ダークマターの候補粒子に対する宇宙物理・宇宙論的制限

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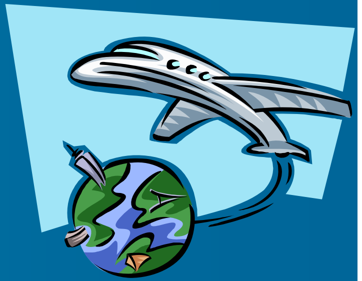

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- Brief review of Big-bang Nucleosynthesis (BBN)

- Brief review of Supersymmetry (SUSY) and Supergravity (SUGRA)

- Lightest SUSY Particle (LSP) Dark Matter (DM) in Minimal SUSY Standard Model (MSSM), Constrained MSSM (CMSSM) and mSUGRA

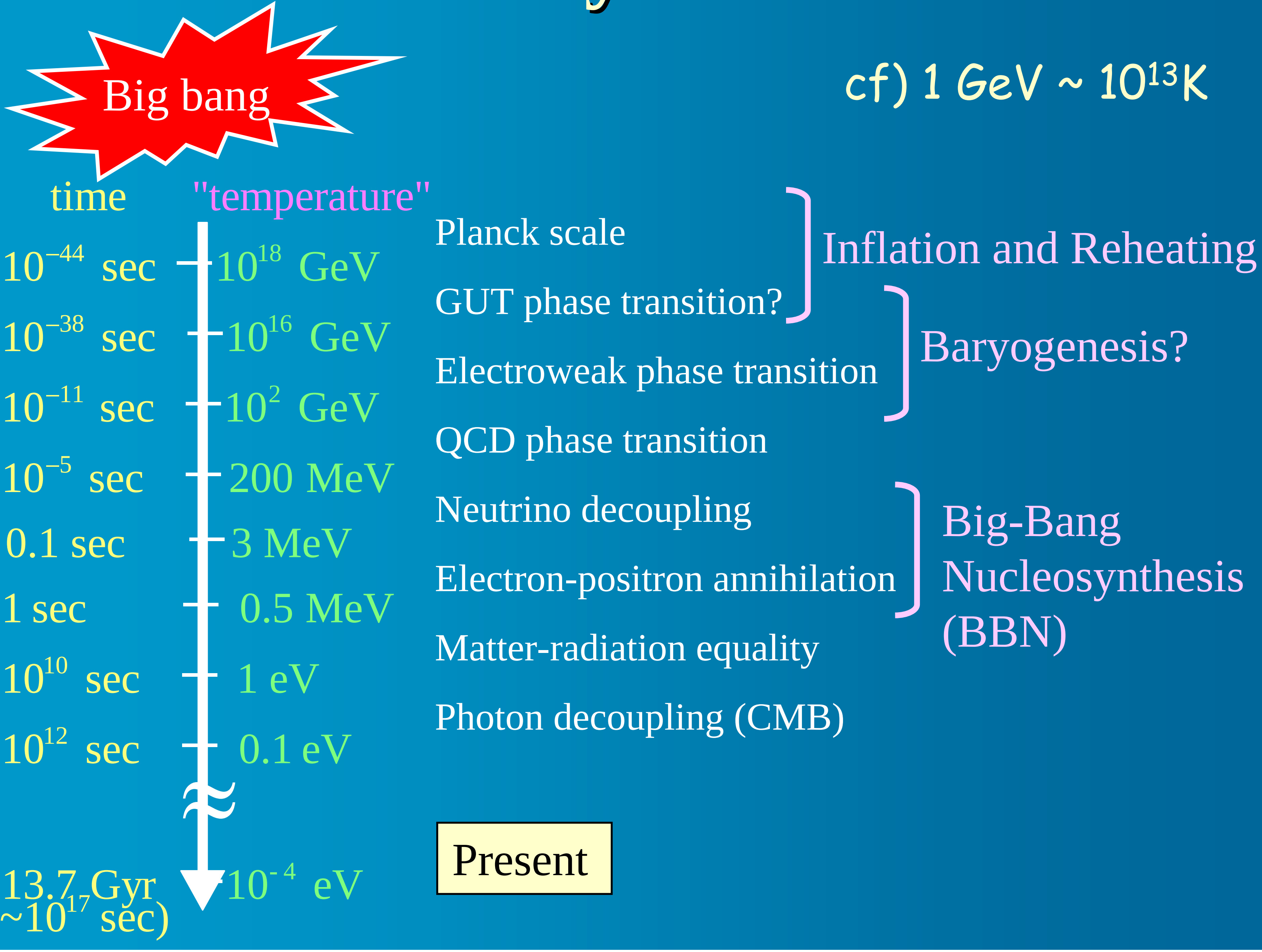
- Cosmological and astrophysical constraints on Lightest SUSY Particle (LSP) and Next LSP (NLSP)

- Solving lithium problem

Brief review of
Big-bang nucleosynthesis (BBN)

Thermal history of the Universe

cf) 1 GeV ~ 10^{13}K



Big bang

time	"temperature"	
10^{-44} sec	10^{18} GeV	Planck scale
10^{-38} sec	10^{16} GeV	GUT phase transition?
10^{-11} sec	10^{2} GeV	Electroweak phase transition
10^{-5} sec	200 MeV	QCD phase transition
0.1 sec	3 MeV	Neutrino decoupling
1 sec	0.5 MeV	Electron-positron annihilation
10^{10} sec	1 eV	Matter-radiation equality
10^{12} sec	0.1 eV	Photon decoupling (CMB)
13.7 Gyr (~10^{17} sec)	10^{-4} eV	Present

Inflation and Reheating

Baryogenesis?

Big-Bang Nucleosynthesis (BBN)

Thermal history around BBN Epoch

cf) 100 MeV ~ 10^{12}K

10^{-4} sec	100 MeV	Muon annihilation	$(\mu^+ + \mu^- \to 2\gamma)$
	≈		
0.1 sec	2 -- 3 MeV	Neutrino decoupling	$(\nu_e + e^- \not\rightleftarrows \nu_e + e^-)$
1 sec	1 MeV	n/p freezeout	$(n + \nu_e \not\rightleftarrows p + e^-)$
	0.5 MeV	Electron-positron annihilation	$(e^+ + e^- \to 2\gamma)$
10^2 sec	0.1 MeV	Beginning of BBN	
10^3 sec	0.07 MeV	End of (Standard) BBN	

Scenario of BBN

cf) 1 MeV ~ 10^{10}K

1) $T > 1\ \mathrm{MeV}\ (t < 1\mathrm{sec})$

Radiation	$\gamma, e^{\pm}, \nu$
Matter	n, p

Weak interaction is in equilibrium

$$n + e^{+} \leftrightarrow p + \overline{\nu_e}$$

$$\boxed{\frac{n_n}{n_p} = Exp\left[-\frac{Q}{T}\right]}$$

$(\mathrm{Q} \equiv m_n - m_p \sim 1.29\ \mathrm{MeV})$

2) $T \sim 1\ \mathrm{MeV}\ (t \sim 1\ \mathrm{sec})$ cf) 1 MeV ~ 10^{10}K

Feezeout of weak interaction

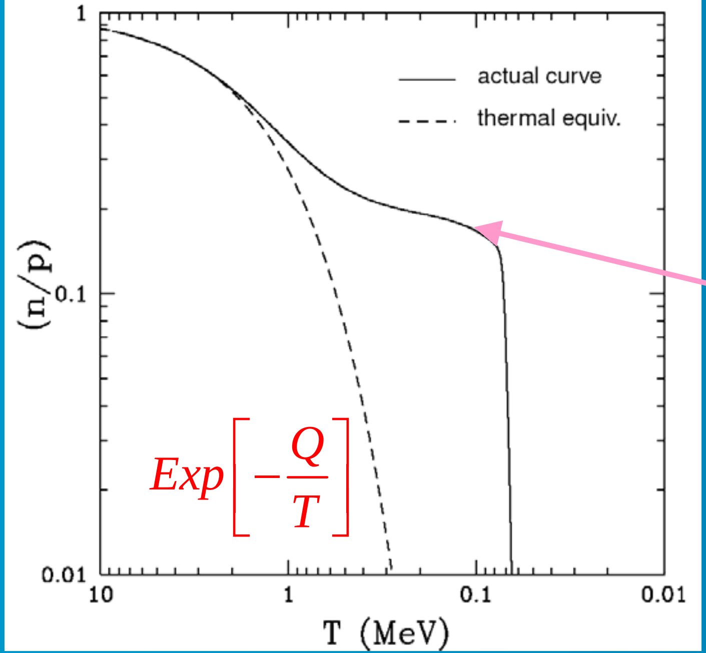
- Weak interaction rate $\quad \Gamma_{n\leftrightarrow p} \sim \sigma_{n\leftrightarrow p} n_e \sim G_F^2 T^5$
- Hubble expansion rate $\quad H = \dfrac{\dot{a}(t)}{a(t)} \sim T^2 / M_{pl}$

$$\frac{\Gamma}{H} \approx \left(\frac{T}{0.8\ \mathrm{MeV}} \right)^3$$

$\Gamma < H \quad (T < 0.8\ \mathrm{MeV} \equiv T_f)$ ⇨ $\left(n_n / n_p \right)$ is fixed

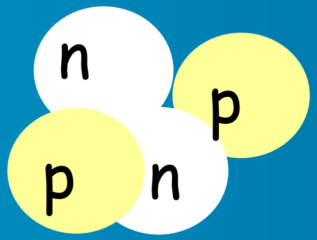
$$\boxed{\left(\frac{n_n}{n_p} \right)_{\text{freezeout}} \approx Exp\left[-\frac{Q}{T_f} \right]}$$

He4 mass fraction



$$\left(\frac{n_n}{n_p}\right)_{\text{freezeout}} \approx \frac{1}{7}$$

^4He



$$n_{^4\text{He}} = n_n/2$$

$$Y_p \equiv \frac{\rho_{^4\text{He}}}{\rho_B} \approx \frac{4\times \cancel{m_N} \times n_{^4\text{He}}}{\cancel{m_N} \times (n_n + n_p)} \approx \frac{2(n_n/n_p)_{\text{freezeout}}}{(n_n/n_p)_{\text{freezeout}} + 1} \approx 0.25$$

3) $T \sim 0.1\ \mathrm{MeV}\ (t \sim 100\ \mathrm{sec})$

cf) 0.1 MeV ~ 10^9K

$$p + n \to D + \gamma$$

$T \ll B_D = 2.2\ \mathrm{MeV}$

4) $T < 0.1\ \mathrm{MeV}\ (t > 100\ \mathrm{sec})$

$$n_D / n_H \sim 16.3(T / m_N)^{3/2}\eta\ \ \exp[B_D / T]\ >\ 0.01$$

$$D + D \to T + p,\ \ {}^3\mathrm{He{+}n}$$

$$T + D\ ({}^3\mathrm{He} + D) \to {}^4\mathrm{He{+}n}\ ({}^4\mathrm{He{+}p})$$

A little D and ^{3}He are left as cold ashes

There is no stable nuclei for A=5,8. Mass 7 nuclei are produced a little.

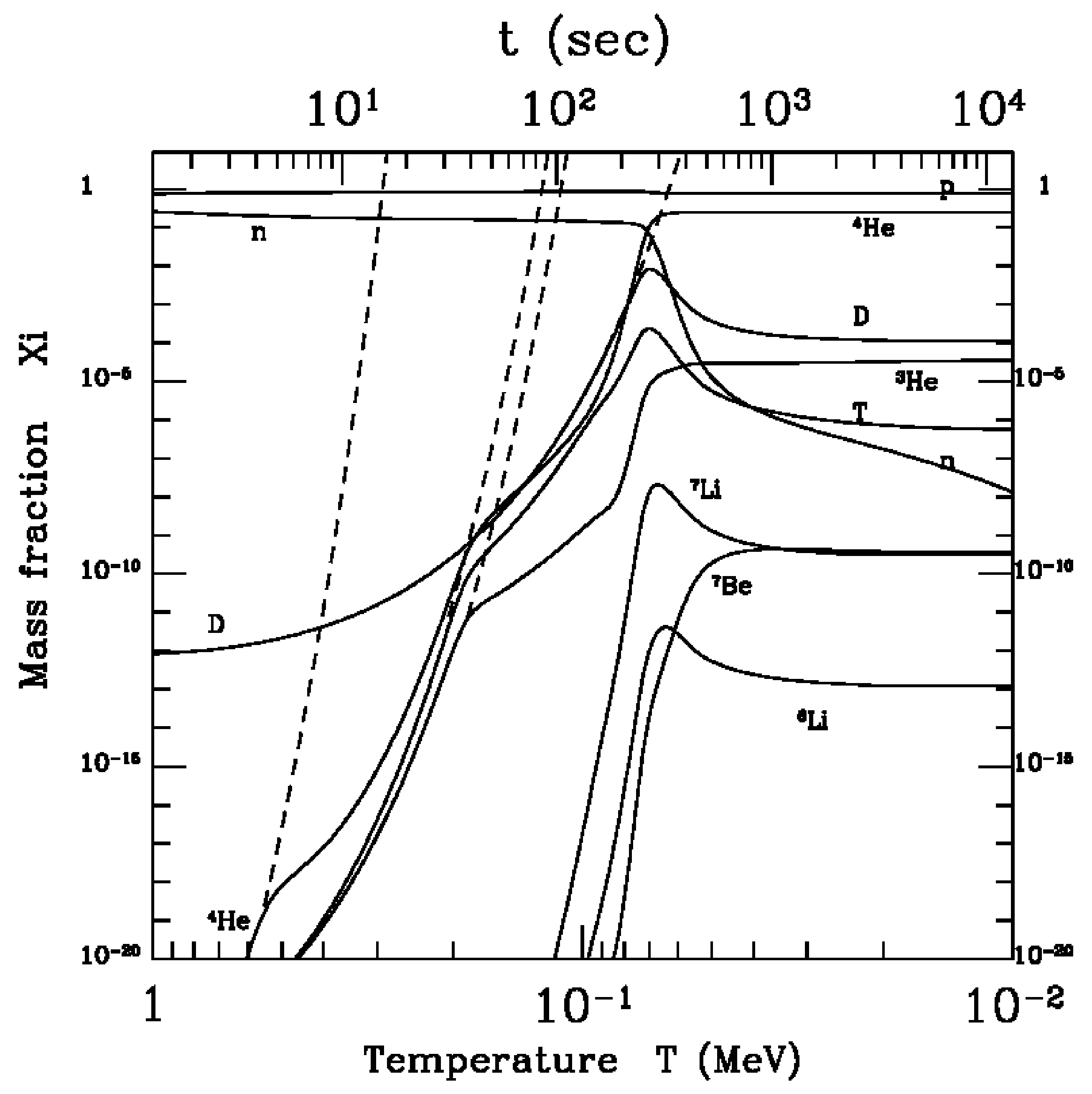
$${}^4\mathrm{He} + T \to {}^7\mathrm{Li}{+}\gamma$$

$${}^4\mathrm{He} + {}^3\mathrm{He} \to {}^7\mathrm{Be}{+}\gamma$$

↳ $${}^7\mathrm{Be} + e^- \to {}^7\mathrm{Li}{+}\nu_\mathrm{e}$$

$${}^4\mathrm{He} + D \to {}^6\mathrm{Li}{+}\gamma$$

Time evolution of light elements



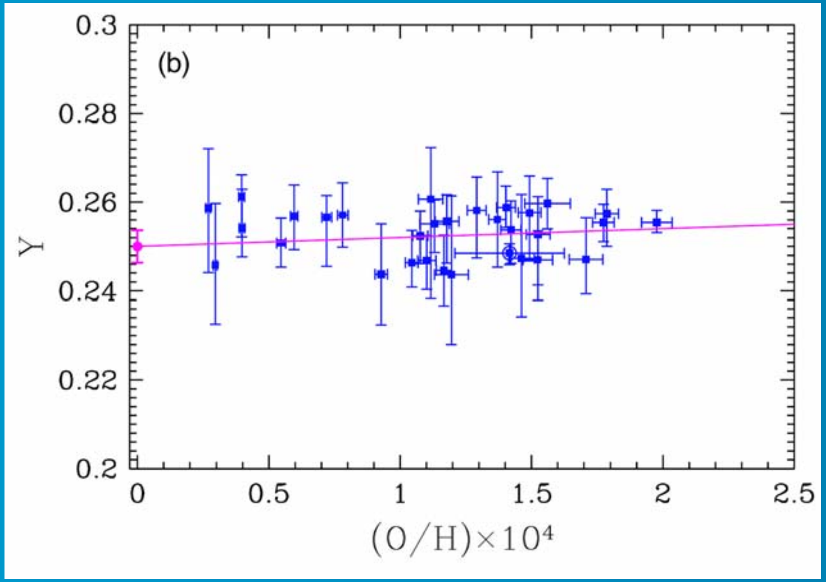
Observational light element abundances

1) ^{4}He

●Observe the recombination line in Metal poor extragalactic H II region, or blue compact galaxy

●Identifying H II region as He II region

●Extrapolating them into zero metalicity



Fukugita, Kawasaki (06)

$$Y_p = 0.250 \pm 0.004$$

Fukugita, Kawasaki (06)

$$Y_p = 0.2474 \pm 0.0028$$

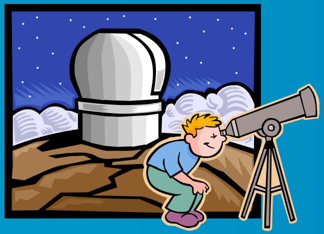
Peimbert, Luridiana, Peimbert (07)

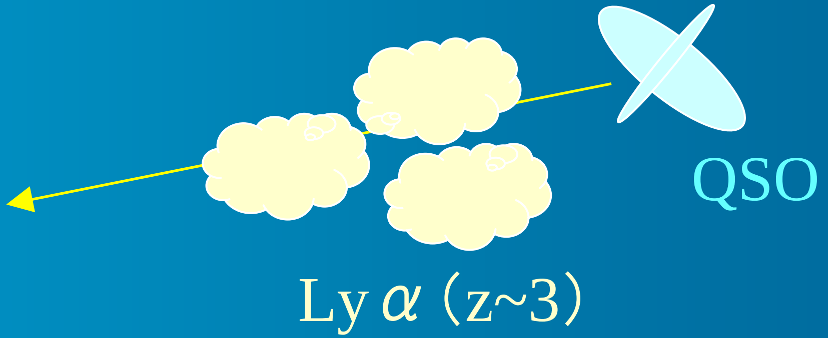
$$Y_p = 0.2516 \pm 0.0011$$

Izotov, Thuan, Stasinska (07)

2) Deuterium

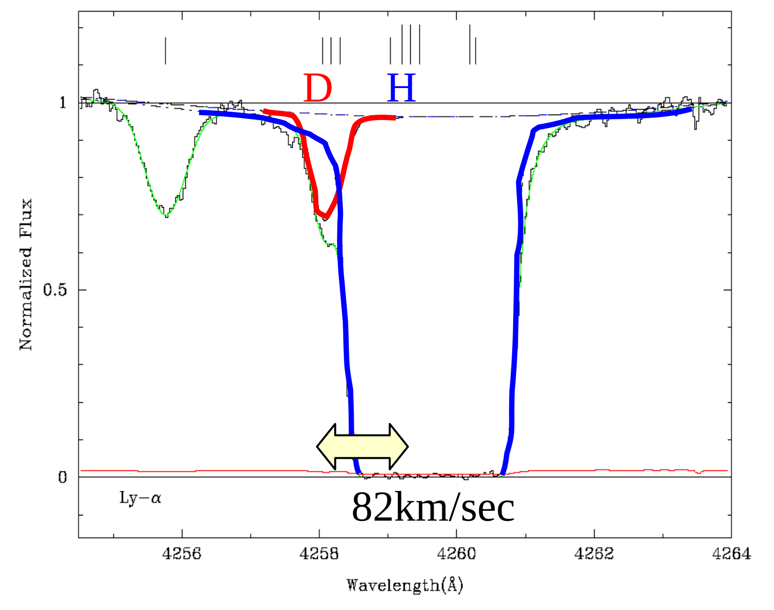
Observed in high redshift QSO absorption system





QSO

Lyα (z~3)



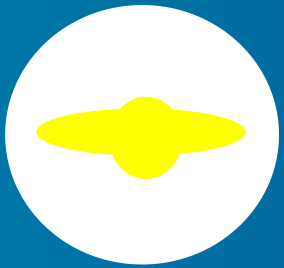
Burles and Tytler (1997)

$$D/H = (2.82 \pm 0.26) \times 10^{-5}$$

O’Meara et al.(2006)

2) Lithium 7

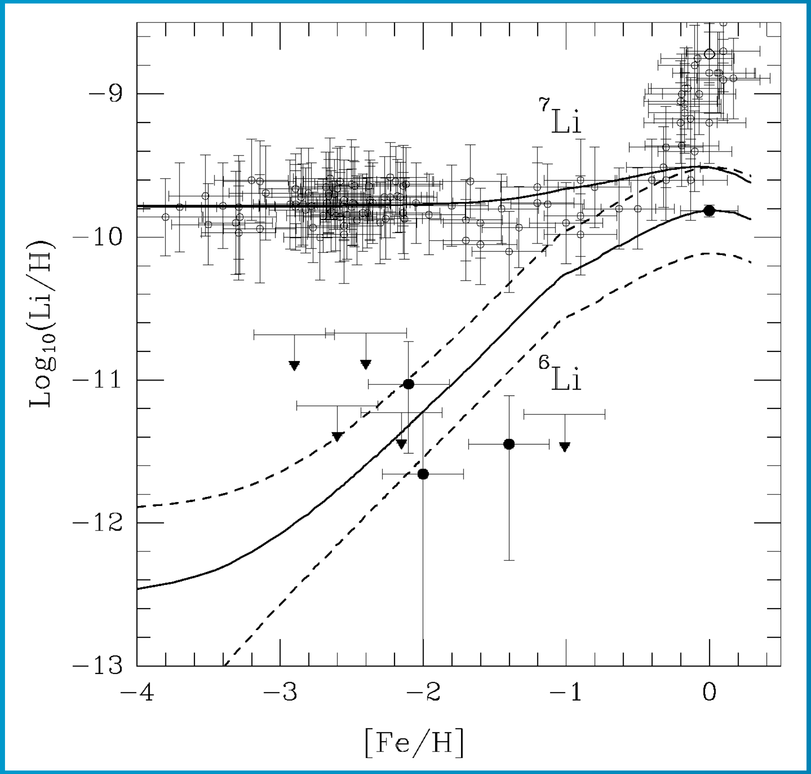
- Observing metal poor halo stars in Pop II



- Abundance does not depend on metalicity so much for

$$T_{\mathrm{eff}} > 5700^{\circ}\mathrm{K}\ (\propto M),\quad [\mathrm{Fe}/H] < \text{-}2$$

“Spite’s plateau”



Lemoine et al., 1997

$$\mathrm{Log}_{10}\left({}^{7}\mathrm{Li}/\mathrm{H}\right) = -9.90 \pm 0.09$$

Bonifacio et al (2006)

Observational Light Element Abundances

- He4 $Y_p = 0.2516 \pm 0.004$

Fukugita, Kawasaki (2006)

Peimbert,Lridiana, Peimbert(2007)

Izotov,Thuan, Stasinska (2007)

- D $D/H = (2.82 \pm 0.26) \times 10^{-5}$

O'Meara et al. (2006)

- Li7 $\log_{10}\left({}^{7}\mathrm{Li}/\mathrm{H}\right) = -9.90 \pm 0.09\ (\pm 0.35)_{\mathrm{syst.}}$

Melendez,Ramirez(2004)

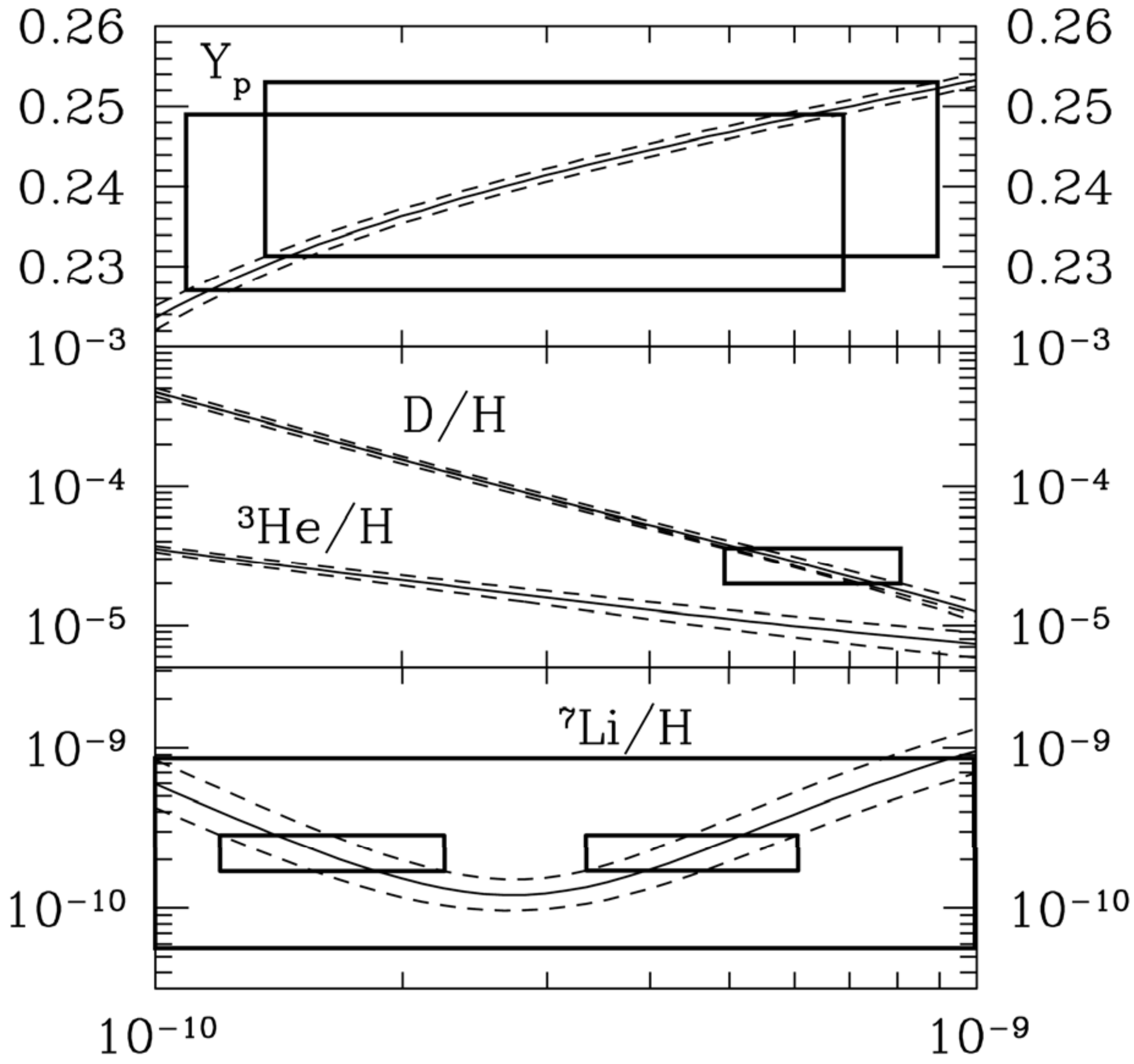
- Li6 ${}^{6}\mathrm{Li}/{}^{7}\mathrm{Li} < 0.046 \pm 0.022\ (\pm 0.106)_{\mathrm{sys}}$

Asplund et al(2006)

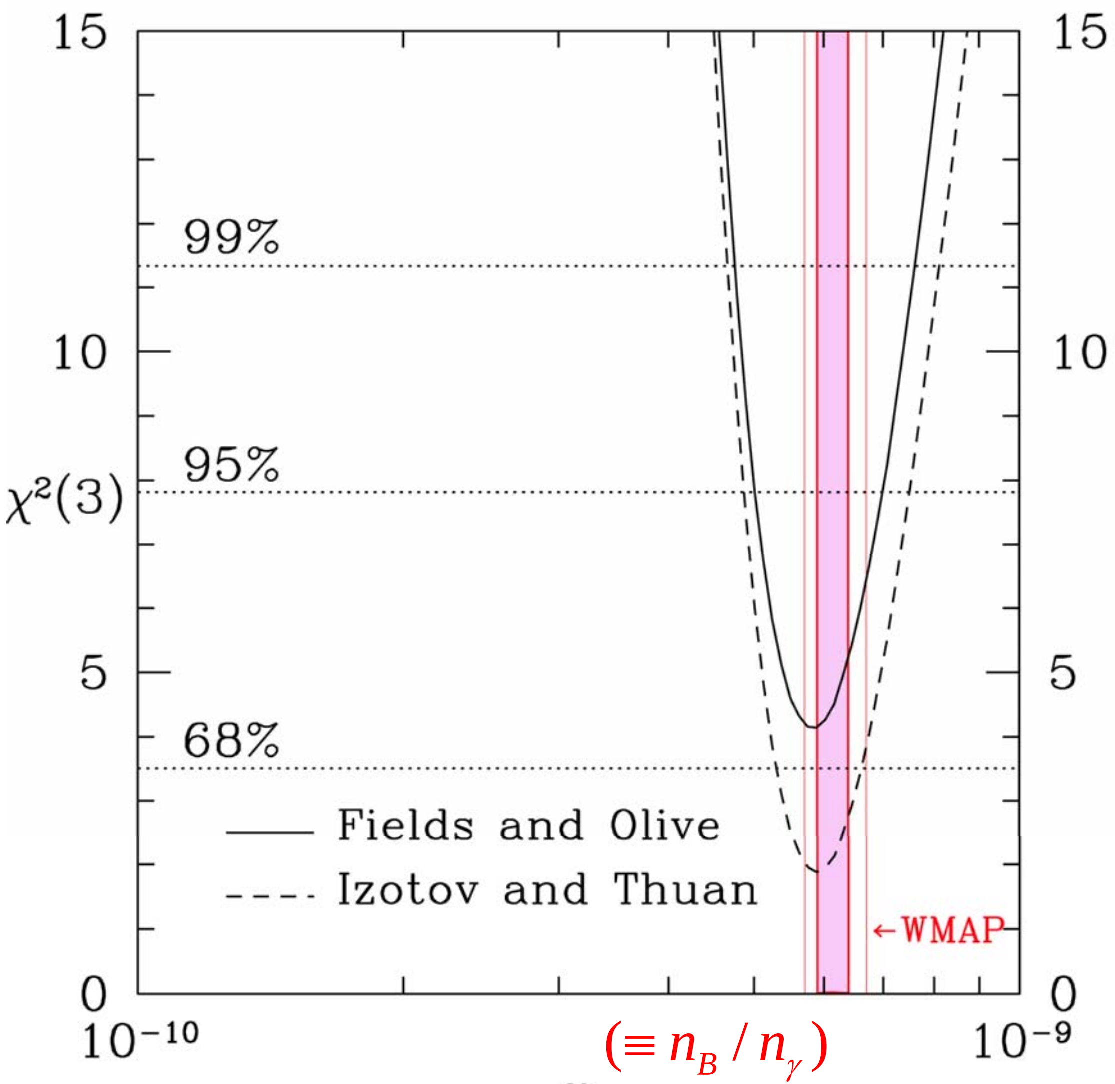
- He3 ${}^{3}\mathrm{He}/D < 0.83 + 0.27$

Geiss and Gloeckler (2003)

SBBN



$\eta \quad (\equiv n_B / n_\gamma)$



$(\equiv n_B / n_\gamma)$

$$\eta_{\mathrm{WMAP}} = (6.225 \pm 0.160) \times 10^{-10}$$

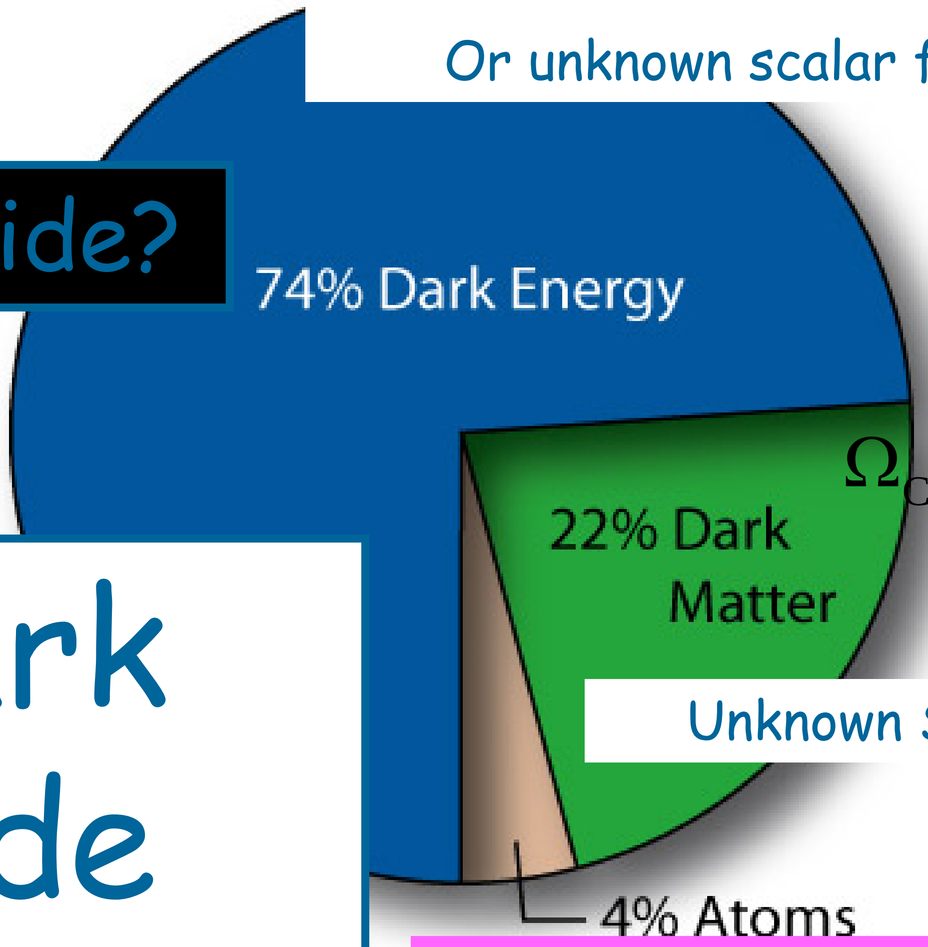
Brief review of Supersymmetry (SUSY)

Dark Matter?

Einstein's Cosmological Constant

Or unknown scalar field?

Dark side?



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

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/SUSGRA

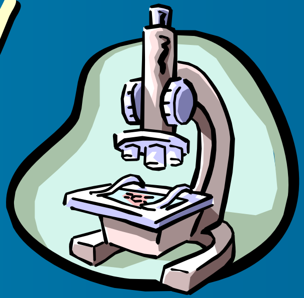
- Neutralino χ (Bino, wino, or higgsinos)

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

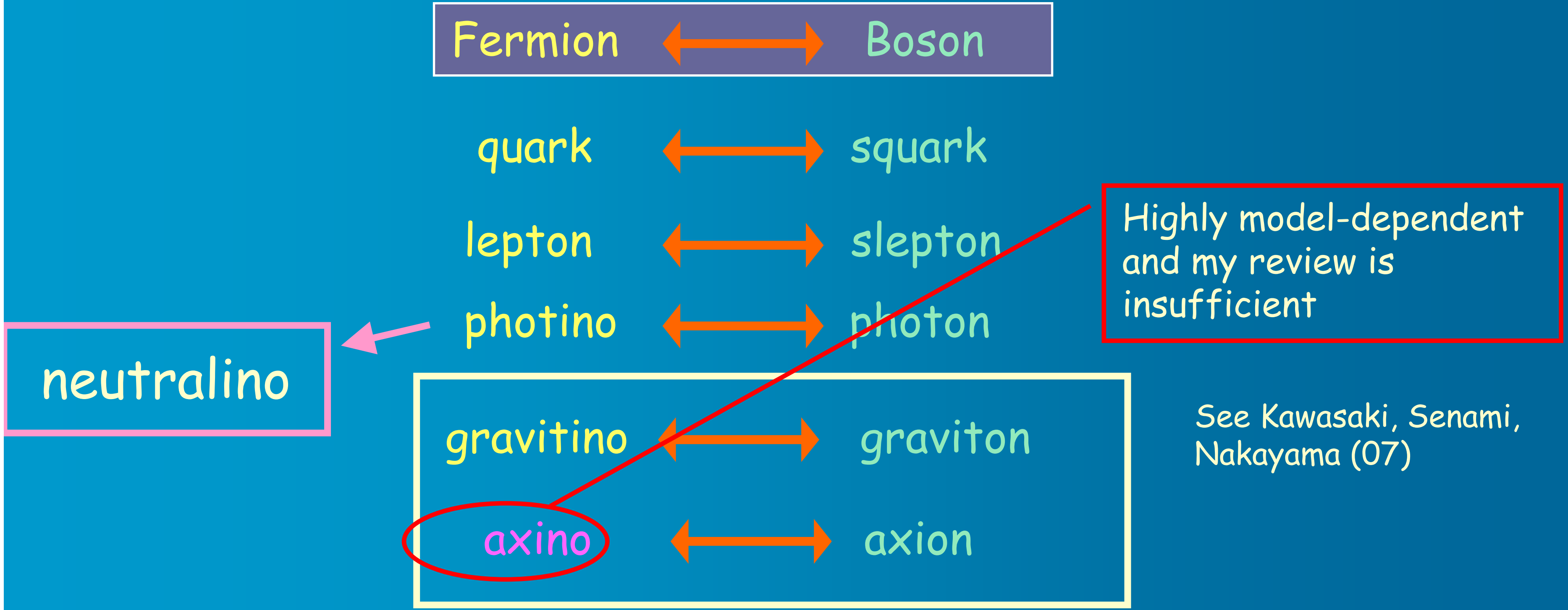
- Gravitino ψ_μ

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

Introduction to SUSY



- Supersymmetry (SUSY)
  - Solving “Hierarchy Problem”
  - Realizing “Coupling constant unification in GUT”



Fermion ⟷ Boson

quark ⟷ squark

lepton ⟷ slepton

photino ⟷ photon

neutralino

gravitino ⟷ graviton

axino ⟷ axion

Highly model-dependent and my review is insufficient

See Kawasaki, Senami, Nakayama (07)

Depending on SUGRA models

Hierarchy Problems

- GUT-scale

$$M_X \approx 10^{14} - 10^{15} GeV$$

- Weak-scale

$$M_W \approx 10^{2}\text{-}10^{3} GeV$$

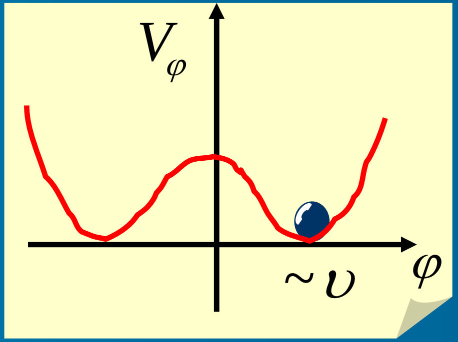
12-13 orders of magnitude !!!

Higgs mass

$$\boxed{m^2_{\varphi 0} = \frac{d^2 V_\varphi}{d\varphi^2} \approx \lambda \upsilon^2 \approx O(M_W^2)}$$

where Higgs's potential

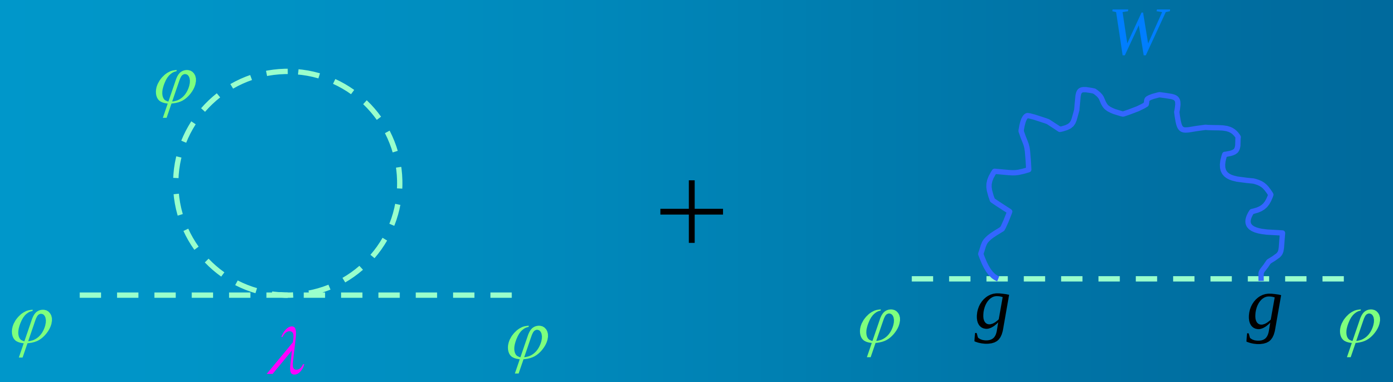
$$V_\varphi = \lambda\left(\varphi^\dagger \varphi - \upsilon^2/2\right)^2$$



c.f) Masses of fermions and vector bosons

$$m_\psi \sim h_\psi \langle\varphi\rangle,\ m_Z \sim g\langle\varphi\rangle$$

Radiative correction to Higgs mass in Quantum Field Theory



$\delta m_\varphi^2 \sim \lambda\Lambda^2 + g^2\Lambda^2$ ⬅ Quadratic divergence

Cut off scale $\Lambda \sim M_X \sim 10^{15}$ GeV

$$\boxed{\delta m_\varphi^2 \sim \left(10^{15}\ \mathrm{GeV}\right)^2\ ?}$$

How can we resolve the problem?

Weak scale in the tree level, $m^2_{\varphi 0} \sim (10^2\,\mathrm{GeV})^2$

In total, $\delta m^2_{\varphi} \sim (10^{15}\,\mathrm{GeV})^2$

$$m^2_{\varphi} \sim m^2_{\varphi\,0} + \delta m^2_{\varphi} \sim (10^{15}\,\mathrm{GeV})^2\ ?$$

To retain the hierarchy, we require an accidental cancellation,

$$m^2_{\varphi\,0} + \delta m^2_{\varphi\,1} + \delta m^2_{\varphi\,2} + \delta m^2_{\varphi 3} + \ldots \sim (10^2\,\mathrm{GeV})^2\ ?$$

$$\left[O(10^{15}\,\mathrm{GeV})\right]^2$$

GDP in USA (2002)?

$ 10,110,087,734,958.95

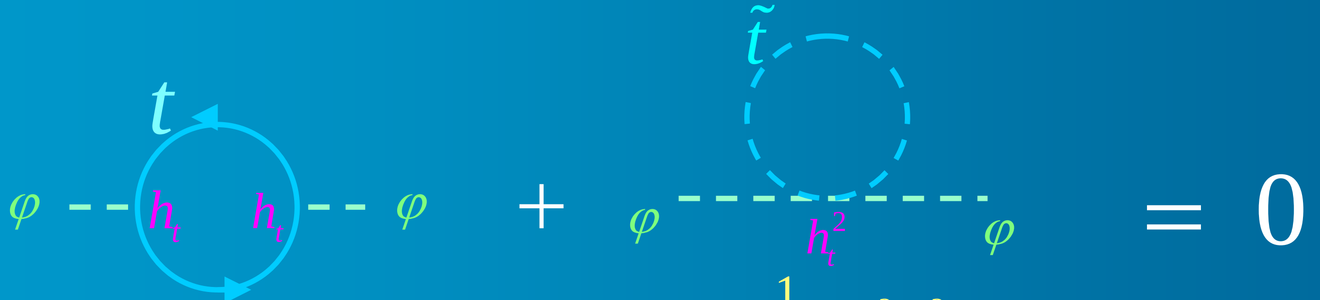
-) $ 10,110,087,734,957.70

$ 1.25

Fine tuning!

Solution in SUSY

In exact SUSY, the quadratic divergence is canceled by both boson and fermion loops.



$$-\frac{1}{(4\pi)^2}h_t^2\Lambda^2 \qquad \frac{1}{(4\pi)^2}h_t^2\Lambda^2$$

Exact SUSY

Even if ~~SUSY~~,

$$\boxed{\delta m_\varphi^2 \sim \frac{1}{(4\pi)^2} h_t^2 m_{\tilde{t}}^2 \ln\left(\frac{\Lambda^2}{m_{\tilde{t}}^2}\right)}$$

We don't need a fine tuning when

$$\boxed{m_{\tilde{t}}^2 \sim m_{\tilde{b}}^2 \sim \ldots \sim O(M_W^2)}$$

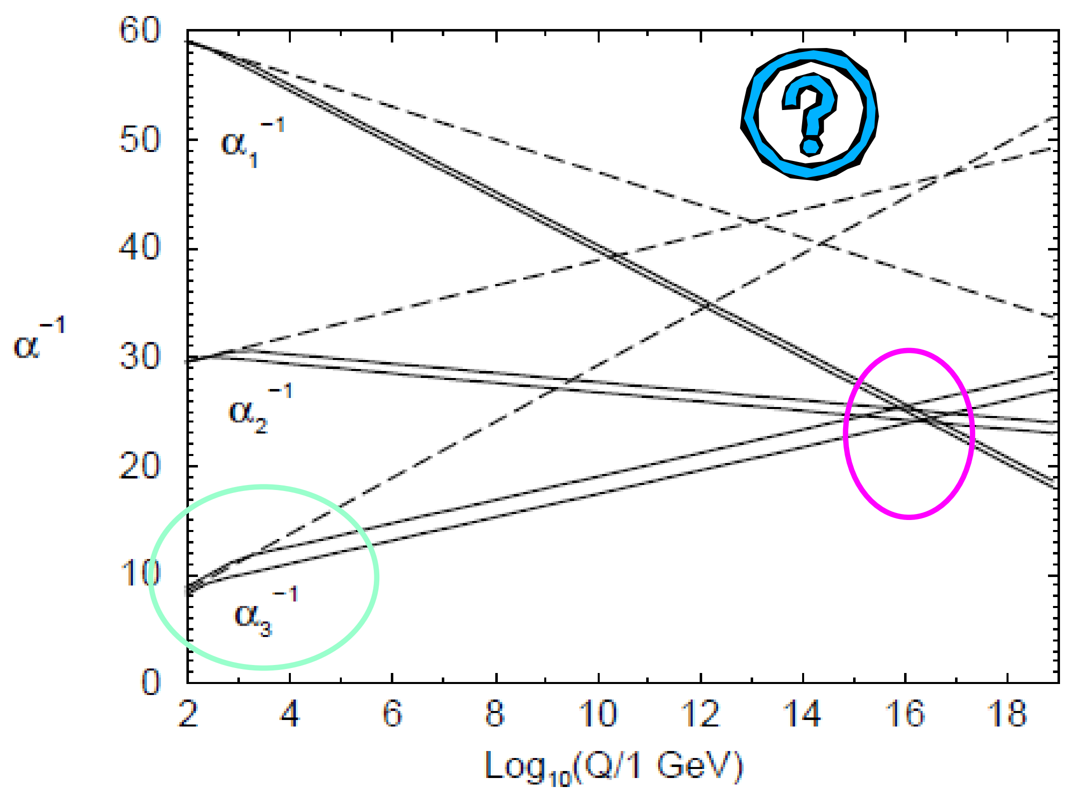
SUSY GUT

The coupling constants are unified at

$$\boxed{M_X \approx 10^{16} GeV}$$

A lot of new particles ,which do not obey the asymptotic free, appear at

$$\boxed{\mu \geq 10^{2} GeV}$$



Martin, "A Supersymmetry Primer"

MSSM

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

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

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

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

- 105 masses, phases and mixing angles!!!

CMSSM

Constrained MSSM

Simplified into only five parameters from 105

Common scalar mass at GUT scale: m_0

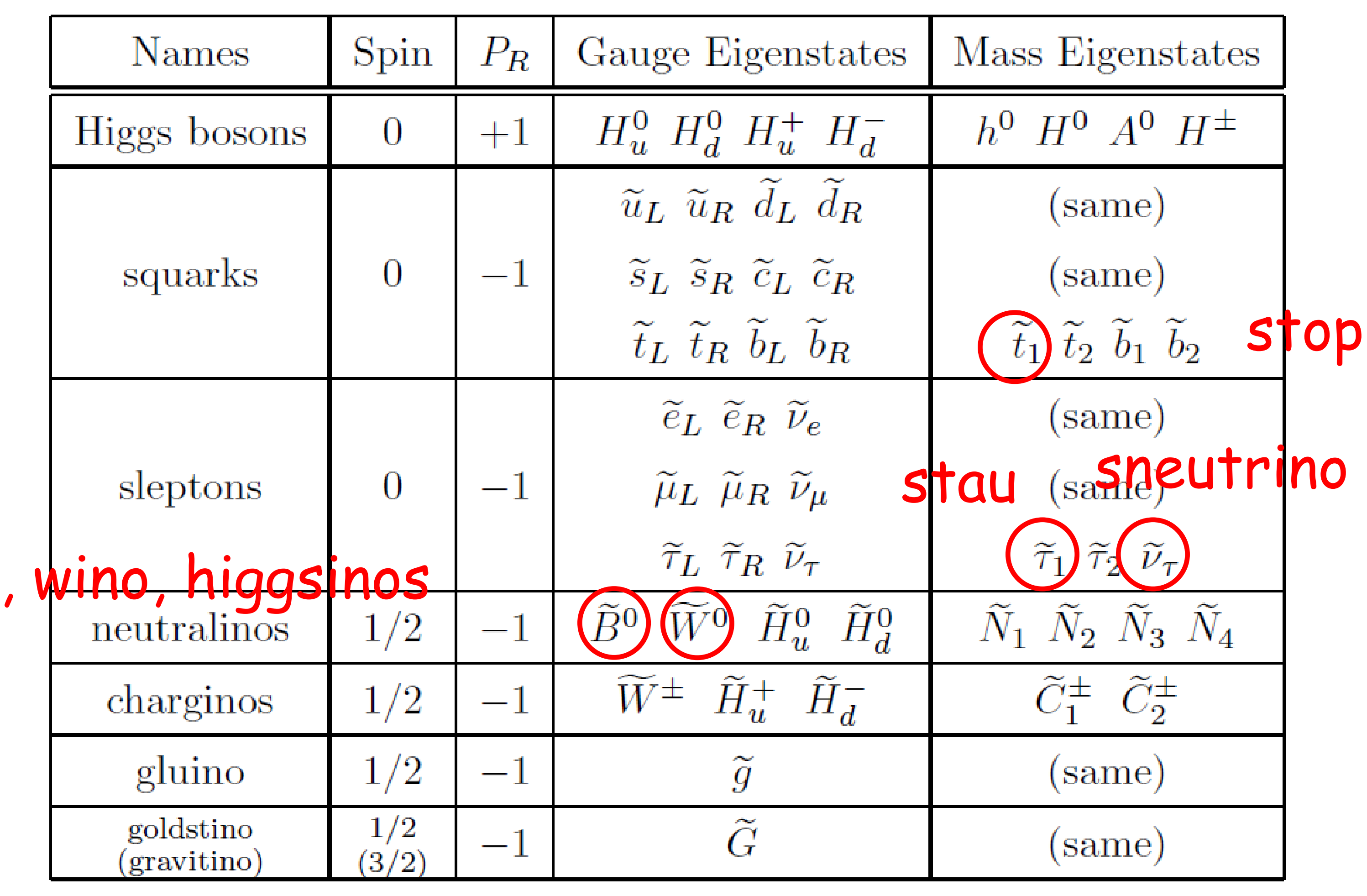
Unified gaugino (fermion) mass at GUT scale: $m_{1/2}$

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

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

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	$\tilde u_L\ \tilde u_R\ \tilde d_L\ \tilde d_R$ $\tilde s_L\ \tilde s_R\ \tilde c_L\ \tilde c_R$ $\tilde t_L\ \tilde t_R\ \tilde b_L\ \tilde b_R$	(same) (same) $\tilde t_1\ \tilde t_2\ \tilde b_1\ \tilde b_2$
sleptons	0	-1	$\tilde e_L\ \tilde e_R\ \tilde \nu_e$ $\tilde \mu_L\ \tilde \mu_R\ \tilde \nu_\mu$ $\tilde \tau_L\ \tilde \tau_R\ \tilde \nu_\tau$	(same) (same) $\tilde \tau_1\ \tilde \tau_2\ \tilde \nu_\tau$
neutralinos	1/2	-1	$\tilde B^0\ \tilde W^0\ \tilde H_u^0\ \tilde H_d^0$	$\tilde N_1\ \tilde N_2\ \tilde N_3\ \tilde N_4$
charginos	1/2	-1	$\tilde W^\pm\ \tilde H_u^+\ \tilde H_d^-$	$\tilde C_1^\pm\ \tilde C_2^\pm$
gluino	1/2	-1	$\tilde g$	(same)
goldstino (gravitino)	1/2 (3/2)	-1	$\tilde G$	(same)

stop

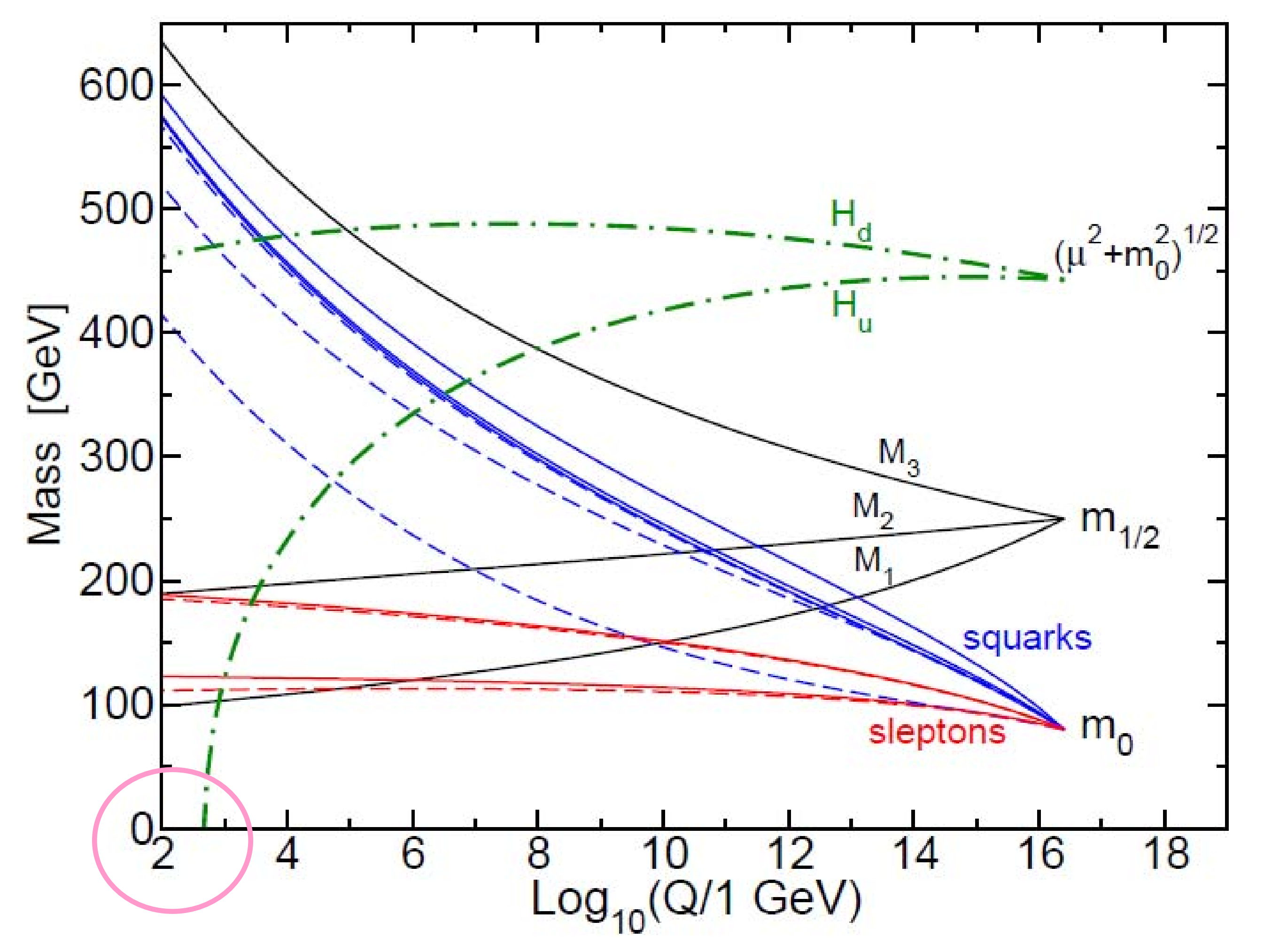
stau

sneutrino

bino, wino, higgsinos

Martin, "A Supersymmetry Primer"

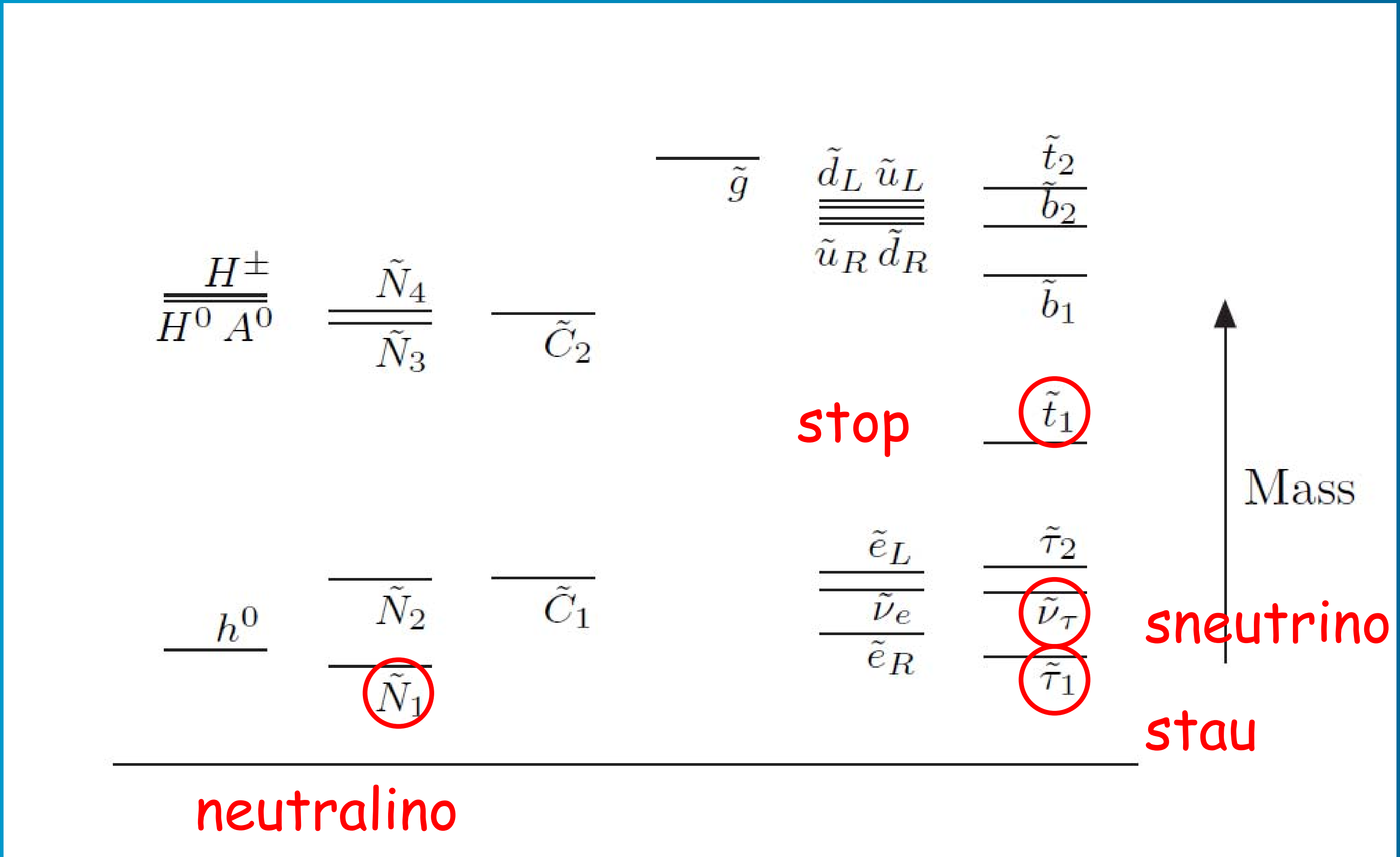
Running of Renormalization Group (RG) Equation in CMSSM



Negative Higgs mass term

Martin, "A Supersymmetry Primer"

Mass spectrum in CMSSM



Martin, "A Supersymmetry Primer"

Lightest SUSY particle (LSP)

- R-parity conservation

  i)Decay

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

(-1) (-1) (+1)

  ii) Pair annihilation/production

$$f + \overline{f} \leftrightarrow \chi + \chi$$

(+1) (+1) (-1) (-1)

Thermal freezeout

Boltzmann equation

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

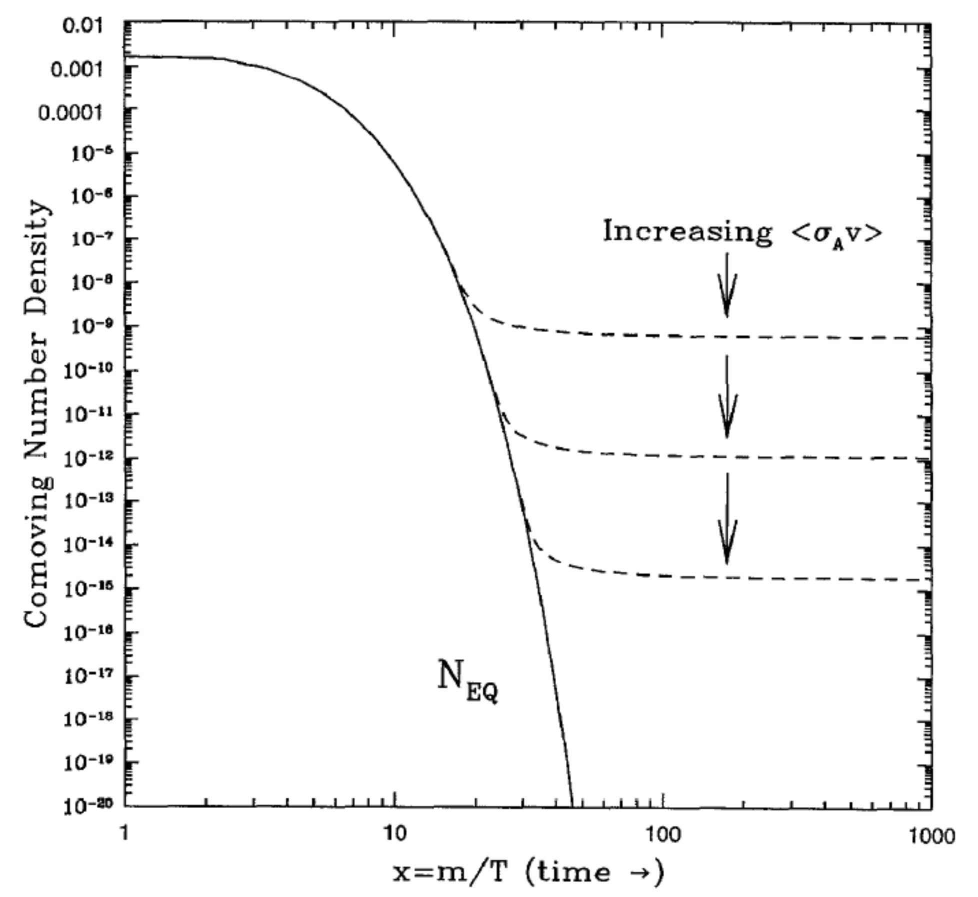
$$n_\chi \sim \left.\frac{3H}{\langle \sigma v\rangle}\right|_{\text{frezeout}}$$

$$T_{\text{Freezeout}} \sim m_\chi / 30$$

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

$_\chi$ does not depend on m$_\chi$

Predicting TeV Physics!!!

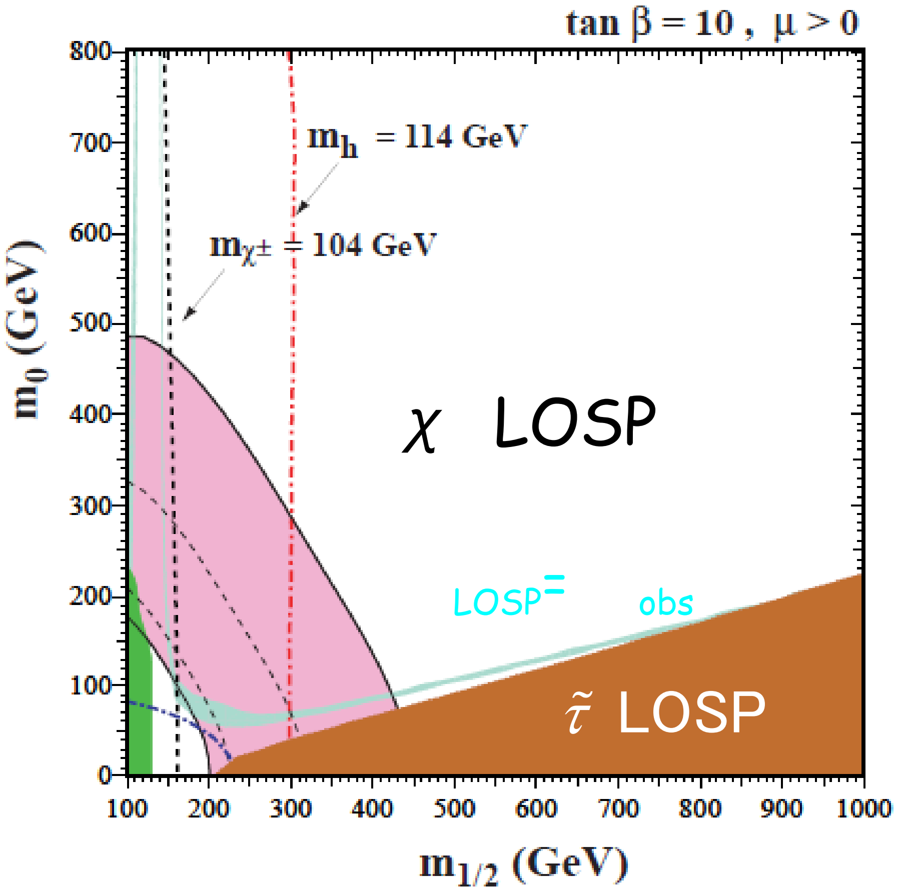


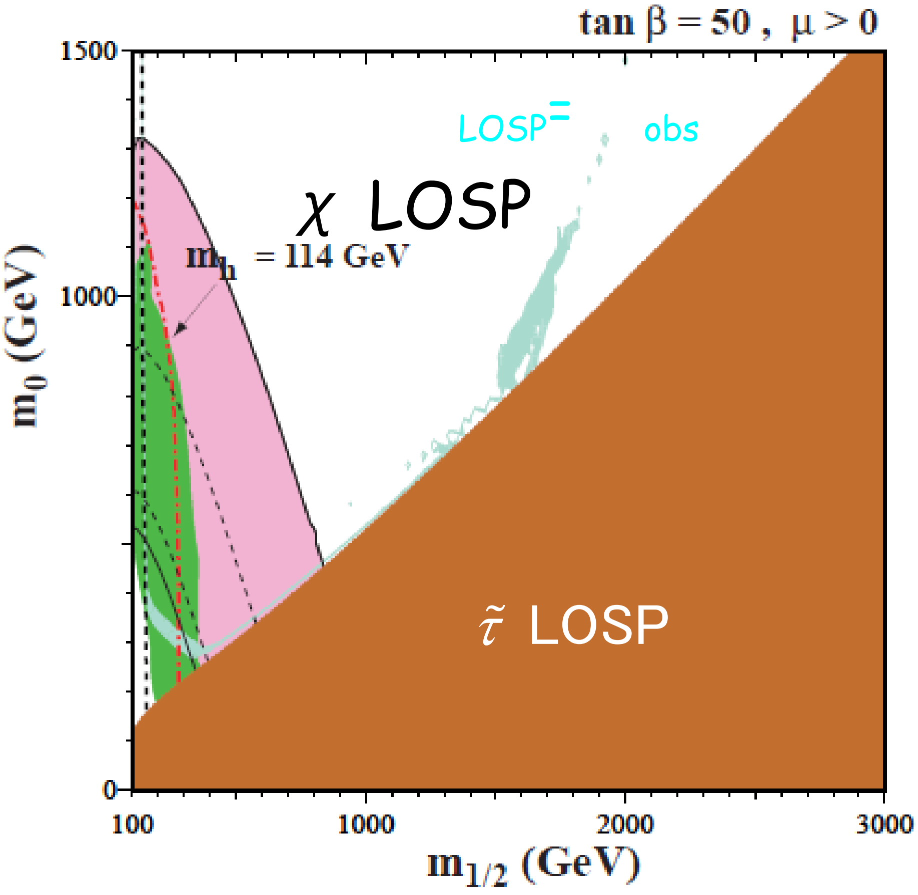
Kolb & Turner

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

LSP (LOSP) in CMSSM

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





Ellis,Olive,Santoso,Spanos(03)

Supergravitiy (SUGRA)

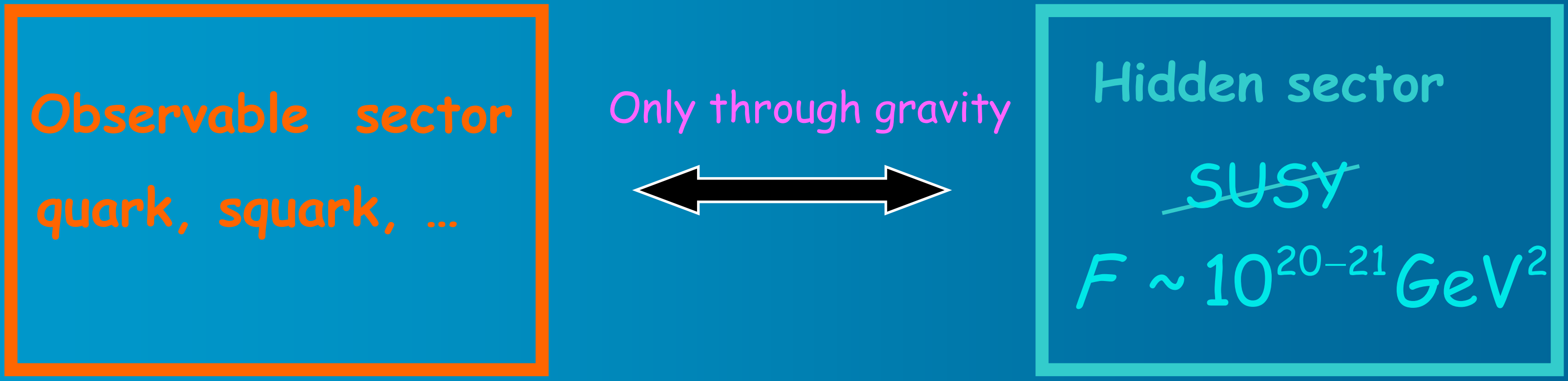
- Local theory of SUSY
  (predicting gravitino)

- 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

quark, squark, …

Only through gravity

Hidden sector

~~SUSY~~

$F \sim 10^{20-21}\,\text{GeV}^2$

- Masses of squarks and sleptons

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

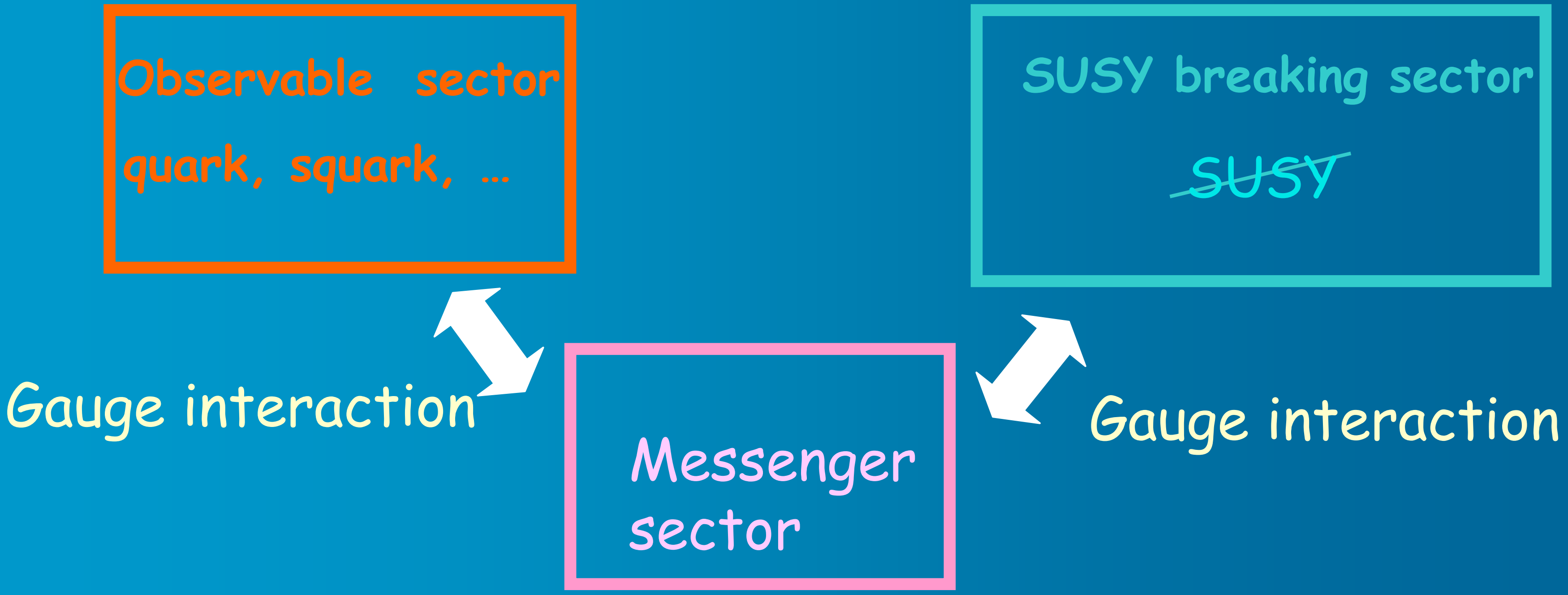
$$(F = 10^{20} - 10^{21}\ \text{GeV})$$

- Gravitino mass

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

SUSY Breaking Models II

- Gauge-mediated SUSY breaking model



Observable sector

quark, squark, …

SUSY breaking sector

~~SUSY~~

Gauge interaction

Messenger sector

Gauge interaction

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

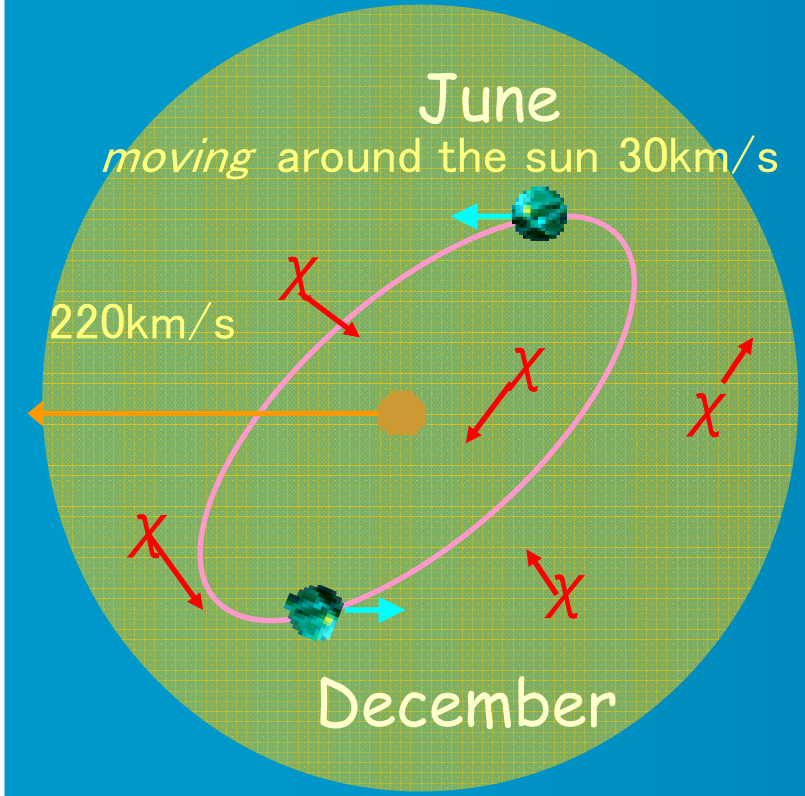
Lightest SUSY particle (LSP) may be necessarily the gravitino

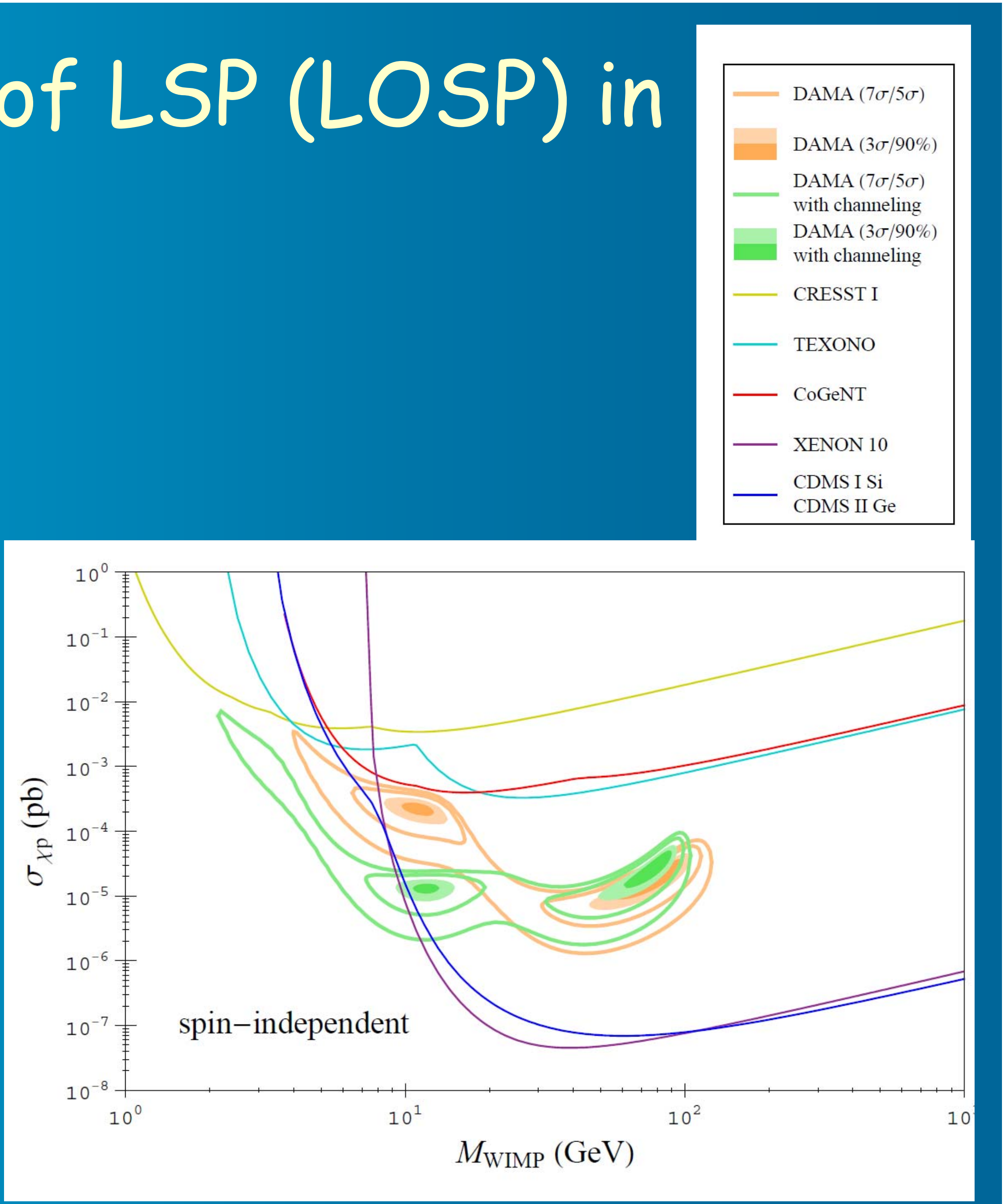
Signature of SUSY particles related with Astrophysics and Cosmology

- 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

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

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

Or gravitino/sneutrino decay with R-parity violation

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

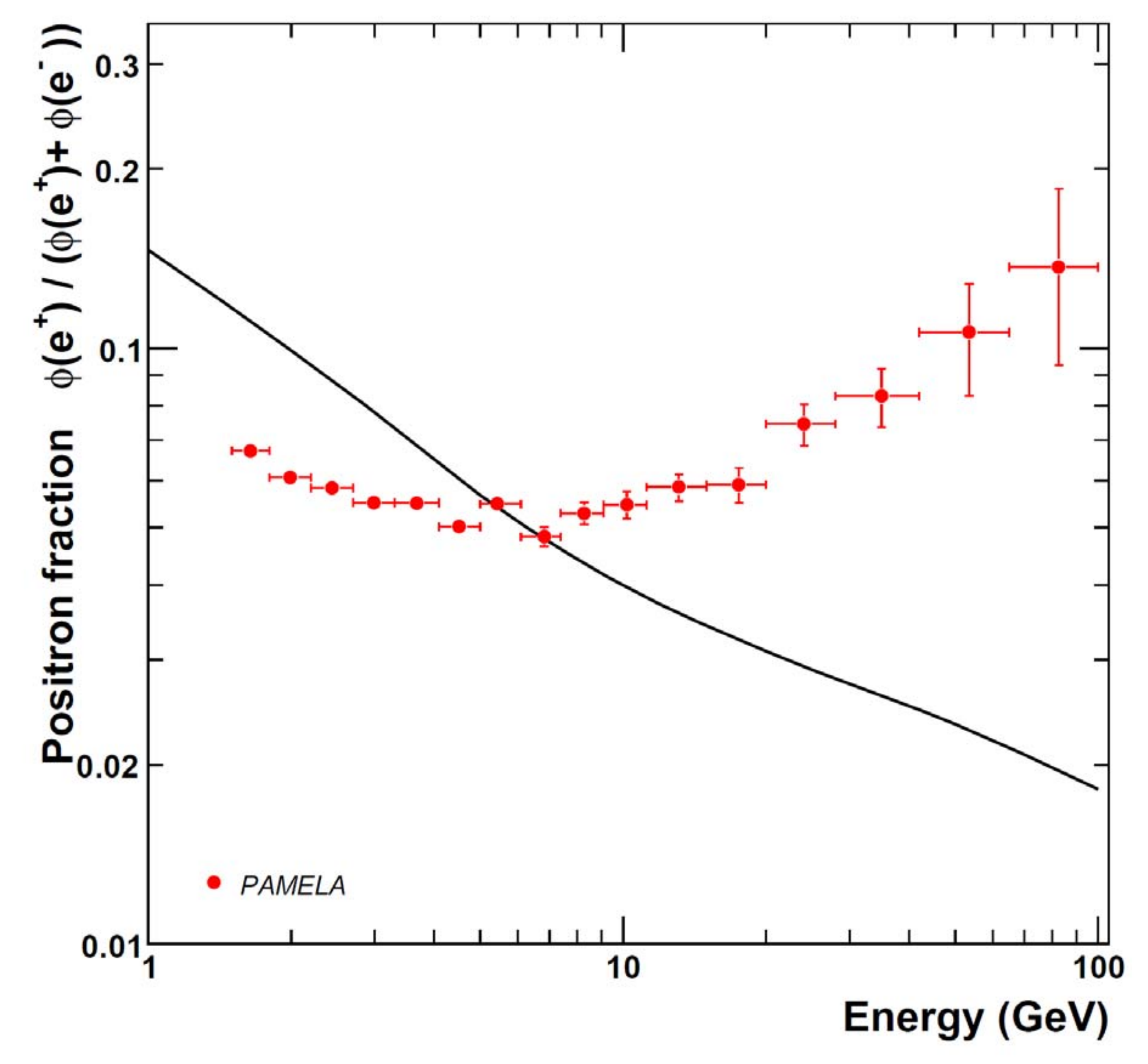
Or hidden gauge boson decay with kinetic mixing

Chen, Takahashi, Yanagida (08)

- Gamma-ray from a point source
- Anti-proton
- Positron
- 511 keV line gamma
- Neutrinos

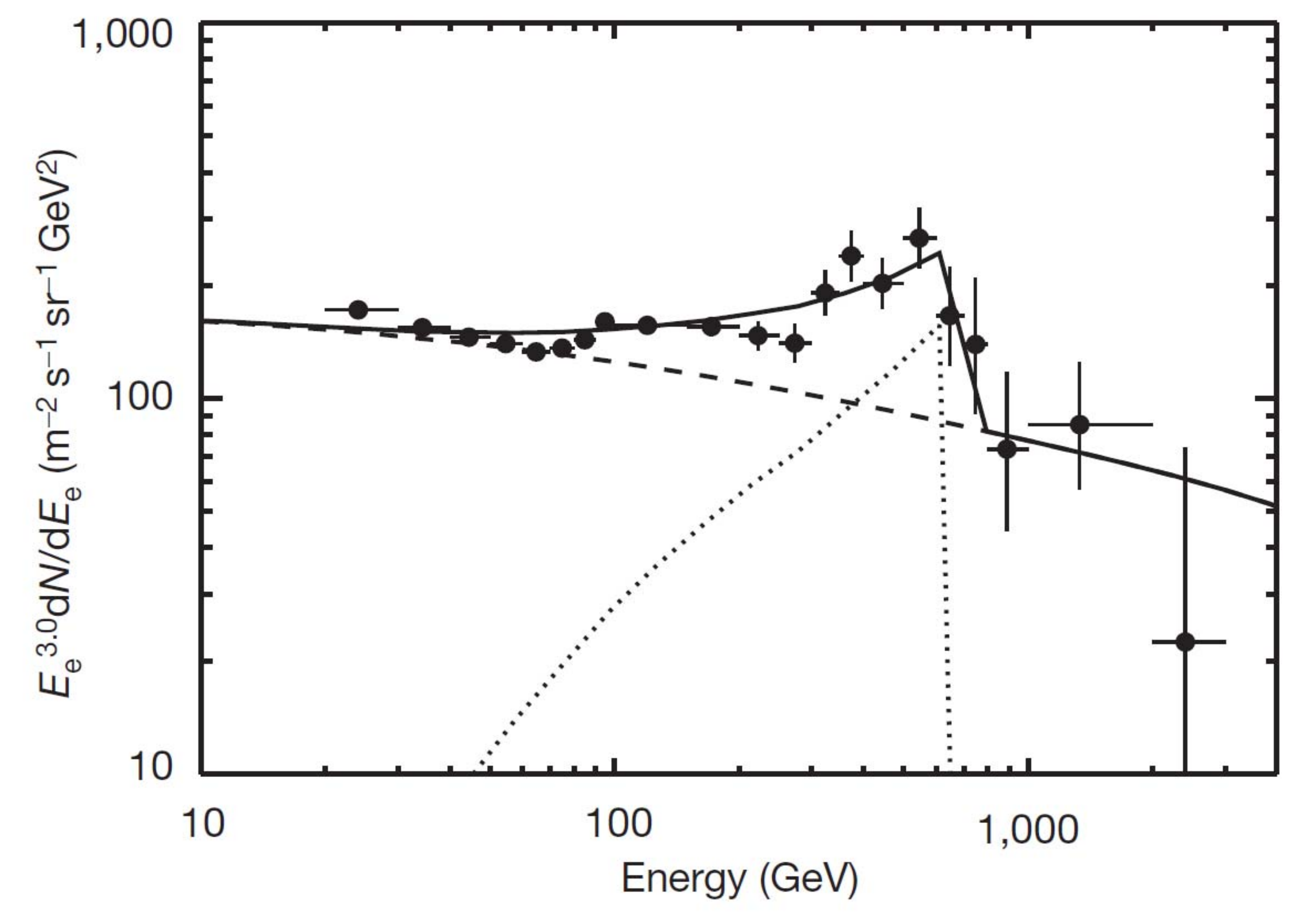
- Synchrotron radio
- WMAP HAZE component
- Nucleosynthesis
- etc…

Positron Excess (PAMELA satellite reported)



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

Electron and positron flux by ATIC2



Chang et al (08)

Positron Excess

Hisano, Kawasaki, Kohri, Nakayama (08)

Diffusion model

$$\frac{\partial}{\partial t} f(E,\vec{x}) = K(E)\nabla^2 f(E,\vec{x}) + \frac{\partial}{\partial E}[b(E) f(E,\vec{x})] + Q(E,\vec{x})$$

Flux

$$\Phi_{e^+}^{(\mathrm{DM})}(E,\vec{x}_\odot) = (c/4\pi) f(E,\vec{x}_\odot)$$

Steady-state solution (Hisano etal, '06)

K(E) and b(E) are taken from (Baltz-Edsjo '99)

Propagating within a few kpc, normalized to fit B/C, Boost Factor (BF) considered for clumpy distributed DM.

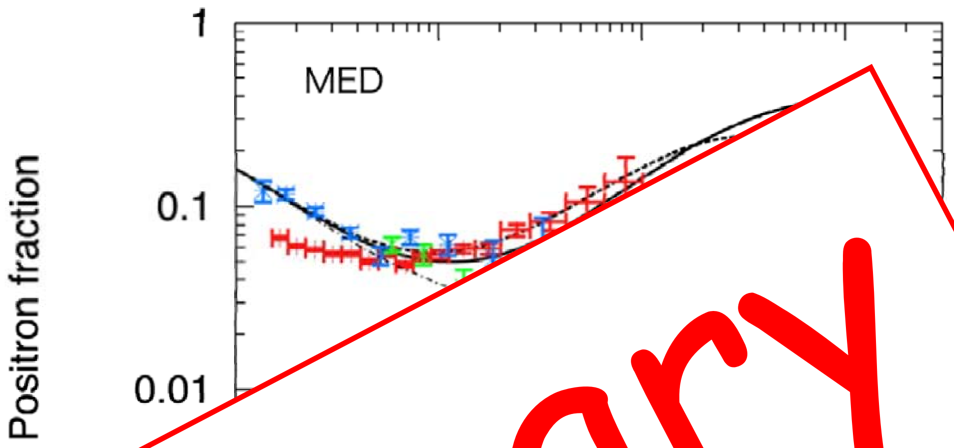
$$r_{\mathrm{propagation}} \sim \sqrt{EK(E)/b(E)} \sim 0.7\mathrm{kpc}(E/\mathrm{GeV})^{-0.17}$$

Positron excess in DM annihilation

Hisano, Kawasaki,
Kohri, Moroi, Nakayama in prep

Diffusion model
Fitted to B/C ratio

$\langle \sigma v \rangle \simeq 1$



Preliminary

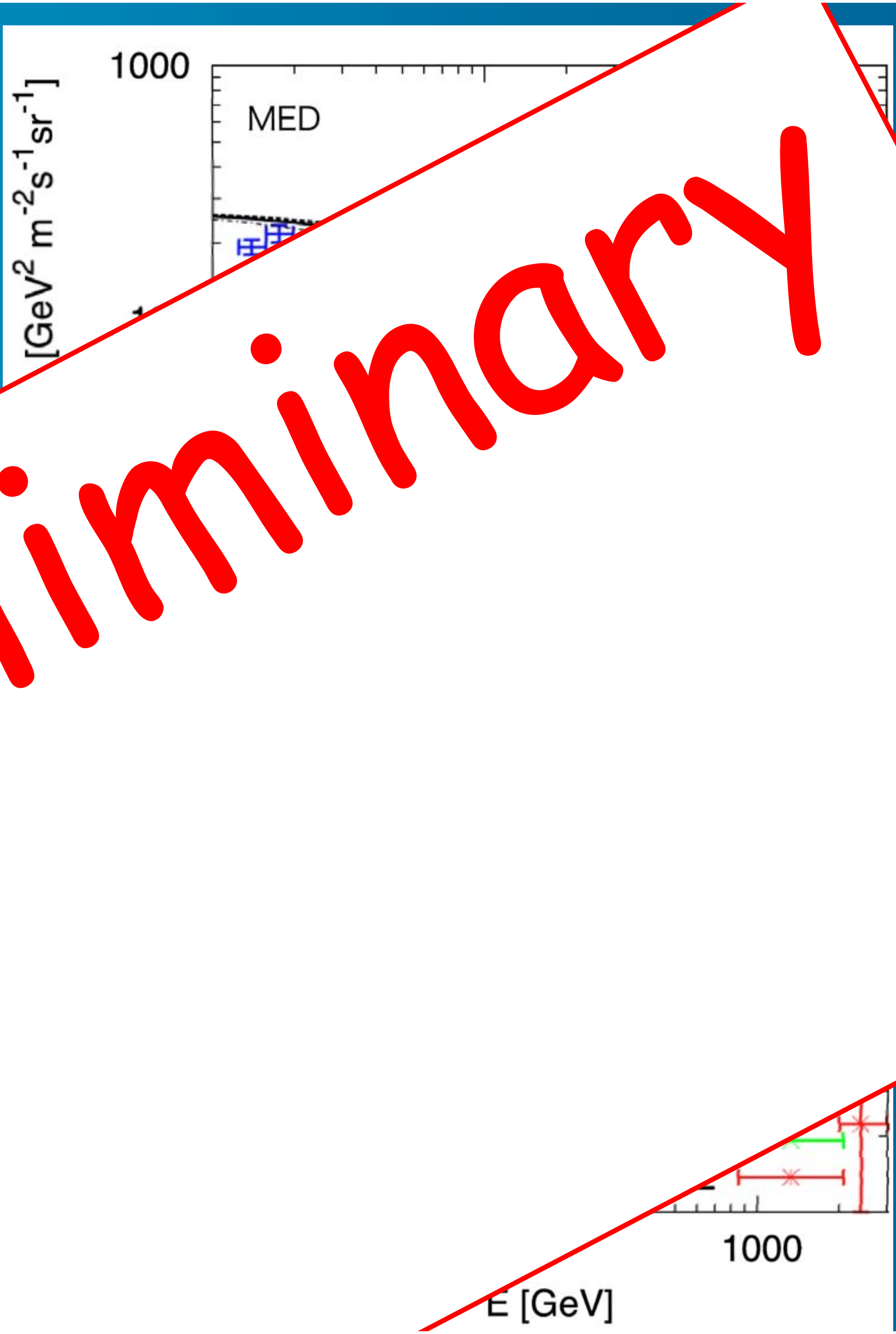
Electron/positron cutoff in DM annihilation

Hisano, Kawasaki,
Kohri, Moroi, Nakayama in prep

Diffusion model

Fitted to B/C

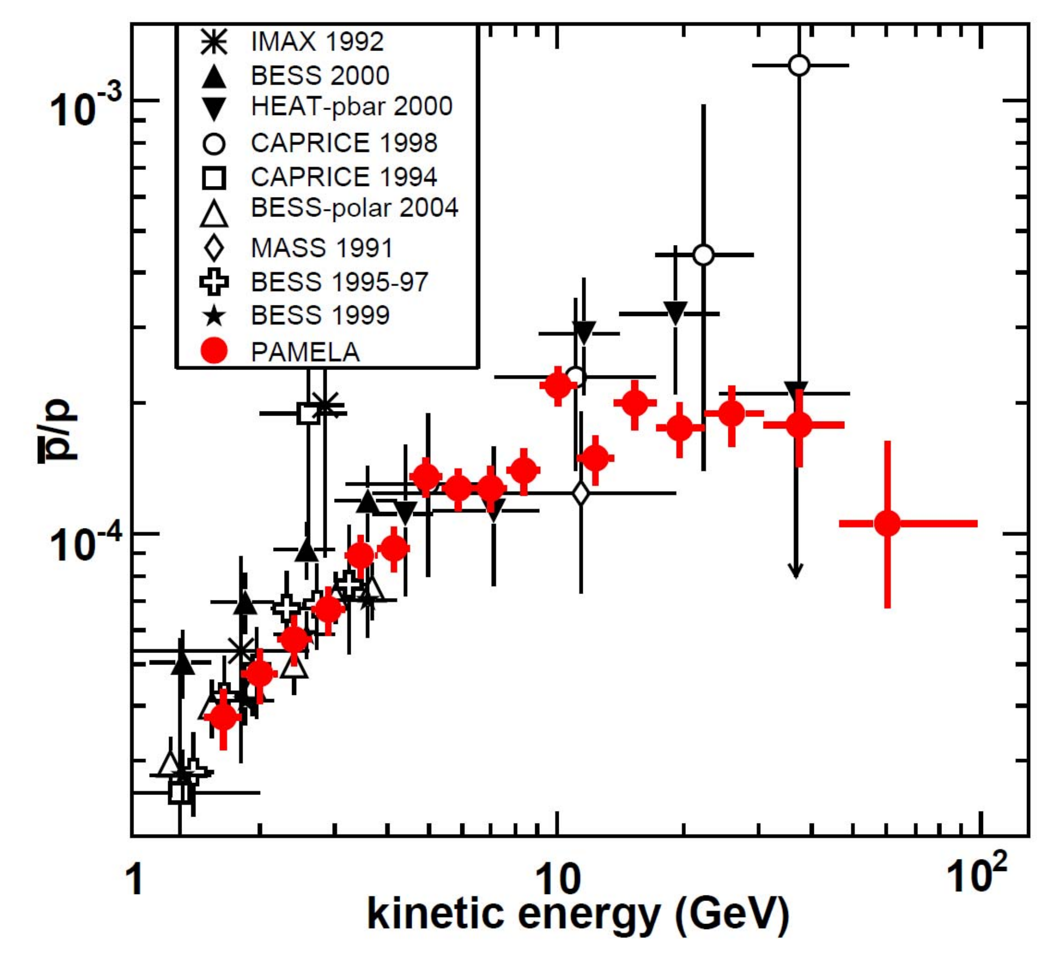
$\langle \sigma v \rangle \sim$



Preliminary

Anti-proton flux (PAMELA satellite reported)

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

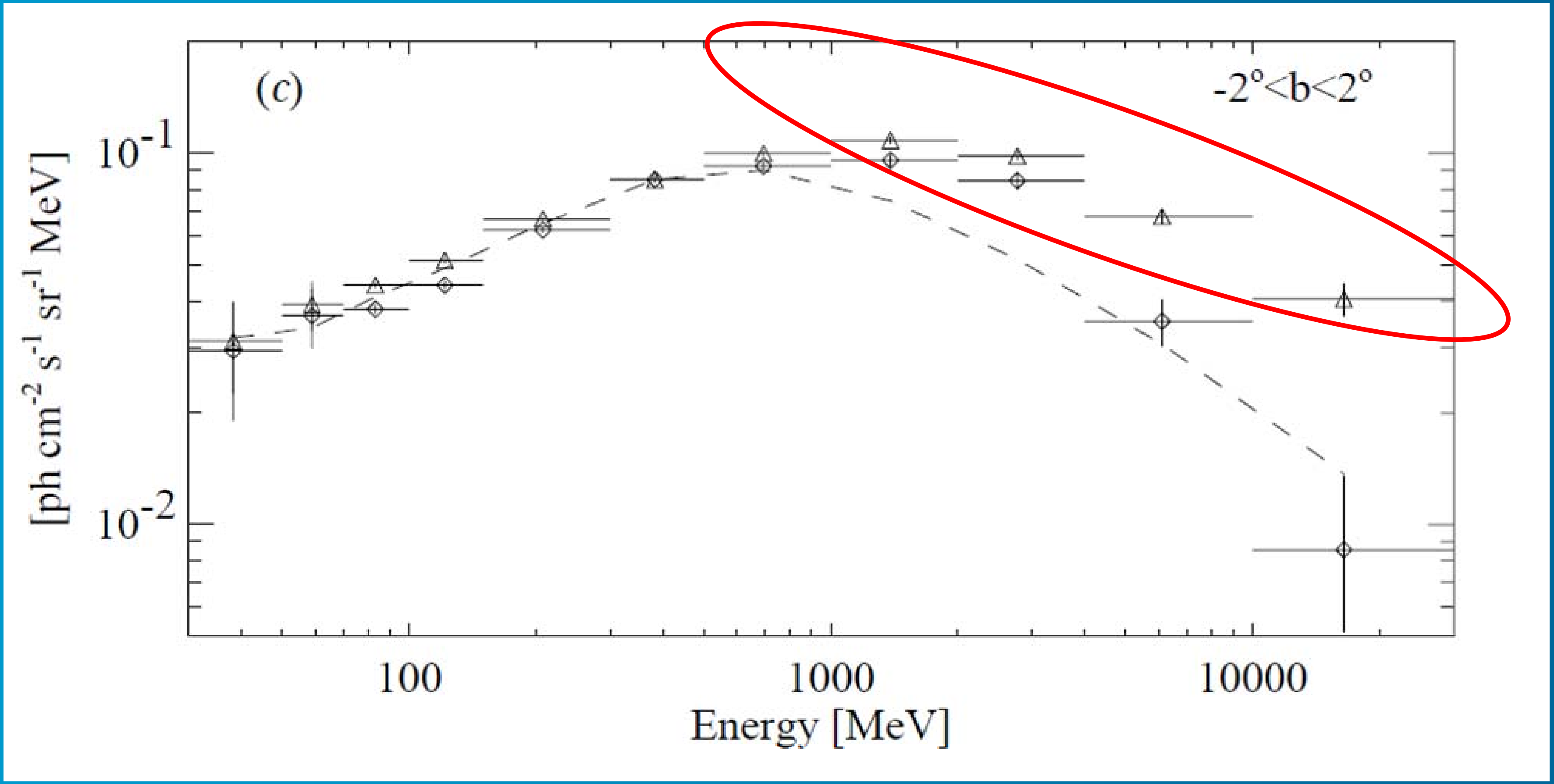


Consistent with secondary production of pp

or Leptonic DM ? by Chen-Takahashi (08)

Gamma-ray anomaly at Galactic Center

(EGRET satellite reported)



Hunter et al (97)

Gamma-ray signal in wino DM annihilation

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

Gamma-ray flux

$$\Phi_\gamma(\psi, E) = \sum_f \frac{\langle \sigma v \rangle_f}{8\pi m_\chi^2} \frac{dN_f^{(\gamma)}}{dE} \int_{\mathrm{l.o.s.}} \rho^2(l) dl(\psi)$$

Averaged over

$$-5^\circ < \ell < 5^\circ$$

$$-2^\circ < b < 2^\circ$$

Profile

Navarro-Frank-White (NFW): cusp structure

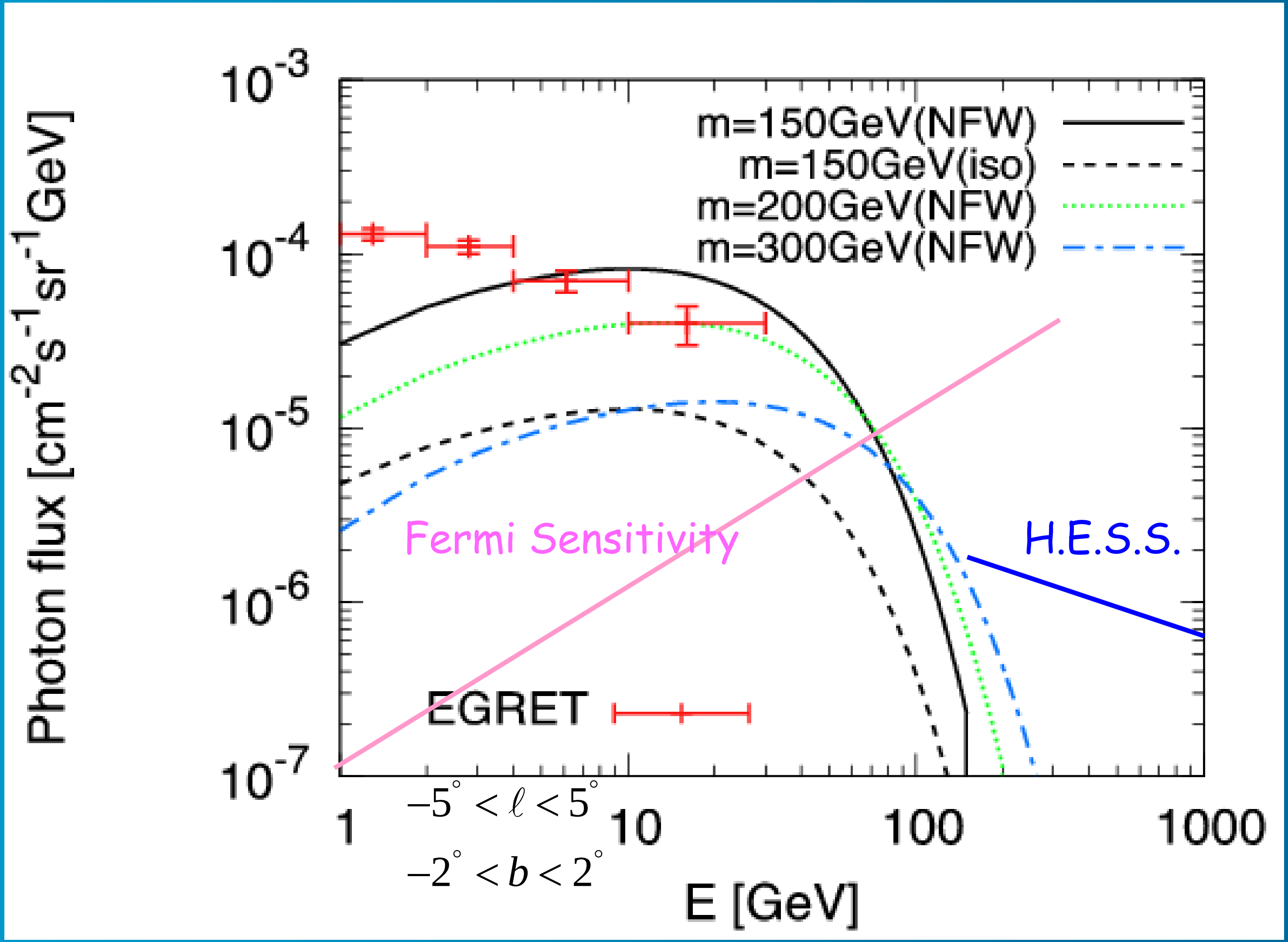
$$\rho \propto r^{-p} \quad (p = 1 - 1.5)$$

Isothermal (iso): core structure

$$\rho \propto 1/[1 + (r/r_0)^q] \quad (q = 2)$$

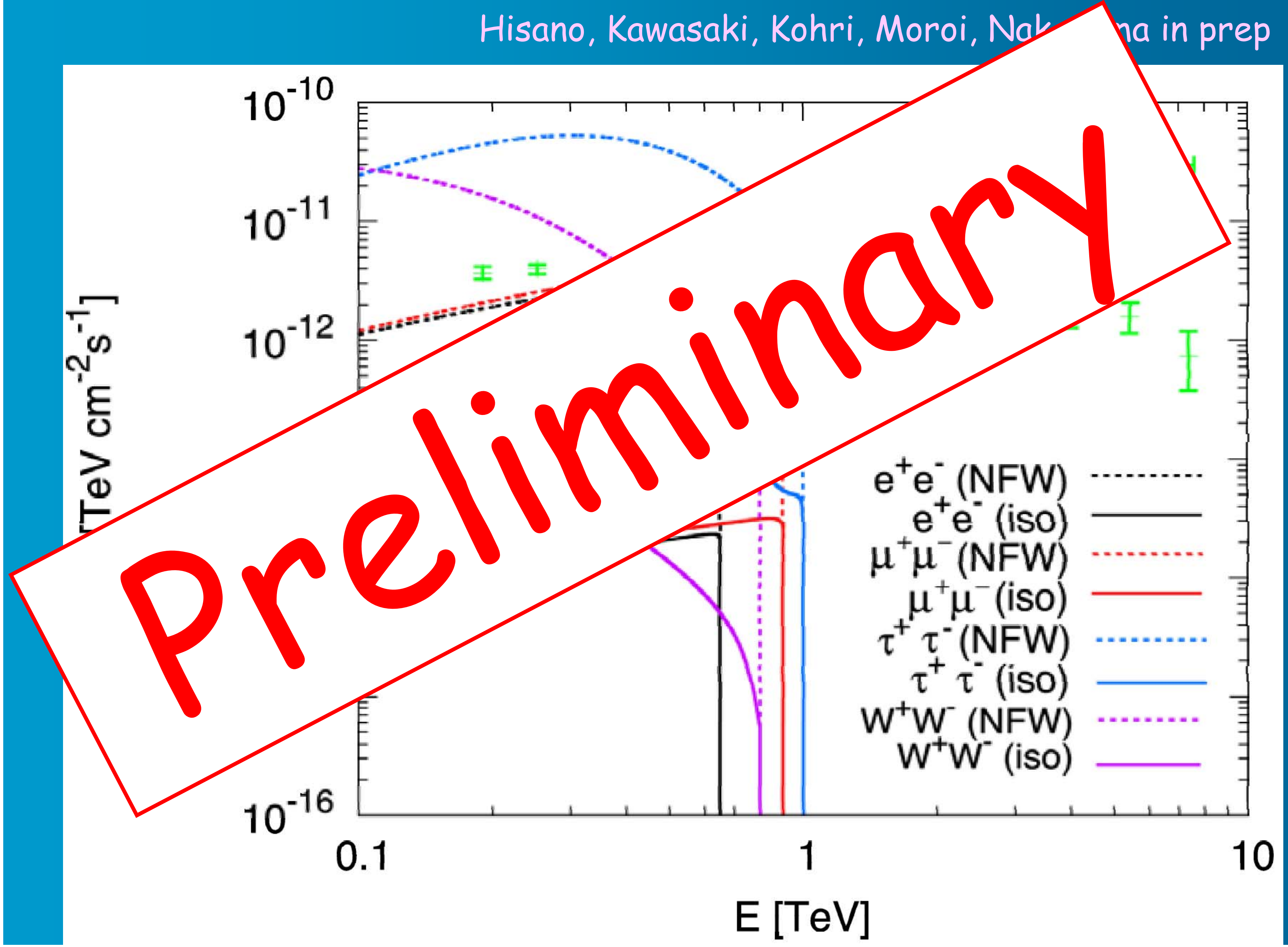
Gamma-ray signal in wino DM annihilation

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



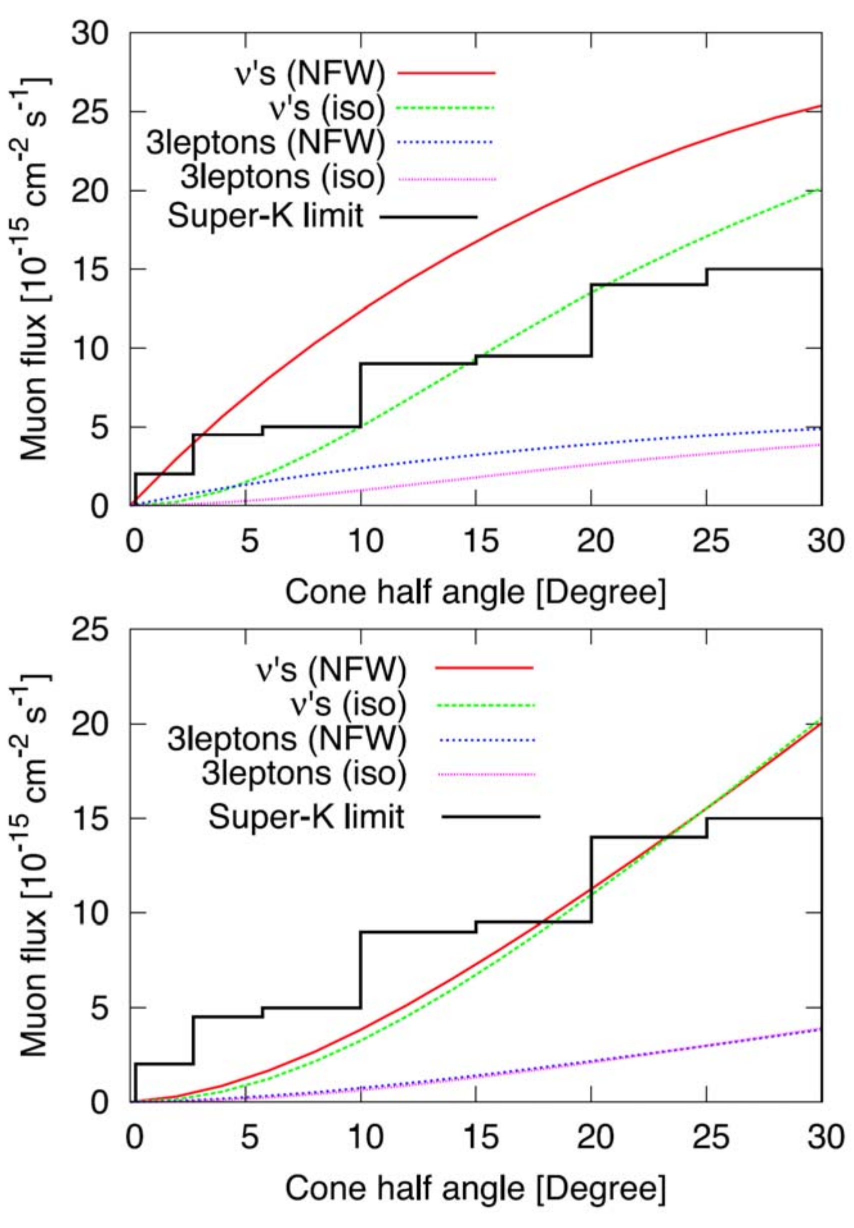
Gamma-ray signal in DM annihilation

Hisano, Kawasaki, Kohri, Moroi, Nak ma in prep



Neutrinos from galactic center expected by PAMELA/ATIC2

Hisano, Kawasaki, Kohri, Nakayama (08)



- Detecting up-going muons in Kamioka
- Annihilation (upper panel) and decay (lower panel)
- Direct-neutrino emission modes with NFW are excluded

Big-Bang Nucleosynthesis (BBN)

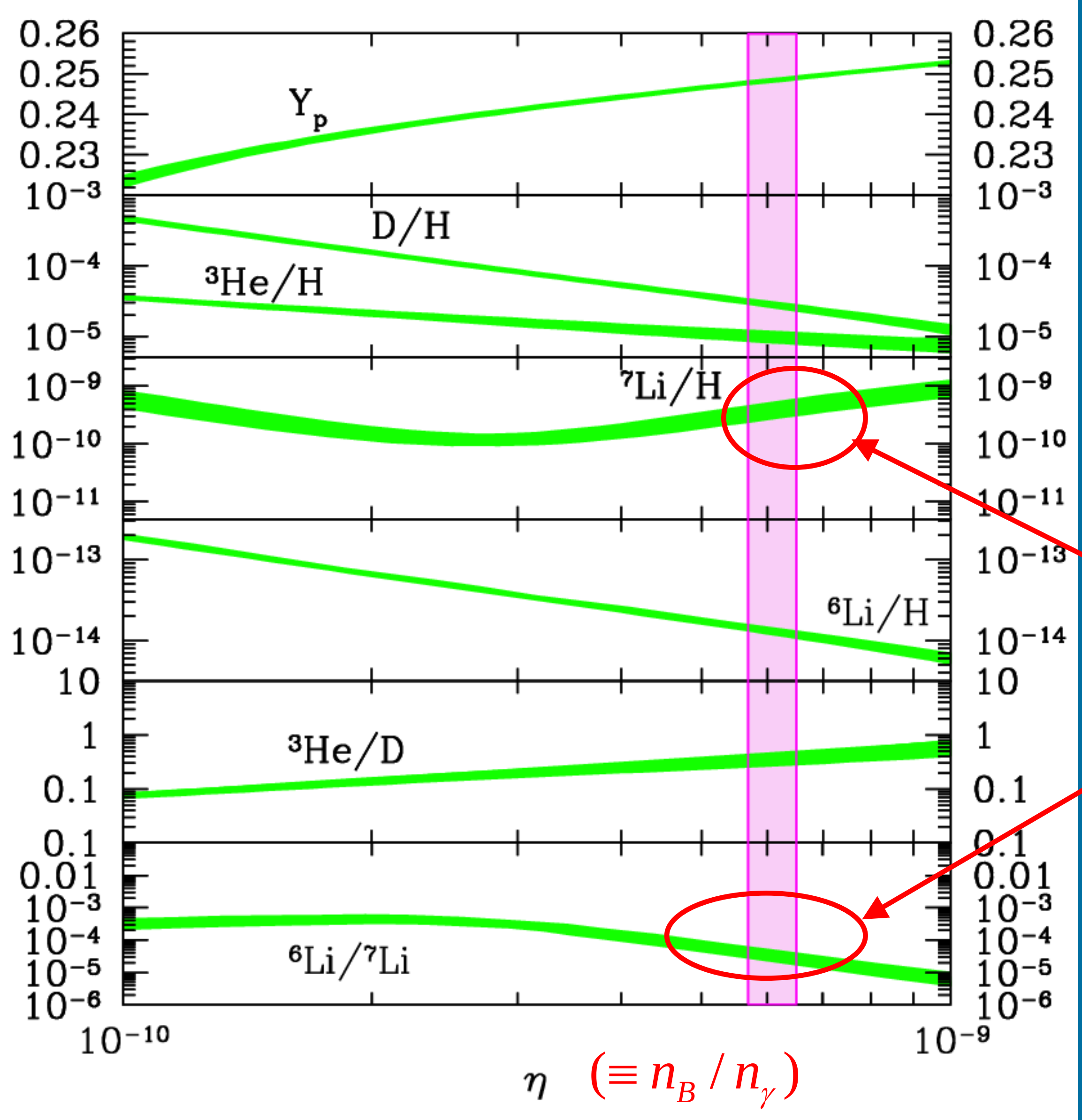
Very strong cosmological tools to study long-lived particles with lifetime of 0.01 sec – 10^{12} sec

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

Lithium Problem

If we adopted smaller systematic errors for observational data of 6Li and 7Li , the BBN theory does not agree with observation of Li abundances.

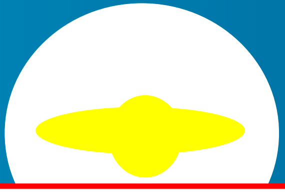
SBBN



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

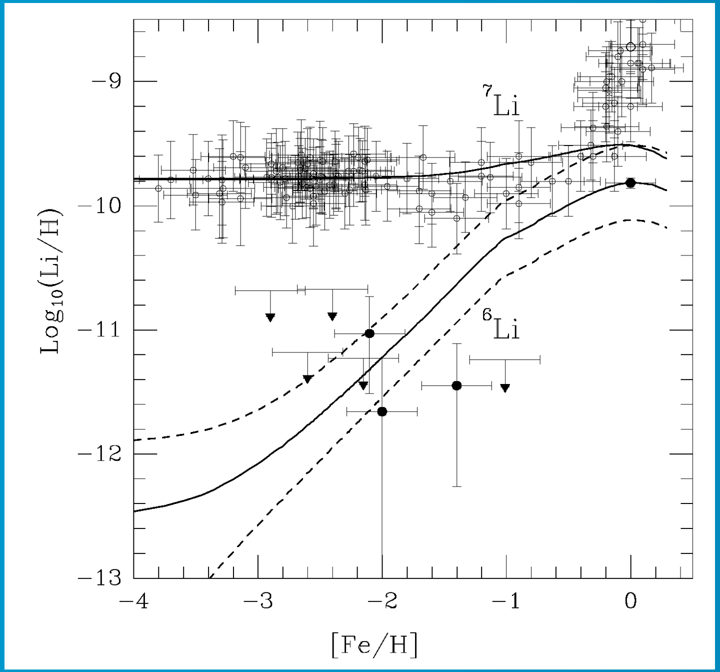
$5\quad 10^{-5}$

Lithium 7



a factor of two or three smaller !!!

- Expected that there is little depletion in stars.



Lemoine et al., 1997

$$^7\mathrm{Li/H} = 1.26^{+0.32}_{-0.21} \times 10^{-10} \quad (1\sigma)$$

$$\log\left(^7\mathrm{Li/H}\right) = -9.90 \pm 0.09 \ (1\sigma)$$

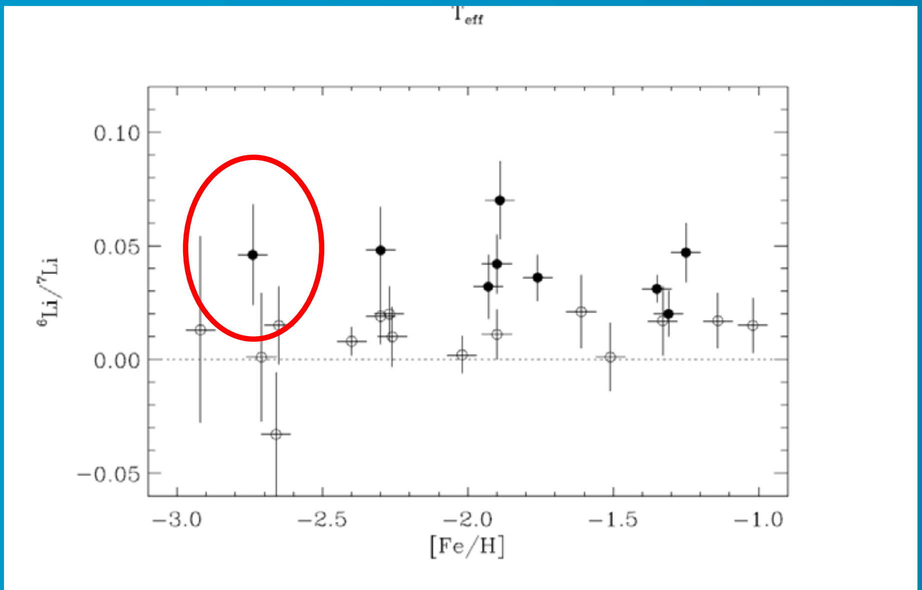
Ryan et al.(2000)

Bonifacio et al.(2006)

Lithium 6

Asplund et al.(2006)

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



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

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

still disagrees with SBBN

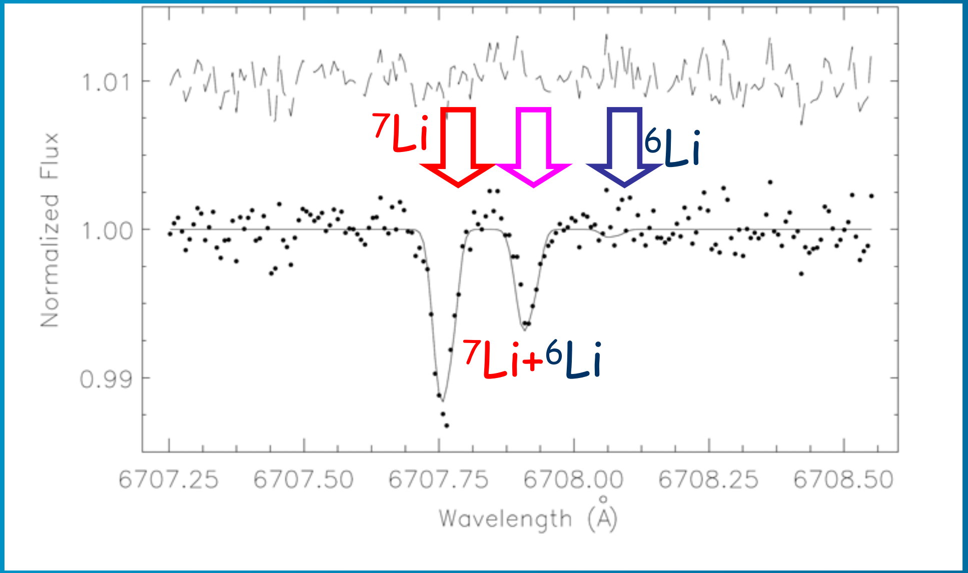
Astrophysically, factor-of-two depletion of Li7 needs a factor of O(10) Li6 depletion (Pinsonneault et al '02)

We need more primordial Li6?

Doppler broadening

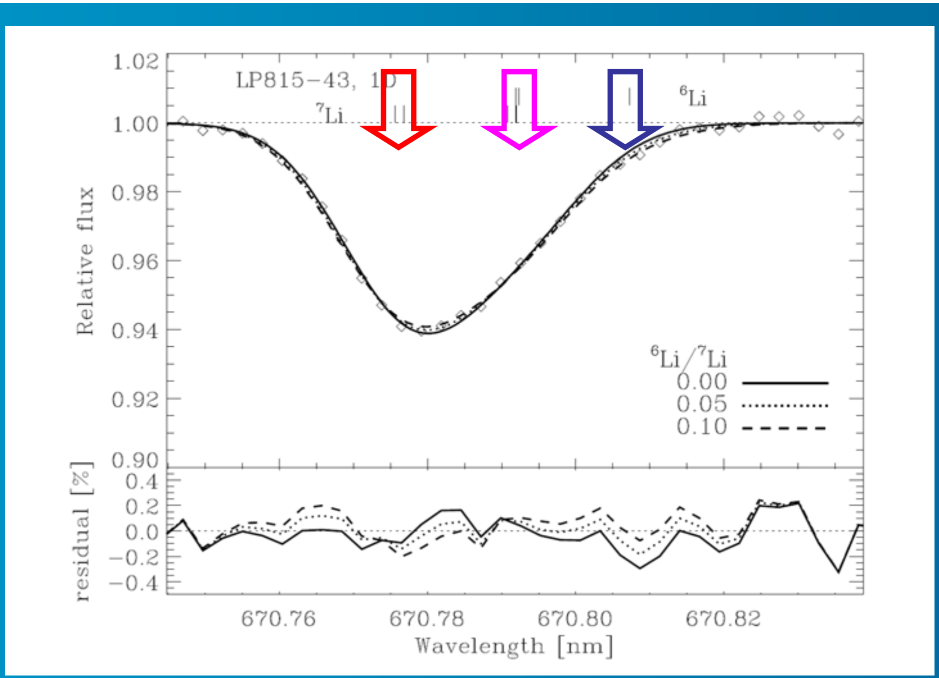
Cold ISM

Knauth, Federman, Lambert (2006)



LP815-43

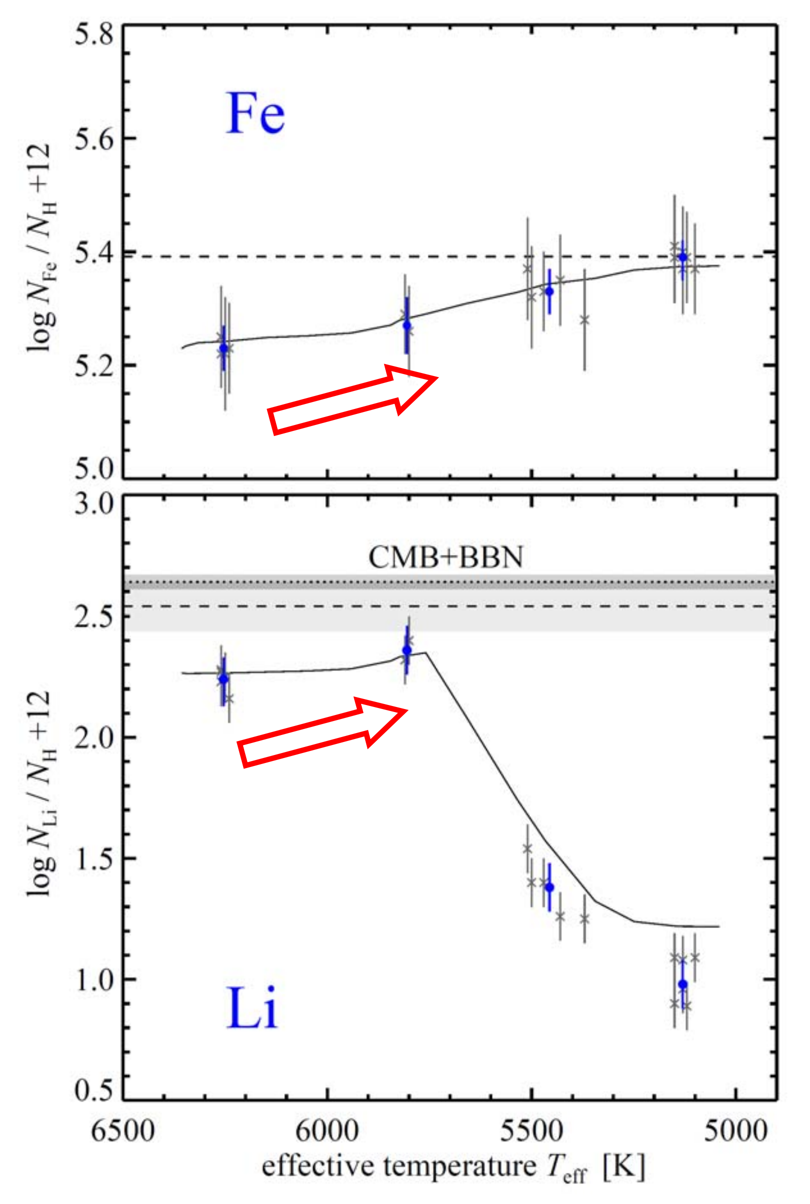
Asplund et al.(2006)



Astrophysical uncertainties in Li7

- Diffusion and convection

Korn et al (2006)



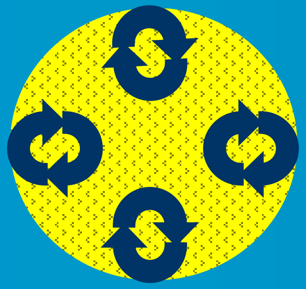
Destruction of Li7 in inner zone of stars

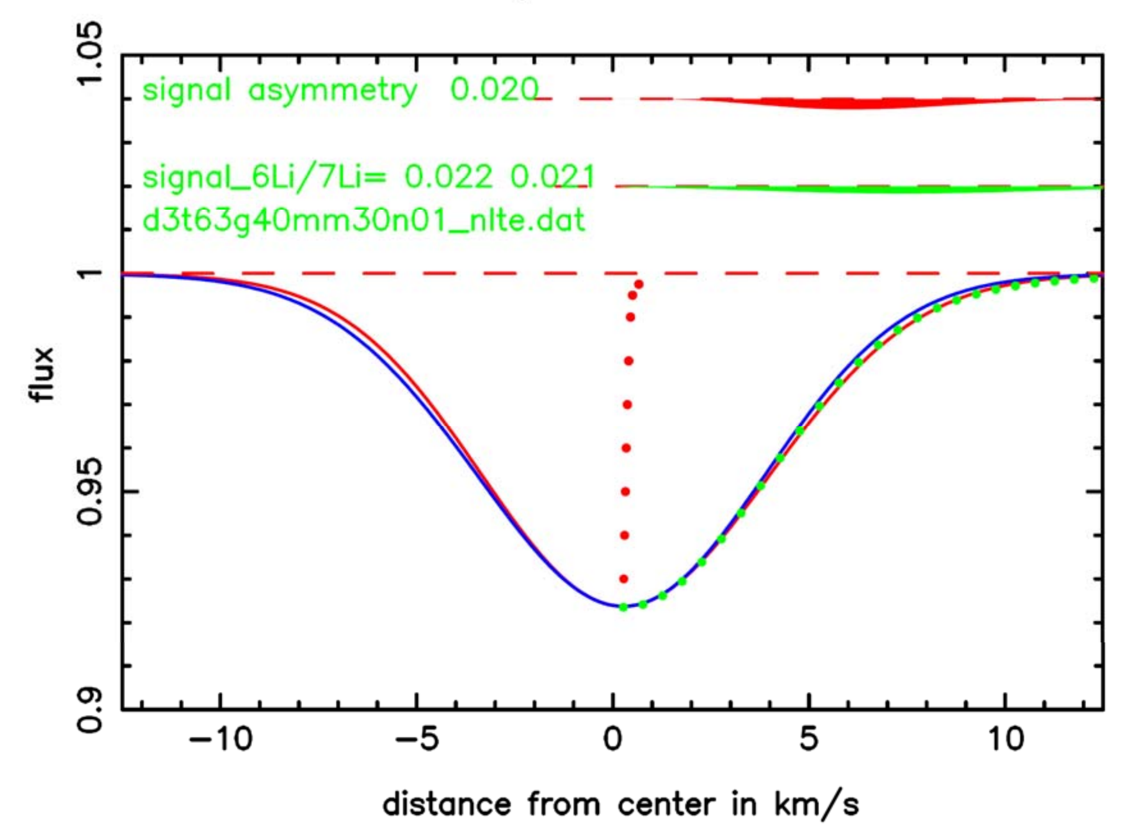
There is a increasing trend of both Iron and Li7 as a function of T_{eff}

Astrophysical uncertainties in Li6

Cayrel, Steffen, Bonifacio, Ludwig and Caffau (2008)

- Asymmetries of the absorption line mimicked by convective motion





My attitude towards Li problem

It might be premature to accept that these observational values are purely primordial

- Adding large systematic errors by hand and constraining (non-)standard cosmological scenarios

- Inventing a new cosmological/particle-physics model to solve Li problem

Constraints on long-lived SUSY particles from BBN

- We add large systematic errors into observational Li7 and Li6 abundacnes

$$\log_{10}\left({}^{7}Li/H\right) = -9.90 \pm 0.09\ (\pm 0.35)_{syst.}$$

Melendez,Ramirez(2004)

$${}^{6}Li/{}^{7}Li < 0.046 \pm 0.022\ (\pm 0.106)_{sys}$$

Asplund et al(2006)

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)

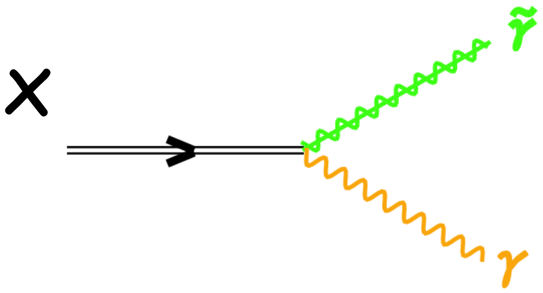
Reno and Seckel (1988), Dimopoulos, Esmailzadeh, Hall, Starkman (1988)

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 mode



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

$$\mathrm{D} + \gamma \to p + n,$$

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

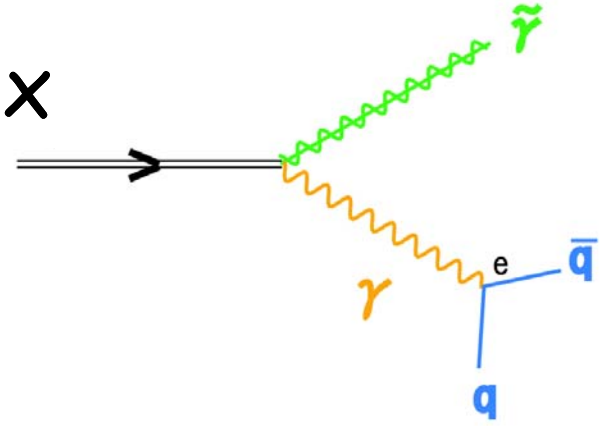
$${}^{3}\mathrm{He} + \gamma \to \mathrm{D} + p + n, \quad \mathrm{etc.}$$

He3/D >~ O(1)

Hadronic decay mode

Reno, Seckel (1988)

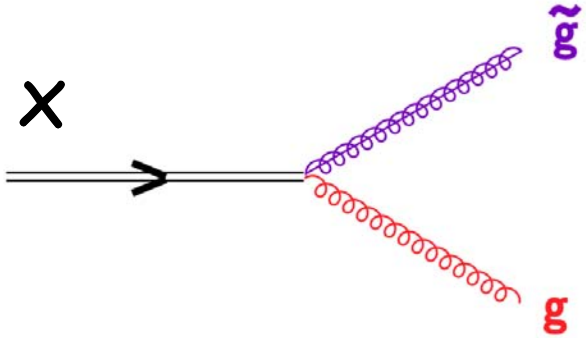
S. Dimopoulos et al.(1989)



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

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 (T > 0.1MeV)

Reno and Seckel (1988) Kohri (2001)

Extraordinary inter-conversion reactions between n and p

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

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

Hadron induced exchange

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

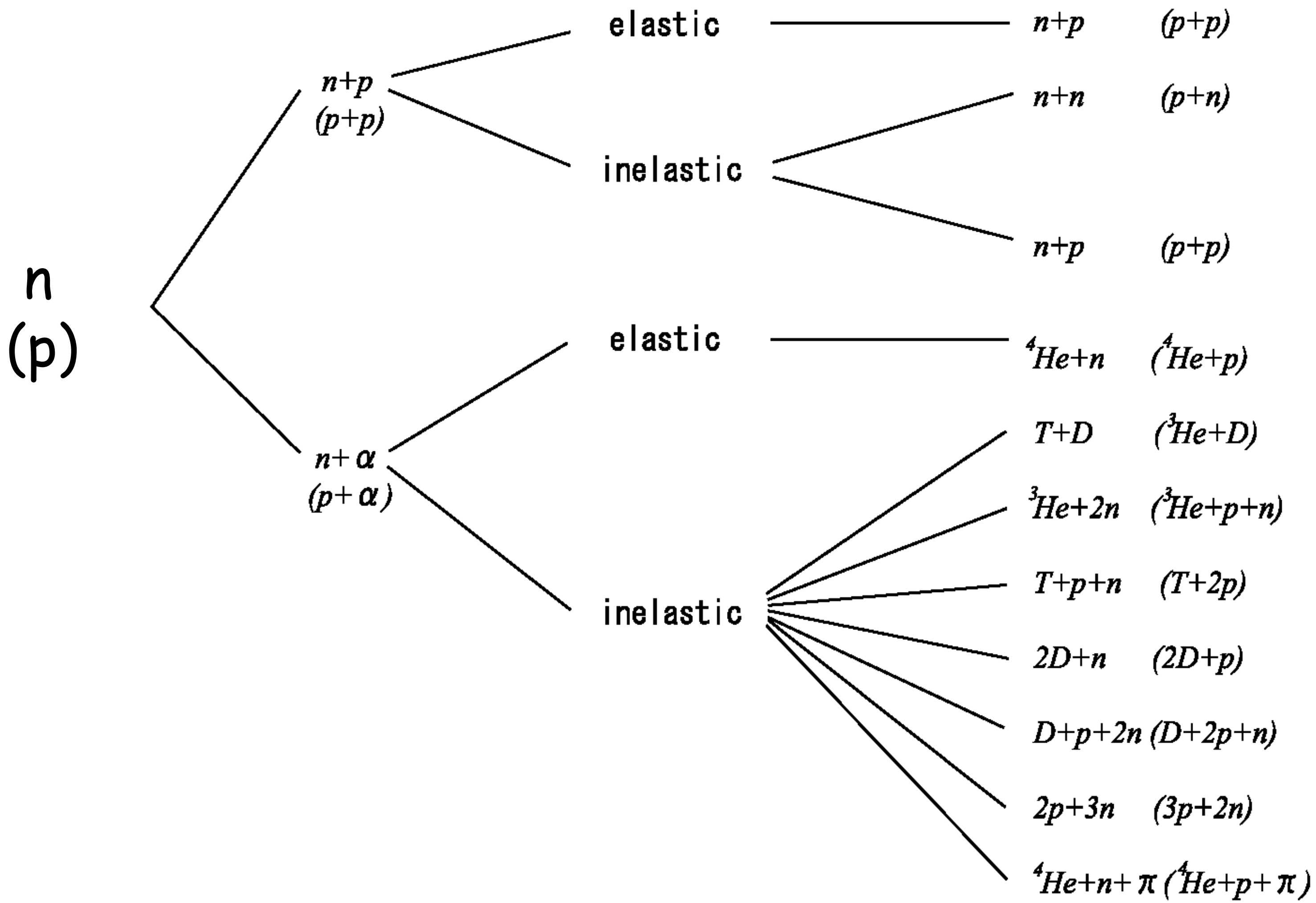
Even after freeze-out of n/p in SBBN

More He4, D, Li7 …

(II) Late stage of BBN (T < 0.1MeV)

Hadronic showers and "Hadro-dissociation"

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



n
(p)

$n+p$
$(p+p)$

elastic

$n+p$ $(p+p)$

inelastic

$n+n$ $(p+n)$

$n+p$ $(p+p)$

$n+\alpha$
$(p+\alpha)$

elastic

$^4\mathrm{He}+n$ $(^4\mathrm{He}+p)$

inelastic

$T+D$ $(^3\mathrm{He}+D)$

$^3\mathrm{He}+2n$ $(^3\mathrm{He}+p+n)$

$T+p+n$ $(T+2p)$

$2D+n$ $(2D+p)$

$D+p+2n$ $(D+2p+n)$

$2p+3n$ $(3p+2n)$

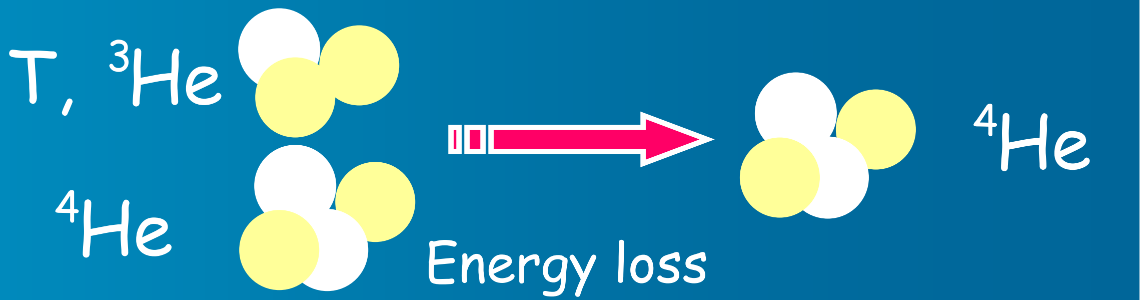
$^4\mathrm{He}+n+\pi$ $(^4\mathrm{He}+p+\pi)$

Non-thermal Li, Be Production by energetic nucleons or photons

dimopoulos et al (1989)
Jedamzik (2000)

$$\mathrm{N}\ (\text{or } \gamma) + {}^{4}\mathrm{He} \rightarrow \begin{cases} {}^{3}\mathrm{He} + \mathrm{X} \\ \mathrm{T} + \mathrm{X} \end{cases}$$

$$\mathrm{N}\ (\text{or } \gamma) + {}^{4}\mathrm{He} \rightarrow {}^{4}\mathrm{He}^{*} + \mathrm{X}$$



T(He3) – He4 collision

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

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

He4 – He4 collision

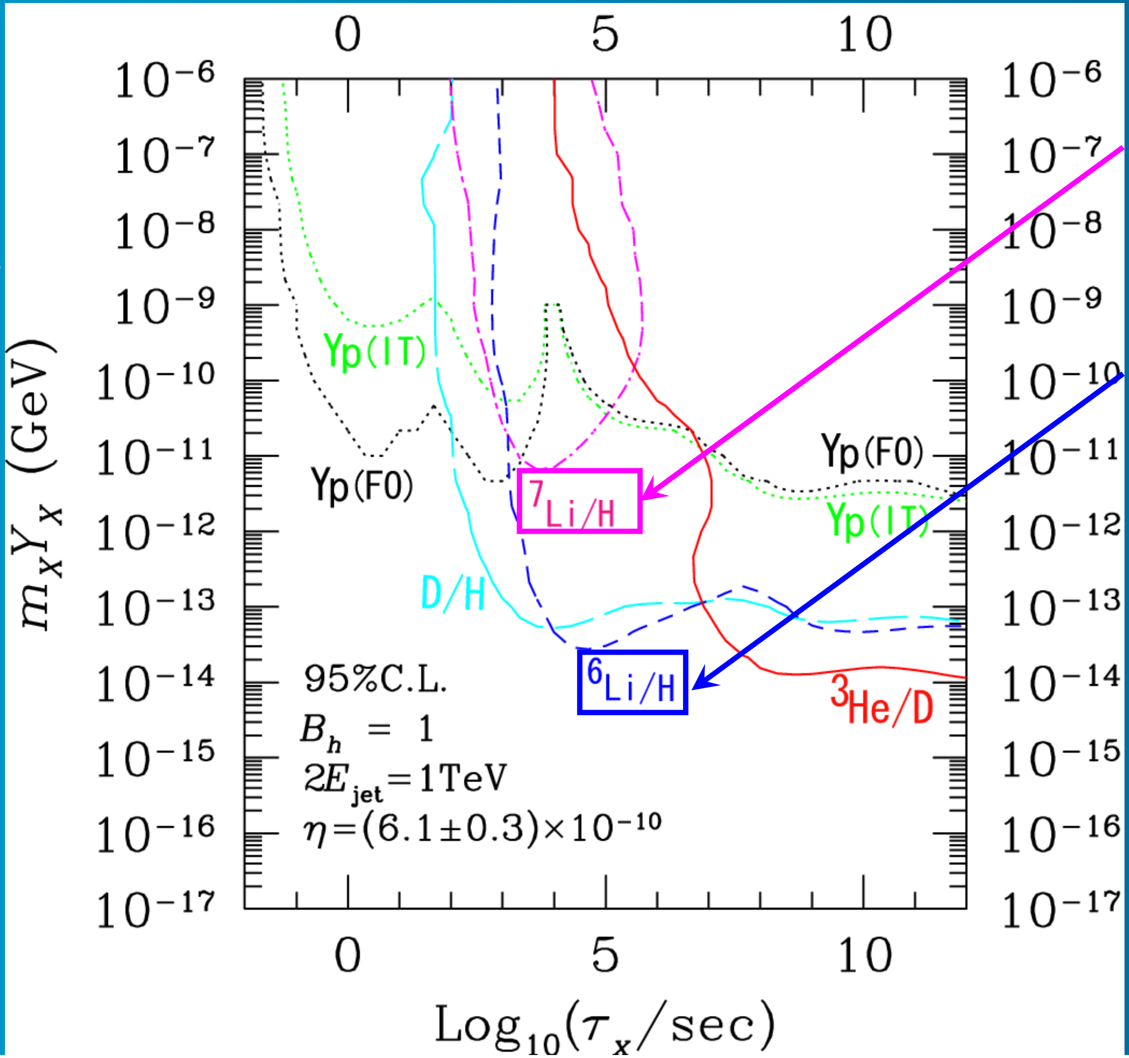
$$^{4}\mathrm{He} + {}^{4}\mathrm{He} \rightarrow {}^{6}\mathrm{Li}, {}^{7}\mathrm{Li}, {}^{7}\mathrm{Be} + \ldots$$

Massive particle X

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

Kawasaki, Kohri, Moroi (04)

$$Y_x \equiv n_x / s$$



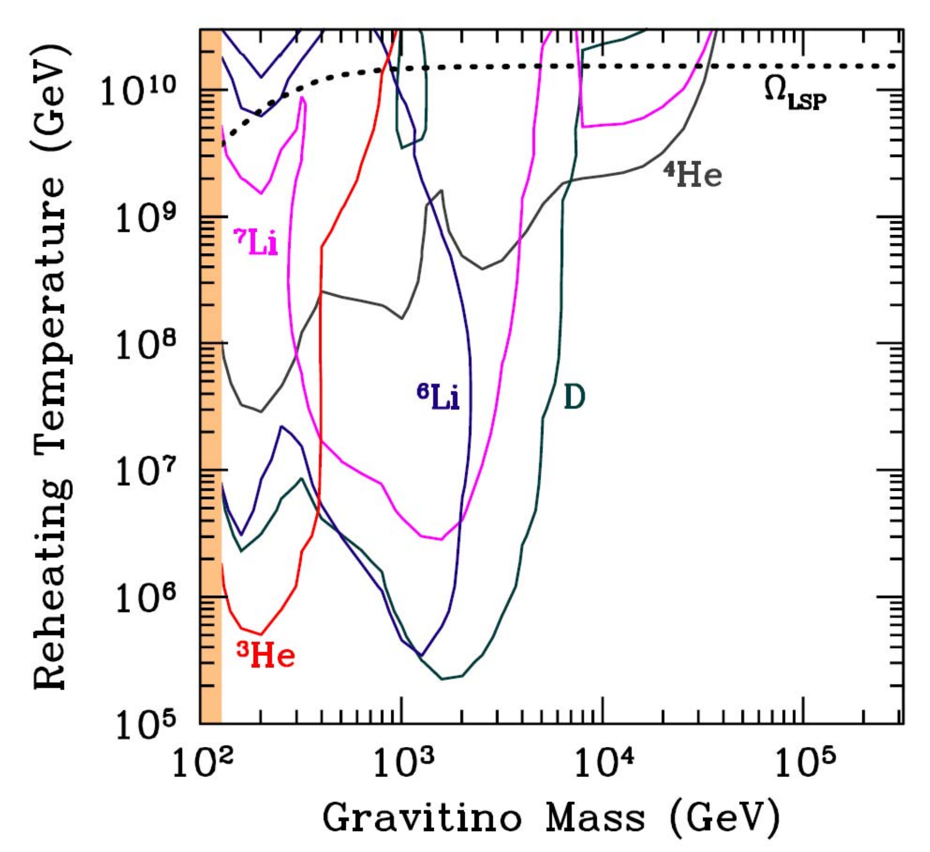
Mild observational upper bound

Mild observational upper bound

Neutralino (bino) LSP and gravitino "NLSP"

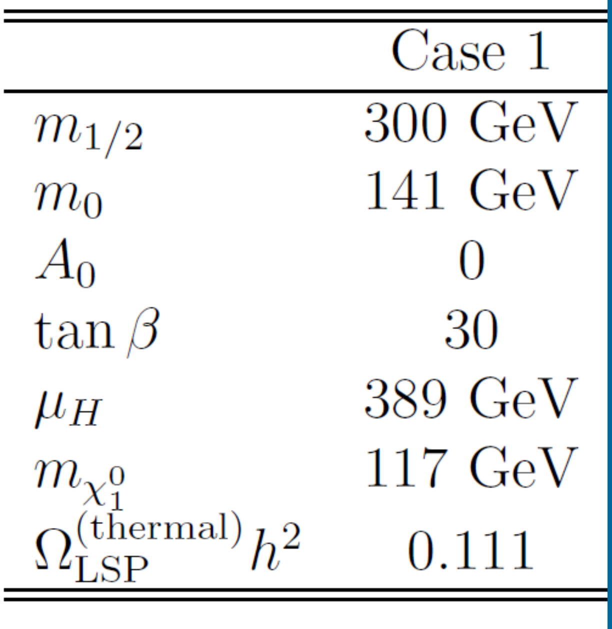
Upper bound on reheating temperature

Kawasaki, Kohri, Moroi, Yotusyanagi (08)



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

$$\tau \sim m_{pl}^2 / m_{3/2}^3$$



	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
$\Omega_{\mathrm{LSP}}^{(\mathrm{thermal})} h^2$	0.111

$$Y_x \equiv n_x / s$$

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)

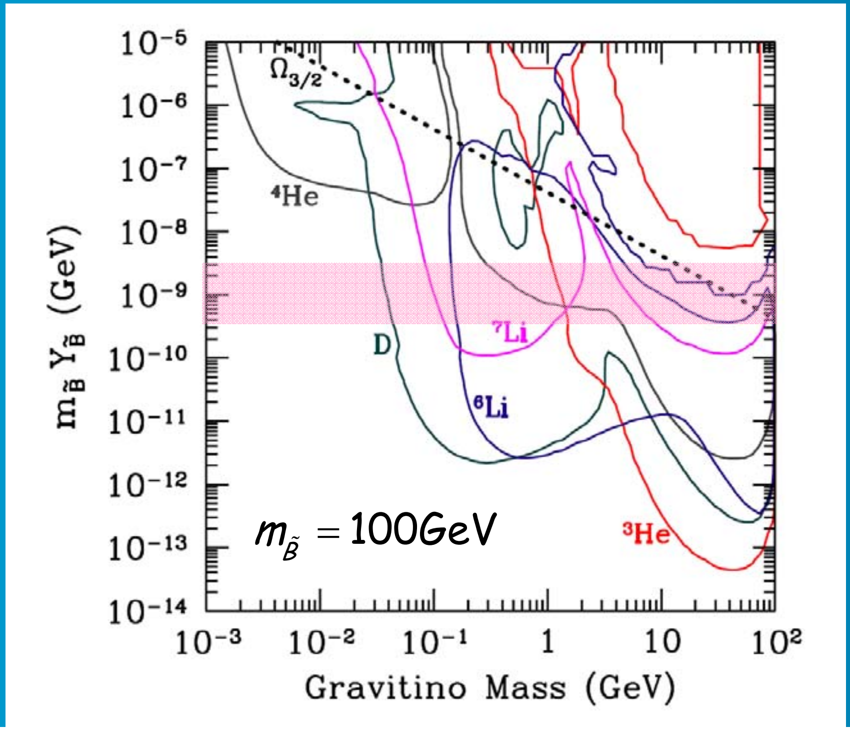
Lifetime

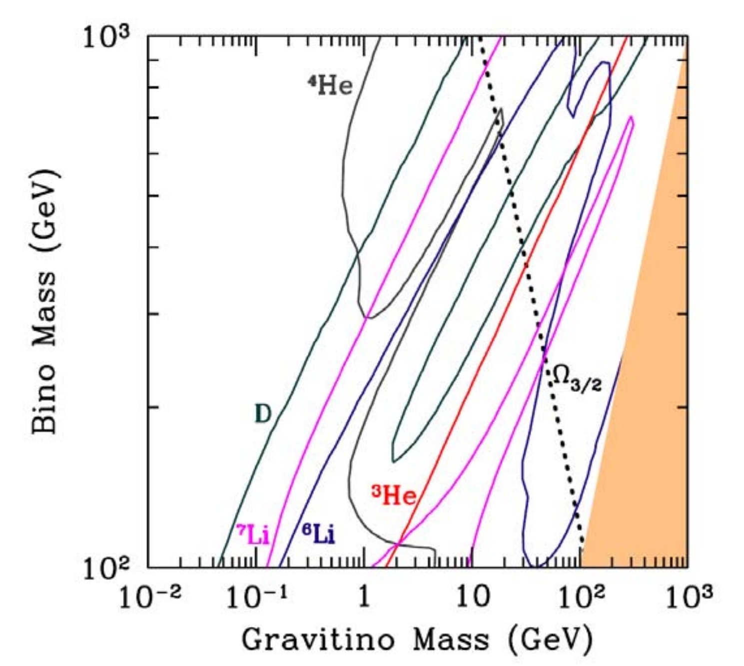
$$\tau \sim m_{3/2}^{2} \enclose{circle}{m_{pl}^{2}} / m_{NLSP}^{5}$$

Relic abundance

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

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.

(left-handed) sneutrino should be unstable

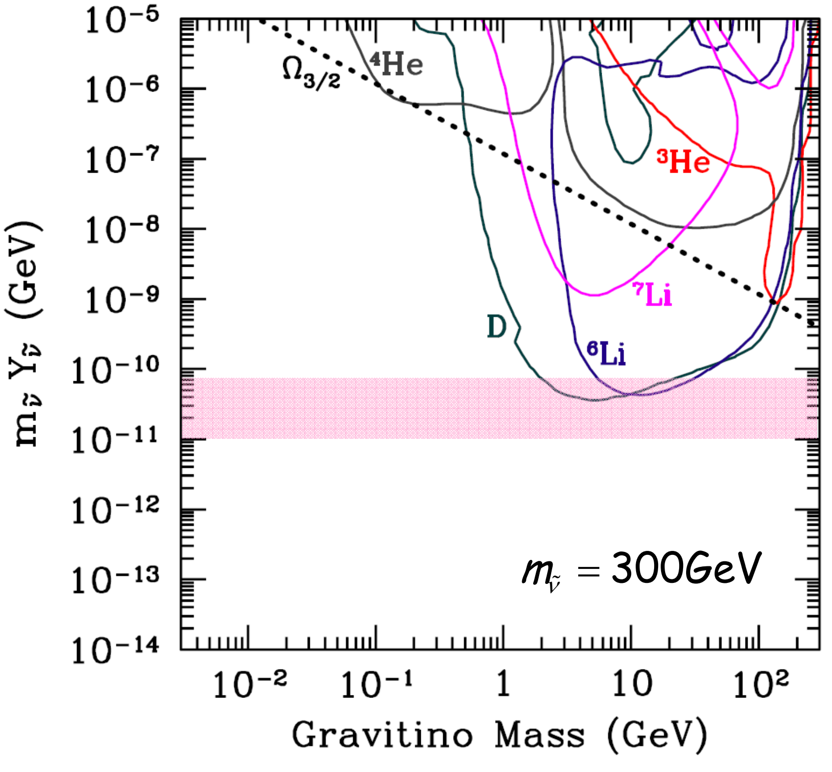
Gravitino LSP and thermally porduced sneutrino NLSP scenario

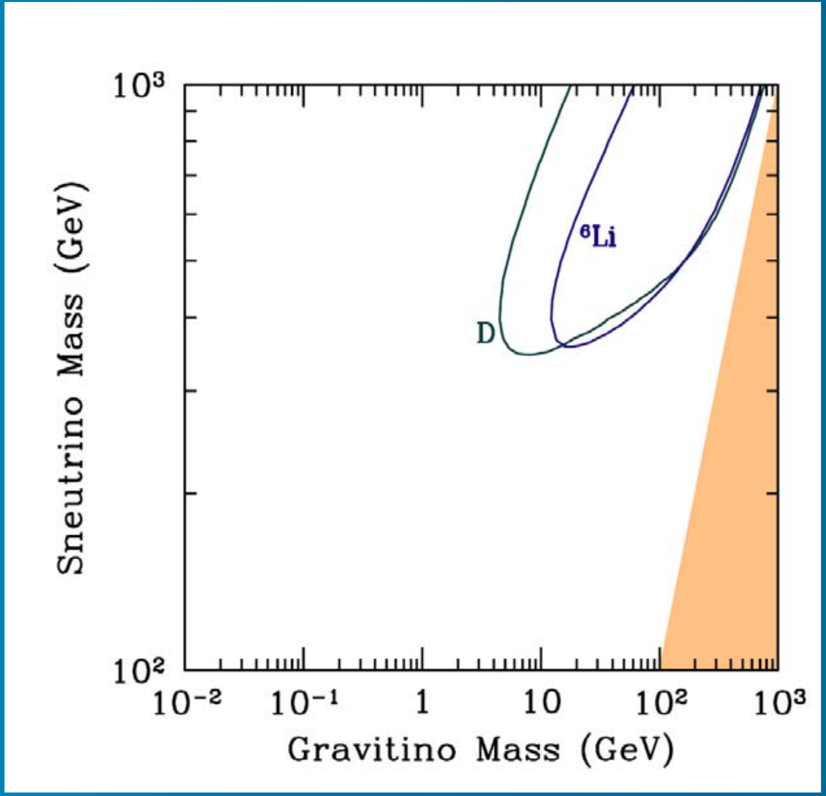
Kawasaki, Kohri, Moroi, Yotsuyanagi (08)

Ellis, Olive, Santoso (08)

Relic abundance

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





No allowed region for DM density with 100GeV sneutrinos

Stau NLSP and gravitino LSP scenario

Stable stau with weak-scale mass (<100TeV) was excluded by the experiments of ocean water

NLSP stau should be unstable

Bound-state effect (see next)

CHArged Massive Particle (CHAMP)

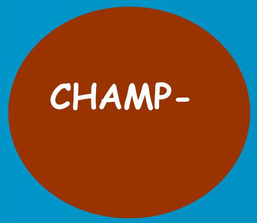
Kohri and Takayama, hep-ph/0605243
See also literature, Cahn-Glashow ('81)

Candidates of long-lived CHAMP in modern cosmology

stau, stop …

"CHAMP recombination" with light elemcts

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



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

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

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

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

- Enhancement of cross section

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

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

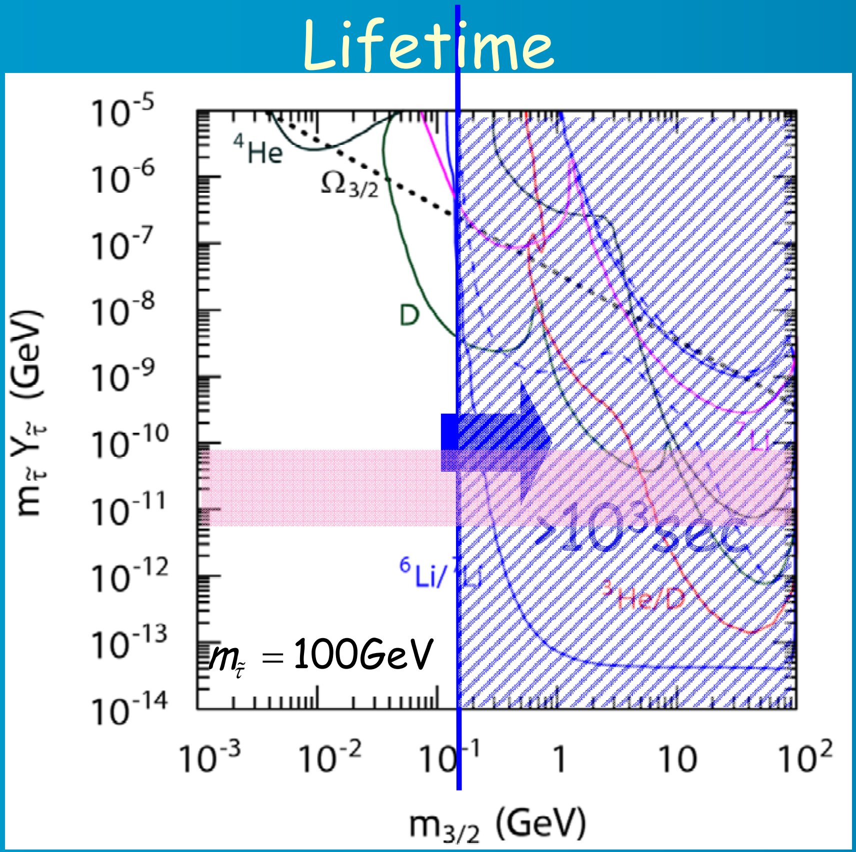
Stau NLSP and gravitino LSP Scenario in gauge mediation

Kawasaki, Kohri, Moroi PLB 649 (07) 436

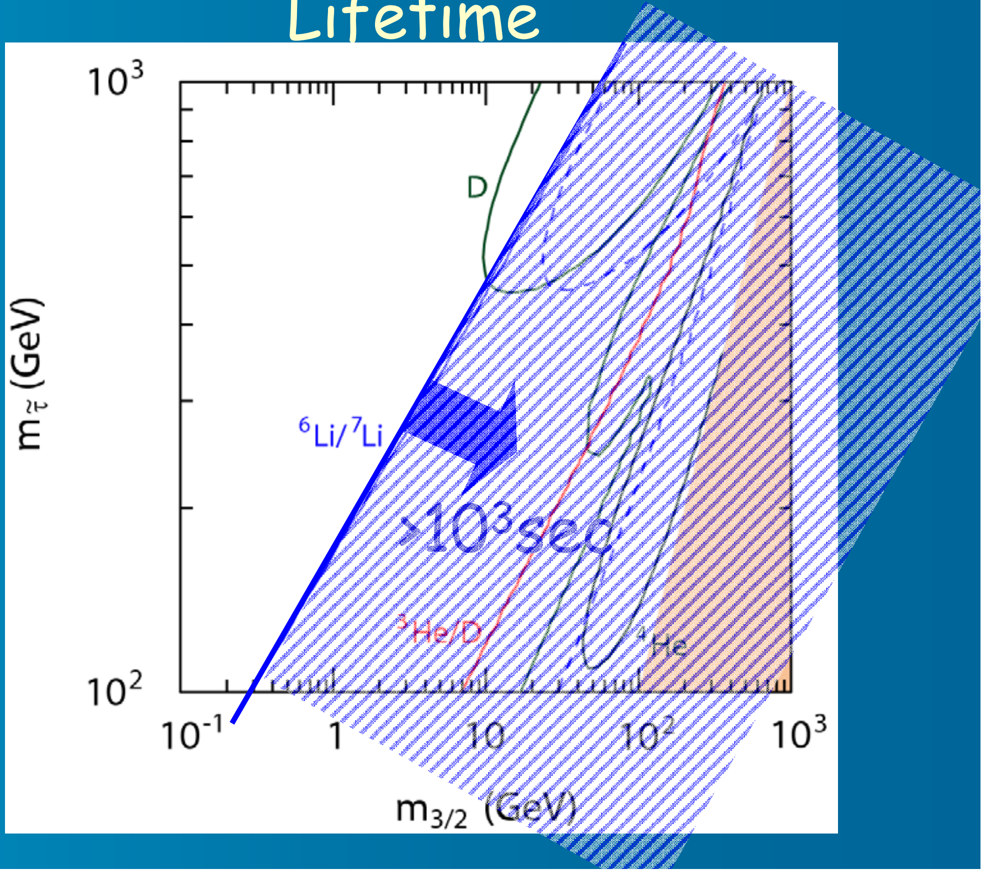
Relic abundance

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

Lifetime



Lifetime



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

Chun, Kim, Kohri, and Lyth (08)

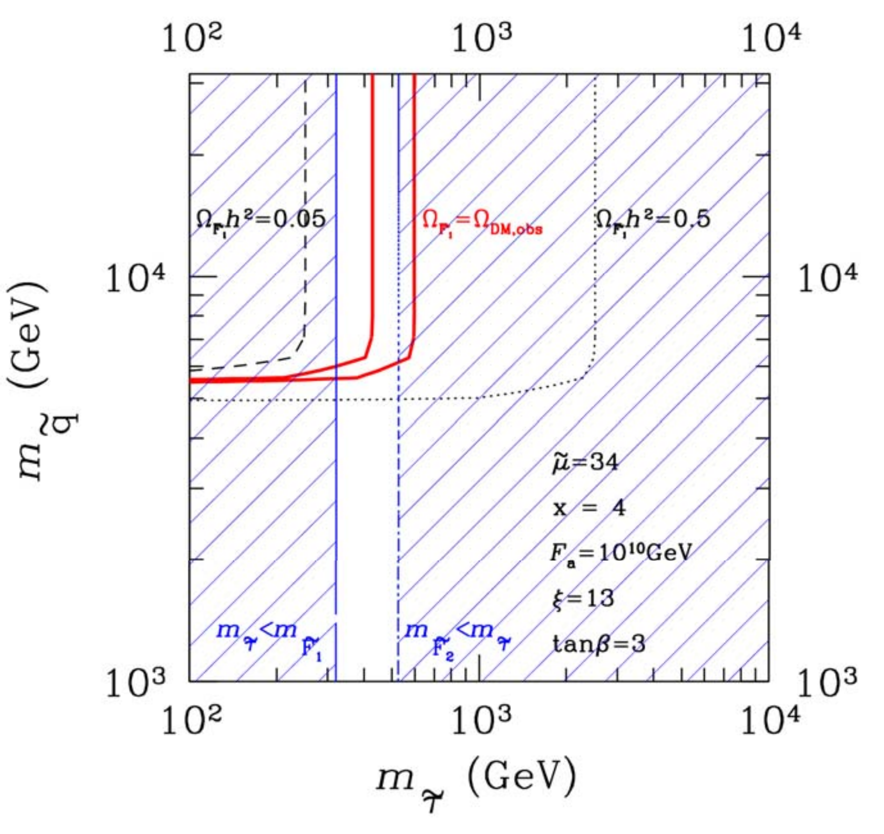
Decaying “flatons”
reheats the universe and
produce staus

$T_R \sim O(10)$ GeV

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

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

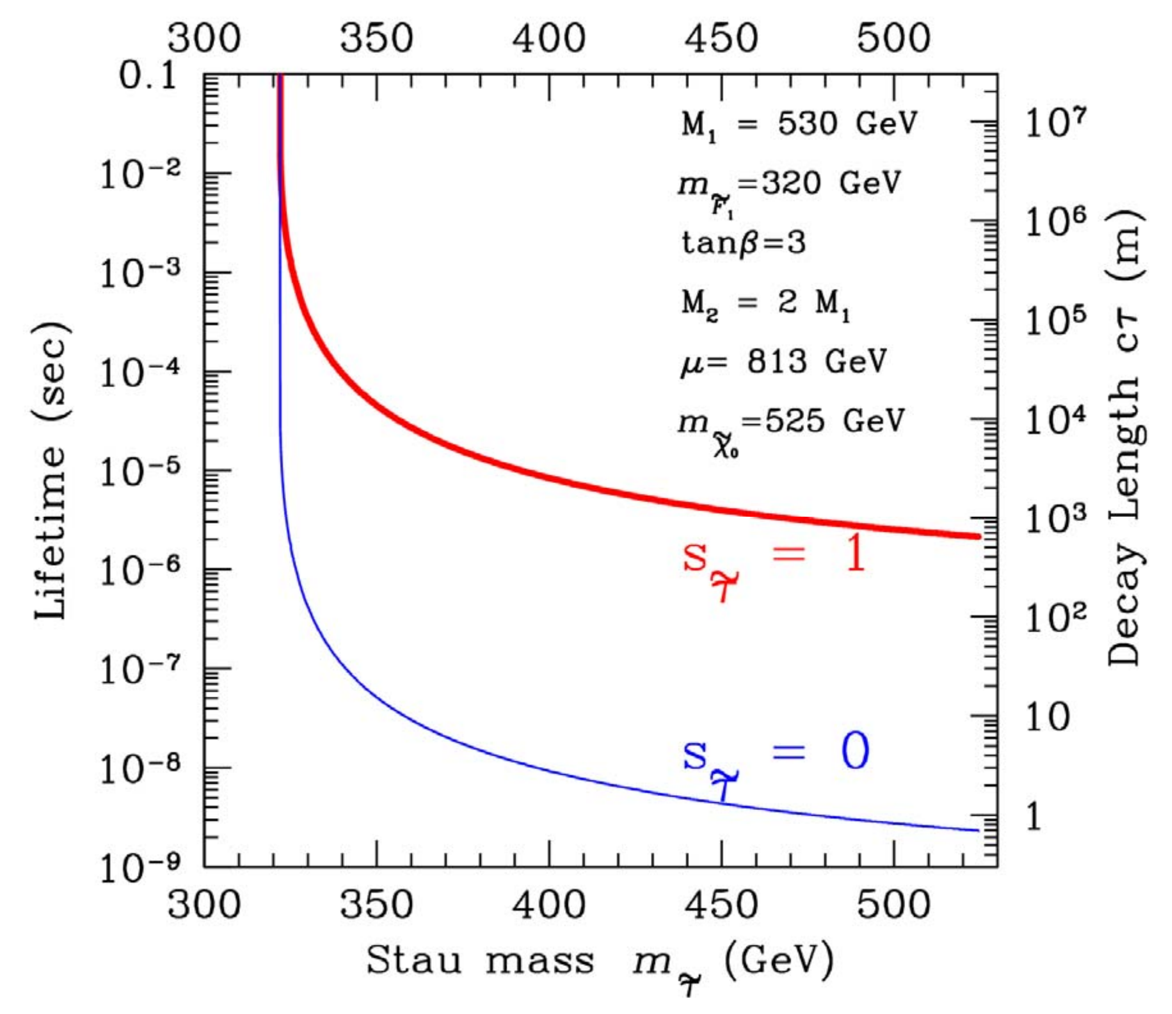
No BBN Catalysis



Stau can be found in LHC!!!

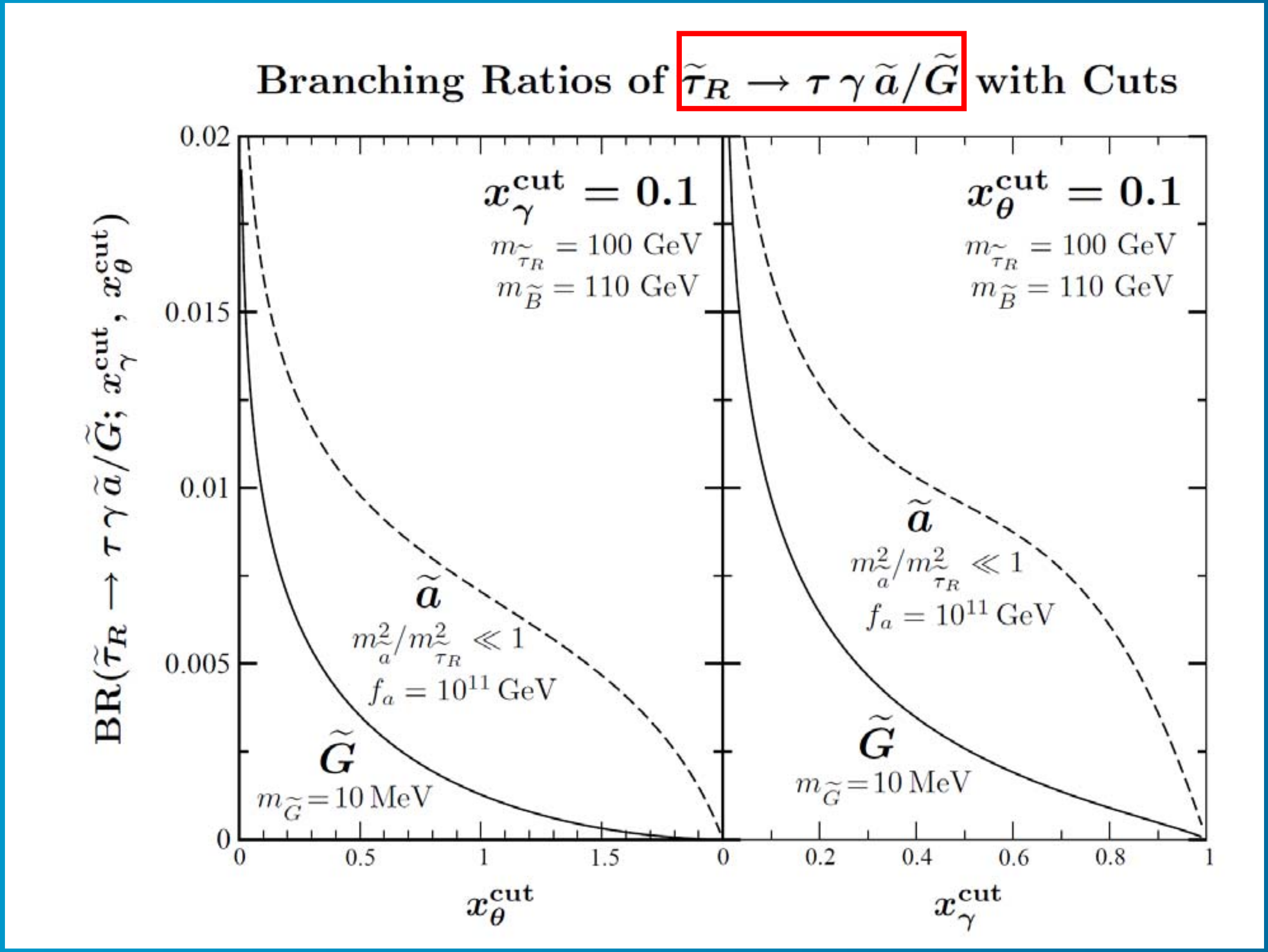
Lifetime of stau NLSP decaying into axino LSP

Chun, Kim, Kohri and Lyth (08)

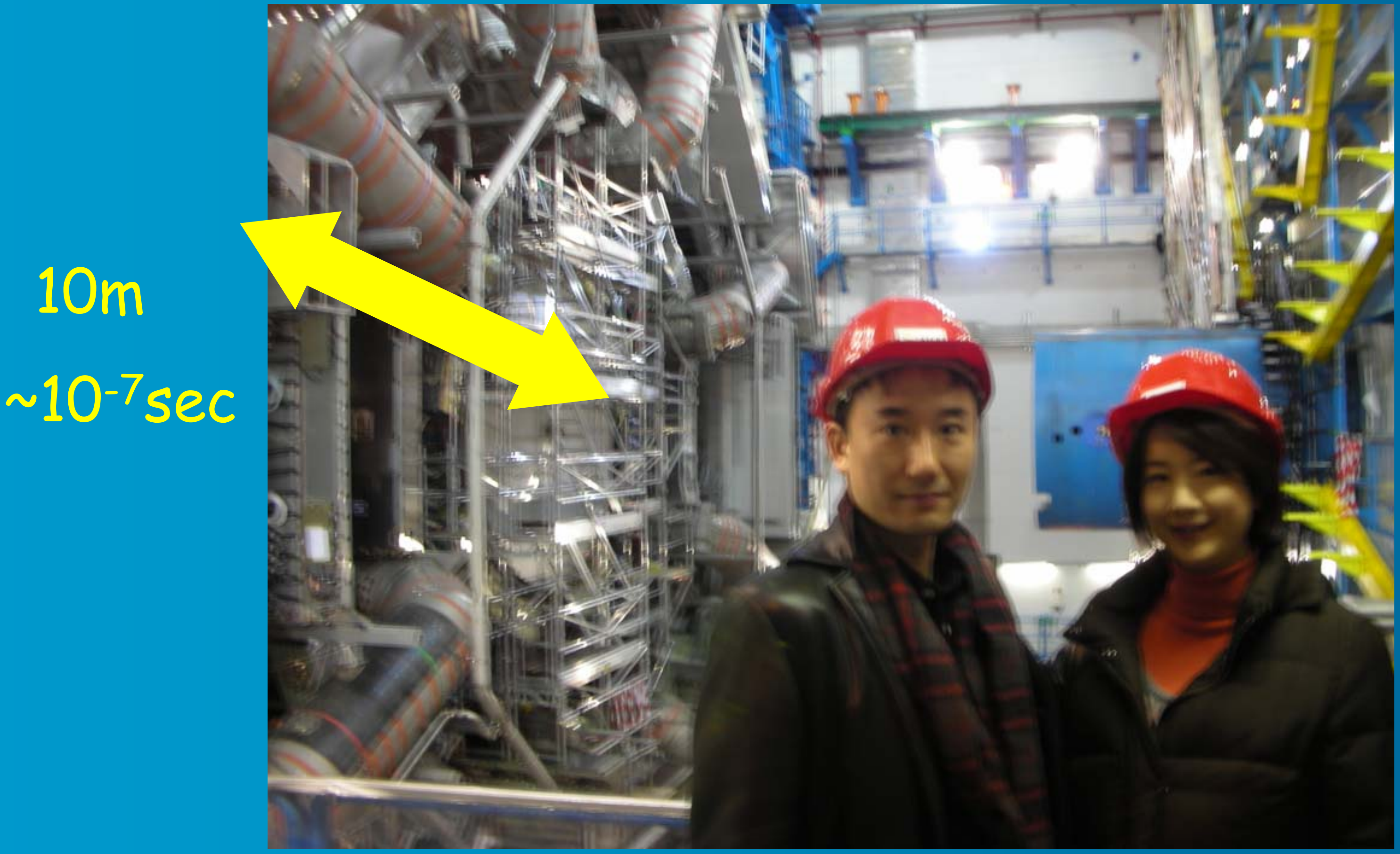


Can we distinguish gravitino from axino in LHC?

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



Large Hadron Collider (LHC)



ATLAS detector in CERN, Geneva, Switzerland

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

Residual annihilation of DM even at around BBN epoch

- To fit the PAMELA and ATIC2 positron signals and EGRET gamma-ray anomaly,

$$\langle \sigma v \rangle \sim 10^{-24} - 10^{-23} cm^3 / s$$

- At least it must emit charged leptons

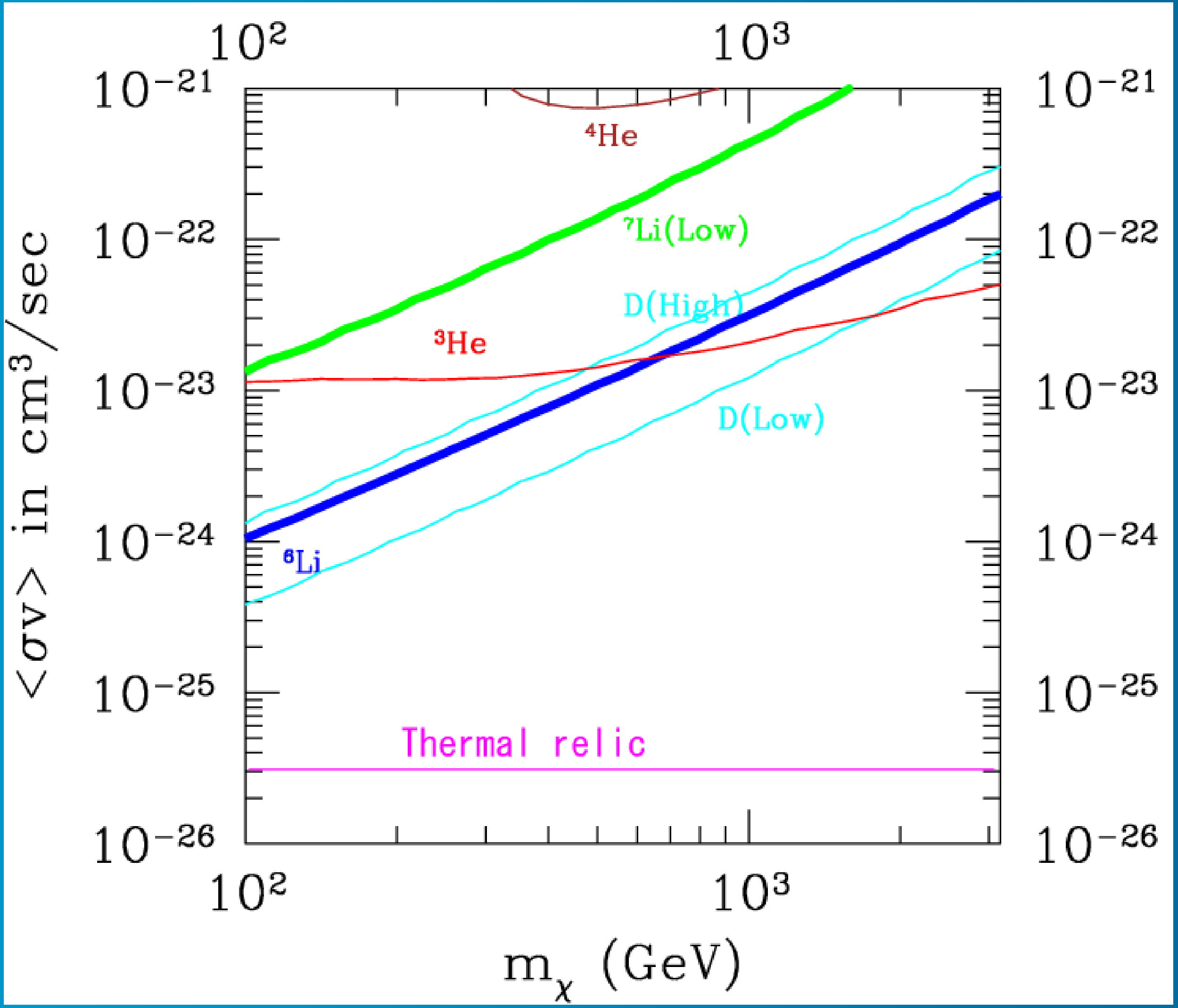
Electromagnetic cascade shower is induced

- It might also emit hadrons

Hadronic cascade shower is induced

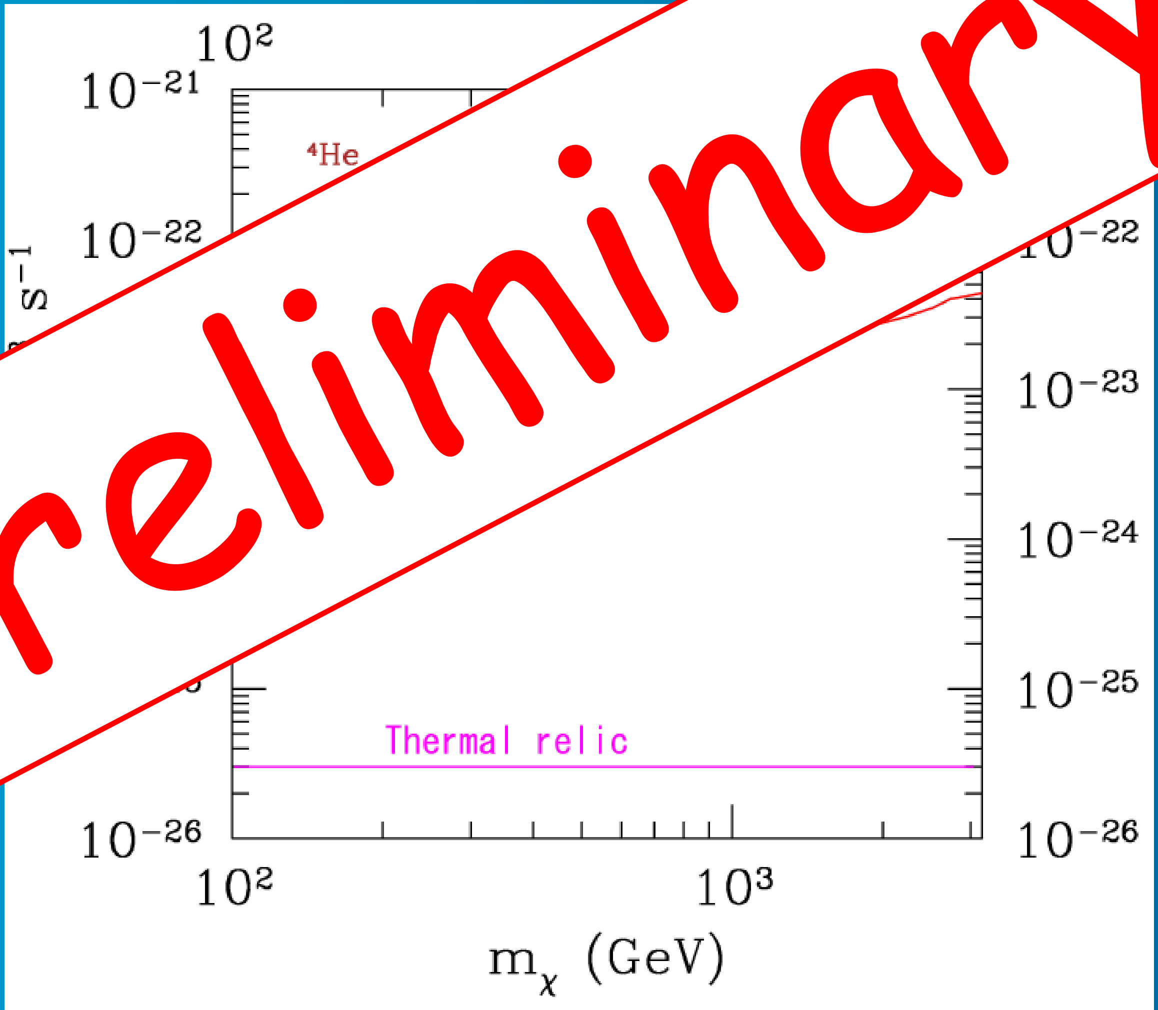
Hadron emission by residual annihilation in BBN epoch

Hisano et al in preparation



Charged-lepton (e^+e^-) emission by residual annihilation in BBN ep

Hi tion



Preliminary

Solving Li problem in new particle physics models

- We do not adopt systematic uncertainties of observational Li7 and Li6 abundances

Can long-lived 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)

- Stop NLSP and gravitino LSP scenario

Kohri and Santoso (08)

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

- Tritium scatters off the background He4 and produces Li6

Dimopoulos et al ('89)

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

Stop NLSP and gravitino LSP

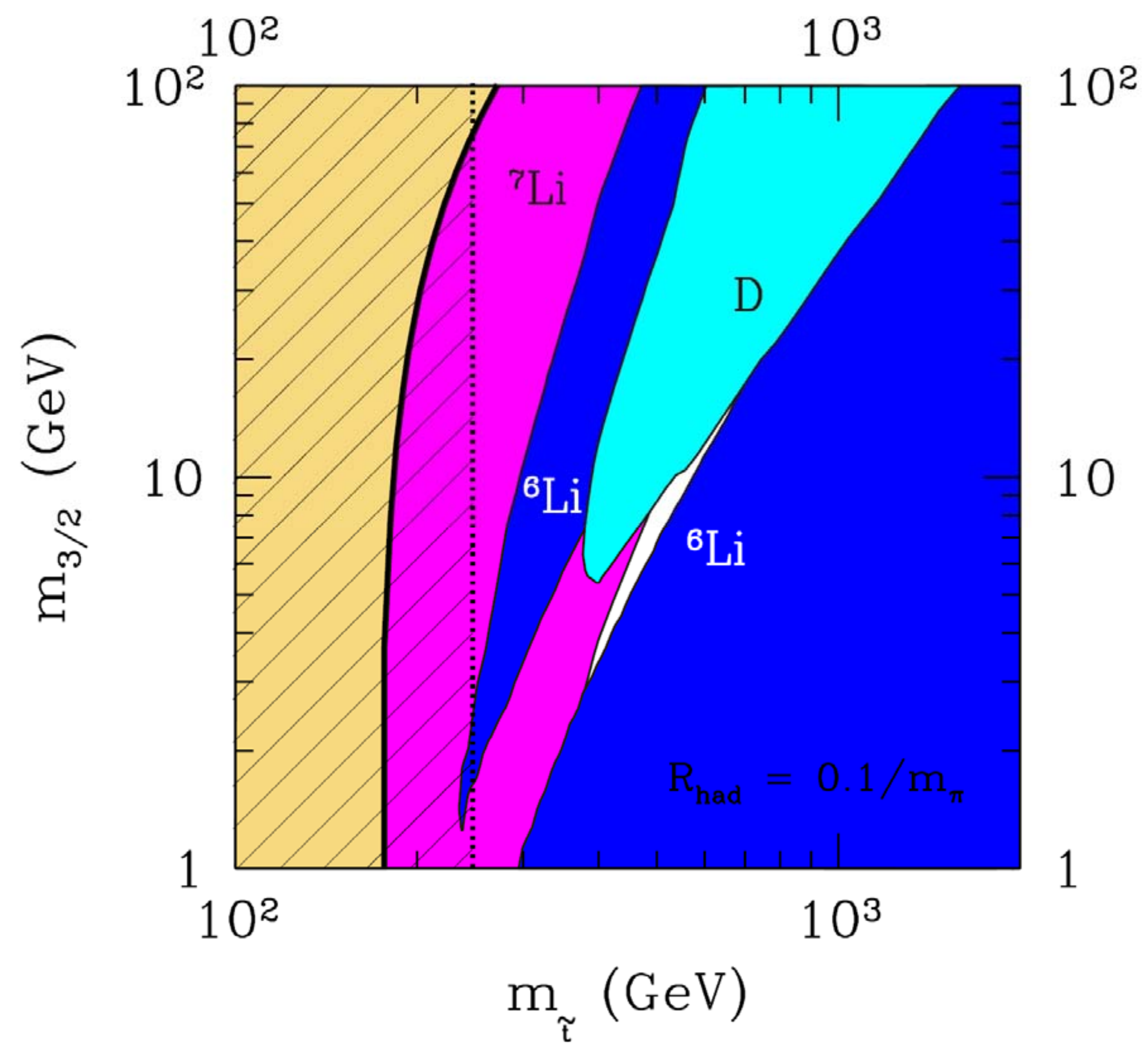
Kohri and Santoso (08)

- Stop can be NLSP in Non-universal Higgs masses (NUHM)
- Stop is confined into "messino" after QCD phase transition
- Second annihilation of stop 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]



Residual annihilation of wino LSP

Hisano, Kawasaki, Kohri, Nakayama(08)

- 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

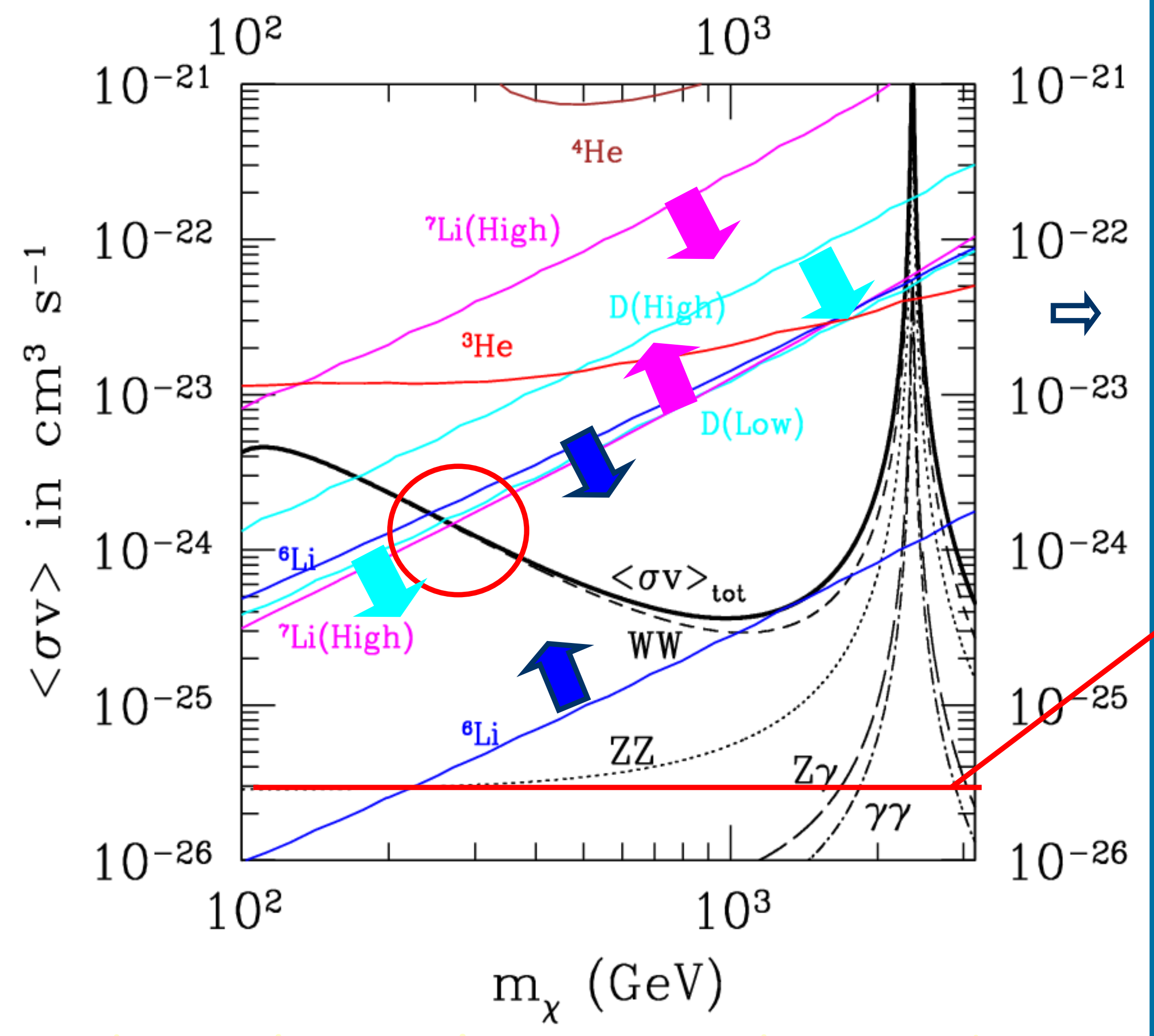
$$\langle \sigma v \rangle >> 3 \times 10^{-26} cm^3 / s$$

$$\tilde{W}\tilde{W} \to WW$$

Even during/after BBN epoch!!!

Residual annihilation of wino-like LSP

Hisano, Kawasaki, Kohri, Nakayama(08)



⇨

Thermal
(bino) DM

We need nonthermal wino production by gravitino decay

Conclusion

- Direct and indirect detections of DM will become more attractive in near future to get information on 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