Combined constraints on dark photons from high-energy collisions, cosmology, and astrophysics

Based on: A. W. Romero Jorge et al., PRD 113 (2026) 055052
A. W. Romero Jorge et al., PRC 112 (2025) 054905

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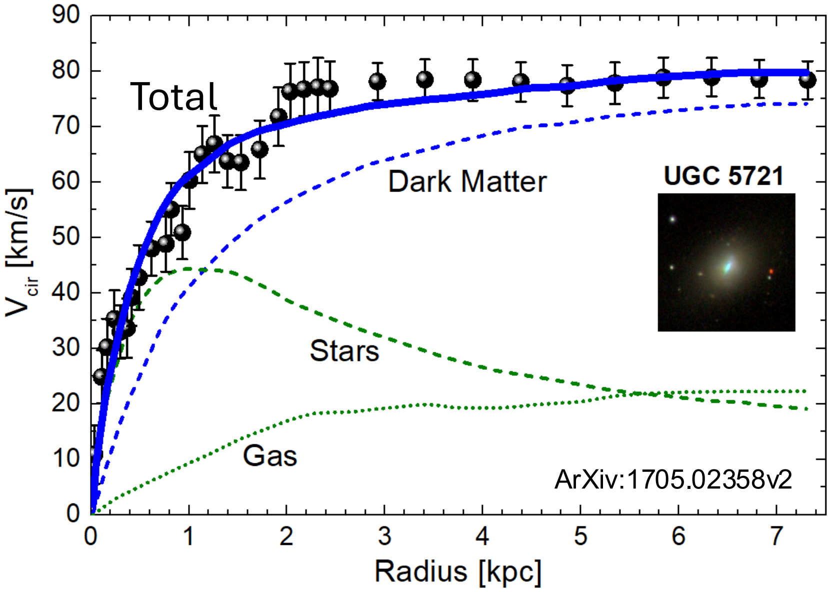
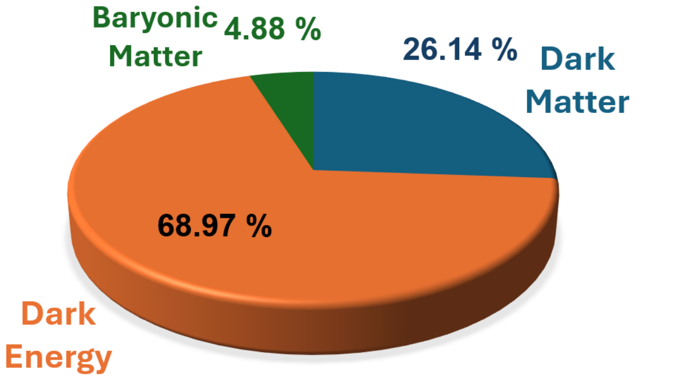
Structure of the Universe

Astrophysical observations based on gravitational effects:

1. **Galaxy Rotation Curves**



Energy Distribution of the Universe



Data from Planck 2018 results (Arxiv: 1807.06209)

G. Bertone & TMPT, Nature 562, 51, 2018

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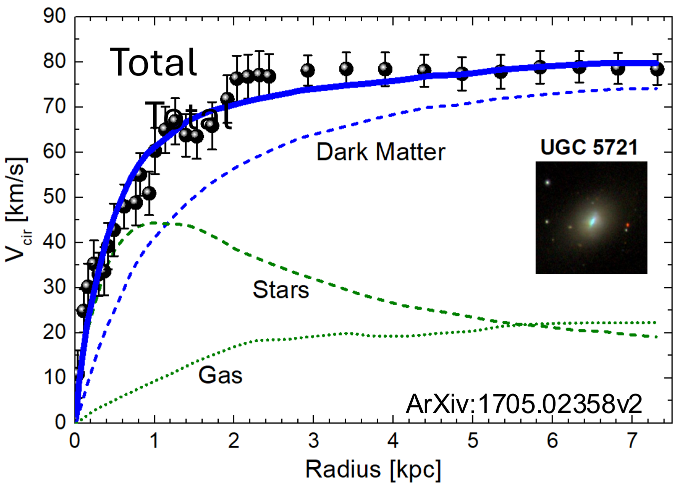
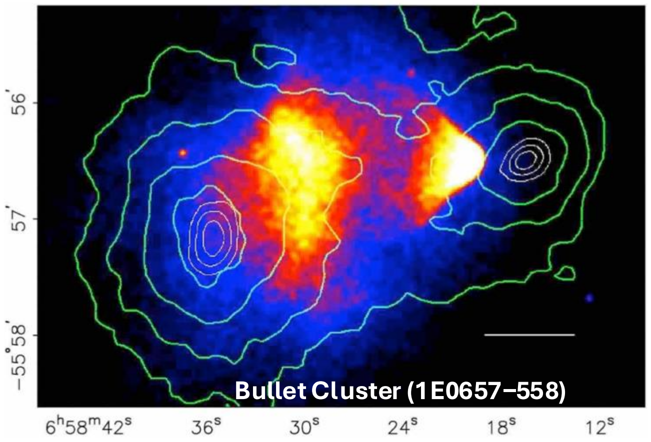
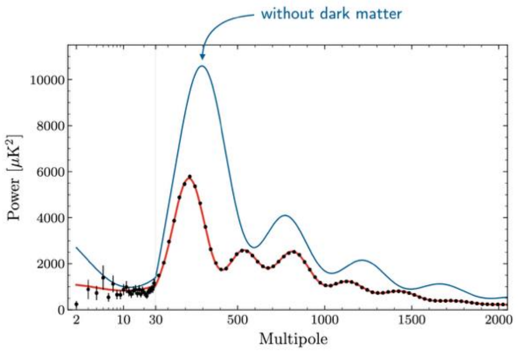


3. Gravitational lensing

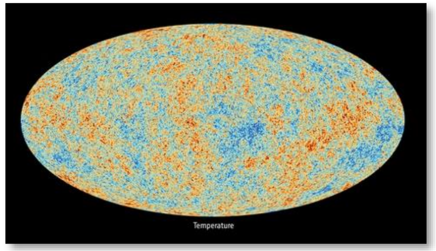


arXiv:0608407

2. Cosmic Microwave Background (CMB)

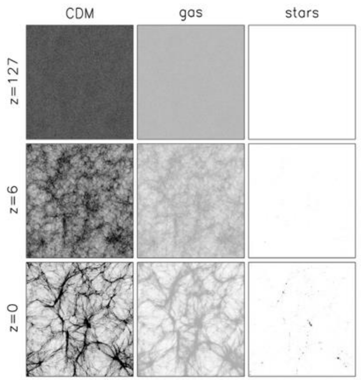


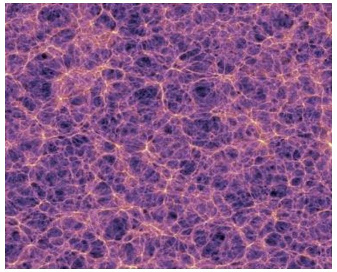
Huang & Bond/ACT)



ESA and the Planck Collaboration.

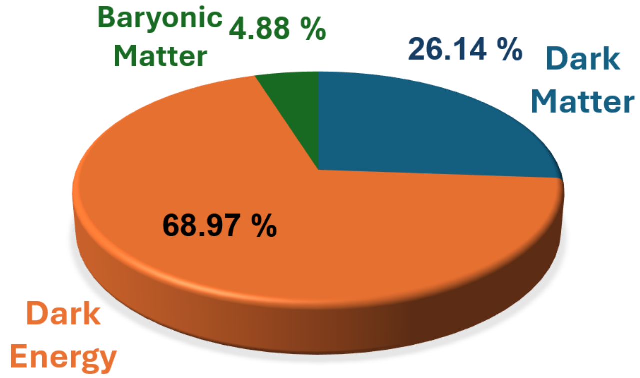
4. Structure Formation





Arxiv.1104.1174

Energy Distribution of the Universe



Data from Planck 2018 results (Arxiv: 1807.06209)

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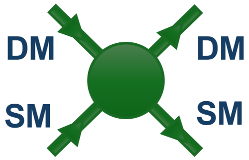
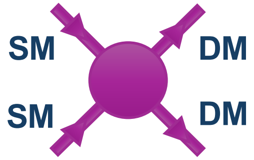
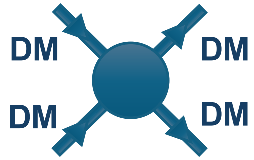
Dark Matter Detection

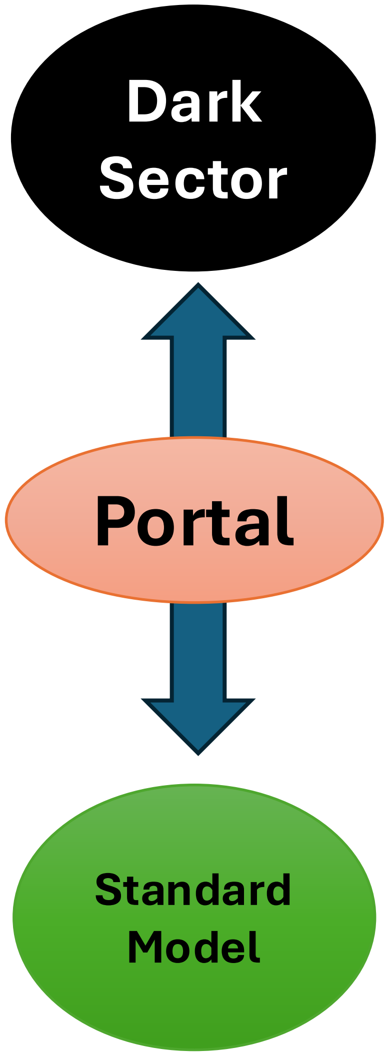
Dark Sector

Dark Matter Detection

Dark Sector

		Experiments	Techniques
Direct Detection		• XENONnT, SuperCDMS • LUX, DAMA/LIBRA • PandaX, DarkSide20k	**Recoil Energy of a collision SM-DM** ○ DM nucleon scatering ○ Bubble chambers ○ Semiconductor detectos
Indirect Detection		• Fermi-LAT • AMS-02, PAMELA • HESS,CTA, IceCube	**DM Decays into SM** ○ XX → SM SM ○ Neutrino telescopes ○ X-rays from DM decays ○ Cosmic rays Anti-DM searches
Particle Colliders		• ATLAS • BaBar • CMS, Belle II	**SM Decays into DM** ○ Kinetic Mixing constraints ○ Fixed-target ○ Invisible higgs decays ○ Dilepton decays ○ Beam dump experiments
Astrophysical Probes		• Plack (CMB), WMAP • GAIA, DES • HUBBLE, LSST	**DM Scattering** ○ DM Thermal Relic Abundance ○ Self-Interacting DM ○ Galaxy Rotation Curves ○ Gravitational Lensing

Dark Matter Portals



Dark Matter Portals

Dark Sector ⇅ **Portal** ⇅ **Standard Model**

	Portal		Mediator Particle	Operator
	**Vector**	⇒	**Dark Photon**	$\mathcal{L} \supset -\frac{\varepsilon}{2} B_{\mu\nu}F'^{\mu\nu}$
	**Neutrino**	⇒	**Sterile neutrinos**	$\mathcal{L} \supset y_N LHN$
	**Higgs**	⇒	**Dark scalars**	$\mathcal{L} \supset (\mu\phi + \lambda\phi^2)H^\dagger H$
	**Axion**	⇒	**Pseudoscalars**	$\mathcal{L} \supset \frac{a}{f_a} F_{\mu\nu}\tilde{F}^{\mu\nu}, \frac{a}{f_a} G_{i\mu\nu}\tilde{G}_i^{\mu\nu}, \ldots$
	Gluon, fermion, dipolar		**Higher dimension op.**	$\mathcal{L} \supset \frac{1}{\Lambda^3}\bar{\chi}\chi F_{\mu\nu}F^{\mu\nu}$. $\mathcal{L} \supset \frac{1}{\Lambda^3}\bar{\chi}\chi G^a_{\mu\nu}G^{a\mu\nu}$.

Dark Matter Portals

Dark Sector

↕

Portal

↕

Standard Model

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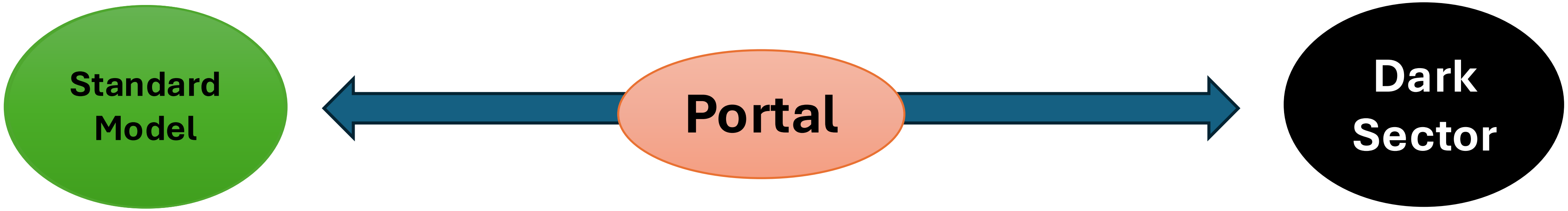
Dark Photon Model with Dark Matter



Dark Photon Model with Dark Matter

Standard Model ⟵ **Portal** ⟶ Dark Sector

Dark Photon

$\mathcal{L}_{SM}$

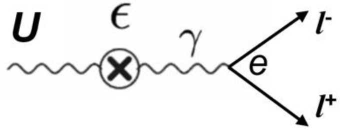
$\mathcal{L}_{mass}(\boldsymbol{m_\chi})$

$$\frac{\boldsymbol{\varepsilon}}{2} F^{\mu\nu} F'_{\mu\nu}$$

$$-\frac{1}{4} F'^{\mu\nu} F'_{\mu\nu} - \frac{1}{2} \boldsymbol{m_U^2} A'^{\mu} A'_{\mu}$$

$$\boldsymbol{g_\chi} A'_\mu J^\mu_\chi$$

$$\alpha' = \varepsilon^2 \alpha$$

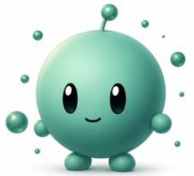


$$\alpha_\chi = \frac{g_\chi^2}{4\pi}$$

$$J^\mu_\chi = \begin{cases} \bar{\chi}\gamma^\mu\chi, \\ \frac{1}{2}\bar{\chi}\gamma^\mu\gamma^5\chi, \\ i(\varphi^\dagger\partial^\mu\varphi - (\partial^\mu\varphi^\dagger)\varphi) \end{cases}$$

Dirac Fermion

Majorana Fermion



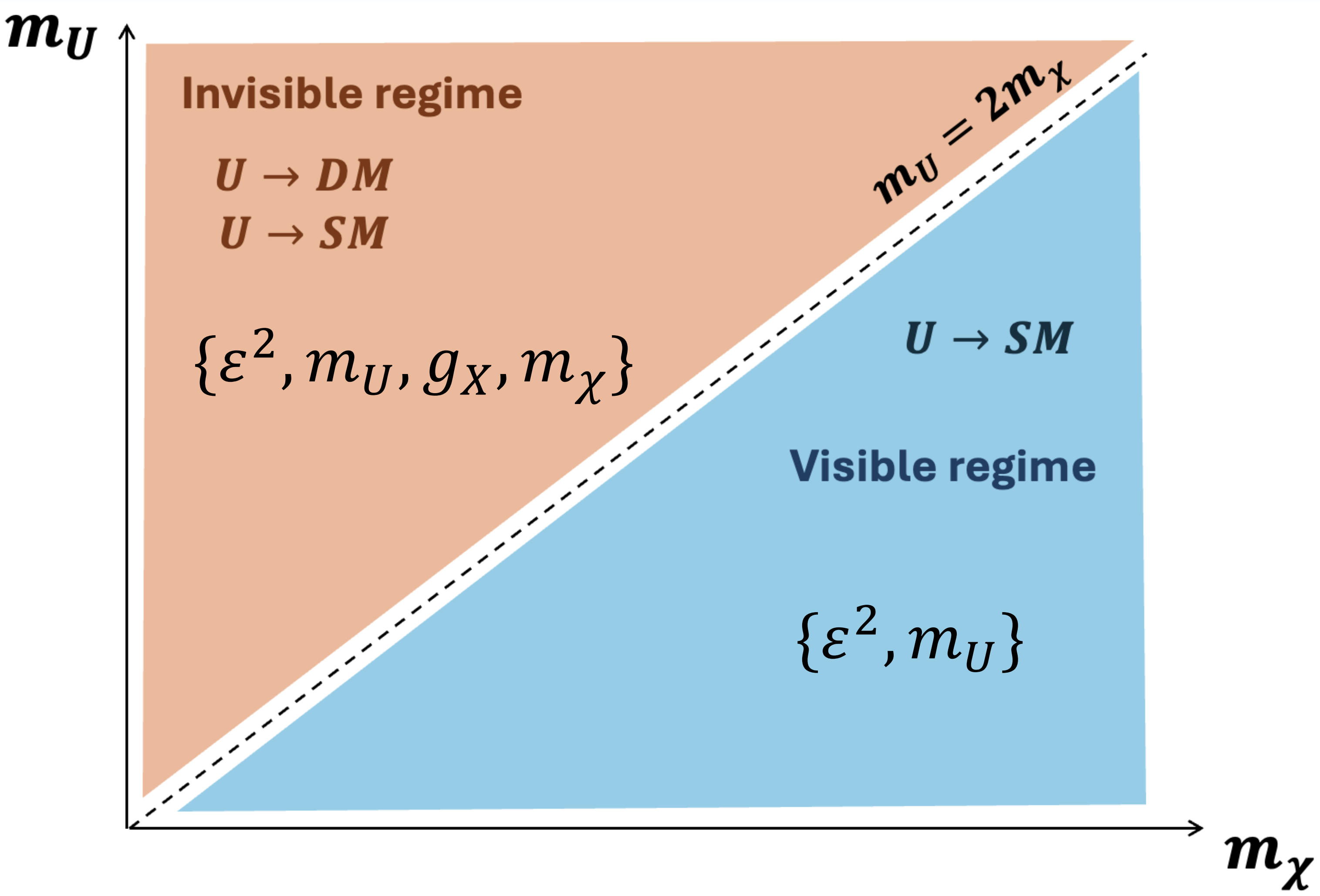
Complex Scalar

- $\boldsymbol{\varepsilon}$ ➡ Kinetic mixing parameter
- $\boldsymbol{m_U}$ ➡ Dark photon mass
- $\boldsymbol{g_\chi}$ ➡ Dark coupling constant
- $\boldsymbol{m_\chi}$ ➡ Dark matter mass

$(\boldsymbol{\varepsilon}, \boldsymbol{m_U})$

$(\boldsymbol{\alpha_\chi}, \boldsymbol{m_\chi})$

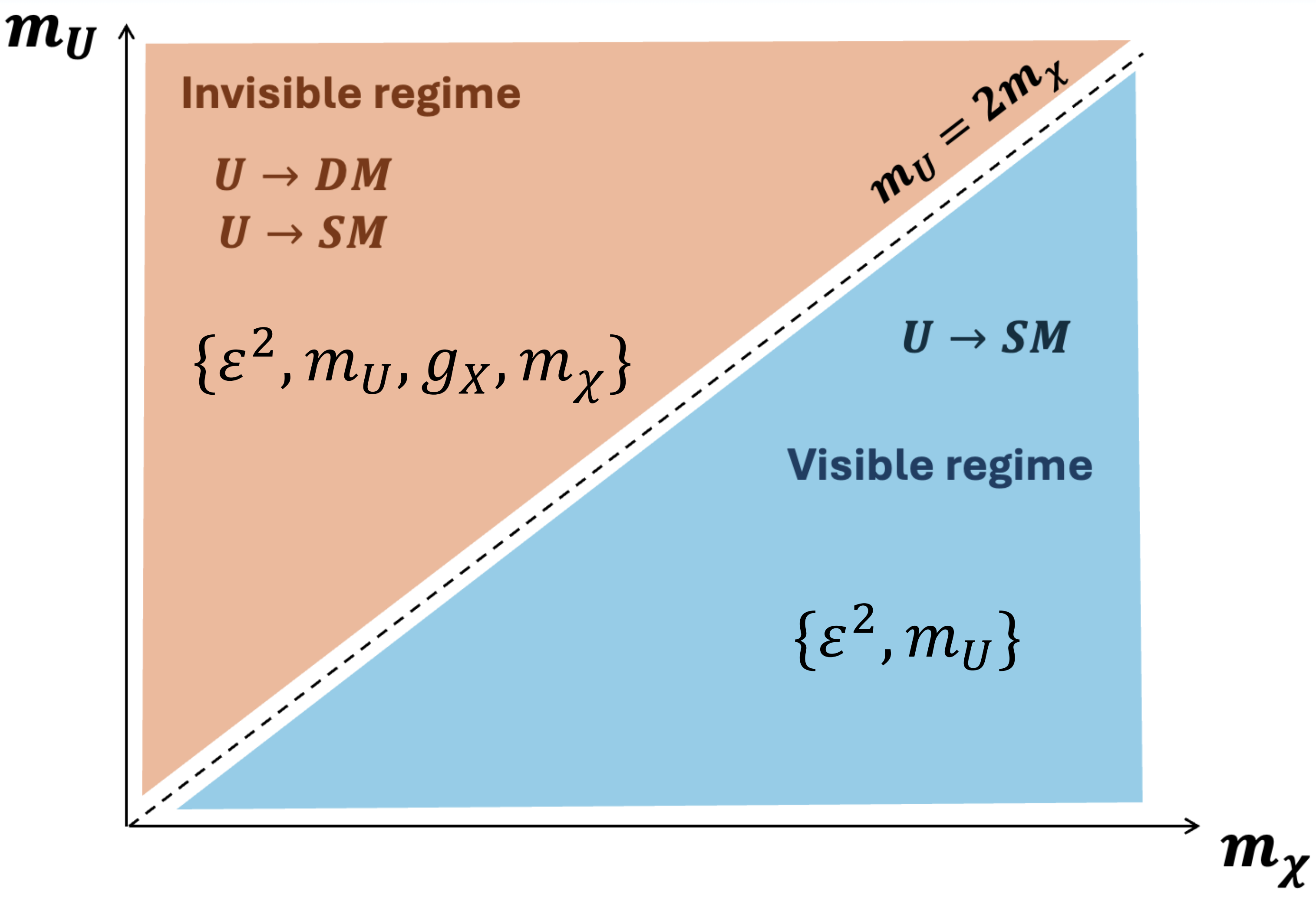
Kinematics $m_U(m_\chi)$



Invisible regime

Visible regime

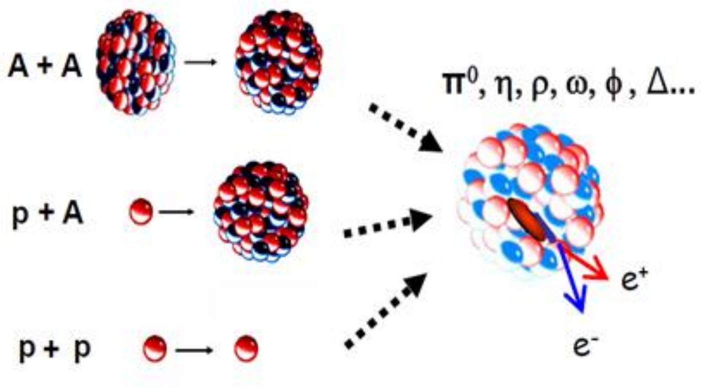
Kinematics $m_U(m_\chi)$



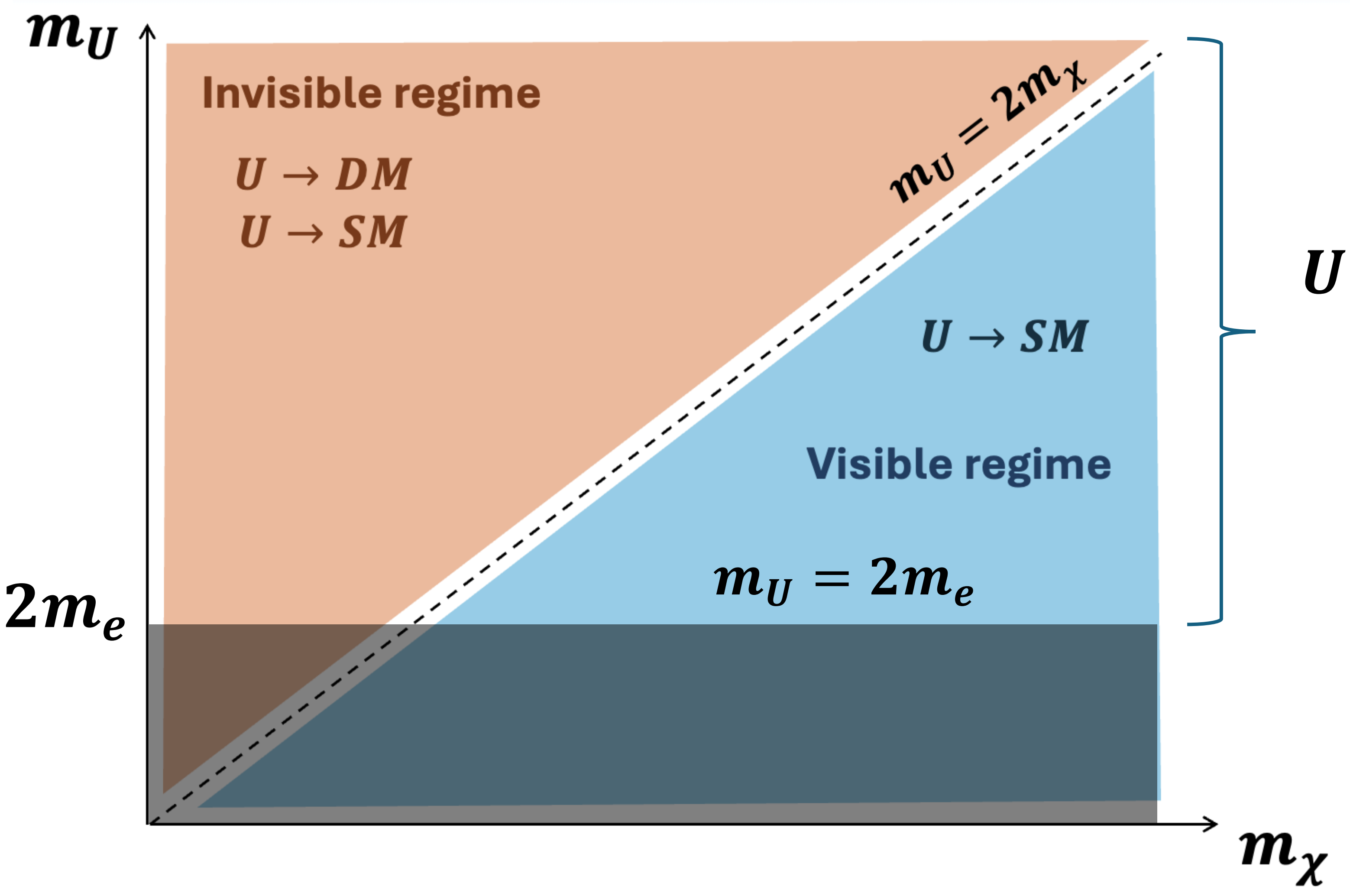
Invisible regime

Visible regime

Is it possible to "detect" dark photons in Heavy-Ion Collisions ?



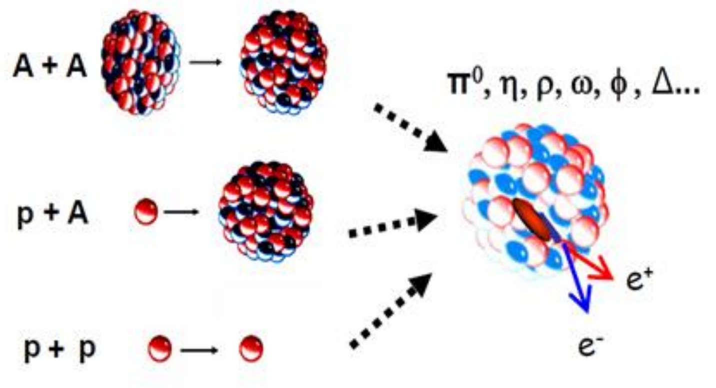
Kinematics $m_U(m_\chi)$



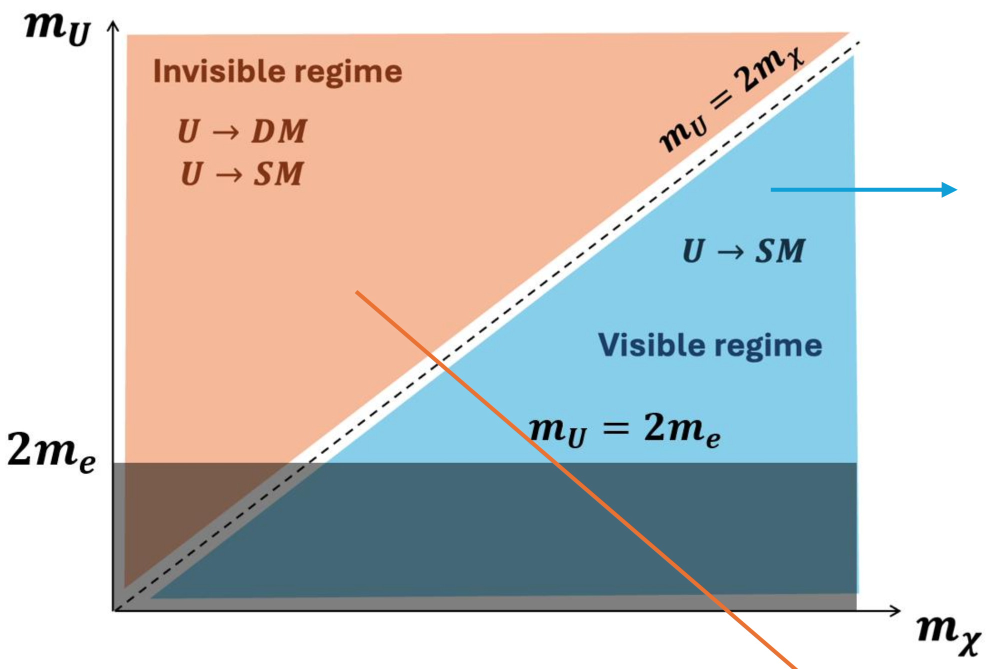
- Invisible regime
- Visible regime
- Below $2m_e$ threshold

$U \to l^+ l^-$

Is it possible to "detect" dark photons in Heavy-Ion Collisions ?

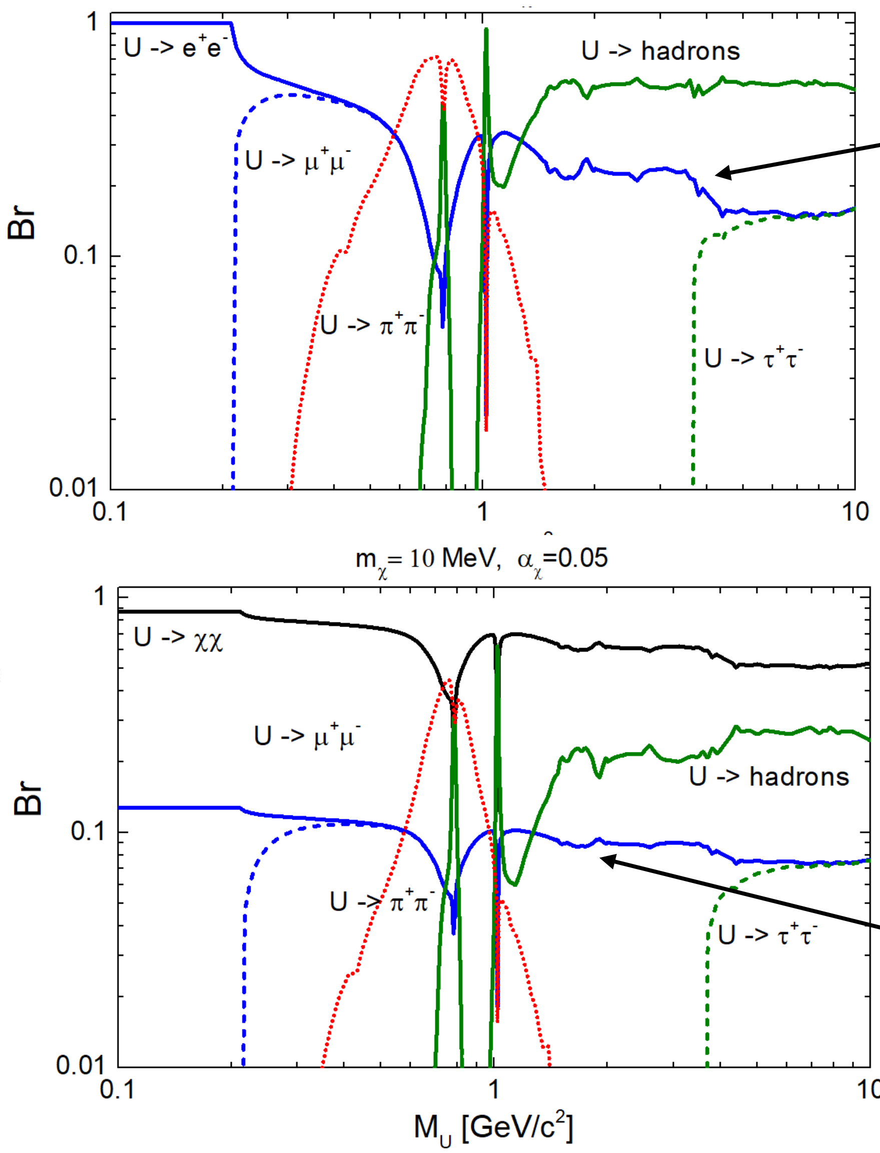


Dark photon decay modes.



$U \to e^+e^-$
$U \to \mu^+\mu^-$
$U \to \tau^+\tau^-$
$U \to hadrons$
$(U \to \pi^+\pi^-, \ldots)$

$m_U < 2m_\chi$



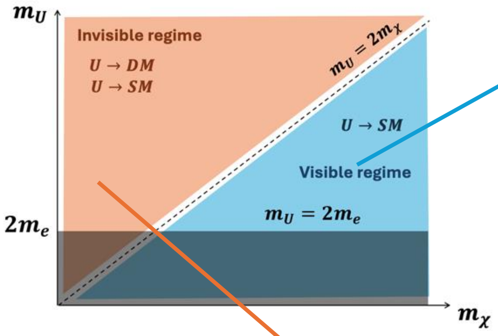
$Br^{U\to e^+e^-}$ dominant

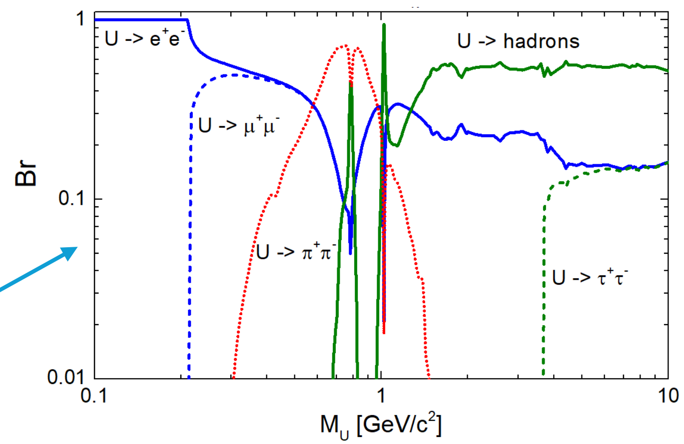
$$\mathrm{Br}(U\to e^+e^-) = \begin{cases} \dfrac{\Gamma(U\to e^+e^-)}{\Gamma_{\rm vis}}, & m_U < 2m_\chi, \\ \dfrac{\Gamma(U\to e^+e^-)}{\Gamma_{\rm vis}+\Gamma_{\rm inv}}, & m_U \geq 2m_\chi, \end{cases}$$

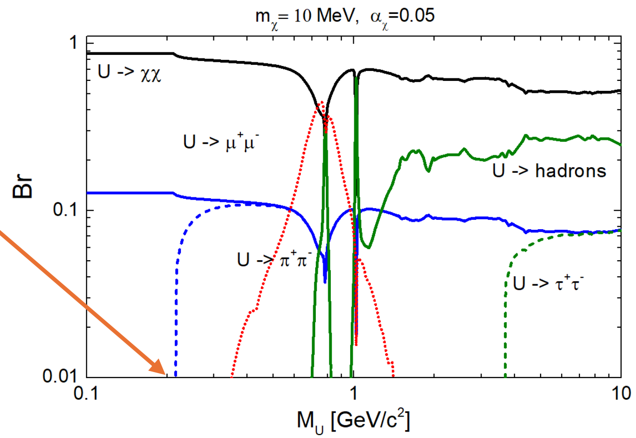
$$\Gamma_{\rm vis}(m_U) = \sum_{\ell=e,\mu,\tau} \Gamma(U\to\ell^+\ell^-) + \Gamma_{\rm had}$$

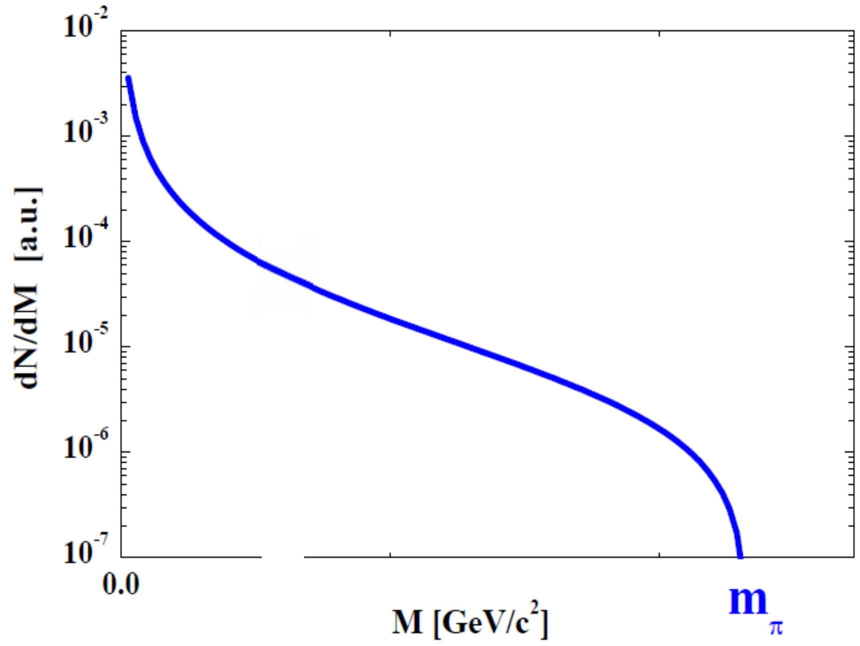
$Br^{U\to e^+e^-}$ suppressed

Dark photon decay modes.



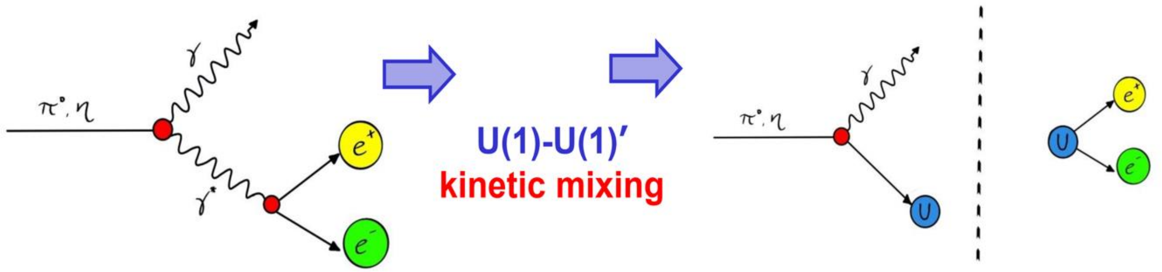




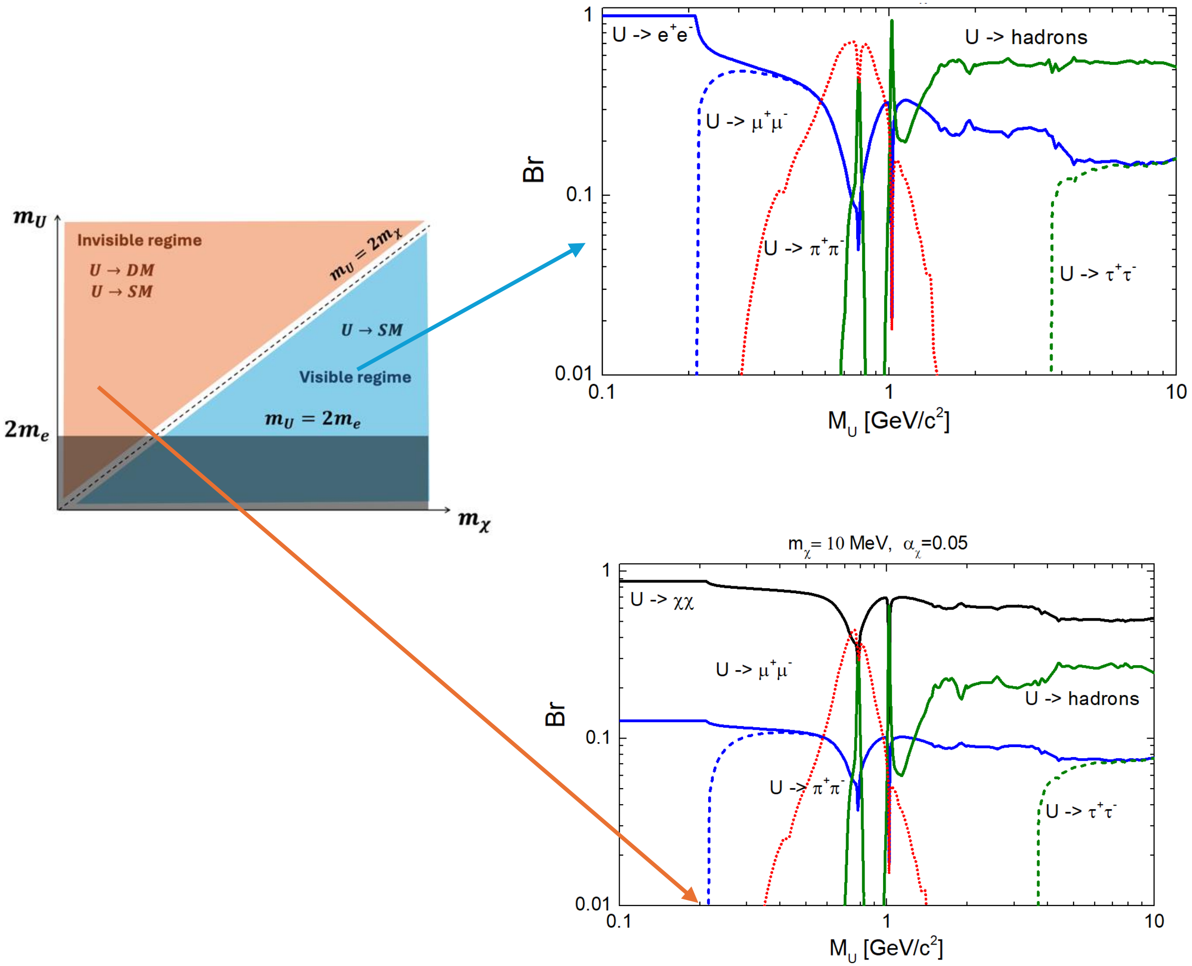


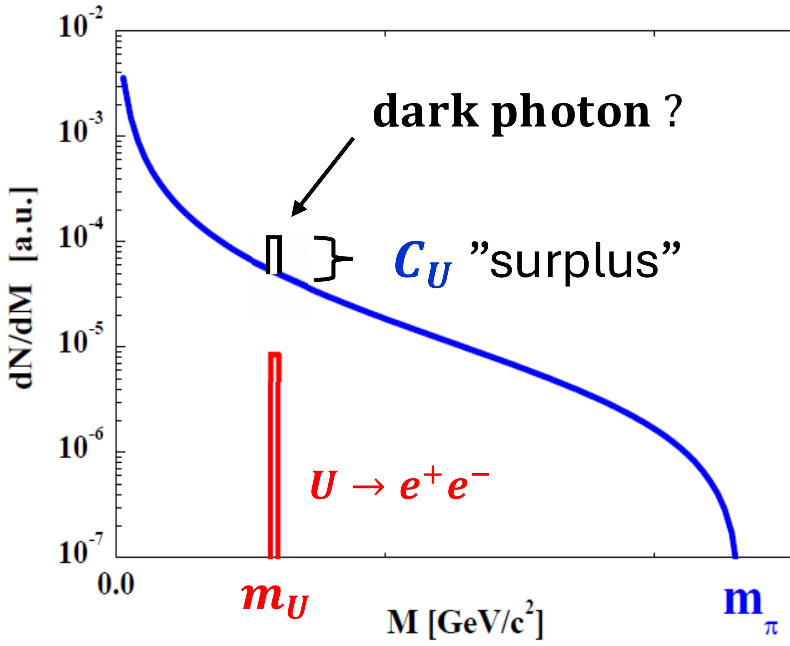
$\pi^0 \to \gamma + e^+e^-$ $\pi^0 \to \gamma + U,$ $U \to e^+e^-$

Standard model **Beyond SM**



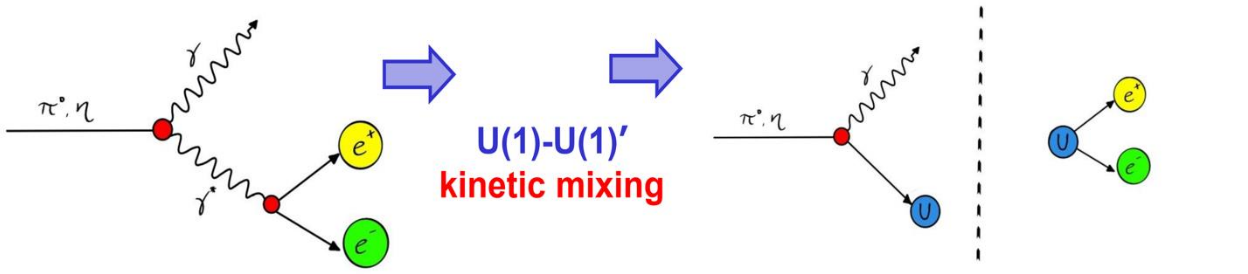
Dark photon decay modes.





$\pi^0 \to \gamma + e^+e^-$ $\pi^0 \to \gamma + U, \quad U \to e^+e^-$

Standard model **Beyond SM**

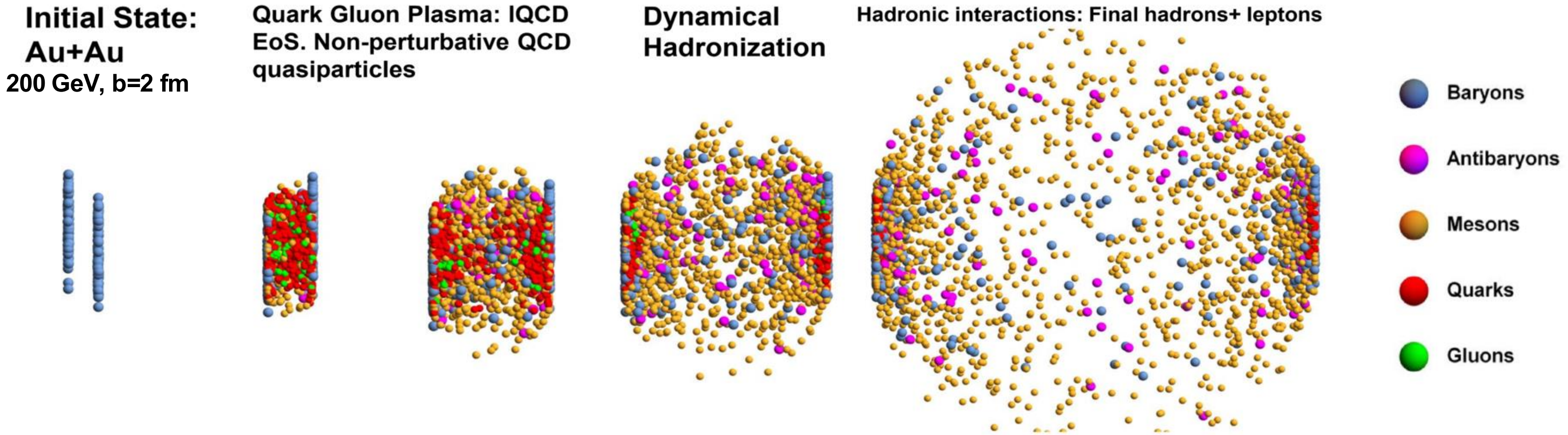


Theoretical modelling of dark photon production

Parton-Hadron-String Dynamics (PHSD) is a non-equilibrium microscopic transport approach for the description of strongly-interacting hadronic and partonic matter created in heavy-ion collisions

Dynamics: based on the solution of generalized off-shell transport equations derived from Kadanoff-Baym many-body theory

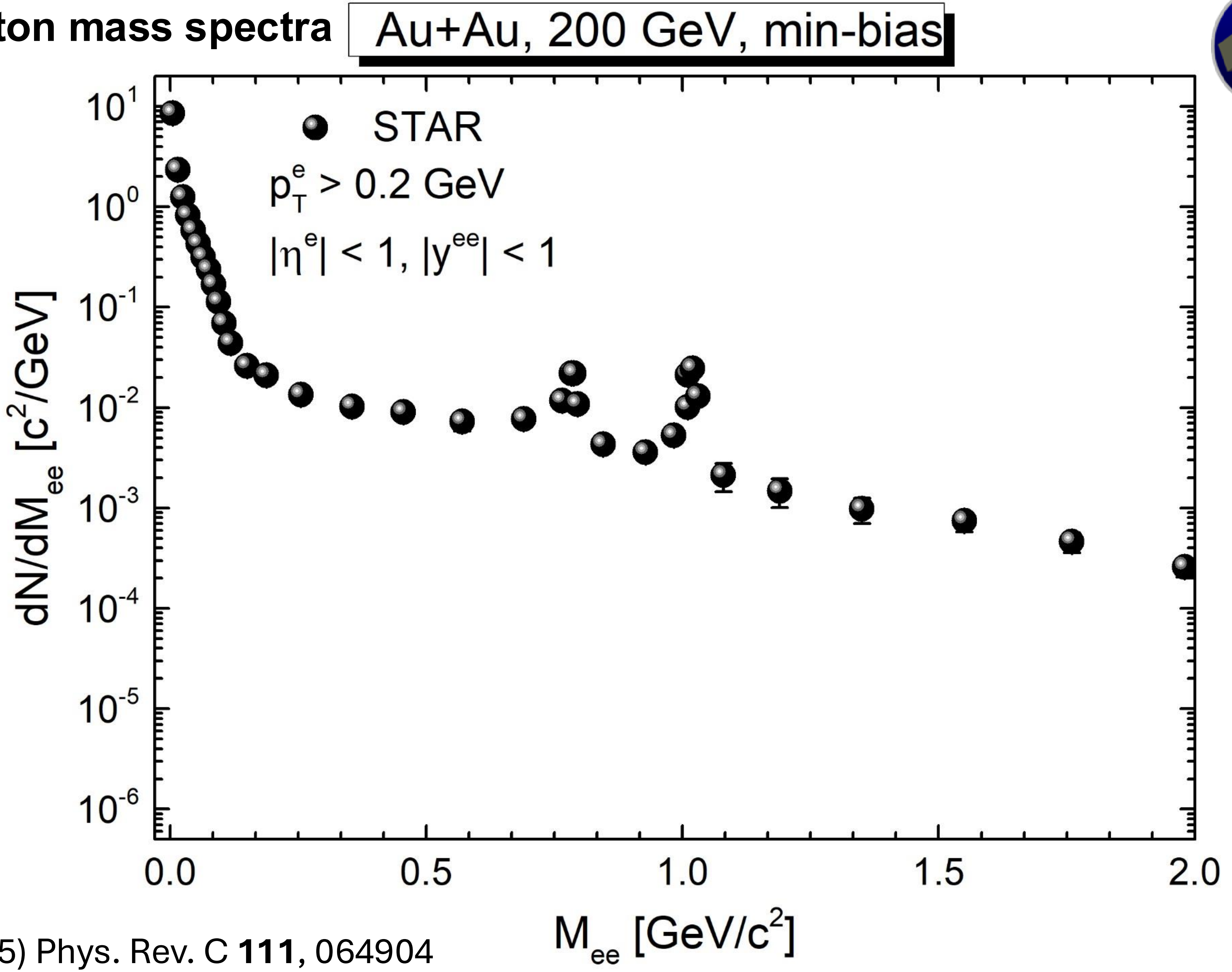
QGP: described by the Dynamical Quasi-Particle Model (DQPM)



➔ PHSD provides a good description of 'bulk' hadronic observables as well as dilepton spectra from SIS to LHC energies

PHSD: W. Cassing, E. Bratkovskaya, PRC 78 (2008) 034919; NPA831 (2009) 215; W. Cassing, EPJ ST 168 (2009)

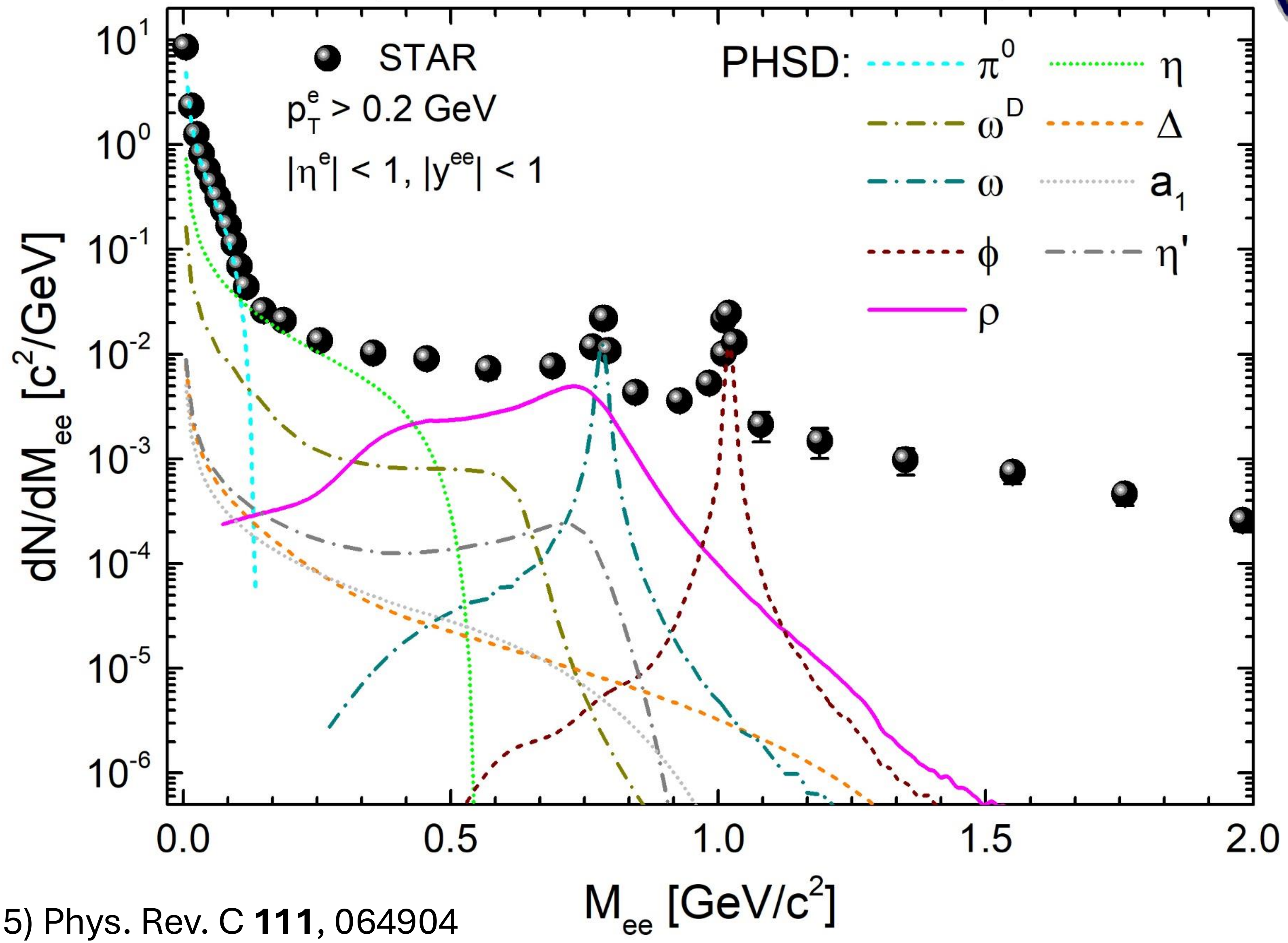
Dilepton mass spectra



See A. Jorge et al. (2025) Phys. Rev. C **111**, 064904

Dilepton mass spectra

Au+Au, 200 GeV, min-bias



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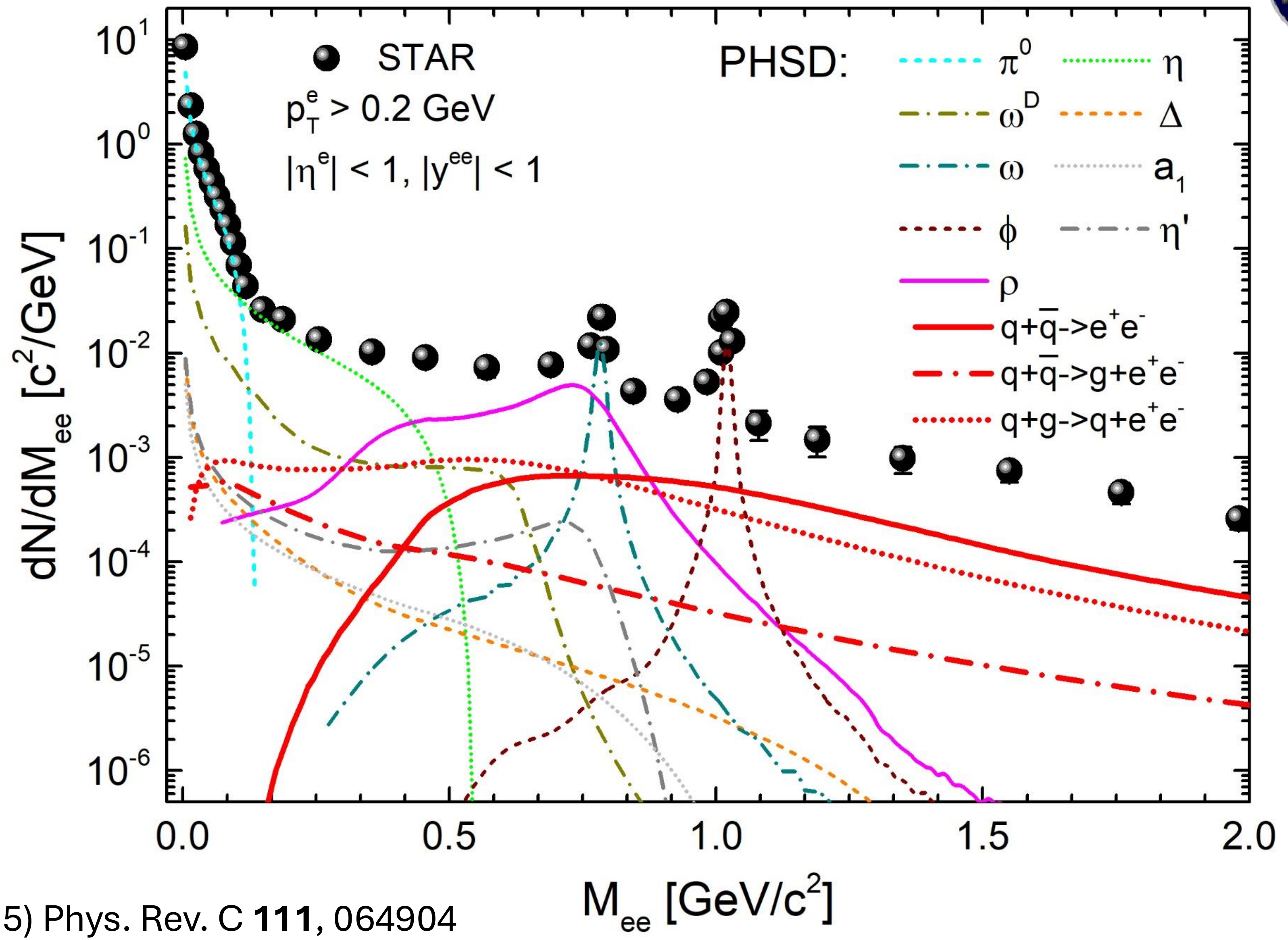

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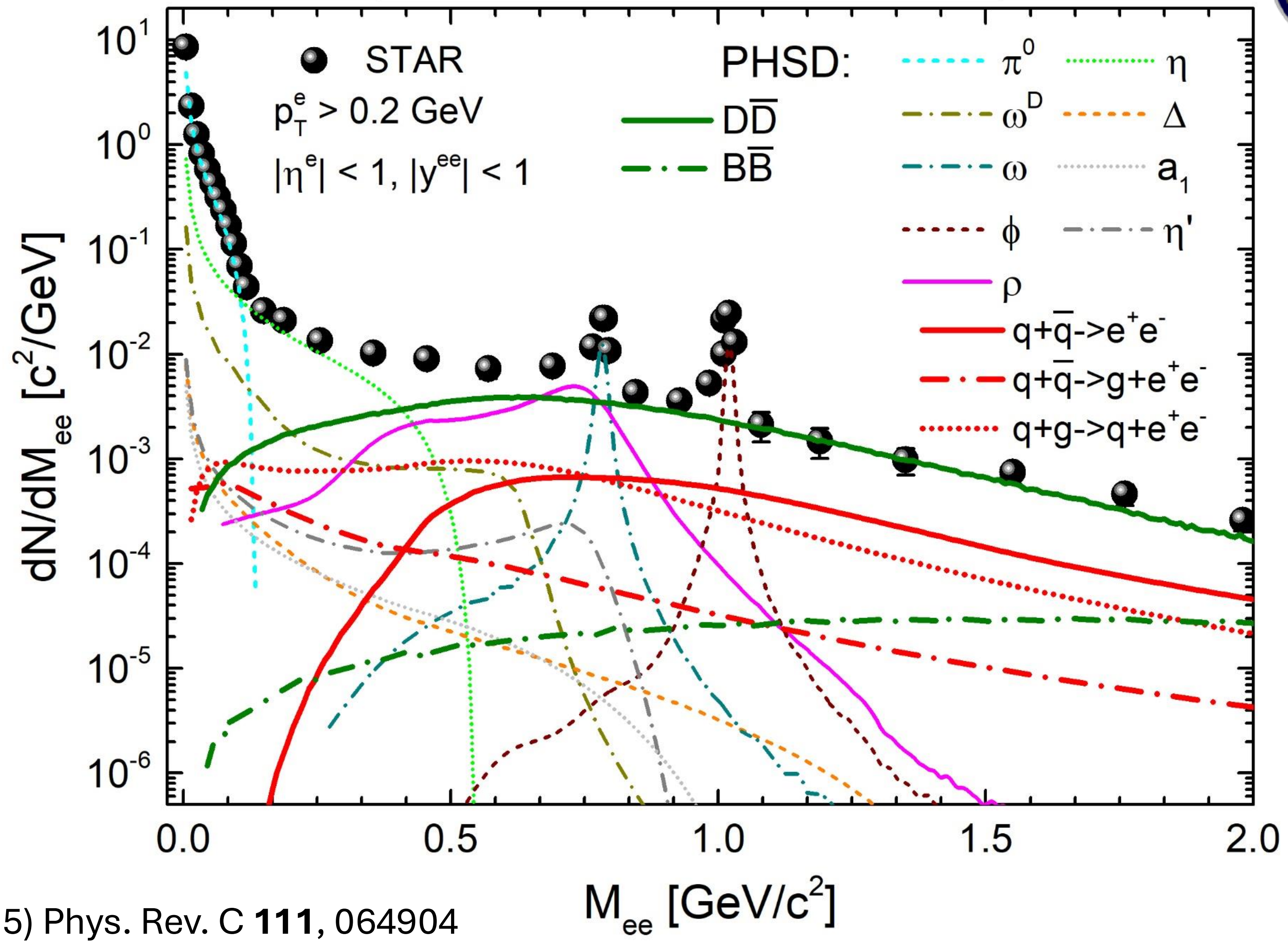

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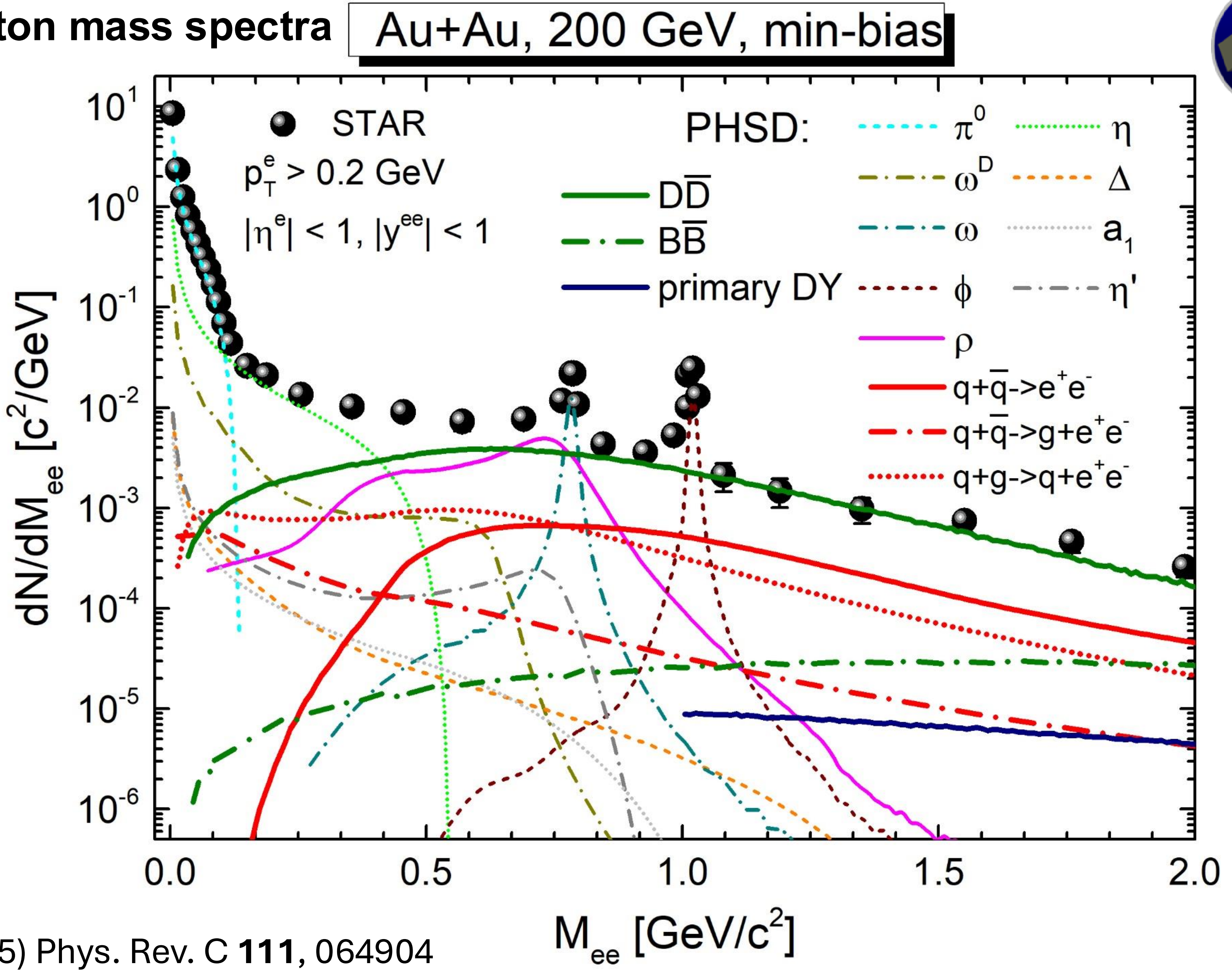

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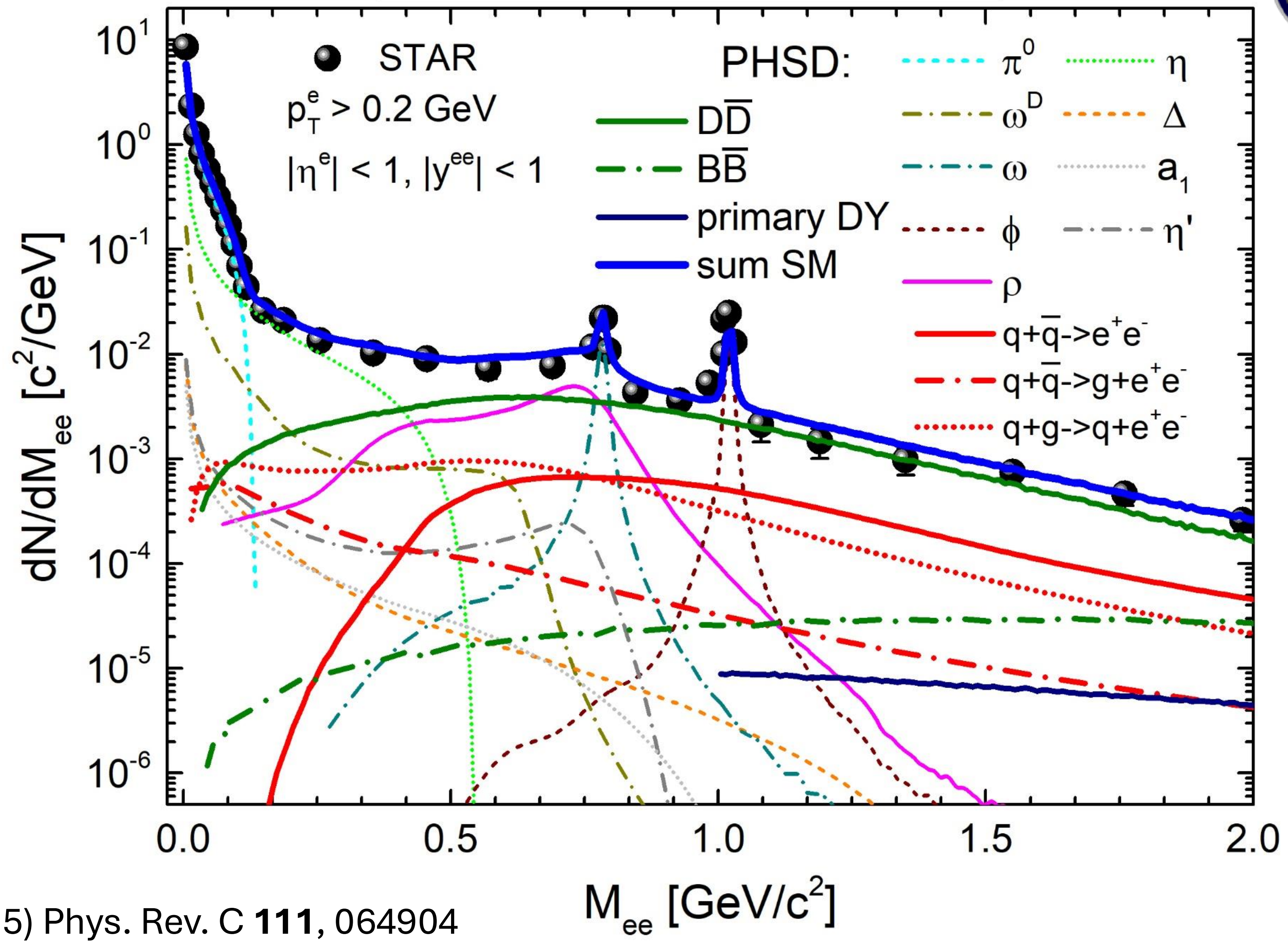
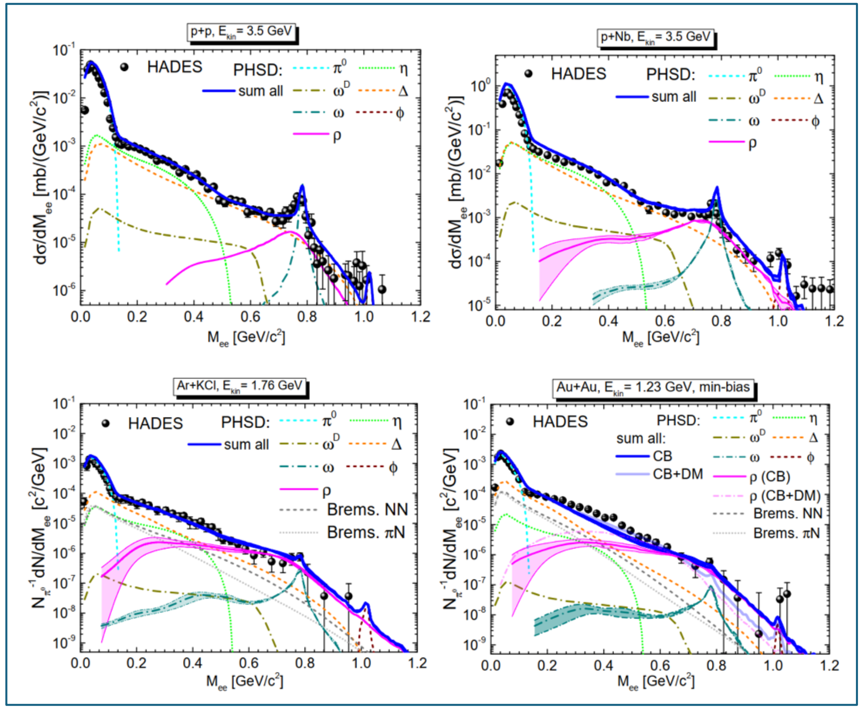
Dilepton mass spectra Au+Au, 200 GeV, min-bias



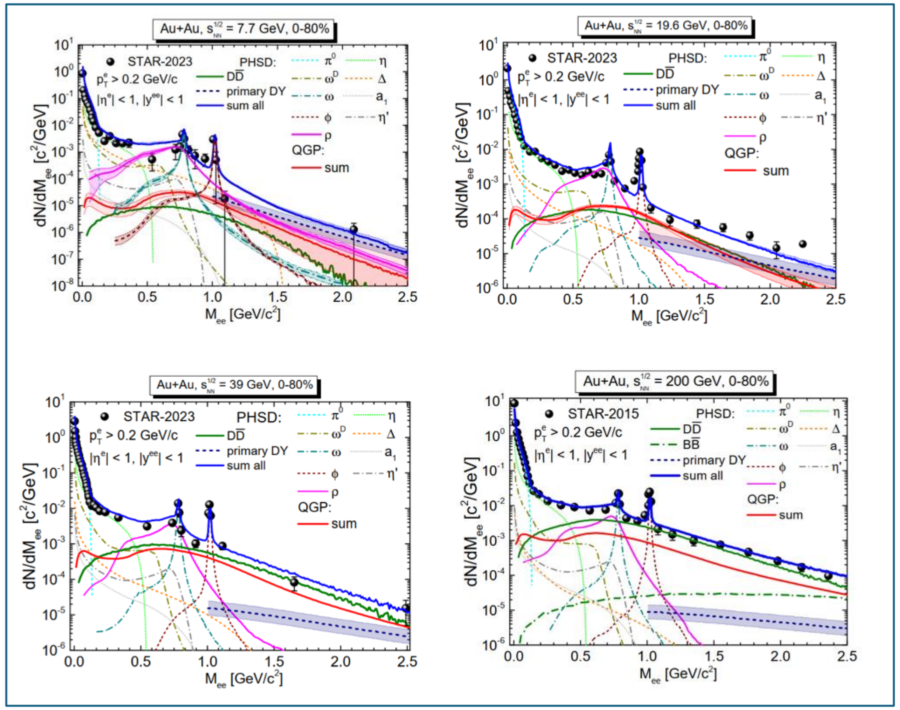
See A. Jorge et al. (2025) Phys. Rev. C **111**, 064904

Dilepton spectra from PHSD from SIS to RHIC energies

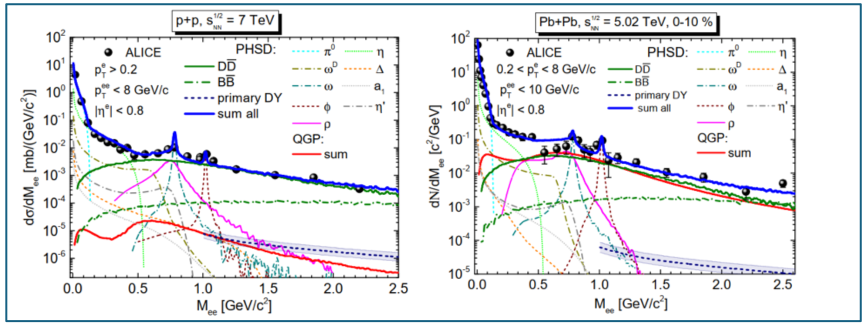
SIS-HADES



BES-RHIC-STAR



LHC-ALICE



- **The STAR/HADES/ALICE data, i.e. SM contributions (including exp. acceptance) are well described by the PHSD**

See A. Jorge et al. (2025) Phys. Rev. C **111**, 064904

Dark photon production in PHSD?

Dark photon production in PHSD

Dalitz Decay

$$\pi^0, \eta, \eta' \rightarrow \gamma U$$
$$\Delta \rightarrow N U$$
$$\omega \rightarrow \pi^0 U$$
$$K^+ \rightarrow \pi^+ U$$

Direct Decay

$$\rho, \phi, \omega \rightarrow U$$
$$q\,\bar{q} \rightarrow U$$

$$U \rightarrow e^+ e^-$$

Dark photon production in PHSD

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$\rho, \phi, \omega \rightarrow U$

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Total dilepton yield from dark photon decays of mass m_U:

$$N^{U\rightarrow e^+e^-} = \sum_{h=1} N_h^{U\rightarrow e^+e^-} = \sum_{h=1} N_h \times Br^{h\rightarrow XU} \times Br^{U\rightarrow e^+e^-}$$

$$h \rightarrow X + U$$

$$N_{h\rightarrow XU} = N_h \, Br^{h\rightarrow XU}$$

Dark photon production in PHSD

Dalitz Decay

$\pi^0, \eta, \eta' \to \gamma U$

$\Delta \to N U$

$\omega \to \pi^0 U$

$K^+ \to \pi^+ U$

Direct Decay

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$$h \to X + U$$

$$N_{h \to XU} = N_h \, Br^{h \to XU}$$

$$Br(P \to \gamma U) = \varepsilon^2 Br(P \to \gamma\gamma)\left(1 - \frac{m_U^2}{m_P^2}\right)^3 \qquad P = \pi, \eta, \eta'$$

$$Br(\Delta \to NU) = \varepsilon^2 Br(\Delta \to N\gamma) \int A(m_\Delta) \frac{\lambda^{3/2}(m_\Delta, m_N, m_U)}{\lambda^{3/2}(m_\Delta, m_N, 0)}$$

Based on
B. Batel, et al. (2009) PRD 80, 095024
G. Agakishiev et al. (2014) PLB, 731, 265
A. Berlin et al. (2018) PRD 92, 115017
I. Schmidt et al., PRD 104 (2021) 015008 as used in PHSD

$$Br(\omega \to \pi^0 U) = \varepsilon^2 Br(\omega \to \pi^0\gamma) \frac{\left[(m_\omega^2 - (m_U + m_\pi))(m_\omega^2 - (m_U - m_\pi))\right]^{3/2}}{(m_\omega^2 - m_\pi^2)^3}$$

→ D. Gorbunov et al. (2024) PLB, 852, 138599

$$Br(K^+ \to \pi^+ U) = \frac{\alpha\varepsilon^2}{\pi^2\,\Gamma_T(K)} \frac{m_U}{m_K} W'(m_U) \lambda^{1/2}(m_U, m_k, m_\pi)$$

→ M. Pospelov (2009) PRD 80, 095002

$$Br(V \to U) = \frac{\alpha\varepsilon^2 m_U}{3\Gamma_T(V)} \qquad V = \rho, \phi, \omega$$

→ B. Battel, et al. (2009) PRD 79, 115008

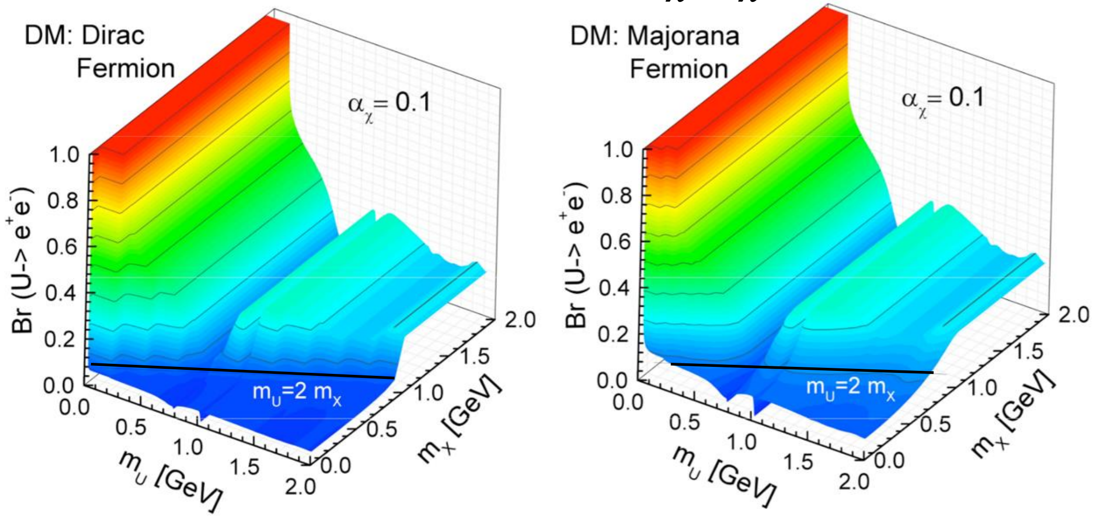
$$Br(q\bar{q} \to U) = \varepsilon^2 \frac{\Gamma^{PHSD}_{q\bar{q} \to e^+e^-}}{\Gamma_T(V)}$$

→ Arxiv: 2507.11163
C. Ahdida et al. (2021) EPJ 81 C, 451

new channels in PHSD

A. W. Romero Jorge et. al, PRC 112 (054905) 2025

$$Br^{U \to e^+e^-}(m_U, m_\chi, \alpha_\chi)$$



A. W. Romero Jorge et. al, PRD 113 (055052) 2026

Procedure to obtain constraints on $\varepsilon^2(m_U)$

For each bin [m_U,m_U +dm] calculate the sum of all U→e+e- contributions (kinematically possible in this mass bin)

1) $$\frac{dN^{sumU}}{dM} = \varepsilon^2 \frac{dN^{sumU}_{\varepsilon^2=1}}{dM}$$

2) $$\frac{dN^{sumU}}{dM} = C_U \frac{dN^{sumSM}}{dM}$$

Obtain constraints by requesting that the total dilepton yield cannot exceed the sum of SM channels by more than a factor C_U in each bin dm.

C_U → **controls the allowed "surplus" dilepton yield resulting from dark photons on top of the total SM yield**

See **arXiv:2507.11163** and
I. Schmidt et al. (2021)
Phys. Rev. D **104**, 015008

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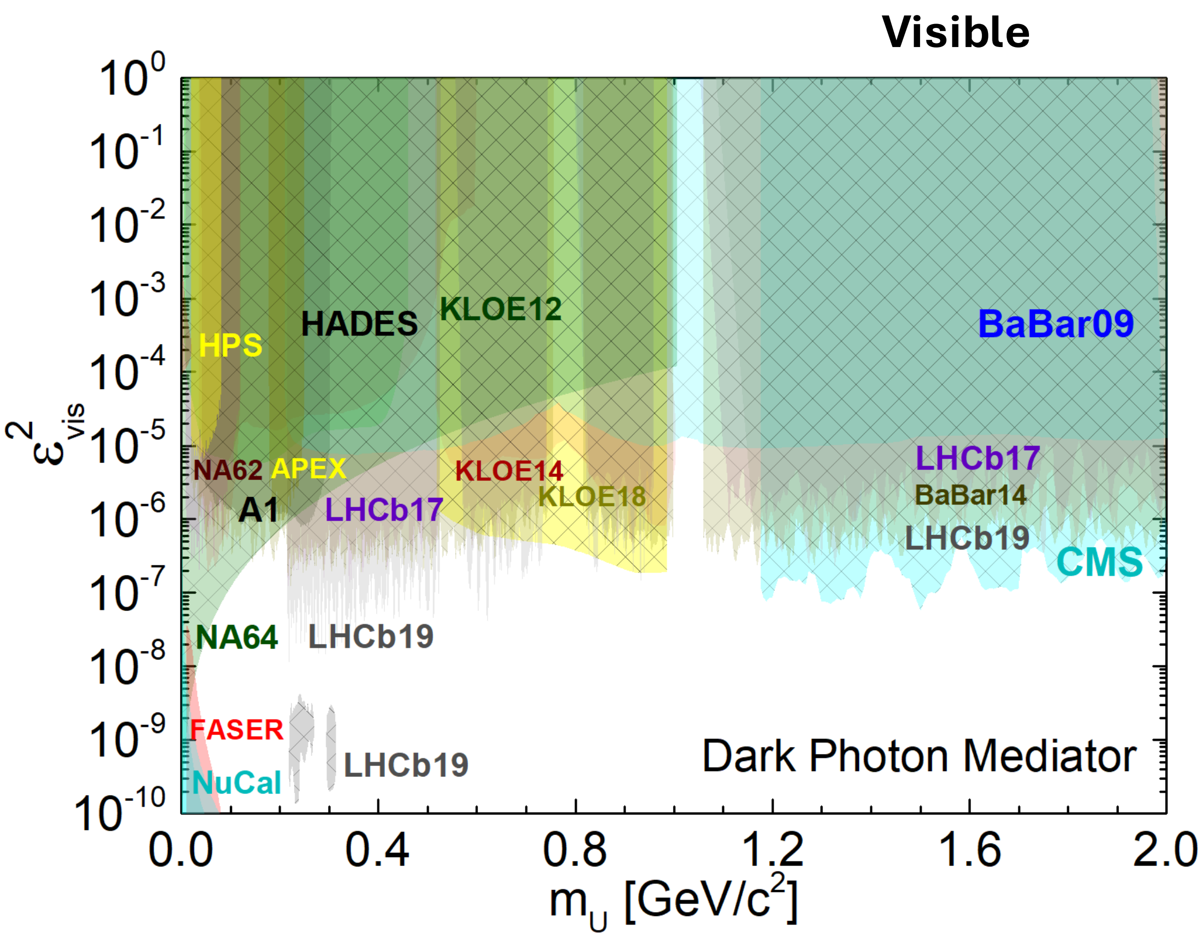
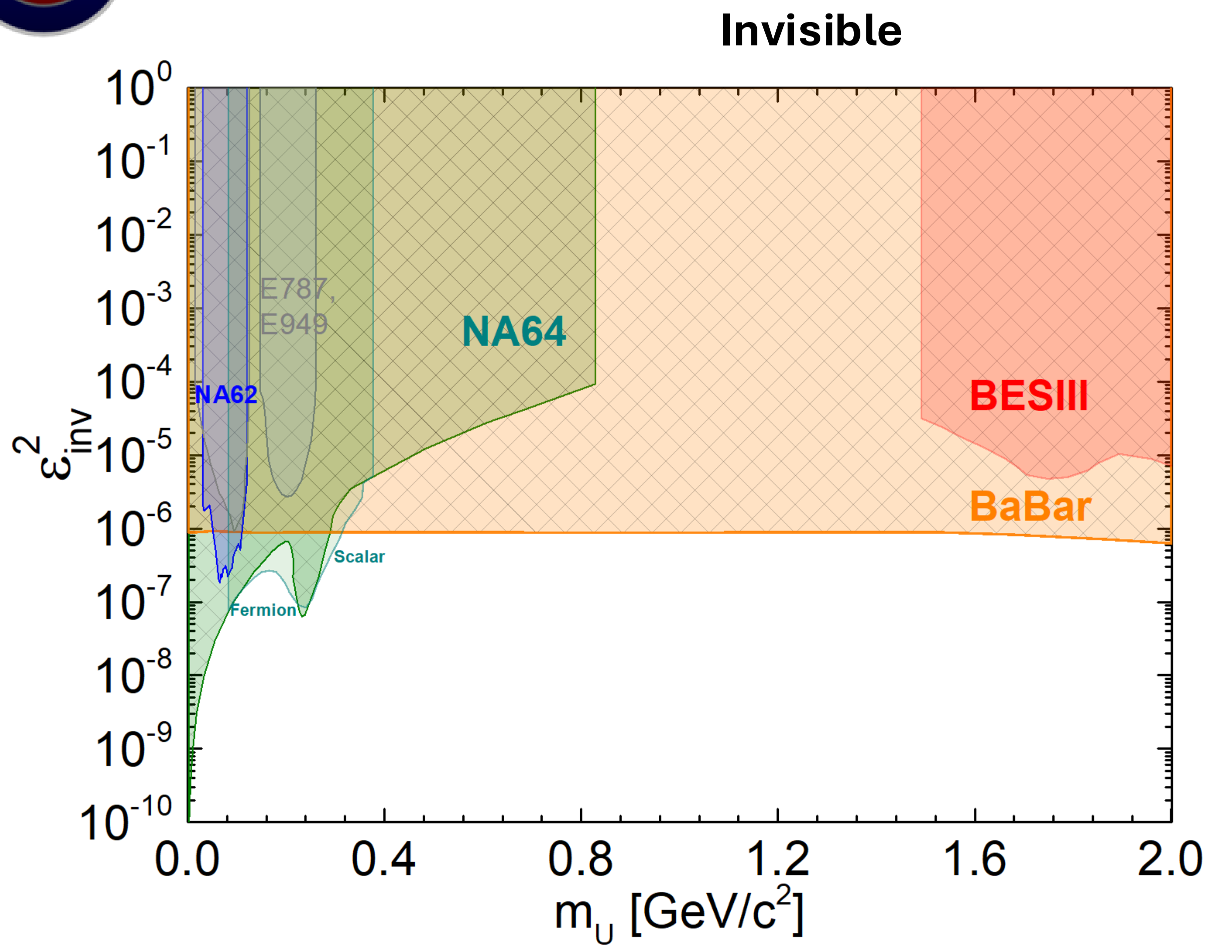
$$\varepsilon^2(m_U, m_\chi, \alpha_\chi) = C_U \cdot \left(\frac{dN^{sumSM}}{dM}\right) \Big/ \left(\frac{dN^{sumU}_{\varepsilon^2=1}}{dM}\right)$$

Calculate $\varepsilon^2(M_U)$ by assuming C_U : e.g. C_U = 5 % DM extra yield to the SM yield

See **arXiv:2507.11163** and I. Schmidt et al. (2021) Phys. Rev. D **104**, 015008

Kinetic Mixing parameter $\varepsilon^2(m_U)$





A. W. Romero Jorge et. al, PRD 113 (055052) 2026

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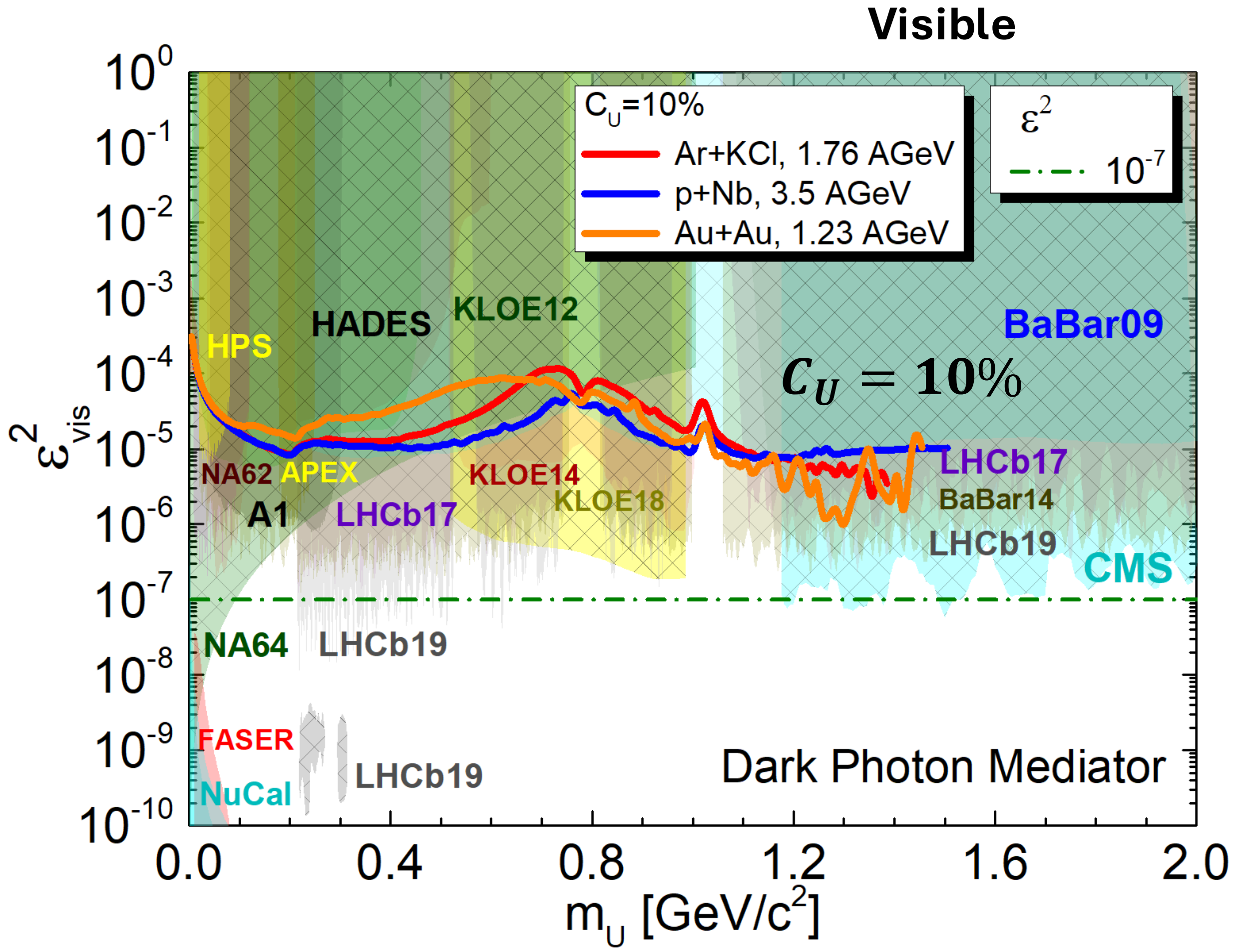
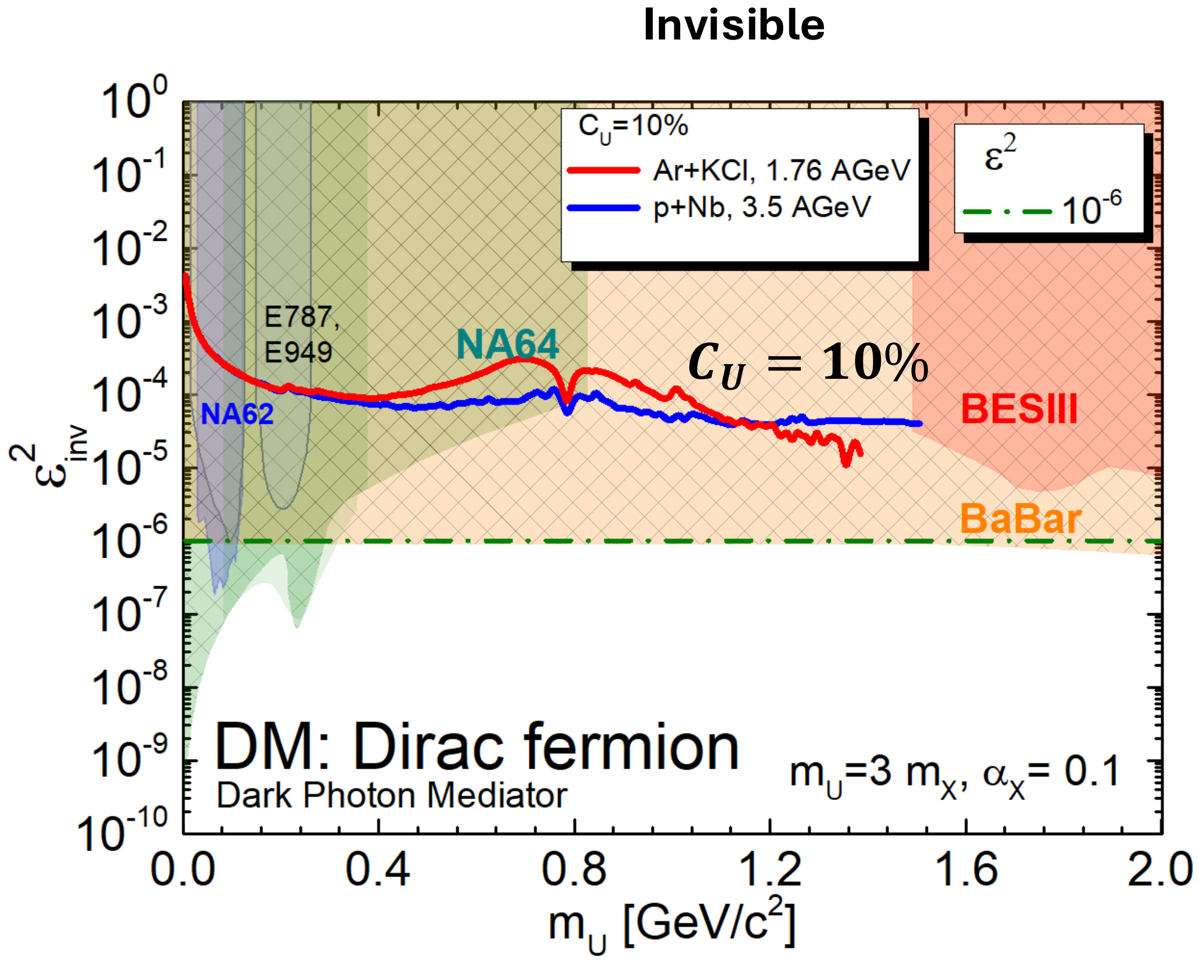
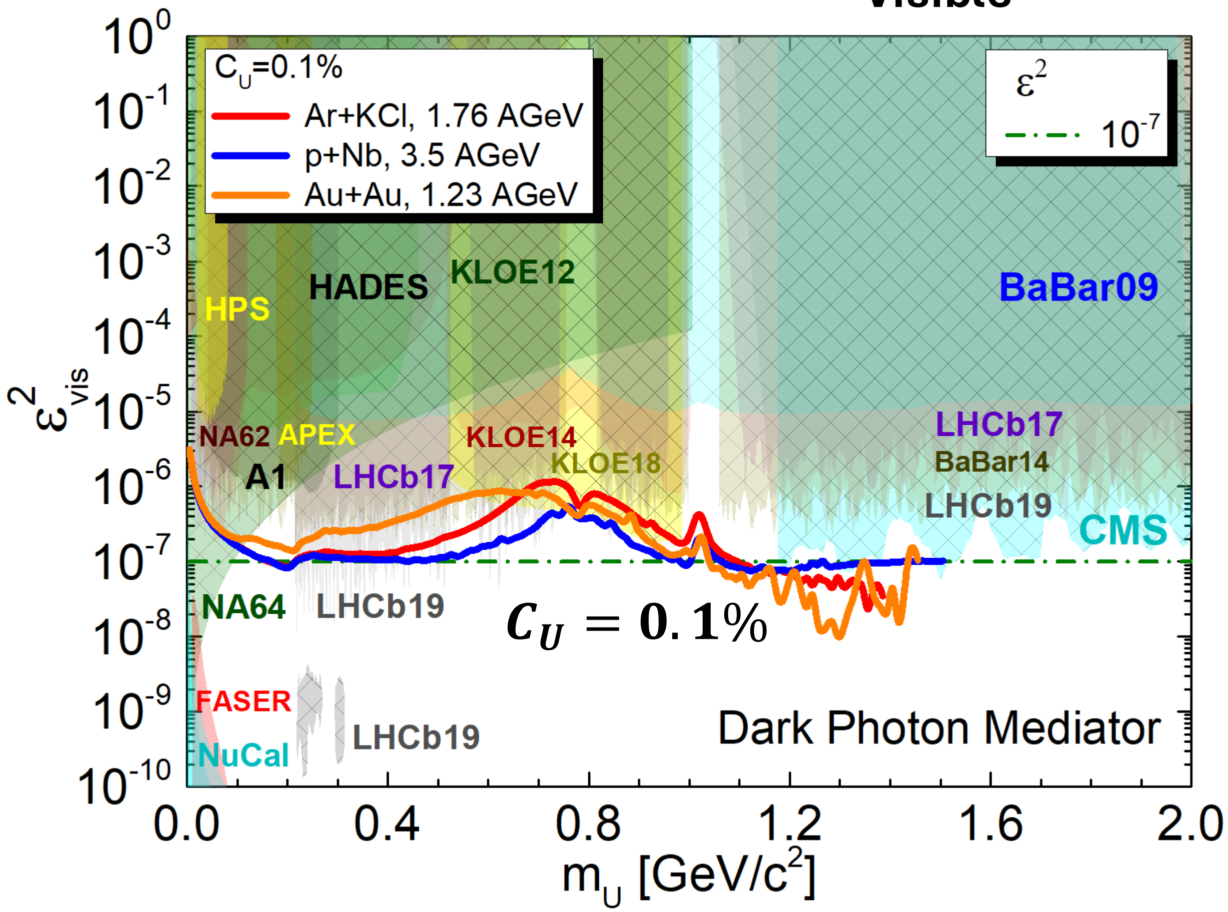




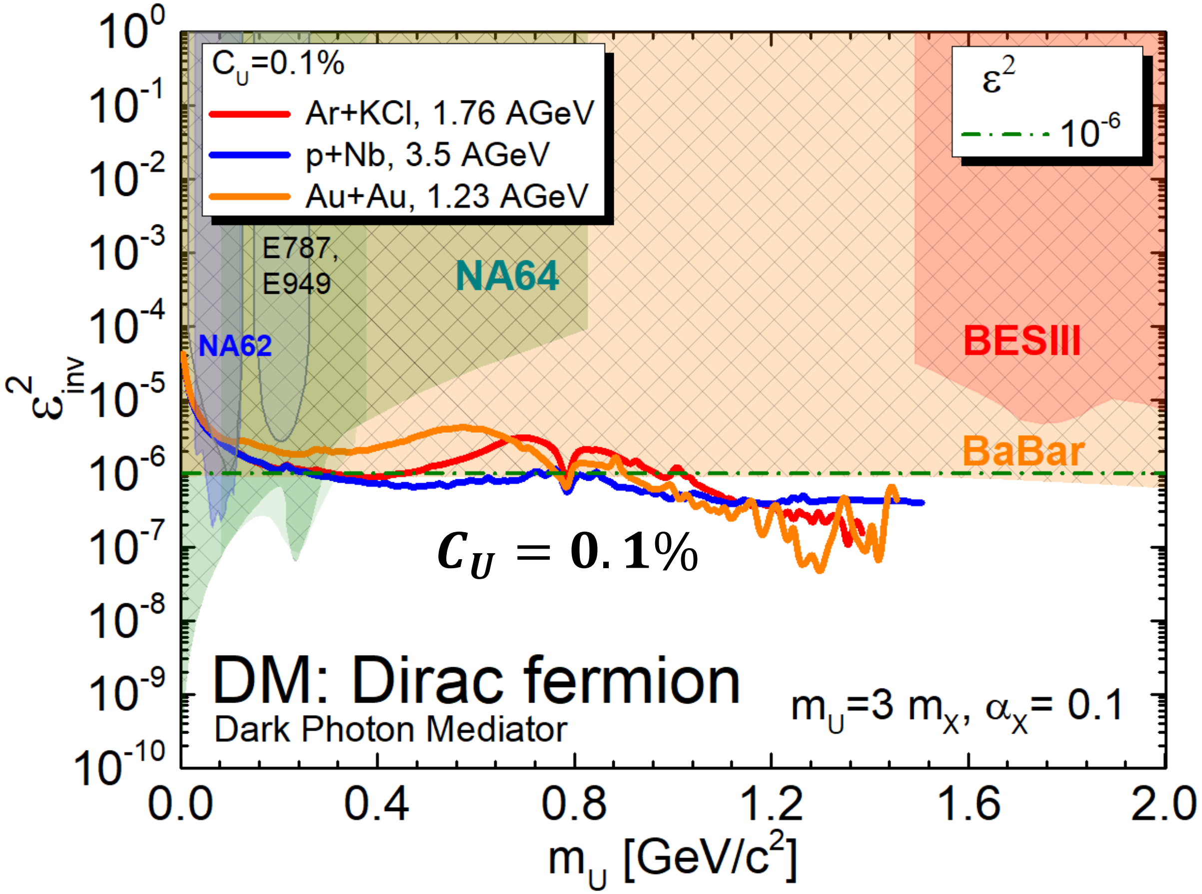
A. W. Romero Jorge et. al, PRD 113 (055052) 2026

Kinetic Mixing parameter $\varepsilon^2(m_U)$

Visible



Invisible



$$\varepsilon^2 \sim 10^{-7}$$

A. W. Romero Jorge et. al, PRD 113 (055052) 2026

Kinetic Mixing parameter $\varepsilon^2(m_U)$

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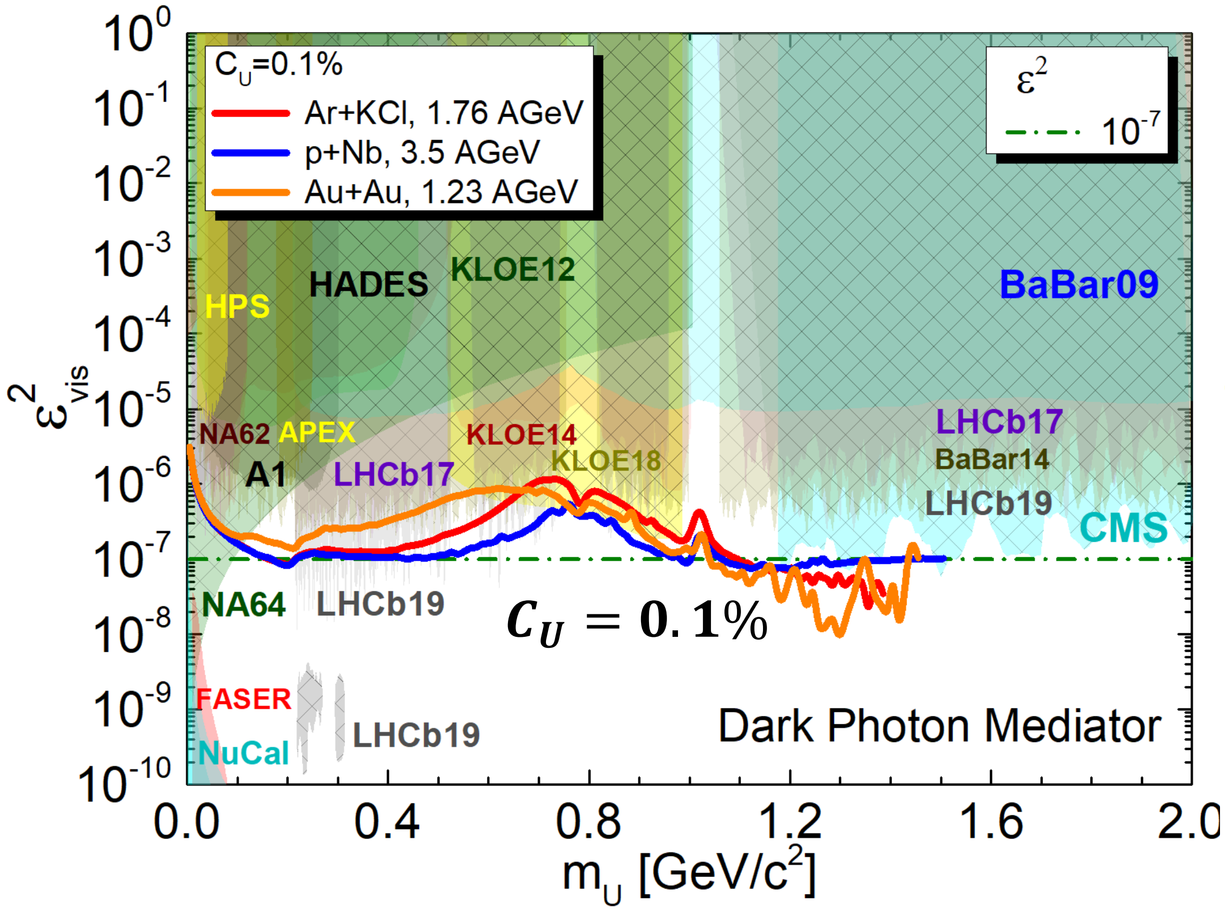
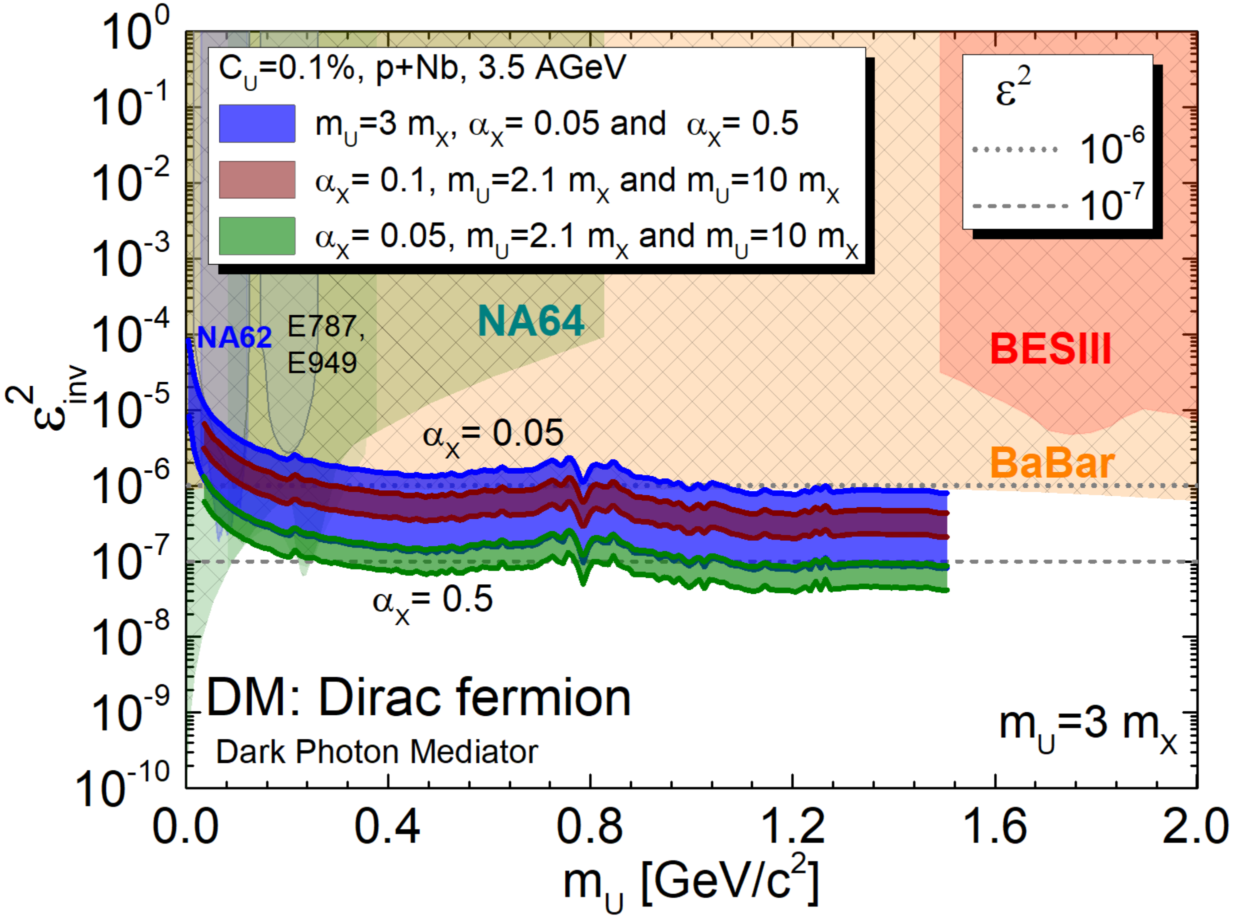


Invisible



$\varepsilon^2 \sim 10^{-7}$

$\varepsilon^2 \sim 10^{-6}, 10^{-8}$

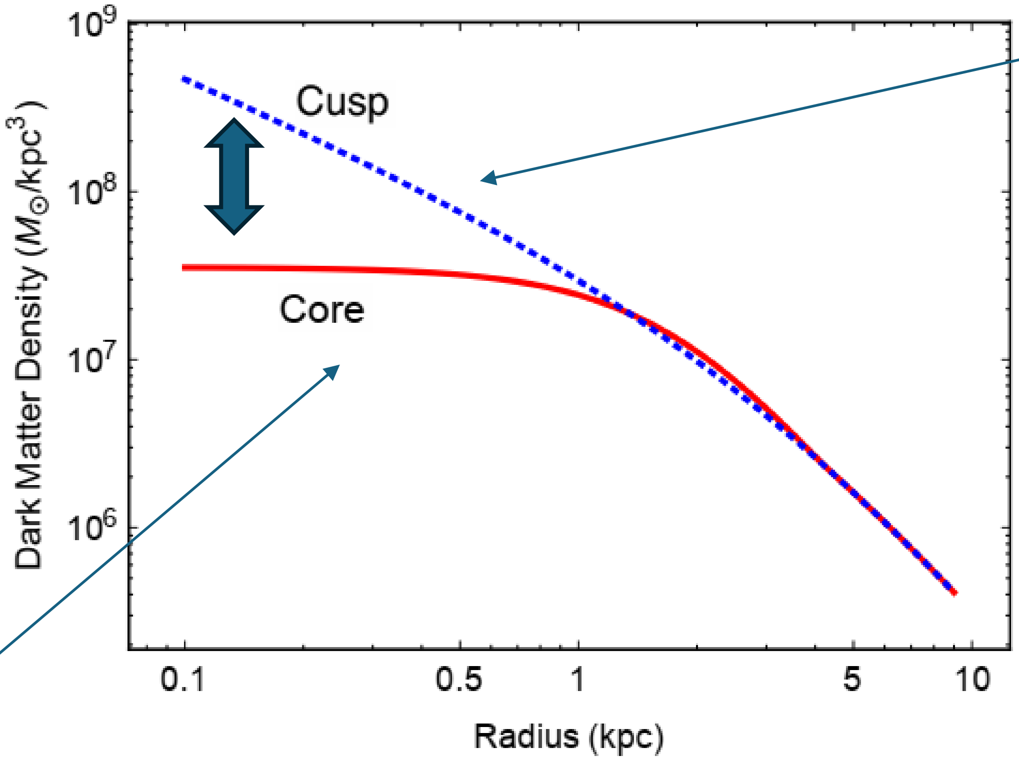
A. W. Romero Jorge et. al, PRD 113 (055052) 2026

Constraints from Astrophysics and Cosmology

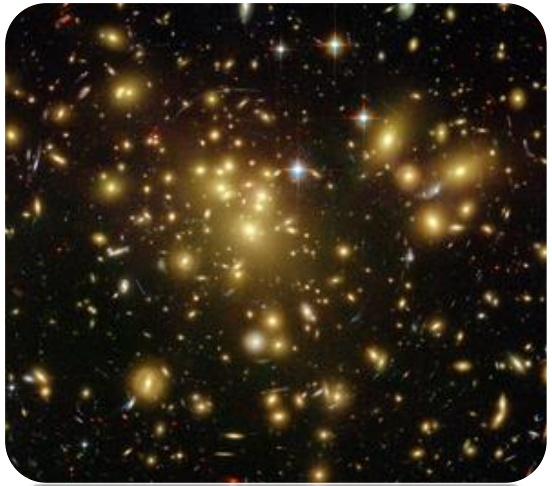
Self-Interacting Dark Matter (SIDM)
Core-Cusp Problem

Small scales

Dwarf galaxies



Large scales

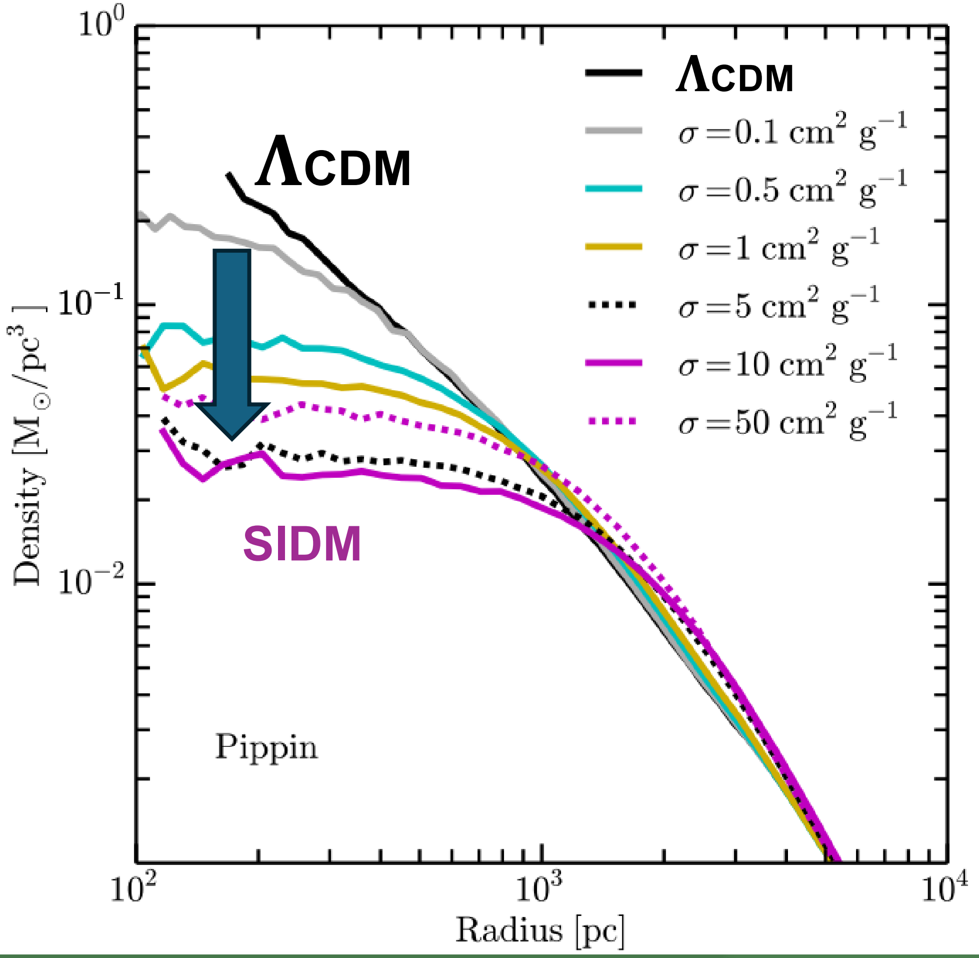


Galaxy clusters

Self-Interacting Dark Matter (SIDM)

Dark Matter Density profile

$$V(r) = \pm \frac{\alpha_X}{r} e^{-m_U r} \begin{cases} + & \text{repulsive} \\ - & \text{attractive} \end{cases}$$



Arxiv.1308.0618

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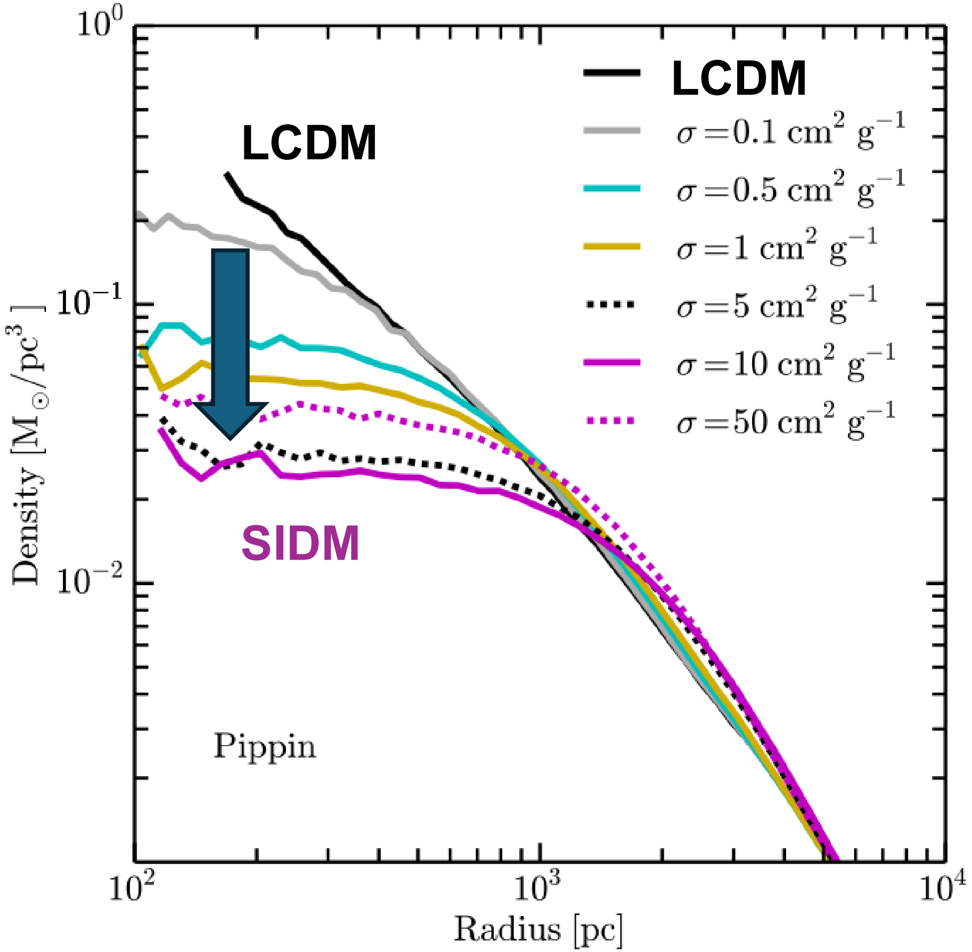

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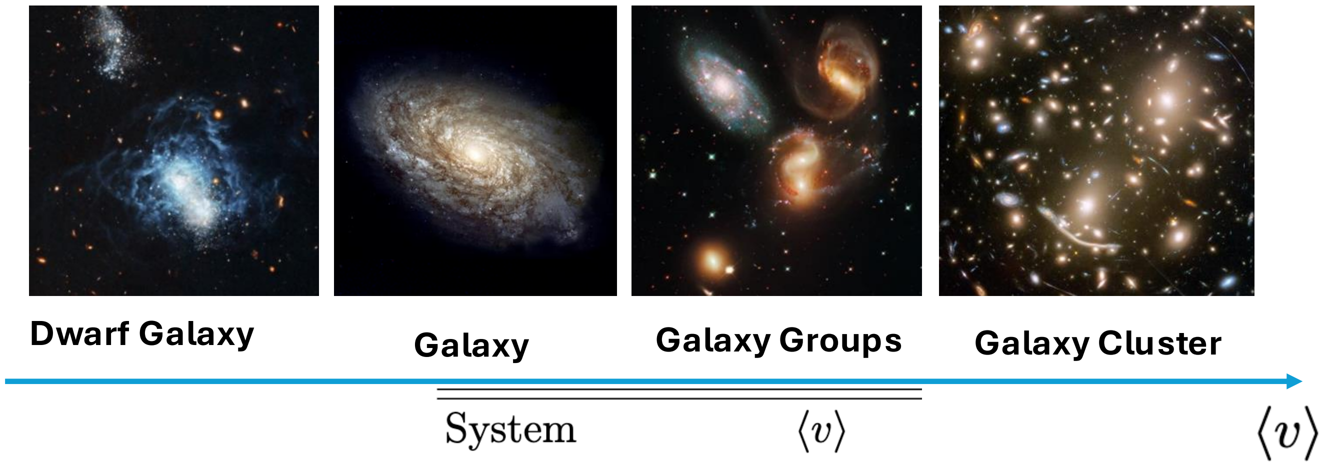
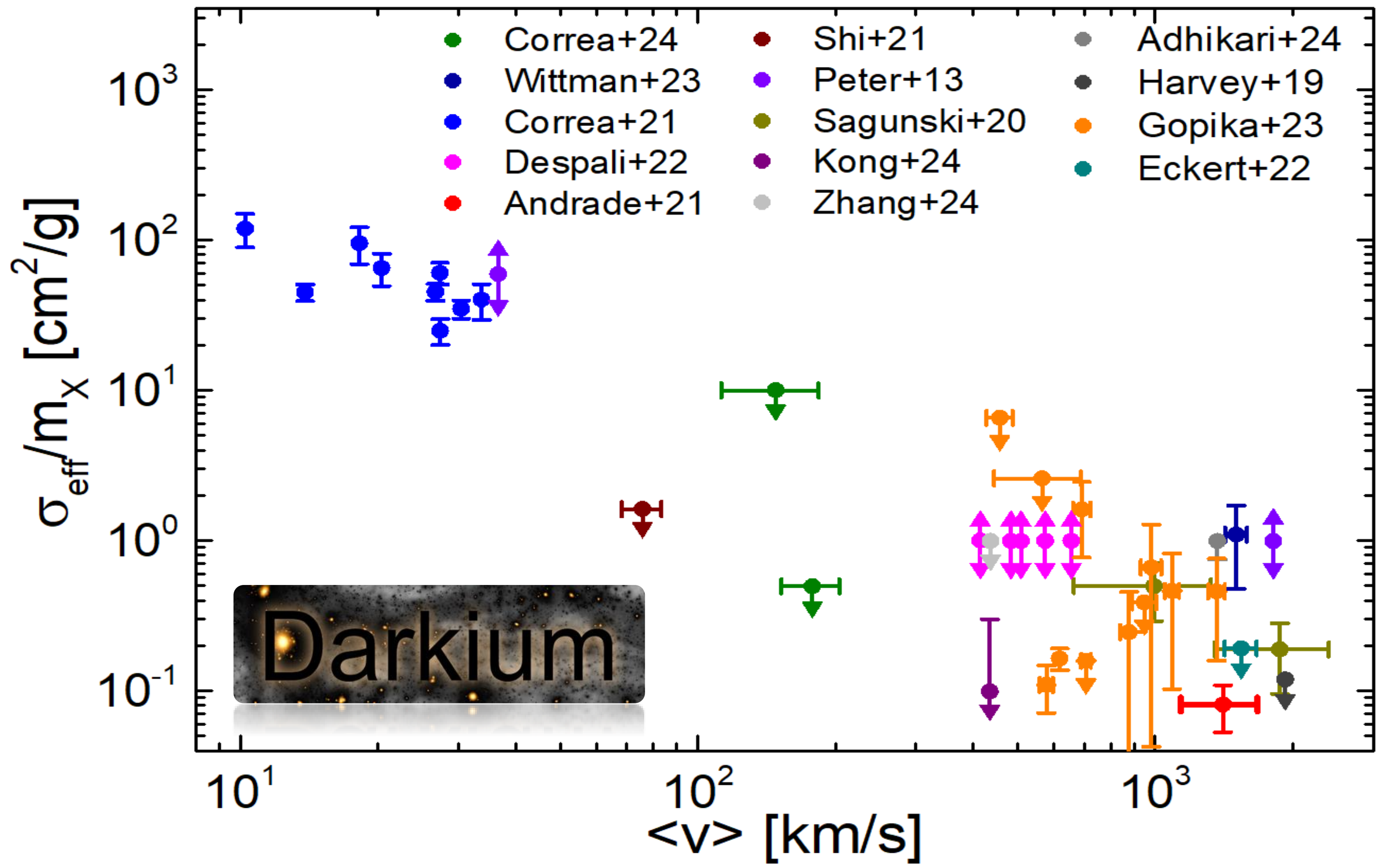


System	$\langle v \rangle$
Dwarf galaxy	50
Galaxy	250
Galaxy group	1150
Galaxy cluster	1900

Arxiv: 2011.04679



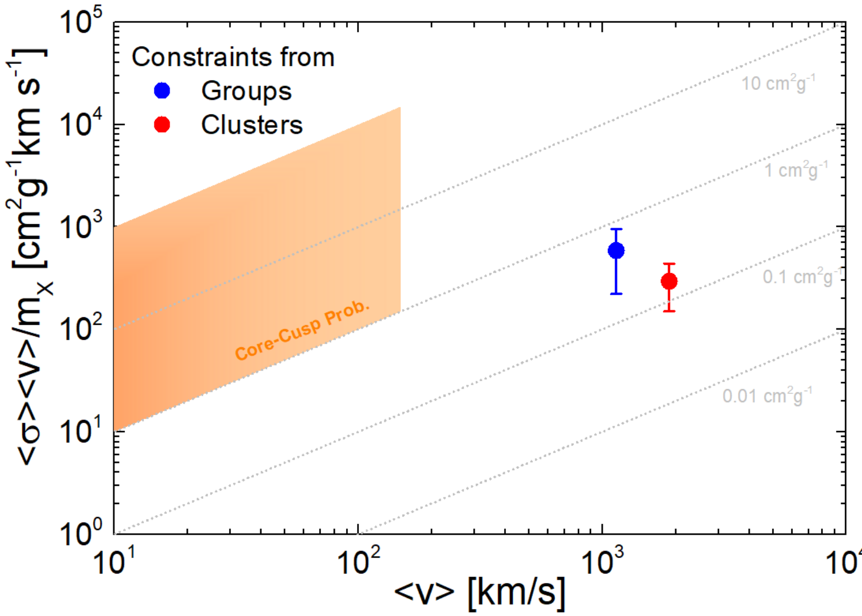
Arxiv: 2310.07750

Effective cross-section Constraints

$$\sigma_{eff} = \frac{3}{2}\frac{\langle \sigma(v)\, v^5 \rangle}{\langle v^5 \rangle}$$

ArXiv: 2205.03392

Galaxy Groups and Clusters Constraints



Arxiv: 2011.04679

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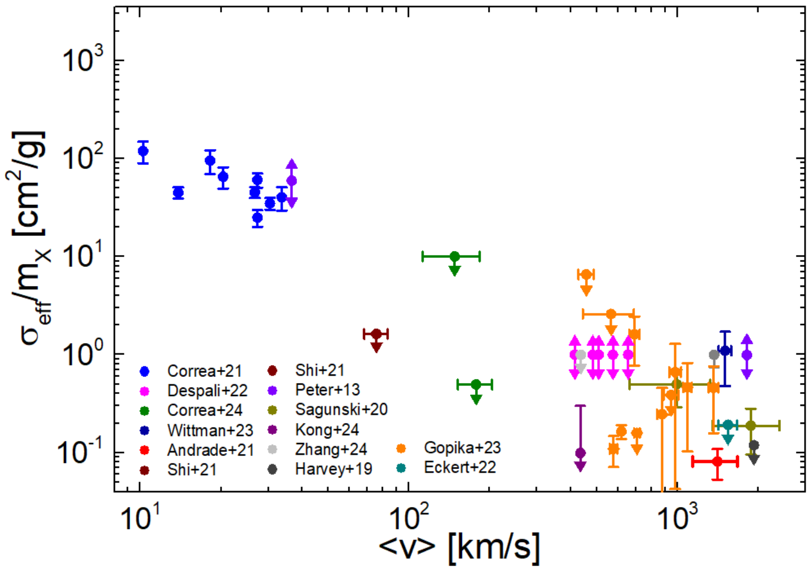
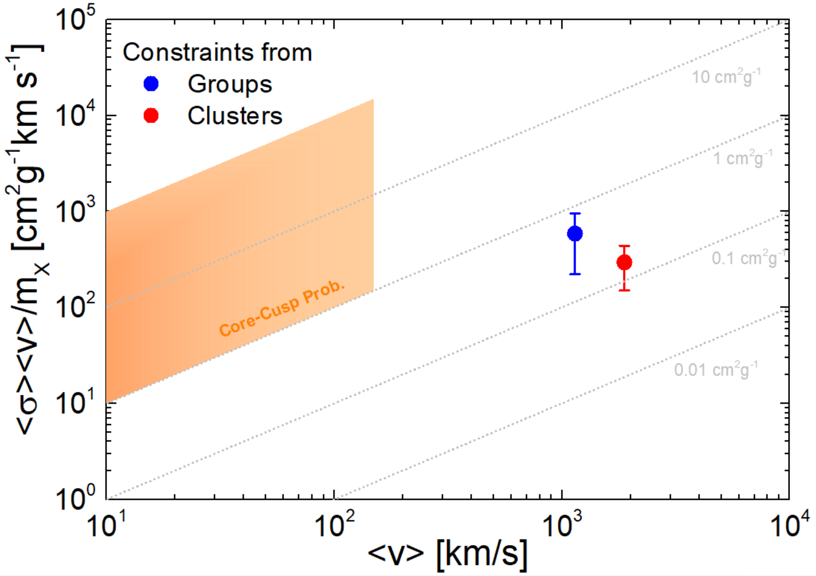




Two-body scattering problem

Schrödinger Equation

$$U(r) = \pm \frac{\alpha_\chi}{r} e^{-m_\phi r}$$

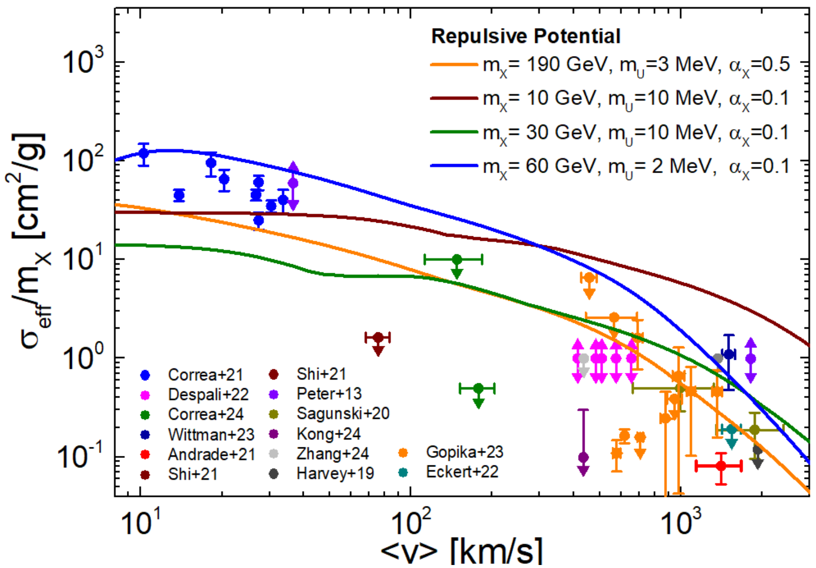
Maxwell–Boltzmann distribution to compute velocity-averaged cross sections

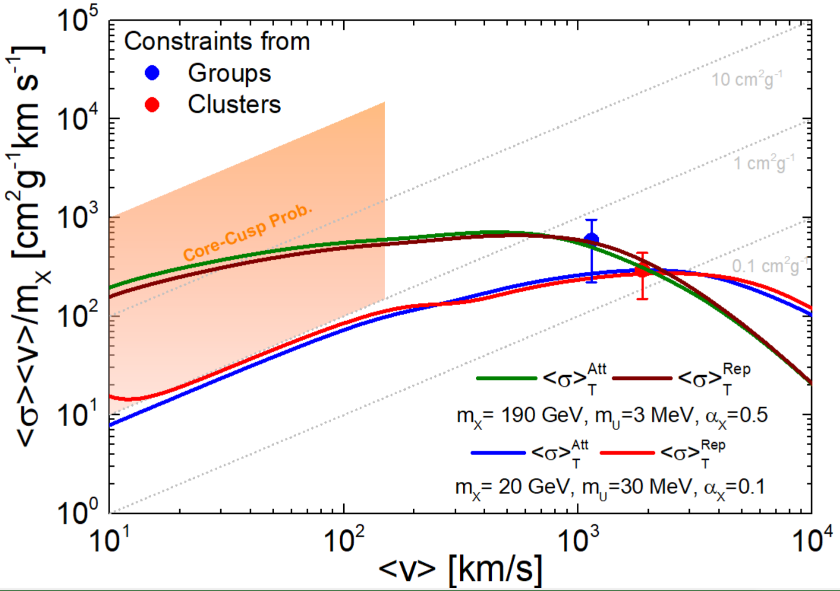
$$f(v) = 4\pi \left(\frac{m_\chi}{2\pi k_B T}\right)^{3/2} v^2\, e^{-\frac{m_\chi v^2}{2k_B T}}$$

Momentum-transfer cross section:

$$\sigma_T = \int d\Omega\, (1 - \cos\theta) \frac{d\sigma}{d\Omega}.$$

Effective cross-section Constraints





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Momentum-transfer cross section:

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CLASSICS

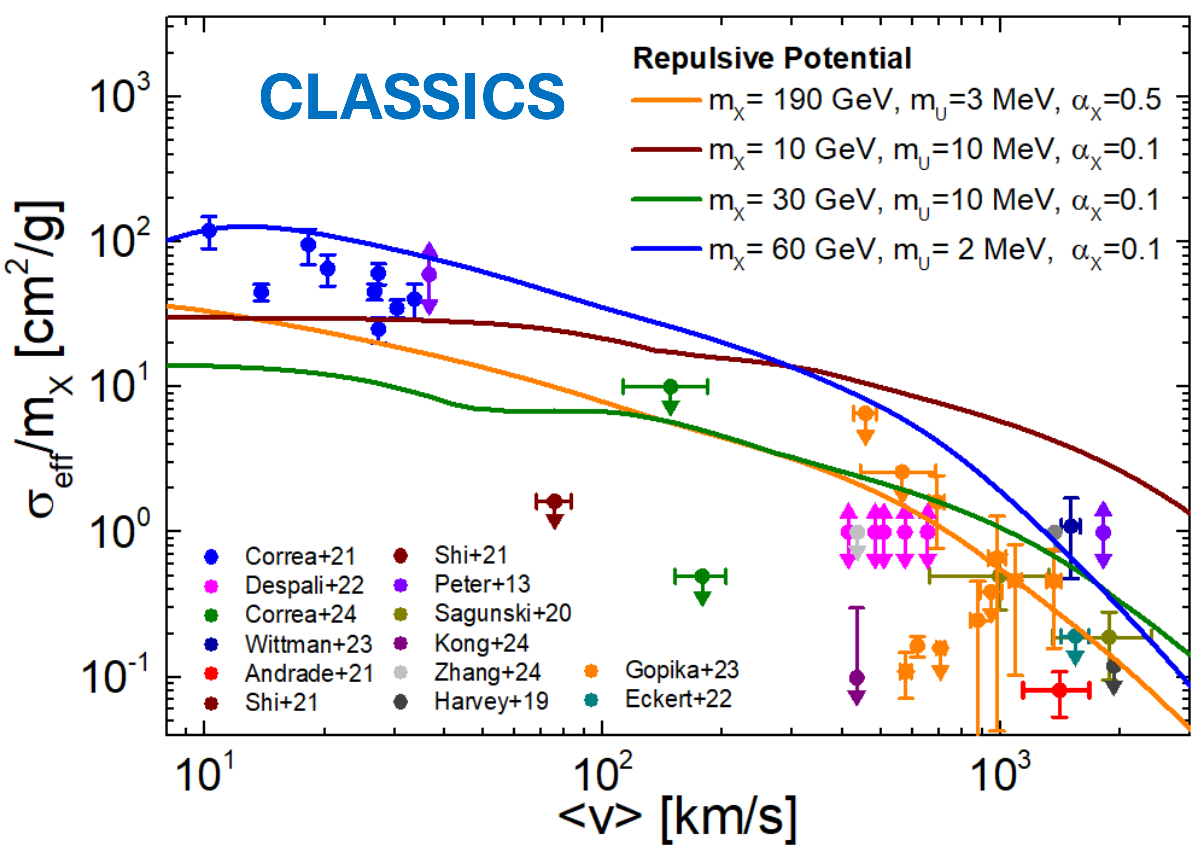
Computes **self-scattering cross sections** for dark matter (DM) particles interacting via a **Yukawa potential:**

CalcuLAtionS of Self Interaction Cross Sections

github.com/kahlhoefer/CLASSICS

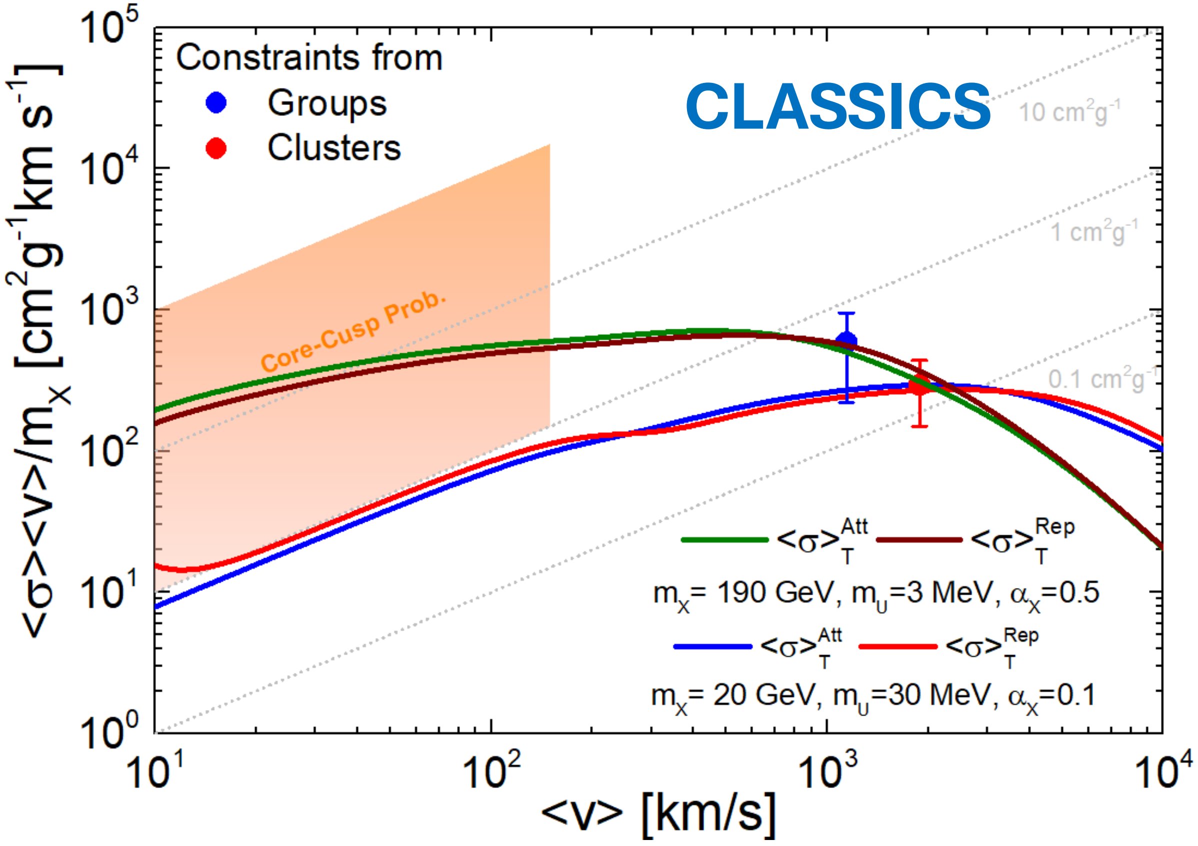
Arxiv: 2011.04679

Effective cross-section Constraints



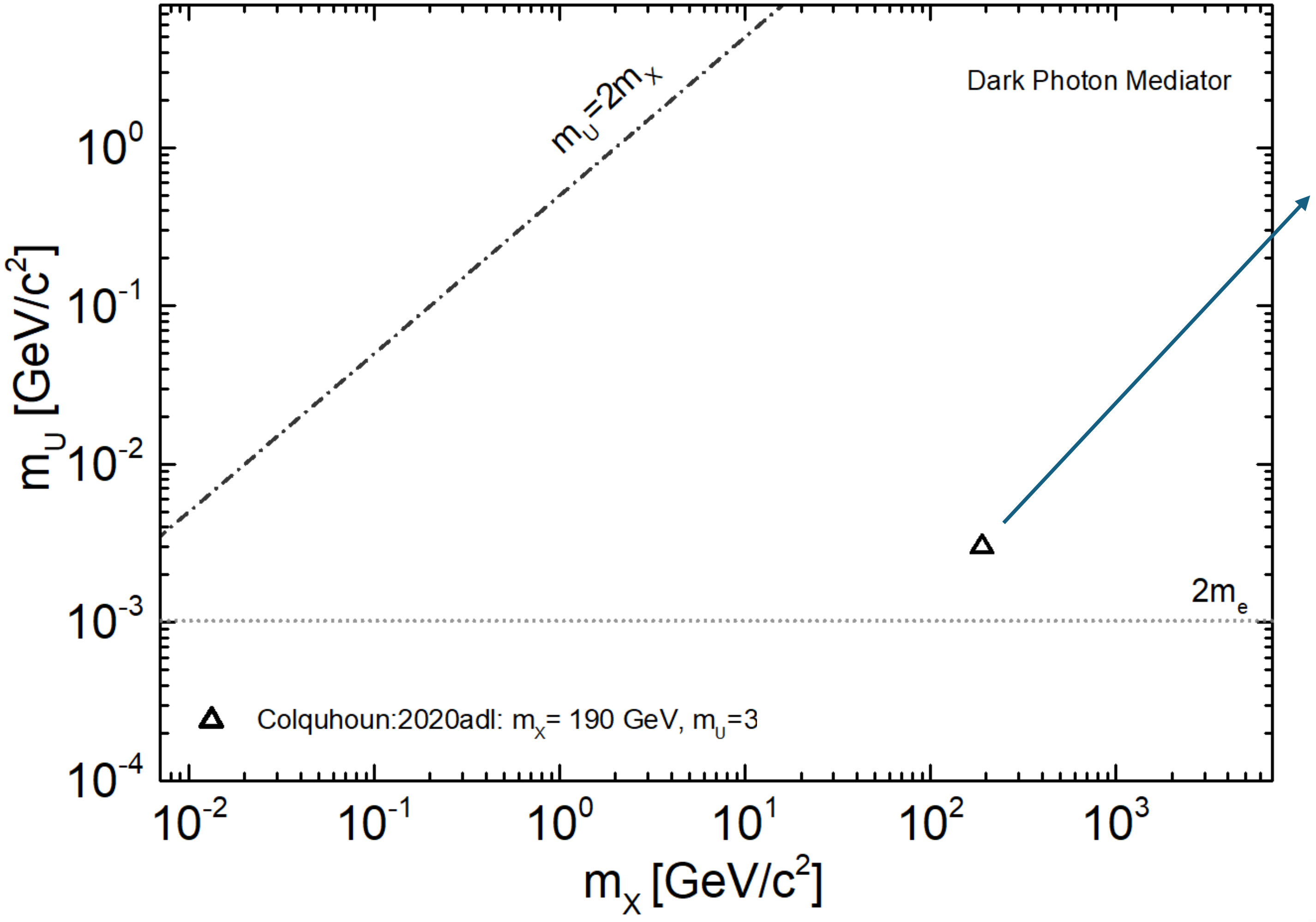
$$m_X \sim 30 - 200 \text{ GeV}$$

Groups and Clusters Constraints

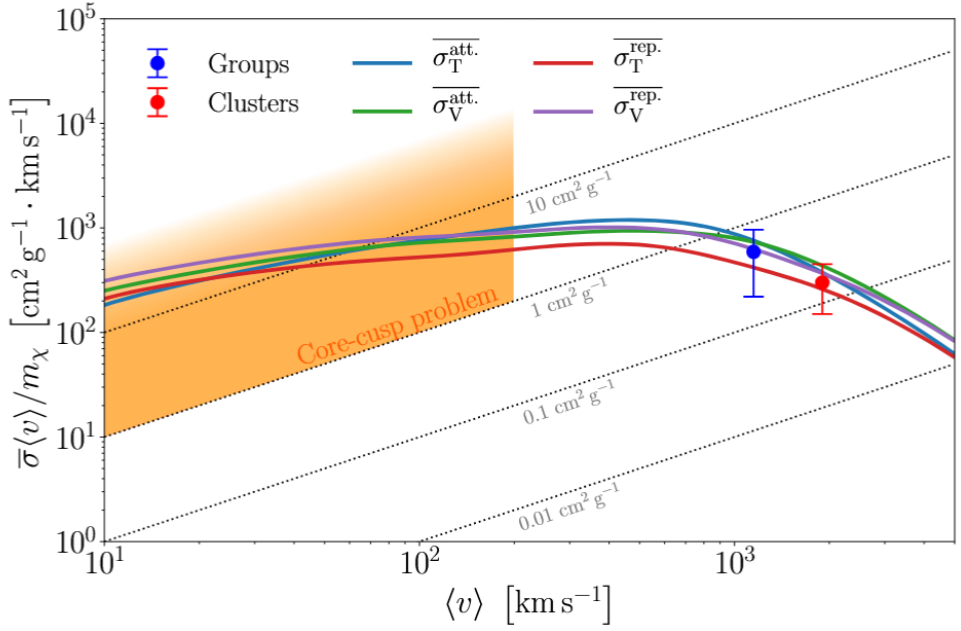


$$m_U \sim 1 - 10 \text{ MeV}$$

Dark Photon Mass vs Dark Matter Mass $m_U(m_X)$



CLASSICS



Benchmark point Phys. Rev. D 103, 035006 (2021)

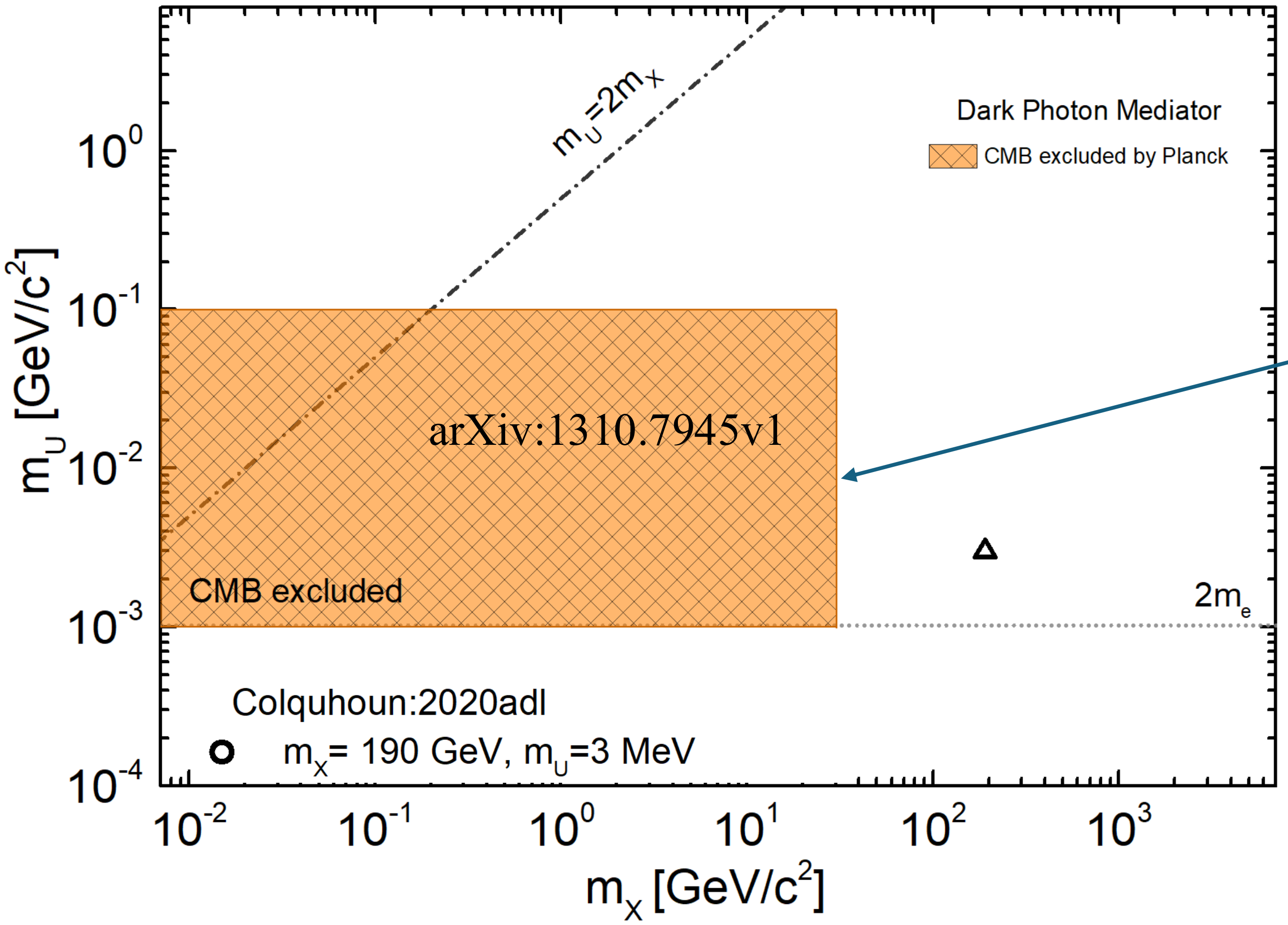
$$m_\chi = 190\ GeV, m_U = 0.003\ GeV$$

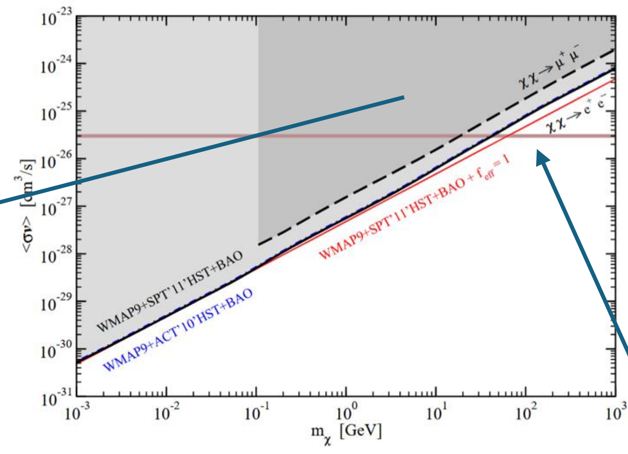
Dark Photon Mass vs Dark Matter Mass $m_U(m_X)$

arXiv:1303.5094 -> WMAP9, SPT'11 and ACT'10

arXiv:1512.08015 -> Plack Measurements

arXiv: 2105.08334 $p_{\rm ann} < 1.6 \times 10^{-27}\,{\rm cm^3 s^{-1}\,GeV^{-1}}$



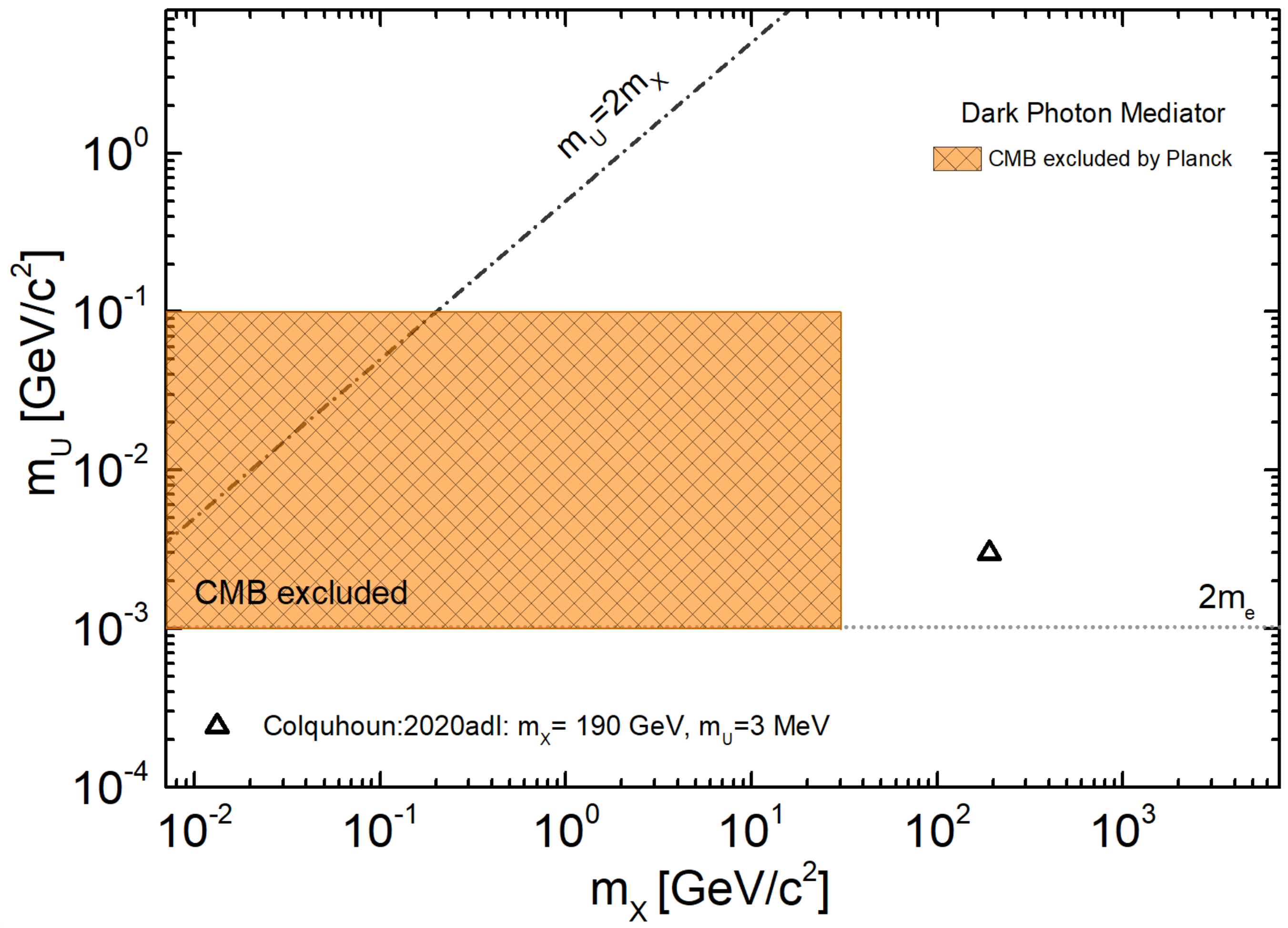


$$p_{\rm ann} \equiv f_{\rm eff}\frac{\langle\sigma v\rangle}{m_\chi},$$

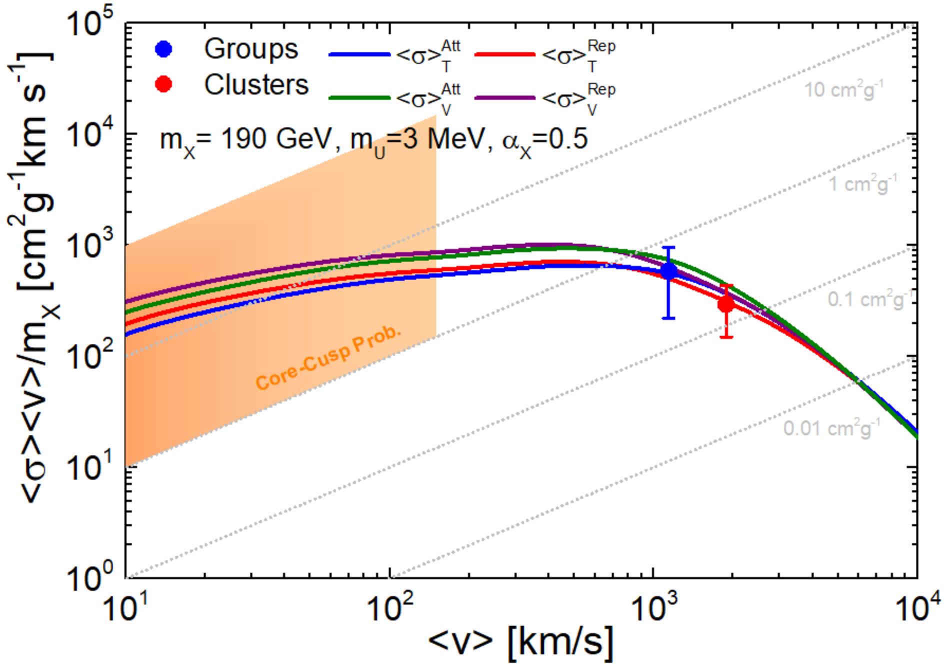
$$\langle\sigma v\rangle \approx 3\times 10^{-26}\ cm^3 s^{-1}$$ arXiv:1303.5094

$$\boldsymbol{\Omega_{DM}h^2 \sim 0.120 \pm 0.001}$$

Dark Photon Mass vs Dark Matter Mass $m_U(m_X)$



Galaxy Groups and Clusters Constraints



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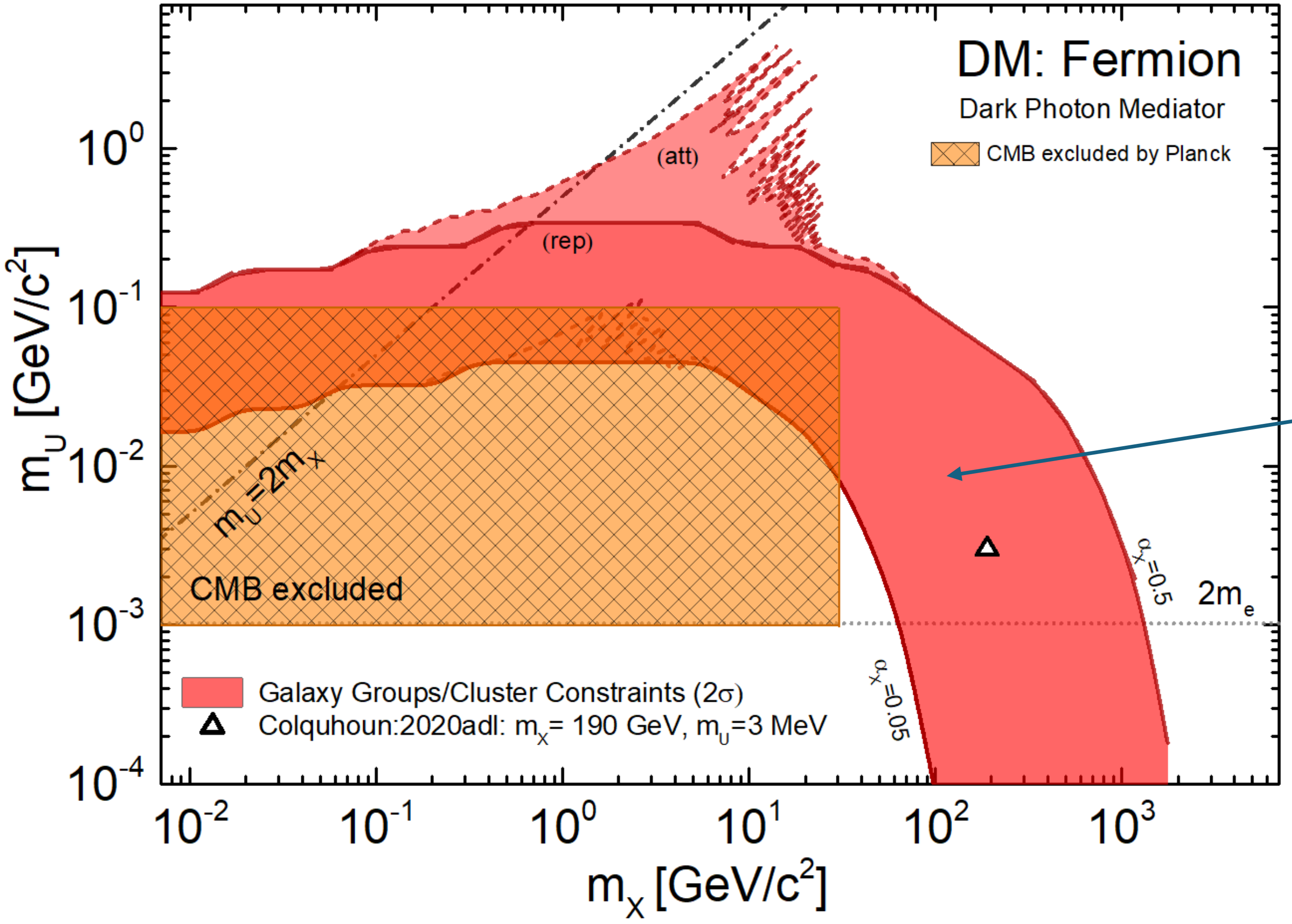

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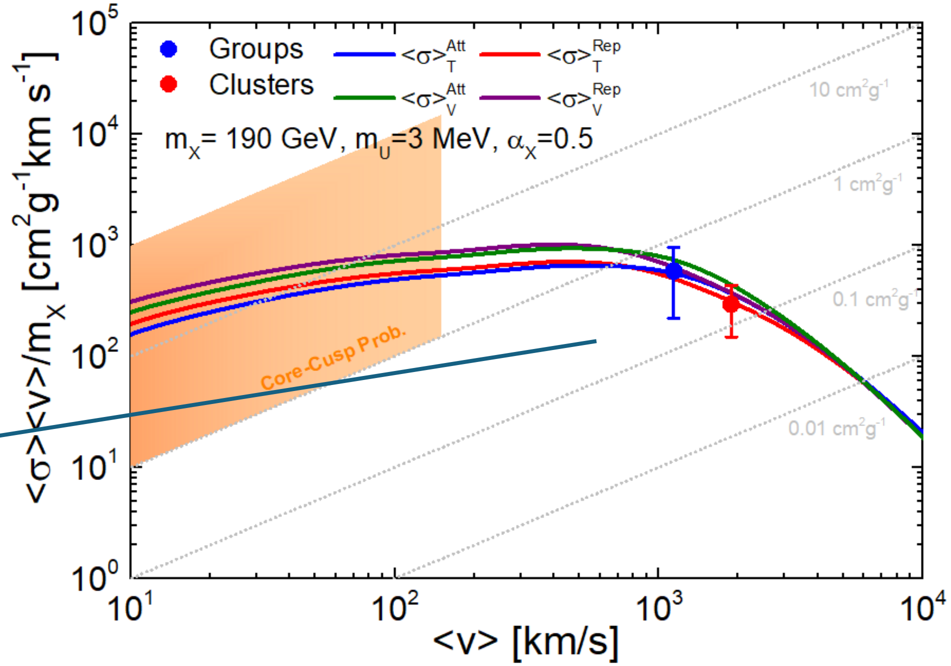

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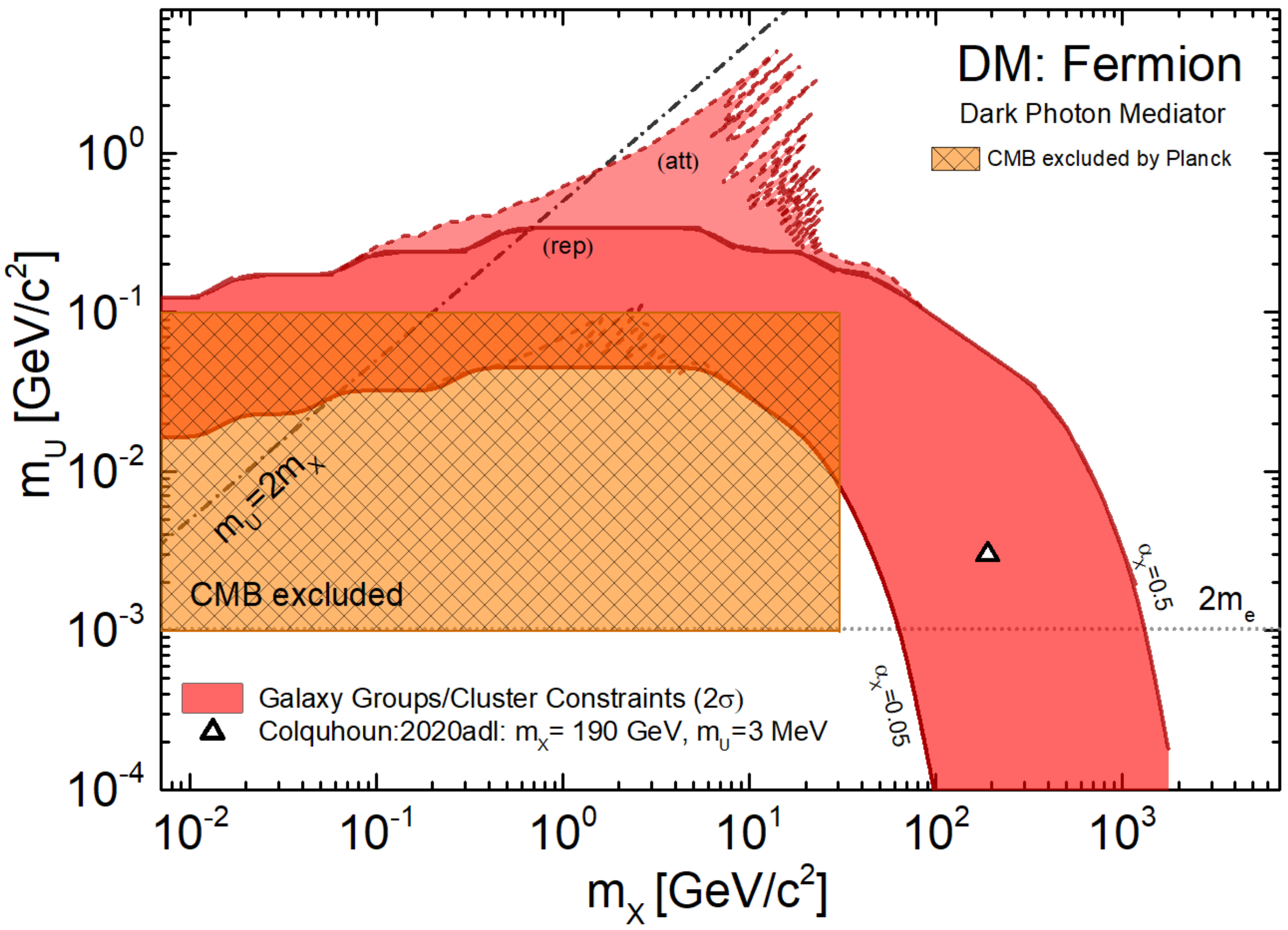
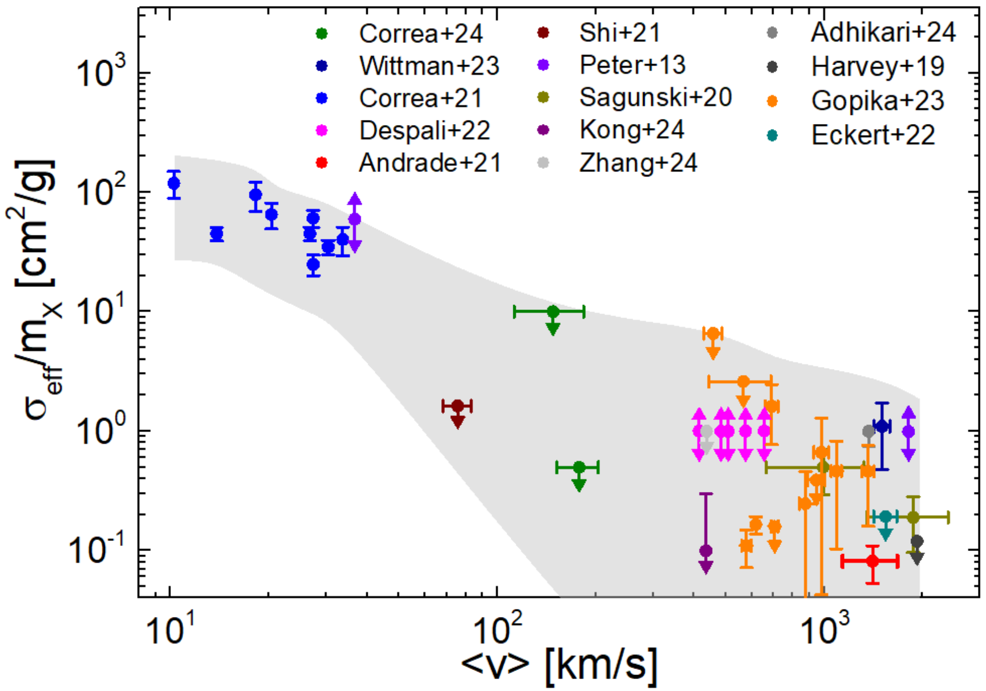


Effective cross-section Constraints



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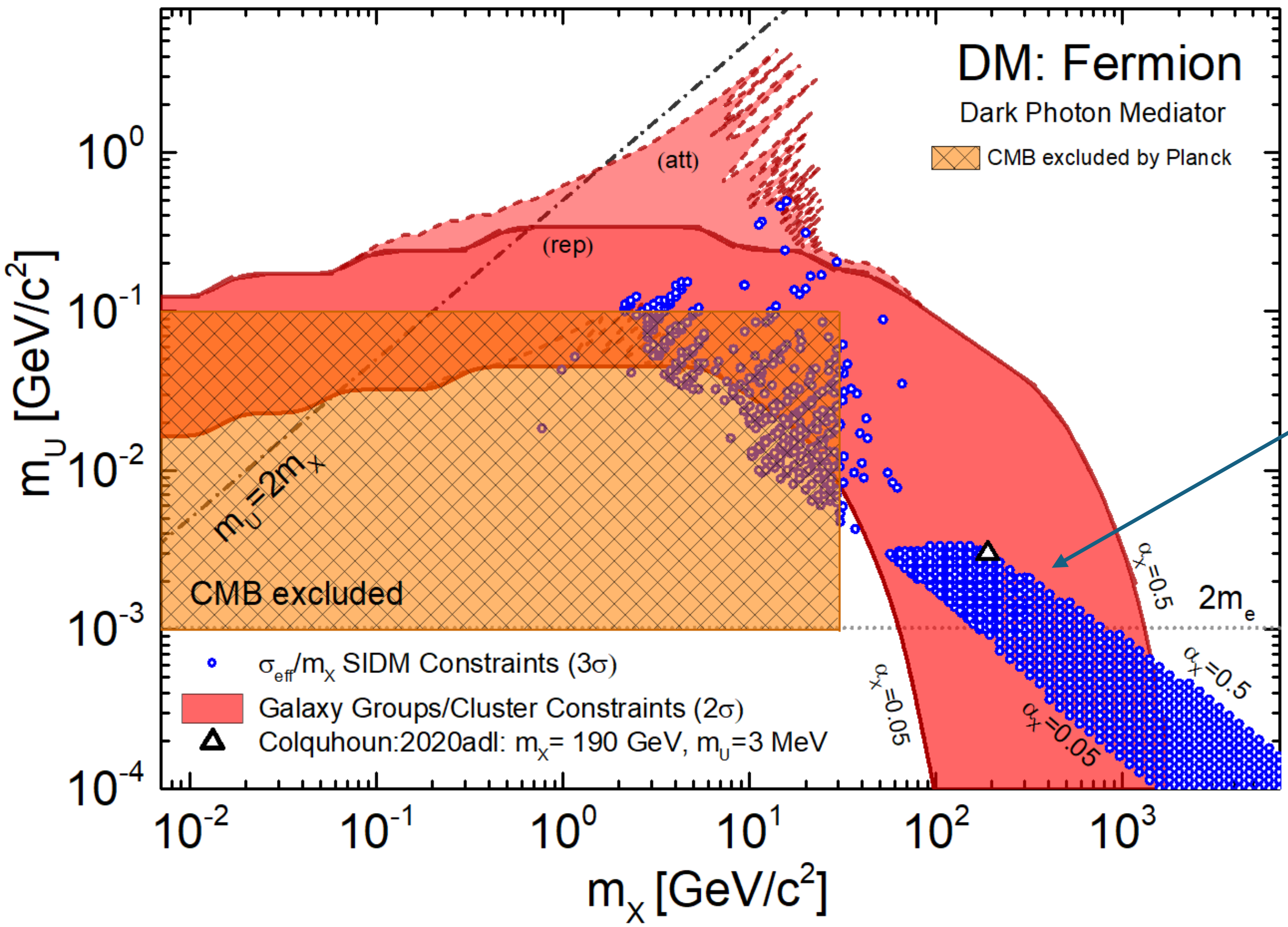
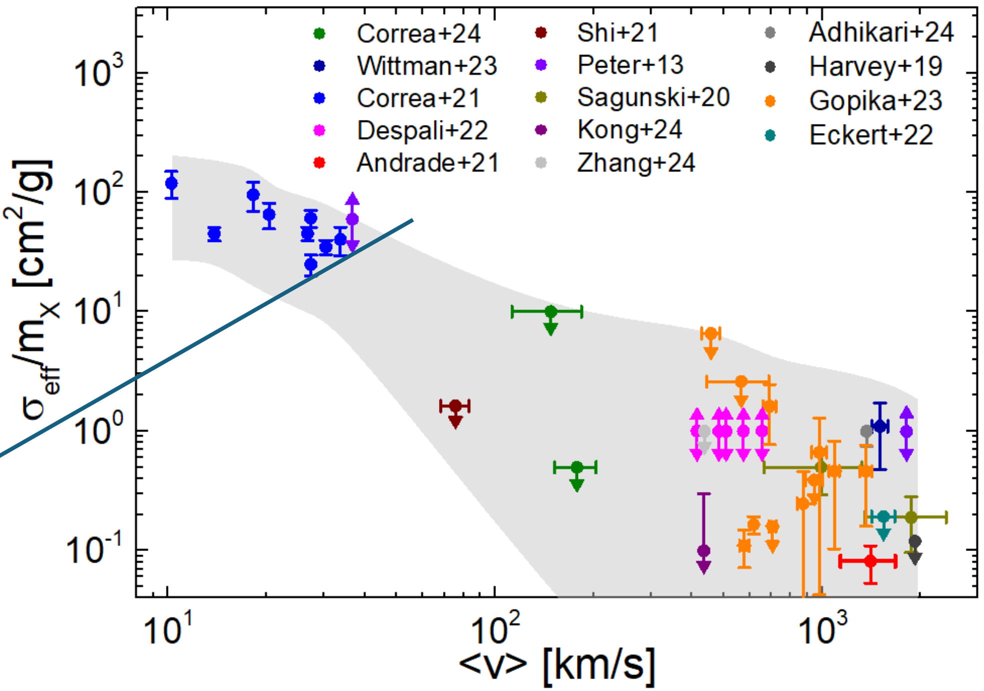
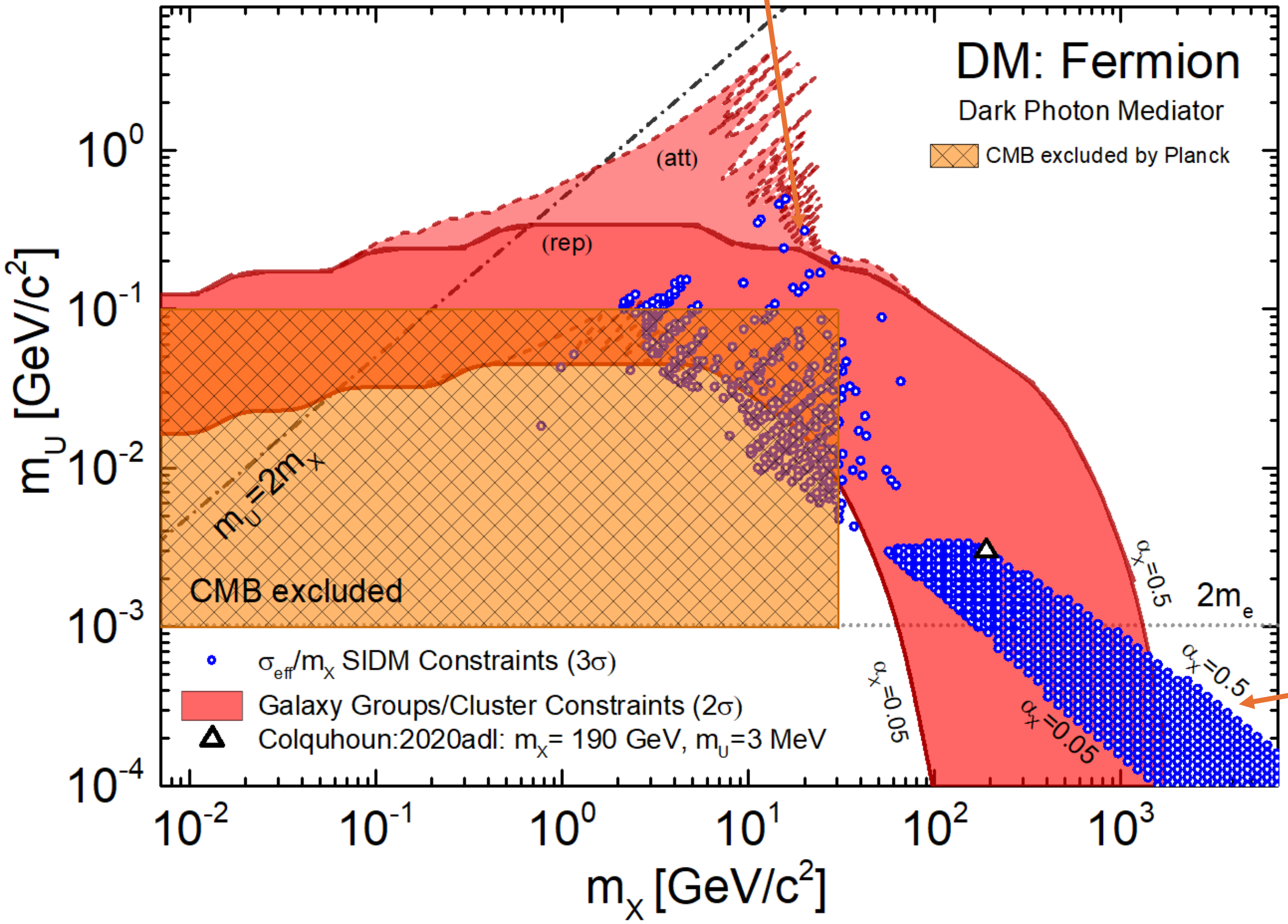


Effective cross-section Constraints

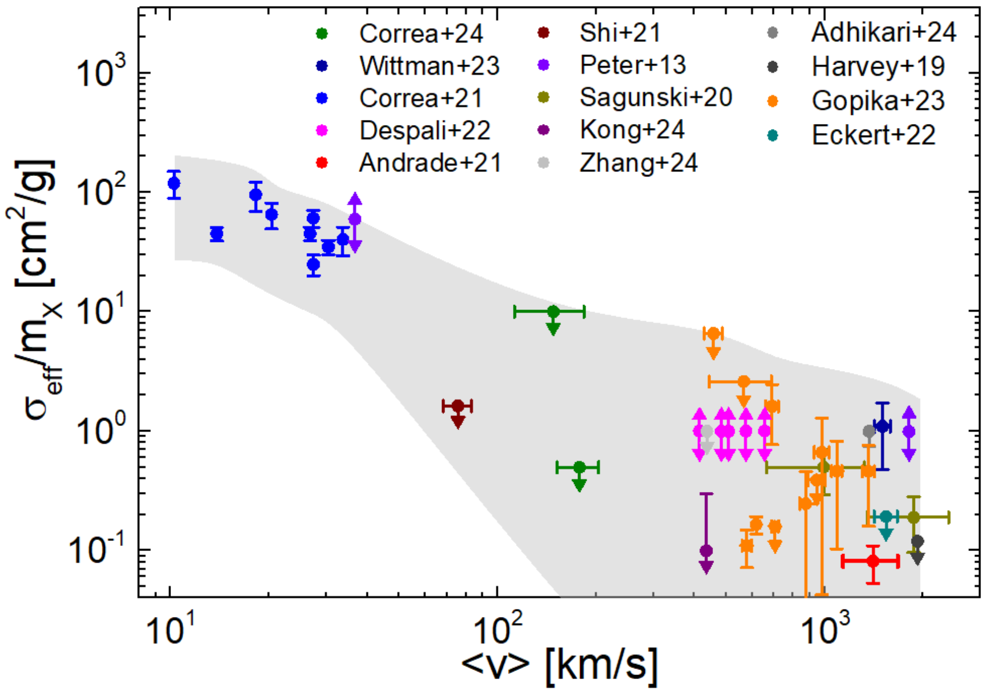


Dark Photon Mass vs Dark Matter Mass $m_U(m_X)$

Attractive Potential



Effective cross-section Constraints



Repulsive Potential

DM energy density?

Thermal Relic Abundance

$$\Omega_{DM} = \frac{\rho_{DM}}{\rho_{cr}} \sim 26.14\ \%$$

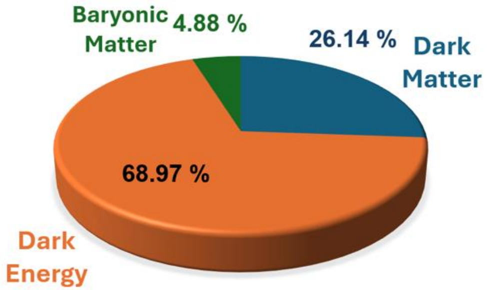
$h = 0.674$

Plack mission CMB: arxiv.1807.06209

$\boldsymbol{\Omega_{DM} h^2 \sim 0.120 \pm 0.001}$

$\Omega_{DM} h^2 > 0.12$ Overproduction

$\Omega_{DM} h^2 < 0.12$ Underproduction



Solve the Boltzmann Equation for the DM relic density at freeze-out

- $m_U \geq 2\, m_X$ Cross-Section is dependent of ε^2

$$\chi\bar{\chi} \to U^* \to f\bar{f} \qquad \mathrm{s-channel}$$

- $m_U < 2\, m_X$ "secluded" case: independent of ε^2

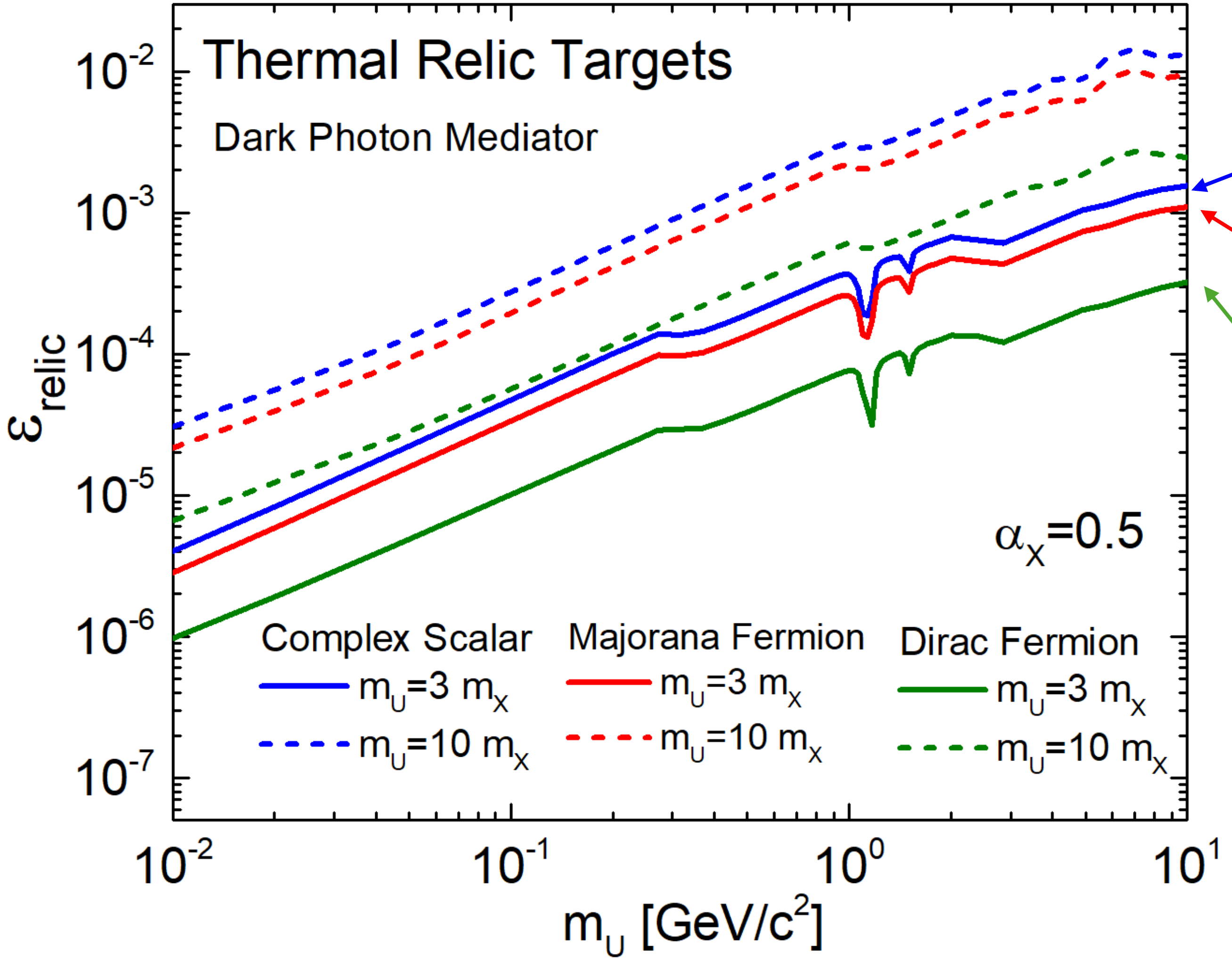
Mediator: Dark Photon

Dark Matter:
- Complex Scalar
- Dirac Fermion
- Majorana Fermion

$\boldsymbol{\varepsilon^2_{relic}(m_U)}$ For fixed values of $\boldsymbol{\alpha_\chi, m_\chi}$

Red DeliVeR Arxiv: 2410.00881

Thermal Relic Abundance



$$\Omega_{DM} h^2 \sim 0.120$$

Complex Scalar

$$\Gamma(U \to \varphi\varphi^\dagger) = \frac{1}{12}\alpha_\chi m_U \left(1 - \frac{4m_\chi^2}{m_U^2}\right)^{3/2}$$

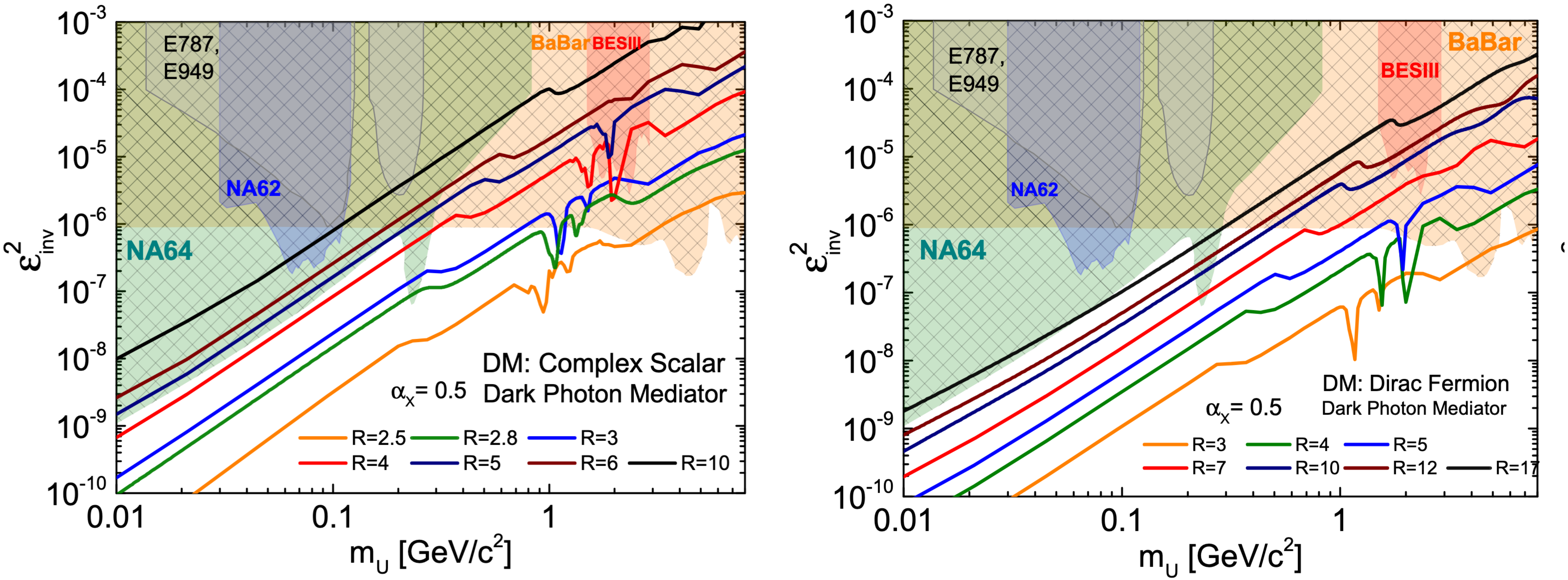
Majorana

$$\Gamma(U \to \chi\chi) = \frac{1}{6}\alpha_\chi m_U \left(1 - \frac{4m_\chi^2}{m_U^2}\right)^{3/2}$$

Dirac Fermion

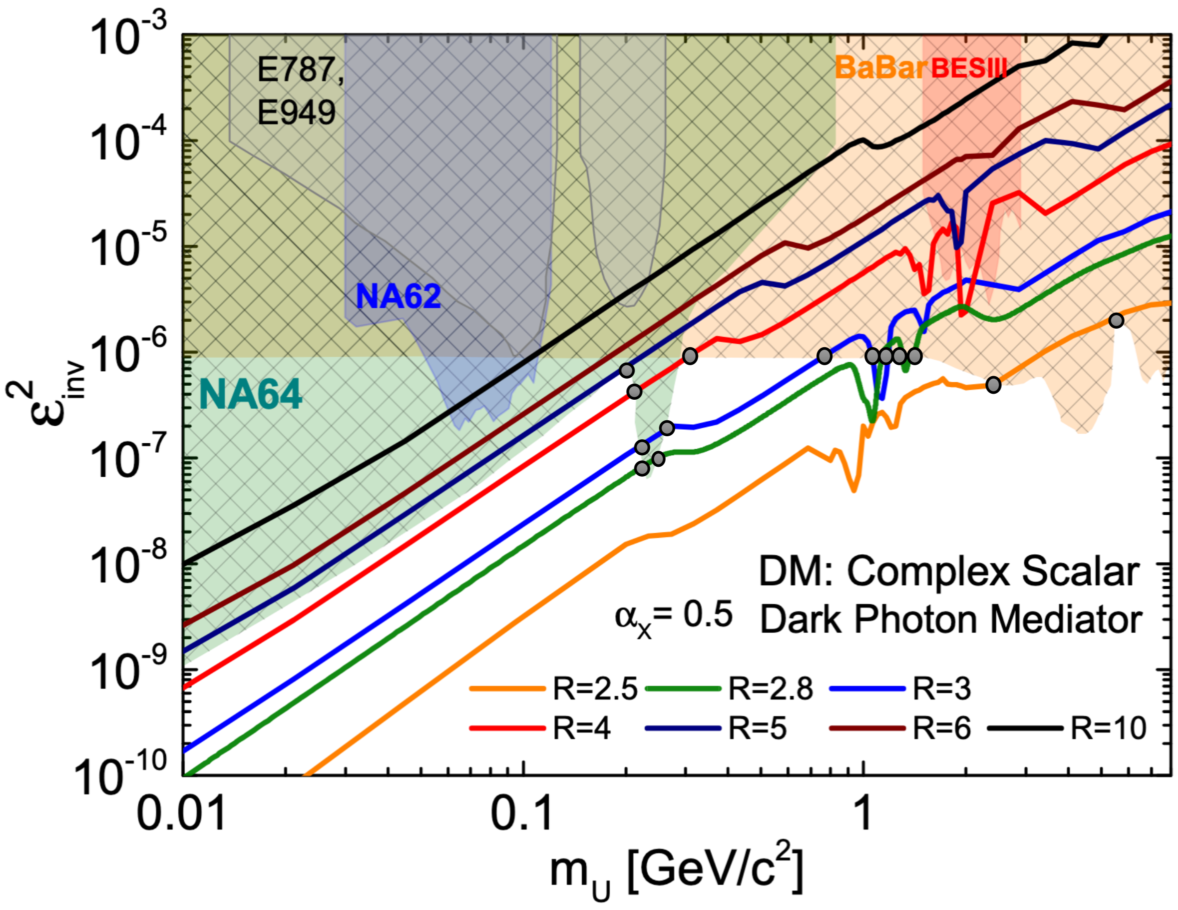
$$\Gamma(U \to \bar{\chi}\chi) = \frac{1}{3}\alpha_\chi m_U \left(1 + \frac{2m_\chi^2}{m_U^2}\right)\sqrt{1 - \frac{4m_\chi^2}{m_U^2}}$$

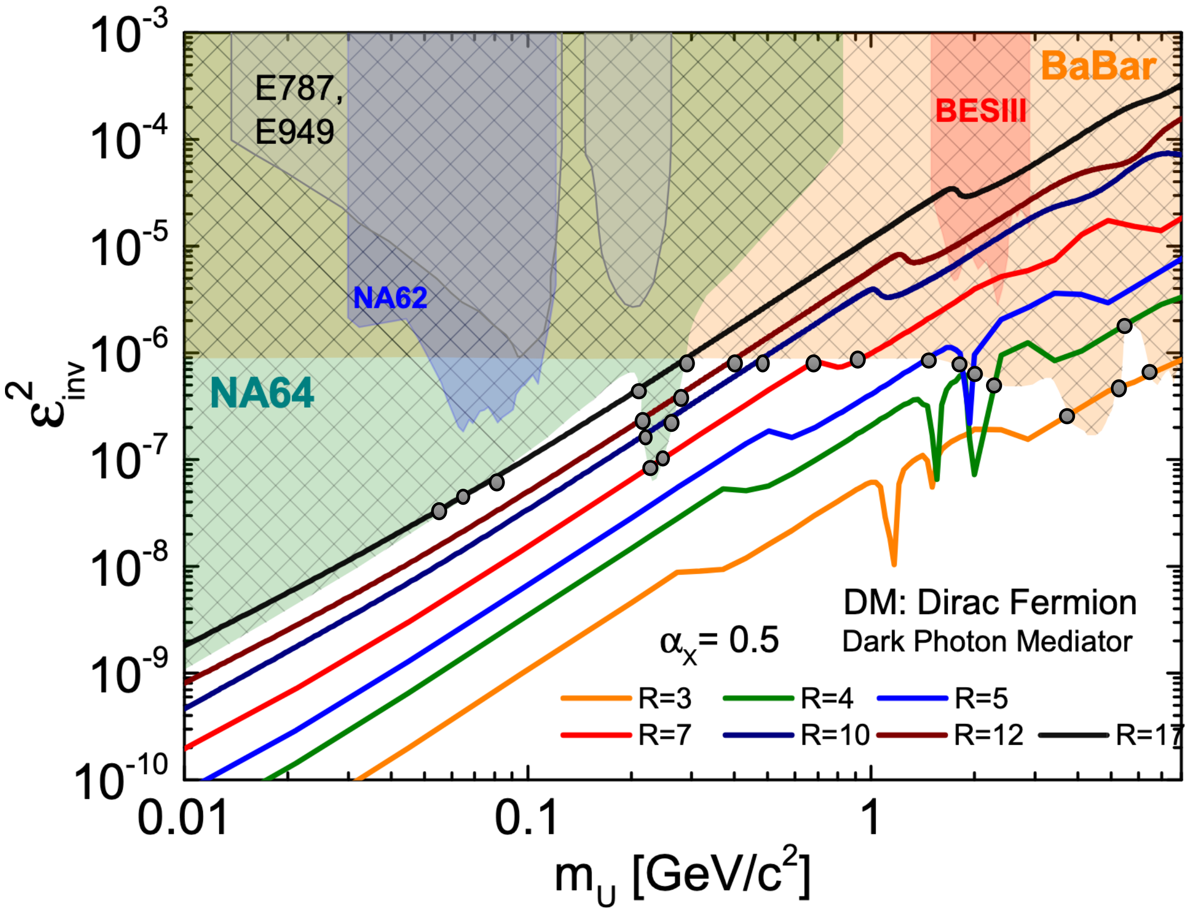
Kinetic Mixing parameter $\varepsilon(m_U)$ and DM thermal Relic Abundance



$$m_U = R\, m_\chi$$

Kinetic Mixing parameter $\varepsilon(m_U)$ and DM thermal Relic Abundance





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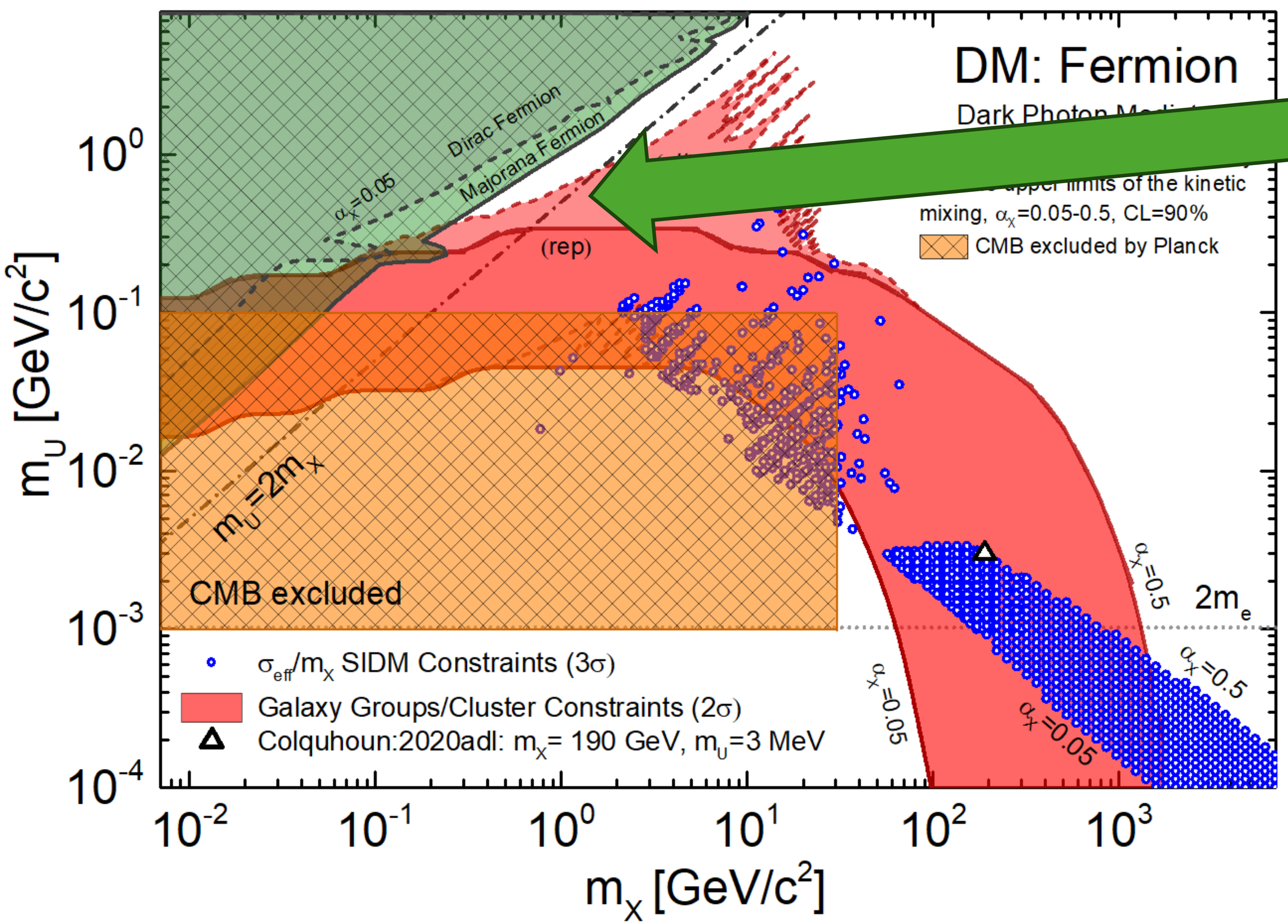

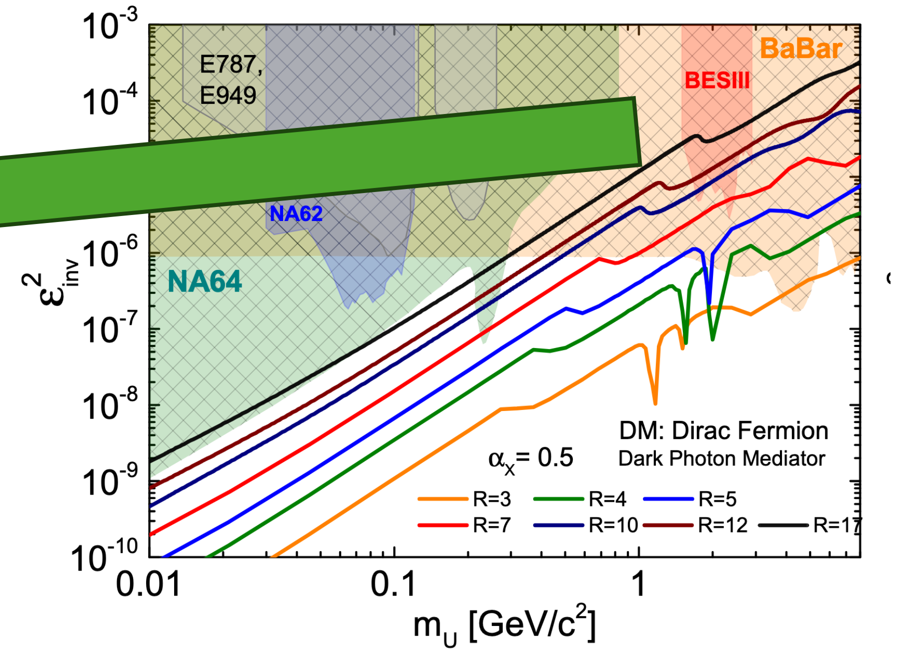

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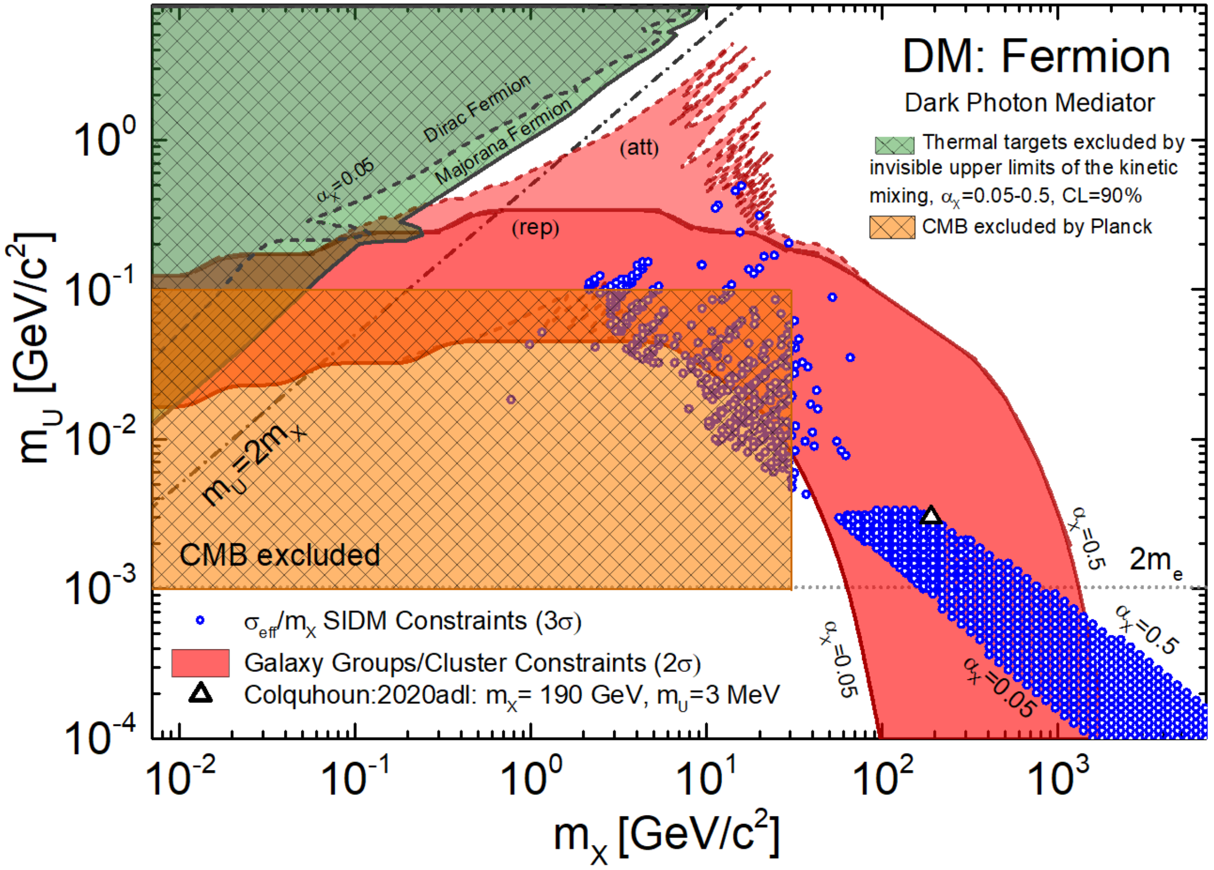

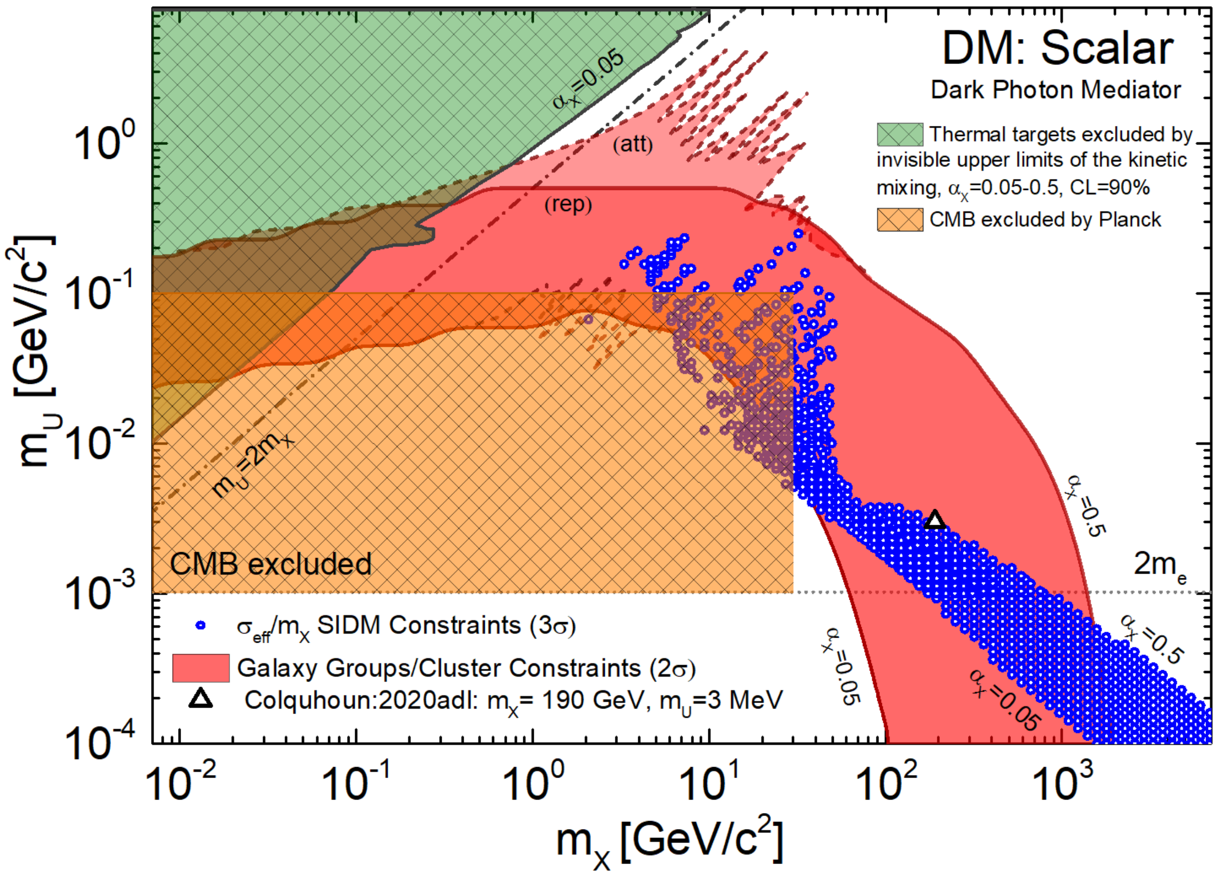

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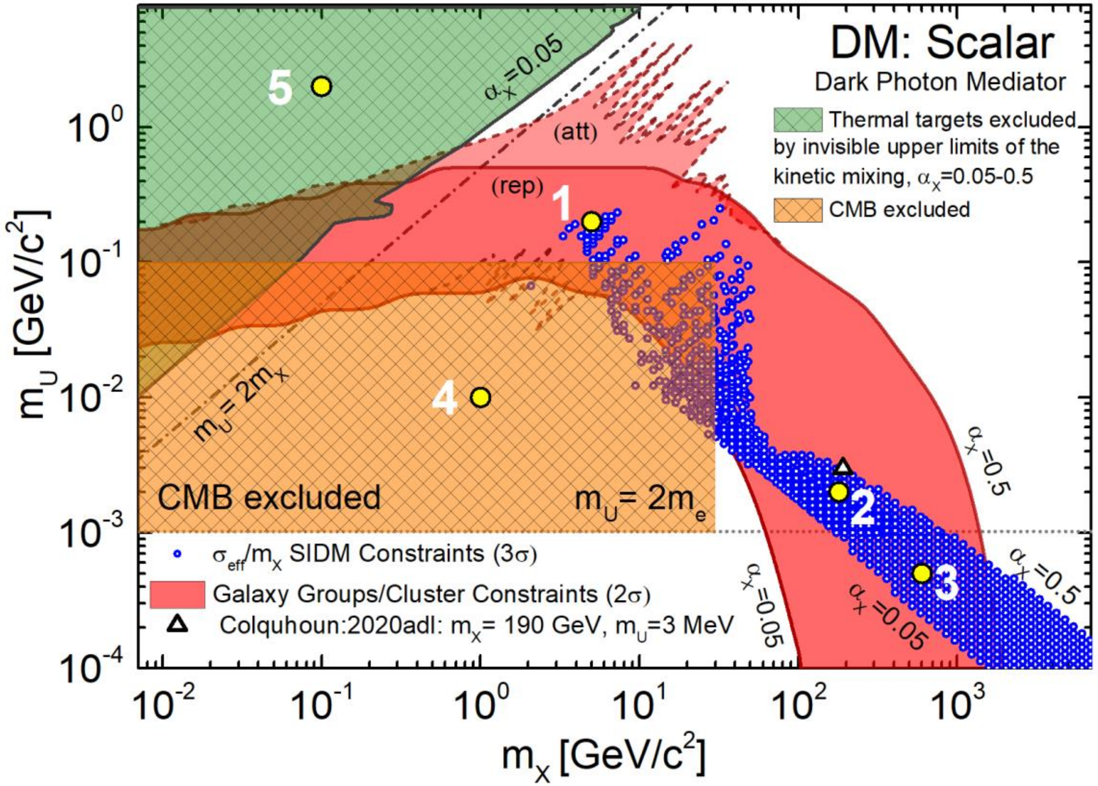

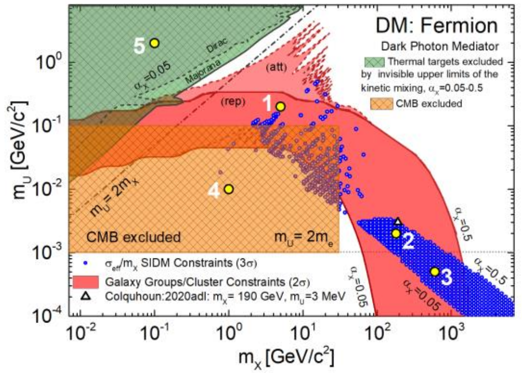

● Possible Benchmark Points

Possible Benchmark Points

1. $m_U \sim 0.1 - 0.2$ GeV, $m_X \sim 5 - 10$ GeV — Good for HIC Searches. Dark photon produced by $\pi^0, \eta, \omega, \Delta$ decays
2. $m_U = 2\ MeV$, $m_X \sim 190$ GeV — Light dark photon and heavy DM. It satisfies σ_{eff} constraints
3. $m_U < 2m_e$, $m_X \sim 200 - 800$ GeV — Stable and long-lived dark photon

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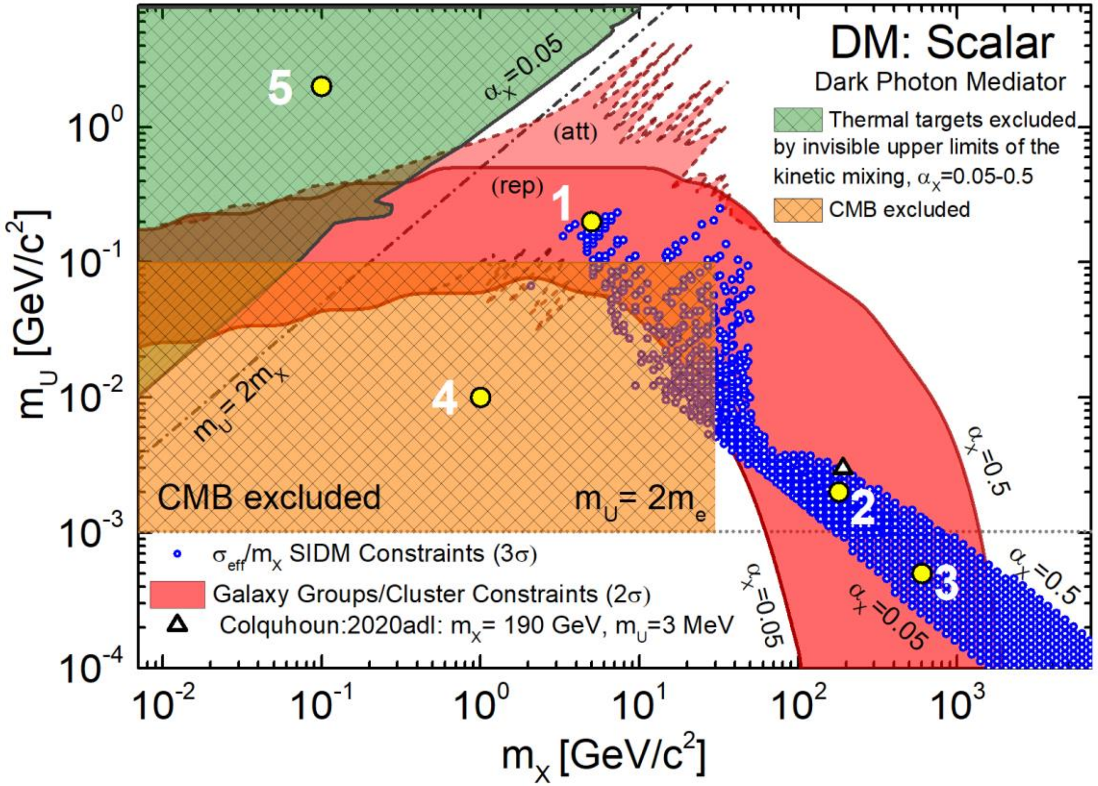

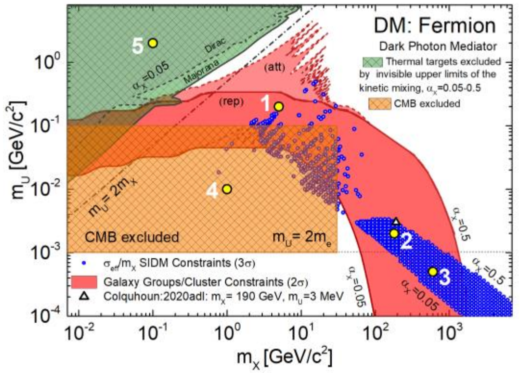

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4. $m_X \sim 10^{-2} - 30$ GeV, $m_U \sim 10^{-3} - 10^{-1}$ GeV — Exclude by CMB
5. $m_X \sim 10^{-2} - 1$ GeV, $m_U > 4\, m_\chi$ — Thermal targets excluded by invisible upper limits

Summary

Heavy-ion dilepton spectra provide a complementary probe of vector portal dark sectors

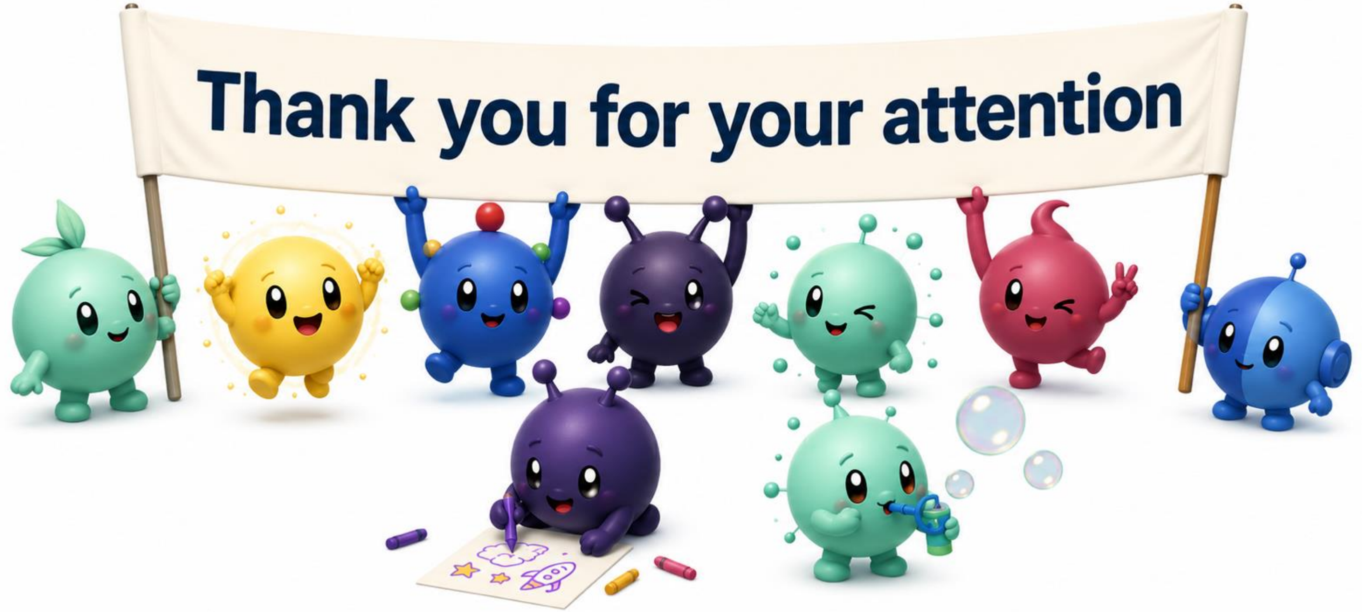
- Experimental accuracy has to be less or equal to 0.1% to "observe" dark photons in the visible regime in dilepton experiments.

Dark matter **thermal relic abundance** condition must be satisfied to ensure compatibility with cosmological observations.

- Different DM candidates require different kinetic mixing values to reproduce the same energy distribution.

Combined constraints from SIDM, HIC and Thermal relic abundance in the $m_U(m_X)$ phase space, allow us to **identify the most promising benchmark points for future searches.**

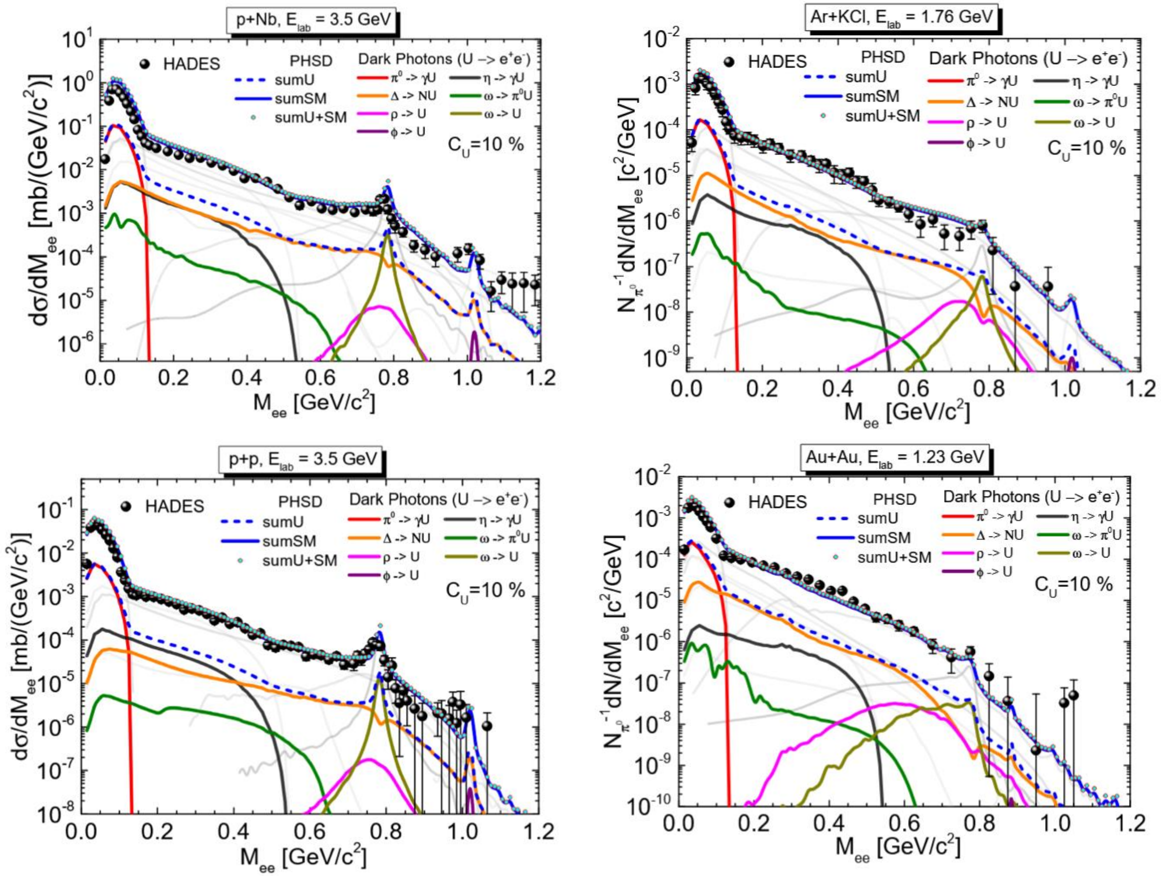
- Heavy (GeV) DM and sub-GeV dark photon mediator might be a promising benchmark area


Thank you for your attention

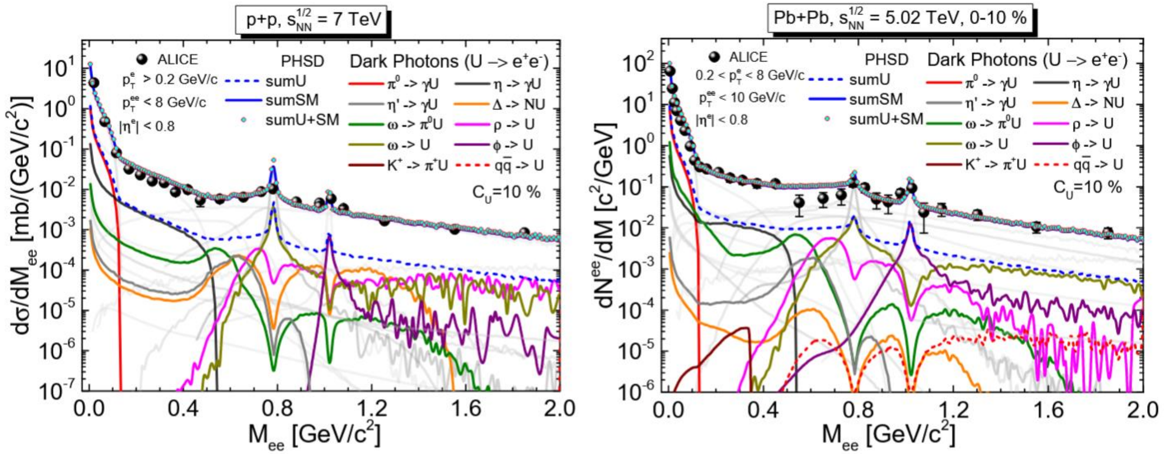
Backup Slides

Dilepton spectra from dark photon decays

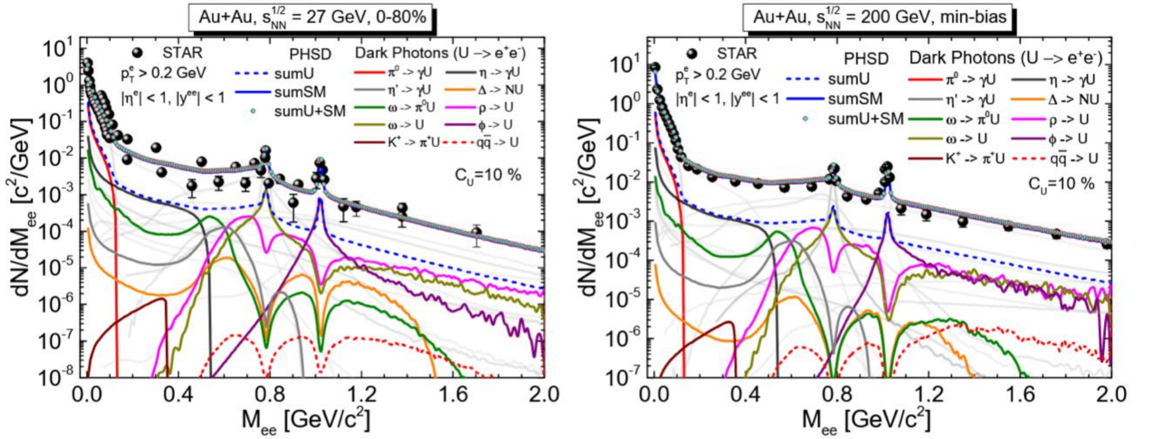
SIS-HADES



BES-RHIC-STAR



LHC-ALICE



- **The contributions from $U \rightarrow e^+e^-$ are added with C_U=10% allowed surplus of the total SM yield ➔ the total sum is still in a good agreement with exp. data**

A. W. Romero Jorge et. al, PRD 113 (055052) 2026

Dark Photon Model with Dark Matter

* for the 'dark photon' or ' *U*- boson': A', V, U, ϕ

Arxiv.1411.1404

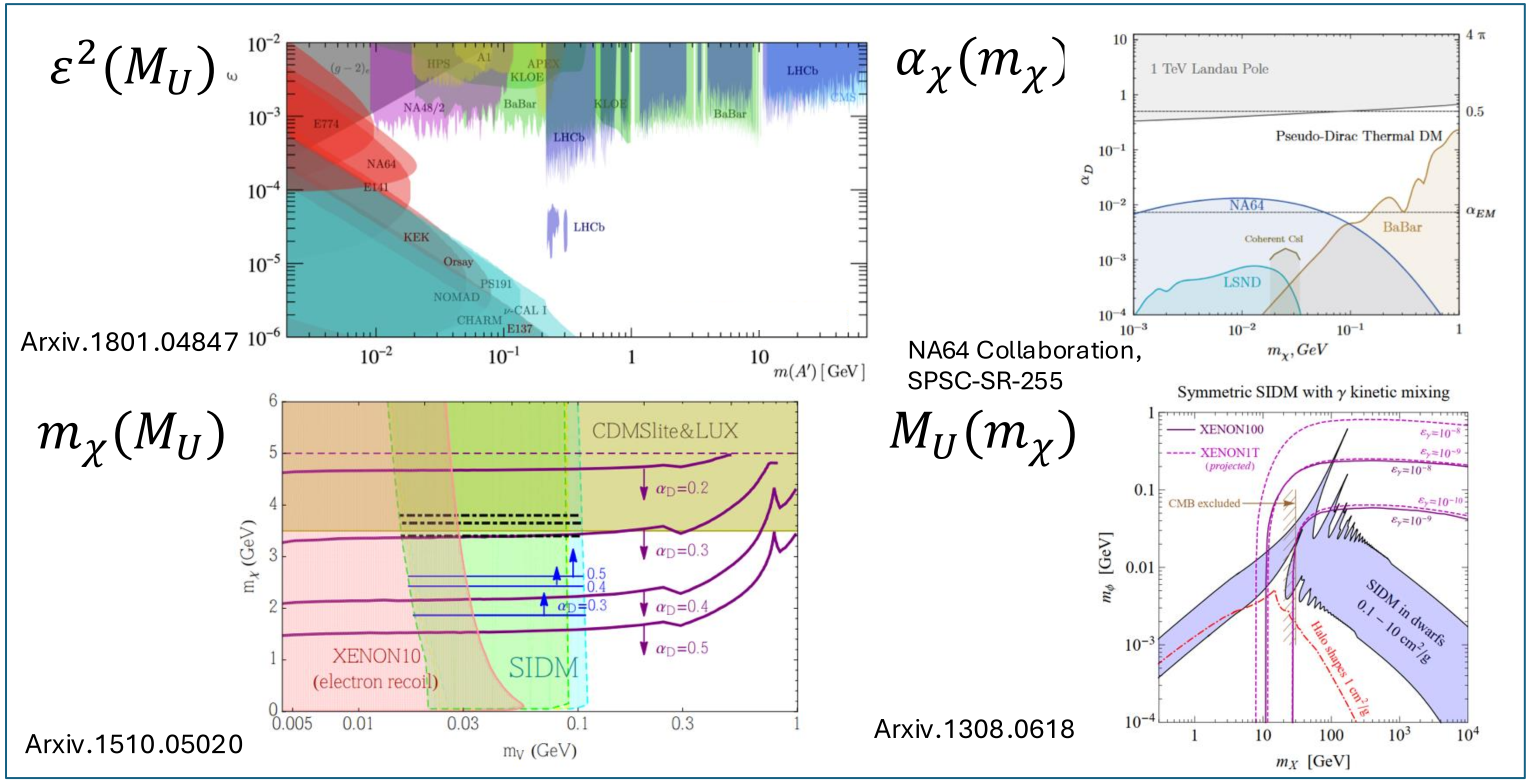
Arxiv:2005.01515

$$\mathcal{L} = \mathcal{L}_{SM} - \frac{1}{4} F'^{\mu\nu} F'_{\mu\nu} - \frac{1}{2} \boldsymbol{m_U^2} A'^{\mu} A'_{\mu} + \frac{\boldsymbol{\varepsilon}}{2} B^{\mu\nu} F'_{\mu\nu} + \boldsymbol{g_\chi} \overline{\mathrm{X}} \gamma^{\mu} \mathrm{X} A'_{\mu} + f(\boldsymbol{m_\chi})$$

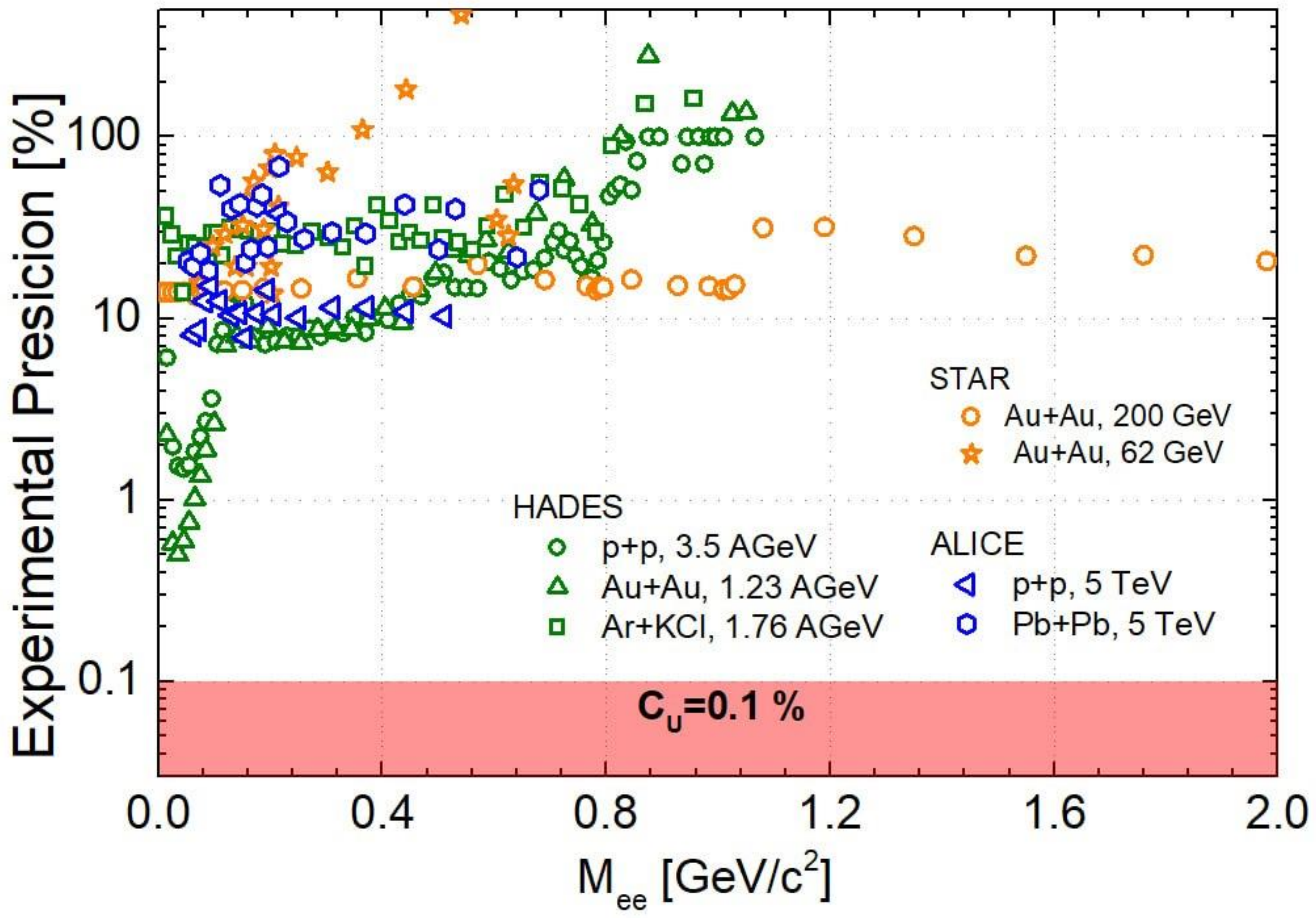
- $\boldsymbol{\varepsilon}$ ➡ **Kinetic mixing parameter**
- $\boldsymbol{m_U}$ ➡ **Dark photon mass**
- $\boldsymbol{g_\chi}$ ➡ **Dark coupling constant**
- $\boldsymbol{m_\chi}$ ➡ **Dark matter mass**

4-free parameters

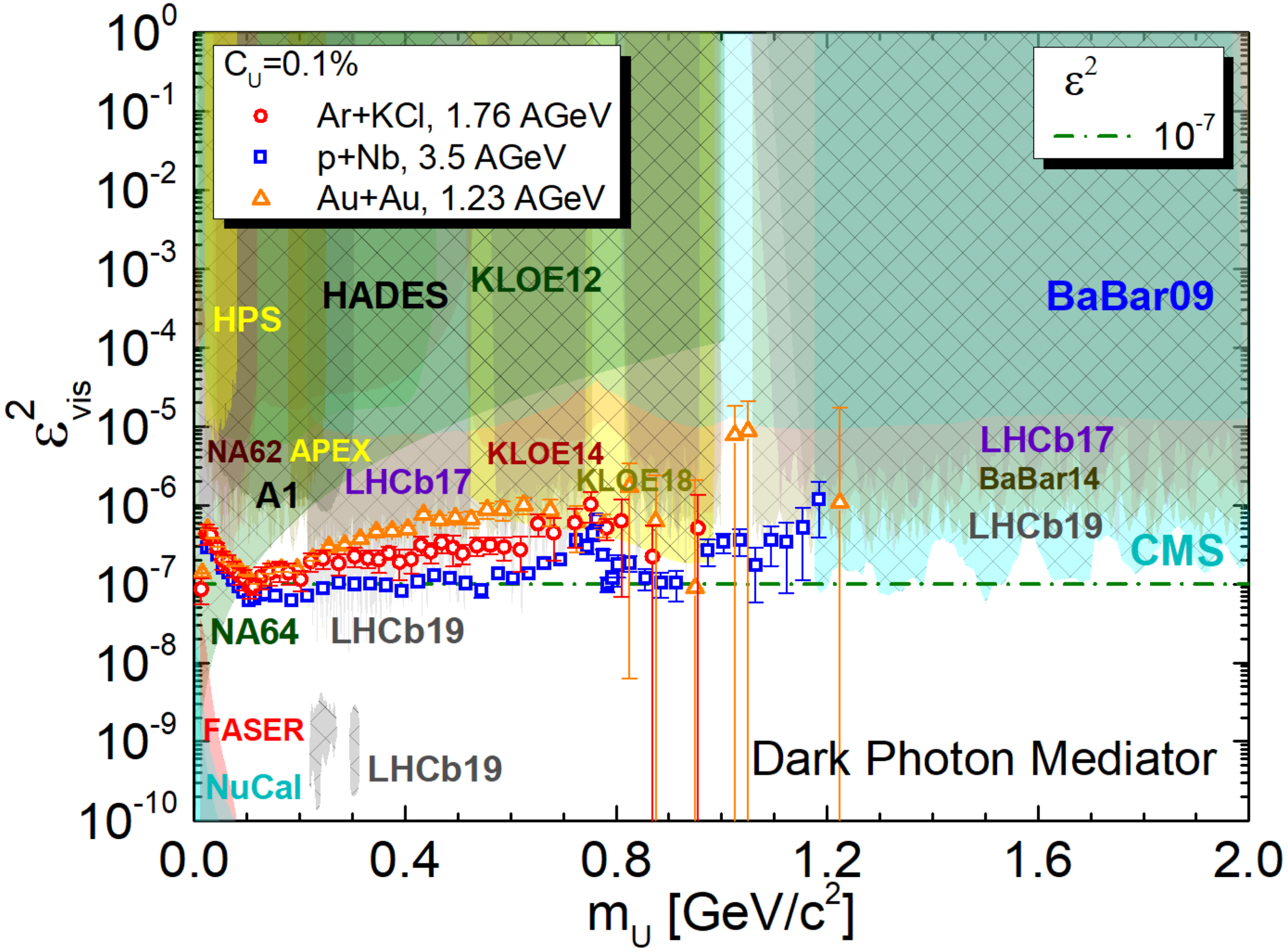
$(\boldsymbol{\varepsilon}, \boldsymbol{m_U})$ $(\boldsymbol{\alpha_X}, \boldsymbol{m_X})$



Local Experimental Presicion from Experiments



Kinetic Mixing parameter $e^2(m_U)$ from Experimental Data



- From **PHSD** (dark photons)

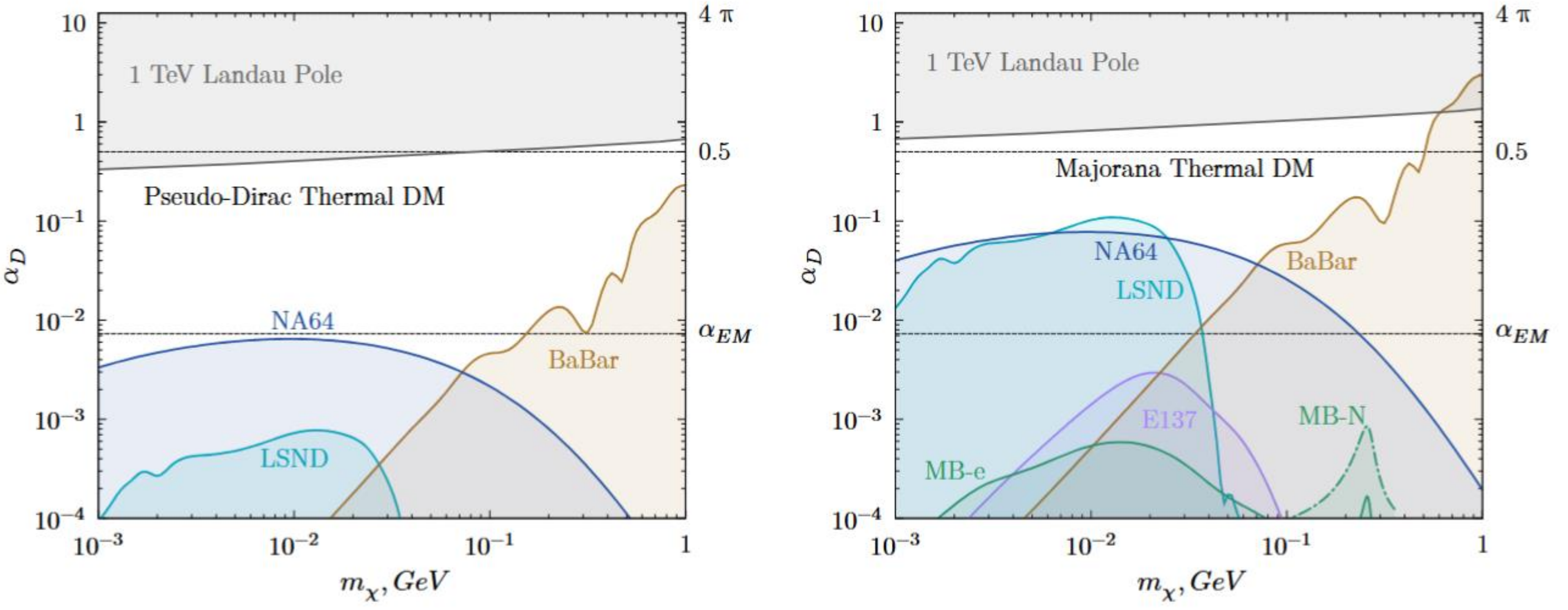
$$\frac{dN^{sumU}}{dM} = \varepsilon^2 \frac{dN^{sumU}_{\varepsilon^2=1}}{dM}$$

- From **Experimental Data** rather than PHSD

$$\frac{dN^{sumU}}{dM} = C_U \frac{dN^{sumSM}}{dM}$$

$$\varepsilon^2(M_U) = C_U \cdot \left(\frac{dN^{sumSM}}{dM}\right) \Big/ \left(\frac{dN^{sumU}_{\varepsilon^2=1}}{dM}\right)$$

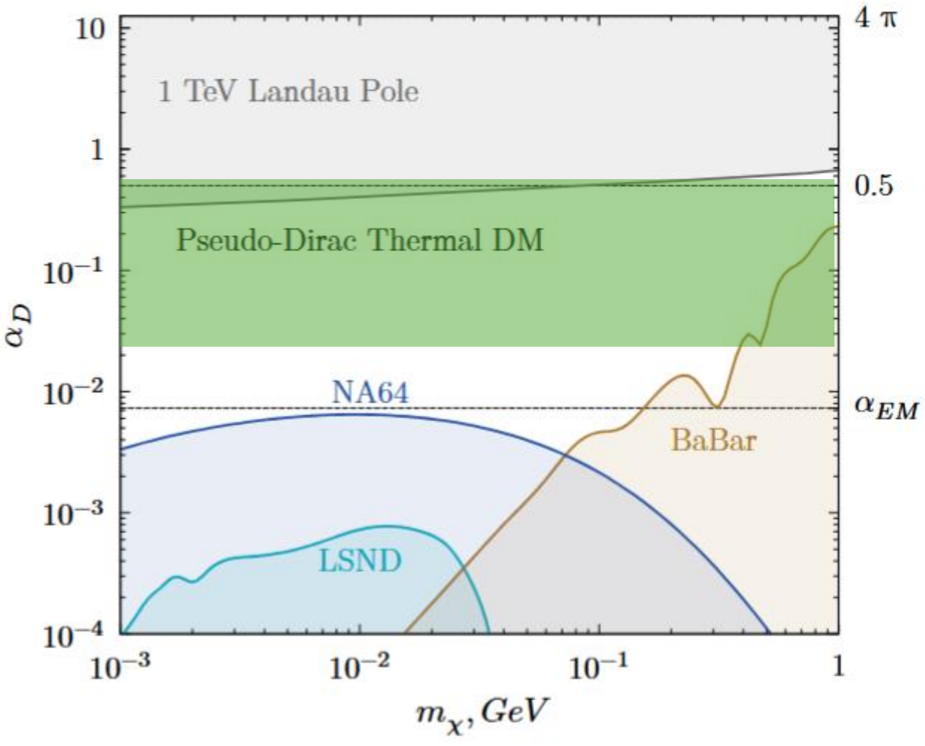
Dark alpha α_χ Limits

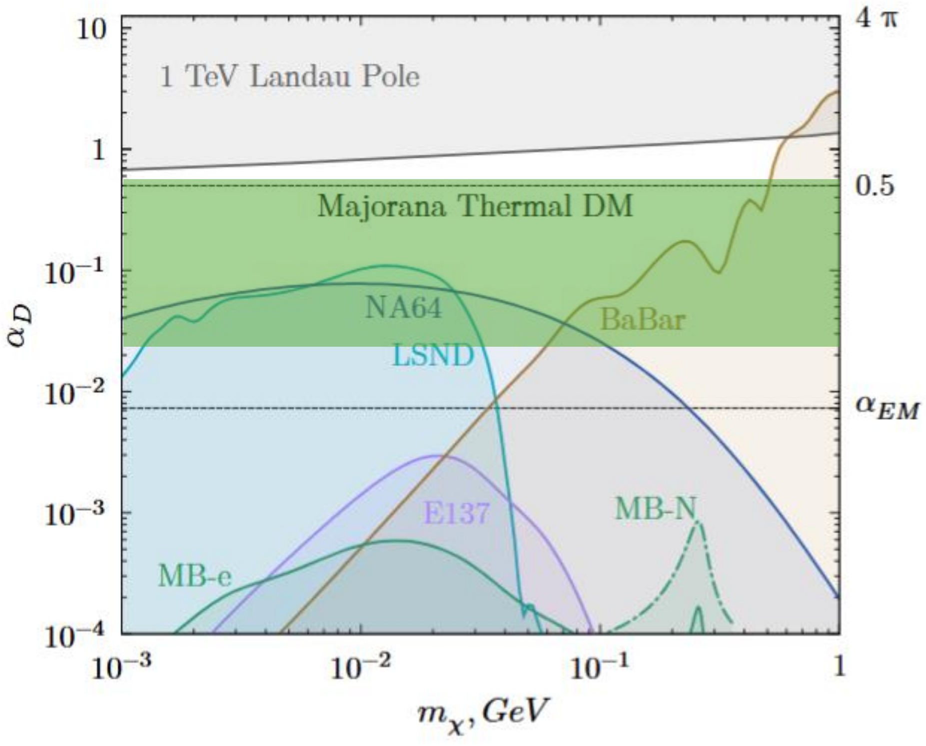


$$0.05 \leq \alpha_\chi \leq 0.5$$

https://cds.cern.ch/record/2677228/files/SPSC-SR-255.pdf

Dark alpha α_χ Limits

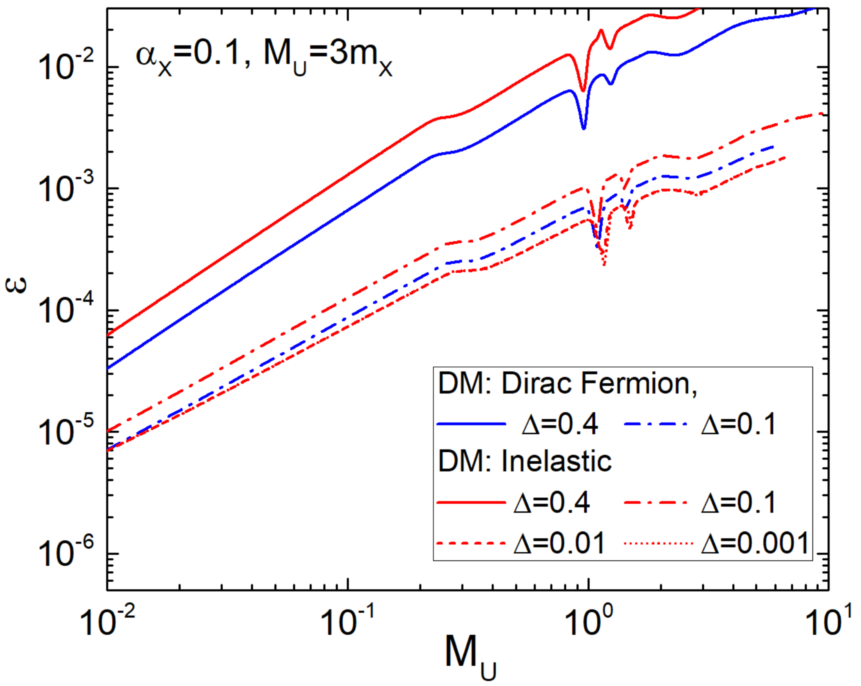


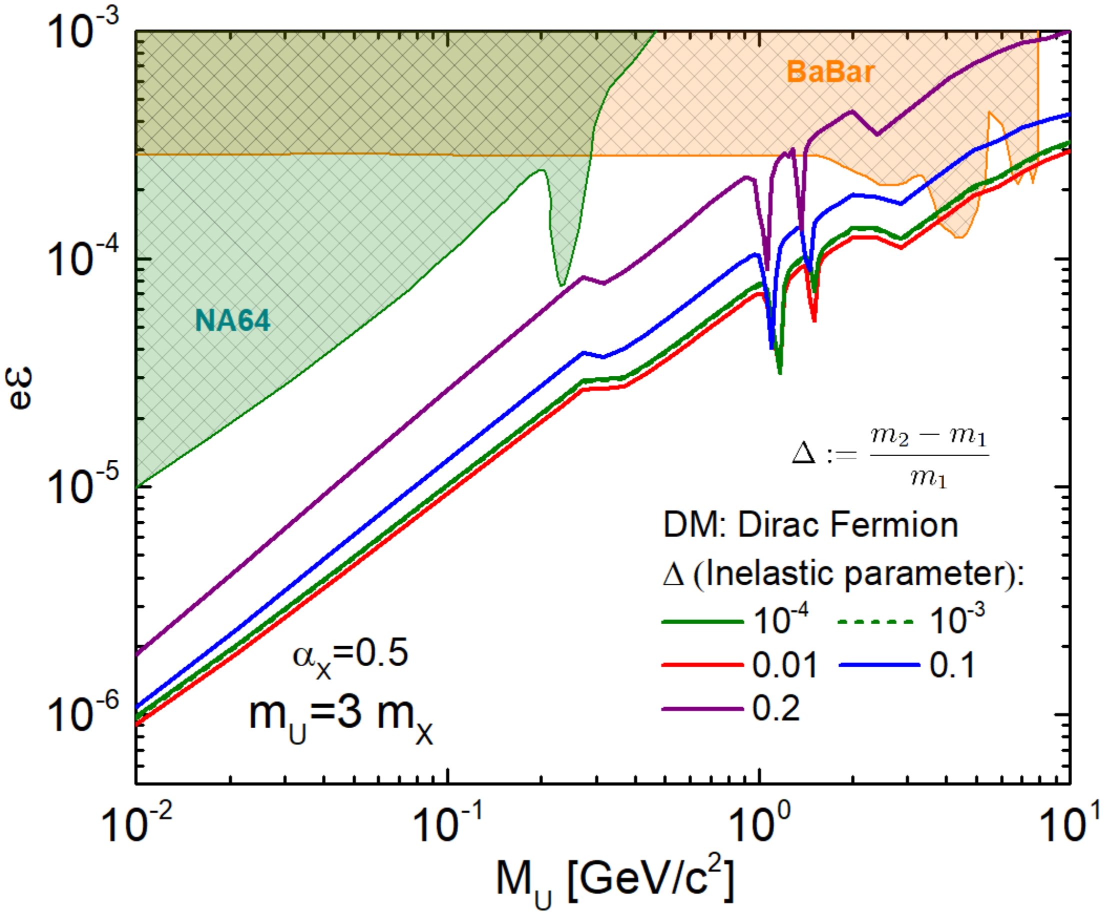


$$0.05 \leq \alpha_\chi \leq 0.5$$

https://cds.cern.ch/record/2677228/files/SPSC-SR-255.pdf

Thermal Target: Inelastic Dark Matter





$U \to X_1 X_2$ Direct Annihilation

$$\Gamma(U \to X_1 X_2) = \frac{\alpha_\chi m_U}{3}\left(1 - \Delta^2 \frac{m_X^2}{m_U^2}\right)^{\frac{3}{2}}\left(1 + \frac{(\Delta+2)^2}{2m_U^2} m_X^2\right)\left(1 - \frac{(\Delta+2)^2}{m_U^2} m_X^2\right)^{1/2}$$

$$\Gamma(U \to X\bar{X}) = \frac{\alpha_\chi m_U}{3}\left(1 + \frac{2m_X^2}{m_U^2}\right)\left(1 - \frac{4m_X^2}{m_U^2}\right)^{1/2} \qquad \Delta = 0$$

$$\Delta = \frac{|m_{\chi_1} - m_{\chi_2}|}{m_{\chi_1}}$$

Type of DM particle in CLASSICS

Particle	*spin*	*dof*		Comments
Scalar	0	1-2	$\sigma_{\text{scalar}} = \sigma_{\text{even}}$	Identical scalar particles must have a **symmetric** spatial wavefunction.
Fermion	1/2	2-4	$\sigma_{\text{fermion}} = \frac{3}{4}\sigma_{\text{odd}} + \frac{1}{4}\sigma_{\text{even}}$	For identical fermions (Majorana or χ–χ for Dirac DM): Antisymmetric spatial wavefunction → **odd** partial waves dominate.
Vector	1	3	$\sigma_{\text{vector}} = \frac{1}{3}\sigma_{\text{odd}} + \frac{2}{3}\sigma_{\text{even}}$	The dark matter candidate is a **spin-1 field** (massive vector boson),

Scalar: Scalar, Complex Scalar

Fermion: Dirac, Majorana

Vector: Massive real vector

DM Widths

Dirac Fermion

$$\Gamma(U \to \bar{\chi}\chi) = \frac{1}{3}\,\alpha_\chi\, m_U \left(1 + \frac{2m_\chi^2}{m_U^2}\right)\sqrt{1 - \frac{4m_\chi^2}{m_U^2}}$$

Majorana

$$\Gamma(U \to \chi\chi) = \frac{1}{6}\,\alpha_\chi\, m_U \left(1 - \frac{4m_\chi^2}{m_U^2}\right)^{3/2}$$

Complex Scalar

$$\Gamma(U \to \varphi\varphi^\dagger) = \frac{1}{12}\,\alpha_\chi\, m_U \left(1 - \frac{4m_\chi^2}{m_U^2}\right)^{3/2}$$

$$\mathcal{L}_{\text{mass}}^{\chi} = \begin{cases} -\,m_\chi\,\bar{\chi}\chi, & \text{Dirac fermion,} \\ -\,\frac{1}{2}\,m_\chi\,\bar{\chi}\chi, & \text{Majorana fermion,} \\ -\,m_\chi^2\,\varphi^\dagger\varphi, & \text{complex scalar.} \end{cases}$$

$$J_\chi^\mu = \begin{cases} \bar{\chi}\gamma^\mu\chi, & \text{Dirac fermion,} \\ \frac{1}{2}\bar{\chi}\gamma^\mu\gamma^5\chi, & \text{Majorana fermion,} \\ i\big(\varphi^\dagger\partial^\mu\varphi - (\partial^\mu\varphi^\dagger)\varphi\big)\,, & \text{complex scalar,} \end{cases}$$

Dark photon coupling to DM

Complex Scalar

Dark photon
is the gauge boson
of a dark gauge symmetry

$g_\chi \, A'_\mu \, J^\mu_\chi$

Real Scalar

$$\phi \to e^{iq_D \alpha(x)} \phi.$$

This requires ϕ to be a **complex scalar field.**

The covariant derivative is $D_\mu \phi = \left(\partial_\mu + i g_D q_D A'_\mu\right) \phi.$

The kinetic term is $\mathcal{L} = |D_\mu \phi|^2 - m_\chi^2 |\phi|^2.$

Expanding the kinetic term gives the interaction

$$\mathcal{L}_{\text{int}} = i g_D q_D A'_\mu \left(\phi^* \partial^\mu \phi - \phi \partial^\mu \phi^*\right) + g_D^2 q_D^2 A'_\mu A'^\mu |\phi|^2.$$

The corresponding $U(1)_D$ current is

$$J^\mu_D = i q_D \left(\phi^* \partial^\mu \phi - \phi \partial^\mu \phi^*\right)$$

So a dark photon can couple directly to complex scalar DM.

A real scalar satisfies $\phi = \phi^*$

But a charged $U(1)_D$ transformation would give

$$\phi \to e^{iq_D \alpha} \phi,$$

which is generally complex. For the field to remain real for any α, one needs

$$q_D = 0.$$

Therefore, a real scalar cannot carry a continuous $U(1)_D$ charge.

Dark photon coupling to DM

Dirac Fermion

A Dirac fermion charged under $U(1)_D$ transforms as

$$\chi \to e^{iq_D\alpha(x)}\chi.$$

The covariant derivative is $D_\mu\chi = \left(\partial_\mu + ig_D q_D A'_\mu\right)\chi.$

The Lagrangian is $\mathcal{L} = \bar{\chi}\left(i\gamma^\mu D_\mu - m_\chi\right)\chi.$

Expanding it gives $\mathcal{L}_{\text{int}} = g_D q_D A'_\mu \bar{\chi}\gamma^\mu\chi.$

The dark current is $J_D^\mu = q_D\bar{\chi}\gamma^\mu\chi.$

This is the standard dark-photon coupling to fermionic DM:

$$\mathcal{L}_{\text{int}} = g_D A'_\mu \bar{\chi}\gamma^\mu\chi.$$

So a dark photon can couple directly to Dirac fermion DM.

Majorana Fermion

A Majorana fermion satisfies $\chi = \chi^c.$

That means the particle is its own antiparticle.

Under $U(1)_D$, $\chi \to e^{iq_D\alpha}\chi,$

while its charge conjugate transforms as $\chi^c \to e^{-iq_D\alpha}\chi^c.$

For the Majorana condition, to remain true after the transformation, we need $e^{iq_D\alpha} = e^{-iq_D\alpha}$

for arbitrary α. This implies $q_D = 0.$

Therefore, a **pure Majorana fermion cannot carry a diagonal** $U(1)_D$ **charge**.

Also, the vector current vanishes identically for a Majorana fermion: $\bar{\chi}\gamma^\mu\chi = 0.$

Dark photon coupling to DM

Axial Majorana coupling

In a broken or chiral dark gauge theory, a Majorana state may have an axial coupling:

$$\mathcal{L}_{\text{int}} = g_D A'_\mu \bar{\chi} \gamma^\mu \gamma^5 \chi.$$

But this is not the minimal vector dark photon coupling. It requires a more specific model structure.

DM Candidate	Direct dark photon coupling?	Reason
Real Scalar	No	Cannot carry a continuous U(1) charge
Complex Scalar	Yes	Has a conserved U(1) current
Dirac Fermion	Yes	Has a vector current $\bar{\chi}\,\gamma^\mu \chi$
Pure Majorana	Not diagonally	The vector current vanishes
Majorana with Axial coupling	Possible	Requires a broken/chiral dark gauge structure

Cross-Section SIDM: Number of collisions

Elastic p+p $\sigma_{pp} = 30\, mbar$

Inelastic p+p $\sigma_{pp} = 60\, mbar$

$$n_{HIC} = 0.1\, fm^3 \sim 10^{38}\, cm^{-3}$$

$$\sigma_{\chi\chi} = 10\, cm^2/g \sim 1.78 \times 10^{-23}\, cm^2/GeV$$

For a DM mass

- $m_\chi = 100\, GeV$

$$\sigma_{\chi\chi} = 1.8 \times 10^{-21}\, cm^2$$
$$\sigma_{\chi\chi} = 1.8 \times 10^{6}\, mbar$$

$$\Gamma = n_\chi\, \sigma\, v$$

$$n_\chi \sim 0.003\, cm^{-3}$$

Number of collisions:

$$N_{coll} = \rho_\chi \frac{\sigma_{\chi\chi}}{m_\chi}\, v\, t$$

$$v \sim 200\, km/s$$

$$t \sim 4 \times 10^{17}\, s$$

$$N_{coll} \sim 50$$ Age of the universe

$$1\, mbar = 10^{-27}\, cm^2$$
$$1\, GeV^{-2} = 0.389 \times 10^{-27}\, cm^2$$

Sommerfeld enhancement

- Long range force in the Yukawa potential $(1/m_U)$ $\alpha_\chi m_\chi \gg m_U$
- Attractive Potential for enhancement
- Small relative velocity $v_{rel} \ll \alpha_\chi$
- Enhancement of the cross-section:

$$\langle \sigma v \rangle_{eff} = S(v) \langle \sigma v \rangle_0$$

$S(v)$ Sommerfeld Factor

$$S(v) = \frac{|\psi(0)|^2}{|\psi_0(0)|^2}$$

$$S(v) \sim \frac{1}{v}$$

$$V(r) = \pm \frac{\alpha_X}{r} e^{-m_U r} \begin{cases} + & \text{repulsive} \\ - & \text{attractive} \end{cases}$$

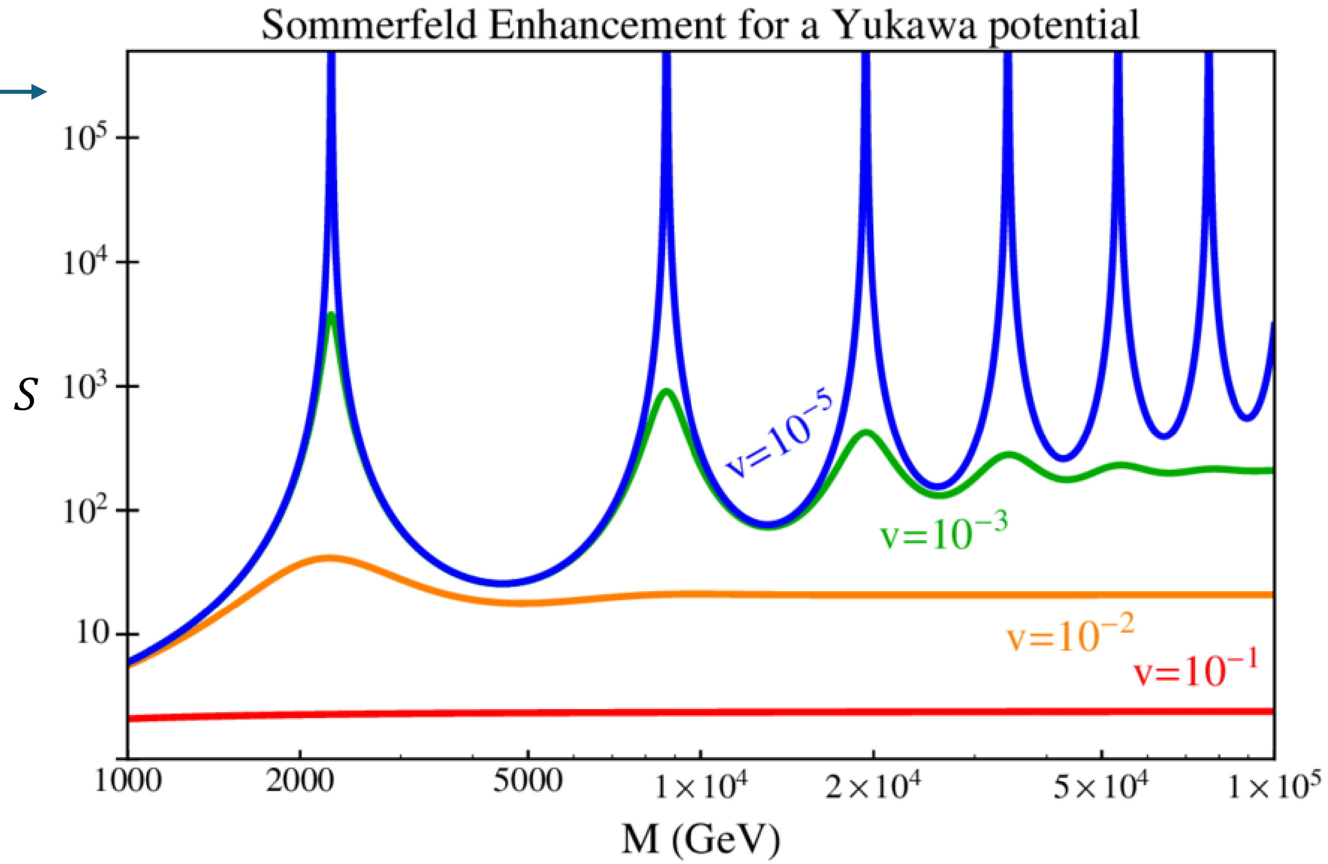
Sommerfeld enhancement

- If $m_U = 0, V(r) = -\frac{\alpha_X}{r}$

$$S(v) = \frac{\pi\alpha_\chi/v}{1 - e^{-\pi\alpha_\chi/v}}$$

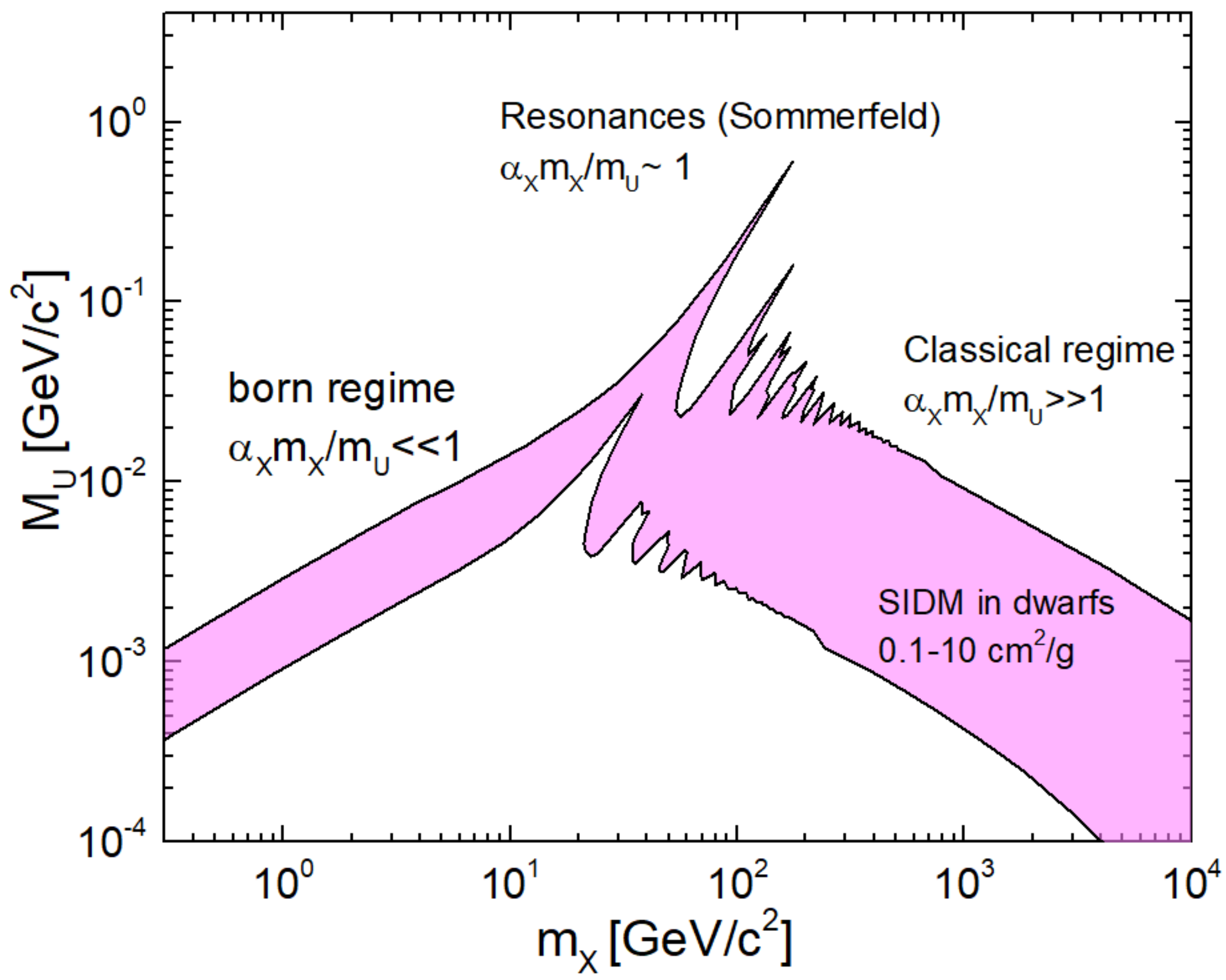
$v \ll \alpha_\chi$

$$S(v) \approx \frac{\pi\alpha_\chi}{v}$$



- If $m_U \neq 0, \quad r_d = \frac{1}{m_U}$

$$S_{max}(v) \approx \frac{\alpha_\chi m_\chi}{m_U}$$

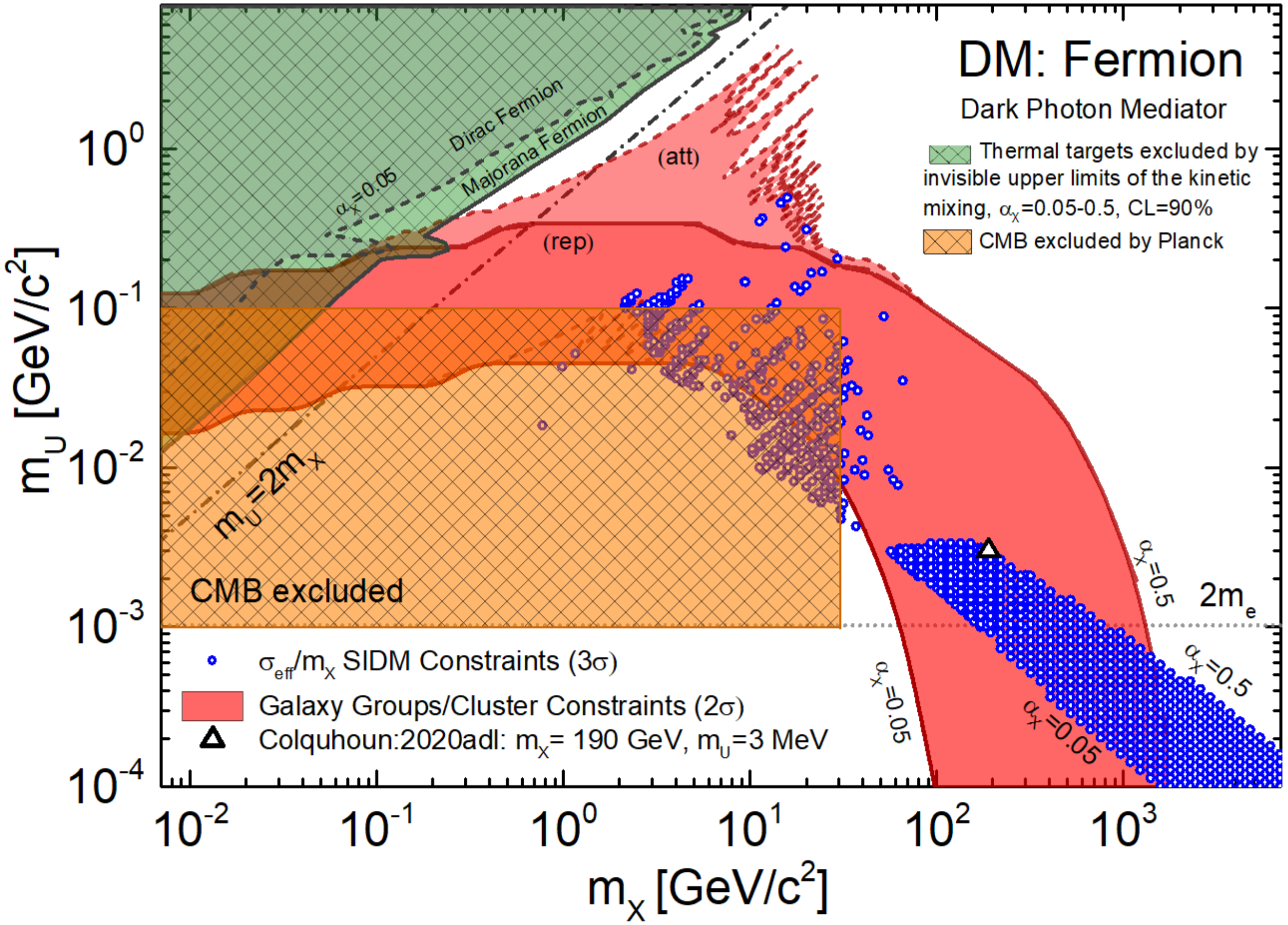


Quasi-bound state for attractive
Potential near zero energy

Short distance force

large distance force

Sommerfeld Enhancement in the Relic density



$$m_U > 2\, m_\chi$$

$$\alpha_\chi m_\chi \gg m_U$$

$$\alpha_\chi \gg 1$$

$$\alpha_\chi \leq 0.5$$

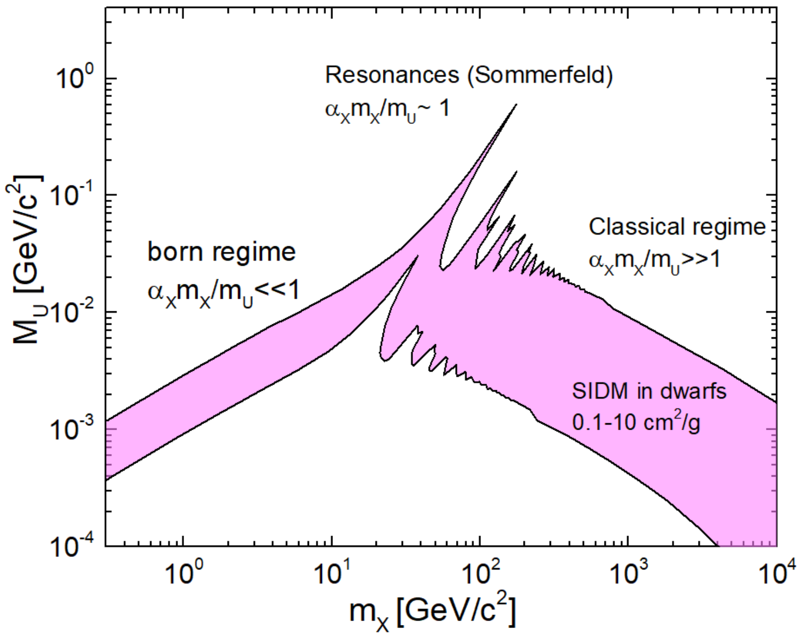
Elastic DM self-scattering

Born limit $\alpha_X m_X \ll m_\phi$

$$\frac{d\sigma}{d\Omega} = \frac{\alpha_\chi^2 m_\chi^2}{\left[m_\chi^2 v_{\rm rel}^2 (1-\cos\theta)/2 + m_\phi^2\right]^2}.$$

$$\frac{d\sigma}{d\Omega} = \frac{\alpha_X^2\, m_X^2}{m_\phi^4}$$

$$\frac{\sigma}{m_X} = \frac{4\pi\alpha_X^2\, m_X}{m_\phi^4}$$



$$\frac{\sigma}{m_X} = \left(\frac{\alpha_X}{10^{-2}}\right)^2 \left(\frac{m_X}{10\ GeV}\right)^1 \left(\frac{m_\phi}{40\ MeV}\right)^{-4}$$

$$0.1 < \sigma/m < 10\ cm^2/g$$

Cosmological Constraint

S. Tulin, H.-B. Yu, and K. M. Zurek, Phys. Rev. **D87**, 115007 (2013), 1302.3898

Thermal Relic Density: Comparison

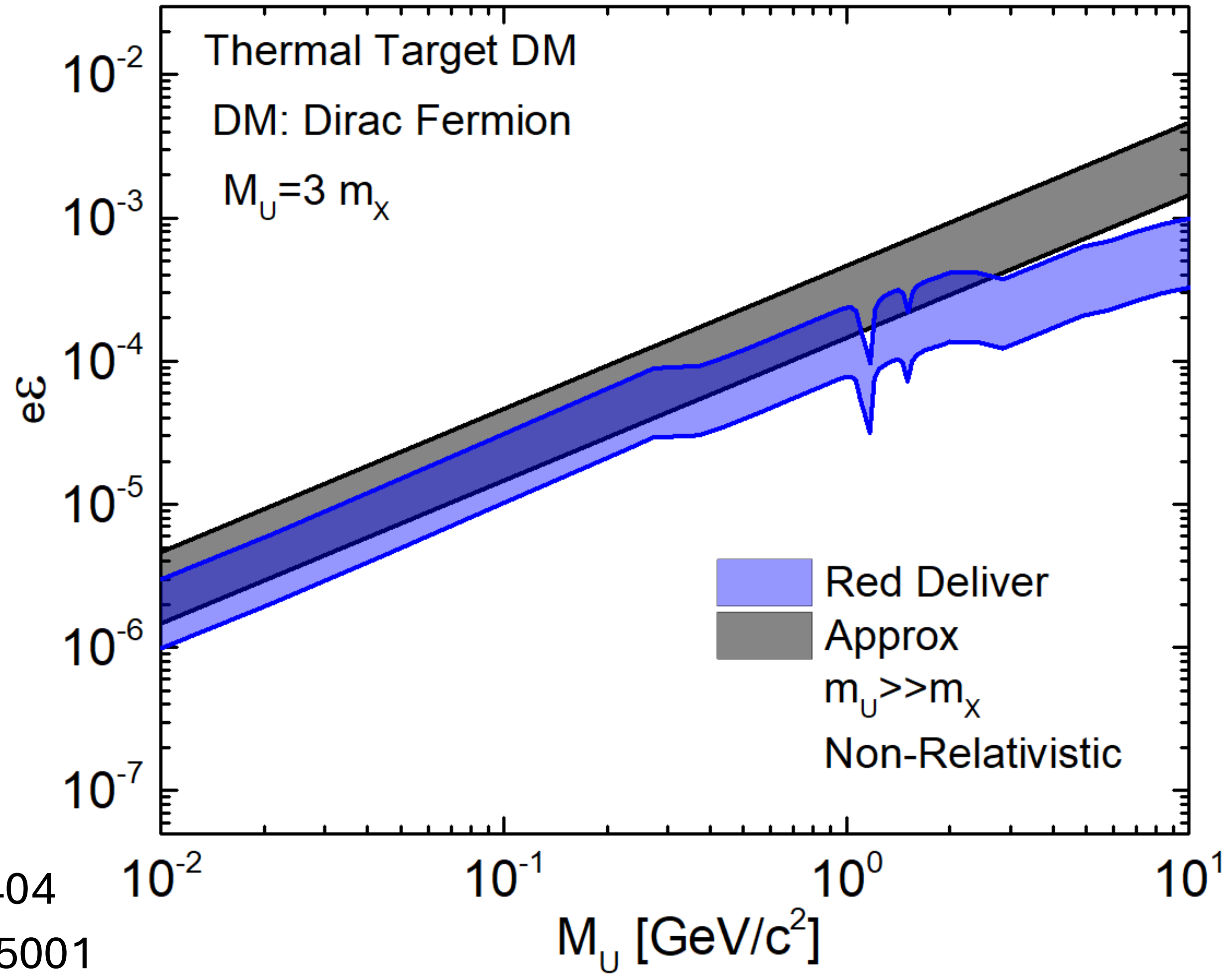
$$\langle \sigma_{\rm ann} v \rangle = \frac{\kappa}{2} \frac{\int_{4m_\chi^2}^{\infty} \sqrt{s}(s-4m_\chi^2)\,\sigma_{\rm ann}(s)\,K_1(\sqrt{s}/T)\,ds}{8m_\chi^4 T K_2^2(m_\chi/T)}$$

$$m_U \gg m_\chi$$

$$\langle \sigma v \rangle \simeq \frac{\pi\,\alpha\,\varepsilon^2\,\alpha_D}{m_\chi^2}\frac{m_\chi^4}{m_{A'}^4} \approx \frac{\pi\,\alpha\,\alpha_D\,\varepsilon^2}{m_\chi^2}\left(\frac{m_\chi}{m_{A'}}\right)^4$$

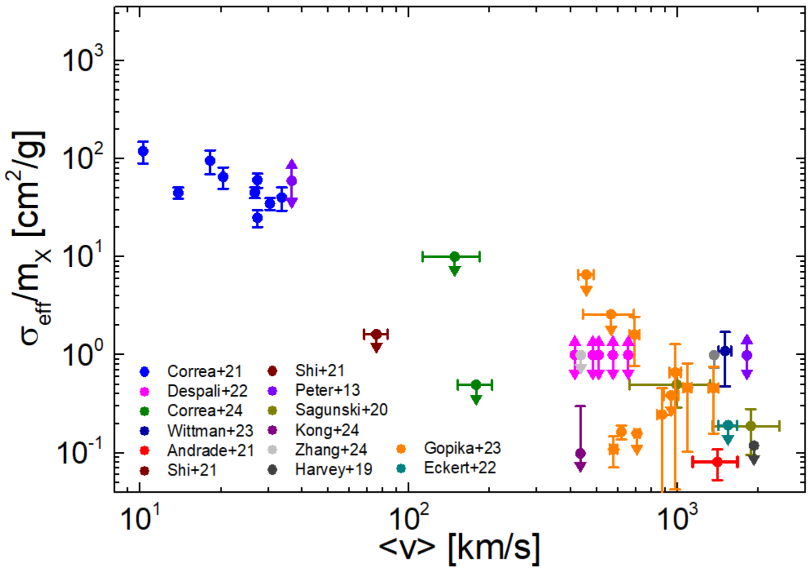
$$\varepsilon^2 \simeq \frac{\langle \sigma v \rangle\, m_\chi^2}{\pi\,\alpha\,\alpha_D}\left(\frac{m_{A'}}{m_\chi}\right)^4 \simeq 1.3\times10^{-8}\left(\frac{m_{A'}}{10\,\mathrm{MeV}}\right)^4\left(\frac{1\,\mathrm{MeV}}{m_\chi}\right)^2\left(\frac{10^{-2}}{\alpha_D}\right)$$

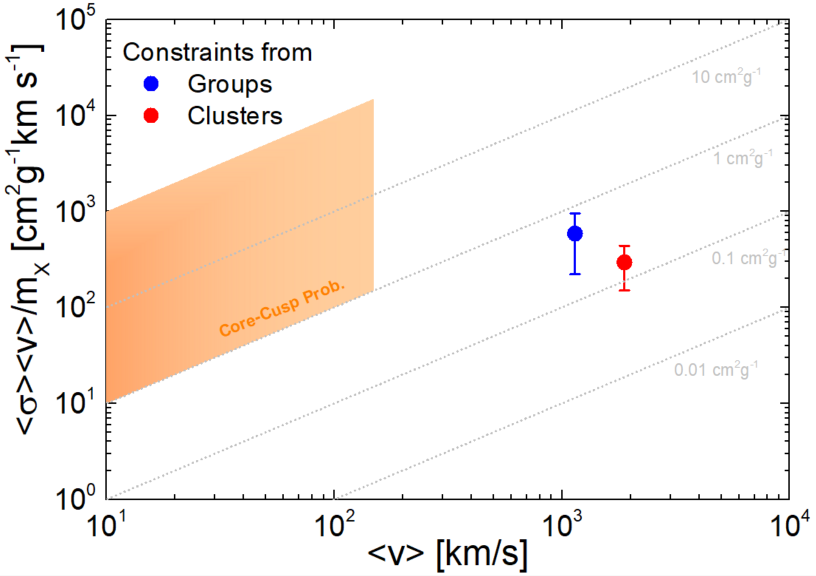
$$\epsilon^2 \simeq 1.3\times10^{-8}\left(\frac{m_{A'}}{10\ \mathrm{MeV}}\right)^4\left(\frac{\mathrm{MeV}}{m_\chi}\right)^2\left(\frac{10^{-2}}{\alpha_D}\right)$$



Arxiv.1411.1404
PhysRevD.99.075001
Arxiv.1801.05447
Arxiv.1307.6554

Effective cross-section Constraints





CLASSICS

CalcuLAtionS of Self Interaction Cross Sections

github.com/kahlhoefer/CLASSICS Arxiv: 2011.04679

Computes approximate **self-scattering cross sections** for dark matter (DM) particles interacting via a **Yukawa potential**:

$$U(r) = \pm \frac{\alpha_\chi}{r} e^{-m_\phi r}$$

- Momentum-transfer cross section

$$\sigma_T = \int d\Omega \,(1-\cos\theta)\, \frac{d\sigma}{d\Omega},$$

- Viscosity cross section

$$\sigma_V = \int d\Omega \,\sin^2\theta\, \frac{d\sigma}{d\Omega}.$$

Maxwell–Boltzmann distribution to compute velocity-averaged cross sections

$$f(v) = 4\pi \left(\frac{m_\chi}{2\pi k_B T}\right)^{3/2} v^2\, e^{-\frac{m_\chi v^2}{2k_B T}}$$

- $\frac{m_X v}{m_U} > 1$ Classical trajectory methods
- $\frac{m_X v}{m_U} \sim 1$ Classical with leading quantum corrections.
- $\frac{m_X v}{m_U} < 1$ Schrödinger Equation in the Born limit (weak dispersion) *(Tulin, Yu & Zurek, arXiv:1302.3898)*

Thermal Relic Abundance

$$\Omega_{DM} = \frac{\rho_{DM}}{\rho_{cr}} \sim 26.14\ \%$$

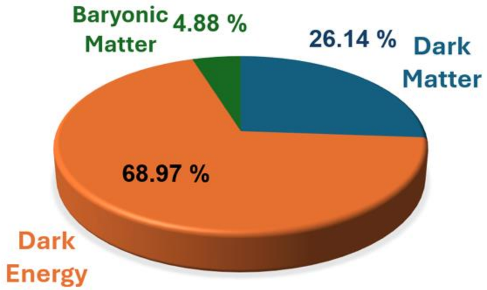
$h = 0.674$

Plack mission CMB: arxiv.1807.06209

$\boldsymbol{\Omega_{DM} h^2 \sim 0.120 \pm 0.001}$

$\Omega_{DM} h^2 > \ 0.12$ Overproduction

$\Omega_{DM} h^2 < \ 0.12$ Underproduction



Red DeliVeR

Arxiv: 2410.00881

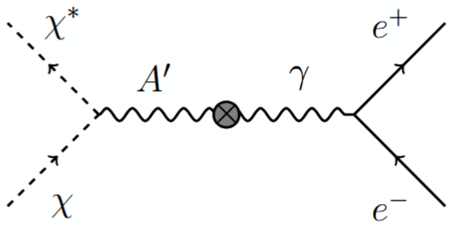
Solve the Boltzmann Equation for the DM relic density at freeze-out

Mediator: Dark Photon

Dark Matter:
- Complex Scalar
- Dirac Fermion
- Majorana Fermion

- $m_U \geq 2\, m_X$ Cross-Section is dependent of ε^2
- $m_U < 2\, m_X$ ”secluded” case: independent of ε^2

$\rightarrow$ $(\boldsymbol{\varepsilon, m_U, \alpha_X, m_X})$



$\boldsymbol{\chi\bar{\chi} \rightarrow U^* \rightarrow f\bar{f}}$ Direct Annihilation

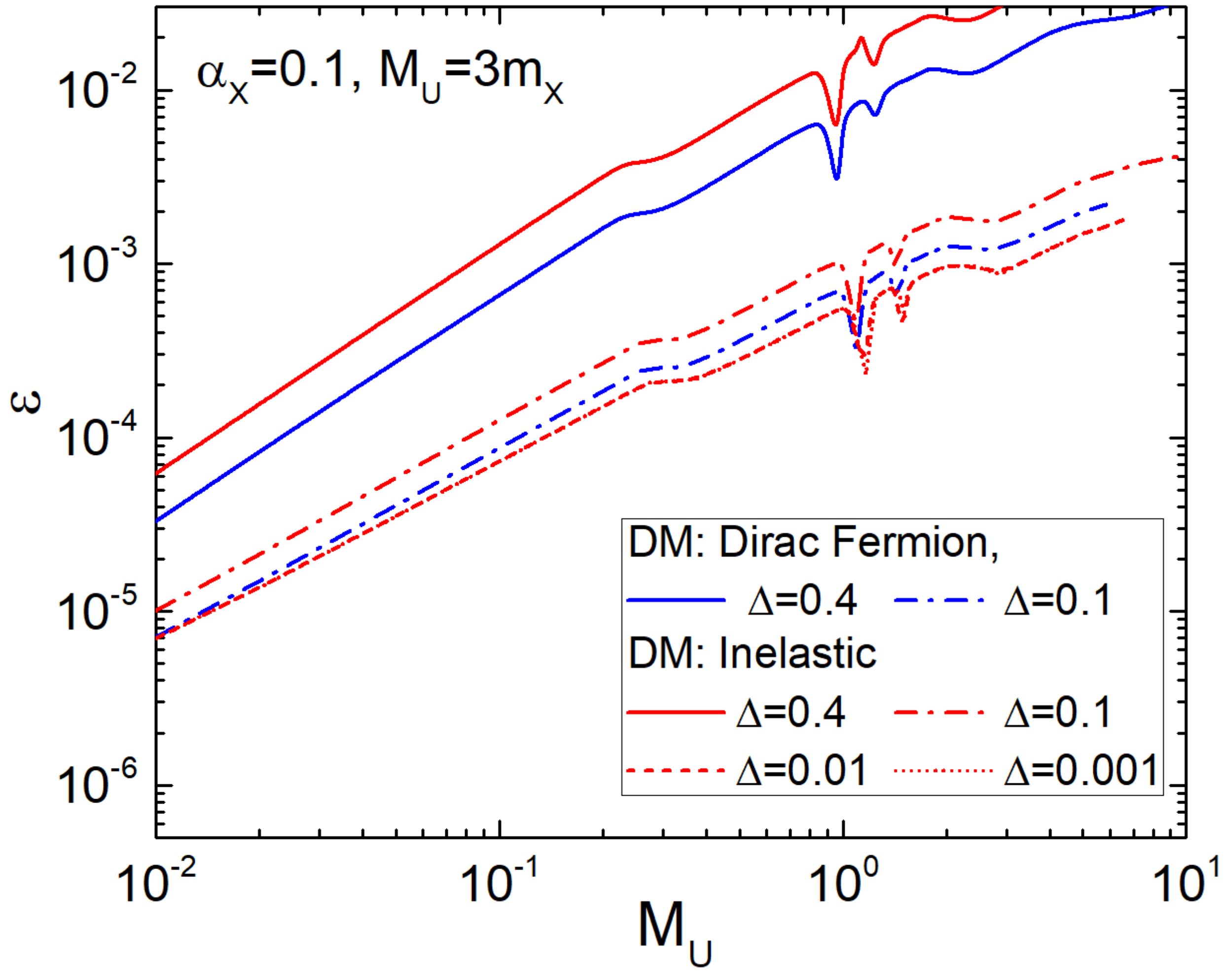
s − channel

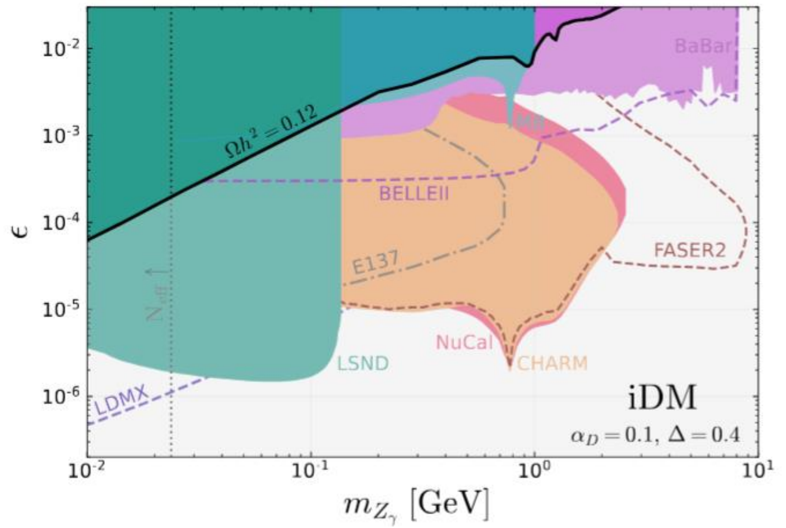
$$\Gamma(\chi\bar{\chi} \rightarrow U^* \rightarrow f\bar{f}) = \varepsilon^2 \frac{\alpha_\chi m_U}{12}\left(1 - \frac{4m_\chi^2}{m_U^2}\right)^{3/2}$$

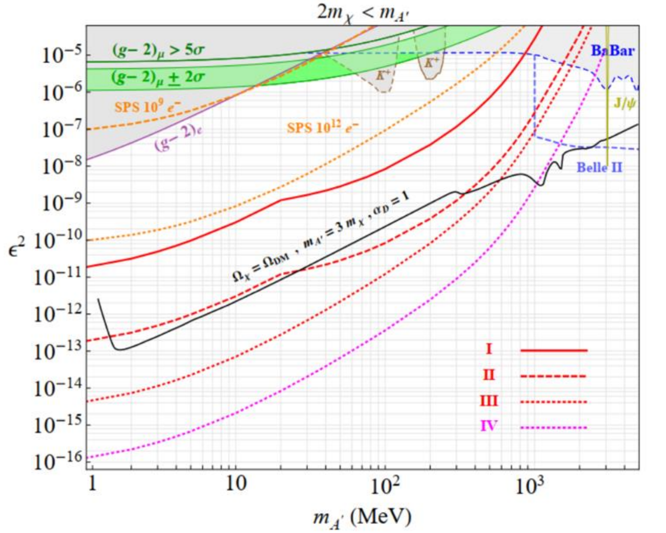
Red DeliVeR

https://arxiv.org/abs/2410.00881

$\{m_\chi, g_\chi, \varepsilon, m_U, \Delta\}$ $\quad R = m_U/m_\chi = 3$





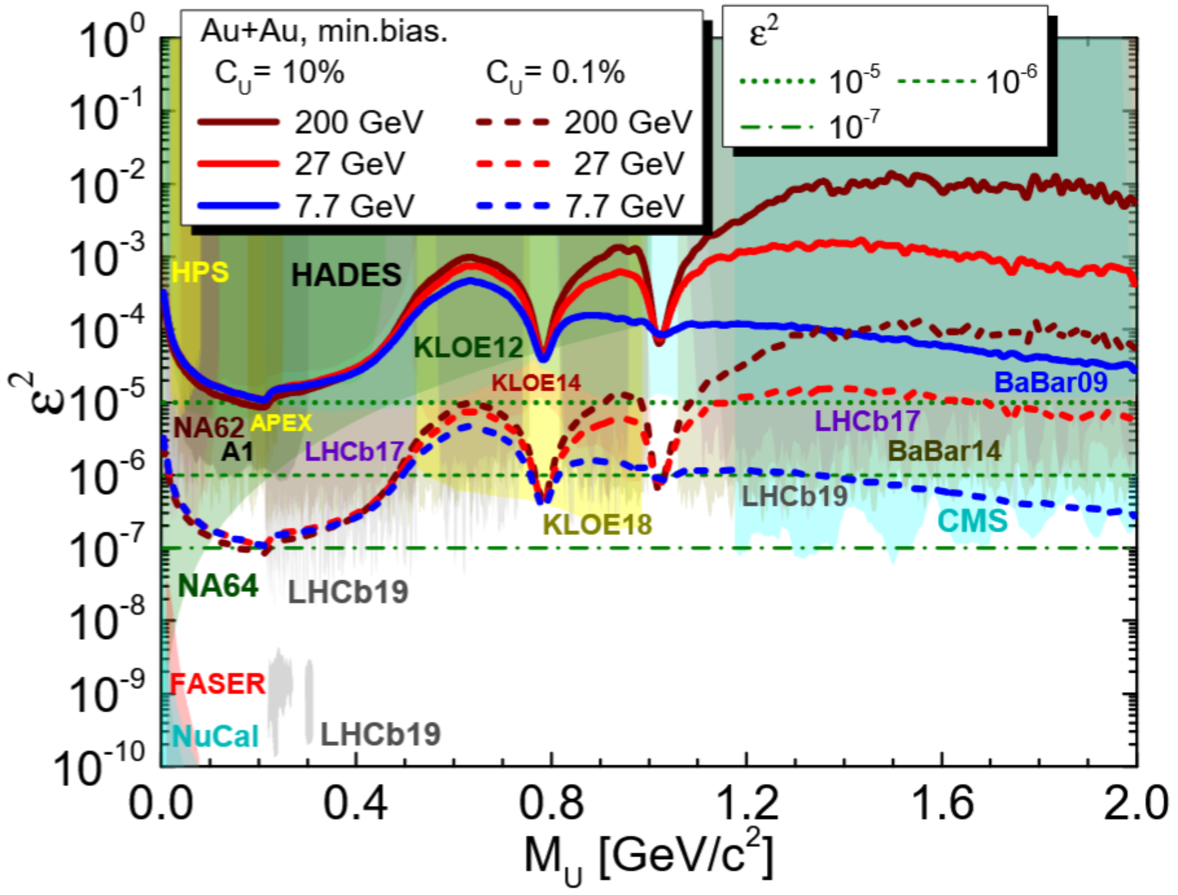


$$\Delta = \frac{|m_{\chi_1} - m_{\chi_2}|}{m_{\chi_1}}$$

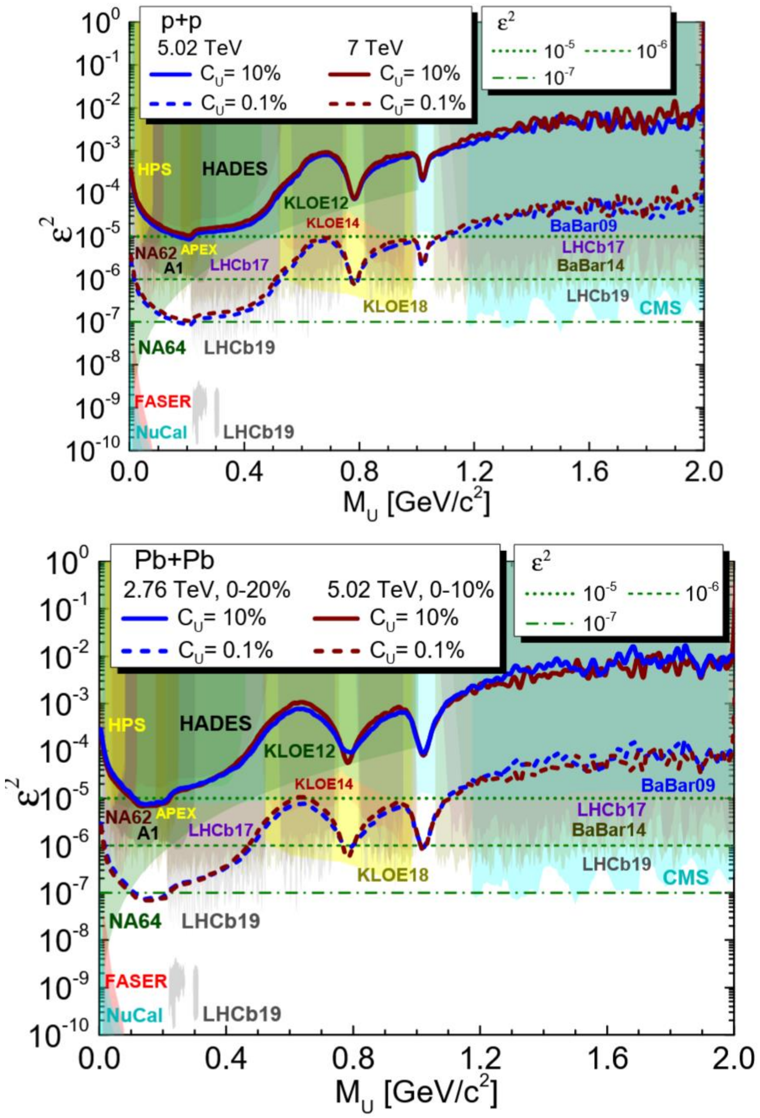
Arxiv.1411.1404

Kinetic Mixing parameter $\varepsilon^2(m_U)$

BES-RHIC-STAR



LHC-ALICE



A. Jorge et al. (2025): **arXiv:2507.11163**