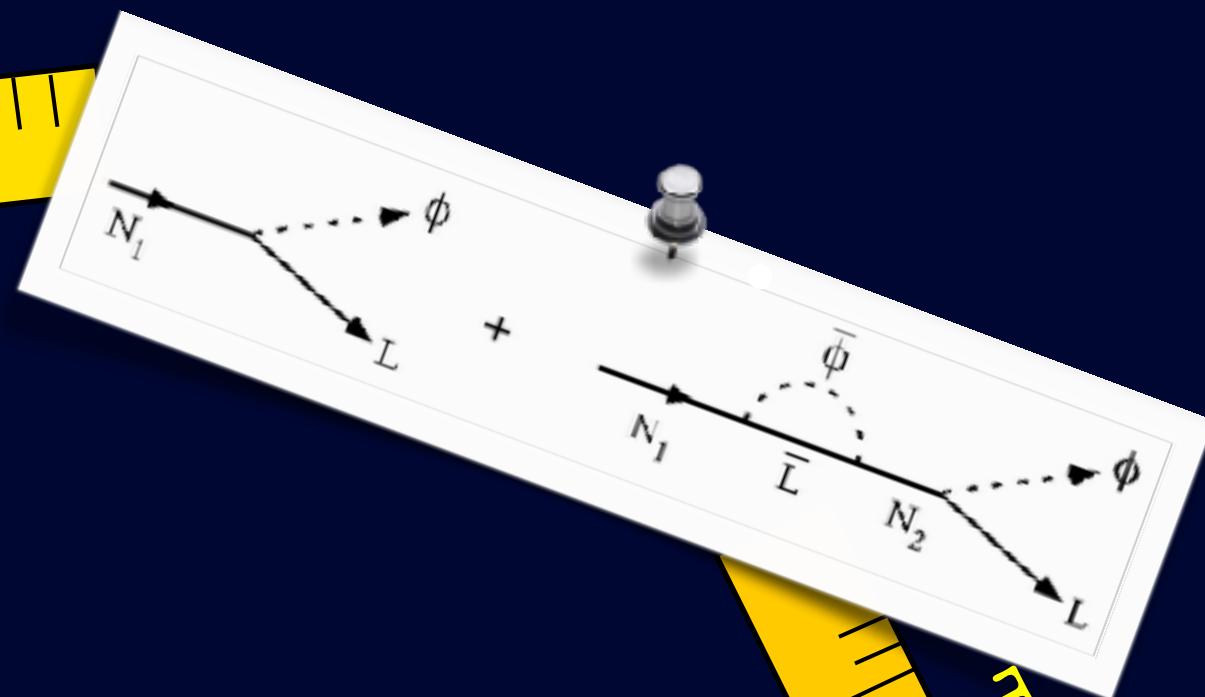




# Sterile Neutrinos

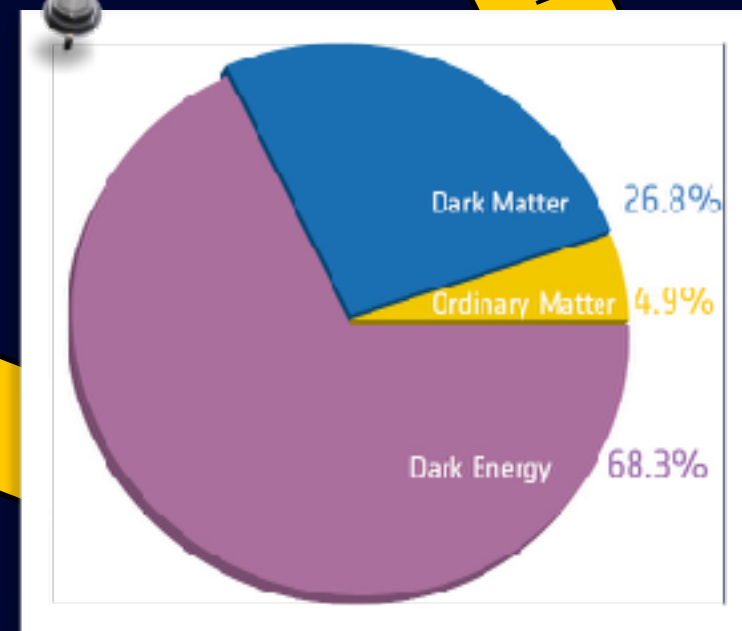
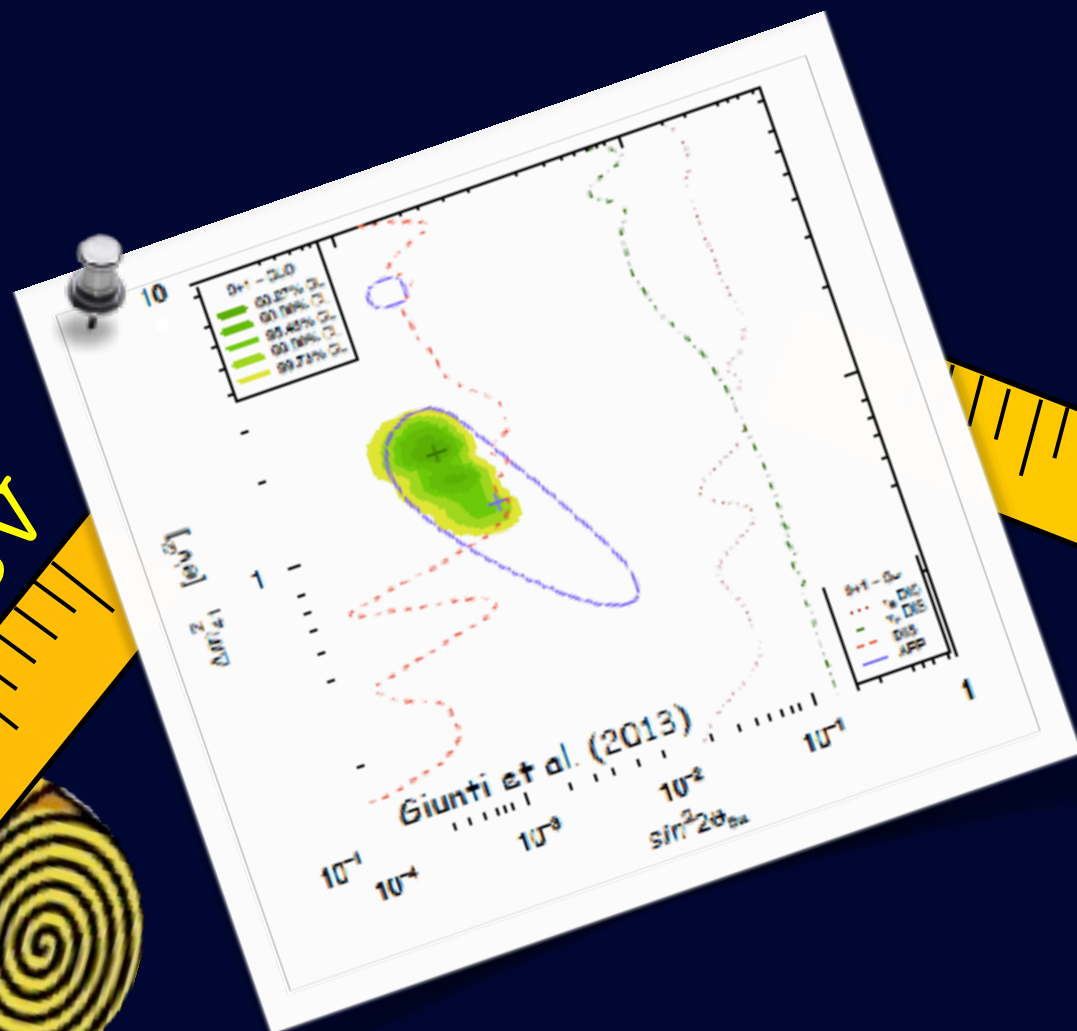
$M_{\text{GUT}}$



TeV

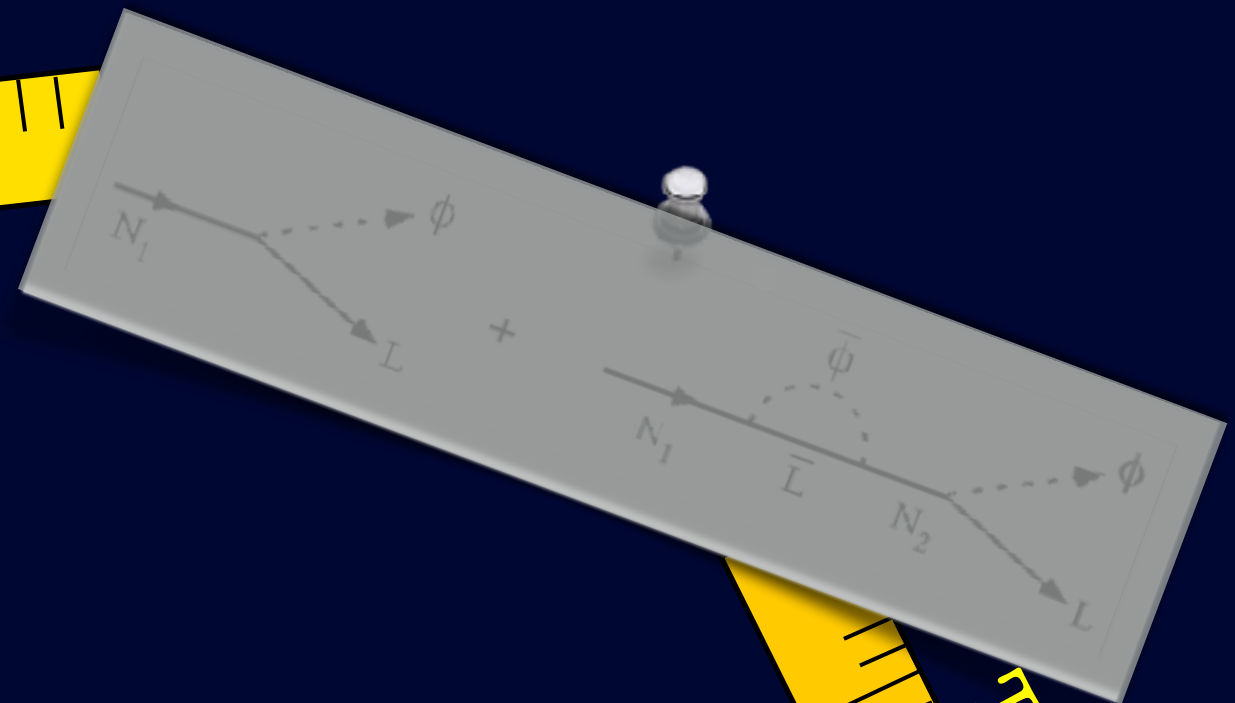
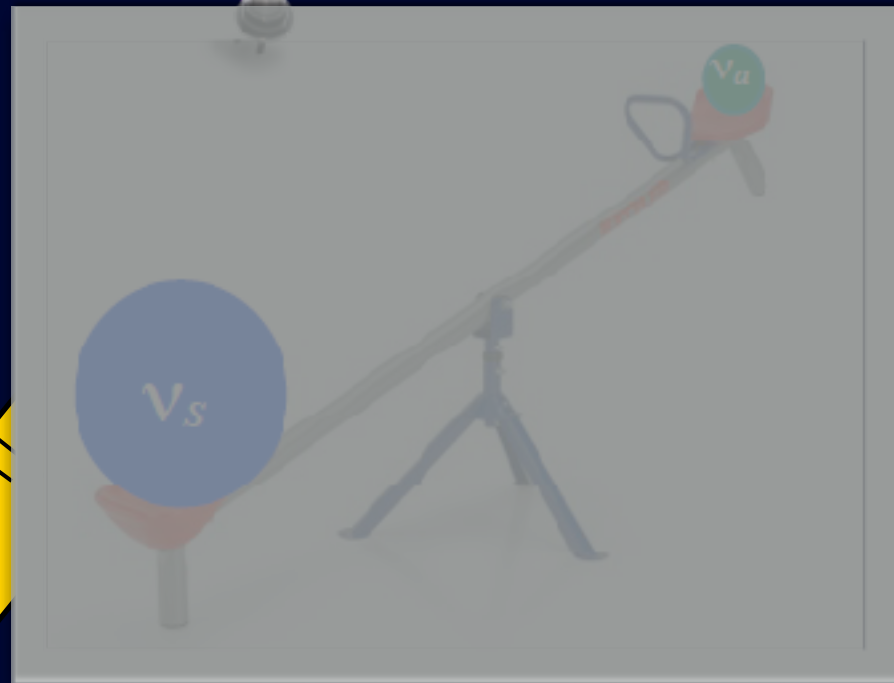
keV

eV



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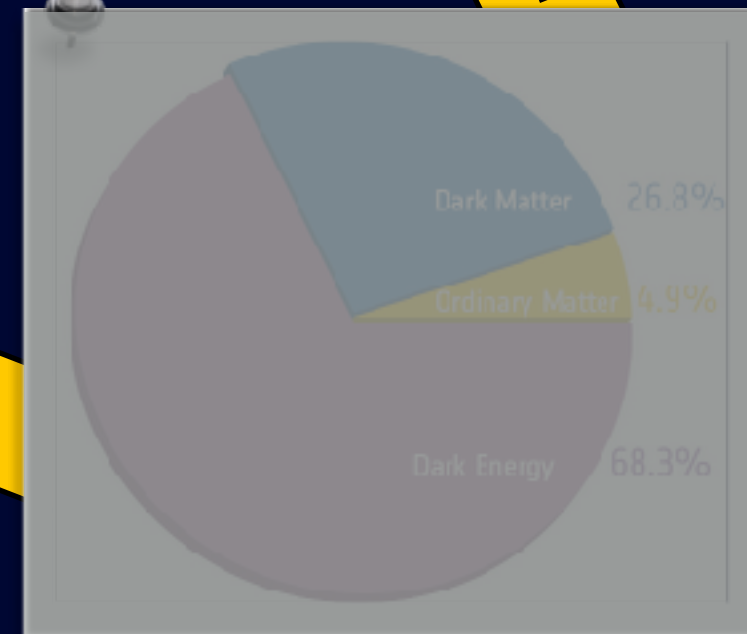
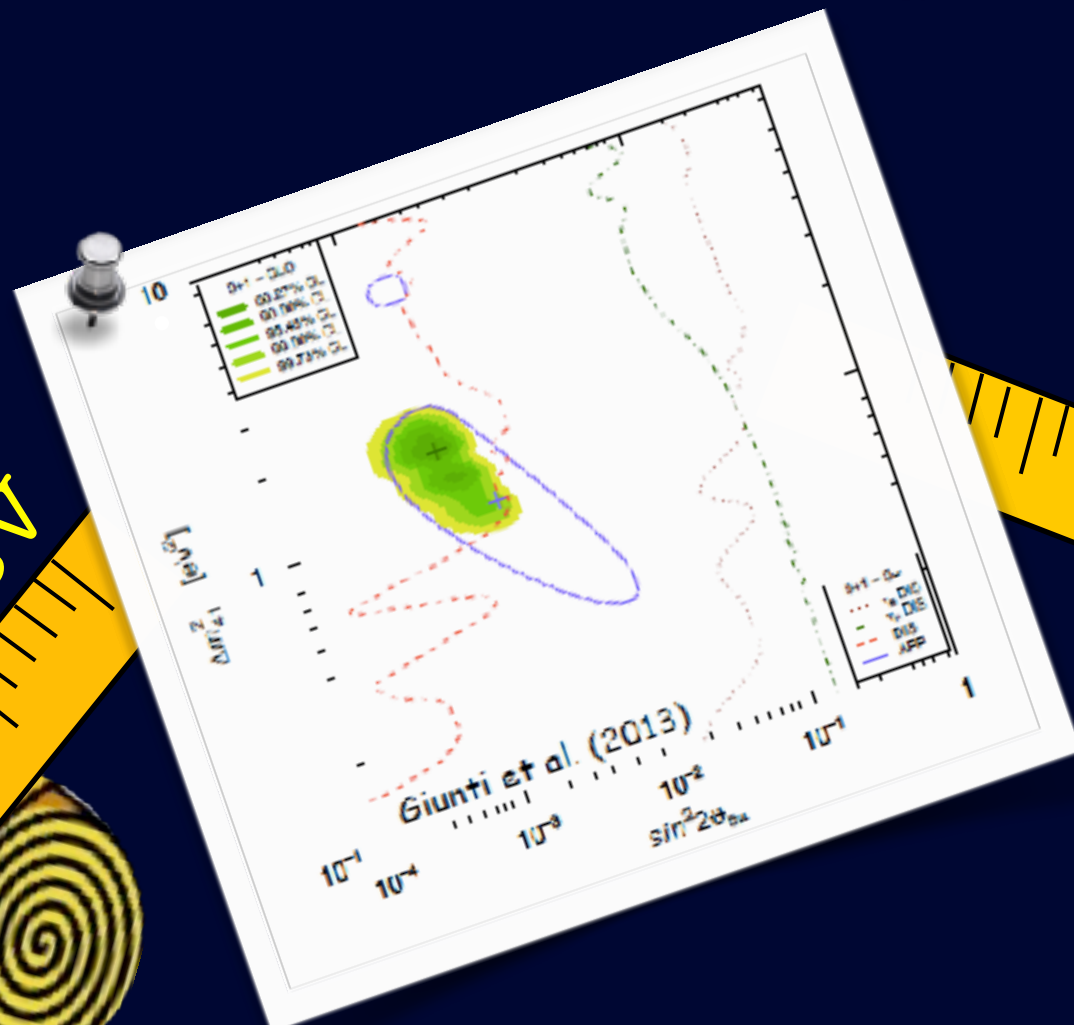
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keV

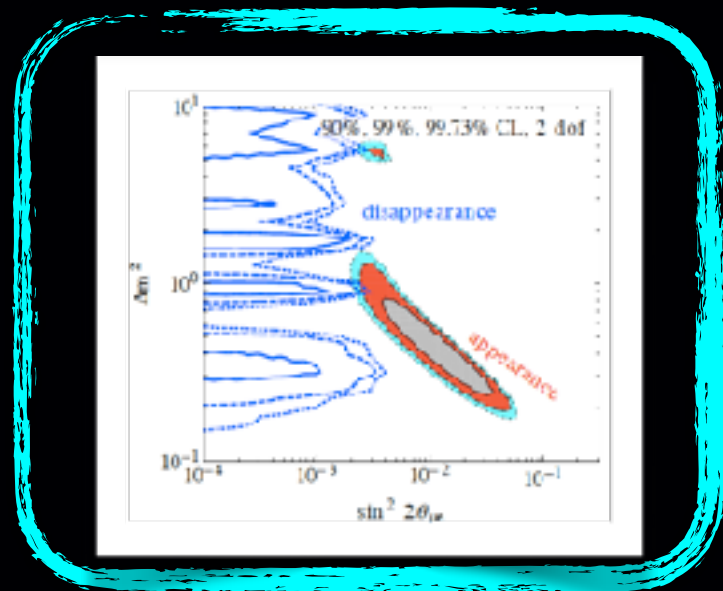
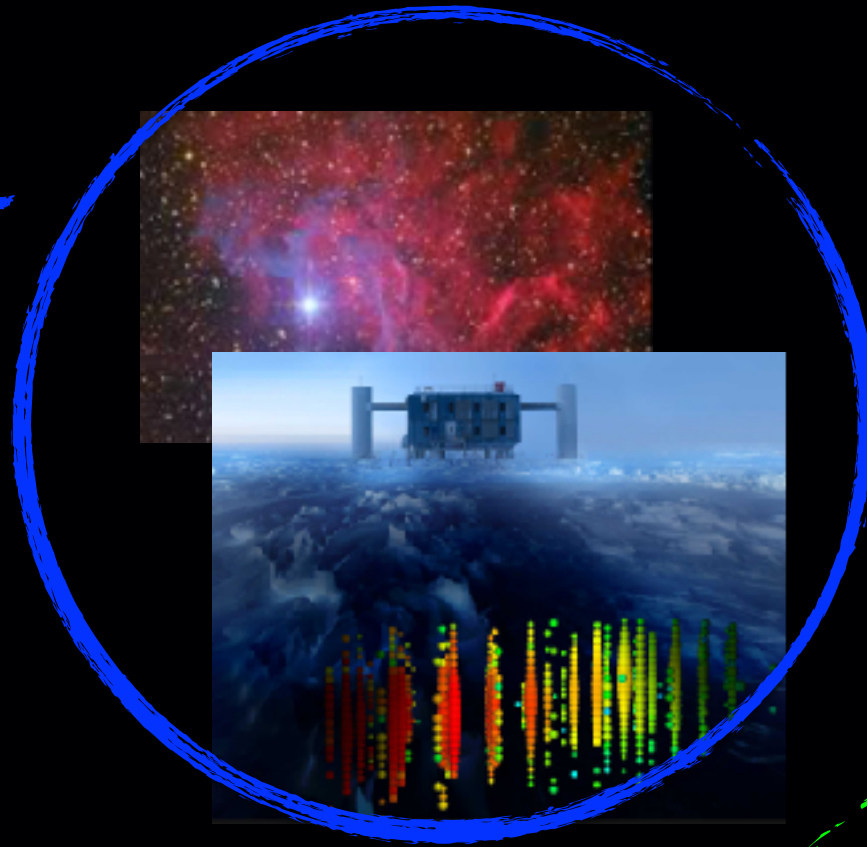
eV





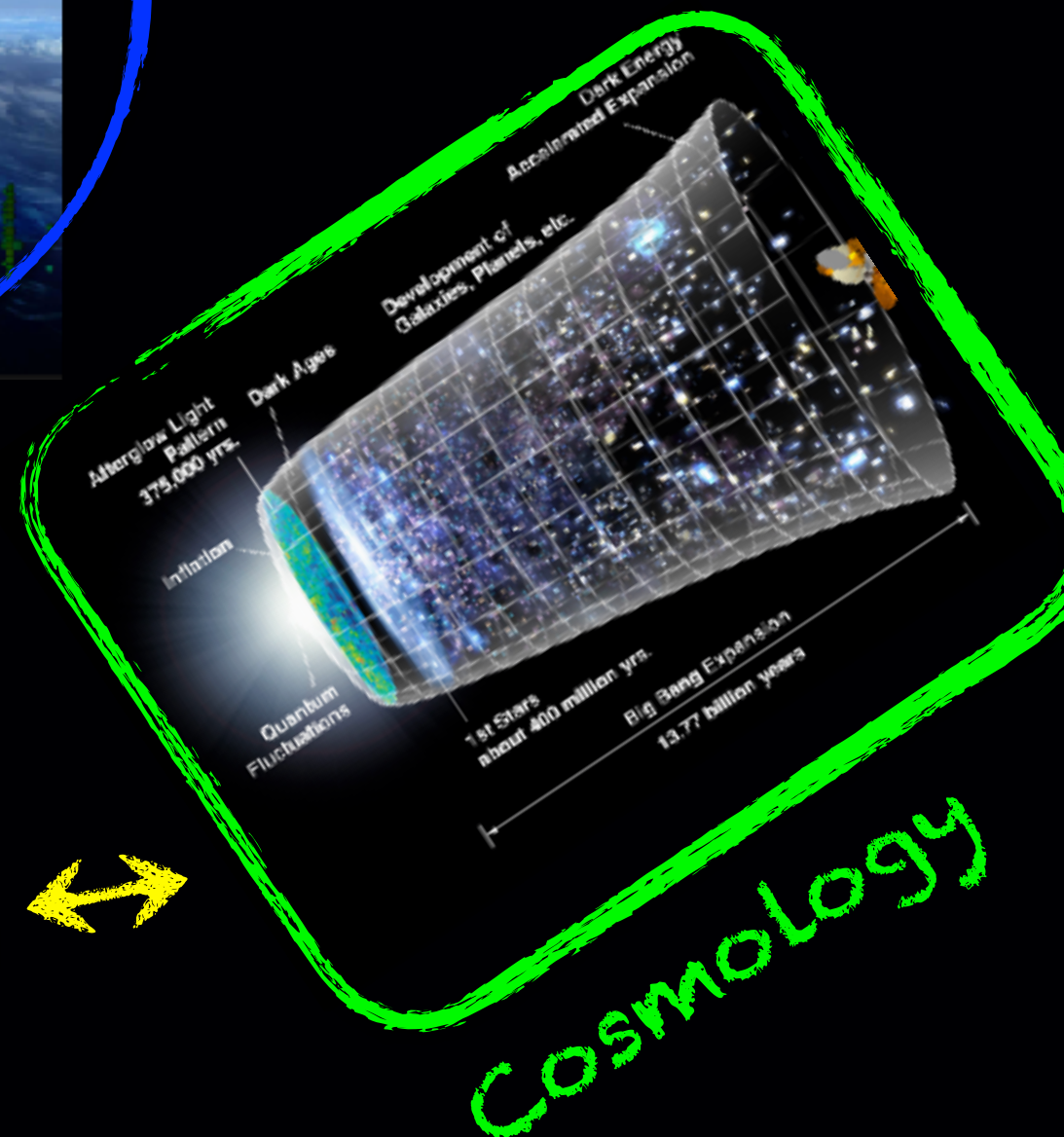
# Multi-surveys approach

Astrophysical  
sources



Laboratory

**Vs**  
&  
*properties*

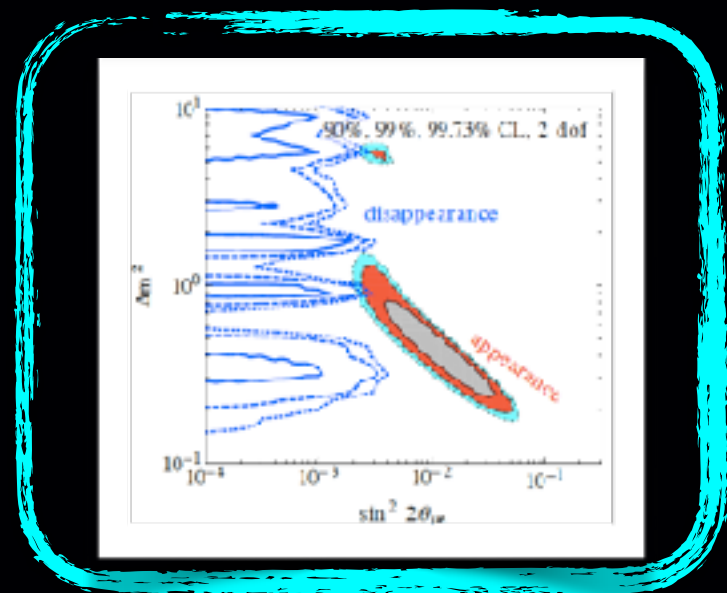
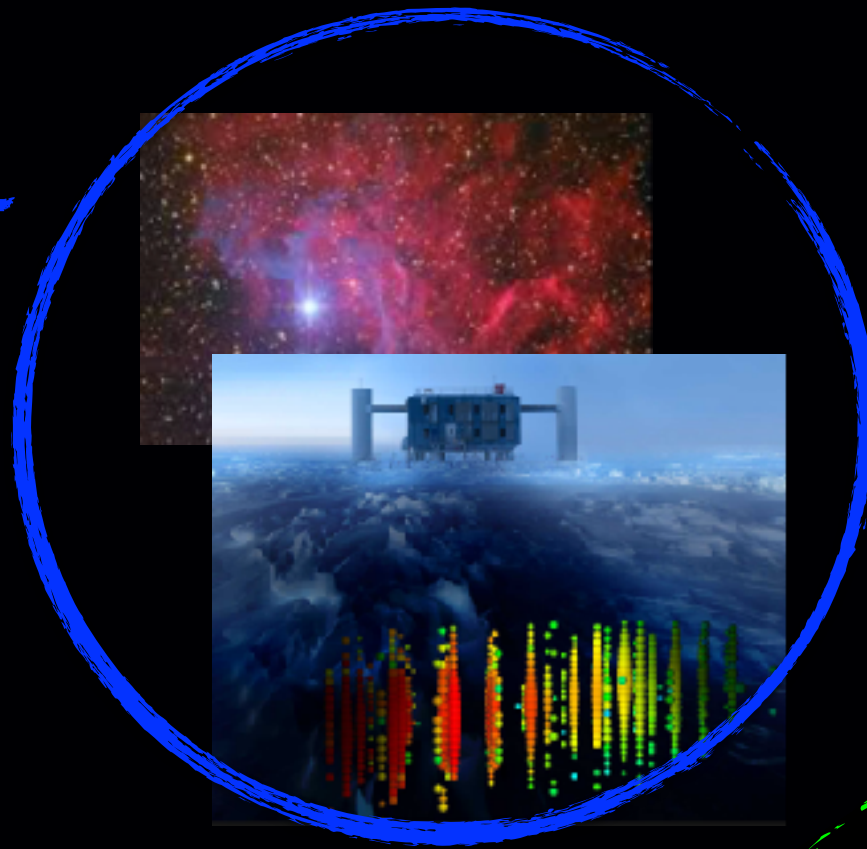


Cosmology



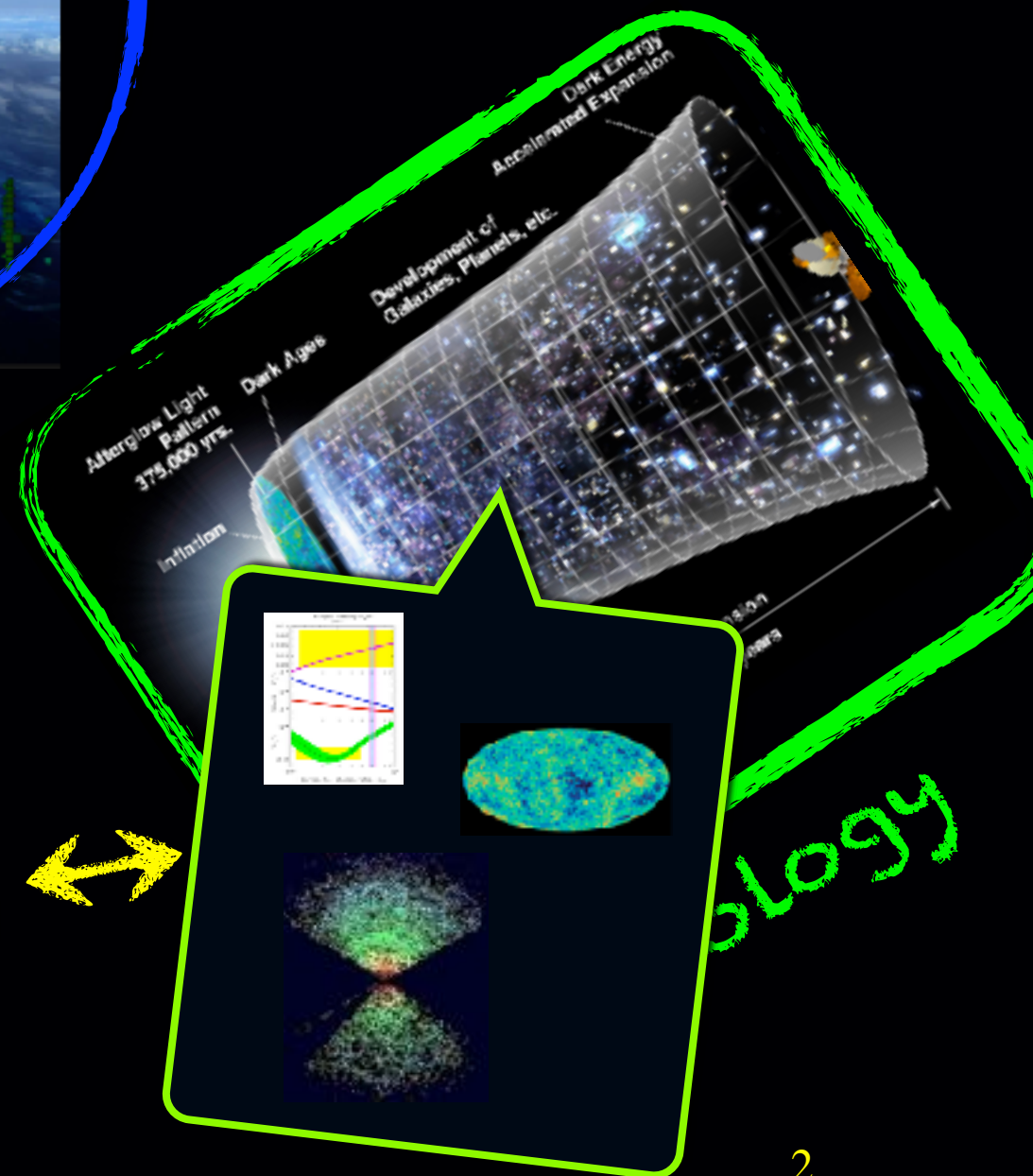
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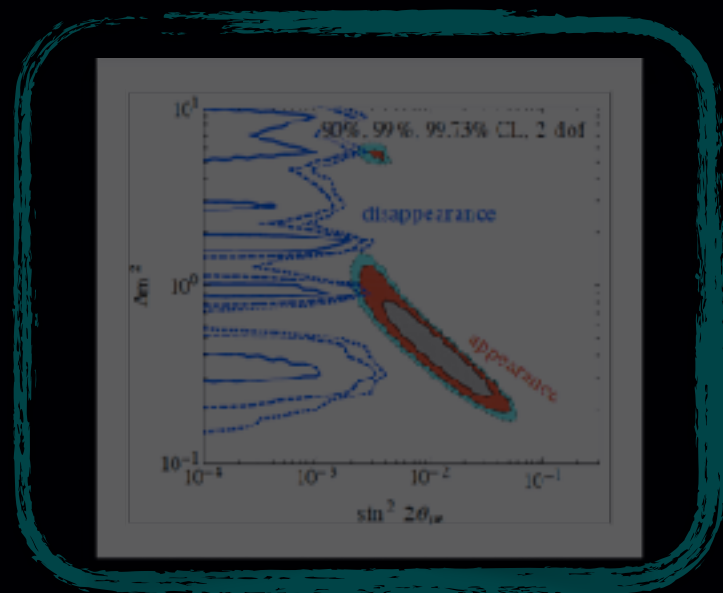
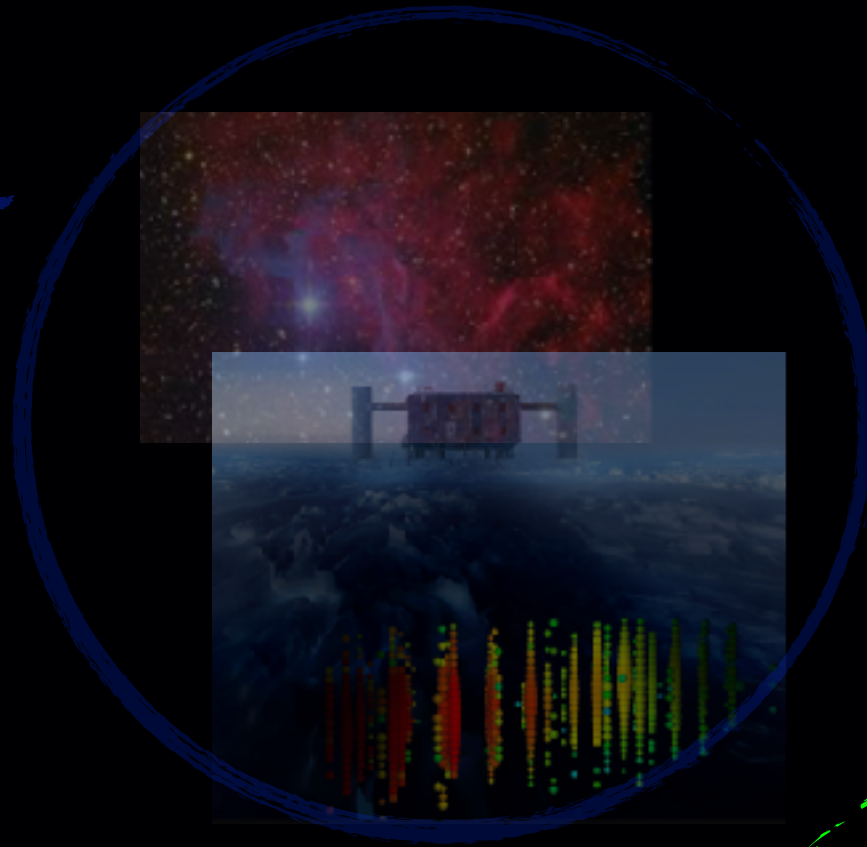
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ology

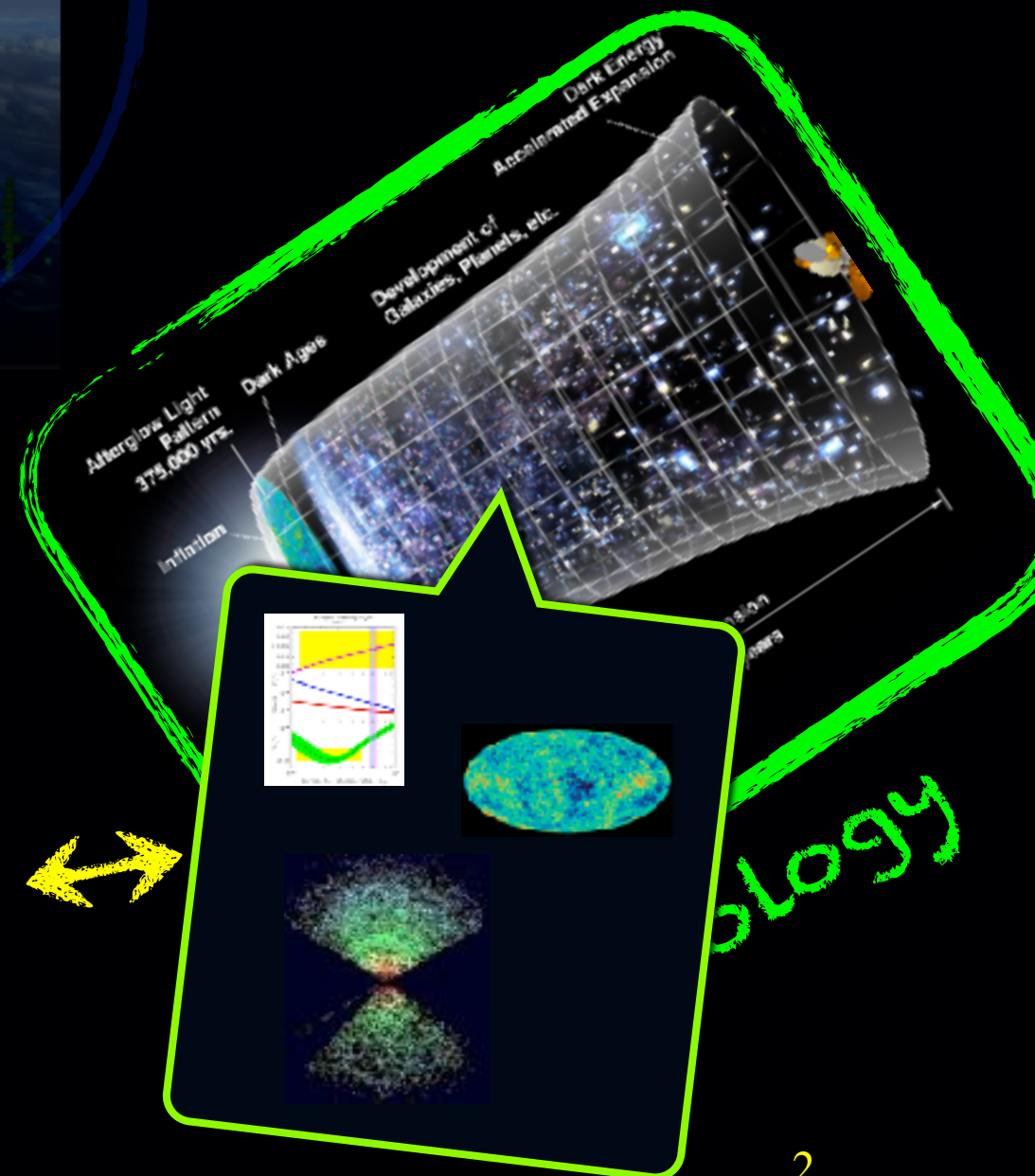
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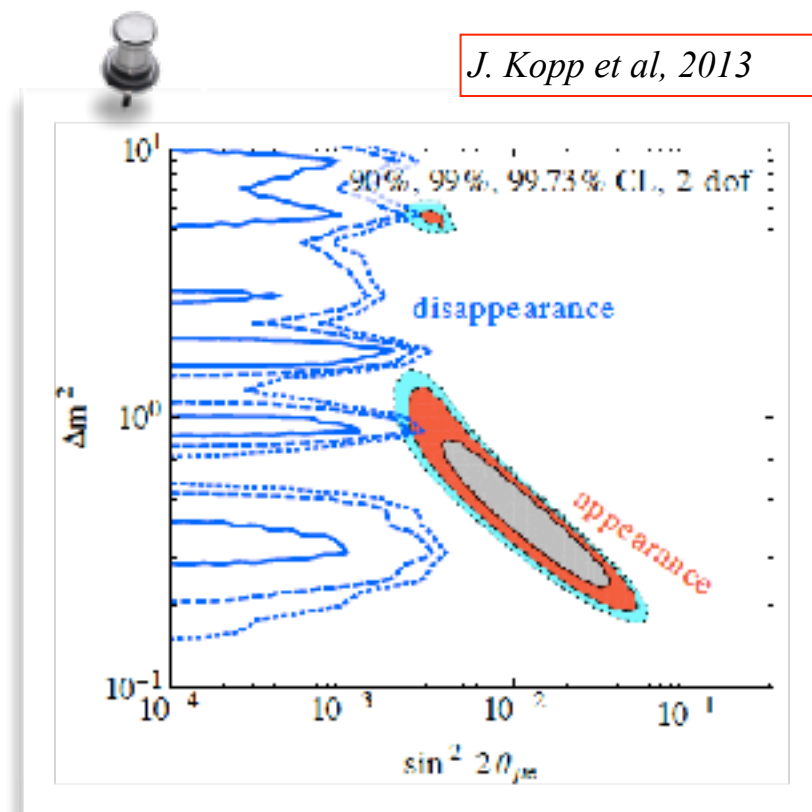
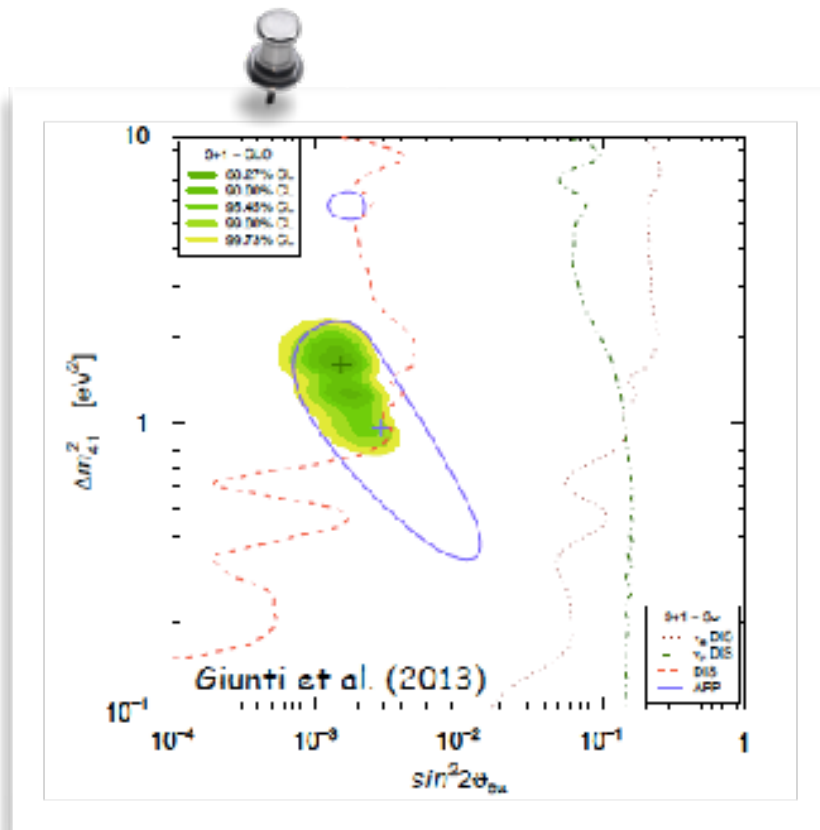
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*...often in tension among themselves...*



3+1, 3+2 schemes

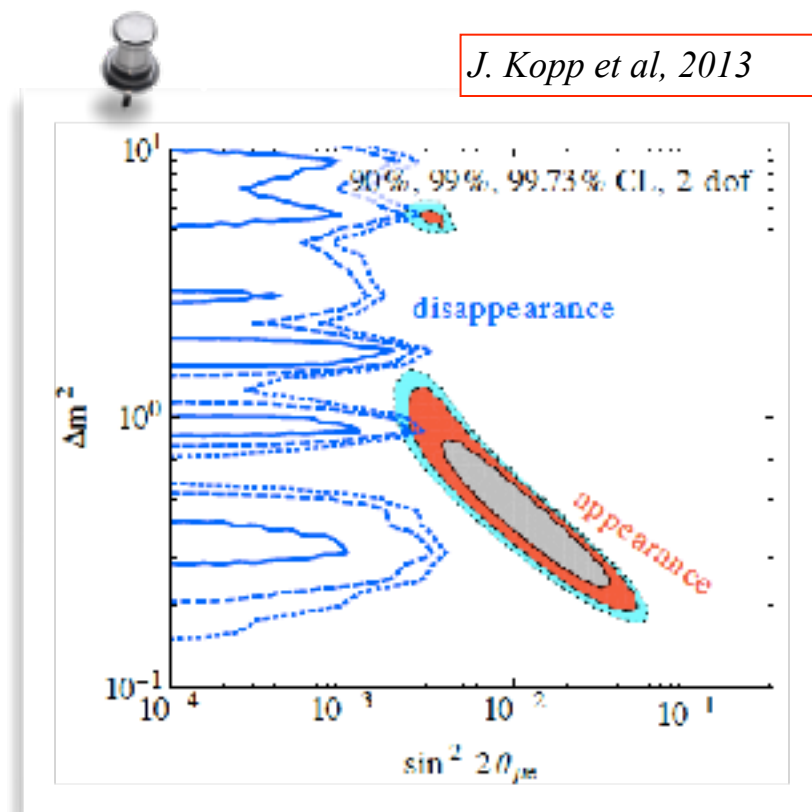
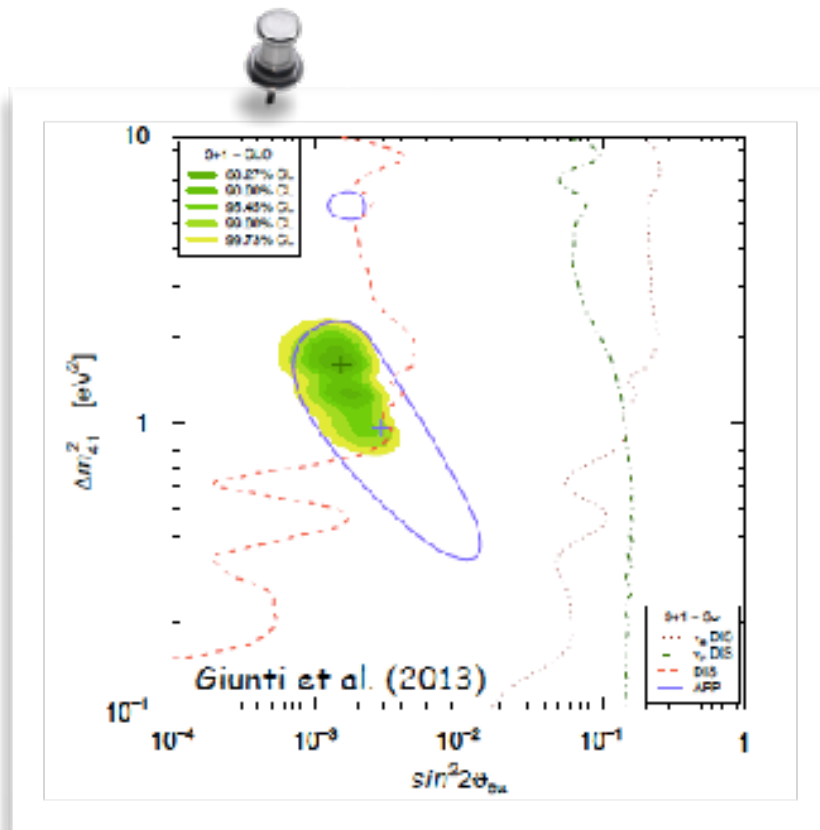
*New bad news are coming from IceCube, Minos, Daya Bay...*

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



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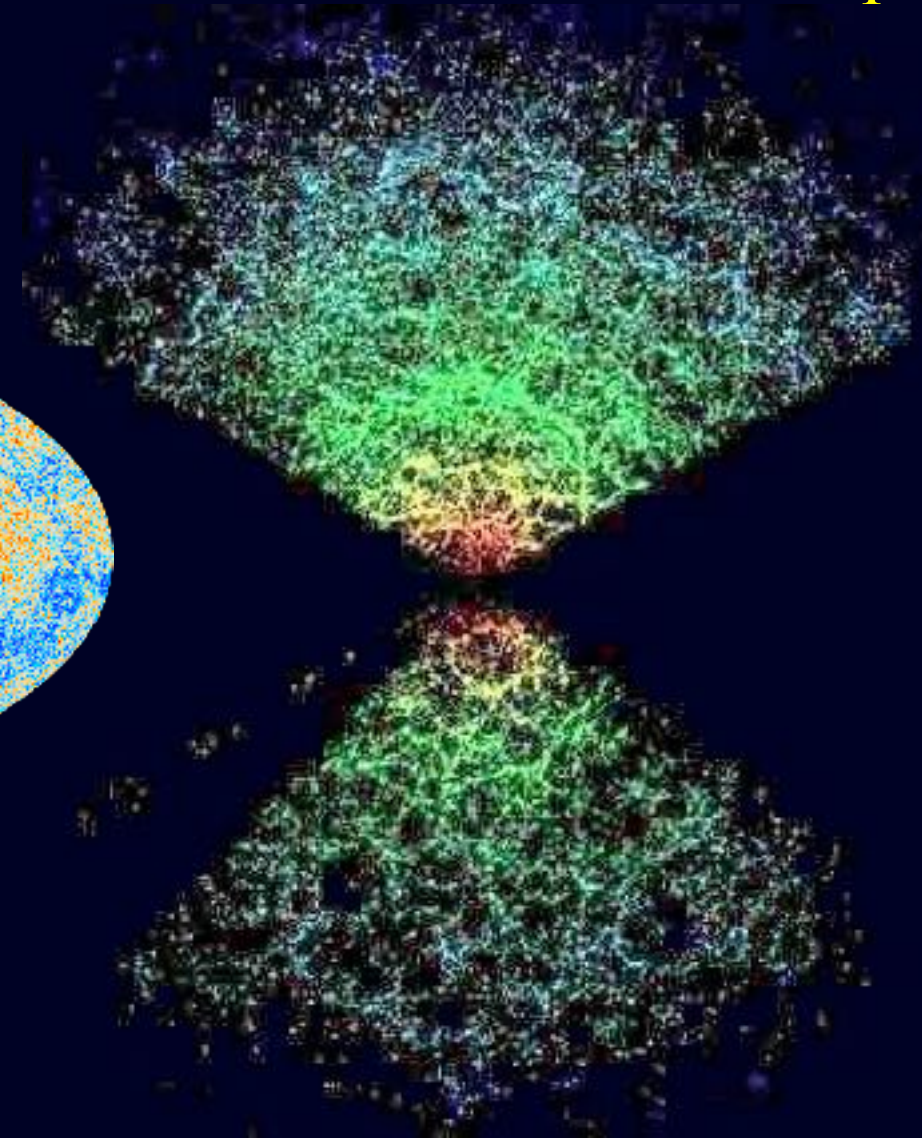
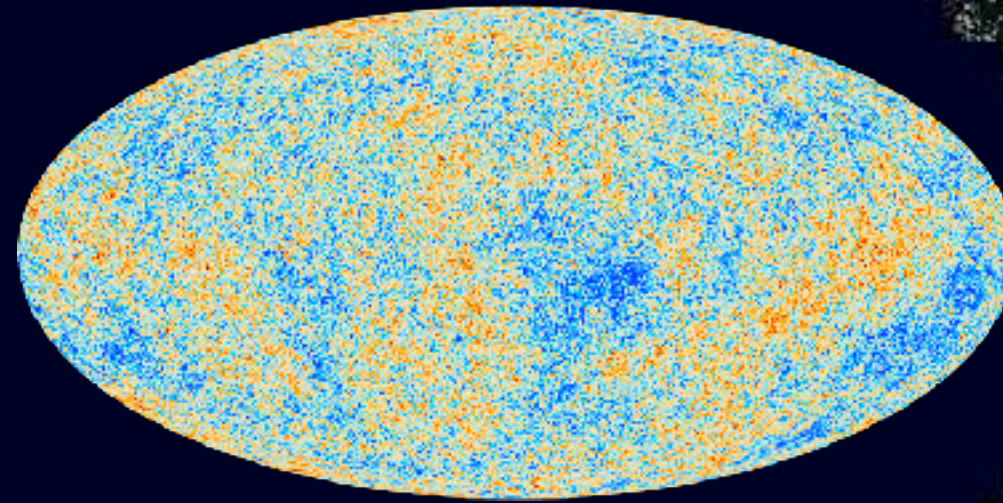
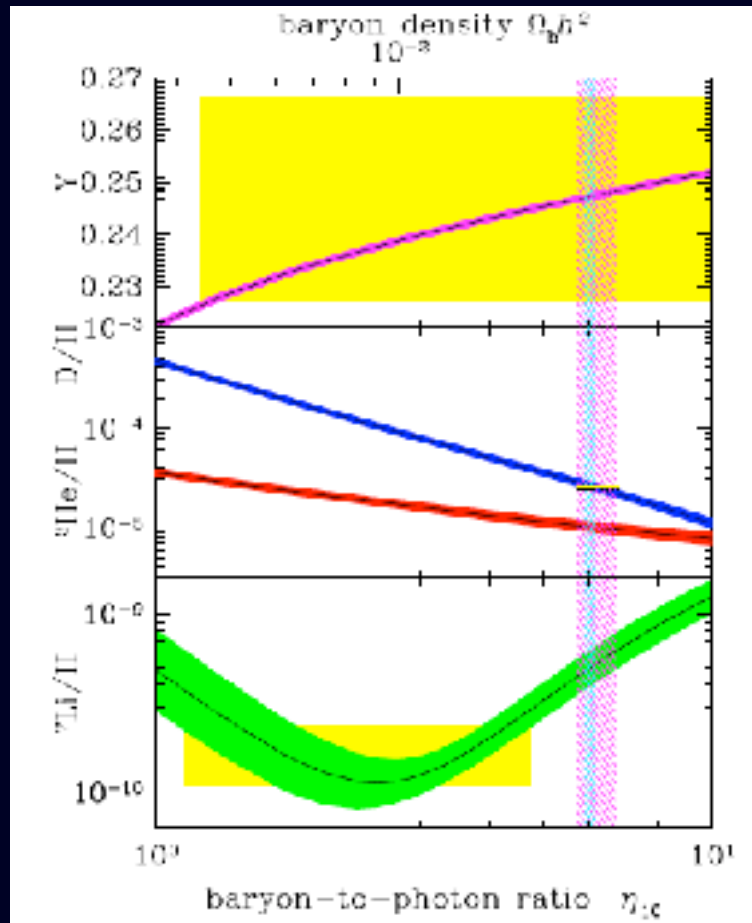
Are eV  $\nu_s$  compatible with cosmology?

# Cosmological observations

1 MeV

1 eV

T



Sensitivity to  $N_{\text{eff}}$  and  $\nu$  flavour (spectra)

Sensitivity to  $N_{\text{eff}}$  and  $\nu$  masses

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



# 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  $N_{\text{eff}}$

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

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

*Mangano et al. 2005*

(+ oscillations)

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

*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...

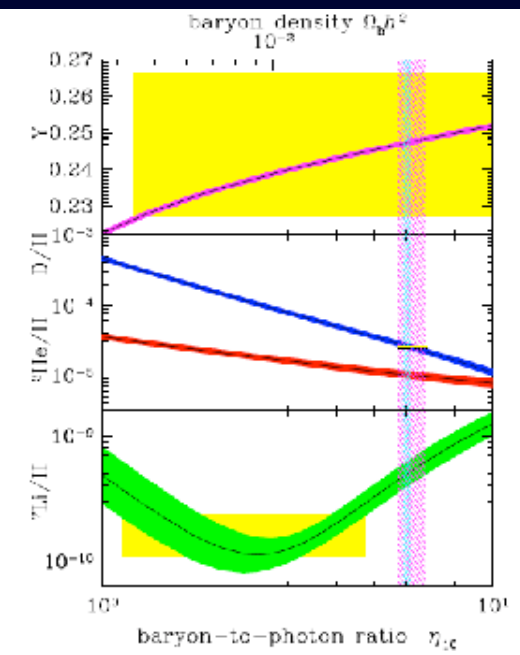


# Impact on Big Bang Nucleosynthesis

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

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

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



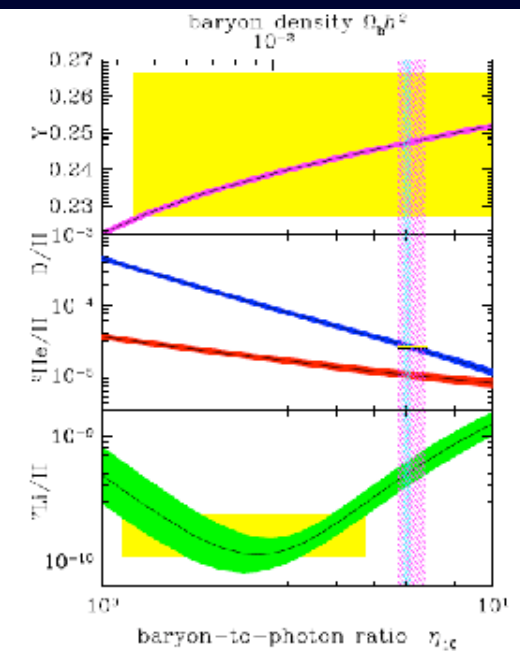
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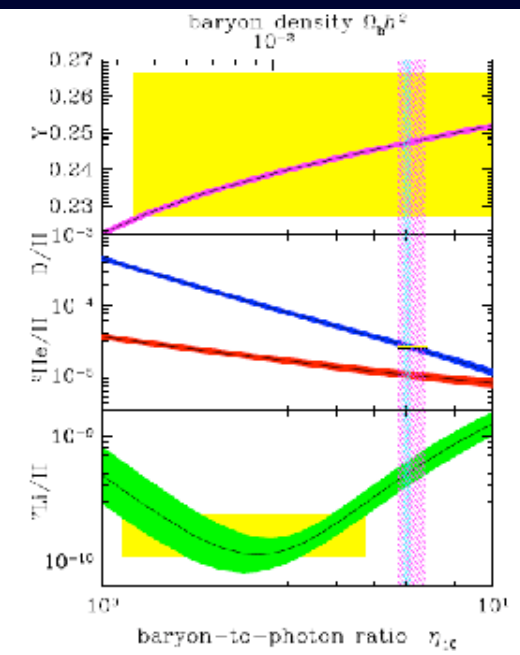


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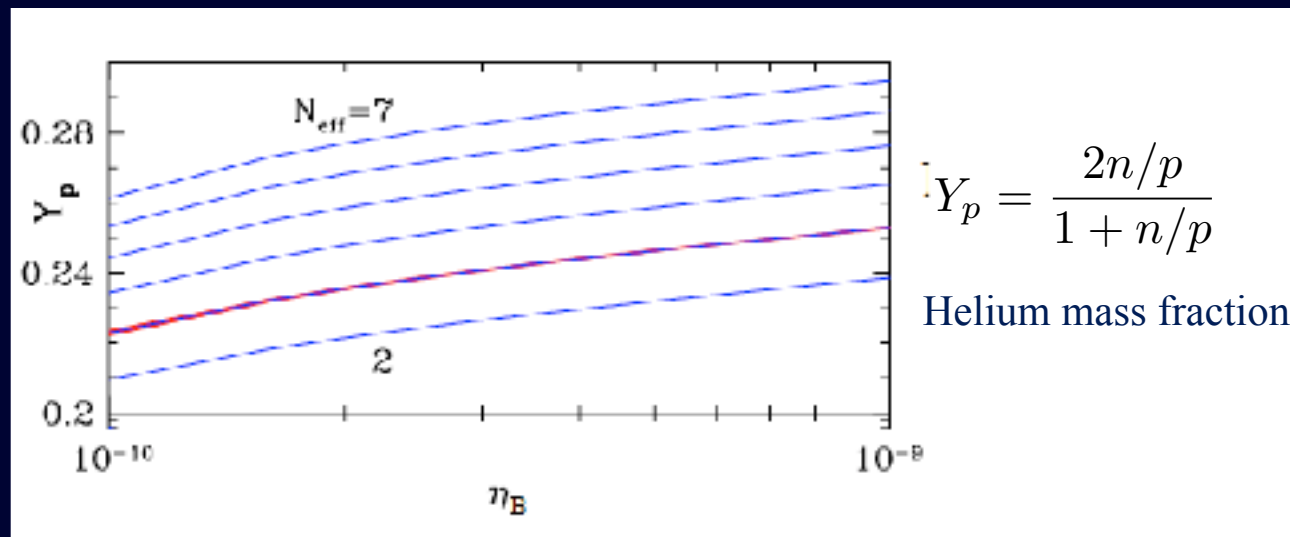
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Sterile  $\nu$  influence on BBN :

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

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



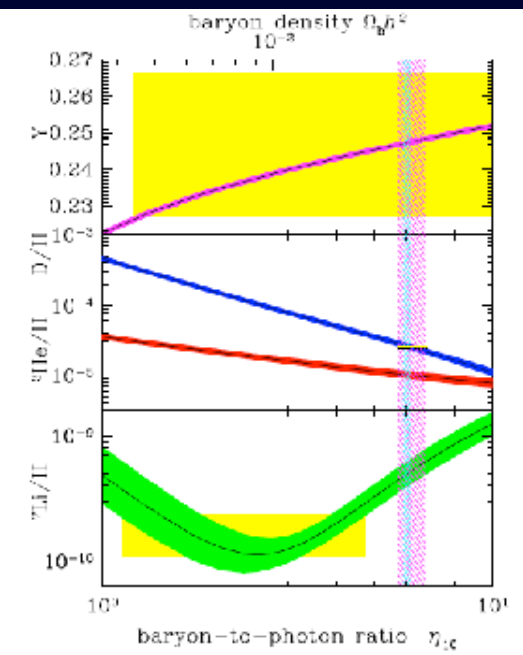


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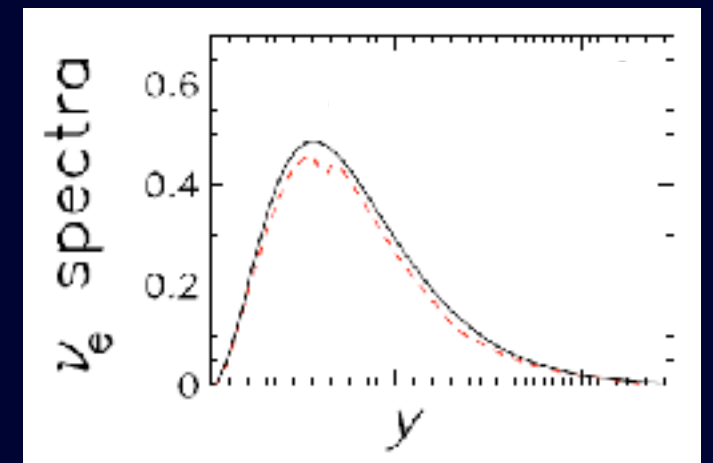


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$$N_{\text{eff}} \uparrow \rightarrow H \uparrow \rightarrow \text{early freeze out} \rightarrow n/p \uparrow \rightarrow ^4\text{He} \uparrow$$

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

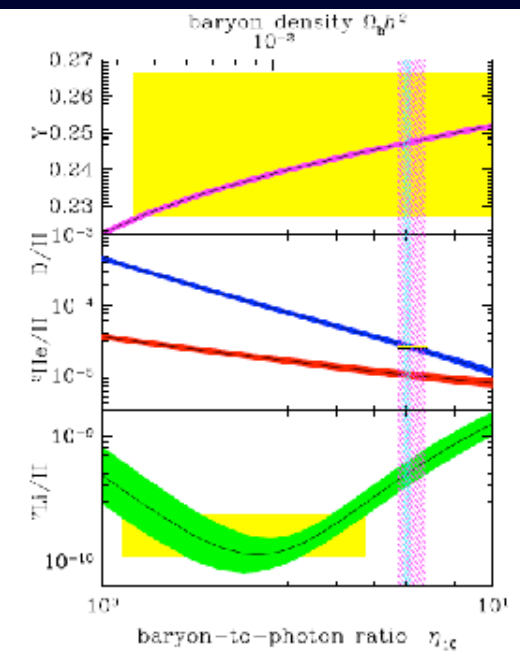


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**BBN constraint on  $\Delta N_{\text{eff}}$  : NO strong preference**

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

*Hamann et al, 2011, Mangano and Serpico. 2012*

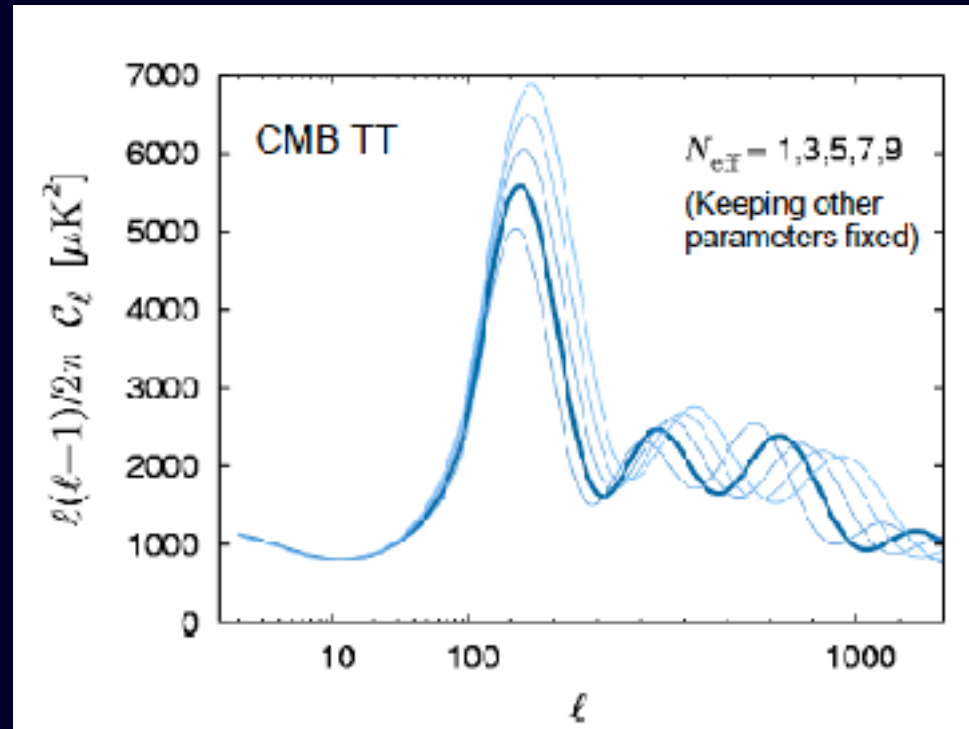
From new precise measure of D in damped Lyman- $\alpha$  system

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

*Cooke, Pettini et al., 2013*

# Impact on CMB

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



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

$$1 + z_{eq} = \frac{\omega_m}{\omega_\gamma} \frac{1}{1 + 0.227 N_{eff}}$$

Lattanzi's talk

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

Same data used to measure other cosmological parameters

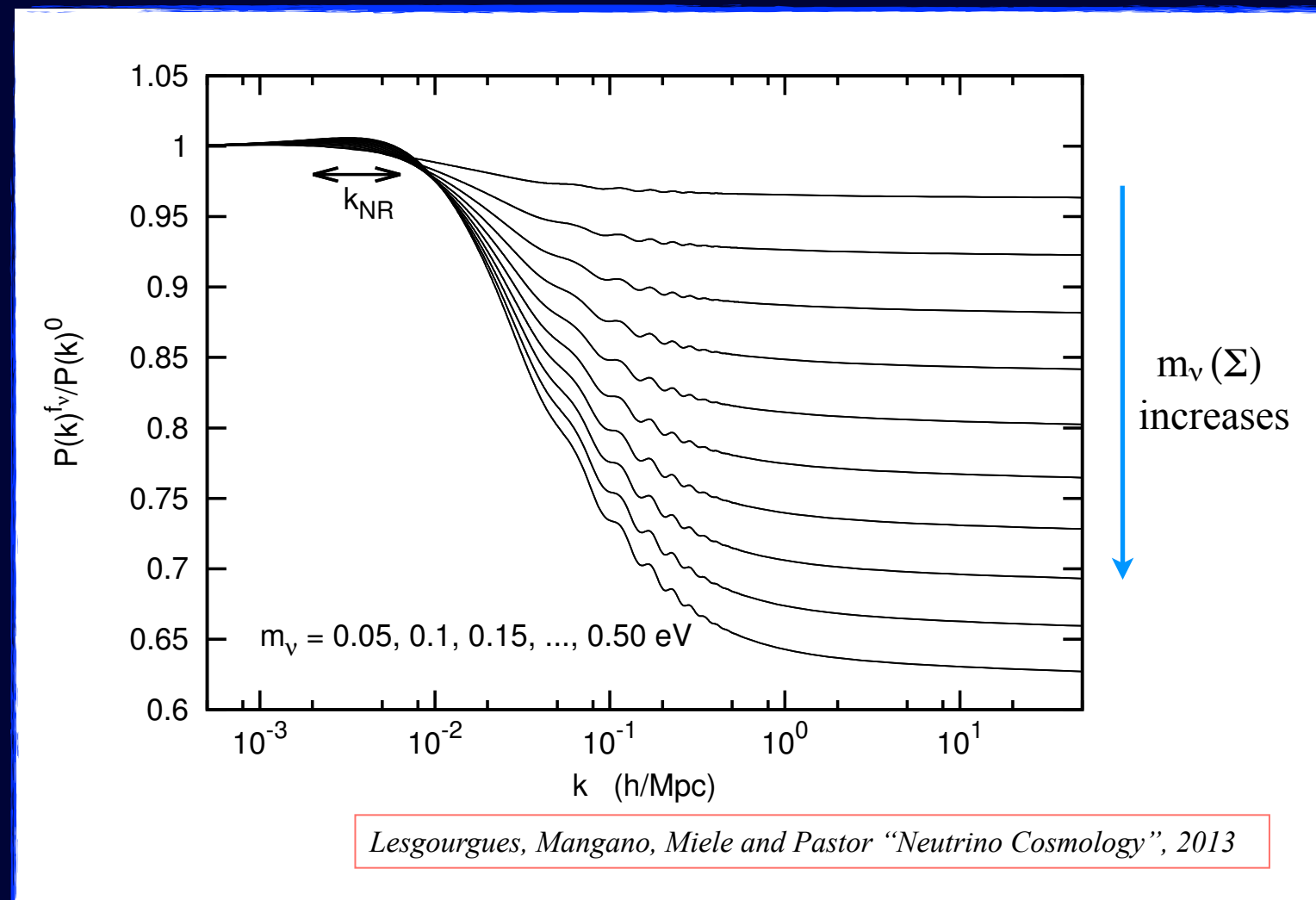
$\rightarrow$  better to combine with other cosmological probes



# Impact on the LSS

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

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



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

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

# Joint constraints on $N_{\text{eff}}$ and $m_{\nu_s}^{\text{eff}}$

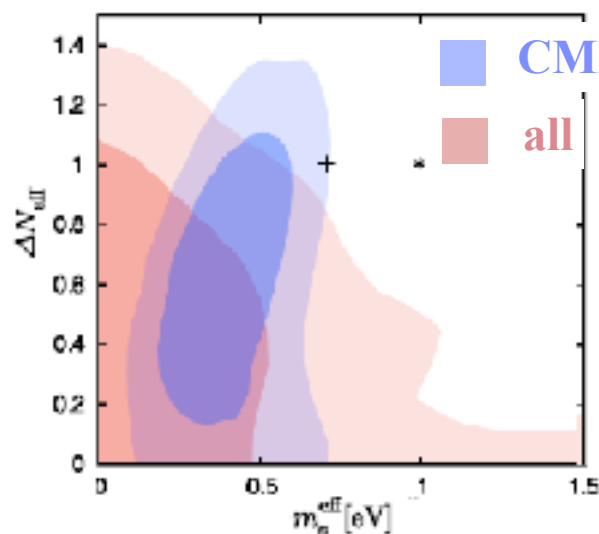
model	Planck TT +	mass bound (eV) (95% C.L.)
Joint analysis $N_{\text{eff}}$ & 1 mass $\nu_s$ (prior $m_{\nu_s}^{\text{ph}} < 10$ eV)	lowP+lensing+BAO	$N_{\text{eff}} < 3.7$ $m_{\nu_s}^{\text{eff}} < 0.52$
Joint analysis $N_{\text{eff}}$ & 1 mass $\nu_s$ (prior $m_{\nu_s}^{\text{ph}} < 2$ eV)	lowP+lensing+BAO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

Planck XIII, 2015

$$m_{\nu_s}^{\text{eff}} \equiv (94, 1 \Omega_\nu h^2) \text{eV}$$

$$m_{\nu_s}^{\text{eff}} = \rho_{ss} m_{\nu_s}^{\text{ph}}$$

Hamann and Hasenkamp, 2013

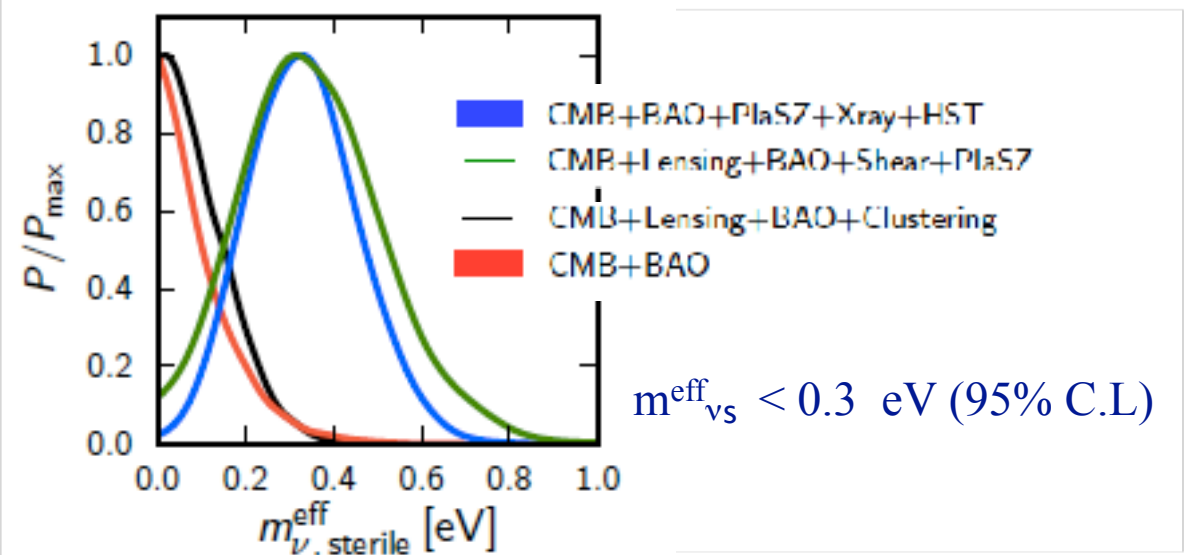


$$\Delta N_{\text{eff}} = 0.61 \pm 0.30$$

$$m_{\nu_s}^{\text{eff}} = 0.41 \pm 0.13 \text{ eV} \quad (68\% \text{ C.L.})$$

all= CMB+H0+ C+ CFHTLens

L. Verde et al, 2014



$$m_{\nu_s}^{\text{eff}} < 0.3 \text{ eV (95\% C.L.)}$$

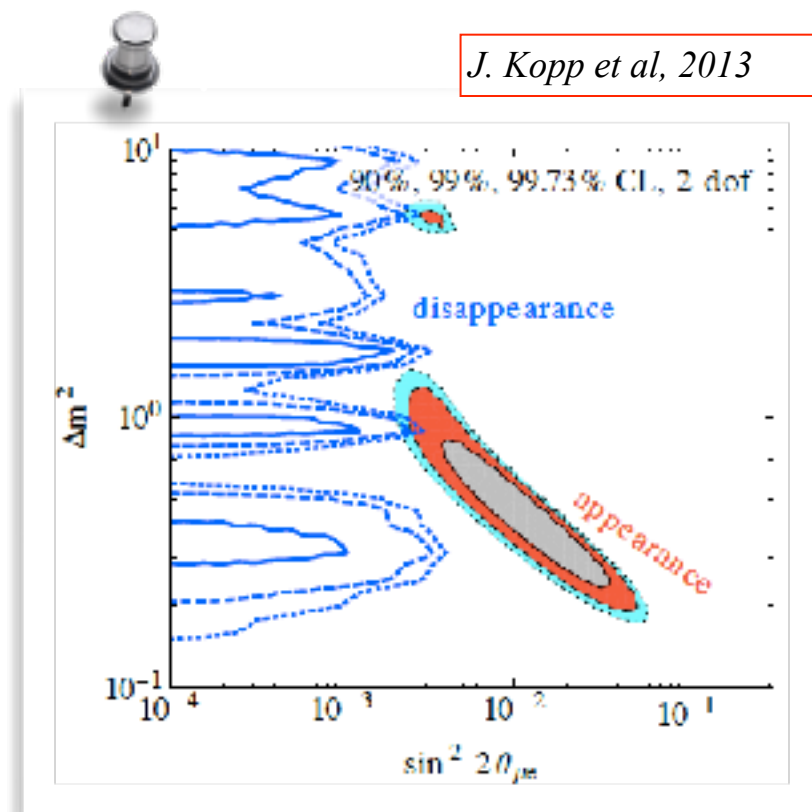
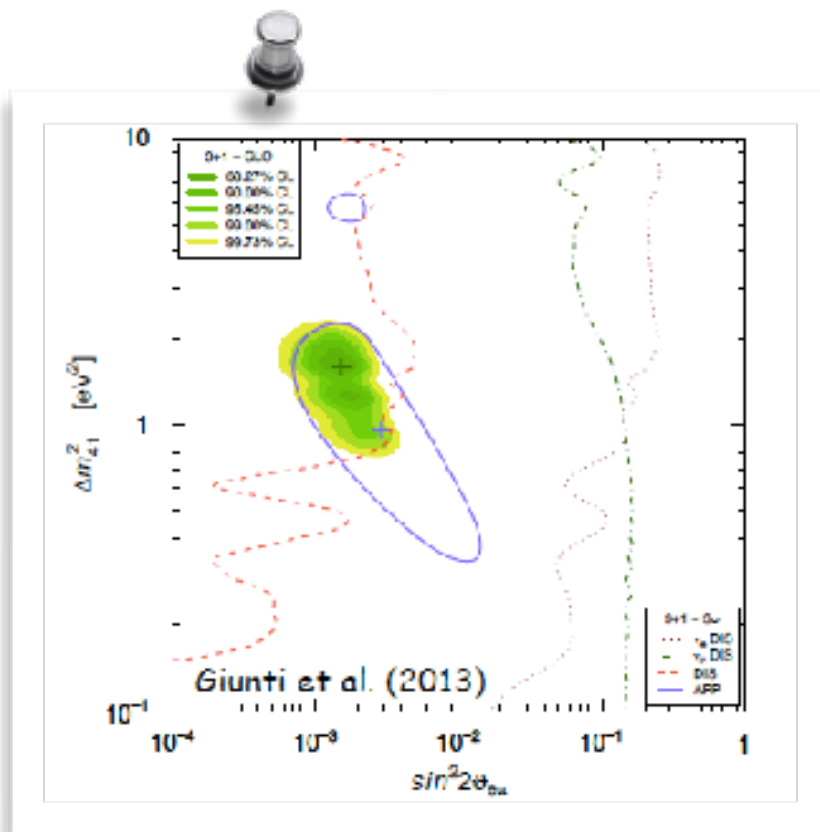
Less stringent mass bound from combined analysis  $\rightarrow m_{\nu_s}^{\text{eff}} < 0.6 \text{ eV}$

# 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...*



3+1, 3+2 schemes

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

Are eV  $\nu_s$  compatible with cosmology?

# Active-sterile flavour evolution

Sterile  $\nu$  are produced in the Early Universe by the mixing with the active species in presence of collisions

(3+1) Scenario

Evolution equation:

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

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

$\nu$  ensemble

$$\Omega = \Omega_{\text{vac}} + \Omega_{\text{mat}} + \Omega_{\nu-\nu} + \dots$$

Vacuum term

MSW effect with  
background medium  
(refractive effect)

refractive  $\nu$ - $\nu$   
self-interactions term

$C[\rho]$

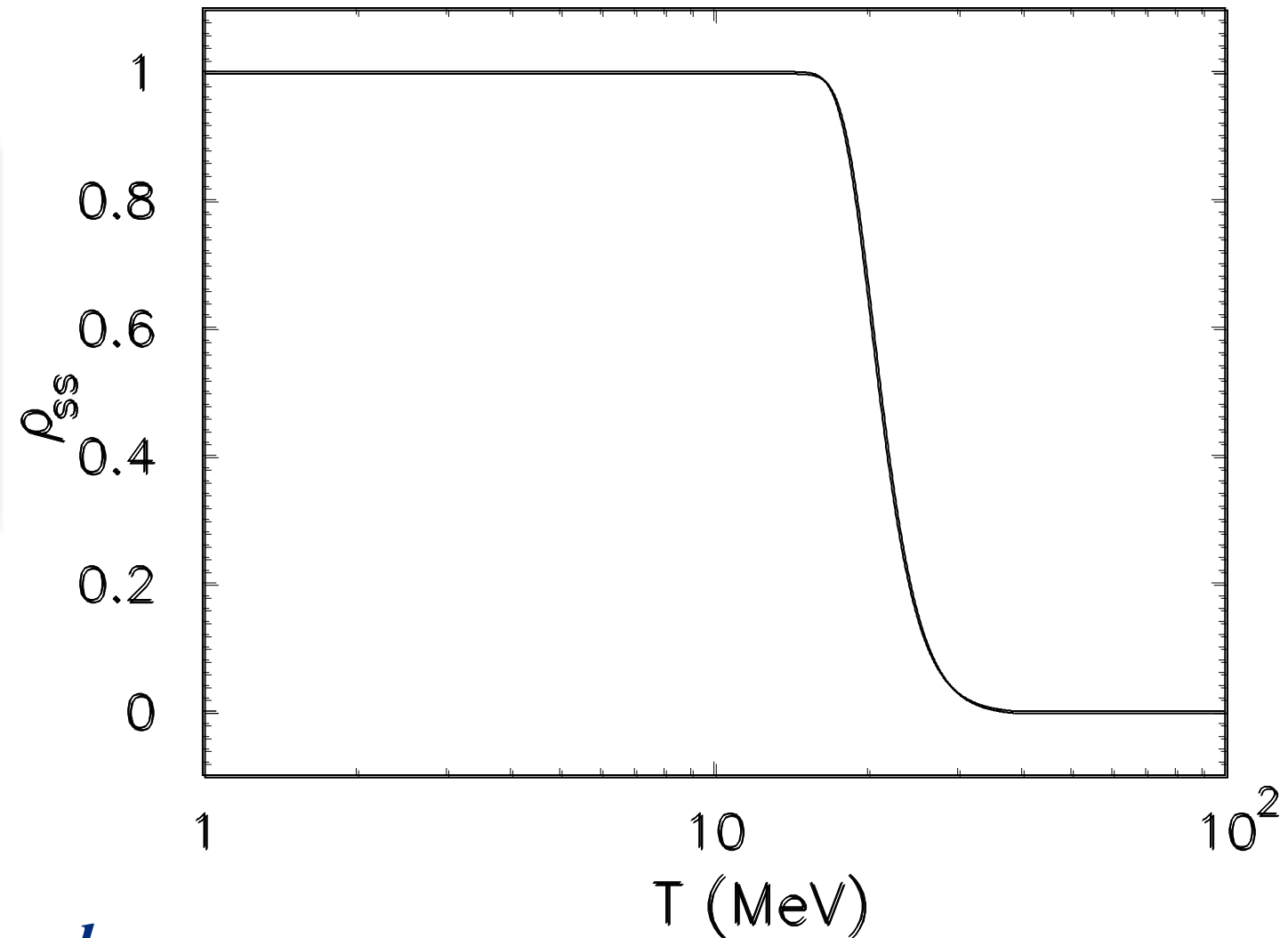
Collisional term

creation, annihilation and all the  
momentum exchanging processes

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



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



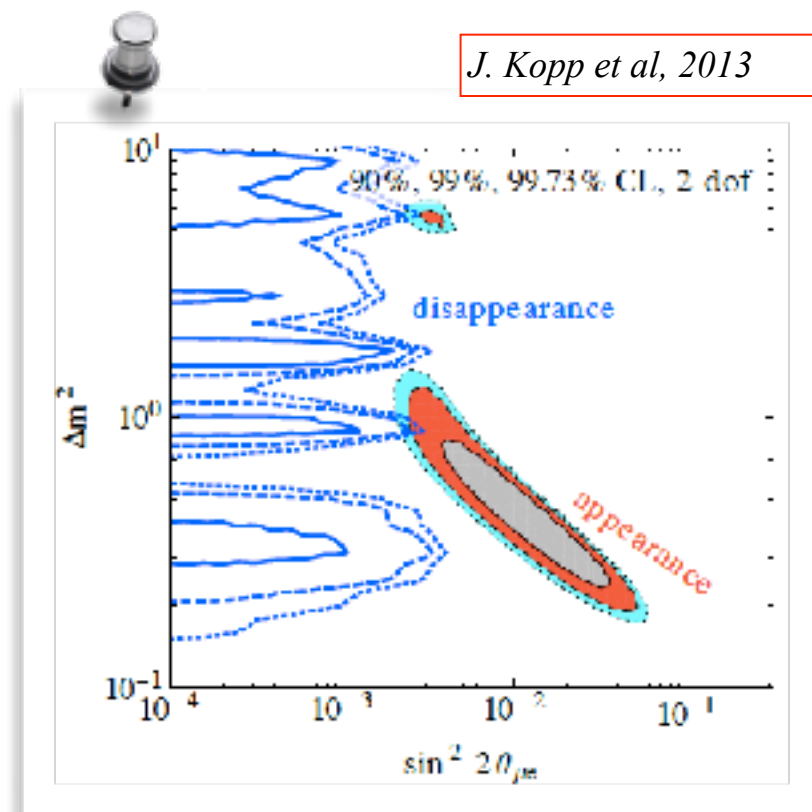
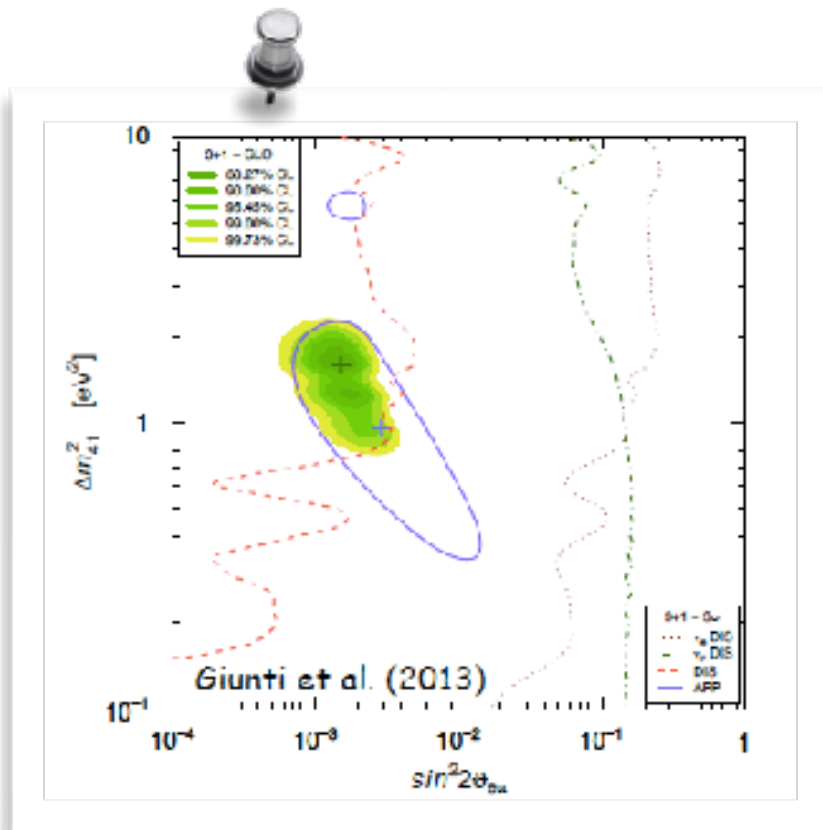
*Comparing with the cosmological bounds:*

*Thermalized sterile  $\nu$  with  $m \sim \mathcal{O}(1 \text{ eV})$  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

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Are eV  $\nu_s$  compatible with cosmology? NO

# Possible solutions...?

- *Different mechanisms to suppress the  $\nu_s$  abundance:*

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

In the presence of large  $\nu$ – $\bar{\nu}$  asymmetries ( $L \sim 10^{-2}$ ) 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**

3. **low reheating scenario**

sterile abundance depends on reheating temperature

*Chu, Dasgupta & Kopp 2015*

*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. 2014*

*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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## **Inflationary Freedom**

Shape of primordial power spectrum of scalar perturbations different from the usual power-law

# *Sterile production with primordial neutrino asymmetry*

*Foot and Volkas, 1995*

Introducing  $L = \frac{n_\nu - n_{\bar{\nu}}}{n_\gamma}$   $\longrightarrow$  Suppress the thermalization of sterile neutrinos ( $\rho_{ss} \downarrow$ )  
(Effective  $\nu_a$ - $\nu_s$  mixing reduced by large matter term  $\propto L$ )

$$\Omega = \Omega_{\text{vac}} + \Omega_{\text{mat}} + \underbrace{\Omega_{\nu-\bar{\nu}}}_{=L} \longrightarrow \text{asymmetric term} \propto (\varrho - \bar{\varrho})$$

**Caveat :** L can also generate MSW-like resonant flavour conversions among active and sterile neutrinos enhancing their production

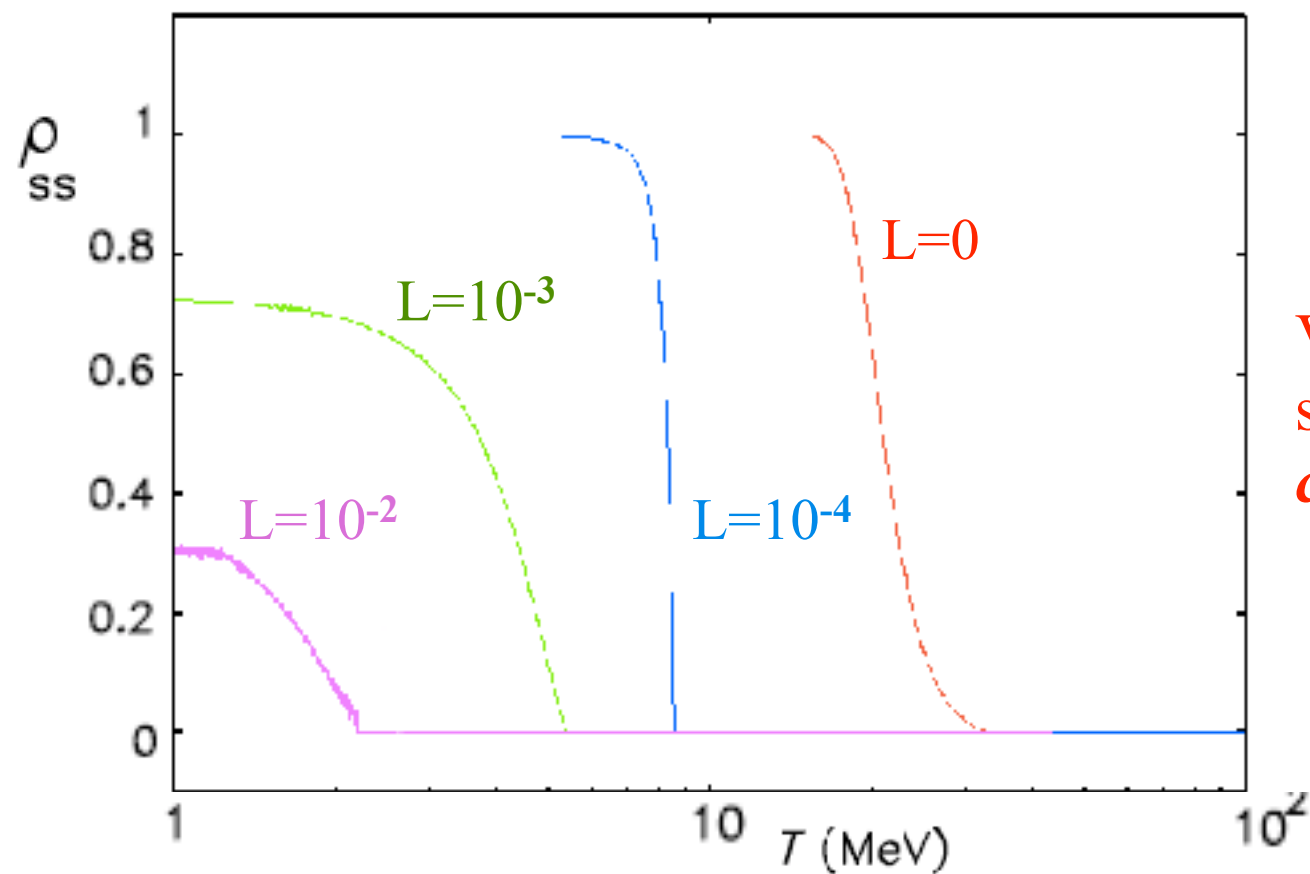


large L are necessary to reach the suppression

# *Sterile production by neutrino asymmetry*

$\rho_{ss}$  and spectra of active neutrinos (in particular  $\nu_e$ ) as function of the  $\nu$  *asymmetry parameter*.  $\rightarrow$  evaluation of the cosmological consequences

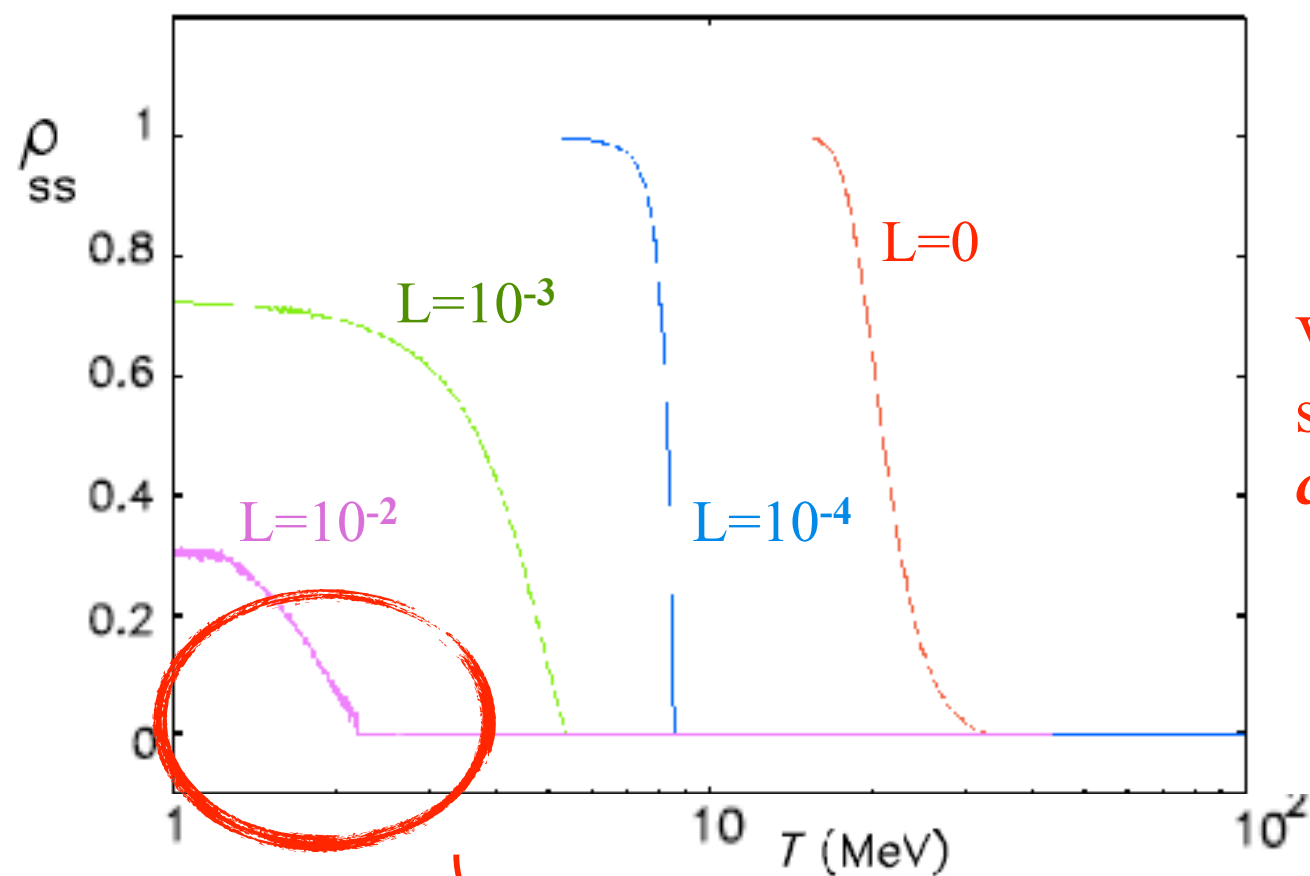
$$L_\alpha \simeq 0.68 \xi_\alpha \left( \frac{T_\nu}{T_\gamma} \right)^3$$



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

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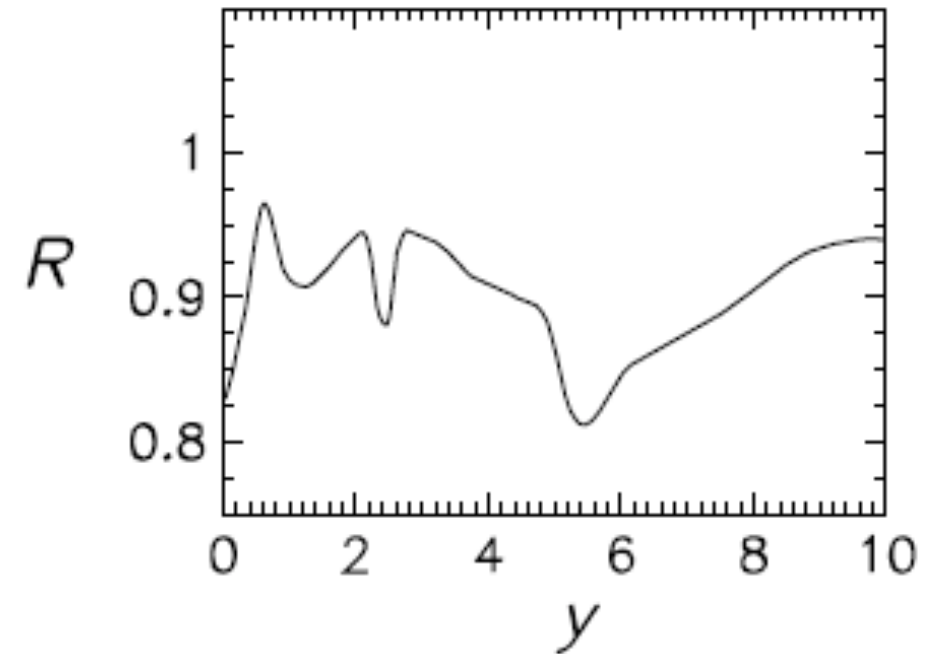
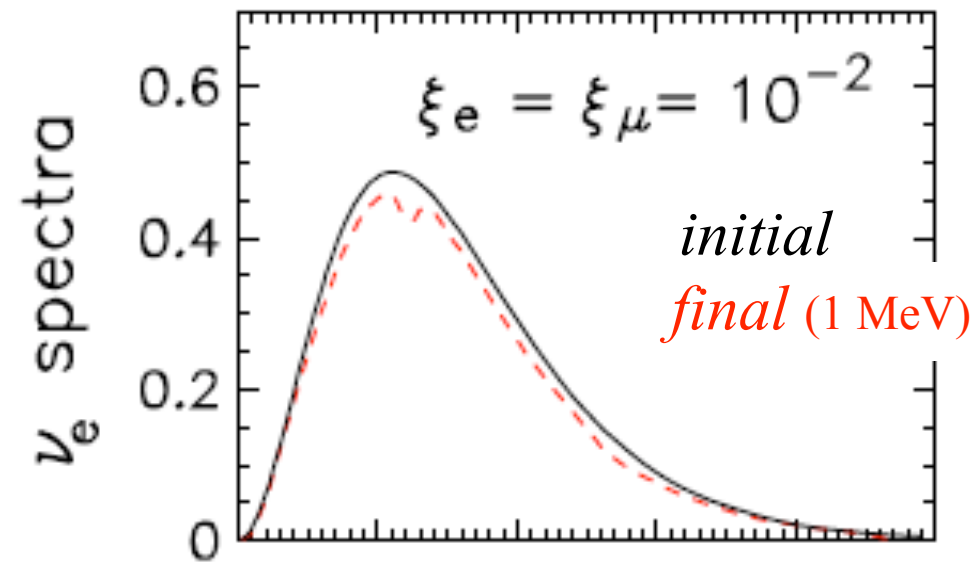


Very large asymmetries are necessary to suppress the sterile neutrino abundances leading to *non trivial consequences on BBN*

*conversions occur at  $T \sim T_\nu$  decoupling  
 $\Rightarrow$  active not repopulated anymore by  
collisions ( $\rho_{ee} < 1$ )*



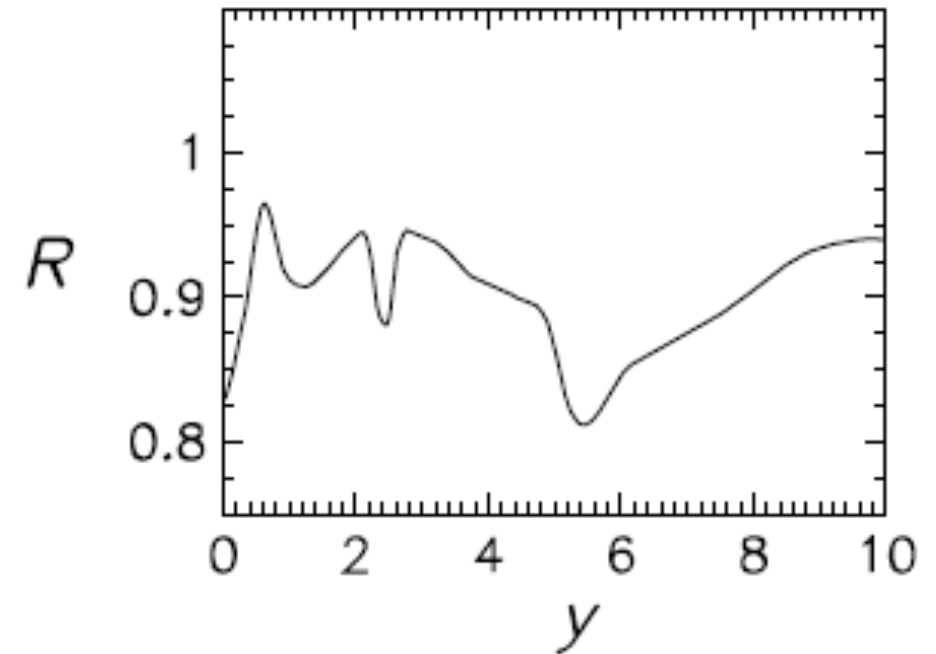
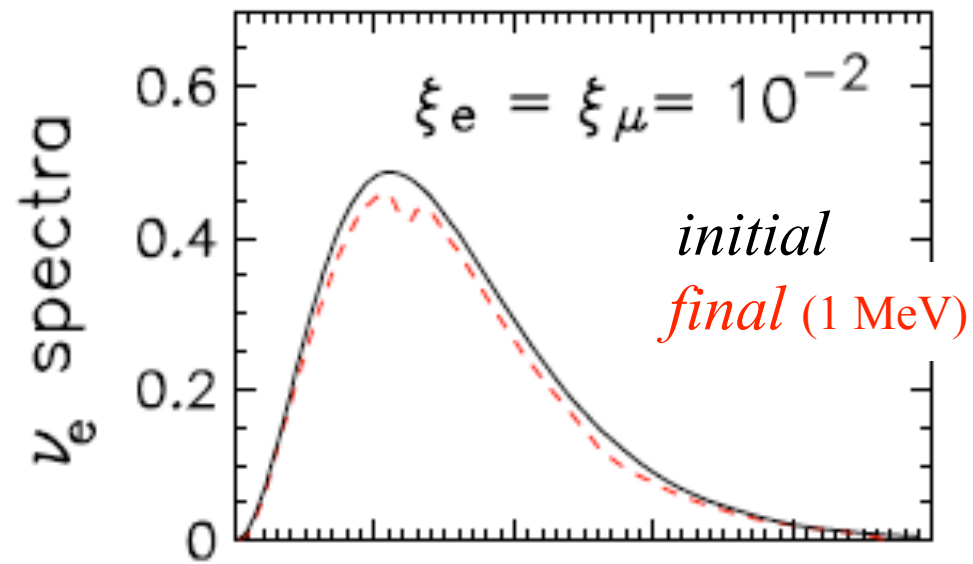
# Consequences on BBN



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

$\nu_e$  spectra distorted  $\rightarrow$  implications on BBN

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

Helium mass fraction

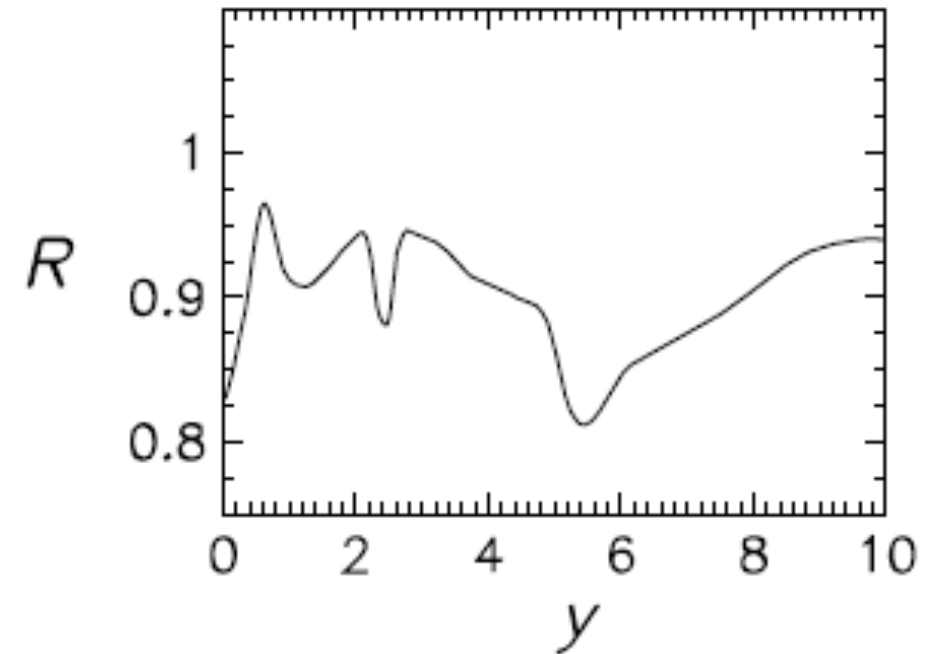
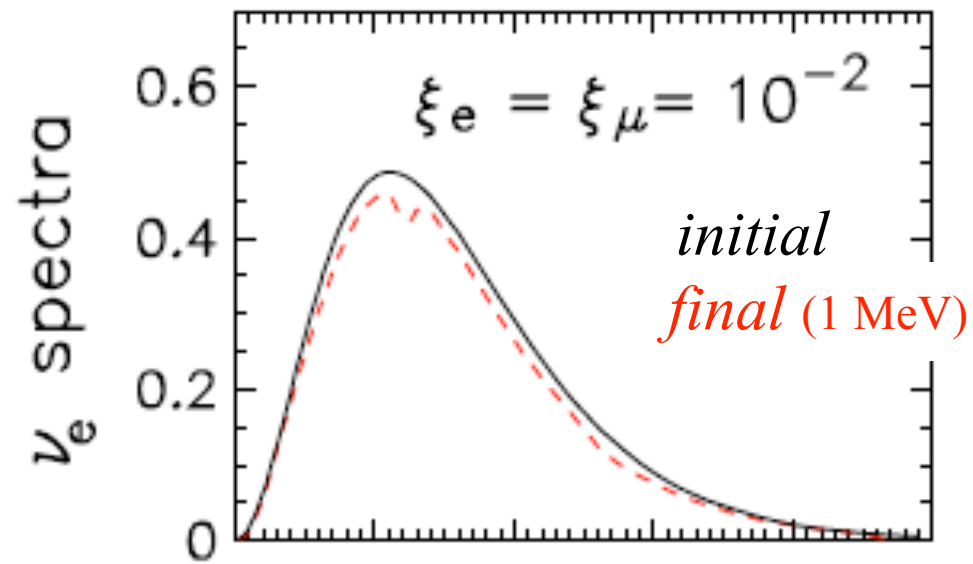
$Y_p$   $\uparrow$

with respect to the standard BBN and also to the BBN + L (no  $\nu$ s)

$H^2$   $\uparrow$

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with respect to the standard BBN and also to the BBN + L (no  $\nu$ s)

*The suppression of  $\nu$ s by L asymmetry is not for free  $\rightarrow$  difficult to accomodate with BBN*

# Possible solutions...?

- *Different mechanisms to suppress the  $\nu_s$  abundance:*

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

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

2. **“secret” interactions for sterile neutrinos**

3. **low reheating scenario**

sterile abundance depends on reheating temperature

- *Modification of cosmological models*

## **Inflationary Freedom**

Shape of primordial power spectrum of scalar perturbations different from the usual power-law



# *Secret interactions for sterile neutrinos*

Different authors have assumed the Standard Model (SM) is augmented by one extra species of light ( $\sim$  eV) neutrinos  $\nu_s$ , 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  $\nu$  feel a new potential that can suppresses active-sterile mixing** (*through an effective  $\nu_a$ - $\nu_s$  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



**→  $\nu$ SI 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  $\nu$  mediated by a **massive gauge boson X** :

$$\nu_s - \nu_s \text{ interaction strength } G_X = \frac{\sqrt{2}}{8} \frac{g_X^2}{M_X^2} \quad \text{for } T < M_X$$

Evolution equation:

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

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

$$C[\rho] = C_{SM} + \underbrace{C_{Secr}}_{\propto G_X^2}$$

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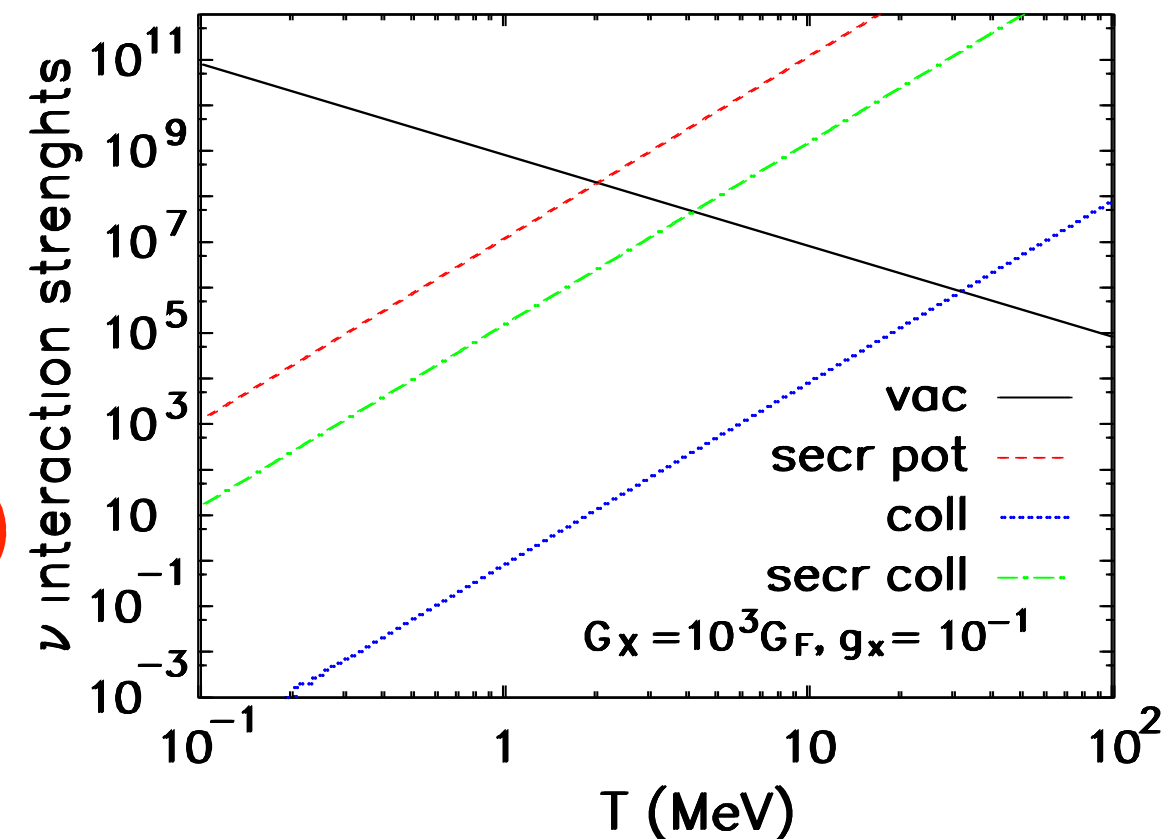
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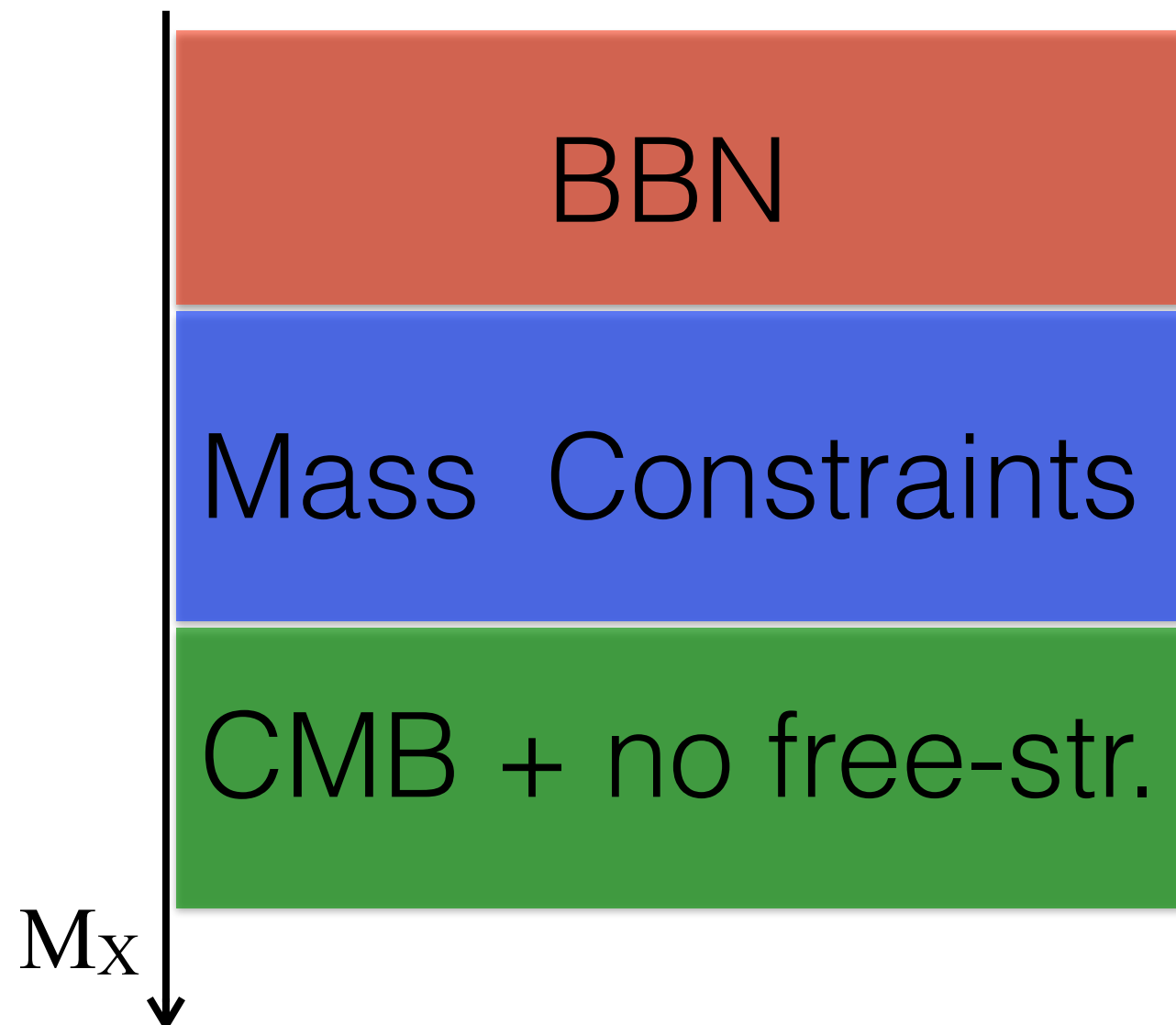
$\propto G_X$

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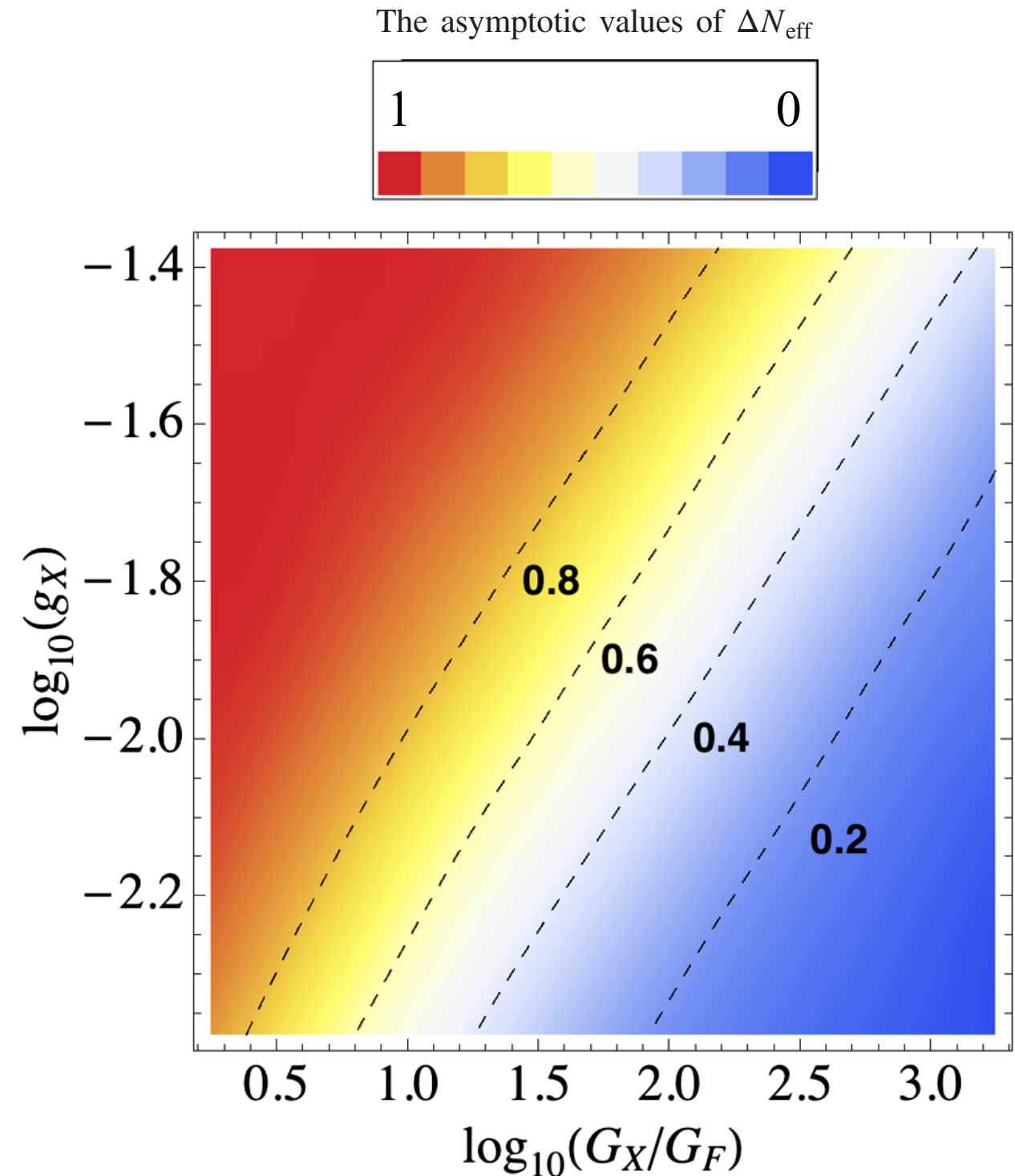
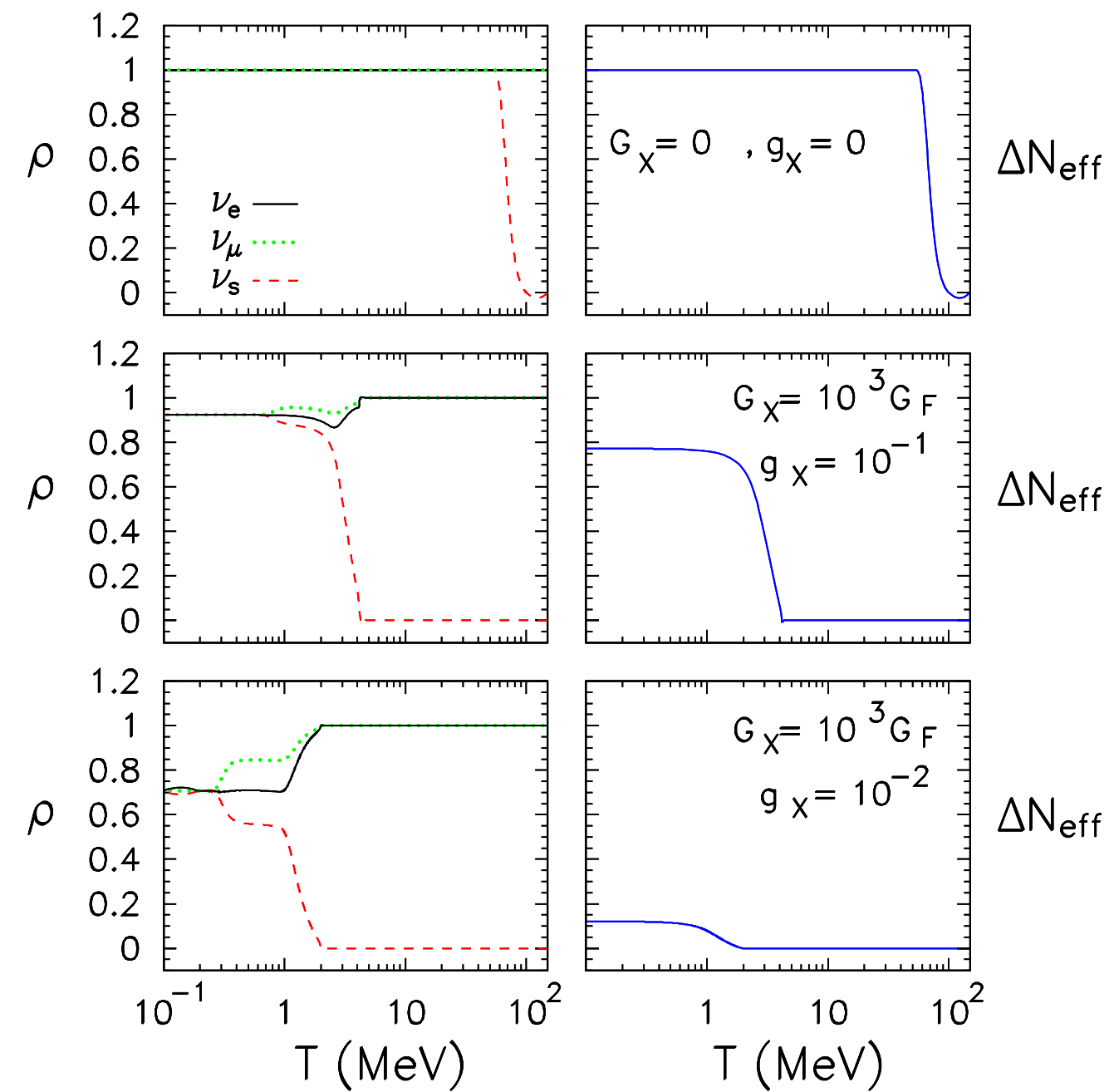
$\propto G_X^2$



# Constraints for sterile nSI (Vector boson)



# BBN constraints for sterile $\nu$ SI (vector)



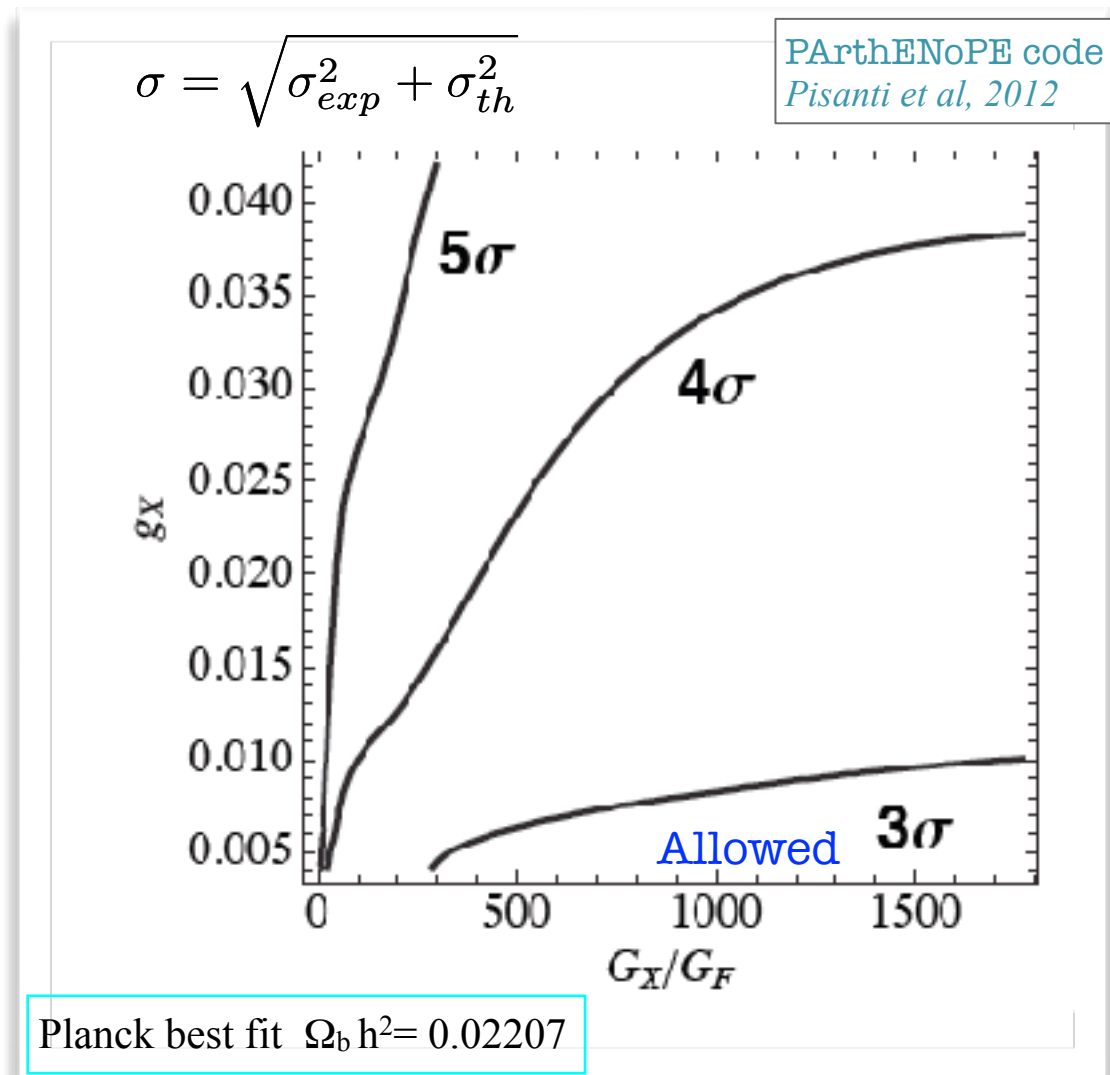
*Saviano, Pisanti, Mangano, Mirizzi 2014*



# BBN constraints for sterile $\nu$ SI (vector)

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

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



## Deuterium yield

Experimental reference value:

$${}^2\text{H}/\text{H} = (2.53 \pm 0.04) \times 10^{-5}$$

$\underbrace{\hspace{10em}}_{\sigma_{\text{exp}}}$

*R. Cooke et al, 2013*

Translating in a bound for the mediator mass:

mass permitted:  $M_X \leq 40 \text{ MeV}$

*Saviano, Pisanti, Mangano, Mirizzi 2014*

# Mass constraints for sterile $\nu$ SI (vector)

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

**Very strong secret collisional term leads to a quick flavor equilibrium**

*Stodolsky, 1987*

$$\begin{array}{ccc}
 (\rho_{ee}, \rho_{\mu\mu}, \rho_{\tau\tau}, \rho_{ss})_{\text{initial}} & \longrightarrow & (\rho_{ee}, \rho_{\mu\mu}, \rho_{\tau\tau}, \rho_{ss})_{\text{final}} \\
 (1, 1, 1, 0) & & (3/4, 3/4, 3/4, 3/4)
 \end{array}$$



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

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

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

*The flavour evolution leads to a large population of  $\nu$ s, in conflict with the cosmological mass bound*

$$m_{\text{st}}^{\text{eff}} = \rho_{ss} \sqrt{\Delta m_{\text{st}}^2} = \frac{3}{4} \sqrt{\Delta m_{\text{st}}^2} \quad \text{lower value in the } 2\sigma \text{ range from anomalies gives } m_s^{\text{eff}} \sim 0.8 \text{ eV}$$

*in tension with the CMB and LSS conservative bounds on sterile mass ( $< 0.6 \text{ eV}$ )*

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

**Secret interaction scenario: disfavored  $M_X > 0.1 \text{ MeV}$  ( $\Leftrightarrow \sim 10^9 G_F$ )**

*Mirizzi, Mangano, Pisanti Saviano, 2014*

# A surprising effect on $N_{\text{eff}}$

After the production,  $\nu_s$  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:  $n_{\nu \text{ TOT}}$  must be constant



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

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

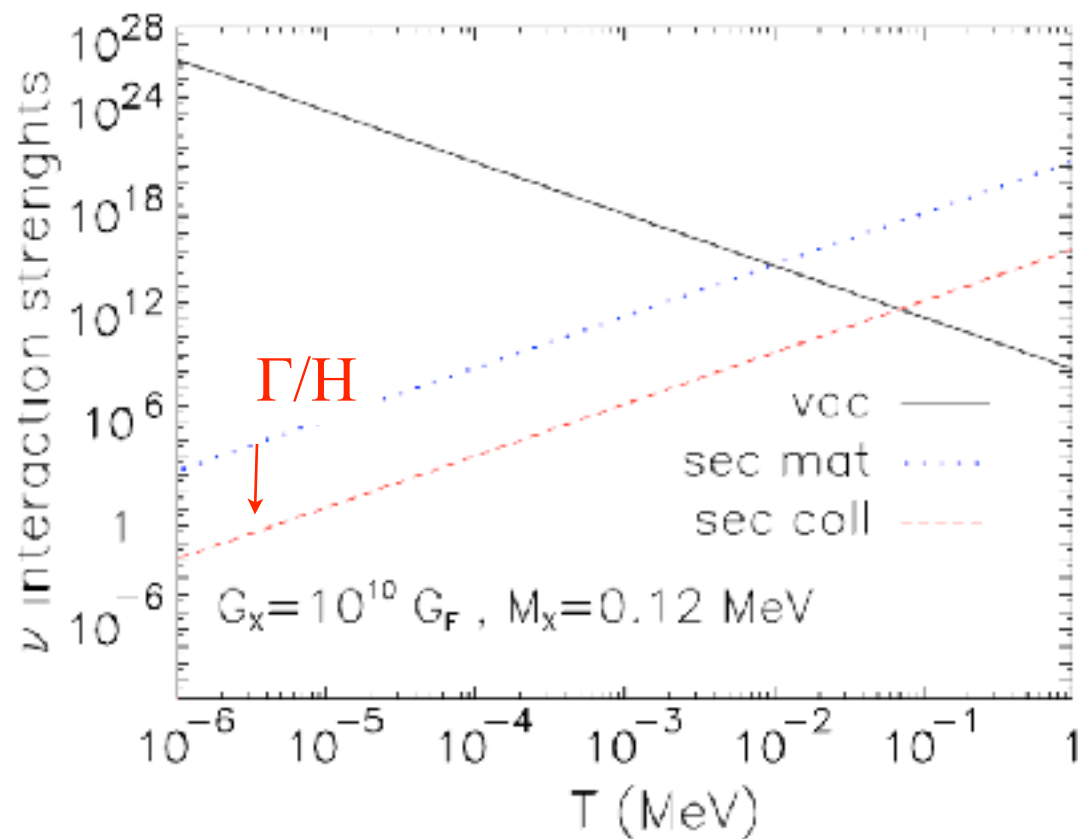


$$\epsilon_{\nu, \text{fin}} = 4 \times \left( \frac{3}{4} \right)^{4/3} \times \frac{7}{8} \left( \frac{4}{11} \right)^{4/3} \epsilon_\gamma$$

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

# CMB constraints for sterile $\nu$ SI (vector)

For  $M_X \leq 0.1 \text{ MeV}$  ( $\geq 10^{10} G_F$ )  $\rightarrow \nu_s$  could be still coupled at CMB and LSS epoch  $\rightarrow$  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  $G_X = \frac{\sqrt{2}}{8} \frac{g_X^2}{M_X^2}$

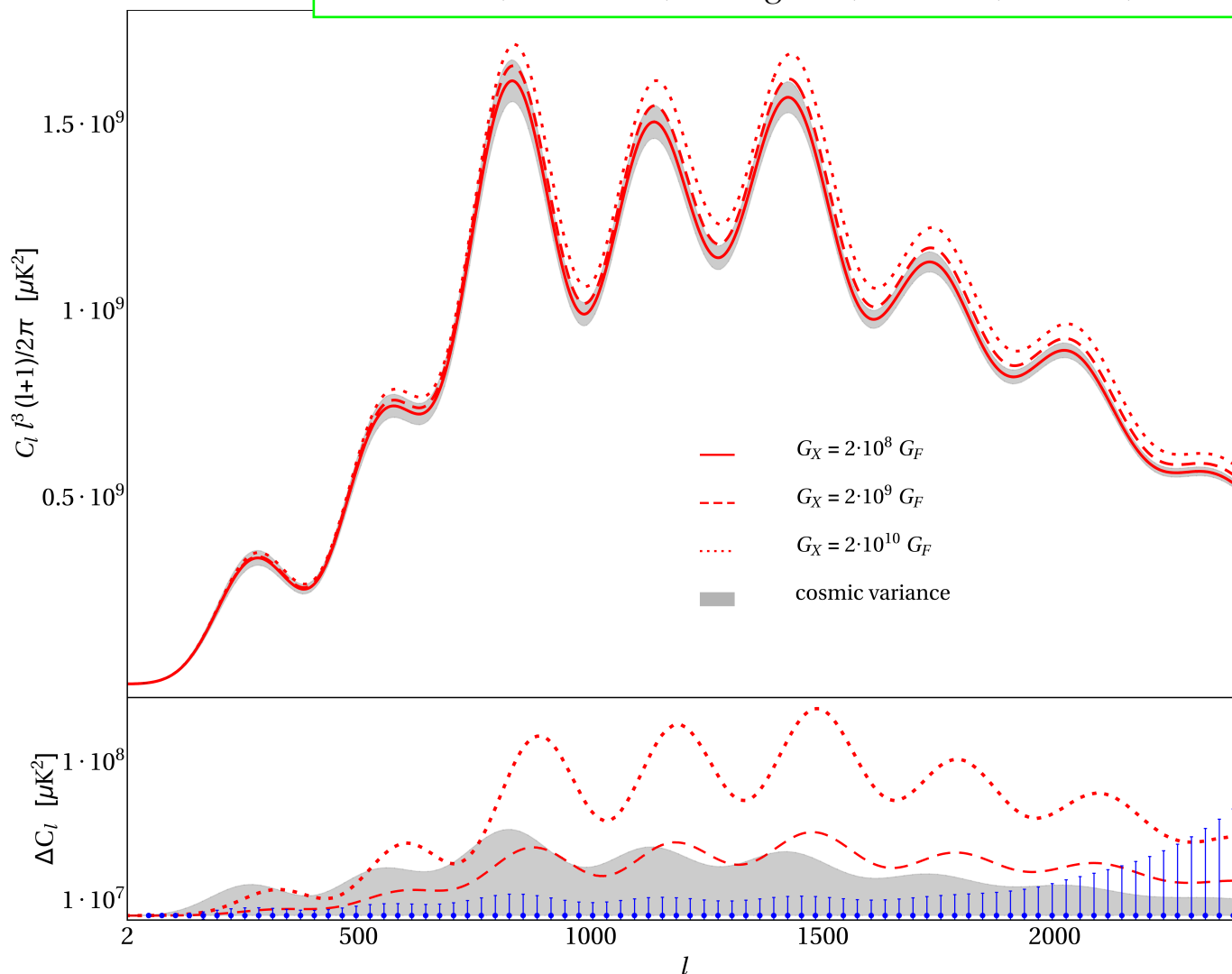
Scattering rates between mass eigenstates  $\rightarrow$  projection from the flavour basis through the mixing matrix

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

# CMB constraints for sterile $\nu$ SI (vector)

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

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



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

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

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

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

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

$$\dot{\Psi}_{i,\ell} = \frac{k}{2\ell+1} \frac{q}{\epsilon} \left[ \ell \Psi_{i,(\ell-1)} - (\ell+1) \Psi_{i,(\ell+1)} \right] - \Gamma_{ij} \Psi_{j,\ell} \quad (\ell \geq 3)$$

**NOTE:  $N_{\text{eff}} = 2.7$**

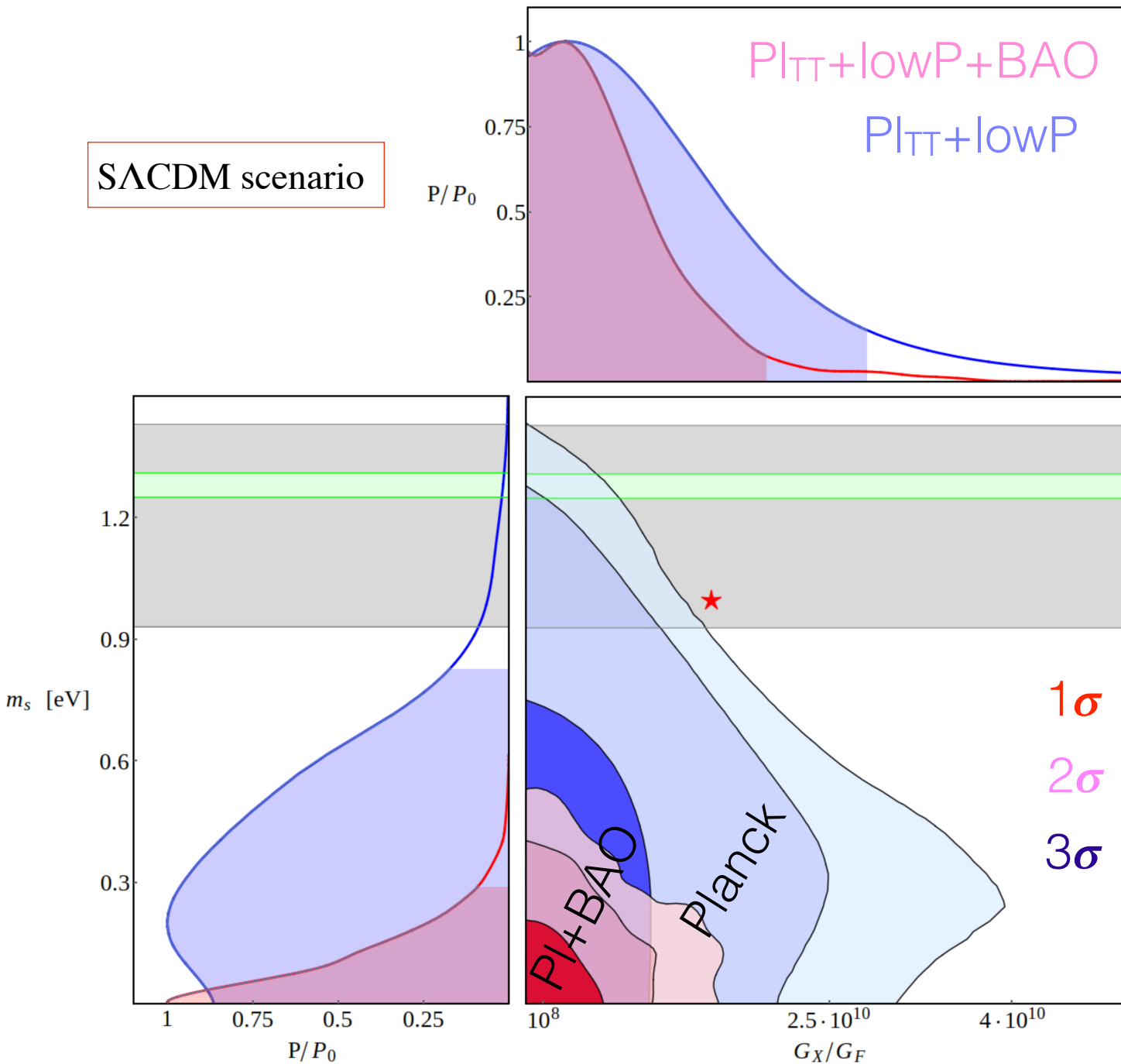
As long as  $\Gamma > H$ , interacting neutrinos behave as perfect fluid  $\rightarrow$  shear and higher moments are exponentially suppressed.

**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 $\nu$ SI (vector)

SACDM scenario



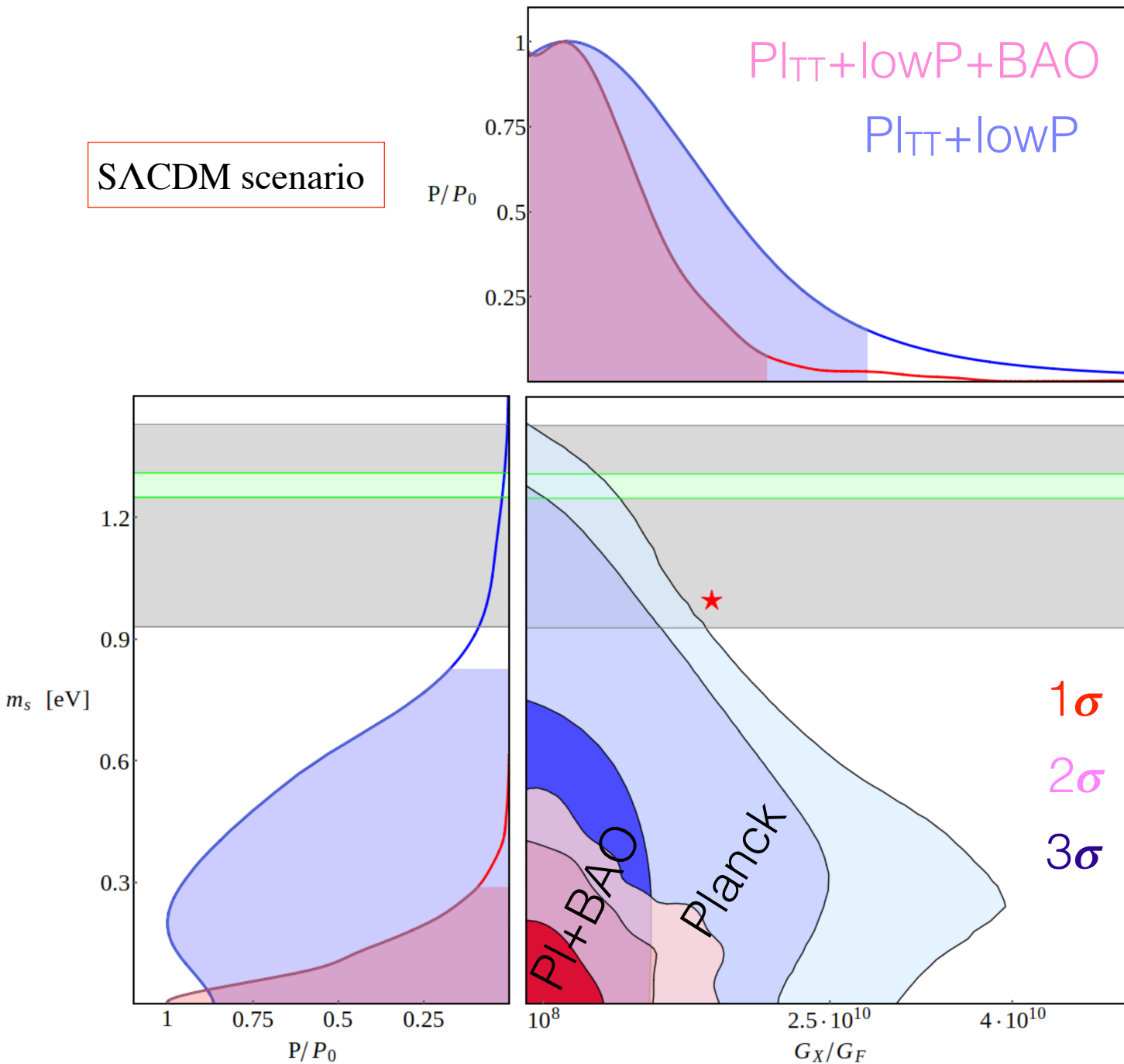
Forastieri, Lattanzi, Mangano, Mirizzi, Natoli, Saviano, 2017

	Description
$\Lambda$ CDM	Standard six-parameter $\Lambda$ CDM, $N_{\text{eff}} = 3.046$ .
SACDM_GX0	Sterile neutrino extension, $N_{\text{eff}} = 2.7$ , $m_s$ free, “small” $G_X$ ( $\sim 10^8 G_F$ ).
<del>SACDM</del>	Sterile neutrino extension, $N_{\text{eff}} = 2.7$ , $m_s$ and $G_X$ free.
SACDM_Narrow	Sterile neutrino extension, $N_{\text{eff}} = 2.7$ , $G_X$ free, $m_s = 1.27 \pm 0.03$ eV (gaussian prior).
SACDM_Broad	Sterile neutrino extension, $N_{\text{eff}} = 2.7$ , $G_X$ free, $0.93 \text{ eV} \leq m_s \leq 1.43 \text{ eV}$ (flat prior).

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

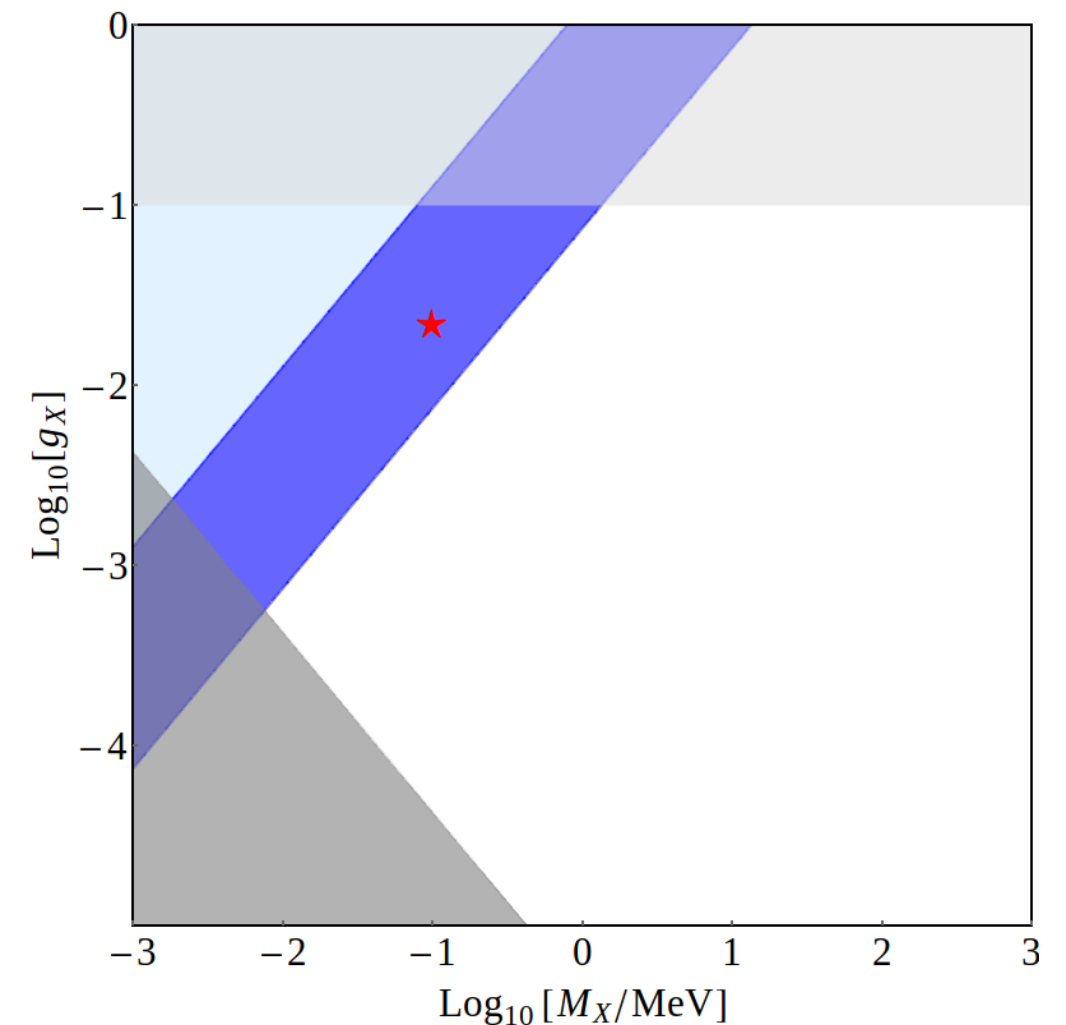
# CMB constraints for sterile $\nu$ SI (vector)

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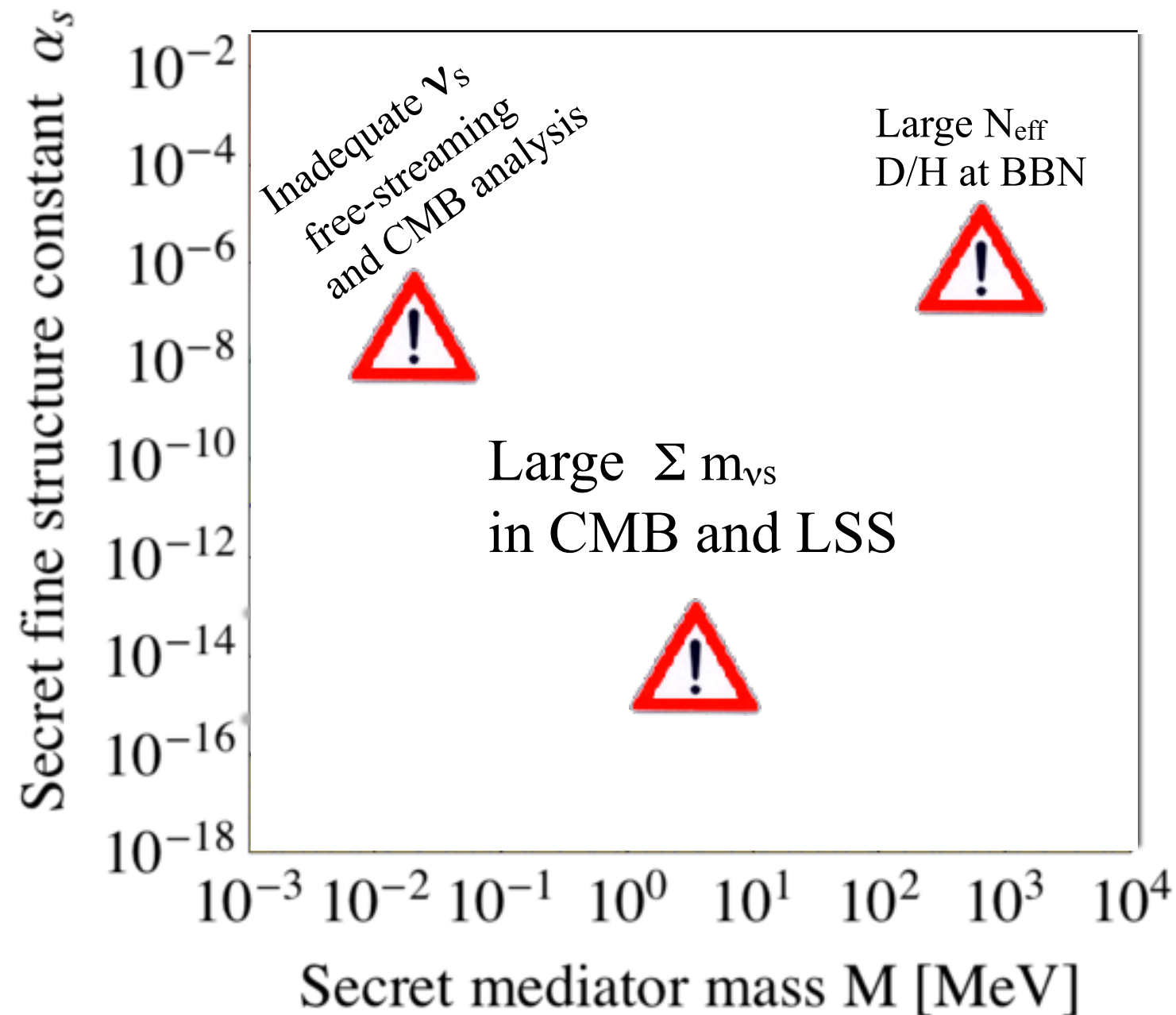
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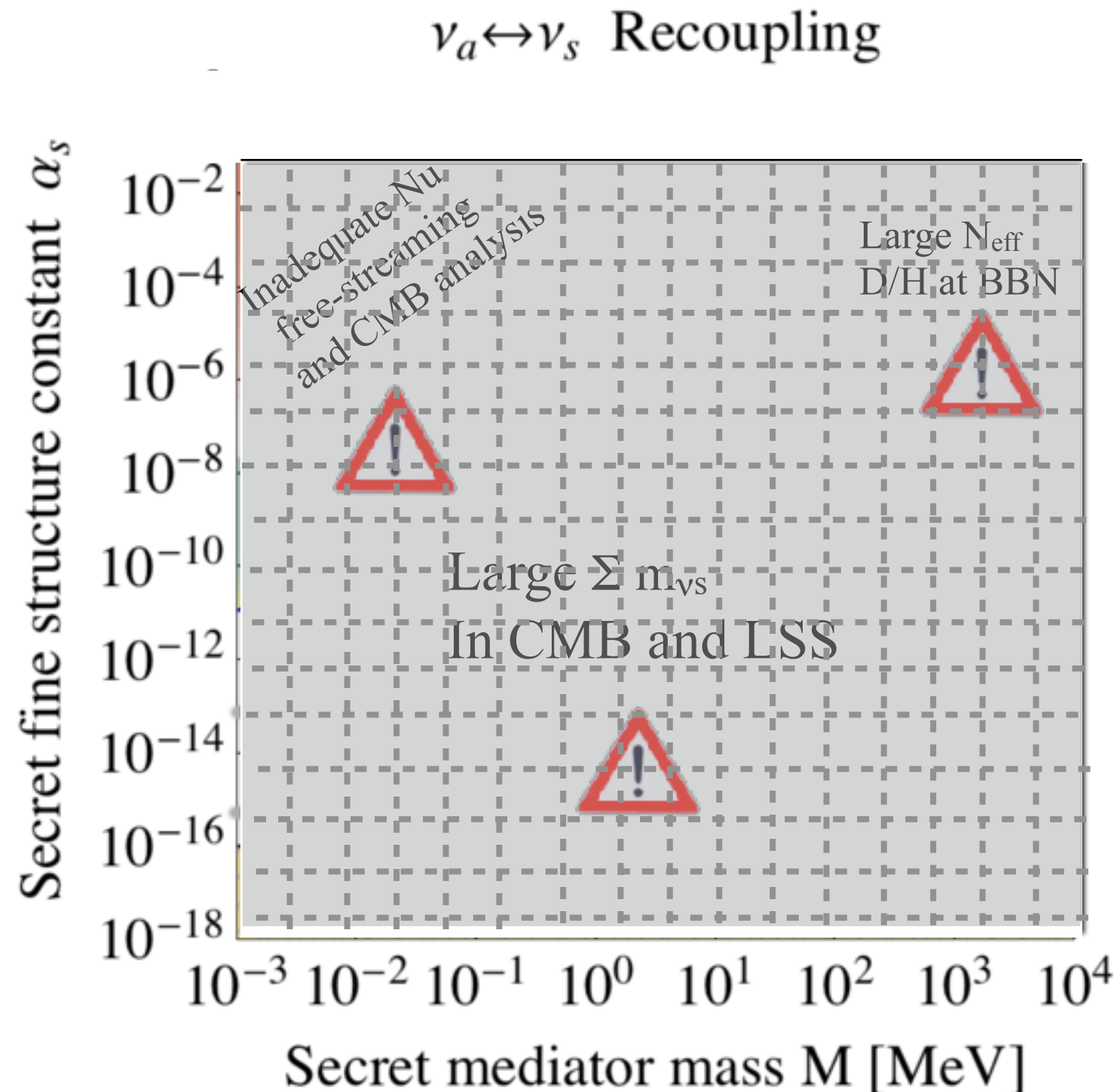
# Summary Plot

$\nu_a \leftrightarrow \nu_s$  Recoupling



*see also Chu, Dasgupta & Kopp 2015*

# 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

$$N_{\text{eff}} \sim 3$$

$$m_{\nu_s}^{\text{eff}} < 0.6 \text{ eV}$$

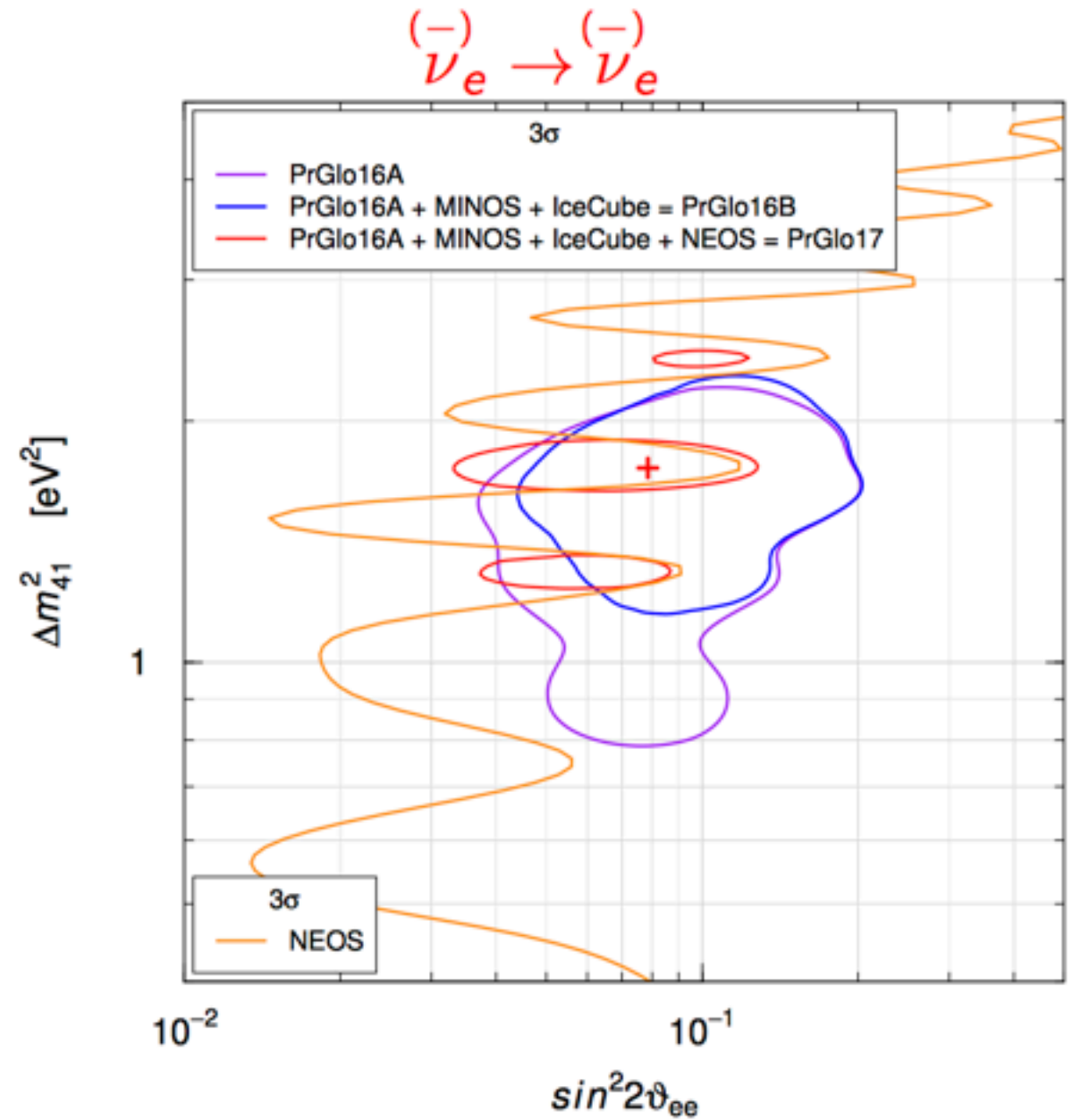
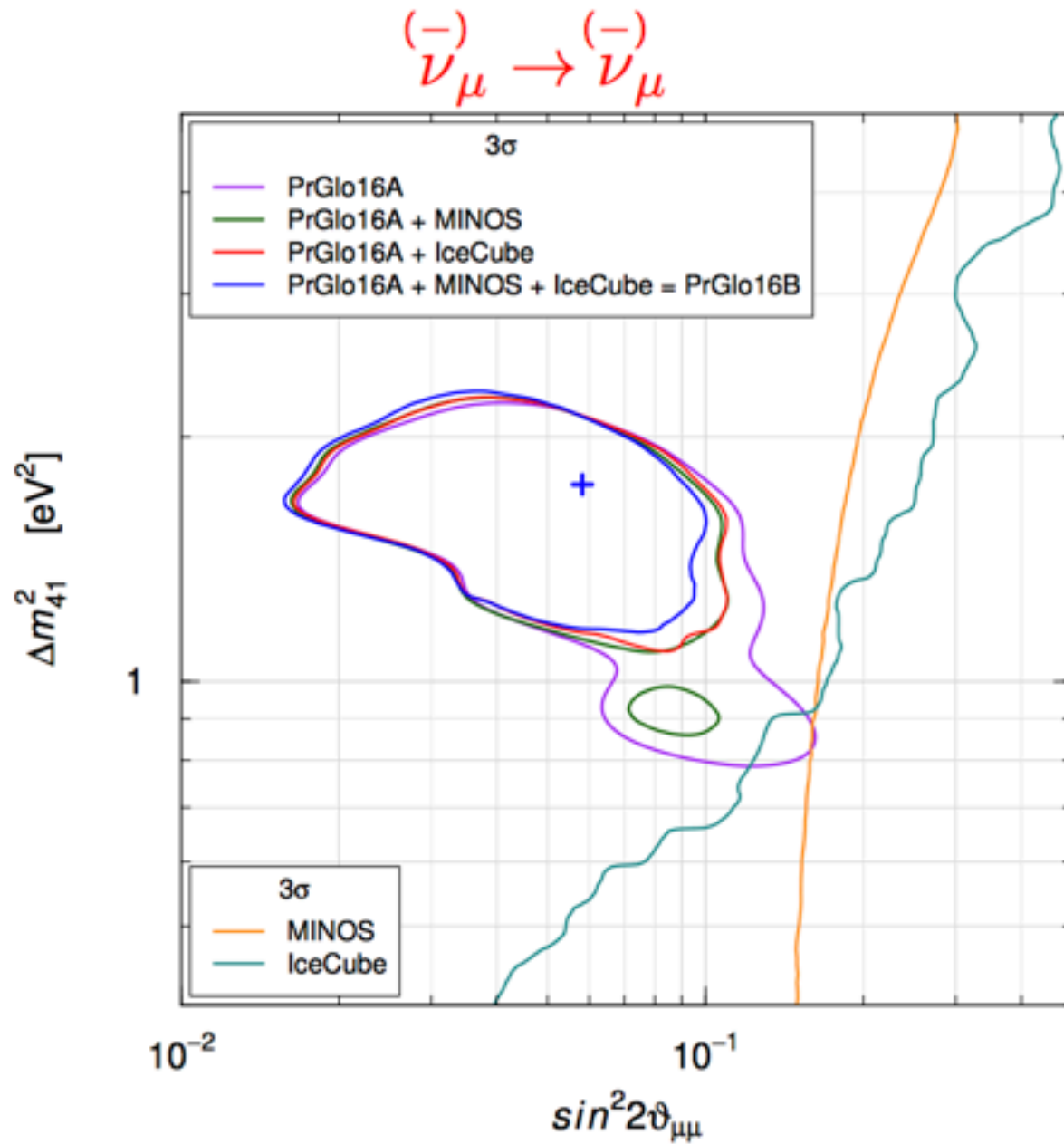
- Thermalized eV sterile  $\nu$  *incompatible* with cosmological bounds:  
Too many for BBN and CMB and too heavy for structure formation
- New exotics scenarios are required (primordial neutrino asymmetry, hidden interactions, inflationary freedom...) →  
→ *however the reconciliation with cosmology is not guaranteed and in some cases disfavoured (neutrino asymmetry) and excluded (secret interactions)*





THANK YOU

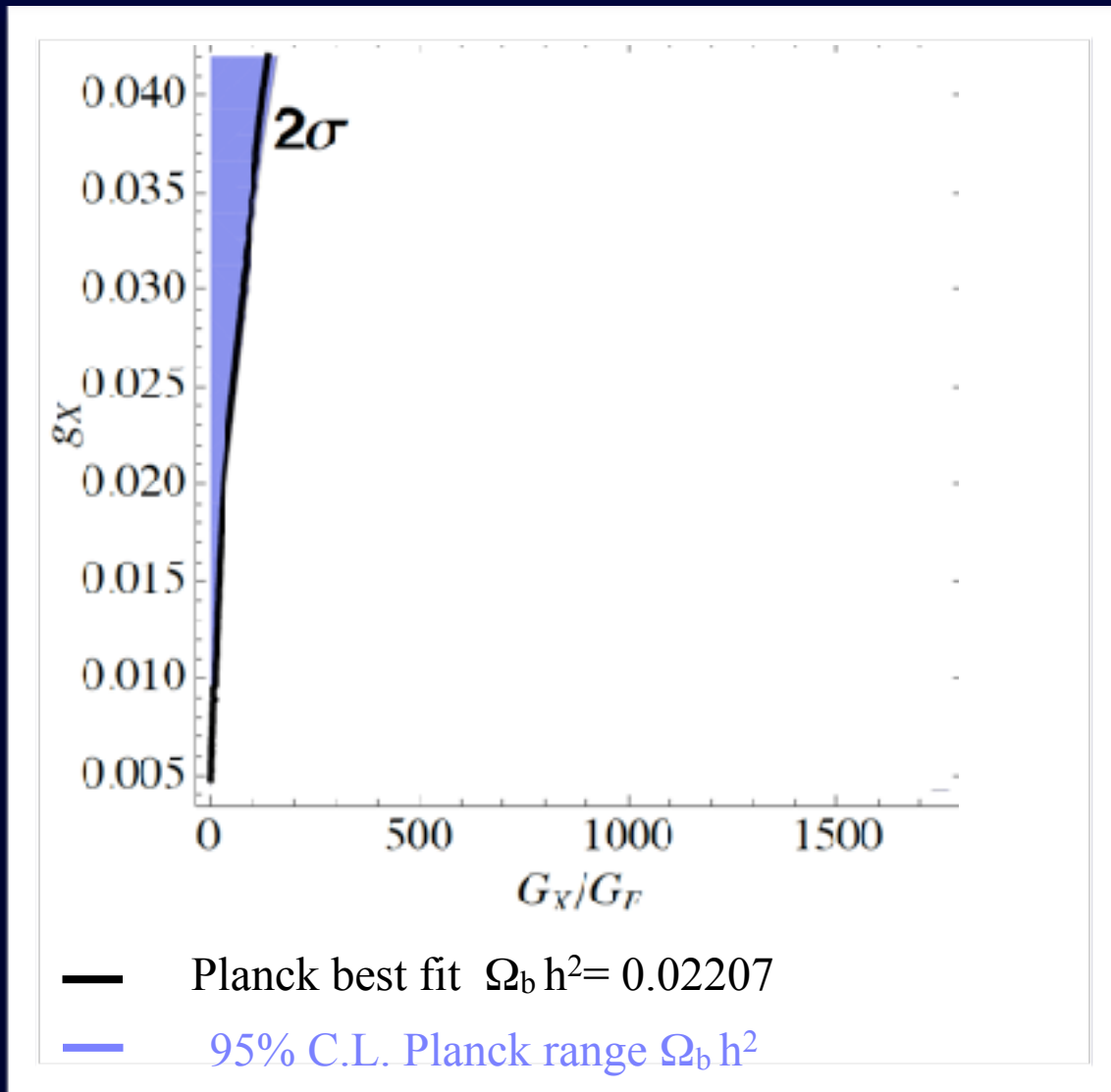
# Effects of MINOS, IceCube and NEOS



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

# BBN constraints

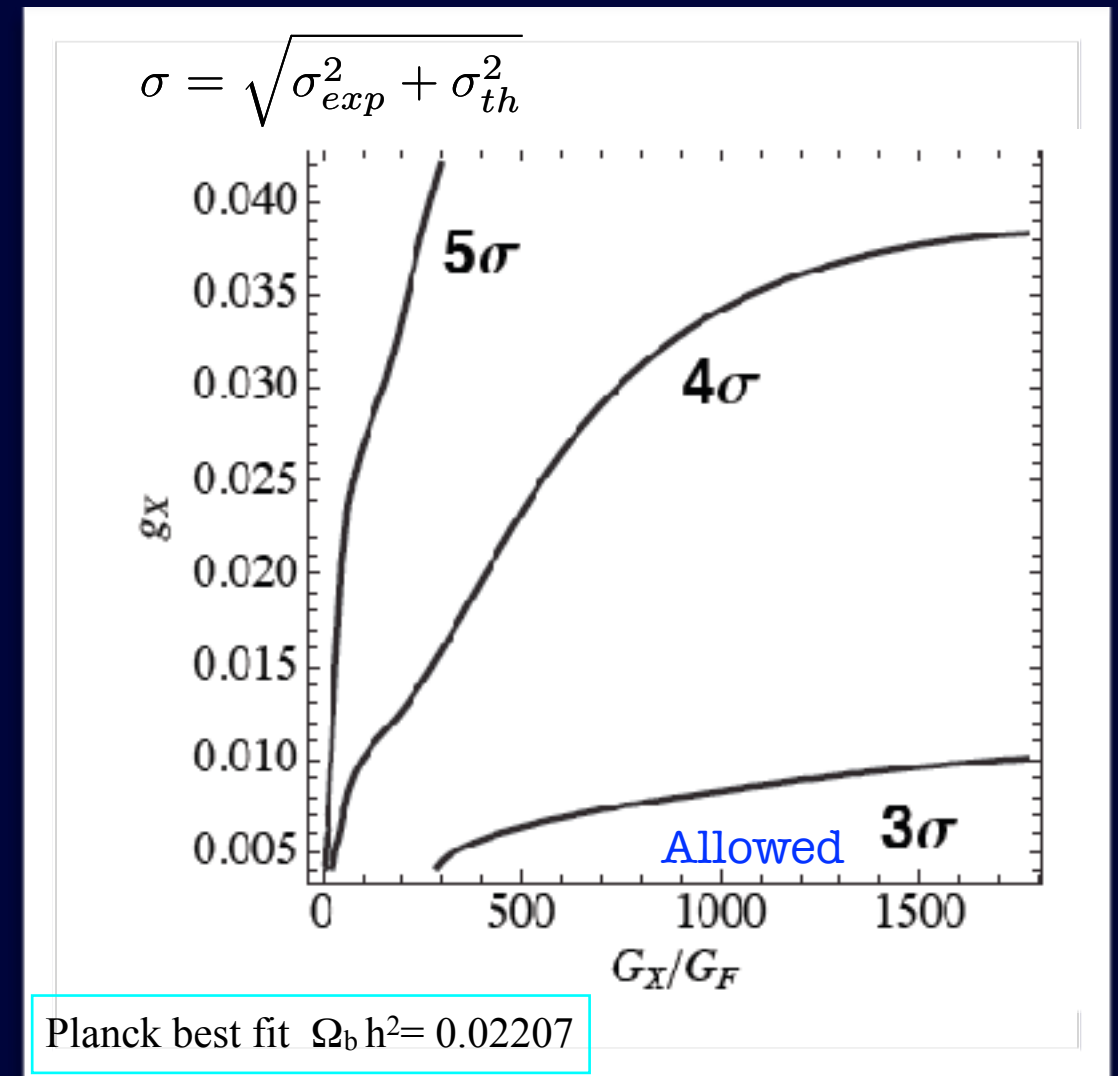
**$^4\text{He}$  yield**



**$D$  yield**

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

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



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

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

PARthENoPE code  
 Pisanti et al, 2012

Most of the parameter space excluded at  $3\sigma$   $M_X \geq 40 \text{ MeV}$

# Connection with the DM

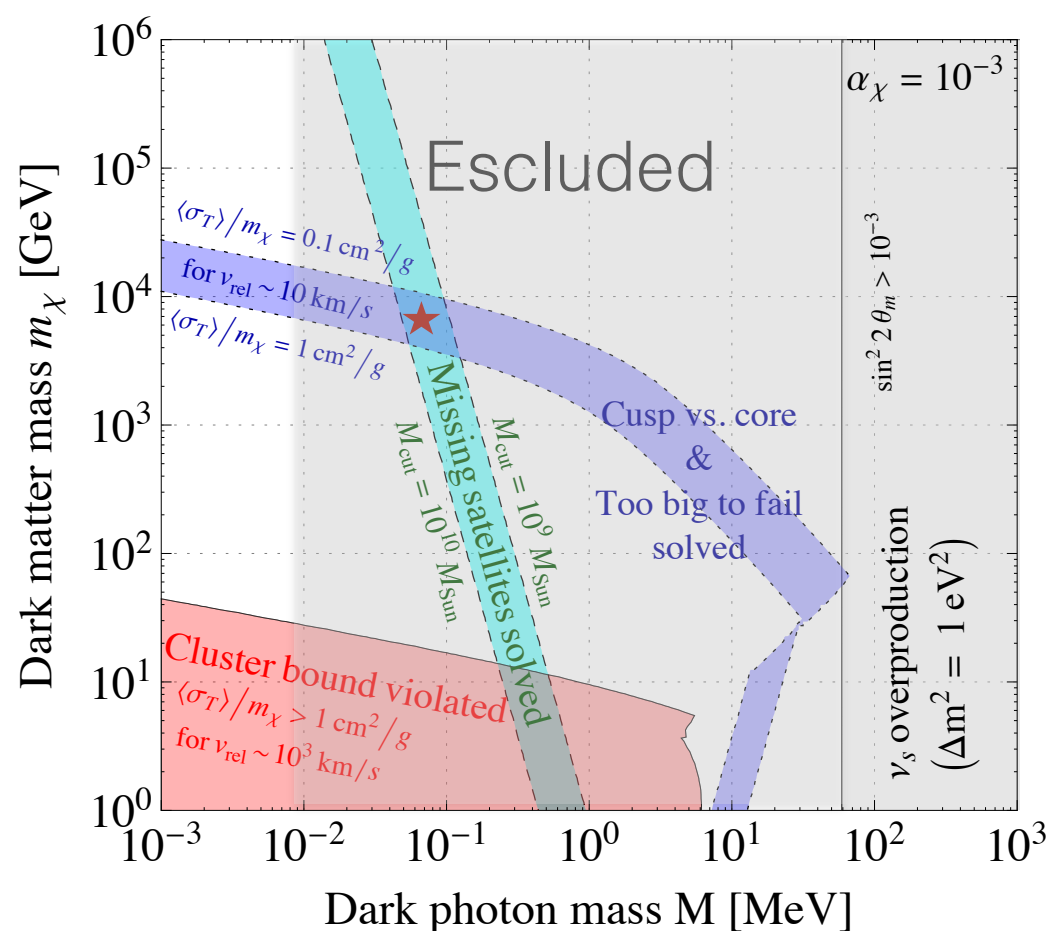
If a new force exists, it is plausible that not only (sterile) neutrinos, but also DM particles couple to it

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

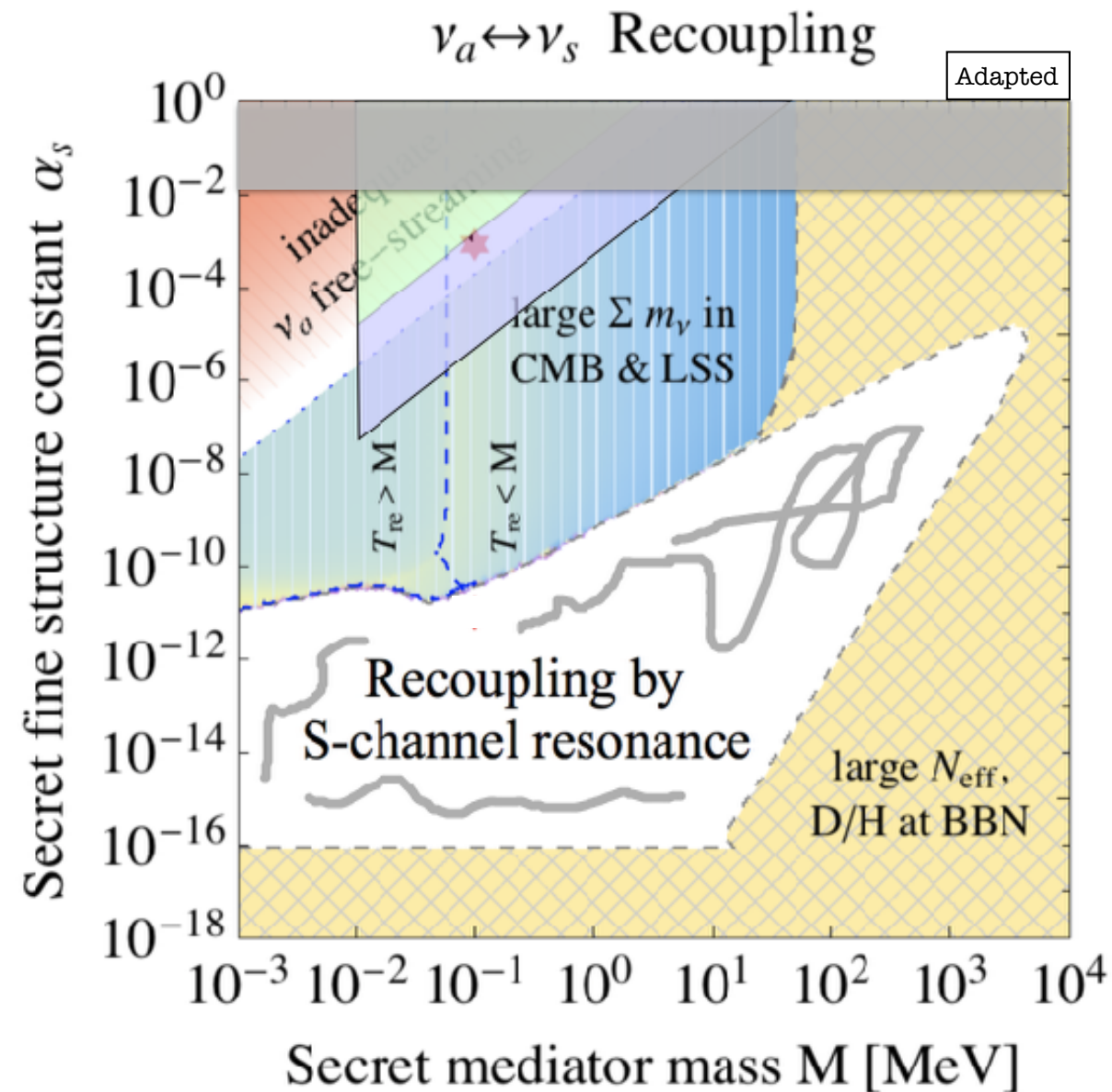
This scenario may solve all of the small-scale structure issues mentioned above. Indeed, the efficient scattering of DM would lead to late kinetic decoupling, delaying the formation of the smallest protohalos.

(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



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

*Chu, Dasgupta and Kopp 2015*

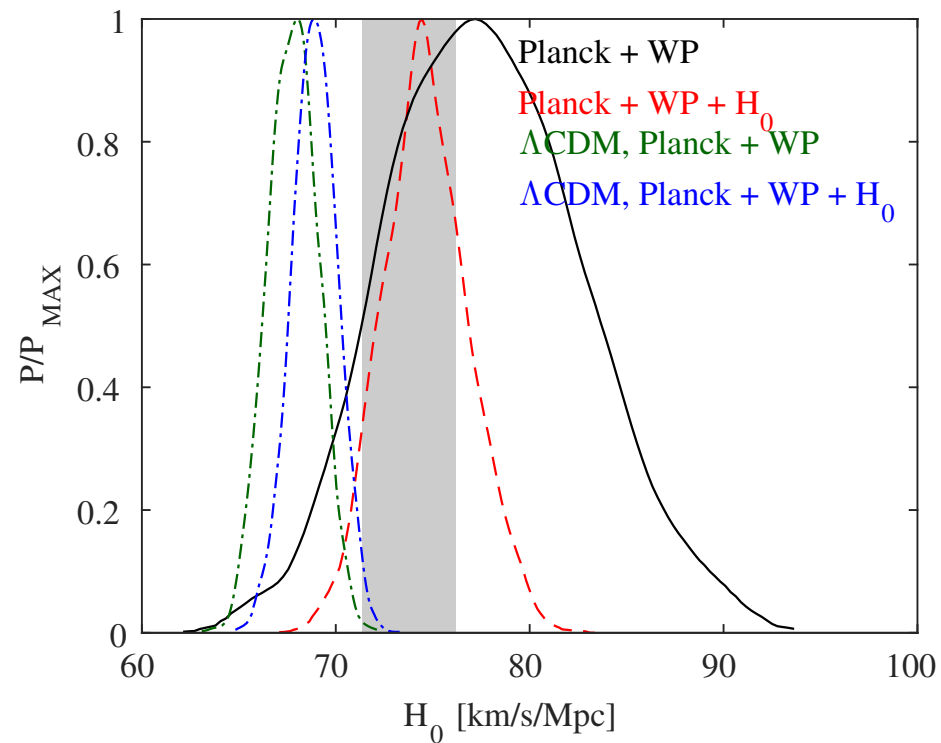
Possible hint (very dependent on the set of data used): in pseudoscalar model,  $10^{-6} \lesssim g_s \lesssim 10^{-5}$  would reconcile eV sterile  $\nu$ ,  $H_0$ ,  $\nu$  SI. Also link to the DM small scale problem.

*Archidiacono et al. 2015*



# Pseudoscalar model

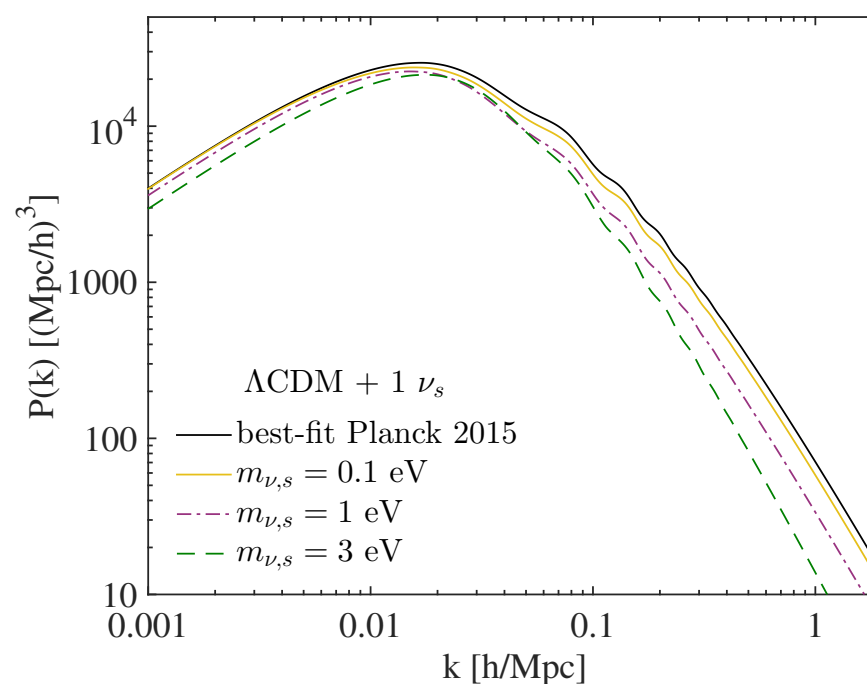
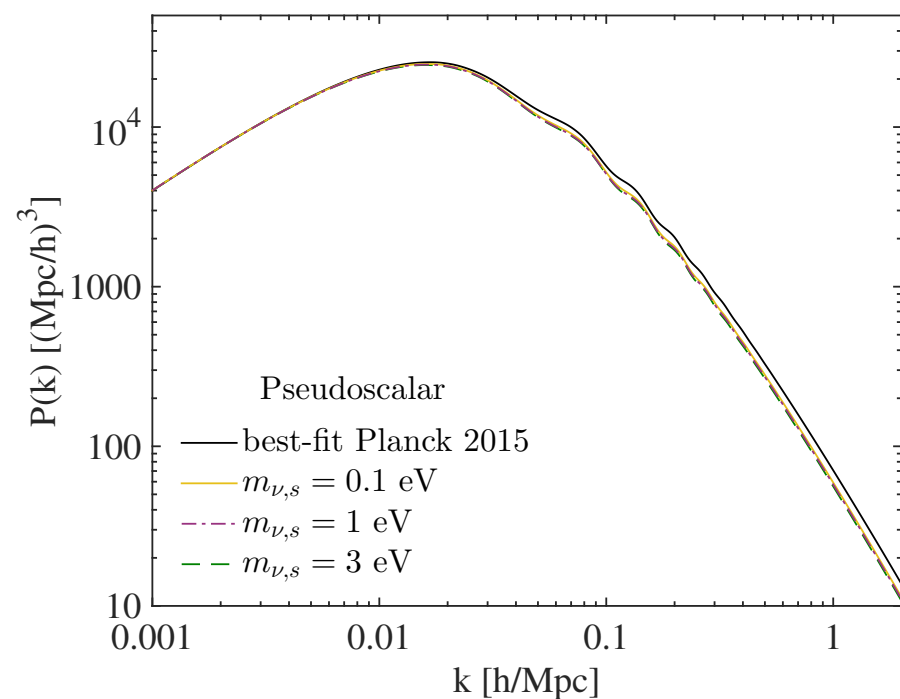
Sterile neutrino is coupled to a new light pseudoscalar with mass  $m_\phi \ll 1\text{eV}$  with  $\mathcal{L} \sim g_s \phi \bar{\nu} \gamma_5 \nu$ .



Possible hint:

$10^{-6} \lesssim g_s \lesssim 10^{-5}$  would reconcile eV sterile  $\nu$ ,  $H_0$

Also connection to the DM small scale problem.

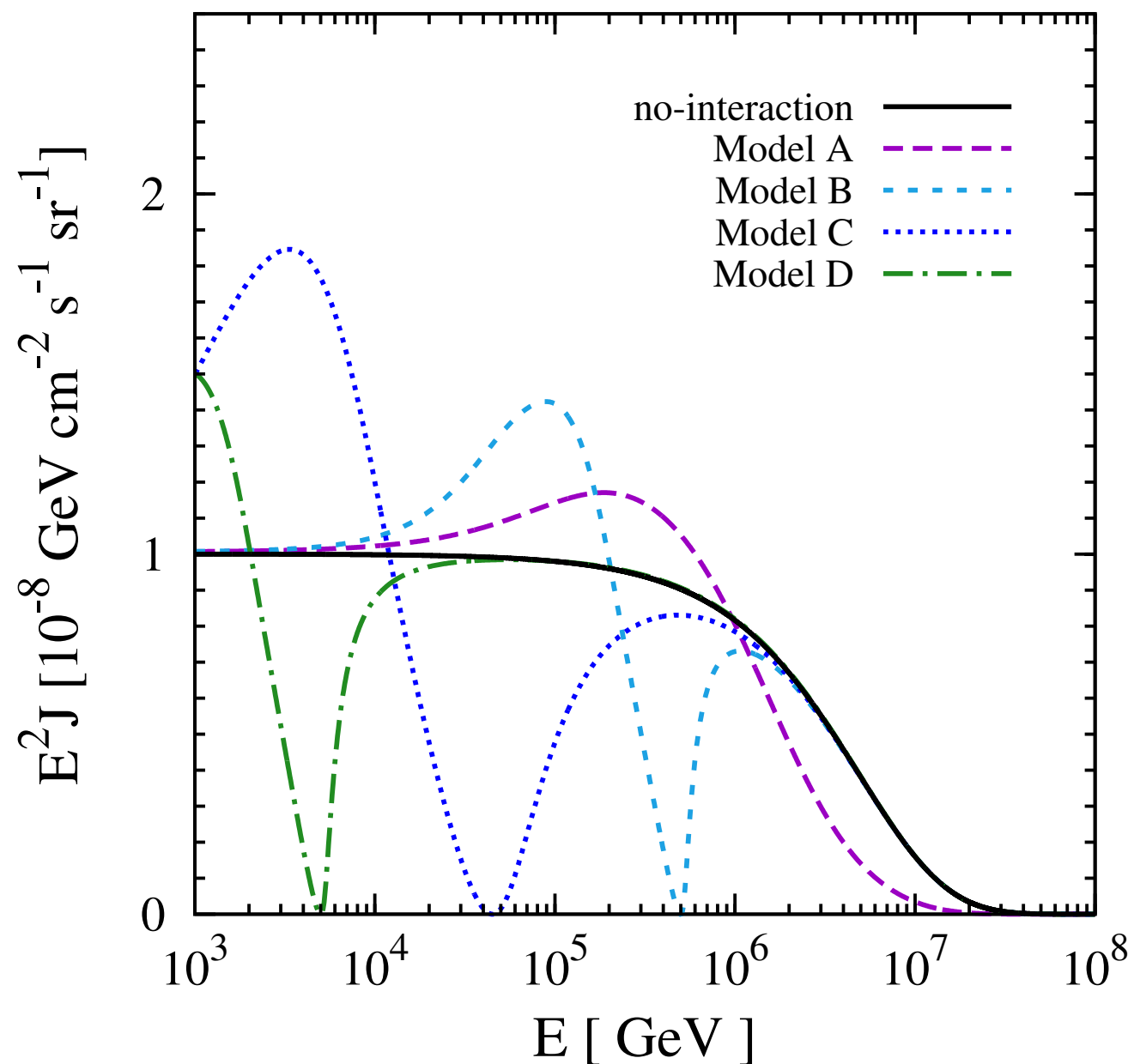


*Archidiacono et al. 2015,*

*Archidiacono et al. 2016*

# "scalar" $\nu$ SI impact on IceCube spectra

Emitted spectra



$$\mathcal{L}_0(E) \propto E^{-\gamma} e^{-E/E_{\text{cut}}}$$

$$\gamma = 2 \text{ and } E_{\text{cut}} = 10^7 \text{ GeV}$$

	A	B	C	D
$g$	0.3	0.03	0.03	0.01
$M [\text{MeV}]$	100	10	3	1
$\tau (1 \text{ PeV})$	$\sim 0.7$	$\sim 0.6$	$\sim 0.2$	$\sim 0.002$
$E_{\text{res}} [\text{PeV}]$	50	0.5	0.045	0.005