Solving the cosmological « lithium problem » with a sterile neutrino

A loophole to the standard theory of electromagnetic cascade

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Talk based on
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In collaboration with
Pasquale D. Serpico (LAPTh)

RWTH AACHEN UNIVERSITY

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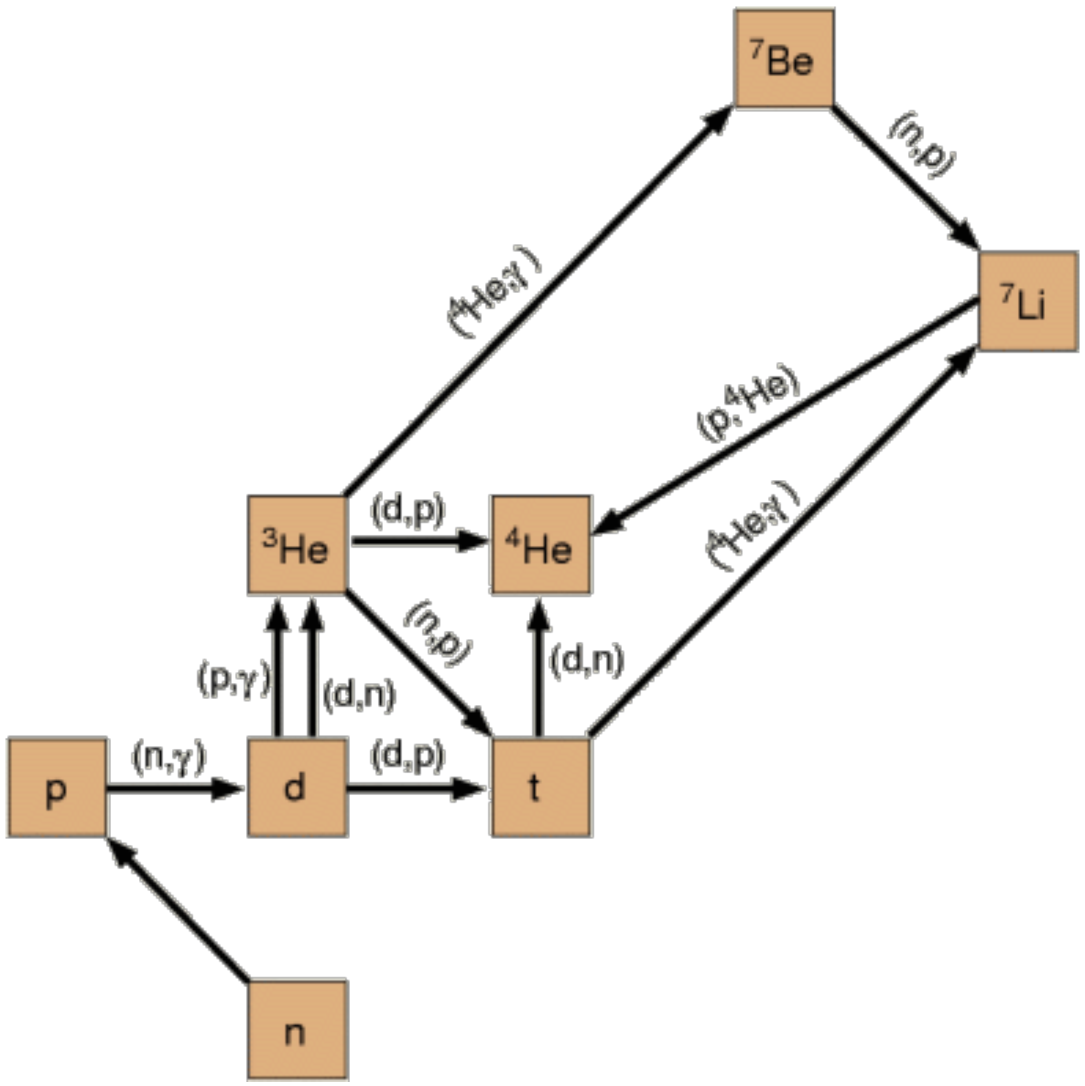
LAPTh

Big Bang Nucleosynthesis in a nutshell

- Happened 10 - 200 s after the BB when the Universe had T = [30,70] keV
- Main nucleus form ^{4}He : $Y_p = 4n_{4He}/n_B \approx 0.25$, others $\mathcal{O}(10^{-5} - 10^{-10})$



A typical reaction network, © Achim Weiss

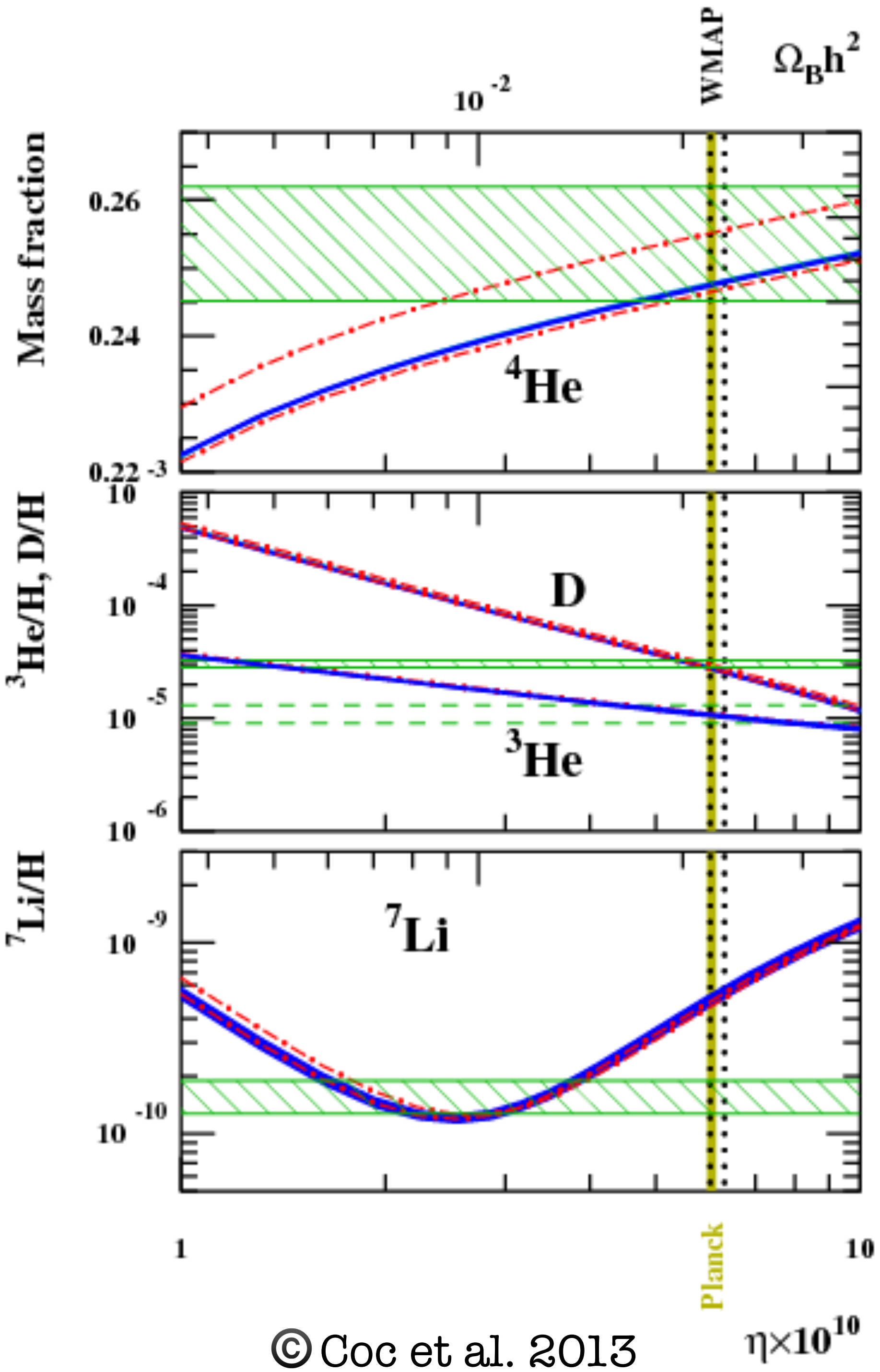
Only one free parameter :

The photon-to-baryon ratio

$$\eta \equiv \frac{n_b}{n_\gamma} \sim 6 \times 10^{-10}$$

=> All abundances can be computed using numerical algorithm such as PArthENoPE

Main results



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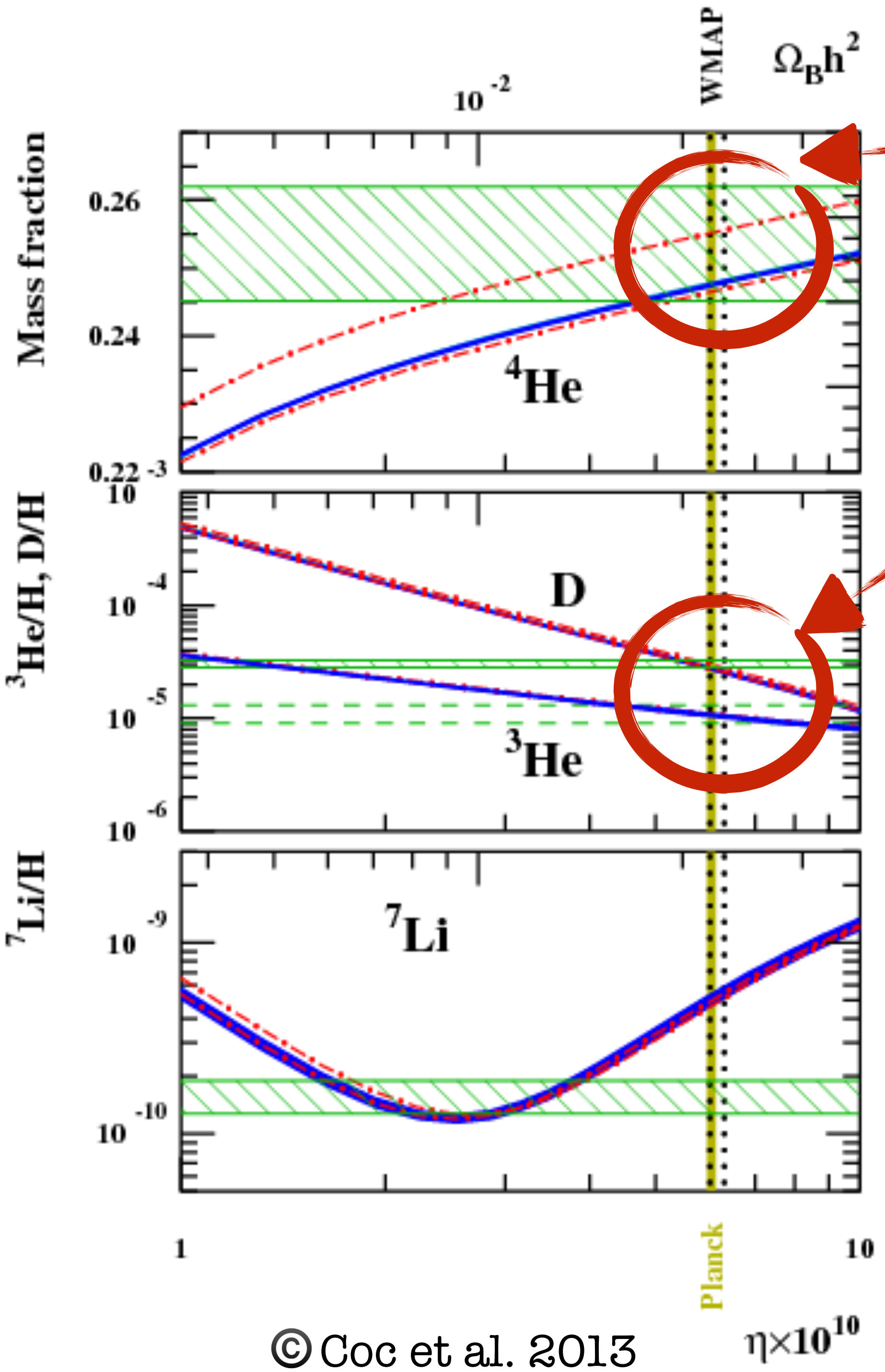

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For 3 nuclei :

Strong observational constraints

$$Y_p > 0.2368$$

$$2.56\times10^{-5} < {}^2\mathrm{H/H} < 3.48\times10^{-5}$$

$$^3\mathrm{He/H} < 1.5\times10^{-5}$$

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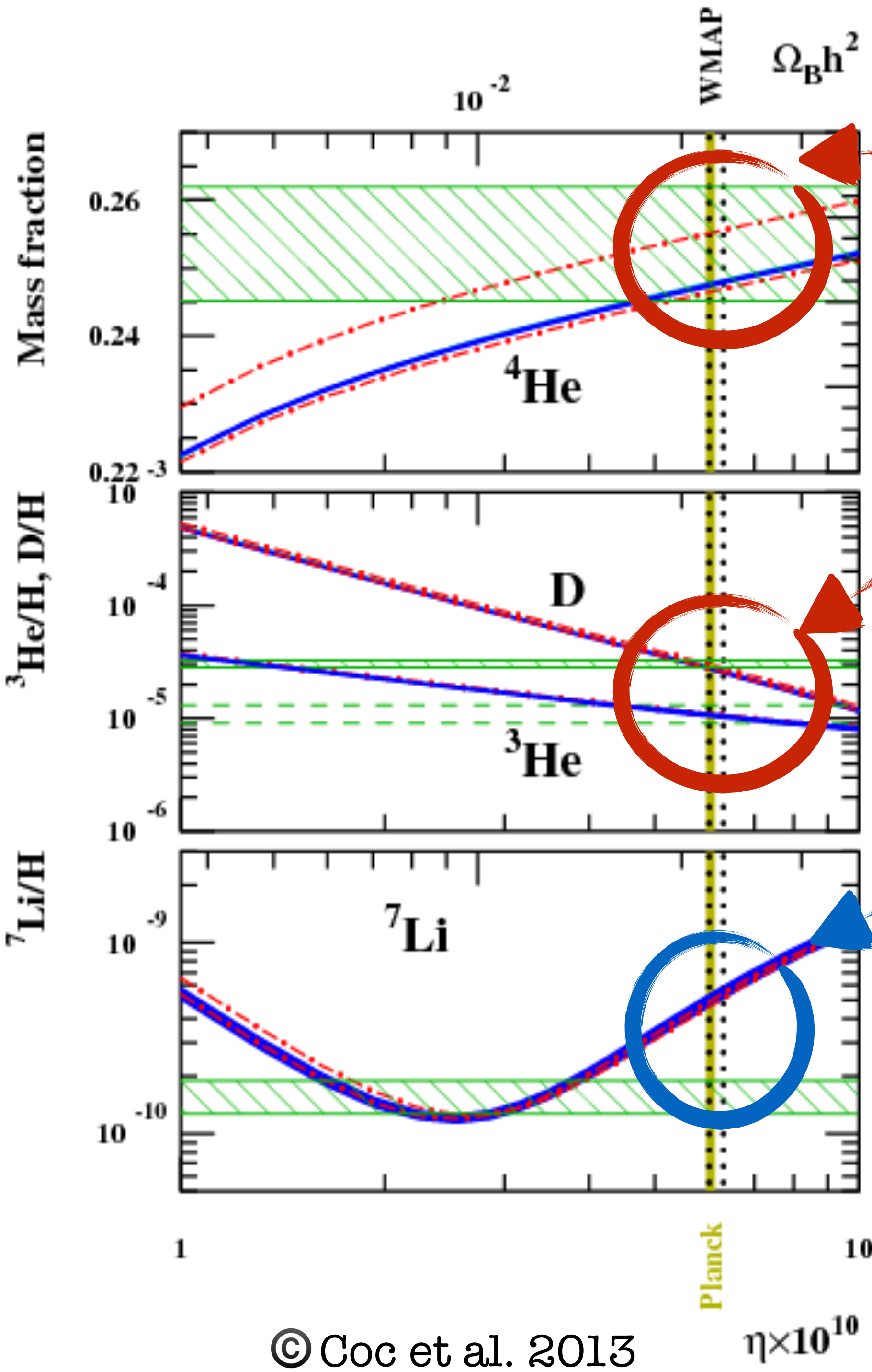

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Overprediction of the ^{7}Li abundance

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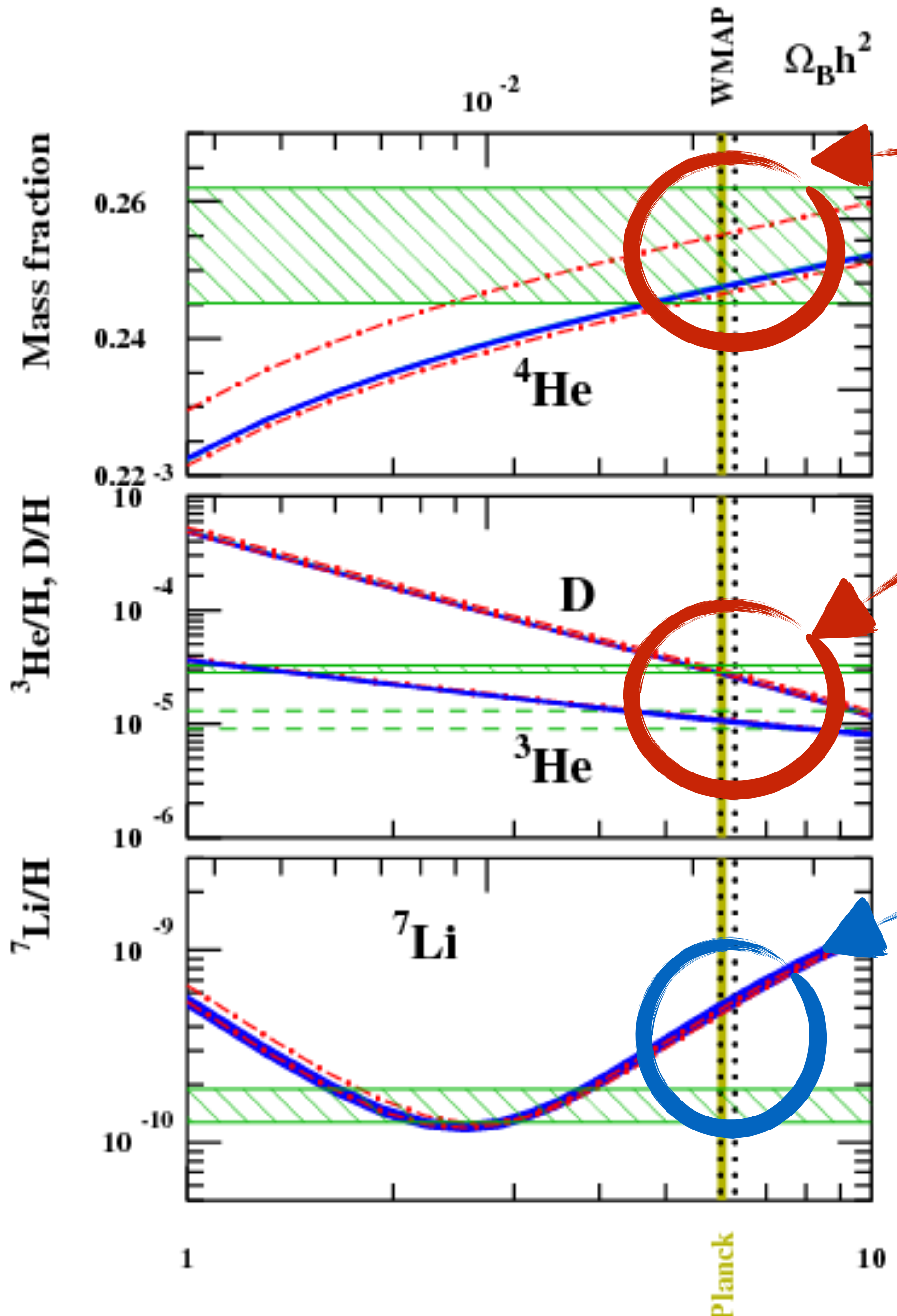

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Lithium is indirectly produced !

$$^3\mathrm{He} + {}^4\mathrm{He} \rightarrow {}^7\mathrm{Be} + \gamma$$

followed by

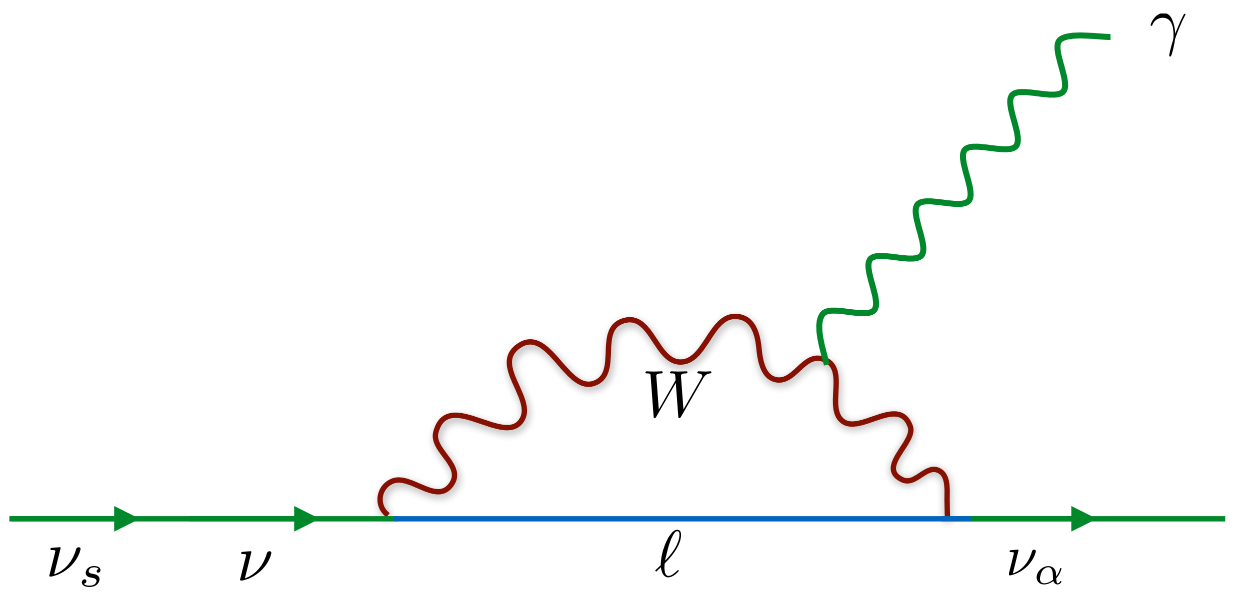
$$^7\mathrm{Be} + e^- \rightarrow {}^7\mathrm{Li} + \nu_e, \;\; \tau_{\mathrm{Be}} \sim 53\mathrm{d}$$

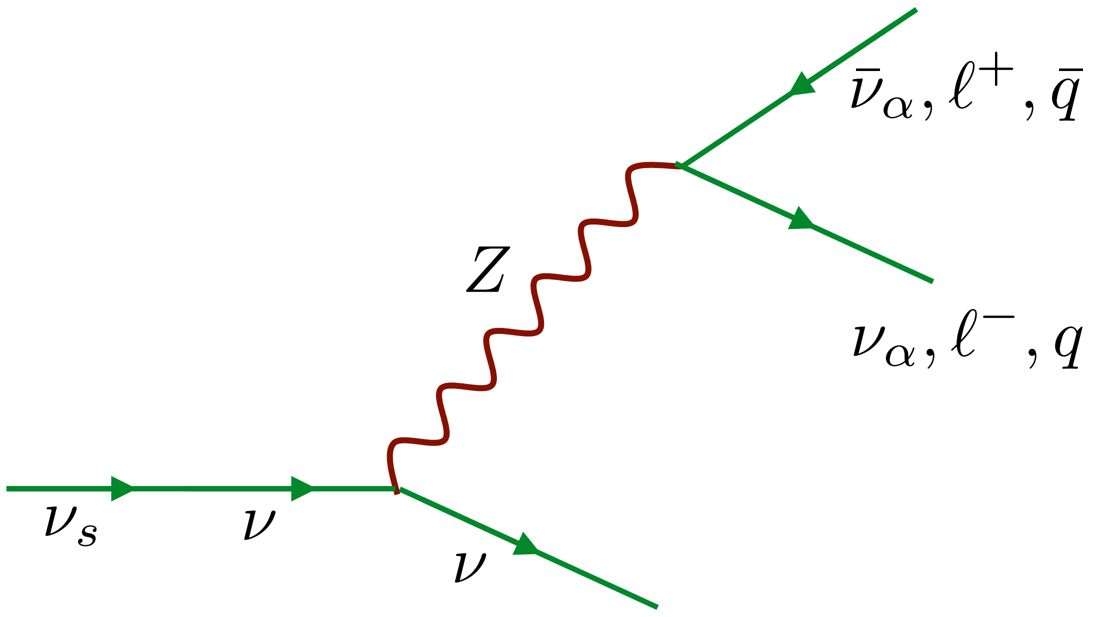
One has to destroy the Beryllium !

see e.g. hep-ph/0308083
hep-ph/0008138
astro-ph/0410175

Sterile Neutrino and the BBN

- Modification of N_{eff} affects the expansion rate and the BBN outcome;
- If coupling $\nu_s \leftrightarrow \nu_e$, modification of the weak rates affects the n-p equilibrium which (mostly) sets the ^{4}He abundance;
- Eventually, creation of a lepton asymmetry influencing BBN;
- Decay products directly interacting with nuclei can modify BBN yields.





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$$^{7}\mathrm{Be} + \gamma \to {}^{4}\mathrm{He} + {}^{3}\mathrm{He}$$

$E_{threshold}(Be) = 1.58$ MeV
$E_{threshold}(De) = 2.2$ MeV

One « trick » : if $1.6 < E_0 < 2.2$ MeV
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However, this was known to fail, why would it work now?

Electromagnetic Cascade in a nutshell

We want to describe electromagnetic energy injection in a plasma of photons (very few e+e-, nuclei) :
what is the resulting metastable distribution of photons ?

Basic processes are (at high energies)

$$\gamma\gamma_{\rm th} \to e^+e^-$$

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Particle multiplication and energy redistribution

The first process has a threshold, below it

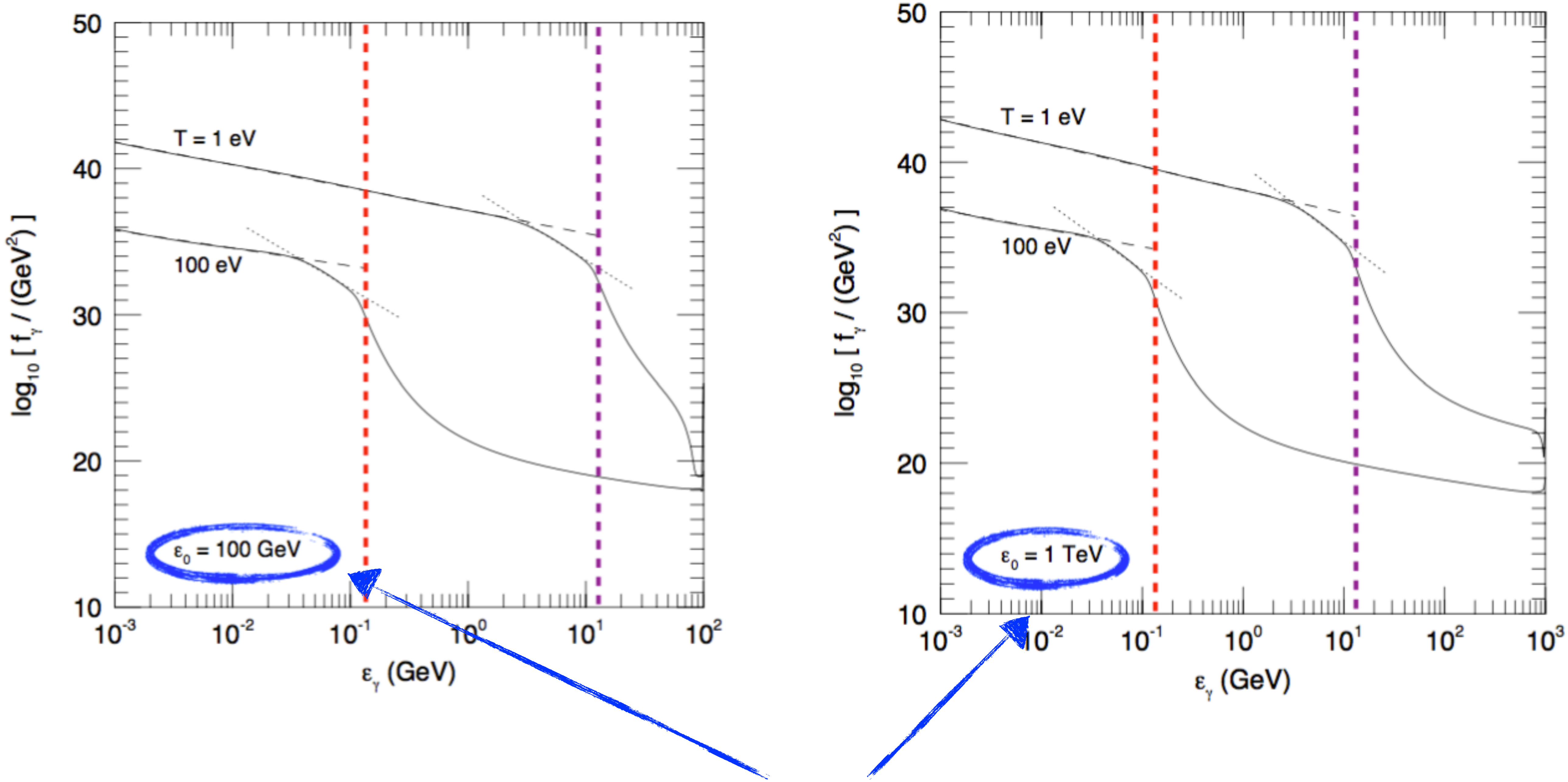
$$\gamma\gamma_{\rm th} \to \gamma\gamma$$

and eventually (very low rates)

$$\gamma N \to eN \qquad \gamma e_{\rm th} \to \gamma e$$

Kawasaki & Moroi, ApJ 452,506 (1995)

This has been shown to lead to a universal spectrum



- Shape independent of the energy / temperature of the bath: Only dictates the overall normalisation;
- Threshold due to pair production.

Typically, after the end of standard BBN (5 keV) :

$$E_{\rm cutoff}(1~{\rm keV}) \sim 12~{\rm MeV} \qquad E_{\rm cutoff}(10~{\rm eV}) \sim 1.2~{\rm GeV}$$

All cases simulated inject energy such that $E_\gamma \gg E_{\rm cutoff}$
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After « standard » BBN :
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If $E_{\rm threshold} < E_0 < E_{\rm cutoff}$
results in the literature are wrong !

Consider a photon injection and start by neglecting diffused electrons.
Remaining processes are :

$$\gamma\gamma_{\rm th} \rightarrow \gamma\gamma,\ \gamma e^{\pm}_{\rm th} \rightarrow \gamma e^{\pm},\ \gamma N \rightarrow N e^{\pm}$$

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$$\frac{\partial f_\gamma(E_\gamma)}{\partial t} = -\Gamma_\gamma(E_\gamma, T(t)) f_\gamma(E_\gamma, T(t)) + \mathcal{S}(E_\gamma, t)$$

whose stationary solution is

$$f^{\rm S}_\gamma(E_\gamma) = \frac{\mathcal{S}(E_\gamma, t)}{\Gamma_\gamma(E_\gamma, t)}$$

Hubble rate much smaller than
all particle physics interaction rate,
thus neglected

where for a decaying particle

$$\mathcal{S}(E_\gamma, t) = \frac{n^0_\gamma \zeta_X (1+z(t))^3\, e^{-t/\tau_X}}{E_0 \tau_X} p_\gamma(E_\gamma, t)$$

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Destruction from its photodissociation

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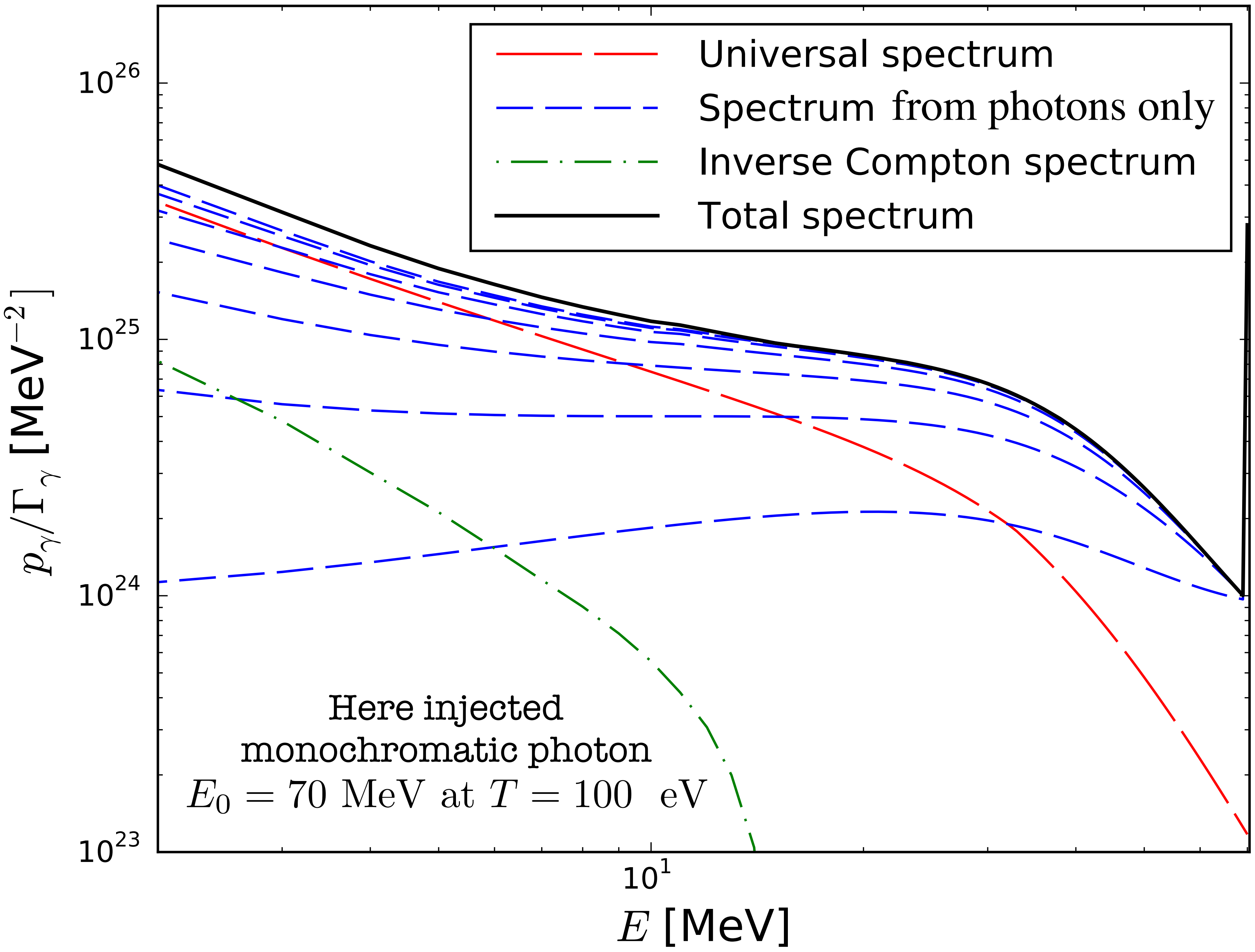
Typical results for a given energy and a given temperature of the thermal bath



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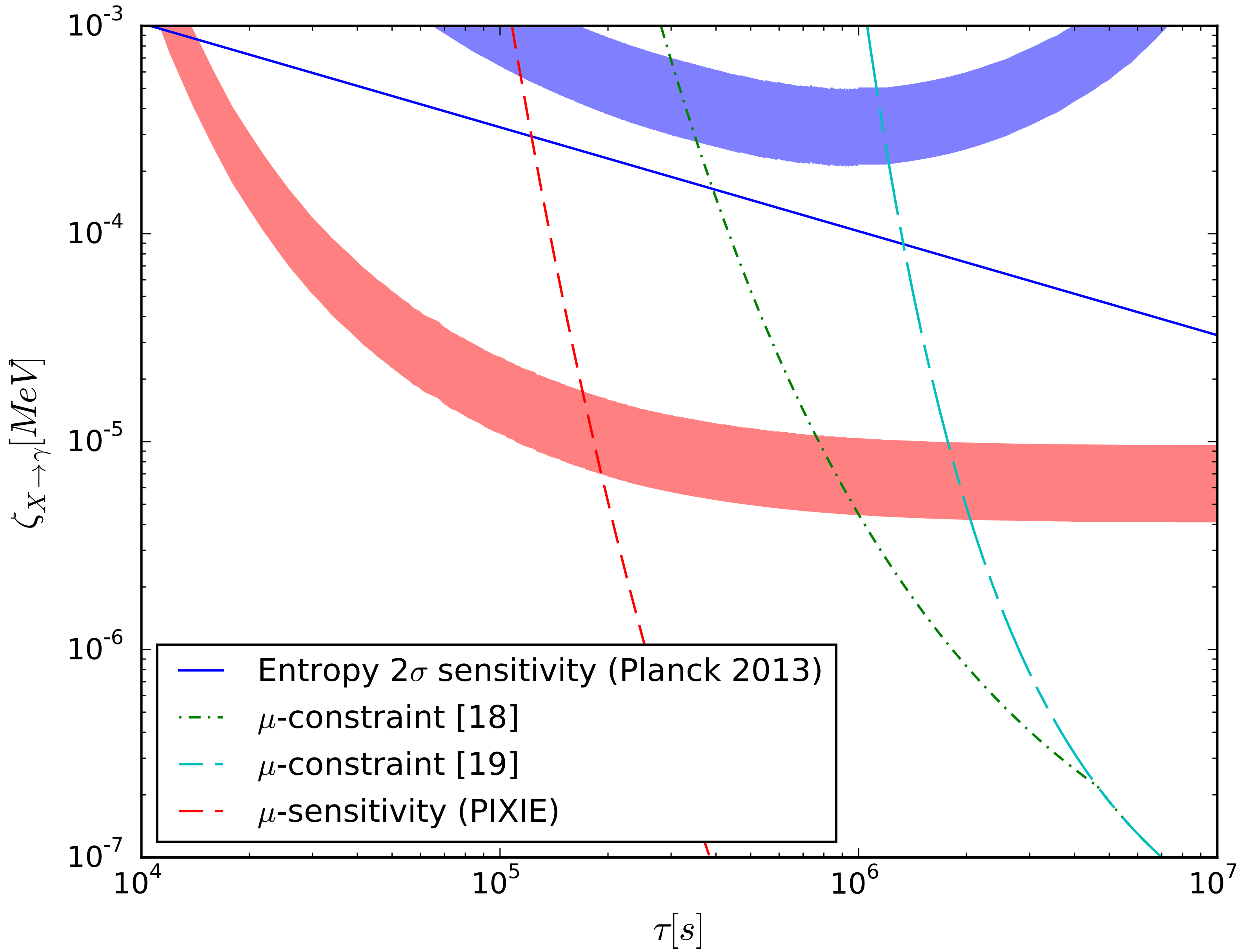

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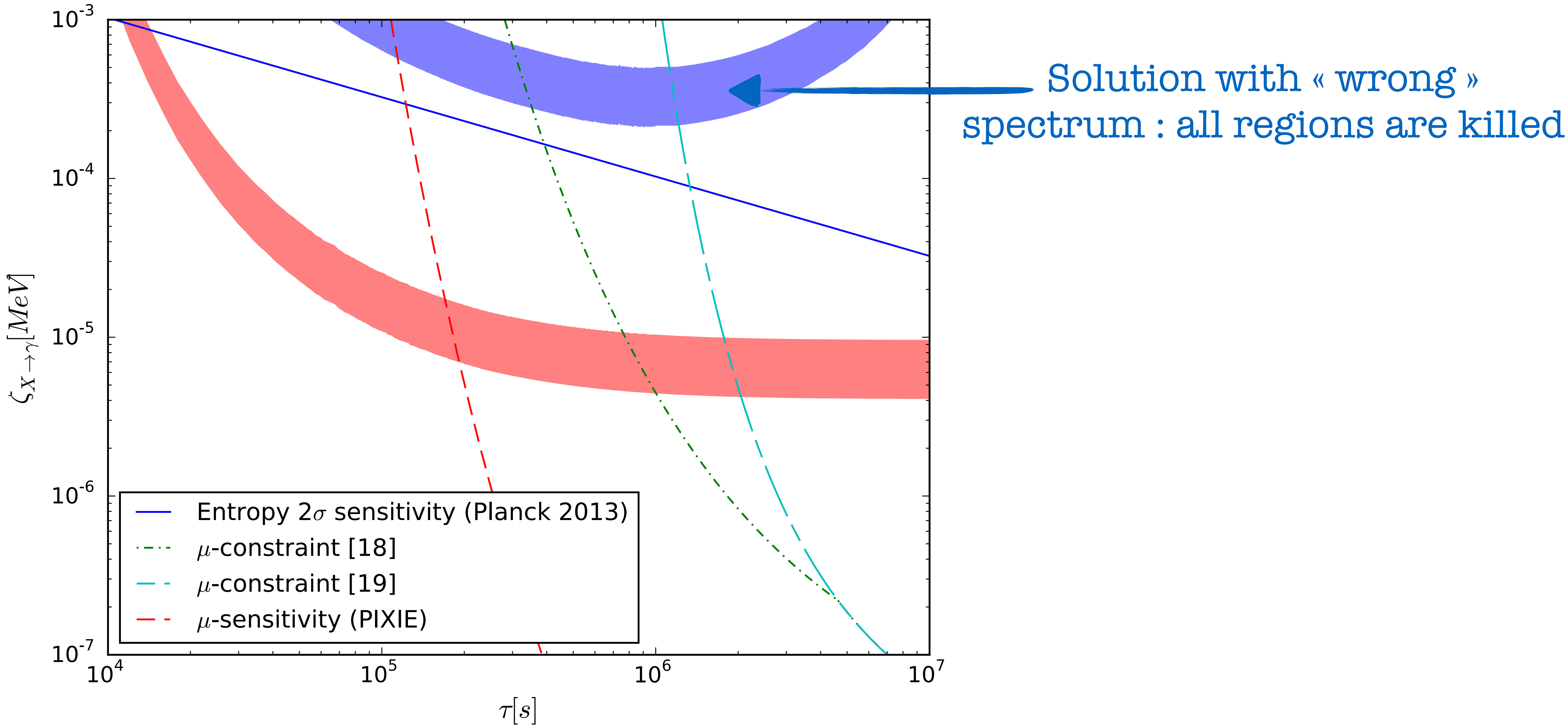

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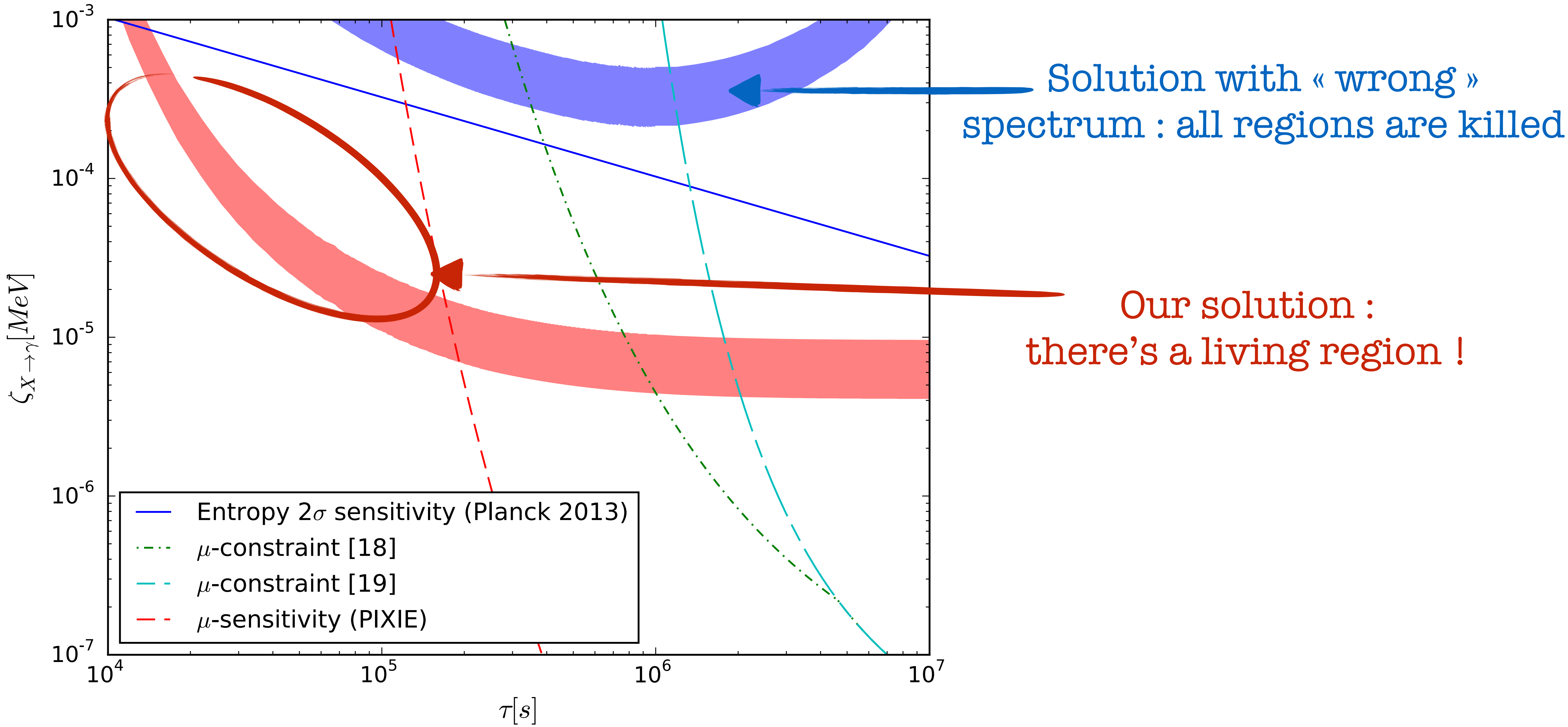
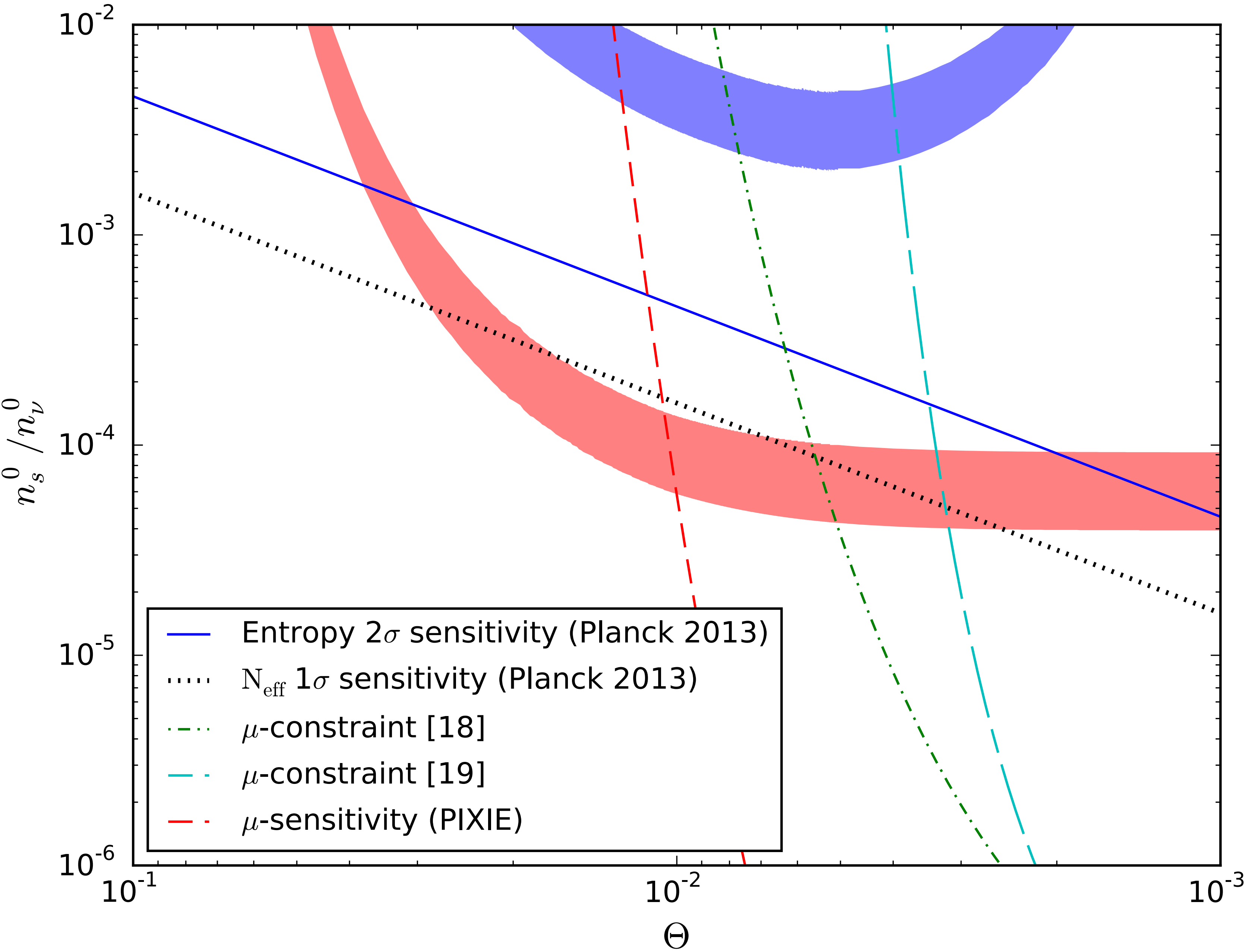


Try with a « real » model that was known to fail when using universal spectrum : the Sterile (majorana) Neutrino

H. Ishida, M. Kusakabe and H.Okada, PRD 90, 8, 083519 (2014)



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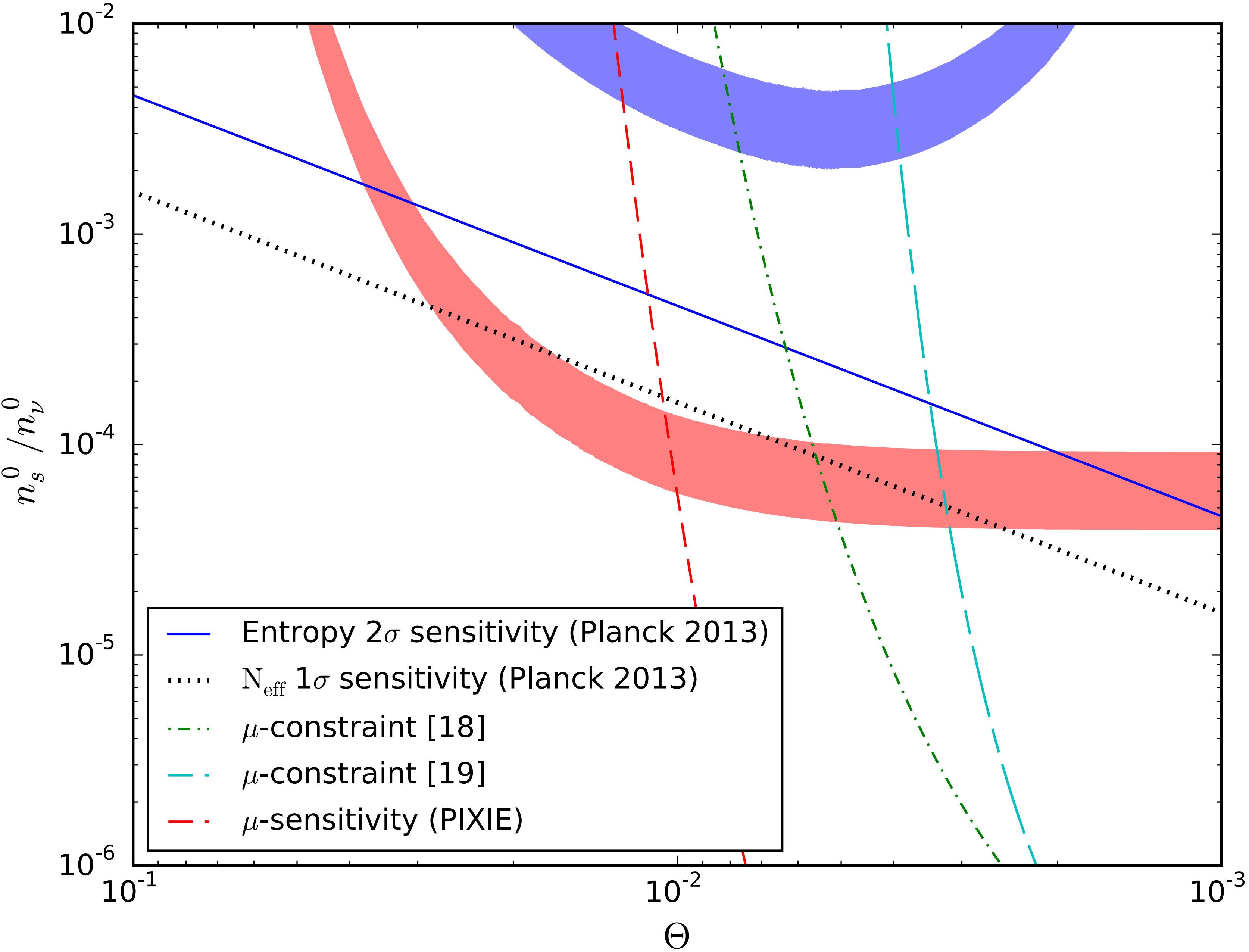

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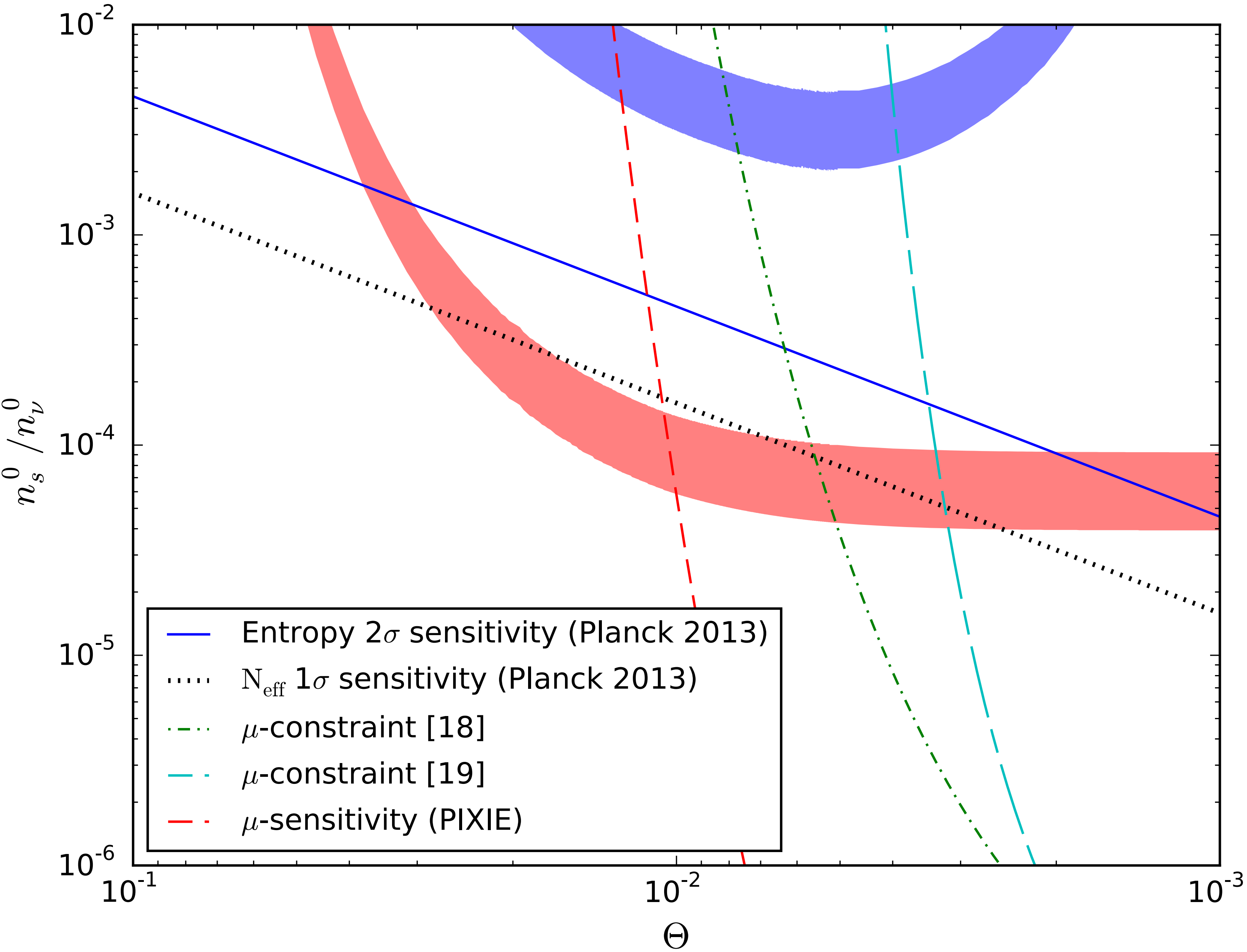

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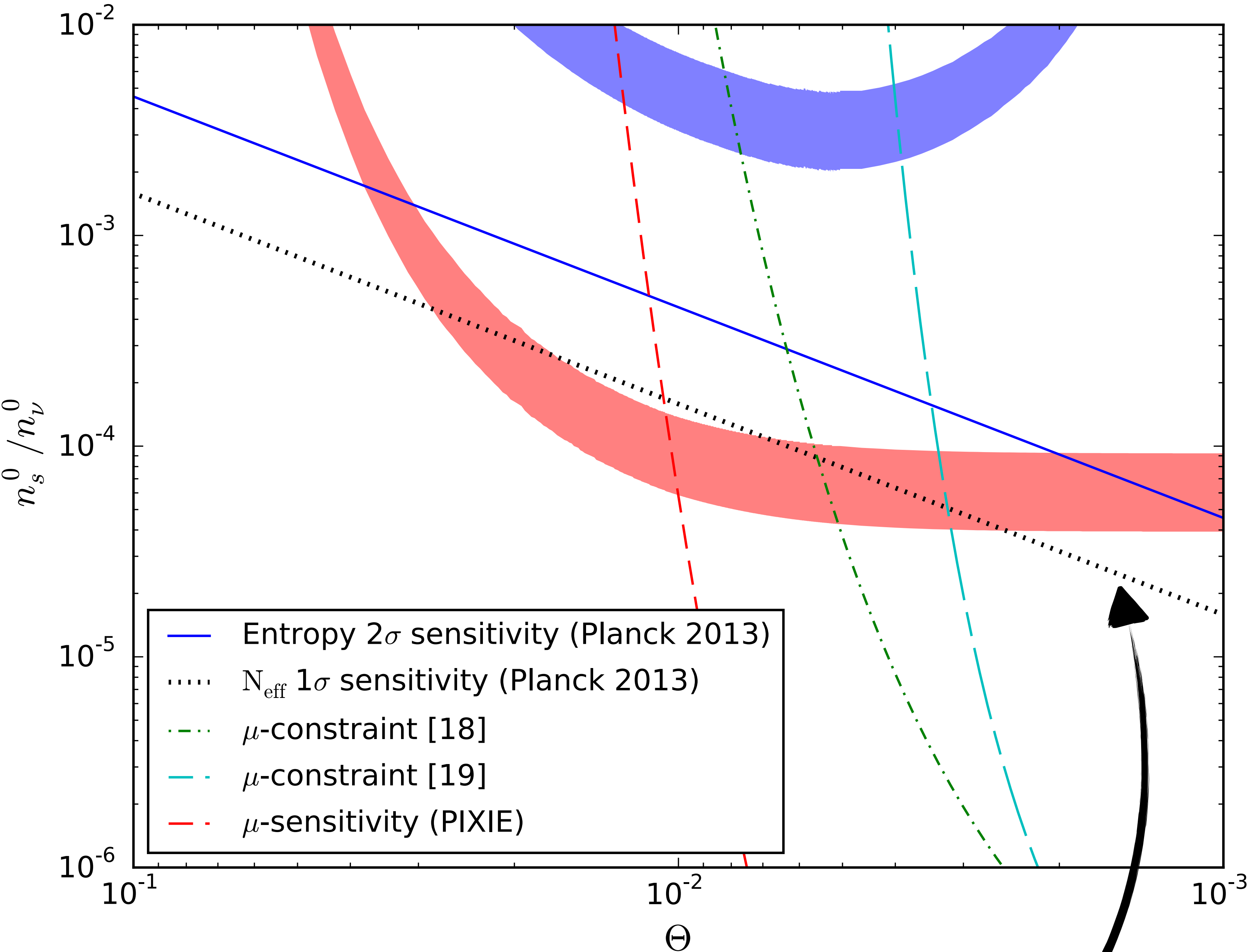

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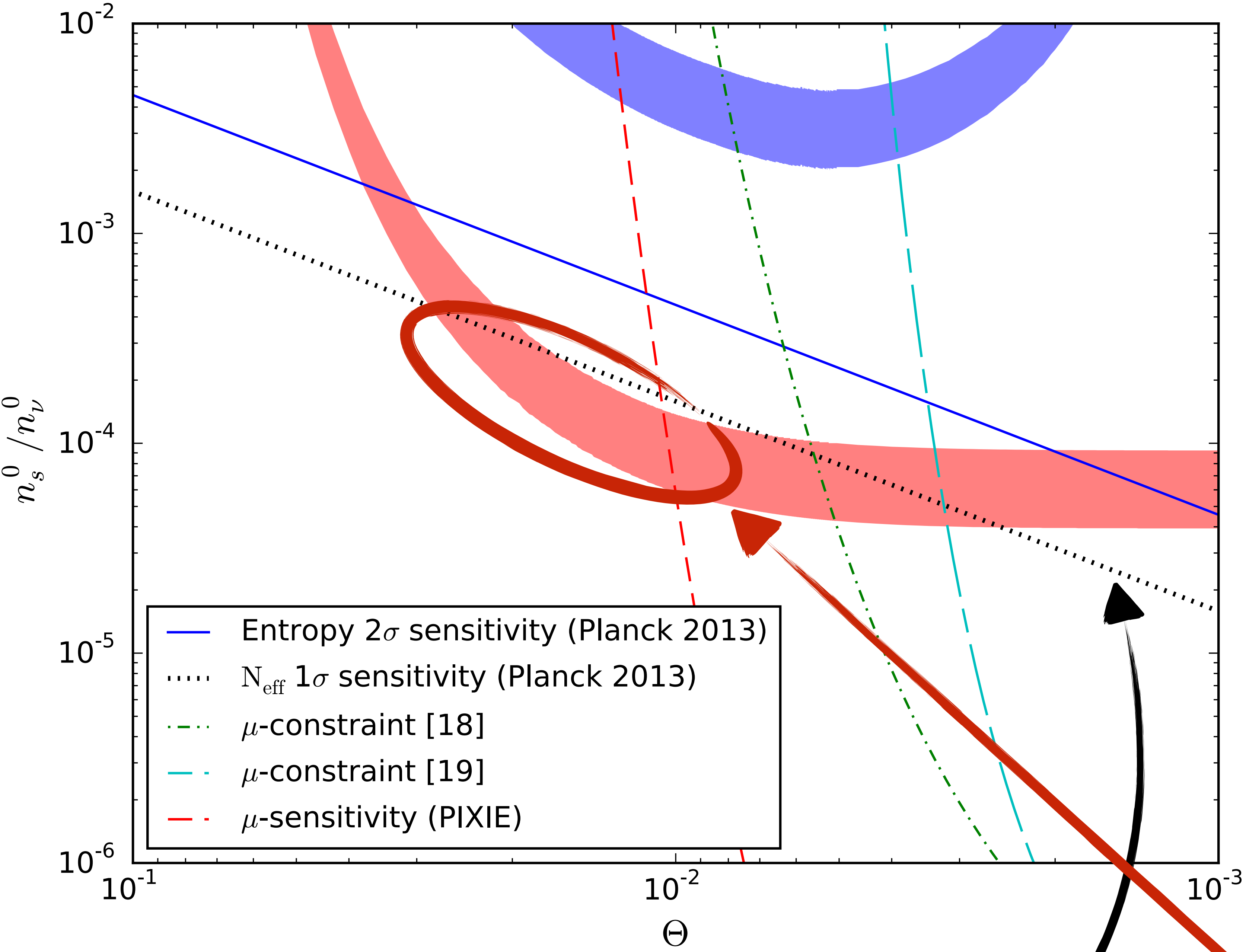

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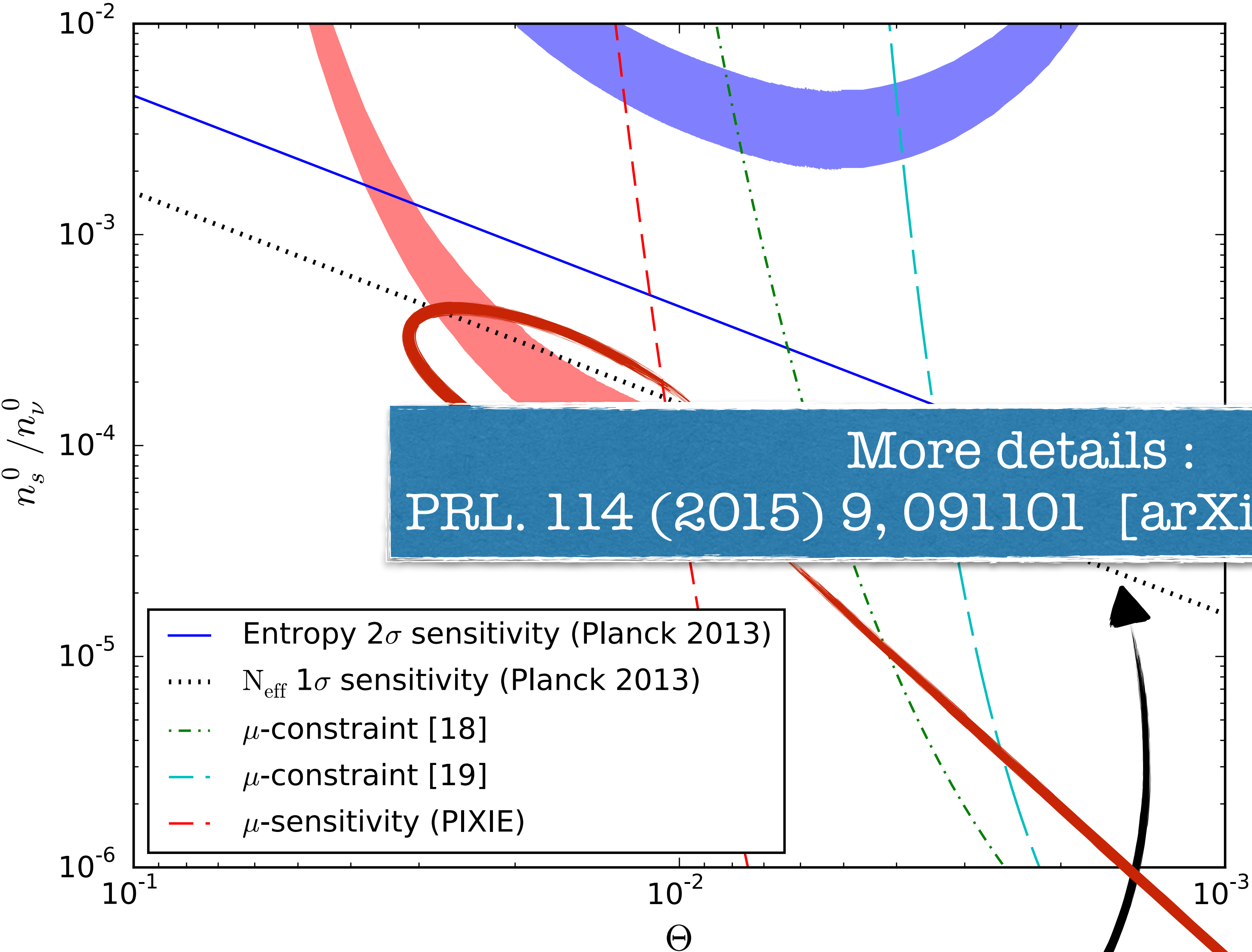

More details :
PRL. 114 (2015) 9, 091101 [arXiv:1502.01250]

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- We have shown that the universality hypothesis breaks down. The resulting spectrum can be very different from the universal one.

- We have shown how it might ease particle physics (electromagnetic) solution to the lithium problem, as illustrated with the sterile neutrino model.
- The same phenomenon also has important consequences for BBN bounds : they are more stringent and non-universal.

Thanks for your attention !