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eV sterile ν problem and cosmological bounds for secret interactions

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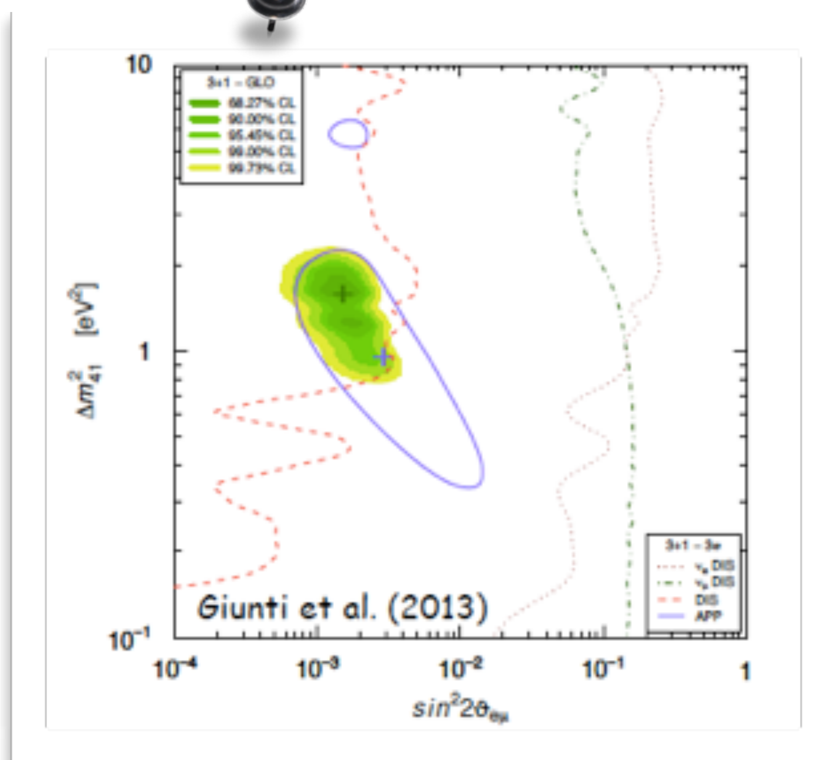
eV Sterile Neutrino

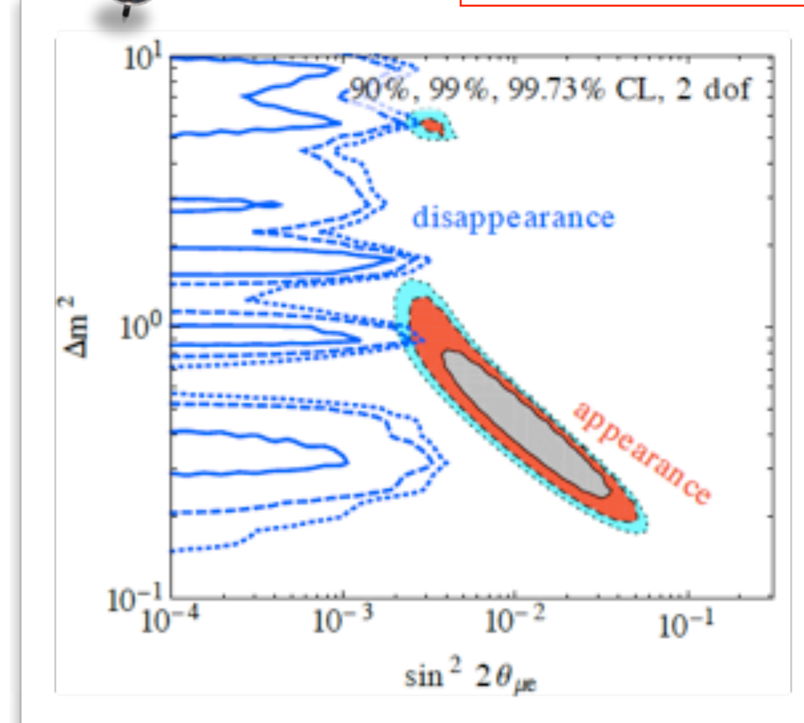
The investigation on Light Sterile Neutrinos has been stimulated by the presence of anomalous results from neutrino oscillation experiments

- **LNSD**
- **MiniBooNE**
- **Gallium**
- **Reactor**

see
White paper, Abazajian et al., 2012



J. Kopp et al, 2013



3+1, 3+2 schemes

...sometimes in tension among themselves...
appearance VS disappearance

...waiting new data (IceCube...)

eV

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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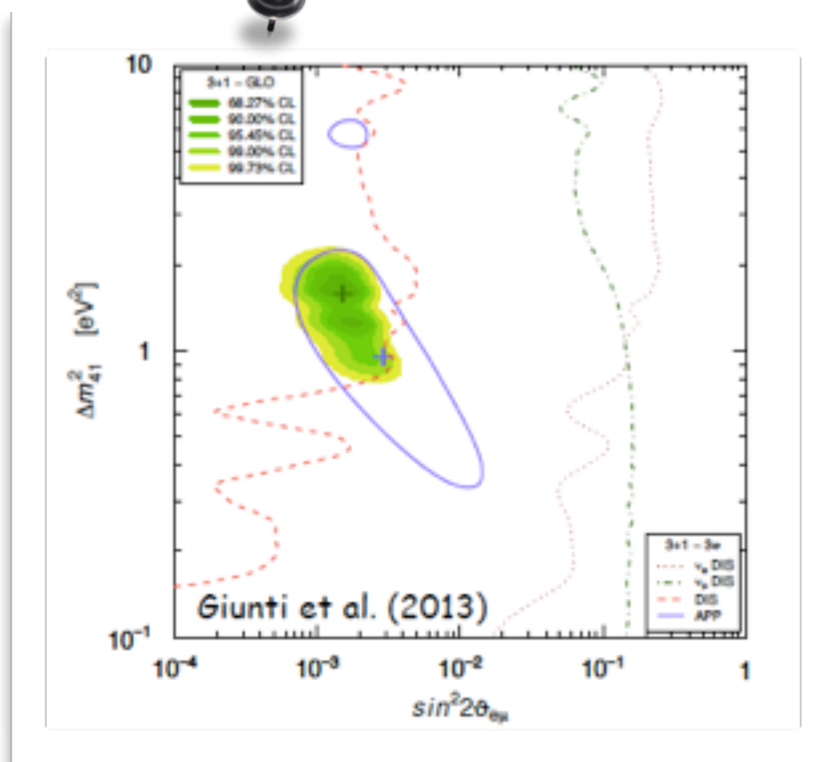

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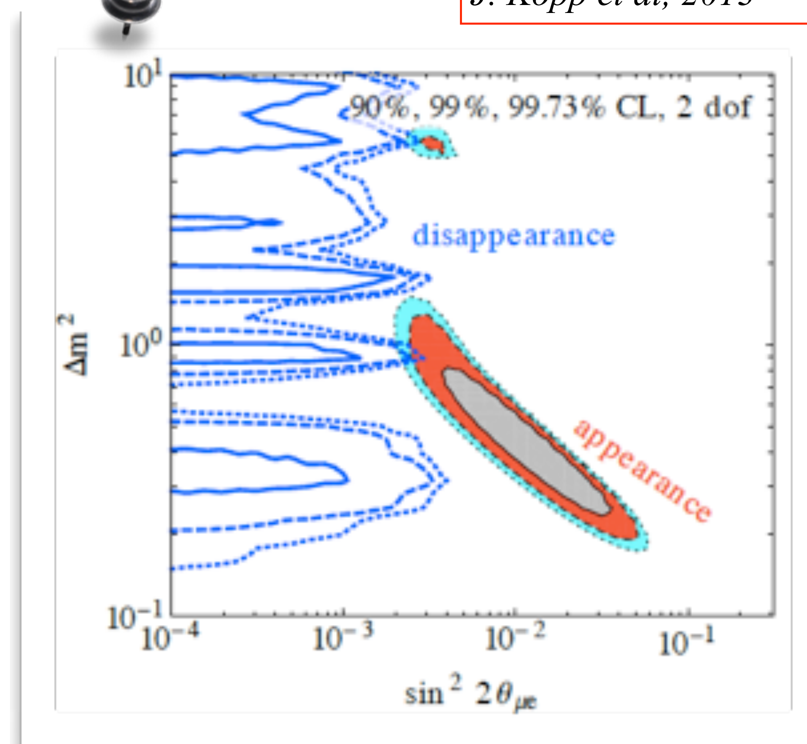

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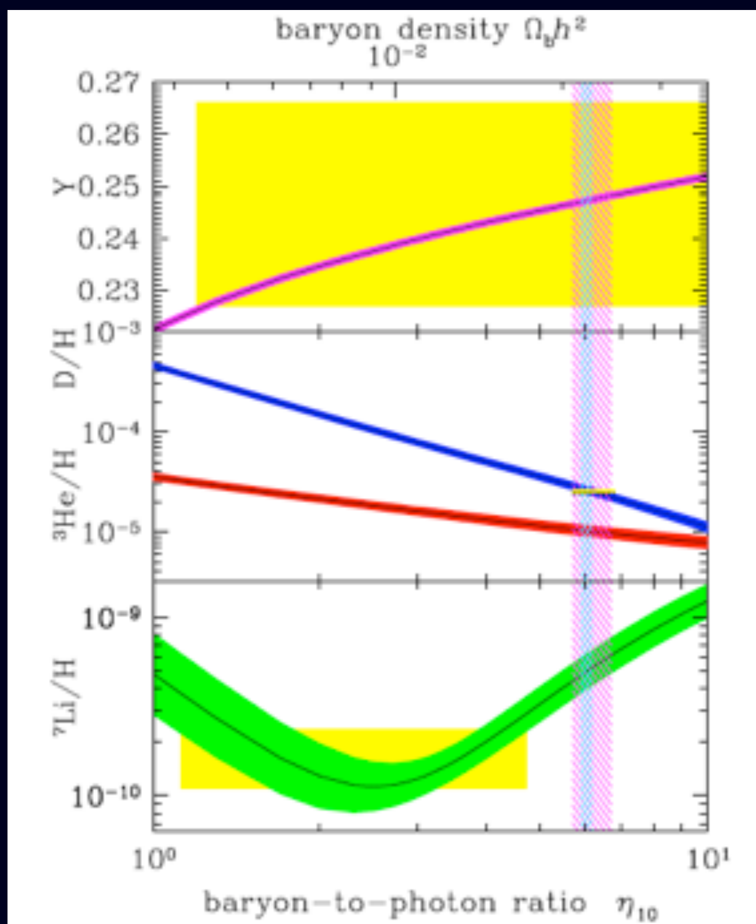
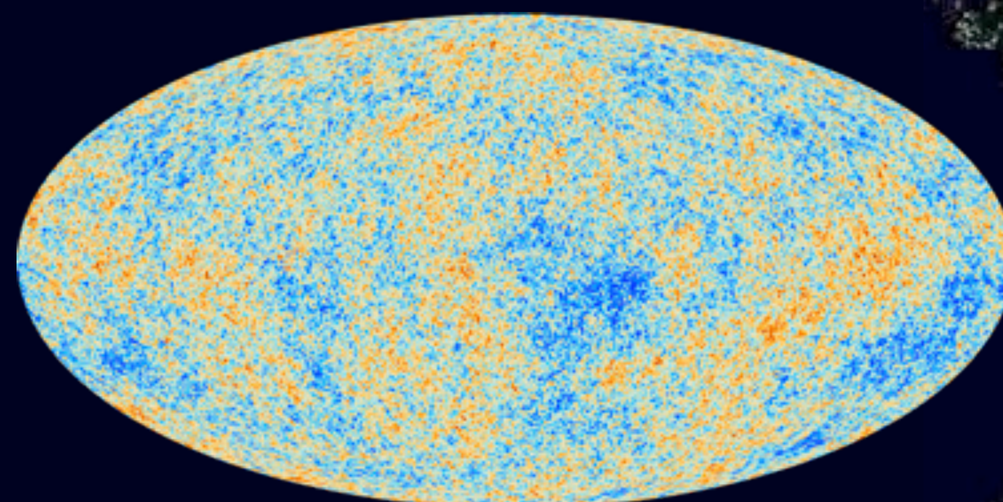
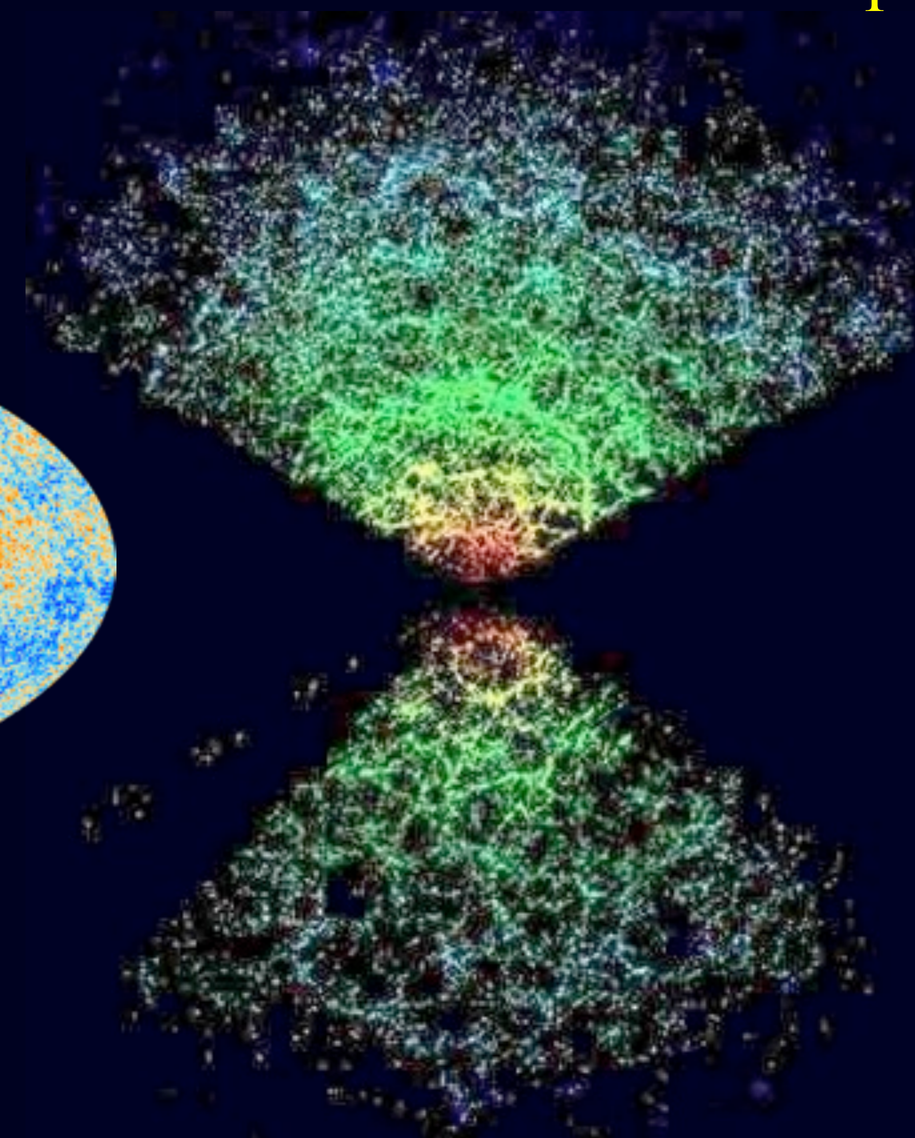
Are eV ν_s compatible with cosmology?

Cosmological observations

1 MeV — 1 eV — T







Sensitivity to N_{eff} and ν flavour

Sensitivity to N_{eff} and ν masses

Radiation Content in the Universe

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 $N_{\rm eff}$

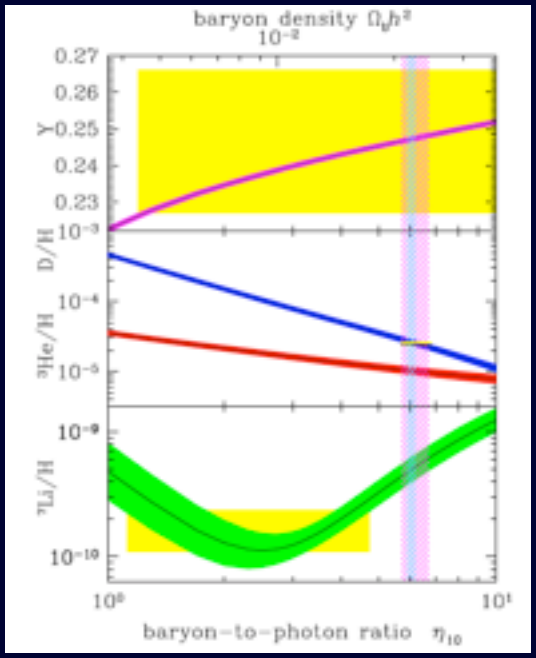
$$\varepsilon_\nu + \varepsilon_x = \frac{7}{8}\frac{\pi^2}{15}T_\nu^4 N_{\rm eff} = \frac{7}{8}\frac{\pi^2}{15}T_\nu^4 (N_{\rm eff}^{\rm SM} + \Delta N)$$

$N_{\rm eff}^{\rm SM} = 3.046$ *due to non-instantaneous neutrino decoupling* *Mangano et al. 2005*

(+ oscillations)

$\Delta N =$ 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...

Di Bari et al. 2013, Boehm et al. 2012, Conlon and Marsh, 201,3 Gelmini, Palomarez-Ruiz, Pascoli, 2004

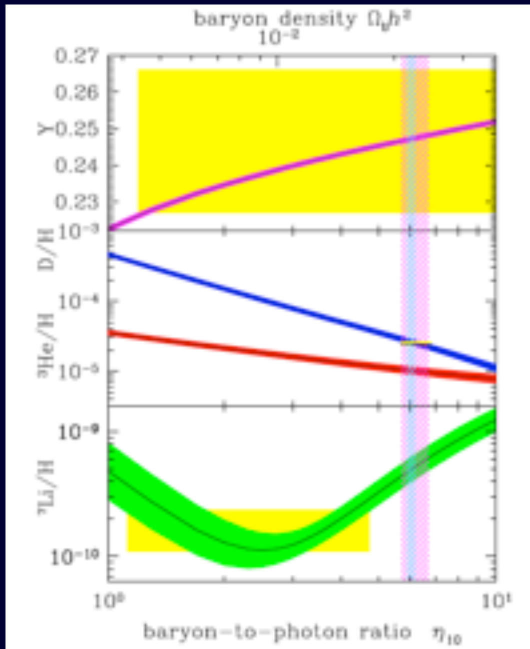


Impact on Big Bang Nucleosynthesis

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*

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



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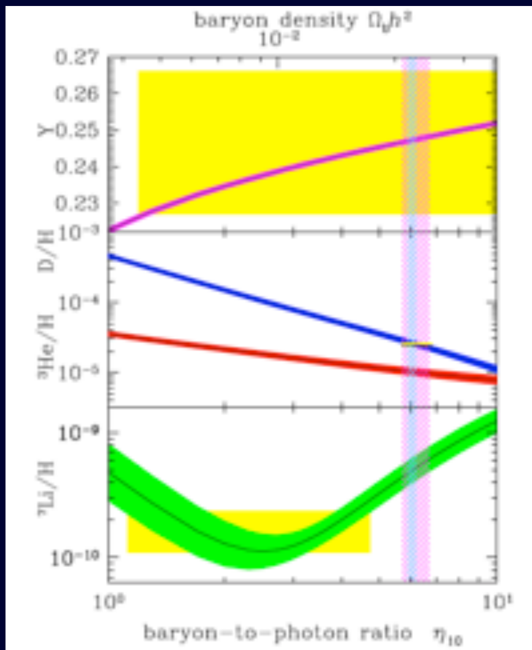
Sterile *ν* influence on BBN :



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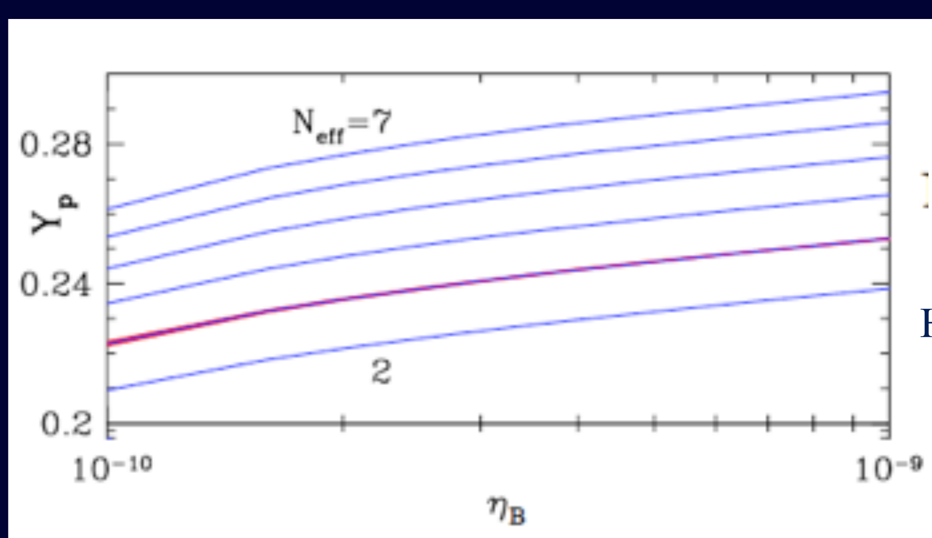
Sterile ν influence on BBN :

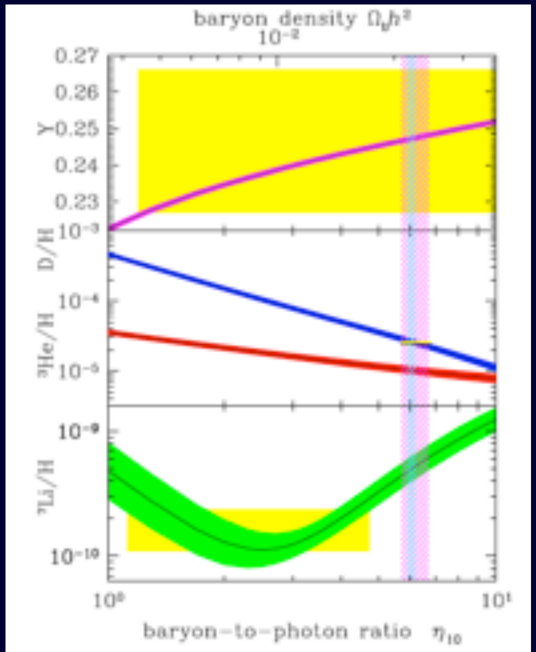
- contribution to the radiation energy density governing H before and during BBN

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



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

Helium mass fraction



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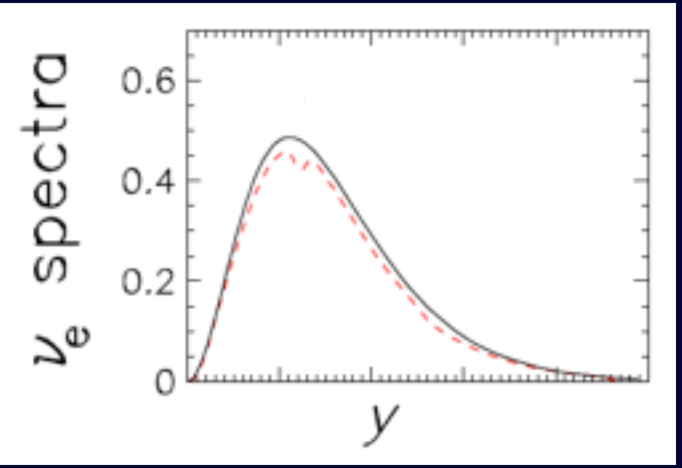
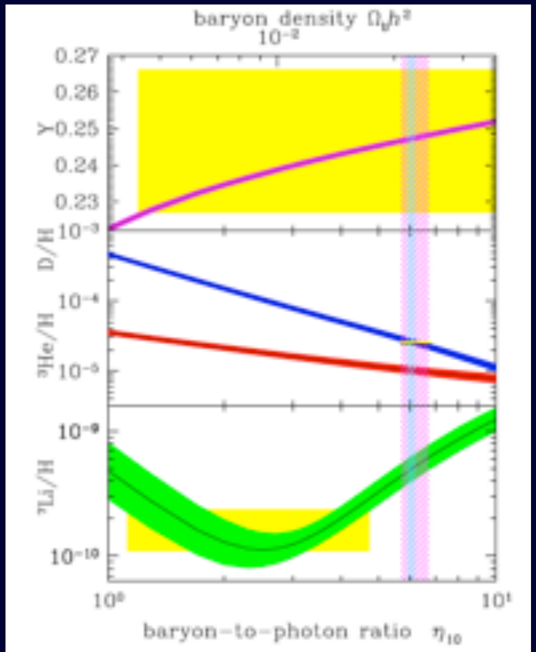
- oscillating with the active neutrinos, can distort the active spectra which are the basic input for BBN





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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

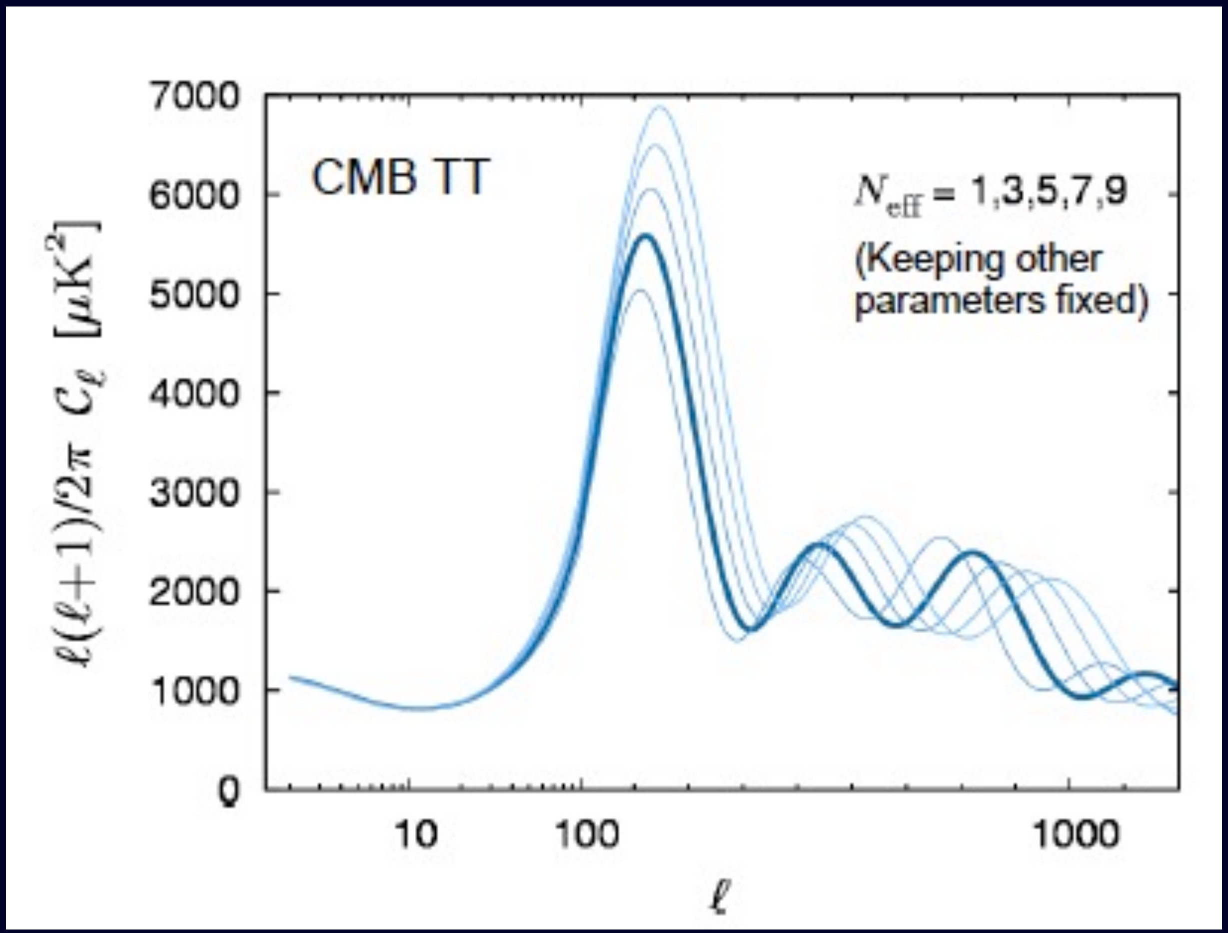
From new precise measure of D in damped Lyman-α system

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

Cooke, Pettini et al., 2013

Impact on CMB and LSS

If sterile neutrinos are still relativistic at the CMB epoch, they impact the CMB spectrum

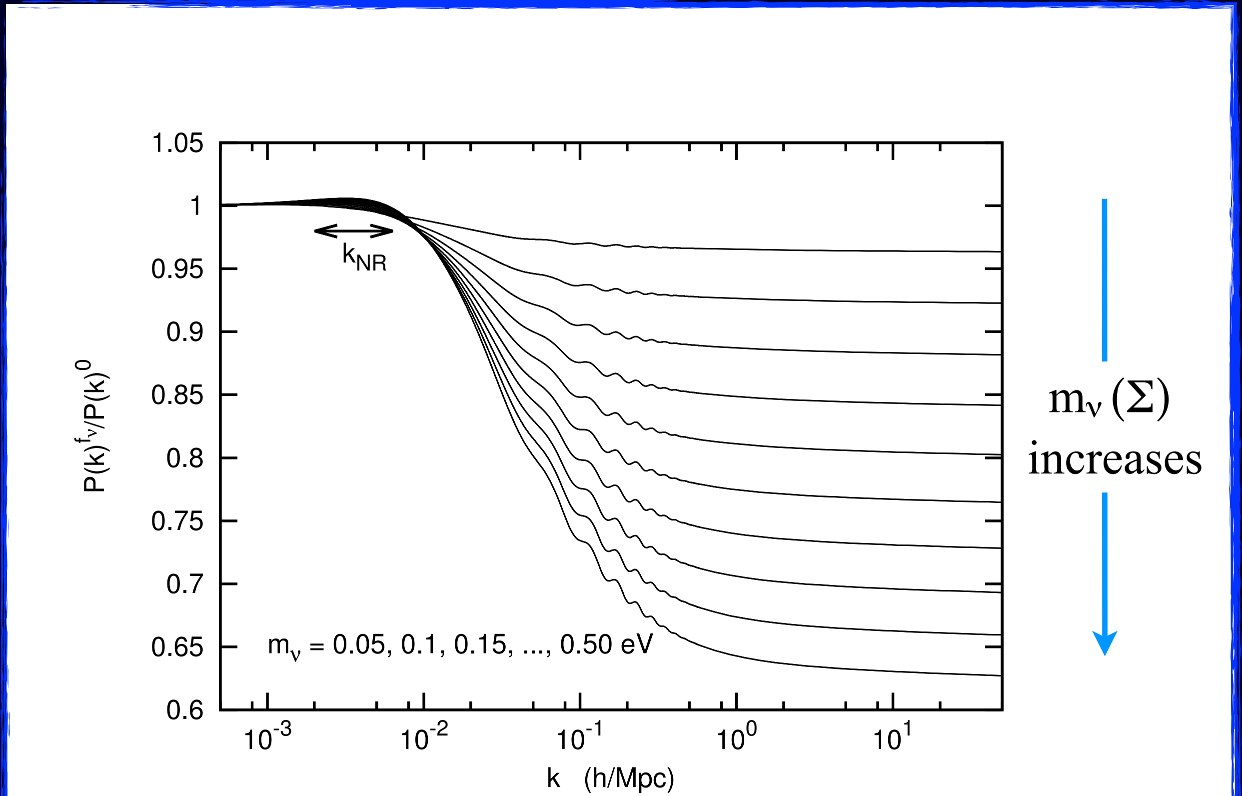


degeneracy among the parameters → necessary to combine with other cosmological probes

See Archidiacono's and Wong talks

The small-scale matter power spectrum P(k > k$_{nr}$) 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_{eff} and $m^{eff}_{\nu s}$

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

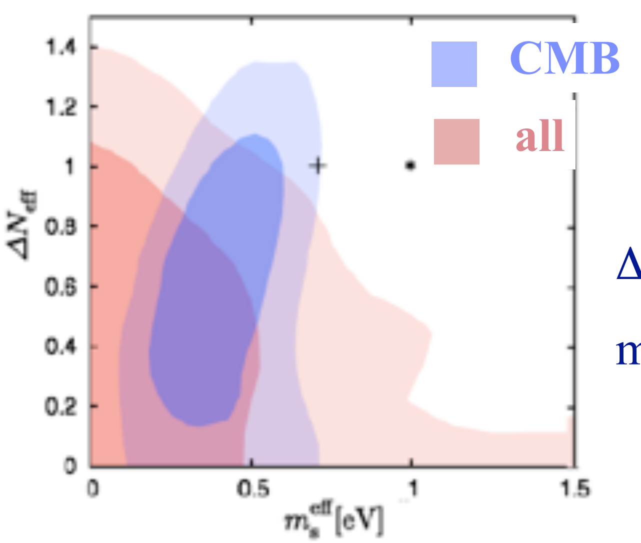
Planck XIII, 2015

See Galli's talk

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

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

Hamann and Hasenkamp, 2013

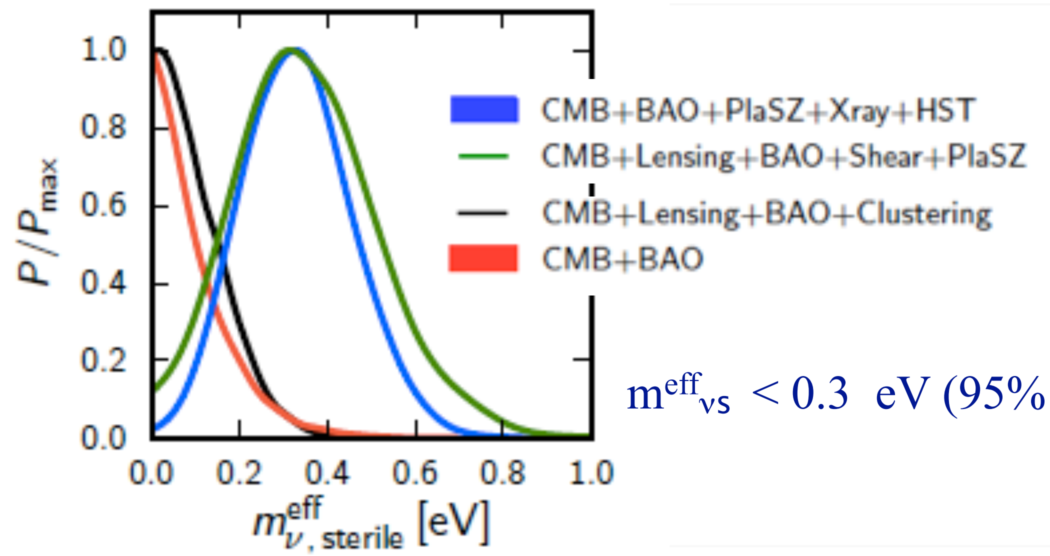


all= CMB+H0+ C+ CFHTLens

ΔN_{eff} = 0.61 +- 0.30

$m^{eff}_{\nu s}$ = 0.41+-0.13 eV (68% C.L.)

L. Verde et al, 2014



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

Less stringent mass bound from combined analysis → $m^{eff}_{\nu s}$ < 0.7 eV

Active-sterile flavour evolution

Sterile ν are produced in the Early Universe by the mixing with the active species in presence of collisions

(3+1) Scenario

Evolution equation:

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

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

ν ensemble

Stodolsky , Raffelt and Sigl,1992 ; Sigl and Raffelt 1993;

$$\Omega = \Omega_{\rm vac} + \Omega_{\rm mat} + \Omega_{\nu-\nu} + \ldots$$

Vacuum term

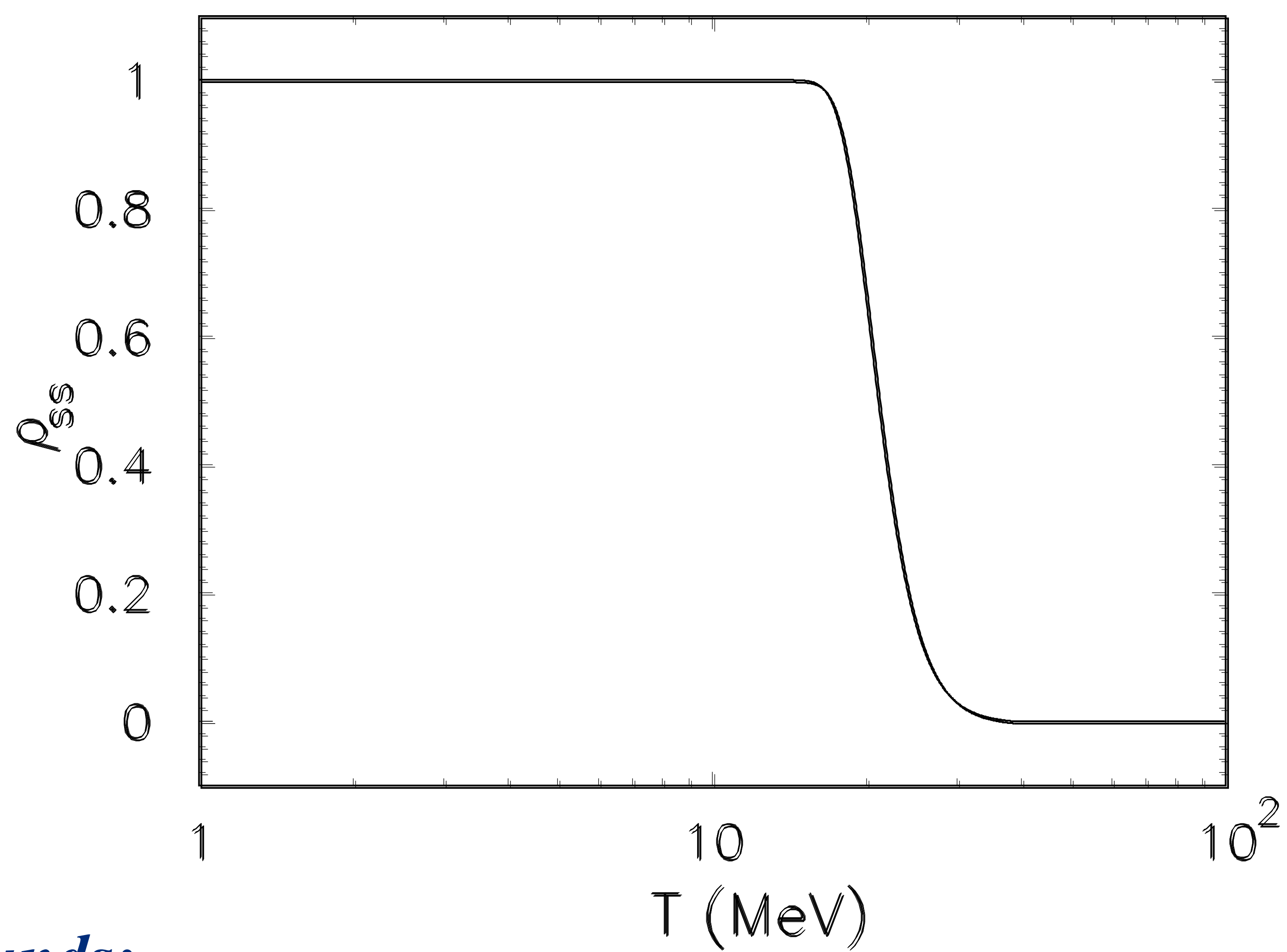
MSW effect with background medium *(refractive effect)*

***refractive* ν−ν *self-interactions* term**

$C[\rho]$ **Collisional term**

creation, annihilation and all the momentum exchanging processes

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



Comparing with the cosmological bounds:

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

- 3+1: 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 ν−ν asymmetries (L~10^{-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

Possible solutions...?

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

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

   In the presence of large $\nu-\nu$ asymmetries ($L \sim 10^{-2}$) sterile production strongly suppressed. Mass bound can be evaded

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   sterile abundance depends on reheating temperature

- ***Modification of cosmological models***

  Inflationary Freedom

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Secret interactions for sterile ν_s

Hannestad, Hansen & Tram, 2013

4-fermion point-like interaction: new secret self-interactions among sterile ν mediated by a massive gauge boson X : $M_X << M_W$

→ *Suppress the thermalization of sterile neutrinos*
(Effective ν_a-ν_s mixing reduced by a large matter term)

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

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- Only for sterile sector... → *secret interactions apparently unconstrained...*

Caveat: **can also generate MSW-like resonant flavor conversions and collisional induced conversions among active and sterile neutrinos, enhancing their production**

↓

consequences on cosmological bounds at low temperature

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Caveat: can also generate MSW-like resonant flavor conversions and collisional induced conversions among active and sterile neutrinos, enhancing their production

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consequences on cosmological bounds at low temperature

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

see Archidiacono's talk

Dasgupta and Kopp, 2013
Bringmann et al, 2013

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for pseudo-scalar model see Archidiacono's talk

Evolution equation:

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

$$\Omega = \Omega_{\text{vac}} + \Omega_{\text{mat}} + \Omega_{\nu-\nu} + \Omega^{\text{secr}}_{\nu_s-\nu_s}$$

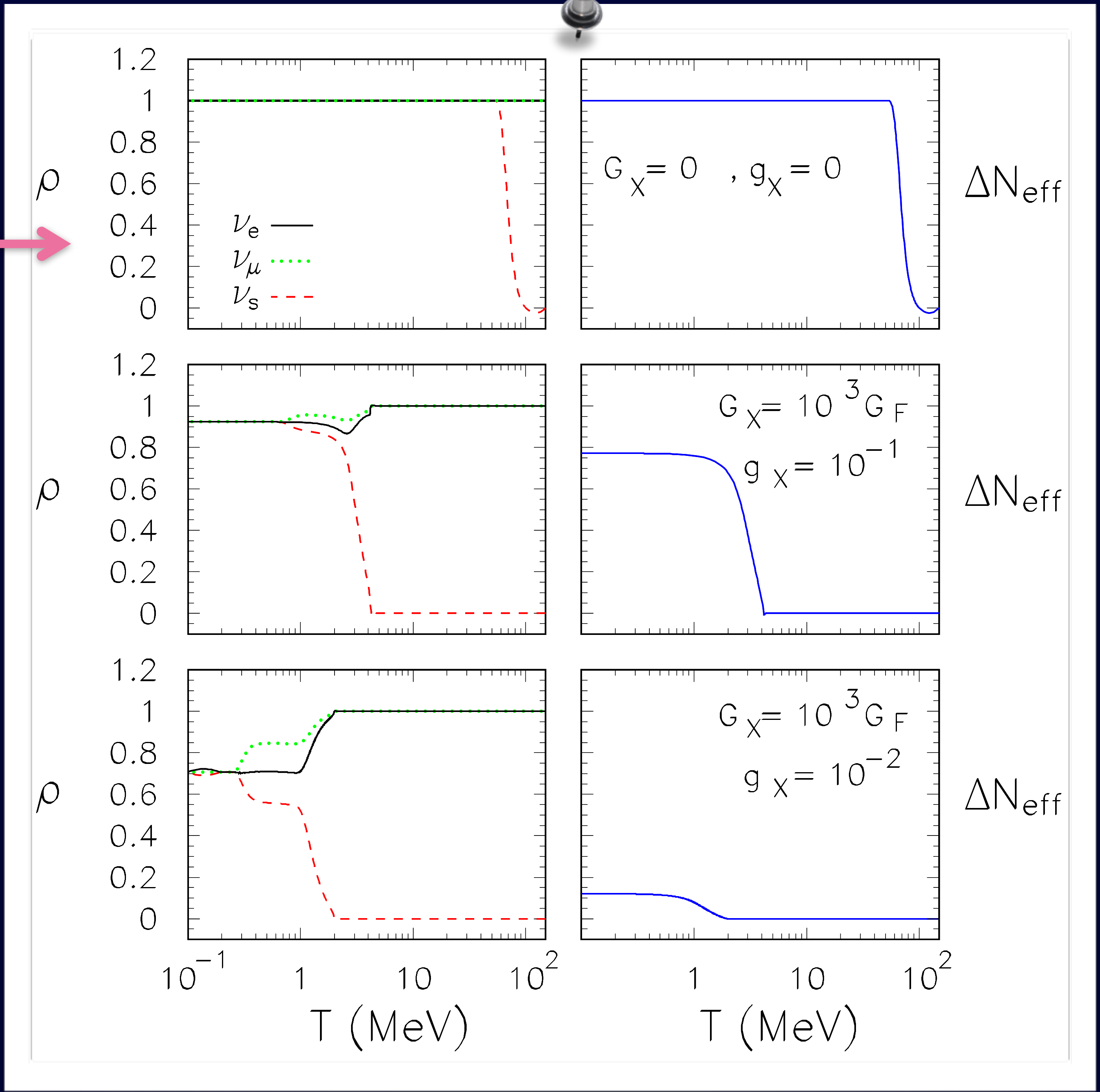
$\Omega_{\text{mat}}, \Omega_{\nu-\nu} \propto G_F$; $\Omega^{\text{secr}}_{\nu_s-\nu_s} \propto G_X$

$$C = C_{\text{SM}} + C_{\text{secr}}$$

$C_{\text{SM}} \propto G_F^2$; $C_{\text{secr}} \propto G_X^2$

Sterile production by secret interactions

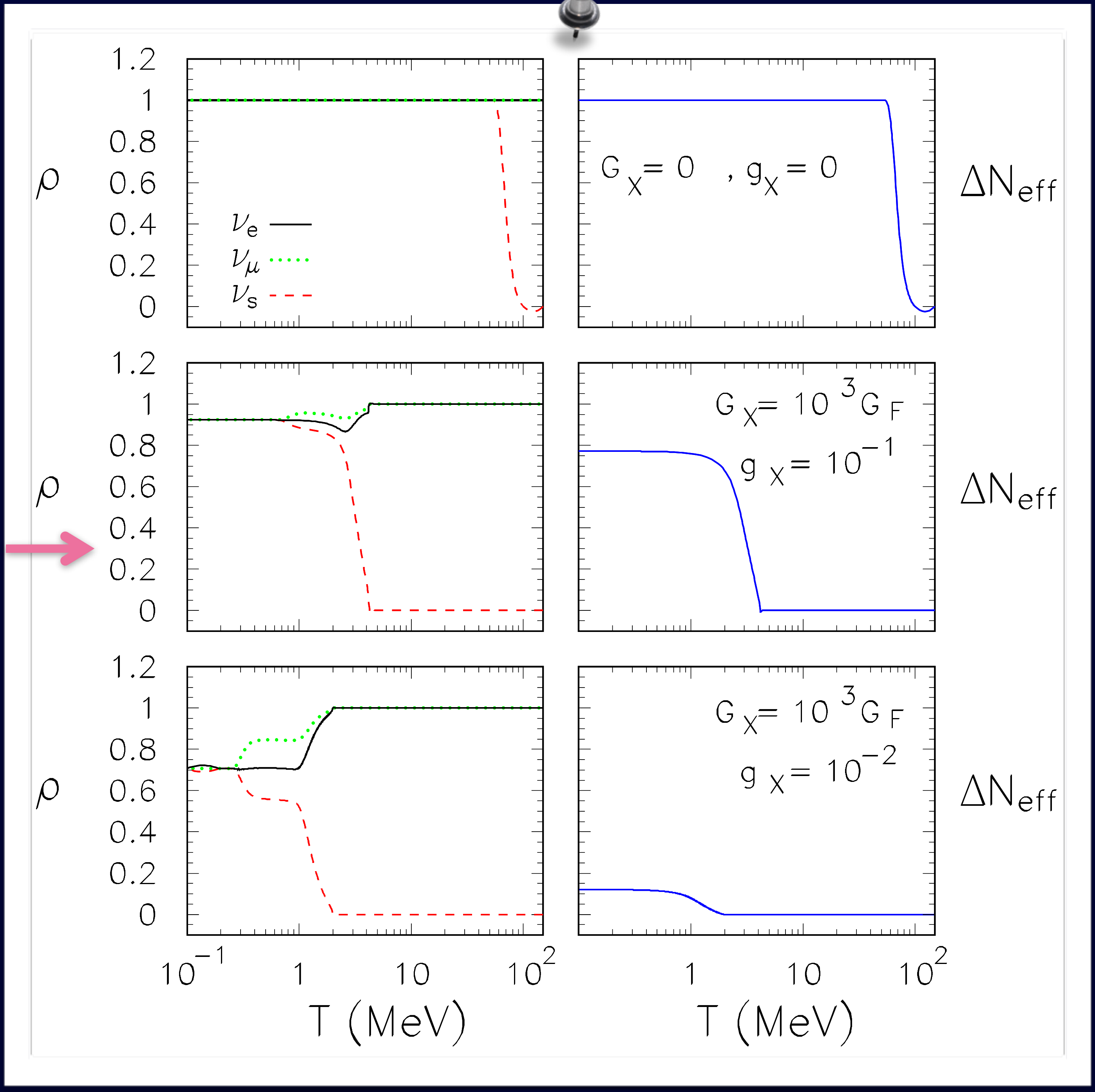
Standard case: as expected the sterile are copiously produced and thermalize



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

Sterile production by secret interactions

Secret interactions: shift of the conversions at lower T. Flavor equilibrium induced by the collisional term



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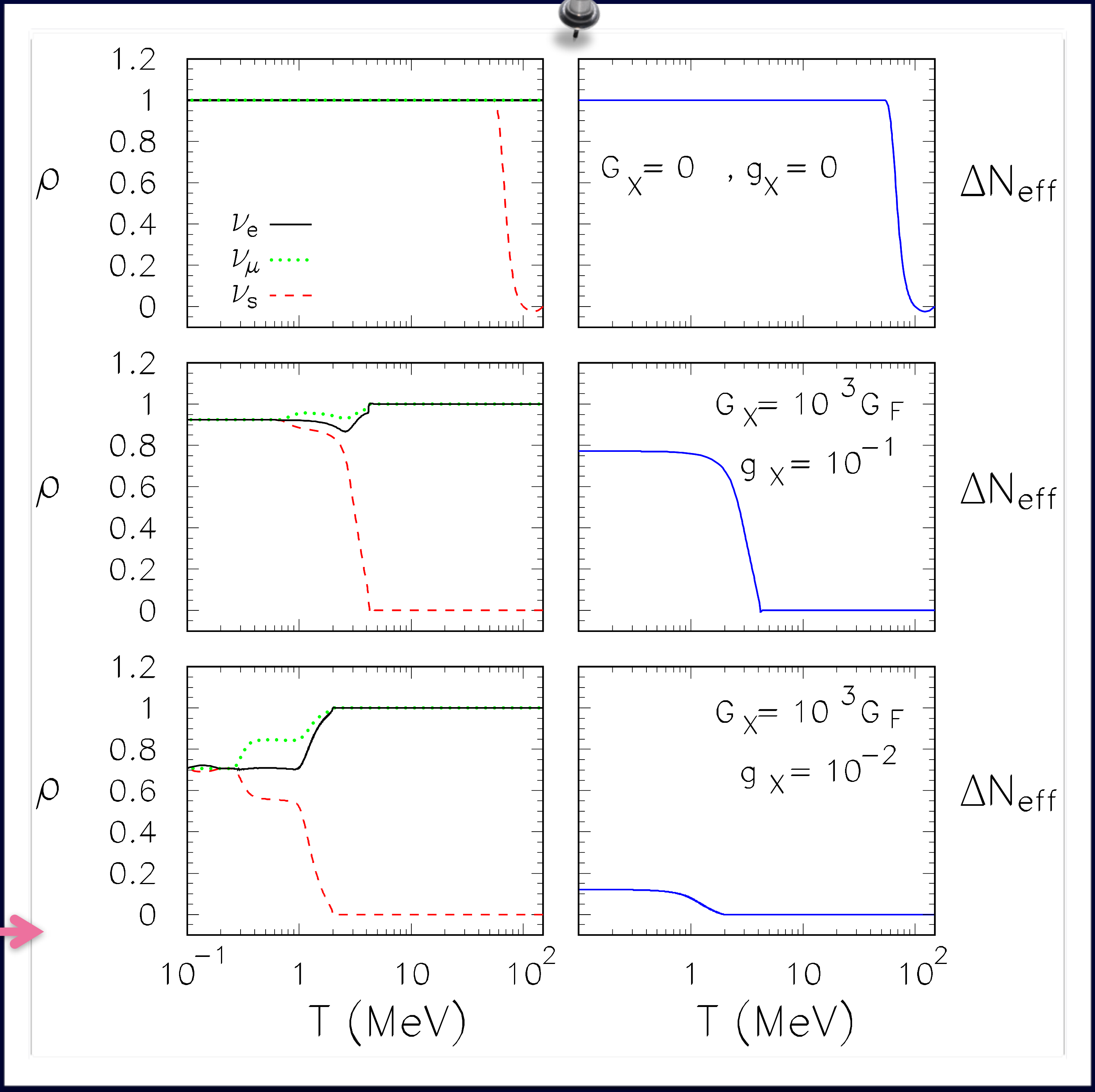


Secret interactions: conversions around 1 MeV, sterile ν partially suppressed, flavor equilibrium.

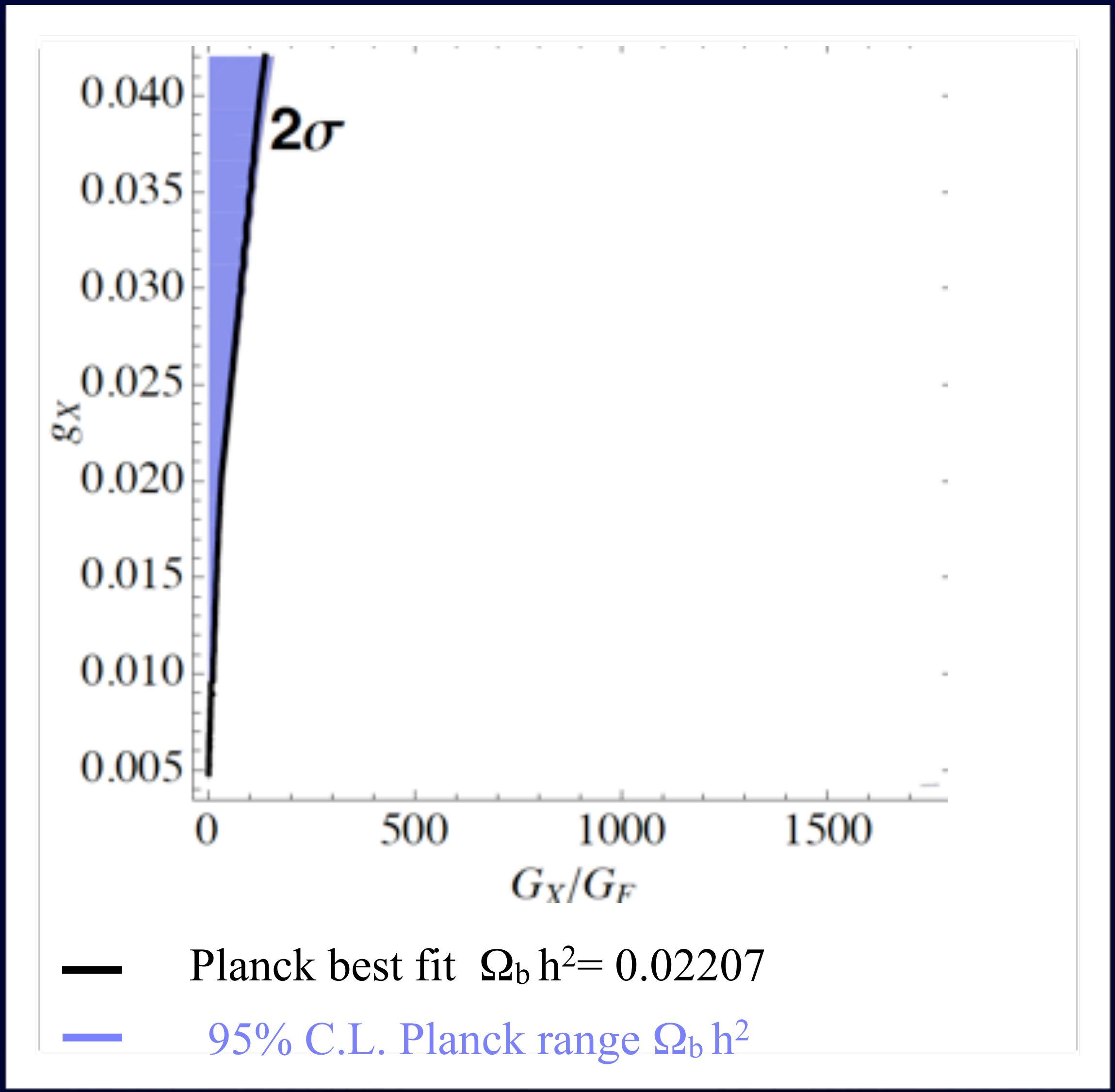
Note that also ν_e and ν_μ the are depleted: crucial for N_{eff} (strongly reduced) but also for BBN

$\rho_{ee} = 0.7, \quad \Delta N_{eff} = 0.18$

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

BBN constrains

^{4}He yield



Experimental reference value: $Y_p = 0.2551 \pm 0.0022$

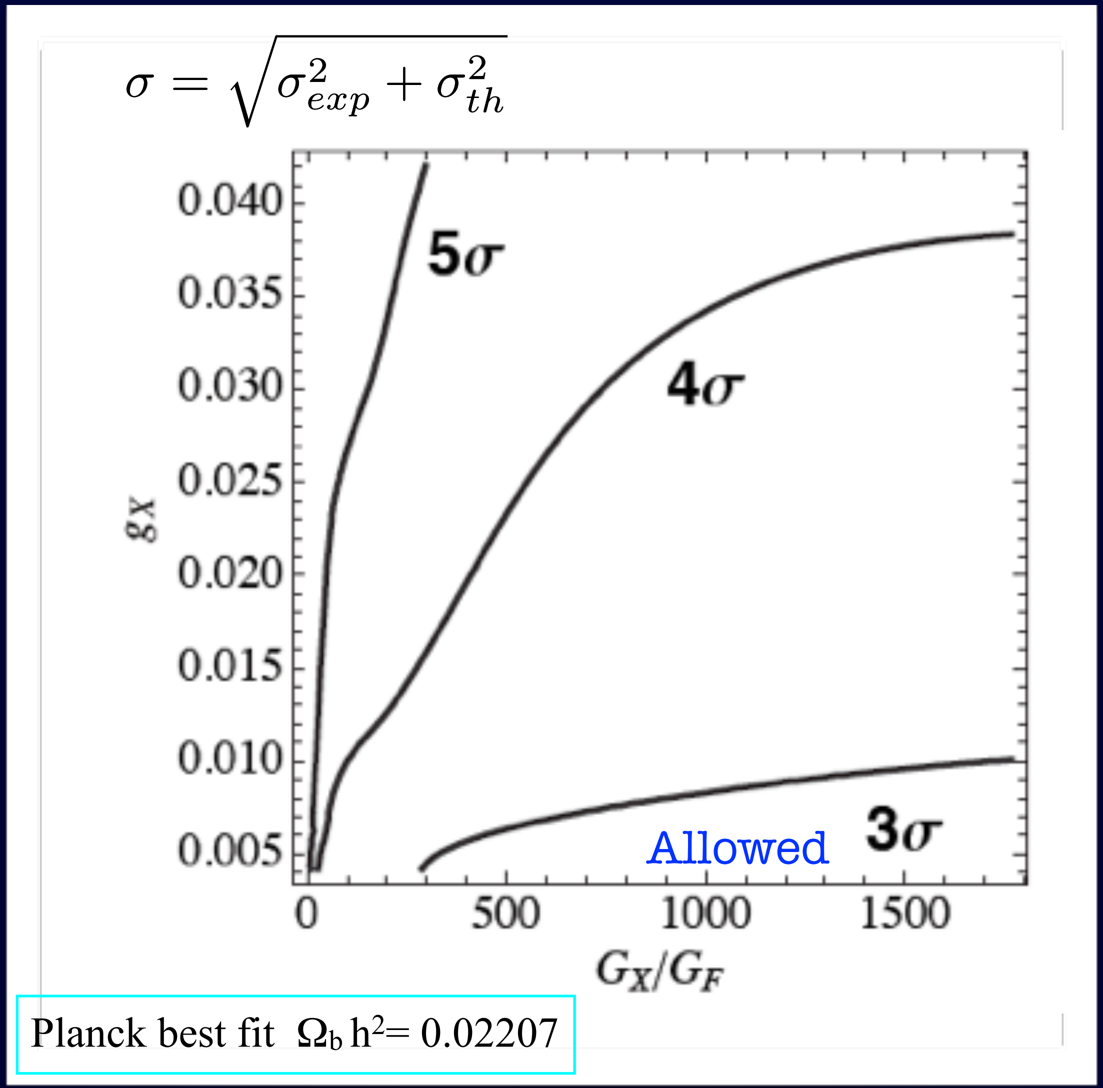
Saviano, Pisanti, Mangano, Mirizzi 2014, ArXiv: *1409.1680*

PArthENoPE code
Pisanti et al, 2012

D yield

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

Uncertainty on the reaction $d(p,\gamma)^3$He → $\sigma_{th} = 0.062 \times 10^{-5}$



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

Mass constrains

lower M_X ↔ very large G_X ($> 10^5\, G_F$) → very strong secret collisional term leading to a quick flavor equilibrium

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

The flavour evolution (scattering-induced decoherent production) leads to a large population of sterile states *Stodolsky, 1987*

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

(1, 1, 1, 0) (3/4, 3/4, 3/4, 3/4)

Mirizzi,Mangano, Pisanti Saviano, 2014, ArXiv:1410.1385

Impact on the mass bound:

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

→ the laboratory lower value in the 2σ range gives $m_{\rm st}^{\rm eff} \sim 0.8$ eV

BUT... ***the less stringent cosmological bounds on sterile mass give* 0.7** eV

Secret interaction scenario: disfavored $M_X \geq 0.1$ MeV

Conclusions

- eV sterile ν ***incompatible*** with cosmological bounds:
  too heavy for structure formation

- possible but not guaranteed reconciliation via suppression of sterile abundance:

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- 400 MeV > M_X > 0.1 MeV → mechanism strongly disfavoured by BBN bounds and by sterile mass bounds

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- M_X < 0.1 MeV → unconstrained at the moment: ν_s still coupled at CMB and LSS epochs → no free-streaming

Present cosmological mass bound obtained considering free-streaming ν

→ an appropriated analysis should be performed for 4-fermion model

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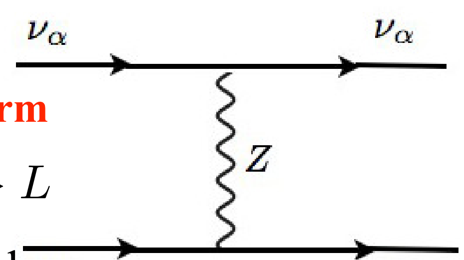
Present cosmological mass bound obtained considering free-streaming ν
→ an appropriated analysis should be performed for 4-fermion model

relevant also for small scale DM problems: the game is still open

Chu, Dasgupta and Kopp, 2015

Thank you!

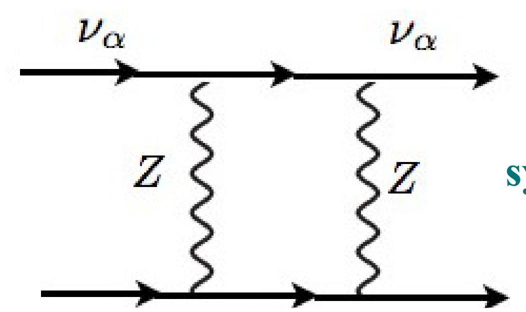
Equations of motion



asymmetric term

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

usually neglected



symmetric term

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

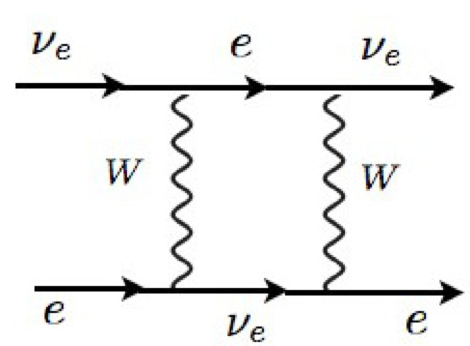
Vacuum term
with M neutrino mass matrix
U M^2U†

refractive ν−ν term
self-interactions of ν with the ν background:
off-diagonal potentials ➠ non-linear EoM

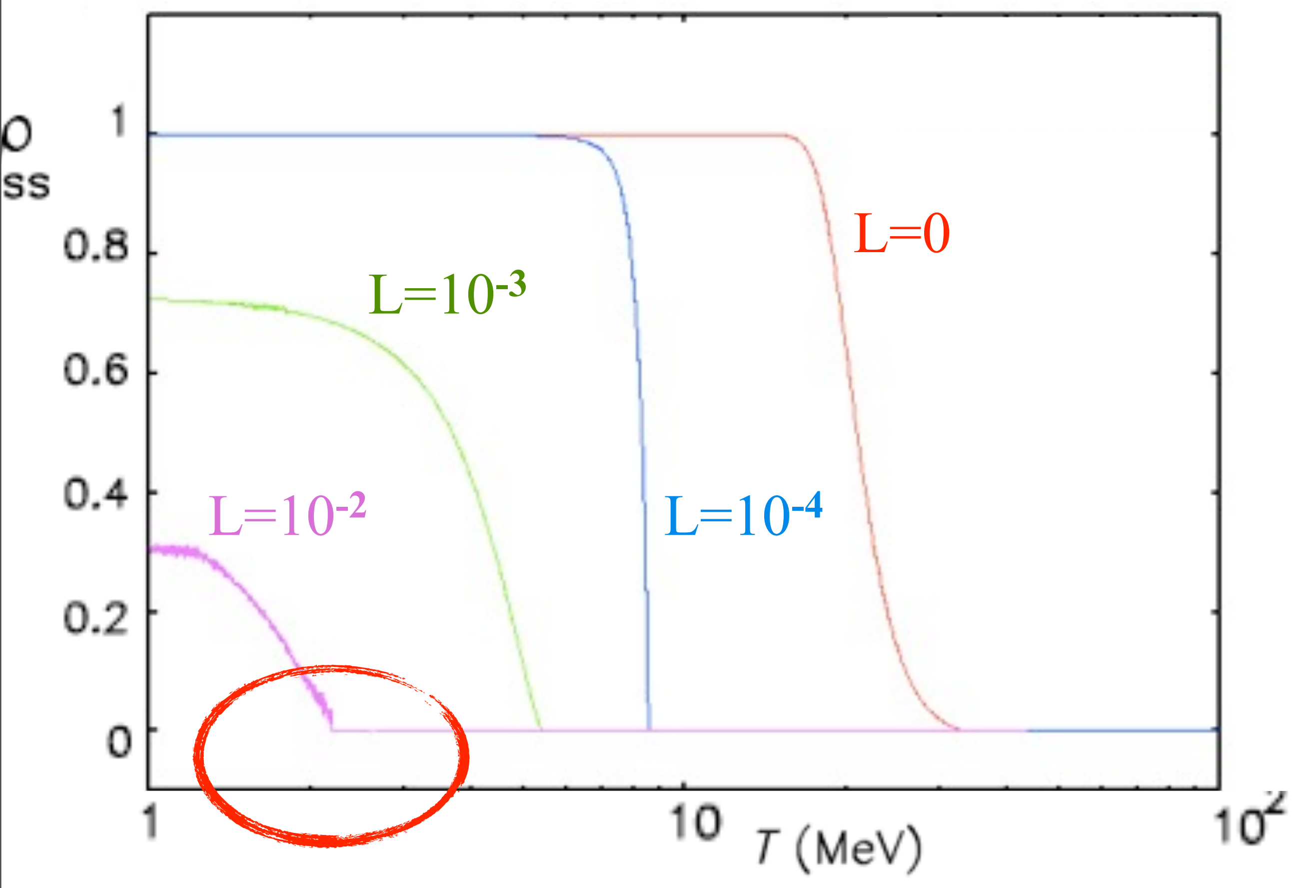
$$\Omega = \frac{\mathsf{M}^2}{2p} + \sqrt{2}\, G_{\rm F}\left[-\frac{8p}{3}\left(\frac{\mathsf{E}_\ell}{M_{\rm W}^2} + \frac{\mathsf{E}_\nu}{M_{\rm Z}^2}\right)\right] + \sqrt{2}\, G_{\rm X}\left[-\frac{8p\mathsf{E}_{\rm s}}{3M_{\rm X}^2}\right]$$

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

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



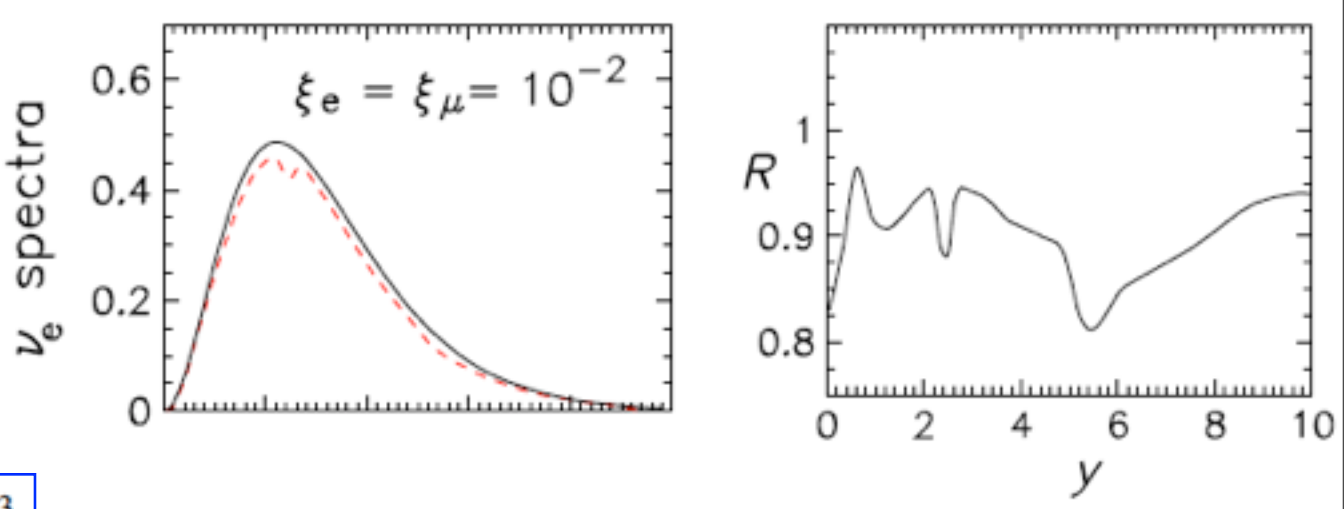
Sterile production by neutrino asymmetry



conversions occur at $T \sim T_\nu$ decoupling

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

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

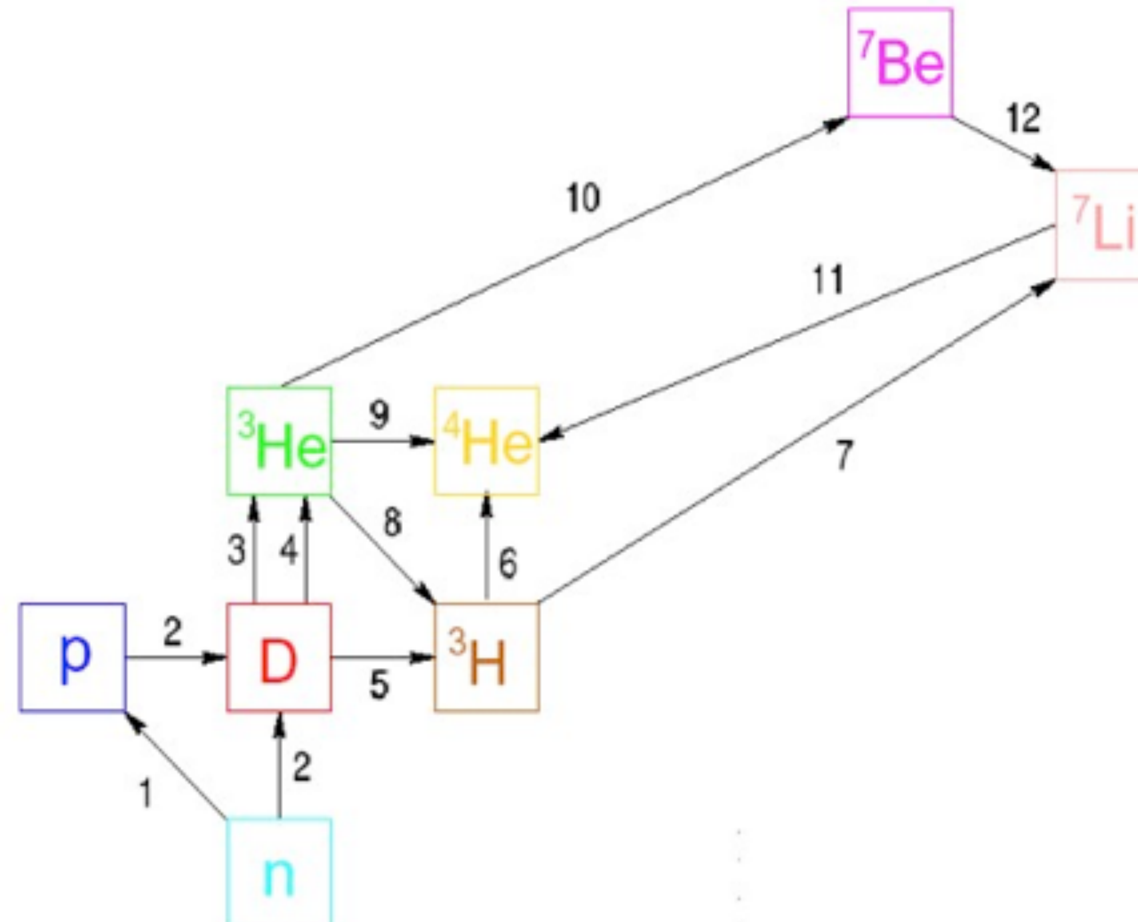


$$L_\alpha \simeq 0.68\,\xi_\alpha \left(\frac{T_\nu}{T_\gamma}\right)^3$$

Big Bang Nucleosynthesis

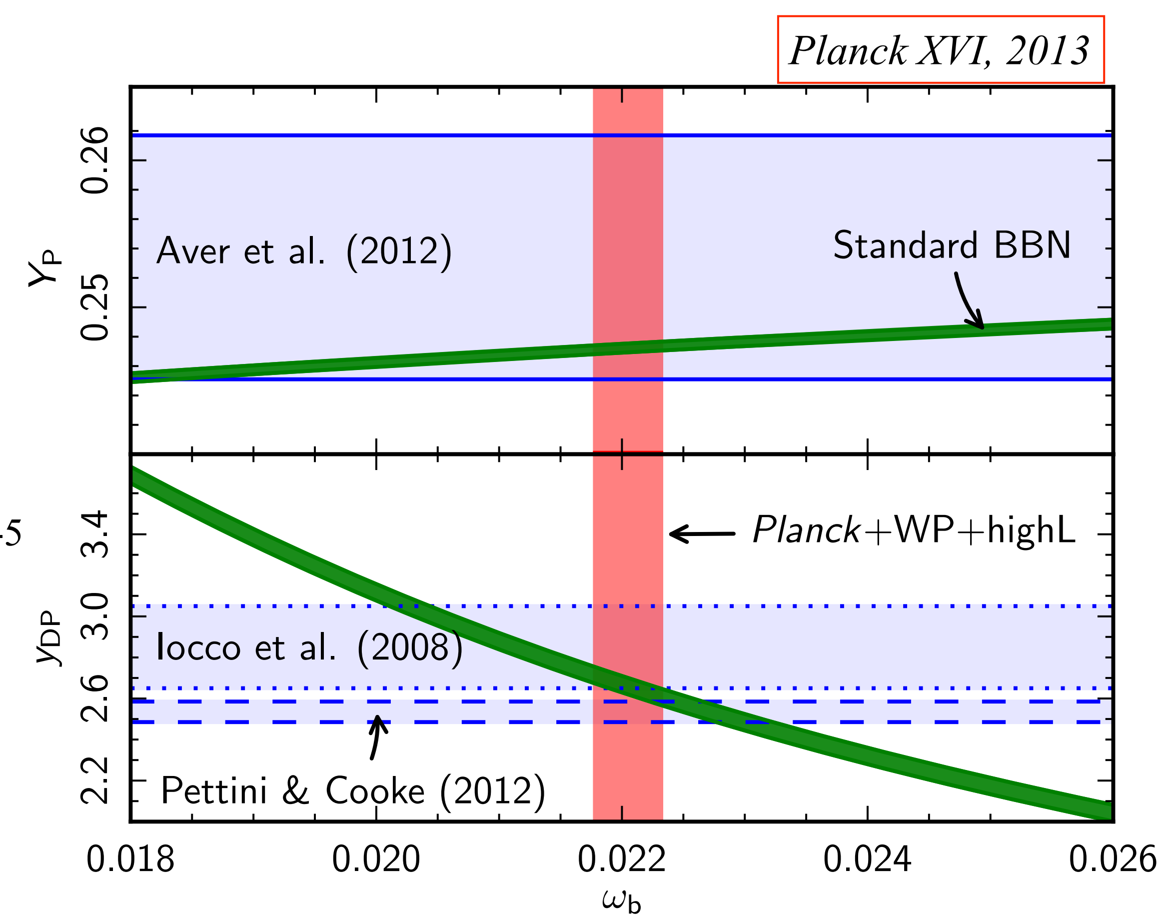
✱ 0.1-0.01 MeV
Formation of light nuclei starting from D

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



^{4}He

D $\times 10^{-5}$



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

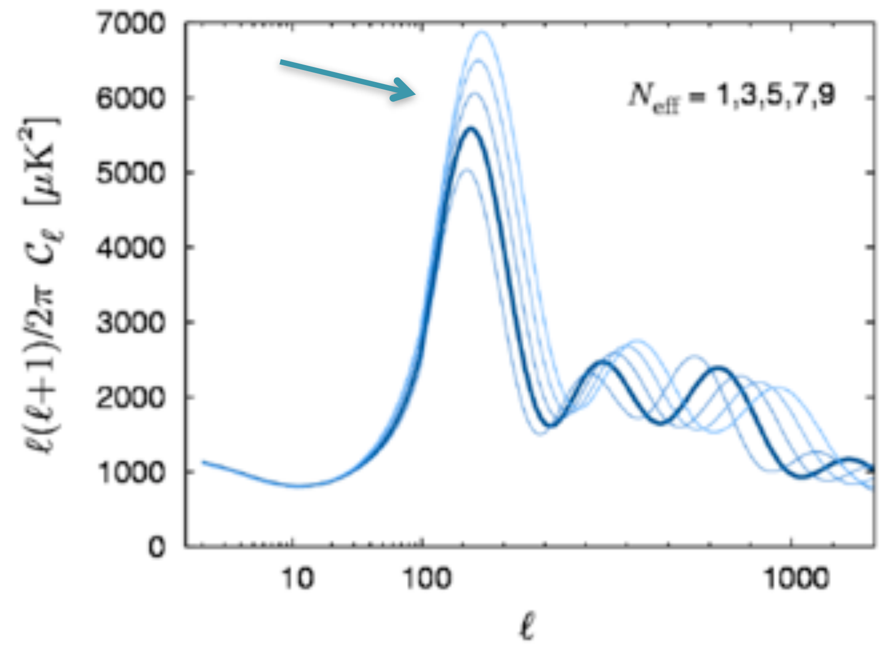
Blue regions: primordial yields from measurements performed in different astrophysical environments

$\omega_b = 0.02207 \pm 0.00027$

Impact on CMB

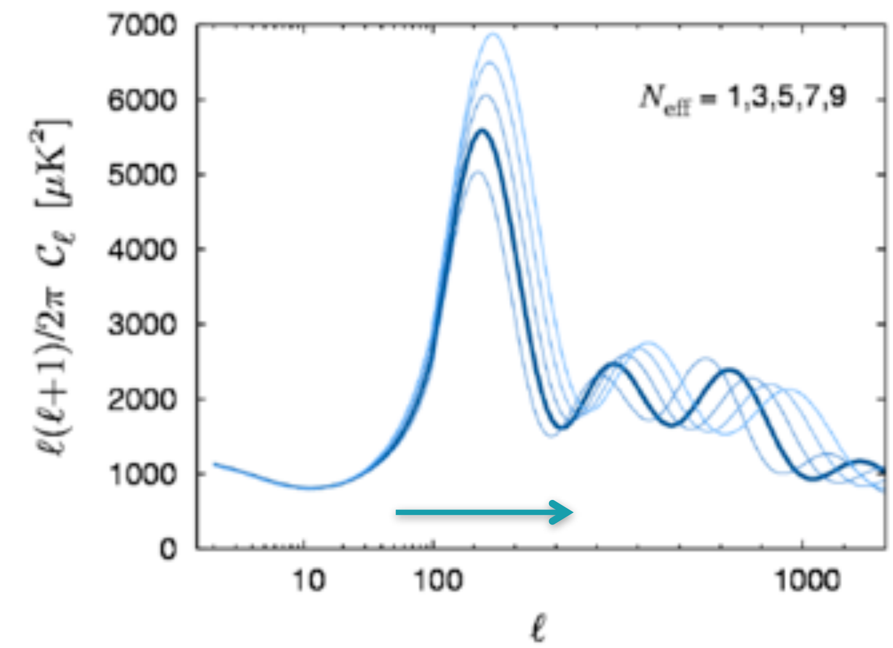
Matter-radiation equality

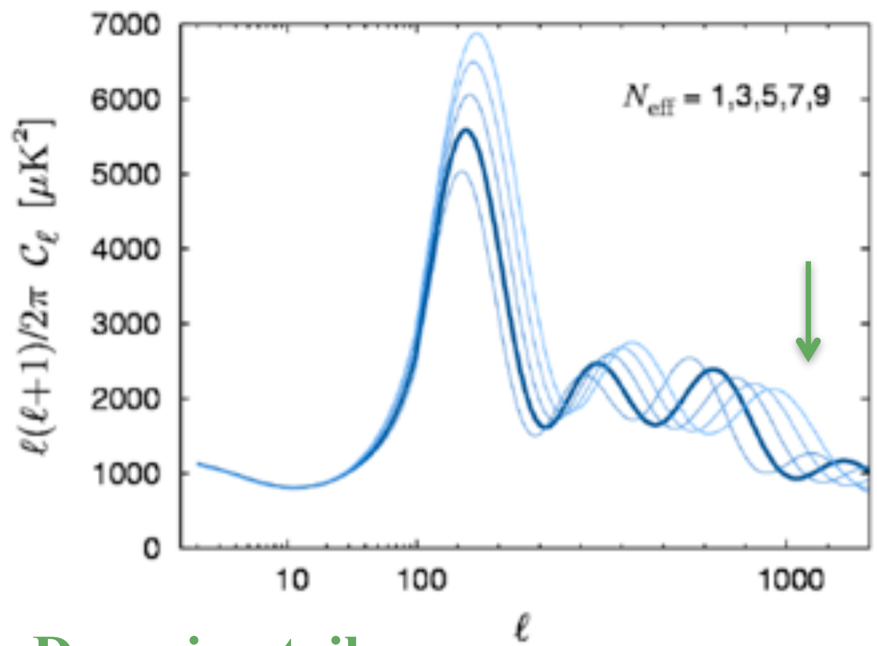
degenerate with Ω_m



Sound horizon/angular positions of the peaks

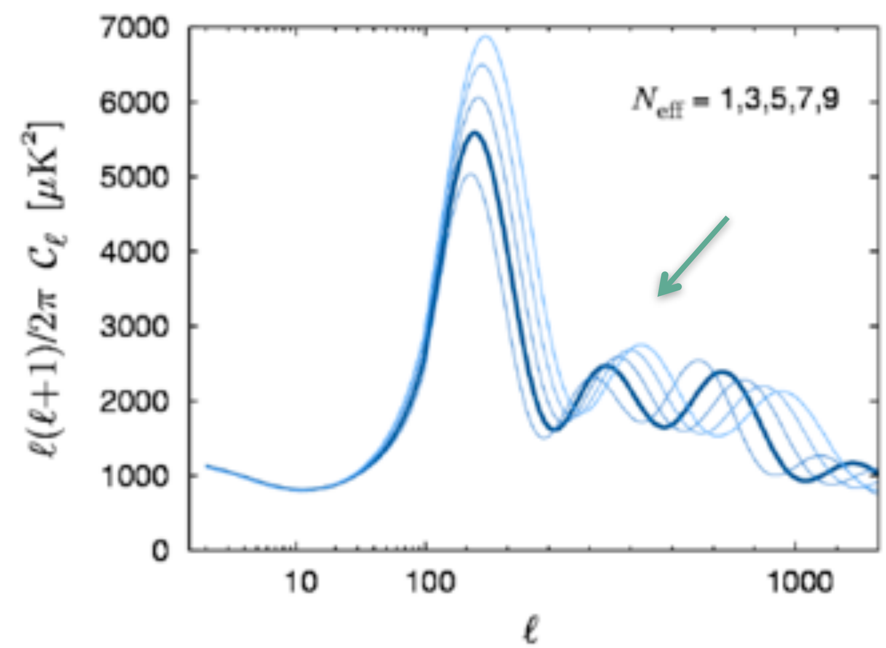
degenerate with H_0 and Ω_m





Damping tail

degenerate with Y_p



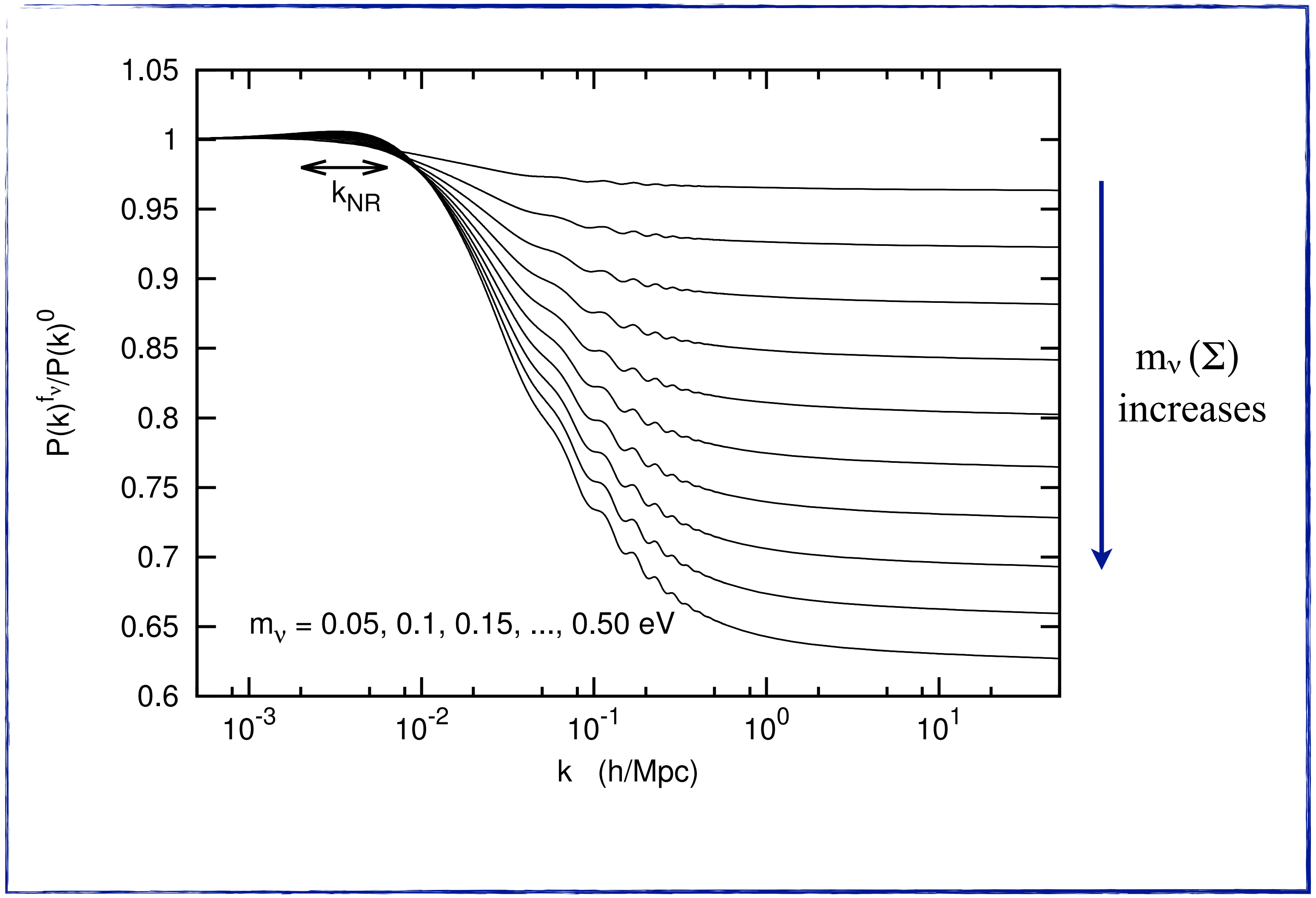
Anisotropic stress

(partially) degenerate with A_s and n_s

Impact on the LSS

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

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

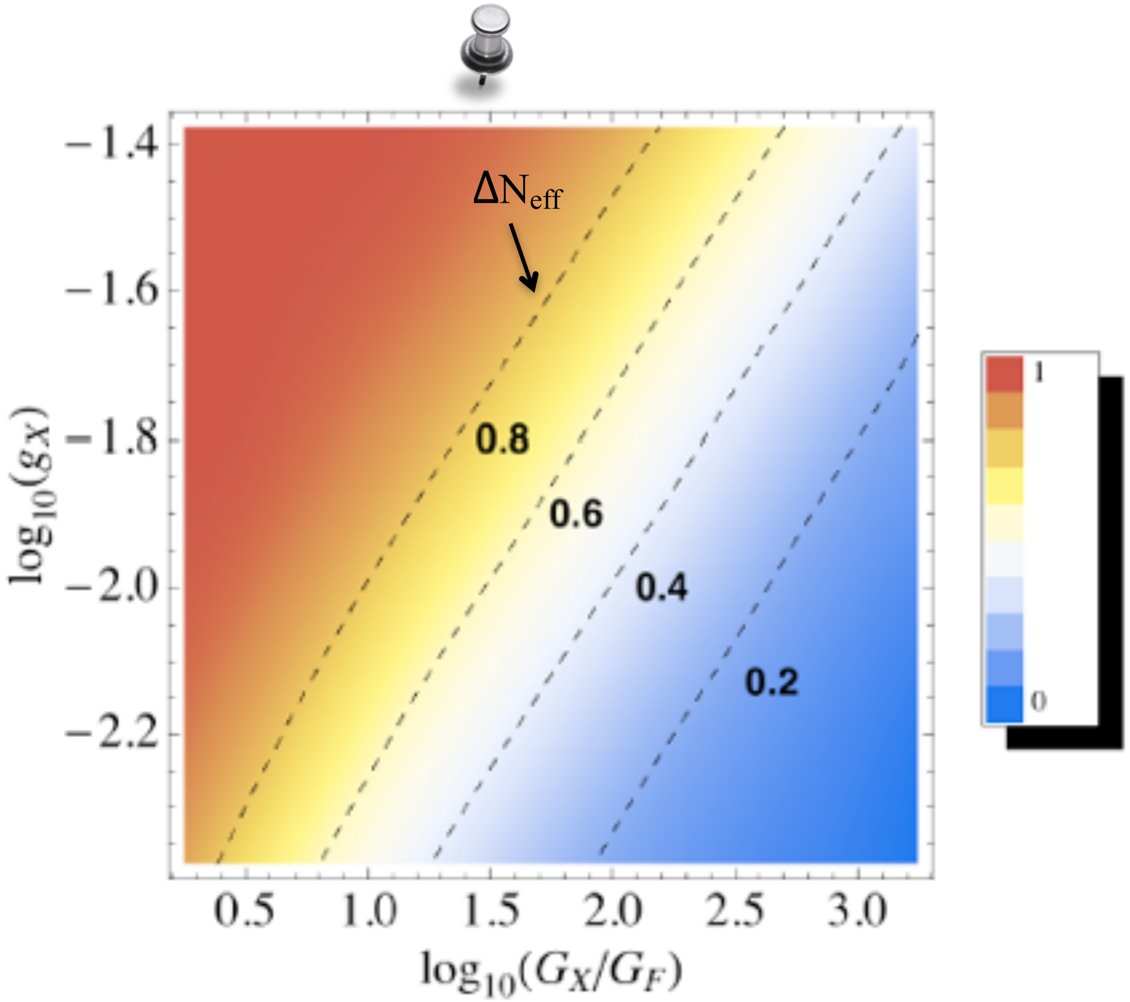


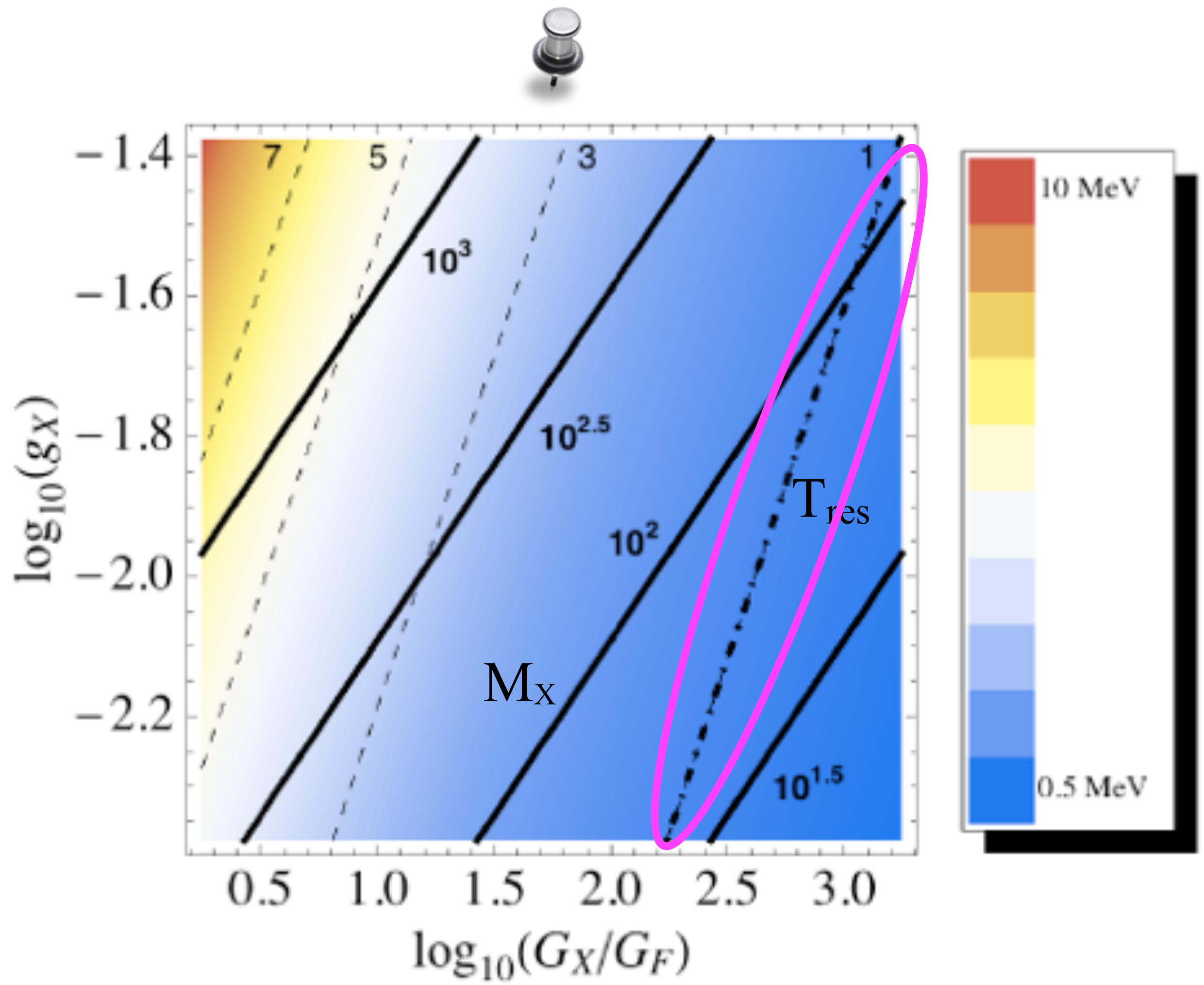
$$f_\nu \equiv \frac{\rho_\nu}{(\rho_{\rm cdm} + \rho_{\rm b} + \rho_\nu)} = \frac{\Omega_\nu}{\Omega_{\rm m}}$$

$$\Delta P(k)/P(k) \simeq -8 f_\nu$$

Secret interactions and BBN

Asymptotic values of ΔN_{eff} versus G_X and g_X

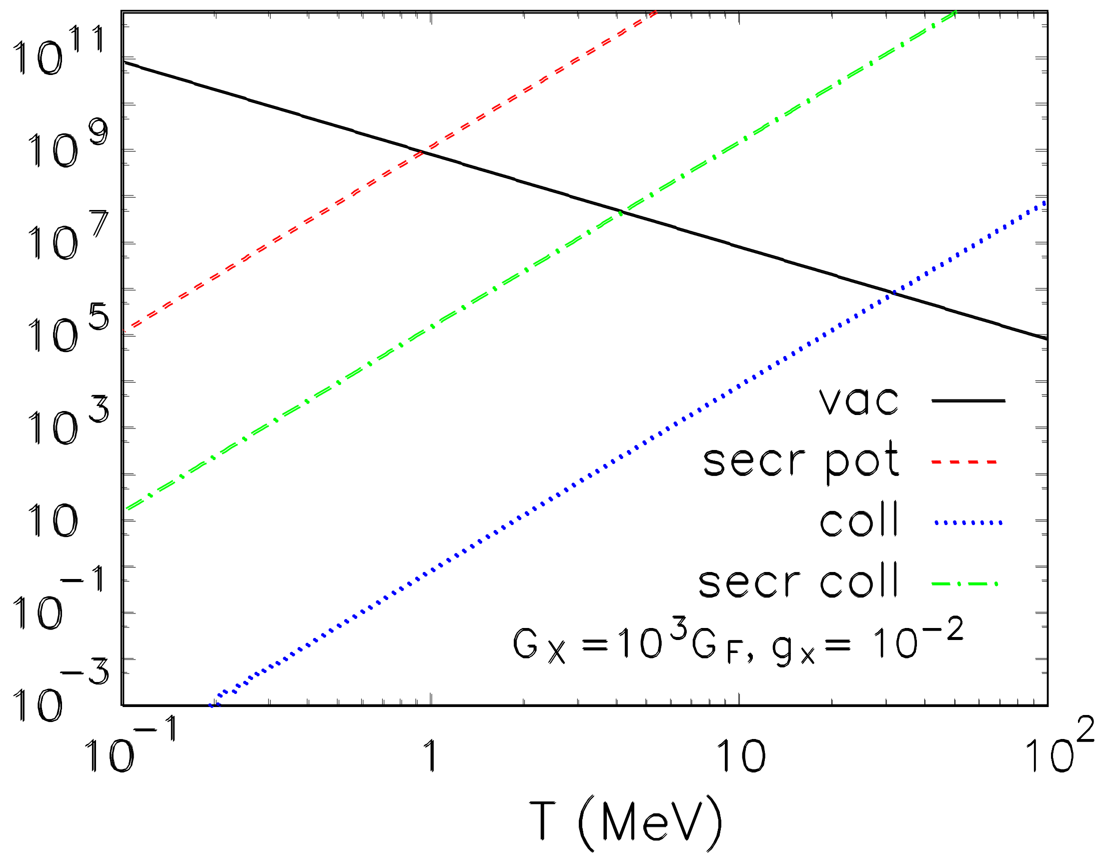


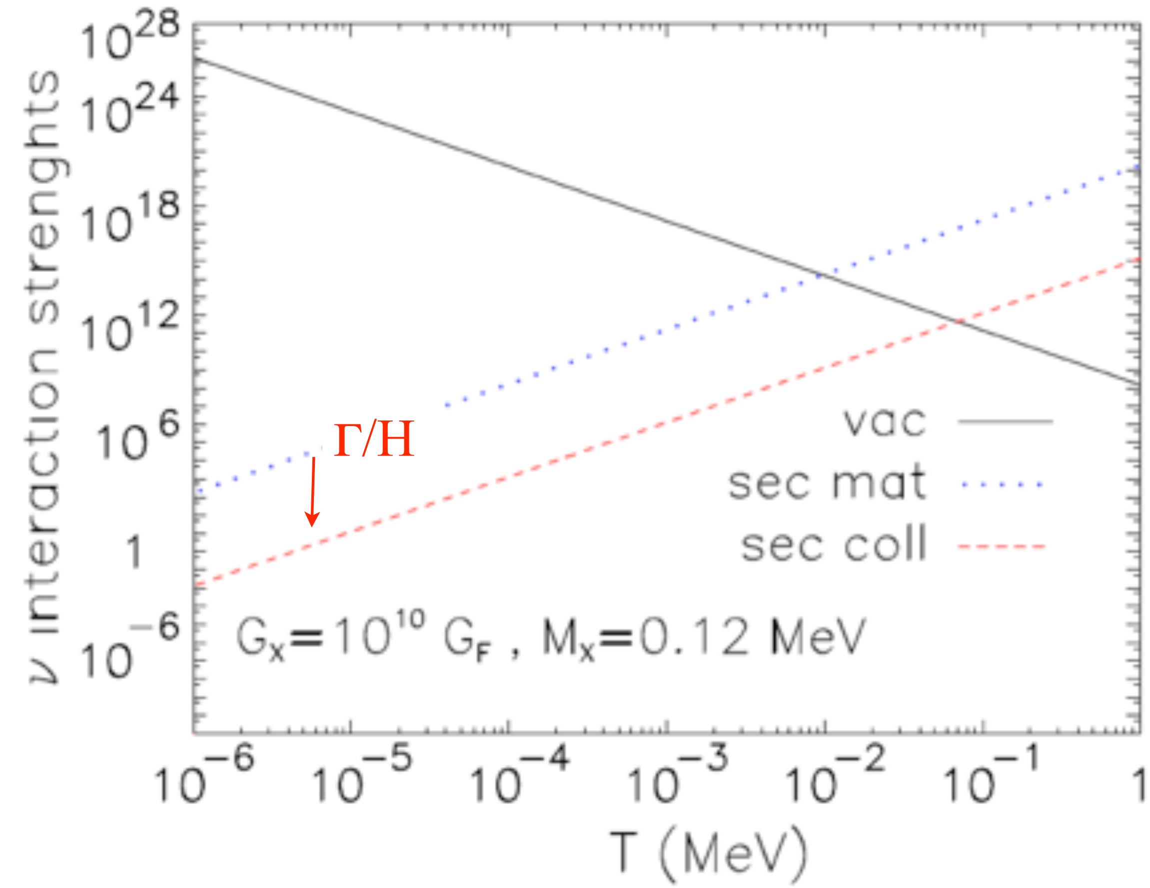


Resonance temperature in the plane (G_X, g_X)

Dashed curves: constant T_{res} contours

Solid curves: constant M_X contours


vac
secr pot
coll
secr coll
$G_X = 10^3 G_F$, $g_X = 10^{-2}$
T (MeV)


ν interaction strenghts
vac
sec mat
sec coll
Γ/H
$G_x = 10^{10}\, G_F$, $M_x = 0.12$ MeV
T (MeV)

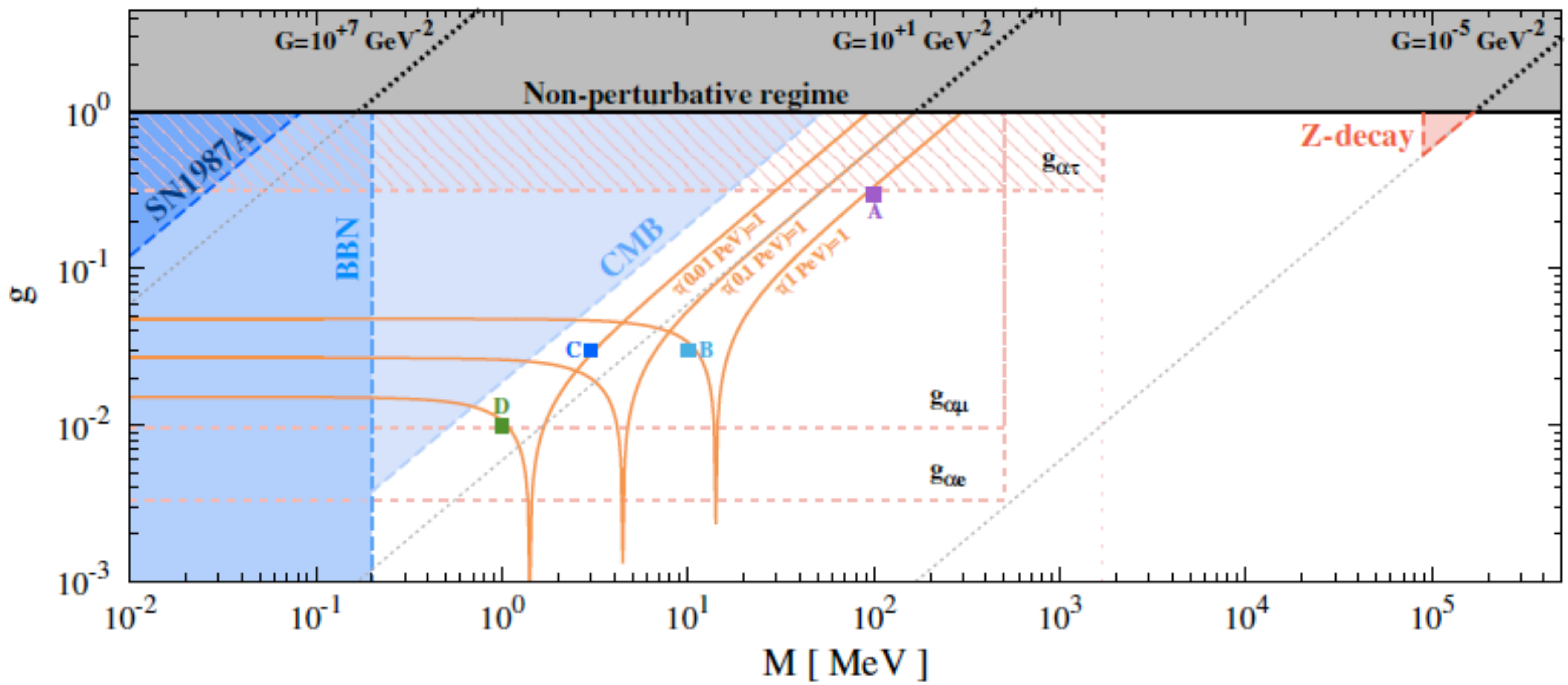


FIG. 1. Present constraints and future sensitivity to νSI in terms of neutrino coupling, g, and mediator mass, M, with diagonal dotted contours shown for values of the dimensionful coupling G. The blue shaded regions are excluded by astrophysical and cosmological considerations based on SN 1987A [6], BBN [34], and the CMB [35, 36]. The pink dashed lines indicate flavor-dependent limits based on laboratory measurements of meson and lepton decays [37]; we consider only the weakest limit, for ν_τ, to be robustly excluded for all flavors, and it is shaded. The red shaded region is excluded based on measurement of Z-boson decay [9]. The gray shaded region indicates the non-perturbative regime. *The orange lines are contours of unit optical depth for different initial neutrino energies (Eq. 10), indicating the approximate boundary of the parameter space above which IceCube is sensitive to νSI. The squares represent the example parameters (given in Table I) used in our calculations.*

Kenny C. Y. Ng and John F. Beacom, 2014