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Light sterile neutrinos with pseudoscalar interactions in cosmology

Based on [JCAP 08 (2016) 067]

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Neutrino Oscillations

Analogous to CKM mixing for quarks: [Pontecorvo, 1958] [Maki, Nakagawa, Sakata, 1962]

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

ν_α flavour eigenstates, $U_{\alpha k}$ PMNS mixing matrix, ν_k mass eigenstates.

Current knowledge of the 3 active ν mixing: [PDG - Olive et al. (2015)]

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

$$\begin{aligned} \Delta m^2_{SOL} &= (7.53 \pm 0.18) \cdot 10^{-5}\ \mathrm{eV}^2 & &= \Delta m^2_{21} \\ \Delta m^2_{ATM} &= (2.44 \pm 0.06) \cdot 10^{-3}\ \mathrm{eV}^2 (\mathrm{NO}) & &= |\Delta m^2_{32}| \simeq |\Delta m^2_{31}| \\ &= (2.49 \pm 0.06) \cdot 10^{-3}\ \mathrm{eV}^2 (\mathrm{IO}) & & \end{aligned}$$

$$\begin{aligned} \sin^2(2\theta_{12}) &= 0.846 \pm 0.021 \\ \sin^2(2\theta_{23}) &= 0.999^{+0.001}_{-0.018} (\mathrm{NO}) - 1.000^{+0.000}_{-0.017} (\mathrm{IO}) \\ \sin^2(2\theta_{13}) &= 0.085 \pm 0.005 \end{aligned}$$

See various talks in next days

CP violating phase $\delta_{\rm CP}$ still unknown. Hint: $\delta_{\rm CP} = -\pi/2$? [T2K Collaboration, 2015]

Short Baseline (SBL) anomaly

[SG et al., JPG 43 (2016) 033001]

Problem: anomalies in SBL experiments ⇒ { errors in flux calculations? / deviations from 3-ν 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 3.8σ excess of $\bar{\nu}_e$ events [Aguilar et al., 2001]

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

Gallium calibration of GALLEX and SAGE Gallium solar neutrino experiments give a 2.7σ anomaly (disappearance of ν_e) [Giunti, Laveder, 2011]

MiniBooNE (inconclusive) search for $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$, with $L/E = 0.2 \div 2.6$ m/MeV. No ν_e excess detected, but $\bar{\nu}_e$ excess observed at 2.8σ [MiniBooNE Collaboration, 2013]

Possible explanation:

Additional squared mass difference

$$\Delta m^2_{\text{SBL}} \simeq 1\ \text{eV}^2$$

See various talks in next days

3+1 Neutrino Model

SBL anomalies $\Rightarrow \Delta m^2_{\text{SBL}} \simeq 1\ \text{eV}^2$

$\Downarrow$

Existence of an additional neutrino degree of freedom,
mass around 1 eV, no weak interaction $\Rightarrow$ *light, sterile neutrino (LSν)*

$\Downarrow$

3 active ($m_i \ll 1$ eV) + 1 sterile ($m_s \simeq 1$ eV) ν scenario

We must update our mixing paradigm:

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

ν_s is mainly ν_4:

$$m_s \simeq m_4 \simeq \sqrt{\Delta m^2_{41}} \simeq \sqrt{\Delta m^2_{\text{SBL}}}$$

Active ν:
$\sum m_{\nu,\text{active}} \simeq 0$

Sterile ν:
$0.82 \leq m_s^2/\text{eV}^2 \leq 2.19$ (3σ)
[SG et al., 2016]

(Relativistic) LSν in cosmology: $\Delta N_{\rm eff}$

Radiation energy density ρ_r in the early Universe:

$$\rho_r = \left[1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{\rm eff}\right]\rho_\gamma = \left[1 + 0.2271 N_{\rm eff}\right]\rho_\gamma$$

ρ_γ photon energy density, 7/8 is for fermions, $(4/11)^{4/3}$ due to photon reheating after neutrino decoupling

- $N_{\rm eff} \to$ all the radiation contribution not given by photons
- $N_{\rm eff} \simeq 1$ correspond to a single family of active neutrino, in equilibrium in the early Universe
- Active neutrinos: $N_{\rm eff} = 3.046$ [Mangano et al., 2005] due to not instantaneous decoupling for the neutrinos
- + Non Standard Interactions: $3.040 < N_{\rm eff} < 3.059$ [de Salas et al., 2016]
- additional LSν contributes with $\Delta N_{\rm eff} = N_{\rm eff} - 3.046$:

$$\Delta N_{\rm eff} = \frac{\rho_s^{\rm rel}}{\rho_\nu} = \left[\frac{7}{8}\frac{\pi^2}{15}T_\nu{}^4\right]^{-1}\frac{1}{\pi^2}\int dp\, p^3 f_s(p)$$ [Acero et al., 2009]

ρ_ν energy density for one active neutrino species, $\rho_s^{\rm rel}$ energy density of LSν when relativistic,
p neutrino momentum, $f_s(p)$ momentum distribution, $T_\nu = (4/11)^{1/3}\, T_\gamma$

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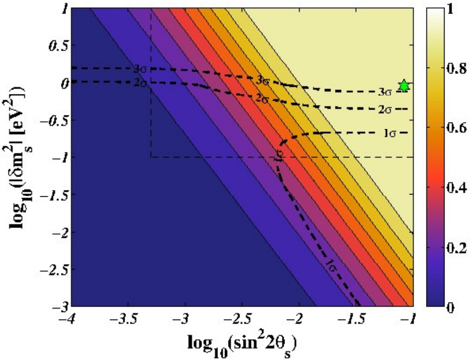
LSν thermalization

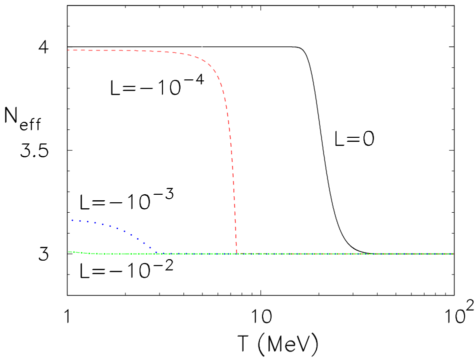
Using SBL best-fit parameters for the LSν (Δm^2_{41}, θ_s):

[Hannestad et al., JCAP 1207 (2012) 025]



(colors coding $\Delta N_{\rm eff}$)

[Mirizzi et al., PRD 86 (2012) 053009]



(L: lepton asymmetry)

Unless $L \gtrsim \mathcal{O}(10^{-3})$, $\Delta N_{\rm eff} \simeq 1$

See also: [Saviano et al., PRD 87 (2013) 073006], [Hannestad et al., JCAP 08 (2015) 019]

(Non-relativistic) LSν in cosmology: $m_s^{\rm eff}$ and m_s

$m_s \simeq 1$ eV $\to \nu_s$ is non-relativistic today ($T_\nu \propto 10^{-4}$ eV)
LSν density parameter today:

$$\omega_s = \Omega_s h^2 = \frac{\rho_s}{\rho_c} h^2 = \frac{h^2}{\rho_c}\frac{m_s}{\pi^2}\int dp\, p^2 f_s(p)$$ [Acero et al., 2009]

ρ_s energy density of non-relativistic LSν, ρ_c critical density and h reduced Hubble parameter

Alternatively:

$$m_s^{\rm eff} = 94.1\,{\rm eV}\,\omega_s$$

[Planck 2013 Results, XVI]

The factor ($94.1\,{\rm eV}$) is the same for the active neutrinos:

$$\omega_{\nu,\text{active}} = \sum_{\text{active}} m_\nu/(94.1\,{\rm eV})$$

If $f_s(p) = f_{\rm active}(p)$, $m_s^{\rm eff} \equiv m_s$

Thermal production $\Longrightarrow f_s(p) = \frac{1}{e^{p/T_s}+1} \Longrightarrow m_s^{\rm eff} = \Delta N_{\rm eff}^{3/4} m_s$

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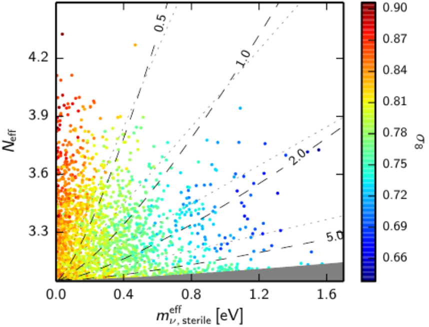
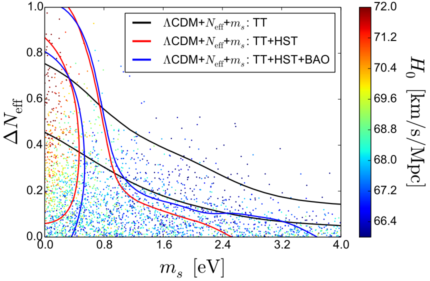
LSν constraints from cosmology

CMB+local: [Planck Collaboration, 2015]



$\begin{cases} N_{\rm eff} < 3.7 \\ m_s^{\rm eff} < 0.52 \text{ eV} \end{cases}$ (TT+lensing+BAO) [$m_s < 5$ eV]

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



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 LSν incompatible with $m_s \simeq 1$ eV!

TT=Planck 2015 TT + lowTEB

All the constraints are at 2σ CL

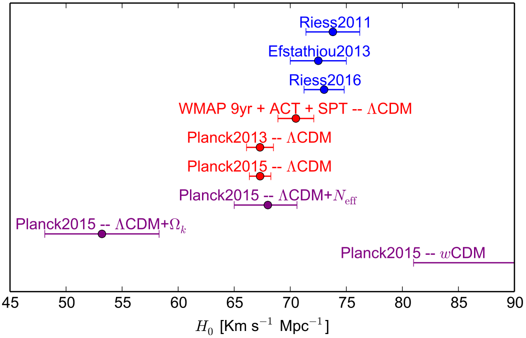
Tensions on the Hubble parameter

Hubble parameter today:
$v = H_0 d$, with $H_0 = H(z = 0)$

Local measurements: $H(z = 0)$, local and independent on evolution (model independent, but systematics?)

CMB measurements (probe $z \simeq 1100$):
H_0 from the cosmological evolution
(model dependent, well controlled systematics)

68% CL error bars



Using HST Cepheids:
[Efstathiou 2013] $H_0 = 72.5 \pm 2.5\,\text{Km s}^{-1}\ \text{Mpc}^{-1}$
[Riess et al., 2016] $H_0 = 73.02 \pm 1.79\,\text{Km s}^{-1}\ \text{Mpc}^{-1}$ (most recent)

(ΛCDM model - CMB data only)
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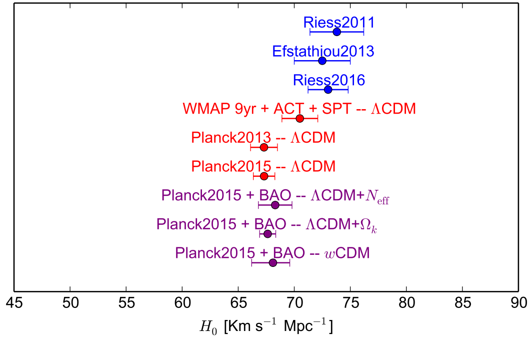

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Tensions on the matter perturbations at small scales

Assuming ΛCDM model:

σ_8: rms fluctuation in total matter (baryons + CDM + neutrinos) in $8h^{-1}$ Mpc spheres, today;
Ω_m: total matter density today divided by the critical density

CFHTLenS weak lensing data alone
[Heymans et al., 2013] (68% CL):

$$\sigma_8(\Omega_m/0.27)^{0.46\pm0.02} = 0.774 \pm 0.04$$

CMB results
[Planck 2013] (68% CL):

$$\sigma_8(\Omega_m/0.27)^{0.46} = 0.89 \pm 0.03$$

Planck SZ Cluster Counts
[Planck 2013 Results XX] (68% CL):

$$\sigma_8(\Omega_m/0.27)^{0.3} = 0.764 \pm 0.025$$

Planck + WMAP pol + ACT/SPT
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$$\sigma_8(\Omega_m/0.27)^{0.3} = 0.87 \pm 0.02$$

Qualitatively similar results from *SPT* clusters, *Chandra Cluster Cosmology Project*.

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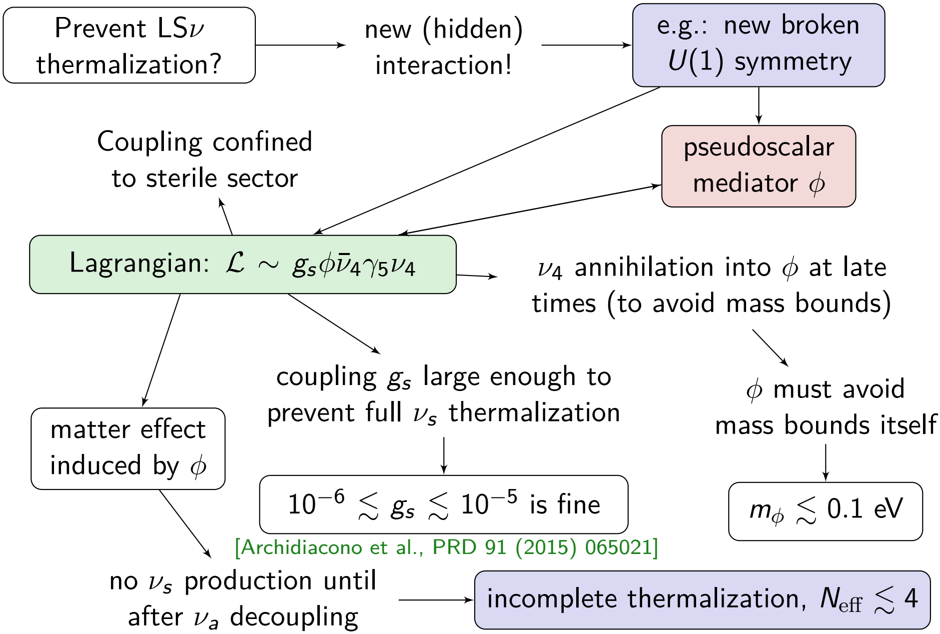
Alert!

- is the nonlinear evolution well known?
  see e.g. [Planck 2015 Results, papers XIII and XIV]
- are we taking into account all the astrophysical systematics?
  [Joudaki et al., 2016] [Kitching et al., 2016]

Adding a new interaction

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



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]

ϕ coupled to ν_4 + IceCube flux made of active flavor neutrinos

→ very small mixing with ν_4 and interaction rate with ϕ [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] → $g_s \lesssim 10^{-4}$

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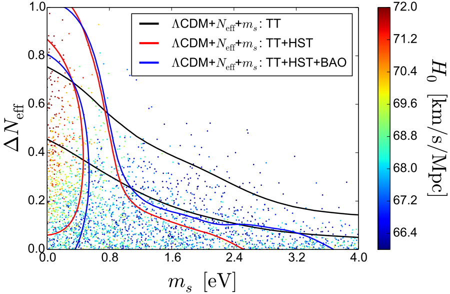
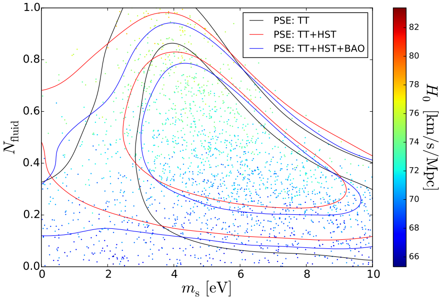
Results - I

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

Standard LSν model:
$\mathbf{\Lambda CDM}+\mathbf{N}_{\rm eff}+\mathbf{m_s}$
(ΛCDM params+free $N_{\rm eff}$ and m_s)



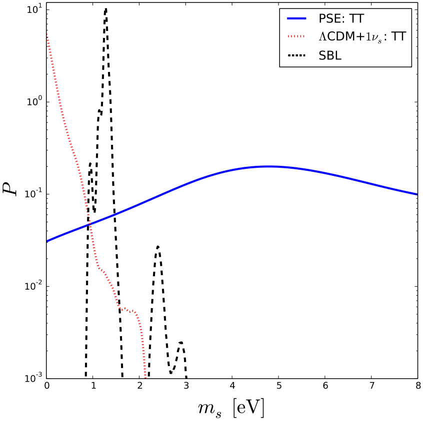
Pseudoscalar model (**PSE**):
$N_{\rm eff} = 3.046 + N_{\rm fluid}$
$N_{\rm fluid}$: ν_s+ϕ contributions

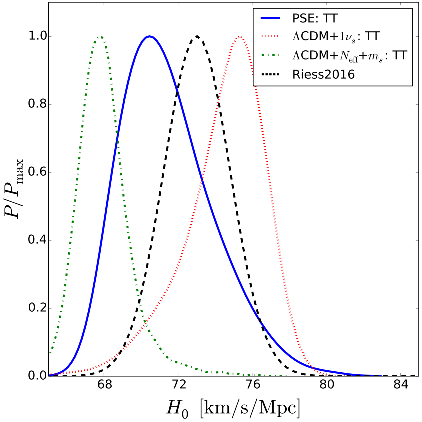


- Problems with $\Delta N_{\rm eff} = 1$? solved (incomplete thermalization due to suppression of active-sterile oscillations in primordial plasma);
- mass bounds avoided
  $\Rightarrow$ large m_s allowed and preference for $m_s \simeq 4$ eV;
- high values of H_0 predicted by cosmology
  $\Rightarrow$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

Results - II

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





- PSE: posterior on m_s wider
- preference for high **SBL** peaks? (agreement with recent results by [IceCube, 2016] and [MINOS, 2016])

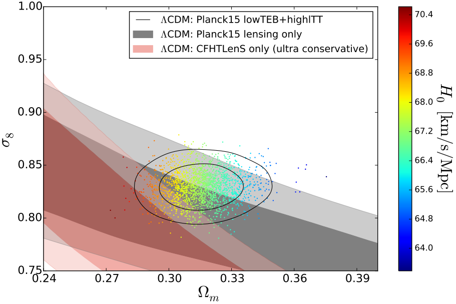
- PSE: very close to **Riess2016** results (better than ΛCDM$+N_{\rm eff}+m_s$)
- ΛCDM$+1\nu_s$: even higher H_0, but from $\Delta N_{\rm eff}=1$ and $m_s\simeq 0$.

Results - III

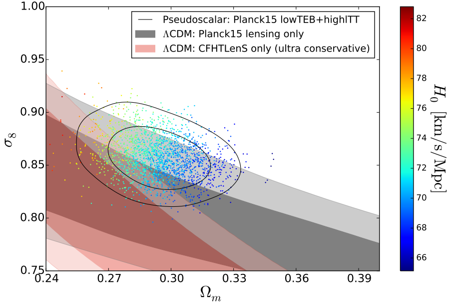
[Archidiacono, SG et al., JCAP 08 (2016) 067]

What about the σ_8 tension (matter perturbations at small scales)?

ΛCDM model:



Pseudoscalar model:

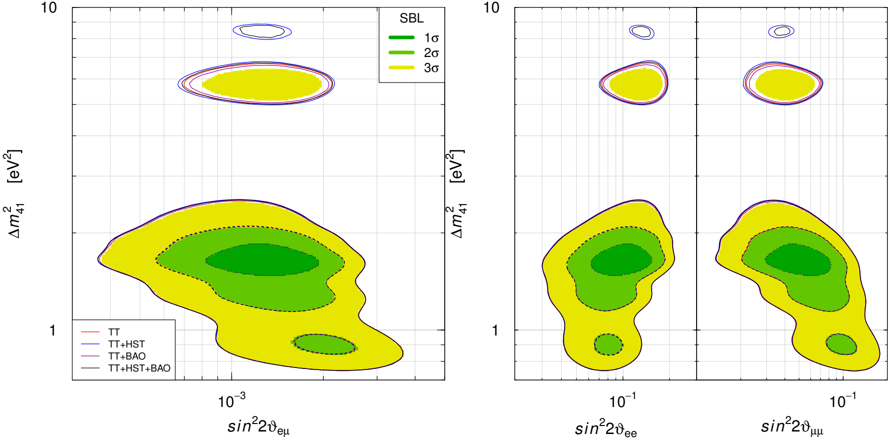


- smaller Ω_m today. Good?
- Also higher $\sigma_8 \Longrightarrow$ no improvement! The tension remains.
- due to higher H_0, not to reduced matter fluctuations.

Joint Results

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

Cosmological results as a prior in SBL analysis:



Cosmological constraints are too much permissive!

- Regions at $\Delta m^2_{41} \simeq 6$ eV^2 (slightly) enlarged
- (small) new region at $\Delta m^2_{41} \simeq 8.5$ eV^2 appears (3σ CL only)
- Towards [IceCube, 2016] and [MINOS, 2016] hints for $\Delta m^2_{41} \gtrsim 1$ eV?

Conclusions

- light ν_s ($m_s \simeq 1$ eV) from SBL analysis **?**
- full thermalization incompatible with cosmological measurements ✗
  (given mass and mixing angles from SBL oscillations)
- H_0 and σ_8 problems **?**
- New interaction mediated by a pseudoscalar ϕ:
  - hidden in the sterile sector, no fifth force constraints ✓
  - light pseudoscalar to avoid mass bounds after ν_s annihilation ✓
  - avoid full ν_s thermalization in the early Universe ($10^{-6} \lesssim g_s \lesssim 10^{-5}$) ✓
  - matter effect induced by ϕ allows $N_{\rm eff} \lesssim 4$ ✓
- Results:
  - preference for large m_s ✓

    Towards IceCube and MINOS recent results ?
  - preference for H_0 compatible with local measurements ✓
  - no solution to matter fluctuations at small scales ✗

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  - preference for large m_s ✓

    Towards IceCube and MINOS measurements
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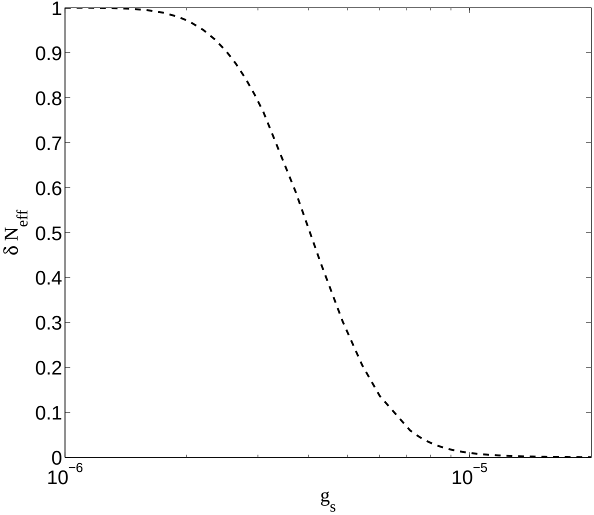
Thank you for the attention

ΔN_{eff} and pseudoscalar interaction

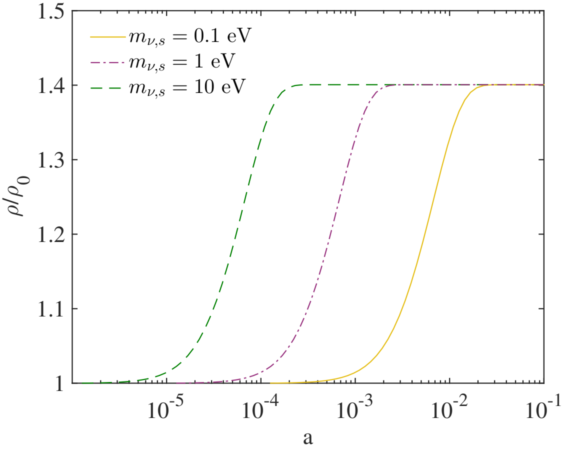
[Archidiacono et al., PRD 91 (2015) 065021]



obtained with $\sin^2(2\theta_s) = 0.05$, $m_s = 1$ eV

LSν annihilation

[Archidiacono et al., PRD 93 (2016) 045004]



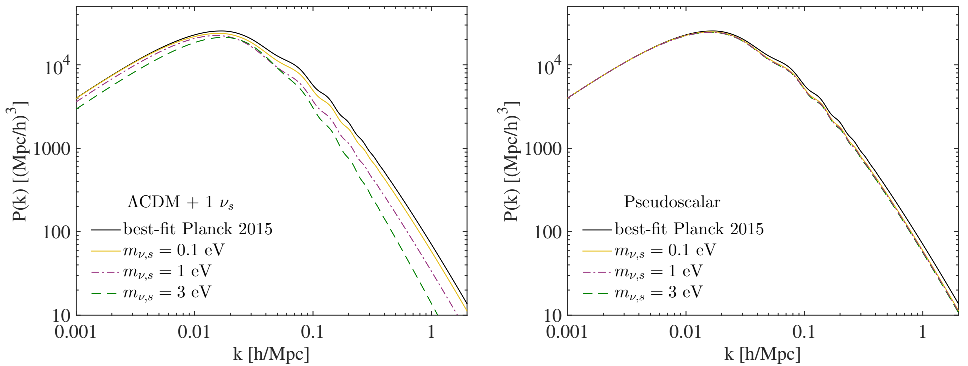
ν_s annihilation into pseudoscalars $\Longrightarrow$ energy density increased

$\rho_0 \longrightarrow$ density of 1 active neutrino family – $\rho \longrightarrow$ density of $\nu_s + \phi$

LSν annihilation and matter power spectrum

[Archidiacono et al., PRD 93 (2016) 045004]

ΛCDM+1ν_s pseudoscalar model



Divergences for small momentum transfer?

$\nu_s - \phi$ interaction = flavor measurement ⟶ contribution to ν_4 thermalization.

[Cherry et al., 2016]: $\nu_s - \phi$ scattering $\propto p^{-2}$ for small $p > m_\phi$ → divergence for $m_\phi \lesssim 0.1$ eV? ← in vacuum!

in vacuum! ↓ matter effect? → charge neutral medium → Debye screening

Debye screening ↓ effective screening mass m_D

effective screening mass m_D → pion exchange: $m_D \propto T$ → more efficient than $\nu_s - \phi$ (complexity of mesons)

effective screening mass m_D → QED: $m_D \propto eT$ → less efficient than $\nu_s - \phi$ (potential PSE: r^{-3} vs QED: r^{-2})

effective screening mass m_D ↓ our case? complex calculation!

our case? complex calculation! → $m_D \propto T$? ⟶ $\Gamma \propto n_{\nu_s} g_s^4 / T^2$ ⟶ negligible (g_s^4)!

our case? complex calculation! → $m_D \propto g_s T$? ⟶ Can lead to additional thermalization.

our case? complex calculation! ↓ agnostic view ⟶ Screening is just additional contribution to $N_{\rm eff}$.