Sudbury, ON, Canada

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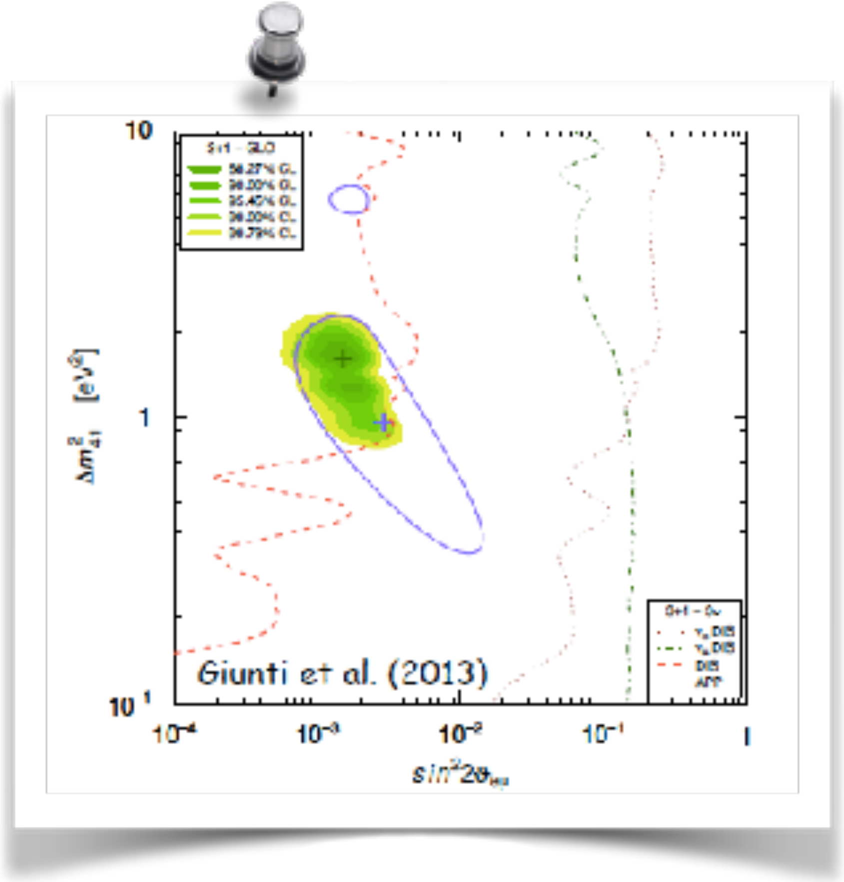
Secret interactions for eV sterile neutrinos and cosmological implications

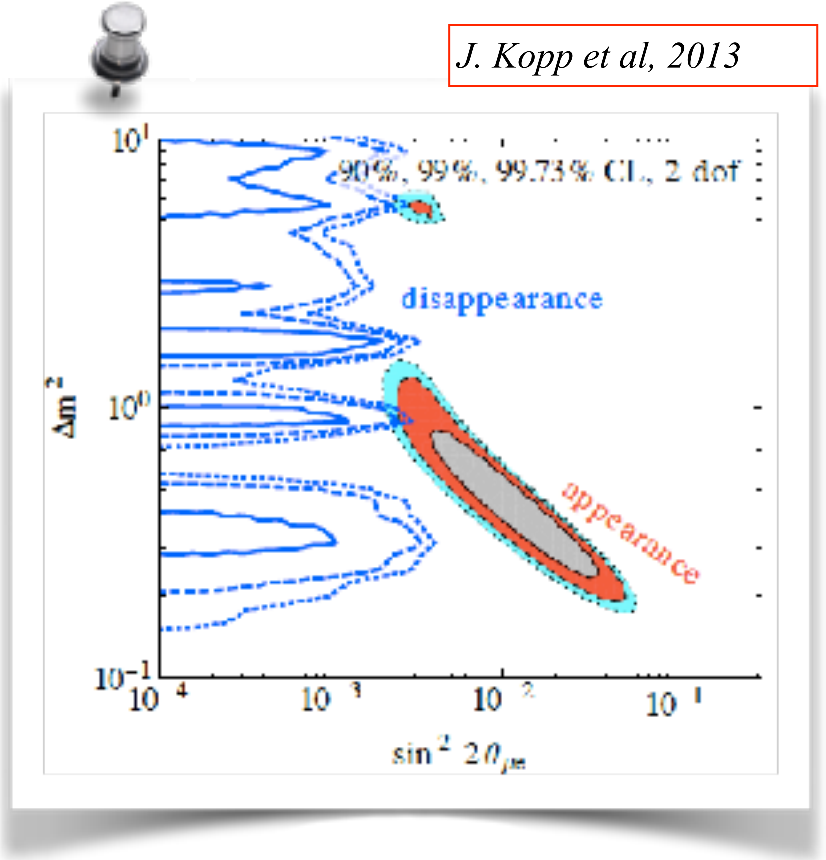
Ninetta Saviano
Mainz University

eV Sterile Neutrino

The investigation on Light Sterile Neutrinos has been stimulated by the presence of anomalous results from neutrino oscillation experiments (LNSD, MiniBoone, Gallium, Reactor) *see White paper, Abazajian et al., 2012*

…often in tension among themselves…

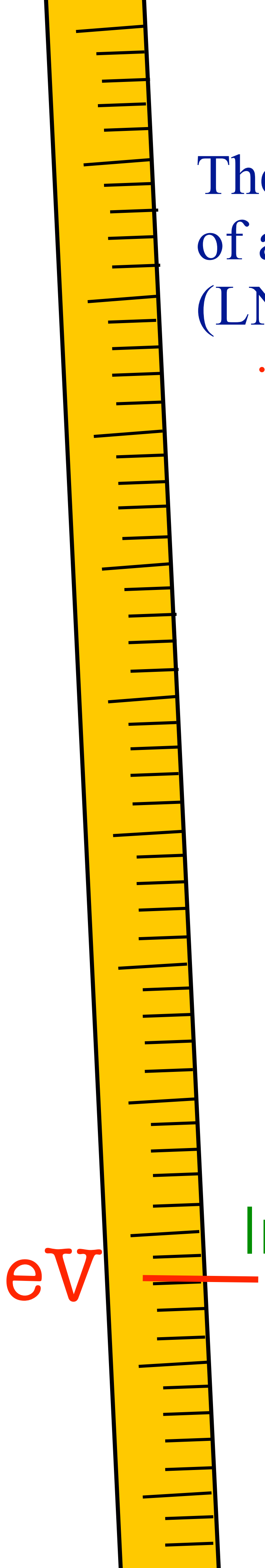



J. Kopp et al, 2013

3+1, 3+2 schemes

New bad news are coming from IceCube, Minos, Daya Bay…

Interpretation: ***1*** (or more) ***sterile neutrino*** with $\Delta m^2 \sim O$ (eV^2) and $\theta_s \sim O(\theta_{13})$



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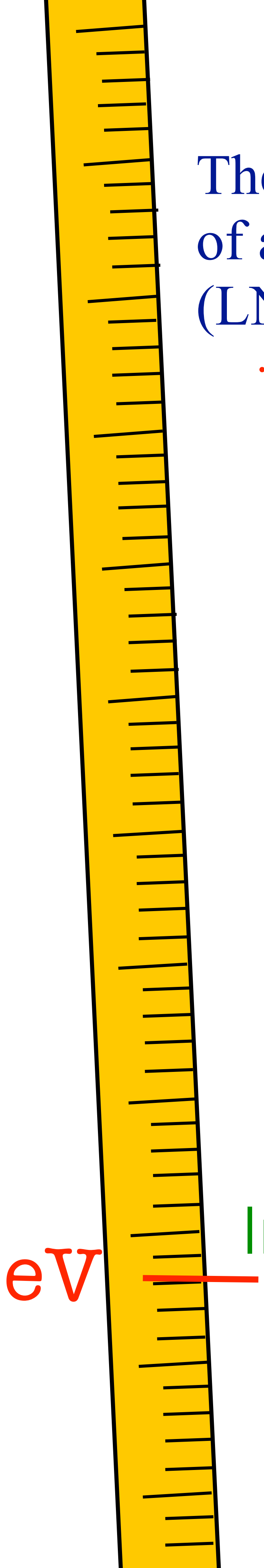

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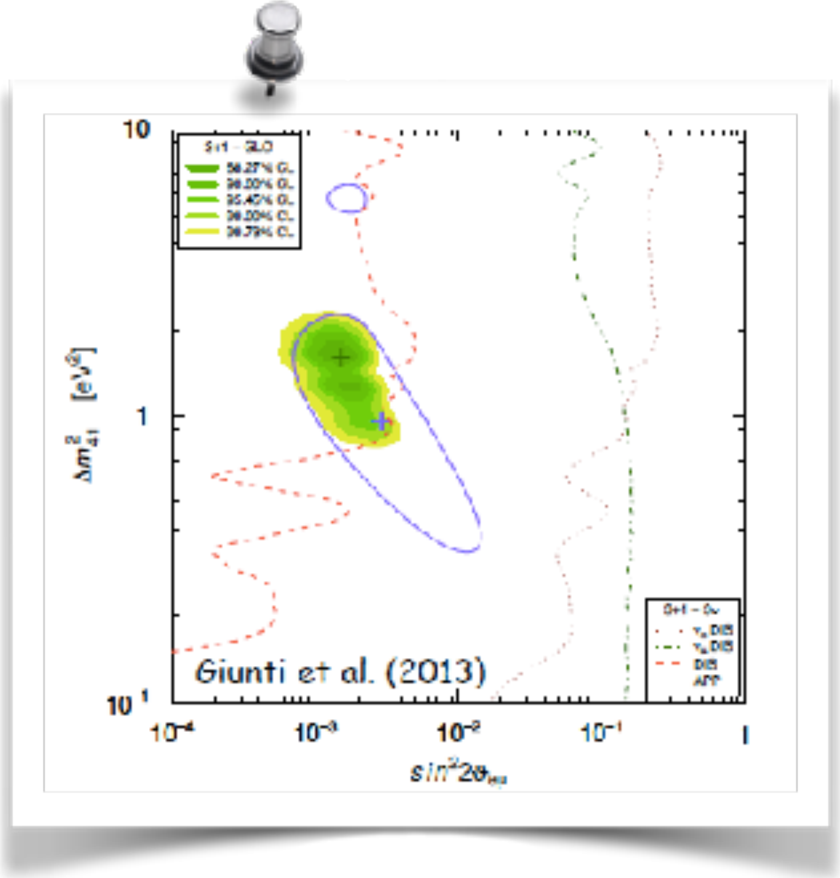

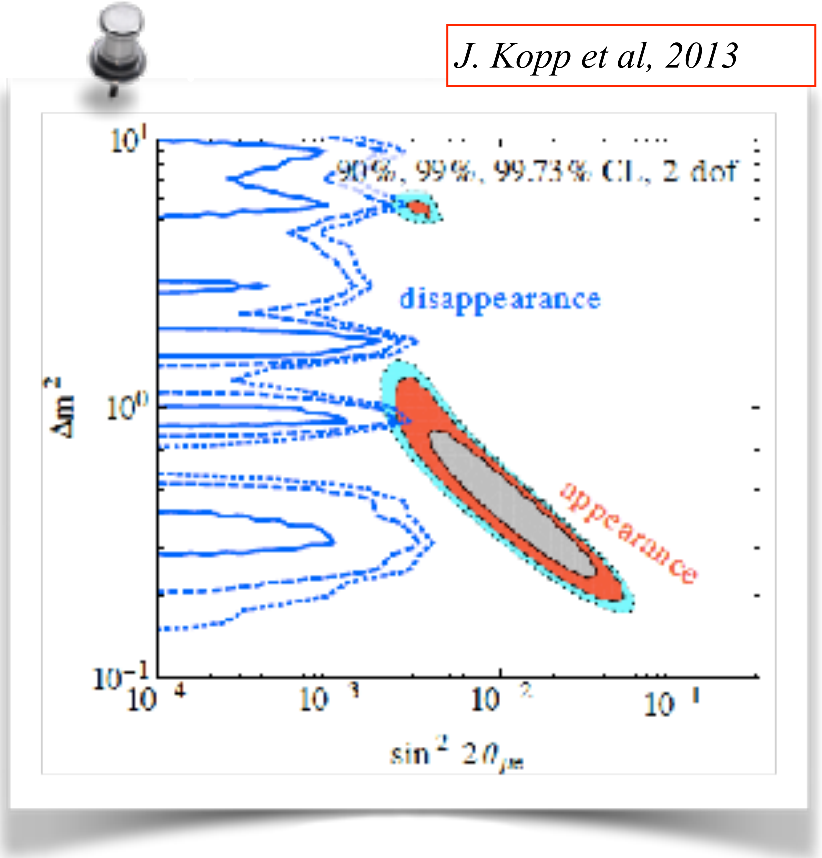

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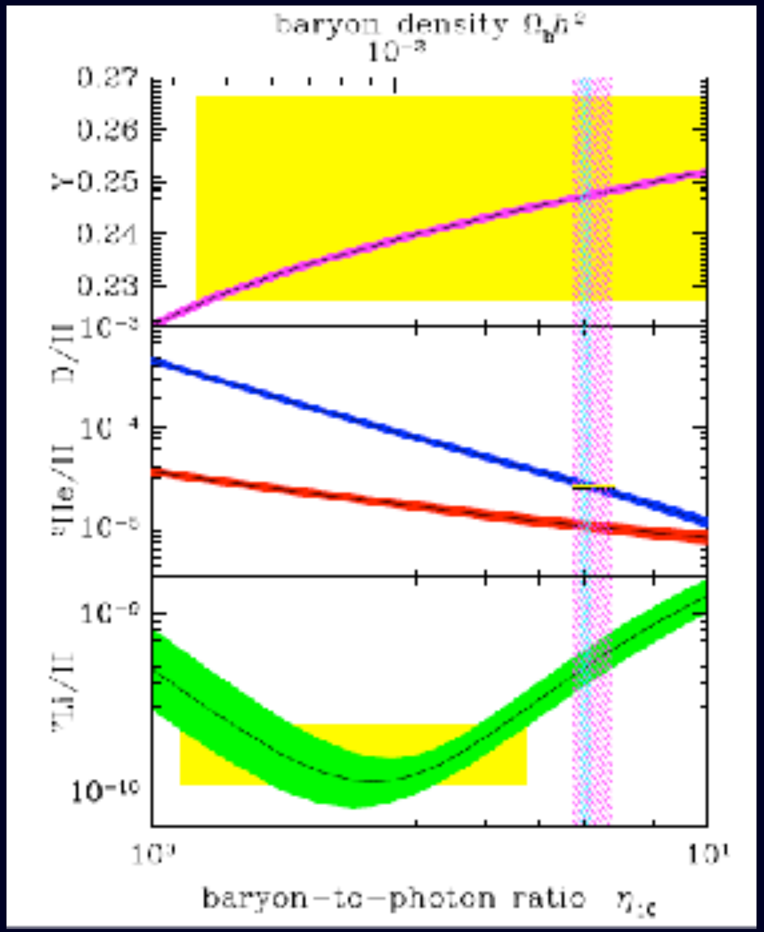
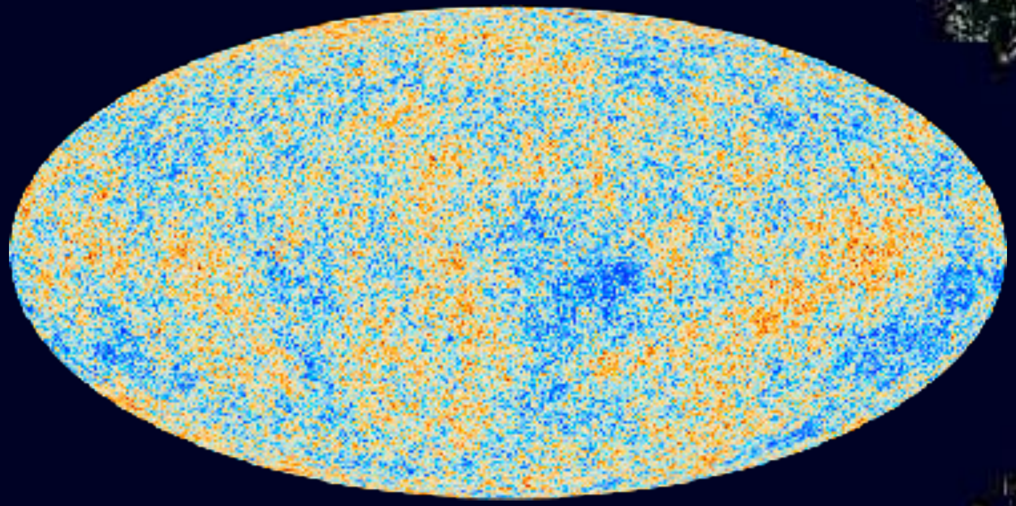
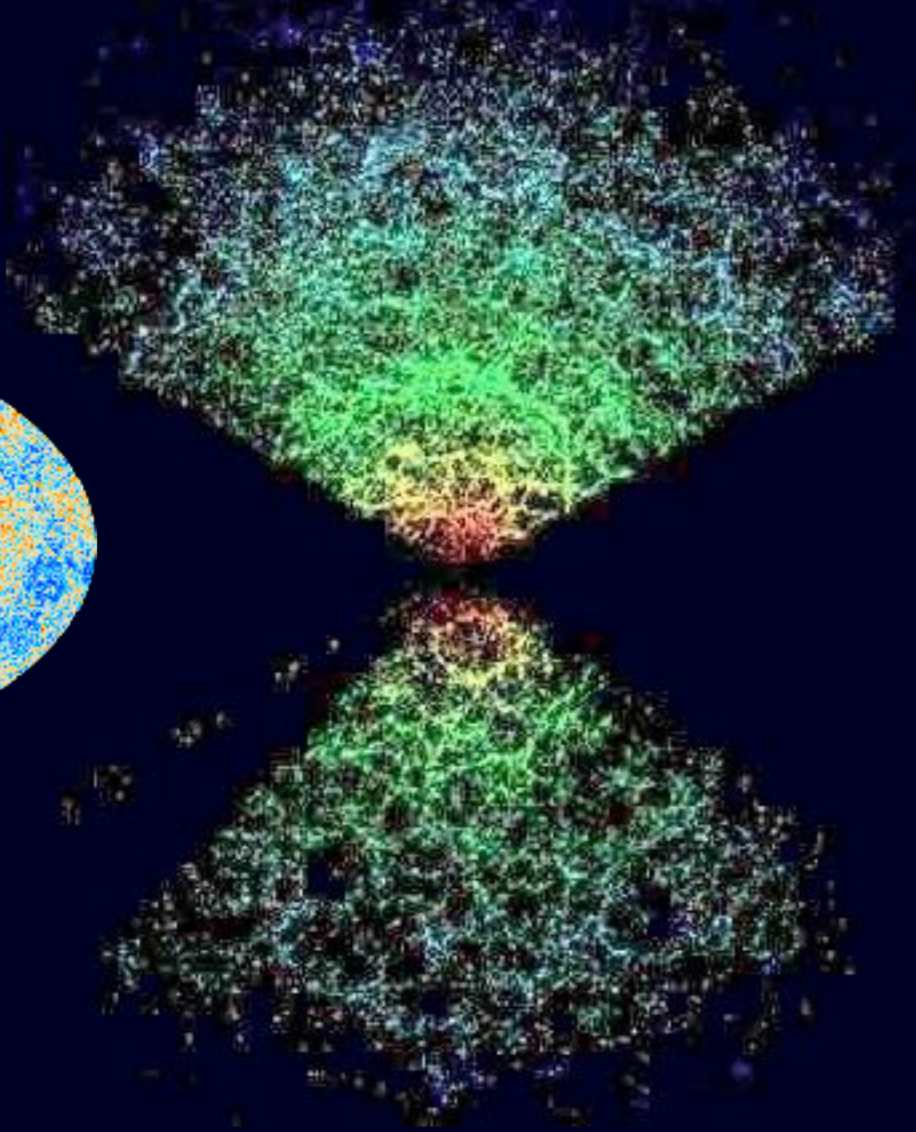
Are eV ν_s compatible with cosmology?

Cosmological observations







Sensitivity to N_{eff} and ν flavour (spectra)

Sensitivity to N_{eff} and ν masses

(and to other proprieties, i.e. neutrino interactions…)

Radiation Content in the Universe

PASTOR'S and HAMANN'S TALKS

At T $<$ m_e , the radiation content of the Universe is

$$\varepsilon_R = \varepsilon_\gamma + \varepsilon_\nu + \varepsilon_x$$

The non-e.m. energy density is parameterized by the effective numbers of neutrino species N_{eff}

$$\boxed{\varepsilon_\nu + \varepsilon_x = \frac{7}{8}\frac{\pi^2}{15}T_\nu^4 N_{\text{eff}} = \frac{7}{8}\frac{\pi^2}{15}T_\nu^4(N_{\text{eff}}^{\text{SM}} + \Delta N)}$$

$N_{\text{eff}}^{\text{SM}} = 3.046$ *due to non-instantaneous neutrino decoupling*

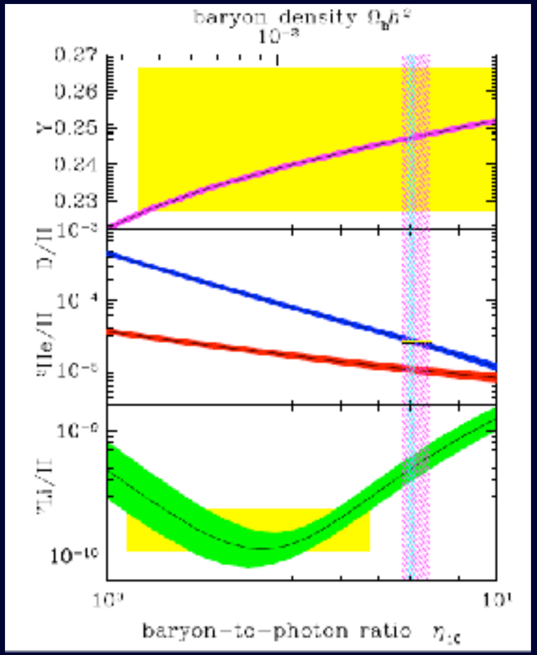
Mangano et al. 2005

(+ oscillations)

($N_{\text{eff}}^{\text{SM}} = 3.045$, recent recalculation)

De Salas & Pastor, 2016

$\Delta N =$ Extra Radiation: axions and axion-like particles, **sterile neutrinos** (totally or partially thermalized), neutrinos in very low-energy reheating scenarios, relativistic decay products of heavy particles...



Impact on Big Bang Nucleosynthesis

At T~1- 0.01 MeV production of the primordial abundances of light elements, in particular ^{2}H, ^{4}He

When $\Gamma_{n\longleftrightarrow p} < H$ ➜ *neutron-to- proton ratio freezes out*

$$\frac{n_n}{n_p} = \frac{n}{p} = e^{-\Delta m/T} \to 1/7$$

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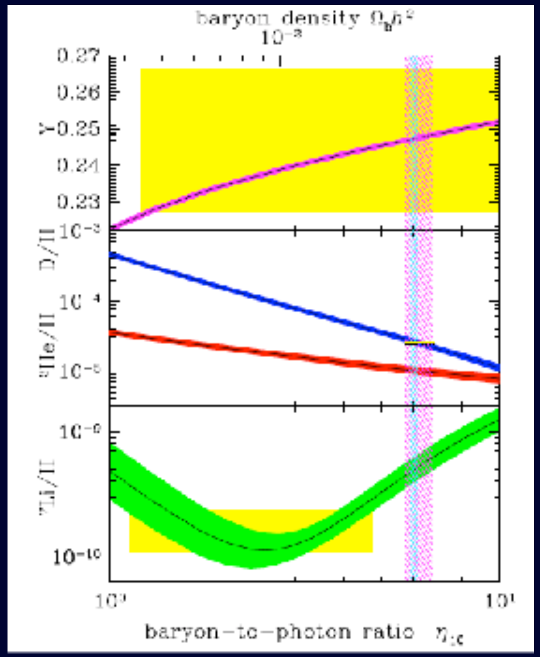

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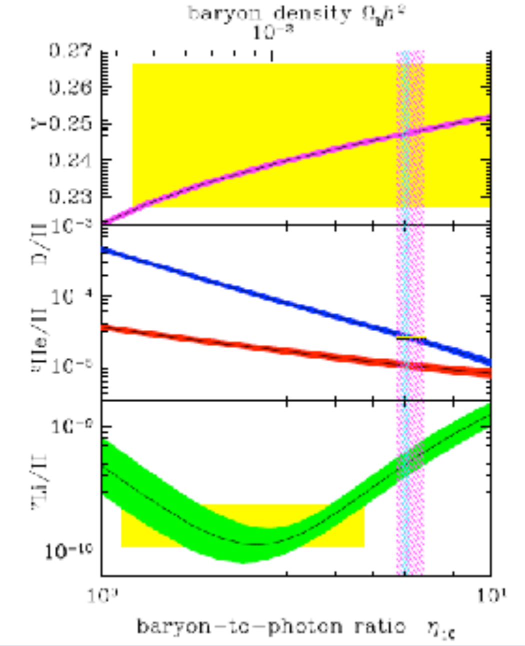
Sterile *ν* influence on BBN :

- ✦ contribution to the radiation energy density governing H before and during BBN

$N_{eff}\uparrow$ ➡ $H\uparrow$ ➡ early freeze out ➡ $n/p \uparrow$ ➡ $^4He\uparrow$, $^2H\uparrow$



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BBN constraint on ΔN_{eff} : NO strong preference

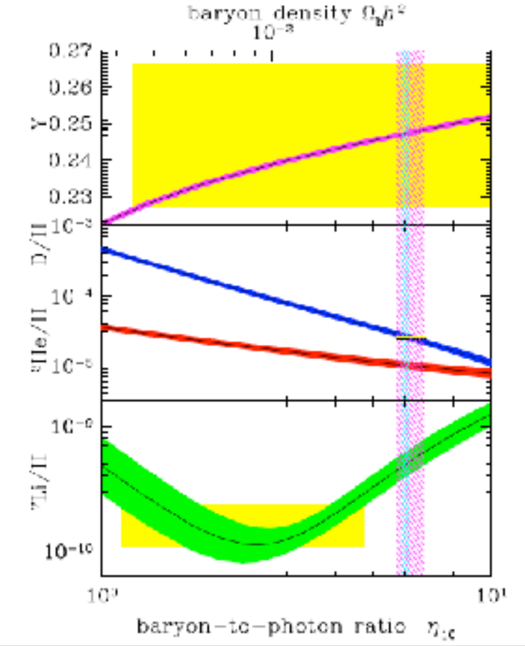
$\Delta N_{eff} \leq 1$ (95% C.L.)

Hamann et al, 2011, Mangano and Serpico. 2012

From new precise measure of D in damped Lyman-α system

$N_{eff} = 3.28 \pm 0.28$,1 extra d.o.f. ruled out at 99.3 C.L.

Cooke, Pettini et al., 2013



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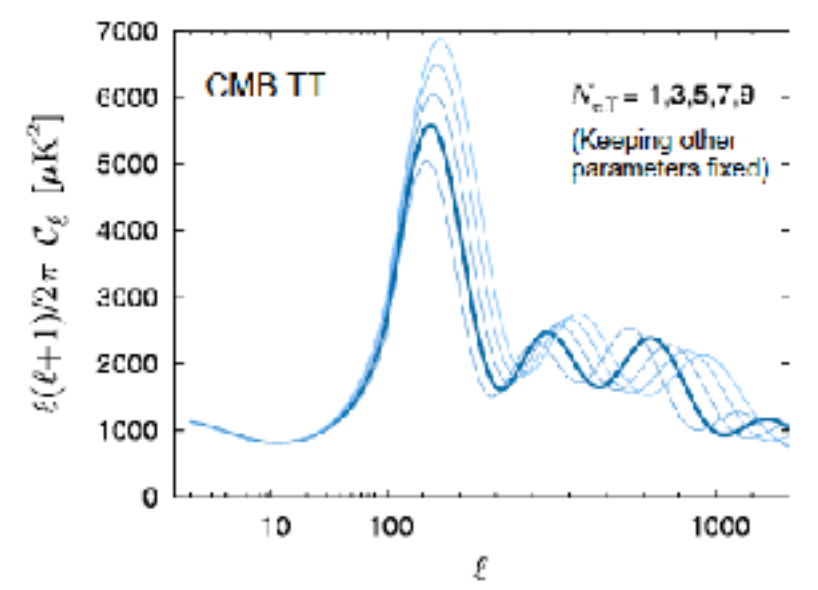
Cooke, Pettini et al., 2013

- oscillating with the active neutrinos, can distort the active spectra which are the basic input for BBN

Impact on CMB and LSS



- *$N_{\rm eff}$* affect the time of ***matter-radiation equality*** ➟ consequences on the amplitude of the first peak and on the peak locations

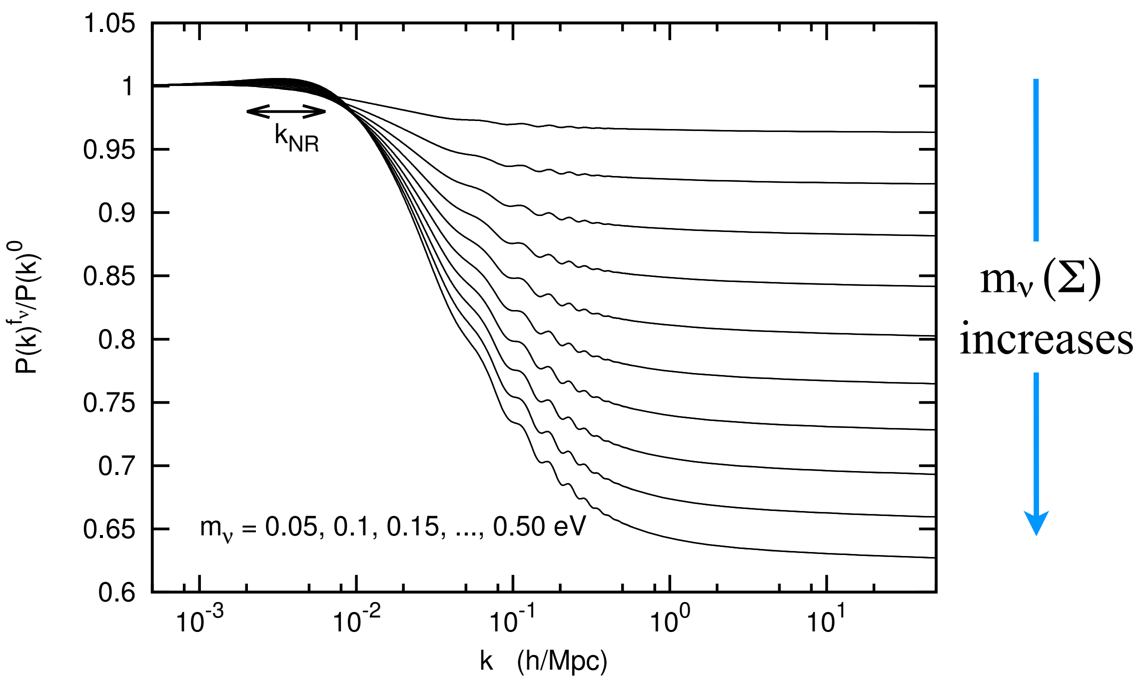
- Neutrino mass (background and perturbation level, suppression of the lensing…)

- Neutrino Interactions

degeneracy among the parameters → necessary to combine with other cosmological probes

The small-scale matter power spectrum P(k > $k_{\rm nr}$) is reduced in presence of massive ν:

- ✓ **free-streaming neutrinos do not cluster**
- ✓ **slower growth rate of CDM (baryon) perturbations**



Lesgourgues, Mangano, Miele and Pastor "Neutrino Cosmology", 2013

Joint constraints on $N_{\rm eff}$ and $m^{\rm eff}_{\nu s}$

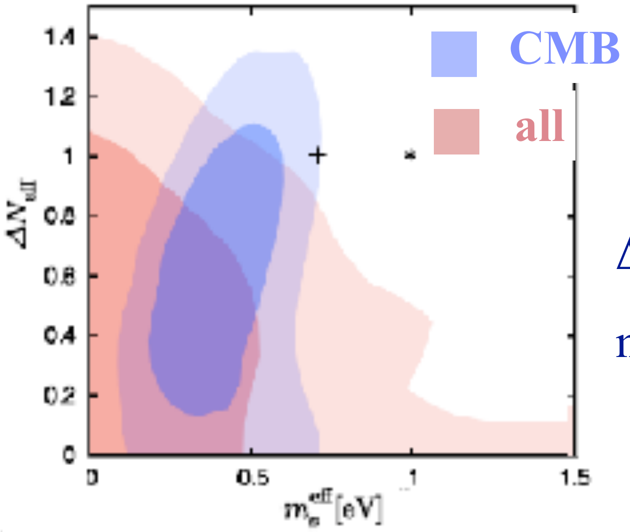
model	**Planck TT** **+**	**mass bound (eV)** **(95% C.L.)**
Joint analysis $N_{\rm eff}$ & 1 mass ν_s (prior $m^{\rm ph}_{\nu s}$ <10 eV)	lowP+lensing+BAO	$N_{\rm eff} < 3.7$ $m^{\rm eff}_{\nu s} < 0.52$
Joint analysis $N_{\rm eff}$ & 1 mass ν_s (prior $m^{\rm ph}_{\nu s}$ <2 eV)	lowP+lensing+BAO	$N_{\rm eff} < 3.7$ $m^{\rm eff}_{\nu s} < 0.38$

Planck XIII, 2015

$$m^{\rm eff}_{\nu s} \equiv (94,1\ \Omega_\nu h^2)\text{eV}$$

$$m^{\rm eff}_{\nu s} = \rho_{ss}\ m^{\rm ph}_{\nu s}$$

Hamann and Hasenkamp, 2013



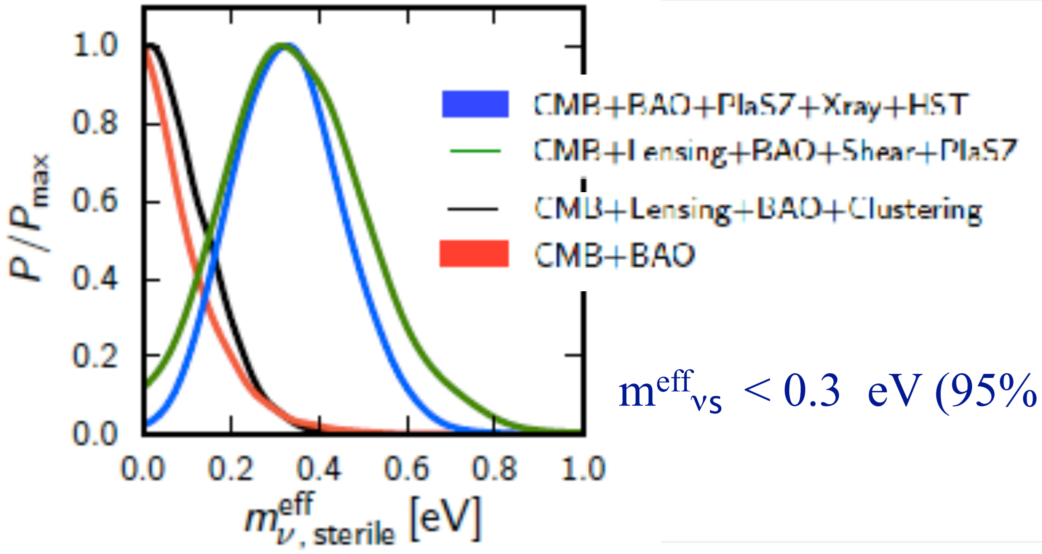
$\Delta N_{\rm eff} = 0.61$ +- 0.30

$m^{\rm eff}_{\nu s} = 0.41$+-0.13 eV

(68% C.L.)

all= CMB+H0+ C+ CFHTLens

L. Verde et al, 2014



$m^{\rm eff}_{\nu s} < 0.3$ eV (95% C.L)

Less stringent mass bound from combined analysis $\longrightarrow m^{\rm eff}_{\nu s} < 0.6$ eV

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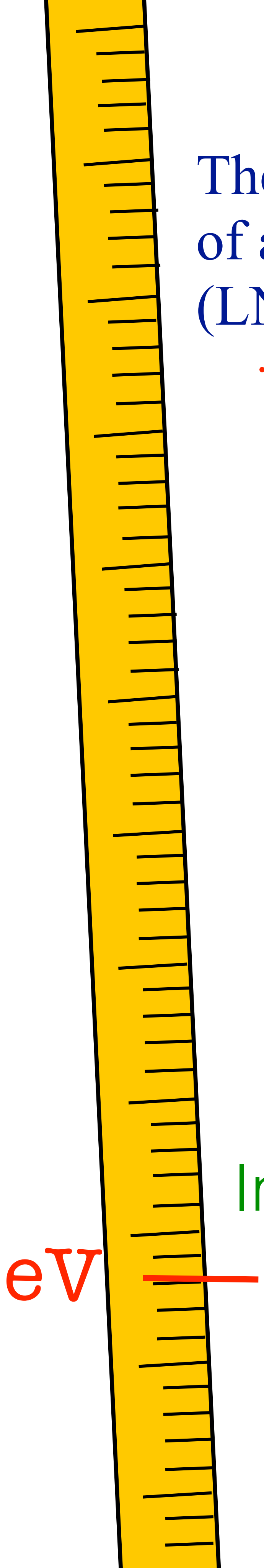
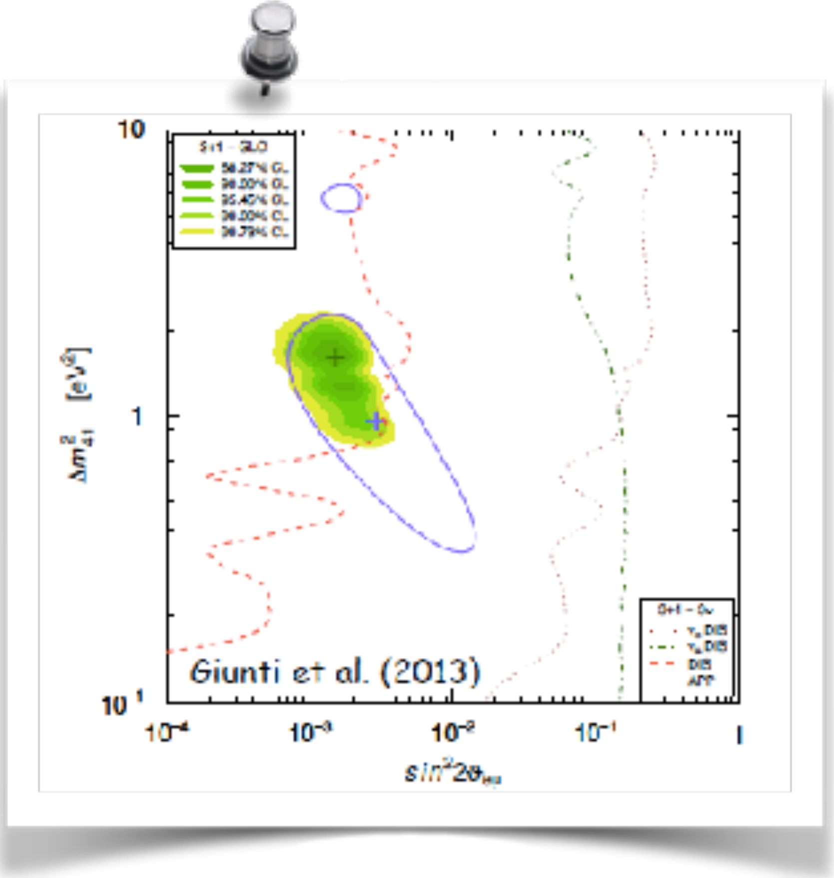
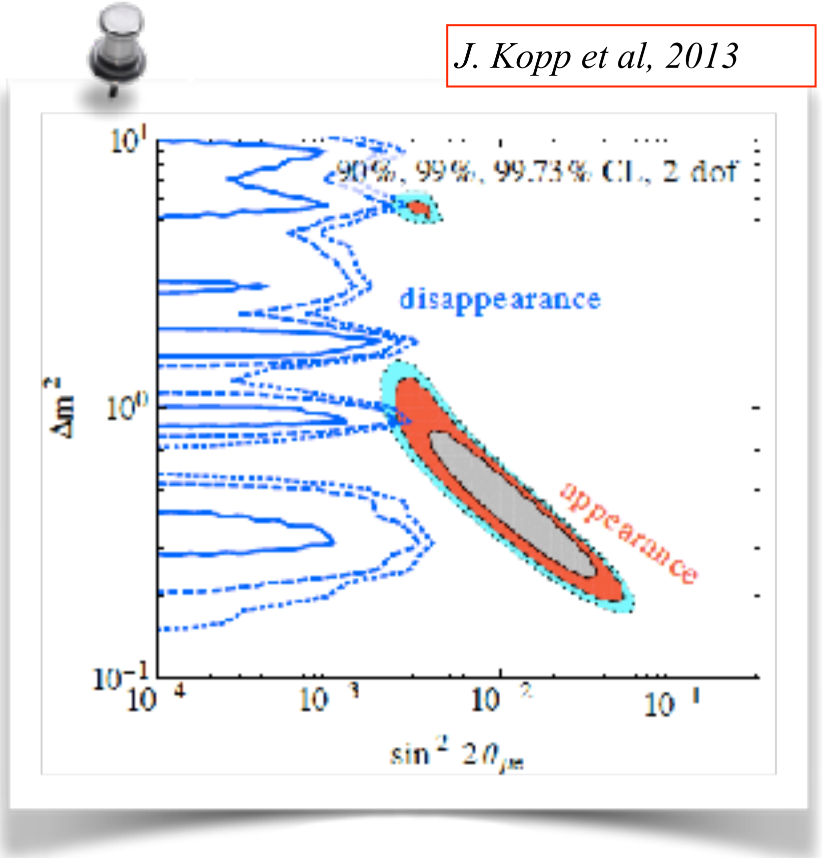




J. Kopp et al, 2013



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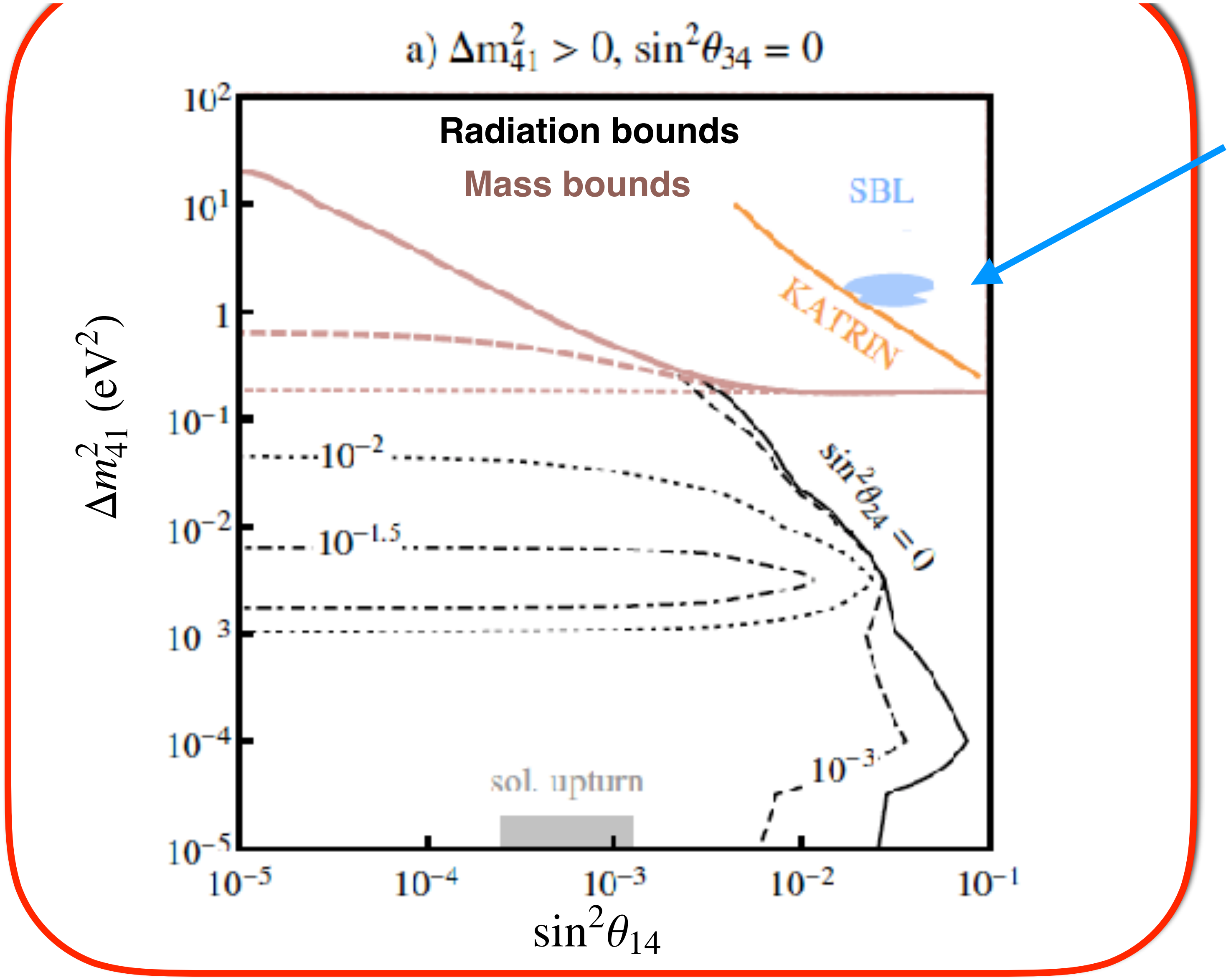
Interpretation: ***1*** (or more) ***sterile neutrino*** with $\Delta m^2 \sim O$ (eV^2) and $\theta_s \sim O$ (θ_{13})

Are eV ν_s compatible with cosmology? NO

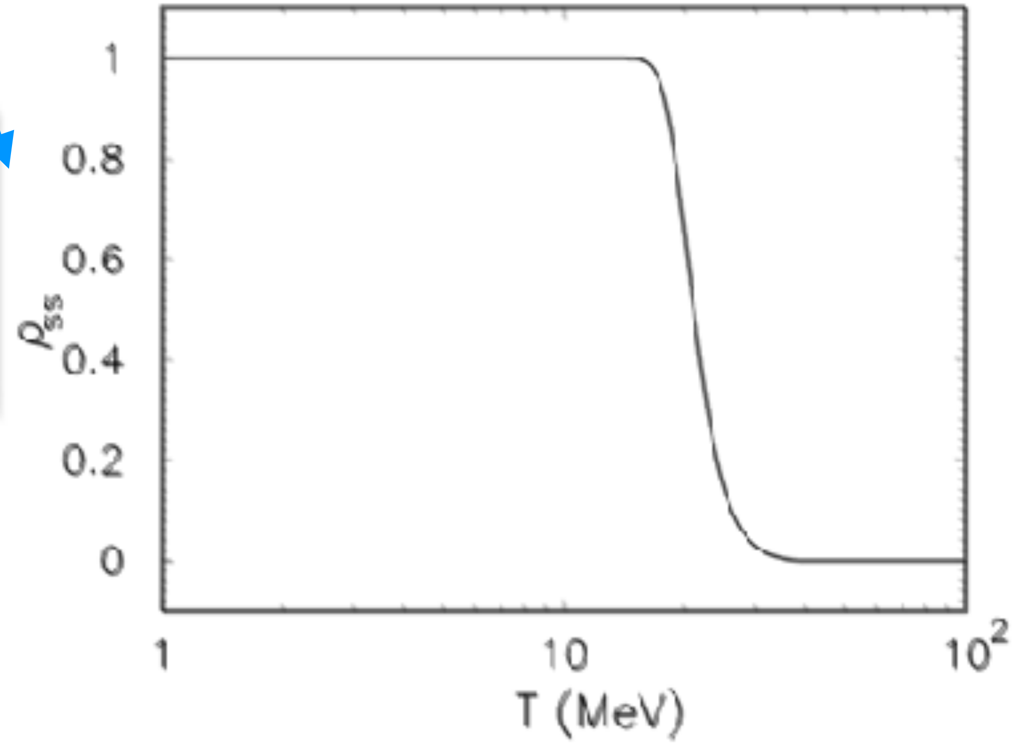
…because

Planck constraints on the parameter space of ν oscillation:



Mirizzi, Mangano, Saviano et al 2013, arXiv1303.5368

For the mass and mixing parameters preferred by laboratory sterile ν are copiously produced, reaching 1 extra d.o.f



See also Elvin-Poole' S TALK

Thermalized sterile ν with* m ~ $\mathcal{O}$(1 eV) *strongly disfavored by cosmological constraints

- 3+1: Too ***many*** for BBN and too ***heavy*** for LSS/CMB
- 3+2: Too ***heavy*** for LSS/CMB and too ***many*** for BBN/CMB

Possible solutions...?

- ***Different mechanisms to suppress the ν_s abundance:***

1. **large $\nu-\bar{\nu}$ asymmetries**

   In the presence of large $\nu-\nu$ asymmetries ($L\sim10^{-2}$) sterile production strongly suppressed. Mass bound can be evaded

   *Mirizzi, **N.S.**, Miele, Serpico 2012*
   Saviano et al., 2013
   Hannestad, Tamborra and Tram 2012
   Chu & Cirelli, 2006
   Di Bari et al, 2001

2. **"secret" interactions for sterile neutrinos**

   Hannestad et al., 2013,
   Dasgupta and Kopp 2013,
   Bringmann et al., 2013
   Archidiacono et al., 2014
   Saviano et al.,2014
   *Mirizzi, Mangano, Pisanti, **N.S**.*

3. **low reheating scenario**

   sterile abundance depends on reheating temperature

   Gelmini, Palomarez-Ruiz, Pascoli, 2004
   Yaguna 2007

- ***Modification of cosmological models***

Inflationary Freedom

Shape of primordial power spectrum of scalar perturbations different from the usual power-law *Gariazzo, Giunti Laveder, 2015*

Efficacy reduced by more recent paper *Di Valentino et al 2016*

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Secret interactions for sterile neutrinos

Different authors have assumed the Standard Model (SM) is augmented by one extra species of light (~ eV) neutrinos νs, which do not couple to the SM gauge bosons but experiment a new force

Hannestad et al., 2013,, Dasgupta and Kopp 2013, Bringmann et al., 2014

Such a new interaction can have profound effects on active-sterile neutrino conversion in the early Universe, **since sterile ν feel a new potential that can suppresses active-sterile mixing** *(through an effective* ν_a-ν_s *mixing reduced by a large matter term)*

Caveat: ⚠ they also generate ***MSW resonance*** and ***strong collisional production***, increasing their abundance, with non trivial consequences on the cosmological observables

➜ **νSI constraints from cosmological probes**

If the new mediator interaction X also couples to Dark Matter possible attenuation of some of the small scale structure problems ("missing satellites" problem...)

SI in the flavour evolution

new secret self-interactions among sterile ν mediated by a **massive gauge boson X** :

ν_s - ν_s *interaction strength* $G_X = \frac{\sqrt{2}}{8}\frac{g_X^2}{M_X^2}$ for T < M_X

Evolution equation:

$$\boxed{i\frac{d\rho}{dt} = [\Omega, \rho] + C[\rho]}$$

$$\Omega = \Omega_{vac} + \Omega_{mat} + \Omega_{\nu-\nu} + \boxed{\Omega^{Secr}_{\nu_s-\nu_s}}$$

$\propto G_X$

$$C[\rho] = C_{SM} + \boxed{C_{Secr}}$$

$\propto G_X^2$

$$\rho_{\mathbf{p}} = \begin{pmatrix} \rho_{ee} & \rho_{e\mu} & \rho_{e\tau} & \rho_{es} \\ \rho_{\mu e} & \rho_{\mu\mu} & \rho_{\mu\tau} & \rho_{\mu s} \\ \rho_{\tau e} & \rho_{\tau\mu} & \rho_{\tau\tau} & \rho_{\tau\tau} \\ \rho_{se} & \rho_{s\mu} & \rho_{s\tau} & \rho_{ss} \end{pmatrix}$$

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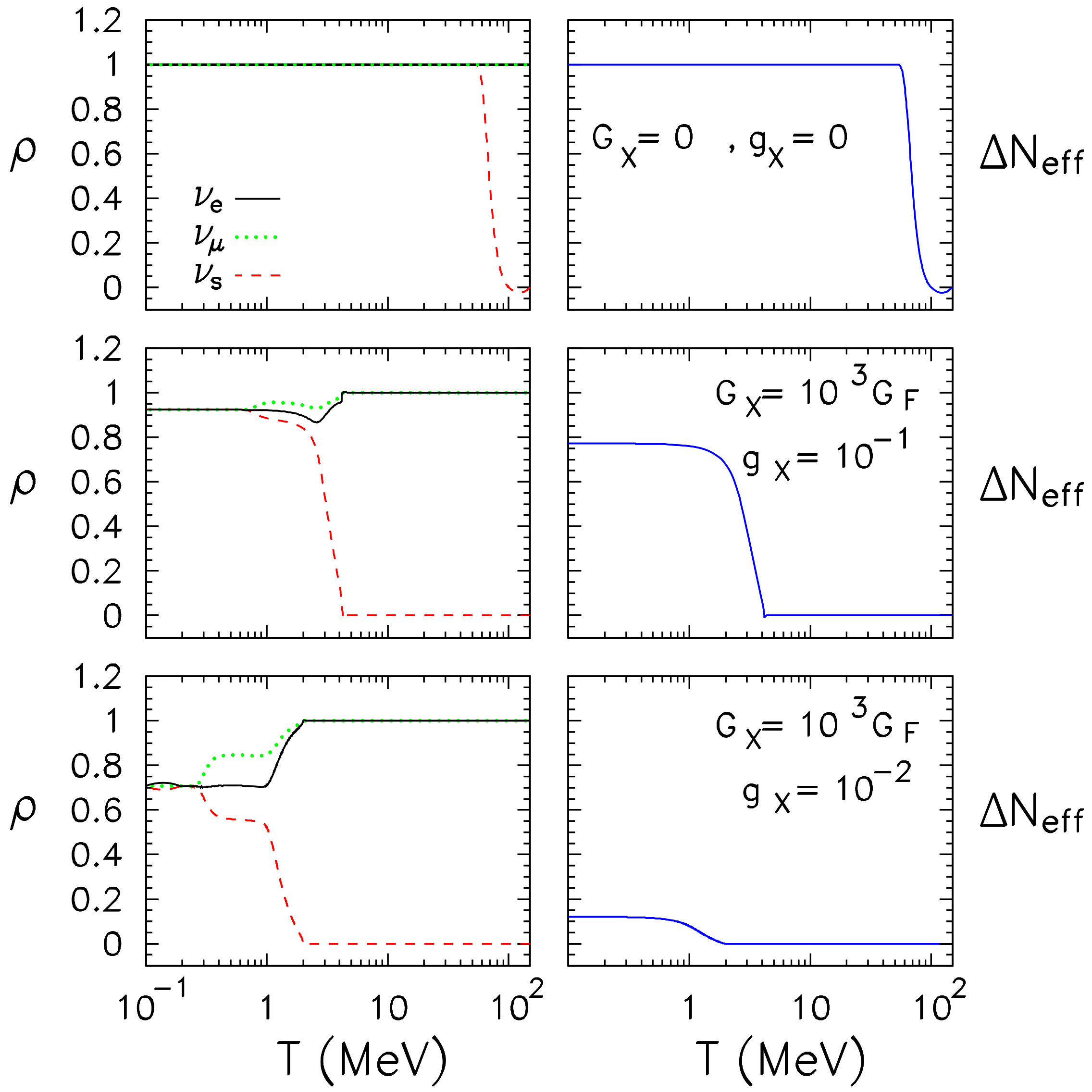
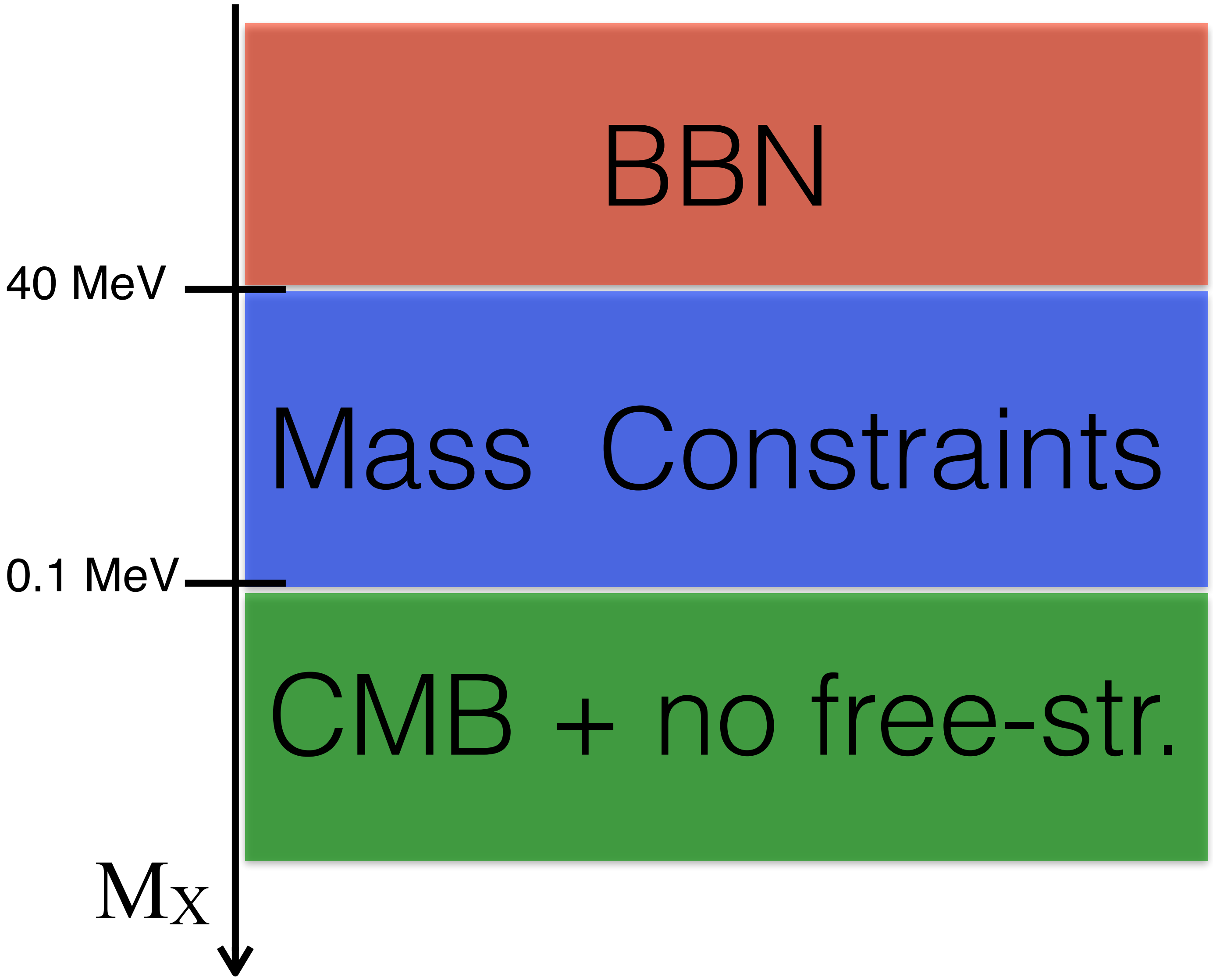


Saviano, Pisanti, Mangano, Mirizzi 2014

Constraints for sterile nSI (Vector boson)



BBN

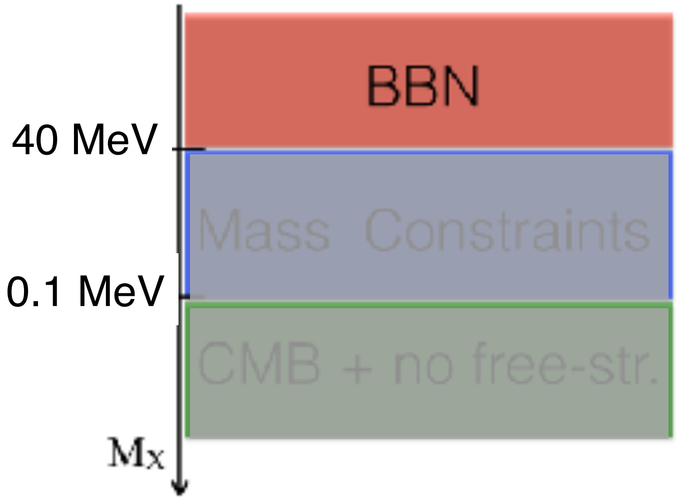
40 MeV

Mass Constraints

0.1 MeV

CMB + no free-str.

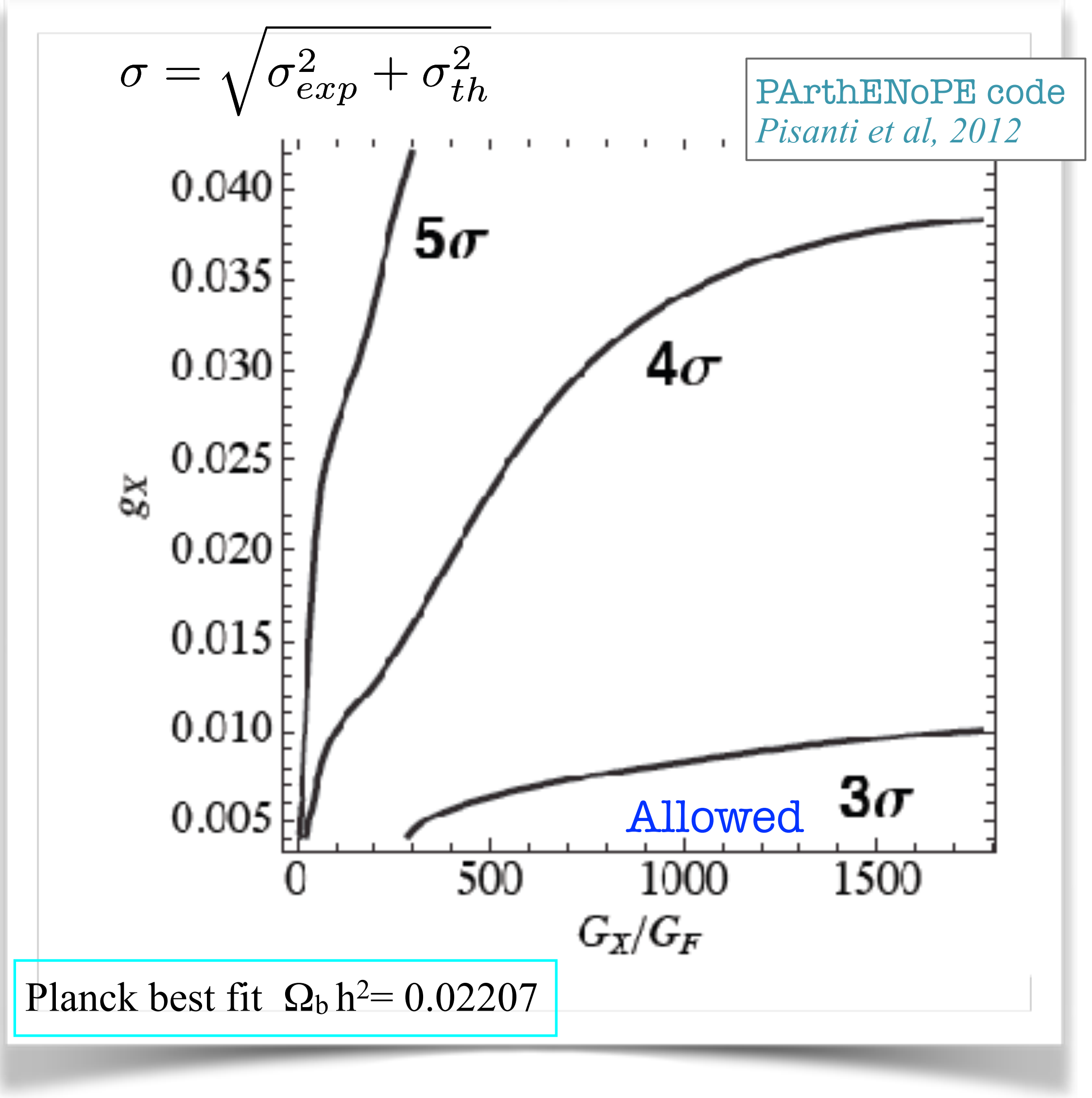
M_X



BBN constraints for sterile νSI

After the ν oscillation in the range of g_X and G_X relevant for BBN, we have both :

$\Delta N_{eff} > 0$ and distortions of the active ν_e spectra



$$\sigma = \sqrt{\sigma_{exp}^2 + \sigma_{th}^2}$$

PArthENoPE code
Pisanti et al, 2012

Planck best fit $\Omega_b h^2 = 0.02207$

Deuterium yield

Experimental reference value:

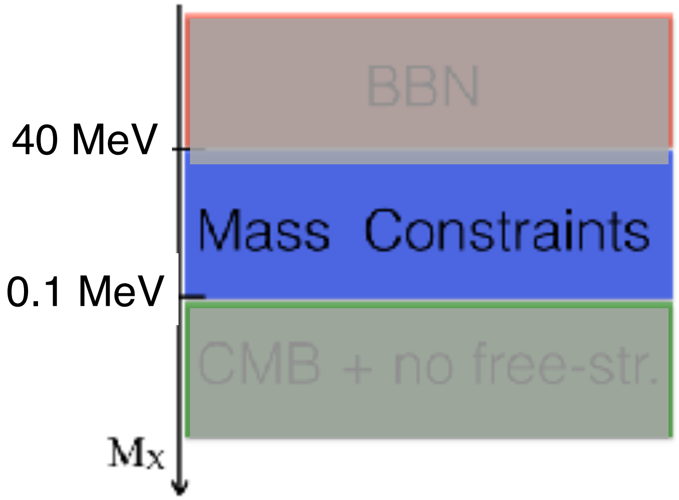
$$^2H/H = (2.53 \pm \underbrace{0.04) \text{ x } 10^{-5}}_{\sigma_{exp}}$$

R. Cooke et al, 2013

Translating in a bound for the mediator mass:

mass permitted: $M_X \leq 40$ MeV

Saviano, Pisanti, Mangano, Mirizzi 2014



Mass constraints for sterile νSI

Constraint on lower M_X ↔ very large G_X ($> 10^5\, G_F$)

Very strong secret collisional term leads to a quick flavor equilibrium

Stodolsky, 1987

$$(\rho_{ee},\ \rho_{\mu\mu},\ \rho_{\tau\tau},\ \rho_{ss})_{\textbf{initial}} \rightarrow (\rho_{ee},\ \rho_{\mu\mu},\ \rho_{\tau\tau},\ \rho_{ss})_{\textbf{final}}$$

$$(1,\ 1,\ 1,\ 0) \qquad (3/4,\ 3/4,\ 3/4,\ 3/4)$$

The flavour evolution leads to a large population of νs, in conflict with the cosmological mass bound

$$m_{\rm st}^{\rm eff} = \rho_{ss}\sqrt{\Delta m^2_{\rm st}} = \frac{3}{4}\sqrt{\Delta m^2_{\rm st}}$$ lower value in the 2σ range from anomalies gives $m^{\rm eff}{}_s \sim 0.8$ eV

in tension with the CMB and LSS conservative bounds on sterile mass (< 0.6 eV)

Secret interaction scenario: disfavored $M_X > 0.1$ MeV (⇔ ~ $10^9\, G_F$)

Mirizzi,Mangano, Pisanti Saviano, 2014

A surprising effect on $N_{\rm eff}$

After the production, ν_s have a "grey-body" spectrum ($\rho_{ss} = 3/4$)....

.... but the collisions and oscillations are still active pushing all neutrinos to a common FD distribution

Constraint: $n_{\nu\,\rm TOT}$ must be constant

↓

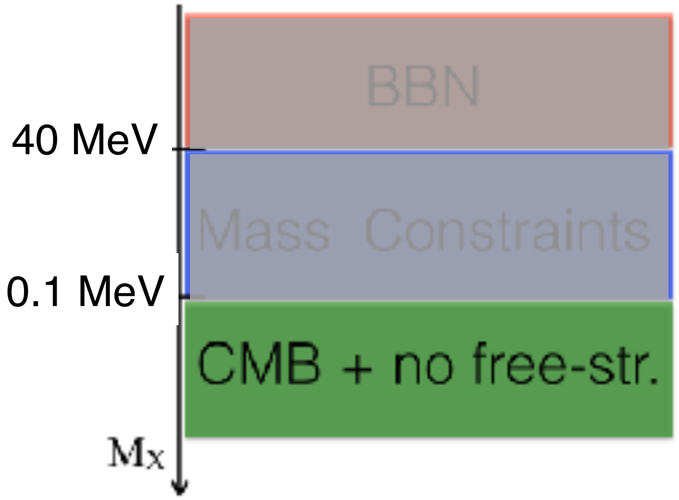
$T\nu$ is reduced by a factor $(3/4)^{1/3}$,
leading to an effect on the radiation density

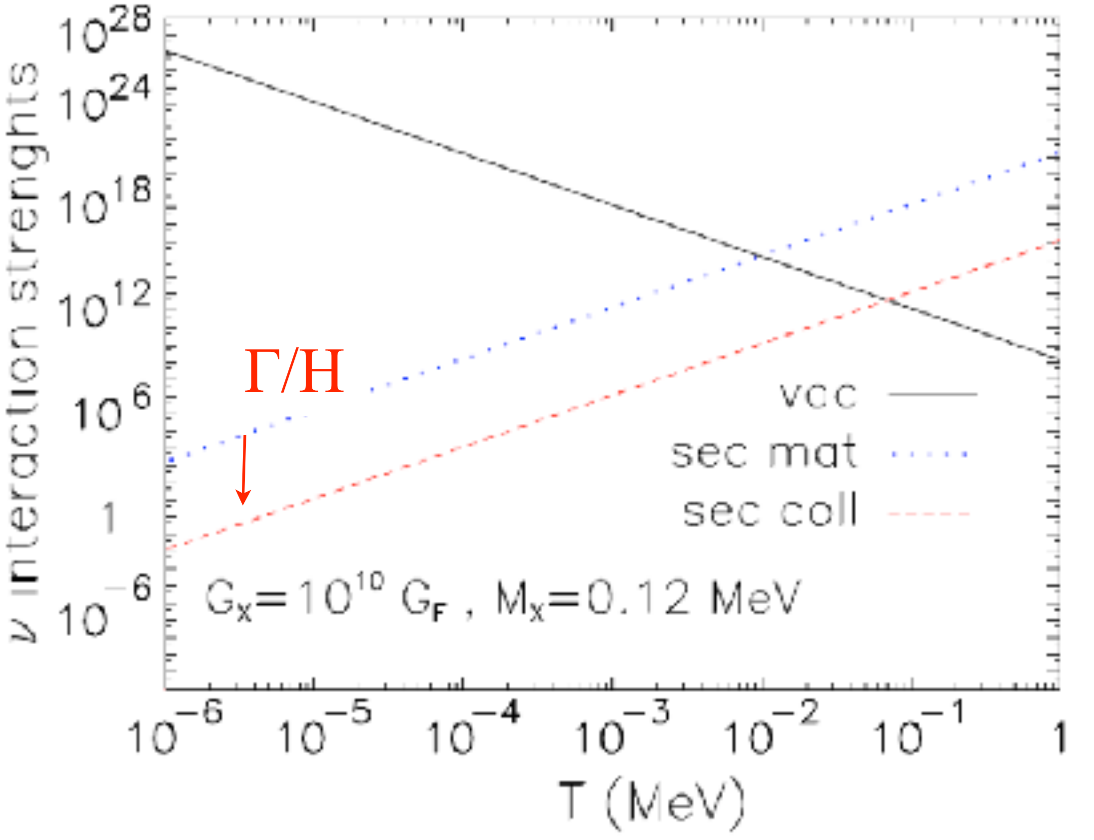
$$\epsilon_{\nu,\rm in} = 3 \times \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} \epsilon_\gamma \quad \Rightarrow \quad \epsilon_{\nu,\rm fin} = 4 \times \left(\frac{3}{4}\right)^{4/3} \times \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} \epsilon_\gamma$$

$$N_{\rm eff} \sim 4 \times \left(\frac{3}{4}\right)^{4/3} \sim 2.7$$

Mirizzi, Mangano, Pisanti Saviano, 2014

CMB constraints for sterile νSI





For **$M_X \leq 0.1$ MeV ($\geq 10^{10}$ G_F)** →
ν_s could be still coupled at CMB and LSS epoch → possible no free-streaming.

↓

an appropriated analysis should be performed

We derive our mass bounds, taking into account neutrino scattering via secret interactions and we also take into account the increased density and pressure perturbations in the neutrino fluid, induced by collisions with strength

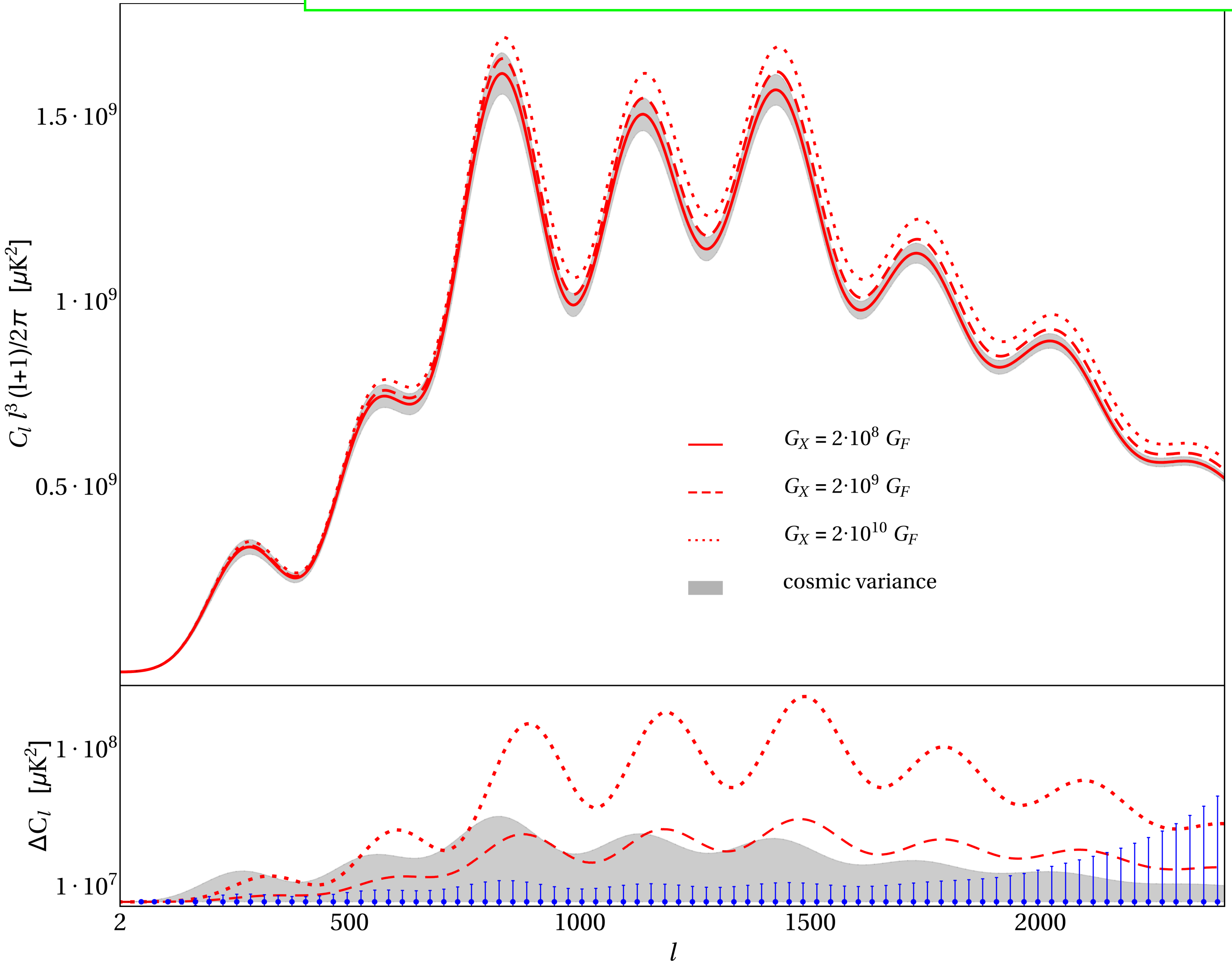
$$G_X = \frac{\sqrt{2}}{8}\frac{g_X^2}{M_X^2}$$

Forastieri, Lattanzi, Mangano, Mirizzi, Natoli, Saviano, 2017

CMB constraints for sterile νSI

Effect of interactions among neutrino species on the evolution of cosmological perturbations:

Forastieri, Lattanzi, Mangano, Mirizzi, Natoli, Saviano, 2017



$$\hat{L}[\delta f] = \hat{C}[\delta f]$$

$$\delta f \equiv f_0 \Psi$$

$$\dot{\Psi}_{i,0} = -\frac{4}{3}\frac{q}{\epsilon}\Psi_{i,1} - \frac{2}{3}\dot{h}\,,$$

$$\dot{\Psi}_{i,1} = k^2\frac{q}{\epsilon}\left(\frac{1}{4}\Psi_{i,0} - \Psi_{i,2}\right)\,,$$

$$\dot{\Psi}_{i,2} = \frac{q}{\epsilon}\left(\frac{4}{15}\Psi_{i,1} - \frac{3}{10}k\Psi_{i,3}\right) + \frac{2}{15}\dot{h} + \frac{4}{5}\dot{\eta} - \Gamma_{ij}\Psi_{j,2}\,,$$

$$\dot{\Psi}_{i,\ell} = \frac{k}{2\ell+1}\frac{q}{\epsilon}\left[\ell\Psi_{i,(\ell-1)} - (\ell+1)\Psi_{i,(\ell+1)}\right] - \Gamma_{ij}\Psi_{j,\ell}$$

$$(\ell \geq 3)$$

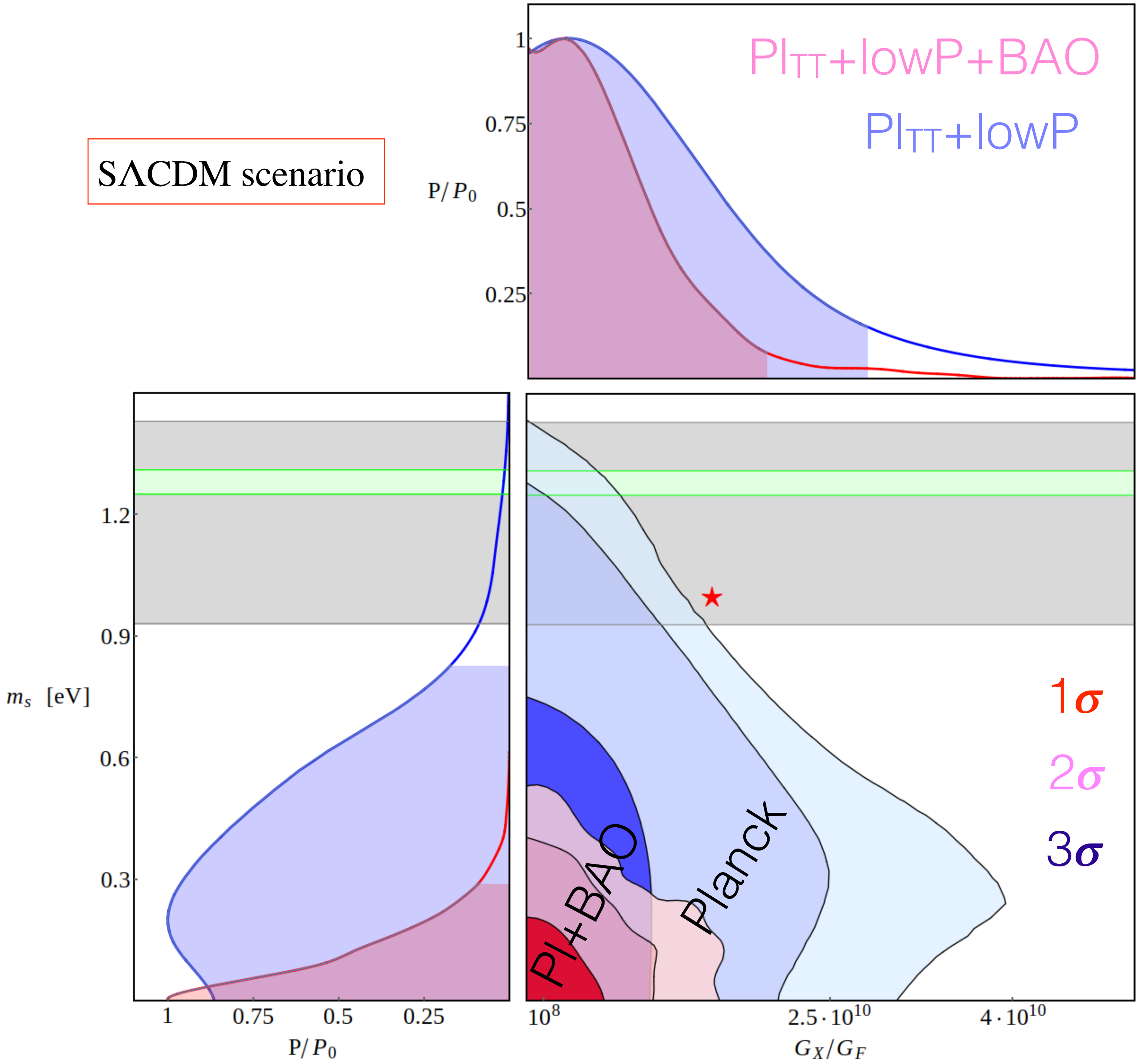
NOTE: $N_{\mathrm{eff}} = 2.7$

As long as Γ > H, interacting neutrinos behave as perfect fluid —> shear and higher moments are exponentially suppressed.

Net effect: density and pressure perturbations are enhanced with respect to the non-interacting case, propagating to the photon fluid, and thus to CMB anisotropies

CMB constraints for sterile νSI

SΛCDM scenario



	Description
ΛCDM	Standard six-parameter ΛCDM, $N_{\rm eff} = 3.046$.
SΛCDM_GX0	Sterile neutrino extension, $N_{\rm eff} = 2.7$, m_s free, "small" G_X ($\sim 10^8 G_F$).
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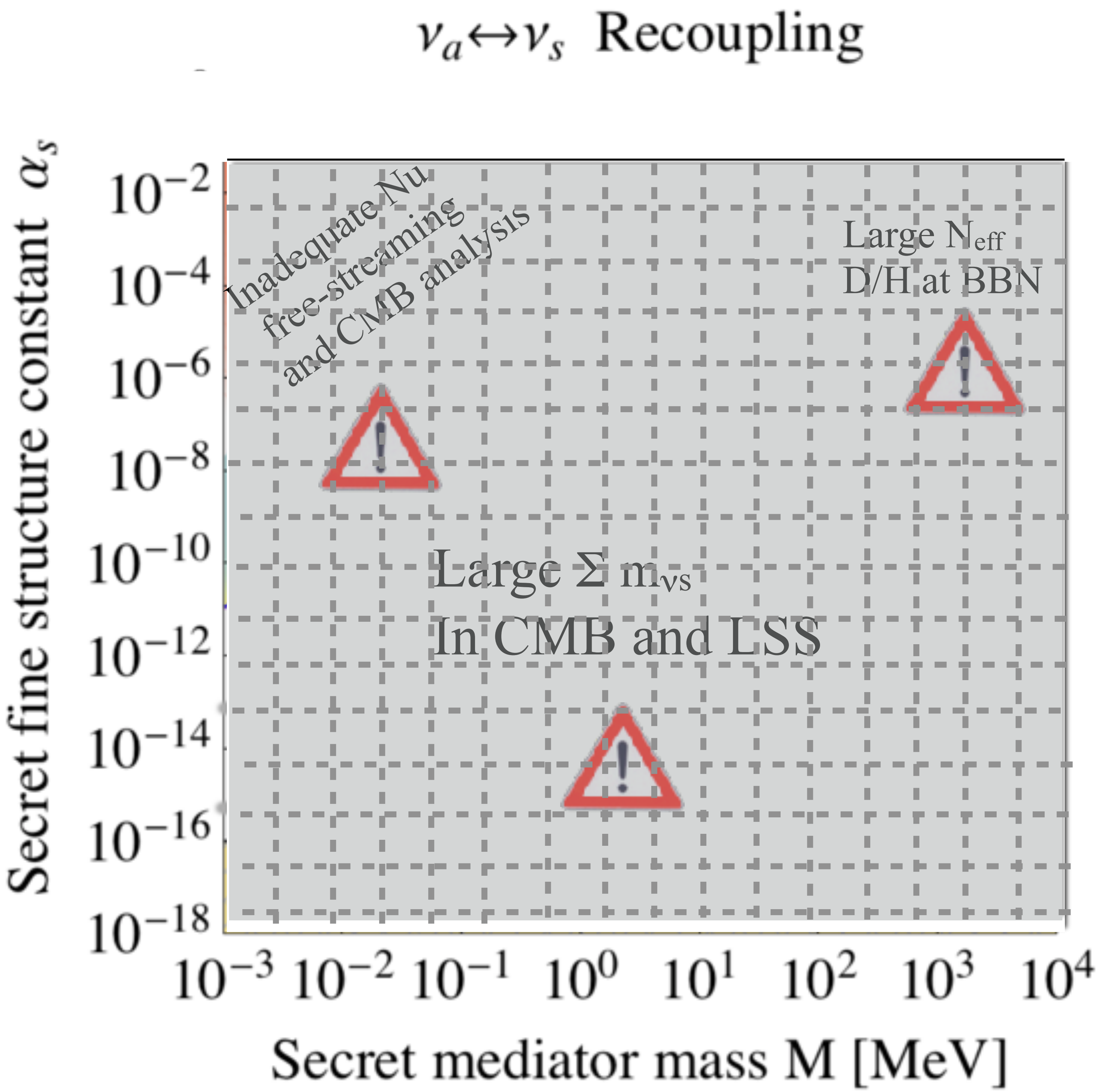
SΛCDM_Broad	Sterile neutrino extension, $N_{\rm eff} = 2.7$, G_X free, 0.93 eV $\leq m_s \leq$ 1.43 eV (flat prior).

Parameter	SΛCDM
$\Omega_b h^2$	0.02197±0.00021
$\Omega_c h^2$	$0.1144^{+0.0016}_{-0.0015}$
$100\theta_{MC}$	$1.04332^{+0.00090}_{-0.00063}$
τ	0.074 ± 0.018
n_s	0.9392 ± 0.0063
$\ln(10^{10}A_s)$	3.038 ± 0.036
G_X/G_F	$< 1.97 \times 10^{10}$
m_s	< 0.29
H_0	65.26 ± 0.68

Forastieri, Lattanzi, Mangano, Mirizzi, Natoli, Saviano, 2017

Summary Plot



Refined calculations show that all **the parameter space seems to be excluded** (due also to the X-mediated s-channel process leading to efficient sterile neutrino production)

Chu et al., in preparation

Conclusions

- neutrino cosmology is entering the precision epoch

$N_{eff} \sim 3$ $m^{eff}_{\nu s} < 0.6$ eV

- Thermalized eV sterile *ν* ***incompatible*** with cosmological bounds:

Too many for BBN and CMB and too heavy for structure formation

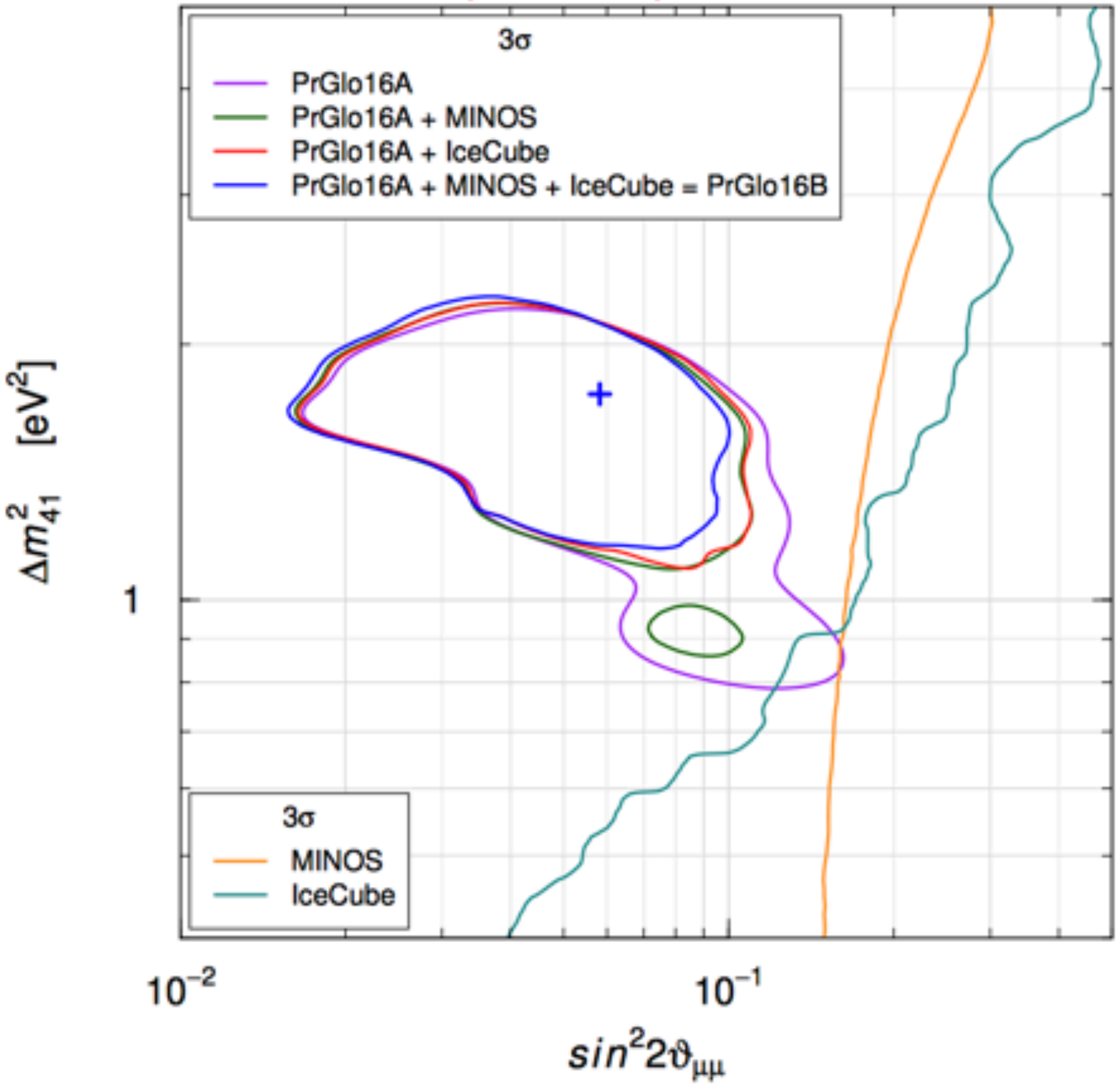
- New exotics scenarios are required (primordial neutrino asymmetry, hidden interactions, inflationary freedom...) →

→ ***however the reconciliation with cosmology is not guaranteed and in some cases disfavoured (neutrino asymmetry) and excluded (secret interactions)***

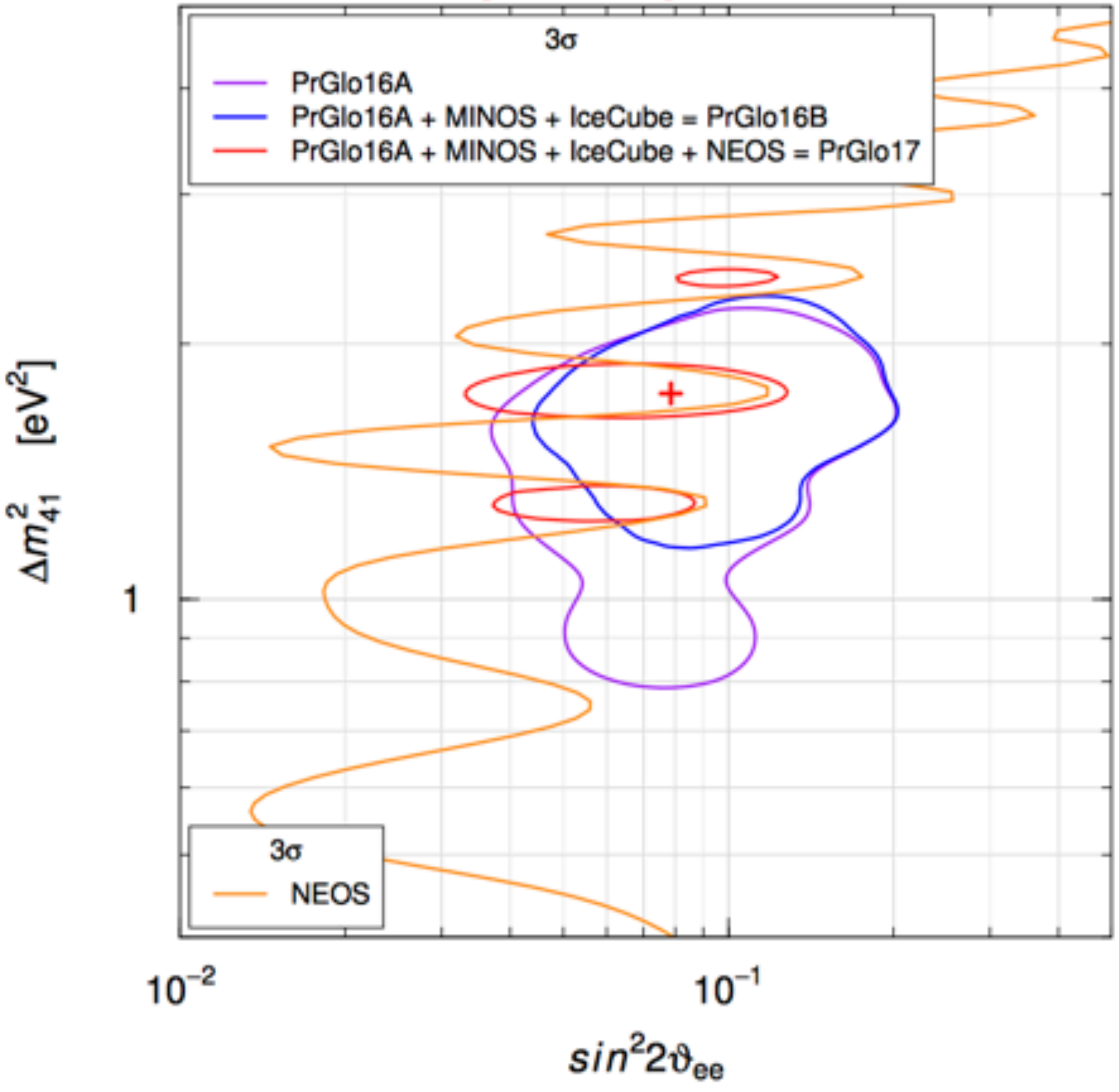
Very hard to accommodate sterile neutrino with cosmology

THANK YOU

Effects of MINOS, IceCube and NEOS



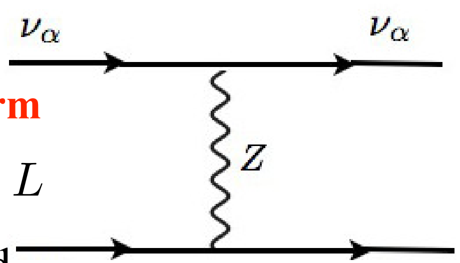
$\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_\mu$



$\overset{(-)}{\nu}_e \to \overset{(-)}{\nu}_e$

IceCube effect in agreement with
Collin, Arguelles, Conrad, Shaevitz, PRL 117 (2016) 221801

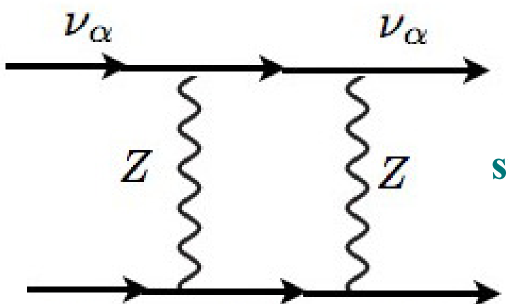
Equations of motion



asymmetric term

$\propto (\varrho - \overline{\varrho}) \leftrightarrow L$

usually neglected



symmetric term

$\propto (\varrho + \overline{\varrho})$

refractive ν−ν term

self-interactions of ν with the ν background:

off-diagonal potentials ➠ non-linear EoM

Vacuum term
with M neutrino mass matrix
U M^2U†

$$\Omega = \frac{\mathsf{M}^2}{2p} + \sqrt{2}\,G_{\mathrm{F}}\left[-\frac{8p}{3}\left(\frac{\mathsf{E}_\ell}{M_{\mathrm{W}}^2}+\frac{\mathsf{E}_\nu}{M_{\mathrm{Z}}^2}\right)\right] + \sqrt{2}\,G_{\mathrm{X}}\left[-\frac{8p\mathsf{E}_{\mathsf{s}}}{3M_{\mathrm{X}}^2}\right]$$

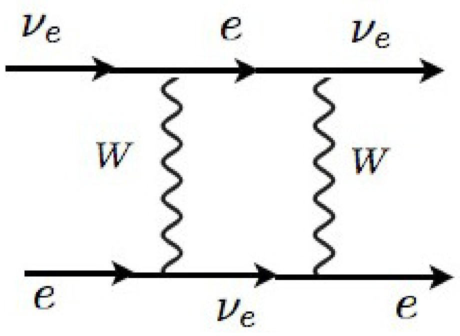
MSW effect with background
medium *(refractive effect)*

charged lepton asymmetry subleading ($O(10^{-9})$) ➜

➜ 2th order term: “symmetric” matter effect

sum of e$^-$ - e$^+$ energy densities ε

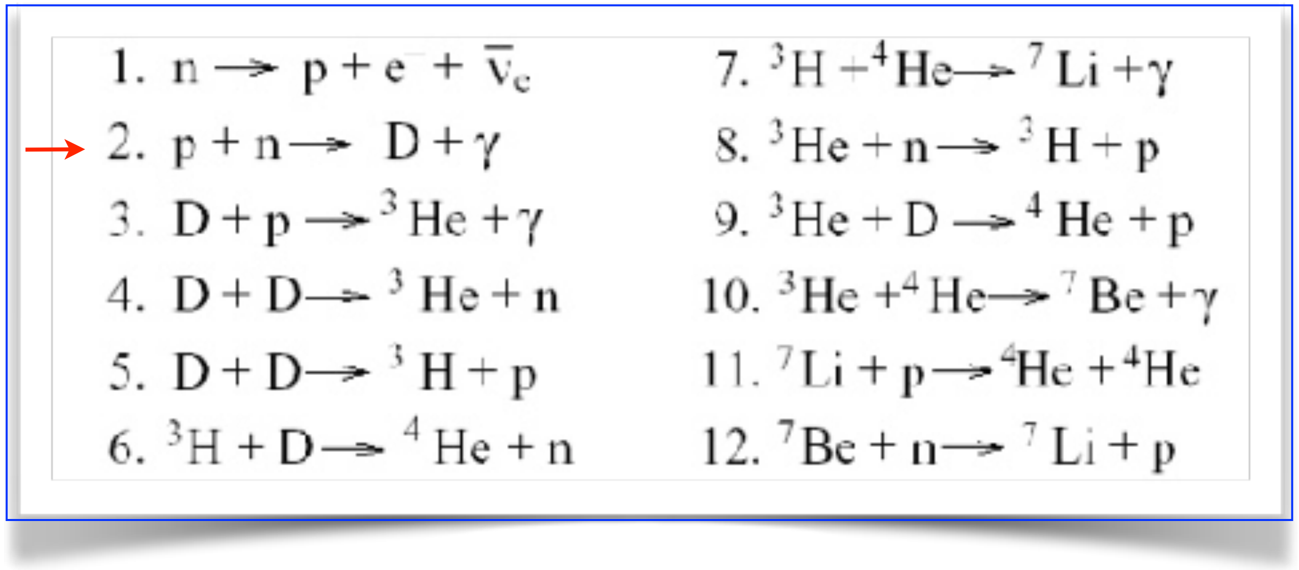
$$\mathsf{E}_\ell \equiv \mathrm{diag}(\varepsilon_e, 0, 0, 0)$$



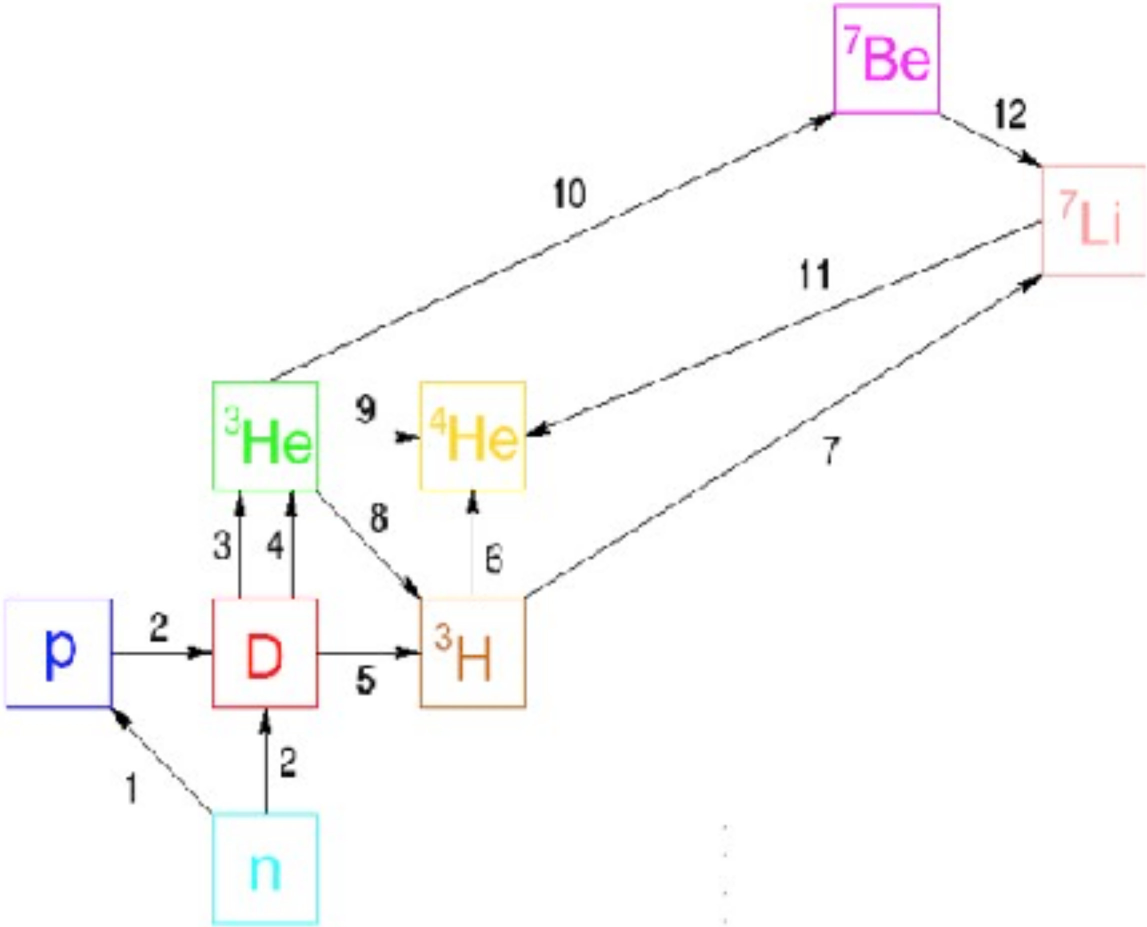
Big Bang Nucleosynthesis

✱ 0.1-0.01 MeV

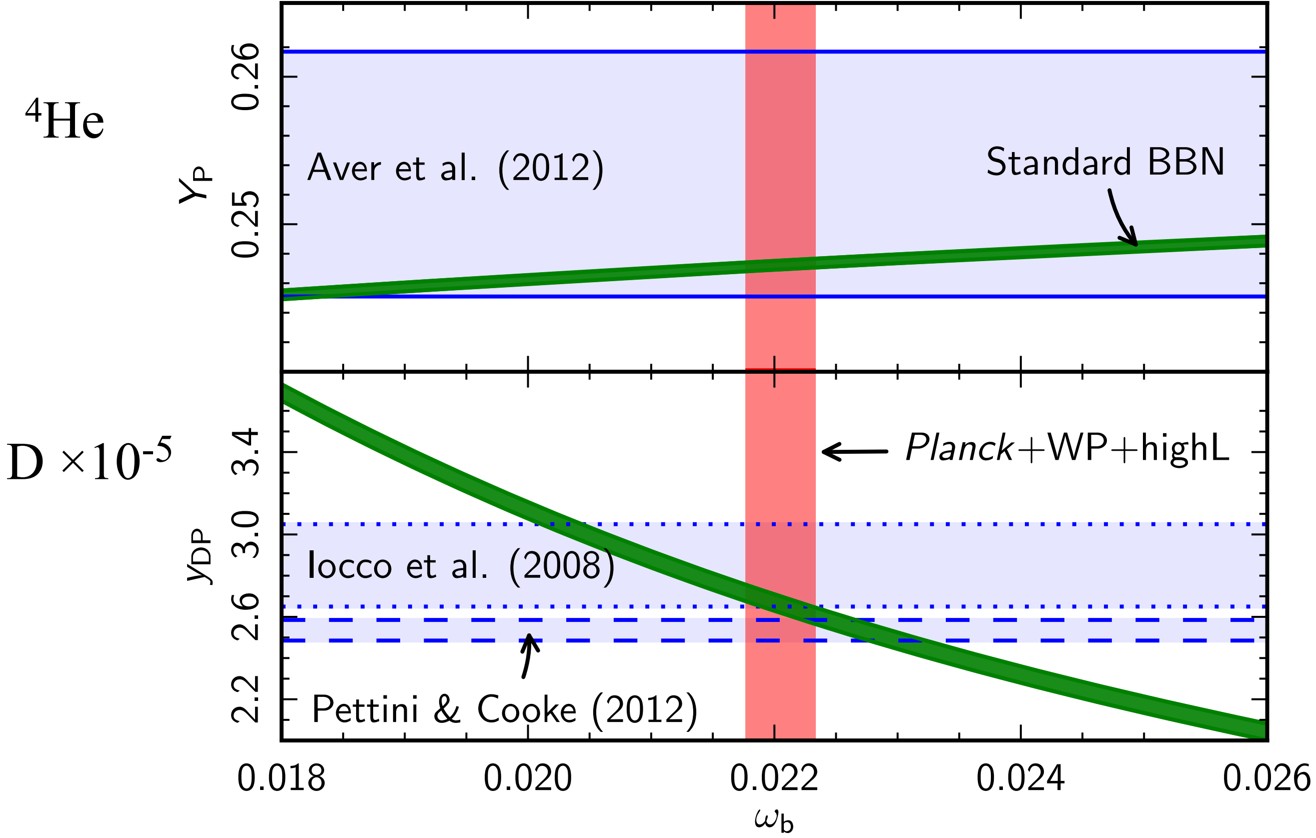
Formation of light nuclei starting from D



1. $n \rightarrow p + e^- + \bar{\nu}_e$
2. → $p + n \rightarrow D + \gamma$
3. $D + p \rightarrow {}^3He + \gamma$
4. $D + D \rightarrow {}^3He + n$
5. $D + D \rightarrow {}^3H + p$
6. ${}^3H + D \rightarrow {}^4He + n$
7. ${}^3H + {}^4He \rightarrow {}^7Li + \gamma$
8. ${}^3He + n \rightarrow {}^3H + p$
9. ${}^3He + D \rightarrow {}^4He + p$
10. ${}^3He + {}^4He \rightarrow {}^7Be + \gamma$
11. ${}^7Li + p \rightarrow {}^4He + {}^4He$
12. ${}^7Be + n \rightarrow {}^7Li + p$



Planck XVI, 2013



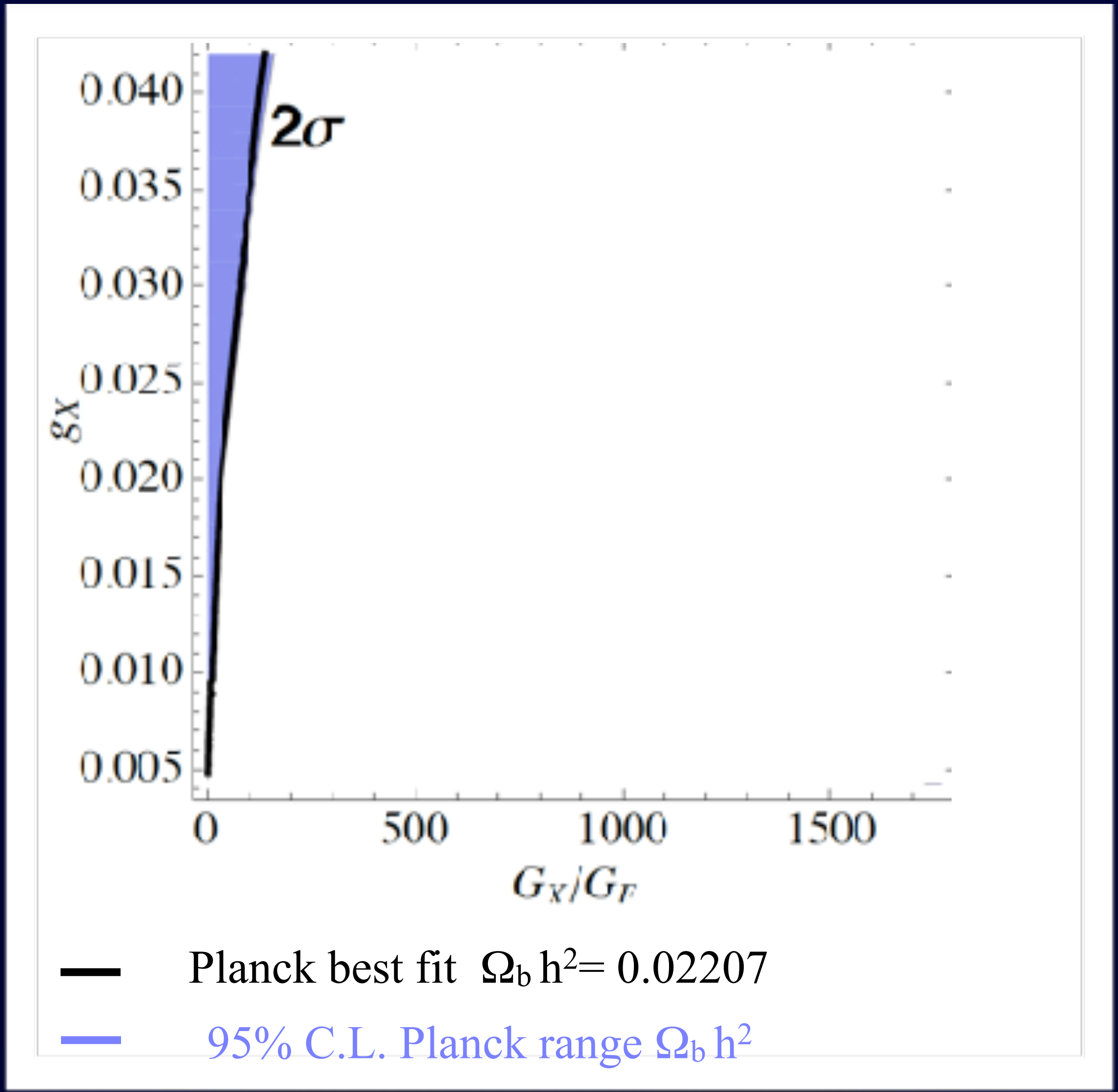
Prediction for ^{4}He and D in a **standard** BBN obtained by Planck collaboration using `PArthENoPE`

Blue regions: primordial yields from measurements performed in different astrophysical environments

$\omega_b = 0.02207 \pm 0.00027$

BBN constrains

^{4}He yield



Experimental reference value: Y_p = 0.2551+- 0.0022

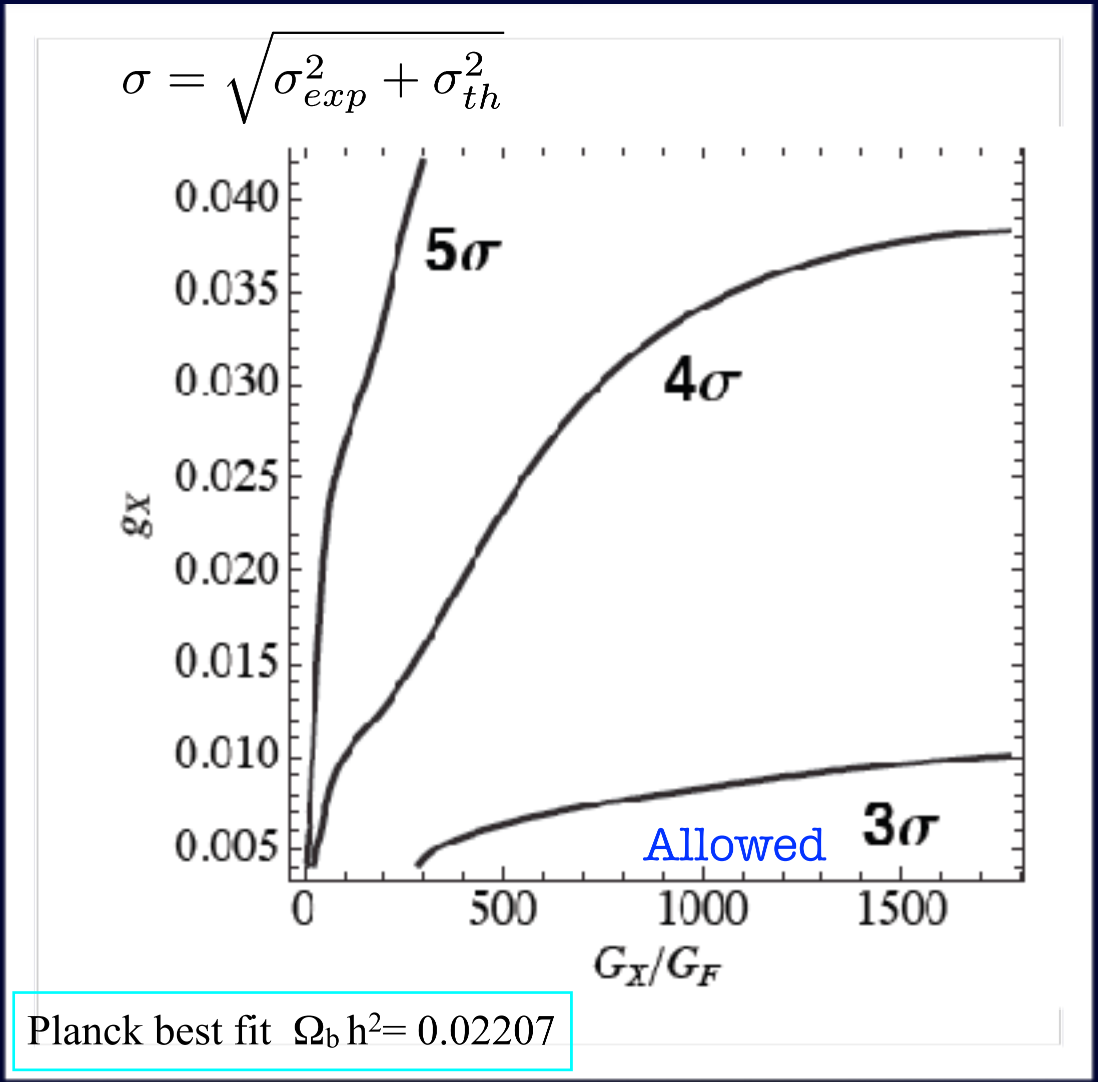
Saviano, Pisanti, Mangano, Mirizzi 2014, ArXiv: *1409.1680*

PArthENoPE code
Pisanti et al, 2012

D yield

Experimental reference value: $^2\mathrm{H/H} = \underbrace{(2.53 \pm 0.04)}_{\sigma_{exp}} \times 10^{-5}$

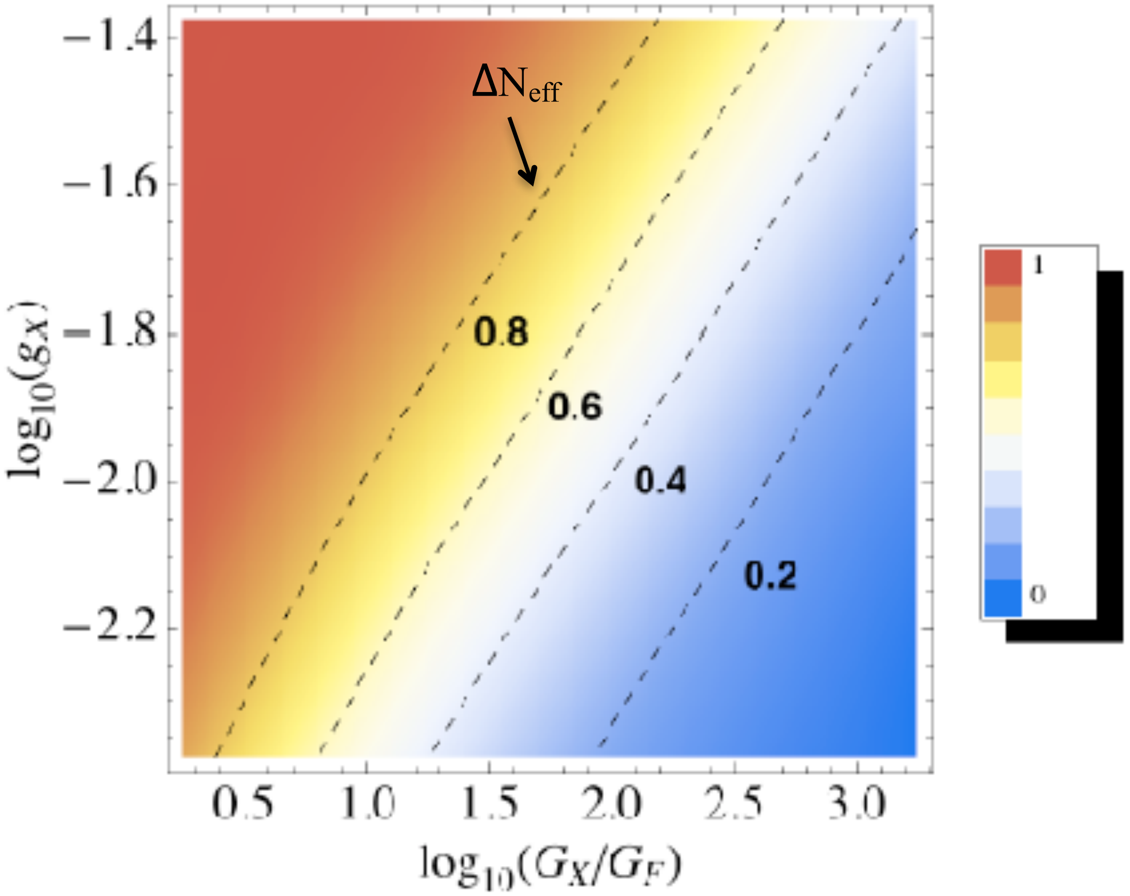
Uncertainty on the reaction $d(p, \gamma)^3$He ➜ σ_{th}= 0.062 X10^{-5}

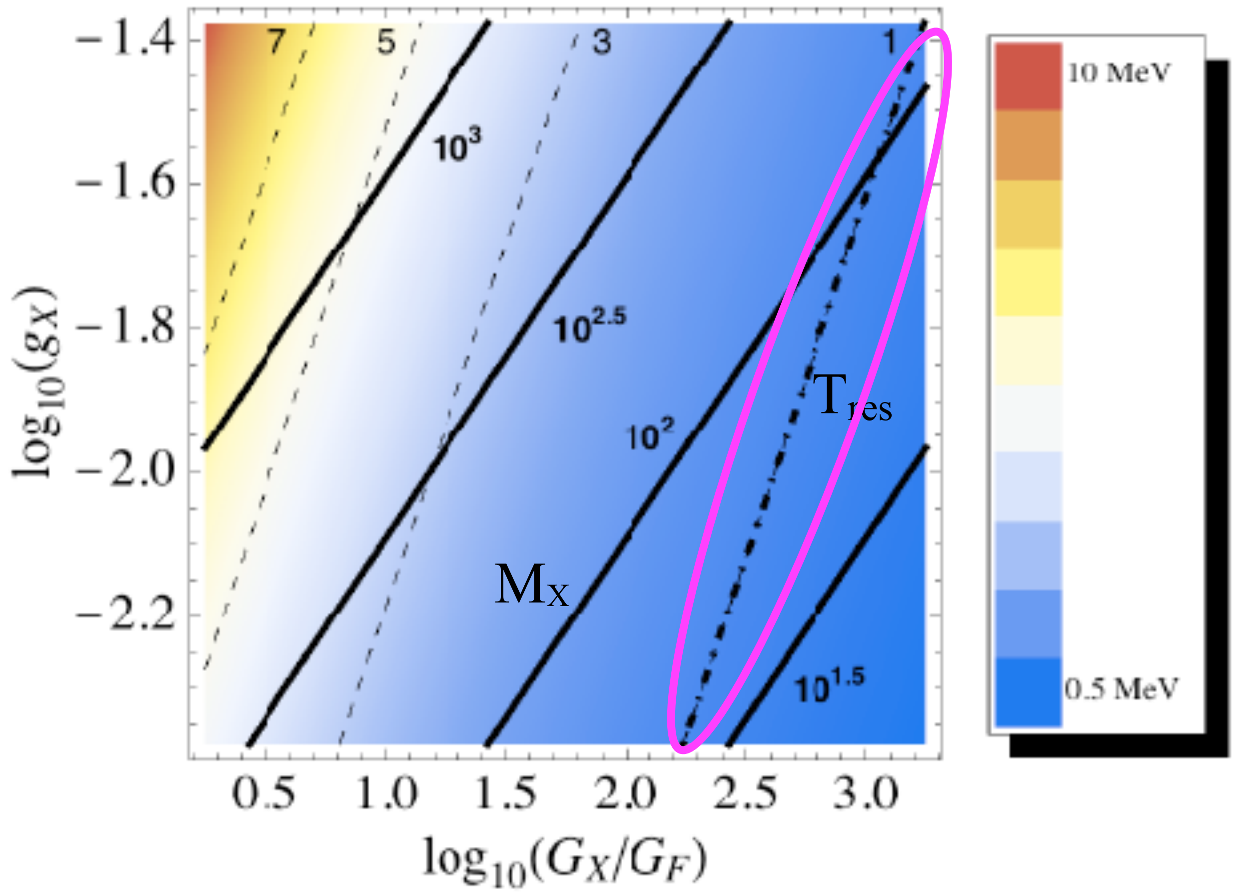


Most of the parameter space excluded at 3σ $M_X \geq 40$ MeV

Secret interactions and BBN

Asymptotic values of $\Delta N_{\rm eff}$ versus G_X and g_X





Resonance temperature in the plane (G_X, g_X)

Dashed curves: constant T_{res} contours

Solid curves: constant M_X contours

Mass constraints for sterile νSI (vector)

Constraint on lower M_X ↔ very large G_X ($> 10^5\, G_F$)

Very strong secret collisional term leads to a quick flavor equilibrium

Stodolsky, 1987

$$\Gamma_t \simeq \langle P(\nu_\alpha \to \nu_s) \rangle_{\rm coll} \Gamma_X$$

$$\Gamma_X \simeq G_X^2 T_\nu^5 \frac{p}{\langle p \rangle} \frac{n_s}{n_a}$$

$$\langle P(\nu_\alpha \to \nu_s) \rangle_{\rm coll} \simeq \frac{1}{2} \sin^2 2\theta_{\alpha s}$$

$(\rho_{ee}, \rho_{\mu\mu}, \rho_{\tau\tau}, \rho_{ss})_{\rm initial} \longrightarrow (\rho_{ee}, \rho_{\mu\mu}, \rho_{\tau\tau}, \rho_{ss})_{\rm final}$

$(1, \quad 1, \quad 1, \quad 0) \qquad (3/4, 3/4, 3/4, 3/4)$

↓

The flavour evolution leads to a large population of ν_s, in conflict with the cosmological mass bound

$$m_{\rm st}^{\rm eff} = \rho_{ss} \sqrt{\Delta m_{\rm st}^2} = \frac{3}{4} \sqrt{\Delta m_{\rm st}^2}$$

lower value in the 2σ range from anomalies gives $m^{\rm eff}_s \sim 0.8$ eV

in tension with the CMB and LSS bounds on sterile mass (< 0.5 eV)

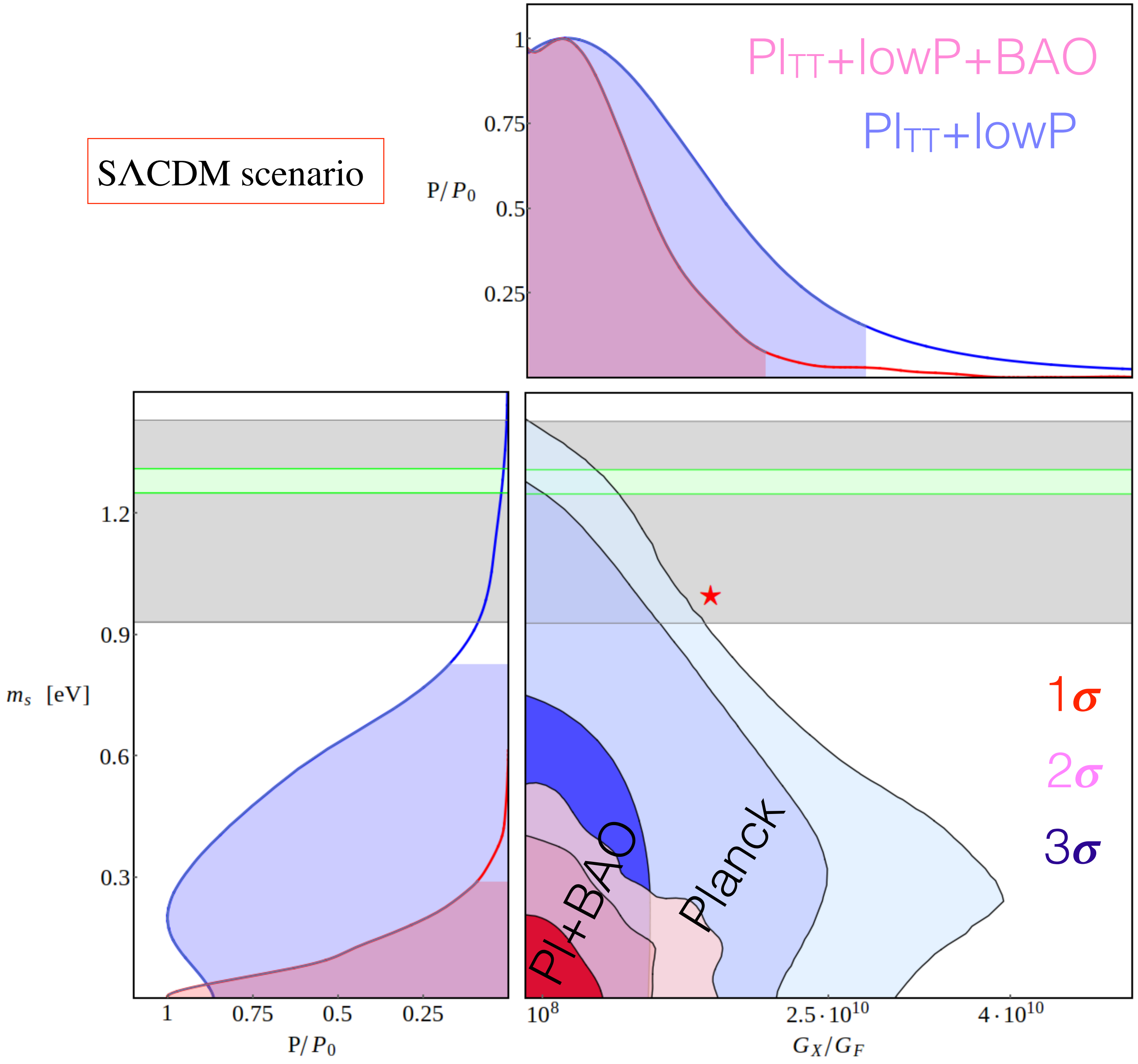
Planck XVI, 2015, Hamann and Hasenkamp, 2013,Giusarma et al 2016…

Secret interaction scenario: disfavored $M_X > 0.1$ MeV (⇔ ~ $10^9\, G_F$)

Mirizzi,Mangano, Pisanti Saviano, 2014

CMB constraints for sterile νSI

SΛCDM scenario



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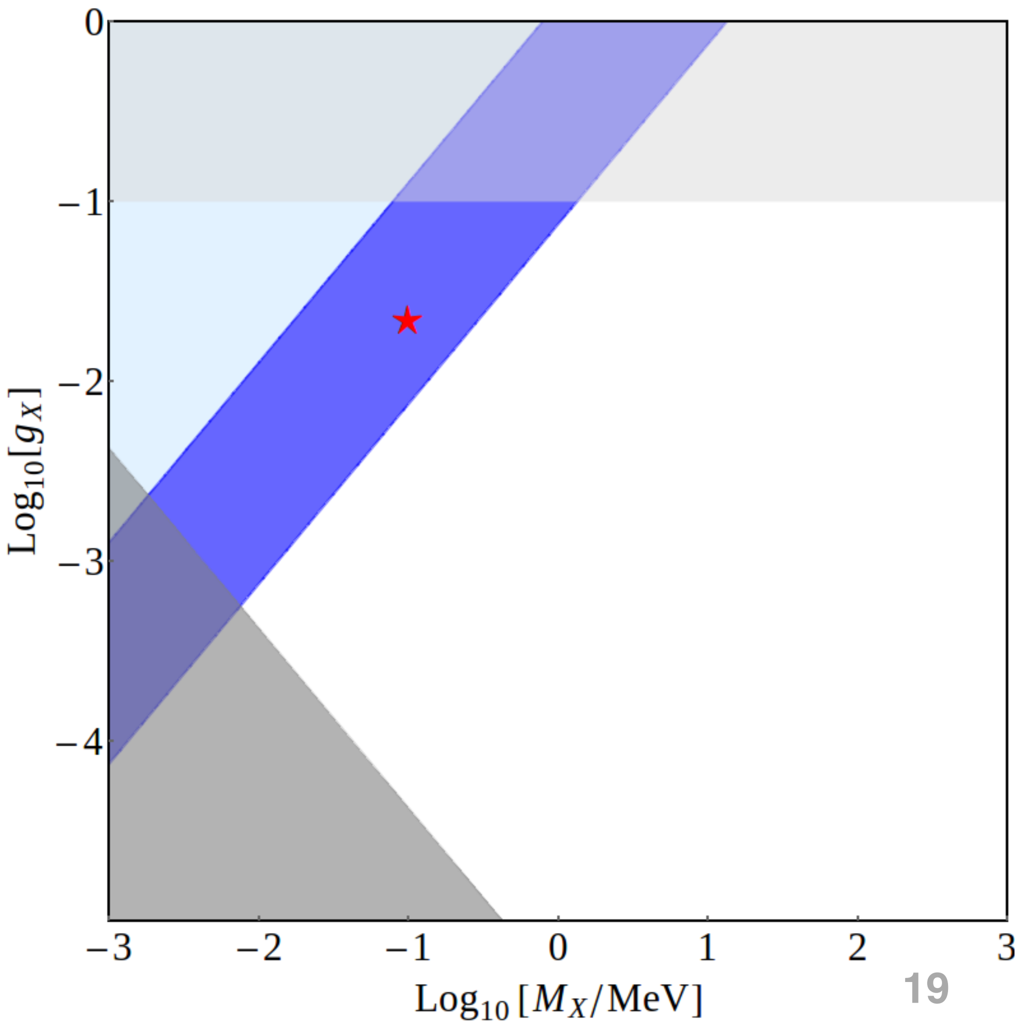


Forastieri, Lattanzi, Mangano, Mirizzi, Natoli, Saviano, 2017

Secret interactions and cosmological perturbations

$$\hat{L}[\delta f] = \hat{C}[\delta f]$$

$$\delta f \equiv f_0 \Psi$$

$\hat{C}[\delta f] \simeq \delta f/\tau_c,\ \tau_c = \langle an\sigma v\rangle^{-1}$ so-called relaxation time approximation —> $\Gamma = \tau_c^{-1} \sim a\, G_X^2 T_\nu^5$

$$\frac{\partial \Psi_i}{\partial \tau} + i\frac{q(\vec{k}\cdot\hat{n})}{\epsilon}\Psi_i + \frac{d\ln f_0}{d\ln q}\left[\dot{\phi} - i\frac{q(\vec{k}\cdot\hat{n})}{\epsilon}\psi\right] = -\Gamma_{ij}\Psi_j$$

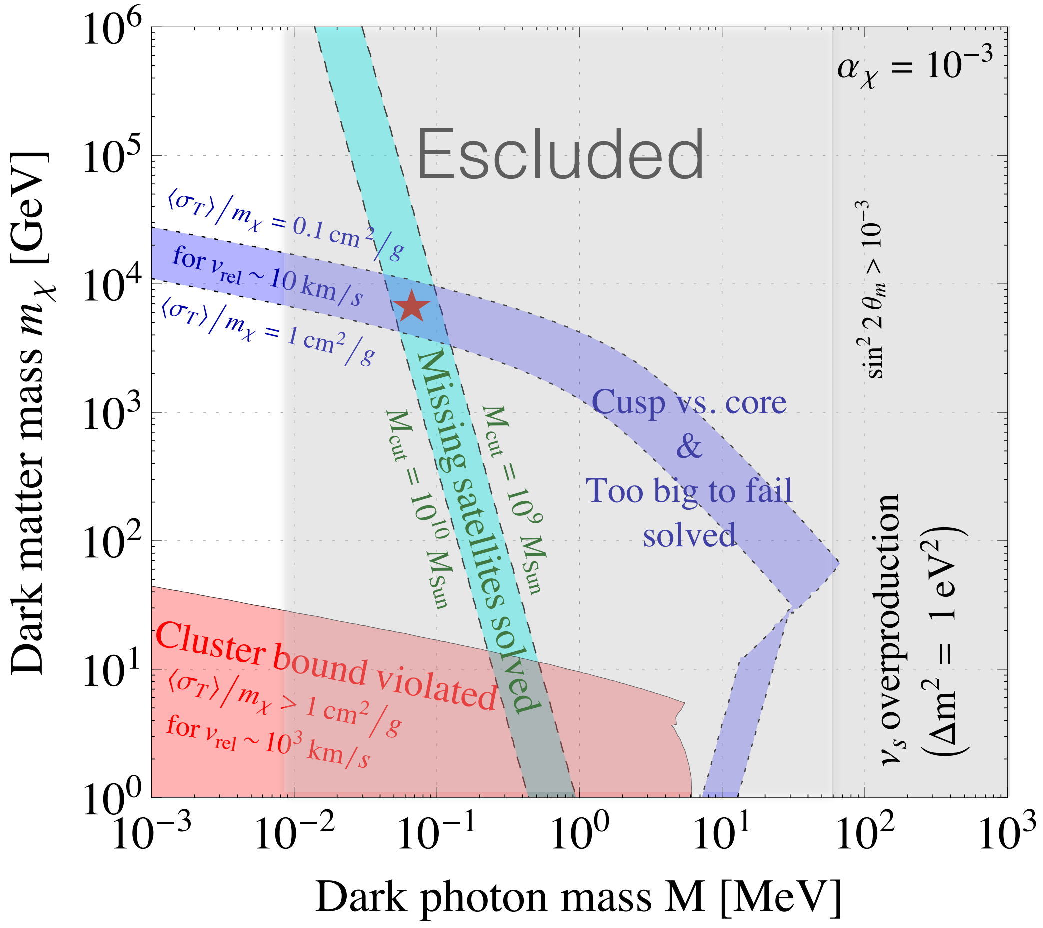
$$\nu_s \simeq \sin\theta_s \nu_1 + \cos\theta_s \nu_4$$

$$\Gamma_{ij} = \begin{bmatrix} \sin^2\theta_s & 0 & 0 & \sin\theta_s\ \cos\theta_s \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ \sin\theta_s\ \cos\theta_s & 0 & 0 & \cos^2\theta_s \end{bmatrix} (3/2)(\zeta(3)/\pi^2)\, aG_X^2\, T_\nu^5$$

Connection with the DM

If a new force exists, it is plausible that not only (sterile) neutrinos, but also DM particles couple to it

"***neutrinophilic DM***" $\mathcal{L}_{\rm int} \supset -g_\chi \bar{\chi} \not{V} \chi - g_\nu \bar{\nu} \not{V} \nu$

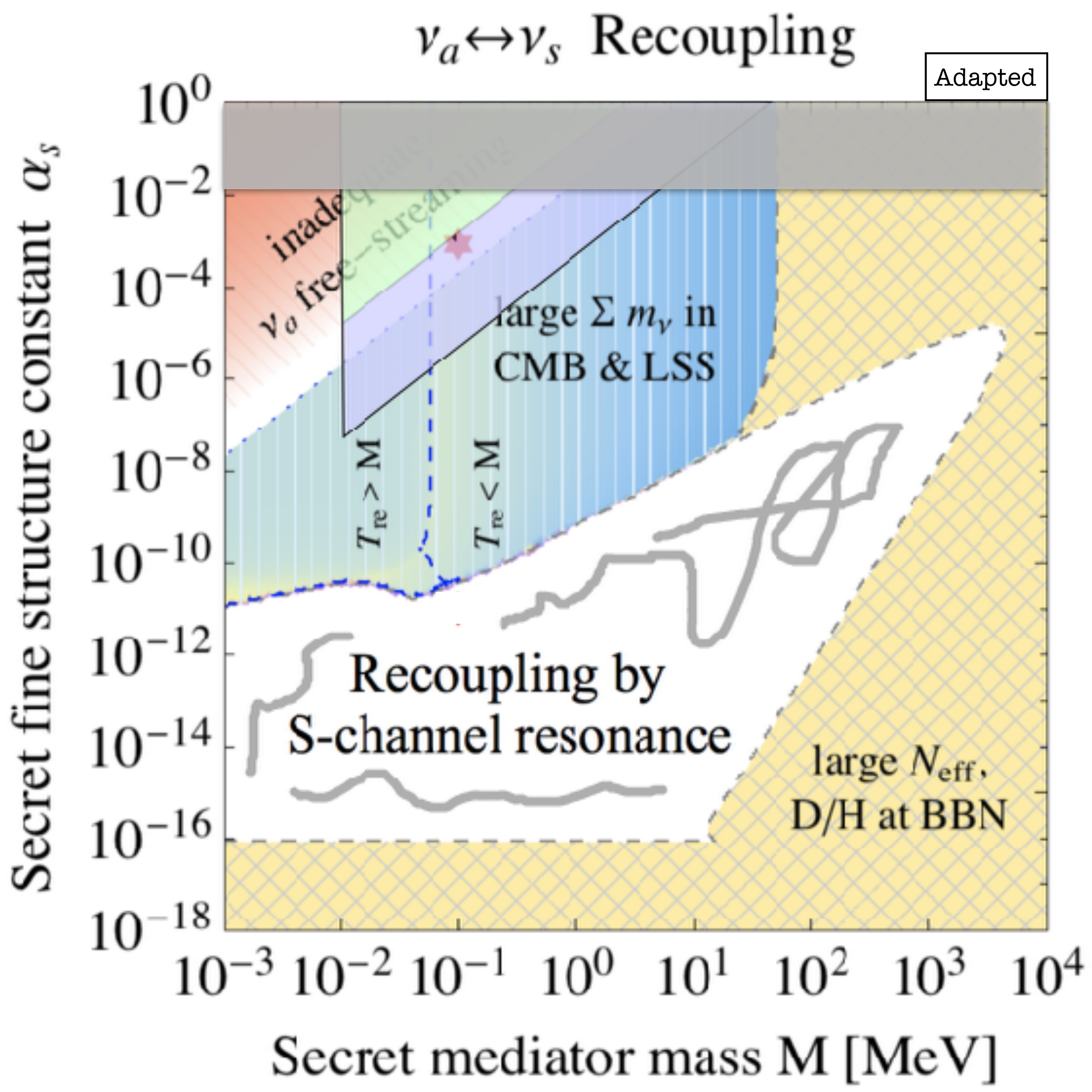


This scenario may solve all of the small-scale structure issues mentioned above. Indeed, the efficient scattering of DM would lead to late kinetic decoupling, delaying the formation of the smallest protohalos.

(Barions?)

van den Aarssen, Bringmann and Pfrommer 2012, Dasgupta and Kopp 2013, Bringmann, Hasenkamp, Kersten 2014, Cherry, Friedland, Shoemaker 2014, Archidiacono et al. 2015….

Summary Plot



Chu, Dasgupta and Kopp 2015

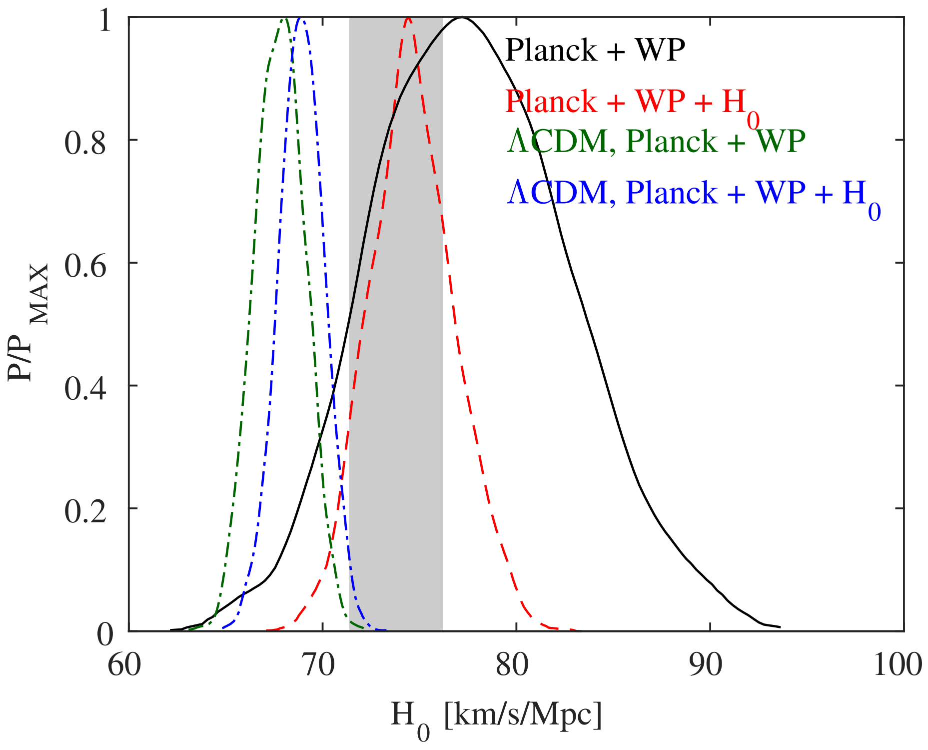
Similar plot obtained by
Cherry, Friedland, Shoemaker 2016
using present data and future
sensitivity of IceCube

Possible hint (very dependent on the set of data used): in pseudoscalar model, $10^{-6} \lesssim g_s \lesssim 10^{-5}$ would reconcile eV sterile ν , H_0, ν SI. Also link to the DM small scale problem.

Archidiacono et al. 2015

Pseudoscalar model

Sterile neutrino is coupled to a new light pseudoscalar with mass $m_\phi \ll 1\mathrm{eV}$ with $\mathcal{L} \sim g_s \phi \bar{\nu} \gamma_5 \nu$



Possible hint:

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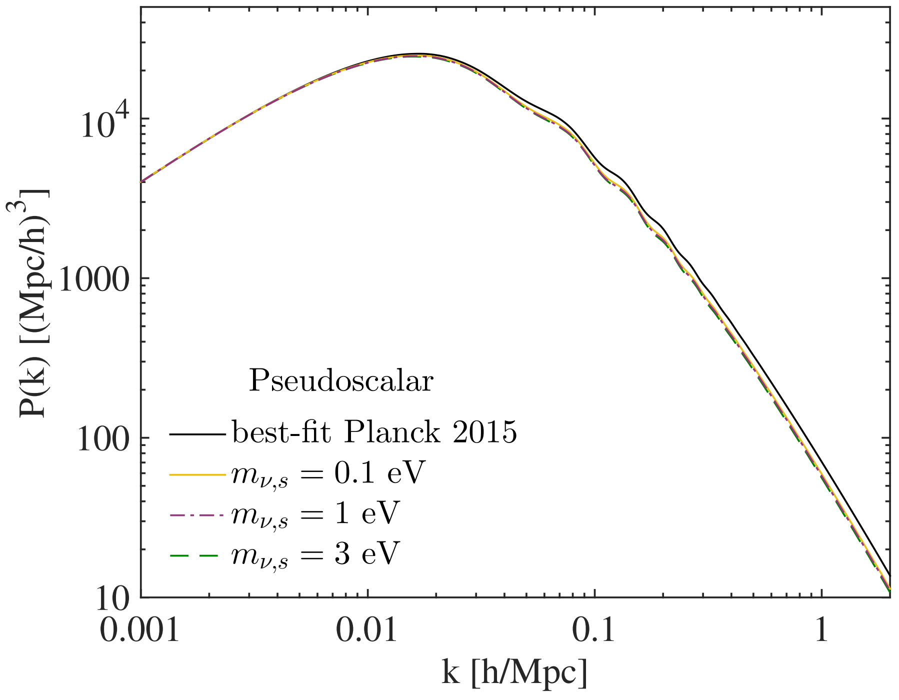
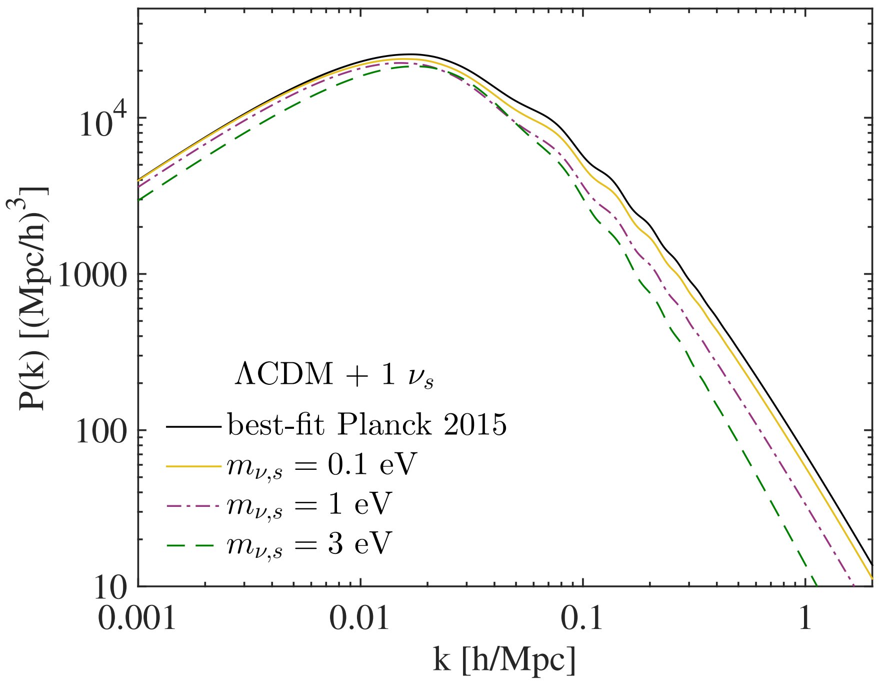
Also connection to the DM small scale problem.

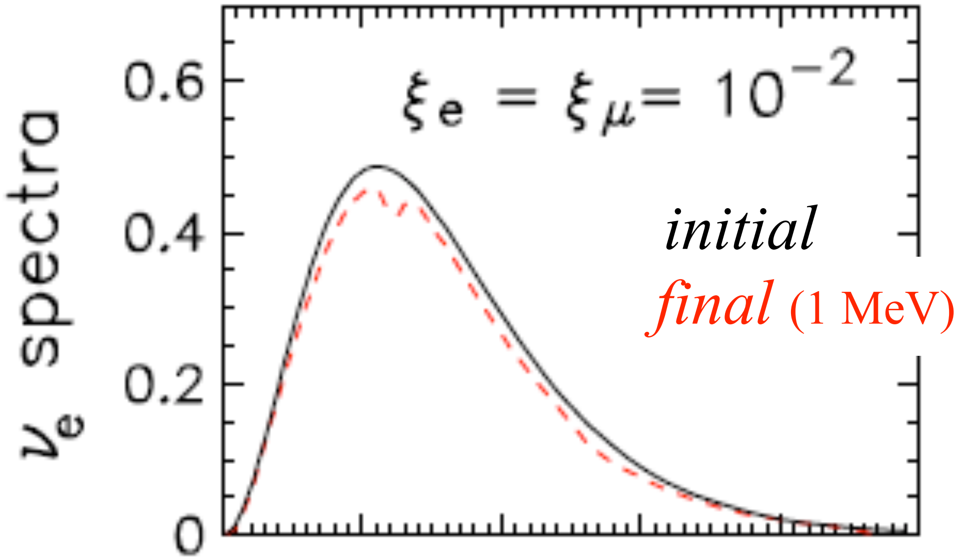


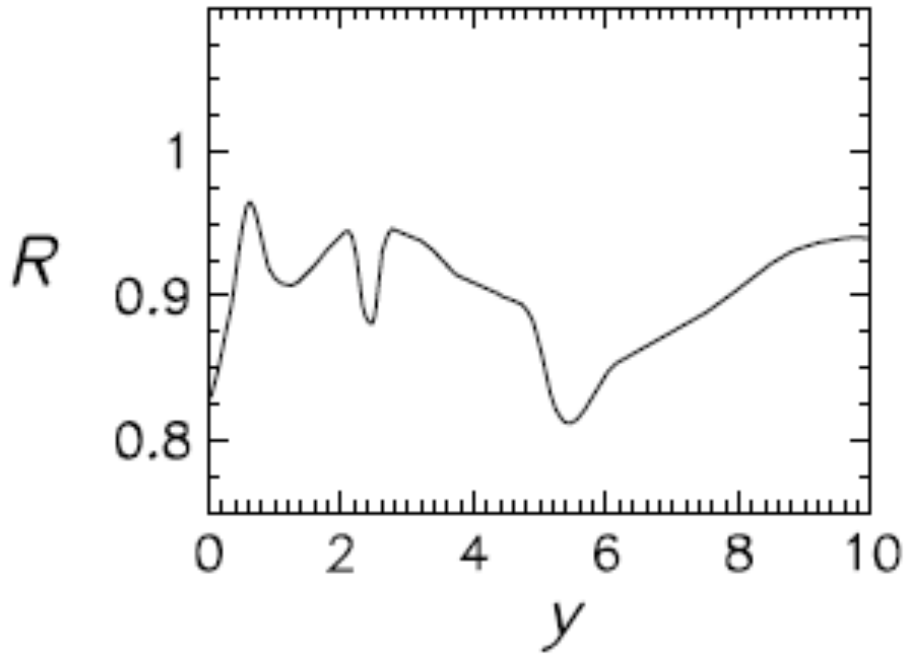


Archidiacono et al. 2015,

Archidiacono et al. 2016

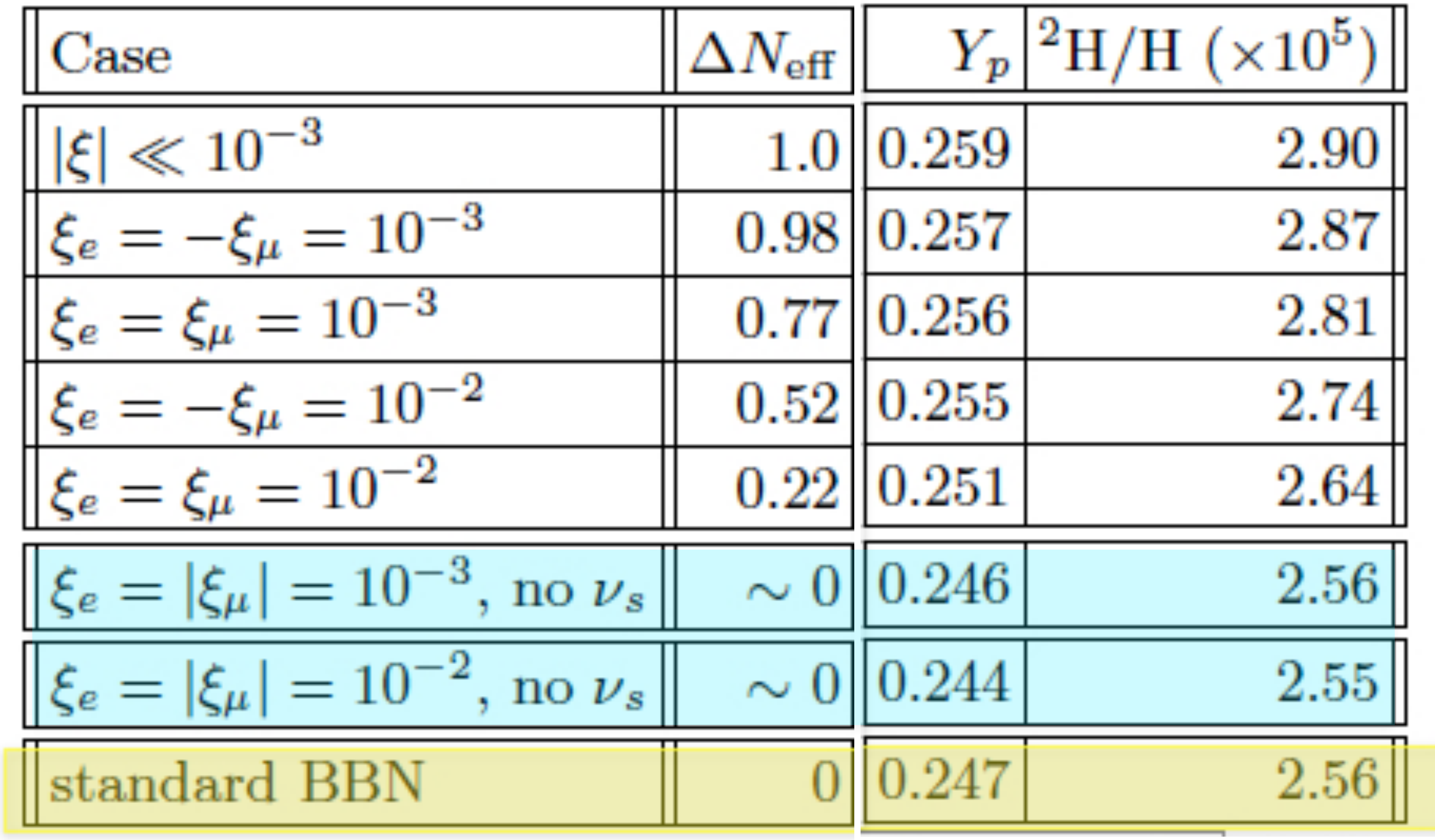
Consequences on BBN





$$L_\alpha \simeq 0.68\,\xi_\alpha \left(\frac{T_\nu}{T_\gamma}\right)^3$$

ν_e spectra distorted → implications on BBN



Case	$\Delta N_{\rm eff}$	Y_p	^{2}H/H ($\times 10^5$)
$\lvert\xi\rvert \ll 10^{-3}$	1.0	0.259	2.90
$\xi_e = -\xi_\mu = 10^{-3}$	0.98	0.257	2.87
$\xi_e = \xi_\mu = 10^{-3}$	0.77	0.256	2.81
$\xi_e = -\xi_\mu = 10^{-2}$	0.52	0.255	2.74
$\xi_e = \xi_\mu = 10^{-2}$	0.22	0.251	2.64
$\xi_e = \lvert\xi_\mu\rvert = 10^{-3}$, no ν_s	~ 0	0.246	2.56
$\xi_e = \lvert\xi_\mu\rvert = 10^{-2}$, no ν_s	~ 0	0.244	2.55
standard BBN	0	0.247	2.56

$$Y_p = \frac{2(n/p)}{1 + n/p}$$

Helium mass fraction

Y_p ↑

H^2 ↑

Sterile production by neutrino asymmetry

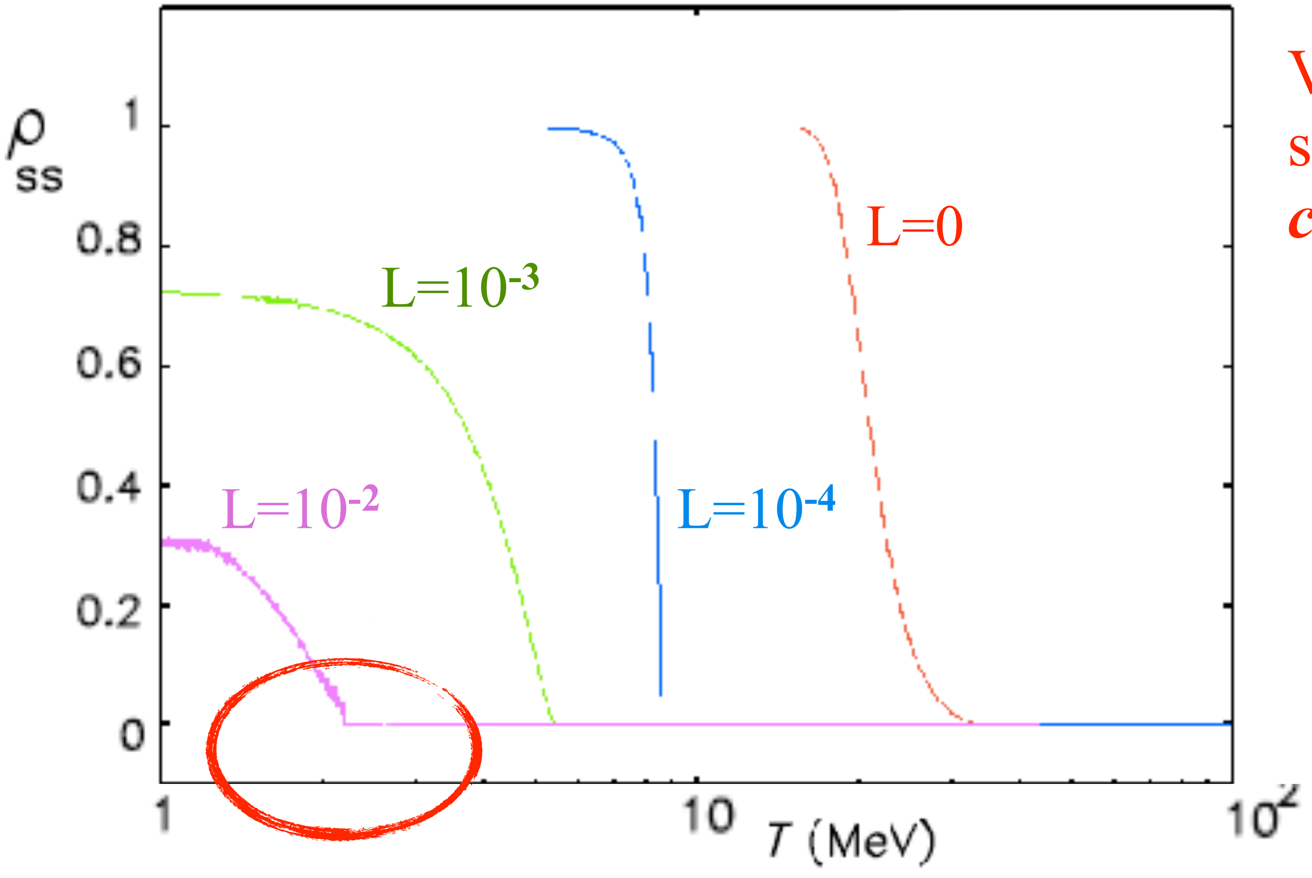
✓ ρ_{ss} and distortions of ν_e spectra as function of the ν ***asymmetry parameter***

→ evaluation of the cosmological consequences

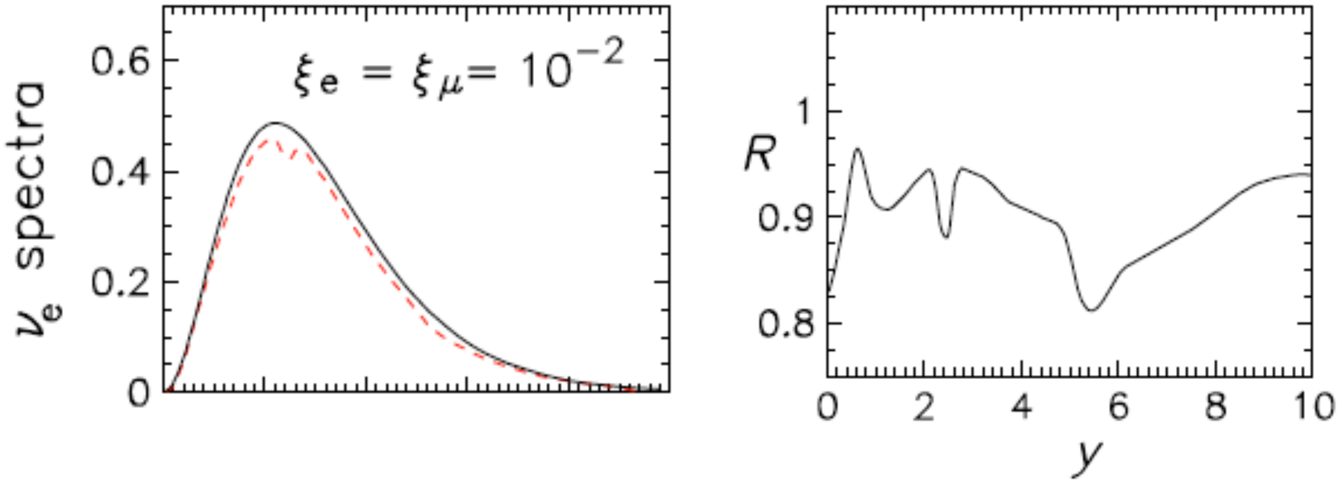
✗ Very challenging task, involving time consuming numerical calculations

→ few representative cases

$$\boxed{L_\alpha \simeq 0.68\,\xi_\alpha\left(\frac{T_\nu}{T_\gamma}\right)^3}$$



Very large asymmetries are necessary to suppress the sterile neutrino abundances leading to ***non trivial consequences on BBN***



conversions occur at **T ~ T$_\nu$** *decoupling*

⇒ *active not repopulated anymore by collisions* ($\rho_{ee} < 1$)