Relic Sterile Neutrino Sensitivity to Early Cosmology

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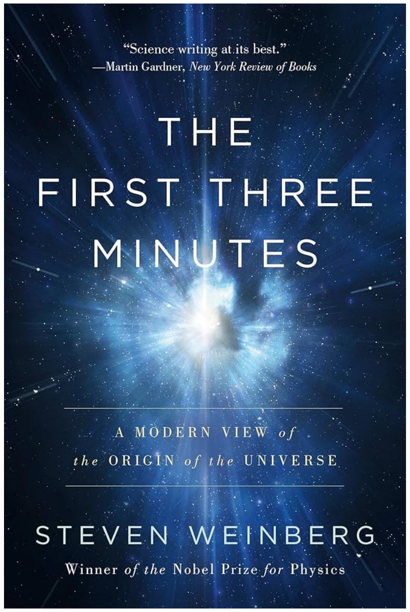
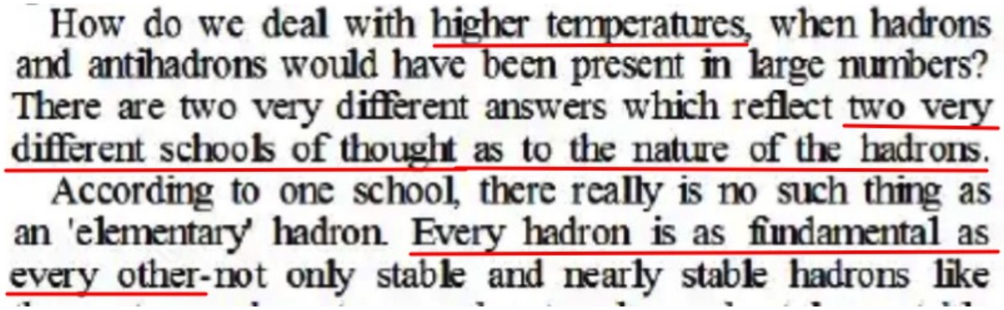
1970’s popular book

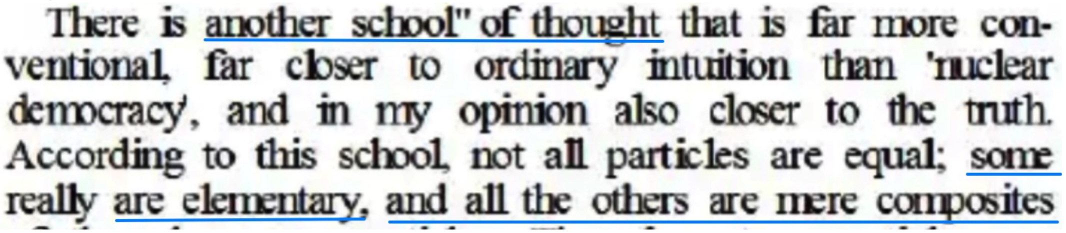




How do we deal with higher temperatures, when hadrons and antihadrons would have been present in large numbers? There are two very different answers which reflect two very different schools of thought as to the nature of the hadrons.

According to one school, there really is no such thing as an 'elementary' hadron. Every hadron is as fundamental as every other-not only stable and nearly stable hadrons like

Geoffrey Chew’s “Bootstrap” predicted a maximum temperature $T_{\rm Hagedorn} \simeq 150$ MeV at which the number of degrees of freedom became infinite



There is another school" of thought that is far more conventional, far closer to ordinary intuition than 'nuclear democracy', and in my opinion also closer to the truth. According to this school, not all particles are equal; some really are elementary, and all the others are mere composites

These are quarks- and when QCD was proven the correct theory, with finite d.o.f+ assuming radiation domination, one can follow the history of the Universe up to very high T - giving rise to the Standard Pre-BBN cosmology

But being able to compute something does not make it so...

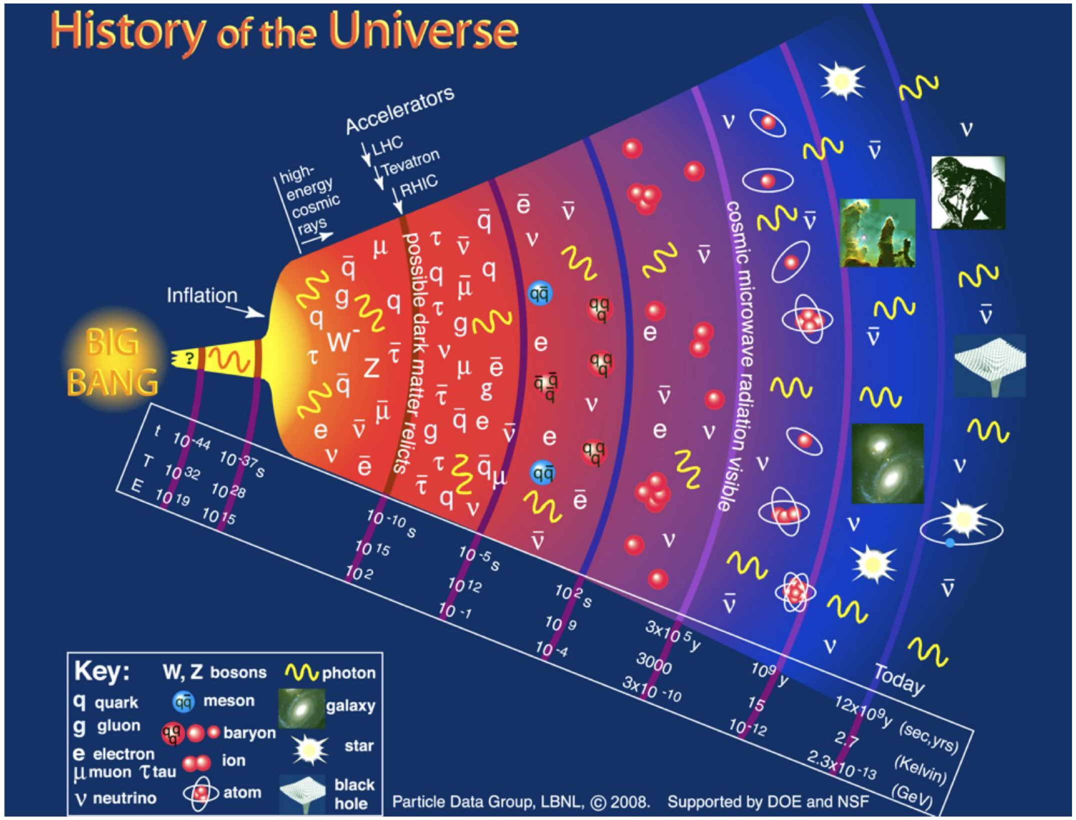
All data confirm the Big-Bang Model of a hot early Universe expanding adiabatically ($T \sim 1/a$)

Std pre-BBN cosmology shown before BBN
(Big-Bang Nucleosynthesis)
t≃3-20min T≃MeV(blue line)

Radiation domination to Matter domination
t≃66kyr T≃1 eV

CMB emitted (atoms form)
(Cosmic Microwave Background)
t≃380kyr T≃ 0.3 eV

Today (Planck + other)
t=13.798± 0.037×10^9ys



Particle Data Group, LBNL, © 2008. Supported by DOE and NSF

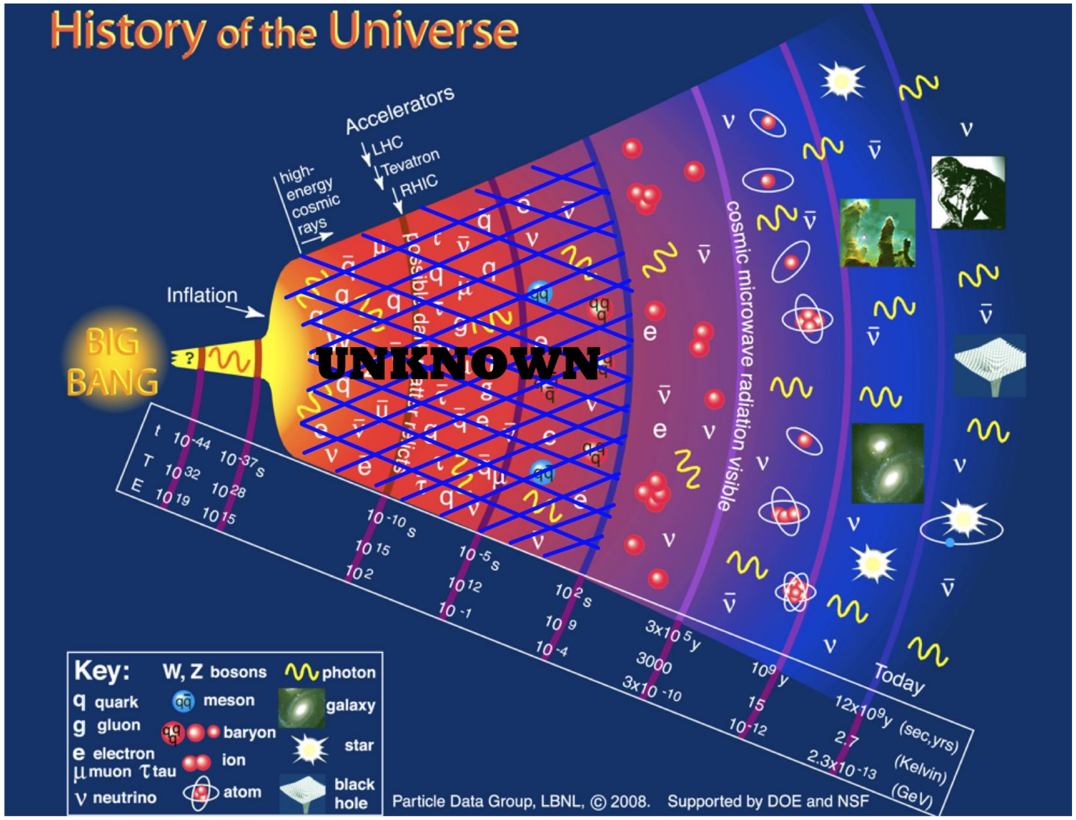
All data confirm the Big-Bang Model of a hot early Universe expanding adiabatically $(T \sim 1/a)$

Earliest data (D, ^{4}He and ^{7}Li):
BBN (Big-Bang Nucleosynthesis)
t $\simeq$ 3-20min T$\simeq$ MeV

Thus cosmology before
T $\simeq$ 5 MeV is UNKNOWN

$T_{\rm RH} \geq$ 5.96 MeV Barbieri etal 2025,
$T_{\rm RH} \geq$ 1.8 MeV Hasegawa et al 2019,
De Salas et al 2015, De Bernardis et al 2008,
Hannestad 2004, Kawasaki et al 1999 and 2000

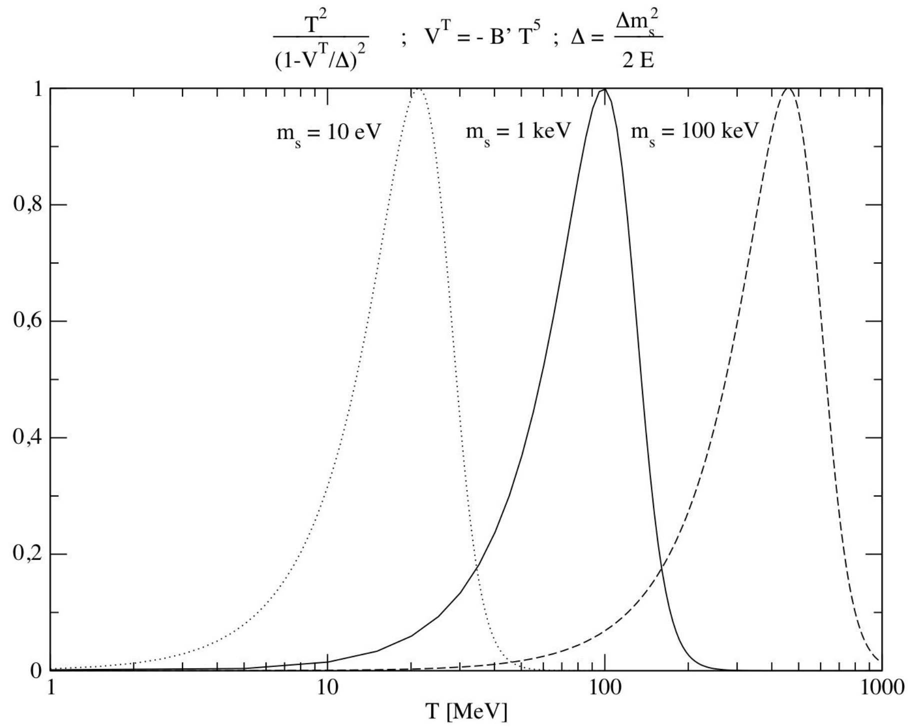
For sterile neutrinos produced in this era, **different viable cosmological assumptions imply different relic abundance and spectrum**



With standard cosmological assumptions Sterile neutrinos rate of production through non-resonant active-sterile oscillations (DW scenario) has a sharp peak at

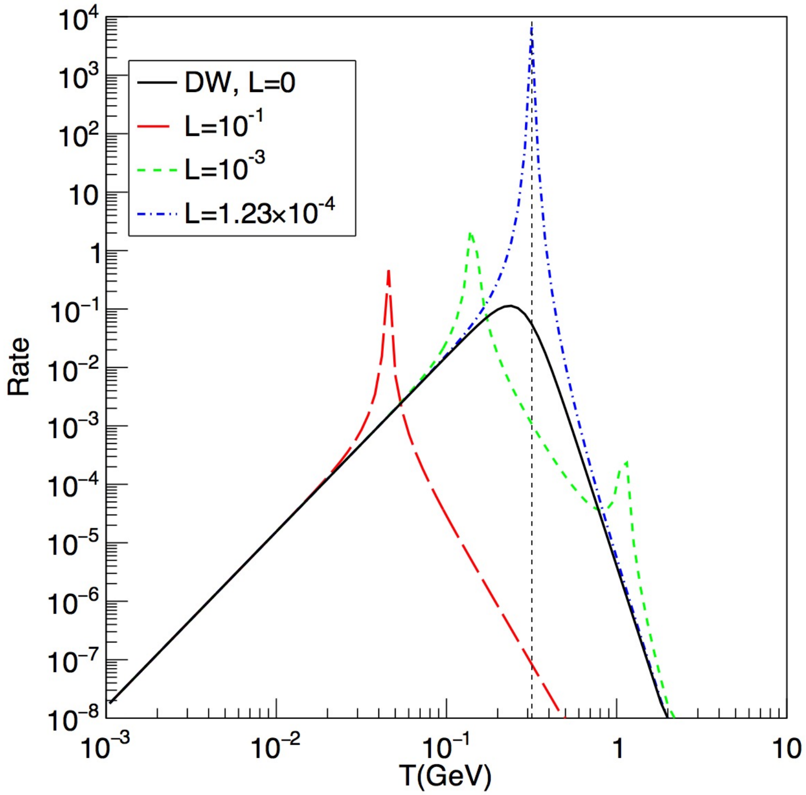
$T_{\rm max} \simeq 130\text{MeV} \left(\frac{m_s}{1\ \rm keV}\right)^{1/3} > 5$ MeV for $m_s > 0.057$ eV (Dodelson, Widrow 1994)

$\frac{1}{f_\nu}\left(\frac{df_s}{dT}\right)_E$



Also rate of resonant production (Shi-Fuller) of sterile neutrinos: e.g. m_s =1keV produced at similar temperatures

(Fig. from Philip Lu)



Assume sterile neutrinos only coupled through active-sterile mixing

Singlet right handed neutrino ν_s mixed with an active neutrino ν_a

$|\nu_a\rangle = \cos\theta\ |\nu_L\rangle + \sin\theta\ |\nu_H\rangle$

$|\nu_s\rangle = -\sin\theta\ |\nu_L\rangle + \cos\theta\ |\nu_H\rangle$

θ is the mixing angle, ν_L and ν_H are the light and heavy mass eigenstates.

The Boltzmann Equation for the phase-space density distribution f_s depends on Hubble expansion rate H (f_a is a Fermi-Dirac distribution)

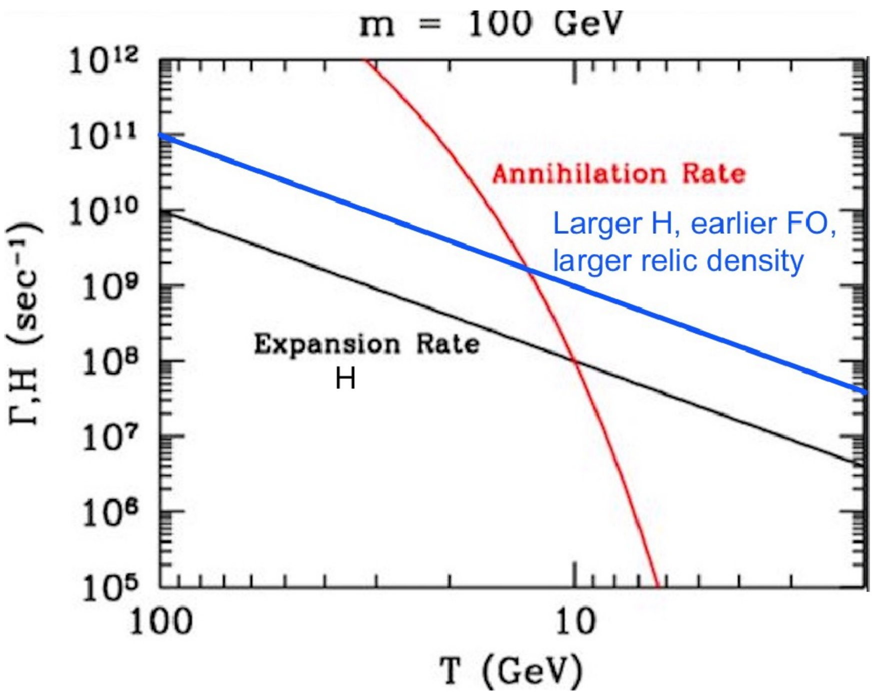
$$-\left(\frac{\partial f_s(E,T)}{\partial T}\right)_{E/T=\epsilon} \simeq \frac{\Gamma(E,T)}{HT} f_a(E,T)$$

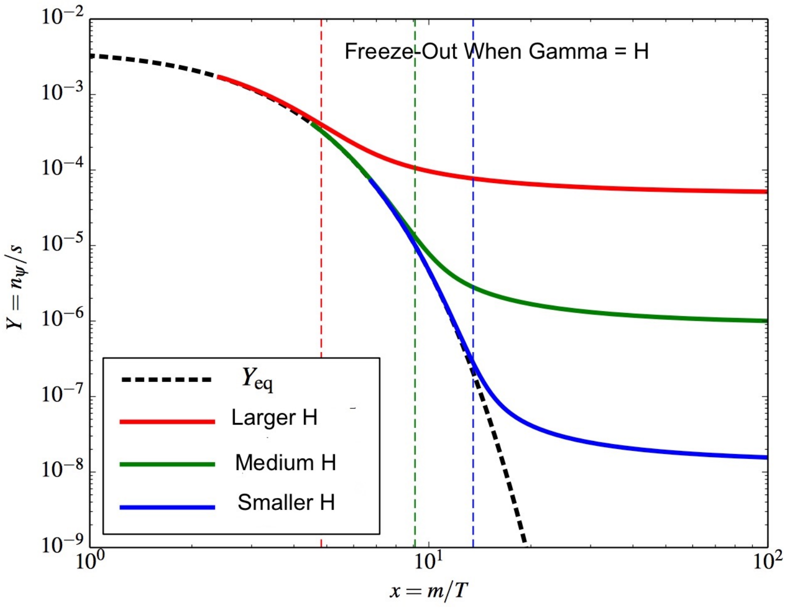
Thus a larger (smaller) H suppresses (enhances) the Freeze-In production

Here the conversion rate is $\Gamma \simeq \dfrac{1}{4}\sin^2(2\theta_{\rm medium})\Gamma_a$ and

$$\sin^2(2\theta_{\rm medium}) = \frac{\sin^2(2\theta)}{\sin^2(2\theta) + \left[\cos(2\theta) - 2\epsilon T(V_D + V_T)/m_s^2\right]^2}$$

Notice that in Freeze Out the effect of a non-standard H is the opposite!





See e.g. G.G. and P. Gondolo, PRD 74 (2006) 023510, ; G.G., P. Gondolo, A. Soldatenko and C. E. Yaguna, PRD 74 (2006) 083514 and PRD 76 (2007) 015010; G.G. Ji-Haeng Huh and Rehagen JCAP 08 (2013) 003

Usual cosmological assumptions for $T > 5$ MeV

- $T_{\rm RH}$, the highest temperature of the radiation dominated epoch of the Universe in which BBN occurs, is large.

- The Universe is radiation dominated up to $T_{\rm RH}$, and

$$H_{\rm Std} = \sqrt{\frac{8\pi G\rho(T)}{3}} = \left(\frac{T^2}{M_{\rm Pl}}\right)\sqrt{\frac{8\pi^3 g_*(T)}{90}}; \qquad \rho(T) = \left(\frac{\pi^2}{30}\right) g_*(T)T^4$$

- The particle content is that of the Standard Model, besides possibly some few other particles specified

- The entropy of matter and radiation is conserved, during/after the production of sterile neutrinos (thus scale factor $a \sim 1/T$)

Some viable cosmological models differ greatly from this we call “Standard” pre-BBN cosmology

Other cosmological assumptions for $T > 5$ MeV

In many well motivated models, the cosmological history could be different than typically assumed, e.g.based on

moduli decay E.g. Moroi & Randall-1999, Kitano, Murayama & Ratz-2008, Kawasaki, Moroi & Yanagida-1996

quintessence E.g. Salati-2003, Profumo & Ullio-2003, Pallia-2005

or extra dimensions.... E.g. Randall & Sundrum 1999, Durrer 2005

But I am not advocating for any pre-BBN cosmology model! My interest is to consider them as a source of uncertainty of cosmological/astrophysical limits on pre-BBN relics- and also see how these relic could point to any of them.

Non-std scenarios are more complicated and usually not complete (e.g. baryon number generation). But if a experimental result would hint at one of them, they could be completed.

Much work has been done on non-standard cosmologies; what follows is an idiosyncratic choice.

Some “non-Standard” pre-BBN cosmologies

- **Models that only change the pre-BBN Hubble parameter H**

  These models alter H(T) without an extra entropy production in matter and radiation, so that for $T > T_{\rm tr}$: $H = \eta \left(\frac{T}{T_{\rm tr}}\right)^{\beta} H_{\rm Std}$ with η and β real parameters (and $\eta > 0$)

- **Low reheating temperature (LRT) models**

  Entropy in matter and radiation is produced: not only H(T) is different, but also the dependence of the temperature T on the scale factor a is different.

  Simple example: a scalar field ϕ oscillating around its true minimum while decaying, that dominates the energy density of the Universe. The Universe becomes radiation dominated with temperature $T_{\rm RH}$ only after ϕ decays. Before, the radiation bath is a small component, thus the amount of ν_s produced at $T > T_{\rm RH}$ is also small, and neglecting it the relic density can be computed analytically.

Low Reheating Temperature

Neglect production before radiation domination. Non-resonant production suppressed if $T_{\rm RH} << T_{\rm max}$. Analytic result Gelmini, Palomares-Ruiz, Pascoli PRL 93 (2004) 081302

$$\frac{n_{\nu_s}}{n_{\nu_\alpha}} \simeq 10 \, \sin^2(2\theta) \left(\frac{T_{RH}}{5 \ {\rm MeV}}\right)^3$$

(confirmed numerically by C. Yaguna, JHEP 06 (2007) 002), thus $\Omega_s h^2 = (m_s n_{\nu_s}/\rho_c) h^2$ is

$$\Omega_{\nu_s} h^2 \simeq 0.1 \ \left(\frac{\sin^2(2\theta)}{10^{-3}}\right) \left(\frac{m_s}{1 \ {\rm keV}}\right) \left(\frac{T_{\rm RH}}{5 \ {\rm MeV}}\right)^3$$

Standard: $\left[\Omega_{\nu_s} h^2 \approx 0.1 \left(\frac{\sin^2(2\theta)}{3 \times 10^{-7}}\right) \left(\frac{m_s}{1 \, {\rm keV}}\right)^2\right]$

Examples of models that only change the pre-BBN H

- Extra contributions to the energy density of the Universe increase H:

  -Brans-Dicke-Jordan cosmological model Kamionkowski & Turner-1990...

  -models with anisotropic expansion Barrow-1982; Kamionkowski & Turner-1990; Profumo, Ullio-2003...,

  - scalar-tensor models Santiago, Kalligas & Wagoner-1998, Damour & Pichon-1998, Catena, Fornengo, Masiero, Pietroni & Rosati; 2004; Catena, Fornengo, Masiero, Pietroni & Schelke-2007, Meehan & Whittingham-2015...

  -kination models Salati-2002, Profumo & Ullio-2003, Bettoni & Rubio-2021...

  -many others e.g. Barenboim & Lykken-2006 and 2007; Arbey & Mahmoudi-2008, D'Eramo, Fernandez & Profumo-2017 and 2018, Mahanta & Borah-2019, Trojanowski, Brax & van de Bruck-2020, Chan, Chen, Xu & Han-2021, Duran, Morrison & Profumo-2021, Allahverdi & Osinski-2022...

- H may be decreased in some scalar-tensor models Catena, Fornengo, Masiero, Pietroni, & Schelke-2007

H(T) for several pre-BBN cosmological models

"LRT": Low T_{RH}

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"ST1": scalar tensor

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"K": kination

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"Std": standard radiation-dominated

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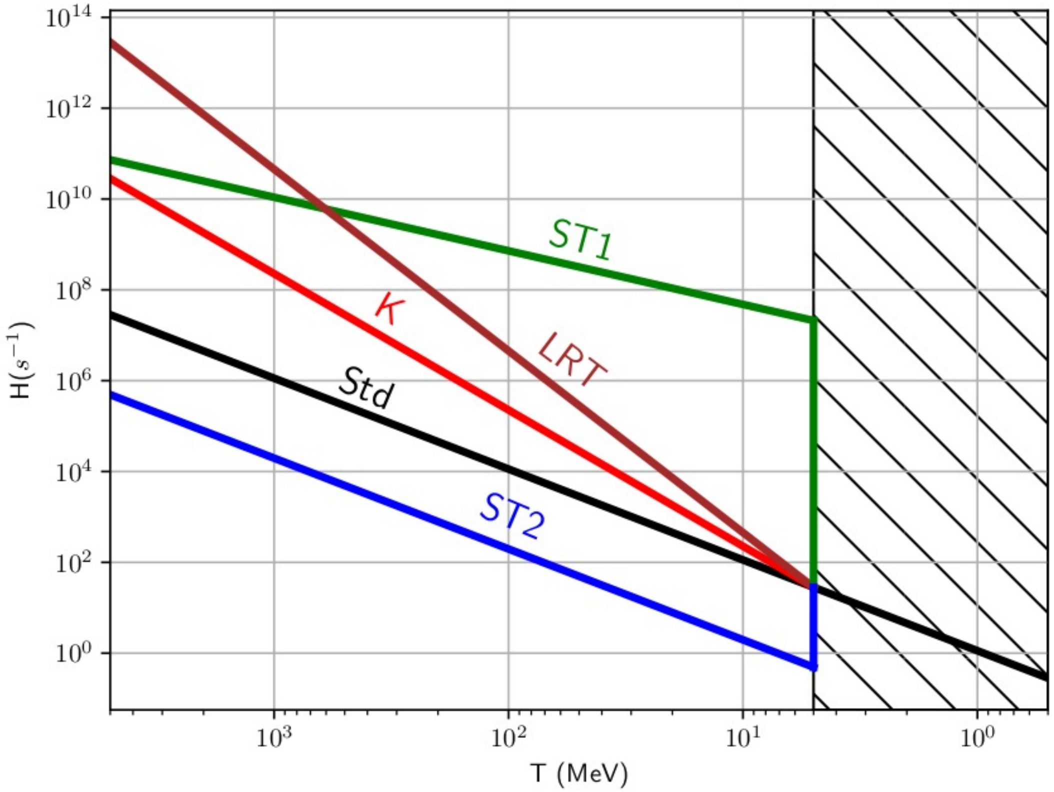
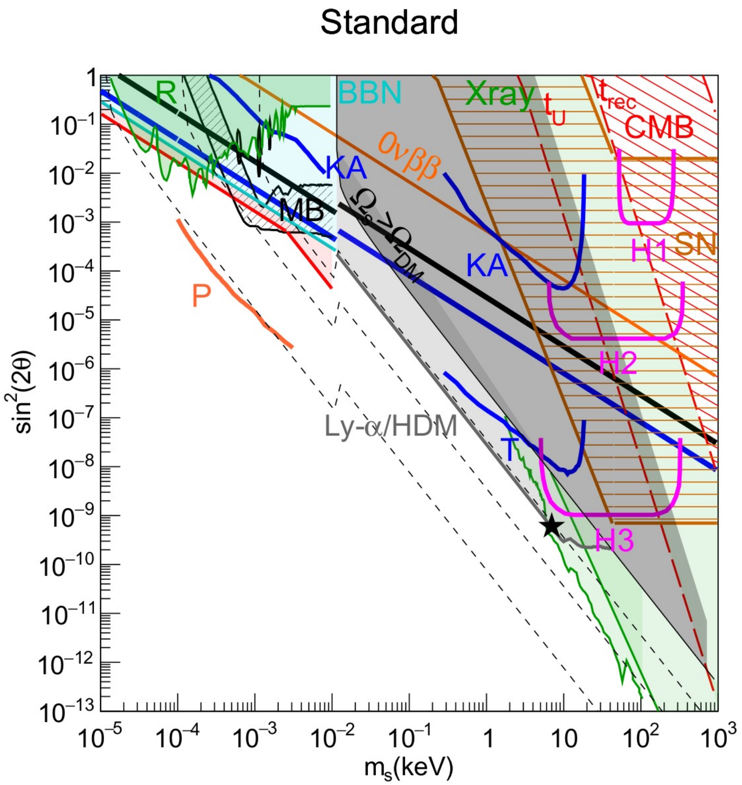
"ST2" : scalar tensor



Limits on ν_s produced via non-resonant active-sterile flavor oscillations with ν_e (all analytic calculations)

G.B. Gelmini, Philip Lu and Volodymyr Takhistov, 2006.09553, JCAP12, 047 (2019) [1909.13328], Phys. Lett. B800, 135113 (2020) [1909.04168]

- $g_\star$ =10.75 for ms $<$ 11.5 eV, and $g_\star$ =30 above
- thick blue and black lines: two estimates of thermalization
- thick red for $m_s < 10$eV the combined CMB Neff and meff
- cyan: Neff during BBN
- gray region: $\Omega_s > \Omega_{DM}$ - dashed lines: 0.1 to 10^{-3} of DM
- light gray: excluded by Ly-α - horizontally hatched brown: potential SN limits
- green: X-rays including DEBRA to $t_{\rm rec}$
- diagonally hatched red: CMB spectral distortions
- $\star$: putative 3.5keV signal - MB= LSND/MiniBooNE,
- ovals: reactor DANSS/NEOS- PTOLEMY(P) 100 g-yr reach
- green R: reactor Daya Bay, Bugey-3, PROSPECT
- KATRIN(KA), TRISTAN 3y(T) and H: HUNTER reach



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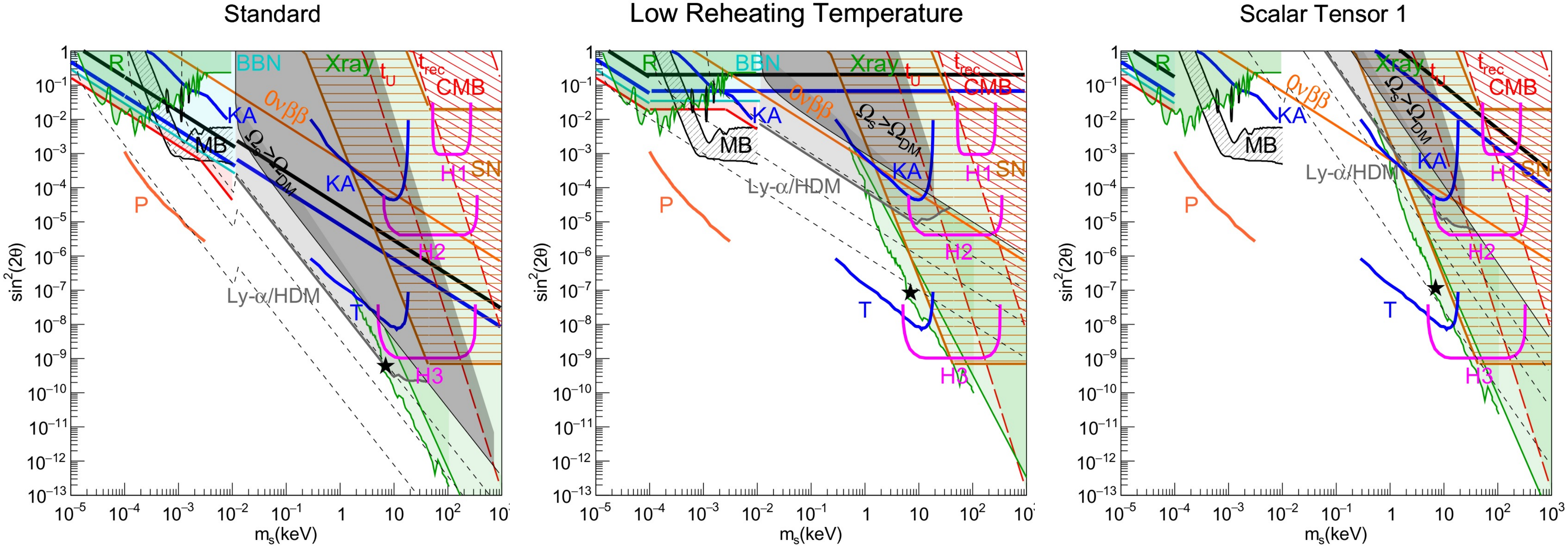


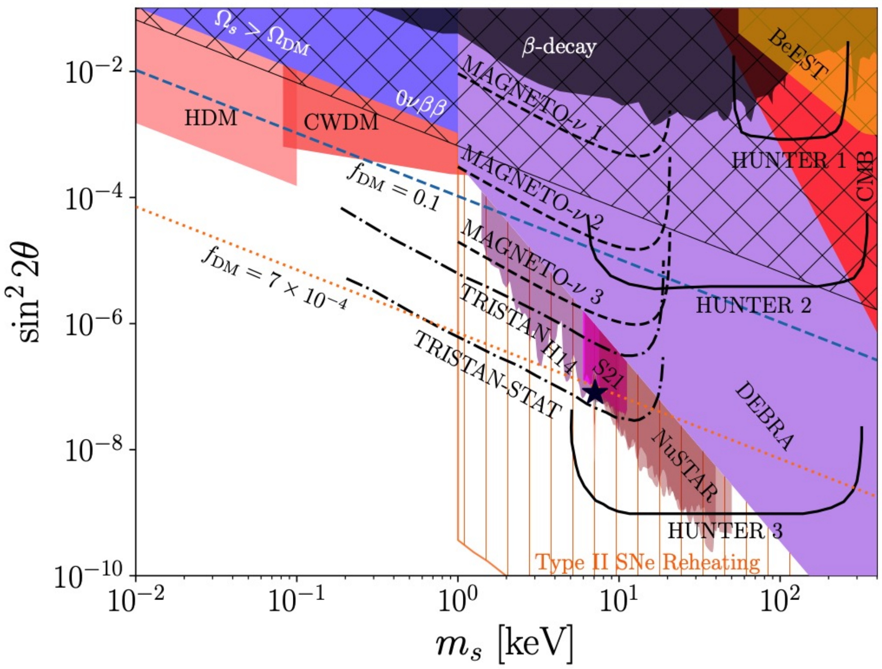
MB= LSND/MiniBooNE, ovals: reactor DANSS/NEOS, ⋆= 3.5 keV line, R= reactor Daya Bay, Bugey-3, PROSPECT BBN-$N_{\rm eff}$, CMB-$N_{\rm eff}$,$m_{\rm eff}$, KA= KATRIN, T=TRISTAN, P= PTOLEMY 100 g-yr, H1, H2, H3= HUNTER phase1 and upgrade.

In LTR and ST1: ⋆ moves to $\sin^2 2\theta = 10^{-7}$ and MB allowed by cosmology. DANSS/NEOS: allowed by cosmology only in ST1.

Spectrum also changes: $<p/T>$=3.15 (Std), 4.11(LRT), 2.89 (ST1)

Limits on ν_s produced via non-resonant active-sterile flavor oscillations with ν_e A newer data compilation for LRT of 5MeV

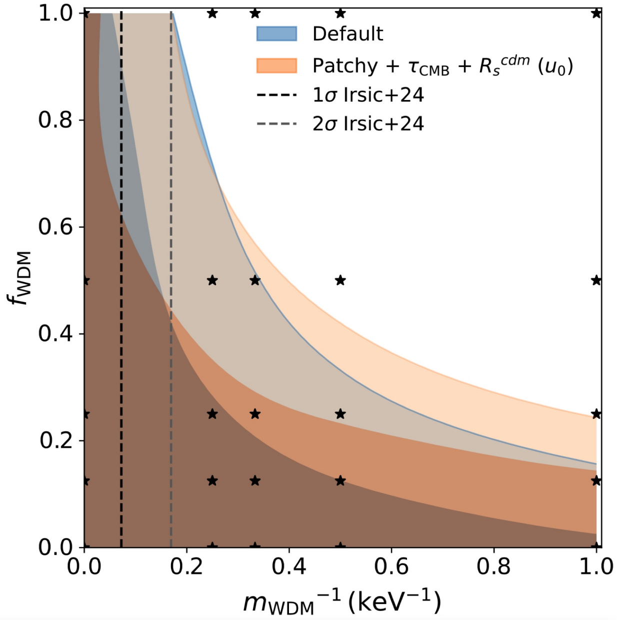
K. Abazajian and H. Garcia Escudero PRD 108 (2023) 12, 123036 [2309.11492]



Spectrum also changes: $<p/T>$=3.15 (Std), 4.11(LRT)

Relic Spectrum is Important for WDM even a subdominant WDM component in Cold+Warm DM models, $f_{\rm WDM} = \Omega_{\rm WDM}/\Omega_{\rm DM}$

High-z Lyman-α forest limits (O. Garcia-Gallego et al. PRD 112 (2025) 4, 043502 [2504.06367]) on thermal fermion can be approximately extended to ν_s using only $\langle p/T \rangle$



$$m_s \simeq 4.46\text{keV}\frac{\langle p/T \rangle}{3.15}\left[\frac{10.75}{g_*(T_{\rm prod})}\right]^{\frac{1}{3}}\left[\frac{m_{\rm therm}}{1\ \text{keV}}\right]^{\frac{4}{3}}\left[\frac{0.12}{f_{\rm WDM}\Omega_{\rm DM}h^2}\right]^{\frac{1}{3}}$$

(G. Gelmini, p. Lu and V. Takhistov JCAP 12 (2019) 047 [1909.13328]; Viel etal PD 71 (2005) 063534 [astro-ph/0501562]; Baur etal JCAP 12 (2017) 013 [1706.03118]

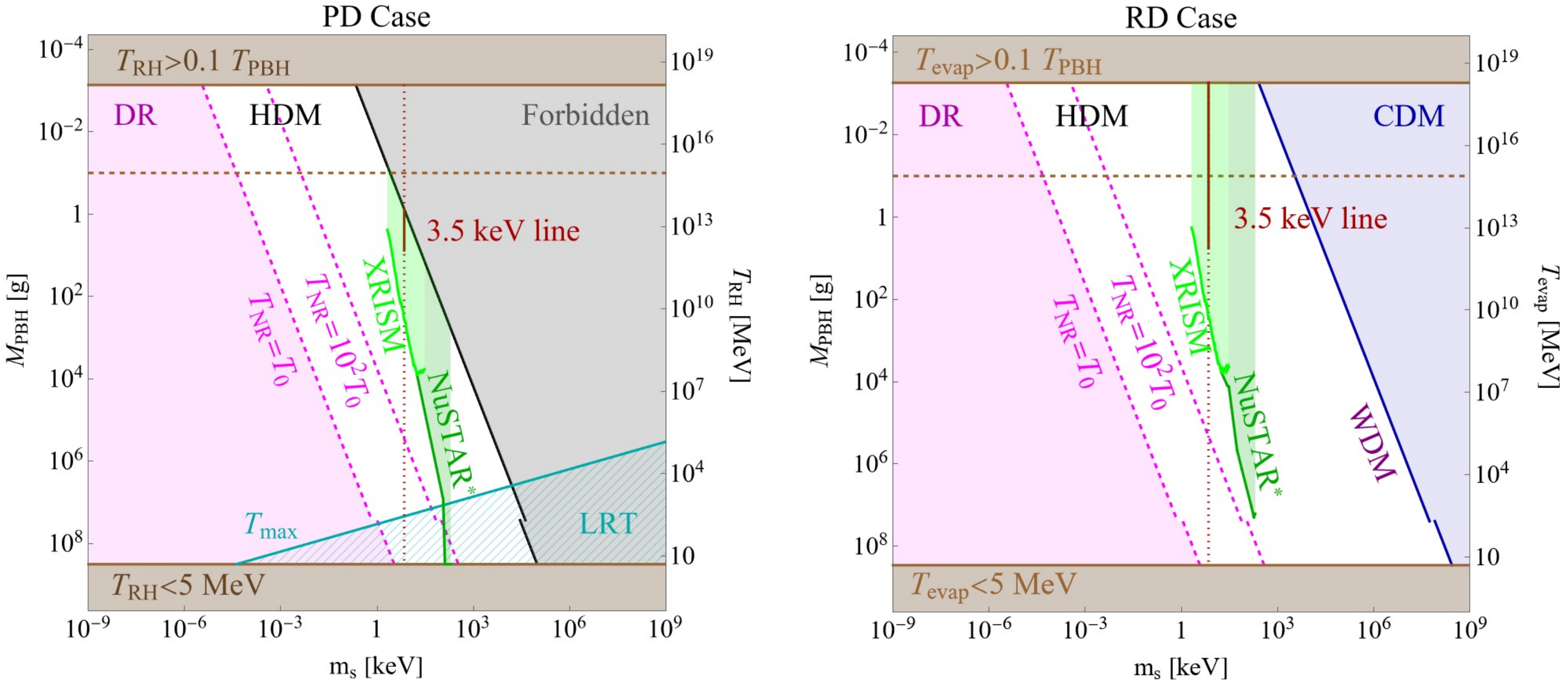
Mass limits can be very different if ν_s spectrum differs considerably from thermal e.g. in “PBH Sterile Neutrinogenesis”

Primordial Black Hole Sterile Neutrinogenesis

(Chen, Gelmini, Lu, Takhistov PLB 852, 138609, [2309.12258]; and JCAP 07, 059 [2312.12136])

Due to gravitational coupling $\sim m_s$, ν_s could be produced in evaporation of early PBH population, - independent of mixing, if Hawking Temp. $T_H = (8\pi M_{\rm PBH})^{-1} > m_s$ either if PBH MD before evaporation or not (RD)

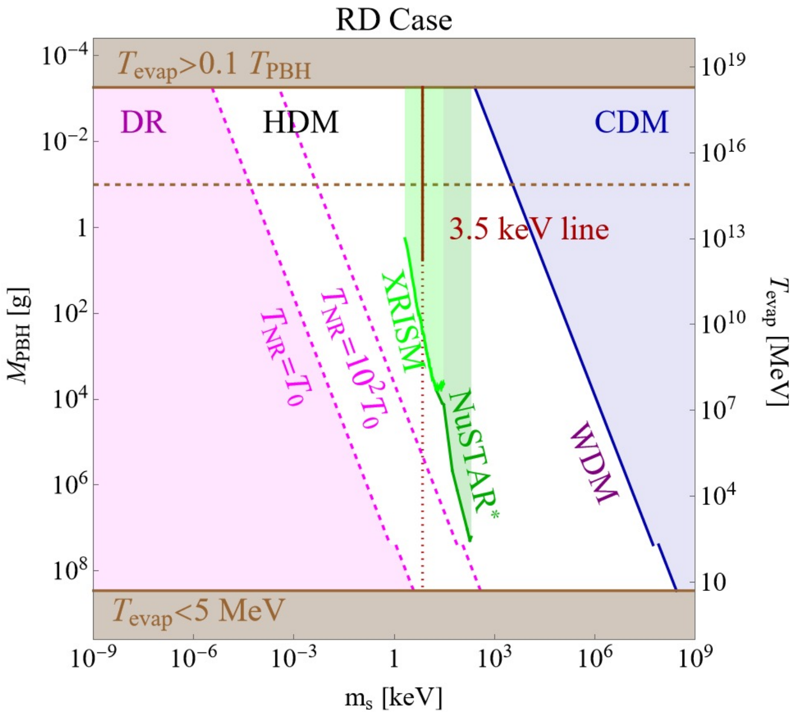
(Monochromatic PBH mass function, formation via inhomogeneity collapse at horizon crossing)



DR=Dark Radiation at present; X-rays could be observed; LRT: $T_{\rm RH} < T_{\rm max}$ of DW rate

Primordial Black Hole Sterile Neutrinogenesis

if PBH do not MD (Chen, Gelmini, Lu, Takhistov PLB 852,138609 [2309.12258]; JCAP 07(2024) 059 [2312.12136])



At ν_s production $\langle p\rangle \simeq 6T_H$ very hot

$$\frac{\langle p\rangle}{T_{\rm evap}} \simeq 1.5\times 10^7 \left(\frac{M_{\rm PBH}}{10^8{\rm g}}\right)^{1/2} \left(\frac{g_*(T_{\rm evap})}{10.75}\right)^{1/4}$$

+ impose mixing small enough so just redshift after:

ν_s can be Dark Radiation, HDM, WDM or CDM

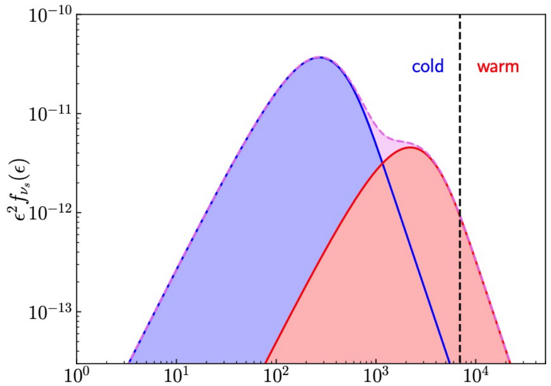
WDM if $m_s \simeq$ 0.3 MeV-0.3TeV! NOT keV's!!!

DR=Dark Radiation at present; X-rays could be observed; LRT: $T_{\rm RH} < T_{\rm max}$ of DW rate

- There is an additional subdominant population of ν_s produced via $\nu_a - \nu_s$ mixing... but for $m_s >$ MeV DW too warm, so $< 0.1\rho_{\rm DM}$- Leads to idea of multiple populations of the same ν_s

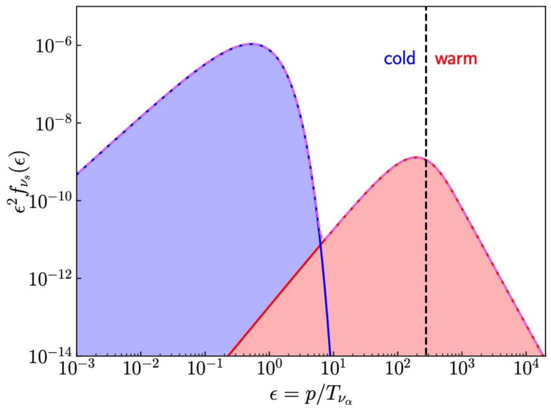
Multiple populations of the same sterile neutrino produced by different mechanisms in different epochs (Chen, Gelmini, Lu, Takhistov JCAP05 (2026) 083 [2507.17830])

In this case just $\langle \epsilon \rangle = \langle p/T \rangle$ not enough to characterize the spectrum. Many possibilities



- about equal parts CDM and WDM
- as function of $\epsilon = p/T$ at $T = 3$ MeV
- vertical dashed $\langle \epsilon \rangle$ boundary CDM/WDM (corresponding to thermal relic mass limit 5.7 keV limit for 0.5 WDM fraction in Garcia-Gallego et al. PRD 112 (2025) 4, 043502 [2504.06367])

Up: Two PBH ν-genesis, $M_1 = 1$g (blue),$M_2 = 66$g (red)

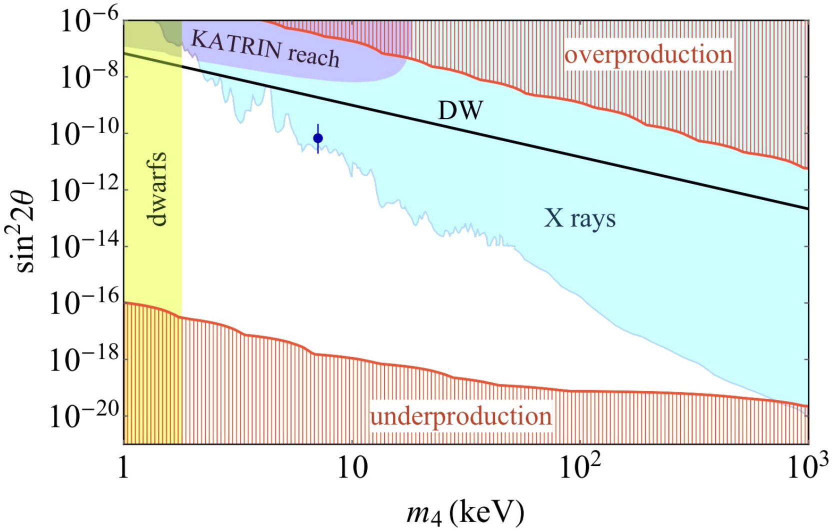


Down: 600GeV singlet scalar decay (colder-blue) (Kusenko PRL97 (2006) 241301) and PBH ν-genesis $M =$0.11g (red)

Requires ν_s extra couplings for production in singlet decay

Combining Non-Standard Cosmology and NS Interactions

Leads to an even reacher phenomenology-E.g. ν_s **DM with active neutrinos NSI** Studied by De Gouvêa, Sen, Tangarife and Zhang, in 2019, assuming a scalar mediator. Fig. shows region where there are values of mediator coupling and mass such that the ν_s accounts for all the DM ("DW" line without NSI)



Kelly, Sen, Tangarife and Zhang, in 2020 considered instead several vector mediated NSI with the same idea. Revised by Vogel, Garcia Escudero, Froustey, and Abazajian in 2025

Cosmological dependence of ν_s DM with Self-Interacting ν_a Chichiri, Gelmini, Lu and Takhistov, 2111.04087 For a scalar mediator- following De Gouvêa et al 2019

ST1 scalar tensor

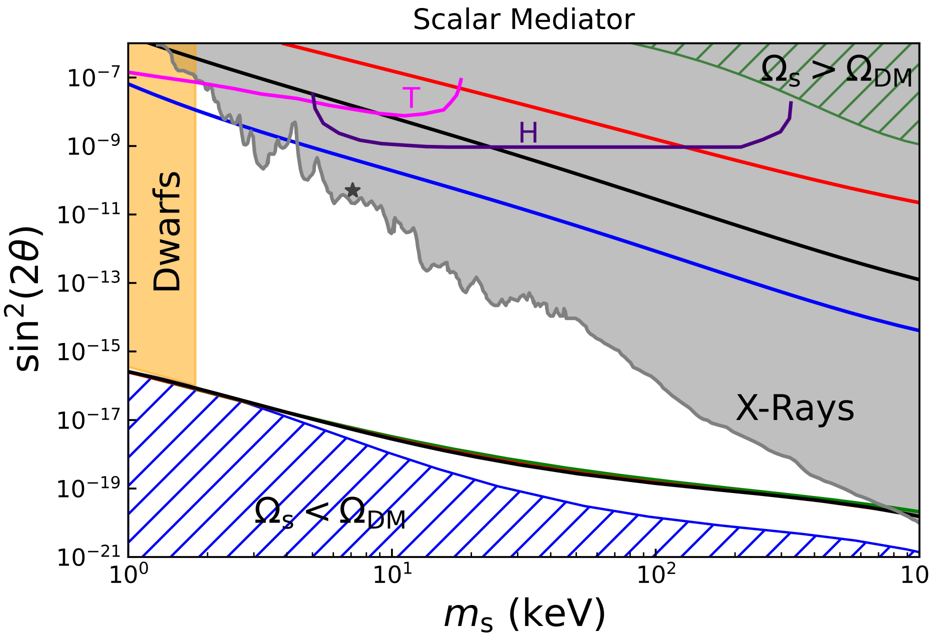
Kination

Standard

ST2 scalar tensor

.

“Dwarfs”: Tremaine-Gunn limit using dwarf spheroidal galaxies

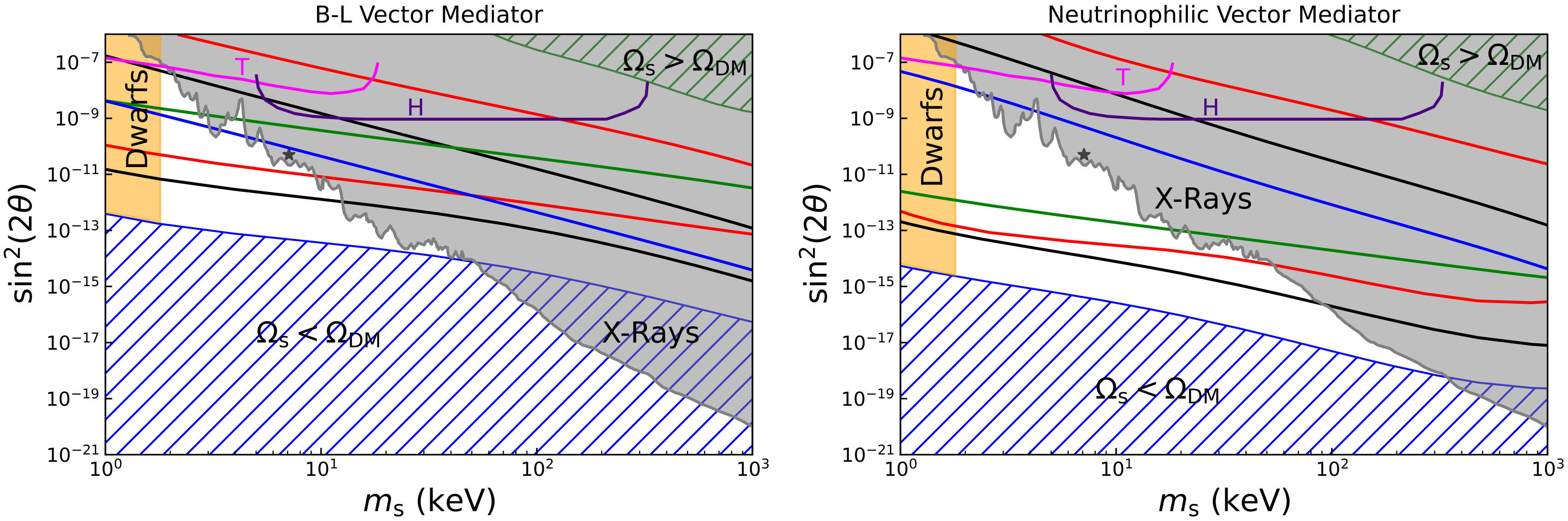


Instead of the region in between the black lines assuming just the standard cosmology the uncertainty due to our ignorance of the pre-BBN cosmology opens up for ν_s to constitute all of the DM in between the shaded regions!

Cosmological dependence of ν_s DM with Self-Interacting ν_μ

Chichiri, Gelmini, Lu and Takhistov, 2111.04087

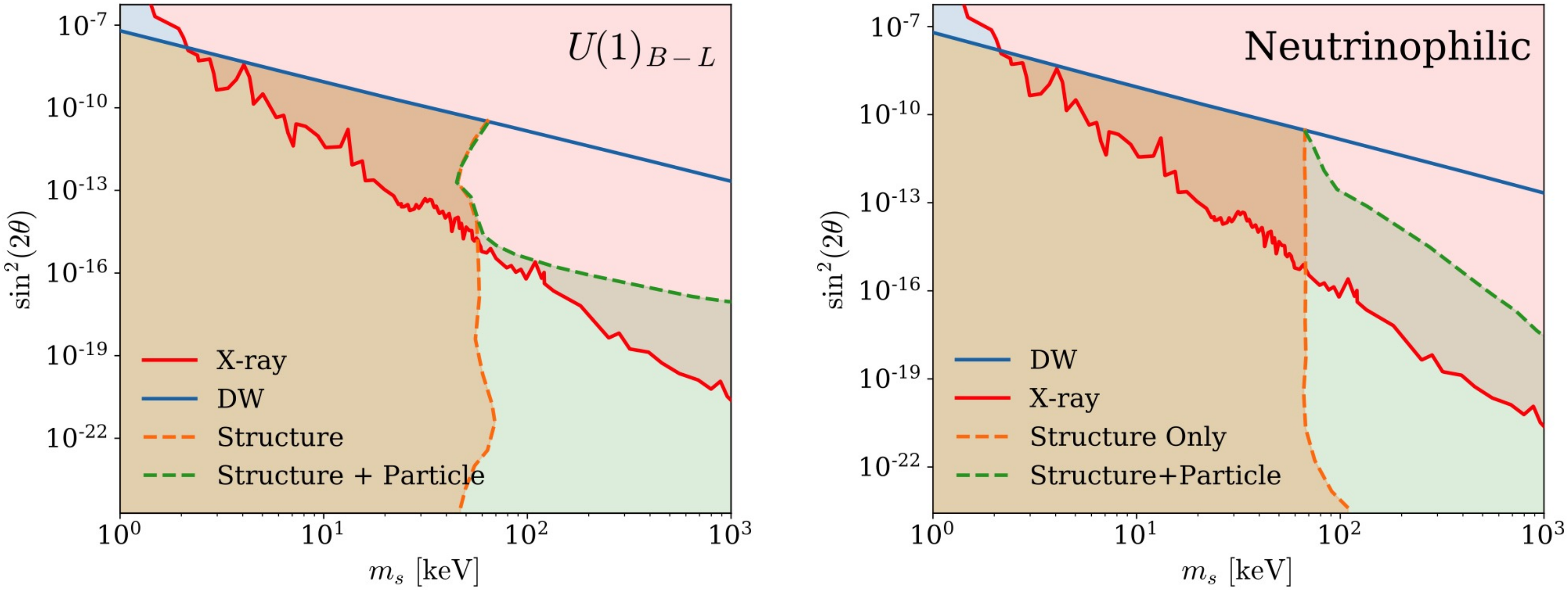
For two vector mediator models- following Kelly et al 2020



Again, the region in between the black lines for the standard cosmology opens up to be between the shaded regions! Here, ν_s constitute all the DM-TRISTAN and HUNTER reach forbidden by X-ray limits. Could these models allow for a discovery of a ν_s in TRISTAN or HUNTER? Yes if they constitute a fraction f <1 of the DM.

Cosmological dependence of ν_s DM with Self-Interacting ν_μ

For two vector mediator models- Vogel et al 2025 find the parameter entirely closed in the Std-cosmology

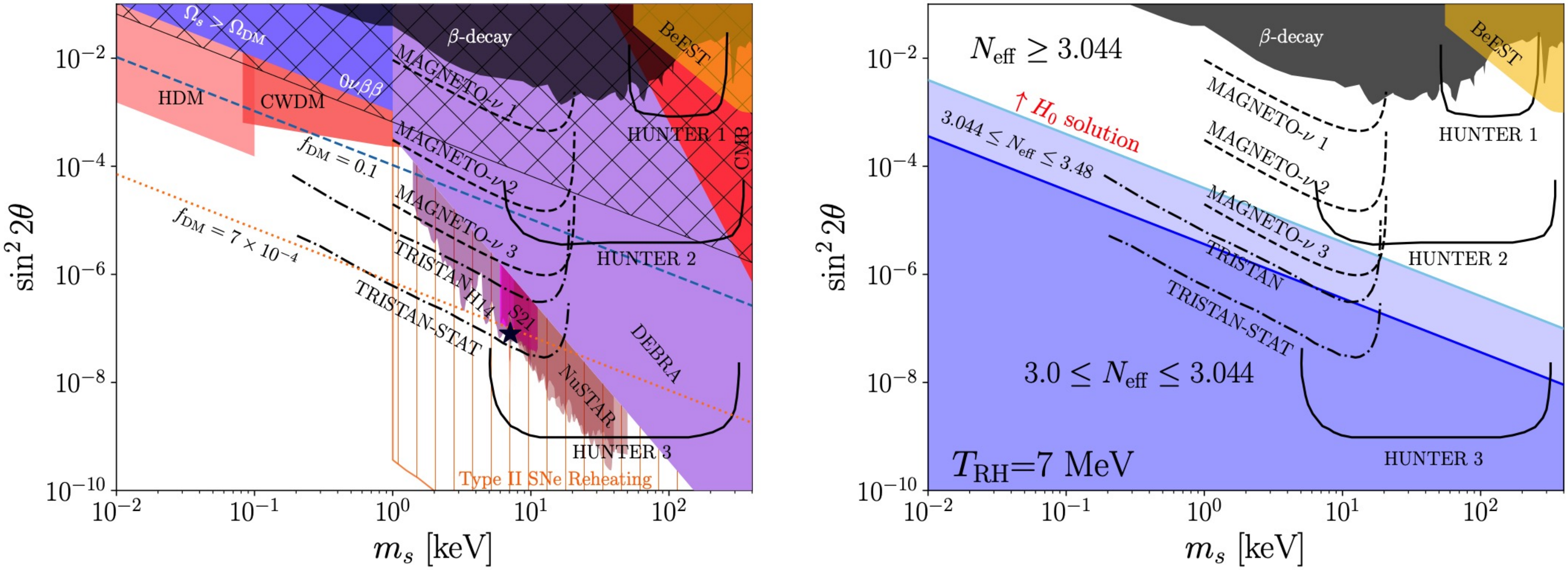


But non-standard cosmology may allow to open up parameter space.

Combining Non-Standard Cosmology and NS Interactions

Leads to an even reacher phenomenology-E.g. **LRT vs LRT $+\nu_s$ dark decay**

Abazajian and Garcia Escudero PRD 108 (2023) 12, 123036 [2309.11492]



Colored regions become allowed with Low $T_{\rm RH} + \nu_s$ dark decay.

Combining Non-Standard Cosmology and NS Interactions

Leads to an even reacher phenomenology-E.g. **LRT vs LRT $+\nu_s$ dark decay**

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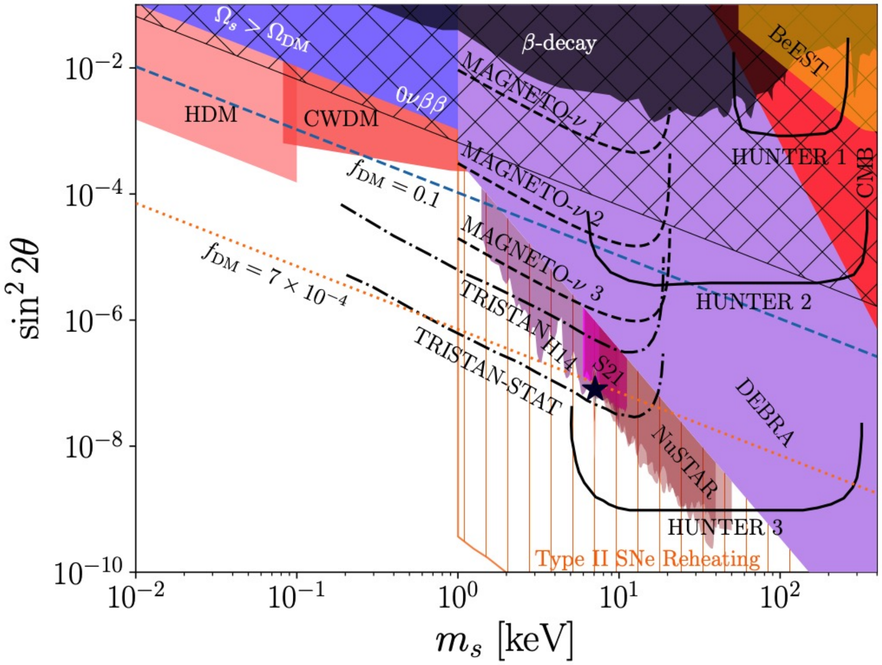
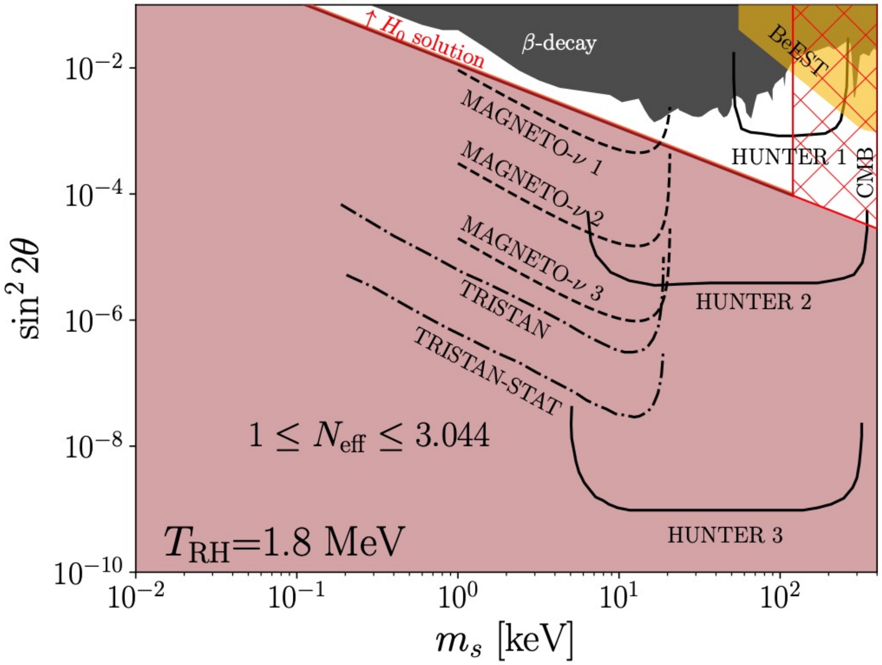




Larger regions become allowed with Low $T_{\rm RH} + \nu_s$ dark decay as $T_{\rm RH}$ lowers!
(Although 1.8 MeV is probably too given present constraints)

Conclusions

If discovered sterile neutrinos could be the earliest remnants of the Universe, from the pre-BBN epoch yet unknown of the Universe.

Our ignorance of the cosmology at the moment they are produced introduces uncertainties in all the cosmological/astrophysical limits that depend on their predicted relic abundance and momentum distribution, which should be taken into account when interpreting experimental and observational results.

On the other hand, if a sterile neutrino is ever discovered if could give some information about the pre-BBN cosmology (e.g. if a 7 keV neutrino, corresponding to the putative 3.5 keV X-ray line, would be discovered in the laboratory with mixing $\sim 10^{-7}$, it could point towards an ST1 or Low Reheating Temperature cosmologies)

When considering neutrino NSI, the interplay between their effects and those of non-standard cosmologies is critical.

EXTRA SLIDES

Low Reheating Temperature- Late decaying scalar field ϕ

- $T < T_{\rm RH}$ **radiation dominates, H = H**$_{\rm standard}$

- $T > T_{\rm RH}$ **oscillating ϕ domination:** H $\simeq \rho_\phi^{1/2}/M_P \propto T^4$ (McDonald 1991; Giudice, Kolb, Riotto, 2001)

  [Use $\dot\rho = -3H(\rho+p) + \Gamma_\phi \rho_\phi$ with $p = \rho/3$, $\rho \simeq T^4$ and $\rho_\phi \simeq M_P^2 H^2$. Then use $H \sim t^{-1}$ and write $T \sim t^\alpha$. Then match the powers of t in all terms: $\dot\rho \sim t^{4\alpha-1} \sim H^2 \sim t^{-2}$ and determine $\alpha = -(1/4)$. Thus $H \sim 1/t \sim T^4$.]

  Since at $T = T_{\rm RH}$, H $\simeq T_{\rm RH}^2/M_P$, it is H $\simeq T^4/(T_{\rm RH}^2/M_P)$. Thus,
  $\rho_\phi \simeq T^8/T_{RH}^4$ and while $\rho_\phi a^3 \simeq {\rm const}$, $T \propto a^{-3/8}$ and H $\sim a^{-3/2}$
  (as in matter domination)

Since the radiation bath is a small component of the total density, the amount of sterile neutrinos produced at $T > T_{\rm RH}$ is small and neglecting it the relic density can be computed analytically

Models that only change the pre-BBN H: Kination Salati-02; M. Joyce-01...

Period in which the kinetic energy of a scalar field ϕ (quintessence?) dominates: $\rho_{\rm total} \simeq \dot\phi^2/2 \sim a^{-6} \sim T^6$, with $T \sim a^{-1}$ as usual.

[Klein-Gordon Eq. for an homogeneous field: $d\dot\phi + 3(da/a)\dot\phi = 0$ for $V = 0$ so $\dot\phi \sim a^{-3}$]

Only condition, ratio $\eta_\phi = \rho_\phi/\rho_\gamma << 1$ at $T \simeq 1$ MeV (during BBN)

$$\text{H}_{\rm kination} \sim \sqrt{\rho_{\rm total}} \simeq \sqrt{\eta_\phi}\left(\frac{T}{1{\rm MeV}}\right) H_{\rm standard} \sim T^3$$

Assuming H=H$_{\rm standard}$ i.e. $\eta_\phi \simeq 1$ at T $= 5$ MeV, means $\eta_\phi < 1/25 = 0.4$ at T$<$ 1 MeV which corresponds to $\Delta N_{\rm eff} <$ 0.04/0.14$=$ 0.29. But it continues decreasing ($\eta_\phi \sim (T\ /\ 5{\rm MeV})^2$). E.g. $\eta_\phi \simeq 0.0004$, $\Delta N_{\rm eff} \simeq$ 0.0004/0.14$=$ 0.0029 at the end of the “Deuterium bottleneck”, $T \simeq$ 0.1 MeV, when D becomes stable and BBN can proceed in earnest .

Models that only change the pre-BBN Hubble parameter H:

Scalar-tensor models of gravity have a scalar field coupled only through the metric tensor to the matter fields. The expansion of the Universe drives the scalar field towards a state where the theory is indistinguishable from GR at a low T_ϕ, before BBN.

Model we call **ST1** Catena, Fornengo, Masiero, Pietroni, Rosati; 04

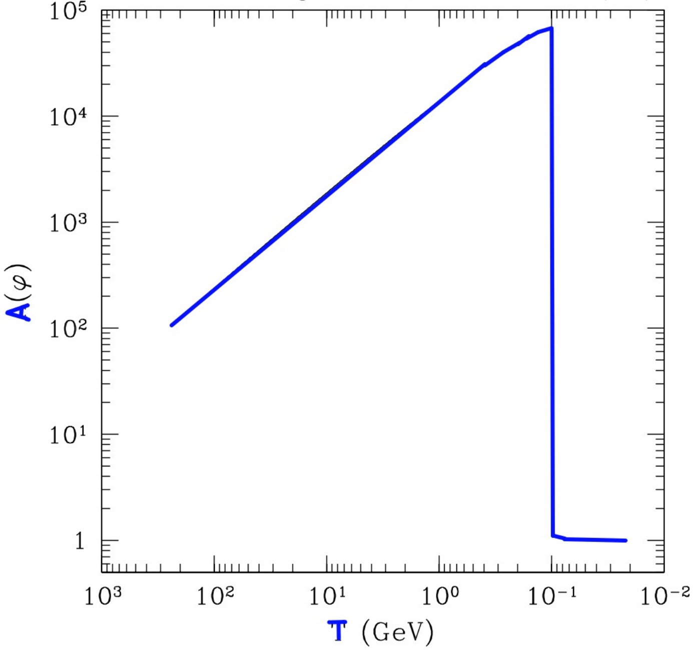
At $T > T_\phi$: H $\simeq A$ H$_{\rm standard} \sim T^{1.2}$, $A > 1$,

At T_ϕ: function A drops sharply to 1, H=H$_{\rm standard}$

Authors mention T_ϕ can be at the BBN scale.

We take T_ϕ = 5 MeV.

R. Catena, N. Fornengo, A. Masiero, M. Pietroni, F. Rosati (2004)



Model we call **ST2** Catena, Fornengo, Masiero, Pietroni, Schelke; 07

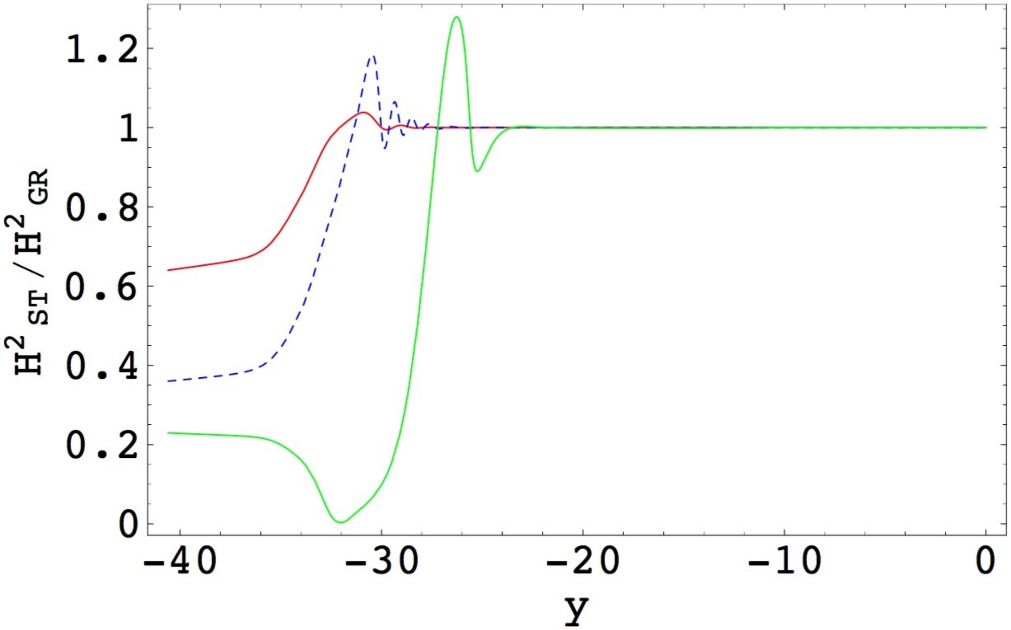
With more than one matter sector (one "visible" and the other "hidden")

H can be reduced to as much as H=0.03 H$_{\rm standard}$

We assume a transition also at T=5MeV

Models that only change the pre-BBN Hubble parameter H: Scalar-tensor models of gravity: ST2 Catena, Fornengo, Masiero, Pietroni, Schelke; 07

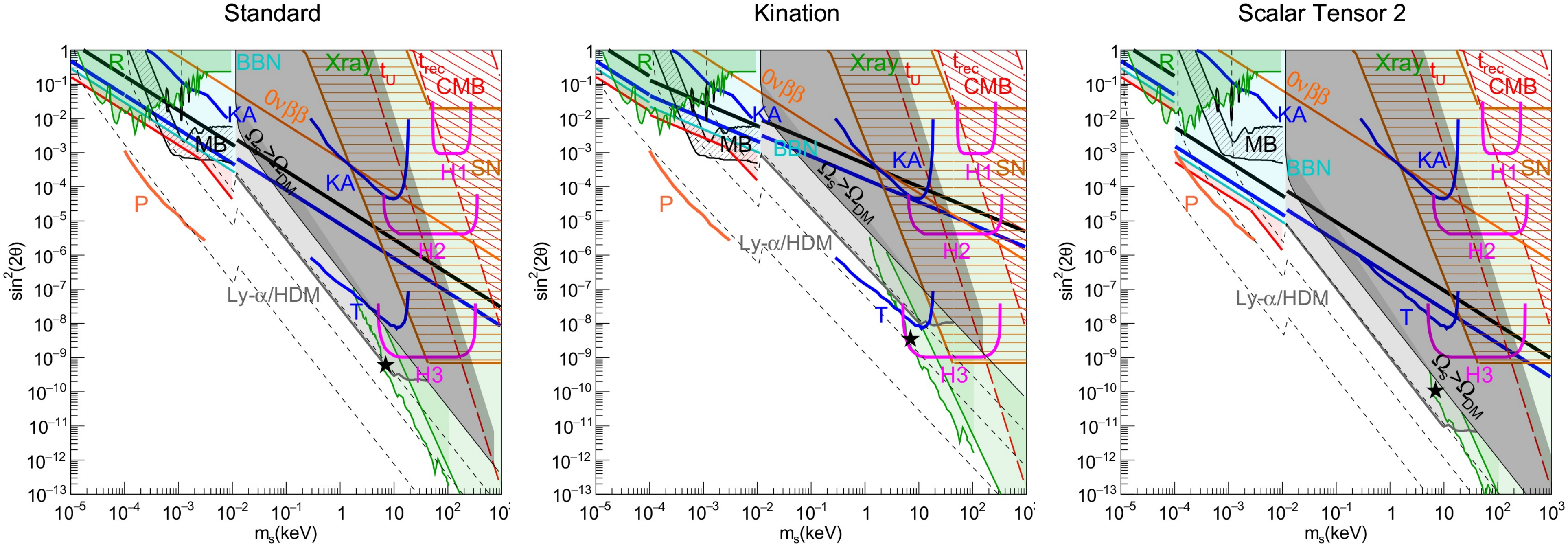
Model we assume is closest to green line.
$y = \ln(T_0/T)$ (T_0 is present temperature)
Here the min is at $y =-28$ ($T \simeq 100$ MeV)
$T = 5$ MeV corresponds to $y = -23.8$
possible with a slightly different choice
of parameters



Our ST2 model corresponds to a collection of models close to the green line, each one with minimum where ν_s production is maximum

Limits on ν_s produced via non-resonant active-sterile flavor oscillations with ν_e (all analytic calculations)

G.B. Gelmini, Philip Lu and Volodymyr Takhistov, 2006.09553, JCAP12, 047 (2019) [1909.13328], Phys. Lett. B800, 135113 (2020) [1909.04168]


Standard Kination Scalar Tensor 2

MB= LSND/MiniBooNE, ovals: reactor DANSS/NEOS, ⋆= 3.5 keV line, R= reactor Daya Bay, Bugey-3, PROSPECT BBN-$N_{\rm eff}$ CMB-$N_{\rm eff}$,$m_{\rm eff}$ KA= KATRIN, T=TRISTAN, P= PTOLEMY 100 g-yr, H1, H2, H3= HUNTER phase1 and upgrade.

In K: ⋆ moves to $\sin^2 2\theta \simeq 10^{-8}$ and MB partially allowed by cosmology. in ST2 bounds are stronger.

Spectrum also changes: $<p/T>$=3.15 (Std), 3.47(K), 3.15 (ST2)

If ν_s constitute a fraction f of the DM in the NSI models just shown.

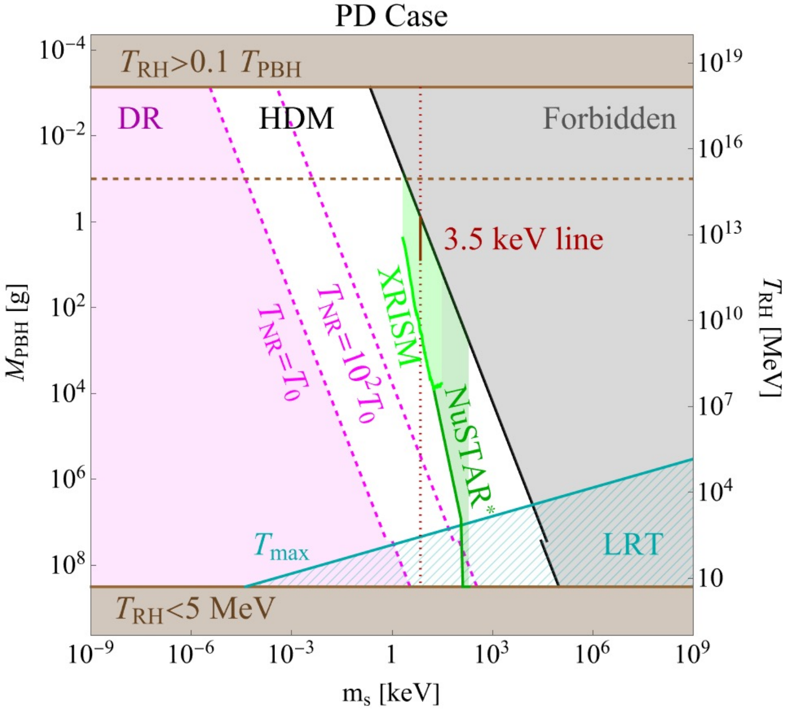
Since $f \sim \sin^2 2\theta$ for the small mixing in our figures, the region shown for $\Omega_s = \Omega_{DM}$ would move down in our plots by a factor f in $\sin^2 2\theta$.

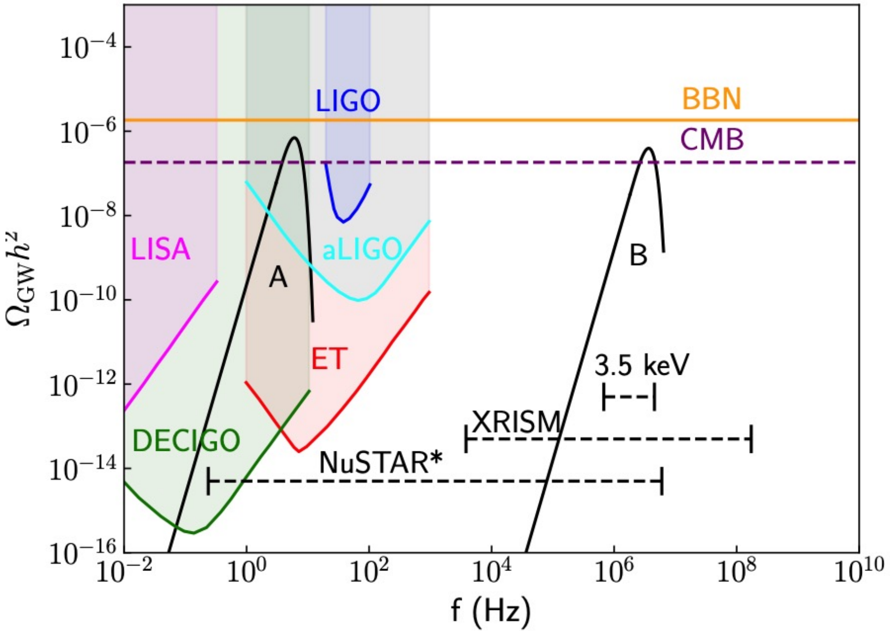
The region forbidden by X-ray observation would move upwards. The boundary of the region forbidden by X-rays observations corresponds to a fixed X-ray flux, i.e. it is proportional to the ν_s density times decay rate, and this product is independent of $\sin^2 2\theta$. Thus, if the density decreases by f, the X-ray upper limits move upwards towards larger mixings by a factor of $1/f$ in $\sin^2 2\theta$.

TRISTAN and HUNTER laboratory experiments are forbidden by X-ray bounds for sterile neutrino DM, but would evade these limits for sterile neutrinos that are sufficiently underdense, and considering the uncertainties associated with the unknown pre-BBN cosmology.

Primordial Black Hole Sterile Neutrinogenesis

if PBH Matter Dominate (Chen, GG, Lu, Takhistov PLB852,138609 [2309.12258]; JCAP07, 059 [2312.12136])



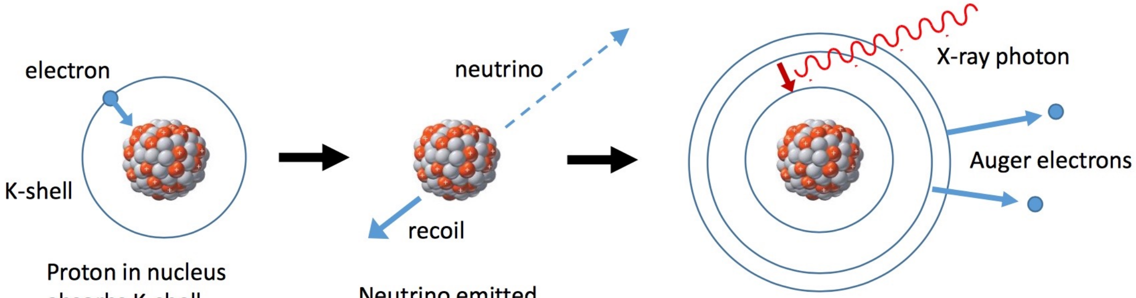


DR=Dark Radiation at present; X-rays could be observed; LRT: $T_{\rm RH}<T_{\rm max}$ of DW rate

- ν_s cannot be a large DM component (only DR or HDM)
- But fast reheating at evaporation could lead to GW's- Possible signature: X-rays + GW's

HUNTER (Heavy Unseen Neutrinos by Total Energy-momentum Reconstruction)

K-capture experiment, measuring the mass of a ν_s coupled to e



Proton in nucleus
absorbs K-shell
atomic electron

Neutrino emitted
Nucleus recoils

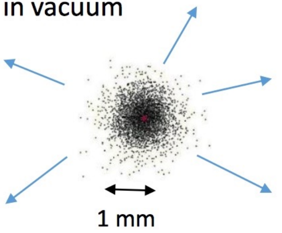
X-ray emitted
Auger electrons emitted

make precision momentum measurements of:

- recoil ion
- X-ray photon
- Auger electrons

calculate missing ν momentum

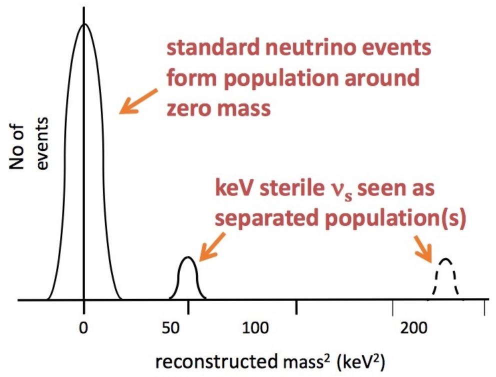
- Cloud of ^{131}Cs atoms (10 day half-life) suspended in vacuum



Reconstruct neutrino mass for large number of events

$$m_\nu^2 = \underbrace{[Q - E_a - E_\gamma - E_N]^2}_{\text{missing energy}} - \underbrace{[\,\mathbf{p}_\gamma + \mathbf{p}_{ea} + \mathbf{p}_N]^2}_{\text{missing momentum}}$$

Reconstructed mass spectra:



HUNTER

Requires advanced versions of two established techniques

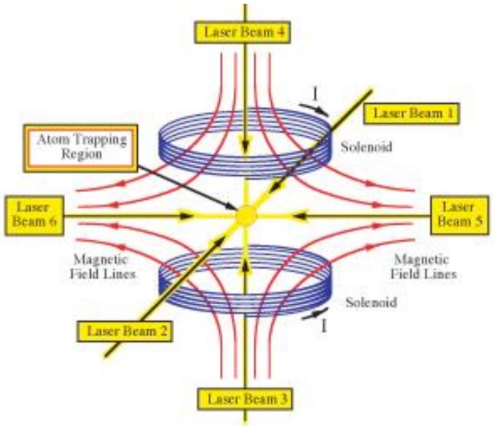
MOT - Magneto-Optical Trap

Developed for over 20 years for
cooling and suspension of neutral atoms

No of trapped atoms: 10^6 - 10^{10}

Atom temperature: 10 - 100 μK

(Atomic & Molecular Optics Group UCLA)

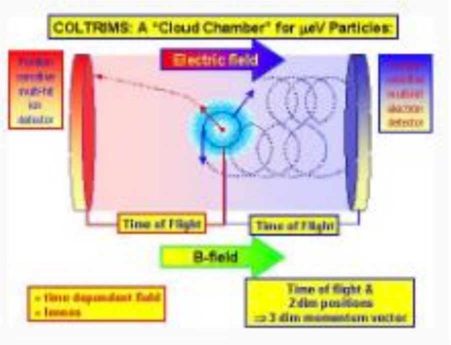


COLTRIMS – COLd Target Recoil Ion Mass Spectroscopy

Used extensively for 20 years for 3-D studies of
atom-atom and photon atom collisions

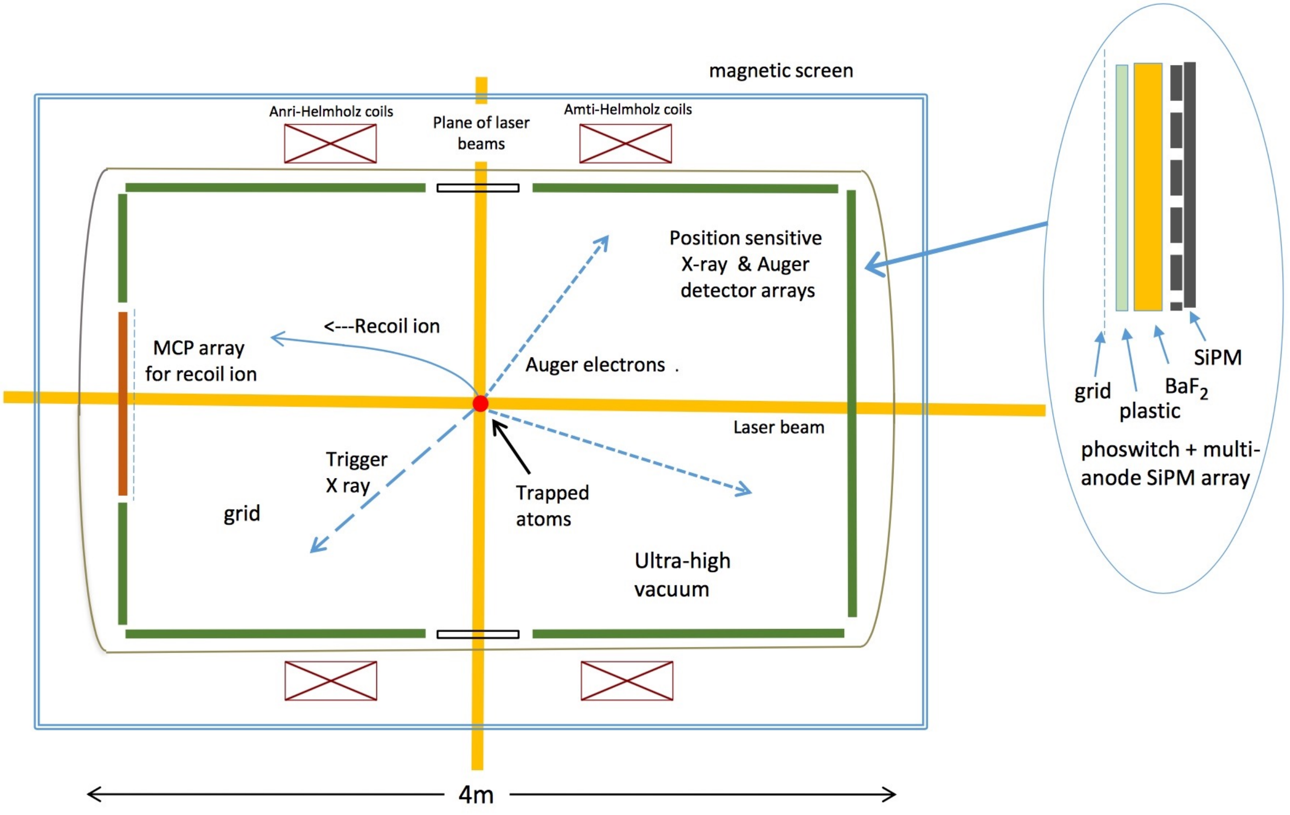
time of flight precision 200 ps
spatial precision (MCP) 40 μm

(supplied by Roentdek, Germany)



HUNTER

Original (2016) suggestion for 4π collection and time-of flight measurement



HUNTER

HUNTER experiment (**H**eavy **U**nseen **N**eutrinos by **T**otal **E**nergy-momentum **R**econstruction)

Phase 1 (proof of principle) funded by Keck Foundation