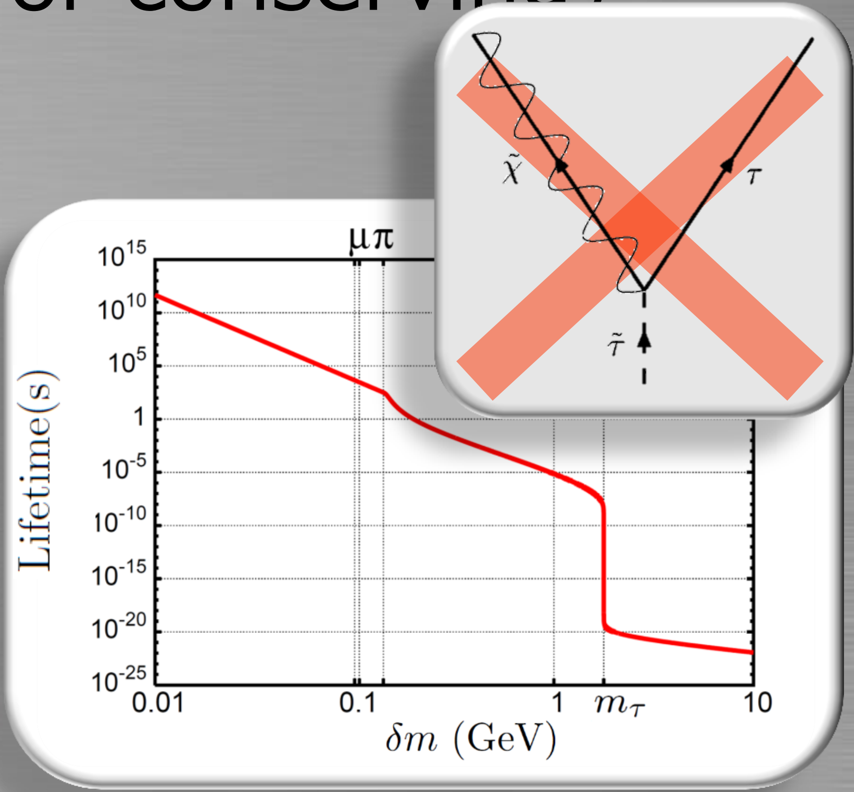


Region in solid line:
Consistent with observed dark matter abundance

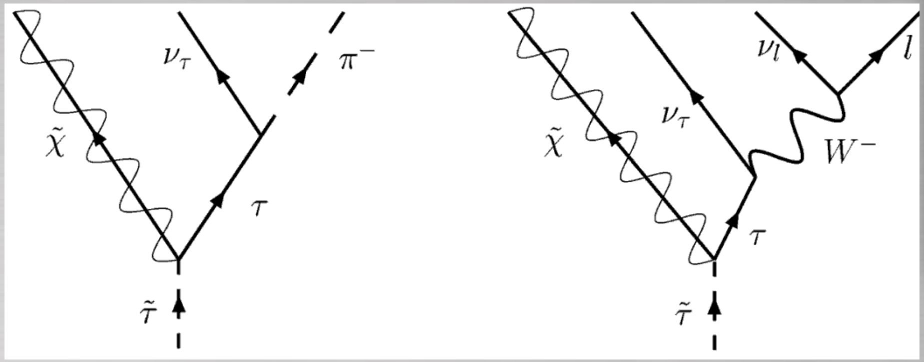
Red cross points:
Consistent with observed light elements abundance

Collider signal (flavor conserving)

- ☑ $\delta m < m_\tau$ の領域では位相空間の抑圧によりスタウNLSPが長寿命化



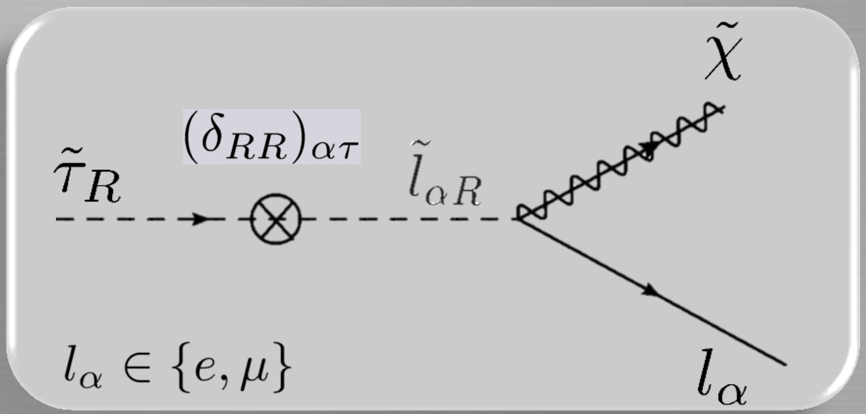
- ☑ 可能な崩壊モード



- ☑ 期待されるシグナル：ほとんどのスタウは既存の検出器を突き抜ける
  もし検出器内で崩壊すれば、ソフトなレプトン

- ☑ 既存の検出器の外に、ストッパー兼検出器が必要となりそう

Collider signal (flavor violating)



$$\Gamma(\tilde{\tau}_R \to \tilde{\chi} l_\alpha) = \frac{g_2^2}{2\pi m_{\tilde{\tau}_R}} |g_{\tau\alpha}|^2 (\delta m)^2$$

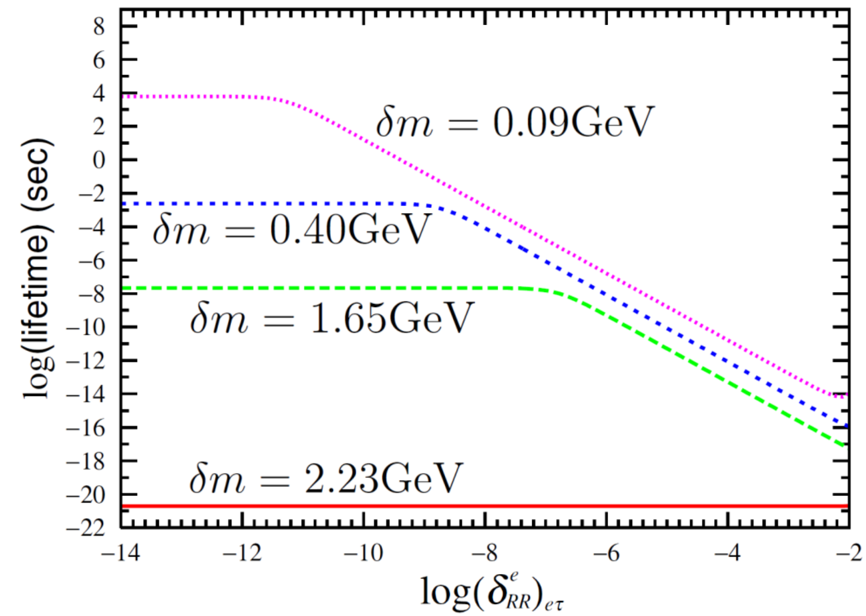
$$g_{\tau\alpha} = \tan\theta_W \frac{M_{R\tau} M_{R\alpha}}{M_{R\tau}^2 - M_{R\alpha}^2} (\delta_{RR}^e)_{\alpha\tau}$$

$$(\delta_{RR})_{\alpha\tau} = \frac{\Delta M_{RR\alpha\tau}^2}{M_{R\alpha} M_{R\tau}}$$

Signal in neutralino DM scenario

(flavor violating)

$\beta\gamma = 2$	5 cm	50 cm	3.1 m	5.8 m	25.0 m
10^{-5} sec	0.04	0.36	2.2	4.1	17.8
10^{-6} sec	0.36	3.6	22.1	41.3	175.1
10^{-7} sec	3.6	35.6	216.0	395.3	1461.9
10^{-8} sec	35.6	343.0	1731.0	2658.3	4223.5
10^{-9} sec	343.0	2425.6	4265.5	4289.7	4290.0
10^{-10} sec	2425.6	4289.0	4290.0	4290.0	4290.0
10^{-11} sec	4289.0	4290.0	4290.0	4290.0	4290.0
10^{-12} sec	4290.0	4290.0	4290.0	4290.0	4290.0



- 質量差がタウ質量以下の場合
  - 寿命測定により世代混合を決定
  - かなり小さな世代混合も決定可能

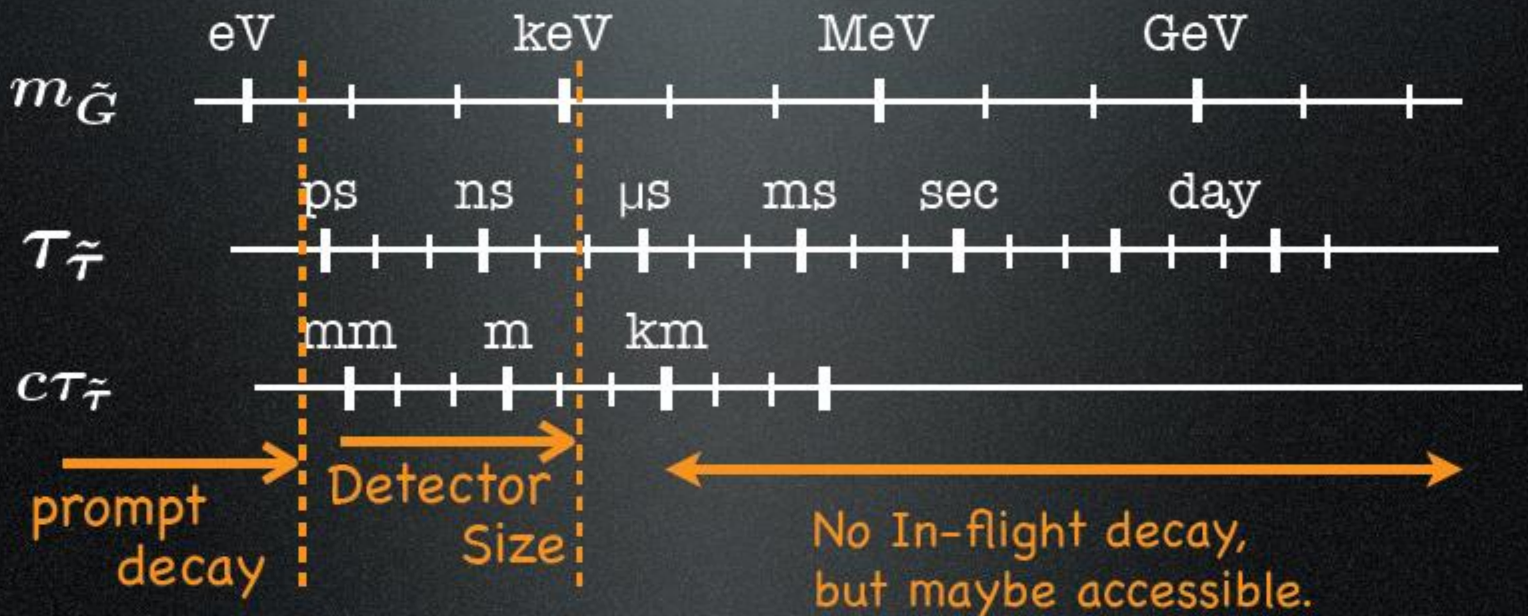
検出器内のスタウ飛跡の数え上げ
(ある距離までに崩壊する数)

Lifetime in gravitino DM scenario

$$\Gamma(\tilde{\tau} \to \tilde{G}\tau) \simeq \frac{m_{\tilde{\tau}}^5}{48\pi m_{\tilde{G}}^2 M_{\rm pl}^2}\left(1 - \frac{m_{\tilde{G}}^2}{m_{\tilde{\tau}}^2}\right)^4$$

Lifetime (decay length) of NLSP stau

e.g., for $m_{\tilde{\tau}} = 100$ GeV ,



From Hamaguchi-san's slide