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Cosmology and Sterile Neutrinos

Phenomenology and constraints

9 October 2017 - Collider Physics and the Cosmos - GGI Firenze

1. Introduction of cosmology
    - Cosmic Microwave Background (CMB)
    - The ΛCDM model
    - Tensions between local and CMB measurements
2. Light sterile neutrinos
    - Oscillations anomalies
    - Light sterile neutrino as a possible solution
3. Light sterile neutrino and cosmology
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    - As a non-relativistic particle
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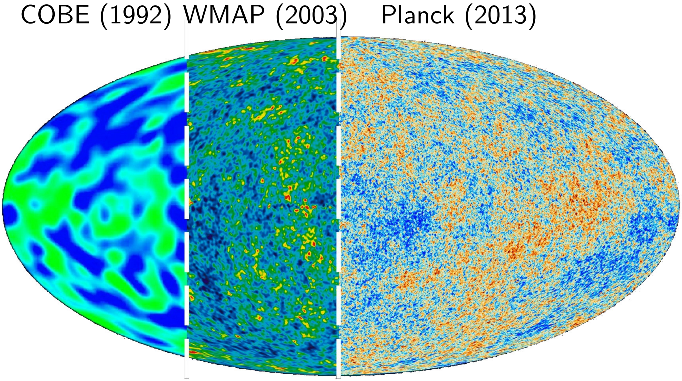
Cosmic Microwave Background (CMB)

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.

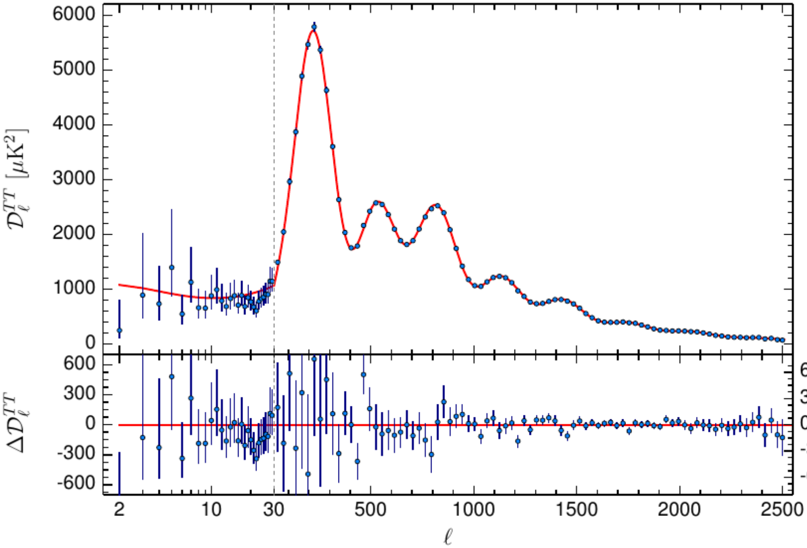
Anisotropies at the level of 10^{-5}: very high precision measurements are needed.
Improvement of the CMB experiments in 20 years:



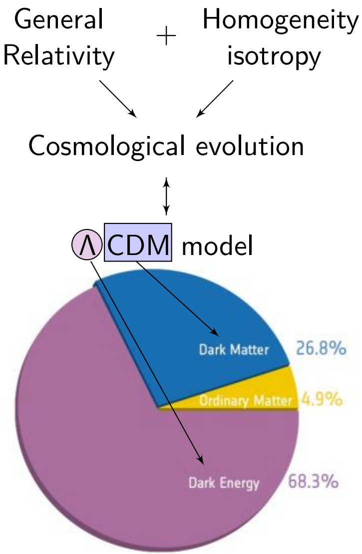
Planck DR2 results - Temperature

[Planck Collaboration, 2015]

Planck DR2 temperature auto-correlation power spectrum:



Cosmological parameters



General Relativity + Homogeneity isotropy

Cosmological evolution

ΛCDM 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;
- ...

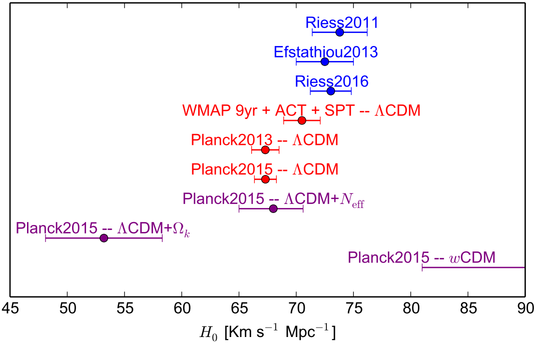
Tension I: the Hubble parameter

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] $H_0 = 72.5 \pm 2.5\,\mathrm{Km\ s^{-1}\ Mpc^{-1}}$
[Riess et al., 2016] $H_0 = 73.24 \pm 1.74\,\mathrm{Km\ s^{-1}\ Mpc^{-1}}$
(most recent)

(ΛCDM model - CMB data only)
[Planck 2013]: $H_0 = 67.3 \pm 1.2\,\mathrm{Km\ s^{-1}\ Mpc^{-1}}$
[Planck 2015]: $H_0 = 67.27 \pm 0.66\,\mathrm{Km\ s^{-1}\ Mpc^{-1}}$

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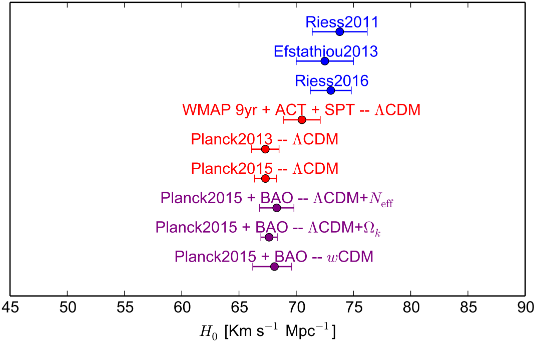

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Tension II: the matter distribution at small scales

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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$\sim 2.5\sigma$ discrepancy!

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Similar results from *Planck SZ* and *SPT* clusters, *CFHTLenS*, *DES* 1yr, ...

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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]

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

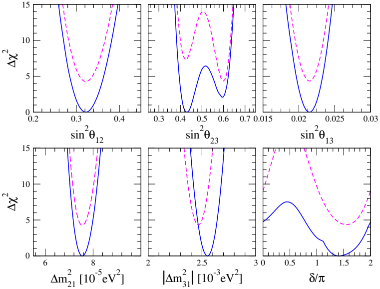
ν_α flavour eigenstates, $U_{\alpha k}$ PMNS mixing matrix, ν_k mass eigenstates.

Current knowledge of the 3 active ν mixing: [de Salas et al. (2017)]

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

$$\begin{aligned}
\Delta m^2_{21} &= (7.56 \pm 0.19) \cdot 10^{-5}\ \mathrm{eV}^2 \\
|\Delta m^2_{31}| &= (2.55 \pm 0.04) \cdot 10^{-3}\ \mathrm{eV}^2\ (\mathrm{NO}) \\
&= (2.47^{+0.04}_{-0.05}) \cdot 10^{-3}\ \mathrm{eV}^2\ (\mathrm{IO})
\end{aligned}$$

$$\begin{aligned}
\sin^2(\theta_{12}) &= 0.321^{+0.018}_{-0.016} \\
\sin^2(\theta_{13}) &= 0.0216^{+0.009}_{-0.008}\ (\mathrm{NO}) \\
&= 0.0216^{+0.008}_{-0.009}\ (\mathrm{IO}) \\
\sin^2(\theta_{23}) &= 0.40 - 0.48 \& 0.56 - 0.62\ (2\sigma, \mathrm{NO}) \\
&= 0.41 - 0.44 \& 0.56 - 0.63\ (2\sigma, \mathrm{IO})
\end{aligned}$$



CP violating phase δ_{CP} still unknown. Hint: $\delta_{\mathrm{CP}} \simeq 3/2\pi$?

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 ⇒ 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 also [SG et al., 2017]

3+1 Neutrino Model

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

$\downarrow$

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

$\downarrow$

light sterile neutrino (LSν)

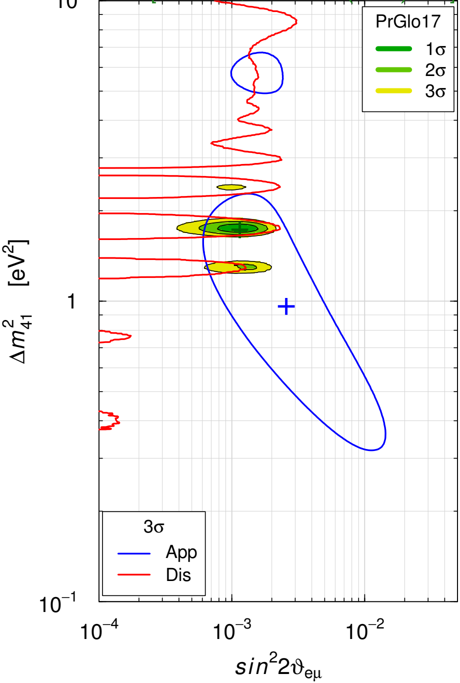
3 (active) + 1 (sterile) mixing:

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

ν_s is mainly ν_4:

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

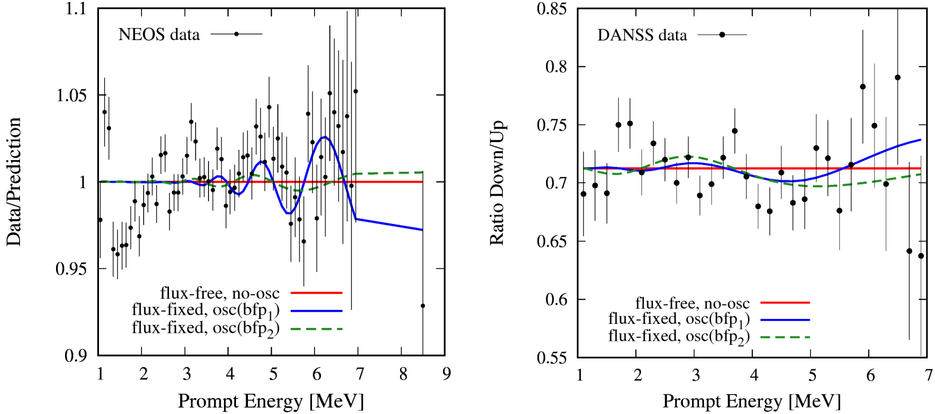
assuming $m_4 \gg m_i$ $(i = 1, 2, 3)$



[SG et al., JHEP 06 (2017) 135]

LSν hints from reactors?

[Dentler et al., 1709.04294]



No absolute flux, only ratios at different distances!

blue, "bfp1":

fit of reactor data

$$\Delta m^2_{41} \simeq 3\ \text{eV}^2$$

$$\sin^2 2\theta_{14} \simeq 0.12$$

green, "bfp2":

fit of all disappearance data

$$\Delta m^2_{41} \simeq 1.7\ \text{eV}^2$$

$$\sin^2 2\theta_{14} \simeq 0.06$$

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(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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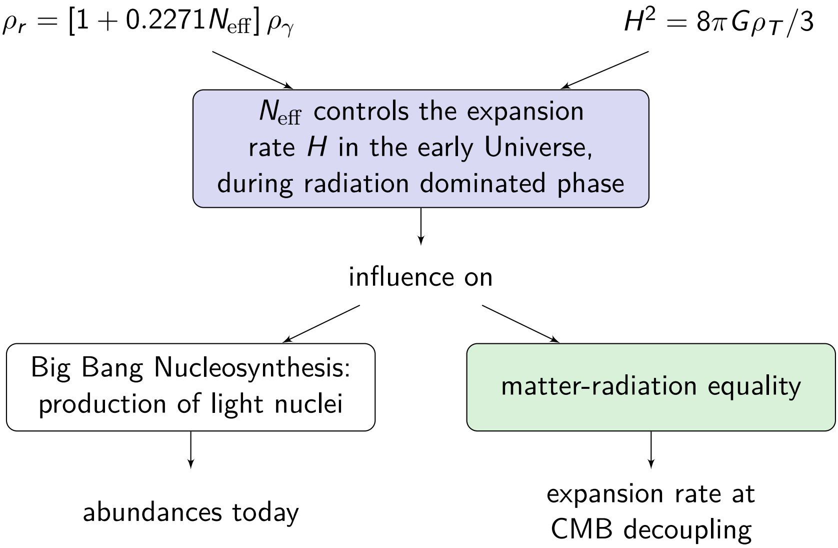
Additional Radiation in the Early Universe



$\rho_r = [1 + 0.2271 N_{\rm eff}]\, \rho_\gamma$

$H^2 = 8\pi G \rho_T / 3$

$N_{\rm eff}$ controls the expansion rate H in the early Universe, during radiation dominated phase

influence on

Big Bang Nucleosynthesis: production of light nuclei

matter-radiation equality

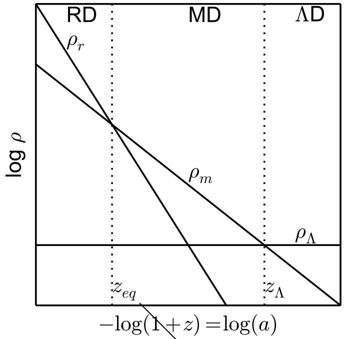
abundances today

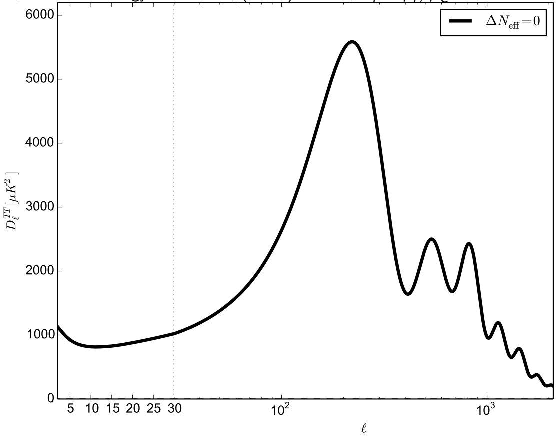
expansion rate at CMB decoupling

Additional Radiation: Effects on the CMB

Starting configuration:

RD: Radiation Dominated, MD: Matter Dominated, ΛD: Dark Energy Dominated; $(1+z) = a^{-1}$; $\omega_i = \rho_i/\rho_C$



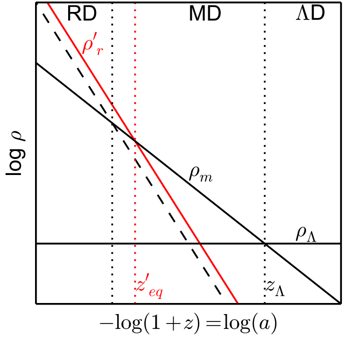


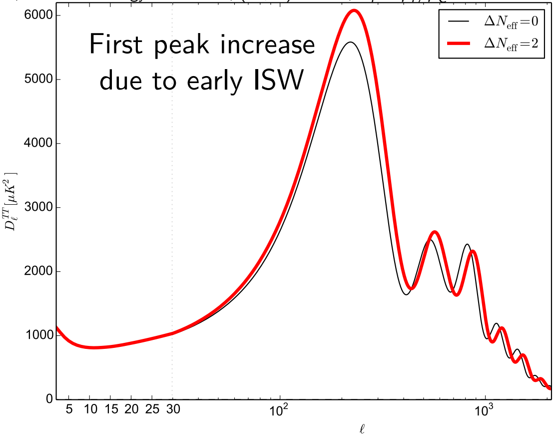
$$1 + z_{\rm eq} = \frac{\omega_m}{\omega_r} = \frac{\omega_m}{\omega_\gamma}\frac{1}{1+0.2271\,N_{\rm eff}}$$

Additional Radiation: Effects on the CMB

If we increase $N_{\rm eff}$, all the other parameters fixed:

RD: Radiation Dominated, MD: Matter Dominated, ΛD: Dark Energy Dominated; $(1+z) = a^{-1}$; $\omega_i = \rho_i/\rho_C$





At z_{CMB}: higher $H \propto \rho_r \Rightarrow$ smaller comoving sound horizon $r_s \propto H^{-1}$

$\Rightarrow$ decrease of the angular scale of the acoustic peaks $\theta_s = r_s/D_A$

$\Rightarrow$ shift of the peaks at higher ℓ

Additional Radiation: Effects on the CMB

If we increase $N_{\rm eff}$, plus ω_m to fix $z_{\rm eq}$:

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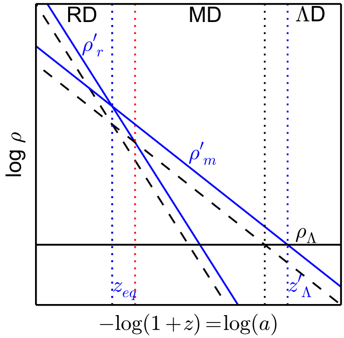

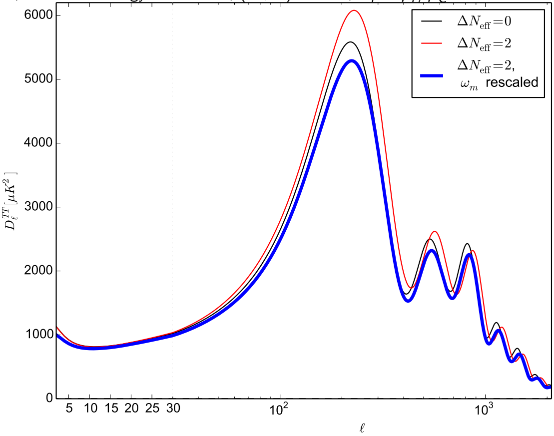

- Contribution from early ISW effect restored (first peak)
- different slope of the Sachs-Wolfe plateau, peak positions, envelope of high-ℓ peaks $\Rightarrow$ due to later z_Λ

Additional Radiation: Effects on the CMB

If we increase $N_{\rm eff}$, plus ω_m, ω_Λ to fix $z_{\rm eq}$, z_Λ:

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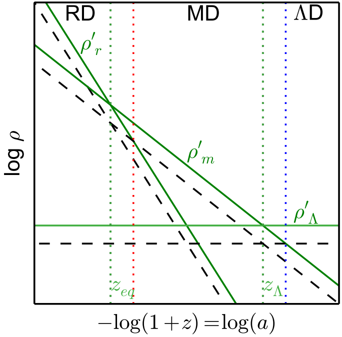
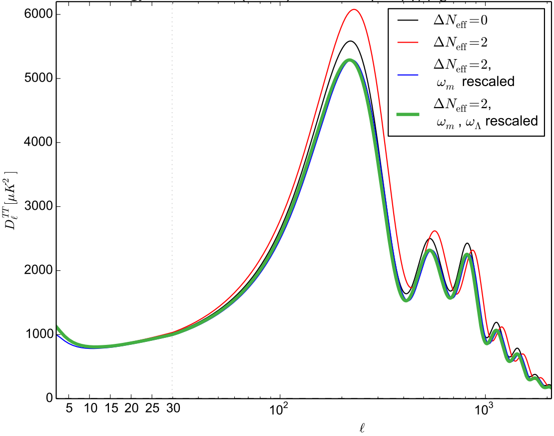
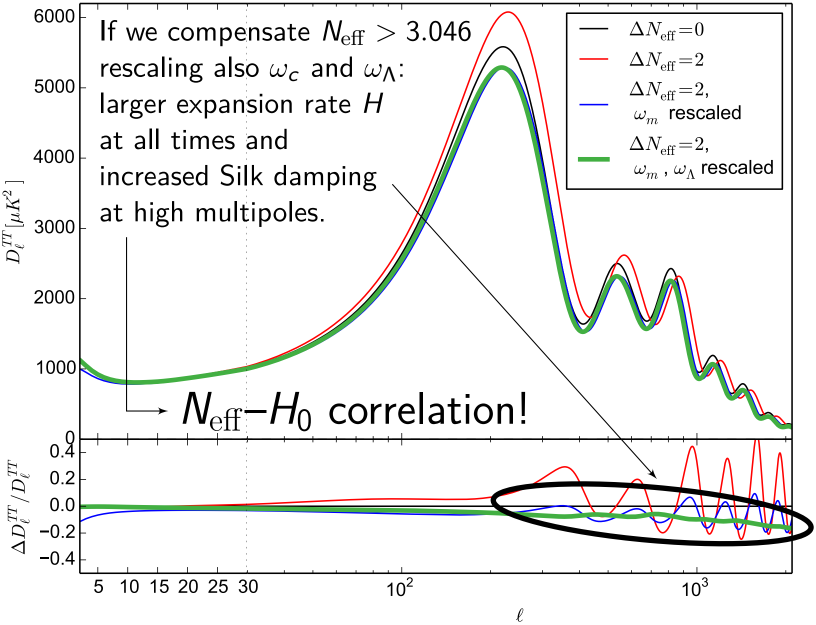




- peak positions recovered;
- slope of the Sachs-Wolfe plateau recovered;
- peak amplitude not recovered!

Additional Radiation: Effects on the CMB



If we compensate $N_{\rm eff} > 3.046$ rescaling also ω_c and ω_Λ: larger expansion rate H at all times and increased Silk damping at high multipoles.

$N_{\rm eff}$–H_0 correlation!

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

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

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

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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:

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

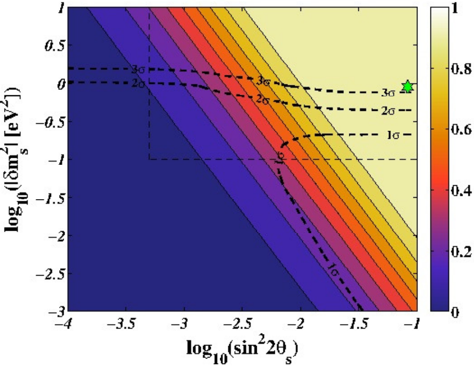
If $f_s(p) = f_{\rm active}(p)$, $m_s^{\rm eff} \equiv m_s$

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

LSν thermalization

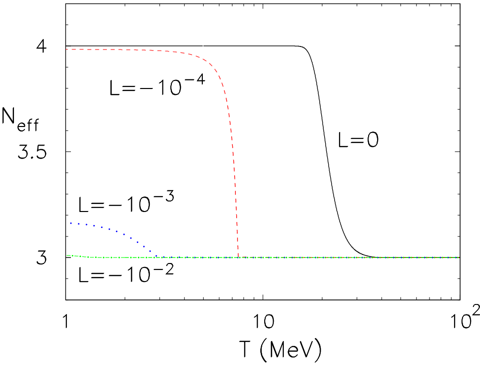
Using SBL best-fit parameters for the LSν (Δm^2_{41}, θ_s):

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



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

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



(L: lepton asymmetry)

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

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]

Impact of non-cold species on the CMB

$$1 + z_{\rm eq} = (\omega_b + \omega_c)/\omega_r$$

independent of m_ν

$\omega_m^0 = \omega_b^0 + \omega_c^0 + \omega_\nu^0$ today

mass of species relativistic at recombination
affect late time evolution only

small effects on the SW plateau
(cosmic variance, degeneracies...)

Effects on the early ISW effect

$$\frac{\Delta C_\ell}{C_\ell} \simeq -\left(\frac{\sum m_\nu}{0.1\text{ eV}}\right)\%$$

effects on the position of peaks

$$\theta_s = r_s(\eta_{LS})/D_A(\eta_{LS})$$

$$D_A = \int_0^{z_{rec}} \frac{dz}{H(z)}$$

(this effect can be compensated reducing H_0)

correlation m_ν–H_0

["Neutrino Cosmology", Lesgourgues et al.]

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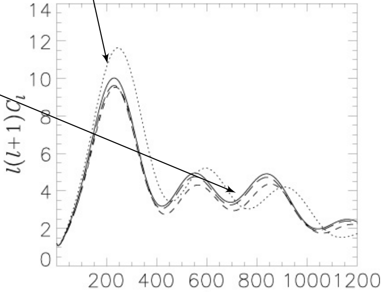


["Neutrino Cosmology", Lesgourgues et al.]

Free-streaming - I

Non-cold relics ⟹ damping in the perturbations due to free-streaming

Growth equation: $$\ddot{\delta}+\underbrace{\boxed{2H\dot{\delta}}}_{\text{Hubble drag}}-\underbrace{\boxed{c_s^2k^2\frac{\delta}{a^2}}}_{\text{pressure}}=\underbrace{\boxed{4\pi G_N\rho\,\delta}}_{\text{gravity}}$$

Jeans scale: pressure=gravity

$$k_J\equiv\sqrt{\frac{4\pi G_N\rho}{c_s^2(1+z)^2}}$$

$k < k_J$
growth of density perturbations

$k > k_J$
no growth can occur

neutrino free-streaming scale

$$\boxed{k_{fs}(z)\equiv\sqrt{\frac{3}{2}\frac{H(z)}{(1+z)\sigma_{v,\nu}(z)}}\simeq 0.7\left(\frac{m_\nu}{1\text{ eV}}\right)\sqrt{\frac{\Omega_M}{1+z}}h/\text{Mpc}}$$

ρ energy density of a given fluid
$\delta=\delta\rho/\rho$ perturbation (single fluid)
c_s sound speed of the fluid

$\sigma_{v,\nu}(z)$ ν velocity dispersion
$H=H(z)$ Hubble factor at redshift z
h reduced Hubble factor today

Free-streaming - II

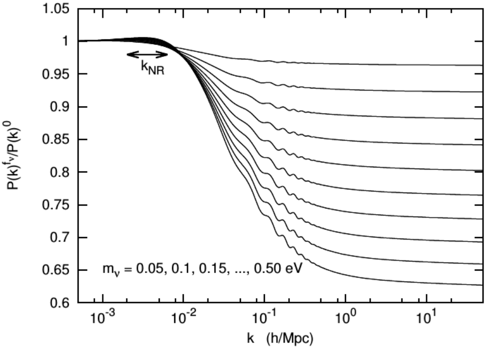
Damping occurs for all $k \gtrsim k_{\rm nr}$

k_{nr}: corresponding
to ν non-relativistic transition

Plot: $\dfrac{P_{m_\nu>0}(k)}{P_{m_\nu=0}(k)}$

- top to bottom: $m_\nu = 0.05$ eV
  to $m_\nu = 0.5$ eV
- $\dfrac{\Delta P}{P} \simeq -\dfrac{8\Omega_\nu}{\Omega_M} \simeq -\dfrac{\sum m_\nu}{0.01\ \rm eV}\%$

["Neutrino Cosmology", Lesgourgues et al.]
(fixed h, ω_m, ω_b, ω_Λ)

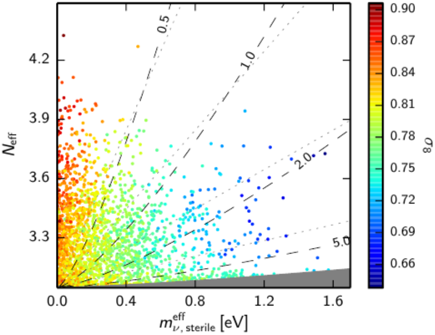


Expected constraints from future surveys:

- Planck CMB + DES: $\sigma(m_\nu) \simeq 0.04$–$0.06$ eV [Font-Ribera et al., 2014]
- Planck CMB + Euclid: $\sigma(m_\nu) \simeq 0.03$ eV [Audren et al., 2013]

LSν constraints from cosmology

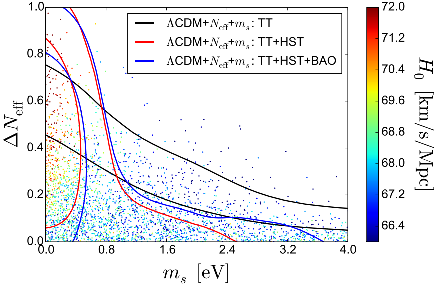
CMB+local: [Planck Collaboration, 2015]



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

(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

Incomplete Thermalization

Active-sterile oscillations in the early Universe:

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

[Hannestad et al., 2012] [Mirizzi et al., 2012]

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

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

Some ideas:

- 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; 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 ν_s production [Rehagen et al., 2014]

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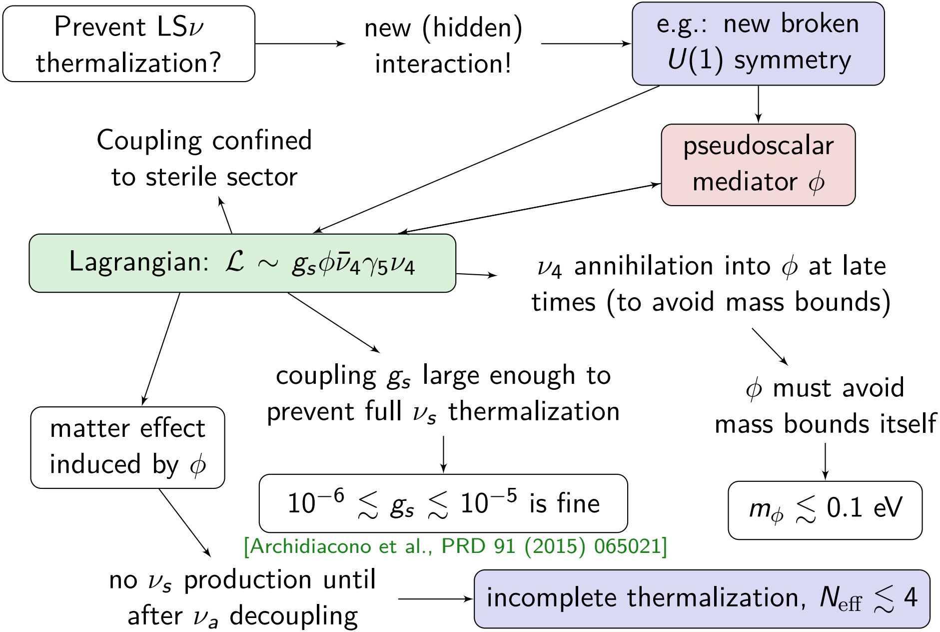
Adding a new interaction

[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

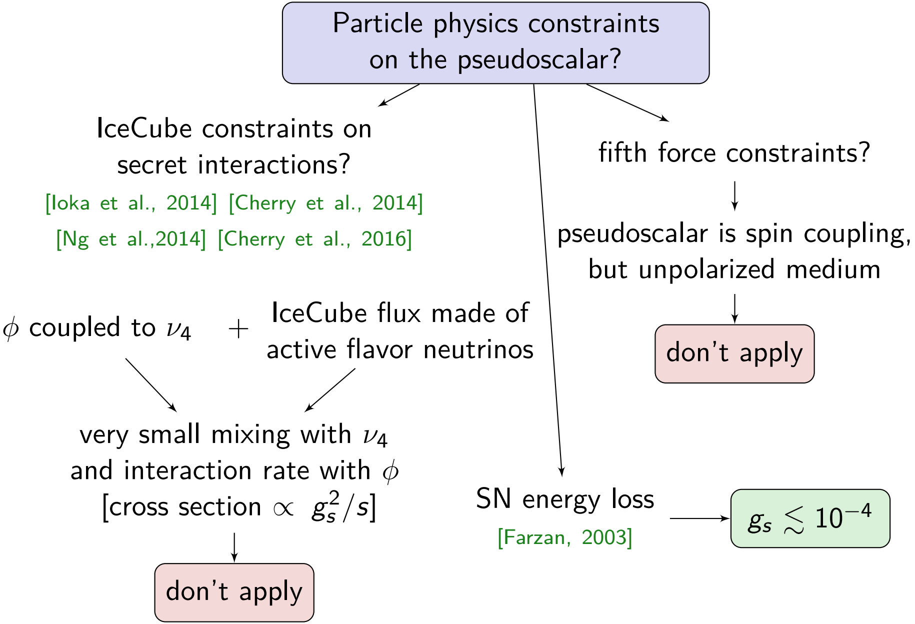
[Archidiacono et al., PRD 91 (2015) 065021]

$m_\phi \lesssim 0.1$ eV

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

SN energy loss

[Farzan, 2003]

$g_s \lesssim 10^{-4}$

fifth force constraints?

pseudoscalar is spin coupling, but unpolarized medium

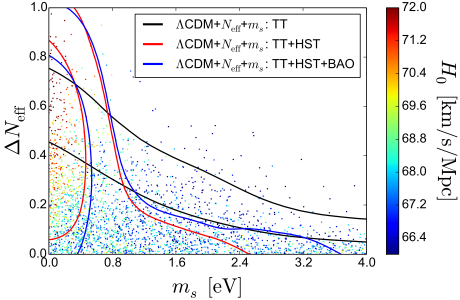
don't apply

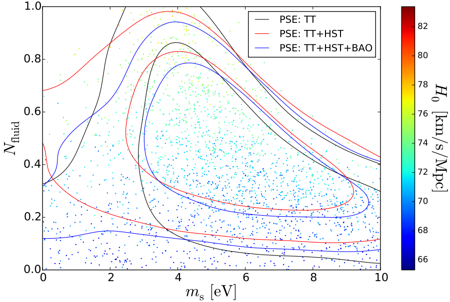
Results - I

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

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

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

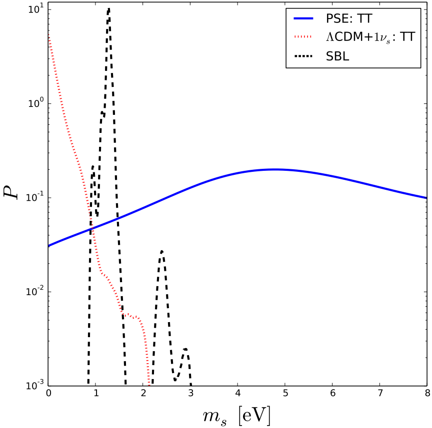


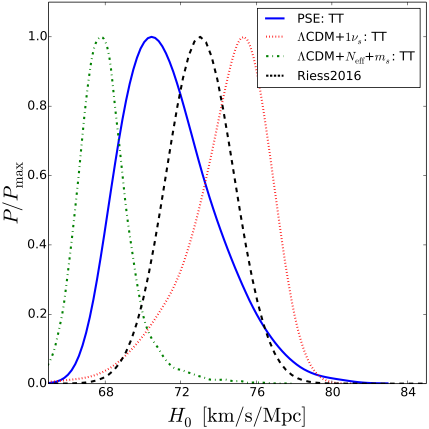


- Problems with $\Delta N_{\rm eff} = 1$? solved (incomplete thermalization due to suppression of active-sterile oscillations in primordial plasma);
- mass bounds avoided
  $\Rightarrow$ large m_s allowed and preference for $m_s \simeq 4$ eV;
- high values of H_0 predicted by cosmology
  $\Rightarrow$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

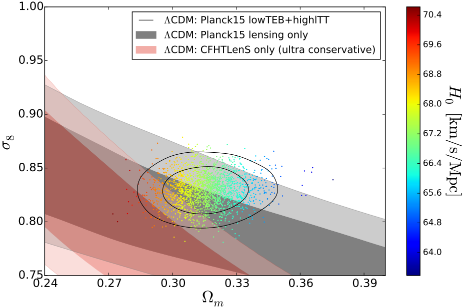
- PSE: very close to **Riess2016** results (better than ΛCDM+$N_{\rm eff}+m_s$)
- ΛCDM+$1\nu_s$: even higher H_0, but from $\Delta N_{\rm eff}=1$ and $m_s \simeq 0$.

Results - III

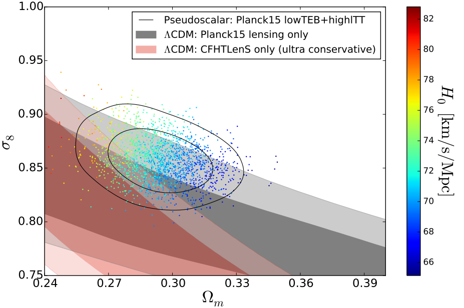
[Archidiacono, SG et al., JCAP 08 (2016) 067]

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.

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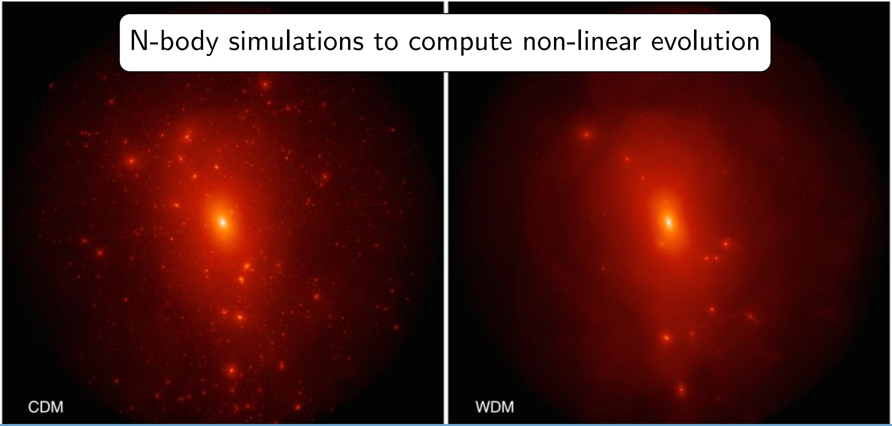
keV sterile neutrino effects

[keV ν white paper, JCAP 01 (2017) 025]

$m_{\rm sn} \simeq \mathcal{O}(\mathrm{keV}) \xrightarrow{\qquad\qquad}$ non-relativistic at CMB decoupling

indistinguishable from Cold Dark Matter at the CMB level

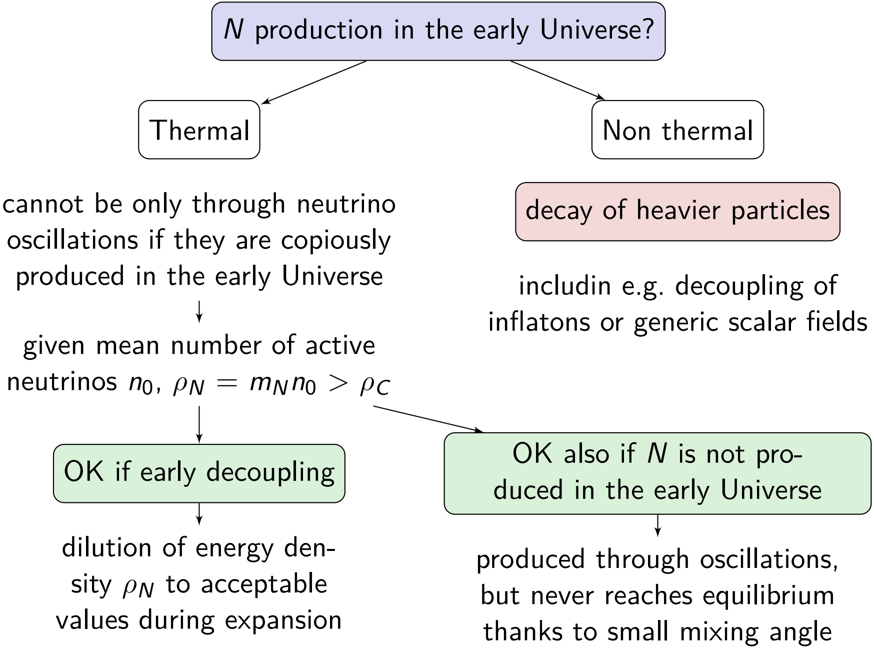
but its free-streaming affects small scales! → Warm Dark Matter (WDM)



N-body simulations to compute non-linear evolution

Production in the early Universe

[keV ν white paper, JCAP 01 (2017) 025]



N production in the early Universe?

Thermal

Non thermal

cannot be only through neutrino oscillations if they are copiously produced in the early Universe

↓

given mean number of active neutrinos n_0, $\rho_N = m_N n_0 > \rho_C$

↓

OK if early decoupling

↓

dilution of energy density ρ_N to acceptable values during expansion

decay of heavier particles

includin e.g. decoupling of inflatons or generic scalar fields

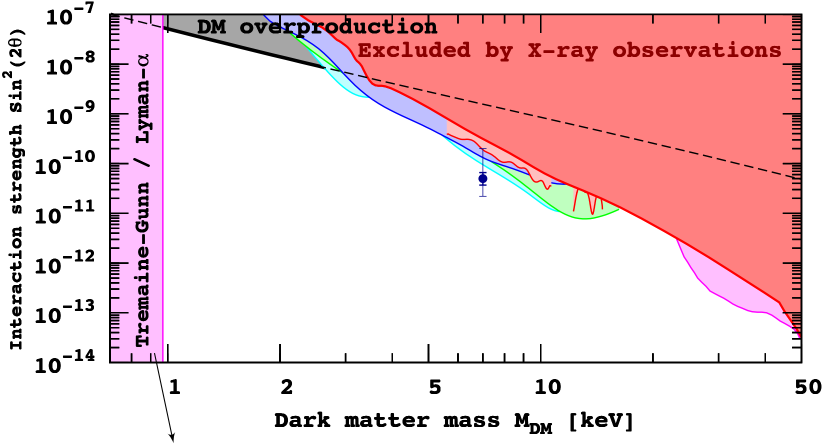
OK also if N is not produced in the early Universe

↓

produced through oscillations, but never reaches equilibrium thanks to small mixing angle

Constraints - I

[keV ν white paper, JCAP 01 (2017) 025]

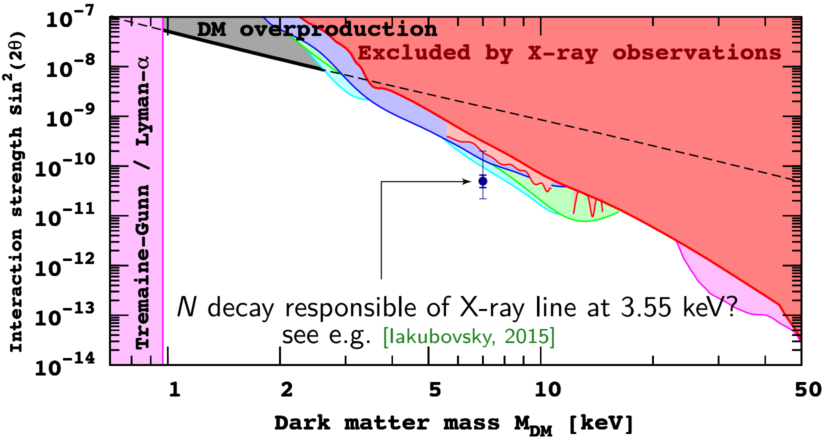


[Tremaine-Gunn 1979]

phase space distribution
in galaxy cannot exceed
degenerate Fermi gas

Constraints - I

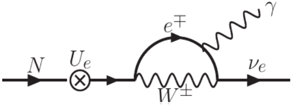
[keV ν white paper, JCAP 01 (2017) 025]



N decay responsible of X-ray line at 3.55 keV?
see e.g. [Iakubovsky, 2015]

radiative decay $N \to \nu + \gamma$

with $E_\gamma = E_\nu = m_{\rm sn}/2 \longrightarrow$ X-rays

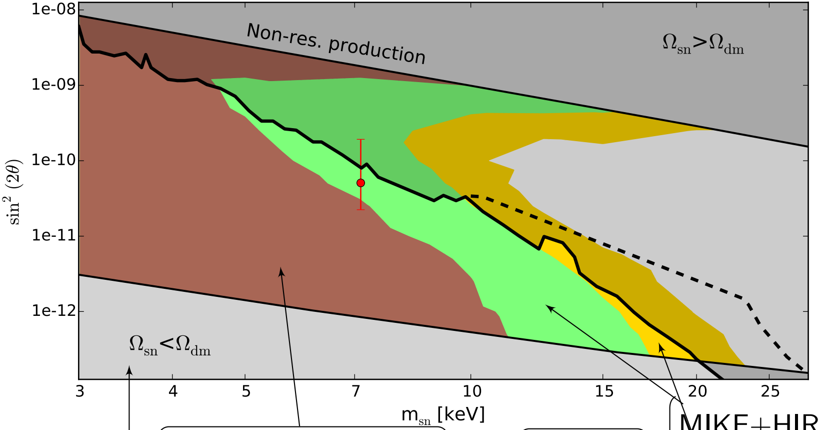


$$\Gamma_{N\to\gamma\nu} \simeq 1.38 \times 10^{-22} \sin^2 2\theta \left(\frac{m_{\rm sn}}{\rm keV}\right)^5 s^{-1}$$

Constraints - II

[Schneider, JCAP 04 (2016) 059]

assuming resonant production = in presence of large lepton asymmetry



MW satellites galaxies

N cannot be all the DM

Lyman-α

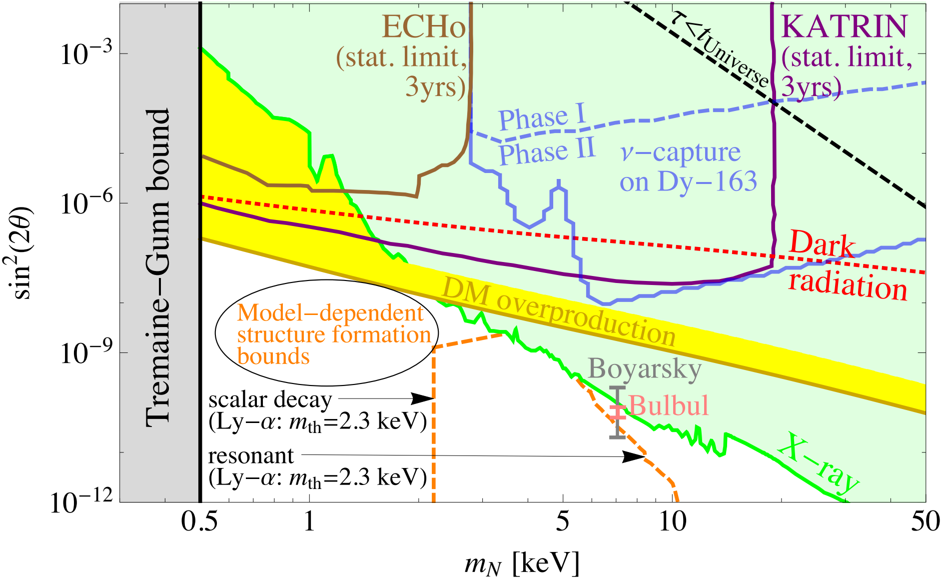
MIKE+HIRES

BOSS

from power spectrum measurements obtained through Lyman-α observations

Constraints - III

[keV ν white paper, JCAP 01 (2017) 025]



Astrophysics bounds stronger than those at terrestrial experiments!

Conclusions

- Universe evolution explained well by ΛCDM model
    - cosmological constraints on standard particles (neutrinos) ✓
    - tensions between cosmological and local measurements (H_0, σ_8) ✗
        - unaccounted systematics or new physics ?
- light ($m_s \simeq 1$ eV) sterile neutrino (LSν) ?
    - mixing $\longrightarrow$ LSν thermalized in the early Universe
    - cosmological bounds disfavor a thermalized, $m_s \simeq 1$ eV neutrino ✗
    - if $\Delta N_{\rm eff} < 1$, the LSν is allowed ✓
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    - detectable by PTOLEMY ? (depends on $\Delta N_{\rm eff}$)
    - new hidden sterile neutrino-pseudoscalar (ϕ) interaction ?
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        - $\Delta N_{\rm eff} \lesssim 1$ allowed by matter effects induced by ϕ ✓
        - LSν can reduce H_0 and σ_8 tensions ✓?
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    - cannot be thermal production
    - effects at small scales (free-streaming!)
    - bounds from Ly-α, satellite galaxies, X-ray surveys, ...

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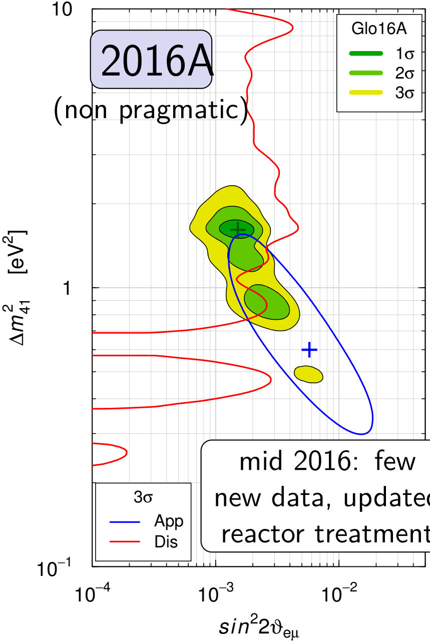
Thanks for the attention!

6 Sterile neutrino

2017 update of global 3+1 fit

[SG et al., JHEP 06 (2017) 135]



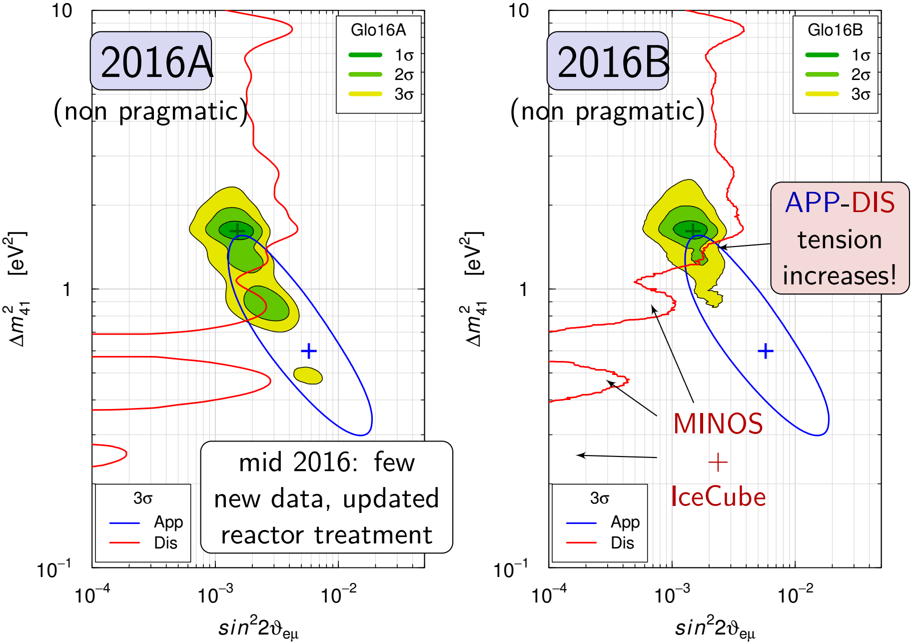
2016A

(non pragmatic)

mid 2016: few new data, updated reactor treatment

2017 update of global 3+1 fit

[SG et al., JHEP 06 (2017) 135]



2016A

(non pragmatic)

mid 2016: few new data, updated reactor treatment

2016B

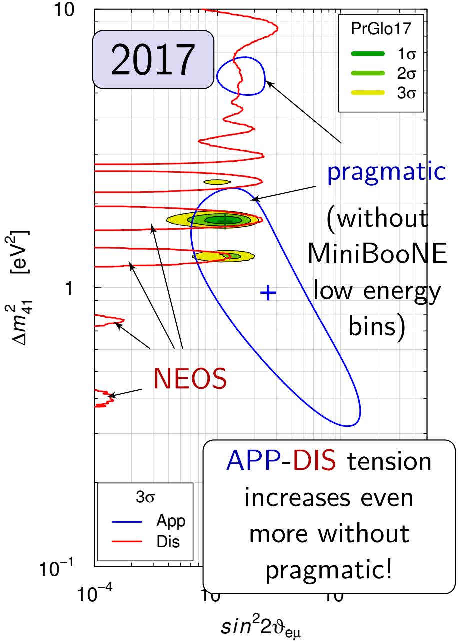
(non pragmatic)

APP-DIS tension increases!

MINOS + IceCube

2017 update of global 3+1 fit

[SG et al., JHEP 06 (2017) 135]

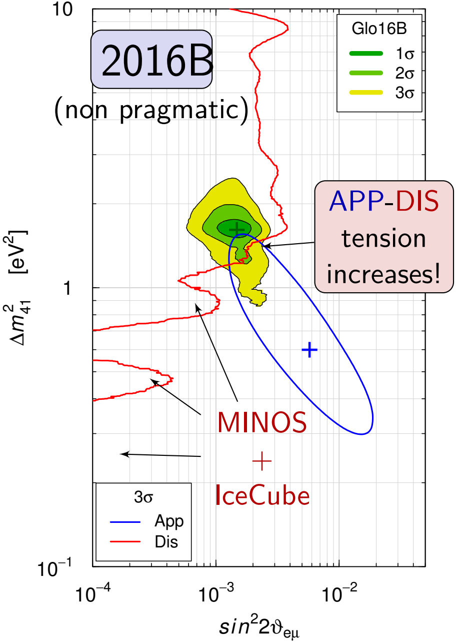


pragmatic

(without MiniBooNE low energy bins)

NEOS

APP-DIS tension increases even more without pragmatic!



(non pragmatic)

APP-DIS tension increases!

MINOS + IceCube