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# Light sterile neutrinos in the early universe

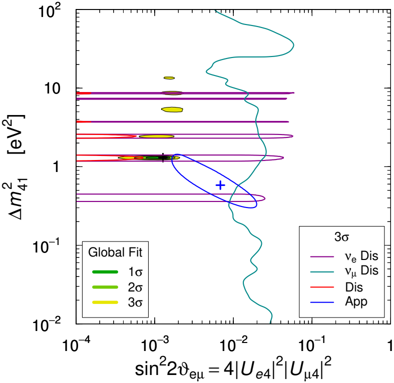
XI CPAN Meeting, Oviedo (ES), 21–23/10/2019

1 *Light sterile neutrino*

2 *Light sterile neutrino and cosmology*

3 *A new interaction to solve the thermalization problem?*

4 *Conclusions*



# Three Neutrino Oscillations

Analogous to CKM mixing for quarks:

[Pontecorvo, 1968]
[Maki, Nakagawa, Sakata, 1962]

$$\nu_\alpha = \sum_{k=1}^{3} U_{\alpha k} \nu_k \quad (\alpha = e, \mu, \tau)$$

$\nu_\alpha$ flavour eigenstates, $U_{\alpha k}$ PMNS mixing matrix, $\nu_k$ mass eigenstates.

## Current knowledge of the 3 active $\nu$ mixing: [de Salas et al. (2018)]

$\Delta m^2_{ji} = m^2_j - m^2_i$, $\theta_{ij}$ mixing angles
NO: Normal Ordering, $m_1 < m_2 < m_3$
IO: Inverted Ordering, $m_3 < m_1 < m_2$

$$\Delta m^2_{21} = (7.55^{+0.20}_{-0.16}) \cdot 10^{-5}\ \mathrm{eV}^2$$

$$|\Delta m^2_{31}| = (2.50 \pm 0.03) \cdot 10^{-3}\ \mathrm{eV}^2\ (\mathrm{NO})$$

$$= (2.42^{+0.03}_{-0.04}) \cdot 10^{-3}\ \mathrm{eV}^2\ (\mathrm{IO})$$

$$\sin^2(\theta_{12}) = 0.320^{+0.020}_{-0.016}$$

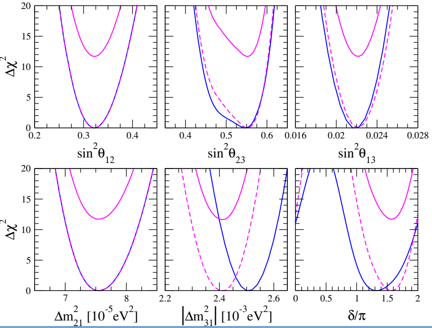
$$\sin^2(\theta_{13}) = 0.0216^{+0.008}_{-0.007}\ (\mathrm{NO})$$

$$= 0.0222^{+0.007}_{-0.008}\ (\mathrm{IO})$$

$$\sin^2(\theta_{23}) = 0.547^{+0.020}_{-0.030}\ (\mathrm{NO})$$

$$= 0.551^{+0.018}_{-0.030}\ (\mathrm{IO})$$

First hints for $\delta_{\mathrm{CP}} \simeq 3/2\pi$



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talk by M. Tórtola tomorrow

see also: http://globalfit.astroparticles.es

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$= (2.42^{+}_{-0.04}) \cdot 10^{-3}$ …

$\sin^2(\theta_{12})$ …

… $^{+0.008}_{-0.007}$ (NO)

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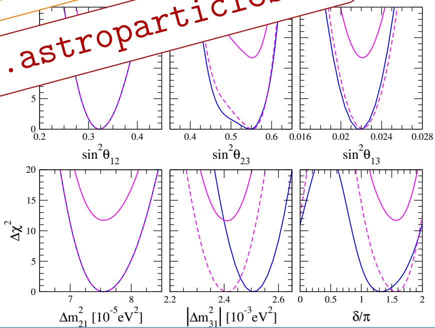


# Short Baseline (SBL) anomaly

[SG+, JPG 43 (2016) 033001]

Problem: anomalies in SBL experiments → { errors in flux calculations? / deviations from 3-$\nu$ description? }

A short review:

**LSND** search for $\bar{\nu}_\mu \to \bar{\nu}_e$, with $L/E = 0.4 \div 1.5$ m/MeV. Observed a $3.8\sigma$ excess of $\bar{\nu}_e$ events [Aguilar et al., 2001]

**Reactor** re-evaluation of the expected anti-neutrino flux $\Rightarrow$ disappearance of $\bar{\nu}_e$ events compared to predictions ($\sim 3\sigma$) with $L < 100$ m [Mention et al, 2011], [Azabajan et al, 2012]

**Gallium** calibration of GALLEX and SAGE Gallium solar neutrino experiments give a $2.7\sigma$ anomaly (disappearance of $\nu_e$) [Giunti, Laveder, 2011]

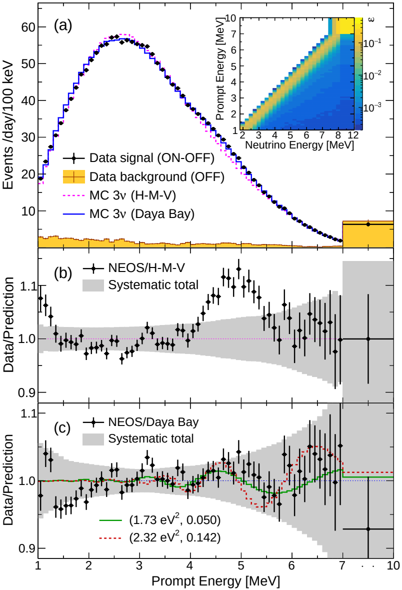
**MiniBooNE** See next

**Possible explanation:**

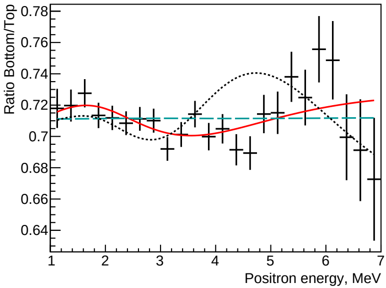
Additional squared mass difference $\Delta m^2_{\text{SBL}} \simeq 1\ \text{eV}^2$

# Recent results. . .

[NEOS, PRL 118 (2017) 121802]




[DANSS, PLB 787 (2018) 56]

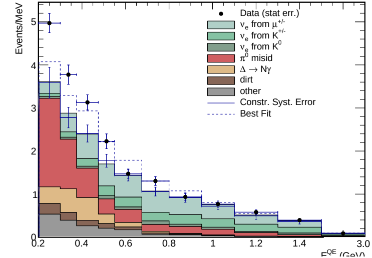


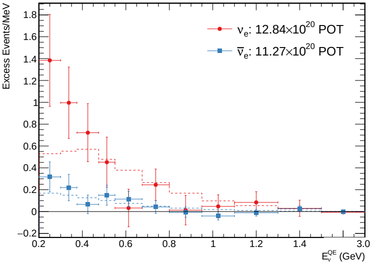

first *model independent* indications in favor of SBL oscillations

DANSS alone gives a $\Delta\chi^2 \simeq 13$ in favor of a light sterile neutrino!

# Recent results. . .

[MiniBooNE, PRL 121 (2018) 221801]



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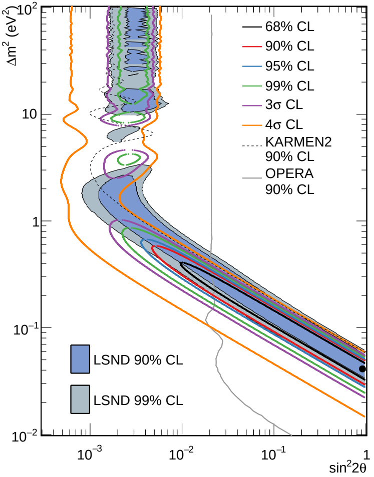

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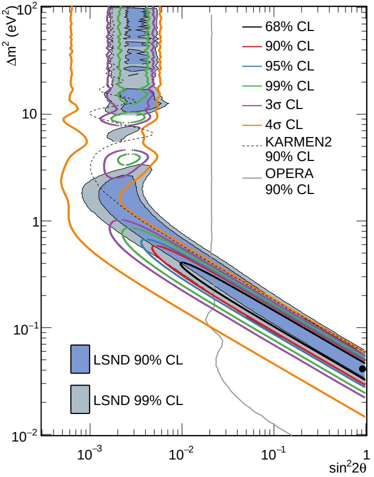
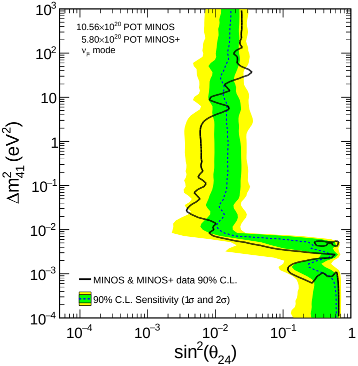



[MINOS+, PRL 122 (2019) 091803]




MiniBooNE is incompatible with MINOS+ when combined with NEOS&DANSS

# 3+1 Neutrino Model

new $\Delta m^2_{SBL} \Rightarrow$ 4 neutrinos!

$\downarrow$

$\nu_4$ with $m_4 \simeq 1$ eV,
no weak interactions

$\downarrow$

light sterile neutrino (LS$\nu$)

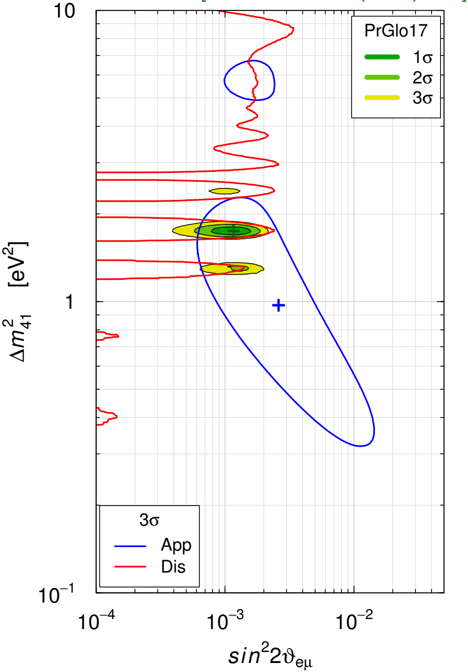
3 (active) + 1 (sterile) mixing:

$$\nu_\alpha = \sum_{k=1}^{3+1} U_{\alpha k}\nu_k \quad (\alpha = e, \mu, \tau, s)$$

$\nu_s$ is mainly $\nu_4$:
$$m_s \simeq m_4 \simeq \sqrt{\Delta m^2_{41}} \simeq \sqrt{\Delta m^2_{SBL}}$$

assuming $m_4 \gg m_i$ $(i = 1, 2, 3)$

[SG+, JHEP 06 (2017) 135]



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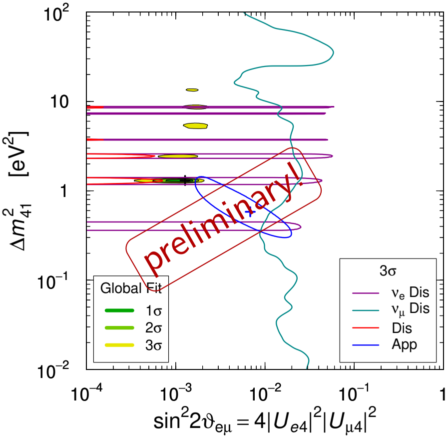

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[SG+, work in progress]

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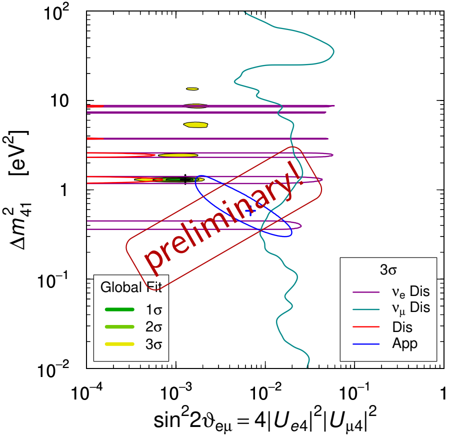
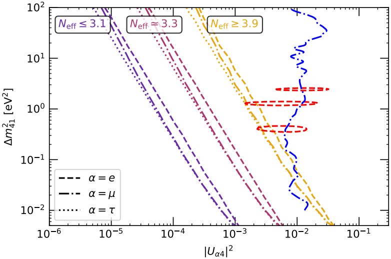



can $\nu_4$ thermalize in the early Universe through oscillations?



$N_{\rm eff} \leq 3.1$
$N_{\rm eff} \simeq 3.3$
$N_{\rm eff} \geq 3.9$
$\alpha = e$
$\alpha = \mu$
$\alpha = \tau$
$\Delta m^2_{41}$ [eV$^2$]
$|U_{\alpha 4}|^2$

# $\nu$ oscillations in the early universe

[SG+, JCAP 07 (2019) 014]

comoving coordinates: $a = 1/T \quad x \equiv m_e\, a \quad y \equiv p\, a \quad z \equiv T_\gamma\, a \quad w \equiv T_\nu\, a$

density matrix: $$\varrho(x,y) = \begin{pmatrix} \varrho_{ee} \equiv f_{\nu_e} & \varrho_{e\mu} & \varrho_{e\tau} & \varrho_{es} \\ \varrho_{\mu e} & \varrho_{\mu\mu} \equiv f_{\nu_\mu} & \varrho_{\mu\tau} & \varrho_{\mu s} \\ \varrho_{\tau e} & \varrho_{\tau\mu} & \varrho_{\tau\tau} \equiv f_{\nu_\tau} & \varrho_{\tau s} \\ \varrho_{se} & \varrho_{s\mu} & \varrho_{s\tau} & \varrho_{ss} \equiv f_{\nu_s} \end{pmatrix}$$

$$\frac{\mathrm{d}\varrho(y,x)}{\mathrm{d}x} = \sqrt{\frac{3m_{\mathrm{Pl}}^2}{8\pi\rho_{\mathrm{T}}}} \left\{ -i\frac{x^2}{m_e^3}\left[\frac{\mathbb{M}_{\mathrm{F}}}{2y} - \frac{8\sqrt{2}G_{\mathrm{F}}\,y m_e^6}{3x^6}\left(\frac{\mathbb{E}_\ell}{m_W^2}+\frac{\mathbb{E}_\nu}{m_Z^2}\right), \varrho\right] + \frac{m_e^3 G_{\mathrm{F}}^2}{(2\pi)^3 x^4 y^2}\mathcal{I}(\varrho)\right\}$$

$m_{\mathrm{Pl}}$ Planck mass – $\rho_T$ total energy density – $m_{W,Z}$ mass of the $W$, $Z$ bosons – $G_{\mathrm{F}}$ Fermi constant – $[.,.]$ commutator

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$$\mathbb{M}_{\mathrm{F}} = U \mathbb{M} U^\dagger$$

$$\mathbb{M} = \mathrm{diag}(m_1^2, \ldots, m_N^2)$$

$$U = R^{34} R^{24} R^{14} R^{23} R^{13} R^{12} \qquad \text{e.g.} \quad R^{14} = \begin{pmatrix} \cos\theta_{14} & 0 & 0 & \sin\theta_{14} \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ -\sin\theta_{14} & 0 & 0 & \cos\theta_{14} \end{pmatrix}$$

$$|U|^2 = \begin{pmatrix} \ldots & \ldots & \ldots & \sin^2\theta_{14} \\ \ldots & \ldots & \ldots & \cos^2\theta_{14}\sin^2\theta_{24} \\ \ldots & \ldots & \ldots & \cos^2\theta_{14}\cos^2\theta_{24}\sin^2\theta_{34} \\ \ldots & \ldots & \ldots & \cos^2\theta_{14}\cos^2\theta_{24}\cos^2\theta_{34} \end{pmatrix}$$

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lepton densities — neutrino densities — (only for active neutrinos)

take into account matter effects in oscillations

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$\mathcal{I}(\varrho)$ collision integrals

take into account neutrino-electron scattering and pair annihilation

2D integrals over the momentum, take most of the computation time

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from continuity equation $\dot{\rho} = -3H(\rho + P)$

$$\frac{\mathrm{d}z}{\mathrm{d}x} = \frac{\sum_{\ell=e,\mu}\left[\frac{r_\ell^2}{r}J(r_\ell)\right] + G_1(r) - \frac{1}{2\pi^2 z^3}\int_0^\infty dy\, y^3 \sum_{\alpha=e}^{s}\frac{\mathrm{d}\varrho_{\alpha\alpha}}{\mathrm{d}x}}{\sum_{\ell=e,\mu}\left[r_\ell^2 J(r_\ell) + Y(r_\ell)\right] + G_2(r) + \frac{2\pi^2}{15}}$$

$r = x/z$, $r_\ell = m_\ell/m_e\, r$ $\quad$ $J(r)$, $Y(r)$ from non-relativistic transition of $e^\pm$, $\mu^\pm$

$G_1(r)$ and $G_2(r)$ from electromagnetic corrections

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neutrino temperature $w$: same equation as $z$, but electrons always relativistic

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$m_{\mathrm{Pl}}$ Planck mass – $\rho_T$ total energy density – $m_{W,Z}$ mass of the $W$, $Z$ bosons – $G_{\mathrm{F}}$ Fermi constant – $[.,.]$ commutator

$$\mathbb{M}_{\mathrm{F}} = U \mathbb{M} U^\dagger \qquad \mathbb{E}_\ell = \mathrm{diag}(\rho_e, \rho_\mu, 0, 0) \qquad \mathbb{E}_\nu = S_a \left(\int dy y^3 \varrho\right) S_a$$

$\mathcal{I}(\varrho)$ collision integrals

from continuity equation $\dot\rho = -3H(\rho + P)$

$$\frac{\mathrm{d}z}{\mathrm{d}x} = \frac{\sum_{\ell=e,\mu}\left[\frac{r_\ell^2}{r}J(r_\ell)\right] + G_1(r) - \frac{1}{2\pi^2 z^3}\int_0^\infty dy\, y^3 \sum_{\alpha=e}^{s}\frac{\mathrm{d}\varrho_{\alpha\alpha}}{\mathrm{d}x}}{\sum_{\ell=e,\mu}\left[r_\ell^2 J(r_\ell) + Y(r_\ell)\right] + G_2(r) + \frac{2\pi^2}{15}}$$

neutrino temperature $w$: same equation as $z$, but electrons always relativistic

initial conditions: $\varrho_{\alpha\alpha}$ = Fermi-Dirac at $x_{\mathrm{in}} \simeq 0.001$, with $w = z \simeq 1$

# $\nu$ oscillations in the early universe

[SG+, JCAP 07 (2019) 014]

comoving coordinates: $a = 1/T \quad x \equiv m_e\, a \quad y \equiv p\, a \quad z \equiv T_\gamma\, a \quad w \equiv T_\nu\, a$

density matrix: $$\varrho(x,y) = \begin{pmatrix} \varrho_{ee} \equiv f_{\nu_e} & \varrho_{e\mu} & \varrho_{e\tau} & \varrho_{es} \\ \varrho_{\mu e} & \varrho_{\mu\mu} \equiv f_{\nu_\mu} & \varrho_{\mu\tau} & \varrho_{\mu s} \\ \varrho_{\tau e} & \varrho_{\tau\mu} & \varrho_{\tau\tau} \equiv f_{\nu_\tau} & \varrho_{\tau s} \\ \varrho_{se} & \varrho_{s\mu} & \varrho_{s\tau} & \varrho_{ss} \equiv f_{\nu_s} \end{pmatrix}$$

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$m_{\mathrm{Pl}}$ Planck mass, $\rho$ total energy density, $m$ mass of the W, Z bosons, $G$ Fermi constant, [ , ] commutator

**FORTran-Evolved PrimordIAl Neutrino Oscillations (FortEPiaNO)**

**https://bitbucket.org/ahep_cosmo/fortepiano**

will be public soon

from continuity equation $\dot\rho = -3H(\rho + P)$

$$\frac{\mathrm{d}z}{\mathrm{d}x} = \frac{\sum_{\ell=e,\mu}\left[\,r \quad\right] \quad ) - \frac{1}{2\pi^2 z^3}\int_0^\infty dy\, y^3 \sum_{\alpha=e}^{s}\frac{\mathrm{d}\varrho_{\alpha\alpha}}{\mathrm{d}x}}{\sum_{\ell=e,\mu}\left[r_\ell^2 J(r_\ell) + Y(r_\ell)\right] + G_2(r) + \frac{2\pi^2}{15}}$$

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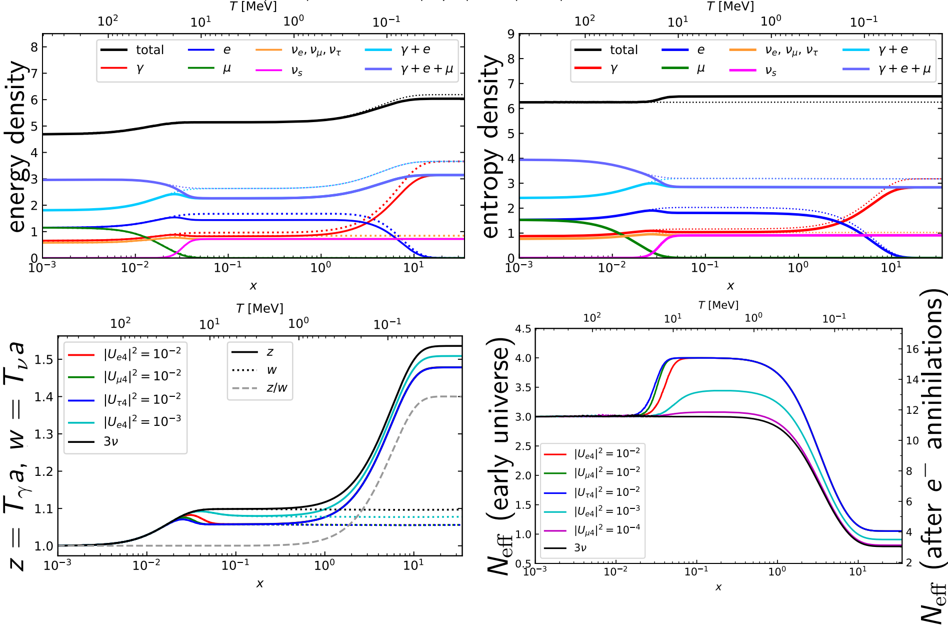
# Energy, entropy, temperatures, $N_{\rm eff}$

[SG+, JCAP 07 (2019) 014]

dashed: $3\nu$, solid: $|U_{e4}|^2 = 10^{-2}$, $|U_{\mu4}|^2 = |U_{\tau4}|^2 = 0$. $\Delta m^2_{41} = 1.29$ eV$^2$ always



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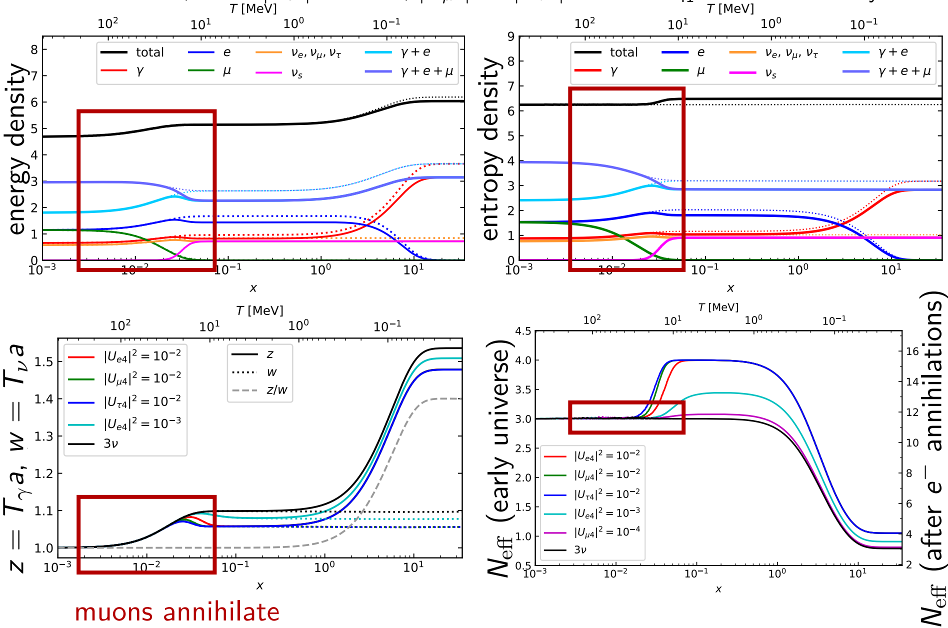


muons annihilate

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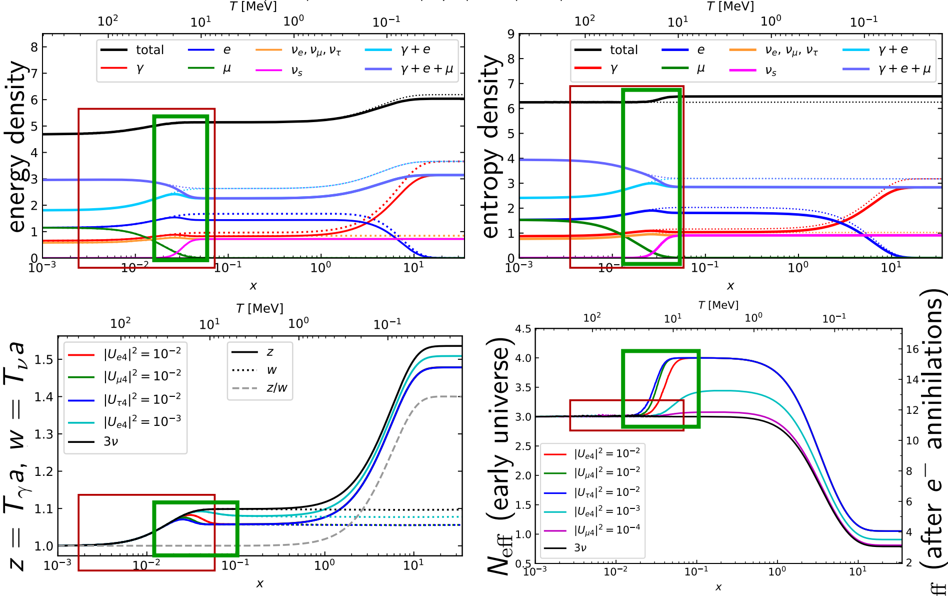


muons annihilate

$\nu_s$ thermalizes

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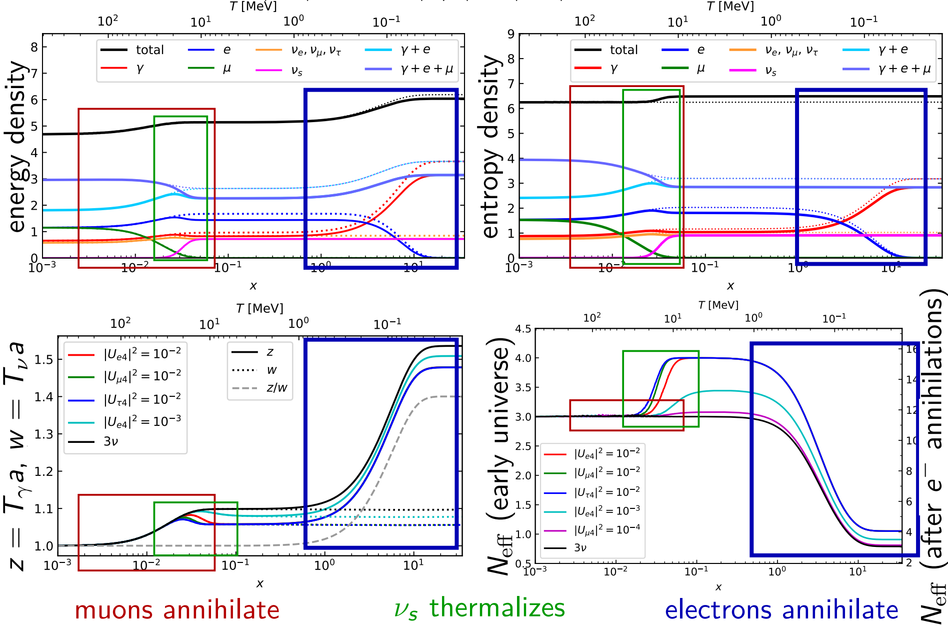
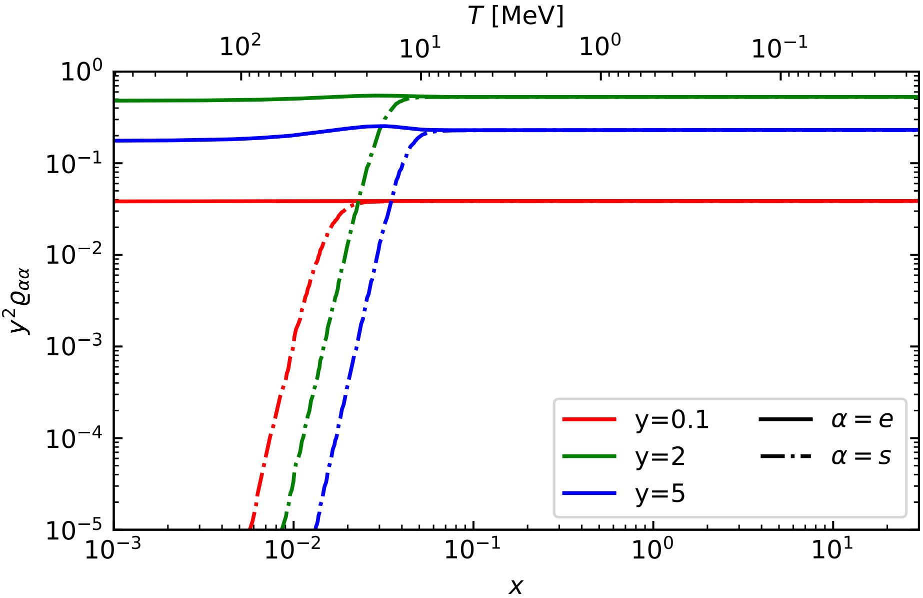


# Momentum distributions



$\Delta m^2_{41} = 1.29$ eV$^2$, $|U_{e4}|^2 = 10^{-2}$, $|U_{\mu4}|^2 = |U_{\tau4}|^2 = 0$, $N_{\rm eff} \simeq 4.05$



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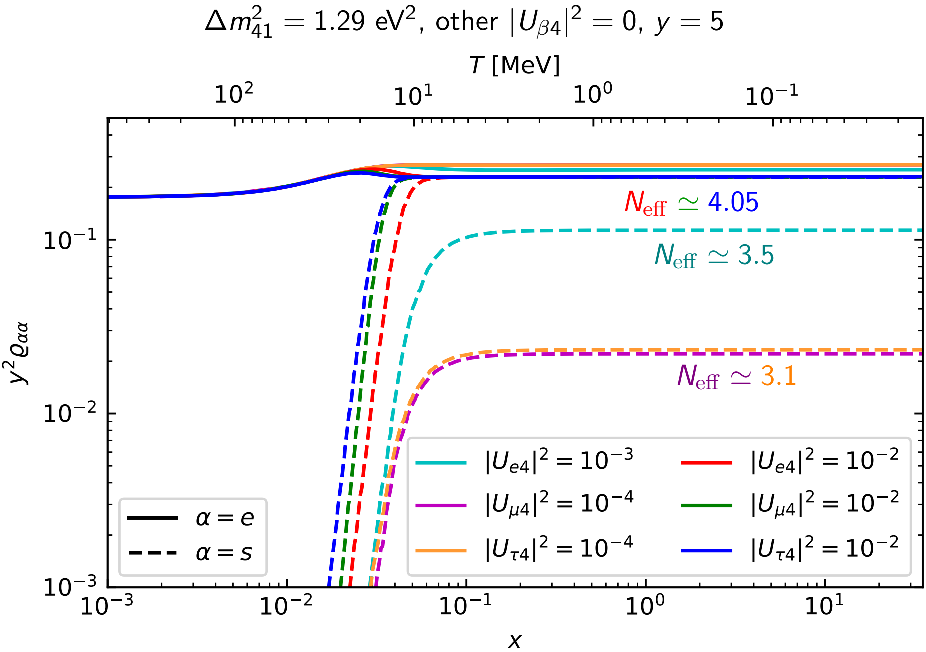
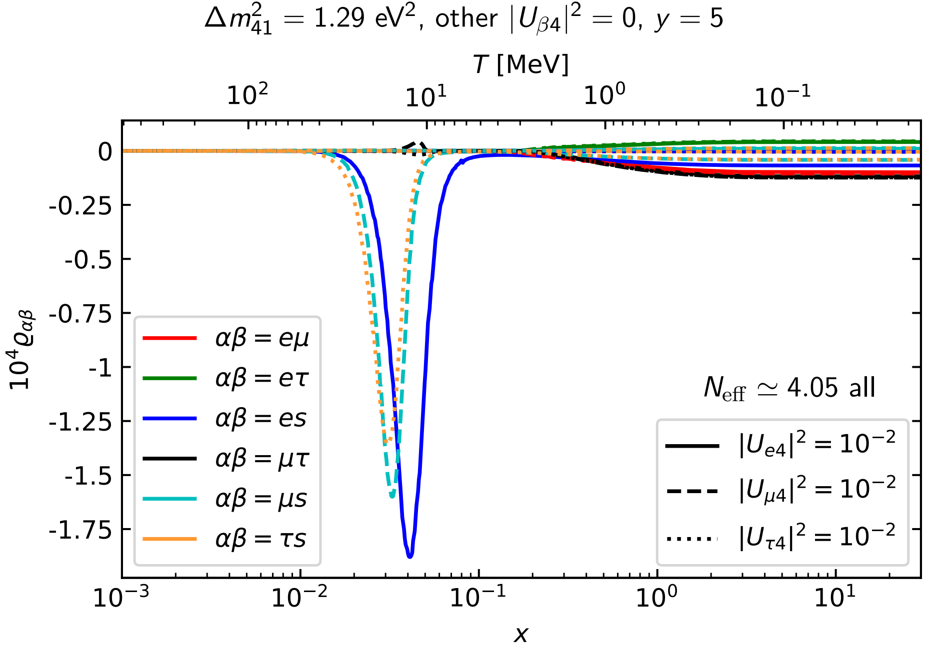
[SG+, JCAP 07 (2019) 014]



# Momentum distributions

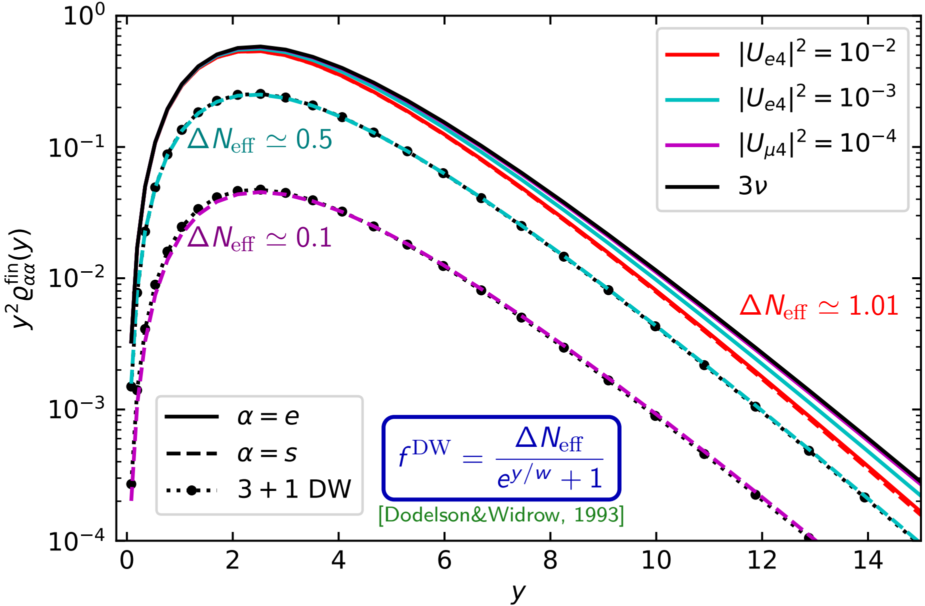
[SG+, JCAP 07 (2019) 014]



# Momentum distributions

[SG+, JCAP 07 (2019) 014]

$\Delta m^2_{41} = 1.29$ eV$^2$, other $|U_{\beta 4}|^2 = 0$, $\Delta N_{\rm eff} = N_{\rm eff} - N_{\rm eff}^{\rm active}$

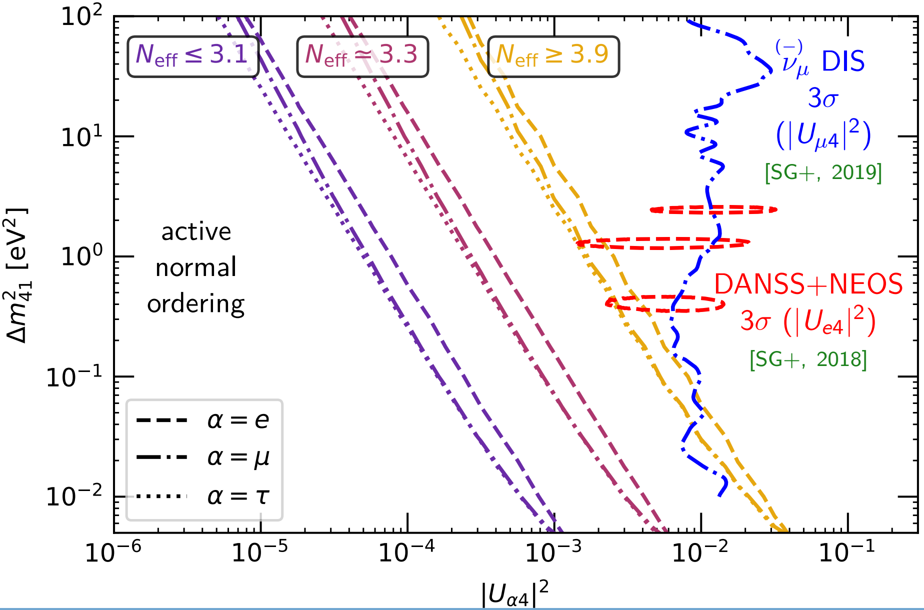



$$f^{\rm DW} = \frac{\Delta N_{\rm eff}}{e^{y/w}+1}$$

[Dodelson&Widrow, 1993]

# $N_{\rm eff}$ and the new mixing parameters

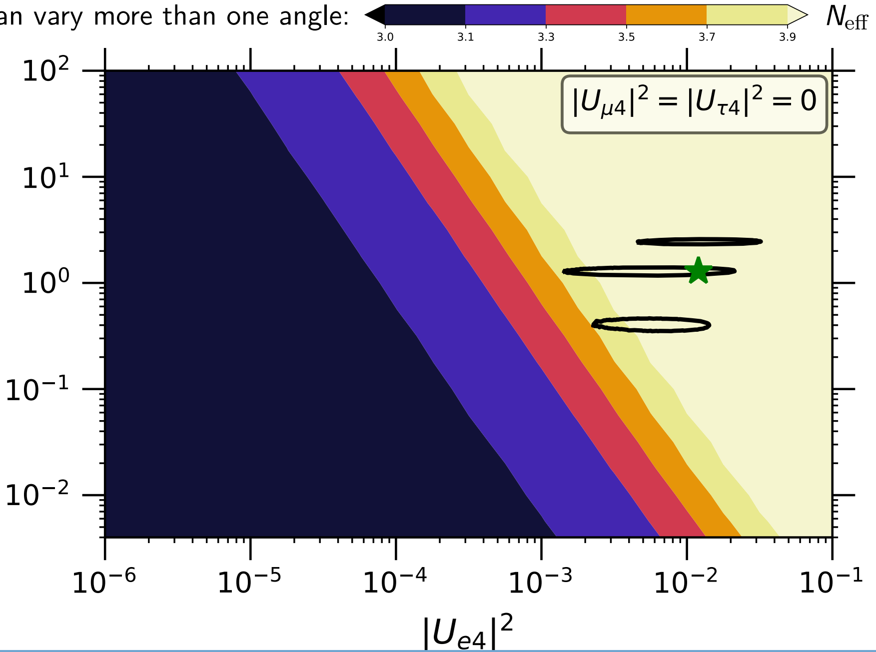
Only vary one angle and fix two to zero: do they have the same effect?



# $N_{\text{eff}}$ and the new mixing parameters

[SG+, JCAP 07 (2019) 014]

We can vary more than one angle:



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[SG+, JCAP 07 (2019) 014]

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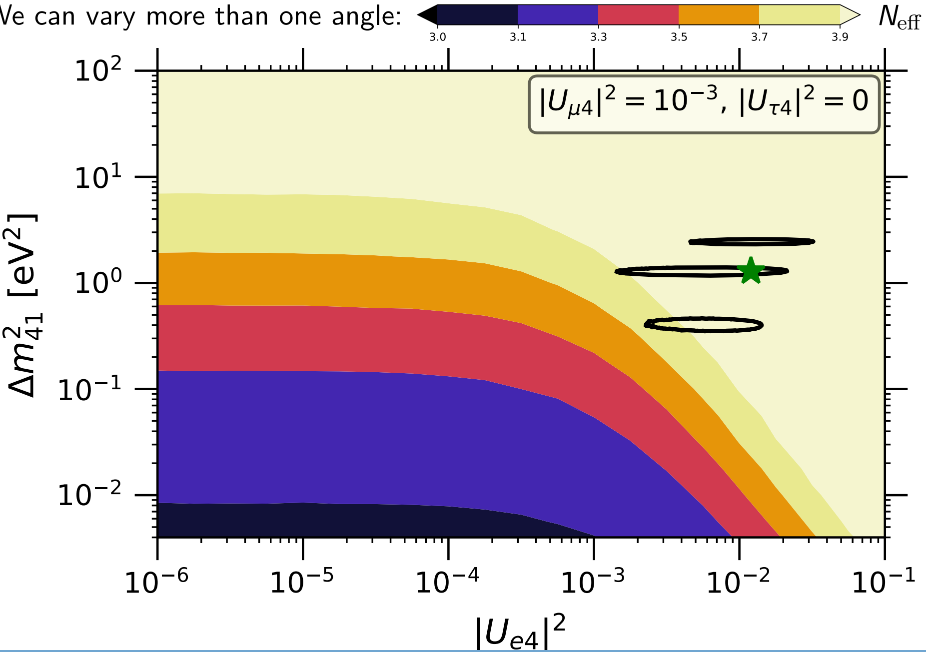

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[SG+, JCAP 07 (2019) 014]

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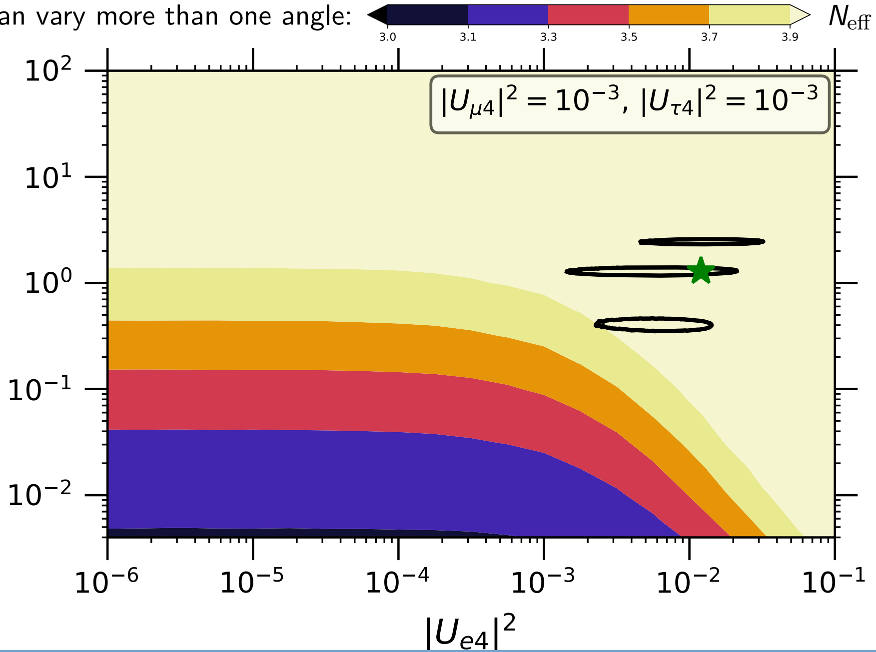
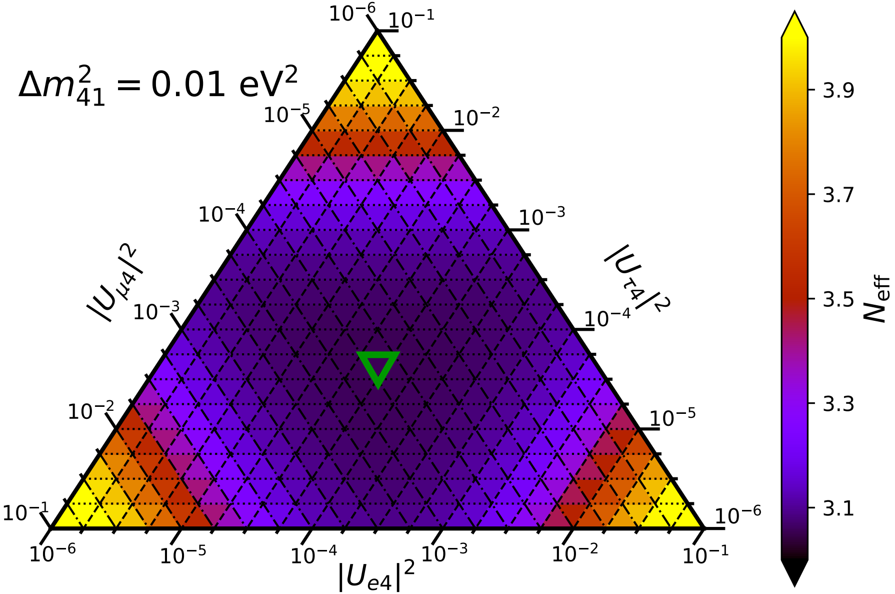


# $N_{\text{eff}}$ and the new mixing parameters

[SG+, JCAP 07 (2019) 014]

Sort of ternary plot (sum of $|U_{\alpha 4}|^2$ does not add up to 1!):



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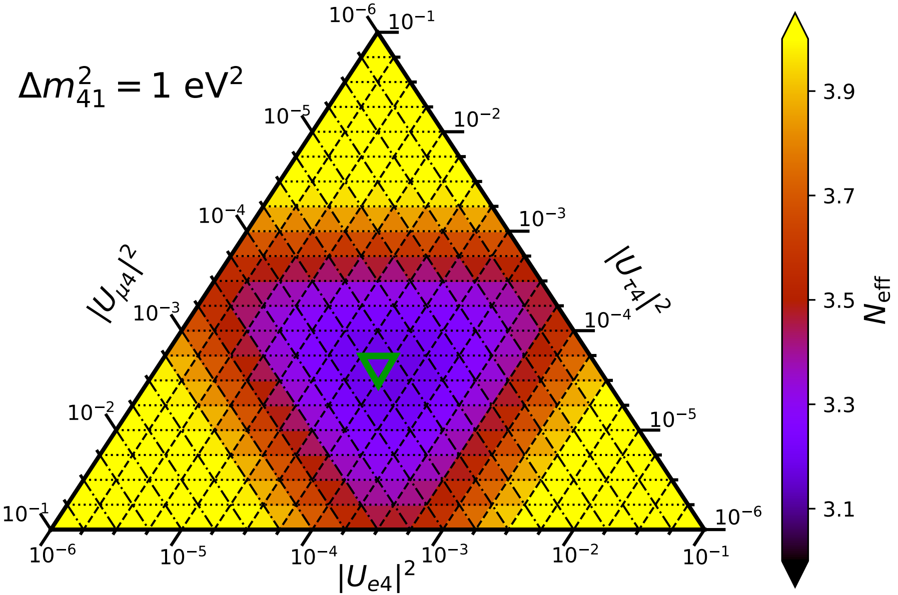

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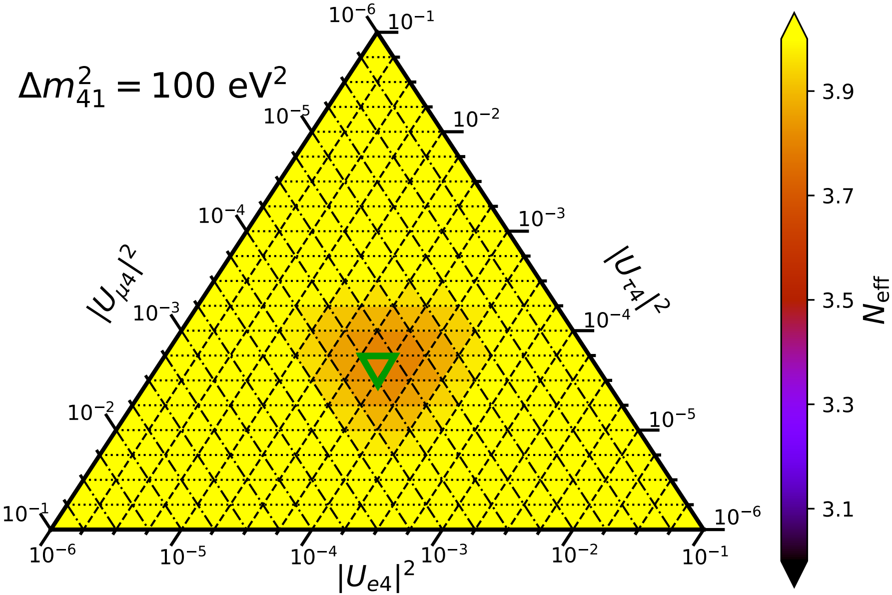
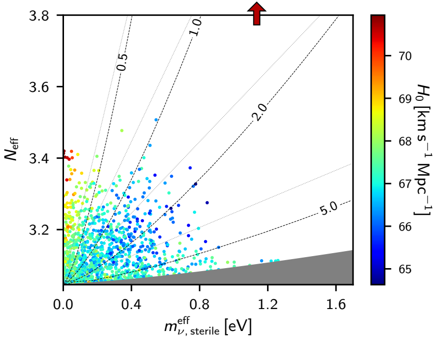
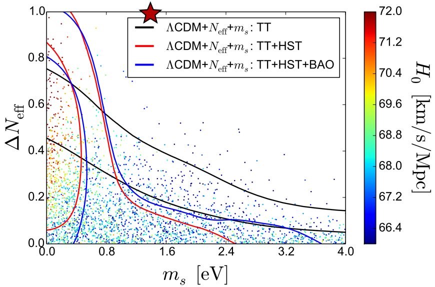


# LS$\nu$ constraints from cosmology

CMB+local: [Planck Collaboration, 2018]




[Archidiacono et al., JCAP 08 (2016) 067]




$\begin{cases} N_{\rm eff} < 3.29 \\ m_s^{\rm eff} < 0.65 \text{ eV} \end{cases}$ (Planck18+BAO) [$m_s$ < 10 eV]

| dataset | free $\Delta N_{\rm eff}$ [$m_s$ < 10 eV] | $\Delta N_{\rm eff} = 1$ |
|---|---|---|
| (TT) | $N_{\rm eff} < 3.5$ | $m_s < 0.66$ eV |
| (+$H_0$) | $N_{\rm eff} < 3.9$ | $m_s < 0.55$ eV |
| (+BAO) | $N_{\rm eff} < 3.8$ | $m_s < 0.53$ eV |

BBN constraints: $N_{\rm eff} = 2.90 \pm 0.22$ (BBN+$Y_p$) [Peimbert et al., 2016]

**Summary: $\Delta N_{\rm eff} = 1$ from LS$\nu$ incompatible with CMB and BBN!**

Planck18=Planck 2018 TT,TE,EE + lowE + lensing    All the constraints are at $2\sigma$ CL

# Incomplete Thermalization

**Active-sterile oscillations in the early Universe:**

mixing parameters from SBL data $\Longrightarrow \Delta N_{\rm eff} \simeq 1$

[SG+, 2019]

Many probes constrain $\Delta N_{\rm eff} < 1$. Do we need

- a mechanism to suppress oscillations and full thermalization of $\nu_s$?
- to compensate $\Delta N_{\rm eff} = 1$ with additional mechanisms in Cosmology?

Some ideas (an incomplete list!):

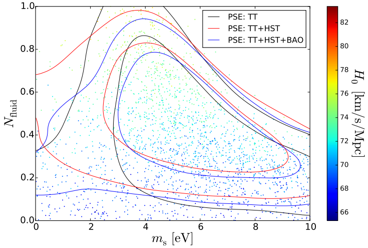
- large lepton asymmetry [Foot et al., 1995; Mirizzi et al., 2012; many more]
- new neutrino interactions [Bento et al., 2001; Dasgupta et al., 2014; Hannestad et al., 2014; Saviano et al., 2014; Archidiacono et al. 2016; many more]
- entropy production after neutrino decoupling [Ho et al., 2013]
- very low reheating temperature [Gelmini et al., 2004; Smirnov et al., 2006]
- time varying dark energy components [Giusarma et al., 2012]
- larger expansion rate at the time of $\nu_s$ production [Rehagen et al., 2014]
- freedom in the Primordial Power Spectrum (PPS) of scalar perturbations from inflation compensate damping due to $N_{\rm eff} \neq 3.046$ [SG et al., 2015]

1 *Light sterile neutrino*

2 *Light sterile neutrino and cosmology*

## 3 *A new interaction to solve the thermalization problem?*

4 *Conclusions*



# Adding a new interaction

[Archidiacono, SG et al., JCAP 08 (2016) 067]

Prevent LS$\nu$ thermalization? → new (hidden) interaction! → e.g.: new broken $U(1)$ symmetry

pseudoscalar mediator $\phi$

Lagrangian: $\mathcal{L} \sim g_s \phi \bar{\nu}_4 \gamma_5 \nu_4$

Coupling confined to sterile sector

$\nu_4$ annihilation into $\phi$ at late times (to avoid mass bounds)

$\phi$ must avoid mass bounds itself

$m_\phi \lesssim 0.1$ eV

coupling $g_s$ large enough to prevent full $\nu_s$ thermalization

$10^{-6} \lesssim g_s \lesssim 10^{-5}$ is fine

matter effect induced by $\phi$

[Archidiacono et al., PRD 91 (2015) 065021]

no $\nu_s$ production until after $\nu_a$ decoupling → incomplete thermalization, $N_{\rm eff} \lesssim 4$

# Constraints on the pseudoscalar interaction?

**Particle physics constraints on the pseudoscalar?**

IceCube constraints on secret interactions?

[Ioka et al., 2014] [Cherry et al., 2014] [Ng et al.,2014] [Cherry et al., 2016]

- $\phi$ coupled to $\nu_4$ + IceCube flux made of active flavor neutrinos
- → very small mixing with $\nu_4$ and interaction rate with $\phi$ [cross section $\propto g_s^2/s$]
- → **don't apply**

fifth force constraints?

- → pseudoscalar is spin coupling, but unpolarized medium
- → **don't apply**

SN energy loss [Farzan, 2003] → $g_s \lesssim 10^{-4}$

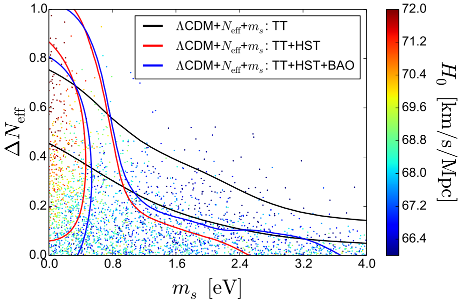
# Results

[Archidiacono, SG et al., JCAP 08 (2016) 067]

Standard LS$\nu$ model:

$\mathbf{\Lambda CDM + N_{\rm eff} + m_s}$

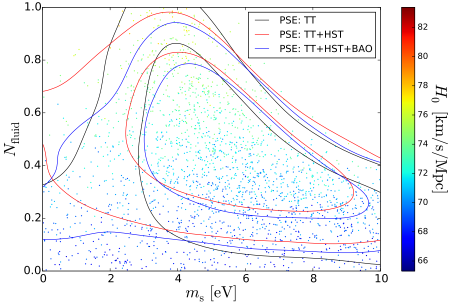
($\Lambda$CDM params+free $N_{\rm eff}$ and $m_s$)




Pseudoscalar model (**PSE**):

$N_{\rm eff} = 3.046 + N_{\rm fluid}$

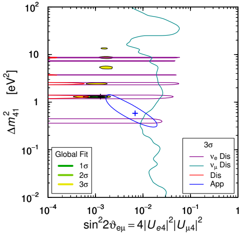
$N_{\rm fluid}$: $\nu_s + \phi$ contributions



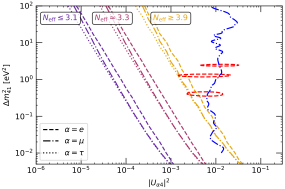

- Problems with $\Delta N_{\rm eff} = 1$? solved (incomplete thermalization due to suppression of active-sterile oscillations in primordial plasma);
- mass bounds avoided
  $\Rightarrow$ large $m_s$ allowed and (mild) preference for $m_s \simeq 4$ eV;
- high values of $H_0$ predicted by cosmology
  $\Rightarrow$ more compatible with local measurements.

# Conclusions

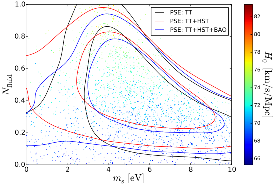
1 Unclear status of LS$\nu$ searches:
APP-DIS tension!
Systematics or LS$\nu$ or new physics?




2 oscillations in the early
universe $\Rightarrow$ $N_{\rm eff} \simeq 4.05$
Planck constrains $N_{\rm eff} \lesssim 3.3$!




3 Reconcile LS$\nu$ and cosmology
with new pseudoscalar interaction,
also mitigating $H_0$ tension!



# Conclusions

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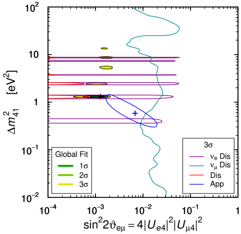


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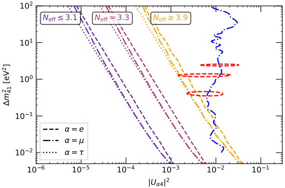


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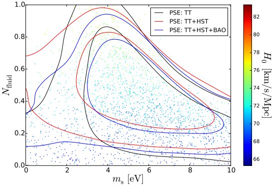
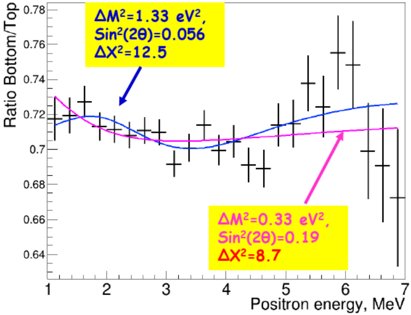



**Thank you for the attention!**

# DANSS in 2019



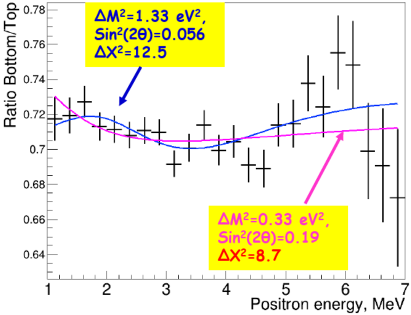
old data



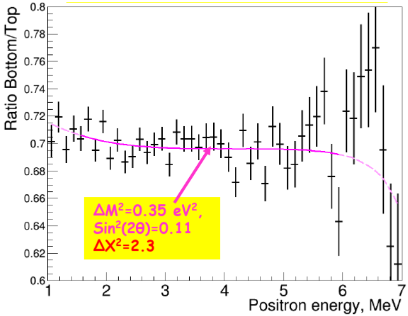
# DANSS in 2019

[Danilov@EPS-HEP, 2019]

old data




new data



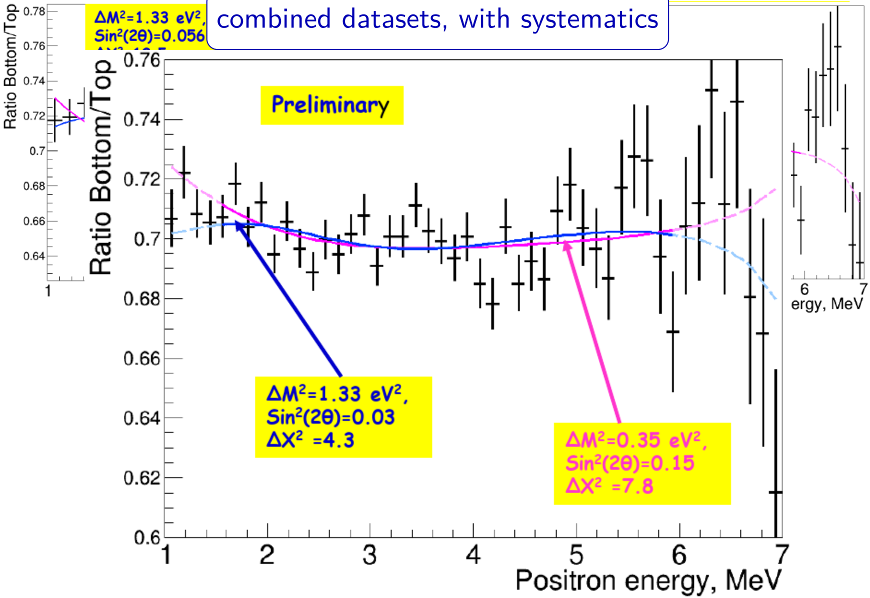

New analysis also considers systematics!

# DANSS in 2019

[Danilov@EPS-HEP, 2019]

old data — new data

combined datasets, with systematics



# DANSS in 2019

[Danilov@EPS-HEP, 2019]