International Center for
Quantum-field Measurement Systems for
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WPI research center at KEK

Two-sided story of sterile neutrinos: Production under the X-ray limit

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Based on [M. Chen, G. B. Gelmini, P. Lu, and V. Takhistov, Phys.Lett.B 852 (2024) 138609, arXiv: 2309.12258 & JCAP 07 (2024) 059, arXiv: 2312.12136]

Introduction

Sterile neutrino

Sterile neutrinos with no weak interactions (right-handed) can be added to the Standard Model (SM).

- Motivation: massive neutrinos, minimal extension.
- Mixing:

$$|\nu_a\rangle = \cos\theta|\nu_1\rangle + \sin\theta|\nu_2\rangle;$$
$$|\nu_s\rangle = -\sin\theta|\nu_1\rangle + \cos\theta|\nu_2\rangle;$$

- Sterile neutrinos can be created via mixing dependent mechansims such as active-sterile oscillation.
- Detecting through X-rays due to $\nu_s \to \nu\gamma$

Production Mechanism

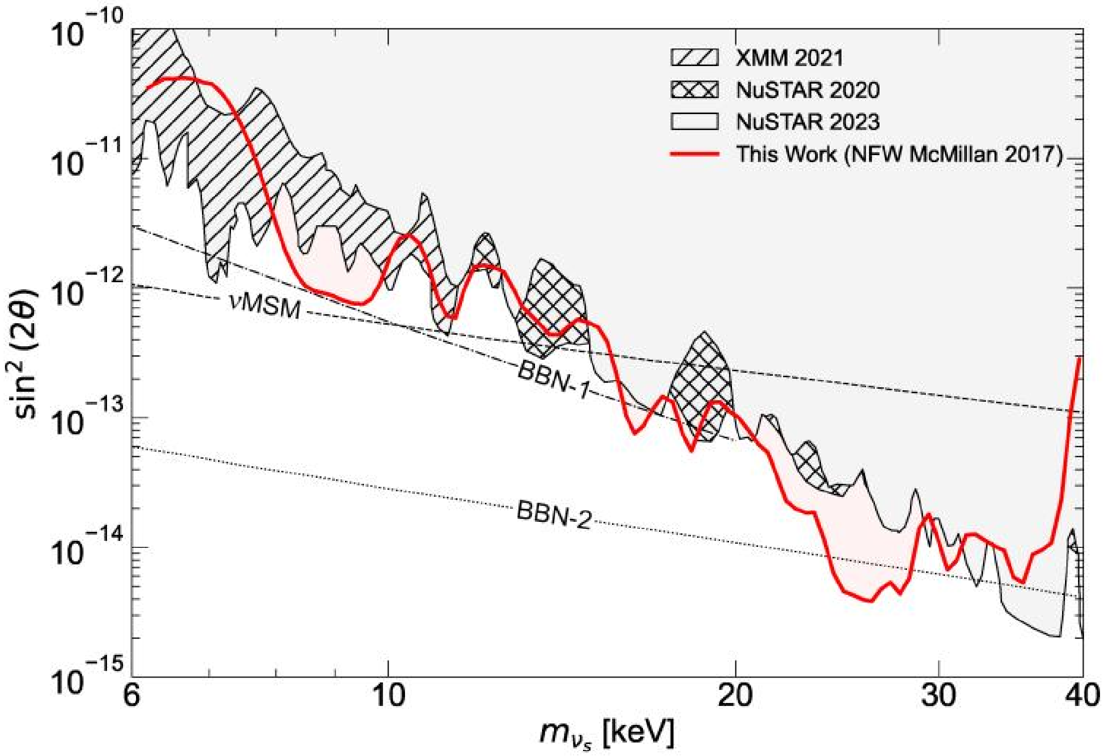
- Doldson & Widrow S. dodelson and L. M. Widrow, Phys.Rev.Lett. 72 (1994) 17-20 [hep-ph/9303287]
  - Maximum production temperature: $T_{\max} \simeq 133\ \mathrm{MeV} \left(\frac{m_s}{\mathrm{keV}}\right)^{1/3}$
  - Density fraction

$$f_{s,\mathrm{osc}} = 2.7 \times 10^{-4} \left(\frac{\sin^2 2\theta}{10^{-10}}\right) \left(\frac{m_s}{\mathrm{keV}}\right)^2 \left(\frac{30}{g_*(T_{\max})}\right)^{3/2}$$

$$f_{s,osc}^{\mathrm{LRT}} \simeq 1 \times 10^{-7} \left(\frac{\sin^2 2\theta}{10^{-10}}\right) \left(\frac{m_s}{\mathrm{keV}}\right) \left(\frac{T_{RH}}{5\ \mathrm{MeV}}\right)^3 \qquad \text{if} \quad T_{\mathrm{RH}} < T_{\max}$$

- Many other production mechanisms

X-ray Decays



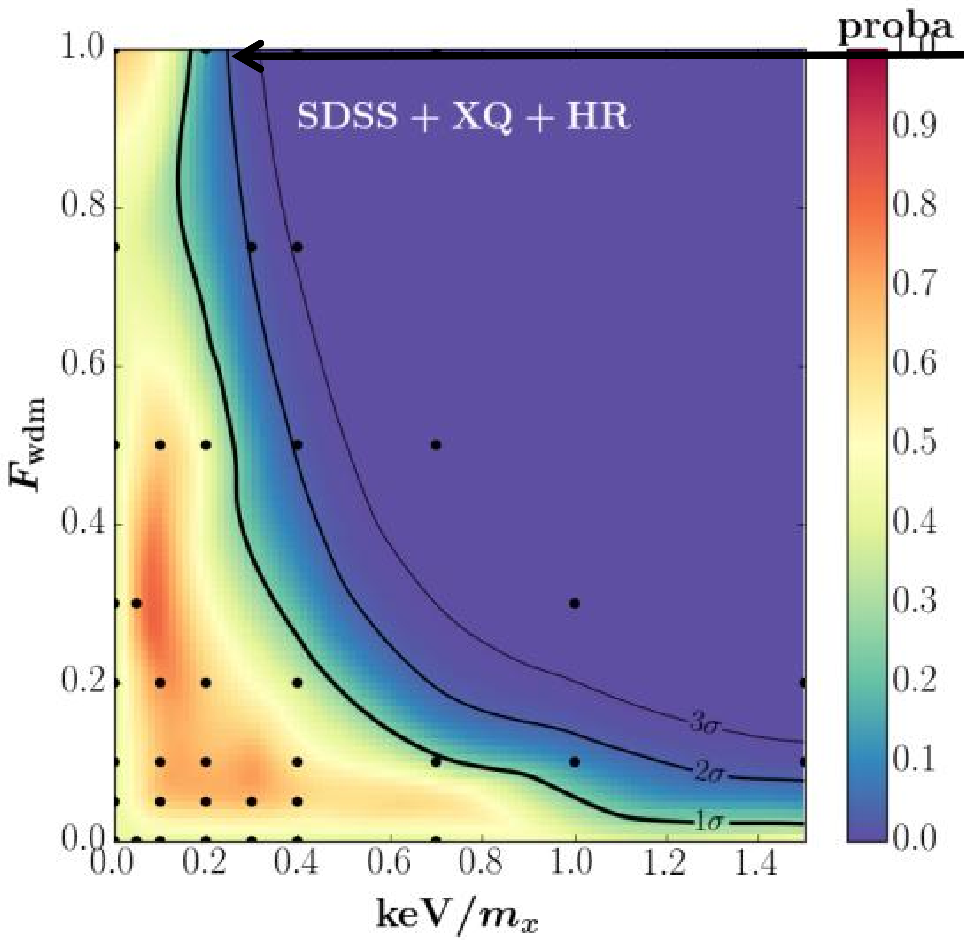
R. A. Krivonos, V. V. Barinov,2, Mukhin, and D. S. Gorbunov, Phys.Rev.Lett. 133 (2024) 26, 261002 [2405.17861]

Decay rate:

$$\Gamma = 1.38 \times 10^{-32} \mathrm{s}^{-1} \left(\frac{\sin^2 2\theta}{10^{-10}}\right) \left(\frac{m_\chi}{\mathrm{keV}}\right)^5$$

- Constrain $\sin^2 2\theta$ for $f_s = 1$
- Constrain $f_s \sin^2 2\theta$ for $f_s < 1$

Lyman-alpha bound



J. Baur et al., JCAP 12 (2017) 013 [1706.03118]

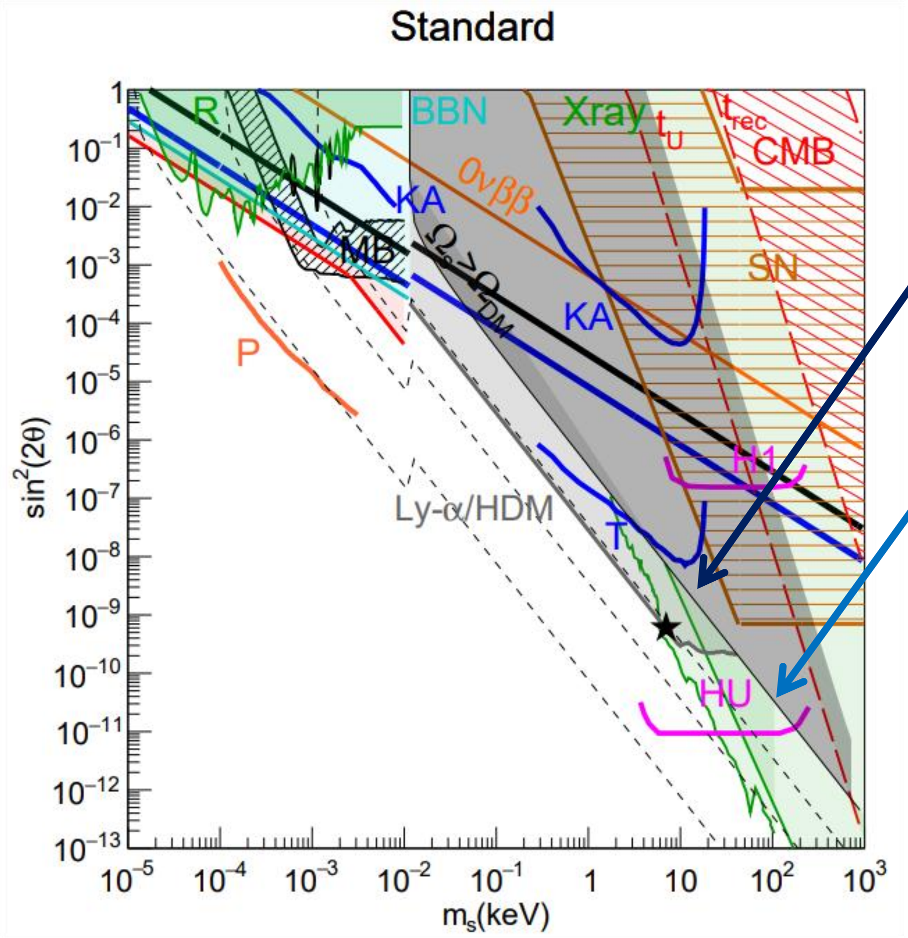
DM fermion disfavored

$$m_{\rm therm} \leq 3{\rm keV}$$

This bound can be extended to sterile neutrinos

$$m_s \simeq 4\,{\rm keV}\left(\frac{\langle\epsilon\rangle}{3.15}\right)\left(\frac{m_{\rm therm}}{\rm keV}\right)^{4/3}\left(\frac{10.75}{g_*}\right)^{1/3}$$

Motivation



G. B. Gelmini, P. Lu, and V. Takhistov, JCAP 12 (2019) 047 [1909.13328]

Too hot to make up the whole of DM

Excluded by X-ray limit

Possible new production mechanism less restricted by neutrino interactions?

PBH Neutrinogenesis

PBH Evaporation

PBHs emit Hawking radiation with an approximately blackbody spectrum

- PBHs with mass $M_{\rm PBH}$ and density fraction $f_{\rm evap}$
  - Radiation domination(RD) if $f_{\rm evap} < 1$
  - PBH domination(PD) if $f_{\rm evap} = 1$
- Hawking temperature

$$T_{\rm PBH} = \frac{M_{\rm Pl}^2}{8\pi M_{\rm PBH}} = 1.06 \times 10^5 \ {\rm GeV} \left(\frac{10^8 {\rm g}}{M_{\rm PBH}} \right)$$

- Evaporation temperature:

$$T_{\rm evap} \simeq 43 \ {\rm MeV} \left(\frac{10^8 {\rm g}}{M_{\rm PBH}} \right)^{3/2} \left(\frac{10.75}{g_*(T_{\rm evap})} \right)^{1/4} \left(\frac{g_H}{110} \right)^{1/2}$$

PBH neutrinogenesis

Current sterile neutrino density fraction due to PBH:

$$f_s = \frac{\rho_s(T_0)}{\rho_{\rm DM}} \simeq 2\times 10^{-6} f_{\rm evap}\left(\frac{m_s}{\rm keV}\right)\left(\frac{10^8 {\rm g}}{M_{\rm PBH}}\right)^{1/2}\left(\frac{10.75}{g_*(T_{\rm evap})}\right)^{1/4}$$

$$\simeq 1\times 10^{-6} f_{\rm evap}\left(\frac{m_s}{\rm keV}\right)\left(\frac{T_{\rm evap}}{5\ {\rm MeV}}\right)^{1/3}\left(\frac{10.75}{g_*\left(T_{\rm evap}\right)}\right)^{1/6}.$$

Does not depend on the mixing angle

⇩

New parameter space $(m_s, T_{\rm evap}(M_{\rm PBH}))$

Relic momentum

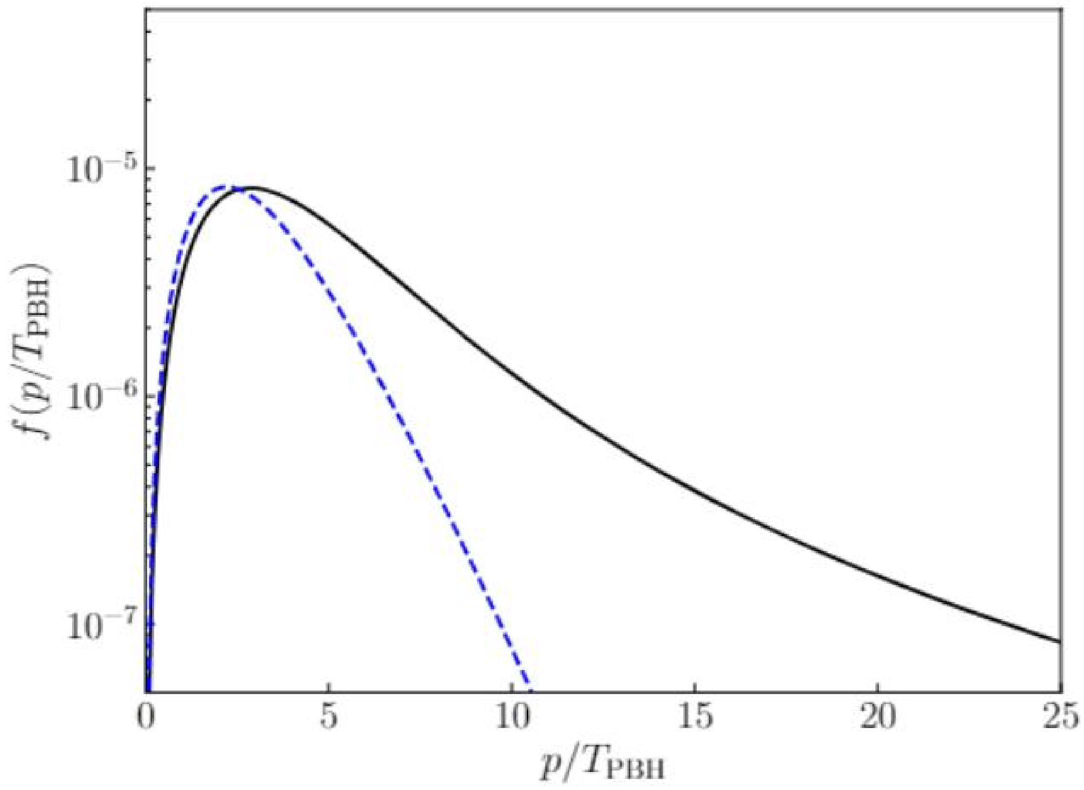
For spin-1/2 particles, peaks at
$E = 4.5 T_{\rm PBH}$

Average scaled momentum at evaporation

$$\langle \epsilon \rangle = \frac{\langle p \rangle}{T_{\rm evap}} \simeq \frac{6.3\, T_{\rm PBH}}{T_{\rm evap}}$$

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

Much larger than $\langle \epsilon \rangle_{\rm FD} = 3.15$ from a fermi-dirac spectrum.



M. Chen, G. B. Gelmini, P. Lu, and V. Takhistov, JCAP 07 (2024) 059 [2312.12136]

Additional Constraint

- Condition: $f_s > f_{s,\mathrm{osc}}$

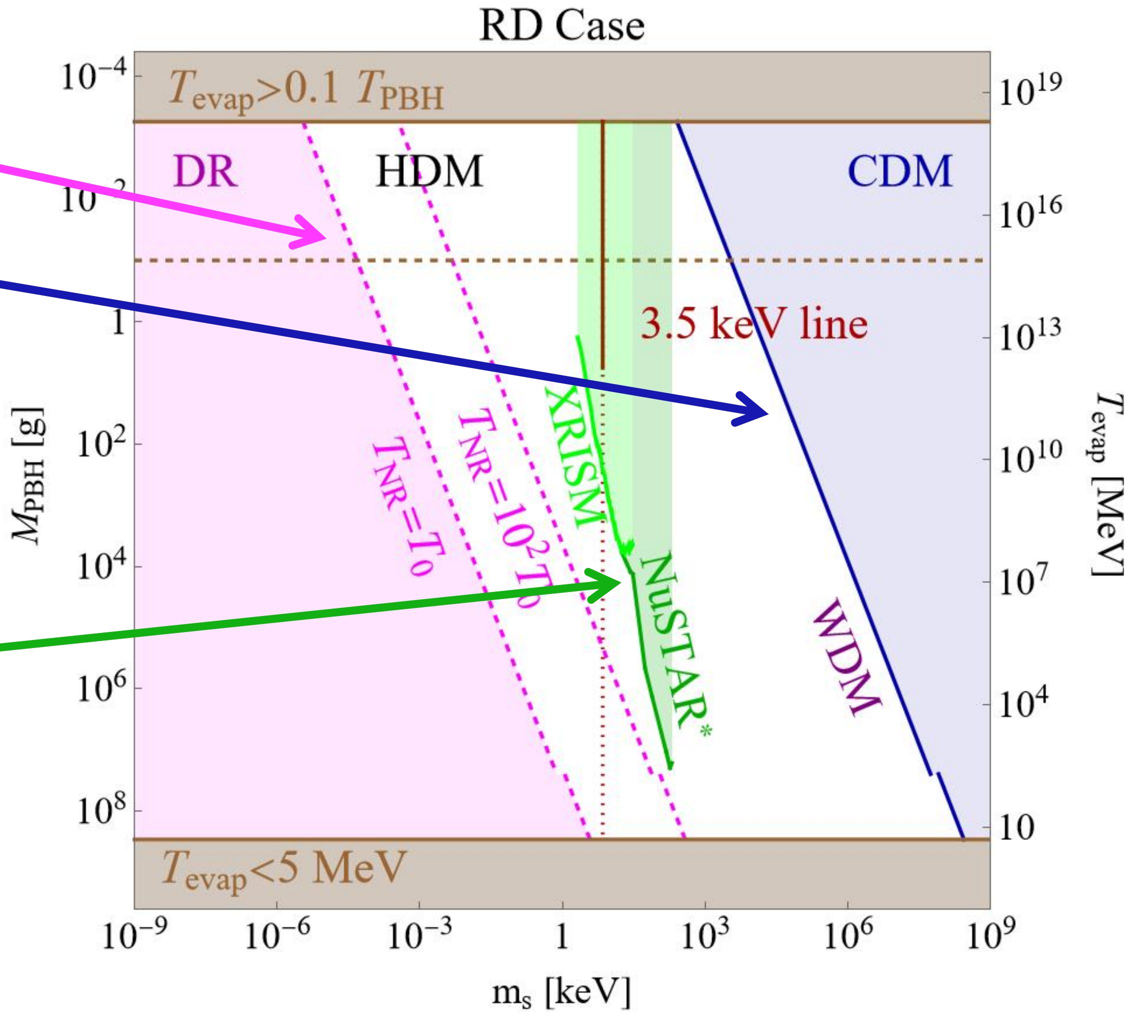
- Bound on the mixing:

$$\sin^2(2\theta) < 4\times10^{-13} f_{\mathrm{evap}} \left(\frac{\mathrm{keV}}{m_s}\right) \left(\frac{10.75}{g_*(T_{\mathrm{evap}})}\right)^{1/6} \left(\frac{g_*(T_{\mathrm{max}})}{30}\right)^{3/2} \left(\frac{T_{\mathrm{evap}}}{5\ \mathrm{MeV}}\right)^{1/3}$$

$$\sin^2(2\theta) < 1\times10^{-9} \left(\frac{10.75}{g_*(T_{\mathrm{RH}})}\right)^{1/6} \left(\frac{5\ \mathrm{MeV}}{T_{\mathrm{RH}}}\right)^{8/3} \qquad T_{\mathrm{RH}} < T_{\mathrm{max}}$$

Regions and limits-RD

- Nonrelativistic Limit
- Lyman-alpha limit
  - WDM
    $$f_{evap} \simeq 4 \times 10^{-3} \left(\frac{g_*(T_{evap})}{10.75} \right)^{1/3}$$
  - Above the bound
    $$f_s = 1$$
- X-ray signals
  - bounds
    $$f_s > f_{s,osc}$$

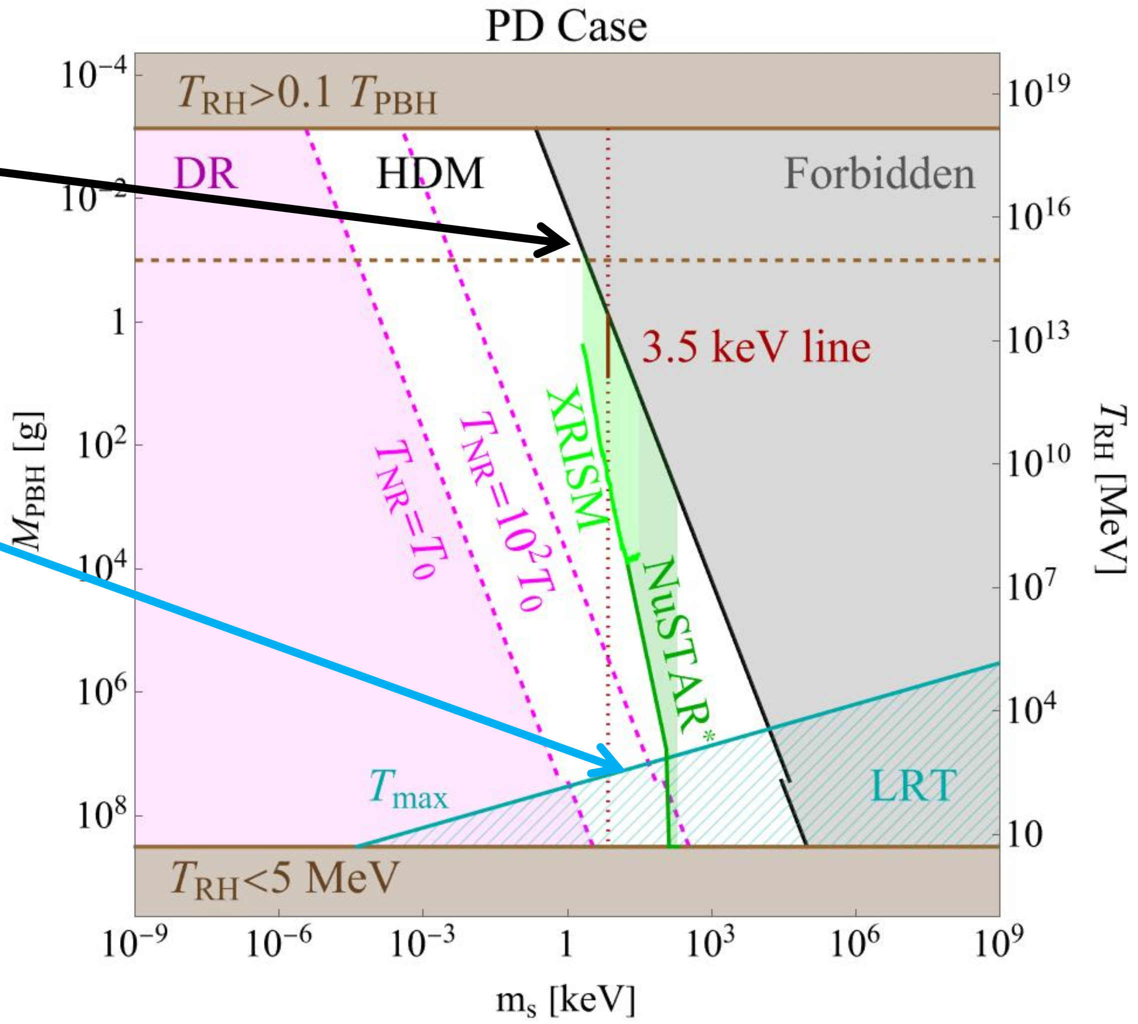


M. Chen, G. B. Gelmini, P. Lu, and V. Takhistov, JCAP 07 (2024) 059 [2312.12136]

Regions and limits-PD

- Forbidden region
  - HDM condition
    $f_s < 0.1$

- Low Reheating Region



M. Chen, G. B. Gelmini, P. Lu, and V. Takhistov, JCAP 07 (2024) 059 [2312.12136]

Gravitational Signal

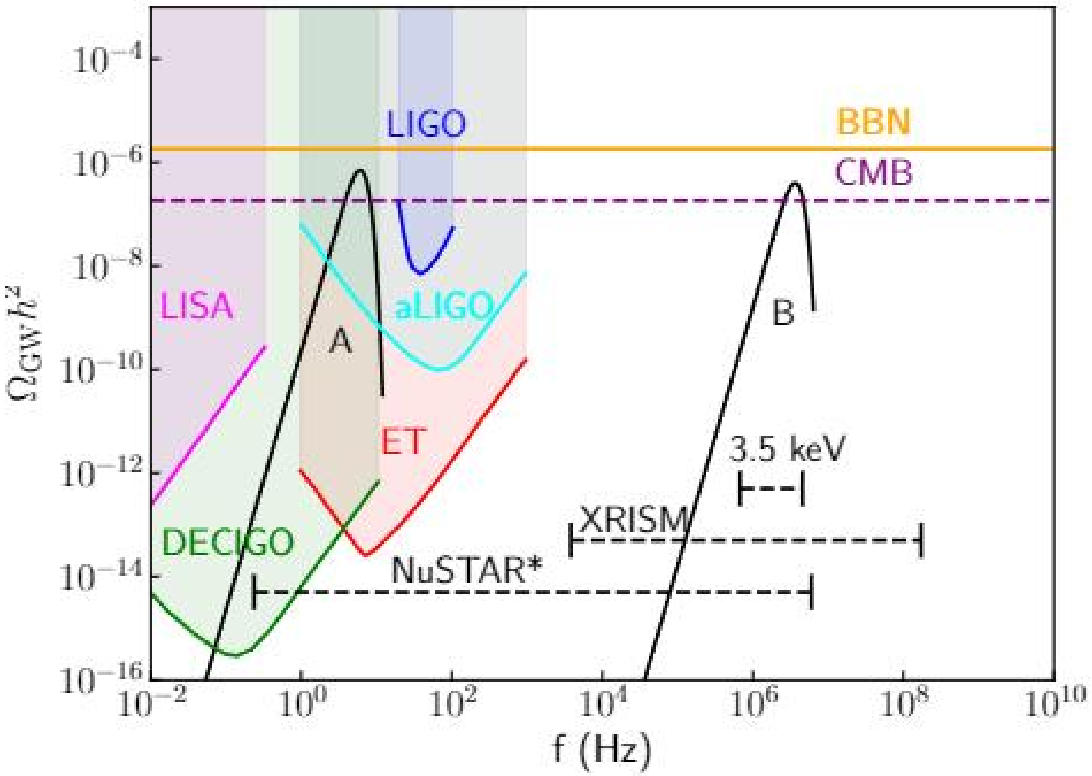
- Induced GWs from PBH evaporation
- UV cut-off frequency:

$$f_{\rm UV} = 1.7 \times 10^3 \text{ Hz} \left(\frac{M_{\rm PBH}}{10^4 {\rm g}}\right)^{-5/6}$$

- Present density of GWs at the peak

$$\Omega^{\rm peak}_{\rm GW,0} h^2 = 1.64 \times 10^{-6} \left(\frac{\gamma}{0.2}\right)^{\frac{7}{9}} \left(\frac{\beta}{10^{-8}}\right)^{\frac{16}{3}} \left(\frac{M_{\rm PBH}}{10^7 {\rm g}}\right)^{\frac{34}{9}}$$

- Very optimistic examples:
  - A: $M_{\rm PBH} = 2 \times 10^7$ g, $\beta = 6 \times 10^{-9}$
  - B: $M_{\rm PBH} = 1$ g, $\beta = 8 \times 10^{-4}$



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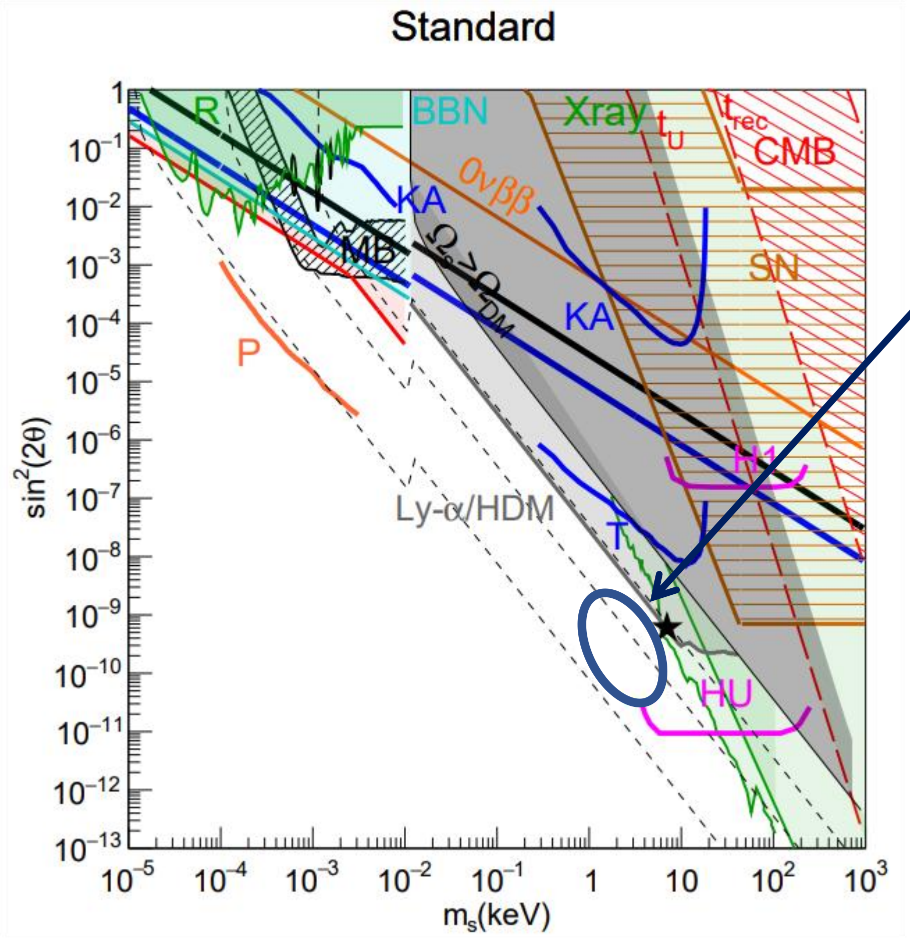
Novel Coincident Signal: X-rays+GWs

Two-populations

M. Chen, G. B. Gelmini, P. Lu, and V. Takhistov, In preparation

Observation



G. B. Gelmini, P. Lu, and V. Takhistov, JCAP 12 (2019) 047 [1909.13328]

Low mass area where

- **DW density fraction**

$$f_{s,\mathrm{DW}} \sim 0.1$$

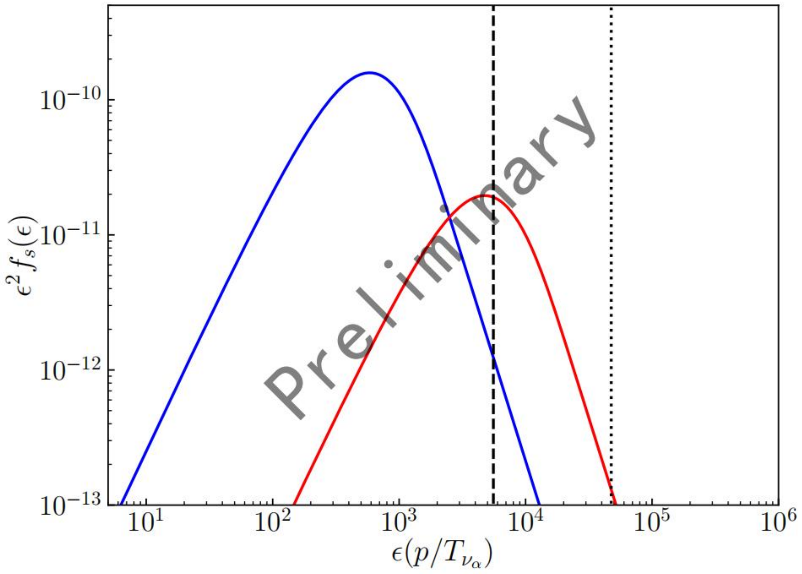
- **Other mechanism**
  - Colder
  - Density fraction ~ 0.9

Example

This appears in many models:

PBH neutrinogenesis, Dodelson-Widrow, Shi-Fuller…

E.g.



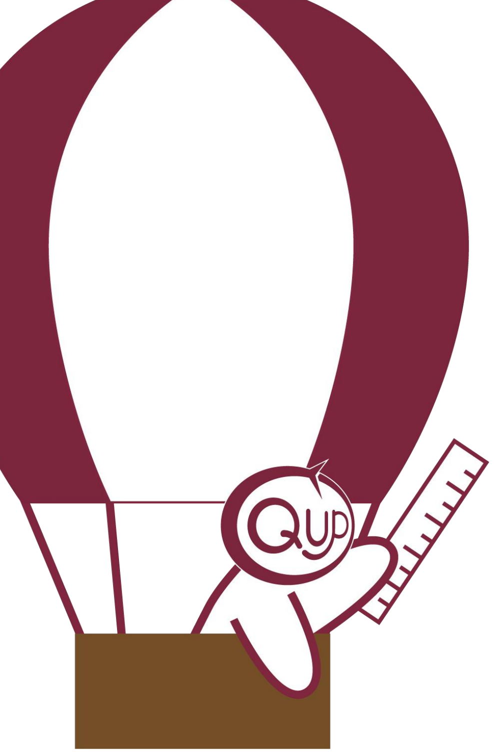
Summary

- Sterile neutrinos can be detected by their decay $\nu_s \to \nu\gamma$. Current X-ray limit ruled out the possibility of producing the whole of DM through DW mechanism.

- Sterile neutrino produced due to PBH evaporation does not depend on the mixing, thus not constrained by the X-ray limit. Sterile neutrinos can be cold/warm in the RD case.

- X-ray signal can be correlated to GW signal to show the possible existence of such mechanism.

- Two sterile neutrinos populations produced with different mechanisms can produce all of the DM under the X-ray limit.



Thank You

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