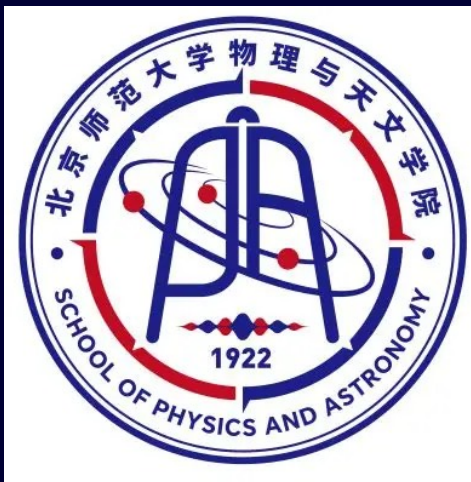


CDEX Annual Meeting 2025 - Beijing

课题四进展及计划：MeV轻暗物质理论研究

安海鹏（清华）、康现伟（北师大）、晁伟（北师大）



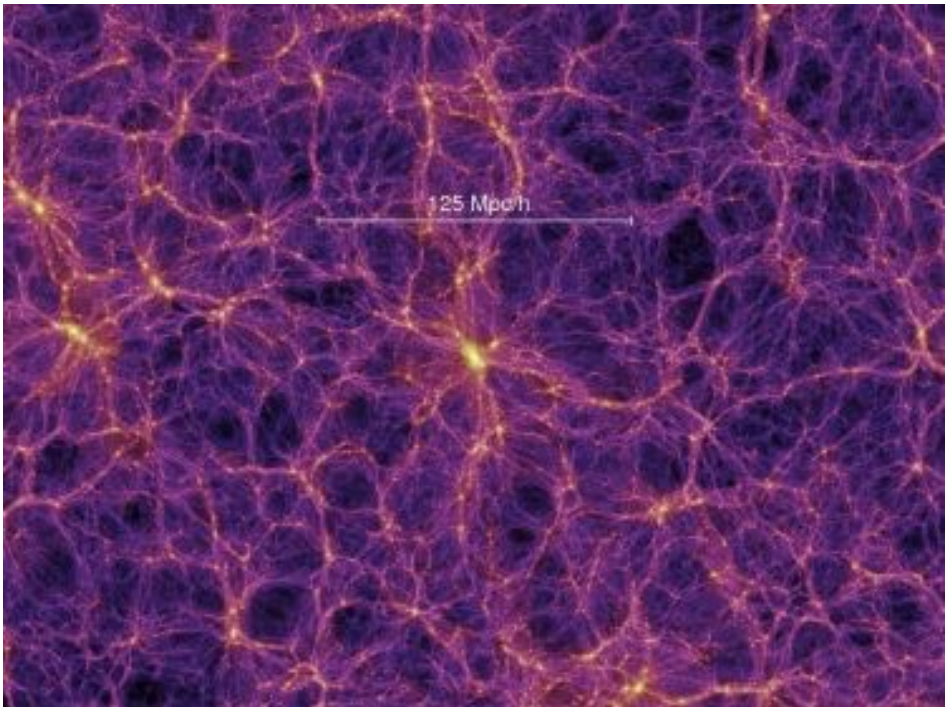
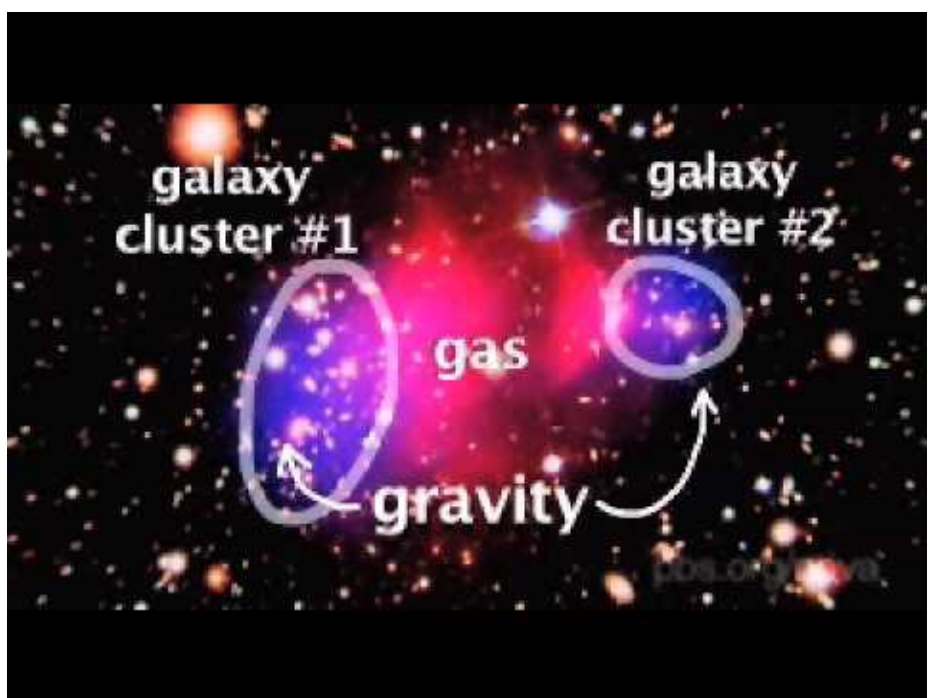
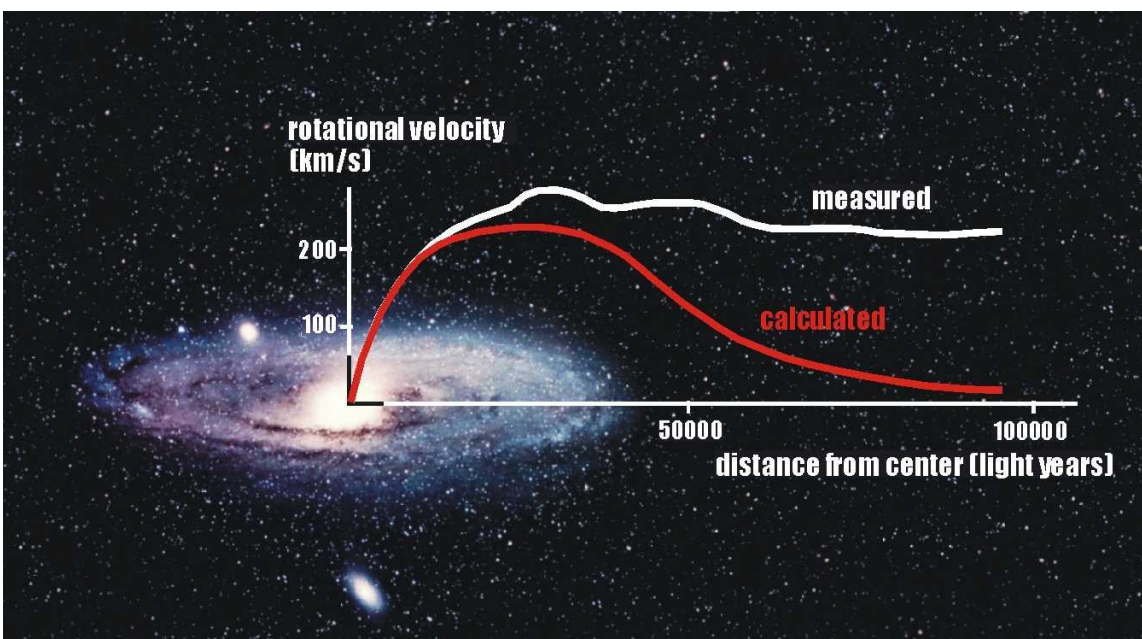
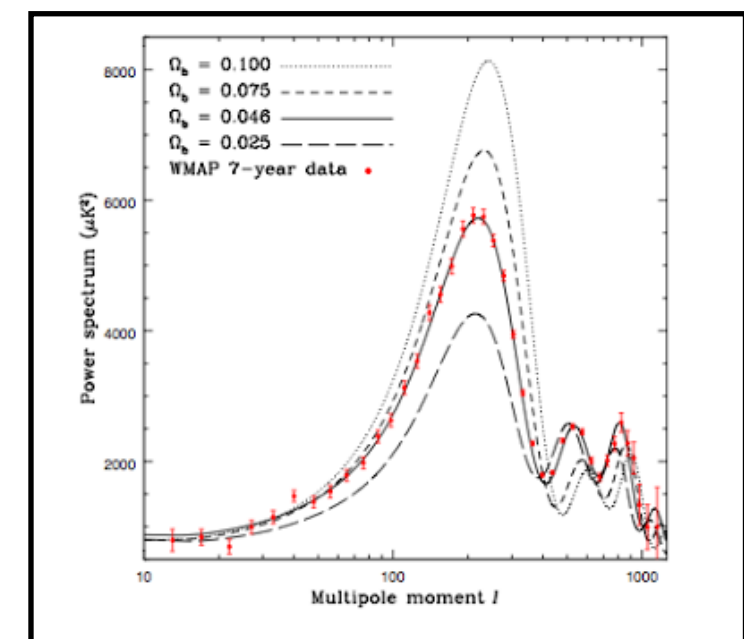
晁伟 (WEI CHAO)
北京师范大学 (BEIJING NORMAL UNIVERSITY)

2025.12.14



New physics beyond the SM-dark matter

Evidence of dark matter



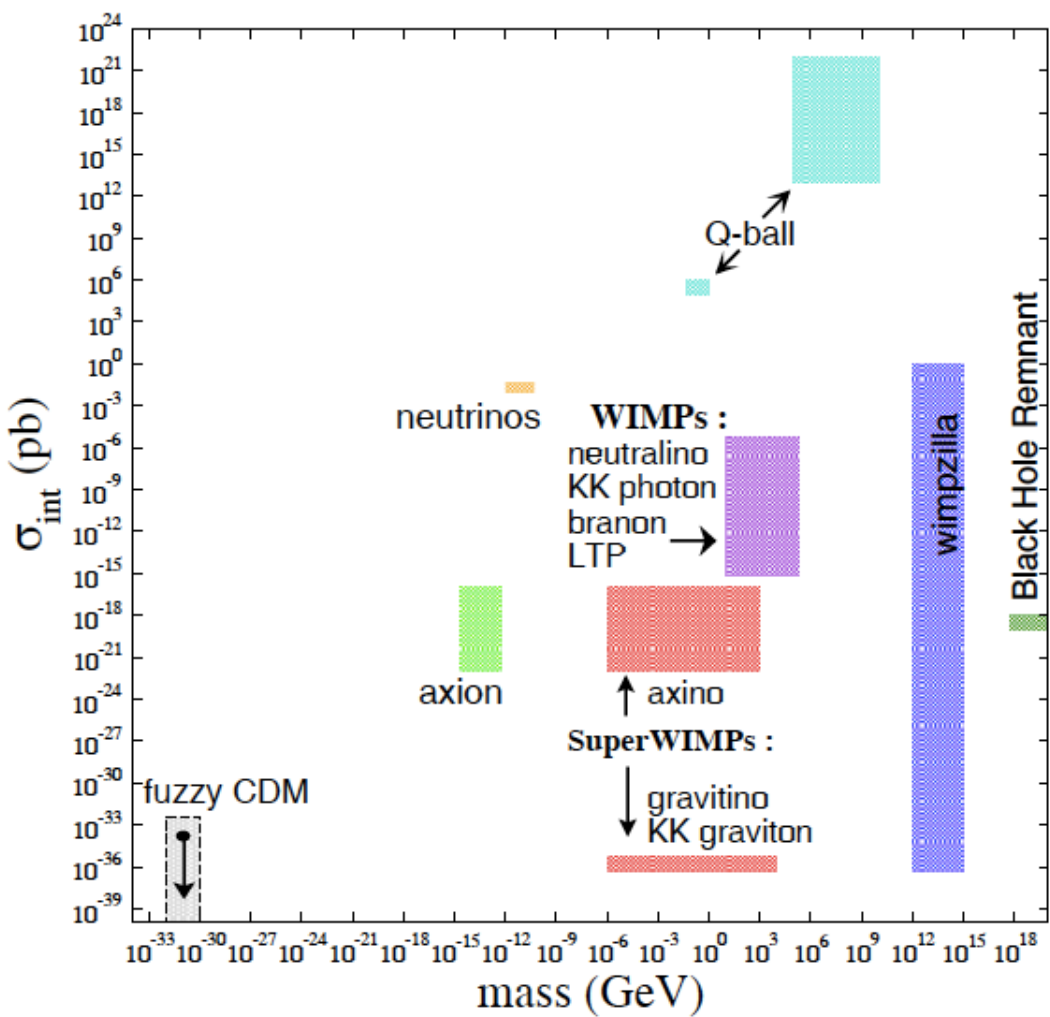
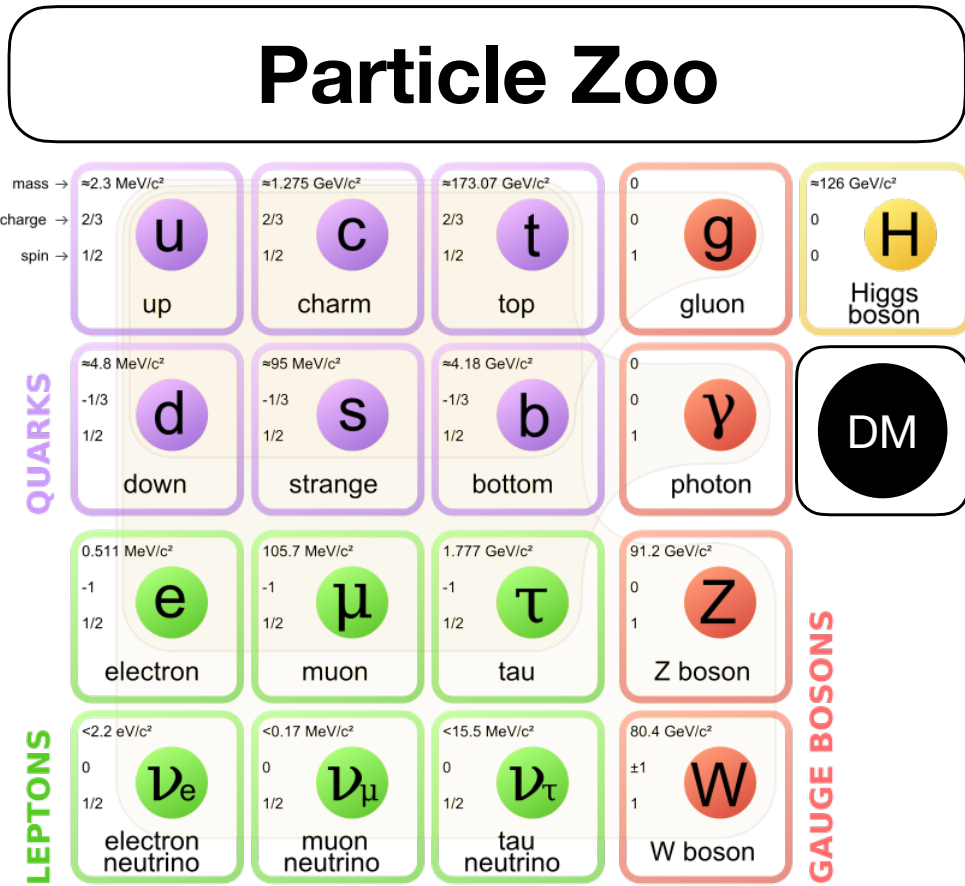
What is dark matter?

Mass

Spin

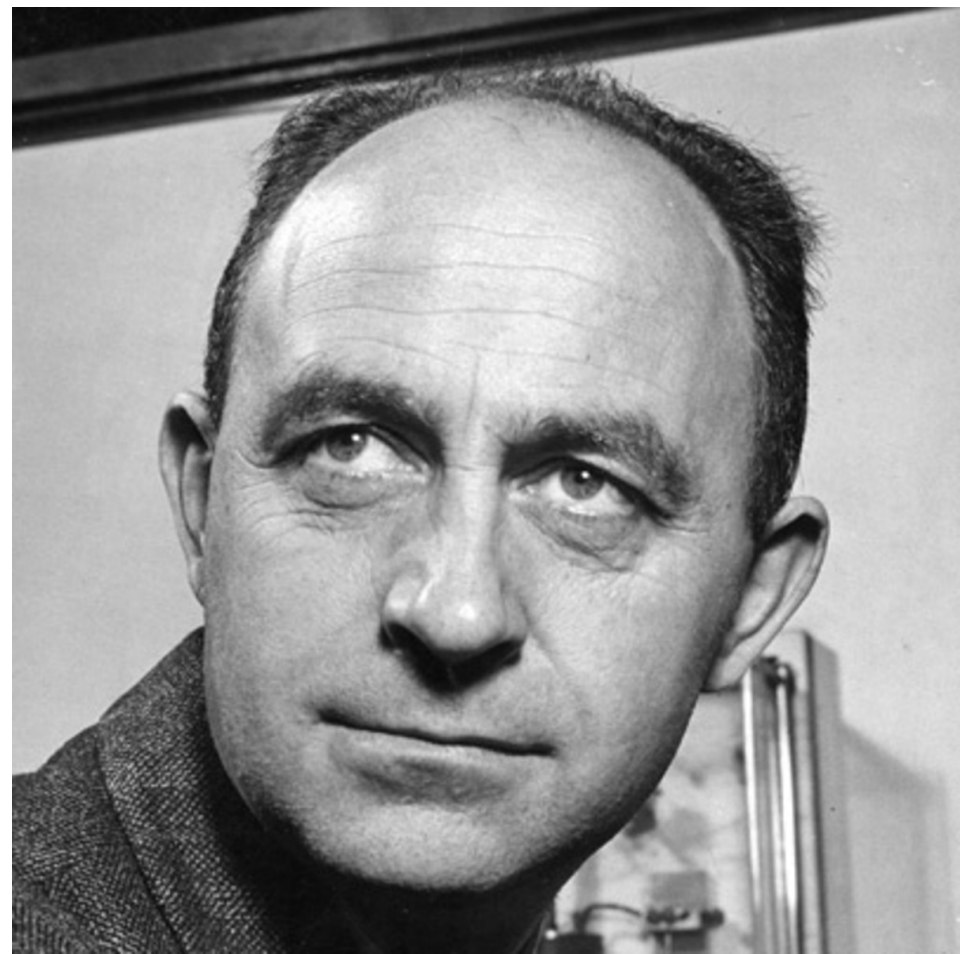
Interactions

Neutral, non-baryonic, weakly interacting particle!



Possible dark matter candidate

The WIMP Miracle!



Assuming DM is in thermal equilibrium in the early universe

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

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

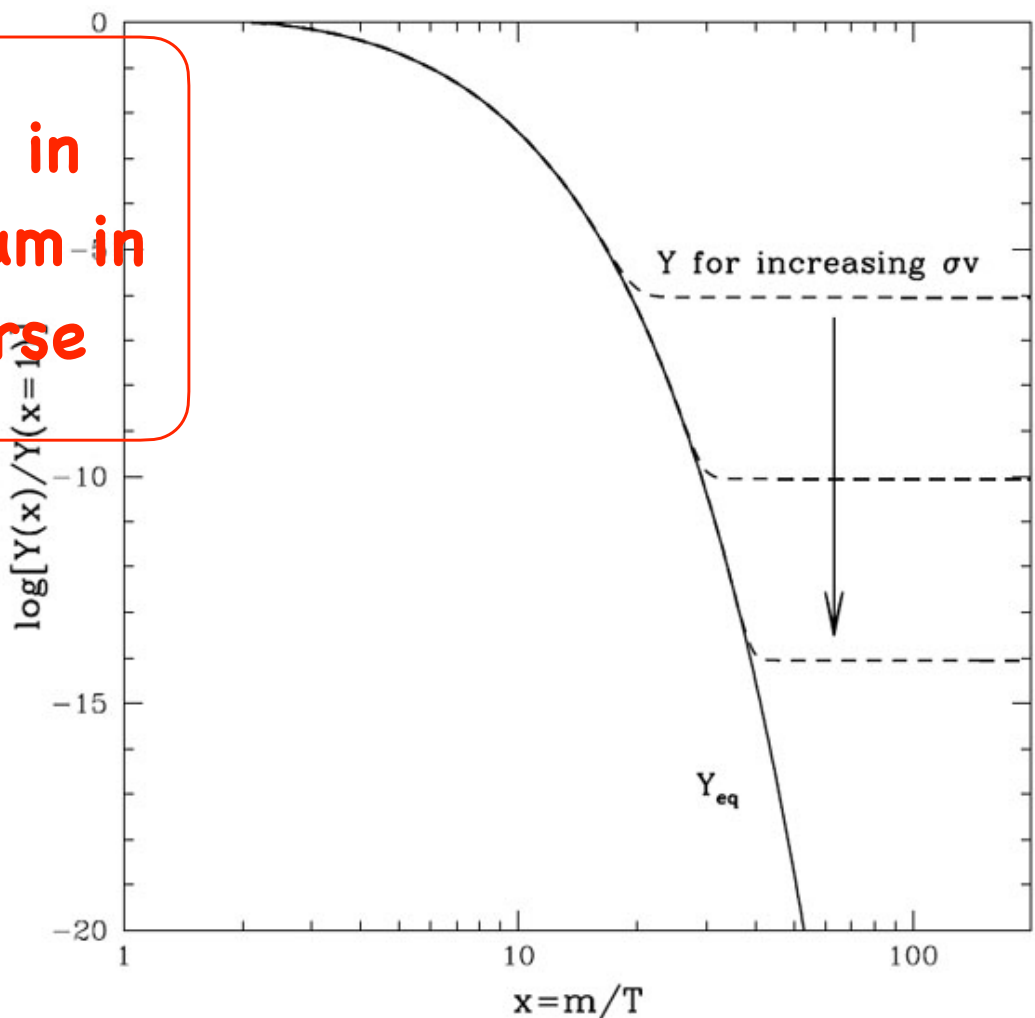
New mass scale: 100 GeV

The weak coupling

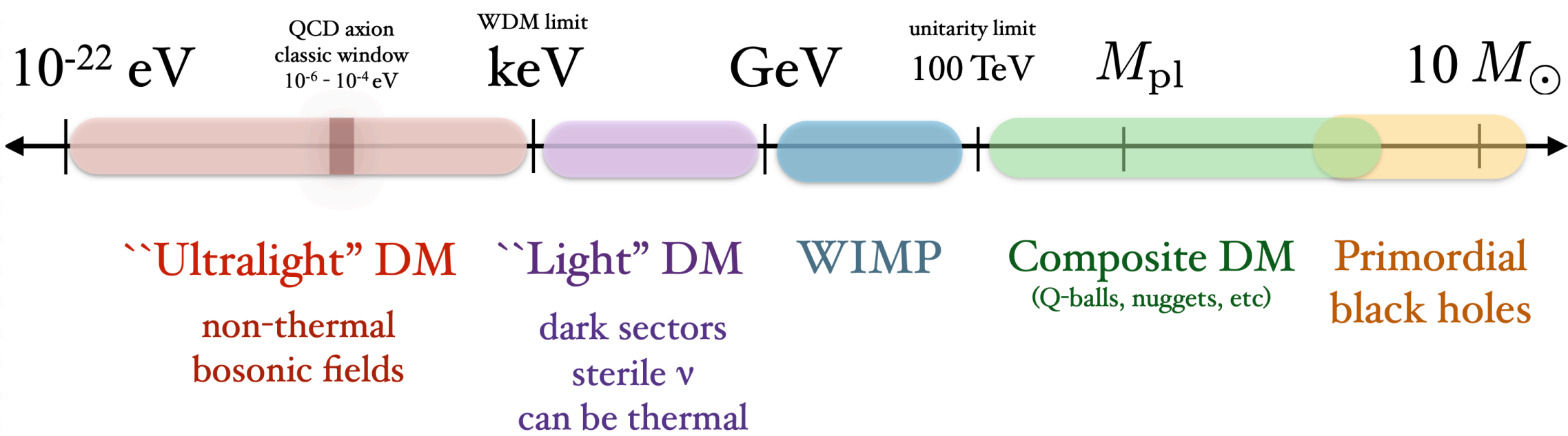
The relic density:

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

$m_\chi \sim 100 \text{ GeV}$
 $g_\chi \sim 0.6$
 $\Omega_\chi \sim 0.1$



Dark matter candidate



Brief History:

WIMP

- Axion
- Sub-GeV
- Primordial black hole

- Super heavy DM
- Super light DM

...

Direct detections in underground lab

Relevant Formulas

The WIMP event rate

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

Exposure

DM density

Nuclear Form Factor

Two uncertainties:

local measures use the vertical kinematics of stars near the Sun

Global measurement extrapolate rho from rotation curve

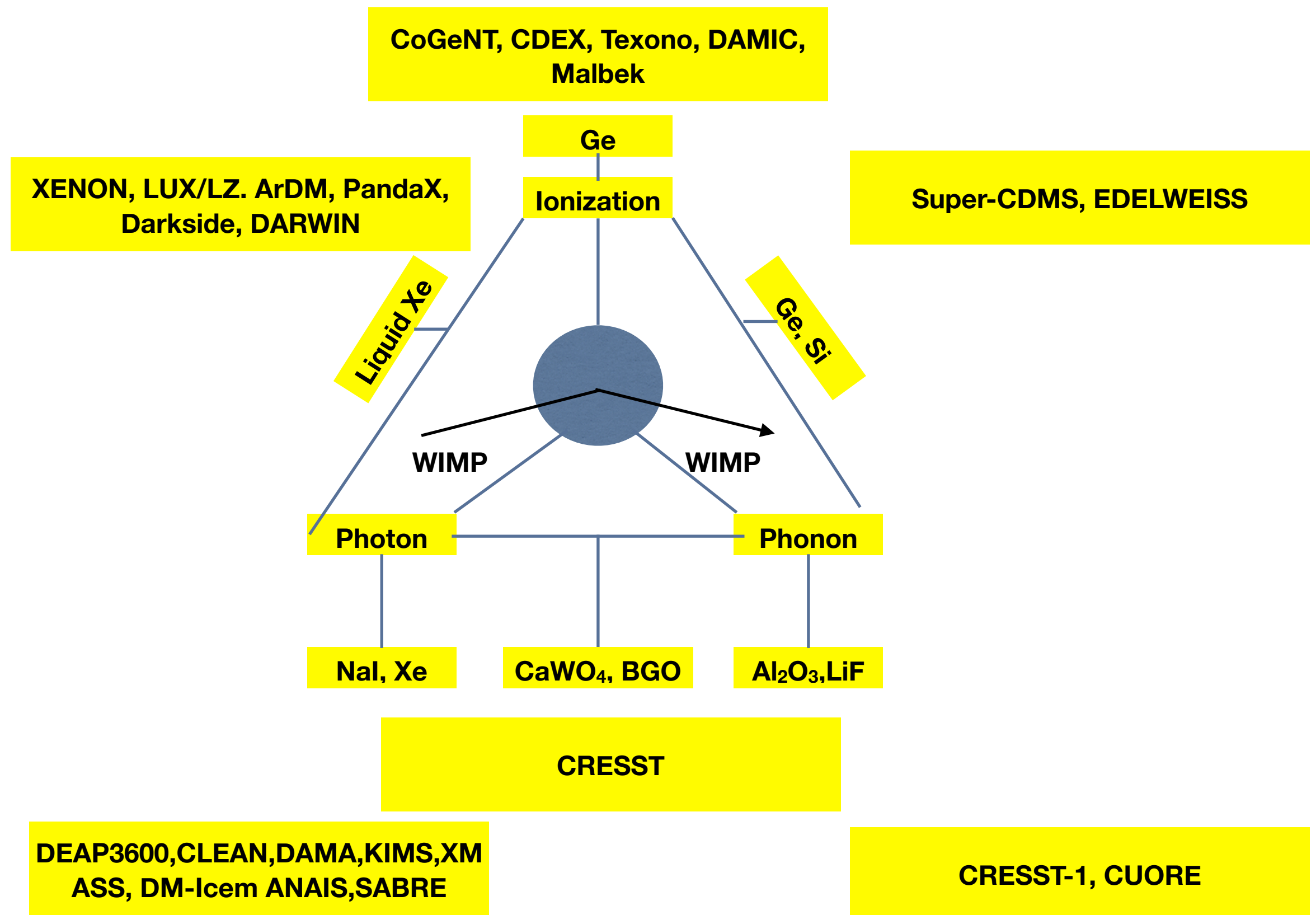
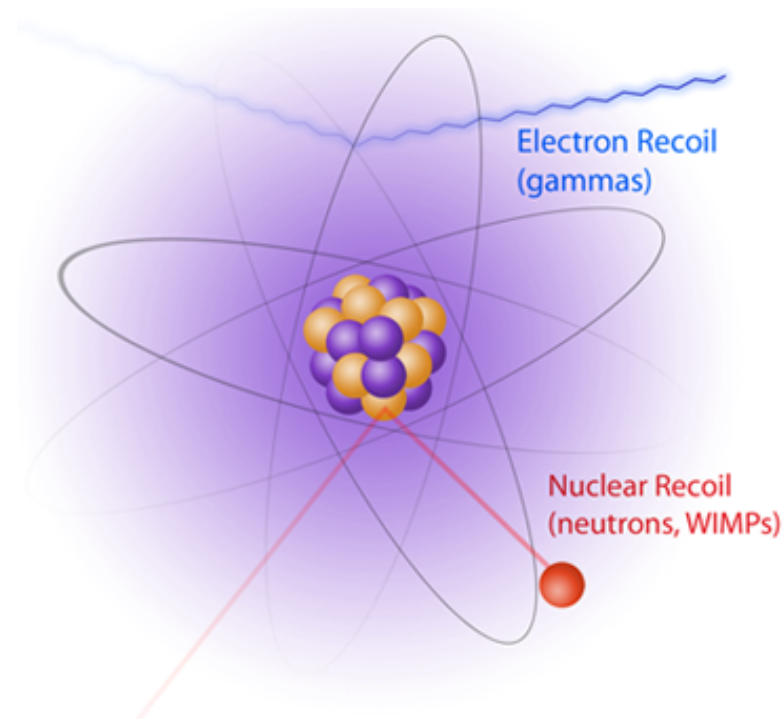
ρ_{DM}

Maxwell Boltzmann distribution:

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

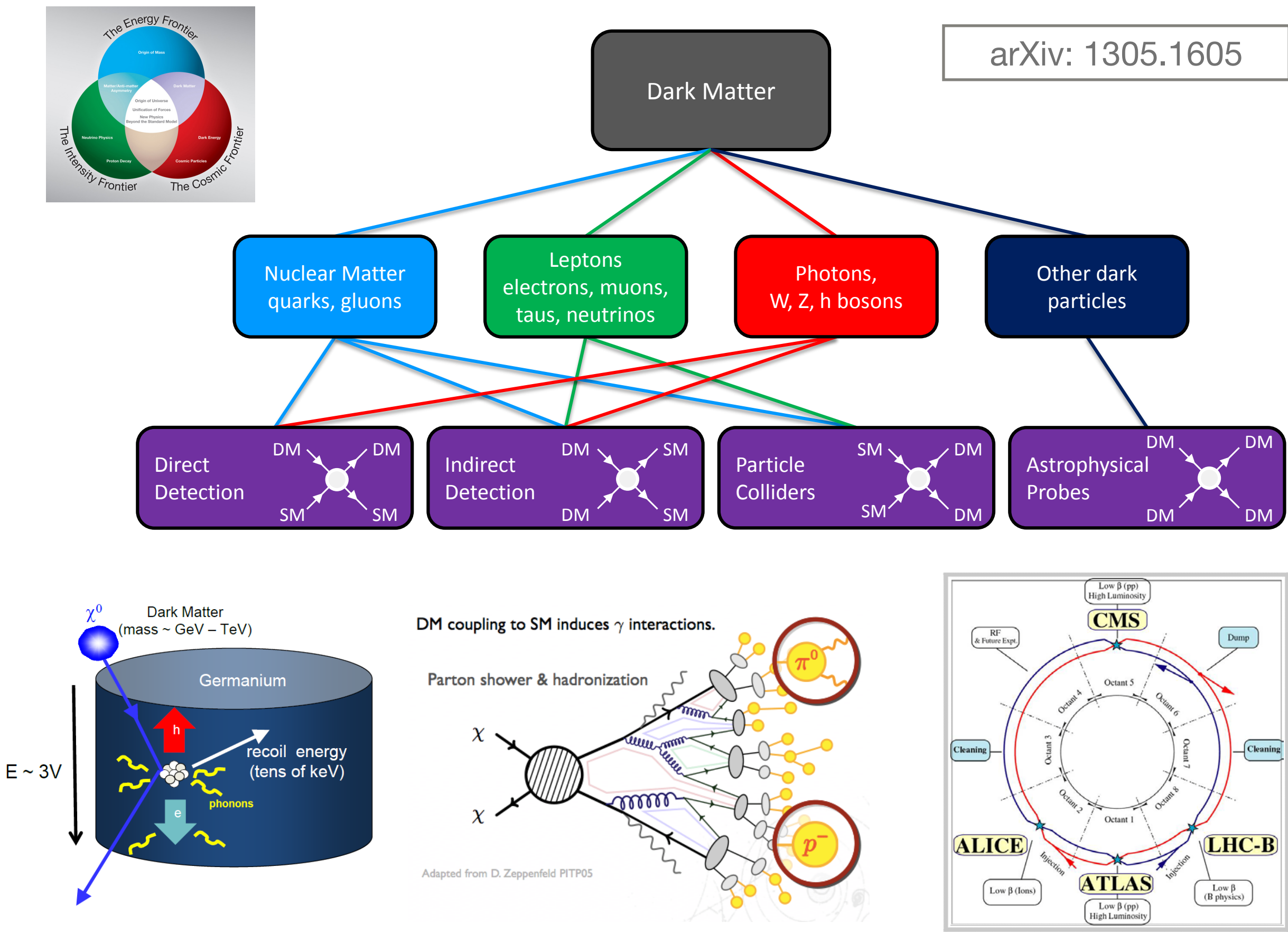
$$\int_{v_{\min}} \frac{f(\vec{v})}{v} d^3v = \frac{1}{2v_0 \eta_E} [\text{erf}(\eta_+) - \text{erf}(\eta_-)] - \frac{1}{\pi v_0 \eta_E} (\eta_+ - \eta_-) e^{-\eta_{\text{esc}}^2}$$

Possible signals of direct detection experiments

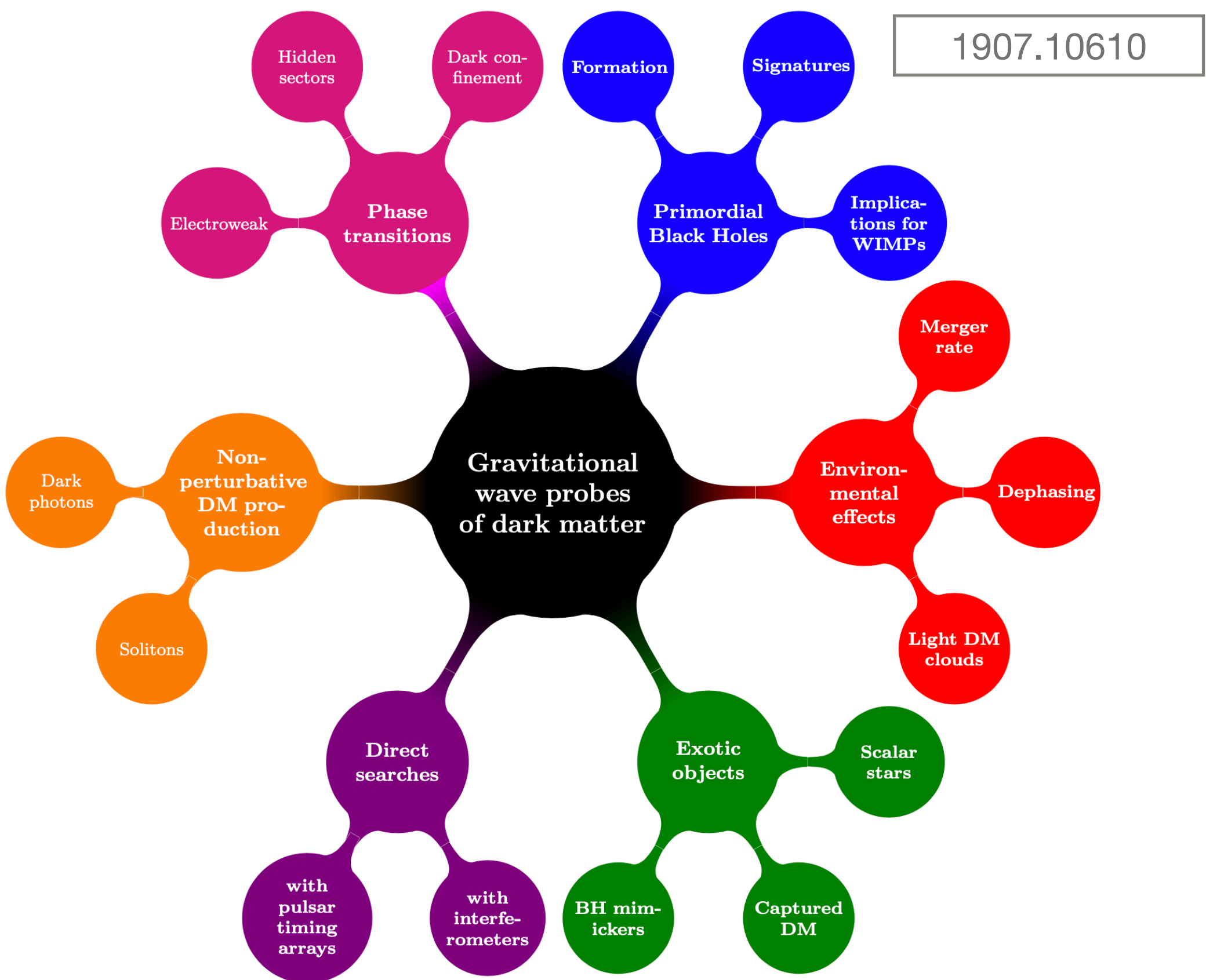


DM Dectections

Traditional methods

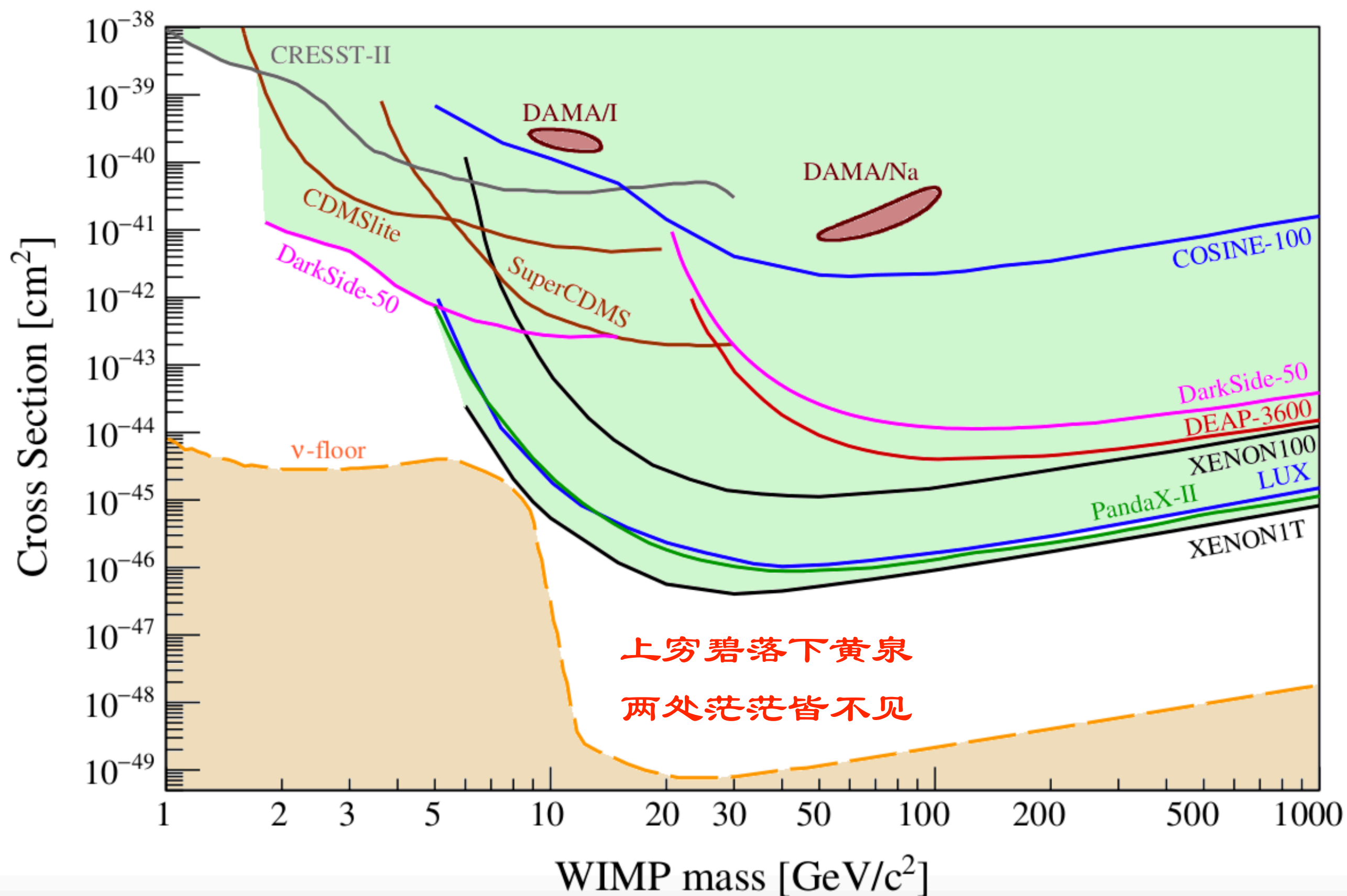


Modern strategies



Status

Status



What for next?

- Precision calculations of scattering cross section;
- Systematic study of neutrino floor;
- Exploring new direct detection technology;
- Moving to low mass regime, investigating sub-GeV DM;
- Moving to high mass regime, superheavy DM;
- MOND;
- Non-particle DM: PBG Q-ball...
- ...

中微子与暗物质的直接探测：中微子地板

中微子核子弹性散射

标准模型中的中微子核子相干弹性散射

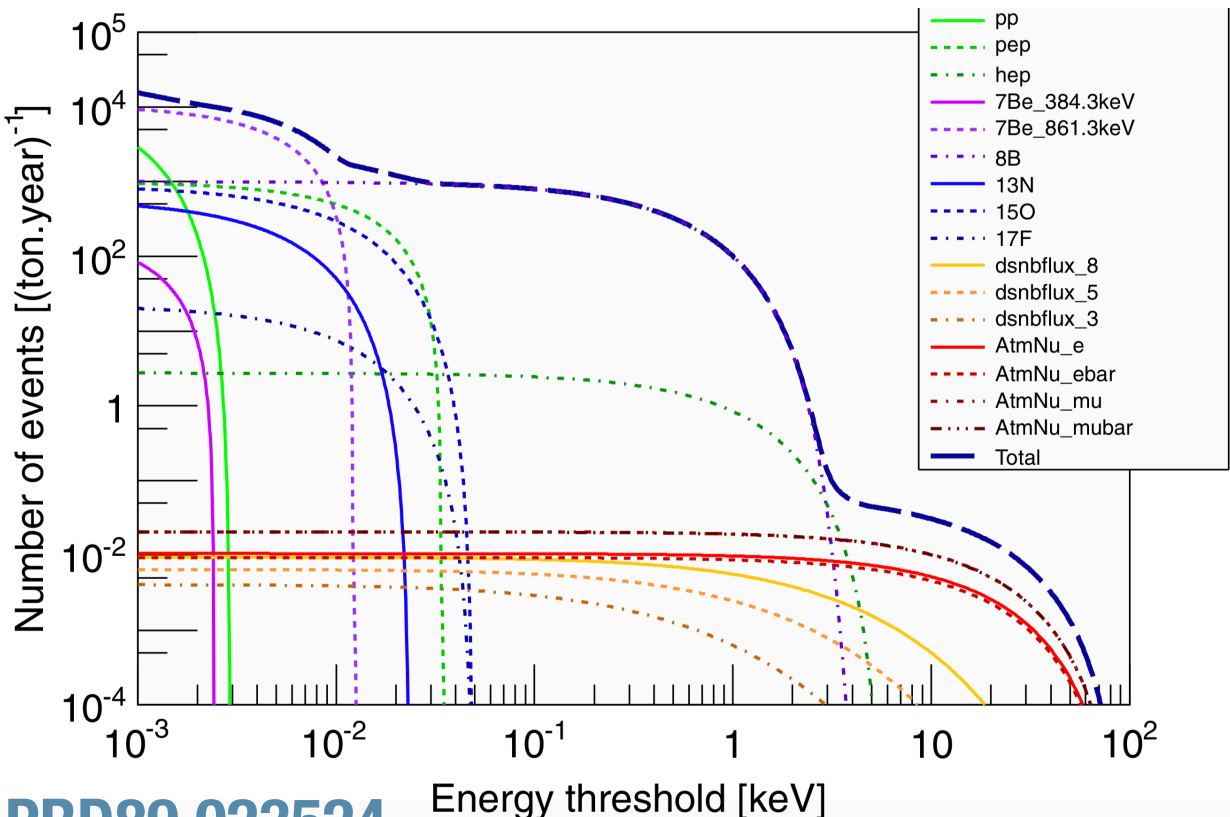
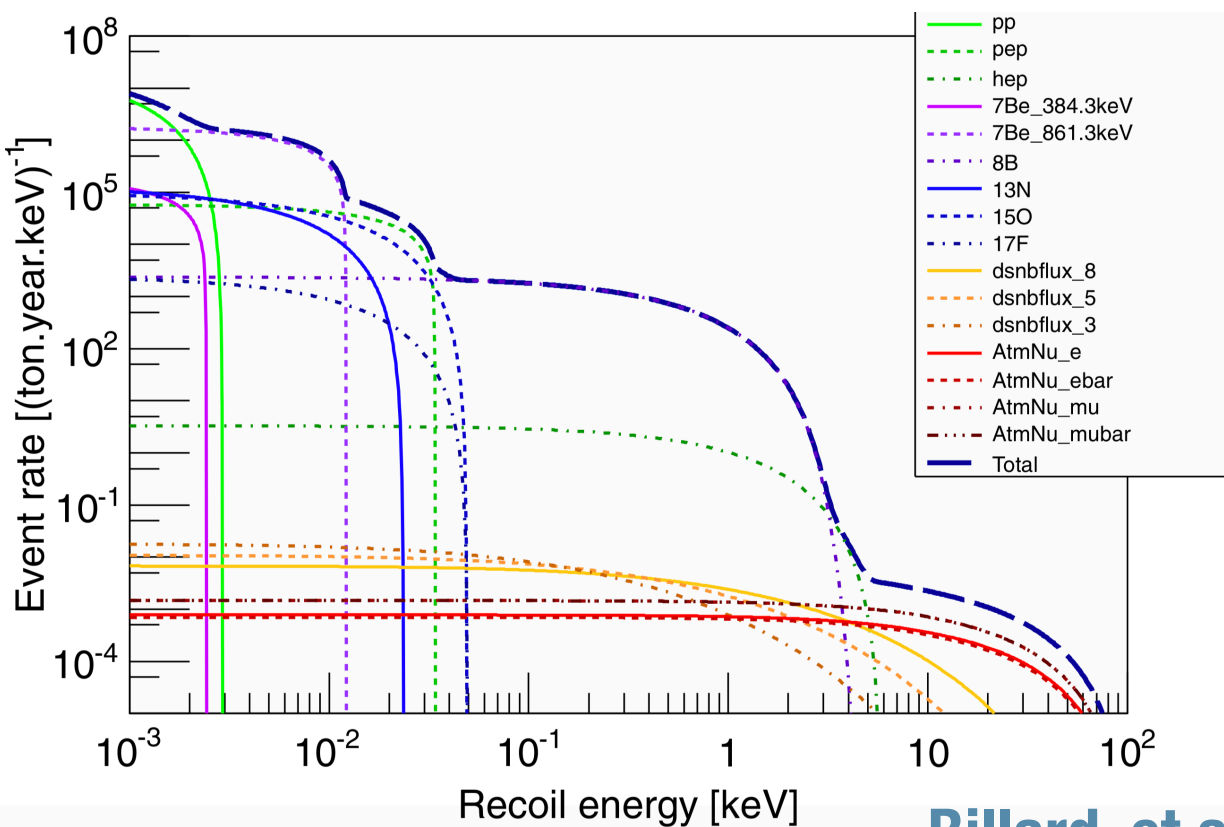
$$\frac{d\sigma_\nu}{dE_R} = \frac{G_F^2}{4\pi} Q_{\nu N}^2 m_N \left(1 - \frac{m_N E_R}{2E_\nu^2}\right) F^2(E_R)$$

Weak hyper-charge of
target nucleus

Nuclear form factor

期待的事例数

$$N = \frac{\epsilon}{m_N} \int_{E_T}^{E_{max}} dE_R \int dE_\nu \frac{d\phi_\nu}{dE_\nu} \frac{d\sigma_\nu}{dE_R}$$



Billard, et al., PRD89,023524

地板问题

WIMP微分事例数

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

Exposure

DM density

Nuclear Form Factor

Neutrino event rate

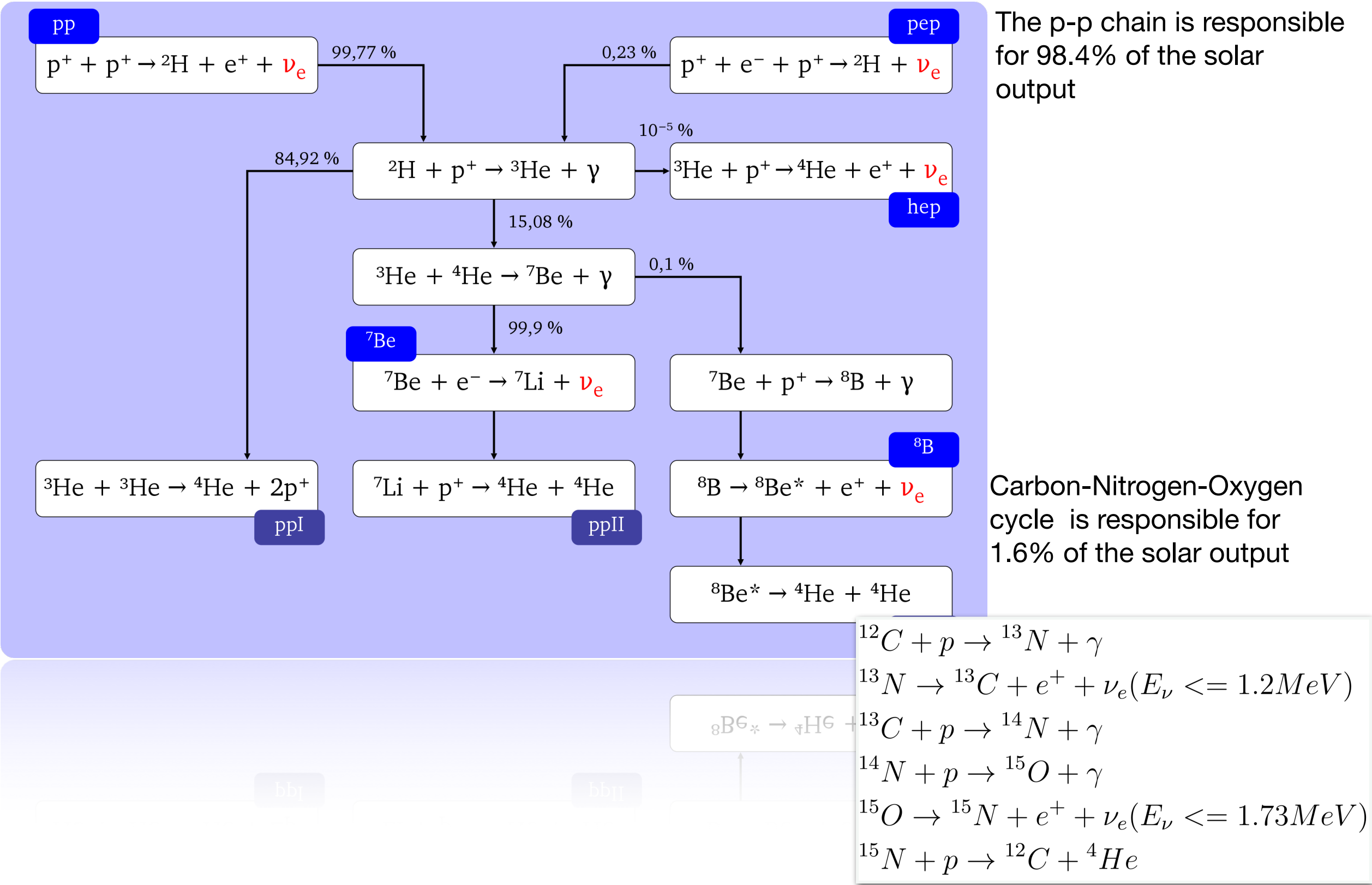
$$\frac{dR_\nu}{dE_R} = MT \times \frac{1}{m_N} \int_{E_\nu^{min}} \frac{d\phi_\nu}{dE_\nu} \frac{d\sigma_\nu}{dE_R}$$

中微子地板

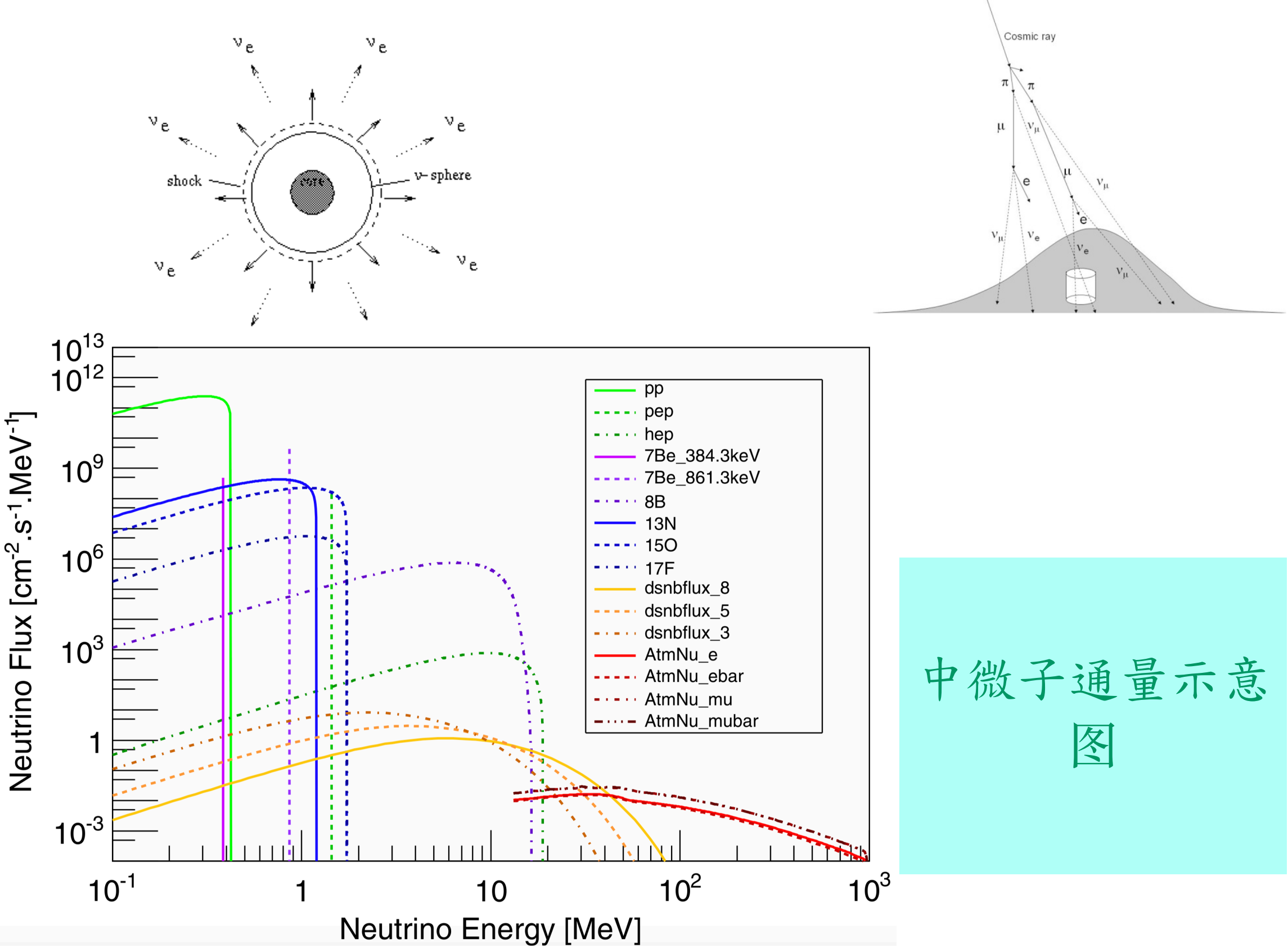
$$\sigma_n^0 = \frac{2.3}{m} \int_{E_R} \left(\frac{1}{m_N} \int_{E_\nu^{min}} \frac{d\phi_\nu}{dE_\nu} \frac{d\sigma_\nu}{dE_R} \right) \left(\frac{\rho_{DM} A^2}{2m_{DM} \mu_n^2} \int_{E_R}^{E_R^{max}} F^2(E_R) dE_R \int_{v_{min}} \frac{f(\vec{v})}{v} d^3v \right)^{-1}$$

中微子与暗物质的直接探测：中微子地板

相关的中微子源：太阳中微子



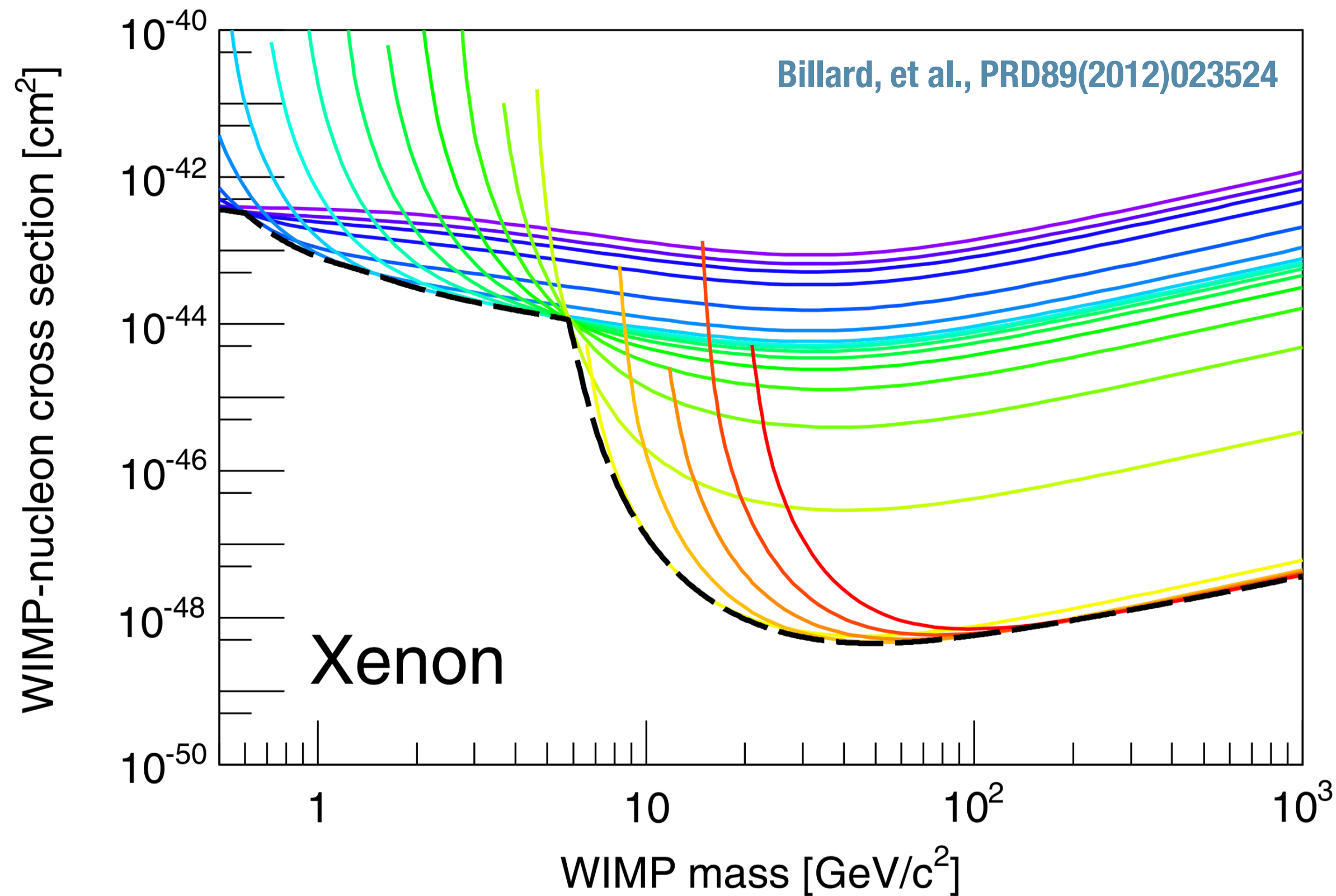
相关的中微子源：大气与超新星中微子



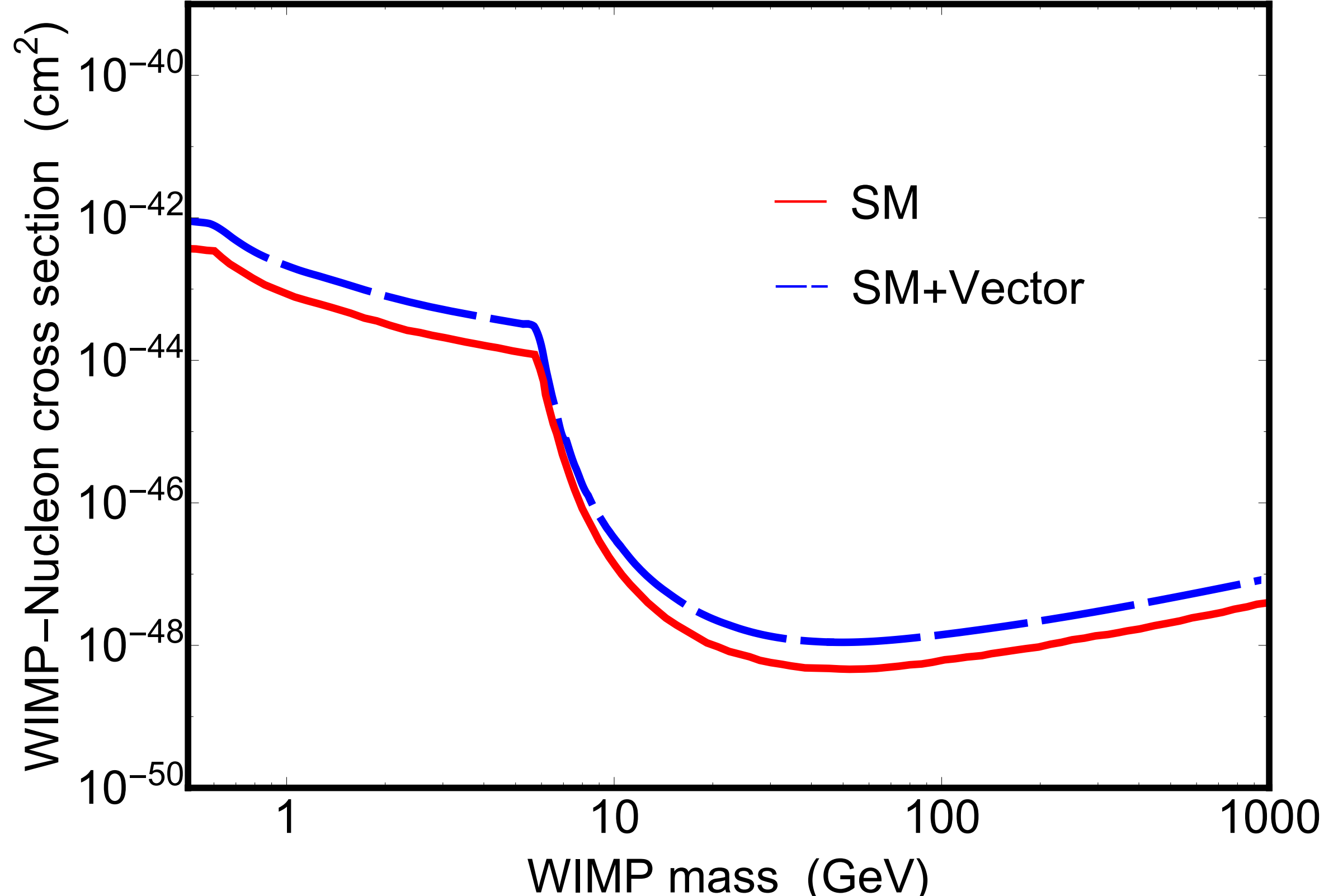
中微子通量示意图

中微子与暗物质的直接探测：中微子地板

标准模型的限制



非标准相互作用的限制

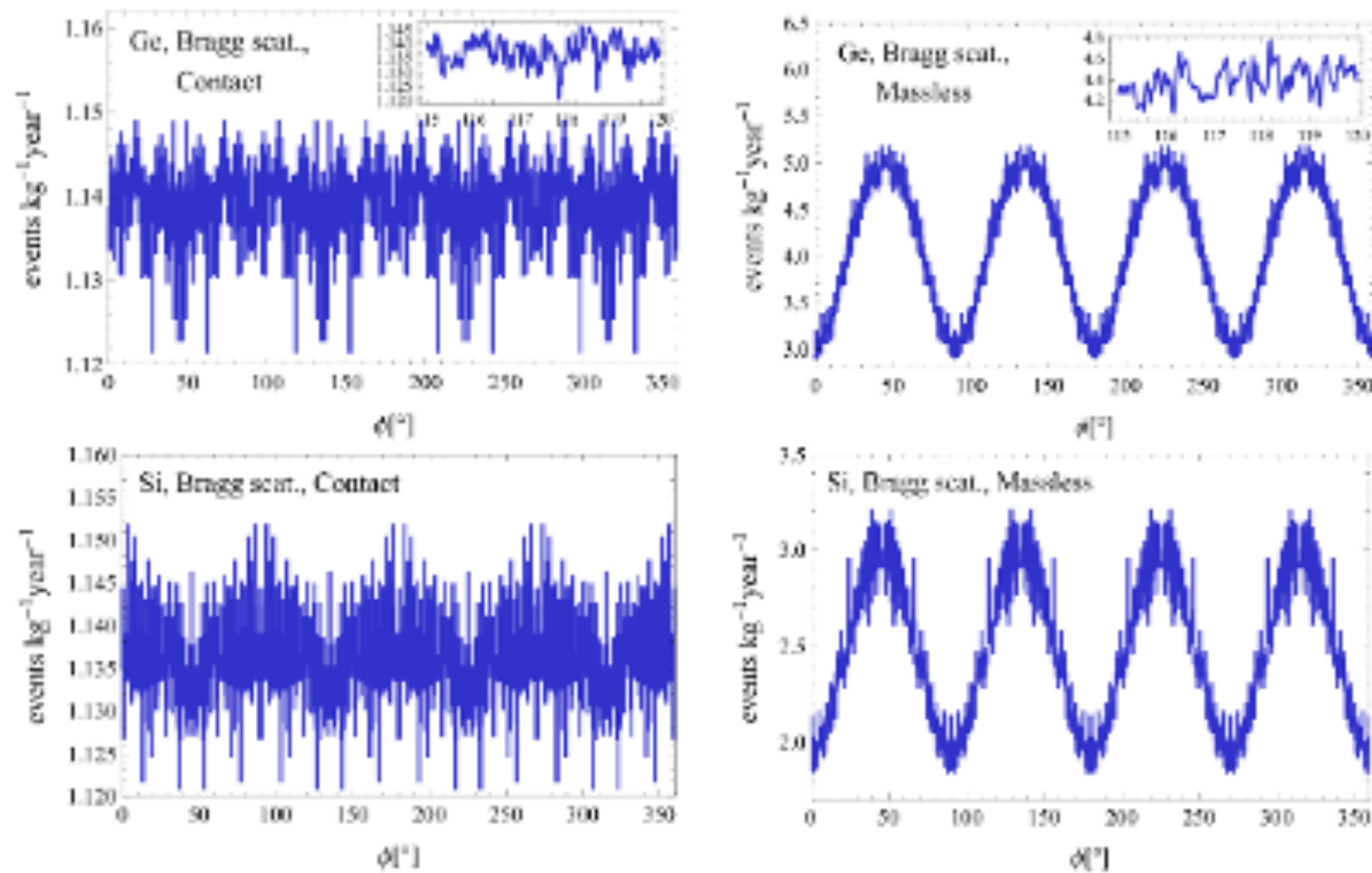


课题四的研究方向

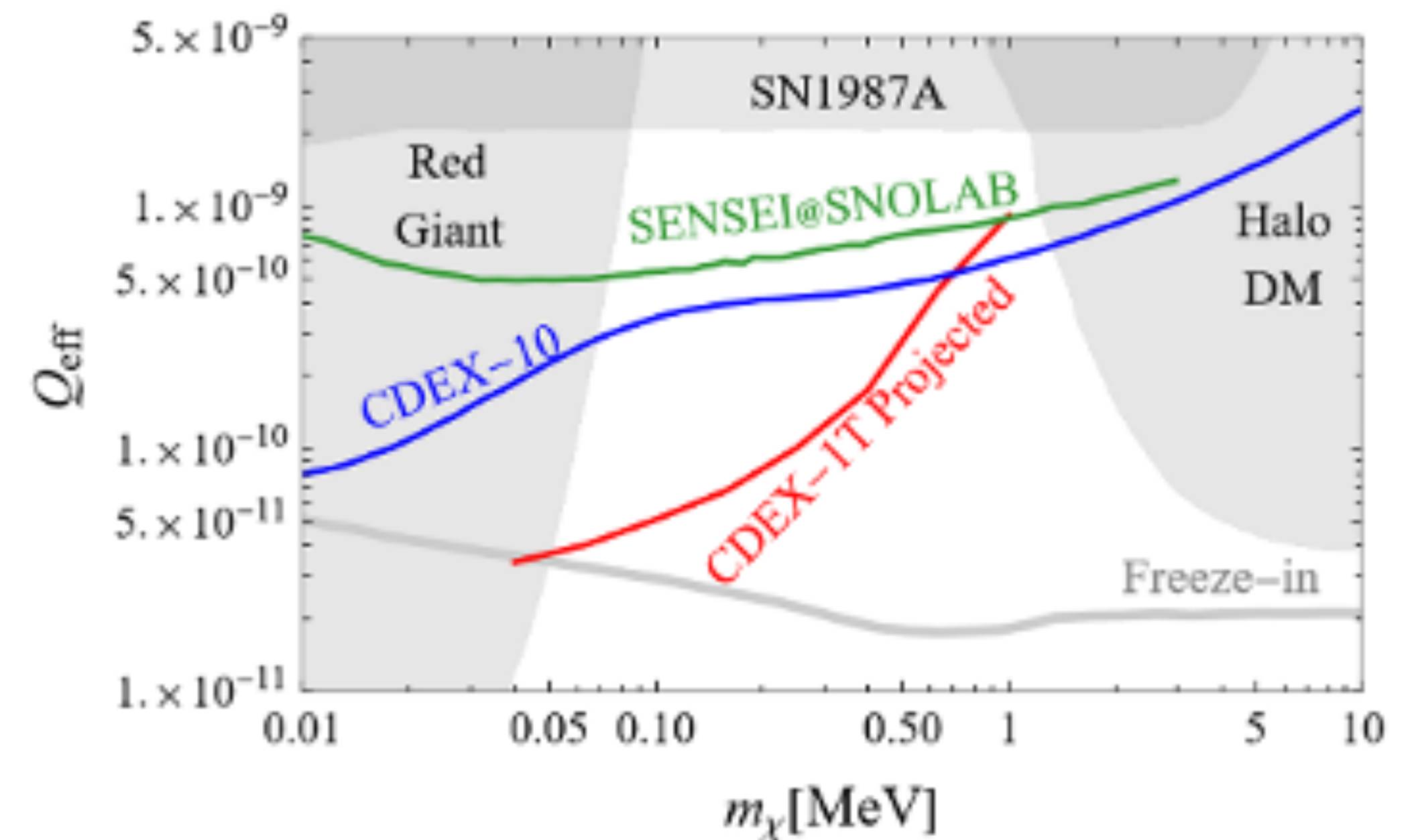
- 利用高纯锗探测器的单晶体性质来探测方向性暗物质的天调制信号；
- 利用**CDEX**探测器寻找暗物质的自相互作用；
- 构造新的暗物质模型，并针对新的暗物质模型寻找新的暗物质探测手段。

课题四代表性成果一

- 利用高纯锗探测器的单晶体性质来探测方向性暗物质的天调制信号；



Haipeng An, Haoming Nie, arxiv:2502.21140



课题四代表性成果

- 构造新的暗物质模型，并针对新的暗物质模型寻找新的暗物质探测手段，本年度有四个正式的工作发表
1. In Situ Measurement of Dark Photon Dark Matter Using Parker Solar Probe: Going beyond the Radio Window, **H An, et al., PRL 134 (2025) 171001**; 文章被选为PRL的编辑推荐和物理亮点，并被自然杂志报道。
 2. Axion-inflation baryogenesis via new U(1) gauge symmetries, **Wei Chao, et al., JCAP 02 (2025) 030**;
 3. Probing Sub-eV Dark Photon, Scalar and Axion-like Particle Dark Matters with Transmon Qubits, **Wei Chao, et al., Phys. Dark Univ. 50 (2025) 102171**;
 4. Pseudo-Dirac sterile neutrino dark matter, Wei Chao, et al., **Eur. Phys. J. C 85 (2025) 8, 855**;

Outline



○ Detecting bosonic DM with transmon qubit

Probing light bosonic DM with transmon qubits,

W. Chao, Yu Gas, Mingjie Jin, X.S. Liu and Xilei Sun,

Phys.Dark Univ. 50 (2025) 102171

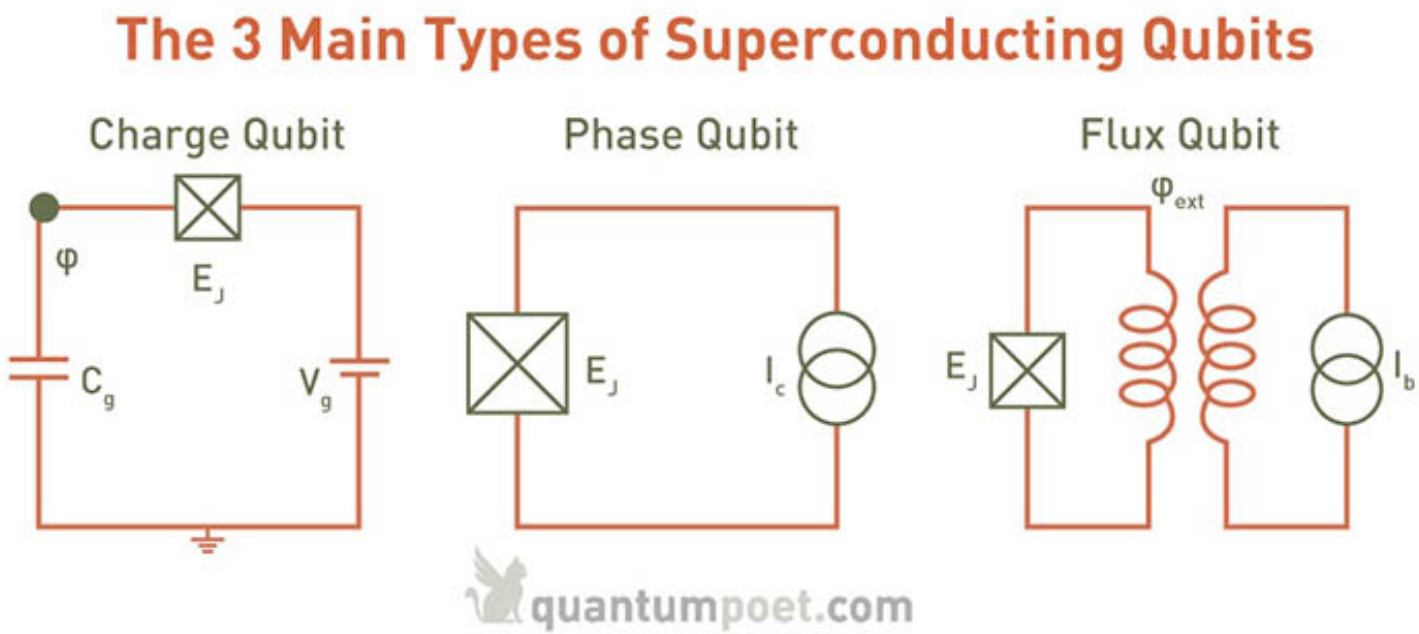
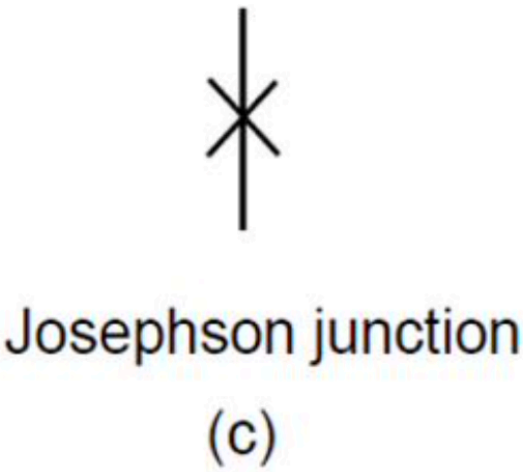
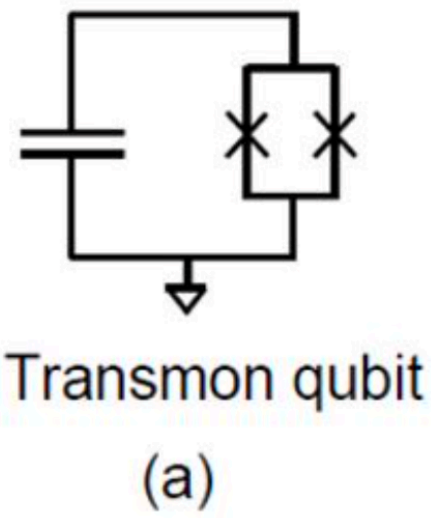
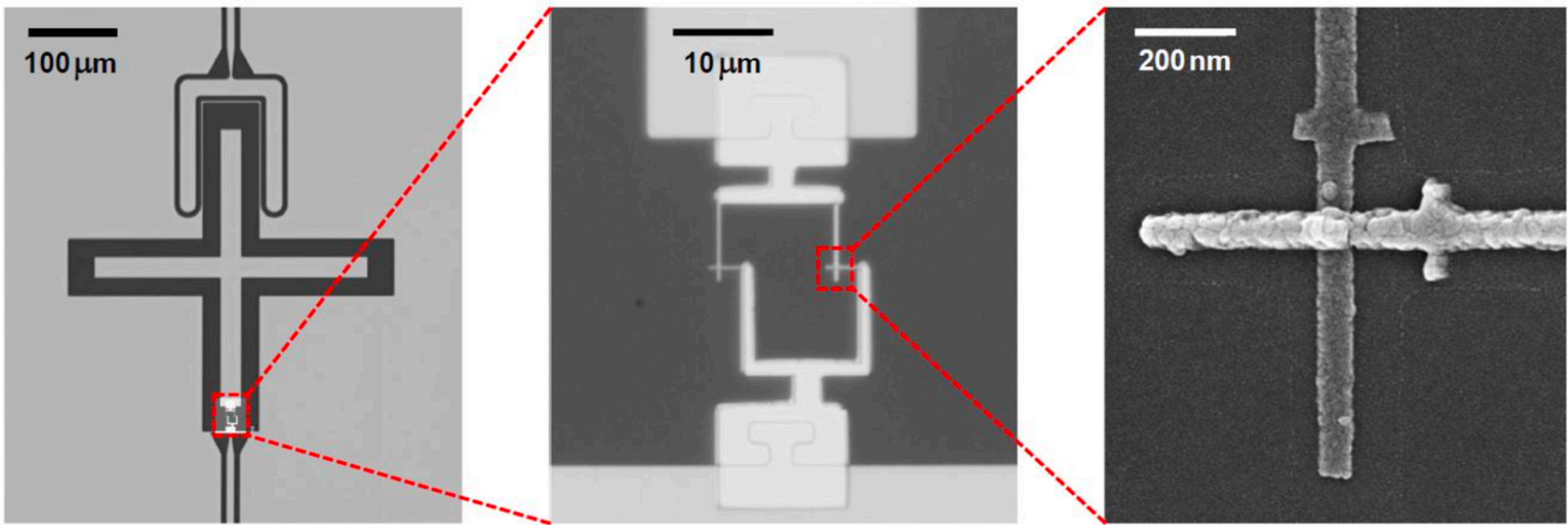
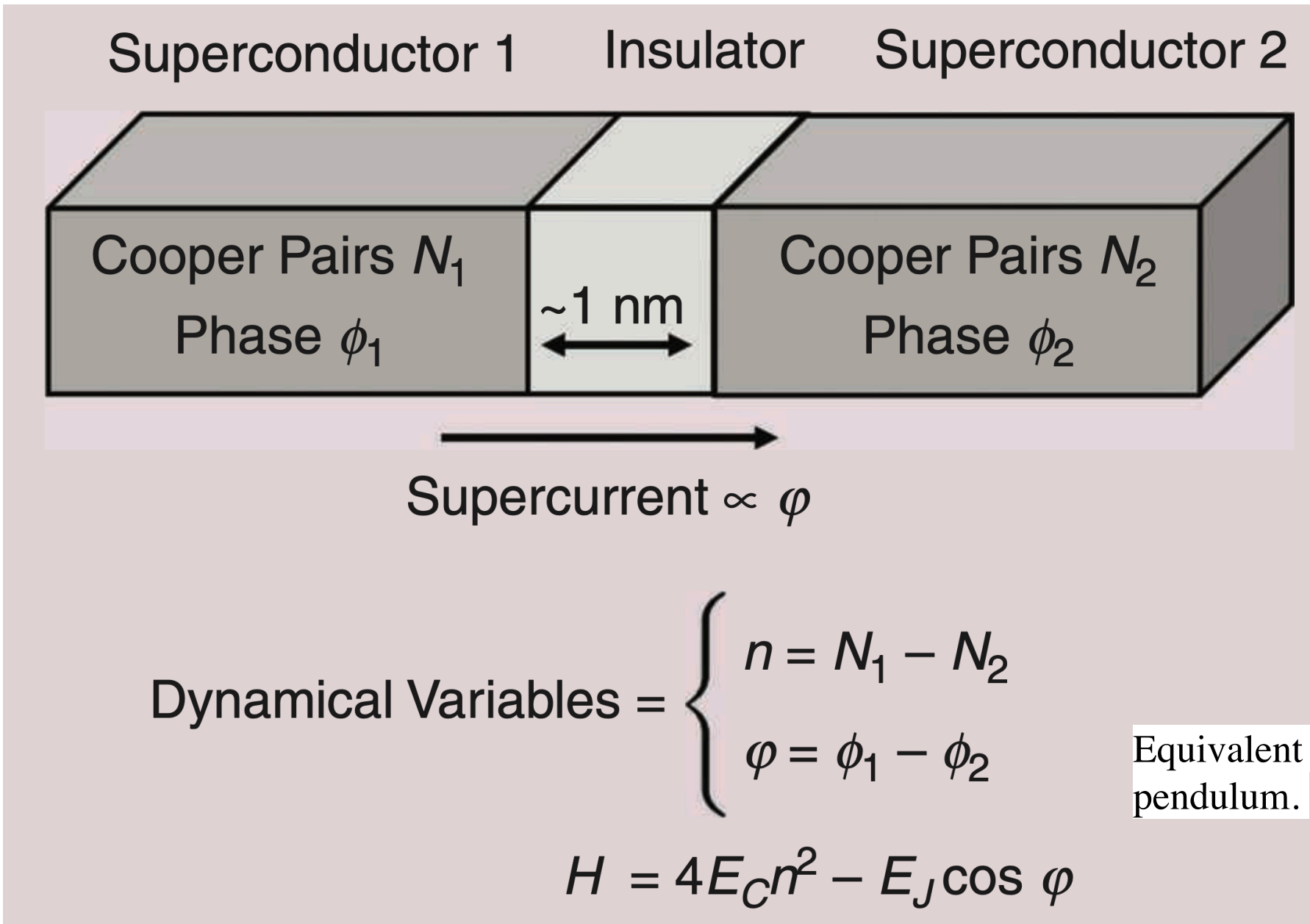
○ Sterile neutrino as the dark matter

Pseudo-Dirac sterile neutrino dark matter

W. Chao, et al.,

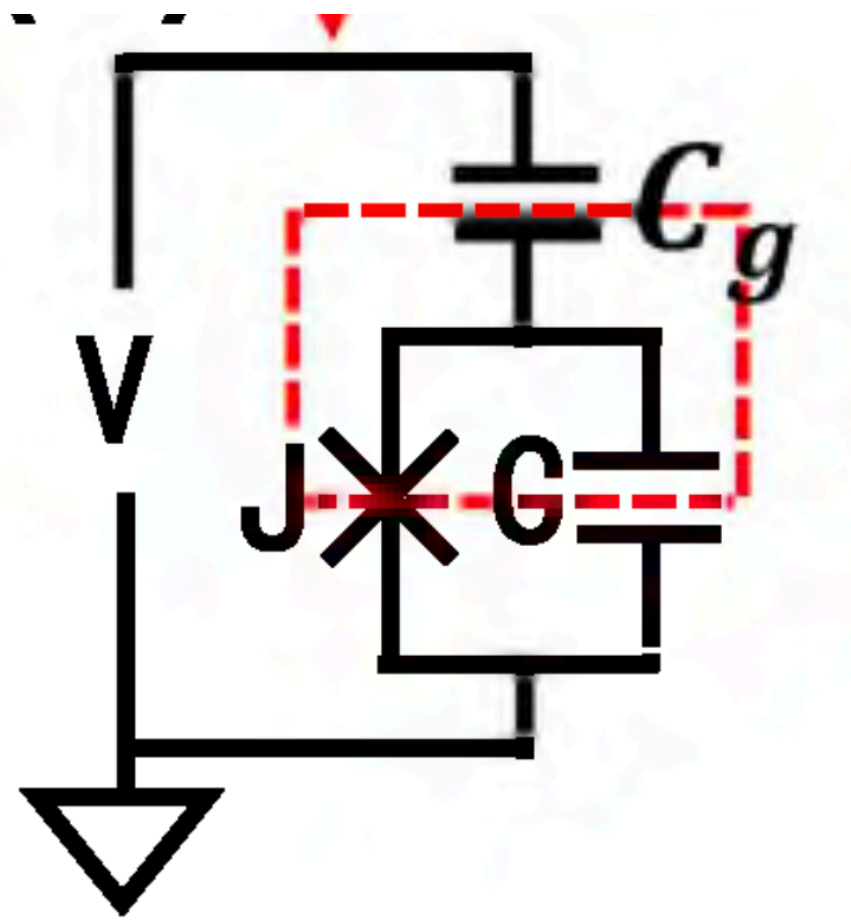
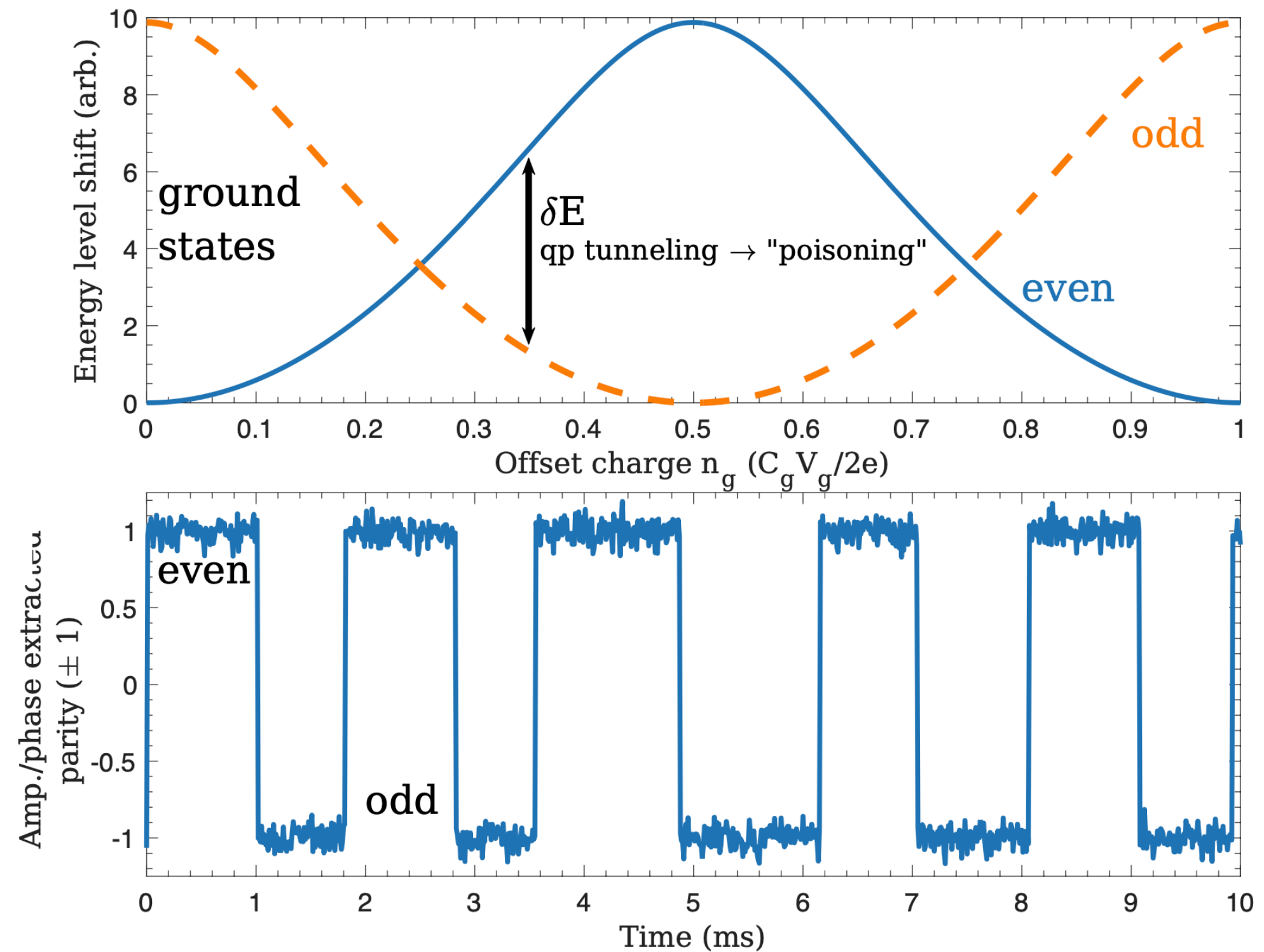
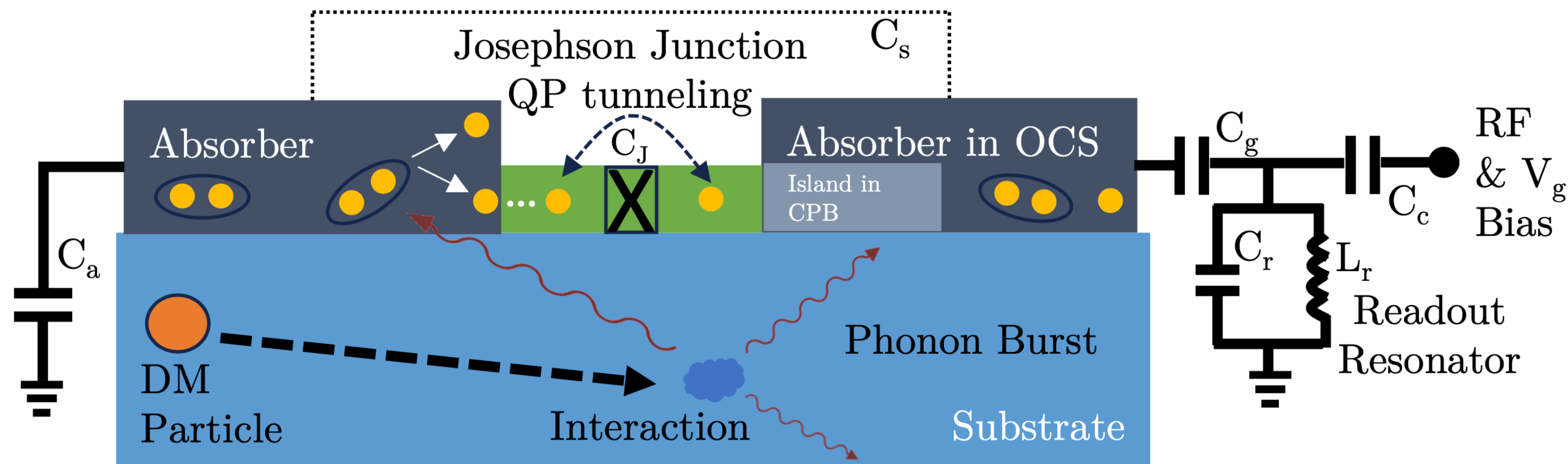
EPJC 85(2025)8,855

传输子量子比特



For the introduction of superconducting qubits, I refer you to prof. Zhihui Peng's slide for detail.

超导量子比特作为暗物质探测器

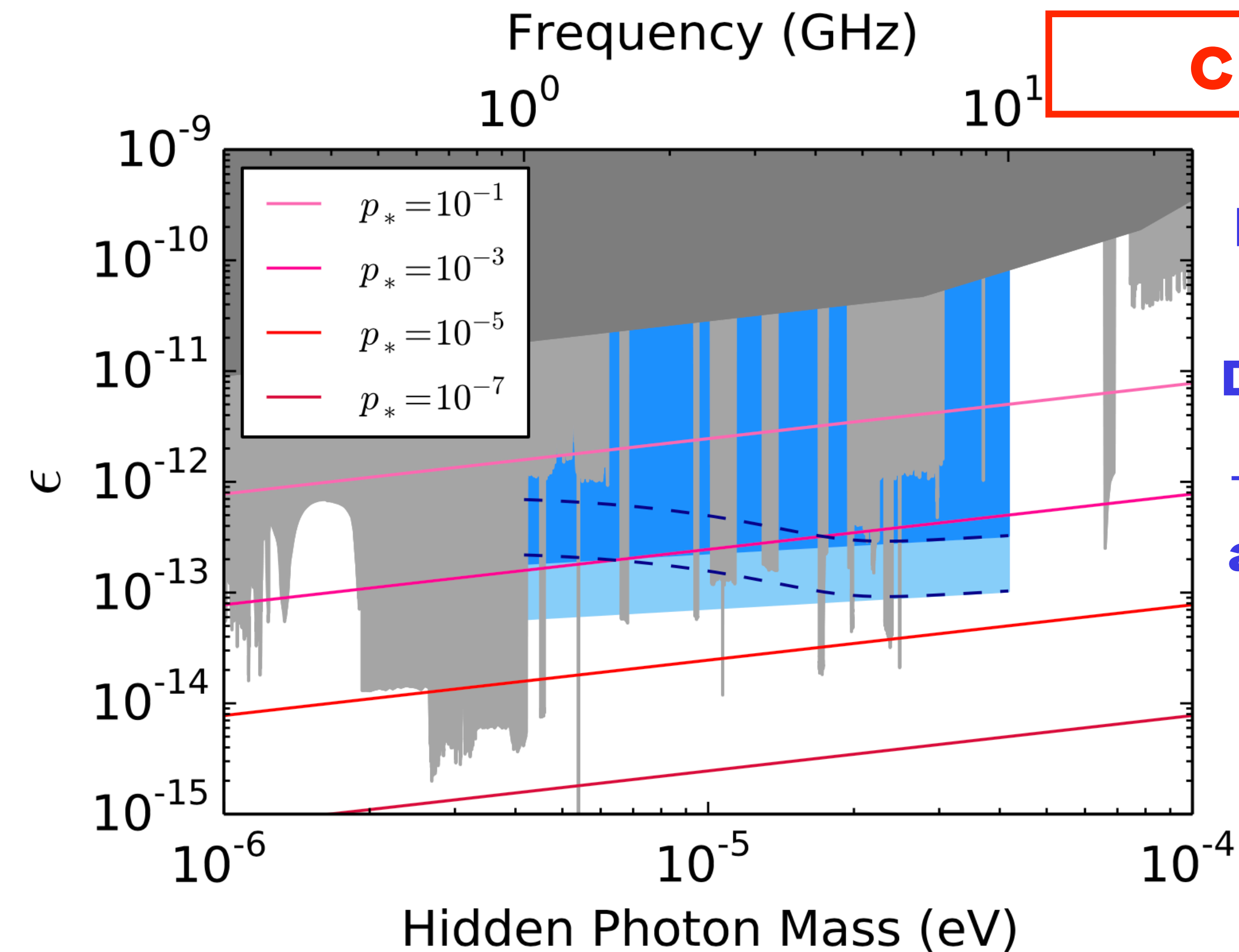


$$H_{CPB} = 4E_C \left(\hat{n} - n_g + \frac{P-1}{4} \right)^2 - E_j \cos \hat{\phi}$$

Pictures taken from arXiv: 2405.17192

传输子量子比特探测暗光子

Chen, et al., PRL 131, 211001 (2023)



Hamiltonian

$$H_0 = \frac{1}{2}CV^2 - J \cos \theta$$

DP induced electric field $\vec{E}^X = \epsilon \sqrt{2\rho_{\text{DM}}} \vec{n}_X \sin m_x t$

→ Oscillations between the ground state and the excited state!

$$\begin{aligned}
 p_{ge}(\tau) \simeq & 0.12 \times \kappa^2 \cos^2 \Theta \left(\frac{\epsilon}{10^{-11}} \right)^2 \left(\frac{f}{1 \text{ GHz}} \right) \\
 & \times \left(\frac{\tau}{100 \text{ } \mu\text{s}} \right)^2 \left(\frac{C}{0.1 \text{ pF}} \right) \left(\frac{d}{100 \text{ } \mu\text{m}} \right)^2 \\
 & \times \left(\frac{\rho_{\text{DM}}}{0.45 \text{ GeV/cm}^3} \right),
 \end{aligned}$$

传输子量子比特探测玻色子暗物质

Quasiparticle excitation:

$$\frac{dn_{qp}}{dt} = -\Gamma_R - \Gamma_T + \Gamma_G \quad \bullet \text{ Phys. Rev. Lett. 117, 117002 (2016).}$$

Γ_R : **Recombination rate**

$$\Gamma_R = \bar{\Gamma} n_{PQ}^2$$

Γ_T : **Trapping rate**

$$\Gamma_T = \bar{\Gamma}' n_{PQ}$$

Γ_G : **Generating rate induced by DM absorption or scattering!**

In equilibrium:

$$\Gamma_G = \bar{\Gamma} n_{QP}^2 + \Gamma_T n_{QP}$$

传输子量子比特探测玻色子暗物质

The number of phonon per unit time per unit mass:

$$R = \frac{\pi \sigma_\chi n_\chi}{\rho_T \mu^2} \int d^3 v f_\chi(v) \int \frac{d^3 q}{(2\pi)^3} F_{\text{med}}^2(q) S(q, \omega_q)$$

Full phonon energy:

$$E = \int d\omega \omega \times \frac{dR}{d\omega} \times M \times T$$

Number of quasiparticles produced:

$$N = \frac{\varepsilon}{2\Delta} \omega R M T$$

Produced quasi particle density per unit time:

$$n'_{qp} = N/V/T = \frac{\varepsilon}{2\Delta} \omega R \rho_T = \frac{\varepsilon}{2\Delta} \int d\omega \omega \frac{dR}{d\omega} \times \rho_T$$

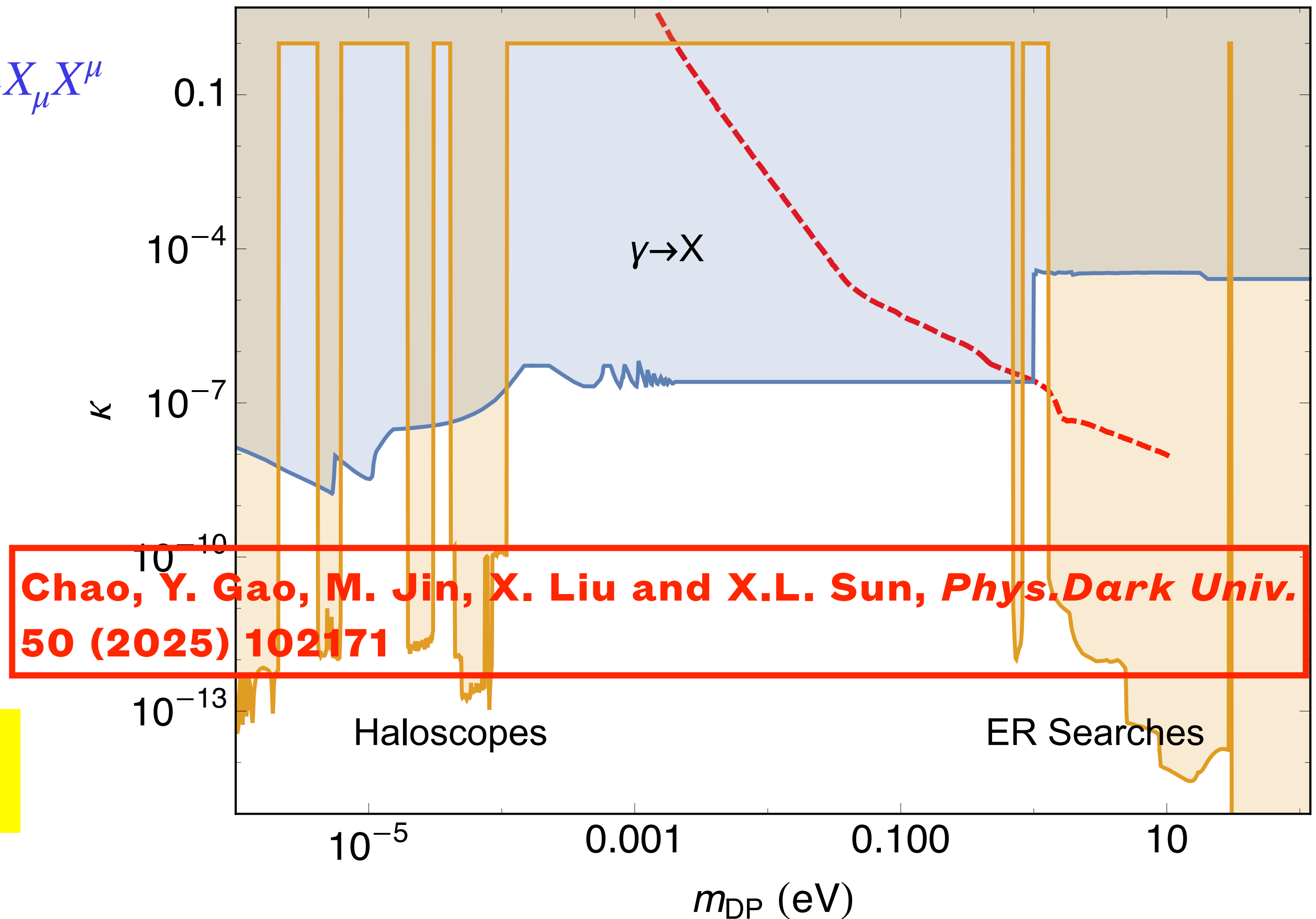
传输子量子比特探测玻色子暗物质

$$\mathcal{L}_{\text{DP}} \supset -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}X_{\mu\nu}X^{\mu\nu} + \frac{\varepsilon}{2}F_{\mu\nu}X^{\mu\nu} + \frac{1}{2}m_X^2 X_\mu X^\mu$$

$$R_{\text{DP}} = \frac{\rho_{\text{DP}}}{\rho_T} \kappa^2 \text{Im} \left[-\frac{1}{\varepsilon(\omega)} \right]$$

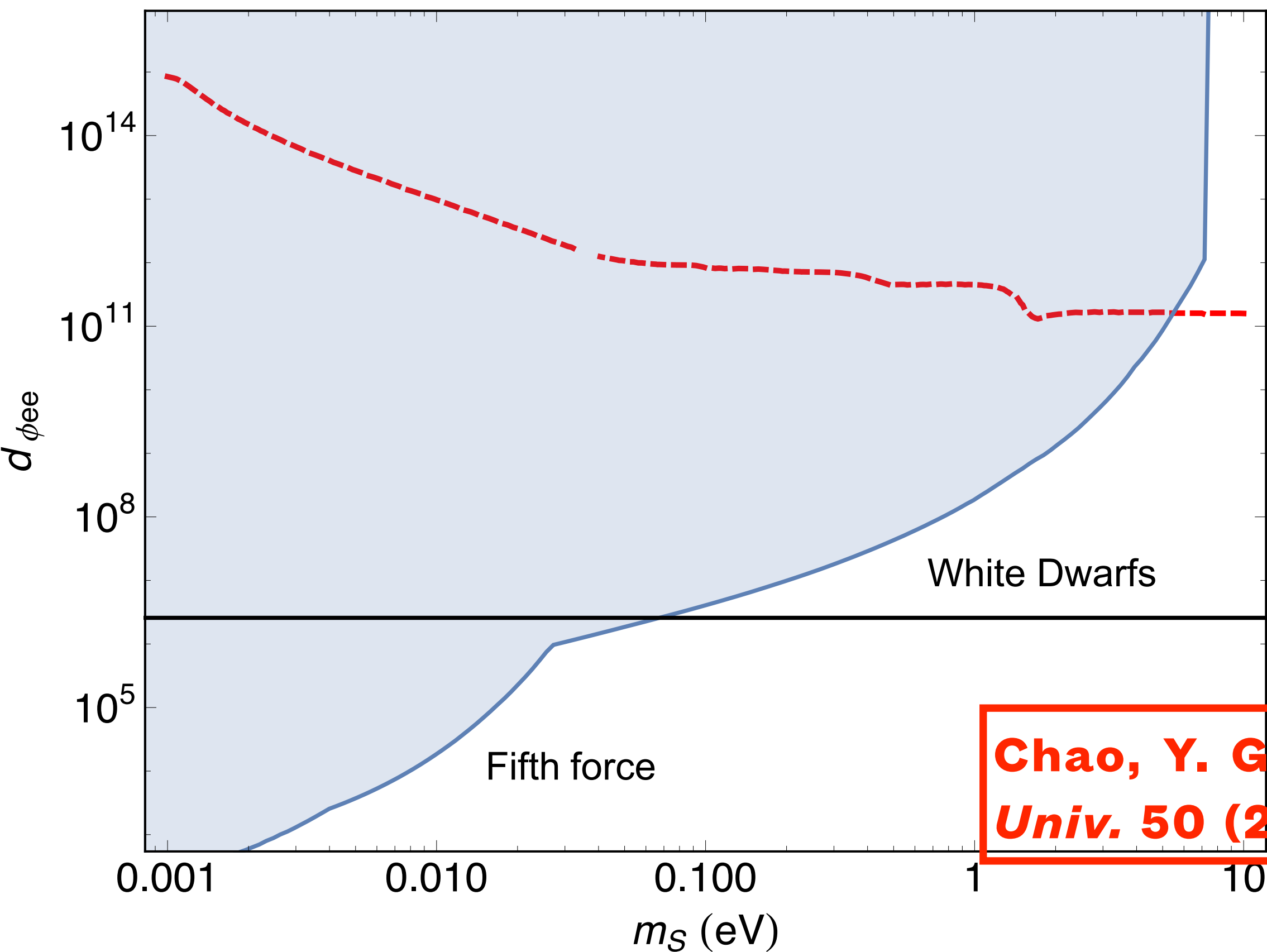
$$n_{qp} < 0.04 \mu m^{-3}$$

D. Riste et al., Nature Communications 4 (2013), 10.1038/ncomms2936

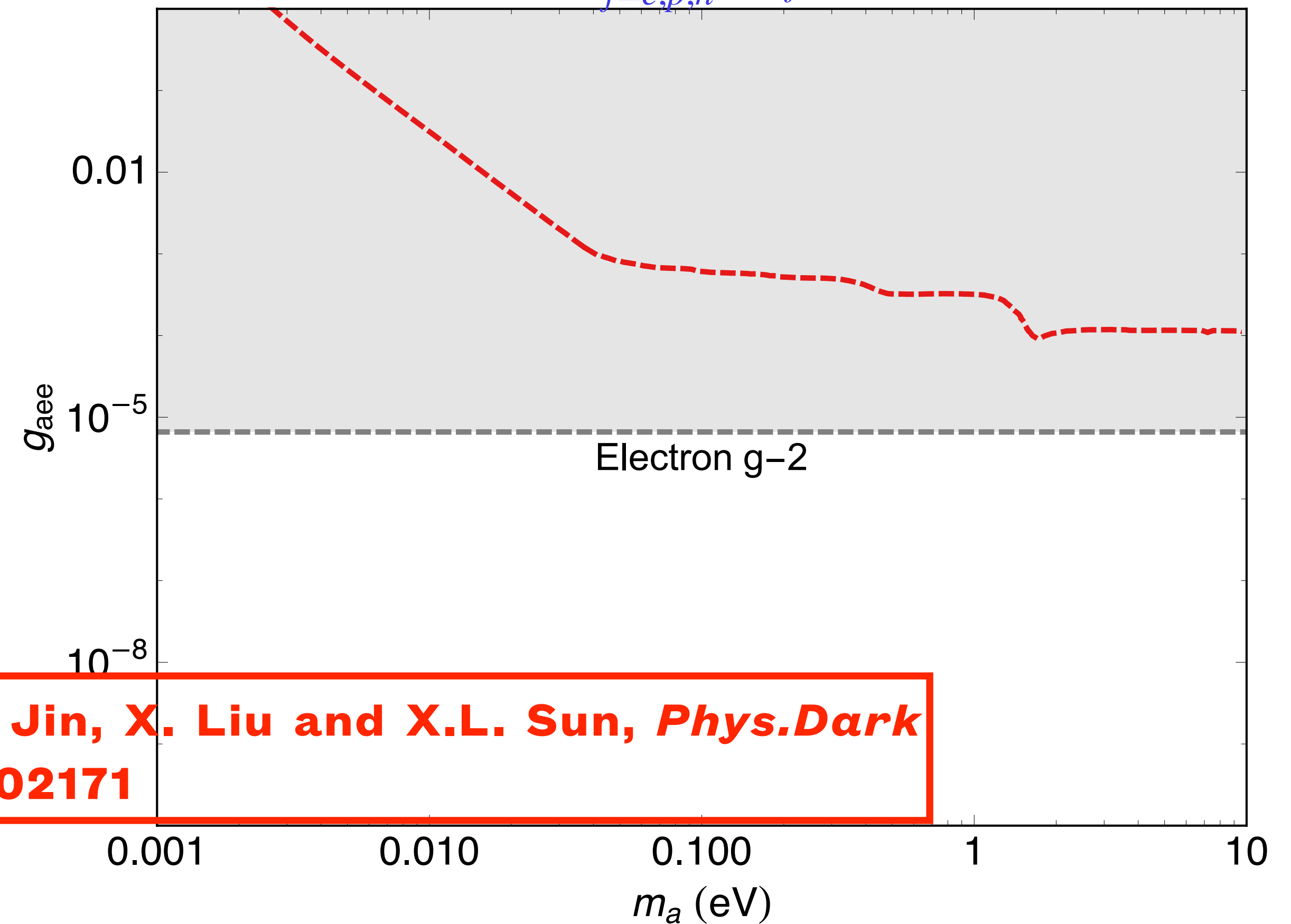


传输子量子比特探测玻色子暗物质

$$\mathcal{L} \supset \sum_{f=e,p,n} d_{\phi ff} \phi \bar{f} f$$



$$\mathcal{L} \supset \sum_{f=e,p,n} \frac{g_{aff}}{2m_f} \partial_\mu a \bar{f} \gamma^\mu \gamma^5 f$$



Chao, Y. Gao, M. Jin, X. Liu and X.L. Sun, *Phys.Dark Univ.* 50 (2025) 102171

Outline

- Detecting bosonic DM with transmon qubit

Probing light bosonic DM with transmon qubits,

W. Chao, Yu Gas, Mingjie Jin, X.S. Liu and Xilei Sun,

Phys.Dark Univ. 50 (2025) 102171



- Sterile neutrino as the dark matter

Pseudo-Dirac sterile neutrino dark matter

W. Chao, et al.,

EPJC 85(2025)8,855

中微子与暗物质：惰性中微子暗物质

惰性中微子暗物质的物理动机

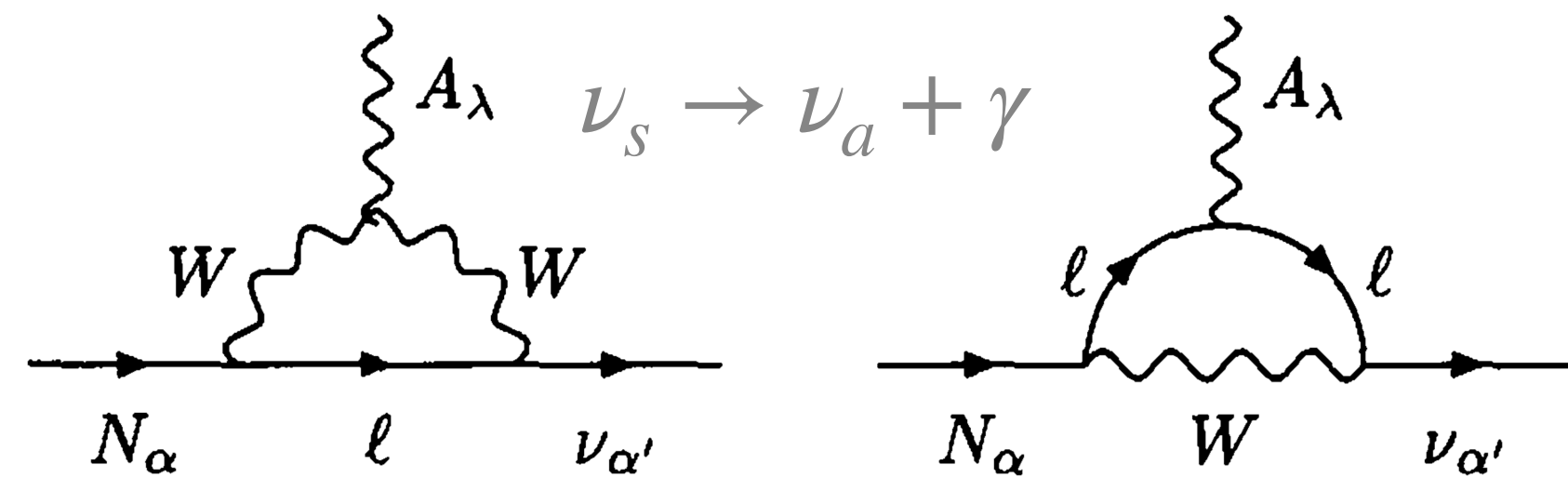
- Non-zero neutrino masses predict the existence of sterile neutrino.
- Sterile neutrino mass may range from the eV scale to the GUT scale.
- Active neutrinos is stable but cannot be dark matter candidate.
- KeV-scale sterile neutrino dark matter can solve the small scale issues of the cold dark matter(core/cusp;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

惰性中微子暗物质的发展历史

- 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

中微子与暗物质：惰性中微子暗物质

信号



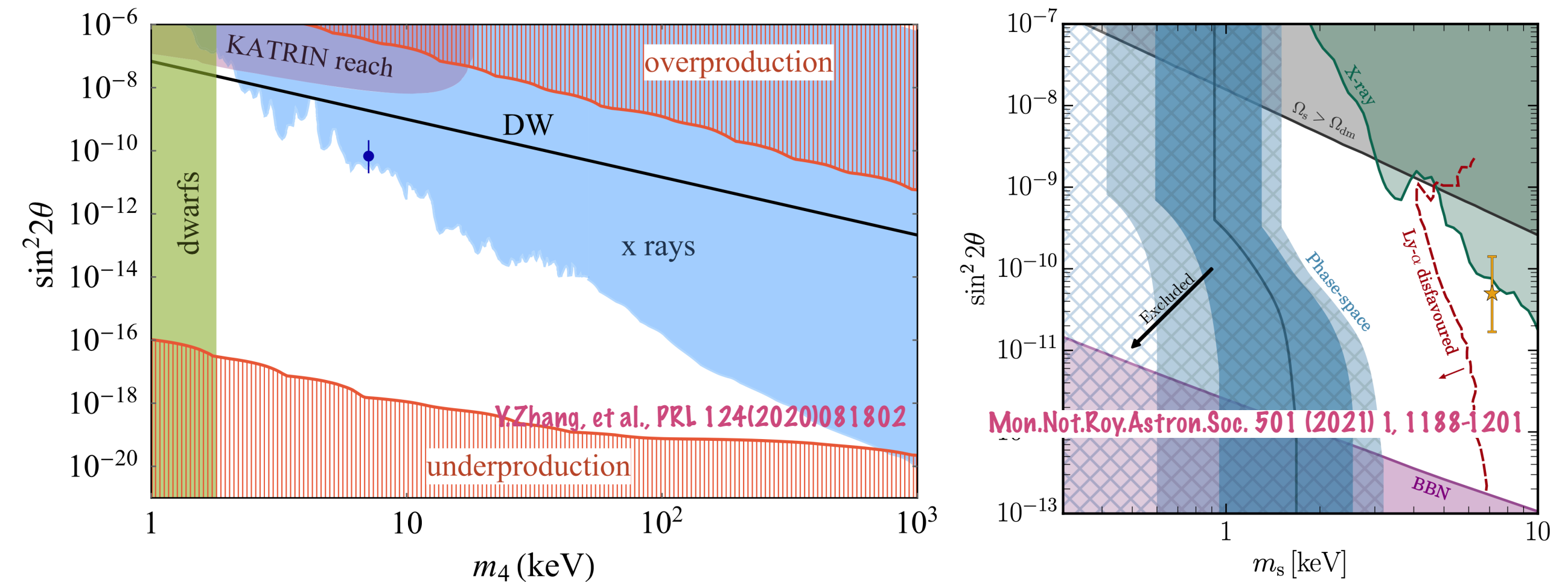
$$\Gamma_\gamma = 1.62 \times 10^{-28} s^{-1} \left(\frac{\sin^2 2\theta}{7 \times 10^{-11}} \right) \left(\frac{m_s}{7 \text{ keV}} \right)^5$$

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

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.

实验限制



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

中微子与暗物质：惰性中微子暗物质

赝狄拉克惰性中微子暗物质

拉氏量 $\mathcal{L}_{\text{Pseudo-Dirac}} = M \overline{S}_L N_R + \frac{1}{2} \overline{S}_L \mu S_L^C + \text{h.c.}$

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

典型的例子: Inverse Seesaw Mechanism

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

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

质量本征值: $M_{1,2} \approx M \pm \mu$

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

置换对称性

汤川相互作用的置换对称性:

$$\mathcal{L} \sim \mathcal{A} \overline{\nu}_L^a N_R + \mathcal{A} \overline{\nu}_L^\alpha S_L^C + \mathcal{M} \overline{S}_L N_R + \frac{1}{2} \mu \overline{S}_L S_L^C + \frac{1}{2} \mu \overline{N}_R^C N_R + \text{h.c.}$$

$N_R \leftrightarrow S_L^C$

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

$\theta_{12} \ll 1$

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

混合矩阵: $U = V_{23} V_{12}$

质量本征值: $M_{s_1} \approx \mathcal{M} + \mu \quad M_{s_s} \approx \mathcal{M} - \mu$

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

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

中微子与暗物质：惰性中微子暗物质

质量本征态的相互作用

A: 汤川相互作用: $\bar{S}_L \phi N_R \rightarrow -\frac{1}{2} (\phi \bar{s}_1 s_1 - \phi \bar{s}_2 s_2)$

No Yukawa interaction between s_1 and s_2 !

B: 汤川相互作用:

$$\bar{S}_L \phi S_L^C + \bar{N}_R^C \phi N_R \rightarrow \frac{1}{2} \sin 2\theta \bar{\nu}_a \phi s_1 + \frac{1}{2} \sin^2 \theta \bar{\nu}^a \phi \nu^a + \frac{1}{2} \cos^2 \theta \bar{s}_1 \phi s_1 + \bar{s}_2 \phi s_2 + \dots$$

No Yukawa interactions between s_2 and other fermions!

C: 规范相互作用:

$$\bar{S}_L \gamma^\mu S_L + \bar{N}_R \gamma^\mu N_R \rightarrow -\sin \theta \bar{\nu}_a \gamma^\mu P_L s_3 + \cos \theta \bar{s}_2 \gamma^\mu P_L s_3 + \text{h.c.}$$

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

两种情形

Scenario-I ✓

$$\begin{aligned} m_{A'} &\ll m_{s_2} < m_{s_1} \\ \Gamma(s_1 \rightarrow s_2 + A') &\approx \frac{1}{3.3 \times 10^{12} s} \left(\frac{g'}{10^{-15}} \right)^2 \frac{m_{s_1}}{10 \text{ keV}} \left(1 - \frac{m_{s_2}^4}{m_{s_1}^4} \right) \\ \Gamma(s_2 \rightarrow \nu_a + A') &\approx \frac{1}{4.2 \times 10^{22} s} \left(\frac{g'}{10^{-15}} \right)^2 \frac{m_{s_2}}{10 \text{ keV}} \left(\frac{\sin \theta}{10^{-5}} \right)^2 \end{aligned}$$

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

$$m_{s_1} > 2m_{s_2} \quad \text{and} \quad m_{s_2} + m_{A'} > m_{s_1} \quad \boxed{s_1 \rightarrow s_2 + s_2 + \nu_a}$$

中微子与暗物质：惰性中微子暗物质

暗物质丰度

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

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

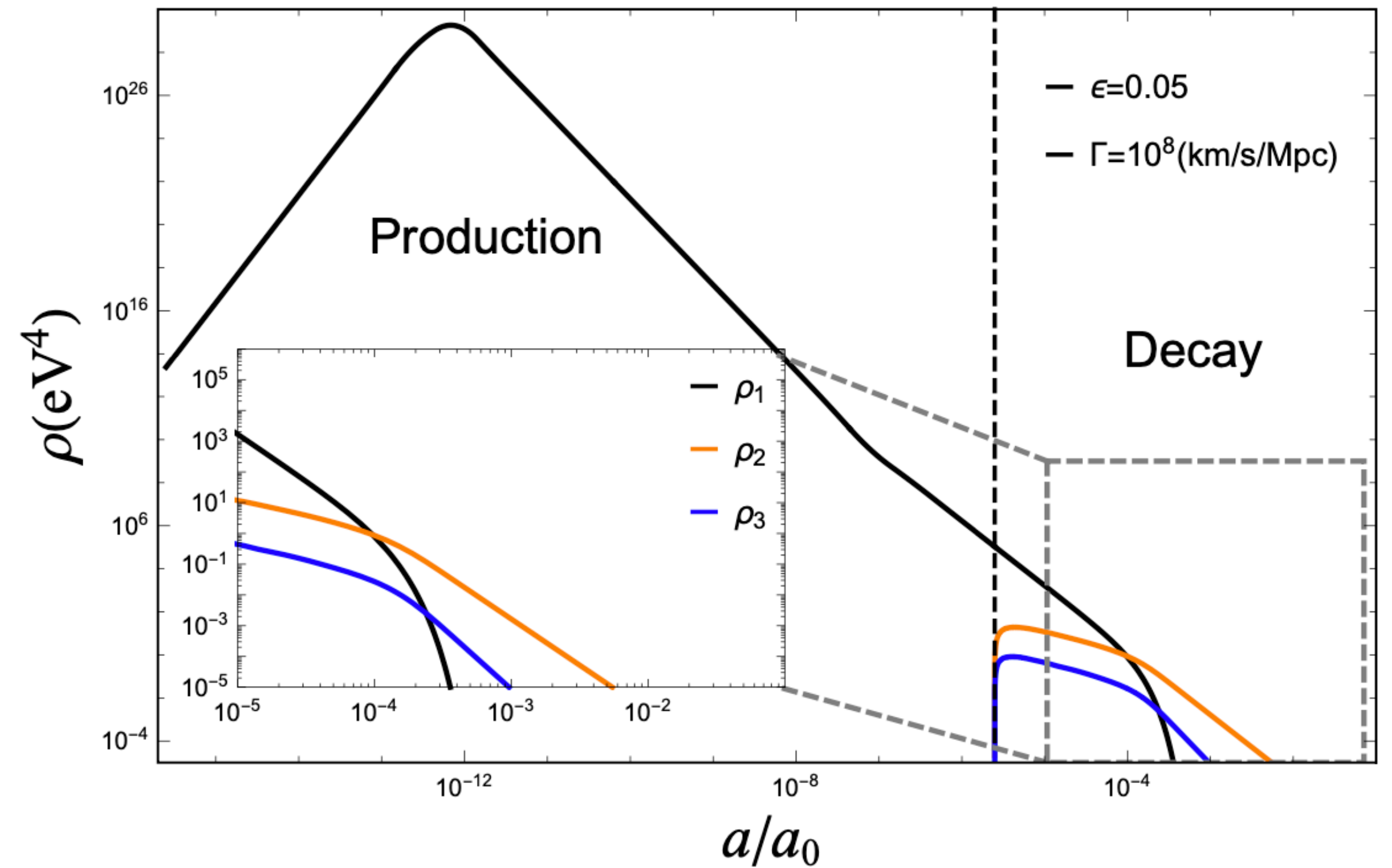
- S_1 then decay into s_2 , which is the dark matter candidate

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

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

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

能量密度示意图



中微子与暗物质：惰性中微子暗物质

可能的信号

- X-ray ? : $\times$

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: $\times$

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 new interaction is very weak.

- The effective number of neutrinos: $\checkmark$

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

有效中微子代数作为间接探测信号!



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 $s_1 \rightarrow s_2 + A'$ may increase the N_{eff}

$$\begin{aligned} \dot{\rho}_{A'} + 4H\rho_{A'} &\approx \frac{1}{2} \left(1 - \frac{m_2^2}{m_1^2} \right) \rho_{s_1} \Gamma(s_1 \rightarrow s_2 A') \\ \frac{dT_\gamma}{dt} &= -HT_\gamma \end{aligned} \quad \rightarrow \quad \Delta N_{\text{eff}}^{\text{CMB}} = \frac{8}{7} \left(\frac{11}{4} \right)^{4/3} \frac{\rho_{A'}}{\rho_\gamma}$$

中微子与暗物质：惰性中微子暗物质

有效中微子代数

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

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

According to the chain role:

$$\frac{dT_\nu}{dt} = -4Ht + \frac{\mathcal{C}_{\nu_e} + 2\mathcal{C}_{\nu_\mu}}{12\rho_\nu/T_\nu}$$
$$\frac{dT_\gamma}{dt} = -\frac{4H\rho_\gamma + 3H(\rho_e + P_e) + \mathcal{C}_{\nu_e} + 2\mathcal{C}_{\nu_\mu} + 3HT_\gamma dP_{intt}/dT_\gamma}{\partial\rho_\gamma/\partial T + \partial\rho_e/\partial T + Td^2P_{int}/dT^2}$$

物理图像与实验限制



$$T_{\nu_e}^{dec} = 1.50 \text{ MeV} \quad T_{\nu_{\mu,\tau}}^{dec} = 2.48 \text{ MeV}$$

Constraints, PDG

	Model	95%CL	Ref.
CMB alone			
Pl18[TT,TE,EE+lowE]	Λ CDM+ N_{eff}	$2.92^{+0.36}_{-0.37}$	[34]
CMB + background evolution + LSS			
Pl18[TT,TE,EE+lowE+lensing] + BAO	Λ CDM+ N_{eff}	$2.99^{+0.34}_{-0.33}$	[34]
” + BAO + R18	Λ CDM+ N_{eff}	3.27 ± 0.15 (68%CL)	[39]
” +5-params.	” +5-params.	2.85 ± 0.23 (68%CL)	[38]

中微子与暗物质：惰性中微子暗物质

新物理的贡献

$$\sum_i \rho_{\nu_i} + \rho'_R = N_{eff} \left(\frac{7}{8} \frac{\pi^2}{15} T_\nu^4 \right) = (3.046 + \Delta N_{eff}) \rho_\nu^0$$

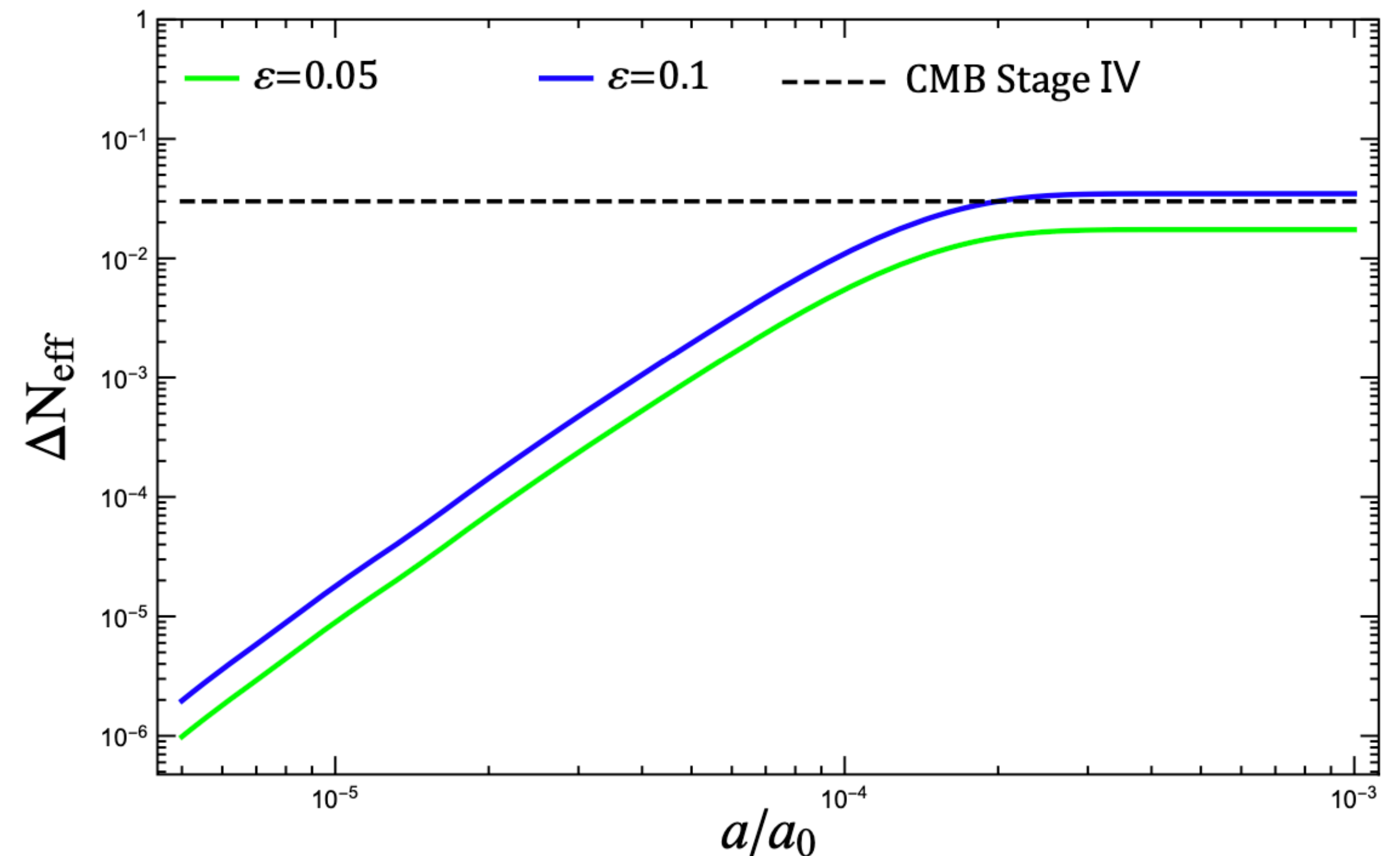
ρ_{ν_i} : **SM neutrinos**

ρ'_R : **Other relativistic energy densities**

$$\rho_R = \rho_\gamma + \rho_\nu + \rho'_R \quad \rightarrow$$

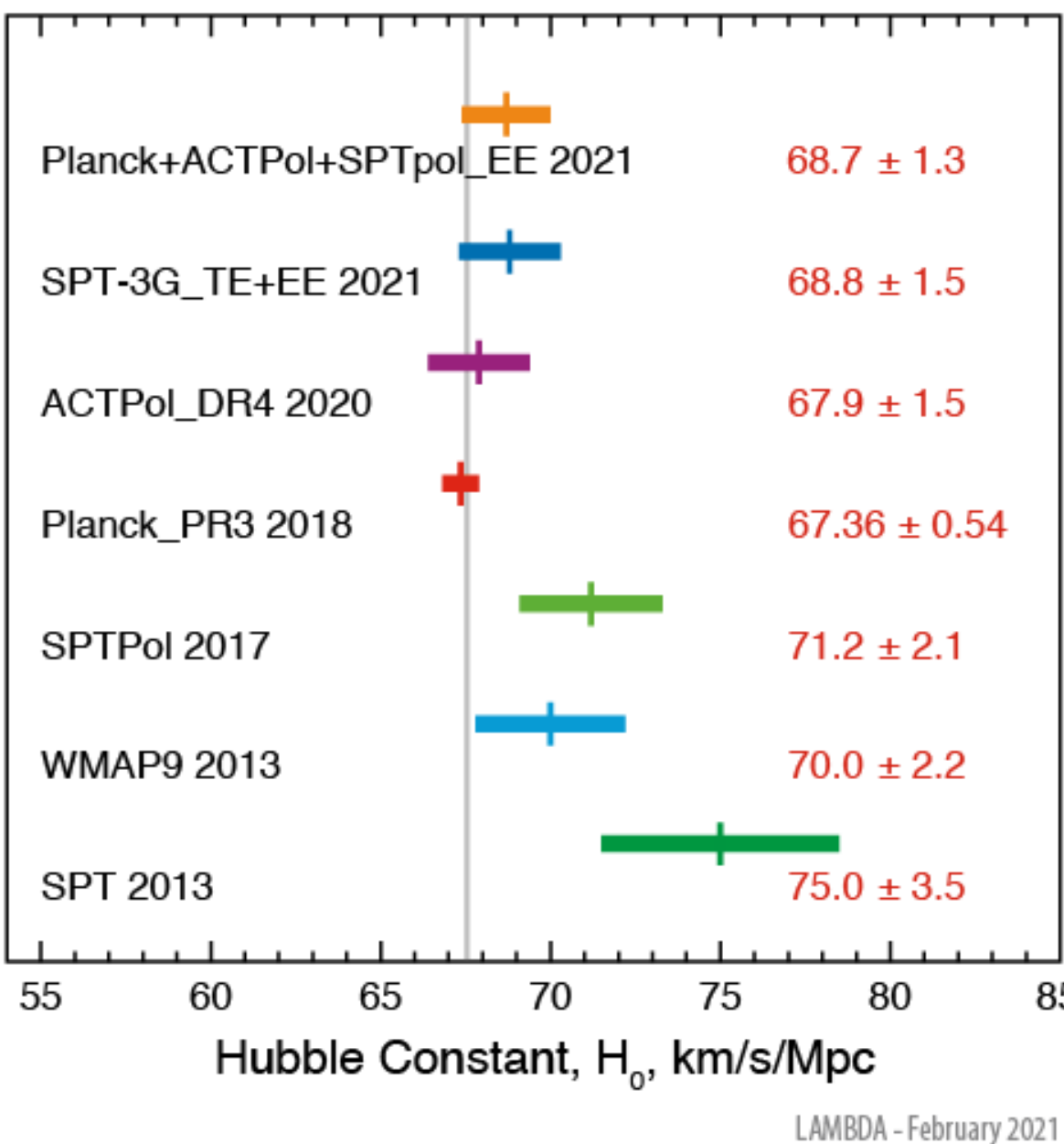
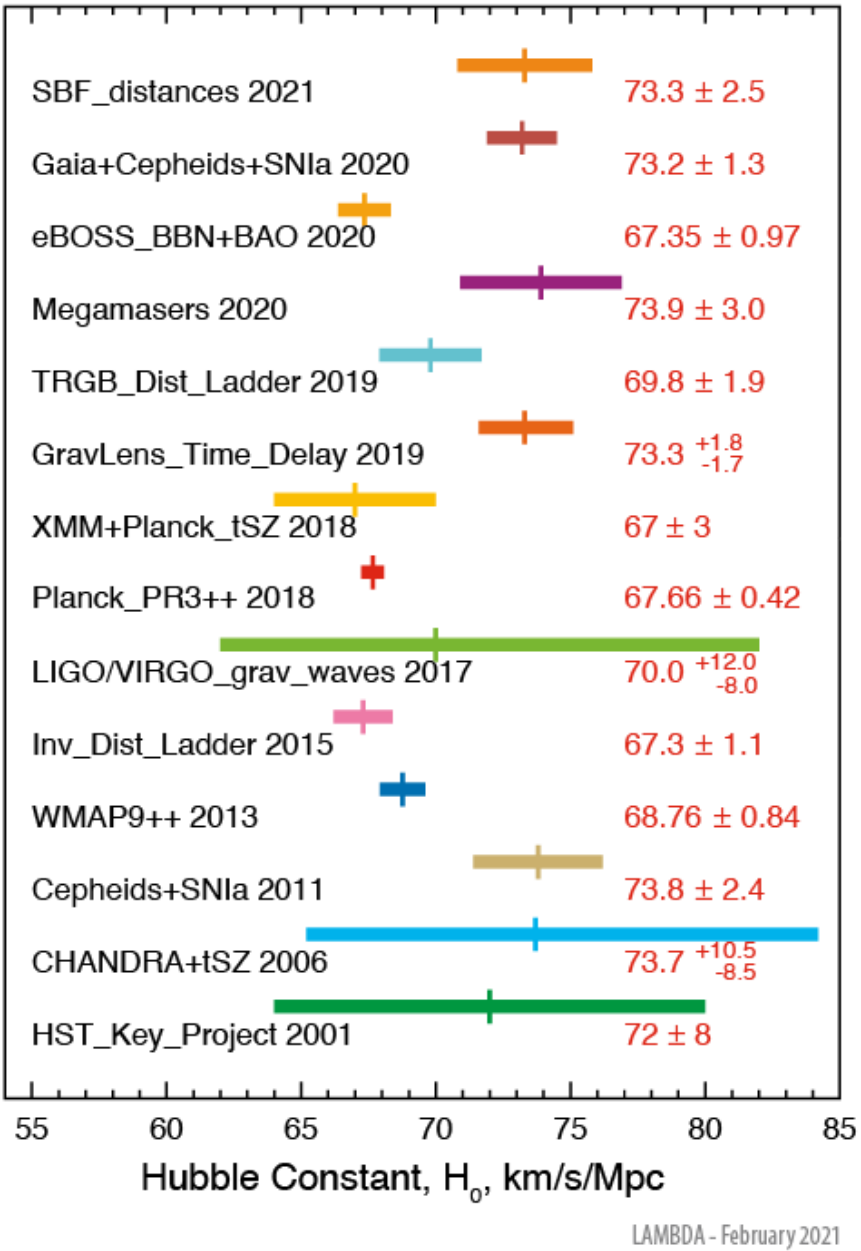
Effective numbers of neutrinos at CMB is a signal of new physics beyond the SM! (CMB stage IV: $\Delta N_{eff} = 0.03$)

赝狄拉克惰性中微子的贡献



中微子与暗物质：惰性中微子暗物质

哈勃冲突



粒子物理的解决方案

- ✓ 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

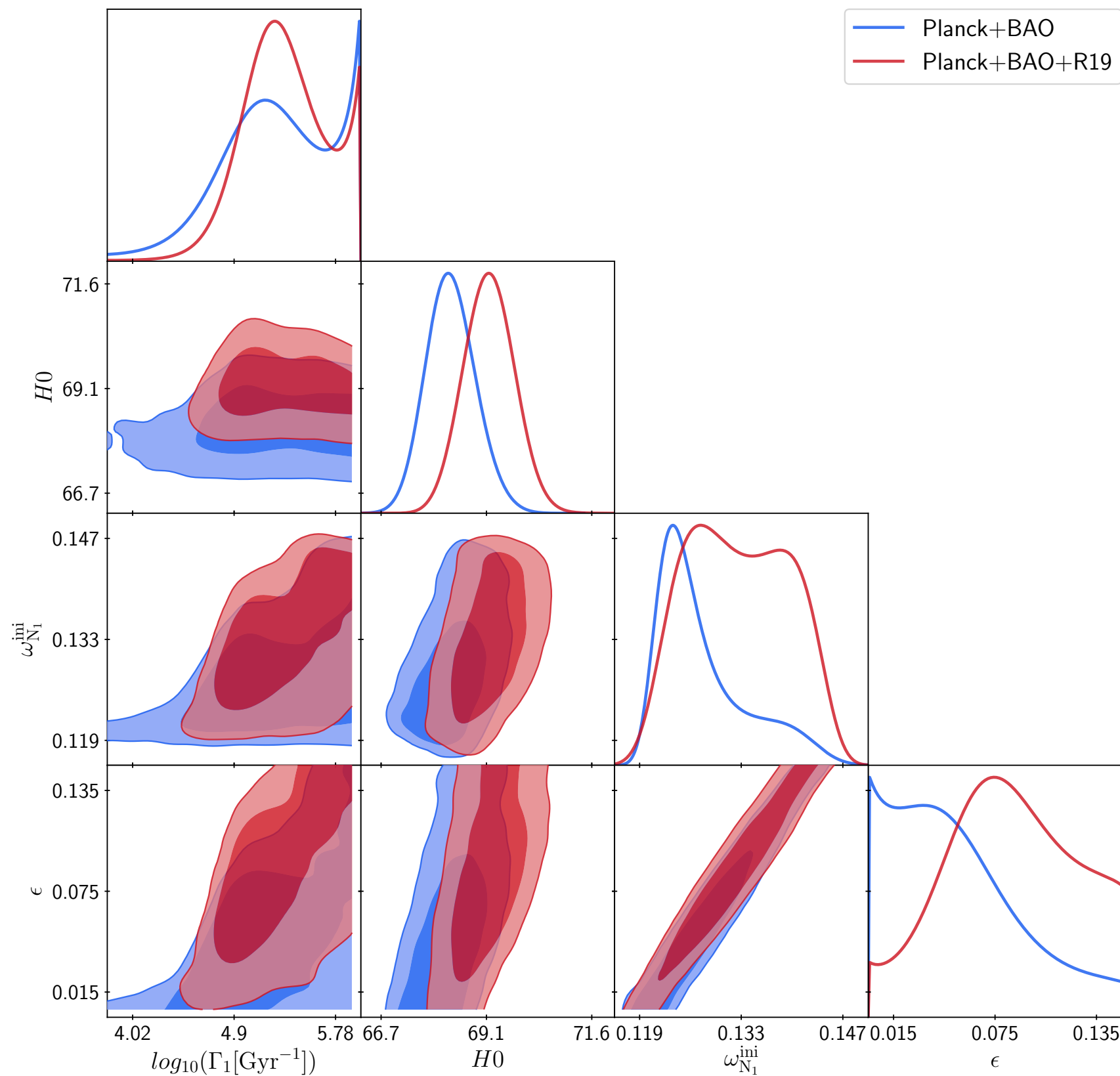
$$H_0 = (73.24 \pm 1.74) \text{ km s}^{-1} \text{ Mpc}^{-1} \text{ VS } H_0 = (67.27 \pm 0.66) \text{ km s}^{-1} \text{ Mpc}^{-1}$$

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

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

中微子与暗物质：惰性中微子暗物质

Class+MontePython



参数

Param	Λ CDM Planck+BAO mean $\pm\sigma$	DNDM Planck+BAO mean $\pm\sigma$	DNDM Planck+BAO+R19 mean $\pm\sigma$
$100\ \omega_b$	$2.242^{+0.013}_{-0.014}$	$2.241^{+0.016}_{-0.016}$	$2.258^{+0.015}_{-0.015}$
$\log_{10}(\Gamma_1)$	-	>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	$0.9664^{+0.0039}_{-0.004}$	$0.973^{+0.0053}_{-0.0076}$	$0.9805^{+0.0064}_{-0.0086}$
τ_{reio}	$0.05718^{+0.0072}_{-0.0076}$	$0.05774^{+0.0068}_{-0.008}$	$0.06155^{+0.0072}_{-0.0083}$
$\omega_{N_1}^{ini}$	$0.1194^{+0.00098}_{-0.00099}$	$0.1278^{+0.0032}_{-0.0086}$	$0.1329^{+0.0071}_{-0.0076}$
ϵ	-	<0.06889	$0.09233^{+0.04}_{-0.048}$
σ_8	$0.8104^{+0.0063}_{-0.0062}$	$0.8189^{+0.0077}_{-0.01}$	$0.8243^{+0.0096}_{-0.012}$

$-\ln L_{\min} = 1412.44, \text{ minimum } \chi^2 = 2825$

总结与下一步的工作计划

- 本年度的研究成果比较集中于自由探索研究了以下几个方面：
 1. 超轻暗物质的电磁波探测手段；
 2. 超轻暗物质的超导体探测手段
 3. 传统轻暗物质模型的问题解决
 4. 轻暗物质的宇宙学信号
- 总结（**BNU**部分）
 - 工作集中于暗物质的自由探索，希望能做出实验有实质贡献的工作；
 - 与实验组的有效交流尚待加强；
- 下一步 的工作计划（**BNU**部分）
 - 加强与**CDEX**实验组的交流、讨论与实质性的合作；
 - 针对加速性**MeV**质量区间暗物质以及中微子非标准相互作用在**CDEX**实验中的信号进行研究；
 - 对**Ge**晶体的可能声子信号进行探索；
 -

**Thank You for
Your Attention!**