Exploring Ultralight Scalar Assistance in Sterile Neutrino Dark Matter:

Cold Spectrum and Unusual X/Gamma-ray Signatures

Yuxuan He（何雨轩）

Peking University

2023.12.5@KASHIWA DARK MATTER

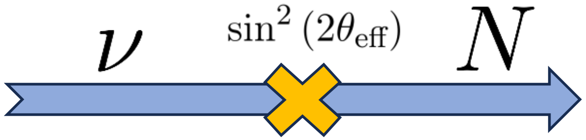
SYMPOSIUM 2023

JCAP 09 (2023) 047 2305.08095,

YXH , Jia Liu, Xiaolin Ma and Xiao-Ping Wang

Introduction

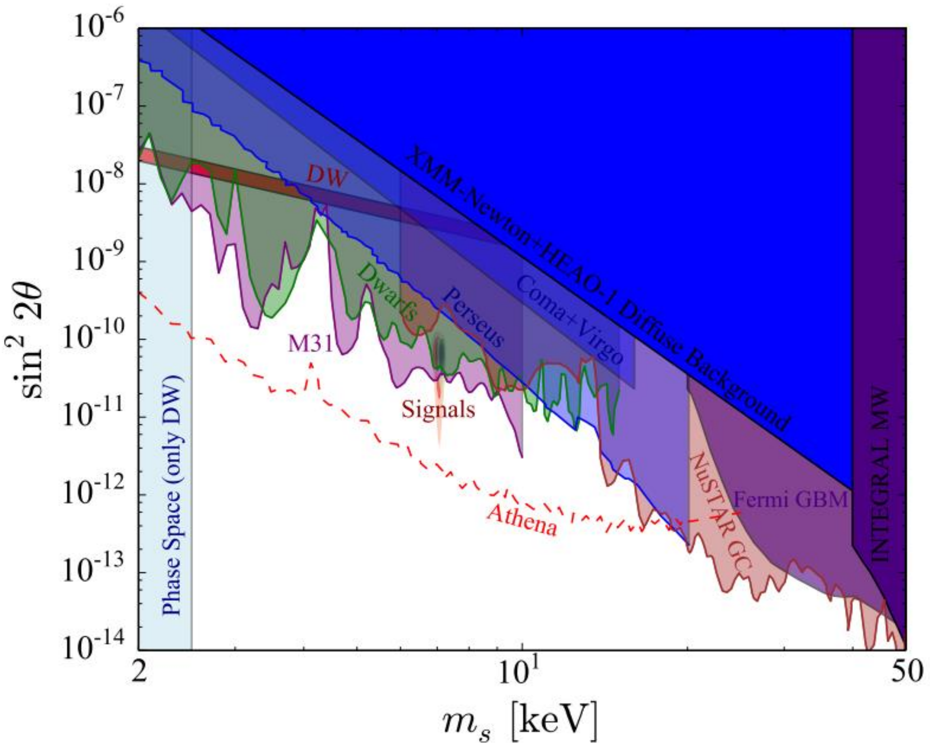
- Sterile neutrino dark matter
- Dodelson-Widrow (DW) mechanism



$$\frac{\partial}{\partial t}f_N(p,t)-Hp\frac{\partial}{\partial p}f_N(p,t)\approx\frac{1}{4}\Gamma_{\rm SM}(p,T)\sin^2(2\theta_{\rm eff})\left[f_\nu(p,t)-f_N(p,t)\right]$$

S. Dodelson and L. M. Widrow 1994

- Mixing induced Gamma/X ray signals



K. Abazajian et. al. 1705.01837

$$\Gamma_{N\to\nu\gamma}=\frac{9\alpha G_F^2}{2048\pi^4}\sin^2(2\theta)\,m_N^5$$
$$=1.361\times10^{-29}\ {\rm s}^{-1}\left(\frac{\sin^2(2\theta)}{10^{-7}}\right)\left(\frac{m_N}{1{\rm keV}}\right)^5$$

Introduction

- WDM constraints

Sterile neutrino produced in DW mechanism have thermal distribution, there are stringent constraints on light DM. DW sterile neutrino DM mass need $m_N > 92\ \mathrm{keV}$ I. Zelko et. al 2205.09777

- Alternative production mechanisms of sterile neutrino dark matter

Shi-Fuller mechanism X. Shi and G. M. Fuller. 9810076

GUT-scale scenario A. Kusenko et. al. 1006.1731

Higgs production mechanism K. Petraki and A. Kusenko, 0711.4646

Ultralight Scalar assistant production A. Berlin and D. Hooper, 1610.03849

Ultralight Scalar Assistance production mechanism

- Basic idea

Consider a time dependent mixing angle

$$\frac{\partial}{\partial t} f_N(p,t) - Hp\frac{\partial}{\partial p} f_N(p,t) \approx \frac{1}{4}\Gamma_{\mathrm{SM}}(p,T)\sin^2(2\theta_{\mathrm{eff}})\left[f_\nu(p,t) - f_N(p,t)\right]$$

time dependent

Induced by couple to ultralight back ground scalar field

mixing angle takes large value at early universe

But tiny at today

time dependent

$$\Gamma_{N\to\nu\gamma} = \frac{9\alpha G_F^2}{2048\pi^4}\sin^2(2\theta)\, m_N^5$$
$$= 1.361\times 10^{-29}\ \mathrm{s}^{-1}\left(\frac{\sin^2(2\theta)}{10^{-7}}\right)\left(\frac{m_N}{1\mathrm{keV}}\right)^5$$

Ultralight Scalar Assistance production mechansim

- Model set up

Begin with following Lagrangian

$$-\mathcal{L} = \left[\frac{1}{2}(m_N + \lambda\phi)\overline{N^c}N + y\phi\bar{\nu}N^c + h.c.\right] + \frac{1}{2}m_\phi^2\phi^2$$

After diagonalization

$$m_\nu(\phi) = \frac{1}{2}\left[\sqrt{(\lambda\phi + m_N)^2 + 4(y\phi)^2} - (\lambda\phi + m_N)\right]$$

$$m_N(\phi) = \frac{1}{2}\left[\sqrt{(\lambda\phi + m_N)^2 + 4(y\phi)^2} + (\lambda\phi + m_N)\right]$$

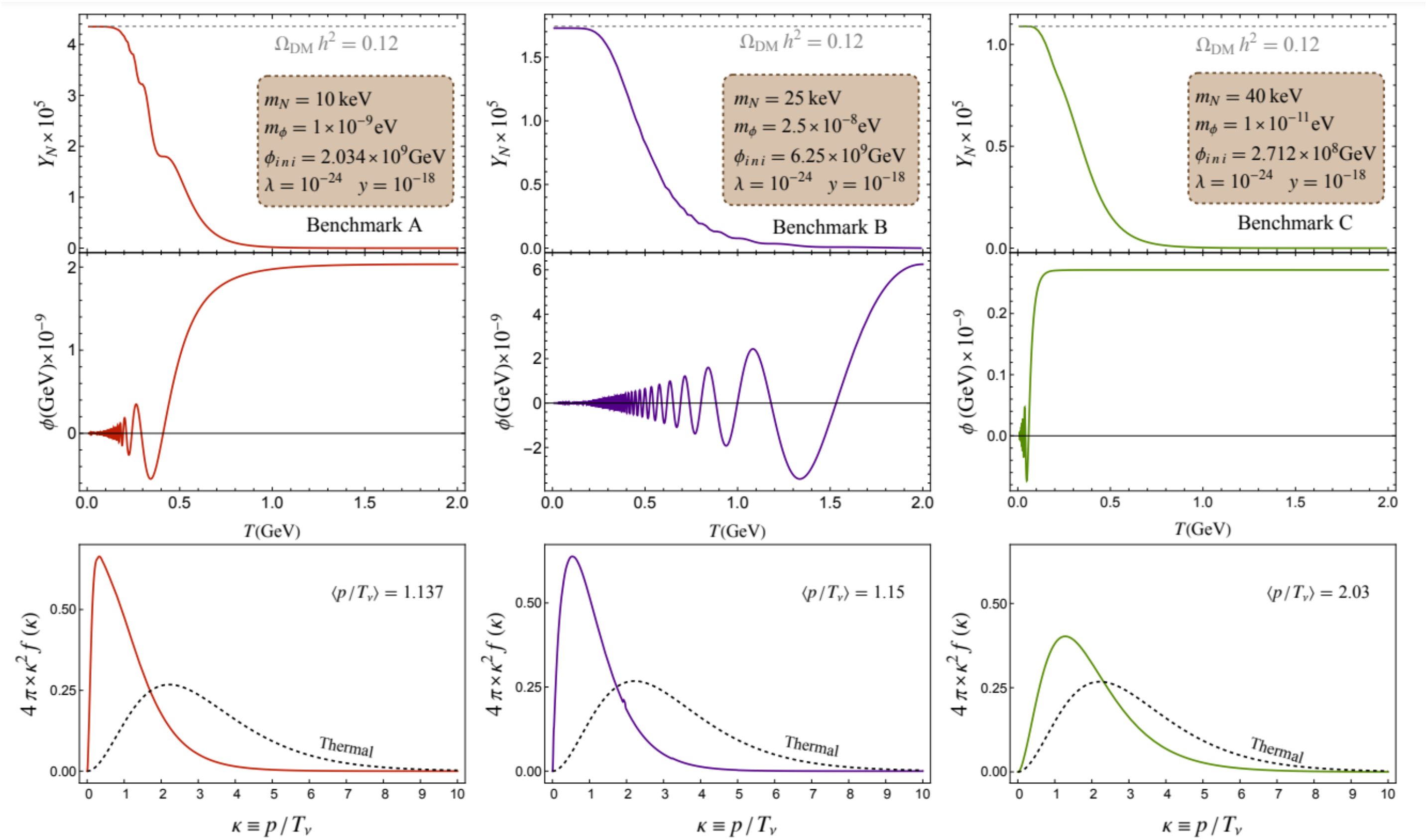
We get field dependent mixing angle

$$\tan\theta = \frac{y\phi}{m_N(\phi)}$$

Ultralight scalar obeying EOM $\ddot{\phi} + 3H\dot{\phi} + \frac{\partial V_\phi}{\partial \phi} = 0$

Ultralight Scalar Assistance production mechanism

- Production driven by ultralight scalar



$m_\phi > 3H(T_{\max})$

$m_\phi < 3H(T_{\max})$

Ultralight Scalar Assistance production mechanism

- Constraints on parameter space
- Long range force between DM mediated by ultralight scalar $\beta \equiv \lambda M_{\rm pl}/\sqrt{4\pi} m_N < 2.2$

H. Davoudiasl et. al, 1804.01098 S. C. F. Morris et. al., 1304.2196

- mixing term induced dark matter decay $N \to \nu + \phi$

$$\Gamma(N \to \nu\phi) = y^2 m_N/(16\pi)$$

- We choose parameter space

λ	y	$m_\phi(\mathrm{eV})$	$\phi_{\rm ini}(\mathrm{GeV})$	$m_N(\mathrm{keV})$
10^{-24}	$\lesssim \mathcal{O}(10^{-18})$	$\mathcal{O}(10^{-22} \sim 10^{-9})$	$\mathcal{O}(10^{8} \sim 10^{9})$	$\mathcal{O}(10 \sim 1000)$

Cold Spectrum

- Energy spectrum of DW sterile neutrino

The effective mixing angle is

$$\sin^2(2\theta_{\rm eff}) \equiv \frac{\Delta^2(p)\sin^2(2\theta)}{\Delta^2(p)\sin^2(2\theta)+\Gamma_{\rm SM}^2/4+\left(\Delta(p)\cos(2\theta)-V^T(p)\right)^2}$$

Neglect tiny terms

$$\frac{f_N(y)}{f_\nu(y)} \propto \sin^2(2\theta) y \int_0^{x_{ini}} \frac{1}{(1+x^2y^2)^2} dx.$$

with $y = p/T \quad x \propto T^3$

sterile neutrino takes thermal distribution

$$f_N(y) \propto f_\nu(y) \propto \frac{1}{1+e^y}$$

Cold Spectrum

- Colder spectrum due to time dependent mixing angle

When production during oscillation $m_\phi > 3H(T_{\max})$

approximately $\phi \propto T^{3/2}$ $\sin^2(2\theta) \propto T^3 \propto x$

the distribution given by $$\frac{f_N(y)}{f_\nu(y)} \propto y \int_0^{x_{ini}} \frac{x}{(1+x^2y^2)^2} dx$$

Spectrum suppressed in large y

$$f_N(y) \propto \frac{1}{y} f_\nu(y) \propto \frac{y^{-1}}{1+e^y}$$

- Colder spectrum due to entropy injection

$$f_N(T_f, p) = \int_{T_{\rm ini}}^{T_f} h\left(p\left(\frac{g_{\star s}(T_2)}{g_{\star s}(T_f)}\right)^{1/3} \frac{T_2}{T_f}, T_2\right) dT_2$$

Cold Spectrum

- Even more cool spectrum

scalar coupling changed to $\frac{\phi^n}{\Lambda^{n-1}}\bar{\nu}N^c$

then $\sin^2(2\theta) \propto \phi^{2n}$

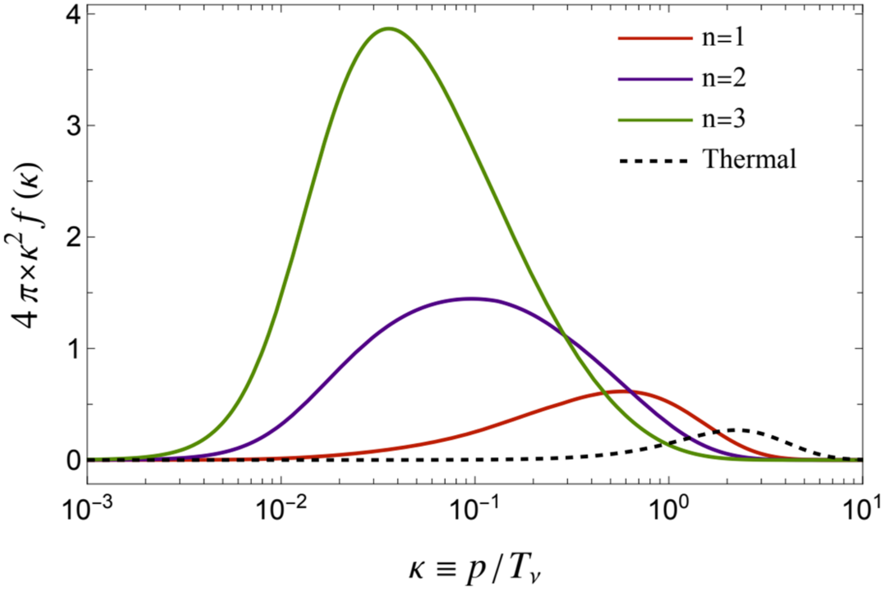
Previous argument give

$$\sin^2(2\theta) \propto T^{3n} \propto x^n$$

And

$$f_N(y) \propto \frac{1}{y^n} f_\nu(y) \propto \frac{y^{-n}}{1+e^y}$$

Sterile neutrino DM can be further cold

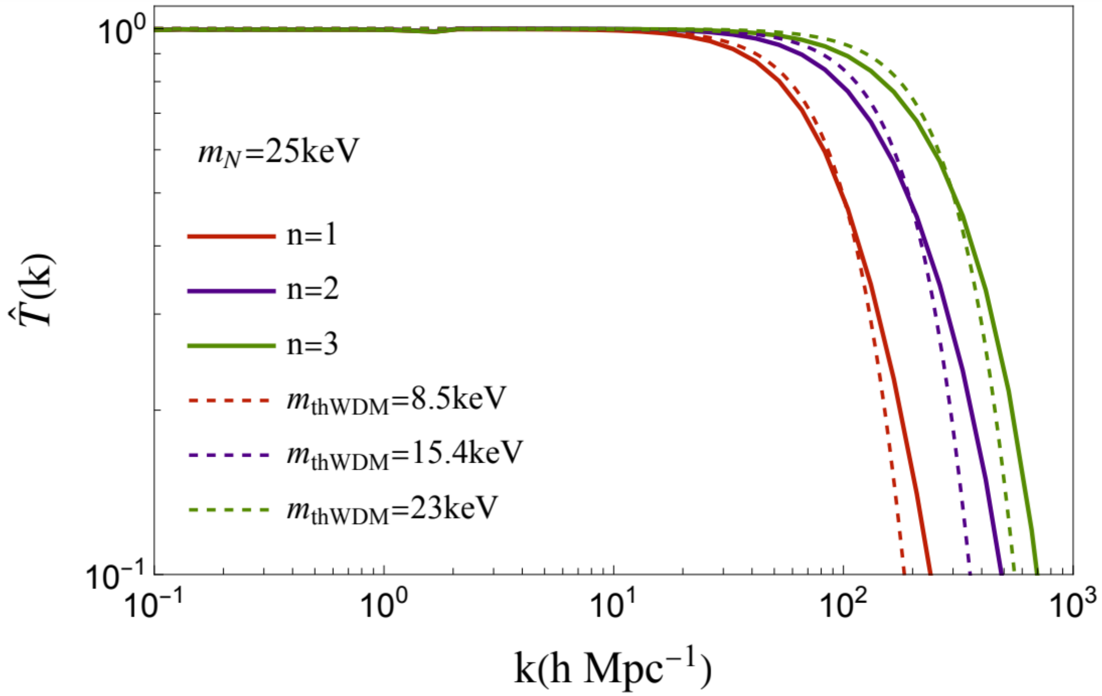


Cold Spectrum

- Transfer function and constraints $\hat{T}_{\rm WDM}(k) \equiv \sqrt{\frac{P(k)}{P_{\rm CDM}(k)}}$

Can be fit with thWDM $\hat{T}_{\rm thWDM}(k) = [1 + (\alpha k)^{2\mu}]^{-5/\mu}$

P. Bode, J. P. Ostriker, and N. Turok. 2001



The DW mechanism mass should larger

92keV

Less constrained

Unusual X/Gamma-ray Signatures

- Today's scalar field takes tiny value

$$\rho_\phi \simeq 1.7 \times 10^{-16} \frac{\mathrm{GeV}}{\mathrm{cm}^3} \times \sqrt{\frac{m_\phi}{10^{-10}\mathrm{eV}}} \left(\frac{\phi_{\mathrm{ini}}}{10^9 \mathrm{GeV}} \right)^2 \mathcal{F}(T_0)$$

- The local scalar field is also relied on density dependent potential

$$\partial V_\phi / \partial \phi \simeq \lambda n_N + \left(m_\phi^2 + \frac{2y^2 n_N}{m_N} \right) \phi$$

Which have stationary field value

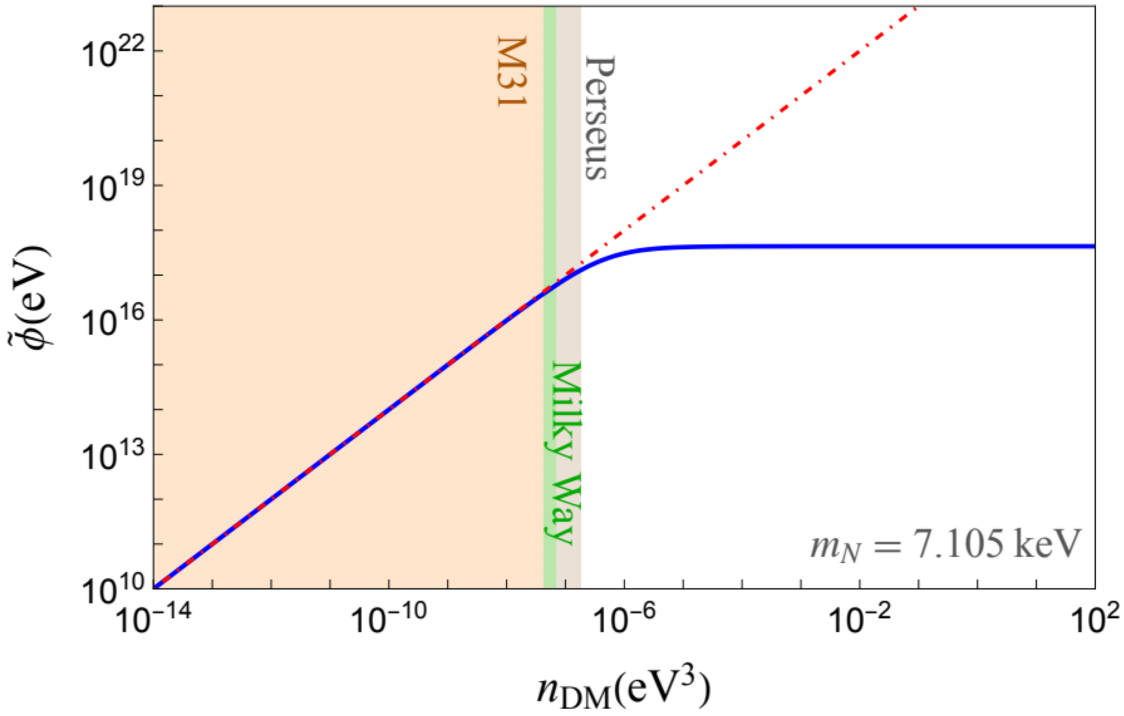
$$\tilde{\phi} \sim \lambda n_{\mathrm{DM}} / m_\phi^2$$

And scalar field oscillate around its stationary value

$$\phi_0 \simeq \tilde{\phi} + \hat{\phi} \cos(m_\phi t + \theta_0)$$

Unusual X/Gamma-ray Signatures

- Density dependence of scalar field



- The scalar field will saturated at $\frac{2m_N m_\phi^2(\sqrt{y^2(3\lambda^2+y^2)}-y^2)}{3\lambda^2 y^2}$ with maximal

$$\tilde{\phi}_{\max} \sim \frac{m_N(\sqrt{y^2(3\lambda^2+y^2)}-y^2)}{3\lambda y^2}$$

Unusual X/Gamma-ray Signatures

- Density dependent mixing angle

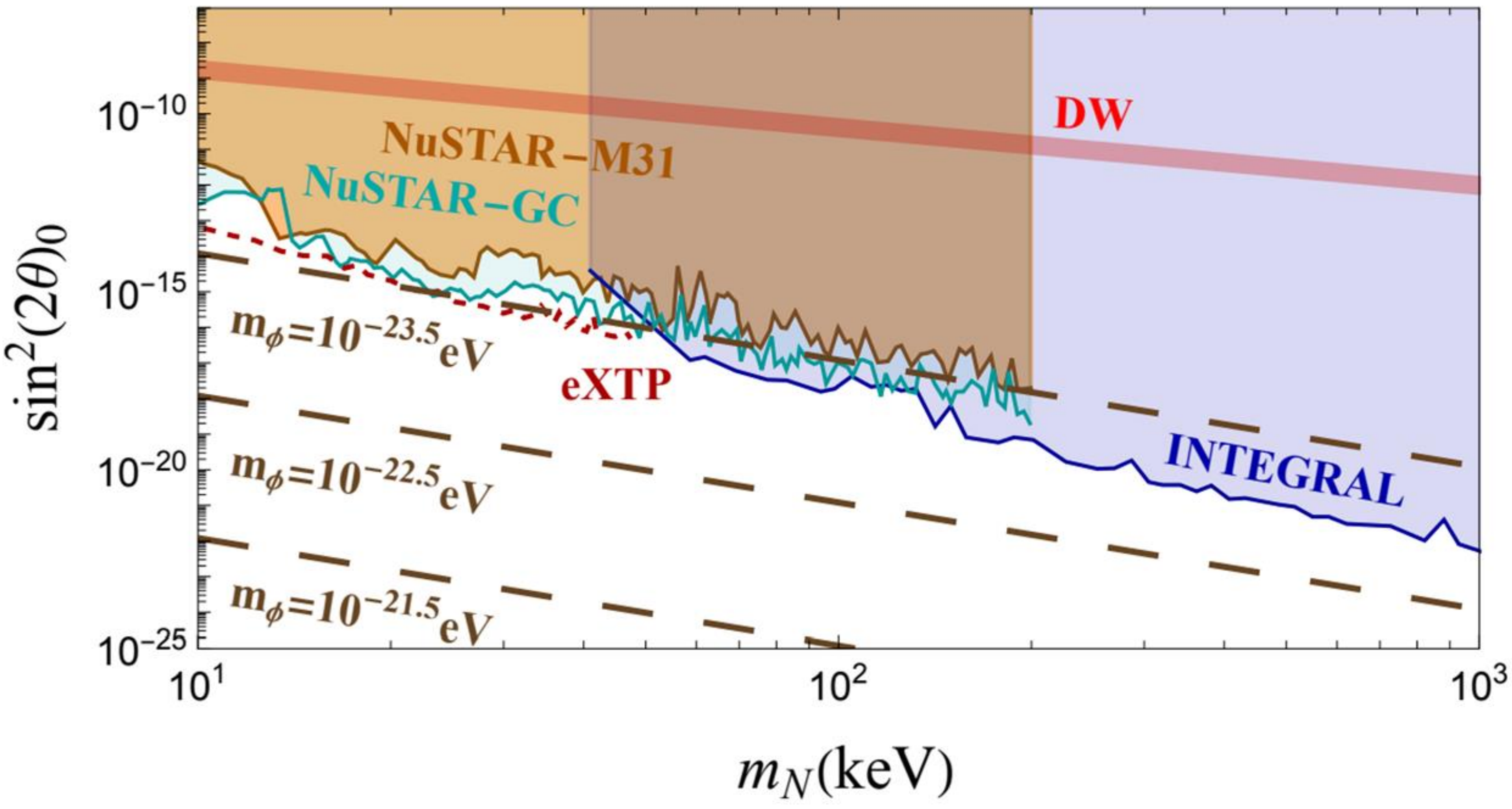
$$\langle \sin^2(2\theta) \rangle \simeq 4 \left\langle \frac{y^2 \phi_0^2}{m_N^2} \right\rangle = \frac{4y^2}{m_N^2} \left(\frac{\lambda^2 n_{DM}^2}{m_\phi^4} + \frac{\rho_\phi}{m_\phi^2} \right)$$

- Unusual density dependent flux

$$F = \frac{9\alpha G_F^2}{2048\pi^5} \cdot \frac{\lambda^2 y^2}{m_\phi^4} \int d\Omega_{\text{f.o.v.}} \int_{\text{l.o.s}} dr \; \rho_{\text{DM}}^3 \left(\sqrt{d^2 + r^2 - 2dr\cos\varphi} \right)$$

Unusual X/Gamma-ray Signatures

- Constraints from X/Gamma-ray observations



Conclusion

- Scalar assistant mechanism for sterile neutrino DM production can relax X/Gamma ray constraints
- This mechanism can successfully provide a colder dark matter spectrum compared with DW mechanism
- With sterile neutrino scalar coupling, there are detectable X/Gamma ray signals with density dependent feature.

Thank You

Back up

- Boltzmann eq

$$\frac{\partial}{\partial t} f_N(p,t) - Hp\frac{\partial}{\partial p} f_N(p,t) \approx \frac{1}{4}\Gamma_{\mathrm{SM}}(p,T)\sin^2(2\theta_{\mathrm{eff}})\left[f_\nu(p,t) - f_N(p,t)\right]$$

$$\sin^2(2\theta_{\mathrm{eff}}) \equiv \frac{\Delta^2(p)\sin^2(2\theta)}{\Delta^2(p)\sin^2(2\theta) + \Gamma_{\mathrm{SM}}^2/4 + \left(\Delta(p)\cos(2\theta) - V^T(p)\right)^2}$$

$$V_\alpha^T(p) = -\frac{8\sqrt{2}G_F p_\nu}{3m_Z^2}\left(\langle E_{\nu^\alpha}\rangle n_{\nu^\alpha} + \langle E_{\bar\nu^\alpha}\rangle n_{\bar\nu^\alpha}\right) - \frac{8\sqrt{2}G_F p_\nu}{3m_W^2}\left(\langle E_\alpha\rangle n_\alpha + \langle E_{\bar\alpha}\rangle n_{\bar\alpha}\right)$$

$$f_N(T_f,p) = \int_{T_{\mathrm{ini}}}^{T_f} h\left(p\left(\frac{g_{\star s}(T_2)}{g_{\star s}(T_f)}\right)^{1/3}\frac{T_2}{T_f}, T_2\right) dT_2 \; V_\phi = \frac{1}{2}m_\phi^2\phi^2 + \frac{1}{2}m_N(\phi)\langle\overline{N^c}N + h.c.\rangle - \frac{1}{\pi^2}T^4 J_F\left[\frac{m_\nu(\phi)^2}{T^2}\right]$$

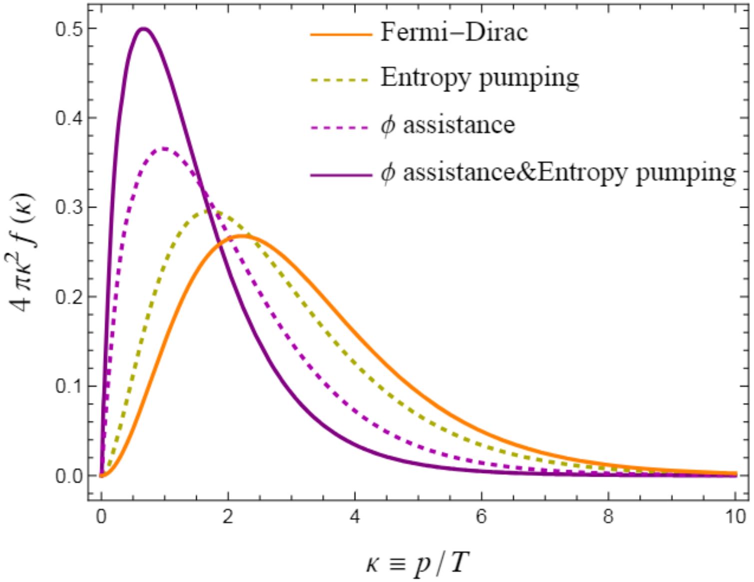
$$h(p,T) = \frac{1}{-4H(T)T}\Gamma_{\mathrm{SM}}(p,T)\sin^2(2\theta_{\mathrm{eff}})f_\nu(p,t)\cdot\left(1 + \frac{1}{3}\frac{d\ln g_{\star s}(T)}{d\ln T}\right)$$

$$\phi'' - \phi'\frac{g_{\star s}(T)'}{g_{\star s}(T)} + \phi\frac{(\partial V_\phi/\partial\phi)}{H(T)^2T^2}\cdot\left(1 + \frac{1}{3}\frac{d\ln g_{\star s}(T)}{d\ln T}\right)^2 = 0,$$

$$n_N(T_f) = \frac{1}{(2\pi)^3}\int d^3\vec{p}\cdot f_N\left[T_f, p, \sin^2(2\theta_{\mathrm{eff}})(\phi)\right].$$

Back up

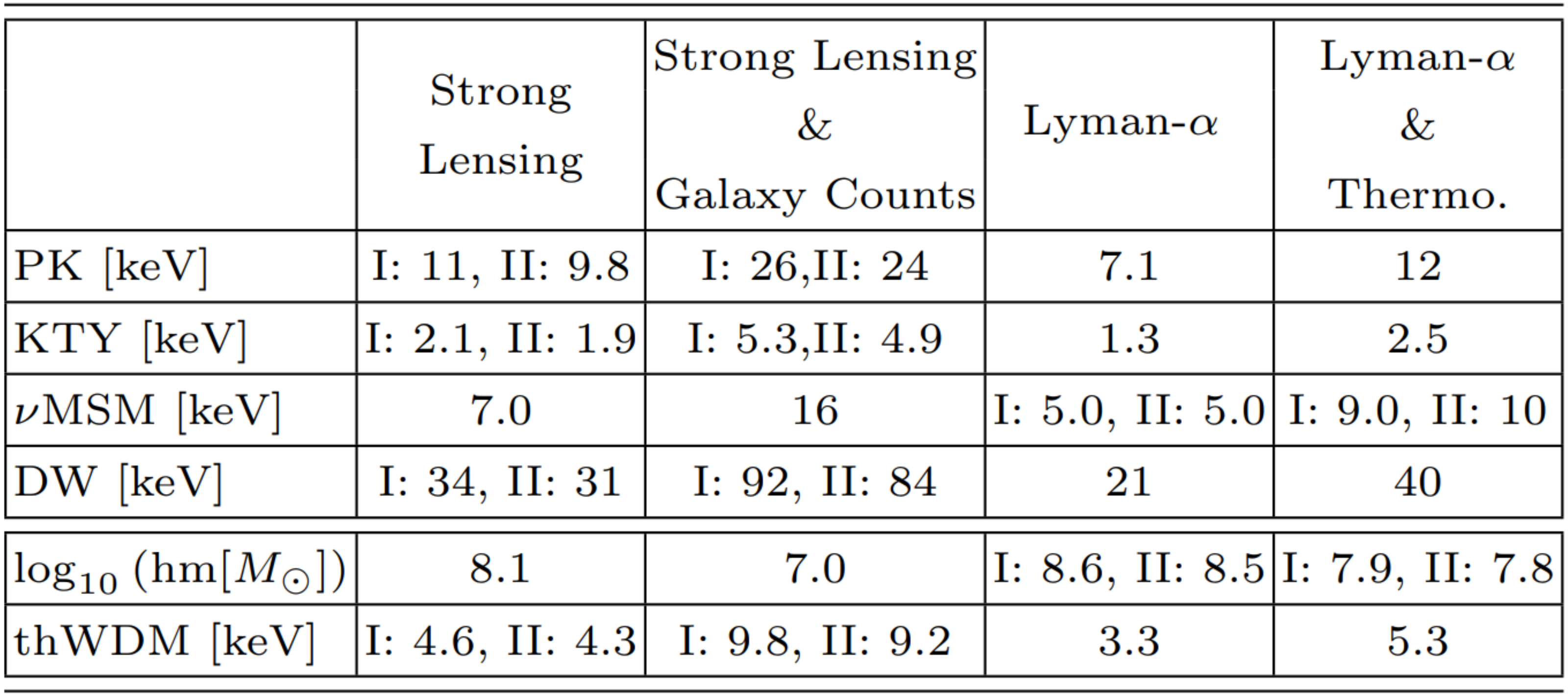
- Effects that cool the spectrum



- Transfer function of thWDM

$$\alpha(m_{\rm thWDM}) = 0.049\left(\frac{m_{\rm thWDM}}{\rm keV}\right)^{-1.11}\left(\frac{\Omega_{\rm thWDM}}{0.25}\right)^{0.11}\left(\frac{h}{0.7}\right)^{1.22}$$

Back up



	Strong Lensing	Strong Lensing & Galaxy Counts	Lyman-α	Lyman-α & Thermo.
PK [keV]	I: 11, II: 9.8	I: 26,II: 24	7.1	12
KTY [keV]	I: 2.1, II: 1.9	I: 5.3,II: 4.9	1.3	2.5
νMSM [keV]	7.0	16	I: 5.0, II: 5.0	I: 9.0, II: 10
DW [keV]	I: 34, II: 31	I: 92, II: 84	21	40
$\log_{10}(\mathrm{hm}[M_\odot])$	8.1	7.0	I: 8.6, II: 8.5	I: 7.9, II: 7.8
thWDM [keV]	I: 4.6, II: 4.3	I: 9.8, II: 9.2	3.3	5.3