A quick view for dark matter and a history of the universe

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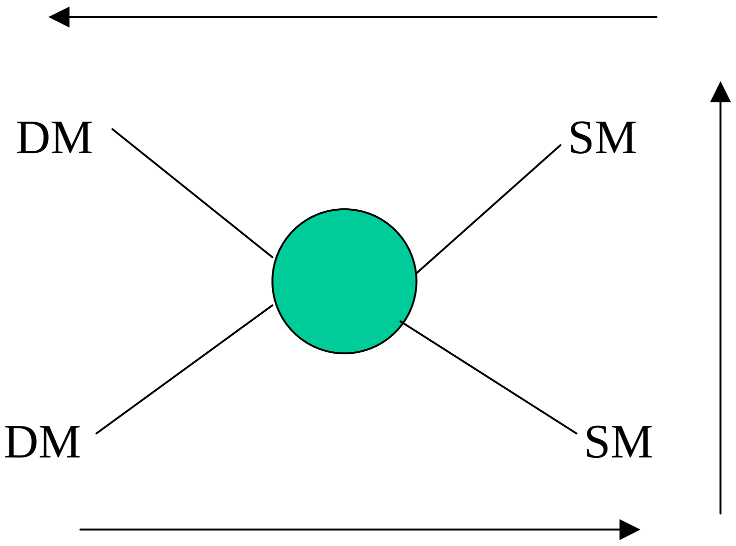
Lunch meeting at YITP (2010)

The most famous candidate of dark matter:
Stable Weakly Interacting Massive Particles (WIMPs)

Dark Matter pair creation (collider)



Dark Matter – SM matter scattering
(Kinetic decoupling…Early Universe
/Dark Matter direct detection)

$\Gamma \sim \sigma_{elas}\, v\ \, n_{SM}$

$n_{SM} \sim\ n_{\gamma}, n_{e}, \cdots$
(no Boltzmann suppression)

Dark Matter pair annihilation
(freeze out(chemical decoupling)..Early Universe = dark matter indirect detection)

?…Boost factor

$\Gamma \sim \sigma_{ann}\, v\ \, n_{DM}$

$n_{DM} \sim\ e^{-m/T}$ (early universe)

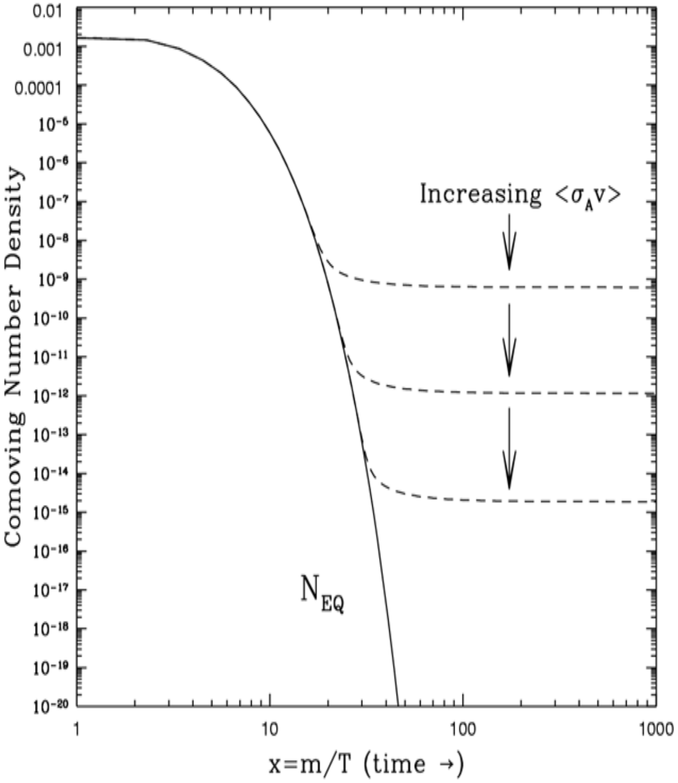
[1] WIMP thermally frozen dark matter relic density

Naturalness for dark matter relic density in TeV new physics
Parity, TeV mass scale and EW coupling strength
→ fix the nature of dark matter chemical decoupling
and give the correct observed DM relic density.

$$\sigma \sim \alpha^2 / m^2$$

Weak scale mass/Weak coupling
→ $\Omega \sim O(0.1)$

…learn the early universe at collider!



[2] WIMP as Cold Dark Matter

…Collisionless with SM?→(Now yes, Past No)
Kinetic decoupling

Can Dark Matter be unstable ?
Present Dark Matter is same as the primordial one ?

(WIMP is not dark(collisionless) in the ealy Universe.)

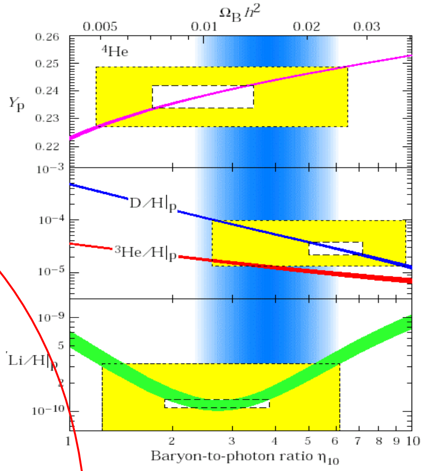
Microscopic properties of primardial DM
might be different from those of present DM.

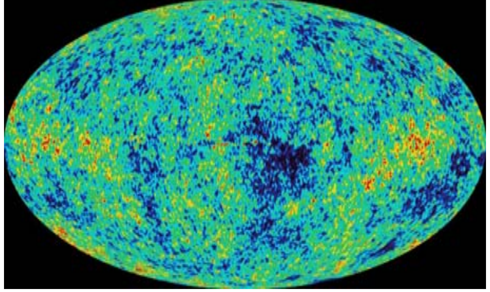
$\Gamma \sim \sigma v n_{SM} \ll H \sim T^2 / M_{pl}$

$\Omega_{TH} \ll 1$

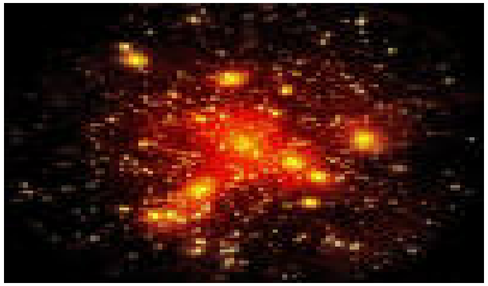
Reheating

BBN PDG2002



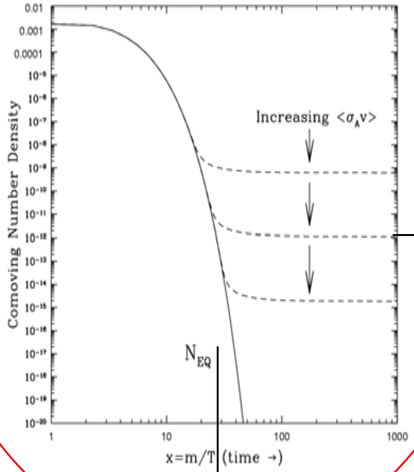


CMB



Large scale strucure

pDM chemical decoupling



pDM transition to present DM

e.g pDM decay: $m_{pDM} \sim m_{DM}$?

$\Omega_{DM} \sim (m_{DM}/m_{pDM})\Omega_{pDM}$

Matter-Radiation equality

T

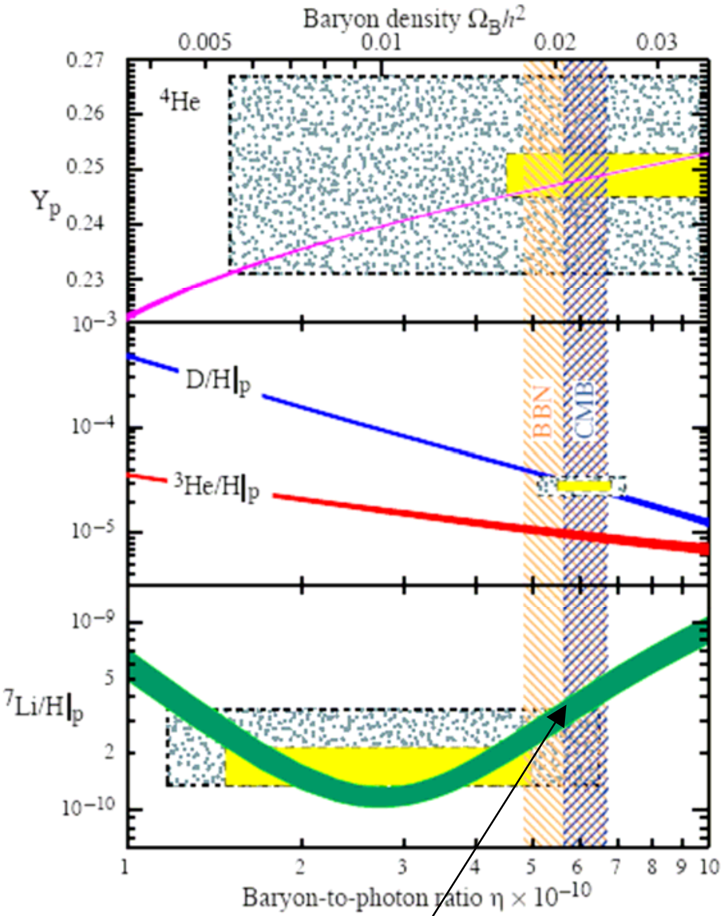
$T_f \sim m/25$

1MeV-50keV

T~keV
(Gravitino LSP case)

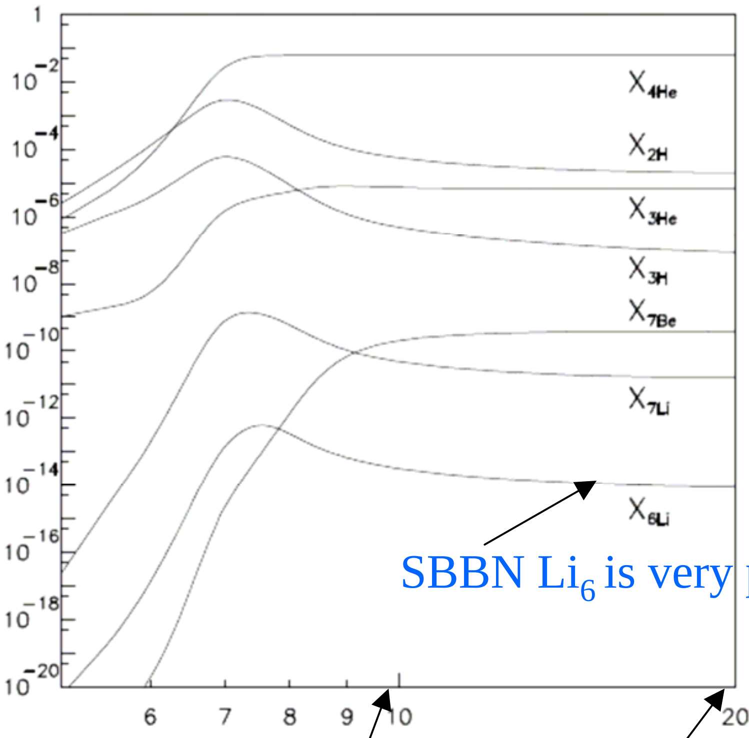
0.1eV

SBBN with CMB baryon-to-photon ratio and observed abundance of light elements



PDG(2006)

Low ^{7}Li



SBBN Li_6 is very poor

m_e/T

50keV

25keV

SBBN processes decouple until T=20keV

Puzzle from astrophysics in SBBN Check nuclear reaction rate....Li7 and Li6.

$Li_{6,7}$ are indicating problems of SBBN theory ?

K.Olive et al(2003)

Nuclear reaction rates in SBBN have been well fixed by experiments and solar neutrino observations

→ It is unlikely that the Li anomaly is explained by primordial origin within SBBN theory.

Metallicity dependence (in low metallicity region) for observed $Li_{6,7}$ ~ flat

→ observed one ~ primordial one

Anomalous changes of nuclear reaction rate is possible only at primordial era ?

Bound state of a light element and a negatively charged CHAMP during/after BBN

K.Kohri, F.Takayama(2006)

Bound state production

Photo destruction

$$[\frac{\partial}{\partial t}n_X]_{\rm capture} \simeq -<\sigma_r v>(n_C n_X - n_{(C,X)} n_\gamma(E > E_{\rm bin}))$$

$$n_\gamma(E > E_{\rm bin}) \equiv n_\gamma \frac{\pi^2}{2\zeta(3)}(\frac{m_X}{2\pi T})^{3/2} e^{-\frac{E_{\rm bin}}{T}}$$

$$n_\gamma = \frac{2\zeta(3)}{\pi^2} T^3$$

$$\longrightarrow \qquad T_c \simeq \frac{E_{\rm bin}}{40}$$

Heavier elements may be captured in earlier time.

$T_c(^7Be)$ ~ 37keV, $T_c(^7Li)$ ~ 25 keV

SBBN process completely decouple at T ~ 50-20keV

All exponential suppression is significant at below this T

Coulomb suppression (Low T)

Boltzmann suppression (low T)

β decay of neutron etc (small Hubble rate)

$\tau_n = 885.7 \pm 0.8$ s

The abundance of heavier than Li may be changed from SBBN value.

CHAMP BBN (CBBN)

K.Kohri, F.T (2006), M.Pospelov (2006), M.Kaplinghat, A.Rajaraman(2006),
R.Cyburt,J.Ellis,B.Field,K.Olive,V.Spanos(2006)….

Naive guess works (K.Kohri, F.Takayama(2006))

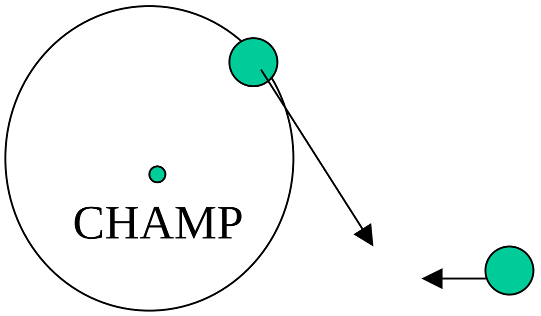
The bound state can change nuclear reaction rates in BBN

$$\begin{aligned}\sigma_{\text{fusion}} v &= (\sigma_S + \sigma_P v^2 + \ldots.) F_{ab}(v) \\ &= \sigma_0 v(v) \frac{2\pi Z_a Z_b \alpha}{v} e^{-\frac{2\pi Z_a Z_b \alpha}{v}}\end{aligned}$$

→ Coulomb suppression weaken

Thermal average for momentum distribution of light elements
→ competition between Coulomb suppression and Boltzmann suppression

Kinematics is also changed due to bound state
→ change of short distance reaction rate



The bound nuclei's kinematic features can be different from thermal nuclei.

Bound light element wave function localized near by the bound CHAMP. (In detail, M.Kaplinghat, A.Rajaraman(2006))
→Decaying bound CHAMP may hit bound light element at relatively higher rate than freely propagating cases

Prospects of collider experiments for extremely long lived CHAMP search

Discovery (Heavily Ionizing Track, TOF etc): Stable inside detector

M.Drees, X.Tata(1990),J.Goity,W.Kossler,M.Sher(1993)J.Feng,T.Moroi(1998)

Tevatron $m_C \sim 180\text{GeV}$ ($L=10\text{fb}^{-1}$, stable stau inside collider detector)
→LHC $m_C \sim 700\text{GeV}$

Mass, Couplings with SM particles, Lifetime, Decay properties

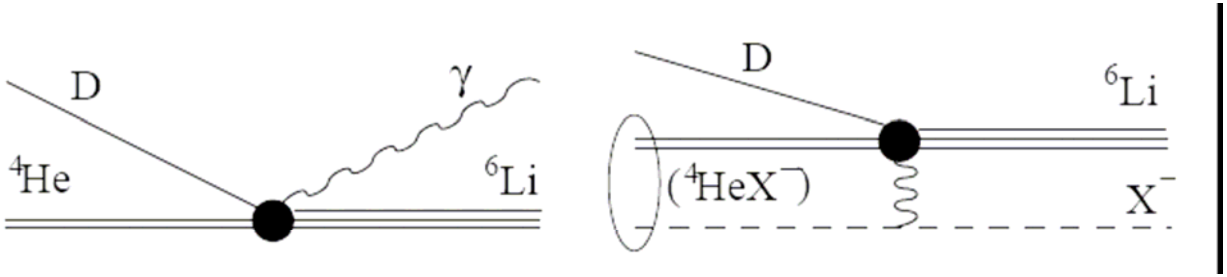
Trapping CHAMPs

B.T.Smith, J.Feng(2004) K.Hamaguchi,Y.Kuno,T.Nakaya,M.Nojiri(2004)

Virtual Photon processes (M.Pospelov(2006))

$$\text{SBBN}: \ {}^4\text{He} + \text{D} \rightarrow {}^6\text{Li} + \gamma; \qquad Q = 1.47\text{MeV}$$

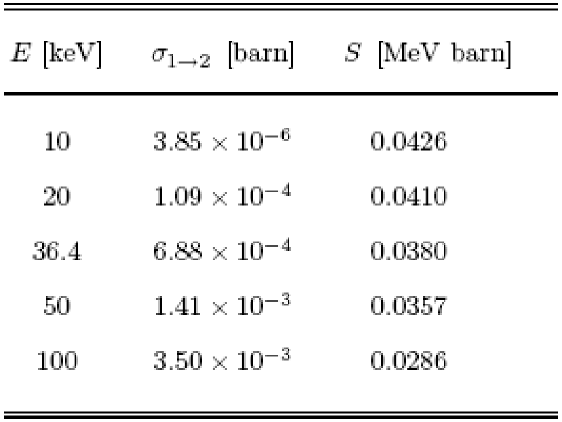
$$\text{CBBN}: \ ({}^4\text{He}X^-) + \text{D} \rightarrow {}^6\text{Li} + X^-; \ Q \simeq 1.13\text{MeV}$$



→Significant ^{6}Li production relative to the SBBN case

(Lifetime >> 10^3 sec)

: cross section ~ O(10^7) enhancement



E [keV]	$\sigma_{1\to2}$ [barn]	S [MeV barn]
10	3.85×10^{-6}	0.0426
20	1.09×10^{-4}	0.0410
36.4	6.88×10^{-4}	0.0380
50	1.41×10^{-3}	0.0357
100	3.50×10^{-3}	0.0286

K.Hamaguchi,T. Hatsuda, M.Kamimura, Y.Kino,T.Yanagida(2007)

CBBN and primordial ^{6}Li abundance

Catalyzed BBN constrain number density
of CHAMPs not the energy density

$$\frac{dn_{^4\mathrm{He}}}{dt} + 3Hn_{^4\mathrm{He}} = - < \sigma_{\mathrm{rec}} v > \left(n_C n_{^4\mathrm{He}} - n_{(C,^4\mathrm{He})}\tilde{n}_\gamma\right) + \frac{1}{\tau_C} n_{(C,^4\mathrm{He})}$$

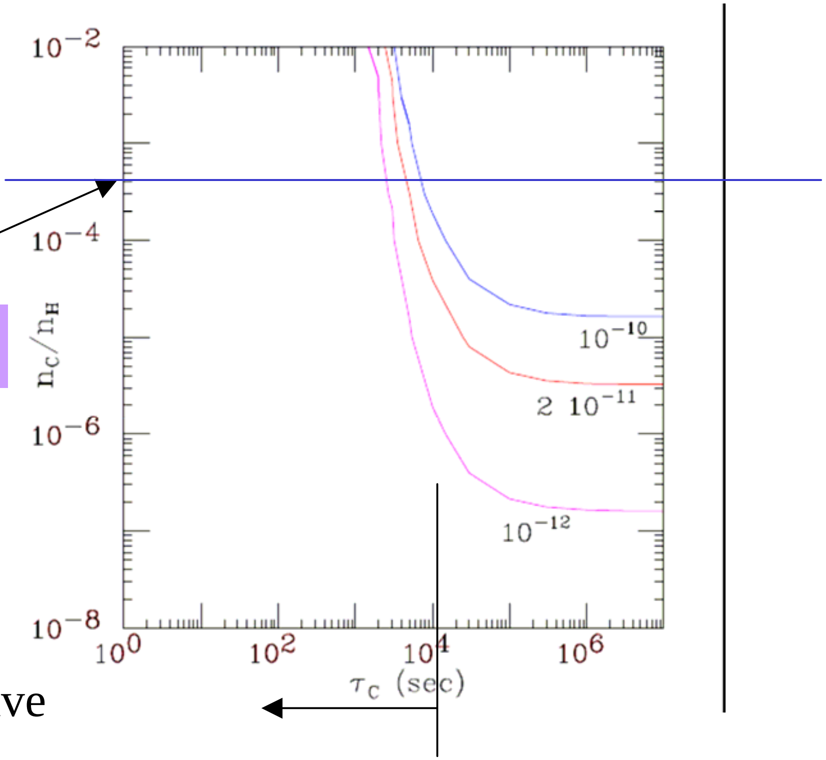
$$\frac{dn_C}{dt} + 3Hn_C = - < \sigma_{\mathrm{rec}} v > \left(n_C n_{^4\mathrm{He}} - n_{(C,^4\mathrm{He})}\tilde{n}_\gamma\right) + < \sigma^{CBBN}_{^6\mathrm{Li}} v > n_{(C,^4\mathrm{He})} n_D - \frac{1}{\tau_C} n_C$$

$$\frac{dn_{(C,^4\mathrm{He})}}{dt} + 3Hn_{(C,^4\mathrm{He})} = < \sigma_{\mathrm{rec}} v > \left(n_C n_{^4\mathrm{He}} - n_{(C,^4\mathrm{He})}\tilde{n}_\gamma\right) - < \sigma^{CBBN}_{^6\mathrm{Li}} v > n_{(C,^4\mathrm{He})} n_D - \frac{1}{\tau_C} n_{(C,^4\mathrm{He})}$$

$$\frac{dn_{^6\mathrm{Li}}}{dt} + 3Hn_{^6\mathrm{Li}} = < \sigma^{CBBN}_{^6\mathrm{Li}} v > n_{(C,^4\mathrm{He})} n_{\mathrm{D}}$$

$$\frac{dn_{\mathrm{D}}}{dt} + 3Hn_{\mathrm{D}} = - < \sigma^{CBBN}_{^6\mathrm{Li}} v > n_{(C,^4\mathrm{He})} n_{\mathrm{D}}$$

Standard m_C =100GeV



DM from CHAMP decays may be possible to have the desired relic density if $\tau < 10^4$ sec.

Fumihiro Takayama(2007)

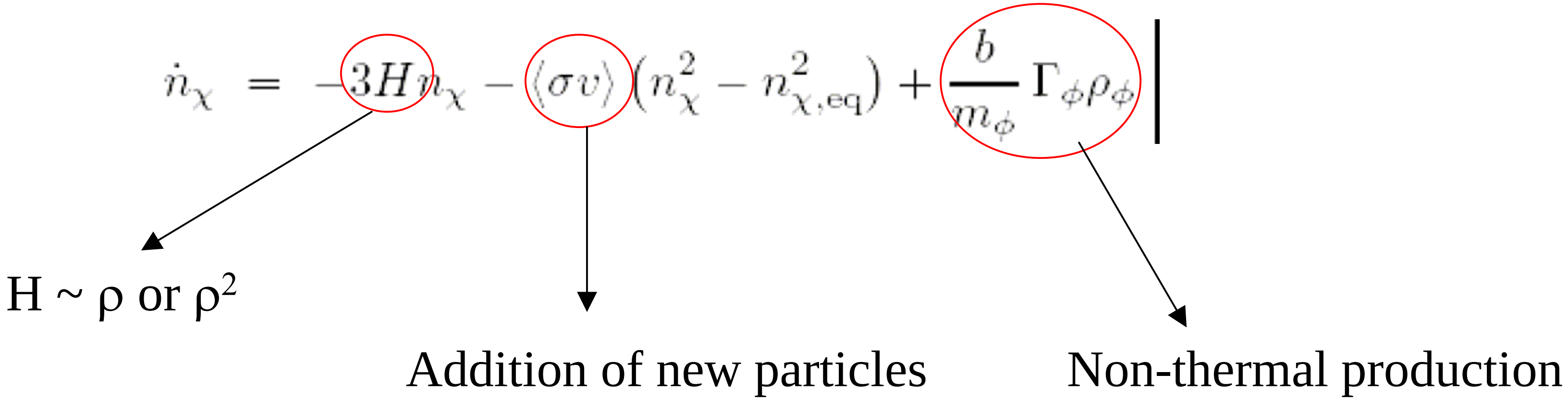
Potentially this scenario can modify the SBBN prediction, but
it seems that this scenario(e.g in gravitino LSP) tends to overproduce Li_6 .

But if nature is taking such long-lived CAHMP with $\tau > 10^3$ sec , then…
What is the impact of catalyzed BBN on the history of the Universe?

We were assuming thermal freeze-out of CHAMPs….

→ toward non-standard reheating scenario?

Beyond standard radiation dominated universe



$$\dot{n}_\chi = -3Hn_\chi - \langle \sigma v \rangle (n_\chi^2 - n_{\chi,\mathrm{eq}}^2) + \frac{b}{m_\phi}\Gamma_\phi \rho_\phi$$

$H \sim \rho$ or ρ^2

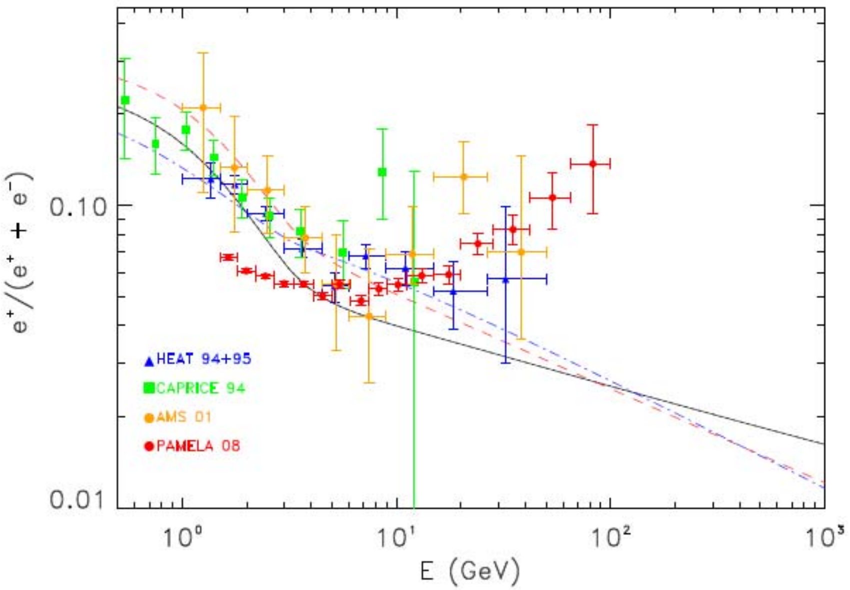
Addition of new particles

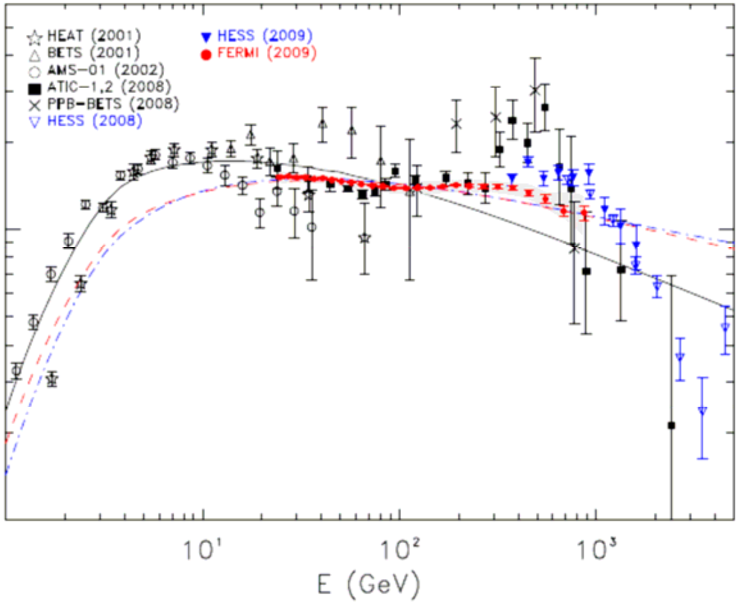
Non-thermal production

If primordial dark matter has the lifetime longer than age of the unvierse and they are decaying now, ….

A candidate of primary high energy cosmic rays

Recent data have indicate primary electrons/positrons sources





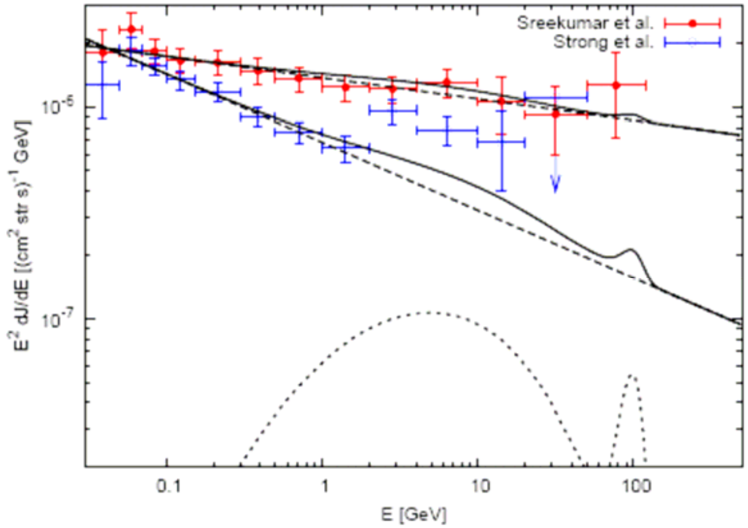
arXiv:0905.0636

Future prospects (e.g Decaying Gravitino dark matter case)

(a) Fermi/PAMELA era

mG=200GeV

Typically gravitino decay provides a line in the edge of the photon spectrum
→indicate the mass scale of gravitino if we could identify it.



(IC/FSR contributions is not included
For off disk direction, IC is small.)

W.Buchmuller, A.Ibarra, T.Shindou,F.Takayama,D.Tran(2009)

Dark matter seems requiring the extension of the particle standard model, that is, at least, we need a new particle.

Currently we know the existence of dark matter through the gravitational effects. But several new satellite/underground/collider experiments in coming years expect further understanding for dark matter properties beyond the gravitational properties and the history of our universe.

The understanding of microscopic properties of dark matter and the roles in history of the Universe is one of good target for particle physicists to study.

By getting new observational facts and learning further dark matter properties, dark matter may probe new information e.g forces hidden from our visible particles and may become a clue to know how to extend the particle physics standard model.