Title: Particle Dark Matter and the Light Element Abundances

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Abstract:

# Particle Dark Matter and the Light Element Abundances

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# Outline of Talk

I. Anomalies in the Light-Element Abundances:

II. BBN with Weak Mass-Scale Relic Particles decaying at $\tau \approx 1000$ sec

III. Late-time ($\tau > 10^6$ sec) BBN with Charged Relic Particles

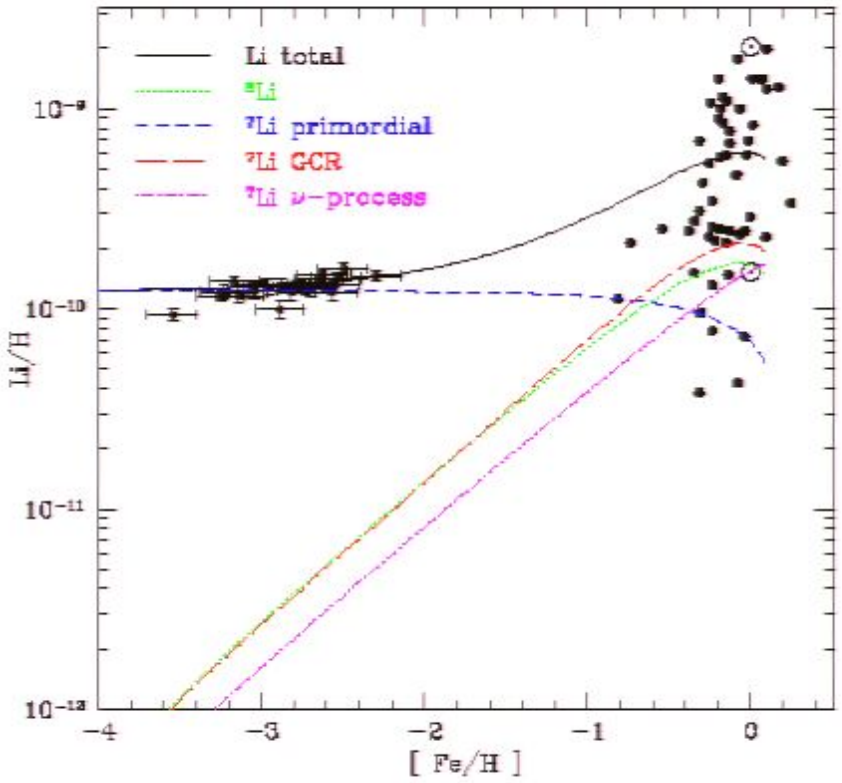
IV. BBN Limits on Charged Relic Particles

V. Simultaneous Solutions to the Lithium Problems in the CMSSM

# I. Anomalies in the Light Element Abundances:

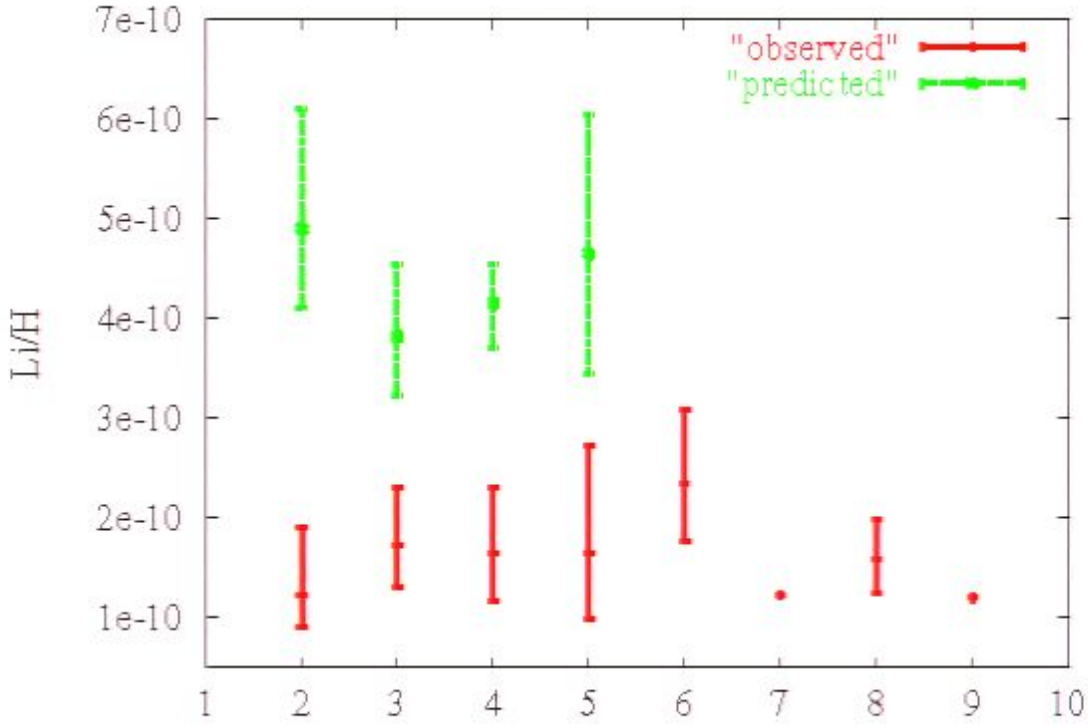
# The $^7$Li Spite plateau

Spite & Spite 82, Bonifacio & Molaro 97, Ryan *et al* 99, Asplund et al 04, Melendez Ramirez 04, Boesgard *et al.* 05, Charbonnel & Primas 05




## Interpretation - the Primordial $^7$Li Abundance

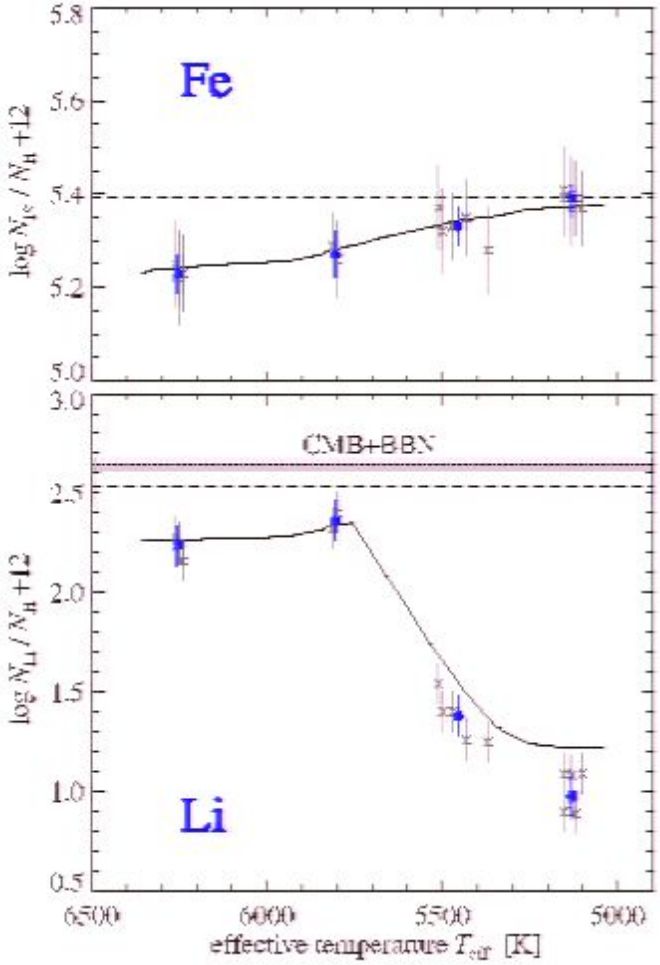
# The $^{7}$Li Problem




Ryan *et al* 00; Bonifacio & Molaro 97; Charbonnel & Primas 05; Boesgard *et al* 05, Melendez & Ramirez 04; Asplund *et al* 05; Bonifacio *et al* 03, Zhang & Zhao 04
Burles *et al* 01; Cyburt *et al* 04; Coc *et al* 04; Cuoco *et al* 04

# $^7$Li depletion by atomic diffusion in PopII stars

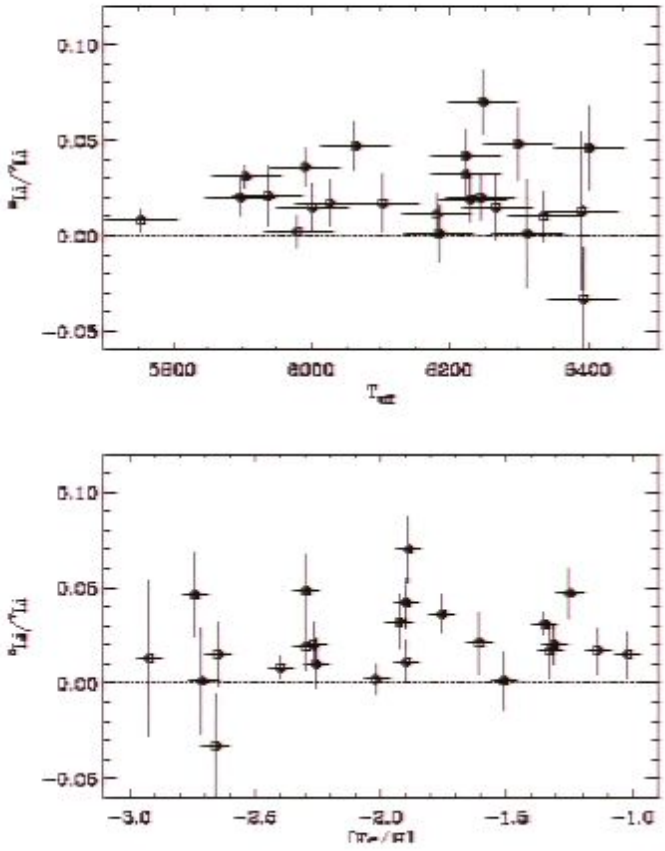
Korn *et al.*



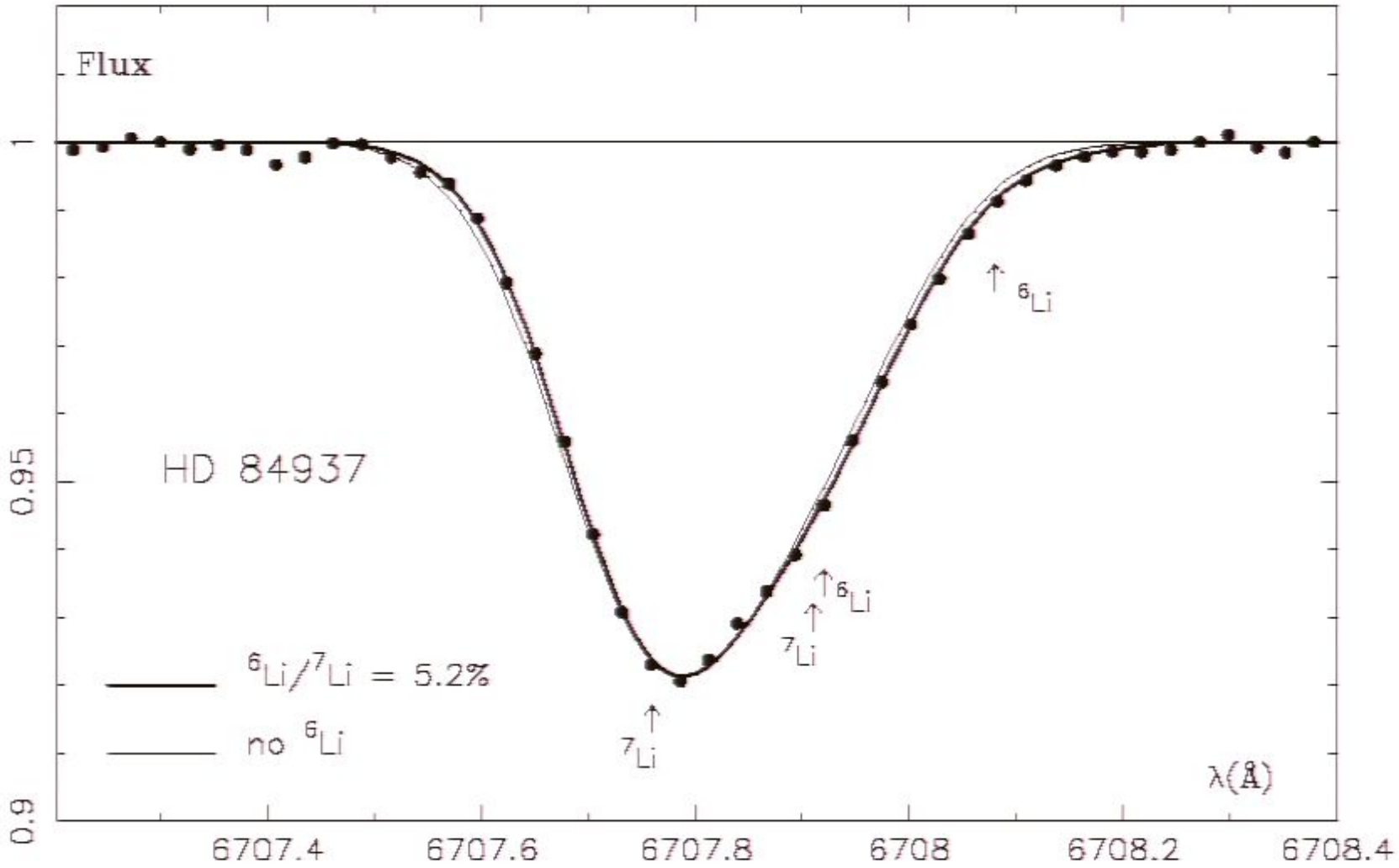
# $^6$Li/$^7$Li at low metallicity

Asplund, Lambert, Nissen, Primas, and Smith 05 (astro-ph/0510636)

A statistical excess at $^6$Li/$^7$Li $> 0$



# $^6$Li/H observations



# The Origin of $^6$Li ?

Thermal $^6$Li synthesis during BBN is believed to be negligible due to:

- the inefficiency of D$(\alpha,\gamma)^6$Li
- the energy threshold on $^3$H$(\alpha,n)^6$Li and $^3$He$(\alpha,p)^6$Li

$^6$Li is traditionally believed to originate in galactic cosmic ray nucleosynthesis (along, with $^9$Be, and B)

- via $\mathrm{p},\alpha + \mathrm{CNO} \rightarrow \mathrm{LiBeB}$
- and some $\alpha + \alpha \rightarrow Li$

# The $^6$Li energetics problem:

need *100 eV/nucleon* to synthesize $^6\mathrm{Li/H} \sim 5 \times 10^{-12}$

standard cosmic rays may provide 5 eV/nucleon (up to $[Z] \sim -2.7$

only very efficient accretion on central black hole, or large fraction of baryons in supermassive $\sim 100 M_\odot$ stars may provide the required cosmic rays

# $^6$Li ,$^7$Li **Situation Summary**

$^7$Li observed factor $2-3$ lower in old stars than produced in SBBN Astrophysical Solutions: Depletion in stars, Nuclear cross sections, Stellar Atmospheres

$^6$Li observed factor $1000$ higher in old stars than produced in SBBN Astrophysical Solutions: Very early cosmic ray population, solar flares, observational error

# II. BBN with Weak Mass-Scale Relic Particles decaying at $\tau \approx 1000$ sec

# $^6$Li ,$^7$Li in cascade nucleosynthesis

## $^6$Li production:

Electromagnetic:

$$\gamma + {}^4\mathrm{He} \rightarrow {}^3\mathrm{H} + p$$

$$^3\mathrm{H} + {}^4\mathrm{He} \rightarrow {}^6\mathrm{Li} + n$$

at $T \lesssim 0.1$ keV

Hadronic:

$$n + {}^4\mathrm{He} \rightarrow {}^3\mathrm{H} + p + n$$

$$^3\mathrm{H} + {}^4\mathrm{He} \rightarrow {}^6\mathrm{Li} + n$$

at $T \lesssim 10$ keV

$^7$Li destruction: $^7\mathrm{Be} + n \rightarrow {}^7\mathrm{Li} + p$; $^7\mathrm{Li} + p \rightarrow {}^4\mathrm{He} + {}^4\mathrm{He}$

at $T \approx 30$ keV

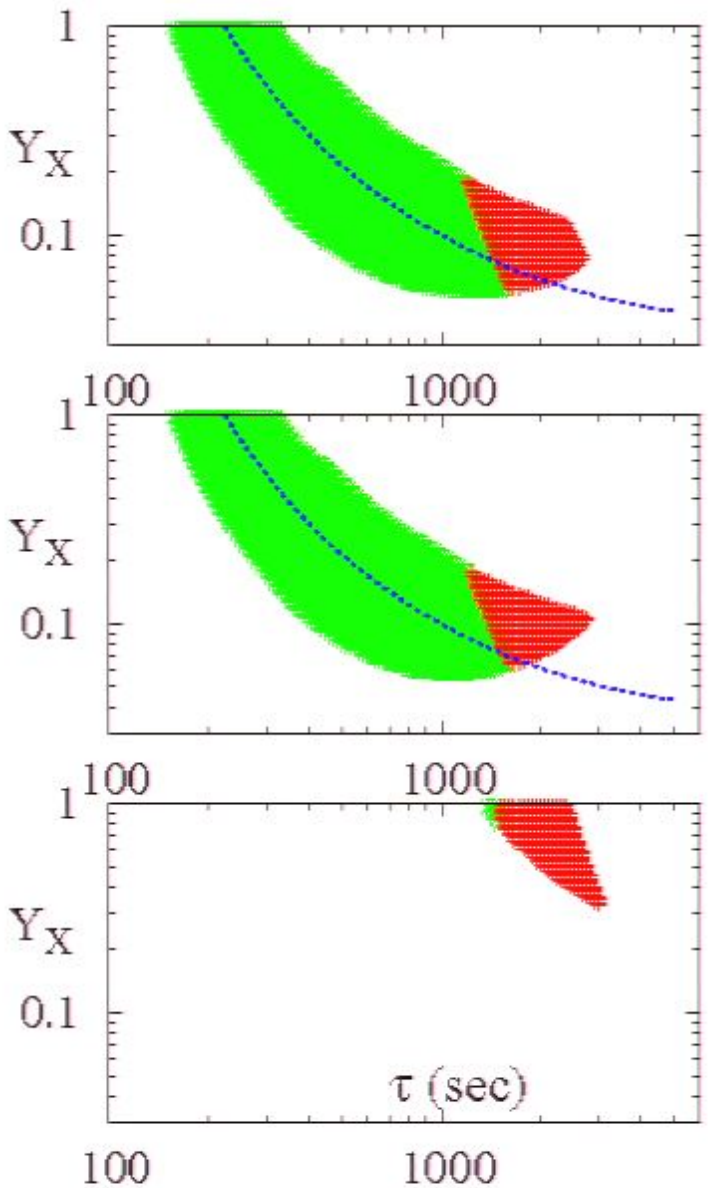
# $^6$Li ,$^7$Li in catalytic bound state BBN

Pospelov 06, Kohri & Takayama 06, Kaplinghat & Rajaraman 06, Cyburt *et al* 06, Hamaguchi *et al.* 07, Bird *et al* 07, Kawasaki *et al.* 07, Takayama 07, Jittoh *et al.* 07, K.J. 07, Kusakabe *et al* 07a,07b

- reaction $^2\mathrm{H}+^4\mathrm{He}\rightarrow{}^6\mathrm{Li}+\gamma$ is replaced by $^2\mathrm{H}+(^4\mathrm{He}\text{-}X^-)\rightarrow{}^6\mathrm{Li}+X^-$ $\rightarrow 10^7$ times more efficient
- $(^7\mathrm{Be}\text{-}X^-)+p\rightarrow(^8\mathrm{B}\text{-}X^-)$ may lead to some reduction of $^7\mathrm{Be}$
- ...

# Effects of bound states ?

$M = 1\,\text{TeV}$
$B_h = 10^{-4}$



# III. Late-time ($\tau > 10^6$ sec) BBN with Charged Relic Particles

# Effects of bound states ?

$M = 1\,\text{TeV}$
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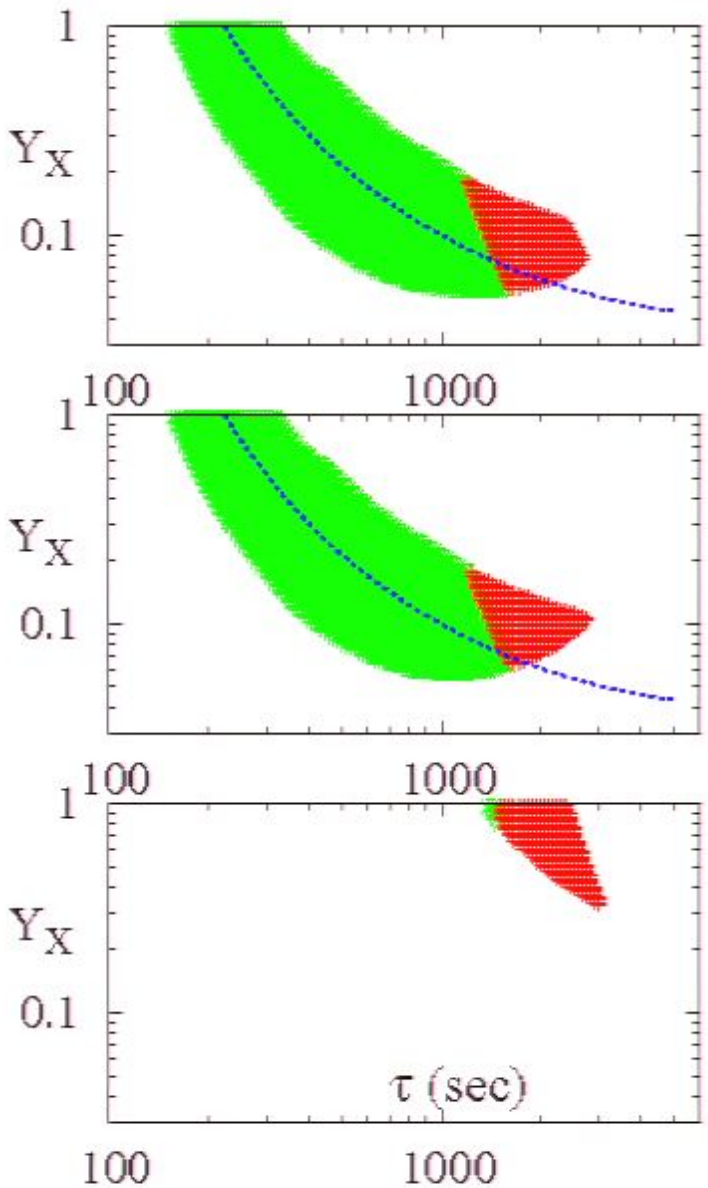


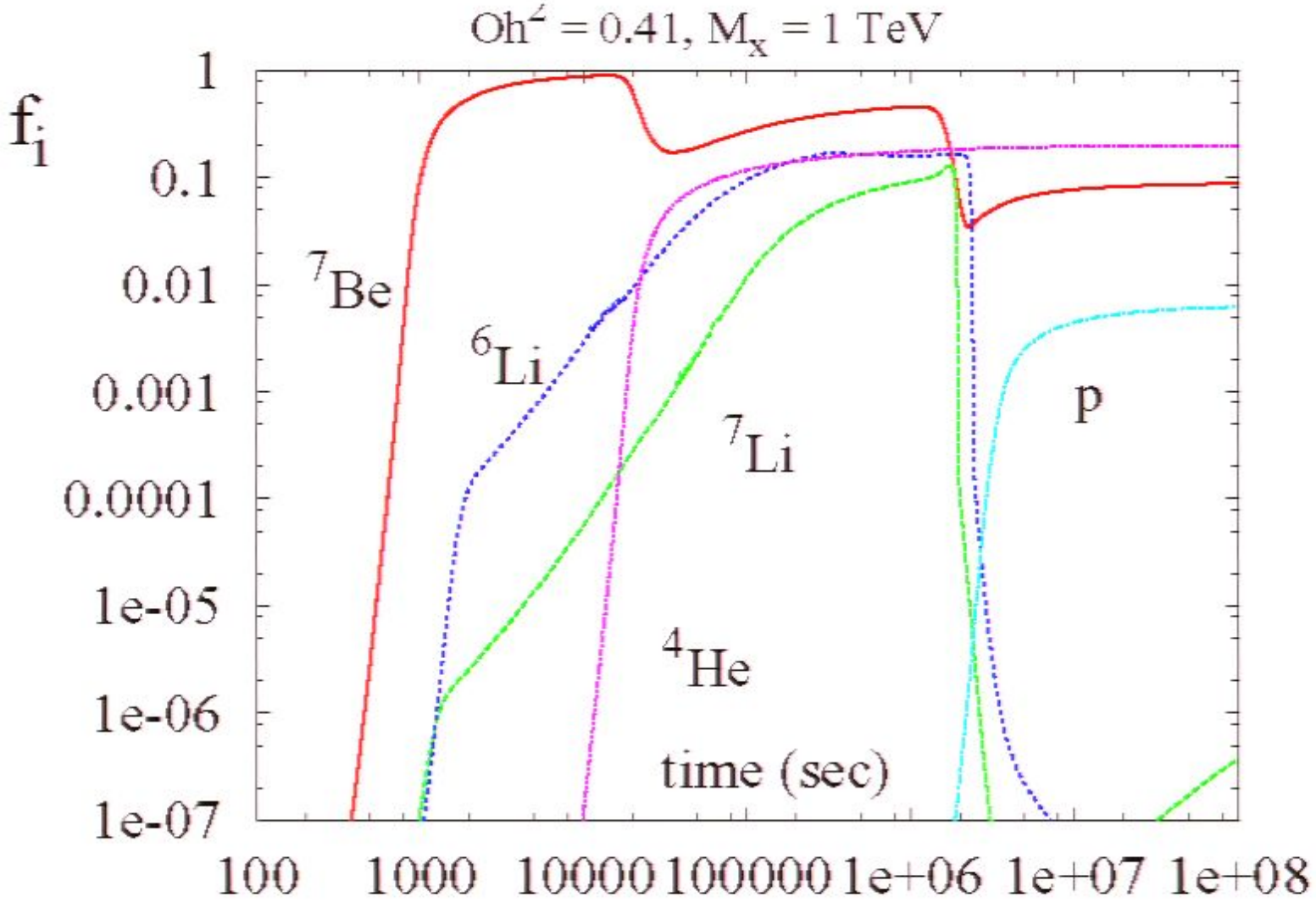

combined

only $B_h = 10^{-4}$

only bound states

# III. Late-time ($\tau > 10^6$ sec) BBN with Charged Relic Particles

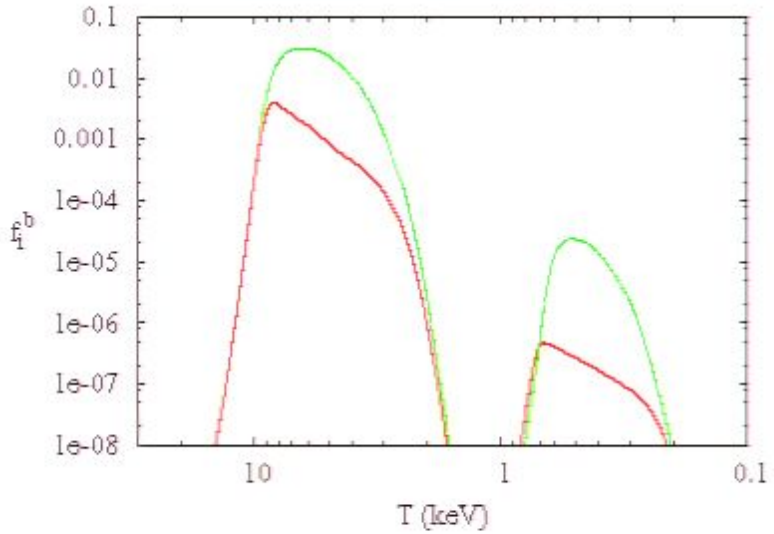
# Fraction of nuclei bound to $X^-$



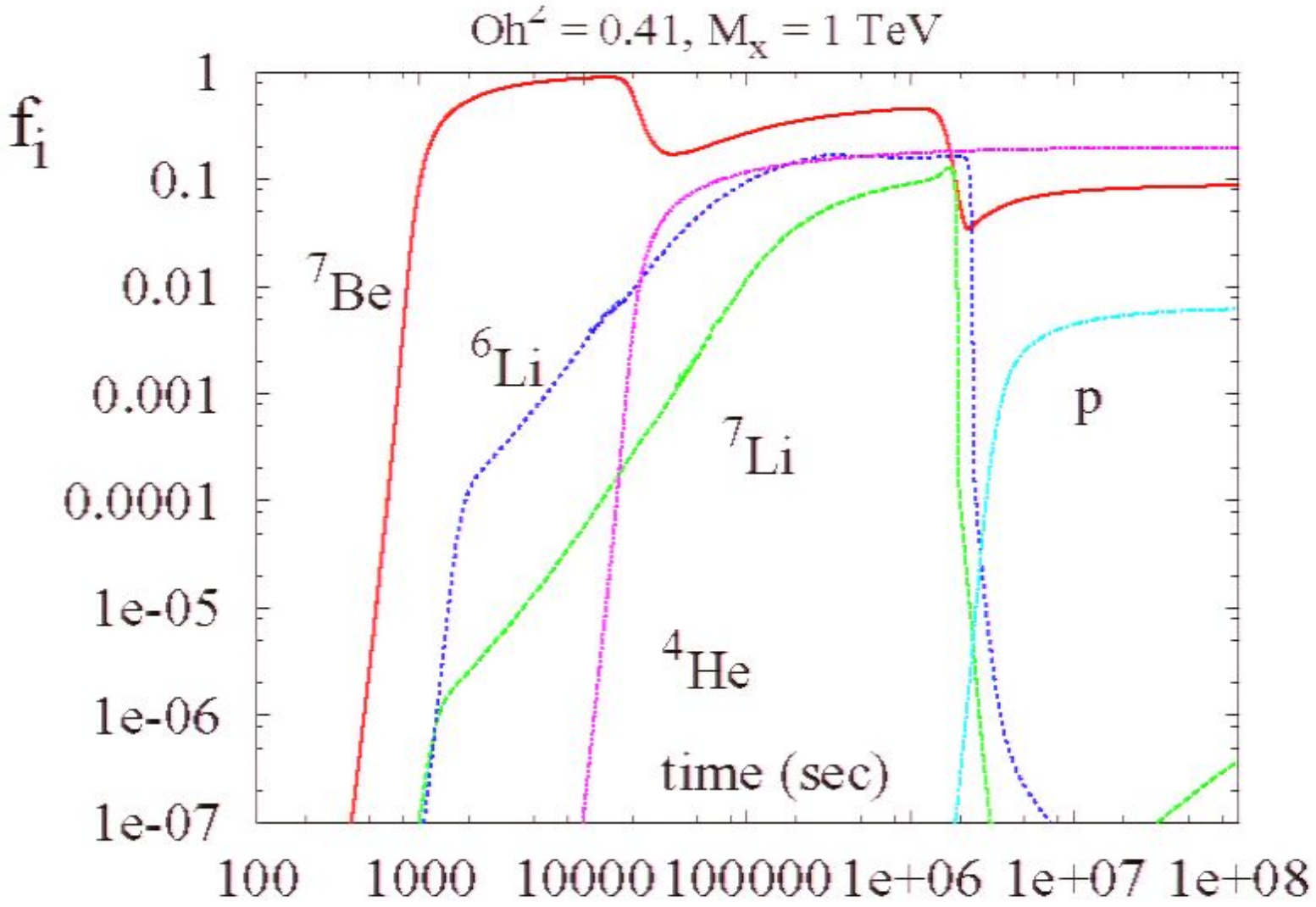
# Two Comments

I. Recombination coefficients at high temperature $\sim 50\%$ reduced

II. Photodisintegration of bound states by non-thermal photons



# Fraction of nuclei bound to $X^-$



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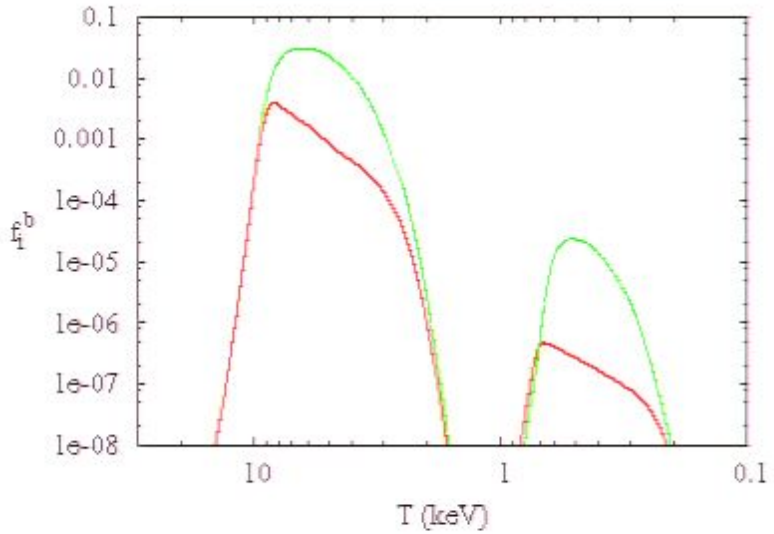

# Reactions without Coulomb barrier ...

| No. | $(AX) + B \rightarrow C + X$ | $S_\gamma$ | $l_C$ | $l^i_{Coul}$ |
|---|---|---|---|---|
| 1 | $(^4\text{He-}X^-) + {}^2\text{H} \rightarrow {}^6\text{Li} + X^-$ | $10^{-8}$ | 0 | 0,1,2 |
| 2 | $(^4\text{He-}X^-) + {}^3\text{H} \rightarrow {}^7\text{Li} + X^-$ | $8 \times 10^{-5}$ | 1 | 0,1 |
| 3 | $(^4\text{He-}X^-) + {}^3\text{He} \rightarrow {}^7\text{Be} + X^-$ | $4 \times 10^{-4}$ | 1 | 0,1 |
| 4 | $(^1\text{H-}X^-) + {}^6\text{Li} \rightarrow {}^7\text{Be} + X^-$ | $10^{-4}$ | 1 | 0,1 |
| 5 | $(^1\text{H-}X^-) + {}^6\text{Li} \rightarrow {}^4\text{He} + {}^3\text{He} + X^-$ | 3 | - | - |
| 6 | $(^1\text{H-}X^-) + {}^7\text{Li} \rightarrow (^8\text{Be-}X^-) + \gamma$ | $10^{-3}$ | 1 | 0,1 |
| 7 | $(^1\text{H-}X^-) + {}^7\text{Be} \rightarrow {}^8\text{B} + X^-$ | $3 \times 10^{-5}$ | 1 | 0,1 |
| 8 | $(^2\text{H-}X^-) + {}^4\text{He} \rightarrow {}^6\text{Li} + X^-$ | $10^{-8}$ | 0 | 0,1,2 |
| 9 | $(^3\text{H-}X^-) + {}^4\text{He} \rightarrow {}^7\text{Li} + X^-$ | $8 \times 10^{-5}$ | 1 | 0,1 |

...

| No. | $(AX) + B \rightarrow C + X$ | enhancement |
|---|---|---|
| 10 | ${}^{2}\mathrm{H}({}^{1}\mathrm{H}{-}X^{-}, X^{-}){}^{3}\mathrm{He}$ | $1.25 \times 10^{2}$ |
| | ${}^{1}\mathrm{H}({}^{2}\mathrm{H}{-}X^{-}, X^{-}){}^{3}\mathrm{He}$ | |
| 11 | ${}^{3}\mathrm{H}({}^{1}\mathrm{H}{-}X^{-}, X^{-}){}^{4}\mathrm{He}$ | 10.7 |
| | ${}^{1}\mathrm{H}({}^{3}\mathrm{H}{-}X^{-}, X^{-}){}^{4}\mathrm{He}$ | |
| 12 | ${}^{2}\mathrm{H}({}^{3}\mathrm{H}{-}X^{-}, n){}^{4}\mathrm{He}{+}X^{-}$ | 1 |
| | ${}^{3}\mathrm{H}({}^{2}\mathrm{H}{-}X^{-}, n){}^{4}\mathrm{He}{+}X^{-}$ | |
| 13 | ${}^{3}\mathrm{He}({}^{2}\mathrm{H}{-}X^{-}, p){}^{4}\mathrm{He}{+}X^{-}$ | 1 |

# Reactions without Coulomb barrier ...

| No. | $(AX) + B \rightarrow C + X$ | $S_\gamma$ | $l_C$ | $l^i_{Coul}$ |
|---|---|---|---|---|
| 1 | $(^4\text{He-}X^-) + {}^2\text{H} \rightarrow {}^6\text{Li} + X^-$ | $10^{-8}$ | 0 | 0,1,2 |
| 2 | $(^4\text{He-}X^-) + {}^3\text{H} \rightarrow {}^7\text{Li} + X^-$ | $8 \times 10^{-5}$ | 1 | 0,1 |
| 3 | $(^4\text{He-}X^-) + {}^3\text{He} \rightarrow {}^7\text{Be} + X^-$ | $4 \times 10^{-4}$ | 1 | 0,1 |
| 4 | $(^1\text{H-}X^-) + {}^6\text{Li} \rightarrow {}^7\text{Be} + X^-$ | $10^{-4}$ | 1 | 0,1 |
| 5 | $(^1\text{H-}X^-) + {}^6\text{Li} \rightarrow {}^4\text{He} + {}^3\text{He} + X^-$ | 3 | - | - |
| 6 | $(^1\text{H-}X^-) + {}^7\text{Li} \rightarrow (^8\text{Be-}X^-) + \gamma$ | $10^{-3}$ | 1 | 0,1 |
| 7 | $(^1\text{H-}X^-) + {}^7\text{Be} \rightarrow {}^8\text{B} + X^-$ | $3 \times 10^{-5}$ | 1 | 0,1 |
| 8 | $(^2\text{H-}X^-) + {}^4\text{He} \rightarrow {}^6\text{Li} + X^-$ | $10^{-8}$ | 0 | 0,1,2 |
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...

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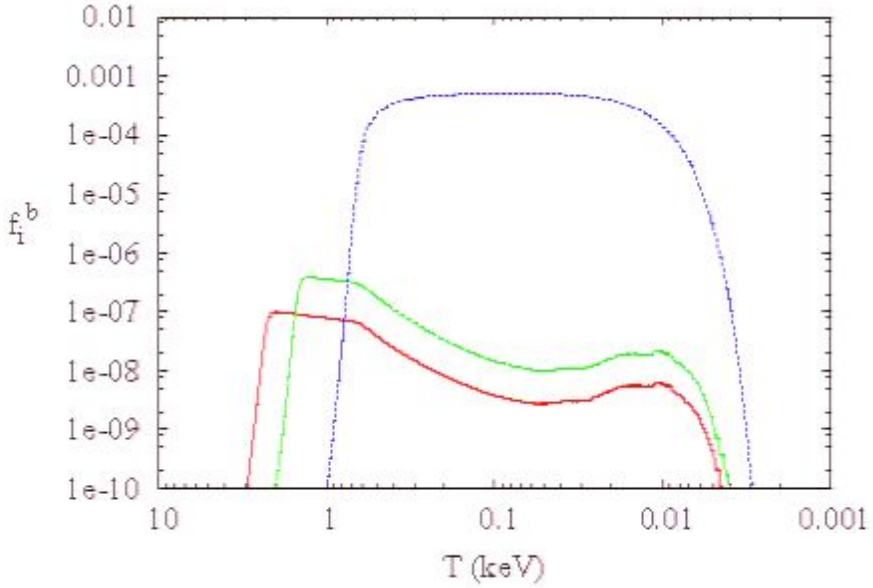
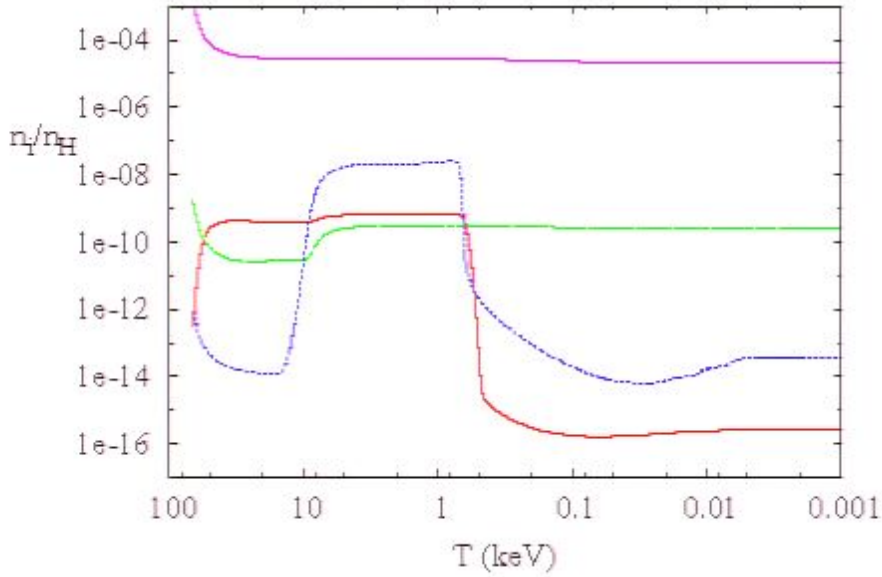
| | $^{1}\mathrm{H}(^{3}\mathrm{H}{-}X^{-}, X^{-})^{4}\mathrm{He}$ | |
| 12 | $^{2}\mathrm{H}(^{3}\mathrm{H}{-}X^{-}, n)^{4}\mathrm{He}{+}X^{-}$ | 1 |
| | $^{3}\mathrm{H}(^{2}\mathrm{H}{-}X^{-}, n)^{4}\mathrm{He}{+}X^{-}$ | |
| 13 | $^{3}\mathrm{He}(^{2}\mathrm{H}{-}X^{-}, p)^{4}\mathrm{He}{+}X^{-}$ | 1 |

# A third round of BBN !



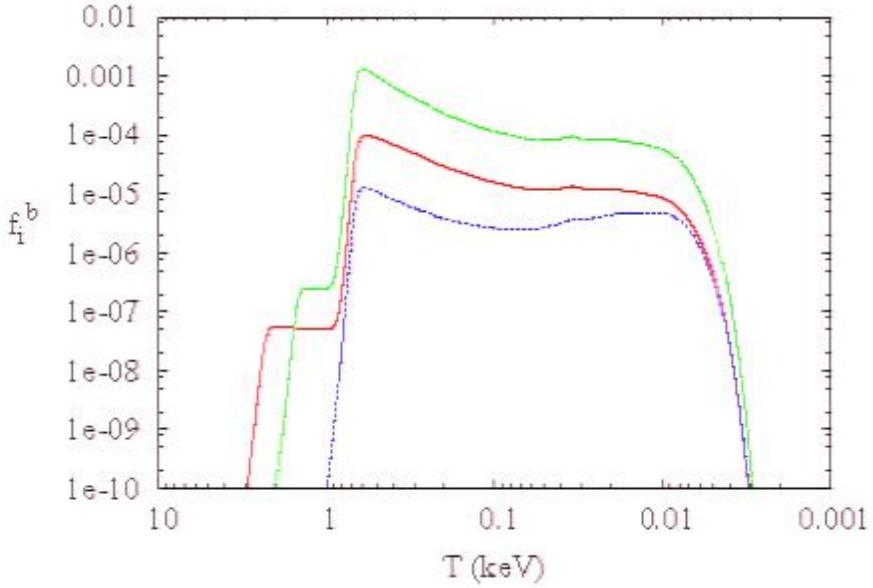



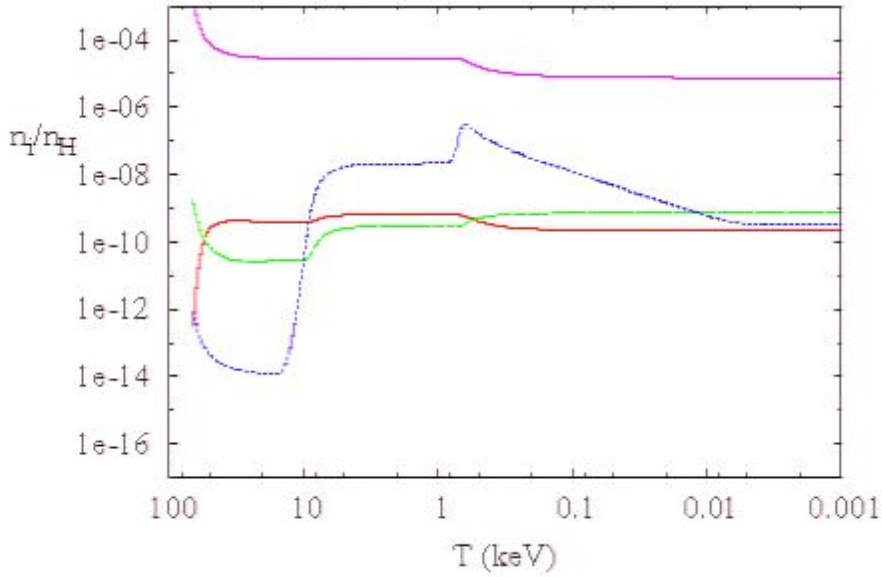

$$\Omega_X h^2 = 0.01, M_X = 100\mathrm{GeV}, \tau_X = 10^{10}\,\mathrm{sec}$$

# but ...

| No. | $(AX) + B \rightarrow C + X$ | rate $[\mathrm{cm}^3\mathrm{s}^{-1}]$ |
|---|---|---|
| 14 | $(^1\mathrm{H}{-}X^-) + {}^2\mathrm{H} \rightarrow (^2\mathrm{H}{-}X^-) + {}^1\mathrm{H}$ | $8.8 \times 10^{-15}$ |
| 15 | $(^1\mathrm{H}{-}X^-) + {}^3\mathrm{H} \rightarrow (^3\mathrm{H}{-}X^-) + {}^1\mathrm{H}$ | $1.4 \times 10^{-15}$ |
| 16 | $(^2\mathrm{H}{-}X^-) + {}^3\mathrm{H} \rightarrow (^3\mathrm{H}{-}X^-) + {}^2\mathrm{H}$ | $1.0 \times 10^{-14}$ |
| 17 | $(^1\mathrm{H}{-}X^-) + {}^4\mathrm{He} \rightarrow (^4\mathrm{He}{-}X^-) + {}^1\mathrm{H}$ | $3.6 \times 10^{-17}$ |
| 18 | $(^2\mathrm{H}{-}X^-) + {}^4\mathrm{He} \rightarrow (^4\mathrm{He}{-}X^-) + {}^2\mathrm{H}$ | $2.9 \times 10^{-16}$ |
| 19 | $(^3\mathrm{H}{-}X^-) + {}^4\mathrm{He} \rightarrow (^4\mathrm{He}{-}X^-) + {}^3\mathrm{H}$ | $8.0 \times 10^{-16}$ |

# which ...


0.01
0.001
1e-04
1e-05
1e-06
1e-07
1e-08
1e-09
1e-10
$f_i^b$
10
1
0.1
0.01
0.001
T (keV)


1e-04
1e-06
1e-08
1e-10
1e-12
1e-14
1e-16
$n_i/n_H$
100
10
1
0.1
0.01
0.001
T (keV)

# Nuclear Rates uncertain:

Cross section for, e.g., $^2\mathrm{H} + (^4\mathrm{He}\tilde{\tau}) \rightarrow {}^6\mathrm{Li} + \tilde{\tau}$

Evaluated in the Born approximation with parametric $^6\mathrm{Li}$ wave function

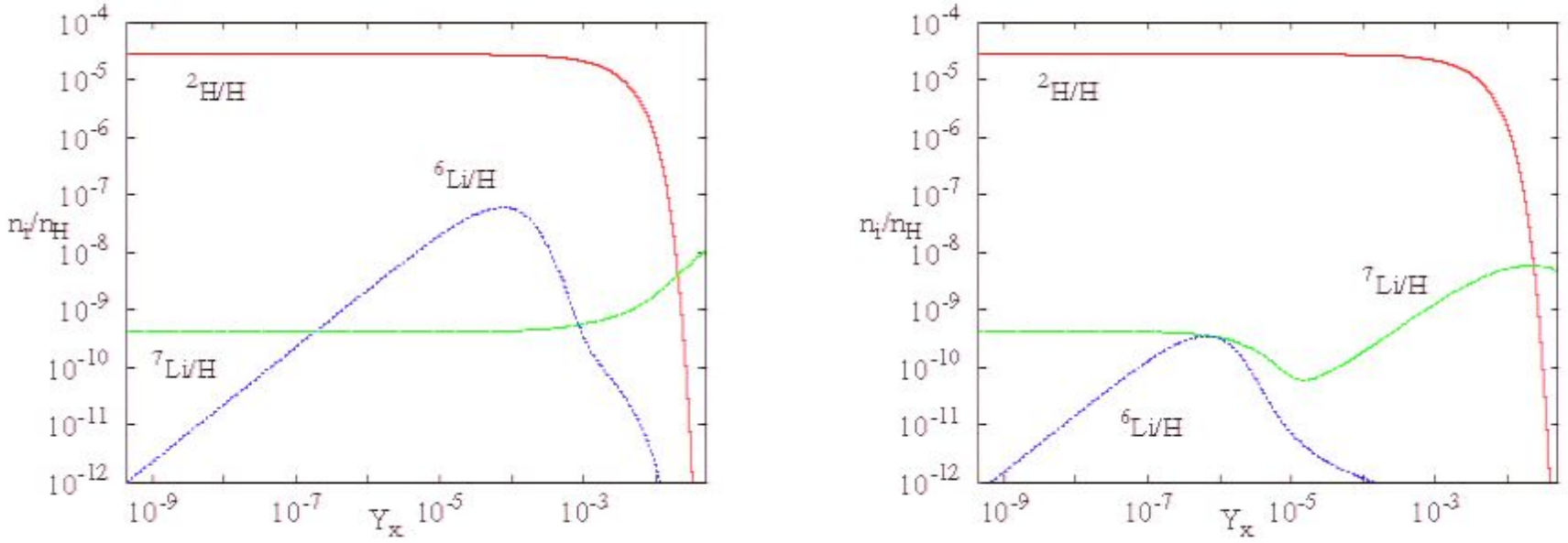
$$\frac{\Delta w}{\Delta t} = \frac{\sigma v}{V} = \frac{2\pi}{\hbar} \int \frac{\mathrm{d}^3 p}{(2\pi\hbar)^3} \delta(E_f - E_i) |\langle i|H_{\mathrm{int}}|f\rangle|^2 \qquad (1)$$

with $H = H_0 + H_{\mathrm{int}}$, $H_0|i\rangle = E_i|i\rangle$, $H_0|f\rangle = E_f|f\rangle$

$$\langle i|H_{\mathrm{int}}|f\rangle = \int \mathrm{d}^3 s \int \mathrm{d}^3 \rho \Phi_f^C(s) \Phi_f^{^6\mathrm{Li}}(\rho) Q(s,\rho) \Phi_i^C(r_{\mathrm{D}}) \Phi_i^{\mathrm{Bohr}}(r_{\mathrm{He}}) \qquad (2)$$

with $Q = e^2 \left( \frac{s_i s_j \rho_i \rho_j}{s^3} - \frac{1}{3} \frac{\rho^2}{s^3} \right)$ and $s$ CM between $^4\mathrm{He}$ and $^2\mathrm{H}$ and $\rho$ relative coordinate $r_4 - r_2$

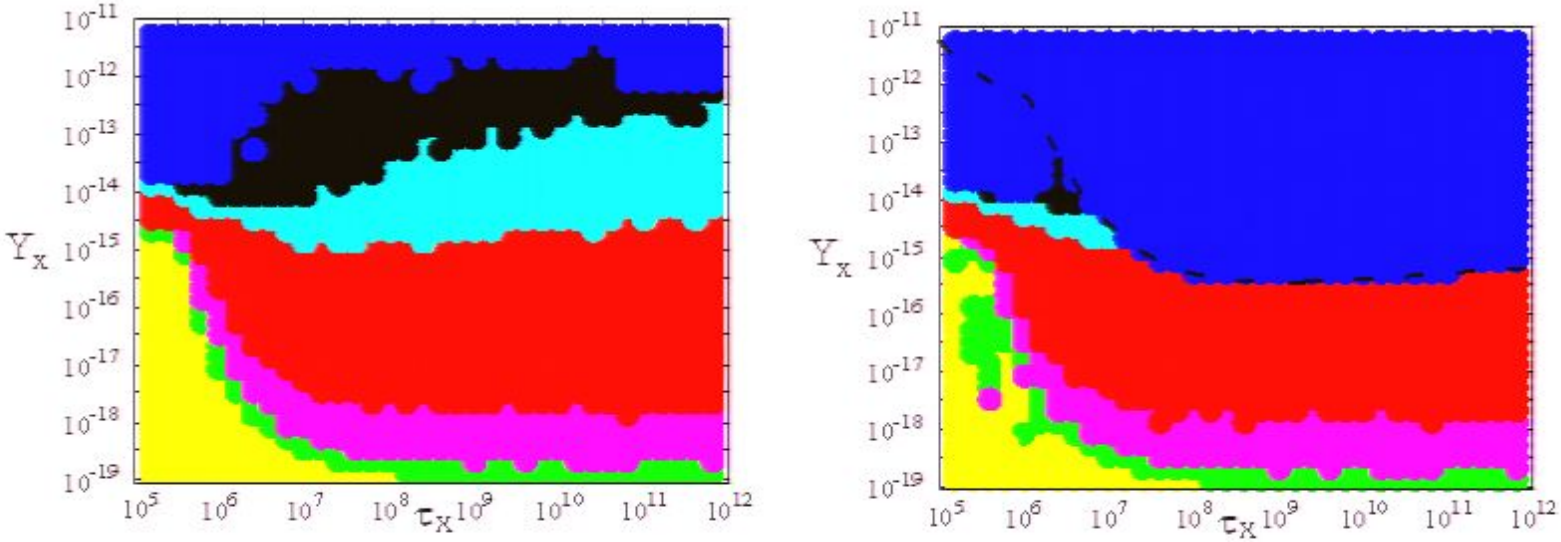
# ... considerable uncertainties in predictions ...




*left panel*: Born approximation *right panel* $(^1H - X) + {}^6\mathrm{Li} \rightarrow$ factor 3 increased, $(^1H - X) + {}^2\mathrm{H}, {}^4\mathrm{He} \rightarrow$ .. factor 30 reduced

# IV. BBN Limits on Charged Relic Particles:

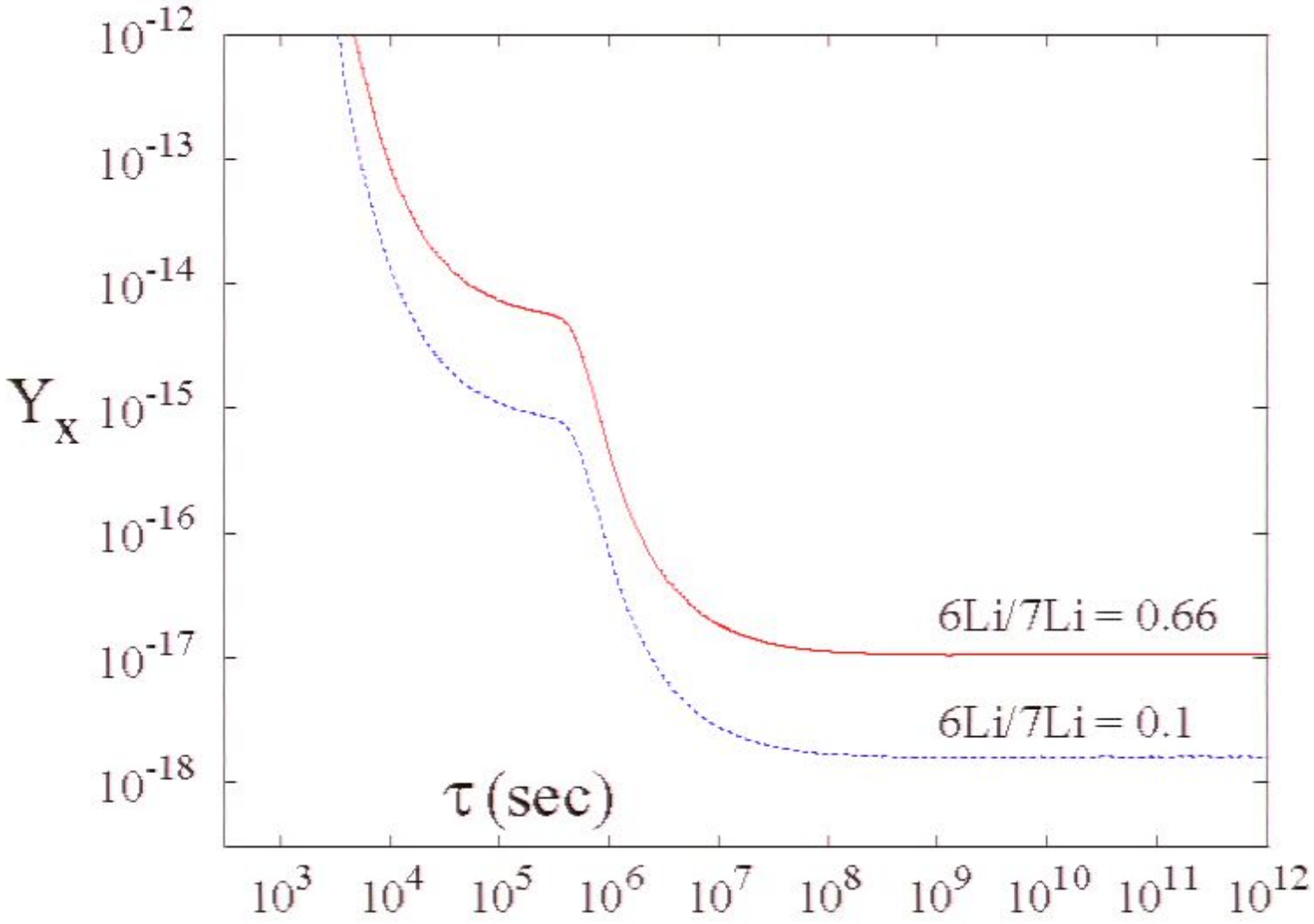
# Constraints on charged relics from BBN uncertain !




including electromagnetic energy release

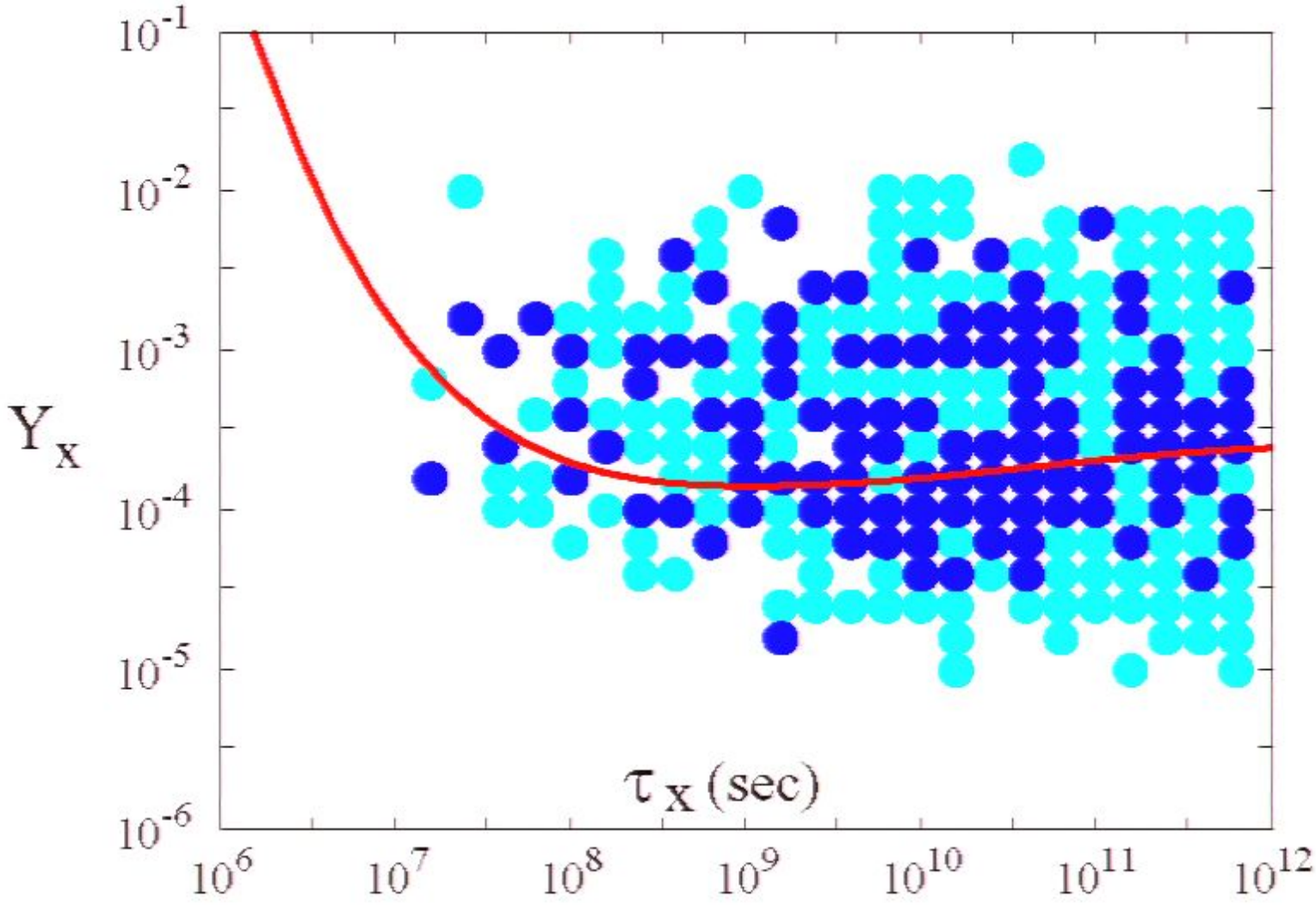
A Monte-Carlo analysis is necessary !

# Possibly severe constraints due to $(^2\mathrm{H} - X^-) + {}^4\mathrm{He} \to {}^6\mathrm{Li} + X^-$ ?



# IV. Simultaneous Solutions to the Lithium Problems in the CMSSM:

# At late times ?



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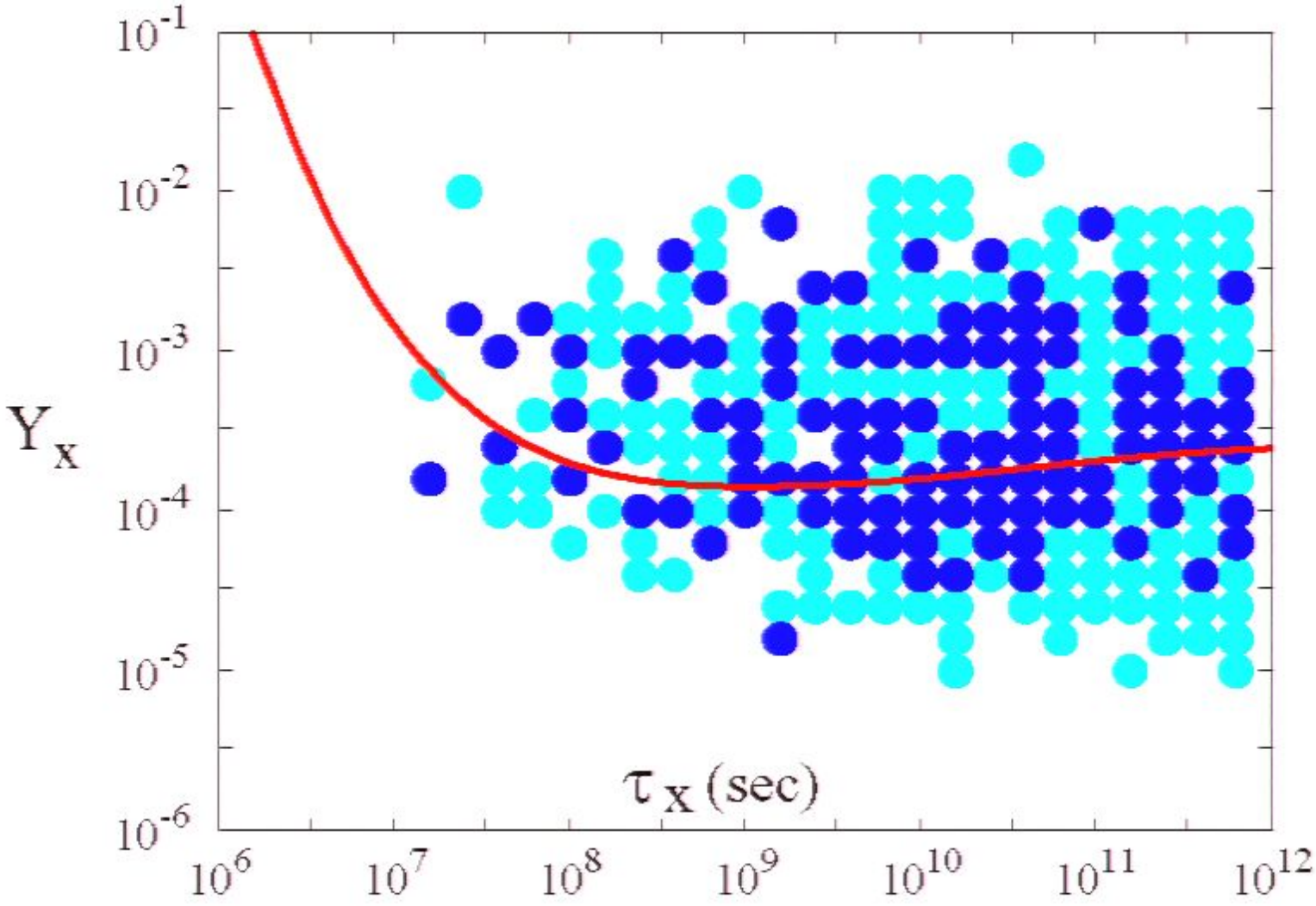
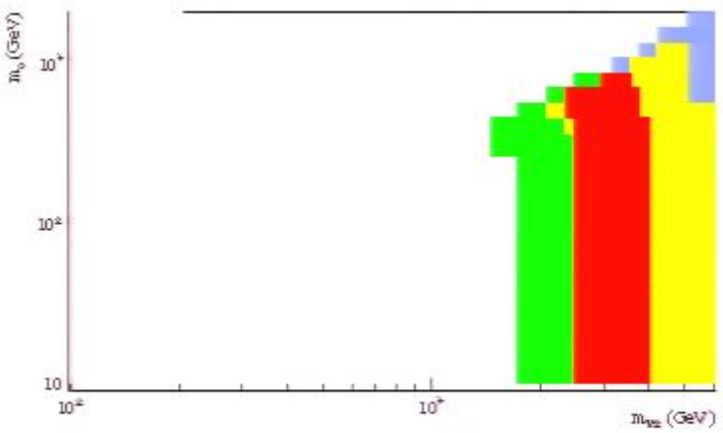
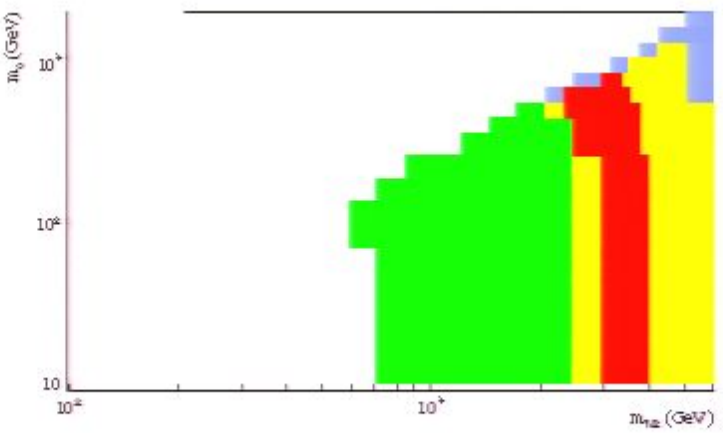
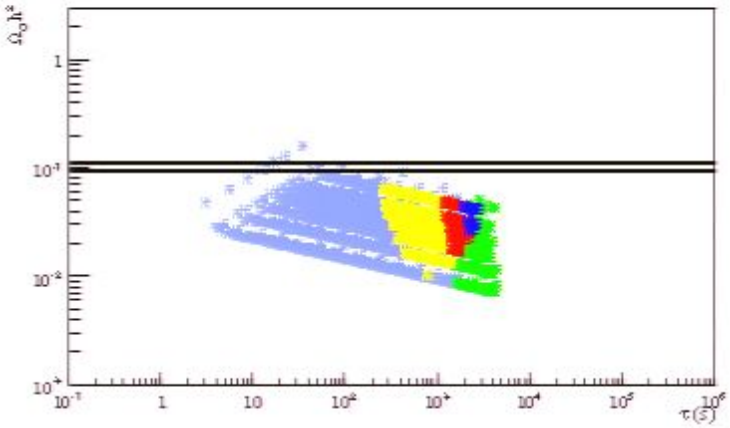
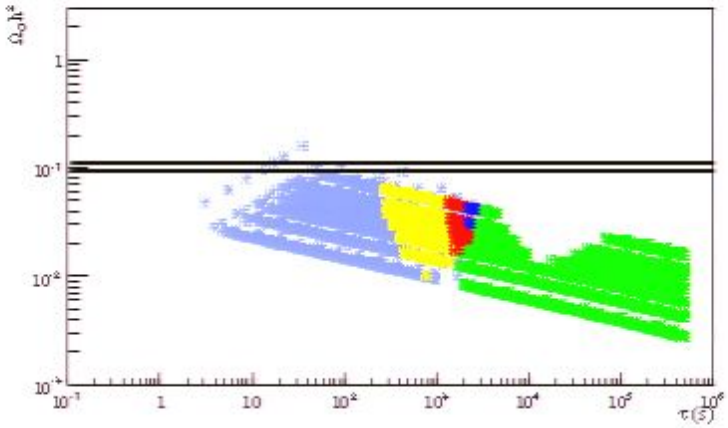


# Solutions at $\tau_X \sim 1000$ sec, CMSSM at $\tan\beta = 10$



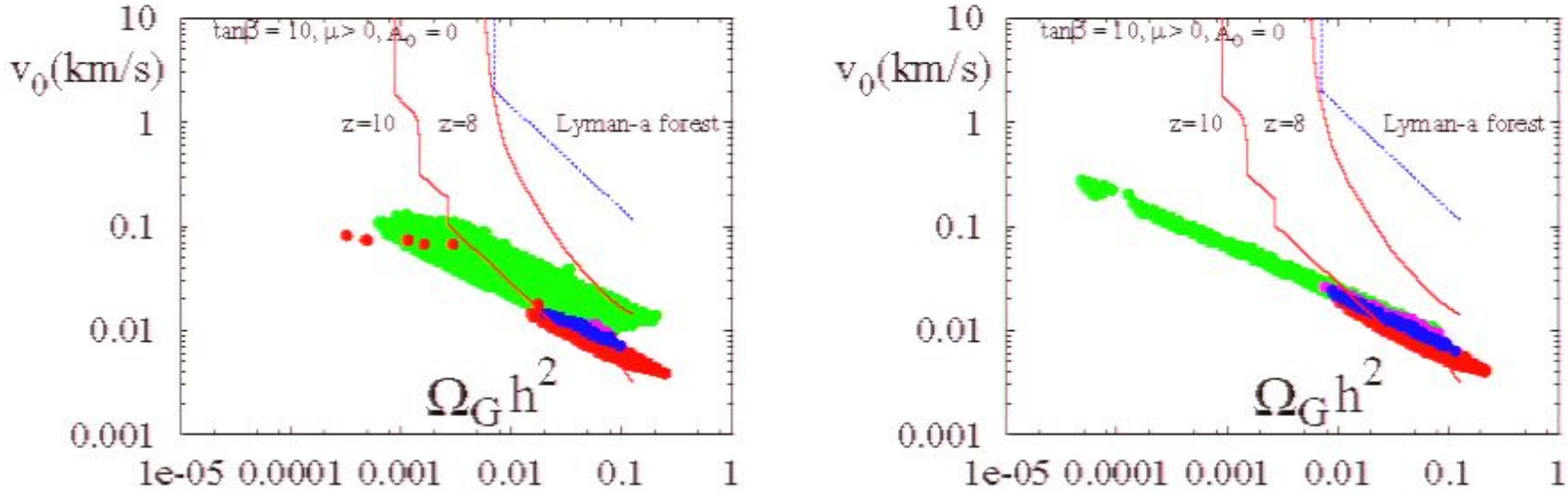

bound state effects included

not included

Bailly, Moultaka, K.J. 08

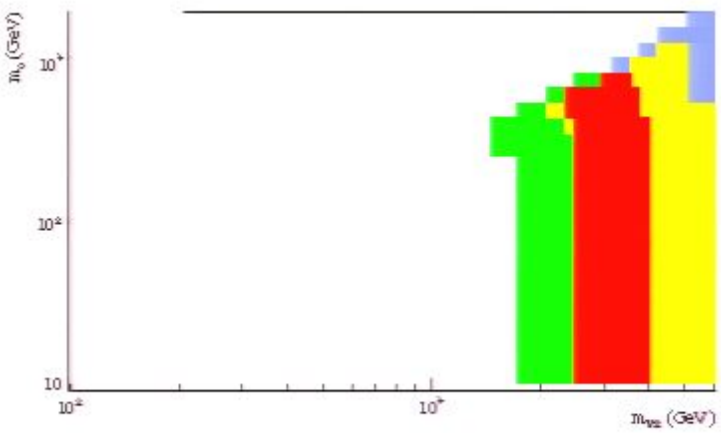
# Gravitino Warm Dark Matter and Cosmic Lithium

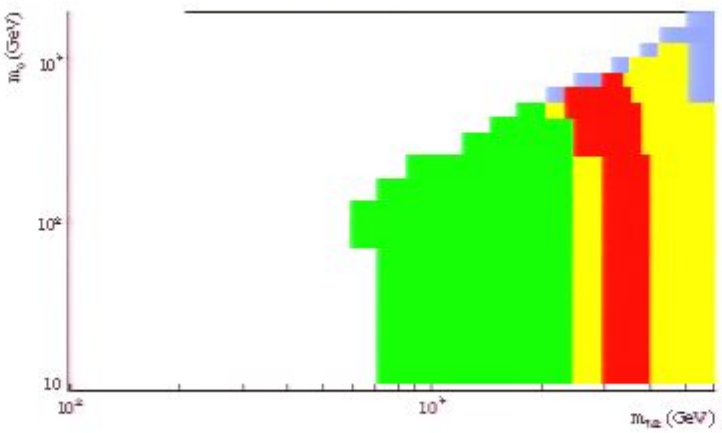
## CMSSM with gravitino LSP:

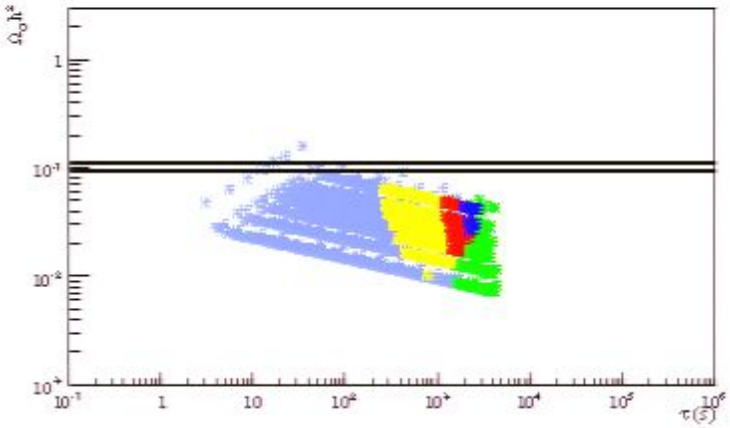


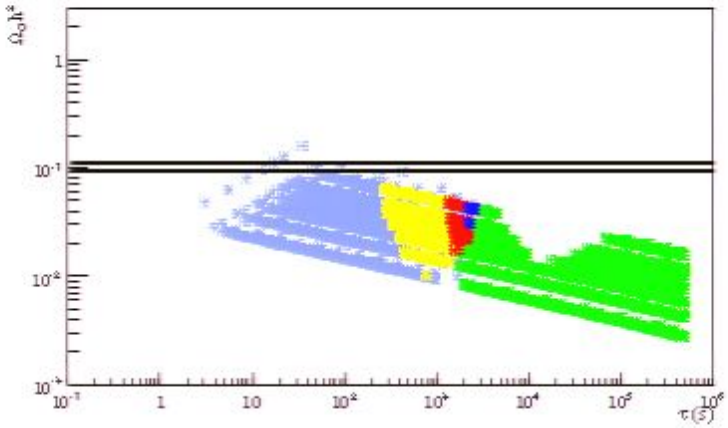

K.J., Choi, Roszkowski, Ruiz de Austri 05, K.J., Lemoine, Moultaka 05, Viel *et al. 05*

# Solutions at $\tau_X \sim 1000$ sec, CMSSM at $\tan\beta = 10$



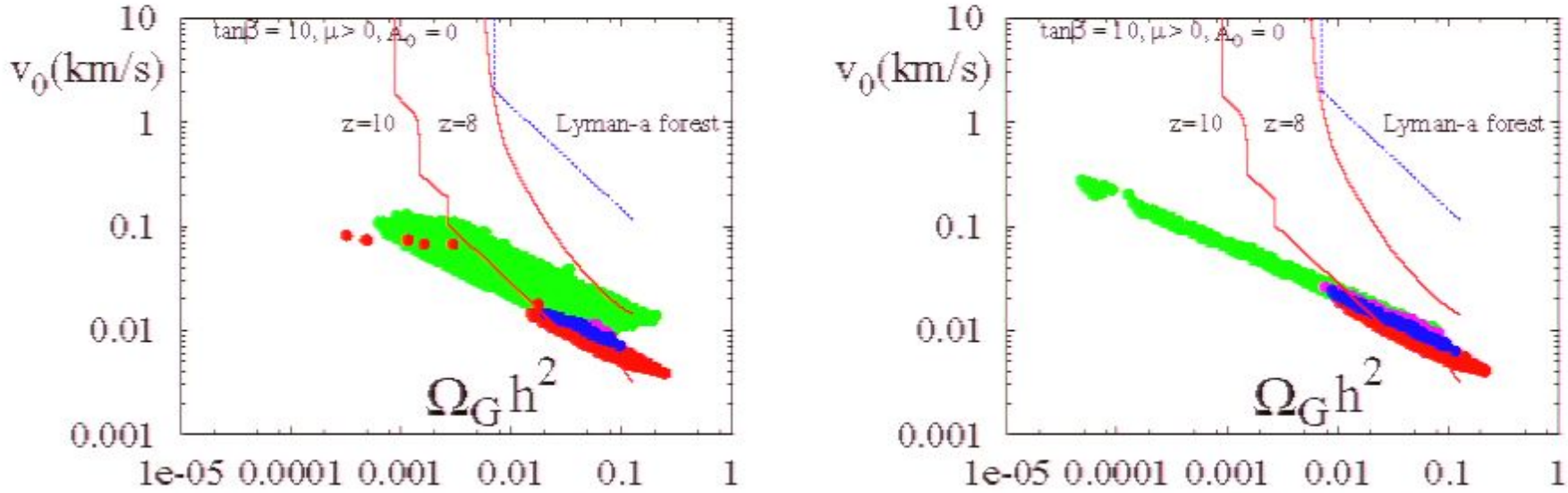

bound state effects included

not included

Bailly, Moultaka, K.J. 08

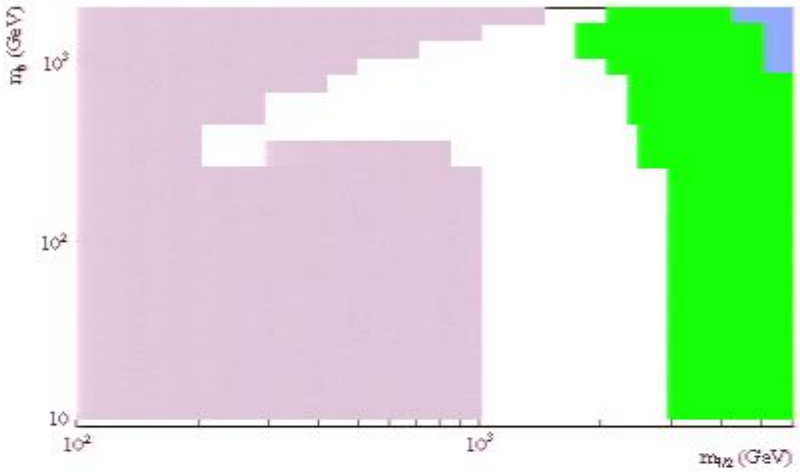
# Gravitino Warm Dark Matter and Cosmic Lithium

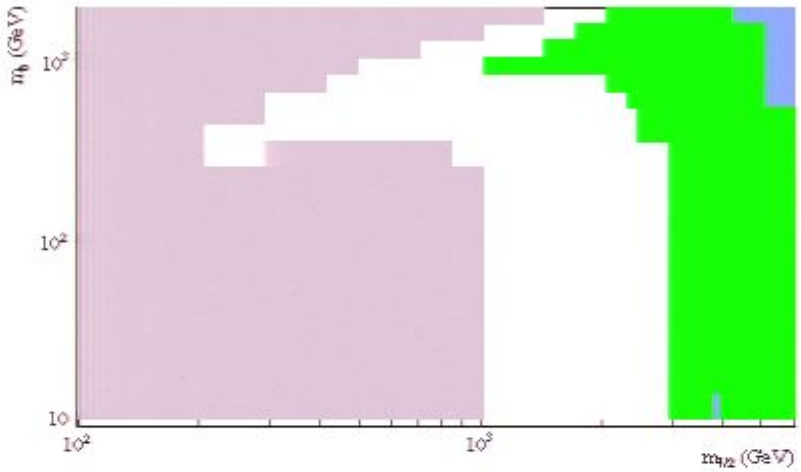
## CMSSM with gravitino LSP:

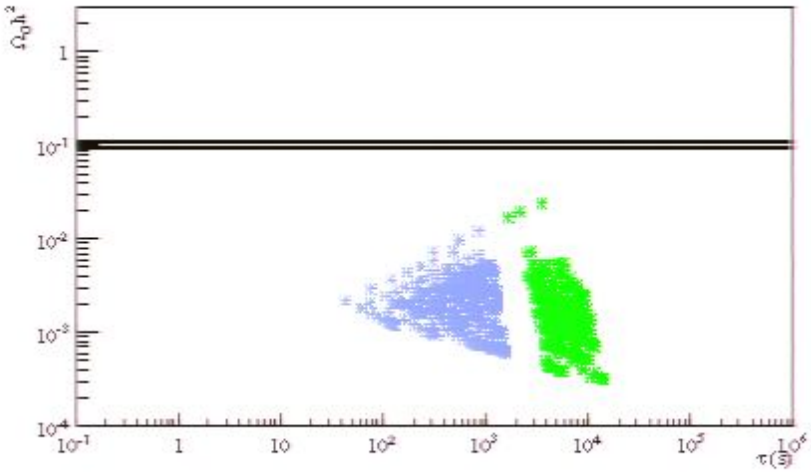


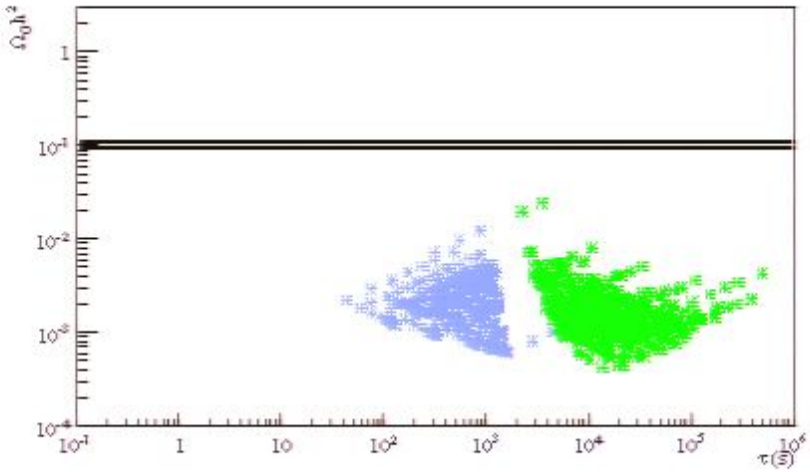

K.J., Choi, Roszkowski, Ruiz de Austri 05, K.J., Lemoine, Moultaka 05, Viel *et al. 05*

# Solutions at $\tau_X \sim 1000$ sec, CMSSM at $\tan\beta = 60$



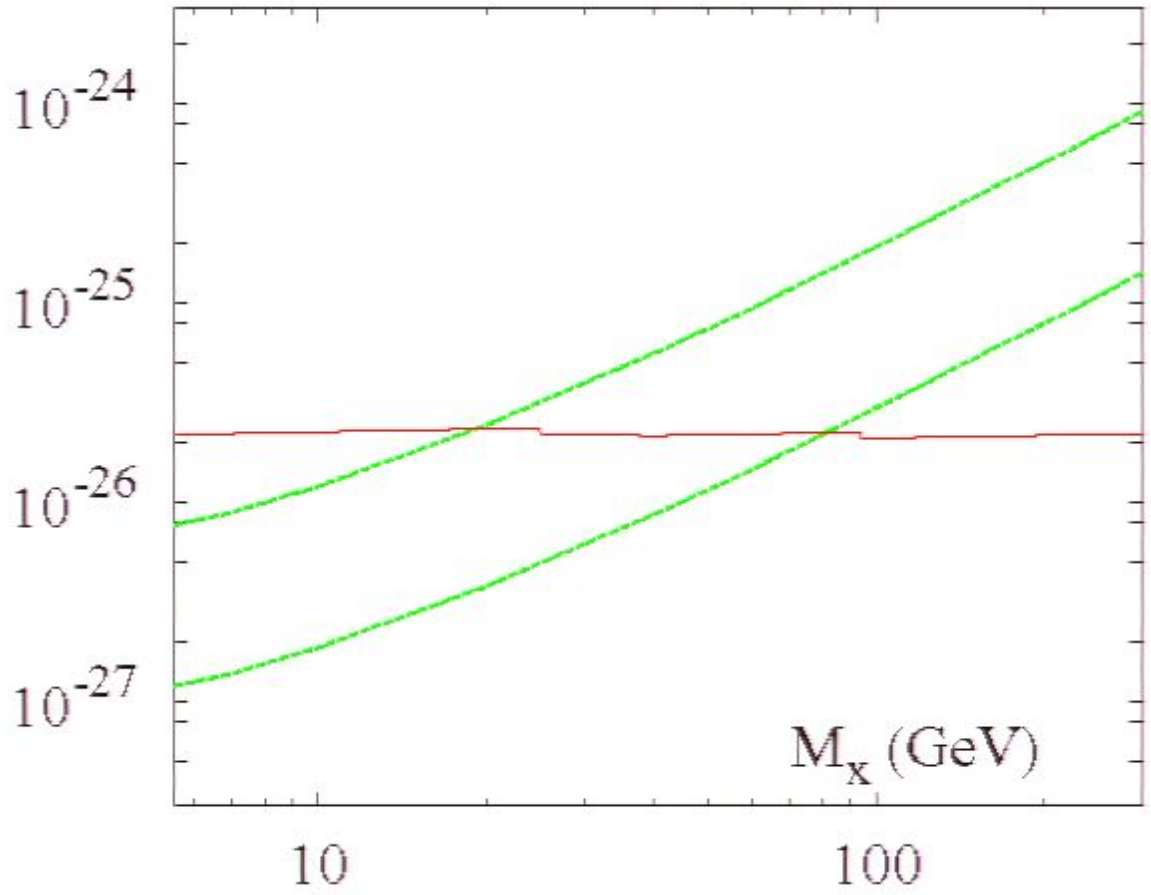




bound state effects included

not included

# $^6$Li production by residual dark matter annihilations



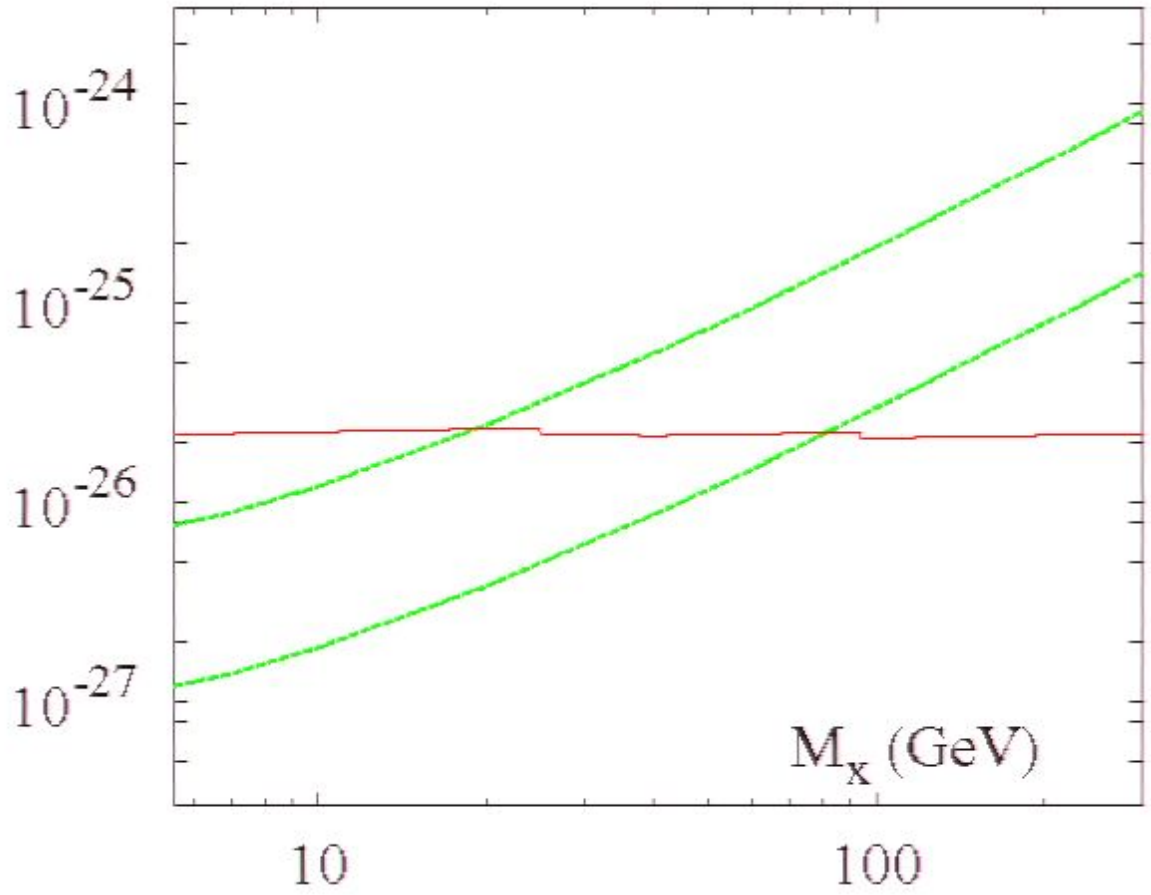

K.J. 04

# Conclusions

- Big Bang Nucleosynthesis is very useful in constraining the properties of dark matter
- the $^6$Li and $^7$Li abundances are observed with "anamolous" abundances
- Dark Matter may be the reason for that

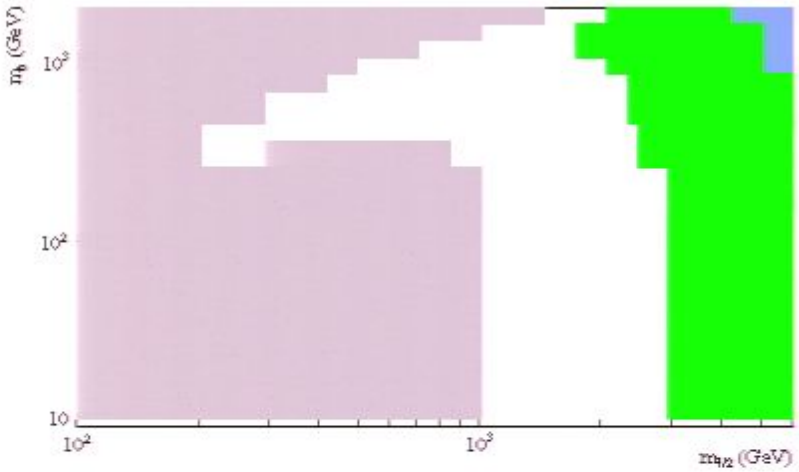
- nevertheless, both with $^6$Li and $^7$Li much is not understood yet ... more work needed from all sides
- ultimately, a connection between the lithium isotope(s) and dark matter has to have independent confirmation (i.e. LHC, indirect detection, ...)

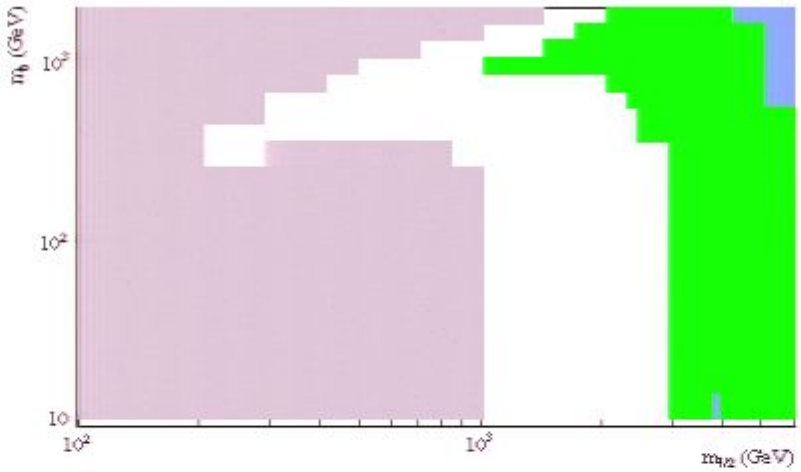
# $^6$Li production by residual dark matter annihilations

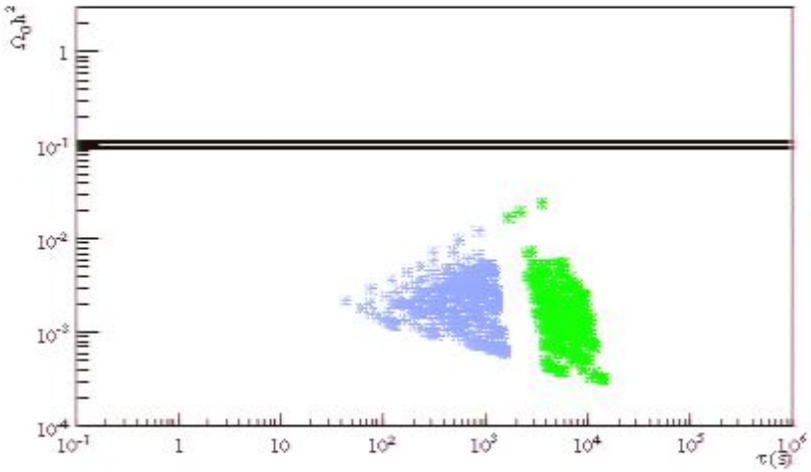


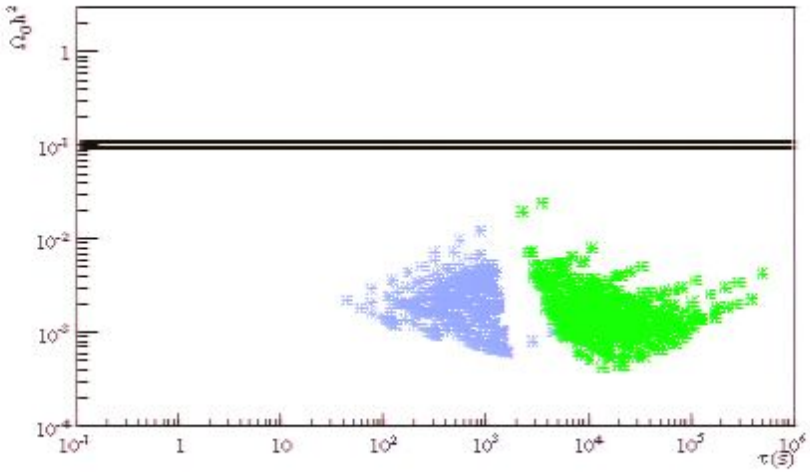

K.J. 04

# Solutions at $\tau_X \sim 1000$ sec, CMSSM at $\tan\beta = 60$



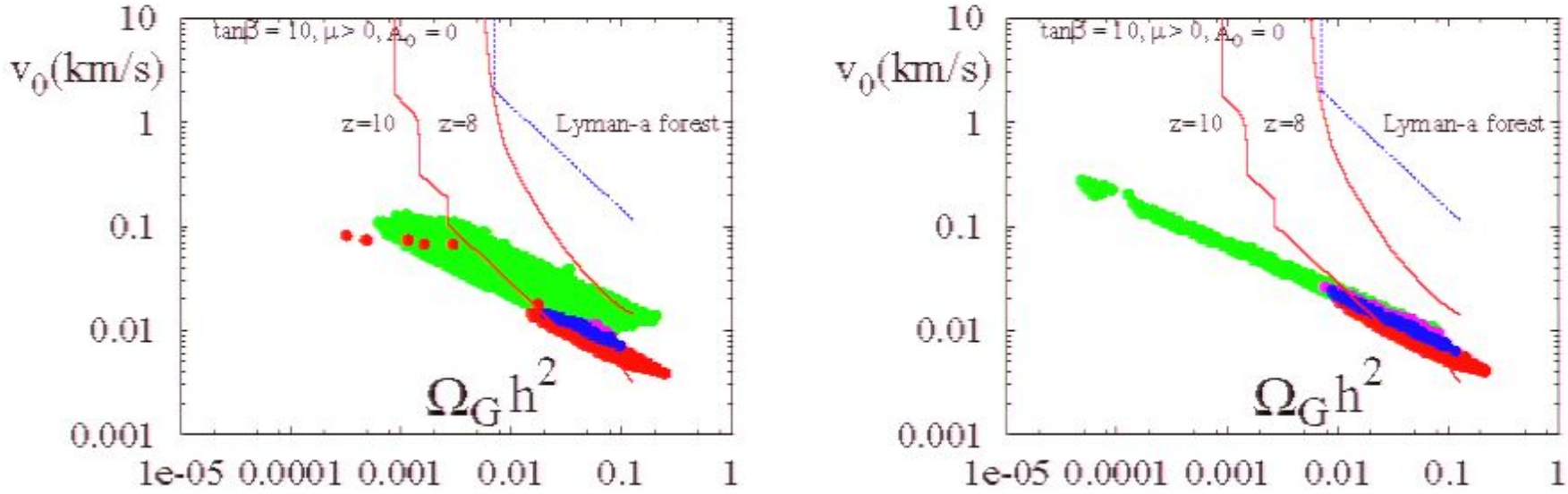




bound state effects included

not included

# Gravitino Warm Dark Matter and Cosmic Lithium

## CMSSM with gravitino LSP:

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