Interplay between Neutrino & Dark Matter

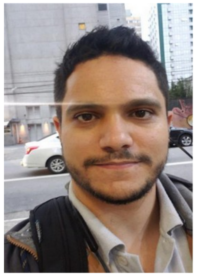
Shao-Feng Ge

葛 韶 锋

gesf@sjtu.edu.cn


马凯


马小东


Pedro Pasquini


盛杰


孔垂范


谭亮

上海交通大學
SHANGHAI JIAO TONG UNIVERSITY

紫金山暗物质研讨会
December 30, 2023

李政道研究所
Tsung-Dao Lee Institute

Outline

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1) Overview

2) Sterile ν DM

3) Heavy Right-Handed Neutrino DM

4) Absorption DM @ Direct Detection Experiments

5) Environmental Mass with Dark NSI

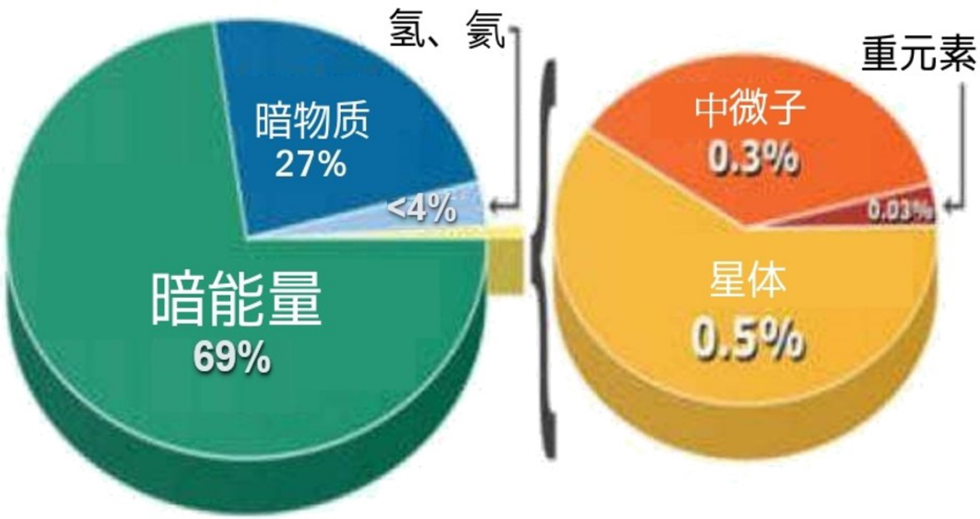
6) ν Mass with Cosmic Gravitational Focusing

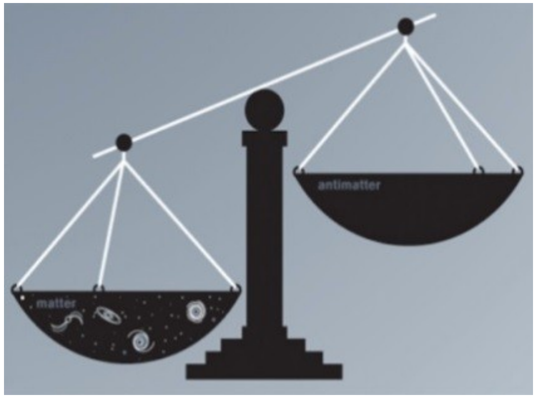
7) Summary

Matter World

暗物质是什么？怎么产生的?

暗物质主导了物质世界的形成





可见物质的起源?

轻子生成机制

两者之间存在怎样的关联?

Minimal Neutrinos

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Georg G. Raffelt

Stars as Laboratories for Fundamental Physics

The Astrophysics of Neutrinos, Axions, and Other Weakly Interacting Particles

In the standard model, neutrinos have been assigned the most minimal properties compatible with experimental data: zero mass, zero charge, zero dipole moments, zero decay rate, zero almost everything.

Almost the same for dark matter!

Neutrino vs Dark Matter

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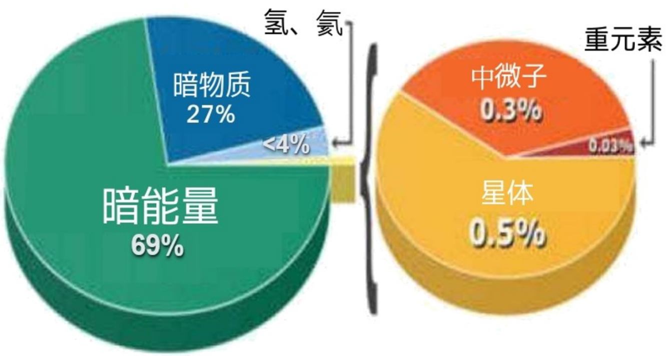
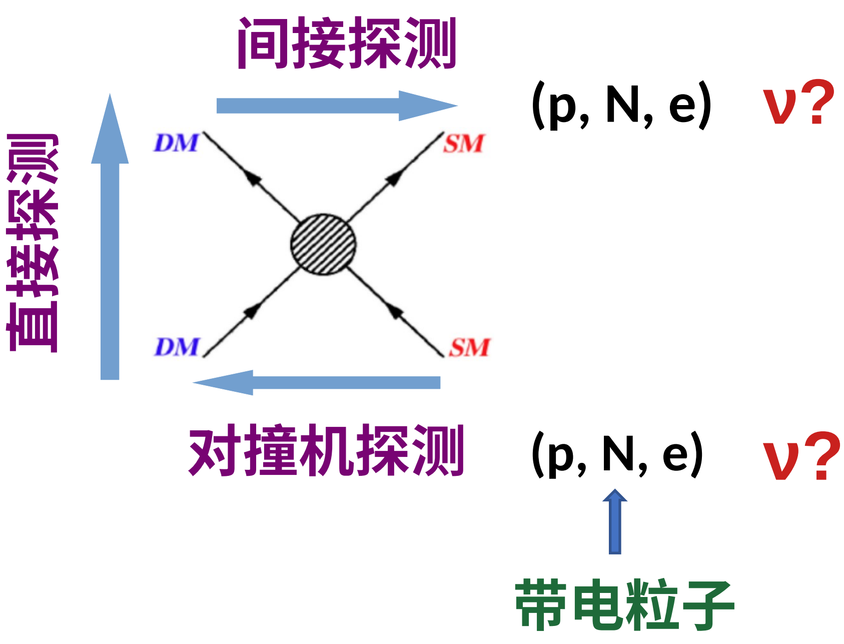
- 都对理解宇宙中的物质世界起关键作用
- 都是电中性物质
- 都和普通物质的相互作用很弱
- 都在宇宙早期就脱耦
- 背后是否有一个全新的分区?
- 两者之间是否有关联?
- ……





Are Neutrinos Dark Matter?

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PHYSICAL REVIEW LETTERS

VOLUME 39 | 25 JULY 1977 | NUMBER 4

Cosmological Lower Bound on Heavy-Neutrino Masses

Benjamin W. Lee[(a)]
Fermi National Accelerator Laboratory,[(b)] *Batavia, Illinois 60510*

and

Steven Weinberg[(c)]
Stanford University, Physics Department, Stanford, California 94305
(Received 13 May 1977)

The present cosmic mass density of possible stable neutral heavy leptons is calculated in a standard cosmological model. In order for this density not to exceed the upper limit of 2×10^{-29} g/cm^3, the lepton mass would have to be *greater* than a lower bound of the order of 2 GeV.

Lee & Weinberg, PRL77

Are Neutrinos Dark Matter?

Cosmological Upper Bound on Heavy-Neutrino Lifetimes

Duane A. Dicus[a] and Edward W. Kolb[a]
Center for Particle Theory, University of Texas at Austin, Austin, Texas 78712

and

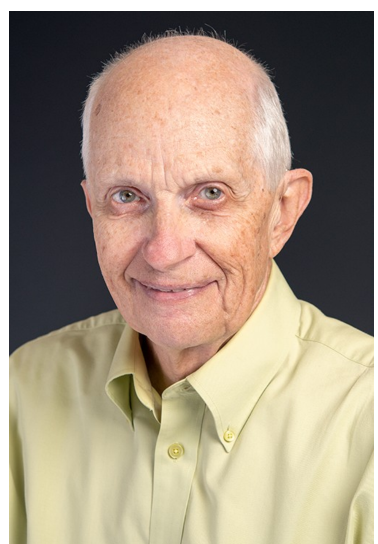
Vigdor L. Teplitz[b]
Department of Physics, Virginia Polytechnic Institute and State University, Blacksburg, Virginia 24061

(Received 31 May 1977)

An upper bound on the lifetime of a massive, neutral, weakly interacting lepton, ν_H, is derived from standard big-bang cosmology. Saturation of the bound and reasonable assumptions about the weak interaction of the ν_H then yield a prediction of approximately 10 MeV for its mass.

Duane Dicus, Kolb & Teplitz, PRL77

和 Lee-Weinberg 文章前后页



Duane Alfred Dicus

November 23, 1938– September 7, 2022

University of Texas

Sterile Neutrino

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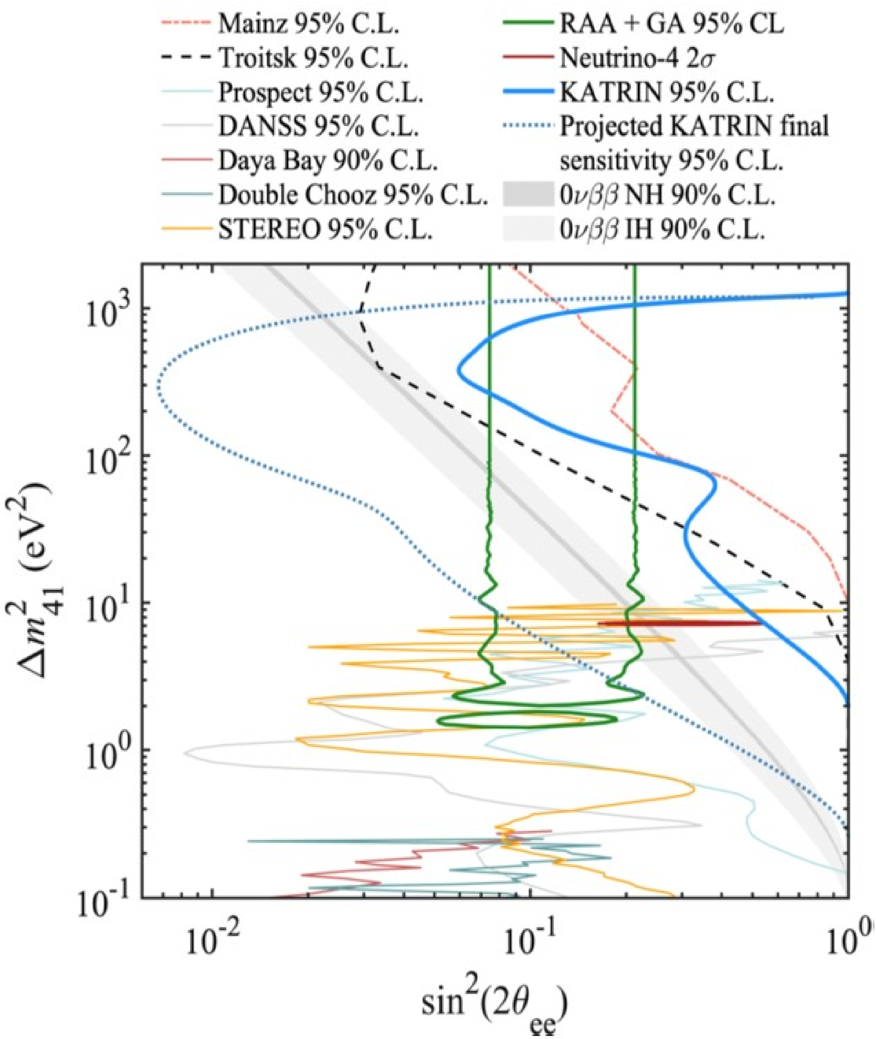
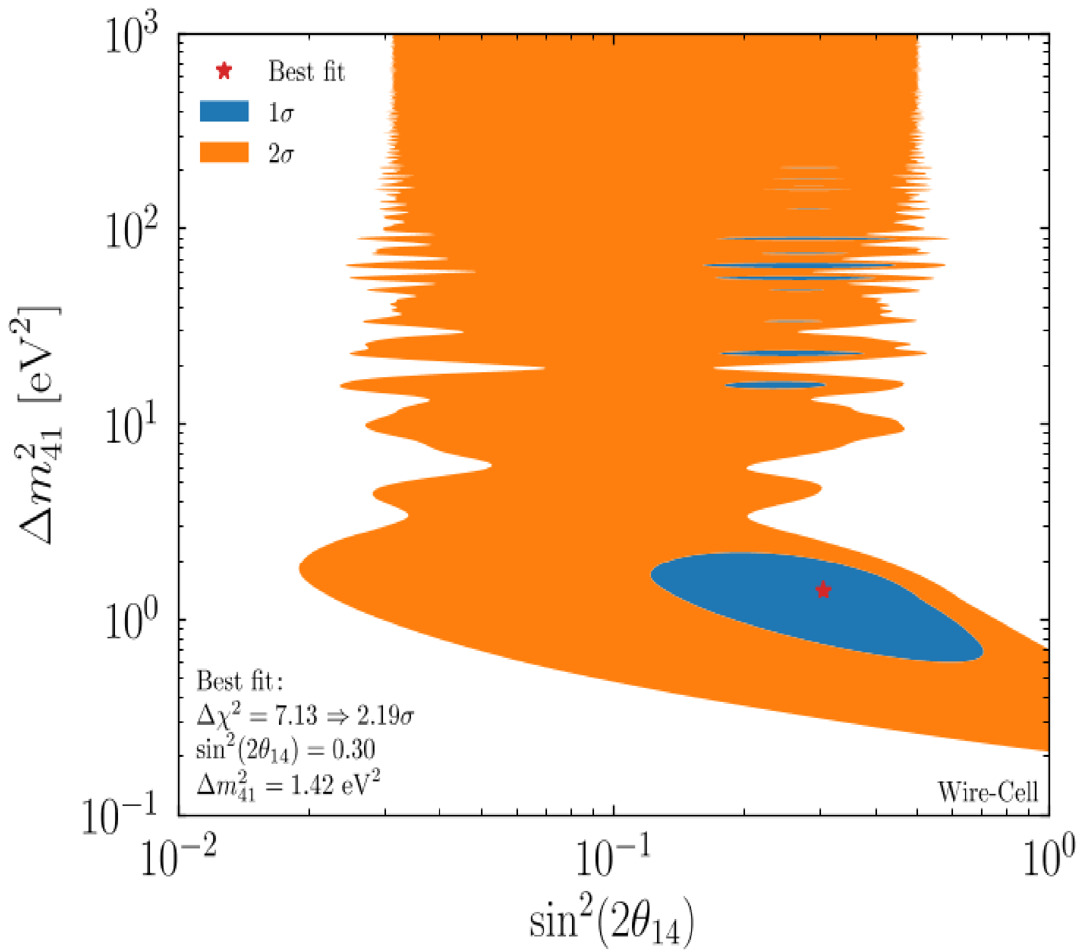


Schoppmann [2109.13541]

Latest result @ MicroBooNE



Denton [2111.05793]

主要限制 eV sterile neutrino

Dodelson-Widrow Mechanism

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- If only neutrino oscillation => oscillation back & forth

$$\sin^2 2\theta \sin^2\left(\delta m^2 \frac{L}{4E}\right) \Rightarrow \overline{P_{as}} = \frac{1}{2}\sin^2 2\theta_{as}$$

- Neutrino collision with nuclei = Quantum measurement

$$\left(\frac{\partial}{\partial t} - H\,E\,\frac{\partial}{\partial E}\right) f_s(E,t) = \left[\frac{1}{2}\sin^2(2\theta_M(E,t))\Gamma(E,t)\right] f_a(E,t)$$

Hubble constant H denotes the influence of cosmological expansion.

$f_s(E,t)$ and $f_a(E,t)$ are the time-dependent momentum distribution functions

$$f_a(E,t) = \frac{1}{e^{E/T}+1}$$

$$\Gamma(E,t) \simeq \frac{7\pi}{24} G_F^2 T^4 E$$

不断转化为惰性中微子

active neutrino interaction rate

Astro & Cosmo Constraints

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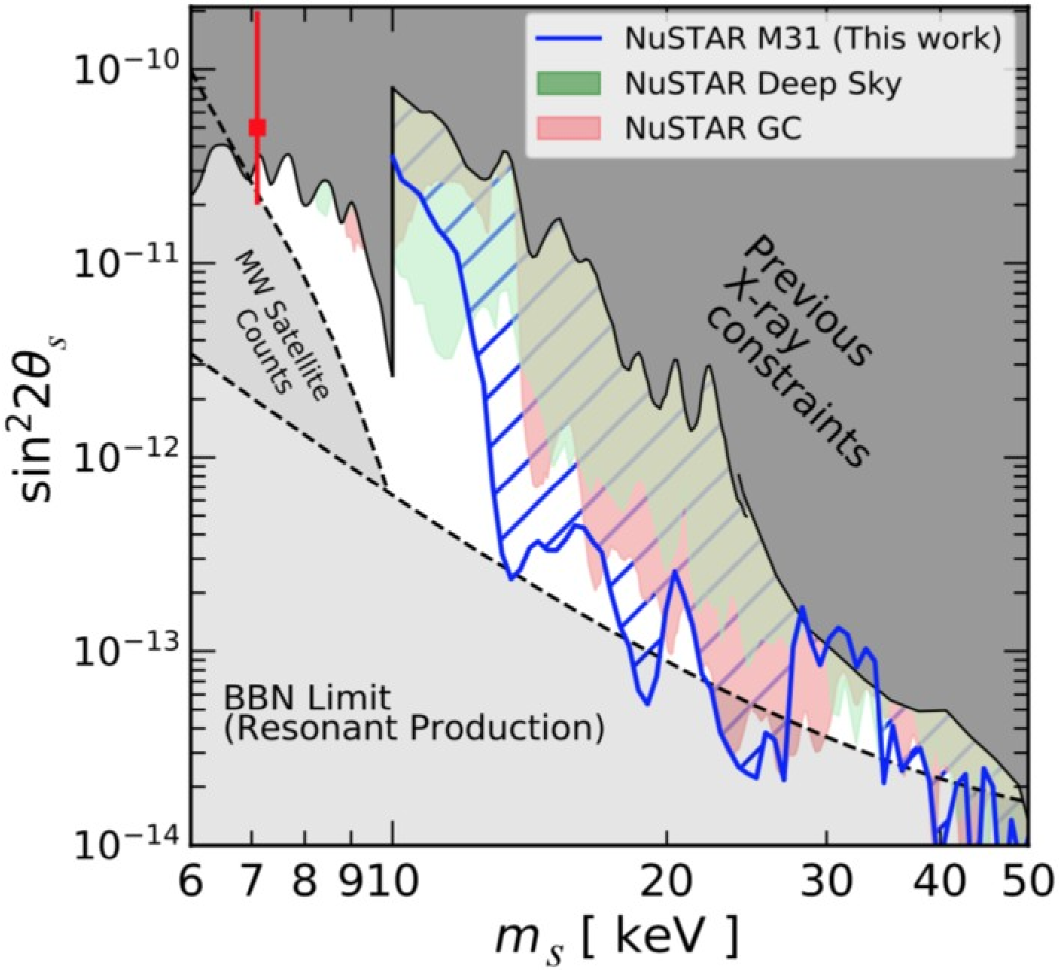


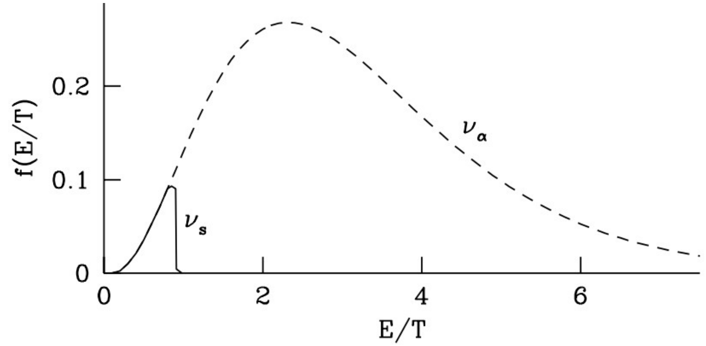
Ng, Roach, Perez, Beacom, Horiuchi, Krivonos, Wik [1901.01262]

Improved DW Mechanisms

- Resonant production

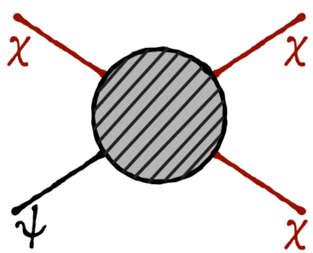
Shi & Fuller, PRL99 [astro-ph/9810076]

$$\sin^2 2\theta_{as}^m = \frac{\sin^2 2\theta_{as}}{\sin^2 2\theta_{as} + \left(\cos 2\theta_{as} \mp \frac{E_\nu V}{\Delta m_{as}^2}\right)^2}$$



- Pandemic Mechanism

Bringmann, Depta, Hufnagel, Ruderman, Schmidt-Hoberg [2103.16572]



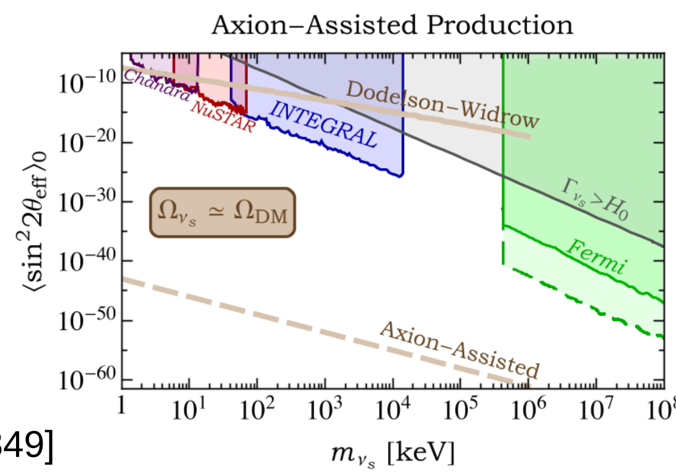
$$n_\chi(t) \sim \frac{1}{a^3} e^{\langle \sigma v \rangle_{\rm tr} n_\psi^{\rm eq} t}$$

Bringmann, Depta, Hufnagel, Kersten, Ruderman, Schmidt-Hoberg [2206.10630]

- Axion Assisted Production

$$\sin^2 2\theta_m \simeq \frac{\Delta^2 \langle \sin^2 2\theta_{\rm eff} \rangle}{\Delta^2 \langle \sin^2 2\theta_{\rm eff} \rangle + (\Delta - V_T)^2}$$

$$\Delta \equiv m_{\nu_s}^2 / 2E_\nu$$



Berlin & Hooper [1610.03849]

Active-Sterile Conversion

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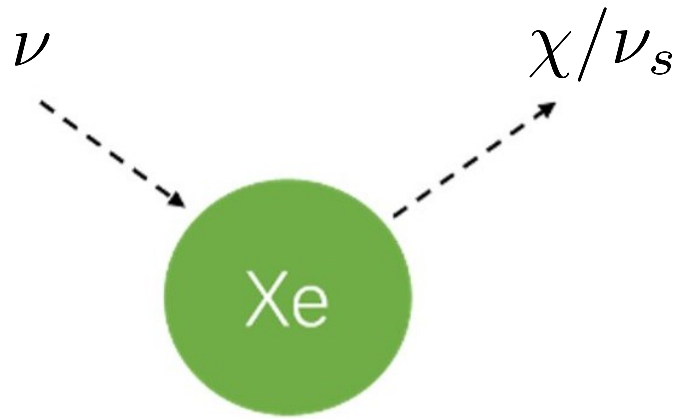
Recoil matrix element |M|² with a light mediator

$$(2m_eT_r + m_s^2)\frac{(y_S^\nu y_S^e)^2(2m_e + T_r) + (y_P^\nu y_P^e)^2 T_r}{8\pi E_\nu^2(2m_eT_r + m_\phi^2)^2}$$



$$\nu + e \to \nu_s + e$$

- **Active ν final state**

$$m_s \to 0 \quad m_\phi \to 0$$

$$|\mathcal{M}|^2 \sim \begin{cases} \frac{1}{T_r^2} & \text{Scalar (S)} \\ \text{const} & \text{Pseudo-scalar (P)} \end{cases}$$

Pseudo-scalar mediator is also enhanced at low energy.

- **Active-Sterile Conversion**

$$m_s \gtrsim \sqrt{2m_eT_r}$$

$$|\mathcal{M}|^2 \sim \frac{1}{T_r}$$

SFG, Pedro Pasquini, Jie Sheng [Phys.Lett.B 810 (2020) 135787]

SFG, Pedro Pasquini, Jie Sheng [JHEP 05 (2022) 088]

Testing light DM @ ν Exps

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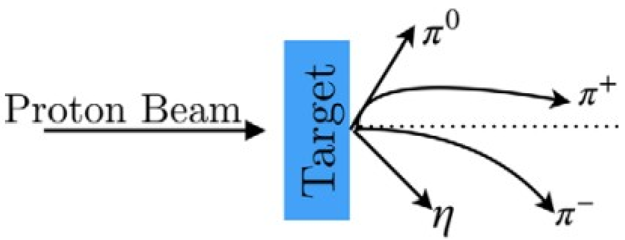
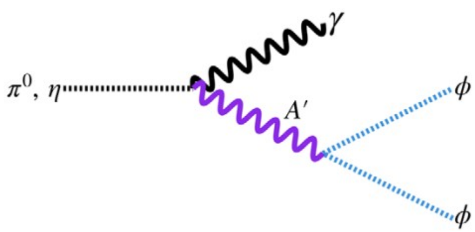
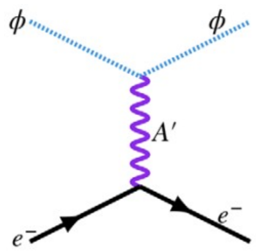
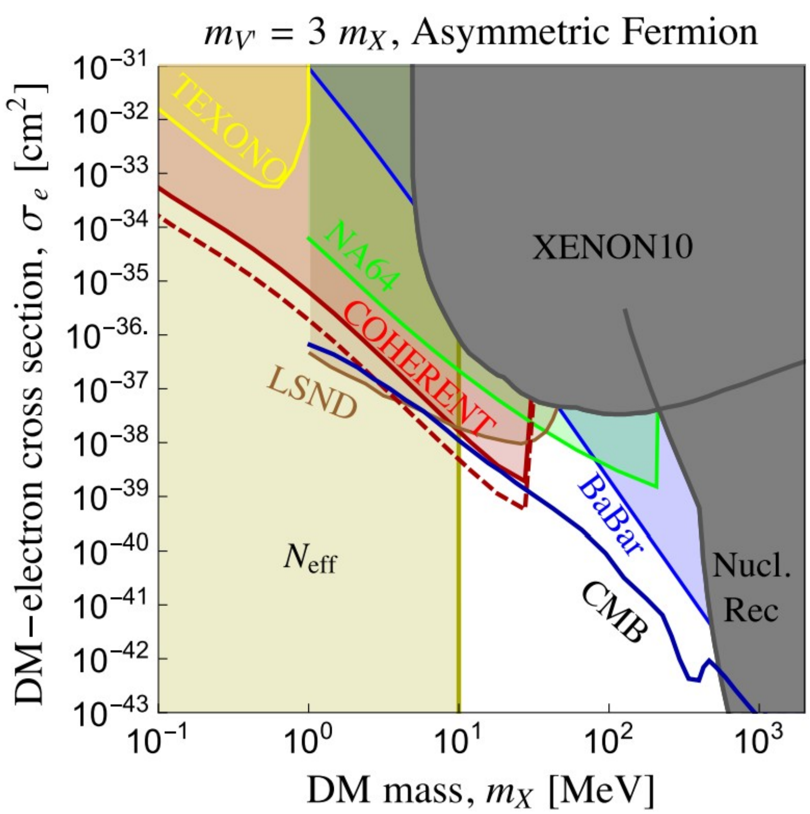
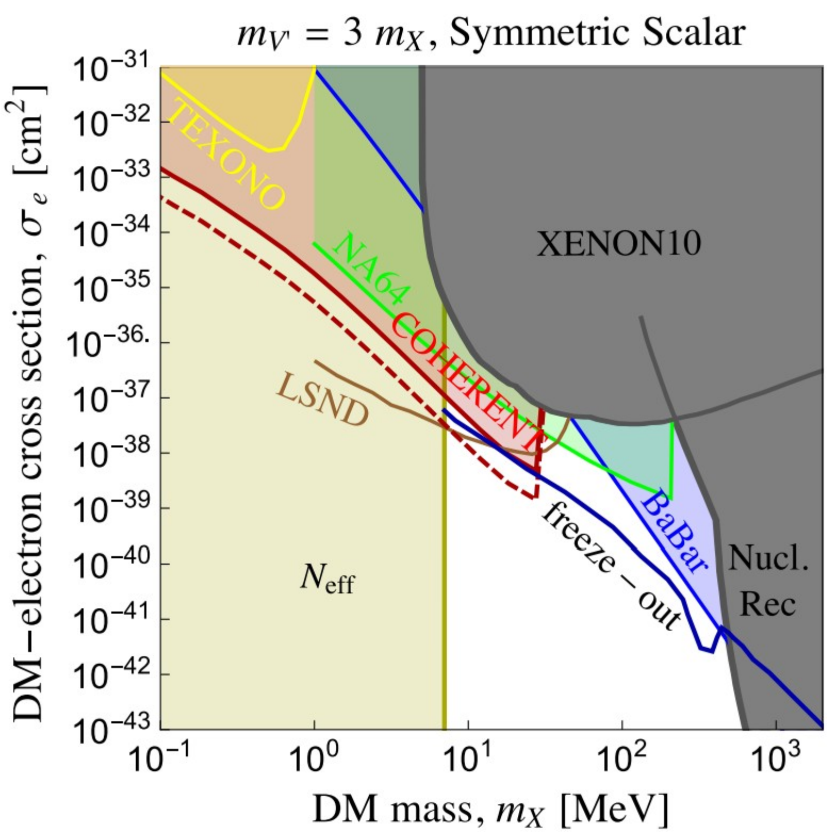






Romeri, Kelly & Machado, PRD 19 [arXiv:1903.10505]





SFG & Ian Shoemaker, JHEP 11 (2018) 066 [arXiv: 1710.10889]

Seesaw Mechanism（跷跷板机制）

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- **Heavy neutrinos ($\mathcal{N}$)**

$$\bar{\nu} M_D \mathcal{N} + h.c. + \overline{\mathcal{N}} M_N \mathcal{N} = \begin{pmatrix} \bar{\nu} & \overline{\mathcal{N}} \end{pmatrix} \begin{pmatrix} 0 & M_D \\ M_D^T & M_N \end{pmatrix} \begin{pmatrix} \nu \\ \mathcal{N} \end{pmatrix}$$

required by **Grand Unification Theory（大统一理论）**

- **Seeaw Mechanism**

The diagonalization of the full mass matrix

$$\begin{pmatrix} 0 & M_D \\ M_D^T & M_N \end{pmatrix} \Rightarrow M_\nu = -M_D \frac{1}{M_N} M_D^T$$

M_D ~ $O(100)$ GeV, **M_N** ~ $O(10^{15})$ GeV → M_ν ~ $O(0.01)$ eV

Light neutrino mass M_ν is suppressed by the heavy ones

柳田勉、何小刚：
我们来玩跷跷板吧

Seesaw with Right-Handed ν & DM

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$$M_\nu = -M_D \frac{1}{M_N} M_D^T \quad \Rightarrow \quad \mathrm{Det}(M_\nu) \propto \frac{1}{\mathrm{Det}(M_N)}$$

(for NH)	-1σ	Best Value	$+1\sigma$
$\Delta m_s^2 \equiv \Delta m_{12}^2\,(10^{-5}\mathrm{eV}^2)$	7.37	7.56	7.75
$\lvert\Delta m_a^2 \equiv \Delta m_{13}^2\rvert\,(10^{-3}\mathrm{eV}^2)$	2.51	2.55	2.59

- **The lightest neutrino mass could be zero: $m_{1,3} \to 0$**
- **Needs only 2 right-handed neutrinos N_R**
- **Effectively, the 3rd N_R could be infinitely heavy to decouple**
- **Could the 3rd N_R be DM?**

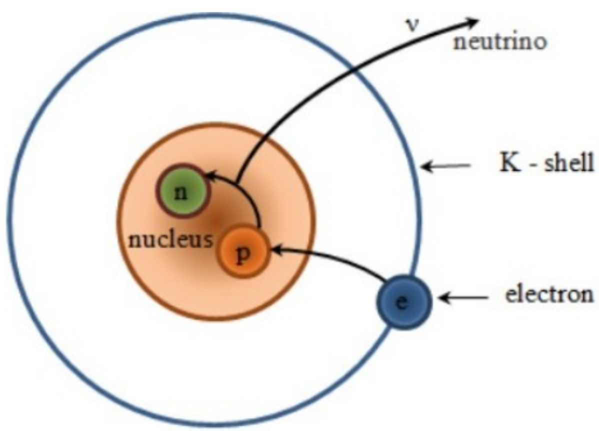
P. Cox, C. Han, and T. T. Yanagida, “Right-handed Neutrino Dark Matter in a U(1) Extension of the Standard Model,” JCAP01(2018) 029, [arXiv:1710.01585]

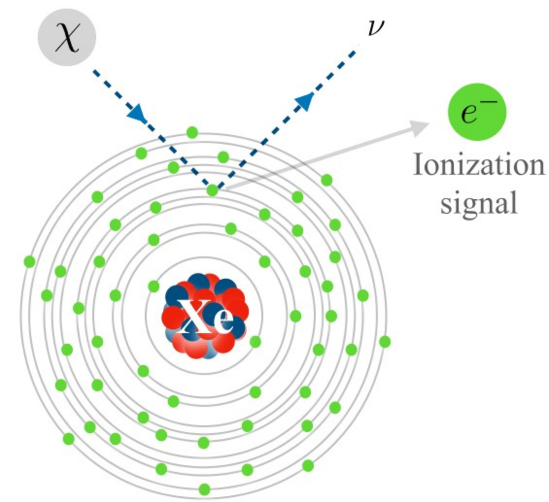
Cheng, Sheng & Yanagida [arXiv:2312.15637]

K-Shell Electron Capture for ν

王淦昌

1942 – Kan Chang Wang proposed using K-shell electron capture for detecting neutrino





$$e^- + {}^{Z}_{A}N \rightarrow {}^{Z-1}_{A}N + \nu$$

$$\chi + e \rightarrow \nu + e$$

Kan Chang Wang, *A Suggestion on the Detection of the Neutrino*, Phys. Rev., 61, 97 (1942)

Kan Chang Wang, *Proposed Methods of Detecting the Neutrino* , Phys. Rev., 71, 645-646 (1947)

Boosting recoil with mass

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- **Elastic Scattering**

$$\chi + N/e \to \chi + N/e \qquad E_r \approx \frac{4m_\chi m_N}{(m_\chi + m_N)^2} T_\chi$$

- **Exothermic**

$$X'\, e^- \to X\, e^- \qquad E_R \simeq \Delta m \left(1 - \frac{v_{\rm DM}}{v_e} \cos\theta_e\right)$$

He, Wang & Zheng [JCAP21, 2007.04963]

Aboubrahim, Althueser, Klasen, Nath & Weinheimer [2207.08621]

- **Fermionic absorption**

$$\chi + e \to \nu + e \qquad E_r \approx \frac{m_\chi^2}{2m_e} \qquad m_\chi \sim \mathcal{O}(10)\,\mathrm{keV}$$

Dror, Elor, McGehee & Yu [2011.01940]

See also Dror, Elor & McGehee [1905.12635, 1908.10861]

Direct Detection

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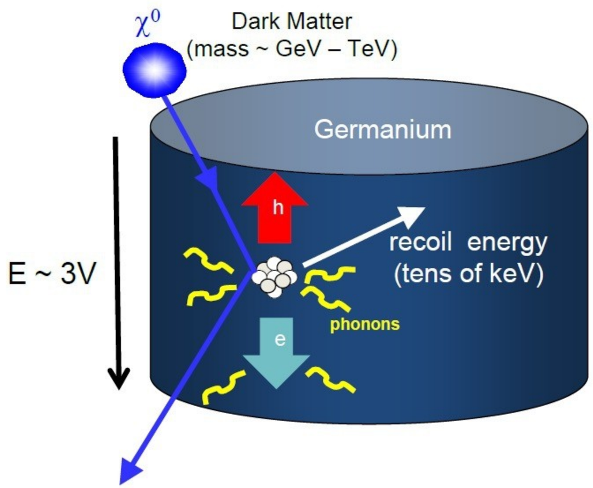
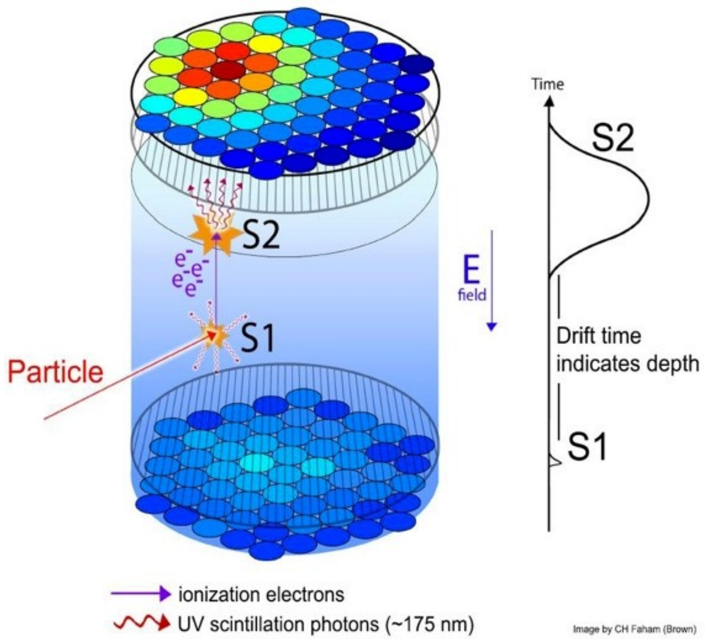
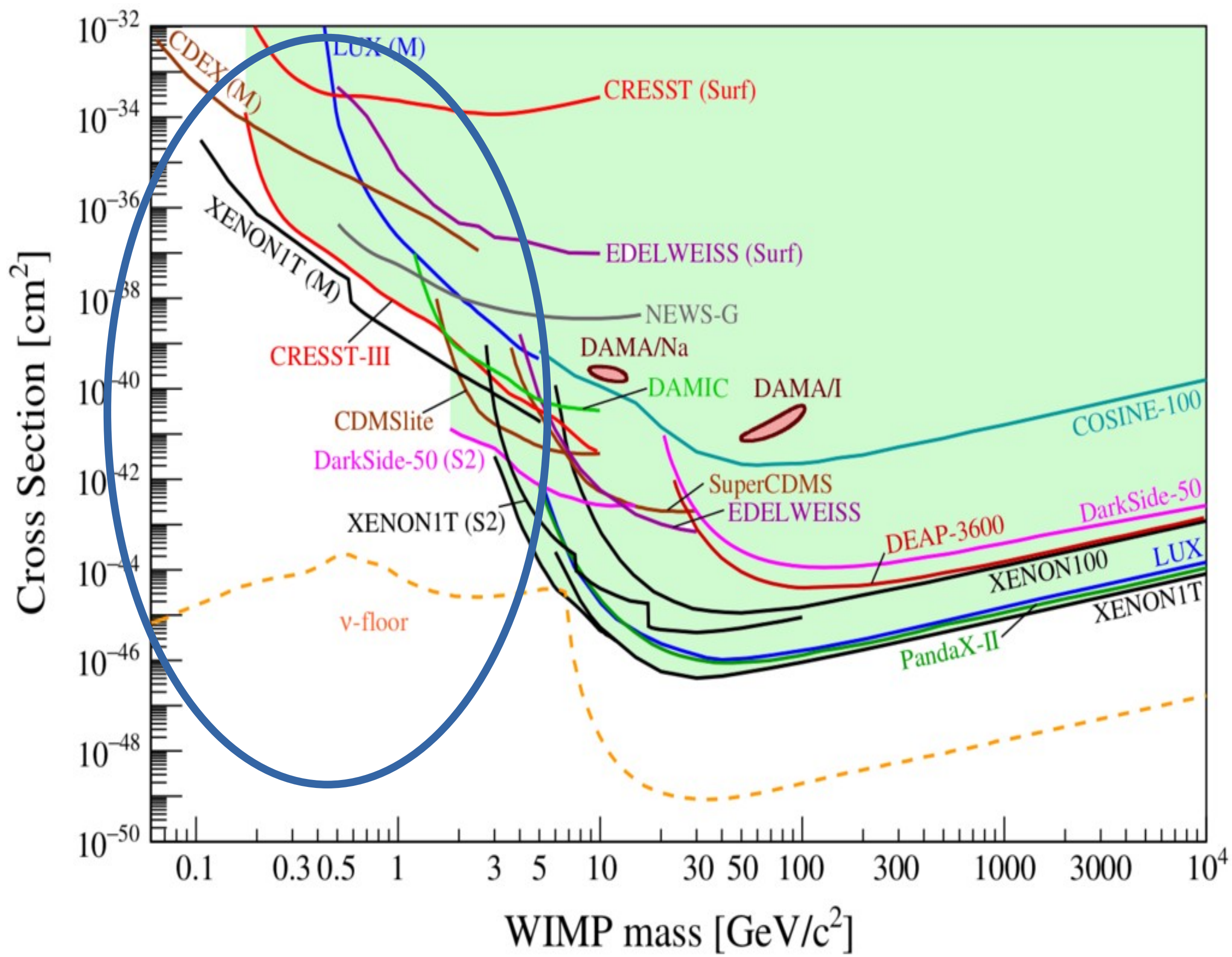


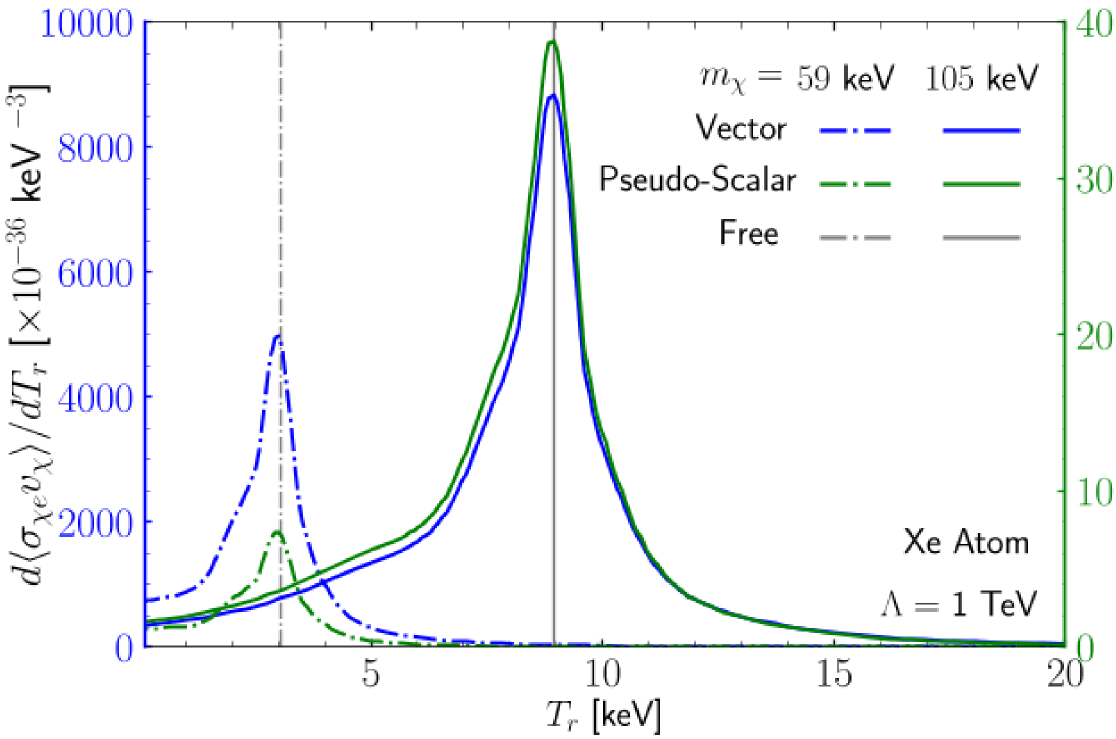




APPEC Committee Report [2104.07634]

Kinematics of Absorption DM

$$\chi + e \to \nu + e \qquad E_r = \frac{m_\chi^2}{2(m_e + m_\chi)} \approx \frac{m_\chi^2}{2m_e}$$



$$\frac{d\langle\sigma_{\chi e} v_\chi\rangle}{dT_r} = \sum_{nl} (4l+2) \frac{1}{T_r} \frac{m_\chi - \Delta E_{nl}}{16\pi m_e^2 m_\chi} |\mathcal{M}|^2(\mathbf{q}) K_{nl}(T_r, |\mathbf{q}|),$$

SFG, Xiao-Gang He, Xiao-Dong Ma, Jie Sheng [JHEP 05 (2022) 191]

SFG, Pedro Pasquini, Jie Sheng [JHEP 05 (2022) 088]

PandaX-4T & Lepton Colliders

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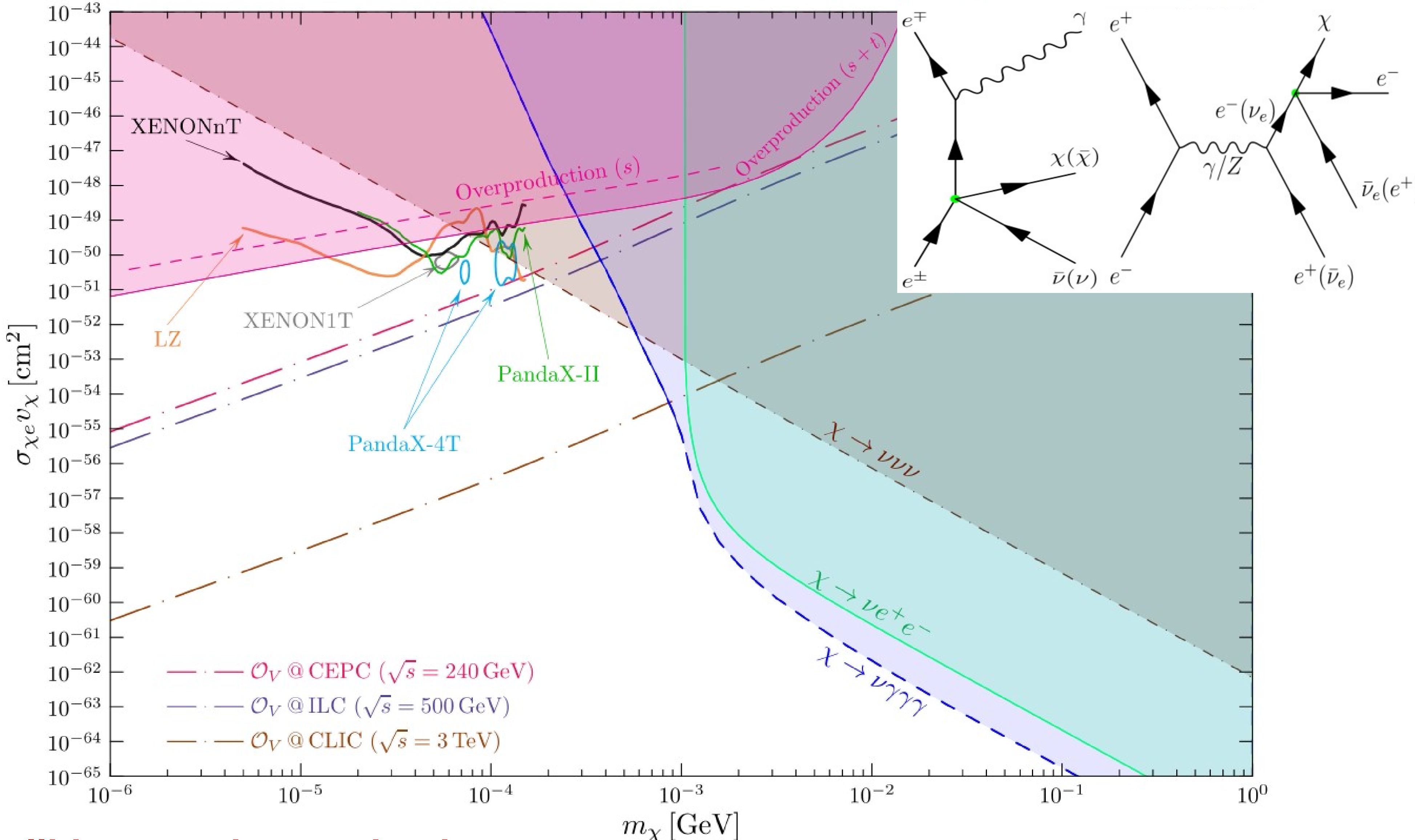

Collider searches probe the dark sector, not just DM

SFG, Kai Ma, Xiao-Dong Ma, Jie Sheng [arXiv:2306.00657]

Tiny-Varying Neutrino Mass

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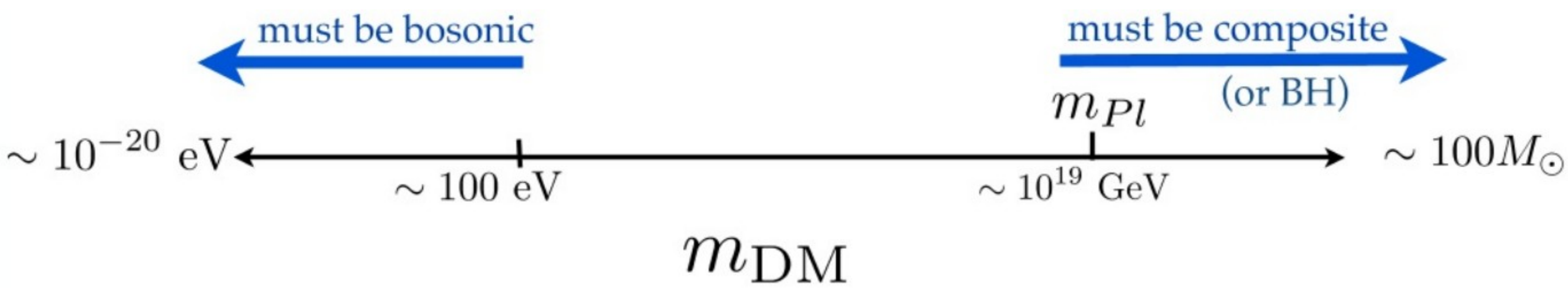
- **Wave DM can be as light as 10^{-22} eV**



$$-\mathcal{L} = \frac{1}{2} m_\phi^2 \phi^2 + \frac{1}{2} M_{\alpha\beta} \bar{\nu}_\alpha \nu_\beta + y_{\alpha\beta} \phi \bar{\nu}_\alpha \nu_\beta + h.c.$$

- **Bose-Einstein Condensation** $\langle \phi \rangle \neq 0$ **ν Mass term**

$$\phi(x) \simeq \frac{\sqrt{2\,\rho_{\rm DM}(x)}}{m_\phi} \cos\left[m_\phi \left(t - \vec{v} \cdot \vec{x} \right) \right]$$

Berlin [1608.01307]

Zhao [1701.02735]

Brdar, Kopp, Liu, Prass & Wang [1705.09455]

Time-Varying oscillation probabilities!

Time-Dependent Oscillation

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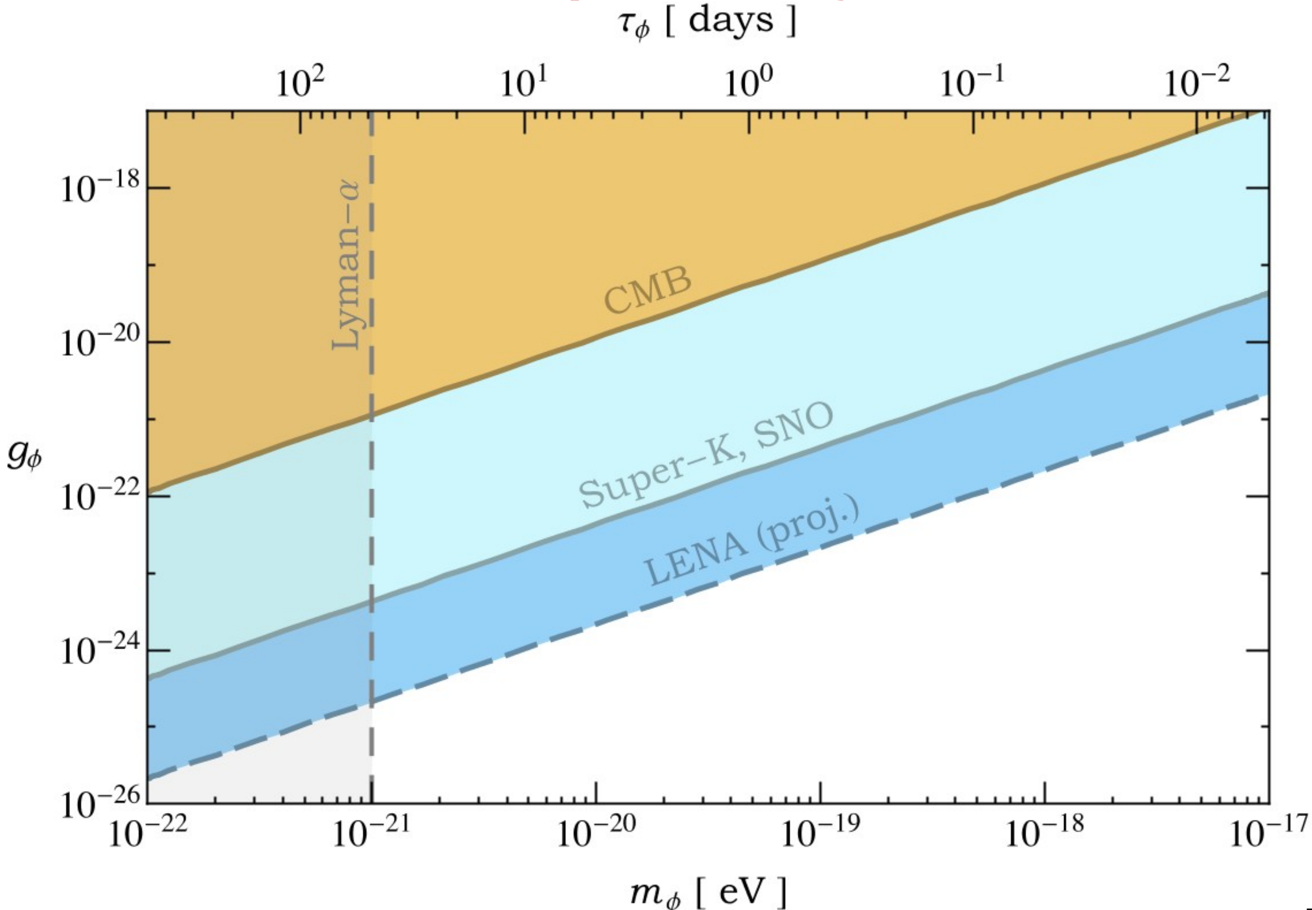
$$\sin\theta_{12}(t) \simeq \sin\theta_{12} + \frac{\cos\theta_{12}}{\Delta m_{12}} \frac{g_\phi \sqrt{2\,\rho_{\rm DM}}}{m_\phi} \cos m_\phi t$$

- **Neutrino oscillation probability varies with time!**



通过中微子振荡探测暗物质

Berlin [1608.01307]

Dark NSI with Forward Scattering

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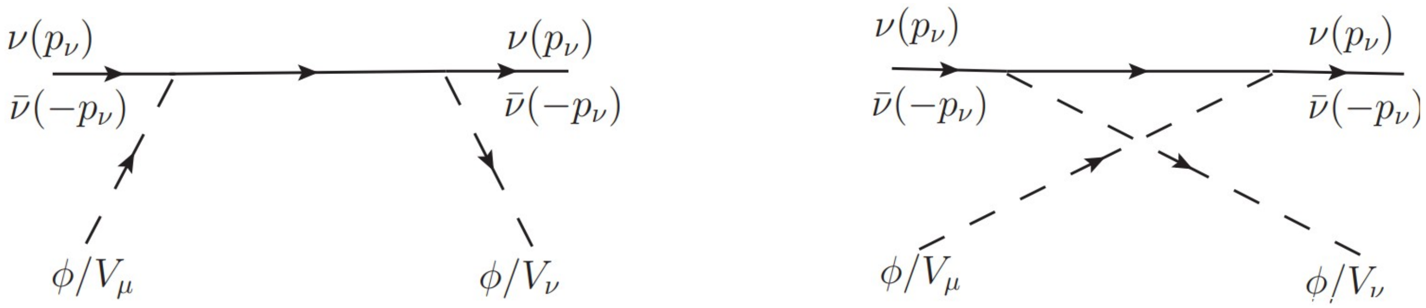
$$-\mathcal{L} = \frac{1}{2} m_\phi^2 \phi^2 + \frac{1}{2} M_{\alpha\beta} \bar{\nu}_\alpha \nu_\beta + y_{\alpha\beta} \phi \bar{\nu}_\alpha \nu_\beta + h.c.$$

- Forward scattering in DM medium



$$H = \frac{M^2}{2E_\nu} - \frac{1}{E_\nu} \sum_j y_{\alpha j} y^*_{j\beta} \frac{\rho_\chi}{m_\phi^2} \equiv \frac{M^2 + \delta M^2}{2E_\nu}$$

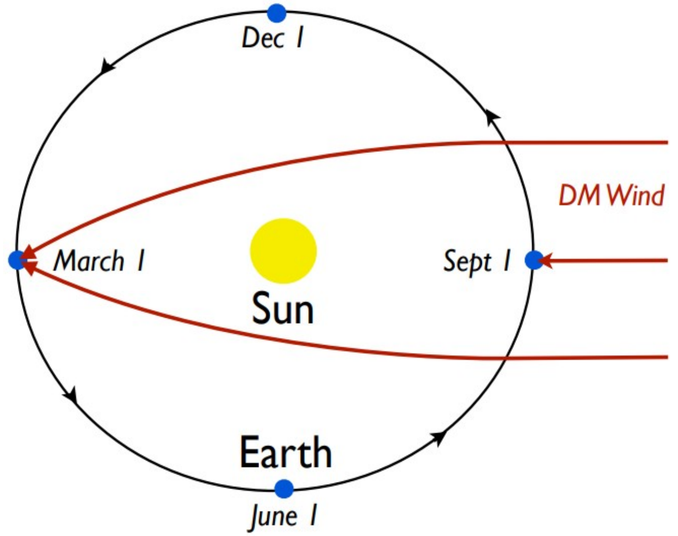
- With $1/E_\nu$ dependence, the **dark potential** is promoted to mass

Dark NSI can fake neutrino mass! Neutrino may not be genuine but environmental!

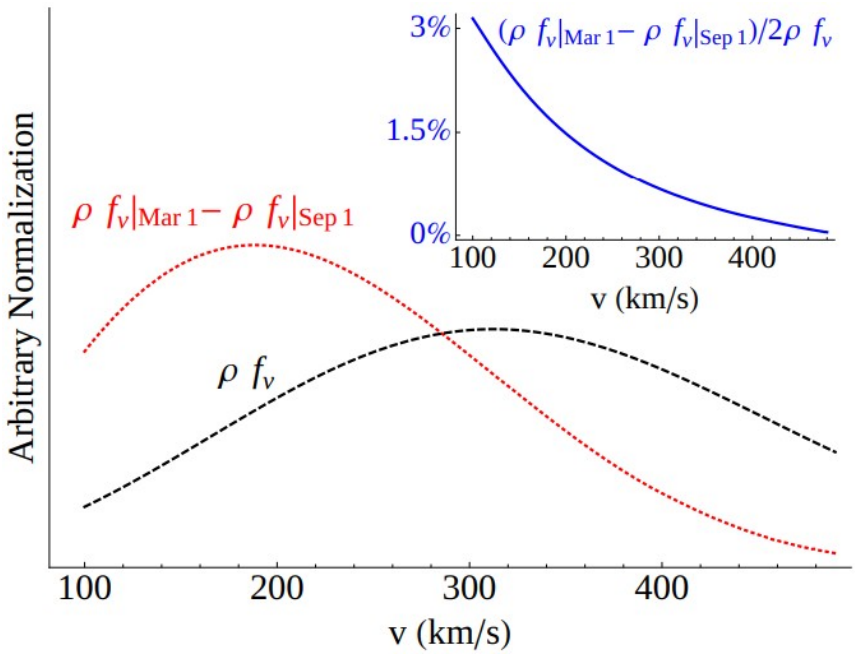
SFG, Murayama [1904.02518]
SFG, PoS NuFact2019 (2020) 108
SFG, J.Phys.Conf.Ser. 1468 (2020) 1, 012125

SFG, Chui-Fan Kong, Alexei Smirnov, to appear soon

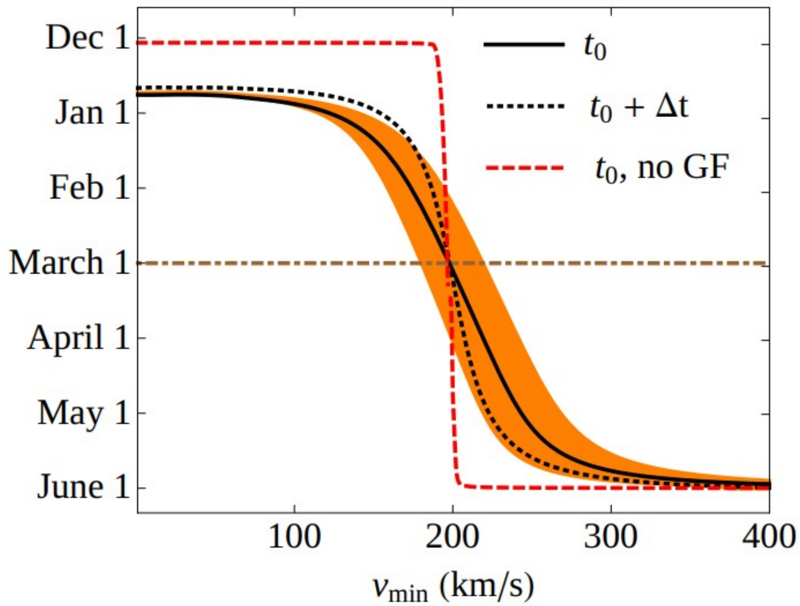
DM Gravitational Focusing



- **Density enhancement**



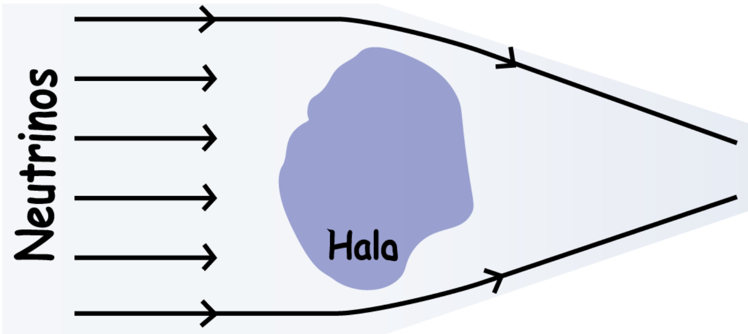
- **Modulation phase shift**

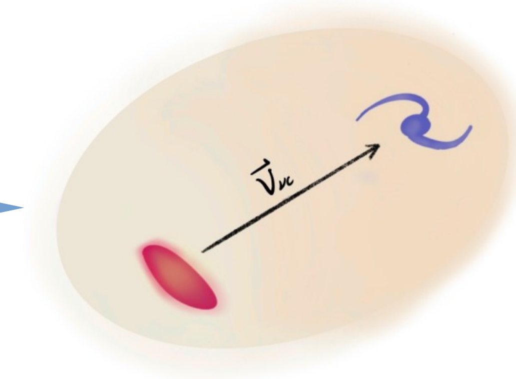


Lee, Lisanti, Peter, Safdi, Phys. Rev. Lett. 112, 011301 (2014) [arXiv:1308.1953]

Bozorgnia & Schwetz, JCAP 08 (2014) 013 [arXiv:1405.2340]

Cosmic Gravitational Focusing





$$\delta_m = \delta_{m0} + \sum_{i=1}^{3} \frac{\delta\rho_{\nu_i}}{\rho_m}$$

Density enhancement downwind!

$$\delta\rho_\nu(-\mathbf{x}) = -\delta\rho_\nu(\mathbf{x})$$

$$\widetilde{\delta}_m \equiv \widetilde{\delta}_{m0}(1 + i\widetilde{\phi})$$

$$[\widetilde{A}(\mathbf{k})]^* = \int d\mathbf{x} e^{i\mathbf{k}\cdot\mathbf{x}} A(\mathbf{x}) = \int d\mathbf{x} e^{-i\mathbf{k}\cdot\mathbf{x}} A(-\mathbf{x})$$

$$= -\int d\mathbf{x} e^{-i\mathbf{k}\cdot\mathbf{x}} A(\mathbf{x}) = -\widetilde{A}(\mathbf{k})$$

SFG, Pedro Pasquini, Liang Tan [arXiv:2312.16972]

3rd Cosmic Measurement of ν Masses

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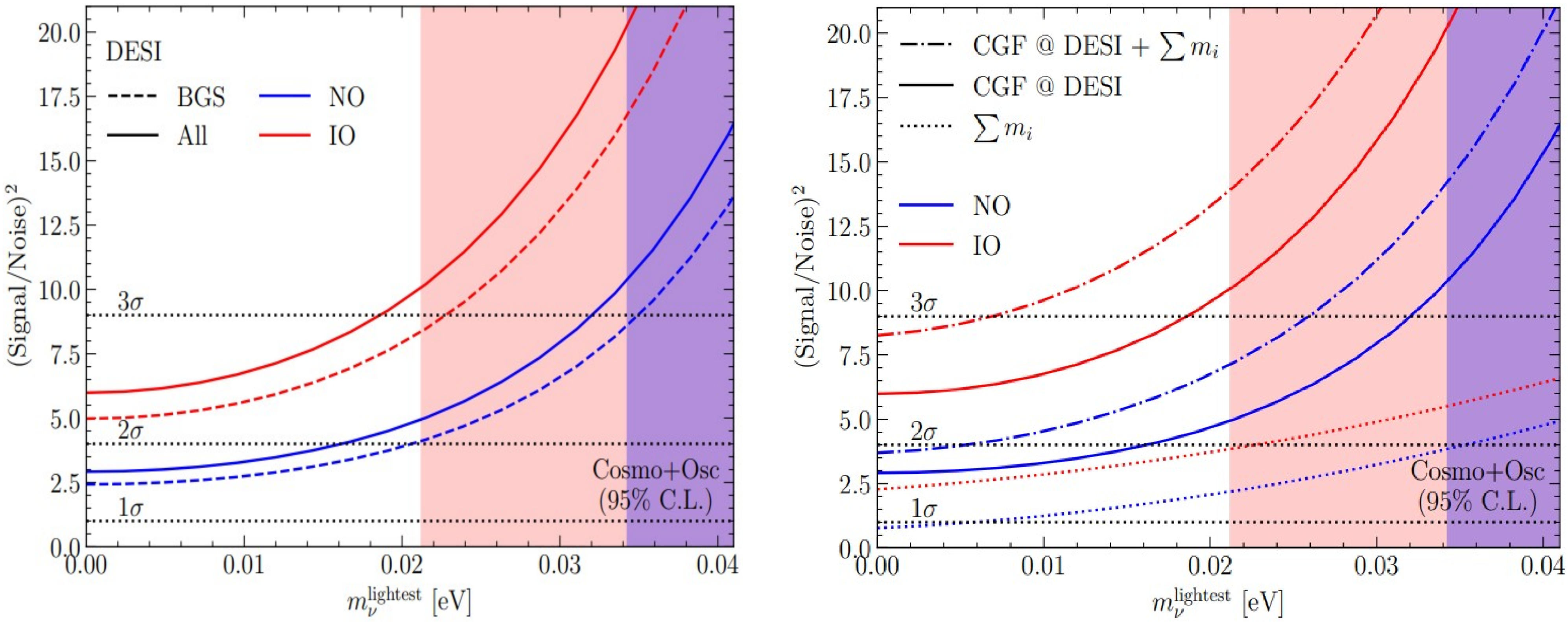
$$\text{Im}\left[\tilde{\delta}_{g\alpha}\left(\tilde{\delta}_{g\beta}\right)^*\right] \propto \left(\mathbf{v}_{\nu c}\cdot\hat{\mathbf{k}}\right)\left(f_0 m_\nu^4 + f_1 m_\nu^2 T^2 + f_2 T^4\right)$$



SFG, Pedro Pasquini, Liang Tan [arXiv:2312.16972]

3rd Cosmic Measurement of ν Masses

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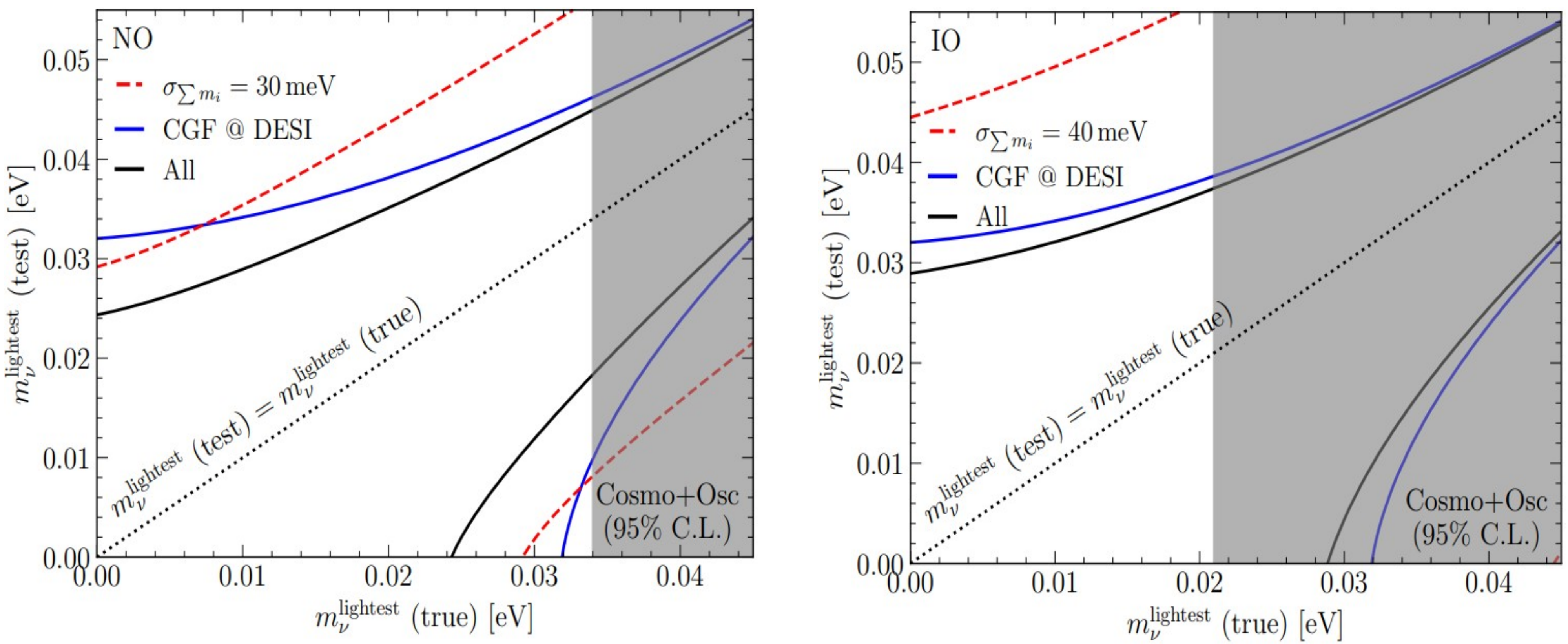
$$\mathrm{Im}\left[\tilde{\delta}_{g\alpha}\left(\tilde{\delta}_{g\beta}\right)^*\right] \propto \left(\mathbf{v}_{\nu c} \cdot \hat{\mathbf{k}}\right)\left(f_0 m_\nu^4 + f_1 m_\nu^2 T^2 + f_2 T^4\right)$$



DESI, Euclid, Subaru PFS, **CSST**

SFG, Pedro Pasquini, Liang Tan [arXiv:2312.16972]

Summary

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1) Overview

2) Sterile ν DM

3) Heavy Right-Handed Neutrino DM

4) Absorption DM @ Direct Detection Experiments

5) Environmental Mass with Dark NSI

6) ν Mass with Cosmic Gravitational Focusing

7) Summary

Thank You

Backup Slides

Galaxy Categories

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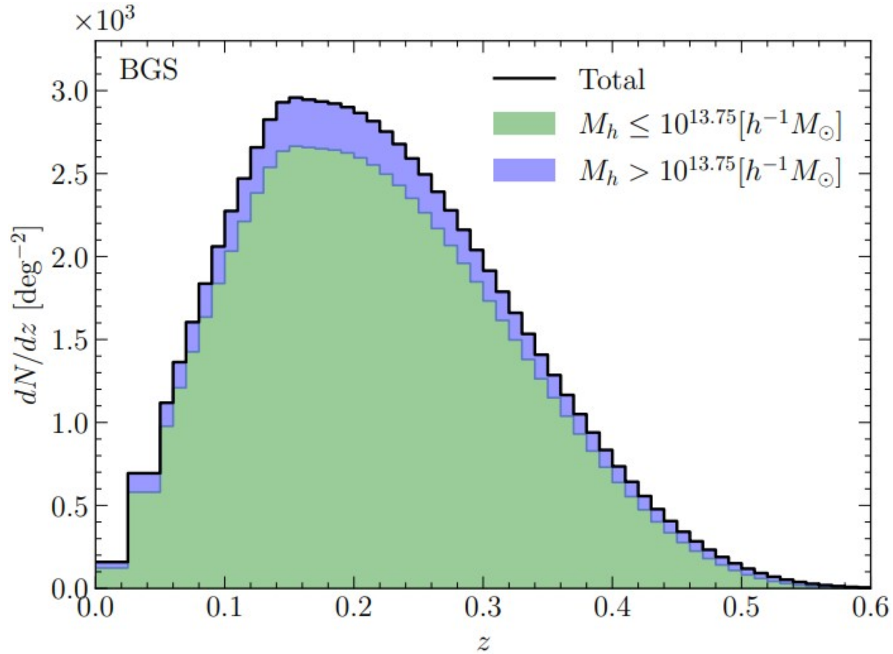

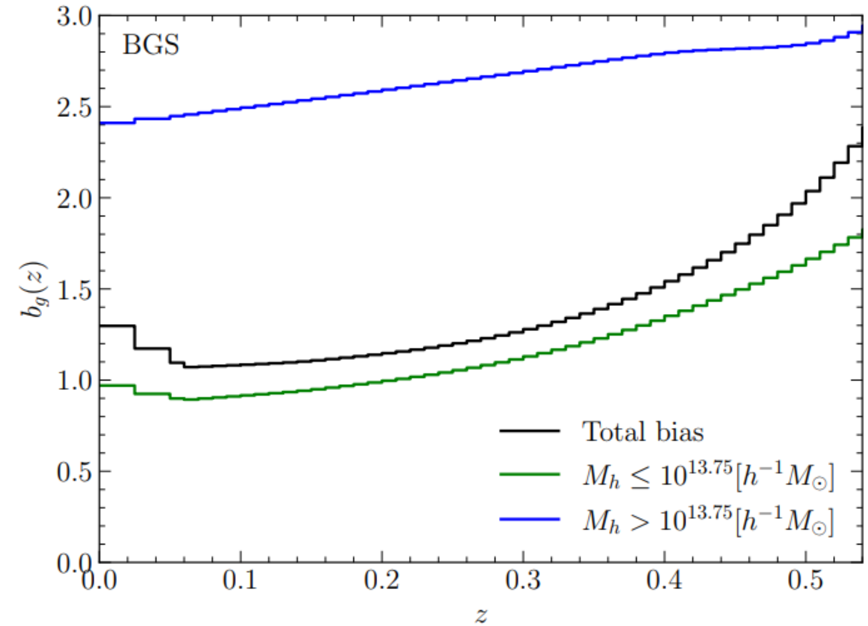

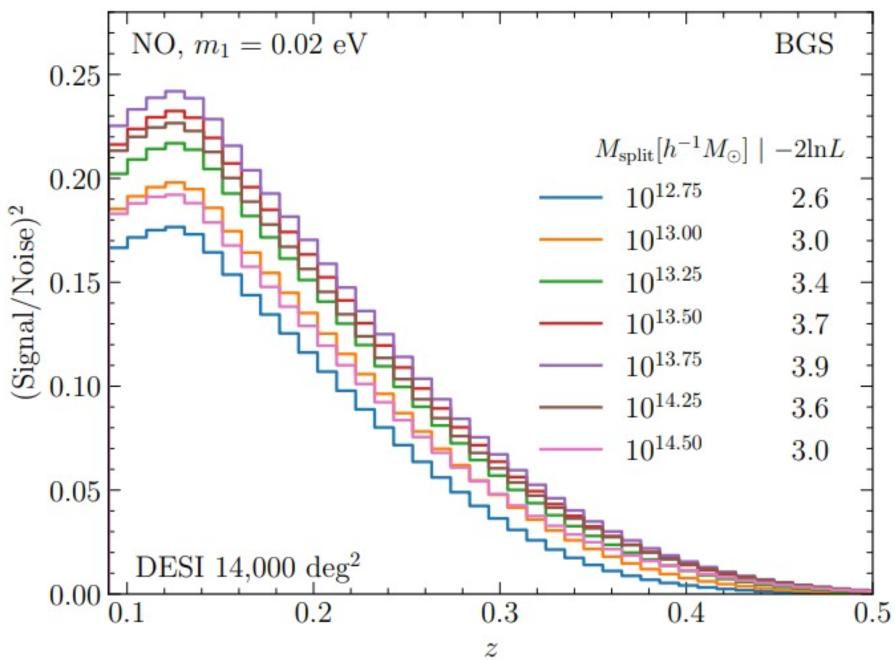

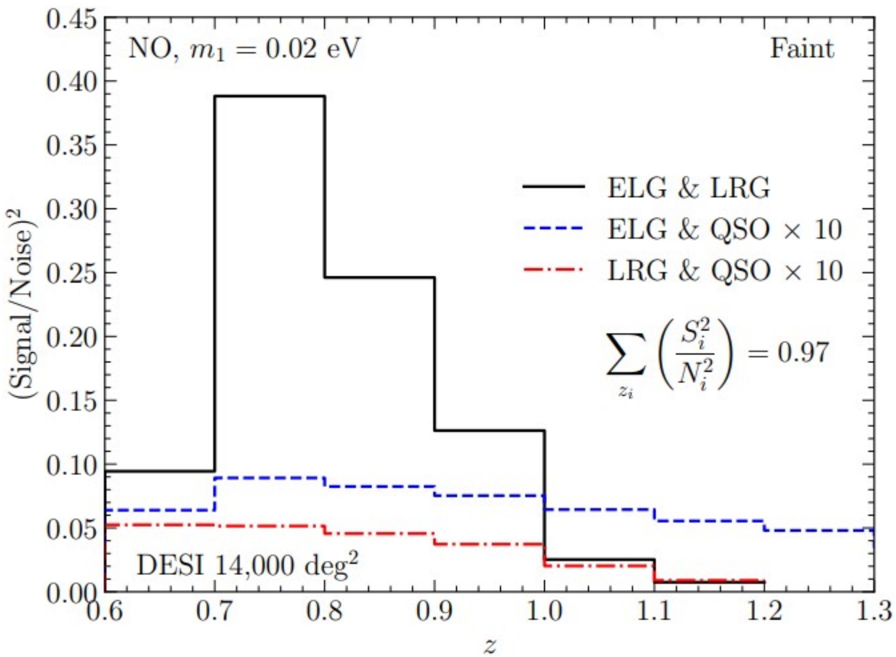

Scales

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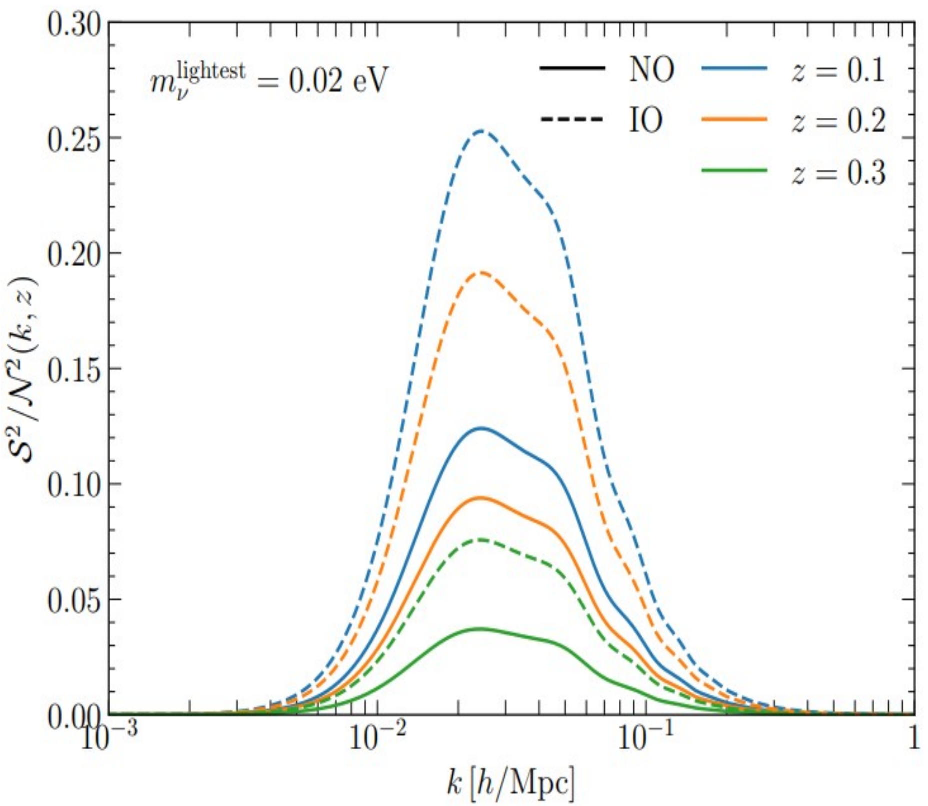

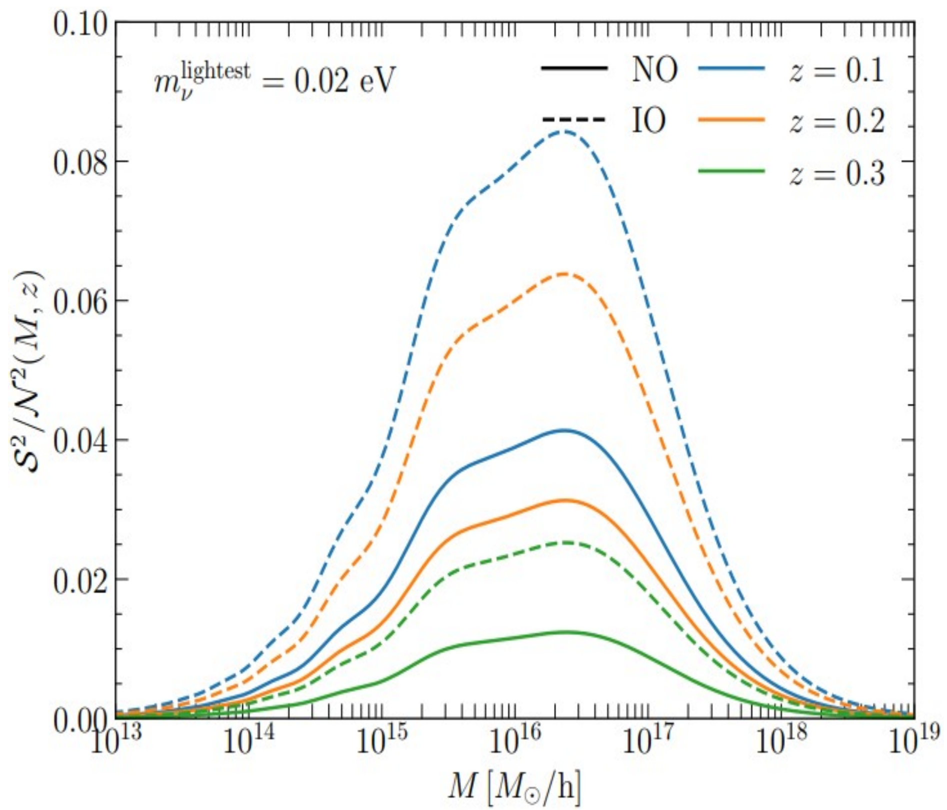

SFG, Pedro Pasquini, Liang Tan [arXiv:2312.16972]