Can mirror matter alleviates the BBN "lithium problem" ?

Alain Coc

(**C**entre de **S**ciences **N**ucléaires et de **S**ciences de la **M**atière, Orsay)

Elisabeth Vangioni and Jean-Philippe Uzan

(**I**nstitut d' **A**strophysique de **P**aris)

- Standard Big-Bang Nucleosynthesis: the "lithium problem"
- Mirror Matter and neutron oscillations in BBN
- Mirror Matter as Dark Matter

[Coc Vangioni & Uzan (arXiv:1303.1935) PRD 87 (2013) 123530]

Primordial (Big-Bang) Nucleosynthesis

One of the three observational evidences of Big-Bang Model besides the expansion of the Universe and the CMB.

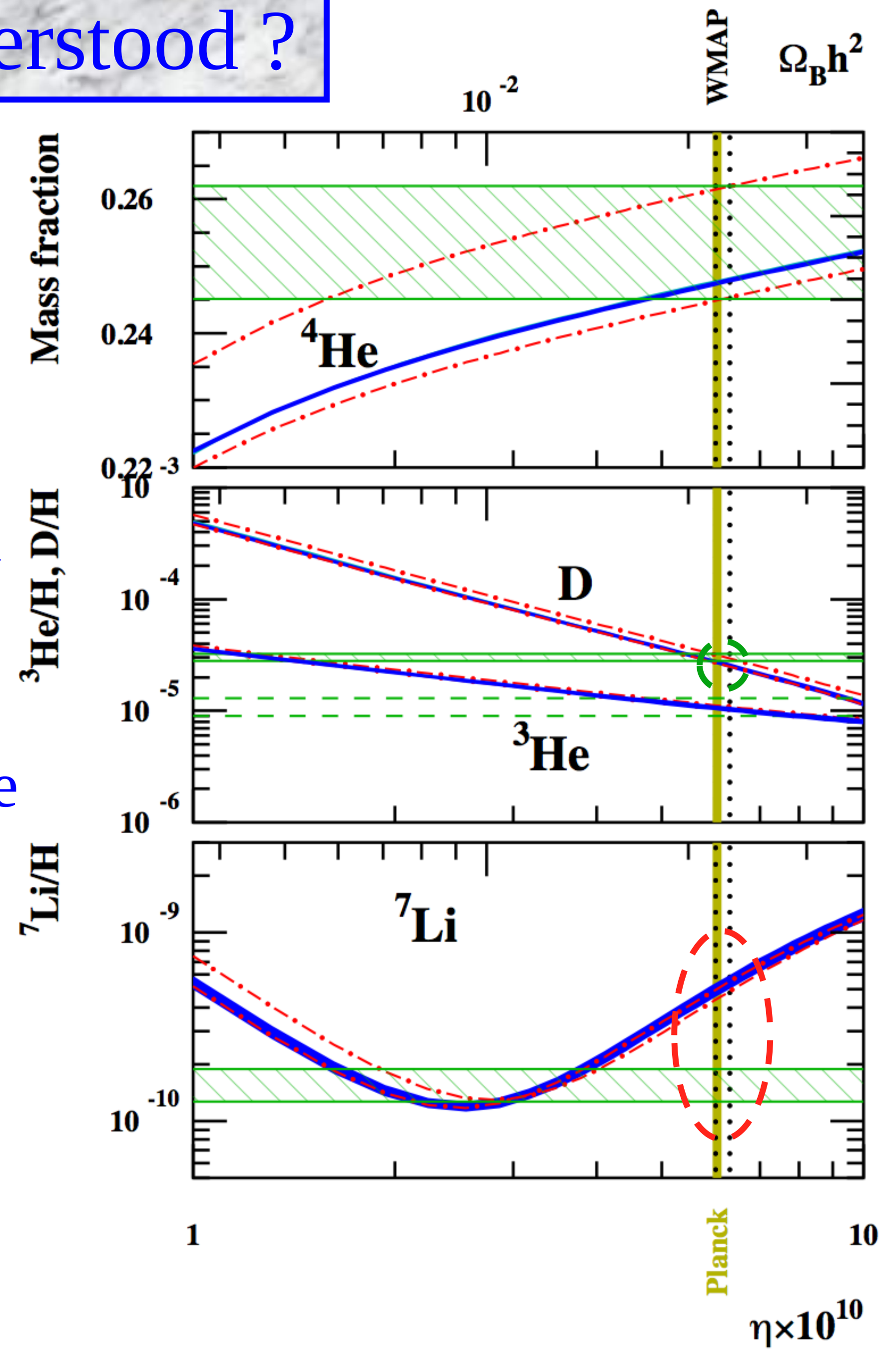
Reproduces the light-elements ^{4}He, D, ^{3}He, ^{7}Li primordiaabundances over a range of nine orders of magnitudes

- First determination of the baryonic density of the Universe, (1-3) $\times 10^{-31}$ g/cm^3 *[Wagoner 1973]*, need for baryonic dark matter, now superseded by CMB *[WMAP, Plank]*
- First estimate of the number of light neutrino families, $N_\nu \leq 3$ *[Yang, Schramm, Steigman, Rood 1979]*, now superseded by LEP

SBBN is now a parameter free model that can be used to probe of the physics of the early Universe

Is Standard BBN well understood ?

- Monte-Carlo (rate uncertainties) BBN calculation function of η or $\Omega_b h^2$ compared with observations
- Using most recent
  - Nuclear data (essentially from laboratory experiments)
  - Abundance determinations (from observations of primitive objects)
- At η given by Planck
  - ✓ Agreement for ^{4}He, D and ^{3}He
  - ✓ Difference of a factor of ≈ 3 for Li !
  - ✓ $2.89 < N_{eff} < 4.22$

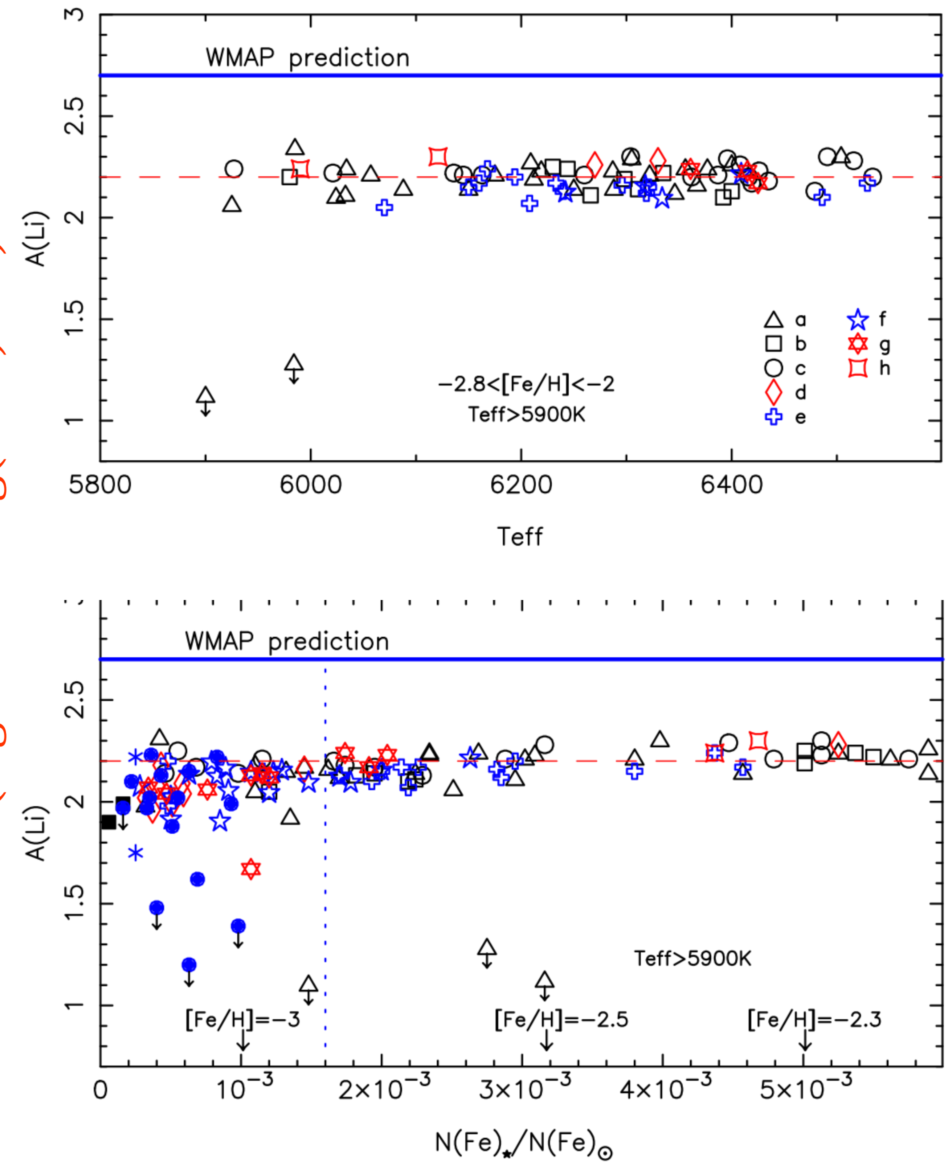


Primordial Li from observations

[Spite, Spite & Bonifacio 2012]

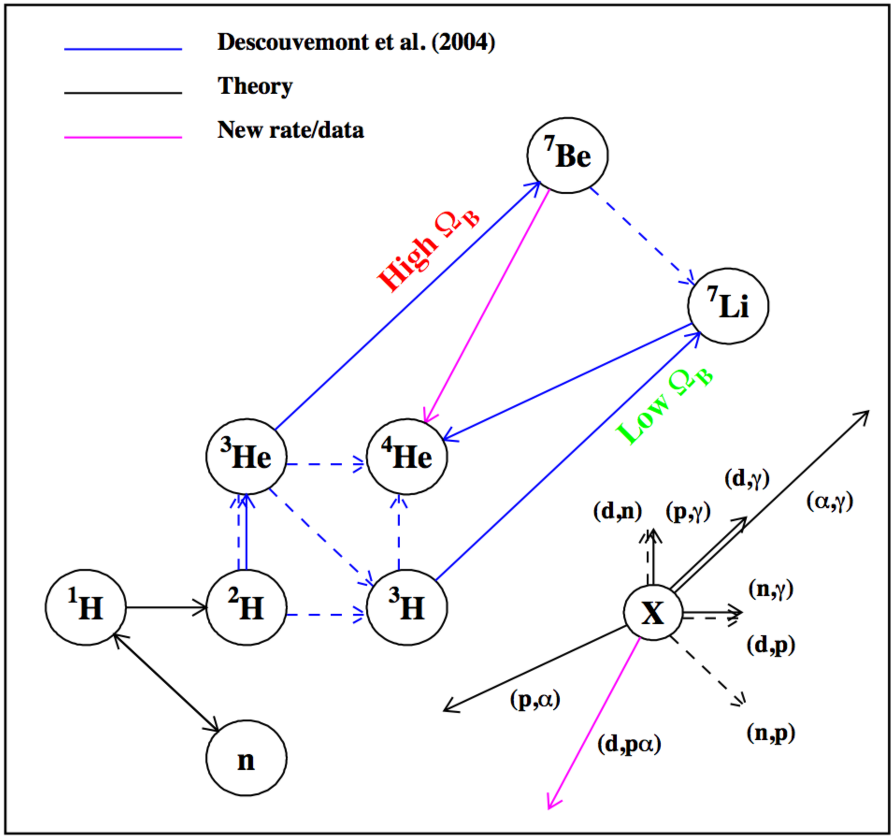
- Lifetime of $M < 0.9\,M_\odot$ stars > 15 Gy
- Oldest (lowest metallicity e.g. Fe) stars in galactic halo
- For T_{eff} > 5900 K, no deep convection and no Li surface depletion (?)
- Atomic, turbulent diffusion and mass loss interplay could restore the plateau (with ad hoc parameters) *[Richard+ 2005; Vick+ 2013]*
- Nuclear solution ?
- Exotic solutions ?

(log scale : Log(Li/H)+12) !



Li in the Cosmos, Paris, Feb. 2012, http://www.iap.fr/lithiuminthecosmos2012

Nuclear solution to the Li problem ?



At η_{WMAP} ^{7}Li from ^{7}Be post BBN decay

Tentatives nuclear solutions:
^{7}Be destruction by:

1. Supplementary reactions e.g. ^{7}Be(d,p)^{8}Be*$\rightarrow 2\alpha$

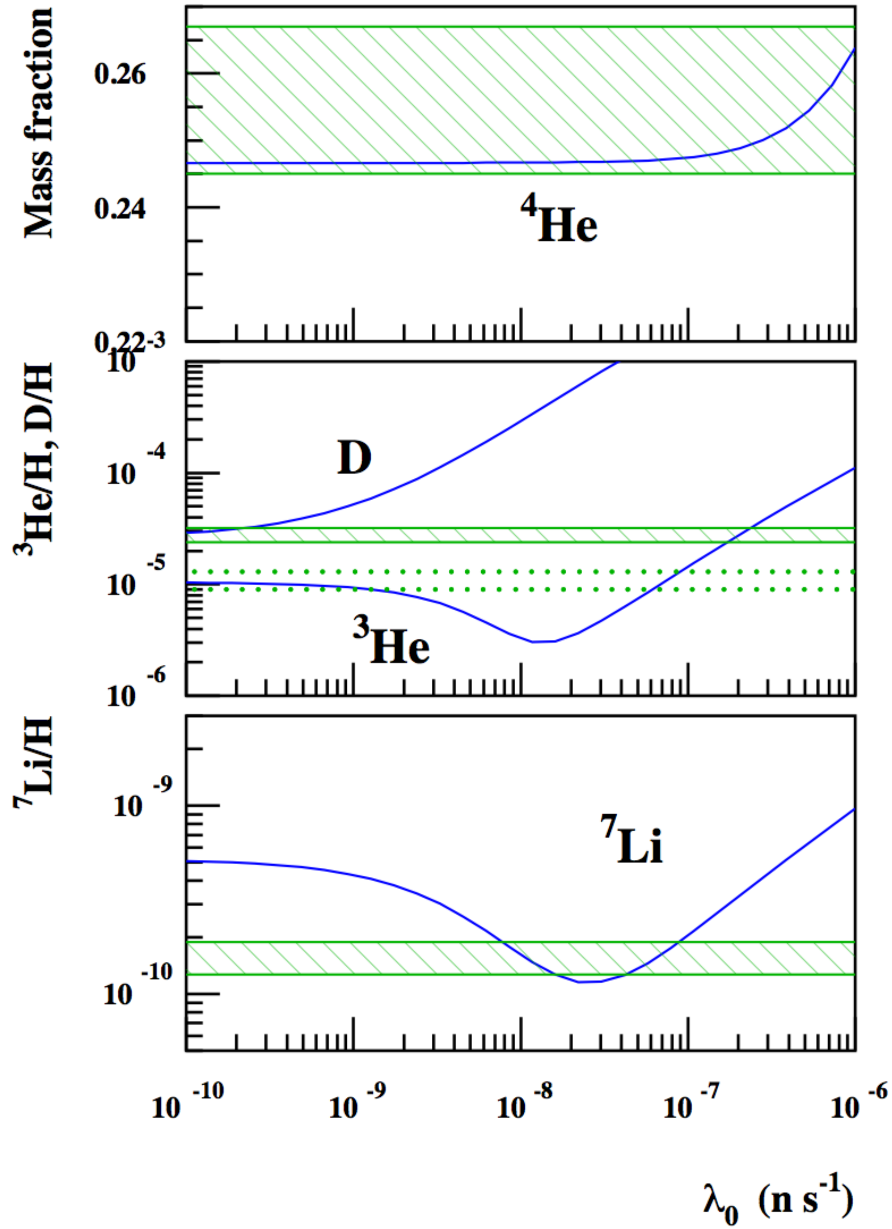
1. Extra neutron sources in ^{7}Be(n,p)^{7}Li(p,α)^{4}He destruction channel

Late neutron injection alleviate the Li problem

- Late time injection alleviate the Li problem at the expense of (harmless) D overproduction *[Jedamzik 2004; Coc+ 2007; Albornoz Vásquez+ 2012]*

- Due to higher neutron abundance at late time: $^{7}Be(n,p)^{7}Li(p,\alpha)^{4}He$

- Need extra neutron source
  - Exotic ?
  - Nuclear ? *[Coc+ 2012]*



Mirror matter

- Mirror matter (noted with a prime "´" or "M")
  - Postulated to restore global Parity symmetry *[Li & Yang 1956]*
  - Same particles but opposite parity, almost only gravitational interaction with ordinary matter, Dark Matter candidate *[Berezhiani+ 1996,...; Foot+ 1997,.....; Ciarcelluti+ 2008,....]*
  - Microphysics (including nuclear physics) identical in both sectors
  - But different cosmologies ($T' \neq T$ and $\eta' \neq \eta$) due to inflation

$$\boxed{\mathcal{L}=\mathcal{L}_{G}(e,u,d,\varphi,\ldots)+\mathcal{L}_{G}(e',u',d',\varphi',\ldots)+\mathcal{L}_{mix}}$$

  - Neutral particles (e.g. neutrons) could oscillate between the two worlds
  - Experimental search of neutron oscillations (at ILL, Grenoble, $\tau_{osc} > 414$ s *[Serebrov+ 2008]*)

Thermodynamics in the Standard Model

Cosmological distances $\propto R \equiv (1+z)^{-1}$ $(z = \text{redshift})$

Rate of expansion $\propto$ (radiation energy density)$^{1/2}$

① $$\boxed{\frac{1}{R}\frac{dR}{dt} \propto \sqrt{\rho_{e\gamma\nu}^{rad}(T)} \propto \sqrt{g_*^{e\gamma\nu}(T)}\,T^2}$$

$$g_*^{e\gamma\nu} = 2 + \frac{7}{8}\left(2 \times \boxed{N_\nu}\left[\frac{T_\nu}{T}\right]^4 + 2 \times 2\right)$$

$T_\nu = T$ for $T \gg 1$ MeV

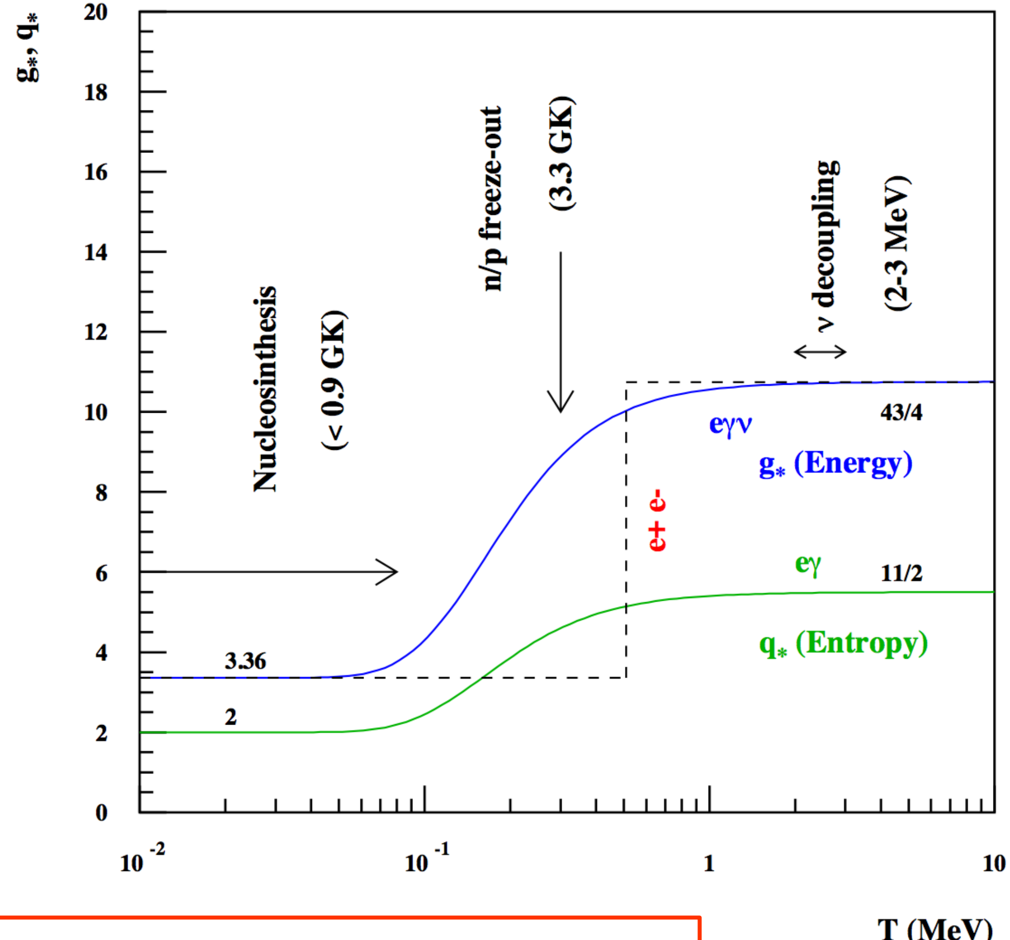
② $$\boxed{R^3 T_\nu^3 = Cste}$$

③ $$\boxed{R^3 q_*^{e\gamma}(T)\,T^3 = Cste}$$

Entropy constant

$T_\nu = T \times (4/11)^{1/3}$ for $T \ll 1$ MeV

g_*, q_* = spin factors



$$\boxed{①+②+③ \Rightarrow \rho_b(t) \propto \Omega_b\, R^3(t),\ T(t) \text{ and } T_\nu(t)}$$

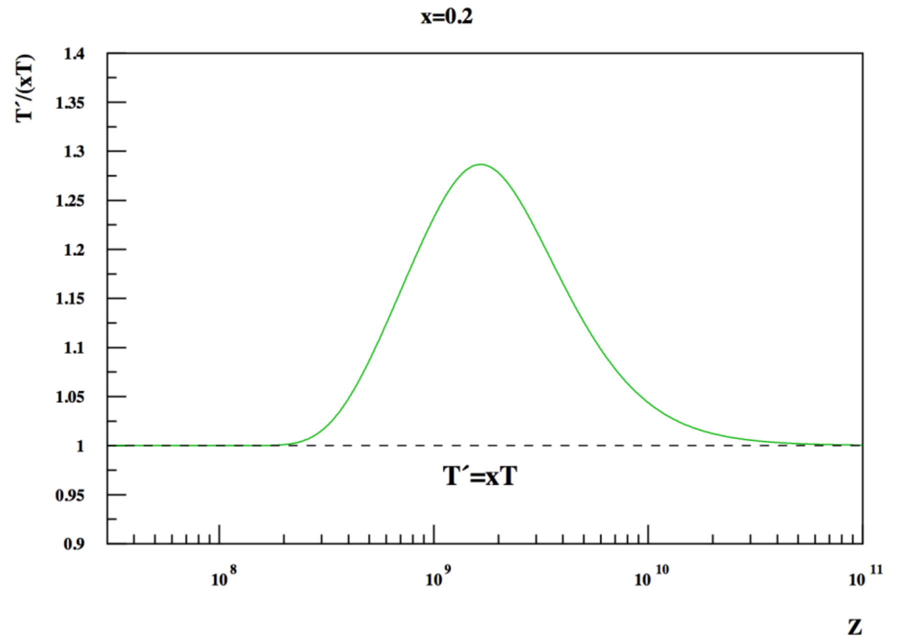
Thermodynamics with Mirror Matter

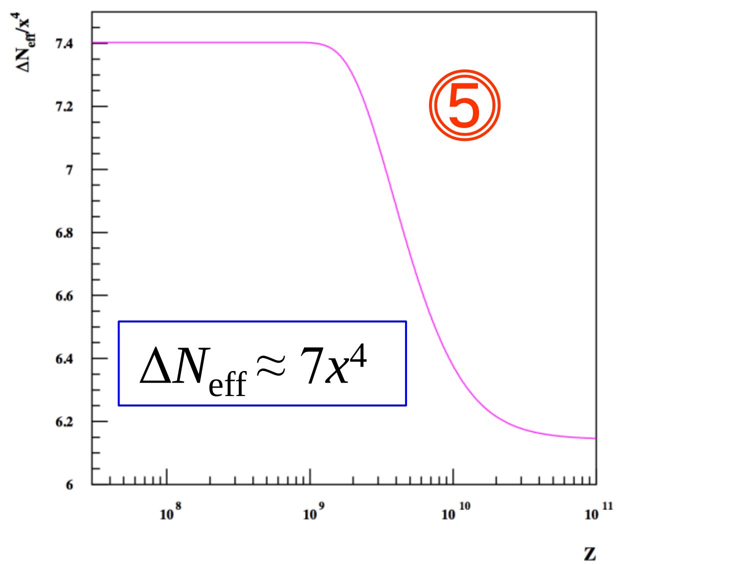
Increased radiation density $\rho_{e\gamma\nu} \longrightarrow \rho_{e\gamma\nu} + \rho'_{e\gamma\nu}$ in ① but BBN (^{4}He) limits

④ $$\Delta N_{\text{eff}} \equiv \frac{r'(T')}{\frac{7}{8} a_R T_\nu^4} \leq 1.22$$

Need a lower temperature in M-world: $T'_\nu / T_\nu = x < 1$, a constant while $T'/T \approx x$ for the photon temperatures

- $x \lesssim 0.65$ from BBN (④ & ⑤)
- But no BBN constraint on η': i.e. allows DM = Mirror Matter





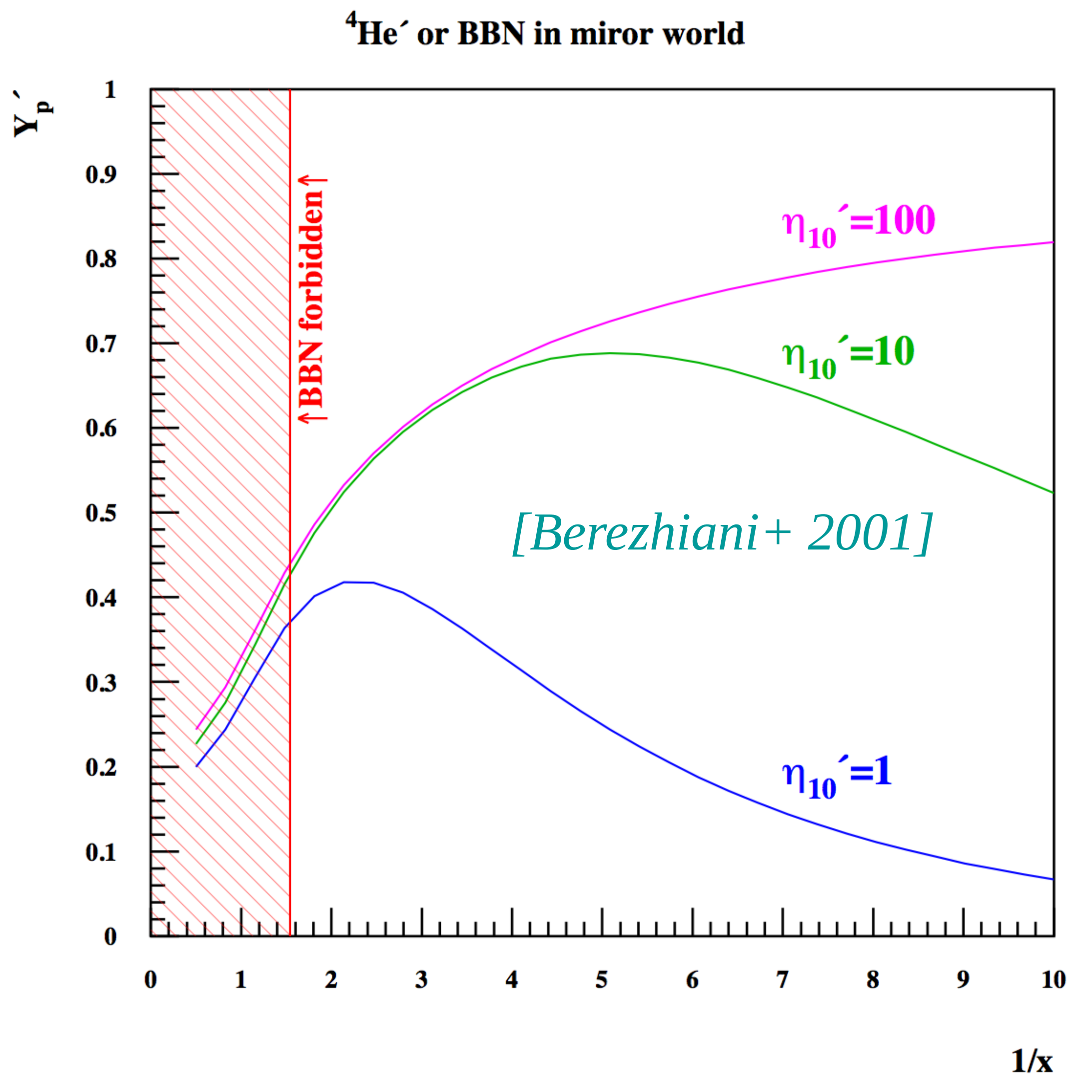
BBN in the Mirror World

Depending on $x \lesssim 0.65$ and η' values, a ≠ BBN in the M-World *[e.g. Ciarcelluti PhD]*:

- ≠ ^{4}He´ abundance
- ≠ Stellar evolution
- ....

and

- ≠ M-neutron (n´) abundance!☺But for low η' values ☹



Neutron oscillations

Only neutral particles can interact, non-gravitationally, between the two worlds: neutrinos (sterile-neutrinos*[e.g. Foot+ 1996]*), photons (millicharged particles*[Foot 2012]*), neutrons ($\mathcal{L}_{\mathrm{mix}}$).

Off-diagonal terms in the mass matrix allows oscillations:

$$M = \begin{pmatrix} m - \dfrac{i}{2\tau_{\mathrm{n}}} & \dfrac{1}{\tau_{\mathrm{osc}}} \\ \dfrac{1}{\tau_{\mathrm{osc}}} & m - \dfrac{i}{2\tau_{\mathrm{n}}} \end{pmatrix}$$

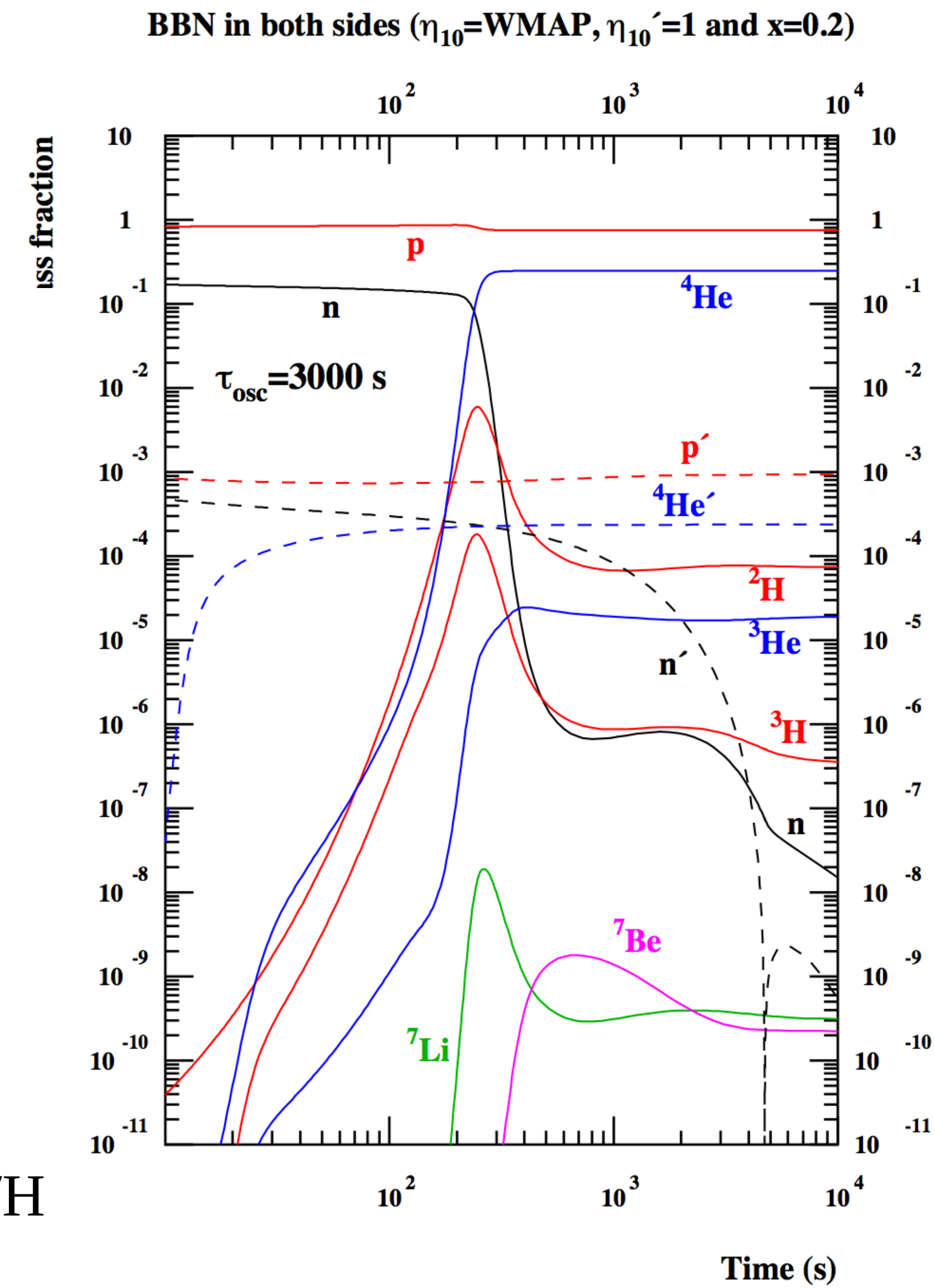
$$n' \propto e^{-t/\tau_{\mathrm{n}}} \cos^2\left(t/\tau_{\mathrm{osc}}\right)$$

To allow for late time neutron injection:

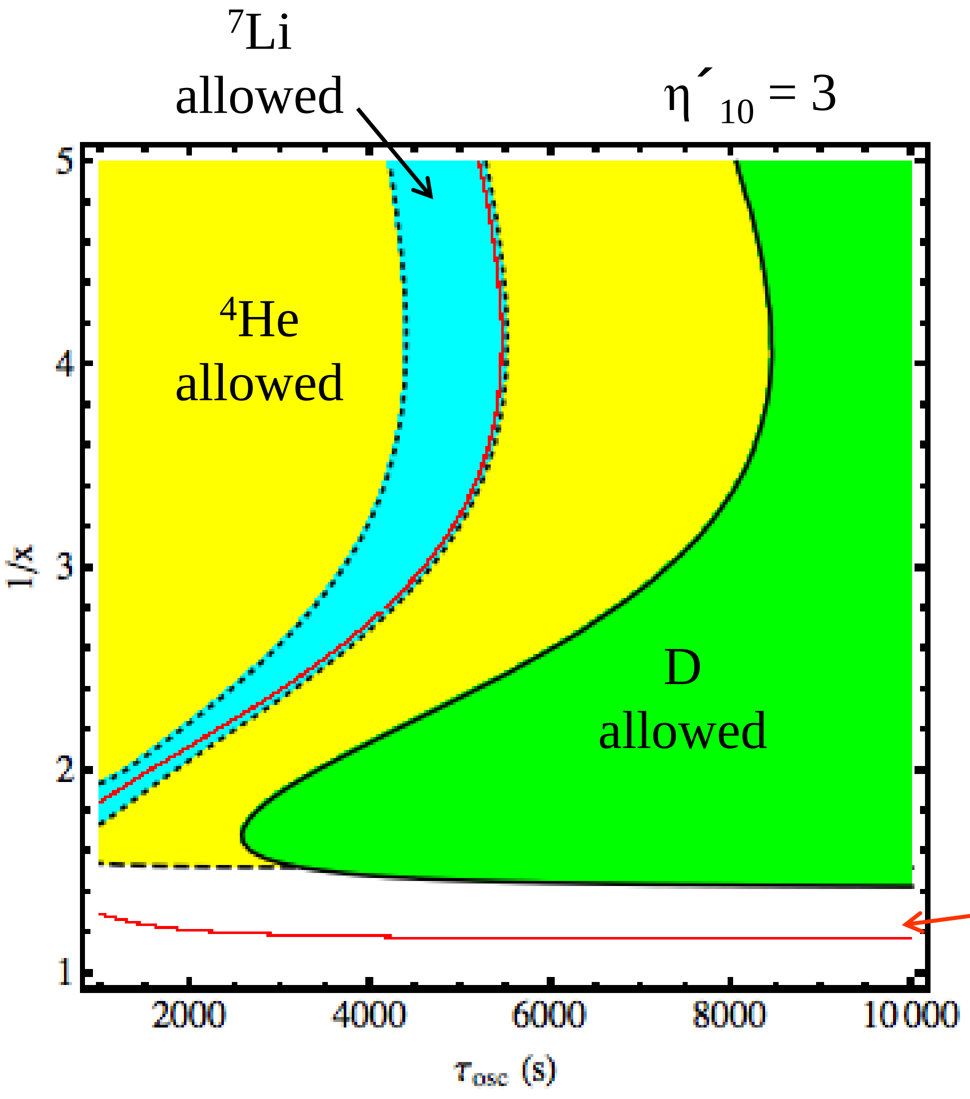
- n´ abundance remains high, i.e. low η'
- Oscillation time $\tau_{\mathrm{osc}} \sim 1000$ s, i.e. BBN time scale

BBN with Mirror Matter

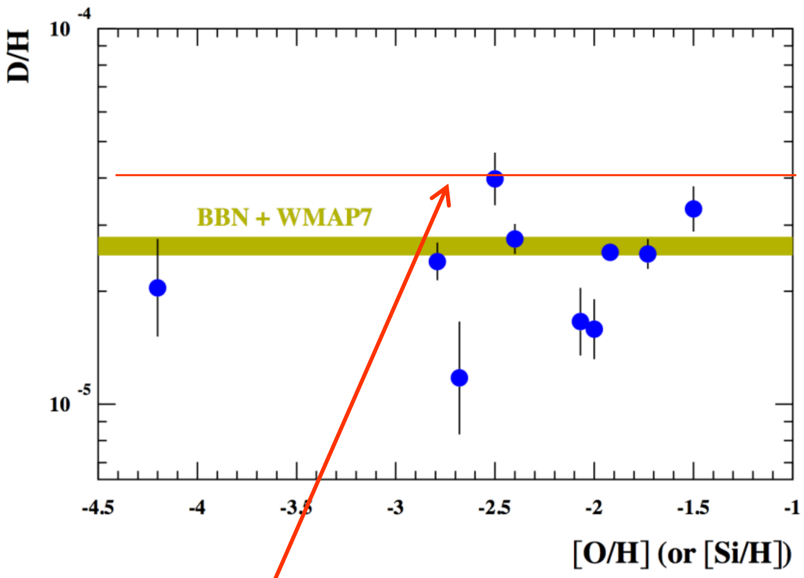
- ➢ Same isotopes (with ´), same cross sections, 3 parameters:
- ➢ Temperature ratio $x = T'/T$
- ➢ Baryonic density $\eta' \neq \eta$
- ➢ Oscillation time τ_{osc}
- ⇨ Excess mirror neutrons can oscillate to normal neutrons i.e. $n' \rightarrow n$
- ⇨ Destroy excess ^{7}Be
- ⇨ with τ_{osc} compatible with experiments (> 414 s *[Serebrov+ 2008]*)
- ⇨ At the expense of a higher D/H



Mirror Matter can reconcile BBN with observations



Primordial D/H: from observations of remote cosmological clouds on the line of sight of quasars

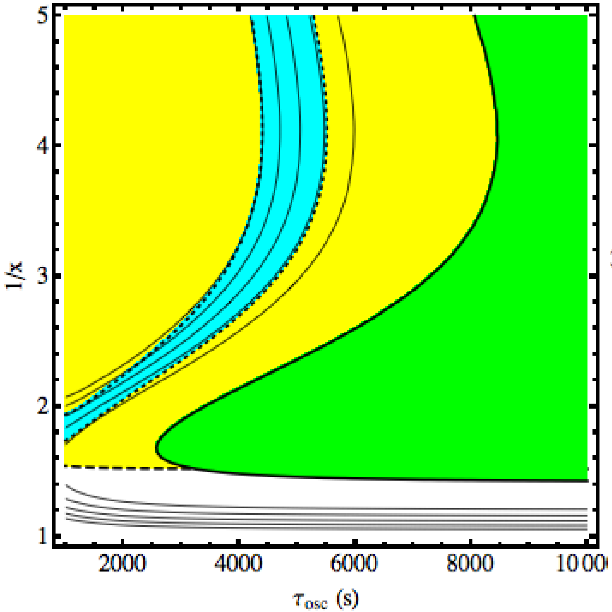


D/H = 4 10^{-5}

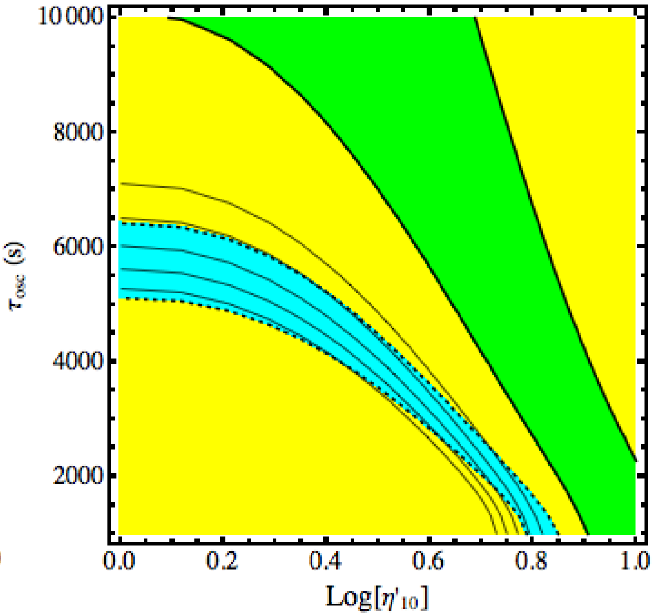
[Olive+ 2012]

Mirror Matter can reconcile BBN with observations

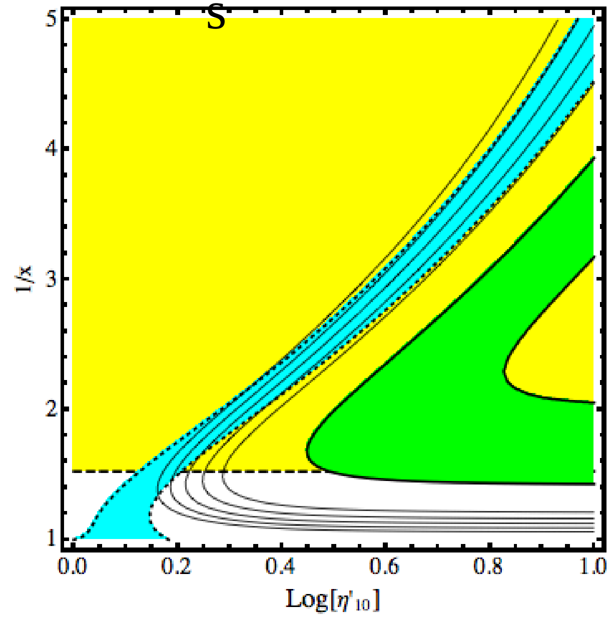
$\eta'_{10} = 3$



$1/x = 3$



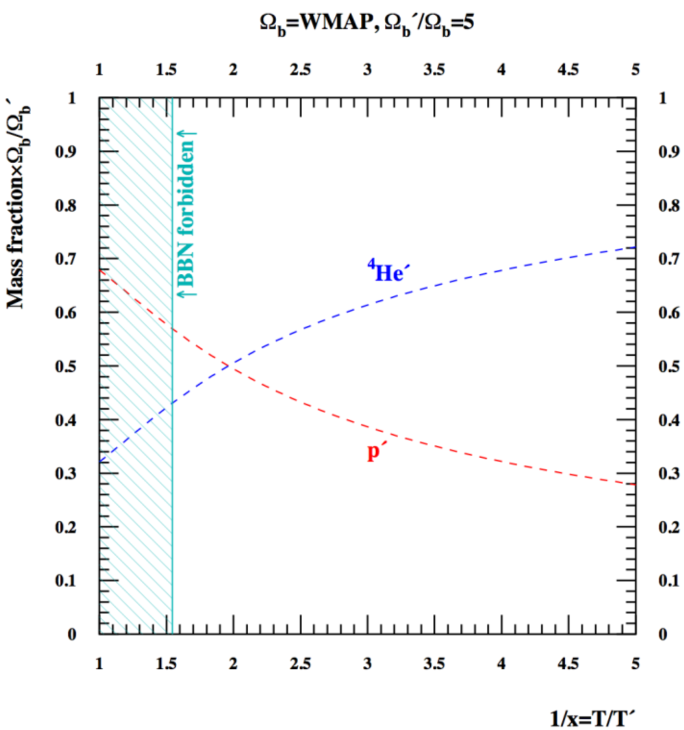
$\tau_{osc} = 3 \times 10^3$ s

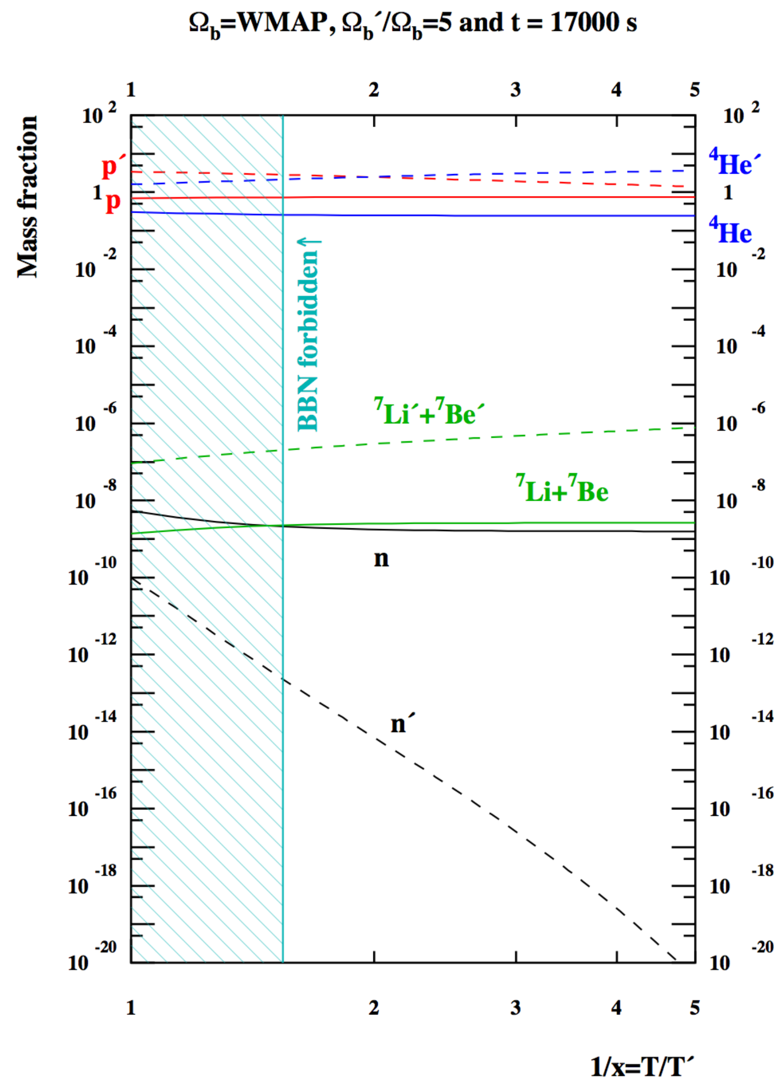


D/H = (3.8, 4.0, 4.2, 4.4, 4.6) $\times 10^{-5}$

Dark Matter = Mirror Matter : no help for ^{7}Li

When $\Omega_b{}' / \Omega_b \approx 5$ to identify Dark Matter with Mirror Matter, mirror neutrons are too scarce
W





Dark Matter = Mirror Matter ? *[Foot 2010; 2013]*

Photons M-photons interactions $\qquad \mathcal{L}_{\rm mix} = \frac{\epsilon}{2} F'_{\mu\nu} F^{\mu\nu} \quad (\varepsilon \sim 10^{-9})$

⇒ M-charged particles seen as millicharged (εe) particles

⇒ M-nuclei (A',Z') can scatter off ordinary nuclei (A,Z) with a Rutherford cross-section reduced by ε^2 and *recoil detected!*

MM is self interacting and dissipative as ordinary matter ≠ WIMPs

⇒ Different DM halo spatial and velocity distributions:

⇒ Compatible with the DAMA, CoGeNT, CRESST-II and CDMS/Si signals and no signals in other experiments according to *Foot 2013 [arXiv:1209.5602v3]*

Conclusions

- SBBN + WMAP/Planck in good agreement with D and ^{4}He observations
- However disagreement (factor of ≈3) with Li observations *[Spite, Spite & Bonifacio 2012, Fields 2011]*
  - Nuclear : most probably no
  - Stellar depletion (diffusion+turbulence) *[Korn et al. 2006, Richard et al. 2005]* ? Need to be uniform!
  - Cosmology or particle physics : dark/supersymmetric particle decay or catalysis, variation of constants, axion BEC, **mirror matter** .... ?