UCI Department of Physics & Astronomy

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Visible in the lab and invisible in cosmology: decaying sterile neutrinos

Helena Garcia Escudero
Kevork N. Abazajian

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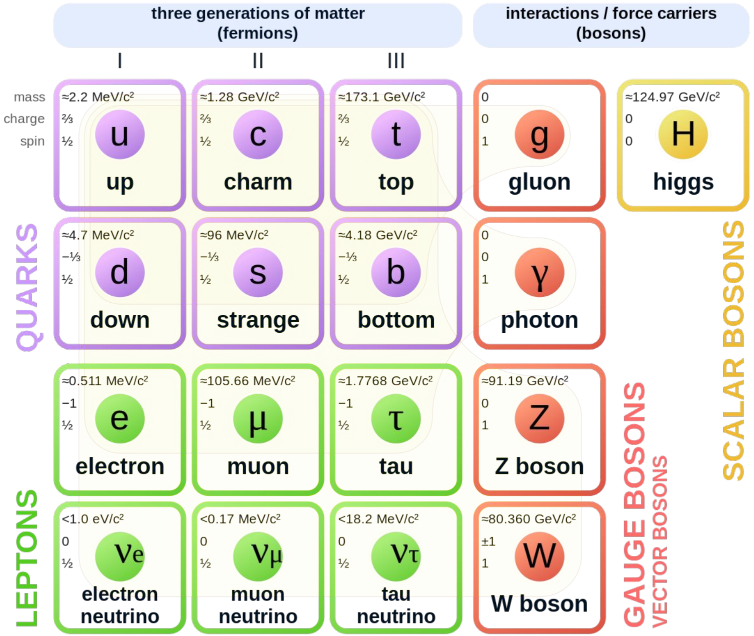
Introduction: Neutrino physics

Standard Model of Elementary Particles



✓ **mass-squared differences/mixing angles.**

✗ **absolute masses, mass-hierarchy, CP violating phase,...**

Neutrino Properties

we know the *mass-squared* differences:

$$\begin{cases} \delta m^2_{\odot} \approx 7.6 \times 10^{-5}\,\mathrm{eV}^2 \\ \delta m^2_{\mathrm{atm}} \approx 2.4 \times 10^{-3}\,\mathrm{eV}^2 \end{cases}$$

$$\boxed{\begin{pmatrix} |\nu_e\rangle \\ |\nu_\mu\rangle \\ |\nu_\tau\rangle \end{pmatrix} = U_m \begin{pmatrix} |\nu_1\rangle \\ |\nu_2\rangle \\ |\nu_3\rangle \end{pmatrix}}$$

Pontecorvo-Maki-Nakagawa-Sakats matrix

$$U_m = U_{23}\,U_{13}\,U_{12}\,M$$

$$U_{23} \equiv \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix}$$

$$U_{13} \equiv \begin{pmatrix} \cos\theta_{13} & 0 & e^{i\delta}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{-i\delta}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix}$$

$$U_{12} \equiv \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

4 parameters

$$\theta_{12}, \theta_{23}, \theta_{13}, \delta$$

$$\theta_{12} \approx 0.59^{+0.02}_{-0.015}$$

$$\theta_{23} \approx 0.785^{+0.124}_{-0.124} \approx \frac{\pi}{4}$$

$$\theta_{13} \approx 0.154^{+0.065}_{-0.065}$$

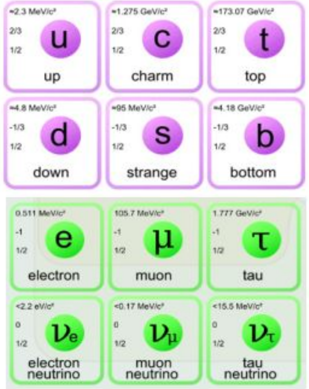
$$\delta = CP \text{ violating phase} =?$$

Introduction: Sterile neutrinos

Neutrino mass generation is an original hidden sector theory

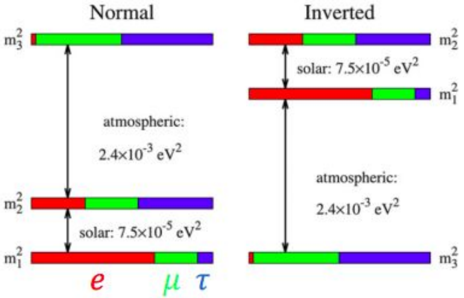
Neutrino oscillations → Neutrino mass → sterile neutrinos (dark fermions)

Left handed	right handed
✓	✓
✓	✓
✓	✓
✓	MISSING



Unseen in existing neutrino interactions

sterile/right-handed neutrinos



“Mixing” matrix

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}=\begin{pmatrix}c_{e1} & c_{e2} & c_{e3}\\ c_{\mu1} & c_{\mu2} & c_{\mu3}\\ c_{\tau1} & c_{\tau2} & c_{\tau3}\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

Bruno Pontecorvo

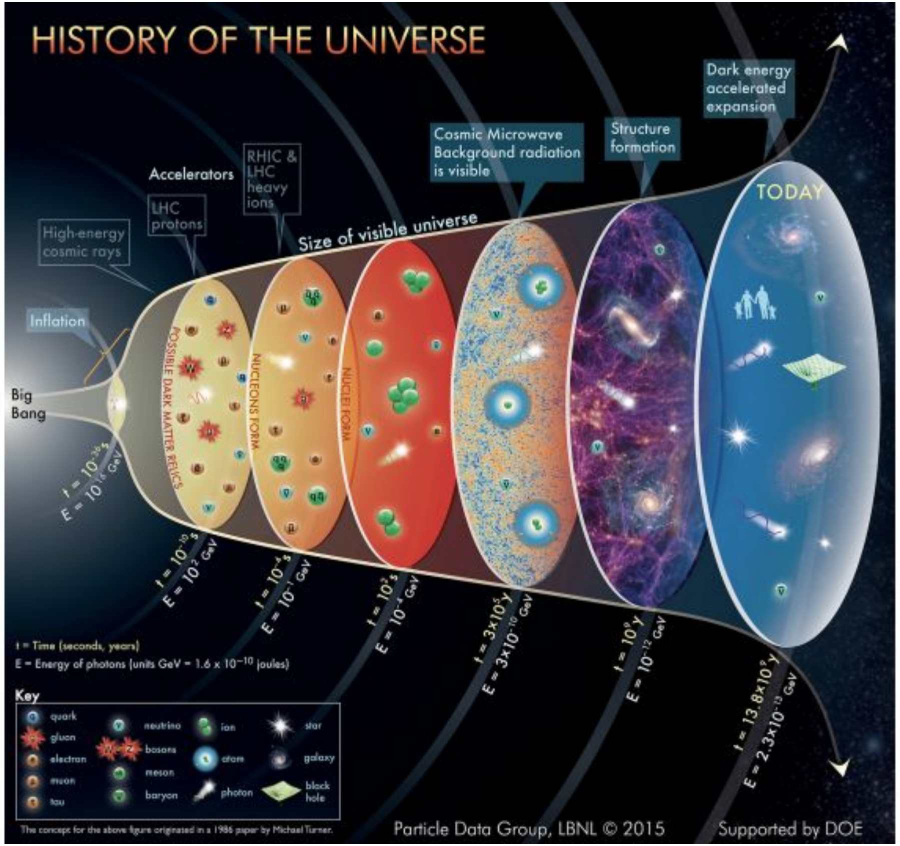
recognized that the handedness of the weak interactio
meant that non-zero neutrino rest mass could enable neutrino spin flip from active, left-handed states, to **“sterile”**, right-handed states.

Soviet Physics – JETP **26**, 984 (1968)

$$\left\{\begin{aligned}&\delta m_\odot^2 \approx 7.6\times10^{-5}\,\mathrm{eV}^2\\ &\delta m_{\mathrm{atm}}^2 \approx 2.4\times10^{-3}\,\mathrm{eV}^2\end{aligned}\right.$$

- We need 2 ~ 100GeV sterile neutrinos to produce the 2 known mass difference scales
(only hidden sector model with evidence for its existence from lab) https://arxiv.org/pdf/1204.5379.pdf
- 3rd sterile neutrino has complete freedom!
- Sterile neutrinos in the keV scale are viable **candidates** for **dark matter**.

Thermal History Universe: Low reheating Scenarios

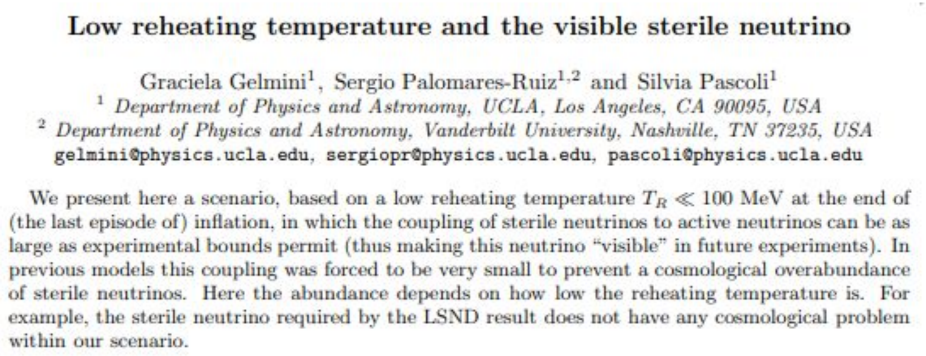


The concept for the above figure originated in a 1986 paper by Michael Turner.

Particle Data Group, LBNL © 2015

Supported by DOE

- We don’t know cosmology before BBN ($\gtrsim$ 5MeV).
- Earliest data relative abundances of light elements formed during BBN.
- What if we consider a low reheating temperature of the Universe?



Low reheating temperature and the visible sterile neutrino

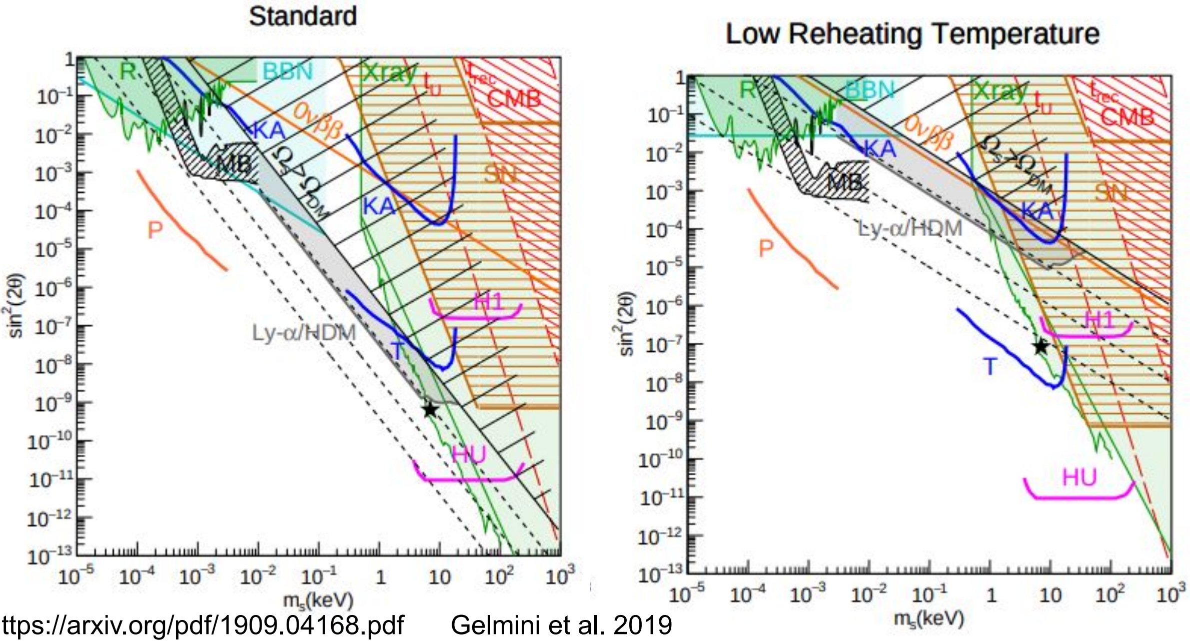
Graciela Gelmini[1], Sergio Palomares-Ruiz[1,2] and Silvia Pascoli[1]
[1] *Department of Physics and Astronomy, UCLA, Los Angeles, CA 90095, USA*
[2] *Department of Physics and Astronomy, Vanderbilt University, Nashville, TN 37235, USA*
`gelmini@physics.ucla.edu`, `sergiopr@physics.ucla.edu`, `pascoli@physics.ucla.edu`

We present here a scenario, based on a low reheating temperature $T_R \ll 100$ MeV at the end of (the last episode of) inflation, in which the coupling of sterile neutrinos to active neutrinos can be as large as experimental bounds permit (thus making this neutrino “visible” in future experiments). In previous models this coupling was forced to be very small to prevent a cosmological overabundance of sterile neutrinos. Here the abundance depends on how low the reheating temperature is. For example, the sterile neutrino required by the LSND result does not have any cosmological problem within our scenario.

https://arxiv.org/pdf/astro-ph/0403323.pdf

Low reheating temperature

In low reheating universes, the sterile neutrino becomes “visible” !!



https://arxiv.org/pdf/1909.04168.pdf Gelmini et al. 2019

-Cosmological bounds not robust.

-Direct laboratory searches (results independent of cosmology) can test both, particle physics and cosmology.

-A visible sterile neutrino could be the first preBBN remnant.

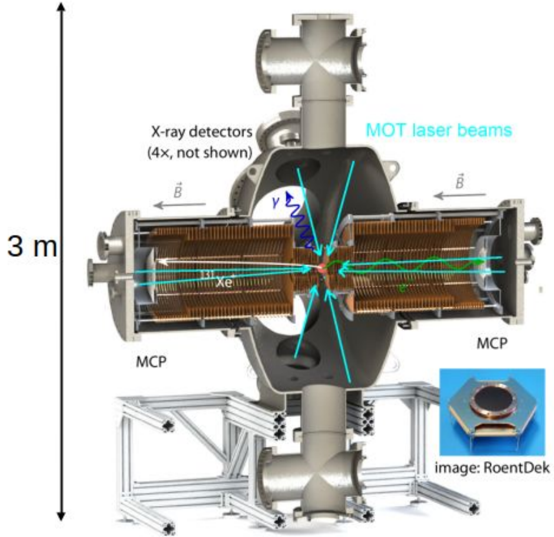
BSM Neutrino Sector Examples

LOW REHEATING INFLATION AND STERILE NEUTRINOS:
Decay/re-heat “close” or during/after BBN (Kishimoto, Kusenko 2012; Rasmussen et al.2021; Gelmini et al. 2021)

Existing lab limits: HUNTER, KATRIN/TRISTAN, MAGNETO-ν, PTOLEMY

HUNTER spectrometer

Heavy Unseen Neutrinos by Total Energy-momentum Reconstruction



- kinematic reconstruction experiment to search for keV-mass sterile neutrinos using electron capture isotope 131Cs (t = 9.7 days).
- ^{131}Cs is held in a magneto-optical trap and laser cooled to 20 μK
- with sufficient resolution to probe the mν = 30 - 300 keV mass range.

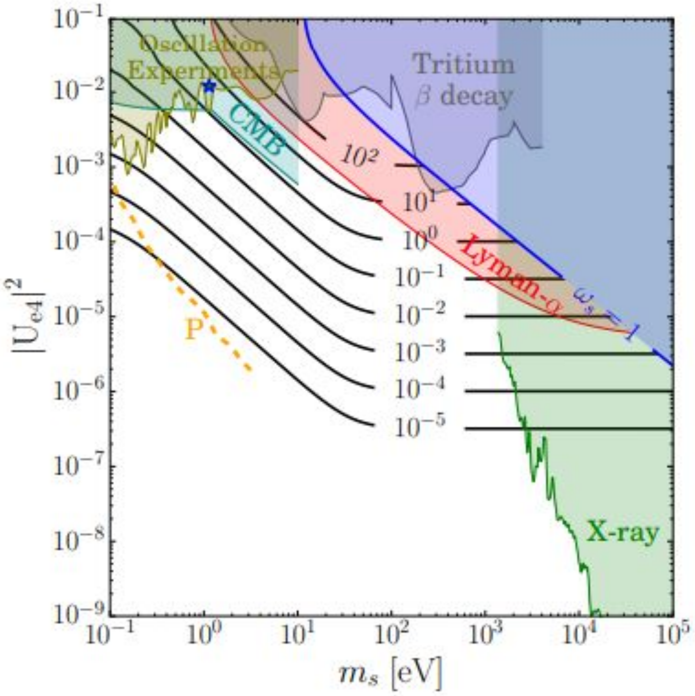
https://hudsongroup.physics.ucla.edu/content/hunter-sterile-neutrino-search

Sterile neutrinos would be visible to nuclear physics experiments!

PTOLEMY-type experiments

Detect Cosmic Neutrino Background (CNB) from neutrino capture on β-decay nuclei.

https://arxiv.org/pdf/2212.14192.pdf

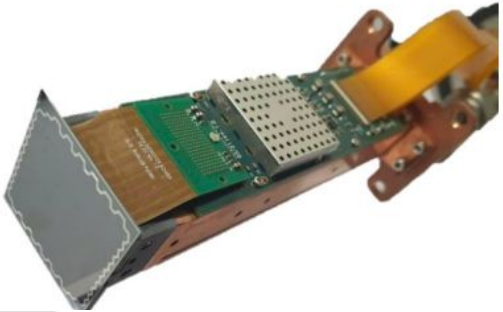


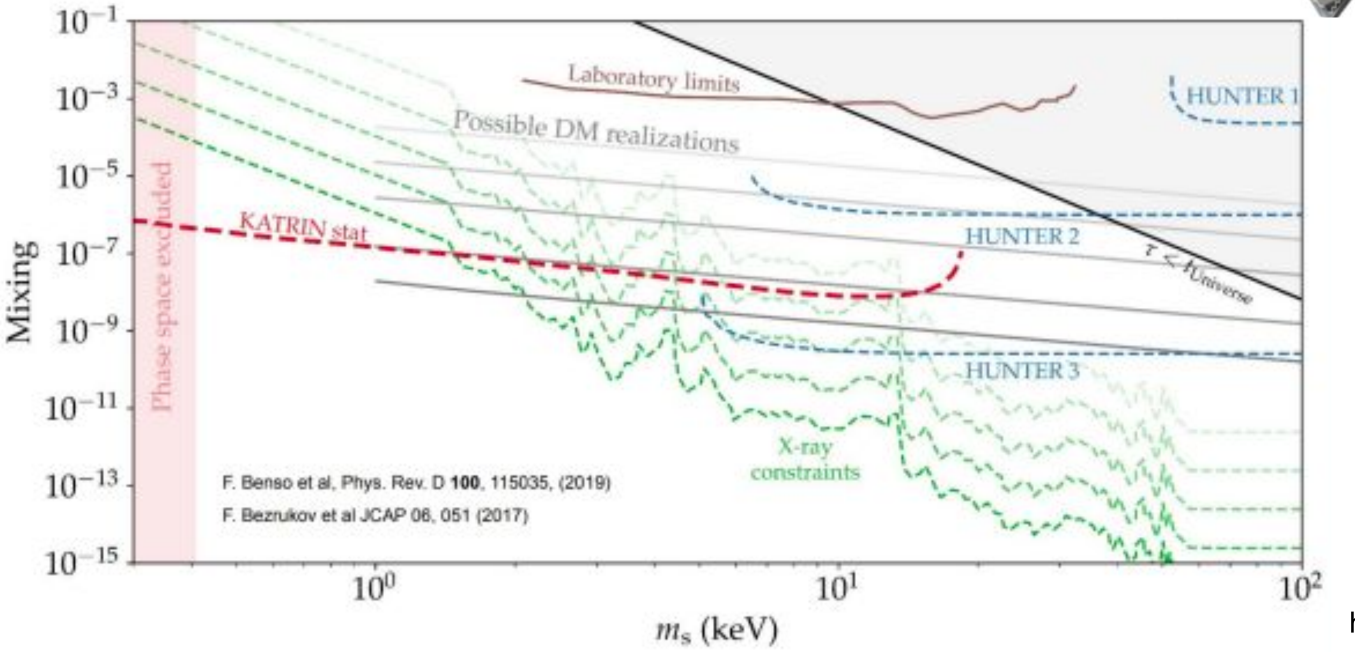
Laboratory experiments: HUNTER, KATRIN/TRISTAN, MAGNETO-ν, PTOLEMY

KATRIN/TRISTAN (detector)

Main goal of directly determining the effective electron anti-neutrino mass.

Spectroscopic measurement of the tritium β-decay spectrum.





F. Benso et al, Phys. Rev. D **100**, 115035, (2019)

F. Bezrukov et al JCAP 06, 051 (2017)

New detector system TRISTAN detector currently being developed

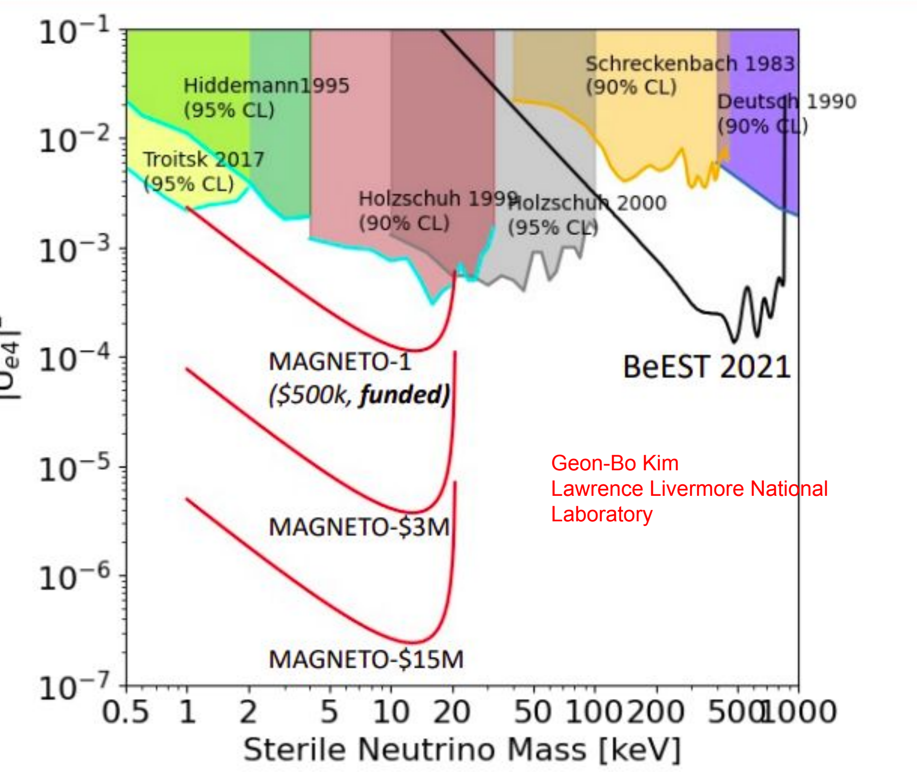
- Extend measurement interval to several keV
- Improve laboratory-based sensitivity to keV-scale sterile neutrinos

https://arxiv.org/pdf/2207.06337.pdf

Laboratory experiments: HUNTER, KATRIN/TRISTAN, MAGNETO-ν, PTOLEMY

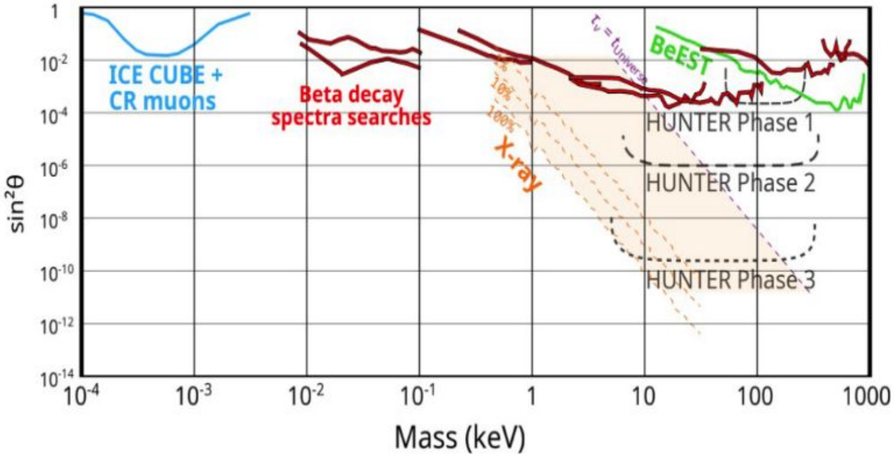
MAGNETO-ν SENSITIVITY

MAGNETO-ν upcoming experiment is a search for keV sterile neutrino in 241Pu beta decays with magnetic quantum sensors.



Geon-Bo Kim
Lawrence Livermore National Laboratory

HUNTER SENSITIVITY

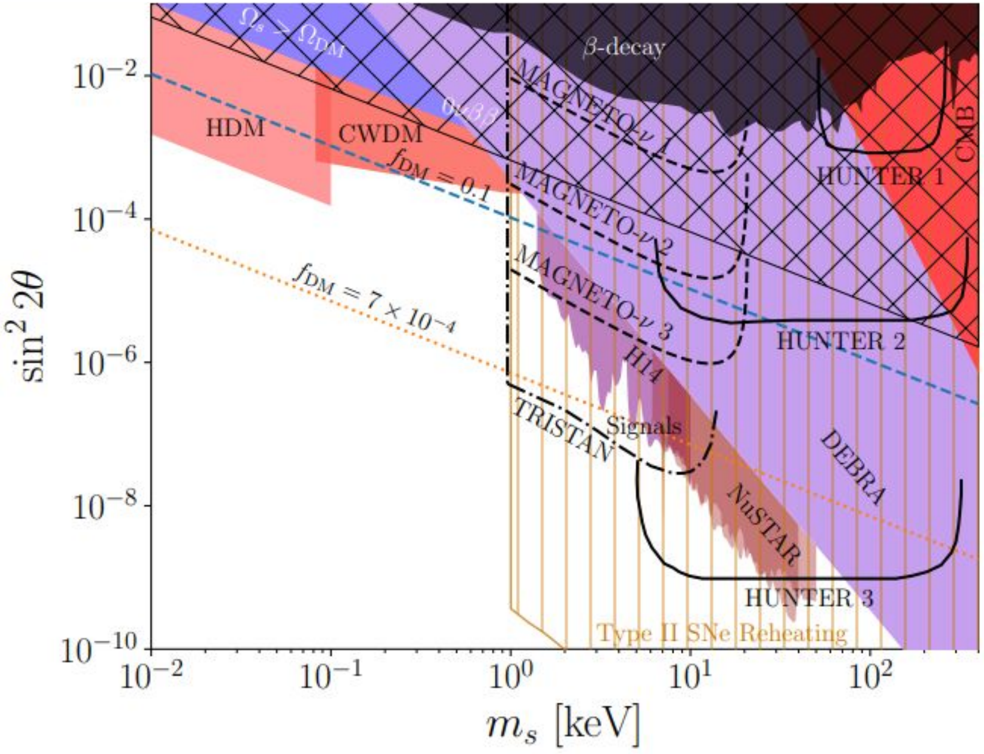


HUNTER kinematic [illegible]

Tight cosmological constraints

Within the Standard (usual) thermal history of the Universe

very constrained by cosmology in this parameter space!



https://arxiv.org/pdf/2203.07377.pdf

What does cosmology say?

What must happen in cosmology if these experiments see something? Dark decay could be involved

Majoron fields

Blocking Active-Sterile Neutrino Oscillations in the Early Universe with a Majoron Field

Bento et al. (https://arxiv.org/abs/hep-ph/0108064)

Light boson mediator

A ménage à trois of eV-scale sterile neutrinos, cosmology, and structure formation

Dasgupta et al . (https://arxiv.org/abs/1310.6337)

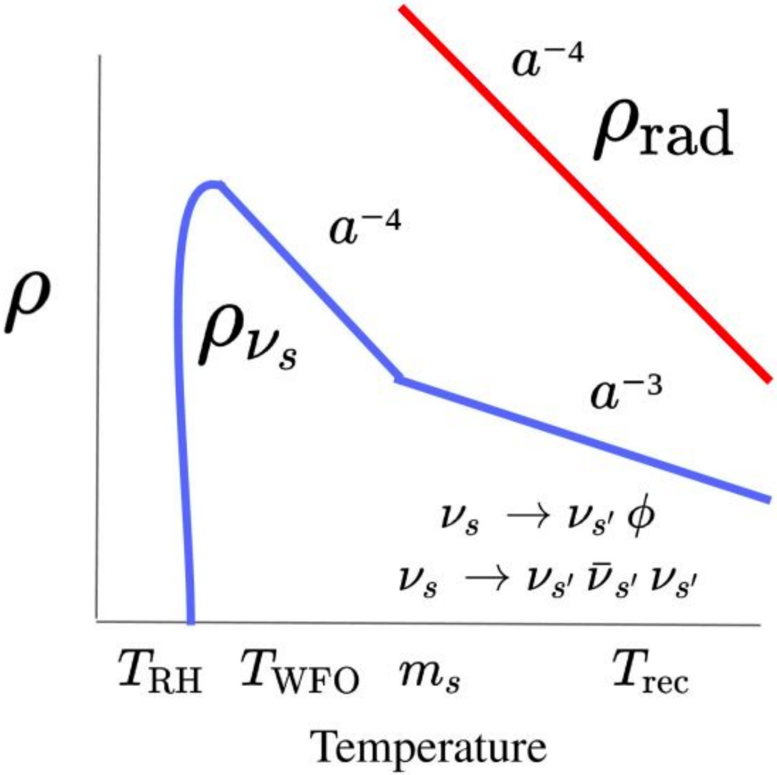
phase transitions

Probing sterile neutrino dark matter in the PTOLEMY-like experiment

Choi et al (https://arxiv.org/abs/2212.14192)

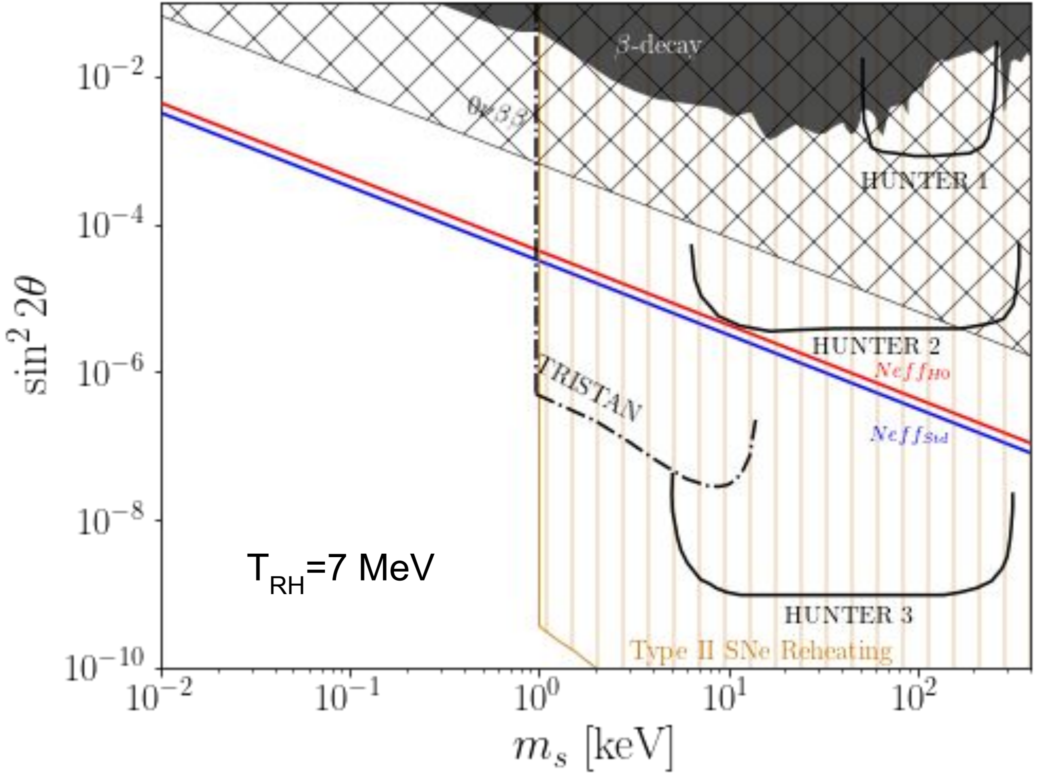
Cosmological Invisible Decay of Light Sterile Neutrinos

Gariazzo et al (https://arxiv.org/abs/1404.6160)



Dark decay calculations

Within a low reheating scenario, a dark decay through a Z’ or a new scalar, can lead to 3 body or 2 body decay to relativistic particles:



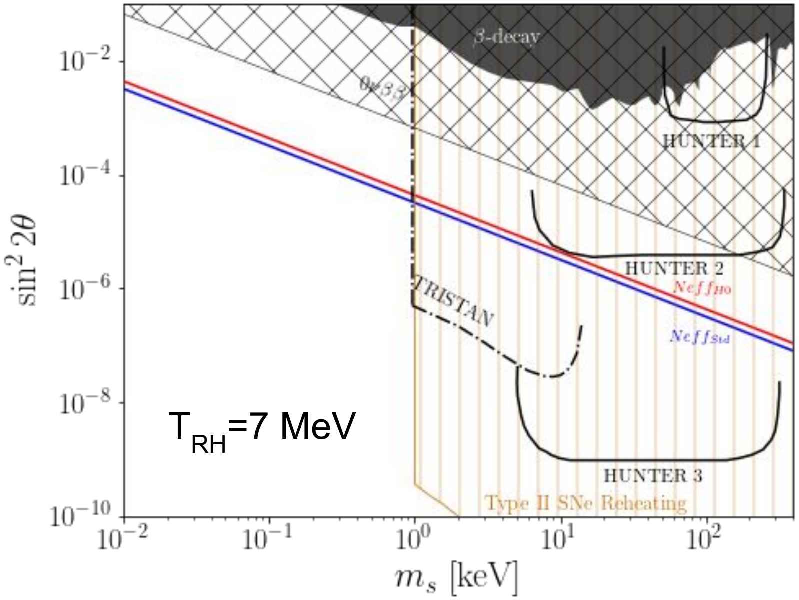
1. Happen without violating cosmological constraints!
2. Can provide extra N_{eff} to alleviate Hubble tension

Increase matter density at early times

$$H_0 = H_{\rm rec} \frac{\int_{t_{\rm rec}}^{t_0} \frac{c\, dt/t_0}{[\rho(t)/\rho_0]^{1/2}}}{\int_0^{t_{\rm rec}} \frac{c_s(t)\, dt/t_{\rm rec}}{[\rho(t)/\rho(t_{\rm rec})]^{1/2}}}$$

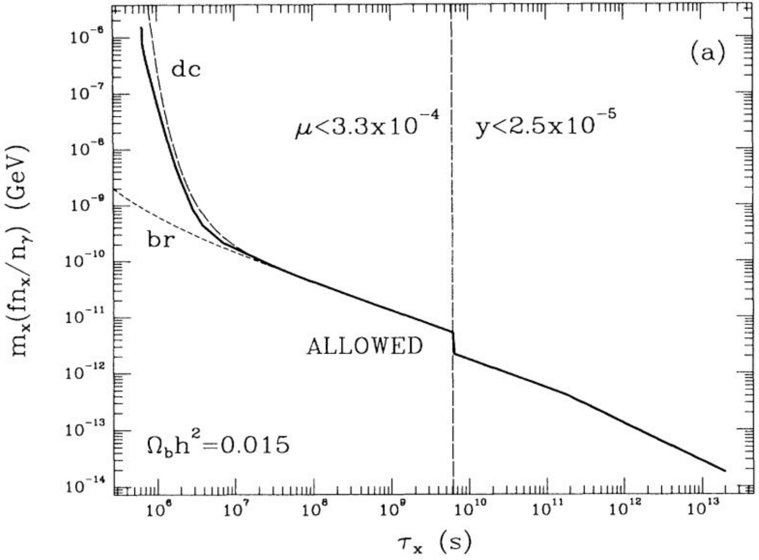
Sterile Neutrino Sensitivity in the next Generation of Searches

- high mixing angle → large production → early decay
- Small mixing angle → small production → late decay to boost abundance relative to relativistic sector
- Looking at radiative decay, in late-decay scenarios most constraining at **large masses**, but still **not significant effect on CMB spectral parameters** (by a factor ~10).



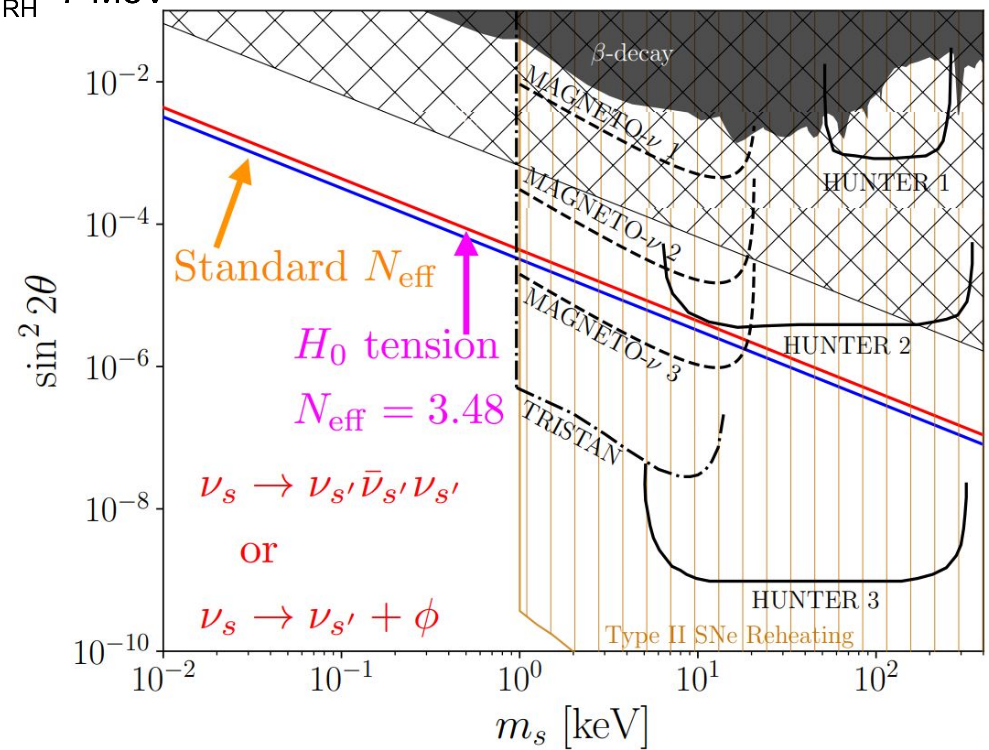
T_{RH}=7 MeV

Hu et al. (https://doi.org/10.1103/PhysRevLett.70.2661)



MAIN CONCLUSION

T_{RH}=7 MeV

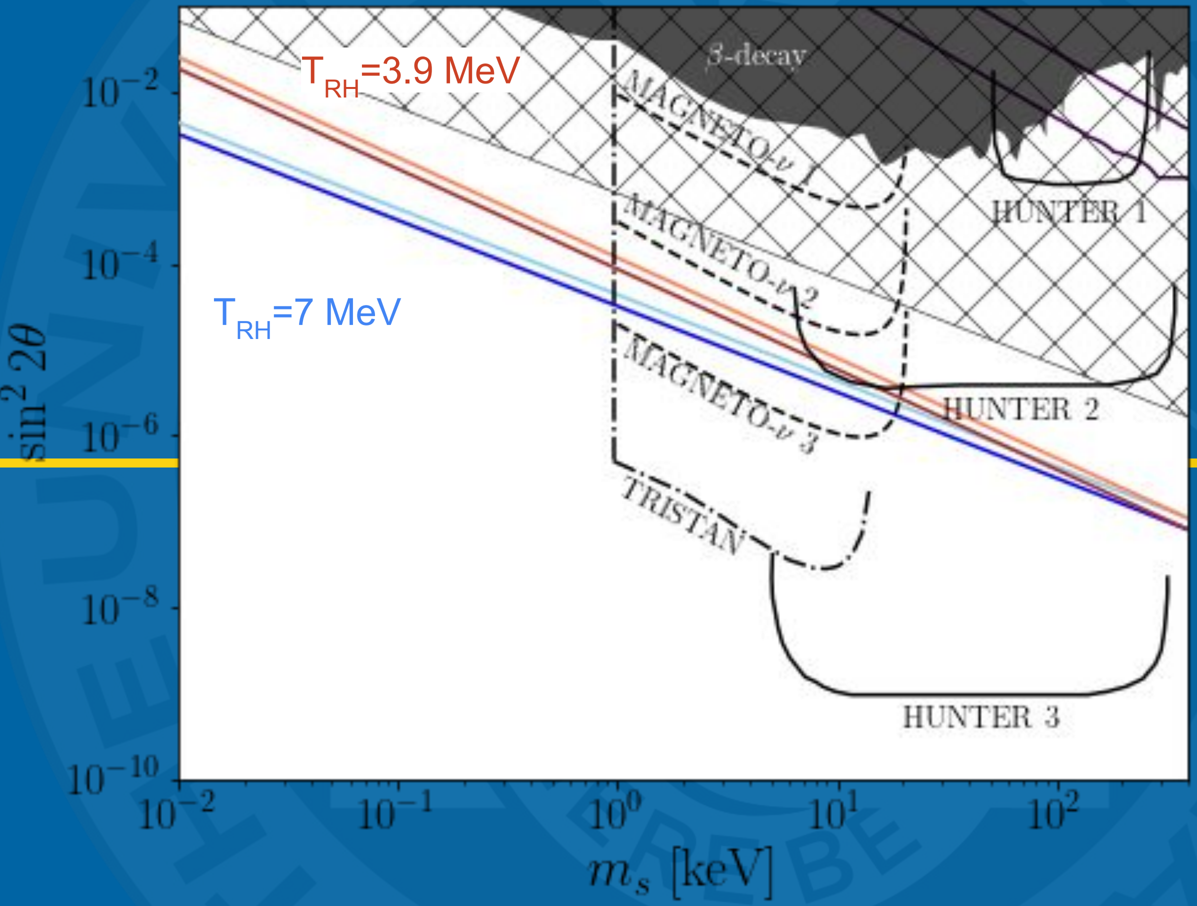


Abazajian, García Escudero in progress (2023)

Current/upcoming laboratory experiments may reveal (within the next few years) an exotic early Universe, explaining the first detected remnant from the untested pre-BBN era in the Universe.

THANK YOU FOR YOUR ATTENTION!

QUESTIONS?



T_{RH}=3.9 MeV

T_{RH}=7 MeV

New Journal of Physics
The open access journal for physics

A mini review on Affleck–Dine baryogenesis

Rouzbeh Allahverdi[1] **and Anupam Mazumdar**[2]
[1] Department of Physics and Astronomy, University of New Mexico,
Albuquerque, NM 87131, USA
[2] Consortium for Fundamental Physics, Lancaster University, LA1 4YB, UK
E-mail: rouzbeh@unm.edu and a.mazumdar@lancaster.ac.uk

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Abstract. The Affleck–Dine mechanism is an attractive scenario for generating the observed baryon asymmetry of the universe utilizing flat directions in the scalar potential of supersymmetric theories. In this mini review, we describe this mechanism in its original version, its explicit realization within the minimal supersymmetric standard model and its variants. We discuss the formation of a condensate along the flat directions in the inflationary era, its post-inflationary evolution leading to baryogenesis and its fate. In some cases the condensate may fragment into non-topological solitons, known as Q-balls, during its evolution. In models of gravity-mediated supersymmetry breaking, the Q-balls can be long-lived, in which case their decay will be the source of all baryons and dark matter in the form of the lightest supersymmetric particle. In models of gauge-mediated supersymmetry breaking, the Q-balls can be absolutely stable and form dark matter that can be searched for directly.

doi:10.1088/1367-2630/14/12/125013