Cosmological models with long-lived SUSY particles

Kazunori Kohri

（郡　和範）

Physics Department, Lancaster University

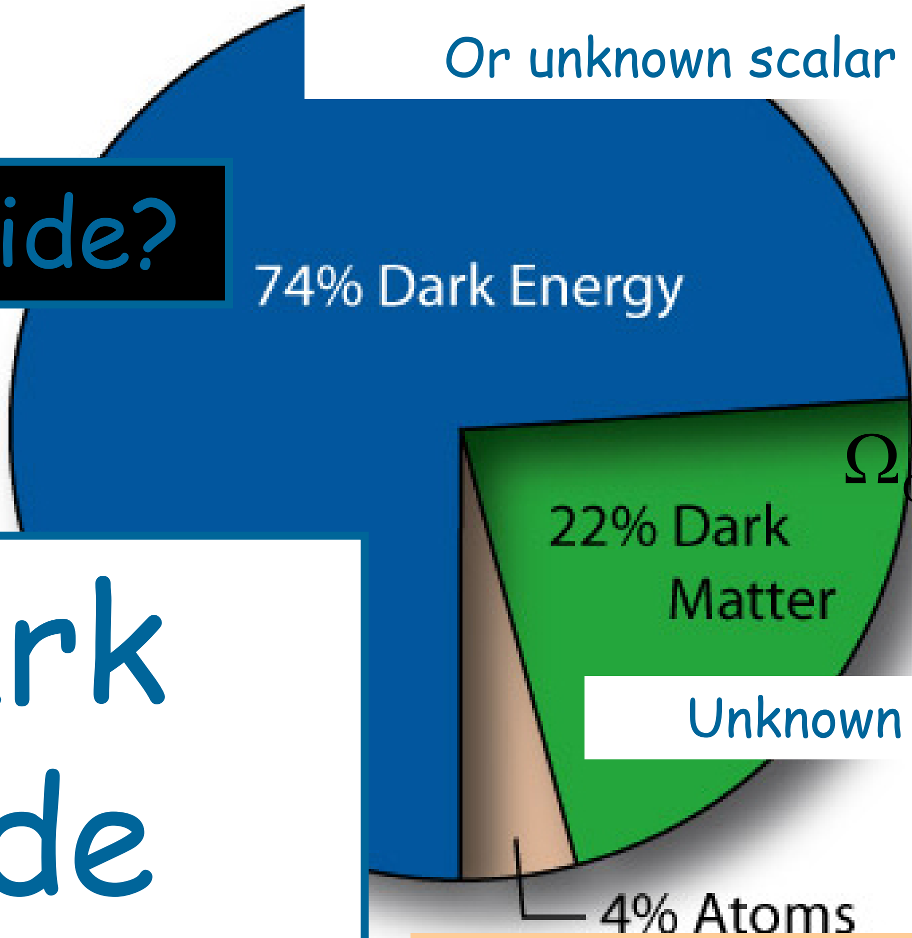
United Kingdom

Dark Matter?

Einstein's Cosmological Constant

Or unknown scalar field?

Dark side?



$\Omega_{\mathrm{CDM}} h^2 \approx 0.1$

Dark side?

Unknown SUSY particles?

Dark Side 96%

Light side (Baryon) 4%

http://map.gsfc.nasa.gov/media/060916

Realistic candidates of particle dark matter in SUSY/SUGRA

- Neutralino χ (~100% Bino or photino)

  Most famous Lightest Supersymmetric Particle (LSP) with m_χ ~100GeV (appears even in global SUSY)

- Gravitino ψ_μ

  super partner of graviton with spin 3/2 and $m_{3/2} \lesssim$ 100GeV (massive only in SUGRA (local SUSY))

Contents

- Introduction to Supsersymmetry (SUSY) and Supergravity (SUGRA)
- Lightest SUSY Particle (LSP) Dark Matter (DM) in Minimal SUSY Standard Model (MSSM)
- LSP DM in Constrained MSSM (CMSSM) and mSUGRA
- Cosmological and astrophysical constraints on LSP and Next LSP (NLSP)

Introduction to SUSY

Supersymmetry (SUSY)

- Solving "Hierarchy Problem"
- Realizing "Coupling constant unification in GUT"

Fermion	⟷	Boson
quark	⟷	squark
lepton	⟷	slepton
photino	⟷	photon
gravitino	⟷	graviton
axino	⟷	axion

photino → neutralino

Highly model-dependent and my review is insufficient

See Kawasaki, Senami, Nakayama (07)

Depending on SUGRA models

MSSM

- Minimal extension of Standard Model to supersymmetry including two Higgs doublets

$$W_{MSSM} = -\bar{u} y_u Q H_u + \bar{d} y_d Q H_d + \bar{e} y_e L H_d$$

~~$\bar{d} y_d Q H_u^*$~~ because of holomorphism in super pot.

$$H_u = \begin{pmatrix} h_u^+ \\ h_u^0 \end{pmatrix} \qquad H_d = \begin{pmatrix} h_d^0 \\ h_d^- \end{pmatrix}$$

- 105 masses, phases and mixing angles!!!

CMSSM

Constrained MSSM

Simplified into only five parameters from 105

① Common scalar mass at GUT scale: m_0

② Unified gaugino (fermion) mass at GUT scale: $m_{1/2}$

③ Ratio of Higgs vacuum expectation values: $\tan\beta \equiv \frac{\langle H_u^0 \rangle}{\langle H_d^0 \rangle}$

④ Higgs/higgsino mass parameter (or its signature): μ

⑤ tri-linear coupling A_0

Super particles in CMSSM

Names	Spin	P_R	Gauge Eigenstates	Mass Eigenstates
Higgs bosons	0	+1	$H_u^0\ H_d^0\ H_u^+\ H_d^-$	$h^0\ H^0\ A^0\ H^\pm$
squarks	0	−1	$\widetilde{u}_L\ \widetilde{u}_R\ \widetilde{d}_L\ \widetilde{d}_R$	(same)
			$\widetilde{s}_L\ \widetilde{s}_R\ \widetilde{c}_L\ \widetilde{c}_R$	(same)
			$\widetilde{t}_L\ \widetilde{t}_R\ \widetilde{b}_L\ \widetilde{b}_R$	$\widetilde{t}_1\ \widetilde{t}_2\ \widetilde{b}_1\ \widetilde{b}_2$
sleptons	0	−1	$\widetilde{e}_L\ \widetilde{e}_R\ \widetilde{\nu}_e$	(same)
			$\widetilde{\mu}_L\ \widetilde{\mu}_R\ \widetilde{\nu}_\mu$	(same)
			$\widetilde{\tau}_L\ \widetilde{\tau}_R\ \widetilde{\nu}_\tau$	$\widetilde{\tau}_1\ \widetilde{\tau}_2\ \widetilde{\nu}_\tau$
neutralinos	1/2	−1	$\widetilde{B}^0\ \widetilde{W}^0\ \widetilde{H}_u^0\ \widetilde{H}_d^0$	$\widetilde{N}_1\ \widetilde{N}_2\ \widetilde{N}_3\ \widetilde{N}_4$
charginos	1/2	−1	$\widetilde{W}^\pm\ \widetilde{H}_u^+\ \widetilde{H}_d^-$	$\widetilde{C}_1^\pm\ \widetilde{C}_2^\pm$
gluino	1/2	−1	$\widetilde{g}$	(same)
goldstino (gravitino)	1/2 (3/2)	−1	$\widetilde{G}$	(same)

stop

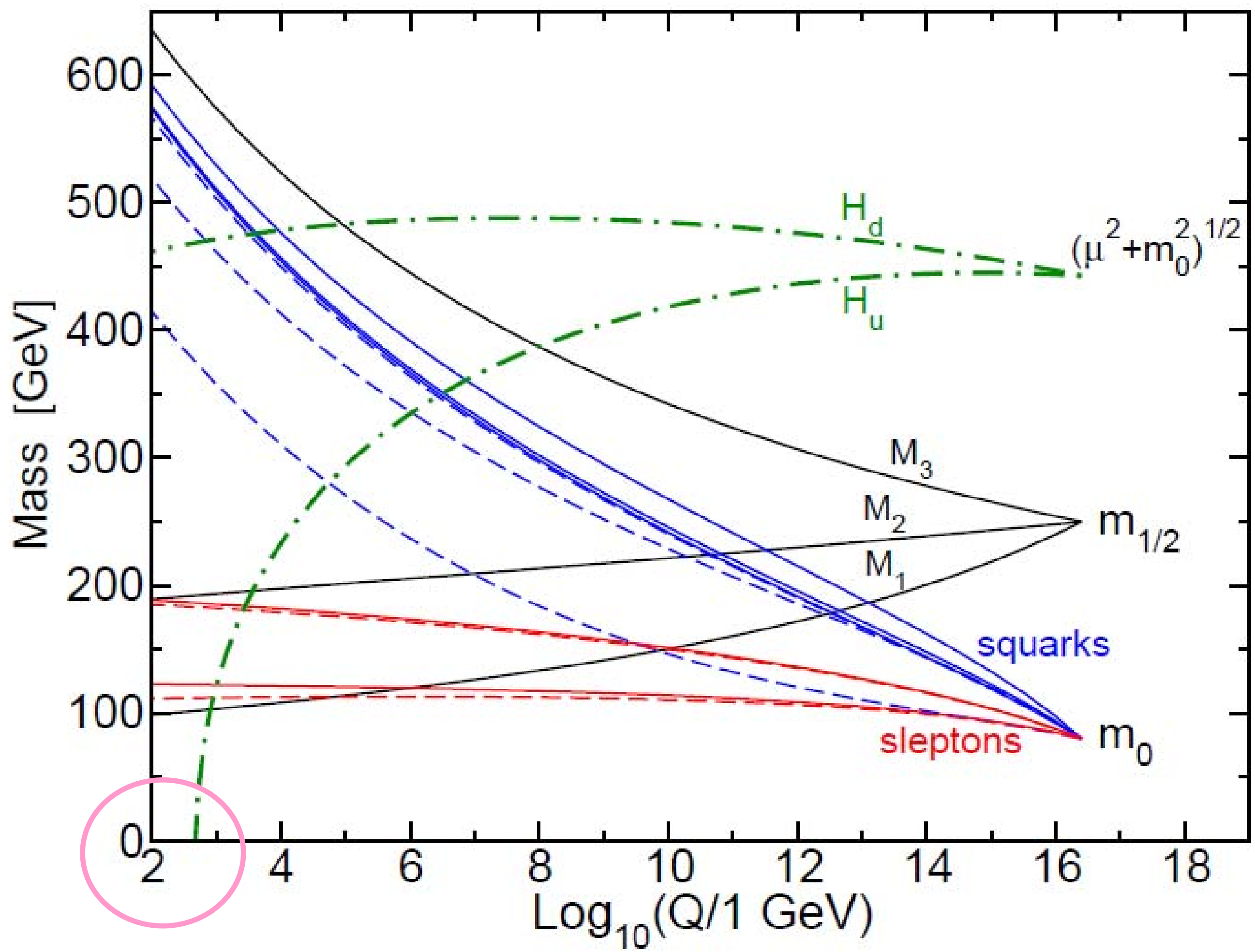
sneutrinos

stau

bino, wino, higgsinos

Martin, "A Supersymmetry Primer"

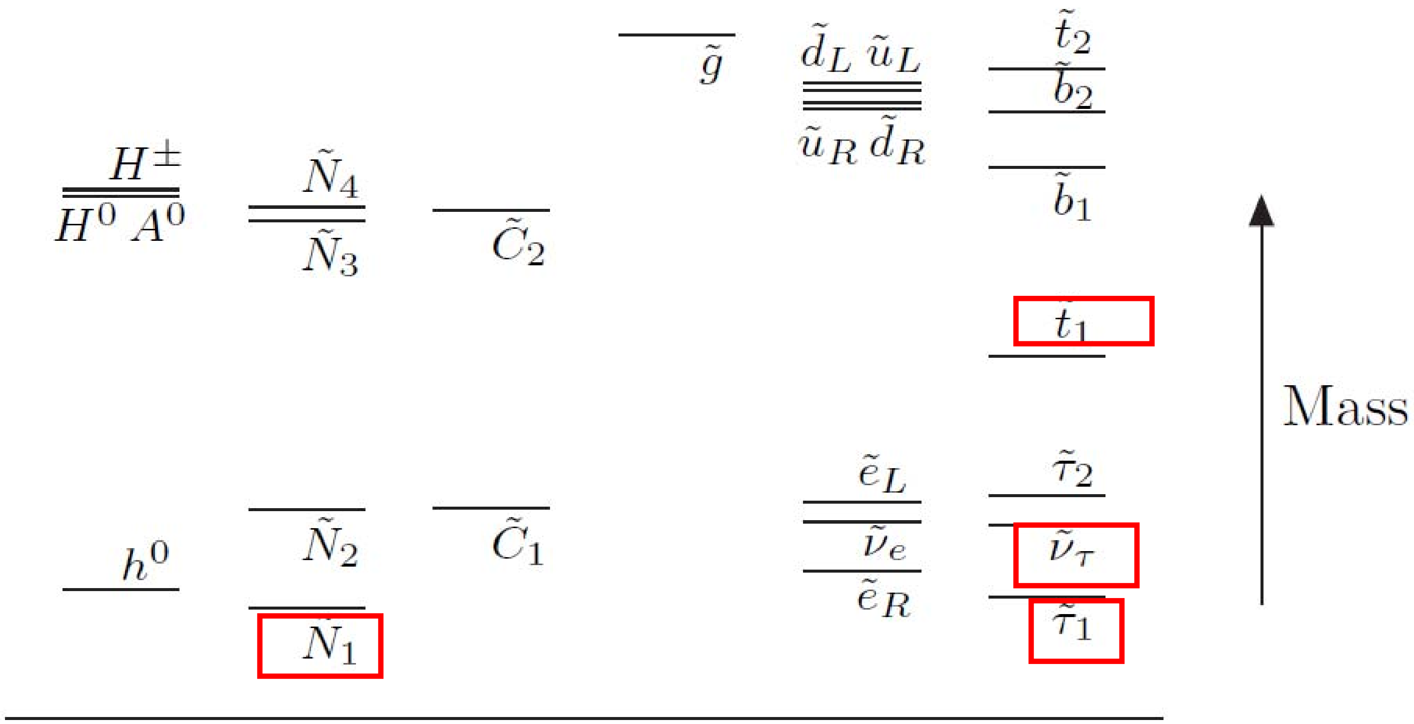
Running of Renormalization Group (RG) Equation in CMSSM



Negative Higgs mass term

Martin, "A Supersymmetry Primer"

Mass spectrum in CMSSM



Martin, "A Supersymmetry Primer"

Thermal freezeout

Boltzmann equation

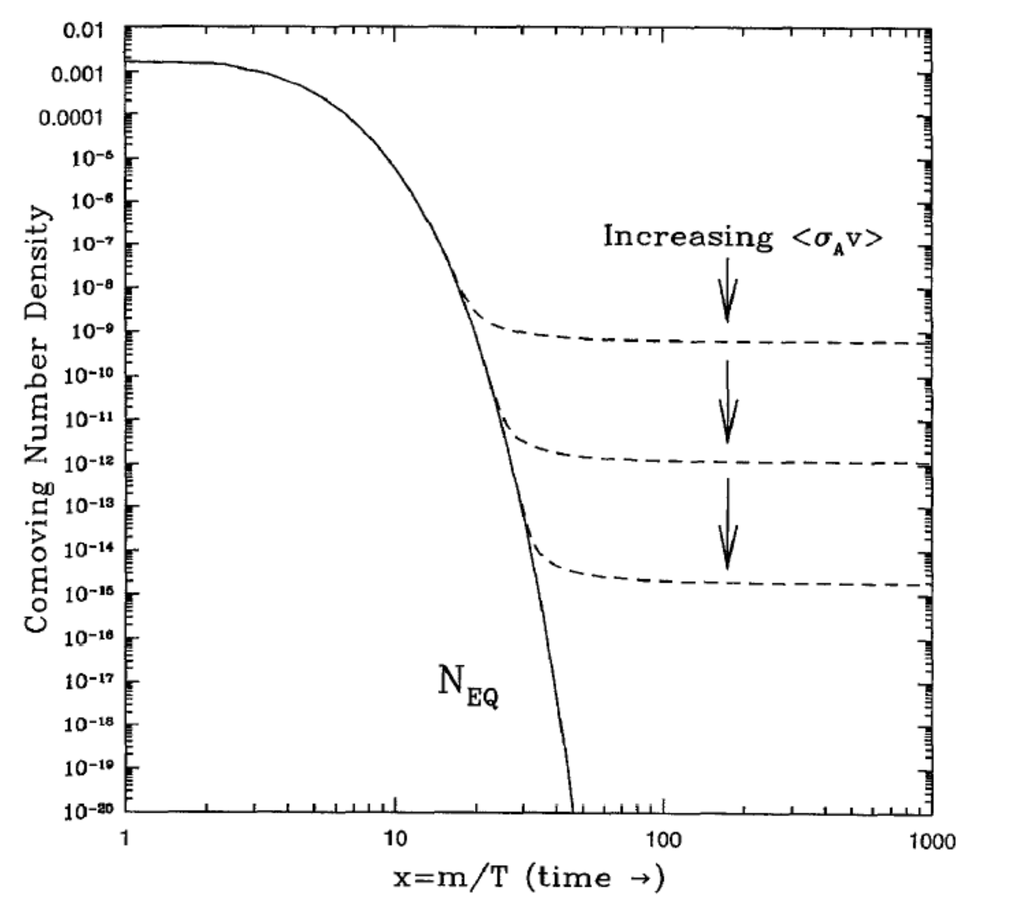
$$\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle\sigma_A v\rangle\left[(n_\chi)^2 - (n_\chi^{eq})^2\right]$$

$$n_\chi \square \left.\frac{3H}{\langle\sigma v\rangle}\right|_{\text{frezeout}}$$

$$T_{\text{Freezeout}} \square m_\chi / 25$$

$$\Omega_\chi h^2 \square 0.1\left(\frac{\langle\sigma v\rangle}{\left(0.1/\text{TeV}\right)^2}\right)^{-1}$$

Ω does not depend on m_χ

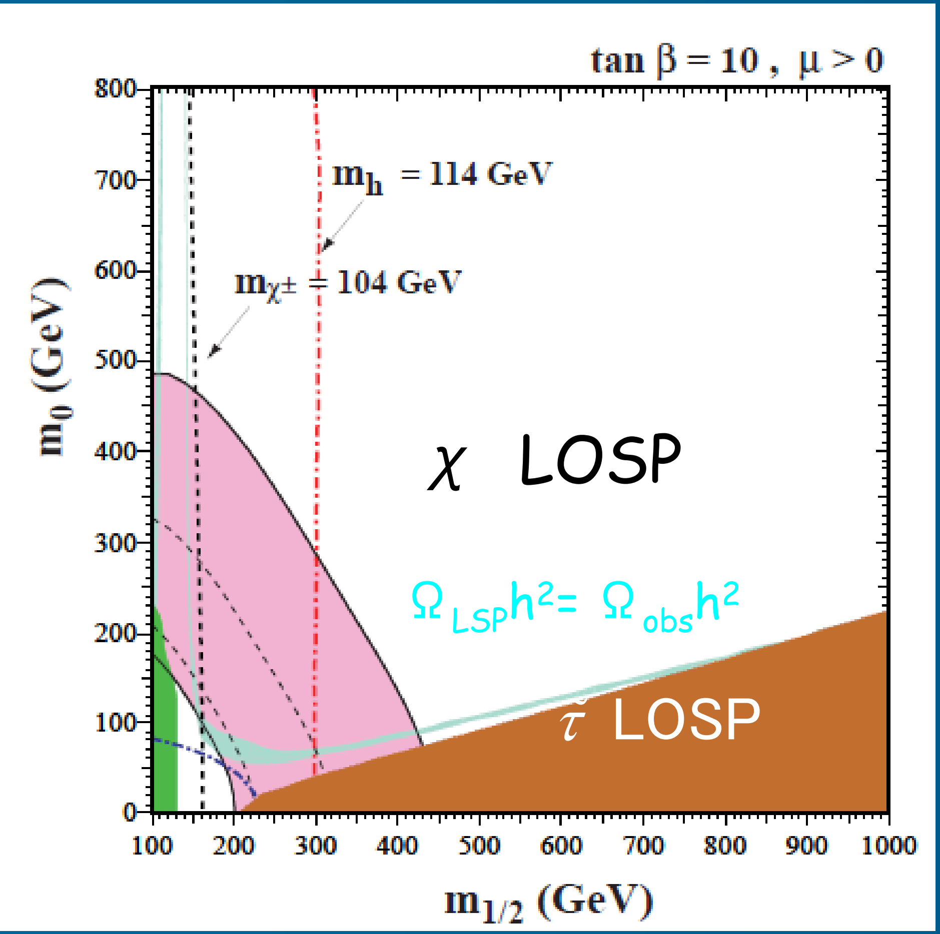


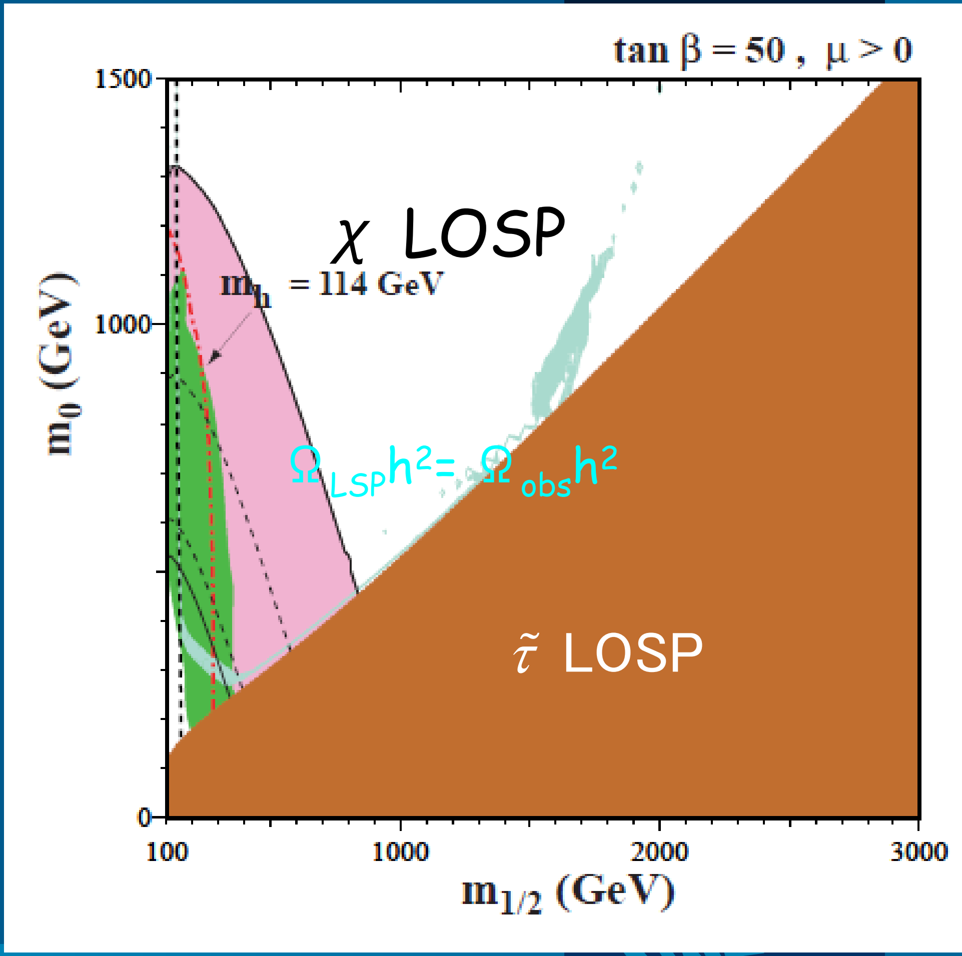
Kolb & Turner

Predicting TeV Physics!!!

LSP (LOSP) in CMSSM

Neutralino or Scalar tau lepton (Stau) is the Lightest Ordinary SUSY Particle (LOSP)





Ellis,Olive,Santoso,Spanos(03)

Supergravitiy (SUGRA)

- Local theory of SUSY
  (predicting gravitino)

- Models of supersymmetry breaking
  (gravitino mass production by eating goldstino which appears in spontaneous symmetry breaking)

- Including general relativity
  (Unifying space-time symmetry with local SUSY transformation)

SUSY Breaking Models

- Gravity mediated SUSY breaking model

Observable sector		Hidden sector
quark, squark, …	Only through gravity ⟷	~~SUSY~~
		$F \sim 10^{20-21} GeV^2$

- Masses of squarks and sleptons

$$m_{\tilde{q}}, m_{\tilde{\ell}} = F / M_{pl} = 10^2 - 10^3 \ GeV$$

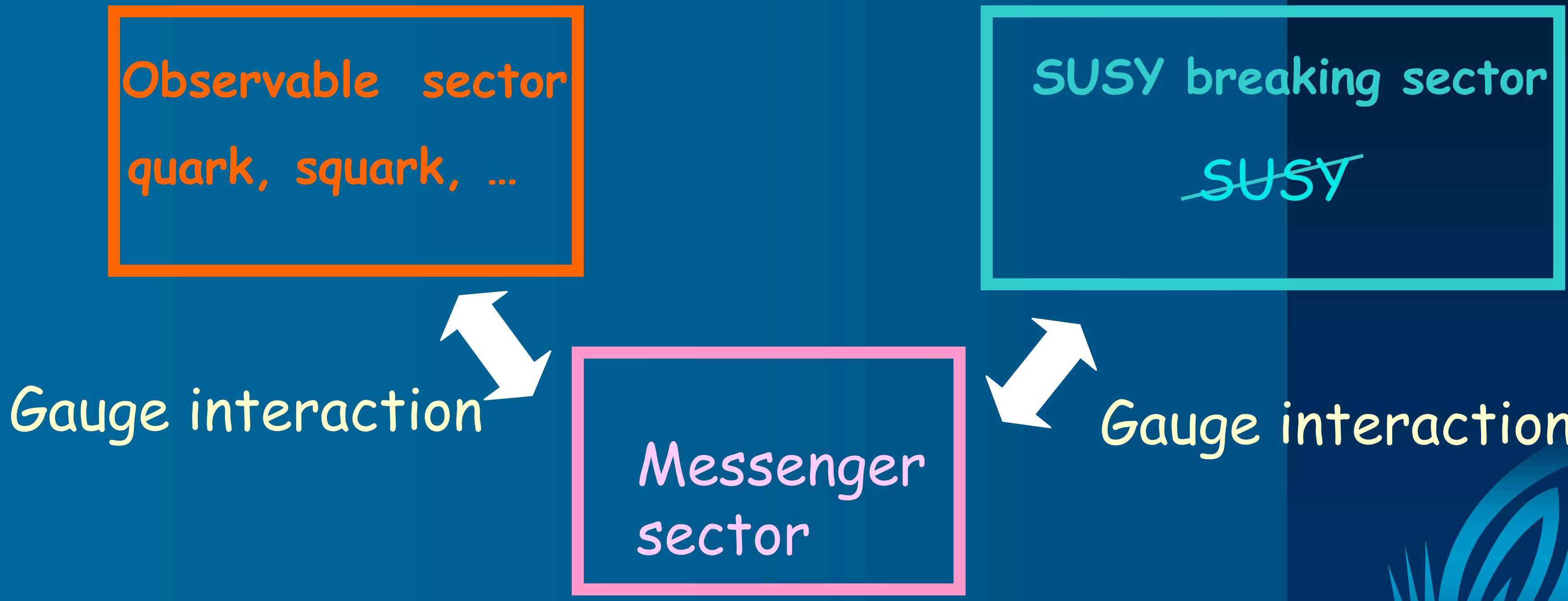
$$(F = 10^{20} - 10^{21} \ GeV)$$

- Gravitino mass

$$m_{3/2} = F / M_{pl} = 10^2 - 10^3 \ GeV$$

SUSY Breaking Models II

- Gauge-mediated SUSY breaking model



$$m_{3/2} \sim F / M_p < 10\text{GeV}$$

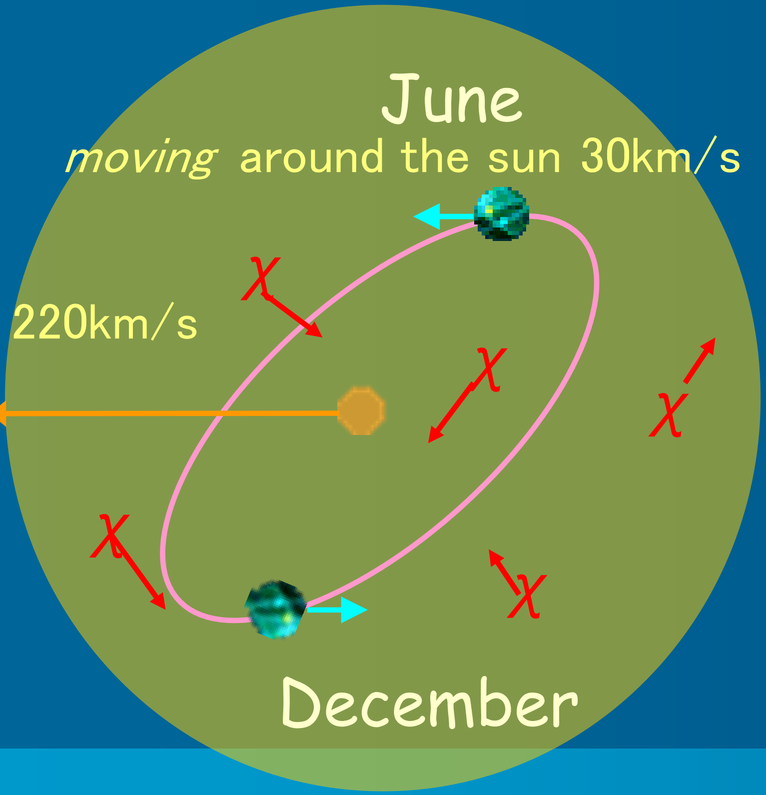
Lightest SUSY particle (LSP) may be necessarily the gravitino

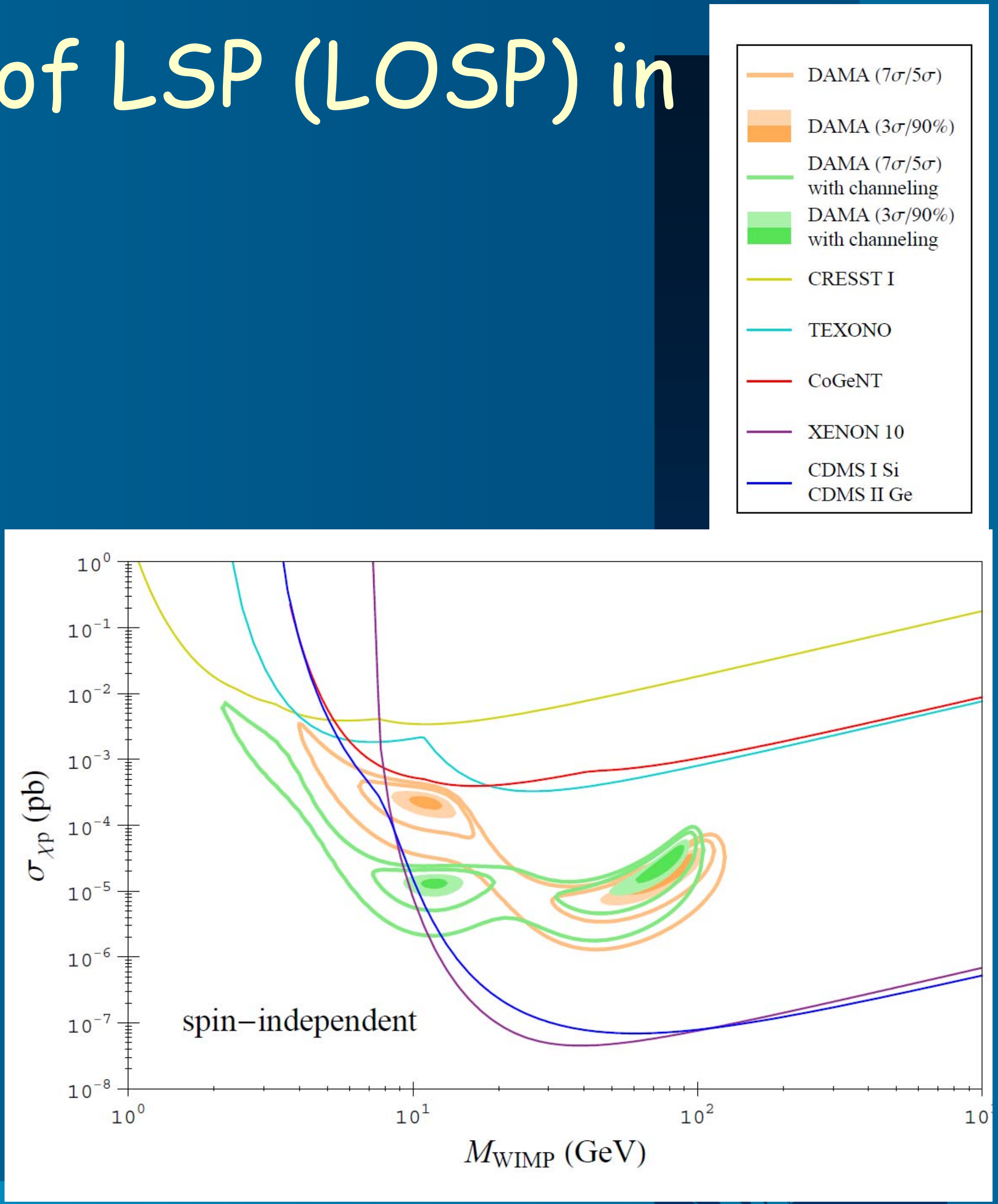
Signature of SUSY particles related with Astrophysics and Cosmology

- Direct detection
- Indirect detection
- Big-bang nucleosynthesis (BBN)
- Cosmic Microwave Background (CMB)
- Diffused gamma-ray background

Direct detection of LSP (LOSP) in CMSSM

Annual modulation





Gelmini, arXiv:0810.3733v1

Indirect detection of LSP (LOSP)

Annihilation signals of neutralino at Galaxy Center, the Sun, near solar system, etc…

Quite a lot of groups have contributed this topic

$$\chi\chi \to WW,\ ZZ,\ Z\gamma,\ 2\gamma,\ e^+e^-$$

$$W, Z \to \text{broad spectrum of } \gamma,\ e^+e^-, p\bar{p}$$

Or gravitino/sneutrino decay with R-parity violation

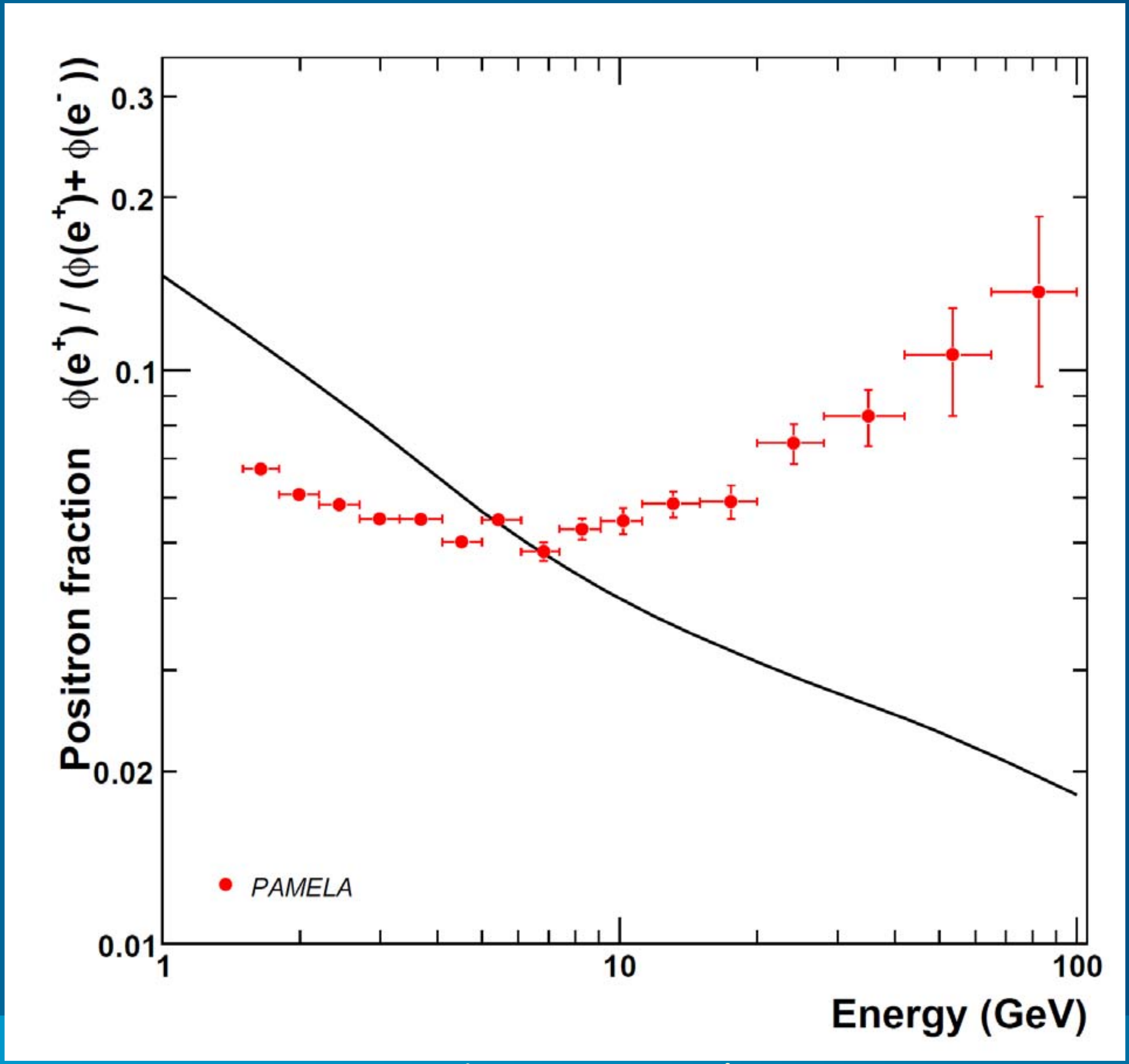
Ibarra, Tran (08), Ishiwata, Matsumoto, Moroi (08), Chen, Takahashi (08)

Or hidden gauge boson decay with kinetic mixing

Chen, Takahashi, Yanagida (08)

- Gamma-ray from a point source
- Anti-proton
- Positron
- 511 keV line gamma
- Neutrinos
- Synchrotron radio
- WMAP HAZE component
- Nucleosynthesis
- etc…

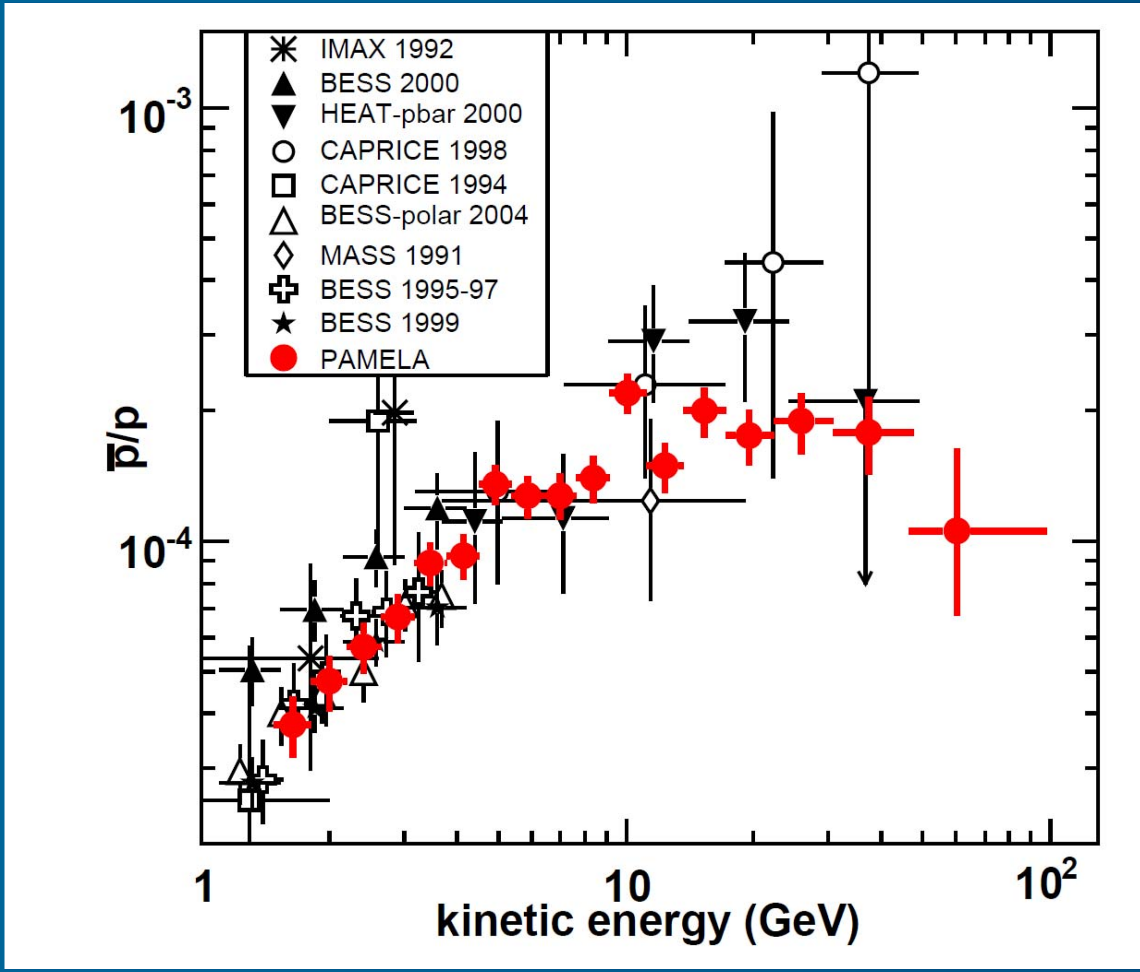
Positron Excess (PAMELA satellite reported)



Adriani et al, arXiv:0810.4995v1 [astro-ph]

Anti-proton flux (PAMELA satellite reported)

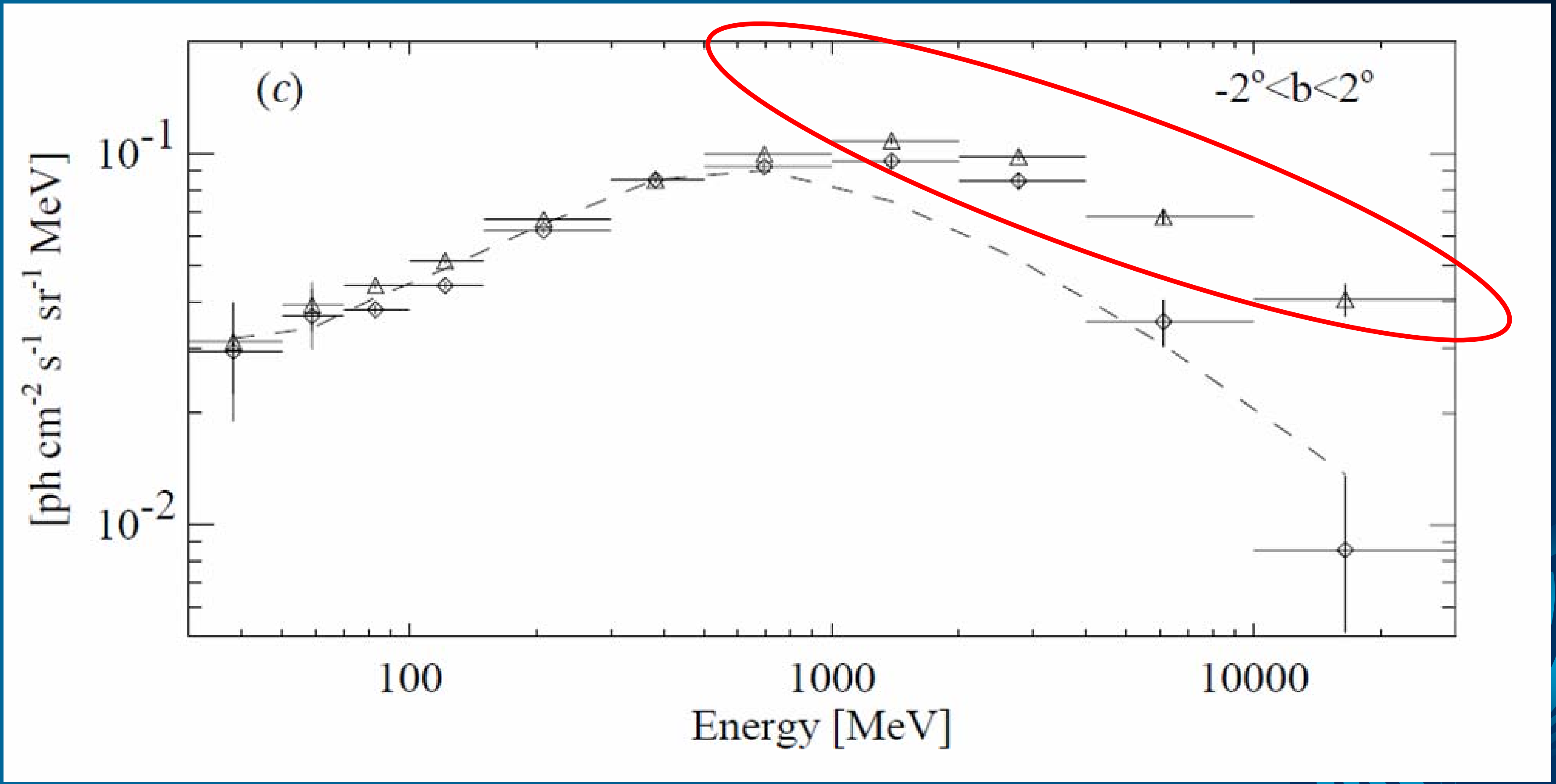
Adriani et al, arXiv:0810.4994v1 [astro-ph]



Consistent with secondary production of pp

or Leptonic DM ? by Chen-Takahashi (08)

Gamma-ray anomaly at Galactic Center
(EGRET satellite reported)



Hunter et al (97)

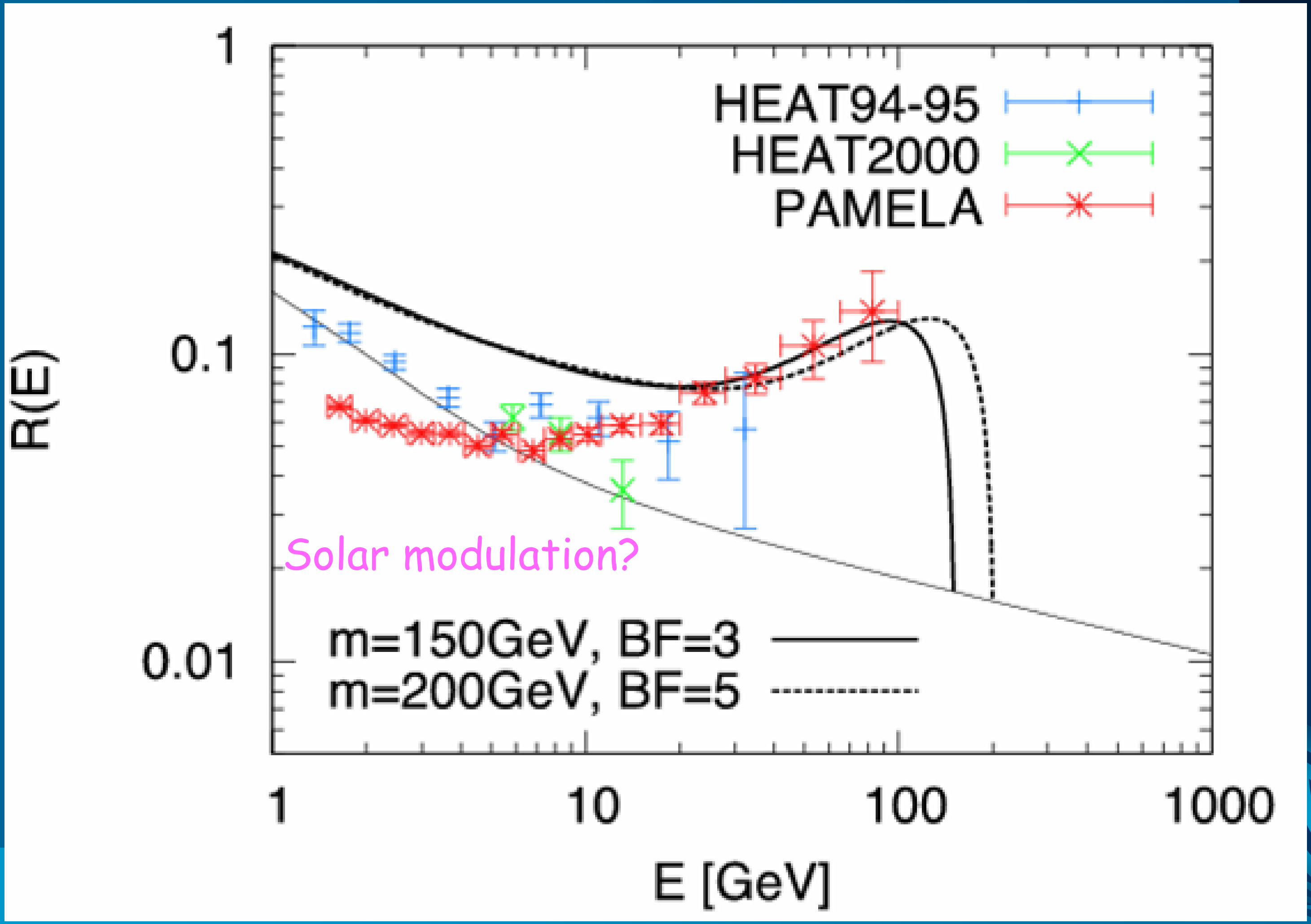
Positron excess in wino DM annihilation

Hisano, Kawasaki, Kohri, Nakayama (08) in preparation

Diffusion model

Fitted to B/C ratio

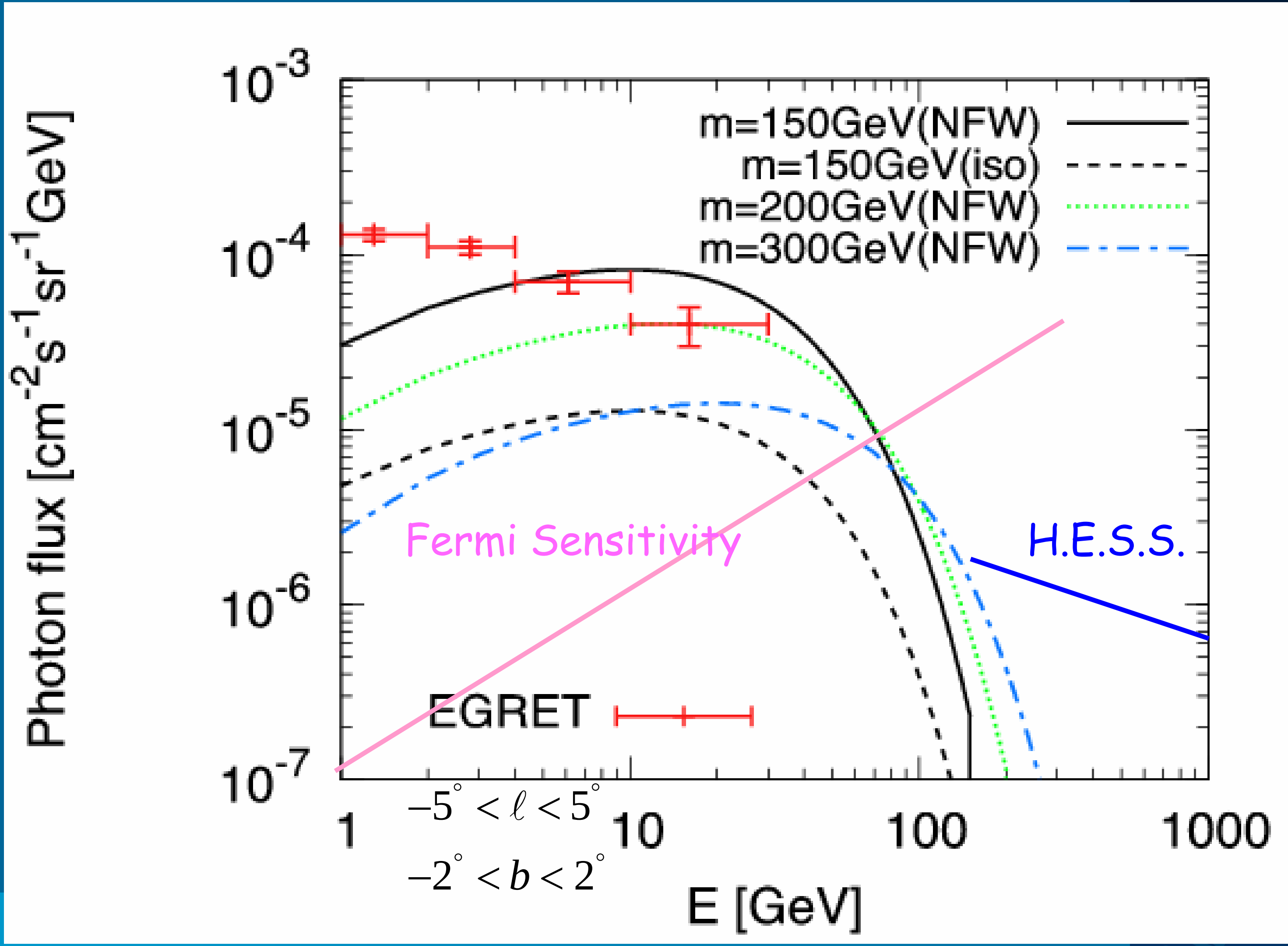
See Kazunori Nakayama's poster talk



Gamma-ray signal in wino DM annihilation

Hisano, Kawasaki, Kohri, Nakayama, arXiv:**0810.1892** [hep-ph]

See Kazunori Nakayama's poster talk



Big-Bang Nucleosynthesis (BBN)

- Very strong cosmological tools to study long-lived particles with lifetime of 0.01 sec – 10^{12} sec

- Theoretical predictions are constrained by observational D, 3He, ^{4}He, ^{6}Li and ^{7}Li abundances <u>with their conservatively-large errors.</u>

Massive particle decaying during/after BBN epoch produces high energy photons, hadrons, and neutrinos

Destruction/production/dilution of light elements

Severer constraints on the number density

Sato and Kobayashi (1977), Lindley (1984,1985), Khlopov and Linde (1984)

Ellis, Kim, Nanopoulos, (1984); Ellis, Nanopoulos, Sarkar (1985)

Kawasaki and Sato (1987)

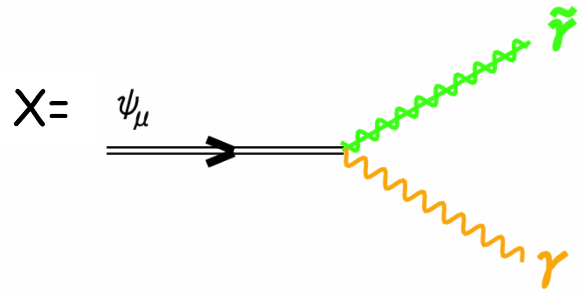
Reno and Seckel (1988), Dimopoulos, Esmailzadeh, Hall, Starkman (1988)

Kawasaki, Moroi (1994), Sigl et al (95), Holtmann et al (97)

Jedamzik (2000), Kawasaki, Kohri, Moroi (2001), Kohri(2001), Cyburt, Ellis, Fields, Olive (2003)

Kawasaki, Kohri, Moroi(04), Jedamzik (06)

Radiative decay scenario



1) Electro-magnetic cascade

$$\gamma + \gamma_{\rm BG} \to e^+ + e^-$$
$$\gamma + e^-_{\rm BG} \to \gamma + e^-, \quad e^- + \gamma_{\rm BG} \to e^- + \gamma$$
$$\gamma + \gamma_{\rm BG} \to \gamma + \gamma$$

2) many soft photons are produced

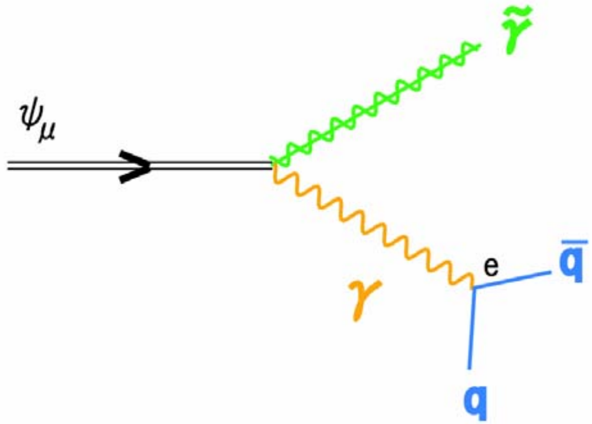
3) Photo-dissociation of light elements

$$\mathrm{D} + \gamma \to p + n,$$
$${}^4\mathrm{He} + \gamma \to {}^3\mathrm{He} + n, \quad \mathrm{T} + p,$$
$${}^3\mathrm{He} + \gamma \to \mathrm{D} + p + n, \quad \mathrm{etc.}$$

Hadronic decay

Reno, Seckel (1988)

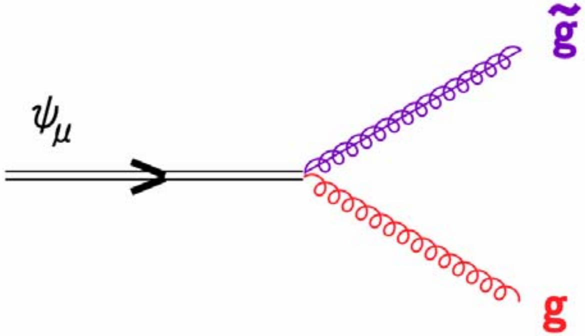
S. Dimopoulos et al.(1989)



$$B_h \approx \alpha / 4\pi \approx 10^{-3}$$

Two hadron jets with

$E_{jet} = m_X / 3$



$$B_h = 1$$

One hadron jet with

$E_{jet} = m_X / 2$

(I) Early stage of BBN (before/during BBN)

Reno and Seckel (1988) Kohri (2001)

Extraordinary inter-conversion reactions between n and p

cf) $n + \pi^+ \rightarrow p + \pi^0$ $\quad p + \pi^- \rightarrow n + \pi^0$

$$\Gamma_{n \leftrightarrow p} = \Gamma^{\text{weak}}_{n \leftrightarrow p} + \Gamma^{\text{strong}}_{n \leftrightarrow p}$$

Hadron induced exchange

$$\Gamma_{n \leftrightarrow p} \uparrow \quad \Rightarrow \quad n/p \uparrow$$

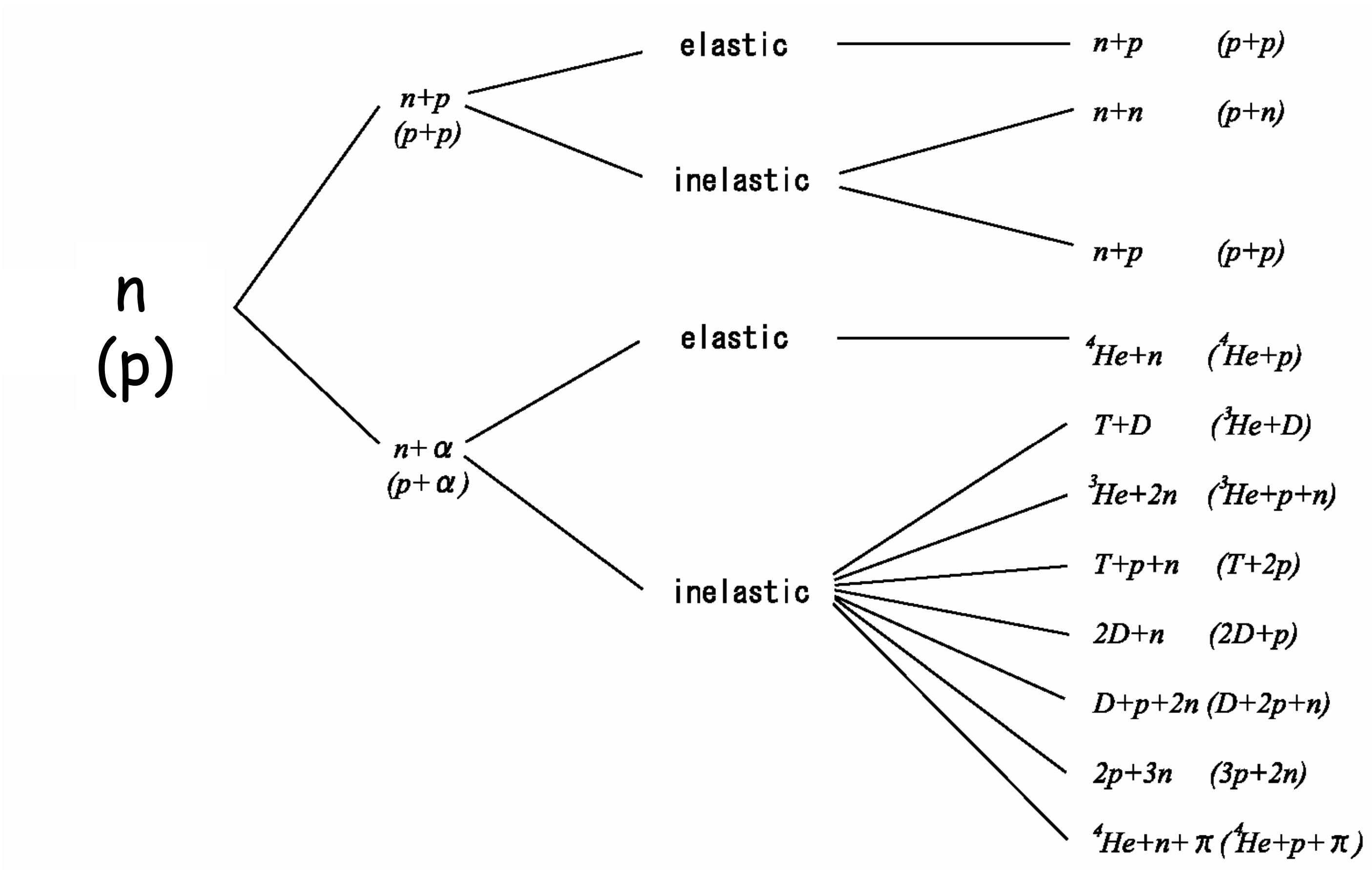
Even after freeze-out of n/p in SBBN

More He4, D, Li7 …

(II) Late stage of BBN

Hadronic showers and "Hadro-dissociation"

S. Dimopoulos et al. (1988)
Kawasaki, Kohri, Moroi (2004)

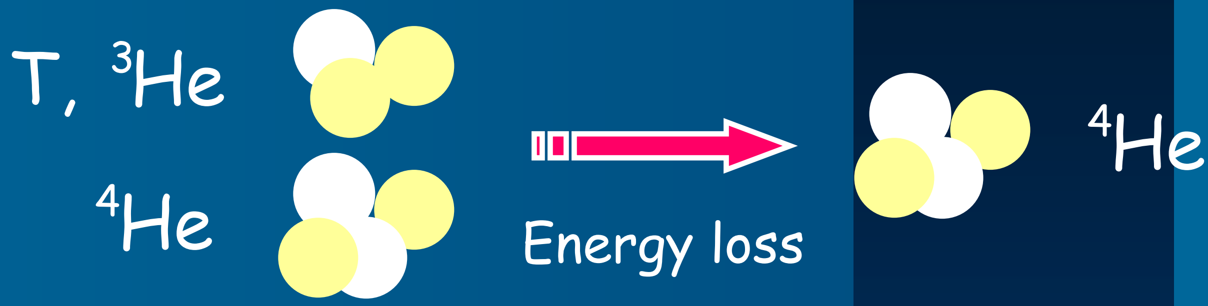


Non-thermal Li, Be Production by energetic hadrons

Dimopoulos et al (1989)

$$N + {}^4He \rightarrow \begin{cases} {}^3He + X \\ T + X \end{cases}$$

$$N + {}^4He \rightarrow {}^4He^* + X$$



① T(He3) – He4 collision

$$T + {}^4He \rightarrow {}^6Li + n \quad [8.4\ MeV]$$

$$^3He + {}^4He \rightarrow {}^6Li + p \quad [7.0\ MeV]$$

② He4 – He4 collision

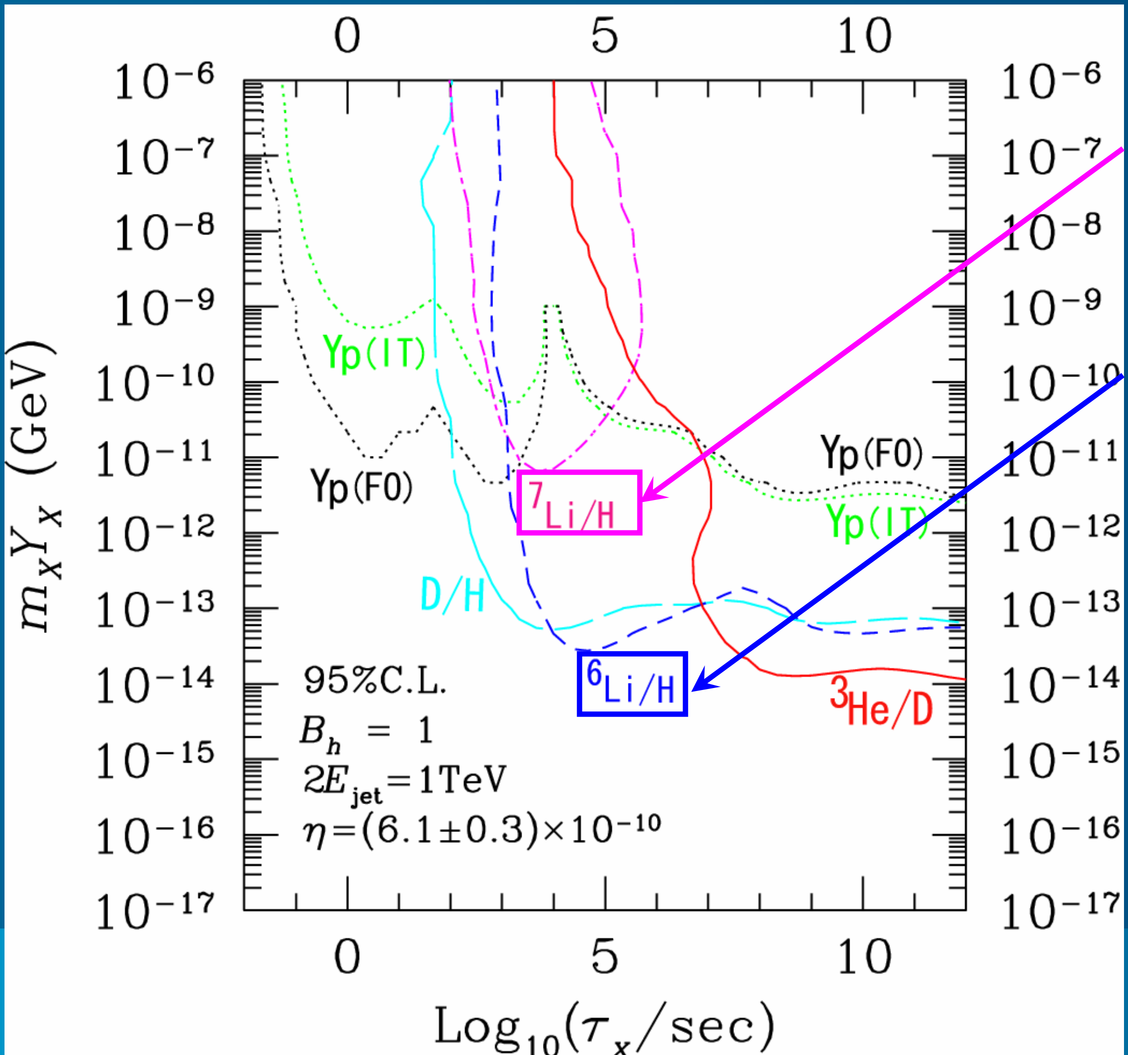
$$^4He + {}^4He \rightarrow {}^6Li, {}^7Li, {}^7Be + \ldots$$

Massive particle X

Upper bounds on $m_x Y_x$ in both photodissociation and "hadrodissociation" scenario

Kawasaki, Kohri, Moroi (04)

$$Y_x \equiv n_x / s$$



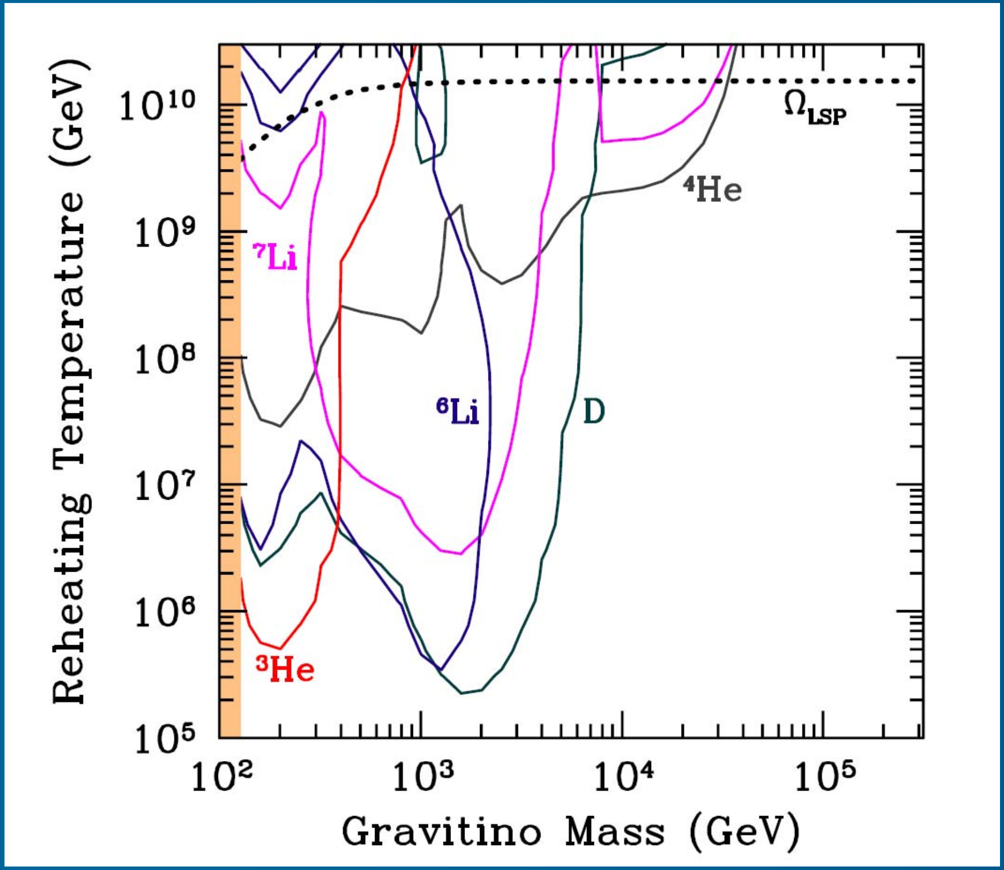
Mild observational upper bound

Mild observational upper bound

Neutralino LSP and gravitino “NLSP”

Upper bound on reheating temperature

Kawasaki, Kohri, Moroi, Yotusyanagi (08)



$$T_R \approx 10^9\,\mathrm{GeV}\left(Y_{3/2}/10^{-12}\right)$$

$$m_{3/2} \approx 500\,\mathrm{GeV}\,(\tau_{3/2}/4\times10^5\,\mathrm{sec})^{-1/3}$$

	Case 1
$m_{1/2}$	300 GeV
m_0	141 GeV
A_0	0
$\tan\beta$	30
μ_H	389 GeV
$m_{\chi_1^0}$	117 GeV
$\Omega_{\rm LSP}^{\rm (thermal)} h^2$	0.111

Neutralino (bino) NLSP and gravitino LSP

Gravitino LSP and thermally porduced neutralino (Bino) "NLSP" scenario

Feng, Su, and Takayama (03)

Steffen (06)

Kawasaki, Kohri, Moroi, Yotsuyanagi (08)

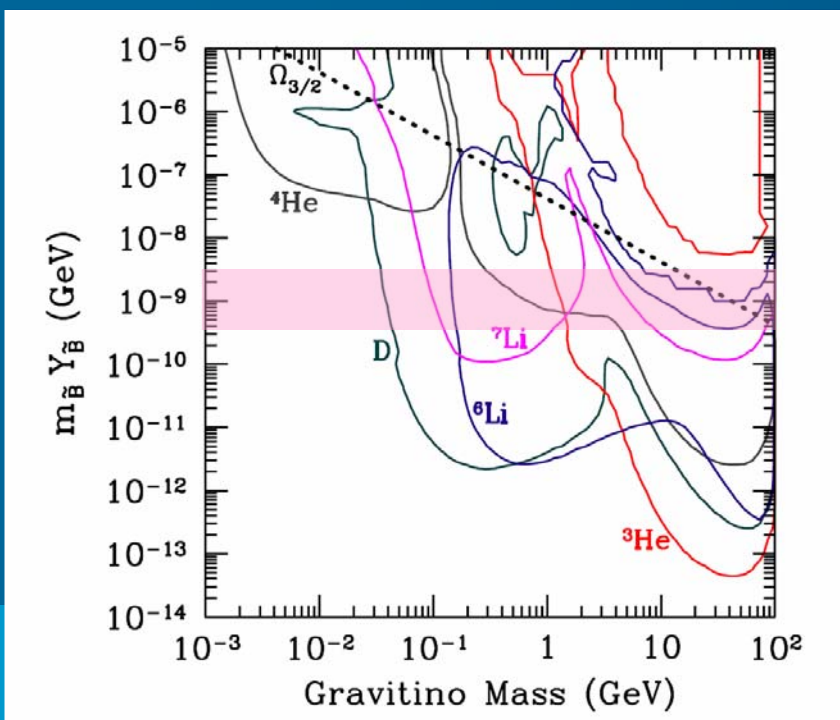
$$\Gamma(\tilde{B} \to \psi_\mu \gamma) = \frac{\cos^2\theta_W}{48\pi M_*^2}\frac{m_{\tilde{B}}^5}{m_{3/2}^2}(1 - x_{3/2}^2)^3(1 + 3x_{3/2}^2)$$

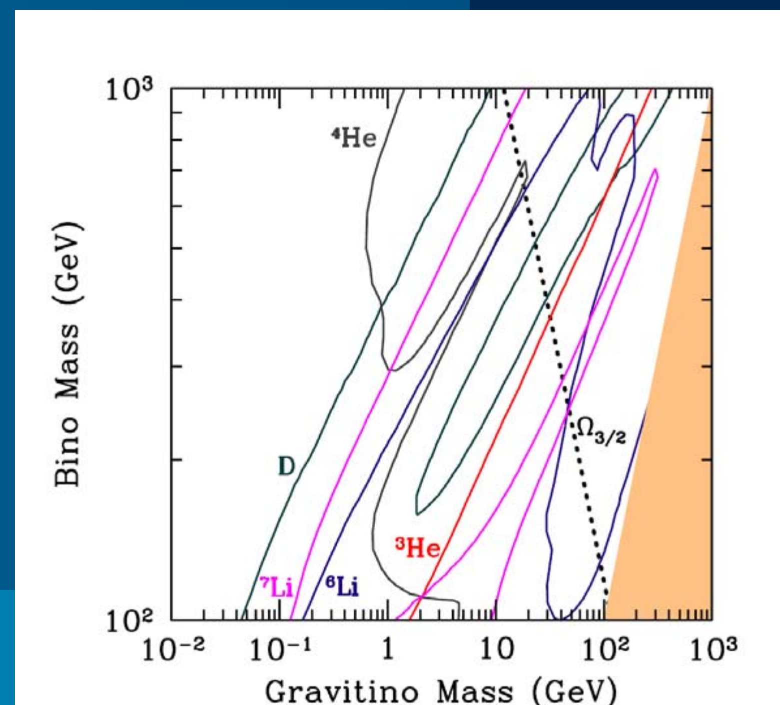
$$\tau \propto m_{3/2}^2 \, m_{pl}^2 / m_{NLSP}^5$$

Relic abundance

$$Y_{\tilde{B}} = 4 \times 10^{-12} \times \left(\frac{m_{\tilde{B}}}{100\ \mathrm{GeV}}\right) \quad : \ \mathrm{bulk}$$

No allowed region for DM density





Sneutrino NLSP and gravitino LSP scenario

Stable (left-handed) sneutrino was excluded by the direct detection experiments because of its large cross section directly-coupled with W/Z bosons.

NLSP (left-handed) sneutrino should be unstable

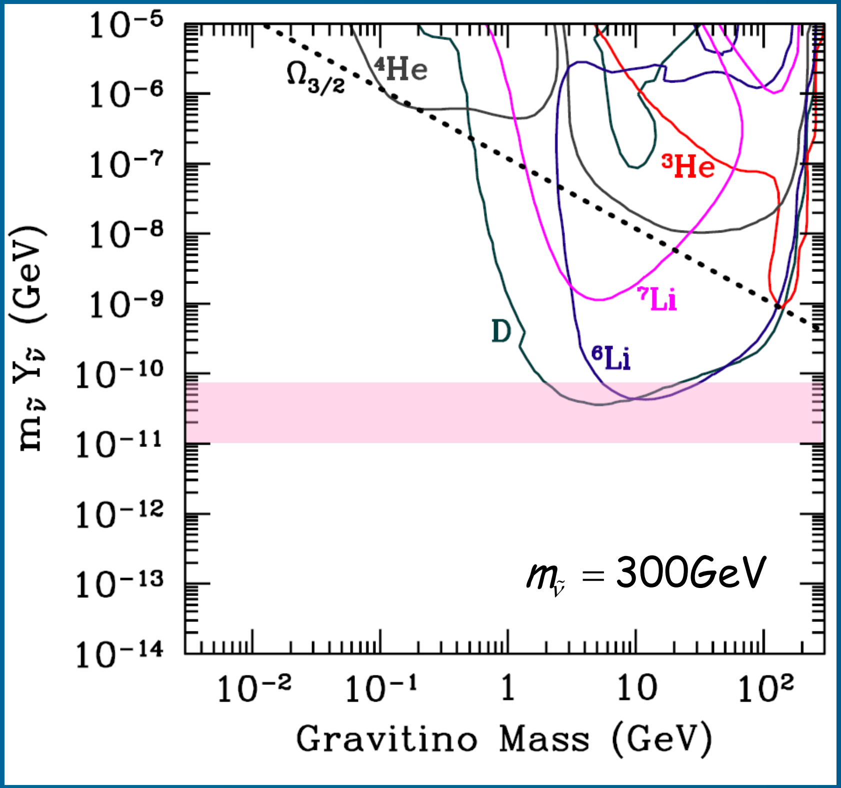
Gravitino LSP and thermally porduced sneutrino NLSP scenario

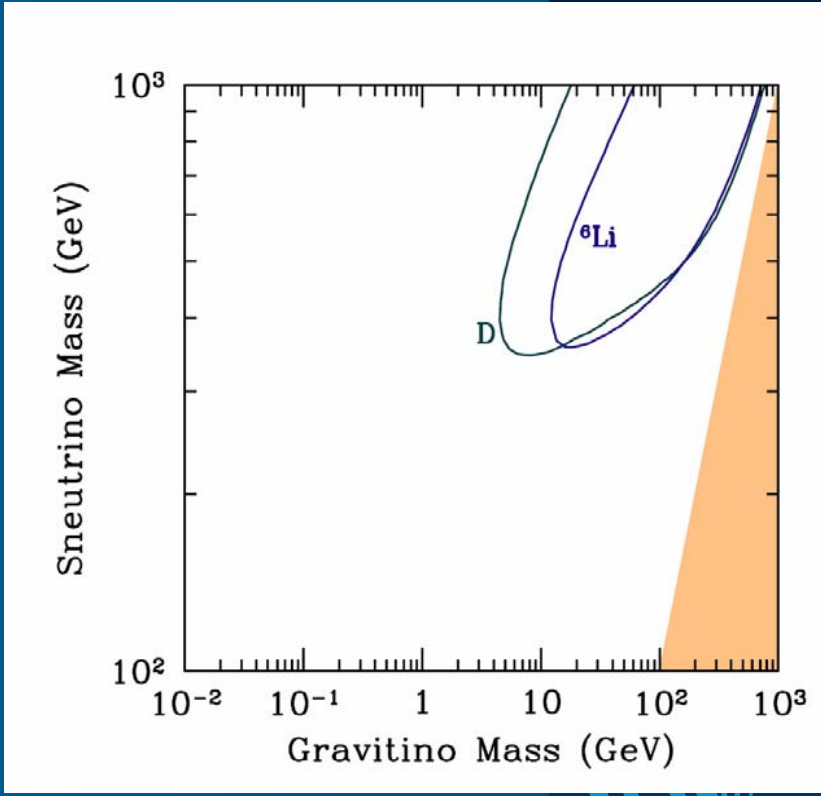
Relic abundance

$$Y_{\tilde{\nu}} \simeq 2 \times 10^{-14} \times \left(\frac{m_{\tilde{\nu}}}{100\ \text{GeV}} \right)$$

Kanzaki Kawasaki, Kohri, Moroi (06)

Kawasaki, Kohri, Moroi, Yotsuyanagi (08)





No allowed region for DM density with 100GeV sneutrinos

Stau NLSP and gravitino LSP scenario

Stable stau with weak-scale mass (<1TeV) was excluded by the experiments of ocean water

NLSP stau should be unstable

Bound-state effect (see next)

CHArged Massive Particle (CHAMP)

Kohri and Takayama, hep-ph/0605243
See also literature, Cahn-Glashow ('81)

Candidates of long-lived CHAMP in modern cosmology

stau, stop …

N+

"CHAMP recombination" with light elemcts

$T_c \sim E_{bin}/40 \sim 10\text{keV}$

$(E_{bin} \sim \alpha^2 m_i \sim 100\text{keV})$

See also the standard recombination between electron and proton, $(T_c \sim E_{bin}/40 \sim 0.1\text{eV}, E_{bin} \sim \alpha^2 m_e \sim 13.6\text{ eV}))$

CHAMP captured-nuclei, e.g., $(C,{}^4He)$ changes the nuclear reaction rates dramatically in BBN

Pospelov's effect

Pospelov (2006),**hep-ph/0605215**

- CHAMP bound state with ^{4}He enhances the rate

$$D + (^4He, C^-) \rightarrow {}^6Li + C^-$$

- Enhancement of cross section

$$\sim (\lambda_\gamma / a_{Bohr})^5 \sim (30)^5 \sim 10^{7-8}$$

Confirmed by Hamaguchi etal (07), hep-ph/0702274

Catalysis BBN is dangerous!!!

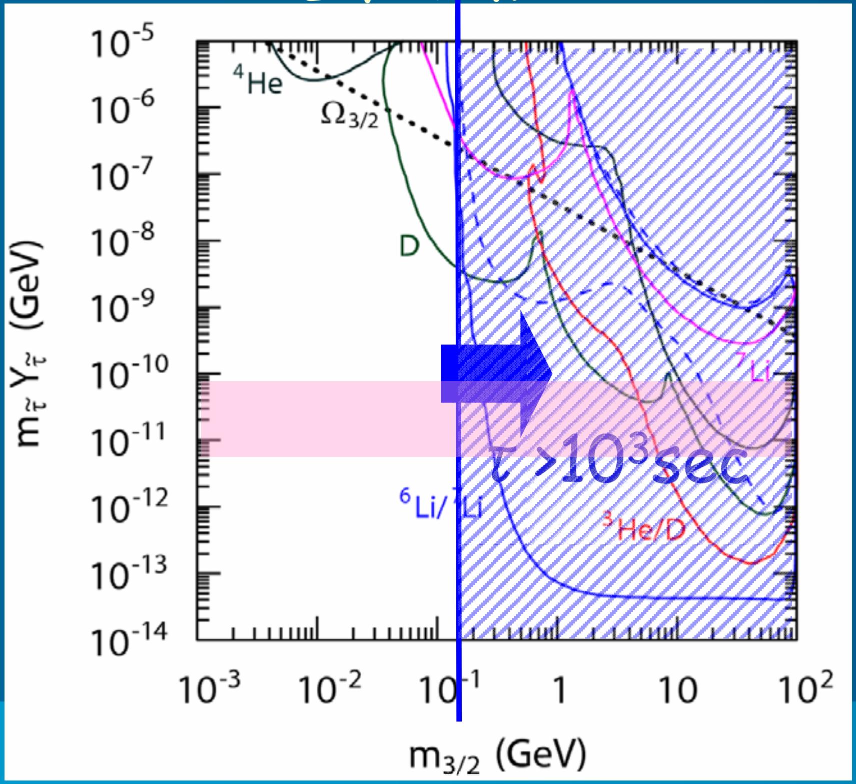
Stau NLSP and gravitino LSP Scenario in gauge mediation

Kawasaki, Kohri, Moroi PLB 649 (07) 436

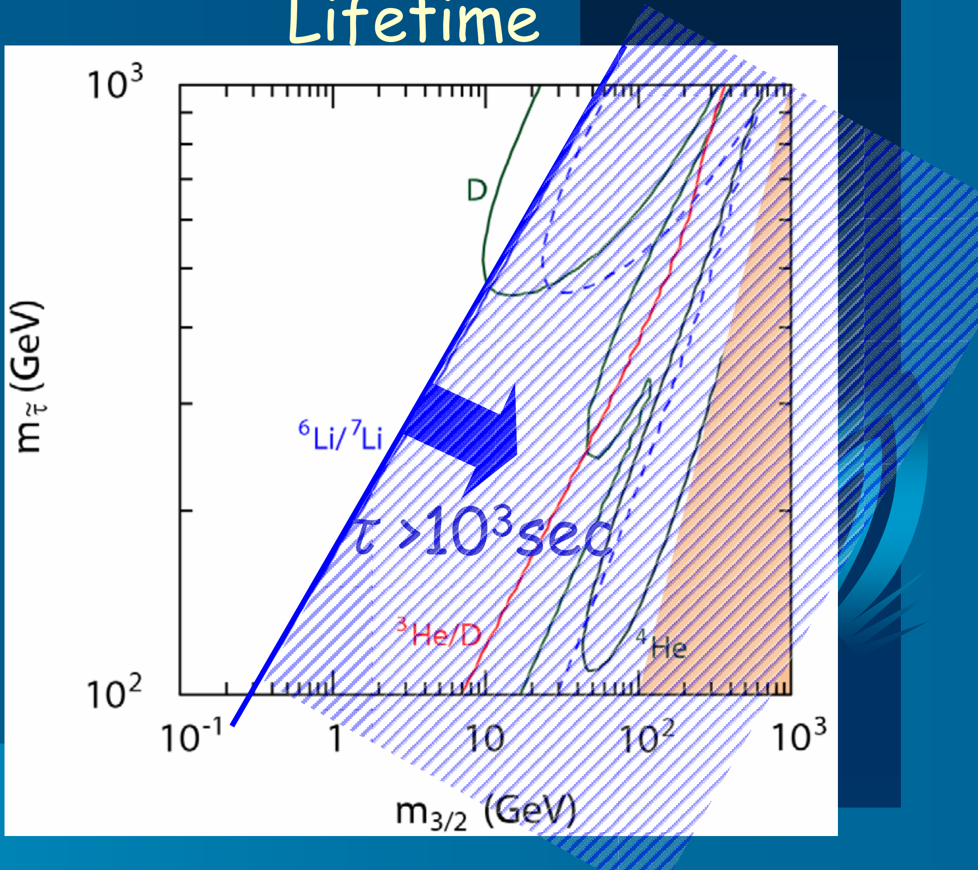
Relic abundance

$$Y_{\tilde{\tau}} \simeq 7 \times 10^{-14} \times \left(\frac{m_{\tilde{\tau}}}{100\ \mathrm{GeV}} \right)$$

Lifetime



Lifetime



Stau NLSP and axino/flatino LSP in DFSZ axion models in Gravity Mediation

Chun, Kim, Kohri, and Lyth (08)

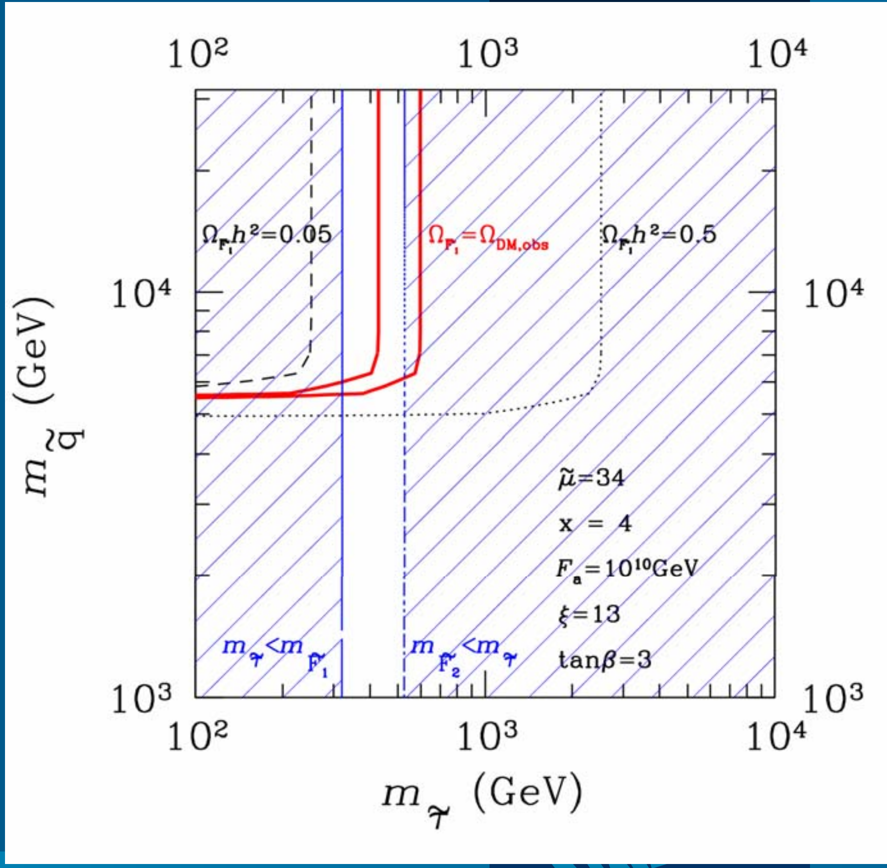
Decaying "flatons" reheats the universe and produce staus

$T_R \sim O(10)$ GeV

Contrary to gravitino LSP models, lifetime of stau is very short due to milder suppression ($\propto F_a^{-2}$) and many couplings.

$$10^{-8}\,\text{sec} \lesssim \tau_{\tilde{\tau}} \lesssim 10^{-2}\,\text{sec}$$

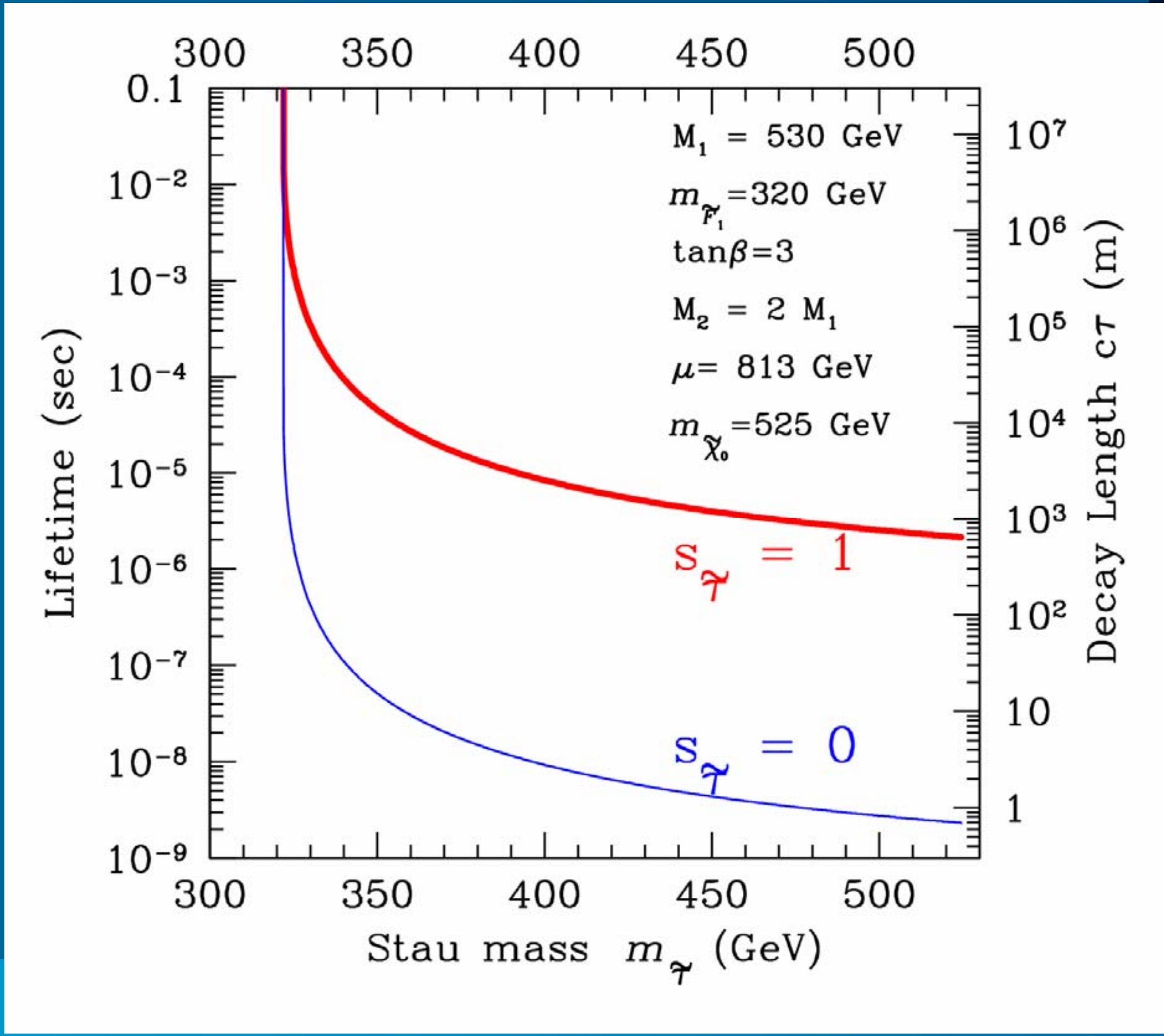
No BBN Catalysis



Stau can be found in LHC!!!

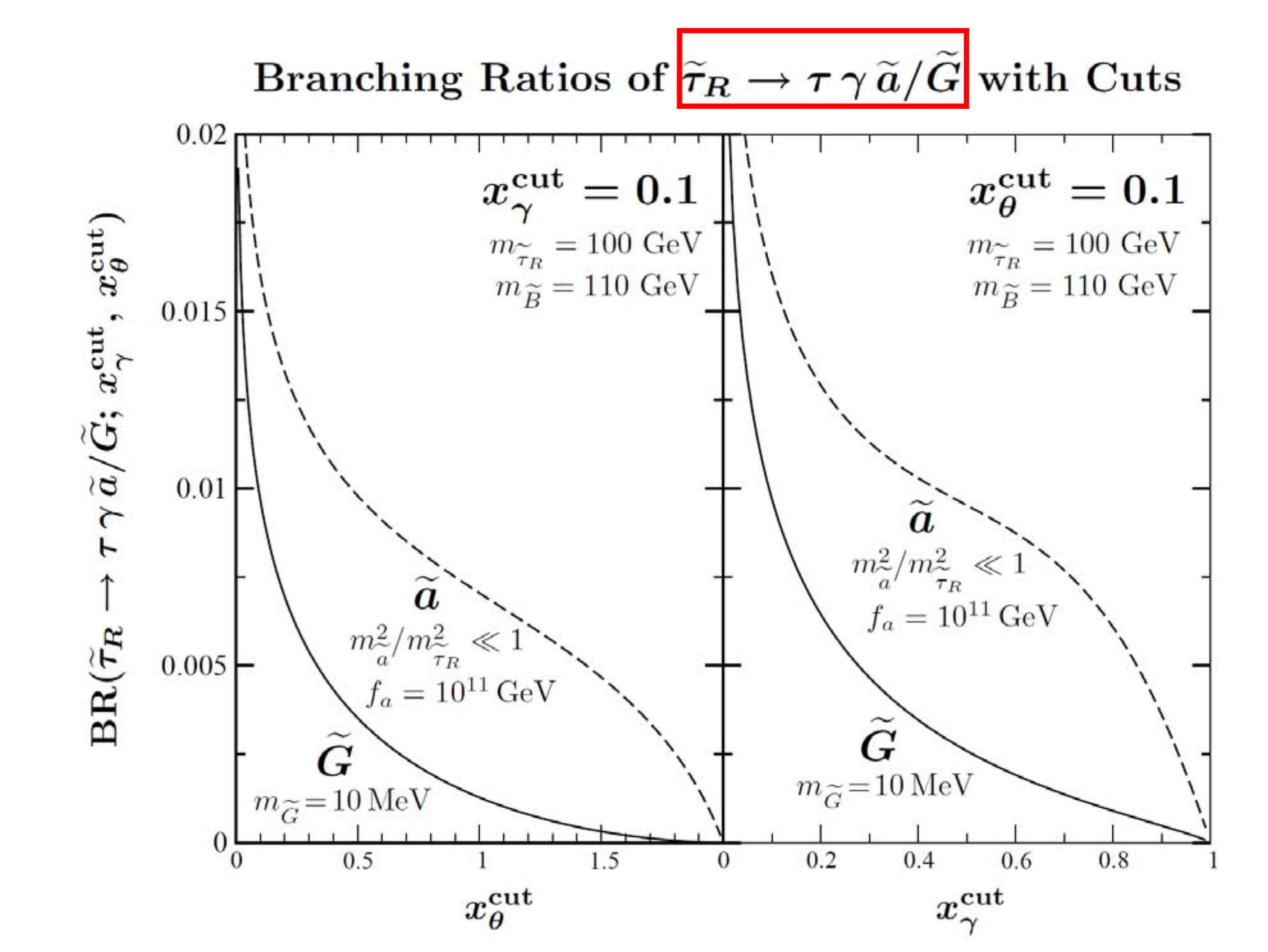
Lifetime of stau NLSP decaying into axino LSP

Chun, Kim, Kohri and Lyth (08)



Can we distinguish gravitino from axino in LHC?

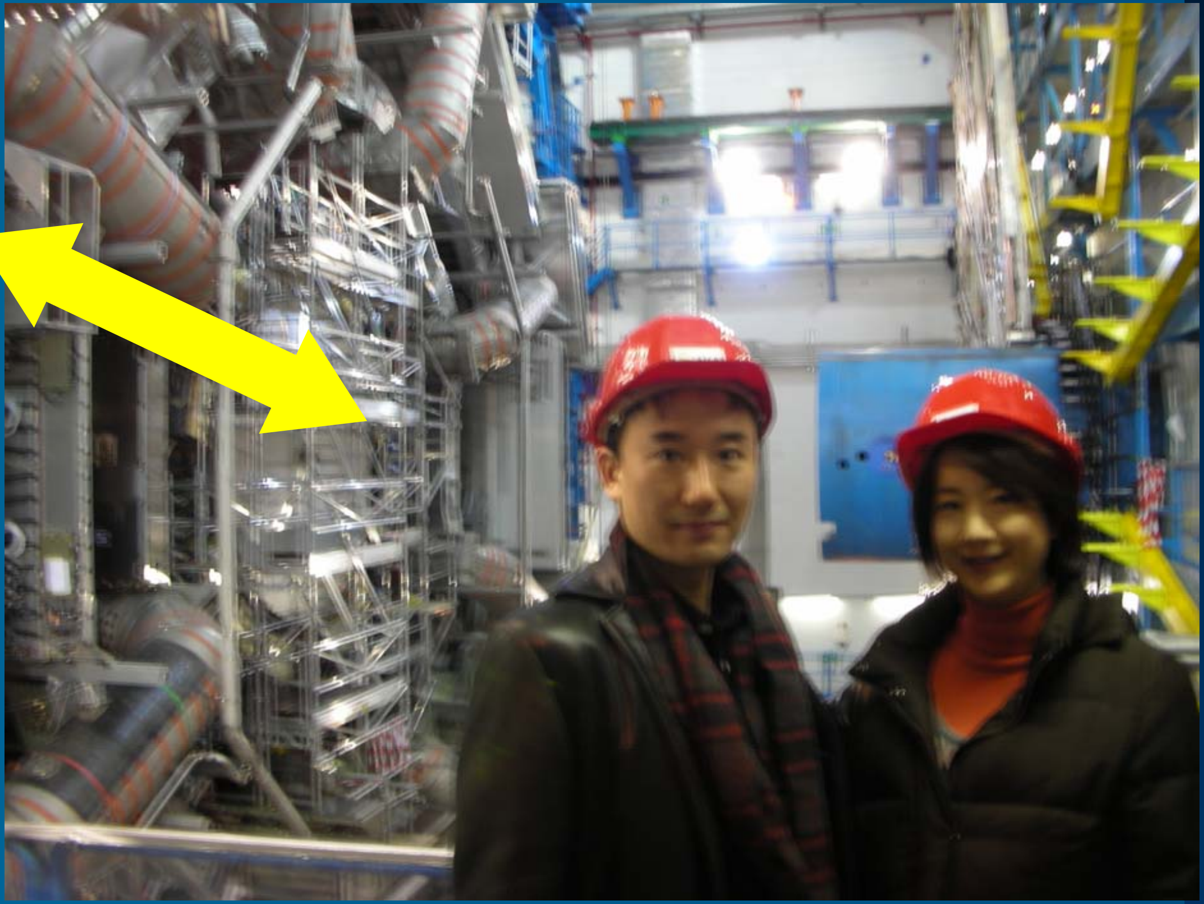
Brandenburg, Covi, Hamaguchi, Roszkowski, Steffen (05)



Large Hadron Collider (LHC)

10m

τ ~10^{-7}sec



ATLAS detector in CERN, Geneva, Switzerland

Place another stopper near ATLAS or CMS to stop long-lived charged SUSY particles (even for $c\tau$ > 10 m)

- 5 m Iron wall Hamaguchi, Kuno, Nakaya, and Nojiri (04)
- Water tank Feng and Smith (04)
- Surrounded rock

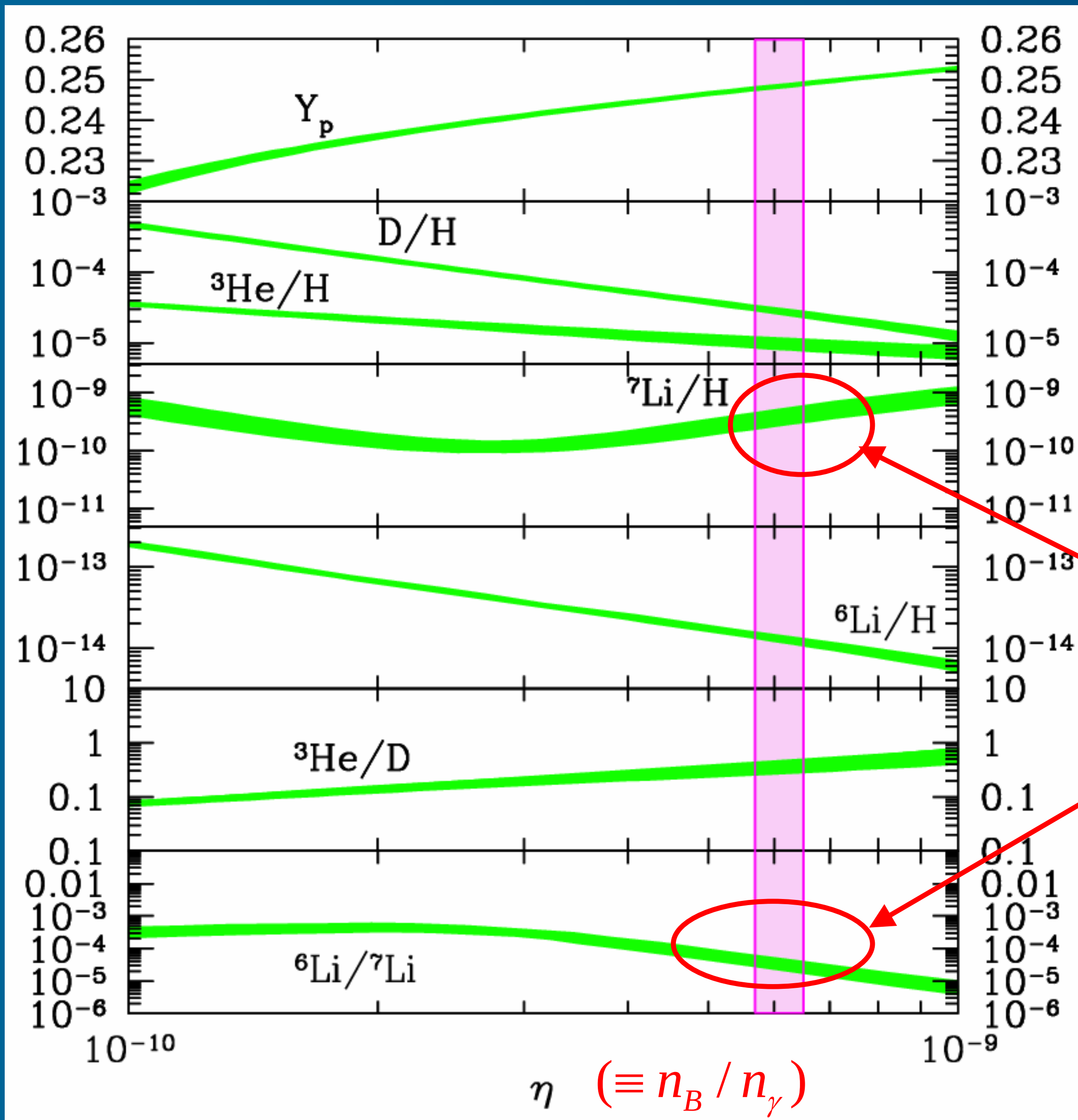
  De Roek, Ellis, Gianotti, Mootgat, Olive and Pape (05)

Lithium Problem

See also Keith Olive's talk

If we adopted smaller systematic errors for observational data for 6Li and 7Li , the theoretical values do not agree with those observational ones.

SBBN



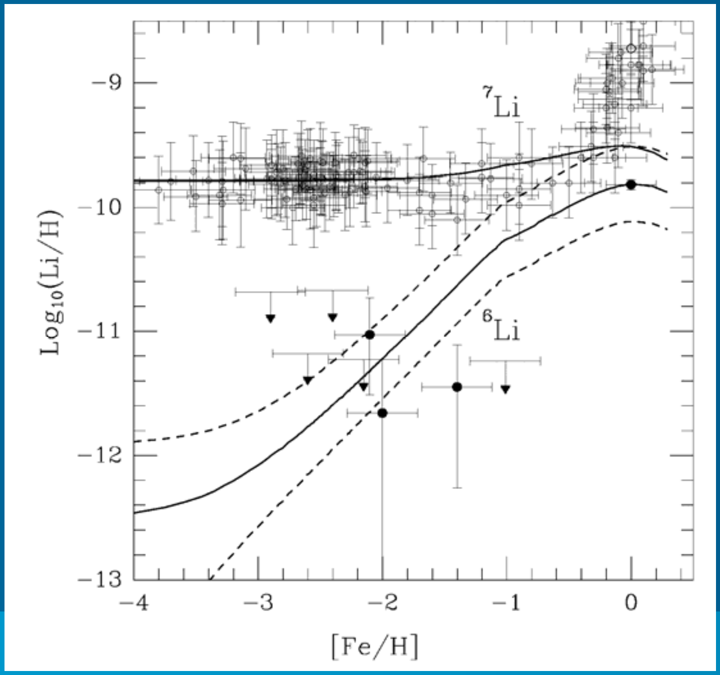
$(4\text{-}5) \times 10^{-10}$

5×10^{-5}

Lithium 7

a factor of two or three smaller !!!

- Expected that there is little depletion in stars.



Lemoine et al., 1997

$$^7Li/H = 2.19^{+2.2}_{-1.1} \times 10^{-10} \quad (1\sigma)$$

Bonifacio et al.(2002)

Melendez,Ramirez(2004)

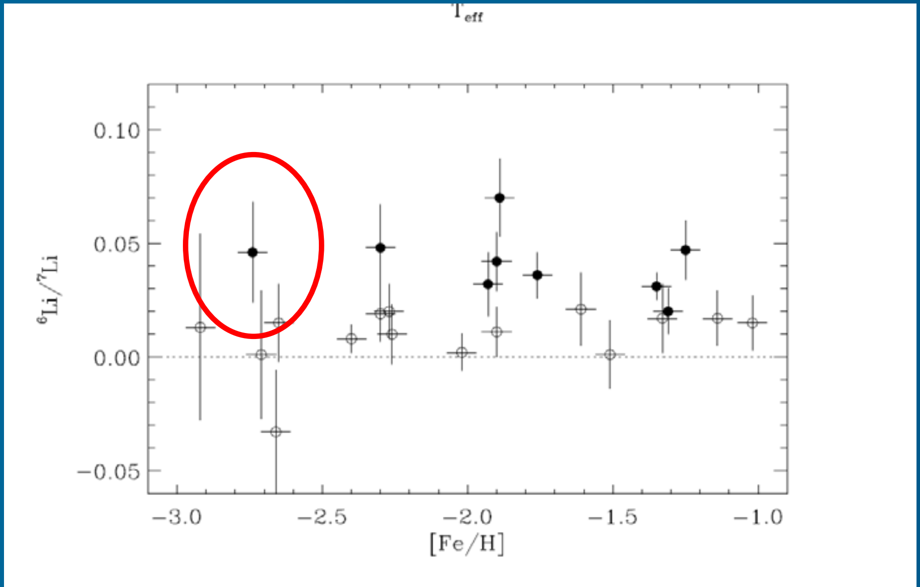
$$^7Li/H = 1.23^{+0.68}_{-0.32} \times 10^{-10} \quad (1\sigma)$$

Ryan et al.(2000)

Lithium 6

Asplund et al.(2006)

- Observed in metal poor halo stars in Pop II
- ^{6}Li plateau?



$$^6\mathrm{Li}/^7\mathrm{Li} = 0.022 - 0.090$$

$$^7\mathrm{Li}/\mathrm{H} \approx (1.1-1.5)\times 10^{-10}$$

still disagrees with SBBN

Astrophysically, factor-of-two depletion of Li7 needs a factor of O(10) Li6 depletion (Pinsonneault et al '02)

We need more primordial Li6?

Can decaying particles solve the Li Problem?

- Neutralino LSP and stau NLSP with small mass deference (<100 MeV)

  Bird,Koopmans,Pospelov(07), Jittoh etal (07,08)

- Residual annihilation of wino-like neutralino LSP with more massive gravitino Hisano et al (08)

  See K. Nakayama's RESCEU talk

- Stop NLSP and gravitino LSP scenario

  Kohri and Santoso (08)

Residual annihilation of wino LSP

Hisano, Kawasaki, Kohri, Nakayama(08)

See Kazunori Nakayama's RESCEU talk

- Non-thermal production of wino LSP by decaying massive such as gravitinos (> O(10) TeV)

$$\psi_\mu \to w + \tilde{w}$$

- Annihilating even after wino's freeze-out time with its larger annihilation rate than bino's

$$\langle \sigma v \rangle >> 3 \times 10^{-26} cm^3 / s$$

Even during/after BBN epoch!!!

Reduction of ^{7}Li and production of ^{6}Li

Jedamzik (04) , Cumberbatch et al (08)

- Copious neutrons and tritiums are produced in hadronic shower process with decay/annihilation
- Reducing Be7 through

Jedazmik ('04)

$$^7\mathrm{Be}(n,p)^7\mathrm{Li}(p,^4\mathrm{He})^4\mathrm{He}$$

$$(^7\mathrm{Li} \text{ is produced later by } ^7\mathrm{Be} + e^- \rightarrow {}^7\mathrm{Li} + \nu_e)$$

- Tritium scatters off the background He4 and produces Li6

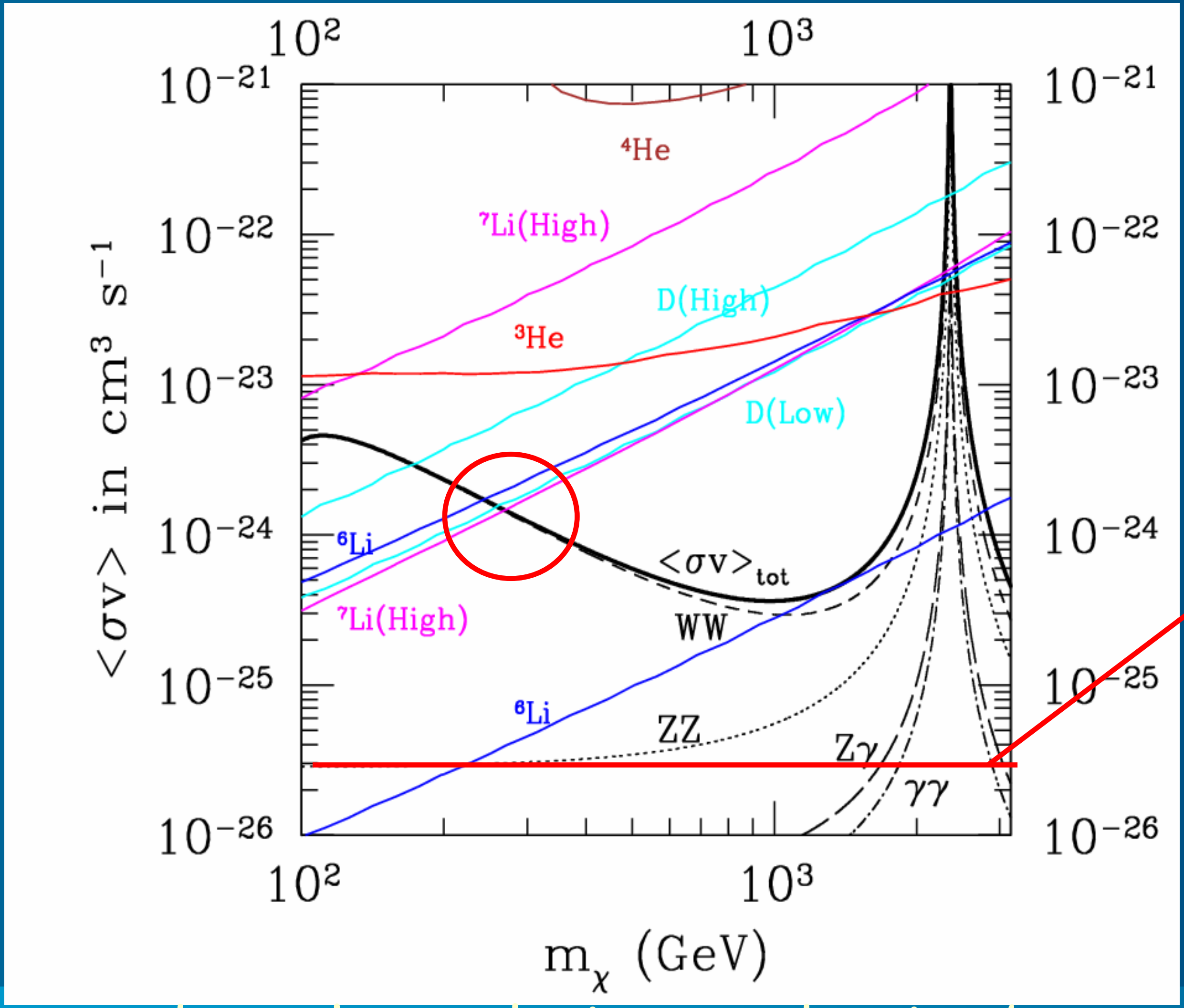
Dimopoulos et al ('89)

$$\mathrm{T} + 4\mathrm{He} \rightarrow {}^6\mathrm{Li} + n$$

Residual annihilation of wino LSP

Hisano et al (08)

See K. Nakayama's RESCEU talk



Thermal (bino) DM

We need nonthermal wino production by gravitino decay

Stop NLSP and gravitino LSP

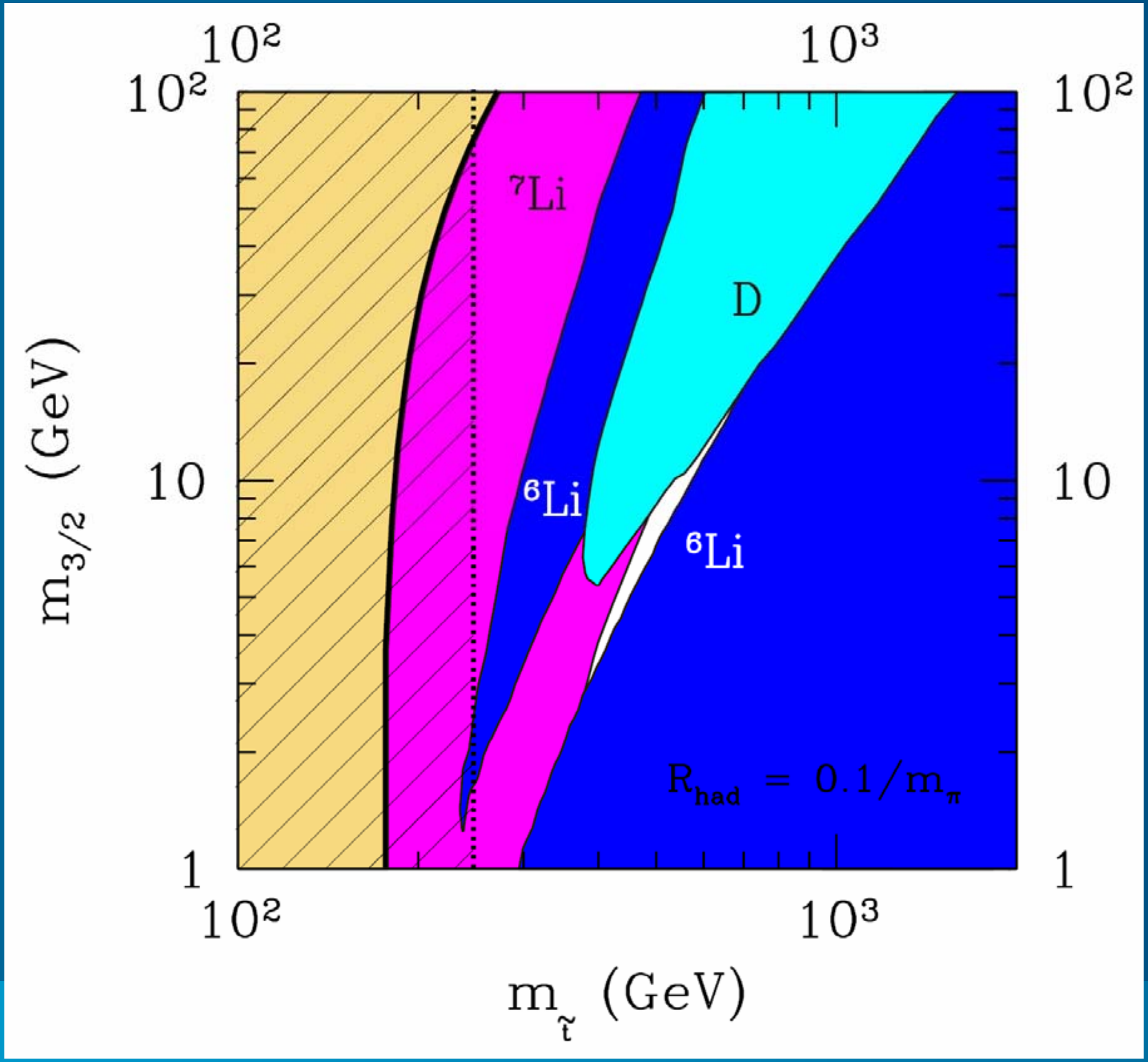
Kohri and Santoso (08)

- Stop is confined into "messino" after QCD phase transition
- Second annihilation of stopa occurs just after QCD phase transition through strong interaction
- Stop number density is highly suppressed, but it is appropriate to solve the Li problem

$$m_{\tilde{t}} n_{\tilde{t}} / s \sim 10^{-14} GeV - 10^{-13} GeV$$

Stop NLSP and gravitino LSP

Kohri and Santoso arXiv:0811.1119v1 [hep-ph]



Conclusion

- Direct and indirect detections of DM will become more attractive in near future to get information for SUSY and SUGRA
- BBN is a strong tool to investigate the long-lived SUSY particles, such as gravitino, neutralino, stau, stop, or axino
- In neutralino LSP and unstable gravitino scenario in gravity mediated SUSY breaking models, the constraint on reheating temperature after primordial inflation is very stringent,

$$T_R \leq 3 \times 10^5 GeV - 10^7 \ GeV$$

$$(\text{for } m_{3/2} = 100 \ GeV \ - 1 TeV)$$

- In gauge mediation, thermal-relic NLSP fails to produce DM gravitino density for natural scales of NLSP masses (100GeV – 1TeV) . We need thermal or nonthermal production of LSP gravitino by the decay of Inflaton, moduli etc.

See Moroi, Murayama, Yamaguchi (93) for thermal production, and Endo, Takahashi, Yanagida (07) for non-thermal production of LSP gravitino

Another ideas

Hooper, Blasi, Serpico (08)

- positrons produced in pulsars