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

Adrian William Romero Jorge (Goethe Uni. Frankfurt & HFHF)

Elena Bratkovskaya (GSI, Darmstadt & Uni. Frankfurt & HFHF)

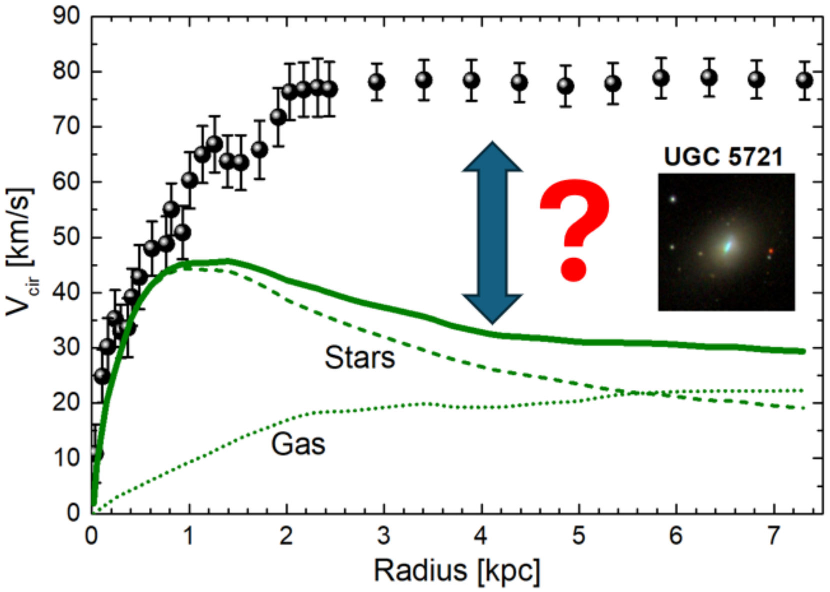
Laura Sagunski (Uni. Frankfurt) & Guanwen Yuan (Uni. Trento) & Taesoo Song (GSI, Darmstadt)

Table of Contents

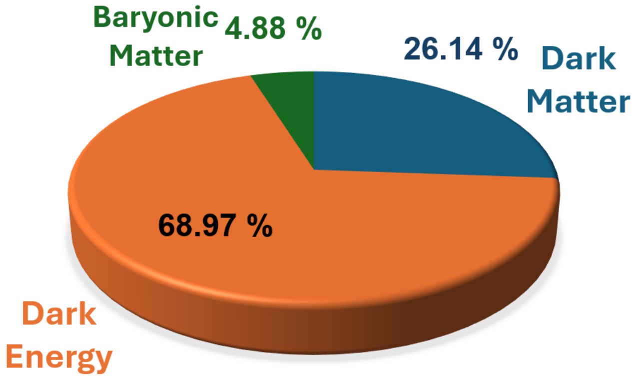
Structure of the Universe

Astrophysical observations based on gravitational effects:

1. Galaxy Rotation Curves



Energy Distribution of the Universe



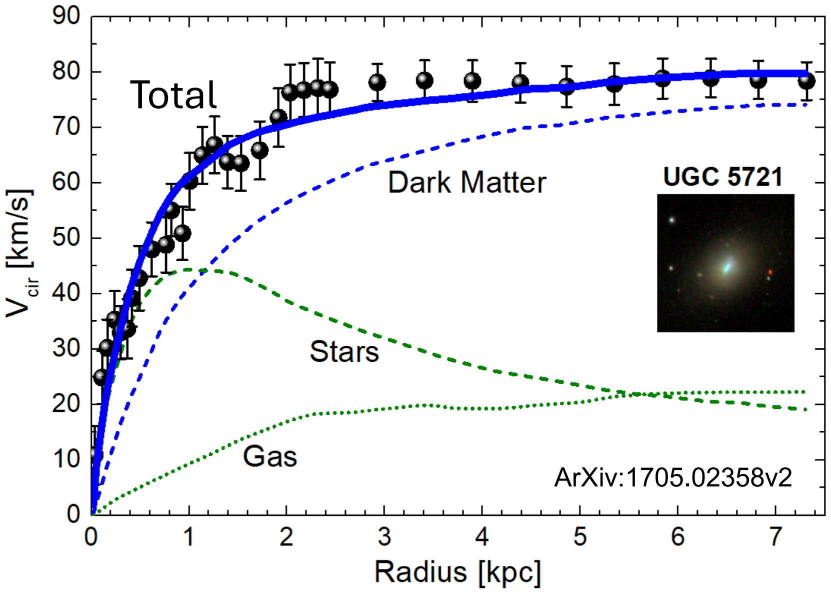
Data from Planck 2018 results (Arxiv: 1807.06209)

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

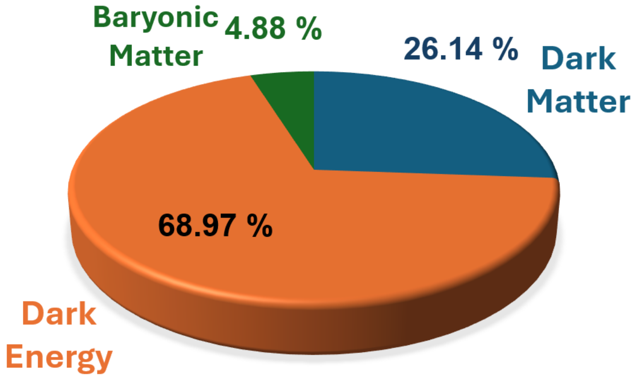
Structure of the Universe

Astrophysical observations based on gravitational effects:

1. Galaxy Rotation Curves



Energy Distribution of the Universe



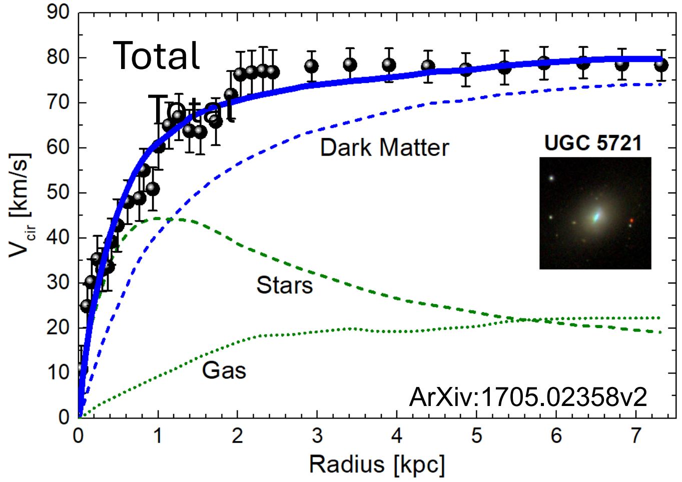
Data from Planck 2018 results (Arxiv: 1807.06209)

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

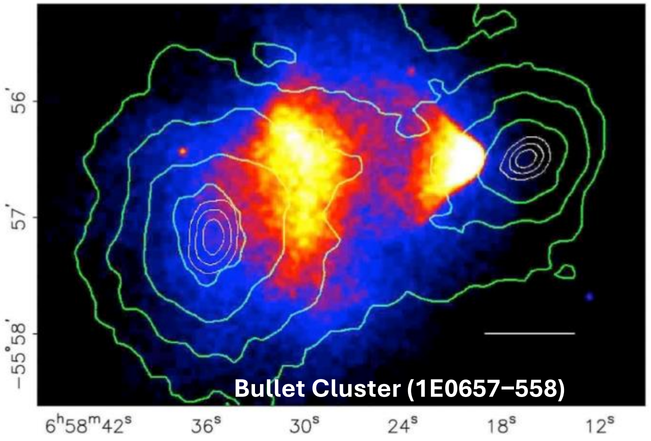
Structure of the Universe

Astrophysical observations based on gravitational effects:

1. Galaxy Rotation Curves

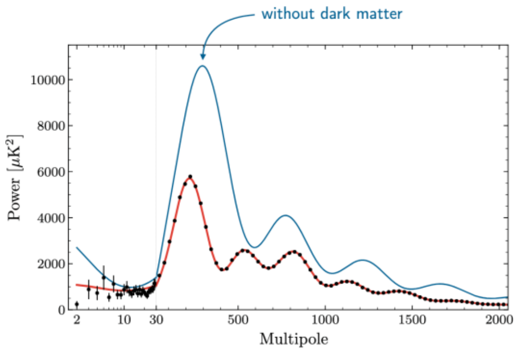


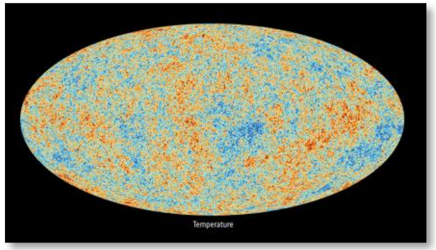
3. Gravitational lensing



arXiv:0608407

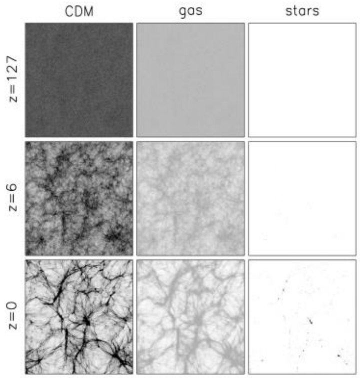
2. Cosmic Microwave Background (CMB)

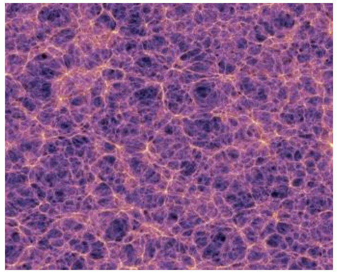




Huang & Bond/ACT) ESA and the Planck Collaboration.

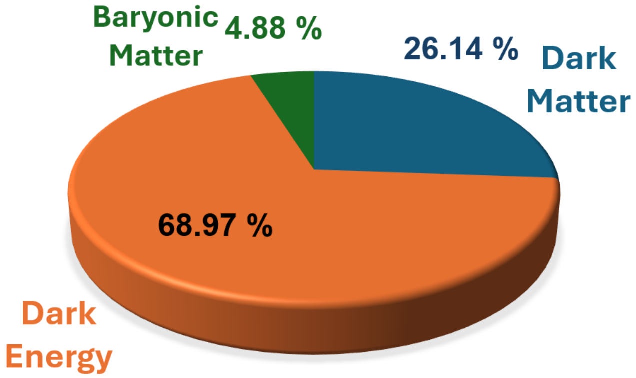
4. Structure Formation





Arxiv.1104.1174

Energy Distribution of the Universe



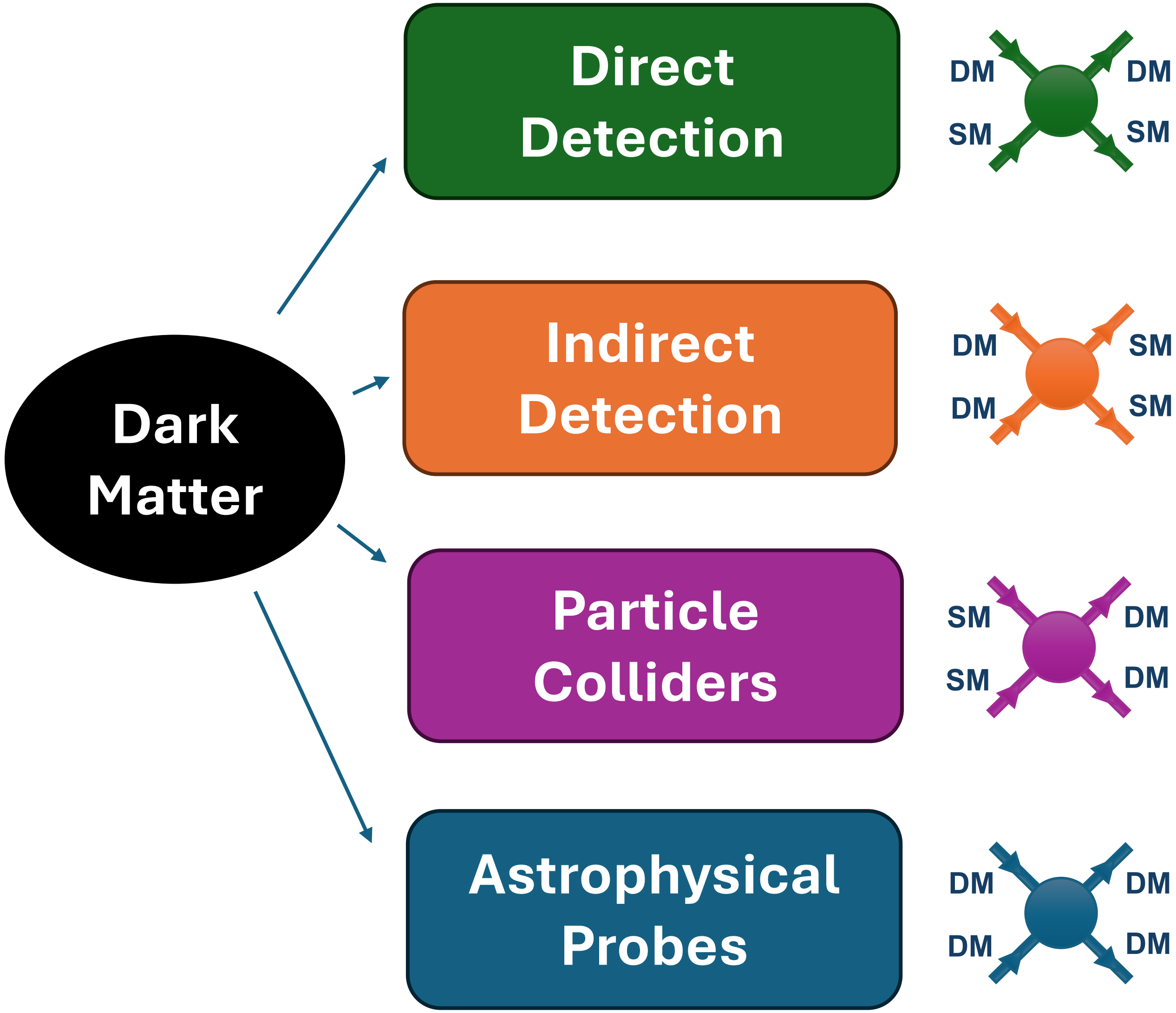
Data from Planck 2018 results (Arxiv: 1807.06209)

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

Dark Matter Detection

Dark
Matter

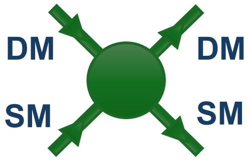
Dark Matter Detection

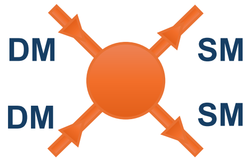


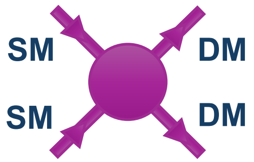
Dark Matter Detection

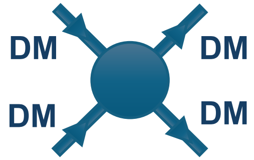
Dark Matter

	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** ○ $XX \rightarrow SM\ SM$ ○ 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

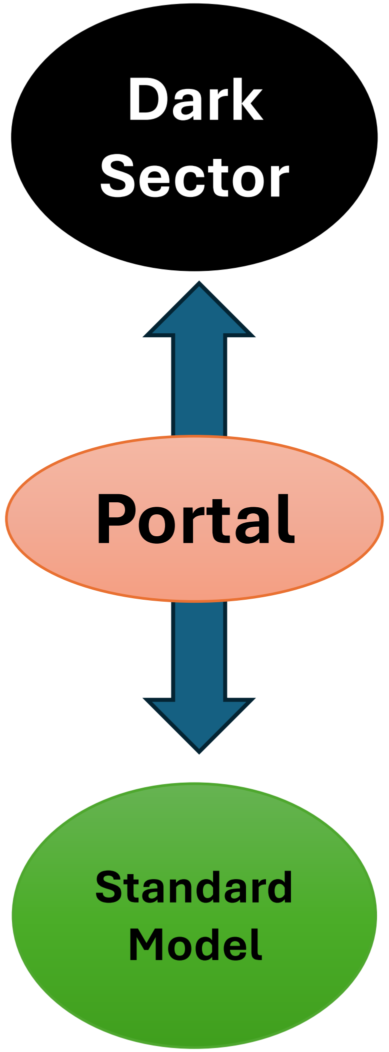




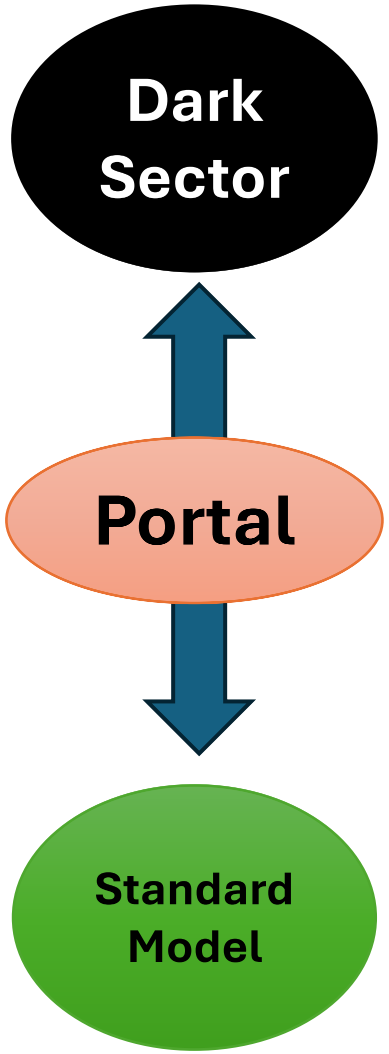




Dark Matter Portals

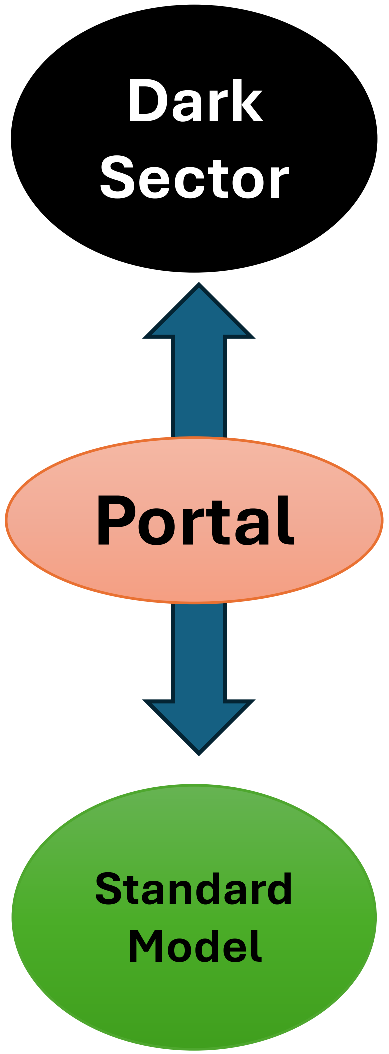


Dark Matter Portals



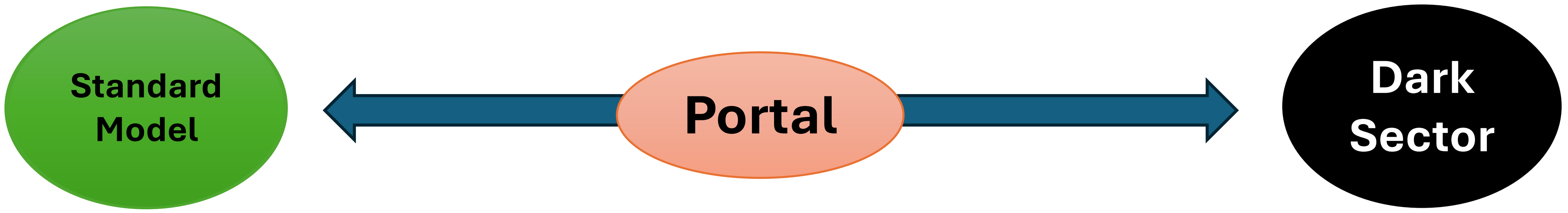
Portal	Mediator Particle	Operator
Vector	Dark Photon	$\mathcal{L} \supset -\frac{\varepsilon}{2} B_{\mu\nu} F'^{\mu\nu}$
Axion	Pseudoscalars	$\mathcal{L} \supset \frac{a}{f_a} F_{\mu\nu}\tilde{F}^{\mu\nu}, \frac{a}{f_a} G_{i\mu\nu}\tilde{G}_i^{\mu\nu}, \ldots$
Higgs	Dark scalars	$\mathcal{L} \supset (\mu\phi + \lambda\phi^2) H^\dagger H$
Neutrino	Sterile neutrinos	$\mathcal{L} \supset y_N L H N$

Dark Matter Portals



Portal	Mediator Particle	Operator
Vector	**Dark Photon**	$\mathcal{L} \supset -\frac{\varepsilon}{2} B_{\mu\nu} F'^{\mu\nu}$
Axion	**Pseudoscalars**	$\mathcal{L} \supset \frac{a}{f_a} F_{\mu\nu}\tilde{F}^{\mu\nu}, \frac{a}{f_a} G_{i\mu\nu}\tilde{G}_i^{\mu\nu}, \ldots$
Higgs	**Dark scalars**	$\mathcal{L} \supset (\mu\phi + \lambda\phi^2) H^\dagger H$
Neutrino	**Sterile neutrinos**	$\mathcal{L} \supset y_N L H N$

Dark Photon Model with Dark Matter



Dark Photon Model with Dark Matter

Standard Model — Portal — Dark Sector

$\mathcal{L}_{SM}$

Dark Photon

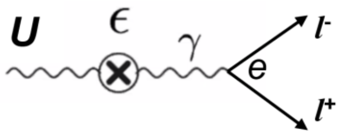
$\mathcal{L}_{mass}(\boldsymbol{m_\chi})$

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

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

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

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

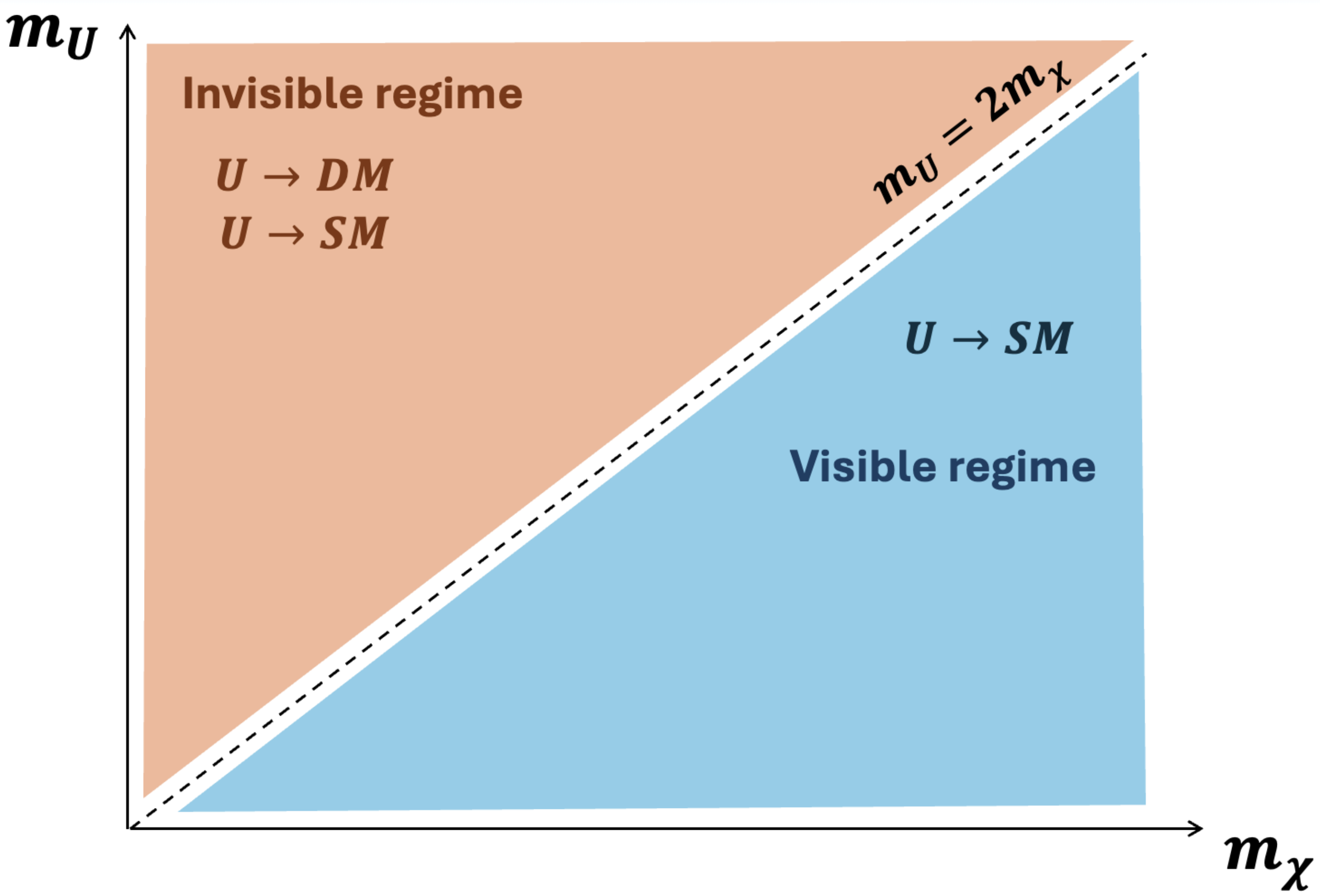


$$\alpha_\chi = \frac{g_\chi^2}{4\pi} \qquad J^\mu_\chi = \begin{cases} \bar{\chi}\gamma^\mu \chi, & \text{Dirac fermion,} \\ \frac{1}{2}\bar{\chi}\gamma^\mu\gamma^5\chi, & \text{Majorana fermion,} \\ i\left(\varphi^\dagger \partial^\mu \varphi - (\partial^\mu \varphi^\dagger)\varphi\right), & \text{complex scalar,} \end{cases}$$

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

4-free parameters $(\boldsymbol{\varepsilon}, \boldsymbol{m_U})$ $(\boldsymbol{\alpha_\chi}, \boldsymbol{m_\chi})$

Kinematics $m_U(m_\chi)$



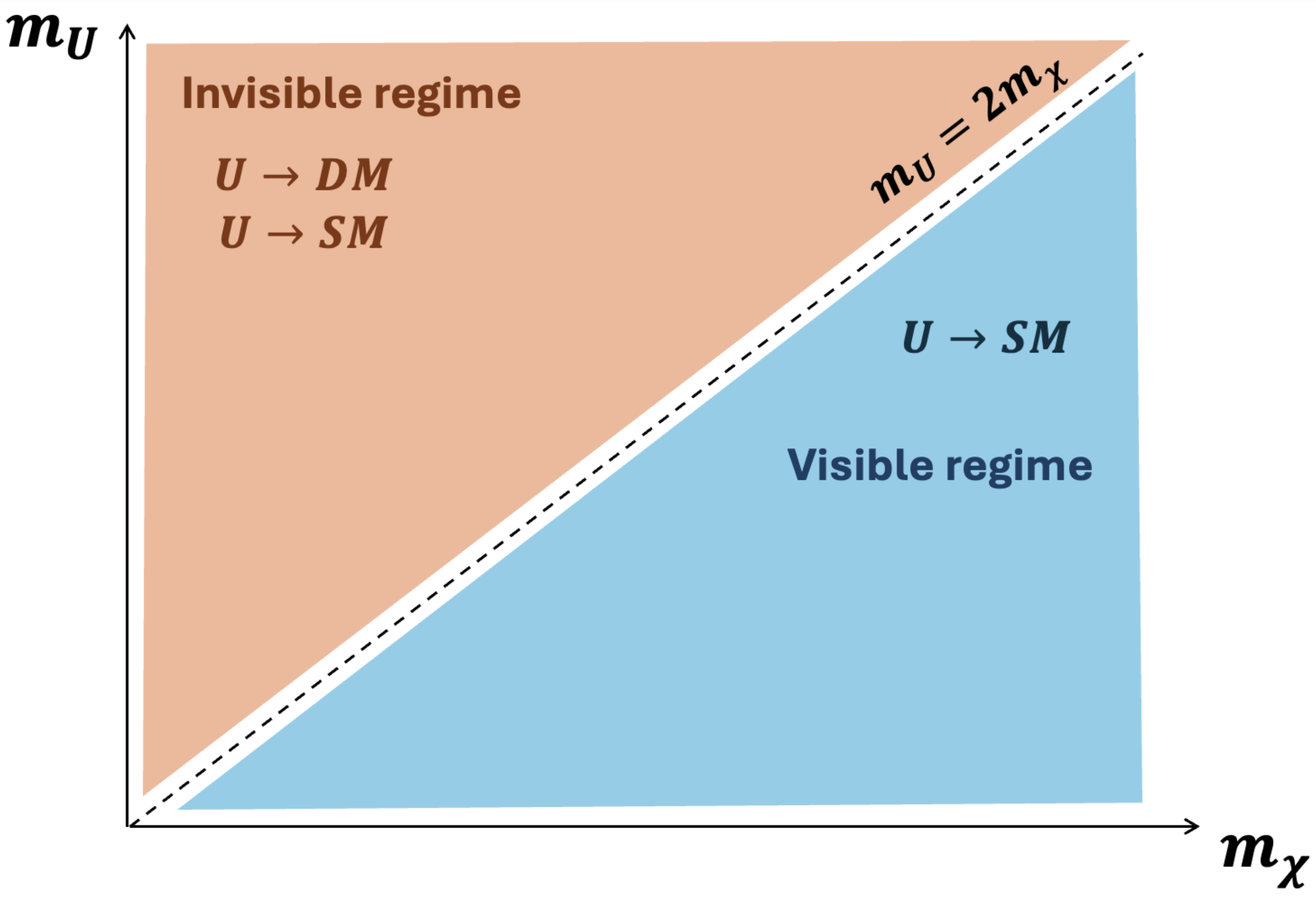
Invisible regime

Visible regime

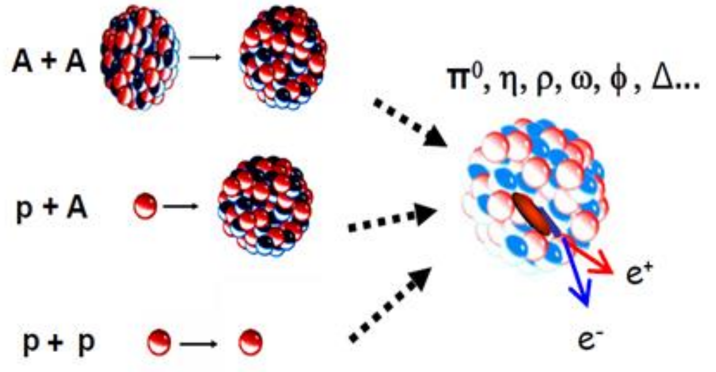
Kinematics $m_U(m_\chi)$

Invisible regime

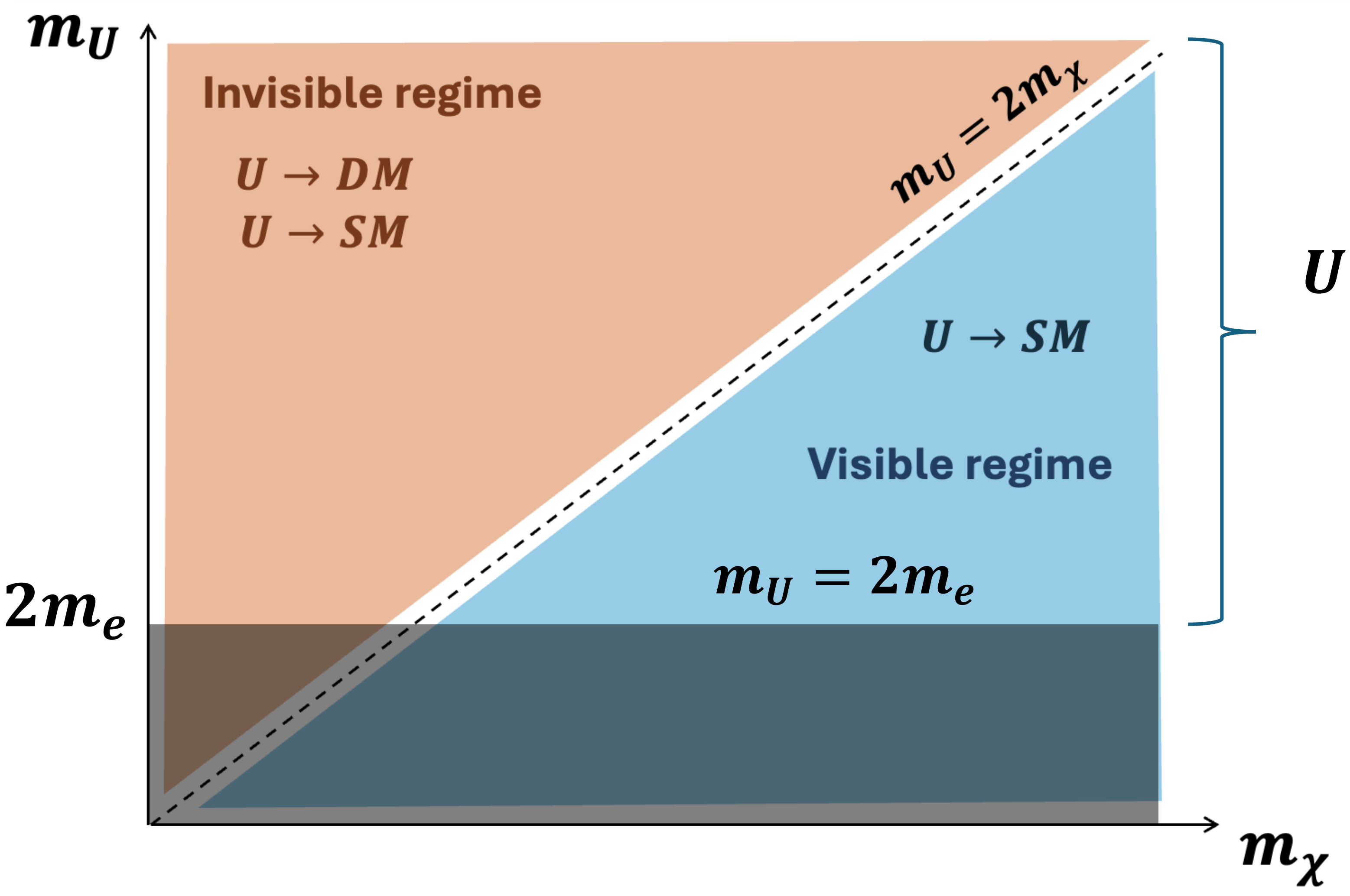
Visible regime

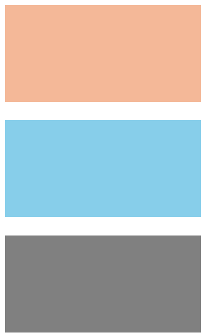


Is it possible to “observe” dark photon in Heavy-Ion Collisions ?



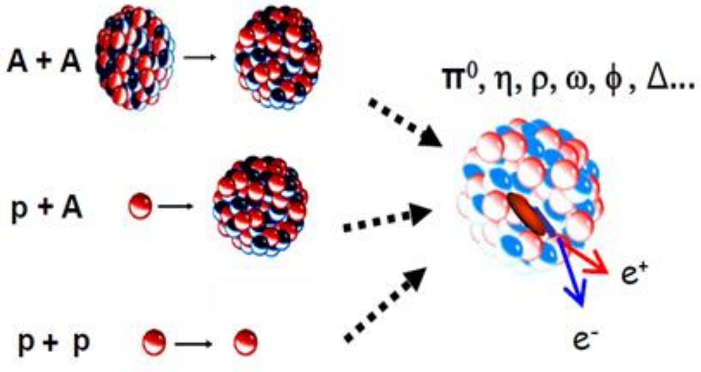
Kinematics $m_U(m_\chi)$



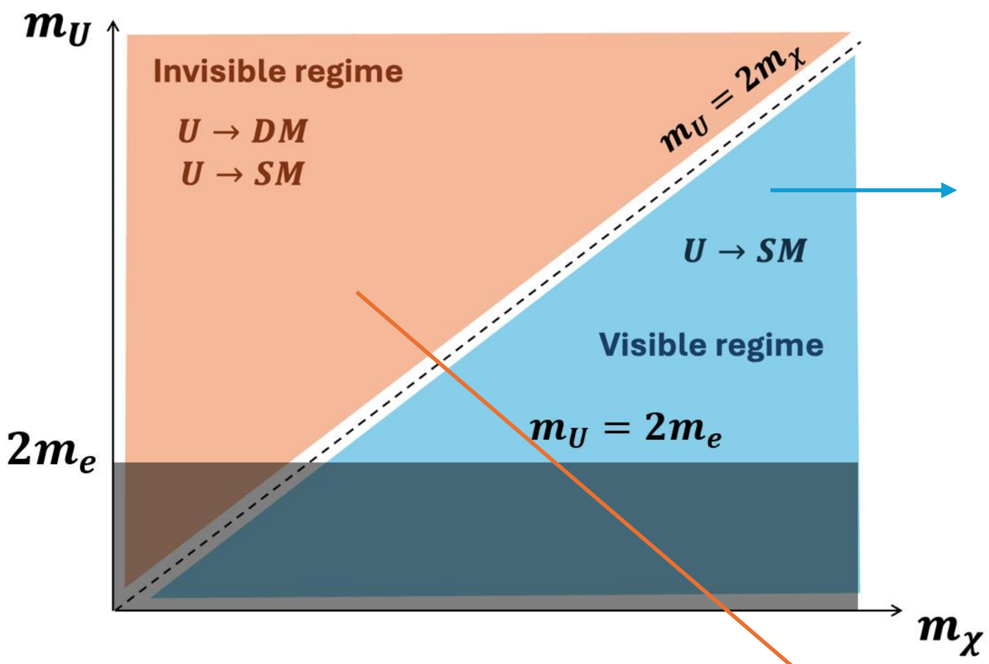


$U \to l^+ l^-$

Is it possible to "observe" dark photon in Heavy-Ion Collisions ?



Dark photon decay modes.



$U \to e^+e^-$

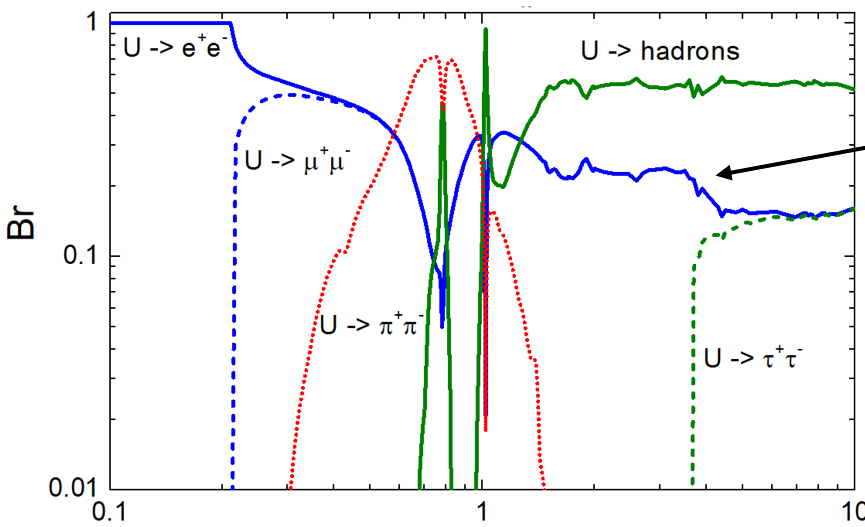
$U \to \mu^+\mu^-$

$U \to \tau^+\tau^-$

$U \to hadrons$

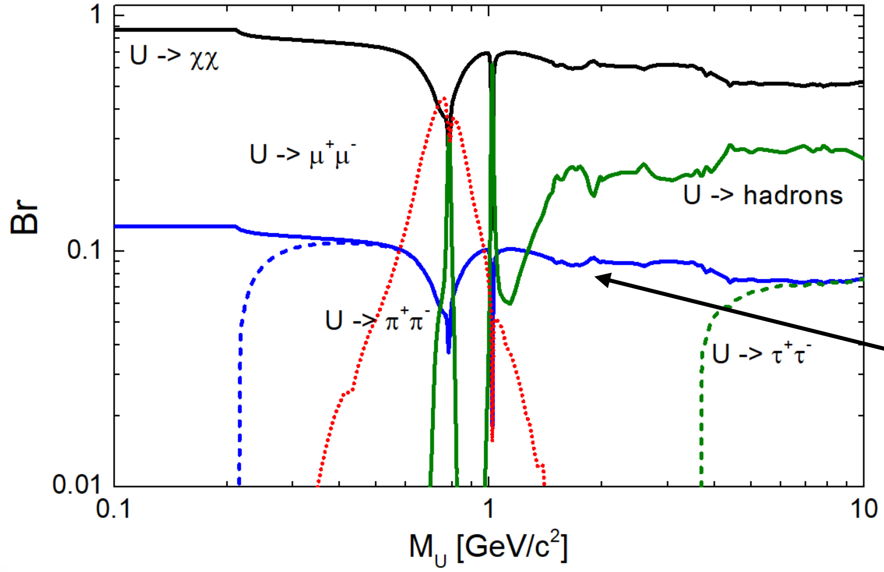
$(U \to \pi^+\pi^-, \ldots)$

$m_U < 2m_\chi$



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

m_χ = 10 MeV, $\hat{\alpha}_\chi$=0.05

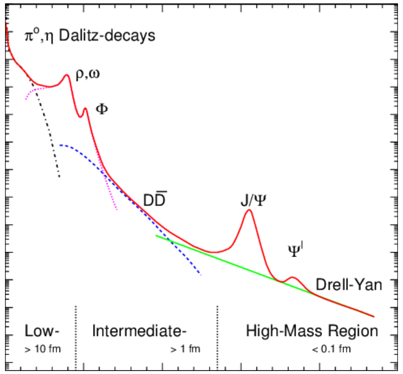


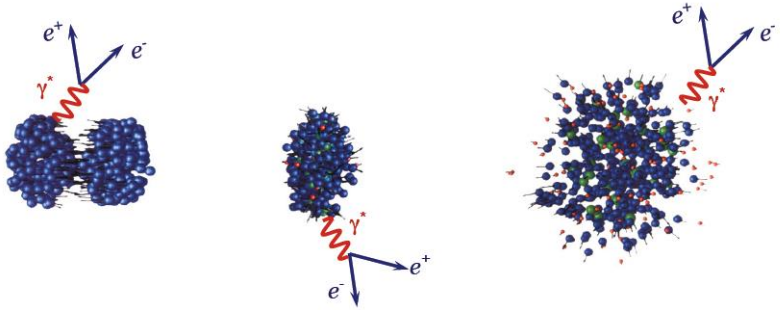
$$\mathrm{Br}(U\to e^+e^-) = \begin{cases} \dfrac{\Gamma(U\to e^+e^-)}{\Gamma_{\rm vis}}, & m_U < 2m_\chi, \\ \dfrac{\Gamma(U\to e^+e^-)}{\Gamma_{\rm vis}+\Gamma_{\rm inv}}, & m_U \geq 2m_\chi, \end{cases}$$

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

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

Possible dark photon observation by dilepton experiments



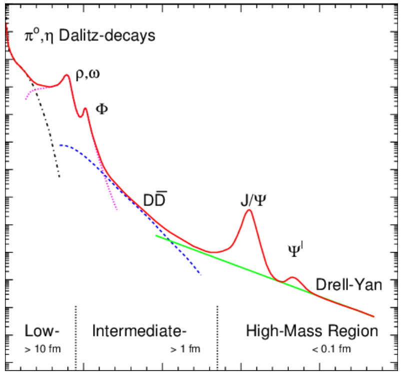


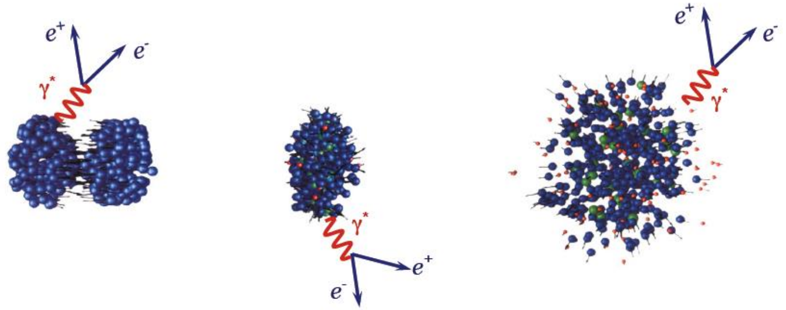
DOI:10.22323/1.238.0033

- **Dilepton spectra from SM sources are well studied by dilepton experiments from SIS to LHC energies (HADES, STAR, ALICE, …)**
- **Hadron production by p+p, p+A, A+A collisions.**
- **Dark photon production in hadronic and partonic decays.**

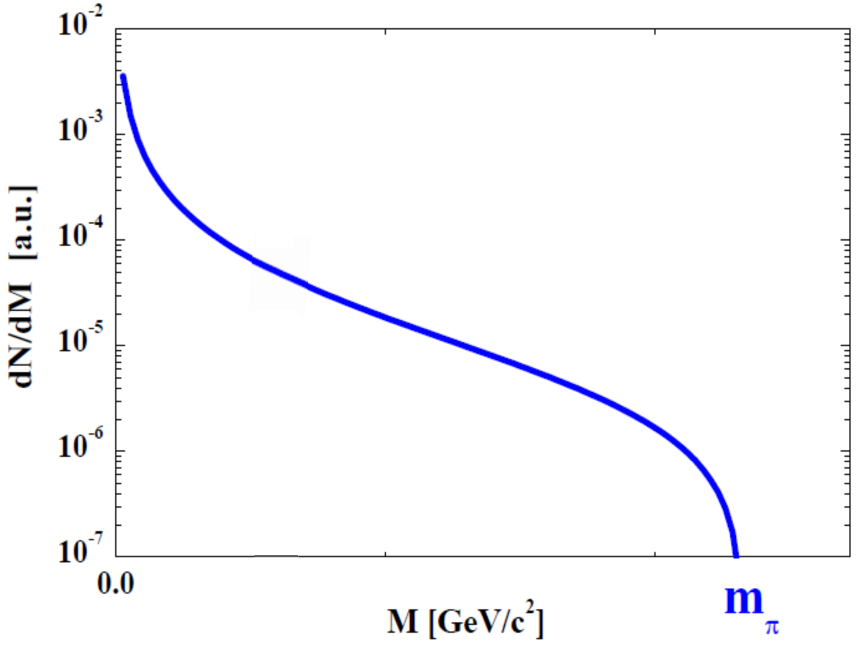
➔ Possibility for an indirect experimental observation of dark photons by electromagnetic decays $U \rightarrow e^{+} e^{-}$ in heavy-ion experiments

Possible dark photon observation by dilepton experiments





DOI:10.22323/1.238.0033



- Dilepton spectra from SM sources are well studied by dilepton experiments from SIS to LHC energies (HADES, STAR, ALICE, …)
- Hadron production by p+p, p+A, A+A collisions.
- Dark photon production in hadronic and partonic decays.

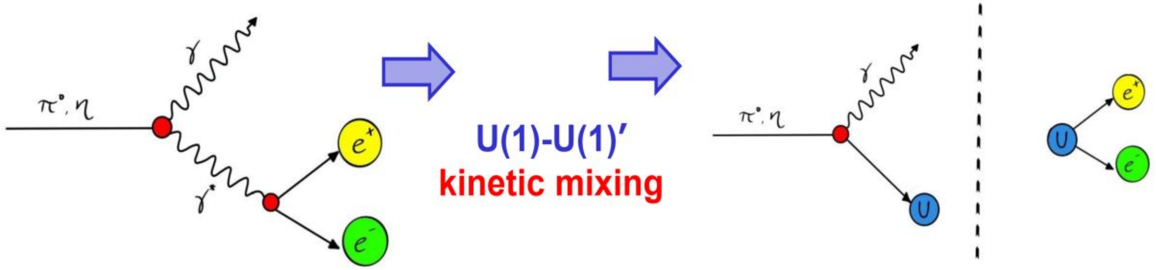
➔ Possibility for an indirect experimental observation of dark photons by electromagnetic decays $U \rightarrow e^+ e^-$ in heavy-ion experiments

$\pi \rightarrow \gamma + e^+e^-$

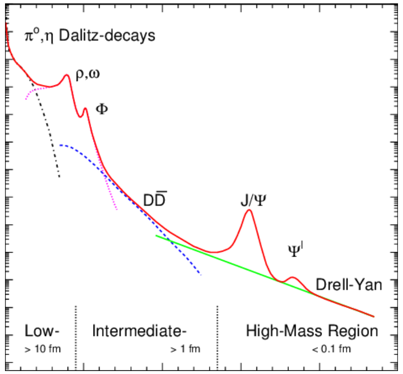
Standard model

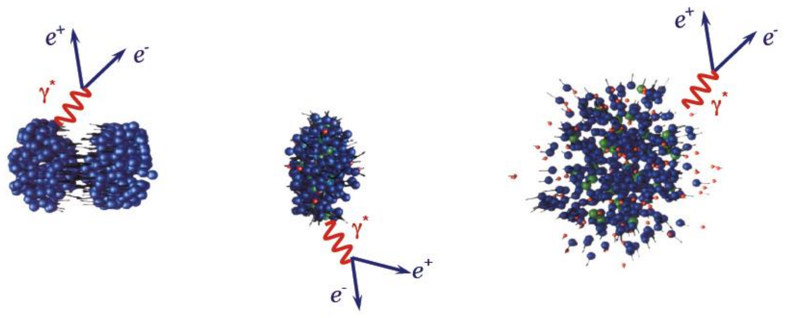
$\pi \rightarrow \gamma + U, \quad U \rightarrow e^+e^-$

Beyond SM

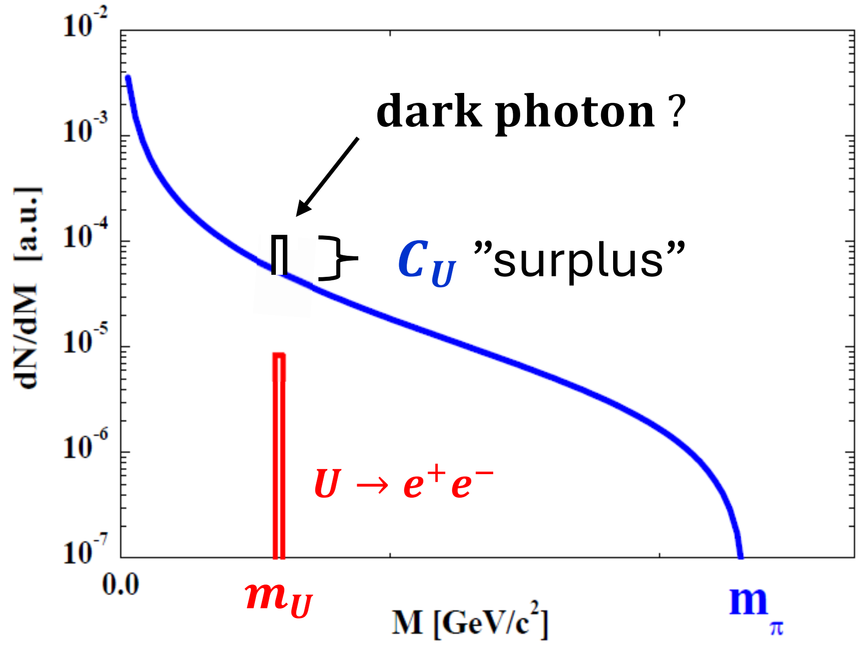


Possible dark photon observation by dilepton experiments





DOI:10.22323/1.238.0033

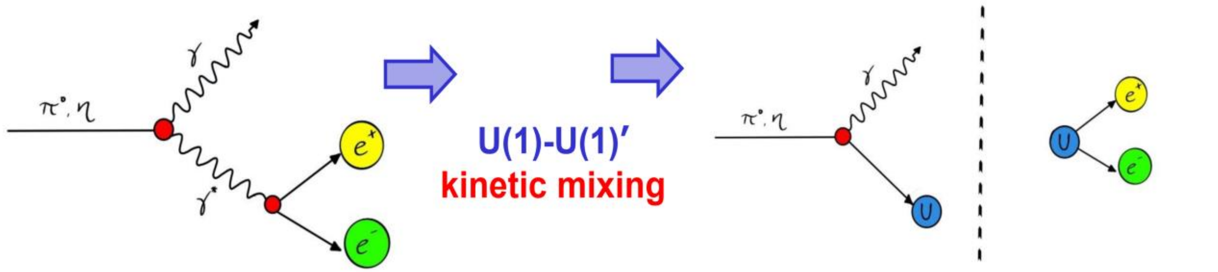


- **Dilepton spectra from SM sources are well studied by dilepton experiments from SIS to LHC energies (HADES, STAR, ALICE, …)**
- **Hadron production by p+p, p+A, A+A collisions.**
- **Dark photon production in hadronic and partonic decays.**

➔ Possibility for an indirect experimental observation of dark photons by electromagnetic decays $U \to e^+ e^-$ in heavy-ion experiments

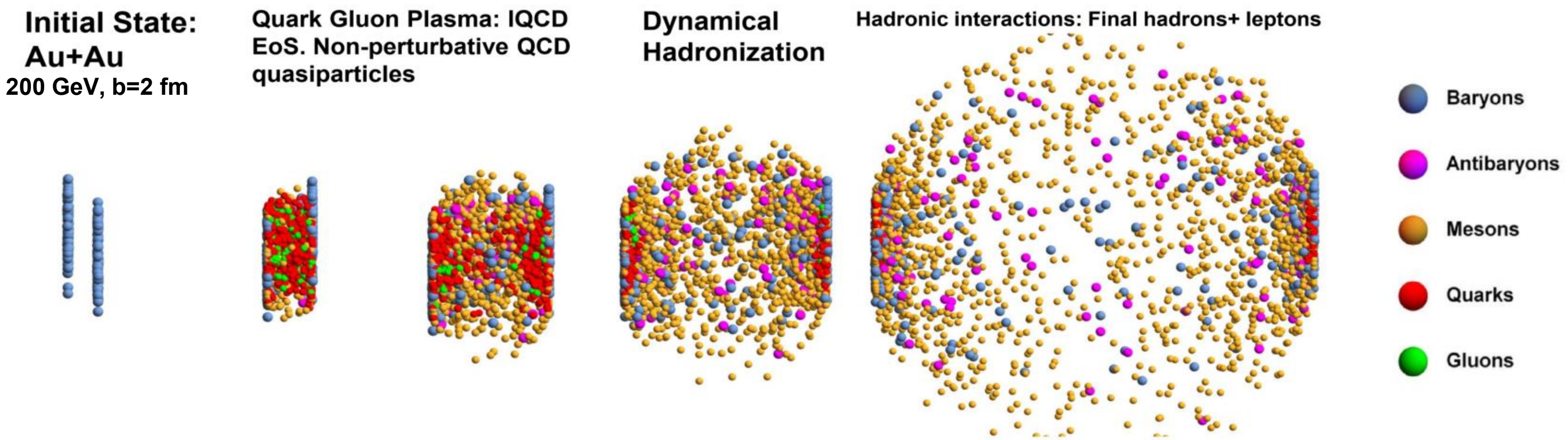
$$\pi \to \gamma + e^+e^- \qquad \pi \to \gamma + U, \quad U \to e^+e^-$$

Standard model **Beyond SM**



Theoretical modelling of dark photon production

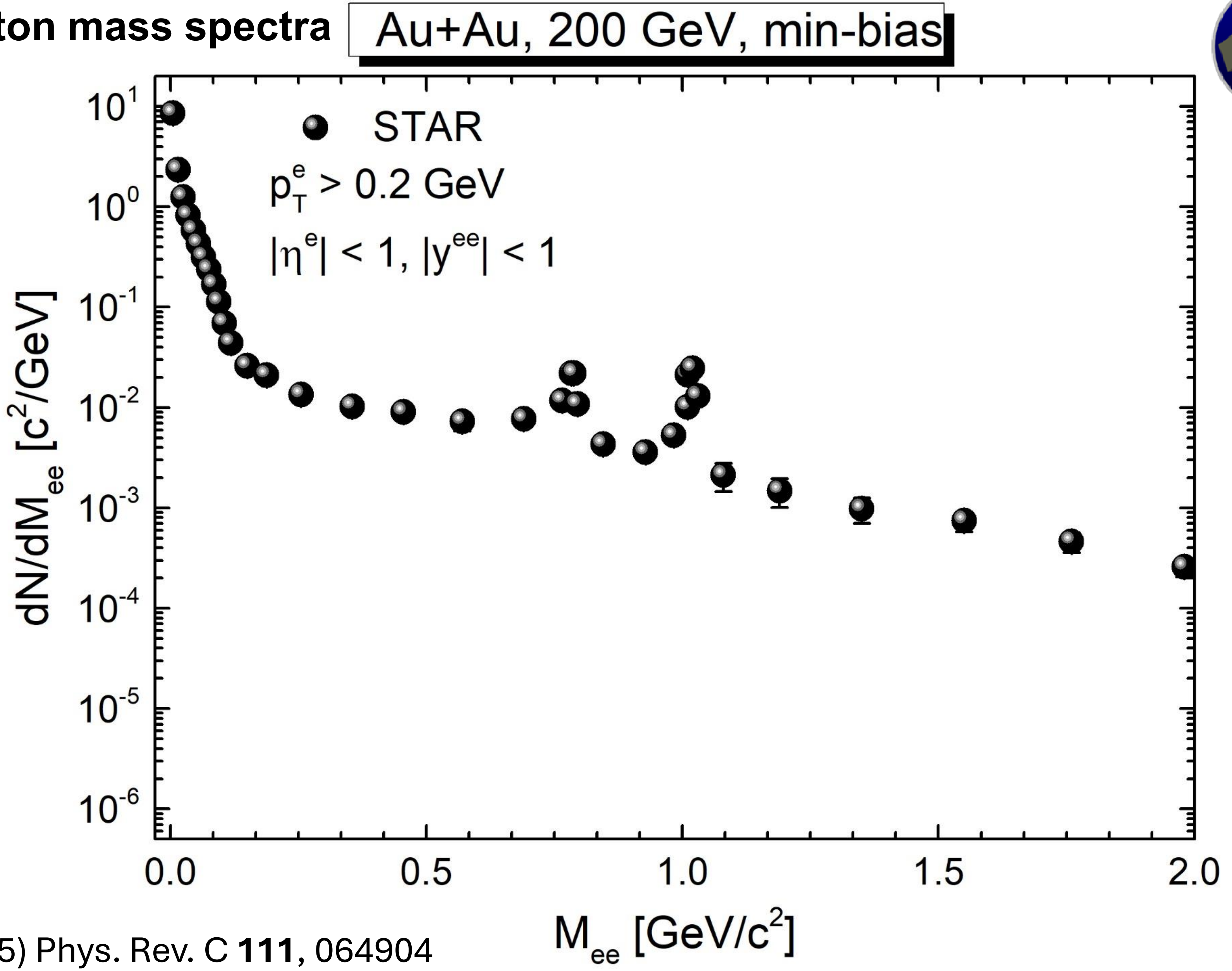
Parton-Hadron-String Dynamics (PHSD) is a non-equilibrium microscopic transport approach for the description of strongly-interacting hadronic and partonic matter created in heavy-ion collisions
Dynamics: based on the solution of generalized off-shell transport equations derived from Kadanoff-Baym many-body theory



➔ 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)

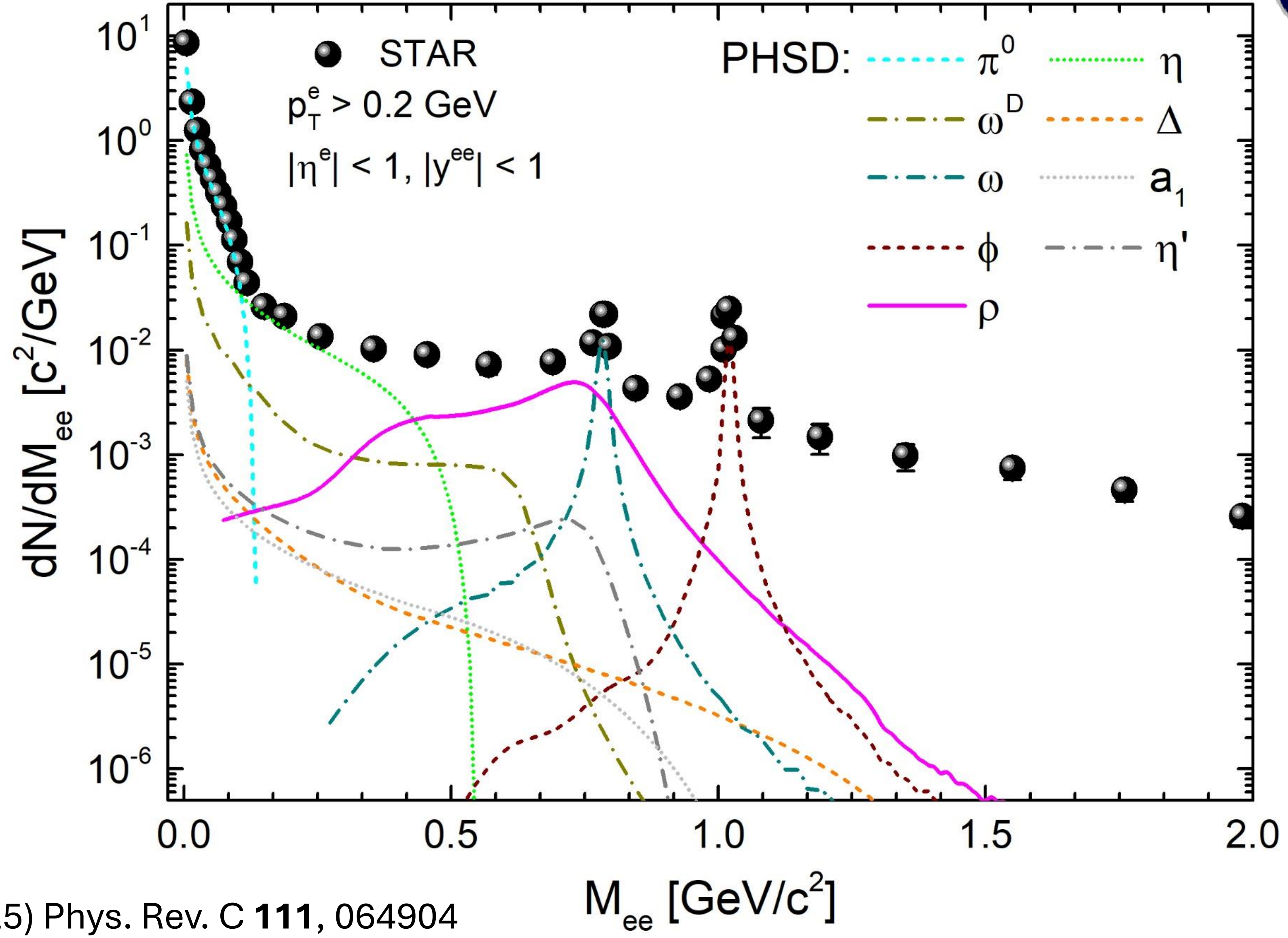
Dilepton mass spectra



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

Dilepton mass spectra

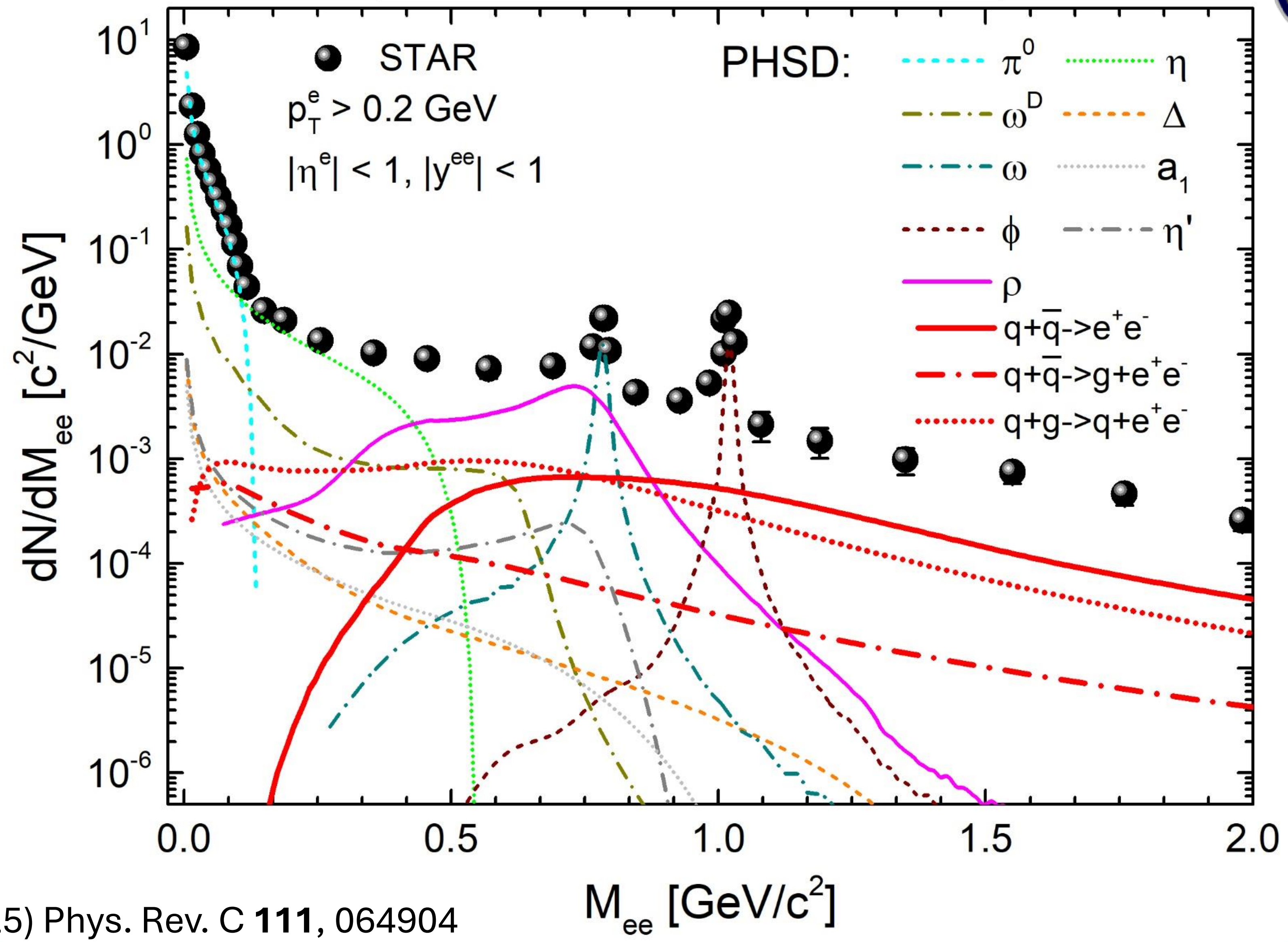
Au+Au, 200 GeV, min-bias



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

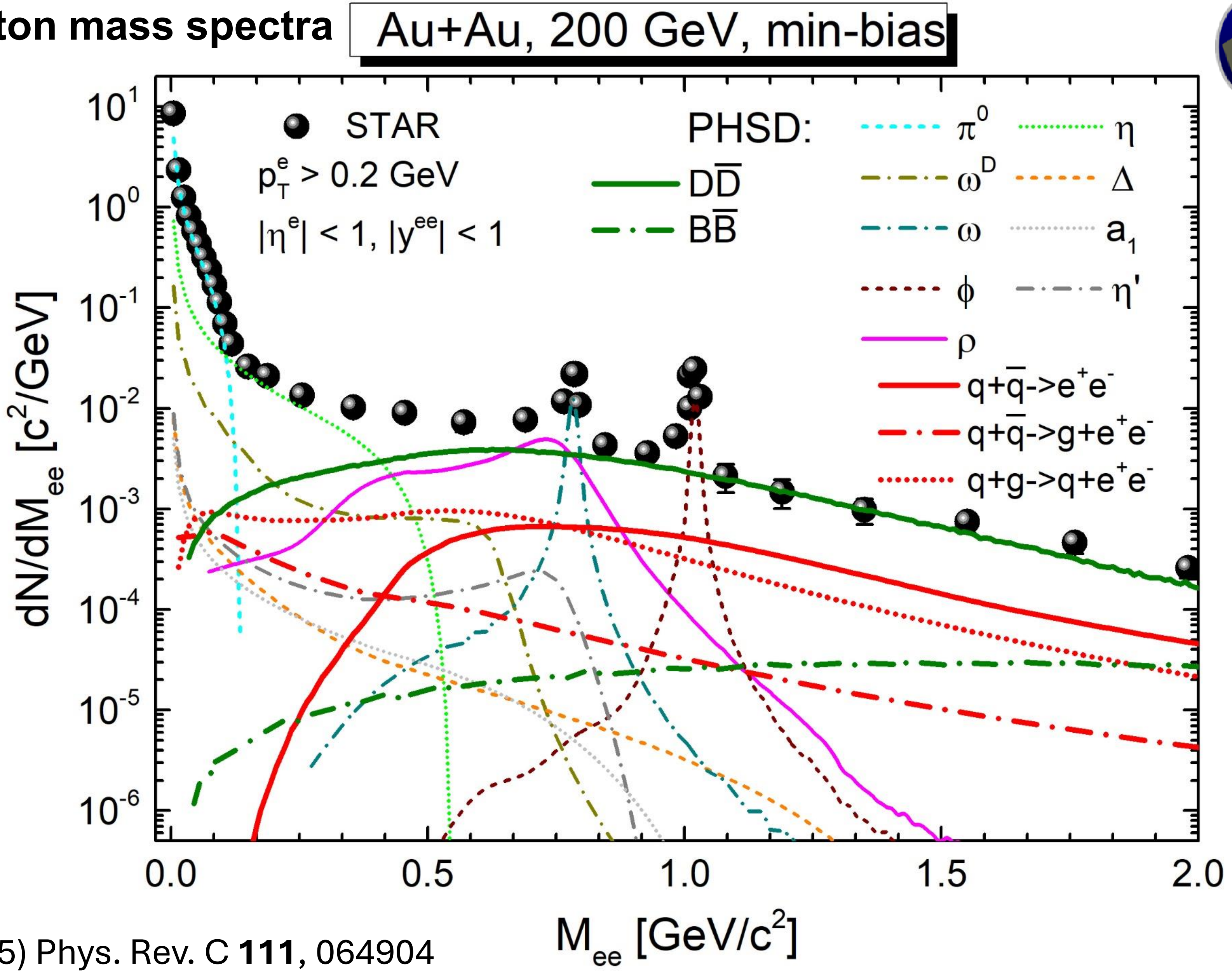
Dilepton mass spectra

Au+Au, 200 GeV, min-bias



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

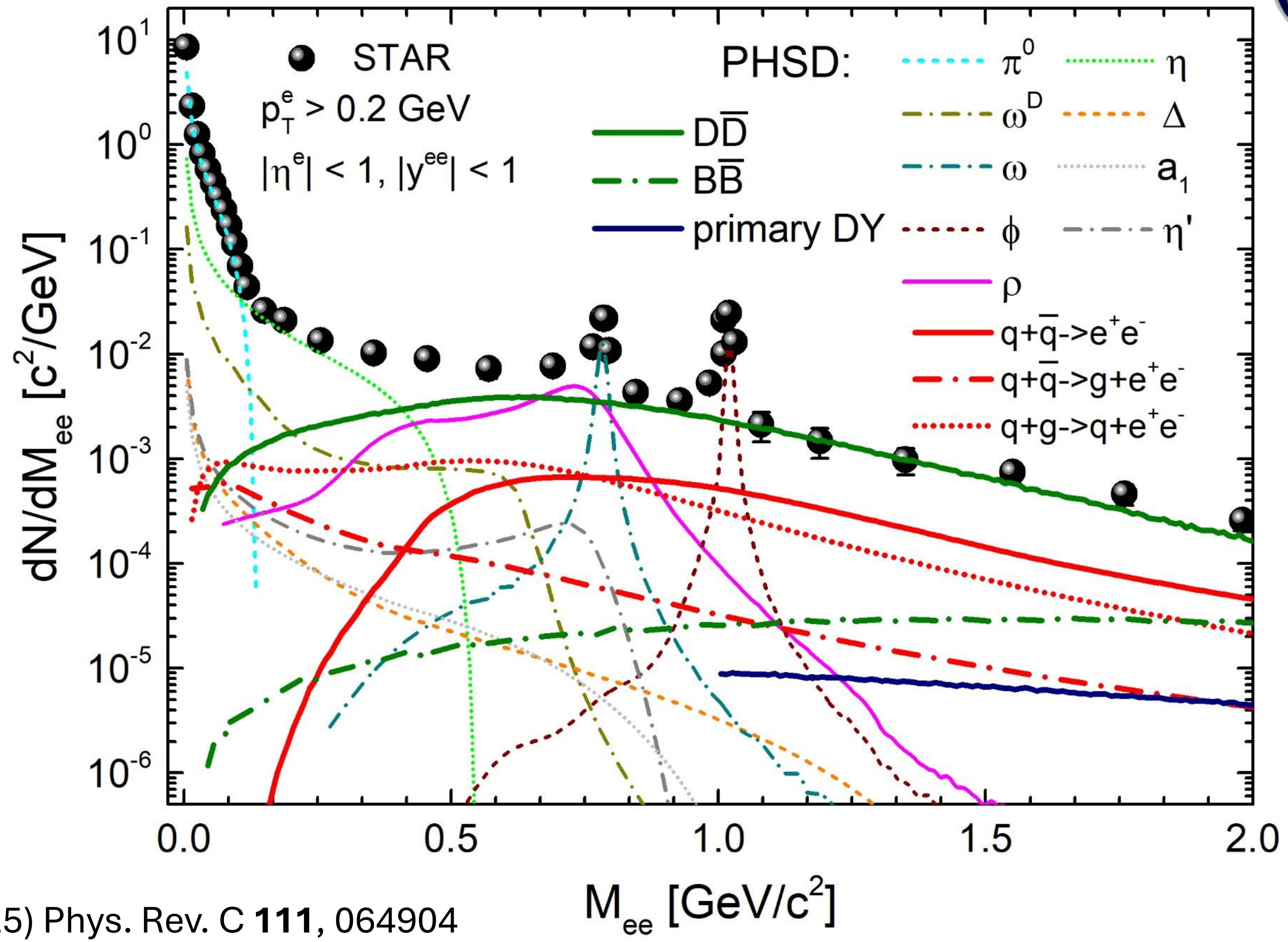
Dilepton mass spectra



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

Dilepton mass spectra

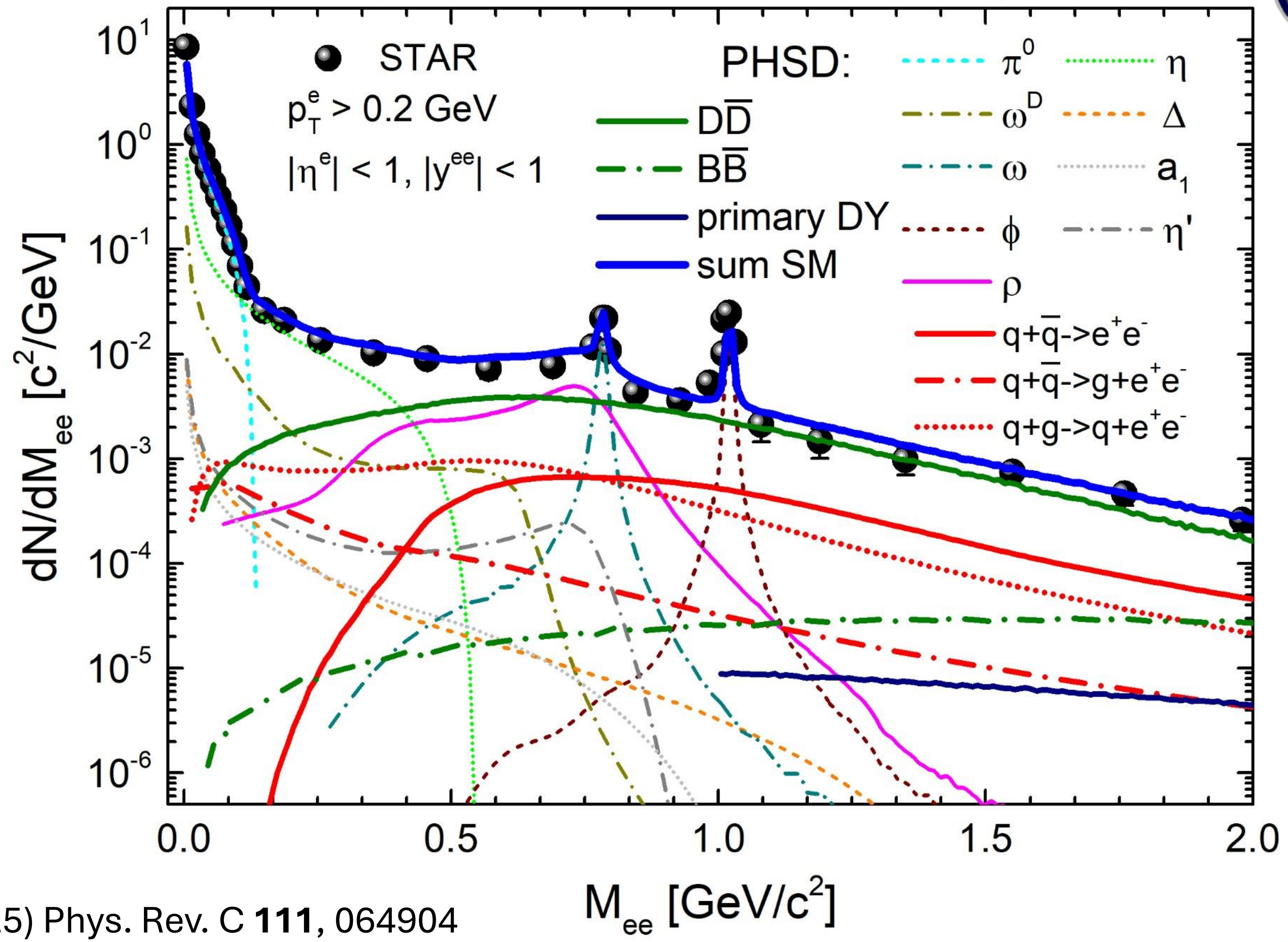
Au+Au, 200 GeV, min-bias



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

Dilepton mass spectra

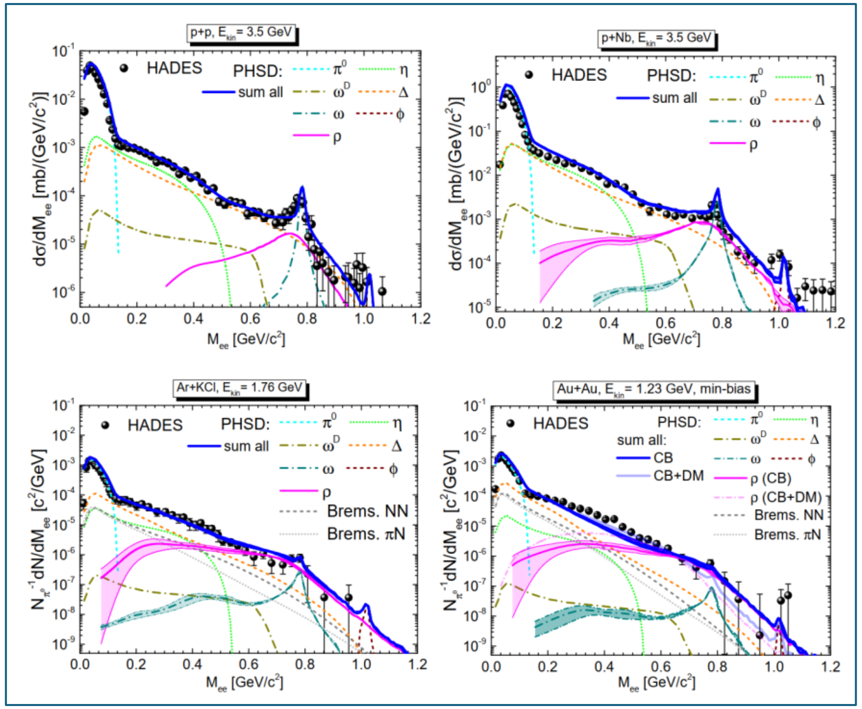
Au+Au, 200 GeV, min-bias



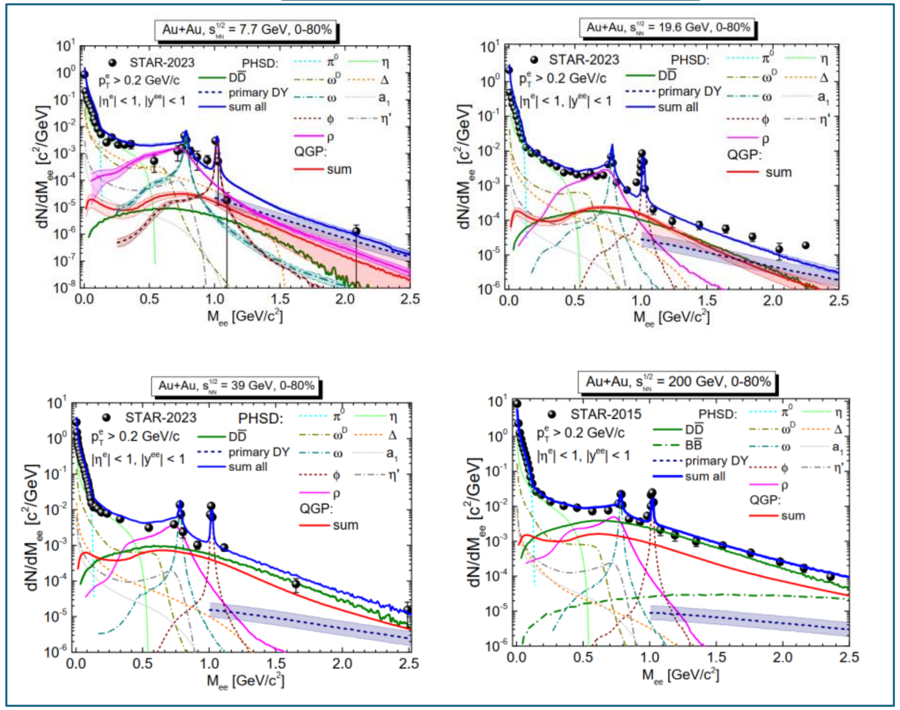
See A. Jorge et al. (2025) Phys. Rev. C **111**, 064904

Dilepton spectra from PHSD from SIS to RHIC energies

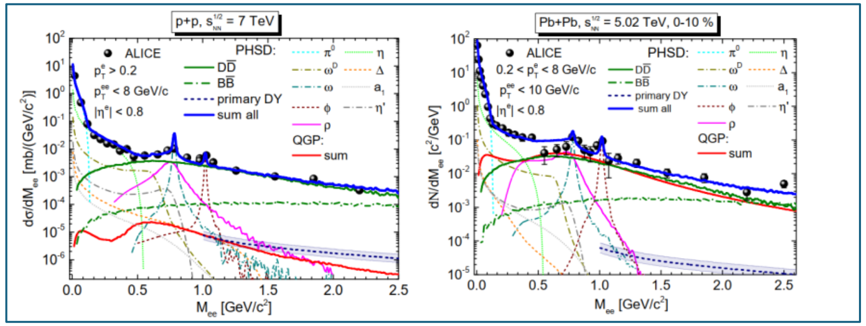
SIS-HADES



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

Dalitz Decay

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

$\Delta \to N U$

$\omega \to \pi^0 U$

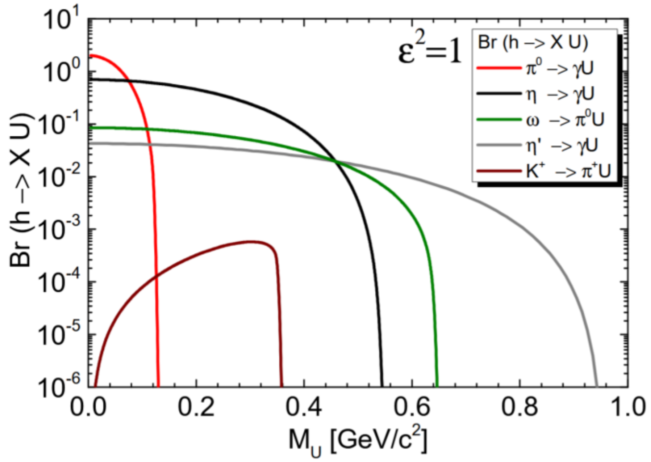
$K^+ \to \pi^+ U$

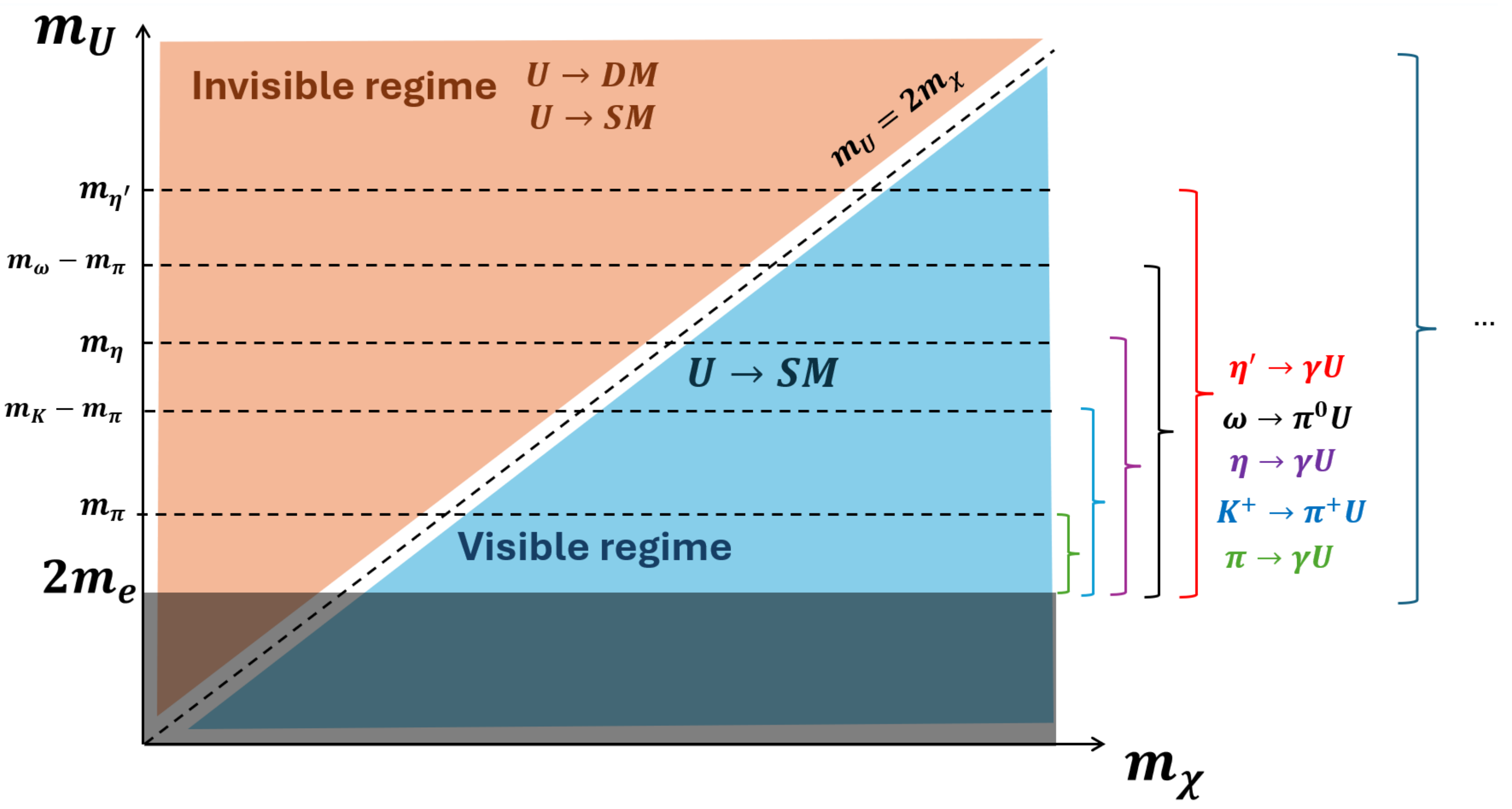
Direct Decay

$\rho, \phi, \omega \to U$

$q\,\bar{q} \to U$

$U \to e^+ e^-$





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

Dark photon production in PHSD

N_h

Total dilepton yield from U-boson decay of mass m_U:

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

$$h \to X + U$$

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

Dark photon production in PHSD

Total dilepton yield from U-boson decay of mass m_U:

N_h

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

$$h \to X + U$$

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

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

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

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

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

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

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

M. Pospelov (2009) PRD 80, 095002

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

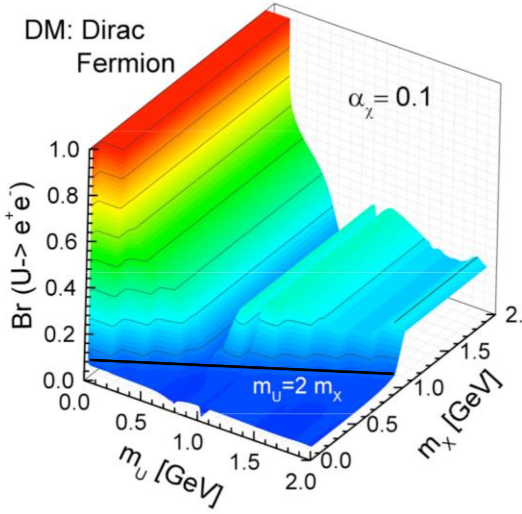
B. Battel , et al. (2009) PRD 79, 115008

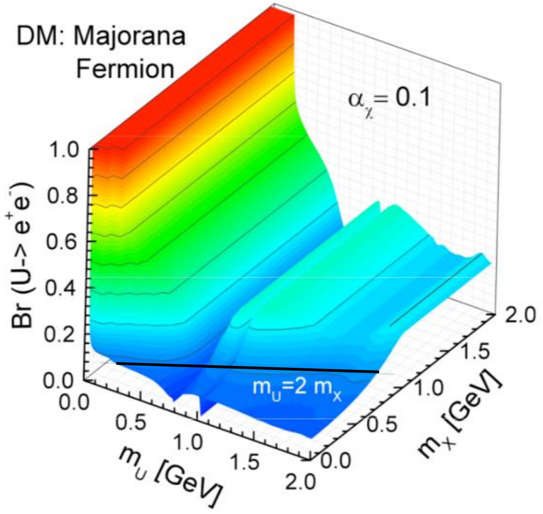
$$Br(q\,\bar q\to U) = \boldsymbol{\varepsilon^2}\frac{\Gamma^{PHSD}_{q\,\bar q\to e^+e^-}}{\Gamma_T(V)}$$

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





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)

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

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

Obtain constraints by requesting that thr 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

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)

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

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

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

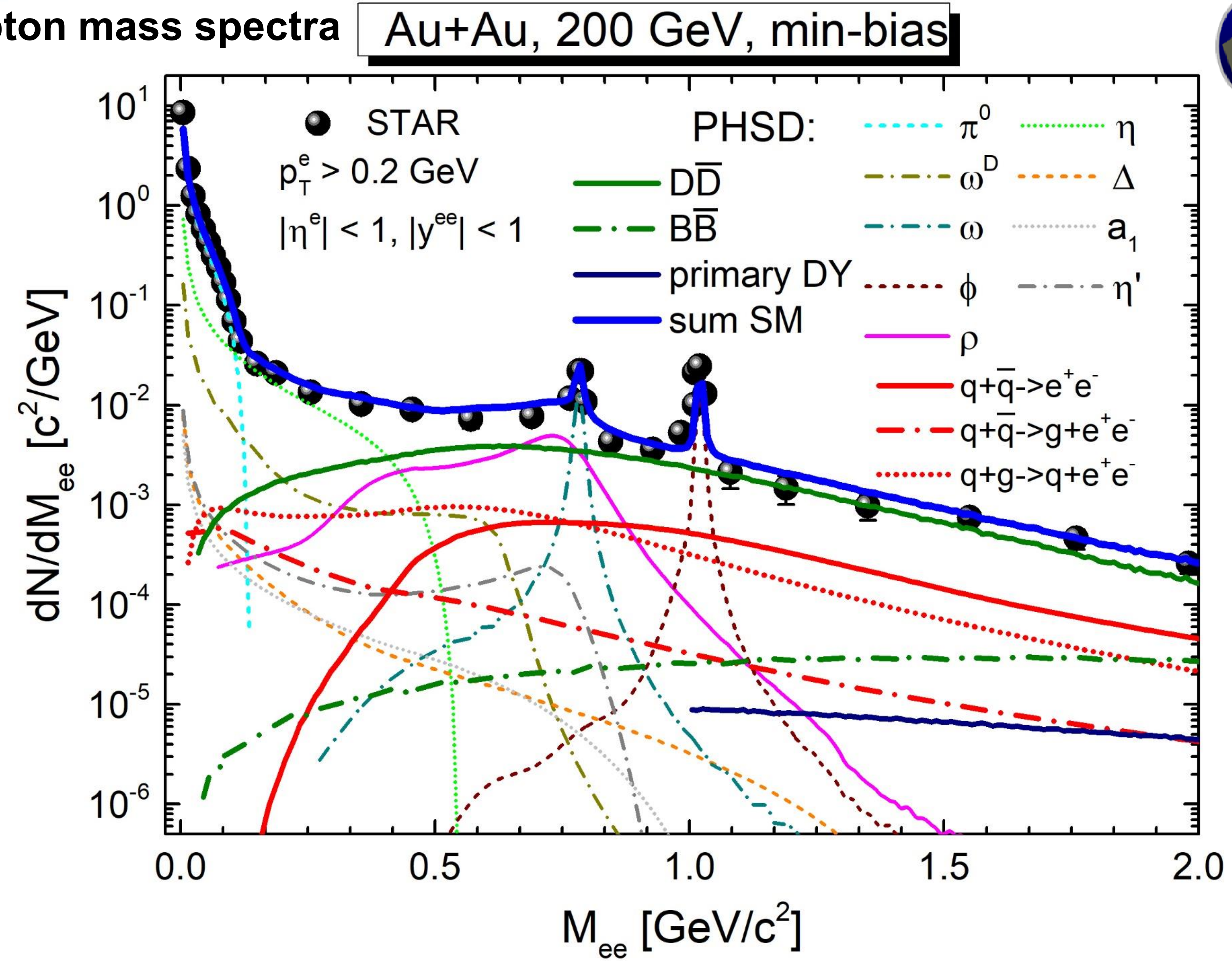
C_U → **controls the allowed "surplus" dilepton yield resulting from dark photons on top of the total SM yield**

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

Calculate $\varepsilon^2(M_U)$ by assuming C_U : e.g. C_U =0.1 % DM extra yield to the SM yield

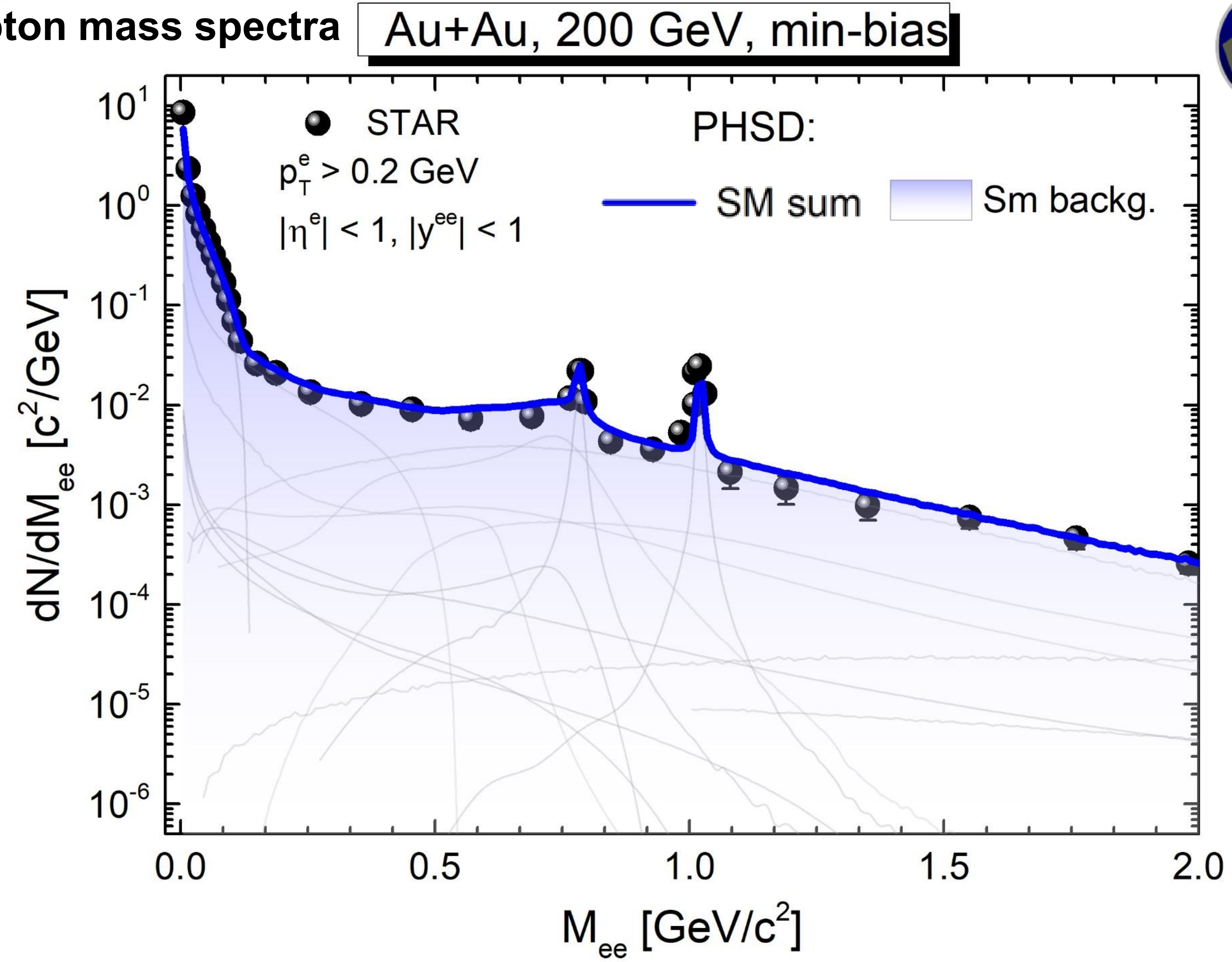
See **arXiv:2507.11163** and
I. Schmidt et al. (2021)
Phys. Rev. D **104**, 015008

Dilepton mass spectra



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

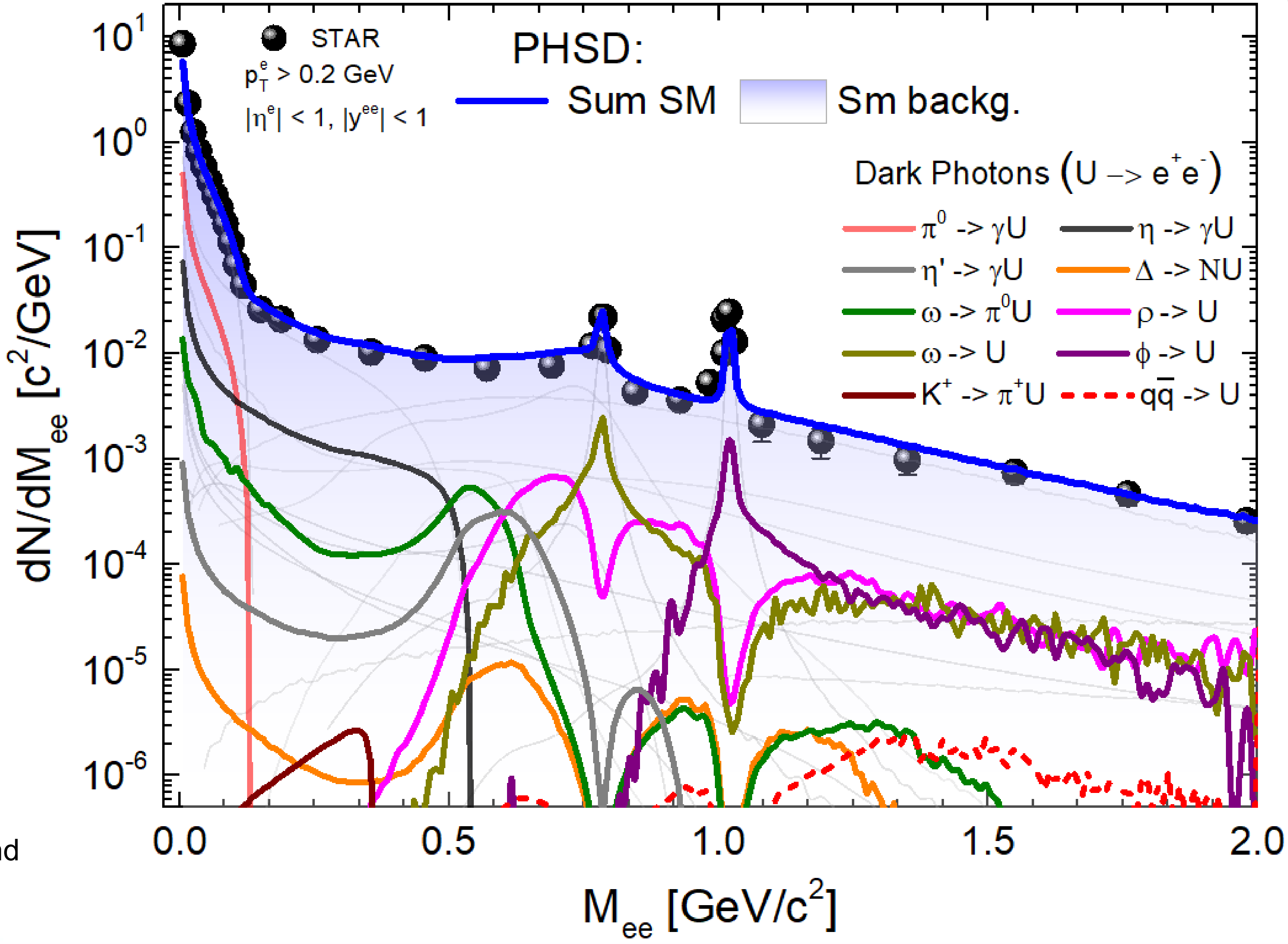
Dilepton mass spectra



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

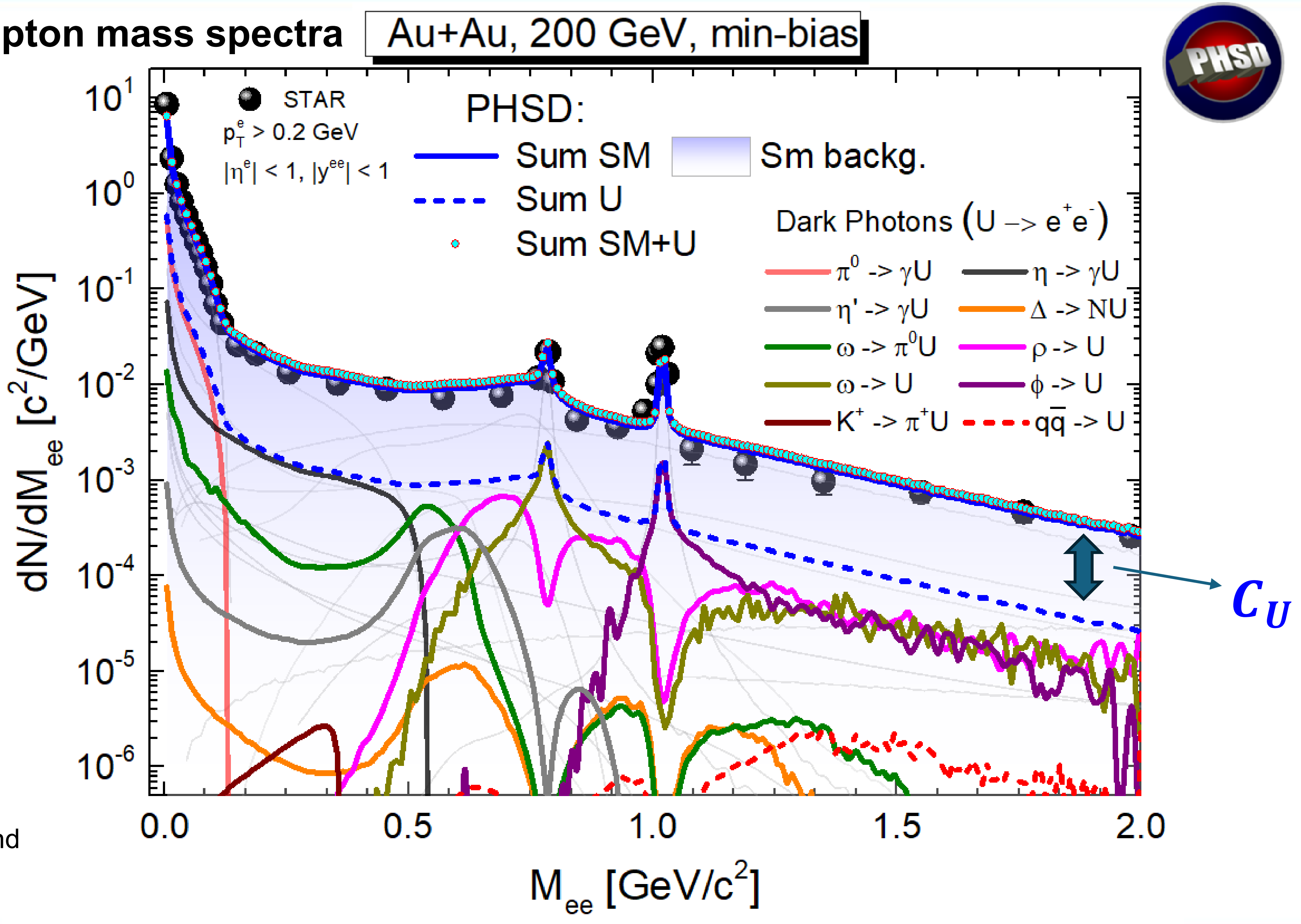
Dilepton mass spectra

Au+Au, 200 GeV, min-bias



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

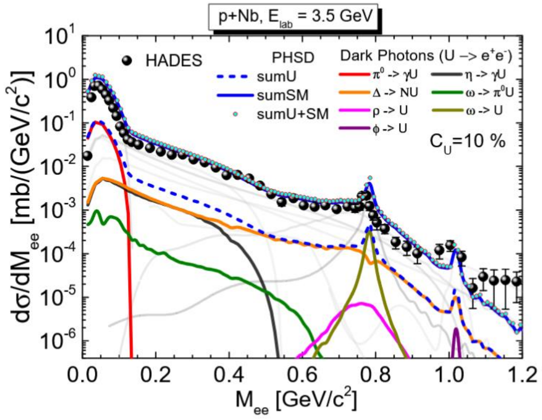
Dilepton mass spectra

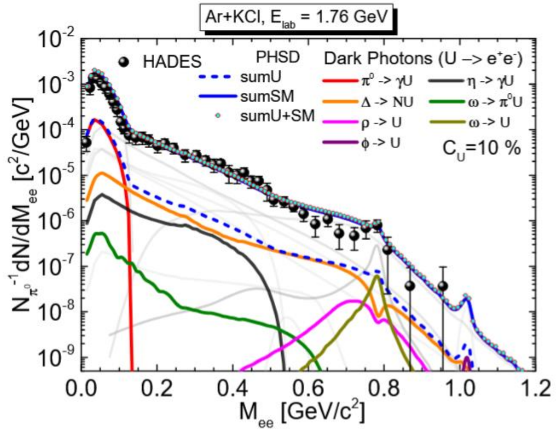


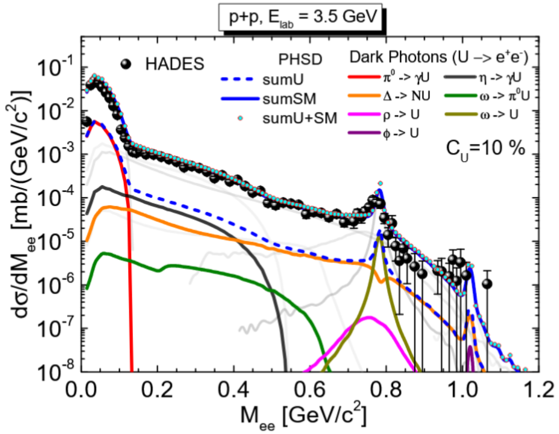
See **arXiv:2507.11163** and I. Schmidt et al. (2021) Phys. Rev. D **104**, 015008

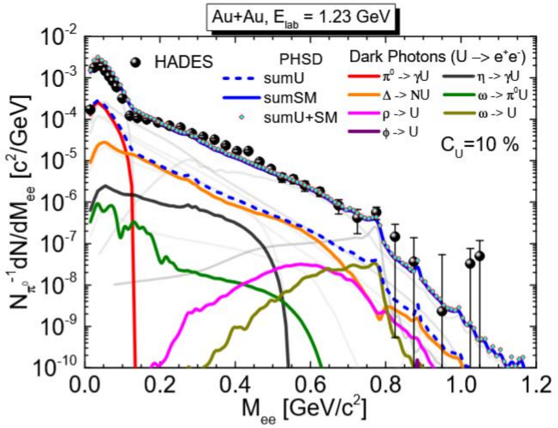
Dilepton spectra from U-boson decays

SIS-HADES

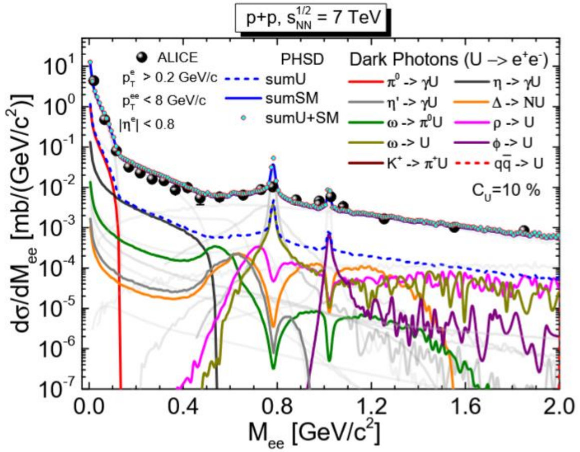


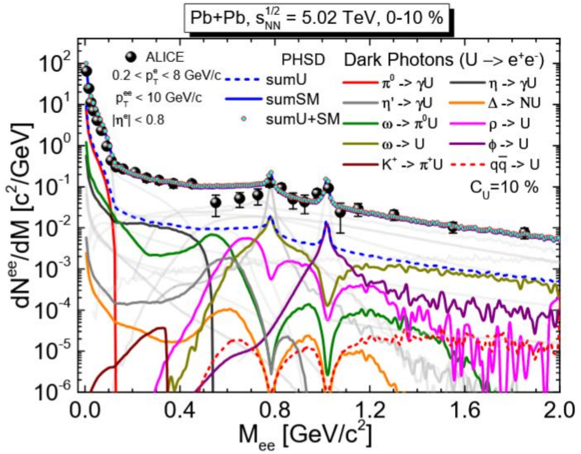




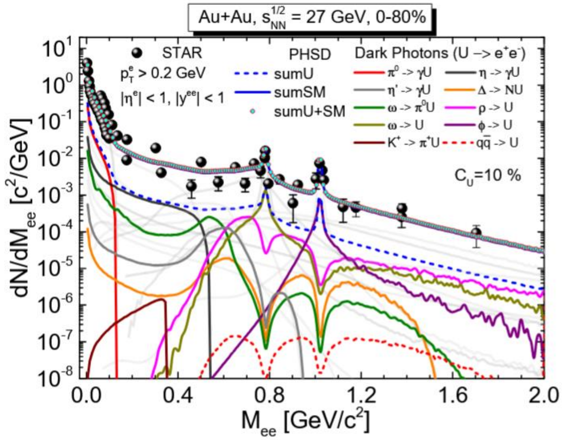


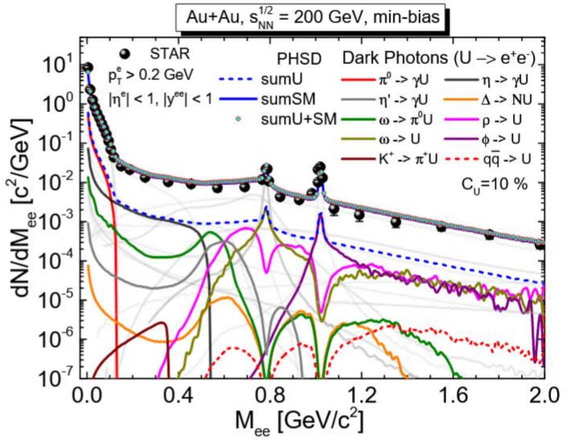
BES-RHIC-STAR





LHC-ALICE



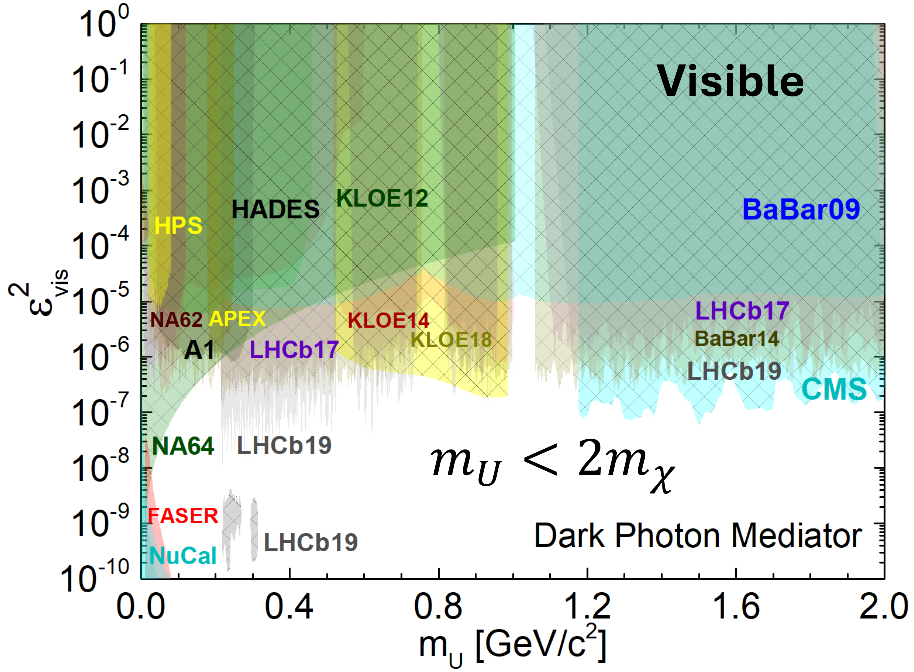


See **arXiv:2507.11163**

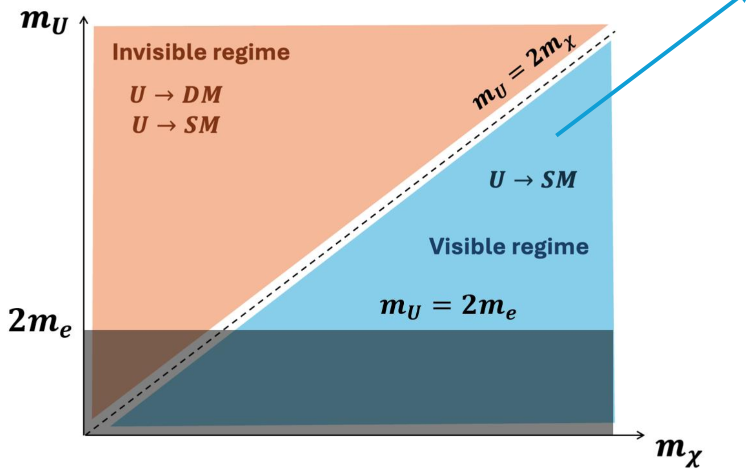
- **The contributions from $U \rightarrow e^+e^-$ are added with C_U=10% allowed surplus of the total SM yield ➔ the total sum is still in a good agreement with exp. data**

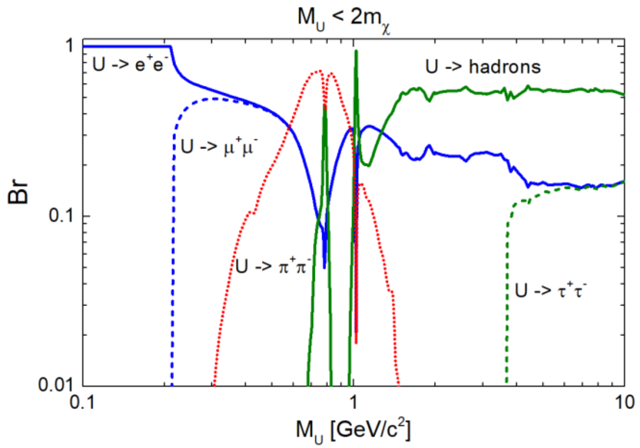
I. Schmidt et al. (2021)
Phys. Rev. D **104**, 015008

Kinetic Mixing parameter $\varepsilon^2(m_U)$: Experimental Upper Limits

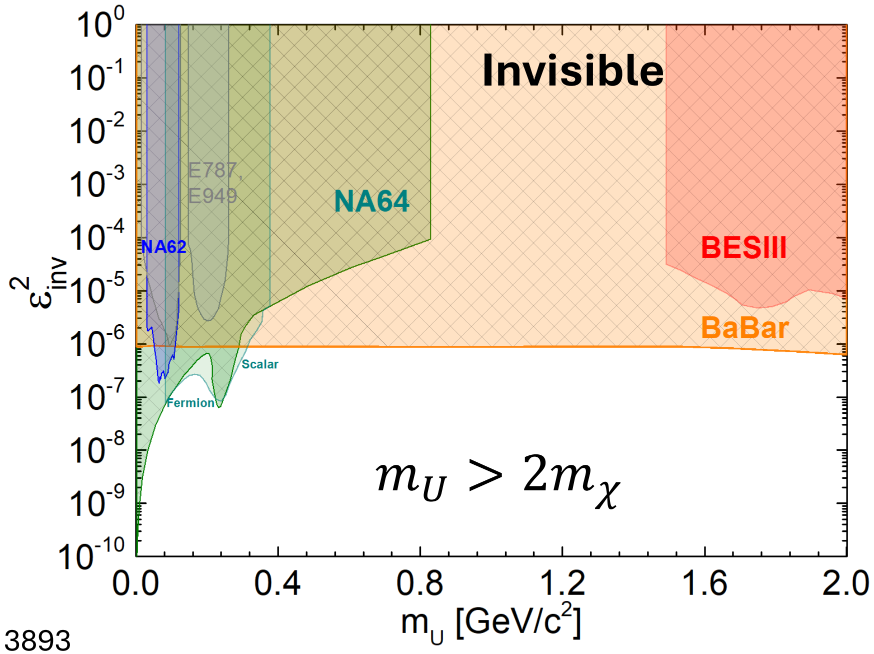


Data from darkcast
Arxiv:1801.04847

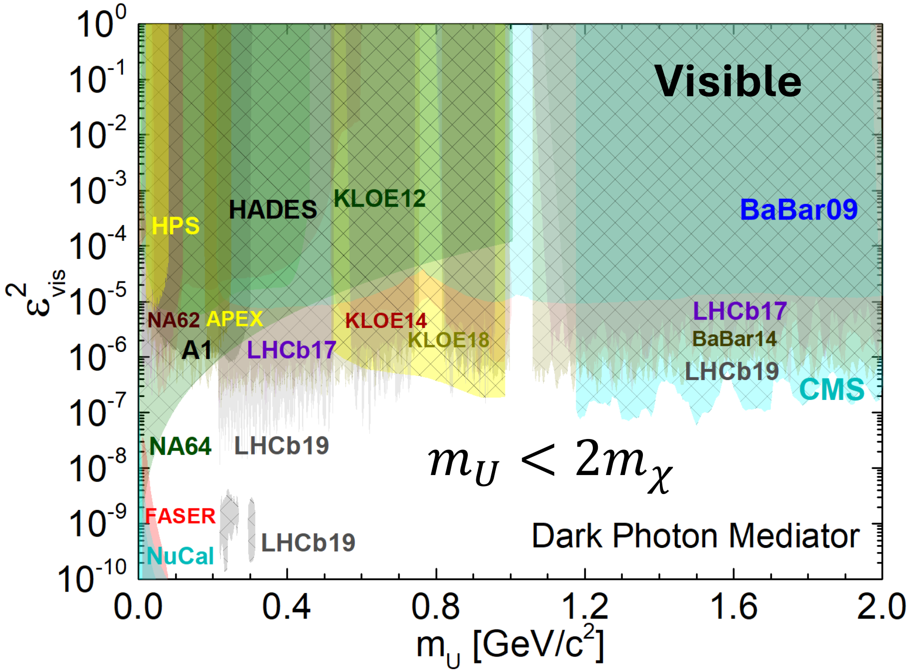




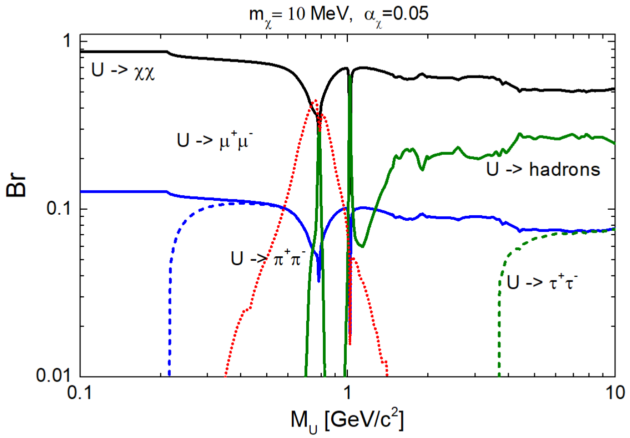
Kinetic Mixing parameter $\varepsilon^2(m_U)$: Experimental Upper Limits

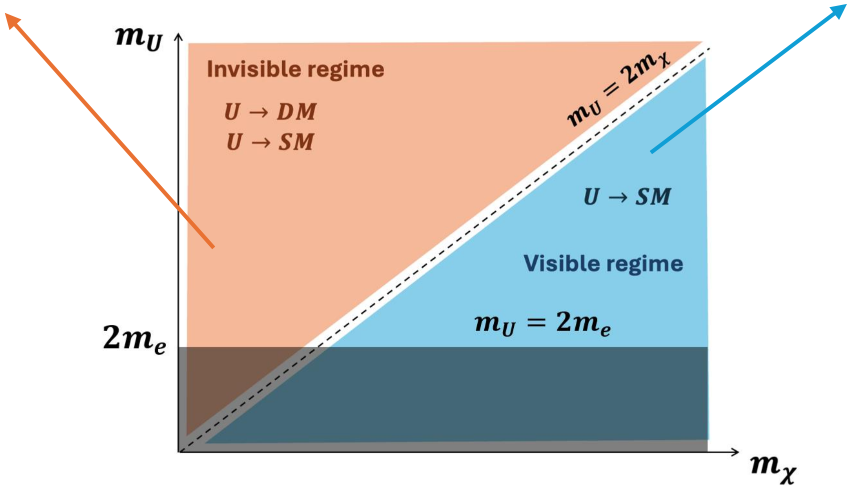


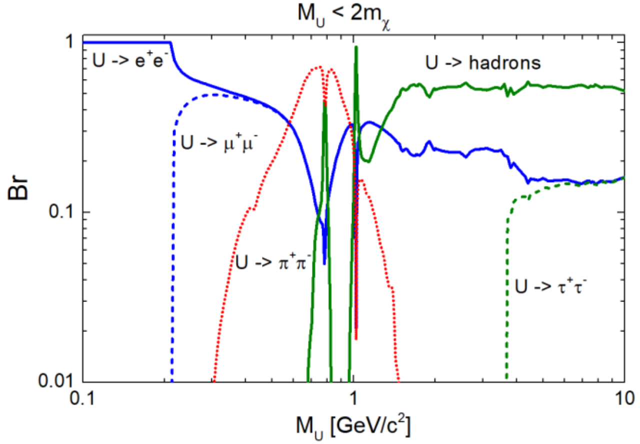
Data from
Arxiv:2209.13893



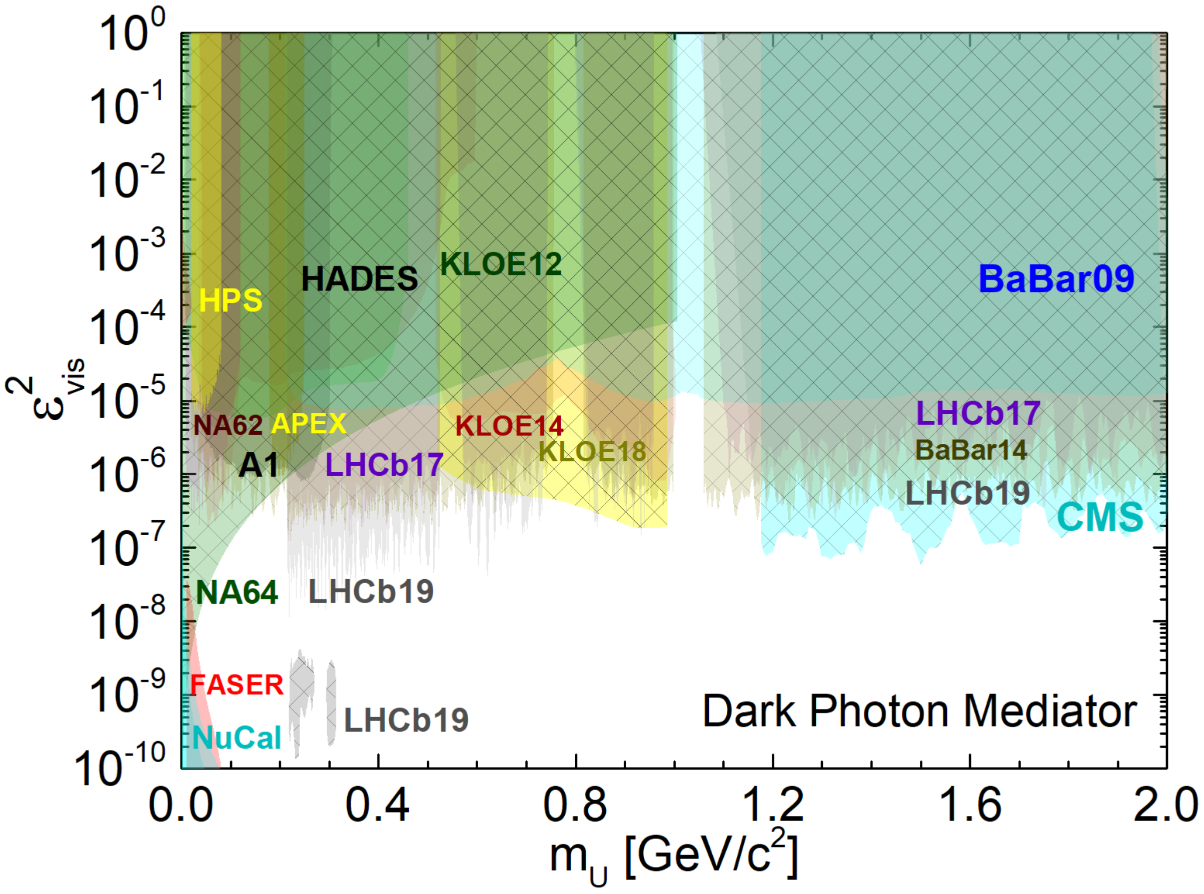
Data from darkcast
Arxiv:1801.04847

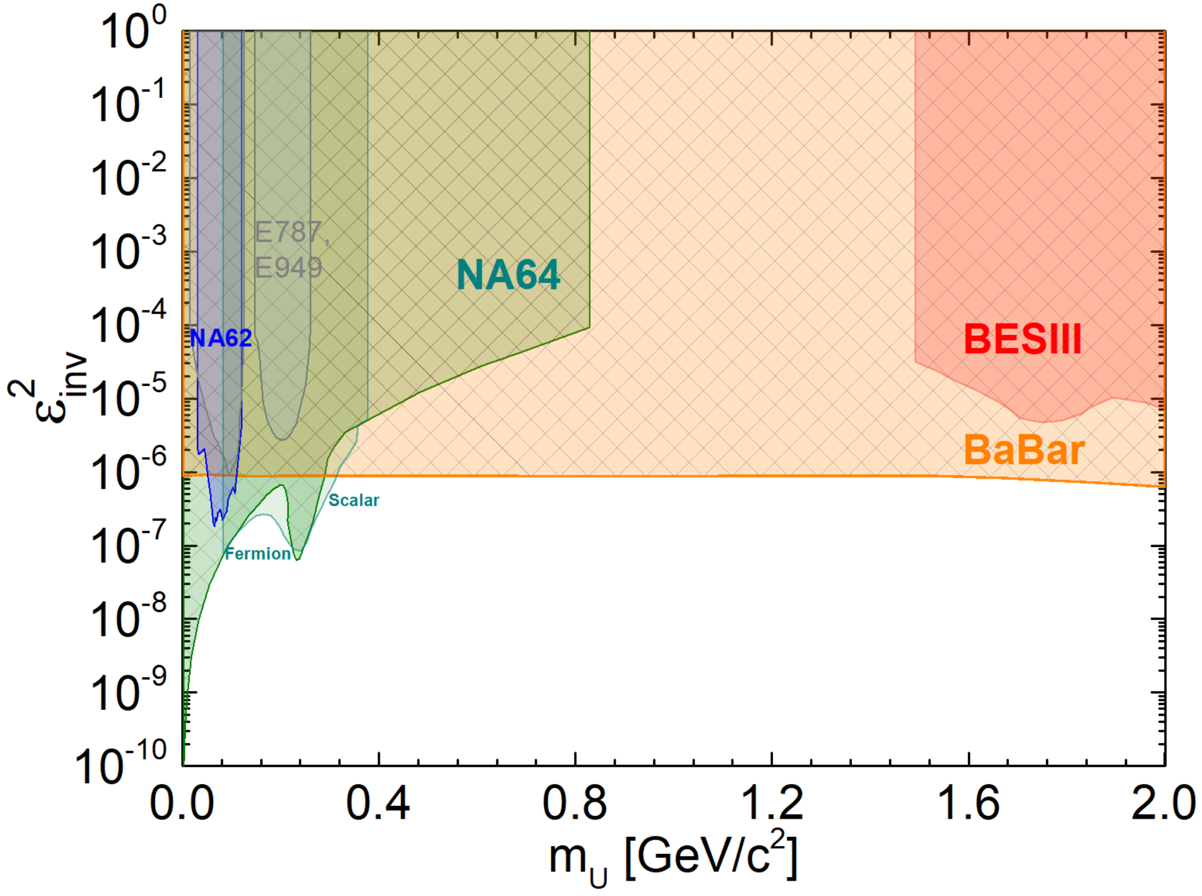






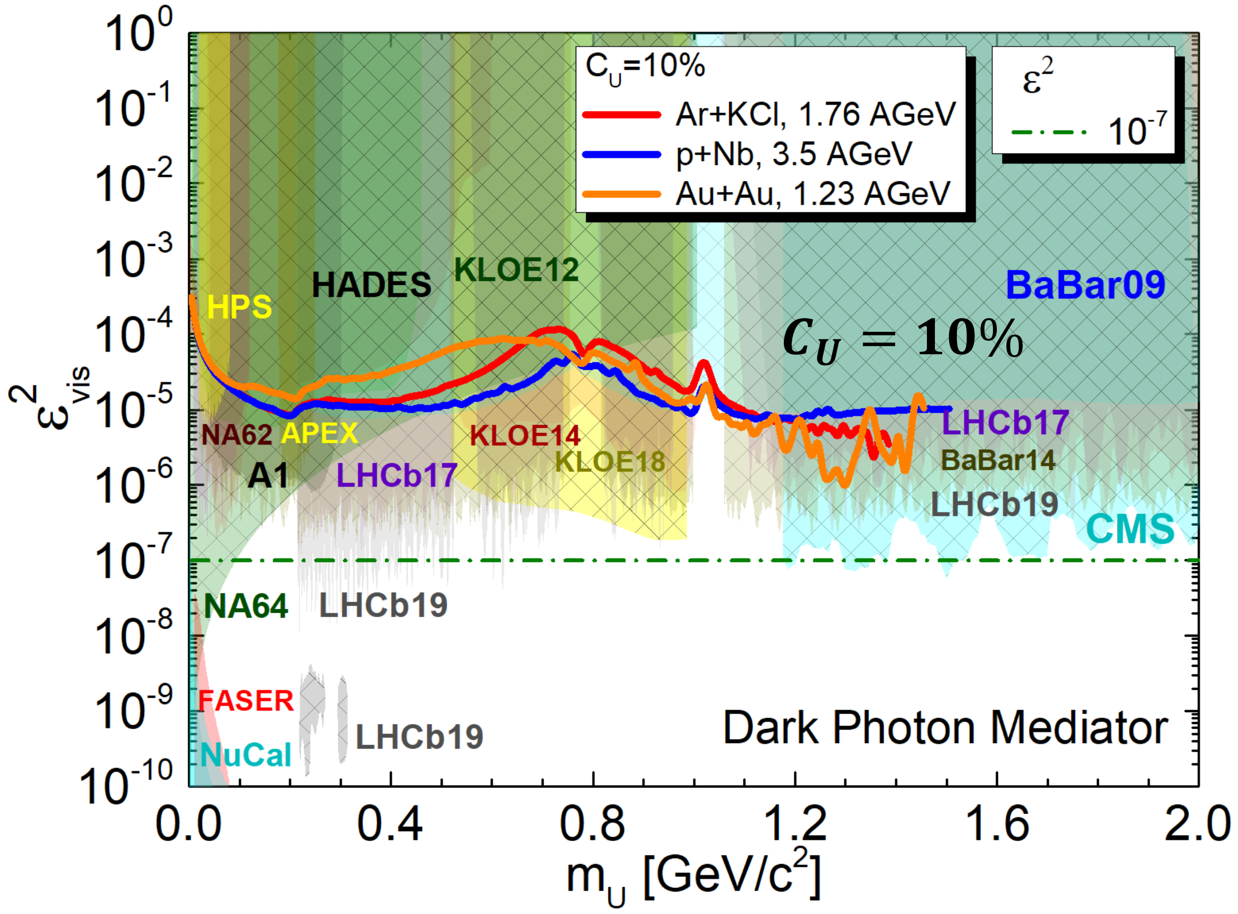
Kinetic Mixing parameter $\varepsilon^2(m_U)$

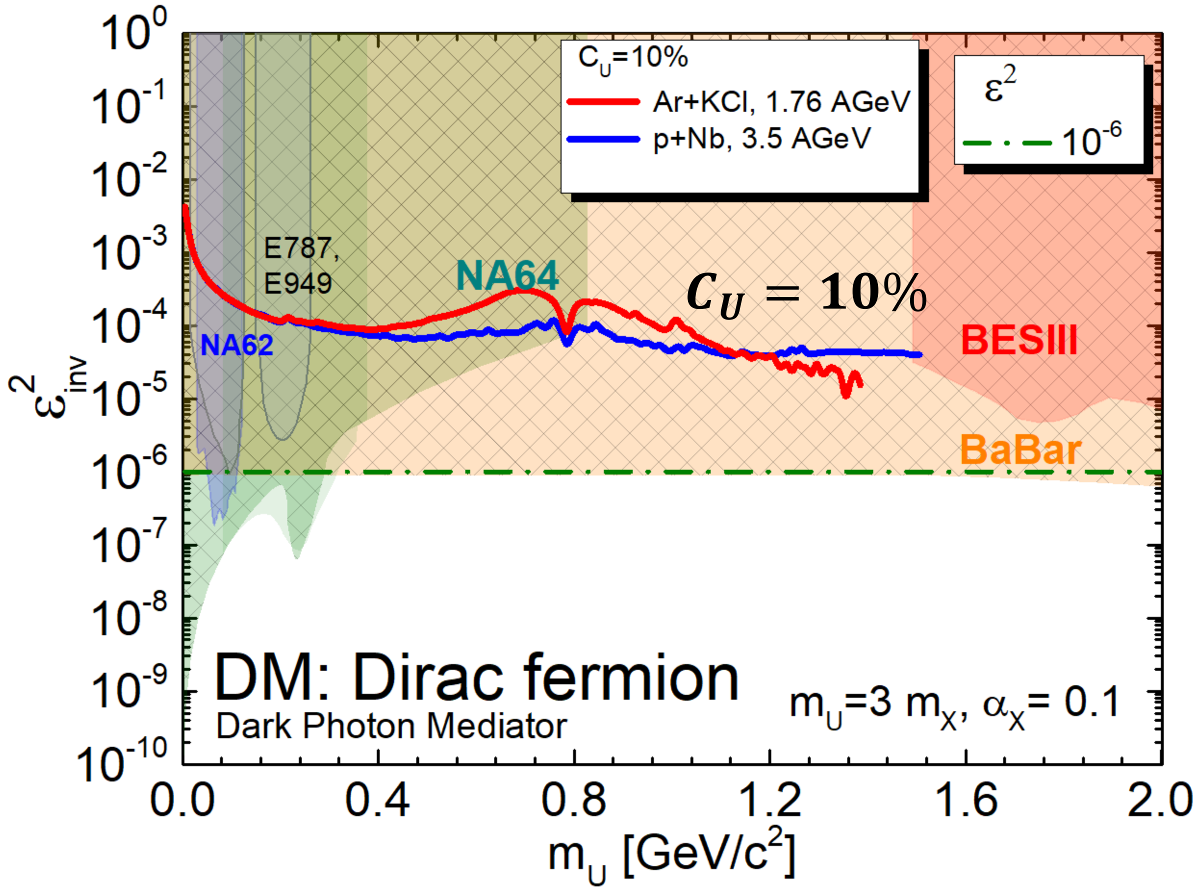




A. Jorge et al. (2025): **arXiv:2507.11163**

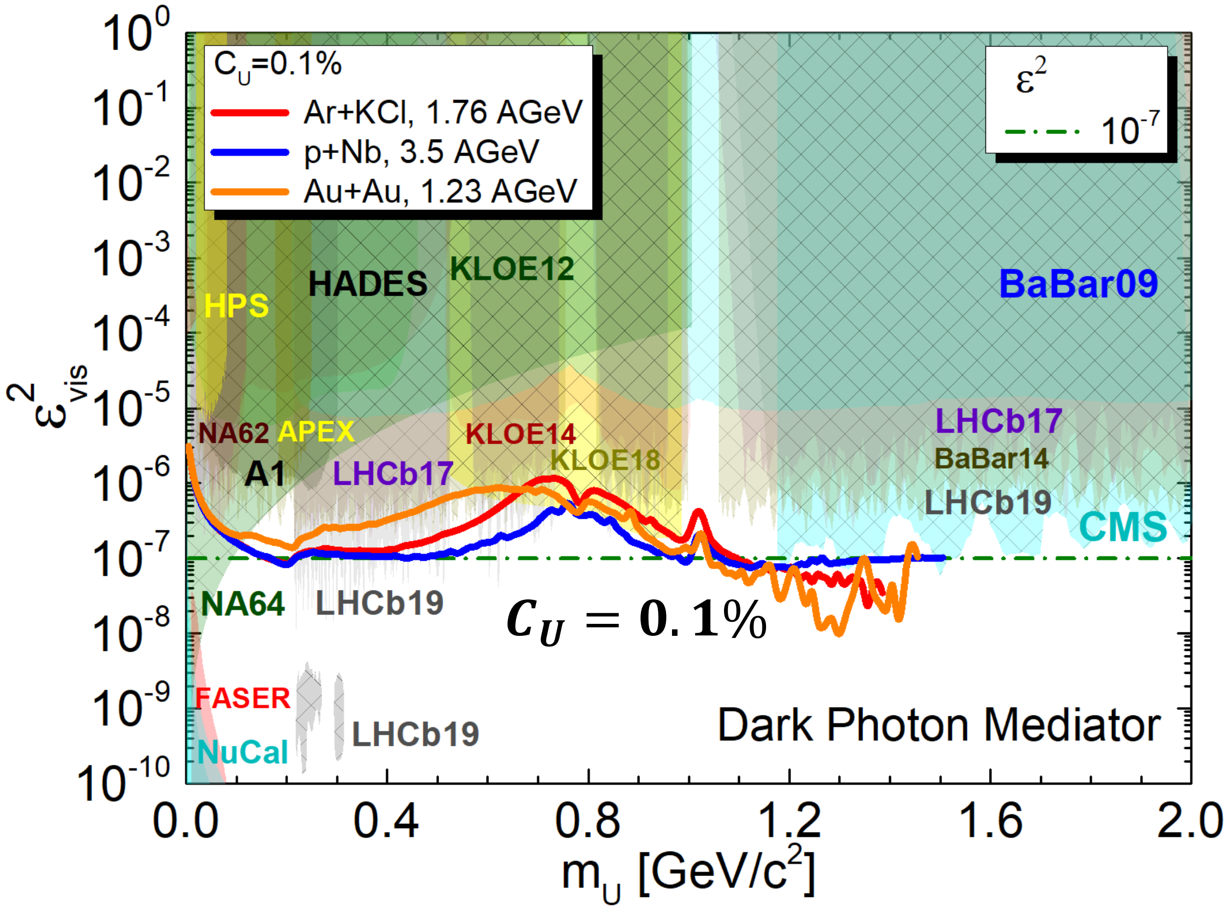
Kinetic Mixing parameter $\varepsilon^2(m_U)$

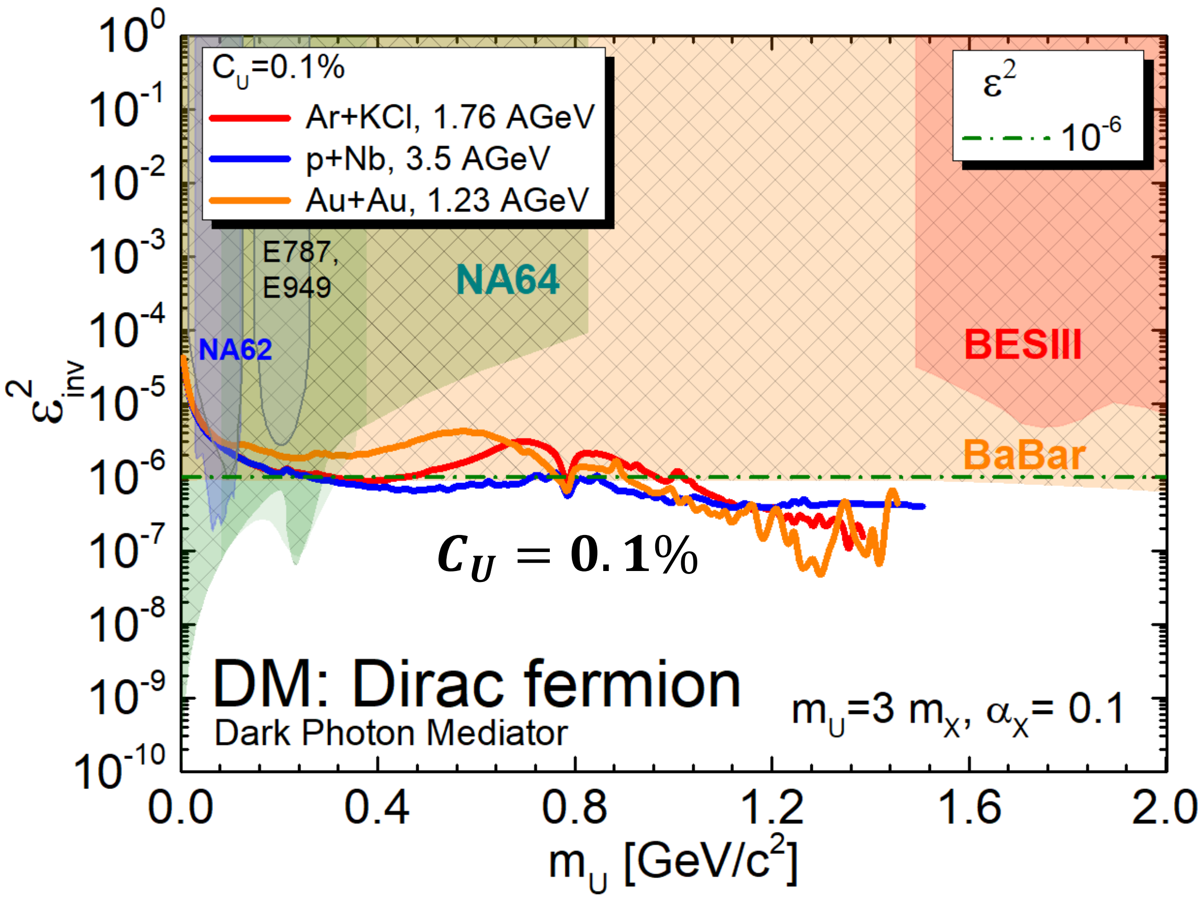




A. W. Romero Jorge et. al, PRD 113 (055052) 2026

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



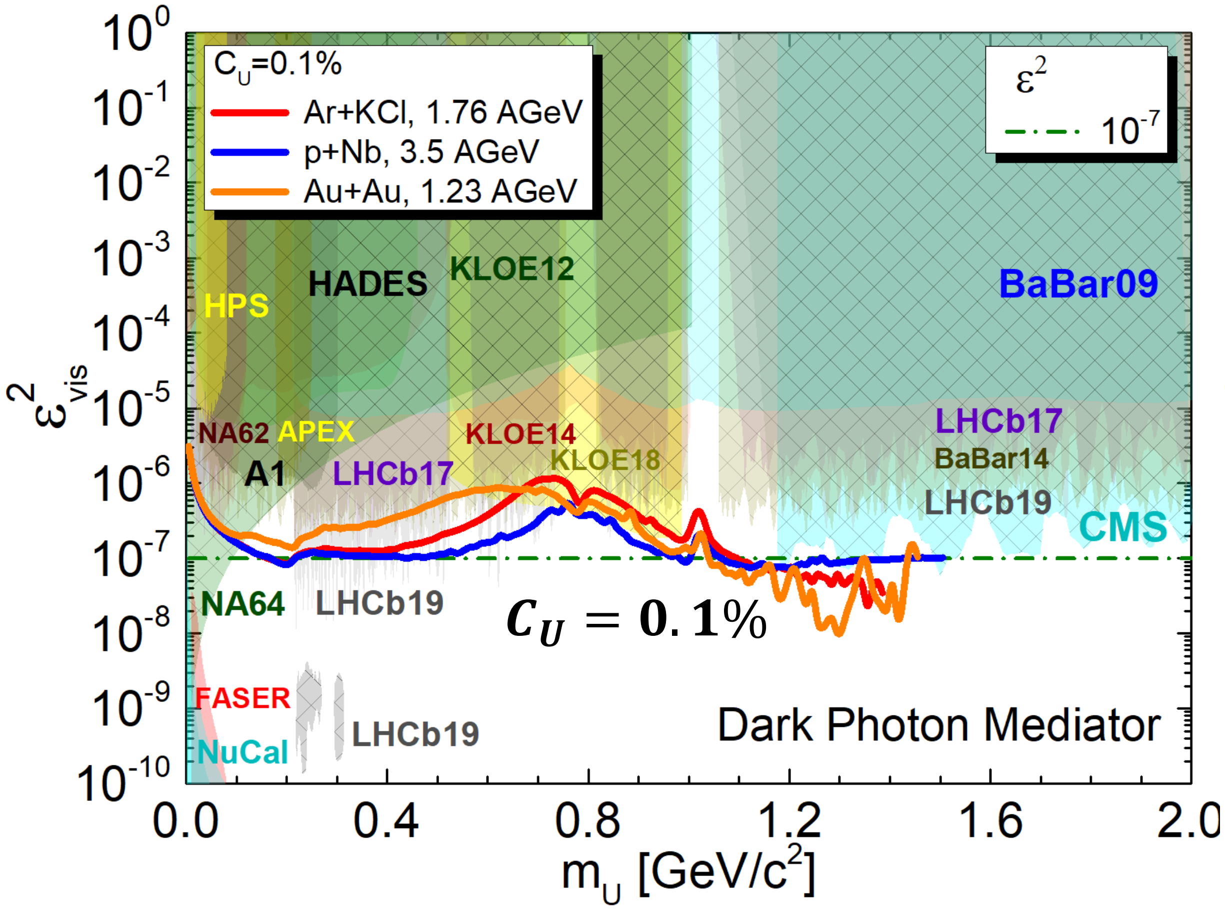


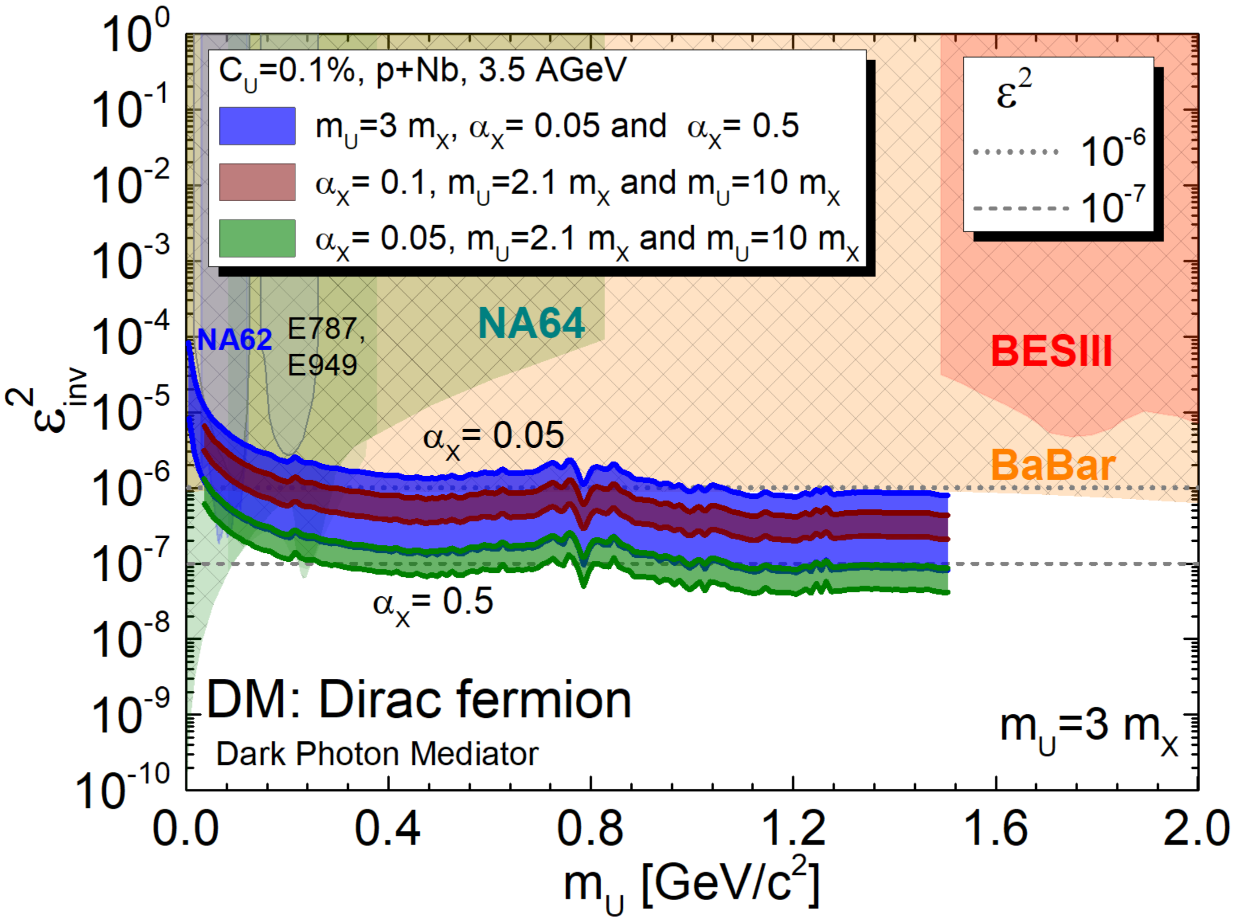
$\varepsilon^2 \sim 10^{-7}$

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

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

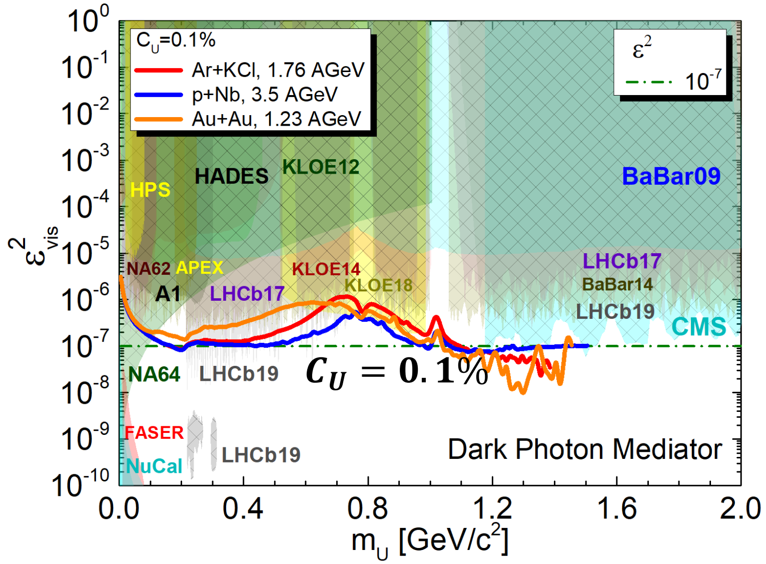
Kinetic Mixing parameter $\varepsilon^2(m_U)$

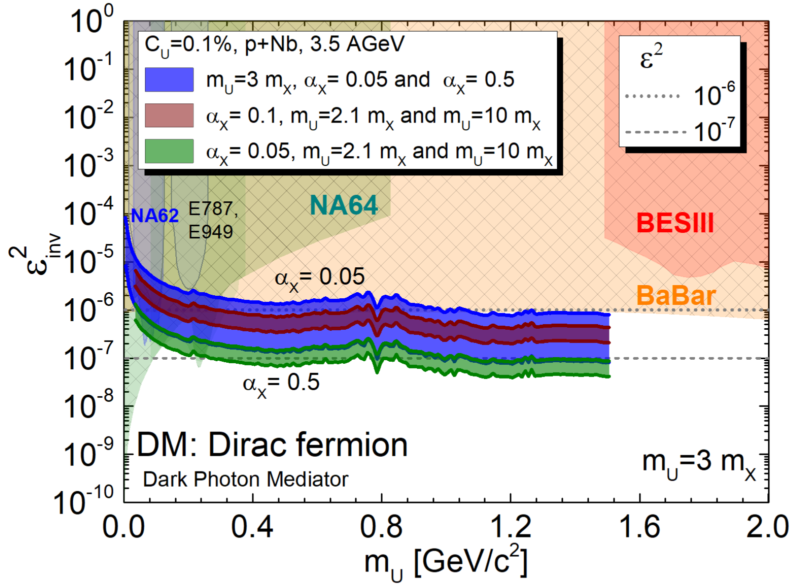




A. W. Romero Jorge et. al, PRD 113 (055052) 2026

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





- **Data from LHCb, KLOE, and CMS demand tighter constraints, compatible only if the possible dark photon contribution is reduced to $C_U = 0.05 - 0.1\%$**
- **These findings are consistent with global experimental exclusion limits, confirming that dilepton measurements are highly sensitive probes for testing dark photon scenarios.**

Experimental data of high precision are needed to reduce the upper limit for ε^2

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

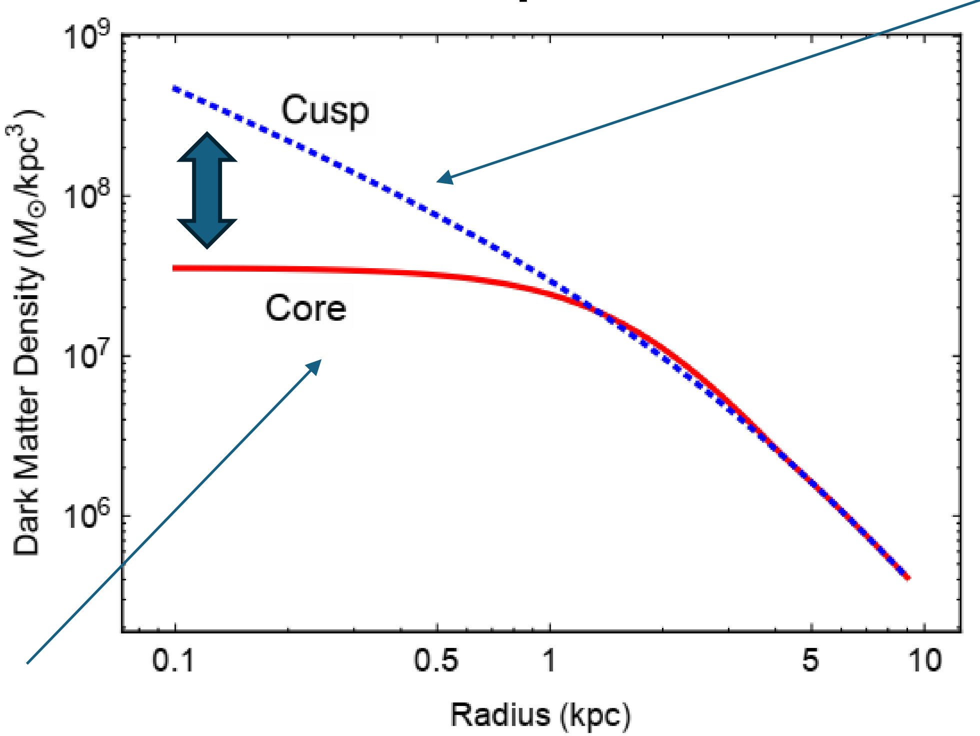
- **The kinetic mixing varies from $\varepsilon^2 = \{10^{-8}, 10^{-6}\}$ due to the free parameters and the surplus between $C_U = \{0.01, 0.1\}\%$**
- **Election of a DM candidate also affect ε^2 due to the decay width $U \to \bar{\chi}\chi$**

Additional Constraints are needed to reduce the parameter space

Constraints from Astrophysics and Cosmology

Self-Interacting Dark Matter (SIDM)
Dark Matter Density profile

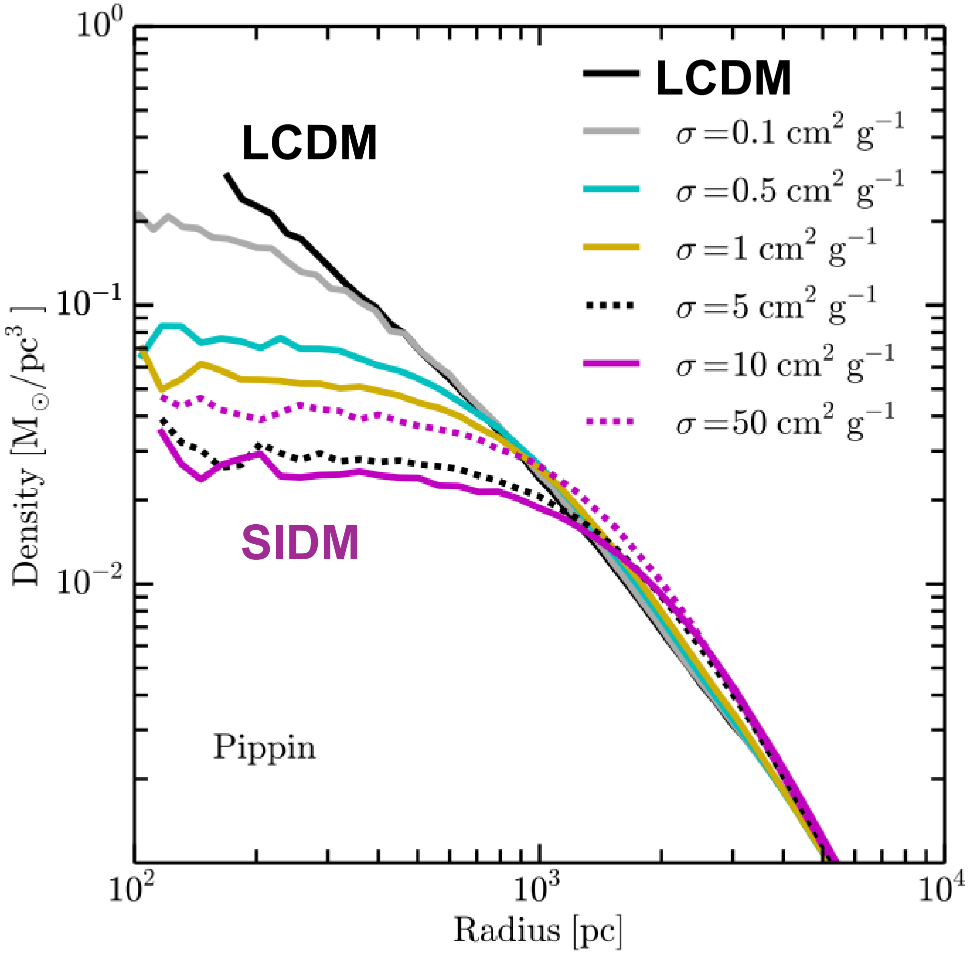
Based on Λ_{CDM} model, describe well Large scales (Galaxy clusters)

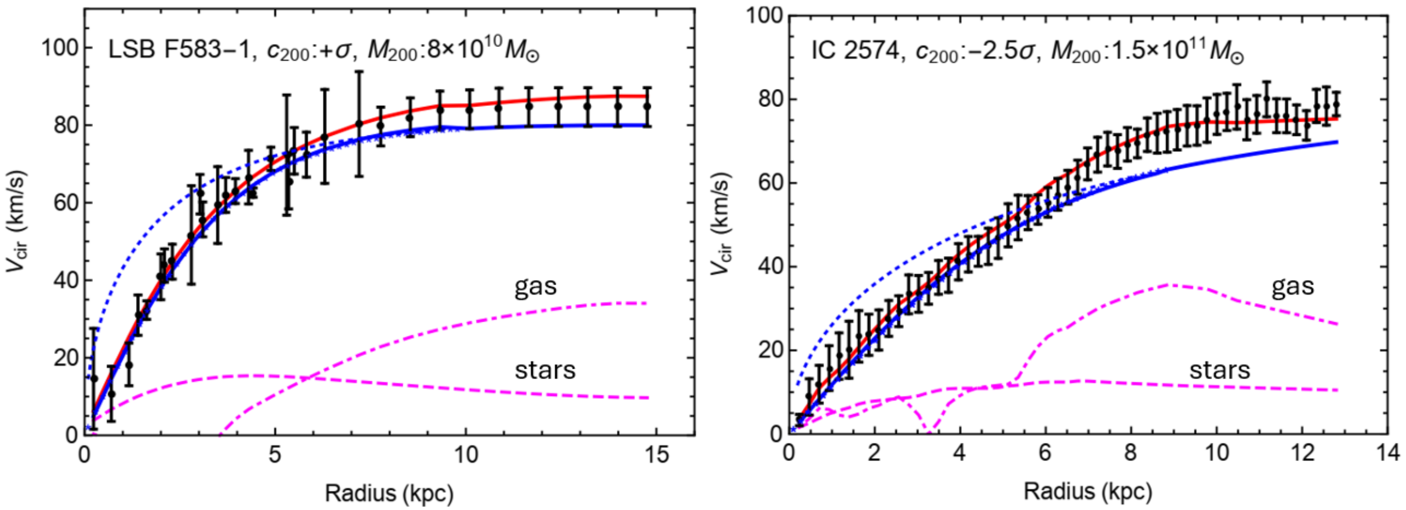


Other observations, small scales (dwarf galaxies)

Self-Interacting Dark Matter (SIDM)

Dark Matter Density profile



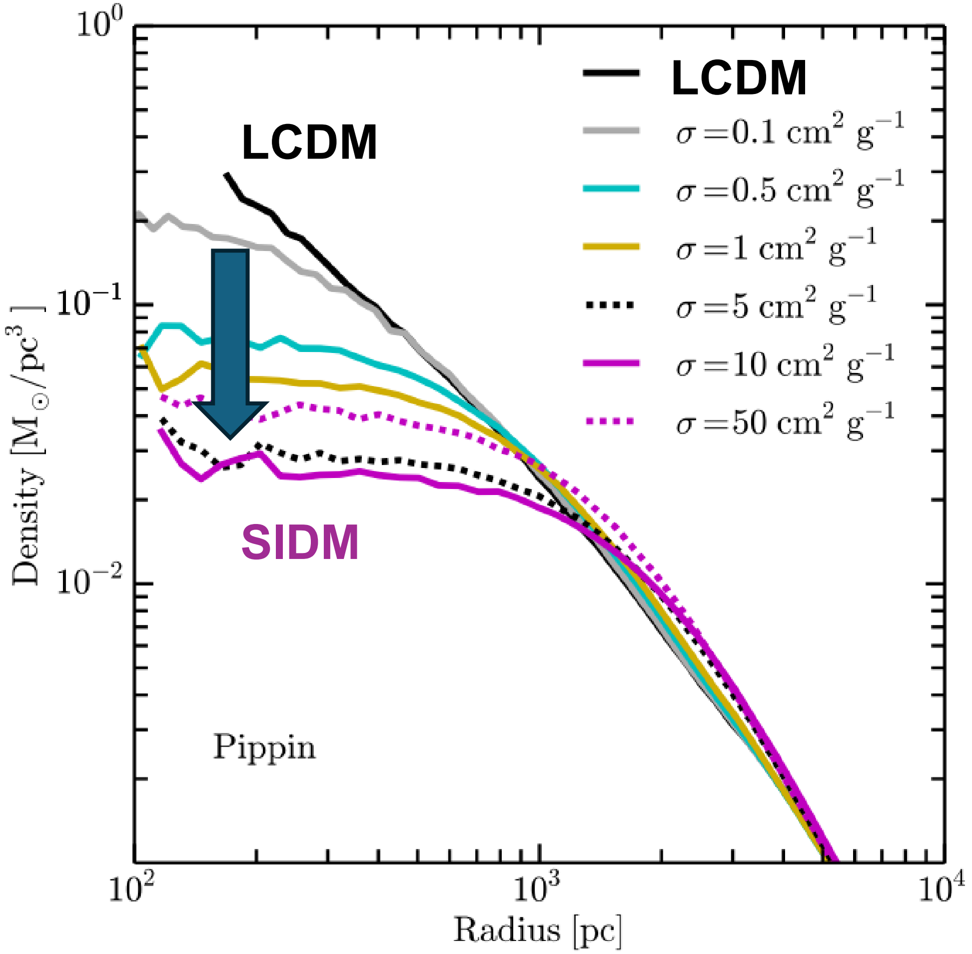


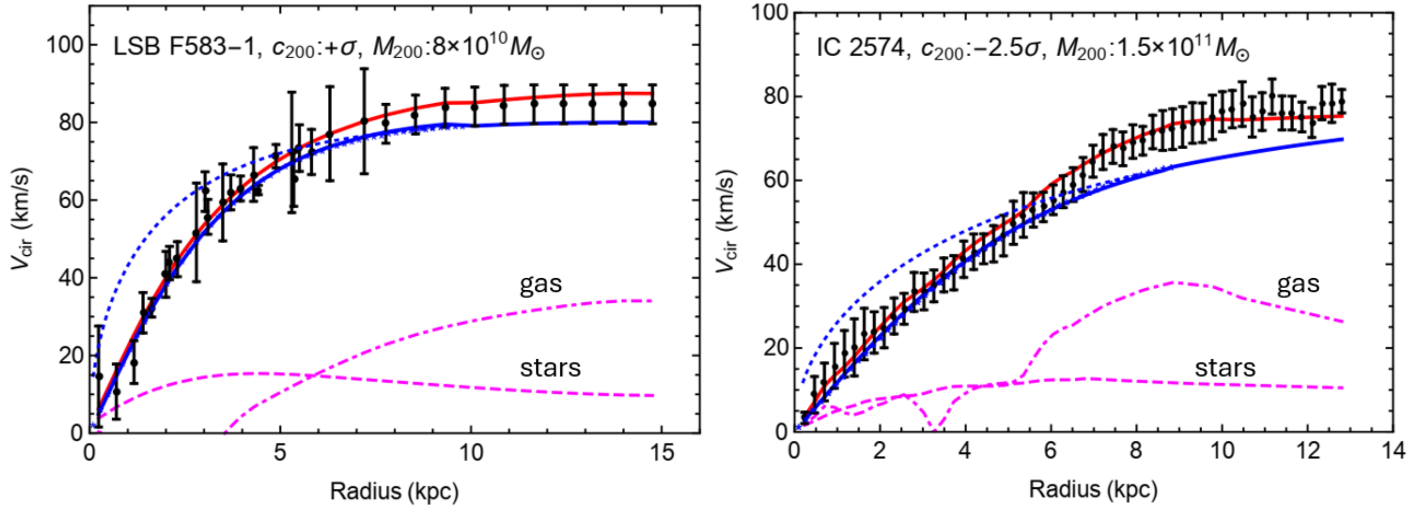
→ *total rotation curves for SIDM with* $\sigma/m = 3\ \mathrm{cm}^2/\mathrm{g}$

→ *CDM halos* No interactions

Arxiv.1308.0618

Self-Interacting Dark Matter (SIDM)
Dark Matter Density profile



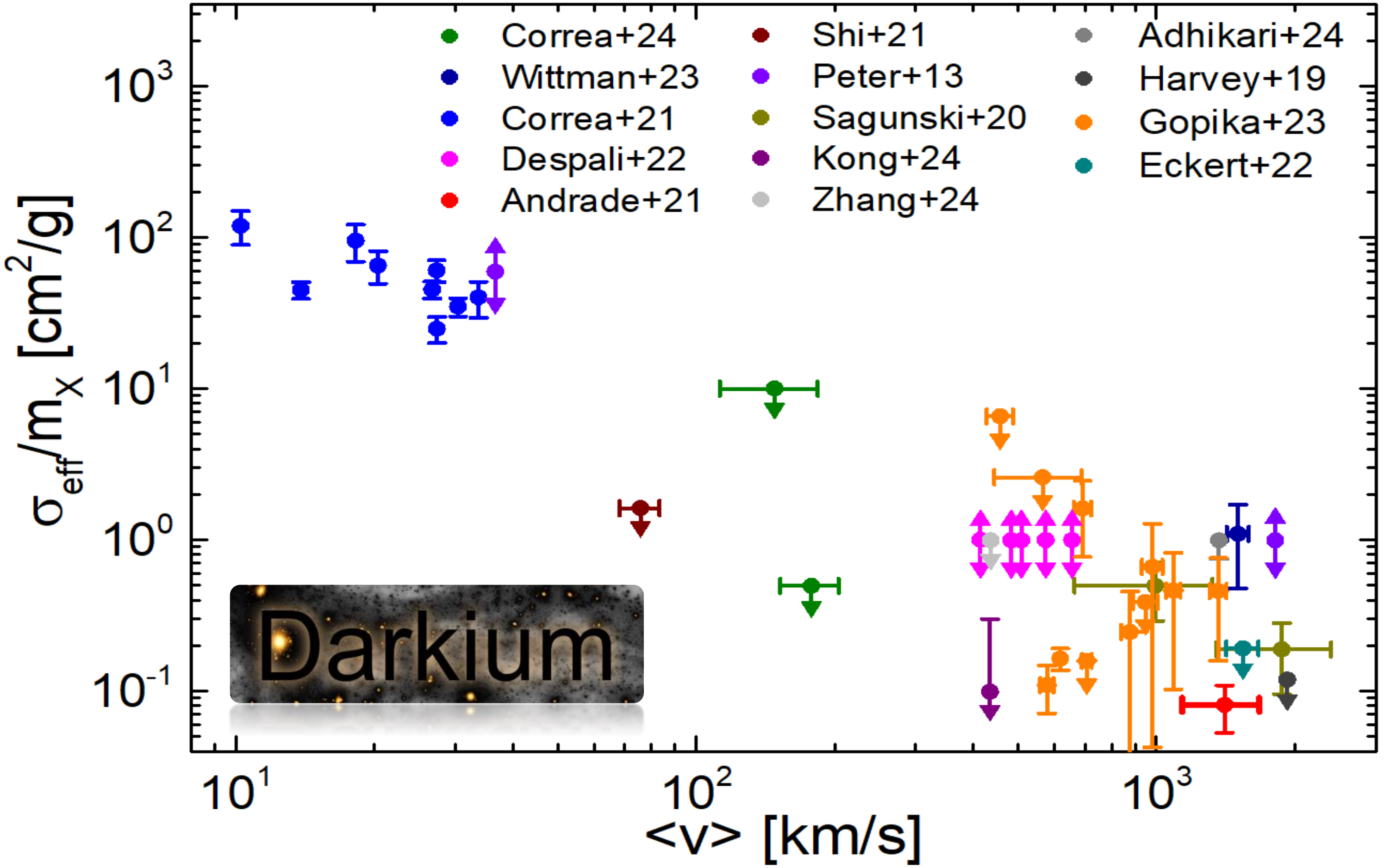


→ *total rotation curves for SIDM with* $\sigma/m = 3\ \mathrm{cm^2/g}$

→ *CDM halos* No interactions

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

Arxiv.1308.0618



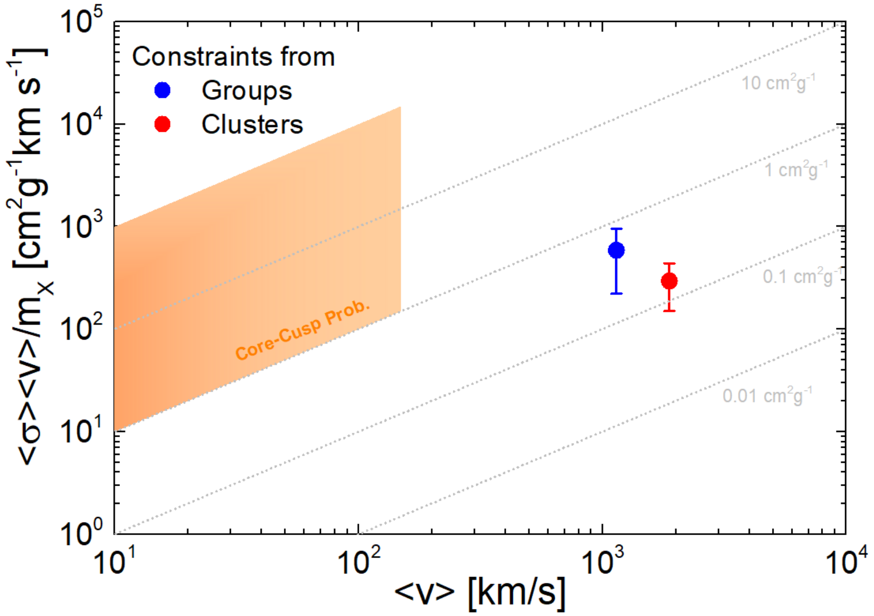
Arxiv: 2310.07750

Effective cross-section Constraints

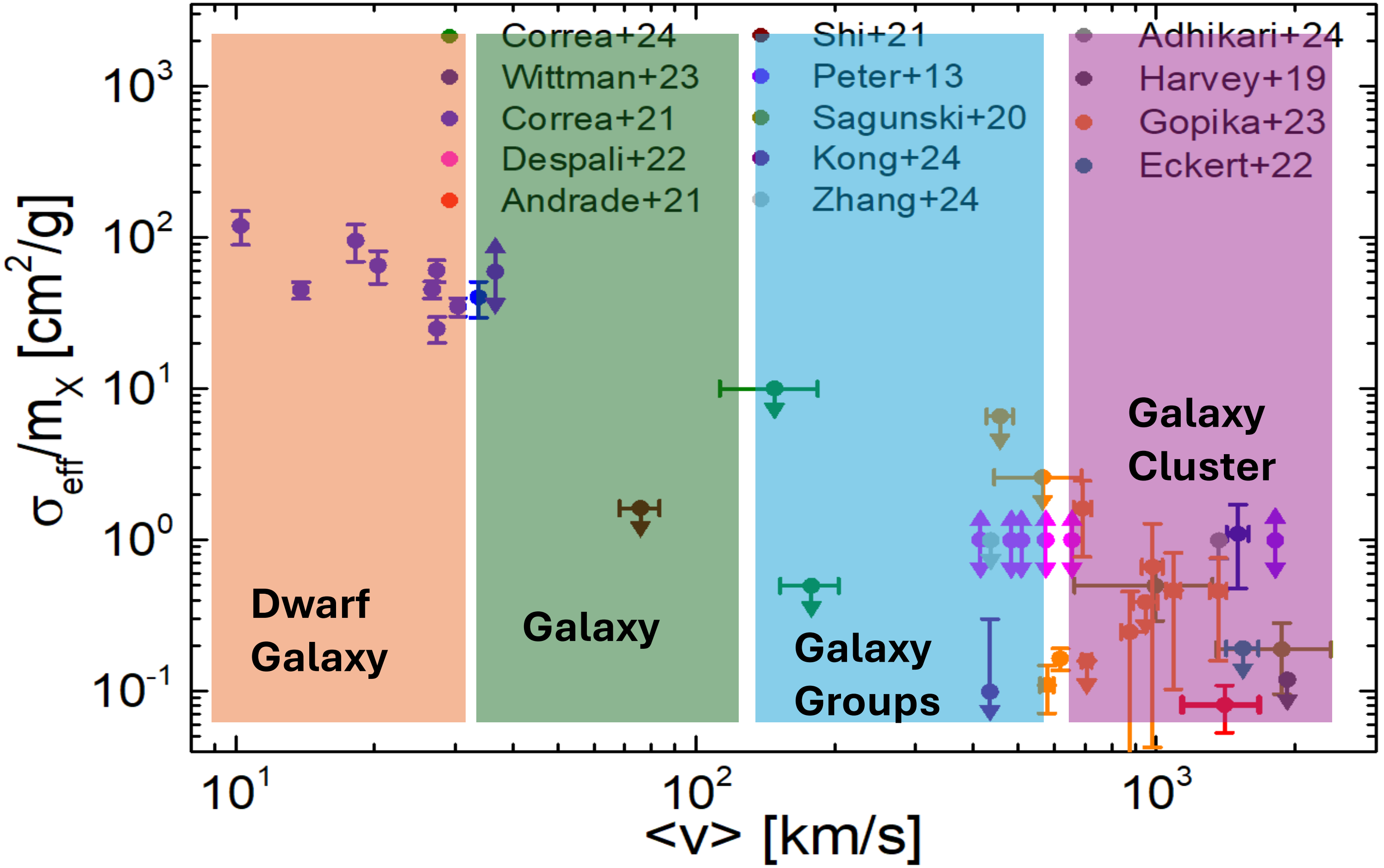
$$\sigma_{eff} = \frac{3}{2}\frac{\langle \sigma(v)\, v^5 \rangle}{\langle v^5 \rangle}$$

ArXiv: 2205.03392

Galaxy Groups and Clusters Constraints



Arxiv: 2011.04679

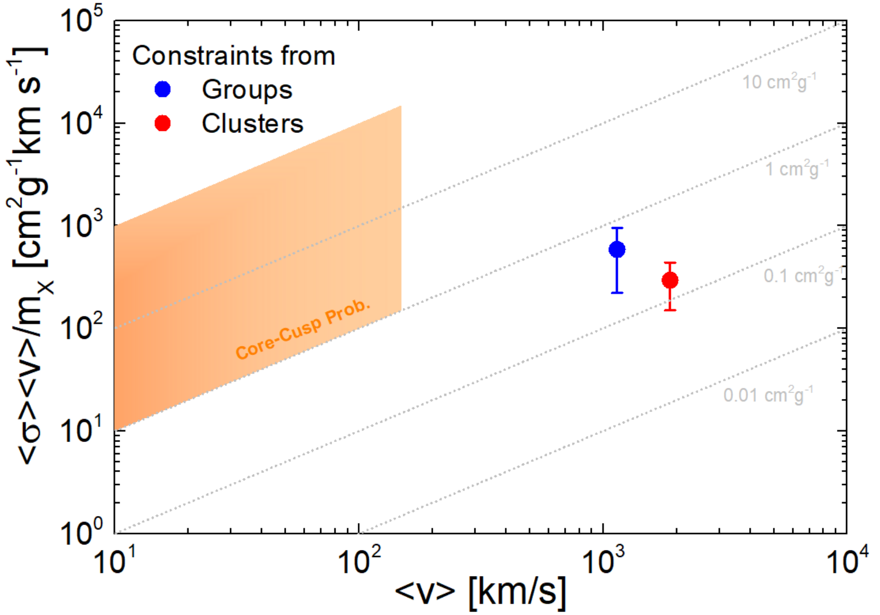


Effective cross-section Constraints

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

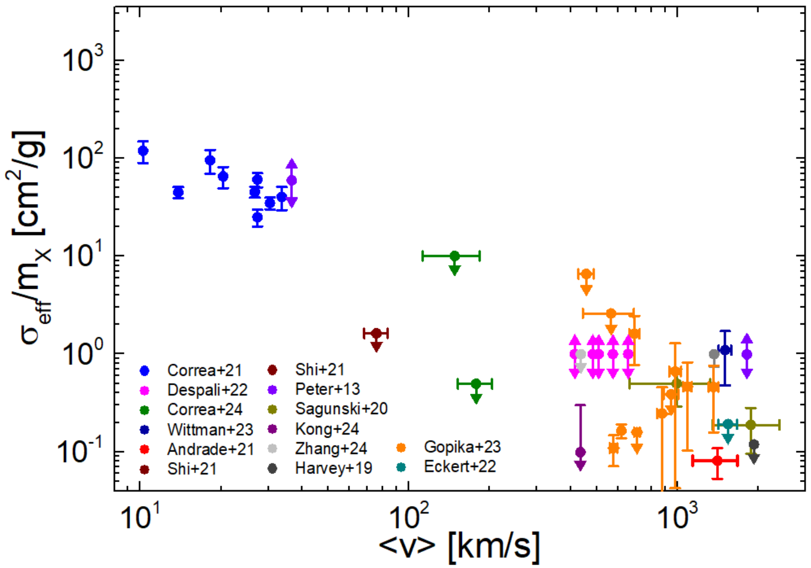
ArXiv: 2205.03392

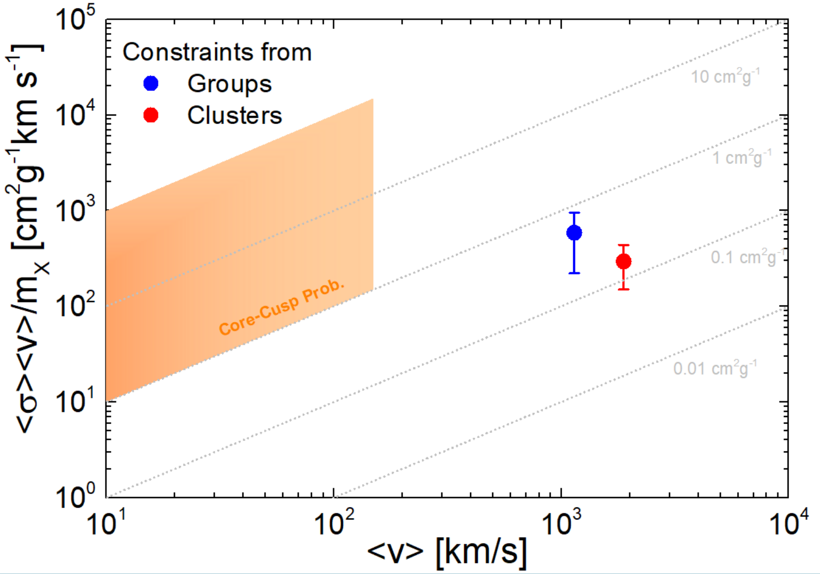
Galaxy Groups and Clusters Constraints



Arxiv: 2011.04679

Effective cross-section Constraints





Two-body scattering problem

Schrödinger Equation

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

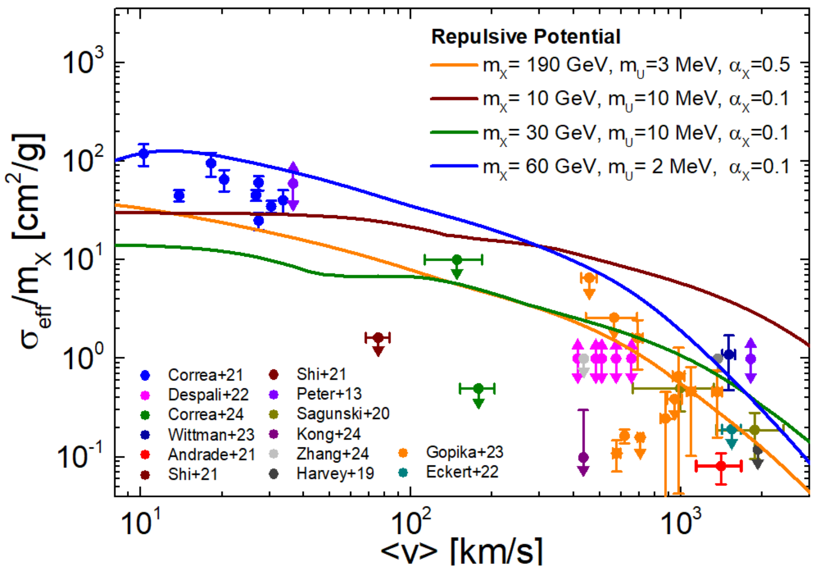
Maxwell–Boltzmann distribution to compute velocity-averaged cross sections

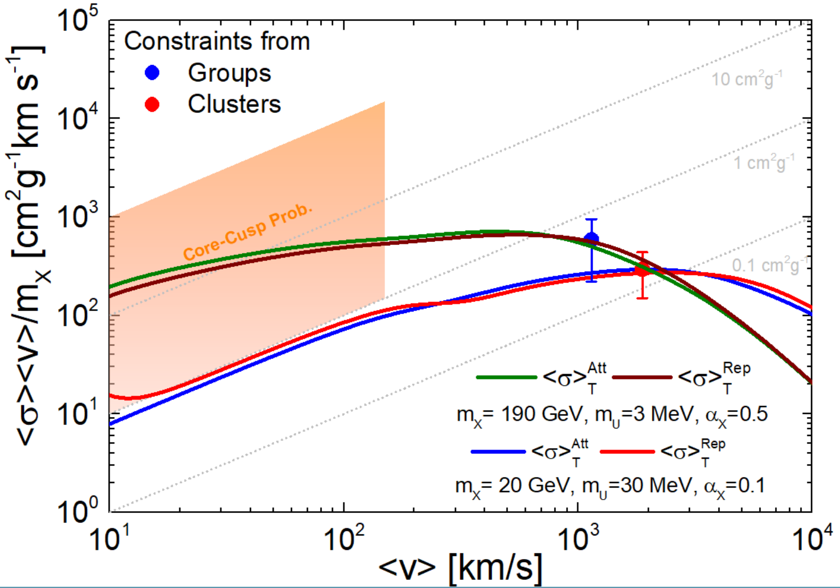
$$f(v) = 4\pi \left(\frac{m_\chi}{2\pi k_B T}\right)^{3/2} v^2 \, e^{-\frac{m_\chi v^2}{2k_B T}}$$

Momentum-transfer cross section:

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

Effective cross-section Constraints





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:

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

CLASSICS

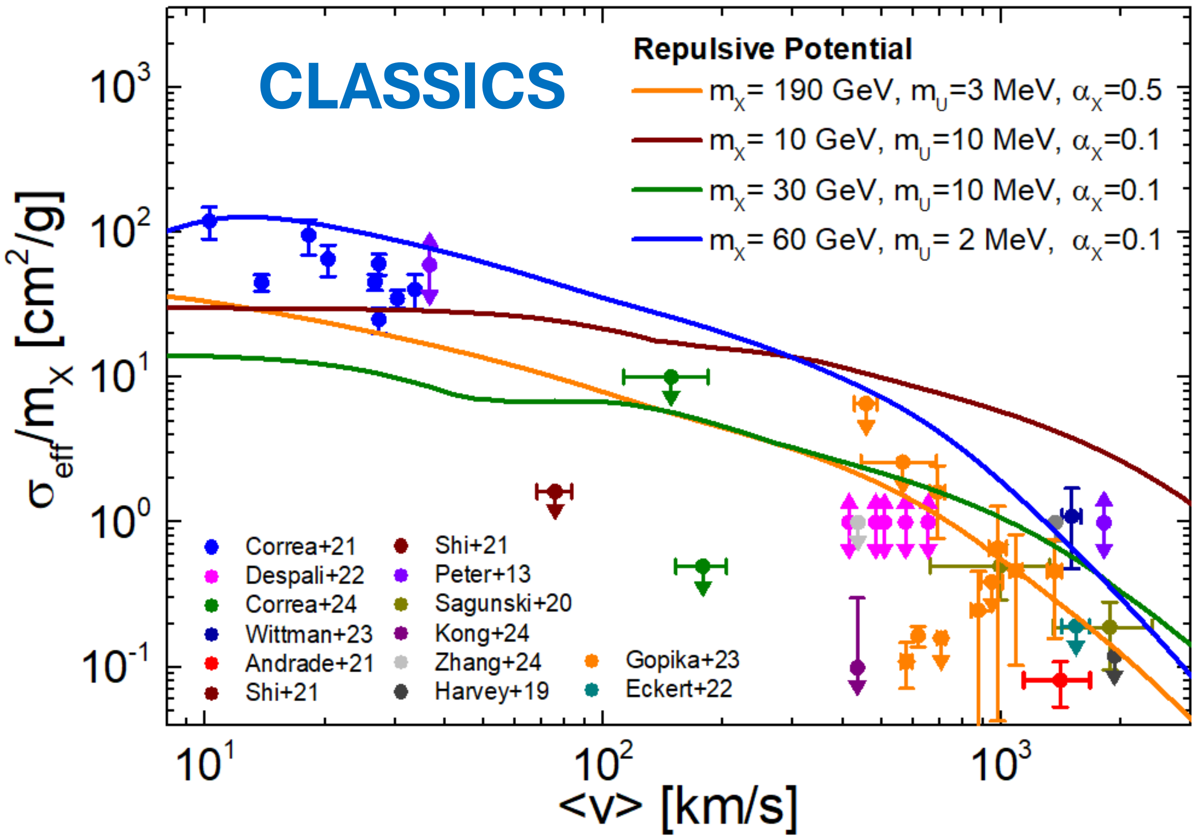
Computes approximate **self-scattering cross sections** for dark matter (DM) particles interacting via a **Yukawa potential:**

CalcuLAtionS of Self Interaction Cross Sections

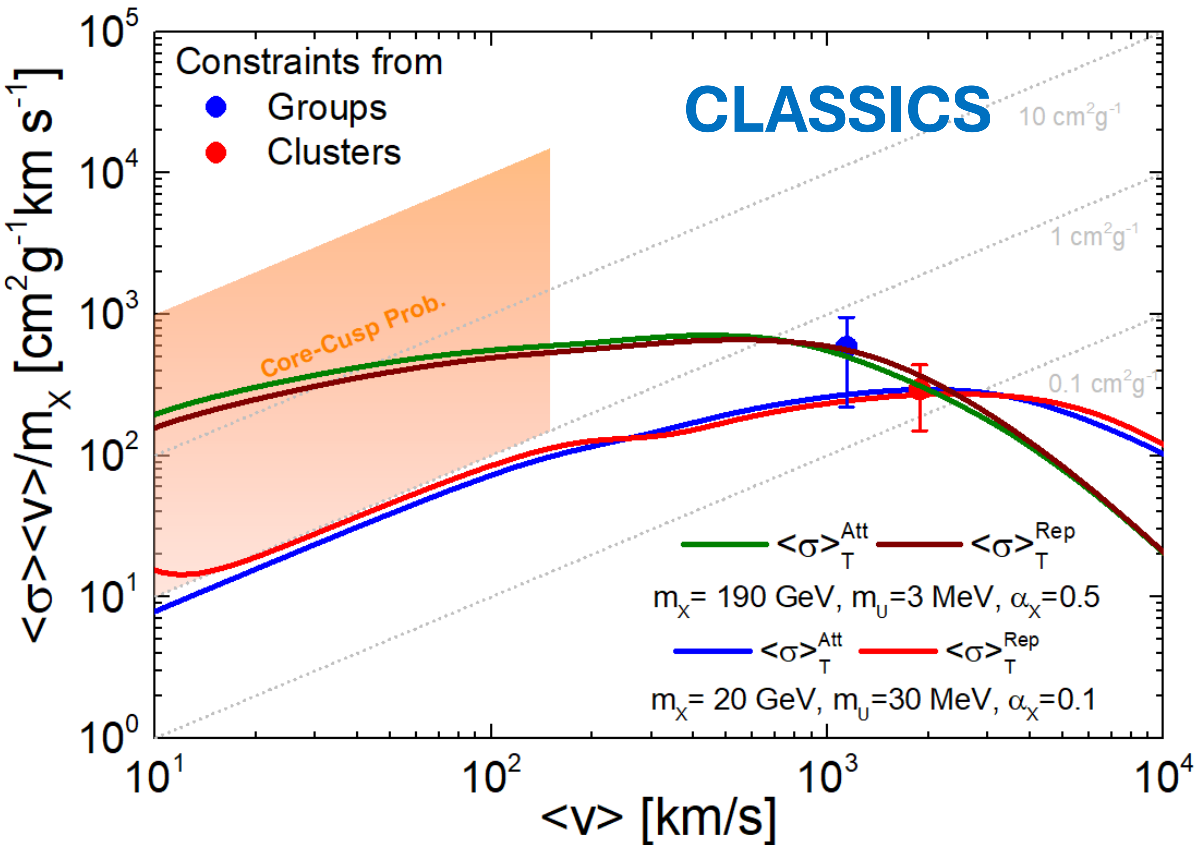
github.com/kahlhoefer/CLASSICS

Arxiv: 2011.04679

Effective cross-section Constraints



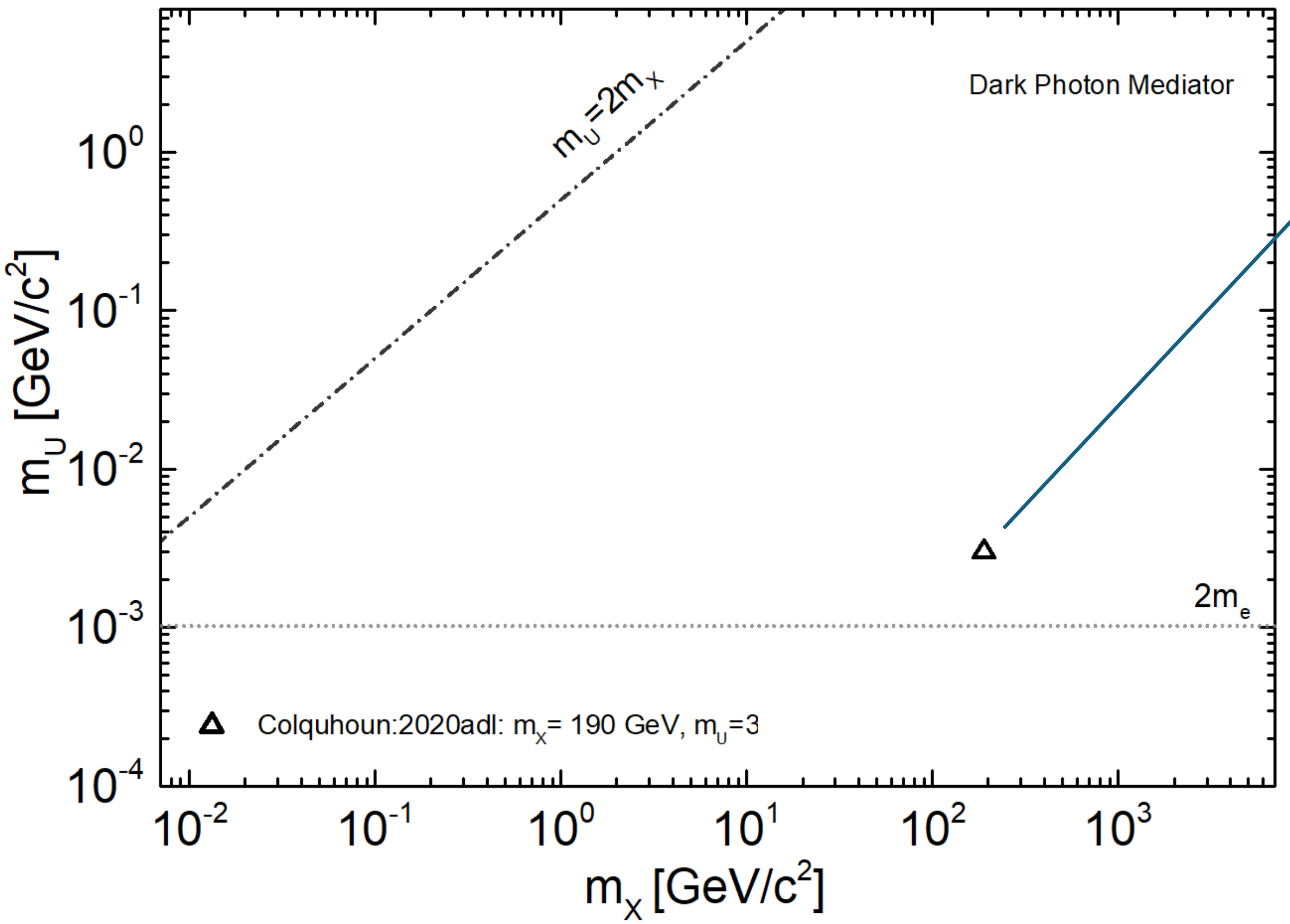
Groups and Clusters Constraints

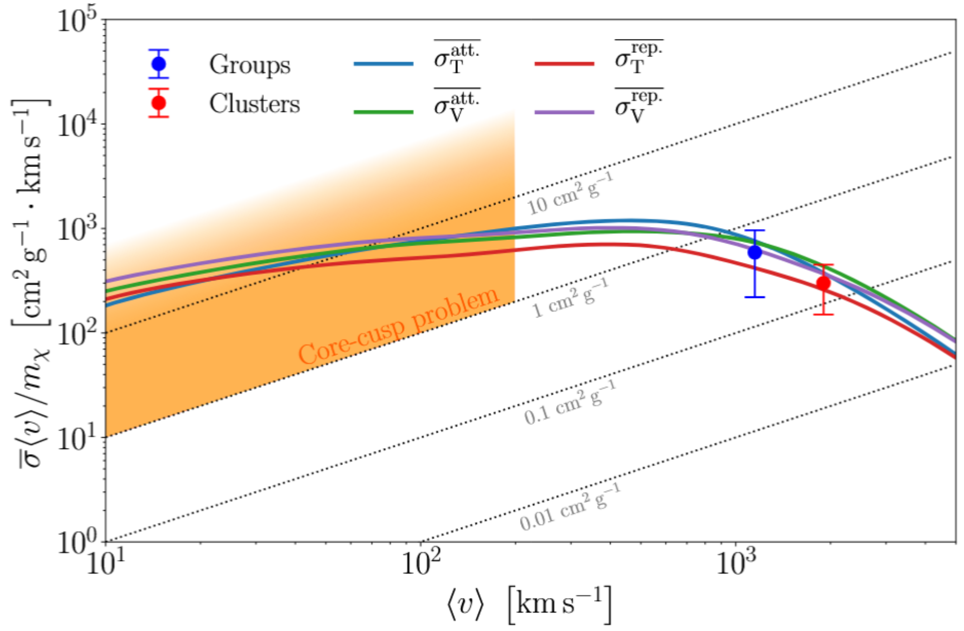


$$\{m_U, m_X, \alpha_X\}$$

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

CLASSICS





Benchmark point Arxiv: 2011.04679

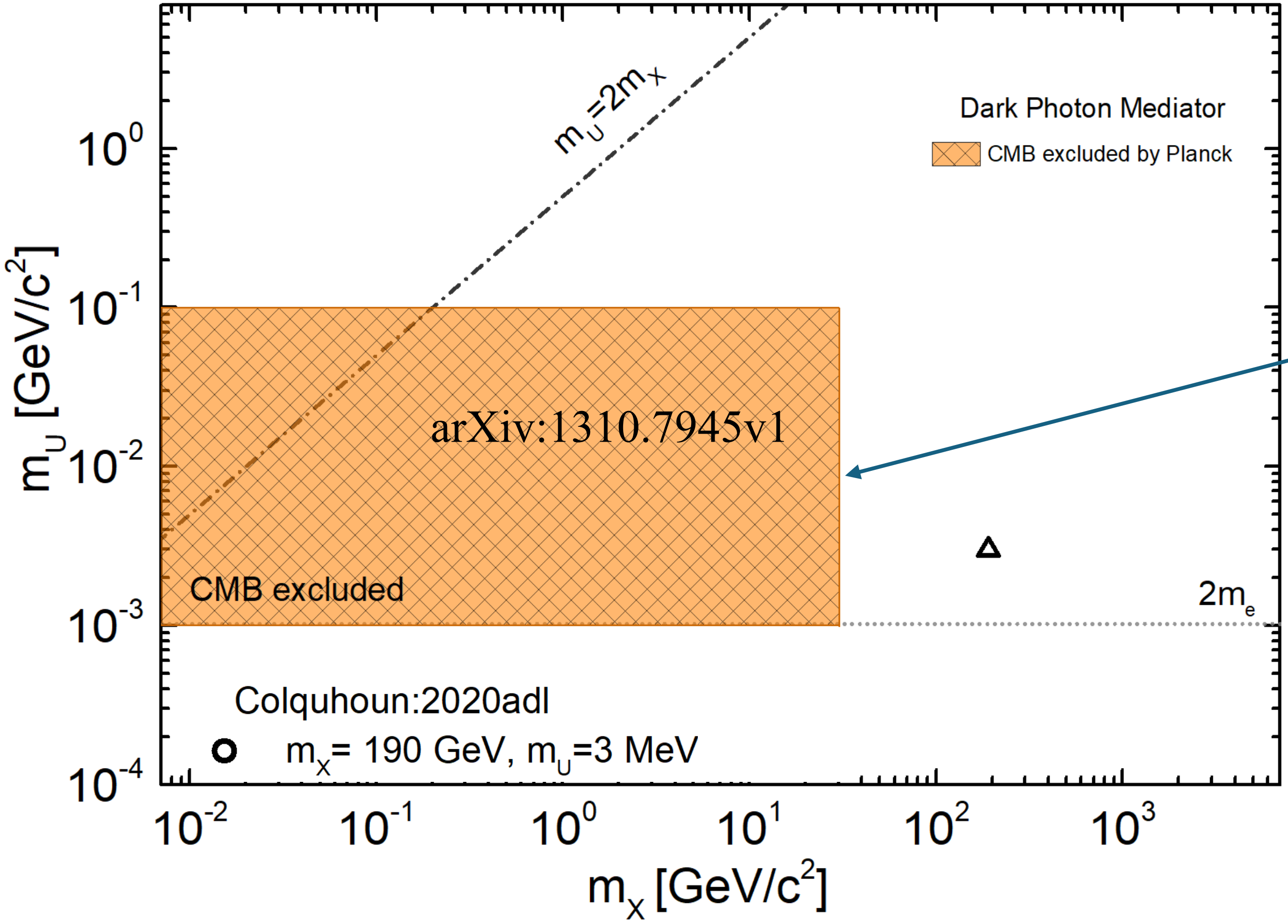
$$m_\chi = 190\ GeV, \alpha_\chi = 0.5, m_U = 0.003\ GeV$$

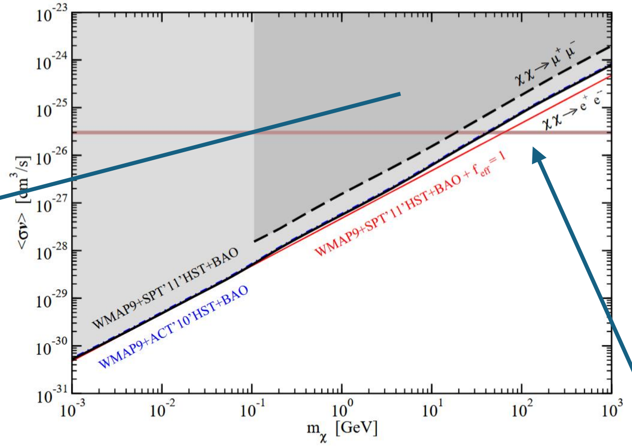
Dark Photon Mass vs Dark Matter Mass $m_U(m_X)$

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

arXiv:1512.08015 -> Plack Measurements

arXiv: 2105.08334

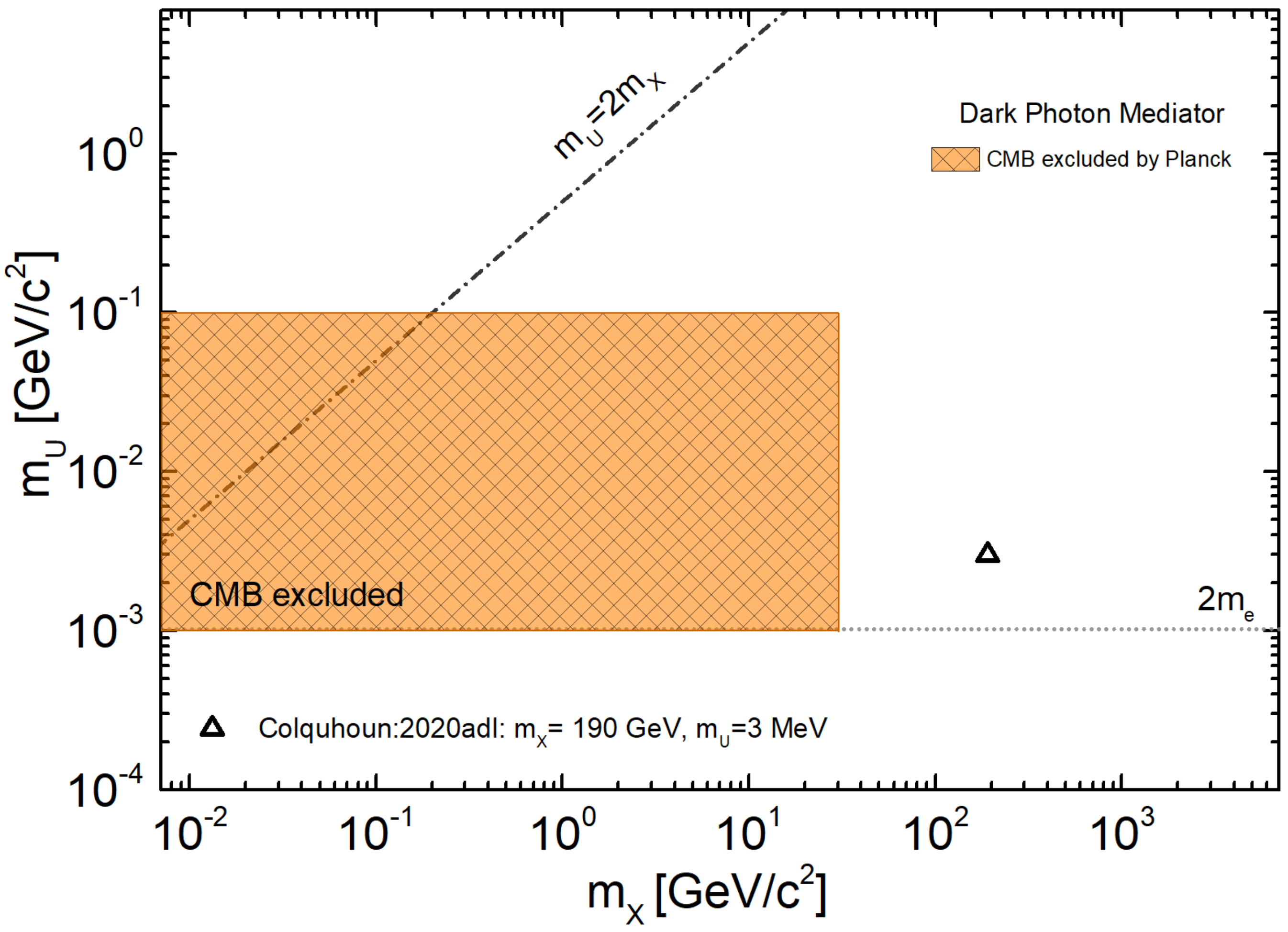




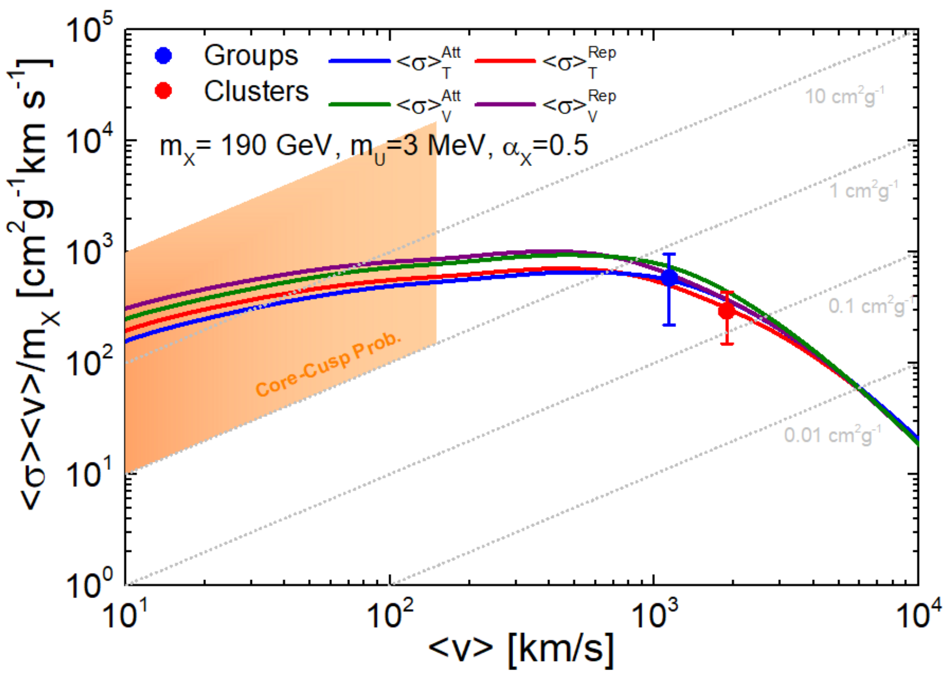
$$\langle \sigma v \rangle \approx 3 \times 10^{-26}\ cm^3 s^{-1}$$ arXiv:1303.5094

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

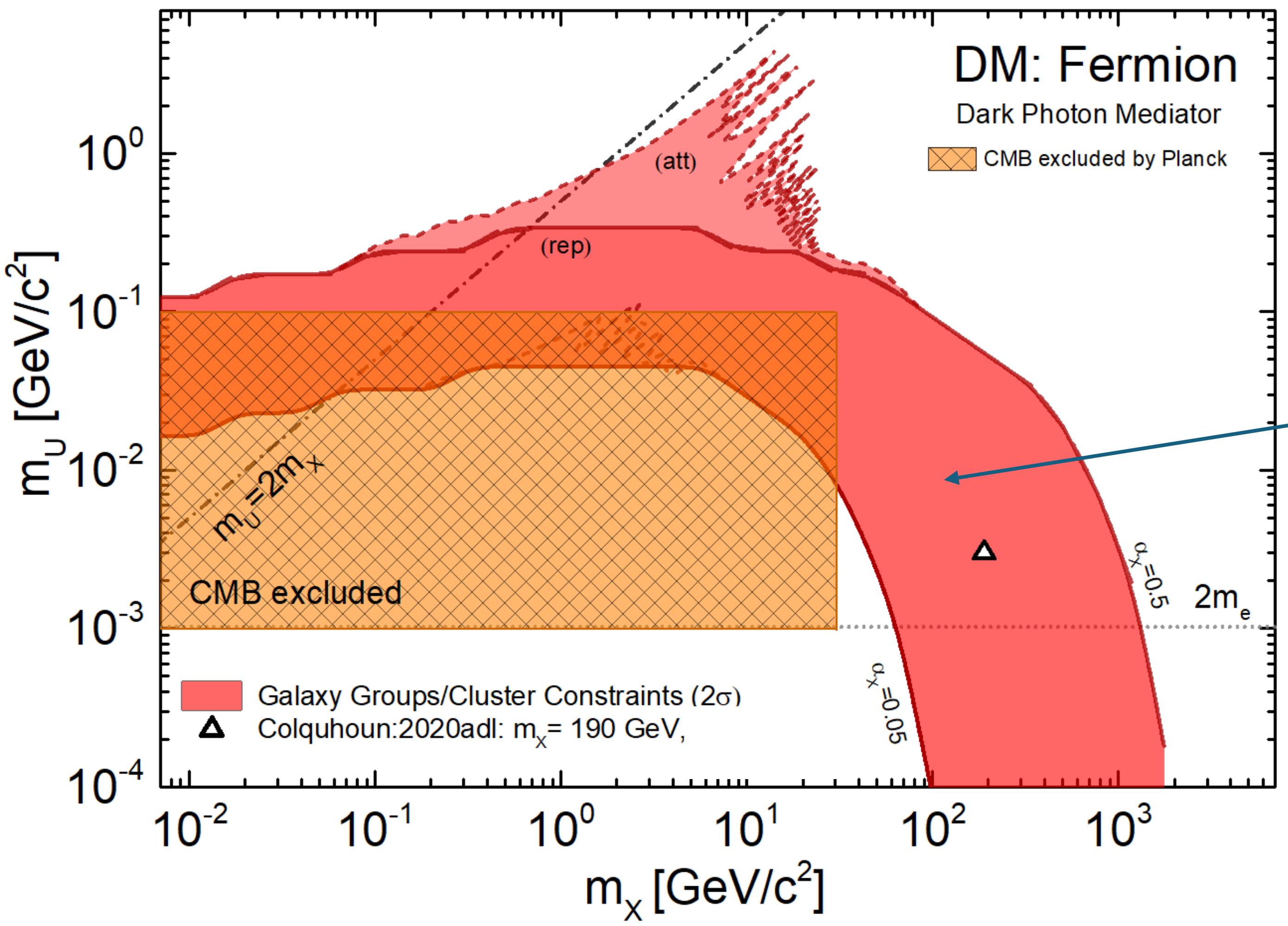
Dark Photon Mass vs Dark Matter Mass $m_U(m_X)$



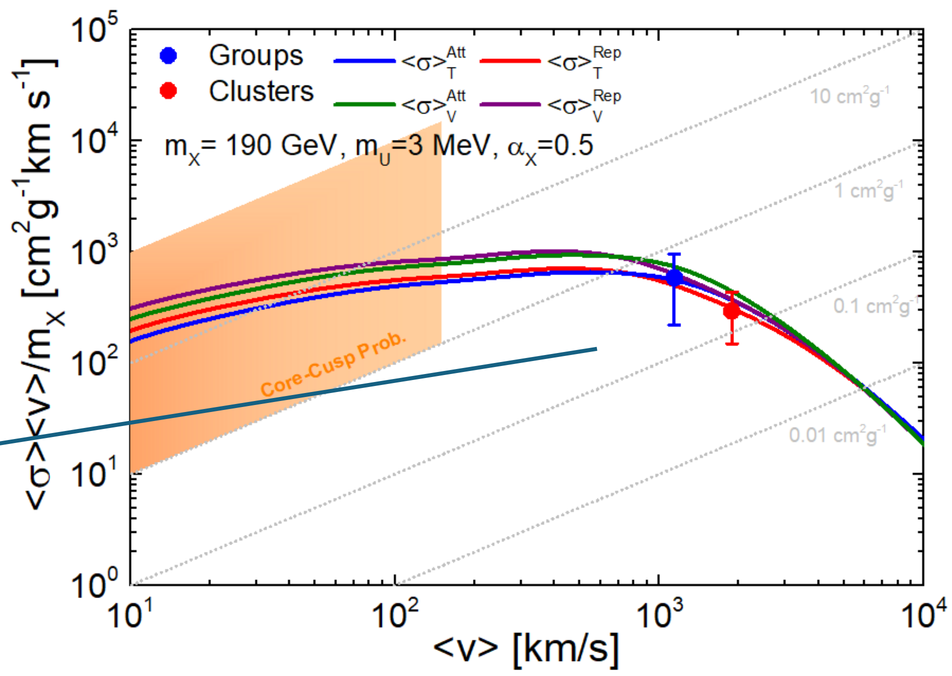
Groups and Clusters Constraints



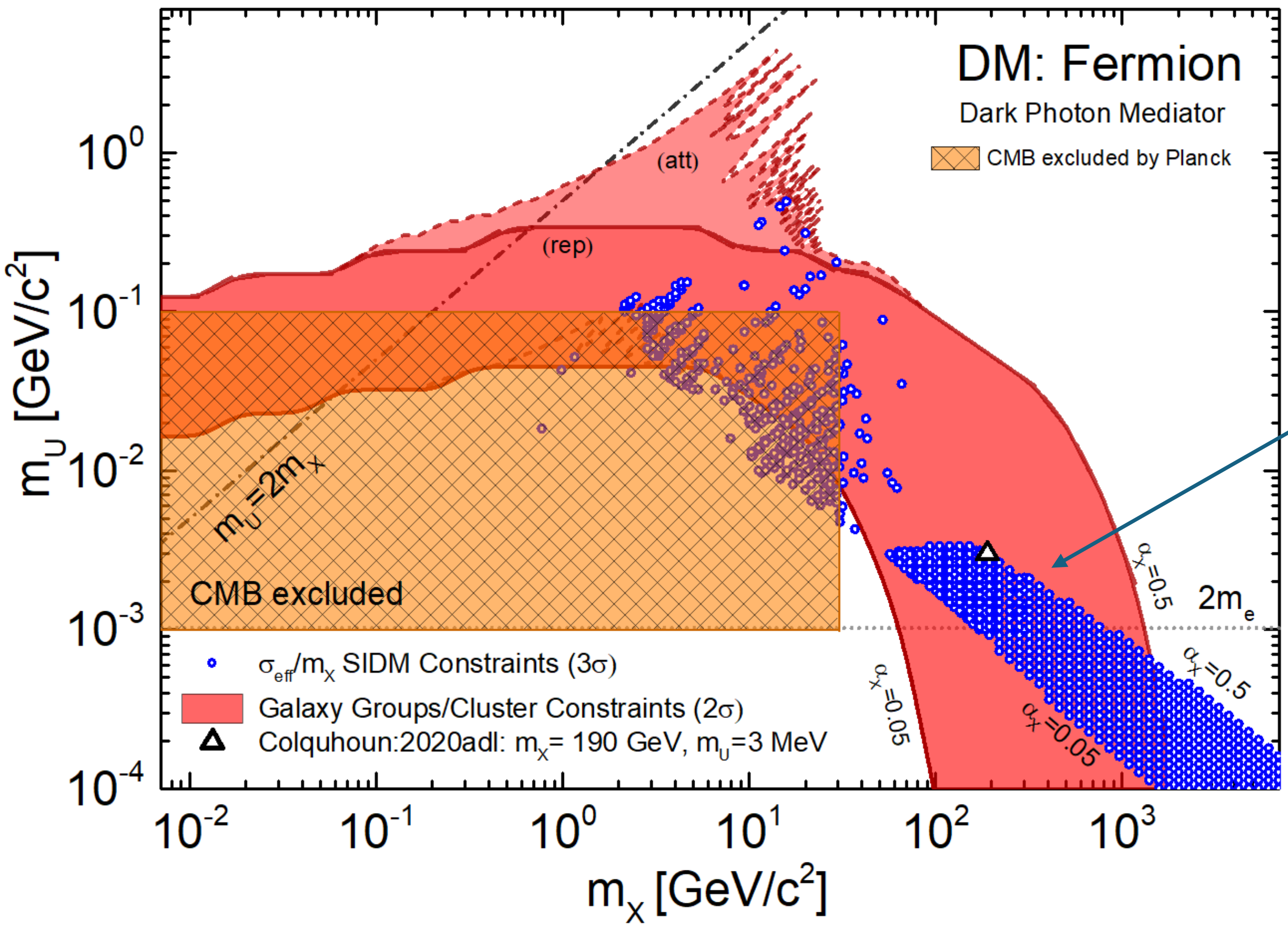
Dark Photon Mass vs Dark Matter Mass $m_U(m_X)$



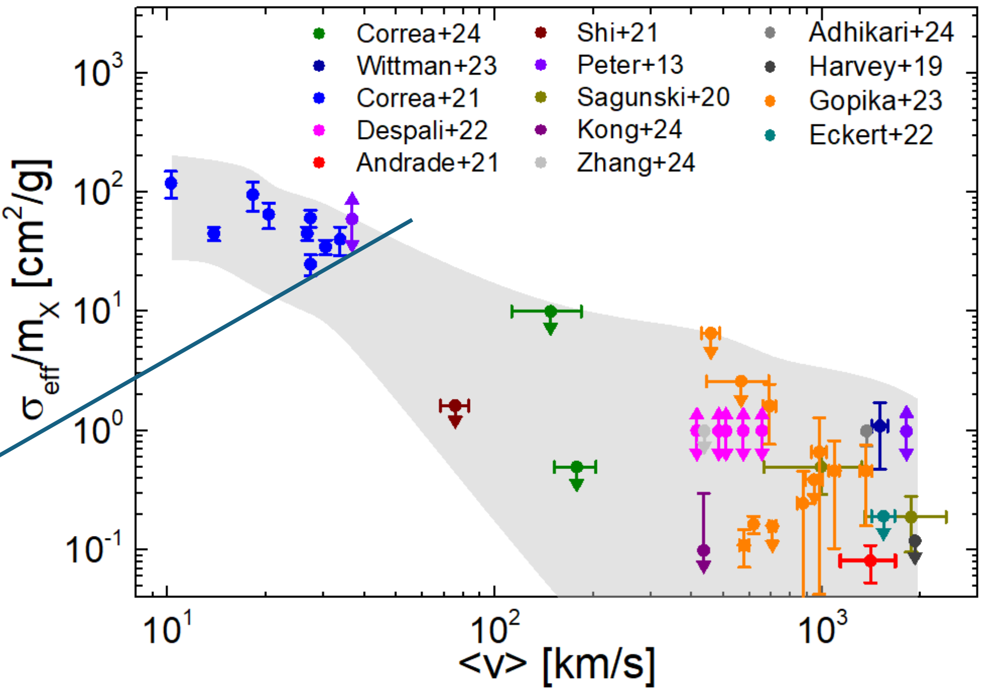
Groups and Clusters Constraints



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

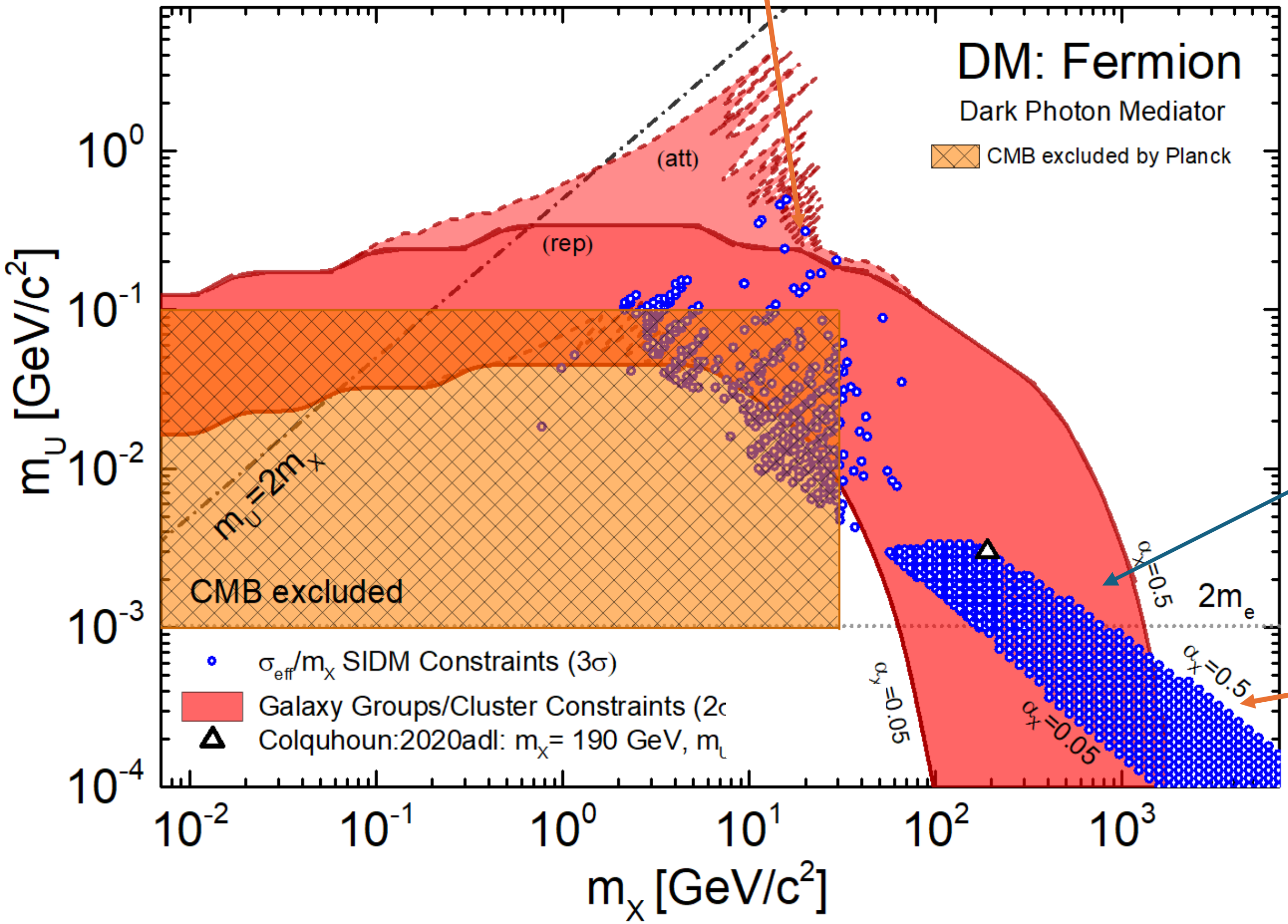


Effective cross-section Constraints

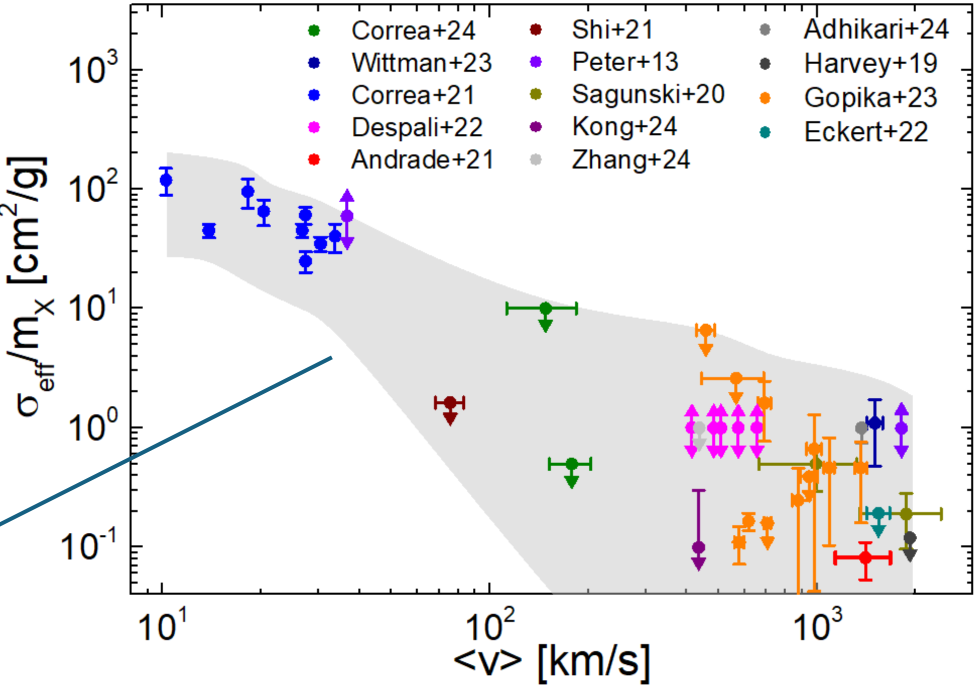


Dark Photon Mass vs Dark Matter Mass $m_U(m_X)$

Attractive Potential



Effective cross-section Constraints



Repulsive Potential

Thermal Relic Abundance

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

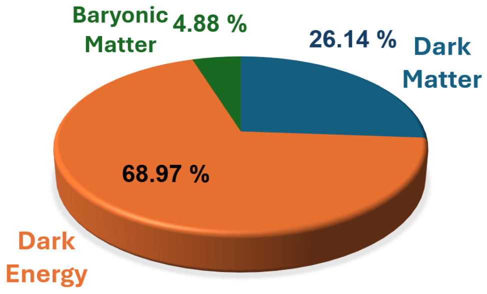
$$h = 0.674$$

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

Mediator: Dark Photon

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

Thermal Relic Abundance

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

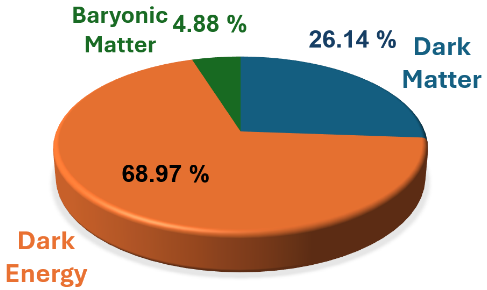
$h = 0.674$

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

Mediator: Dark Photon

Dark Matter: Complex Scalar, Dirac Fermion, Majorana Fermion

$$\varepsilon^2_{relic}(m_U)$$

For fixed values of α_χ, m_χ

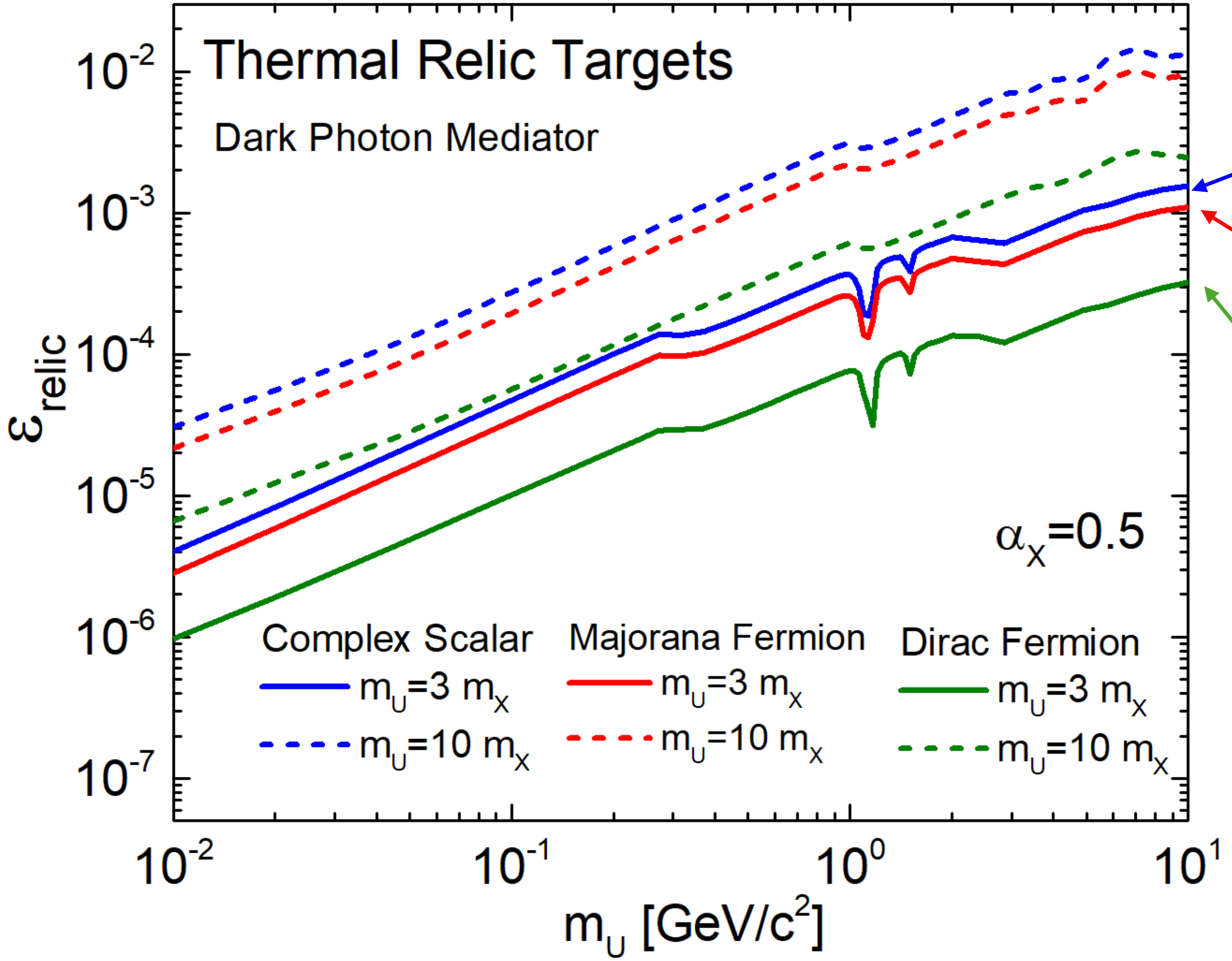
$$\chi\bar{\chi} \to U^* \to f\bar{f} \qquad \text{s} - \text{channel}$$

Red DeliVeR

Arxiv: 2410.00881

Thermal Relic Abundance

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



Complex Scalar

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

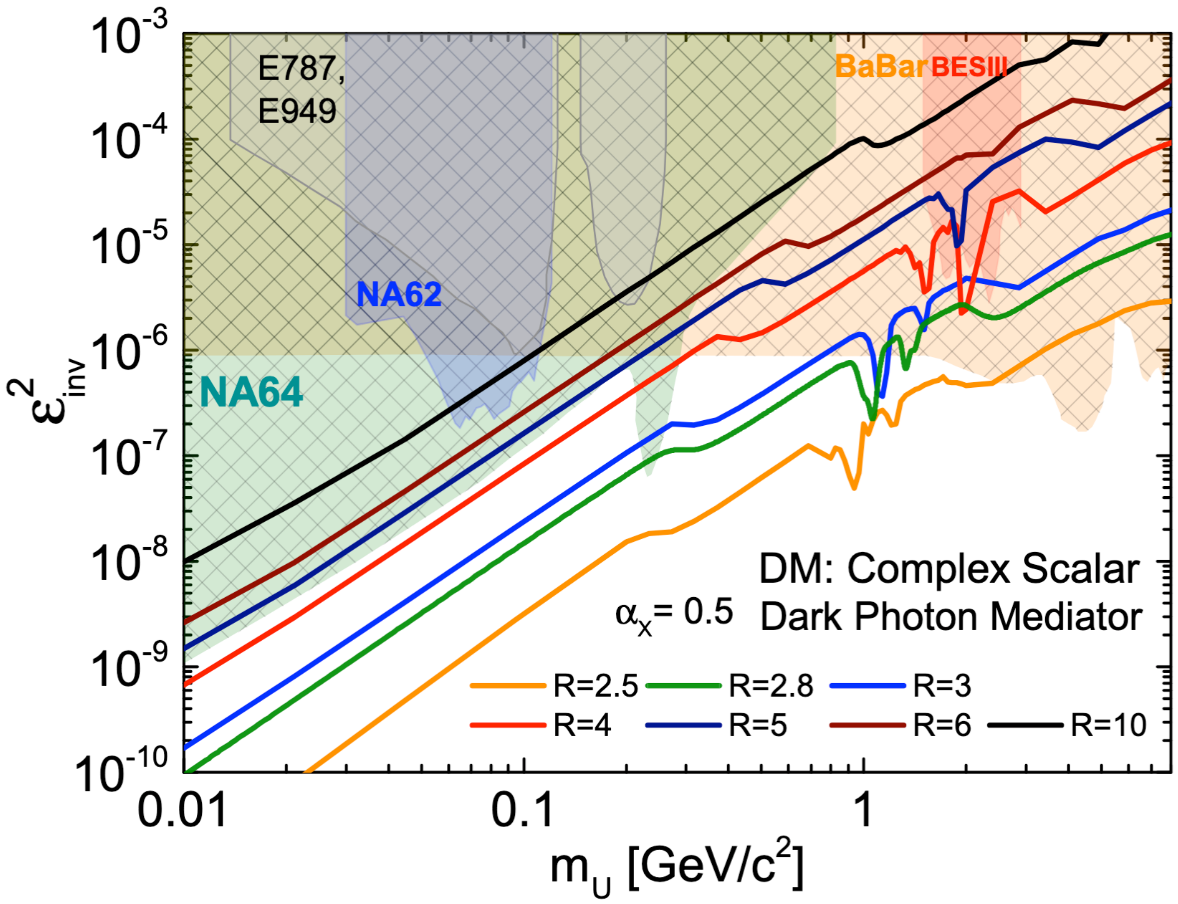
Majorana

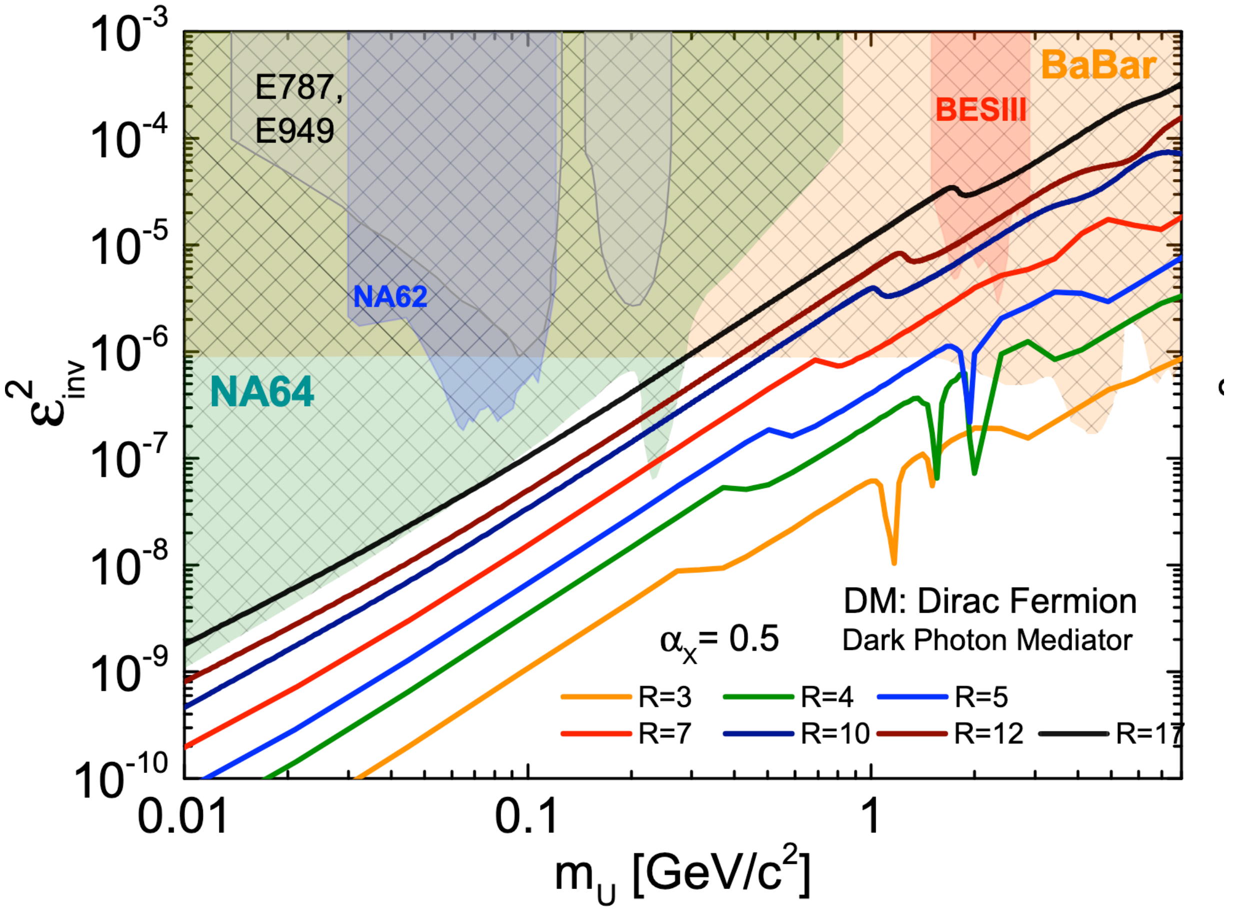
$$\Gamma(U \to \chi\chi) = \frac{1}{6}\,\alpha_\chi\, m_U \left(1 - \frac{4m_\chi^2}{m_U^2}\right)^{3/2}$$

Dirac Fermion

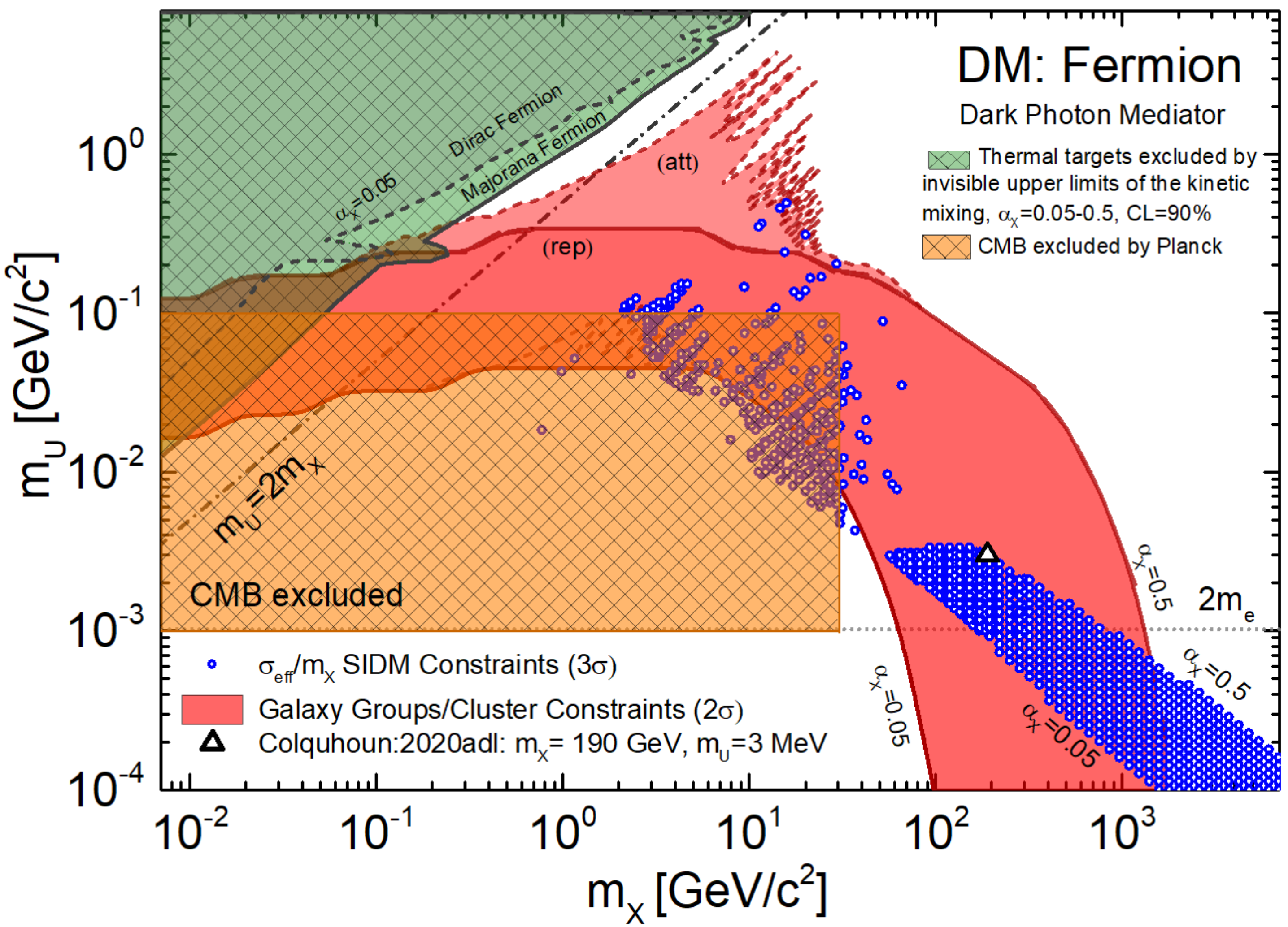
$$\Gamma(U \to \bar{\chi}\chi) = \frac{1}{3}\,\alpha_\chi\, m_U \left(1 + \frac{2m_\chi^2}{m_U^2}\right)\sqrt{1 - \frac{4m_\chi^2}{m_U^2}}$$

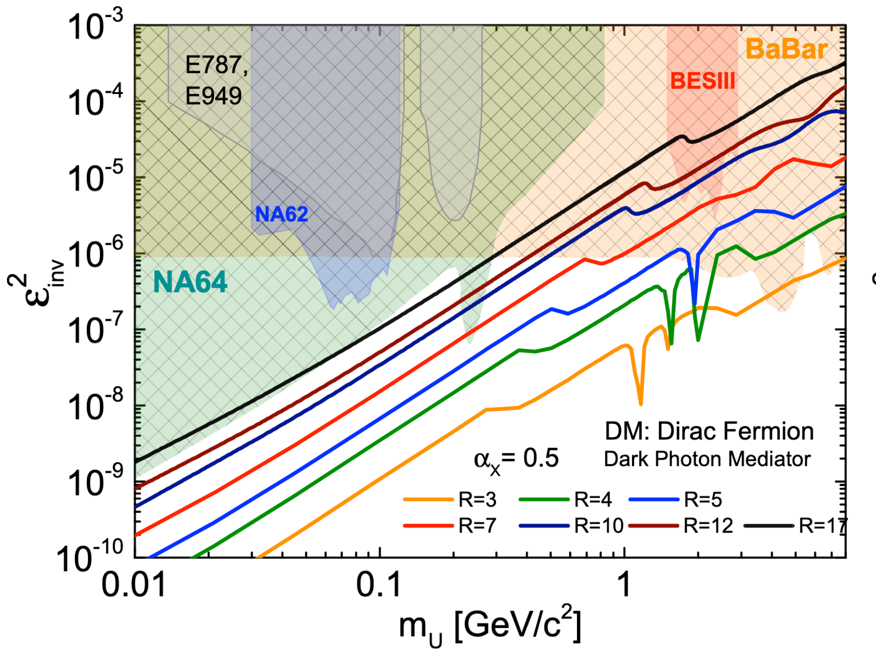
Kinetic Mixing parameter $\varepsilon(m_U)$ and DM thermal Relic Abundance



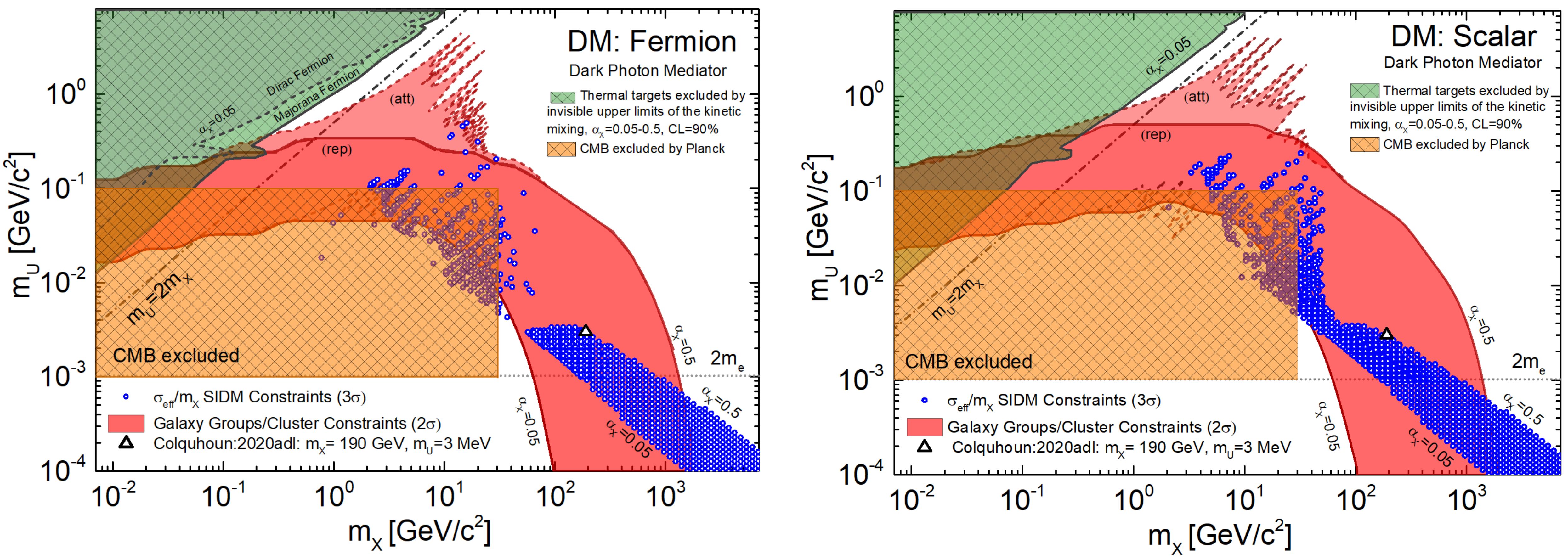


Dark Photon Mass vs Dark Matter Mass $m_U(m_X)$

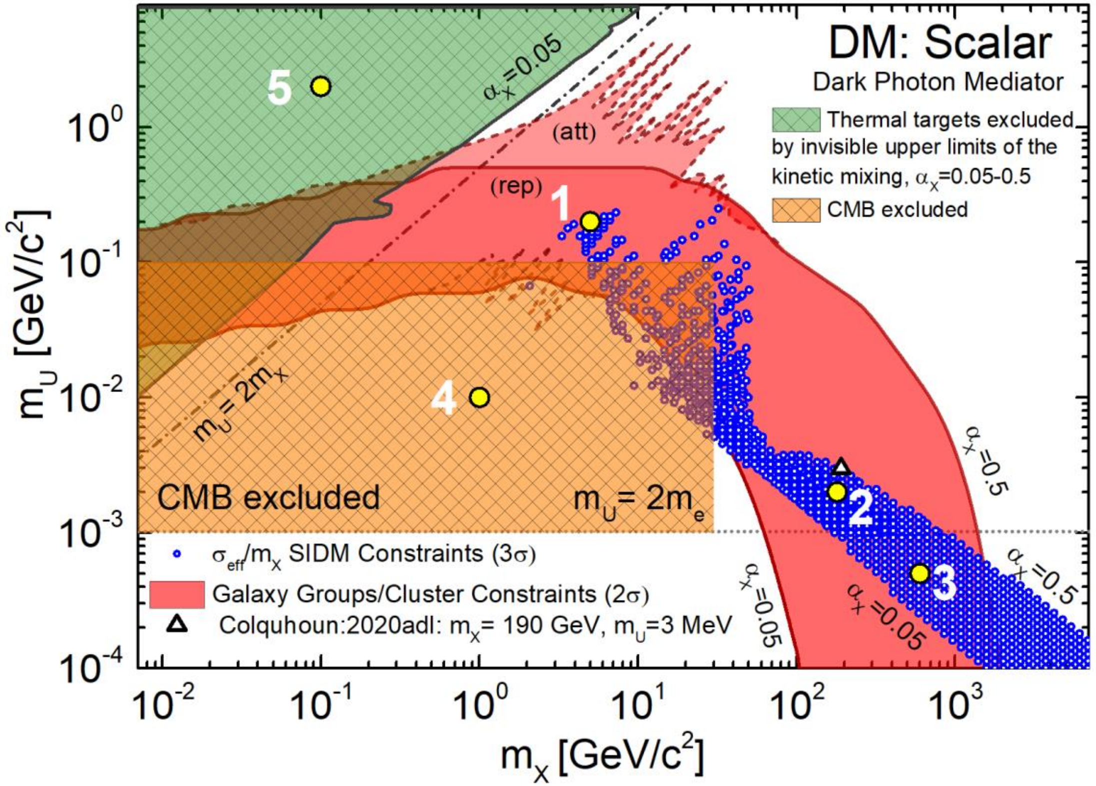




Dark Photon Mass vs Dark Matter Mass $m_U(m_X)$

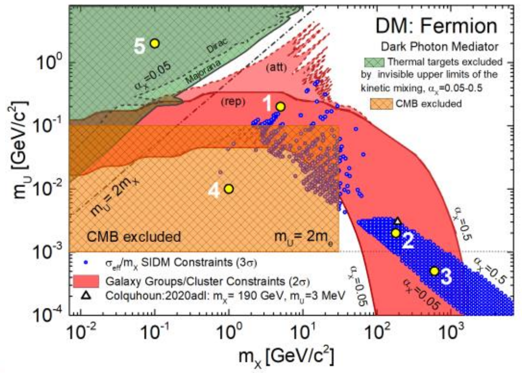


Dark Photon Mass vs Dark Matter Mass $m_U(m_X)$



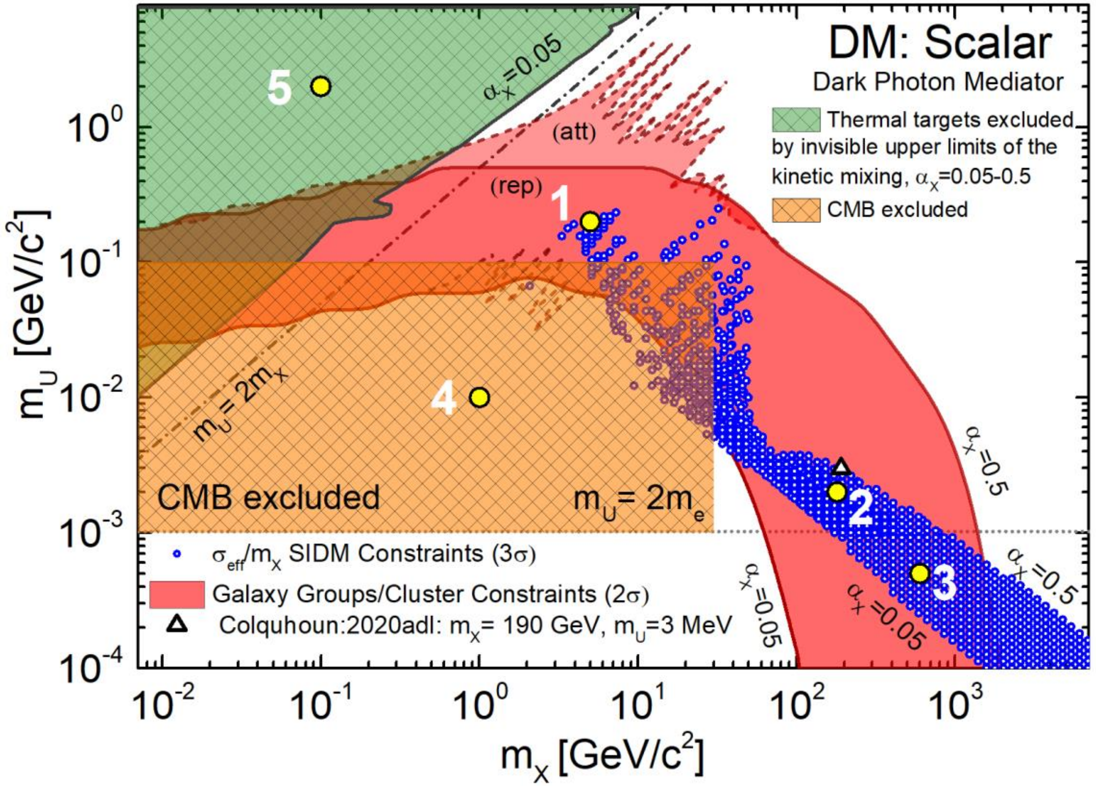
Possible Benchmark Points

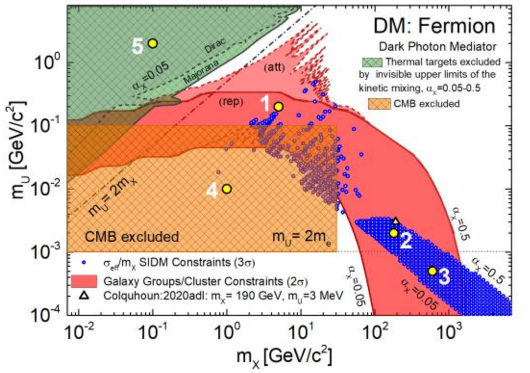
1. $m_U \sim 0.1 - 0.2$ GeV, $m_X \sim 5 - 10$ GeV — Good for HIC Searches. Dark photon produced by $\pi^0, \eta, \omega, \Delta$ decays
2. $m_U = 2\ MeV$, $m_X \sim 190$ GeV — Light dark photon and heavy DM. It satisfies σ_{eff} constraints
3. $m_U < 2m_\chi$, $m_X \sim 200 - 800$ GeV — Stable and long-lived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



Possible Benchmark Points

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





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. $m_U < 2m_\chi$, $m_X \sim 200 - 800$ GeV — Stable and long-lived dark photon

---

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, allowing us to constrain the kinetic mixing parameter $\boldsymbol{\varepsilon}$ through dark photon production and decay within the PHSD transport framework.
- Recent results from **LHCb**, **KLOE**, and **CMS** impose even tighter bounds, which can only be satisfied if the possible dark photon contribution is reduced to $\boldsymbol{C_U = 0.05 - 0.1}\%$ (Invisible regime)
- The **effective cross-section** together with **group and cluster constraints** provides an effective approach to narrowing down the $m_U(m_X)$ parameter space and identifying viable benchmark points.
- Additionally, the **dark matter thermal relic abundance** condition must be satisfied to ensure compatibility with cosmological observations.
- Combine SIDM constraints with Thermal relic abundance constraints in $m_U(m_X)$ phase space.
- Heavy-ion measurements, when interpreted jointly with cosmology and SIDM phenomenology, provide competitive and complementary constraints on dark photon models and help **identify the most promising benchmark points for future searches.**

→Perspectives:

- Explore the axion portal in high energy collisions
- Explore SN core collapse, NS cooling bounds, etc

Thank you for your attention

Backup Slides

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

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

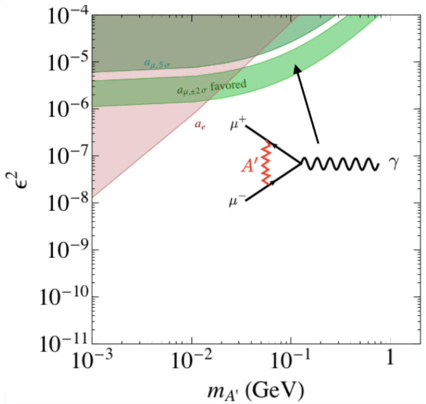
$$\mathcal{L}^\chi_{\text{mass}} = \begin{cases} -\,m_\chi\,\bar{\chi}\chi, & \text{Dirac fermion,} \\ -\,\dfrac{1}{2}\,m_\chi\,\bar{\chi}\chi, & \text{Majorana fermion,} \\ -\,m_\chi^2\,\varphi^\dagger\varphi, & \text{complex scalar.} \end{cases}$$

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

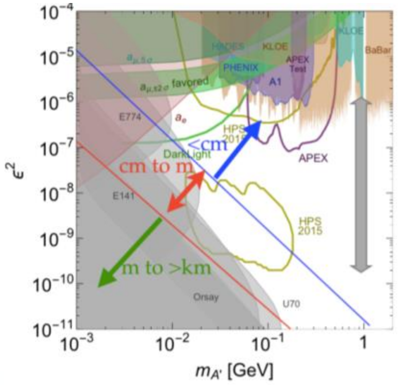
Dark Photons $\varepsilon^2(m_U)$ Visible Constraints

time

2008

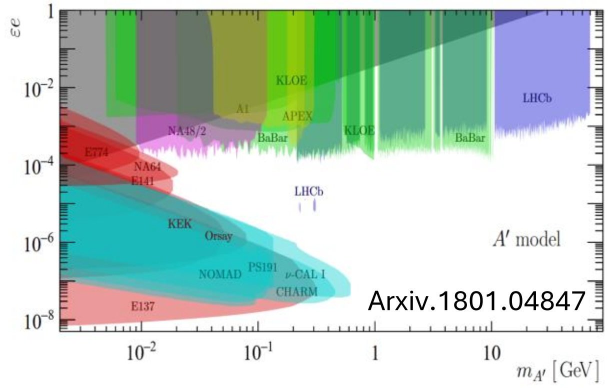


2014

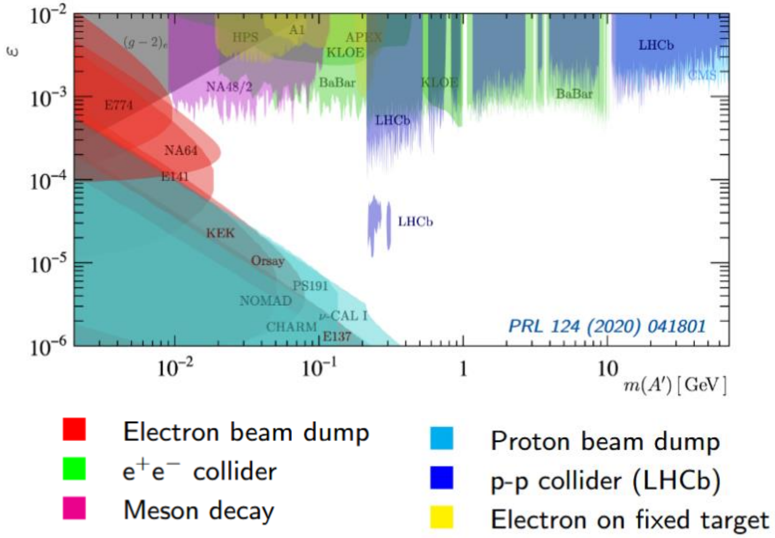


plot illustrations from N.Toro

2018



2020



Dark Photon Model with Dark Matter

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

Arxiv.1411.1404

Arxiv:2005.01515

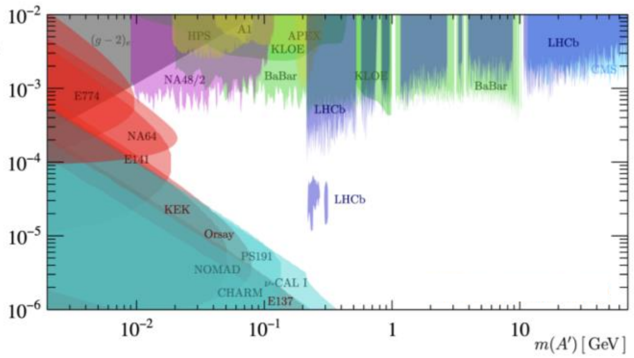
$$\mathcal{L} = \mathcal{L}_{SM} - \frac{1}{4} F'^{\mu\nu} F'_{\mu\nu} - \frac{1}{2} \boldsymbol{m_U^2} A'^{\mu} A'_{\mu} + \frac{\boldsymbol{\varepsilon}}{2} B^{\mu\nu} F'_{\mu\nu} + \boldsymbol{g_\chi} \overline{\mathrm{X}} \gamma^{\mu} \mathrm{X} A'_{\mu} + f(\boldsymbol{m_\chi})$$

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

4-free parameters

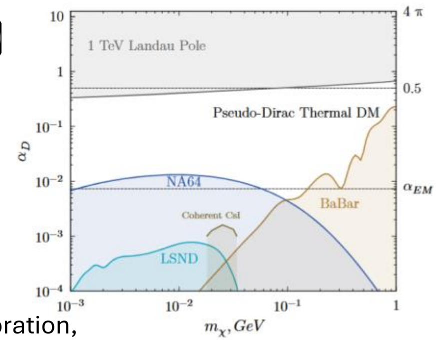
$(\boldsymbol{\varepsilon}, \boldsymbol{m_U})$ $(\boldsymbol{\alpha_X}, \boldsymbol{m_X})$

$\varepsilon^2(M_U)$



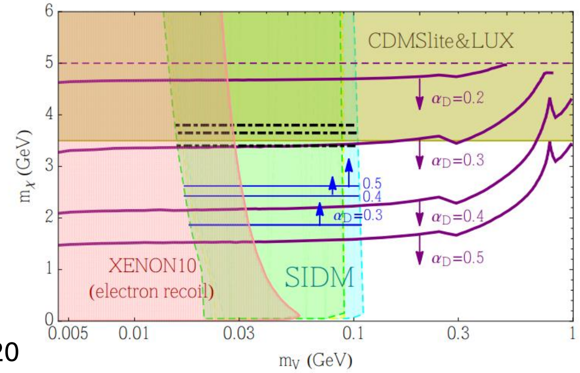
Arxiv.1801.04847

$\alpha_\chi(m_\chi)$



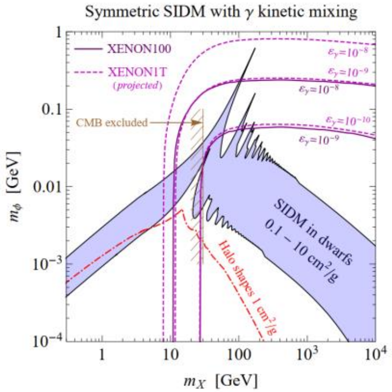
NA64 Collaboration, SPSC-SR-255

$m_\chi(M_U)$



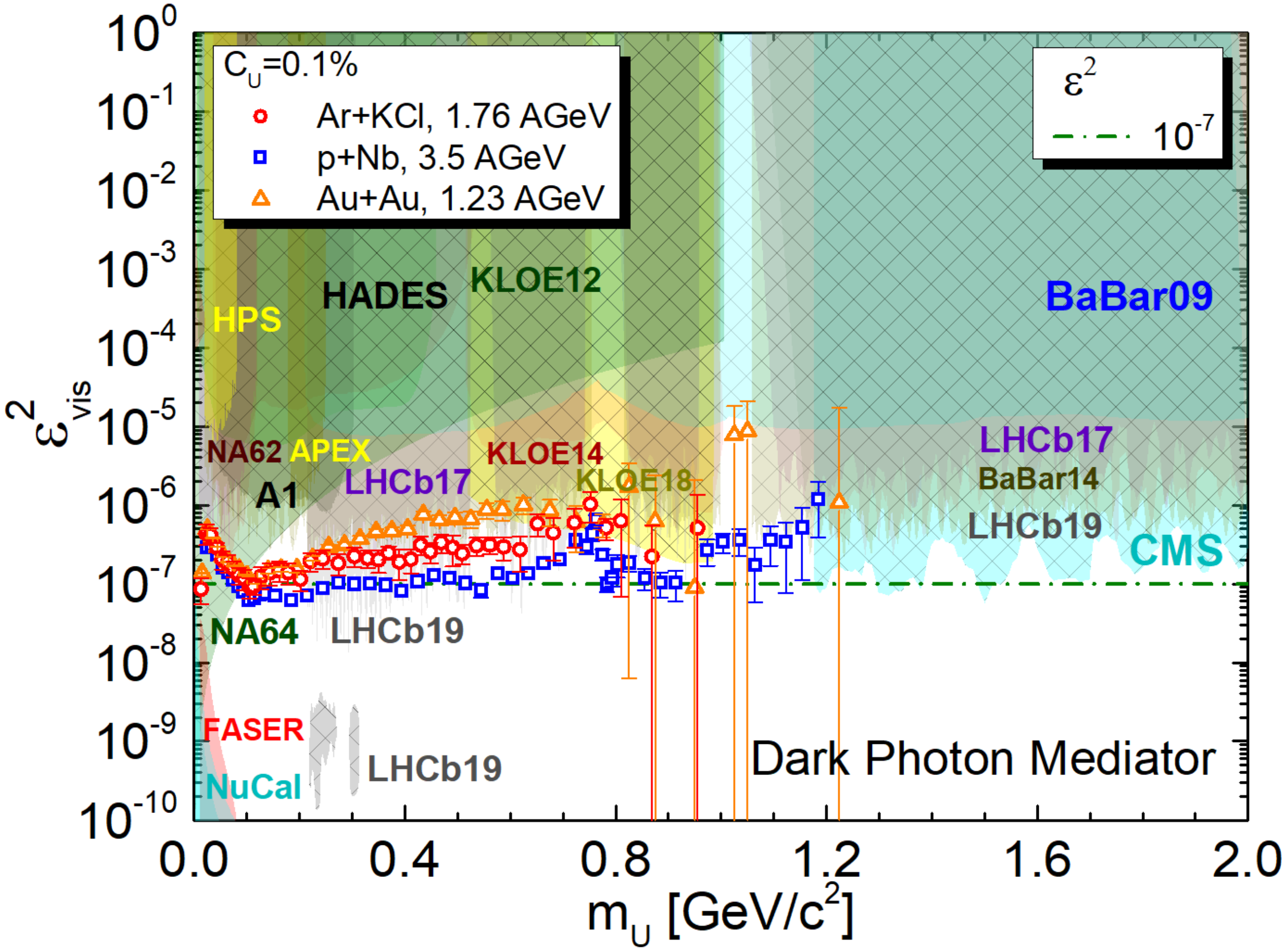
Arxiv.1510.05020

$M_U(m_\chi)$



Arxiv.1308.0618

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



- From **PHSD** (dark photons)

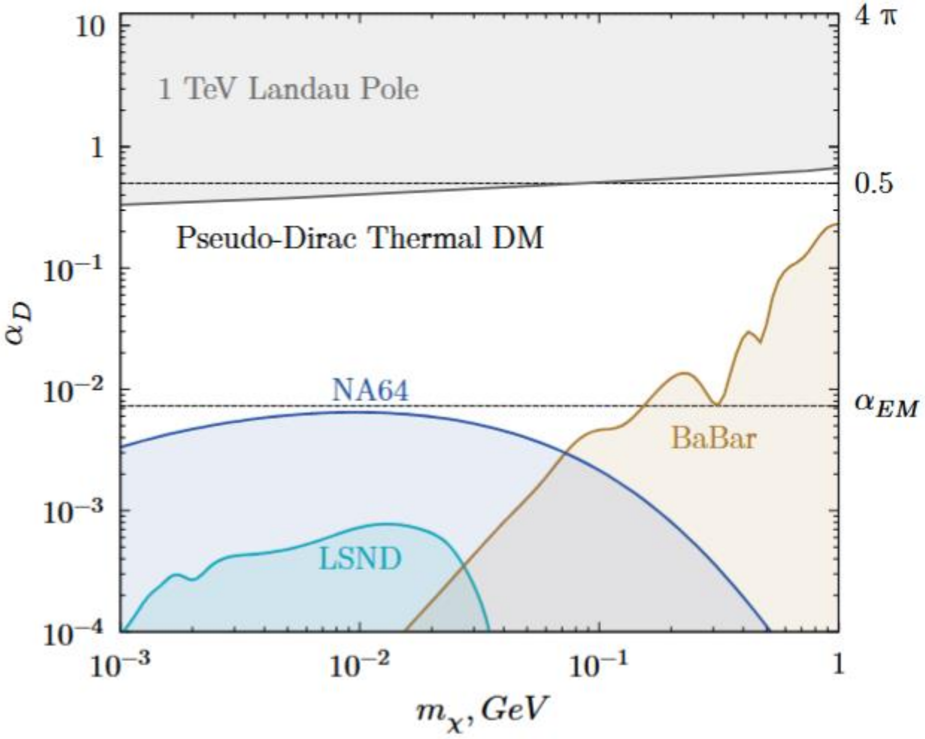
$$\frac{dN^{sumU}}{dM} = \varepsilon^2 \frac{dN^{sumU}_{\varepsilon^2=1}}{dM}$$

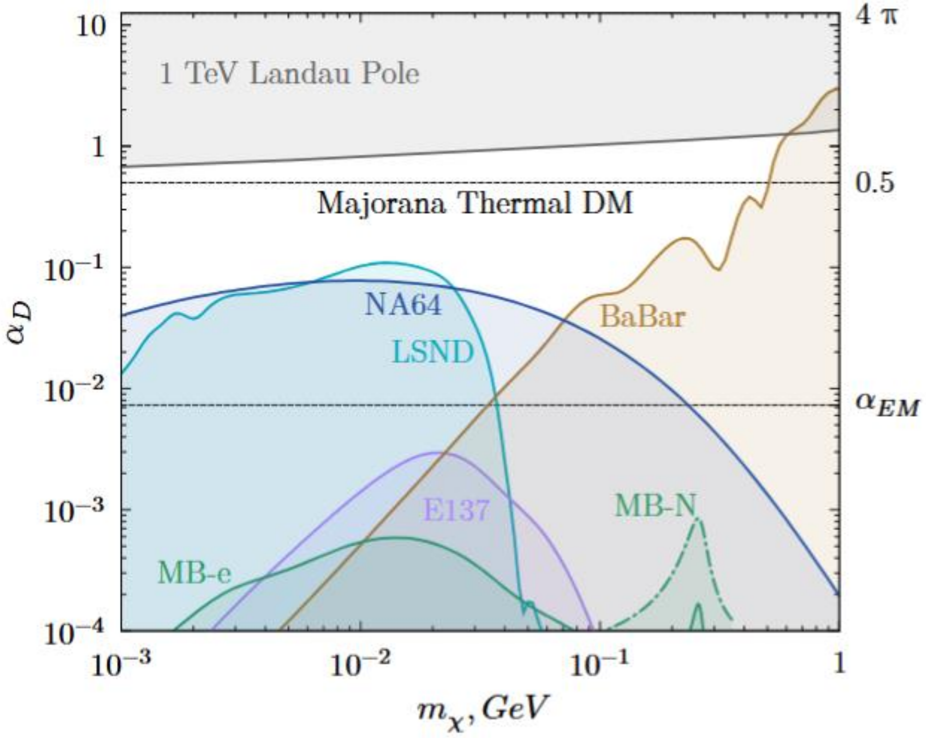
- From **Experimental Data** rather then PHSD

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

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

Dark alpha α_χ Limits





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

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

Construction of the scattering amplitude

1. CLASSICS considers elastic dark-matter self-scattering:

$$\chi + \chi \to \chi + \chi$$

The stationary non-relativistic Schrödinger equation is then solved:

$$\left[-\frac{1}{2\mu}\nabla^2 + V(r)\right]\psi(\mathbf{r}) = E\psi(\mathbf{r}),$$

with the Yukawa potential:

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

2. Partial-wave expansion

the wavefunction can be expanded in partial waves:

$$\psi(\mathbf{r}) = \sum_{\ell=0}^{\infty} R_\ell(r)P_\ell(\cos\theta).$$

Each angular-momentum mode ℓ satisfies the radial Schrödinger equation:

$$\frac{d^2u_\ell}{dr^2} + \left[k^2 - 2\mu V(r) - \frac{\ell(\ell+1)}{r^2}\right]u_\ell(r) = 0,$$

where:

$$u_\ell(r) = rR_\ell(r), \qquad k = \mu v.$$

Construction of the scattering amplitude

3. Extraction of phase shifts

the potential vanishes and the solution behaves asymptotically as:

$$u_\ell(r) \sim \sin\left(kr - \frac{\ell\pi}{2} + \delta_\ell\right).$$

are the partial-wave phase shifts generated by the interaction potential.

Momentum-transfer cross section

The quantity commonly used for SIDM:

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

4. Construction of the scattering amplitude

The scattering amplitude is written as:

$$f(\theta) = \frac{1}{k}\sum_{\ell=0}^{\infty}(2\ell+1)e^{i\delta_\ell}\sin\delta_\ell P_\ell(\cos\theta).$$

The differential scattering cross section is: $$\frac{d\sigma}{d\Omega} = |f(\theta)|^2.$$

Total cross section

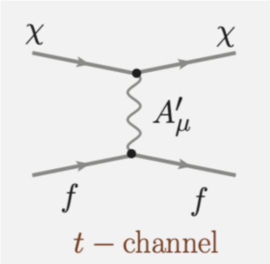
$$\sigma_{\text{tot}} = \int d\Omega\,\frac{d\sigma}{d\Omega}.$$

Using partial waves:

$$\sigma_{\text{tot}} = \frac{4\pi}{k^2}\sum_\ell(2\ell+1)\sin^2\delta_\ell.$$

Why Yukawa Potential?

For t-channel mediator exchange:



the tree-level amplitude is:

$$\mathcal{M}(\mathbf{q}) = -\frac{g_\chi^2}{\mathbf{q}^2 + m_U^2},$$

In the non-relativistic limit:

$$q^0 \ll |\mathbf{q}|,$$

$$q^2 \simeq -\mathbf{q}^2.$$

Therefore, the propagator becomes:

$$\frac{1}{q^2 - m_U^2} \to -\frac{1}{\mathbf{q}^2 + m_U^2}.$$

In quantum mechanics, the potential in coordinate space is obtained from:

$$V(\mathbf{r}) = \int \frac{d^3q}{(2\pi)^3} e^{i\mathbf{q}\cdot\mathbf{r}} \tilde{V}(\mathbf{q}),$$

and in the Born approximation:

$$\tilde{V}(\mathbf{q}) \propto \mathcal{M}(\mathbf{q}).$$

Thus:

$$V(r) \propto \int \frac{d^3q}{(2\pi)^3} \frac{e^{i\mathbf{q}\cdot\mathbf{r}}}{\mathbf{q}^2 + m_U^2}.$$

The well-known Fourier transform is:

$$\int \frac{d^3q}{(2\pi)^3} \frac{e^{i\mathbf{q}\cdot\mathbf{r}}}{\mathbf{q}^2 + m_U^2} = \frac{e^{-m_U r}}{4\pi r}.$$

Therefore:

$$V(r) = -\frac{g_\chi^2}{4\pi} \frac{e^{-m_U r}}{r}.$$

$$\boxed{V(r) = -\alpha_\chi \frac{e^{-m_U r}}{r},}$$

Why Yukawa Potential?

The exponential factor appears because the mediator is massive

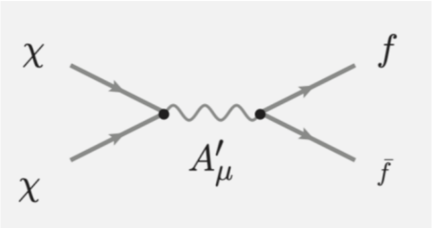
Coulomb limit $m_U \to 0,$

$$V(r) \to \frac{1}{r},$$

The mediator mass therefore determines the interaction range:

$$r_{\text{range}} \sim \frac{1}{m_U}.$$

s-channel



$$m_U > 2m_\chi$$

$$\frac{1}{q^2 - m_U^2 + i m_U \Gamma_U}$$

$$\Gamma_U \ll m_U.$$

$$\Gamma(U \to f^+ f^-) = \varepsilon^2 \frac{\alpha\, m_U}{3} C_f \left(1 + 2\frac{m_f^2}{m_U^2}\right)\left(1 - \frac{4m_f^2}{m_U^2}\right)^{1/2}$$

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

$$\Rightarrow \quad V(r) = -\alpha_\chi \frac{e^{-m_U r}}{r},$$

Constraints on dark matter annihilation from CMB observations before Planck

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

Annihilation cross-section

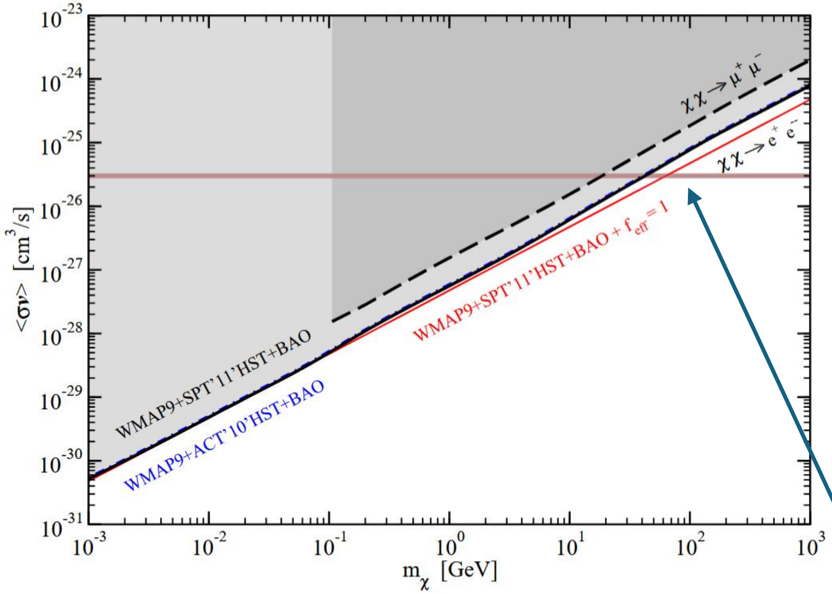
Energy fraction deposited in the plasma

This parameter controls how the DM annihilation modifies the CMB

arXiv:1303.5094 → $m_\chi \leq 30\ GeV$

arXiv:1310.7945v1 → $2m_e \leq m_U \leq 0.1\ GeV$

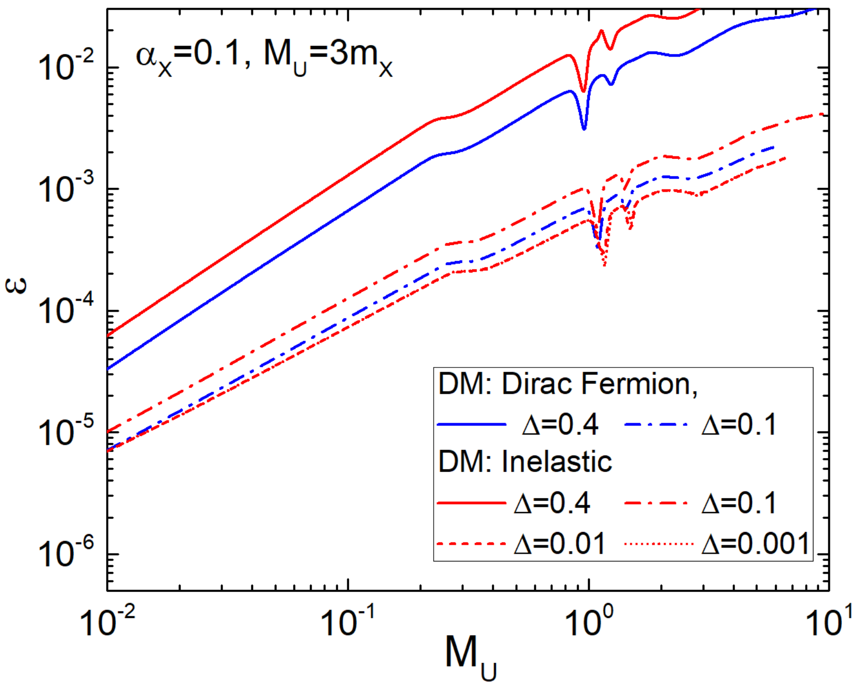
$p_{\mathrm{ann}} < 1.6 \times 10^{-27}\,\mathrm{cm^3 s^{-1}\,GeV^{-1}}$

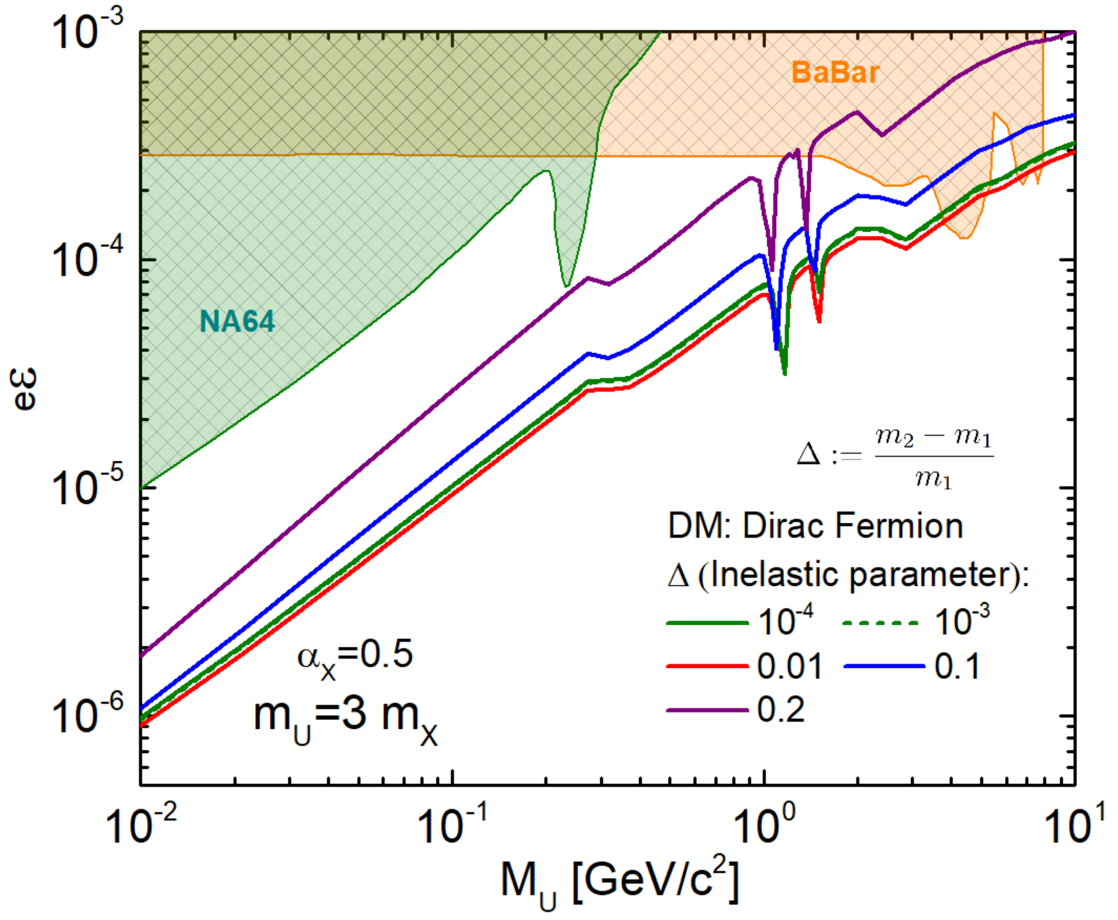


$\langle \sigma v \rangle \approx 3 \times 10^{-26}\ cm^3 s^{-1}$ arXiv:1303.5094

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

Thermal Targets: Elastic Dark Matter





$\boldsymbol{U \to X_1 X_2}$ Direct Annihilation

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

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

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

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

Dark photon coupling to DM

Dark photon
is the gauge boson
of a dark gauge symmetry

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

Complex 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

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

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

Real Scalar

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 $J^\mu_D = q_D\bar{\chi}\gamma^\mu\chi.$

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

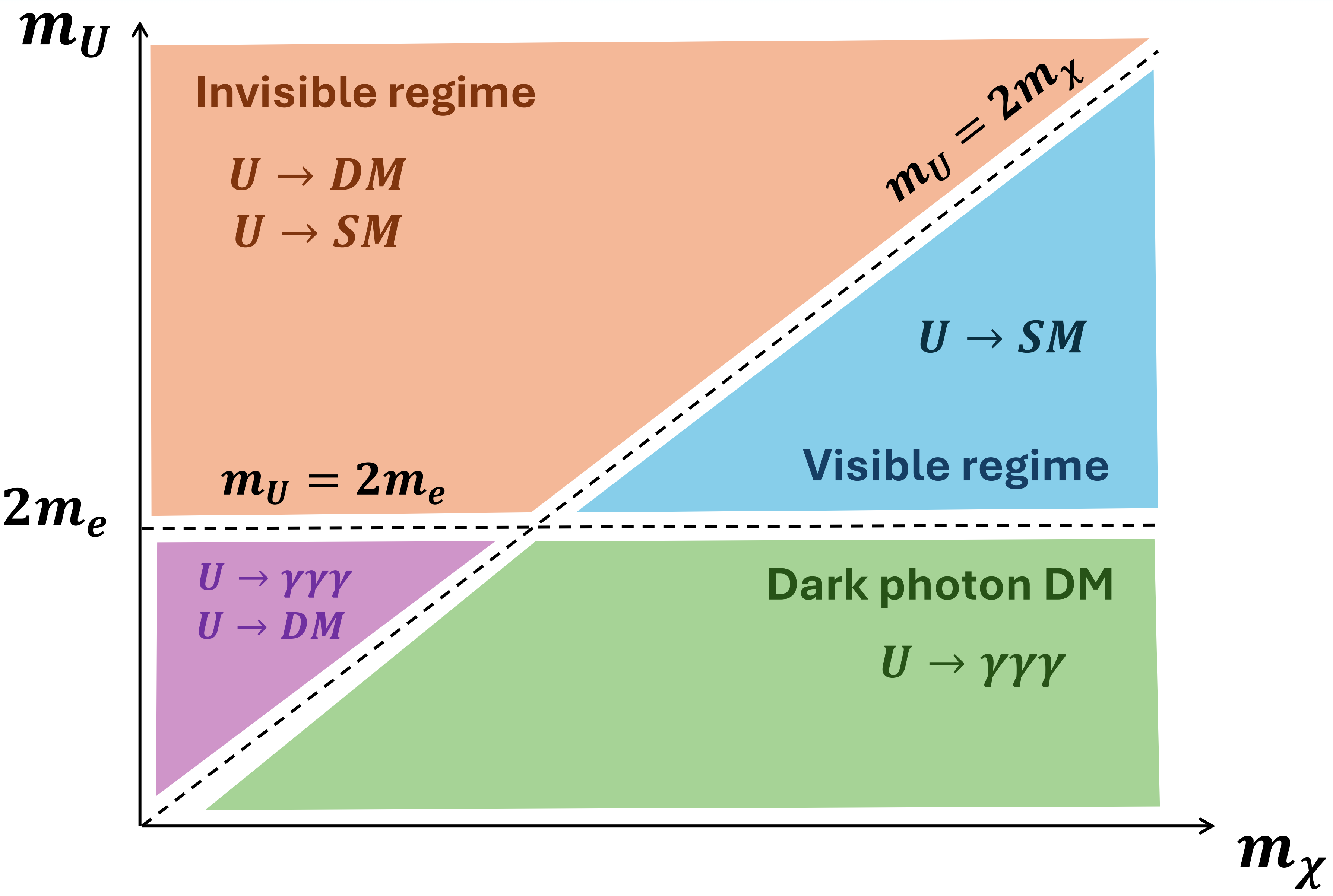
Axial Majorana coupling

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

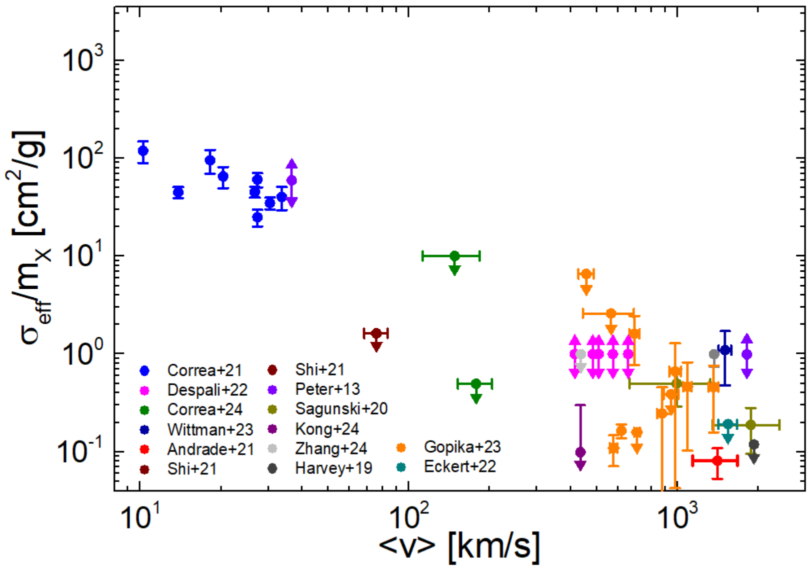
But this is not the minimal vector dark photon coupling. It requires a more specific model structure.

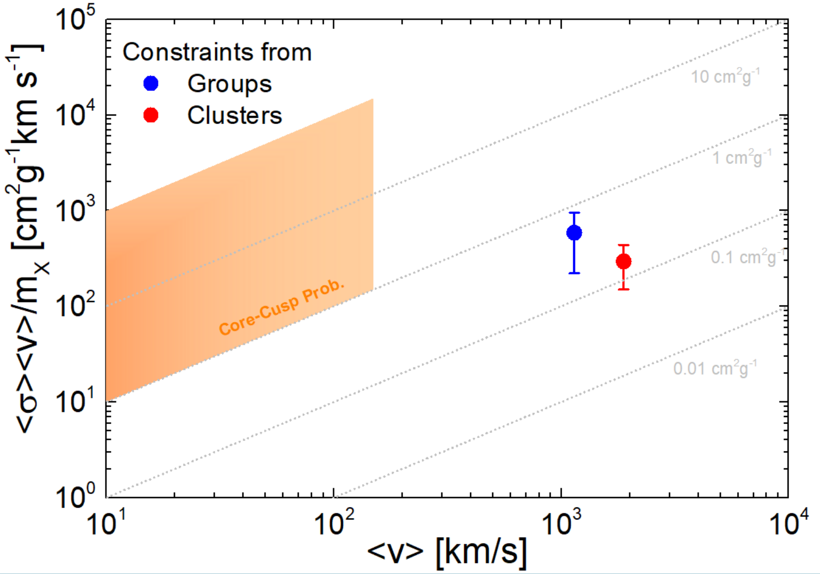
$$\mathcal{L}_{\text{int}} = g_D A'_\mu \bar{\chi}\gamma^\mu\gamma^5\chi.$$

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


m_U
Invisible regime
$U \to DM$
$U \to SM$
$m_U = 2m_\chi$
$U \to SM$
Visible regime
$m_U = 2m_e$
$2m_e$
$U \to \gamma\gamma\gamma$
$U \to DM$
Dark photon DM
$U \to \gamma\gamma\gamma$
m_χ

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

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

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

Thermal Relic Abundance

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

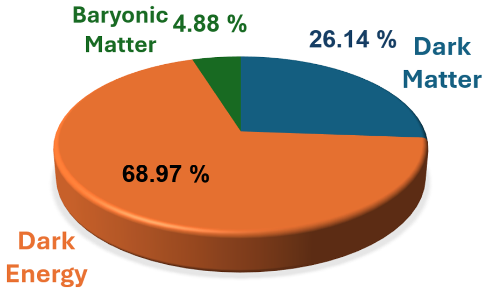
$$h = 0.674$$

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

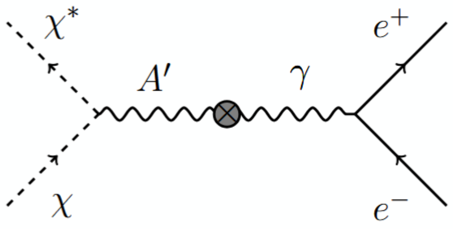
Mediator: Dark Photon

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

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



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

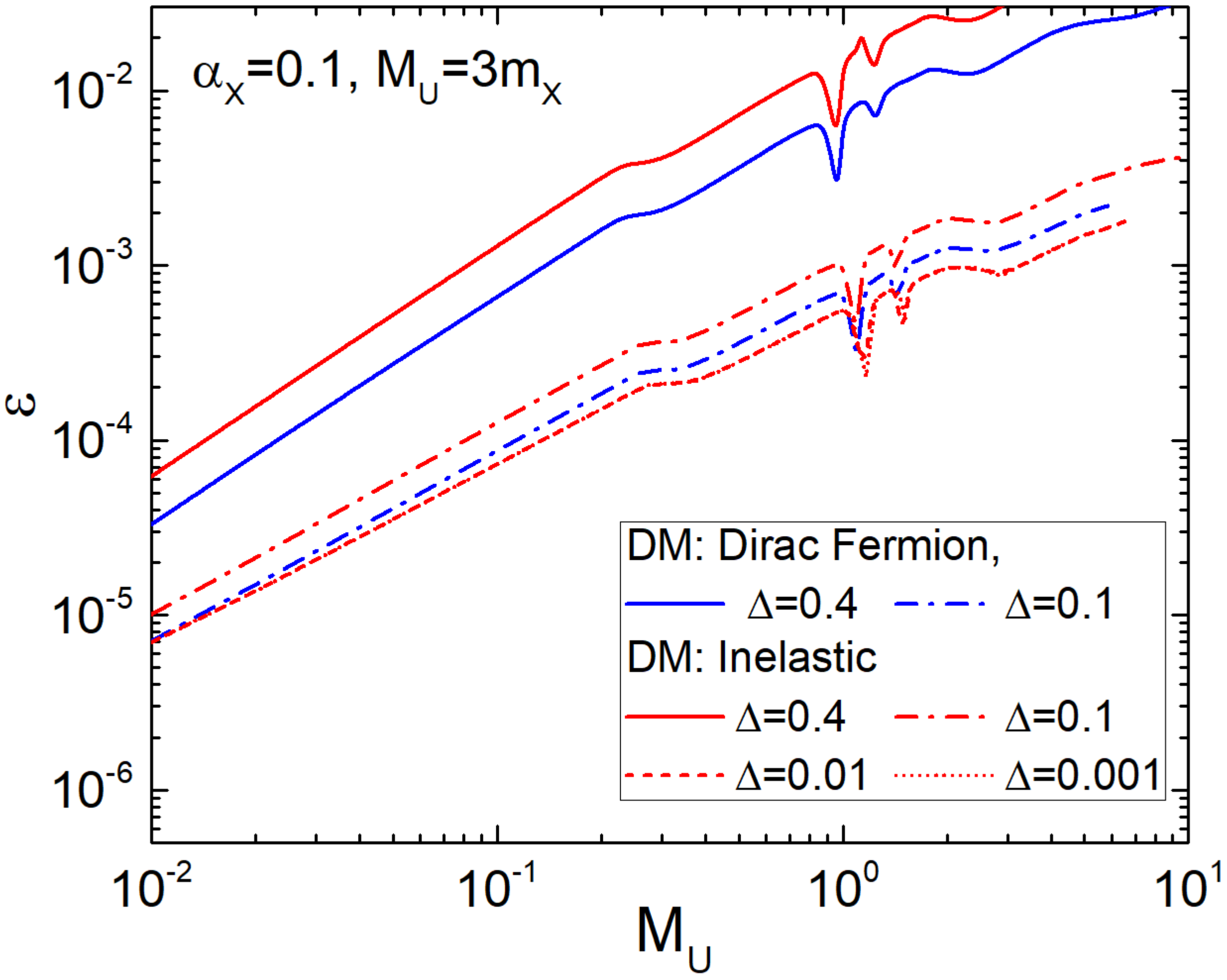
s − channel

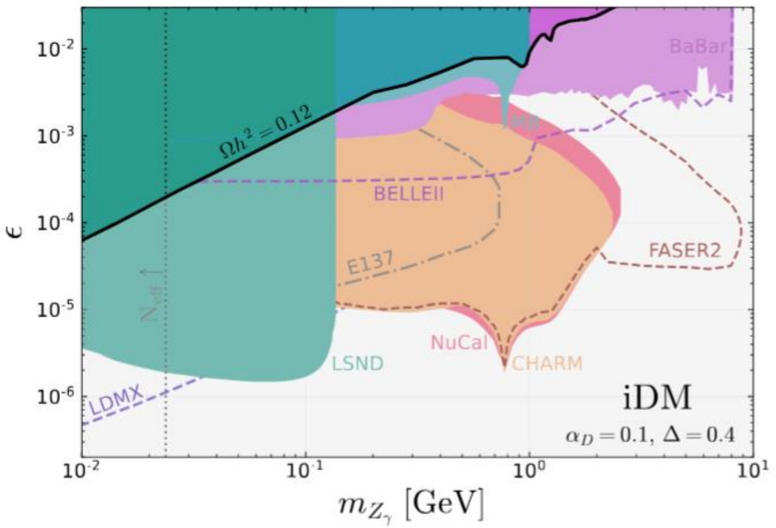
$$\Gamma(\chi\bar{\chi} \to U^* \to f\bar{f}) = \varepsilon^2 \frac{\alpha_\chi m_U}{12} \left(1 - \frac{4m_\chi^2}{m_U^2}\right)^{3/2}$$

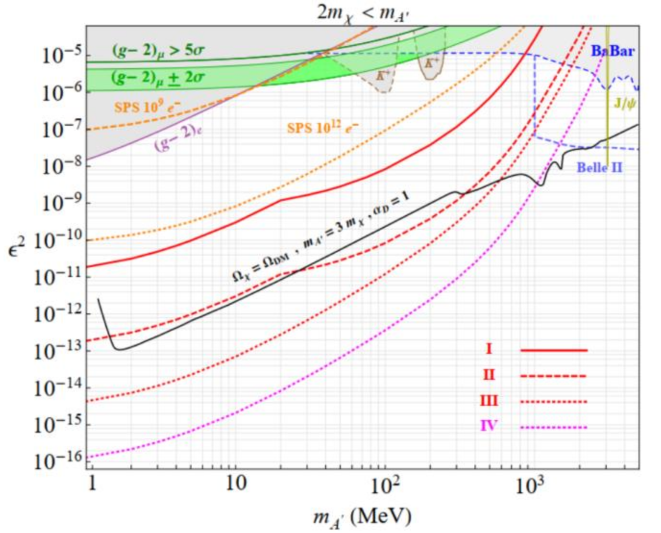
Red DeliVeR

https://arxiv.org/abs/2410.00881

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





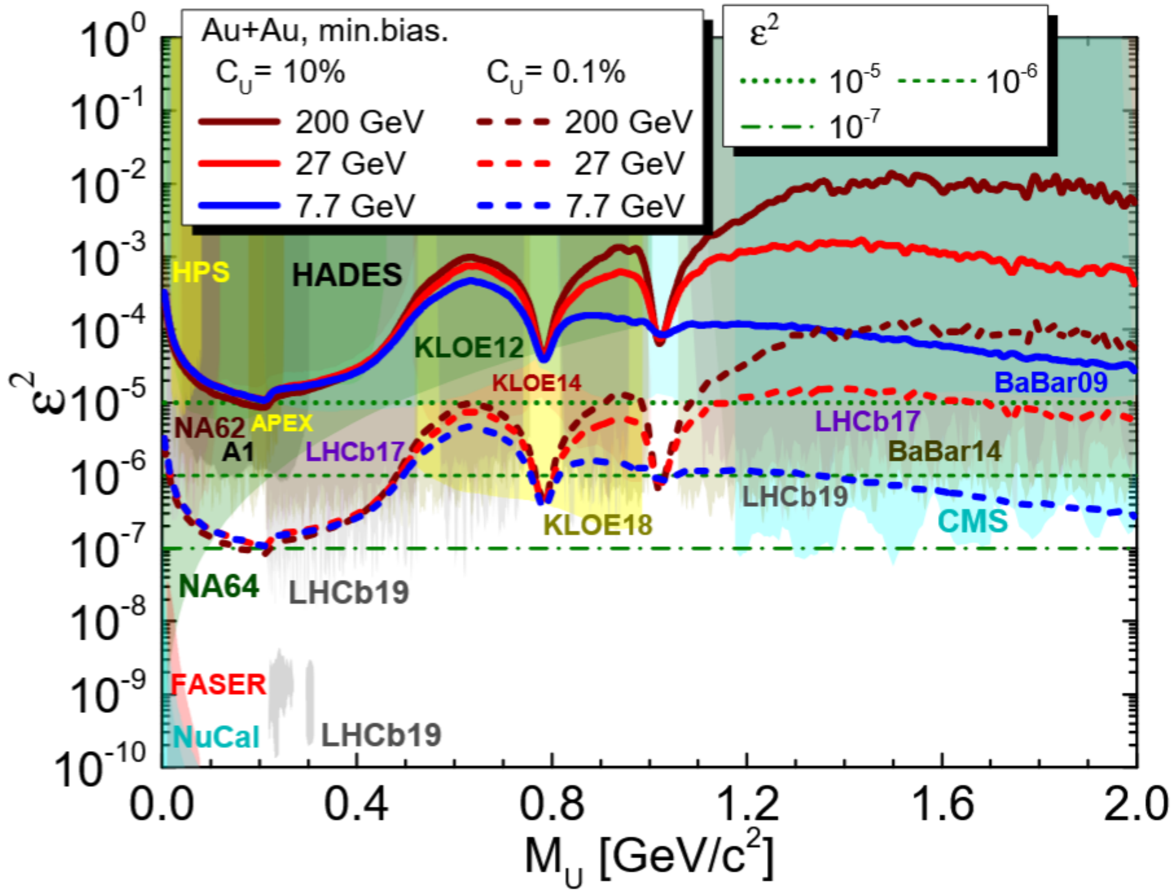


$$\Delta = \frac{|m_{\chi_1} - m_{\chi_2}|}{m_{\chi_1}}$$

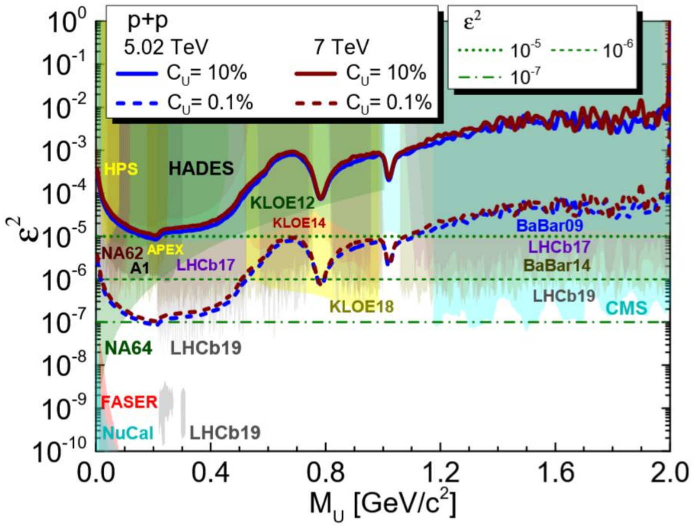
Arxiv.1411.1404

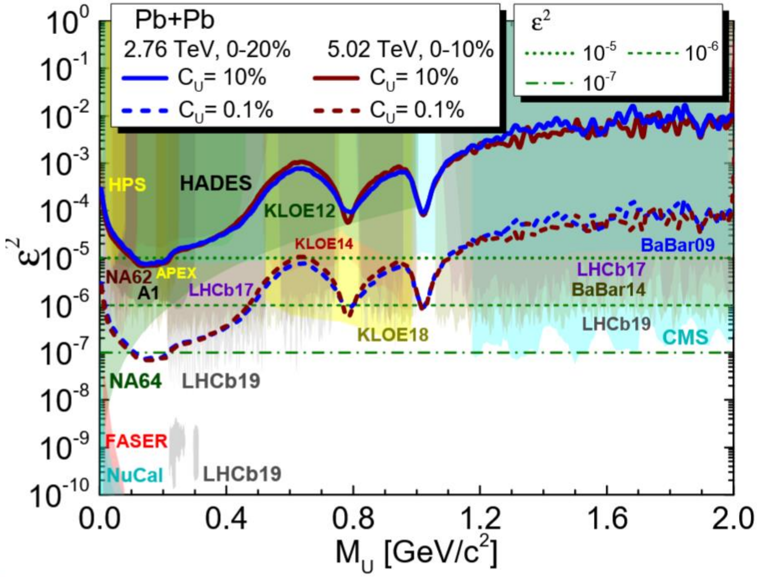
Kinetic Mixing parameter $\varepsilon^2(m_U)$

BES-RHIC-STAR



LHC-ALICE





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