Big Bang Nucleosynthesis

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Outline of Talk

I. Theory of standard BBN

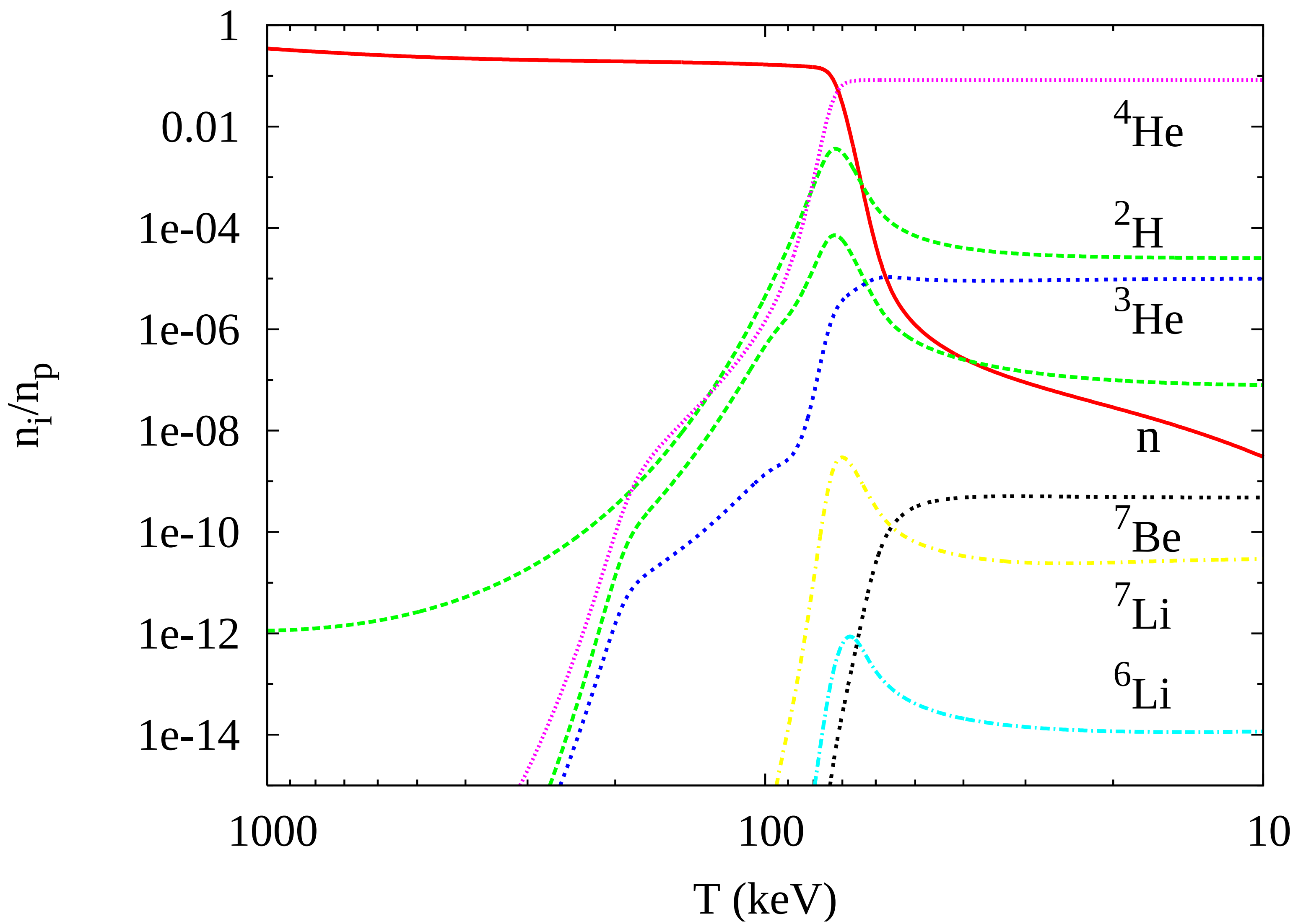
II. Observational determination of primordial light elements abundances/comparison to standard BBN prediction

III. BBN as a probe of the early Universe and Physics beyond the standard model

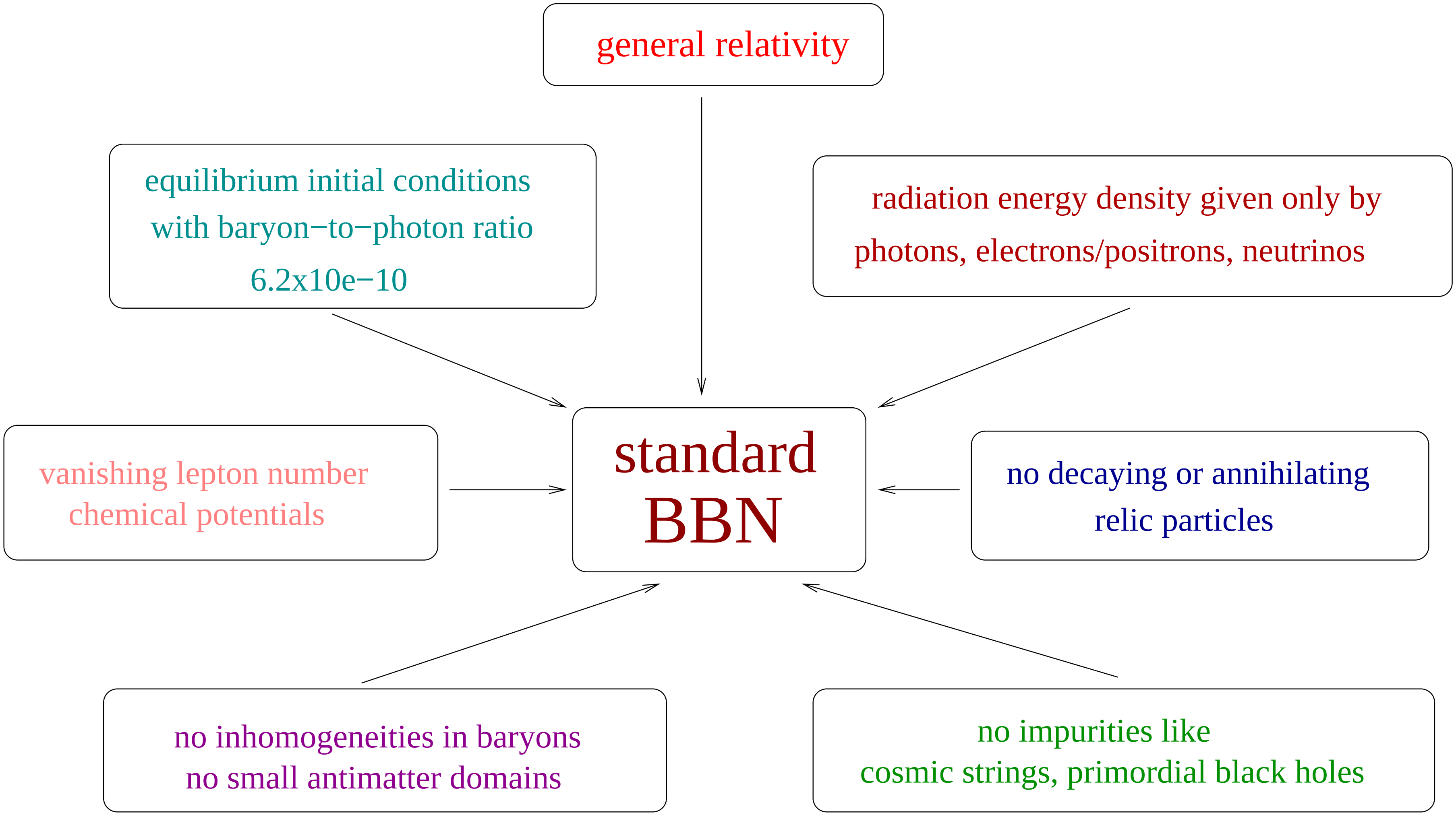
IV. Astrophysical/nuclear physics solutions to the Lithium problem(s)

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

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

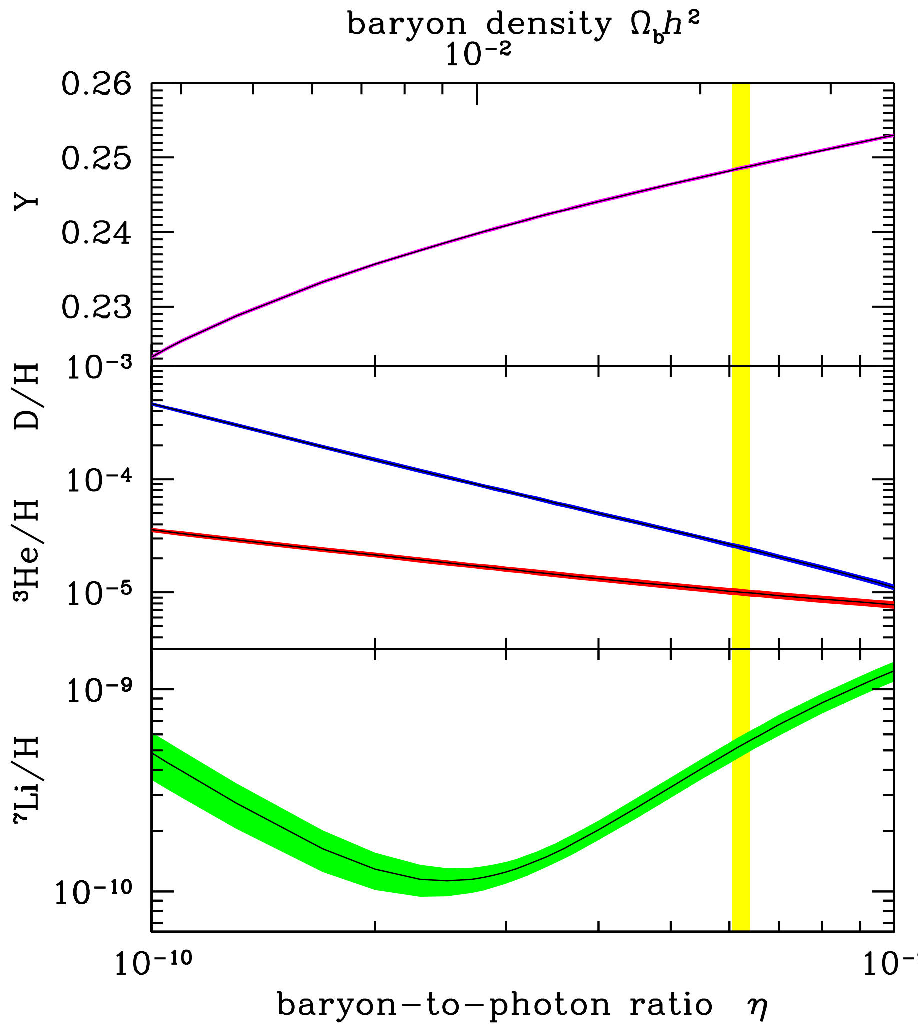


Assumptions underlying Standard Big Bang Nucleosynthesis



SBBN: A one parameter model

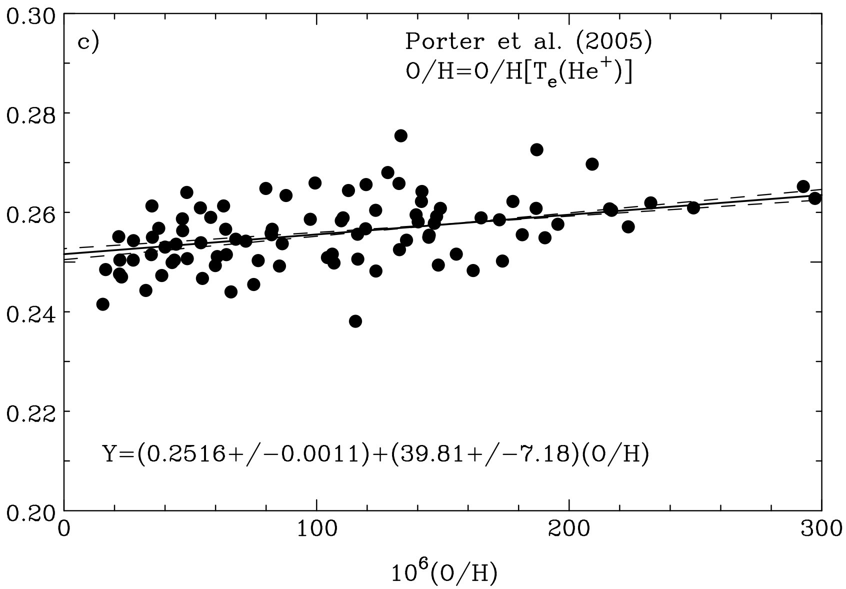
Cyburt *et al.* 08



overconstrained → consistency checks possible

II. Observational determination of primordial light elements abundances/ comparison to standard BBN predictions

Helium-4 from low-metallicity extragalactic HII regions



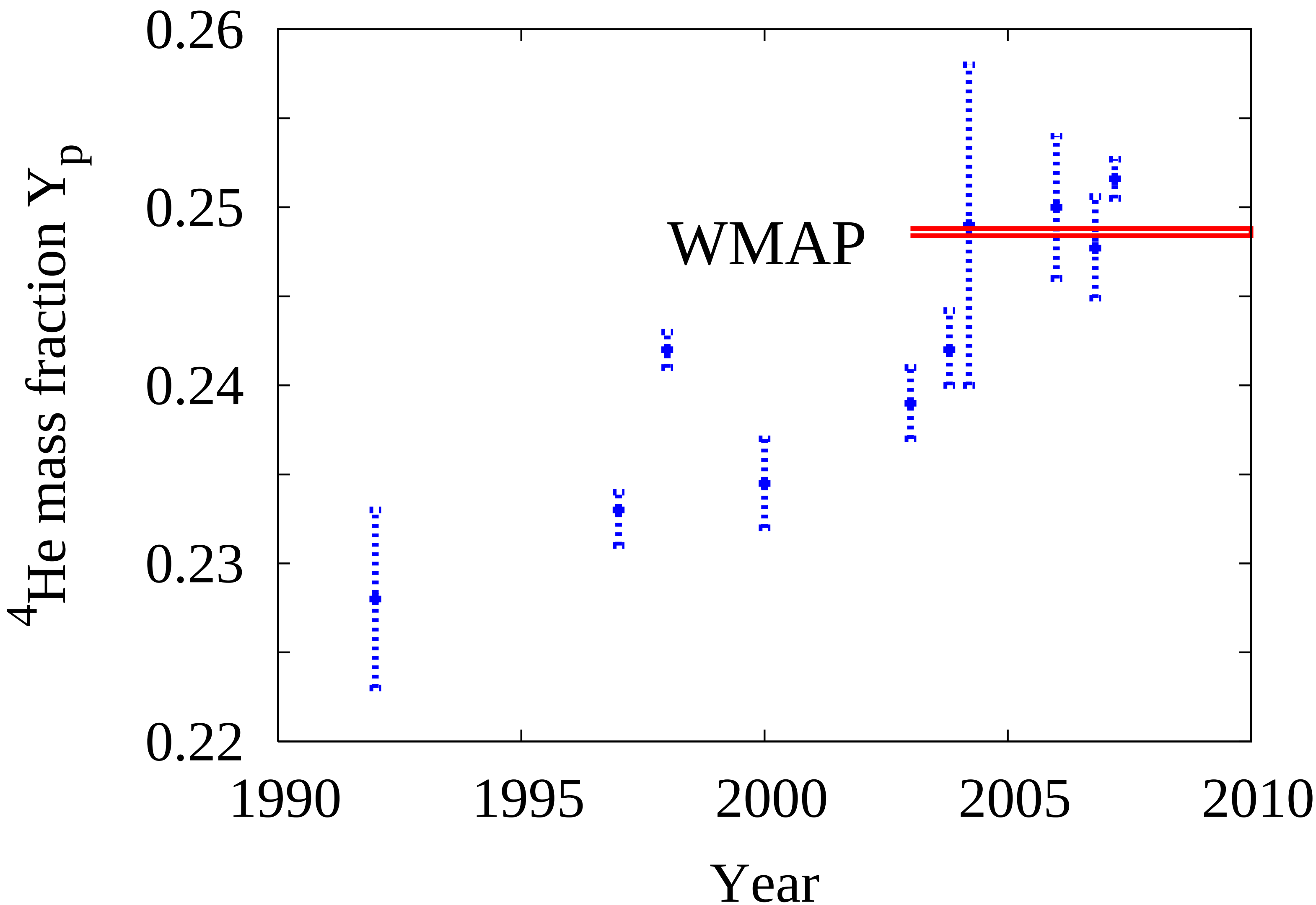
systematic uncertainties

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

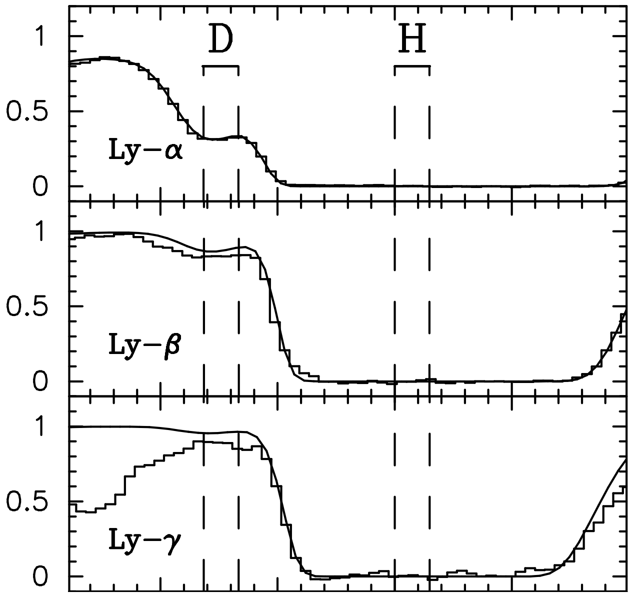
$Y_p = 0.2477 \pm 0.0029, 0.2516 \pm 0.0011$ Peimbert it et. al07, Izotov it et. al07

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

Observational inferred Helium-4 with time

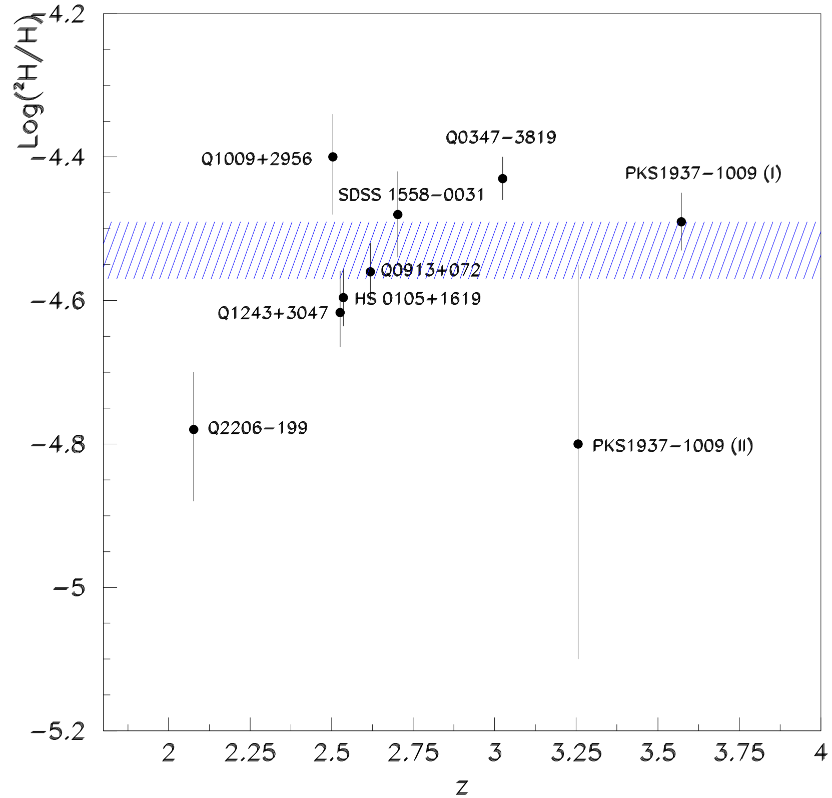


D/H from Quasar Absorption Systems



Tytler,Fan,& Burles 96

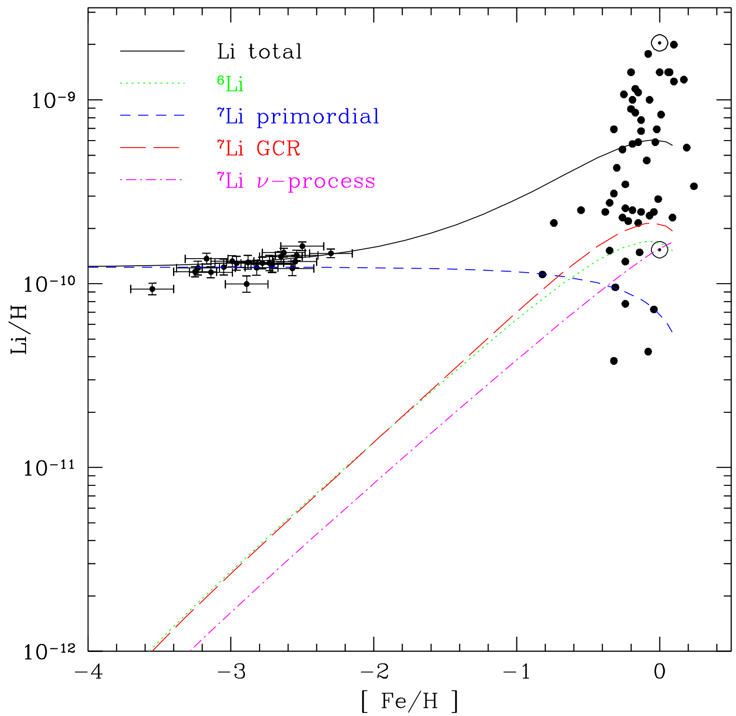
Iocco *et al.* 09

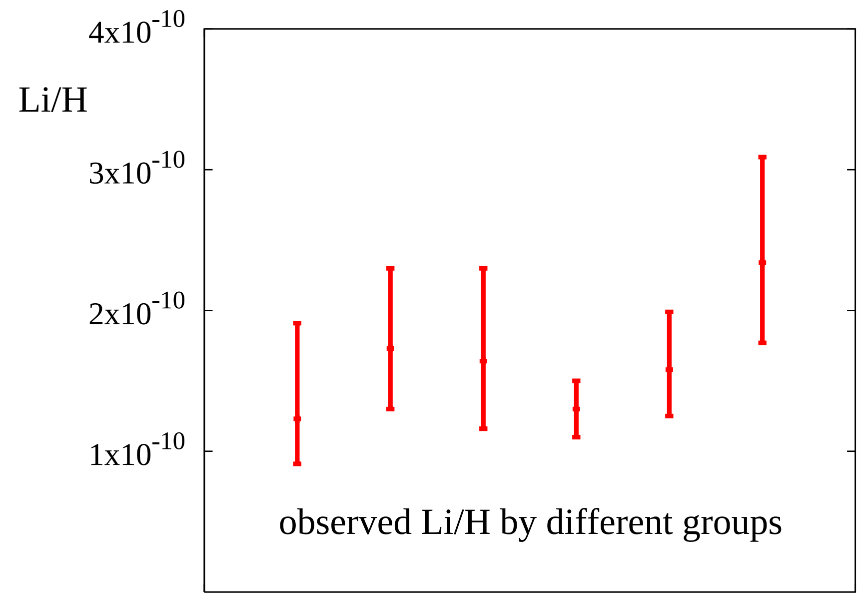


significant dispersion $\rightarrow$ underestimated systematic errors ?

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

The ^{7}Li Spite plateau





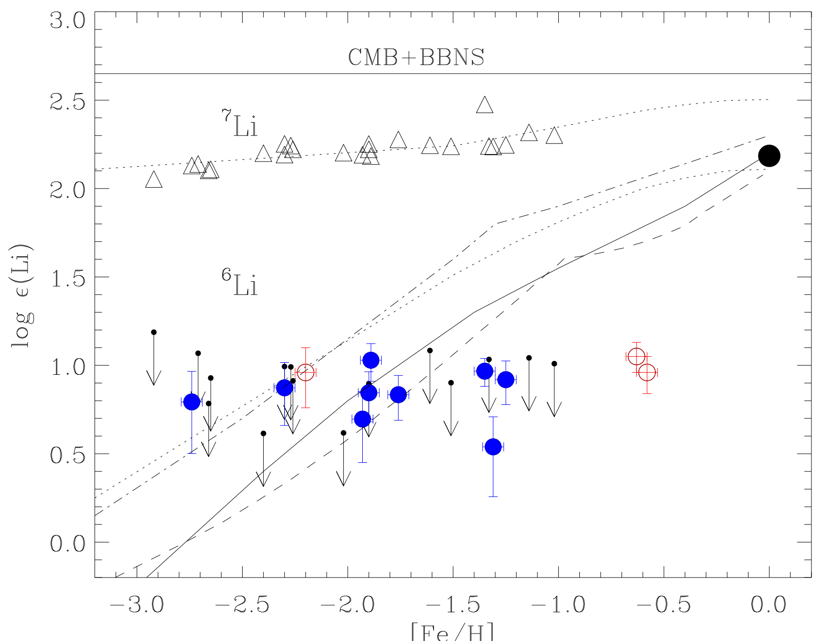
Spite & Spite 82, Bonifacio & Molaro 97, Ryan *et al* 99, Melendez Ramirez 04, Charbonnel & Primas 05, Asplund *et al* 06

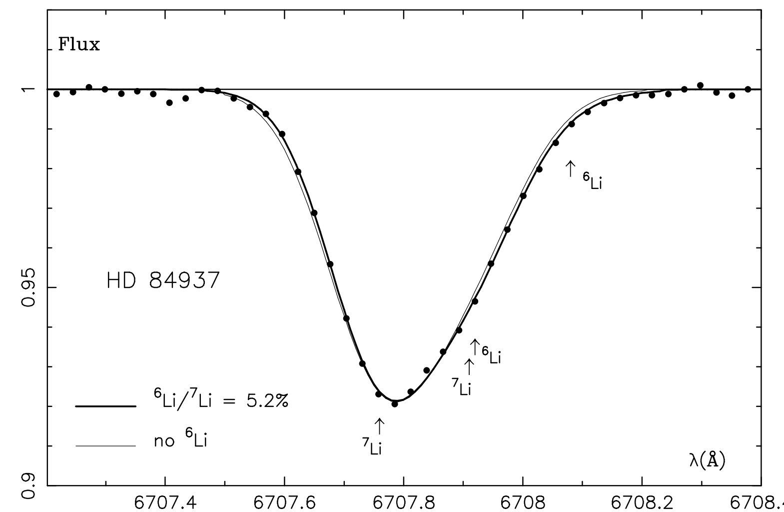
- (almost) no variation with metallicity and stellar temperature
- (almost) no measurable star-to-star scatter
- Interpretation - the Primordial ^{7}Li Abundance

^{6}Li/H observations

Asplund, Lambert, Nissen, Primas, & Smith

06





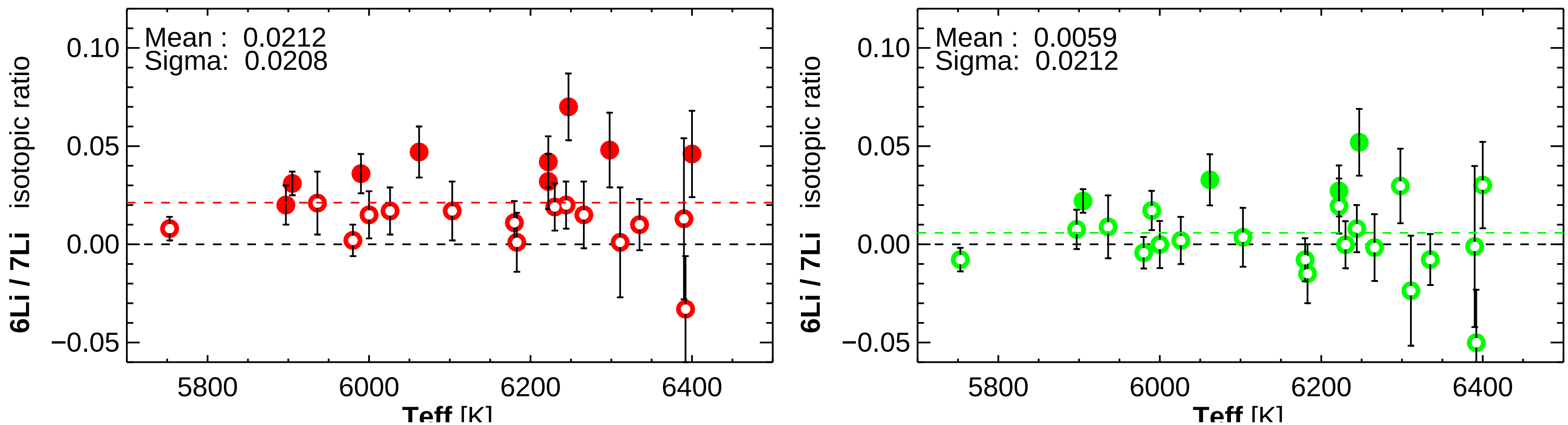
- ^{6}Li and ^{7}Li absorption features blend together
- ^{6}Li from asymmetry of lines
- asymmetry of lines from convective Doppler shifts ?
- non-LTE hydrodynamic simulations of two groups reach opposite conclusions

A second Lithium plateau ?

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

Are the ^{6}Li detections real ?

Steffen, Cayrel, Bonifacio, Ludwig, & Caffau 09



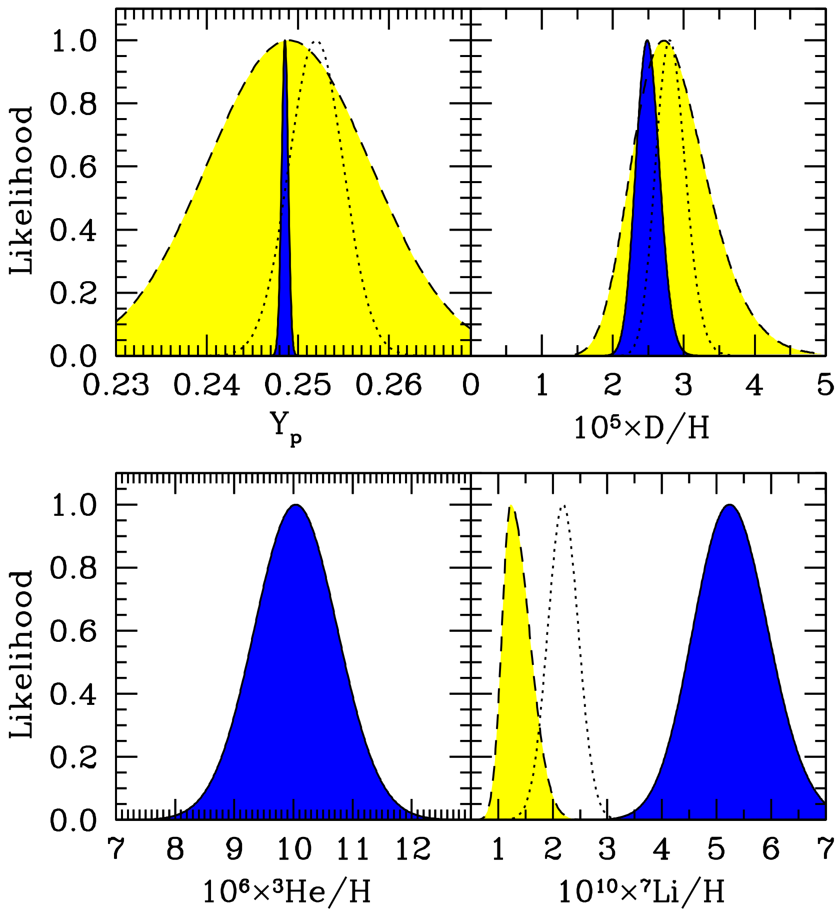
- only four $\sim 2\sigma$ detections
- however, distribution skewed towards positive ^{6}Li/H
- a positive ^{6}Li/H detection in HD84937 by four(!) groups

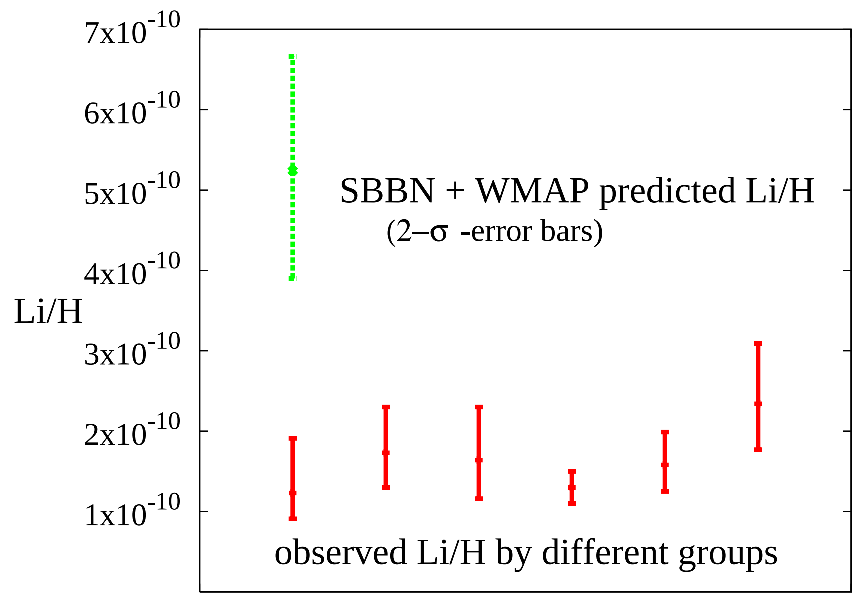
Helium-3/D

$^3\mathrm{He}$/D $\lesssim 1.5$ for solar system Geiss & Gloeckner 07 is secure and useful in constraing non-standard BBN Sigl *et al.* 06

SBBN Predictions against Observations

Cyburt, Fields, & Olive 08





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

Situation Summary

Element	Comparison
$^4\mathrm{He}$	ok/inconclusiv
$^2\mathrm{H}$	good
$^3\mathrm{He}$	inconclusive
$^7\mathrm{Li}$	disagreement
$^6\mathrm{Li}$	?

III. BBN as a probe of the early Universe and Physics beyond the standard model

The BBN early Universe Probe

- the epoch of BBN is (one) of the furthest back reaching precision probe of the early Universe
- Almost all of the theoretical work in BBN the last three decades has been done in exploring non-standard models

- changed expansion rate during BBN
- lepton chemical potentials
- neutrino oscillations, sterile neutrinos, exotic neutrino interactions
- baryon inhomogeneous models, matter-antimatter inhomogeneous models
- varying fundamental constants
- decay and annihilation of relic paticles during BBN
- catalysis of BBN

BBN with decaying and annihilating particles

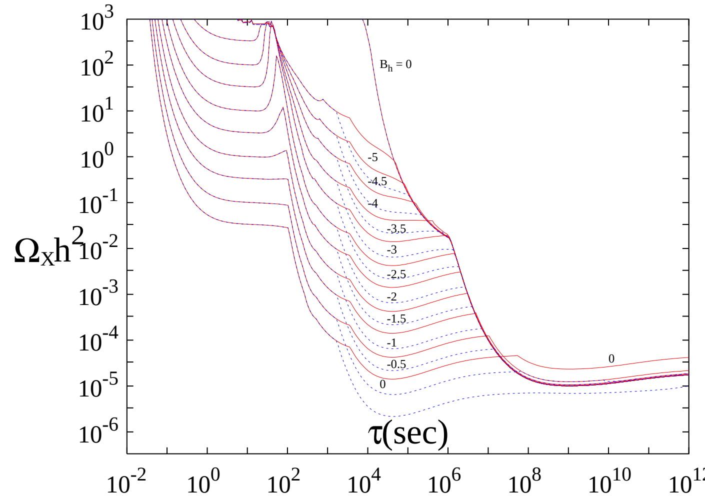
injection of energetic nucleons and mesons

- 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
  ${}^3\mathrm{H} + e^{\pm} \rightarrow {}^3\mathrm{H}' + e^{\pm}$

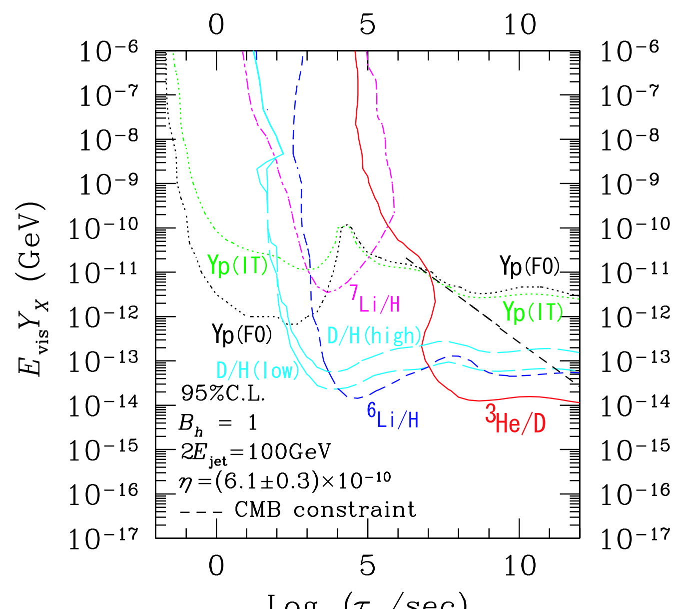
injection of energetic photons and electrons/positrons

- 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

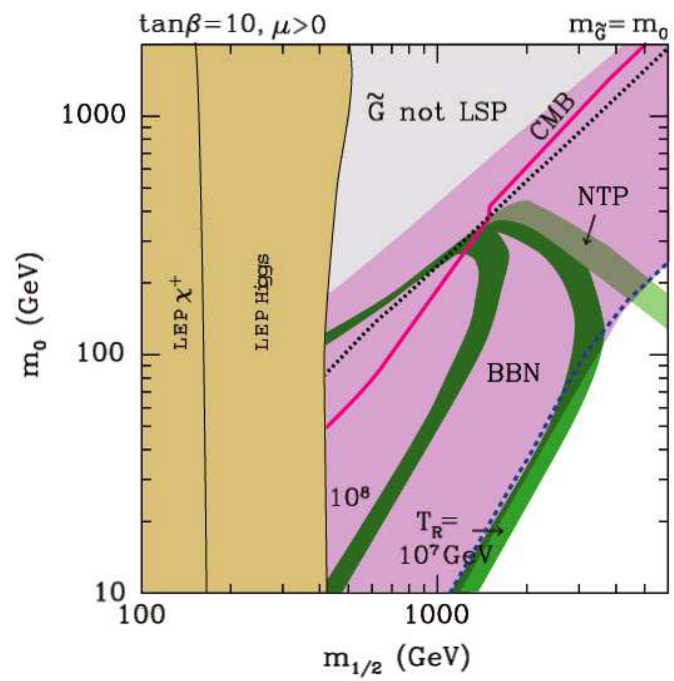


Kawasaki, Kohri, Moroi 04,06

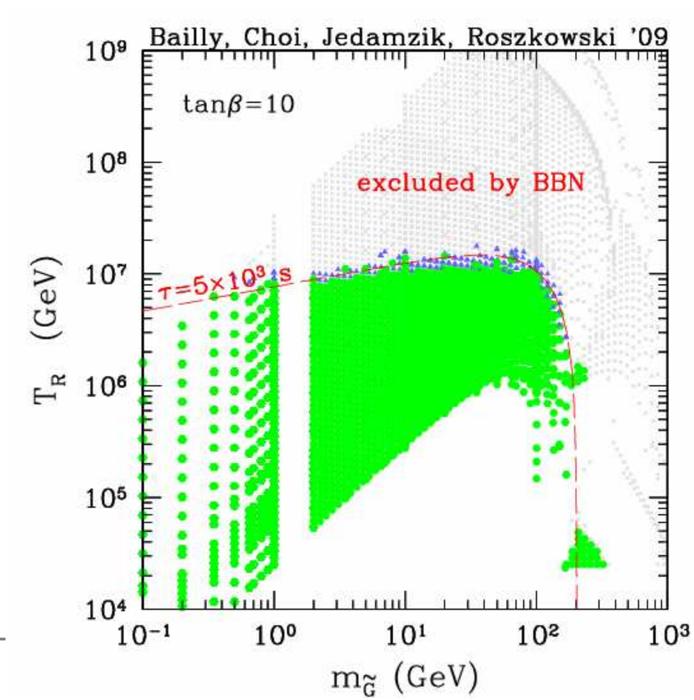


Example: Supersymmetry, BBN, and T_{rh}

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



gravitino LSP $\rightarrow$ NLSP decays dangerous unless $\tau \lesssim 5\times10^3$sec $\rightarrow$ gravitino LSP somewhat lighter than weak scale $\rightarrow$ reheat temperature must be low



$\rightarrow$ supergravity and leptogenesis (in most cases) incompatible

IV. Astrophysical/nuclear physics solutions to the lithium problem(s)

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 $\rightarrow$ 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

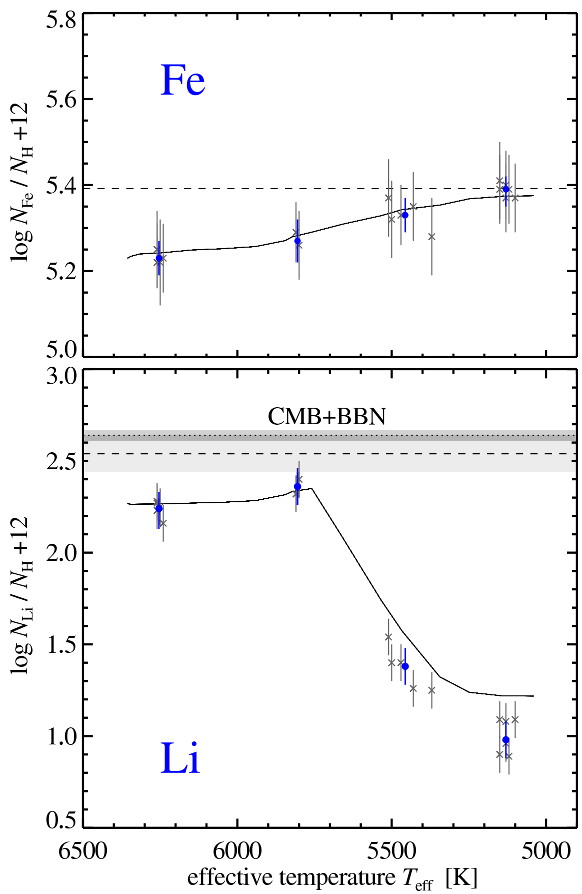
Spite plateau not primordial ?

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

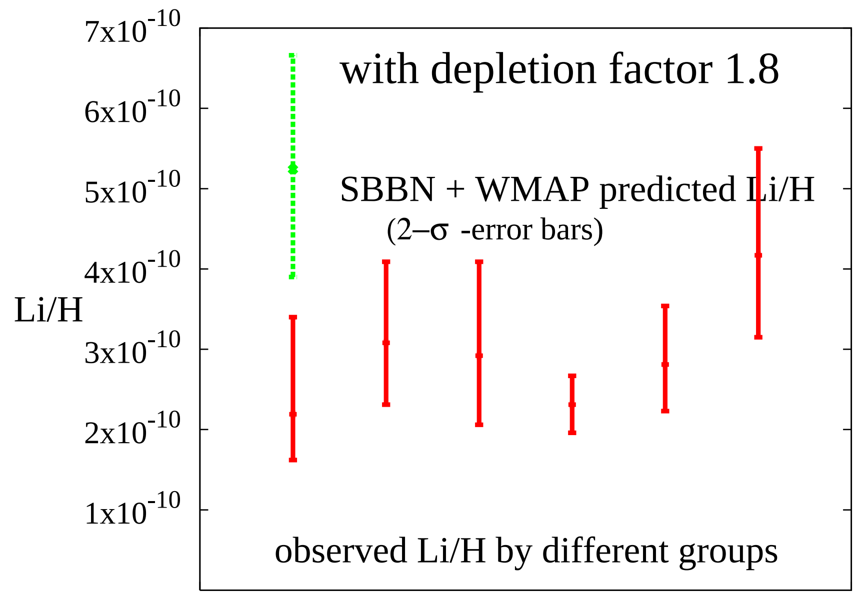
Dispersion ?

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

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



- atomic diffusion
- turbulent mixing



fine-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

$^{6}\mathrm{Li}$ 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 $\alpha + \alpha \rightarrow Li$

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

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

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)

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

$\rightarrow$ possible bydecay/annihilation or relic particles, evaporation of defects

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

charged relic - nuclei bound states during/after BBN

Pospelov 06,07, Kohri & Takayama 06, Kaplinghat & Rajaraman 06, Cyburt *et al* 06, Pradler & Steffen 06, Hamaguchi *et al.* 07, Bird, Koopmans, & Pospelov 07, Kawasaki *et al.* 07, Takayama 07, Jittoh *et al.* 07, Jedamzik 07,08

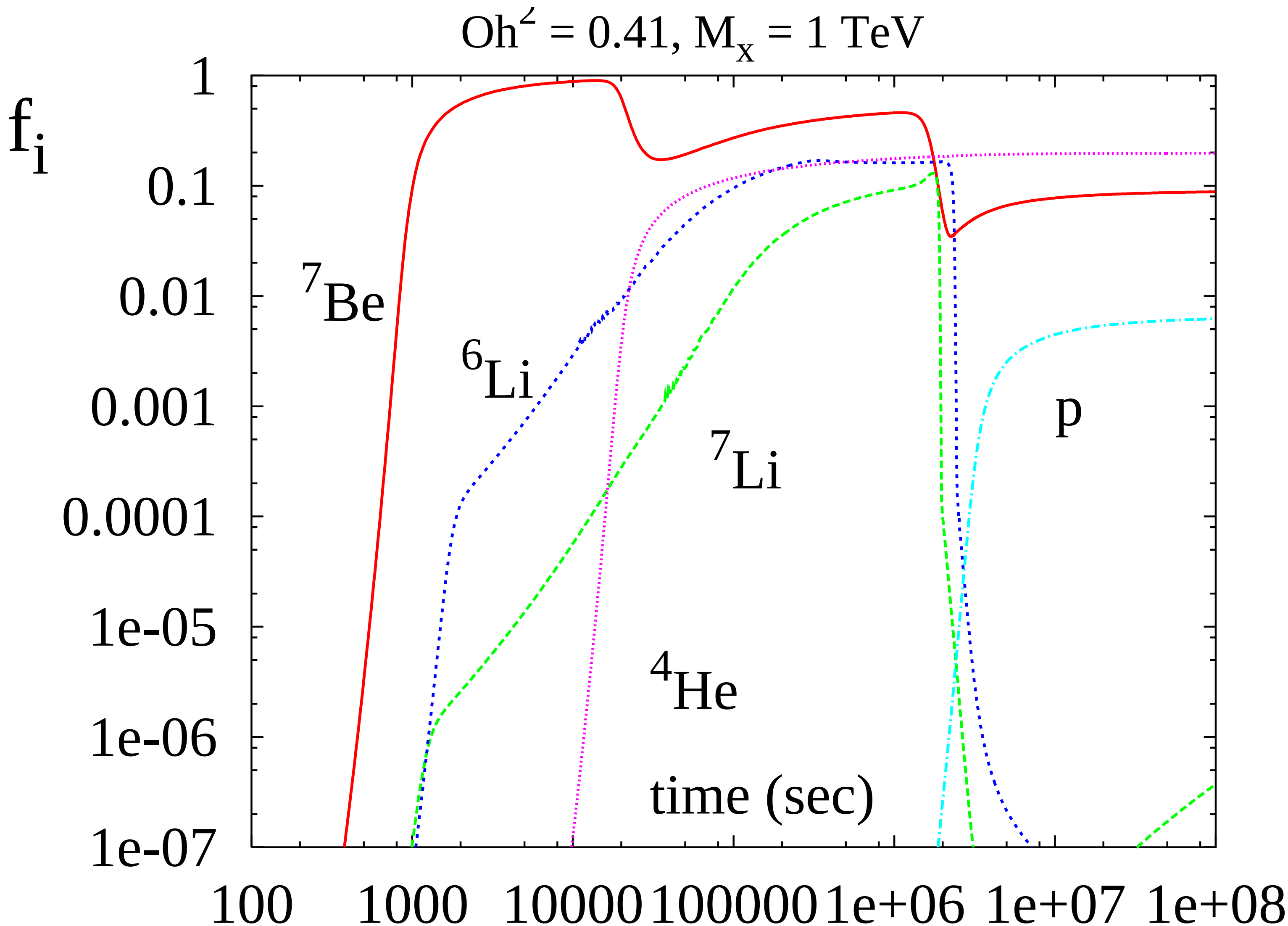
binding energy between nuclei and electrically charged weak mass scale relics appreciable:

$^7\mathrm{Be} + \tilde{\tau} \to (^7\mathrm{Be}\tilde{\tau}) + \gamma$, $^4\mathrm{He} + \tilde{\tau} \to (^7\mathrm{He}\tilde{\tau}) + \gamma$, etc.

Bohr radius of bound nuclei between $2 - 4$ Fermis

$\rightarrow$ formation of bound states towards the end of BBN

Fraction of nuclei bound to X^-



Production of ^{6}Li in catalytic nucleosynthesis

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

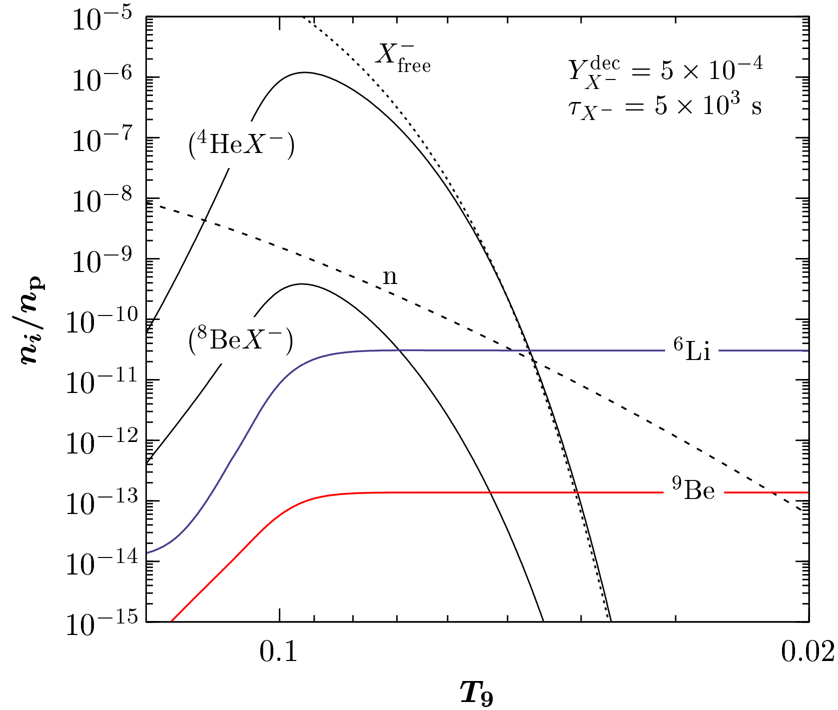
formation of bound states with nuclei

$^7\mathrm{Be} + X^- \rightarrow (^7\mathrm{Be}X^-) + \gamma$ 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



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

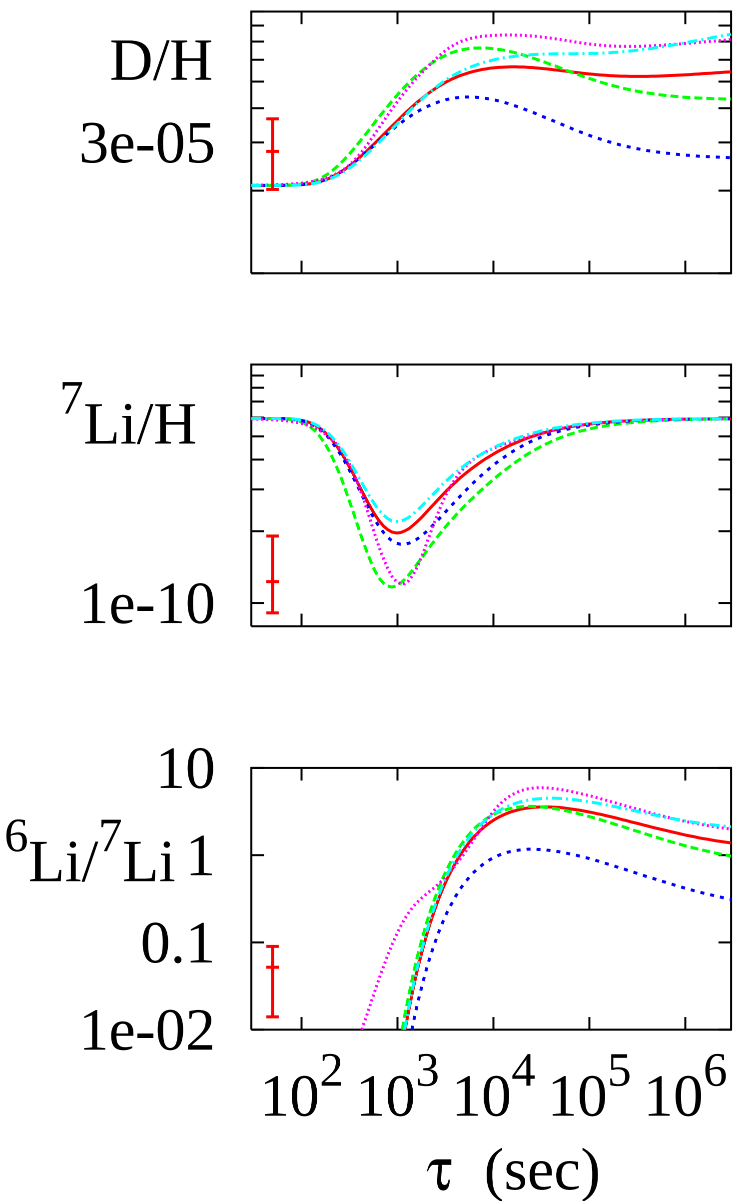
Catalysis and $^6\mathrm{Li}$, $^7\mathrm{Li}$, and $^7\mathrm{Be}$

Catalysis:

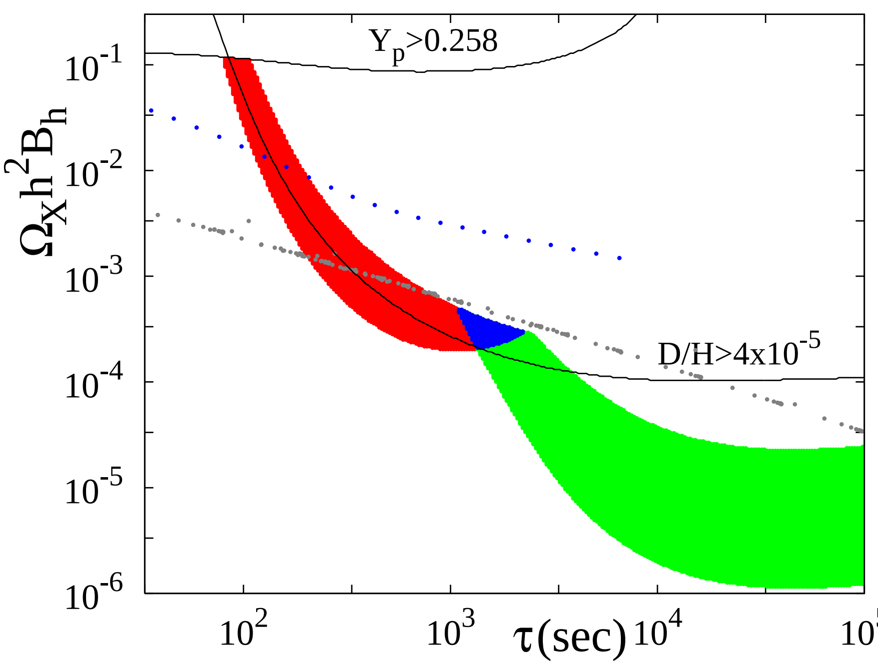
- main production mechanism for $^6\mathrm{Li}$ if $B_h \lesssim 10^{-2}$
- may **not** solve the $^7\mathrm{Li}$ problem, unless $B_h \lesssim 10^{-5}$ rather small and $\Omega_X \gtrsim 10$ rather large
- not clear if may lead to some $^9\mathrm{Be}$ production

The lithium friendly parameter space in cascade nucleosynthesis

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

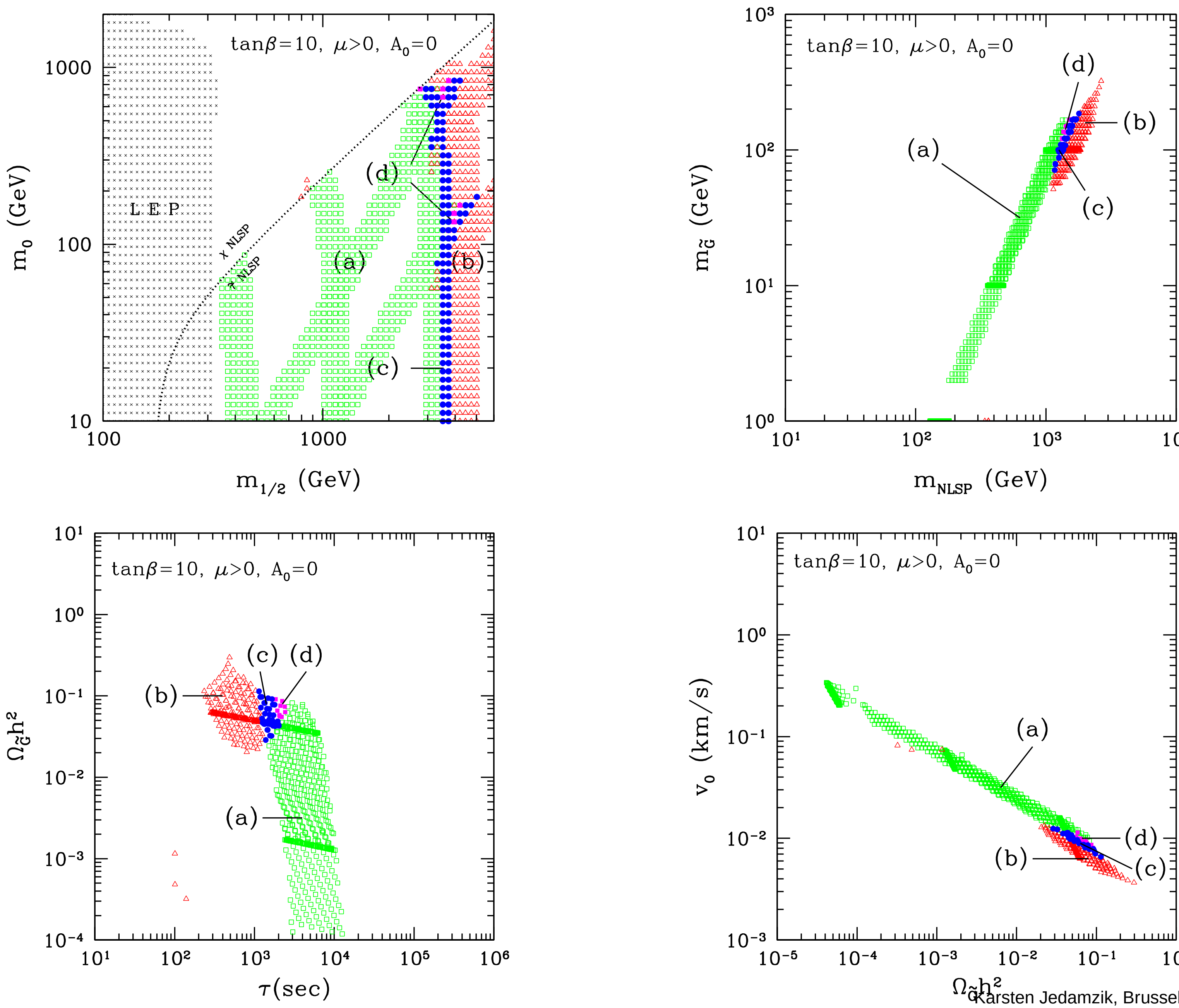
Examples:

Gluino in split supersymmetry

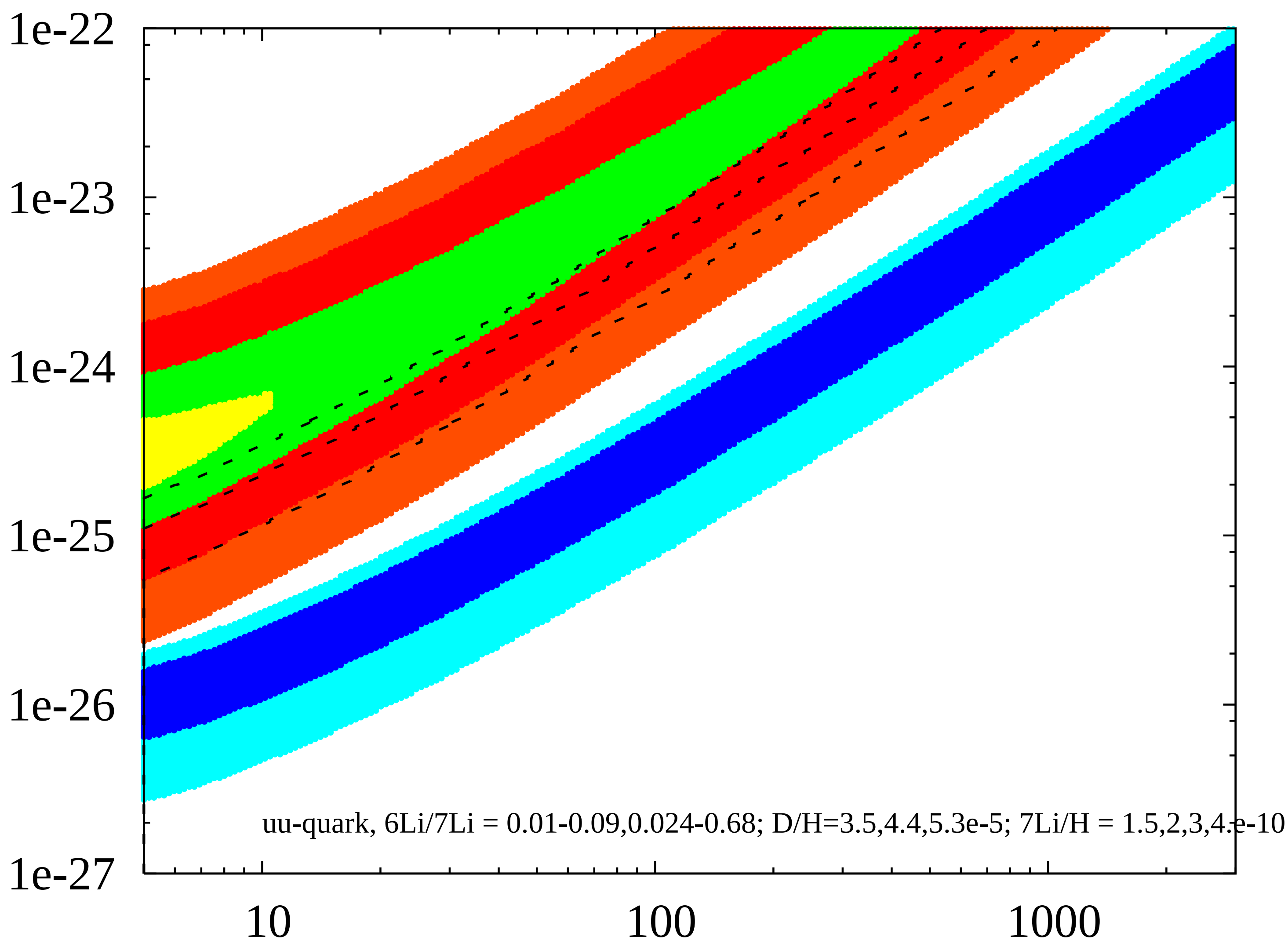
supersymmetric stau Next-to-LSP with gravitino LSP

Example: Gravitino dark matter in the CMSSM

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



Solving the ^{6}Li and ^{7}Li problems by neutralino annihilation ?

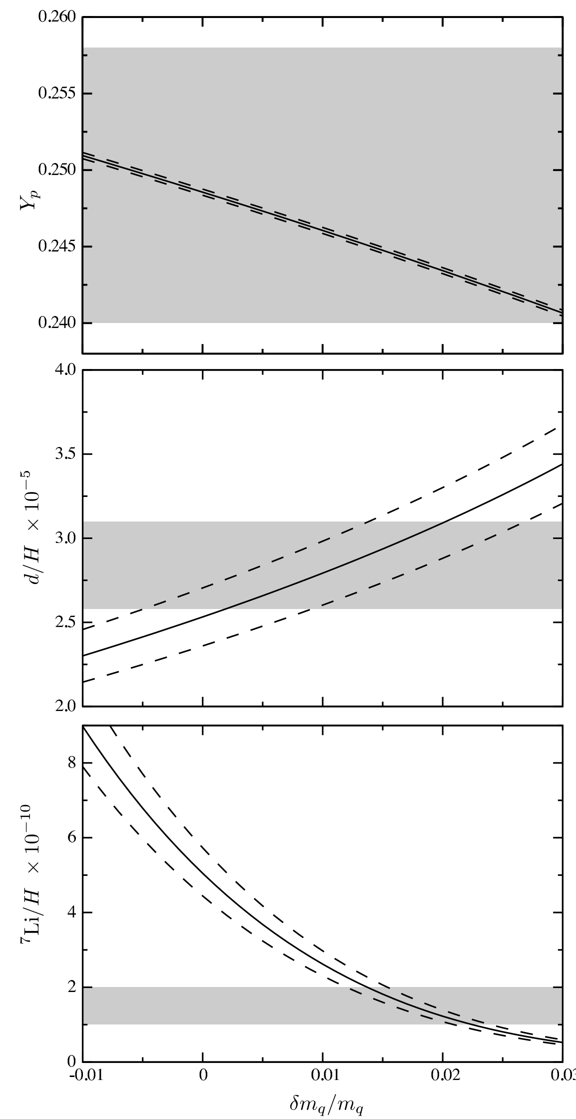


Varying fundamental constants and $^7\mathrm{Li}$

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

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

$\Delta B_d/B_d \approx -0.019 \pm 0.005 \rightarrow$ reduce $^7\mathrm{Li}$ (and $^4\mathrm{He}$)
$\Delta m_q/m_q \approx 0.013 \pm 0.002 \rightarrow$ reduce $^7\mathrm{Li}$



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 $\rightarrow$ 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 continous to be a powerful probe of the early Universe and physics beyond the standard model