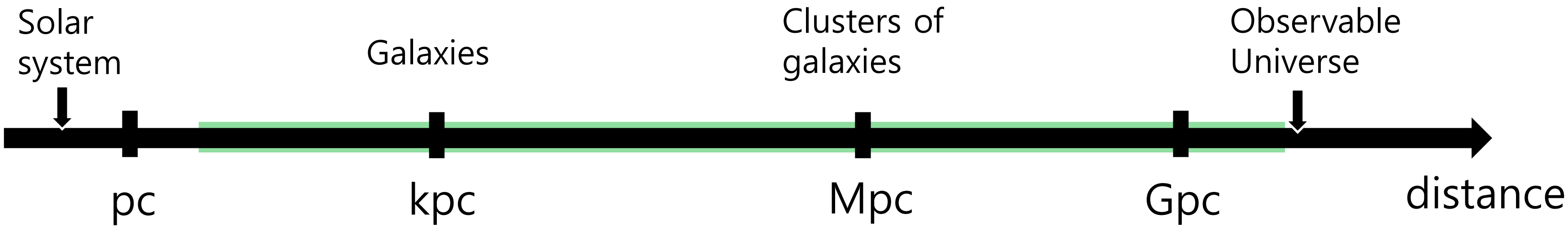
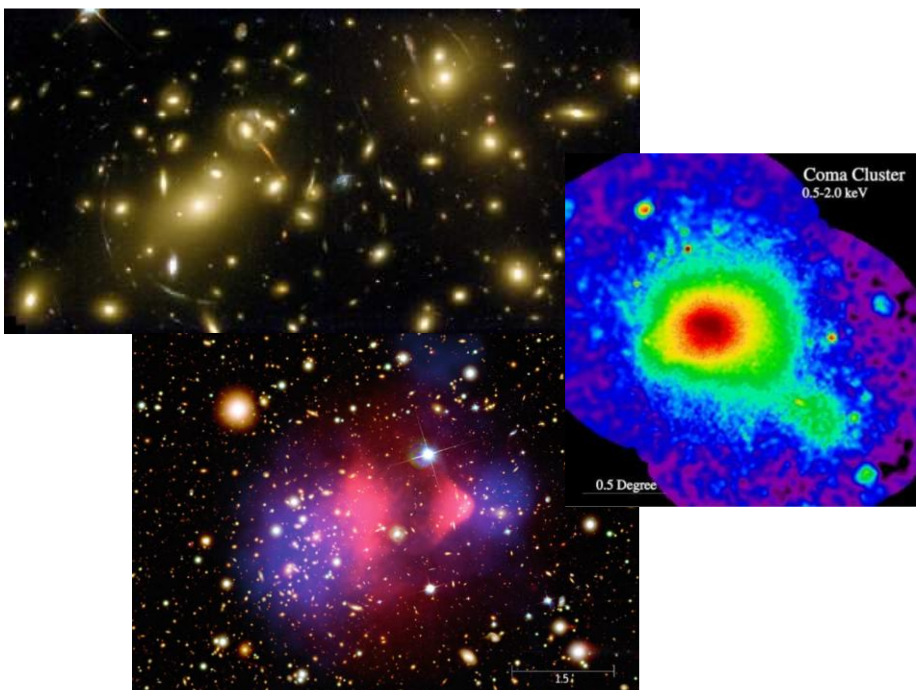
암흑물질 현상론에서 암흑 힉스의 역할

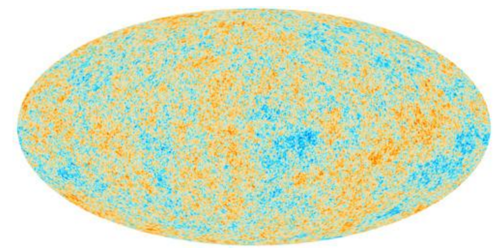
강원대학교
자유전공학부
김종국
jkkim@kangwon.ac.kr

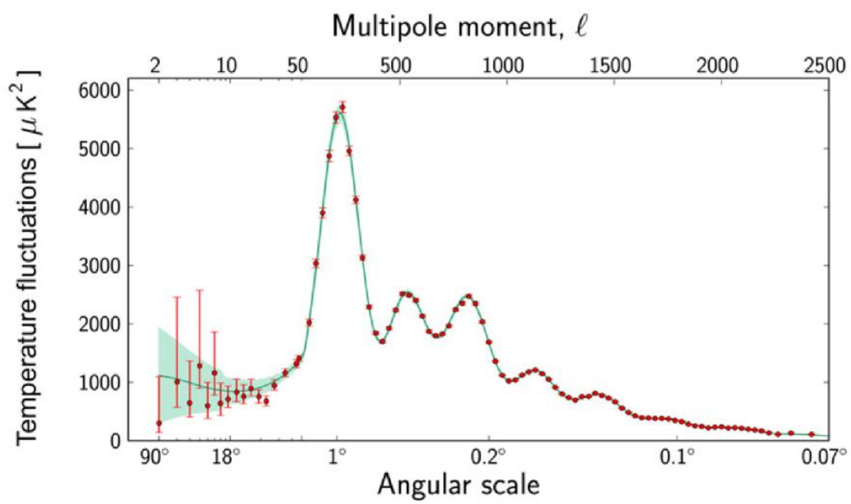
Evidences – Dark Matter

- There are undeniable evidences for dark matter in a wide range of distance scales









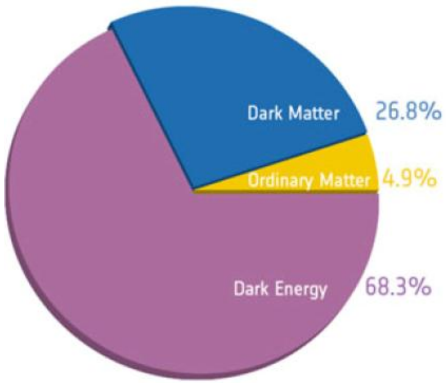
Dark Matter as a particle

- Dark Matter as a particle must be
  - Massive
  - Have existed from early Universe up to now
  - Located around galaxies, clusters
    - Stable or lifetime longer than the age of Universe → new symmetry

  - Dark : No electromagnetic interaction → EM charge singlet

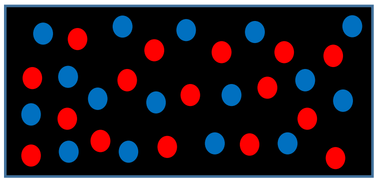
  - 27% of the present energy density of the Universe → $\Omega h^2 = 0.12$

  - Cold : non-relativistic at the time of formation of the first structures

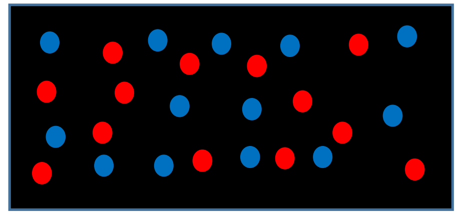


- Cold Dark Matter
  - Weakly Interacting Massive Particle

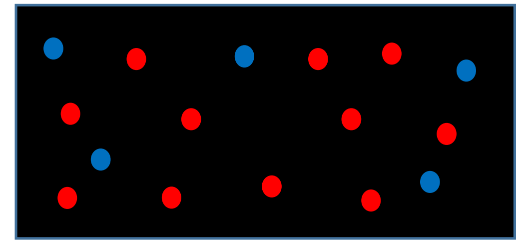
Thermal freeze-out DM production



$T \gg M_{DM}$

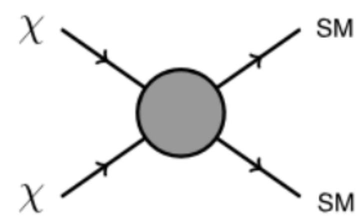


$T \approx M_{DM}$

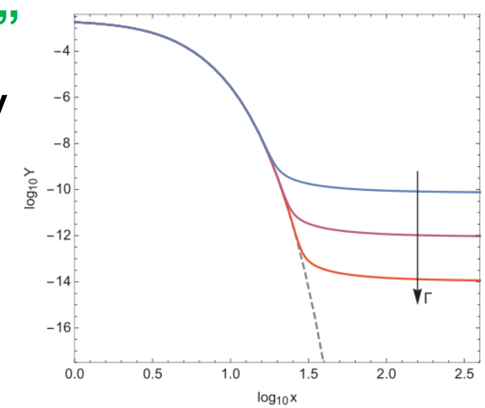


$T \ll M_{DM}$

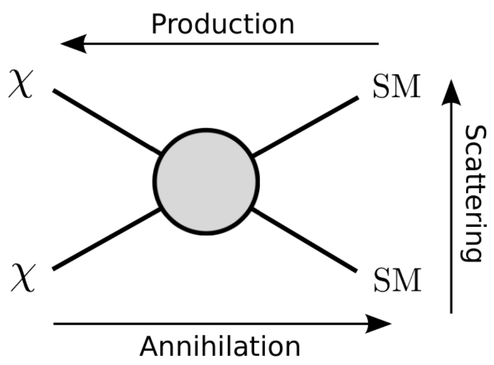
- ● : Dark Matter
- ● : Standard Model



- Dark matter population in an expanding Universe
  - **Dark matter particles can no longer annihilate**
  - **The number of dark matter particles "freeze-out"**
- Standard calculation for WIMP DM relic density
  - The Boltzmann equation $\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle\sigma v\rangle\left(n_\chi^2 - n_{\rm eq}^2\right)$
- Relic density: $\Omega h^2 = 0.12 \rightarrow \langle\sigma v\rangle \sim 10^{-9}\mathrm{GeV}^{-2}$



WIMP Dark Matter



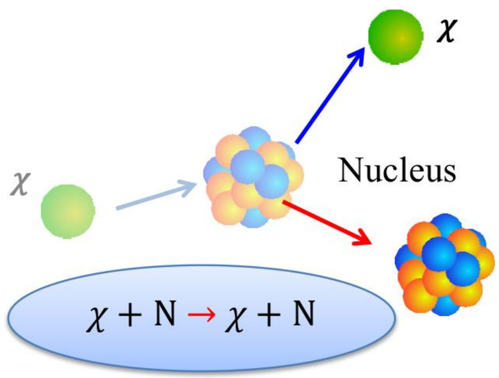
- DM annihilation ($\chi\chi \to XX$)

$$(\sigma v)_{\text{ann.}} \propto \frac{\lambda^2}{m_{\text{DM}}^2}$$

naive expectation by crossing symmetry

$$\sigma_{\text{scat.}} \propto \frac{\lambda^2}{m_{\text{DM}}^2}$$

- DM scattering ($\chi X \to \chi X$)



- Direct detection experiments aim to detect recoil energy from DM-nucleon, DM-electron scattering

WIMP Dark Matter

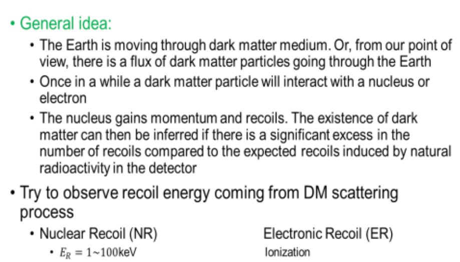
- General idea:

Goodman, Witten, 1985

  - The Earth is moving through dark matter medium. Or, from our point of view, there is a flux of dark matter particles going through the Earth
  - Once in a while a dark matter particle will interact with a nucleus or electron
  - The nucleus gains momentum and recoils. The existence of dark matter can then be inferred if there is a significant excess in the number of recoils compared to the expected recoils induced by natural radioactivity in the detector
- Try to observe recoil energy coming from DM scattering process
  - Nuclear Recoil (NR)
    - $E_R = 1 \sim 100\text{keV}$

Electronic Recoil (ER)

Ionization



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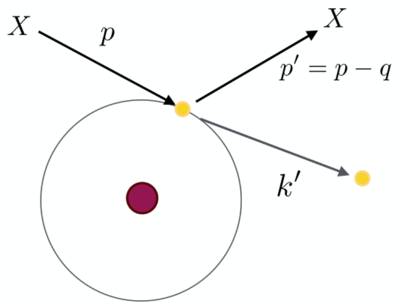
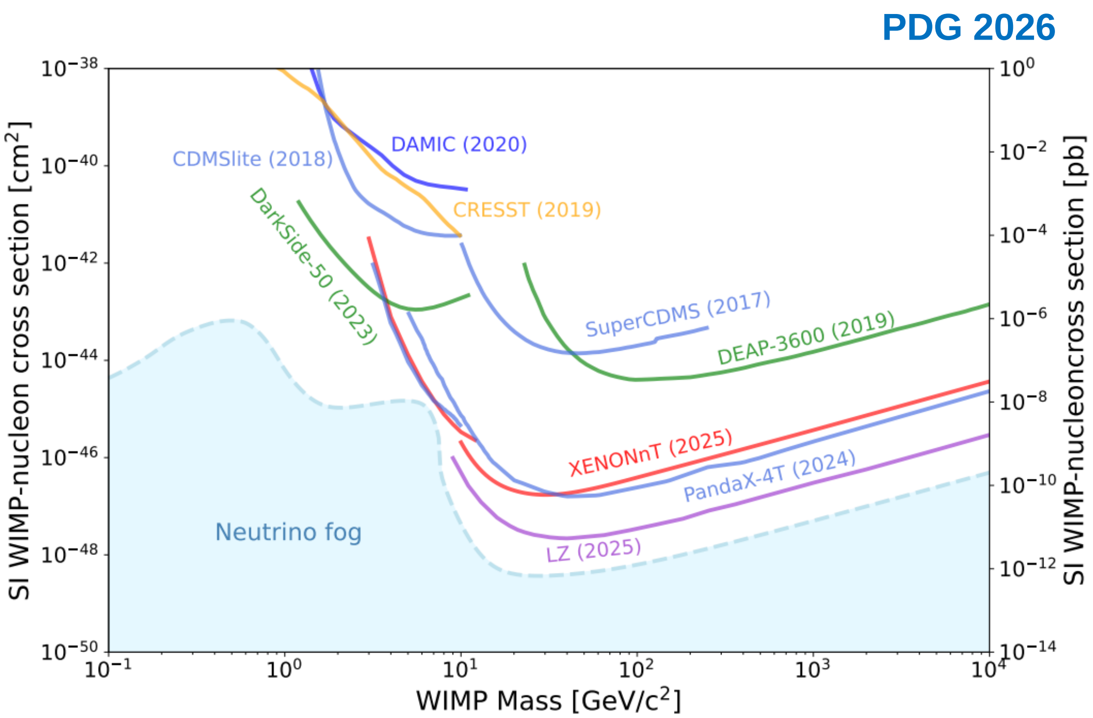


WIMP Dark Matter

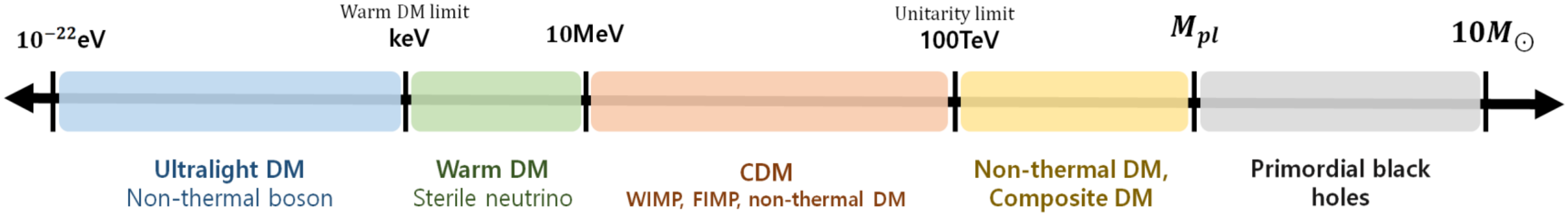
- Null result



- The direct detection experiments give upper bounds on the DM-nucleon scattering cross section
- LZ experiment gives the most stringent bound
  - $\sigma < 3 \times 10^{-48}\mathrm{cm}^2$ for $m_\chi = 100\mathrm{GeV}$

WIMP Dark Matter and beyond

- The mass range of allowed DM candidates



- The motivation for new physics arising from recently reported experimental results
  - $B^+ \to K^+ \nu\bar{\nu}$ excess
  - KM3-NeT neutrino event
  - 511 keV γ-ray excess
  - Fermi-LAT 20 GeV γ-ray excess
  - Null results from dark matter direct detection

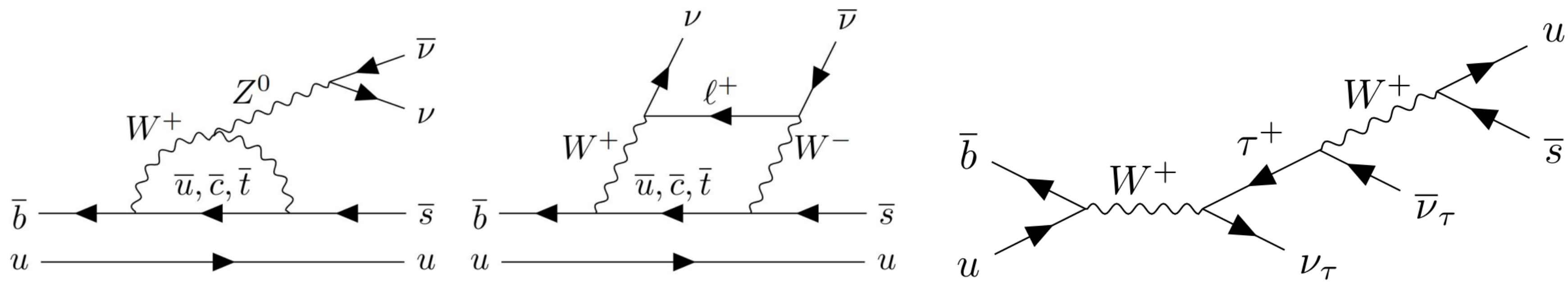
- New signals of dark matter?

Belle II
- $B^+ \to K^+ \nu\bar{\nu}$ excess

arXiv: 2401.10112 with Shu-Yu Ho (Academia Sinica), Pyungwon Ko (KIAS)
arXiv: 2511.20430 with Pyungwon Ko (KIAS)

Measurement of $B^+ \to K^+\nu\bar{\nu}$

- The $B^+ \to K^+\nu\bar{\nu}$ process is known with high accuracy in the SM:
  - $Br(B^+ \to K^+\nu\bar{\nu}) = (5.58 \pm 0.37) \times 10^{-6}$ HPQCD, PRD 2023



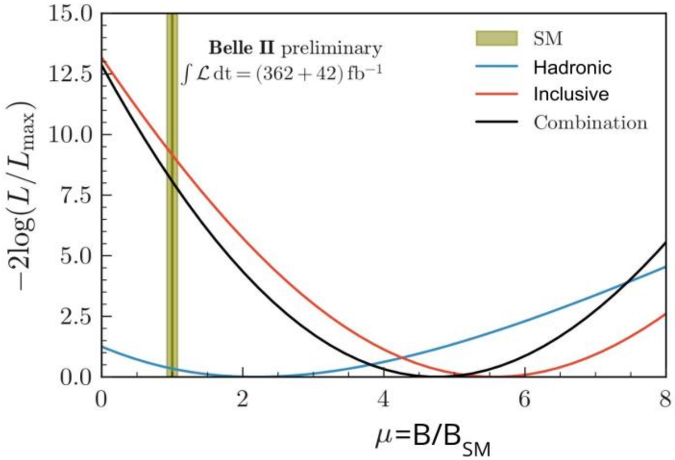
- $\mathcal{L}_{b\to s\nu\bar{\nu}} = -C_\nu \bar{s}_L \gamma^\mu b_L \bar{\nu}\gamma^\mu \nu$

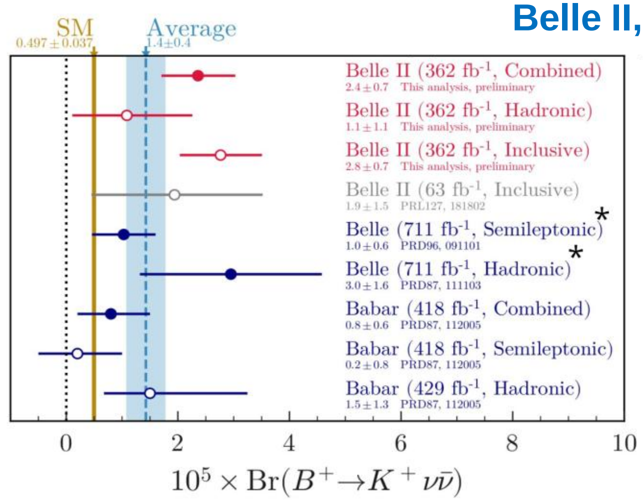
$$C_\nu = \frac{g_W^2}{M_W^2}\frac{g_W^2 V_{ts}^* V_{tb}}{16\pi^2}\left[\frac{x_t^2 + 2x_t}{8(x_t - 1)} + \frac{3x_t^2 - 6x_t}{8(x_t - 1)^2}\ln x_t\right],$$

where $x_t = m_t^2/M_W^2$.

Measurement of $B^+ \to K^+ \nu\bar{\nu}$

Belle II, PRD 2024





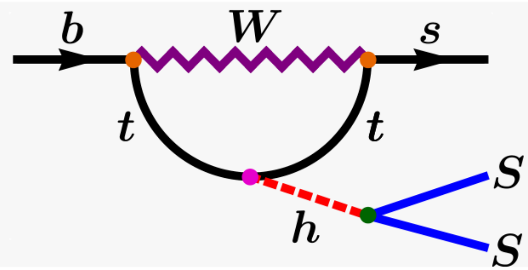
- $Br(B^+ \to K^+ \nu\bar{\nu})_{Exp} = (2.3 \pm 0.7) \times 10^{-5}$
  - Prob(null signal from $B^+ \to K^+ \nu\bar{\nu}$) $= 0.012\%$
  - ➔ Significance of observation: 3.5 σ
  - Prob($B^+ \to K^+ \nu\bar{\nu})_{SM} = 0.17\%$ (2.8σ tension with the SM prediction)

- $Br(B^+ \to K^+ E_{\text{mis}})_{NP} = (1.8 \pm 0.7) \times 10^{-5}$
  - **Indirect NP effects**: The presence of heavy NP particles
  - **Direct NP effects**: the presence of new invisible particles

Solution: 3-body decay

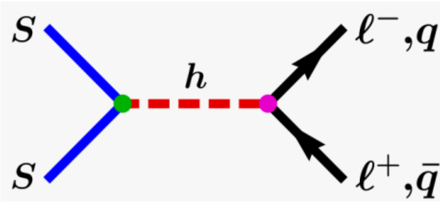
- Singlet scalar DM model ($m_s \leq 2.3\mathrm{GeV}$)

Bird et al, PRL 2004



$$-\mathcal{L}_S = \frac{\lambda_S}{4}S^4 + \frac{m_0^2}{2}S^2 + \lambda S^2 H^\dagger H$$
$$= \frac{\lambda_S}{4}S^4 + \frac{1}{2}(m_0^2 + \lambda v_{EW}^2)S^2 + \lambda v_{EW} S^2 h + \frac{\lambda}{2}S^2 h^2,$$

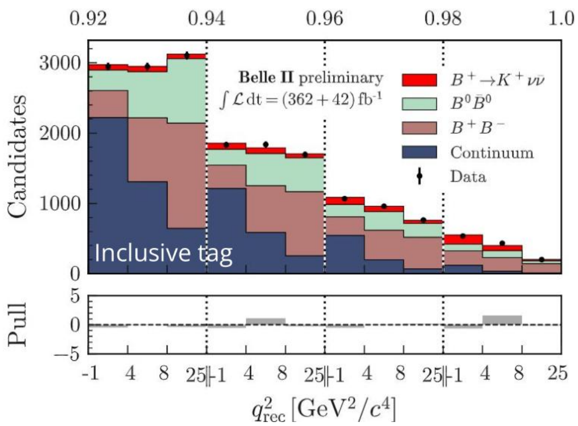
- Belle $\frac{C_{DM}}{C_\nu} \simeq \frac{4.4\lambda M_W^2}{g_W^2 m_h^2}$
- Relic density: $\sigma_{\mathrm{ann}} v_{\mathrm{rel}} = \frac{8 v_{EW}^2 \lambda^2}{m_h^4}\left(\lim_{m_{\tilde{h}} \to 2m_S} m_{\tilde{h}}^{-1} \Gamma_{\tilde{h}X}\right).$

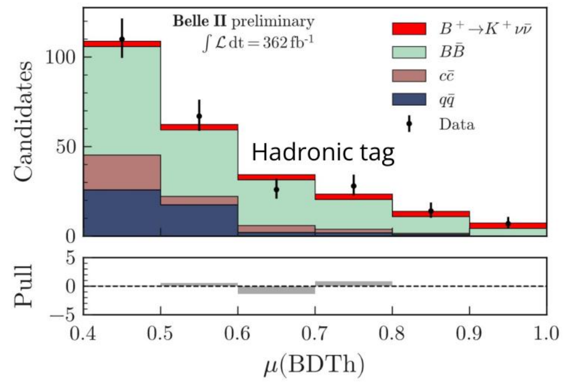


  - λ should be large to fit the relic as well as Belle II
  - $m_s \leq 1\mathrm{GeV}$ is already excluded by BABAR limits (2004 data).

- For $m_\chi \lesssim 20\mathrm{GeV}$, CMB bound (DM annihilation @ $T \sim \mathrm{eV}$) excludes the thermal DM freeze-out determined by *s-wave* annihilation
- **This model does not work anymore.**

Alternative solution: 2-body decay

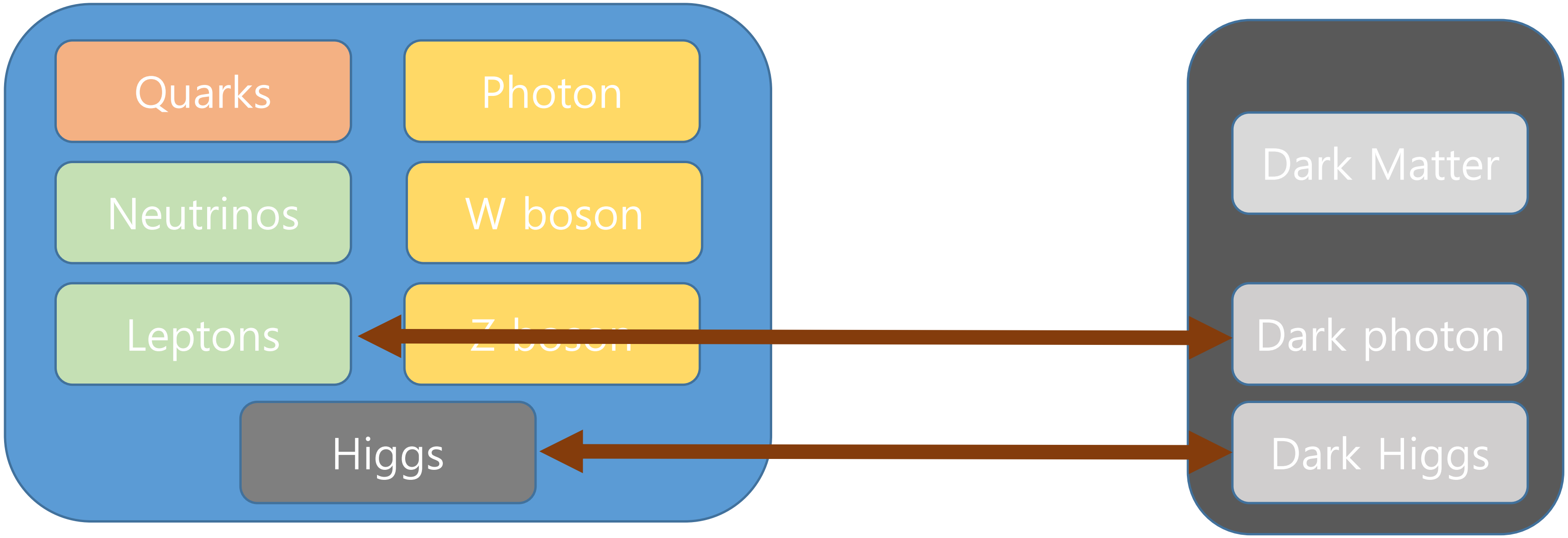




- Belle II provides information on the q^2_{rec} **spectrum**
  - q^2_{rec}: mass squared of the neutrino pair
  - A peak localized around $q^2_{rec} = 4\text{GeV}^2$
  - Two-body decay $(B \to KX), m_X = 2$ GeV
  - 2.8σ tension under the assumption of heavy new physics
  - No excess was found in the BaBar measurements of $B \to K^* \nu\bar{\nu}$
  - A global analysis of the BelleII and BaBar data leads to $\text{Br}(B \to KX) = (5.1 \pm 2.1) \times 10^{-6}$ with a reduced significane of $\approx$ **2.4σ**

$U(1)_{L_\mu - L_\tau}$-charged DM + Dark Higgs

- $U(1)_{dark} \equiv U(1)_{L_\mu - L_\tau}$
  - Let's call Z',$U(1)_{L_\mu - L_\tau}$ gauge boson, dark photon since it couple to DM



- **UV complete** $U(1)_{L_\mu - L_\tau}$-charged **scalar** DM model
- Dark photon Z' gets massive through $U(1)_{L_\mu - L_\tau}$ breaking
- A new singlet scalar (**Dark Higgs**), which mixes with the SM Higgs

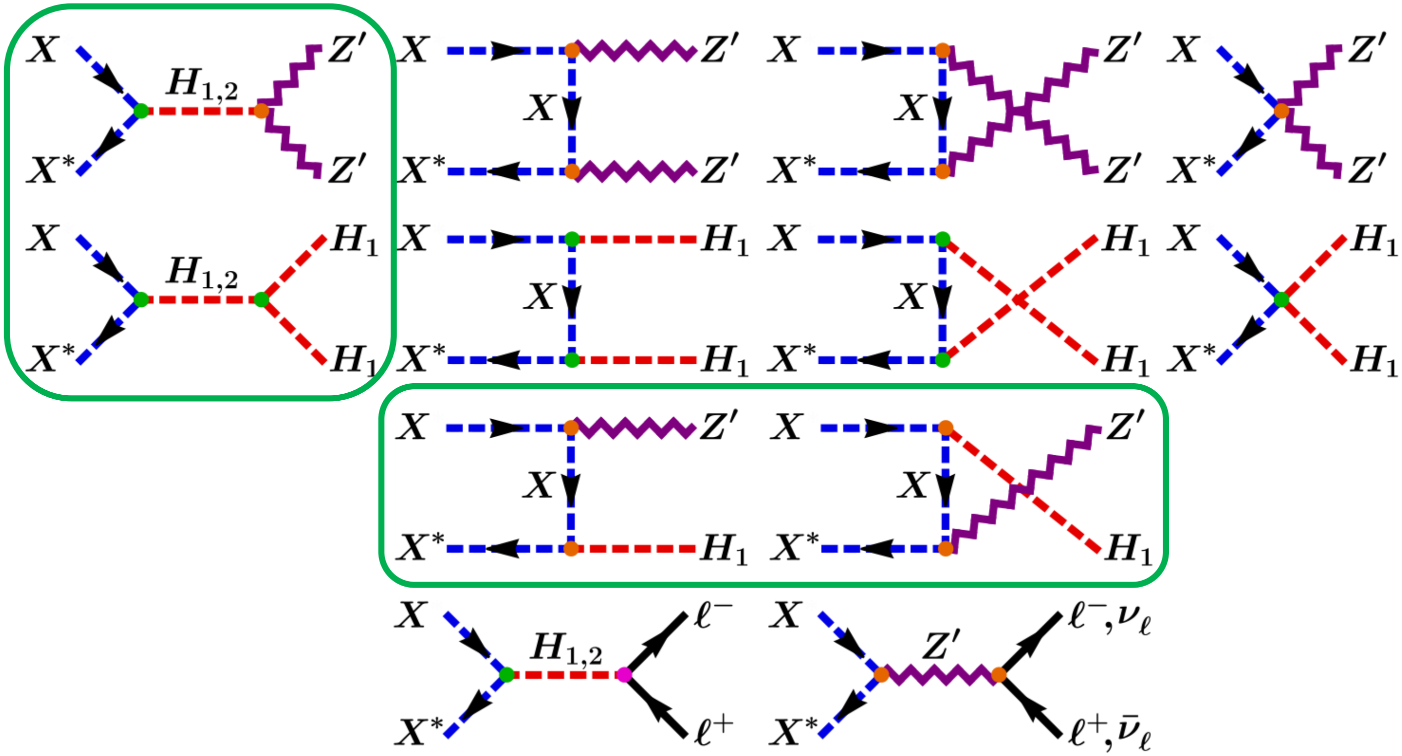
$U(1)_{L_\mu - L_\tau}$-charged DM + Dark Higgs

Baek, **JK**, Ko, 2204.04889

- UV-complete $U(1)_{L_\mu - L_\tau}$-charged scalar DM model

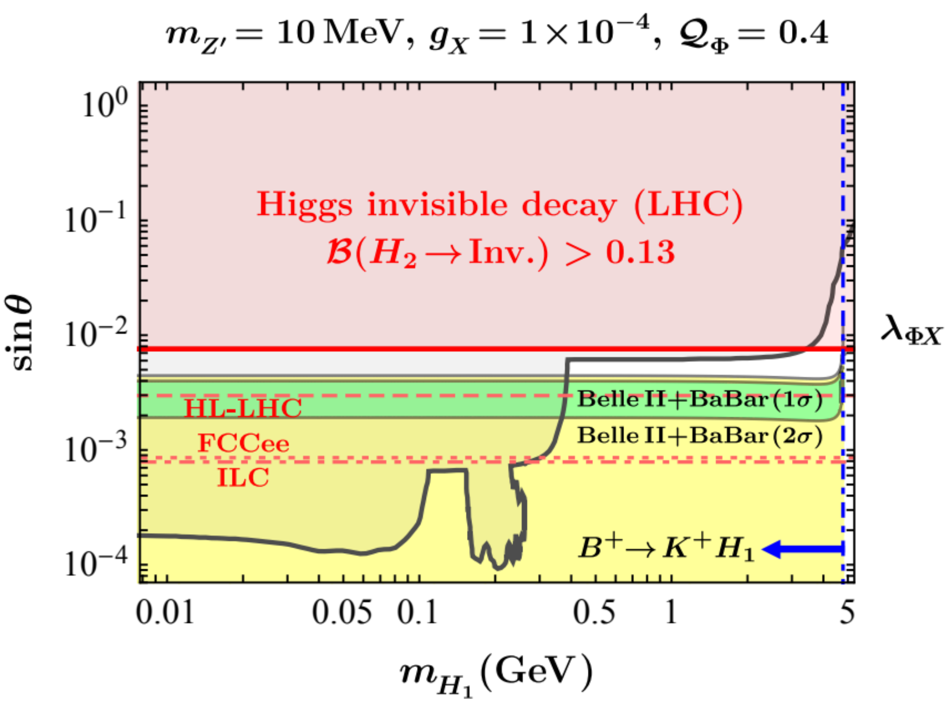
$$\mathcal{L}_{\rm DM} = |D_\mu X|^2 - m_X^2 |X|^2 - \lambda_{\Phi X} |X|^2 \left(|\Phi|^2 - \frac{v_\Phi^2}{2} \right)$$

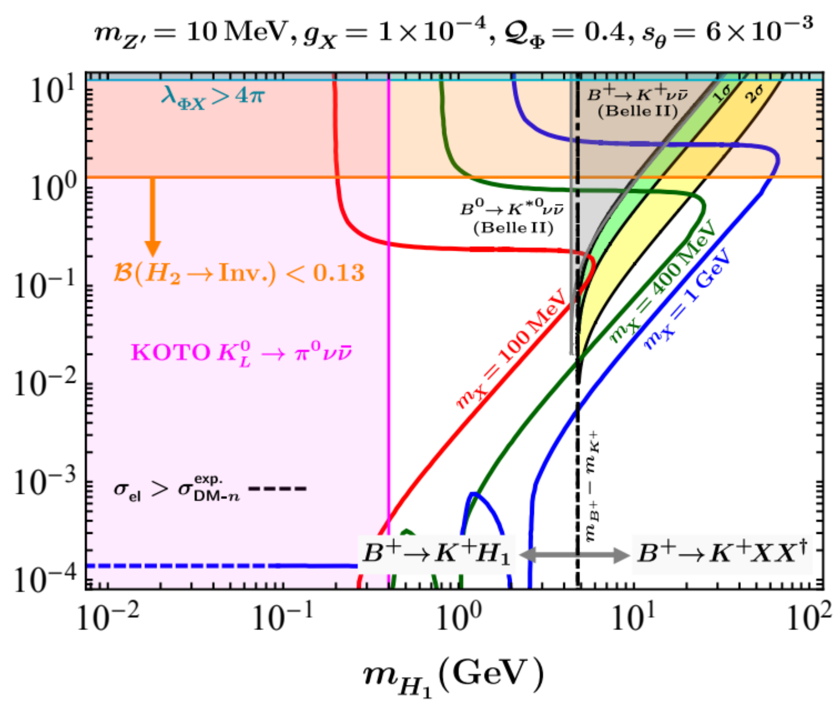
  - DM annihilation channels



BelleII excess: 2- or 3-body decay

- $m_{Z'} = 10\text{MeV},\ g_X = 10^{-4}$ ($m_{Z'} = g_X |Q_\Phi| v_\Phi$)
  - Hubble tension can be relaxed
  - $\Delta a_\mu = 10^{-10}$ **(BMW & CMD-3 collaboration)**
  - **Belle II** (2-body decay): $m_X \lesssim 8\ \text{GeV}\ (m_{H_1} < m_B - m_K)$
  - **Belle II** (3-body decay): $\sim 90\text{MeV} < m_X \lesssim 450\text{MeV}\ (m_{H_1} > m_B - m_K)$





CMB constraints

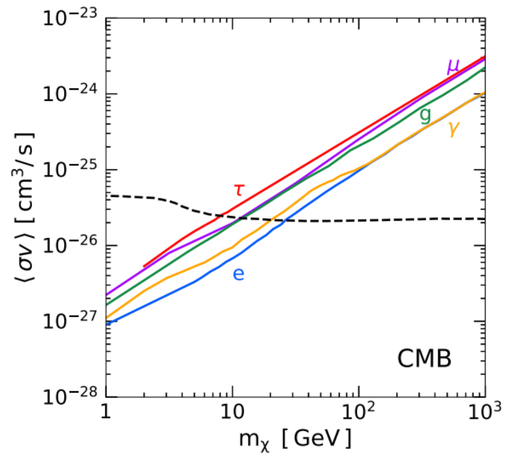
- For $m_X \lesssim 20\mathrm{GeV}$, CMB bound (DM annihilation @ $T{\sim}\mathrm{eV}$) excludes the thermal DM freeze-out determined by *s-wave* annihilation
  - DM annihilation should be mainly in **p-wave**
  - …

p-wave

$$\sigma v = a + b v^2 + O(v^4)$$

s-wave

- Dominant DM annihilation channel
  - $XX^\dagger \to Z'Z', H_1H_1$: **s-wave** annihilation
  - $XX^\dagger \to Z'H_1$: **p-wave** annihilation
- Z' decay
  - A pair of ν
- H_1 decay
  - A pair of DM (open when $m_{H_1} > 2m_X$)
  - A pair of Z' ($Z' \to \nu\nu$)
  - SM particles (suppressed due to small Yukawa coupling & $\sin\theta$)



Local Z_3 scalar DM model

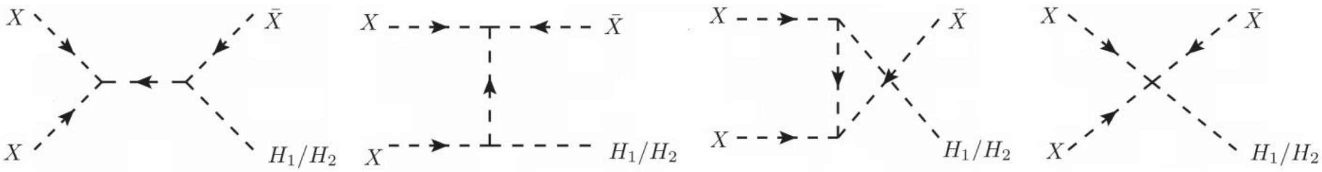
- Local Z_3 scalar DM model
  - $Q_X =, 1\ Q_\Phi = 3$

$$\mathcal{L}_{\rm DM} = D^\mu X^\dagger D_\mu X - m_X^2 X^\dagger X - \lambda_{\Phi X} X^\dagger X \left(\Phi^\dagger \Phi - \frac{v_\Phi^2}{2}\right) + \lambda_3 \left(X^3 \Phi^\dagger + \text{H.c.}\right)$$

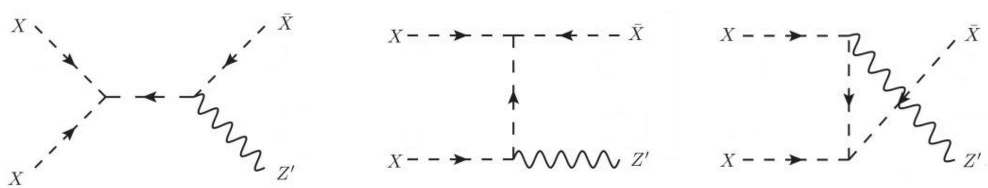
- Boltzmann equation

$$\frac{dY_X}{dx} = -\frac{s(x)\,\langle\sigma v\rangle_{X\bar{X}\to \rm SM}}{H(x)}\left(Y_X^2 - (Y_X^{\rm eq})^2\right) + \frac{1}{2}\frac{s(x)\,\langle\sigma v\rangle_{XX\to\bar{X}Y}}{H(x)}\left(Y_X^2 - Y_X Y_X^{\rm eq}\right)$$

- Semi-annihilation DM channels



(a) (b) (c) (d)



(a) (b) (c)

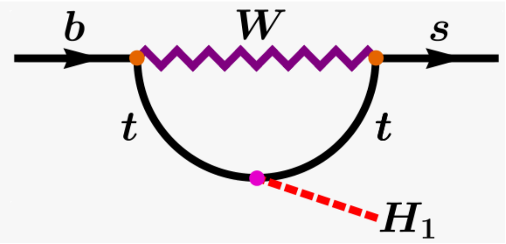
BelleII excess: 2-body decay

- When $m_{H_1} < m_B - m_K$, H_1 is on-shell

$$\Gamma_{B^+\to K^+H_1} \simeq \frac{|\kappa_{cb}|^2\sin^2\theta}{64\pi m_{B^+}^3}\left(\frac{m_{B^+}^2 - m_{K^+}^2}{m_b - m_s}\right)^2 \left[f_0(m_{H_1}^2)\right]^2 \times \sqrt{\mathcal{K}(m_{B^+}^2, m_{K^+}^2, m_{H_1}^2)}$$

form factor

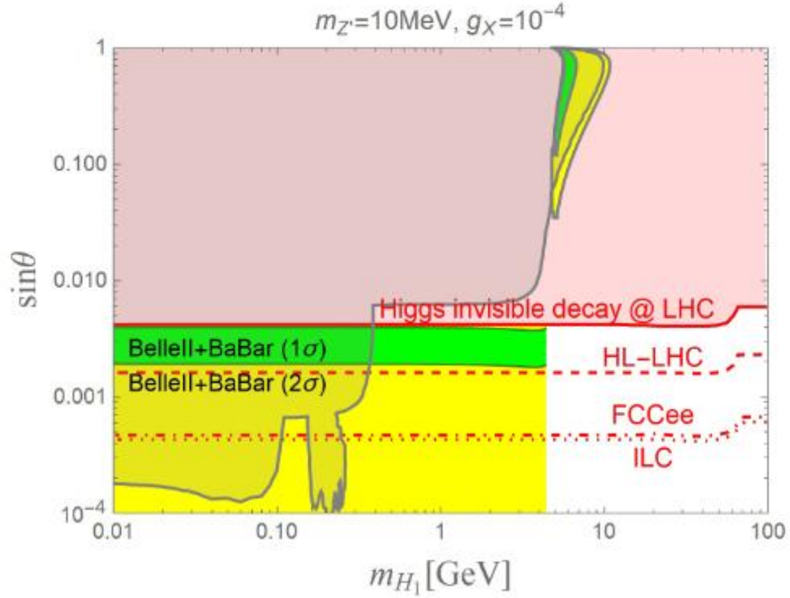
$\sin\theta \ll 1$

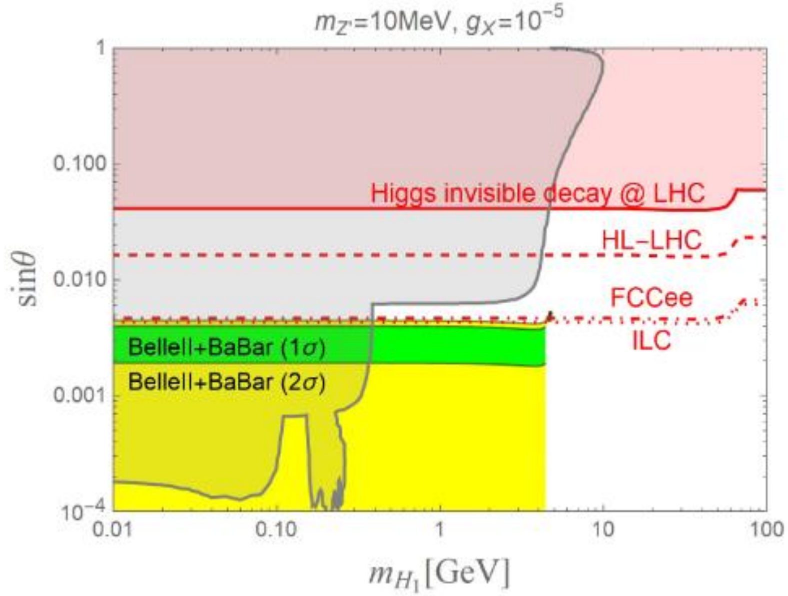


$|\kappa_{cb}| \simeq 6.7\times 10^{-6}$ $\quad \mathcal{K}(a,b,c) = a^2+b^2+c^2-2(ab+bc+ca)$

  - $Br(H_1 \to Z'Z') \approx 1,\ Br(Z' \to \nu\bar{\nu}) \approx 1$

- Local Z_3 scalar DM model



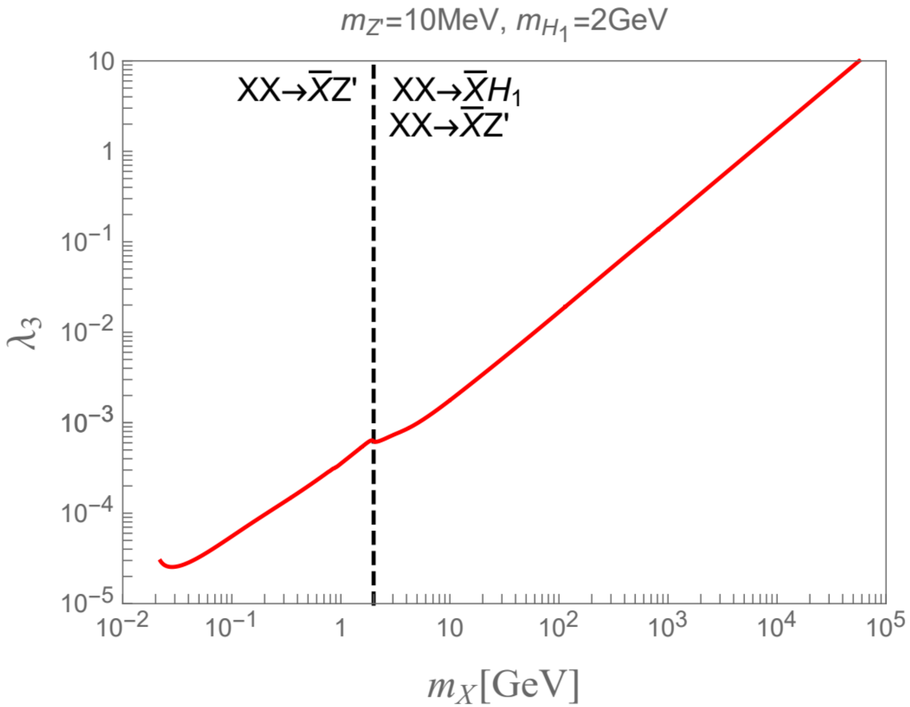


Local Z_3 scalar DM model

- Semi-annihilation:
  - Cross section is independent of the choice of v_ϕ

$$\langle\sigma v\rangle_{XX\to\bar{X}Z'} = \langle\sigma v\rangle_{XX\to\bar{X}H_1} = \frac{27}{64\pi}\frac{\lambda_3^2}{m_X^2}$$

- CMB bound: Dark Higgs, Z' predominantly decays into neutrinos



KM3-230213A
-220PeV neutrino event

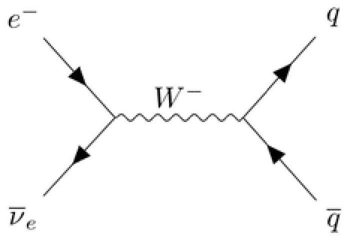
2504.16040 with Sarif Khan, Pyungwon Ko
2509.17129 with Sarif Khan, Hyun Min Lee

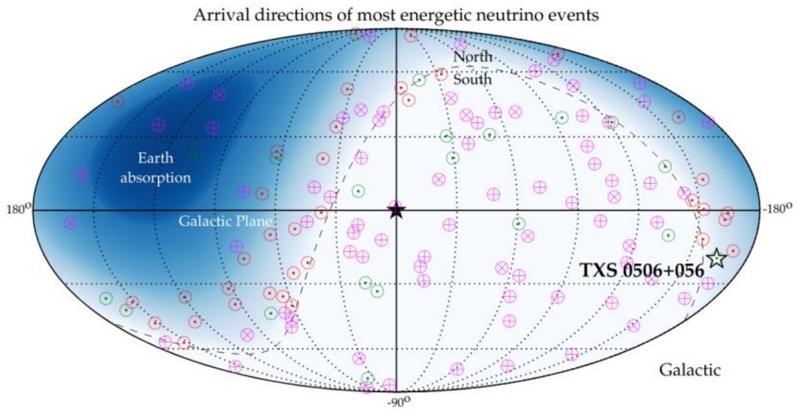
KM3Net event: KM3-230213A

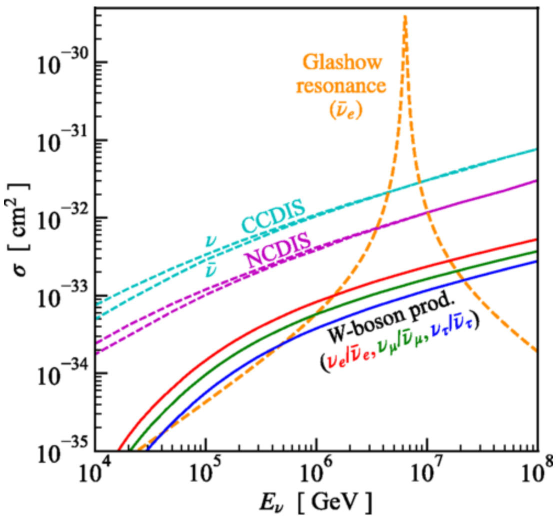
- Former Energy Champion
  - Glashow Resonance @ IceCube
  - $O(100)$ upgoing tracks and HESE events

S. Glashow, Phys. Rev. 118, 316

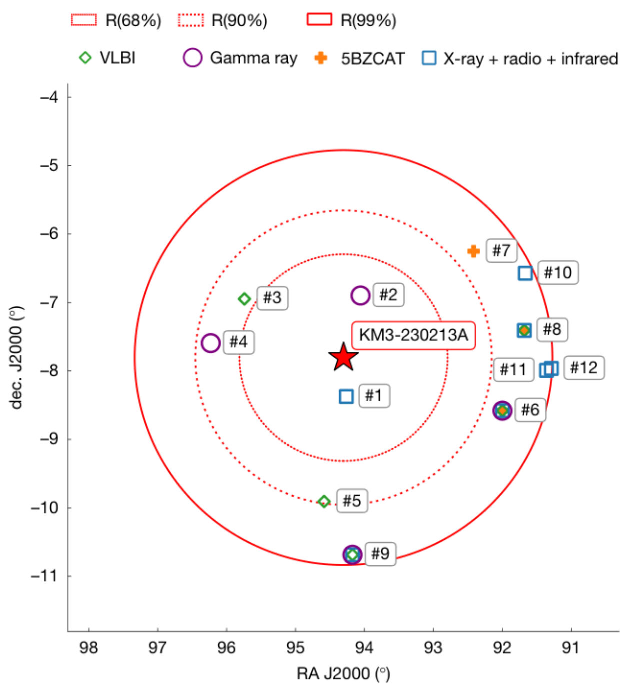
- Glashow resonance: cross section enhancement from on-shell W production
  - $\sigma \propto \frac{1}{(E-E_{res})^2+m_W^2\Gamma^2}$, with $E_{res} = \frac{m_W^2}{2m_e} \approx$ 6.3 PeV

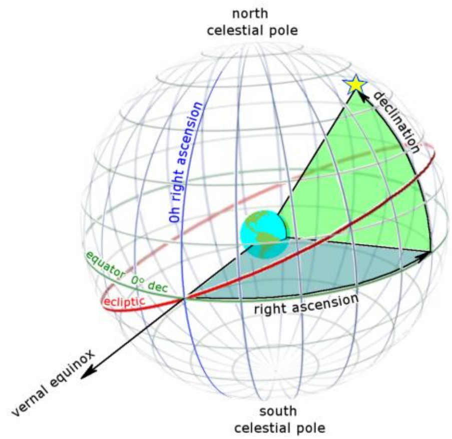






KM3Net event: KM3-230213A





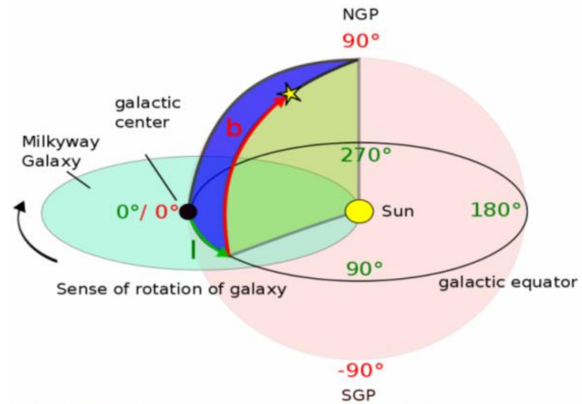
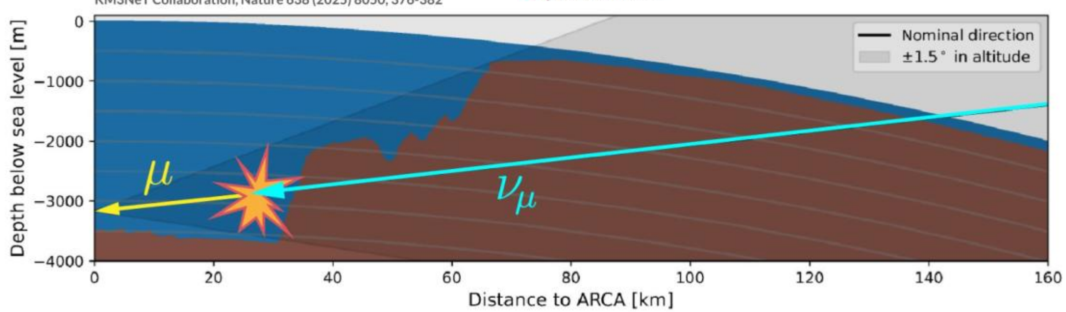


Figure 5: NGP: North Galactic Pole, SGP: South Galactic Pole
l: galactic longitude
b: galactic latitude

KM3NeT Collaboration, Nature 638 (2025) 8050, 376-382

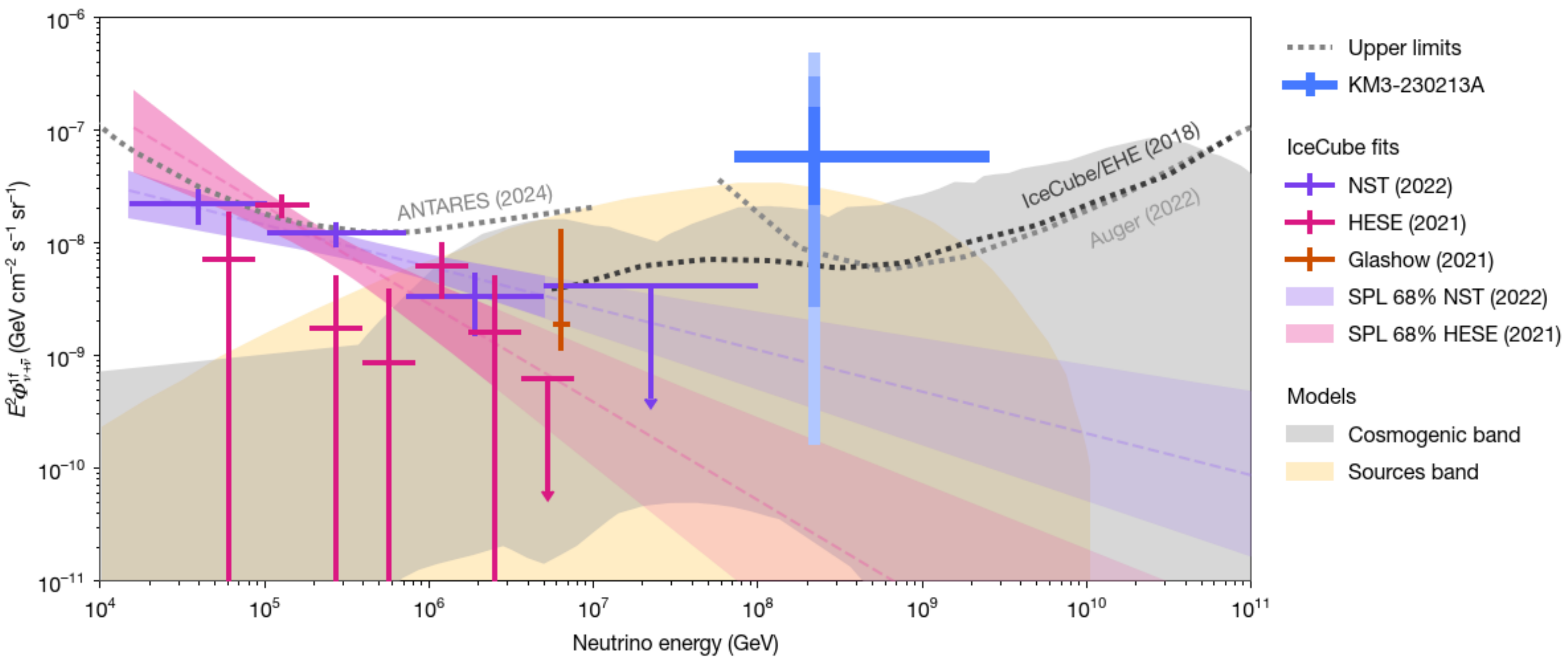


- KM3NeT
  - Consists of two detectors at different locations: ARCA & ORCA
  - ARCA detected a neutrino event on 13 Feb 2023
  - RA: $94.3^\circ \pm 1.5^\circ$, Dec: $-7.8^\circ \pm 1.5^\circ$, $E_\nu = 220^{+570}_{-100}$PeV
  - Galactic coordinate (l,b) = $(216.06^\circ, -11.13^\circ)$

KM3Net event: KM3-230213A

- If we try to understand this as a (diffuse, isotropic) cosmogenic neutrino flux, there is a huge tension with IceCube, ranging from 2.5σ to 3.8σ.
- Considering the central (90%) 72PeV-2.6EeV energy range, the steady isotropic flux that would produce one event is

$$E^2\Phi(E) = 5.8^{+10.1}_{-3.7} \times 10^{-8}\text{GeV cm}^{-2}\text{s}^{-1}\text{sr}^{-1}$$



KM3Net event: KM3-230213A

- What is the origin of the source?
  - Heavy DM with very long lifetime($\tau_{DM} \gg \tau_{\mathrm{Univ}}$)

- The neutrino flux from DM decay is composed of galactic & extragalactic contributions.
  - Galactic component & Extra-galactic component

$$\frac{d^2\Phi^{\mathrm{G}}_{\nu(\gamma)}}{dE_{\nu(\gamma)}d\Omega} = \frac{1}{\tau_{\mathrm{DM}}} \frac{\mathcal{D}}{4\pi M_{\mathrm{DM}}} \frac{dN_{\nu(\gamma)}}{dE_{\nu(\gamma)}}$$

$$\frac{\mathrm{d}J_{\mathrm{eg}}}{\mathrm{d}E_\nu} = D_{\mathrm{eg}} \int_0^\infty \mathrm{d}z \, \frac{\mathrm{d}N_\nu/\mathrm{d}E_\nu\,[(1+z)E_\nu]}{\sqrt{\Omega_\Lambda + \Omega_{\mathrm{m}}(1+z)^3}} \,,$$

$$\mathcal{D} = \frac{1}{\Delta\Omega} \int_{\Delta\Omega} d\Omega \int_0^{s_{\max}} ds \rho(\sqrt{R_{\mathrm{sc}}^2 - 2sR_{\mathrm{sc}}\cos\psi + s^2})$$

$$D_{\mathrm{eg}} = 1.4 \times 10^{-12} \left(\frac{1\,\mathrm{PeV}}{m_{\mathrm{DM}}}\right)\left(\frac{10^{27}\,\mathrm{s}}{\tau_{\mathrm{DM}}}\right)(\mathrm{cm}^2\,\mathrm{s}\,\mathrm{sr})^{-1}$$

  - Suggest the similar magnitude of the Galactic and extragalactic signals

Heavy DM decay

D. Borah et al, 2503.00097

- After Φ acquires a non-zero VEV, the RHNs and Z' acquire masses

$$M_{Z'} = 2 g_{\rm BL} v_{\rm BL}, \quad M_i = \sqrt{2} Y_{N_i} v_{\rm BL}$$

- Lagrangian

$$\mathcal{L}_{\rm fermion} = i \sum_{\kappa=1}^{3} \overline{N_{R_\kappa}} \not{D} N_{R_\kappa} - \sum_{\substack{j=1 \\ \alpha=e,\mu,\tau}}^{3} Y_D^{\alpha j} \, \overline{l_L^\alpha} \tilde{H} N_R^j - \sum_{i,j=1}^{3} Y_{N_{ij}} \Phi \, \overline{N_{R_i}^C} N_{R_j} + \text{h.c.},$$

$$\not{D} \, N_{R_\kappa} = \gamma^\mu \left(\partial_\mu - i g_{\rm BL} \, Z'_\mu \right) N_{R_\kappa}$$

- DM decay widths & lifetime

$$\Gamma(N_1 \to \nu_\alpha \, h(Z)) = \frac{|Y_D^{\alpha 1}|^2 M_1}{32\pi},$$

$$\Gamma(N_1 \to l_\alpha^- \, W^+) = \frac{|Y_D^{\alpha 1}|^2 M_1}{16\pi}.$$

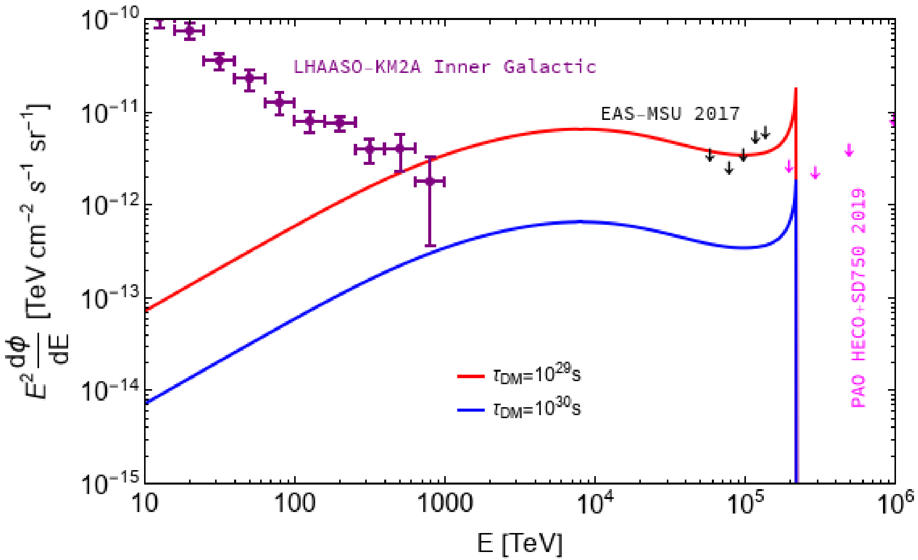
$$\tau_{N_1} \approx 8 \times 10^{28} \, \text{s} \left(\frac{440 \text{ PeV}}{M_1} \right) \left(\sum_\alpha \left| \frac{Y_D^{\alpha 1}}{4.7 \times 10^{-31}} \right|^2 \right)^{-1}$$

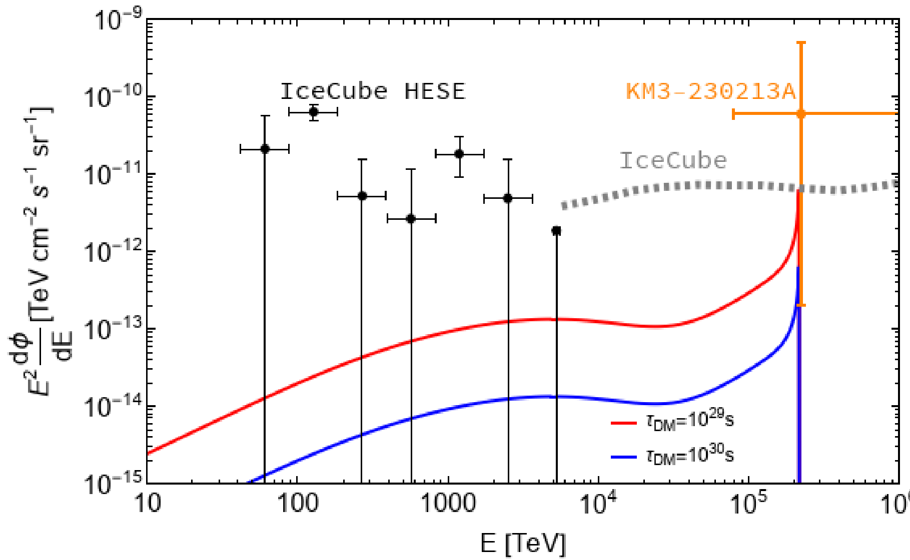
Heavy DM decay

D. Borah et al, 2503.00097

- DM can not be of thermal origin: Violation of the Unitarity bound
- Can not be produced non-thermally via Yukawa portal

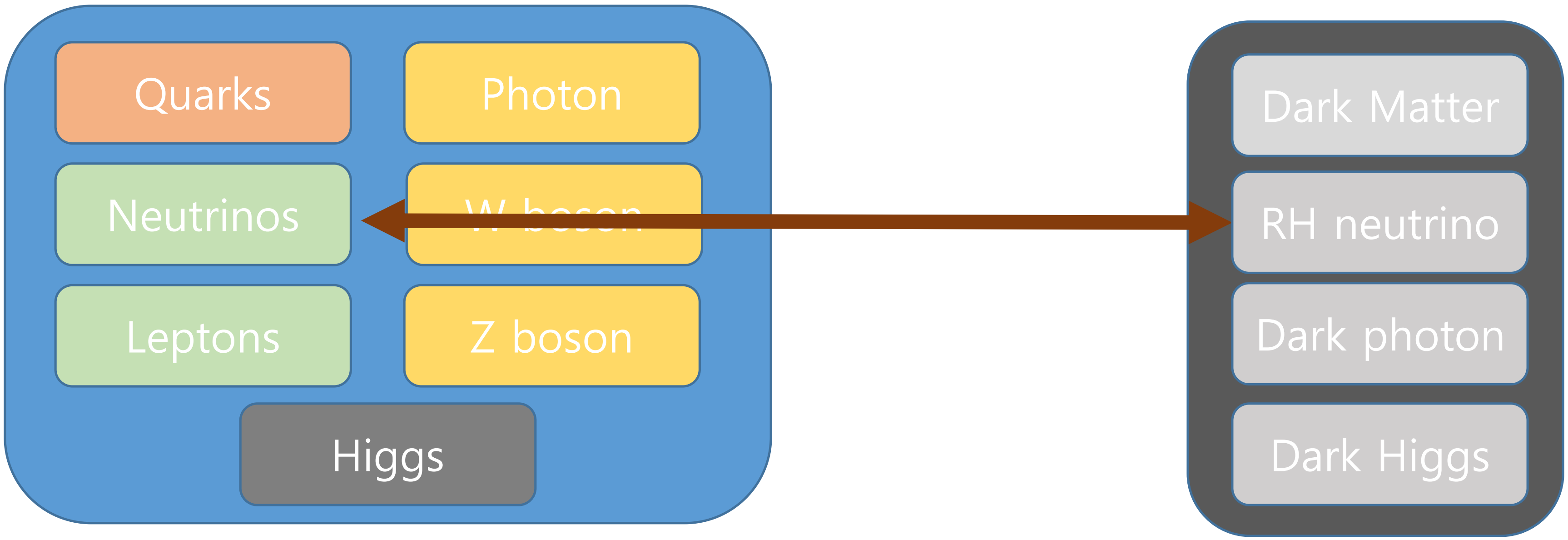
- Freeze-in mechanism
  - Singlet scalar is in thermal equilibrium
  - $\phi \to Z'Z', N_1 N_1$ & $Z' \to N_1 N_1$
- Two-body decay modes: $N_1 \to \nu, h(Z, \gamma)$ & $N_1 \to l^{\pm} W^{\mp}$





Dark $U(1)_D$ DM model

- **UV complete** $U(1)_D$-charged DM model



- **UV complete** $U(1)_D$-charged DM model
- Dark photon Z_D gets massive through $U(1)_D$ breaking
- A new singlet scalar (**Dark Higgs**), which mixes with the SM Higgs

FDM with effective operator

- Lagrangian

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{2}\bar{N} i \partial\!\!\!/ N - \left(\frac{1}{2} m_N \bar{N}^c N + y \bar{L}\widetilde{H} N + \text{h.c.}\right) - \frac{1}{4} X_{\mu\nu} X^{\mu\nu} - \frac{1}{2}\sin\epsilon X_{\mu\nu} F_Y^{\mu\nu}$$
$$+ D_\mu \Phi^\dagger D^\mu \Phi - V(\Phi, H) + \bar{\chi}\left(i D\!\!\!\!/ - m_\chi\right)\chi - \left(\kappa \bar{\chi}\Phi N + \text{h.c.}\right),$$

- After SSB, various higher-dimensional effective Ops

$$\frac{y\kappa}{2}\frac{v_\phi v_H}{m_N}\bar{\chi}\nu, \quad \frac{y\kappa}{2}\frac{v_\phi}{m_N}\bar{\chi} h\nu, \quad \frac{y\kappa}{2}\frac{v_H}{m_N}\bar{\chi}\phi\nu, \quad \frac{y\kappa}{2}\frac{1}{m_N}\bar{\chi}\phi h\nu.$$

  - Mixing between DM and active neutrino $\theta \simeq \frac{y\kappa}{2}\frac{v_\phi v_H}{m_N m_\chi}$

- Decay modes

$$\chi \to Z'\nu, Z\nu, W^\mp l^\pm \sim v_H^2 : v_\phi^2 : 2v_\phi^2.$$
$$\chi \to h\nu, \phi\nu \sim v_\phi^2 : v_H^2$$

FDM with effective operator

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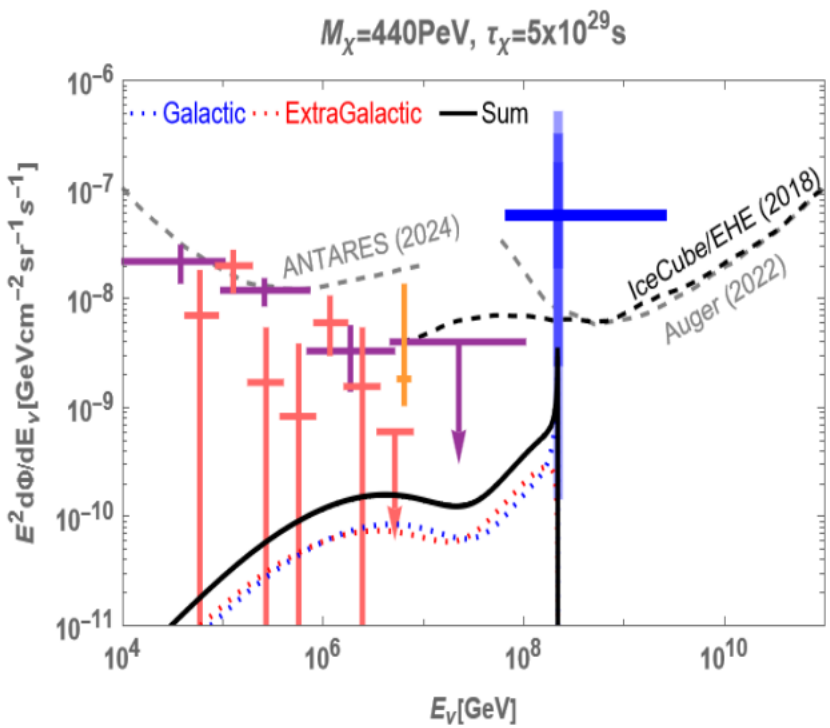
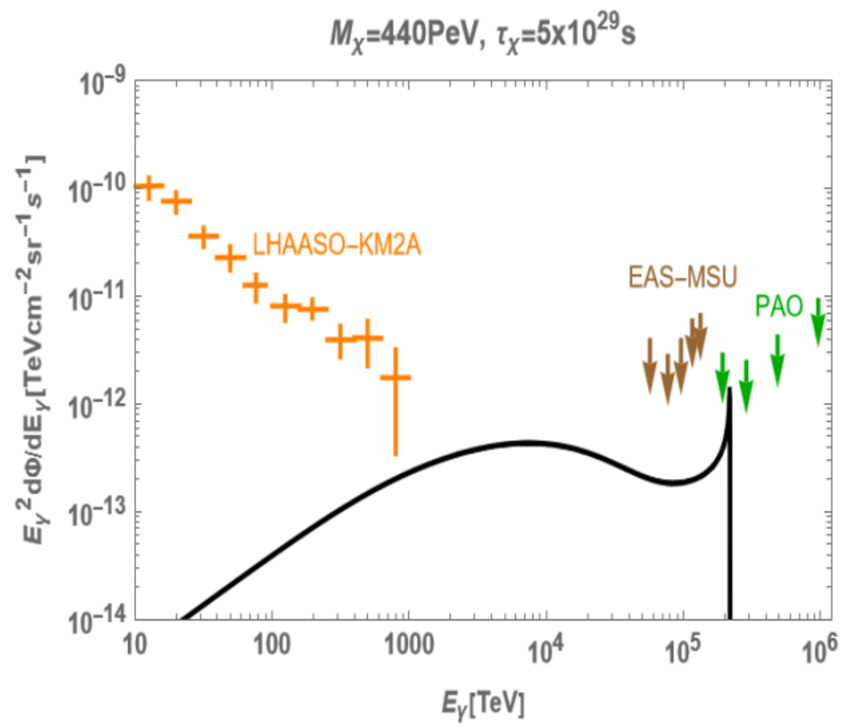




FDM with effective operator

- DM production
  - Thermal freeze-out mechanism fails to generate the correct relic density
  - We consider UV freeze-in mechanism
    → DM production is dominated at very high temperature
  - Cross section $\sigma_{\phi\phi\to\chi\bar{\chi}} = \frac{1}{8\pi s}\left(\frac{2\kappa^2}{M_N}\right)^2\left[\frac{s-4M_\chi^2}{s-4M_\phi^2}\right]^{1/2}\left(s-4M_\chi^2\right)$
  - Boltzmann Eq

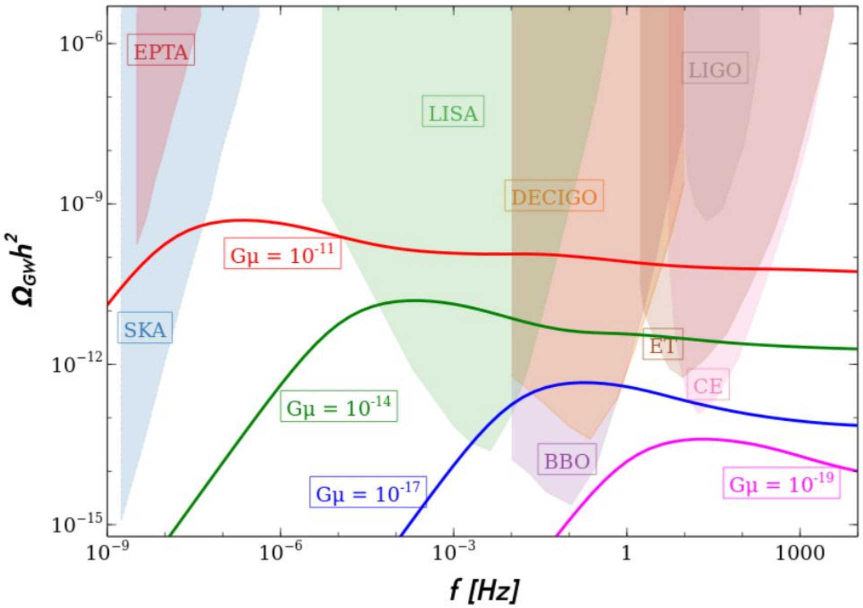
$$\frac{dY_\chi}{dz} = \frac{2M_{sc}s(T)}{z^2\mathcal{H}(T)T}\left[\langle\sigma v\rangle_{\phi\phi\to\bar{\chi}\chi}Y_\phi^2 - \langle\sigma v\rangle_{\bar{\chi}\chi\to\phi\phi}Y_\chi^2\right]$$

$$Y_\chi \simeq \frac{3.6M_{\rm pl}(T_R - T_0)}{\pi^7 g_s\sqrt{g_\rho}}\left(\frac{2\kappa^2}{M_N}\right)^2$$

FDM with effective operator

- Gravitational Waves production from cosmic string

$$\Omega_{GW}^{(k)} = \frac{1}{\rho_c}\frac{2k}{f}\frac{F_\alpha \Gamma^{(k)} G\mu^2}{\alpha(\alpha+\Gamma G\mu)}\int_{t_F}^{t_0} d\tilde{t}\frac{C_{eff}(t_i^{(k)})}{(t_i^{(k)})^4}\left[\frac{a(\tilde{t})}{a(t_0)}\right]^5\left[\frac{a(t_i^{(k)})}{a(\tilde{t})}\right]^3 \theta(t_i^{(k)} - t_F).$$



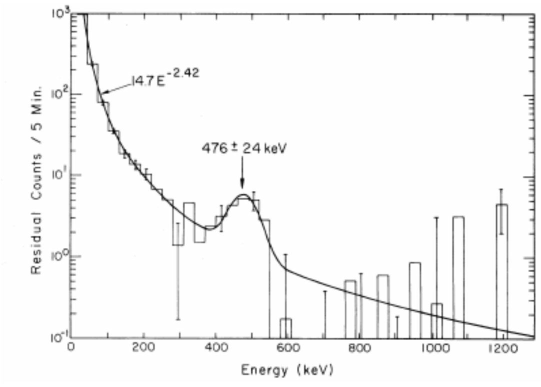
- Interesting GW from string networks with $10^{-19} < G\mu < 10^{-11}$($10^{10}$GeV $< v_\phi < 10^{14}$ GeV)

Galactic center
-511keV γ excess

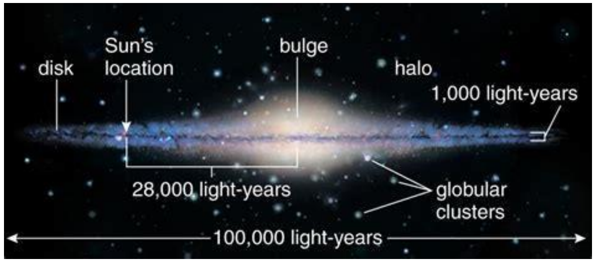
2409.07851 with Sarif Khan, Jinsu Kim, Pyungwon Ko

511keV Gamma-ray excess

- The first discovery in 1973
  - γ-rays from the galactic center (GC) region was detected with a line center at 476 ± 24 keV.



- INTEGRAL/SPI
  - 20 keV – 8 MeV, 500 cm^2,
  - FOV 16deg, angular resolution 2.5deg,
  - Energy resolution: 2.5keV @1.3MeV
  - Data taking: Dec 2002 ~



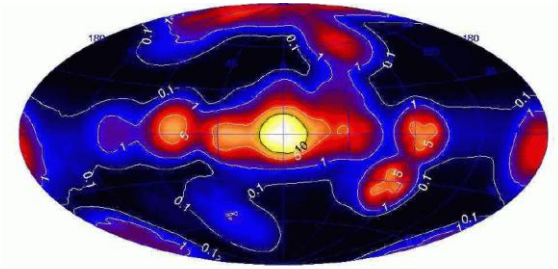


Fig. 1. Map of the effective SPI exposure at 511 keV for the dataset analysed in this work. The contours are labelled in units of 10^7 cm^2 s, corresponding to 13 ks (0.1), 133 ks (1), 667 ks (5), and 1.3 Ms (10) of effective exposure times.

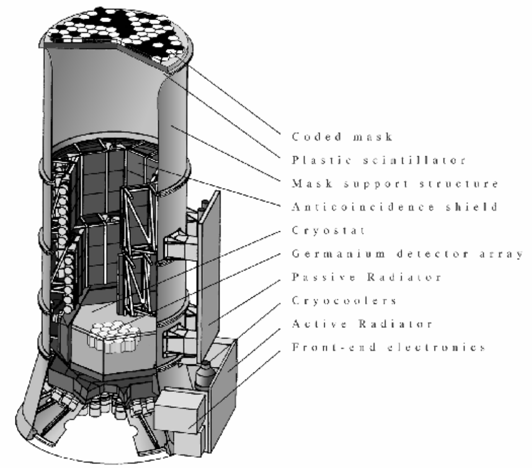
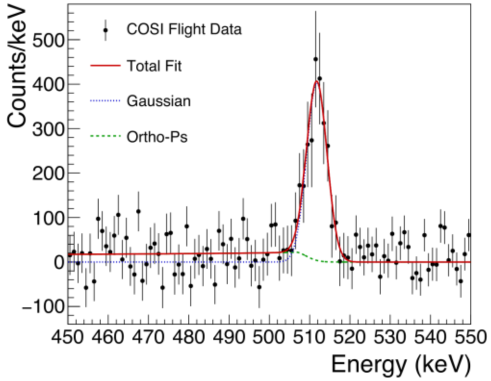


FIGURE 3 : Cutaway view of SPI and its subsystems

511keV Gamma-ray excess

C. Kierans et al, 1912.00110

- Sharp line can obviously be interpreted as originating from the annihilation of non-relativistic e^+e^- pairs.
- $\Phi_{\gamma,511} \simeq (1.02 \pm 0.10) \times 10^{-3}$ ph $\mathrm{cm}^{-2}\mathrm{s}^{-1}$.
- The detection significance is 7.2σ

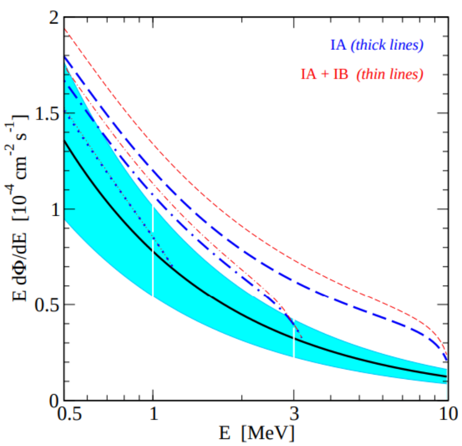


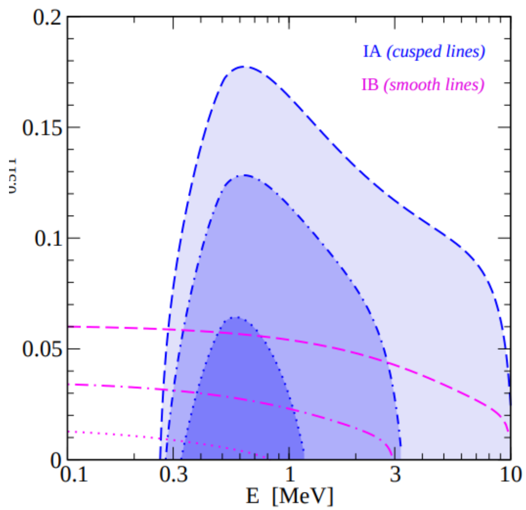
- Positronium
  - Positronium can be in two states **Para-positronium (25%)** and Ortho-positronium (75%) depending on the orientation of the spins of electron and positron
  - Para-positronium represents total spin zero which can **decay to two photons of 511 keV photon energy**.
  - Ortho-positronium represents total spin equal to one and having three states which decays to three photon of lower energy than electron mass.
  - The electron and positron eventually annihilate, releasing energy in the form gamma-rays.

511keV Gamma-ray excess

Beacom et al, PRL 06

- 511 keV line can be produced from the electron and positron through **Inflight annihilation** (IA) and Internal Bremstrahlung (IB).
  - IA can be the potential source 511 keV line if the energy of positron is smaller than 3 MeV and IB is disfavored because broadening shape in spectra.
  - We **consider e^+e^- production below 3 MeV** when we explain the 511 keV



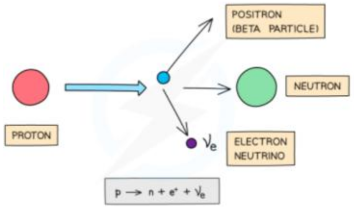


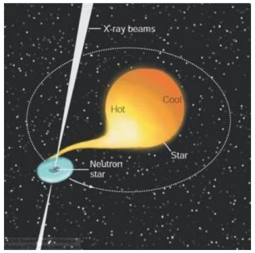
Field	Value
Total intensity	$2.74 \pm 0.25 \times 10^{-3}$ cm^{-1} s^{-1}
Bulge intensity	$0.96 \pm 0.07 \times 10^{-3}$ cm^{-1} s^{-1}
Disk intensity	$1.66 \pm 0.35 \times 10^{-3}$ cm^{-1} s^{-1}
Bulge/disk ratio	0.58 ± 0.13
Bulge extent (σ_ℓ, σ_b)	(8.7, 8.7) [degrees]
Disk extent (σ_ℓ, σ_b)	$(60^{+10}_{-5}, 10.5^{+2.5}_{-1.5})$ [degrees]
Ps fraction f_{Ps} (bulge)	1.080 ± 0.029
Injection energy of e^+	$\lesssim$3 MeV

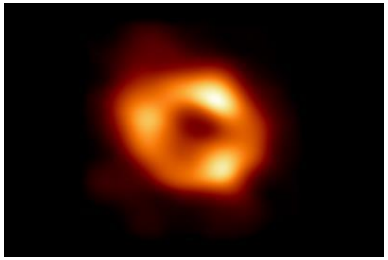
511keV Gamma-ray excess

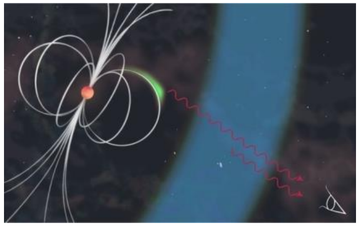
- Various possible Sources of positron

- Astrophysical sources
  - Massive stars, Hypernovae, Cosmic-ray interactions (N + p → π+ → e+), X-ray binaries (HMXB, LMXB), Classical novae, Thermonuclear Type Ia supernovae (SN Ia).









- **Particle physics**
  - DM annihilation or decay

- The shape and flux of the emission impose severe constrains on the principal galactic e+ sources.

511keV Gamma-ray excess

C. Boehm et al, 0408213
Y. Ema et al, 2007.09105
…

- Light WIMP DM annihilation
  - DM annihilation into an e^+e^- pair
  - A positron injection energy smaller than 3MeV
  - s-wave cannot explain due to small cross section
  - p-wave or $\chi\chi \longrightarrow \varphi\varphi, \varphi \longrightarrow e^+e^-$ $(m_\varphi < m_\chi < 6\text{MeV})$

$$\langle \sigma v \rangle_{511} \simeq 5 \times 10^{-31} \left(\frac{M_{\text{DM}}}{3\ \text{MeV}} \right)^2 \frac{\text{cm}^3}{\text{s}},$$

C. Cappiello et al, 2307.15114

- XDM decay: $\chi_0\chi_0 \longrightarrow \chi_1\chi_1,\ \chi_1 \longrightarrow \chi_0 e^+e^-$
  - Relative velocity btw DMs must be above $v_{th} = \sqrt{4\delta m/m_0}$
  - $100\text{GeV} \leq m_\chi \leq 3\text{TeV}$
  - $10^{-19}\text{cm}^3\text{s}^{-1} \lesssim \langle \sigma v \rangle \lesssim 10^{-16}\text{cm}^3\text{s}^{-1}$

511keV Gamma-ray excess

W. Lin et al, 2205.08171

- Galactic 511keV emission has a rather diffuse morphology but is more concentrated towards the GC → focus on the bulge flux
  - Explain the observed Galactic 511keV gamma-ray
  - DM can only constitute a small fraction of DM

$$f_{\mathfrak{f}} \exp(t_{\mathrm{U}}/\tau) < 1.$$

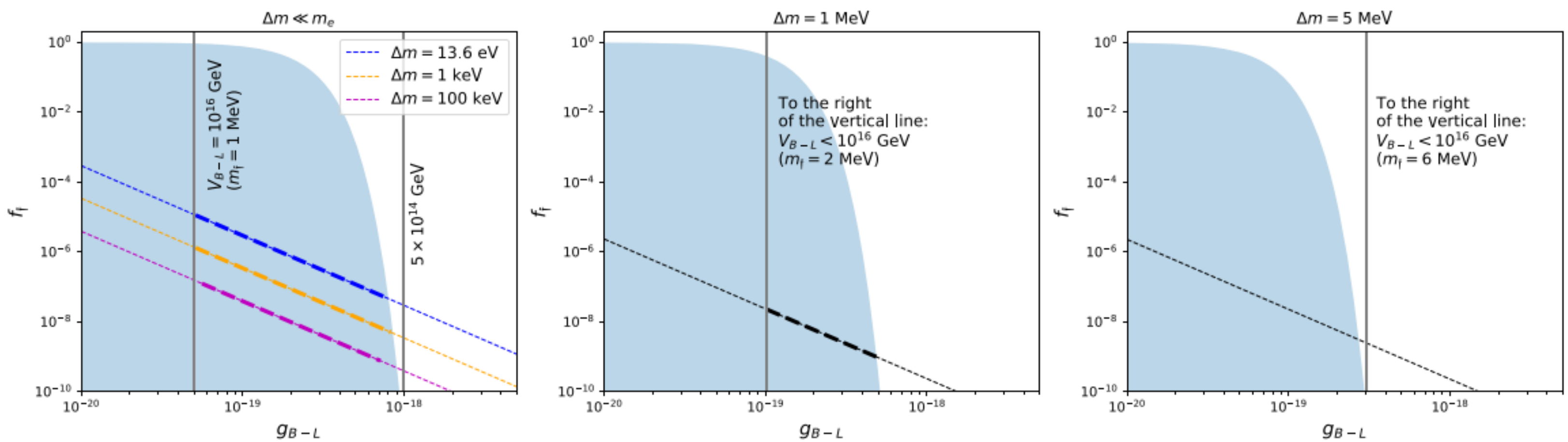
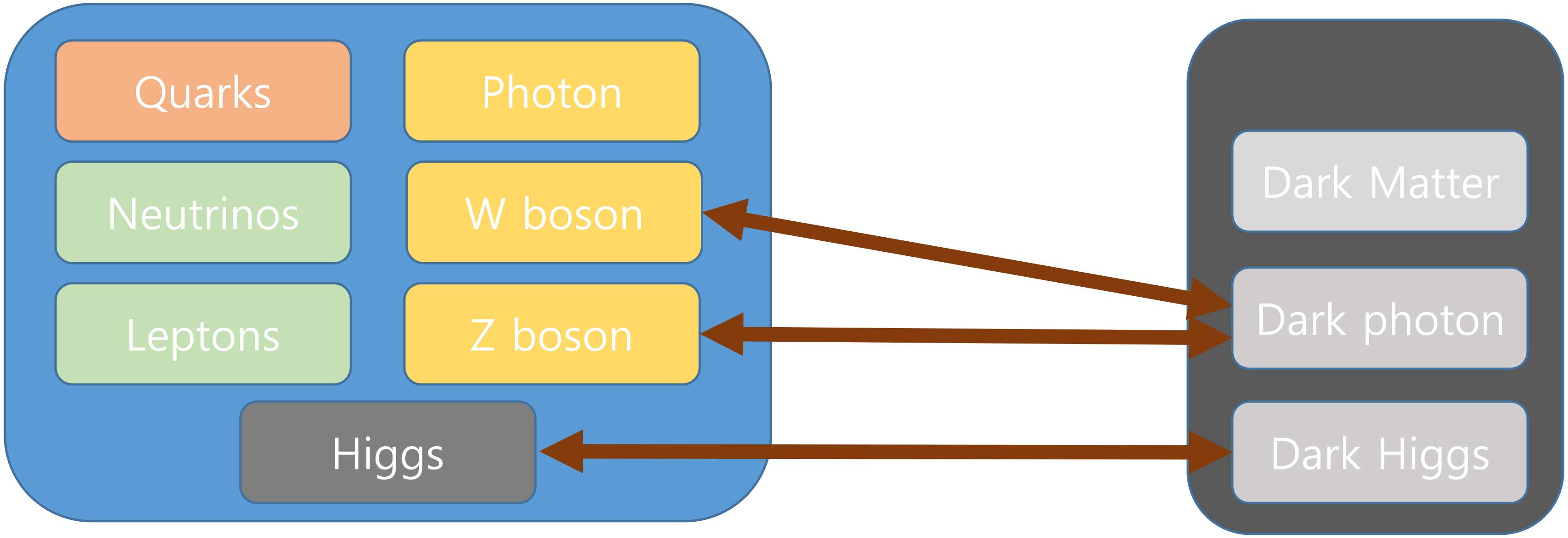


FIG. 2. Parameter space in cases with different $m_{\mathfrak{f}}$ (and $\Delta m \equiv m_{\mathfrak{f}} - 2m_e$). Left: $\Delta m \ll m_e$. The light blue region is the cosmologically viable parameter space. The vertical line indicates the value of $g_{B-L} = m_{\mathfrak{f}}/(2V_{B-L})$ for some specific values of V_{B-L}. The dashed lines are parameters that can account for the bulge positron annihilation flux, while the thicker portions also satisfy the cosmological constraints and the motivation from the seesaw mechanism. Middle: $m_{\mathfrak{f}} = 2$ MeV. Right: $m_{\mathfrak{f}} = 6$ MeV. There is no viable parameter space when $m_{\mathfrak{f}} \gtrsim 6$ MeV.

$$f_{\mathfrak{f}} \left(\frac{g_{B-L}}{10^{-20}}\right)^2 \sqrt{1 - \frac{4m_e^2}{m_{\mathfrak{f}}^2}} \left(1 + \frac{2m_e^2}{m_{\mathfrak{f}}^2}\right) \simeq 2.3 \times 10^{-7}, \quad (4)$$

Dark $U(1)_D$ DM model

- Let's call Z_D,$U(1)_D$ gauge boson, dark photon DM (VDM)
  - Thanks to tiny kinetic mixing



- **UV complete** $U(1)_D$-charged DM model
- Dark photon Z_D gets massive through $U(1)_D$ breaking
- A new singlet scalar (**Dark Higgs**), which mixes with the SM Higgs

Dark $U(1)_D$ DM model

Babu et al, PRD 98

- Lagrangian

$$\mathcal{L}_{\rm M} = \mathcal{L}_{\overline{\rm SM}} - \frac{1}{4}\hat{X}_{\mu\nu}\hat{X}^{\mu\nu} - \frac{\sin\epsilon}{2}\hat{X}_{\mu\nu}\hat{B}^{\mu\nu} + |D\phi_D|^2 + |DH|^2 - V(\phi_D, H)$$

- Scalar potential

$$V(\phi_D, H) = -\mu_D^2|\phi_D|^2 + \lambda_D|\phi_D|^4 - \mu_H^2|H|^2 + \lambda_H|H|^4 + \lambda_{HD}|\phi_D|^2|H|^2 .$$

- Relation between mass and flavor gauge basis (ϵ, ζ)

$$\hat{B}_\mu = \cos\theta_w A_\mu - (\tan\epsilon\sin\zeta + \sin\theta_w\cos\zeta)\, Z_\mu - (\tan\epsilon\cos\zeta - \sin\theta_w\sin\zeta)\, Z_{D\mu} ,$$

$$\hat{X}_\mu = \frac{\sin\zeta}{\cos\epsilon} Z_\mu + \frac{\cos\zeta}{\cos\epsilon} Z_{D\mu} ,$$

$$\hat{W}^3_\mu = \sin\theta_w A_\mu + \cos\theta_w\cos\zeta Z_\mu - \cos\theta_w\sin\zeta Z_{D\mu} .$$

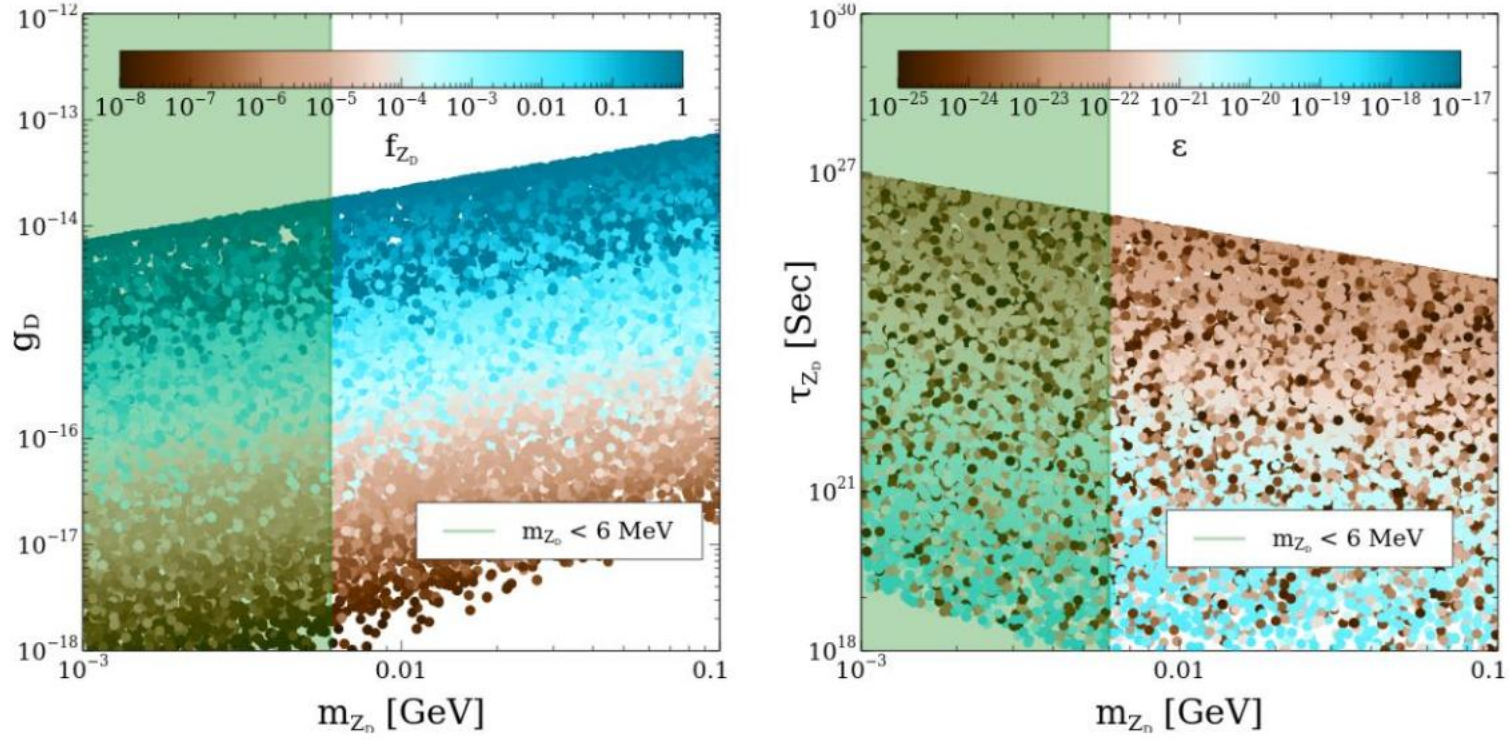
- Scalars after SSB, Z_D gets massive: $m_{Z_D} = g_D|Q_\Phi|v_\Phi$

$$\mathcal{H} = \frac{1}{\sqrt{2}}(0 \;\; v_H + h)^{\mathsf{T}} ,\; \Phi = \frac{1}{\sqrt{2}}(v_\Phi + \phi) \Rightarrow m^2_{h\phi} = \begin{pmatrix} 2\lambda_H v_H^2 & \lambda_{HD} v_H v_D \\ \lambda_{HD} v_H v_D & 2\lambda_D v_D^2 \end{pmatrix}$$

$$h_1 = h\cos\theta + \phi\sin\theta$$
$$h_2 = \phi\cos\theta - h\sin\theta$$

Scatter plots

- Vector DM relic is directly proportional to the square of the gauge coupling g_D
- Any fraction of VDM is allowed for the FIMP case to explain the 511 keV line which was not possible for WIMP case



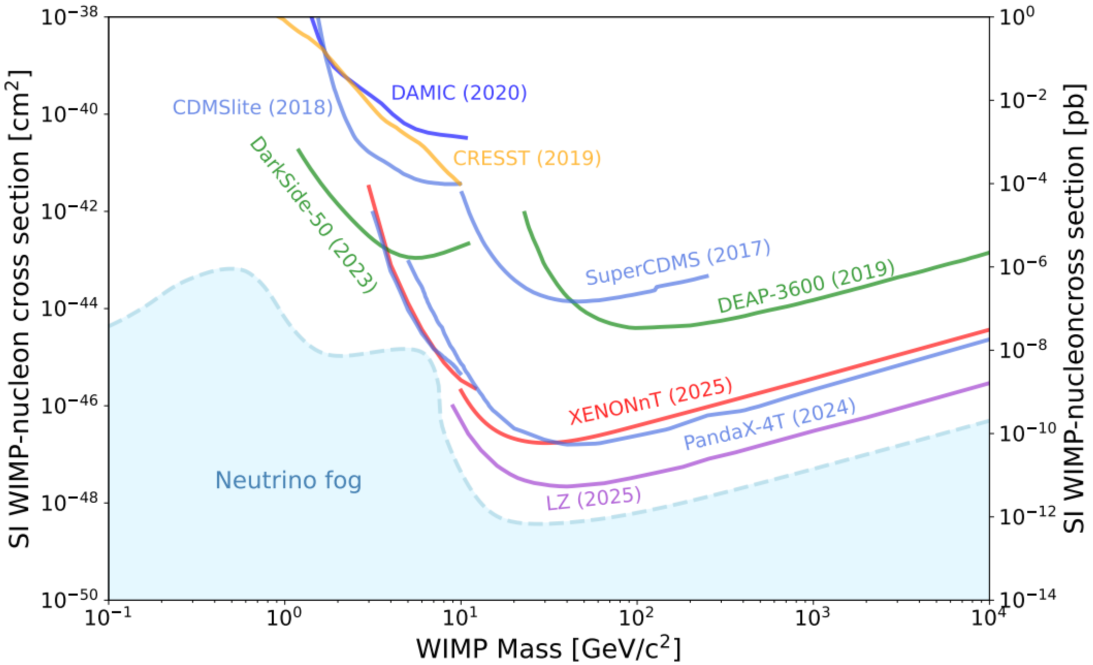
Pseudo Nambu-Goldstone Boson DM

Ongoing work with Junho Kang, Sarif Khan, Hyun Min Lee

WIMP Dark Matter

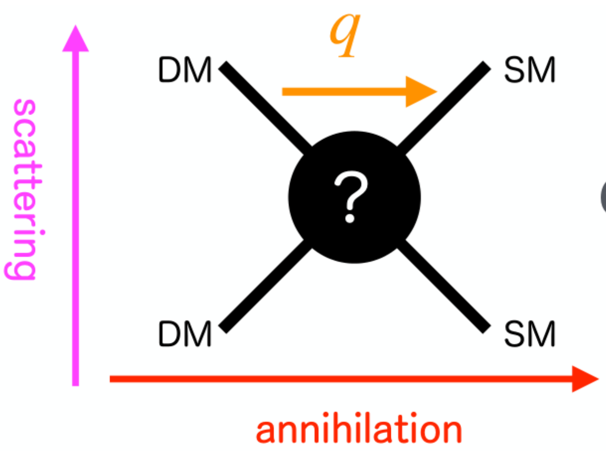
PDG 2026

- Null result



- The direct detection experiments give upper bounds on the DM-nucleon scattering cross section
- LZ experiment gives the most stringent bound
  - $\sigma < 3 \times 10^{-48}\mathrm{cm}^2$ for $m_\chi = 100\mathrm{GeV}$

WIMP Dark Matter



$\propto q^n$

- $q \sim m_\chi$ @ DM annihilation
- $q \sim O(10)$MeV @ direct detection

- If amplitude depends on momentum, we can suppress the scattering amplitude in direct detection while keeping the annihilation process
  - Consider WIMP DM models that have momentum dependent amplitude

Pseudo Nambu-Goldstone DM

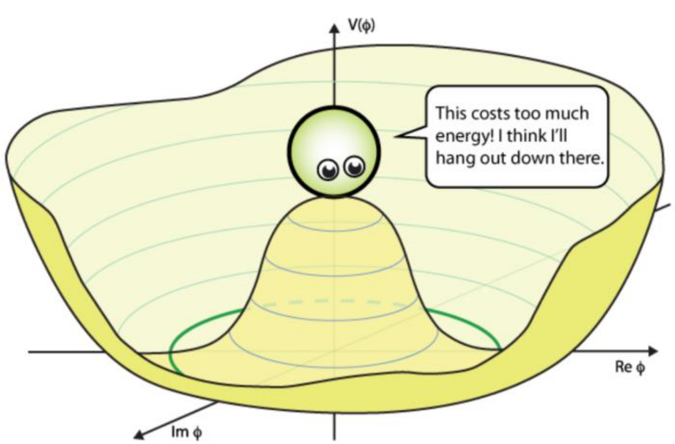
symmetry : $G_{\rm SM} \times U(1)_{\rm global}$ new fields : complex $S \in \mathbf{1}_0$

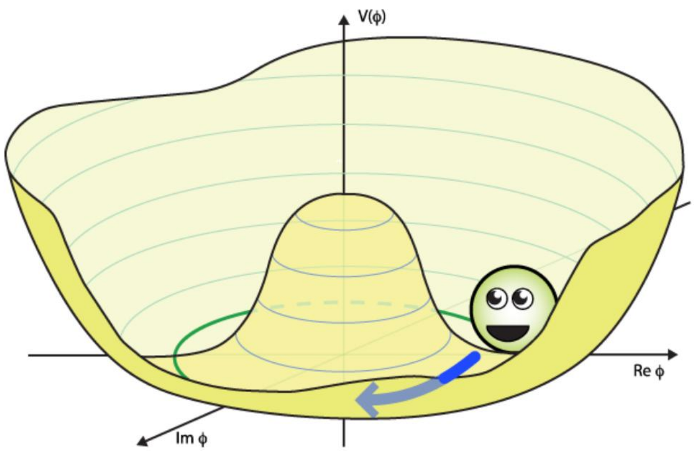
$$V(H,S) = -\frac{\mu_H^2}{2}|H|^2 - \frac{\mu_S^2}{2}|S|^2 + \frac{\lambda_H}{2}|H|^4 + \lambda_{HS}|H|^2|S|^2 + \frac{\lambda_S}{2}|S|^4$$

- After H and S acquire VEVs,

$$H = \begin{pmatrix} 0 \\ \frac{v+h}{\sqrt{2}} \end{pmatrix}, \quad S = \frac{v_s + \tilde{s} + i\chi}{\sqrt{2}} \qquad \begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} h \\ s \end{pmatrix}$$

χ :NGB DM





Thank you very much