KOREA
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ADVANCED
STUDY

Recent $B^+\to K^+\nu\bar{\nu}$ Excess & Muon $g-2$ Illuminating Light DM with Higgs Portal

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Based on arXiv : 2401.10112

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03/Sep/2024

Workshops on Multi-Higgs Models, Instituto Superior Técnico

Evidence of dark matter

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

Solar system

Galaxies

Clusters of galaxies

Observable Universe

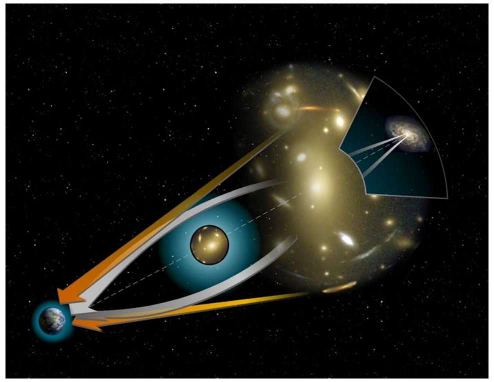
pc

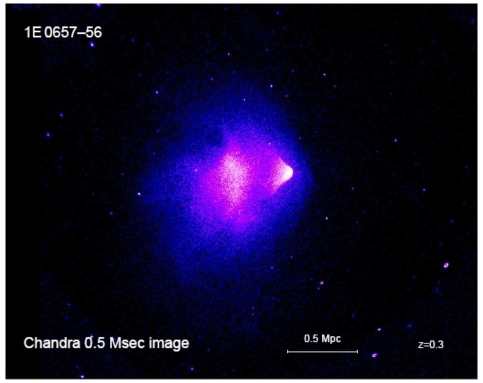
kpc

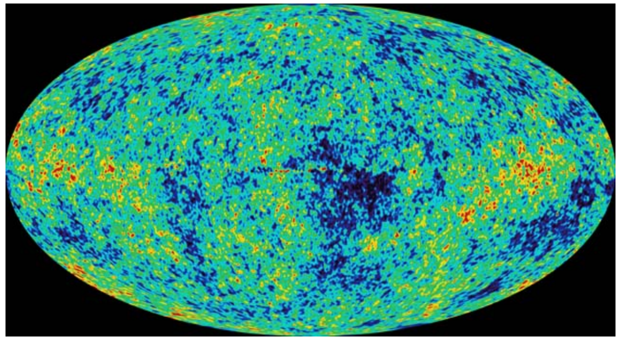
Mpc

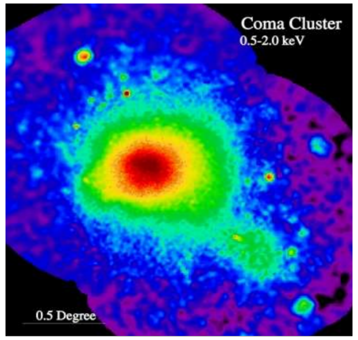
Gpc

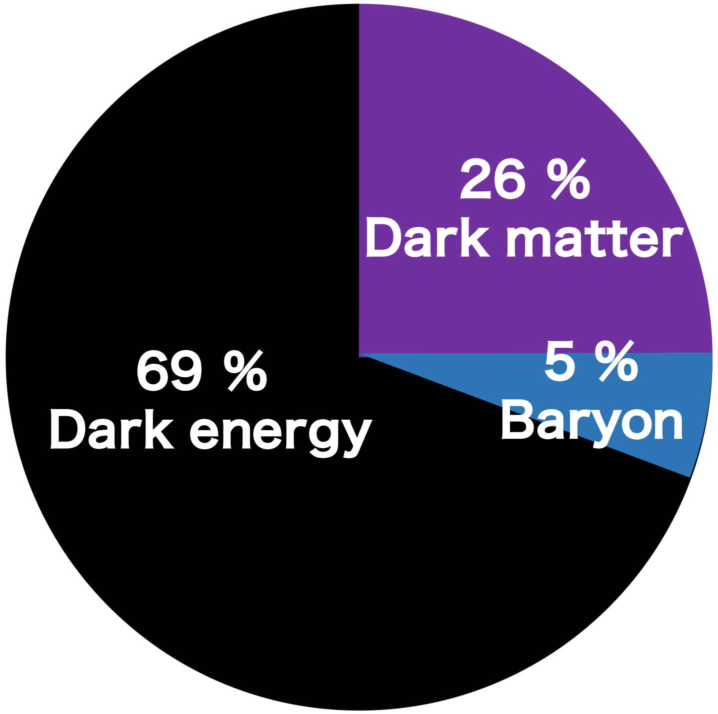
distance

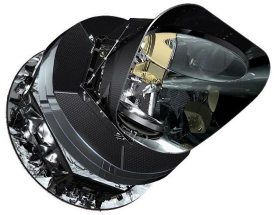






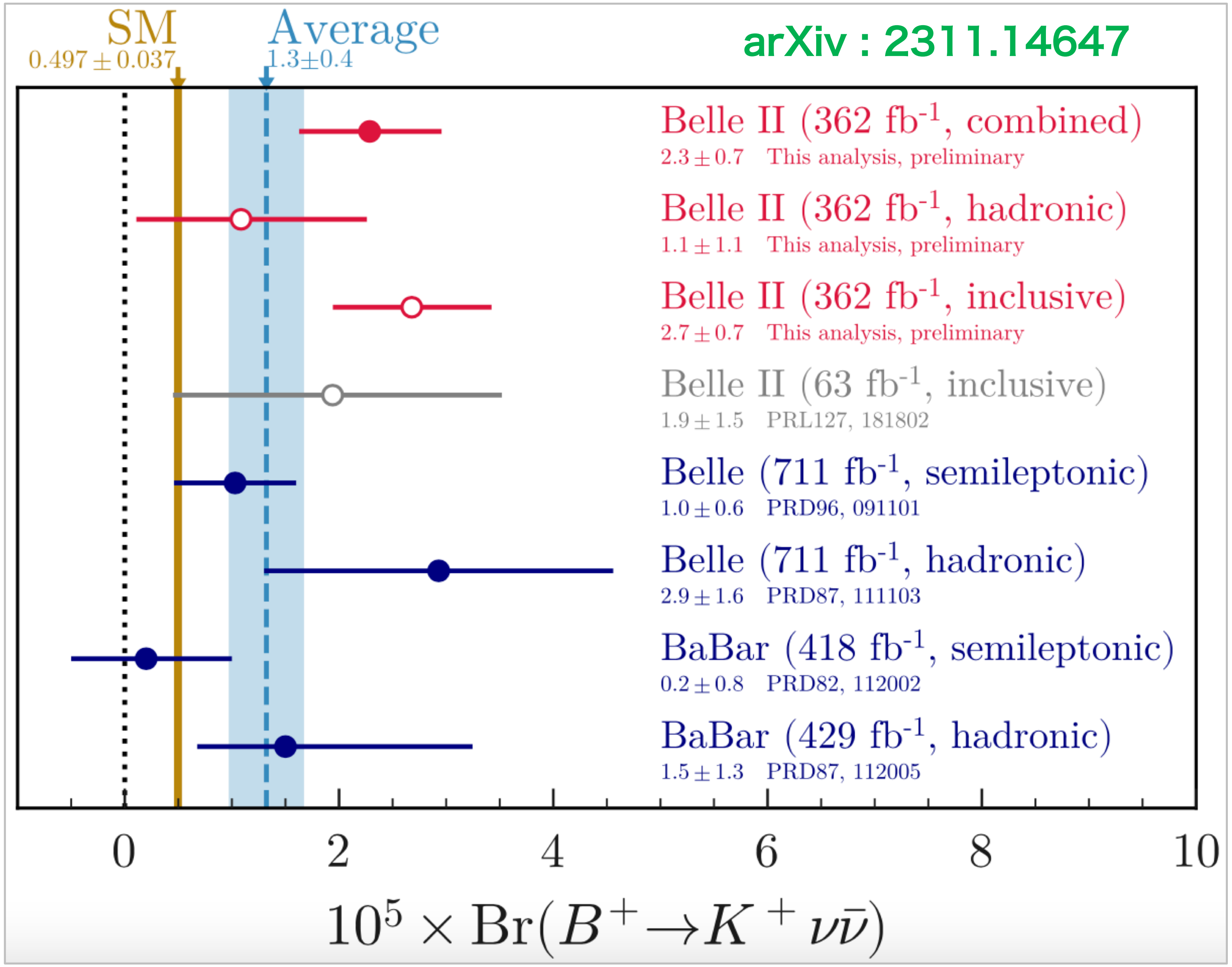






Planck 2018

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



The Belle II has found the first evidence of the $B^+ \to K^+\nu\bar{\nu}$ decay predicted by the SM.

Combined result :
(hadronic + inclusive)

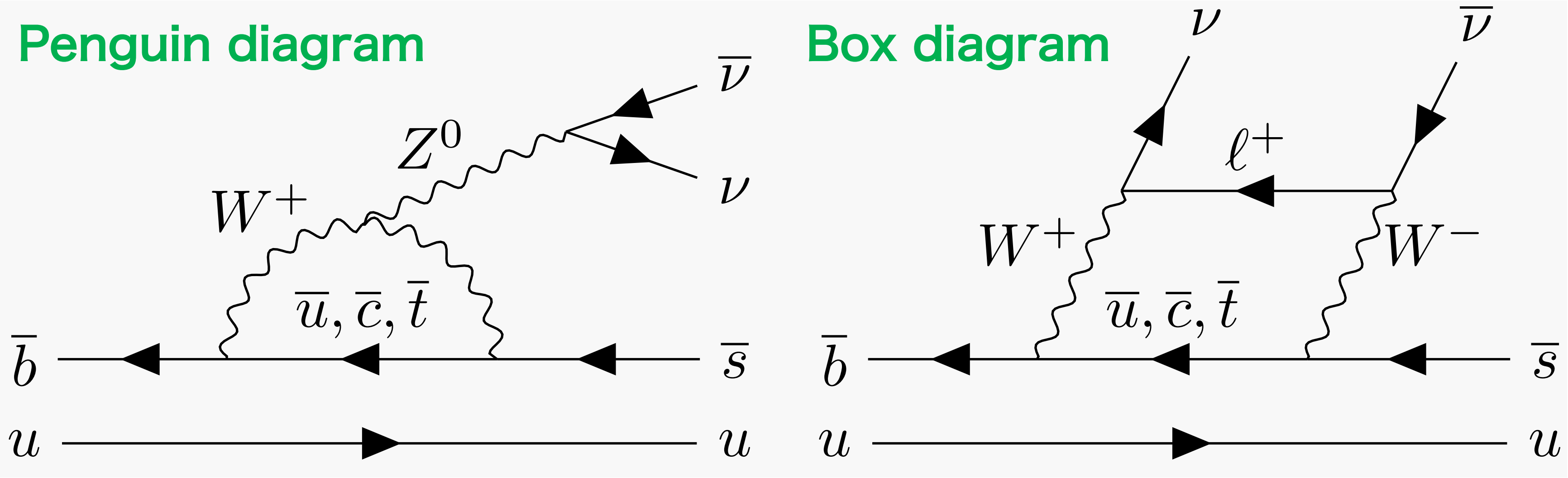
$$\mathcal{B}(B^+ \to K^+\nu\bar{\nu})_{\text{exp.}} = (2.3 \pm 0.7) \times 10^{-5}$$

3.5 standard deviations

Prediction of $B^+ \to K^+ \nu\bar{\nu}$ by the SM

- The decay rate of the $B^+ \to K^+ \nu\bar{\nu}$ process is calculated with high accuracy in the SM.

HPQCD, PRD 2023



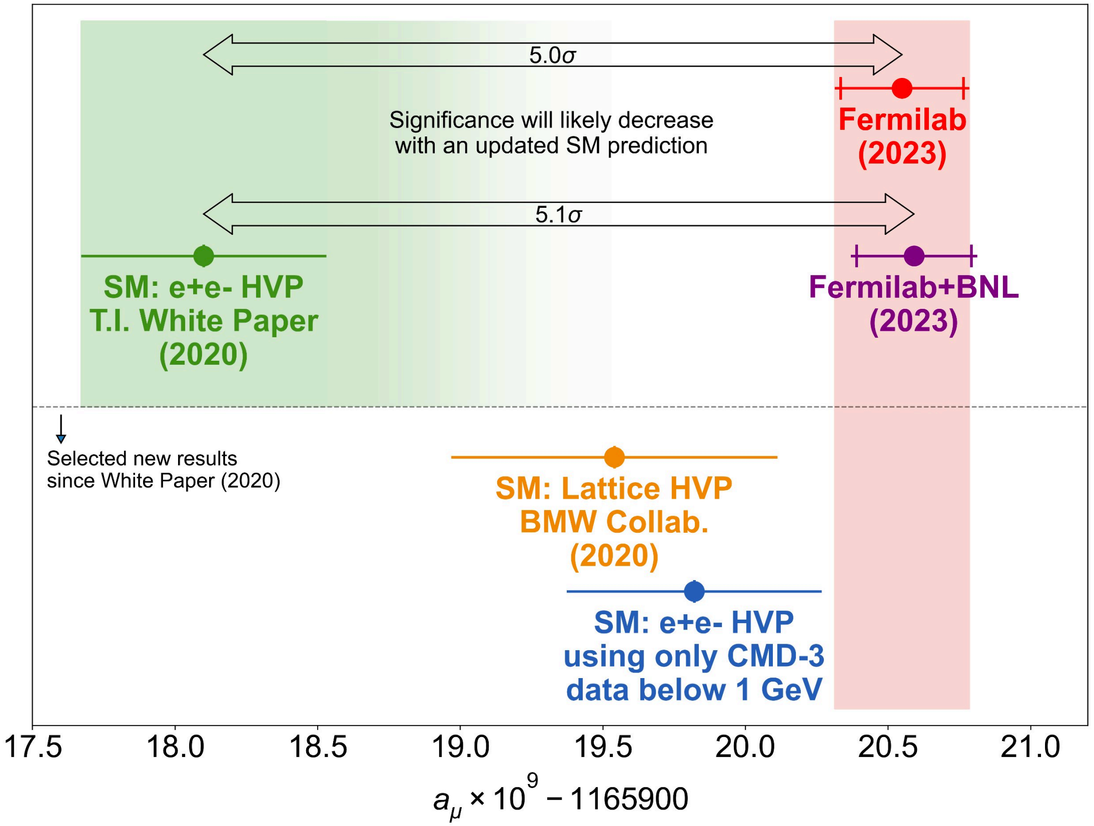
- $\mathcal{B}(B^+ \to K^+ \nu\bar{\nu})_{\text{SM}} = (4.97 \pm 0.37) \times 10^{-6}$
- $\mathcal{B}(B^+ \to K^+ + \text{missing energy}) = (1.8 \pm 0.7) \times 10^{-5}$

$\Longrightarrow$ $B^+ \to K^+ +$ **light dark particles** ?

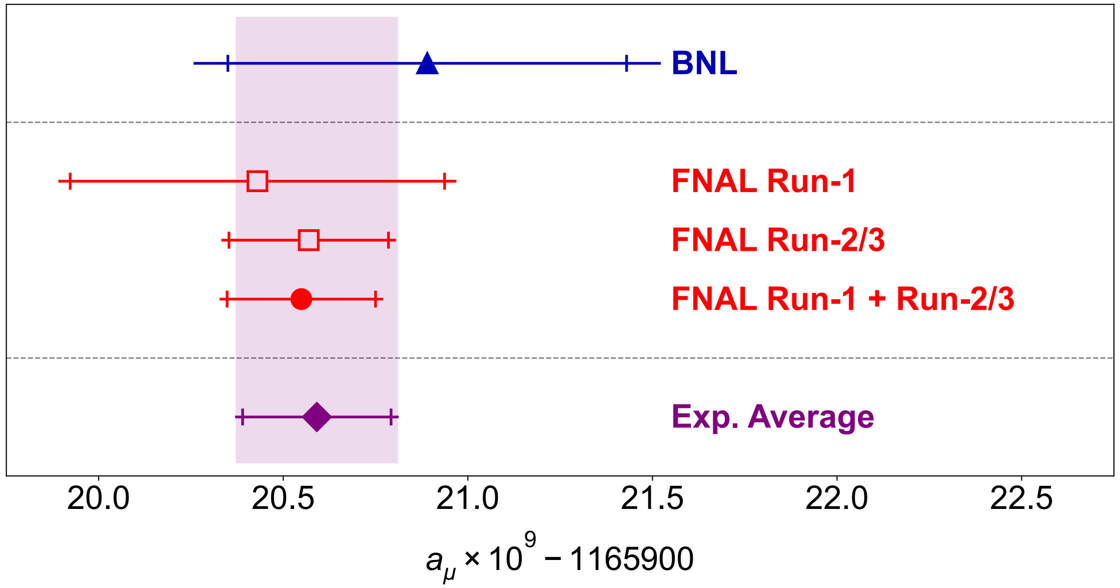
Muon magnetic moment $(g-2)_\mu$

- The Fermilab Muon g-2 experiment improves the precision of their previous result by a factor of 2.

Muon g-2 collaboration, PRL 2023



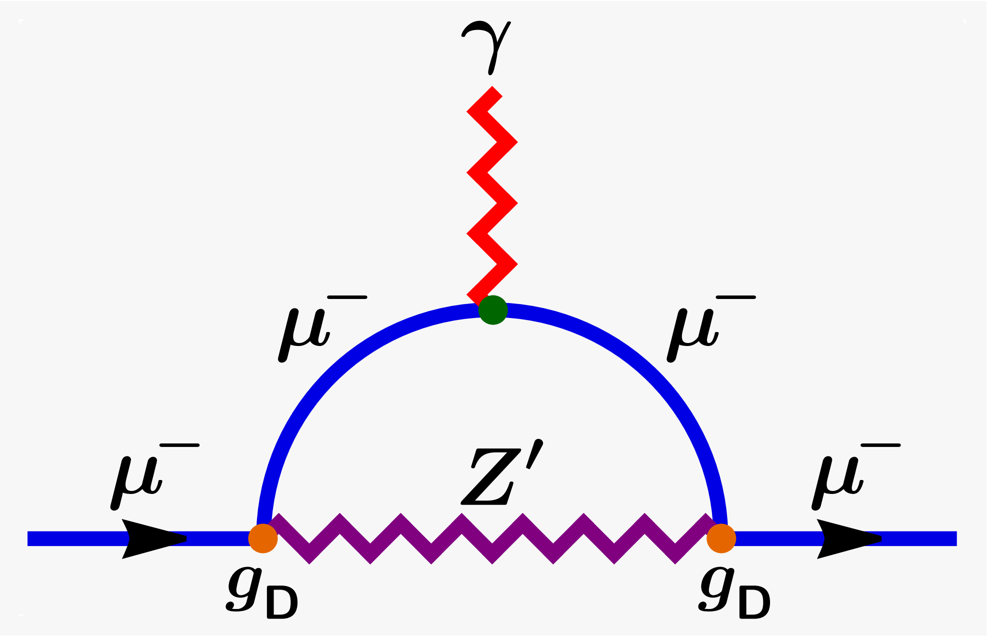
$$a_\mu^{\text{SM}} = 116\,591\,810(43) \times 10^{-11}$$
$$a_\mu^{\text{exp.}} = 116\,592\,059(22) \times 10^{-11}$$



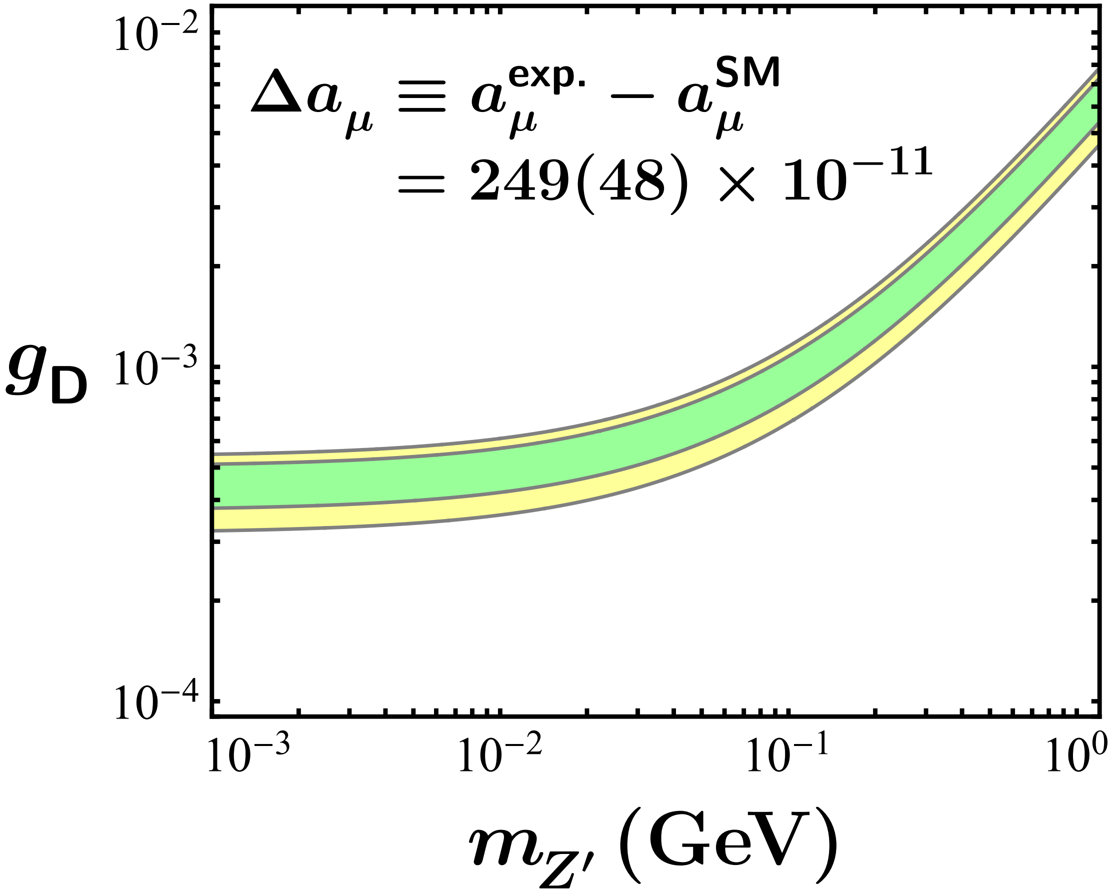
- In this talk, we will consider 5.1 σ is real to be explained by new physics BSM.

A new gauge boson?

- The simplest way to resolve the muon g-2 anomaly is to introduce a new gauge boson which couples to the muon



$$\Delta a_\mu = \frac{g_\mathsf{D}^2}{4\pi^2}\int_0^1 \mathrm{d}x\,\frac{m_\mu^2 x^2(1-x)}{m_\mu^2 x^2 + (1-x)m_{Z'}^2}$$



- $m_{Z'} \sim 10^{(1-2)}\,\mathrm{MeV}$ & $g_\mathsf{D} \sim 10^{-4}$ can explain Δa_μ anomaly

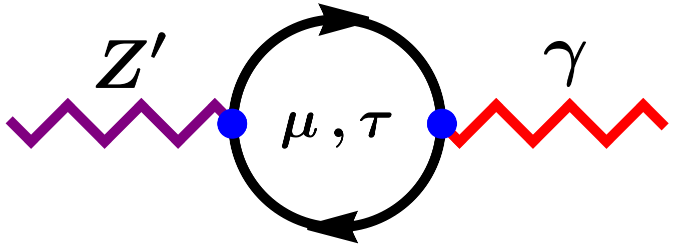
Gauged $\mathrm{U(1)}_{\mathrm{L}_\mu - \mathrm{L}_\tau}$ Model

- Without new fermions, there are three anomaly-free models by gauging one of the three differences of lepton flavors
  - $\mathsf{L}_e - \mathsf{L}_\mu$, $\mathsf{L}_e - \mathsf{L}_\tau$, $\mathsf{L}_\mu - \mathsf{L}_\tau$

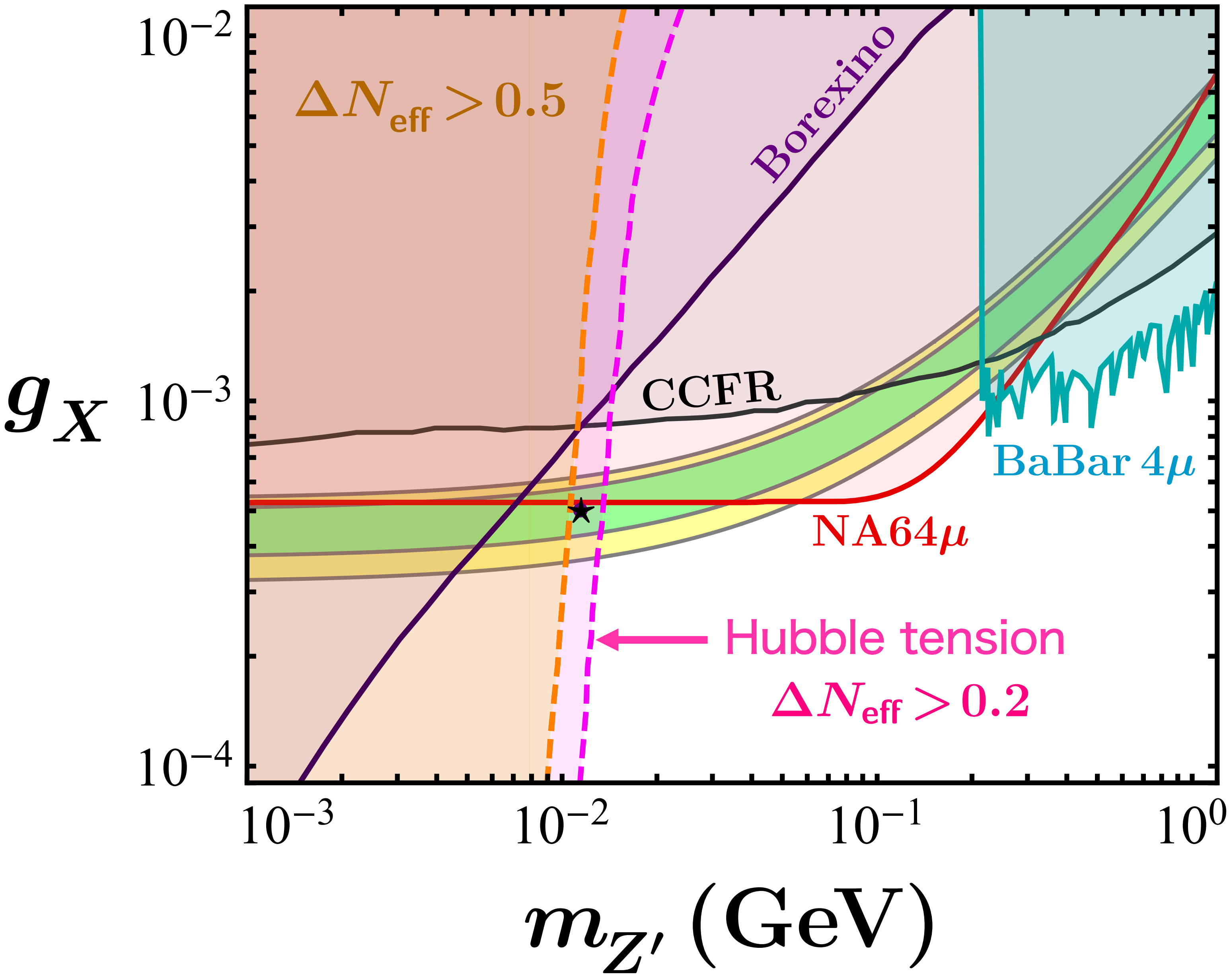
    X. G. He et al, PRD 1991
  - Symmetry including L_e is strongly constrained
  - Charge assignments : $\widehat{\mathcal{Q}}_{\mathsf{L}_\mu - \mathsf{L}_\tau}(\nu_\mu, \nu_\tau, \mu, \tau) = (1, -1, 1, -1)$
- Unavoidable kinetic mixing between Z' and γ

$$\epsilon = -\frac{e g_{\mu-\tau}}{2\pi^2} \int_0^1 dx\, x(1-x) \ln\left[\frac{m_\tau^2 - x(1-x)q^2}{m_\mu^2 - x(1-x)q^2}\right]$$

$$\xrightarrow{q^2 \ll m_\mu^2} -\frac{e g_{\mu-\tau}}{12\pi^2} \ln\left(\frac{m_\tau^2}{m_\mu^2}\right) \simeq -\frac{g_{\mu-\tau}}{70}$$



g_X vs. $m_{Z'}$



$\mathcal{O}(10)$ MeV Z' reaches thermal equilibrium in the early universe and decays into neutrinos, increasing the neutrino number density ($N_{\rm eff}$).

M. Escudero et al, JHEP 2019

Benchmark point

$m_{Z'} = 11.5\,\mathrm{MeV}$

$g_X = 5 \times 10^{-4}$

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

- Particle content & charge assignments

$$\widehat{\mathcal{Q}}_{\mathsf{L}_\mu-\mathsf{L}_\tau}(\nu_\mu,\nu_\tau,\mu,\tau,X,\Phi)=(1,-1,1,-1,\mathcal{Q}_X,\mathcal{Q}_\Phi)$$

$= 1$

complex singlet scalar DM

SM Higgs singlet

- The renormalizable and gauge invariant Lagrangian

$$\begin{aligned}\mathcal{L}=&\,|\mathcal{D}_\rho\Phi|^2+|\mathcal{D}_\rho X|^2-\tfrac{1}{4}(\partial_\rho Z'_\omega-\partial_\omega Z'_\rho)^2-m_X^2|X|^2\\&-g_X\Big(\bar{\mu}\gamma^\rho\mu-\bar{\tau}\gamma^\rho\tau+\bar{\nu}_{L\mu}\gamma^\rho\nu_{L\mu}-\bar{\nu}_{L\tau}\gamma^\rho\nu_{L\tau}\Big)Z'_\rho\\&-\lambda_{\Phi X}|X|^2\Big(|\Phi|^2-\tfrac{1}{2}v_\Phi^2\Big)-\lambda_{HX}|X|^2\Big(|\mathcal{H}|^2-\tfrac{1}{2}v_H^2\Big)\\&-\lambda_{\Phi H}\Big(|\Phi|^2-\tfrac{1}{2}v_\Phi^2\Big)\Big(|\mathcal{H}|^2-\tfrac{1}{2}v_H^2\Big)+\cdots\end{aligned}$$

dark photon

SM Higgs doublet

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

- After electroweak and $\mathbf{U(1)_{L_\mu - L_\tau}}$ symmetry breakings

$$\mathcal{H} = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 & v_H + h \end{pmatrix}^{\mathsf{T}} , \quad \Phi = \frac{1}{\sqrt{2}}(v_\Phi + \phi)$$

- The CP-even neutral components mix with each other

$$H_1 = \phi \cos\theta - h \sin\theta \ , \quad H_2 = \phi \sin\theta + h \cos\theta$$

dark Higgs boson

SM-like Higgs boson

mixing angle

$$m_{H_1} < m_{H_2} \simeq 125\,\mathrm{GeV}$$

- Dark photon mass : $m_{Z'} = g_X |\mathcal{Q}_\Phi| v_\Phi$

- Parameter set : $\left\{ g_X, m_{Z'}, m_X, m_{H_1}, \lambda_{\Phi X}, \mathcal{Q}_\Phi, \sin\theta \right\}$

Higgs invisible decay

- The SM-like Higgs boson has additional decay processes
  - $H_2 \to H_1 H_1, Z' Z', X X^\dagger$ (invisible decay channels)
  - SM Higgs mainly decays into dark photon & dark Higgs

$$\Gamma_{H_2 \to H_1 H_1} \simeq \Gamma_{H_2 \to Z' Z'} \propto \frac{\sin^2\theta \, m_{H_2}^3}{v_\Phi^2} \gg \Gamma_{H_2 \to X X^\dagger} \propto \frac{\sin^2\theta \, \lambda_{\Phi X}^2 v_\Phi^2}{m_{H_2}}$$

- The LHC provides a strong bound on these invisible decays

$$\mathcal{B}(H_2 \to \mathrm{Inv.}) < 0.13$$

PDG 2022

- Typically, $\sin\theta \lesssim 0.01$ in order to satisfy the Higgs invisible decays constraint.

DM relic abundance

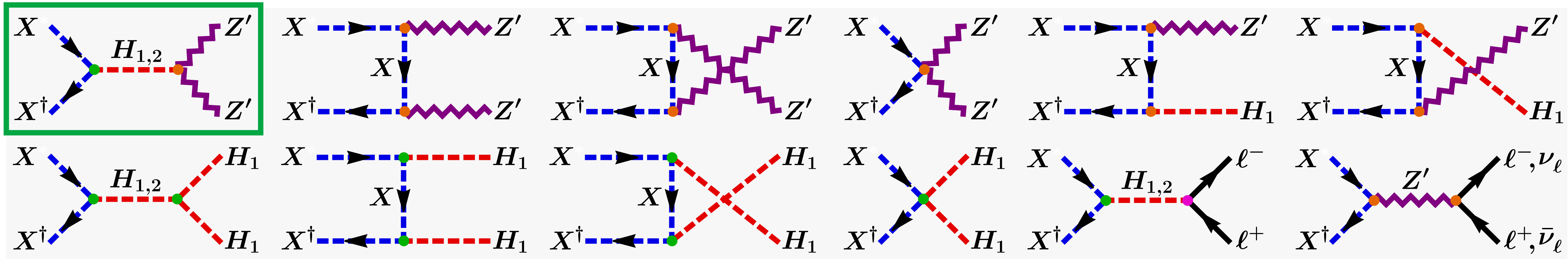
- Thermal WIMP DM relic density

$$\Omega_{\mathsf{WIMP}}\hat{h}^2 = 2\Omega_X \hat{h}^2 \simeq \frac{1.75\times 10^{-10}\mathrm{GeV}^{-2} x_f}{\sqrt{g_*}\,\langle\sigma v\rangle}$$

$$x_f \equiv \frac{m_X}{T_f} \sim 12-19$$

$$g_* \sim 10$$

- Annihilation processes:



$$\langle\sigma v\rangle \simeq \frac{\lambda_{\Phi X}^2}{16\pi m_X^2}\frac{4m_X^4 - 4m_X^2 m_{Z'}^2 + 3m_{Z'}^4}{(m_{H_1}^2 - 4m_X^2)^2 + \Gamma_{H_1}^2 m_{H_1}^2}\sqrt{1-\frac{m_{Z'}^2}{m_X^2}}$$

$$\Gamma_{H_1} \simeq \frac{\lambda_{\Phi X}^2 v_\Phi^2}{16\pi m_{H_1}}\sqrt{1-\frac{4m_X^2}{m_{H_1}^2}}$$

DM direct detection

- In the $\mathbf{U(1)_{L_\mu - L_\tau}}$ DM models without a dark Higgs boson, DM-nucleon/electron scattering is highly suppressed.
  - $\sigma_{\mathrm{el}}(\mathbf{DM} - p) \sim 10^{-46}\,\mathrm{cm}^2$, $\sigma_{\mathrm{el}}(\mathbf{DM} - e) \sim 10^{-51}\,\mathrm{cm}^2$

Holst, D. Hooper, G. Krnjaic, PRL 2022

- In our model, we can have a sizable DM-nucleon scattering process thanks to the light dark Higgs boson exchange.

- DM-nucleon elastic scattering cross section

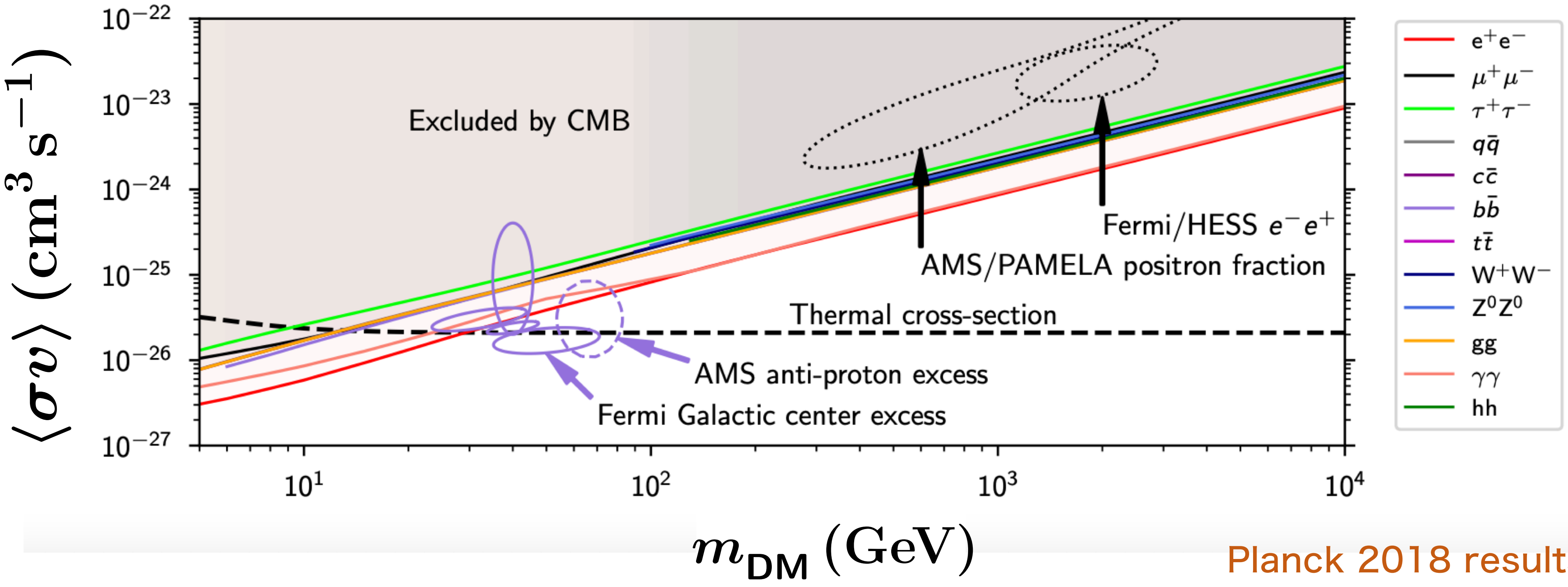
$$\sigma_{\mathrm{el}} \simeq \frac{4\mu_n^2 f_n^2 \lambda_{\Phi X}^2}{\pi}\left(\frac{m_n}{m_X}\right)^2\left(\frac{v_\Phi}{v_H}\right)^2\left(\frac{1}{m_{H_1}^2} - \frac{1}{m_{H_2}^2}\right)^2$$

CMB constraint on light DM mass

- For $m_{\text{DM}} \lesssim \mathcal{O}(10)\,\text{GeV}$, the CMB gives a stringent bound on thermal DM freeze-out determined by s-wave annihilation.

$$m_{\text{DM}} \gtrsim \mathcal{O}(10\,\text{GeV})\left(\frac{\langle\sigma v\rangle}{3\times10^{-26}\text{cm}^3\,\text{sec}^{-1}}\right)$$

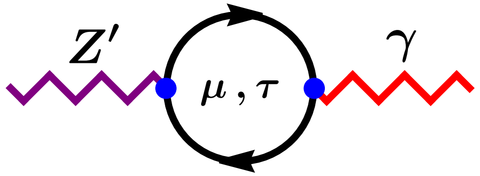
alternative
asymmetric DM
p-wave annihilation
forbidden DM
……



Planck 2018 results.

CMB constraints in our model

- Dominant DM annihilation channel
  - $XX^\dagger \to Z'Z', H_1H_1$ (s-wave) $XX^\dagger \to Z'H_1$ (p-wave)
- Dark photon decay
  - $Z' \to \nu\bar{\nu}$ $(m_{Z'} = 11.5\,\mathrm{MeV}, g_X = 5\times 10^{-4})$
  - $\mathcal{B}(Z' \to e^+e^-) \simeq 10^{-5}$ $(\mathcal{L} = -\epsilon\, g_e \bar{e}\gamma^\rho e Z'_\rho, \epsilon \simeq -g_X/70)$
- Dark Higgs boson decay

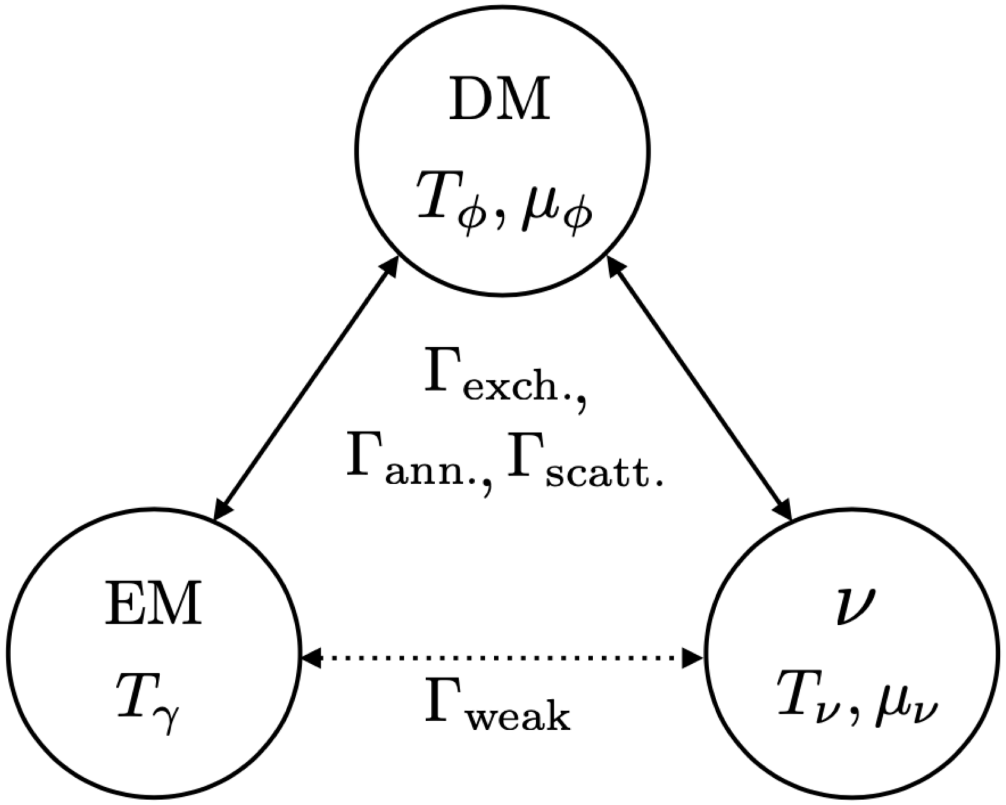


  - $H_1 \to XX^\dagger$, $H_1 \to Z'Z' \to 4\nu$
  - $H_1 \to \ell^+\ell^-$ (suppressed by small Yukawa coupling & mixing angle)
- We can naturally avoid the stringent CMB bound thanks to invisible decay of these dark particles.

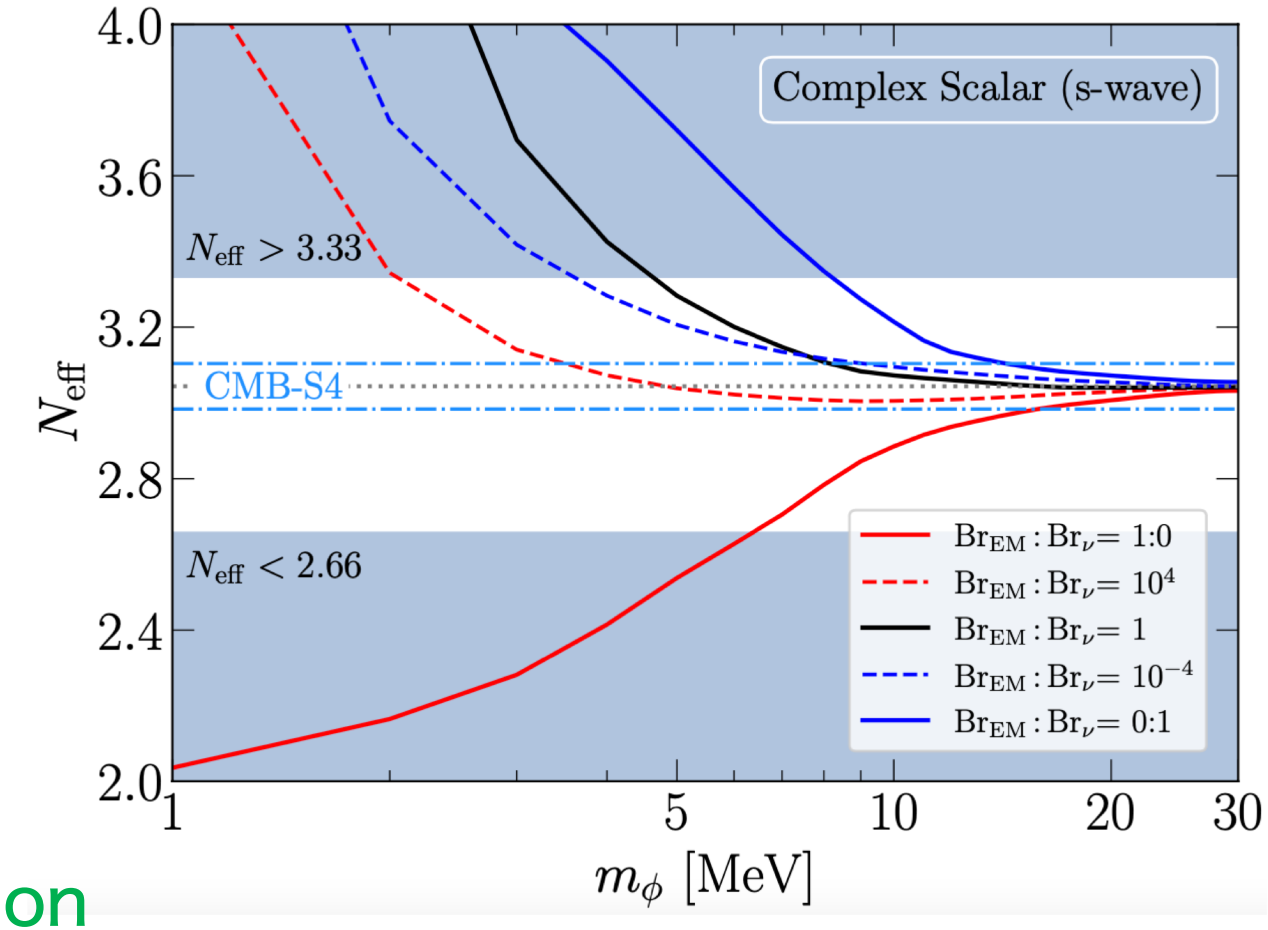
Effective number of neutrino species

- Considering the modification N_{eff} of via light DM s-wave annihilation to neutrinos, complex scalar DM mass below 8.2 MeV is disfavored.

X. Chu & J. Pradler (2023)



three-sector abundance calculation



Two- or Three-body decays at Belle II

- Belle II provides information on the q^2 spectrum
  - A peak localized around $q^2 = 4\ \mathrm{GeV}^2$
  - Two body decay :

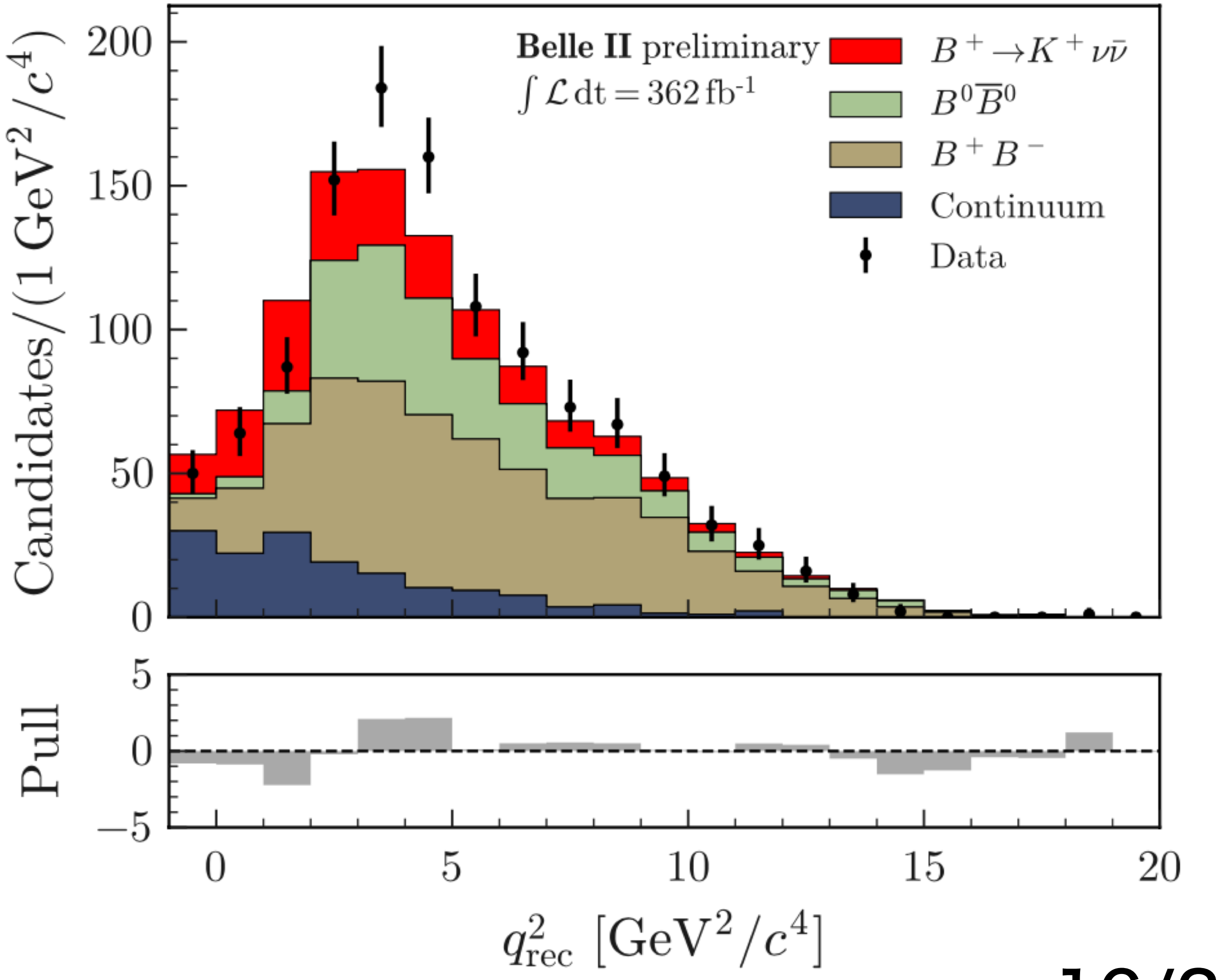
$$B^+ \to K^+ X, m_X = 2\,\mathrm{GeV}$$

W. Altmannshofer et al, 2311.14629

  - Three body decay :

$$B^+ \to K^+ X X, m_X < 0.6\,\mathrm{GeV}$$

K. Fridell et al, 2312.12507



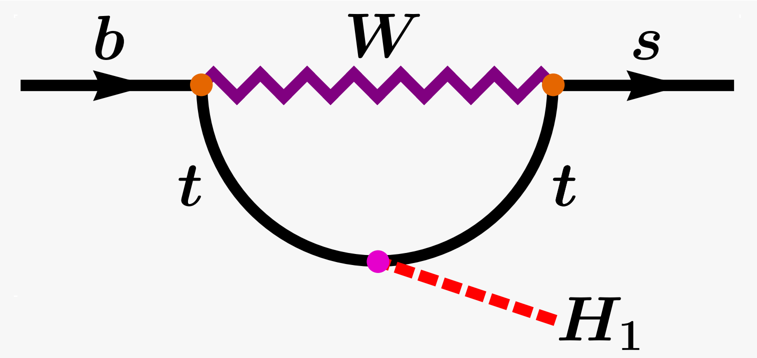
Two- or Three-body decays at Belle II

- When $m_{B^+} - m_{K^+} > m_{H_1}$, the B^+ meson goes through a two body decay

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

form factor

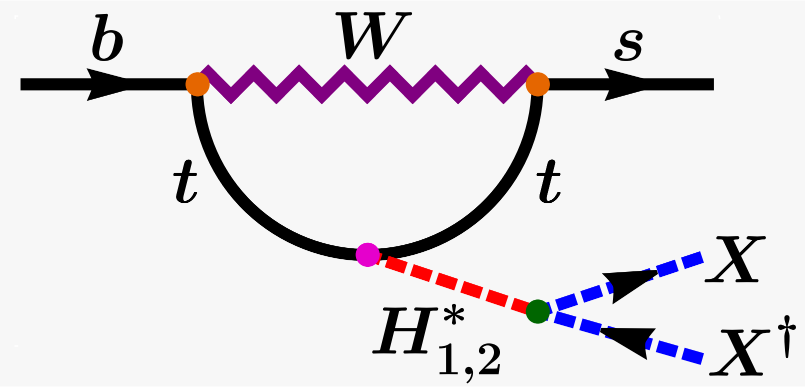
$\sin\theta \ll 1$



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

- When $m_{H_1} > m_{B^+} - m_{K^+} > 2m_X$, the B^+ meson goes through a three body decay

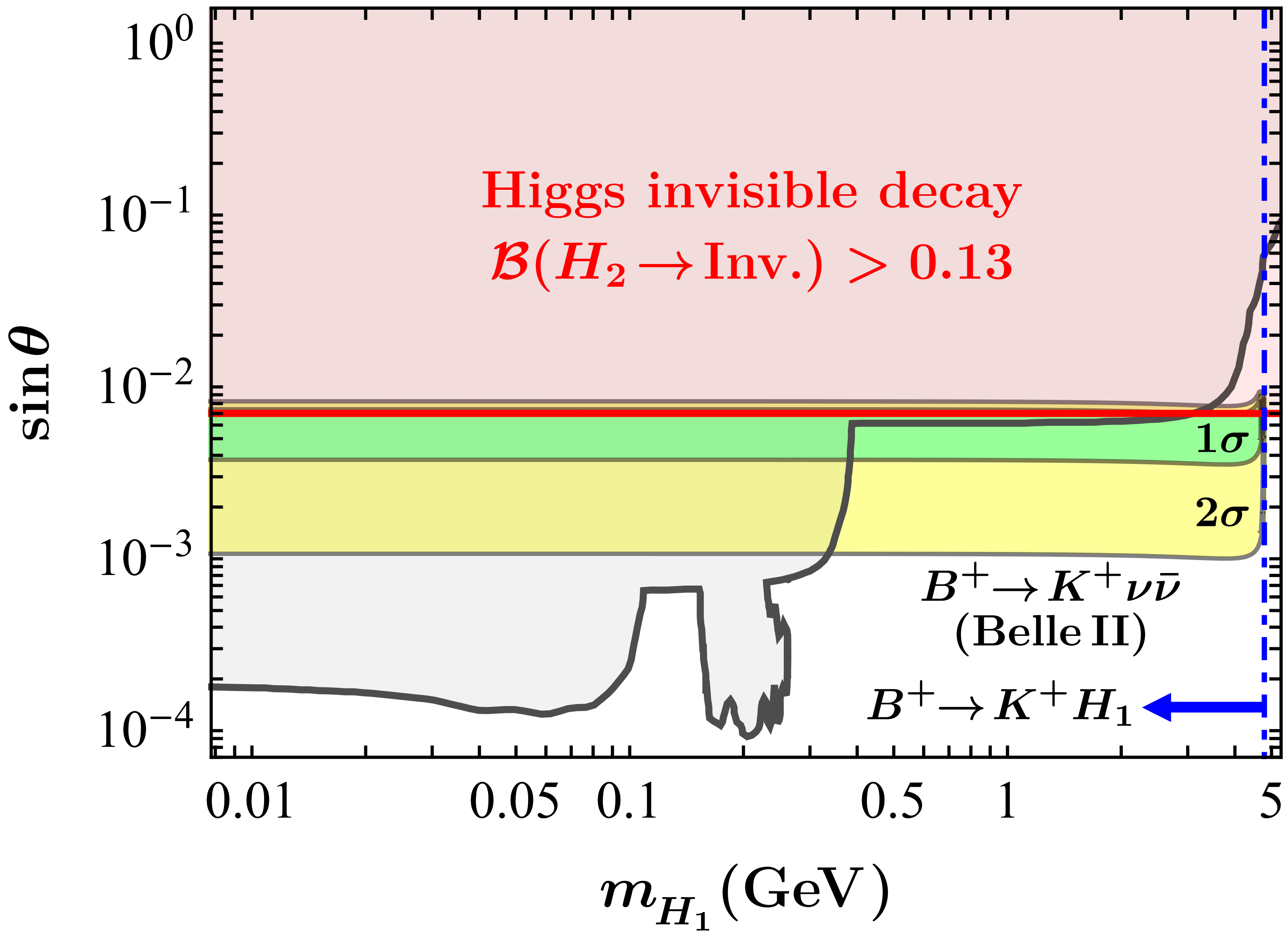
$$\Gamma_{B^+\to K^+XX^\dagger} \simeq \frac{\lambda_{\Phi X}^2 v_\Phi^2 |\kappa_{cb}|^2\sin^2\theta}{1024\pi^3 m_{B^+}^3}\left(\frac{m_{B^+}^2 - m_{K^+}^2}{m_b - m_s}\right)^2 \left(m_{H_1}^2 - m_{H_2}^2\right)^2 \times \int_{4m_X^2}^{(m_{B^+}-m_{K^+})^2} \mathrm{d}q^2 \, \frac{\sqrt{1 - 4m_X^2/q^2}\sqrt{\mathcal{K}(m_{B^+}^2, m_{K^+}^2, q^2)}\left[f_0(q^2)\right]^2}{(q^2 - m_{H_1}^2)^2 (q^2 - m_{H_2}^2)^2}$$



$q^2 = (p_{B^+} - p_{K^+})^2$

$\sin\theta$ vs. m_{H_1}

$m_{Z'} = 11.5\,\mathrm{MeV},\ g_X = 5\times10^{-4},\ \mathcal{Q}_\Phi = 0.4$



The gray shaded area is excluded by Belle II $B^0 \to K^{*0}\nu\bar{\nu}$, KOTO $K_L^0 \to \pi^0\nu\bar{\nu}$, & NA62 $K^+ \to \pi^+ + \mathrm{inv.}$

Allowed value

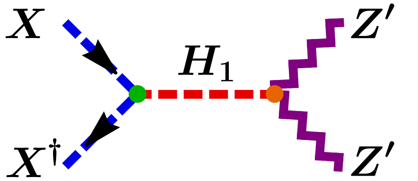
$$10^{-3} \lesssim \sin\theta \lesssim 7\times10^{-3}$$

Our numerical input :

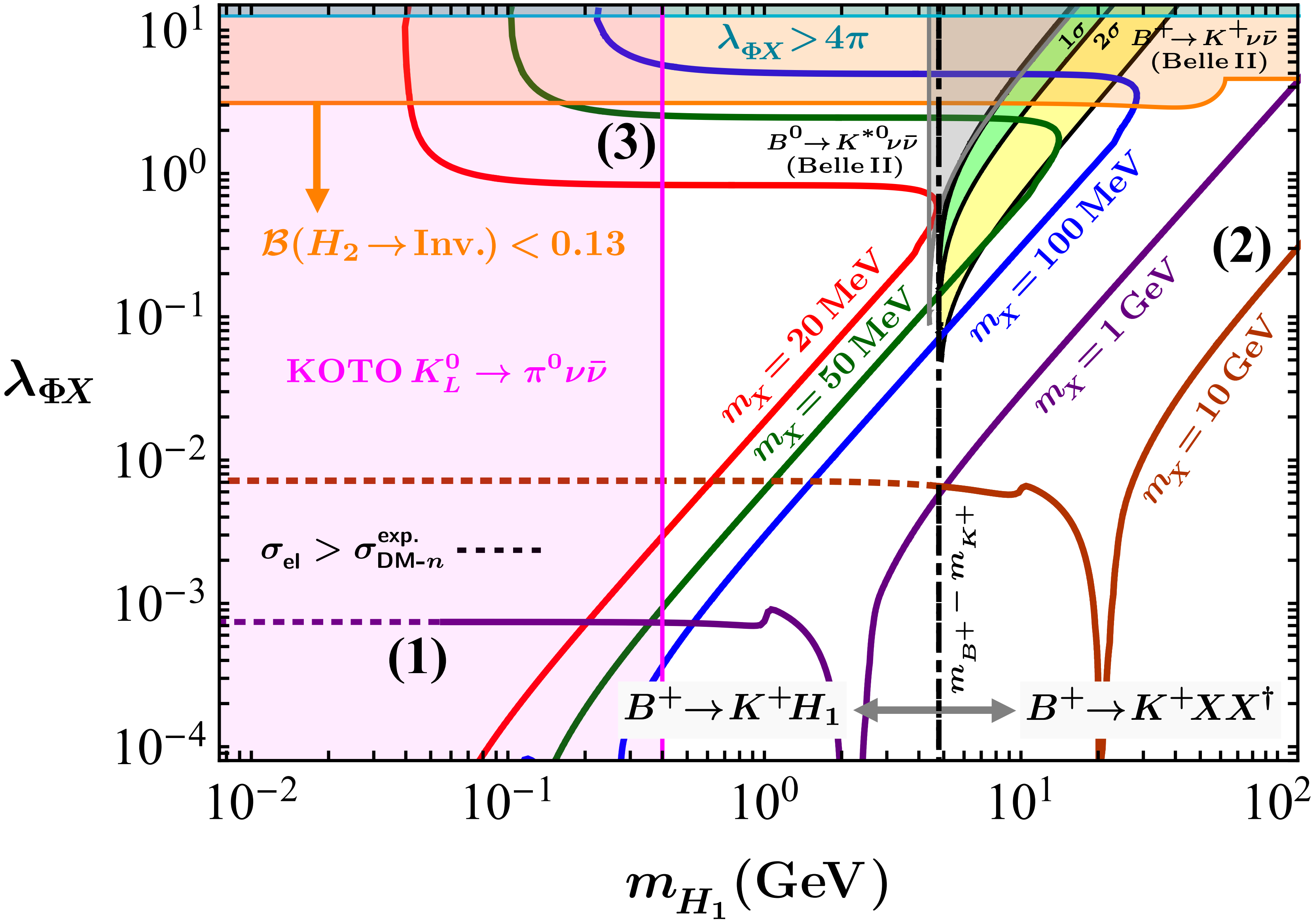
$$\sin\theta = 6\times10^{-3}$$

$\lambda_{\Phi X}$ vs. m_{H_1}

$m_{Z'} = 11.5\,\text{MeV}, g_X = 5\times10^{-4}, \mathcal{Q}_\Phi = 0.4, s_\theta = 6\times10^{-3}$



$m_X^2 \gg m_{Z'}^2$



$$\langle\sigma v\rangle \propto \frac{\lambda_{\Phi X}^2 m_X^2}{(m_{H_1}^2 - 4m_X^2)^2 + \Gamma_{H_1}^2 m_{H_1}^2}$$

$$\Gamma_{H_1}^2 m_{H_1}^2 \propto \lambda_{\Phi X}^4 v_\Phi^4 \sqrt{1 - 4m_X^2/m_{H_1}^2}$$

(1) $\lambda_{\Phi X} \ll 1$ & $m_X^2 \gg m_{H_1}^2$

$$\Rightarrow \langle\sigma v\rangle \propto \frac{\lambda_{\Phi X}^2}{m_X^2} \Rightarrow \lambda_{\Phi X} \simeq \text{const.}$$

(2) $\lambda_{\Phi X} \ll 1$ & $m_{H_1}^2 \gg m_X^2$

$$\Rightarrow \langle\sigma v\rangle \propto \frac{\lambda_{\Phi X}^2 m_X^2}{m_{H_1}^4} \Rightarrow \lambda_{\Phi X} \propto m_{H_1}^2$$

(3) $\lambda_{\Phi X} \gg 1$ & $m_{H_1}^2 \gg m_X^2$

$$\Rightarrow \langle\sigma v\rangle \propto \frac{m_X^2}{\lambda_{\Phi X}^2 v_\Phi^4} \Rightarrow \lambda_{\Phi X} \simeq \text{const.}$$

Conclusions

- In this work, we have studied the simplest UV-completion gauged $\mathbf{U(1)_{L_\mu - L_\tau}}$-charged complex scalar DM model with the dark Higgs mechanism.
- We have found the dark Higgs boson mass,

(KOTO) $0.4\,\mathrm{GeV} \lesssim m_{H_1} \lesssim 10\,\mathrm{GeV}$ ($B^+ \to K^+ \nu\bar{\nu}$ excess)

the complex scalar DM mass,

($\Delta N_{\rm eff}$) $10\,\mathrm{MeV} \lesssim m_X \lesssim 10\,\mathrm{GeV}$ ($B^+ \to K^+ \nu\bar{\nu}$ excess + DM direct detection)

and the dark photon mass $m_{Z'} \sim 10\,\mathrm{MeV}\,,\ \ g_X \sim 5 \times 10^{-4}$

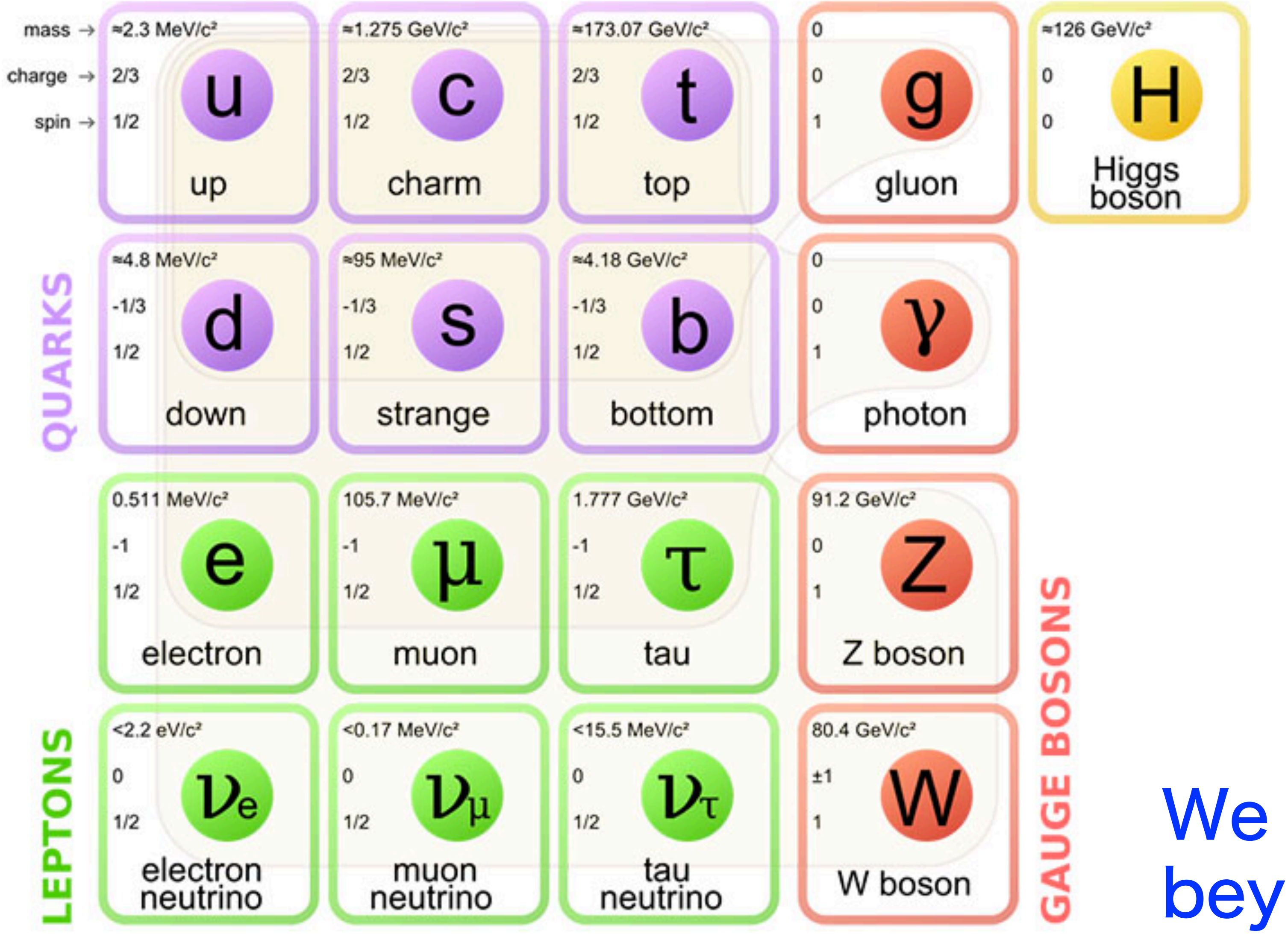
(muon $g-2$ anomaly)

- With these light dark particles, we can have the integrated solution of $B^+ \to K^+ \nu\bar{\nu}$ excess, Δa_μ anomaly, and DM.

Backup

The Standard Model of particle physics

- The Standard Model (SM) is GOOD, but ……



Unsolved problems

- Dark Matter (DM)
- Dark energy
- Neutrino mass
- Baryon asymmetry
- Gravity
- ………

We need new physics beyond the SM (BSM)!!!

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

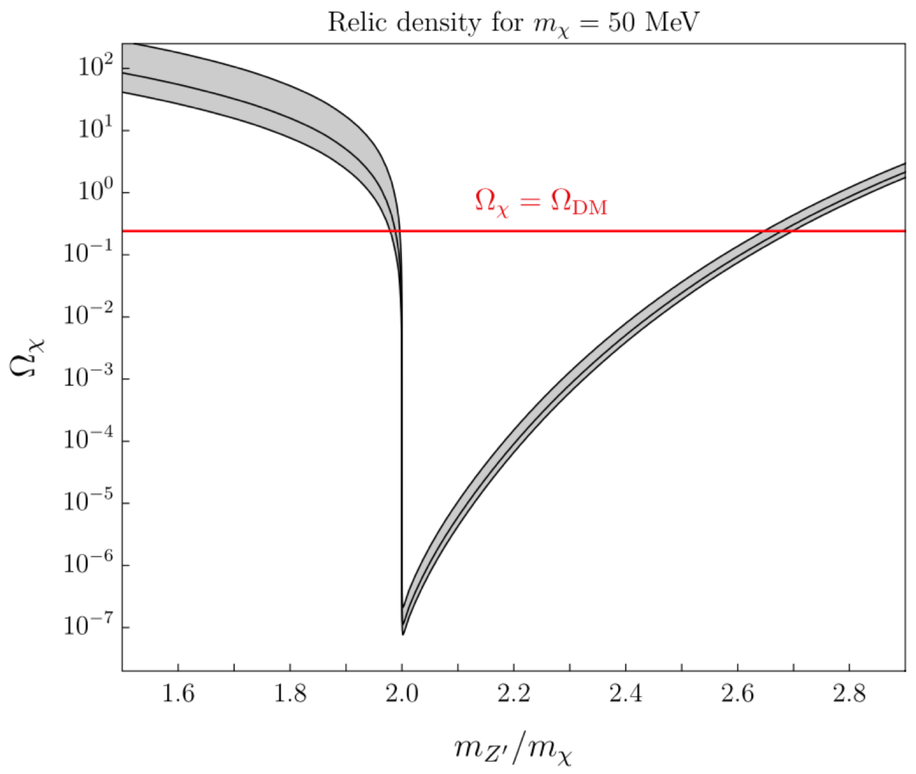
- Conventional $\mathbf{U(1)_{L_\mu - L_\tau}}$-charged fermionic DM ($\chi$) model

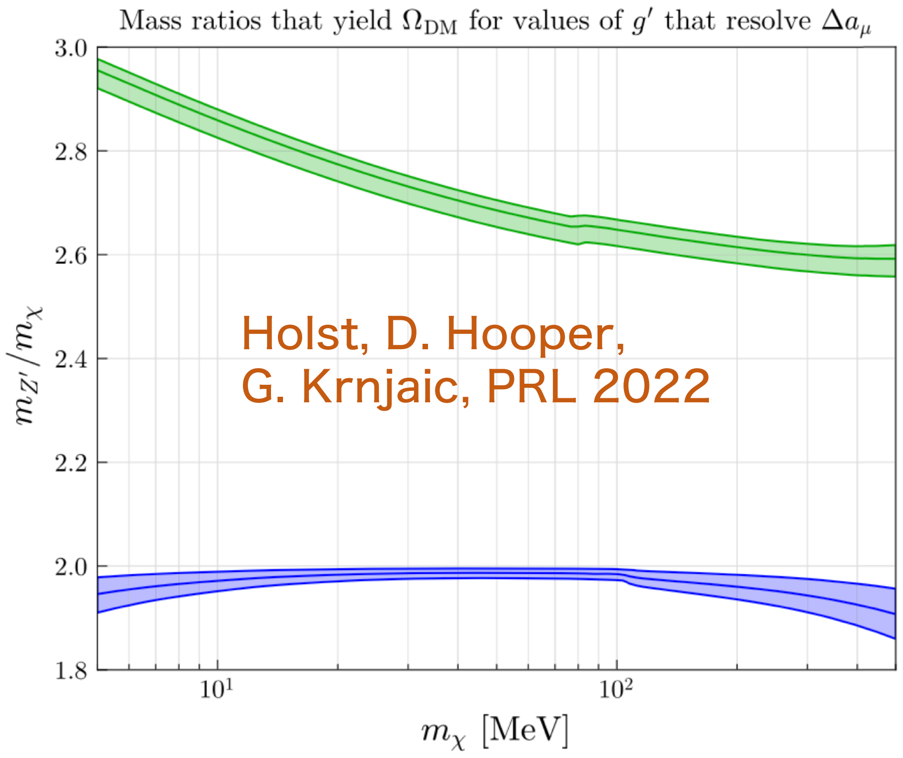
$$\mathcal{L} = \mathcal{L}_{\mathsf{SM}} - \frac{1}{4} Z'_{\rho\omega} Z'^{\rho\omega} + \frac{1}{2} m_{Z'}^2 Z'_\rho Z'^\rho + \overline{\chi}\left(i\gamma^\rho \partial_\rho - m_\chi\right)\chi$$
$$+ g_X Z'_\rho \left(\mathcal{Q}_\chi \overline{\chi}\gamma^\rho \chi + \sum_{\ell = \mu, \tau, \nu_\mu, \nu_\tau} \mathcal{Q}_\ell \overline{\ell} \gamma^\rho \ell \right)$$

- The dark photon Z' plays a role of a messenger particle between DM and the SM leptons.
- The dark photon mass $m_{Z'}$ is put by hand or is generated by the Stueckelberg mechanism. H. Ruegg, M. Ruiz-Altaba (2003)

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

- Dominant annihilation channels : $\chi\bar{\chi} \to Z'^{*} \to \ell^+\ell^-, \nu\bar{\nu}$
  - To explain the muon g-2, $g_X \sim 10^{-4}$, which is too small to get the correct DM relic abundance.
  - Only $m_{Z'} \sim 2m_\chi$ can give the right DM relic abundance.





Holst, D. Hooper,
G. Krnjaic, PRL 2022

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

- Particle content & charge assignments

$$\widehat{\mathcal{Q}}_{\mathsf{L}_\mu - \mathsf{L}_\tau}(\nu_\mu, \nu_\tau, \mu, \tau, X, \Phi) = (1, -1, 1, -1, \underset{=1}{\mathcal{Q}_X}, \mathcal{Q}_\Phi)$$

complex singlet scalar DM

SM Higgs singlet

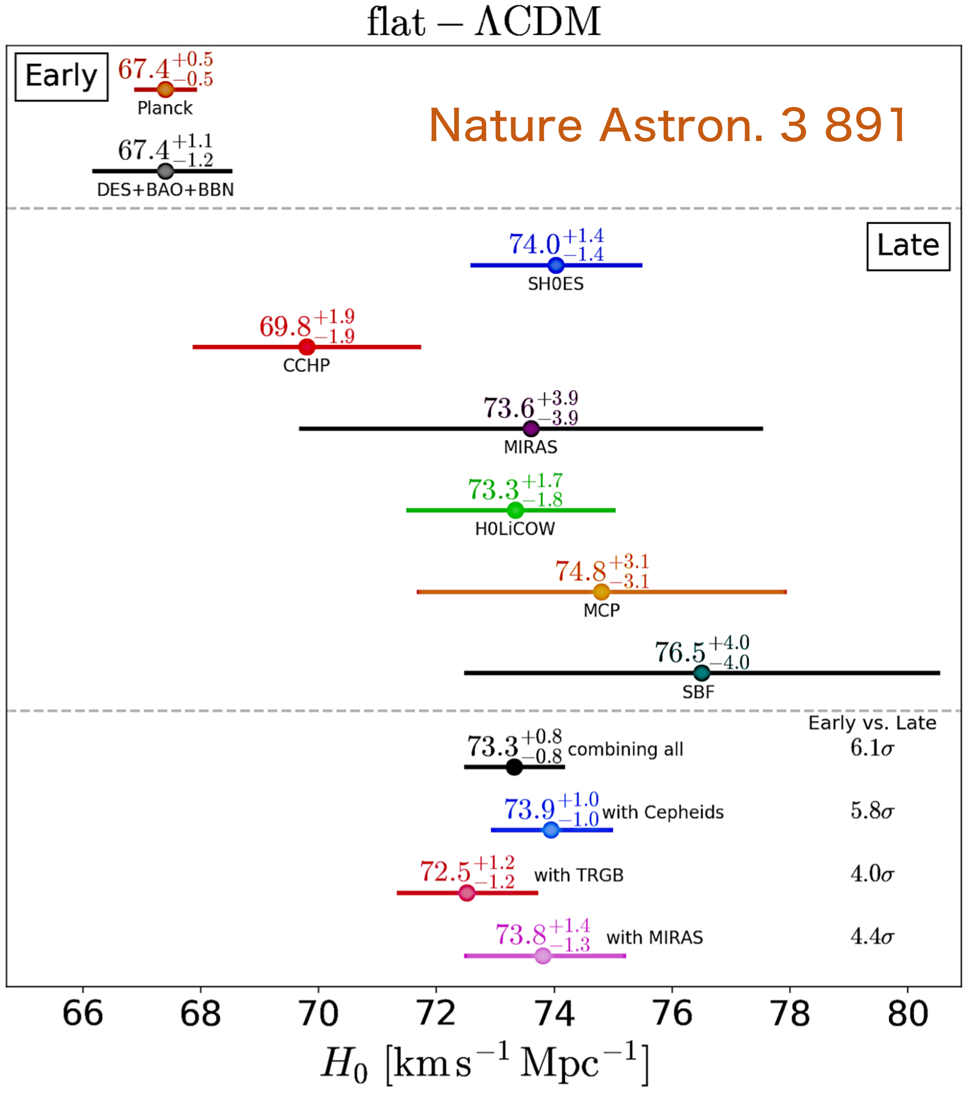
- To make DM absolutely stable, we choose $\mathcal{Q}_\Phi \neq \frac{1}{2}, \frac{1}{3}, \frac{1}{4}, \cdots$
  - e.g. $\mathcal{O}^{(5)} = \frac{1}{\Lambda} X \Phi^{\dagger 4}$ (dark matter decays)

- We also choose $\mathcal{Q}_\Phi \neq 2$ to avoid the mass splitting of X
  - $\mu\left(X^2 \Phi^\dagger + \mathrm{h.c.}\right) \supset \frac{1}{2} \mu v_\Phi (X_R^2 - X_I^2)$

Baek, JK, Ko, 2204.04889

The Hubble tension

- There is a large difference between the early- and late-time determinations of Hubble constant H_0.



Nature Astron. 3 891

Early-time measurement

$$H_0 = 67.4 \pm 0.5\,\mathrm{km/s/Mpc}$$

Late-time measurement

$$H_0 = 73.2 \pm 1.3\,\mathrm{km/s/Mpc}$$

This discrepancy can arise either b/c

- Our distance measurements are incorrect (ΔG_N).
- Cosmological model we use to fit all those distances is wrong (ΔN_{eff}).

$$\Delta N_{\mathrm{eff}}\ \mathrm{v.s.}\ \Delta G_N?$$

What we know about dark matter

- Dark matter as a particle must be
  - Massive : gravitationally interact with ordinary matter
  - Cold : non-relativistic at the time of structures formation
  - Electric neutral : Almost no electromagnetic interaction
  - Stable or with lifetime longer than the age of Universe
  - Non-baryonic matter
  - Making up about a quarter of the energy density of the present universe

What we don’t know about dark matter

- Unknown particle nature of dark matter
  - Mass : $10^{-31} M_{\text{proton}} < M_{\text{DM}} < 5 M_{\odot}$
  - Spin : Scalar or Vector Boson? Dirac or Majorana Fermion?
  - Number of species : There may exist more than one kind of dark matter in the universe. (Occam's razor?)
  - Interactions : Dark matter may have interactions with ordinary matter or itself (SIDM) other than the gravitational interaction.
- Unknown origin of dark matter
  - Thermal : Relic produced from the SM thermal plasma
  - Non-thermal : e.g. coherent oscillation, topological defect,……

Dark matter candidates

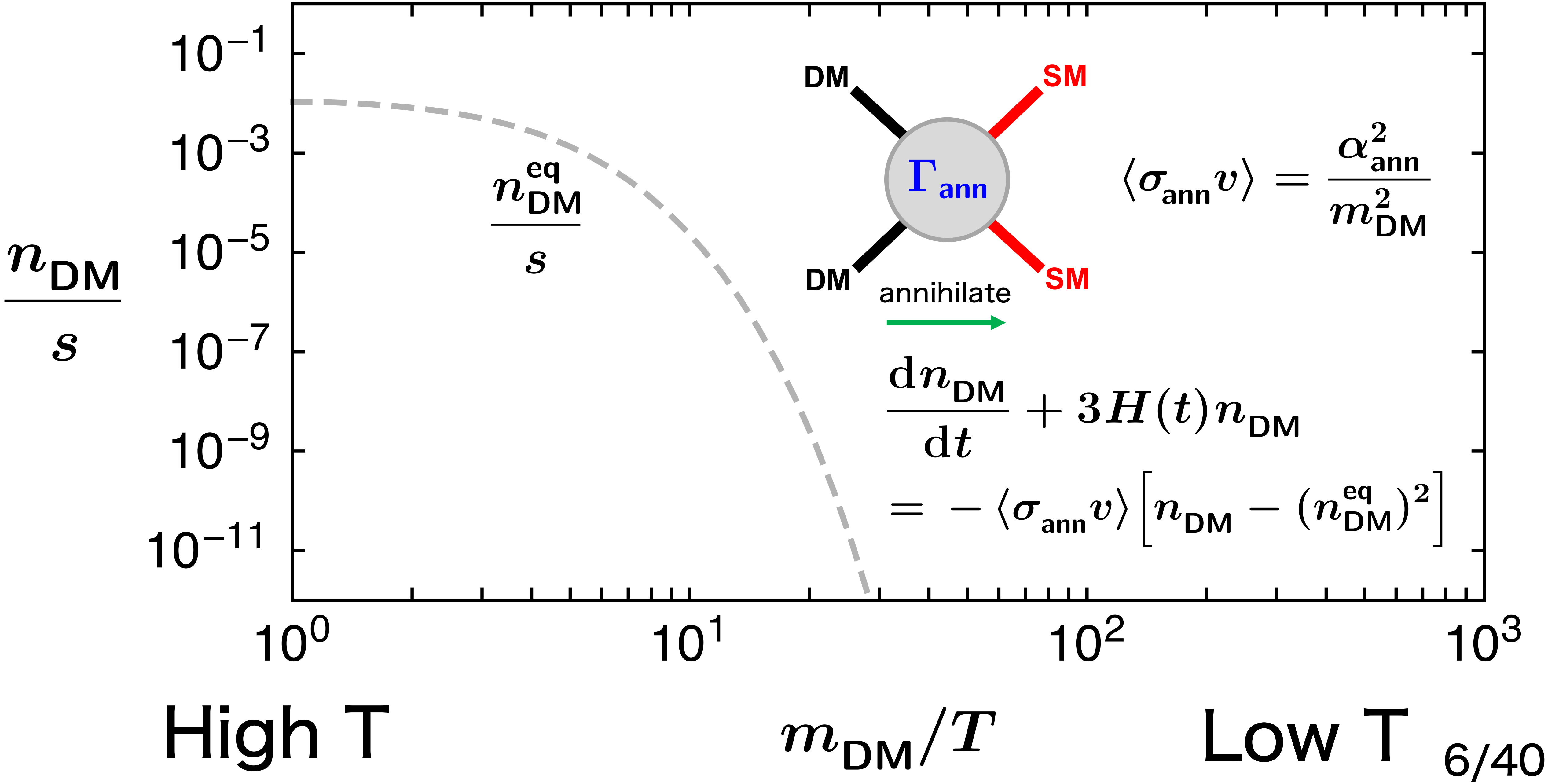
Thermal production

• Weakly interacting massive particles (WIMP)	B.W. Lee & S. Weinberg (1977)
• Strongly interacting massive particles (SIMP)	Y. Hochberg, etal (2014)
• Elastically decoupling relic (ELDER)	E. Kuflik, etal (2016)
• Forbidden dark matter	R. T. D'Agnolo, & J. T. Ruderman (2015)
• ………	

Non-thermal production

• The QCD axion/axion-like particles (ALP)	P. Arias, et al. (2012)
• Feebly interacting massive particles (FIMP)	L. J. Hall (2009)
• Hidden monopole dark matter	H. Murayama, J. Shu (2009)
• Primordial black hole (PBH)	Ya.B. Zel'dovich and I.D. Novikov (1967)
• ………	

Weakly Interacting Massive Particle (WIMP) DM



$$\langle \sigma_{\mathrm{ann}} v \rangle = \frac{\alpha_{\mathrm{ann}}^2}{m_{\mathrm{DM}}^2}$$

$$\frac{\mathrm{d}n_{\mathrm{DM}}}{\mathrm{d}t} + 3H(t)n_{\mathrm{DM}}$$

$$= -\langle \sigma_{\mathrm{ann}} v \rangle \left[n_{\mathrm{DM}} - (n_{\mathrm{DM}}^{\mathrm{eq}})^2 \right]$$

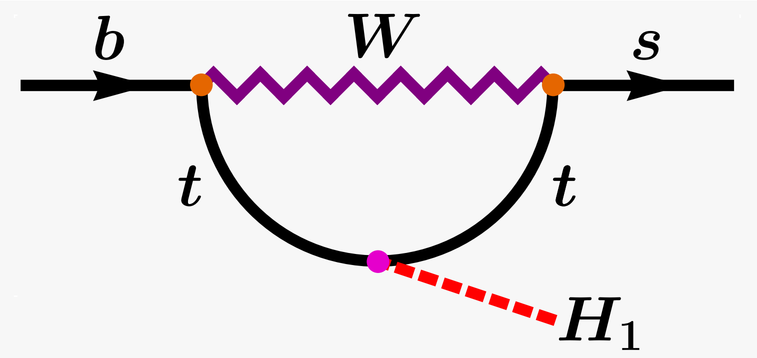
Two- or Three-body decays at Belle II

- When $m_{B^+} - m_{K^+} > m_{H_1}$, the B^+ meson goes through a two body decay

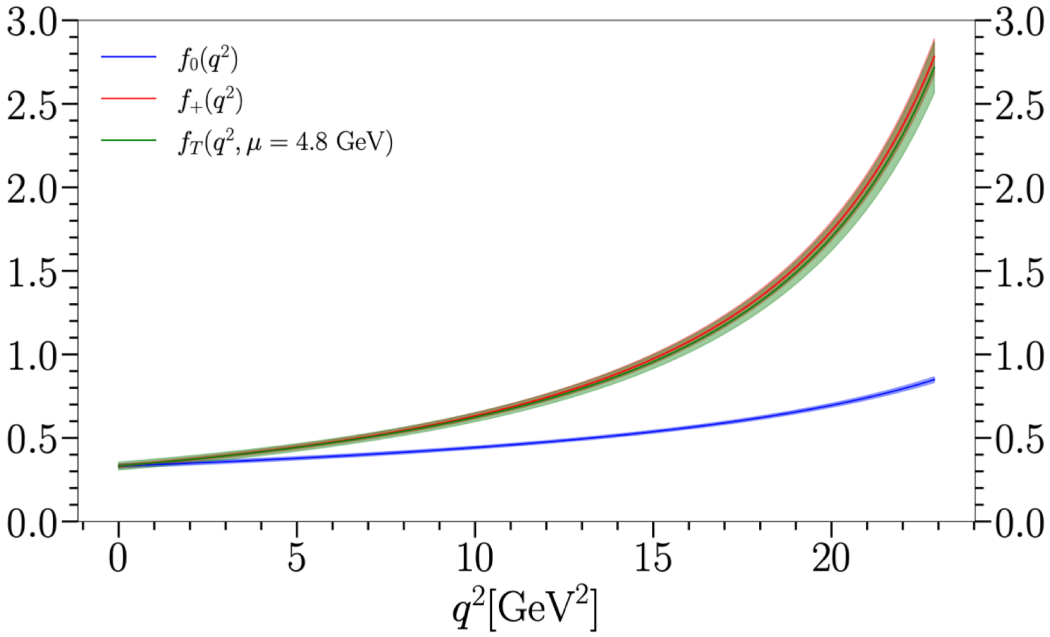
$$\Gamma_{B^+\to K^+H_1} \simeq \frac{|\kappa_{cb}|^2\sin^2\theta}{64\pi m_{B^+}^3}\left(\frac{m_{B^+}^2 - m_{K^+}^2}{m_b - m_s}\right)^2 \underline{\left[f_0(m_{H_1}^2)\right]^2} \times\sqrt{\mathcal{K}(m_{B^+}^2, m_{K^+}^2, m_{H_1}^2)}$$

form factor

$\sin\theta \ll 1$

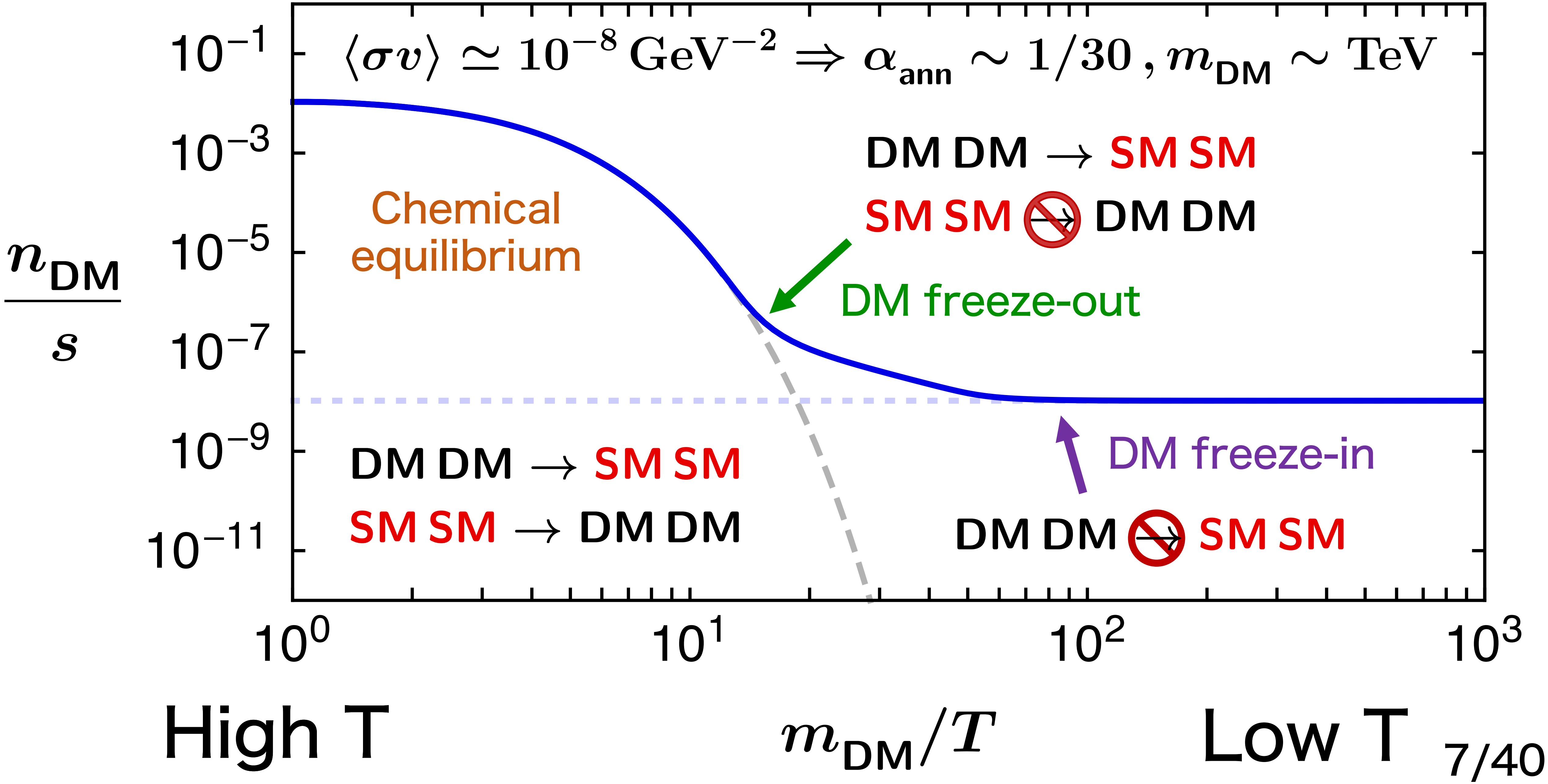


$$|\kappa_{cb}| \simeq 6.7\times 10^{-6} \qquad \mathcal{K}(a,b,c) = a^2 + b^2 + c^2 - 2(ab + bc + ca)$$



W. G. Parrott, C. Bouchard
& C. T. H. Davies, ORD 2023

Weakly Interacting Massive Particle (WIMP) DM



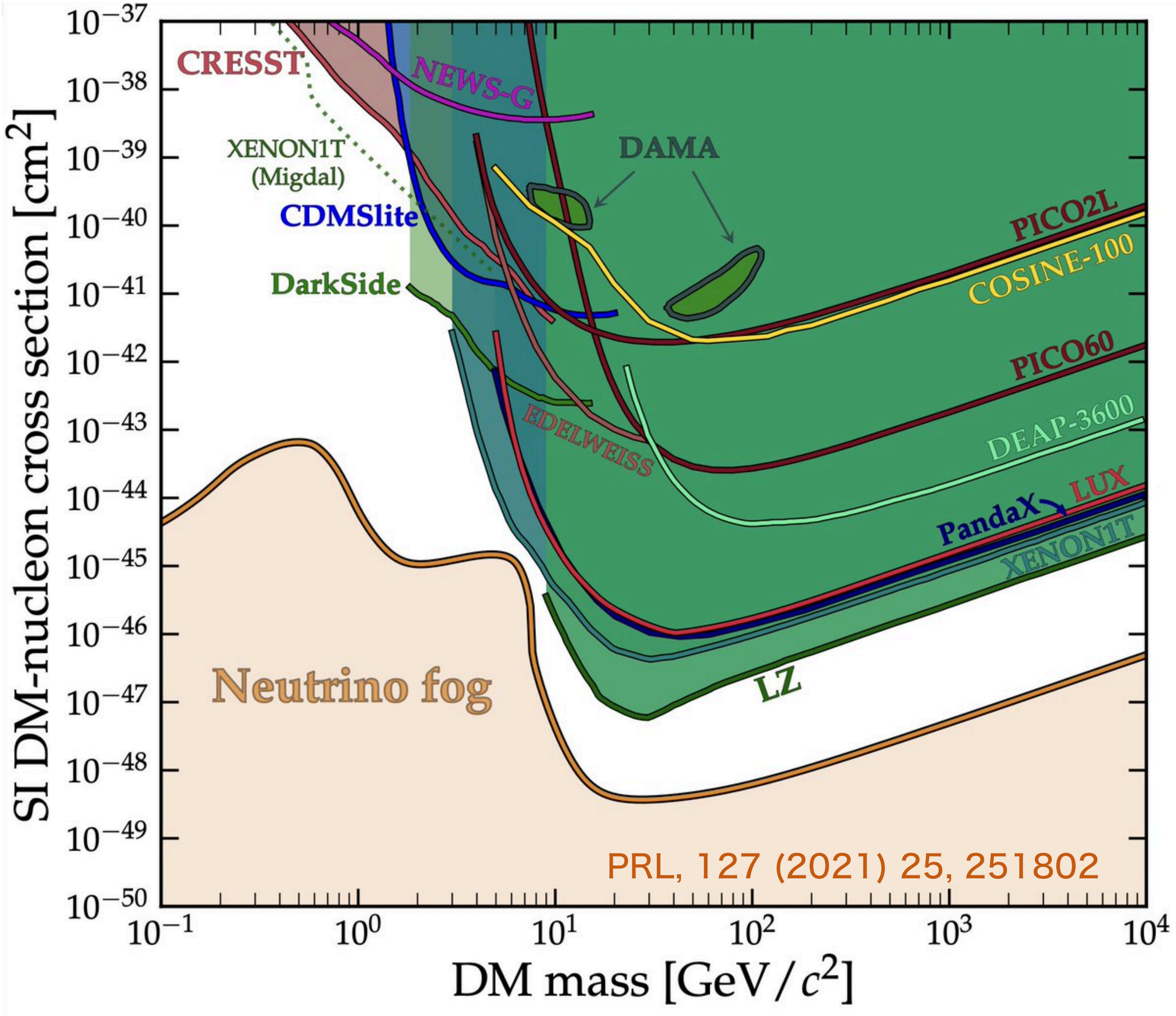
Weakly Interacting Massive Particle (WIMP) DM

Assumptions for WIMP DM (2 to n annihilations)

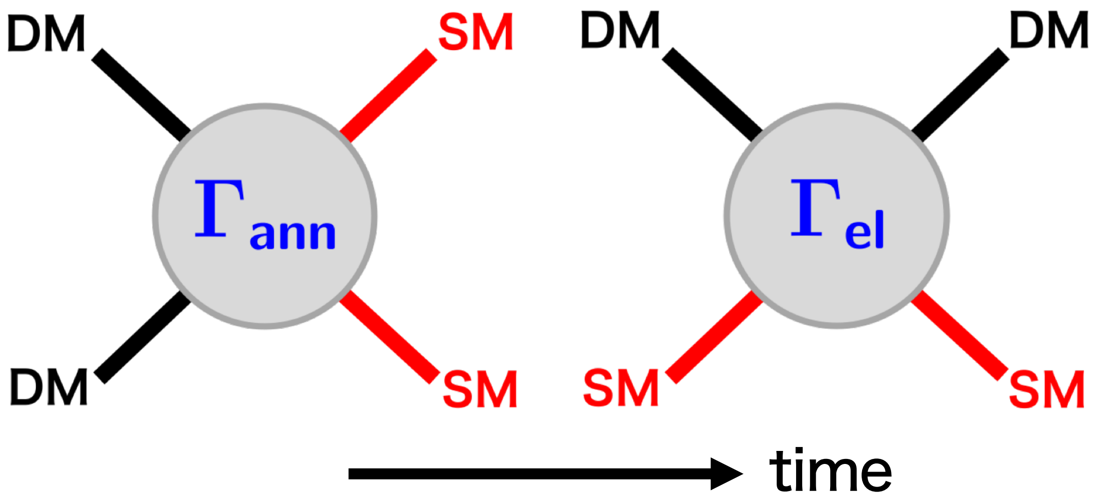
- $\mu_{\text{DM}} = \mu_{\overline{\text{DM}}}$ [$\mu_{\text{DM}} \neq \mu_{\overline{\text{DM}}} \Longrightarrow$ asymmetric DM] D. E. Kaplan, M. A. Luty, & K. M. Zurek (2009)
- $m_{\text{DM}} > m_{\text{SM}}$ [$m_{\text{DM}} < m_{\text{SM}} \Longrightarrow$ forbidden DM] R. T. D'Agnolo, & J. T. Ruderman (2015)
- $T_{\text{FO}} < T_{\text{RH}}$ [$T_{\text{FO}} > T_{\text{RH}} \Longrightarrow$ WIMPs during reheating] Nicolás Bernal & Yong Xu (2022)
- Standard cosmology [$\rho_\phi(a) \propto a^{-(4+n)} \Rightarrow$ relentless DM] F. D'Eramo, etal (2017)
- Collisionless [$\sigma_{\text{SI}} \neq 0 \Longrightarrow$ Self-interacting dark matter]
- T invariance : $|\mathcal{M}_{\text{DMDM}\to\text{SMSM}}|^2 = |\mathcal{M}_{\text{SMSM}\to\text{DMDM}}|^2$ (?)

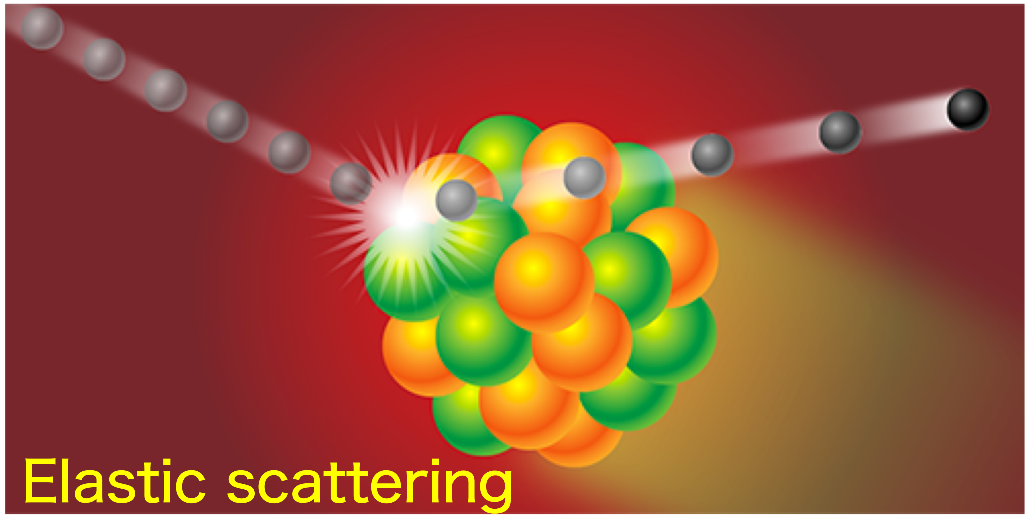
WIMP dark matter direct detections

- Null result of direct detections has cornered WIMP scenario



PRL, 127 (2021) 25, 251802

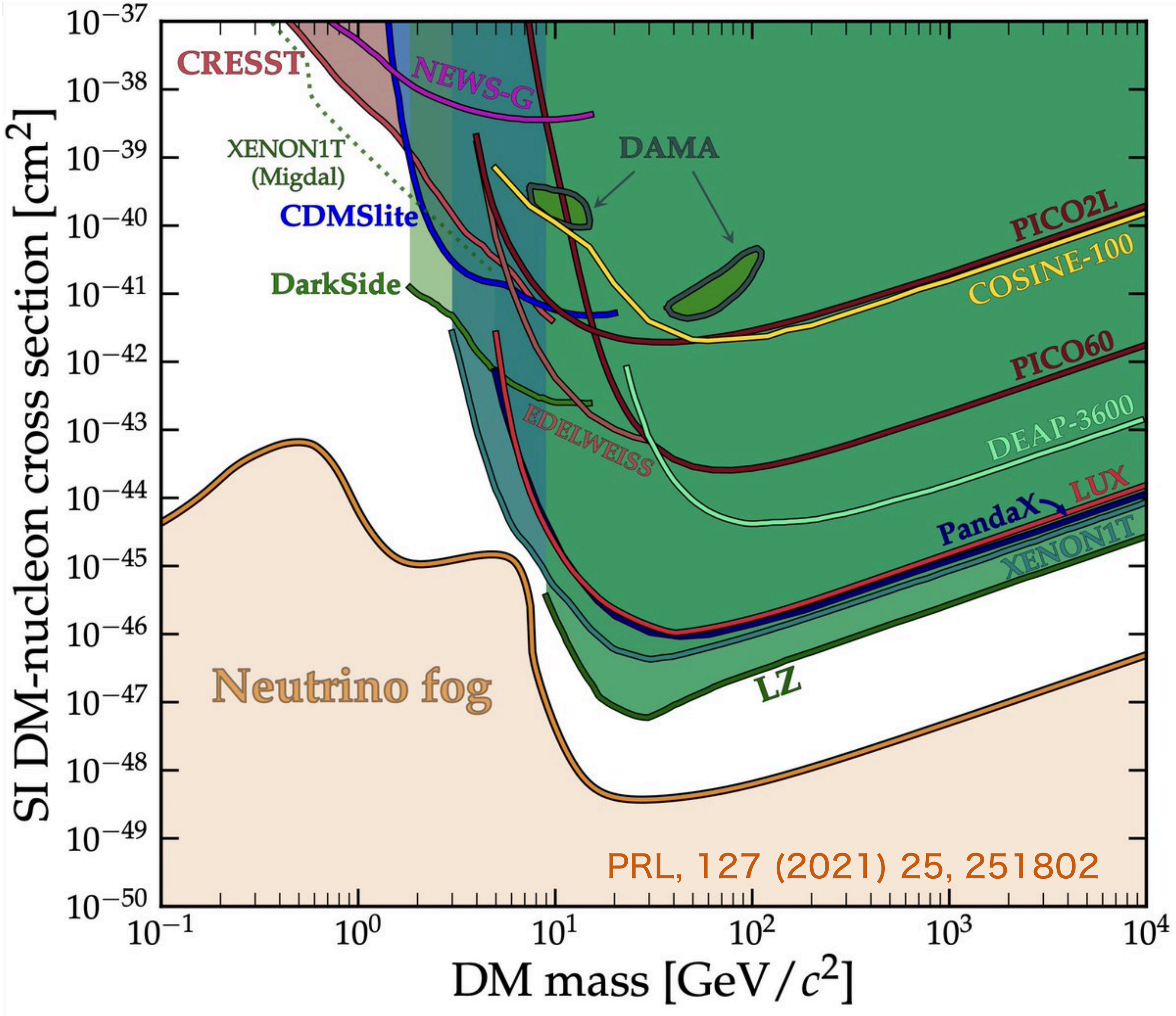




Elastic scattering

WIMP dark matter direct detections

- Null result of direct detections has cornered WIMP scenario



PRL, 127 (2021) 25, 251802

Possible explanations

(1) DM-nucleon cross-section is below the neutrino floor

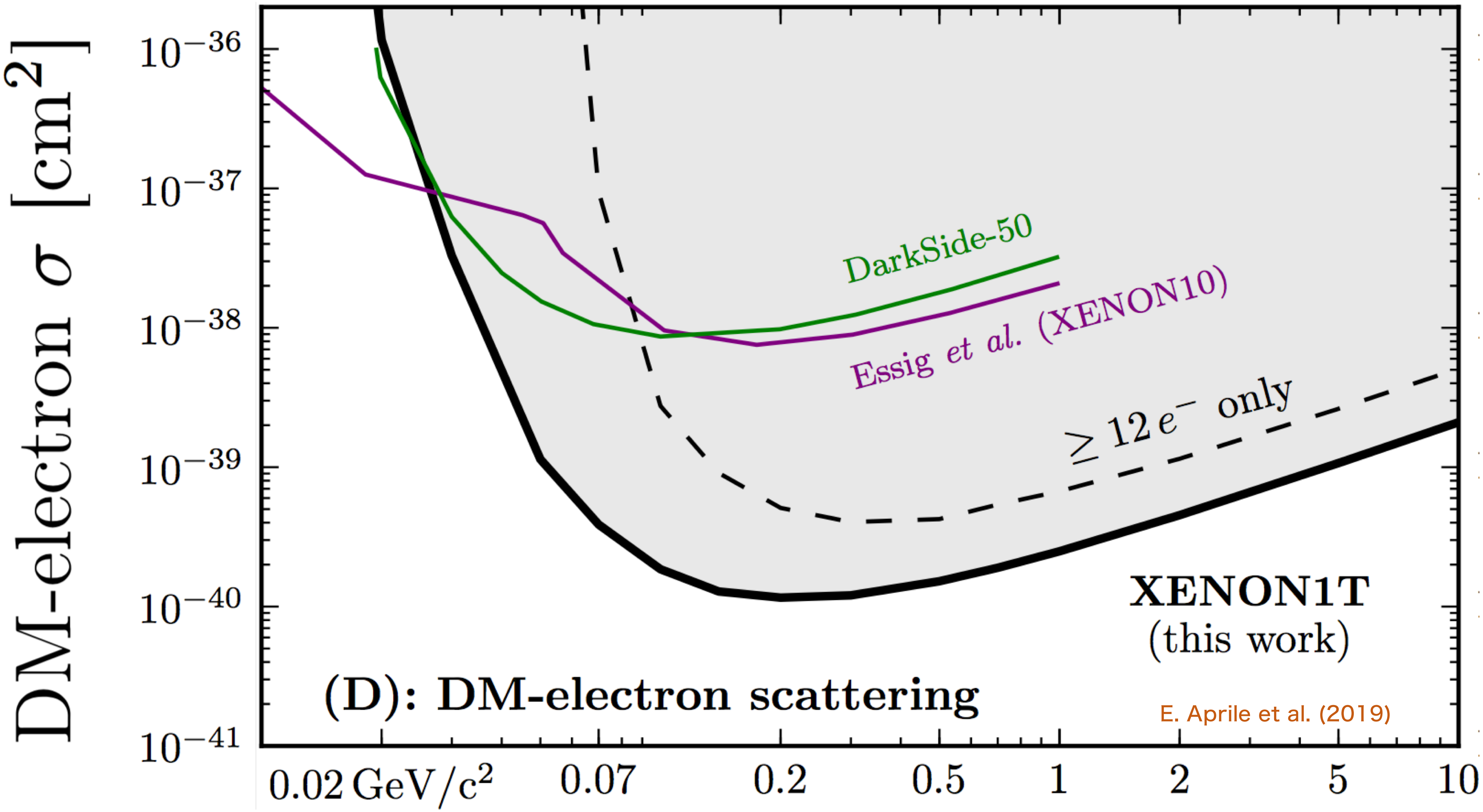
Theor. : pseudo-Nambu-Goldstone boson DM
Exp. : directional DM search, e.g. Cygnus

(2) DM only has gravitational interaction

(3) DM mass is outside the current direct detection search range

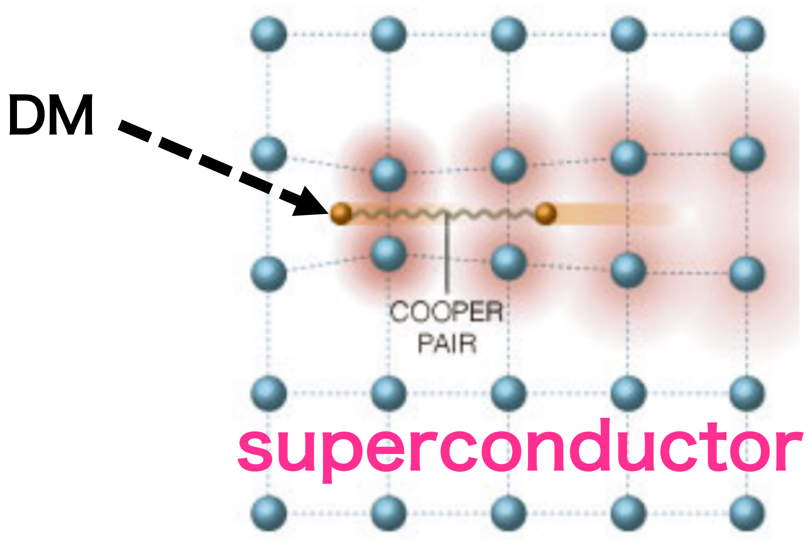
Low/Heavy mass DM?

Direct detections of light dark matter



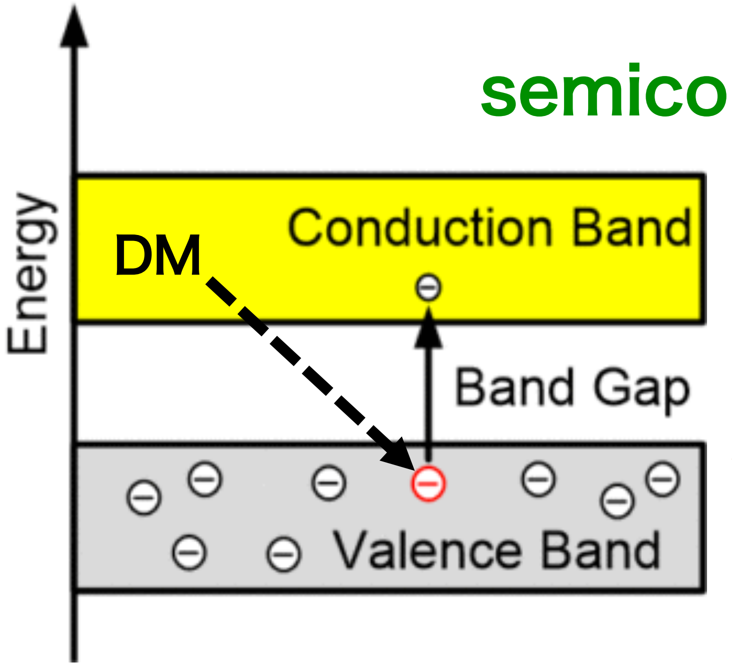
E. Aprile et al. (2019)

Projected detections of light dark matter



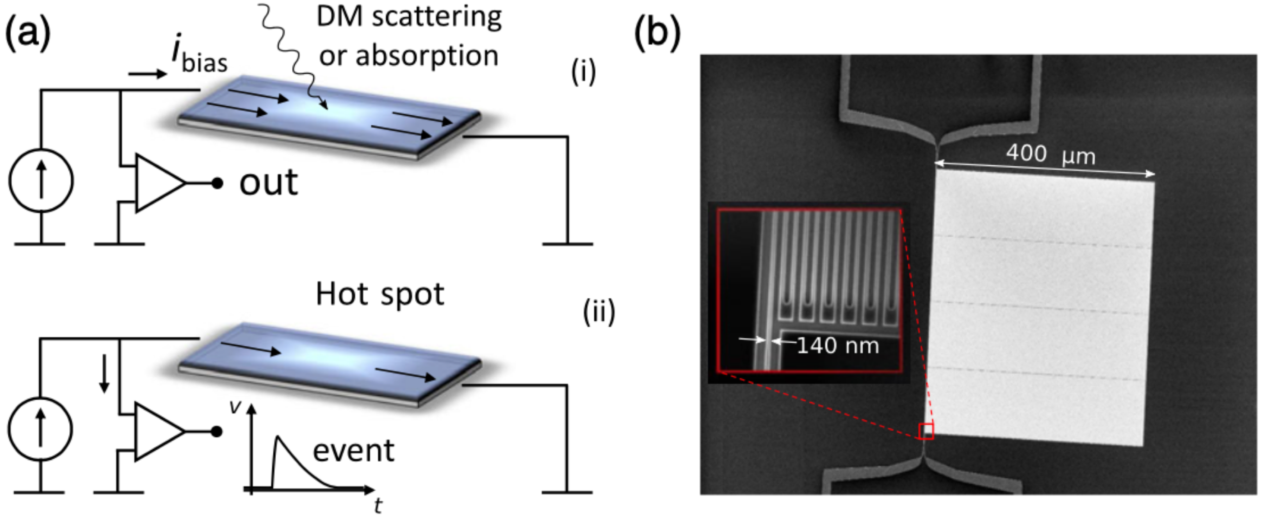
superconductor

Y. Hochberg, et al. (2021)



semiconductor

S. M. Griffin, et al. (2021)

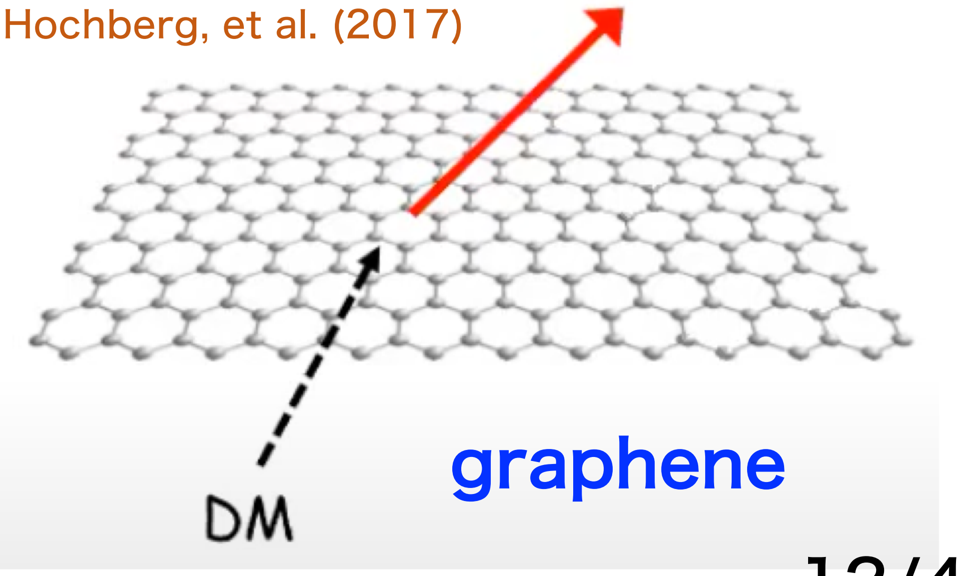


superconducting nanowire

Y. Hochberg, et al. (2019)

electron

Y. Hochberg, et al. (2017)



graphene

Projected detections of light dark matter

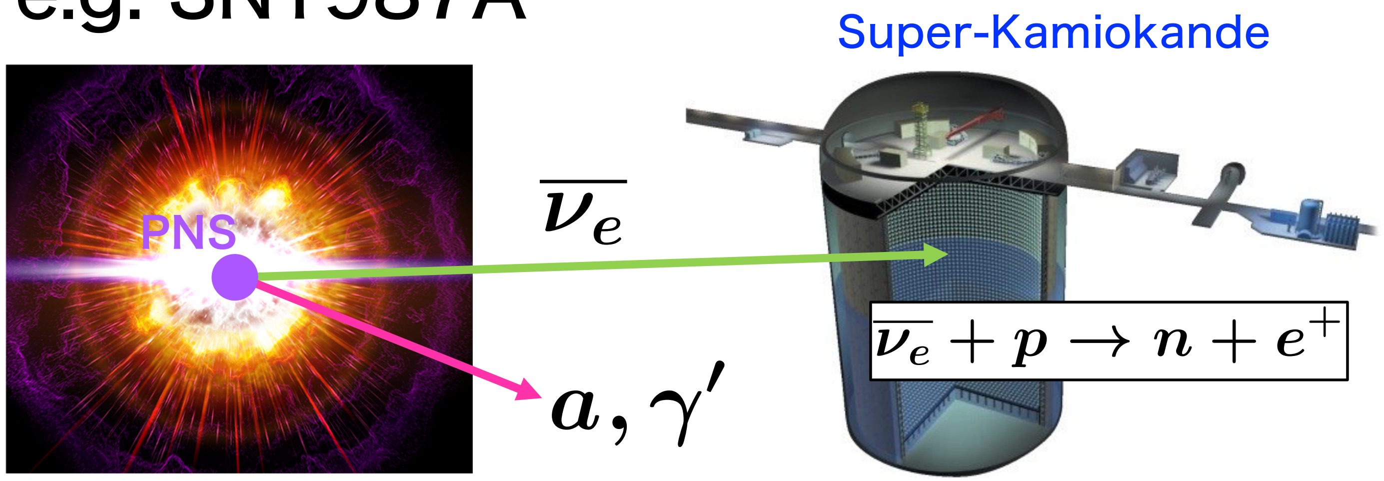
- DM-electron interaction
  - DM scatters off electrons : $E^{\mathrm{scat}}_{\mathrm{dep.}} \sim m_{\mathrm{DM}} v^2_{\mathrm{DM}} \sim 10^{-6} m_{\mathrm{DM}}$
  - DM is absorbed by electrons : $E^{\mathrm{abs}}_{\mathrm{dep.}} \sim m_{\mathrm{DM}}$ $v_{\mathrm{DM}} \sim 10^{-3}\mathrm{c}$

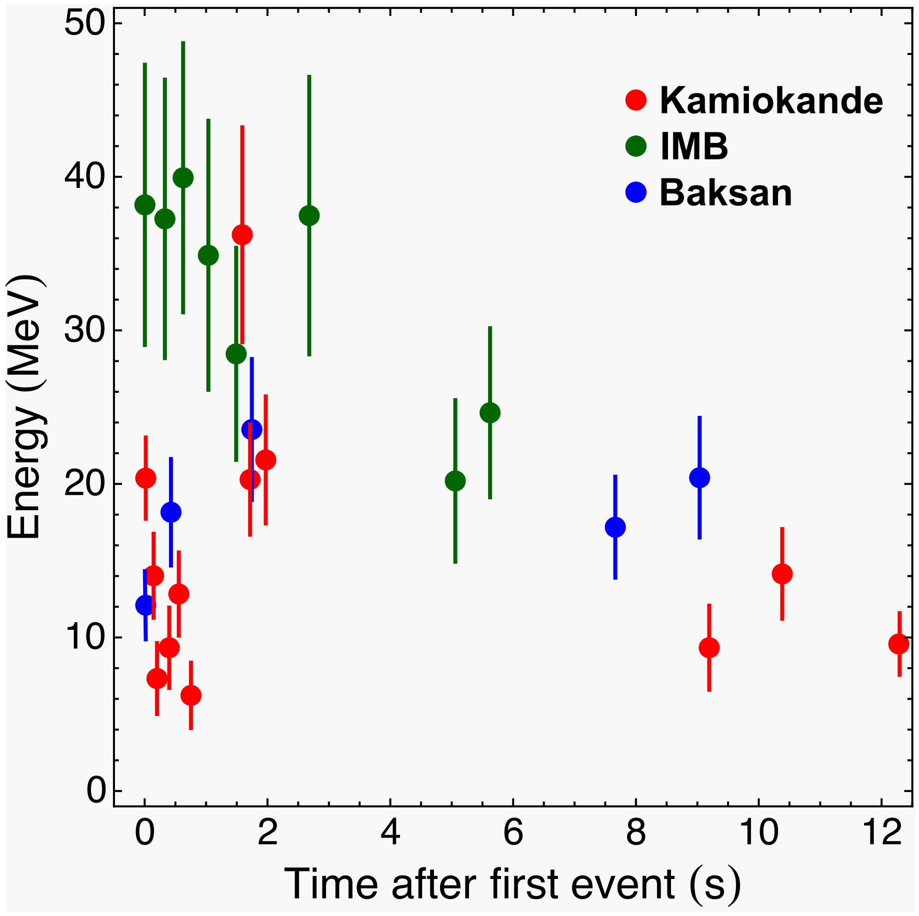
- List of the potential material and their sensitivities

Material	Sensitivitiy	Dark matter mass
Superconductor	$\gtrsim$ meV	$\gtrsim$ keV (scattering) , $\gtrsim$ meV (absorption)
Superconducting nanowire	$\gtrsim$ eV	$\gtrsim$ MeV (scattering) , $\gtrsim$ eV (absorption)
2D material (e.g. graphene)	$\gtrsim$ eV	$\gtrsim$ MeV (scattering)
3D material (e.g. $\mathrm{ZrTe_5}$)	$\gtrsim$ meV	$\gtrsim$ keV (scattering) , $\gtrsim$ meV (absorption)
Semiconductor (e.g. Ge, Si)	$\gtrsim$ eV	$\gtrsim$ MeV (scattering)

Light particle emission from celestial bodies

- Light (DM) particles can be produced copiously from some and hot dense celestial objects such as supernovae (SNe), neutron stars, and white dwarfs.
  - e.g. SN1987A





  - Raffelt's criteria

$$L_{\text{new particle}} < L_\nu \sim 3 \times 10^{52} \text{erg/s}$$

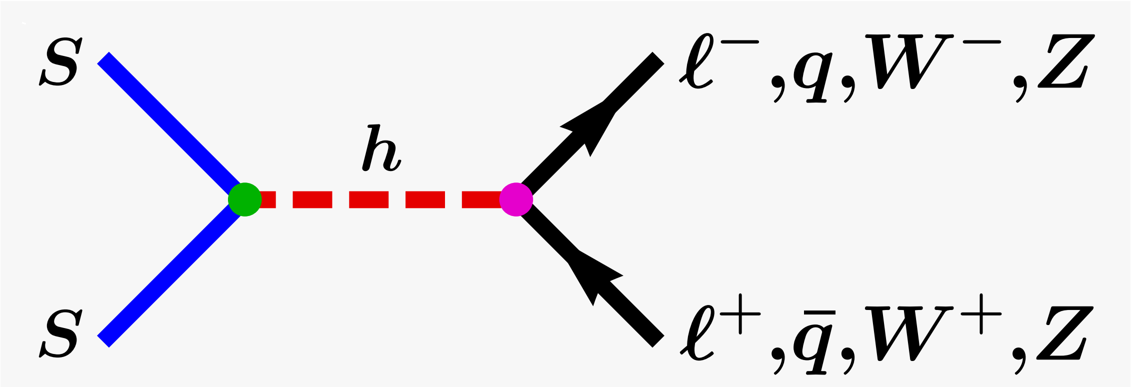
Raffelt `90

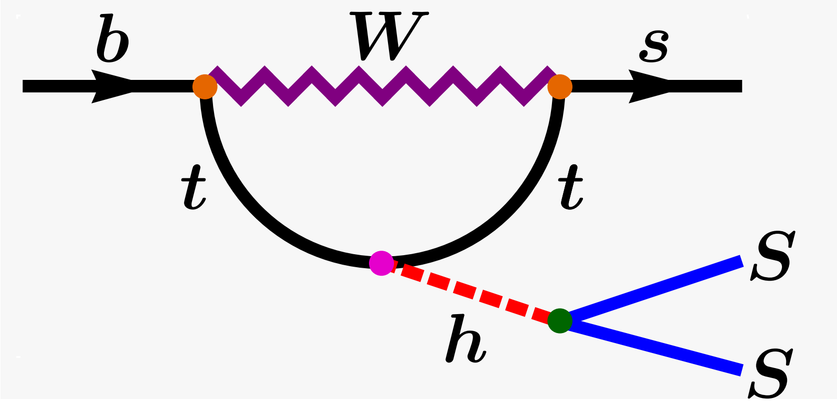
Probing light dark matter by B physics

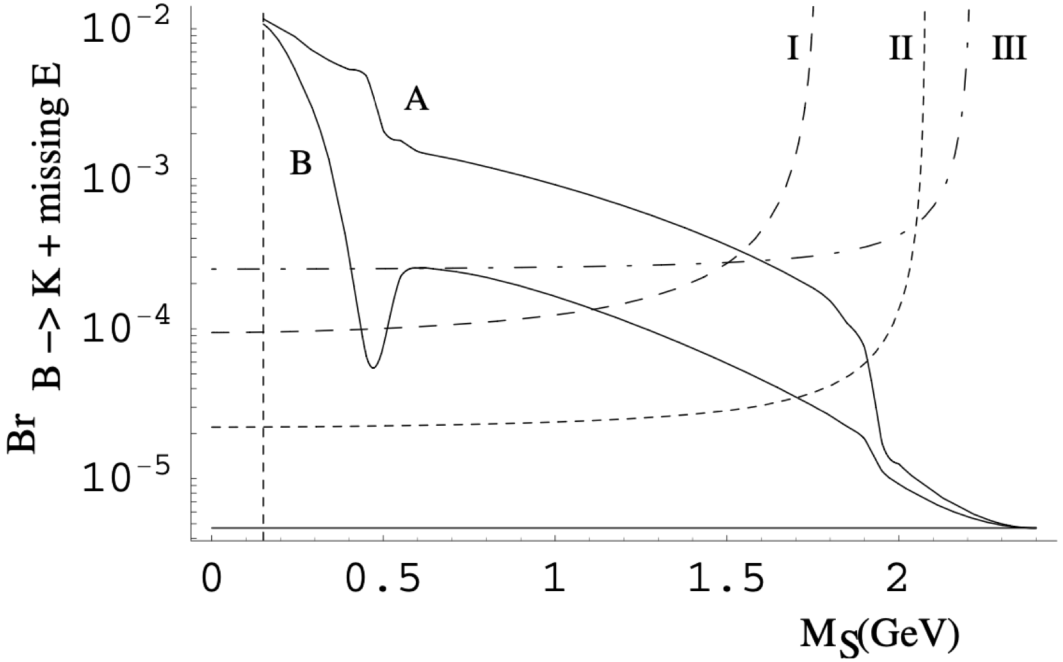
- Real singlet Z_2 scalar dark matter model

Bird et al, PRL 2004

$$-\mathcal{L} = \frac{1}{4}\lambda_S S^4 + \frac{1}{2}m_S^2 S^2 + \lambda v_{\mathsf{EW}} h S^2 + \frac{1}{2}\lambda h^2 S^2$$







λ should be large to fit the relic and BaBar

Probing light dark matter by B physics

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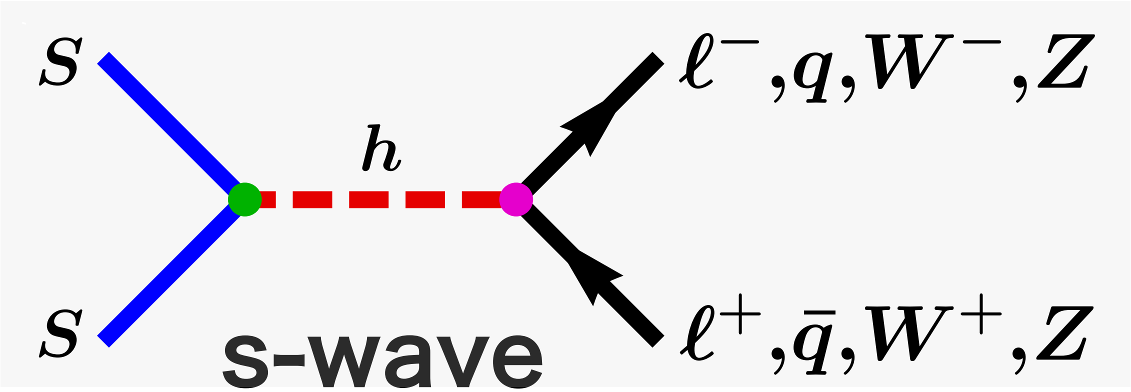

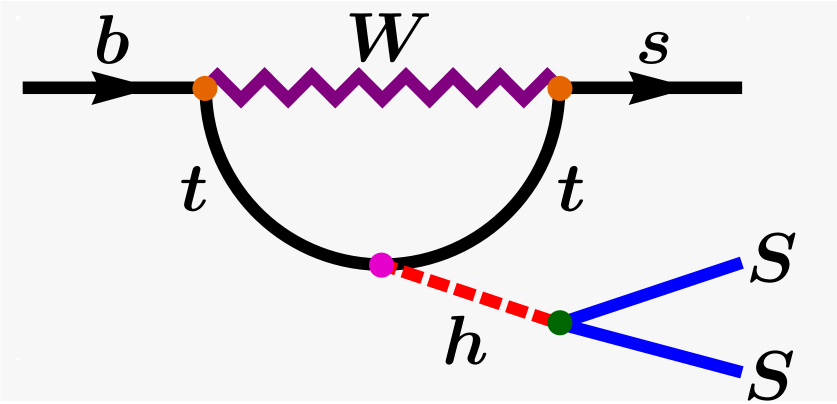

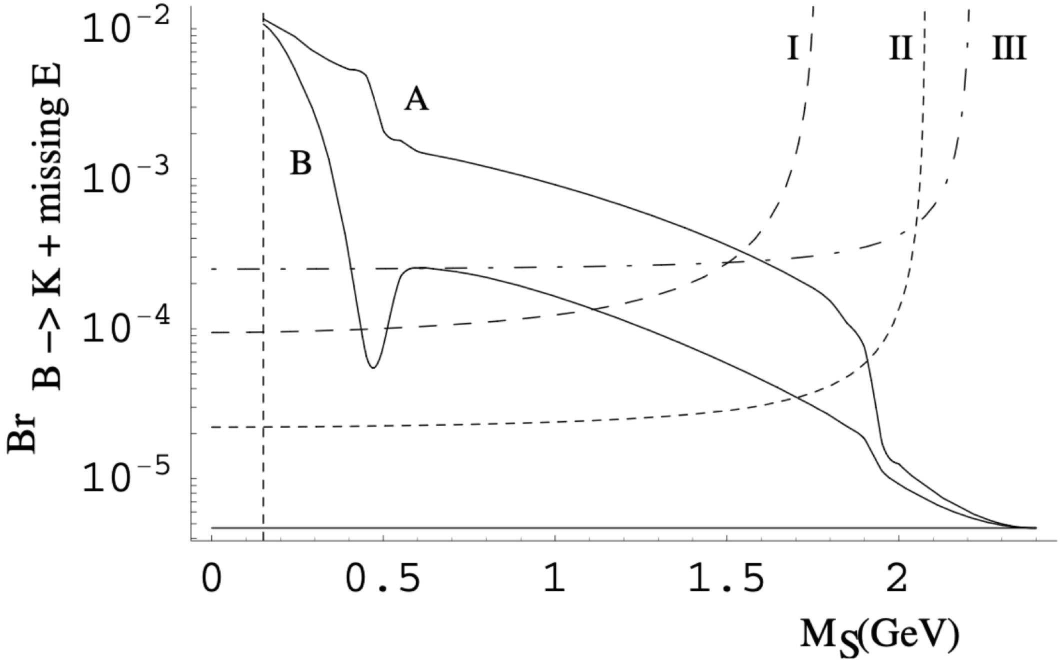

$$m_S \lesssim 2.4\,\mathrm{GeV}$$

CMB constraint on light DM mass

- DM annihilation continues to take place after decoupling & cause significant effects on cosmology and astrophysics.
- Energy released per DM annihilation $E_{\mathsf{DM}} \approx 2m_{\mathsf{DM}}$

$$\left.\frac{\mathrm{d}E}{\mathrm{d}t\,\mathrm{d}V}\right|_{\mathsf{inj.}}(z) = n_{\mathsf{DM}}^2(z)\langle\sigma v\rangle(2m_{\mathsf{DM}}) = \rho_{\mathsf{c}}^2\Omega_{\mathsf{DM,0}}^2(1+z)^6\left(\frac{\langle\sigma v\rangle}{m_{\mathsf{DM}}}\right)$$

$$n_{\mathsf{DM}}(z) = \rho_{\mathsf{c}}\Omega_{\mathsf{DM}}(z)/m_{\mathsf{DM}} = \rho_{\mathsf{c}}\Omega_{\mathsf{DM,0}}(1+z)^3/m_{\mathsf{DM}}$$

Planck → $\langle\sigma v\rangle \leqslant \dfrac{4.1\times10^{-28}\,\mathrm{cm}^3\,\mathrm{sec}^{-1}}{f_{\mathsf{eff}}}\left(\dfrac{m_{\mathsf{DM}}}{\mathrm{GeV}}\right)$