Big Bang Nucleosynthesis and Particle Dark Matter

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Outline of Talk

I. Theory of standard BBN

II. Modified Expansion Rate during BBN

III. Particle Decays/Annihilations during/after BBN

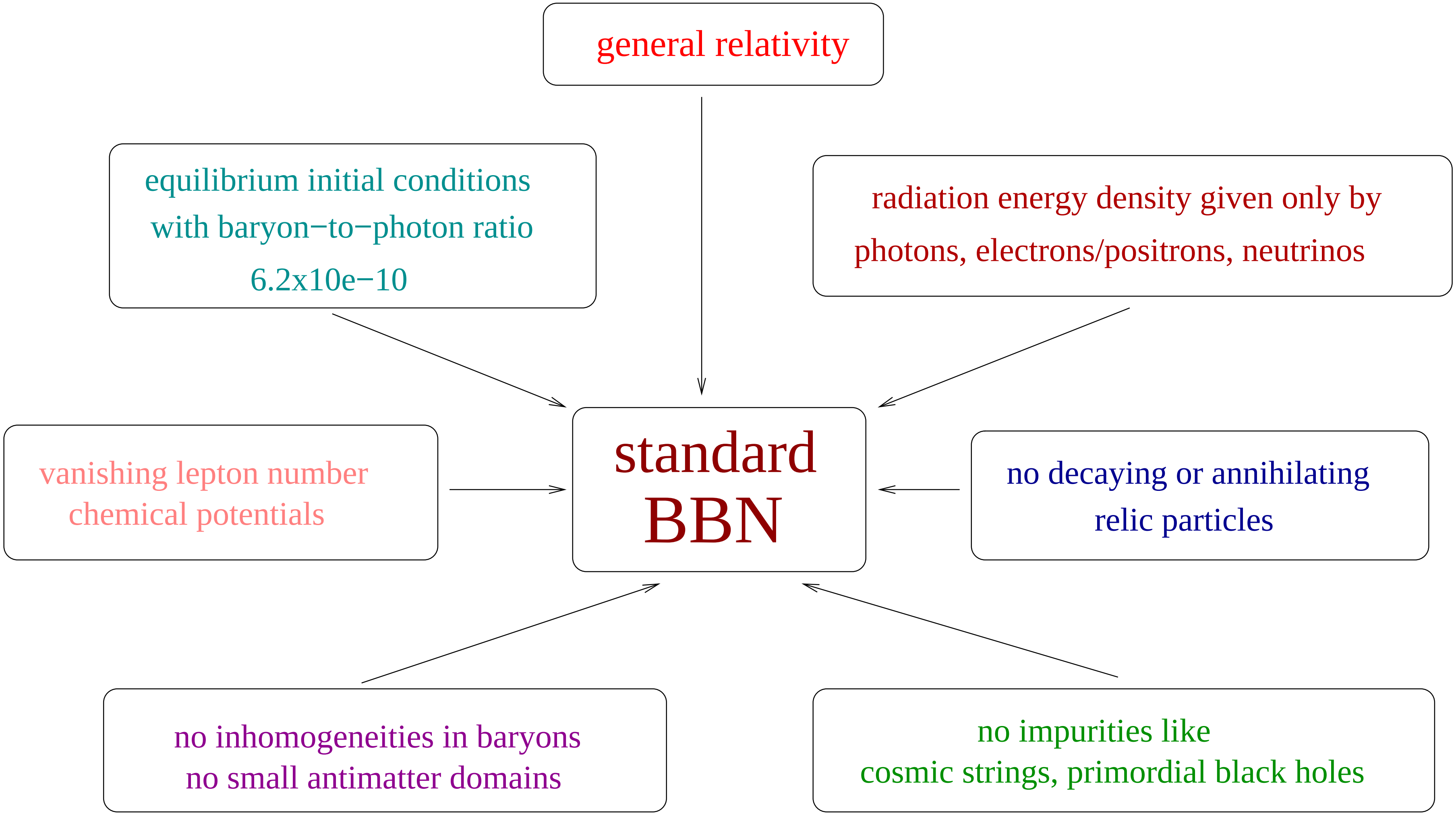
IV. Weak Mass Scale *Charged* Particles during BBN

V. Constraints on SUSY with gravitino LSPs

VI. The Lithium Anomalies

VII. Dark Matter and the Lithium Anomalies

Assumptions underlying Standard Big Bang Nucleosynthesis



general relativity

equilibrium initial conditions
with baryon−to−photon ratio
6.2x10e−10

radiation energy density given only by
photons, electrons/positrons, neutrinos

vanishing lepton number
chemical potentials

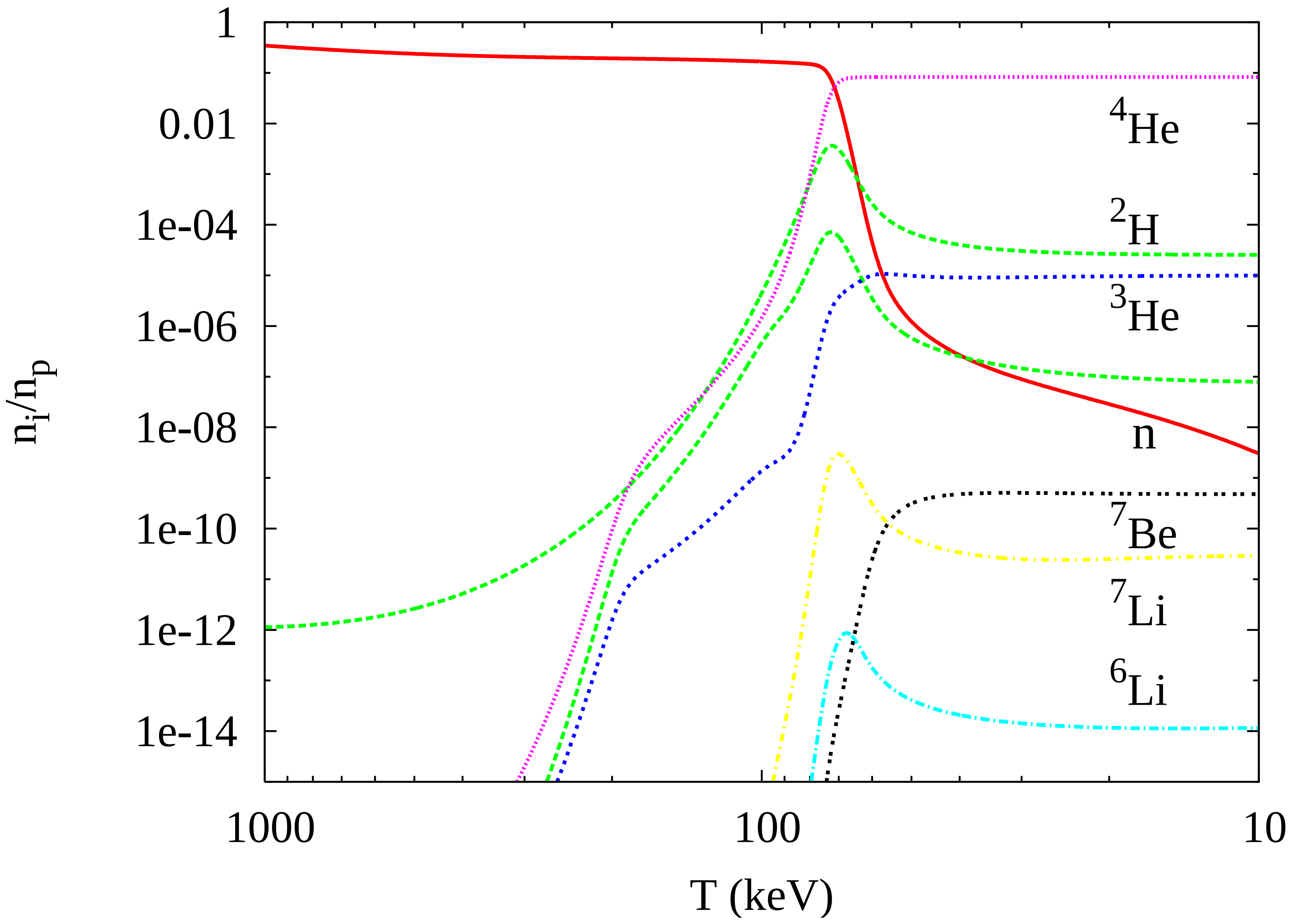
standard
BBN

no decaying or annihilating
relic particles

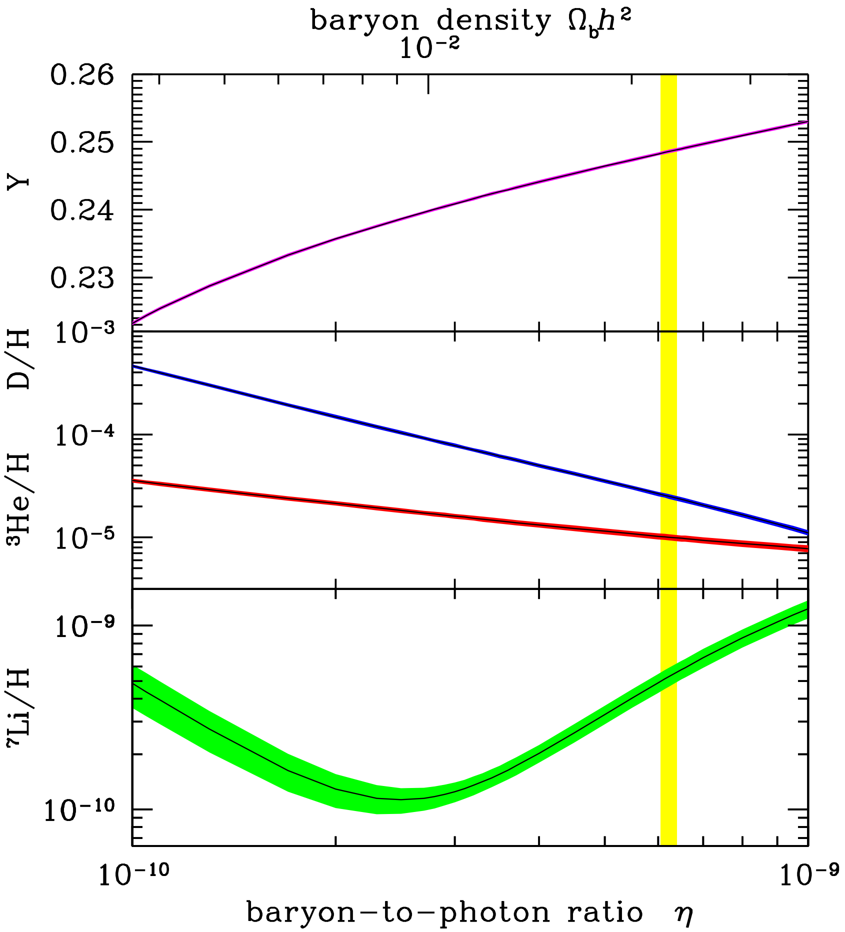
no inhomogeneities in baryons
no small antimatter domains

no impurities like
cosmic strings, primordial black holes

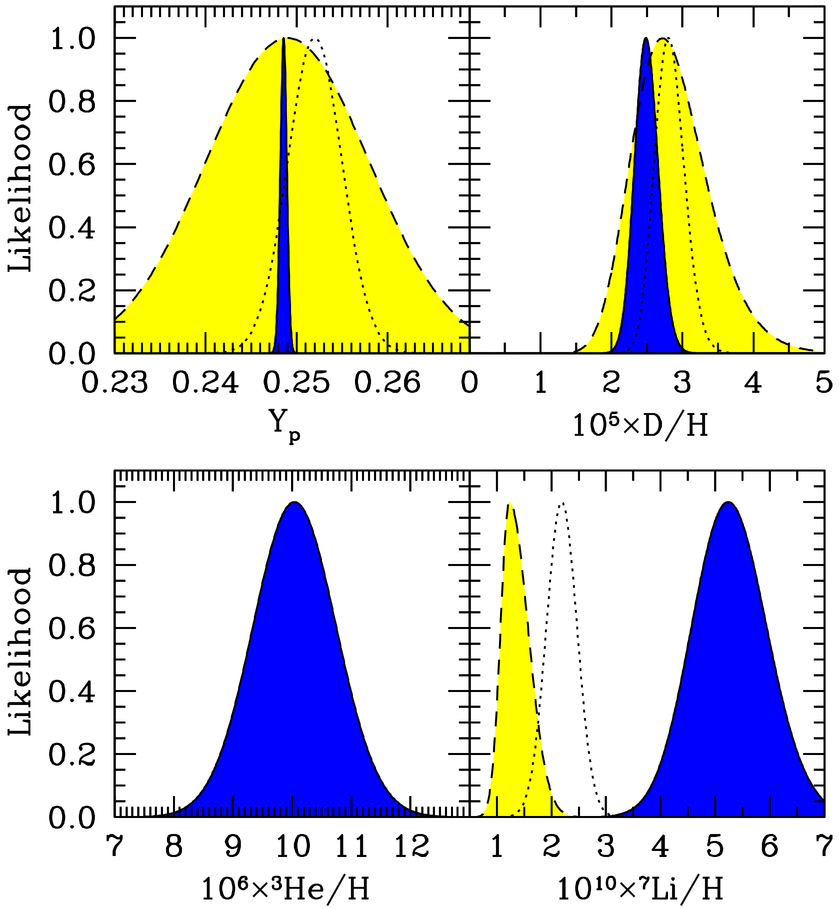
The standard BBN model at $\Omega_b h^2 \approx 0.02273$



SBBN: A one parameter model



Cyburt *et al.* 08



with WMAP $\Omega_b h^2$

overconstrained

→ consistency checks

possible

"Historical" Perspective

BBN had been the main argument for the existence of *non-baryonic* dark matter !!!

II. Modified Expansion Rate during BBN

Constraints on the Expansion Rate at $T \approx 1$ MeV

BBN essentially incorporates all neutrons left-over at $T \approx 80$ keV into $^4\mathrm{He}$

$$Y_p \approx \frac{2(\frac{n_n}{n_p})_{80\mathrm{keV}}}{1+(\frac{n_n}{n_p})_{80\mathrm{keV}}}$$

$$\left(\frac{n_n}{n_p}\right)_{80\mathrm{keV}} \approx \exp\left(\frac{-(m_n-m_p)}{T_f}\right)\left(1-\frac{t_{T_f\to 80\mathrm{keV}}}{\tau_n}\right)$$

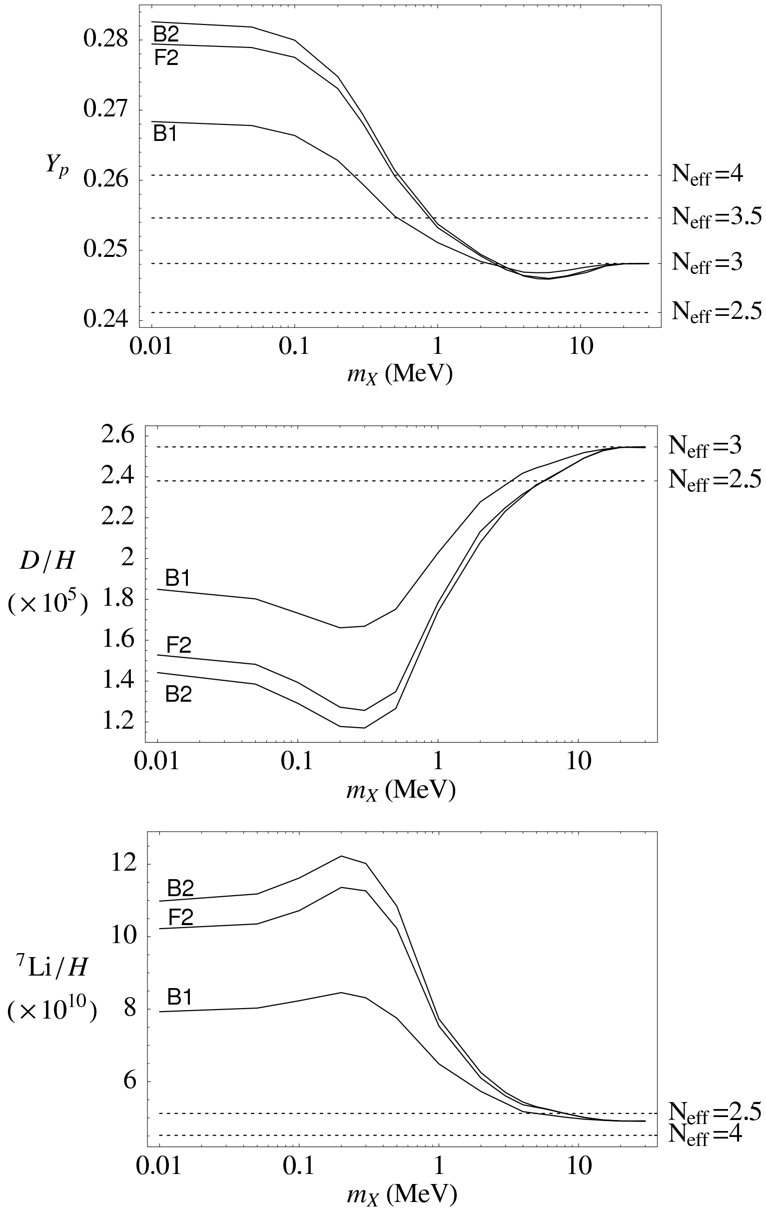
$$T_f: \quad n_{e,\nu}\langle\sigma v\rangle_{weak} = H$$

$\rightarrow$ strong constraints on extra energy density (extra particles, gravitational waves, magnetic fields, scalar fields) and modification of general relativity

$\delta H/H$ should not be larger than $5-10\%$

Constraints on MeV - Dark Matter

Serpico & Raffelt 04



III. Particle Decays/Annihilations during/after BBN

BBN with decaying particles: Hadronic versus Electromagnetic

injection of energetic nucleons and mesons

- charge exchange reactions
  $\pi^- + p \to \pi^0 + n$
- elastic- and inelastic scatterings
  $p + p \to p(n) + (p)n + \pi$'s
- spallation reactions
  $p(n) + {}^4\mathrm{He} \to {}^3\mathrm{H}, {}^3\mathrm{He}, {}^2\mathrm{H} + \ldots.$
- Coulomb stopping of charged nuclei
  ${}^3\mathrm{H} + e^\pm \to {}^3\mathrm{H}' + e^\pm$

Hadronic Effects:
$t \gtrsim 0.1$ sec;
$T \lesssim 3$ MeV

injection of energetic photons and electrons/positrons

- pair production on CMBR
  $\gamma + \gamma_{\mathrm{CMBR}} \to e^- + e^+$
- inverse Compton scattering
  $e^\pm + \gamma_{\mathrm{CMBR}} \to e^\pm + \gamma$
- Bethe-Heitler scattering
  $\gamma + p \to p + e^- + e^+$
- photodisintegration $\gamma + {}^4\mathrm{He} \to {}^3\mathrm{H} + p$

Electromagnetic Effects:
$t \gtrsim 10^5$ sec;
$T \lesssim 3$ keV

No.	Reaction	Channel	Ref.
1	$p + e^{\pm} \to$ elastic	Coulomb	App. D.1.a
2	$p\,(N) + \gamma_{\mathrm{CMBR}} \to$	Thomson	App. D.1.b
3	$n + e^{\pm} \to$	magnetic moment	App. D.1.c
4	$\gamma + \gamma_{\mathrm{CMBR}} \to$	$e^- + e^+$	App. D.2
5	$e^{\pm} + \gamma_{\mathrm{CMBR}} \to$	inverse Compton	App. D.2, D.2.b
6	$\gamma + p(^4\mathrm{He}) \to$	$p(^4\mathrm{He}) + e^- + e^+$	App. D.2.a
7	$\gamma + e^- \to$	Compton	App. D.2.c
8	$\gamma + \gamma_{\mathrm{CMBR}} \to$	$\gamma + \gamma$	App. D.2.d
9	$\gamma + {}^2\mathrm{H} \to$	$p + n$	[36]
10	$\gamma + {}^3\mathrm{H} \to$	${}^2\mathrm{H} + n$	[36]
11		$2n + p$	[36]
12	$\gamma + {}^3\mathrm{He} \to$	${}^2\mathrm{H} + p$	[36]
13		$2p + n$	[36]
14	$\gamma + {}^4\mathrm{He} \to$	${}^3\mathrm{H} + p$	[36]
15		${}^3\mathrm{He} + n$	[36, 37]
16		${}^2\mathrm{H} + {}^2\mathrm{H}$	[36]
17		${}^2\mathrm{H} + n + p$	[36]
18	$\gamma + {}^6\mathrm{Li} \to$	${}^4\mathrm{He} + n + p$	[36, 38]
19		${}^3\mathrm{A} + X$	[36]
20	$\gamma + {}^7\mathrm{Li} \to$	${}^4\mathrm{He} + {}^3\mathrm{H}$	[36, 39]
21		${}^6\mathrm{Li} + n$	[36]
22		${}^4\mathrm{He} + 2n + p$	[36]
23		${}^4\mathrm{He} + {}^2\mathrm{H} + n$	App. D.3
24		${}^6\mathrm{He} + p \to {}^6\mathrm{Li} + p$	App. D.3
25		$2\,{}^3\mathrm{H} + p$	App. D.3
26		${}^3\mathrm{H} + {}^3\mathrm{He} + n$	App. D.3
27	$\gamma + {}^7\mathrm{Be} \to$	${}^4\mathrm{He} + {}^3\mathrm{He}$	[36, 43]
28		${}^6\mathrm{Li} + p$	[36]
29		${}^4\mathrm{He} + 2p + n$	[36]
30		${}^4\mathrm{He} + {}^2\mathrm{H} + p$	App. D.3
31		${}^6\mathrm{Be} + n \to {}^4\mathrm{He} + 2p + n$	App. D.3
32		$2\,{}^3\mathrm{He} + n$	App. D.3
33		${}^3\mathrm{H} + {}^3\mathrm{He} + p$	App. D.3
34	$\pi^+ + n \to$	$\pi^0(\gamma) + p$	[15], App. E.1
35	$\pi^- + p \to$	$\pi^0(\gamma) + n$	[15], App. E.1
36	$K^- + n \to$	$p + X$	[15], App. E.1
37		$n + X$	[15], App. E.1
38	$K^- + p \to$	$n + X$	[15], App. E.1
39		$p + X$	[15], App. E.1
40	$K_L + n \to$	$p + X$	[15], App. E.1
41		$n + X$	[15], App. E.1
42	$K_L + p \to$	$n + X$	[15], App. E.1
43		$p + X$	[15], App. E.1
44	$\bar{p} + p \to$	π's	[15], App. E.2
45	$\bar{n} + p \to$	π's	[15], App. E.2
46	$\bar{p} + n \to$	π's	[15], App. E.2
47	$\bar{n} + n \to$	π's	[15], App. E.2
48	$p + p \to$	elastic	[44, 45], App.E.3
49	$p + {}^4\mathrm{He} \to$	elastic	[44], App.E.3
50	$n + p \to$	elastic	[44, 45], App.E.3
51	$n + {}^4\mathrm{He} \to$	elastic	[44], App.E.3
52	$p + p \to$	$p + p + \pi^0$	[46], App. E.4
53		$n + p + \pi^+$	[46, 47], App. E.4
54		${}^2\mathrm{H} + \pi^+$	[46, 47], App. E.4
55		$p + p + \pi^+\pi^-$	[46], App. E.4
56		${}^2\mathrm{H} + \pi^+\pi^0$	[46], App. E.4
57		${}^2\mathrm{H} + 2\pi^+\pi^-$	[46], App. E.4
58		$p + p + \pi^+\pi^-\pi^0$	[46], App. E.4
59		$n + p + 2\pi^+\pi^-$	[46], App. E.4
60		$p + p + 2\pi^0 + (\pi^0 s)$	[46, 47], App. E.4
61		$n + n + 2\pi^+ + (\pi^0 s)$	[46], App. E.4
62		$n + p + \pi^+ + (\pi^0 s)$	[46, 47], App. E.4
63	$n + p \to$	$p + n + \pi^0 + (\pi^0 s)$	[46], App. E.4
64		${}^2\mathrm{H} + \pi^0 + (\pi^0 s)$	[46], App. E.4
65		$p + p + \pi^-$	[46], App. E.4
66		$n + n + \pi^+$	[46], App. E.4
67		$n + p + \pi^-\pi^+$	[46, 47], App. E.4
68		$p + p + \pi^-\pi^0 + (\pi^0 s)$	[46], App. E.4
69		${}^2\mathrm{H} + \pi^-\pi^+$	[46], App. E.4
70		$n + n + \pi^+ + (\pi^0 s)$	[46, 47], App. E.4
71		$n + p + 2\pi^- 2\pi^+$	[46], App. E.4
72		$n + p + \pi^-\pi^+\pi^0$	[46], App. E.4
73		$p + p + 2\pi^-\pi^+$	[46], App. E.4
74	$p + {}^4\mathrm{He} \to$	${}^3\mathrm{H} + 2p + (\pi s)$	App. E.5,E.6
75		${}^3\mathrm{He} + n + p + (\pi s)$	App. E.5,E.6
76		${}^2\mathrm{H} + 2p + n + (\pi s)$	App. E.5
77		${}^3\mathrm{He} + {}^2\mathrm{H}$	App. E.5,E.6
78		${}^2\mathrm{H} + {}^2\mathrm{H} + p + (\pi s)$	App. E.5
79	$n + {}^4\mathrm{He} \to$	${}^3\mathrm{He} + 2n + (\pi s)$	App. E.5,E.6
80		${}^3\mathrm{H} + n + p + (\pi s)$	App. E.5,E.6
81		${}^2\mathrm{H} + 2n + p + (\pi s)$	App. E.5
82		${}^3\mathrm{H} + {}^2\mathrm{H}$	App. E.5,E.6
83		${}^2\mathrm{H} + {}^2\mathrm{H} + n + (\pi s)$	App E.5
84	$p + {}^6\mathrm{Li} \to$	${}^3\mathrm{He} + {}^4\mathrm{He}$	App. E.5
85	${}^3\mathrm{H} + {}^4\mathrm{He} \to$	${}^6\mathrm{Li} + n$	App. E.6
86	${}^3\mathrm{He} + {}^4\mathrm{He} \to$	${}^6\mathrm{Li} + p$	App. E.6
87	${}^4\mathrm{He} + {}^4\mathrm{He} \to$	${}^6\mathrm{Li} + {}^2\mathrm{H}\,({}^6\mathrm{Li} + p + n)$	App. E.6
88		${}^7\mathrm{Li} + p\,({}^7\mathrm{Be} + n)$	App. E.6
89	${}^3\mathrm{He} + p \to$	elastic	App. E.6
90	${}^3\mathrm{H} + p \to$	${}^3\mathrm{He} + n$	App.E.6
91	${}^3\mathrm{H} + p \to$	elastic	App. E.6
92	${}^3\mathrm{H} \to$	${}^3\mathrm{He} + e^- + \bar{\nu_e}$	[58], App.E.6
93	${}^7\mathrm{Be} + e^- \to$	${}^7\mathrm{Li} + \nu_e$	[58]

The Physics behind the Main Constraints

Overproduction of ...

- ^{4}He : $0.1\text{sec} \lesssim t \lesssim 10^2\text{sec}$

  $\pi^- + p \to \pi^0 + n$ injection of extra neutrons/antinucleons

- ^{2}H : $10^2\text{sec} \lesssim t \lesssim 3 \times 10^3\text{sec}$

  $n + p \to {}^2\text{H} + \gamma$, $N + {}^4\text{He} \to {}^2\text{H} + \ldots$ injection of extra neutrons/energetic nucleons

- ^{6}Li : $3 \times 10^3\text{sec} \lesssim t \lesssim 10^7\text{sec}$

  $N + {}^4\text{He} \to {}^3\text{H} + \ldots$, ${}^3\text{H} + {}^4\text{He} \to {}^6\text{Li} + n$ injection of energetic nucleons

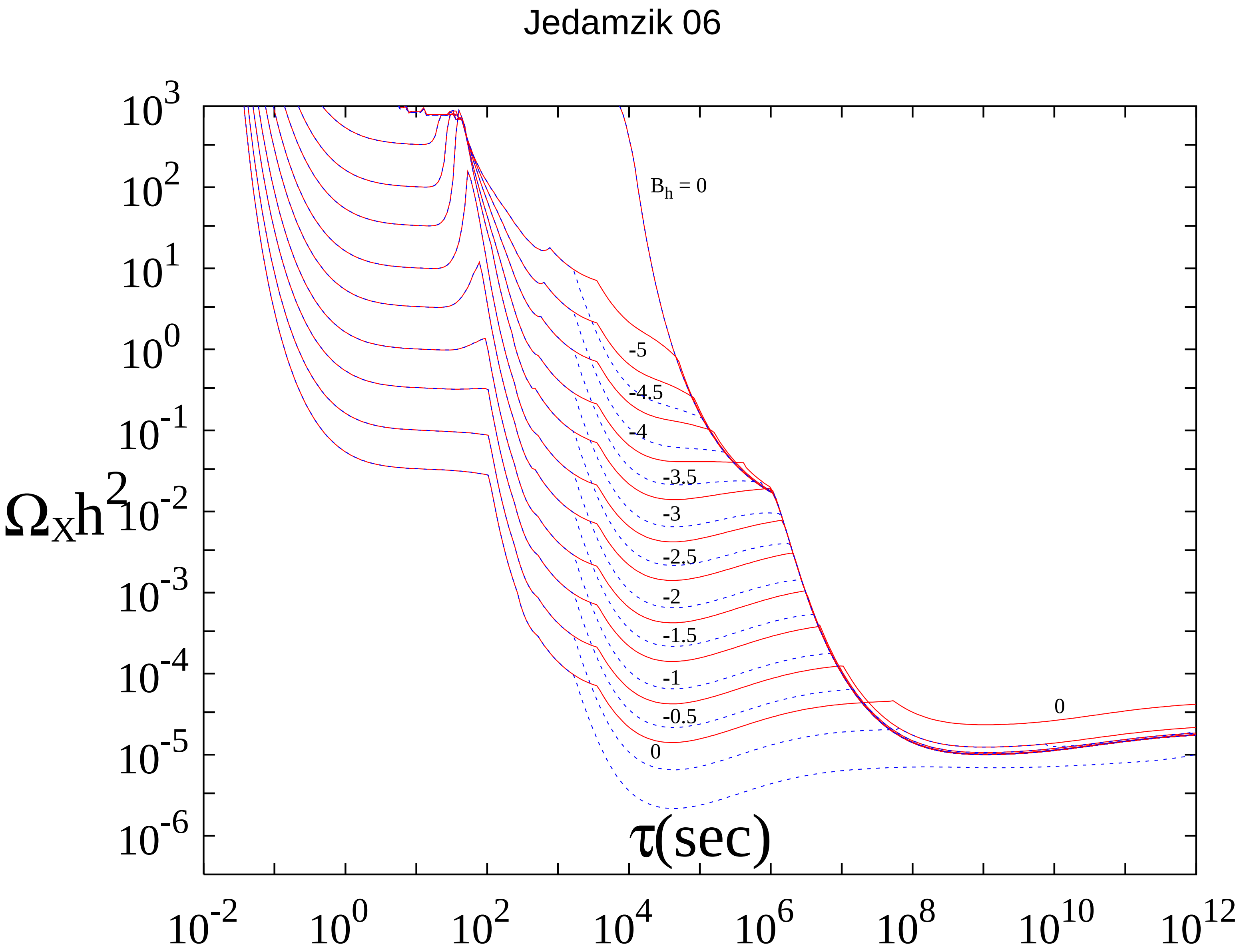
- ^{3}He/^{2}H : $t \gtrsim 10^7\text{sec}$

  $\gamma + {}^4\text{He} \to {}^3\text{He} + \ldots$ injection of γ-rays and energetic $e^\pm$

Helium-3/D Limit IS Secure

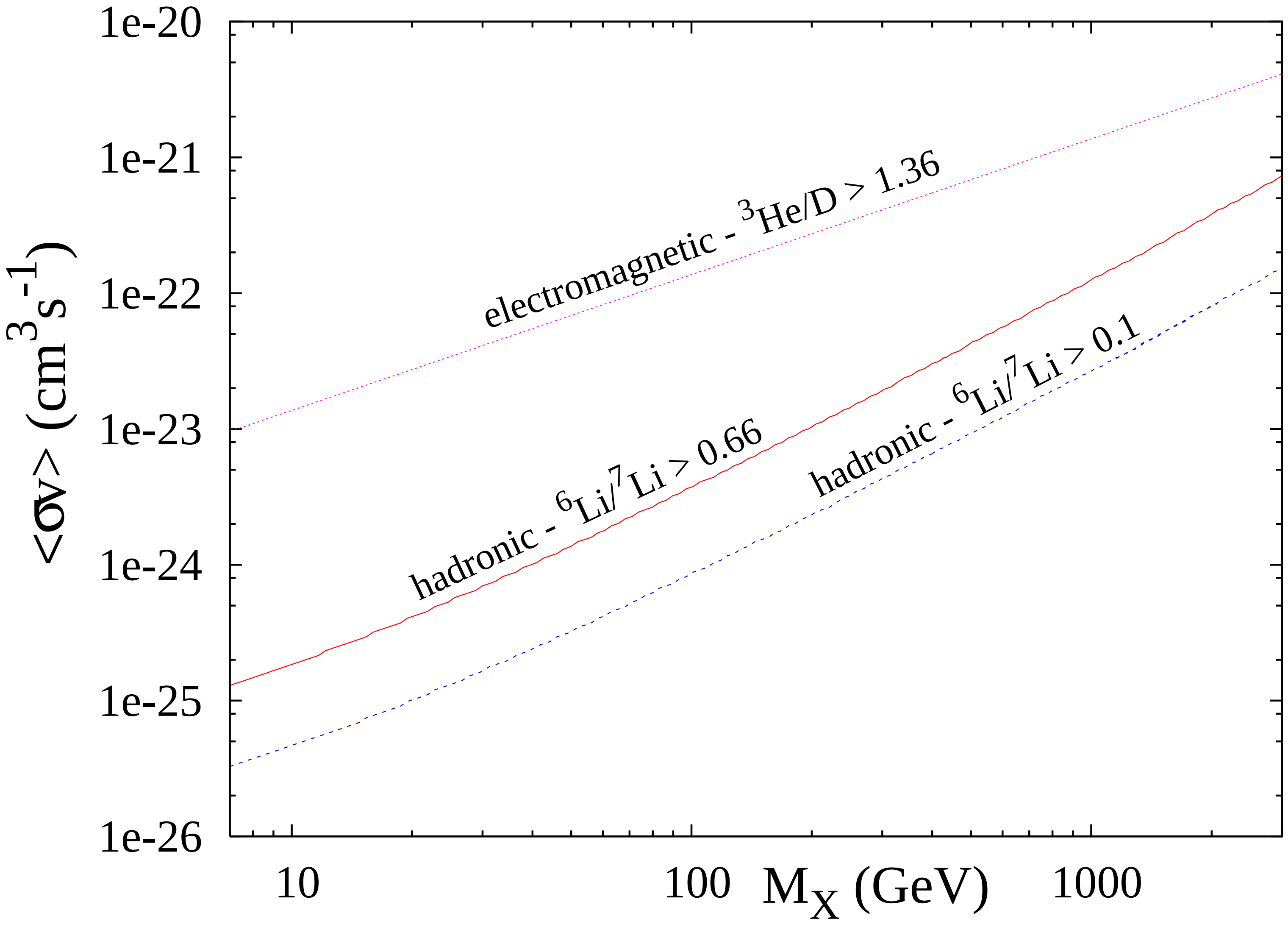
$^3\mathrm{He}$/D $\lesssim 1.5$ for solar system Geiss & Gloeckner 07 is secure and useful in constraing non-standard BBN Sigl *et al.* 96

Decay of Relic Particle



Annihilation of Relic Particle

Jedamzik 04, K.J. & Pospelov 09



IV. Weak Mass Scale *Charged* Particles during BBN

Formation of nuclei-X^- bound states during BBN

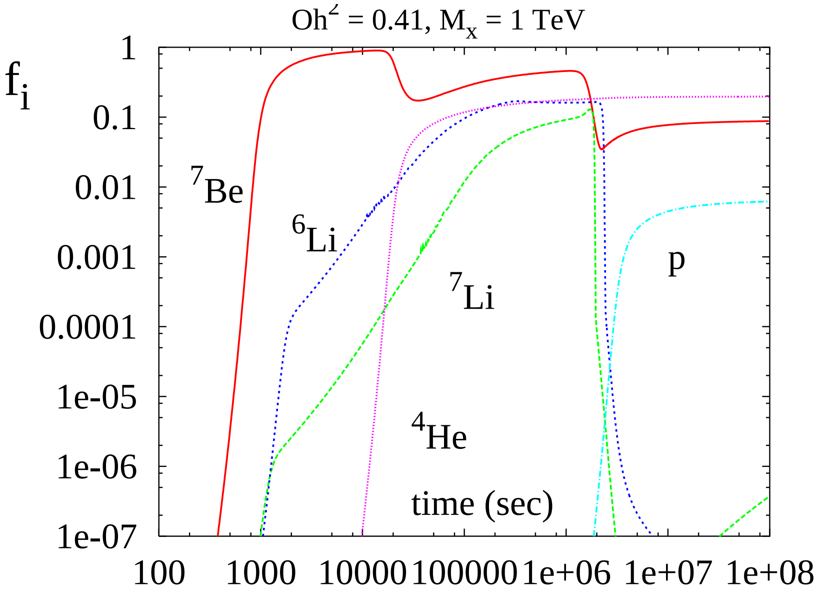
negatively charged weak mass scale particles X^- during BBN $\rightarrow$

formation of bound states with nuclei

$^7\mathrm{Be} + X^- \rightarrow (^7\mathrm{Be}X^-) + \gamma$ at ≈ 30 keV
$^4\mathrm{He} + X^- \rightarrow (^4\mathrm{He}X^-) + \gamma$, at ≈ 10 keV

$$E_b = \frac{Z_N^2 \alpha^2 m_N}{2} \qquad r_{Bohr} = \frac{1}{\alpha Z_N m_N}$$

Pospelov 06, Kohri & Takayama 06, Kaplinghat & Rajaraman 06, Cyburt *et al* 06

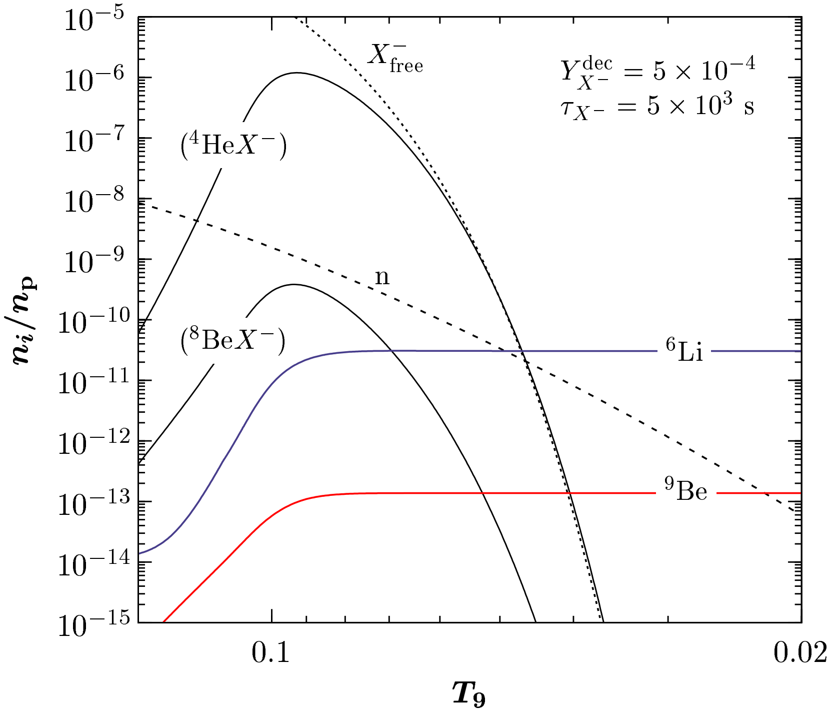


Catalysis of nuclear reactions due to bound states

Pospelov 06,07; Hamaguchi *et al. 07*; Bird *et al. 07*; Kamimura *et al.* 08

X^- acts as catalysator for reactions

$(^4\mathrm{He}X^-) + \mathrm{D} \rightarrow {}^6\mathrm{Li} + X^-$
$(^4\mathrm{He}X^-) + {}^4\mathrm{He} \rightarrow (^8\mathrm{Be}X^-) + \gamma;$
$(^8\mathrm{Be}X^-) + n \rightarrow {}^9\mathrm{Be} + X^-$



important when $B_h \lesssim 10^{-2}$ as with supersymmetric stau !

Catalysis and the abundances of $^6\mathrm{Li}$**,** $^7\mathrm{Li}$**, and** $^7\mathrm{Be}$

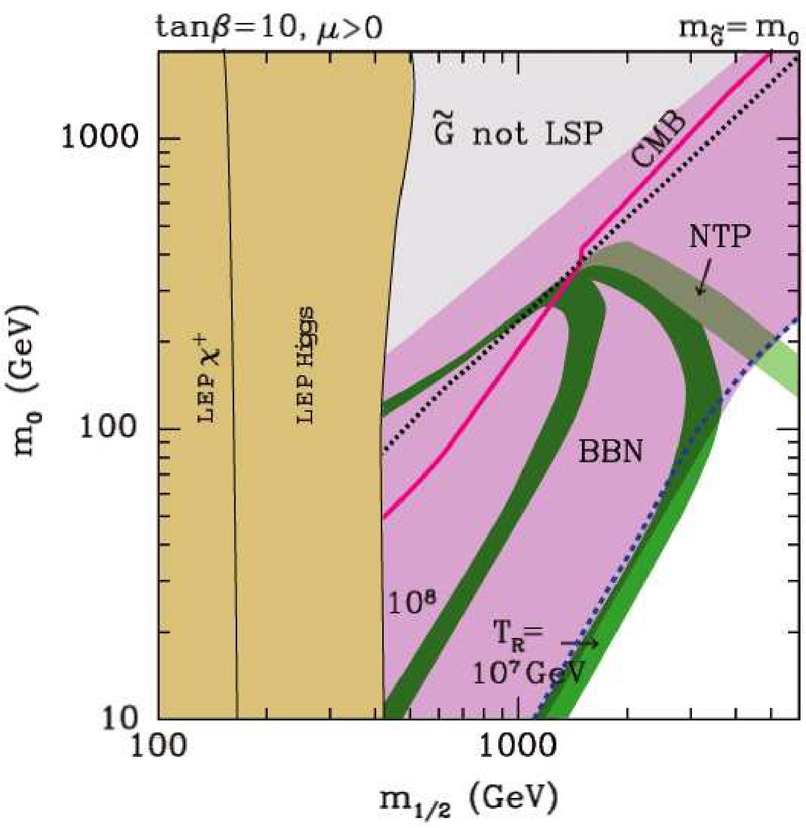
Catalysis:

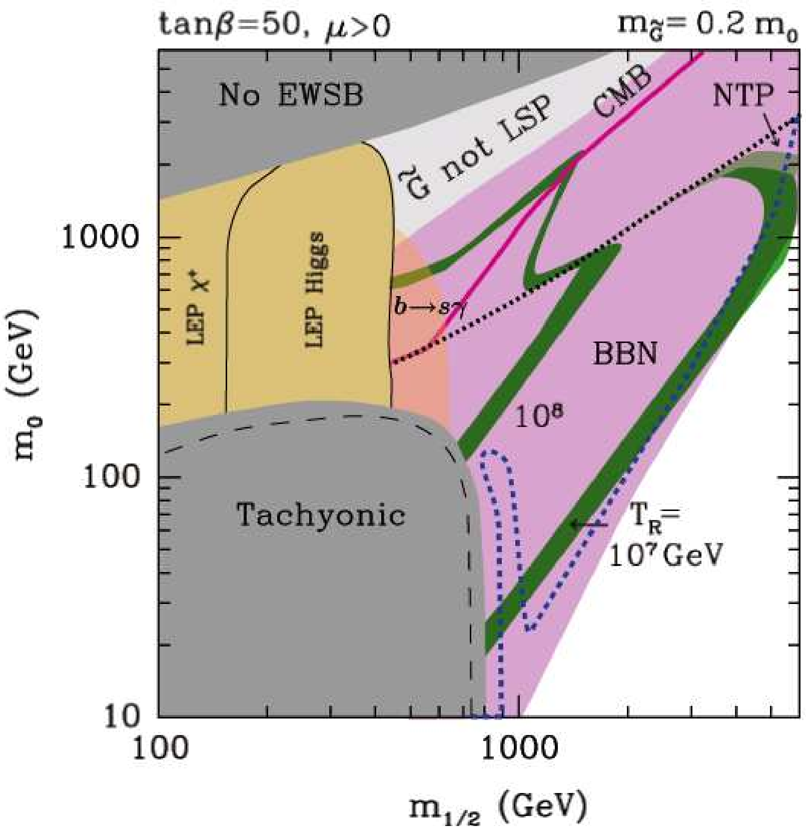
- main production mechanism for $^6\mathrm{Li}$ if $B_h \lesssim 10^{-2}$
- may **not** solve the $^7\mathrm{Li}$ problem, unless $B_h \lesssim 10^{-5}$ rather small and $\Omega_X \gtrsim 10$ rather large
- not clear if may lead to some $^9\mathrm{Be}$ production

V. Constraints on SUSY with gravitino LSPs

The MSSM and gravitino LSPs

Choi *et al* 04; Cerdeno *et al* 06, Bailly *et al* 09

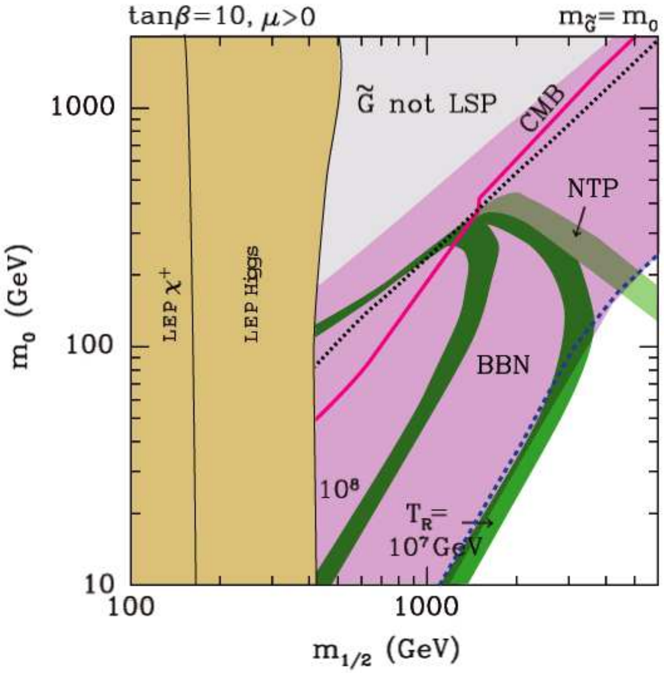


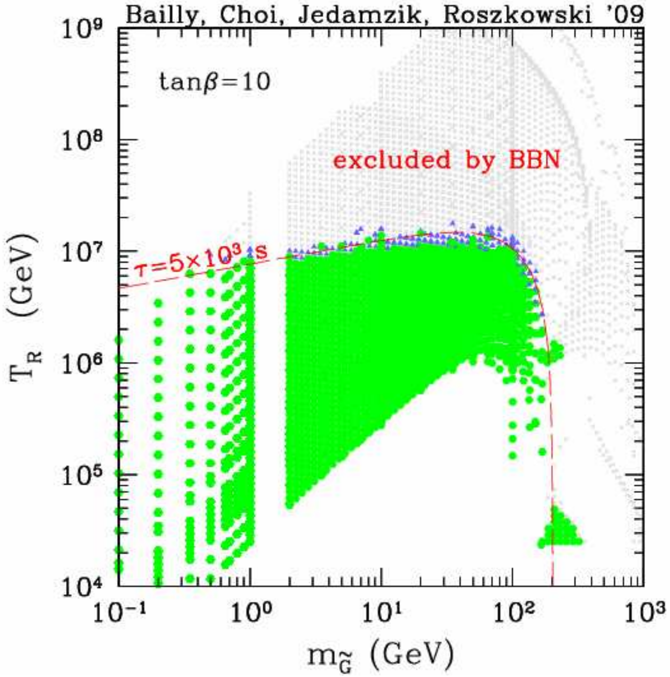


Supersymmetry, BBN, and T_{rh}

gravitino not LSP → T_{rh} must be low to avoid too many decays of thermally produced gravitinos during BBN

gravitino LSP → NLSP decays dangerous unless $\tau \lesssim 5 \times 10^3$sec → gravitino LSP somewhat lighter than weak scale → reheat temperature must be low

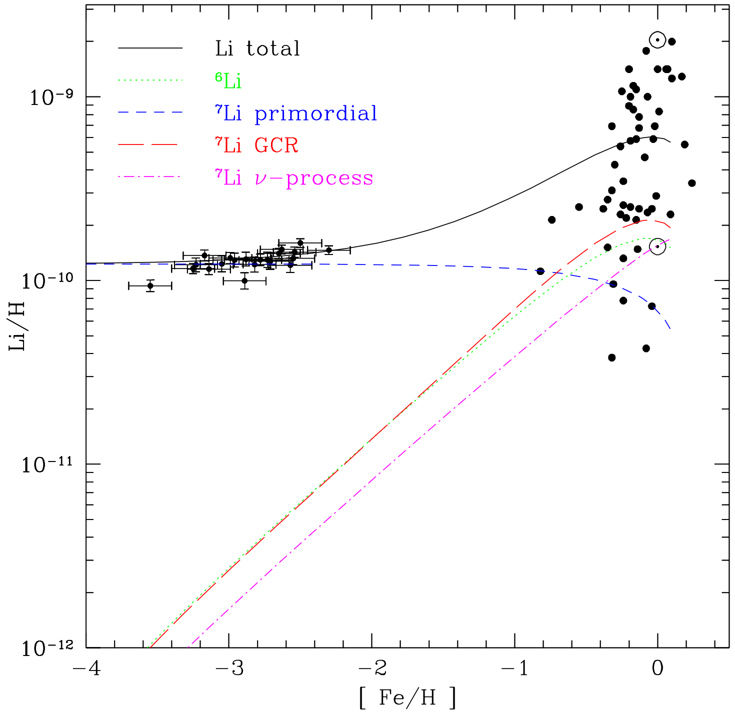


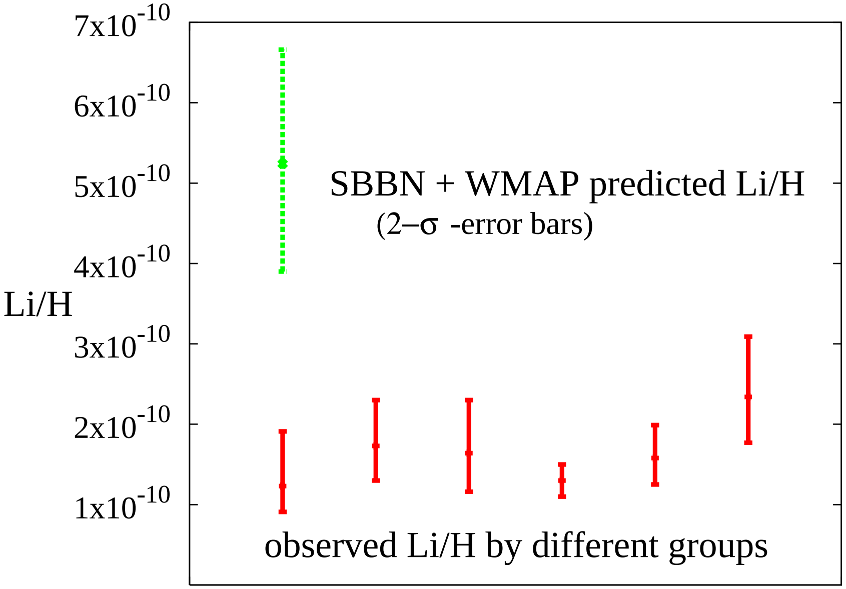


→ supergravity and thermal leptogenesis (in most cases) incompatible

VI. The Lithium Anomalies

The ^{7}Li Spite plateau 1982-2009

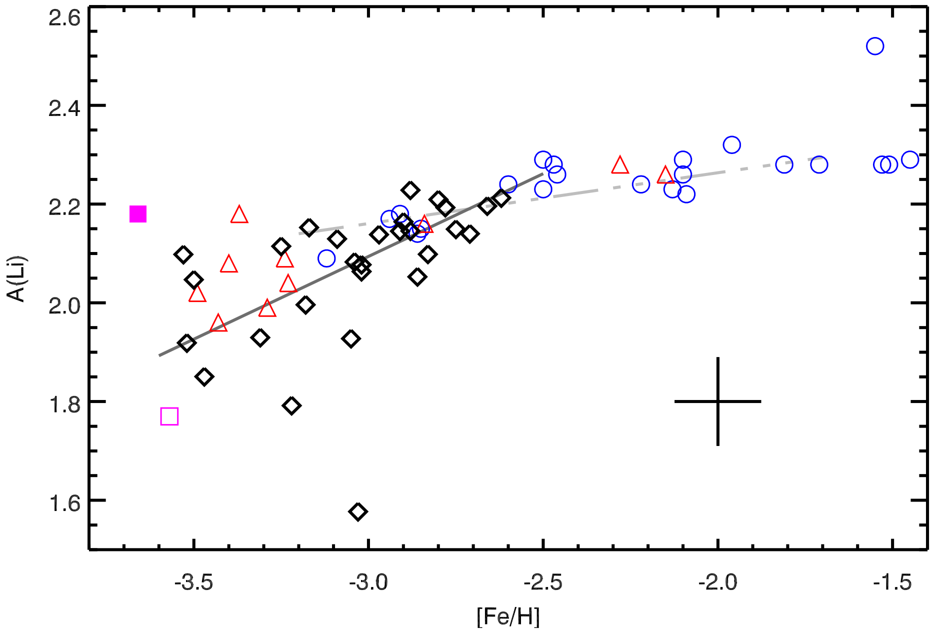




Spite & Spite 82, Bonifacio & Molaro 97, Ryan *et al* 99, Melendez Ramirez 04, Charbonnel & Primas 05, Asplund *et al* 06

- (almost) no variation with metallicity and stellar temperature
- no measurable star-to-star scatter
- Interpretation - the Primordial ^{7}Li Abundance

The ^{7}Li Spite plateau in 2010



Sbordone *et al.* 10, Asplund *et al.*, Aoki *et al.*

- well defined upper envelope - plateau
- no measurable star-to-star scatter at metallicities $[Z]\gtrsim-2.7$
- absence of stars with $^7\mathrm{Li}$/H above plateau

Depletion of Lithium in PopII stars ?

$^7\mathrm{Li}$ is observed in the atmospheres of PopII stars
it may be destroyed via $^7\mathrm{Li}{+}p \rightarrow {}^4\mathrm{He}$ + $^4\mathrm{He}$ in the interieur of the star

atmospheric material transported into the star and $^7\mathrm{Li}$-depleted gas returned to the atmosphere

Spite plateau not primordial ?

Depletion of $^7\mathrm{Li}$ by factor $2-5$ in halo stars is not understood and may currently only be explained with fine-tuned stellar conditions

Dispersion ?

Comments in Sbordone *et al*

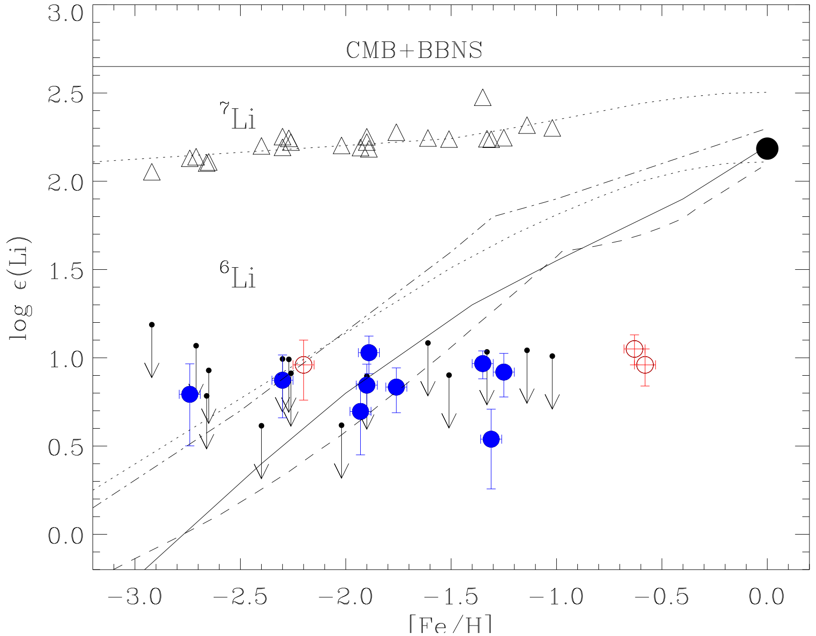
[Fe/H], but with increased scatter at low [Fe/H]. It would also explain why, while the scatter in A(Li) increases at low metallicities, not a single star in this metallicity regime has been found to lie above the Spite plateau level. It would then be consistent

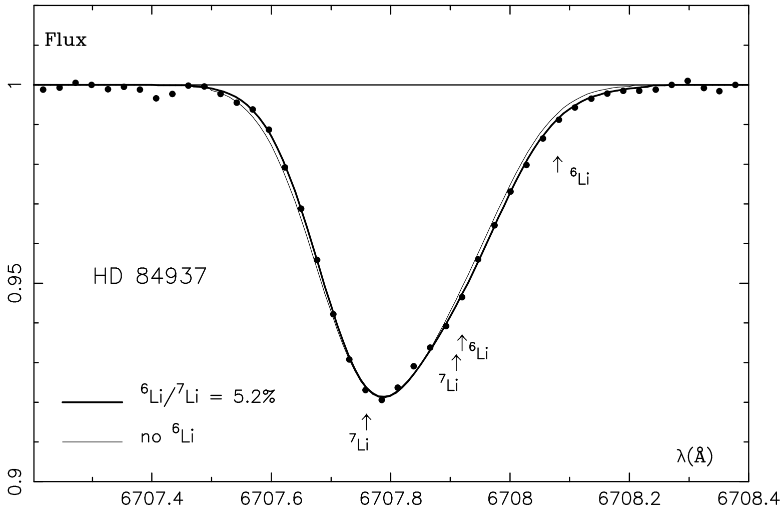
Finally, attributing the extra depletion to atmospheric diffusion / settling would not require a physical "conspiracy" capable to produce exactly the same depletion level regardless of metallicity, stellar rotation, gravity, or effective temperature, as it is often invoked when diffusion is used to explain the Spite plateau.

^{6}Li/H observations

Asplund, Lambert, Nissen, Primas, & Smith

06





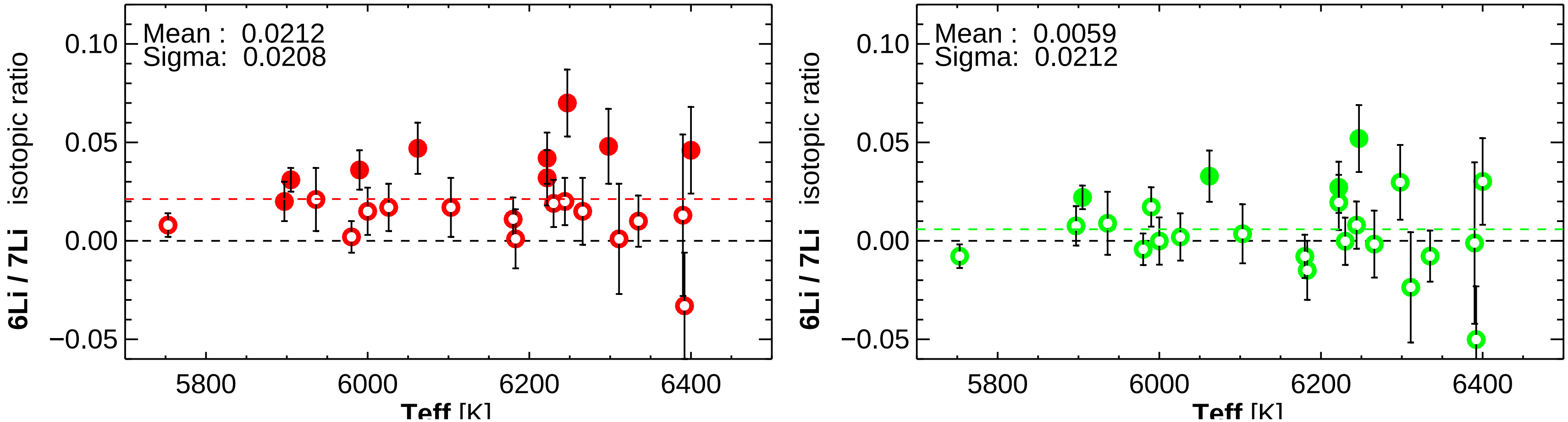
- ^{6}Li and ^{7}Li absorption features blend together
- ^{6}Li from asymmetry of lines
- asymmetry of lines from convective Doppler shifts ?
- non-LTE hydrodynamic simulations of two groups reach somewhat different conclusions

A second Lithium plateau ?

$^6\mathrm{Li}/\mathrm{H} \approx 6 \times 10^{-12}$ compare to standard BBN $^6\mathrm{Li}/\mathrm{H} \sim 10^{-14}$

Are the ^{6}Li detections real ?

Steffen, Cayrel, Bonifacio, Ludwig, & Caffau 09



- fewer (four) $\sim 2\sigma$ detections in Steffen *et al.* compared to (nine) Asplund *et al.*
- however, distribution always skewed towards positive ^{6}Li/H
- a positive ^{6}Li/H detection in HD84937 by four(!) groups

VII. Dark Matter and the Lithium Anomalies

Destruction of $^7\mathrm{Li}$ during BBN due to injection of neutrons

K.J. 04

$^7\mathrm{Li}$ 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

need only 10^{-5} extra neutrons per baryon

some extra $^2\mathrm{H}$ will be also synthesized

→ possible by decay/annihilation of relic particles or evaporation of defects

Production of $^6\mathrm{Li}$ in cascade nucleosynthesis

$^6\mathrm{Li}$ is very easily produced by small "perturbations" of the standard model Dimopoulos *et al.* 88, K.J. 00

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:

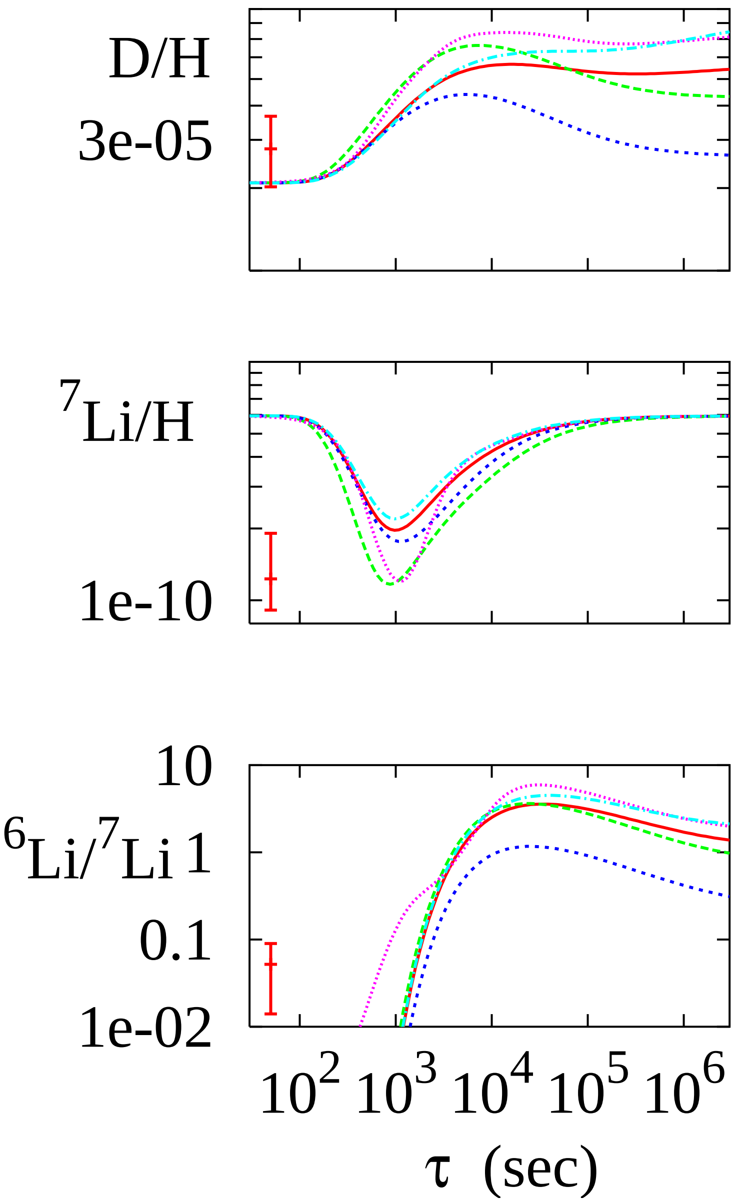
$$n + {}^4\mathrm{He} \rightarrow {}^3\mathrm{H} + p + n$$

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

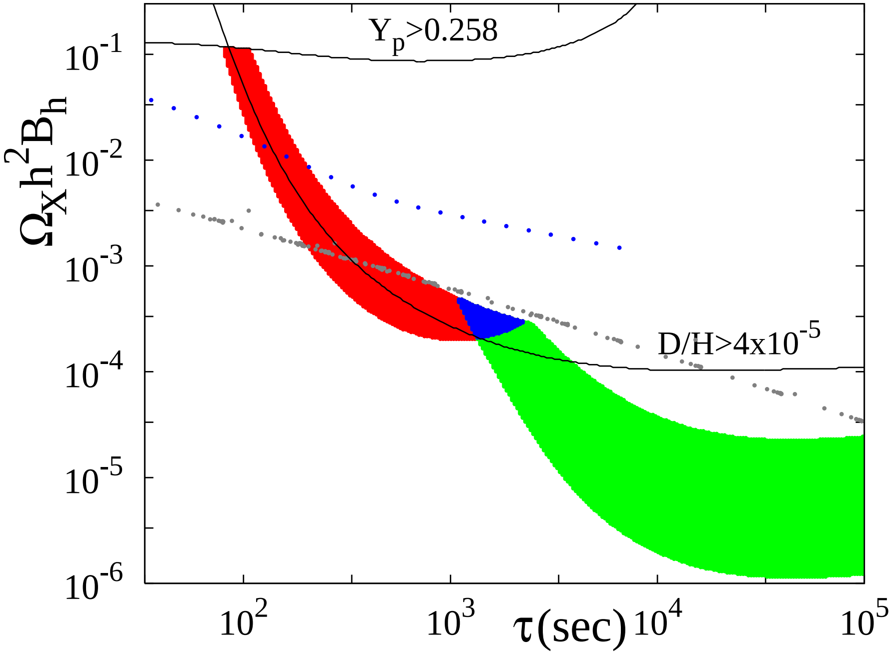
at $T \lesssim 10$ keV

Solutions to the lithium problems through relic particle decay

K.J. 04



Bailly, K.J., Moultaka 08



Signatures at the LHC !

A metastable particle X with life time between $100 - 1000$ sec, **if** not too massive, could be potentially produced at the LHC (since having at least some hadronic interactions), and ...., **if** charged under standard model $U(1)_{\rm EM}$ or $SU(3)$ could be stopped in the detector → smoking gun for non-standard BBN → possible connection to the dark matter

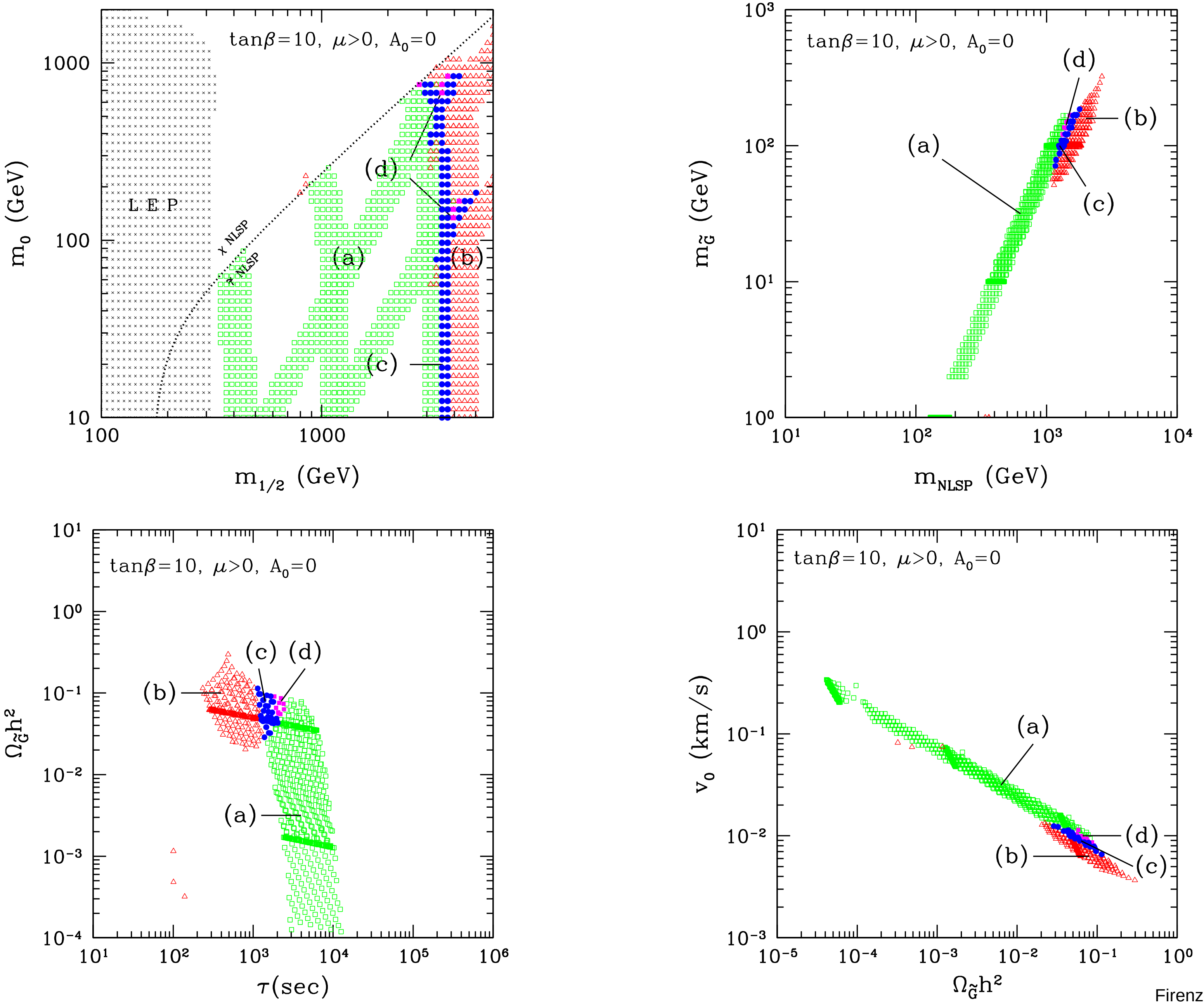
Examples:

Gluino in split supersymmetry

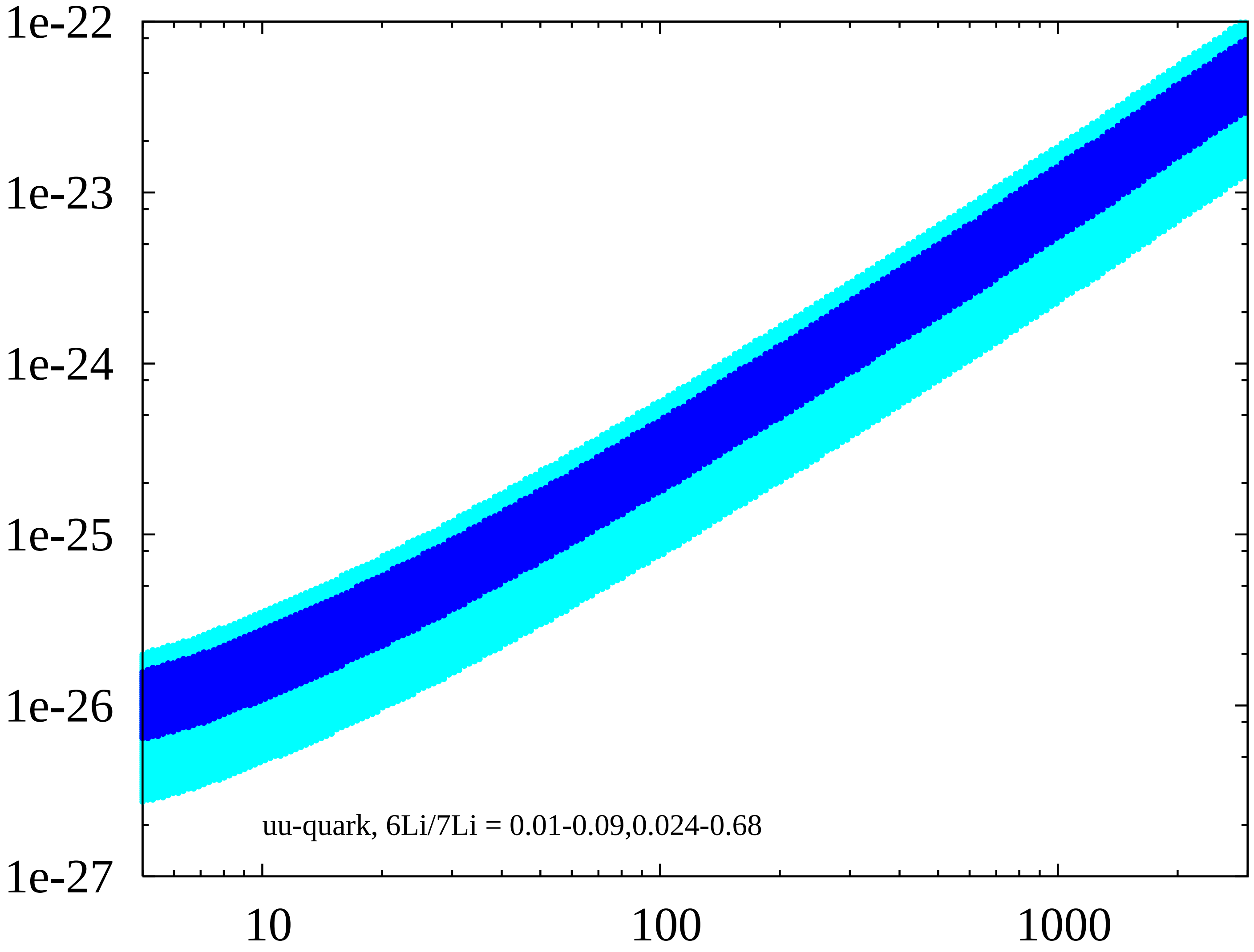
supersymmetric stau Next-to-LSP with gravitino LSP

Example: Gravitino dark matter in the CMSSM

K.J., Choi, Roszkowski, Ruiz de Austri 06



Producing the $^6\mathrm{Li}$ in HD84937 by relic particle annihilation ?



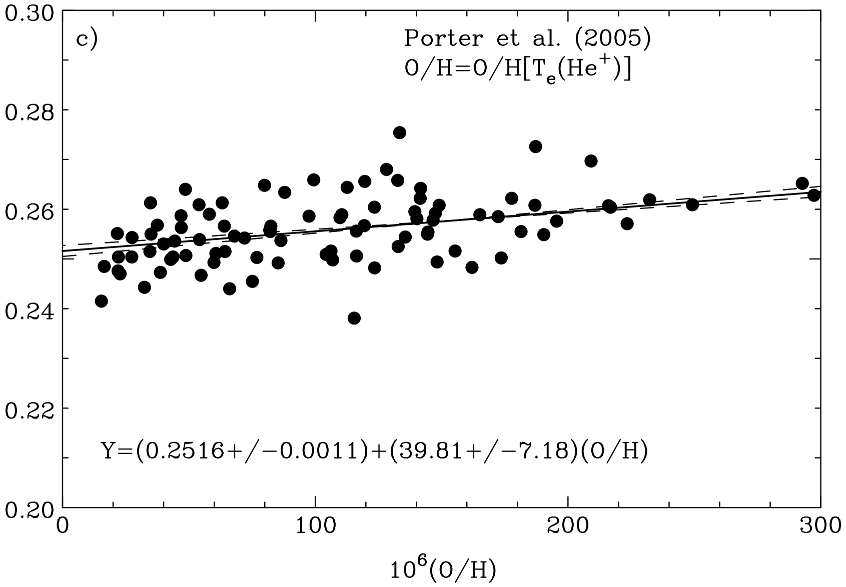
Signatures at the LHC !

if the LHC discovers a light stable neutralino of mass $m \approx 20 - 90\,$GeV and of hadronic annihilation cross section $3 \times 10^{-26}\mathrm{cm}^3\mathrm{s}^{-1}$ as required to explain origin of the dark matter by annihilation freeze-out → explanation of all the $^6\mathrm{Li}$ as claimed to exist in HD84937

Conclusions

- the by standard BBN at η_{WMAP} predicted D (and $^4\mathrm{He}$) are in good agreement with those observed
- in contrast, there is a factor 3-4 discrepancy between SBBN predicted and observationally inferred $^7\mathrm{Li}$
- this discrepancy could possibly be removed if $^7\mathrm{Li}$ is destroyed in Pop II stars, though how this is done exactly is not understood
- alternatively BBN could have been non-standard, e.g. including the decay of a relic particle $\longrightarrow$ potentially testable at the LHC
- observations of the existence of a $^6\mathrm{Li}$ plateau (similiar to the $^7\mathrm{Li}$ Spite plateau) are currently controversial
- BBN continues to be a powerful probe of the early Universe and physics beyond the standard model

Helium-4 from low-metallicity extragalactic HII regions



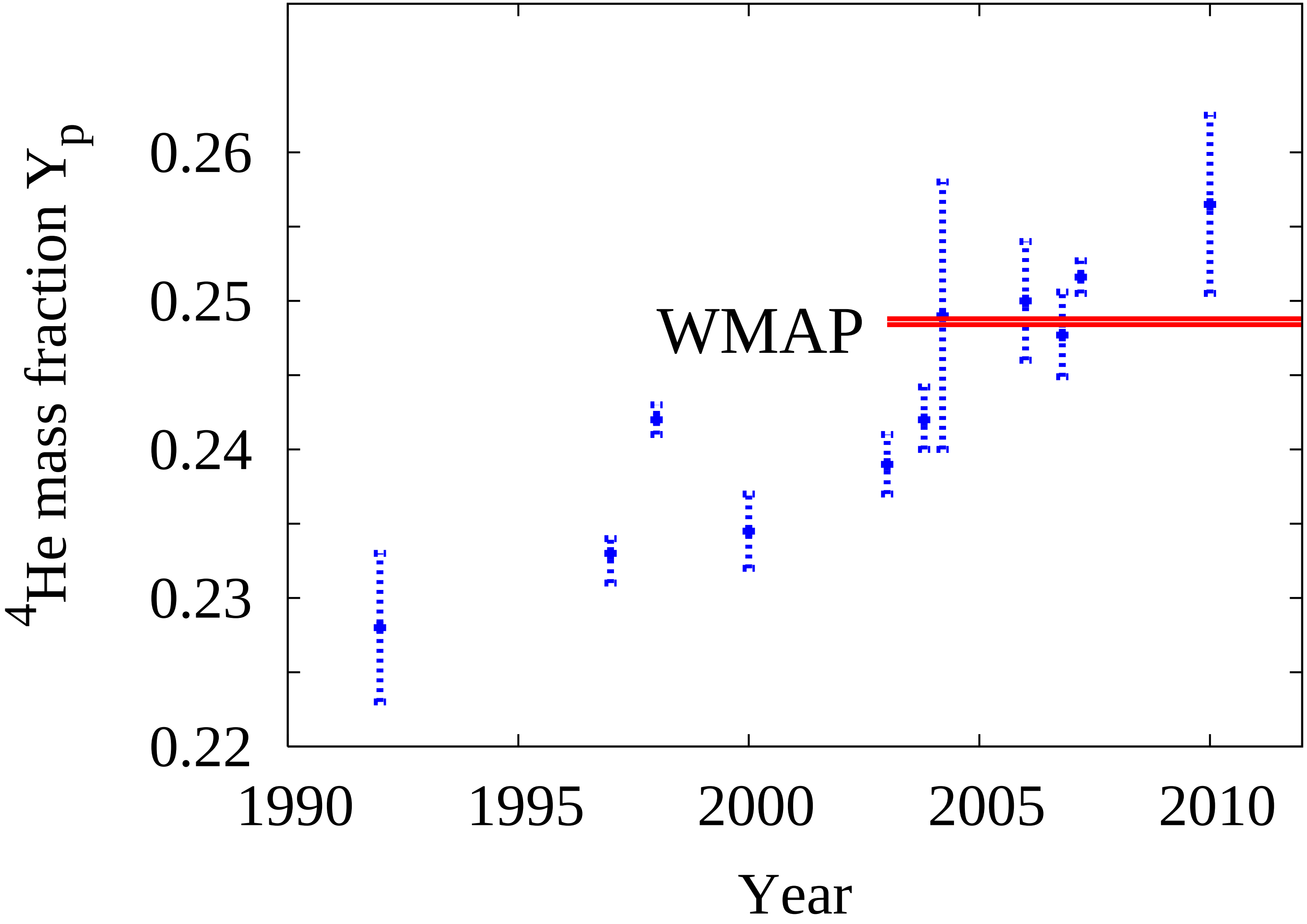
systematic uncertainties

- atomic emissivities (changed Y_p by +0.008 !)
- temperature variations
- ionisation corrections
- underlying stellar absorption

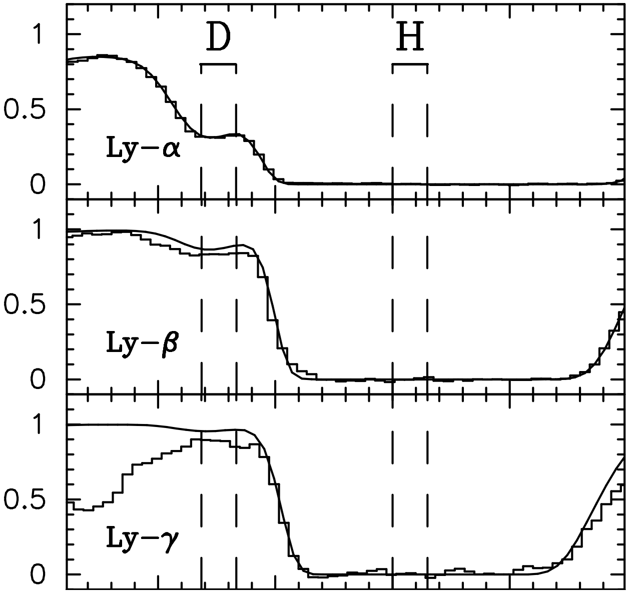
$Y_p = 0.2477 \pm 0.0029, 0.2516 \pm 0.0011$ Peimbert it et. al07, Izotov it et. al07

more realistic error bars: $Y_p = 0.249 \pm 0.009$ Olive & Skillman 04

Observational inferred Helium-4 with time

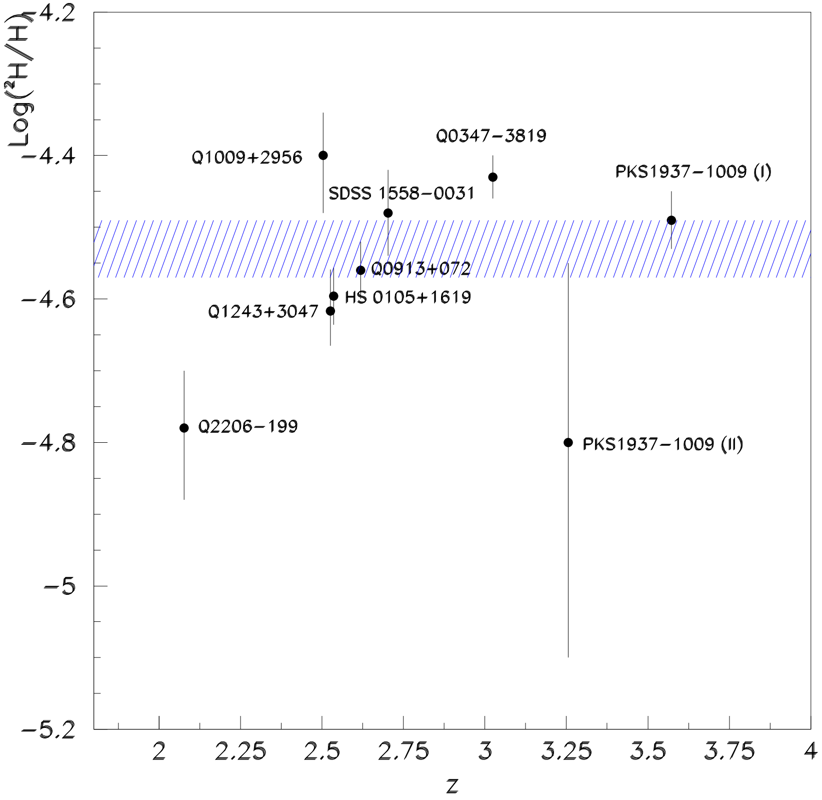


D/H from Quasar Absorption Systems



Tytler,Fan,& Burles 96

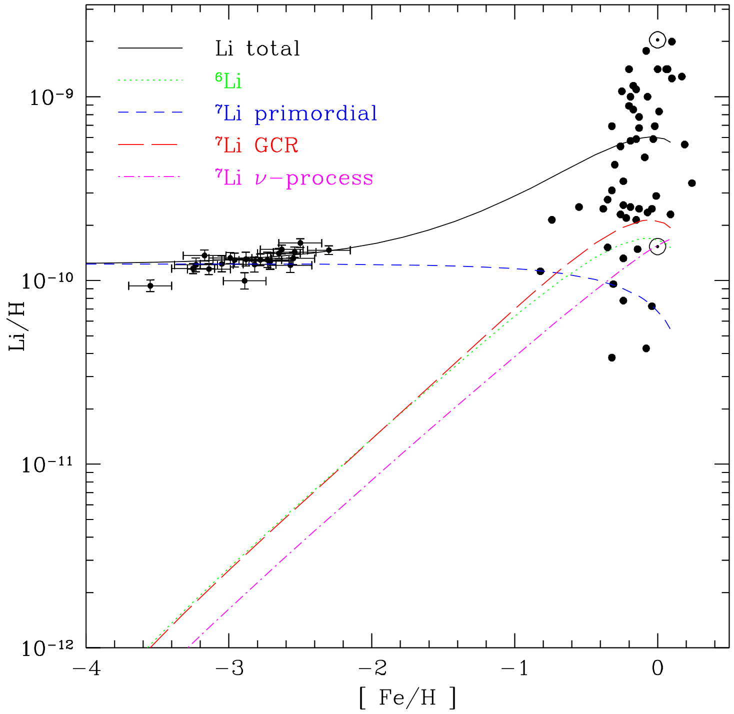
Iocco *et al.* 09

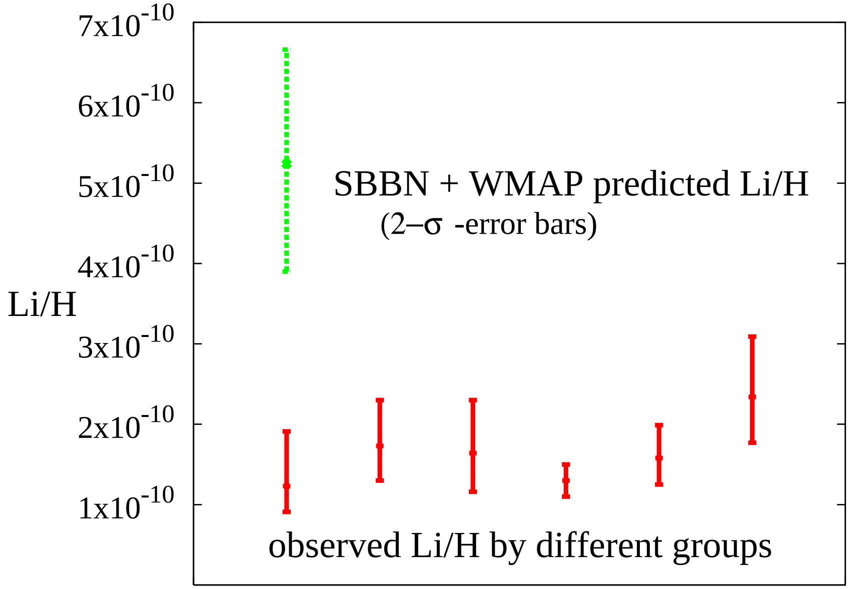


significant dispersion → underestimated systematic errors ?

$$\mathrm{D/H} = 2.98^{+0.29}_{-0.23} \times 10^{-5}$$

The $^{7}\mathrm{Li}$ Spite plateau 1982-2009

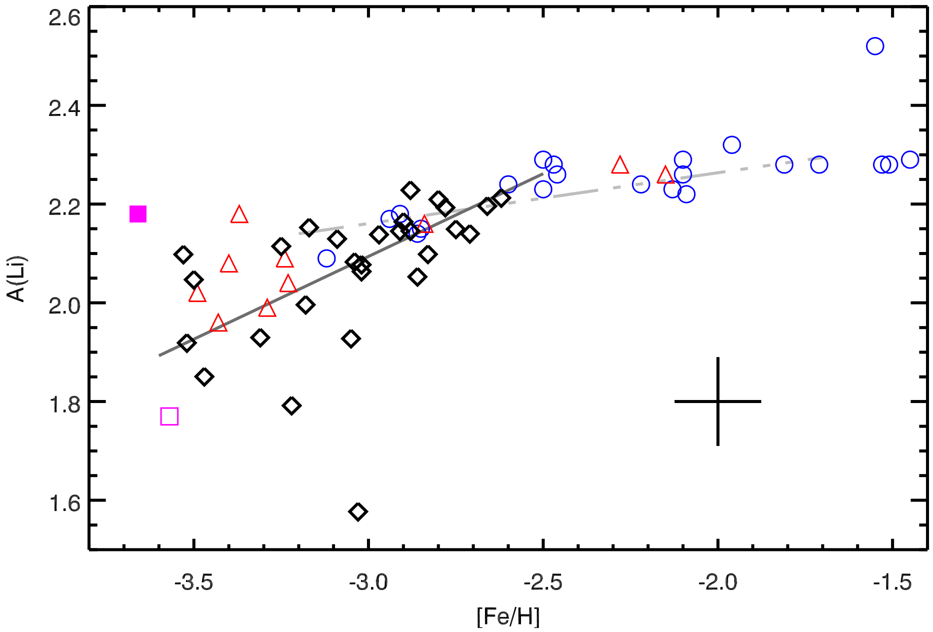




Spite & Spite 82, Bonifacio & Molaro 97, Ryan *et al* 99, Melendez Ramirez 04, Charbonnel & Primas 05, Asplund *et al* 06

- (almost) no variation with metallicity and stellar temperature
- no measurable star-to-star scatter
- Interpretation - the Primordial $^{7}\mathrm{Li}$ Abundance

The ^{7}Li Spite plateau in 2010

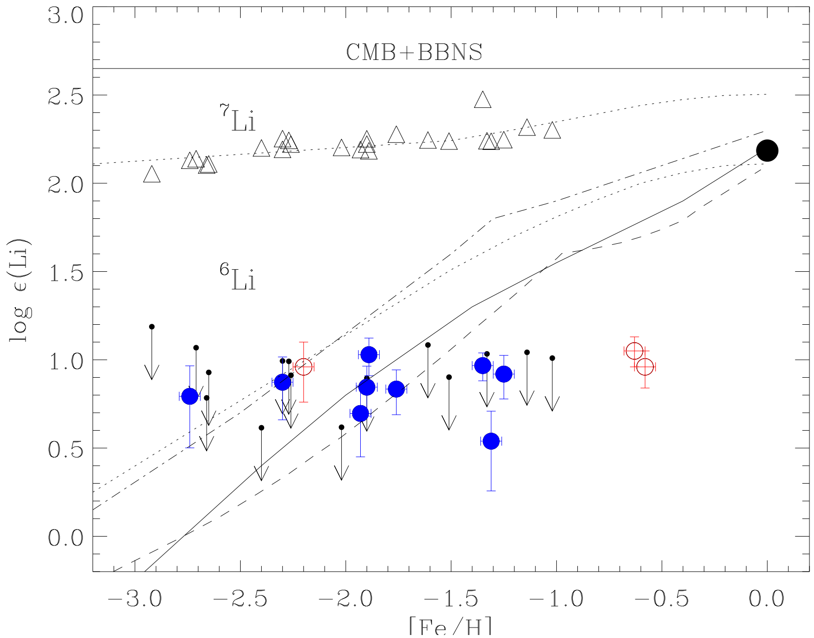


Sbordone *et al.* 10, Asplund *et al.*, Aoki *et al.*

- well defined upper envelope - plateau
- no measurable star-to-star scatter at metallicities $[Z] \gtrsim -2.7$
- absence of stars with ^{7}Li/H above plateau

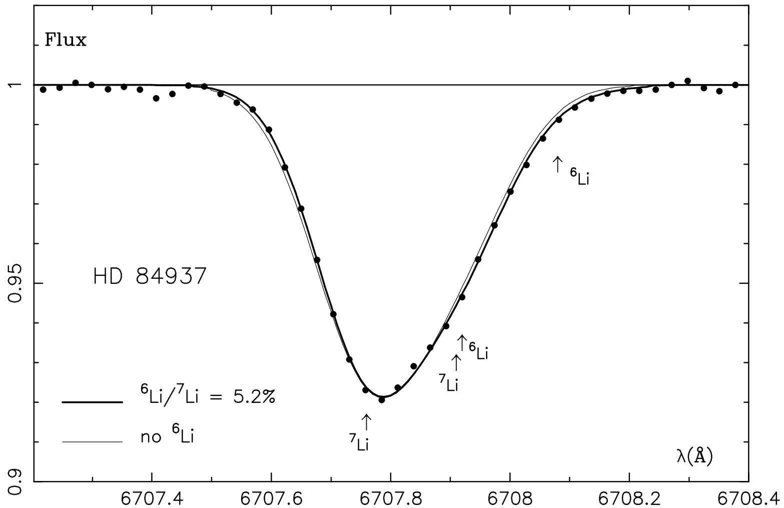
^{6}Li/H observations

Asplund, Lambert, Nissen, Primas, & Smith 06



A second Lithium plateau ?

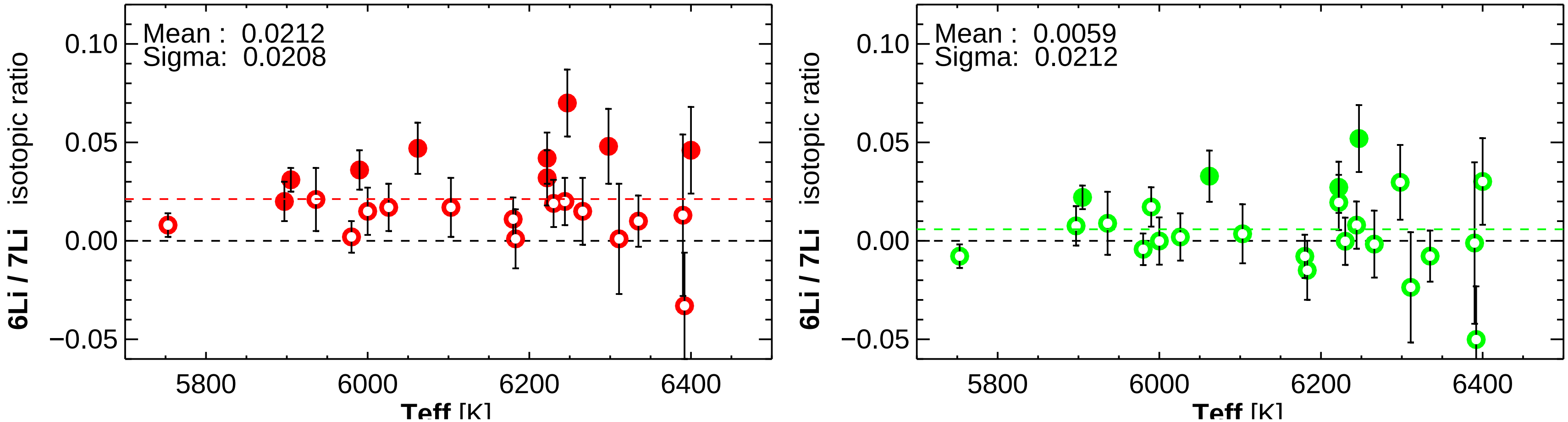
$^6\mathrm{Li/H} \approx 6 \times 10^{-12}$ compare to standard BBN $^6\mathrm{Li/H} \sim 10^{-14}$



- ^{6}Li and ^{7}Li absorption features blend together
- ^{6}Li from asymmetry of lines
- asymmetry of lines from convective Doppler shifts ?
- non-LTE hydrodynamic simulations of two groups reach somewhat different conclusions

Are the ^{6}Li detections real ?

Steffen, Cayrel, Bonifacio, Ludwig, & Caffau 09



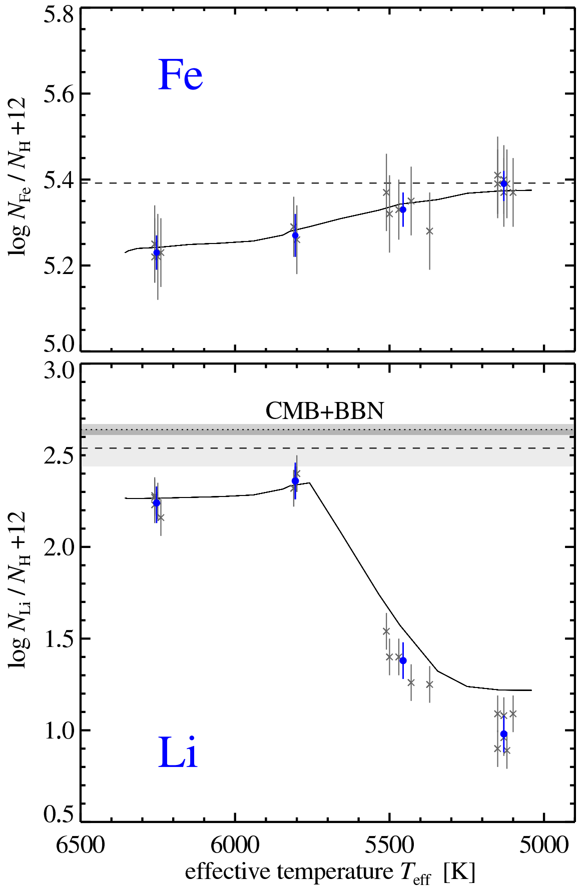
- fewer (four) $\sim 2\sigma$ detections in Steffen *et al.* compared to (nine) Asplund *et al.*
- however, distribution always skewed towards positive ^{6}Li/H
- a positive ^{6}Li/H detection in HD84937 by four(!) groups

Nuclear reactions/stellar atmospheres ?

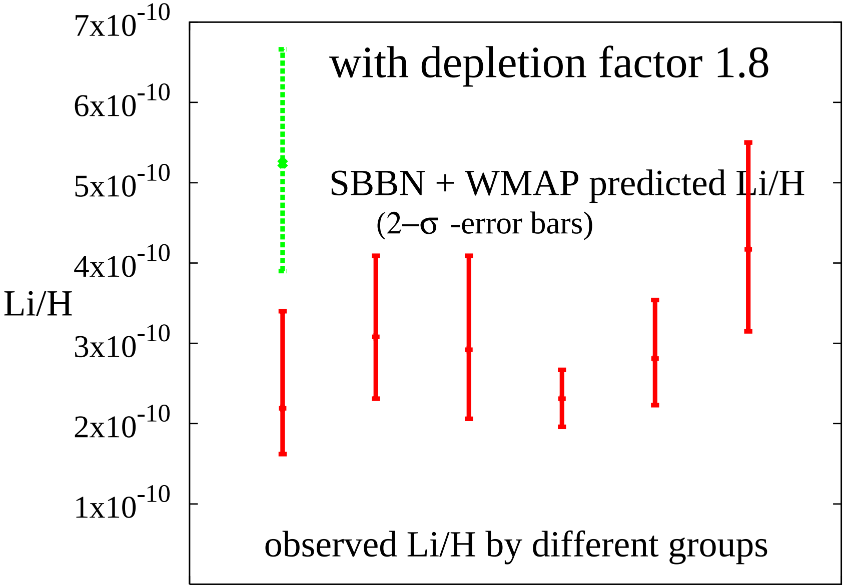
- stellar temperature $\Delta T \sim 900$ K underestimated
  seems impossible
- narrow nuclear resonance in
  $^{7}\mathrm{Be}$ +$^{2}\mathrm{H}\!\rightarrow\,^{9}\mathrm{B}^{*}_{5/2^{+}} \rightarrow 2\,^{4}\mathrm{He} + p$
  Cyburt & Pospelov 09, Angulo *et al.* 05
  seems unlikely but not ruled out → need further measurement

^{7}Li **depletion by atomic diffusion in PopII stars ?**

Korn *et al.*, Richards *et al.*



- atomic diffusion
- turbulent mixing



→ factor 1.8 ^{7}Li depletion

- but stellar models ad hoc and tuned !

- absence of star-to-star scatter ?

tuned turbulent diffusion coefficient $D_T = 400 D^{gs}_{4He}\left(\frac{\rho}{\rho(T_0)}\right)^{-3}$ at $\log(T_0) = 6.0 \pm 0.1$ → $\pm 25\%$

${}^6\mathrm{Li}$ **production by early cosmic rays: Energetics ?**

${}^6\mathrm{Li}$ originates in galactic cosmic ray nucleosynthesis (along, with ${}^9\mathrm{Be}$, and B)

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

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

Suzuki & Inoue 00 Rollinde *et al. 05*,
Prantzos *et al. 05* Nath *et al.* 05

V. Beyond the standard model solutions to the lithium problem(s)

- relic particle decay
- relic particle annihilation
- catalysis during BBN
- varying fundamental constants