Freeze-in Production of Non-Abelian Millicharged Vector Dark Matter

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Based on arXiv: 2512.08622, 2408.11626, 2605.03427, 2111.15503

In collaboration with **C.R.Chen** (NTNU), **M. Du, R. Fang, Z. Liu** (NJU), **T.C. Yuan** (AS)

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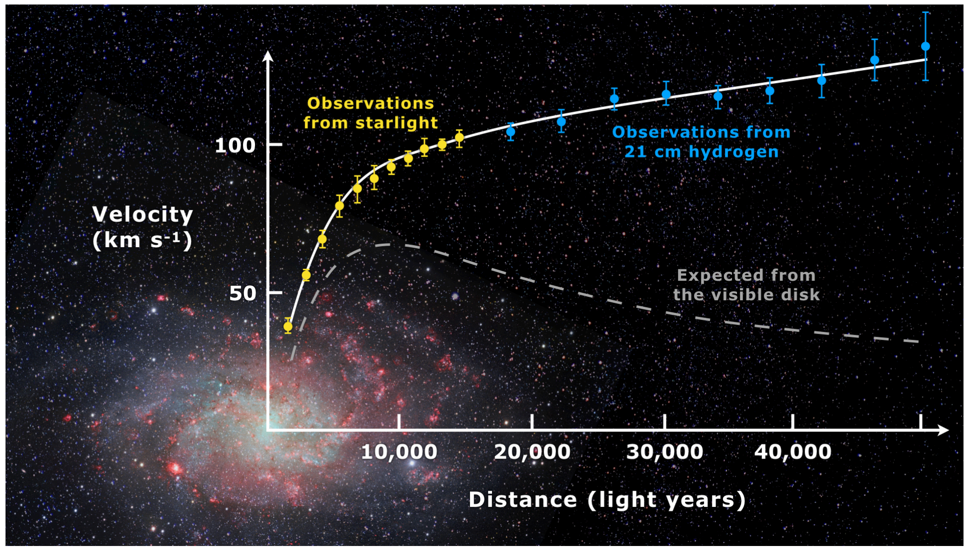
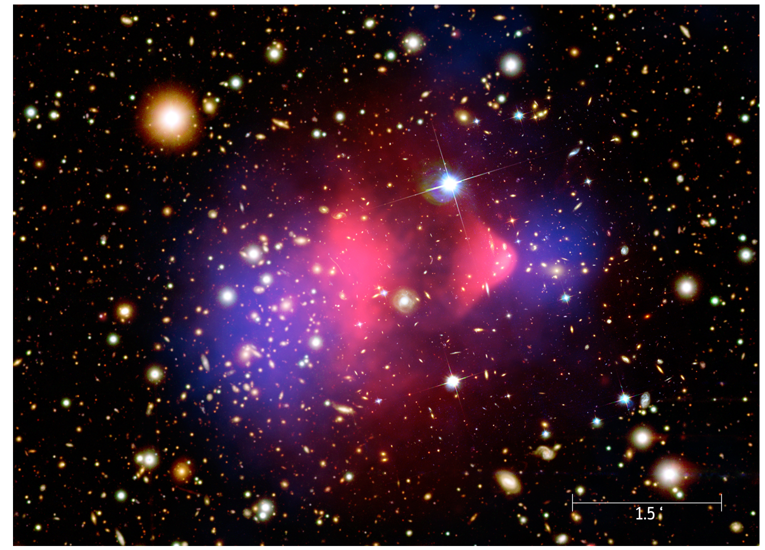
Physics Division 國家理論科學研究中心 物理組

Dark Matter Evidence

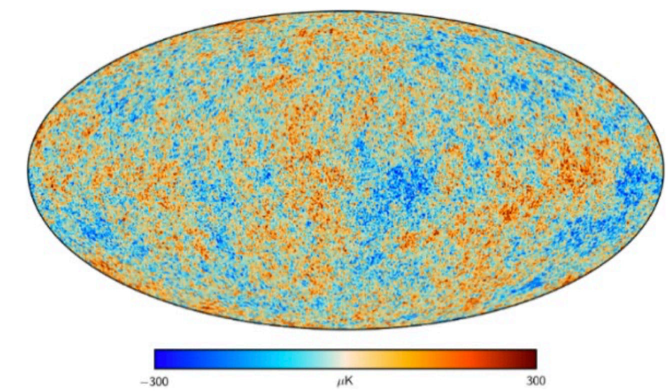
Galactic rotation curve

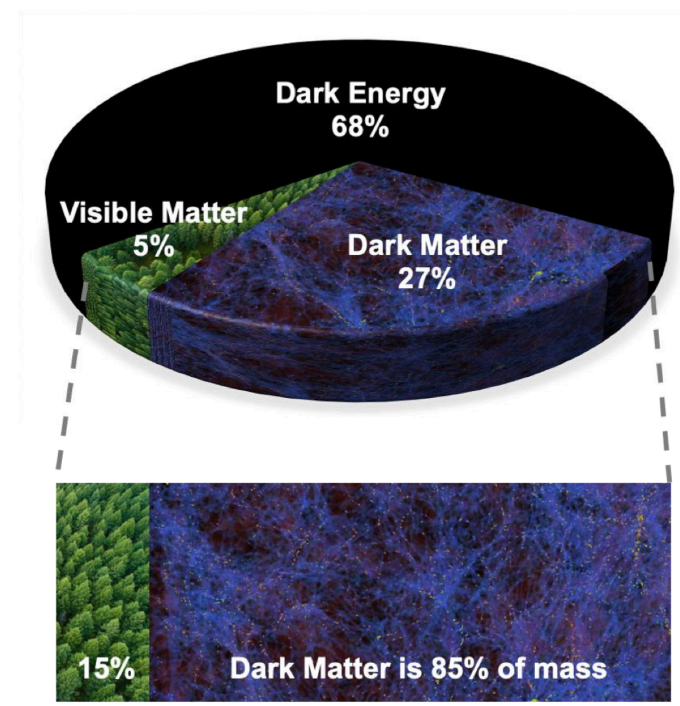


Bullet Cluster



CMB





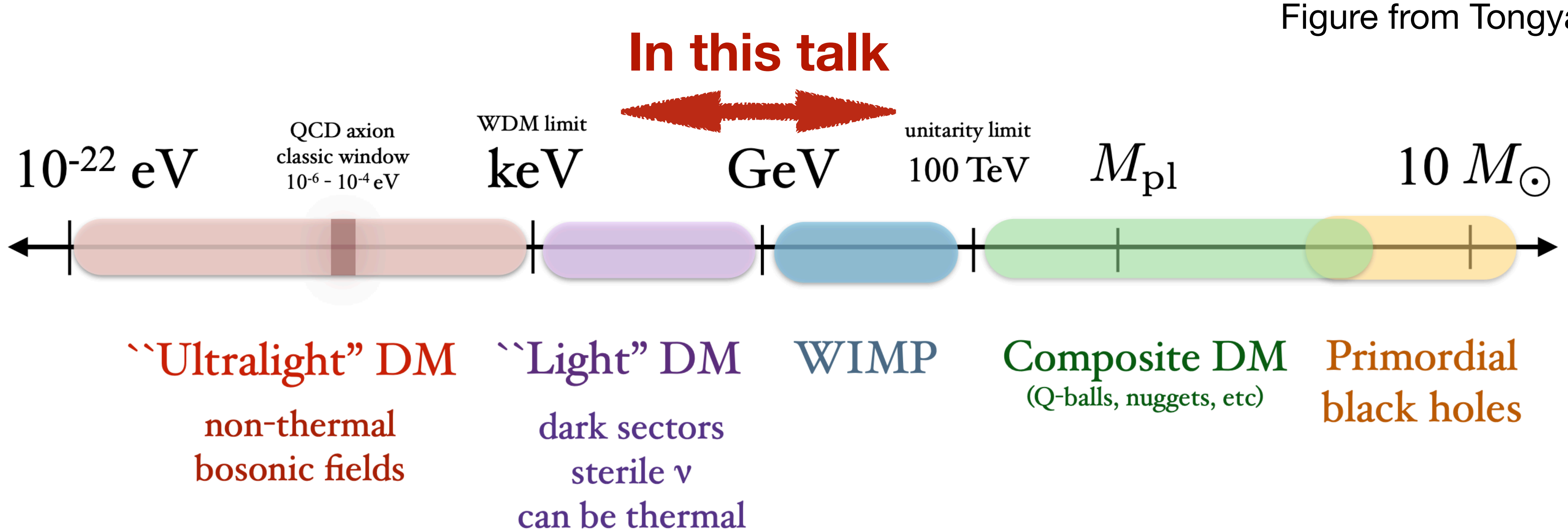
- ✦ Many DM evidences due to its gravitational effects
- ✦ DM is the dominant form of matter in the Universe
- ✦ The nature of DM is still a mystery!

Dark Matter Candidate

✦ Many DM candidates with mass window in a wide range: **100 orders of magnitude**

✦ **Thermal candidates** and **WIMPs** (**keV – 100 TeV** mass range) are the most thoroughly and frequently explored models of DM

Figure from Tongyan Lin 1904.07915



*WIMP: Weakly Interacting Massive Particle

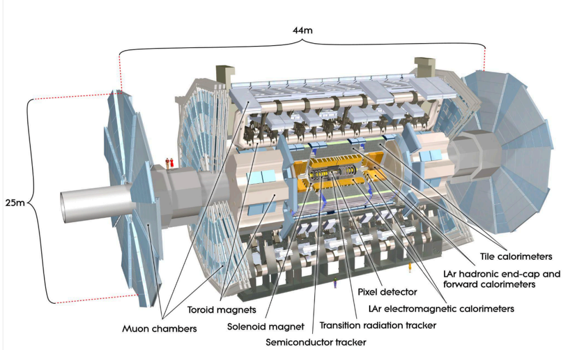
How to detect Dark Matter?

✦ Direct Detection

- DM scatters off nuclei/electrons in underground detectors
- Measure tiny nuclear recoils or ionization signals
- Experiments: XENON1T, LZ, PandaX …

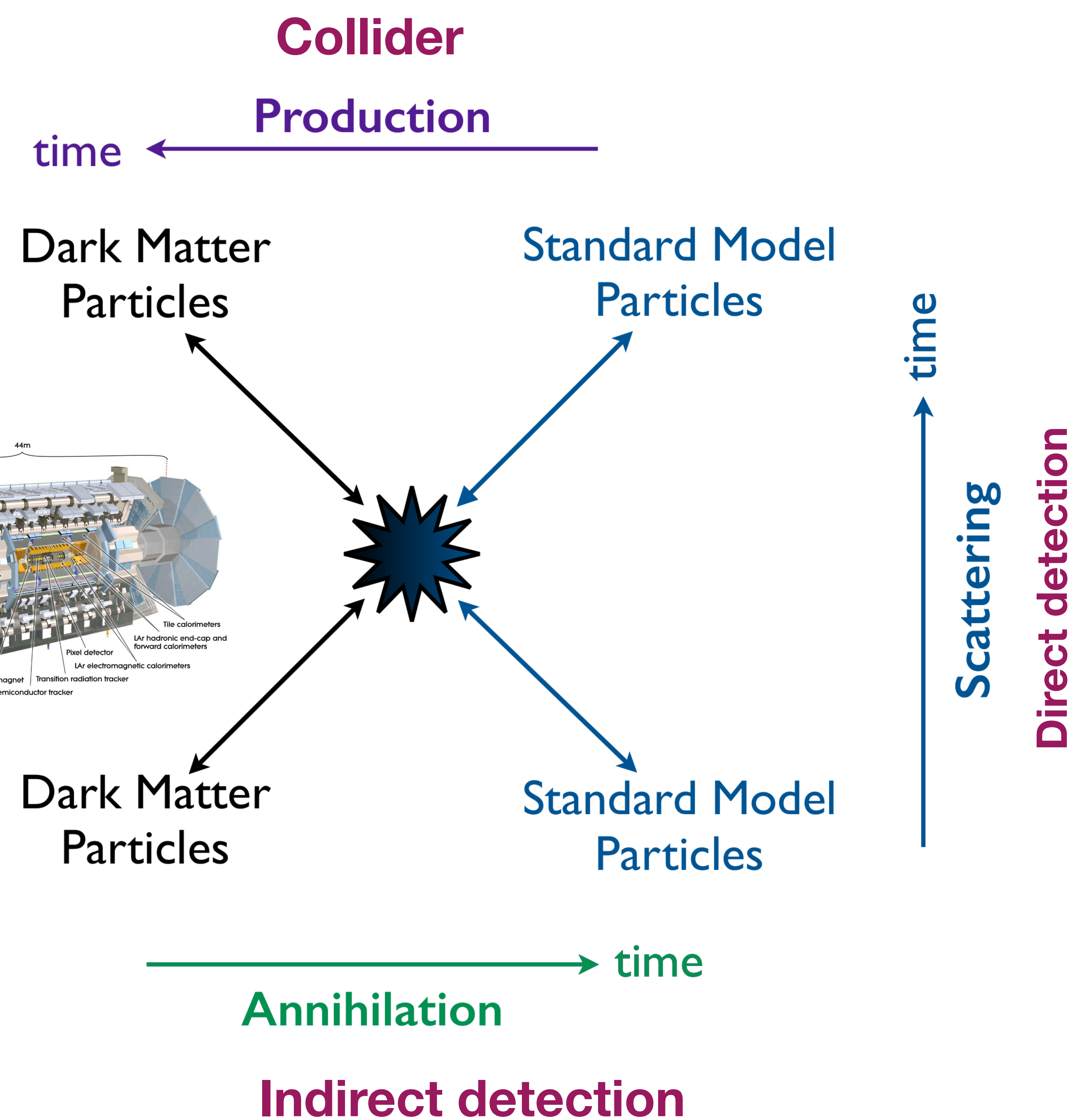
✦ Collider

- Produce DM at high-energy collisions (e.g., LHC)
- Signature: missing transverse energy + visible particles (jets, photons, leptons)



✦ Indirect Detection

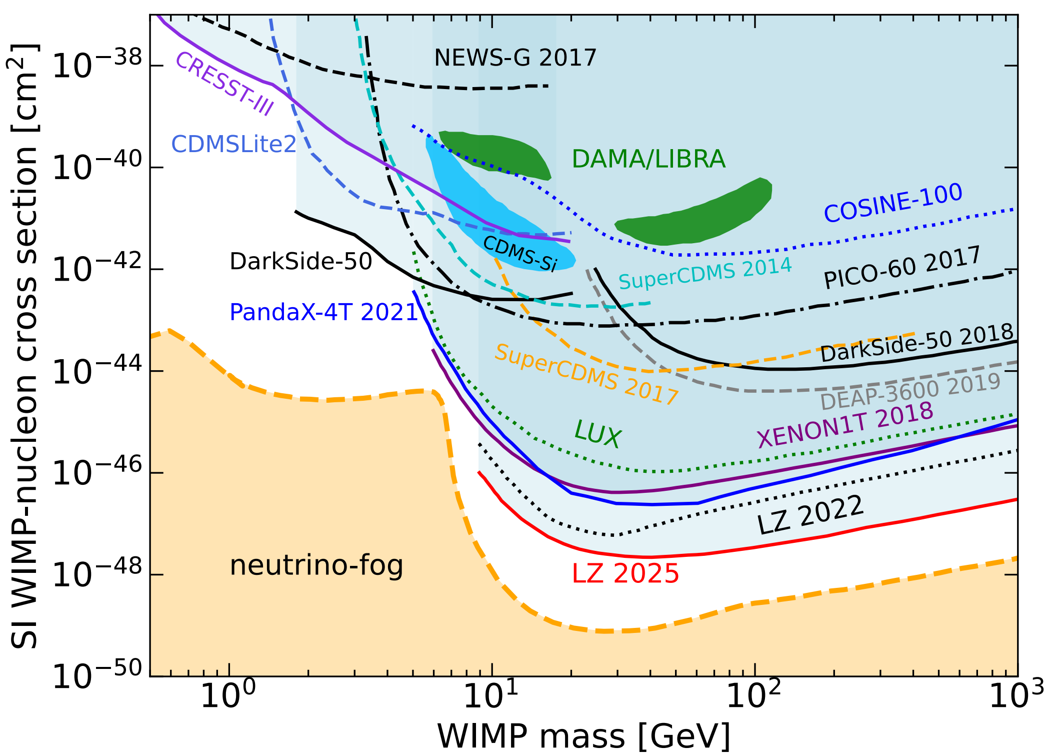
- Look for SM particles produced by dark matter annihilation or decay
- Signals: gamma rays, positrons, antiprotons, neutrinos
- Observatories: Fermi-LAT, AMS-02, IceCube, …



Current Status of Dark Matter Searches

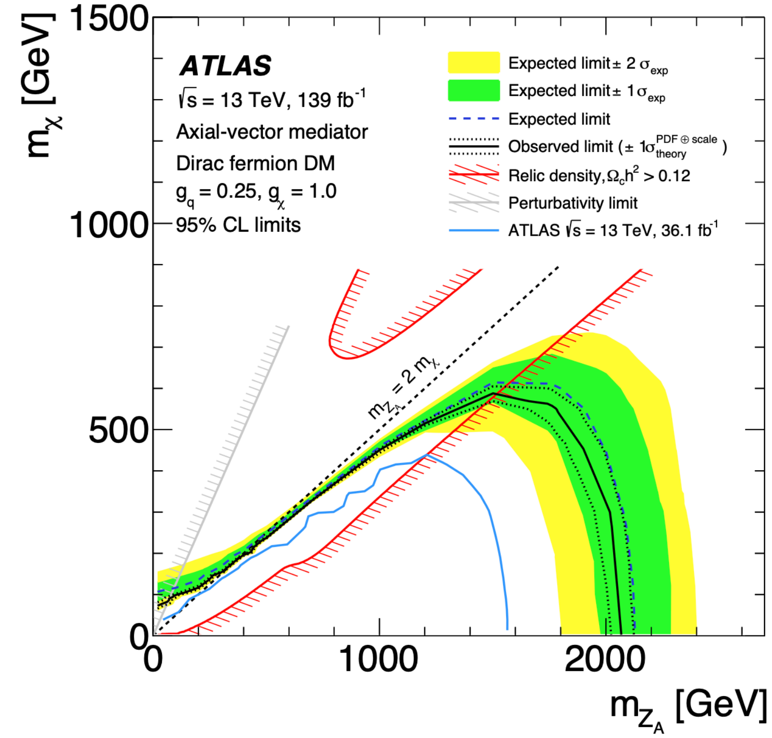
NCTS

Direct detection



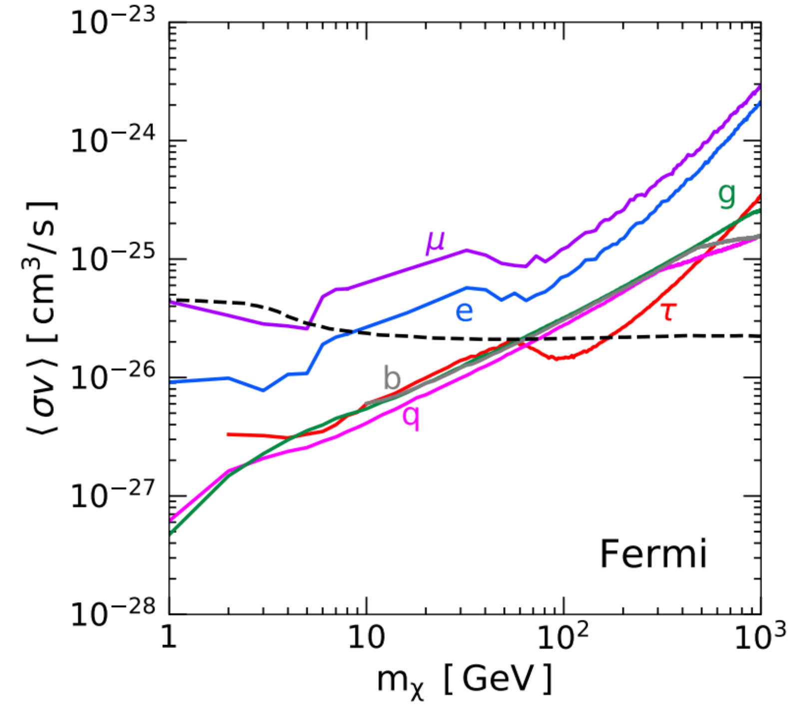
Collider

PRD 103, 112006 (2021)



Indirect detection

PRD 98, 023016 (2018)



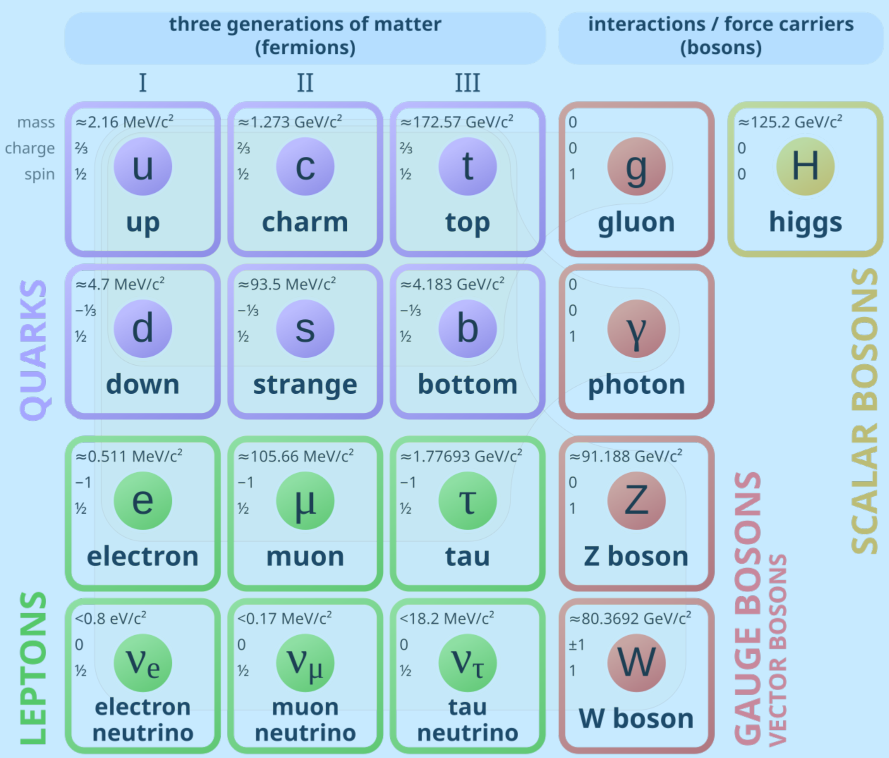
- ✦ No signals from direct detection experiments
- ✦ No confirmed evidence at colliders
- ✦ No confirmed anomalous excesses from indirect detection

➡ Dark matter may interact **very weakly** to visible matter!

Hidden (Dark) Sector Idea

Visible Sector

The particles and forces we know.

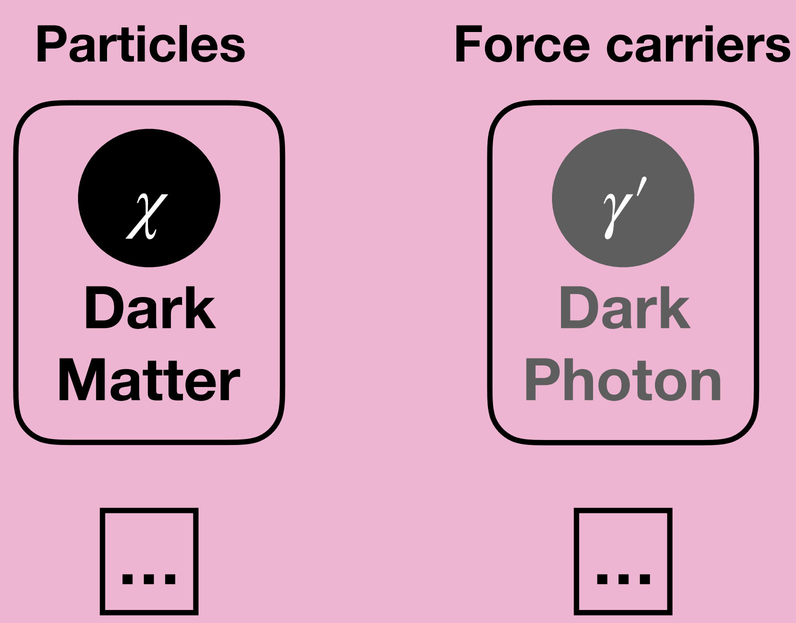


Portal

Extremely weak interactions

Hidden Sector

The particles and forces we don't know.



- Our Universe may exist a **hidden world** which has the **Dark Matter** and its own forces
- This **Hidden world** interacts very feebly with the **visible world** via **portals**.

Portals to Dark Sector

✤ **Vector portal**

$$\mathscr{L} \supset -\frac{\epsilon}{2} F'_{\mu\nu} F^{\mu\nu}$$

✤ **Scalar portal**

$$\mathscr{L} \supset \lambda_{HS} |H|^2 |S|^2$$

✤ **Neutrino Portal**

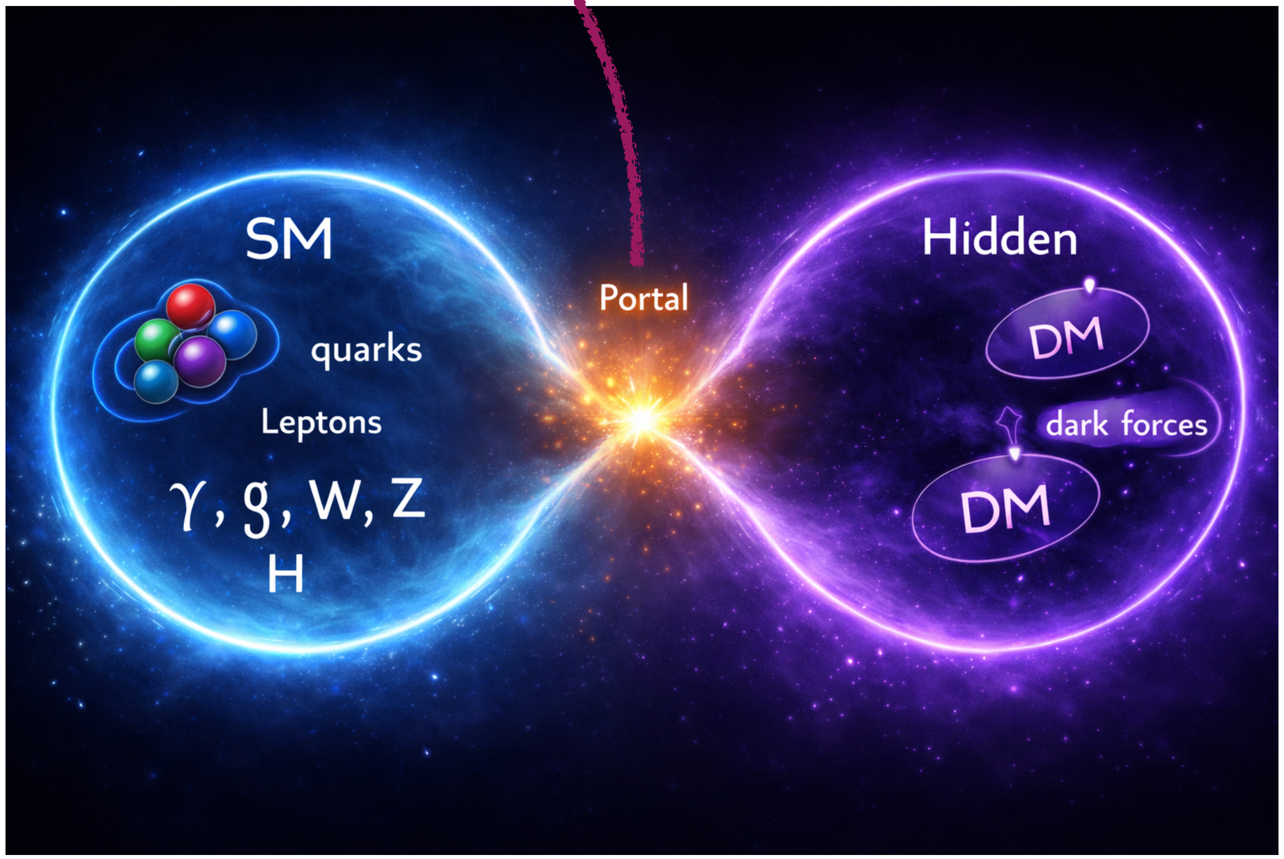
$$\mathscr{L} \supset y_N \bar{L} H N$$

✤ **Axion (Pseudoscalar) Portal**

$$\mathscr{L} \supset \frac{a}{f_a} F_{\mu\nu} \tilde{F}^{\mu\nu}$$

✤ **Axion-Dark Photon Portal**

$$\mathscr{L} \supset \frac{a}{f_a} F'_{\mu\nu} \tilde{F}^{\mu\nu}$$



Vector (Dark Photon) Portal

1. U(1) kinetic mixing

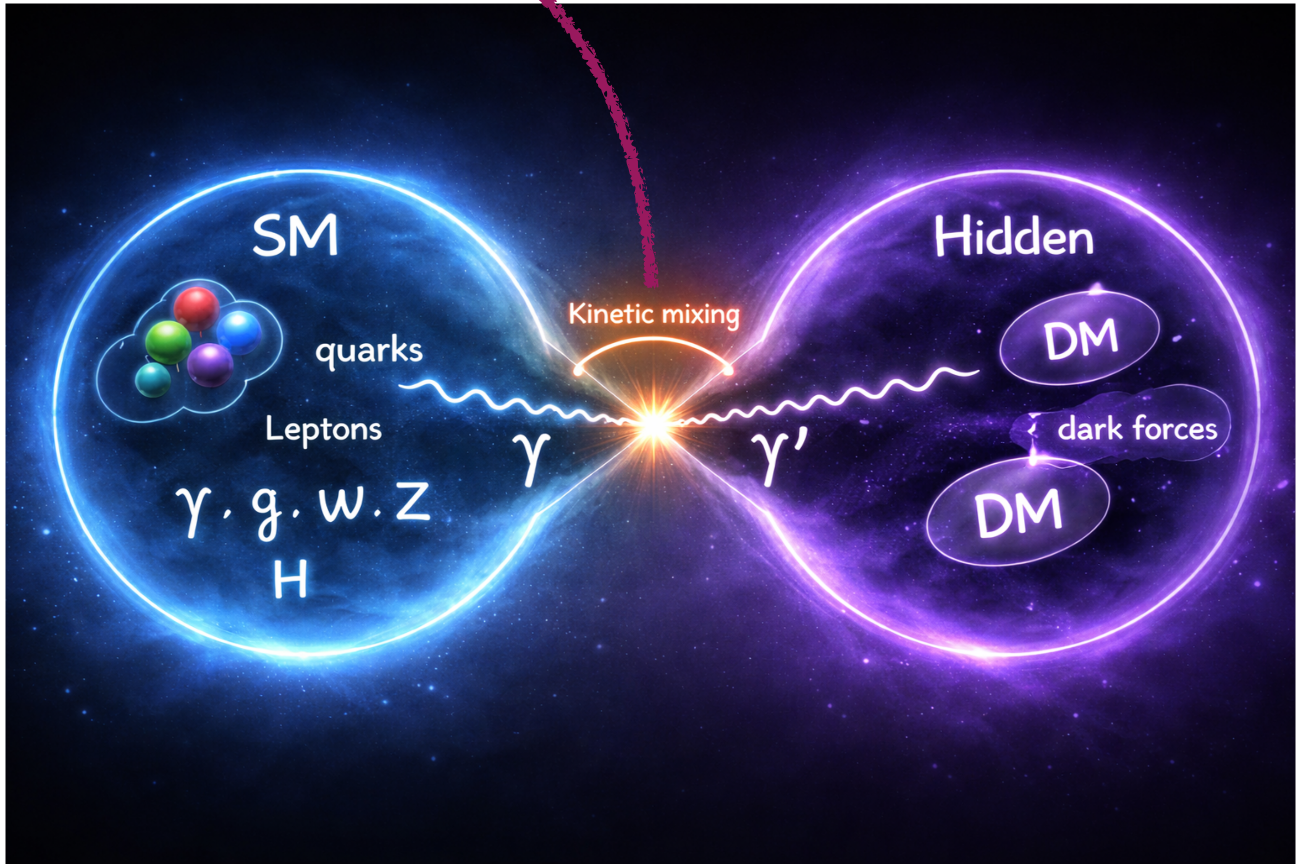
$$\mathscr{L} \supset -\frac{\epsilon}{2} F'_{\mu\nu} F^{\mu\nu}$$

Holdom (1986), +++

2. U(1) Stueckelberg mass mixing

$$\mathscr{L} \supset -\frac{1}{2}(\partial\sigma + m_1 \epsilon B_\mu + m_1 X_\mu)^2$$

D. Feldman, Z. Liu, and P. Nath (2006), +++



3. Abelian—Non-Abelian kinetic mixing

$$\mathscr{L} \supset -\frac{\epsilon}{2} W_D^{3\mu\nu} B_{\mu\nu}$$

Arised from the dim-5/dim-6 operator

$$\mathcal{O}_5 = \frac{c_5}{\Lambda} \mathrm{Tr}\left[\Sigma W_D^{\mu\nu}\right] B_{\mu\nu} \, ,$$

$$\mathcal{O}_6 = \frac{c_6}{\Lambda^2} \left(\Phi^\dagger \sigma^a \Phi\right) W^a_{\mu\nu} B^{\mu\nu}$$

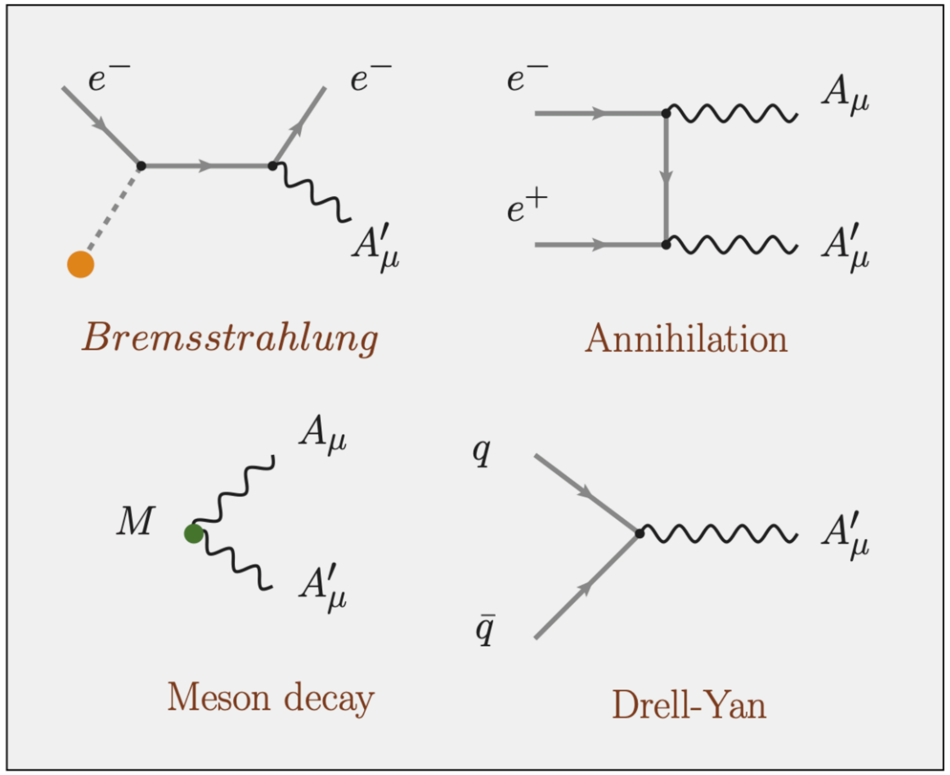
VQT and Tzu-Chiang Yuan (2024, 2025)
P. Ko, Takaaki Nomura, Hiroshi Okada (2021)
G. Barello, Spencer Chang, Christopher A. Newby (2015),
C.A. Arguelles, X-G. He, G. Ovanesyan, T. Peng, Michael J. Ramsey-Musolf (2017)

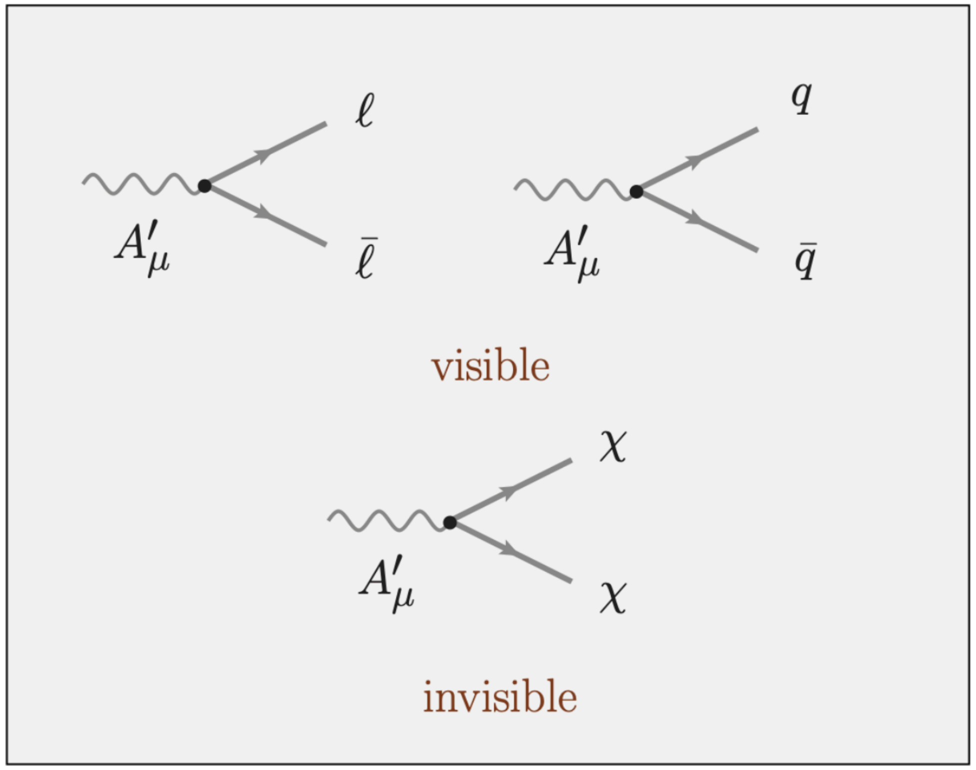
- The interaction between a dark photon A'_μ to SM particle is controlled by the parameter ϵ

$$\mathscr{L} = \epsilon e J^\mu A'_\mu$$

The electromagnetic current

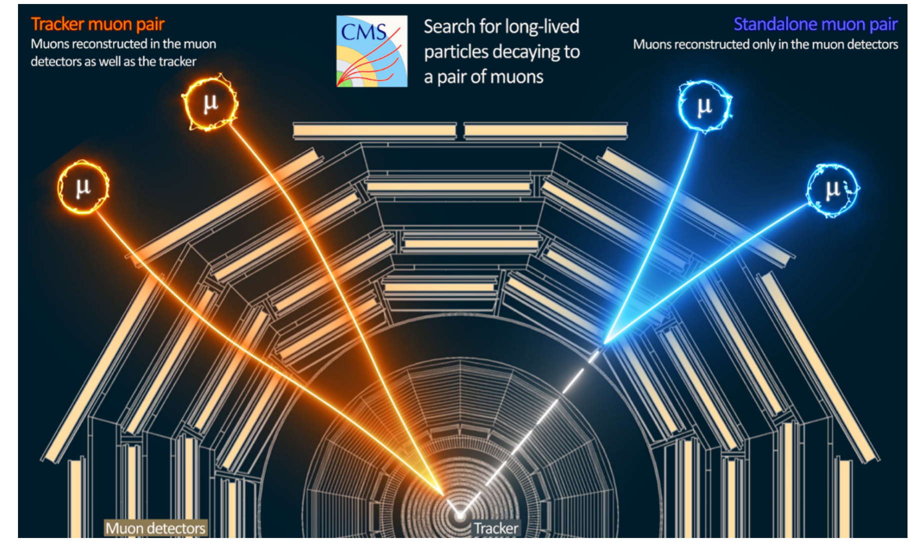
- Production and Decay channels:

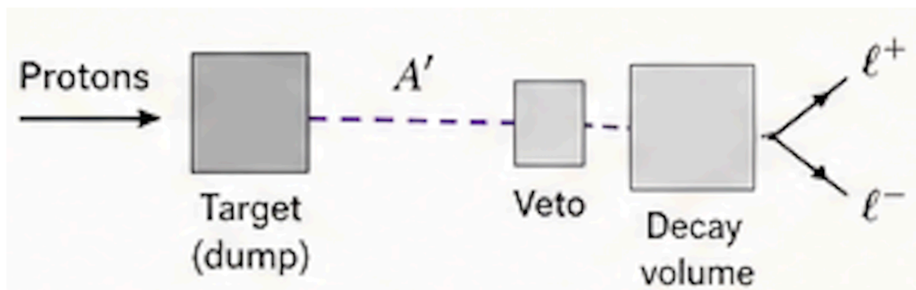


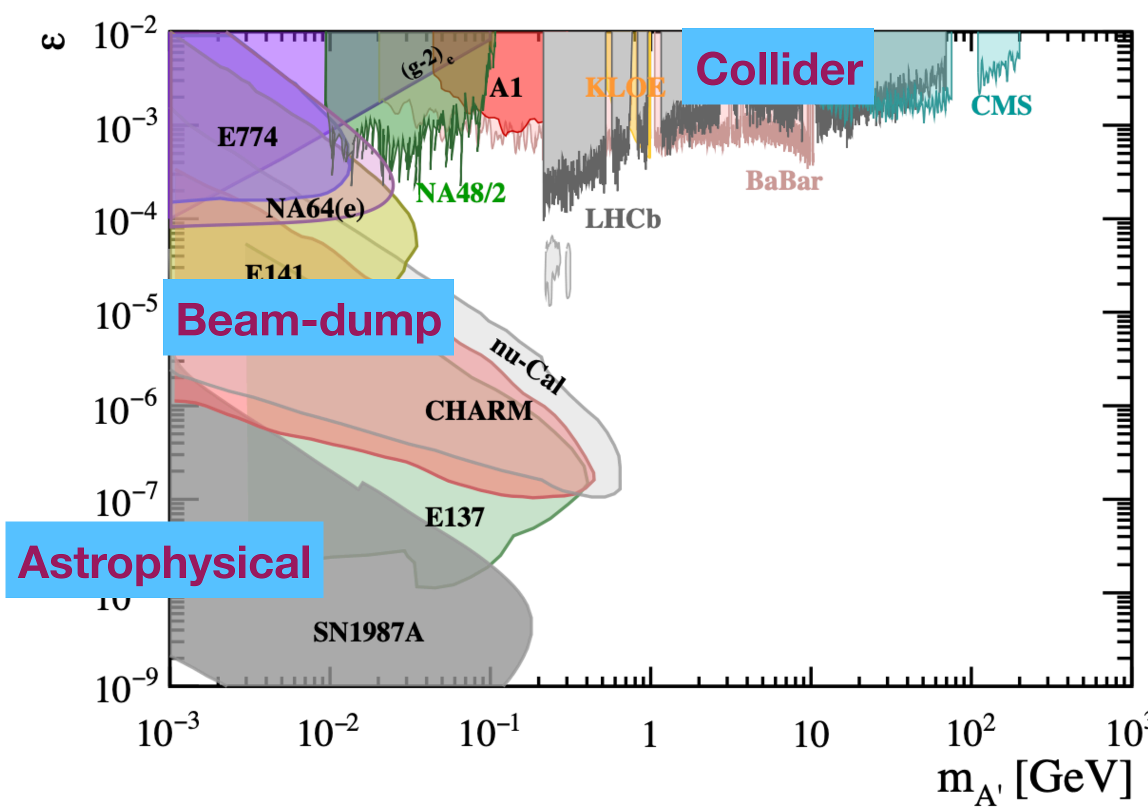


Searches for Massive Dark Photons

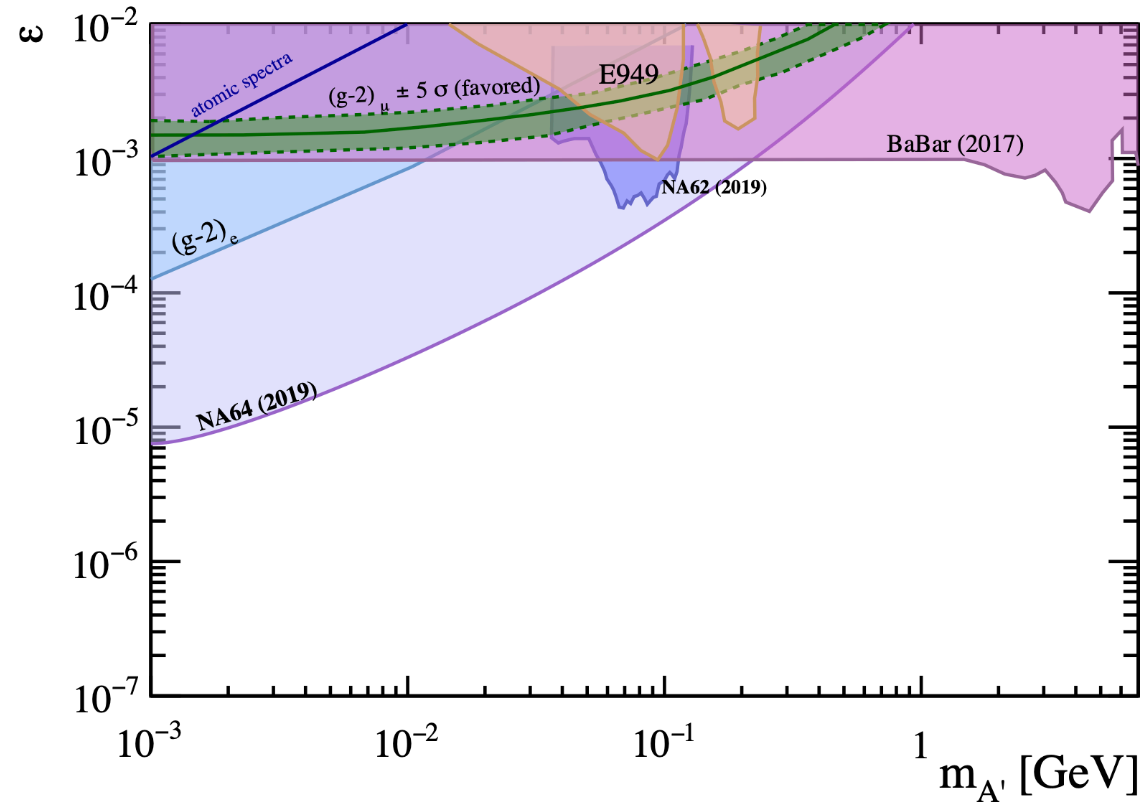
- **Colliders:** Search for resonances in the invariant mass distribution of e^+e^- or $\mu^+\mu^-$ pairs
- **Beam-dump/Fix target experiments:** shooting electron or proton beam to a fixed-target or a dump to generate the dark photon







Visible Decay



Invisible Decay

Searches for Long-lived Dark Photons

✦ LLP dedicated detectors

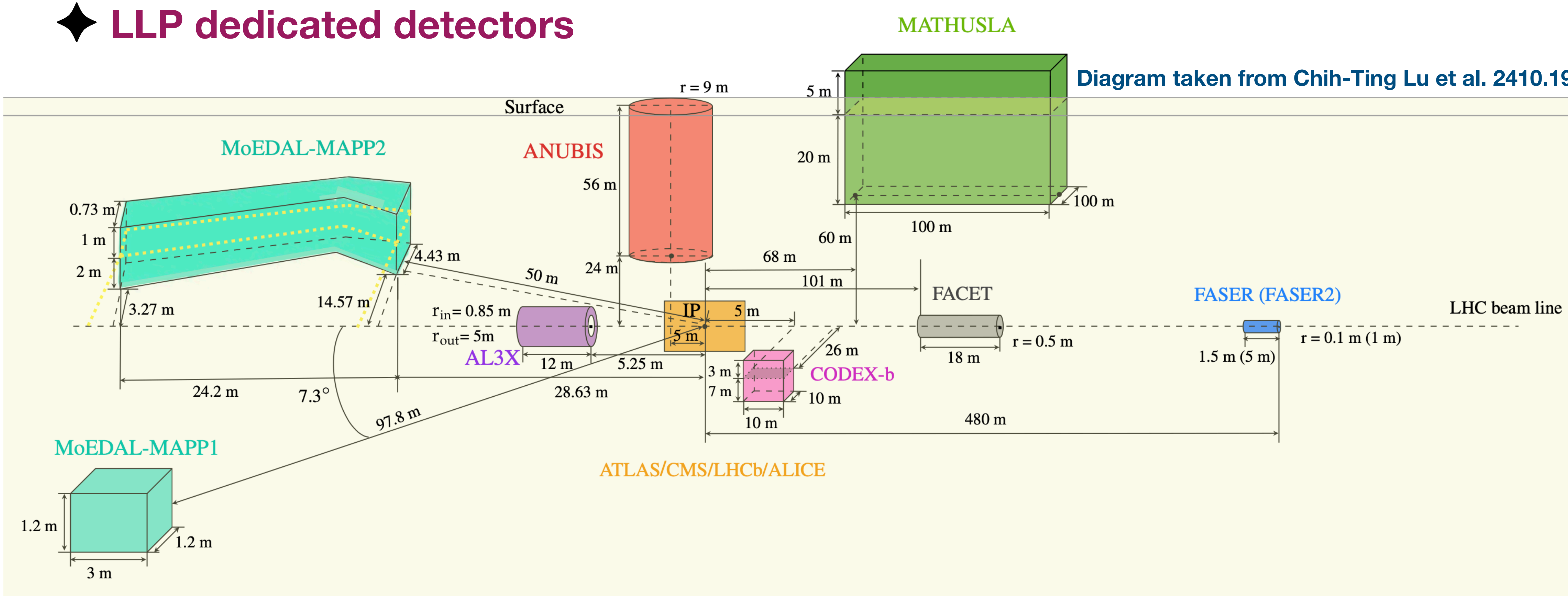


Diagram taken from Chih-Ting Lu et al. 2410.19561

✦ LLP dedicated detectors

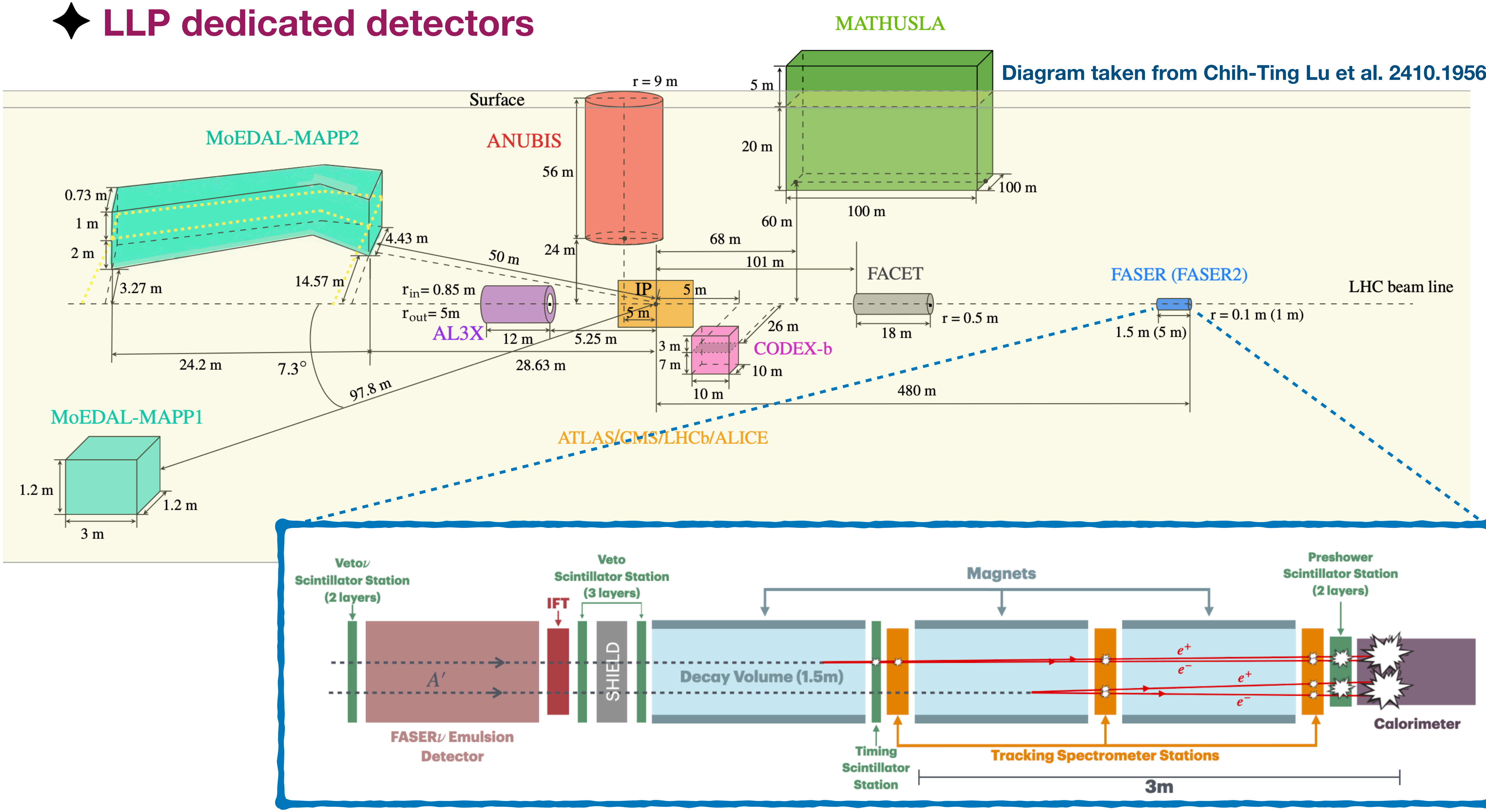
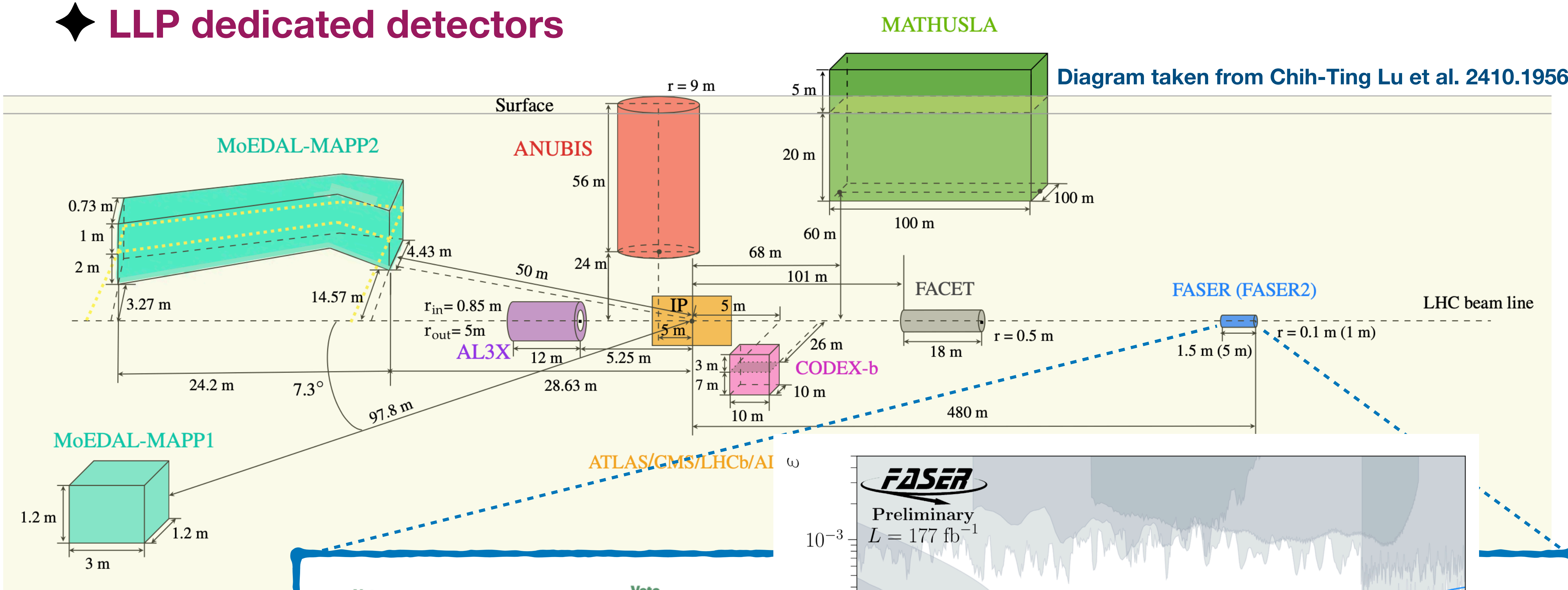


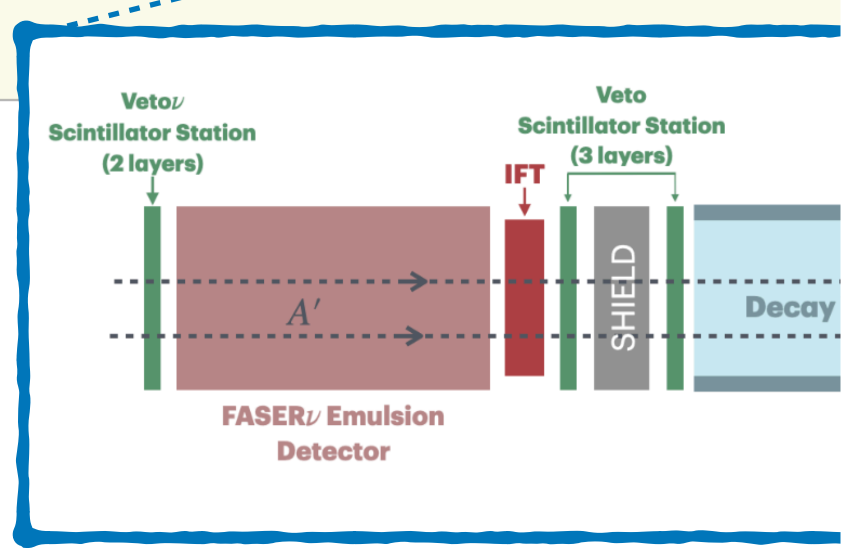
Diagram taken from Chih-Ting Lu et al. 2410.19561

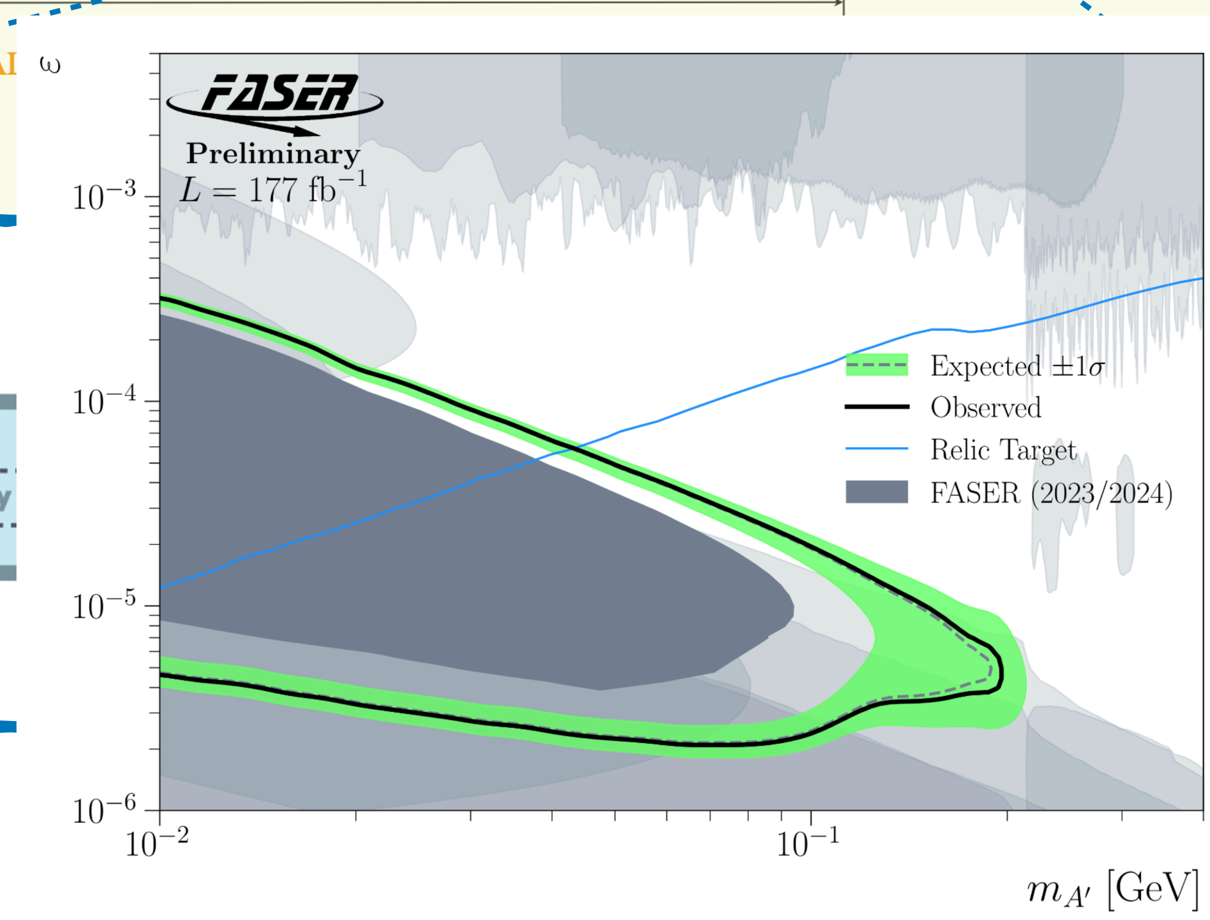
https://faser.web.cern.ch/briefing-20260319

Searches for Long-lived Dark Photons

✦ LLP dedicated detectors







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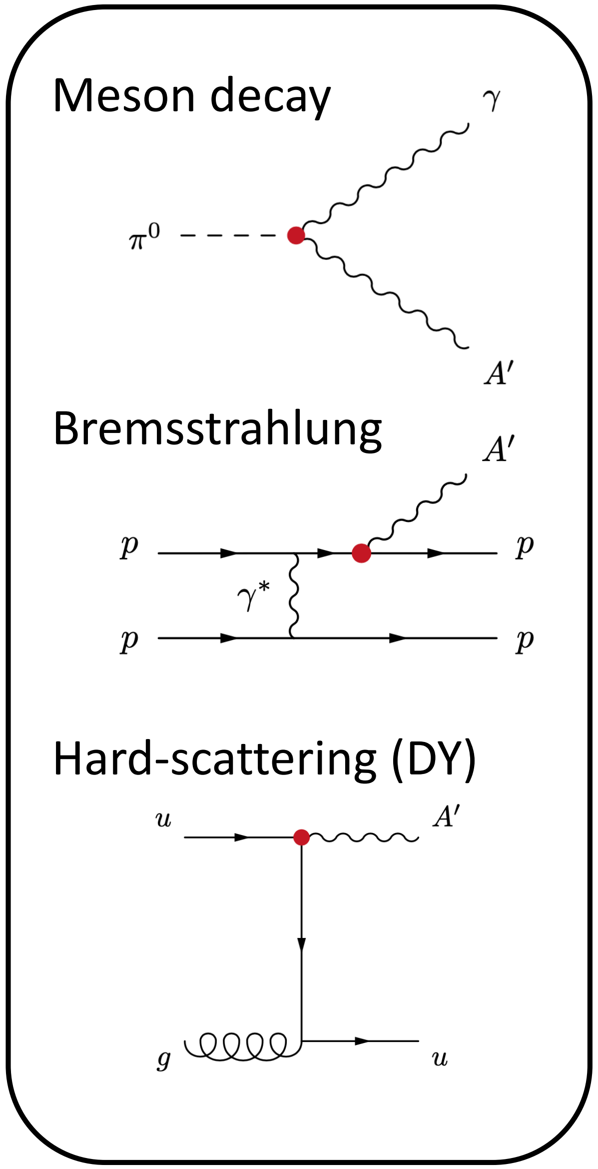
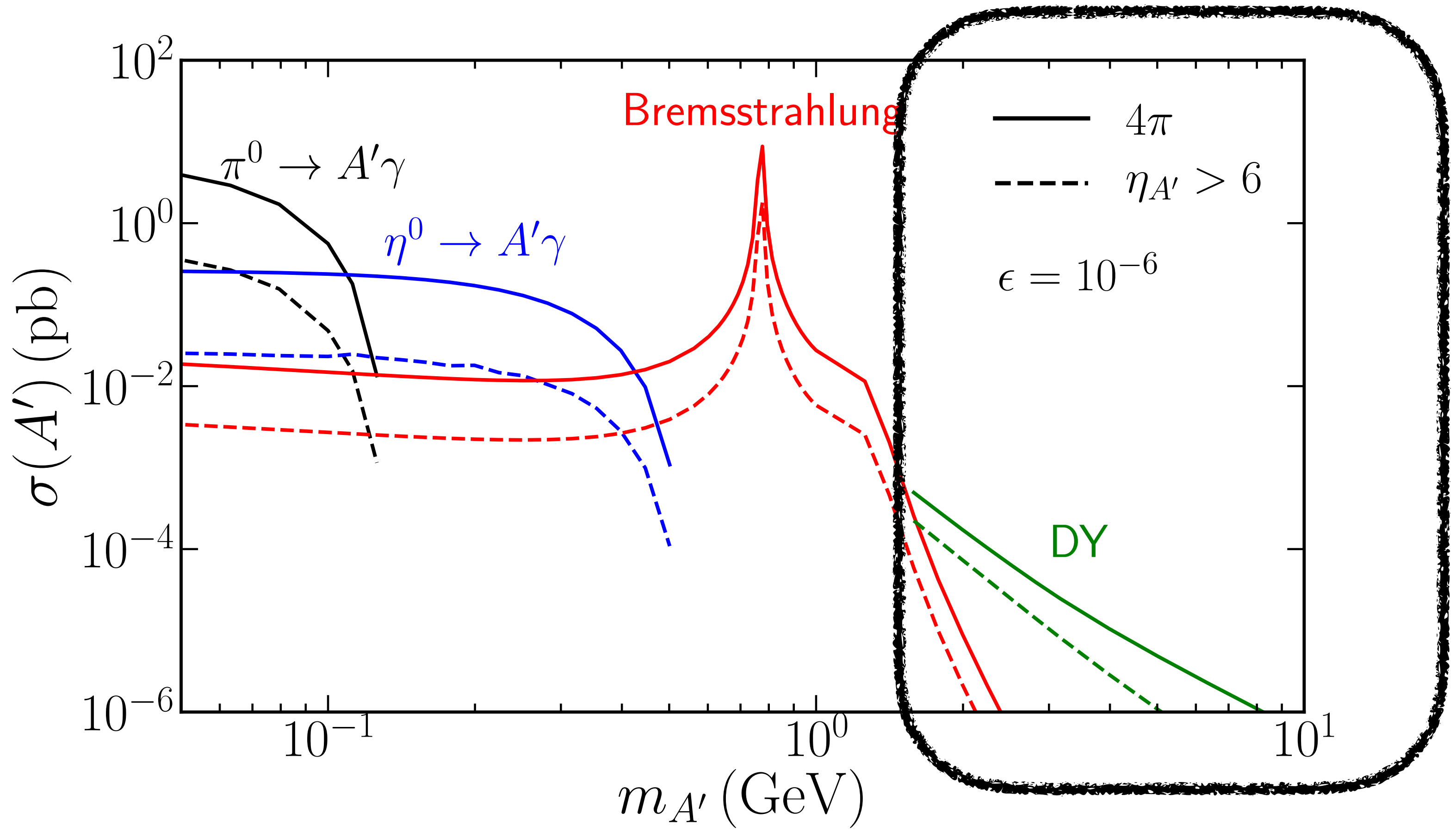
Dark Photon Production at the LHC



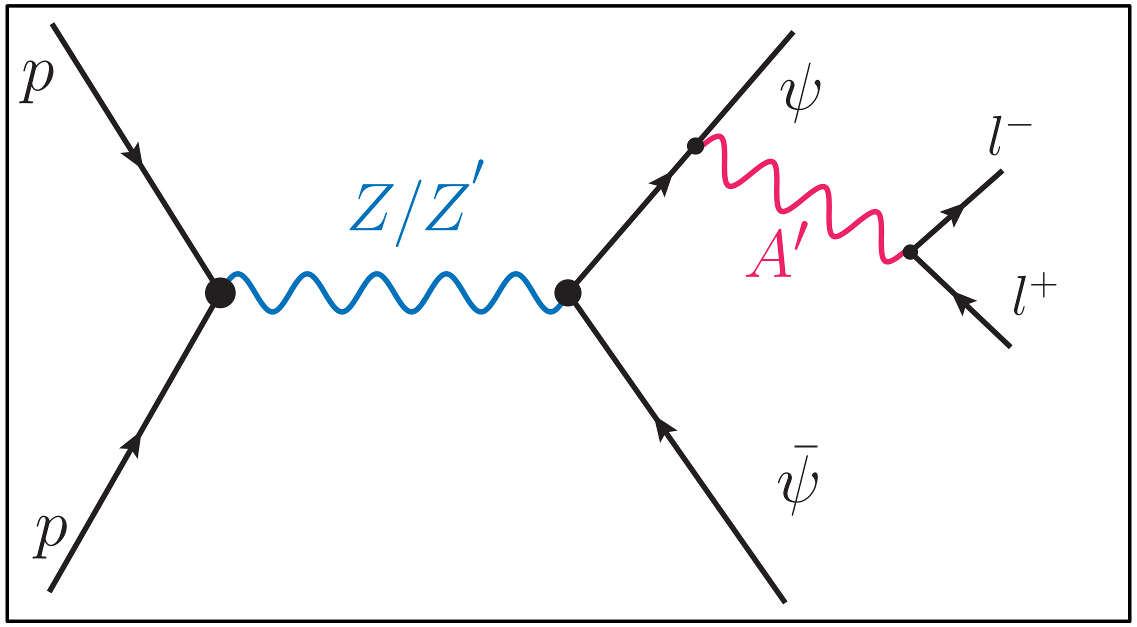


- ✤ **For low mass region, the meson decays and Bremsstrahlung processes are dominant**
- ✤ **For DP mass > 1.5 GeV, the hard-scattering process becomes dominant but the cross section is suppressed.**
- ✤ **Only about 10% of total DP produced in the very forward region.**

✤If future detectors observe LLDP signals with a higher mass region, there must be something beyond this conventional DP model!

Hidden Radiation Channel

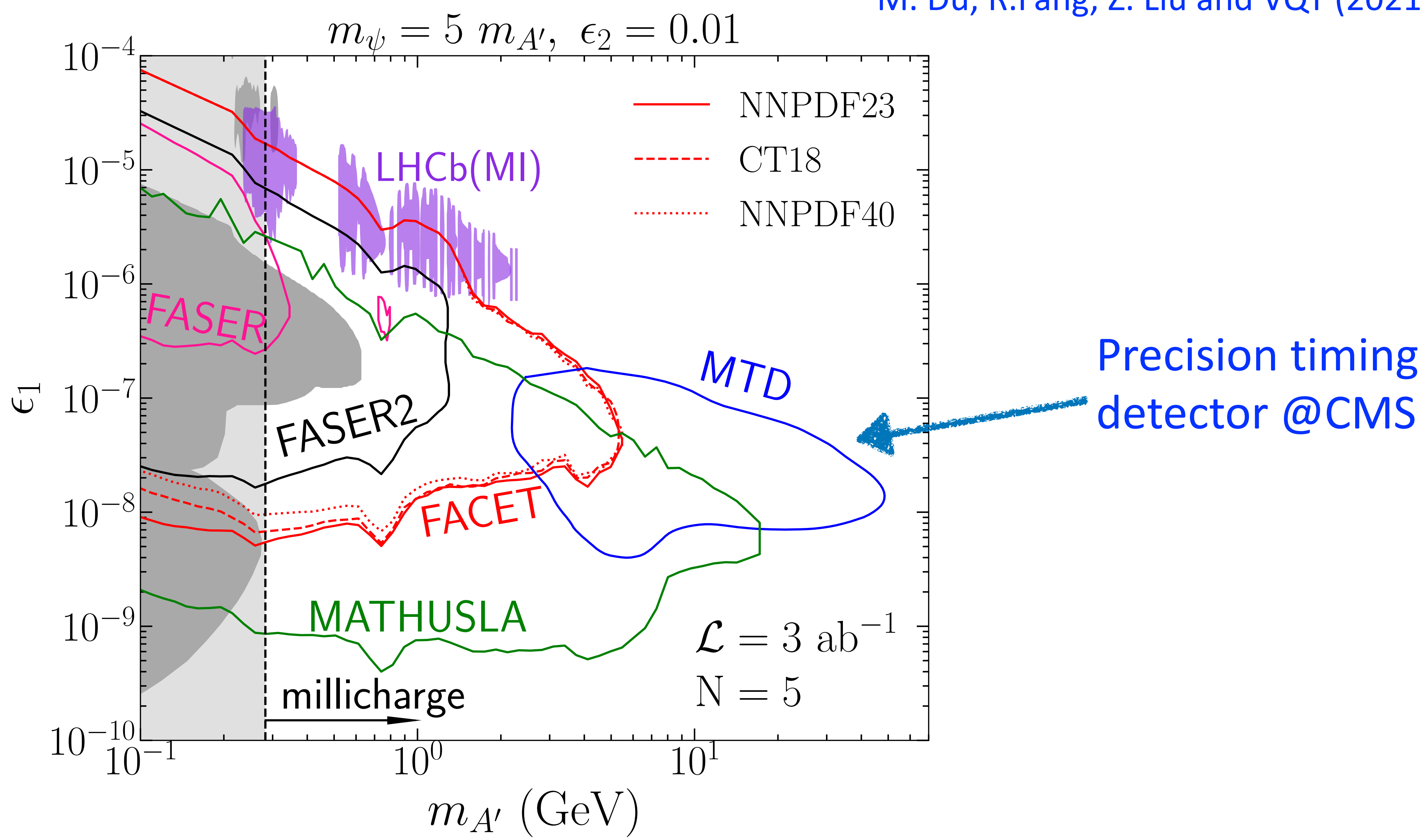
✦ Dark matter is produced via Z or Z' mediators at pp collision and then radiates dark photons



✦A crucial feature: production and decay of dark photon can be separated

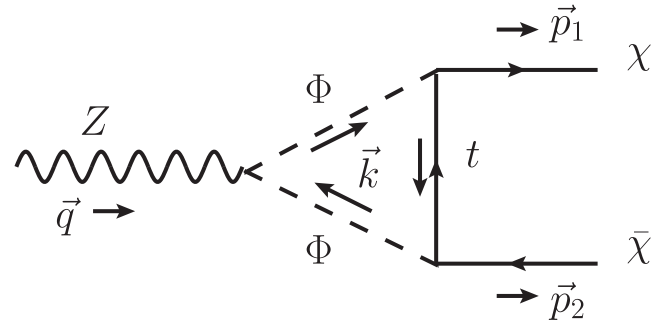
Two-U(1) Stueckelberg model

M. Du, R.Fang, Z. Liu and VQT (2021)

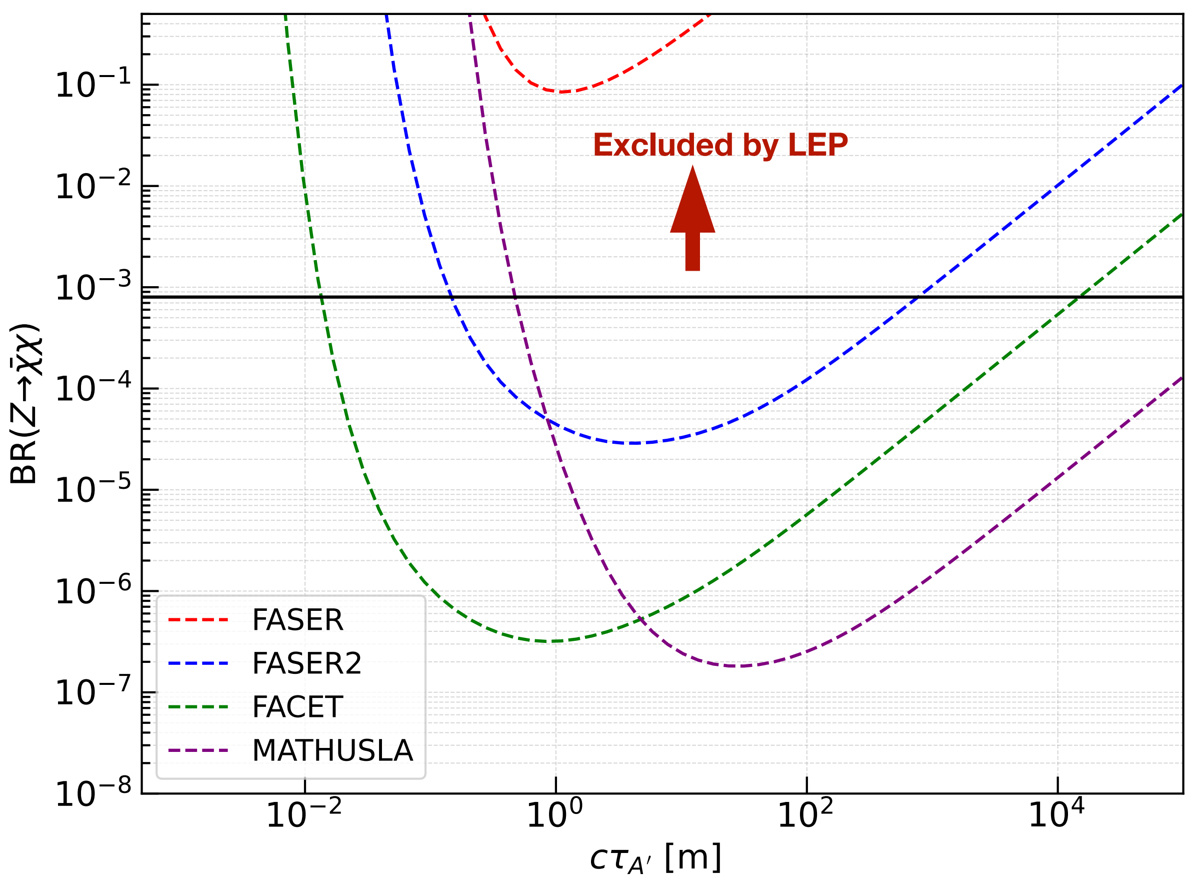


Precision timing and dedicated LLP detectors can complementarily search for DP at mass ~O(10 GeV)

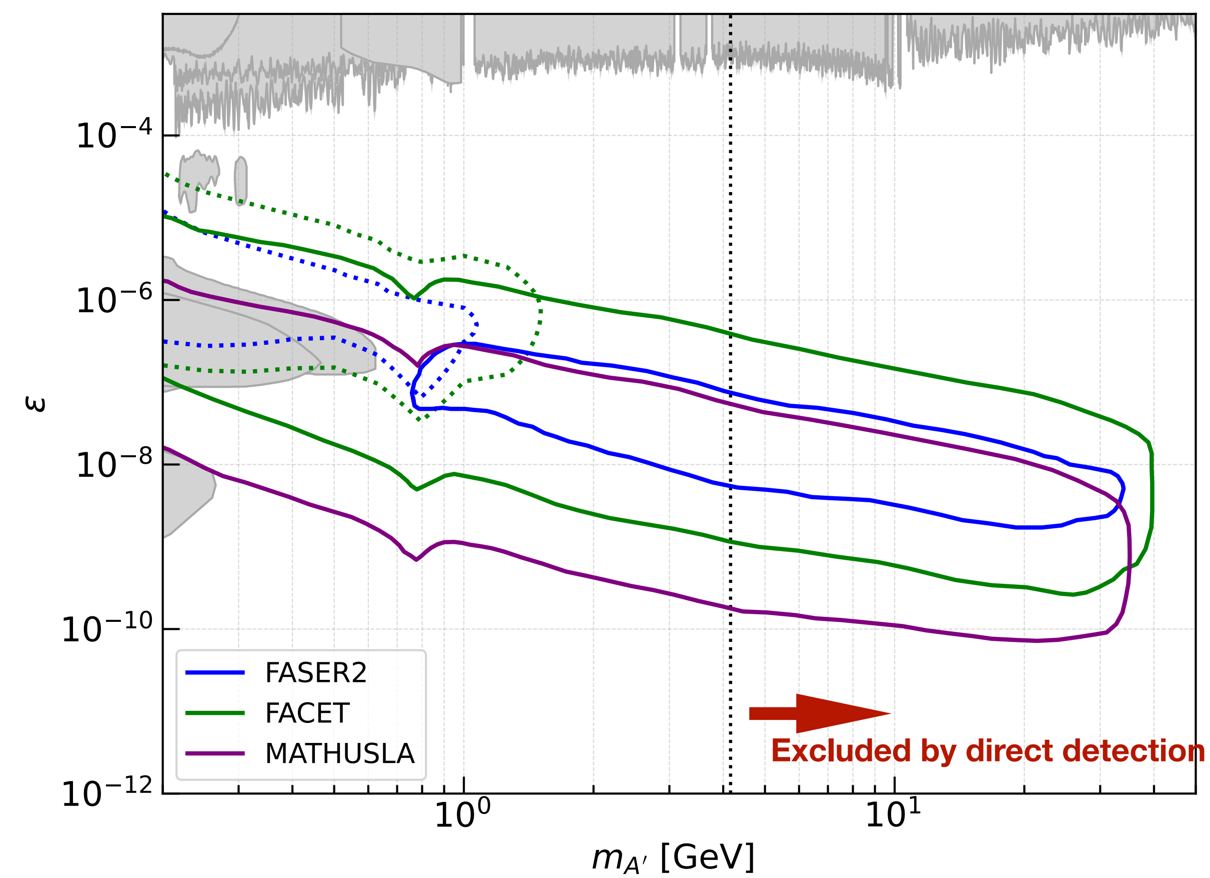
Z decay model



$$m_\chi = 2\ \text{GeV},\ \Delta = \frac{m_{A'} - m_\chi}{m_\chi} = 0.3 \text{ and } \alpha_D \simeq 0.23$$



$$\Delta = 0.3 \text{ and BR}(Z \to \bar{\chi}\chi) = 10^{-4}$$



C.R.Chen, VQT, arXiv:2605.03427

- Solid lines: production from HR channel
- Dotted lines: conventional production channels

- **FASER alone does not surpass the current Z invisible width bound**
- **Future FASER2, FACET, and MATHUSLA improve significantly and can probe the parameter space beyond that in the conventional DP model.**

A non-Abelian Dark Sector

A non-Abelian Dark Sector

- **Dark sector consists a non-Abelian gauge group**

$$G_{\rm SM} \otimes SU(2)_D$$

- **Abelian—Non-Abelian kinetic mixing as the portal**

$$\mathscr{L} \supset -\frac{\epsilon}{2} W_D^{3\mu\nu} B_{\mu\nu}$$

- **The non-Abelian charged gauge bosons can be DM:**
  - Its stability can be ensured by **a gauge symmetry**
  - **Intrinsic self-interacting** with long range dark photon -> **can address** small scale problems (core-cusp, too big to fail, missing satellites) **(1)**
  - **Feebly interaction** with SM -> e.g. via kinetic mixing -> DM relic abundance can be realized by **freeze-in mechanism**
  - **A millicharged particle**

(1) S. Tulin and H. B. Yu (2018), VQT, Nguyen, and Yuan, JCAP 05 (2024) 015; +++

The Model

NCTS

- SM is enlarged with a dark gauge sector $SU(2)_D$ broken by a real dark triplet Higgs Σ

$$\Sigma = \frac{1}{2}\Sigma^a \sigma^a = \frac{1}{2}\begin{pmatrix} \Sigma^0 + v_\Sigma & \sqrt{2}\Sigma^p \\ \sqrt{2}\Sigma^m & -\Sigma^0 - v_\Sigma \end{pmatrix}$$

- After the breaking of $SU(2)_D \to U(1)_D$, the **charged dark vectors** $W_\mu^{p,m} = \frac{1}{\sqrt{2}}(W^1_{D\mu} \mp iW^2_{D\mu})$ obtain a mass $m_{W^{p,m}} = g_D v_\Sigma$ and being **DM candidate**. The $U(1)_D$ charge ensures the DM stable

- The **neutral dark vector** $W^3_{D\mu}$ is **massless** (denoted as Z' in physical state)

- Dimension 5 operator induces Dimension 4 kinetic mixing term:

$$\mathcal{O}_5 = \frac{c_5 g_D g'}{\Lambda}\mathrm{Tr}\left[\Sigma W_D^{\mu\nu}\right] B_{\mu\nu} \quad \xrightarrow{\langle\Sigma\rangle} \quad -\frac{1}{2}\epsilon W_D^{3\mu\nu} B_{\mu\nu}$$

with $\epsilon = -\dfrac{c_5 g_D g' v_\Sigma}{\Lambda}$ referred as **Abelian—Non-Abelian kinetic mixing**.

The Model

✦ The kinetic energy of the gauge sector in the extended model is

$$\mathscr{L}_{\rm kin} = -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4}W^a_{\mu\nu}W^{a\mu\nu} - \frac{1}{4}W^a_{D\mu\nu}W^{a\mu\nu}_D - \frac{1}{2}\epsilon W^{3\mu\nu}_D B_{\mu\nu}$$

✦ Diagonalization of the kinetic terms

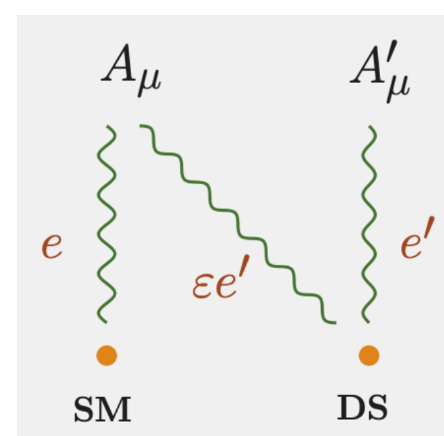
$$\begin{pmatrix} W^3_{D\mu} \\ B_\mu \end{pmatrix} \to \begin{pmatrix} 1 & \frac{-\epsilon}{\sqrt{1-\epsilon^2}} \\ 0 & \frac{1}{\sqrt{1-\epsilon^2}} \end{pmatrix} \cdot \begin{pmatrix} c_\alpha & -s_\alpha \\ s_\alpha & c_\alpha \end{pmatrix} \cdot \begin{pmatrix} W^3_{D\mu} \\ B_\mu \end{pmatrix}$$

✤ Physical observables must be **independent of** α as it reflects a **redundancy** in the choice of basis in the unbroken Abelian subgroup $U(1)_Y \times U(1)_D$

J.-X. Pan, M. He, X.-G. He, and G. Li, NPB 953, 114968 (2020)

✦ We adopt the *millicharged basis* defined by

$$s_\alpha = \epsilon\,, \qquad c_\alpha = \sqrt{1-\epsilon^2}$$



The Model

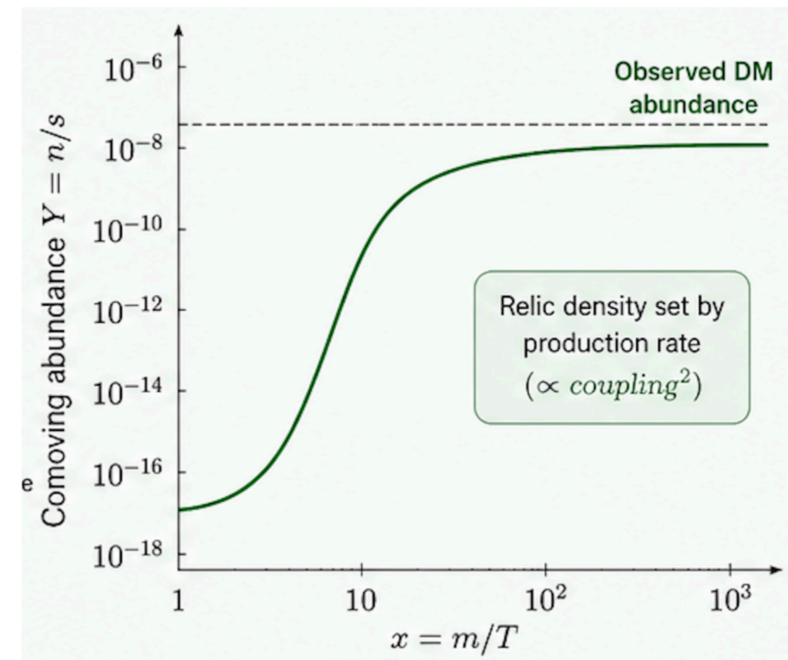
✦ The kinetic mixing diagonalization also induces couplings of DM candidate $W^{(p,m)}$ to physical photon

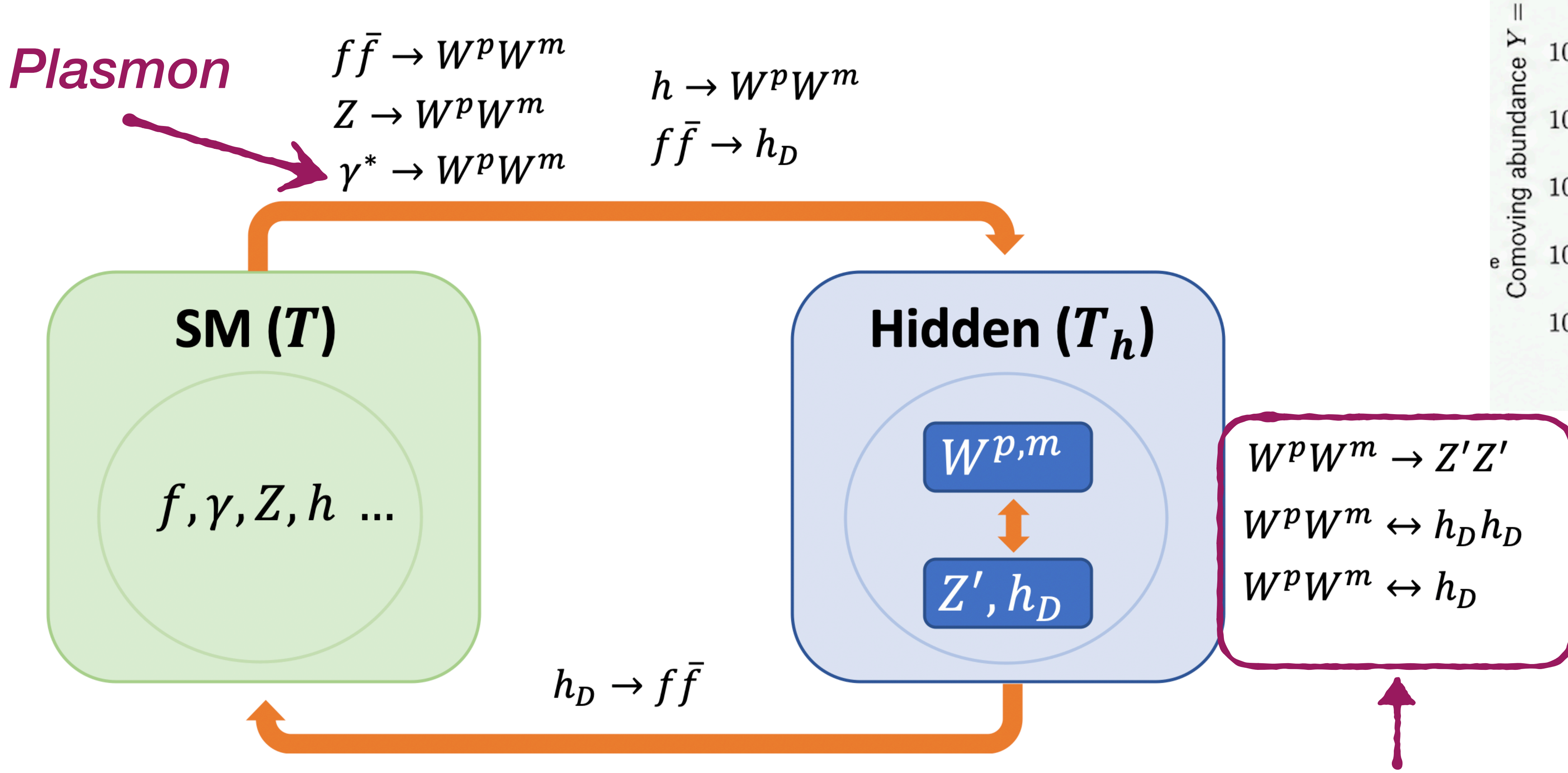
$$\mathscr{L}_{\text{milli}} \supset -ig_D \cos\theta_W \epsilon \left(W^p_{\mu\nu} W^{m\,\mu} - W^m_{\mu\nu} W^{p\,\mu} \right) A^\nu$$

➡ Dark matter is a millicharged particle!

Freeze-in production framework

- Dark sector is **feebly interacting** with the SM visible sector: **kinetic mixing** and **Higgs mixing**
- SM sector and dark sector are **two distinct heat baths** with different temperature T and T_h and a ratio $\xi \equiv T_h/T$ (1)





Strong DS interactions deplete DM abundance

(1) Aboubrahim et al, PRD 103, 075014 (2021); JHEP 09 (2022) 084; JHEP 12 (2021) 148; JHEP 06 (2021) 086; Feng, Li & Nath, PRD 110, 015020 (2024); Li & Nath, PRD 111 (2025) 12, 123007; LHEP 2024 (2024) 502; +++

Coupled Boltzmann Equations

✦ Temperature evolution

$$\frac{d\xi}{dT} = \frac{1}{T}\left[-\xi + \left(\frac{3H(\rho_h + p_h) - J_h}{3H(\rho_v + p_v) + J_h}\right)\frac{d\rho_v}{dT}\left(\frac{d\rho_h}{dT_h}\right)^{-1}\right] \qquad \xi \equiv \frac{T_h}{T}$$

where H is the Hubble parameter, and $\rho_{v,h}$ and $p_{v,h}$ are the energy and pressure densities of the visible and hidden sectors. The source function J_h encodes all energy-exchange processes between the two sectors

✦ Comoving yields evolution $Y_i = n_i/\mathbf{s}$

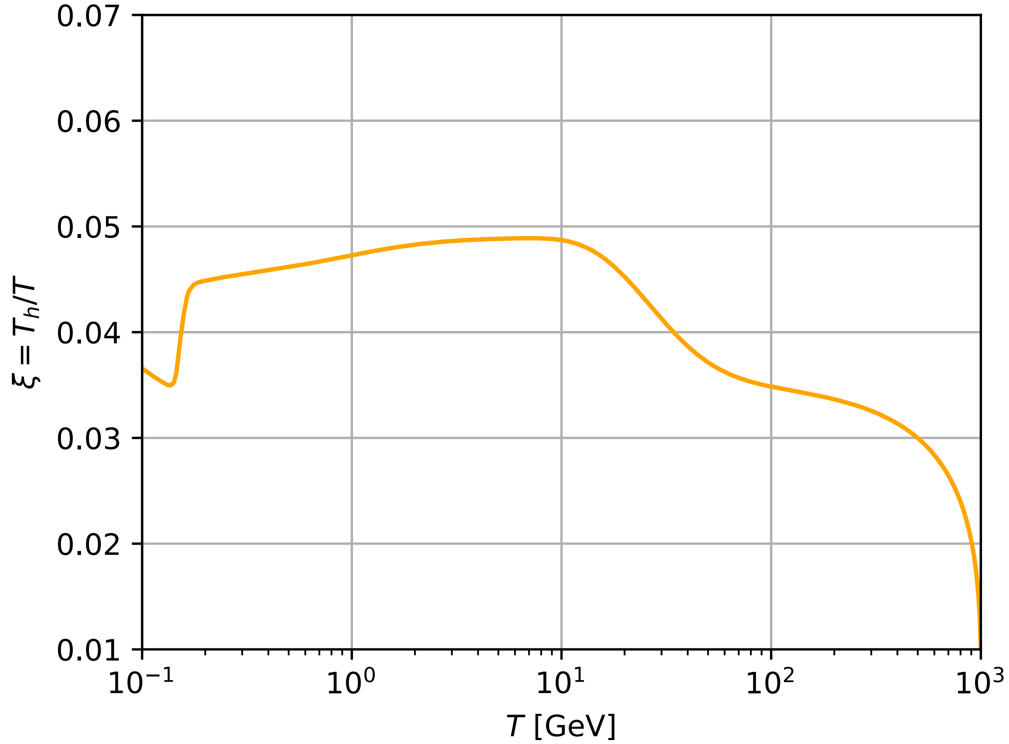
$$\frac{dY_i}{dT} = -\frac{1}{\mathbf{s}}\left[\frac{d\rho_v/dT}{3H(\rho_v + p_v) + J_h}\right]\mathscr{R}_i(T, T_h)\ , \qquad i = W', Z', h_D$$

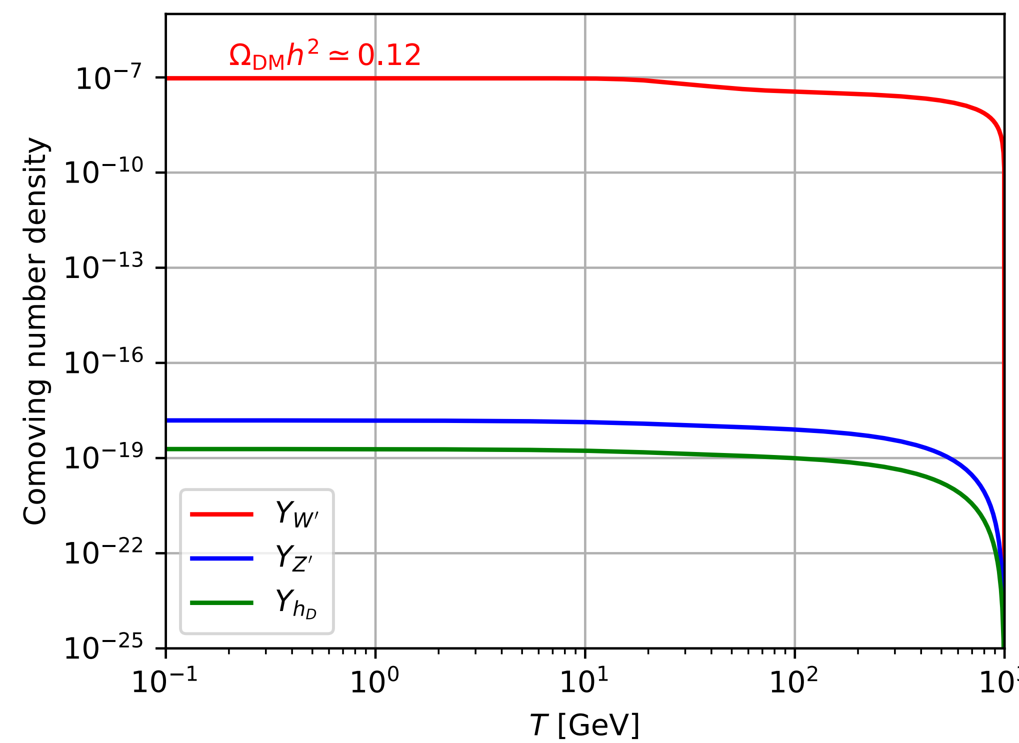
where $\mathbf{s}$ is the total entropy density, n_i the number density, and $\mathscr{R}_i(T, T_h)$ the interaction rate producing species i, including all three **SM to hidden, hidden to SM,** and **hidden to hidden** channels

Benchmark Thermal History

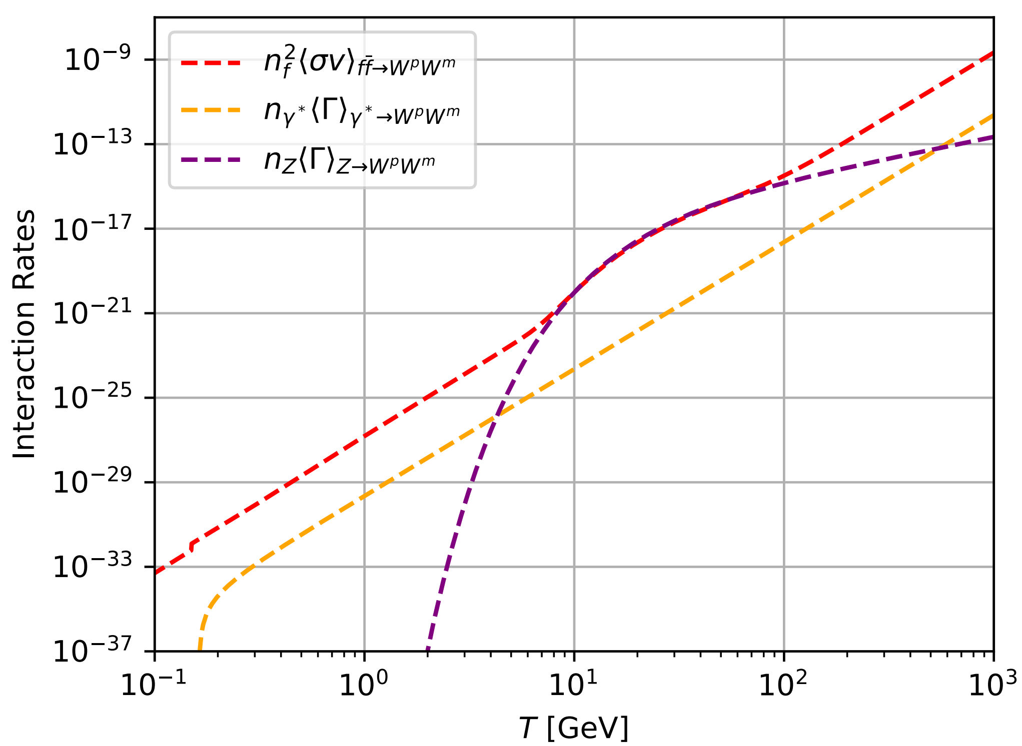
$$BM: m_{W'} = 0.01\ \text{GeV},\ m_{h_D} = m_{W'}/3,\ g_D = 10^{-7},\ \epsilon = 3.8\times10^{-7},\ \delta = 0,\ \sin\beta = 0,\ T_{\rm RH} = 1\text{TeV},\ \xi_0 = 0.01$$

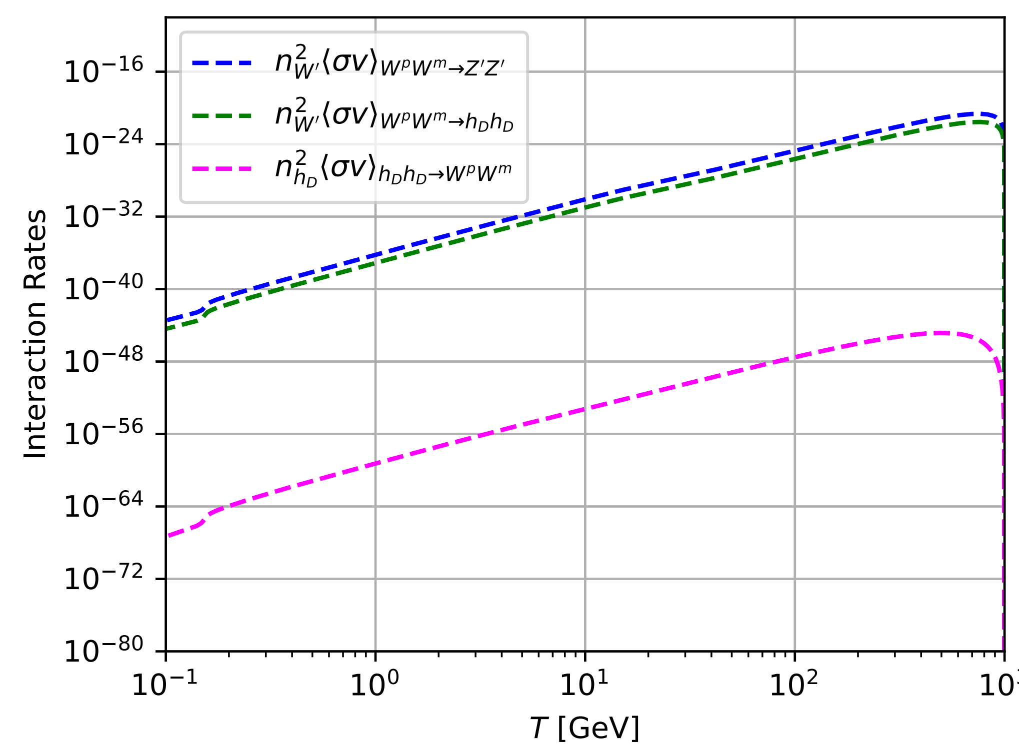
- Relic of dark photon and dark Higgs are subdominant as suppressed by tiny g_D





- Dominated by milli-charged annihilation process $f\bar{f} \to W^pW^m$
- Z and plasmon decays sub-dominated





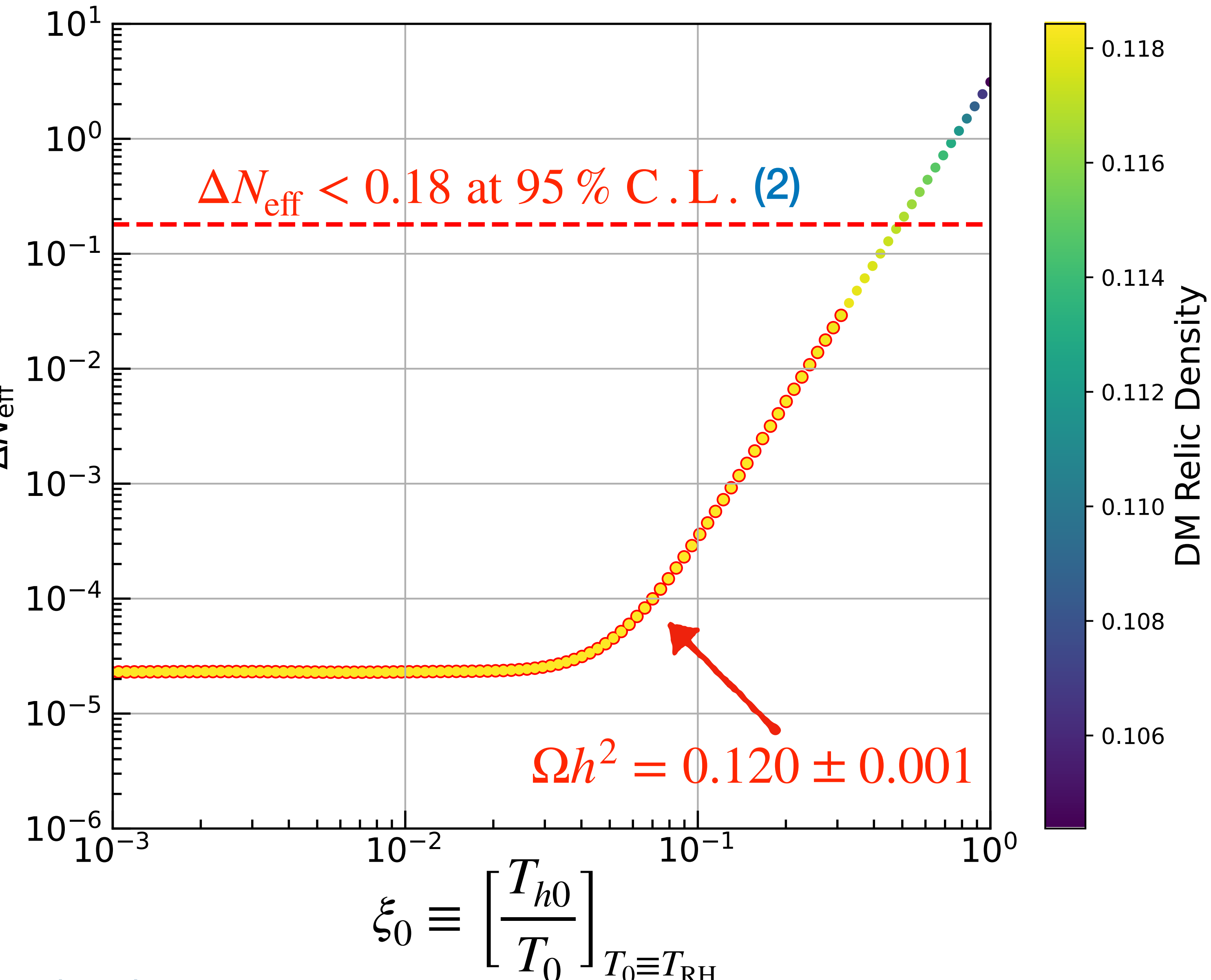
DM relic abundance vs. $N_{\rm eff}$ vs. Reheating Temp.

$$BM: m_{W'} = 0.01\ \text{GeV},\ m_{h_D} = m_{W'}/3,\ g_D = 10^{-7},\ \epsilon = 3.8\times10^{-7},\ \delta = 0,\ \sin\beta = 0,\ T_{\rm RH} = 1\text{TeV}$$

- **Light new particles** contribute to the effective neutrino number $N_{\rm eff}$

$$\Delta N_{\rm eff}(T,\xi)\Big|_{\rm BBN} = \frac{4}{7} g^h_{\rm eff}(T)\left(\frac{11}{4}\right)^{4/3} \xi(T)^4\Big|_{\rm BBN} \quad (1)$$

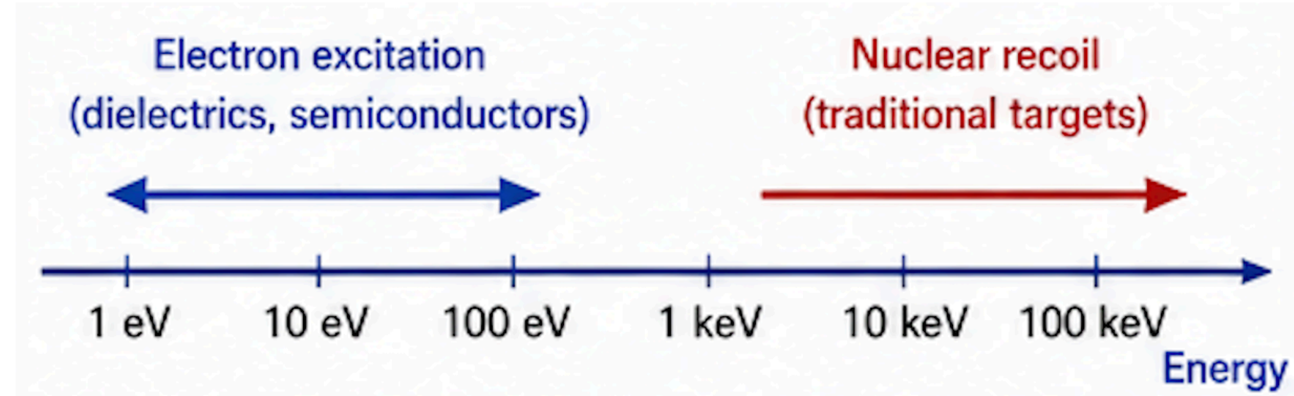
- The reheating temperature is unknown -> affects initial condition.
- Initial condition of temperature ratio between two sectors affects both the **DM relic abundance and $N_{\rm eff}$**
- Larger ξ_0 enhances $\Delta N_{\rm eff}$ while suppressed **DM relic abundance**
- $\xi_0 \gtrsim 0.5$ is excluded by BBN and CMB



(1) J. Li and P. Nath, Phys.Rev.D 108 (2023) 11, 115008; +++
(2) T.-H. Yeh, J. Shelton, K. A. Olive, and B. D. Fields, JCAP 10, 046 (2022)

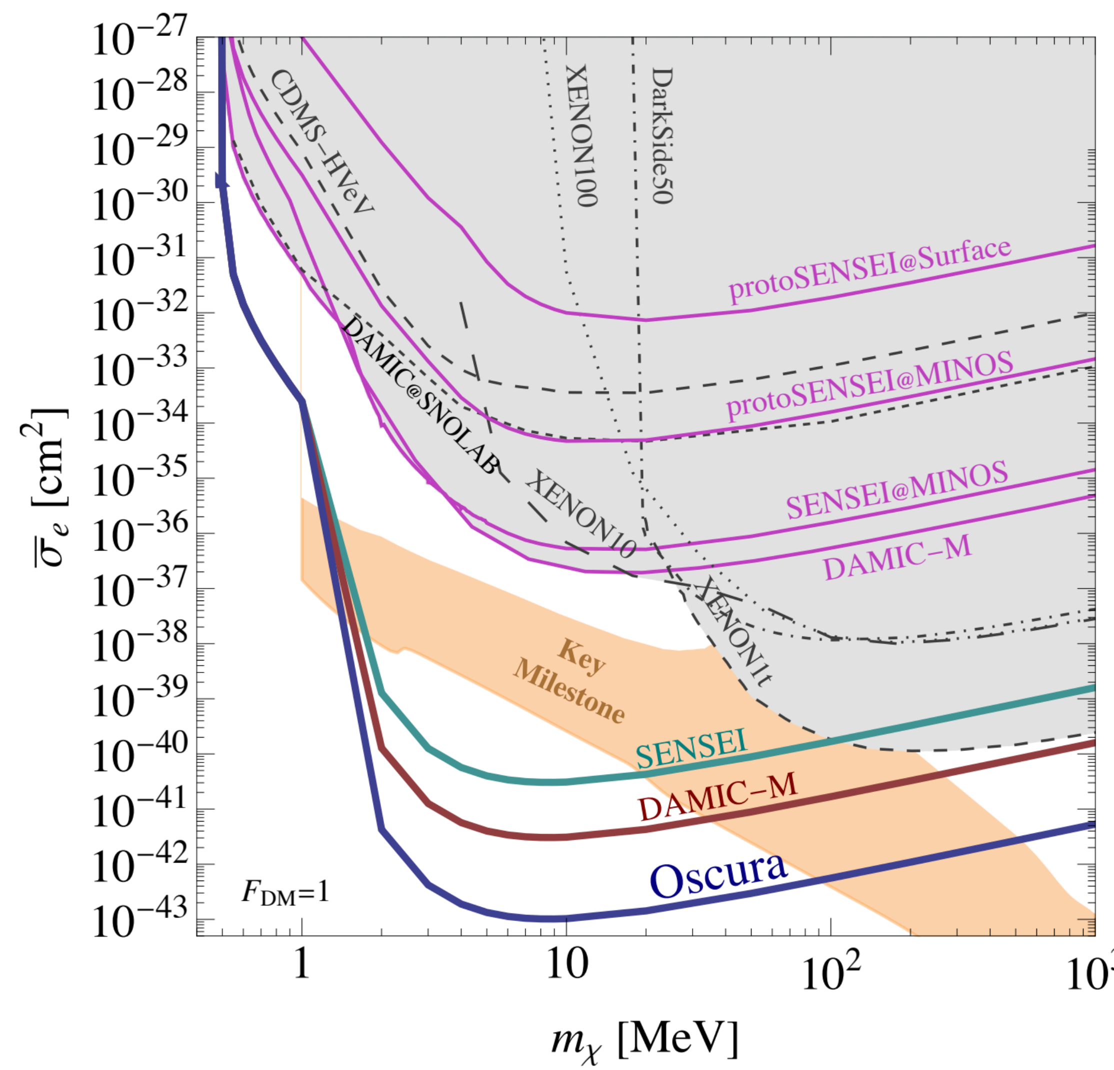
Search for sub-GeV DM

✦ **Sub-GeV DM** gives too little energy to nuclei but can efficiently scatters of electrons



✦ Silicon charge-coupled devices w/ Skipper amplification **(Oscura, SENSEI, DAMIC-M)**

- ✤ Skipper amplifier makes repetitive, non-destructive measurement of the pixel charge, reducing noise to sub-electron levels -> **Ultra low noise**
- ✤ **Sensitive to tiny ionization**
- ✤ **Low threshold enables low-mass searches (1-1000 MeV DM)**



arXiv:2304.04401

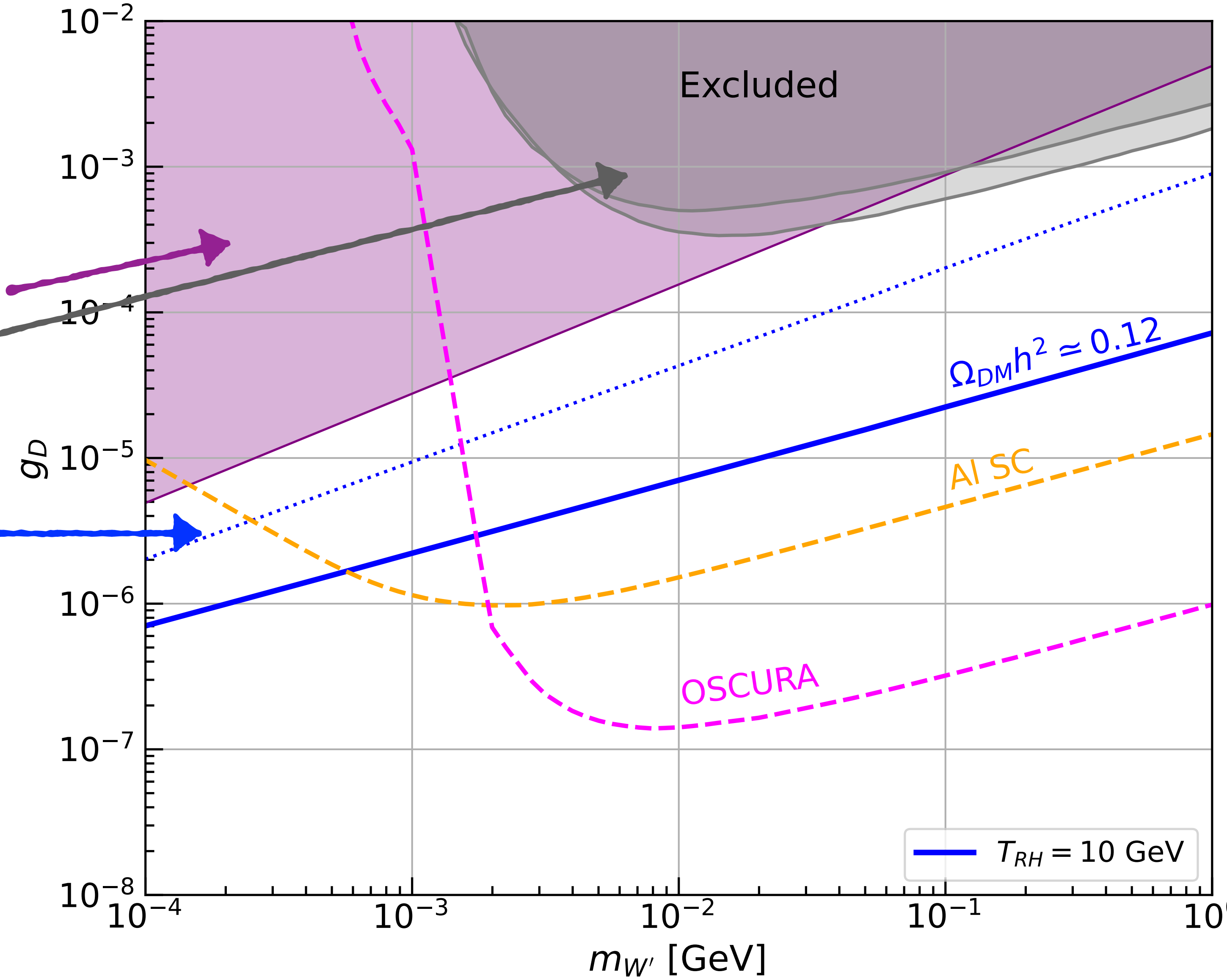
✦ Other proposals are also investigating alternative target materials, such as superconductors and polar crystals.

JINST 18 (2023) no.08, P08016

Direct Detection Prospects

- **Electron recoils** from the process $W' + e^- \to W' + e^-$ for **sub-GeV** DM
- Dominated by photon exchange, while Z and scalar mediated contributions being sub-leading
- Shaded regions are excluded by SIDM from NGC720 galaxy ellipticity and by DMDD from SENSI, DAMIC …
- DM abundance can be depleted for large g_D due to $W^p W^m \to Z'Z'$ and to other DS
- Probed by projected sensitivities from OSCURA (1) and ALSC (2) (Aluminum based superconducting detectors)

$$BM : m_{h_D} = m_{W'}/3,\ \epsilon = 0.5 \times 10^{-7},\ \delta = 0,\ \xi_0 = 0.01$$



(1) B. A. Cervantes-Vergara et al. (Oscura), JINST 18, P08016 (2023), arXiv:2304.04401

(2) Y. Hochberg et al. Phys. Rev. Lett. 127, 151802 (2021), arXiv:2101.08263

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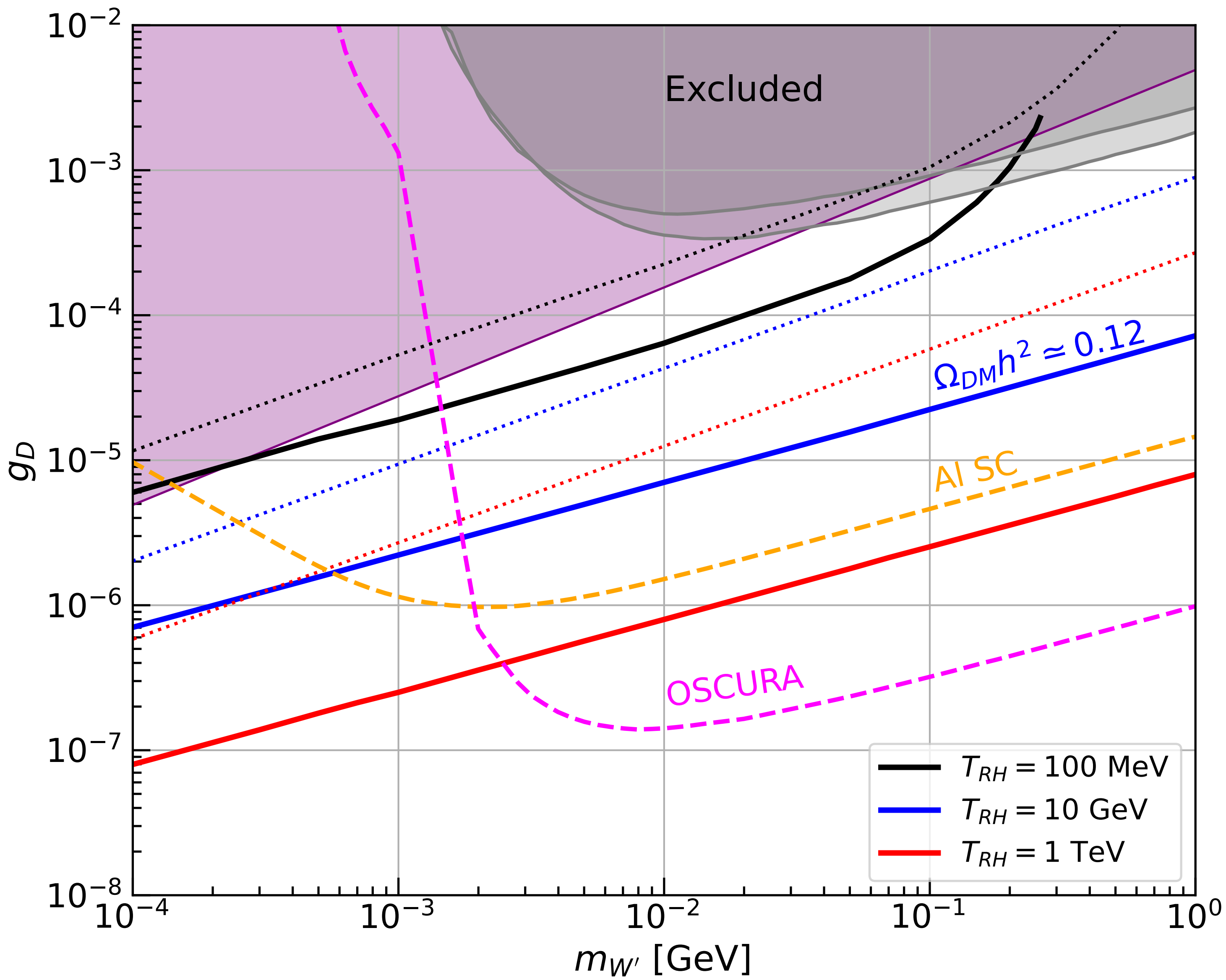


✤ Relic density is sensitive to low T_{RH}

✤ SIDM and DMDD can put a lower bound on T_{RH}

(1) B. A. Cervantes-Vergara et al. (Oscura), JINST 18, P08016 (2023), arXiv:2304.04401

(2) Y. Hochberg et al. Phys. Rev. Lett. 127, 151802 (2021), arXiv:2101.08263

Summary & Outlook

NCTS

- **Hidden sector** provides a well-motivated framework for dark matter, naturally featuring feeble interactions with SM particles.
- The **portal particles** may exhibit long lifetimes, making them promising targets for searches at future **long-lived particle** (LLP) detectors.
- We propose a simple yet realistic model of **two-temperature universe** based on $G_{\rm SM} \otimes SU(2)_D + \Sigma_D$ and **Abelian—Non-Abelian kinetic mixing**.
- **Non-Abelian gauge bosons** becomes a viable **millicharged freeze-in DM** candidate.
- **Future low-threshold direct-detection** experiments can probe this **sub-GeV DM** via electron scattering.
- The two-temperature Universe may also generate observable **gravitational-wave signals** from a strongly first-order phase transition.

Thank You

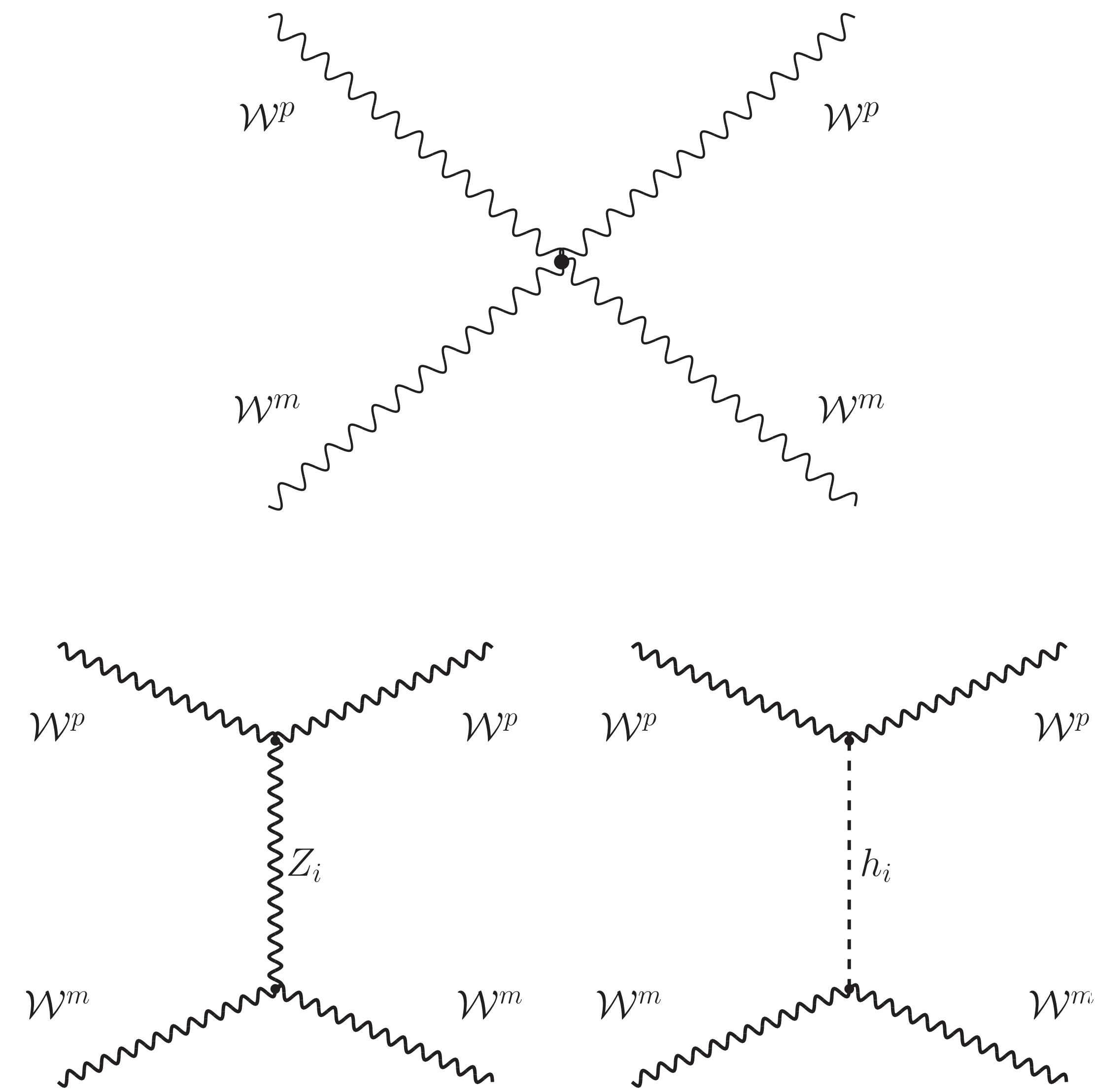
Backup: SIDM

- ✦ Ellipticity profile of the galaxy sets stringent bound on dark sector self-interactions (SIDM)

- ✦ Limits from NGC720 galaxy (1) by the evolution of the velocity anisotropy due to energy transfer:

$$m_{\mathrm{DM}} \left(\frac{0.01}{\alpha_D} \right)^{2/3} \gtrsim 300\mathrm{GeV}$$

- ✦ SIDM helps to solve small scale problems (core-cusp, too big to fail, missing satellites) (2)



(1) Agrawal, Cyr-Racine, Randall, and Scholtz (JCAP 1705(05), 022 (2017))
(2) S. Tulin and H. B. Yu, Phys. Rept. 730, 1-57 (2018); VQT, Nguyen, and Yuan, JCAP 05 (2024) 015; +++

Backup: The source term J_h

$$
\begin{aligned}
J_h \simeq \sum_f \Big\{ & n_f^2 \left[2J_{f\bar{f}\to W^p W^m}(T) + J_{f\bar{f}\to h_D}(T) \right] \\
& + 2n_Z J_{Z\to W^p W^m}(T) + 2n_h J_{h\to W^p W^m}(T) \\
& + 2n_{\gamma*} J_{\gamma*\to W^p W^m}(T) - n_{h_D} J_{h_D\to f\bar{f}}(T_h) \Big\} \,,
\end{aligned}
$$

Backup: Interaction Rates

$$
\begin{aligned}
\mathscr{R}_{W'}(T,T_h) = \sum_{f\in \mathrm{SM}} \left[n_f^2 \langle \sigma v \rangle_{f\bar{f}\to W^p W^m}(T) \right] + n_Z \langle \Gamma \rangle_{Z\to W^p W^m}(T) + n_h \langle \Gamma \rangle_{h\to W^p W^m}(T) \\
+ n_{\gamma^*} \langle \Gamma \rangle_{\gamma^* \to W^p W^m}(T) + n_{h_D} \langle \Gamma \rangle_{h_D \to W^p W^m}(T_h) \\
+ n_{h_D}^2 \langle \sigma v \rangle_{h_D h_D \to W^p W^m}(T_h) - n_{W'}^2 \Big[\langle \sigma v \rangle_{W^p W^m \to h_D}(T_h) \\
+ \langle \sigma v \rangle_{W^p W^m \to Z' Z'}(T_h) + \langle \sigma v \rangle_{W^p W^m \to h_D h_D}(T_h) \Big] ,
\end{aligned}
$$

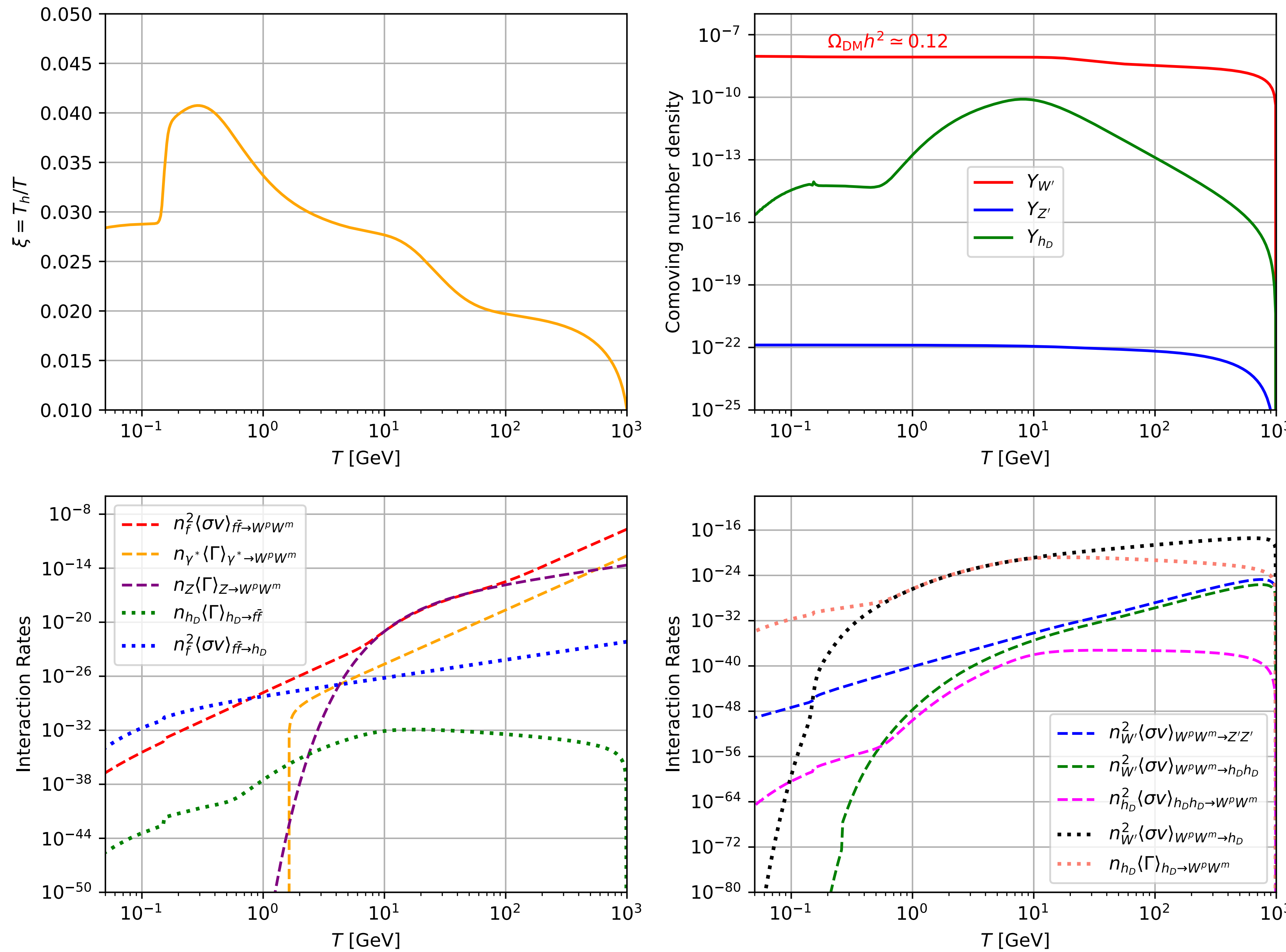
$$
\mathscr{R}_{Z'}(T,T_h) = n_{W'}^2 \langle \sigma v \rangle_{W^p W^m \to Z' Z'}(T_h) ,
$$

$$
\begin{aligned}
\mathscr{R}_{h_D}(T,T_h) = \sum_{f\in \mathrm{SM}} \left[n_f^2 \langle \sigma v \rangle_{f\bar{f}\to h_D}(T) \right] + n_{W'}^2 \Big[\langle \sigma v \rangle_{W^p W^m \to h_D h_D}(T_h) \\
+ \langle \sigma v \rangle_{W^p W^m \to h_D}(T_h) \Big] - n_{h_D}^2 \langle \sigma v \rangle_{h_D h_D \to W^p W^m}(T_h) \\
- n_{h_D} \left[\langle \Gamma \rangle_{h_D \to W^p W^m}(T_h) + \sum_{f\in \mathrm{SM}} \langle \Gamma \rangle_{h_D \to f\bar{f}}(T_h) \right] .
\end{aligned}
$$

Backup: BM2

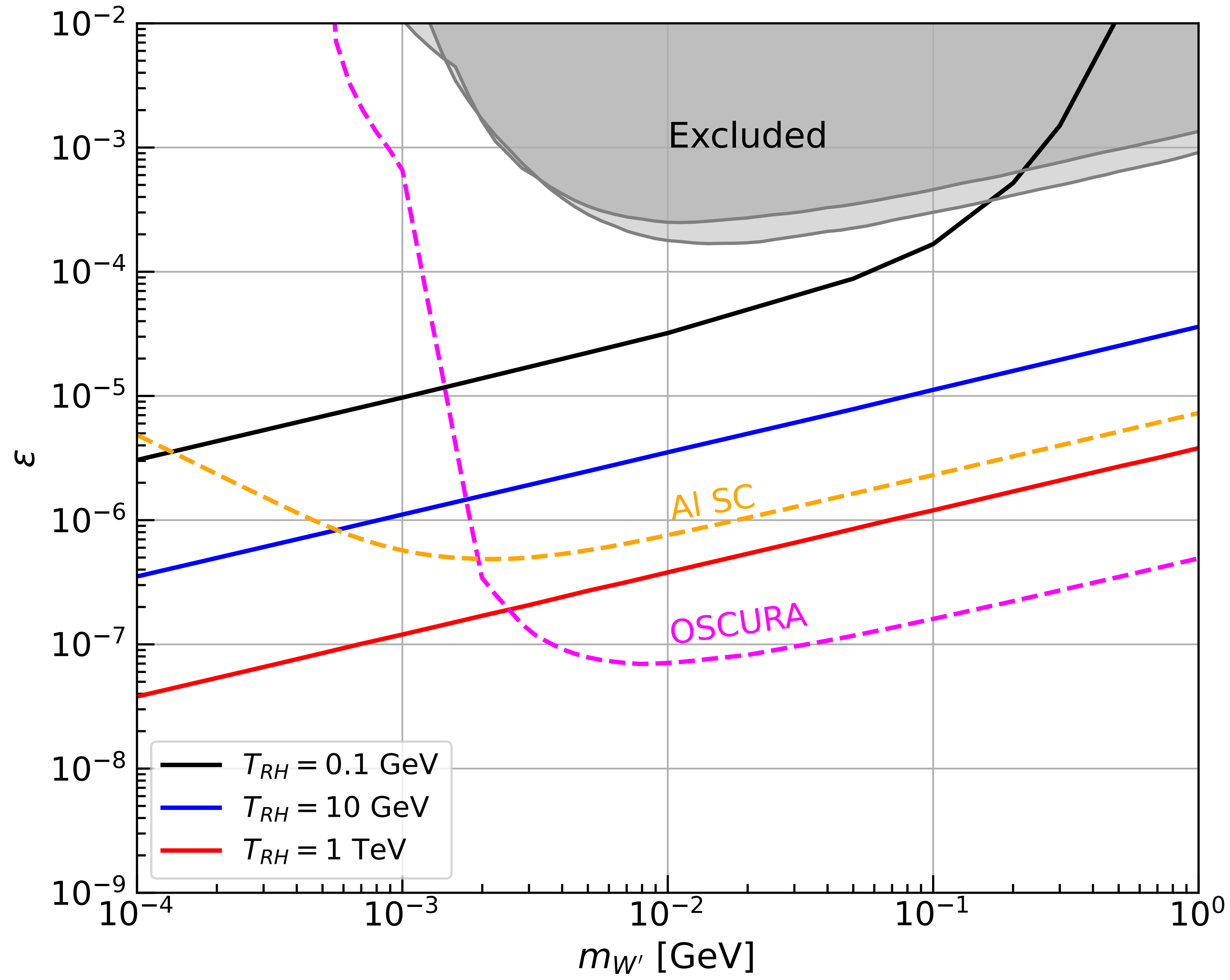
$$m_{W'} = 0.1\ \text{GeV},\ m_{h_D} = 0.4\ \text{GeV},\ g_D = 10^{-7},\ \epsilon = 1.2\times 10^{-6},\ \delta = 0,\ \sin\beta = 10^{-9}$$

- Presence of non-zero Higgs dark scalar mixing opens an additional portal interaction between the dark sector and the SM.
- Richer features in the evolution of ξ and the enhancement of dark Higgs boson yield



Backup: $(\epsilon,\ m_{W'})$ plane

$BM: m_{h_D} = m_{W'}/3,\ g_D = 10^{-7},\ \delta = 0,\ T_{\rm RH} = 1{\rm TeV},\ \xi_0 = 0.01$



Backup: The independence of angle α

✦The process of W+ W- to two physical photons

$$\sum_{\text{pol.}} |M|^2_{W^+W^-\to 2\,\text{photons}} = \frac{1}{2}\left(\sum_{\text{pol.}} |M|^2_{W^+W^-\to\gamma\gamma} + \sum_{\text{pol.}} |M|^2_{W^+W^-\to Z'Z'}\right) + \sum_{\text{pol.}} |M|^2_{W^+W^-\to\gamma Z'}$$

$$= g^4\left(\mathcal{O}_{21}^4 + \mathcal{O}_{23}^4 + 2\mathcal{O}_{21}^2\mathcal{O}_{23}^2\right)\times F$$

$$= e^4 \times F$$

- Where $\mathcal{O}_{ij}$ is the neutral gauge bosons matrix rotation and F is the common invariant function of Mandelstam variables

- It is independence on the rotation angle α

Backup: Experimental Constraints

Monojet at ATLAS

Invisible Z decay