Constraining DARK Radiation From Recent Observations

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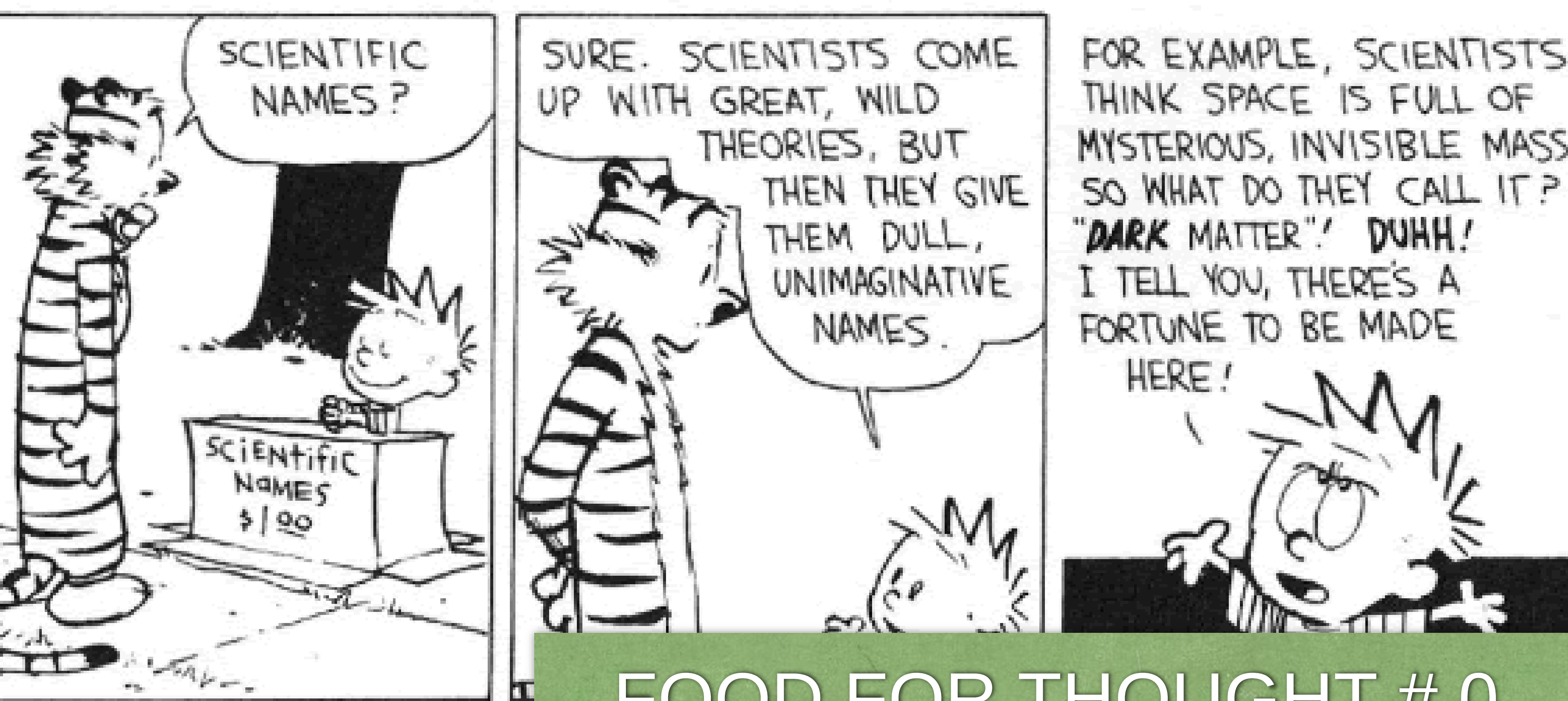
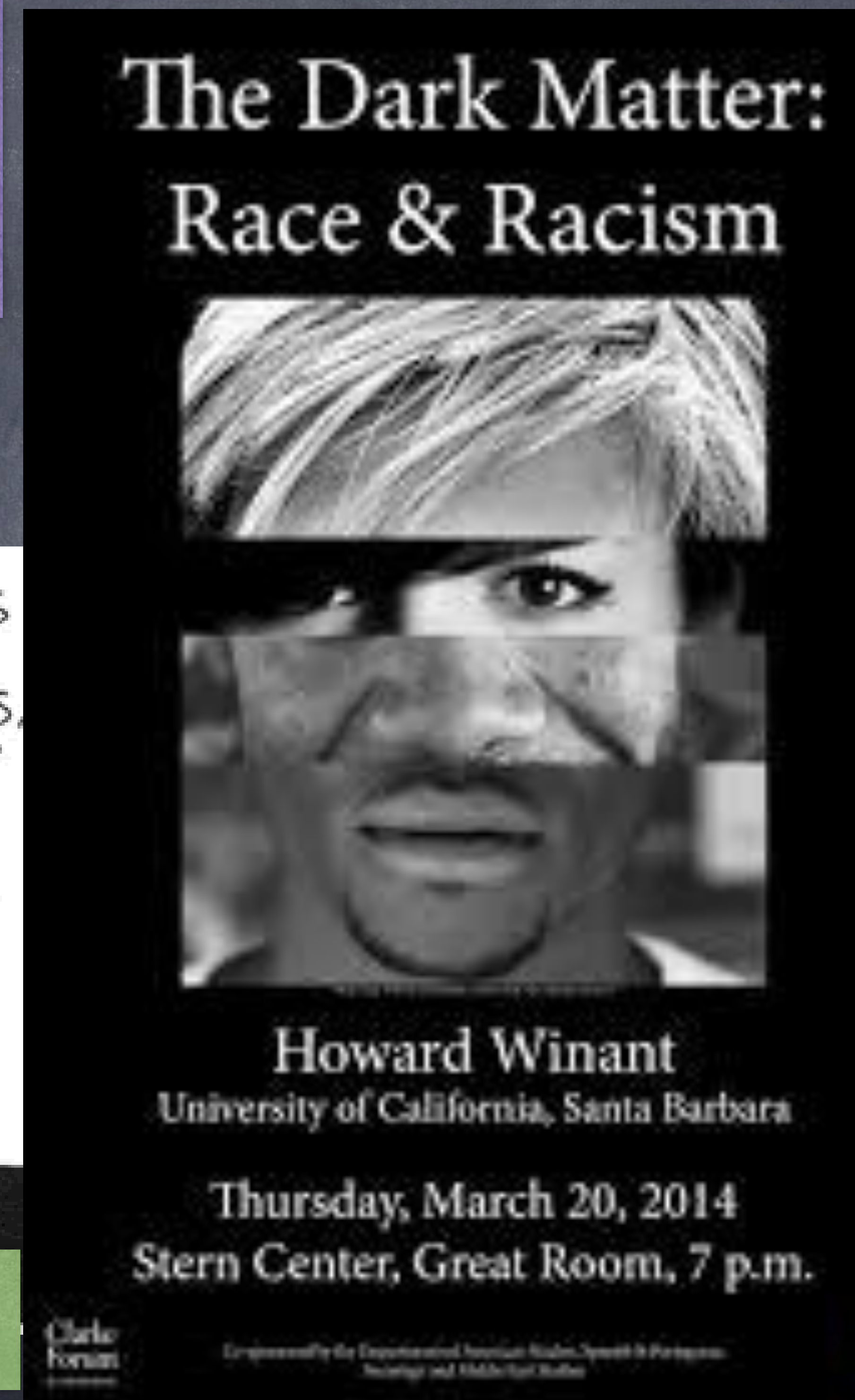
"Vacuums, black holes, anti-matter — it's the elusive and intangible which appeals to me."

SCIENTIFIC NAMES!!





FOOD FOR THOUGHT # 0

Things To Discuss :

-> What is Dark Radiation??

-> A Brief Review of DR History

-> Dark Radiation Theories

-> Confronting DR from CMB

-> Confronting DR from BBN

-> Future Directions

What is Dark Radiation!!

Dark radiation

From Wikipedia, the free encyclopedia

Dark radiation (also **dark electromagnetism**)[1] is a postulated type of radiation that mediates interactions of dark matter.

By analogy to the way photons mediate electromagnetic interactions between particles in the Standard Model (called *baryonic matter* in cosmology), dark radiation is proposed to mediate interactions between dark matter particles.[1] Similar to dark matter particles, the hypothetical dark radiation does not interact with Standard Model particles.

There has been no notable evidence for the existence of such radiation, but since baryonic matter contains multiple interacting particle types, it is reasonable to suppose that dark matter does also. Moreover, it has been pointed out recently that the cosmic microwave background data seems to suggest that the number of effective neutrino degrees of freedom is more than 3.046, which is slightly more than the standard case for 3 types of neutrino.[2] This extra degree of freedom could arise from having a non-trivial amount of dark radiation in the universe. One possible candidate for dark radiation is the sterile neutrino.

NOT TRUE!!

Source: https://en.wikipedia.org/wiki/Dark_radiation

Current energy density of the relativistic energy component:

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

Free parameter (IMP!!)

N_{eff} = 3.046 (SM +NIND)

Then Why The Fuss!!

2010-11 — WMAP7+ACT+SPT — $N_{eff} \sim 4\text{-}5$

2013 — Planck+HST — $N_{eff} = 3.83 \pm 0.54$

2015 — Planck — $N_{eff} = 3.33 \pm 0.24$

2017 — Planck??

If $N_{eff} > 3.12$ hard to explain from standard scenario

Scope for New Physics!!

Future ??

=> Either we find $N_{eff} \sim 3$ (SM).

Ok, we have lots of models!!

=> Or We find $N_{eff} > 3.15$ (BSM)

Now what??

=> Or We find $N_{eff} < 3$ (!!!)

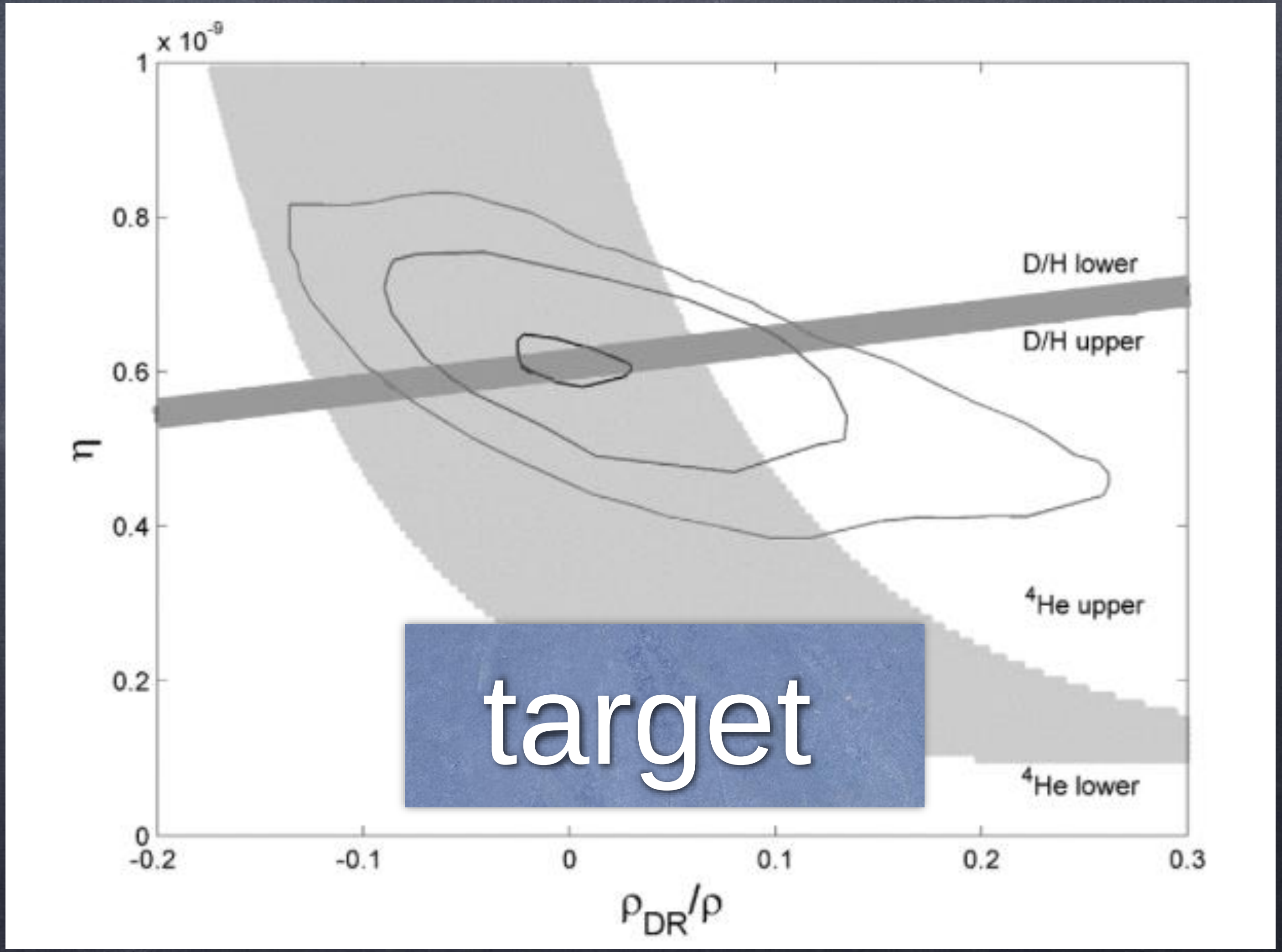
FOOD FOR THOUGHT # 1

Definition of Dark Radiation

Anything scales as a^{-4} => RADIATION

Any presence of radiation beyond $N_{eff]sm}$ => DARK RADIATION

Constrain DR from data



Sasankan,MRG,Mathews,KusakabePhys. Rev. D 95, 083516 (2017)

Possible Theoretical Avenues

* Sterile Neutrino — Hanmann et al arXiv: 1006.5276
* Axions — Hannested et al arXiv: 1004.0696
* Extra Dimensions — Ichiki et al PRD66, 043521 (2002)
* String Motivated LVS — Cicoli et al arXiv: 1308.3562
* and So on…..

Need a Possible way to discriminate the theories!!

Apparatus : CMB + BBN

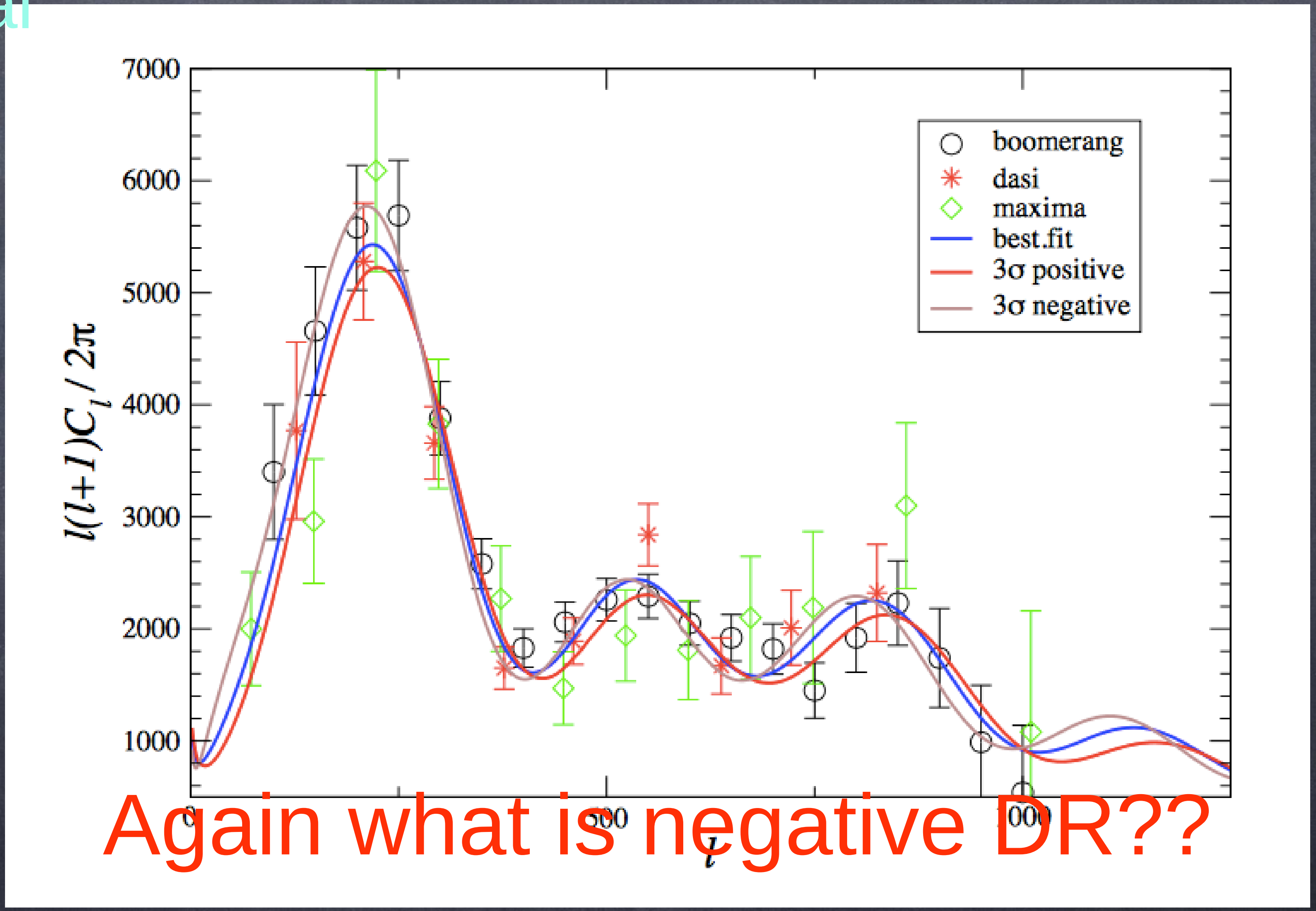
Effect of DR on CMB

e CMB spectrum is affected by the presence of extra relativistic d.o.f.

DR is their influence on the location and amplitude of the acoustic pe

ive dark radiation moves the epoch of matter radiation equality to a la

Prevents the growth of the perturbation inside the horizon and leads to a decay in the gravitational potential



Again what is negative DR??

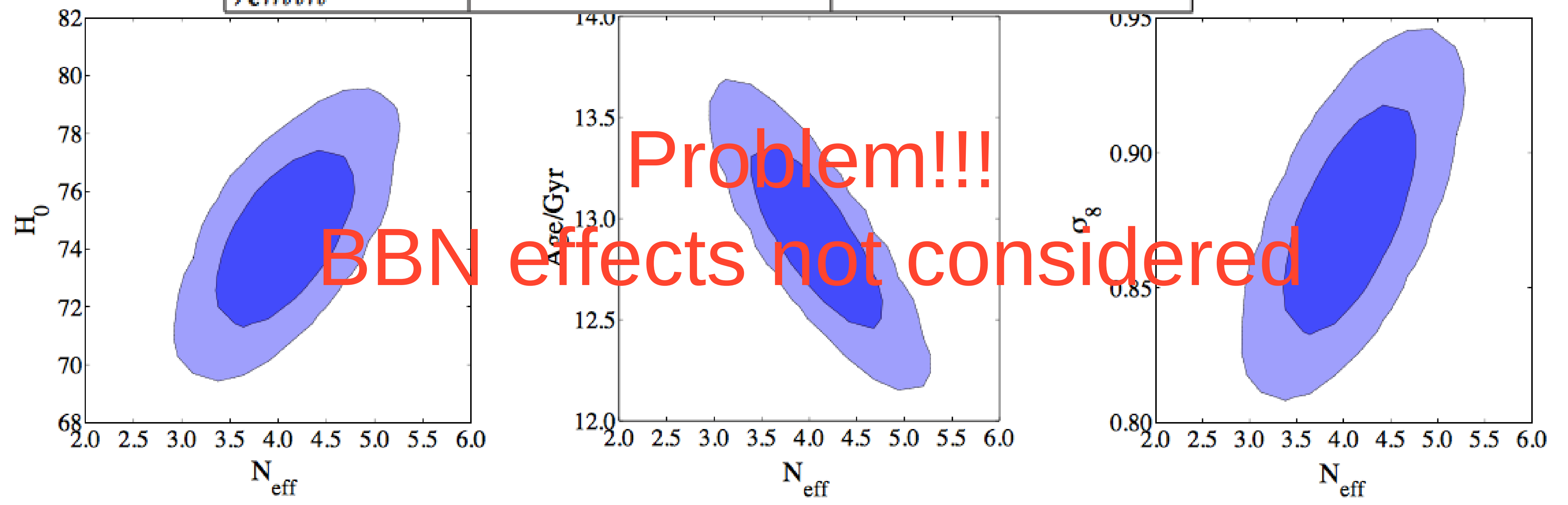
The net result of adding positive dark radiation is therefore an enhanced CMB anisotropy.

The Case For Dark Radiation

$\Omega_b h^2$	0.02229 ± 0.00038	0.02206 ± 0.00081
$\Omega_c h^2$	0.1333 ± 0.0086	0.1313 ± 0.0094
τ	0.082 ± 0.012	0.083 ± 0.014
H_0	74.3 ± 2.2	74.2 ± 2.1
n_s	0.977 ± 0.011	0.972 ± 0.021
$log(10^{10} A_s)$	3.195 ± 0.035	3.196 ± 0.035
A_{SZ}	< 1.2	< 1.4
$A_C[\mu K^2]$	< 14.3	< 14.6
$A_P[\mu K^2]$	< 25.2	< 24.7
$N_{\rm eff}$	$4.08^{+0.18+0.71}_{-0.18-0.68}$	$3.89^{+0.19+0.70}_{-0.19-0.70}$
$c^2_{\rm eff}$	$1/3$	$0.312^{+0.008+0.026}_{-0.007-0.026}$
$c^2_{\rm vis}$	$1/3$	$0.29^{+0.04+0.21}_{-0.06-0.16}$
χ^2_{min}	7594.2	7591.5

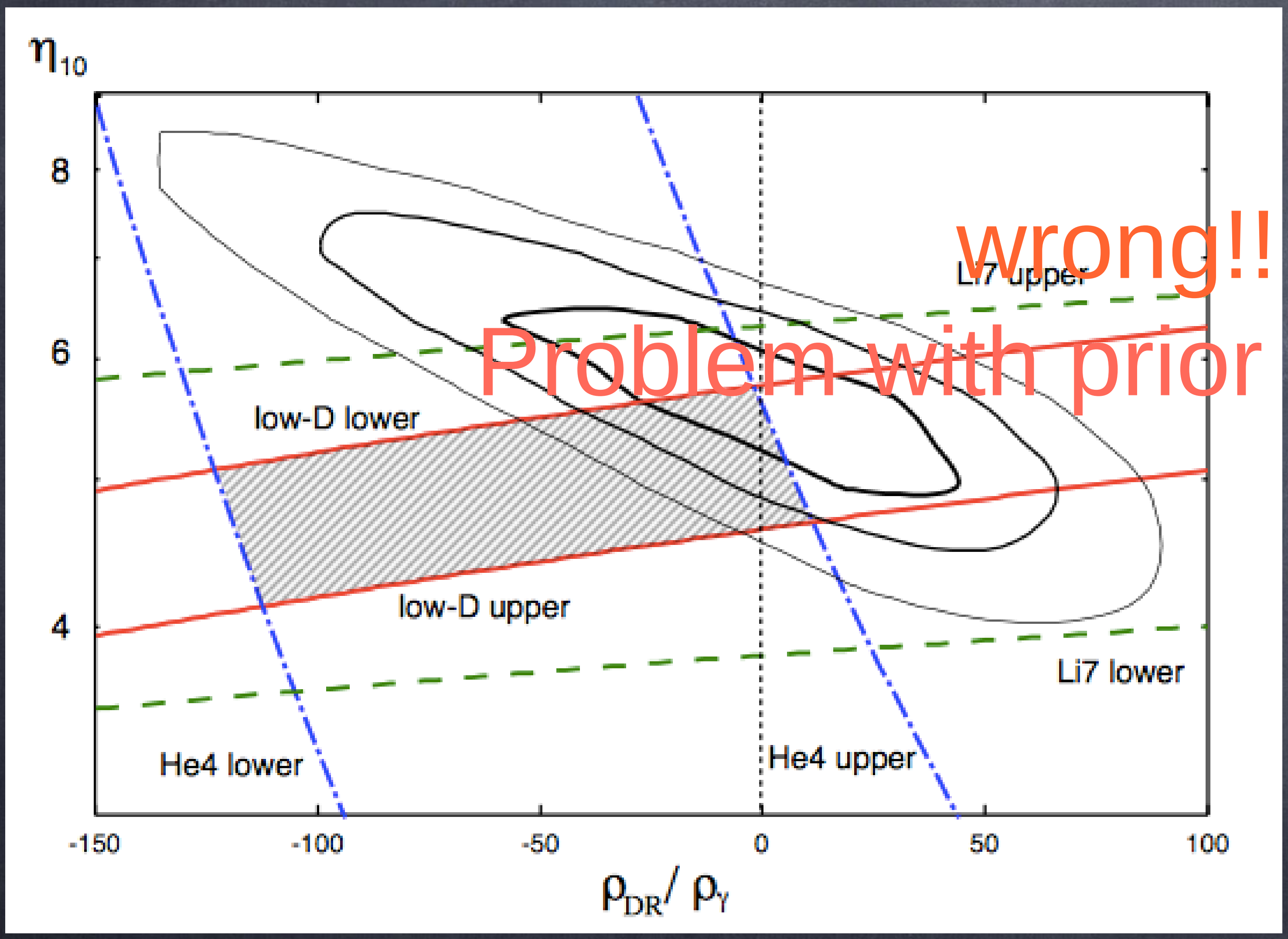
WMAP7+ACT+SPT

Archdiancono et al. [arXiv: 1109.2767]



BBN + CMB Constraints

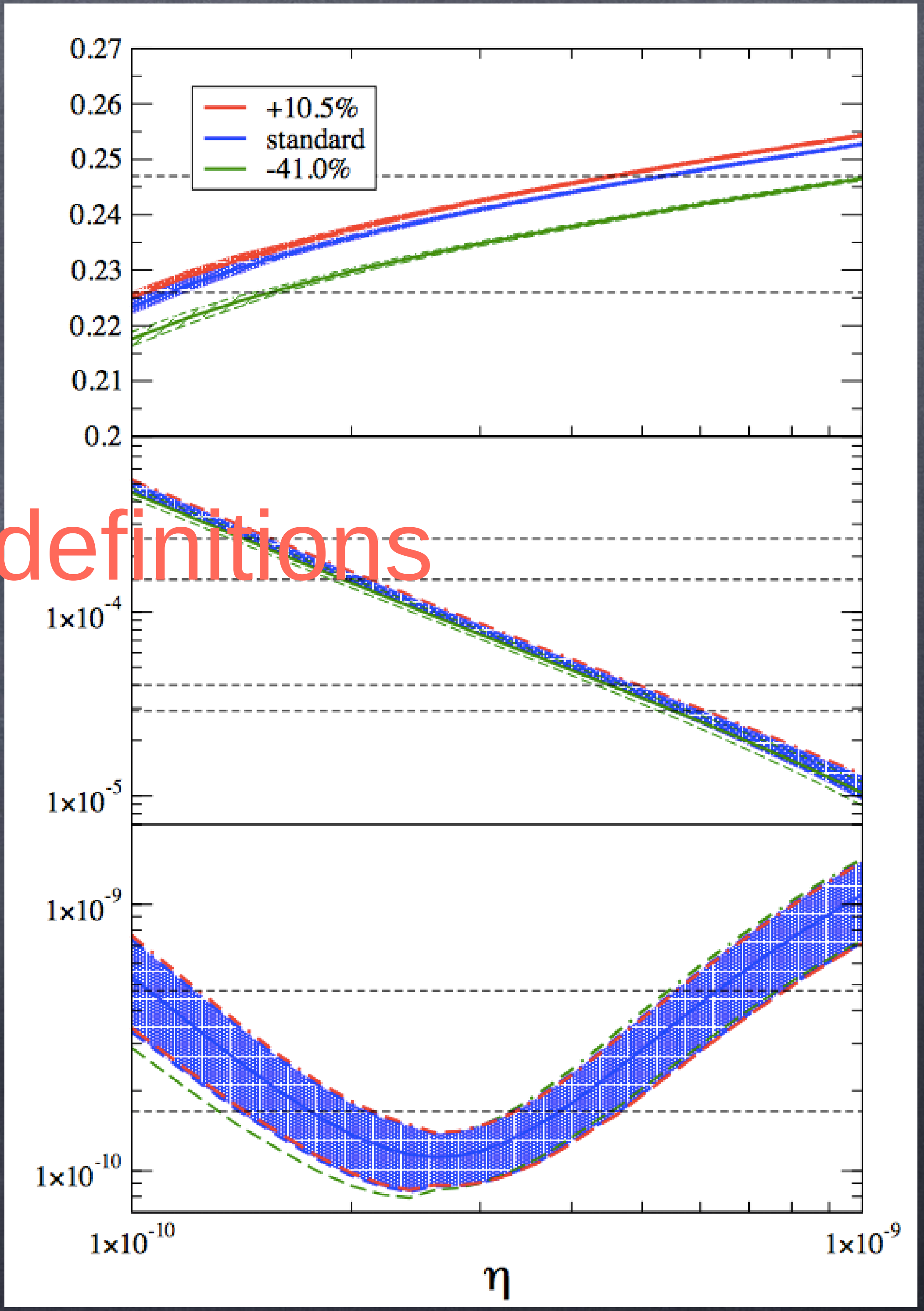
First Idea:



wrong!!

Problem with prior definitions

For RS Dark Radiation

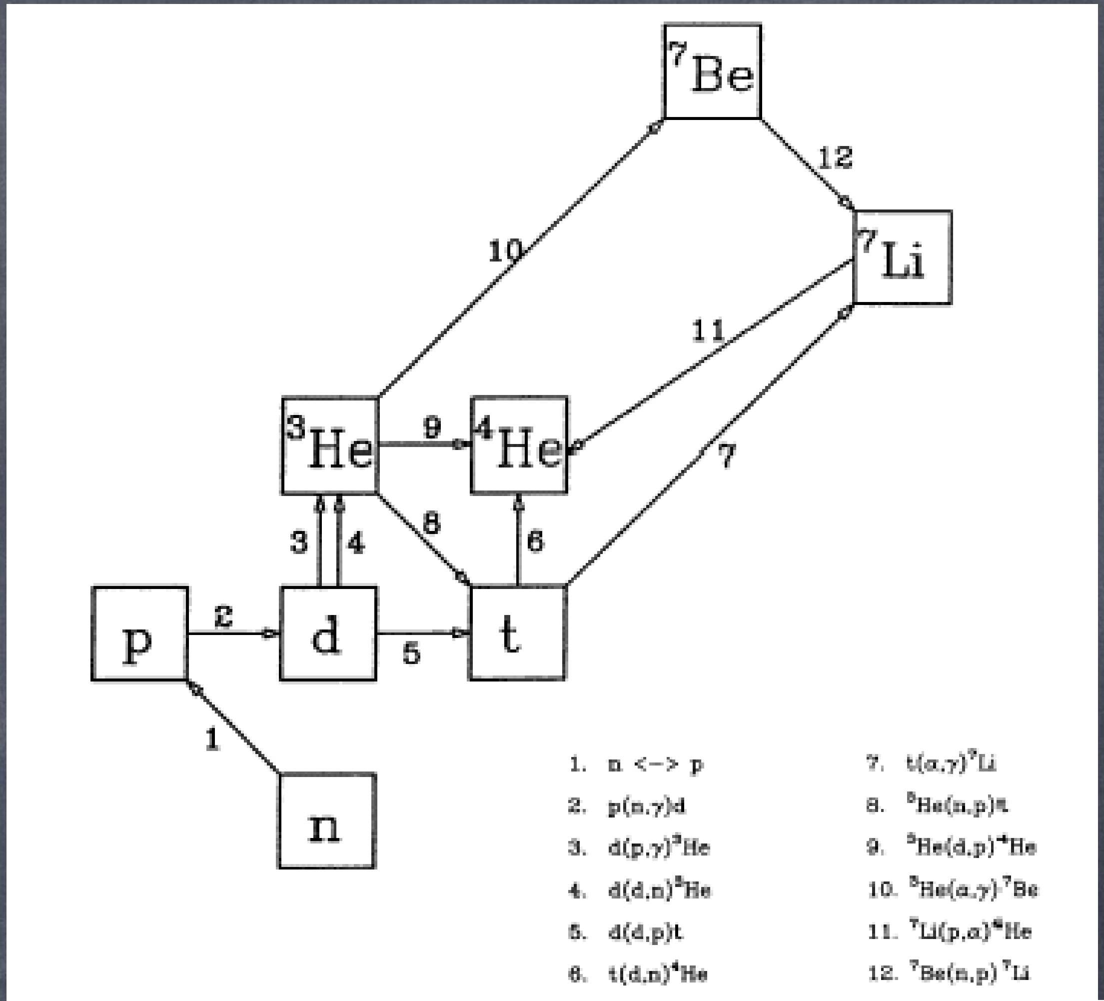


Ichiki et al Phys. Rev. D66, 043521

Effect of DR on BBN

Altering the expansion rate changes the temperature at which various nuclear reactions freeze out.

F. Hoyle and R. J. Taylor, Nature 203, 1108 (1964)



Symbol	Reaction	Symbol	Reaction
R_0	τ_n	R_8	$^3He(\alpha,\gamma)^7Be$
R_1	$p(n,\gamma)d$	R_9	$^3H(\alpha,\gamma)^7Li$
R_2	$^2H(p,\gamma)^3He$	R_{10}	$^7Be(n,p)^7Li$
R_3	$^2H(d,n)^3He$	R_{11}	$^7Li(p,\alpha)^4He$
R_4	$^2H(d,p)^3H$	R_{12}	$^4He(d,\gamma)^6Li$
R_5	$^3He(n,p)^3H$	R_{13}	$^6Li(p,\alpha)^3He$
R_6	$^3H(d,n)^4He$	R_{14}	$^7Be(n,\alpha)^4He$
R_7	$^3He(d,p)^4He$	R_{15}	$^7Be(d,p)2\,^4He$

nuclide i	central value	σ_{ω_b}	σ_{ii}	rate	$\delta\sigma^2/\sigma^2(\%)$
$^2H/H \times 10^5$	2.53	± 0.11	± 0.04	R_2	49
				R_3	37
				R_4	14
$^3He/H \times 10^5$	1.02	$^{+0.01}_{-0.02}$	± 0.03	R_7	80.7
				R_2	16.8
Y_p	0.2480	$^{+0.0002}_{-0.0003}$	± 0.0002	R_0	98.5
$^6Li/H \times 10^{14}$	1.1	± 0.1	$^{+1.7}_{-1.1}$	R_{13}	~ 100
$^7Li/H \times 10^{10}$	4.7	± 0.3	± 0.4	R_{14}	40.9
				R_8	25.1
				R_{15}	16.2
				R_7	8.6

Effect of DR on BBN

y of the dark radiation to the total energy density in relativistic particles at

$$\left(\sum_{i=e,\mu,\tau} \rho_{\nu_i}\right) + \rho_{DR} \equiv (3+\Delta N_\nu)\rho_{\nu_e} \equiv N_{eff}\rho_{\nu_e}$$

$$\rho_{\nu_i} = 2\frac{7}{8}\frac{\pi^2}{30}T_{\nu_i}^4$$

$$n/p = \exp\left(-\Delta m/T\right)$$

the neutron to proton ratio

neutron-proton mass difference

Photon temperature

Effect of DR on BBN

The increased neutron mass fraction from a positive dark radiation term increases the D/H and Yp abundances.

The faster cosmic expansion results in the freeze-out of the deuterium destruction via the reactions $^{2}H(d,n)^{3}He$ and $^{2}H(d,p)^{3}H$ at a higher temperature.

What about Lithium Problem??

FOOD FOR THOUGHT # 2

Some Theoretical Models

- RS Dark Radiation
- Light Sterile Neutrino Models
- Thermal Axion Models
- DR in LVS

RS Dark Radiation

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G_{\rm N}}{3}\rho - \frac{K}{a^2} + \frac{\Lambda_4}{3} + \frac{\kappa_5^4}{36}\rho^2 + \boxed{\frac{\mu}{a^4}}$$

RS Dark Radiation

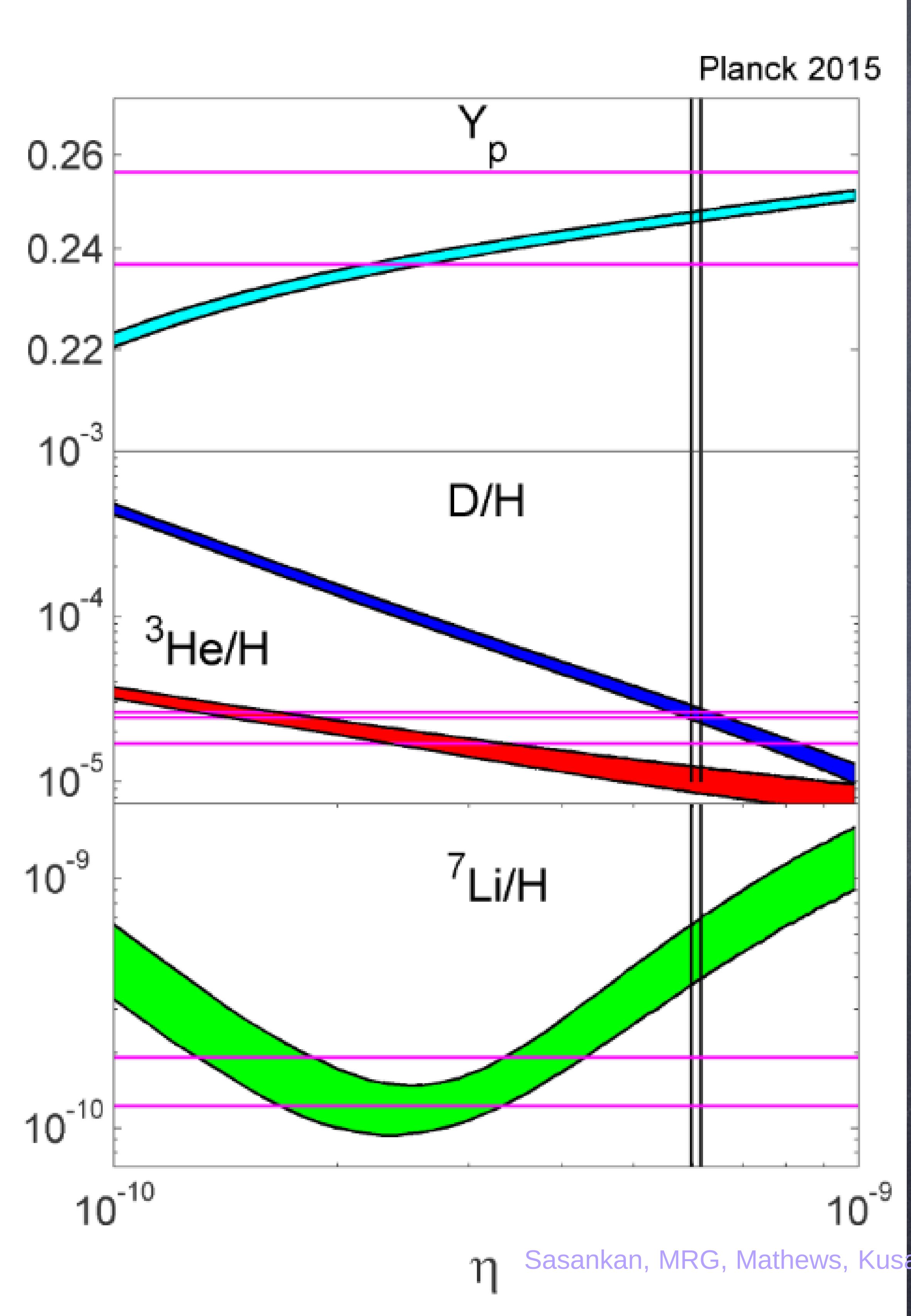
$$G_{\rm N} = \kappa_5^4 \lambda / 48\pi$$

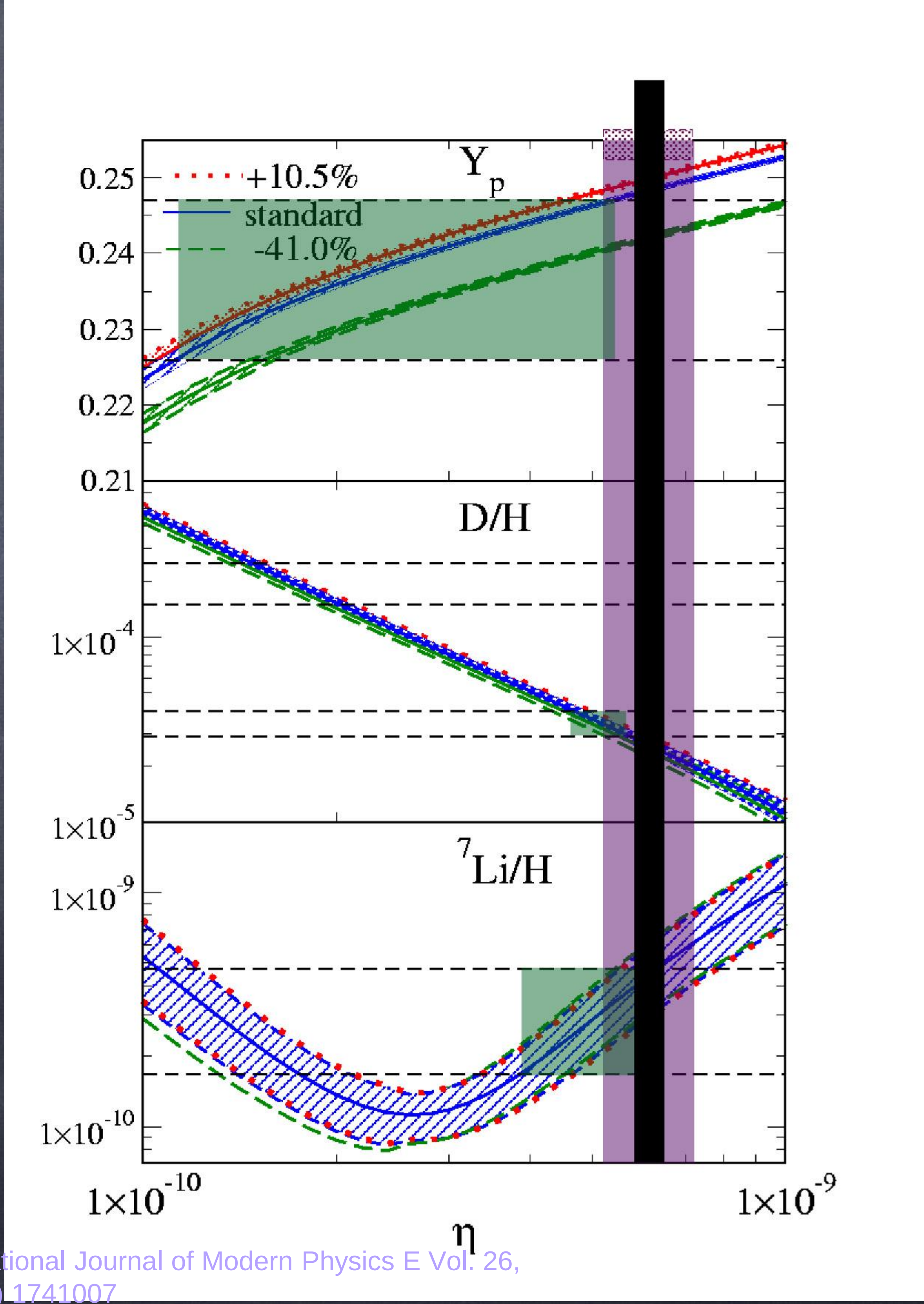
$$\Lambda_4 = \kappa_5^4 \lambda^2 / 12 + 3\Lambda_5 / 4$$

Sasankan, MRG, Mathews, Kusakabe International Journal of Modern Physics E Vol. 26, No. 7 (2017) 1741007

Sasankan,MRG,Mathews,Kusakabe Phys. Rev. D 95, 083516 (2017)

RS Dark Radiation





Sasankan, MRG, Mathews, Kusakabe International Journal of Modern Physics E Vol. 26, No. 7 (2017) 1741007

RS Dark Radiation

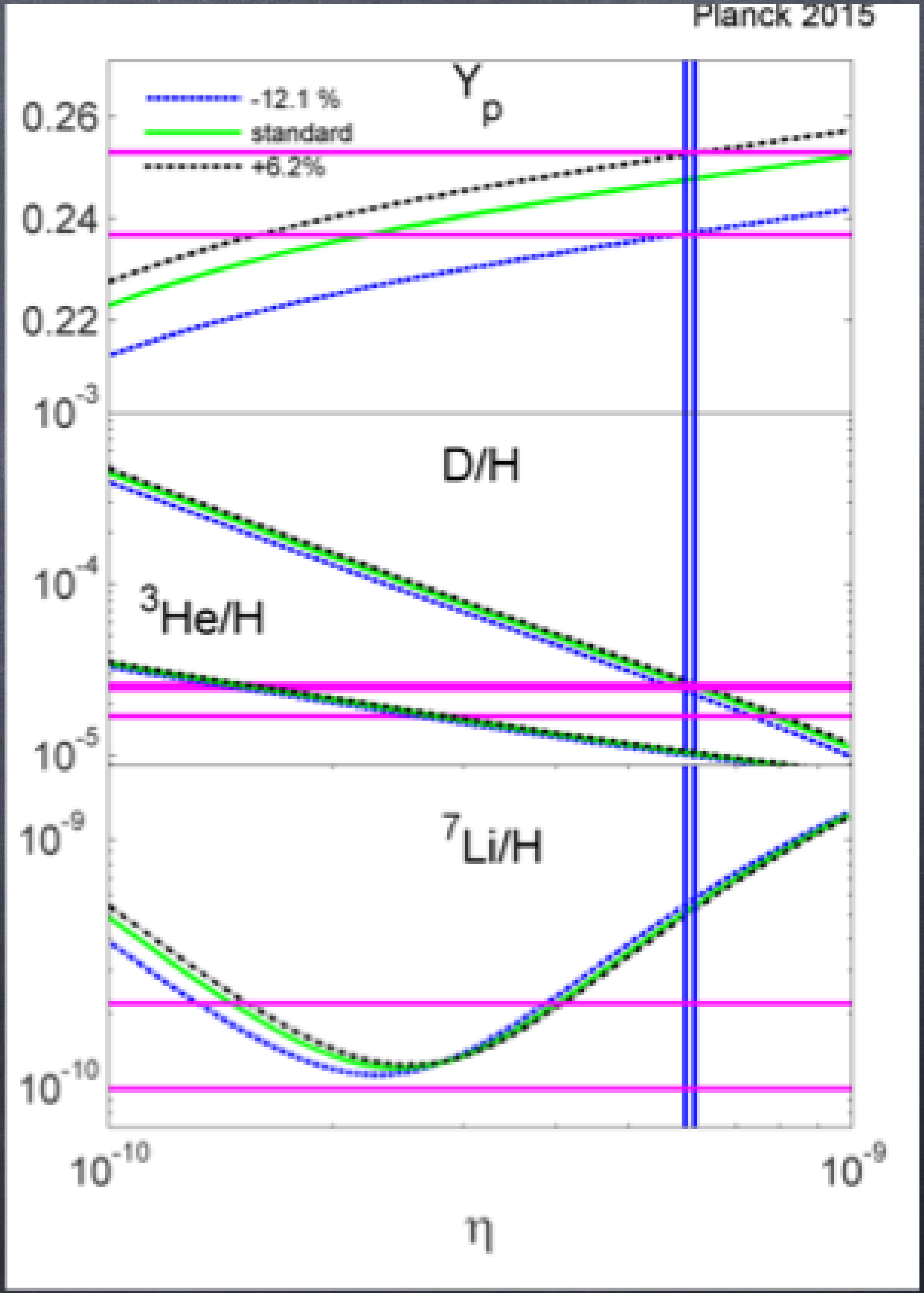
$Y_P = 0.2449 \pm 0.0040$

$2.45\text{X}10^{-5} \leq D/H \leq 2.61\text{X}10^{-5}$

$1.01\text{X}10^{-10} \leq {}^7Li/H \leq 2.20\text{X}10^{-10}$

$$L(\rho_{DR/}/\rho) = \int_\eta L_{D/H} L_{Y_p} d\eta$$

$$L_i = \frac{1}{\sqrt{2\pi}\sigma_i} \exp\left\{ -\frac{[Y_{i,\mathrm{BBN}}(\rho_{DR}/\rho, \eta) - Y_{i,\mathrm{obs}}]^2}{2\sigma_i^2} \right\}$$



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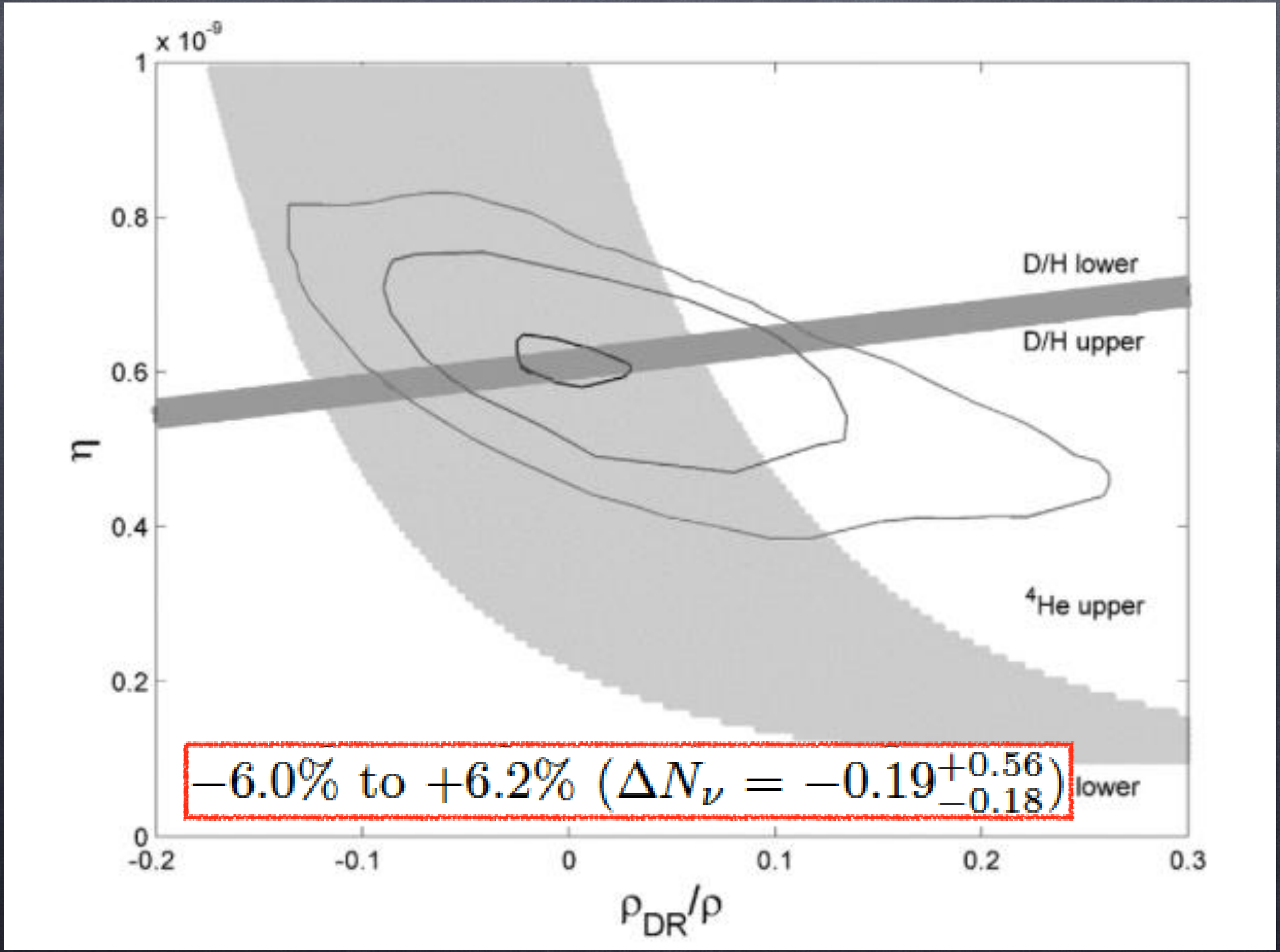
RS Dark Radiation



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Light Sterile Neutrino Models

utrino masses and abundances arising from short baseline oscillatior

$$\nu_\alpha = U_{\alpha i}\, \nu_i$$

$$\Omega_s h^2 \simeq 7 \times 10^{-5} (\Delta m_{41}^2/eV^2) \sum_a (U_{a4}/10^{-2})^2 g_{a/} \sqrt{C_a}$$

Δm_{41}^2 => squared mass of the extra sterile neutrino

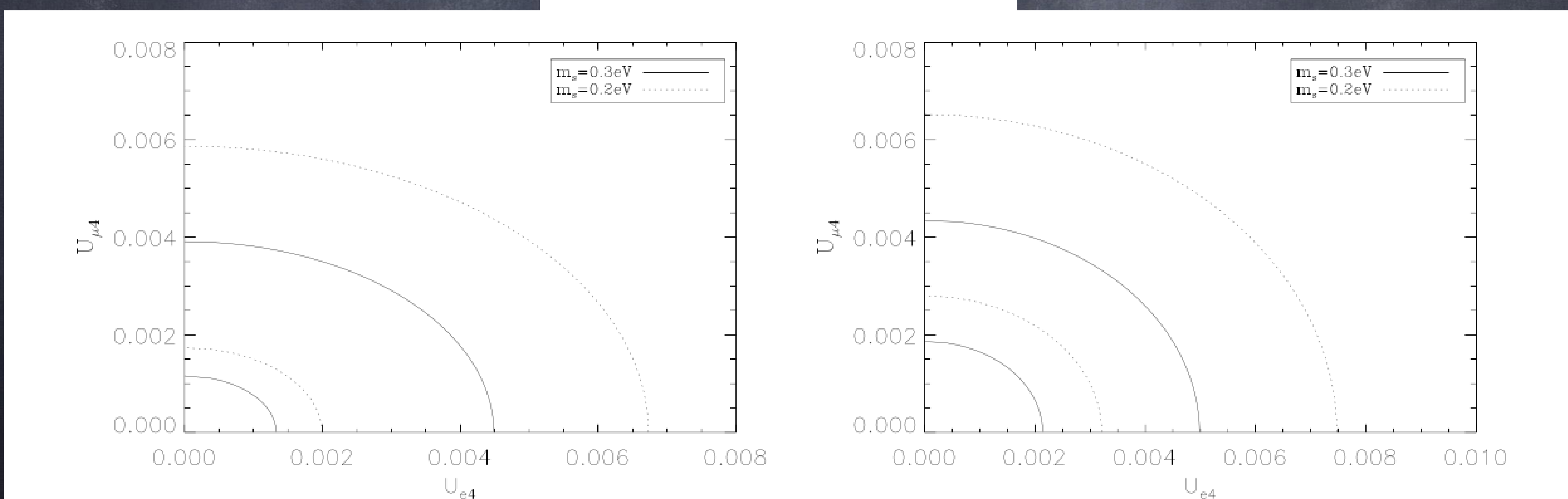
C_a => related to the effective potential describing the interactions of neutrinos with the medium

g_a => Coefficient of the damping factor

Light Sterile Neutrino Models

eutrino mass it is possible to constrain the sterile neutrin

$$\Delta N_{\rm eff} = \frac{\Omega_s h^2}{\frac{7}{8}\left(\frac{4}{11}\right)^{\frac{4}{3}}\Omega_\gamma h^2}$$



Valentino et al (DR candidates after Planck Data)

Light Sterile Neutrino Models

utrino mass will not be relativistic at decoupling and cannot be exploited

elatively large values of the sterile neutrino mixing parameters are exclud

Full MCMC analysis

short baseline data with Planck data most of the parameter space gets d

This is in context of the (3+1) models

(3+2) AND(3+3) models analysis

Thermal Axion Models

$$m_a = \frac{f_\pi m_\pi}{f_a} \frac{\sqrt{R}}{1+R} = 0.6 \text{ eV } \frac{10^7 \, \text{GeV}}{f_a}$$

viation from the SM expected value of N_{eff} due to a thermal hadroni

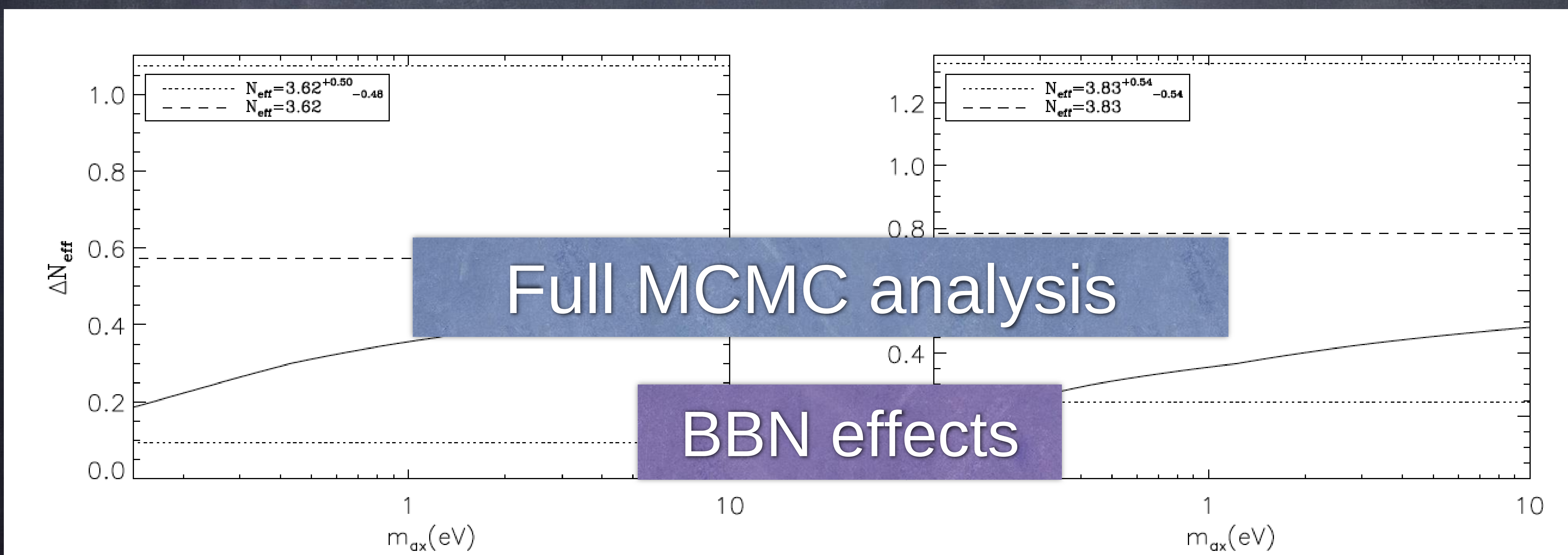
$$\Delta N_{\text{eff}} = \frac{\rho_a}{\rho_\nu} = \frac{4}{3}\left(\frac{3}{2}\frac{n_a}{n_\nu}\right)^{\frac{4}{3}}$$

oupling epoch and is precisely in this range of values the ones in which C

Thermal Axion Models

Axion masses larger than 0.4 eV are excluded by cosmology.

Axion masses less than 0.4 eV can barely provide enough DR.



Dark Radiation in LVS

g theory contains many moduli fields associated with the C-Y geom

Planck coupled fields with decay rate:

$$\Gamma \sim \frac{1}{16\pi}\frac{m_\phi^3}{M_P^2}.$$

SM sector only needs to be reheated

branching rations to hidden sector would lead to over production of d

Dark Radiation in LVS

Reheating is studied under LVS

Volume is stabilized at exponentially large values.

Leading decay channels for the volume modes:

Volume Axions
Visible sector Higgs
#Local closed String axions
Light gauge bosons
Higgs in sequestered hidden sector

Dark Radiation in LVS

Decay to volume axions:

$$\Gamma_{\Phi\to a_b a_b} = \frac{1}{48\pi}\frac{m_\Phi^3}{M_P^2}$$

Decay to visible sector Higgs:

$$\Gamma_{\Phi\to H_u H_d} = \frac{2Z^2}{48\pi}\frac{m_\Phi^3}{M_P^2}$$

Relative fraction of the hidden radiation:

$$f_{hidden} = \frac{1}{1+2Z^2}$$

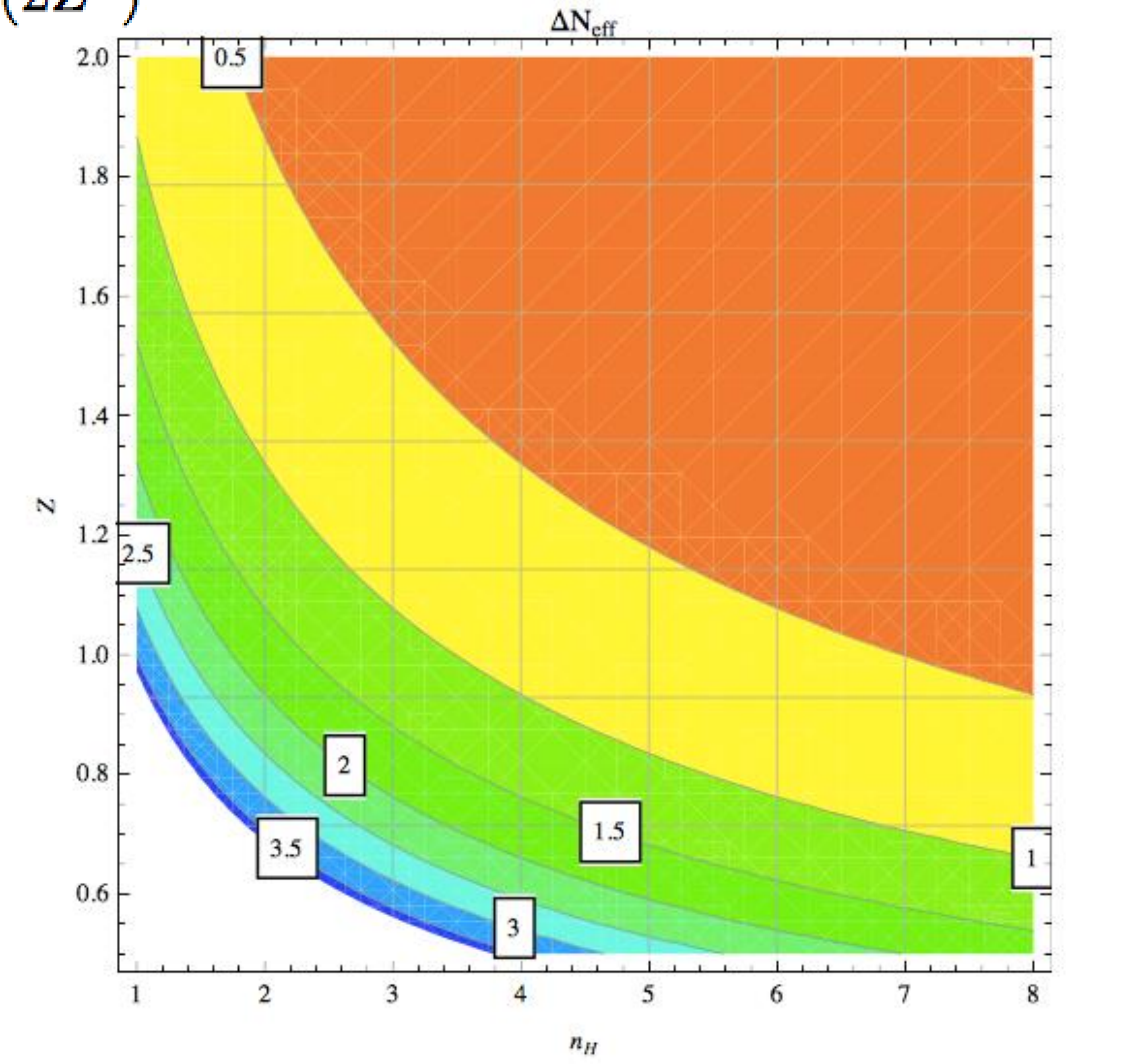
The amount of extra radiation

$$\begin{aligned}\Delta N_{eff} &= 3\frac{\rho_{hidden}}{\rho_{neutrinos}} = \frac{43}{7}\frac{\rho_{hidden}}{\rho_{SM}} \\ &= \frac{43}{7}\frac{f_{hidden}}{1-f_{hidden}}\left(\frac{g(T_{dec})}{g(T_{reheat})}\right)^{1/3}\end{aligned}$$

Dark Radiation in LVS

Cicoli et al arXiv: 1308.3562

$$\kappa = f_{hidden}/(1 - f_{hidden}) = 1/(2Z^2)$$



$$3.12\,\kappa \le \Delta N_{eff} \le 3.48\,\kappa$$

Conclusions

Lots of models of Dark Radiation and not discussed here.

presence of DR, it needs to be precisely constrained from CM

ge lies in the fact that there cannot be a generic constrain or

nodel has to be dealt differently while using CMB+BBN constr

Lots of work needed in this sector

THANK YOU