BBN AND CMB CONSTRAINTS ON LIGHT WIMPS AND DARK RADIATION

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INT Program INT – 15 – 2a :

Neutrino Astrophysics and Fundamental Properties

June 2, 2015

BBN & The CMB WITH A Light WIMP

Very light WIMPs, relics that were in thermal equilibrium in the early Universe when T > m, annihilate late in the early Universe, when T ≈ m, changing the energy and entropy densities at BBN and at recombination.

The light WIMPs need not be the Dark Matter. They could be a subdominant DM component.

An Electromagentically Coupled Light WIMP

A light WIMP that annihilates to $e^{\pm}$ pairs and / or photons, after the neutrinos have decoupled, heats the photons relative to the neutrinos.

$\Longrightarrow$ $(T_{\nu} / T_{\gamma})_0 < (4/11)^{1/3}$ $\Longrightarrow$ $N^0_{eff} < 3$, where $N^0_{eff} = N_{eff}$ in the absence of Dark Radiation.

For m > ~ 1 keV, the extra photons thermalize, diluting the post – BBN baryon to photon ratio.

A Light WIMP Coupled To SM Neutrinos

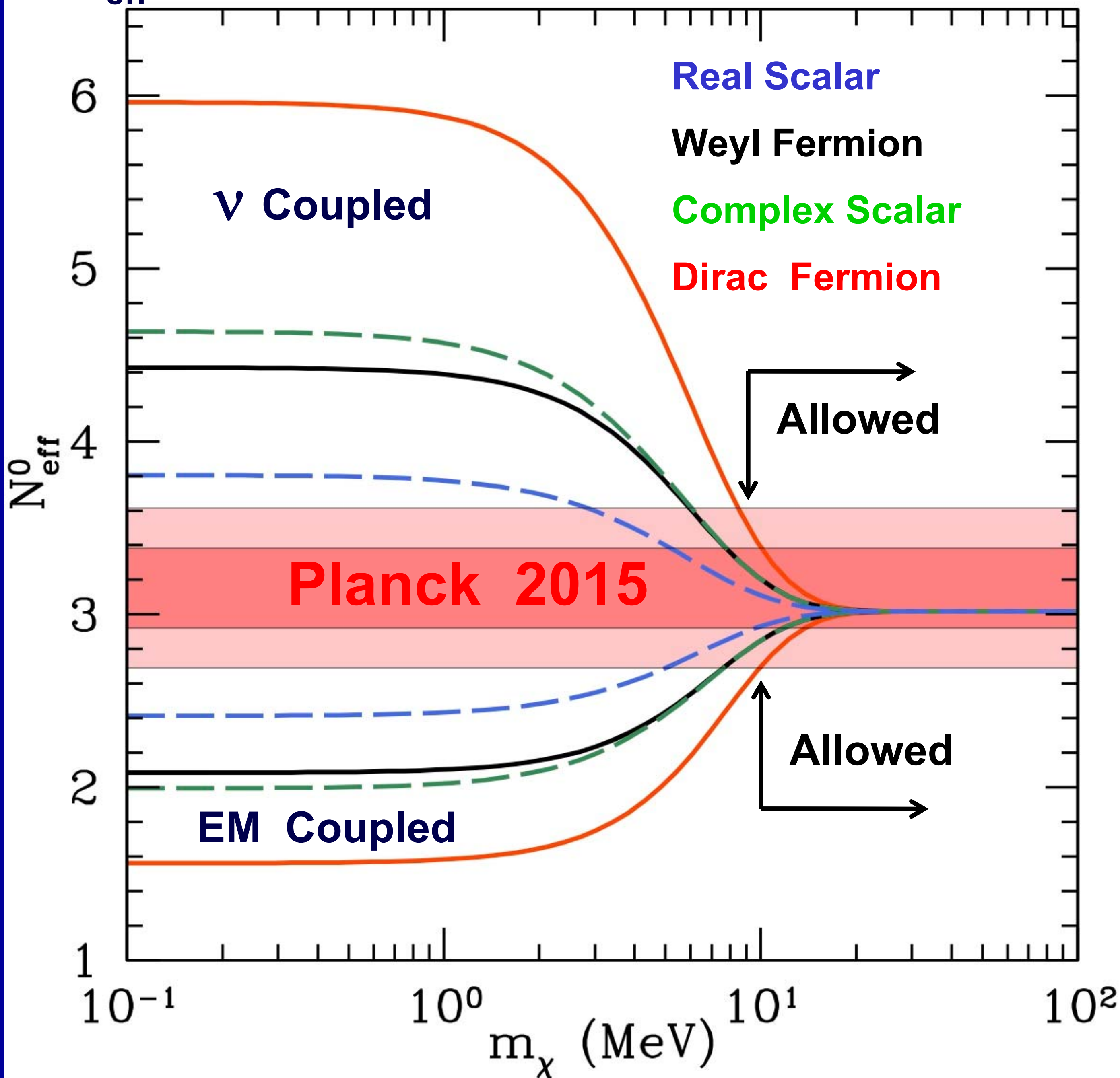
The annihilation of a light WIMP coupled to the SM neutrinos heats the neutrinos relative to the photons $\Longrightarrow$ $(T_\nu / T_\gamma)_0 > (4/11)^{1/3}$ $\Longrightarrow$

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

"Dark Radiation Without Dark Radiation"

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

N_{eff}^0 As A Function Of The WIMP Mass



For an EM Coupled light WIMP in the presence of "Dark Radiation" ($\Delta N_\nu \geq 0$),

$N_{eff} \geq N^0_{eff}$ ($N^0_{eff} \leq 3$)

The CMB sets <u>upper</u> and <u>lower</u> bounds to N_{eff}, leading to an <u>upper</u> bound on ΔN_ν and a <u>lower</u> bound to m_χ.

For a Neutrino Coupled light WIMP in the presence of "Dark Radiation" ($\Delta N_\nu \geq 0$),

$$N_{eff} \geq N^0_{eff} \quad (N^0_{eff} \geq 3)$$

The CMB sets an <u>upper</u> bound to N_{eff}, leading to an <u>upper</u> bound on ΔN_ν and a <u>lower</u> bound to m_χ.

BBN is sensitive to the presence of Dark Radiation ($\Delta N_\nu \geq 0$) because of the change in the expansion rate.

Faster expansion $\Rightarrow$ more neutrons $\Rightarrow$ more ^{4}He.

Faster expansion $\Rightarrow$ less time to burn D to ^{3}He, ^{4}He, and beyond $\Rightarrow$ more D.

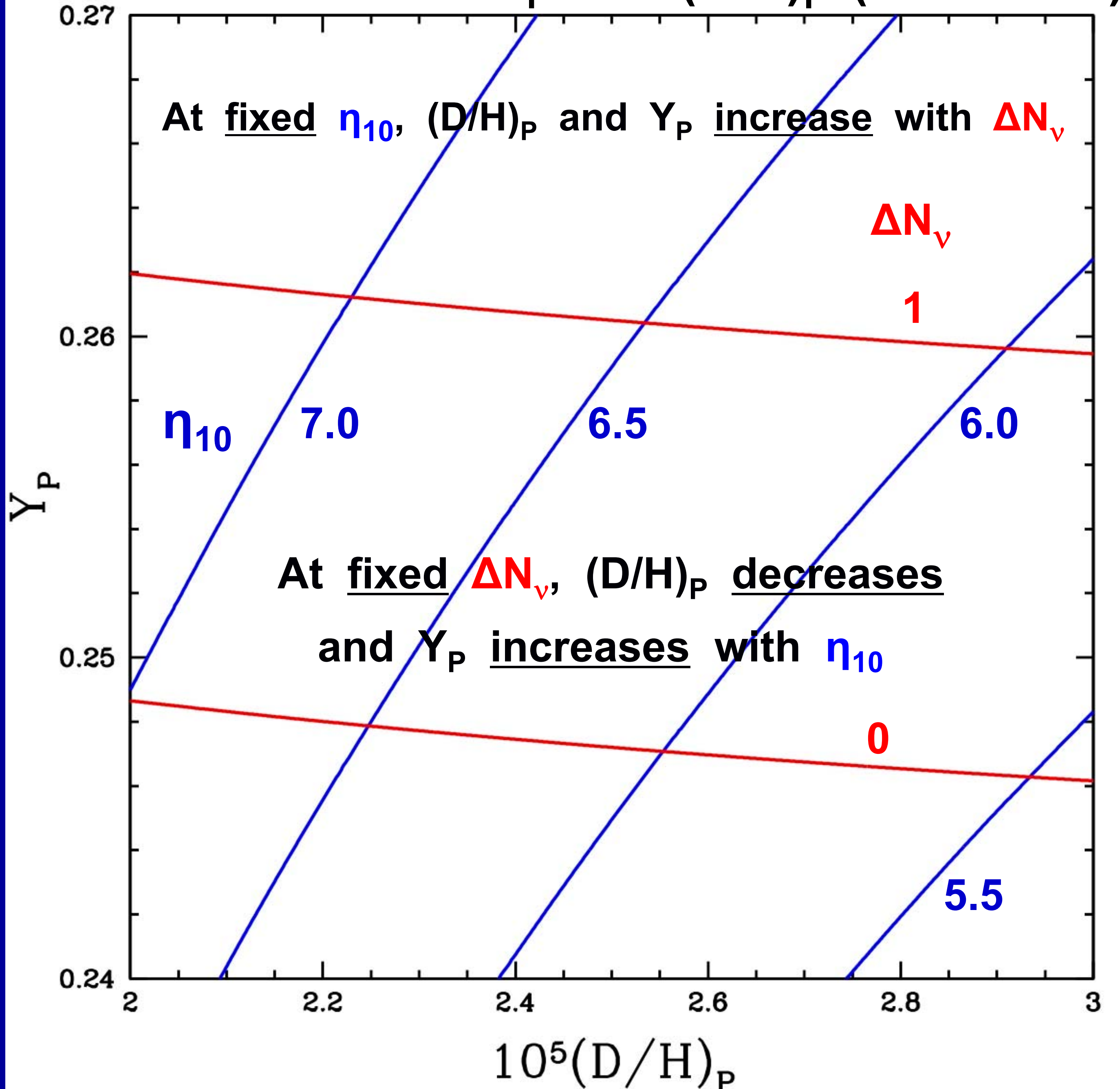
In the absence of a light WIMP, the D and ^{4}He abundances depend on ΔN_ν. The observationally inferred primordial abundances of D and ^{4}He constrain the baryon abundance:

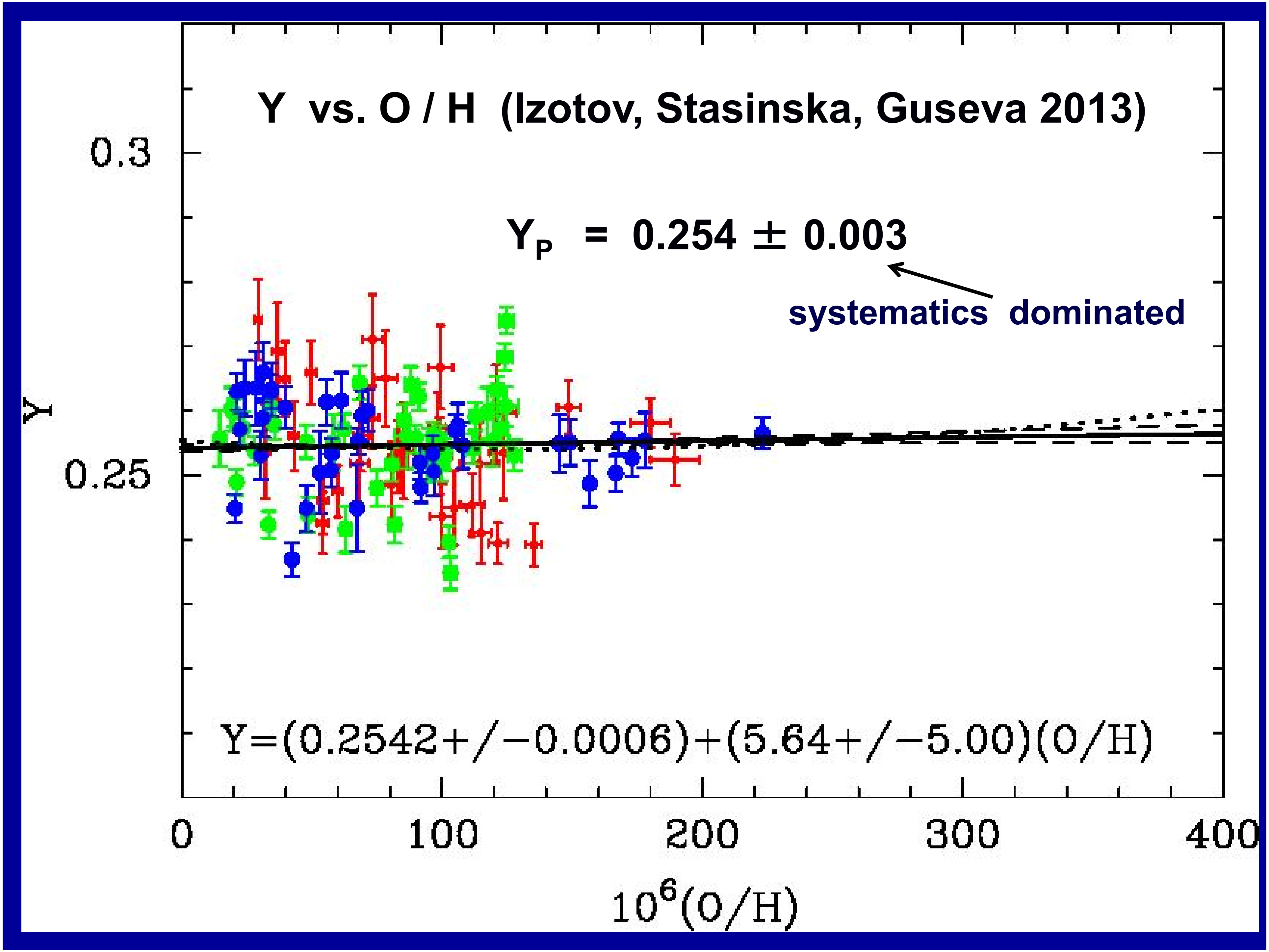
$$\eta_B \equiv (n_N / n_\gamma)_0 \text{ where } \eta_{10} \equiv 10^{10}\,\eta_B = 274\,\Omega_B h^2$$

<u>and</u> Dark Radiation: ΔN_ν ($N_{eff} \approx 3 + \Delta N_\nu$).

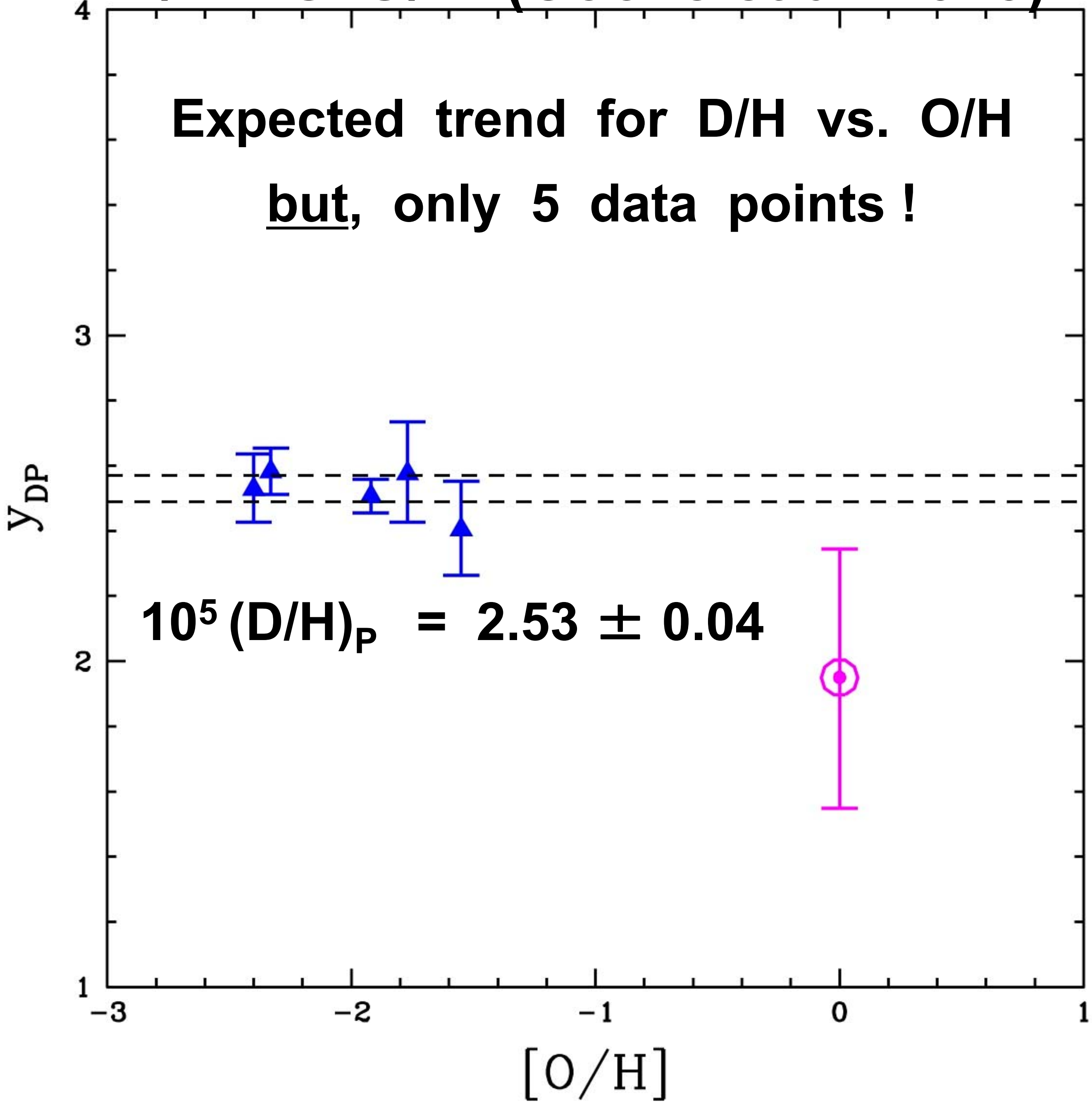
The CMB independently constrains these same parameters.

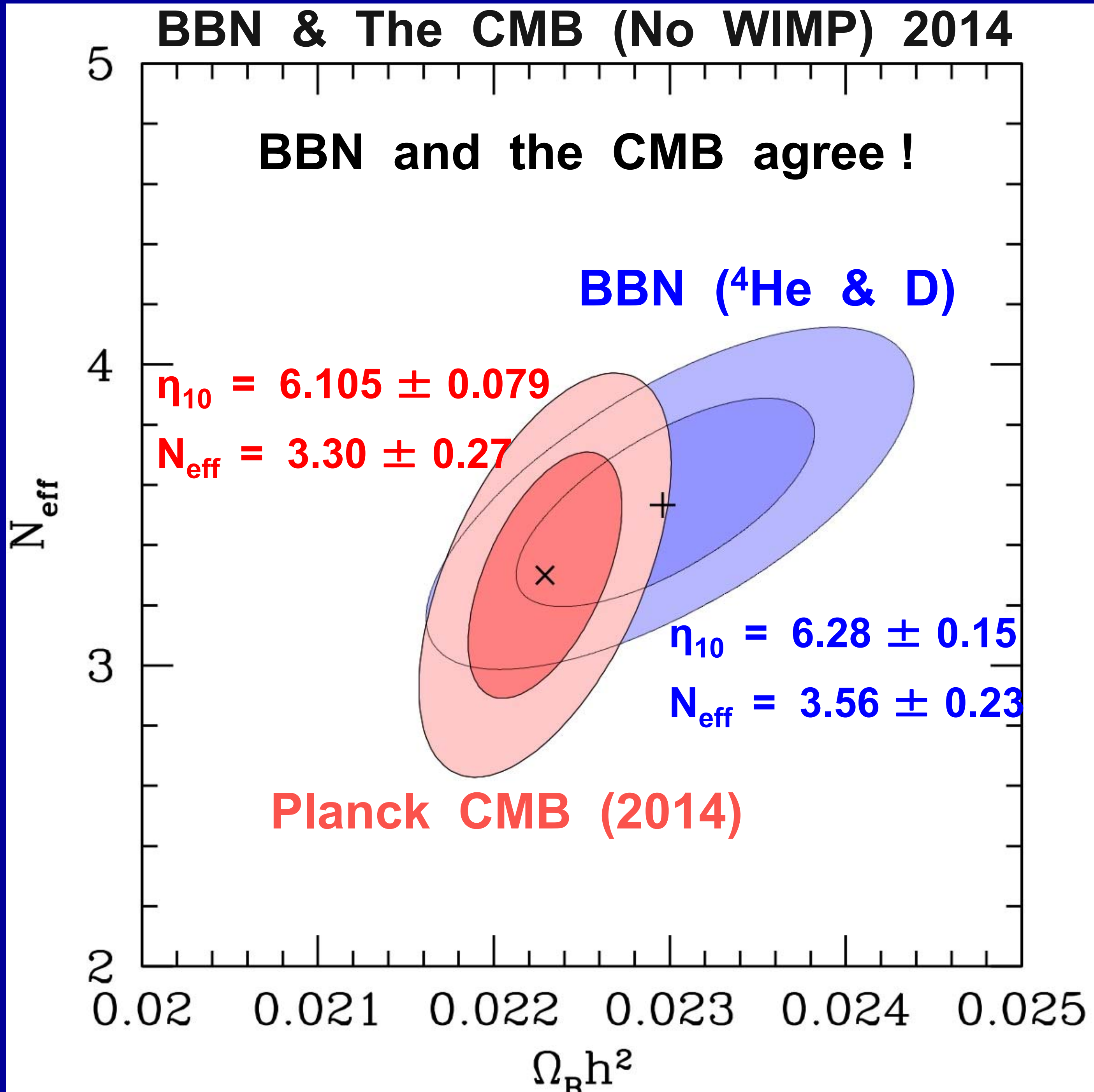
BBN – Predicted Y_P vs. $(D/H)_P$ (No WIMP)

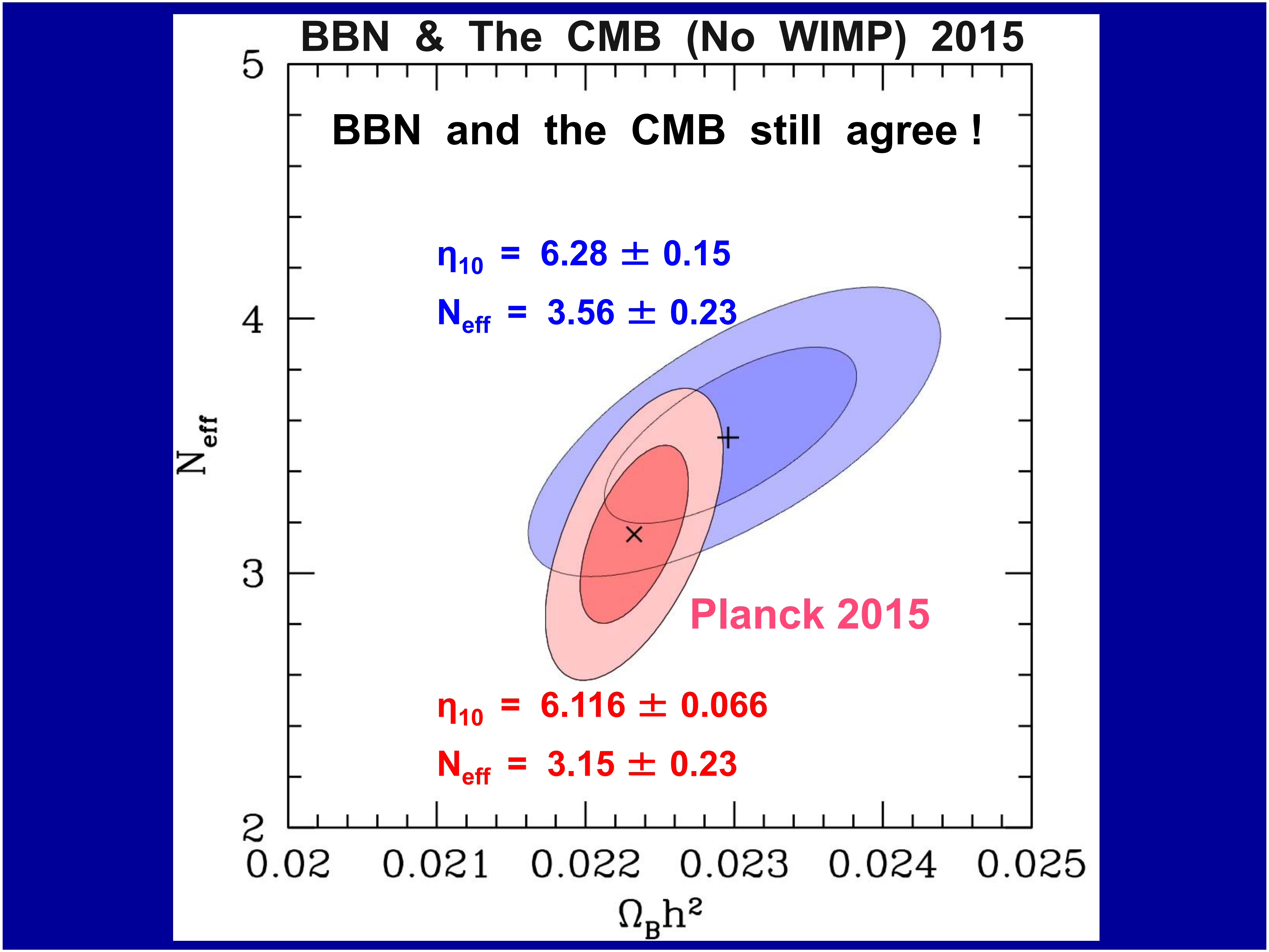


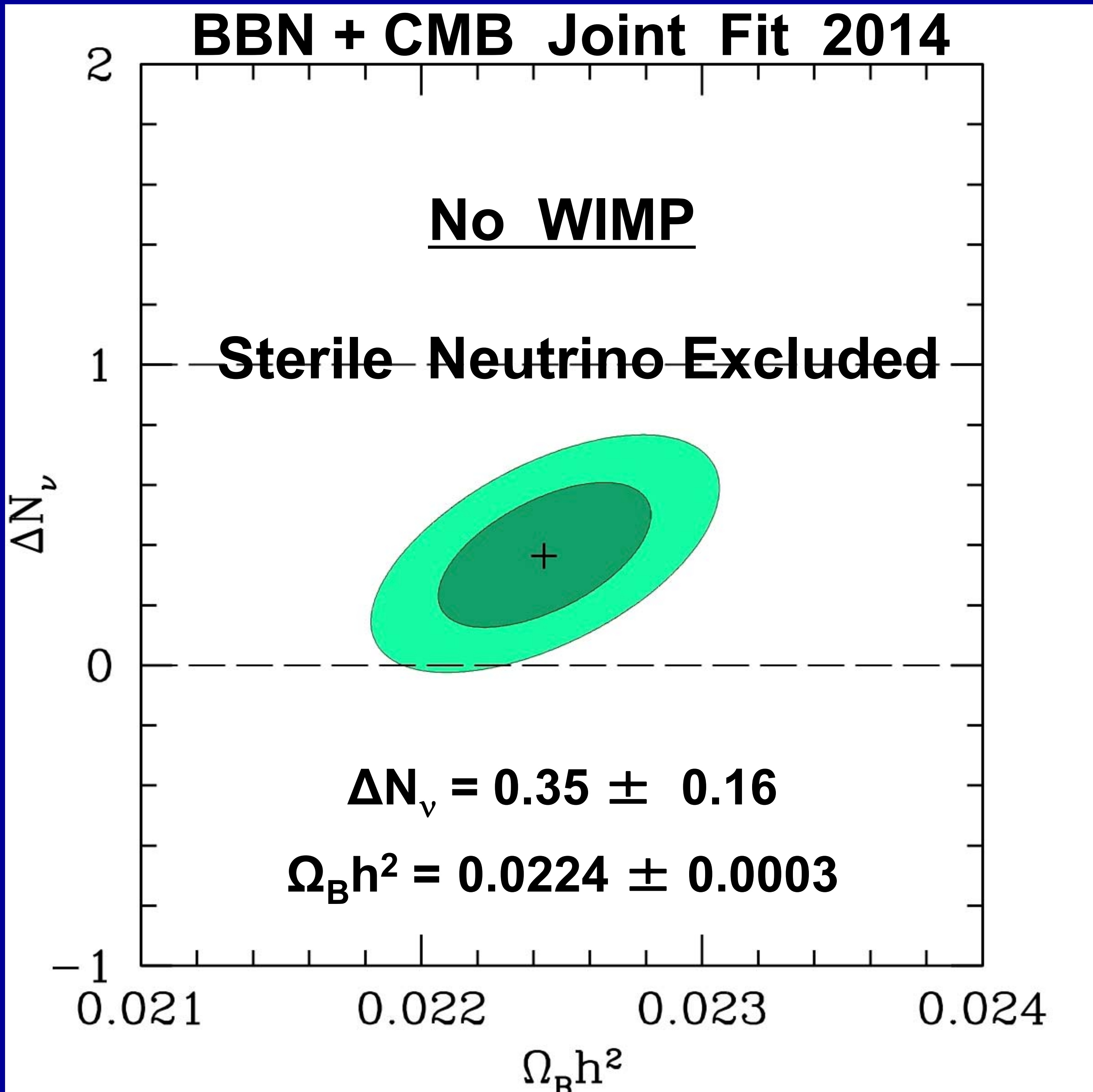

Y vs. O / H (Izotov, Stasinska, Guseva 2013)
Y_P = 0.254 ± 0.003
systematics dominated
Y=(0.2542+/-0.0006)+(5.64+/-5.00)(O/H)
0.3
0.25
Y
0
100
200
300
400
10^6(O/H)

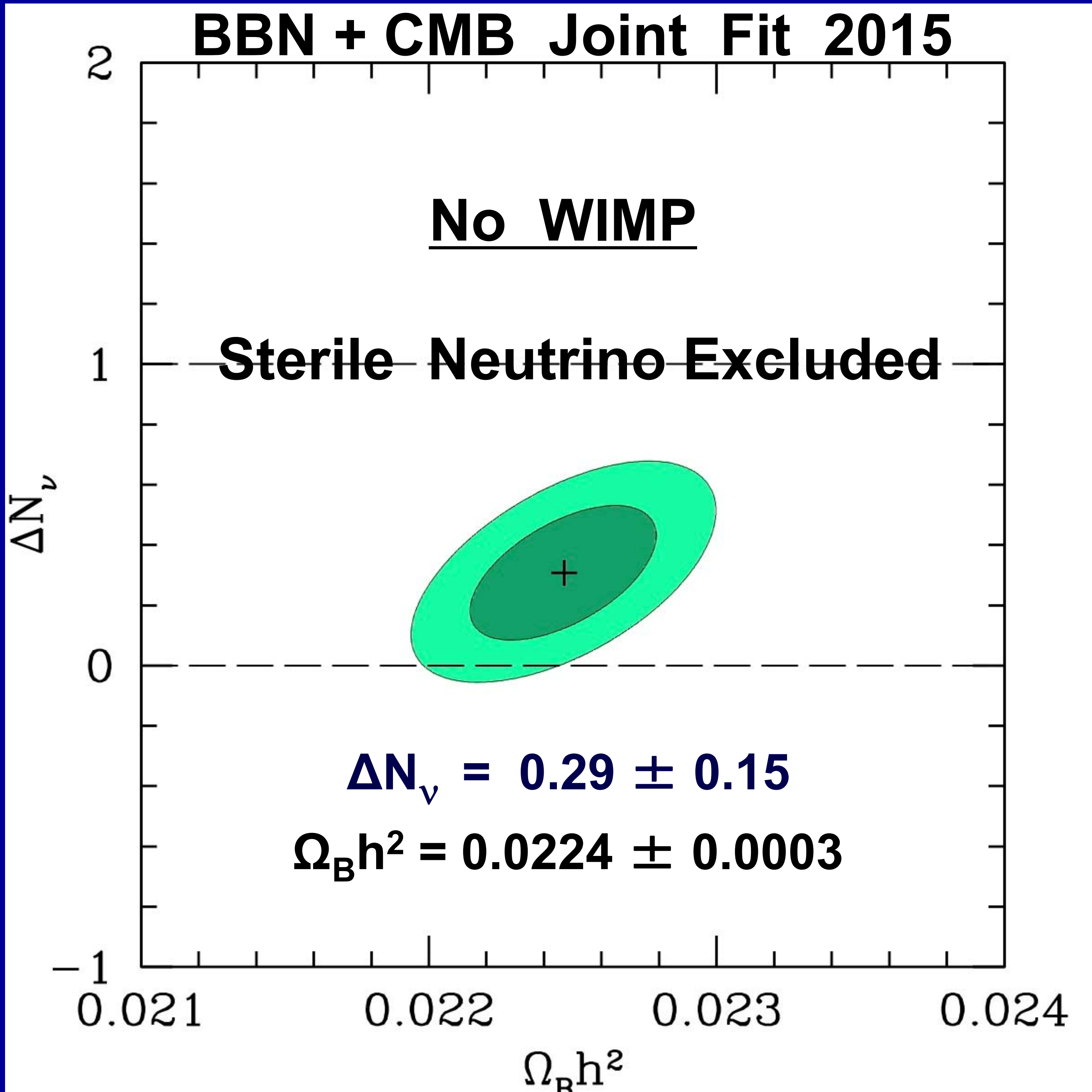
D/H vs. O/H (Cooke et al. 2013)

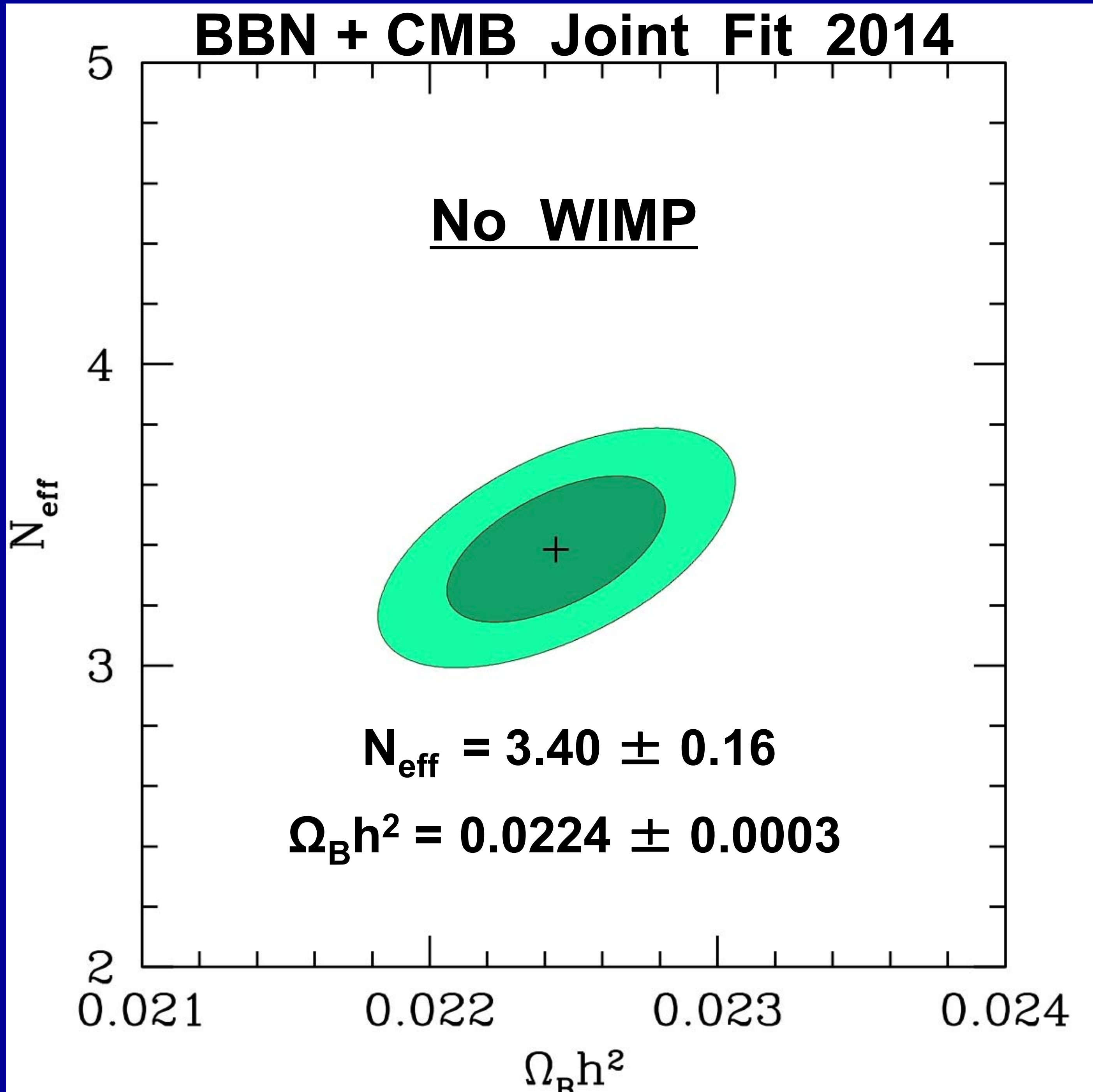


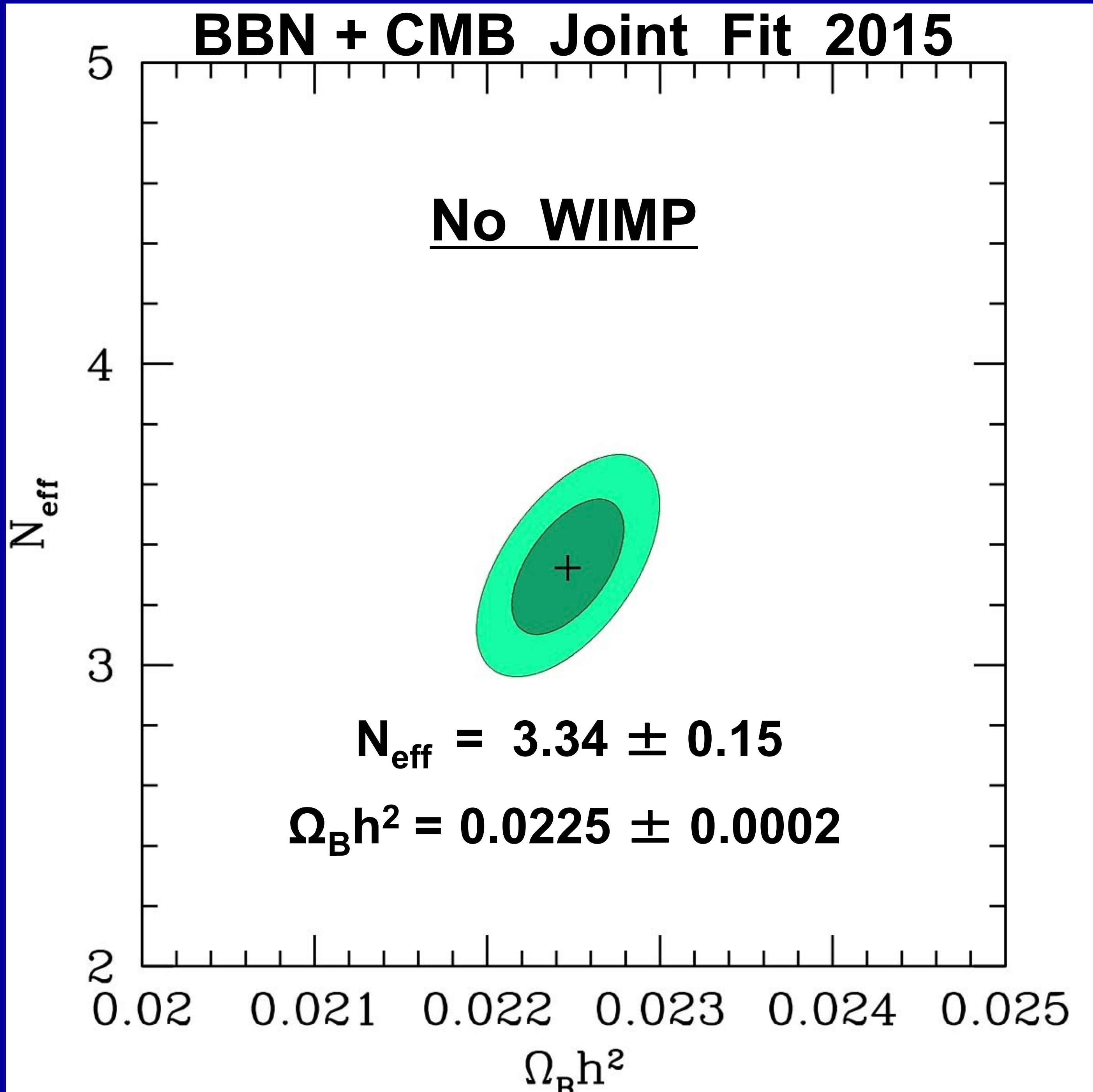

BBN & The CMB (No WIMP) 2014
BBN and the CMB agree !
BBN (^{4}He & D)
η_{10} = 6.105 ± 0.079
N_{eff} = 3.30 ± 0.27
η_{10} = 6.28 ± 0.15
N_{eff} = 3.56 ± 0.23
Planck CMB (2014)
N_{eff}
$\Omega_B h^2$
5
4
3
2
0.02
0.021
0.022
0.023
0.024
0.025


BBN & The CMB (No WIMP) 2015
BBN and the CMB still agree !
η10 = 6.28 ± 0.15
Neff = 3.56 ± 0.23
Planck 2015
η10 = 6.116 ± 0.066
Neff = 3.15 ± 0.23
Neff
ΩBh2
5
4
3
2
0.02
0.021
0.022
0.023
0.024
0.025


BBN + CMB Joint Fit 2014
No WIMP
Sterile Neutrino Excluded
ΔN_ν = 0.35 ± 0.16
Ω_B h² = 0.0224 ± 0.0003
2
1
0
−1
ΔN_ν
0.021
0.022
0.023
0.024
Ω_B h²


BBN + CMB Joint Fit 2015
No WIMP
Sterile Neutrino Excluded
ΔNν = 0.29 ± 0.15
ΩBh² = 0.0224 ± 0.0003
ΔNν
ΩBh²
2
1
0
−1
0.021
0.022
0.023
0.024


BBN + CMB Joint Fit 2014
No WIMP
N_{eff} = 3.40 ± 0.16
$\Omega_B h^2$ = 0.0224 ± 0.0003
5
4
3
2
N_{eff}
0.021
0.022
0.023
0.024
$\Omega_B h^2$

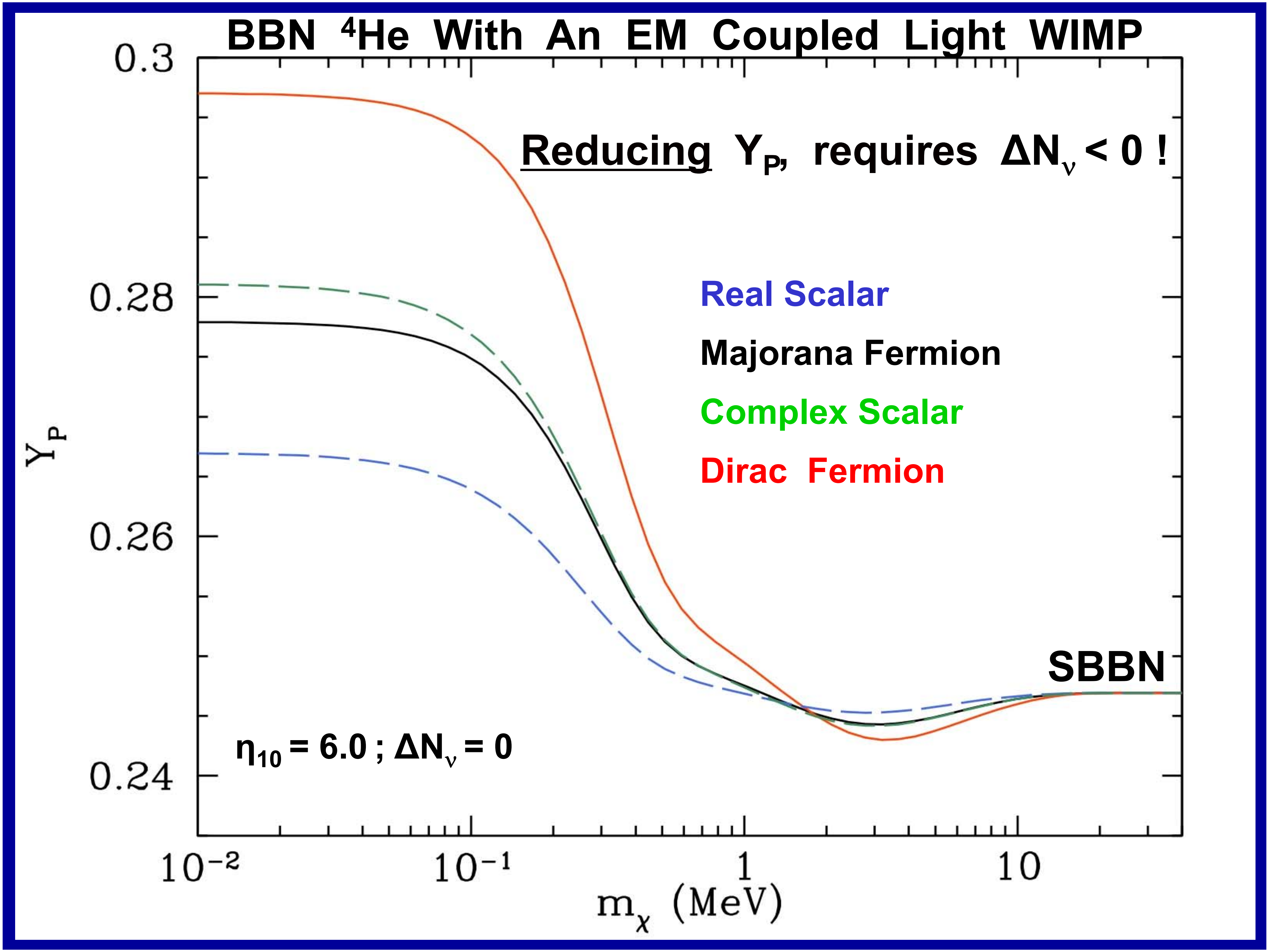

BBN + CMB Joint Fit 2015
No WIMP
N_{eff} = 3.34 ± 0.15
$\Omega_B h^2$ = 0.0225 ± 0.0002
N_{eff}
5
4
3
2
0.02
0.021
0.022
0.023
0.024
0.025
$\Omega_B h^2$

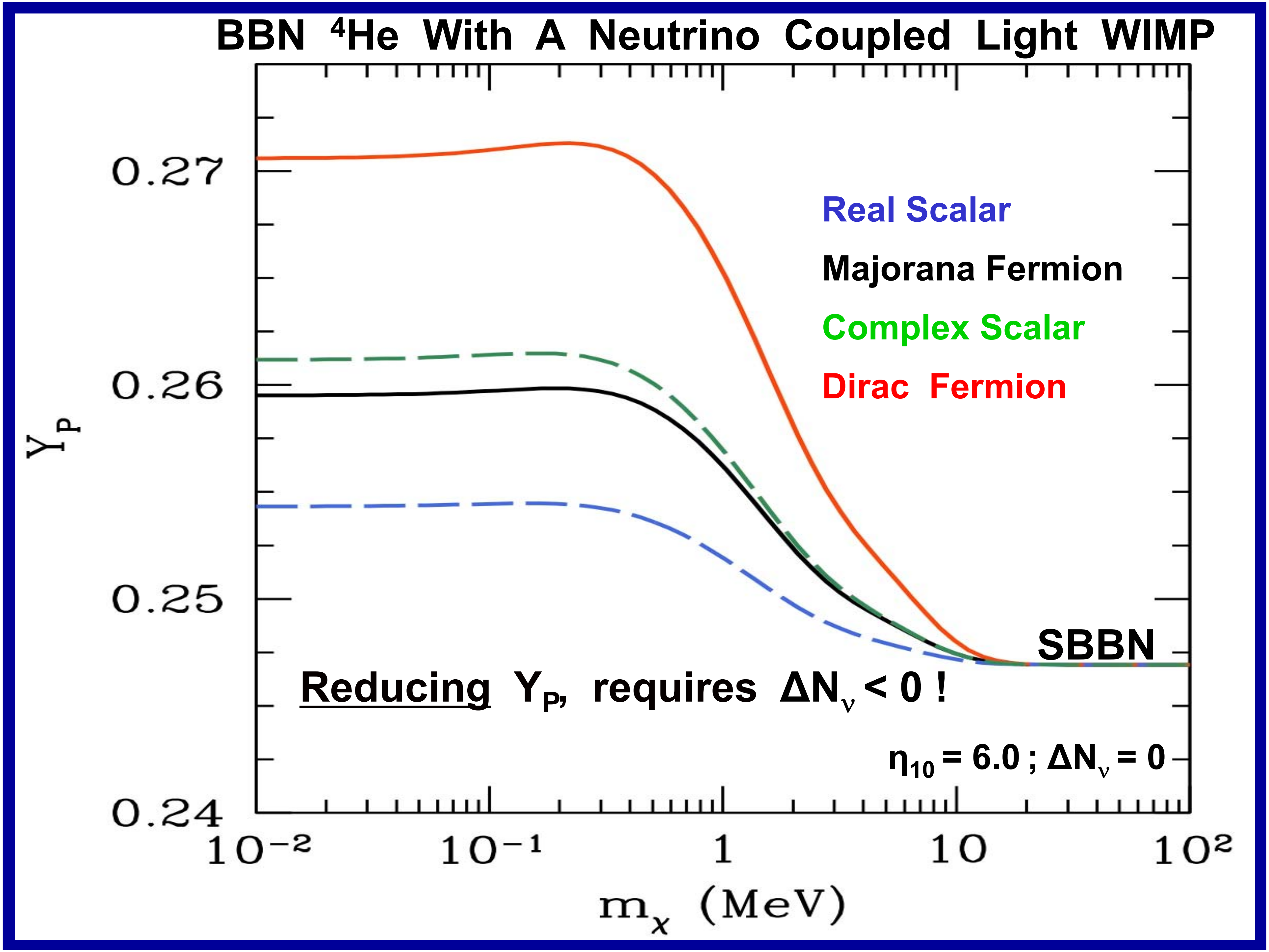
BBN & The CMB With A Light WIMP

There are degeneracies among the WIMP mass and its "nature" and the number of equivalent neutrinos. BBN, in combination with the CMB, can remove some of these degeneracies, constraining the existence and properties of each.

Light WIMPs increase the early Universe energy density, speeding up the expansion rate at BBN (and at recombination).

The main effect of a faster expansion is that more neutrons are available at BBN, leading to the production of more ^4He.


BBN 4He With An EM Coupled Light WIMP
Reducing YP, requires ΔNν < 0 !
Real Scalar
Majorana Fermion
Complex Scalar
Dirac Fermion
SBBN
η10 = 6.0 ; ΔNν = 0
0.3
0.28
0.26
0.24
YP
10−2
10−1
1
10
mχ (MeV)

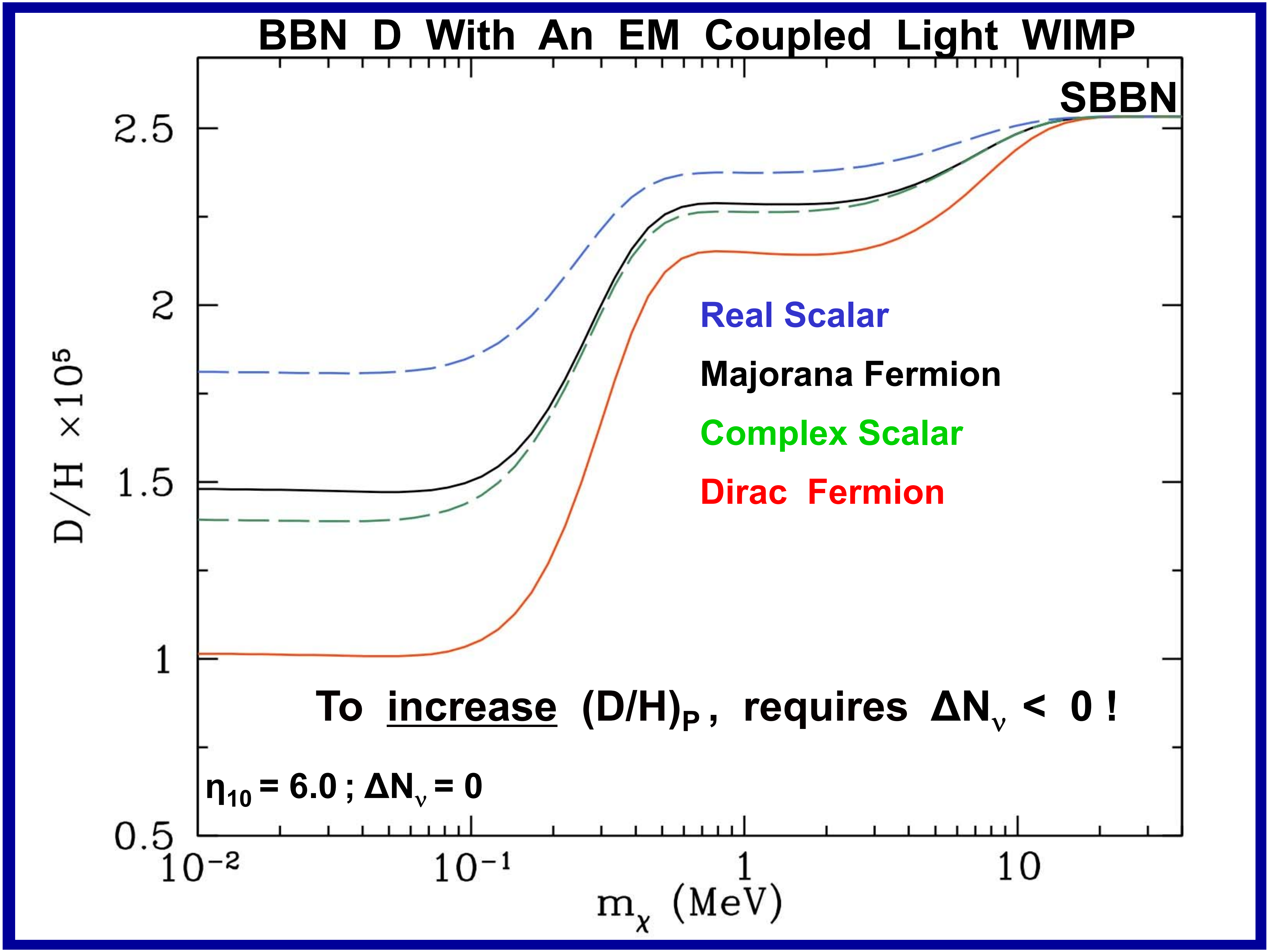


BBN 4He With A Neutrino Coupled Light WIMP
Real Scalar
Majorana Fermion
Complex Scalar
Dirac Fermion
SBBN
Reducing Y_P, requires ΔN_ν < 0 !
η10 = 6.0 ; ΔN_ν = 0
0.27
0.26
0.25
0.24
Y_P
10^-2
10^-1
1
10
10^2
m_χ (MeV)

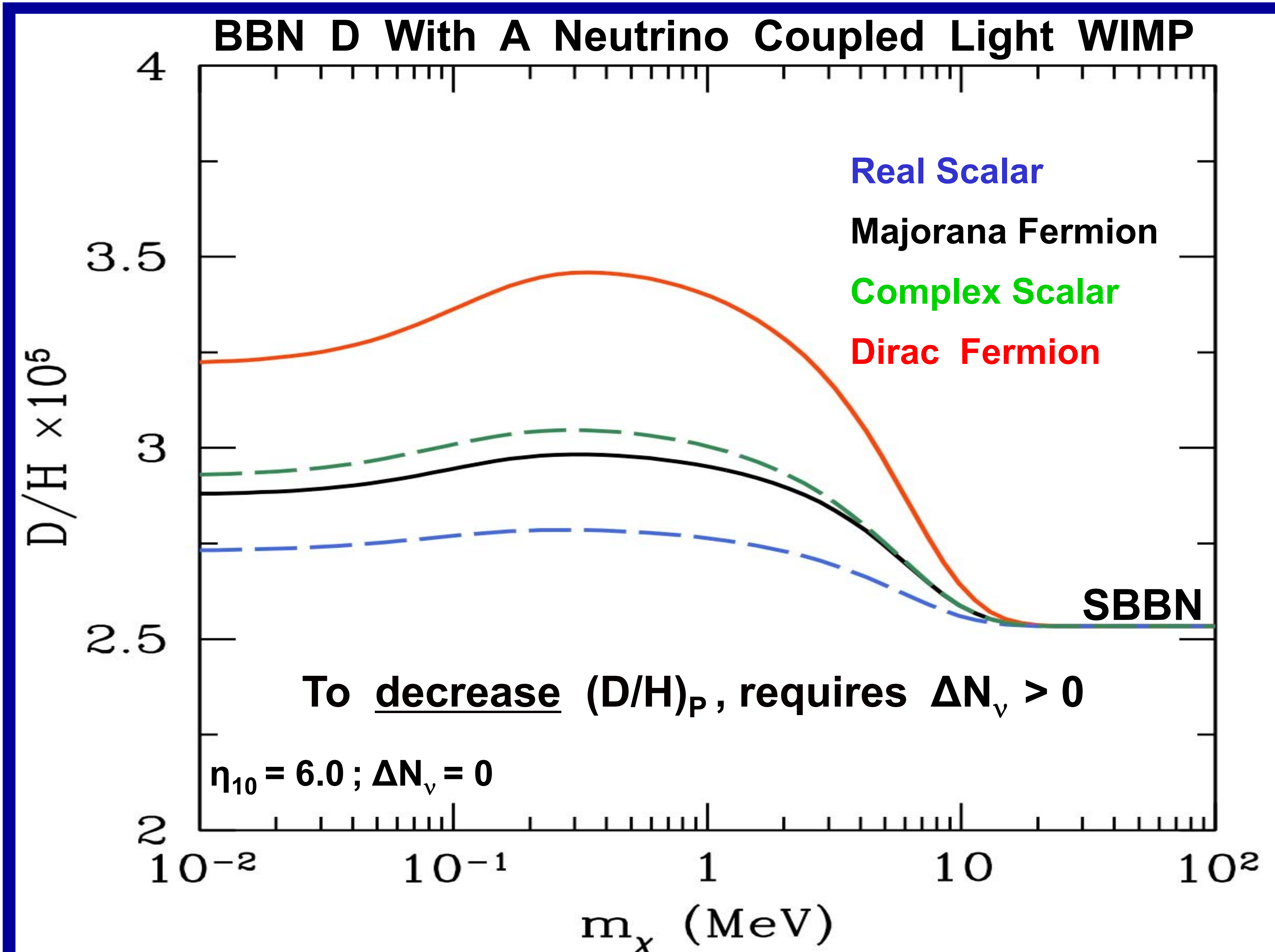
The annihilation of EM coupled light WIMPs creates extra photons, changing the baryon - to - photon ratio at BBN (and at recombination), affecting the BBN nuclear reaction rates.

The main effect of photon production <u>after</u> BBN is a <u>larger</u> baryon - to - photon <u>during</u> BBN, more efficiently destroying D, resulting in a <u>lower</u> primordial D abundance.

The annihilation of Neutrino coupled light WIMPs creates no new photons, but does speed up the expansion rate, leaving less time to destroy D.



BBN D With An EM Coupled Light WIMP
SBBN
2.5
2
1.5
1
0.5
D/H ×10^5
Real Scalar
Majorana Fermion
Complex Scalar
Dirac Fermion
To increase (D/H)_P , requires ΔN_ν < 0 !
η_10 = 6.0 ; ΔN_ν = 0
10^-2
10^-1
1
10
m_χ (MeV)

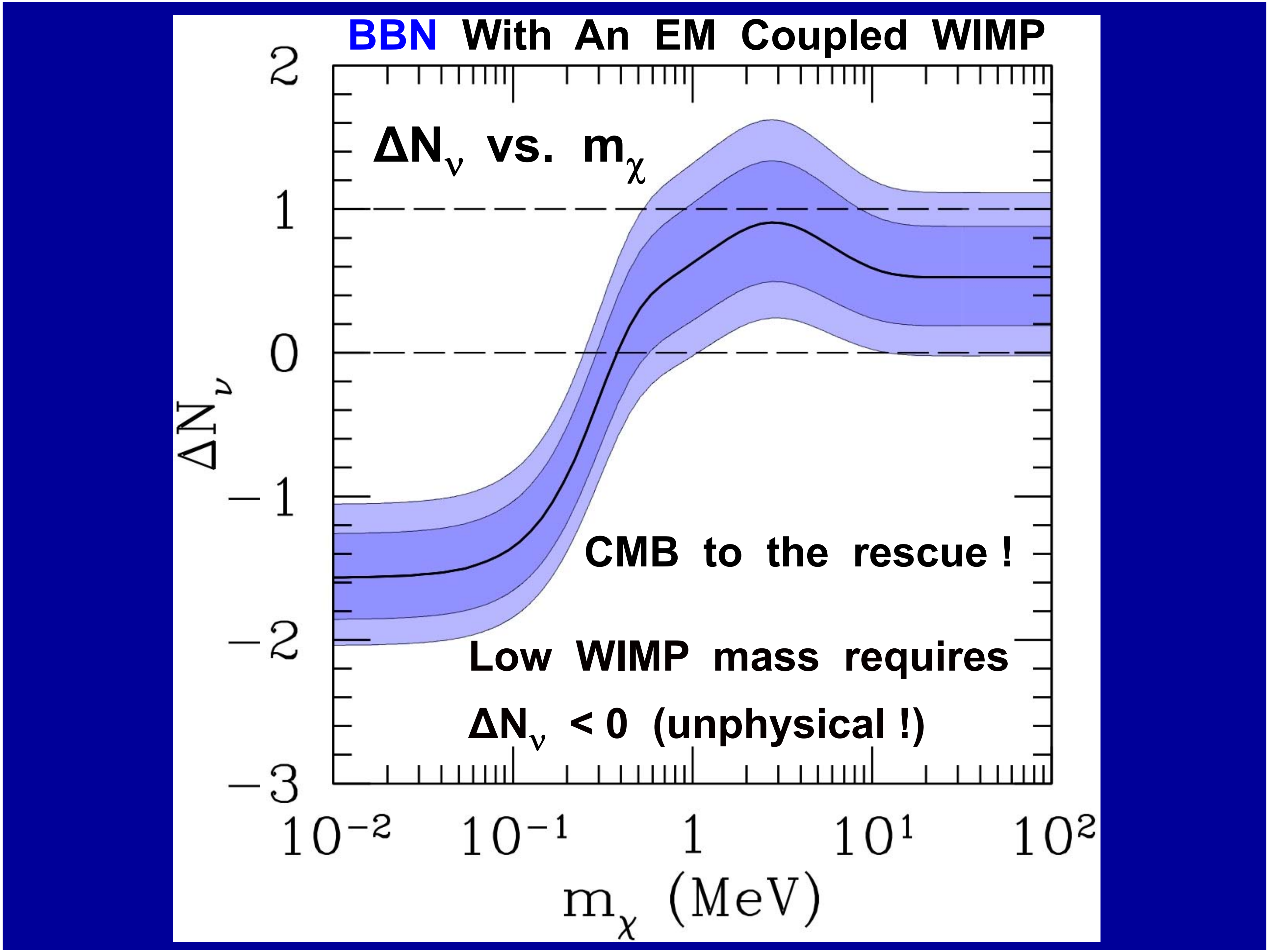

BBN D With A Neutrino Coupled Light WIMP
D/H ×10^5
4
3.5
3
2.5
2
Real Scalar
Majorana Fermion
Complex Scalar
Dirac Fermion
SBBN
To decrease (D/H)P , requires ΔNν > 0
η10 = 6.0 ; ΔNν = 0
10^-2
10^-1
1
10
10^2
mχ (MeV)

BBN And The CMB 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 will "predict" the observationally inferred primordial ^{4}He and D abundances.

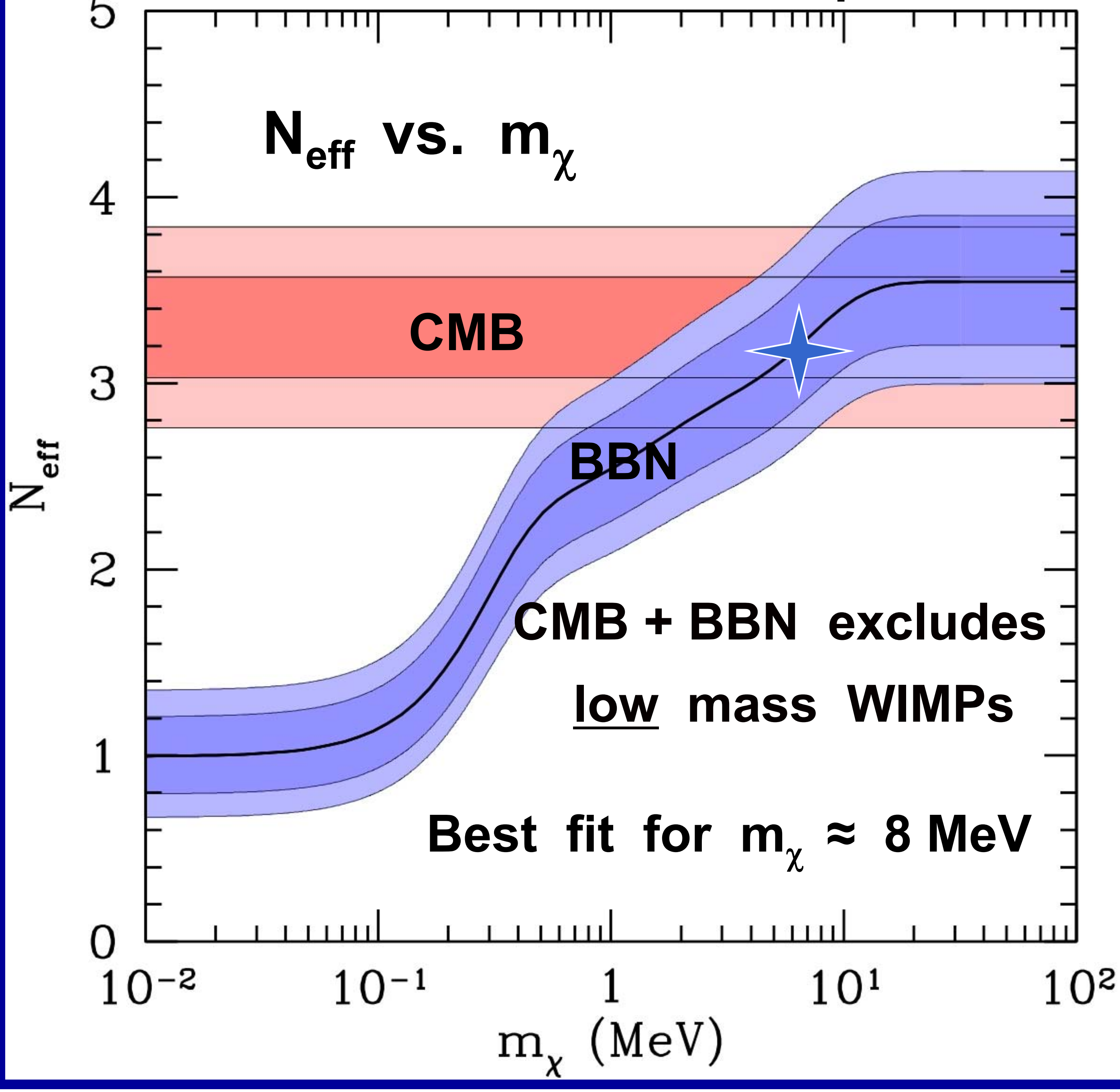
The CMB independently constrains $\Omega_B h^2$ and N_{eff}.

The next slides illustrate this for an EM coupled, Weyl fermion.

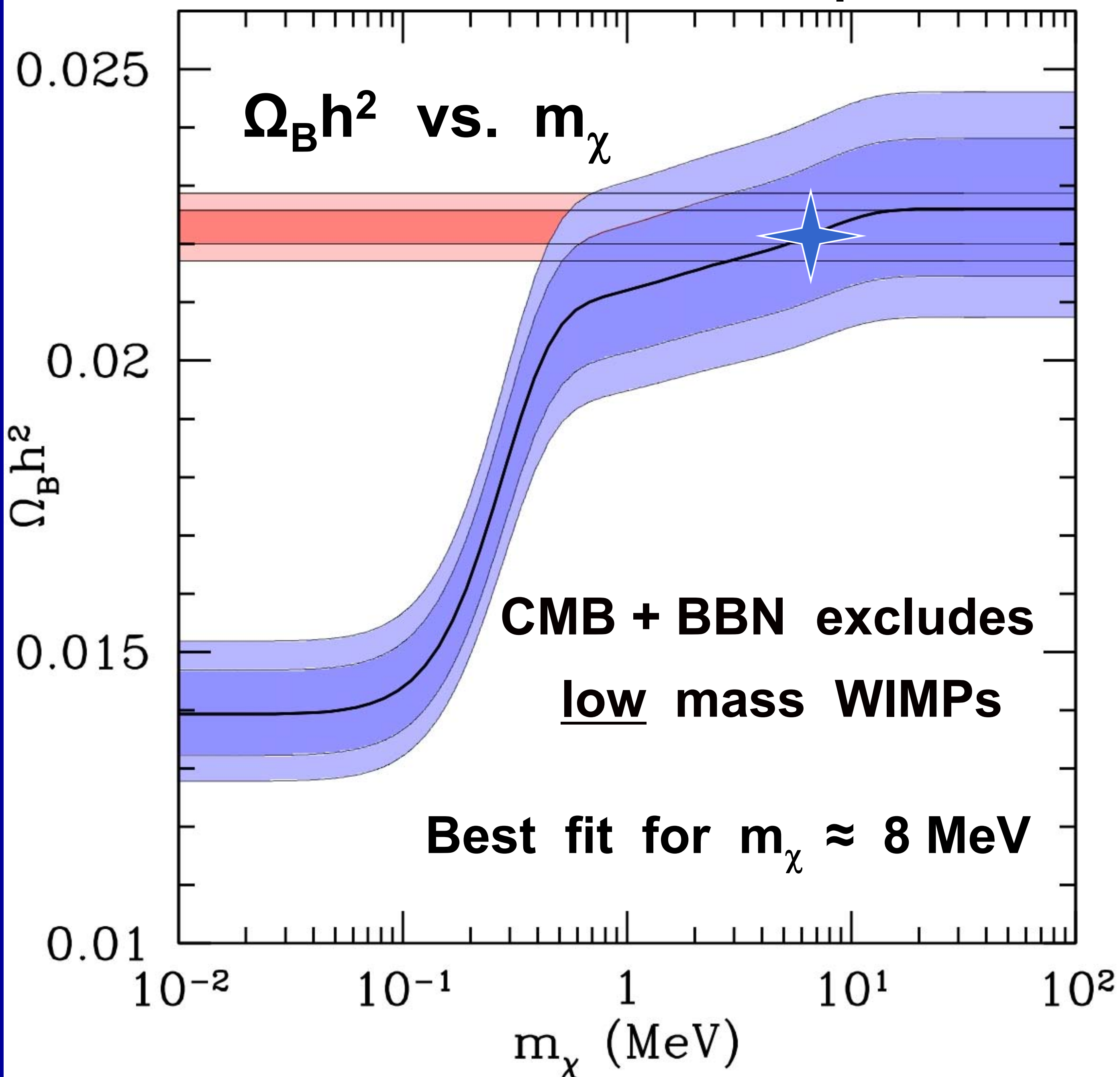


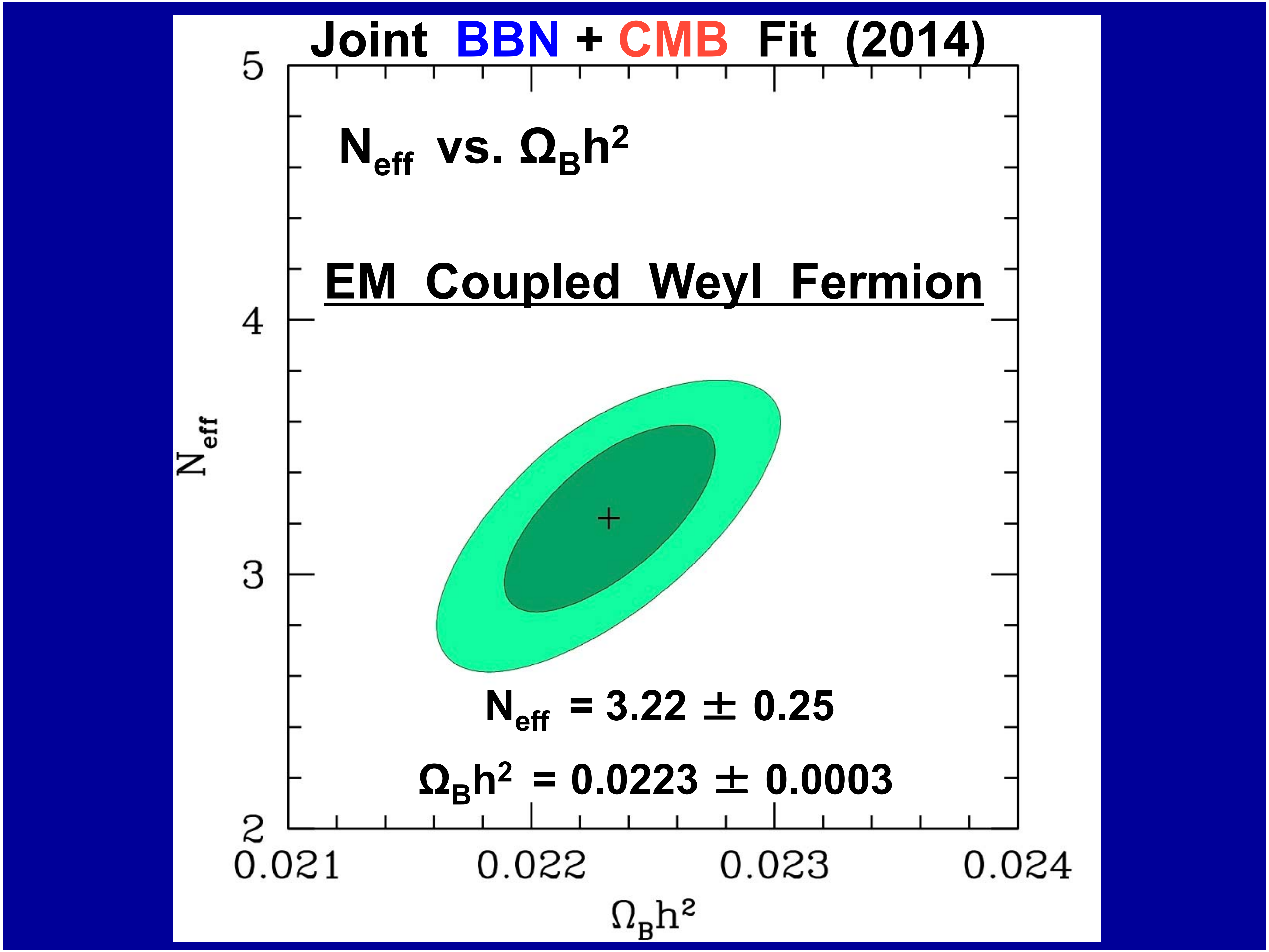
BBN With An EM Coupled WIMP
ΔNν vs. mχ
CMB to the rescue !
Low WIMP mass requires
ΔNν < 0 (unphysical !)
ΔNν
mχ (MeV)
2
1
0
−1
−2
−3
10−2
10−1
1
101
102

BBN & CMB With An EM Coupled WIMP

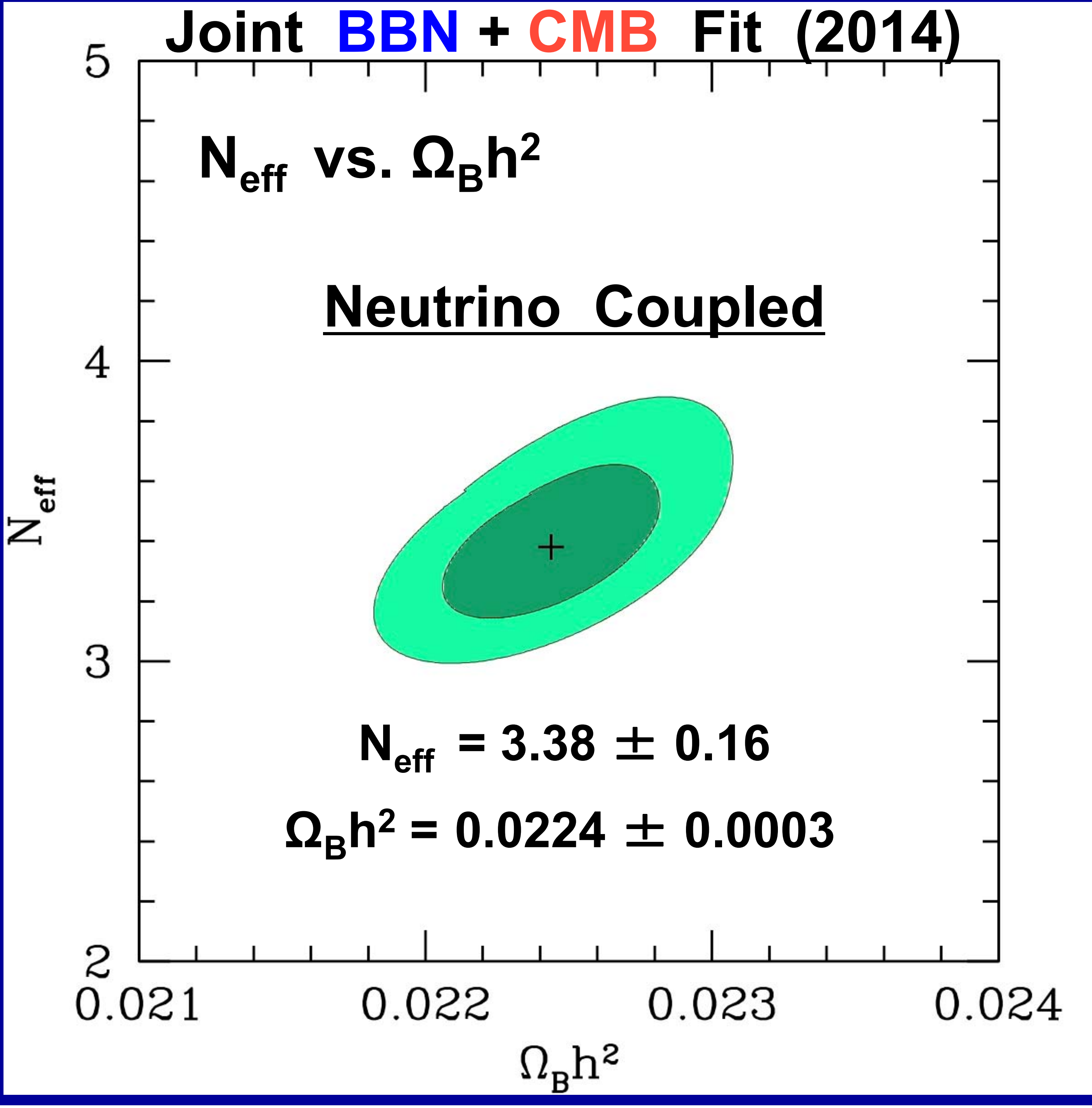


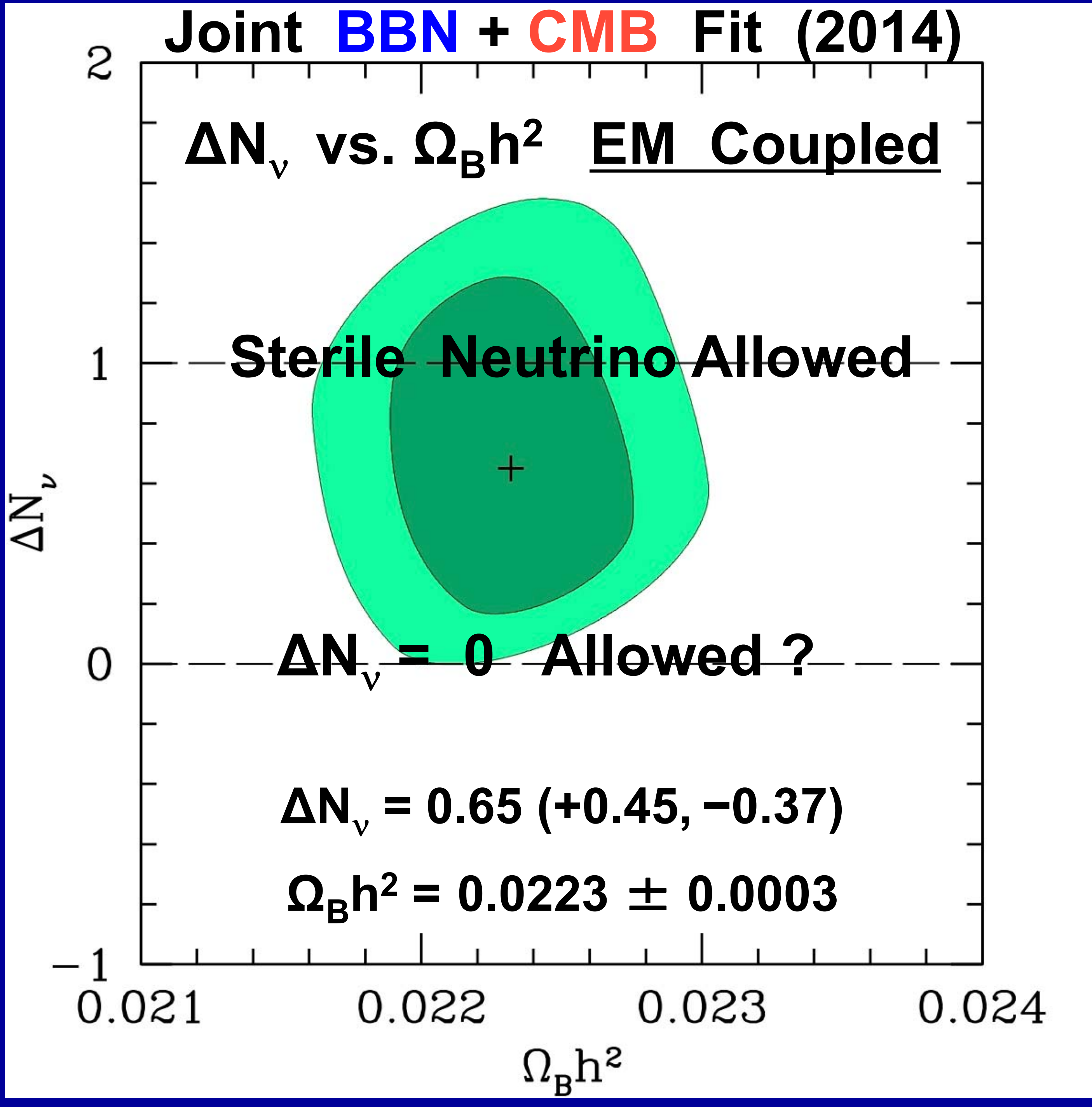
BBN & CMB With An EM Coupled WIMP



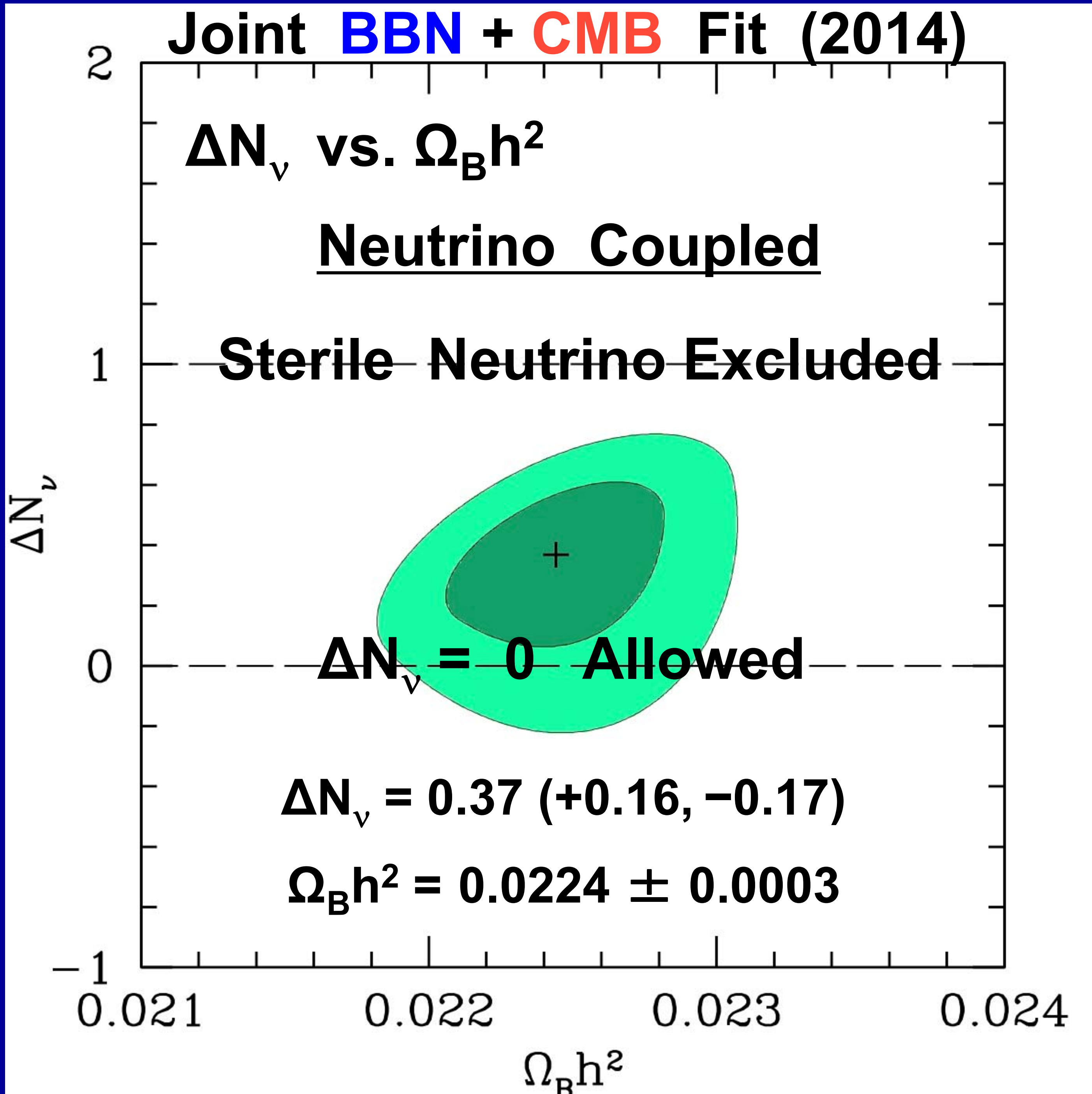


Joint BBN + CMB Fit (2014)
N_eff vs. Ω_B h²
EM Coupled Weyl Fermion
N_eff = 3.22 ± 0.25
Ω_B h² = 0.0223 ± 0.0003
N_eff
Ω_B h²
5
4
3
2
0.021
0.022
0.023
0.024


Joint BBN + CMB Fit (2014)
N_{eff} vs. $\Omega_B h^2$
Neutrino Coupled
N_{eff} = 3.38 ± 0.16
$\Omega_B h^2$ = 0.0224 ± 0.0003
5
4
3
2
0.021
0.022
0.023
0.024
N_{eff}
$\Omega_B h^2$



Joint BBN + CMB Fit (2014)
ΔN_ν vs. Ω_B h² EM Coupled
Sterile Neutrino Allowed
ΔN_ν = 0 Allowed ?
ΔN_ν = 0.65 (+0.45, −0.37)
Ω_B h² = 0.0223 ± 0.0003
2
1
0
−1
0.021
0.022
0.023
0.024
ΔN_ν
Ω_B h²



Joint BBN + CMB Fit (2014)
ΔNν vs. ΩBh²
Neutrino Coupled
Sterile Neutrino Excluded
ΔNν = 0 Allowed
ΔNν = 0.37 (+0.16, −0.17)
ΩBh² = 0.0224 ± 0.0003
2
1
0
−1
0.021
0.022
0.023
0.024
ΔNν
ΩBh²

SUMMARY

In the absence of a Light WIMP, BBN and the CMB agree, allowing for some Dark Radiation. But, a sterile neutrino ($\Delta N_\nu = 1$) is disfavored.

In the presence of a Light, EM Coupled WIMP, BBN and the CMB set a lower bound to the WIMP mass, $\geq$ a few MeV, favoring $m_\chi \approx 10$ MeV, and allowing some Dark Radiation, $\Delta N_\nu \approx 0.65$.

SUMMARY

For a Neutrino Coupled WIMP, BBN and the CMB set a lower bound of a few MeV to the WIMP mass. They favor $m_\chi \approx 35$ MeV (i.e., No Light WIMP !) and allow some Dark Radiation, $\Delta N_\nu \approx 0.29$.

But, a sterile neutrino ($\Delta N_\nu = 1$) is disfavored.