Dark Sector Effective Field Theory

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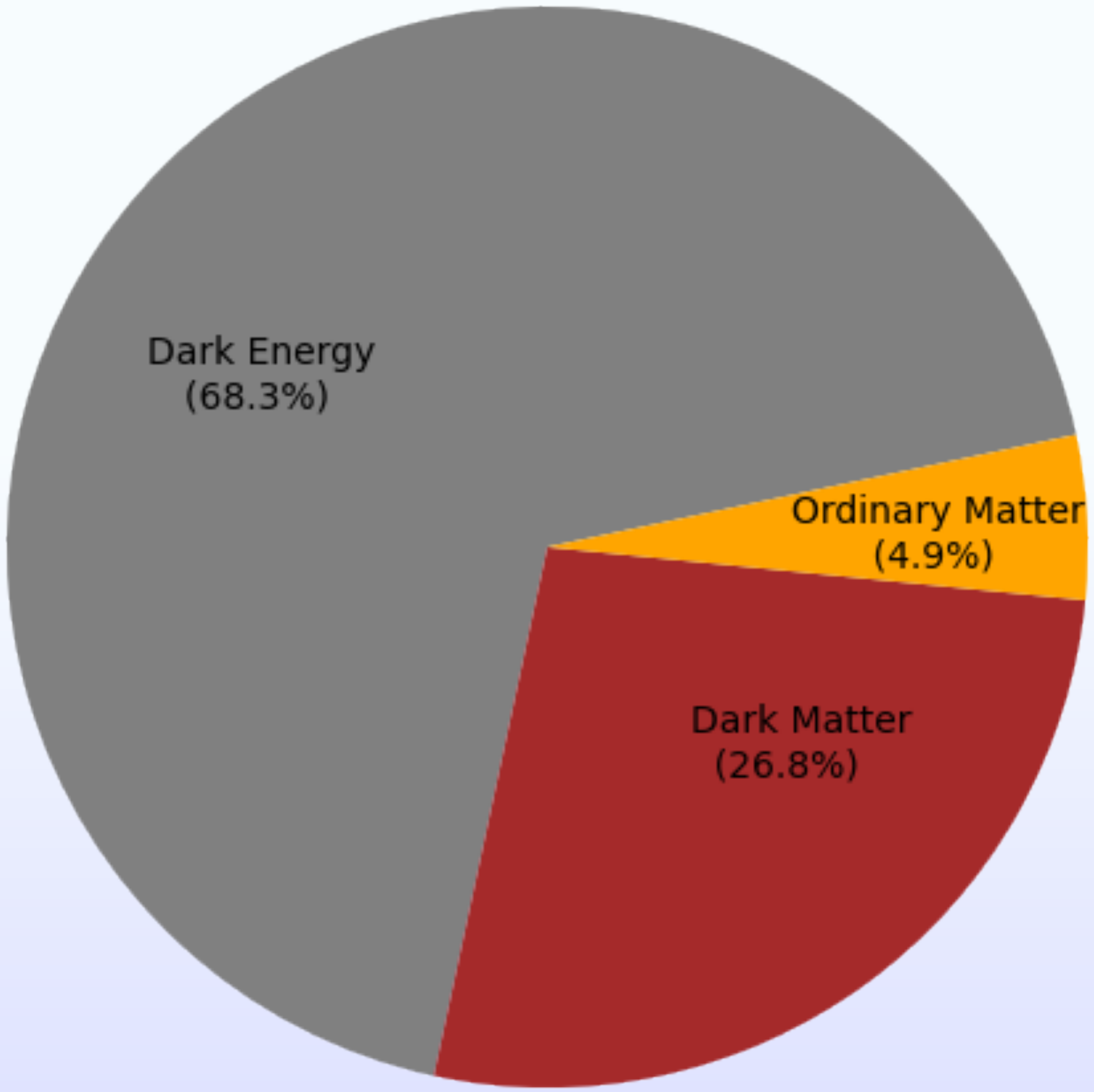
Based on the recent work：Jin-Han Liang, Yi Liao, XDM, Hao-Lin Wang, 2309.12166

Outline

- Introduction
- Dark sector effective field theory (DSEFT)
- Phenomenologies
- Summary

Evidence of the DM



- Galaxy rotation curves
- Gravitational lensing
- Bullet Cluster
- CMB power spectrum
- Structure formation
- N-body simulation
- ...

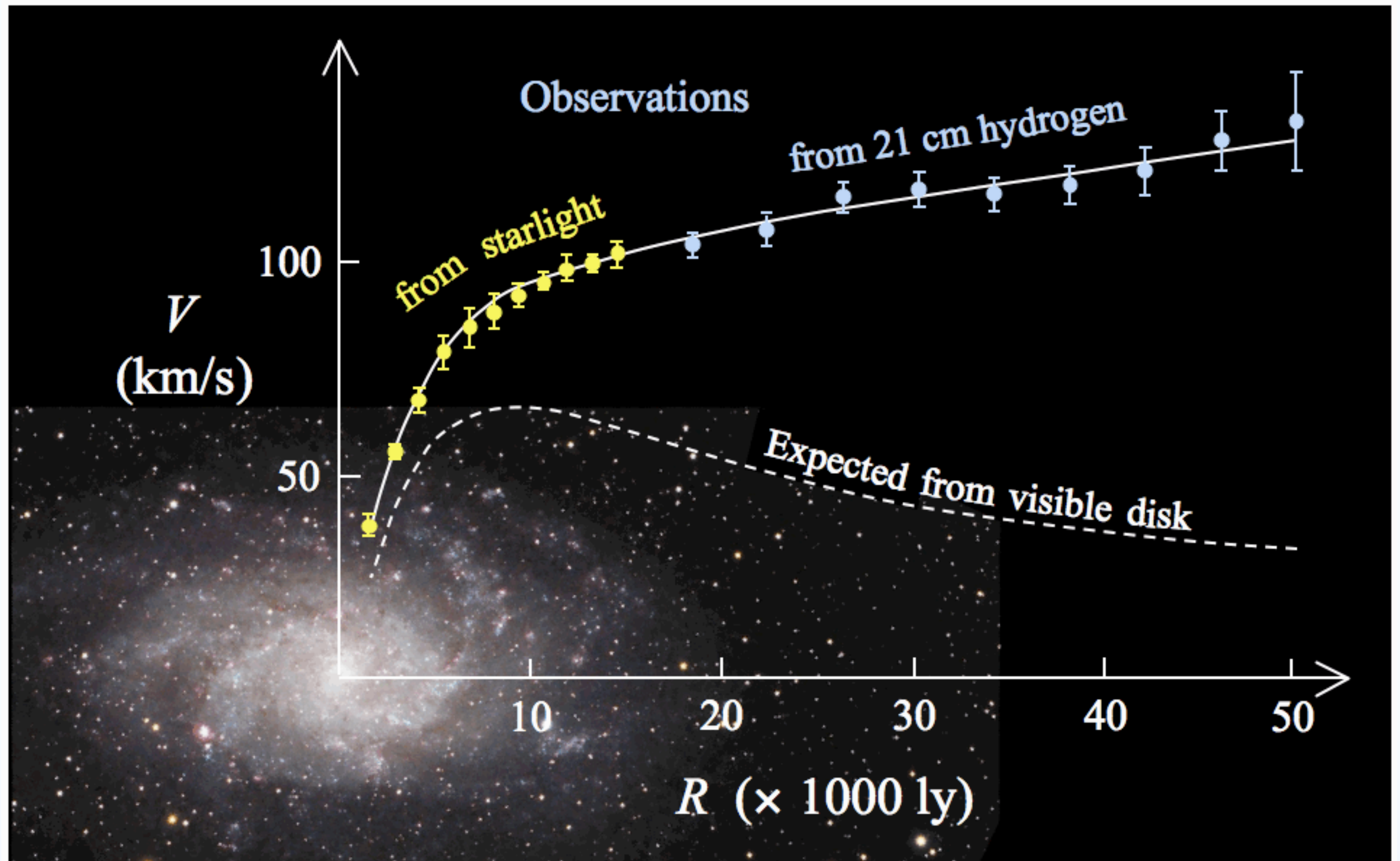
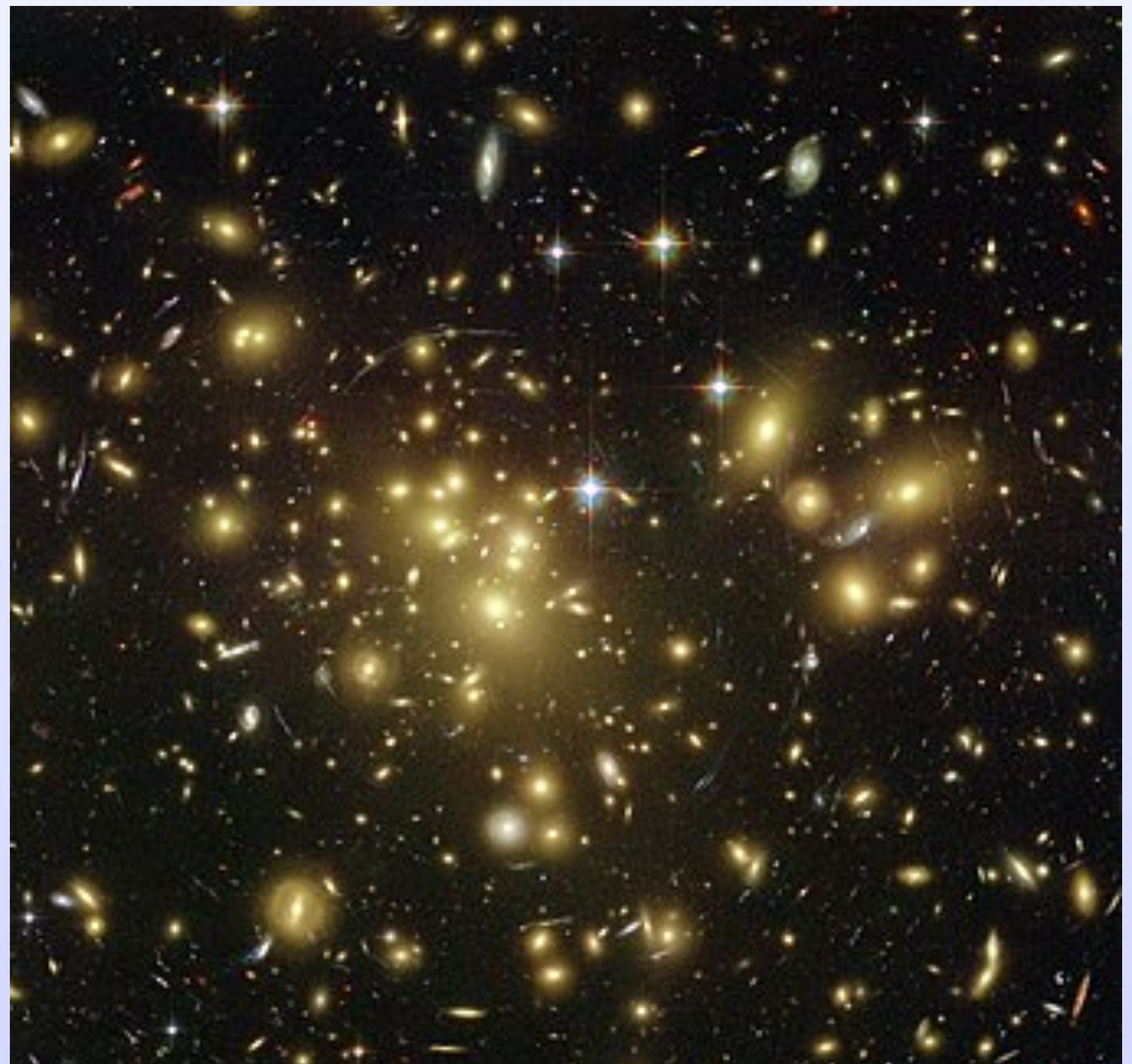


Image credit: Wikimedia Commons user Stefania.deluca


https://en.wikipedia.org/wiki/Dark_matter

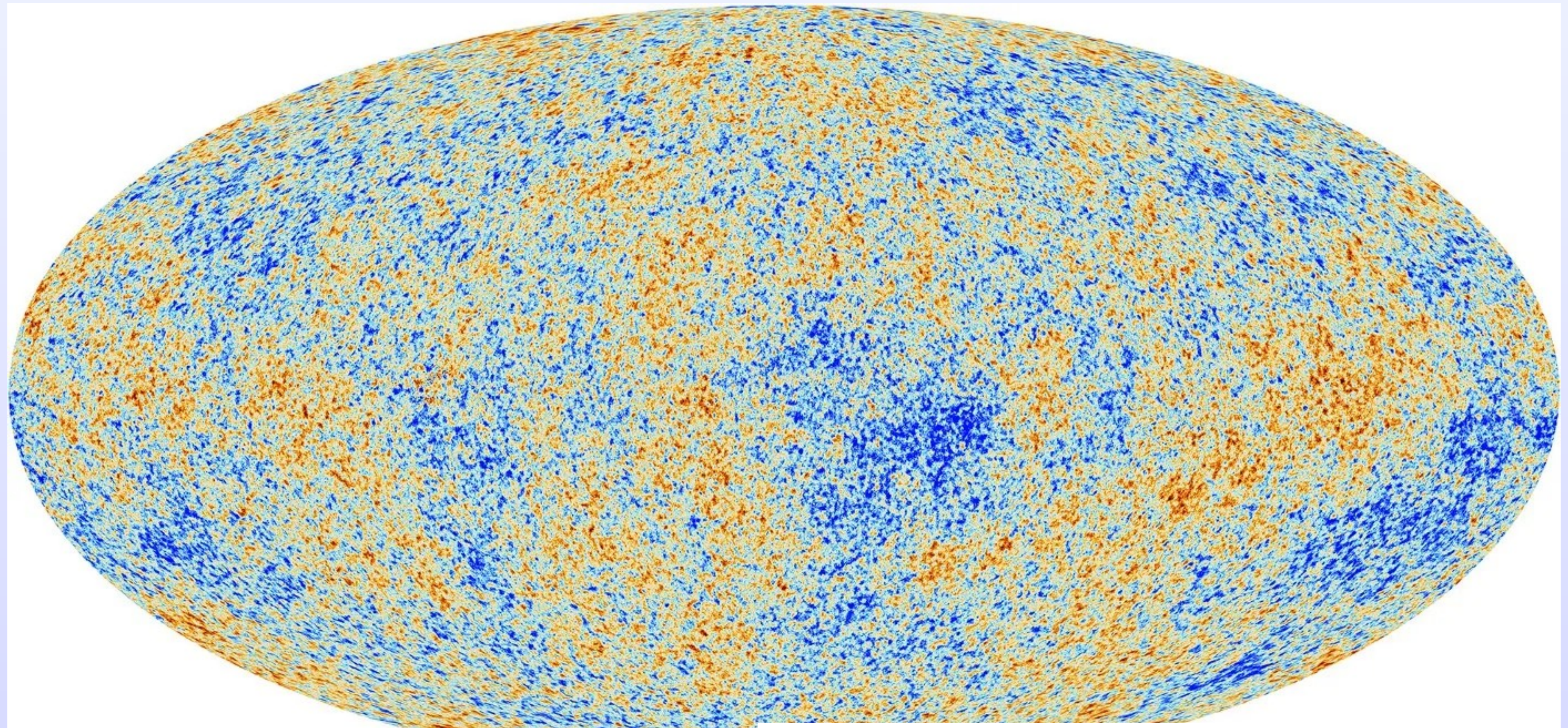
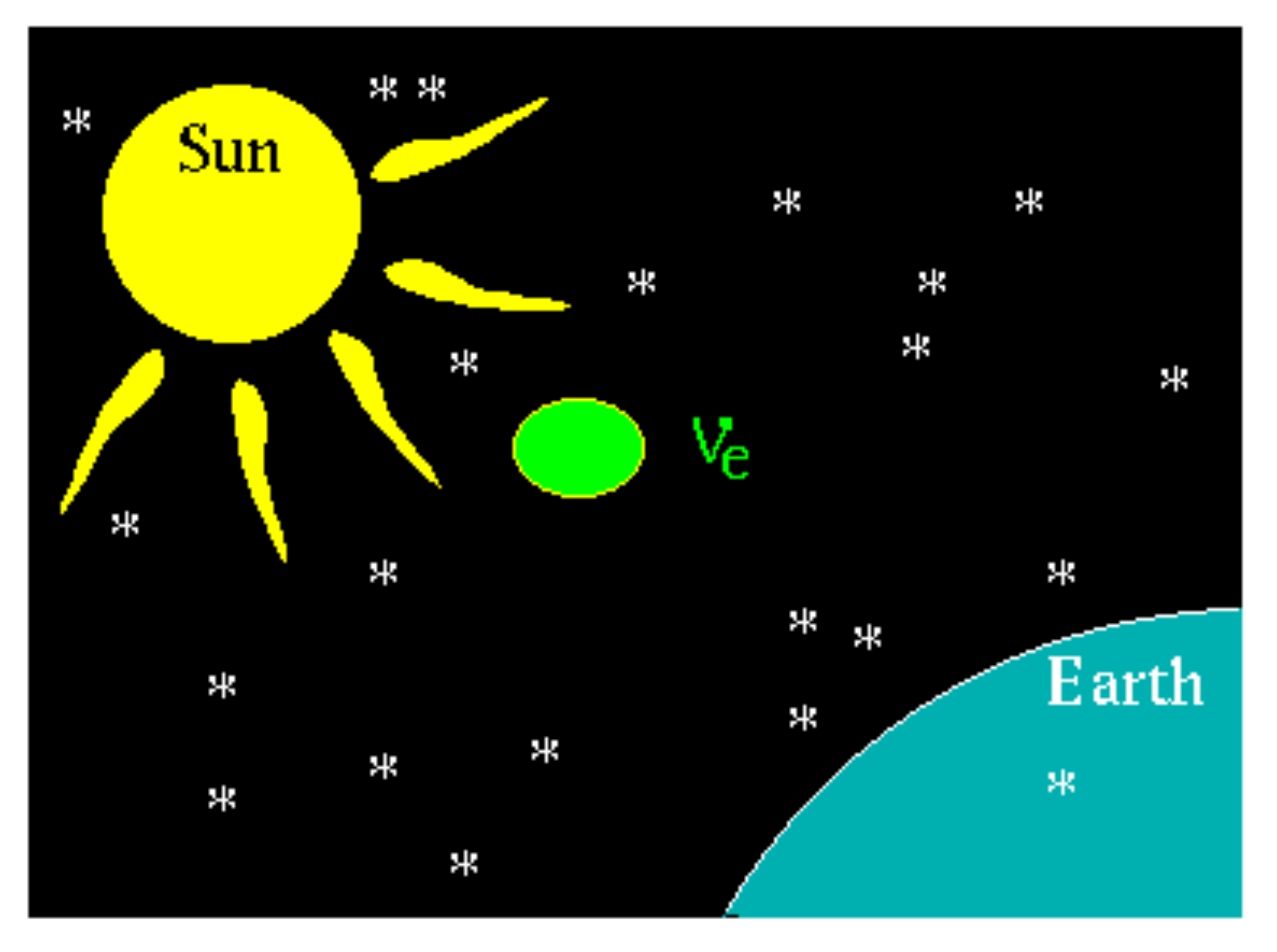


Image credit: ESA and the Planck Collaboration

Other beyond SM physics facts

- Neutrino oscillation => neutrino mass
- Dark energy
- Baryon asymmetry of the Universe
- Anomalies： τ_{neutron}, CDF m_W , muon $g-2$, …

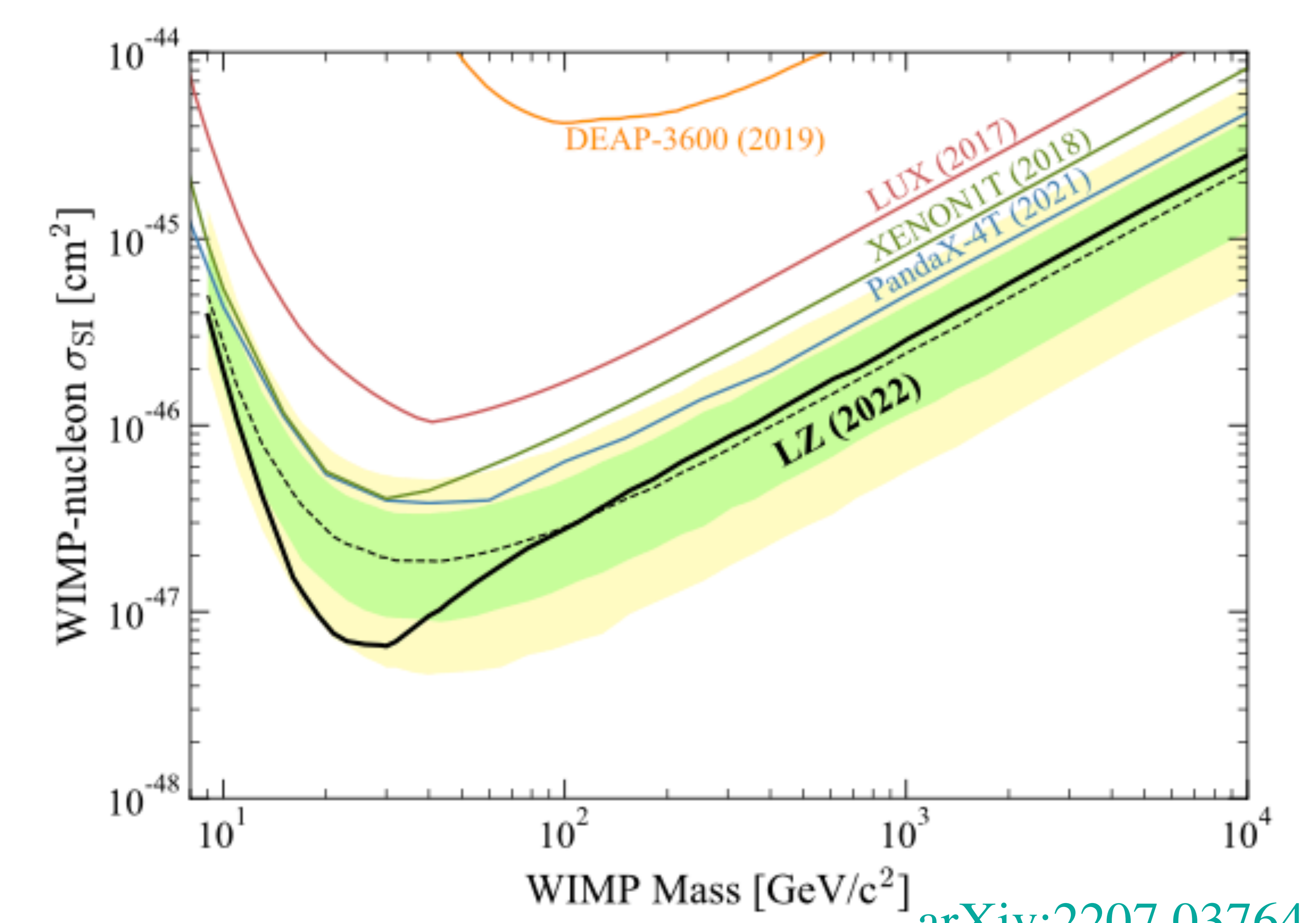


https://lappweb.in2p3.fr/neutrinos/aoscillanim.html

- Strong CP problem
- Higgs hierarchy
- Cosmological constant
- Quantum gravity
- ……

BSM New Physics

Why dark sector?



arXiv:2207.03764

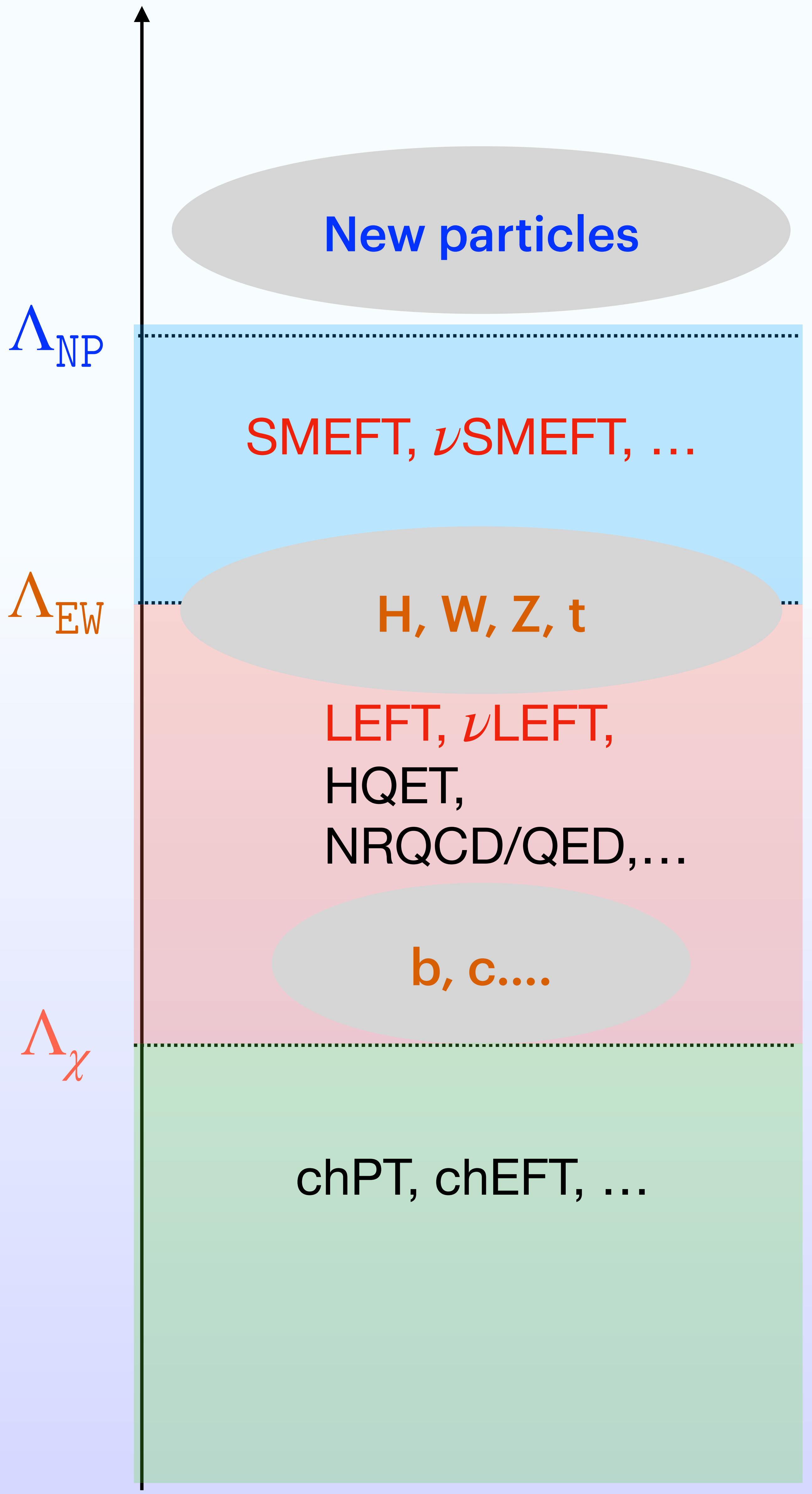
- DM abundance $\approx$ 4 $\times$ SM contribution;
- Strong constraints on heavy dark matter particles;
- Light DM are more viable, usually accompanied by other light degrees of freedom.

Bottom-up approach — EFT

Most processes searching for DM effects are at low energy, far below the EW scale: DM (in-) direct detection

EFT framework

Merit: Model independent study of NP effects for low energy observables



The ingredients of the DSEFT

- **LEFT framework with symmetry:** $\mathtt{SU(3)_c} \times \mathtt{U(1)_{em}}$

- **SM Fields:** $\Psi = \{u,\ d, s,\ c,\ b;\ \ e,\ \mu,\ \tau\};\ \ \nu_L = \{\nu_{eL},\ \nu_{\mu L}, \nu_{\tau L}\};\ \ F,\ G$

- **New light ones:**

$$\mathtt{scalar}: \phi,\ S; \quad \mathtt{fermion}: \chi,\ \psi; \quad \mathtt{vector}: X,\ V$$

- **Power counting: canonical dimension** d

- **Range:** $E \ll \Lambda_{\mathrm{EW}}$

SM+ a single particle

- SM + scalar: ALPEFT = SM+ axion-like particle
- SM + fermion: nuSMEFT = SM + sterile neutrino
- SM + vector: dark photon EFT = SM + dark photon
- DMEFT: DM + a stable Z_2 DM particle (spin-0, 1/2, 1, 3/2)

SM+ two different particles

(1) scalar-scalar-SM ($\phi - S-$SM);

(2) fermion-fermion-SM ($\chi - \psi-$SM);

(3) vector-vector-SM ($X - V-$SM);

(4) scalar-fermion-SM ($\phi - \chi-$SM);

(5) scalar-vector-SM ($\phi - X-$SM);

(6) fermion-vector-SM ($\chi - X-$SM).

Our work
2309.12166

SMEFT framework:

Y. Liao, XDM, 1612.04527, J.-H. Yu et al, 2105.09329

I. Brivio et al, 1701.05379
J. Brod et a;, 1710.10218

J. C. Criado et al, 2104.14443

J. Aebischer et al, 2202.06968
H. Song, H. Sun, J.-H. Yu , 2305.16770, 2306.05999.
Grojean, J. Kley, Y. Yao, 2307.08563.

LEFT framework:

M. Bauer et al, 2012.12272

R. Harnik, G. D. Kribs, 0810.5557

J. Fan, M. Reece, L.-T. Wang, 1008.1591]

E. Del Nobile, F. Sannino, 1102.3116]

R. Ding, Y. Liao, 1201.0506

J. Kumar, D. Marfatia , 1305.1611]

T. Alanne, F. Goertz. 1712.07626

C. Arina, J. Hajer, P. Klos , 2105.06477

X-G. He, XDM, G. Valencia, 2209.05223

With the light one as DM candidate

Techniques to reach the non-redundant operators

- **Integration by parts(IBP)**: $0 \stackrel{!}{=} D(\mathcal{Q}_1\mathcal{O}_2) = D(\mathcal{Q}_1)\mathcal{O}_2(\checkmark) + \mathcal{Q}_1 D(\mathcal{O}_2)(\times), \cdots$
- **Equation of motion(EoM) & Field redefinition**: $iD_\mu\gamma^\mu Q(\times) = Y_u u\tilde{H}(\checkmark) + Y_d dH(\checkmark), \cdots$
- **Fierz identity(FI)**: rearrangement of the fermion bilinears:

$$(\overline{\Psi_{1L}}\Psi_{2R})(\overline{\Psi^C_{3R}}\Psi_{4R}) = -(\overline{\Psi_{1L}}\Psi_{3R})(\overline{\Psi^C_{4R}}\Psi_{2R}) - (\overline{\Psi_{1L}}\Psi_{4R})(\overline{\Psi^C_{2R}}\Psi_{3R}), \cdots$$

- **Group identity (GI)**: $\left(T^A\right)_{ab}\left(T^A\right)_{cd} = \frac{1}{2}\delta_{ad}\delta_{bc} - \frac{1}{2N}\delta_{ab}\delta_{cd}, \ \cdots$
- **Schouten identity (SI)**: $\epsilon_{ij}\epsilon_{kl} = \epsilon_{il}\epsilon_{kj} - \epsilon_{ik}\epsilon_{lj}, \cdots$
- **Dirac gamma matrix(DG)**: $\sigma_{\mu\nu}P_\pm = \mp\frac{1}{2}i\epsilon_{\mu\nu\rho\sigma}\sigma^{\rho\sigma}P_\pm, \cdots$
- **Bianchi identity (BI)**: $D_\nu\tilde{X}^{\mu\nu} = 0.$

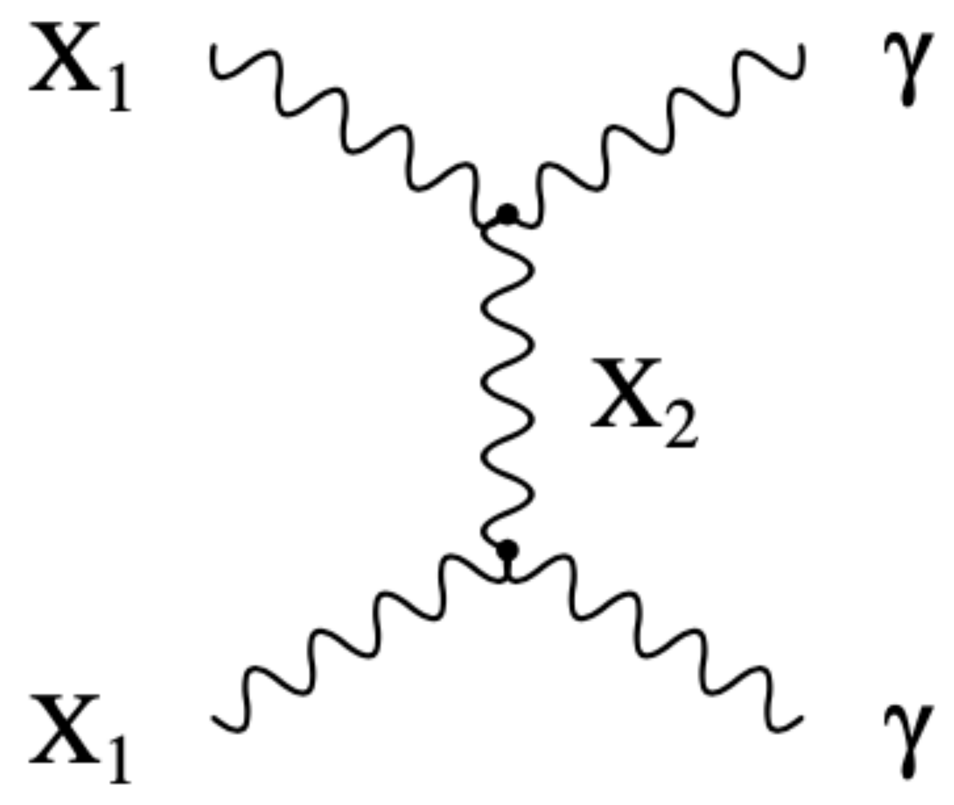
Classification of all DSEFT operators

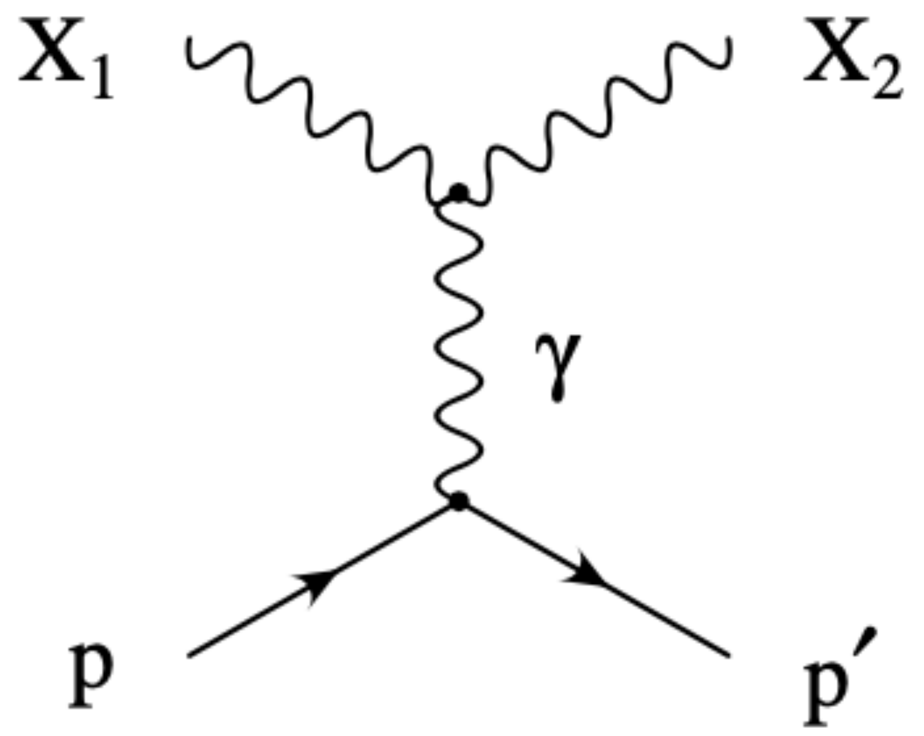
Dimension	scalar-scalar-SM	fermion-fermion-SM	vector-vector-SM	scalar-fermion-SM	scalar-vector-SM	fermion-vector-SM
Dim 4	—	—	FXV	$(\overline{\nu_L}\chi)\phi + \mathrm{h.c.}$	—	$(\overline{\nu_L}\chi)X + \mathrm{h.c.}$
Dim 5	$(\overline{\Psi}\Psi)\phi S$	$(\bar{\chi}\psi)F$	$(\overline{\Psi}\Psi)XV$	—	$FX\phi D$ $(\overline{\Psi}\Psi)X\phi$	$(\overline{\nu_L}\chi)XD + \mathrm{h.c.}$
Dim 6	$(\overline{\Psi}\Psi)\phi SD$	$(\bar{\chi}\psi)(\overline{\Psi}\Psi)$	$FXVD^2$ F^2XV, G^2XV $(\overline{\Psi}\Psi)XVD$	$(\overline{\nu_L}\chi)\phi F + \mathrm{h.c.}$	$(\overline{\Psi}\Psi)X\phi D$	$(\overline{\nu_L}\chi)XF + \mathrm{h.c.}$
Dim 7	$(\overline{\Psi}\Psi)\phi SF$ $(\overline{\Psi}\Psi)\phi SG$ $(\overline{\Psi}\Psi)\phi SD^2$	$(\bar{\chi}\psi)F^2$ $(\bar{\chi}\psi)G^2$ $(\bar{\chi}\psi)(\overline{\Psi}\Psi)D$	$(\overline{\Psi}\Psi)XVD^2$ $(\overline{\Psi}\Psi)FXV$ $(\overline{\Psi}\Psi)GXV$	$(\overline{\nu_L}\chi)\phi FD$ $(\overline{\Psi}\Psi)(\overline{\nu_L}\chi)\phi$ $(\bar{d}u)(\bar{\chi}\ell)\phi$ $(\bar{d}u)(\bar{\chi}\ell)\phi$ $+\mathrm{h.c.}$	$X\phi F^2D, X\phi G^2D$ $(\overline{\Psi}\Psi)FX\phi, (\overline{\Psi}\Psi)GX\phi$ $(\overline{\Psi}\Psi)X\phi D^2$	$(\overline{\nu_L}\chi)XFD$ $(\overline{\Psi}\Psi)(\overline{\nu_L}\chi)X$ $(\bar{\chi}\ell)(\bar{d}u)X$ $(\bar{\chi}u)(dd)X$ $+\mathrm{h.c.}$

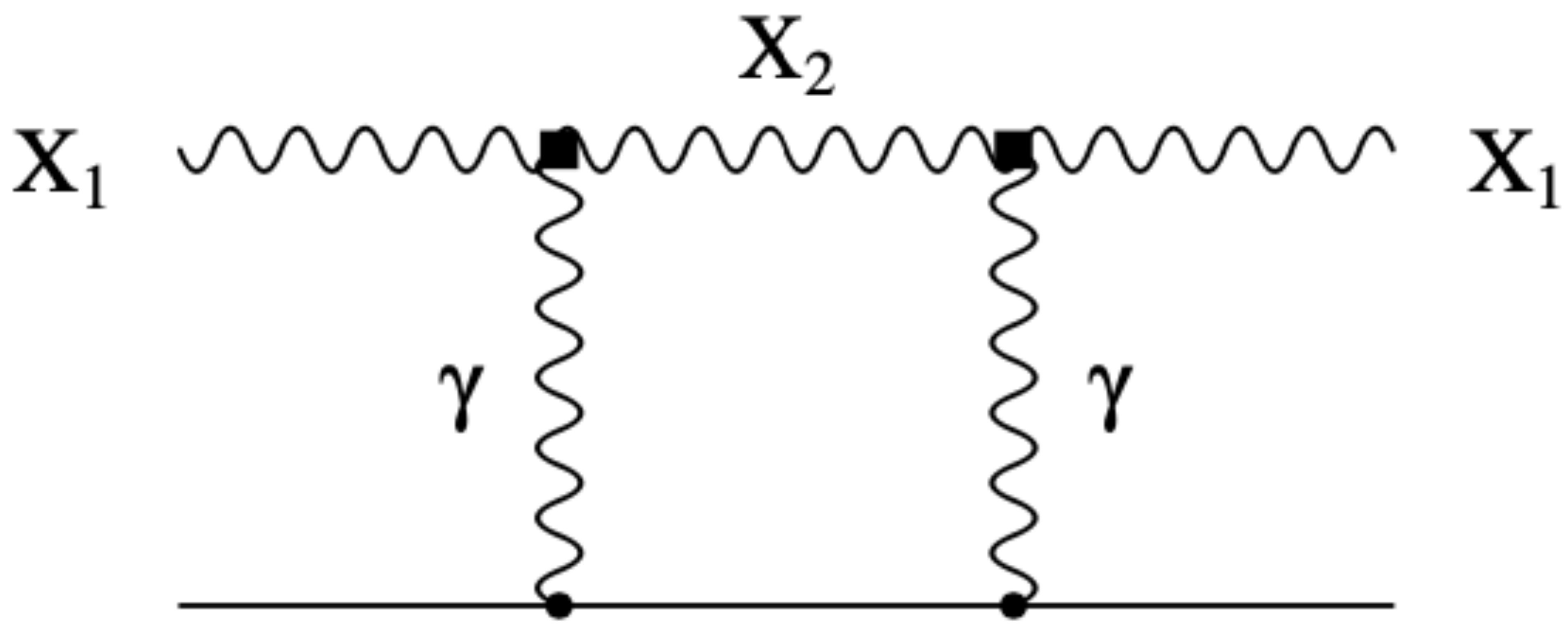
Phenomenologies

Exotic vector DM interaction

$$F^{\mu}{}_{\nu} X_{\mu\rho} V^{\nu\rho}, \quad \tilde{F}^{\mu}{}_{\nu} X_{\mu\rho} V^{\nu\rho}$$

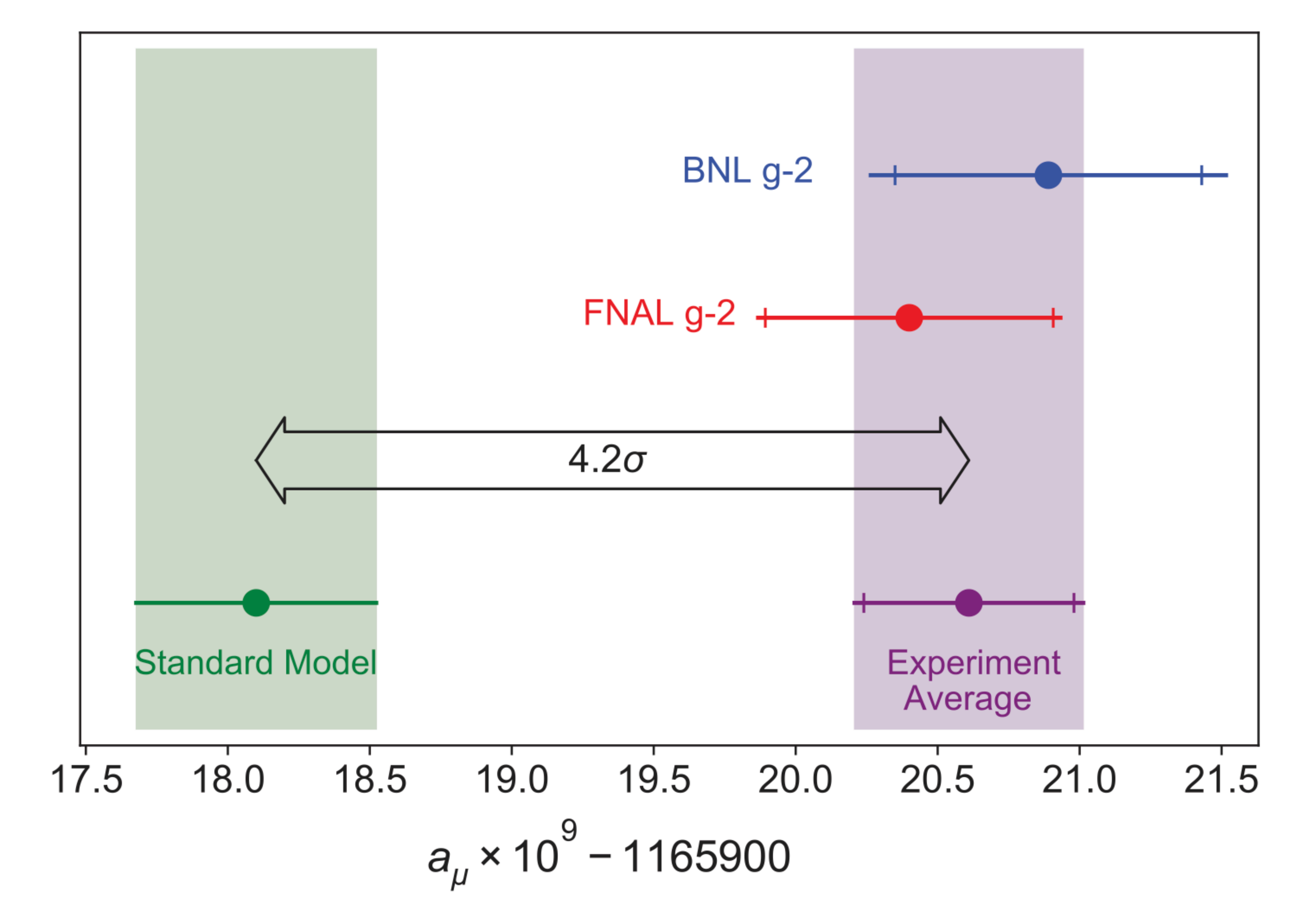






J. Aebischer et al, 2202.06968

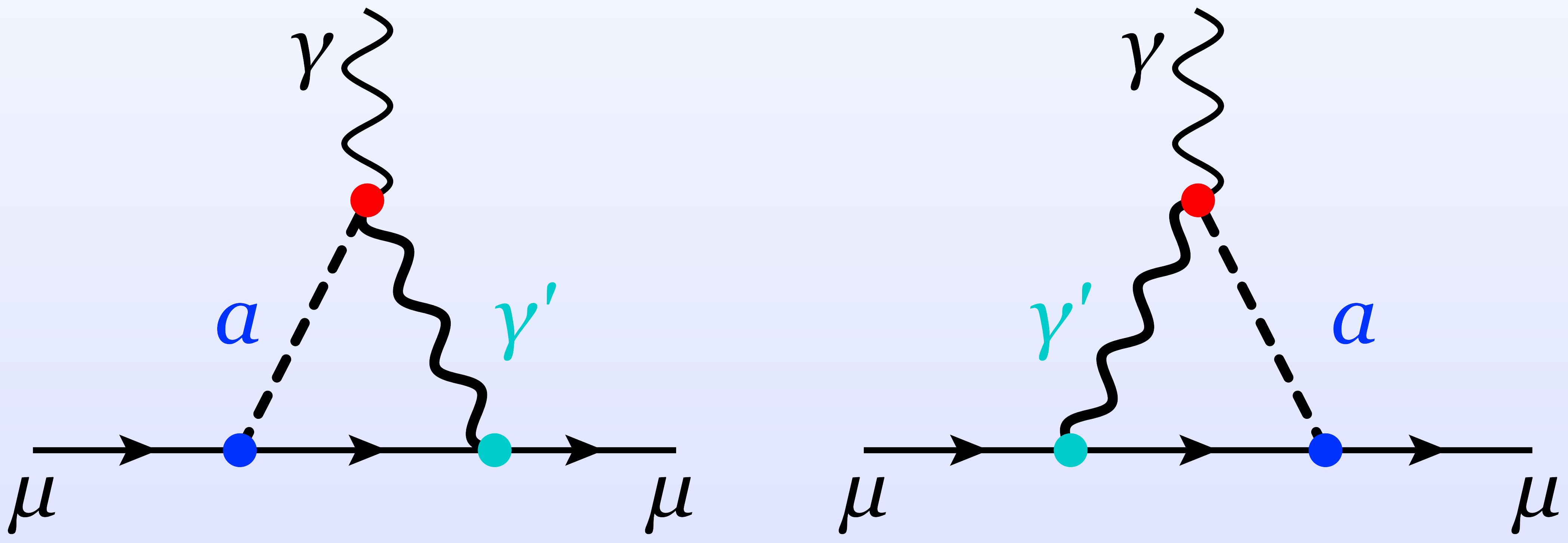
Dark axion portal to explain the Δa_μ



https://journals.aps.org/prl/pdf/10.1103/PhysRevLett.126.141801

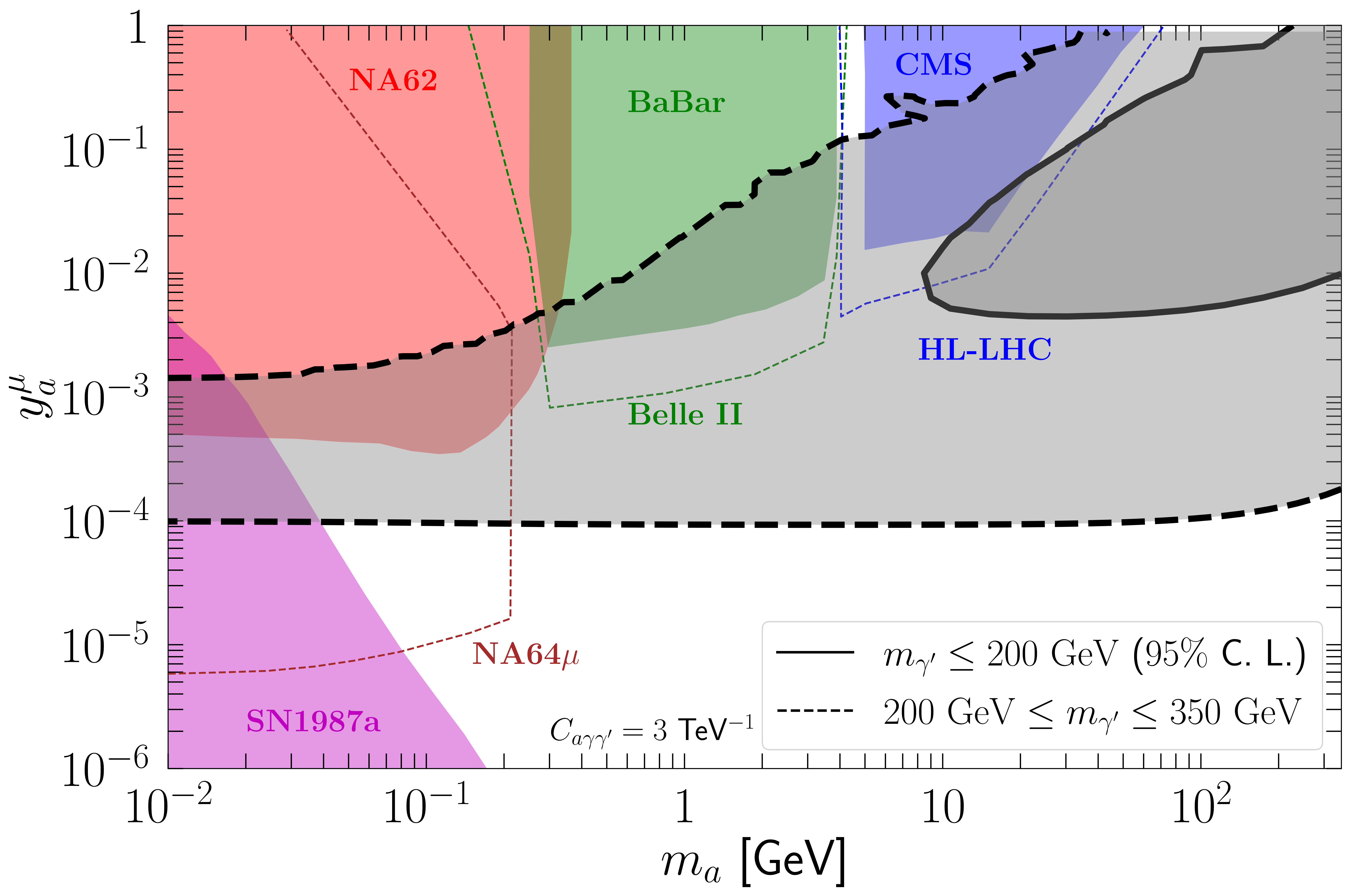
$\boxed{aF^{\mu\nu}\widetilde{X}_{\mu\nu}}$ → dark photon γ'

ALP: axion-like particle **photon** γ



$$\mathscr{L} \ni y_a^\mu a\bar{\mu}\left(i\gamma_5\right)\mu - \epsilon e\bar{\mu}\gamma^\nu\mu X_\nu$$

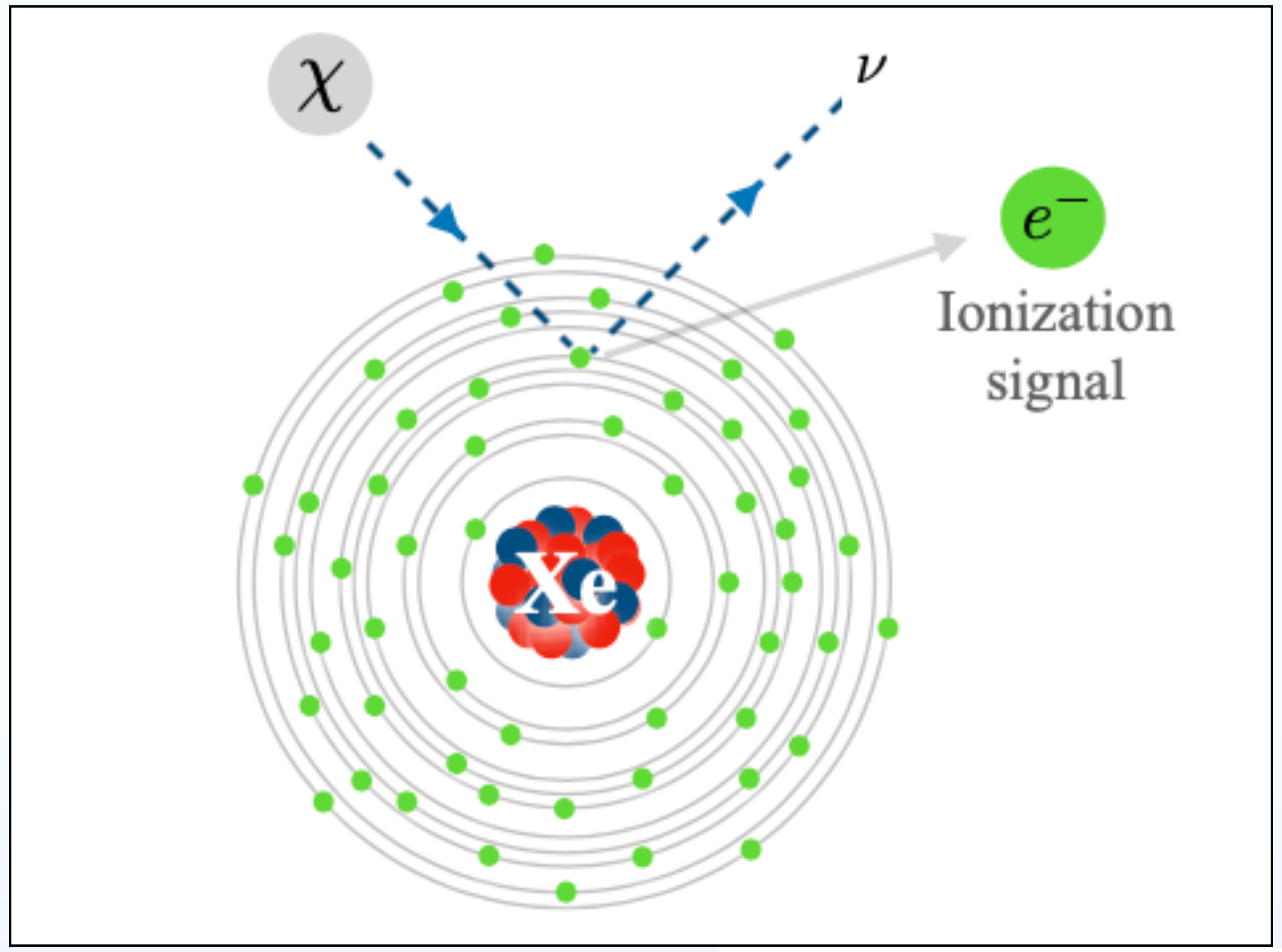
Shao-Feng Ge, XDM, Pedro Pasquini, 2104.03276



The dark axion portal can surprisingly save the ALP and dark photon for explaining the muon anomalous magnetic moment.

Fermionic absorption DM on electron or nuclear target

$$(\bar{e}\Gamma e)(\nu\Gamma\chi), \quad (\bar{q}\Gamma q)(\nu\Gamma\chi)$$



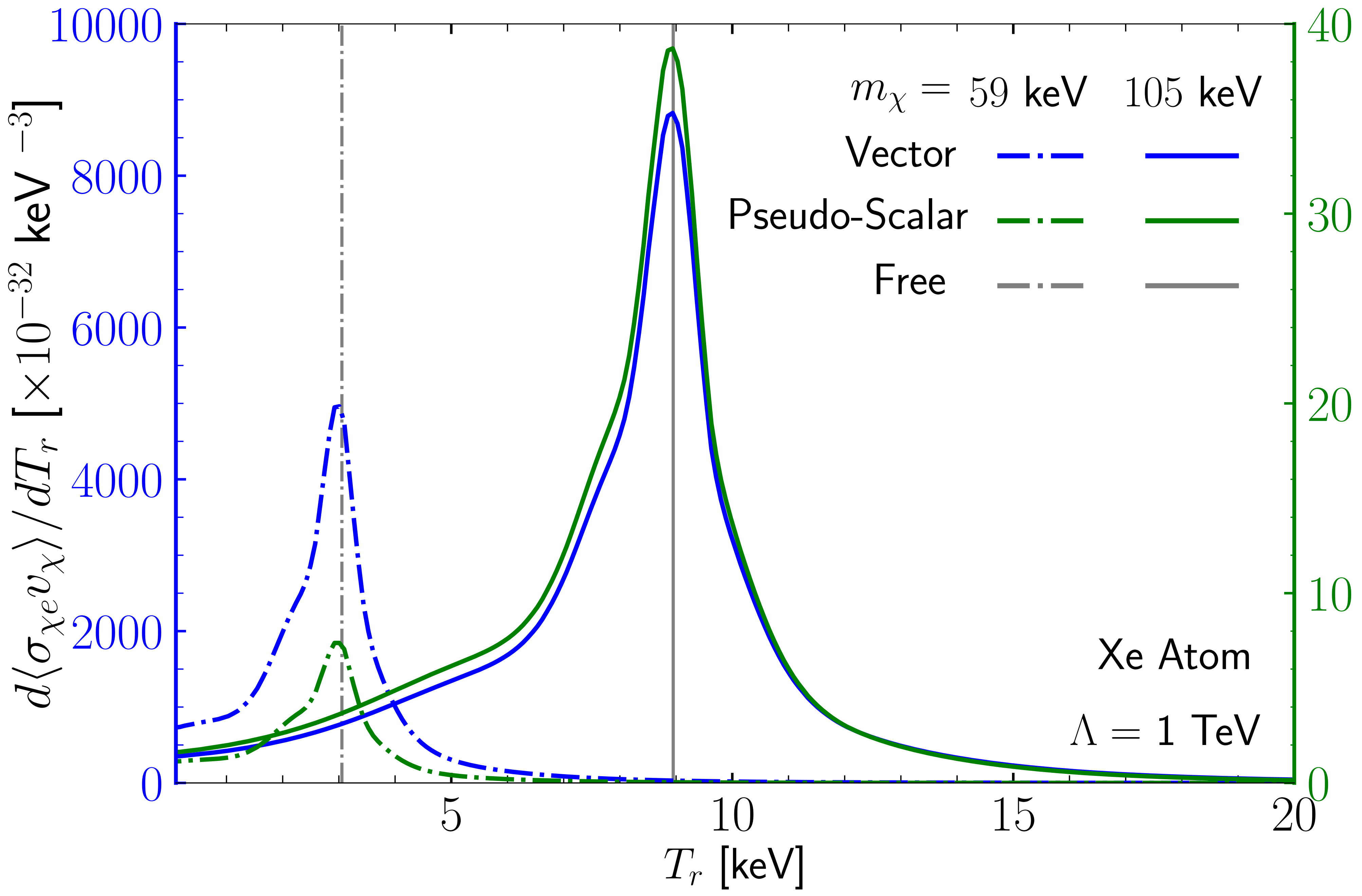
Dror, Elor, McGehee, T-T. Yu: 2011.01940,
Dror, Elor, McGehee 1905.12635,
Dror, Elor, McGehee 1908.10861,
Li, Liao, Zhang, 2201.11905

- Recoil energy in free case:

$$T_r \approx \frac{m_\chi^2}{2(m_\chi + m_e)} \approx 8\,\mathrm{keV}\left(\frac{m_\chi}{100\,\mathrm{keV}}\right)^2$$

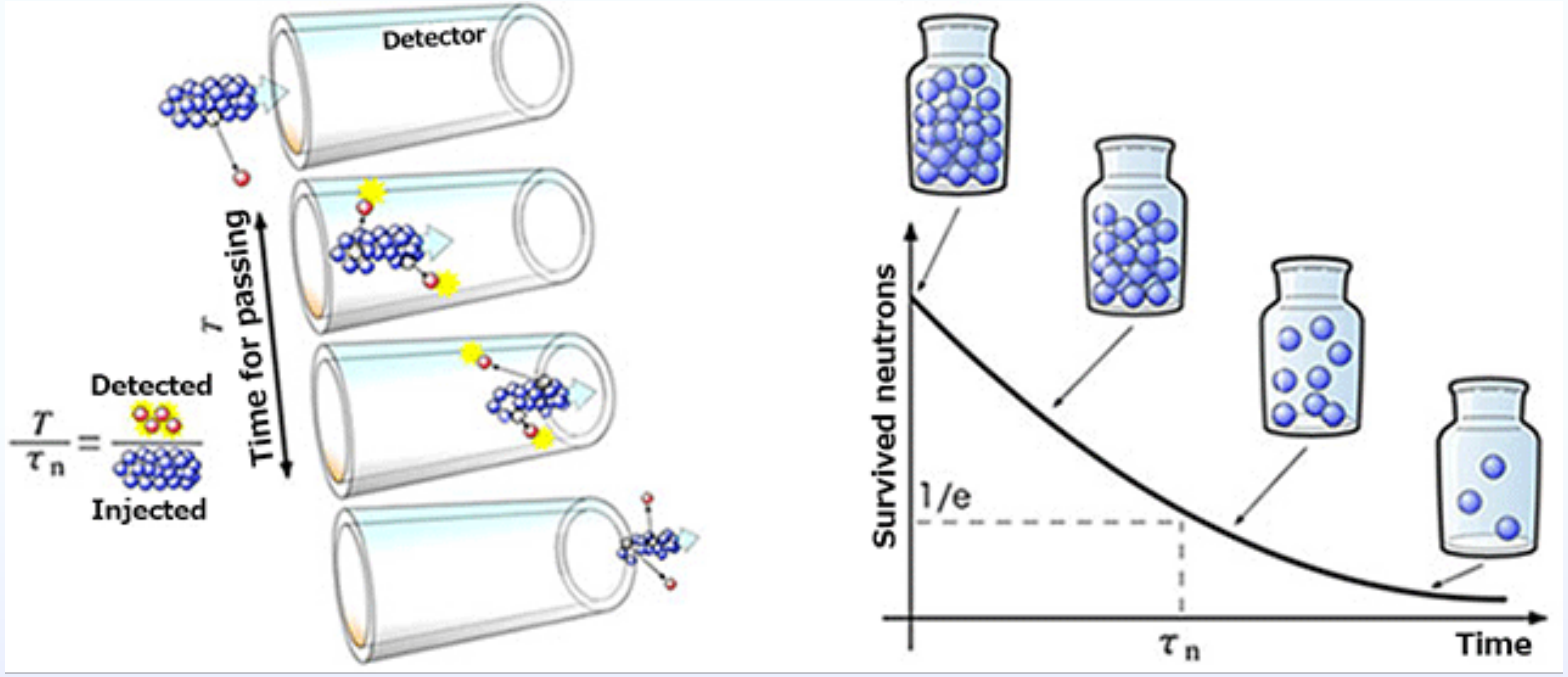
- Unique signature in D.D. exp.:

Peak-type energy spectrum



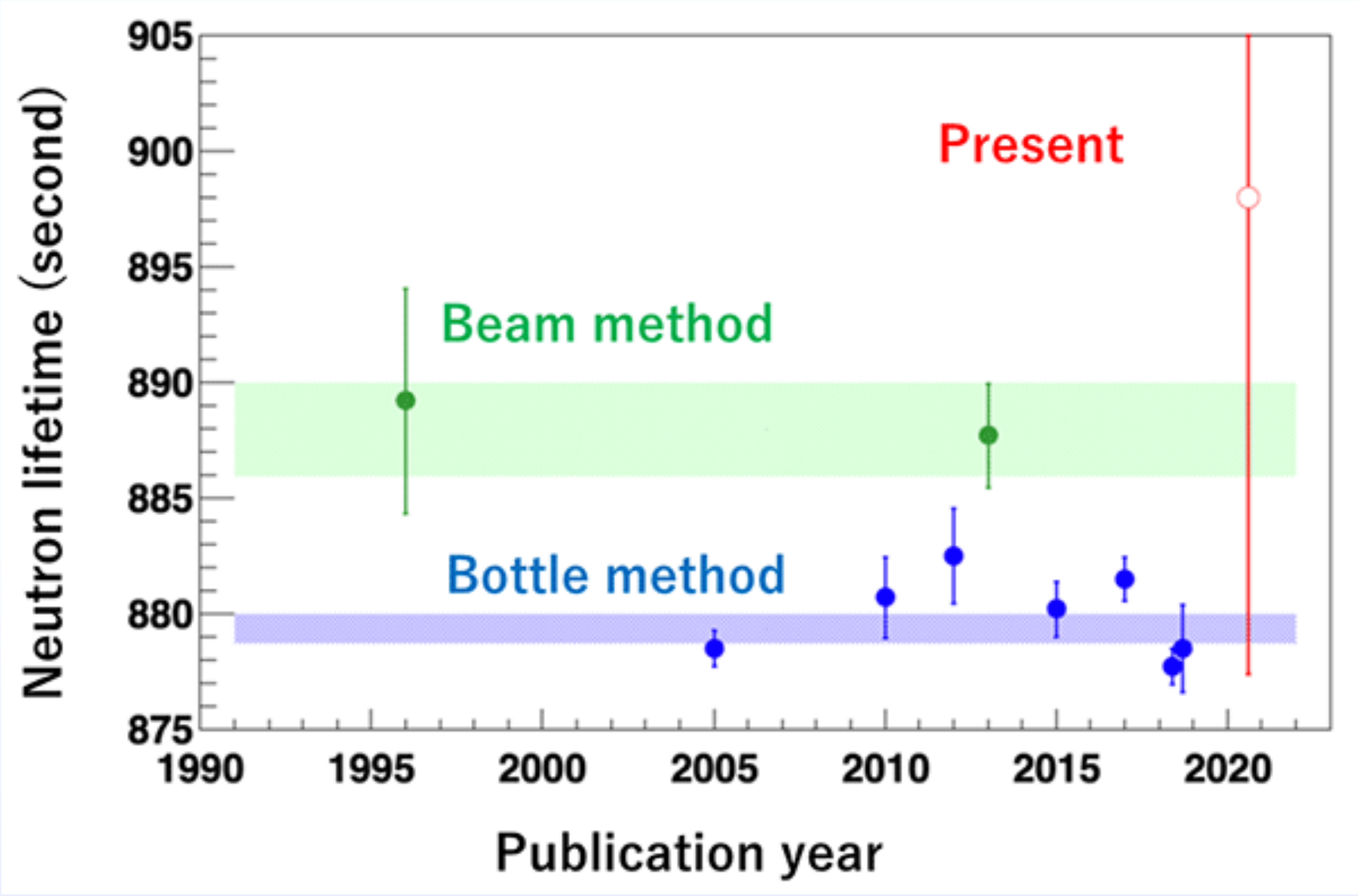
Shao-Feng Ge, Xiao-Gang He, XDM and Jie Sheng, 2201.11497

Neutron dark decay mode for its lifetime anomaly



Beam method

Bottle method



https://www.icepp.s.u-tokyo.ac.jp/en/information/20210129.html

One solution: additional neutron dark decay mode

$$\Gamma_n^{\mathrm{dark}} = \Gamma_n^{\mathrm{tot}} - \Gamma_n^{\beta} = \tau_n^{-1} - \tau_{n,\beta}^{-1} = (8.184 \pm 1.688) \times 10^{-30}\,\mathrm{GeV}\,.$$

DSEFT

A natural framework to induce neutron dark decay

Fermion – scalar : $n \to \chi + \phi$

$$\mathcal{O}^{\mathrm{LR}}_{\phi\chi} = \epsilon^{ijk}(\bar{\chi}P_L d_i)(\overline{d^{\mathrm{C}}_j}P_R u_k)\phi,$$
$$\mathcal{O}^{\mathrm{RL}}_{\phi\chi} = \epsilon^{ijk}(\bar{\chi}P_R d_i)(\overline{d^{\mathrm{C}}_j}P_L u_k)\phi,$$
$$\mathcal{O}^{\mathrm{LL}}_{\phi\chi} = \epsilon^{ijk}(\bar{\chi}P_L d_i)(\overline{d^{\mathrm{C}}_j}P_L u_k)\phi,$$
$$\mathcal{O}^{\mathrm{RR}}_{\phi\chi} = \epsilon^{ijk}(\bar{\chi}P_R d_i)(\overline{d^{\mathrm{C}}_j}P_R u_k)\phi\,.$$

Fermion – vector : $n \to \chi + X$

$$\mathcal{O}^{\mathrm{LLL}}_{\chi X} = \epsilon^{ijk}(\bar{\chi}\gamma_\mu P_L d_i)(\overline{d^{\mathrm{C}}_j}P_L u_k)X^\mu,$$
$$\mathcal{O}^{\mathrm{RRR}}_{\chi X} = \epsilon^{ijk}(\bar{\chi}\gamma_\mu P_R d_i)(\overline{d^{\mathrm{C}}_j}P_R u_k)X^\mu,$$
$$\mathcal{O}^{\mathrm{LRR}}_{\chi X} = \epsilon^{ijk}(\bar{\chi}\gamma_\mu P_L d_i)(\overline{d^{\mathrm{C}}_j}P_R u_k)X^\mu(\mathrm{A}),$$
$$\mathcal{O}^{\mathrm{RLL}}_{\chi X} = \epsilon^{ijk}(\bar{\chi}\gamma_\mu P_R d_i)(\overline{d^{\mathrm{C}}_j}P_L u_k)X^\mu(\mathrm{A}),$$
$$\mathcal{O}^{\mathrm{LLR}}_{\chi X1} = \epsilon^{ijk}(\bar{\chi}P_L d_i)(\overline{d^{\mathrm{C}}_j}\gamma_\mu P_R u_k)X^\mu,$$
$$\mathcal{O}^{\mathrm{RRL}}_{\chi X1} = \epsilon^{ijk}(\bar{\chi}P_R d_i)(\overline{d^{\mathrm{C}}_j}\gamma_\mu P_L u_k)X^\mu,$$
$$\mathcal{O}^{\mathrm{LLR}}_{\chi X2} = \epsilon^{ijk}[(\bar{\chi}P_L d_i)(\overline{u^{\mathrm{C}}_j}\gamma_\mu P_R d_k) + (\bar{\chi}P_L u_i)(\overline{d^{\mathrm{C}}_j}\gamma_\mu P_R d_k)]X^\mu(\mathrm{S}),$$
$$\mathcal{O}^{\mathrm{RRL}}_{\chi X2} = \epsilon^{ijk}[(\bar{\chi}P_R d_i)(\overline{u^{\mathrm{C}}_j}\gamma_\mu P_L d_k) + (\bar{\chi}P_R u_i)(\overline{d^{\mathrm{C}}_j}\gamma_\mu P_L d_k)]X^\mu(\mathrm{S}),$$

Nucleon matrix element

Chiral perturbation theory plus lattice QCD

$$\text{Chiral symmetry}: \quad SU(3)_\mathrm{L} \otimes SU(3)_\mathrm{R}$$

$$\mathbf{8}_\mathrm{L} \otimes \mathbf{1}_\mathrm{R}: \quad \mathcal{O}^{\mathrm{LL}}_{\phi\chi}, \ \mathcal{O}^{\mathrm{LLL}}_{\chi X}$$

$$\mathbf{1}_\mathrm{L} \otimes \mathbf{8}_\mathrm{R}: \quad \mathcal{O}^{\mathrm{RR}}_{\phi\chi}, \ \mathcal{O}^{\mathrm{RRR}}_{\chi X}$$

$$\mathbf{3}_\mathrm{L} \otimes \bar{\mathbf{3}}_\mathrm{R}: \quad \mathcal{O}^{\mathrm{LR}}_{\phi\chi}, \ \mathcal{O}^{\mathrm{RLL}}_{\chi X}$$

$$\bar{\mathbf{3}}_\mathrm{L} \otimes \mathbf{3}_\mathrm{R}: \quad \mathcal{O}^{\mathrm{RL}}_{\phi\chi}, \ \mathcal{O}^{\mathrm{LRR}}_{\chi X}$$

$$\mathbf{6}_\mathrm{L} \otimes \mathbf{3}_\mathrm{R}: \quad \mathcal{O}^{\mathrm{LLR}}_{\chi X1,2}(\times)$$

$$\mathbf{3}_\mathrm{L} \otimes \mathbf{6}_\mathrm{R}: \quad \mathcal{O}^{\mathrm{RRL}}_{\chi X1,2}(\times)$$

Higher order in ChPT power counting

$$\xi = \exp\left[\frac{i\sqrt{2}\Pi(x)}{F_0}\right],$$

$$\Pi = \begin{pmatrix} \frac{\pi^0}{\sqrt{2}} + \frac{\eta}{\sqrt{6}} & \pi^+ & K^+ \\ \pi^- & -\frac{\pi^0}{\sqrt{2}} + \frac{\eta}{\sqrt{6}} & K^0 \\ K^- & \bar{K}^0 & -\sqrt{\frac{2}{3}}\eta \end{pmatrix}$$

$$B = \begin{pmatrix} \frac{1}{\sqrt{2}}\Sigma^0 + \frac{1}{\sqrt{6}}\Lambda^0 & \Sigma^+ & p \\ \Sigma^- & -\frac{1}{\sqrt{2}}\Sigma^0 + \frac{1}{\sqrt{6}}\Lambda^0 & n \\ \Xi^- & \Xi^0 & -\sqrt{\frac{2}{3}}\Lambda^0 \end{pmatrix},$$

Chiral matching

- Chiral transformation: $B \to hBh^\dagger$, $\xi \to L\xi h^\dagger = h\xi R^\dagger$, with $h \in \mathrm{SU}(3)_\mathrm{V}$
- Spurion or external sources: $\mathscr{P}_{x_\mathrm{L}\otimes y_\mathrm{R}} \sim C_i \bar{\chi}\phi(X)$
- Leading order matching result:

$$\alpha \mathrm{Tr}\left[\mathscr{P}_{\mathbf{3}_\mathrm{L}\otimes\bar{\mathbf{3}}_\mathrm{R}}\xi^\dagger B_\mathrm{L}\xi^\dagger + \mathscr{P}_{\bar{\mathbf{3}}_\mathrm{L}\otimes\mathbf{3}_\mathrm{R}}\xi B_\mathrm{R}\xi\right] + \beta \mathrm{Tr}\left[\mathscr{P}_{\mathbf{8}_\mathrm{L}\otimes\mathbf{1}_\mathrm{R}}\xi B_\mathrm{L}\xi^\dagger + \mathscr{P}_{\mathbf{1}_\mathrm{L}\otimes\mathbf{8}_\mathrm{R}}\xi^\dagger B_\mathrm{R}\xi\right]$$

- Low energy constants: $\alpha = -\beta = -0.0144(3)(21)\ \mathrm{GeV}^3$

Aoki, Izubuchi, Shintani, Soni: 1705.01338

Constraints

- Nuclear stability: requiring the stable nuclei to be not perturbed by these interactions (the **Q-value** of nuclear decay < the **separation energy** for a neutron in the nucleus)

$$937.900\,\mathrm{MeV} < M \equiv m_\chi + m_\phi < 939.565\,\mathrm{MeV}$$ from beryllium

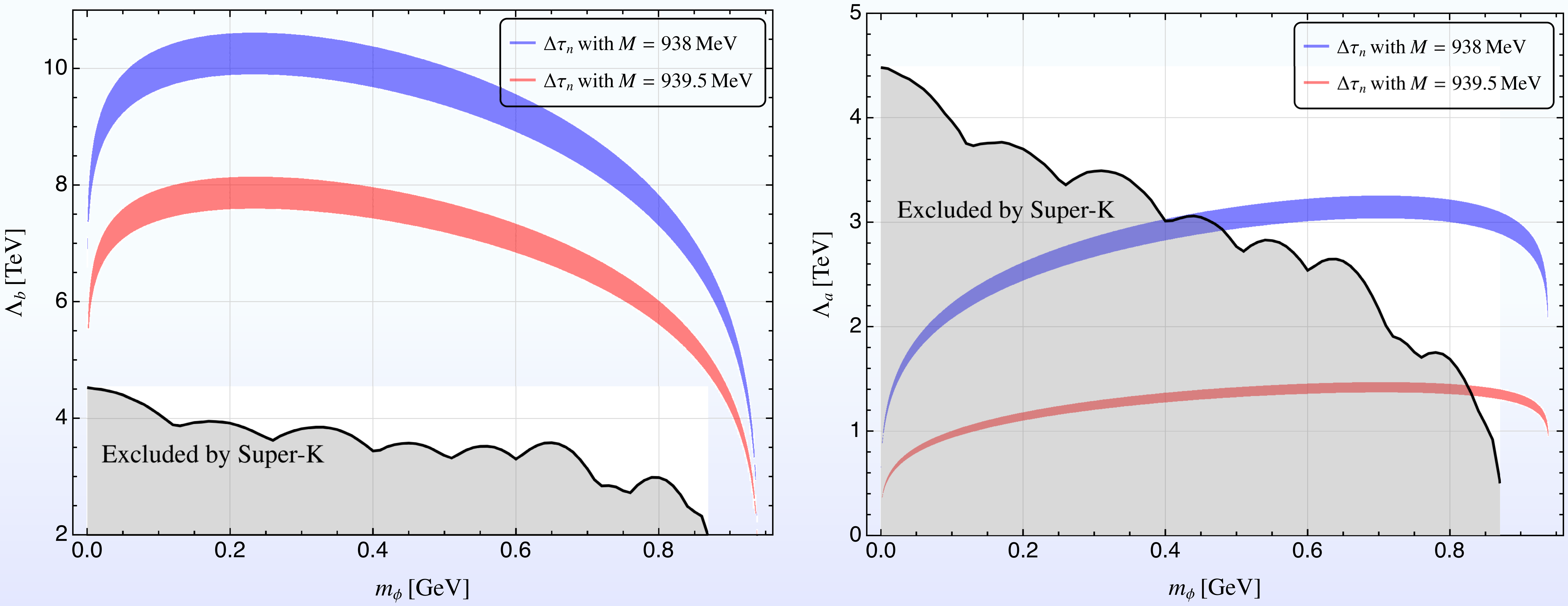
B. Fornal and B. Grinstein, 1801.01124

- The kinematic constraint leads the dark particles as **DM candidate**

- DM-neutron annihilation constraint: $\chi + n \to \phi + \pi^0, \pi^0 \to 2\gamma$

Super-K: $n \to \bar{\nu} + \pi^0$ Super-Kamiokande Collaboration : 1305.4391

Fermion+scalar case as an example



$$\Gamma_{n\to\chi\phi} = \frac{\alpha_n^2 \lambda^{\frac{1}{2}}(m_n^2, m_\chi^2, m_\phi^2)}{\pi m_n^3} \left\{ \frac{1}{\Lambda_a^6}\left[(m_n - m_\chi)^2 - m_\phi^2\right] + \frac{1}{\Lambda_b^6}\left[(m_n + m_\chi)^2 - m_\phi^2\right] \right\},$$

$$\Lambda_{a,b}^{-3} = \frac{1}{8}\left[\left(C_{\phi\chi}^{\mathrm{LR}} - C_{\phi\chi}^{\mathrm{LL}}\right) \mp \left(C_{\phi\chi}^{\mathrm{RL}} - C_{\phi\chi}^{\mathrm{RR}}\right)\right]$$

The DSEFT can accommodate the neutron lifetime anomaly.

Conclusion

- The DSEFT is introduced in which the effective operators involving two different dark particles coupling to SM fields;

- The effective operators up to dim 7 are constructed for six different categories:

SS-SM, FF-SM, VV-SM, SF-SM, SV-SM, FV-SM

- Interesting phenomenologies are discussed concerning the DM puzzle and experimental anomalies;

- Outlook: explore its rich pheno from other observables as well as their UV completion.

Thank you for your time!