The Cosmic Lithium Abundances and Physics beyond the Standard Model

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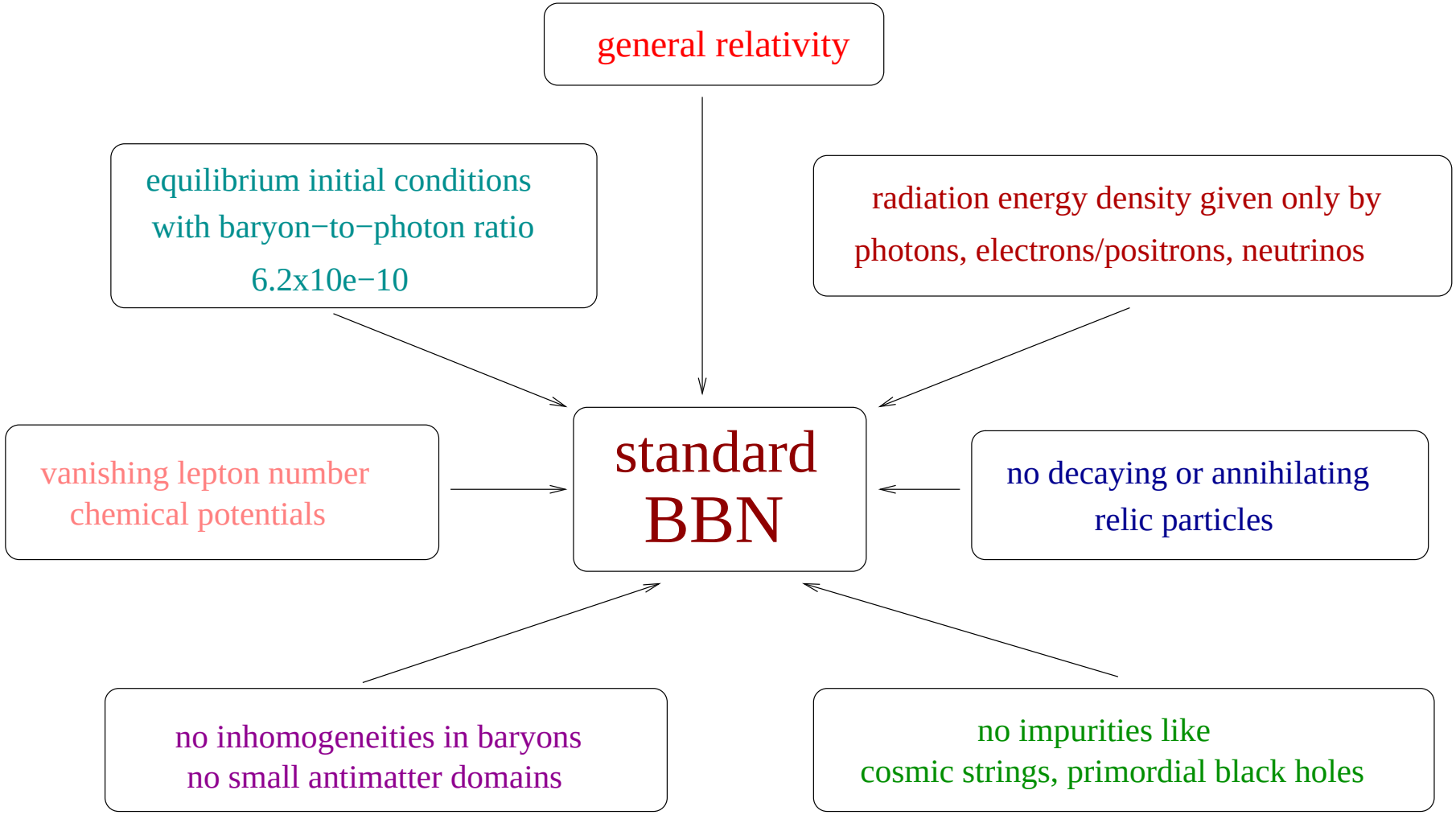
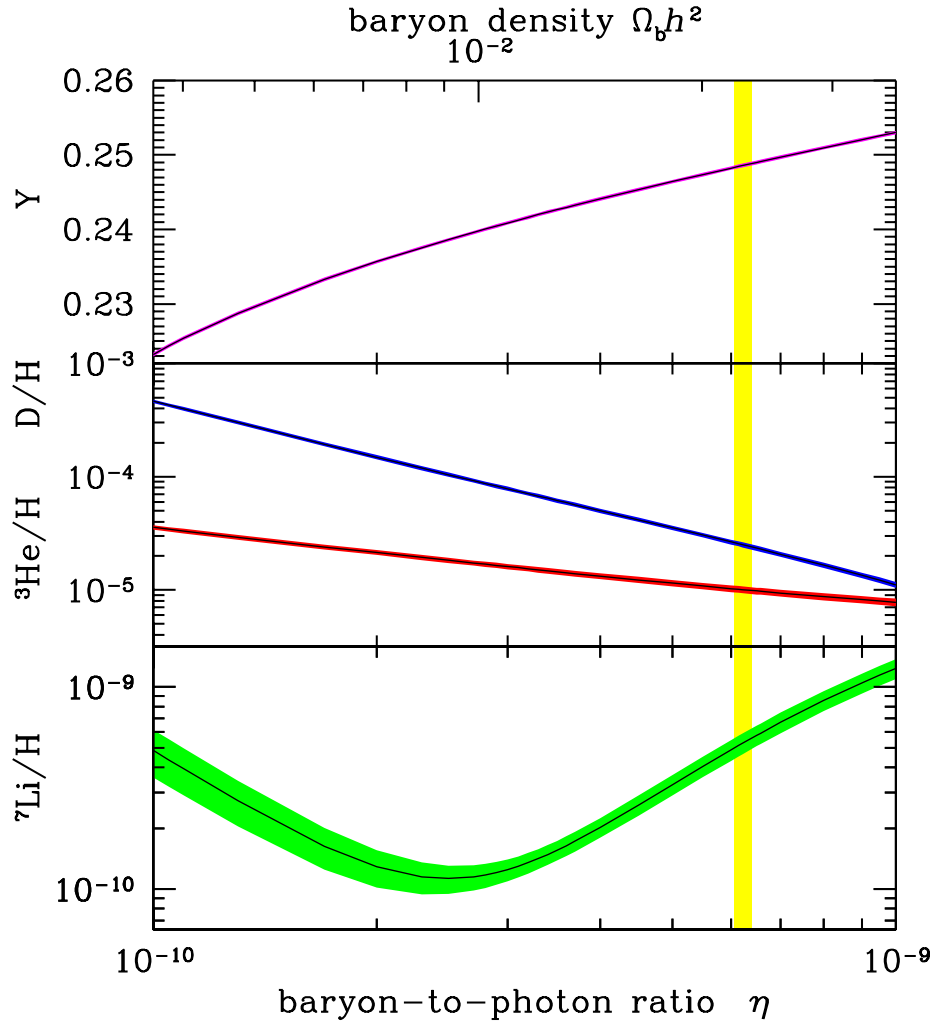
The Big Bang Nucleosynthesis standard model



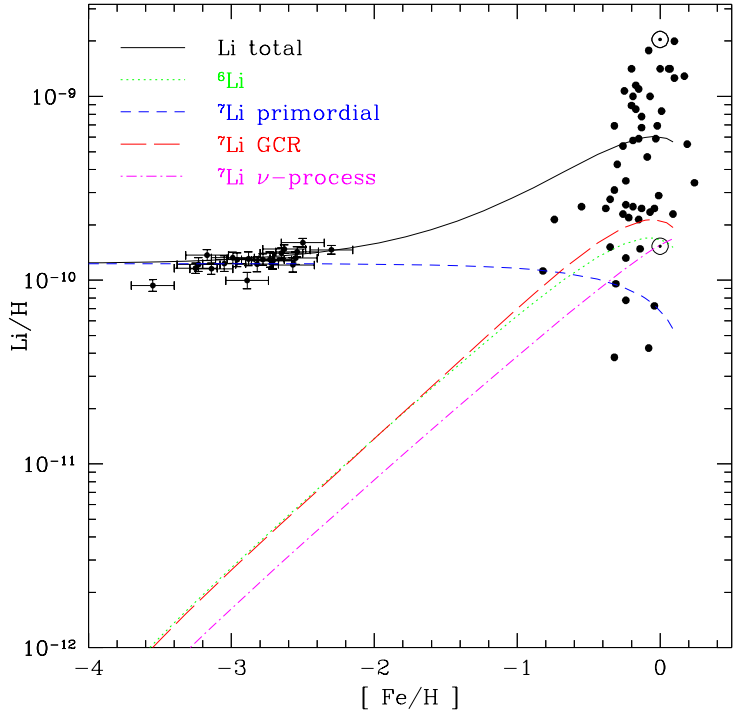
SBBN: A one parameter model

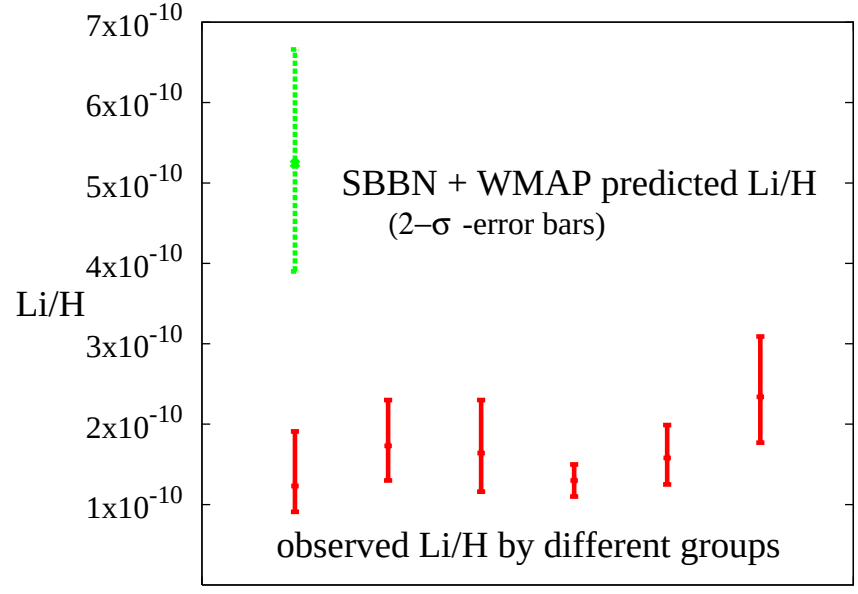
Cyburt *et al.* 08



overconstrained → consistency checks possible

The ^{7}Li Spite plateau





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

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

^{7}Li discrepancy $4.2 - 5.3\sigma$

Nuclear reactions/stellar atmospheres ?

- stellar temperature $\Delta T \sim 900\,\mathrm{K}$ 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 $\rightarrow$ need further measurement

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

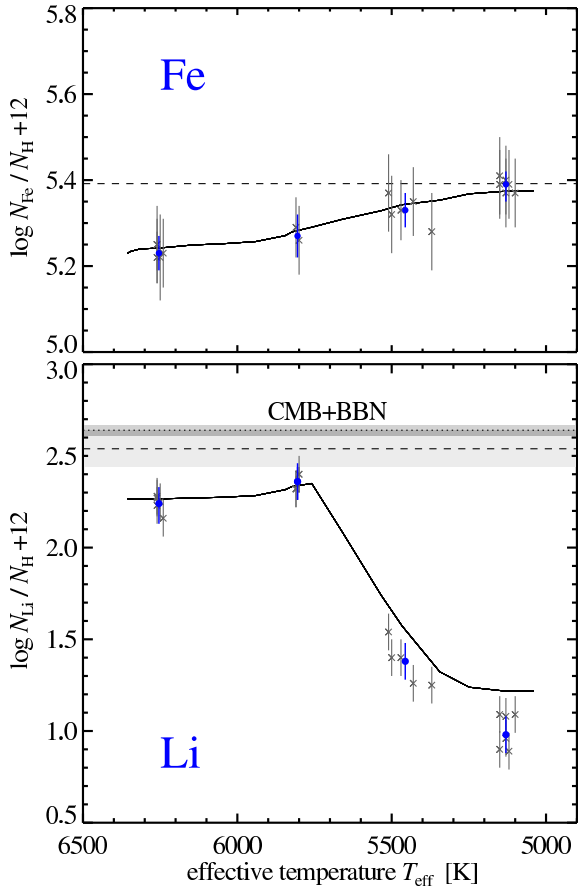
Spite plateau not primordial ?

Depletion of $^7\mathrm{Li}$ by factor $2-4$ in halo stars is not understood and may currently only be explained with fine-tuned stellar conditions

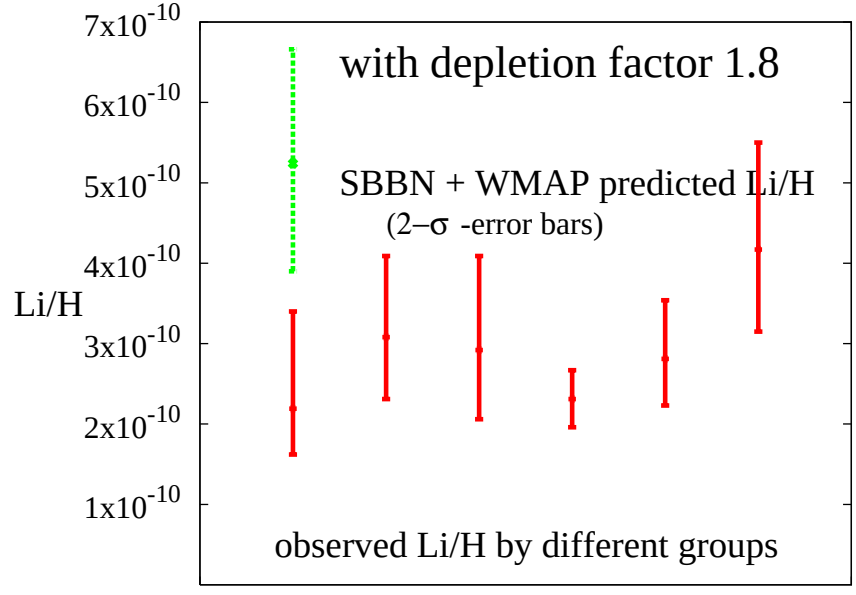
Dispersion ?

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

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



- atomic diffusion
- turbulent mixing



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

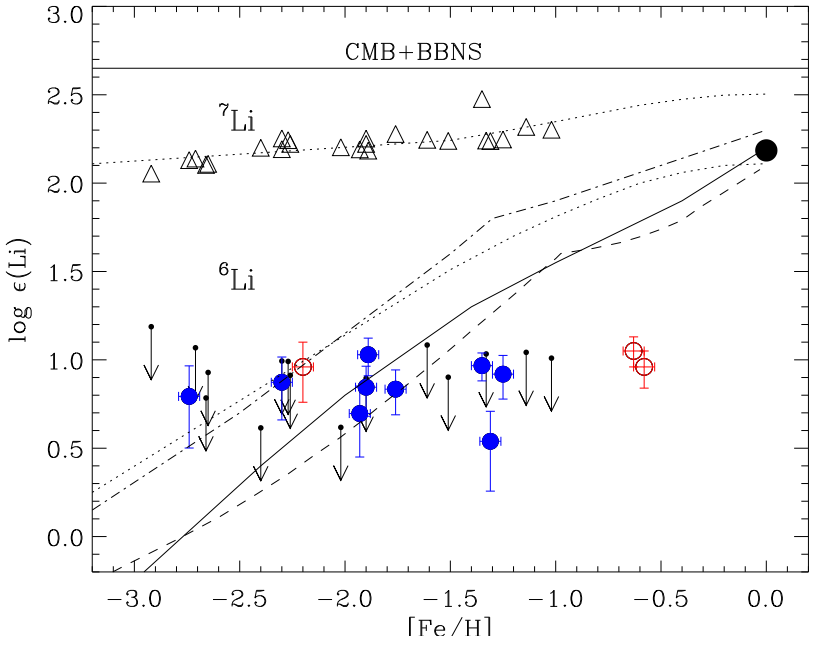
$\rightarrow$ factor 1.8 ^{7}Li depletion

but stellar models ad hoc and tuned

^{6}Li/H observations

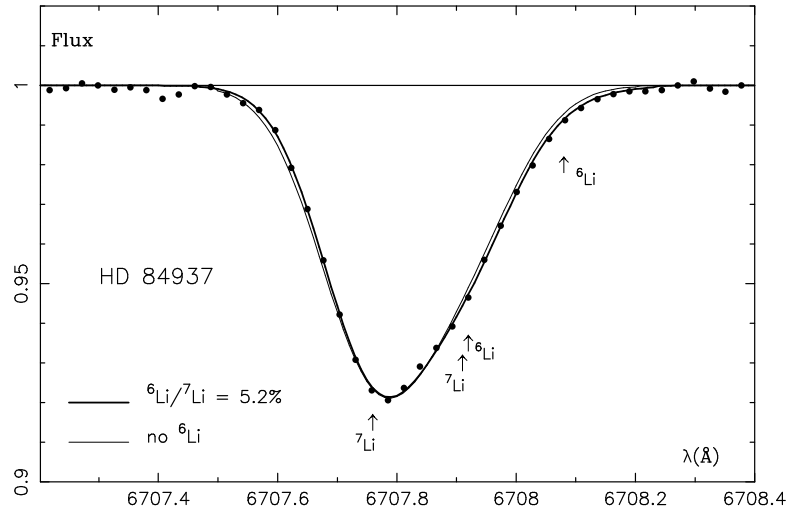
Asplund, Lambert, Nissen, Primas, & Smith

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 opposite conclusions

^{6}Li production by early cosmic rays: Energetics ?

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

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

need **100 eV/nucleon** to synthesize ^{6}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

if ^{6}Li exists in these stars of the abundance as claimed $\rightarrow$ something important about the Universe has been learned

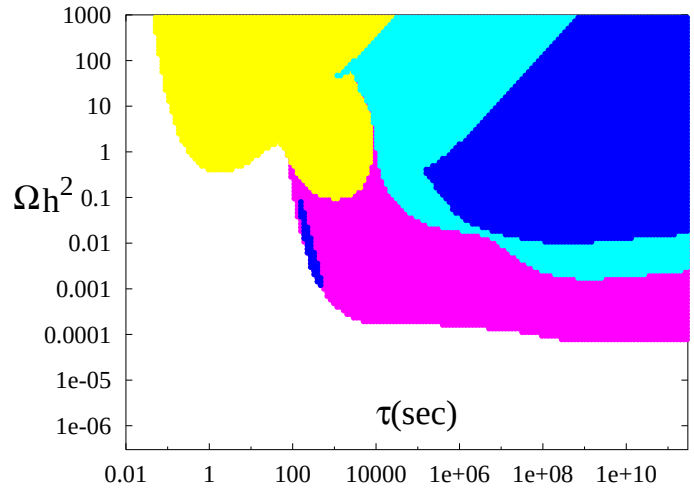
BBN with decaying and annihilating particles

injection of energetic nucleons and mesons

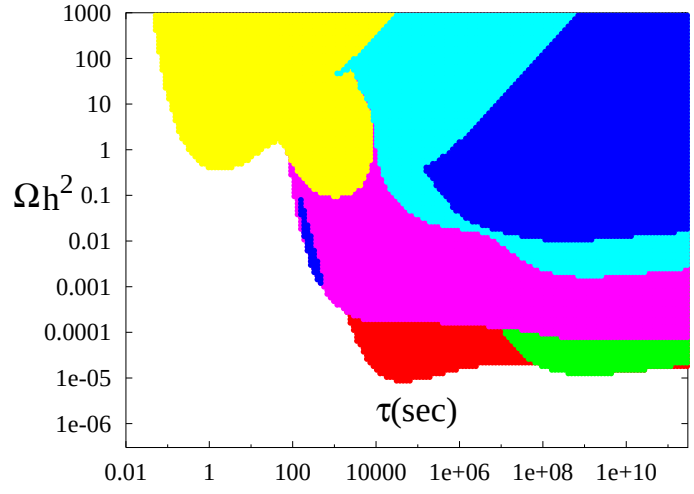
- charge exchange reactions
  $\pi^- + p \rightarrow \pi^0 + n$
- elastic- and inelastic scatterings
  $p + p \rightarrow p(n) + (p)n + \pi$'s
- spallation reactions
  $p(n) + {}^4\mathrm{He} \rightarrow {}^3\mathrm{H}, {}^3\mathrm{He}, {}^2\mathrm{H} + ...$
- Coulomb stopping of charged nuclei
  ${}^3\mathrm{H}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

injection of energetic photons and electrons/positrons

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



Jedamzik 04,06



including ${}^3\mathrm{He}$ **/D** < 1.72; ^{6}**Li/**^{7}**Li** < 0.1875

Destruction of ^{7}Li during BBN by injection of neutrons

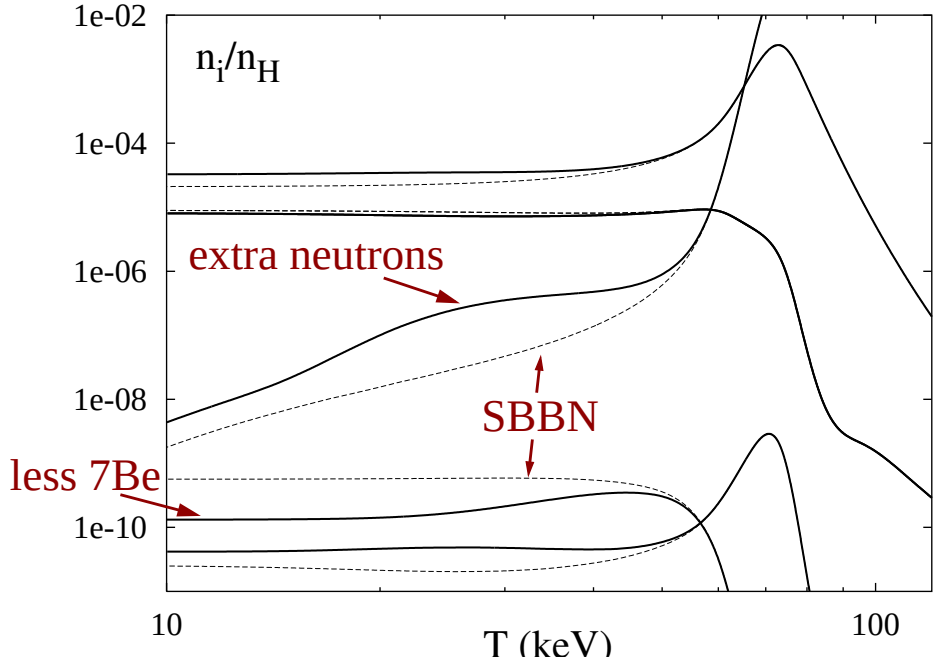
K.J. 04

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

at $T \approx 30$ keV

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

some extra ^{2}H will be also synthesized



Production of ^{6}Li in SBBN

production of ^{6}Li in SBBN by D + ^{4}He $\rightarrow$ ^{6}Li + γ which is quadrupole suppressed $\rightarrow$ ^{6}Li/H$\sim 10^{-14}$

Production of ^{6}Li in cascade nucleosynthesis

^{6}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

Production of ^{6}Li in catalytic nucleosynthesis

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

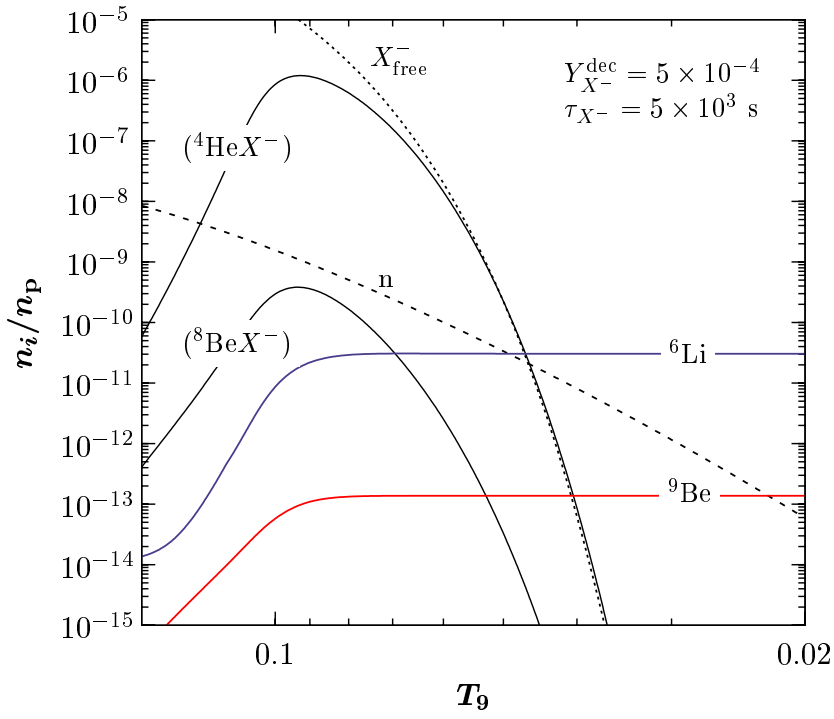
formation of bound states with nuclei

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

X^- acts as catalysator for reactions

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

Pospelov 06,07, Kamimura *et al.* 08, ...



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

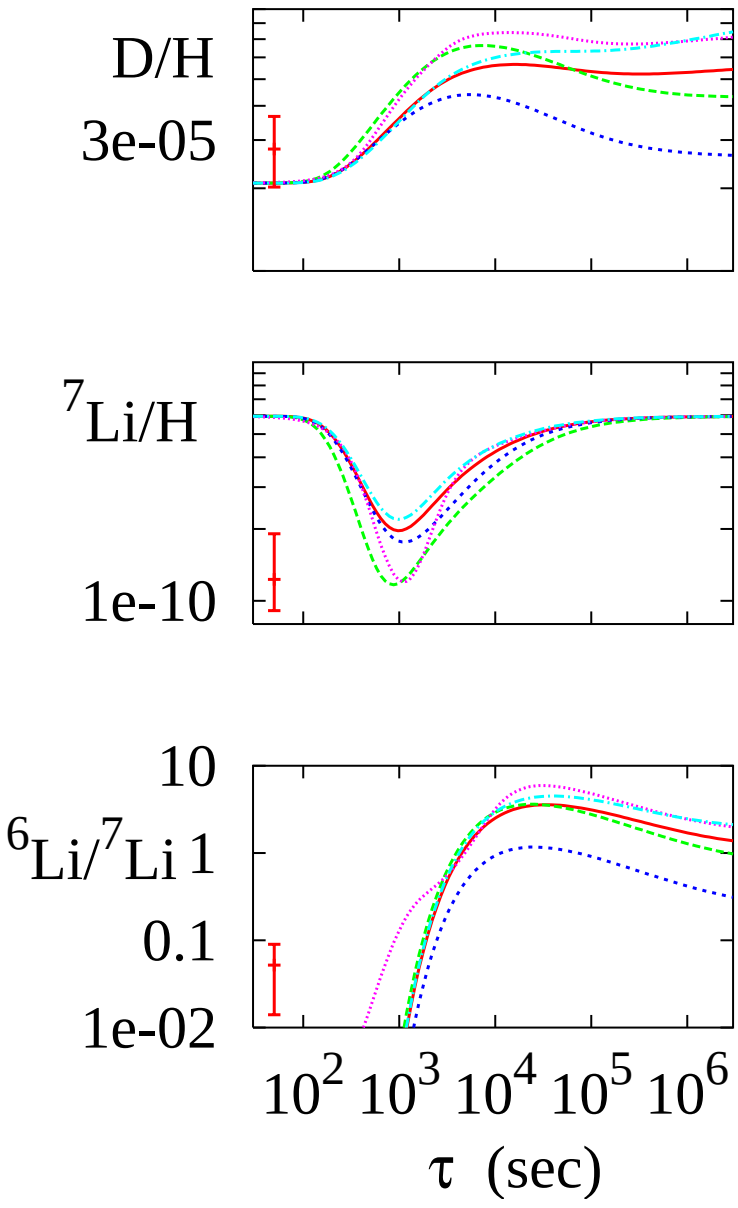
Catalysis and ^{6}Li, ^{7}Li, and ^{7}Be

Catalysis:

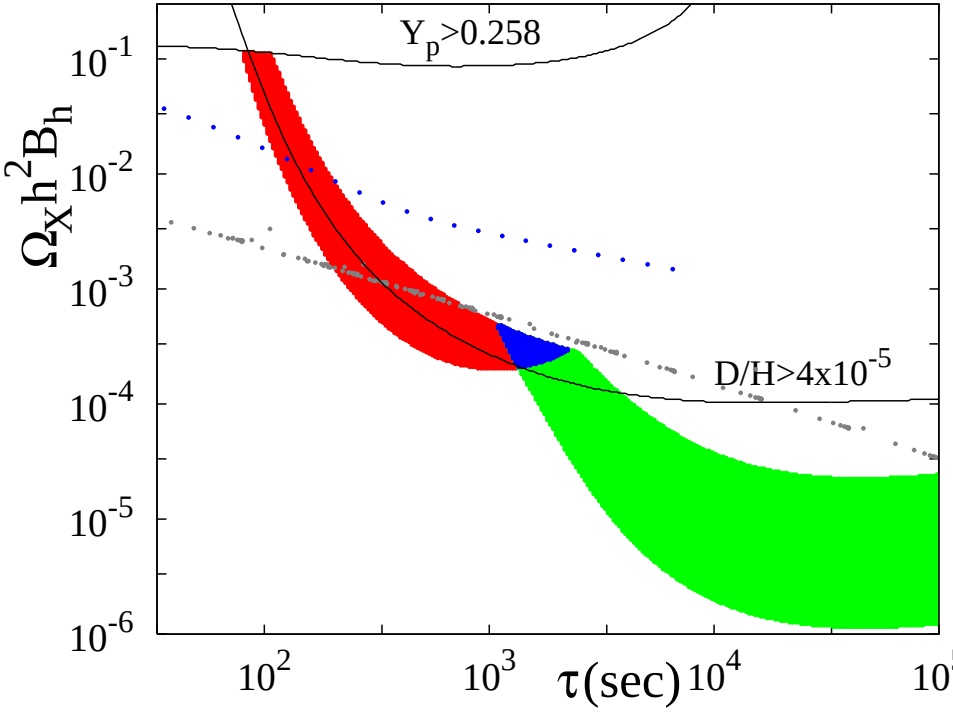
- main production mechanism for ^{6}Li if $B_h \lesssim 10^{-2}$
- may **only** solve the ^{7}Li problem, if $B_h \lesssim 10^{-5}$ rather small and $\Omega_X \gtrsim 10$ rather large
- not clear if may lead to some ^{9}Be production

The lithium friendly parameter space

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** electromagnetically or strongly interacting stopped in the detector $\rightarrow$ smoking gun for non-standard BBN $\rightarrow$ possible connection to the dark matter

Examples:

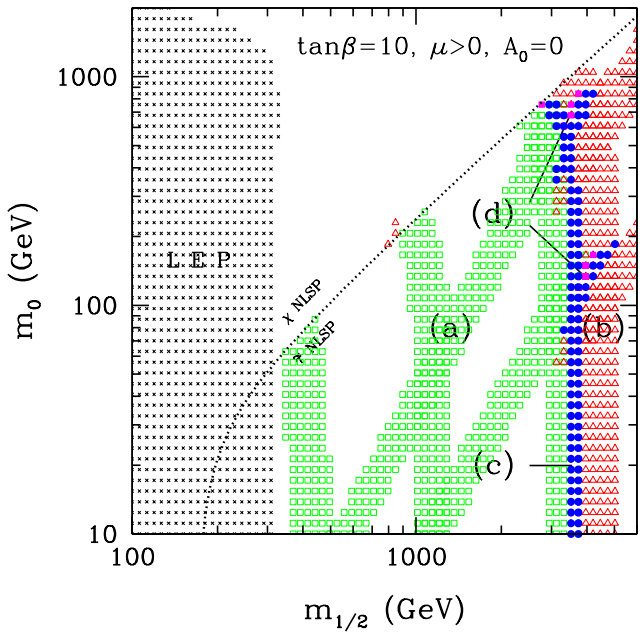
supersymmetric gravitino

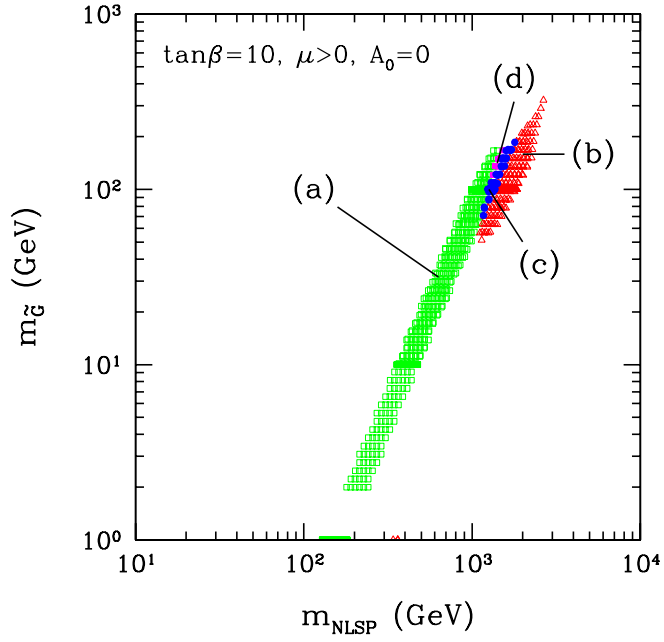
supersymmetric stau Next-to-LSP with gravitino LSP

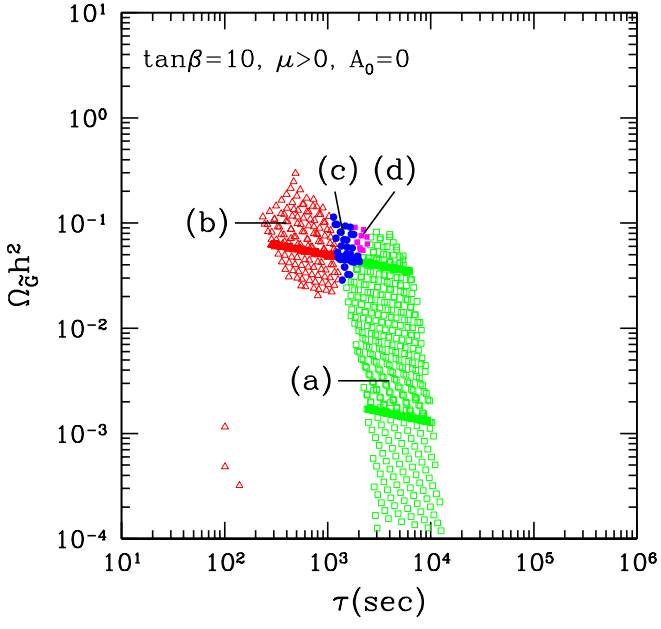
gluino in split supersymmetry

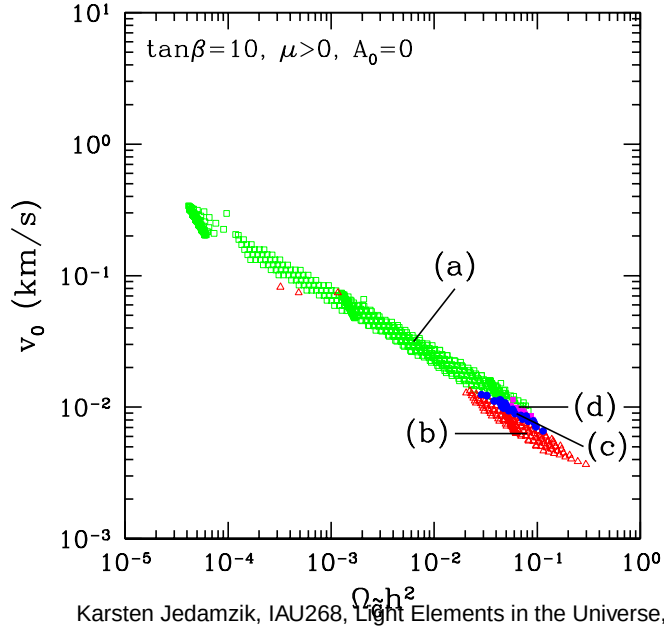
Example: Gravitino dark matter in the CMSSM

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

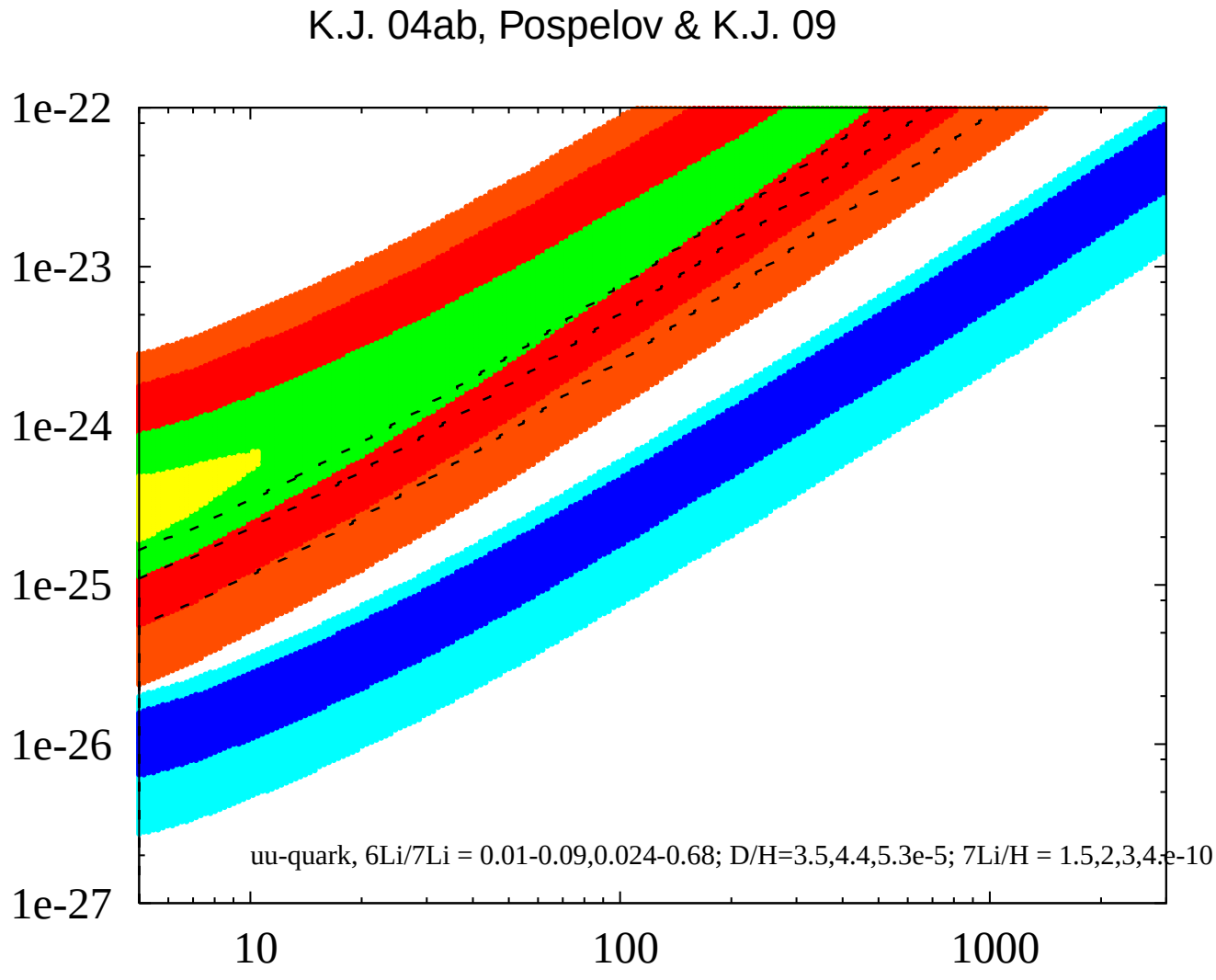








Production of cosmic ^{6}Li by neutralino annihilation



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 $\rightarrow$ explanation of all the $^6\mathrm{Li}$ as claimed to exist in HD84937

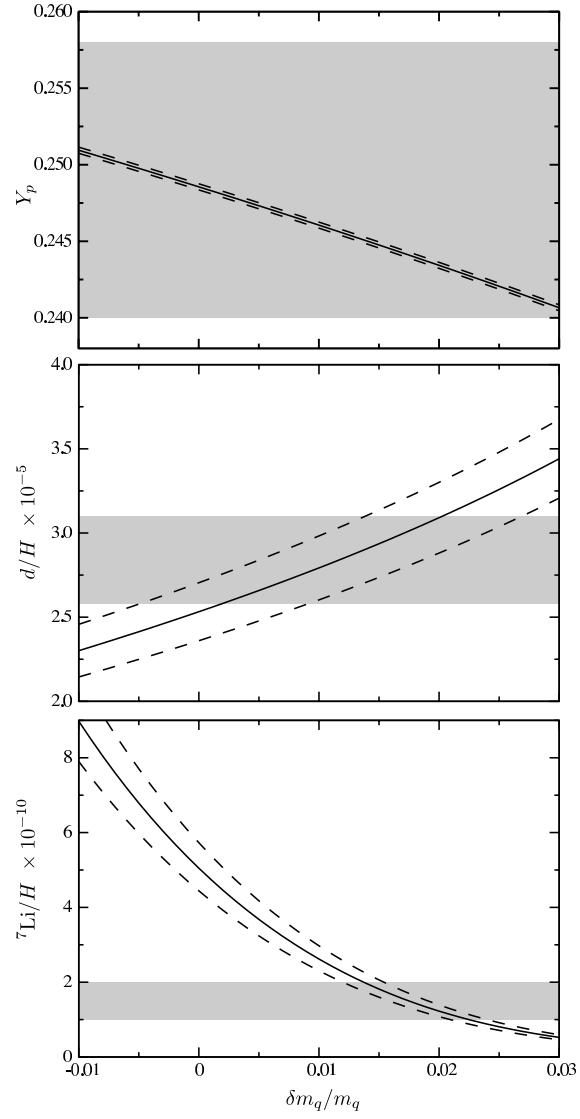
Varying fundamental constants and ^{7}Li

Dmitriev, Flambaum, & Webb 04, Dent, Stern, & Wetterich 07, Berengut, Flambaum, & Dmitriev 09

^{7}Li depends strongly on B_d and $B_{^7\mathrm{Be}}$

$\Delta B_d/B_d \approx -0.019 \pm 0.005 \rightarrow$ reduce ^{7}Li (and ^{4}He)

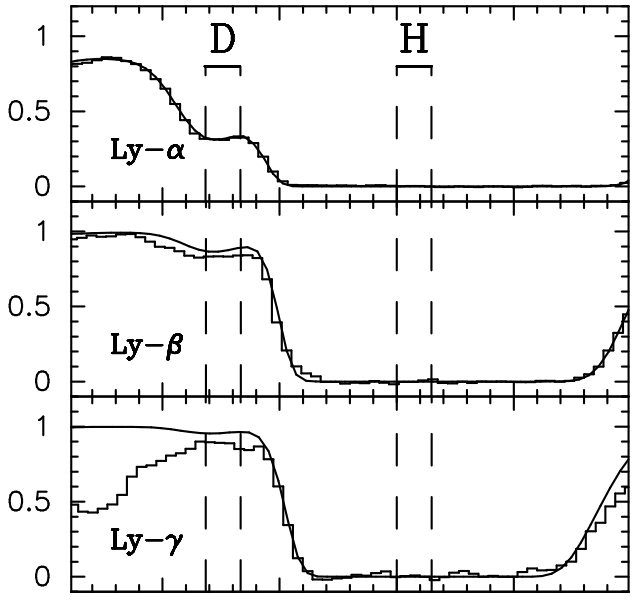
$\Delta m_q/m_q \approx 0.013 \pm 0.002 \rightarrow$ reduce ^{7}Li



Conclusions

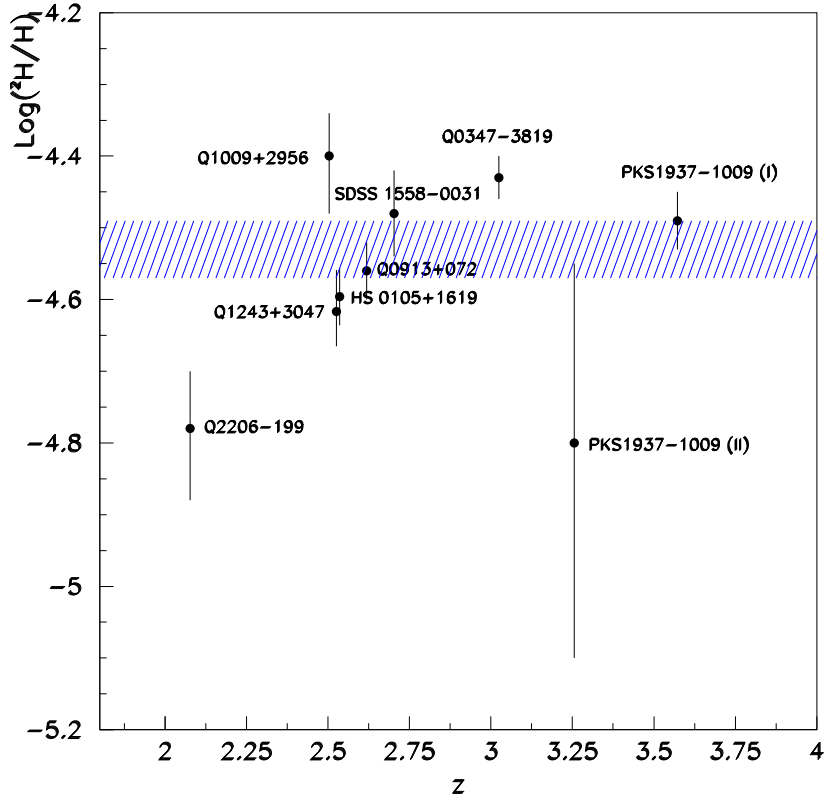
- the by standard BBN at $\eta_{\rm WMAP}$ predicted D (and $^4{\rm He}$) are in good agreement with those observed
- in contrast, there is a factor 3-4 discrepancy between SBBN predicted and observationally inferred $^7{\rm Li}$
- this discrepancy could possibly be removed if $^7{\rm Li}$ is destroyed 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 $\rightarrow$ potentially testable at the LHC
- accelerators ultimately may teach us that the apparent anomalies in the cosmic $^7{\rm Li}$ (and $^6{\rm Li}$) abundance are ultimately connected to the dark matter

D/H from Quasar Absorption Systems



Tytler,Fan,& Burles 96

Iocco *et al.* 09



significant dispersion → underestimated systematic errors ?

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