Strong Upper Limits on Sterile Neutrino Warm Dark Matter

Hasan Yüksel, John F. Beacom & Casey R. Watson, Phys. Rev. Lett. 101, 121301 (2008)

Masaki Mori

ICRR CANGAROO group internal seminar, October 24, 2008

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NEWS

Sep 26, 2008

Hope fades for neutrino dark matter

Physicists in the US have cast further doubt on whether a controversial neutrino is a potential candidate for dark matter — a mysterious substance that makes up nearly a quarter of the mass of the universe.

John Beacom (http://www.physics.ohio-state.edu/~beacom/) and Hasan Yuksel from Ohio State University and Casey Watson from Millikin University, Illinios have analysed data from the International Gamma-Ray Astrophysics Laboratory (INTEGRAL) satellite to rule out a range of possible mass values that "sterile" neutrinos, a candidate for dark matter, can take.

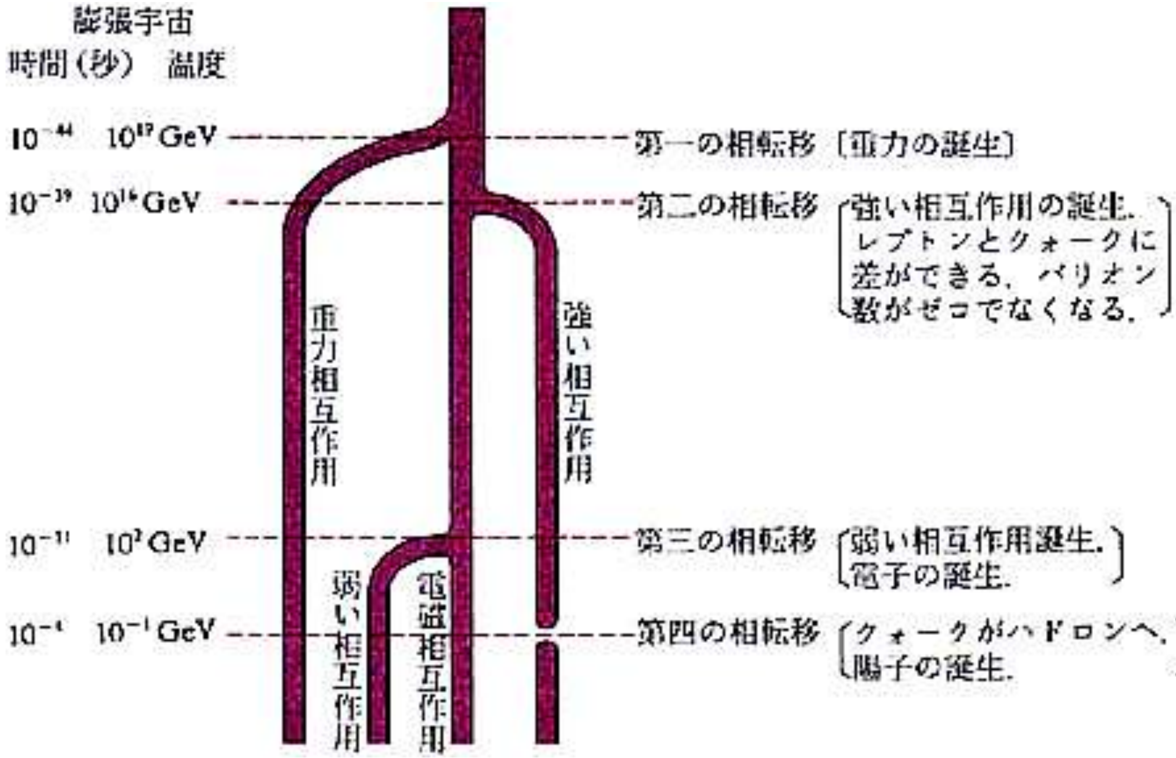
Neutrinos, which do not have an electric charge, currently come in three types or "flavours" — electron, muon and tau — that are each "active" meaning they interact via the nuclear weak force. Neutrinos also oscillate from one flavour to another as they travel, implying they have a mass.

In 1995, researchers based at the Liquid Scintillating Neutrino Detector (LSND) at Los Alamos looked at the oscillations between anti-muon and anti-electron neutrinos. To account for a discrepancy in the measured mass difference — a property that governs neutrino oscillation — they proposed a fourth, or "sterile" neutrino, which does not interact via the electroweak force and has a mass below about 1 eV.

Dark matterの分類

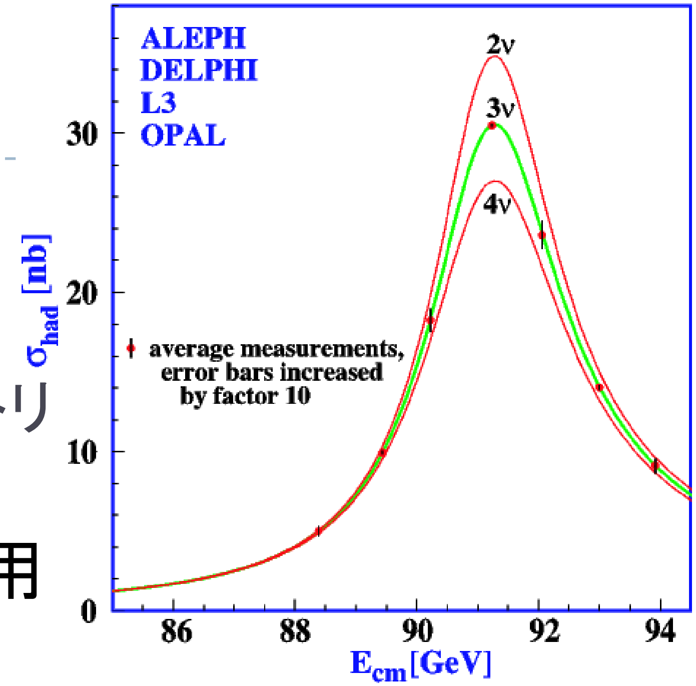
- Hot dark matter
  - 宇宙初期に熱平衡
  - クォーク・ハドロン相転移以降に粒子数がFreeze
  - < 1 MeVニュートリノ
  - Free streaming dampingにより短いスケールの揺らぎは消えるため、宇宙の構造形成はトップダウン型（銀河がつくれない！）
- Warm dark matter
  - 宇宙初期に熱平衡
  - クォーク・ハドロン相転移以前に粒子数がFreeze
  - 0.1-100 keV Sterile（「非活性」）ニュートリノ
- Cold dark matter
  - 粒子が非相対論的な時期に粒子数がFreeze、あるいは熱平衡に達することがない
  - > 1MeVニュートリノ、アクシオン、WIMP (Weakly Interacting Massive Particle: ex. ニュートラリーノ)
  - 揺らぎはスケールによらないため、ボトムアップ型の構造形成が可能

初期宇宙における相互作用の分化



初期宇宙での温度降下によって真空の相転移が起こり相互作用が分化してきたという，現代の「力の統一理論」のパラダイムを表現した図 （佐藤文隆、1976）

Particle Data Book 2008



Sterile neutrino

- LEP→ニュートリノの世代数は 2.987±0.016
  - 弱い相互作用する標準理論のニュートリノのみ
- Sterile neutrino: 重力のみで相互作用
  - 右巻きニュートリノ ν_R or 左巻き反ニュートリノ $\overline{\nu_L}$
  - Dirac質量で通常のニュートリノと混合 $L = -m\left(\overline{\nu_L}\nu_R + \overline{\nu_R}\nu_L\right)$
  - Majorana質量も可能 $L = -m\overline{\nu_L^c}\nu_L + \text{h.c.}$
  - Seasaw機構で通常のニュートリノは軽く、Sterileニュートリノは重くなりうる
  - νMSMモデルではGeV-keVの質量

Watson et al. PR D74, 033009 (2008)

Dark matterと構造形成

- ΛCDM (Λ[cosmological constant]+Cold dark matter)の問題点
  - 観測されるより多くの小規模構造
  - 3D計算に見られる銀河中心での密度過剰
- Warm DM
  - < 0.25Mpc(m_X/keV)$^{-4/3}$の構造形成はsuppress→観測に合致
  - 宇宙の再電離を遅らせる→WMAP3の結果で制限
  - Sterile neutrino WDMについての間接的制限
    - CDMの小規模clustering
    - 3D galaxy power spectrum
    - Lyman-α forest
  - → m_s >1.7keV or m_s >14 keV (simulation依存などで議論あり)
  - バリオン数やレプトン数の非対称性や、元素合成などにも影響

Plausible mass and mixing parameters for WDM

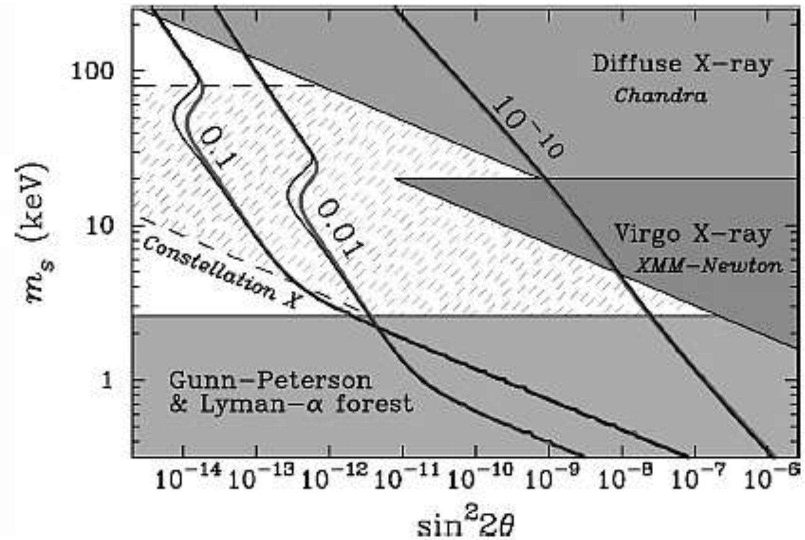


FIG. 4. Shown is the parameter space available for sterile neutrino dark matter, with varying lepton-number cosmologies. The contours (numbered by their initial lepton number) are positions in the mass and mixing angle space where sterile neutrinos produce critical densities of $\Omega_s h^2 = 0.15$. The thin (thick) lines are for first-order (crossover) QCD transitions ($T_{\mathrm{crit}} = 150$ MeV). Also shown are the excluded regions (shaded gray) from small scale structures—the Gunn-Peterson bound and Lyman-α forest—and halo phase space densities, the resolution of the diffuse x-ray background by *Chandra*, and observations of the Virgo cluster by *XMM-Newton*. The dashed region is that which may be probed by the proposed *Constellation-X* mission [18].

Watson et al. PR D74, 033009 (2008)

Sterile neutrino WDM model

- Predominantly decay to 3 ν_α (α=e,μ,τ)

$$\Gamma_{3\nu} \simeq 8.7 \times 10^{-31}\ \mathrm{s}^{-1}\left(\frac{\sin^2 2\theta}{10^{-10}}\right)\left(\frac{m_s}{\mathrm{keV}}\right)^5,$$

- Radiative decay $\nu_s \to \nu_{e,\mu,\tau} + \gamma$ (Dirac mass)

$$\Gamma_s \simeq 6.8 \times 10^{-33}\ \mathrm{s}^{-1}\left(\frac{\sin^2 2\theta}{10^{-10}}\right)\left(\frac{m_s}{\mathrm{keV}}\right)^5. \quad =1/\tau$$

- X-ray luminosity

$$L_{x,s} = E_{\gamma,s} N_s \Gamma_s = \frac{m_s}{2}\left(\frac{M_{\mathrm{DM}}}{m_s}\right)\Gamma_s$$

$$\simeq 6.1 \times 10^{32}\ \mathrm{erg\ s}^{-1}\left(\frac{M_{\mathrm{DM}}}{10^{11} M_\odot}\right)\left(\frac{\sin^2 2\theta}{10^{-10}}\right)\left(\frac{m_s}{\mathrm{keV}}\right)^5.$$

- X-ray line fux at $E_{\gamma,s}$ = $m_s/2$

$$\Phi_{x,s} \simeq 5.1 \times 10^{-18}\ \mathrm{erg\ cm}^{-2}\ \mathrm{s}^{-1}\left(\frac{D}{\mathrm{Mpc}}\right)^{-2}\left(\frac{M_{\mathrm{DM}}}{10^{11} M_\odot}\right) \times \left(\frac{\sin^2 2\theta}{10^{-10}}\right)\left(\frac{m_s}{\mathrm{keV}}\right)^5.$$

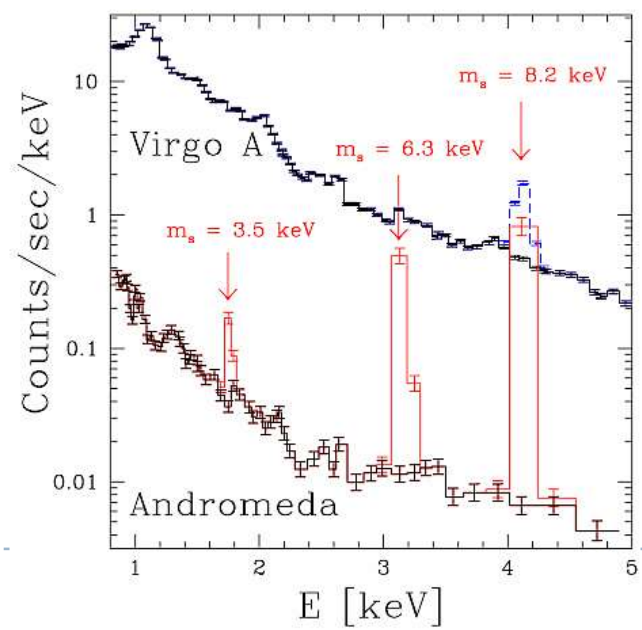
- Density-production relationship (assuming T_{QCD}=170MeV and n_b/n_γ=10^{-10})

$$m_s = 3.27\ \mathrm{keV}\left(\frac{\sin^2 2\theta}{10^{-8}}\right)^{-0.615}\left(\frac{\Omega_s}{0.24}\right)^{0.5}.$$

$$\therefore \quad \Phi_{x,s}(\Omega_s) \simeq 3.5 \times 10^{-15}\ \mathrm{erg\ cm}^{-2}\ \mathrm{s}^{-1}\left(\frac{D}{\mathrm{Mpc}}\right)^{-2}\left(\frac{M_{\mathrm{DM}}}{10^{11} M_\odot}\right)\left(\frac{\Omega_s}{0.24}\right)^{0.813}\left(\frac{m_s}{\mathrm{keV}}\right)^{3.374}.$$

Sterile neutrinoの放射崩壊による制限

- ラインX線 : $E_{\gamma,s} = m_s/2$ via $\nu_s \rightarrow \nu_{e,\mu,\tau} + \gamma$
- Cosmic X-ray Background (CXB)
  - XMM/HEAO-I: m_s <9.3 keV [Boyarsky et al. 2006]
- Galaxies/clusters
  - Vir A (M87): m_s <8.2 keV [Abazajian 2006]
  - Vir A, Coma: m_s <6.3 keV [Abazajian & Koushiappas 2006]
  - Andromeda: m_s <3.5 keV [Watson et al. 2006]



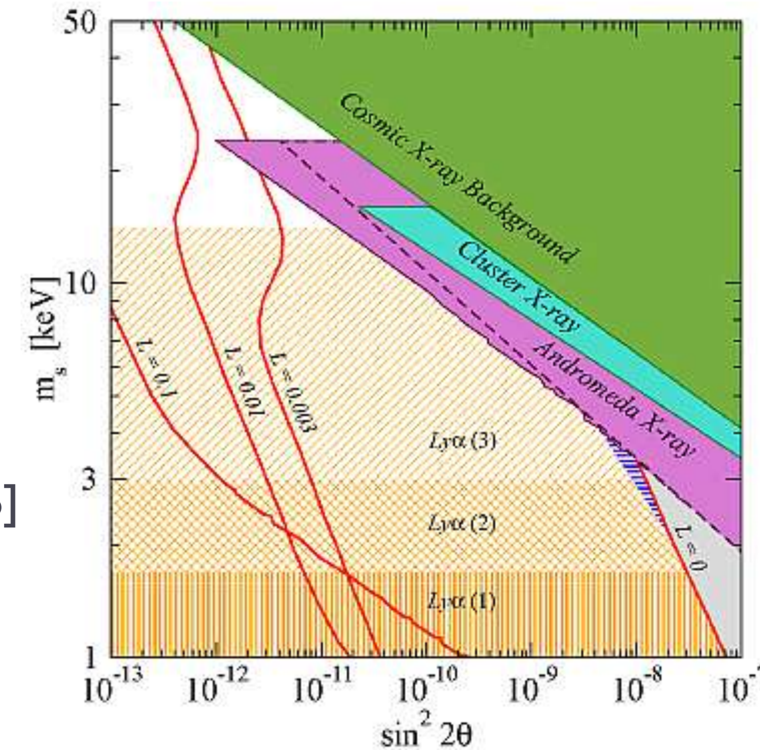


FIG. 2 (color online). Here we present constraints on m_s as a function of mixing angle, $\sin^2 2\theta$, assuming that all dark matter is comprised of sterile neutrinos. To facilitate comparisons, we adopt many of the conventions used by Abazajian and Koushiappas [35]. For $L = 0$, the thick, solid line corresponds to $\Omega_s = 0.24$ [Eq. (5)], while the shaded region to the right corresponds to $\Omega_s > 0.24$. Three density-production relationships associated with $\Omega_s = 0.3$ and $L \gg 10^{-10}$ are also shown [35]. The two previous *direct* radiative decay ($\nu_s \rightarrow \nu_{e,\mu,\tau} + \gamma$) upper limits (both 95% C.L.) are based on measurements [55–58] of the cosmic x-ray background [59] and *XMM* observations [60,62,63] of Virgo A (M87) and the Coma cluster [33,35,61]. The most stringent direct limits, from the present work (also 95% C.L.), are based on *XMM* observations of the Andromeda galaxy [64]. The region bounded by the dashed line is excluded by the "$\Gamma_{\gamma,tot}$-scaling method," while the region above the solid, slightly jagged line is excluded by the more accurate "direct data method" (see Sec. V). The *indirect* lower limits (all 95% C.L.) labeled Lyα(1) and Lyα(2) were derived in Ref. [33], while Lyα(3) was derived in Ref. [34]. Sterile neutrinos that occupy the horizontally hatched region could explain pulsar kicks [50–54].

INTEGRALラインガンマ線探索

- Teegarden and Watanabe (2006)
  - Point and diffuse sources in the Milky Way
  - SPI data, 20-8000 keV
  - Tested for lines of intrinsic width 0, 10 100 & 1000 keV
- Large-scale regions around Galactic center
  - 13 degree^{r} (exposure 1.9×10^{6}s) and 30 degree^{r} (3.6×10^{6}s)
  - Upper limits on flux from an unknown line emission
  - Average flux away from GC (>30deg) was subtracted – cancels all cosmic signal and part of halo signal
  - Limits around GC: $<10^{-4}$photons cm^{-2}s^{-1} (3.5σ)

Milky Way dark matter decay flux

- Photon flux within an angle ψ from GC

$$\mathcal{I}(\psi) = \frac{\rho_{sc} R_{sc}}{4\pi m_s \tau} \mathcal{J}(\psi),$$

Dimensionless line of sight integral (R_{sc}: solar circle)

$$\mathcal{J}(\psi) = \frac{1}{\rho_{sc} R_{sc}} \int_0^{\ell_{\max}} d\ell\, \rho\left(\sqrt{R_{sc}^2 - 2\ell R_{sc} \cos\psi + \ell^2}\right),$$

$$\therefore \quad \frac{\rho_{sc} R_{sc}}{4\pi m_s \tau} = (4.3 \times 10^{-6}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}\ \mathrm{sr}^{-1}) \left[\frac{\sin^2 2\theta}{10^{-10}}\right]\left[\frac{m_s}{\mathrm{keV}}\right]^4.$$

- Number of photons within ψ

$$\mathcal{F}_s = \int_{\Delta\Omega} d\Omega\, \mathcal{I}(\psi) = \frac{\rho_{sc} R_{sc}}{4\pi m_s \tau} \int_{\Delta\Omega} d\Omega\, \mathcal{J}(\psi),$$

- Lower bound for the integral when ρ_{sc} is constant within R_{sc}: $J(\psi)\sim 2$, $\Delta\Omega = 2\pi(1-\cos\psi) = 0.16$ (for $\psi = 13°$)

Milky Way dark matter decay flux (cont.)

- Realistic dark matter density profile:
  - NFW / Moore / Kravtsov profiles

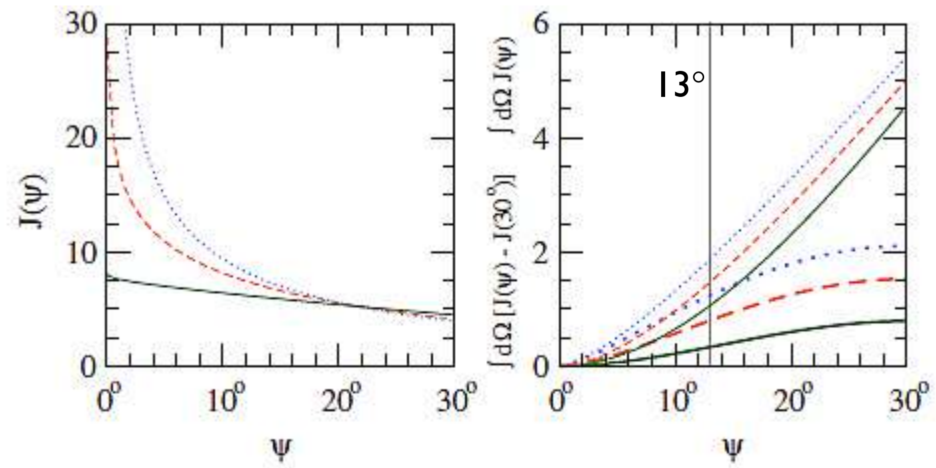
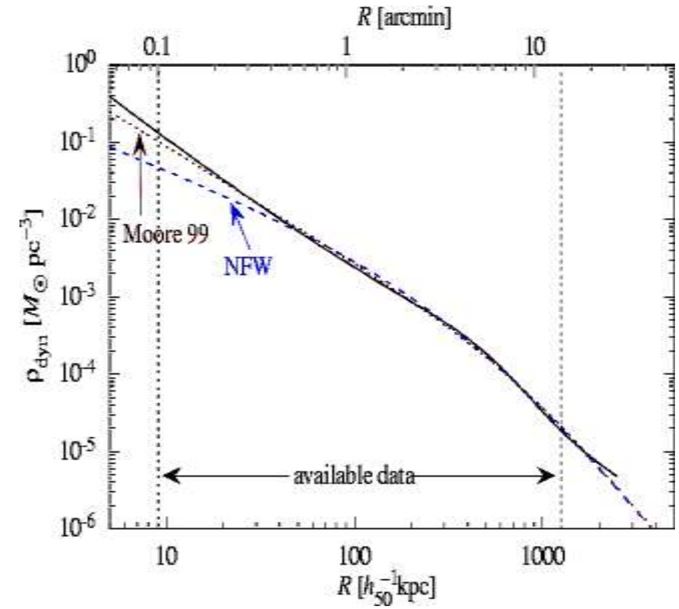


FIG. 2 (color online). Left: The line of sight integral $\mathcal{J}(\psi)$ as a function of the pointing angle ψ with respect to the Galactic center direction for the three different profiles considered (Kravtsov, NFW, and Moore, in order of solid line, dashed line, and dotted line). Right: Integrals up to the angle ψ of $\mathcal{J}(\psi)$ (thin upper lines) and $\mathcal{J}(\psi) - \mathcal{J}(30^\circ)$ (thick lower lines). The gray line at 13° marks the field of view for the INTEGRAL flux limit, and we chose $\int_{\Delta\Omega} d\Omega[\mathcal{J}(\psi) - \mathcal{J}(30^\circ)] \simeq 0.5$ as a conservative value for our subsequent constraints.

Durret et al., AA 432, 809 (2005)



Constraints on sterile neutrinos

- Upper limits from subtraction

$$\Delta \mathcal{F}_s = \frac{\rho_{sc} R_{sc}}{4\pi m_s \tau} \int_{\Delta\Omega} d\Omega[\mathcal{J}(\psi) - \mathcal{J}(30°)].$$

$\cong$ 0.5 (conservative limits for ψ=13°)

  - 3 times larger limit for ψ=30°, but flux is also 2-3 times larger
  - $\rightarrow$ Results are rather robust against angular region
- Constraints on mass and mixing: flux < INTEGRAL limit

$$\mathcal{F}_{\lim}(E) > \frac{\rho_{sc} R_{sc}}{4\pi m_s \tau} \int_{\Delta\Omega} d\Omega[\mathcal{J}(\psi) - \mathcal{J}(30°)].$$

(next page figure)

  - This assumes sterile neutrinos comprise all of the required dark matter.

Mass and mixing parameter space

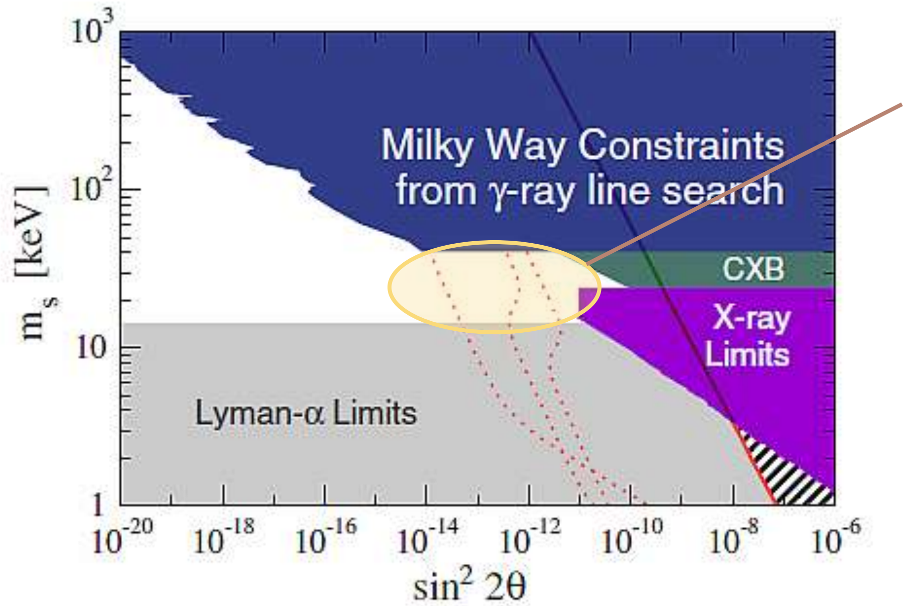


FIG. 1 (color online). The sterile neutrino dark matter mass m_s and mixing $\sin^2 2\theta$ parameter space, with shaded regions excluded. The strongest radiative decay bounds are shown, labeled as Milky Way (this Letter), CXB [11], and x-ray Limits (summarized using Ref. [12]; the others [13] are comparable). The strongest cosmological bounds [9] are shown by the horizontal band (see caveats in the text). The excluded Dodelson-Widrow [3] model is shown by the solid line; rightward, the dark matter density is too high (stripes). The dotted lines are models from Ref. [14], now truncated by our constraints.

Now plausible in only this region!

"Hope fades for neutrino dark matter…"

Smirnov & Zukanovich Funchal, PR D74, 013001 (2006)

Previous limits