PRIN NAT-NET
kick-off meeting

Napoli
27 Gennaio 2020

WP2
Beyond the Standard ν Framework

Antonio & Ninetta

WP2 - Beyond the standard neutrino framework

- ✔ **Light sterile neutrino oscillations in the light of upcoming laboratory and cosmological data; (see also WP4)**
- ✔ **Constraints on new neutrino interactions; (see also WP4)**
- ✔ **Neutrinoless double beta decay beyond light Majorana neutrinos;**
- ✖ **Long-distance and multi-messenger tests of dispersion relations;**
- ✔ **Neutrinos as components or signals of dark matter; (see also WP3)**
- ✔ **Neutrino model building and leptogenesis.**

Outline

Probing light sterile neutrinos and NSI at LBLs **(A)**

Investigating see-saw mechanisms at SHIP **(A)**

$0\nu2\beta$ decay BSM [see-saw SO(10) GUT] **(A)**

ν phenomenology from leptogenesis in SO(10) (A)

Light sterile neutrinos in cosmology **(N)**

Secret interactions and heavy sterile neutrinos **(N)**

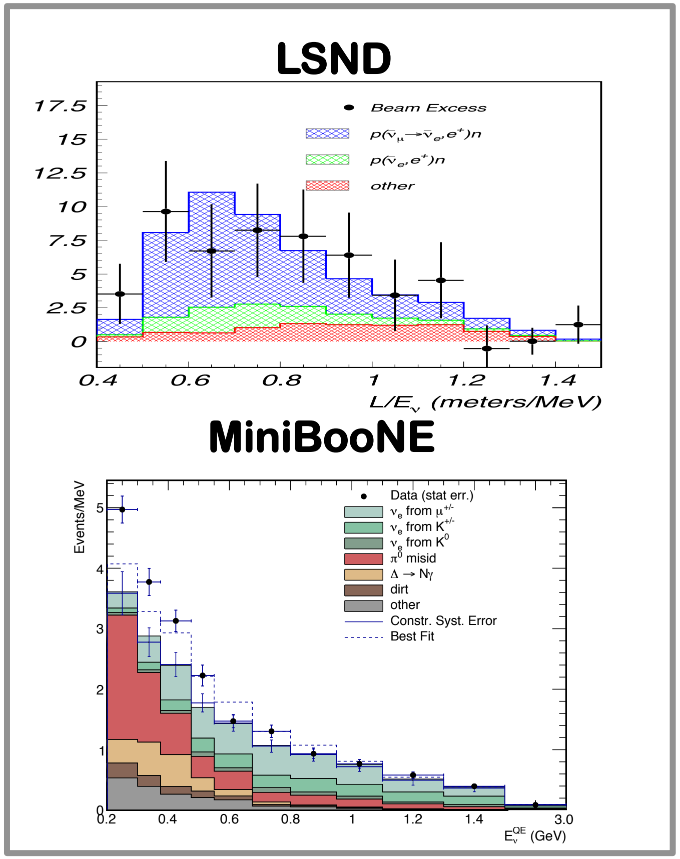
Neutrino-Dark Matter connections **(N)**

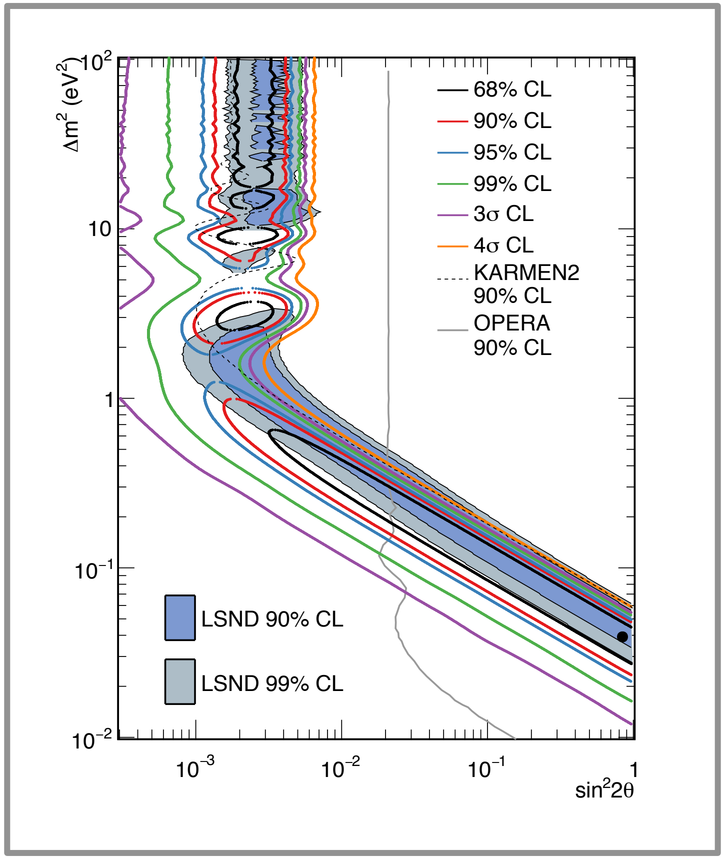
SBL anomalies: I) accelerators

(unexplained ν_e appearance in a ν_μ beam)

3.8σ

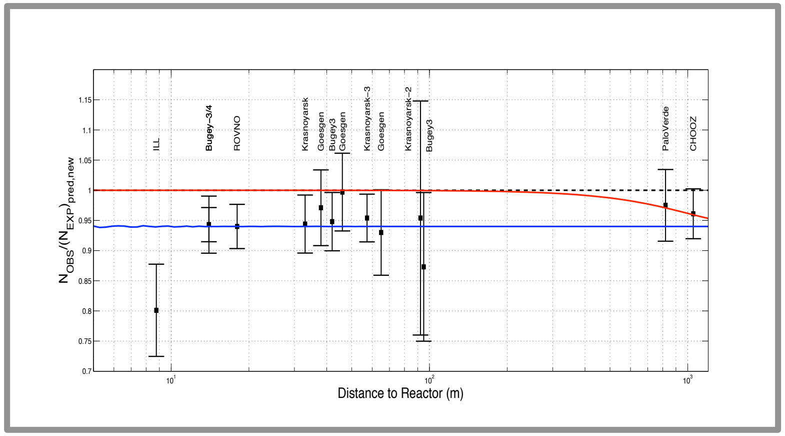
4.8σ



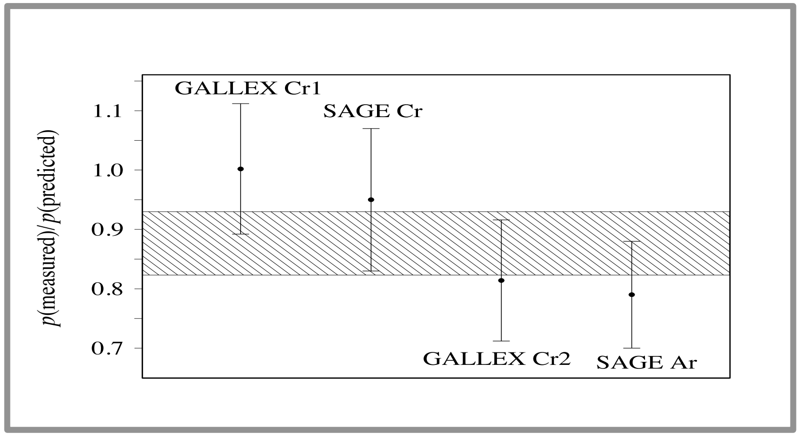


II) Reactor rates and solar calibration

(unexplained ν_e disappearance)



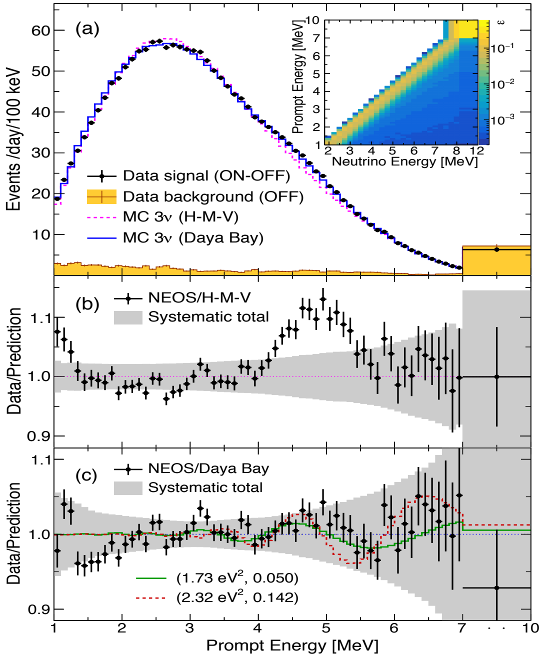
Mention et al. arXiv:1101:2755 [hep-ex]



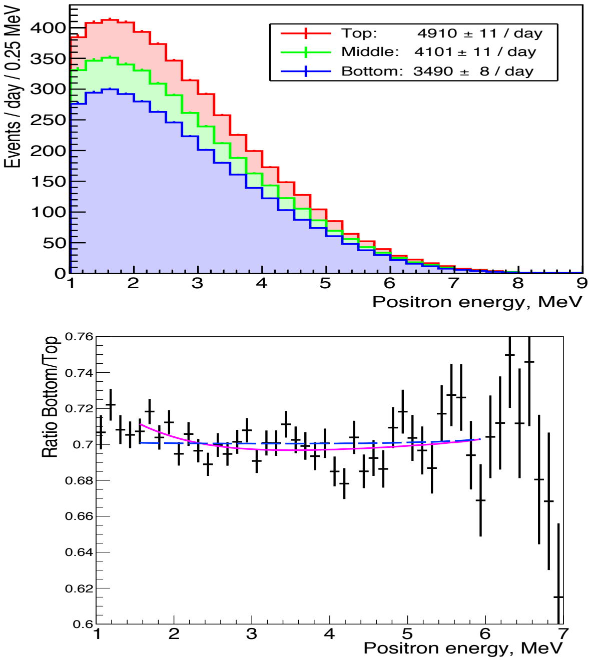
SAGE coll., PRC 73 (2006) 045805

III) Reactor spectra

NEOS arXiv:1610:05134



DANSS arXiv:1911:10140



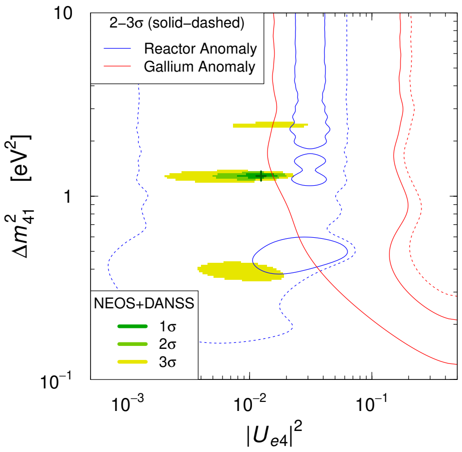
$$\chi^2_{4\nu} - \chi^2_{3\nu} = -6.5$$

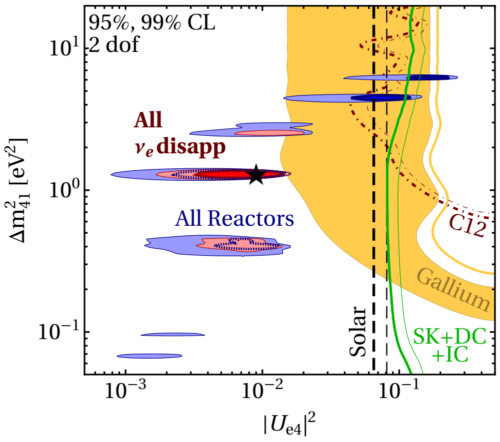
$$\chi^2_{4\nu} - \chi^2_{3\nu} = -7.8$$

Best fit points very similar: $(\sin^2 2\theta,\, \Delta m^2) \simeq (0.05,\, 1.4\mathrm{eV}^2)$

3+1 fits

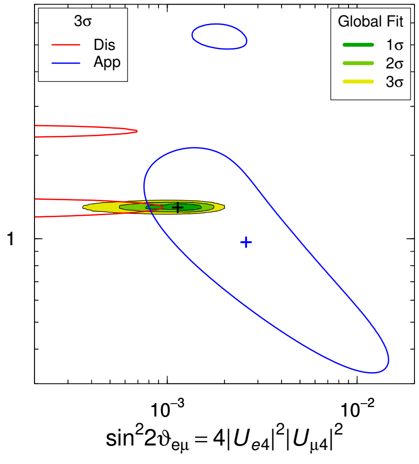
Gariazzo et al.
2018





Dentler et al.
2018

Gariazzo et al.
2018

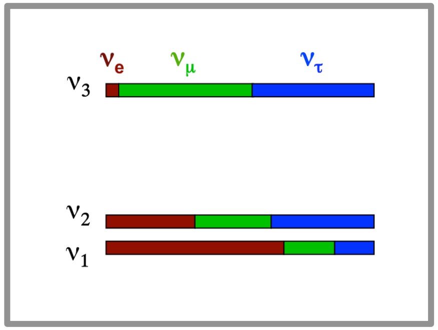


How to enlarge the 3-flavor scheme

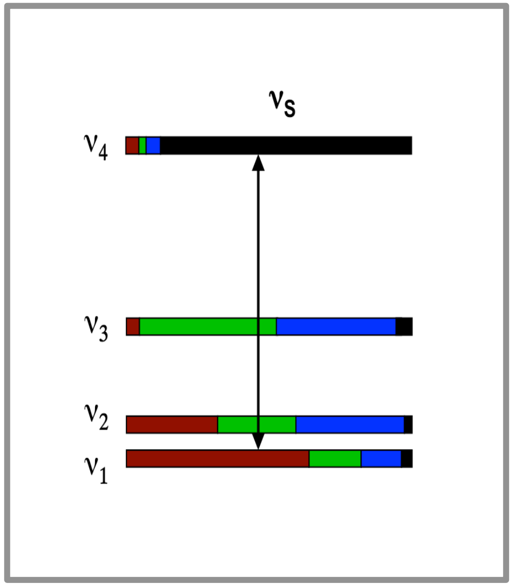
3ν scheme

Δm^2_{atm}

Δm^2_{sol}



3+1 scheme

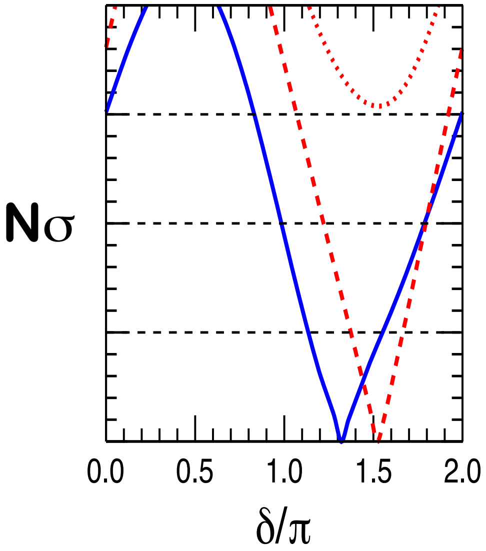


$|U_{s4}| \sim 1$

$\Delta m^2_{14} \sim 1 \text{ eV}^2$

At LBL the effective 2-flavor SBL description is no more valid and calculations should be done in the 3+1 (or 3+N_s) scheme

It is timely to pose a new question



3-flavor fit
Capozzi, Lisi, Marrone, A.P,
PPNP 102, 48 (2018)

LBL experiments start to be sensitive to the CP violating phase δ

Can sterile neutrinos generate observable CP violating effects at LBL experiments?

Question basically ignored in the past !

Mixing Matrix in the 3+1 scheme

$$U = \tilde{R}_{34}\, R_{24}\, \tilde{R}_{14}\, \underbrace{R_{23}\, \tilde{R}_{13}\, R_{12}}_{3\nu}$$

$$R_{ij} = \begin{bmatrix} c_{ij} & s_{ij} \\ -s_{ij} & c_{ij} \end{bmatrix}$$

$$\tilde{R}_{ij} = \begin{bmatrix} c_{ij} & \tilde{s}_{ij} \\ -\tilde{s}^*_{ij} & c_{ij} \end{bmatrix}$$

$$\begin{aligned} s_{ij} &= \sin\theta_{ij} \\ c_{ij} &= \cos\theta_{ij} \\ \tilde{s}_{ij} &= s_{ij} e^{-i\delta_{ij}} \end{aligned}$$

$$3\nu \begin{cases} \text{3 mixing angles} \\ \text{1 Dirac phase} \\ \text{2 Majorana phases} \end{cases} \qquad 3+1 \begin{cases} 6 \\ 3 \\ 3 \end{cases} \qquad 3+N \begin{cases} 3+3N \\ 1+2N \\ 2+N \end{cases}$$

In general, we have additional sources of CPV

A new interference term in the 3+1 scheme

N. Klop & A.P., PRD (2015)

- $\Delta_{14} >> 1$: fast oscillations are averaged out

- But interference of Δ_{14} & Δ_{13} survives and is observable

$$\boxed{P^{4\nu}_{\mu e} \simeq P^{\rm ATM} + P^{\rm INT}_{\rm I} + P^{\rm INT}_{\rm II}}$$

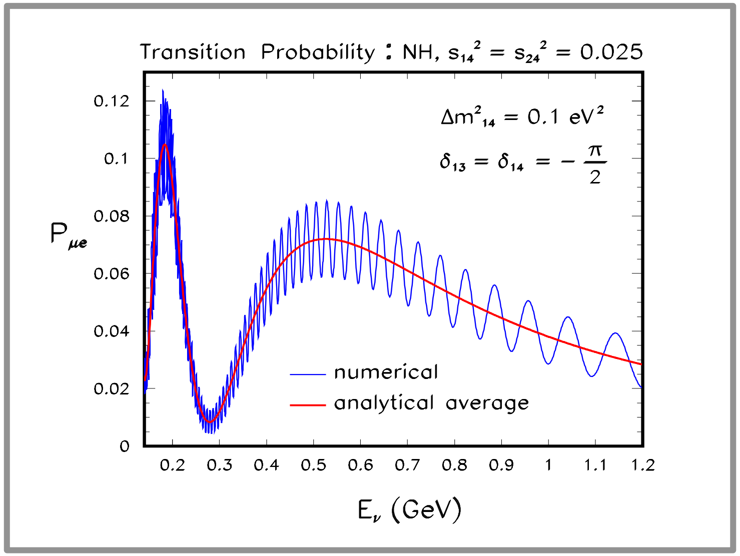
$s_{13} \sim s_{14} \sim s_{24} \sim 0.15 \sim \varepsilon$

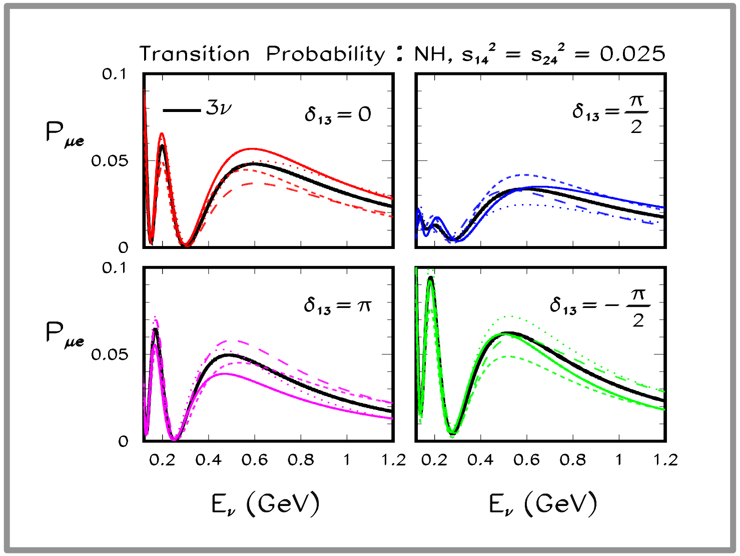
$\alpha = \delta m^2/\Delta m^2 \sim 0.03 \sim \varepsilon^2$

$$\begin{cases} P^{\rm ATM} \simeq 4 s^2_{23} \underline{s^2_{13}} \sin^2\Delta & \sim \varepsilon^2 \\ P^{\rm INT}_{\rm I} \simeq 8 \underline{s_{13}} s_{23} c_{23} s_{12} c_{12} (\underline{\alpha}\Delta) \sin\Delta \cos(\Delta + \delta_{13}) & \sim \varepsilon^3 \\ P^{\rm INT}_{\rm II} \simeq 4 \underline{s_{14}}\, \underline{s_{24}}\, \underline{s_{13}} s_{23} \sin\Delta \sin(\Delta + \delta_{13} \boxed{- \delta_{14})} & \sim \varepsilon^3 \end{cases}$$

Sensitivity to the new CP-phase δ_{14}

Numerical examples of 4ν probability





The fast oscillations get averaged out due to the finite energy resolution

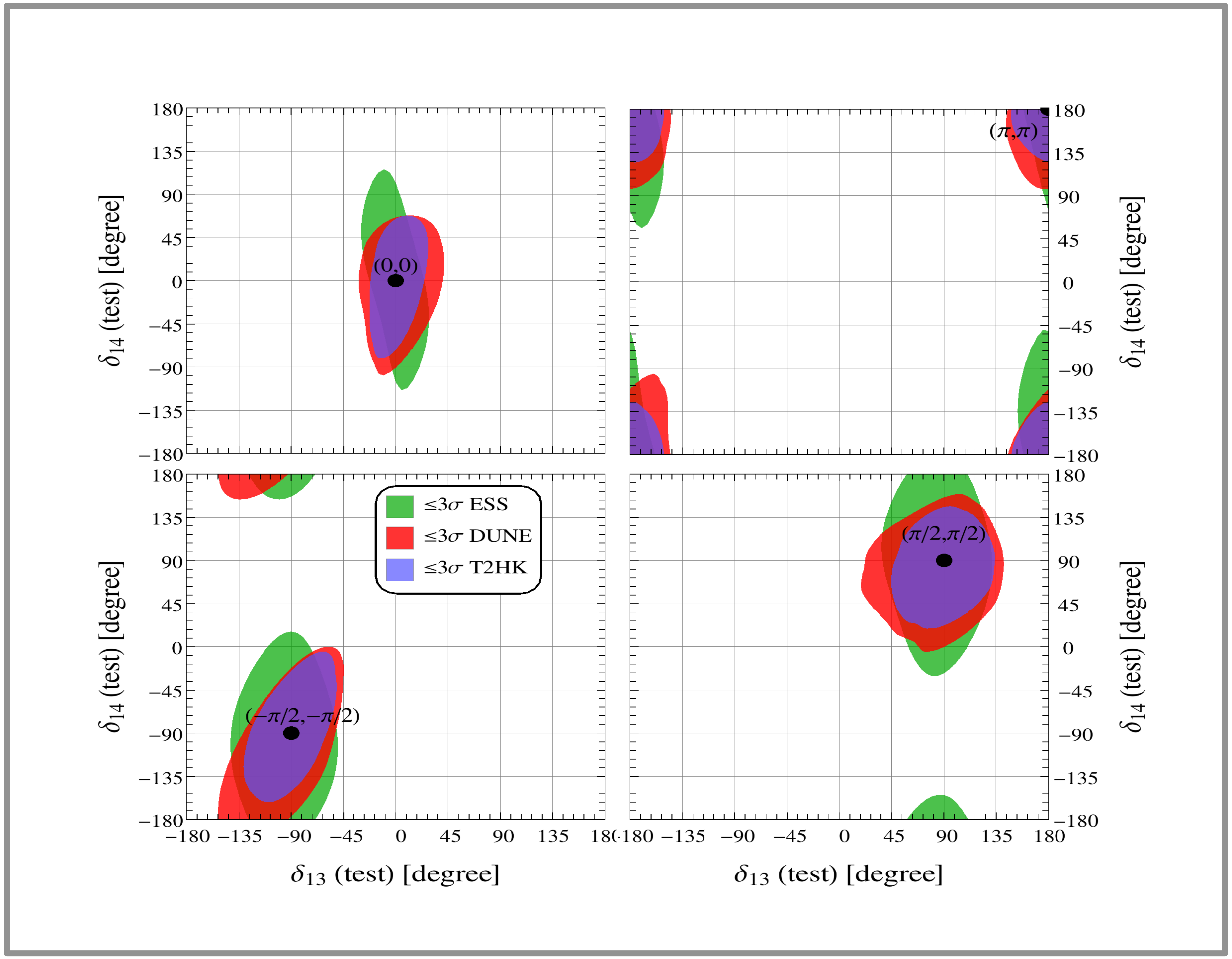
Different line styles
⇔
Different values of δ_{14}

Consequences for T2K, NOνA, DUNE, T2HK, ESSνSB

Analized in several papers in collaboration with:
Agarwalla and Chatterjee,
Capozzi, Giunti, Laveder
A.P. Invited Review for Universe (to appear)

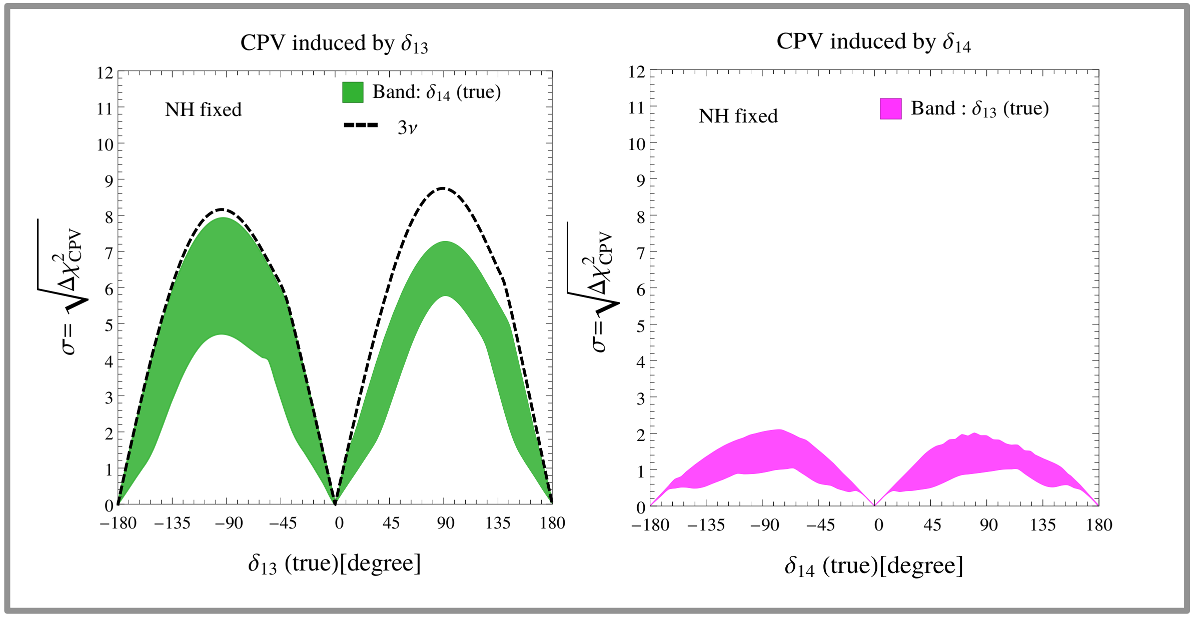
Reconstruction of the CP phases

Agarwalla, Chatterjee, Palazzo, JHEP 2019



CPV discovery potential

ESSνSB



- Sensitivity to CPV induced by δ_{13} reduced in 3+1 scheme
- Poor sensitivity to the new CP-phases δ_{14}
- Second oscillation maximum is not optimal for steriles

Present developments (I)

Optimization of ESSνSB for sterile neutrinos

The benchmark configuration considers L = 540 km.
Our preliminary results suggest that working with a shorter baseline would provide more sensitivity to CPV induced by sterile neutrinos preserving the sensitivity to standard CPV.

Agarwalla, Chatterjee, A.P (in preparation)

Present developments (II)

Impact of sterile ν in real data of T2K and NOvA

In a previous work (A.P., PLB 2016) we have shown that the effects of light sterile neutrinos were already visible. In particular, there was a weak sensitivity to the new CP-phase δ_{14}. We plan to update such a work taking into account the latest data of these experiments.

Chatterjee & A.P. (in preparation)

Neutrino oscillations in the presence of NSI

$$\mathcal{L}^{eff} = \mathcal{L}_{SM} + \frac{c^{d=5}}{\Lambda}\mathcal{O}^{d=5} + \frac{c^{d=6}}{\Lambda^2}\underset{\nwarrow\,\textbf{NSI}}{\mathcal{O}^{d=6}} + \dots$$

$$\delta\mathcal{L}_{\rm NSI} = -2\sqrt{2}\,G_F\sum_{f,P}\epsilon^{fP}_{\alpha\beta}\left(\overline{\nu_\alpha}\gamma^\mu P_L\nu_\beta\right)\left(\bar{f}\gamma_\mu P f\right)$$

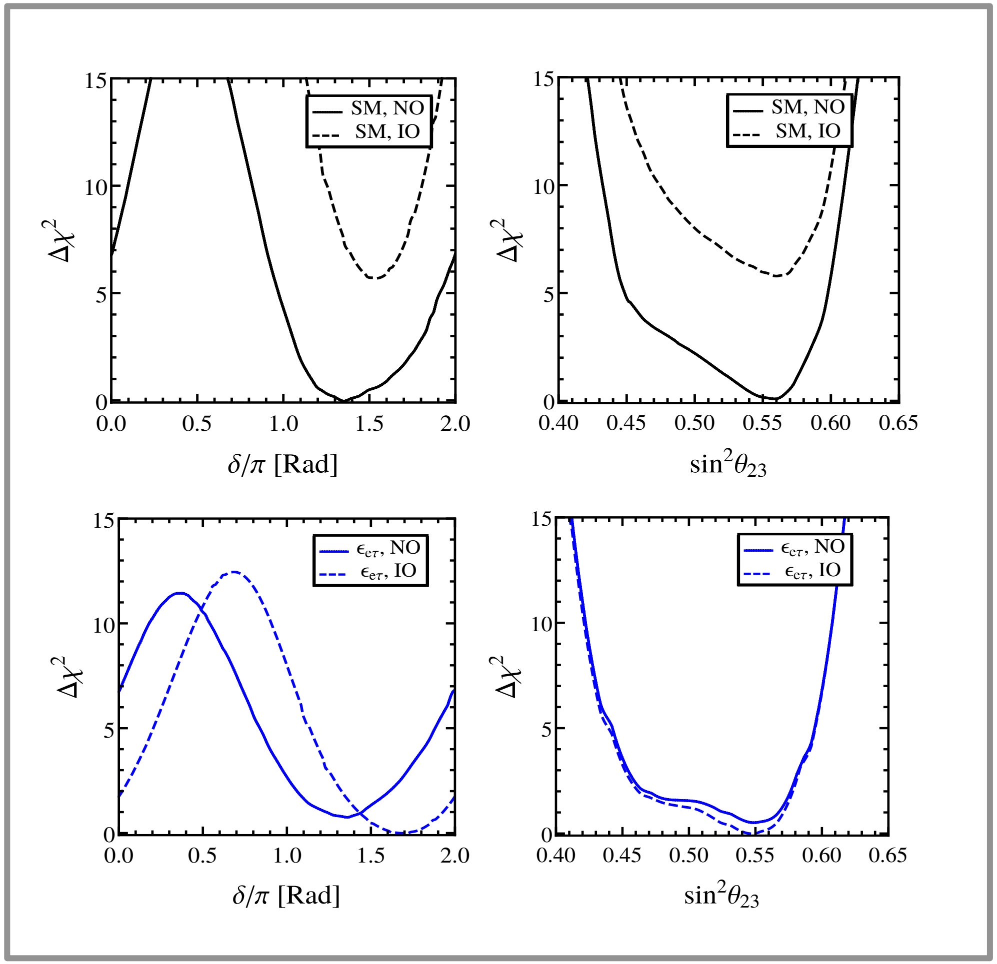
$$H = U\begin{bmatrix} 0 & 0 & 0 \\ 0 & k_{21} & 0 \\ 0 & 0 & k_{31} \end{bmatrix}U^\dagger + V_{\rm CC}\begin{bmatrix} 1+\varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{e\tau} \\ \varepsilon^*_{e\mu} & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau} \\ \varepsilon^*_{e\tau} & \varepsilon^*_{\mu\tau} & \varepsilon_{\tau\tau} \end{bmatrix}$$

$$V_{\rm CC} = \sqrt{2}G_F N_e \simeq 7.6\,Y_e \times 10^{-14}\left[\frac{\rho}{\rm g/cm^3}\right]\,\text{eV},$$

NSIs wash out the indication of normal mass ordering

Capozzi, Chatterjee, A.P., arXiv: 1908.06992 (submitted to PRL)

SM



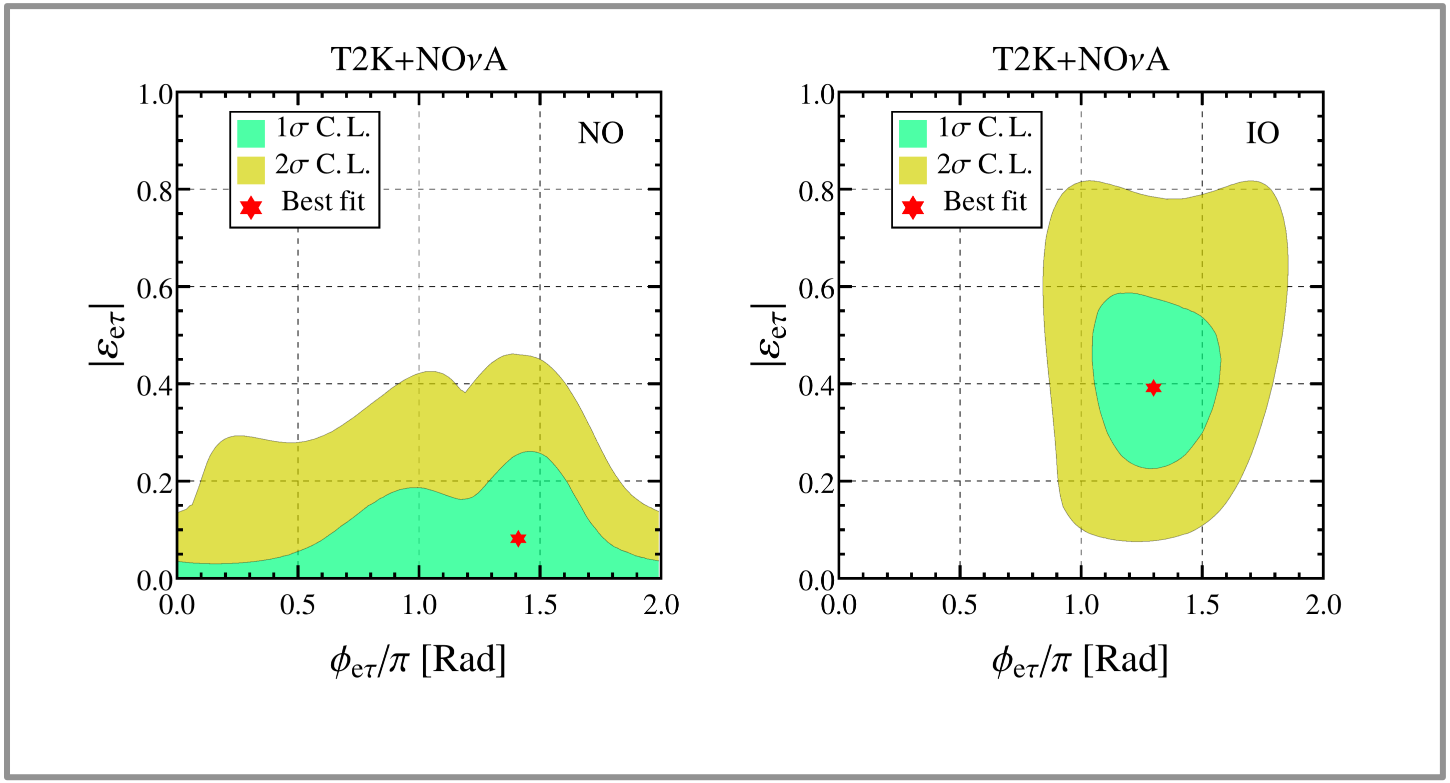
SM + NSI

T2K+NOvA

Latest data

This occurs because NSI are required only in IO

Capozzi, Chatterjee, A.P., arXiv: 1908.06992 (submitted to PRL)



Present developments

Sensitivity of DUNE to NMO in the presence of NSI

In the recent work 1908.06962 submitted to PRL we have shown that in the presence of NSI, the indication in favor of NO is lost (NO and IO are degenerate). We are now investigating if it is possible to break such a degeneracy with future LBL experiments.

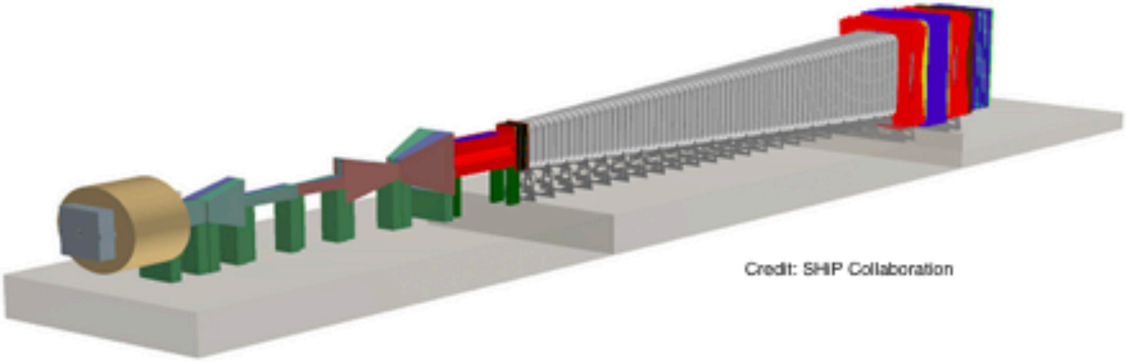
Chatterjee & A.P. (in preparation)

Indagare i meccanismi di seesaw: l'esperimento SHiP

Damiano Fiorillo

M. Chianese, S. Morisi, G. Miele

Int. Jour. Mod. Phys. A 34, 8



Credit: SHIP Collaboration

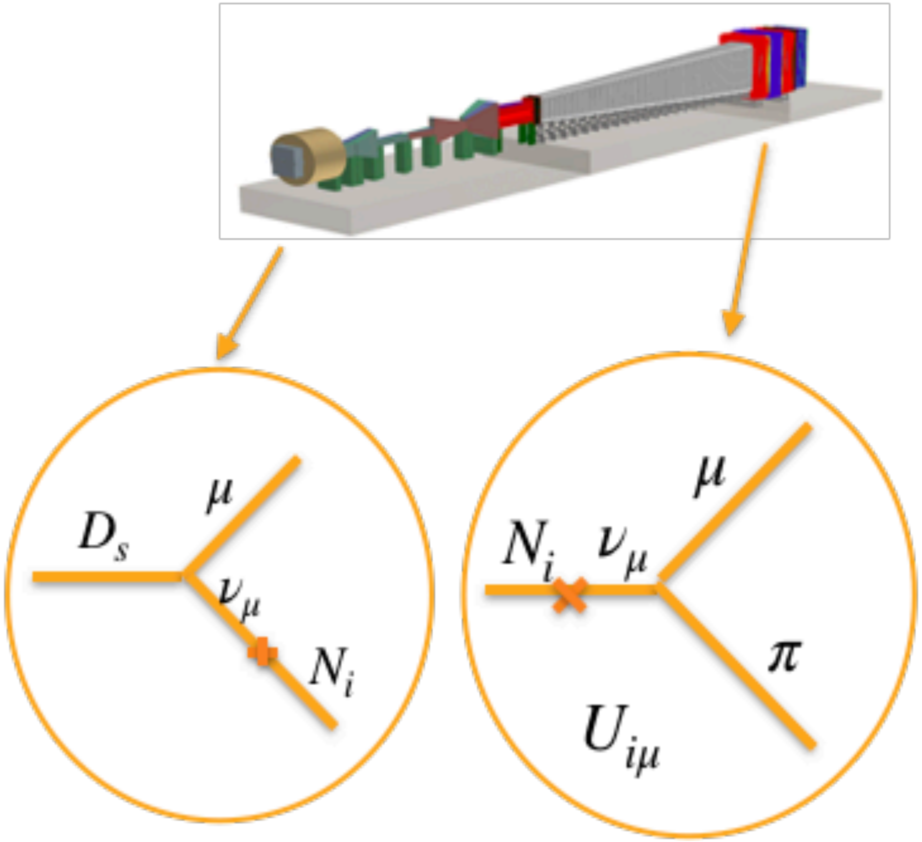
Esperimento SHiP

- Search for Hidden Particles
- Fascio di protoni da 400 GeV che incide su target adronico
- Deflessione dei muoni di background
- Spettrometro ad una distanza di 50 m

- Probabilità proporzionale a

$$U_\mu^2 = \sum_i |U_{\mu i}|^2$$

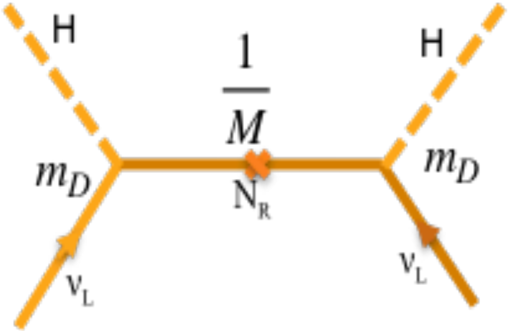
SHiP Collaboration, JINST 07, C07007



Meccanismo di seesaw (type 1)

Minkowski,1977
Gell-Mann, Ramond, Slansky, 1977

- Masse dei neutrini oltre il Modello Standard
- Scelta minimale: due Heavy Neutral Leptons (HNL)



$$\frac{m_D^2}{M}$$

$$M \gg m_D$$

$$M_\nu = \begin{bmatrix} 0_{3\times3} & m_{D(3\times2)} \\ m^T_{D(2\times3)} & M_{2\times2} \end{bmatrix} \quad U^T M_\nu U = diag \quad U = \begin{bmatrix} & & & U_{e4} & U_{e5} \\ & PMNS & & U_{\mu4} & U_{\mu5} \\ & & & U_{\tau4} & U_{\tau5} \\ U_{4e} & U_{4\mu} & U_{4\tau} & & \\ U_{5e} & U_{5\mu} & U_{5\tau} & & \end{bmatrix}$$

Minimal seesaw model
T. Asaka e M. Shaposhnikov, Phys. Lett. B

PMNS Pontecorvo-Maki-Nakagawa-Sakata

Predizioni per il mixing angle

- Studio teorico di $U^2 = \sum_{\alpha i} |U_{\alpha i}|^2$
- Modello con due right-handed neutrinos con $M \sim \mathcal{O}(GeV)$
- Matrice di massa completa
- Parametrizzazione di Casas-Ibarra
- Per ogni scelta delle masse dei right-handed, l'angolo di rotazione complesso è libero

$$M_\nu = \begin{bmatrix} 0 & m_D \\ m_D^T & M \end{bmatrix}$$

$$m_D = U_{PMNS}\sqrt{m_\nu}R\sqrt{M}$$

Matrice di rotazione 2x3 con un angolo di rotazione complesso $\theta' + i\theta''$

J. Casas e A. Ibarra, Nucl. Phys. B 618, 171

Predizioni per il mixing angle

- Previsione basata sull'analogia con il caso di singolo flavor

$$U^2 \sim \left(\frac{m_D}{M}\right)^2 \sim \frac{m_\nu}{M} \qquad m_\nu = \frac{m_D^2}{M}$$

- Per $M \sim 1 GeV$ e $m_\nu \sim 0.1 eV$

$$U^2 \sim 10^{-10}$$

- In realtà m_D è amplificata di un fattore $\cos(\theta' + i\theta'') \sim e^{\theta''}$

$$m_D = U_{PMNS}\sqrt{m_\nu}R\sqrt{M}$$

- Correzione alla previsione

$$U^2 \sim \frac{m_\nu}{M}e^{2\theta''}$$

- Può diventare anche di ordine 10^{-2}

Antush et al., JHEP, 124

Limiti provenienti dal seesaw

- Se θ'' è troppo grande, $m_D \gg M$ e la condizione di seesaw viene meno

Upper bound su U^2

- Se $\theta'' = 0$, troviamo il valore minimo per U^2

Lower bound su U^2

- Predizioni teoriche per i bound
- Mixing molto elevati, vicini all'upper bound, richiedono θ'' grandi ed una struttura limite

Limiti provenienti dal seesaw

- Generazione Monte Carlo dei parametri
- Ci occorrono separatamente $U_e^2 = \sum |U_{ei}|^2, \ \ U_\mu^2$ e U_τ^2 per il confronto con le curve di sensibilità di SHiP
- Ulteriore lower limit proveniente dalla compatibilità con Big Bang Nucleosynthesis

$$\tau < 0.1s$$

τ vita media degli HNL, mediata su entrambi

Approssimativamente $\frac{1}{\tau} \sim U^2 G_F^2 M^5 > 10 s^{-1}$ quando $T = 1MeV$

Canetti et al., Phys.Rev. D87 093006

Limiti provenienti dal double beta decay

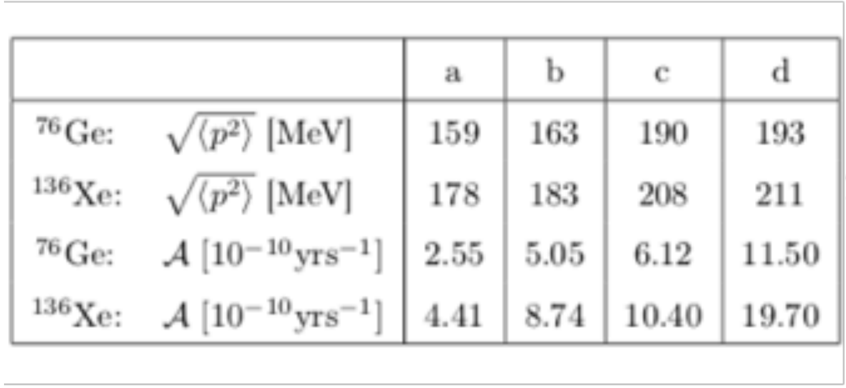
- La vita media per il neutrinoless double beta decay deve essere maggiore del bound sperimentale
- Upper bound sul mixing

$$T^{Ge} = 8.0 \times 10^{25} s$$

GERDA Collaboration, 1803.11100

$$T^{Xe} = 10.7 \times 10^{25} s$$

KamLAND-Zen Collaboration, Phys. Rev. Lett. 117, 082503

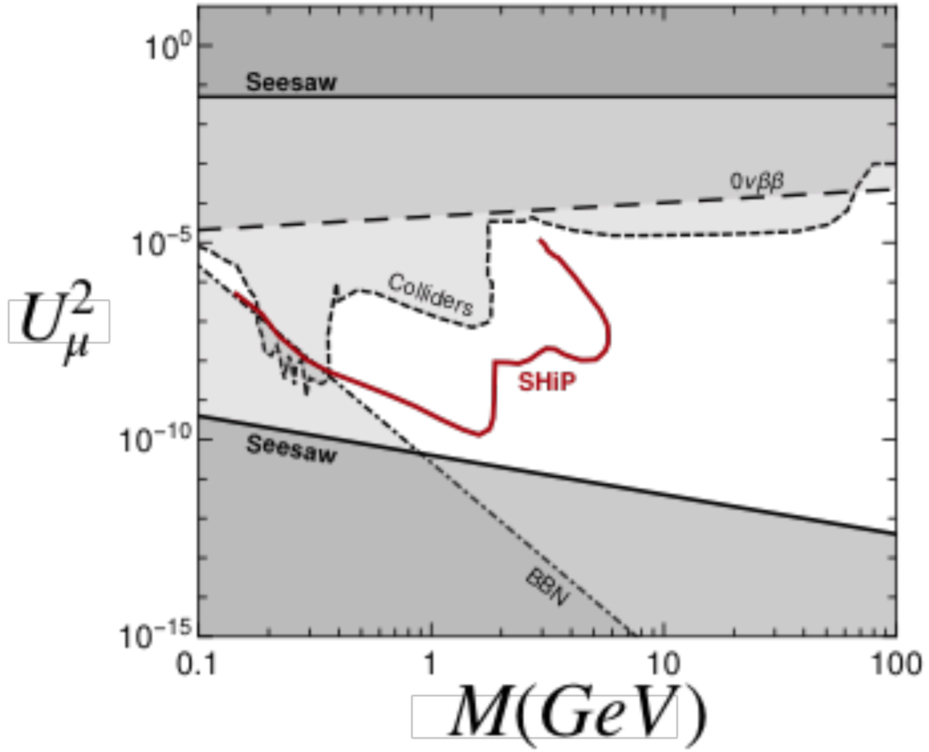


		a	b	c	d
^{76}Ge:	$\sqrt{\langle p^2 \rangle}$ [MeV]	159	163	190	193
^{136}Xe:	$\sqrt{\langle p^2 \rangle}$ [MeV]	178	183	208	211
^{76}Ge:	$\mathcal{A}\ [10^{-10} \text{yrs}^{-1}]$	2.55	5.05	6.12	11.50
^{136}Xe:	$\mathcal{A}\ [10^{-10} \text{yrs}^{-1}]$	4.41	8.74	10.40	19.70

$$T^{-1} = A \left| \frac{m_p}{< p^2 >} \sum_{k=1}^{3} U_{ek}^2 m_{\nu k} + m_p \sum_{N=1}^{2} \frac{U_{e(N+3)}^2 M_N}{< p^2 > + M_N^2} \right|$$

Faessler et al., Phys.Rev. D90 no.9, 096010

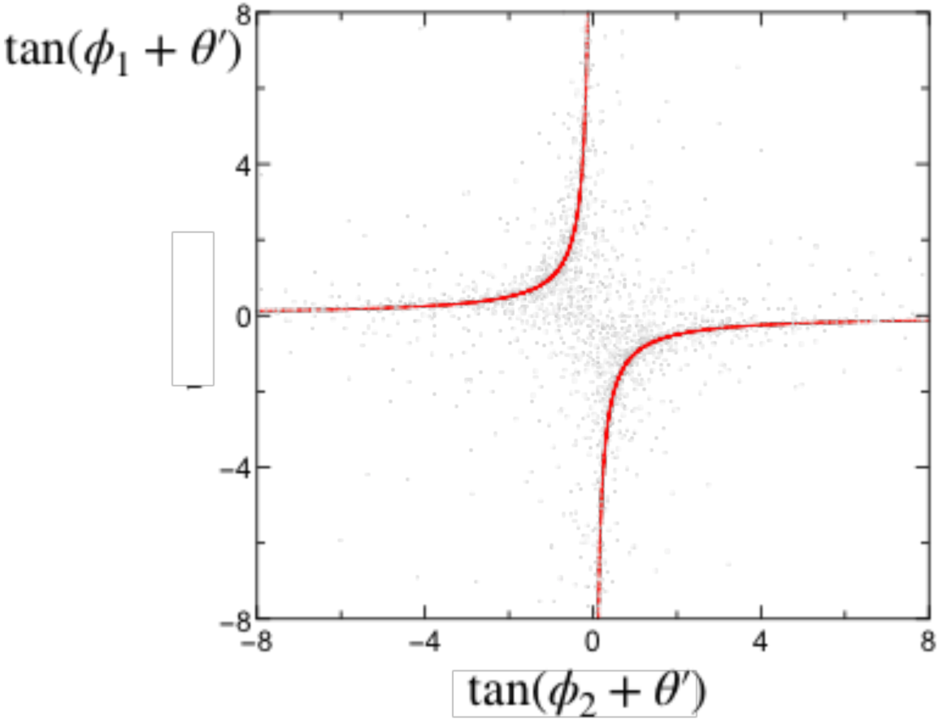
Risultati



- Limiti del double beta decay non competitivi con quelli già provenienti dai colliders
- Limiti del seesaw e di BBN competitivi

Colliders: Deppish et al., 1502.06541

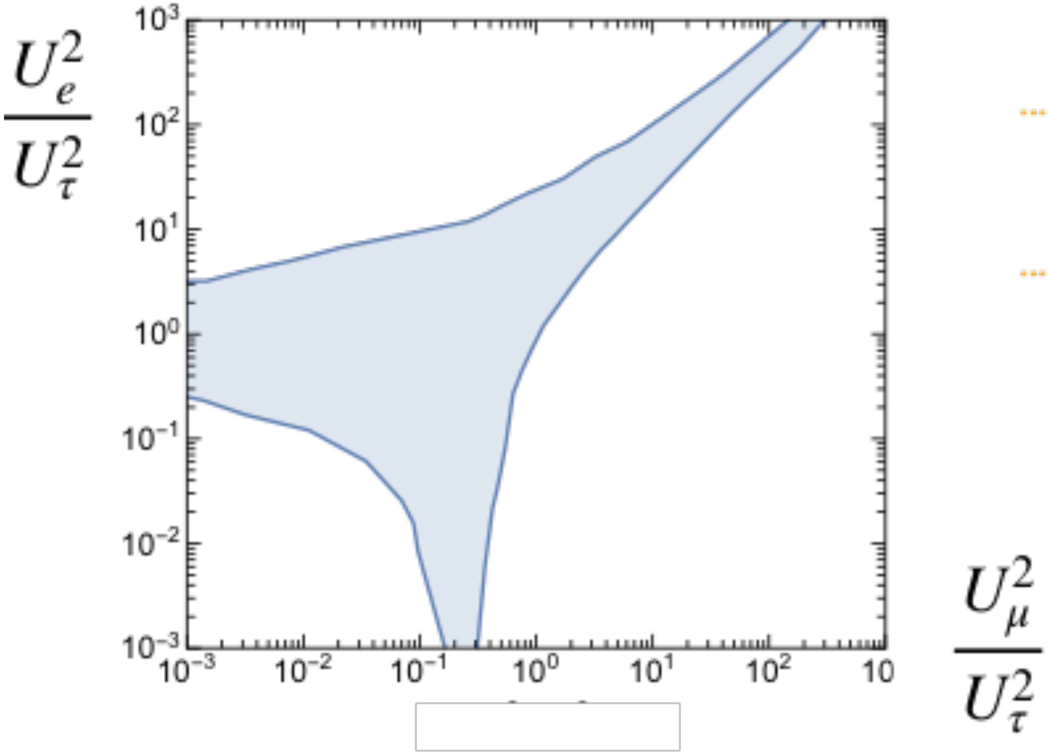
Risultati



- Nel caso di mixing elevati, la matrice di massa dei neutrini raggiunge una struttura limite, con delle relazioni di fase
- Possibile simmetria sottostante?

$$m_D = \begin{bmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \\ m_{31} & m_{32} \end{bmatrix} \qquad \begin{aligned} m_{11} &= |m_{11}| e^{i\phi_1} \\ m_{22} &= |m_{22}| e^{i\phi_2} \end{aligned}$$

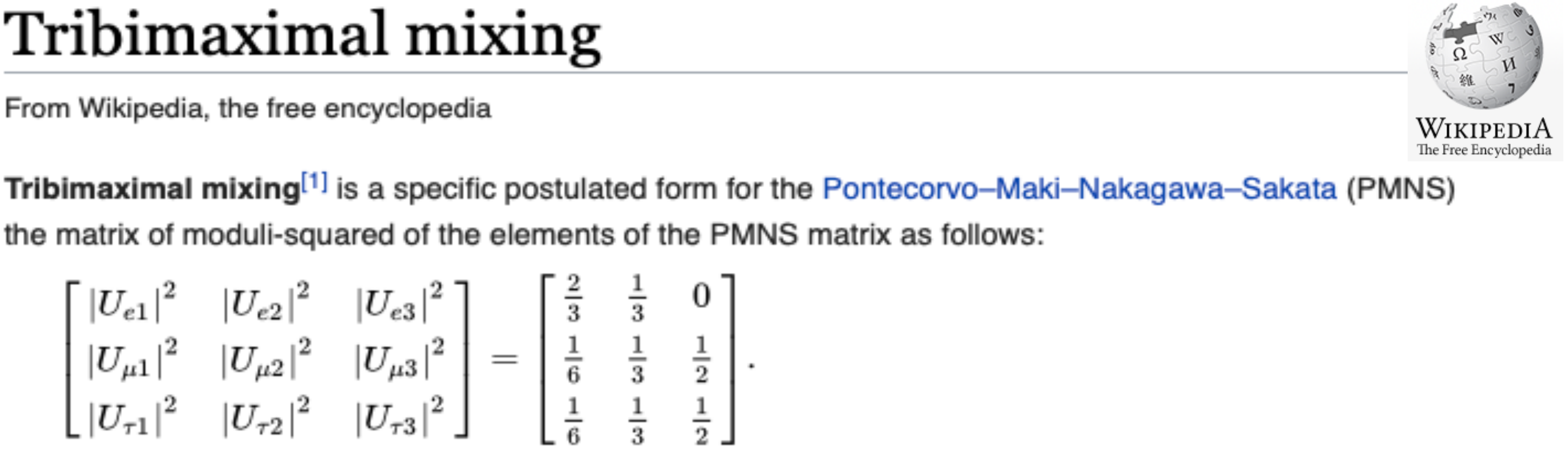
Risultati



- Constraints sui rapporti fra i mixing angles
- Correlazioni fra i parametri della matrice di mixing

Mass-mixing sum rules from gauge symmetry and $0\nu2\beta$ decay: The case of SO(10)

Buccella et al. JHEP 2017

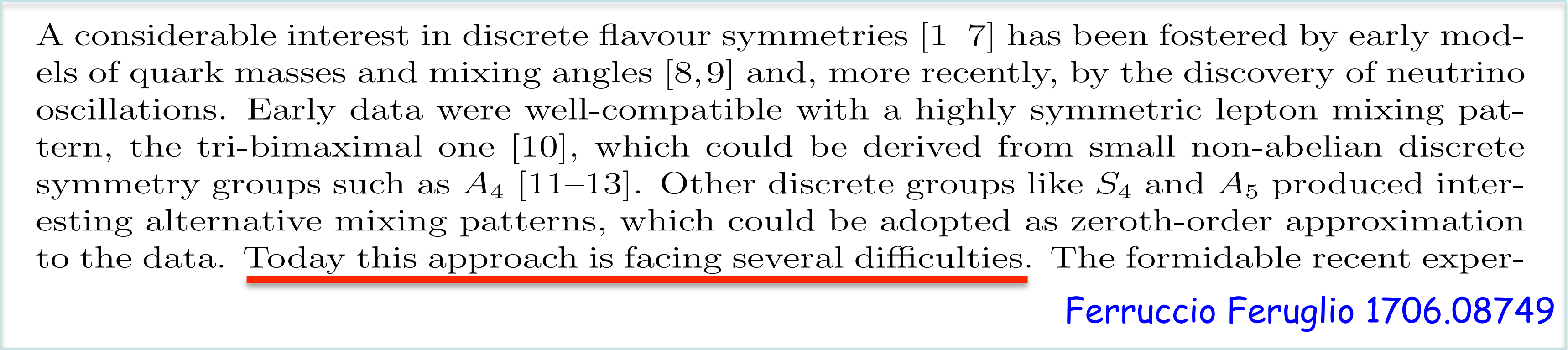


Tribimaximal mixing

From Wikipedia, the free encyclopedia

Tribimaximal mixing[1] is a specific postulated form for the Pontecorvo–Maki–Nakagawa–Sakata (PMNS)
the matrix of moduli-squared of the elements of the PMNS matrix as follows:

$$\begin{bmatrix} |U_{e1}|^2 & |U_{e2}|^2 & |U_{e3}|^2 \\ |U_{\mu1}|^2 & |U_{\mu2}|^2 & |U_{\mu3}|^2 \\ |U_{\tau1}|^2 & |U_{\tau2}|^2 & |U_{\tau3}|^2 \end{bmatrix} = \begin{bmatrix} \frac{2}{3} & \frac{1}{3} & 0 \\ \frac{1}{6} & \frac{1}{3} & \frac{1}{2} \\ \frac{1}{6} & \frac{1}{3} & \frac{1}{2} \end{bmatrix}.$$



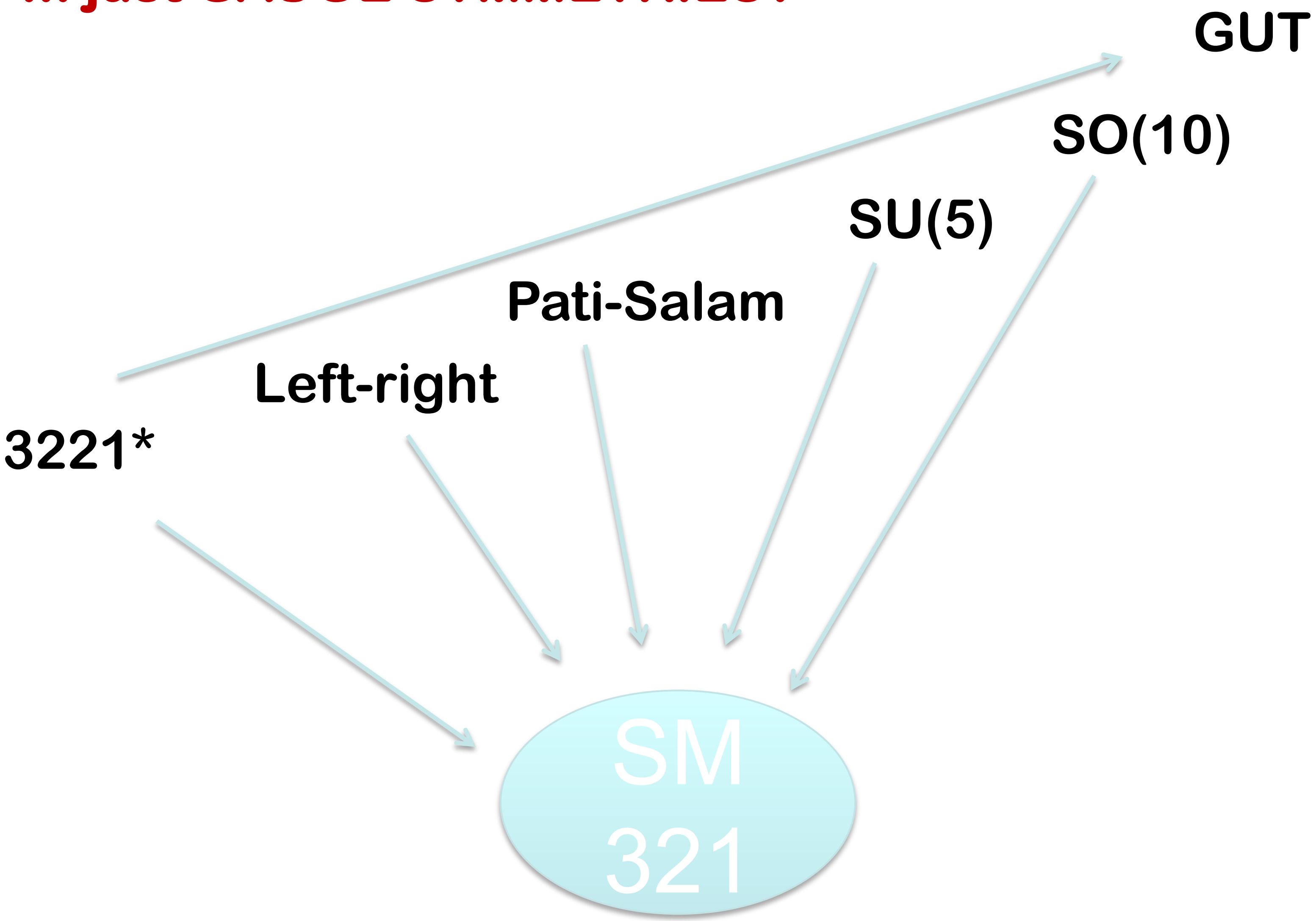
A considerable interest in discrete flavour symmetries [1–7] has been fostered by early models of quark masses and mixing angles [8,9] and, more recently, by the discovery of neutrino oscillations. Early data were well-compatible with a highly symmetric lepton mixing pattern, the tri-bimaximal one [10], which could be derived from small non-abelian discrete symmetry groups such as A_4 [11–13]. Other discrete groups like S_4 and A_5 produced interesting alternative mixing patterns, which could be adopted as zeroth-order approximation to the data. Today this approach is facing several difficulties. The formidable recent exper-

Ferruccio Feruglio 1706.08749

- **Non-vanishing θ_{13} and deviation from maximality of θ_{23}**
- **Many scalars and large corrections from higher order contributions**
- **Quark sector not naturally included**

ANARCHY vs flavor symmetry? or …

… just GAUGE SYMMETRIES?



GUT

SO(10)

SU(5)

Pati-Salam

Left-right

3221*

SM
321

* work in progress: Calabresi, Fiorillo, Miele, Morisi

AN EXAMPLE: MINIMAL SO(10)

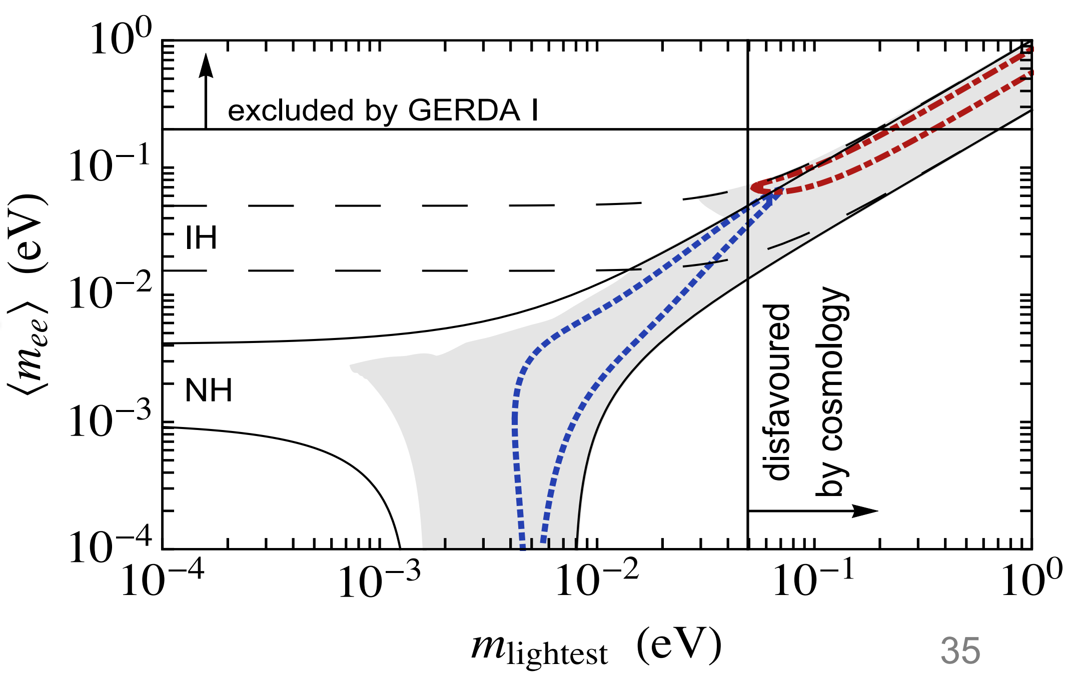
Abud, Buccella IJMPA 2001

- **Type-I seesaw dominant over type-II**
- **Dirac neutrino mass symmetric**
- **Mass and mixing both involved in the sum rule**
- **Upper limit on the heaviest right handed neutrino:** $M_{R3} \lesssim 10^{11}\ GeV$

$$M_R = -m_D^T \frac{1}{m_\nu} m_D$$

$$\boxed{\left| \frac{A^2}{m_1} + \frac{B^2}{m_2 e^{-2i\alpha}} + \frac{C^2}{m_3 e^{-2i\beta}} \right| \lesssim \varepsilon}$$

$$A = \cos\theta_{12}\cos\theta_{23}\sin\theta_{13}e^{i\delta} - \sin\theta_{12}\sin\theta_{23}\,,$$
$$B = \sin\theta_{12}\cos\theta_{23}\sin\theta_{13}e^{i\delta} + \cos\theta_{12}\sin\theta_{23}\,,$$
$$C = \cos\theta_{13}\cos\theta_{23}\,,$$



Neutrino phenomenology from leptogenesis in SO(10)

Buccella et al. EPJC 2018

Lagrangian

$$\mathcal{L} = \quad -\sum_{\alpha\beta} \left(Y^{\ell}\right)_{\alpha\beta} \overline{L}_{L\alpha} H \ell_{R\beta} - \sum_{\alpha i} \left(Y^{\nu}\right)_{\alpha i} \overline{L}_{L\alpha} \tilde{H} N_i + \\ -\frac{1}{2} \sum_{ij} \left(M_R\right)_{ij} \overline{N_i^c} N_j$$

Addition of 3 right-handed SM singlets

$$M_\nu \quad = \quad -M_D \left(M_R\right)^{-1} M_D^T \qquad\qquad M_R \quad = \quad -M_D^T M_\nu^{-1} M_D$$

The leptogenesis process depends on M_D and M_R

$$\epsilon_{i\alpha} = \frac{\Gamma_{N_i \to l_\alpha \phi} - \Gamma_{N_i \to \bar{l}_\alpha \phi}}{\Gamma_{N_i \to l_\alpha \phi} + \Gamma_{N_i \to \bar{l}_\alpha \phi}}$$

CP asymmetries

$$\epsilon_{i\alpha} \quad = \quad \frac{1}{8\pi v^2} \sum_{k \neq i} \left[A_{ik}\, f\left(\frac{M_k^2}{M_i^2}\right) + B_{ik}\, g\left(\frac{M_k^2}{M_i^2}\right) \right]$$

Depend on the elements of M_D

**Experimental fact:
charged lepton masses are hierarchical**

$$Y^{\ell}_{11} \ll Y^{\ell}_{22} \ll Y^{\ell}_{33}$$

Plausible to assume hierarchical Dirac neutrino Yukawa coupling

$$Y^{\nu}_{11} \ll Y^{\nu}_{22} \ll Y^{\nu}_{33}$$

This leads to hierachical heavy right-handed neutrino mass spectrum

$$M_{R_1} \ll M_{R_2} \ll M_{R_3}$$

Davidson-Ibarra Limit can be avoided by imposing a “compact spectrum”

$$M_i \sim 10^{11\pm 2}$$

SO(10) implies a particular structure for M$_D$

$$M_D \approx M_{\mathrm{up}}$$

Baryon asymmetry can be calculated by solving Boltzman equations and compared with experimental value

$$Y_{\Delta B} = (8.65 \pm 0.06) \cdot 10^{-11}$$

$$Y_{\Delta l_\alpha} \equiv Y_{l_\alpha} - Y_{\bar{l}_\alpha}$$

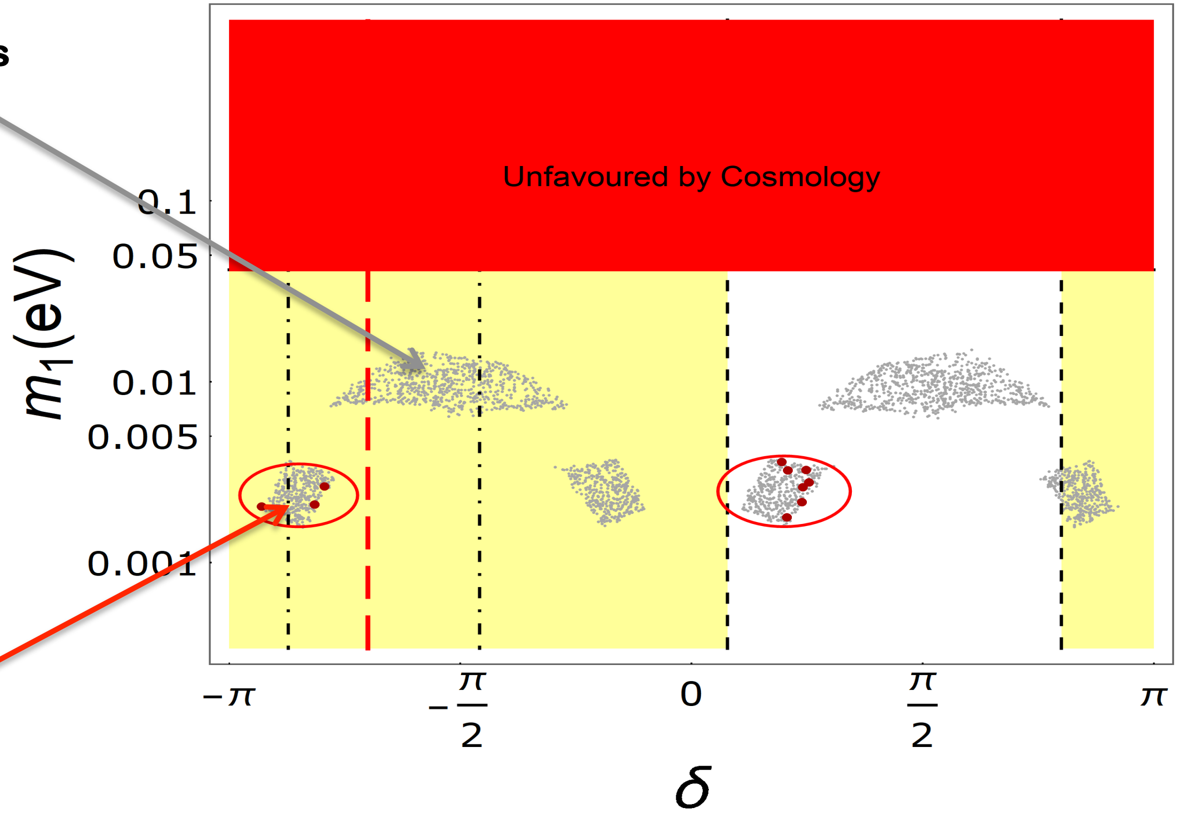
$$Y_{\Delta\alpha} \equiv Y_B/3 - Y_{\Delta L_\alpha}$$

$$Y_{\Delta B} = \frac{28}{79} \sum_\alpha Y_{\Delta\alpha}$$

Predictions for δ and m_1

$M_D = M_{up}$,
compact M_R eigenvalues

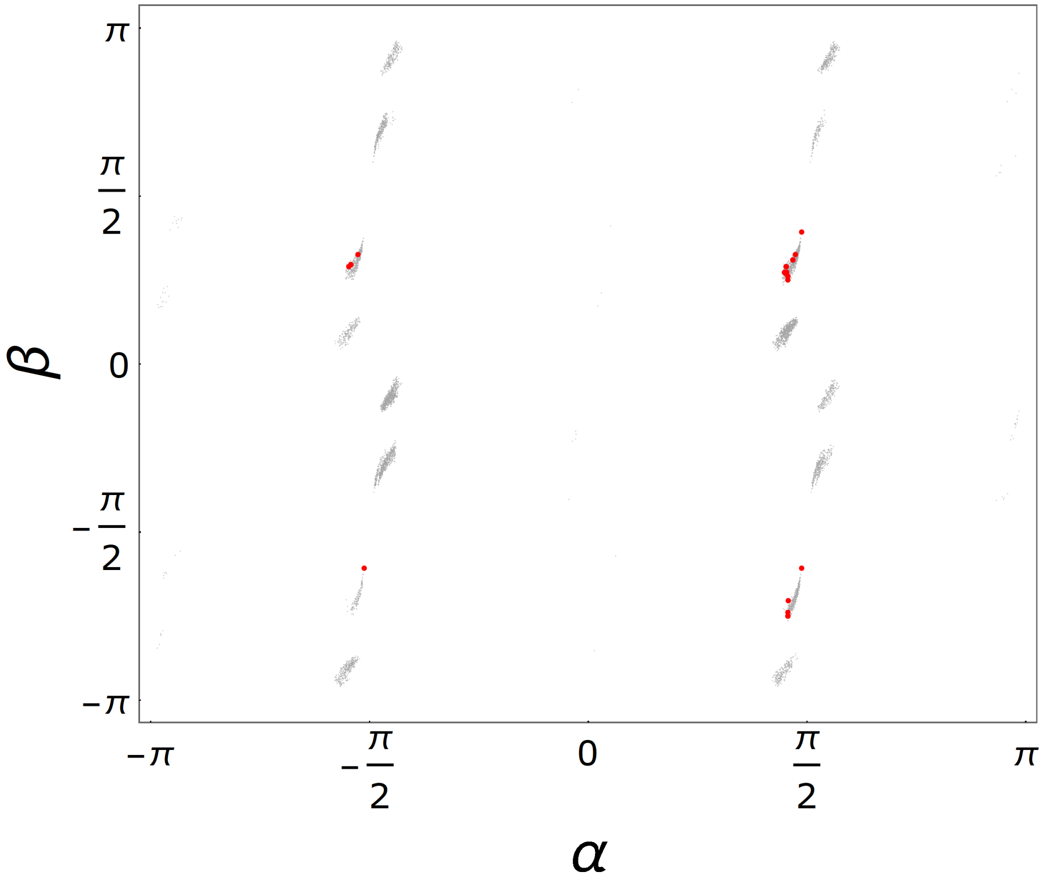
$$M_i \sim 10^{11\pm2}$$



baryogenesis
via
leptogenesis

$$\begin{cases} -0.90\pi < \delta < -0.75\pi \\ m_1 \sim (0.002 - 0.004)\,\text{eV} \end{cases}$$

Predictions for Majorana phases

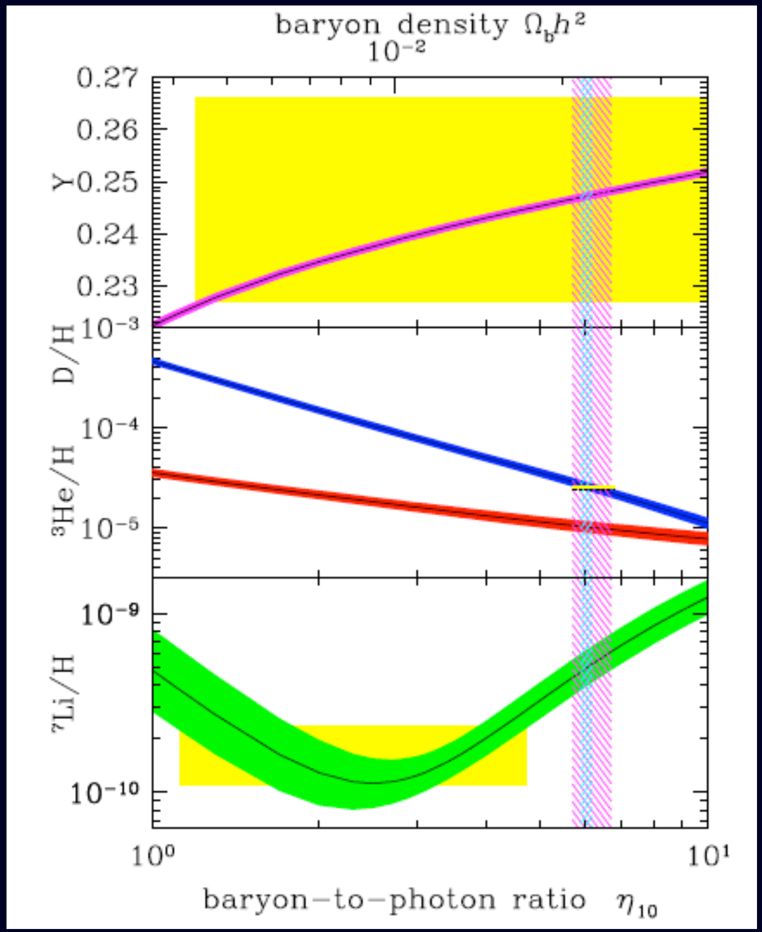


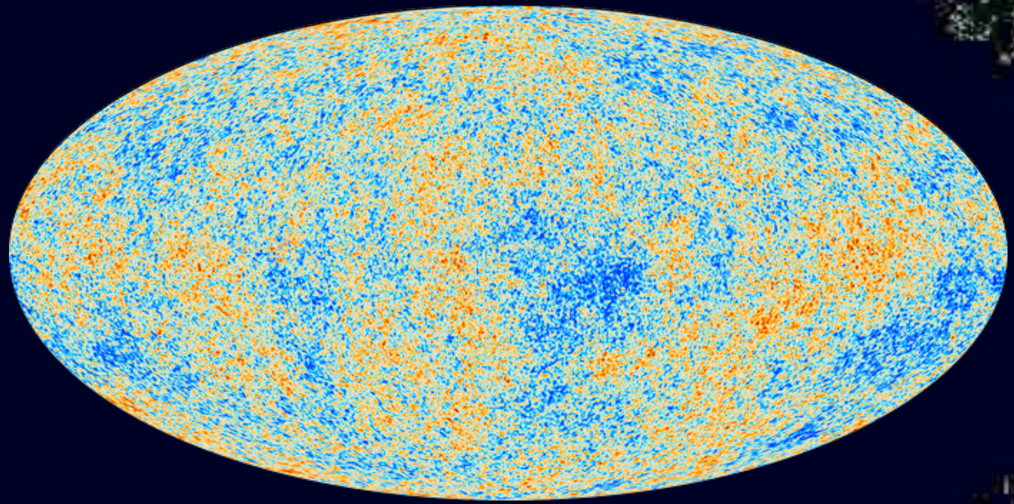
However $m_{\beta\beta}$ is too low (<0.02eV) to be detected

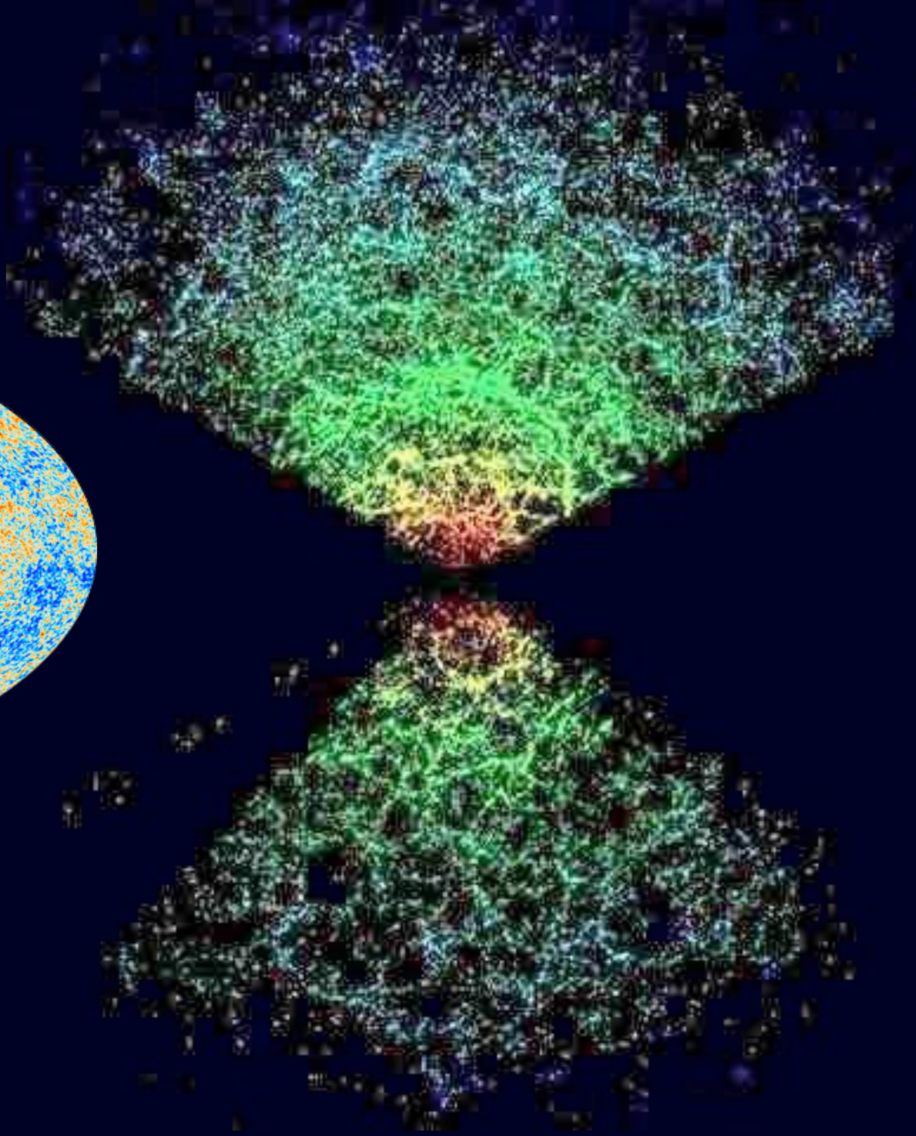
(eV…) ***Sterile neutrinos and cosmology***

- Contribution to Neff
- neutrino mass
- possible distortions of active neutrino spectra
- new interactions…

Cosmological observations







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

Sensitivity to $N_{\rm eff}$ and ν masses

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

Radiation Content in the Universe

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

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

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

Mangano et al. 2005

(+ oscillations)

($N_{\rm eff}^{\rm SM} = 3.045$ 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~1- 0.01 MeV** production of the primordial abundances of light elements, in particular ^2H, ^4He

When $\Gamma_{n\longleftrightarrow p} < H$ ➜ *neutron-to- proton ratio freezes out* $\frac{n_n}{n_p} = \frac{n}{p} = e^{-\Delta m/T} \rightarrow 1/7$

Sterile ν influence on BBN :

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

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

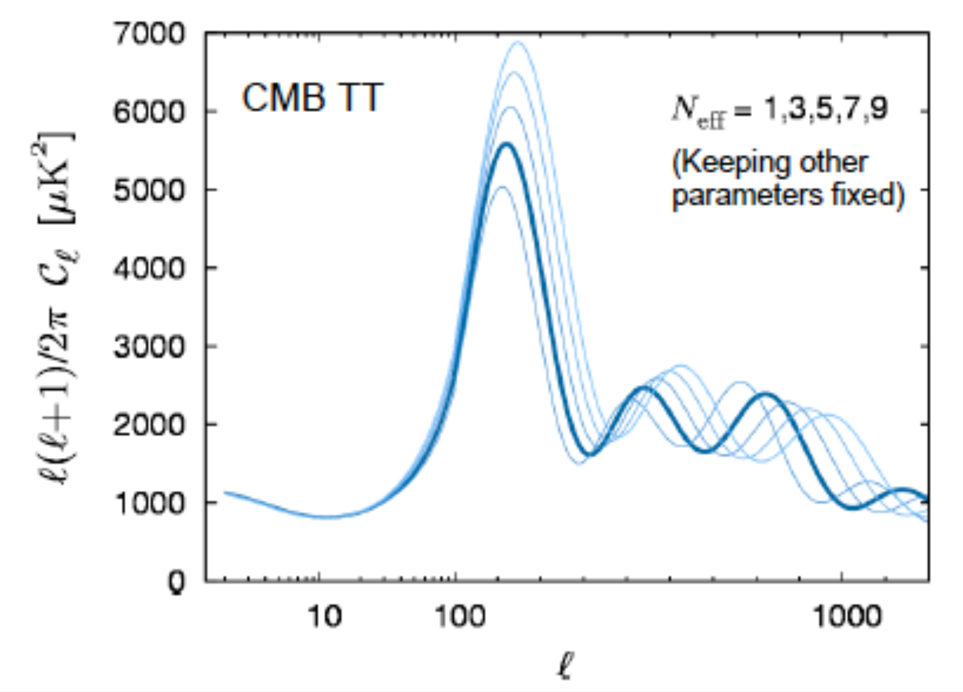
BBN constraint on ΔN_{eff} : **NO preference for extra radiation**

- oscillating with the active neutrinos, can **distort the active spectra** which are the basic input for BBN
- Non standard interaction among (sterile) neutrinos, can **distort the active spectra** and consequently impact the BBN productions

See WP1 and WP4 for further details on BBN

Impact on CMB

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



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

Combined with other cosmological probes: Planck—>Neff ~3

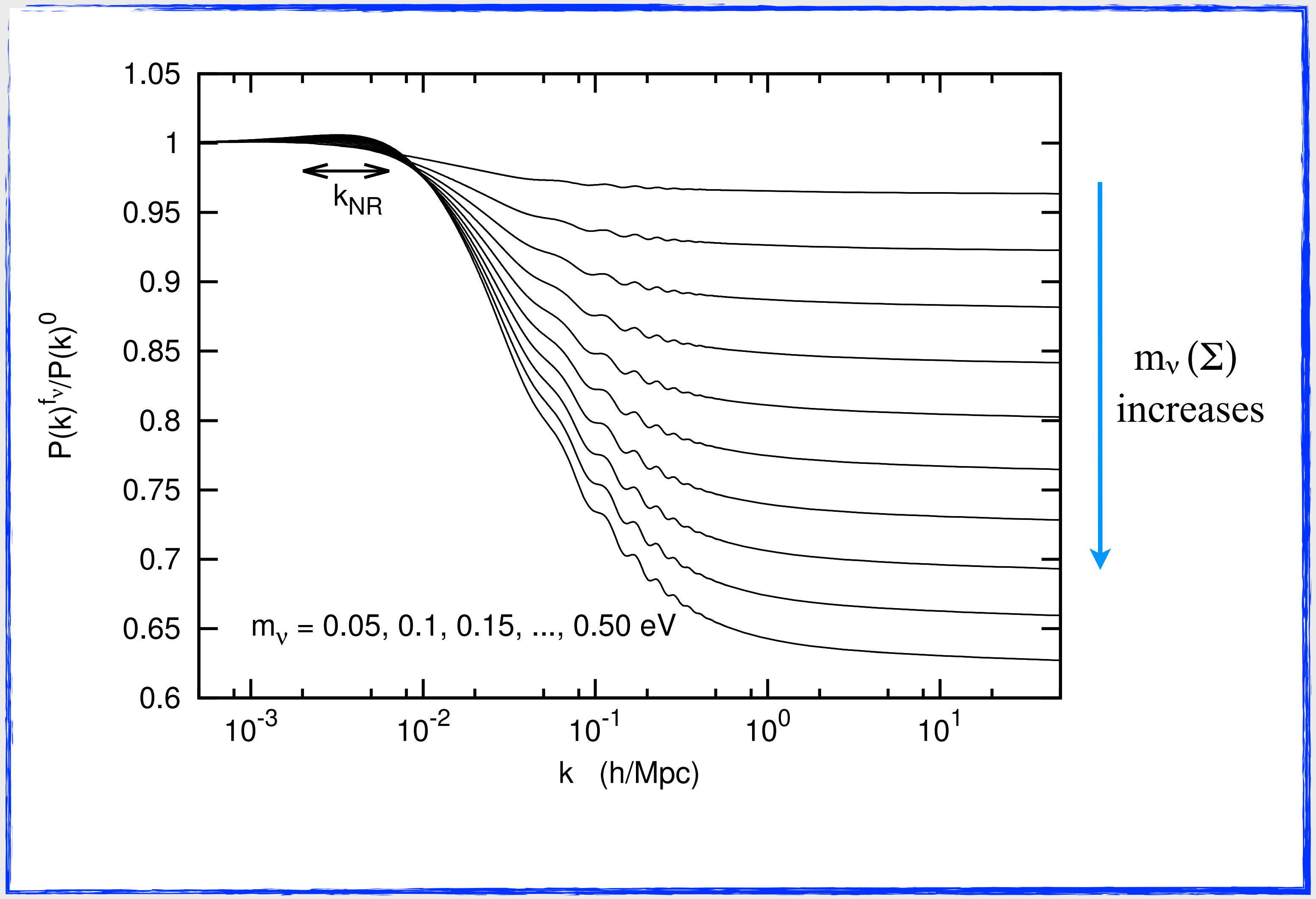
- Neutrino mass (background and perturbation level, suppression of the lensing…)

- Neutrino non standard interactions

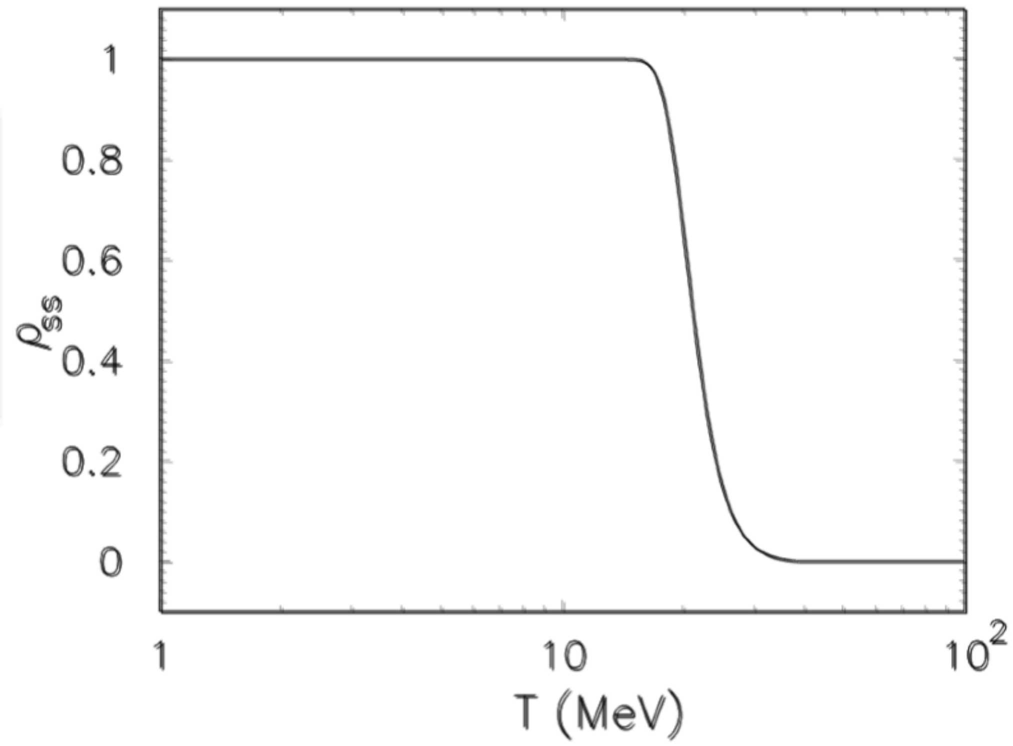
Impact on the LSS

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

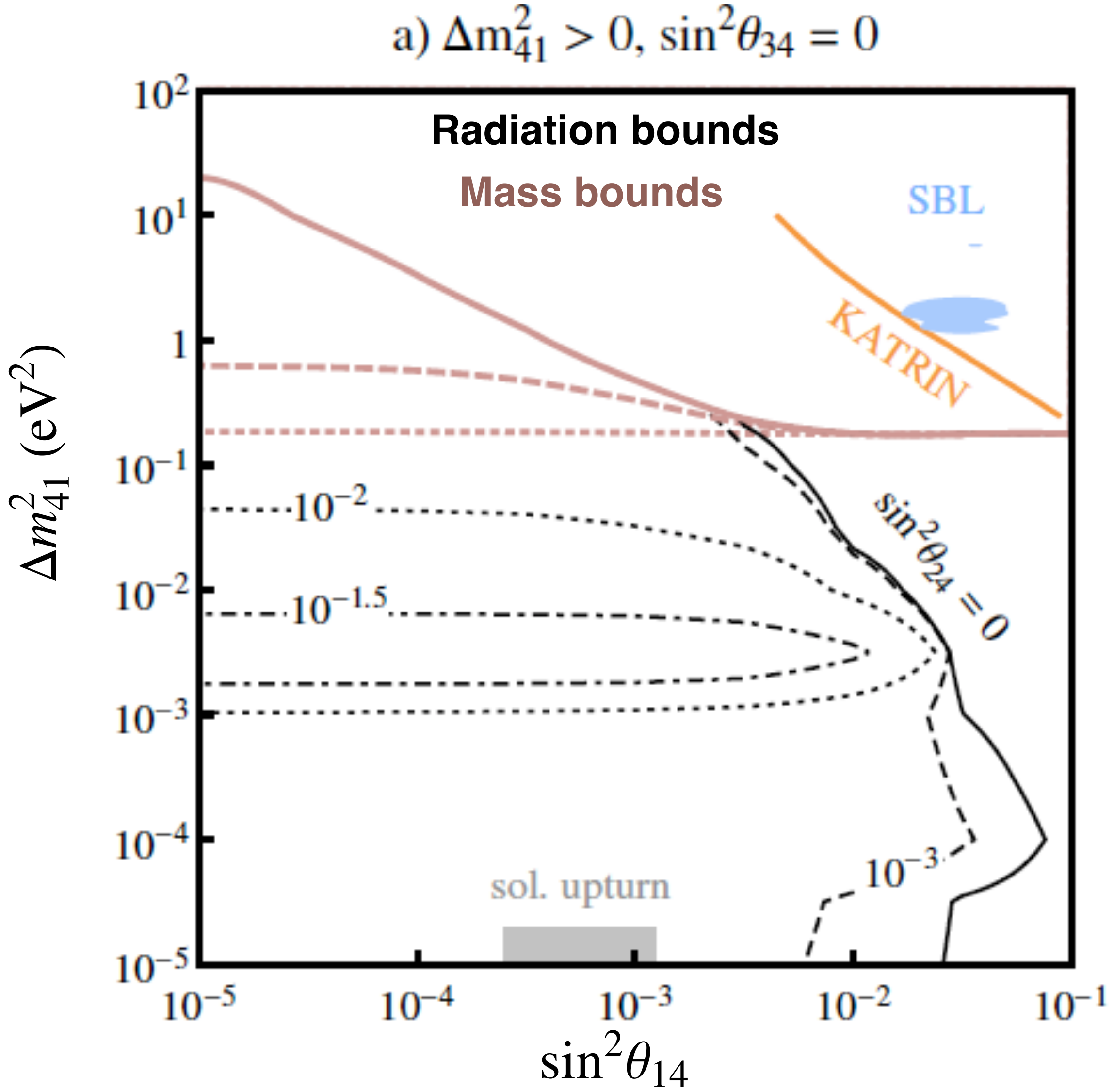


eV sterile Compatibility with cosmology



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

Planck constraints on the parameter space of ν oscillation:



Too many and too heavy
for cosmological observations
(BBN, CMB, LSS)

$$\left.\begin{aligned} N_{\rm eff} &< 3.34, \\ m^{\rm eff}_{\nu,\,\rm sterile} &< 0.23\ {\rm eV}, \end{aligned}\right\} \begin{array}{l} 95\,\%,\ \textit{Planck}\ \text{TT,TE,EE+lowE} \\ \text{+lensing+BAO.} \end{array}$$

Possible solutions?

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

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

$$\boxed{L = \frac{n_\nu - n_{\bar{\nu}}}{n_\gamma}}$$

Introducing L in the flavour evolution equation, this suppresses the thermalization of sterile neutrinos ($\rho_{ss}\downarrow$) by an effective ν_a-ν_s mixing reduced by large matter term ∝ L

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

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

Different authors have assumed the Standard Model (SM) is augmented by one extra species of light (~ eV) neutrinos ν_s, which experiment a new force. 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 *(by 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

Scenario ruled out in case of new vector mediator X by BBN, CMB & mass constraints from different investigations (most of them performed by our group) in the ranges

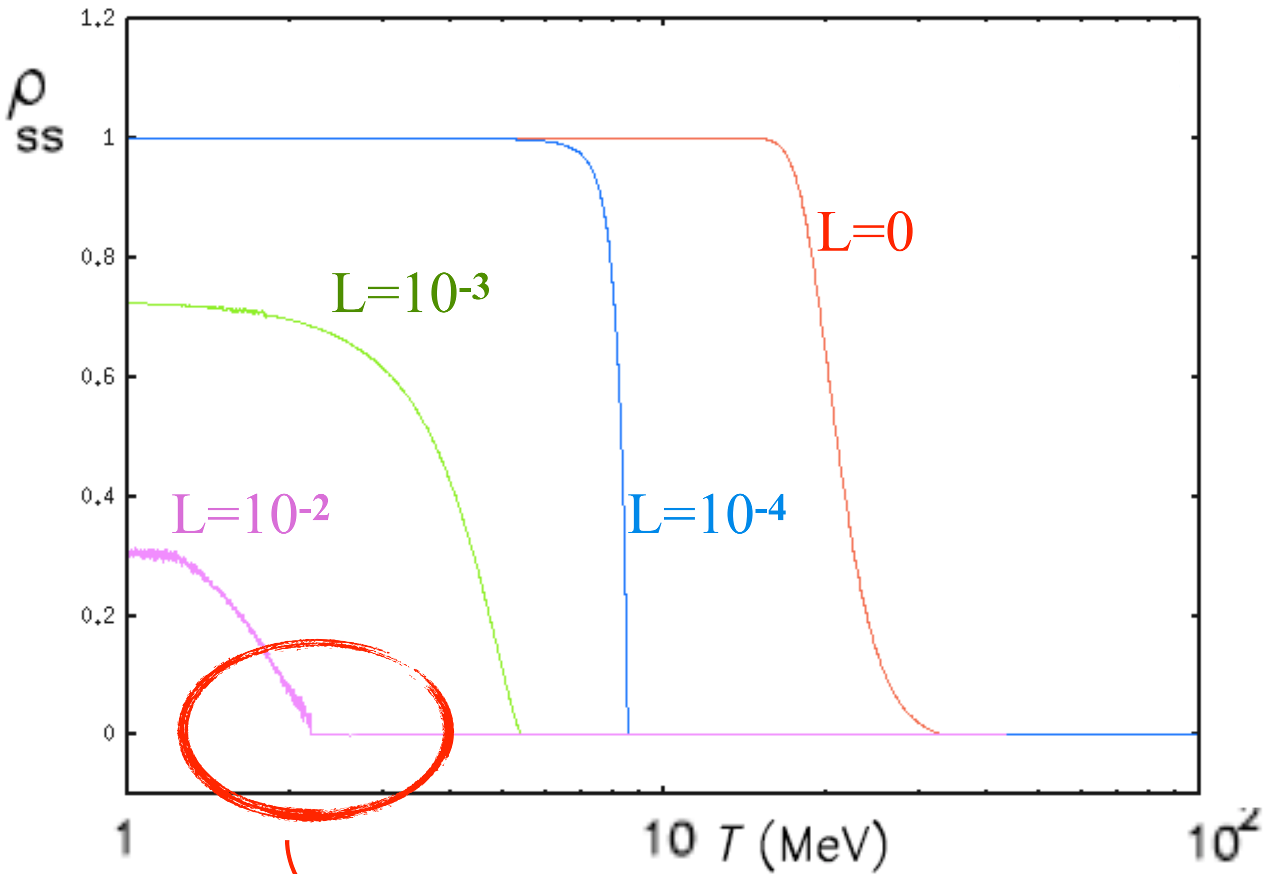
$M_X[10^{-3}, 10^{3}]$MeV and $g_X[10^{-6}, 1]$

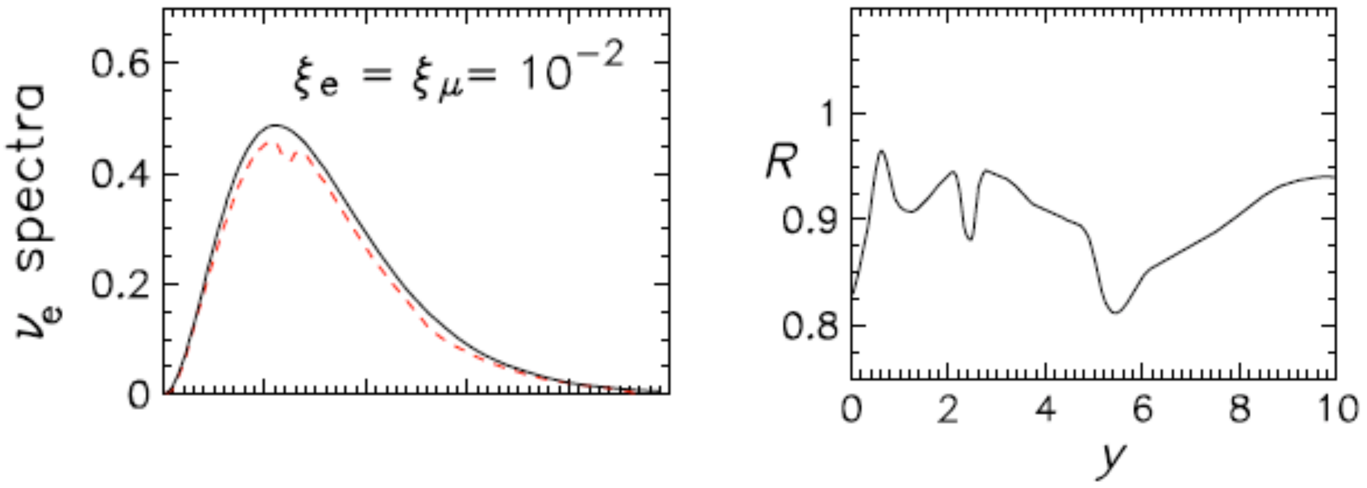
Possible solutions?

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

1. ***large $\nu - \overline{\nu}$ asymmetries*:**

*Mirizzi, **Saviano**., Miele, Serpico 2012; **Saviano** et al., 2013;*





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

If active neutrino spectra (ν_e) are distorted —> possible effects on BBN predictions

Work in progress:
multi-momentum scan in 2-sigma range of the global fit-anomalies, for different values of neutrino asymmetry and BBN theoretical prediction with PARTHENOPE code

Forestieri, Mangano, Miele, Mirizzi, Pesanti e Saviano

Heavy sterile neutrinos projects

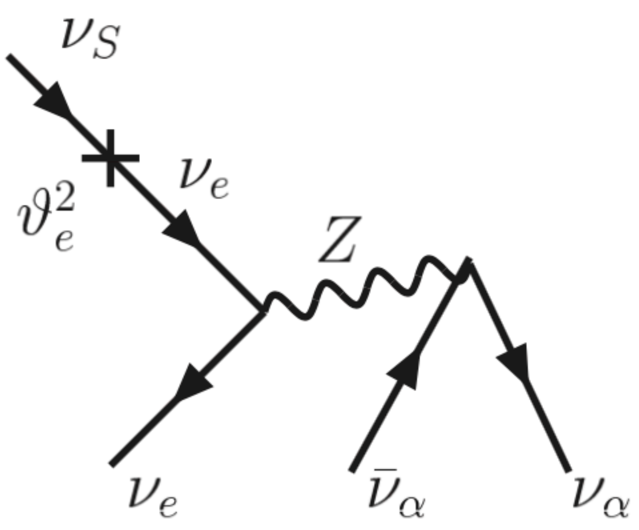
WORK IN PROGRESS:

Influence of heavy ($\mathcal{O}$ 10^2 MeV) sterile neutrinos on primordial nucleosynthesis.

Mastrototaro, Miele, Mirizzi et al…

Massive sterile neutrinos can decay and, due to their feeble interaction strength, their lifetime can be of order seconds.

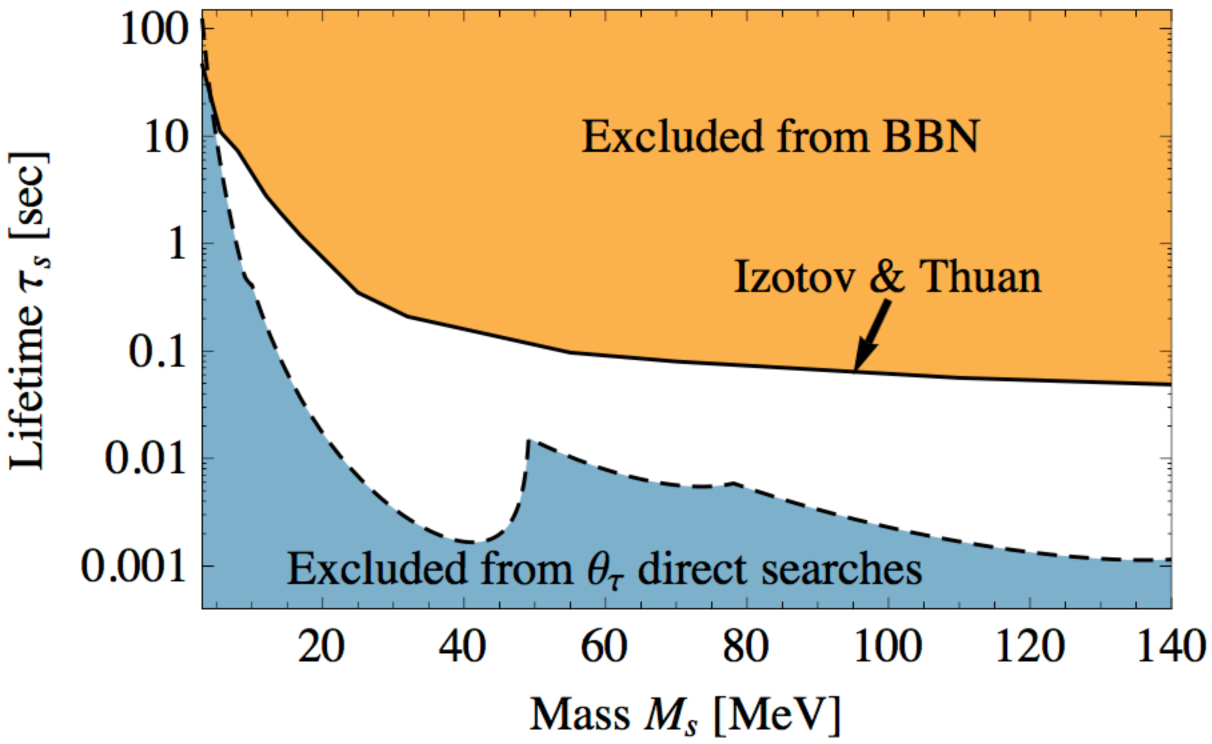
The decay products of the sterile neutrinos are injected into the primordial environment, increasing its temperature and shifting the chemical equilibrium.



For particles that either are not in equilibrium or are about to fall out of it, such as active neutrinos at few MeV, the “injection” modifies the form of their spectra.

Impact on BBN

- through the contribution to the cosmological energy density by speeding up the expansion and enlarging the frozen neutron-to-proton ratio, $r_n = n/p$,
- through its decay products, ν_e , ν_μ , and ν_τ



Paper of Ruchayskiy and Ivashko, 2012

Figure: Comparison of direct accelerator constraints and BBN bounds, based on the Helium-4 measurements in the model where sterile neutrinos mix with ν_τ only.

See WP3 for bound from SN

Next steps:

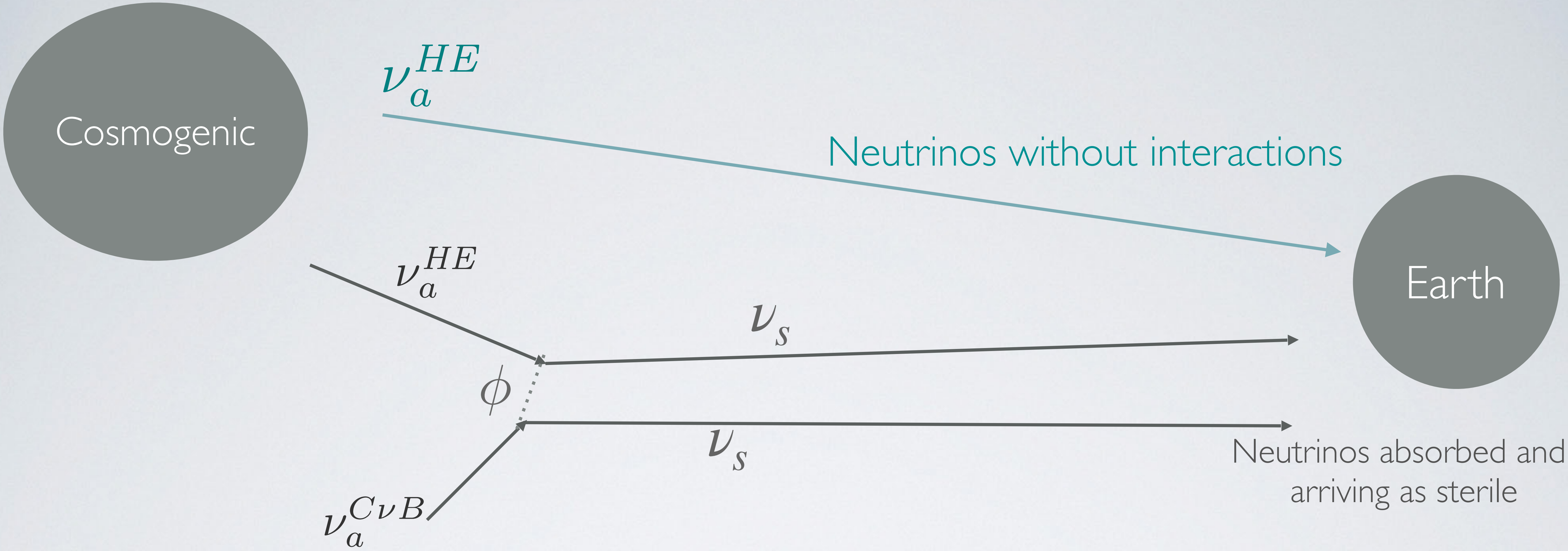
- New BBN bounds
- Investigation for Ms > 140 MeV

Challenging task: two-particle decay channels appear (e.g. $\nu_S \rightarrow \pi^0\nu_\alpha, \pi^\pm e^\mp$) and the procedure of solving Boltzmann equations should be significantly modified.

WORK IN PROGRESS:

Absorption of astrophysical neutrino flux due to secret interactions and massive sterile neutrinos

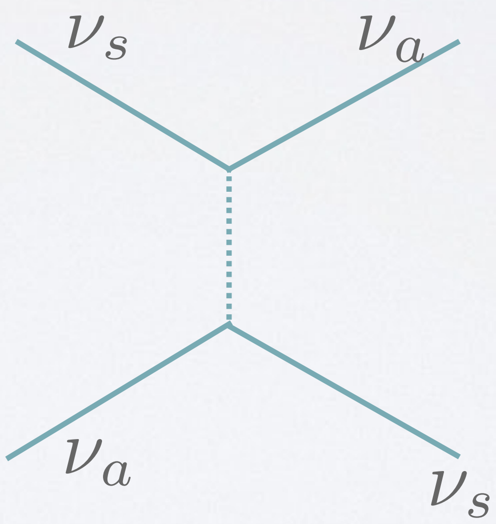
D. Fiorillo, G. Miele, S. Morisi, N. Saviano

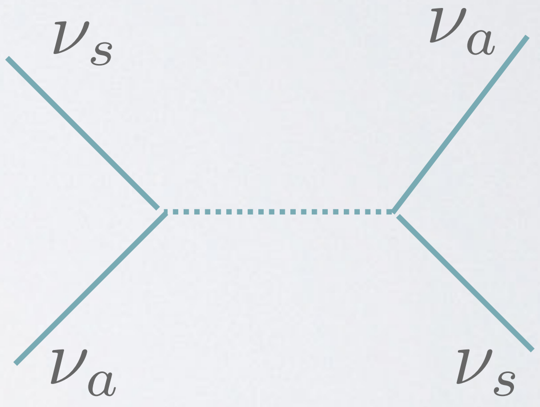


Neutrinos without interactions

Neutrinos absorbed and
arriving as sterile

$C\nu B$: Cosmic neutrino Background





$$\mathcal{L} = -\lambda\bar{\nu}\gamma^5\phi\nu_s$$

$\lambda\,\mathcal{O}(1)$

ϕ new pseudoscalar mediator

Sterile and scalar masses > 0.25 GeV to avoid kaon decay and cosmological constraints

No problem with energy loss in SN since sterile nu would be trapped

PROPAGATION OF ASTROPHYSICAL NEUTRINOS

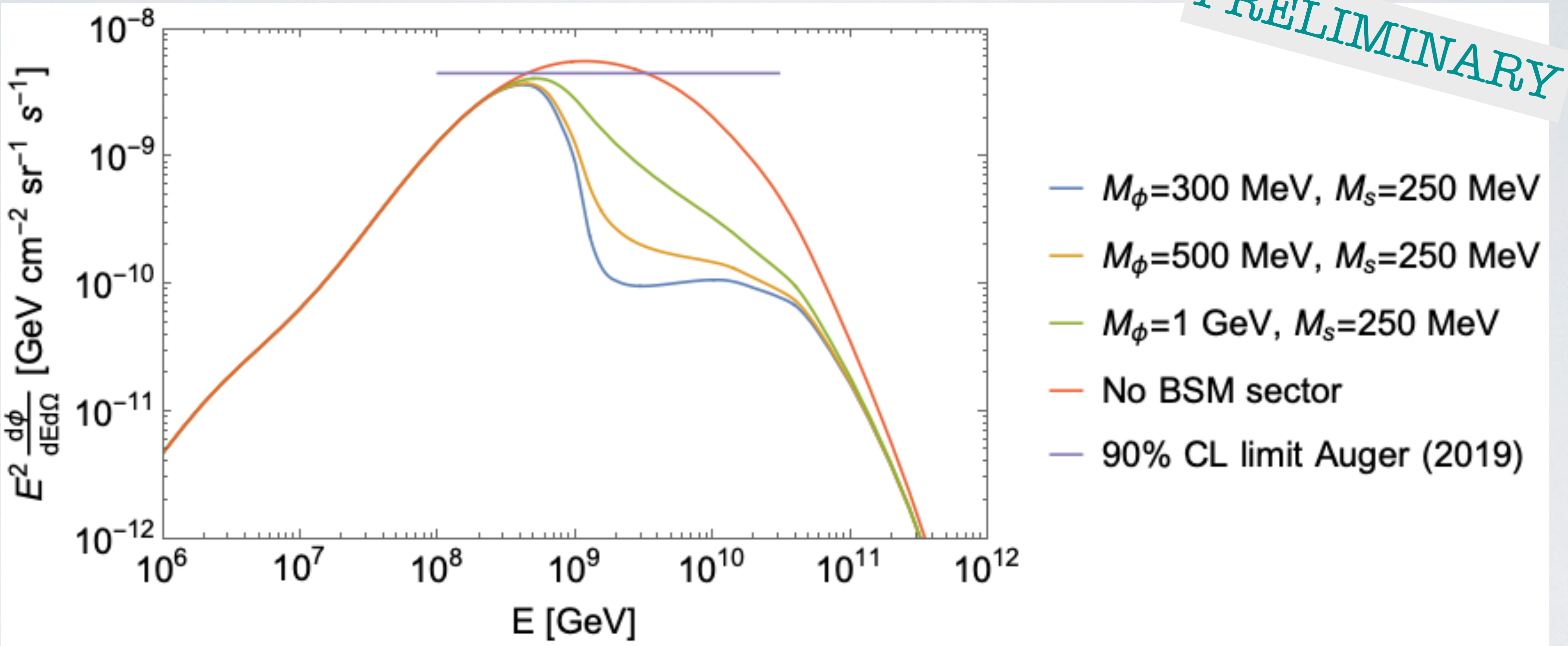
$$\frac{\partial \phi}{\partial l} = -\, n\sigma\phi + n \int dE' \frac{d\sigma}{dE}(E' \to E)\phi(E') + \text{source}$$

Evolution

Absorption

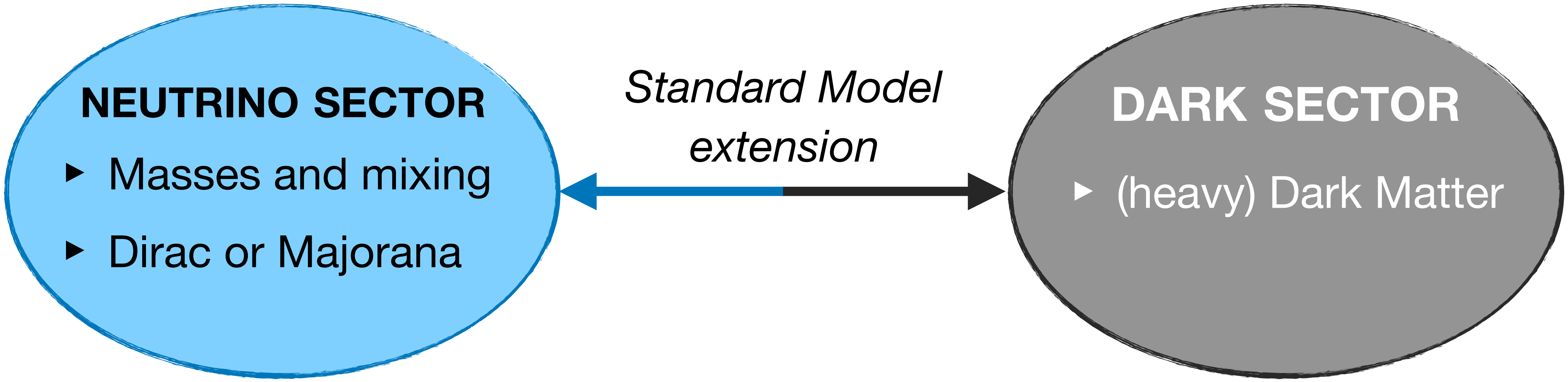
Regeneration

Cosmogenic


PRELIMINARY
$E^2 \frac{d\phi}{dEd\Omega}$ [GeV cm^{-2} sr^{-1} s^{-1}]
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{6}
10^{7}
10^{8}
10^{9}
10^{10}
10^{11}
10^{12}
E [GeV]
M_ϕ=300 MeV, M_s=250 MeV
M_ϕ=500 MeV, M_s=250 MeV
M_ϕ=1 GeV, M_s=250 MeV
No BSM sector
90% CL limit Auger (2019)

Neutrino Physics and Dark Matter

Connecting Neutrino Physics with Dark Matter



NEUTRINO SECTOR

- Masses and mixing
- Dirac or Majorana

Standard Model extension

DARK SECTOR

- (heavy) Dark Matter

Connection *in the present*

Neutrinos are the main messenger to indirectly look for DM.

- Allowed features of a DM signal in Neutrino Telescopes
- Viable leptophilic DM model

Connection *in the past*

The neutrino sector drives the DM production in the Early Universe (Neutrino portal).

- Model to account for a realistic neutrino spectrum and a viable DM relic density.

Goal: find a minimal extension of the SM (bottom-up approach) with a direct link between the two sectors

Neutrinophilic Dark Matter

How to realize a model for 100 TeV Dark Matter decaying only into neutrinos? The main features are:

- requirement of a new global symmetry

→ to forbid all the other decay channels

- Dirac nature of active neutrinos

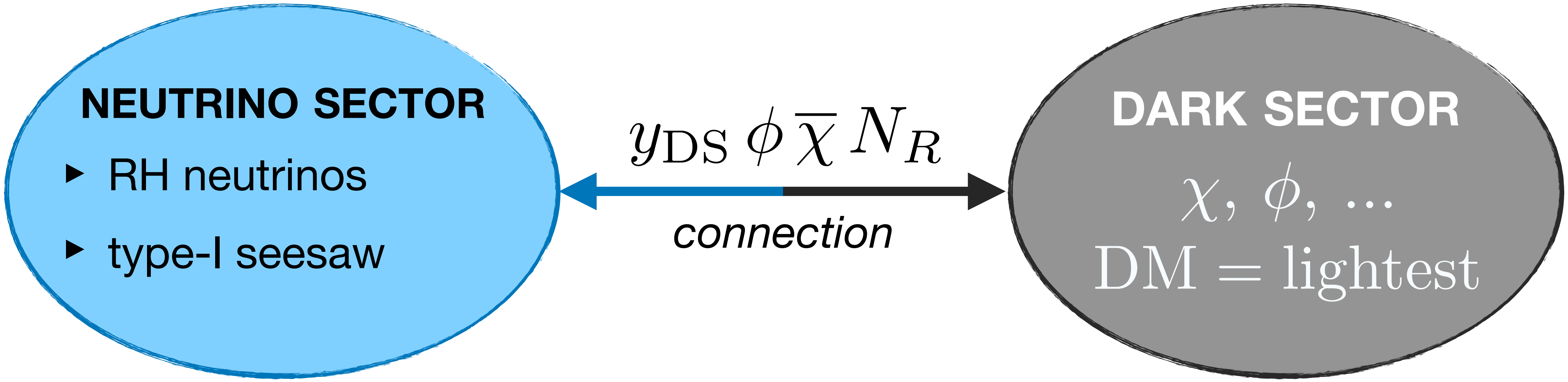
→ to not spoil the new global symmetry (e.g. extended lepton number)

- A reheating temperature of the Universe as low as TeV scale

→ to dilute the overabundant Dark Matter produced via freeze-out

Chianese, Miele, Morisi, Peinado, ***JCAP 1812*** *(see also Chianese and Merle,* ***JCAP 1704****)*

Right-handed neutrino portal



NEUTRINO SECTOR
- RH neutrinos
- type-I seesaw

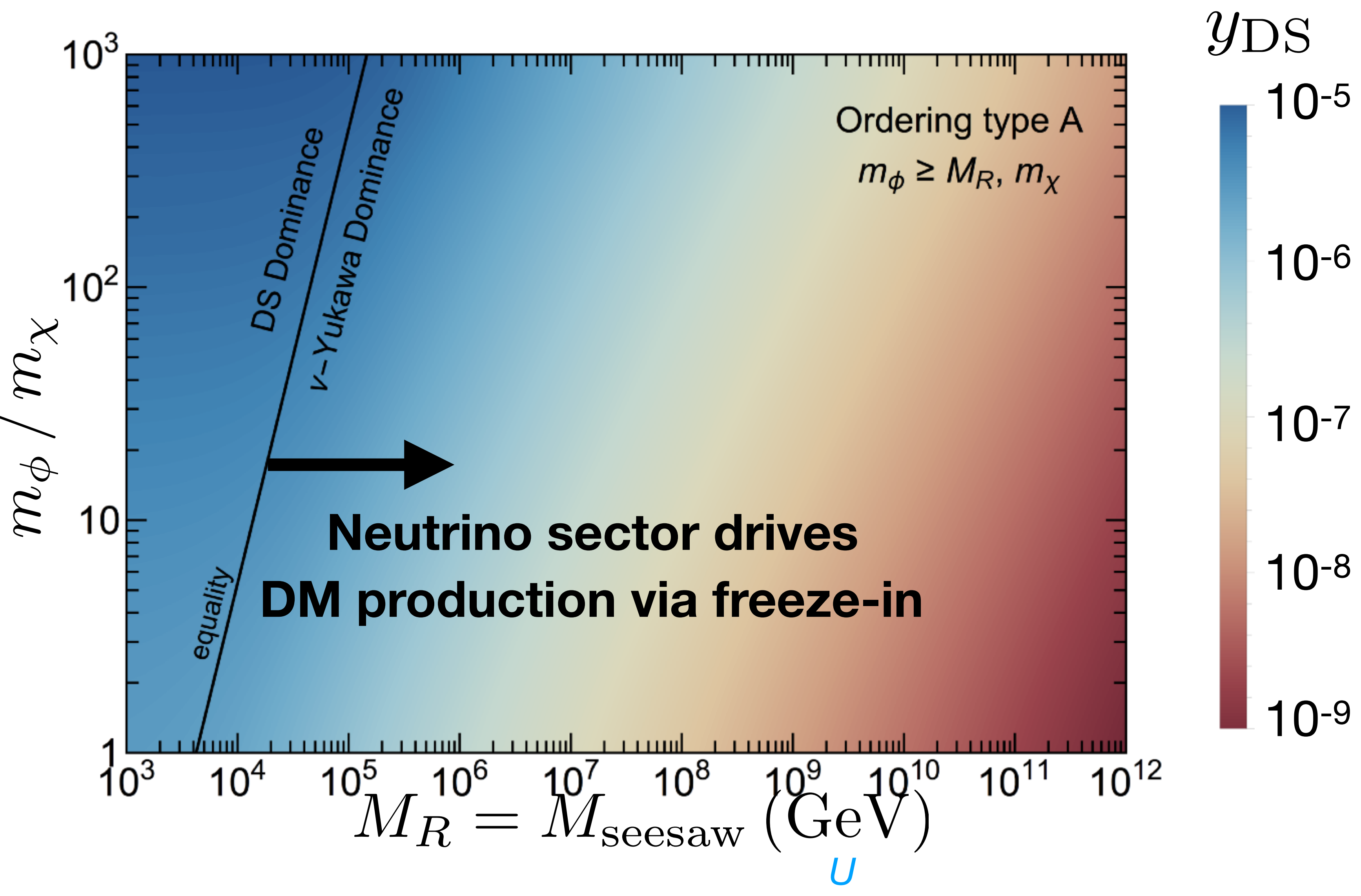
$y_{\rm DS}\, \phi\, \overline{\chi}\, N_R$

connection

DARK SECTOR

$\chi,\ \phi,\ \dots$

$\mathrm{DM} = \mathrm{lightest}$



Key features

- Neutrino-DM relation
- Very heavy DM (FIMPzilla)
- Importance of the initial conditions of the Universe (reheating temperature)
- Contribution from gravity-mediated processes

Next step

Grazie