BBN And The CMB Constrain Equivalent Neutrinos (Dark Radiation)

Gary Steigman

with K. M. Nollett

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The "Effective Number Of Neutrinos"

&

Counting "Equivalent Neutrinos"

In the early Universe the energy density is dominated by the contributions from ER (extremely relativistic) particles. The early Universe is "Radiation Dominated" (R).

When T << m_e , the only ER standard model (SM) particles are the photons and neutrinos.

$$\rho \approx \rho_R = \rho_\gamma + 3\,\rho_\nu >> \rho_B$$

where, $\rho_\nu / \rho_\gamma = 7/8\,(T_\nu / T_\gamma)^4$

The SM neutrinos decouple when $T_\gamma = T_\nu \approx 2 - 3$ MeV, before (barely) $e^\pm$ annihilation.

IF neutrino decoupling were instantaneous, and, IF $T_{\nu d} >> m_e$, then after the $e^\pm$ pairs have annihilated, $(T_\nu / T_\gamma)^3 = 4/11$.

With these assumptions and, in this regime,

$$\rho / \rho_\gamma = 1 + 3\,[\,7/8\,(4/11)^{4/3}\,]$$

N_{eff}, the "Effective Number of Neutrinos",

is defined by : $\rho / \rho_\gamma \equiv 1 + N_{eff} [\, 7/8\, (4/11)^{4/3} \,]$

or, $N_{eff} \equiv 3\, [11/4\, (T_\nu / T_\gamma)^3\,]^{4/3}$ (when $T_\gamma << m_e$).

If neutrino decoupling were instantaneous and, if electrons were massless, $N_{eff} = 3$.

Since $T_{\nu d}$ is not >> m_e, $N_{eff} \approx 3.02$.

Since neutrino decoupling is not instantaneous, $N_{eff} \approx 3.05$.

An **“Equivalent Neutrino”**, ξ, is a very light ($m_\xi \ll m_e$) particle that may, or may not, be a Majorana fermion (“neutrino”).

If ξ is populated in the early Universe, either thermally or via mixing with the SM neutrinos, $\rho_R \rightarrow \rho_R + \rho_\xi \equiv \rho_R + \Delta N_\nu \rho_\nu$.

$\Delta N_\nu = \rho_\xi / \rho_\nu$ is the number of equivalent neutrinos (a measure of dark radiation).

If ξ is a Majorana fermion ("neutrino") and if ξ is fully populated / mixed, $\Delta N_\nu = 1$ (sterile ν).

<u>But</u>, if ξ is a fully populated / mixed, real scalar, $\Delta N_\nu = 4/7$. In general, $\Delta N_\nu \leq 1$ (Dark Radiation).

N_{eff} and ΔN_ν are related by :

$$N_{eff} = N^0_{eff}\,(1 + \Delta N_\nu / 3)\,,\quad N^0_{eff} = 3\,[(11/4)^{1/3}(T_\nu / T_\gamma)_0]^4$$

The expansion rate, the Hubble parameter (H), depends on the mass / energy density : $H \propto \rho^{1/2}$

BBN Predicted Primordial Abundances Depend On Two Physical / Cosmological Parameters (ignoring any lepton (neutrino) asymmetry).

<u>Baryon Density (Nucleon Asymmetry) Parameter</u>

- $\eta_B \equiv n_N / n_\gamma$; $\eta_{10} \equiv 10^{10}\,\eta_B = 274\,\Omega_B h^2$

<u>Expansion Rate (Dark Radiation) Parameter</u>

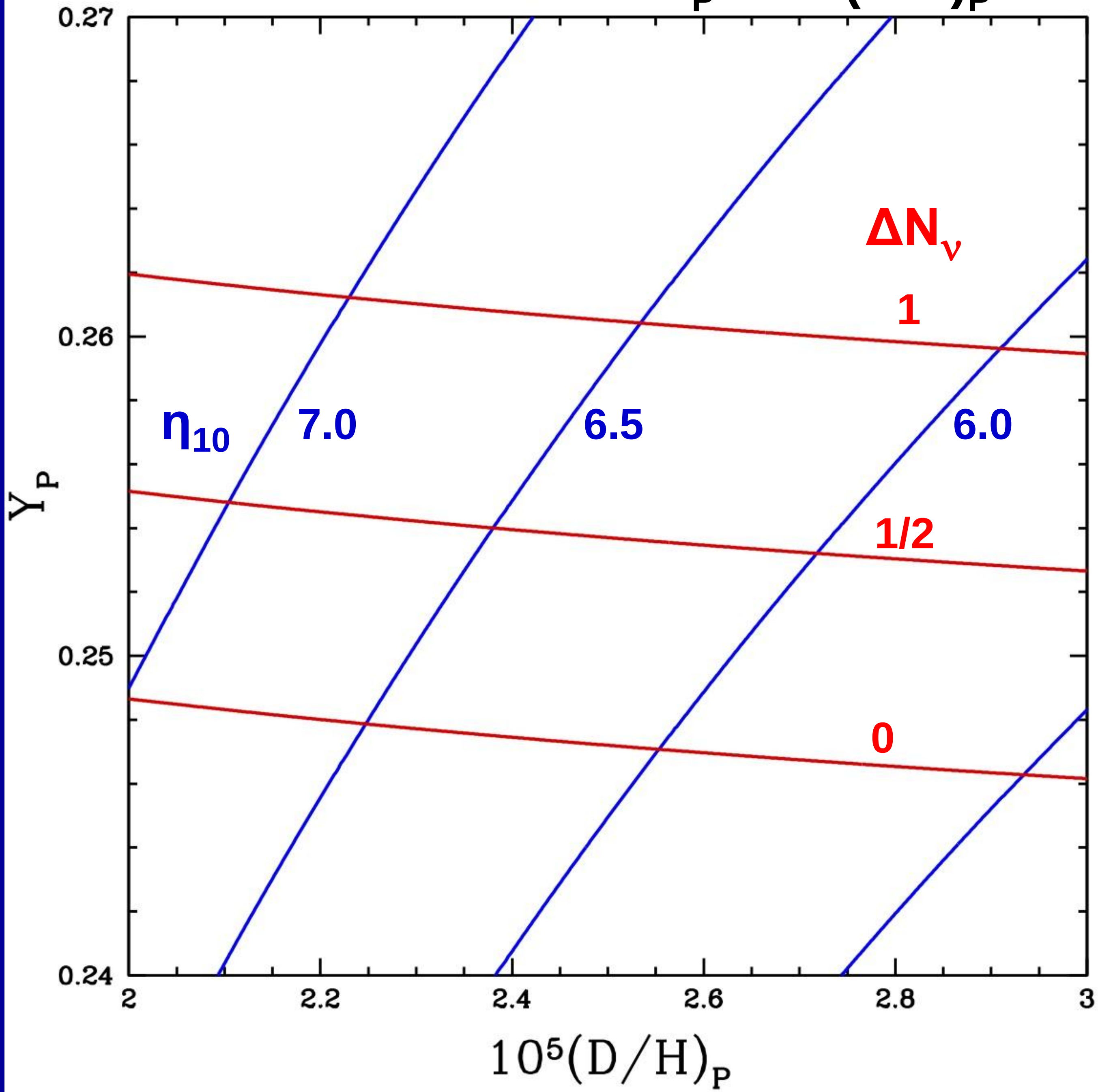
- $S^2 = (H' / H)^2 = \rho' / \rho$; S depends on ΔN_ν (N_{eff})
- **<u>SBBN</u>** : $\Delta N_\nu = 0$ ($S = 1$)

- η_B Probes "Standard" Cosmology / Physics
- D ($y_{DP} = 10^5 (D/H)_P$) is sensitive to η_B
- $\Delta N_\nu \neq 0$ Probes Non - Standard Physics
- ^4He (Y_P) is sensitive to ΔN_ν

* Two parameters (η_B and ΔN_ν)

Two observables (y_{DP} and Y_P)

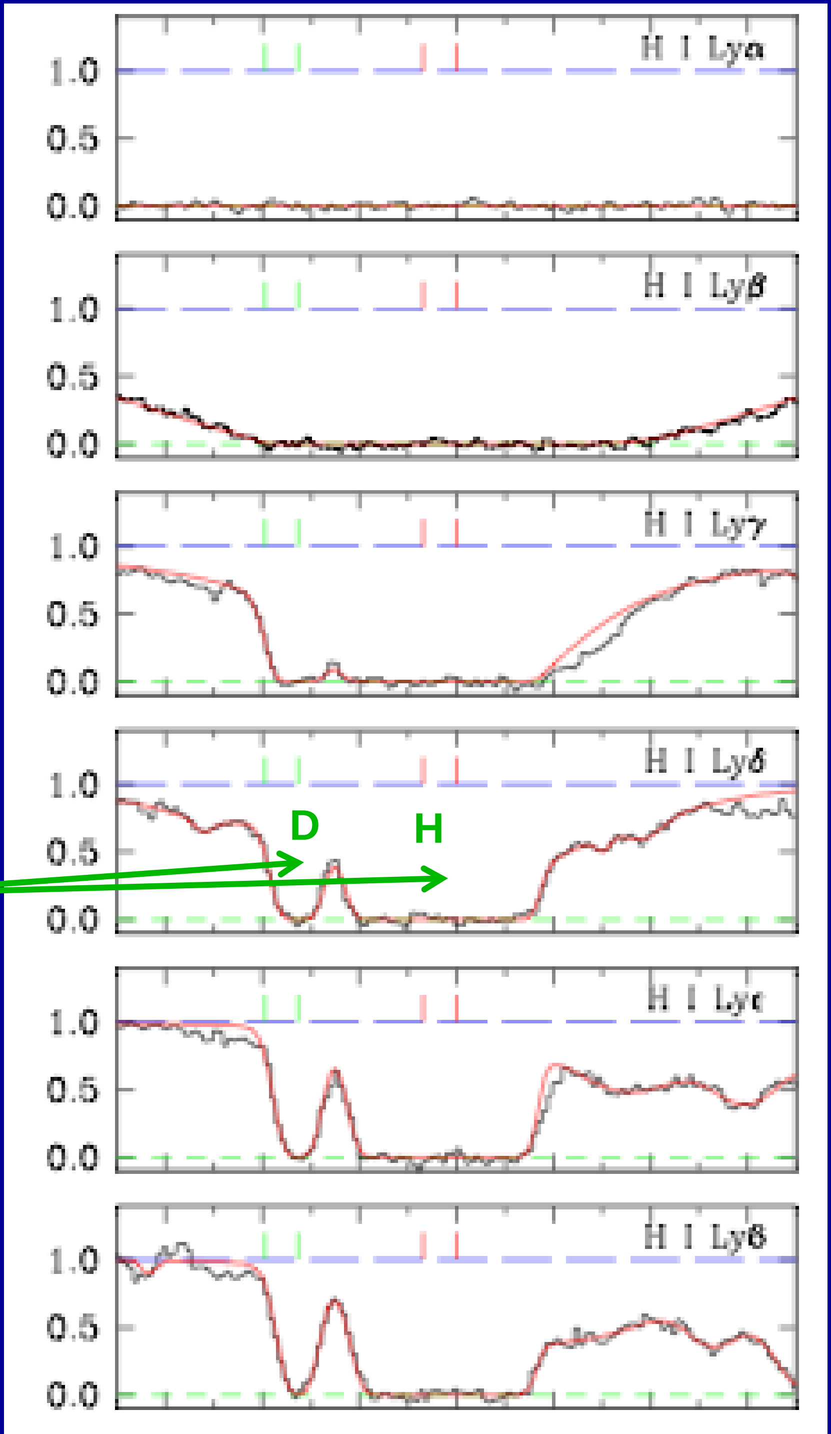
BBN – Predicted Y_P vs. $(D/H)_P$



Primordial (nearly) D

Finding D at low - Z in the Ly - α Forest

D and H absorption spectra are identical, except for an isotope shift of ~ 80 km/s



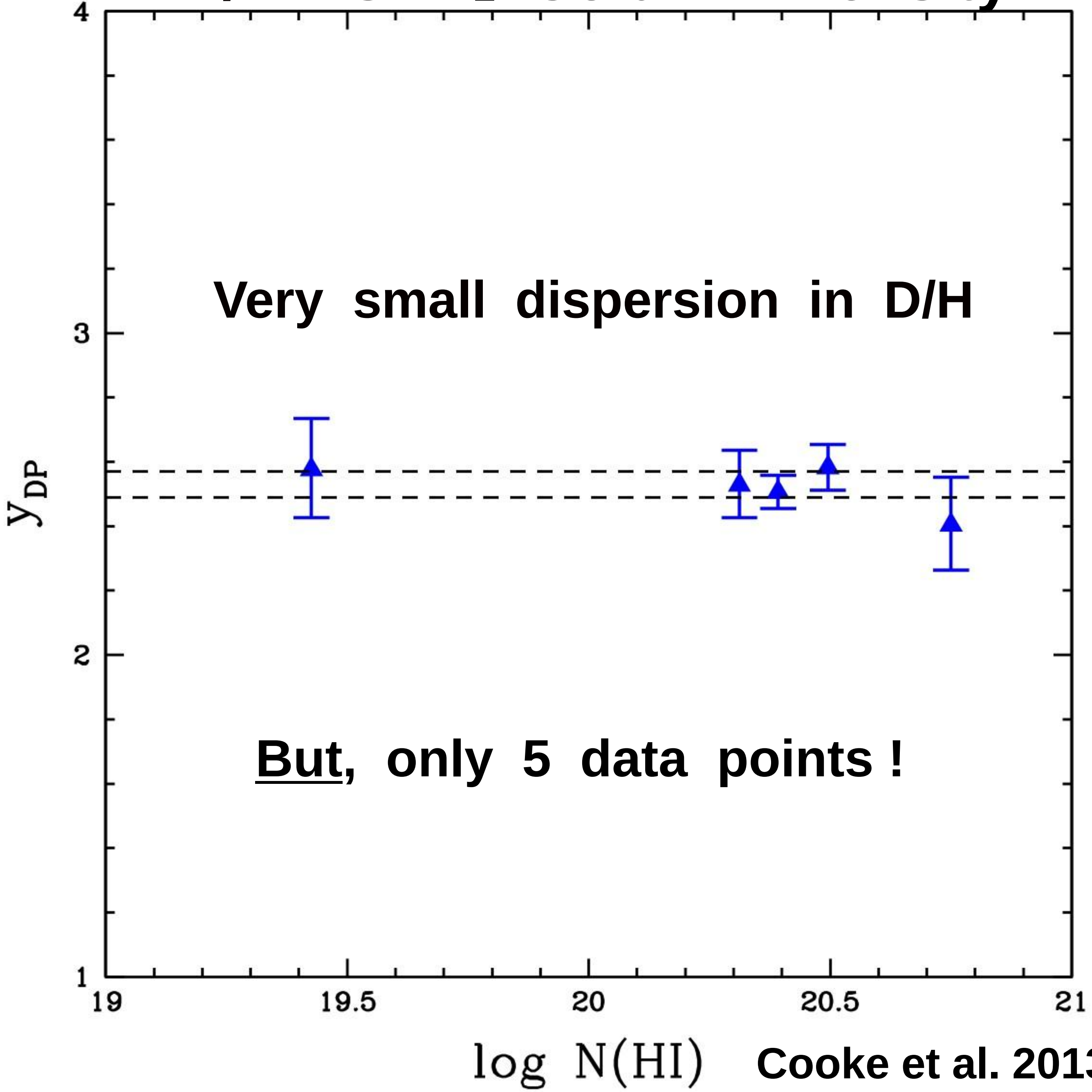
Cooke et al. 2013

Recent Results For Nearly Primordial Deuterium

Previous D observations had large dispersion among the D/H determinations.

Cooke et al. 2013 restricted their analysis to DLAs (log N(H I) > 19), allowing them access to many lines in the Lyman series, helping to reduce some sources of systematic errors.

D/H vs. H I Column Density

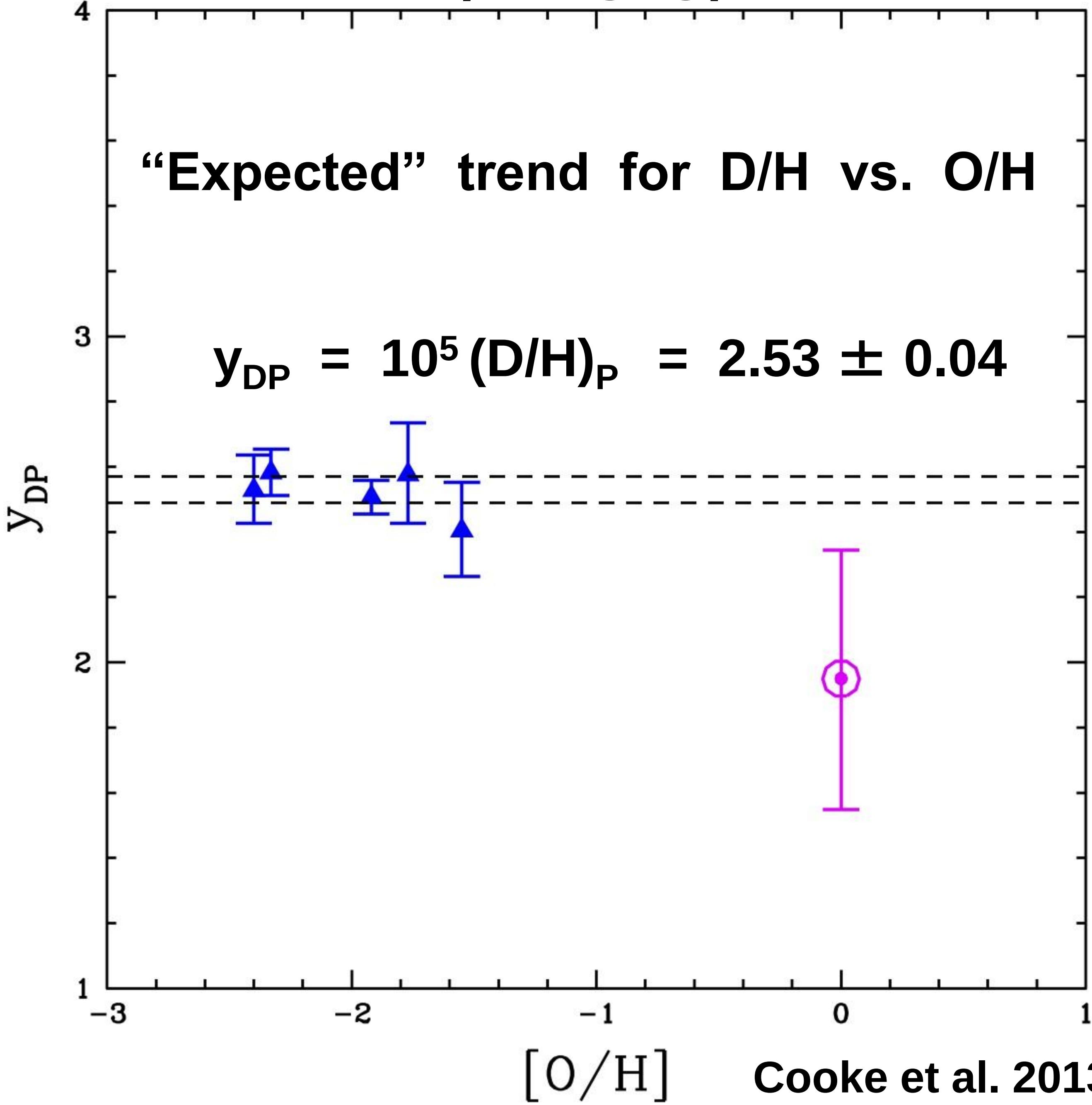


Very small dispersion in D/H

<u>But</u>, only 5 data points !

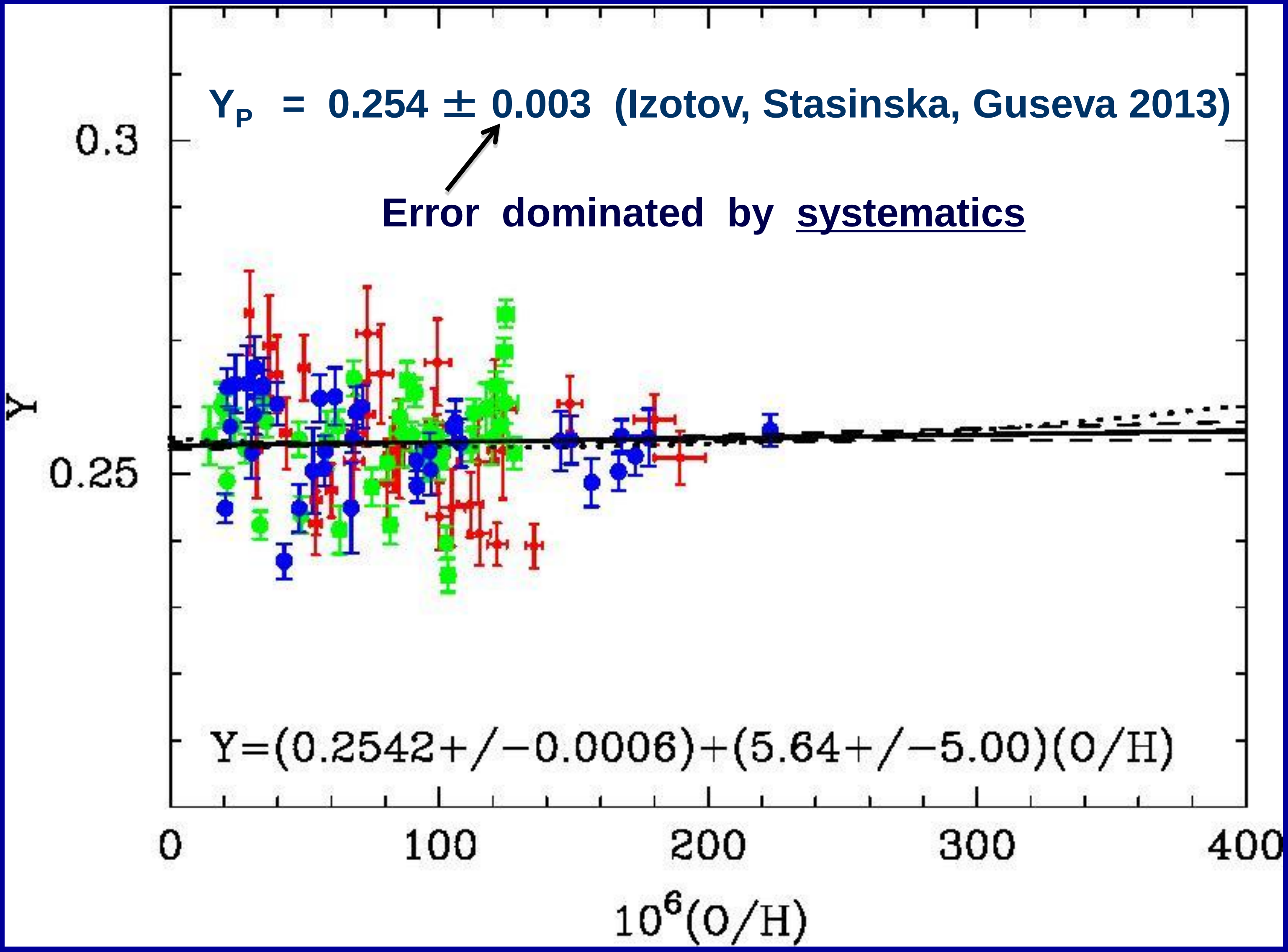
Cooke et al. 2013

D/H vs. O/H

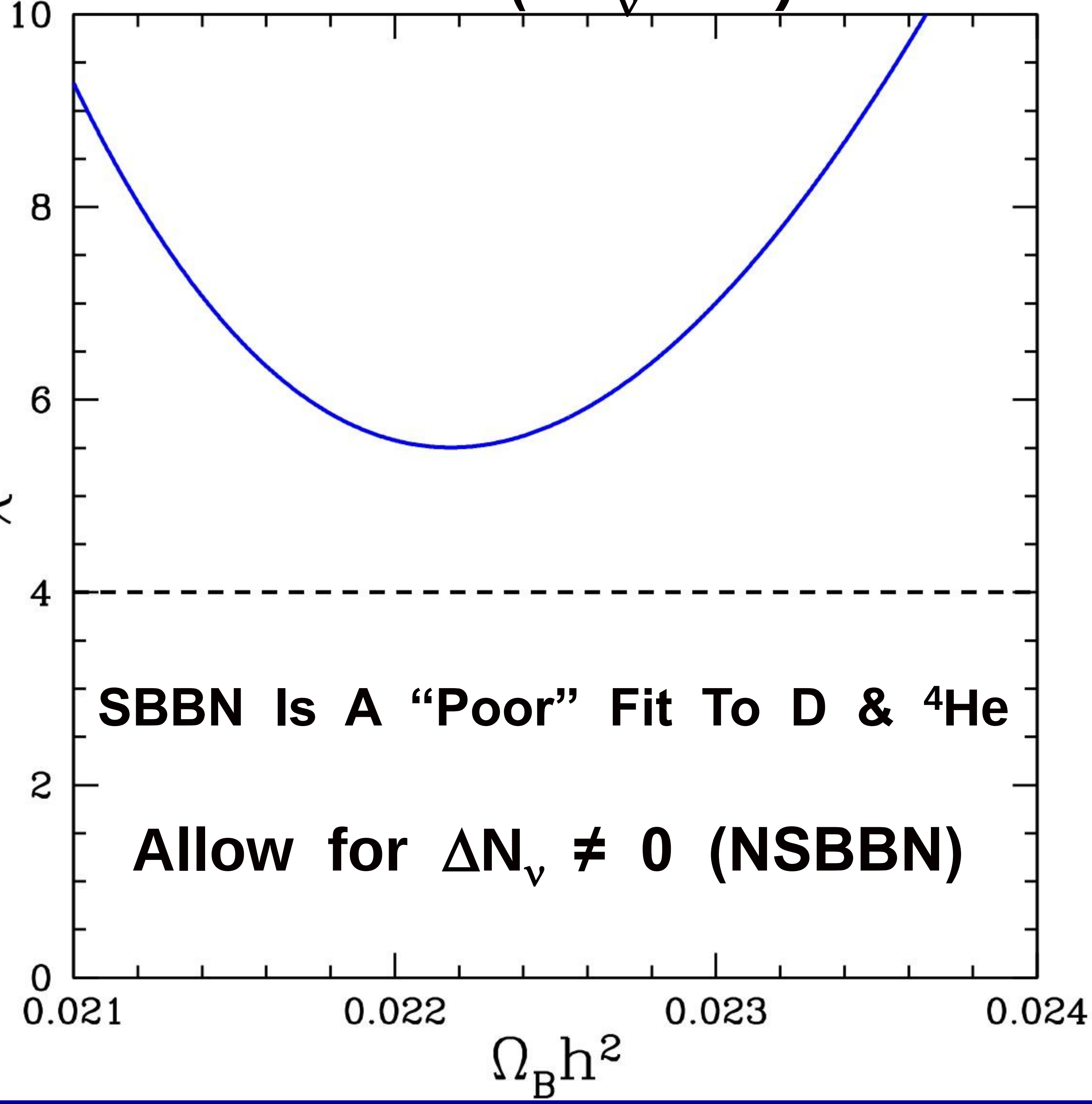


Cooke et al. 2013

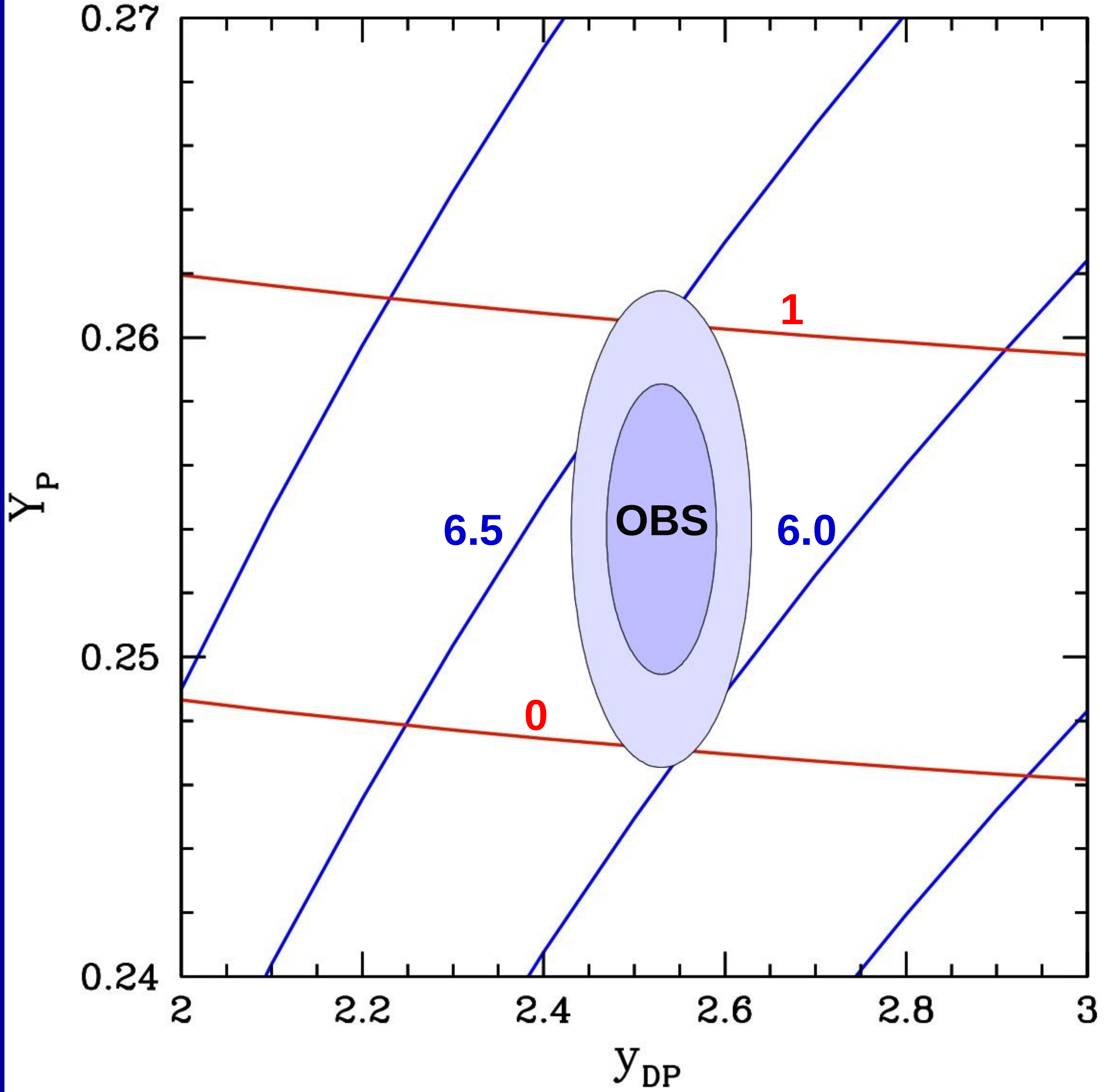
^{4}He/H is inferred from H and He recombinations observed in Low – Z, Extragalactic H II regions.



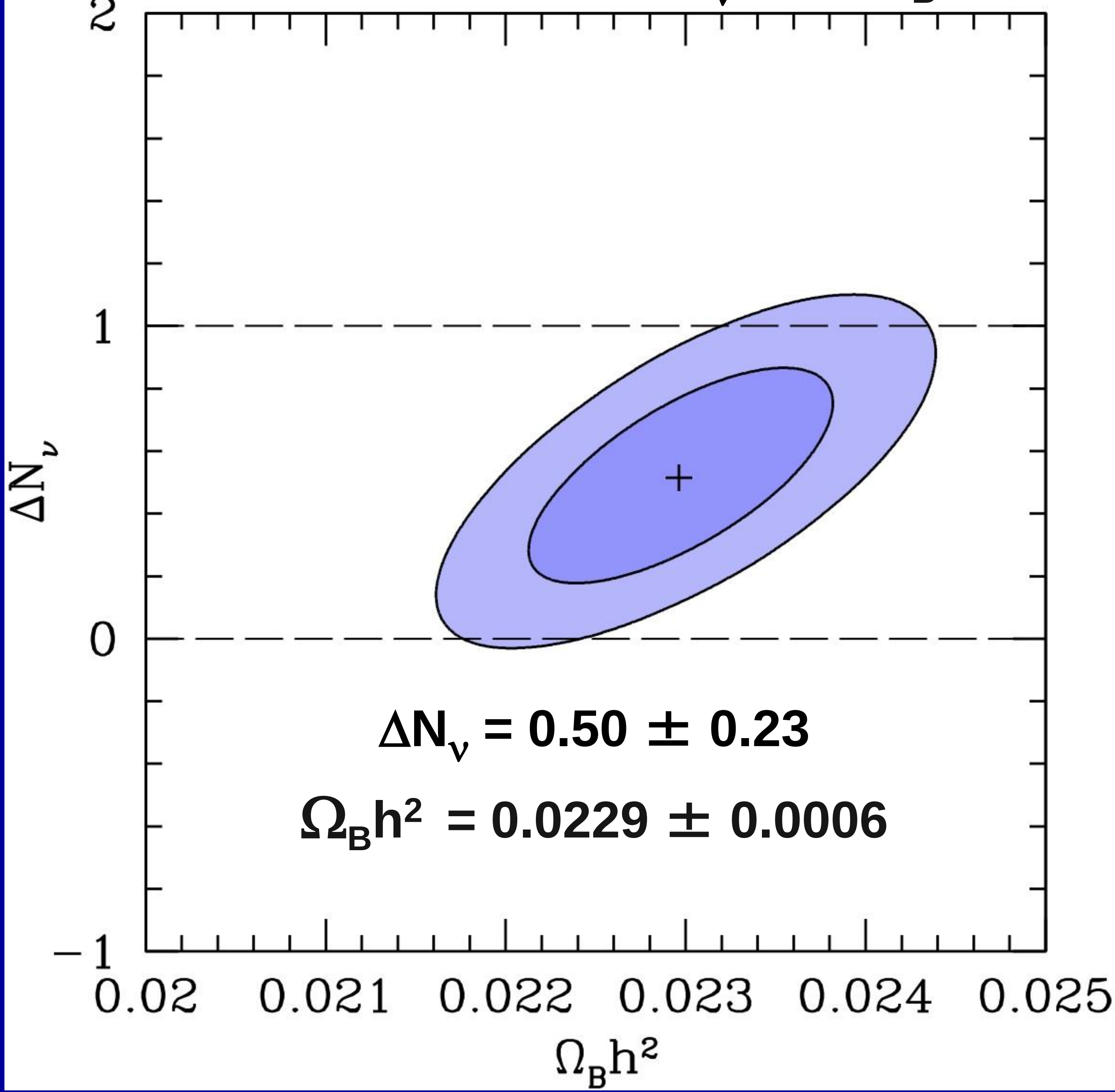
SBBN ($\Delta N_\nu = 0$)



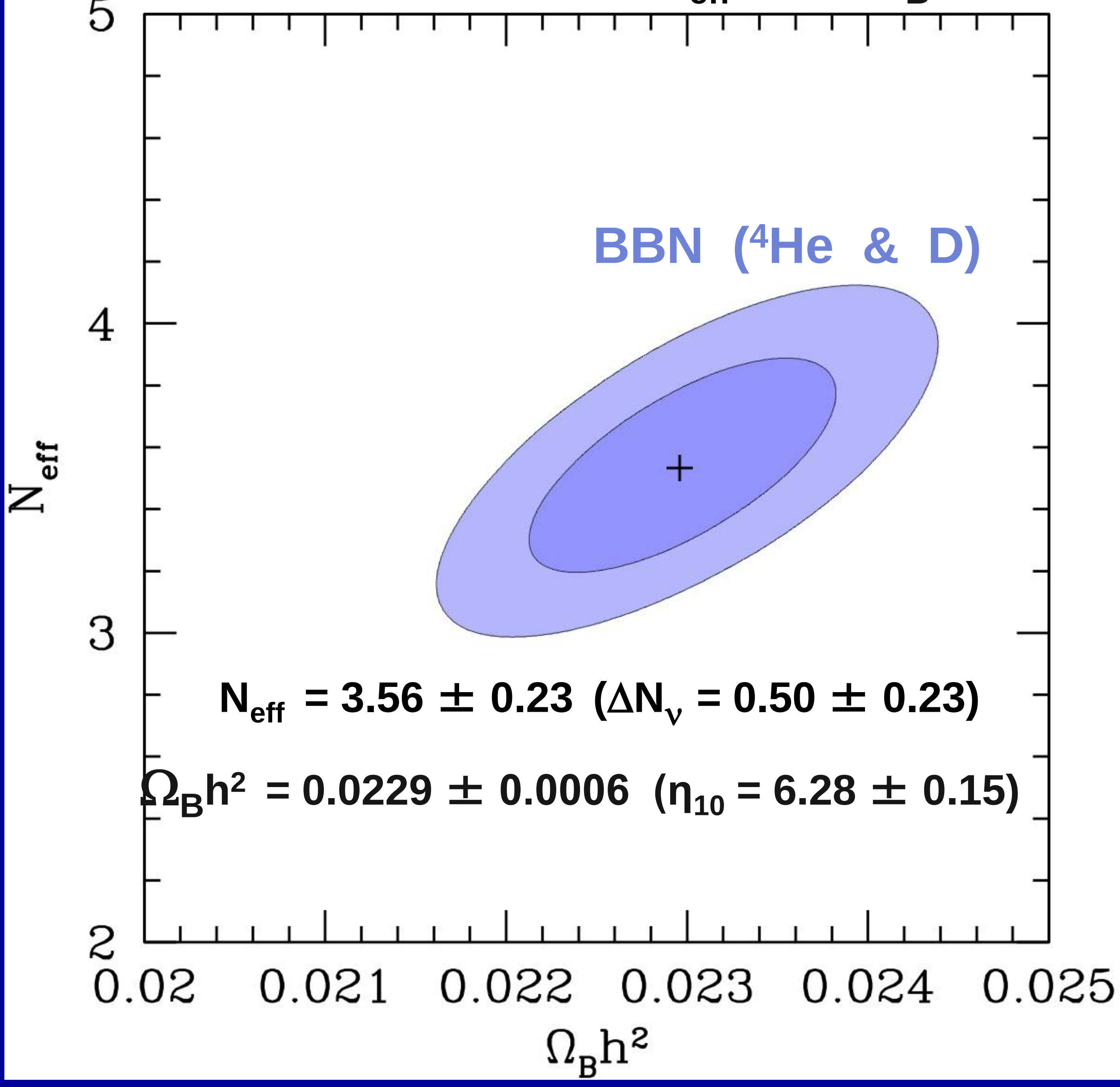
BBN – Predicted & Observed



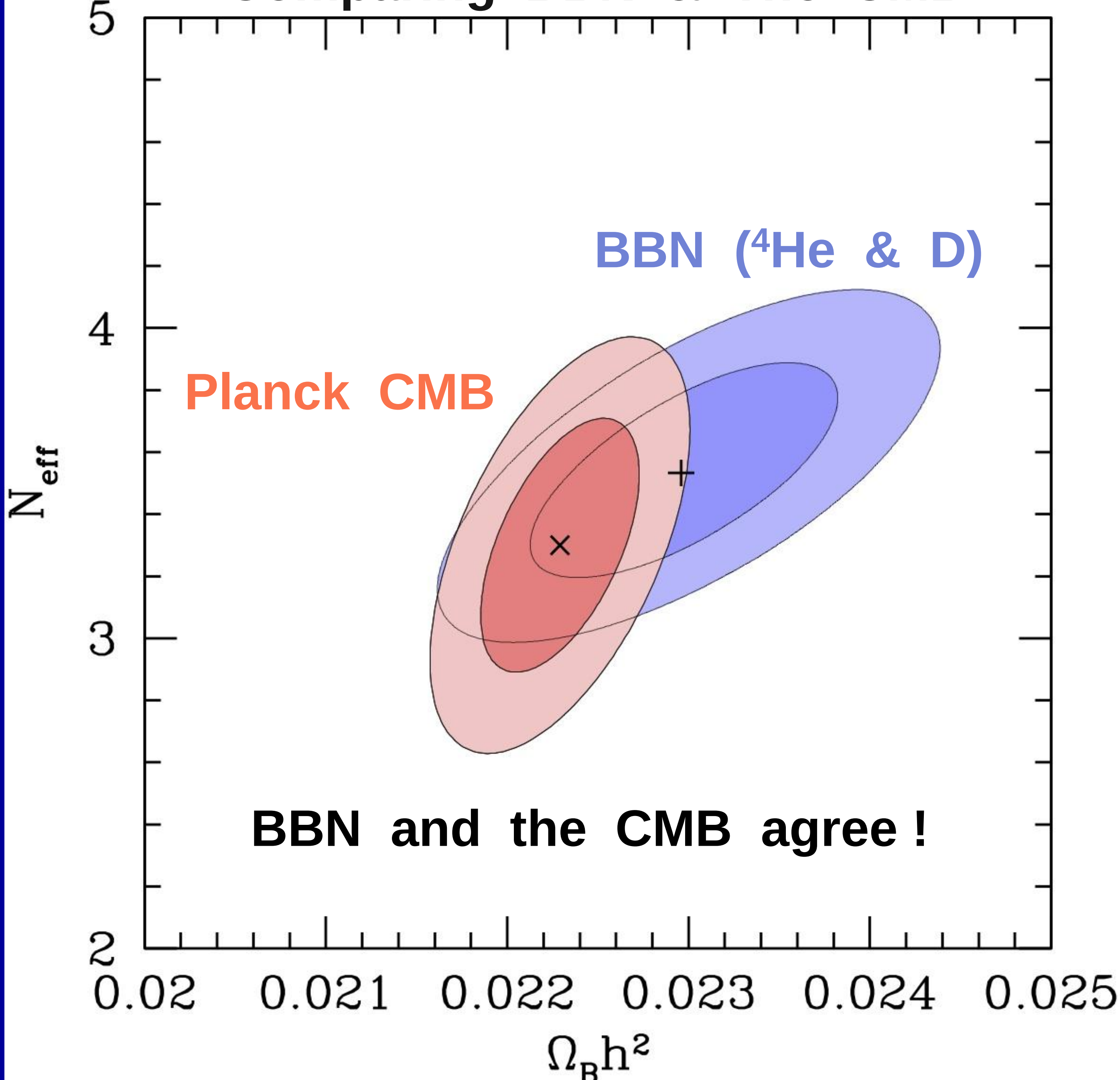
BBN – Predicted ΔN_ν vs. $\Omega_B h^2$



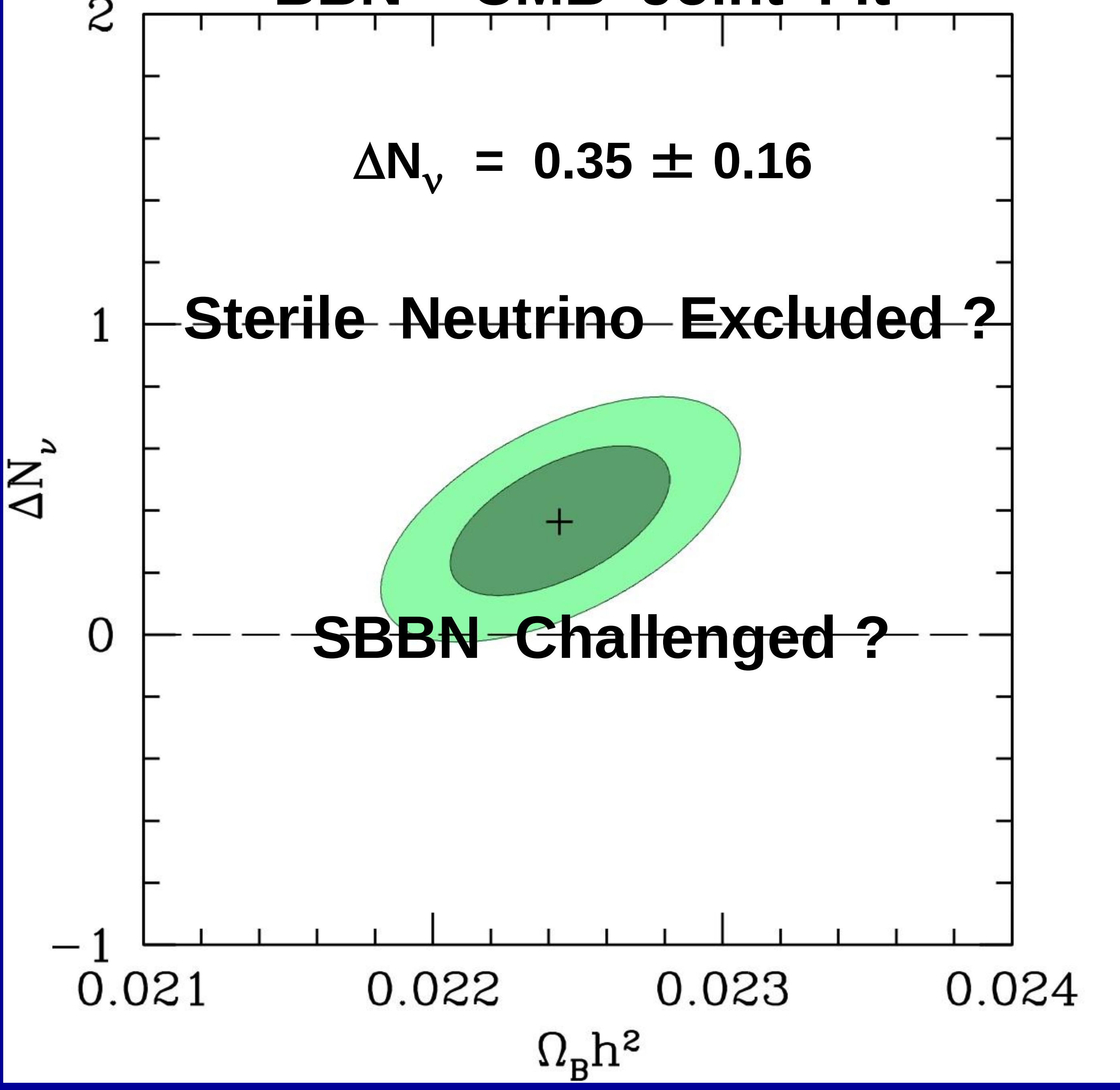
BBN – Predicted N_{eff} vs. $\Omega_B h^2$



Comparing BBN & The CMB



BBN + CMB Joint Fit



Lepton Asymmetry

An Excess of Neutrinos vs. Antineutrinos (or, vice - versa).

Neutrino Mixing (Oscillations) Ensures the SAME asymmetry for all SM Neutrinos.

Lepton Asymmetry is measured by the degeneracy parameter ξ, related to the chemical potential μ, by $\xi = \mu / kT$

($\xi \geq 0$ for more ν than anti - ν).

<u>Electron</u> **Neutrinos and Antineutrinos play key roles in regulating the neutron - to - proton ratio.**

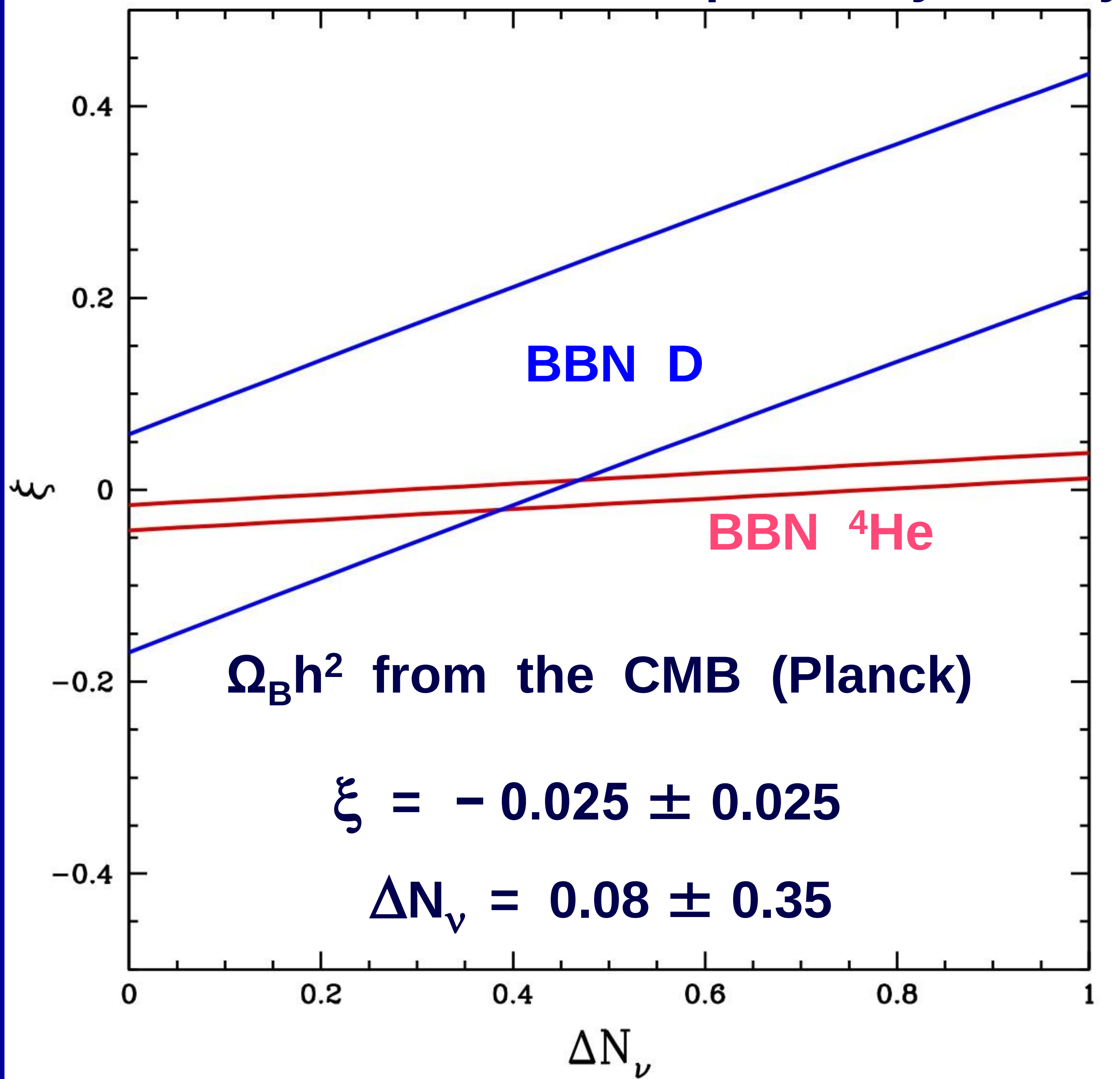
For BBN there are (now) three parameters but, only two observables.

Unless is $|\xi|$ "large", Lepton Asymmetry is invisible to the CMB.

Use the CMB to constrain $\Omega_B h^2$ (η_{10}) .

Use BBN (D & ^{4}He) to constrain ΔN_ν and ξ .

BBN & CMB Constrain Lepton Asymmetry



How do BBN and the CMB change in the presence of a light WIMP ?

BBN & The CMB With A Light WIMP

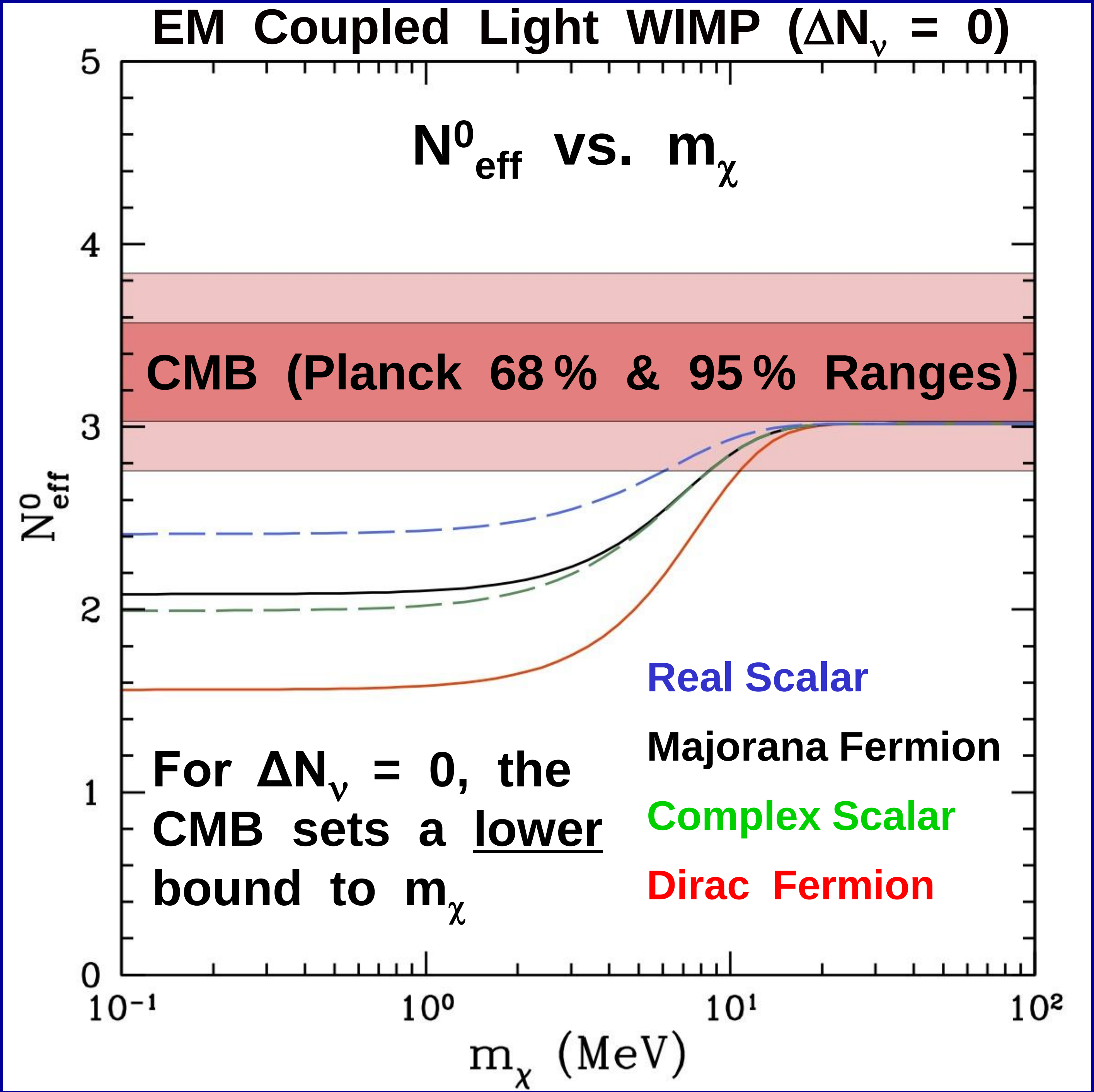
Very light WIMPs, thermal relics, annihilate late in the early Universe, changing the energy and photon densities at BBN and at recombination.

The CMB Confronts A Light WIMP

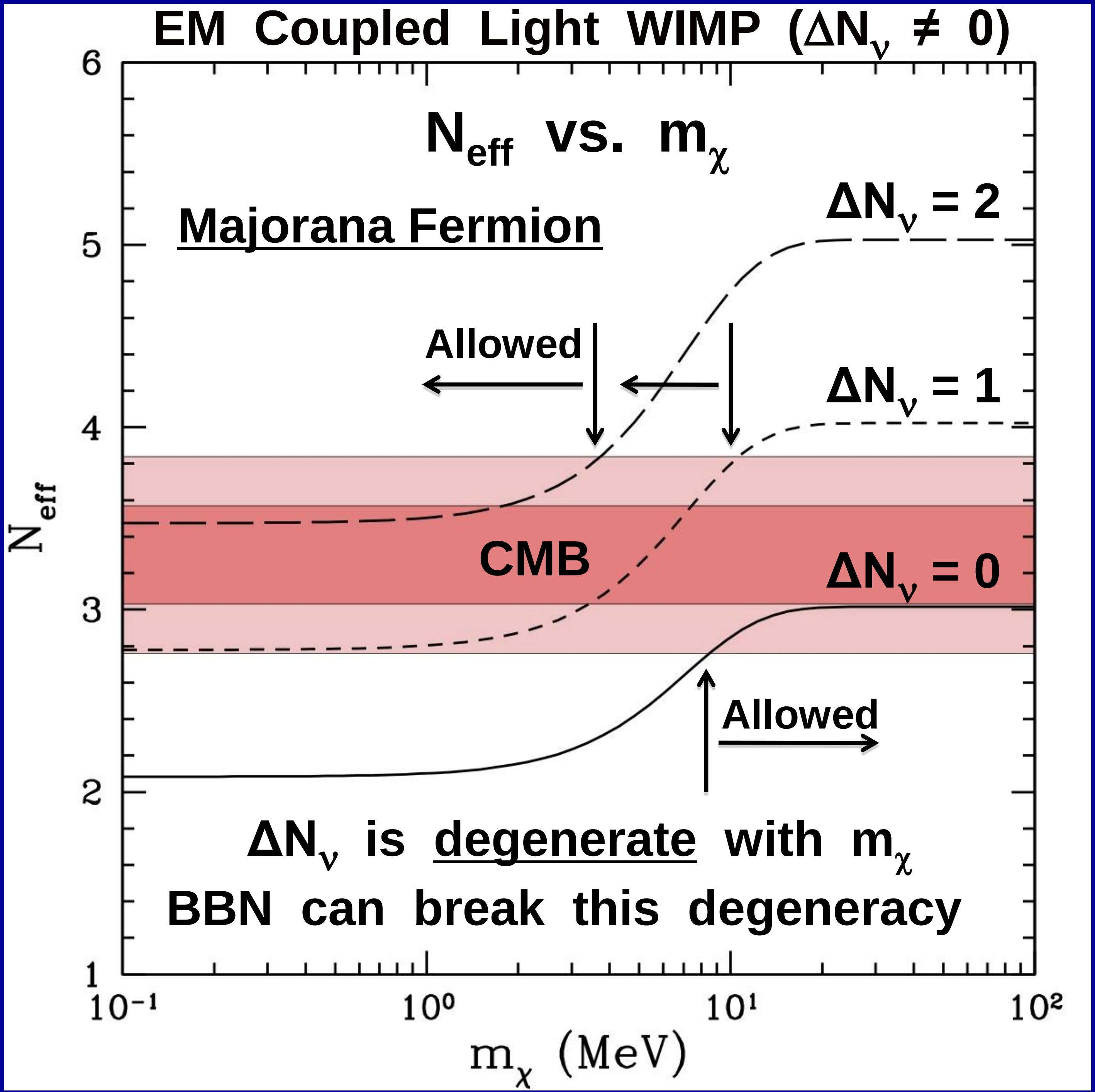
In the presence of an electromagnetically coupled light WIMP ($m_\chi \leq 30$ MeV), the effective number of neutrinos is: $N_{eff} = N^0_{eff}(1 + \Delta N_\nu / 3)$, where N^0_{eff} now depends on the WIMP mass.

The annihilation of an EM coupled, light WIMP heats the photons relative to the neutrinos :

$$(T_\nu / T_\gamma)_0 \leq (4/11)^{1/3} \Rightarrow N^0_{eff} \leq 3 \; ; \; N_{eff} \leq 3 + \Delta N_\nu$$



EM Coupled Light WIMP (ΔN_ν = 0)
N^0_{eff} vs. m_χ
CMB (Planck 68 % & 95 % Ranges)
Real Scalar
Majorana Fermion
Complex Scalar
Dirac Fermion
For ΔN_ν = 0, the CMB sets a lower bound to m_χ
N^0_{eff}
m_χ (MeV)
0
1
2
3
4
5
10^{-1}
10^{0}
10^{1}
10^{2}

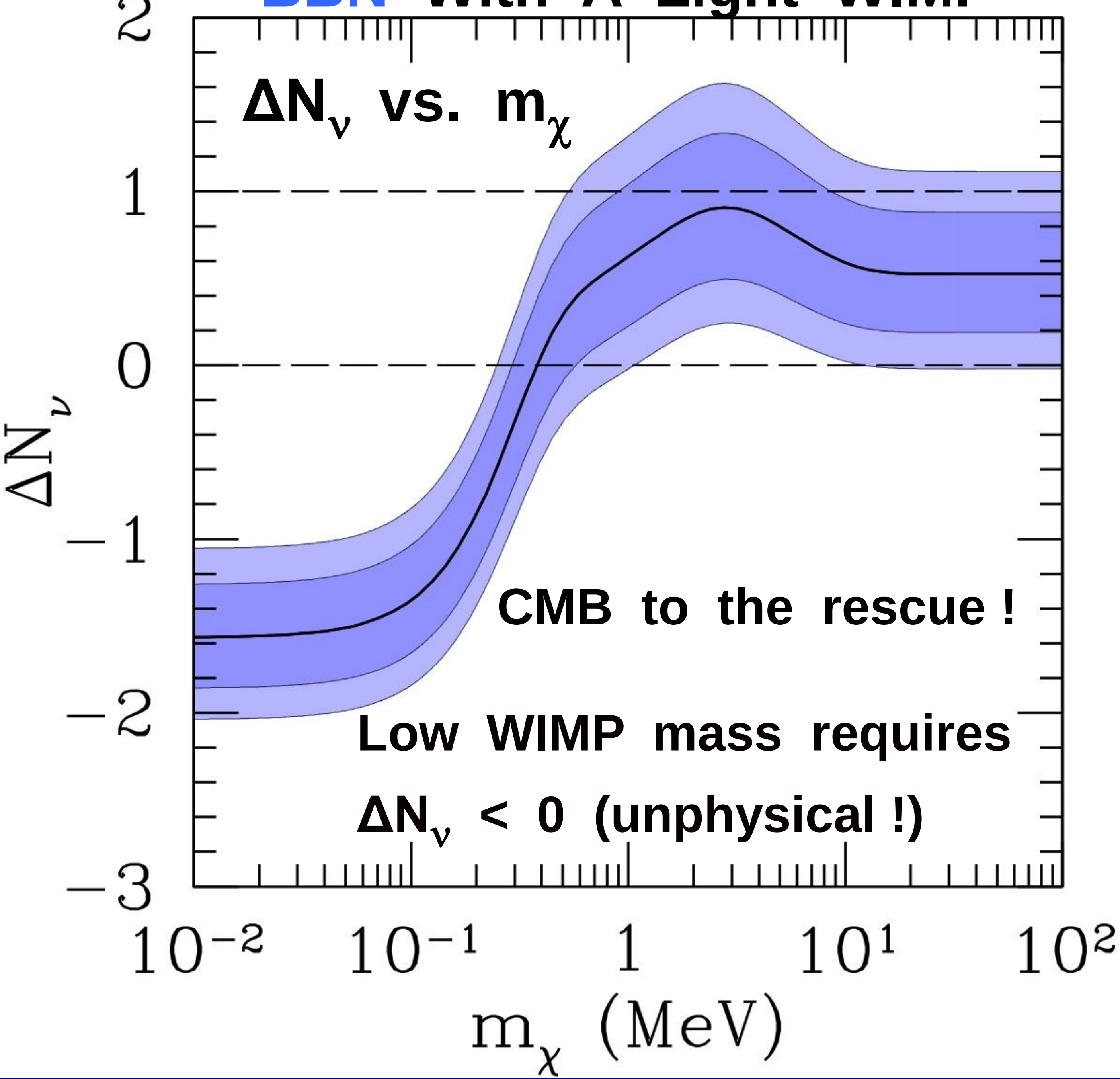


EM Coupled Light WIMP ($\Delta N_\nu \neq 0$)
N_{eff} vs. m_χ
Majorana Fermion
$\Delta N_\nu = 2$
$\Delta N_\nu = 1$
$\Delta N_\nu = 0$
Allowed
CMB
Allowed
ΔN_ν is degenerate with m_χ
BBN can break this degeneracy
N_{eff}
m_χ (MeV)
1
2
3
4
5
6
10^{-1}
10^{0}
10^{1}
10^{2}

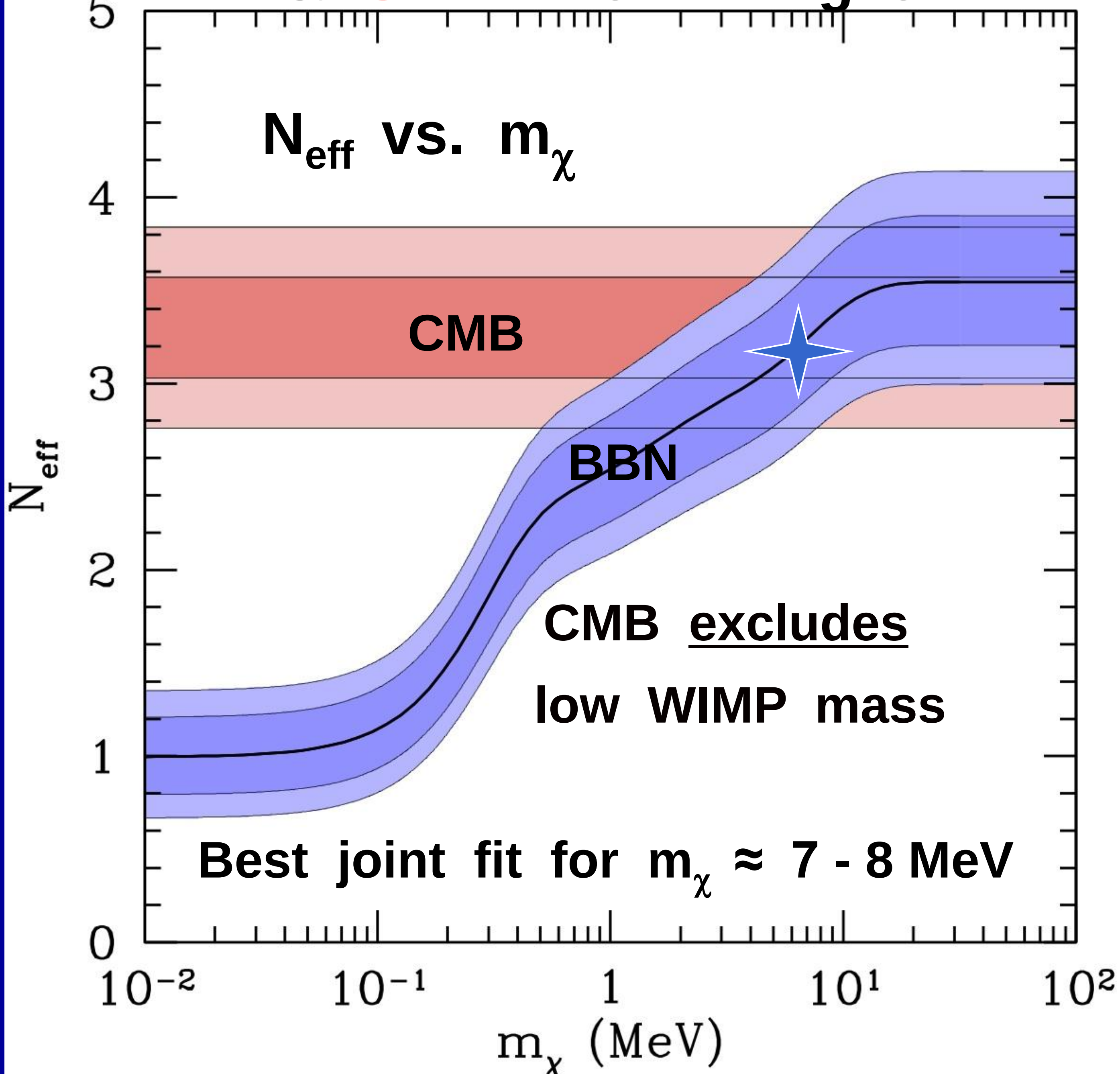
BBN WITH A Light WIMP

For each value of m_χ, a pair of $\{\eta_{10}, \Delta N_\nu\}$ (or, $\{\Omega_B h^2, N_{eff}\}$) values can be found so that BBN predicts – exactly – the observed primordial abundances of ^{4}He and D.

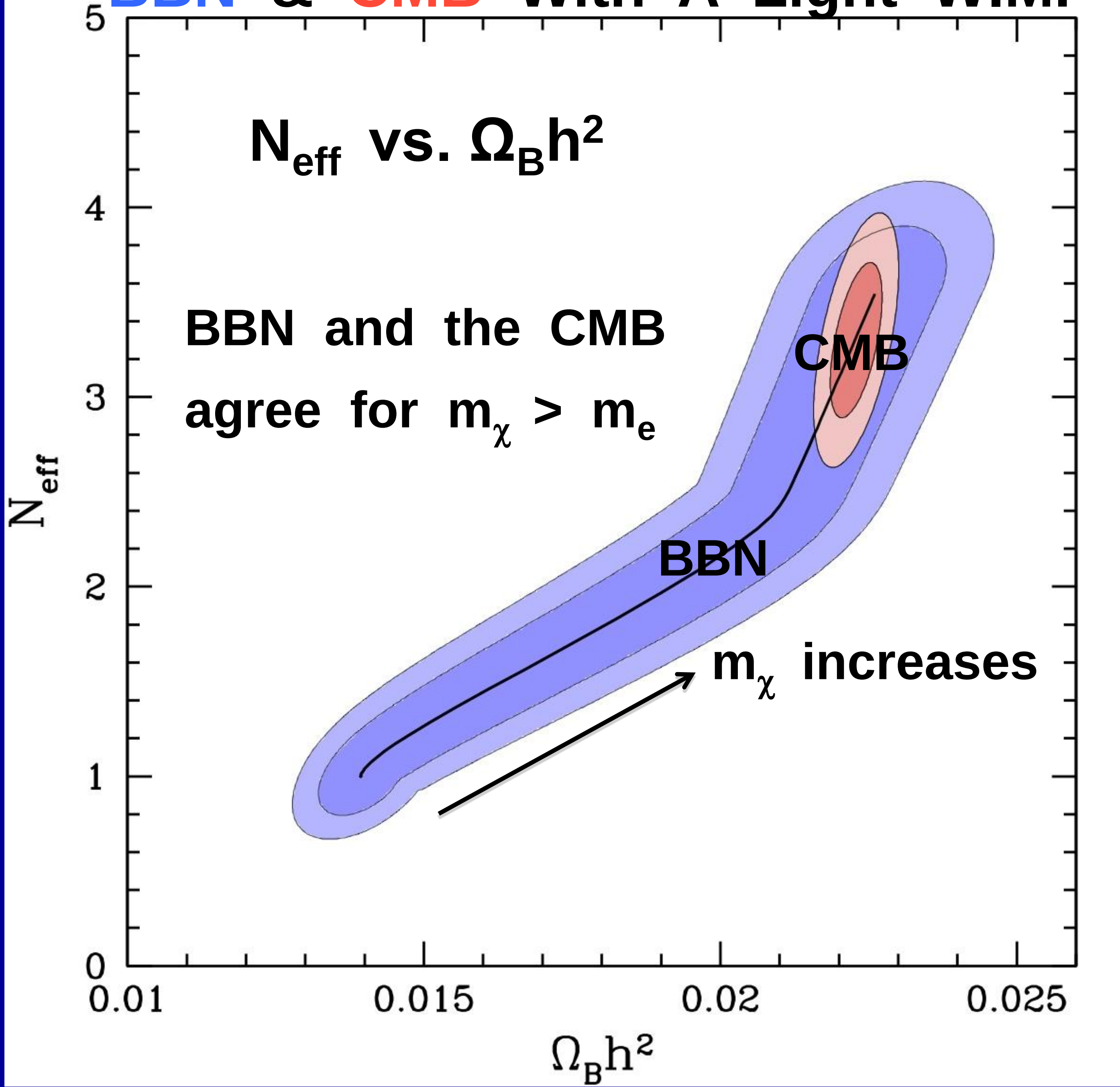
BBN With A Light WIMP



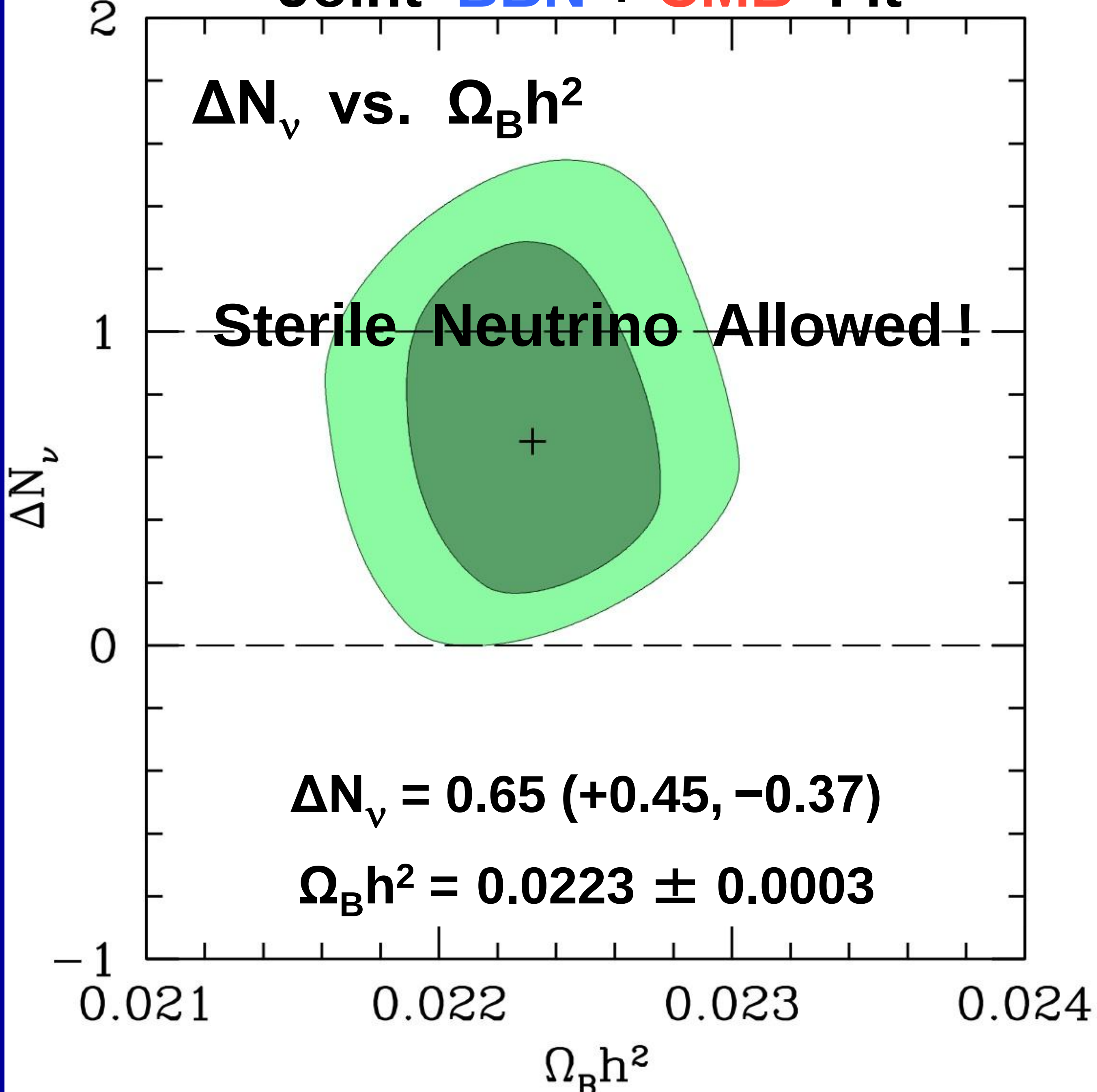
BBN & CMB With A Light WIMP



BBN & CMB With A Light WIMP



Joint BBN + CMB Fit



SUMMARY

BBN & CMB are consistent, constraining light WIMPs and the number of Equivalent Neutrinos.

In the absence of a light WIMP (m_χ > 30 MeV) BBN & CMB are consistent, provided that $\Delta N_\nu \approx 0.35$ ($N_{eff} \approx 3.4$).

But, SBBN ($\Delta N_\nu = 0$) and a sterile neutrino ($\Delta N_\nu = 1$) are both disfavored.

<u>SUMMARY</u>

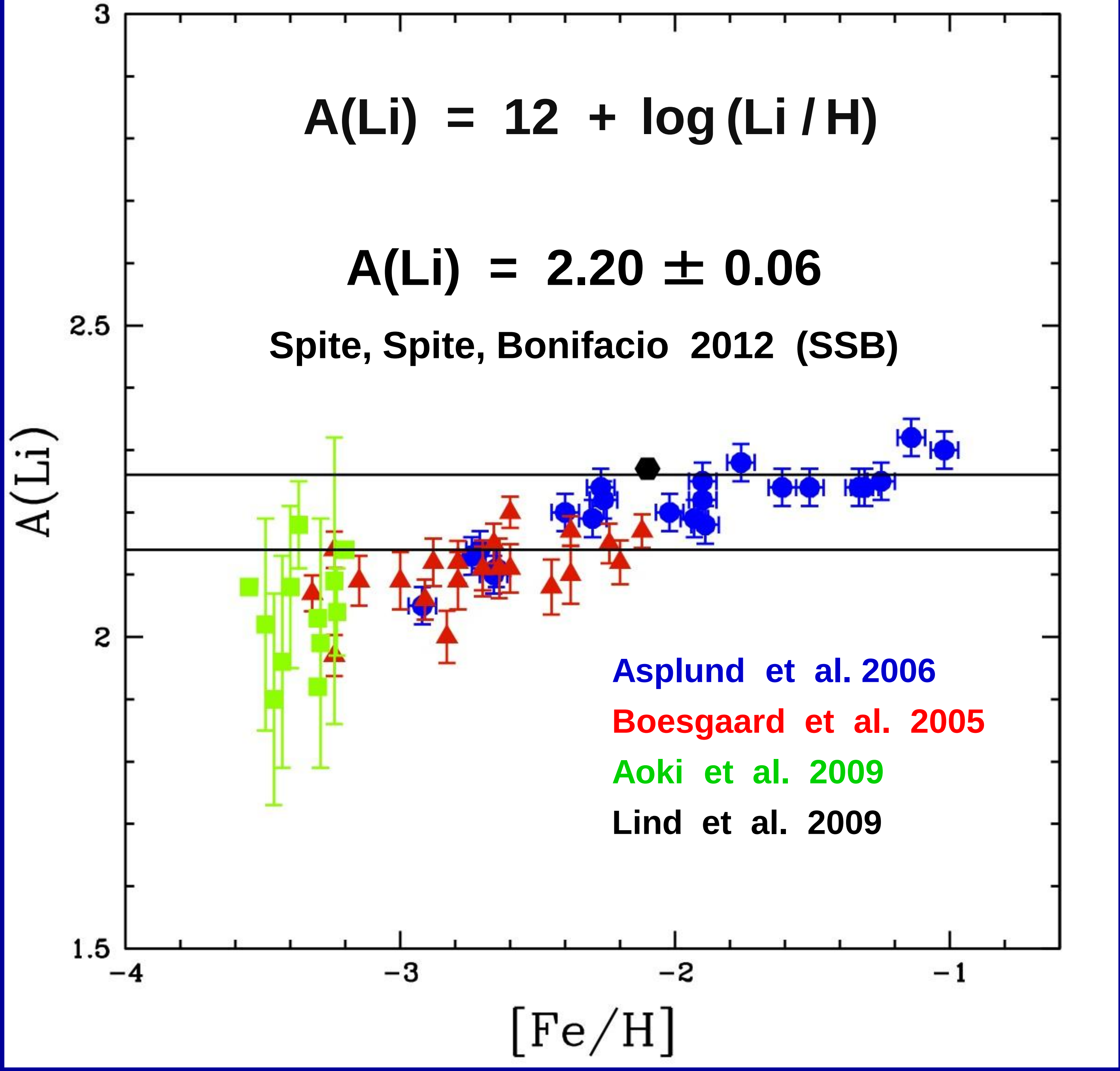
BBN & CMB <u>exclude</u> an EM Coupled WIMP with $m_\chi \leq 1 - 2$ MeV.

BBN & CMB <u>favor</u> an EM Coupled WIMP with $m_\chi \approx 5 - 10$ MeV, allowing for a sterile neutrino.

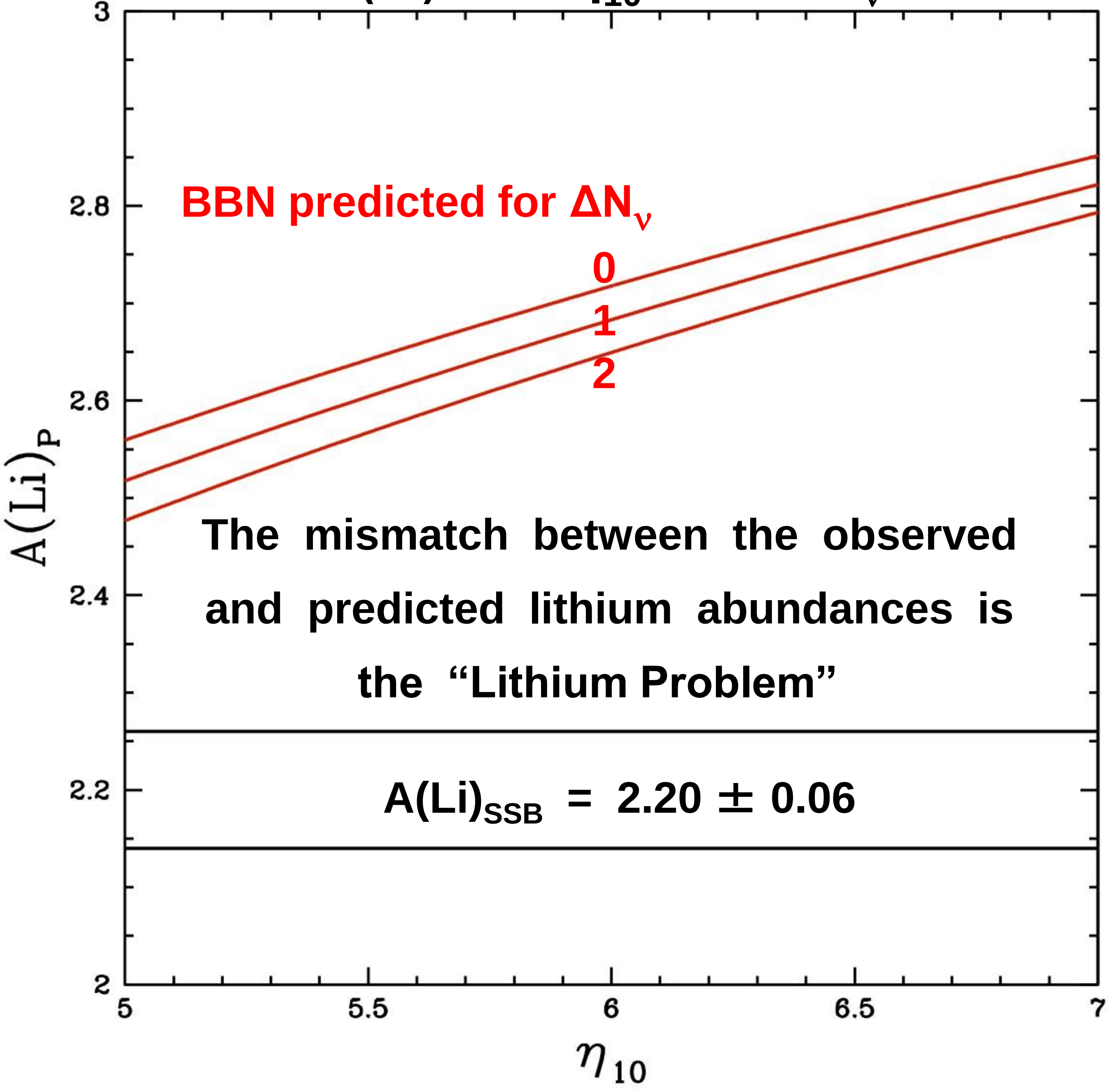
With or without an EM Coupled Light WIMP there is a lithium problem.

EXTRA SLIDES

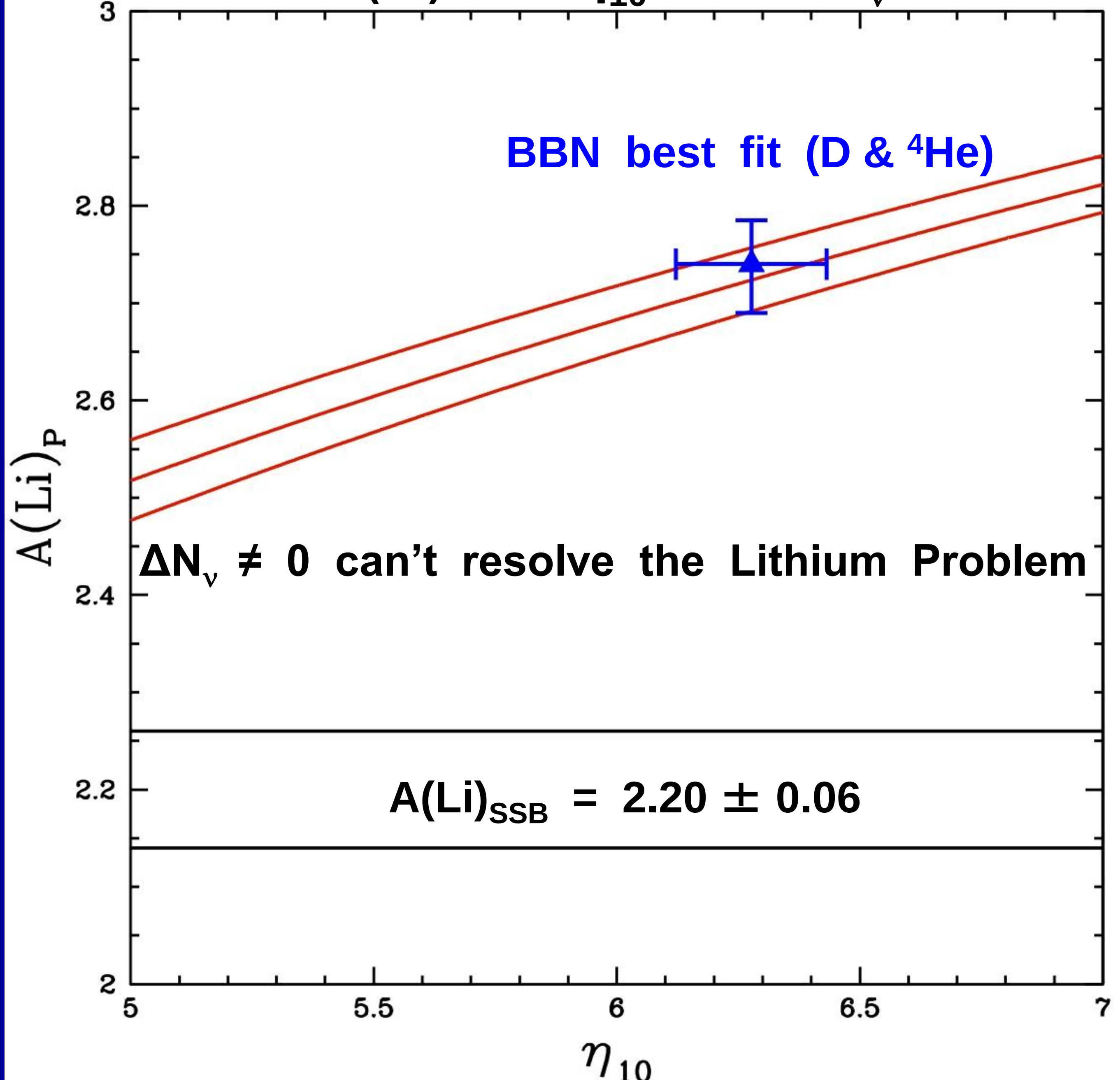
Lithium Observed in Metal Poor Stars



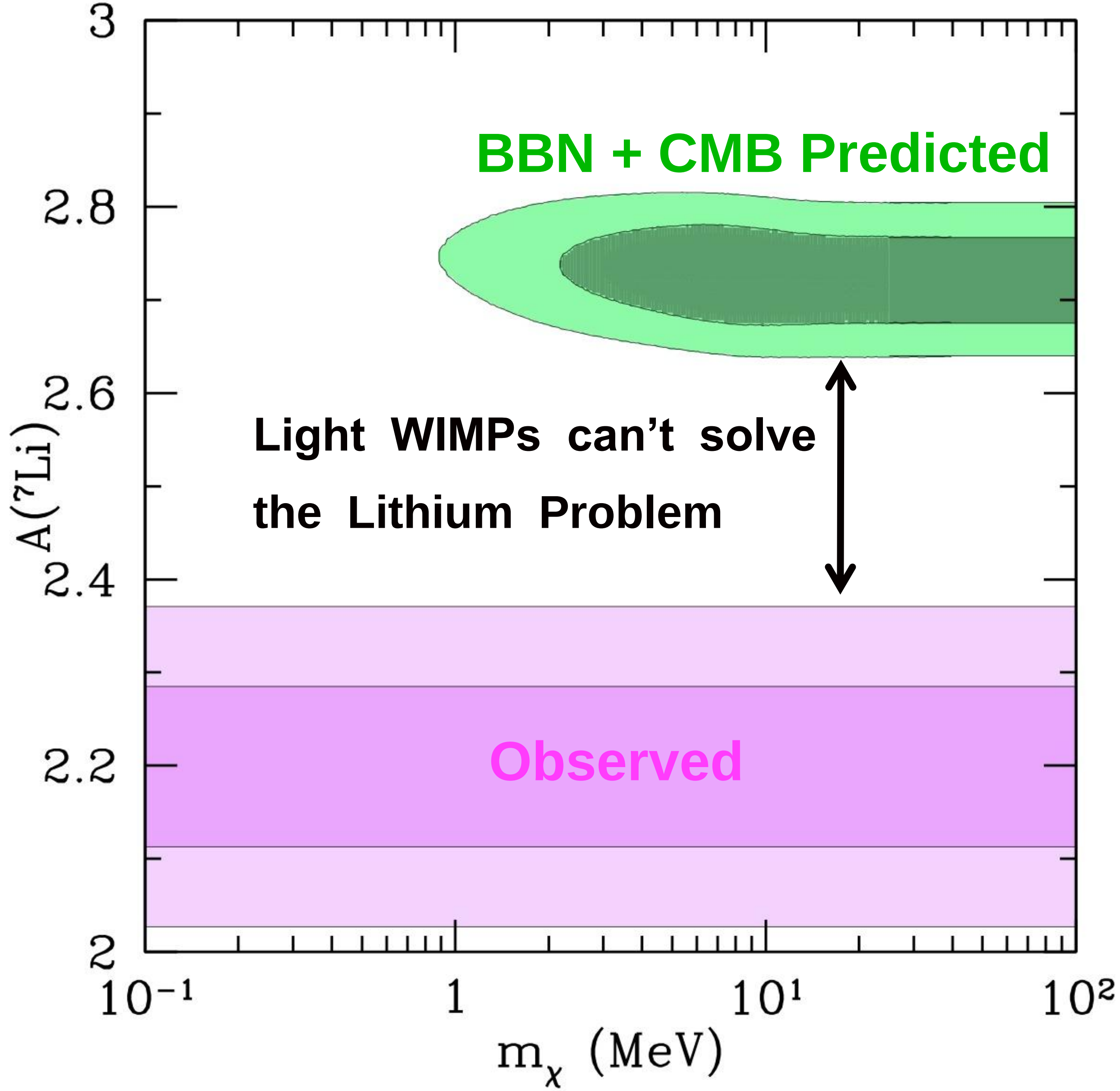
A(Li) vs. η_{10} and ΔN_ν



A(Li) vs. η_{10} and ΔN_ν



Lithium Predicted vs. Observed



MORE EXTRA SLIDES

LIGHT WIMPS COUPLED TO NEUTRINOS

The annihilation of a light WIMP coupled to the SM neutrinos heats the SM neutrinos relative to the photons : $\Rightarrow$ $(T_\nu / T_\gamma)_0 > (4/11)^{1/3}$

$$\Rightarrow N^0_{eff} > 3 \;;\; N_{eff} > 3 + \Delta N_\nu$$

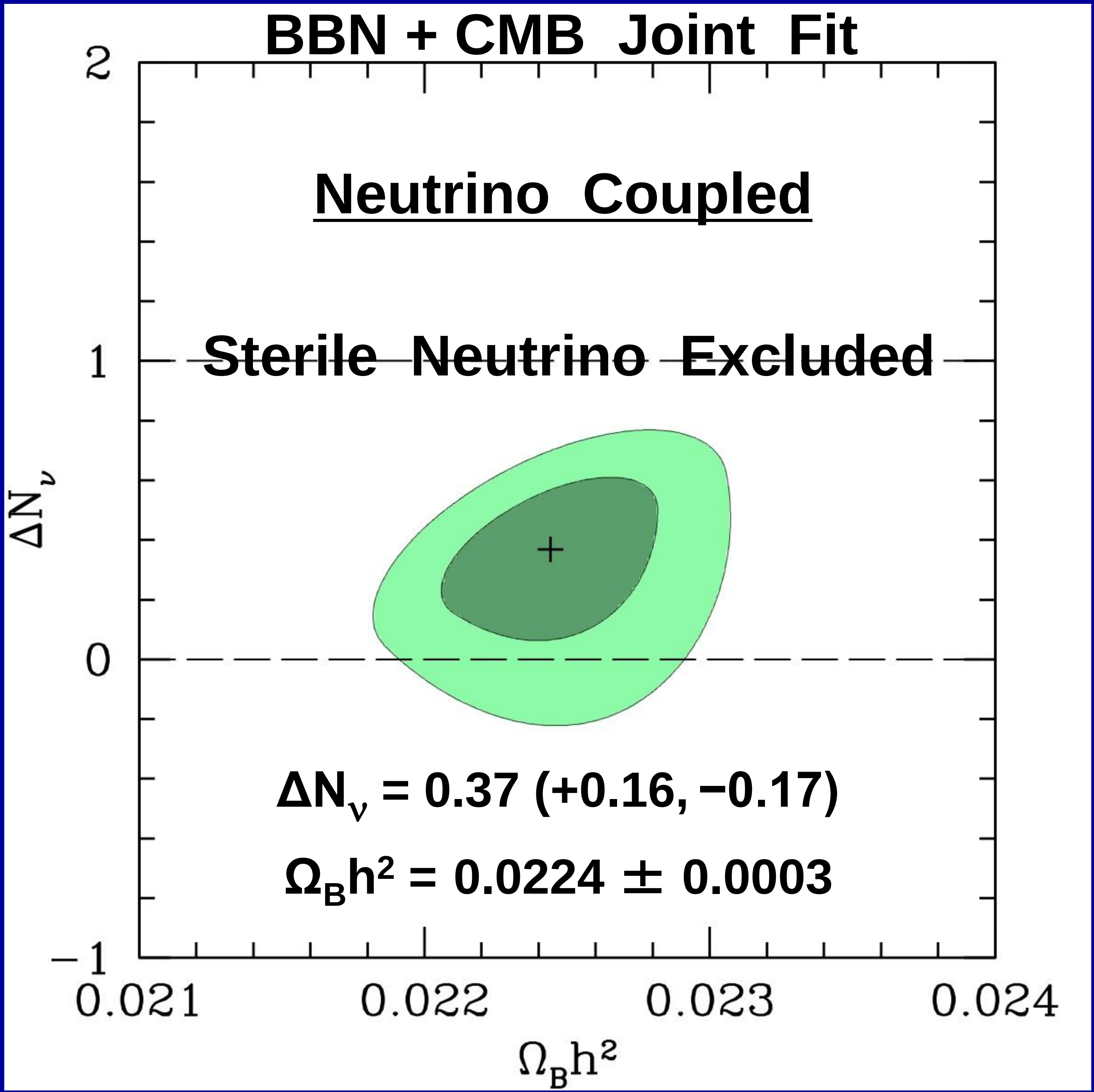
"Dark Radiation Without Dark Radiation"

In this case no additional photons are created, ($\eta_B^{BBN} = \eta_B^{CMB}$), but the Universe expands faster.

BBN With A Neutrino Coupled Light WIMP

In the presence of a neutrino coupled light WIMP the Universe expands faster during BBN, destroying less D and producing more ^{4}He. This disfavors $\Delta N_\nu > 0$ and a low WIMP mass.

For a neutrino coupled light WIMP, BBN (D & ^{4}He) and the CMB favor a "high mass" WIMP (i.e., the NO WIMP limit).



BBN + CMB Joint Fit
Neutrino Coupled
Sterile Neutrino Excluded
ΔN_ν = 0.37 (+0.16, −0.17)
Ω_B h² = 0.0224 ± 0.0003
ΔN_ν
Ω_B h²
2
1
0
−1
0.021
0.022
0.023
0.024

EVEN MORE EXTRA SLIDES

LIGHT WIMPS COUPLED TO NEUTRINOS

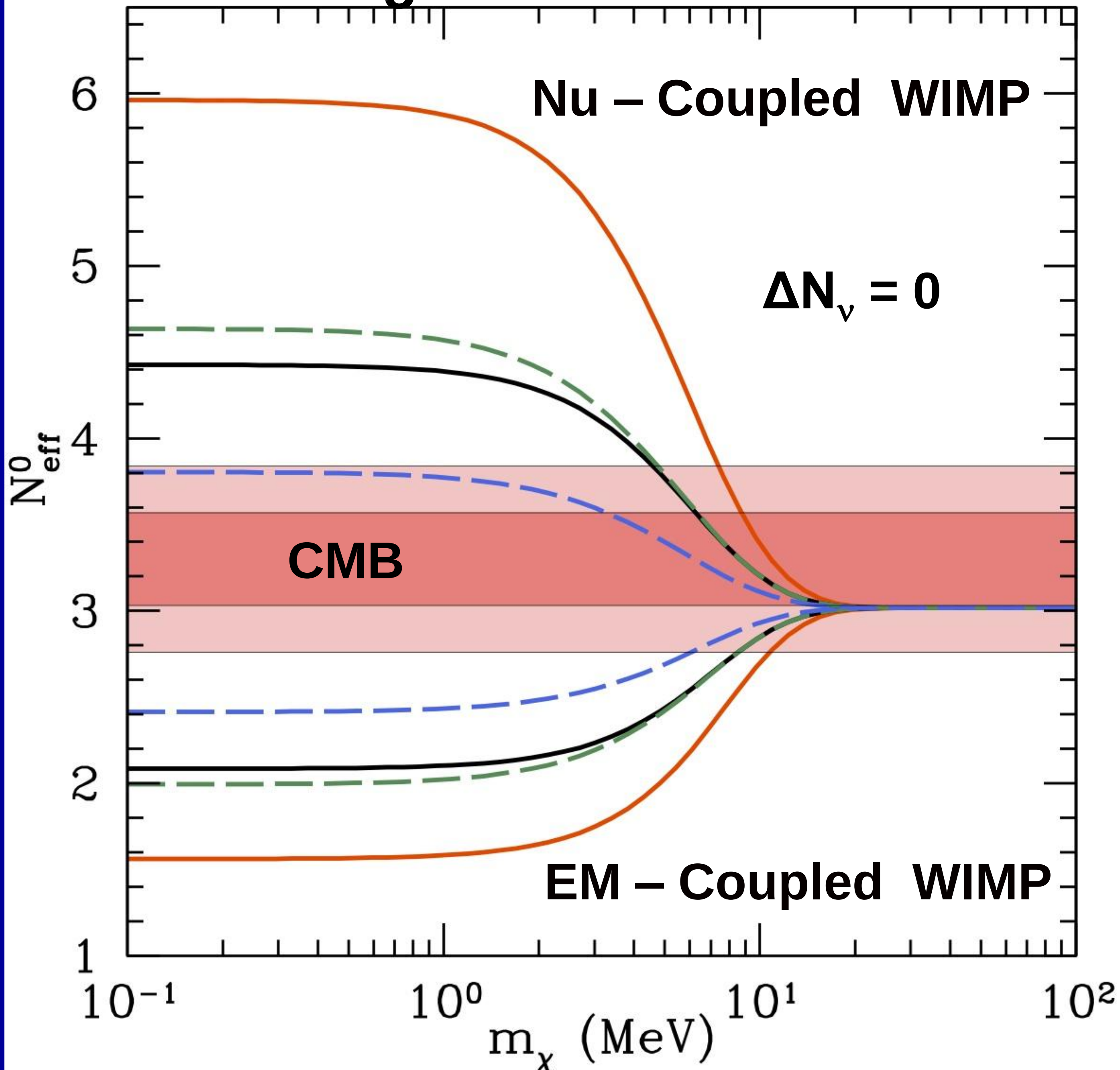
The annihilation of a light WIMP coupled to the SM neutrinos heats the SM neutrinos relative to the photons : $\Rightarrow\ (T_\nu / T_\gamma)_0 > (4/11)^{1/3}$

$$\Rightarrow\ N^0_{eff} > 3\ ;\ N_{eff} > 3\,(1 + \Delta N_\nu /3)$$

"Dark Radiation Without Dark Radiation"

In this case no additional photons are created, but the Universe expands faster.

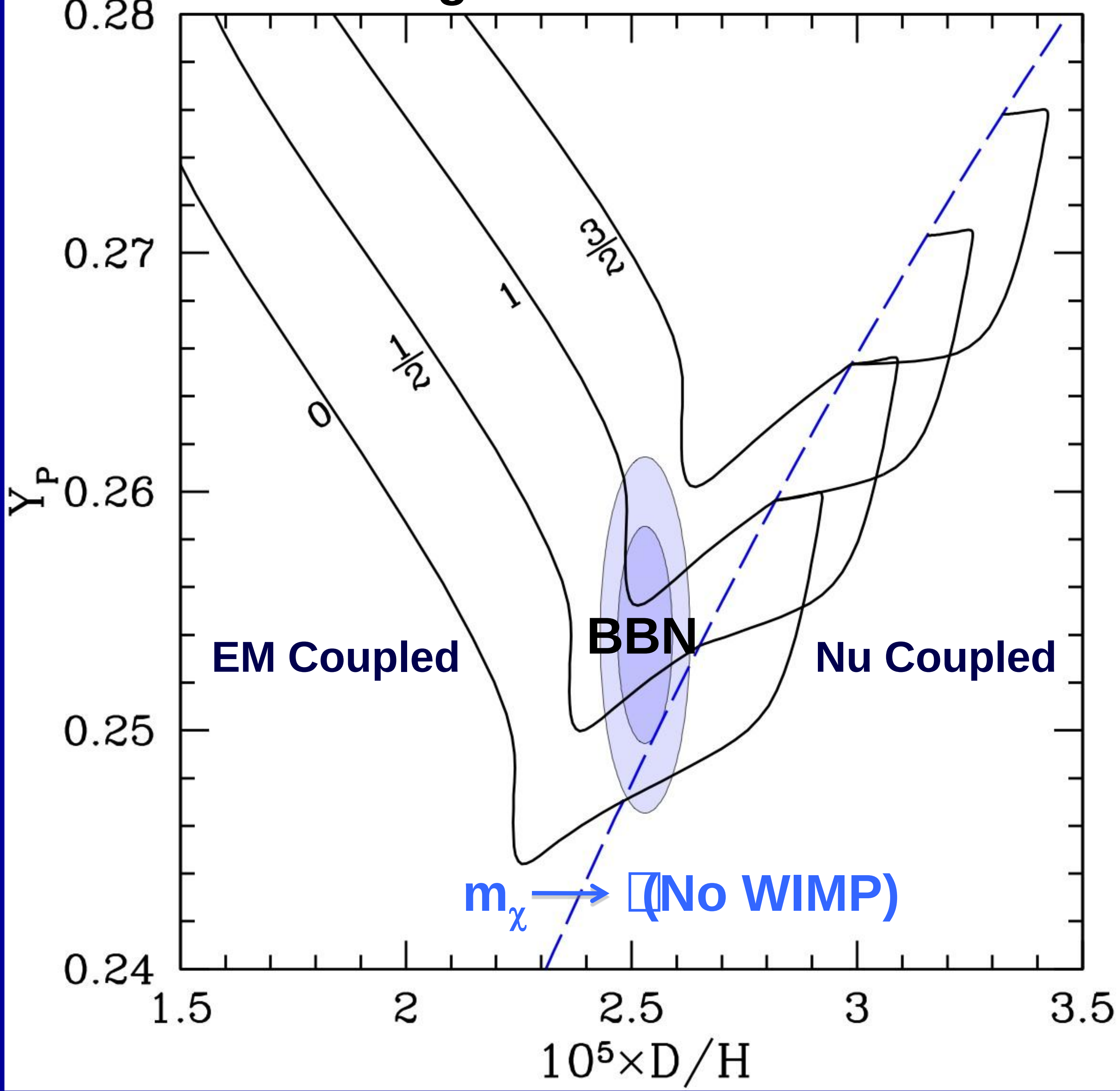
CMB Light WIMP Constraints



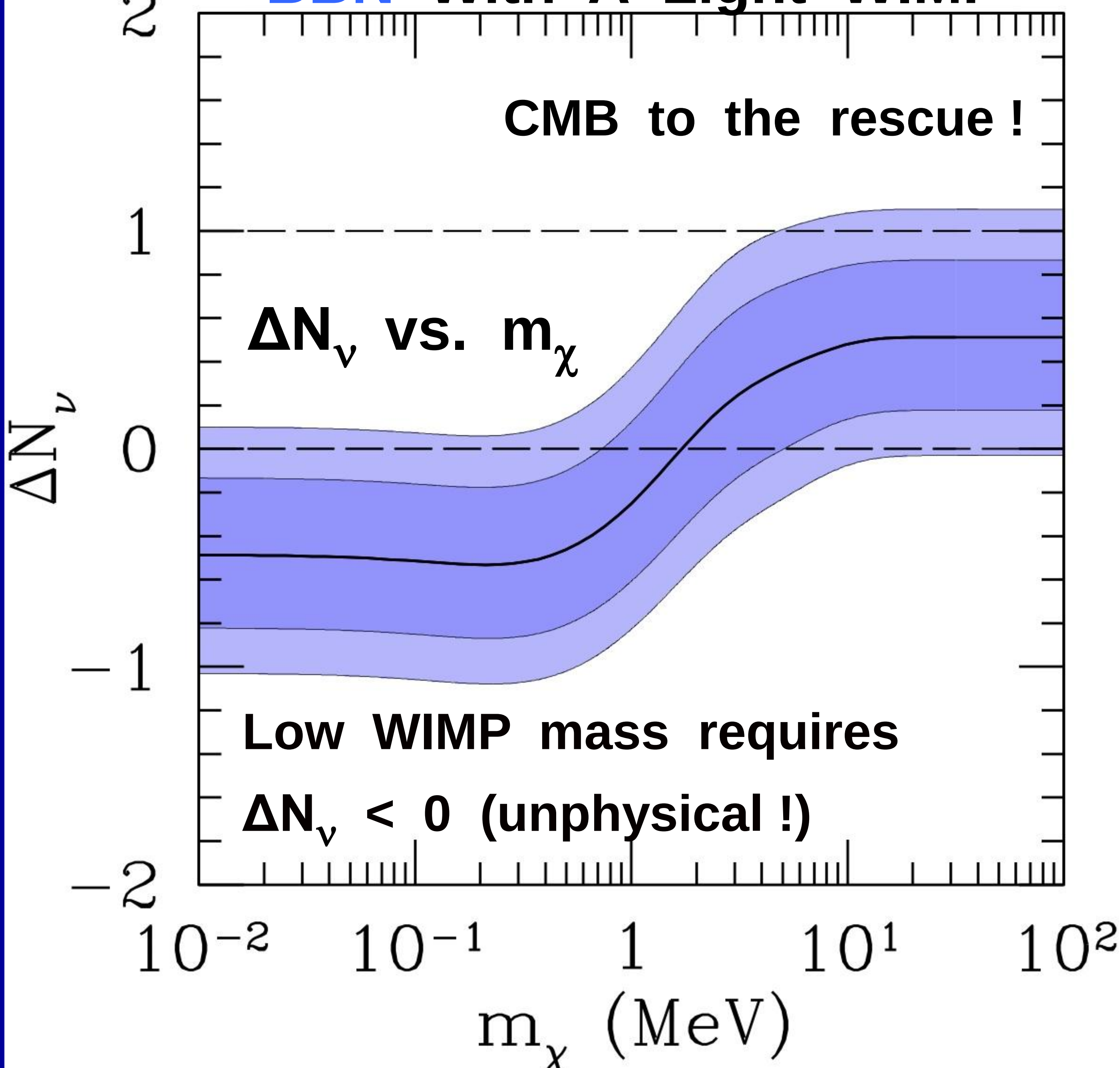
BBN With A Neutrino Coupled Light WIMP

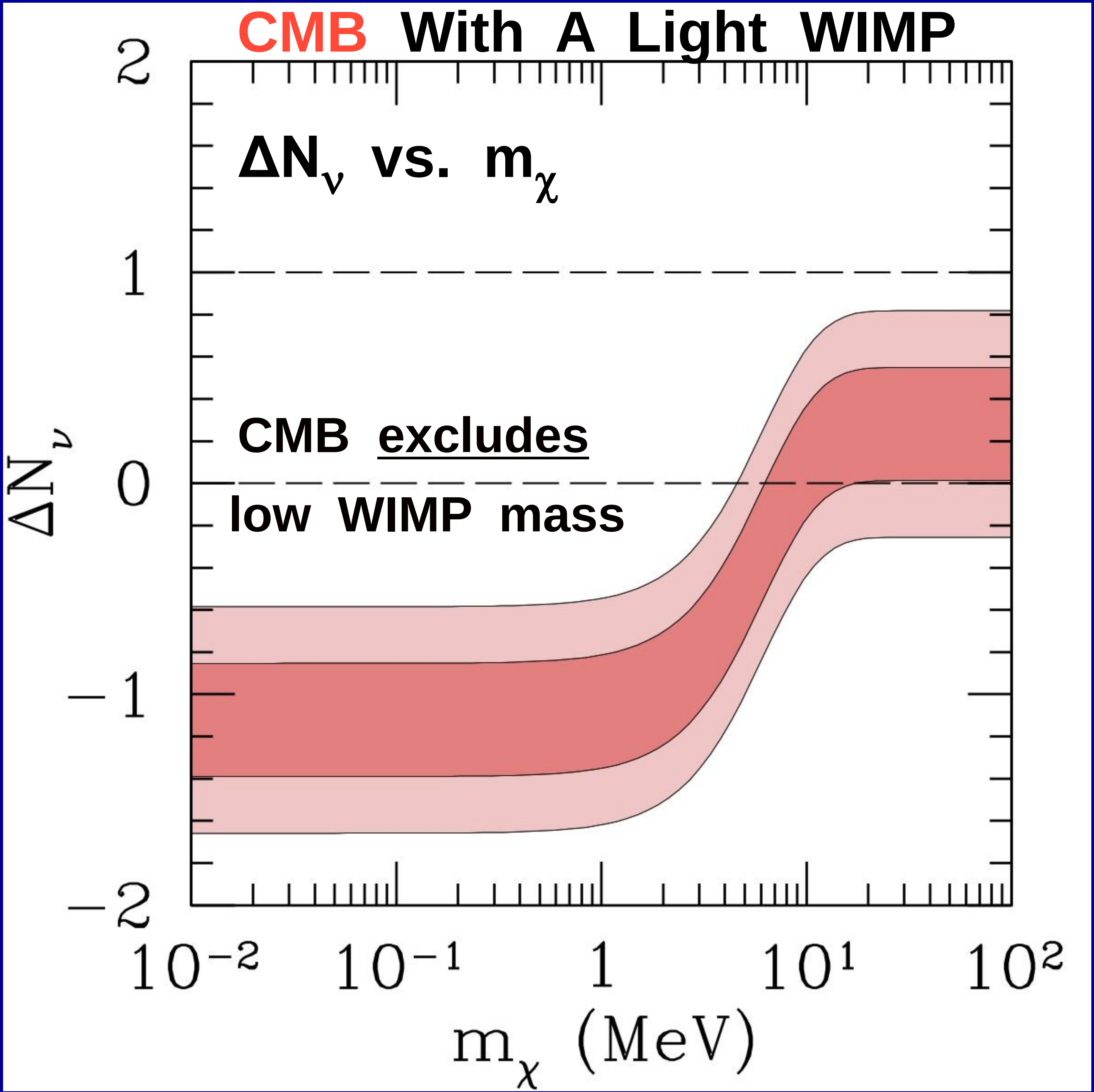
In the presence of a neutrino coupled light WIMP the Universe expands faster during BBN , destroying less D , producing more ^{4}He , and synthesizing less ^{7}Li .

BBN Light WIMP Constraints



BBN With A Light WIMP





CMB With A Light WIMP
ΔNν vs. mχ
CMB excludes
low WIMP mass
ΔNν
2
1
0
−1
−2
10−2
10−1
1
10¹
10²
mχ (MeV)

For a neutrino coupled light WIMP, BBN (D & ^{4}He) and the CMB favor a "high mass" WIMP (i.e., the NO WIMP limit).

As a result, for neutrino coupled light WIMPs, the lithium problem persists.

The lithium problem <u>cannot</u> be solved by a very light, neutrino coupled WIMP.

SUMMARY OF BBN + CMB CONSTRAINTS

For No WIMP And / Or A Neutrino Coupled WIMP

$N_{eff} = 3.40 \pm 0.16$; $\Delta N_\nu = 0.35 \pm 0.16$

$\Omega_B h^2 = 0.0224 \pm 0.0003$ ($\eta_{10} = 6.15 \pm 0.07$)

For An Electromagnetically Coupled WIMP

$N_{eff} = 3.22 \pm 0.25$; $\Delta N_\nu = 0.65\ (+0.45, -0.37)$

$\Omega_B h^2 = 0.0223 \pm 0.0003$ ($\eta_{10} = 6.11 \pm 0.08$)

$m_\chi \approx 5 – 10$ MeV favored

SUMMARY OF BBN + CMB CONSTRAINTS

In the absence of a light WIMP ($m_\chi \geq 30$ MeV) BBN & CMB are consistent, provided that $\Delta N_\nu \approx 0.35$ ($N_{eff} \approx 3.4$). But, SBBN and a sterile neutrino are disfavored. Lithium is a problem !

BBN & CMB exclude an EM Coupled light WIMP with $m_\chi \leq 1 – 2$ MeV .

BBN & CMB favor an EM Coupled light WIMP with $m_\chi \approx 5 – 10$ MeV . Lithium is a problem !

BBN & The CMB With A Light WIMP

Very light WIMPs, thermal relics, annihilate late in the early Universe, changing the energy and photon densities at BBN and at recombination.

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