Title: Catalyzed BBN

Date: May 30, 2008 02:40 PM

URL: http://pirsa.org/08050050

Abstract:

CATALYZED BBN

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M. Pospelov, hep-ph/0605215; PhysRevLett.98.231301
C. Bird, K. Koopmans, and M. Pospelov, hep-ph/0703096
M.Pospelov, arXiv:0712.0647
M. Pospelov, J. Pradler and F. Steffen, in preparation

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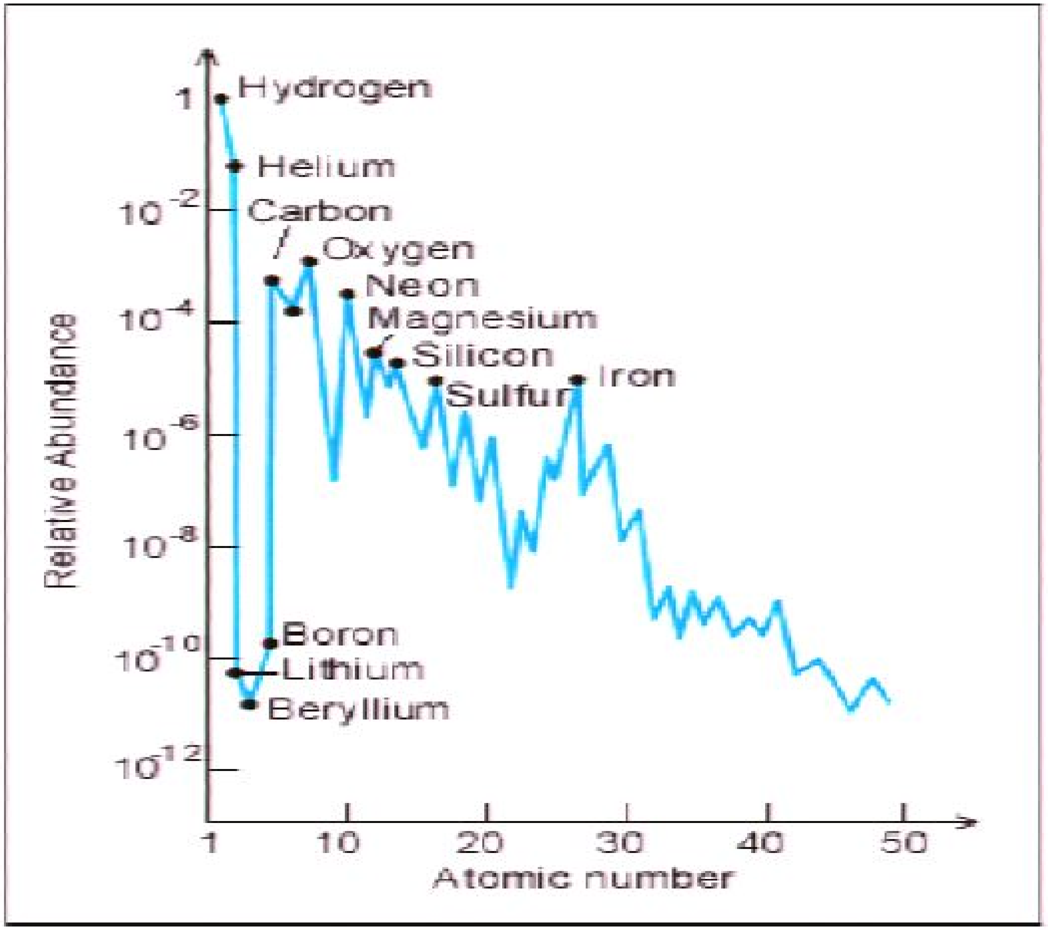
PERIMETER INSTITUTE FOR THEORETICAL PHYSICS

Outline of the talk

1. Introduction: Catalysis of BBN is the third generic way particle physics can have an impact on primordial elements.

- Review of the main catalytic channels in CBBN: ^{6}Li and ^{9}Be enhancement, possible suppression of ^{7}Li+^{7}Be.
- Important changes from (pX^-) states? Absolutely not.
- Avenues for future improvement: nuclear physics calculations
- Conclusions

Elemental Abundance



A<1,2,3,4,7 – BBN; A>12 –Stars;

A=6,9,10,11 –“orphans” (cosmic ray spallation)

BBN and Particle Physics

$$\frac{dn_i}{dt} = -H(T)T\frac{dn_i}{dT} = \left\langle \sigma_{ijk} v \right\rangle n_j n_k + \ldots - \ldots$$

Energy of reactants ~ MeV or less; Initial conditions $n_p \approx n_n$; other $n_i = ($

Particle physics can

- Affect the timing of reactions,

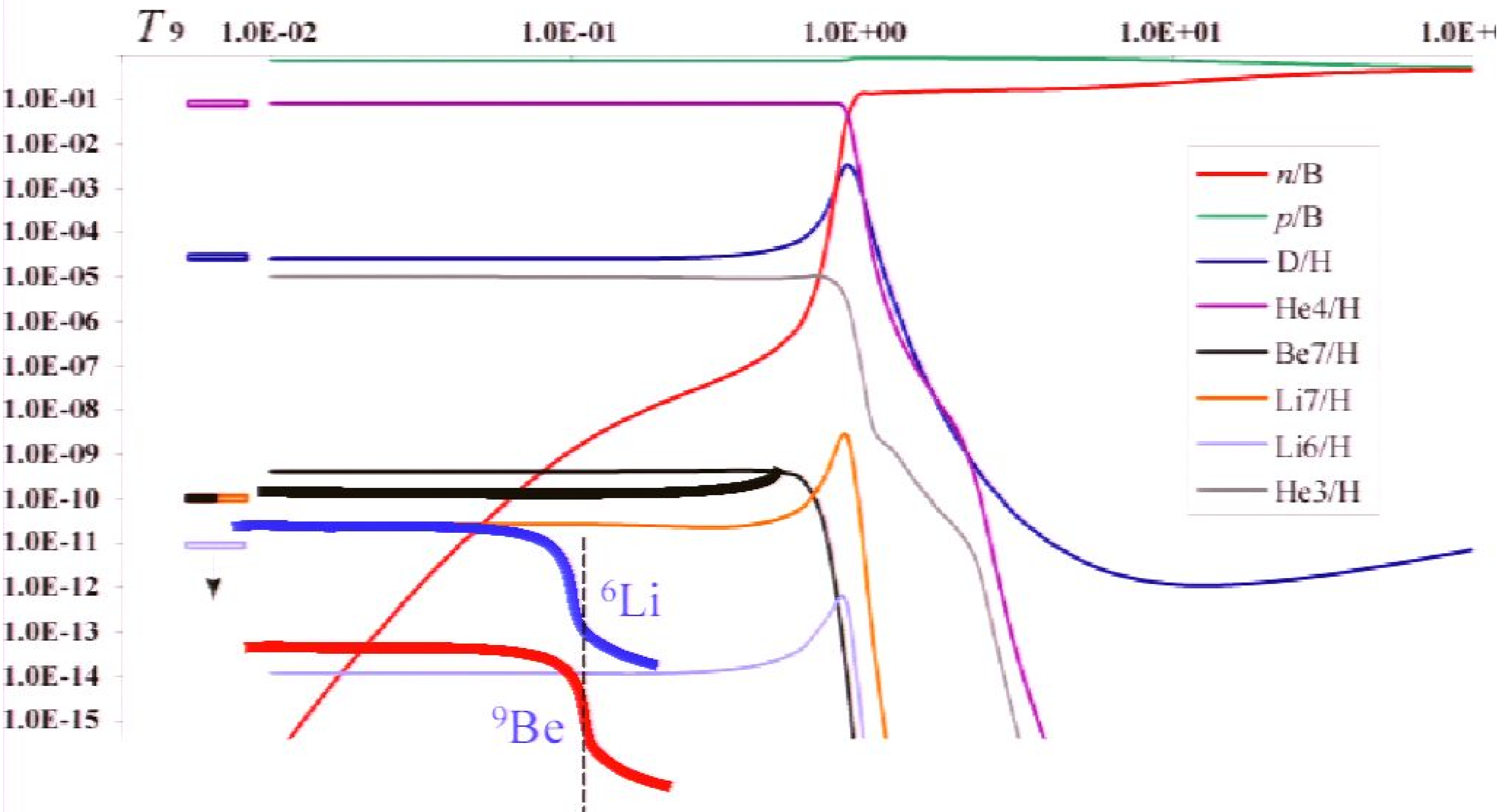
$$H(T) = \text{const} \times N_{\text{eff}}^{1/2} \frac{T^2}{M_{\text{Pl}}}; \quad N_{\text{eff}} = 2 + \frac{7}{8} \times 2 \times 3 + N_{\text{boson}}^{\text{extra}} + \frac{7}{8} N_{\text{fermion}}^{\text{extra}}$$

  via e.g. new thermal degrees of freedom

- Introduce non-thermal channels *e.g.* via late decays or annihilations of heavy particles, $E \gg T$.

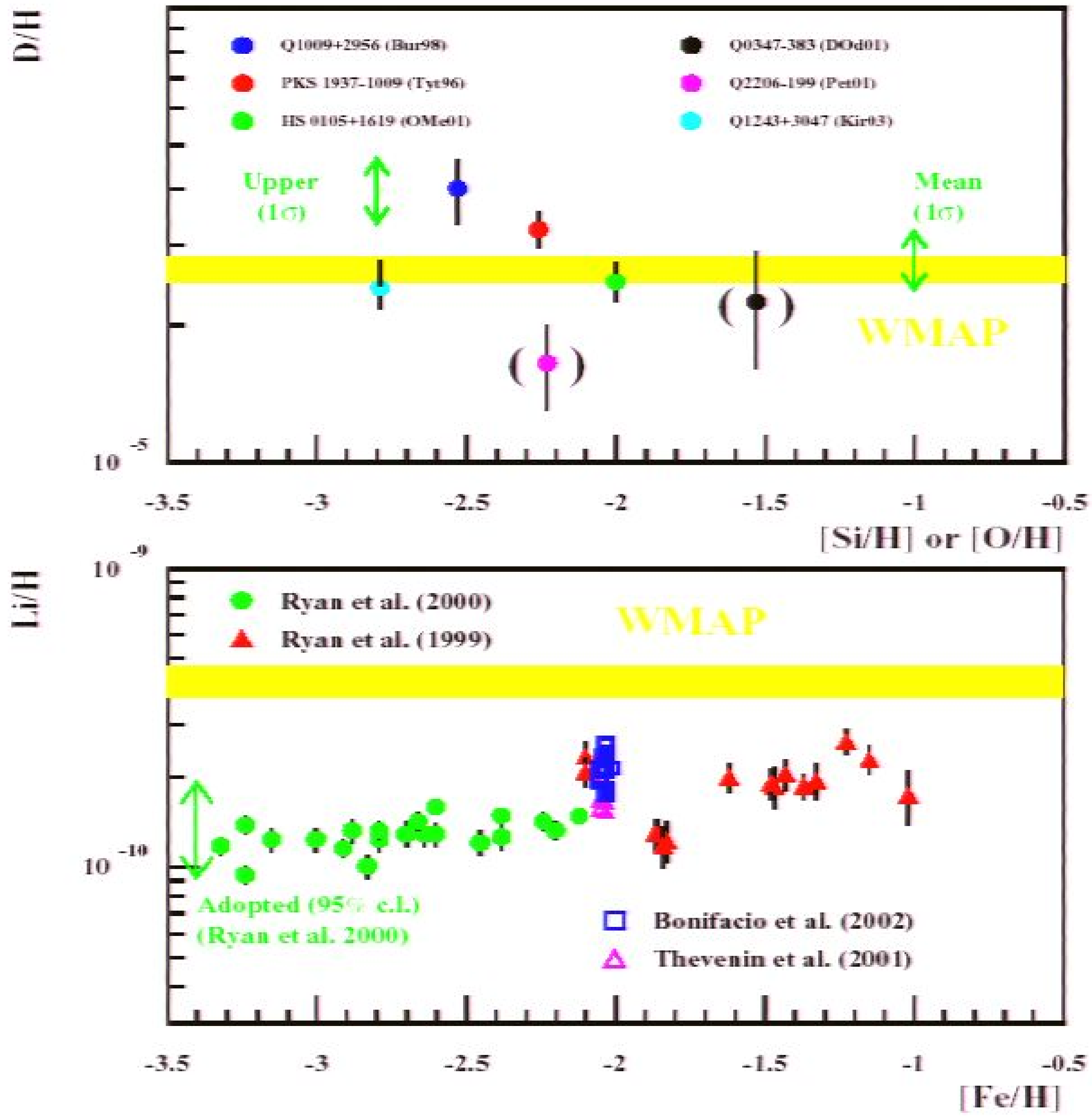
- Provide catalyzing ingredients that change $\langle \sigma_{ijk} v \rangle$ (MP, 2006). Possible catalysts: electroweak scale remnants charged under $U(1)$ or color $SU(3)$ gauge groups.

Catalyzed Production of ^{6}Li and ^{9}Be at 8 KeV, suppression of $^{7}Be+^{7}Li$ at 35 KeV (if lucky)



Catalyzed nucleosynthesis at 5:30a.m.

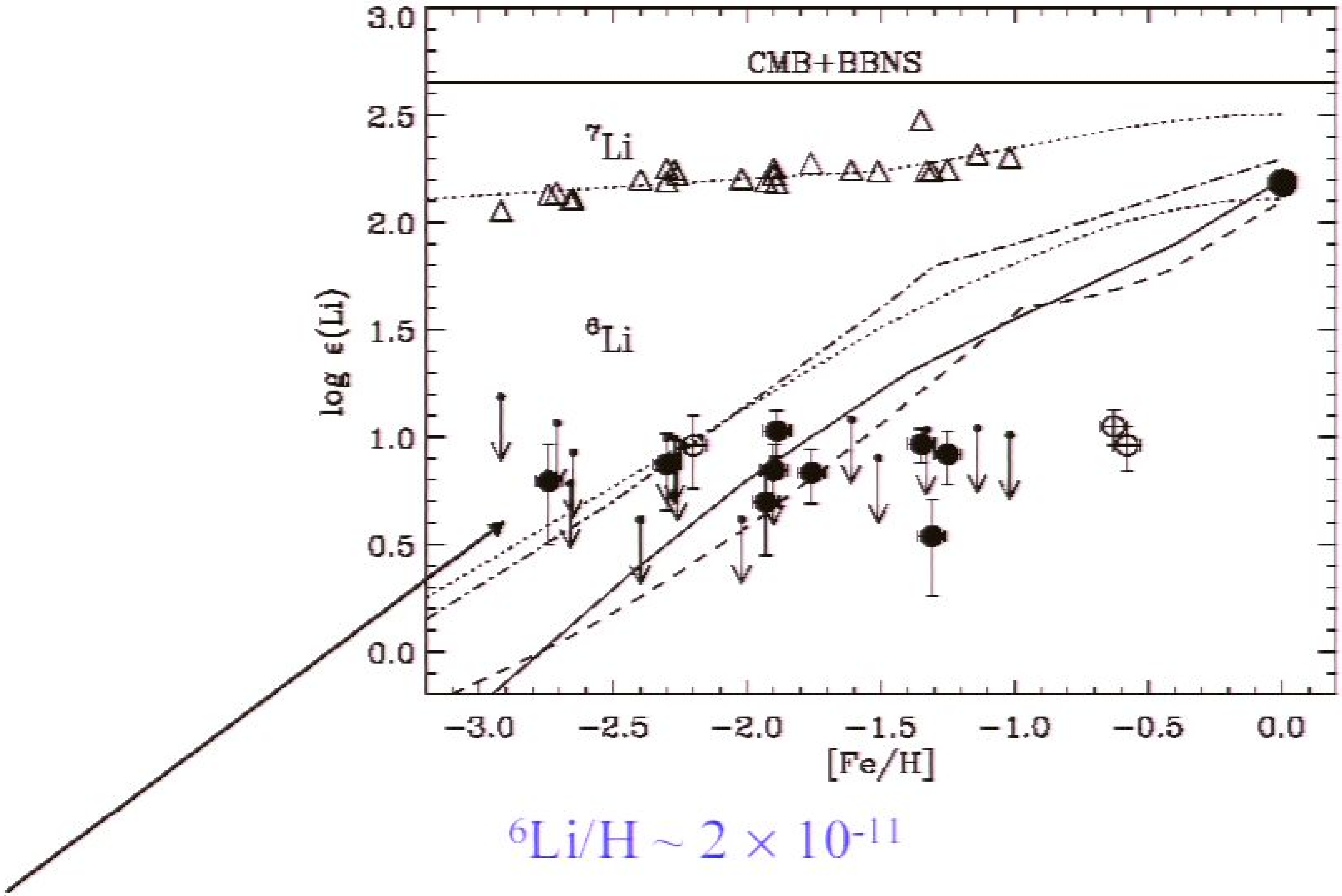
Deuterium and Lithium abundances



Coc et al.
ApJ 2004

Emerging ^{6}Li problem?

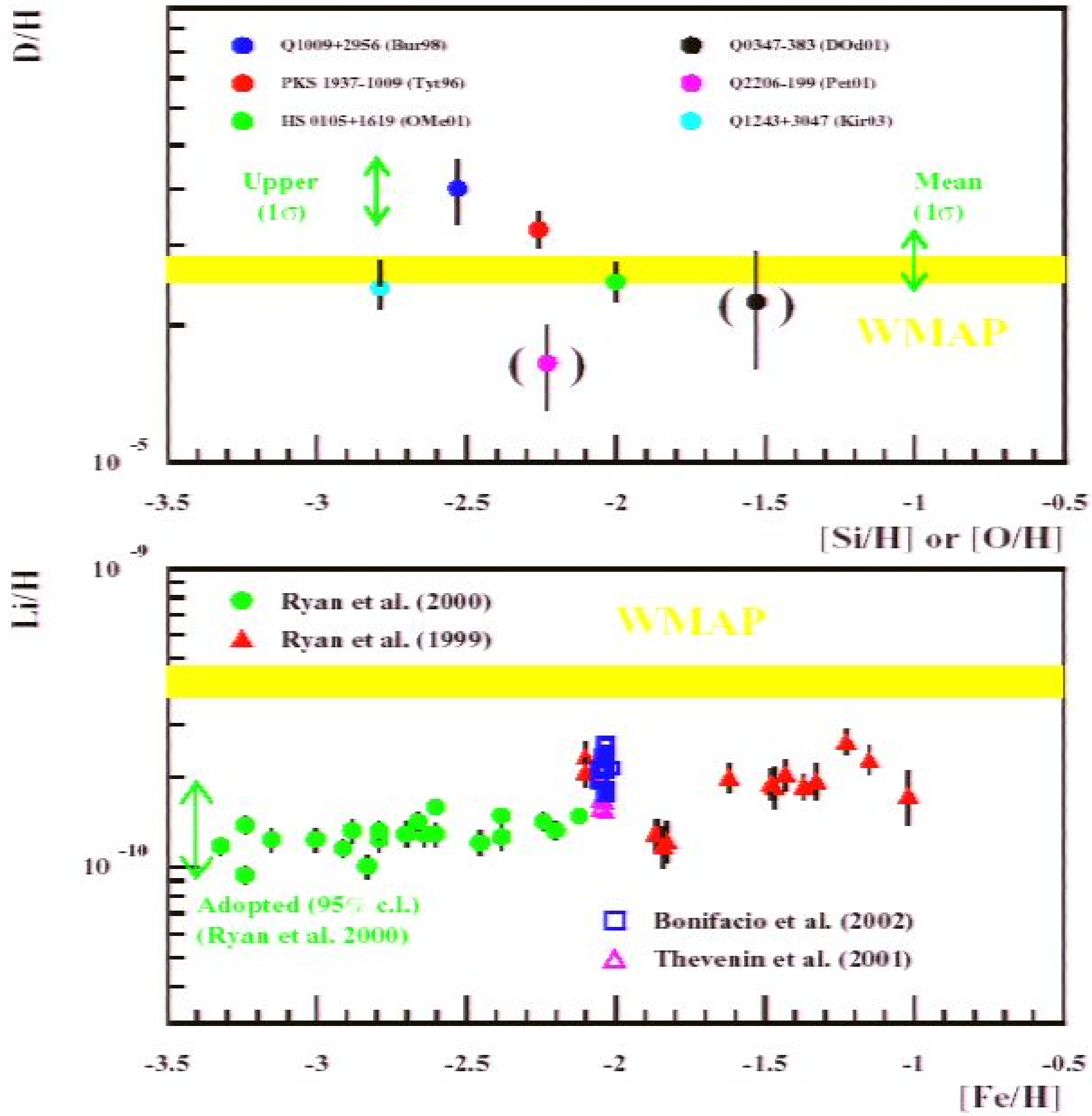
A lot of speculations about primordial ^{6}Li!



$^{6}Li/H \sim 2 \times 10^{-11}$

Unexpected plateau (?) of ^{6}Li with metallicity (Asplund et al., 2005)

Deuterium and Lithium abundances



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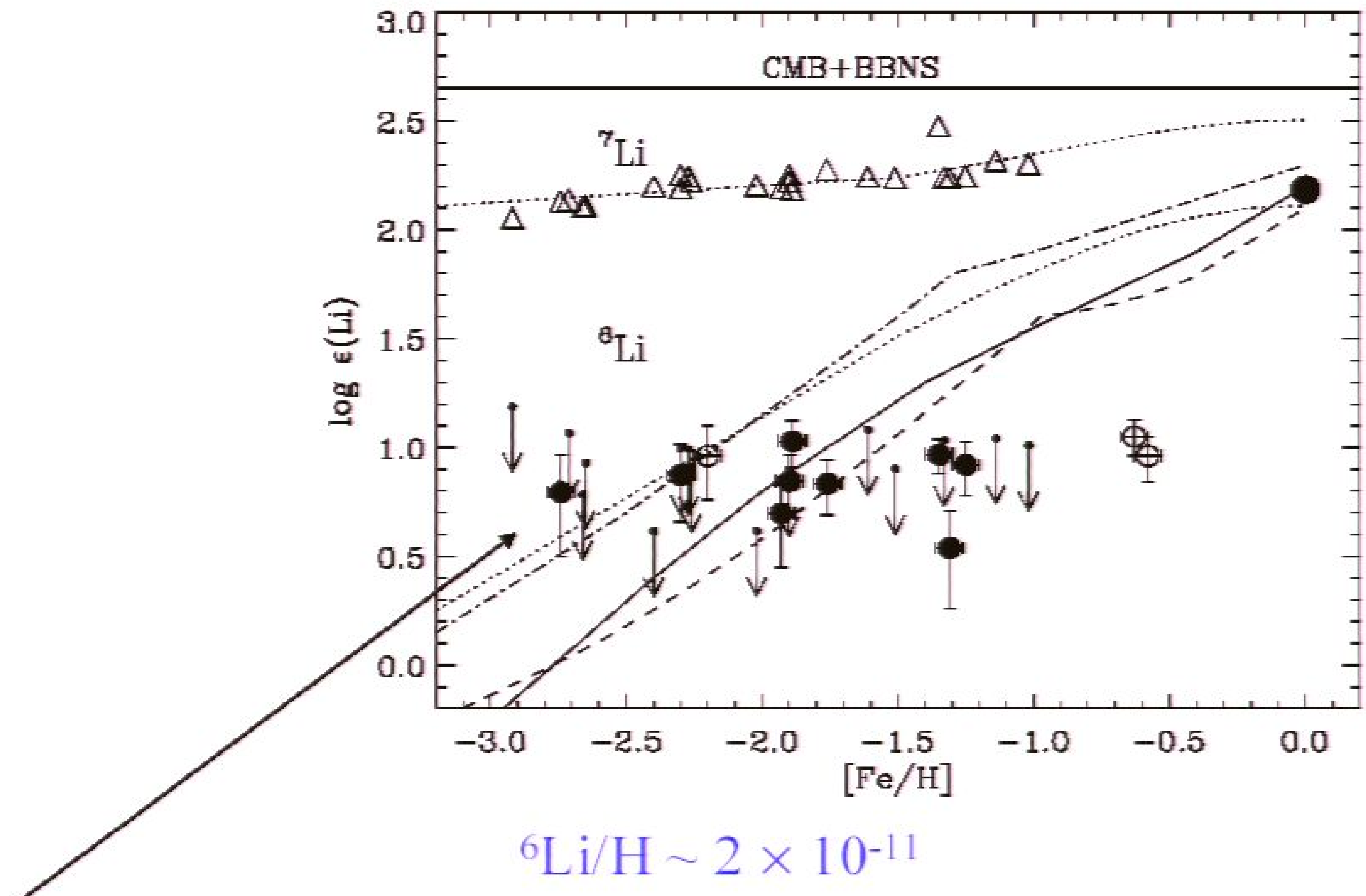
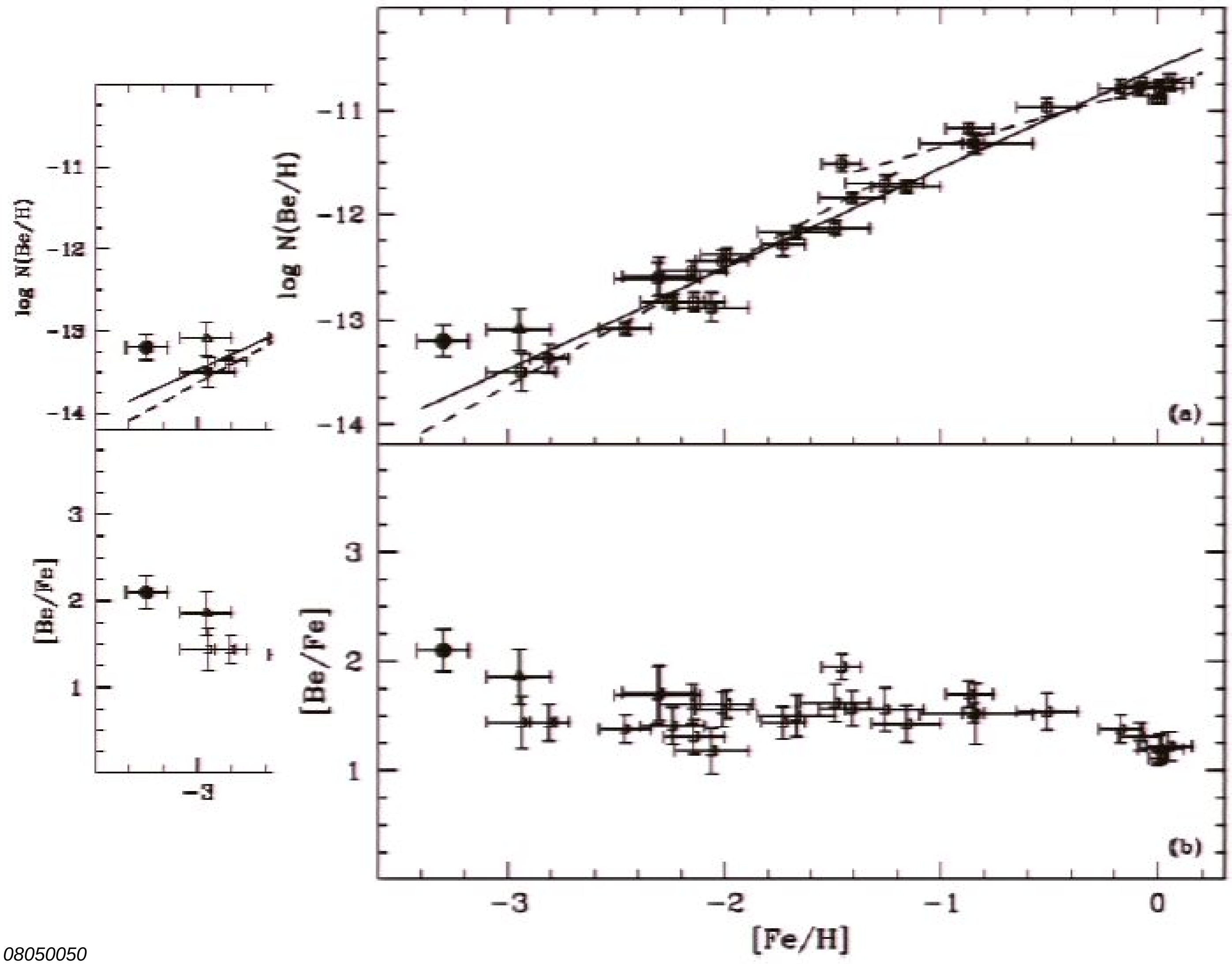


^{6}Li/H ~ 2 × 10^{-11}

Unexpected plateau (?) of ^{6}Li with metallicity (Asplund et al., 2005) 7

^{9}Be vs metallicity

Is there a hint on a "lifted tail"? (Primas et al., 2001)



No serious BBN models ever predicted anything in excess of 10^{-15}

Physics Beyond SM and BBN

1. Timing of reactions can be changed by adding new thermally excited degrees of freedom. Accuracy of observations are sensitive to $N_{\mathrm{eff}} \sim O(1)$. In other words, there is sensitivity to $\Delta\rho_{\mathrm{extra}}/\rho_{\mathrm{total}} \sim 0.3$.

2. Energy injection (e.g. late decays of particles) will have an effect on mostly D, ^{6}Li, ^{7}Li, and ^{3}He/D if $\tau_X > 10^3$ sec for hadronic decays and $\tau_X > 10^5$ sec for electromagnetic decays. Best sensitivity may reach $\Delta E\, n_X/n_\gamma < 10^{-13}$ GeV at $\tau_X > 10^7$ sec.

3. Catalysis of nuclear reactions (via formation of bound states of charged relics X^- with nuclei) will have an effect on ^{6}Li, ^{7}Li, and ^{9}Be. Best sensitivity to $n_X/n_\gamma < 10^{-16}$ for $\tau_X > 10^4$ sec.

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Input parameters for Catalyzed BBN

Suppose that there is an electroweak scale remnant X^- (and X^+), e.g. SUSY partner of electron, μ or τ, with the following properties:

1. Masses are in excess of 100 GeV to comply with LEP/Tevatron.
2. Abundances per baryon Y_X are $O(0.1–0.001)$. In a fully specified model of particle physics they scale as $Y_X \sim (0.01–0.05) m_X/\text{TeV}$.
3. Decay time τ_X is longer than 1000 sec; no constraints on decay channels.

Are there changes in elemental abundances from mere presence of X^-?

Yes! ***Anything at all that*** **sticks to He with binding energy between 150 KeV and 1500 KeV will lead to the catalysis of ^{6}Li production!**

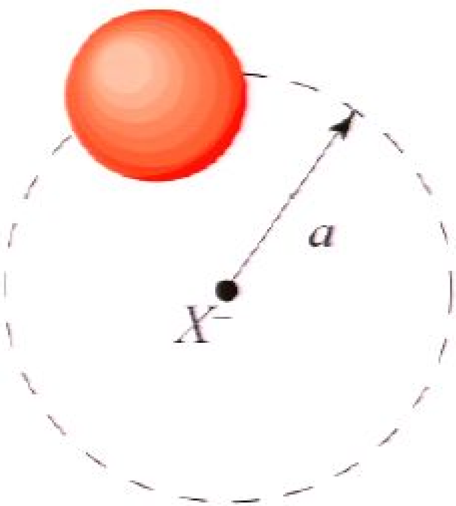
Any quantities of (^{8}BeX) in excess of 10^{-10} at 8 keV will lead to the catalysis of ^{9}Be to $>10^{-13}$ level.

Properties of bound states

$$E_{Bohr} = \frac{Z_{\rm He}^2 \alpha^2 m_{\rm He}}{2} = 397 \text{ KeV}$$

$$E_b = 350 \text{ KeV};\ a = 3.6 \text{ fm}$$

$$T_{recomb} = 8.3 \text{ KeV};\ r_c = 1.7 \text{ fm}$$



(^{4}HeX$^-$)

Bohr radius is 2 times larger than nuclear

$$E_{Bohr} = \frac{Z_{\rm Be}^2 \alpha^2 m_{\rm Be}}{2} = 2787 \text{ KeV}$$

$$E_b = 1350 \text{ KeV};\ a = 1.0 \text{ fm}$$

$$T_{recomb} = 35 \text{ KeV};\ r_c = 2.5 \text{ fm}$$

(^{7}BeX$^-$)

Bohr orbit is within nuclear radius

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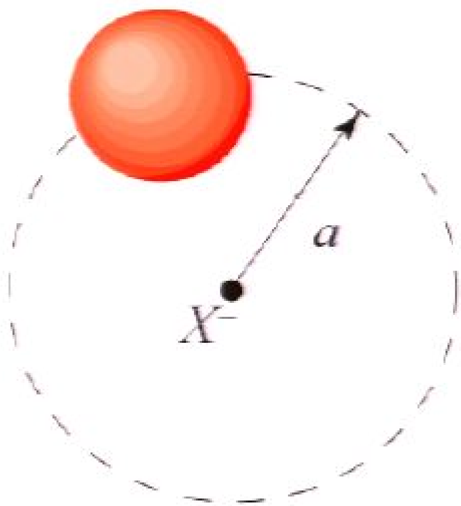

$$E_{Bohr} = \frac{\alpha^2 m_{\mathrm{p}}}{2} = 25\mathrm{KeV}$$

$$T_{recomb} = 0.7\mathrm{KeV};\ a_b = 28\mathrm{fm}$$

$(^4\mathrm{He}X^-)$

Bohr radius is 2 times larger than nuclear

$(\mathrm{p}X^-)$

Bohr orbit is 28 fm

Binding energy and stability thresholds

bound st.	$\lvert E_b^0 \rvert$	a_0	R_N^{sc}	$\lvert E_b(R_N^{sc}) \rvert$	R_{Nc}	$\lvert E_b(R_{Nc}) \rvert$	T_0
^{4}HeX	397	3.63	1.94	352	2.16	346	8.2
^{6}LiX	1343	1.61	2.22	930	3.29	780	19
^{7}LiX	1566	1.38	2.33	990	3.09	870	21
^{7}BeX	2787	1.03	2.33	1540	3	1350	32
^{8}BeX	3178	0.91	2.44	1600	3	1430	34
^{4}HeX	1589	1.81	1.94	1200	2.16	1150	28
DX	50	14	-	49	2.13	49	1.2
pX	25	29	-	25	0.85	25	0.6

Table 1: Properties of the bound states: Bohr a_0 and nuclear radii R_N in fm; binding energies E_b and "photo-dissociation decoupling" temperatures T_0 in KeV.

New Reaction Channels

- Main SBBN channel for ^{6}Li production

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

$$\langle \sigma_{SBBN} v \rangle = \underline{30} T_9^{-2/3} \exp(-\underline{7.435} / T_9^{1/3})$$

in usual astrophysical units. ^{6}Li(SBBN) ~ 10^{-14}

NB: typical pre-exponents for γ reactions are 10^5–10^6,

for photon-less reactions 10^8–10^{10}

- Main CBBN channel for ^{6}Li production

$$(^4\text{HeX}^-) + \text{D} \rightarrow {}^6\text{Li} + \text{X}^-; \quad Q = 1.13\ \text{MeV}$$

$$\langle \sigma_{CBBN} v \rangle = \underline{2.4 \times 10^8} T_9^{-2/3} \exp(-\underline{5.37} / T_9^{1/3})$$

hep-ph/0702274, (Hamaguchi, et al.) finds S-factor 10 times smaller than my original estimate. See Prof. Kamimura talk during this workshop

New Reaction Channels

- A possible SBBN channel for ^{9}Be production

$$^8\mathrm{Be} + \mathrm{n} \rightarrow {}^9\mathrm{Be} + \gamma; \;\; Q = 1.66 \text{ MeV}$$

$\langle \sigma_{SBBN} v \rangle \approx 0.$ Requires triple collisons as ^{8}Be is unstabl

^{9}Be(SBBN) $\sim 10^{-18}$ (B. Fields et al)

- Main CBBN channel for ^{9}Be production

$$(^8\mathrm{BeX}^-) + \mathrm{n} \rightarrow {}^9\mathrm{Be} + \mathrm{X}^-; \;\; Q = 0.26 \text{ MeV}$$

$$\langle \sigma_{CBBN} v \rangle = 2.0 \times 10^9$$

This is a large photonless rate dominated by threshold resonance!

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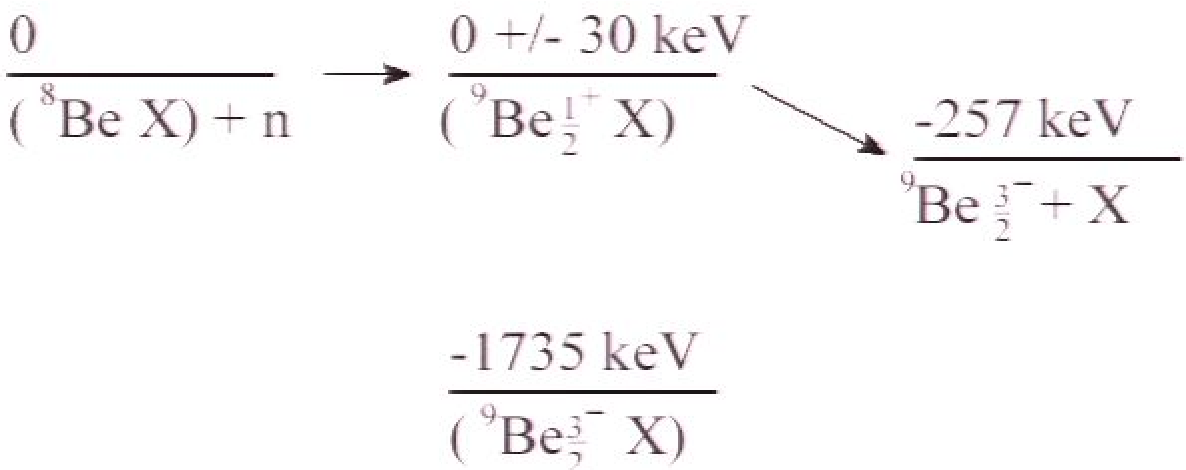
Photon-less production of ^{9}Be in CBBN



Within error bars the ½$^+$ resonance in (^{9}BeX$^-$) is *exactly* at the (^{8}BeX$^-$) + n continuum threshold.

$$\Gamma_{in} \simeq 2(192 E_n \mathrm{keV})^{1/2}, \qquad \Gamma_{out} \simeq 5 \text{ keV} – \text{my estimate}$$

(^{8}BeX) bottleneck

Two sources:

1. Early time: through (^{7}BeX$^-$) $\rightarrow$ (^{8}BX$^-$) $\rightarrow$ (^{8}BeX$^-$)
2. Late time: through (^{4}HeX) $\rightarrow$ (^{8}BeX)

The formation of (^{8}BeX) occurs primarily via *resonant* process

(^{4}HeX) + ^{4}He $\rightarrow$ *(^{8}BeX, n=3) $\rightarrow$ (^{8}BeX, n=3) +γ

For n=3, l=1,2 the resonant energies are 114 and 88 keV.

It turns out that when $T \gg \Gamma_{tot} = \Gamma_{in} \gg \Gamma_{out}$, the Breit-Wigner formula simplifies

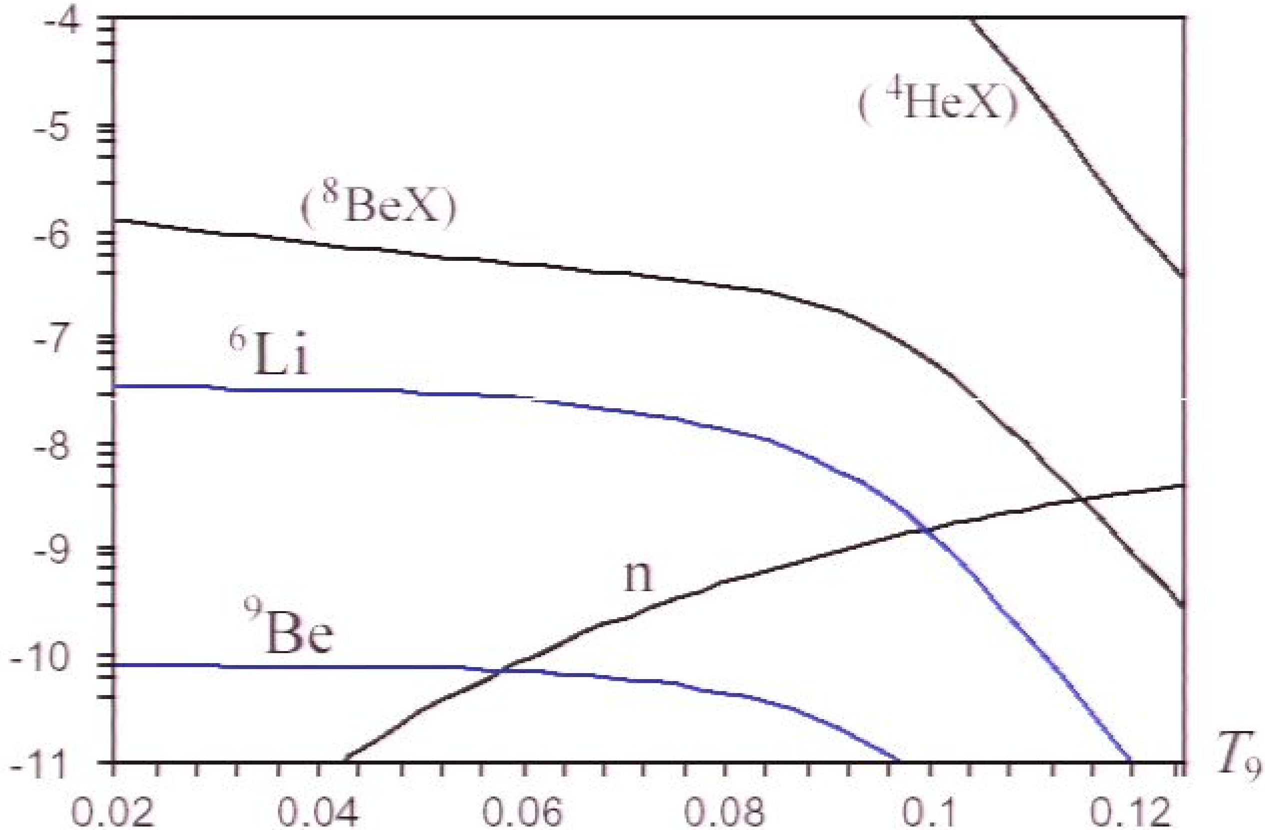
$$\sigma_{BW}(E) = \frac{\sigma_{geom}\Gamma_{in}\Gamma_{out}}{(E-E_R)^2 + \Gamma_{tot}^2/4} \rightarrow \sigma_{geom}\Gamma_{out} \times 2\pi\delta(E-E_R)$$

and gives a total rate that is independent on Γ_{in} that contains all nuclear physics uncertainties !

$10^5\, T_9^{-3/2}(0.95\exp(-1.02/T_9)+0.66\exp(-1.33/T_9))$

^{6}Li and ^{9}Be at 8 KeV

CBBN with $Y_X = 5\times10^{-3}$, $\tau_X=\infty$ as a typical example, resulting in ^{6}Li >10^{-8}, and ^{9}Be>10^{-11} – **Excluded!**

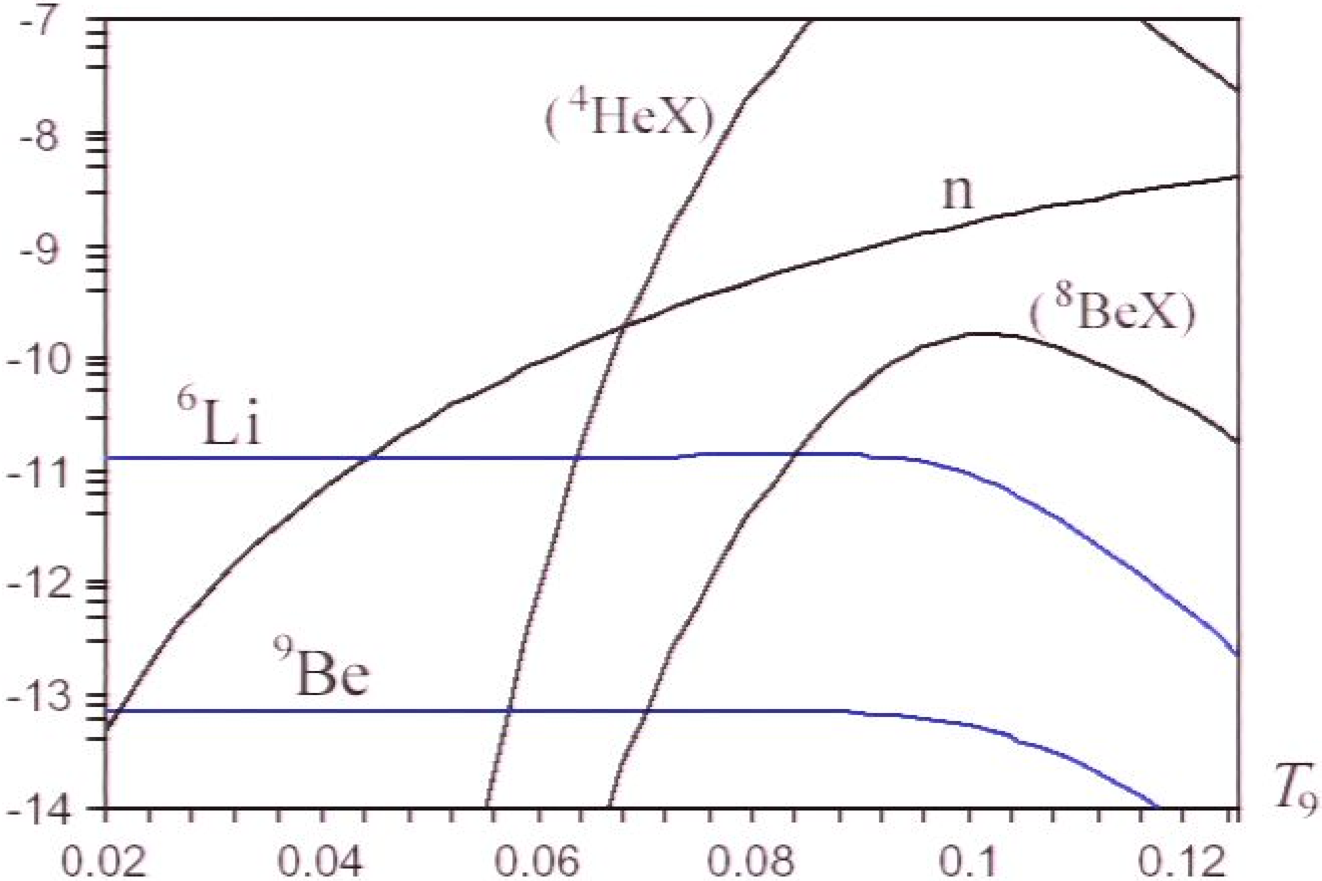


Observationally, ^{6}Li/H < few× 10^{-11}; ^{9}Be/H<few× 10^{-13},

Therefore $Y_X(2\times10^4 \text{sec}) < 10^{-5}$, and typically $\tau_X < 5\times 10^3$ s

^{6}Li and ^{9}Be at 8 KeV

CBBN with $Y_X = 10^{-1}$, τ_X=2000s as a "just so" scenario



^{6}Li/H=1.3× 10^{-11}; ^{9}Be/H=7× 10^{-14}: A very intriguing pattern!!!

^{9}Be/^{6}Li = (2-5)× 10^{-3} - a typical "footprint" of CBBN

Catalytic suppression of ^{7}Be + ^{7}Li

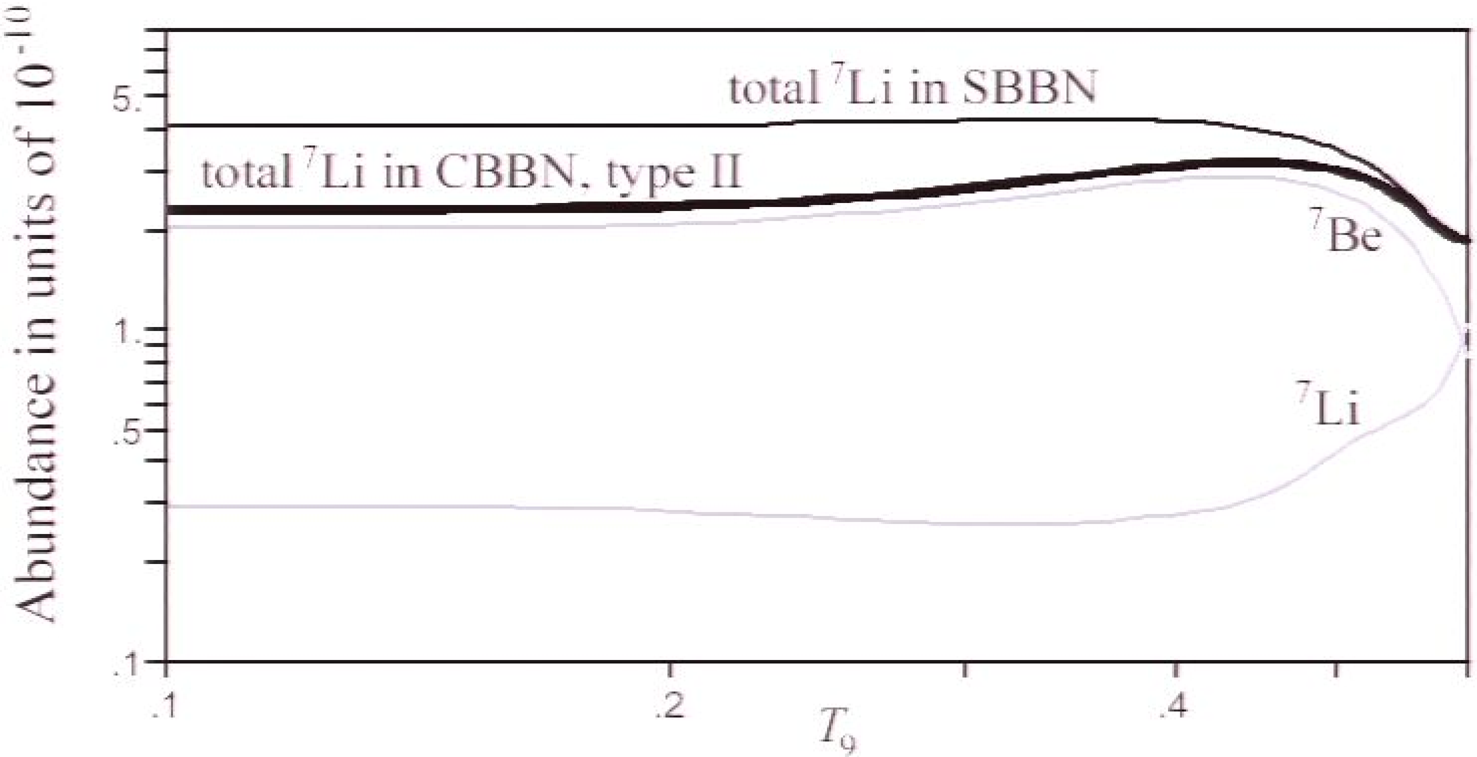
- The "bottleneck" is creation of $(^7\mathrm{Be}X^-)$ bound states that is controlled by $^7\mathrm{Be}+X^- \to (^7\mathrm{Be}X^-) + \gamma$ reaction
- There are two main destruction channels that are catalyzed:

1. p-reaction: $(^7\mathrm{Be}X^-) + \mathrm{p} \to (^8\mathrm{B}X^-) + \gamma$ by a factor of >1000 relative to $^7\mathrm{Be} + \mathrm{p} \to {}^8\mathrm{B} + \gamma$
2. In models of type II, the "capture" of X^- is catalyzed: $(^7\mathrm{Be}X^-) \to {}^7\mathrm{Li} + X^0$,

so that lifetime of $(^7\mathrm{Be}X^-)$ becomes $\ll 1$ sec. ^{7}Li is significantly more fragile and is destroyed by protons "on the spot".

3. There is significant energy injection via $X^+ + X^- \to (X^+X^-) \to$ radiation. If this process has hadronic modes, it also affects Li7.

$^7Be+^7Li$ at 35 KeV



Type II model (fast internal capture),

Y_X=0.05, τ=2000s

Is there a catalysis due to (pX^-) states?

At first sight, there must be an effect. After all, theres is no Coulomb barrier. (Dimopoulos et al, 1989, Kohri and Takayama, 2006, Jedamzik 2007).

Most recently there was a claim (Jedamzik 2007) that a catalytic synthesis of ^{6}Li at 8 keV would be balanced out by catalytic suppression of ^{6}Li below 1 keV because of the

$^6\text{Li} + (pX) \rightarrow X + {}^3\text{He} + {}^4\text{He}$ burning. It would open the high abundance/long lifetime "island" in the parameter space

Is this expectation justified? **NO!** Charge exchange reactions

1. Deplete (pX) – known before but not taken into account properly
2. Shield Li and Be in the (LiX) bound states. The further rate of destruction is exactly 0 in the limit of $m_X \rightarrow \infty$

$(pX^-) + Z$ scattering semiclassically

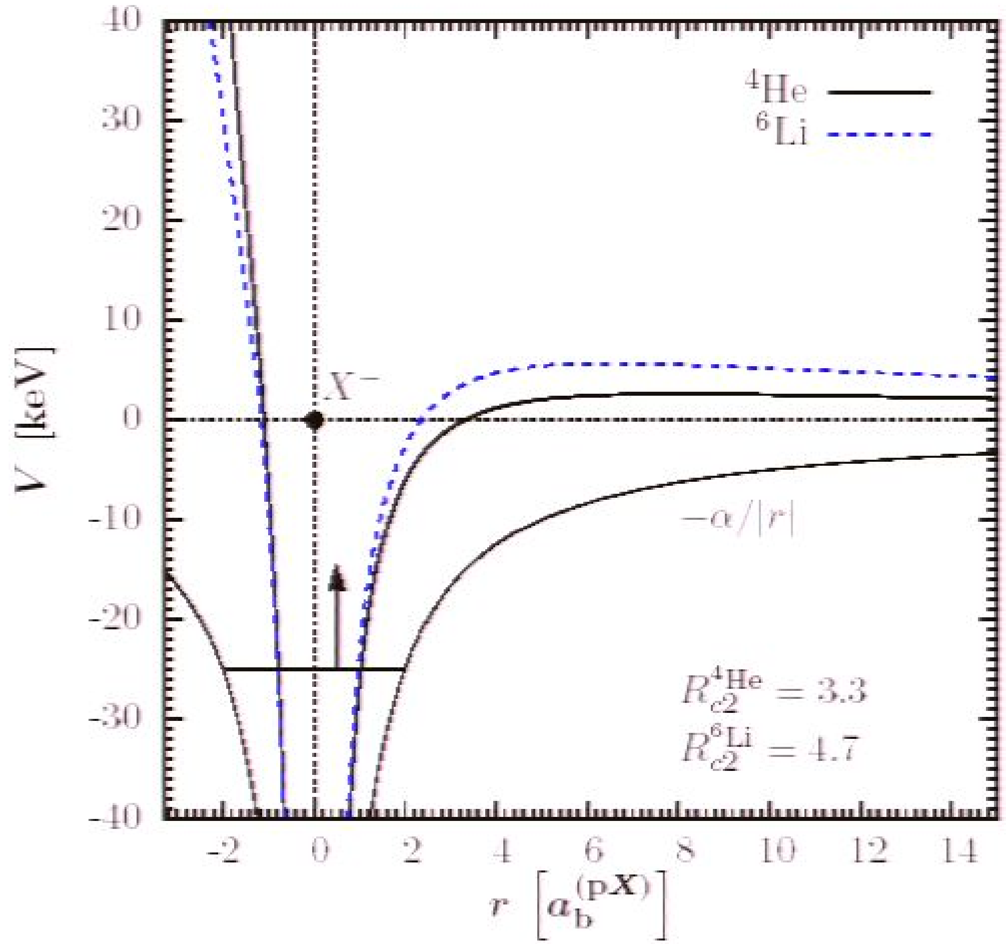
As the distance R between incoming "heavy" (^{4}He, Li, Be…) nucleus and X^- becomes shorter, proton is deconfined and escapes to infinity.

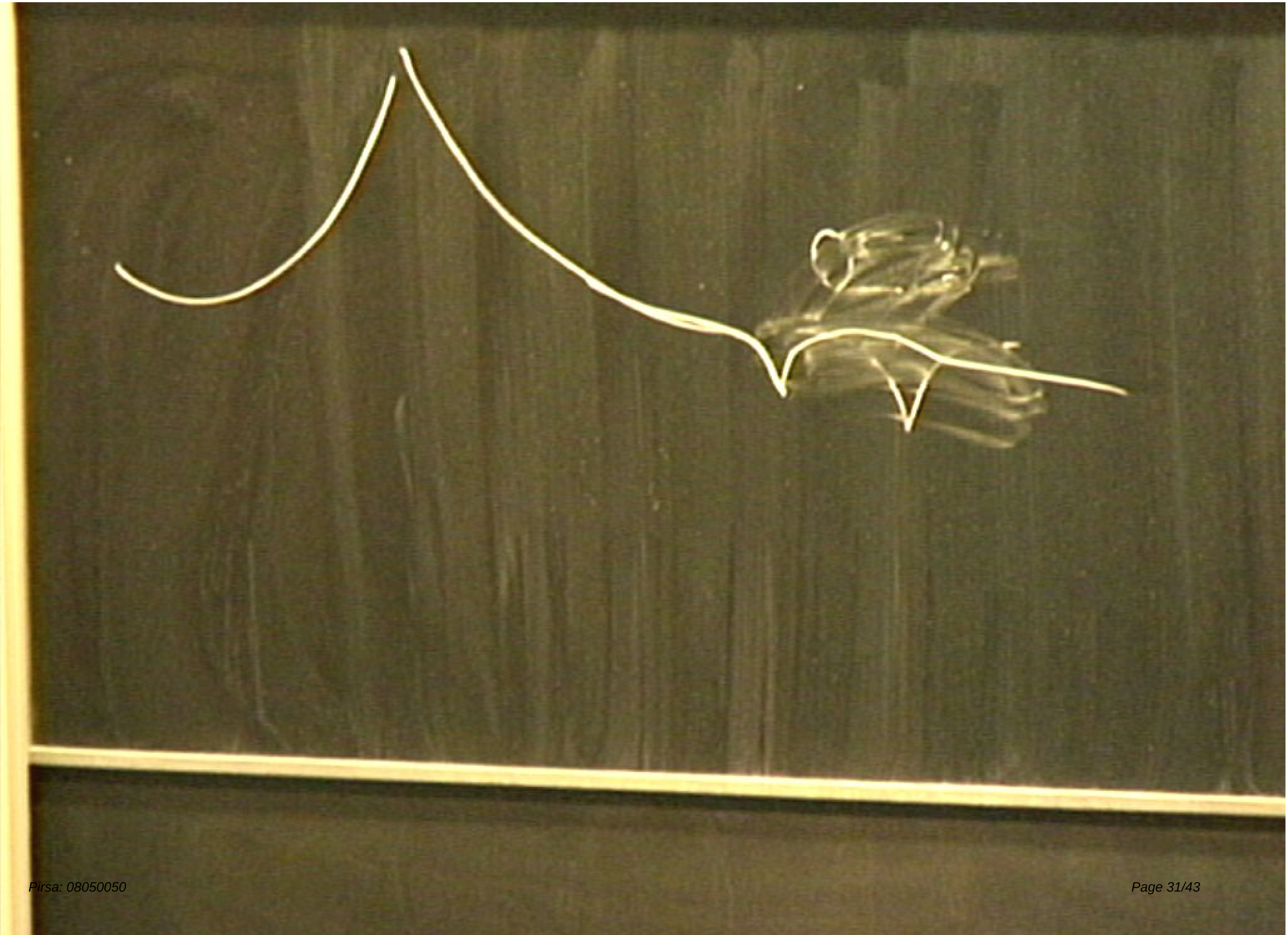
Capture happens to high n,l states of (HeX). Cross section = πR_c^2.

For incoming ^{4}He, this distance is 95fm, $\sigma_{\mathrm{ch\ exch}} \simeq$ 280bn

For incoming ^{6}Li, this distance is 135 fm, $\sigma_{\mathrm{ch\ exch}} \simeq$ 580bn

Not far from unitarity.





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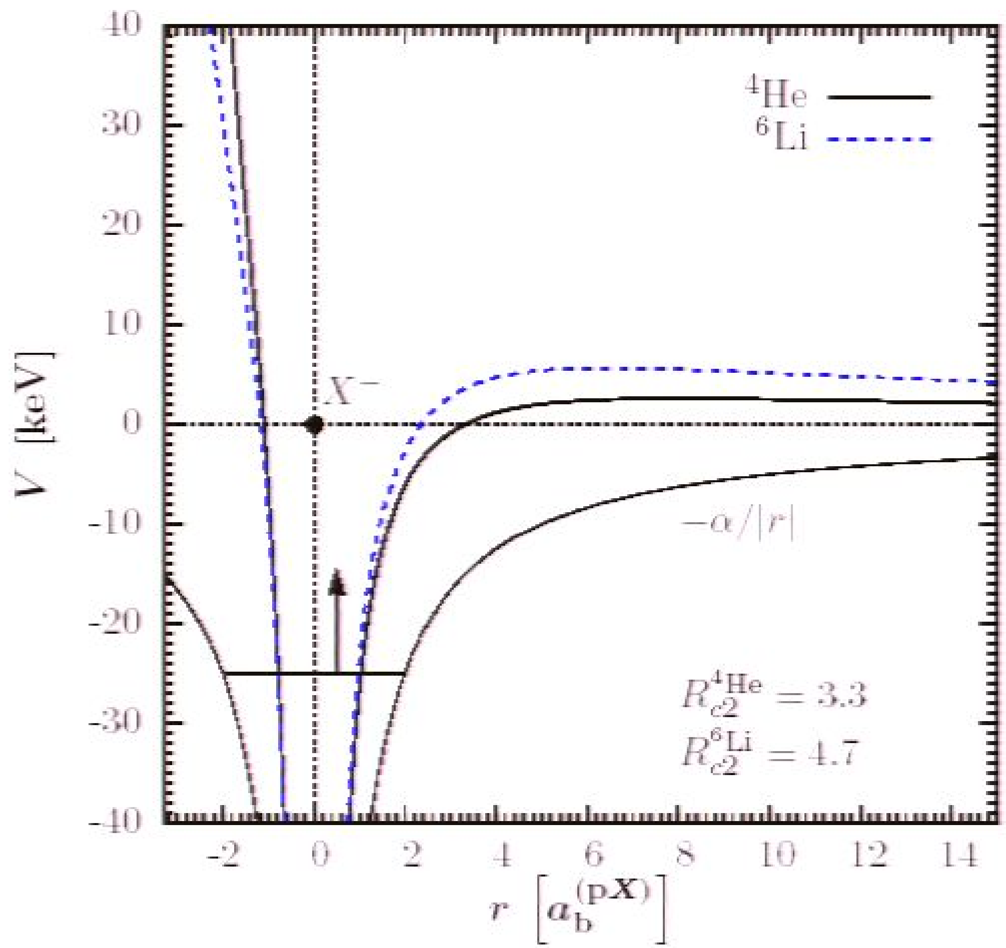


"LiX_3 ammonium and BeX_4 methane"

Charge exchange is much more likely than p tunneling through the Coulomb barrier. Even if for WHATEVER reasons, the rate for $^6Li + (pX) \rightarrow X + {}^3He + {}^4He$ is large, it is still $\sigma_{nucl} < \sigma_{unitarity}$

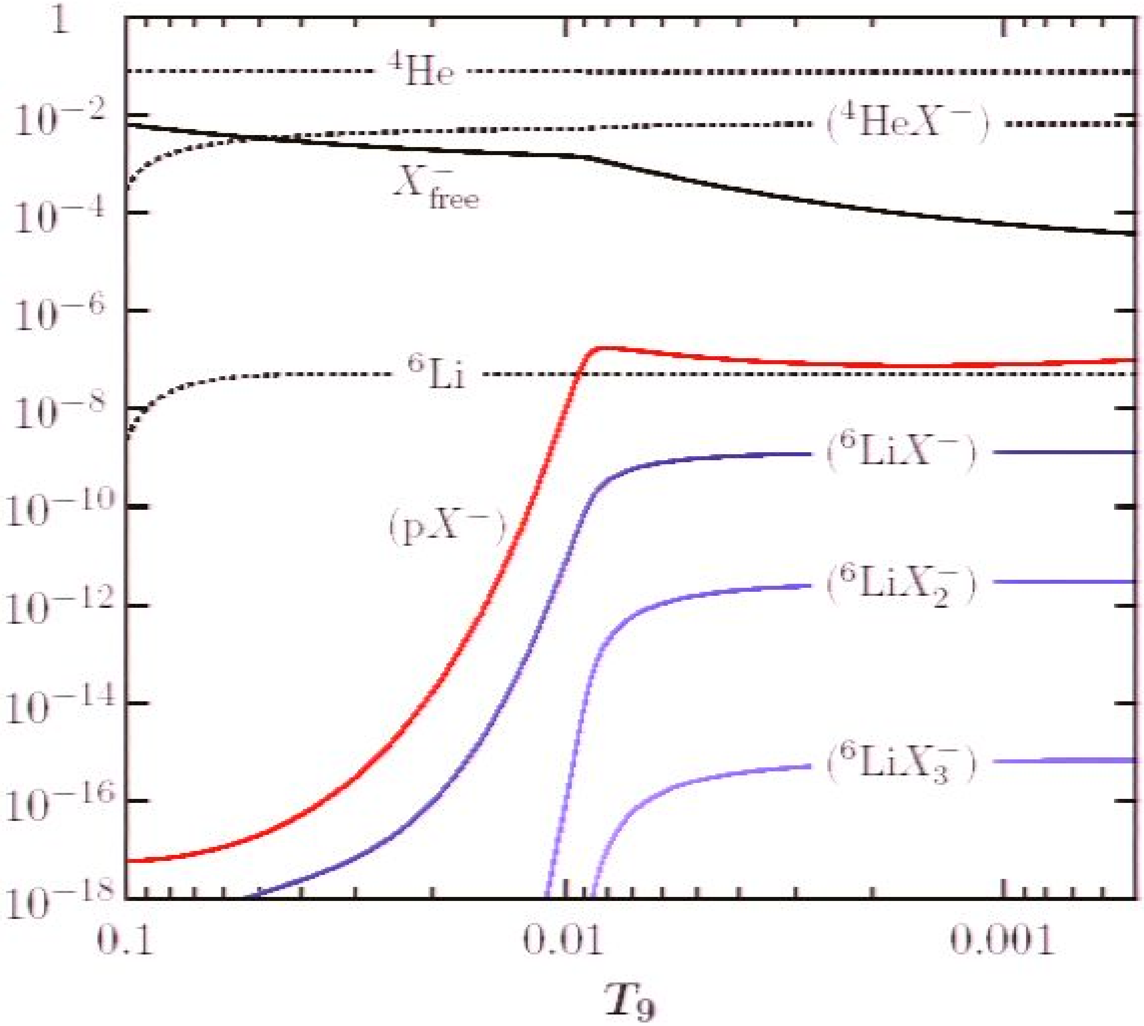
And since $\sigma_{ch\ ex}$ is not far different from $\sigma_{unitarity}$ at least 50% is shielded from destruction. And one needs factors 100-1000.

Li and Be can be burned via the series of successive charge exchanges

$$^6Li + (pX) \rightarrow (^6LiX) + p$$
$$(^6LiX) + (pX) \rightarrow (^6LiX_2) + p$$
$$(^6LiX_2) + (pX) \rightarrow (^6LiX_3) + p$$
$$(^6LiX_3) + p \rightarrow 3X + {}^3He + {}^4He \quad \text{or } 3X + {}^7Be$$

Notice that step 2 and 3 is suppressed as $(m_X)^{-1/2}$

(pX) and (^{6}LiX$_n$) below 1 keV



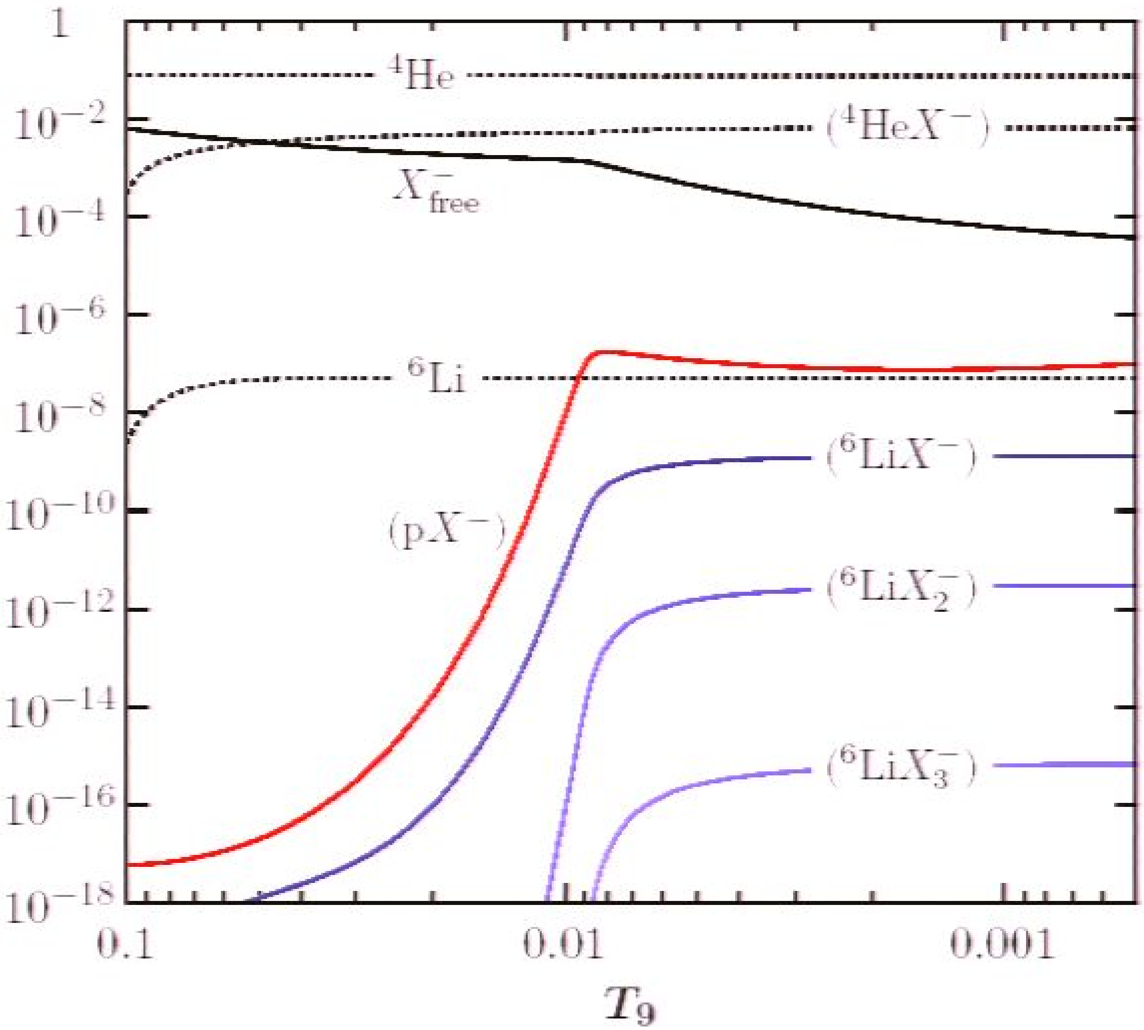
. No effect at all from (pX) catalysis [*is there a catalysis anyways*?]

No allowed islands with large abundance/large lifetime

Input: $Y_X = 10^{-2}$; $\tau_X = \infty$

Only tiny fraction of synthesized Li is affected

(pX) and (^{6}LiX$_n$) below 1 keV



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Open issues in CBBN

^{6}Li: $S_{CBBN}(0)$ for $(^4\mathrm{He}X) + D \to {}^6\mathrm{Li} + X$ needs to be checked by other groups.

^{7}Li + ^{7}Be: Level structure in $(^7\mathrm{Be}X)$ system with better than 30 keV accuracy. The resonant rates (2s resonance in (Be^*X) system in particular) is very close to threshold.

Cross section for $^7\mathrm{Be} + X \to (^7\mathrm{Be}X) + \gamma$

$S_{CBBN}(0)$ for $(^7\mathrm{Be}X) + p \to (^8\mathrm{B}X) + \gamma$

$S_{CBBN}(0)$ for $(^7\mathrm{Be}X) + D \to (^9\mathrm{B}X) \to (^8\mathrm{Be}X) + p$

(Resonances !)

For example: there is a 60 ± 30(?) keV resonance in $(^9\mathrm{B}^*X)$

Just above the threshold of $(^7\mathrm{Be}X) + D$!!!

Open issues in CBBN

^{9}Be: Level structure in (^{9}BeX) system with better than 50 keV accuracy = accurate model for charge distribution.
CBBN cross section for (^{8}BeX) + n $\rightarrow$ ^{9}Be + X
(Dominated by the resonance!)

Resonant formation of (^{4}HeX) + ^{4}He $\rightarrow$ (^{8}BeX) + γ
Resonances again!

Rates of secondary importance: (^{4}HeX) + ^{3}H $\rightarrow$ ^{7}Li + X; (^{4}HeX) + ^{3}He $\rightarrow$ ^{7}Be + X; (pX)-induced reactions;
Rates for X^{--} catalysis (^{12}C is a realistic possibility)

Conclusions

1. In the last two years it was recognized that CBBN is an independent new way how particle physics can affect the outcome of the primordial nuclear reactions, sensitive to abundance of X^-.
2. CBBN pattern: ^{6}Li and ^{9}Be abundances are drastically enhanced, with ratio $^9\text{Be}/^6\text{Li} = (2\text{-}5) \times 10^{-3}$.

   Assuming typical abundances, constraints on lifetime are on the order of $\sim$ 5000 seconds.

   ^{7}Li + ^{7}Be can be suppressed by a factor of ~ 2 if there is O(0.1-0.01) particles.
3. Catalysis by (pX) is not important *regardless* of the issue with nuclear uncertainties.
4. Careful investigation of resonant nuclear rates in CBBN are needed. Resonances!

Open issues in CBBN

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CBBN cross section for (^{8}BeX) + n $\rightarrow$ ^{9}Be + X

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Resonant formation of (^{4}HeX) + ^{4}He $\rightarrow$ (^{8}BeX) + γ

Resonances again!

Rates of secondary importance: (^{4}HeX) + ^{3}H $\rightarrow$ ^{7}Li + X; (^{4}HeX) + ^{3}He $\rightarrow$ ^{7}Be + X; (pX)-induced reactions;

Rates for X^{--} catalysis (^{12}C is a realistic possibility)

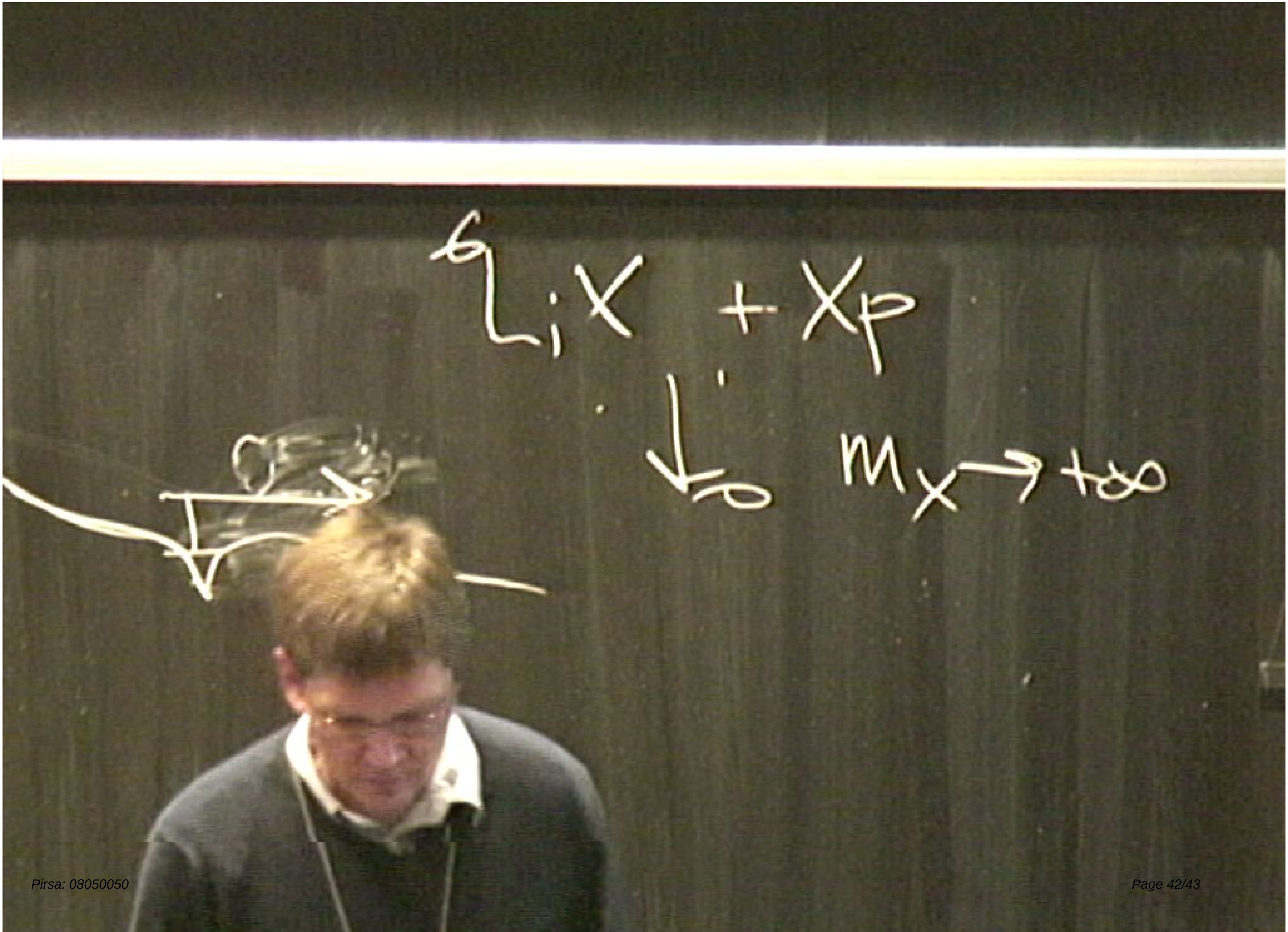
Conclusions

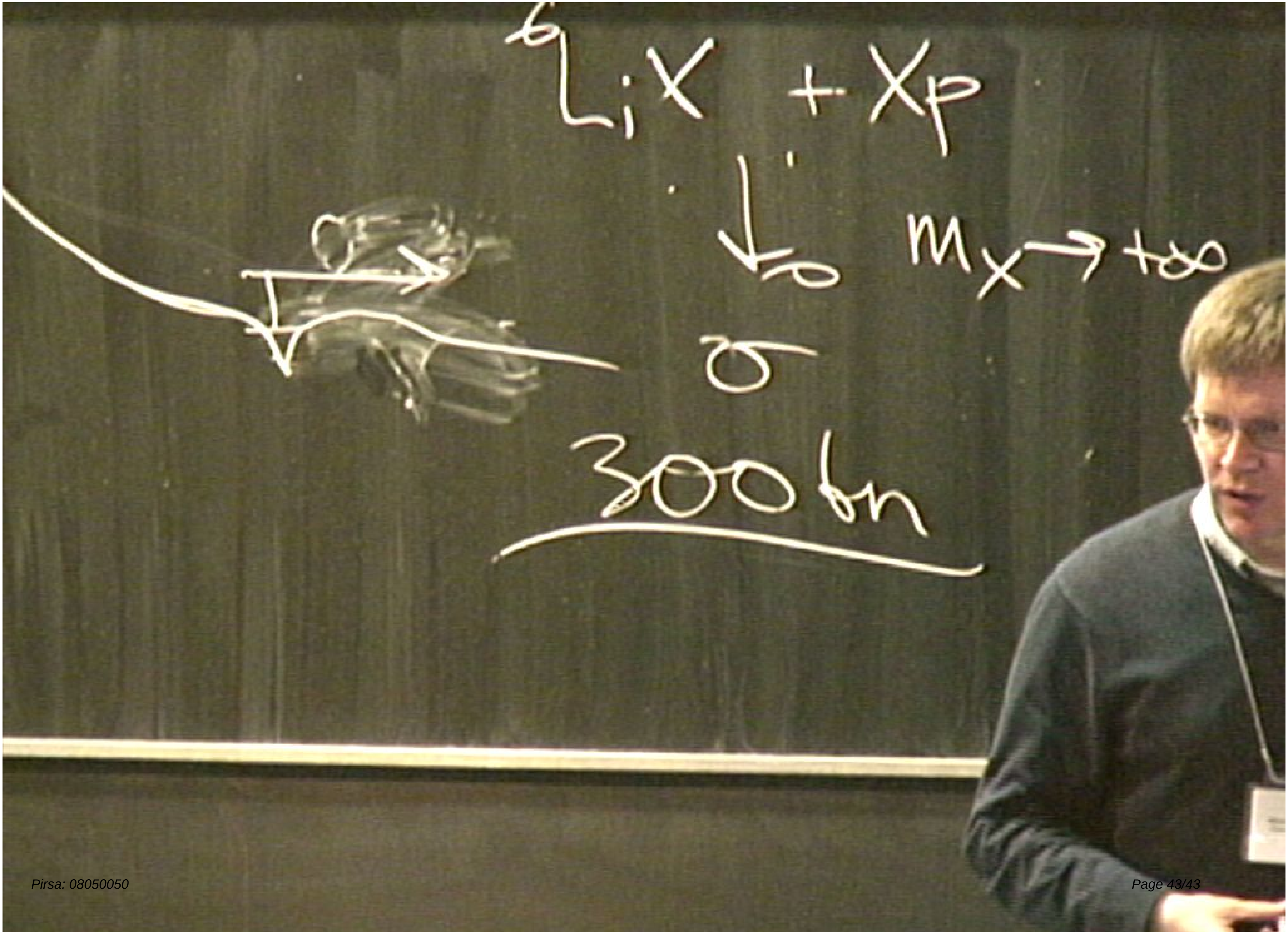
1. In the last two years it was recognized that CBBN is an independent new way how particle physics can affect the outcome of the primordial nuclear reactions, sensitive to abundance of X^-.
2. CBBN pattern: ^{6}Li and ^{9}Be abundances are drastically enhanced, with ratio $^9\text{Be}/^6\text{Li} = (2\text{-}5) \times 10^{-3}$.

   Assuming typical abundances, constraints on lifetime are on the order of $\sim$ 5000 seconds.

   ^{7}Li + ^{7}Be can be suppressed by a factor of ~ 2 if there is O(0.1-0.01) particles.
3. Catalysis by (pX) is not important *regardless* of the issue with nuclear uncertainties.
4. Careful investigation of resonant nuclear rates in CBBN are needed. Resonances!


⁶LiX + Xp


⁶LiX + Xp
m_X → +∞


6LiX + Xp
300 fb