Seminar@IHEP

# Possible connections between neutrino and dark matter

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# Outline

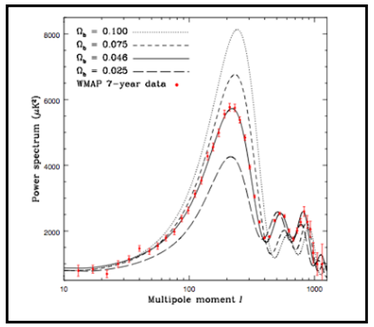
- Brief overview
- Status of dark matter direct detections
- Pseduo-Dirac sterile neutrino dark matter
- Direct detects of neutrino-like DM in condense matter

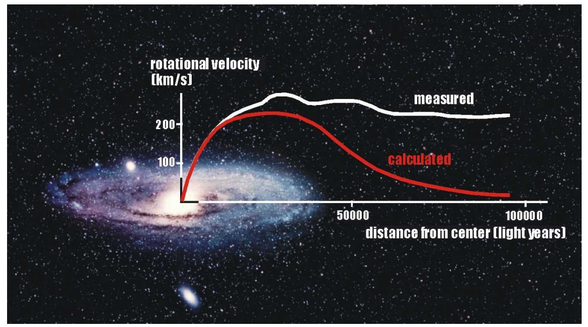
**Based on:**

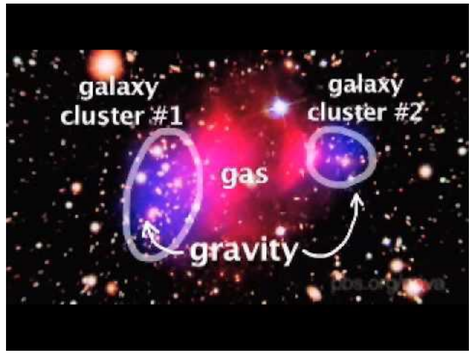
Pseudo-Dirac Sterile Neutrino Dark Matter, W.Chao,, S.Jiang, Z.Wang and Y.Zhou arXiv:2112.14527
A new Direct detection strategy for cosmic neutrino background W.Chao, J.Feng, M.Jin and T.Li arXiv:2112.13777

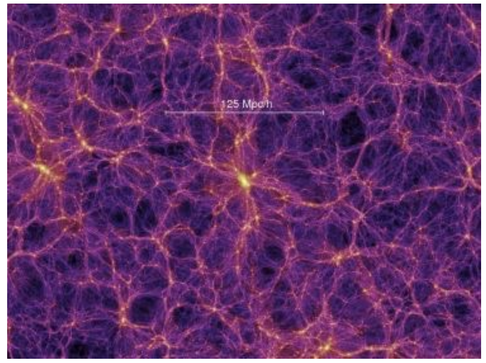
# What is dark matter?

## EVIDENCE FOR DARK MATTER



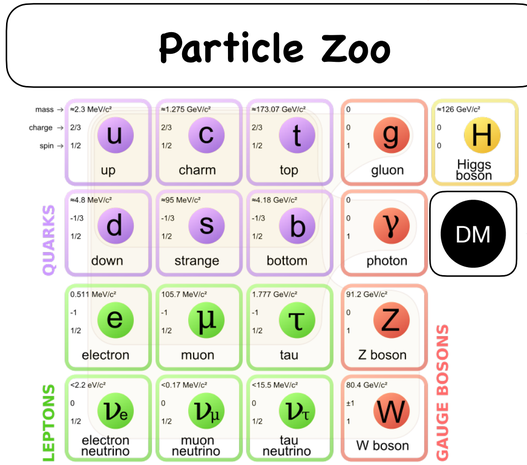



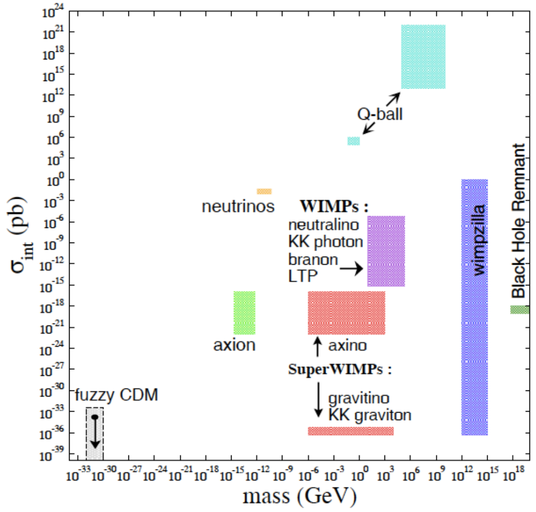
## WHAT IS DARK MATTER?

we don't know!

Mass ✗ Spin ✗ Interactions ✗

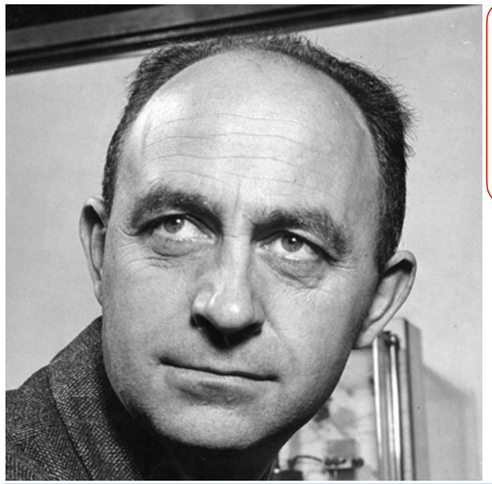
Neutral, non-baryonic, weakly interacting particle!



# Possible dark matter candidate

**The WIMP Miracle!**

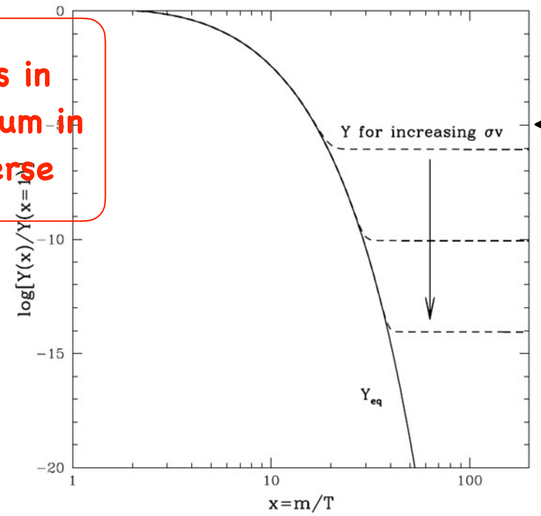


Fermi's constant introduced in 1930s to describe beta decay

$G_F \approx 1.1 \times 10^{-5}\ \mathrm{GeV}^{-2}$

New mass scale: 100 GeV

Assuming DM is in thermal equilibrium in the early universe




The relic density: $\Omega_\chi \sim \frac{1}{\langle \sigma v \rangle} \sim \frac{m_\chi^2}{g_\chi^4}$

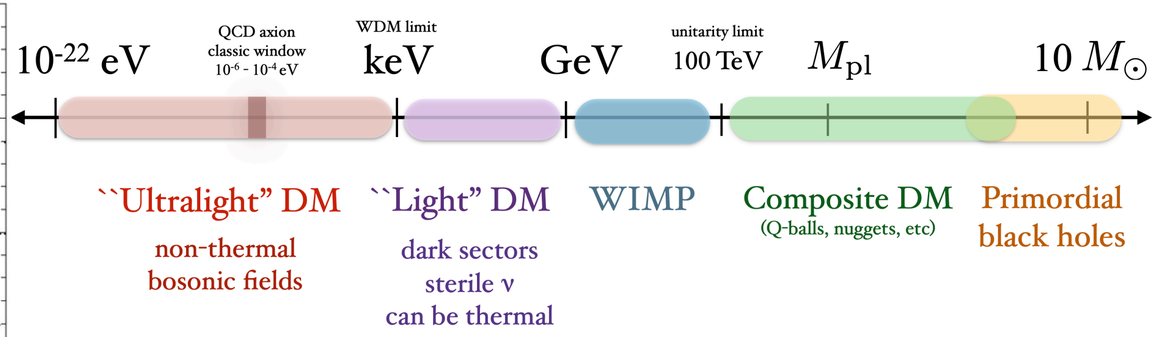
$m_\chi \sim 100\ \mathrm{GeV}$

$g_\chi \sim 0.6$

$\Omega_\chi \sim 0.1$

The weak coupling

**Dark matter candidate**

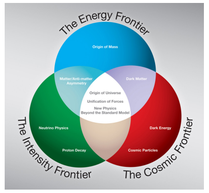



**Brief History:**

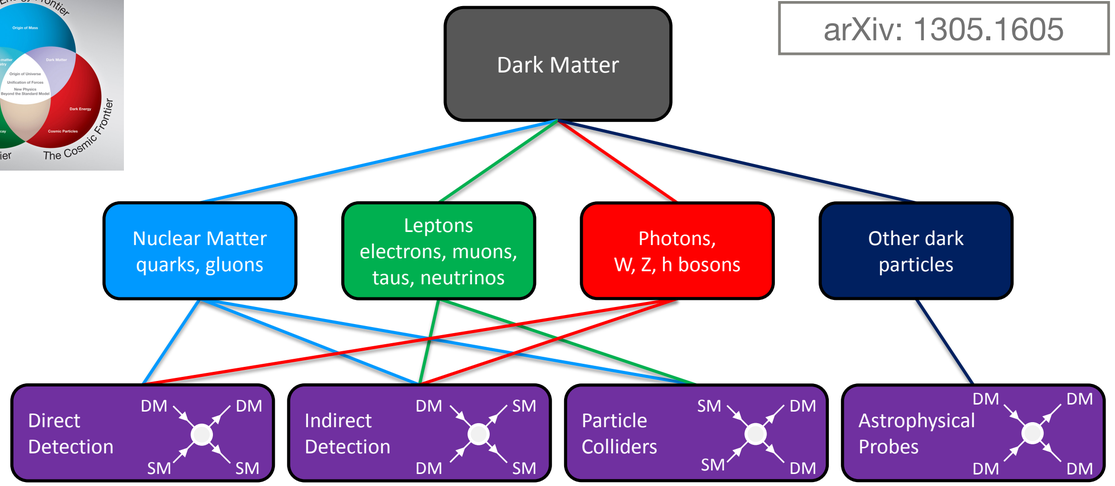
- @ t<2010s, WIMPS
- @ by now,
  - Axion
  - Sub-GeV
  - Primordial black hole
- @ future
  - Super heavy DM ?
  - ……
  - Super light DM ?

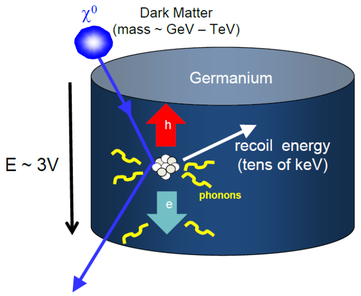
# Ways of probing DM

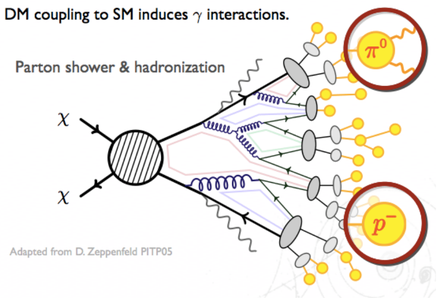
## Traditional methods

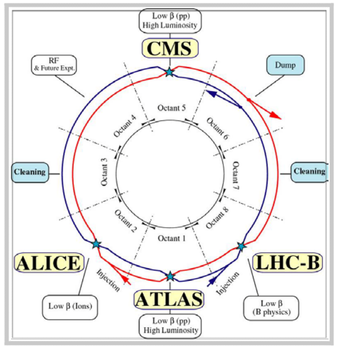



arXiv: 1305.1605



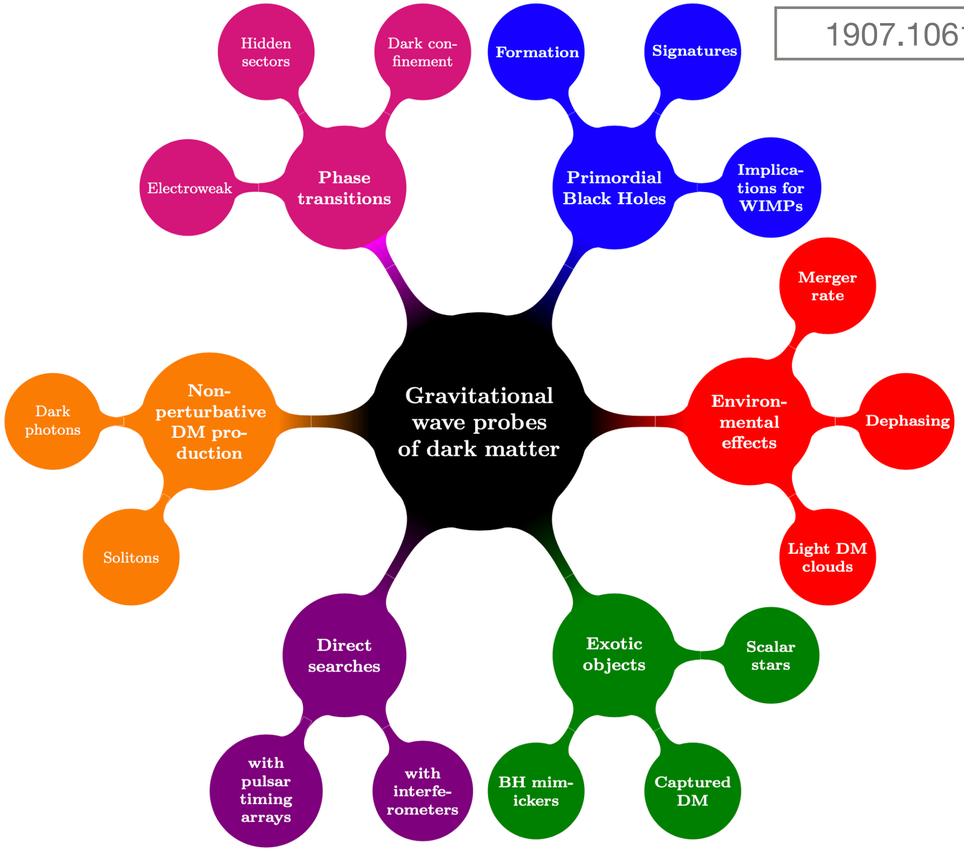




## Modern strategies

1907.10610



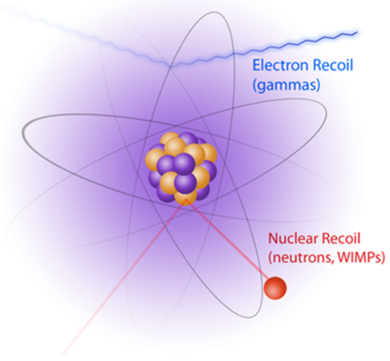
# Direct detections in underground lab

## Relevant Formulas

**The WIMP event rate**

$$\frac{dR}{dE_R} = MT \times \frac{\rho_{\rm DM}\sigma_n^0 A^2}{2m_{\rm DM}\mu_n^2} F^2(E_R) \int_{v_{\rm min}} \frac{f(\vec{v})}{v} d^3v$$

Exposure | DM density | Nuclear Form Factor




**Two uncertainties:**

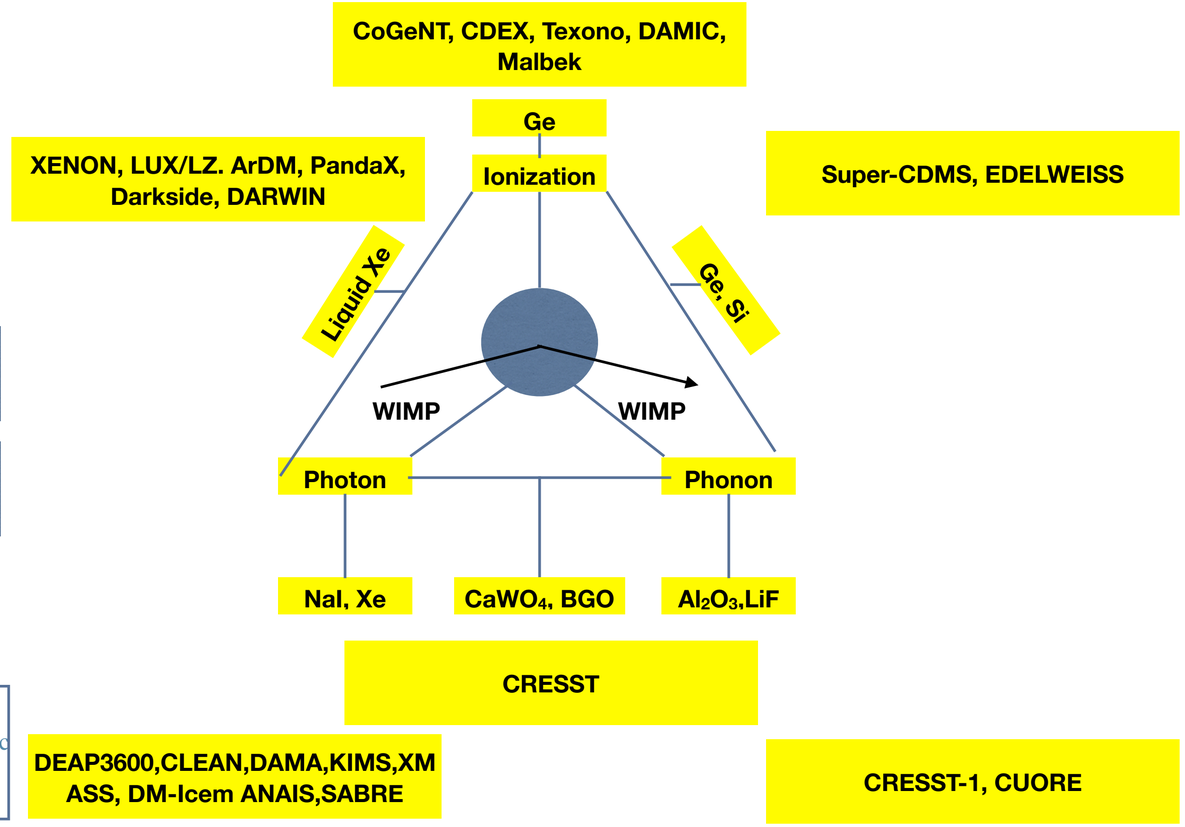
$\rho_{\rm DM}$
- local measures use the vertical kinematics of stars near the Sun
- Global measurement extrapolate rho from rotation curve

**Maxwell Boltzmann distribution:**

$$\rho_{\rm DM} \in [0.2,\ 0.6]\ {\rm GeV/cm^3}$$

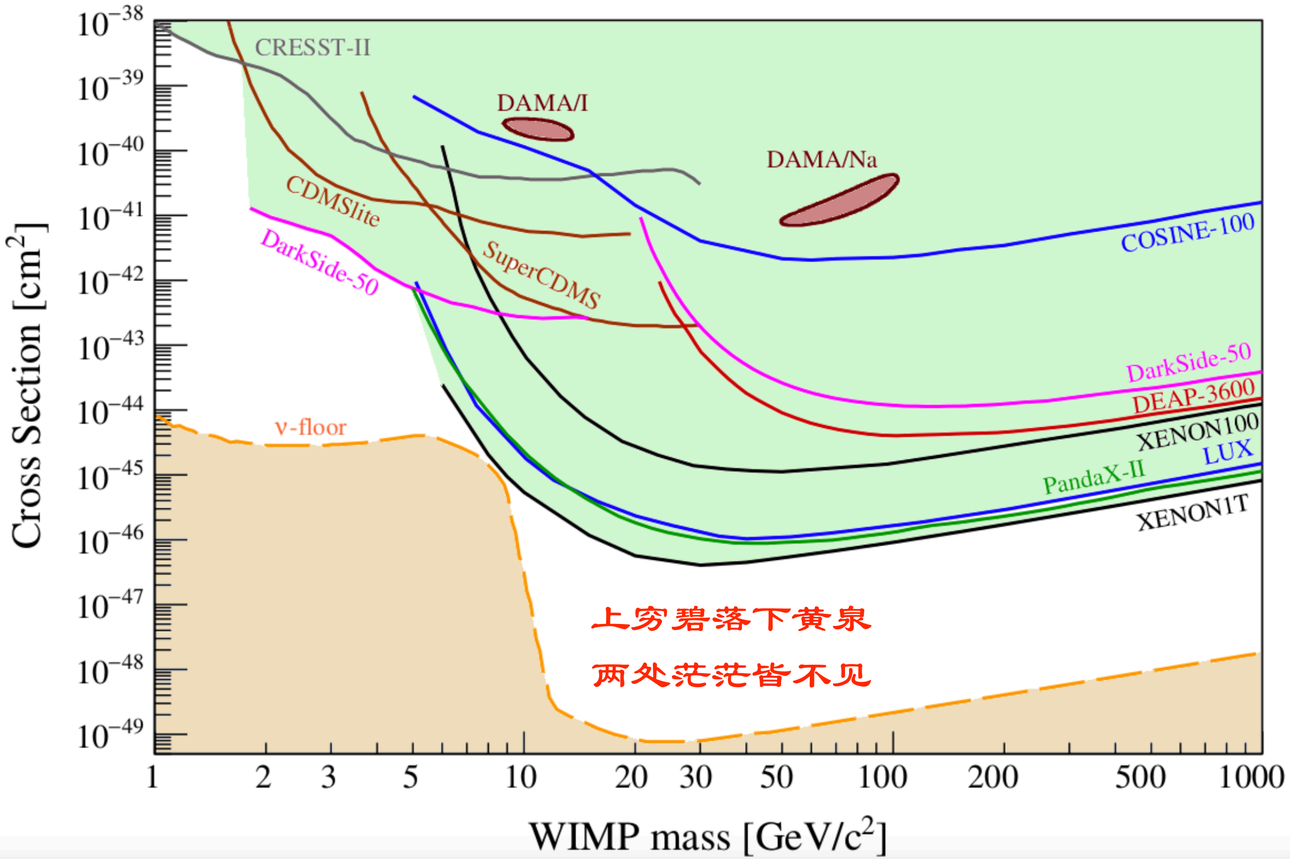
$$\int_{v_{\rm min}} \frac{f(\vec{v})}{v} d^3v = \frac{1}{2v_0\eta_E}\left[{\rm erf}(\eta_+) - {\rm erf}(\eta_-)\right] - \frac{1}{\pi v_0 \eta_E}(\eta_+ - \eta_-)e^{-\eta_{\rm esc}^2}$$

## Possible signals of direct detection experiments



# Status

**Status**




**For next?**

- **WIMP** 拥护派：
  继续赌在中微子地板上能够发现冷暗物质暗物质
  研究新的探测技术（如方向性测量）来探测地板之下的参数空间

- **WIMP** 改革派：
  往低质量区转移，研究**sub-GeV**暗物质及其直接探测
  往高质量区转移，研究超重暗物质的动力学与直接探测

- **WIMP** 反对派：
  发展修改引力
  研究极端暗物质候选者如**FUZZY DM**或原初黑洞等等

# Sterile neutrino dark matter

## Motivation

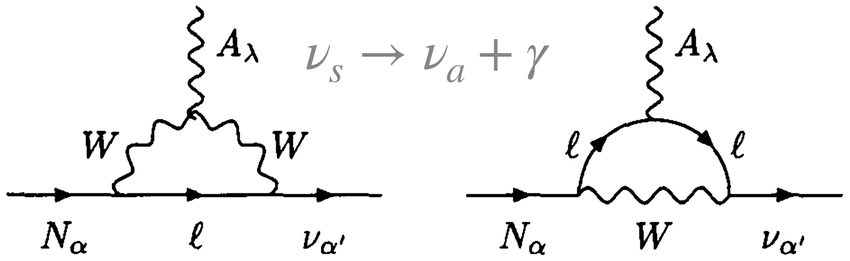
- Non-zero neutrino masses predict the existence of sterile neutrino.
- Sterile neutrino mass may range from the eV scale to the GUT scale.
- Active neutrinos is stable but cannot be dark matter candidate.
- KeV-scale sterile neutrino dark matter can solve the small scale issues of the cold dark matter( core/cusp; massive halos…).

## Brief history

- Super-weak neutrino: Freeze-out in the early Universe (Oliver& Turner 1982)
- KeV sterile neutrino: non-resonant produced via neutrino oscillations through a tiny mixing with active neutrinos(Dodelson&Widrow, 1993)
- Cool sterile neutrino DM: non-zero lepton number resonant enhanced production (Shi&Fuller,1999)
- Detection of sterile neutrino DM via the X-ray

# Situations and possible way out

## Interactions in mass eigenstates



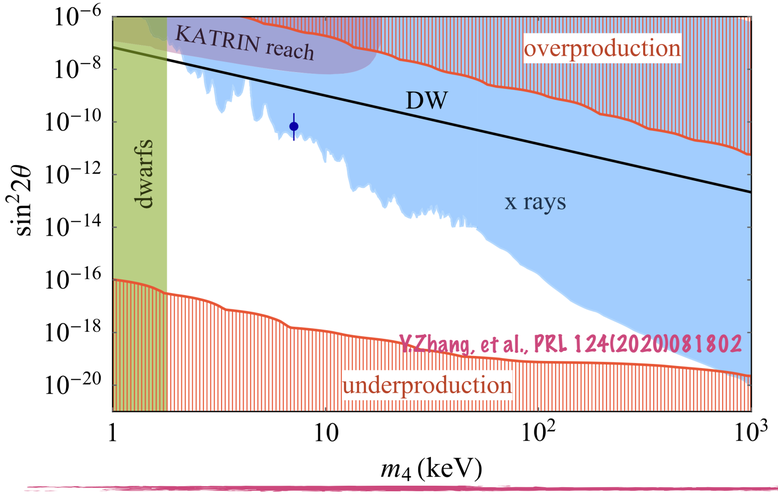

$$\Gamma_\gamma = 1.62 \times 10^{-28} s^{-1} \left(\frac{\sin^2 2\theta}{7 \times 10^{-11}}\right)\left(\frac{m_s}{7\ keV}\right)^5$$

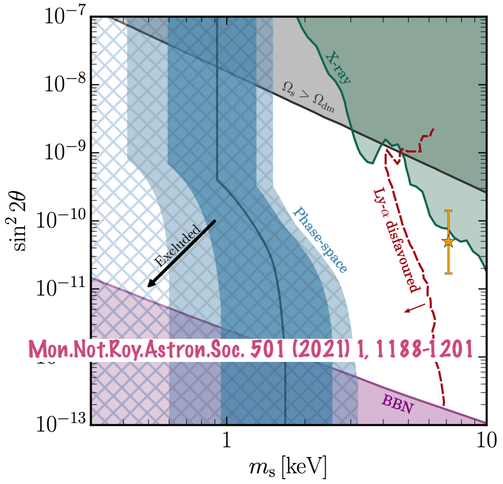
$$E_\gamma \approx \frac{m_s}{2}$$

Good: The life-time of a keV scale sterile neutrino is longer than the age of the universe.

Not too good: Too much sterile neutrino dark matter in galaxies, so it can be constrained by results of standard X-ray astronomy.

## Experimental constraints




What we try to do?

- Exploring possible solution to the problem of DW mechanisms ;
- Further exploring the potential of sterile neutrino dark matter model in releasing the Hubble tension.

Strategy: introducing a pseudo-Dirac sterile neutrino

# Pseudo-Dirac sterile neutrino

## Lagrangian

Lagrangian $\mathscr{L}_{\text{Pseudo-Dirac}} = M\overline{S_L}N_R + \frac{1}{2}\overline{S_L}\mu S_L^C + \text{h.c.}$

$$= \frac{1}{2}\overline{\begin{pmatrix} S_L & N_R^C \end{pmatrix}} \begin{pmatrix} \mu & M \\ M & 0 \end{pmatrix} \begin{pmatrix} S_L^C \\ N_R \end{pmatrix} + \text{h.c.}$$

Typical example: Inverse Seesaw Mechanism

$$M = \begin{pmatrix} 0 & M_D & 0 \\ M_D^T & \mu & M \\ 0 & M^T & 0 \end{pmatrix} \Rightarrow M_\nu \sim M_D M^{-1} \mu M_D^T M^{-1T}$$

Mass eigenstates: $\begin{pmatrix} S_L^1 \\ S_L^2 \end{pmatrix} = U^\dagger \begin{pmatrix} S_L \\ N_R^C \end{pmatrix}$ $\quad U = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} 1 & 0 \\ 0 & e^{i\rho} \end{pmatrix}$

Mass eigenvalues: $M_{1,2} \approx M \pm \mu$

Summary: A Pseudo-Dirac fermion = two Majorana fermions with nearly degenerate masses

## The permutation symmetry

Permutation symmetry in the Yukawa sector:

$$N_R \leftrightarrow S_L^C$$

$$\mathscr{L} \sim \mathscr{A}\overline{\nu_L^a}N_R + \mathscr{A}\overline{\nu_L^a}S_L^C + \mathscr{M}\overline{S_L}N_R + \frac{1}{2}\mu\overline{S_L}S_L^C + \frac{1}{2}\mu\overline{N_R^C}N_R + \text{h.c.}$$

$$\sim \frac{1}{2}\overline{\begin{pmatrix} \nu_L^a & S_L & N_R^C \end{pmatrix}} \begin{pmatrix} M_\nu & \mathscr{A} & \mathscr{A} \\ \mathscr{A} & \mu & \mathscr{M} \\ \mathscr{A} & \mathscr{M} & \mu \end{pmatrix} \begin{pmatrix} \nu_L^{aC} \\ S_L^C \\ N_R \end{pmatrix} + \text{h.c.}$$

$\theta_{12} \ll 1$

$$V_{23} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}} \\ 0 & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{pmatrix} \qquad V_{12} = \begin{pmatrix} c_{12} & -s_{12} & 0 \\ s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Mixing matrix: $U = V_{23}V_{12}$

Mass eigenvalues: $M_{s_1} \approx \mathscr{M} + \mu \qquad M_{s_s} \approx \mathscr{M} - \mu$

Interactions: $\nu_L^a = \cos\theta_{12}\hat{\nu}^a + \sin\theta_{12}s_1$

Summary: Only $s_1$ can be produced in the early universe via neutrino oscillation and the process $s_1 \to \hat{\nu} + \gamma$ is allowed.

# Pseudo-Dirac sterile neutrino

## Interaction between mass eigenstates

A: Yukawa interaction: $\overline{S_L}\phi N_R \to -\frac{1}{2}\left(\phi\overline{s_1}s_1 - \phi\overline{s_2}s_2\right)$

No Yukawa interaction between $s_1$ and $s_2$!

B: Yukawa interactions:

$$\overline{S_L}\phi S_L^C + \overline{N_R^C}\phi N_R \to \frac{1}{2}\sin 2\theta\overline{\nu_a}\phi s_1 + \frac{1}{2}\sin^2\theta\overline{\nu^a}\phi\nu^a + \frac{1}{2}\cos^2\theta\overline{s_1}\phi s_1 + \overline{s_2}\phi s_2 + \cdots$$

No Yukawa interactions between $s_2$ and other fermions!

C: gauge interaction:

$$\overline{S_L}\gamma^\mu S_L + \overline{N_R}\gamma^\mu N_R \to -\sin\theta\overline{\nu_a}\gamma^\mu P_L s_3 + \cos\theta\overline{s_2}\gamma^\mu P_L s_3 + \mathrm{h.c.}$$

$s_2$ couples to both $s_1$ and active neutrino via a vector field!

## Two scenarios

### Scenario-I ✔

$$m_{A'} \ll m_{s_2} < m_{s_1}$$

$$\Gamma(s_1 \to s_2 + A') \approx \frac{1}{3.3\times 10^{12}s}\left(\frac{g'}{10^{-15}}\right)^2 \frac{m_{s_1}}{10\ \mathrm{keV}}\left(1 - \frac{m_{s_2}^4}{m_{s_1}^4}\right)$$

$$\Gamma(s_2 \to \nu_a + A') \approx \frac{1}{4.2\times 10^{22}s}\left(\frac{g'}{10^{-15}}\right)^2 \frac{m_{s_2}}{10\ \mathrm{keV}}\left(\frac{\sin\theta}{10^{-5}}\right)^2$$

For tiny g′, $s_2$ can be dark matter candidate produced via the decay of $s_1$, which is produced in the early universe via neutrino oscillations

### Scenario-II

$m_{s_1} > 2m_{s_2}$ *and* $m_{s_2} + m_{A'} > m_{s_1}$

$$s_1 \to s_2 + s_2 + \nu_a$$

# Pseudo-Dirac sterile neutrino DM

## DM relic density

- $S_1$ is produced in the early universe via neutrino oscillations（DD Mechanism）

$$\frac{df_{N_1}(x,z)}{dz} = \frac{\Gamma \sin^2\theta}{4Hz} f_a \Theta(E - m_{N_1})$$

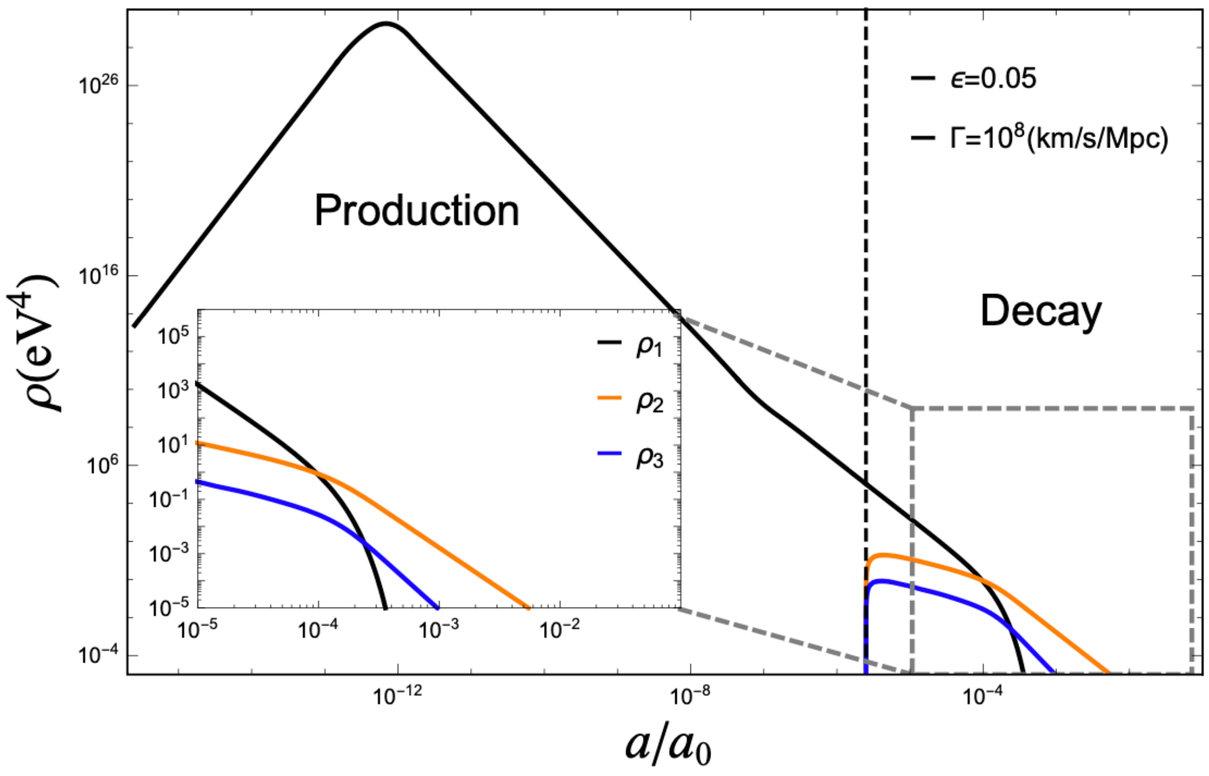
- $S_1$ then decay into $s_2$, which is the dark matter candidate

$$\frac{df_{N_1}(x,z)}{dz} = \frac{\Gamma \sin^2\theta}{4Hz} f_a \Theta(E - m_{s_1}) - \frac{f_{N_1}}{2g_s E_s Hz}\Gamma(N_1 \to N_2 A')$$

$$\frac{df_{N_2}}{dz} = \frac{f_{N_1}}{Hz}\frac{m_{N1}}{E}\Gamma_1(\hat{N}_1 \to \hat{N}_2 + A') - \frac{f_{N2}}{Hz}\frac{m_{N2}}{E}\Gamma_2(\hat{N}_2 \to \hat{\nu} + A')$$

$$\Omega_{s_2} = \frac{m_{s_2} s_0}{2\pi^2 s(z^*)\rho_0}\int_{m_{s_2}}^{\infty} E dE \sqrt{E^2 - m_{s_2}^2} f_{N_2}$$

## Plot



# Pseudo-Dirac sterile neutrino DM

## Possible signals

- X-ray ?: ✗

$S_1$ participates the electroweak interactions and is produced via neutrino oscillations in the early universe, but later on, it will decay into lighter component $s_2$ and $A'$. While $s_2$ cannot decay into active neutrino and gamma!

- Direct detections: ✗

Even if $A'$ mixes with the photon through kinematic mixing, the scattering cross section of the dark matter off the electron is still small, as $g'$ is very weak.

- The effective number of neutrinos: ✔

DM decaying into dark radiation may change the effective number of neutrinos!

## The effective number of neutrino species


$t_1$–$t_2$: Production of the heavier sterile neutrino

$t_2$: Freeze-out of active neutrinos

$t_2$–$t_3$: Decay into lighter sterile neutrino state

$t_3$–now: Sterile neutrino DM decays into active neutrinos

During the epoch $t_2 < t < t_3$, the process $s_1 \to s_2 + A'$ may increase the $N_{eff}$

$$\dot{\rho}_{A'} + 4H\rho_{A'} \approx \frac{1}{2}\left(1 - \frac{m_2^2}{m_1^2}\right)\rho_{s_1}\Gamma(s_1 \to s_2 A')$$

$$\frac{dT_\gamma}{dt} = -HT_\gamma$$

$$\Delta N_{\rm eff}^{\rm CMB} = \frac{8}{7}\left(\frac{11}{4}\right)^{4/3}\frac{\rho_{A'}}{\rho_\gamma}$$

# Pseudo-Dirac sterile neutrino DM

## The effective number of neutrino species

**Effective number of neutrinos:** $\rho_R = \left[1 + \frac{7}{8}\left(\frac{4}{11}\right)^{1/3} N_{eff}\right]\rho_\gamma$

$$N_{eff}^{SM} = \frac{8}{7}\left(\frac{11}{4}\right)^{4/3}\frac{\rho_\nu}{\rho_\gamma} = 3\left(\frac{11}{4}\right)^{4/3}\left(\frac{T_\nu}{T_\gamma}\right)^4 \approx 3.046$$

**Boltzmann eq**

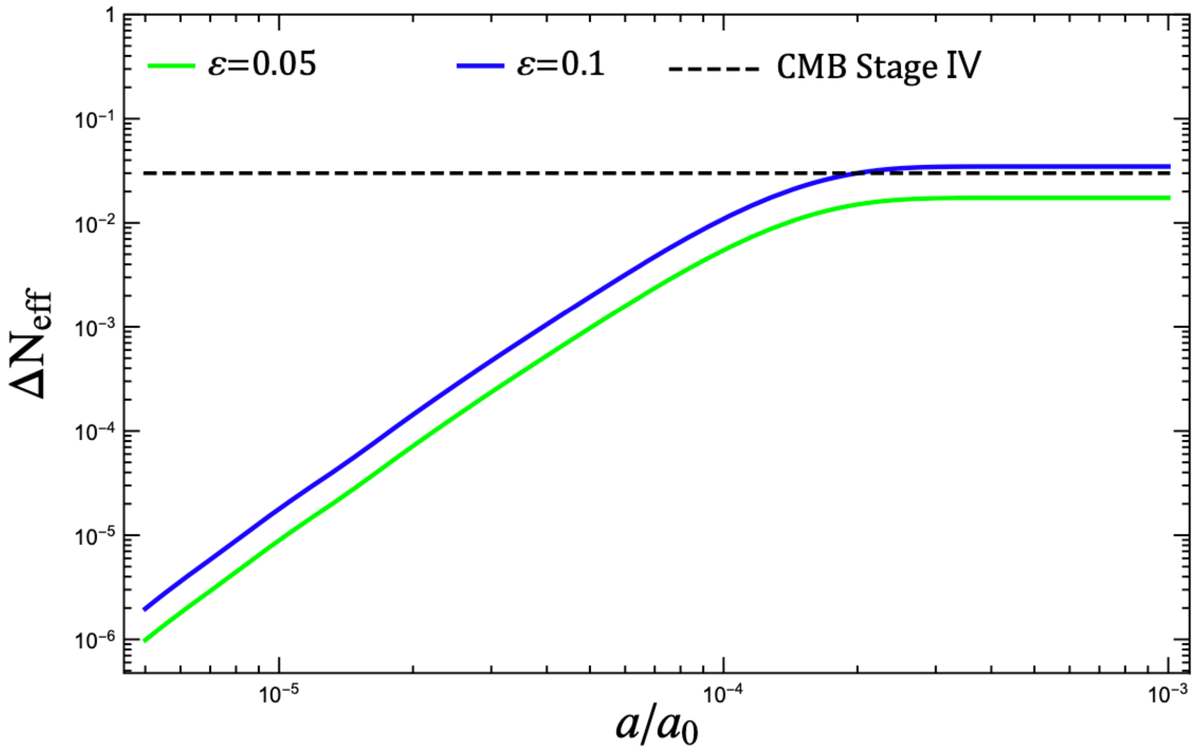
$$\frac{d\rho_{\rm tot}}{dt} + 3H(\rho_{\rm tot} + P_{\rm tot}) = 0 \quad \rightarrow \quad \begin{cases} \dot\rho_{\rm SM} + 3H(\rho_{\rm SM} + P_{\rm SM}) = -\mathscr{C}_{coll} \\ \dot\rho_\nu + 3H(\rho_\nu + P_\nu) = +\mathscr{C}_{coll} \end{cases}$$

**According to the chain role:**

$$\frac{dT_\nu}{dt} = -4Ht + \frac{\mathscr{C}_{\nu_e} + 2\mathscr{C}_{\nu_\mu}}{12\rho_\nu/T_\nu}$$

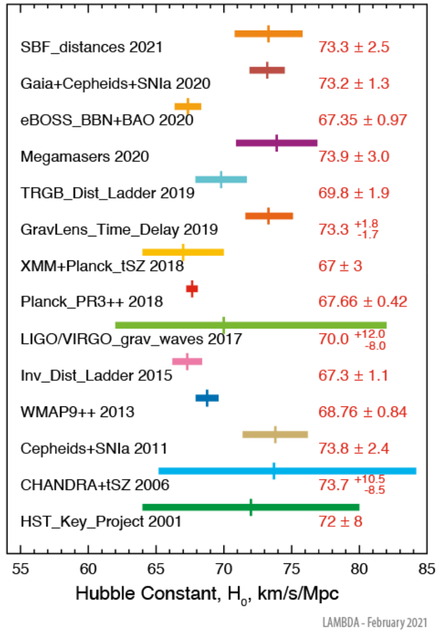
$$\frac{dT_\gamma}{dt} = -\frac{4H\rho_\gamma + 3H(\rho_e + P_e) + \mathscr{C}_{\nu_e} + 2\mathscr{C}_{\nu_\mu} + 3HT_\gamma dP_{\rm intt}/ddT_\gamma}{\partial\rho_\gamma/\partial T + \partial\rho_e/\partial T + Td^2P_{\rm int}/dT^2}$$

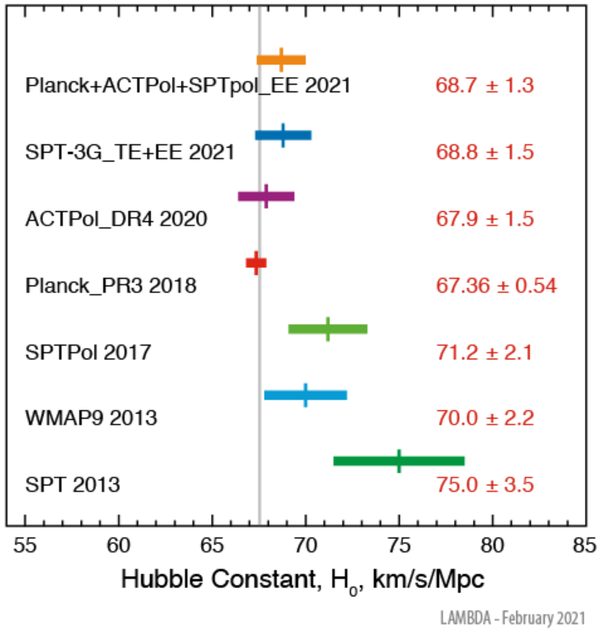
## Illustrative Plot



# Pseudo-Dirac sterile neutrino DM

## The Hubble tension




$$H_0 = (73.24 \pm 1.74) kms^{-1}Mpc^{-1} \; VS \quad H_0 = (67.27 \pm 0.66)\mathrm{kms}^{-1}\mathrm{Mpc}^{-1}$$

## Possible solutions in particle physics

- ✓ Light sterile neutrino
- ✓ Neutrino asymmetry
- ✓ Decay DM
- ✓ Neutrino DM interactions
- ✓ Neutrino Majoron interaction
- ✓ FIMP decay into neutrino
- ✓ …

**Our Strategy**

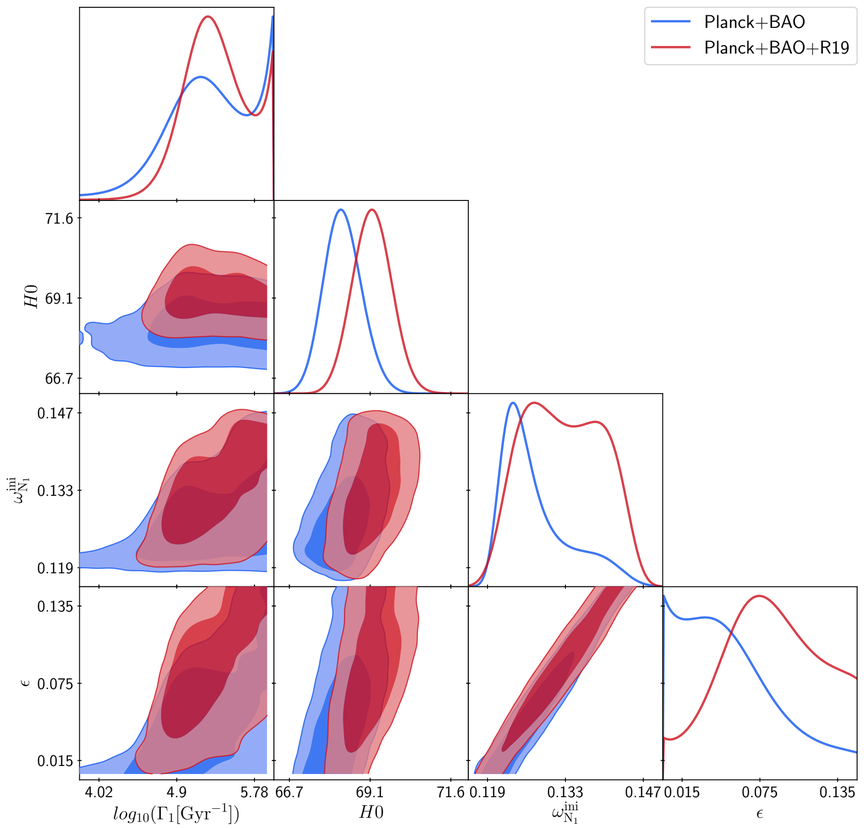
- $s_1$ decays into dark radiation, but this process is constrained by the CMB
- $s_2$ further decays into dark radiation and active neutrinos which enhances the $N_{eff}$ and results in a larger $H_0$

$$\dot{\rho}_{A'} + 4H\rho_{A'} \approx \frac{1}{2}\left(1 - \frac{m_2^2}{m_1^2}\right)\rho_{s_1}\Gamma(s_1 \to s_2 A') + \frac{1}{2}\rho_{s_2}\Gamma(s_2 \to \nu A')$$

$$\frac{dT_\nu}{dt} = \frac{1}{\partial\rho_\nu/\partial T}\left[-4H\rho_\nu + \frac{1}{2}\rho_{s_2}\Gamma(s_2 \to \nu_a A')\right] \Rightarrow \rho'_\nu = 2 \cdot \frac{7}{8}\frac{\pi^2}{30}T_\nu^4$$

# Pseudo-Dirac sterile neutrino DM

## Class+MontePython for MCMC




## Parmeters

| Param | ΛCDM Planck+BAO mean±σ | DNDM Planck+BAO mean±σ | DNDM Planck+BAO+R19 mean±σ |
|---|---|---|---|
| $100\ \omega_b$ | $2.242^{+0.013}_{-0.014}$ | $2.241^{+0.016}_{-0.016}$ | $2.258^{+0.015}_{-0.015}$ |
| $\log_{10}(\Gamma_1)$ | - | $>5.199$ | $>5.32$ |
| $H_0$ | $67.7^{+0.45}_{-0.45}$ | $68.31^{+0.54}_{-0.61}$ | $69.2^{+0.58}_{-0.59}$ |
| $\ln 10^{10} A_s$ | $3.049^{+0.014}_{-0.015}$ | $3.056^{+0.014}_{-0.016}$ | $3.065^{+0.016}_{-0.017}$ |
| $n_s$ | $0.9664^{+0.0039}_{-0.004}$ | $0.973^{+0.0053}_{-0.0076}$ | $0.9805^{+0.0064}_{-0.0086}$ |
| $\tau_{reio}$ | $0.05718^{+0.0072}_{-0.0076}$ | $0.05774^{+0.0068}_{-0.008}$ | $0.06155^{+0.0072}_{-0.0083}$ |
| $\omega_{N_1}^{ini}$ | $0.1194^{+0.00098}_{-0.00099}$ | $0.1278^{+0.0032}_{-0.0086}$ | $0.1329^{+0.0071}_{-0.0076}$ |
| $\varepsilon$ | - | $<0.06889$ | $0.09233^{+0.04}_{-0.048}$ |
| $\sigma_8$ | $0.8104^{+0.0063}_{-0.0062}$ | $0.8189^{+0.0077}_{-0.01}$ | $0.8243^{+0.0096}_{-0.012}$ |

– ln Lmin = 1412.44, minimum $\chi^2$ = 2825

# Direct detections of neutrino-like DM

**Problem: Kinetic energy of light DM is too small**

$$v_{\rm DM} \sim 10^{-3}$$

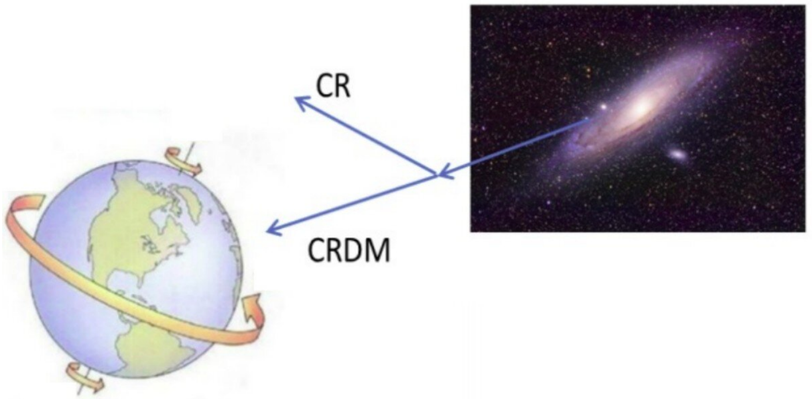
$$E_R \sim \frac{(p_{\rm DM} - p'_{\rm DM})^2}{2m_T} \ll E_{\rm Threshold}$$

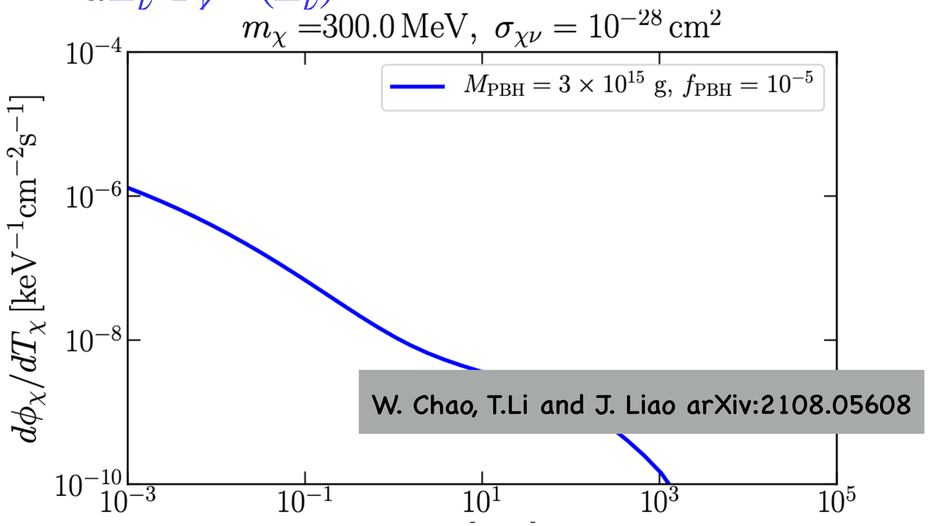
**Strategy-1: Boosted DM**

$$\frac{d\phi_\chi}{dE_\nu} = \int \frac{d\Omega}{4\pi} \int d\ell \frac{\rho_\chi}{m_\chi} \Phi_\nu(E_\nu)\sigma_{\chi\nu} = D_{\rm halo}\Phi_\nu(E_\nu)\frac{\sigma_{\chi\nu}}{m_\chi}$$

$$D_{\rm halo} = 2.02 \times 10^{25} {\rm MeV} \cdot {\rm cm}^{-2}$$

$$\frac{d\phi_\chi}{dT_\chi} = \int dE_\nu \frac{d\phi_\chi}{dE_\nu} \frac{1}{T_\chi^{\rm max}(E_\nu)} \Theta(T_\chi^{\rm max} - T_\chi)$$




W. Chao, T.Li and J. Liao arXiv:2108.05608

# Direct detections of neutrino-like DM

**Strategy-II: Searching for DM using Condense Matter system!**

| DM mass | DM energy or momentum | CM scale |
|---|---|---|
| 50 MeV | $p_\chi \sim 50$ keV | zero-point ion momentum in lattice |
| 20 MeV | $E_\chi \sim 10$ eV | atomic ionization energy |
| 2 MeV | $E_\chi \sim 1$ eV | semiconductor band gap |
| 100 keV | $E_\chi \sim 50$ meV | optical phonon energy |

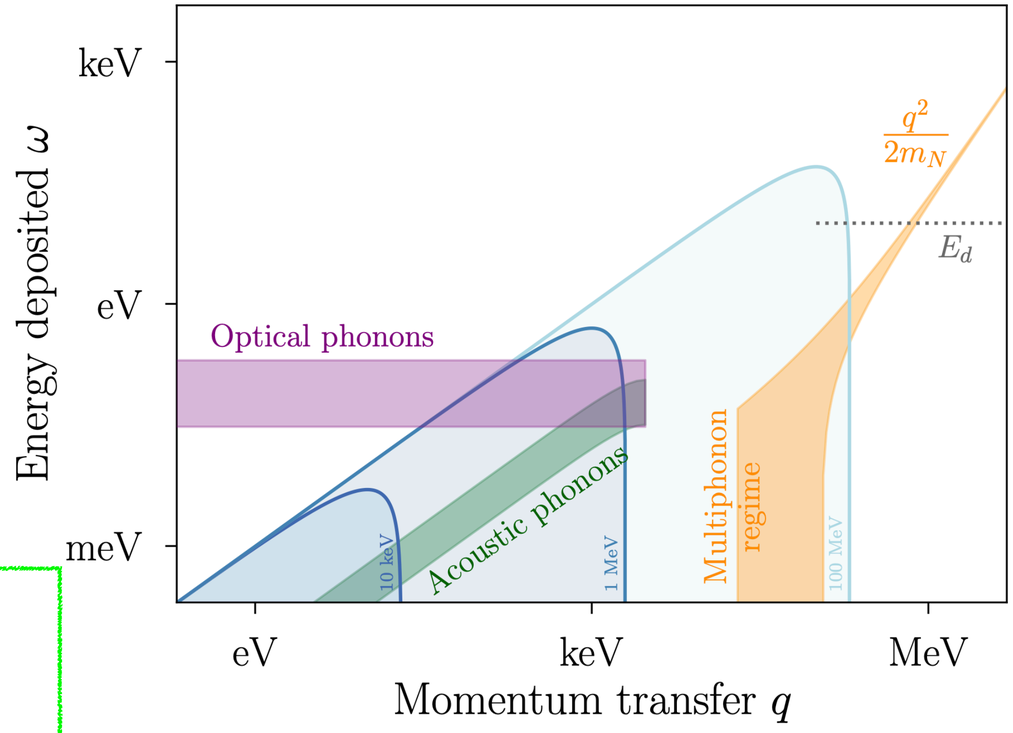
**Fermi's Golden Rule**

$$R_\chi = \frac{1}{\rho_T}\frac{\rho_\chi}{m_\chi}\int d^3v f_\chi(v)\frac{Vd^3p'_\chi}{(2\pi)^3}\sum_f |\langle f, p'_\chi|\Delta H_\chi|i, p_\chi\rangle|^2 2\pi\delta(E_f - E_i - \omega)$$

$$= \frac{1}{\rho_T}\frac{\rho_\chi}{m_\chi}\int \frac{d^3q}{(2\pi)^3} d\omega g(q,\omega)\tilde{V}(q)S(q,\omega)$$

$$= \frac{1}{\rho_T}\frac{\rho_\chi}{m_\chi}\frac{\pi\bar{\sigma}(q)}{\mu_\chi^2}\int \frac{qdq}{(2\pi)^2} d\omega\eta(v_{\min}(q,\omega)) \times S(q,\omega)$$

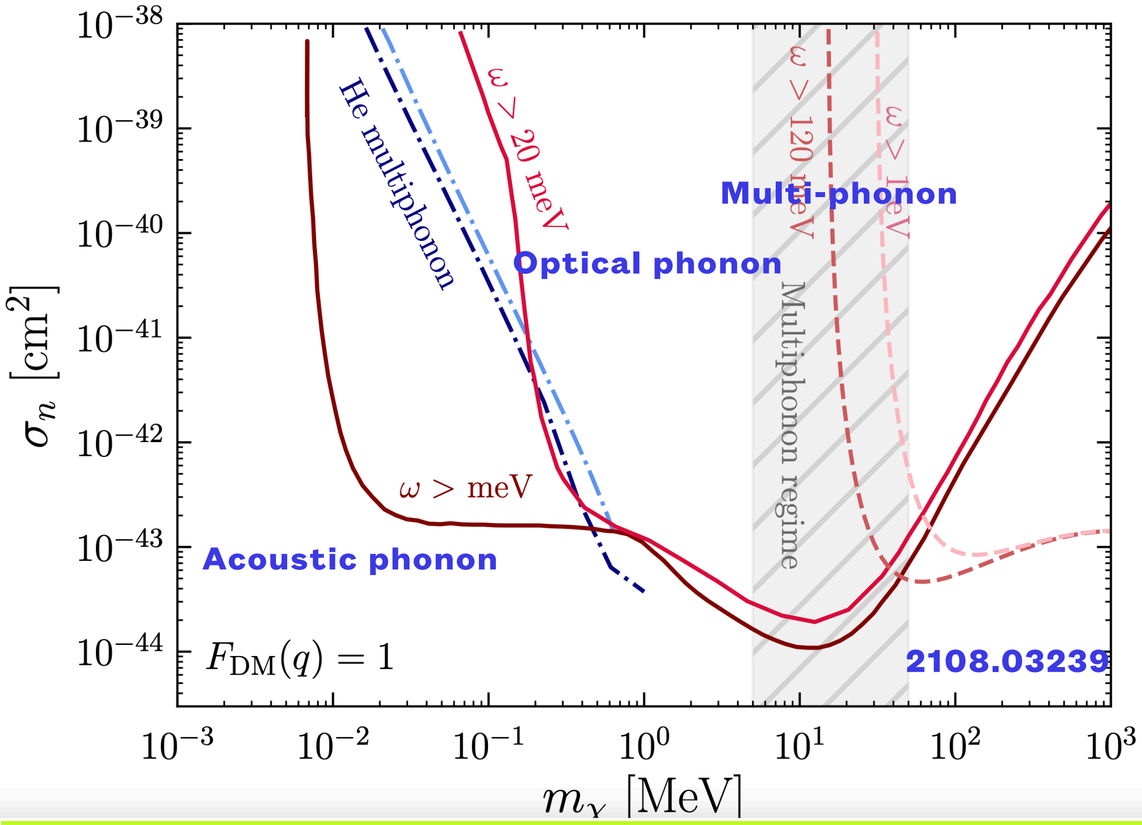
- $S(q,\omega)$: dynamical structure factor from condensed matter
- $\tilde{V}(q)$: potential felled by DM

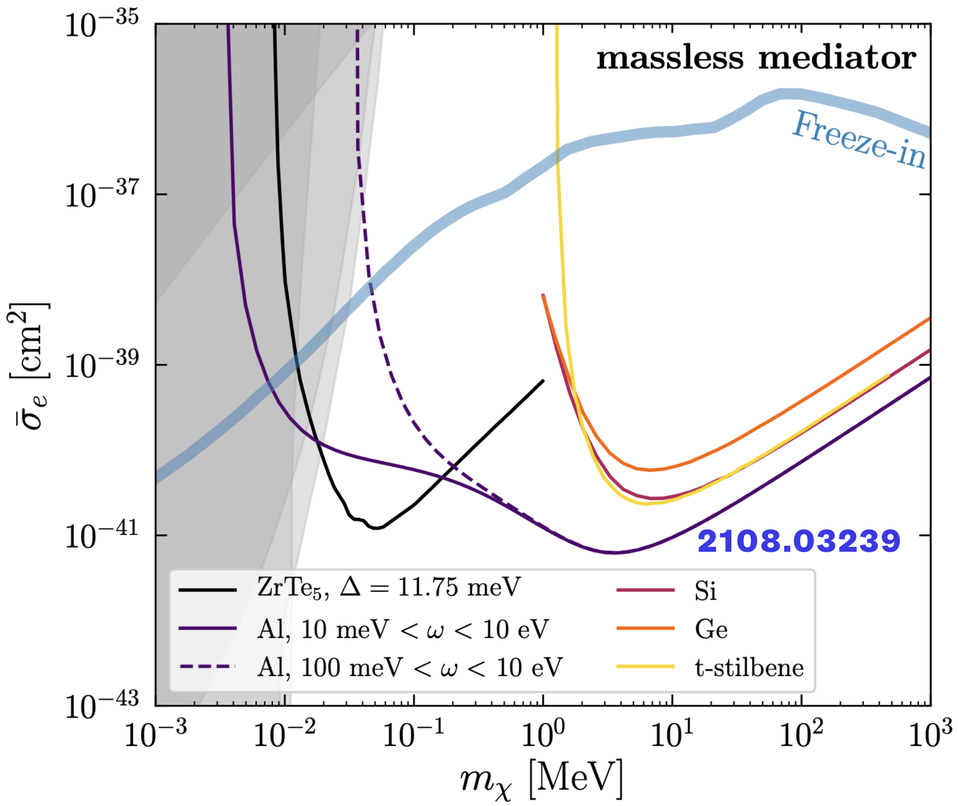


# Direct detections of neutrino-like DM

$$R = \frac{1}{\rho_T}\frac{\rho_\chi}{m_\chi}\frac{\pi\bar{\sigma}(q)}{\mu_\chi^2}\int\frac{qdq}{(2\pi)^2}d\omega\eta(v_{\rm min}(q,\omega))\times S(q,\omega)$$

$$\frac{dR}{d\ln E_R} = N_T\frac{\rho_\chi}{m_\chi}\frac{\bar{\sigma}_e}{8\mu_{\chi e}^2}\int dqq\,|F_{\rm DM}(q)|^2|f_{\rm ion}(k,q)|^2\eta(v_{\rm min})$$



# Direct detections of neutrino-like DM

Open question: What can we do?

**Explore New Physics Using CM-Physics**

- Neutrino physics
  - Cosmic neutrino background
  - Exotic neutrino sources
  - New neutrino interaction
- Dark matter
- ...

**Dive Into CM-Physics and Calculate the $s(q, \omega)$**

Many materials

- Semi-conductor
- Super-conductor
- Dielectrics
- ....

Many collective state

- Phonon
- Plasmon
- Magnon
- ....

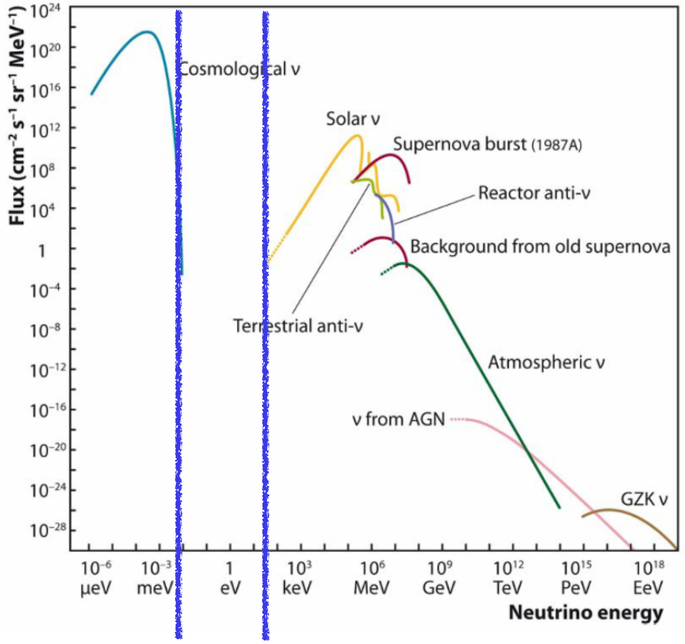
**Exploring New Method for the Calculation of DM DD Cross Section in Superconductor**

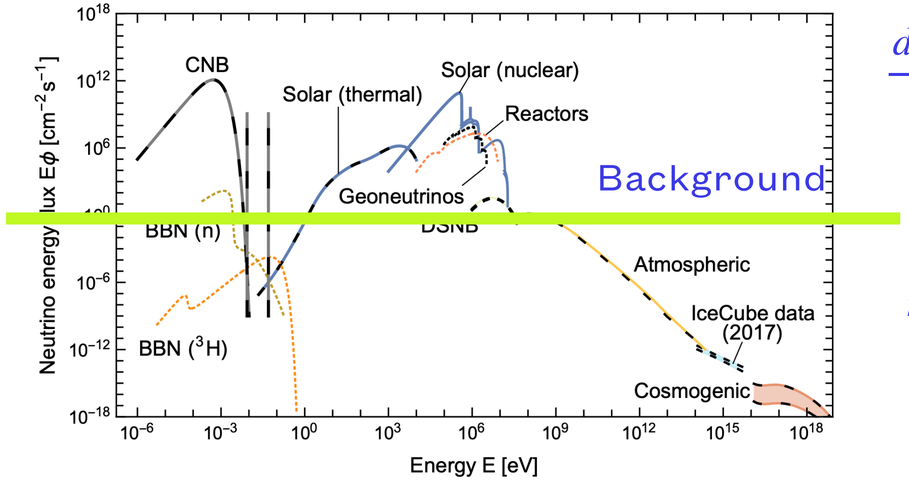
Effective field theory for superconductor

# Direct detections of neutrino-like DM

保守派的拷问：万一暗物质不在这个质量区间，那么这种研究有什么用？

乐天派的辩解：中微子本身就是一种热暗物质，我们可以考虑利用这种手段来探测中微子暗物质，也就是中微子背景




$$\frac{d\Phi_\nu(x)}{dT_\nu} = \int d^3z dT_i \frac{d\Phi_i(z)}{dT_i} \frac{d\bar{\sigma}}{dT_\nu}\bigg|_{\theta=\theta_E} \frac{n_\nu(z)}{|z-x|^2}$$

$$n_\nu \sim 56\ \mathrm{cm}^{-3}$$

# Neutrino(-like) DM in condense matter

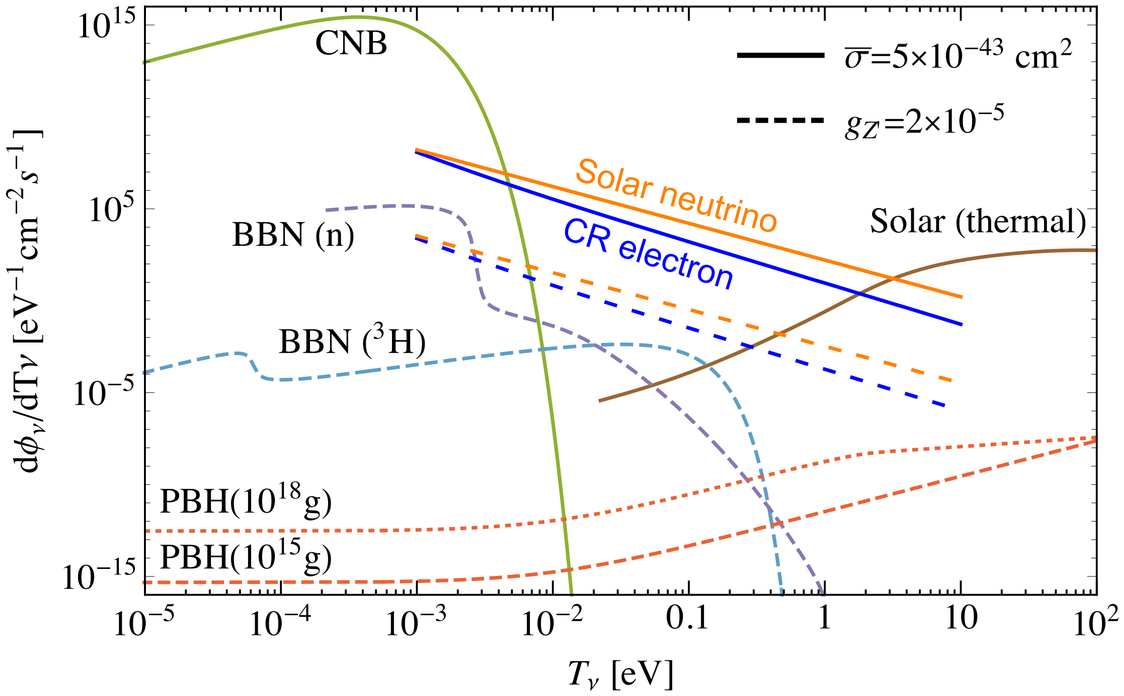
## Boosted neutrino flux

$$\frac{d\Phi_\nu}{dT_\nu} = \int\int\int \frac{d\Omega d\ell dT_i}{4\pi} n_\nu \cdot \frac{d\sigma_{\nu i}}{dT_\nu} \cdot \frac{d\Phi_i}{dT_i}$$

**Model-dependent cross section:**

$$\begin{aligned}\frac{d\sigma_{e\nu}}{dT_\nu} &= \frac{g_{Z'}^4}{8\pi}\{m_e^2(m_\nu - T_\nu) + m_e m_\nu(4T_i - 2T_\nu) \\ &+ m_\nu T_\nu^2 + m_\nu(T_i - T_\nu)^2\} \\ &\times (2m_e T_i + T_i^2)^{-1}(2m_\nu T_\nu + m_{Z'}^2)^{-2} \qquad (3) \\ \frac{d\sigma_{\nu\nu}}{dT_\nu} &= \frac{g_{Z'}^4}{2\pi}\frac{m_\nu(m_\nu + T_i)^2(m_\nu T_i + m_{Z'}^2)^2}{2m_\nu T_i + T_i^2} \\ &(2m_\nu T_\nu + m_{Z'}^2)^{-2}(2m_\nu(T_i - T_\nu) + m_{Z'}^2)^{-2} (4)\end{aligned}$$

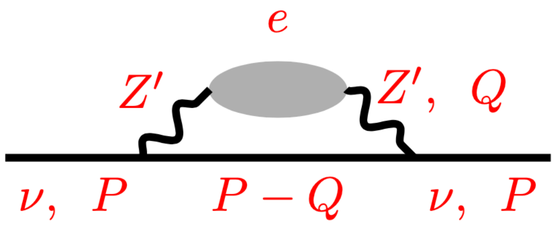
## Plot



# Neutrino(-like) DM in condense matter

## Scattering cross section

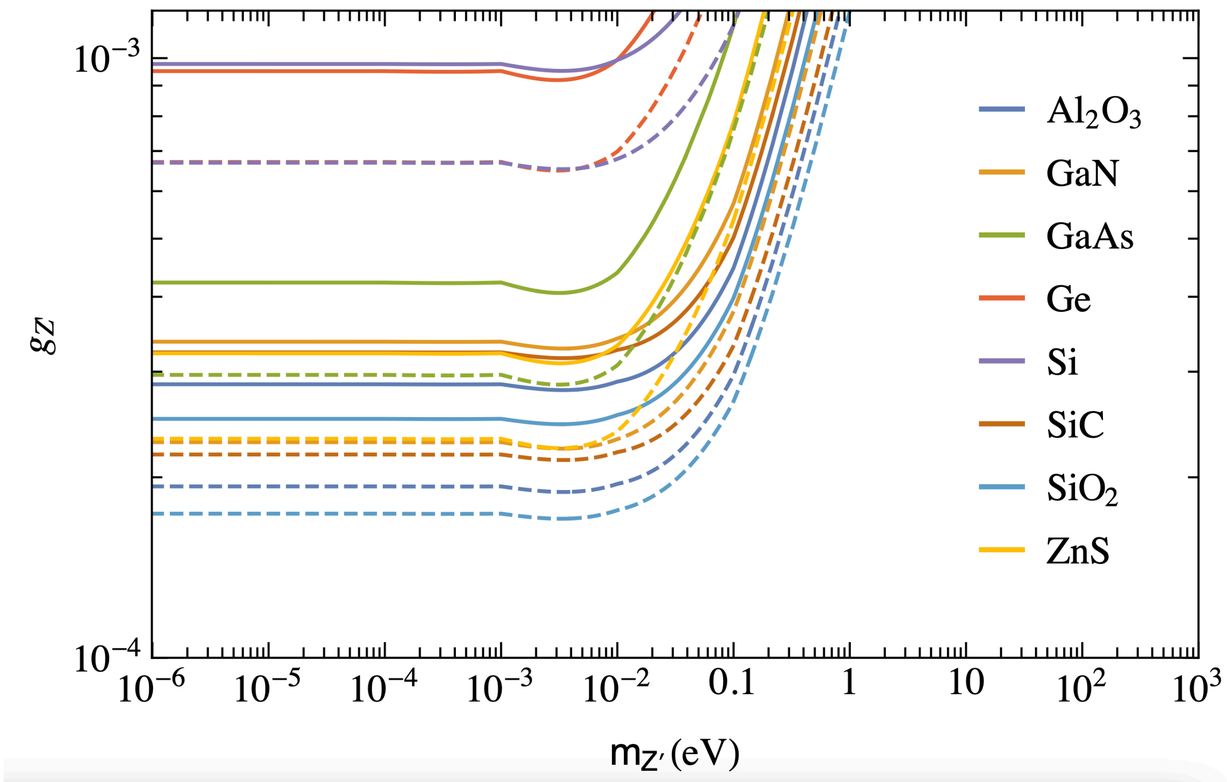
$$\Gamma = \frac{1}{4E}\mathrm{tr}\left[(\not{P}+m_\nu)\Sigma^>(P)\right]$$




$$\Sigma^>(P) = g_Z'^2 \int \frac{d^4Q}{(2\pi)^4}\gamma^\mu S_0^>(P-Q)\gamma^\nu D^>_{\mu\nu}(Q)$$

$$\frac{dR}{d\omega} = \frac{g_{Z'}^4}{(2\pi)^2\rho_T}\int dT_\nu \frac{d\Phi_\nu}{dT_\nu}\int \frac{dq}{E_\nu E'_\nu} \times \frac{q^4}{(q^2+m_{Z'}^2)^2}\delta(E_\nu - E'_\nu - \omega) \times \left(\frac{q^2}{2}+2E_\nu^2+2m_\nu^2\right)\mathrm{Im}\left[\frac{-1}{\varepsilon_L(q,\omega)}\right]$$

## Illustrative Plot (model dependent)



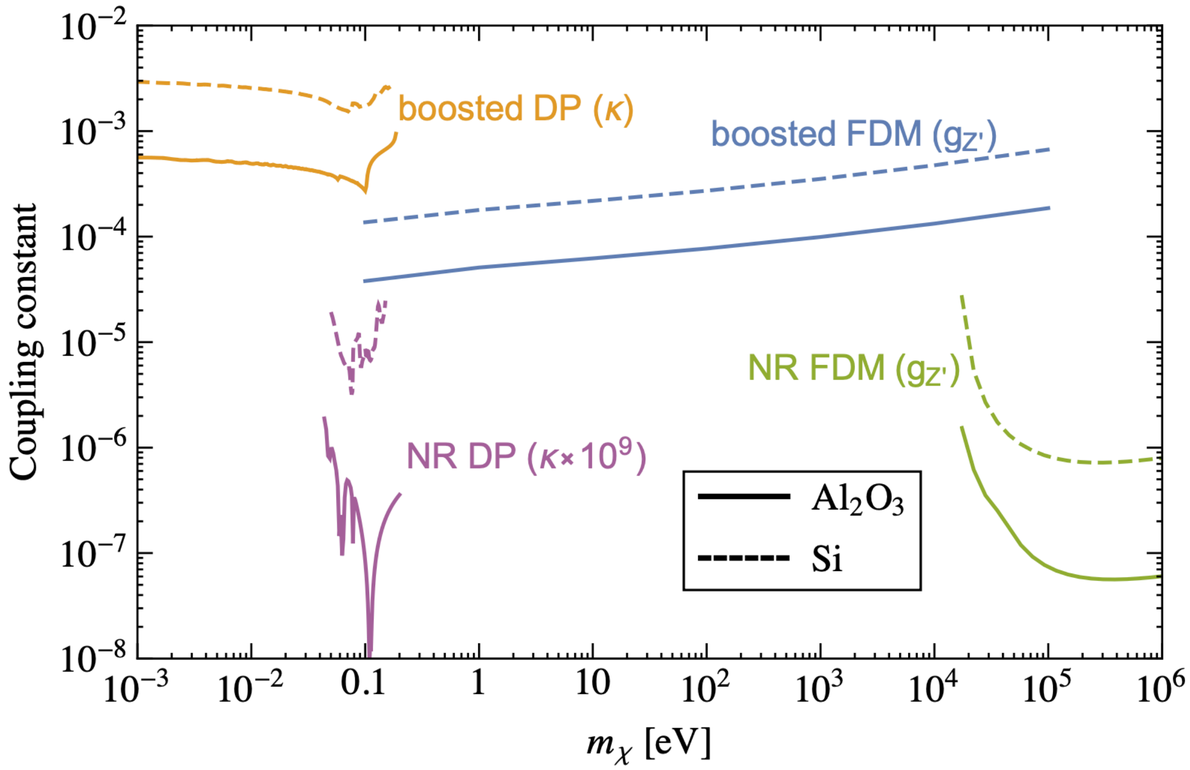
# Neutrino(-like) DM in condense matter

**Dark sector constraints**

For fermionic DM the formula is similar!

For bosonic DM, it can be absorbed by the target!

$$R = \frac{1}{\rho_T}\int dT_{\rm DP}\frac{d\phi_{\rm DP}}{dT_{\rm DP}}\kappa^2 m_{\rm DP}\,{\rm Im}\left[\frac{-1}{\varepsilon_L(m_{\rm DP})}\right]$$



# Neutrino(-like) DM in condense matter

**Model independent formalism!**

**Neutrino Flux:**

$$\frac{d\Phi_\nu}{dT_\nu} = \iiint \frac{d\Omega d\ell dT_i}{4\pi} n_\nu \cdot \frac{d\sigma_{\nu i}}{dT_\nu} \cdot \frac{d\Phi_i}{dT_i}$$

$$\approx \iiint \frac{d\Omega d\ell dT_i}{4\pi} n_\nu \cdot \frac{\bar{\sigma}_{\nu i}}{T_\nu^{\max}} \cdot \frac{d\Phi_i}{dT_i}$$

**Scattering Rate:**

$$\frac{d\Gamma}{d\omega} \approx \frac{1}{\pi}\int d\bar{\sigma} q^2 \mathrm{Im}\left(-\frac{1}{\varepsilon_{\mathrm{L}}}\right) = \frac{1}{\pi}\bar{\sigma} q_m^2 \mathrm{Im}\left(-\frac{1}{\varepsilon_L(q_m,\omega)}\right)$$

**Event Rate:**

$$\frac{dR}{d\omega} \approx \frac{1}{\rho_T}\int dE_\nu \frac{d\Phi_\nu}{dE_\nu}\frac{1}{\pi}\bar{\sigma} q_m^2 \mathrm{Im}\left(-\frac{1}{\varepsilon_L(q_m,\omega)}\right)$$

# Conclusion

- A new sterile neutrino dark matter model is presented which may escape the bound arising from X-ray results.
- A possible constraint on the model is effective number of neutrinos, which can be measured by the future CMB-Stage-IV.
- We further discuss the direct detection signal of neutrino-like dark matter in condensed matter systems. Especially, we discussed the signal of cosmic neutrino background in dark matter direct detection experiments.

**THANK YOU FOR YOUR ATTENTION**