Uncertainties of cosmological/astrophysical limits on sterile neutrinos

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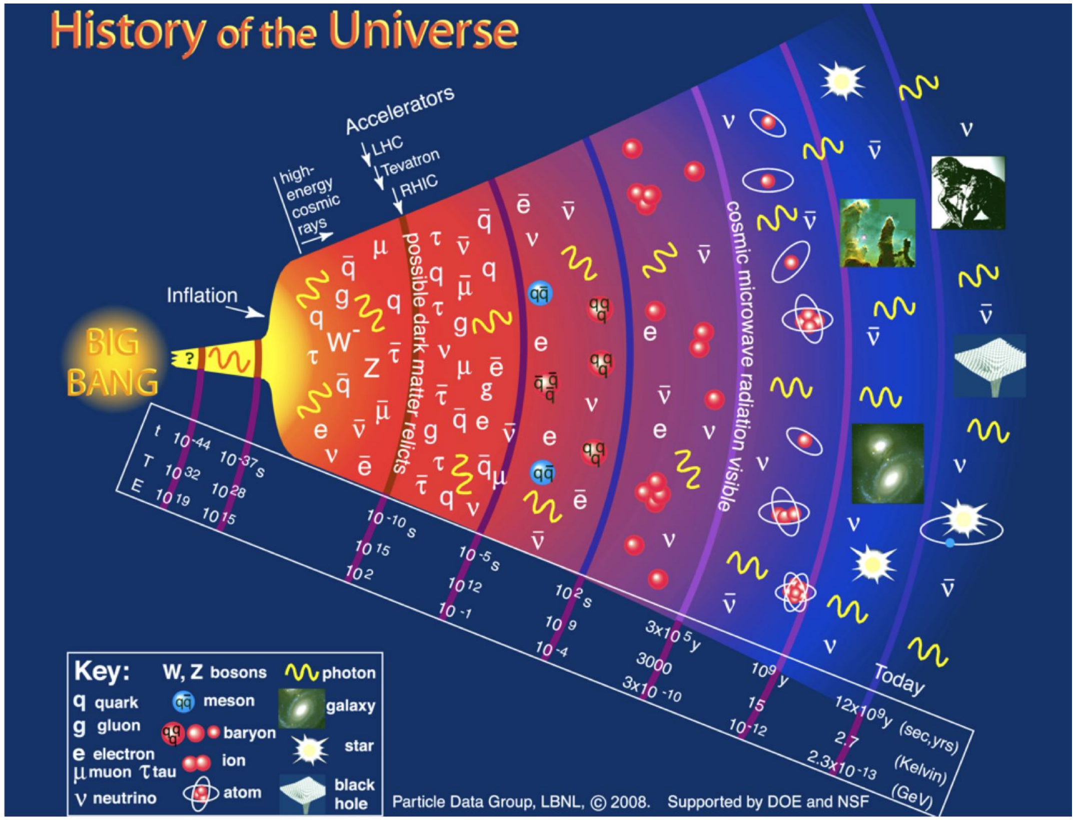
All data confirm the Big-Bang Model of a hot early Universe expanding adiabatically ($T \sim 1/a$)

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

Radiation domination to Matter domination
t$\simeq$66kyr T$\simeq$1 eV

CMB emitted (atoms form)
(Cosmic Microwave Background)
t$\simeq$380kyr T$\simeq$ 0.3 eV

Now (Planck + other)
t=13.798$\pm$ 0.037$\times$10^{9}ys



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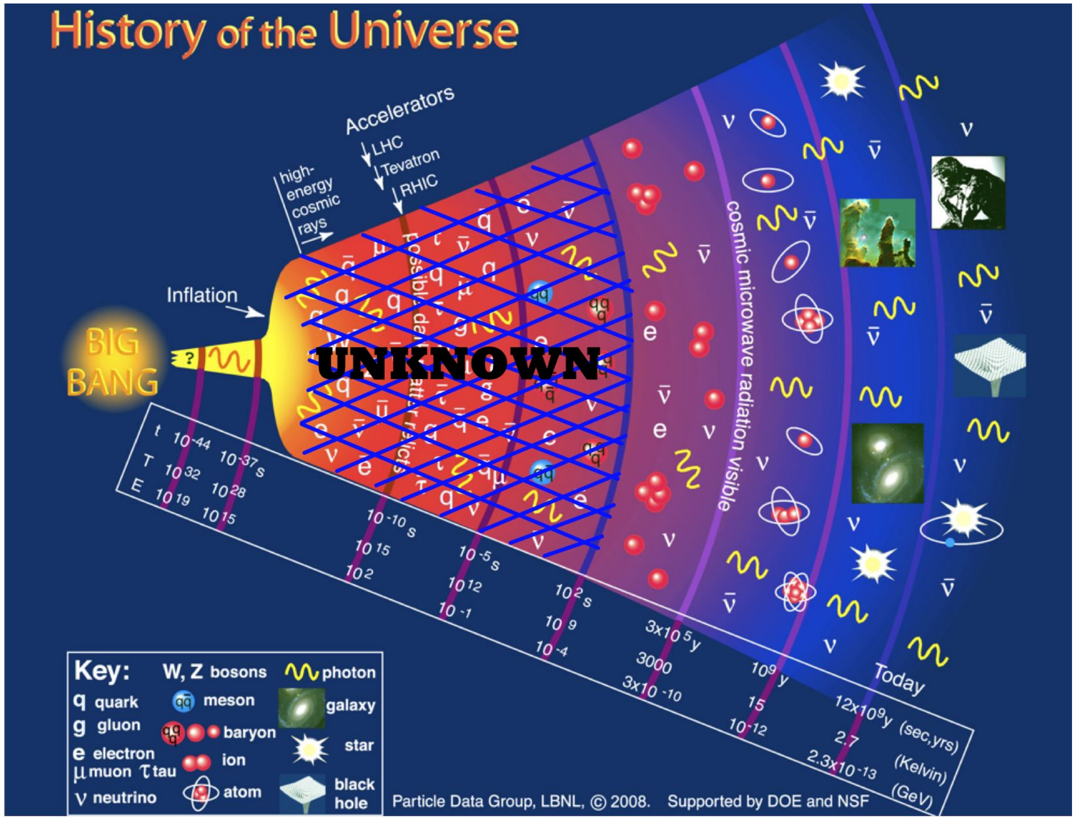
BBN (Big-Bang Nucleosynthesis)
t $\simeq$ 3-20min T$\simeq$ MeV

Cosmology before
T $\simeq$ 5 MeV is UNKNOWN

$T_{\rm RH} \geq$ 5 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**

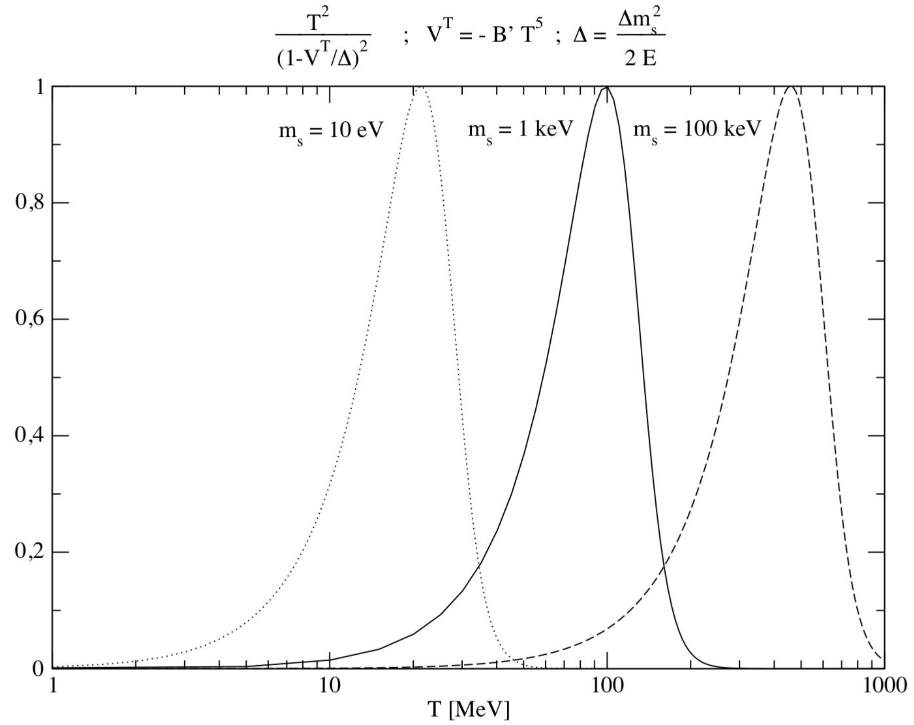


Particle Data Group, LBNL, © 2008. Supported by DOE and NSF

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

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

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



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)

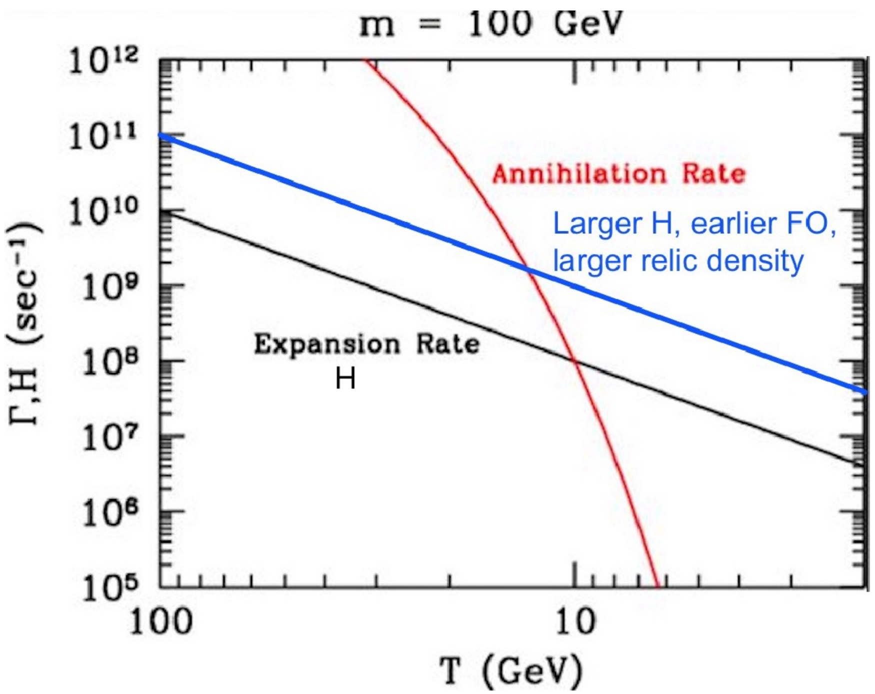
$$-\left(\frac{\partial f_s(E,T)}{\partial T}\right)_{E/T=\epsilon} \simeq \frac{\Gamma(E,T)}{HT} f_a(E,T)$$

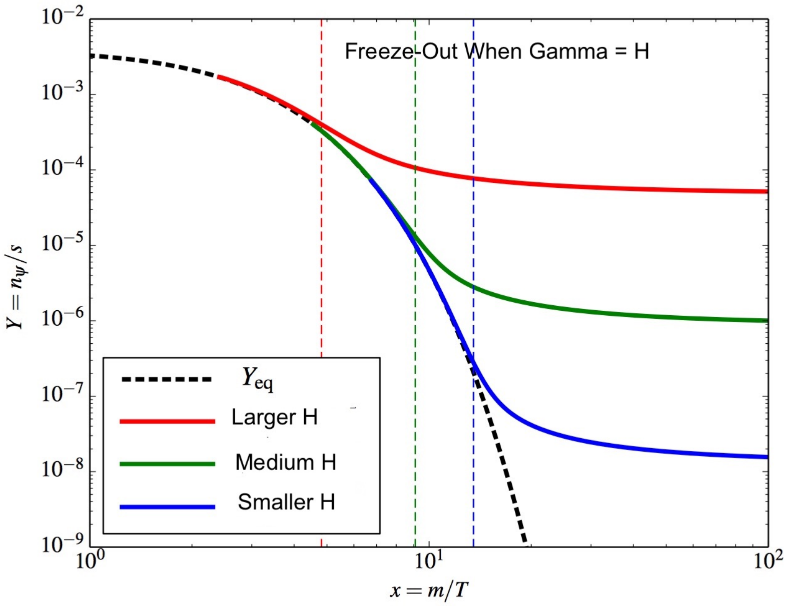
Thus a larger (smaller) H suppresses (enhances) the Freeze-In production

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

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

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, such as those 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

Disclamer: I am not advocating for any pre-BBN cosmology model. My interest is considering them as a source of uncertainty of cosmological/astrophysical limits on particles to qualify claims that a particle is "forbidden by cosmology" (e.g. the LSND-MiniBooNe sterile neutrino or those HUNTER can search for.)

Non-std scenarios are more complicated and in many times not complete (in terms of baryon number generation, for example). But if a experimental result would hint at one of them, they could be completed...

Some “non-Standard” pre-BBN cosmologies

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

  These models alter the thermal evolution of the Universe 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 the value of H but the dependence of the temperature T on the scale factor a is different.

  Simpler 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 the field ϕ decays. Before then the radiation bath is a small component.

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

Low Reheating Temperature

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

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

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

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

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

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

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)

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

Assuming H=$\text{H}_{\rm standard}$ 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 $(\eta_\phi \sim (T \ / \ 5\text{MeV})^2)$. 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$_{\rm standard}$

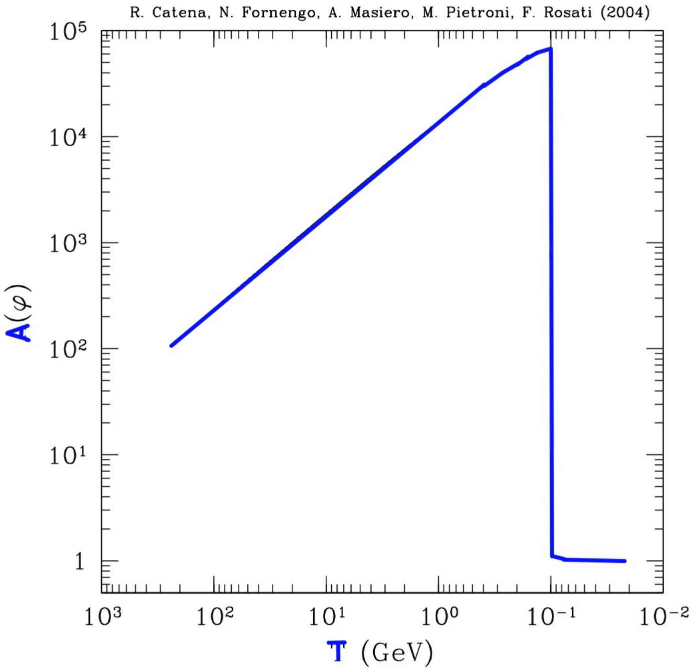
Authors mention T_ϕ can be at the BBN scale.
We take T_ϕ = 5 MeV.

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$_{\rm standard}$

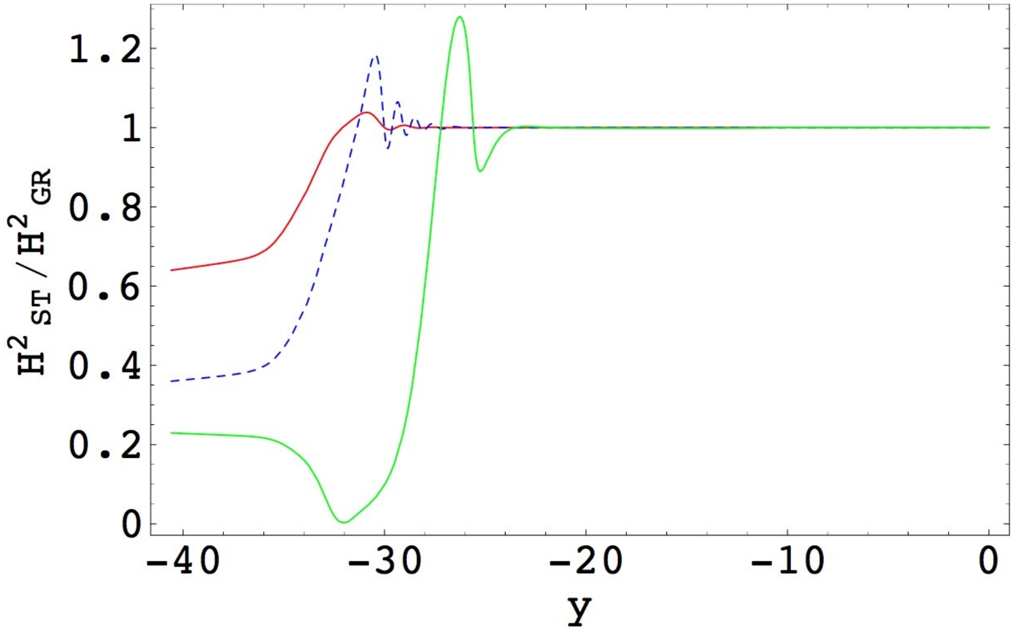
We assume a transition also at T=5MeV



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



H(T) for several pre-BBN cosmological models

"LRT": Low T_{RH}

.

"ST1": scalar tensor

.

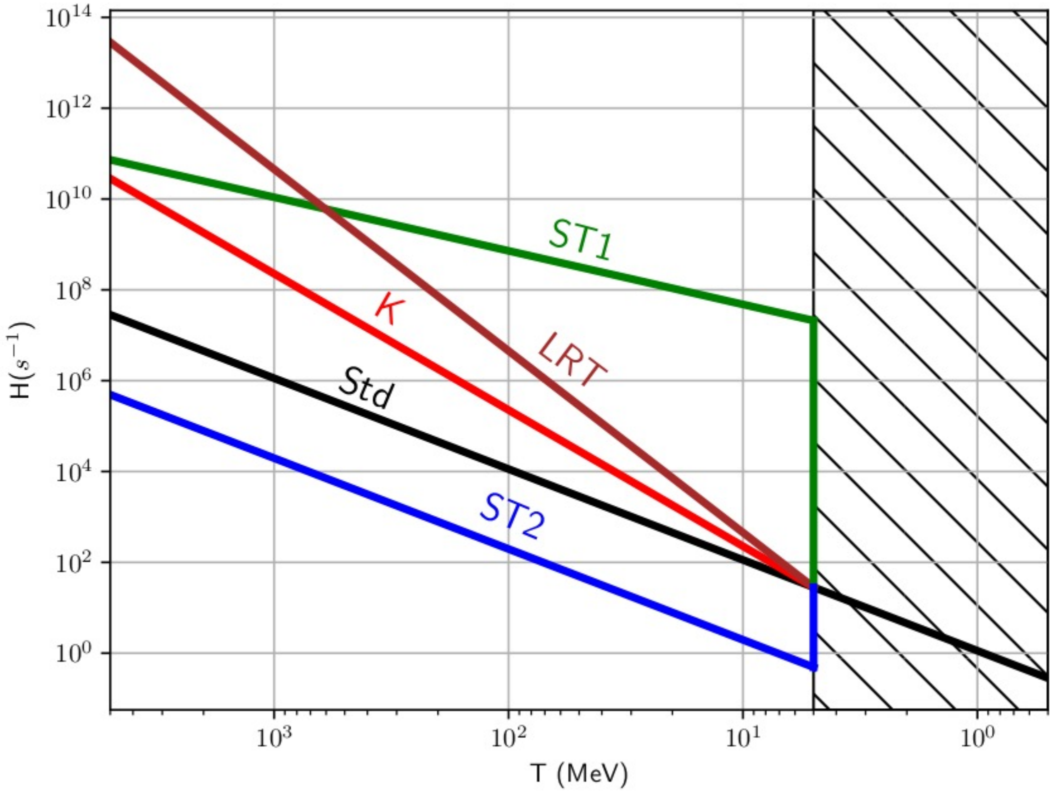
"K": kination

.

"Std": standard radiation-dominated

.

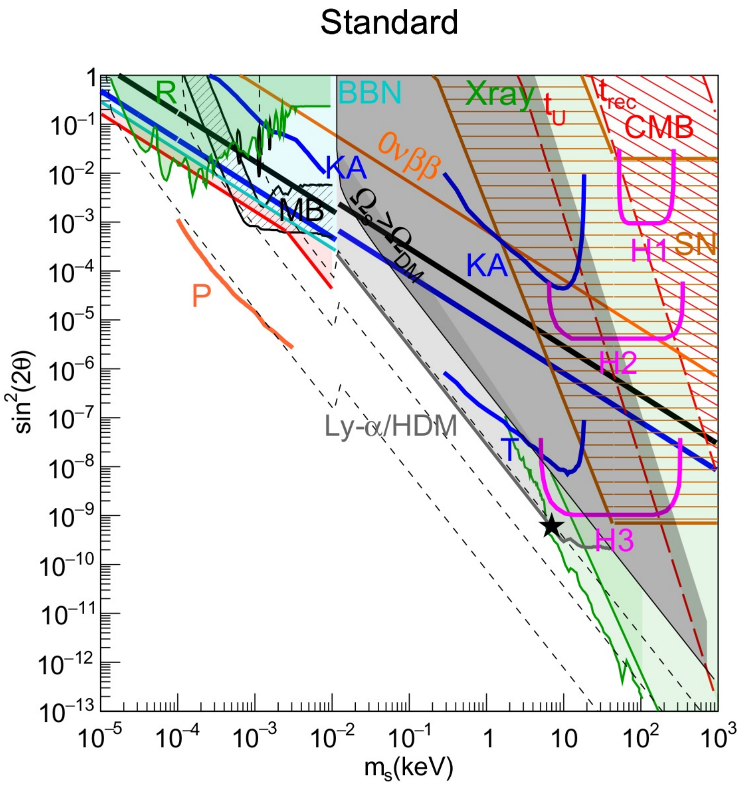
"ST2" : scalar tensor



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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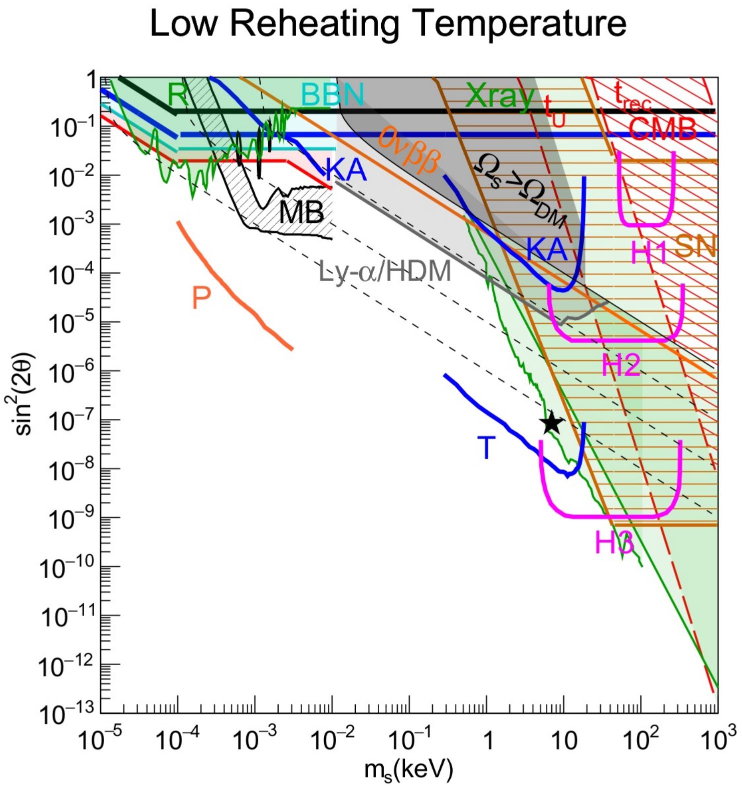

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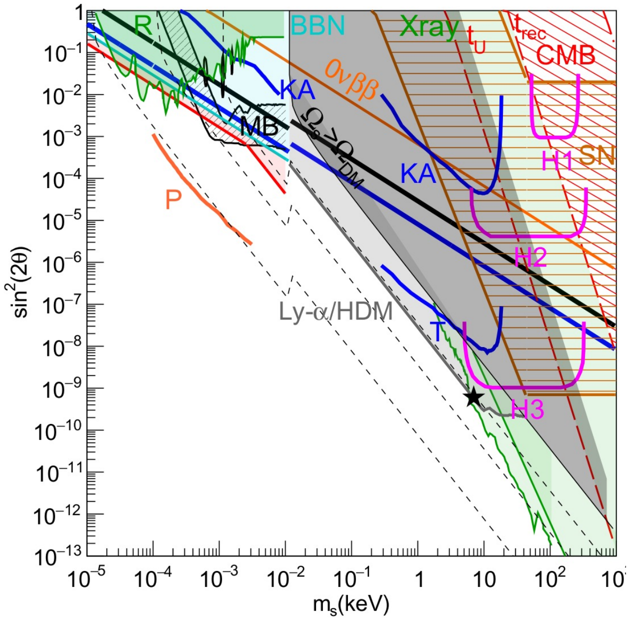
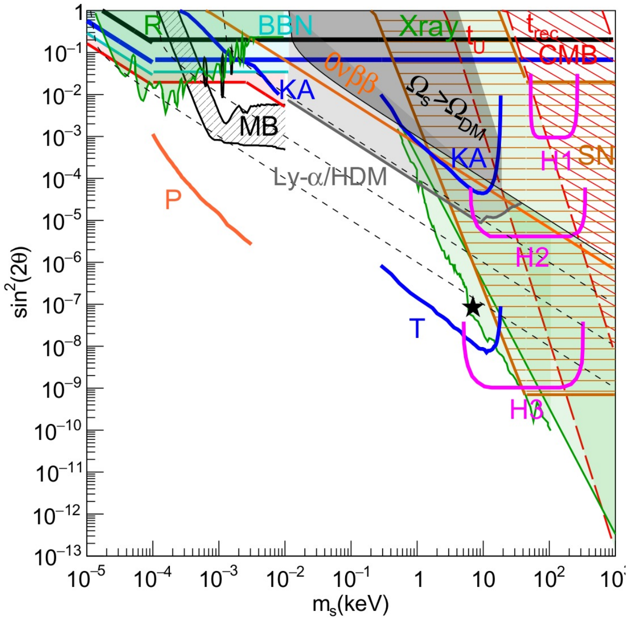
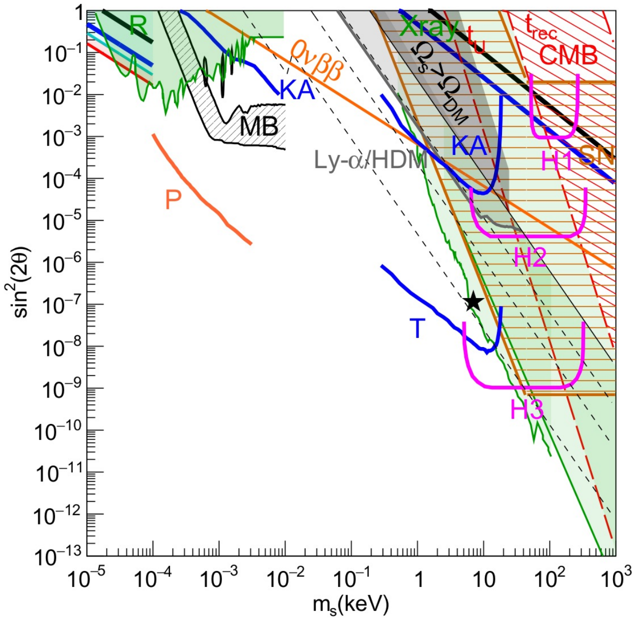
Standard



Low Reheating Temperature



Scalar Tensor 1



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)

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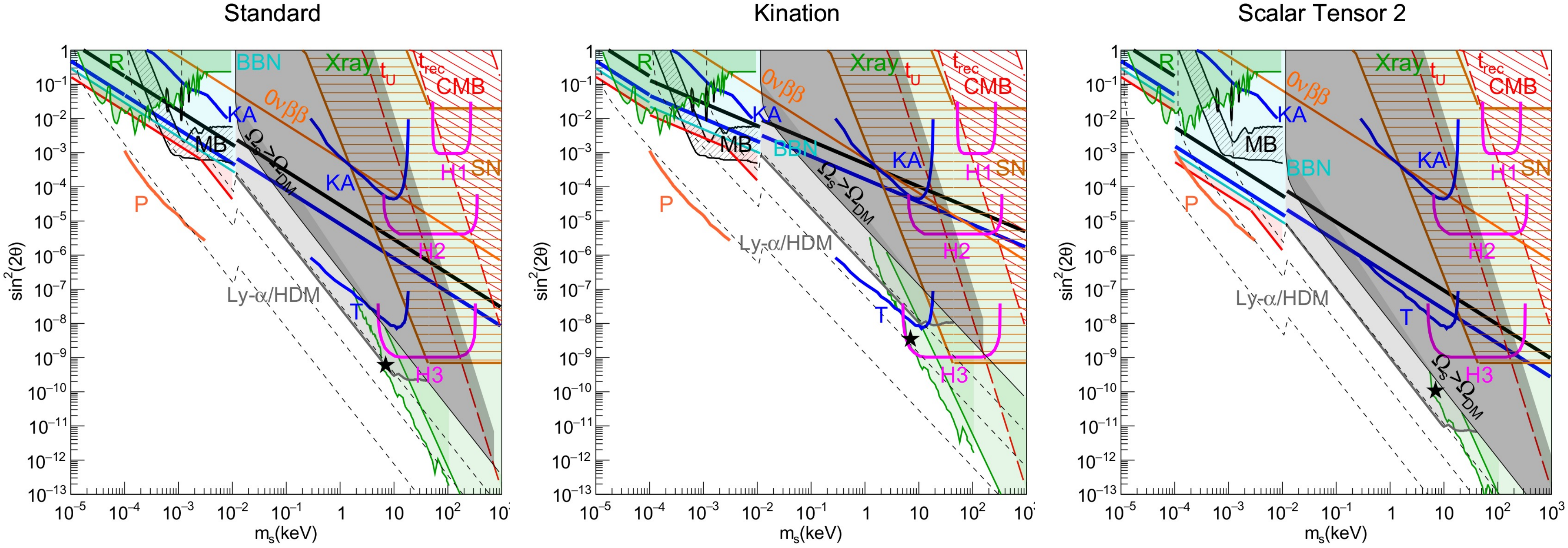


Standard

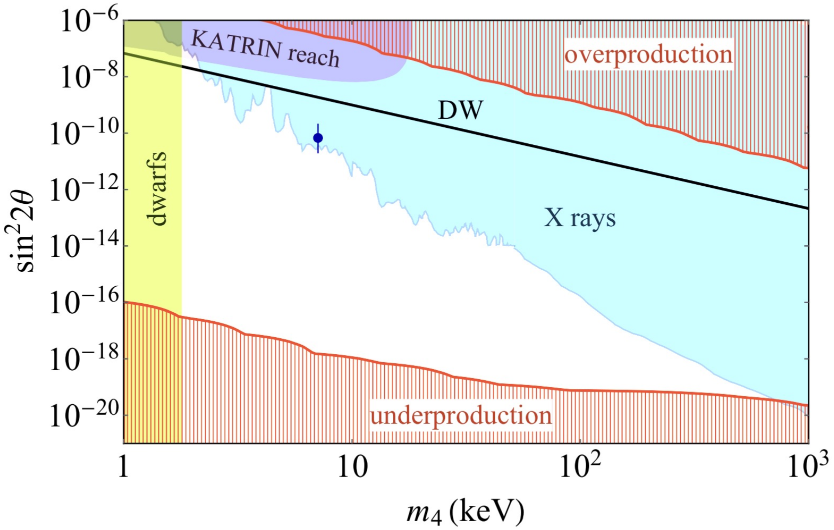
Kination

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

Sterile Neutrino Dark Matter in the presence of self-interacting active neutrinos The production of ν_s with $m_s \simeq keV$ via active-sterile oscillations in the presence of Non-Standard Interactions (NSI) was 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)



K. J. Kelly, M. Sen, W. Tangarife and Y. Zhang, in 2020 considered instead several vector mediated NSI with the same idea.

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

ST1 scalar tensor

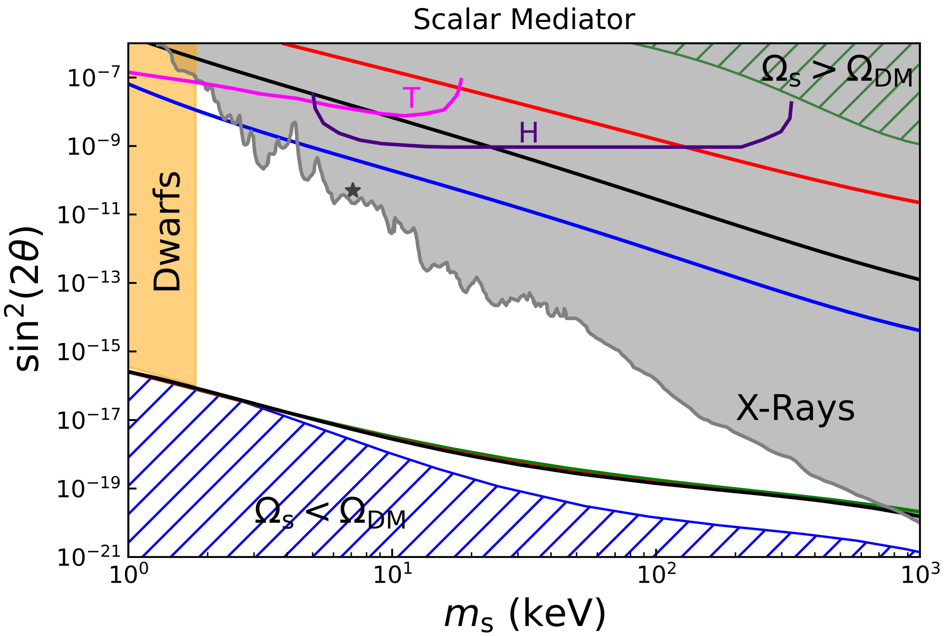
Kination

Standard

ST2 scalar tensor

.

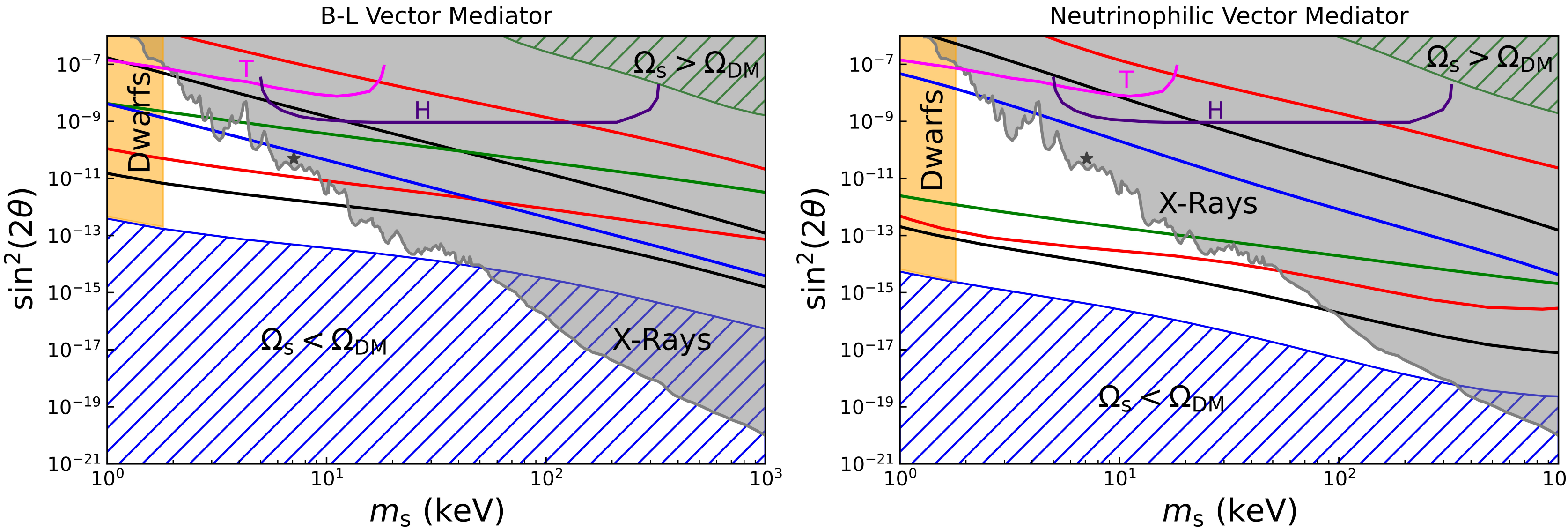
“Dwarfs”: Tremaine-Gunn limit using dwarf spheroidal galaxies



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!

Notice that TRISTAN and HUNTER reach regions are forbidden by X-ray limits.

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



Again, the region in between the black lines for the standard cosmology opens up to be between the shaded regions!

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.

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.

Conclusions

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

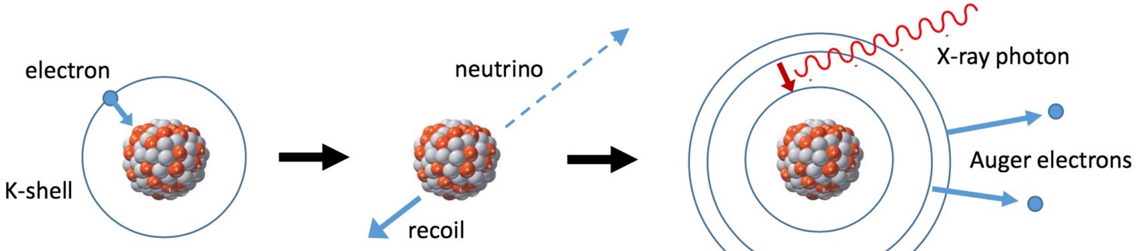
Our ignorance of the cosmology at the moment they are produced introduces uncertainties in all the cosmological/astrophysical limits that depend on their predicted relic abundance and momentum distribution, which should be taken into account when interpreting experimental and observational results.

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).

EXTRA SLIDES

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

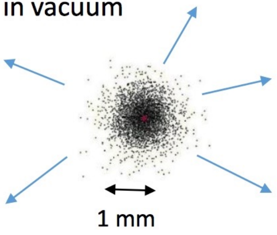
X-ray emitted
Auger electrons emitted

make precision momentum measurements of:
- recoil ion
- X-ray photon
- Auger electrons

↓

calculate missing ν momentum

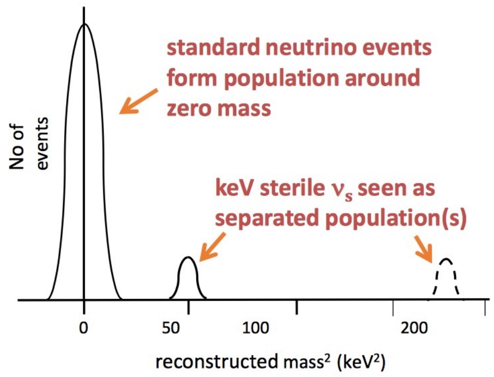
- Cloud of ^{131}Cs atoms (10 day half-life) suspended in vacuum



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

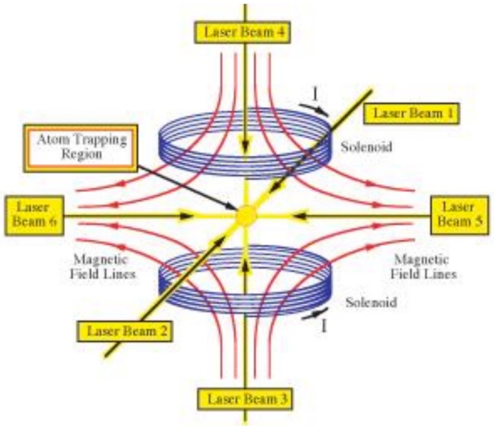
MOT - Magneto-Optical Trap

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)

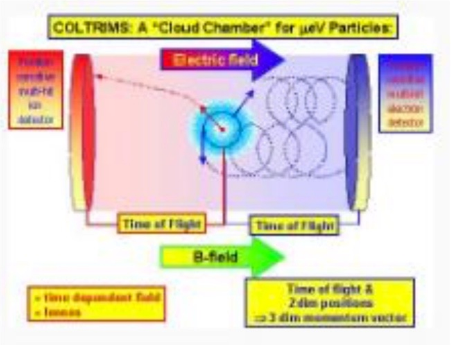


COLTRIMS – COLd Target Recoil Ion Mass Spectroscopy

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)



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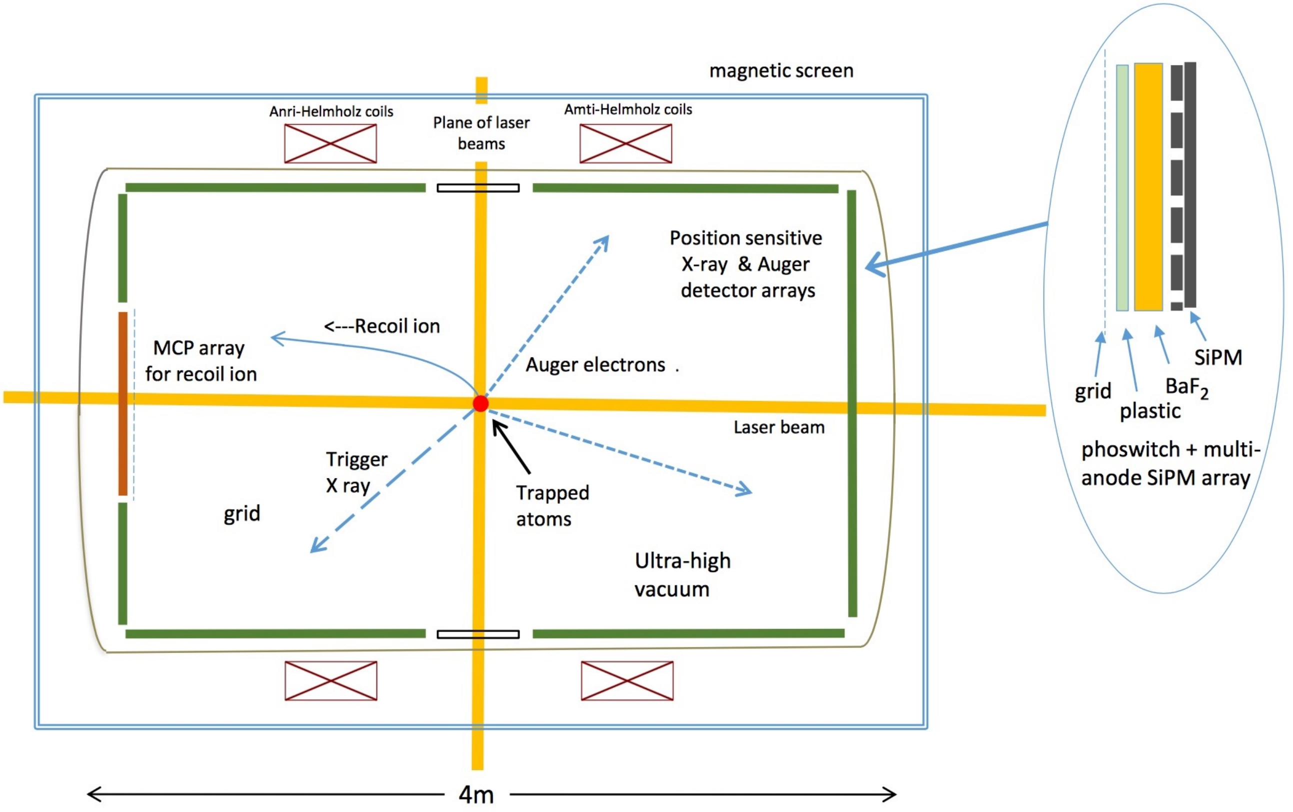
Original (2016) suggestion for 4π collection and time-of flight measurement



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

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