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Dark Matter Sterile Neutrino from Scalar Decay

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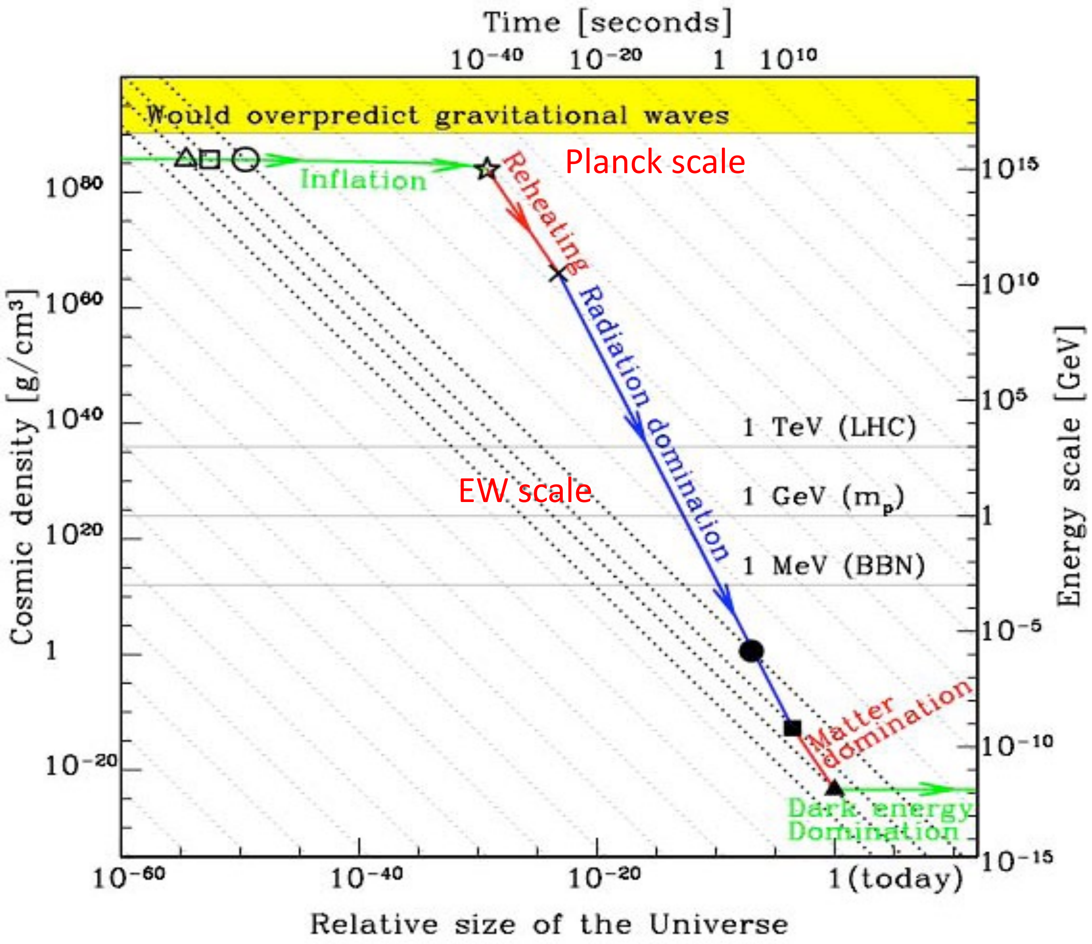
- Introduction
- Particle Physics portal to Cosmology
- Higgs couplings to hidden sector
- keV DM sterile neutrino production
- Cosmological constraints
- Conclusions

L.A. Popa, Universe **2021**, 7, 309
L.A. Popa, arXiv:2110.09392[hep-ph], **2021**

Particle Physics portal to Cosmology



A. Alberecht et al. (2006)

unitarity bound

$\Lambda_U \sim 10^{13}$GeV

$H_* < 2.5 \times 10^{-5} M_{pl}$ (95%CL)

vacuum stability bound

$\Lambda_I \sim 10^{11}$ GeV

Some yet unknown particles/interactions are required to explain:

- neutrino masses and oscillations;
- matter-antimatter asymmetry;
- Dark Matter (DM) nature;
- Cosmological inflation;
- Dark Energy (DE) nature;

  ⋮

Issue: energy scale separation between hidden and visible sectors

Standard Model of Cosmology

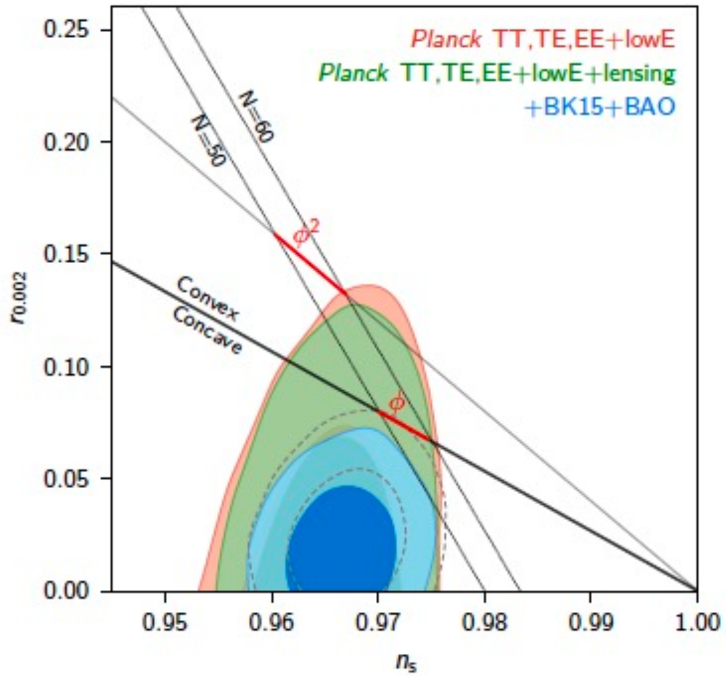
ΛCDM: six free parameters + Inflation + GR

All neededed to describe the present Universe

Parameter	Plik best fit
$\Omega_b h^2$	0.022383
$\Omega_c h^2$	0.12011
$100\theta_{MC}$	1.040909
τ	0.0543
$\ln(10^{10} A_s)$	3.0448
n_s	0.96605

$$H_0 = (67.66 \pm 0.42)\ \mathrm{km\ s^{-1} Mpc^{-1}}, \quad \Omega_m = 0.3111 \pm 0.0056, \quad \Big\}\ \text{68 %, TT,TE,EE +lowE+lensing +BAO.}$$

$$\sum m_\nu < 0.12\ \mathrm{eV} \quad \text{(95 %, } \textit{Planck} \text{ TT,TE,EE+lowE +lensing+BAO).}$$



$$r_{0.002} < 0.056 \quad \text{(95 % CL, } \textit{Planck} \text{ TT,TE,EE +lowE+lensing+BK15)}.$$

$$V_*^{1/4} = \left(\frac{3\pi^2 A_s^*}{2} r_*\right)^{1/4} M_{pl} < 1.6 \times 10^{16}\,\mathrm{GeV} \quad (95\%\mathrm{CL})\,.$$

Planck Collaboration A &A (2020)

Higgs portal interactions to Cosmology

- m_h = 125.10 $\pm 0.14\ GeV$
- m_{top}= 172.6 $\pm$ 1.4 GeV
- No unambiguous signal of NP has been found

SM does not preclude Higgs from having interactions with non SM fields

$\mathcal{O}_2 = H^{\dagger}H$ Lorentz and gauge invariant

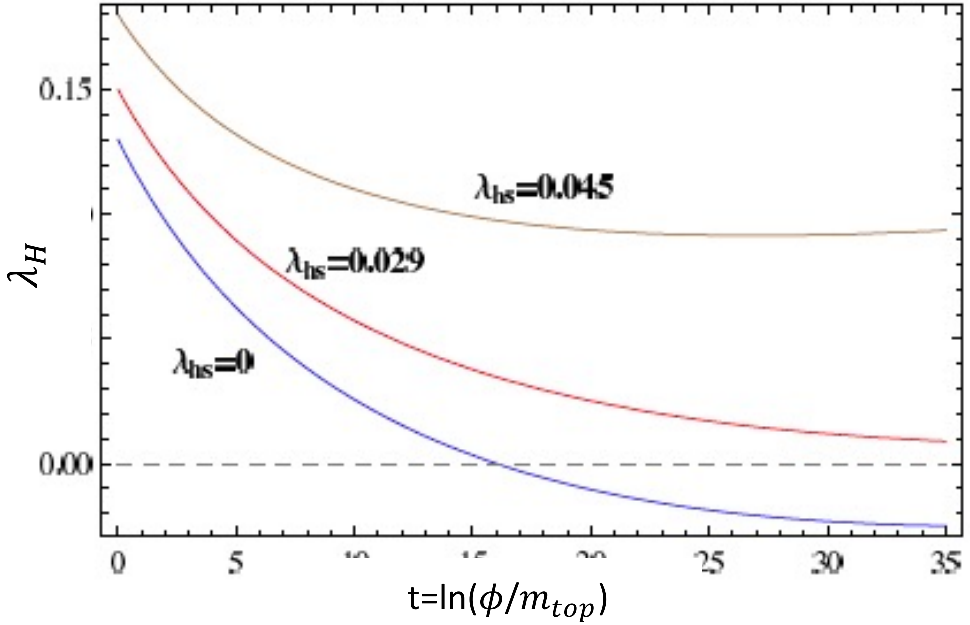
$\downarrow$

$H^{\dagger}H|\phi|^2$

$$V \supset \lambda_{\Phi H}|\Phi|^2 H^{\dagger}H$$

$$\lambda_H = \left[1 - \left(1 - \frac{m_\phi^2}{m_h^2}\right)\sin^2\alpha\right]\lambda_H^{SM}$$

$$m_H = \sqrt{2\lambda_H^{SM}}\ v \qquad v \equiv (\sqrt{2}G_F)^{1/2} = 246.22\ \text{GeV}$$



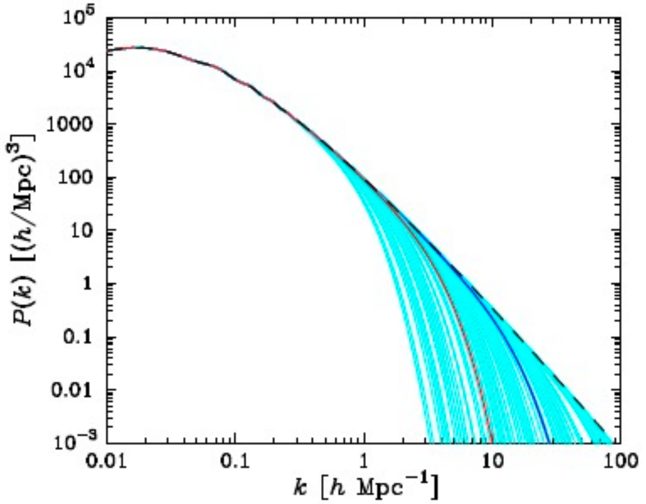
The Higgs plays a special role in probing dark sector by the coupling to hidden scalar states with no SM quantum numbers, preventing the vacuum instability.

keV sterile neutrino from the decay of a singlet scalar field produced via Higgs portal

Motivation:

keV sterile neutrino can simultaneously explain:
- active neutrino oscillations;
- DM properties;
- provide correct DM relic density for structure formation
-matter–antimatter asymmetry of the universe;

The observed ~3.5 keV X-ray line $\rightarrow m_{\nu s} \sim 7.2\ keV$



$$\mathcal{L} \supset -\frac{y_t}{2} \mathrm{S}\, \bar{N} \mathrm{N} \qquad m_N = y_t < \mathrm{S} >$$

$$V = \frac{1}{2} m_S^2\, S^2 + \frac{\lambda_S}{4} S^4 + 2\lambda_H\, (H^\dagger H)\, S^2$$

$$C^S = C_{HH \leftrightarrow SS} + C_{H \rightarrow SS} - C_{S \rightarrow NN}$$

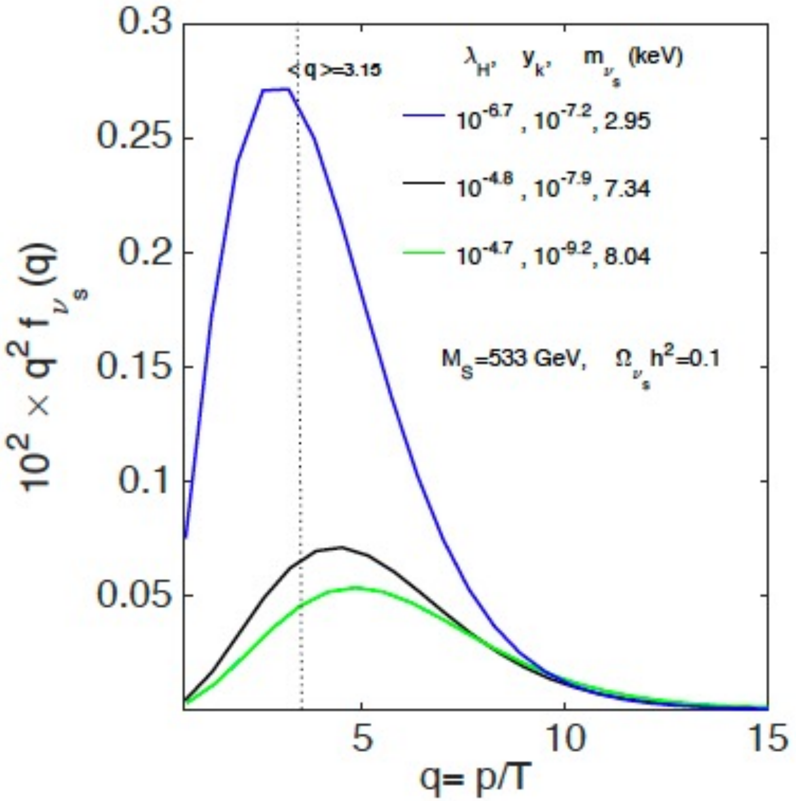
$$C^N = C_{S \rightarrow NN}$$

A. Merle A &A (2018)

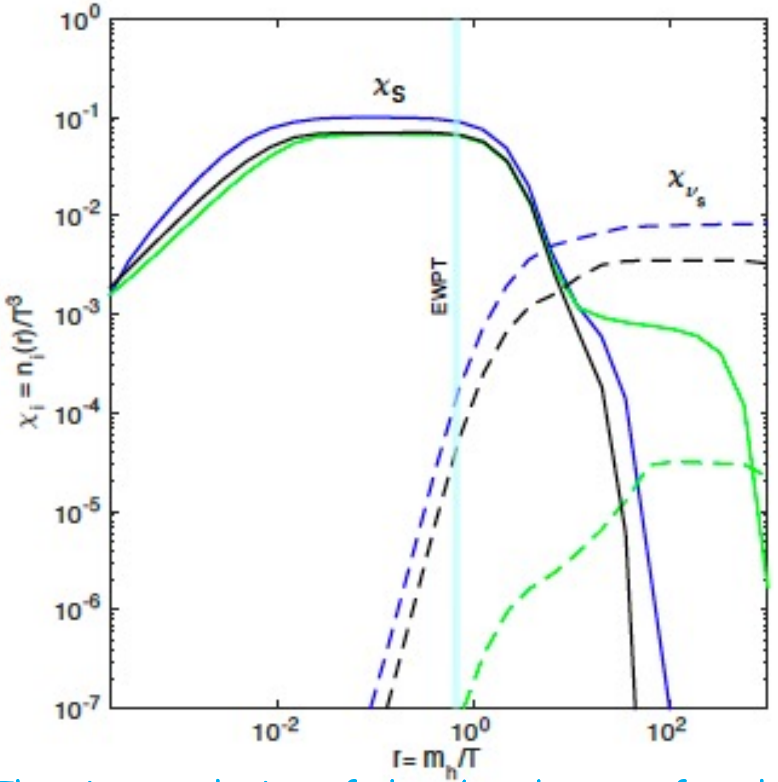
$$\begin{cases} \dfrac{\partial f_i}{\partial r}(\xi, r) = \dfrac{1}{r H(r)} \left(1 - \dfrac{r}{3} \dfrac{\partial}{\partial r} \ln[g_s(r)]\right) \mathcal{C}^i[f_i, f_{j \neq i}], \\ \dfrac{dT}{dt} = -\mathcal{H} T \left(\dfrac{T g_s'(T)}{3 g_s(T)} + 1\right)^{-1} \end{cases}$$

$$n_{\nu_s}(r) = \frac{N}{2\pi^2}\frac{g_s(T)}{g_s(T_0)}\left(\frac{m_0}{r}\right)^3 \int_0^{\xi} \mathrm{d}\xi\, \xi^2 f_{\nu_s}(\xi, r),$$

$$\Omega_{\nu_s} h^2 = \frac{s_0}{s(r)} \frac{m_{\nu_s} n_{\nu_s}(r)}{\rho_c / h^2},$$



The dependence of the sterile neutrino phase-space distributions on the co-moving momentum



The time evolution of the abundances of scalar and sterile neutrino

Cosmological Analysis

$$P_{\Lambda CDM} = \left\{\Omega_b h^2, \Omega_c h^2, \theta_s, \tau, \log(10^{10} A_s), n_s, \sum m_\nu, N_{eff}\right\},$$

$$P_{SDP} = \{m_{\nu_s}, M_S, y_k, \lambda_H\}$$

$$f_{\nu s} = \frac{\Omega_{\nu s}}{\Omega_c}$$

$$\Omega_m = \Omega_c + \Omega_b + \Omega_\nu + \Omega_{\nu s}$$

MCMC Technique

Table 2. Priors and constraints on the additional parameters for SDP models. All priors are uniform in the listed intervals.

SDP Parameter	Prior
m_{ν_s}(keV)	[2, 30]
y_k	$[10^{-10}, 10^{-8}]$
λ_H	$[10^{-8}, 10^{-4}]$
M_S(GeV)	[10, 1000]
$\Omega_{\nu_s} h^2$	[0.001, 0.5]

Cosmological and Astrphysical Datasets breaking the degeneracy f_{WDM} - $m_{\nu s}$

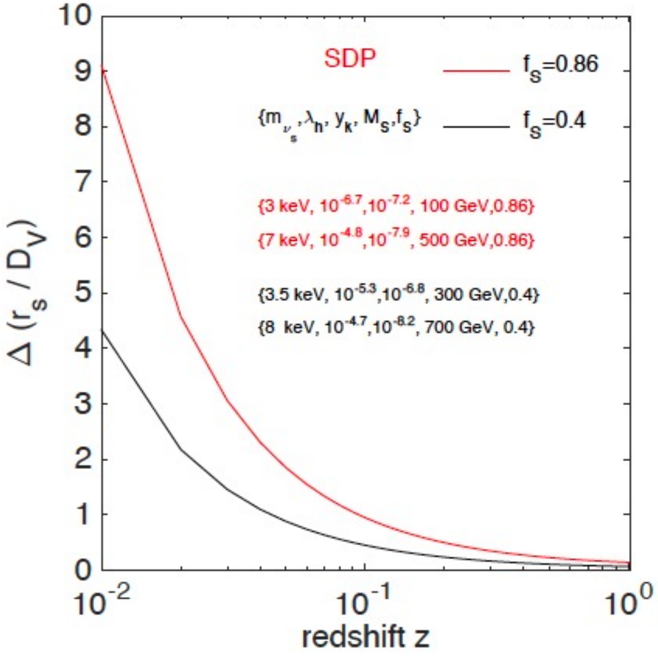
- Planck CMB anisotropy:

TT+TE+EE $2 < \ell < 2500$ $\theta_s = \frac{r_s}{D_A}$ $\theta_d = \frac{r_d}{D_A}$ $\frac{\theta_d}{\theta_s} \sim \sqrt{H} \sim N_{eff}(T_{cmb})$

$$\frac{\theta_d}{\theta_s} \sim N_{eff}(T_{cmb})$$

- BAO measurements: BOSS, CMASS, 6dFGS

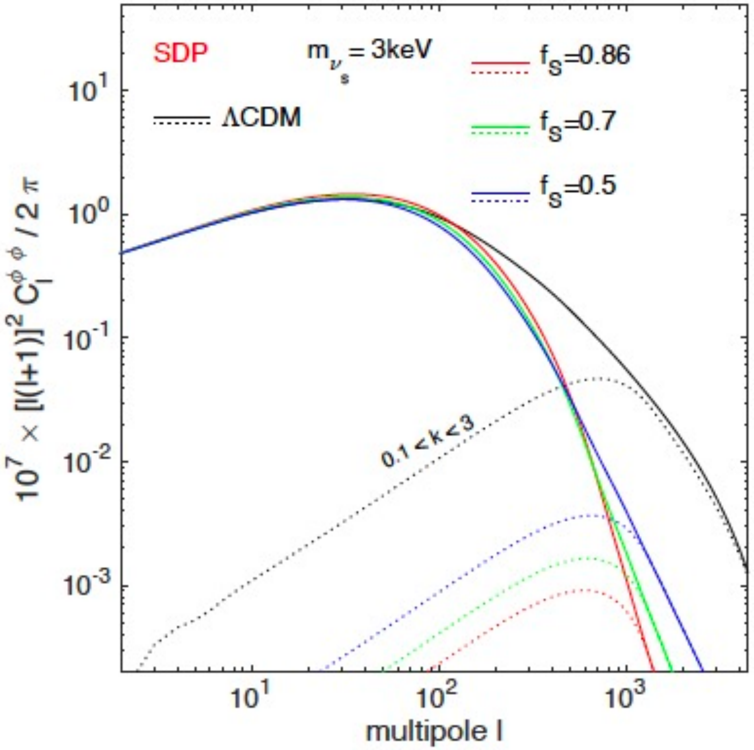
$$D_V(z) = \left[(1+z)^2 D_A^2(z) \frac{cz}{H(z)}\right]^{1/3},$$



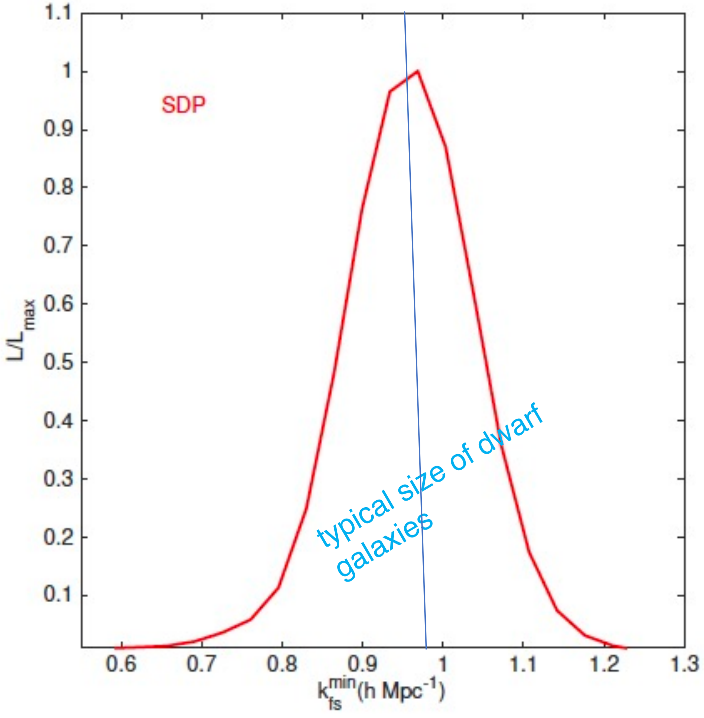
Redshift dependence of the variation of BAO characteristic parameter for models sharing the same sterile neutrino mass fraction.

- Dark Energy Survey (DES) weak lensing power spectrum of galaxies (cosmic shear)

$$C_l^{\phi\phi} = \frac{8\pi}{l^3}\int_0^{\chi^*} d\chi\, D_A(\chi)\left(\frac{D_A(\chi^*) - D_A(\chi)}{D_A(\chi^*)D_A(\chi)}\right)^2 P_\Psi(z(\chi), k = l/D_A(\chi))$$



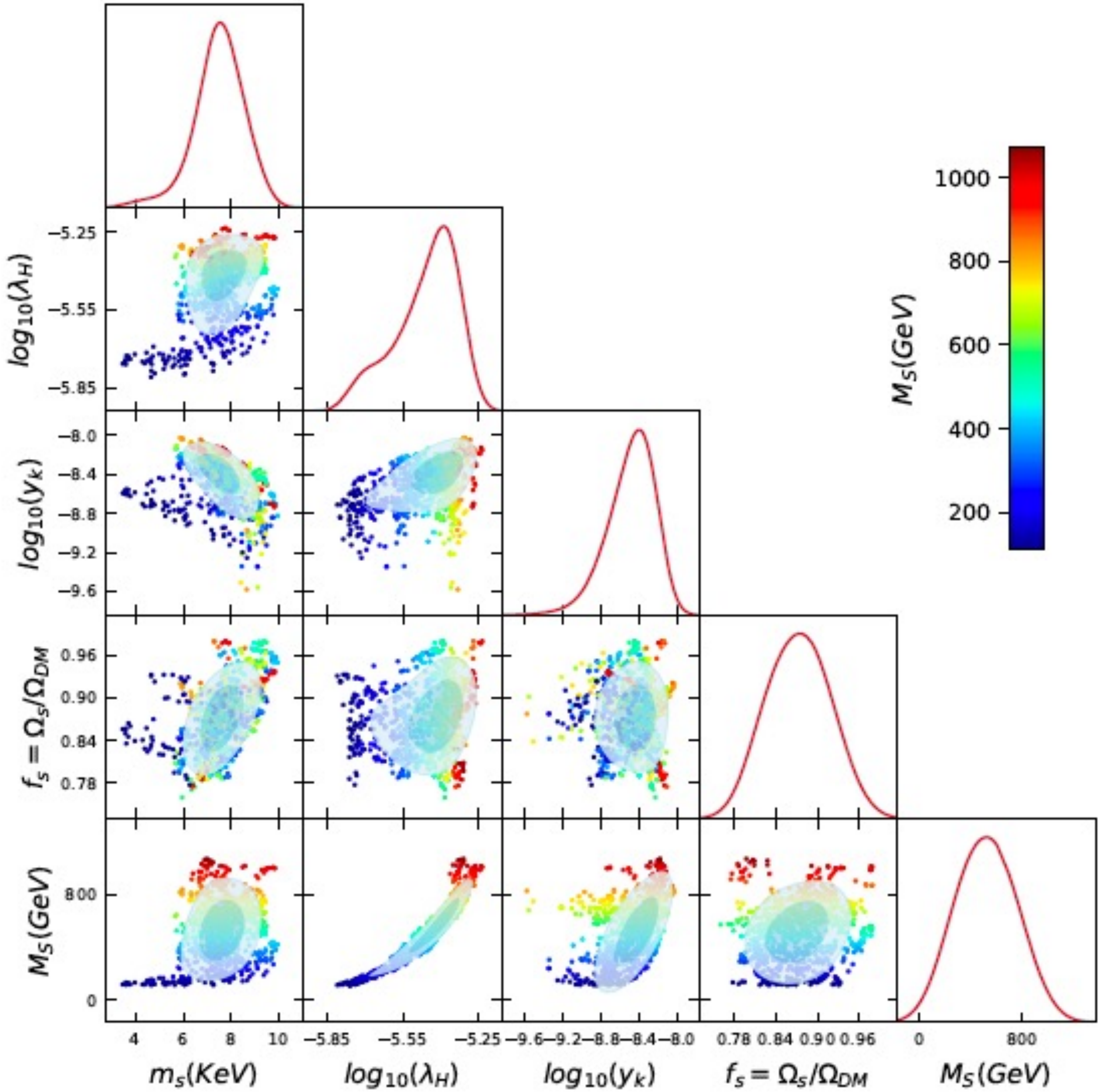
Dependence of deflection angle power spectra on sterile neutrino mass fraction in models sharing the same sterile neutrino mass.



The likelihood probability distribution of the free-streaming horizon wavenumber

Free-streaming horizon wavelength

$$\lambda^0_{fsh} = \int_{T_0}^{T_{prod}} \frac{< v(T) >}{a(T)} \frac{dt}{dT} dT$$



$$m_{\nu_s} = 7.88 \pm 0.73 \text{ keV},$$

$$M_S \simeq 533 \pm 47 \text{ GeV}$$

$$f_S = 0.86 \pm 0.07$$

errors at 95% C.L.

Conclusions

- Higgs portal couplings can solve the cosmological problems associated with the vacuum metastability and energy scale separation between the hidden (dark) and visible sectors.
- Higgs coupling to scalar field with no SM quantum numbers and non-zero VEV can be responsible for keV sterile neutrino DM production.
- The best fit values of sterile neutrino mass are in the parameter space of interest for sterile neutrino DM decay interpretation of the 3.5 keV X-ray line.
- DM sterile neutrino mass fraction is in agreement with the upper limit constraint from the X-ray non-detection and Ly-a forest measurements that rejects f_S=1 at 99 % C.L.
- The Higgs portal can be explored further via collider experiments and astrophysical observations.

We expect that the future BAO and weak lensing surveys, such EUCLID, will provide much more robust constraints on the DM sterile neutrino properties.

Wonderful Time for Astrophysics, Cosmology and Particle Physics !