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New developments in cosmology

Basato sul lavoro svolto presso
Università e sez. INFN di Torino

6 aprile 2017 - CNS4 - Catania

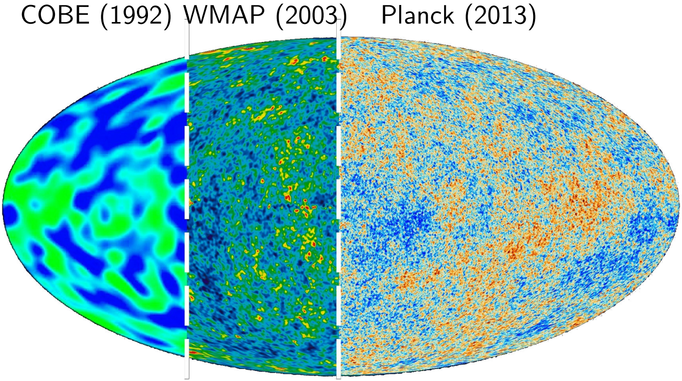
1. Introduction of cosmology
    - Cosmic Microwave Background (CMB)
    - The ΛCDM model
    - Tensions between local and CMB measurements
2. Sterile neutrinos
    - Oscillations anomalies
    - Light sterile neutrino as a possible solution
    - Light sterile neutrino and cosmology
3. New sterile neutrino interaction with pseudoscalar mediator
    - Suppressing thermalization with hidden interactions
    - Cosmological constraints
4. Coupled Dark Energy Scenario

Cosmic Microwave Background (CMB)

Predicted in 1948 (Alpher, Herman): blackbody background radiation at $T \simeq 5$ K.
Discovery (accidental): Penzias, Wilson 1964 → Nobel prize 1978

Observations: perfect black body spectrum at $T_{\rm CMB} = 2.72548 \pm 0.00057$ K [Fixsen, 2009] → CMB is a remnant of the Big Bang.

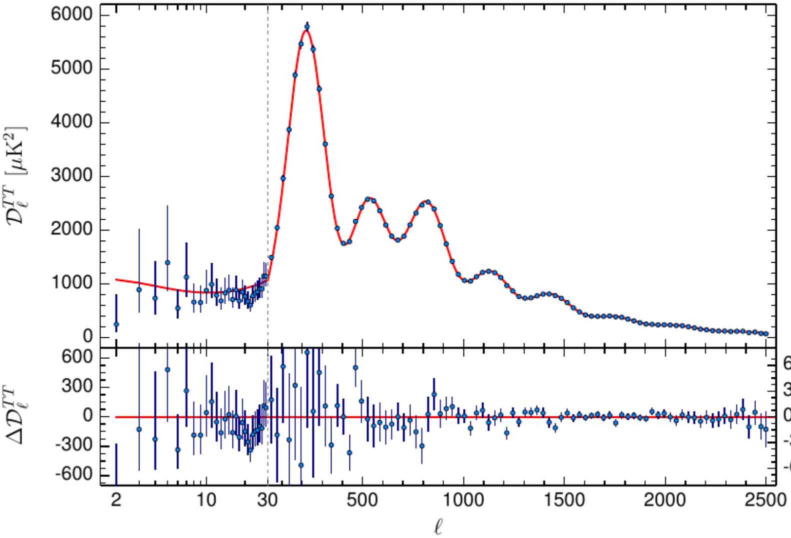
Anisotropies at the level of 10^{-5}: very high precision measurements are needed.
Improvement of the CMB experiments in 20 years:



Planck DR2 results - Temperature

[Planck Collaboration, 2015]

Planck DR2 temperature auto-correlation power spectrum:

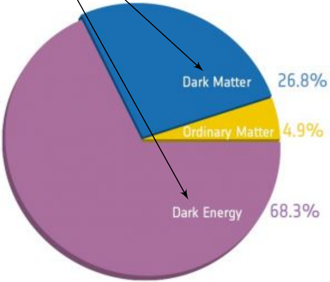


Cosmological parameters

General Relativity + Homogeneity isotropy

Cosmological evolution

Λ CDM model



[Planck collaboration, 2015]

ΛCDM model described by 6 base parameters:

- $\omega_b = \Omega_b h^2$ baryon density today;
- $\omega_c = \Omega_c h^2$ CDM density today;
- τ optical depth to reionization;
- θ angular scale of acoustic peaks;
- n_s tilt and
- A_s amplitude of the power spectrum of initial curvature perturbations.

Other quantities can be studied:

- H_0 Hubble parameter today;
- σ_8 mean matter fluctuations at small scales;
- ...

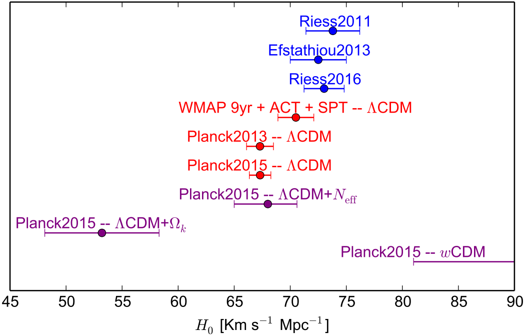
Tension I: the Hubble parameter

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] $H_0 = 73.24 \pm 1.74\,\text{Km s}^{-1}\ \text{Mpc}^{-1}$ (most recent)

(ΛCDM model - CMB data only)
[Planck 2013]: $H_0 = 67.3 \pm 1.2\,\text{Km s}^{-1}\ \text{Mpc}^{-1}$

[Planck 2015]: $H_0 = 67.27 \pm 0.66\,\text{Km s}^{-1}\ \text{Mpc}^{-1}$

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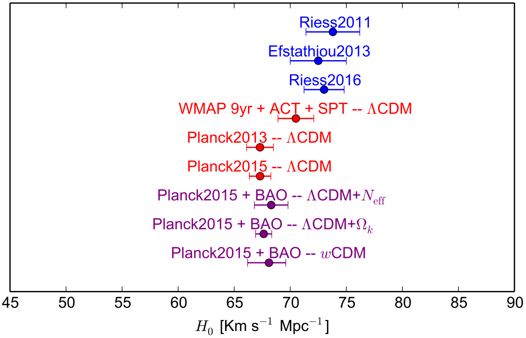

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Tension II: the matter distribution at small scales

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

KiDS-450 (68% CL):
[Hildebrandt et al., 2016]

$$\sigma_8(\Omega_m)^{0.5} = 0.408 \pm 0.021$$

CMB results (68% CL):
[Planck 2015]

$$\sigma_8(\Omega_m)^{0.5} = 0.466 \pm 0.013$$

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Similar results from *CFHTLenS* weak lensing, *Planck SZ* and *SPT* clusters, ...

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Count of satellites galaxies of the Milky Way

Observed (classical + SDSS):

$$N_{\rm sat} = 63 \pm 13$$

Predicted (CDM only):

$$N_{\rm sat} \simeq 160$$

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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]
- did we count all the satellite galaxies? (very difficult detection)

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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 - Patrignani et al. (2016)]

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

$$\begin{aligned}
\Delta m^2_{SOL} &= (7.53 \pm 0.18) \cdot 10^{-5}\ \mathrm{eV}^2 && = \Delta m^2_{21} \\
\Delta m^2_{ATM} &= (2.44 \pm 0.06) \cdot 10^{-3}\ \mathrm{eV}^2 (\mathrm{NO}) && = |\Delta m^2_{32}| \simeq |\Delta m^2_{31}| \\
&= (2.51 \pm 0.06) \cdot 10^{-3}\ \mathrm{eV}^2 (\mathrm{IO})
\end{aligned}$$

$$\begin{aligned}
\sin^2(\theta_{12}) &= 0.304 \pm 0.014 \\
\sin^2(\theta_{23}) &= 0.51 \pm 0.05 (\mathrm{NO}) - 0.50 \pm 0.05 (\mathrm{IO}) \\
\sin^2(\theta_{13}) &= 0.0219 \pm 0.0012
\end{aligned}$$

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

Short Baseline (SBL) anomaly

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

Problem: anomalies in SBL experiments $\Rightarrow \begin{cases} \text{errors in flux calculations?} \\ \text{deviations from 3-}\nu\text{ description?} \end{cases}$

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 $\Rightarrow$ 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]

See also [SG et al., 2017]

Possible explanation:

Additional squared mass difference

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

3+1 Neutrino Model

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

↓

ν_4 with $m_4 \simeq 1$ eV,
no weak interactions

↓

light sterile neutrino (LSν)

3 (active) + 1 (sterile) mixing:

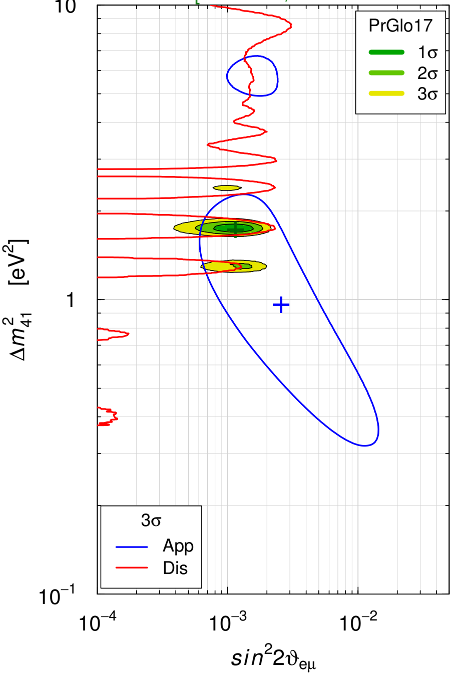
$$\nu_\alpha = \sum_{k=1}^{3+1} U_{\alpha k}\nu_k \quad (\alpha = e, \mu, \tau, s)$$

ν_s is mainly ν_4:

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

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

[SG et al., arxiv:1703.00860]



(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

- $N_{\rm eff} \rightarrow$ 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 $\Delta N_{\rm eff} = N_{\rm eff} - 3.046$:

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

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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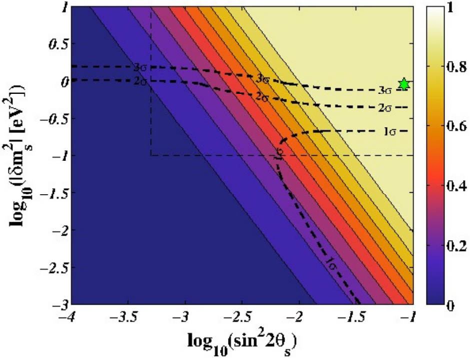
LSν thermalization

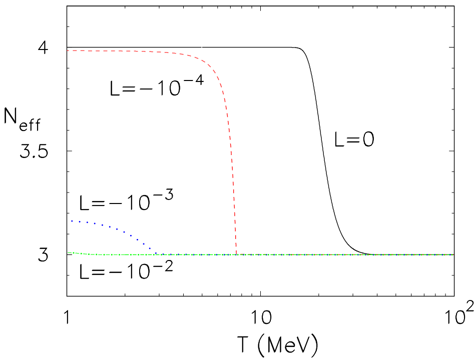
Using SBL best-fit parameters for the LSν (Δm^2_{41}, θ_s):

[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]

[to be precise: $\Delta N_{\rm eff}$ is slightly smaller at CMB decoupling, when the LSν starts to be non-relativistic]

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

$m_s \simeq 1$ eV $\rightarrow \nu_s$ 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:

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

[Planck 2013 Results, XVI]

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

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

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

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

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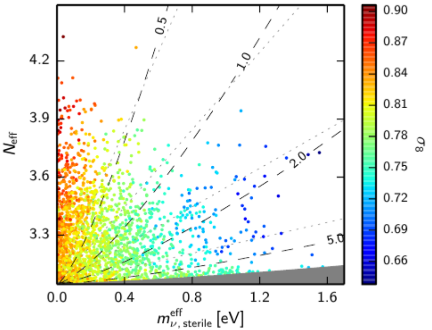
LSν constraints from cosmology

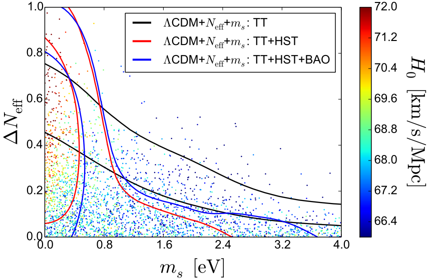
CMB+local: [Planck Collaboration, 2015]



$$\begin{cases} N_{\rm eff} < 3.7 \\ m_s^{\rm eff} < 0.52 \text{ eV} \end{cases}$$

(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]

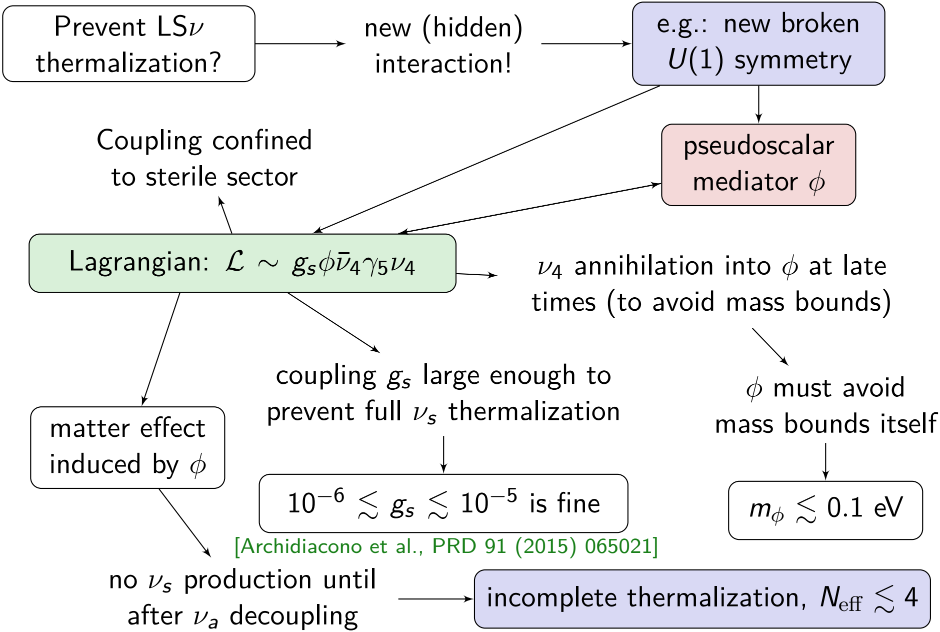
Summary: $\Delta N_{\rm eff} = 1$ from LSν incompatible with $m_s \simeq 1$ eV!

TT=Planck 2015 TT + lowTEB

All the constraints are at 2σ CL

Adding a new interaction

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



Prevent LSν thermalization?

new (hidden) interaction!

e.g.: new broken $U(1)$ symmetry

pseudoscalar mediator ϕ

Coupling confined to sterile sector

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

ν_4 annihilation into ϕ at late times (to avoid mass bounds)

coupling g_s large enough to prevent full ν_s thermalization

ϕ must avoid mass bounds itself

matter effect induced by ϕ

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

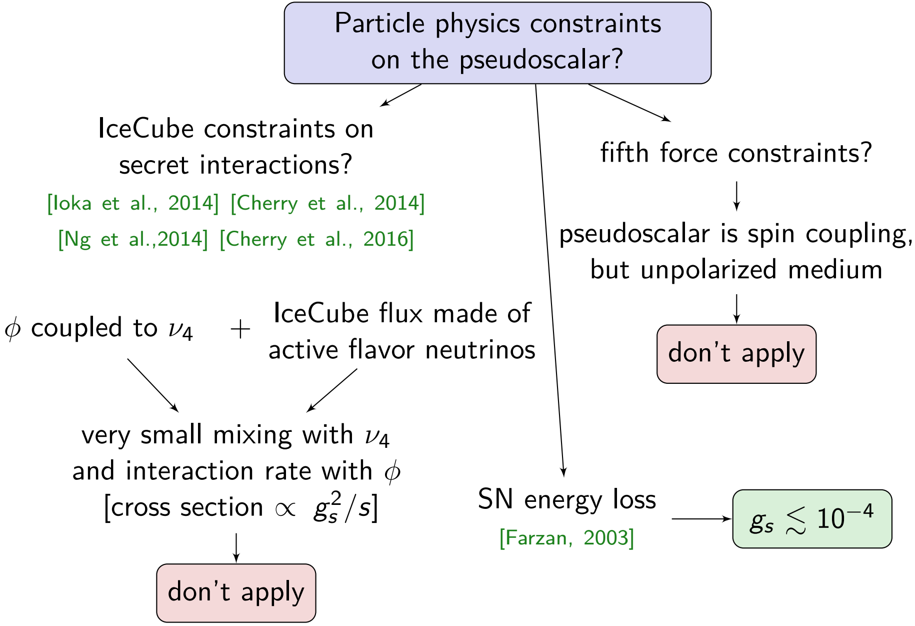
$m_\phi \lesssim 0.1$ eV

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

no ν_s production until after ν_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]

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

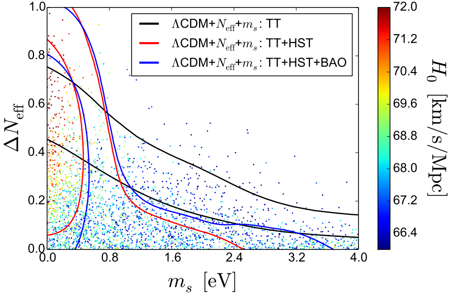
SN energy loss
[Farzan, 2003]

$g_s \lesssim 10^{-4}$

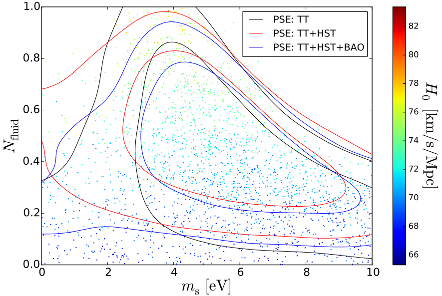
Results - I

[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)



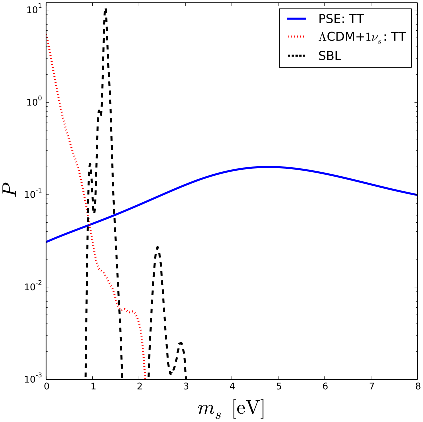
Pseudoscalar model (**PSE**):
$N_{\rm eff}=3.046+N_{\rm fluid}$
$N_{\rm fluid}$: ν_s+ϕ contributions

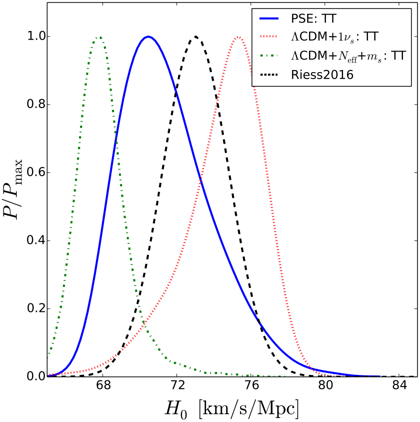


- Problems with $\Delta N_{\rm eff}=1$? solved (incomplete thermalization due to suppression of active-sterile oscillations in primordial plasma);
- mass bounds avoided
  $\Rightarrow$ large m_s allowed and preference for $m_s\simeq 4$ eV;
- high values of H_0 predicted by cosmology
  $\Rightarrow$ more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

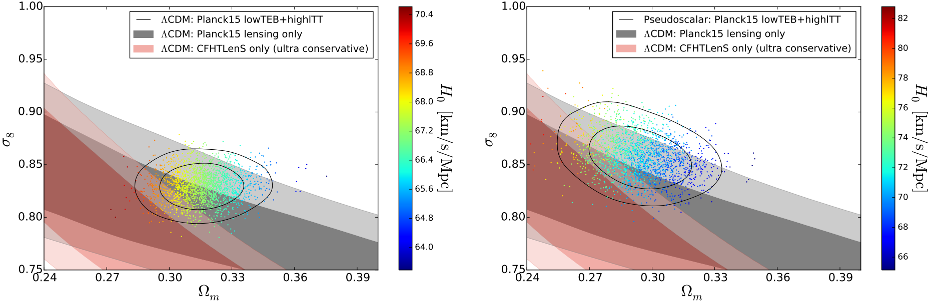
- PSE: very close to **Riess2016** results (better than ΛCDM+$N_{\rm eff}+m_s$)
- ΛCDM+$1\nu_s$: even higher H_0, but from $\Delta N_{\rm eff}=1$ and $m_s \simeq 0$.

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:

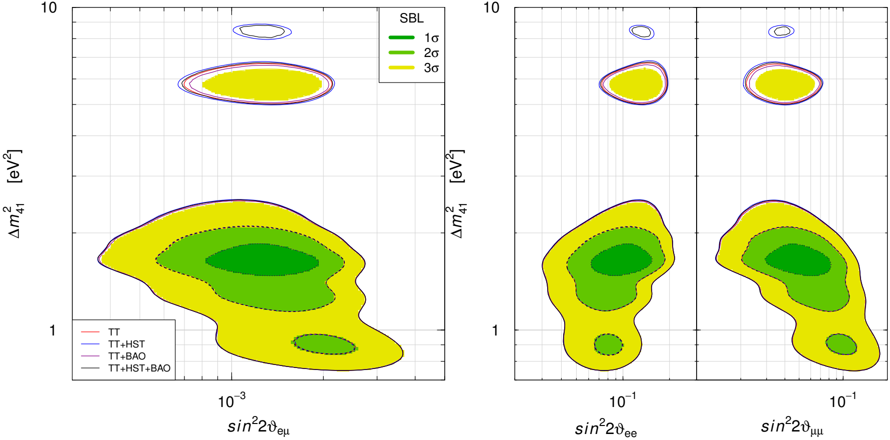


- smaller Ω_m today. Good?
- Also higher $\sigma_8 \Longrightarrow$ no improvement! The tension remains.
- due to higher H_0, not to reduced matter fluctuations.

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?

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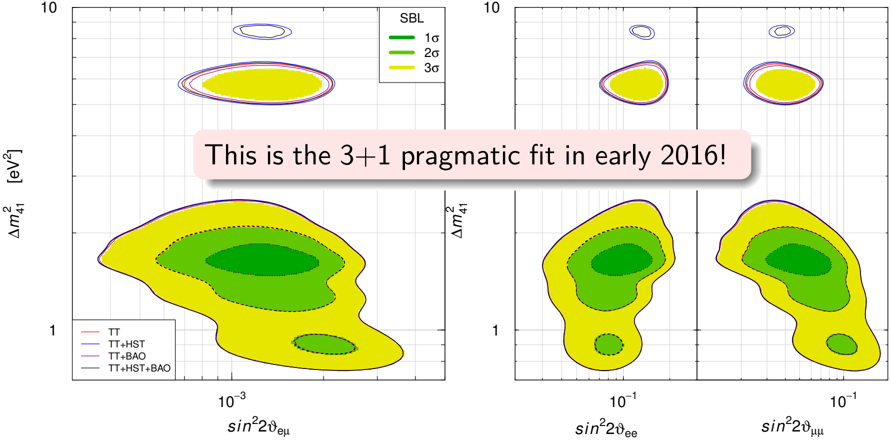

This is the 3+1 pragmatic fit in early 2016!

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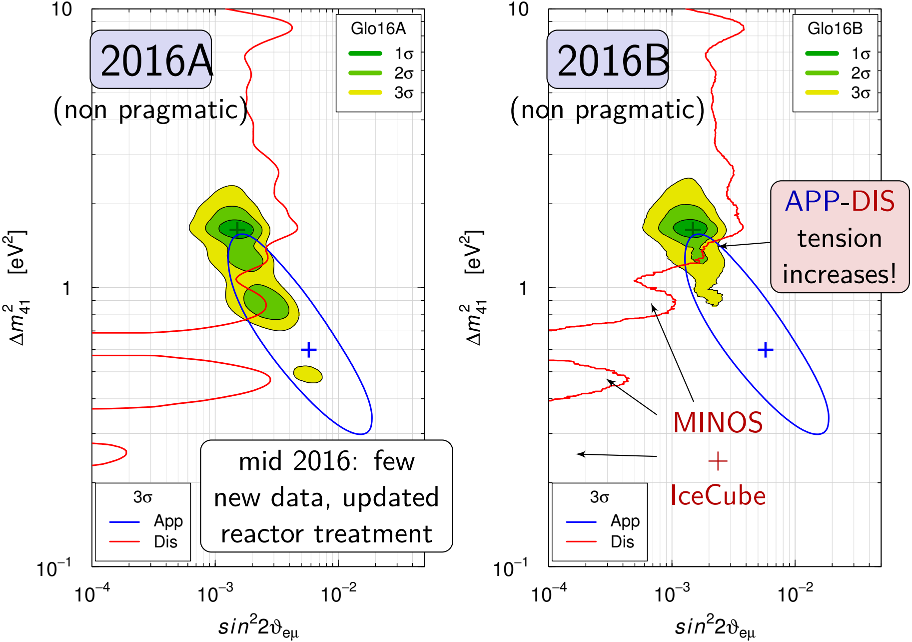
2017 update of global 3+1 fit

[SG et al., arxiv:1703.00860]



2016A

(non pragmatic)

mid 2016: few new data, updated reactor treatment

2016B

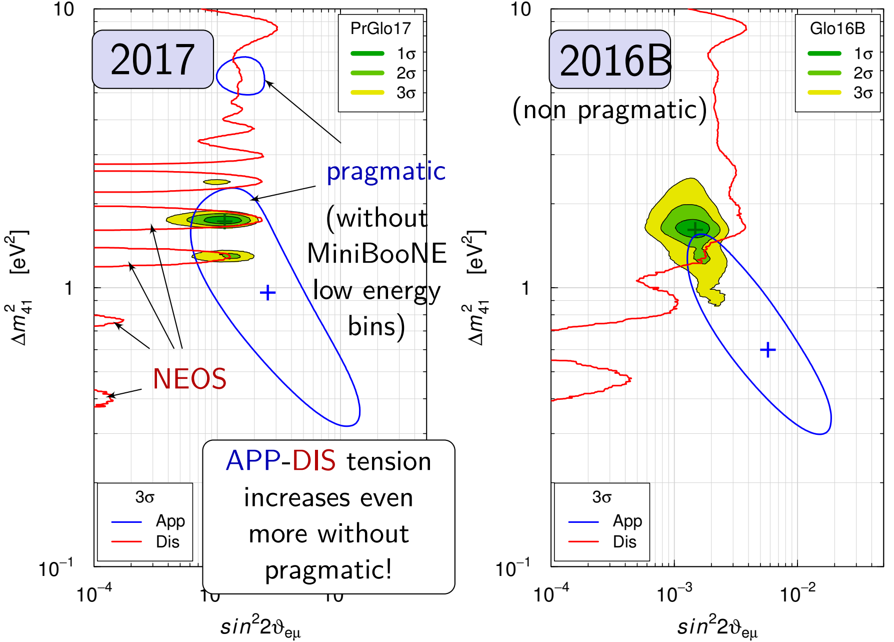
(non pragmatic)

APP-DIS tension increases!

MINOS + IceCube

2017 update of global 3+1 fit

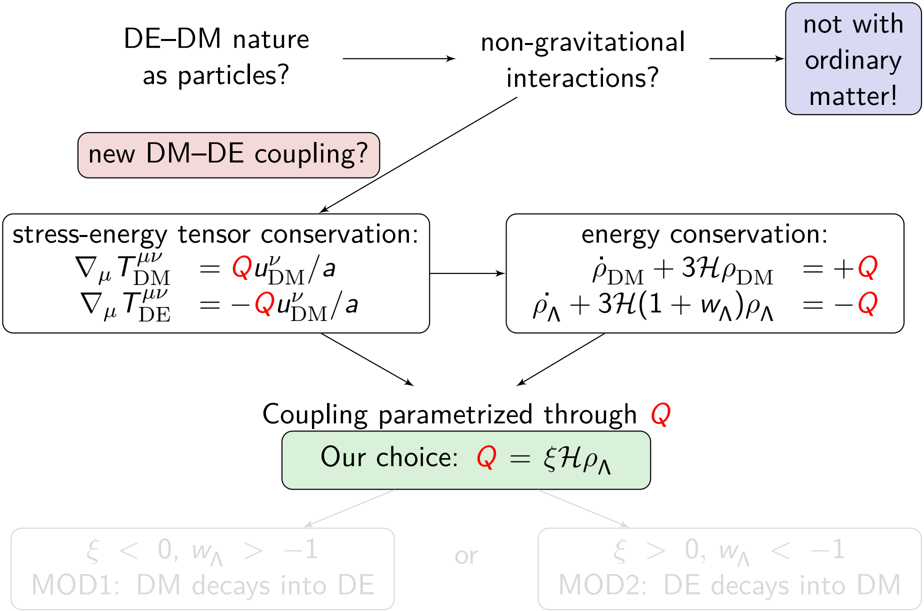
[SG et al., arxiv:1703.00860]



APP-DIS tension increases even more without pragmatic!

Model - I

[Murgia et al., JCAP 1604 (2016) 014]



DE–DM nature as particles?

non-gravitational interactions?

not with ordinary matter!

new DM–DE coupling?

stress-energy tensor conservation:

$$\begin{aligned} \nabla_\mu T^{\mu\nu}_{\rm DM} &= Q u^\nu_{\rm DM}/a \\ \nabla_\mu T^{\mu\nu}_{\rm DE} &= -Q u^\nu_{\rm DM}/a \end{aligned}$$

energy conservation:

$$\begin{aligned} \dot\rho_{\rm DM} + 3\mathcal{H}\rho_{\rm DM} &= +Q \\ \dot{\rho_\Lambda} + 3\mathcal{H}(1+w_\Lambda)\rho_\Lambda &= -Q \end{aligned}$$

Coupling parametrized through Q

Our choice: $Q = \xi\mathcal{H}\rho_\Lambda$

$\xi < 0,\ w_\Lambda > -1$
MOD1: DM decays into DE

or

$\xi > 0,\ w_\Lambda < -1$
MOD2: DE decays into DM

ξ dimensionless coupling parameter – a scale factor – $\mathcal{H}$ Hubble parameter
$\rho_{\rm DM}$ (ρ_Λ) DM (DE) energy density – $u^\nu_{\rm DM}$ DM four-velocity – w_Λ DE equation of state parameter ($p_\Lambda = w_\Lambda\rho_\Lambda$)

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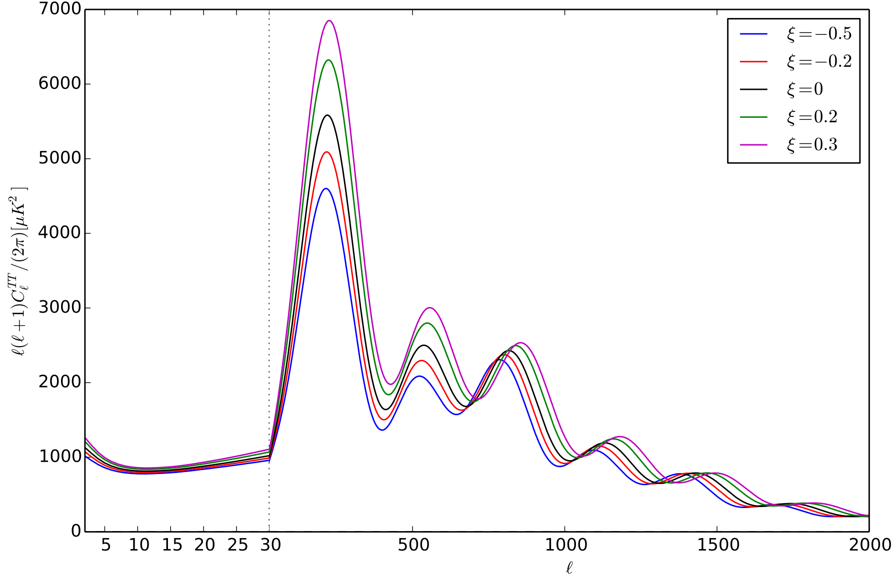
Model - II

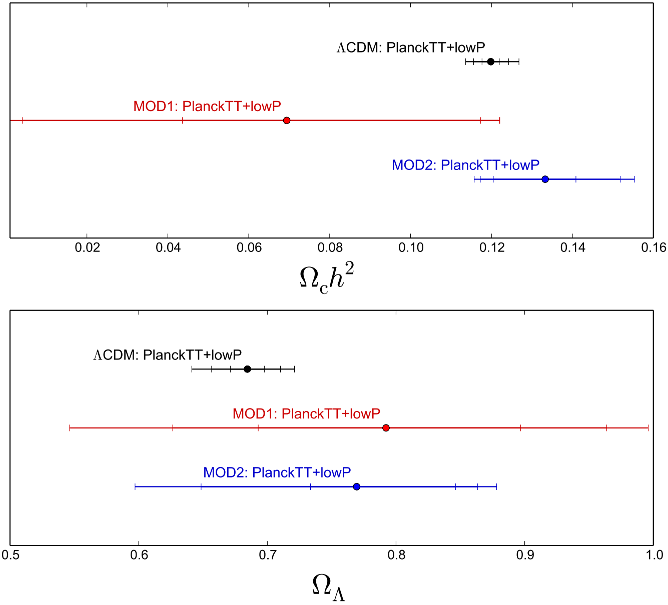
[Murgia et al., JCAP 1604 (2016) 014]

Coupled Dark Energy (CDE) influences the CMB spectrum:



Results - I

[Murgia et al., JCAP 1604 (2016) 014]



- $\Omega_c h^2 \propto \rho_{\rm DM}$ is physical
- MOD1

  DM→DE

  $\Downarrow$

  less DM today
- MOD2

  DE→DM

  $\Downarrow$

  more DM today

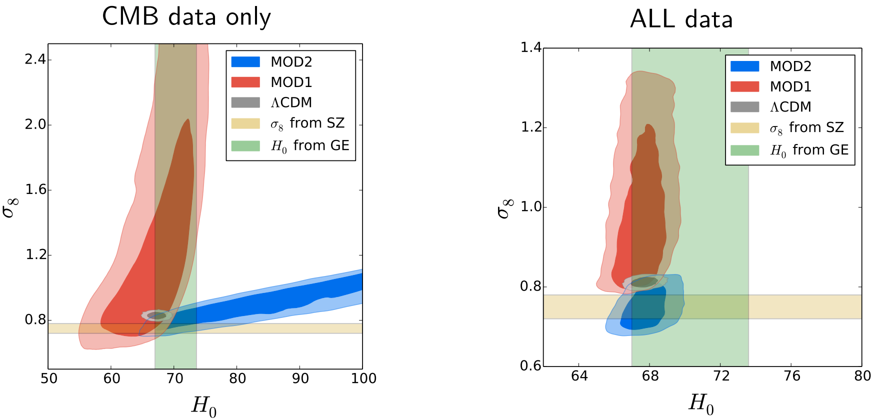
  also higher h!

$\Omega_\Lambda \propto \rho_\Lambda / h^2$ is non-physical, depends on h!

$h = H_0/(100\,\mathrm{Km\ s^{-1}\ Mpc^{-1}})$ dimensionless Hubble parameter

Results - II - H_0 and σ_8 tensions

[Murgia et al., JCAP 1604 (2016) 014]



more DM in the early Universe $\Longrightarrow$ stronger nonlinear evolution in MOD1

$H^2 \propto \rho_\Lambda \propto a^{-3(w_\Lambda+1)-\xi} \Longrightarrow$ higher H_0 in MOD2

MOD2 is better for reconciling CMB and local determinations

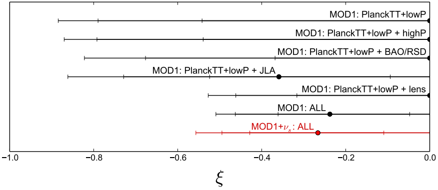
CMB=Planck TT+low-ℓ polarization

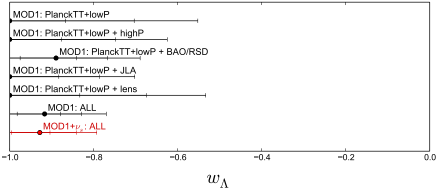
ALL=CMB + high-ℓ polarization + BAO/RSD (BOSS DR11, SDSS MGS, 6dF) + Supernovae (JLA) + Planck lensing trispectrum

Results - III - ξ and w_Λ

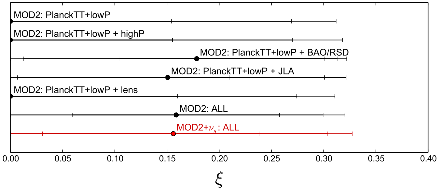
[Murgia et al., JCAP 1604 (2016) 014]

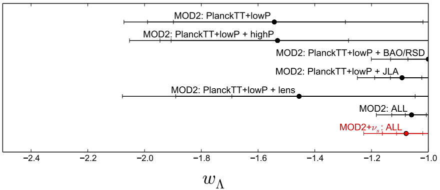
MOD1





MOD2





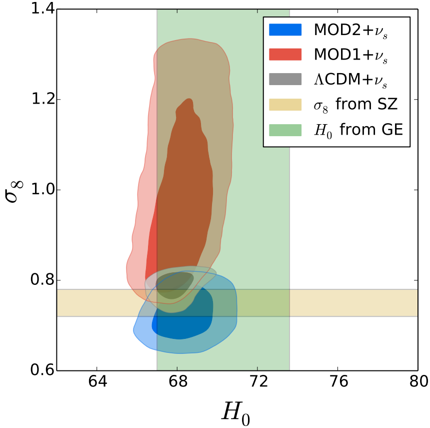
- JLA$\rightarrow$ $\xi \neq 0$?
- BAO/RSD$\rightarrow$ $w_\Lambda \neq -1$?

- CMB$\rightarrow$ poor constraints on w_Λ
- BAO/RSD, JLA$\rightarrow$ preference for less DM today, $w_\Lambda \simeq -1$

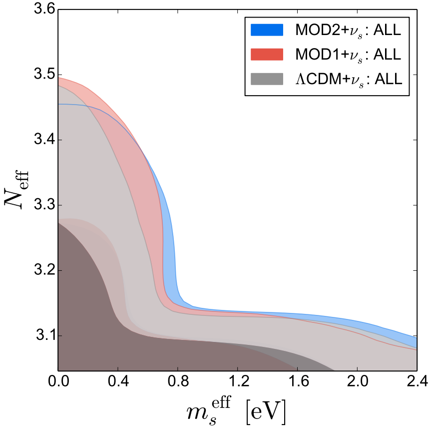
red points: CDE + LSν models

Results - IV - What about LSν?

[Murgia et al., JCAP 1604 (2016) 014]



No significant variations for the 2D contours in the $\sigma_8 - H_0$ plane



CDE models does not affect the LSν bounds!

Upper limits for $m_s^{\rm eff}$, $N_{\rm eff} \lesssim 3.5$ $\Longrightarrow$ thermalized LSν is still disfavoured

Conclusions

- Universe evolution explained well by ΛCDM model
  - cosmological constraints on standard particles (neutrinos) ✓
  - additional particles ?
  - tensions between cosmological and local measurements (H_0, σ_8) ✗
    - unaccounted systematics or new physics ?
- ν oscillations anomalies at Short-Baseline distances
  - light ($m_s \simeq 1$ eV) sterile neutrino (LSν) ?
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    - new mechanisms suppress active-sterile oscillations in the early Universe ?
- new hidden sterile neutrino-pseudoscalar (ϕ) interaction ?
  - light pseudoscalar to avoid mass bounds after LSν annihilation ✓
  - $\Delta N_{\rm eff} \lesssim 1$ allowed by matter effects induced by ϕ ✓
  - larger m_4 preferred ✓
  - LSν can reduce H_0 and σ_8 tensions ✓?
- Coupling between Dark Matter (DM) and Dark Energy (DE) ?
  - can reduce H_0 and σ_8 tensions (DE→DM) ✓
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Grazie dell'attenzione!