DMLab: DarkMatter@Bonn

16-17 October 2025, Bonn, Germany.

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

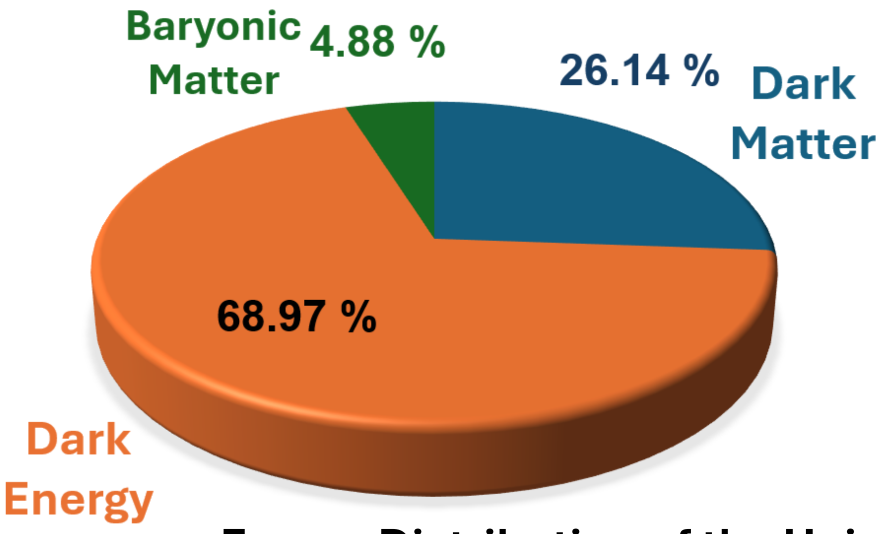
Speaker: Adrian William Romero Jorge (Goethe Uni. Frankfurt & FIAS & HFHF)

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

Collaborators: Taesoo Song (GSI, Darmstadt) & Laura Sagunski (Uni. Frankfurt)

Structure of the Universe

Data from Planck 2028 results (Arxiv: 1807.06209)



Energy Distribution of the Universe

1933: F. Zwicky: observation of the Coma galaxy cluster -> Extra mass

- Dark matter (DM) ~26%
- DM detected by astrophysical observations based on gravitational effects:

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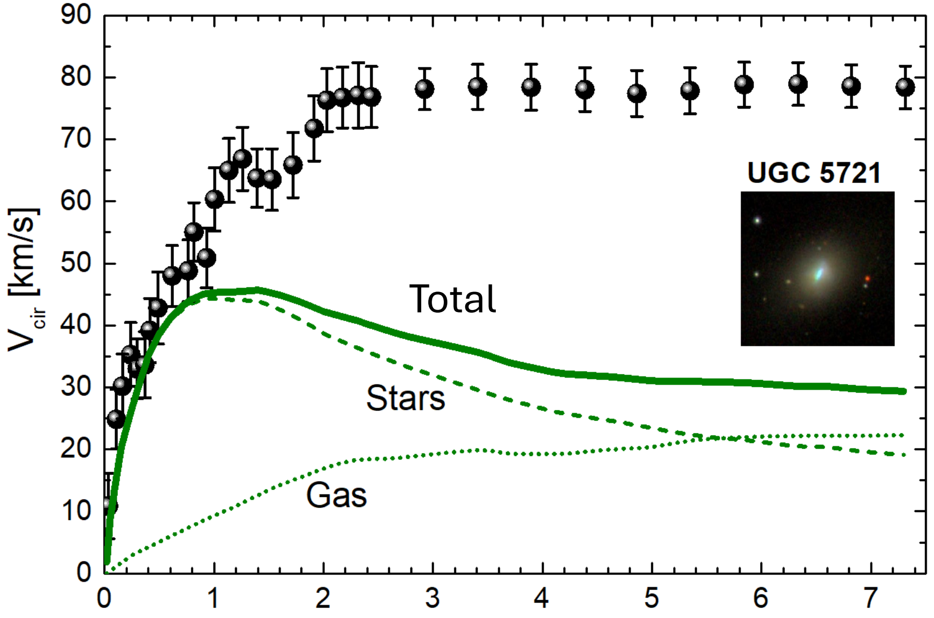

ArXiv:1705.02358v2

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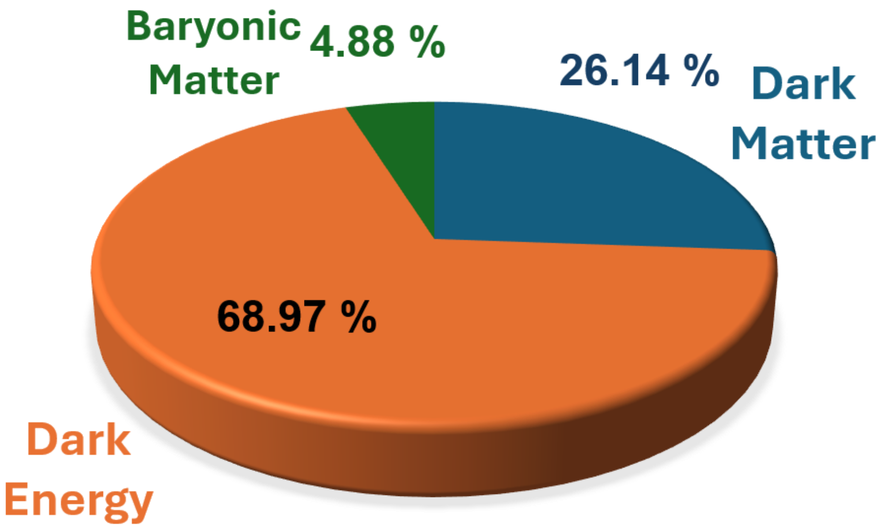

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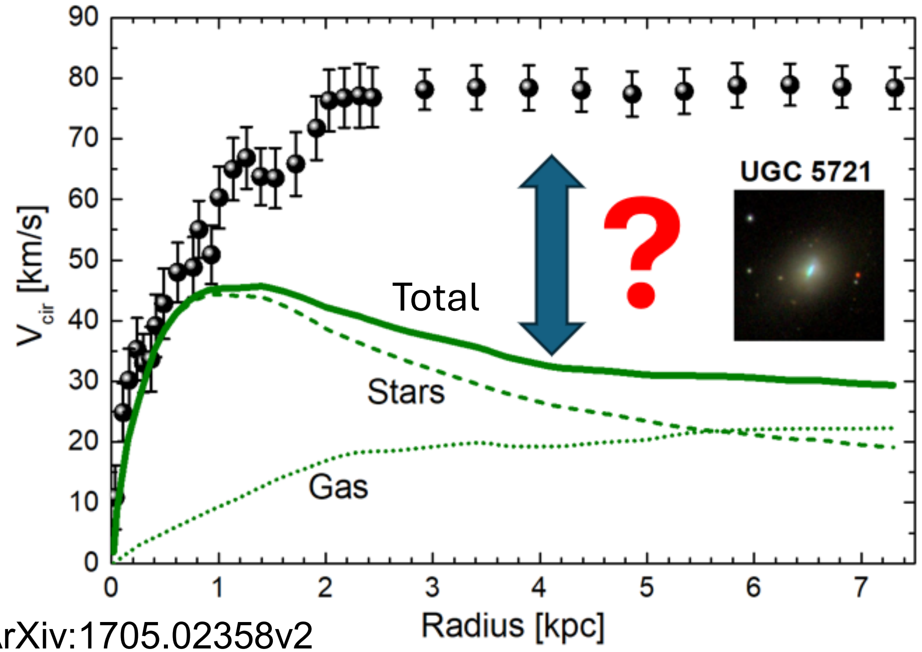

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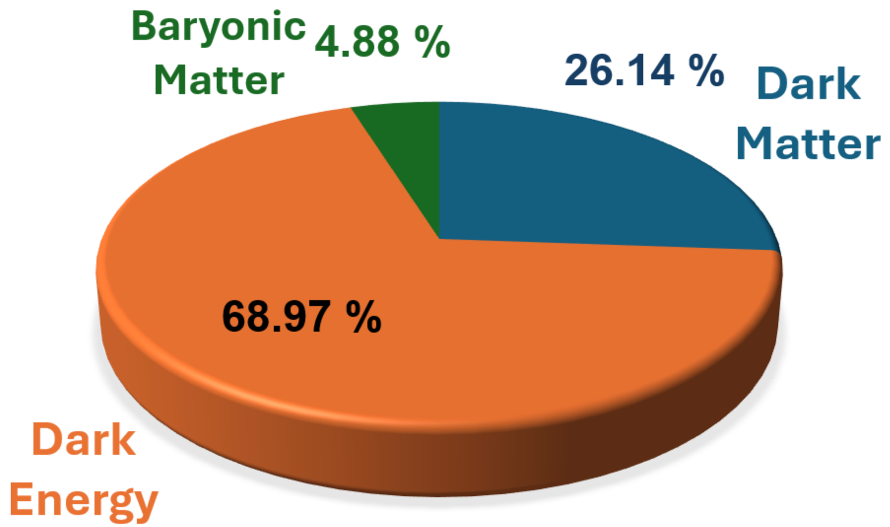

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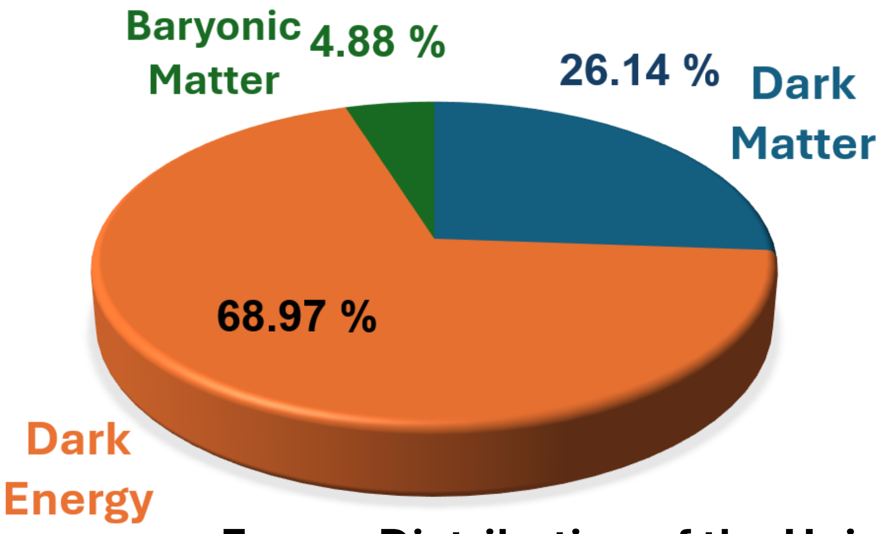

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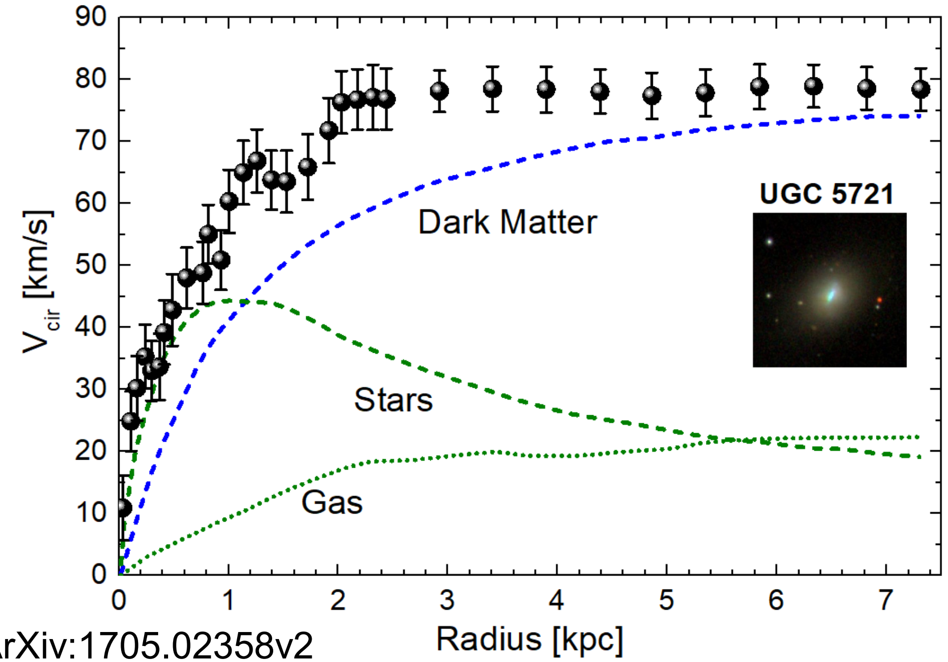

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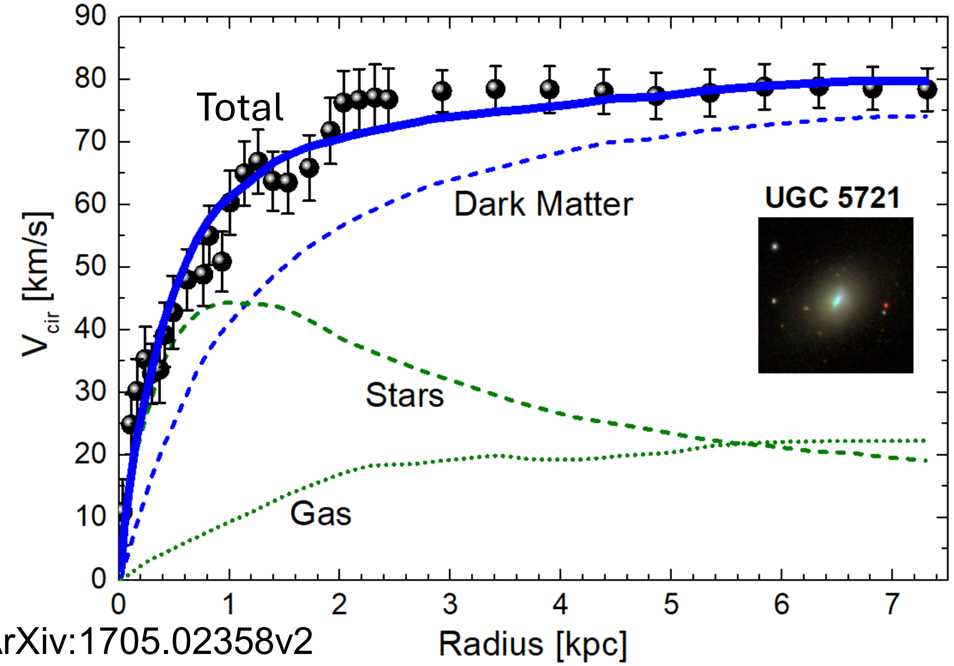

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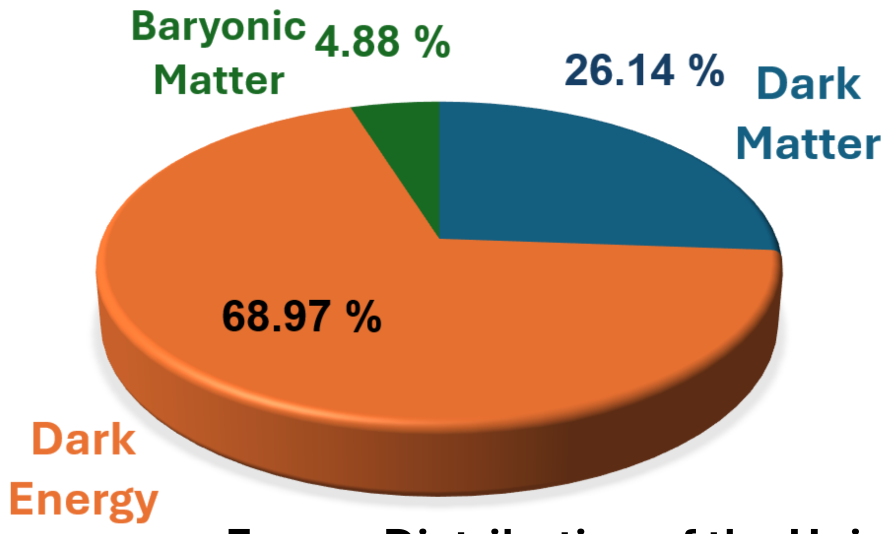

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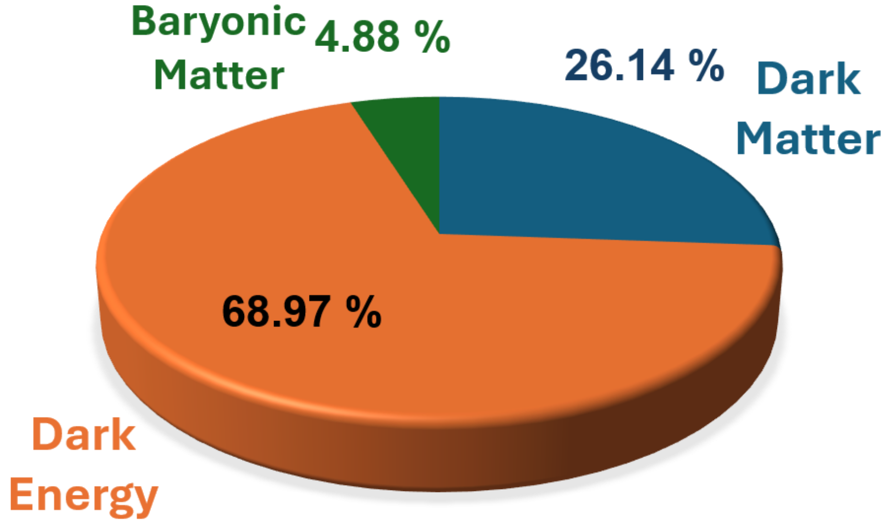

Energy Distribution of the Universe

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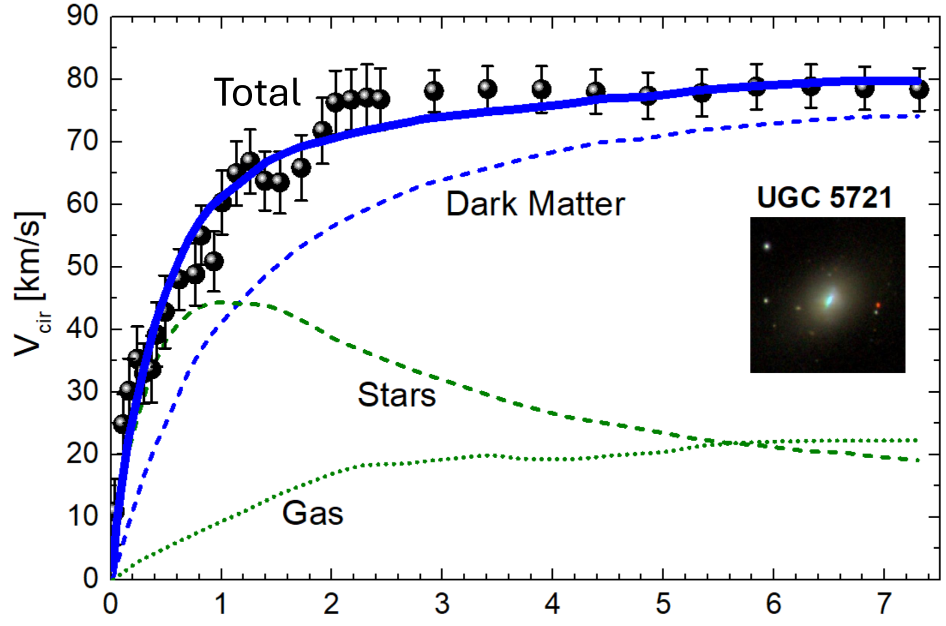

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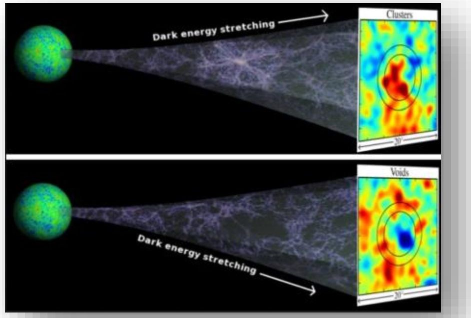
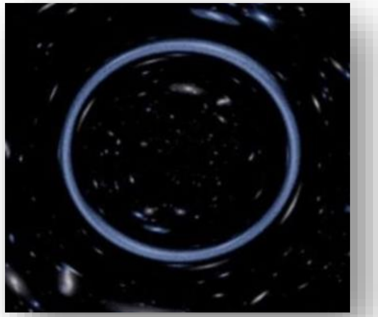
2. Structure Formation



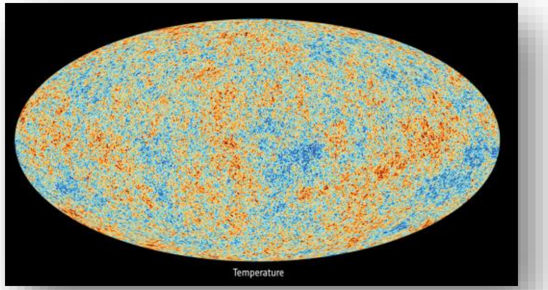
Granett, Neyrinck, Szapudi

3. Gravitational lensing



NASA

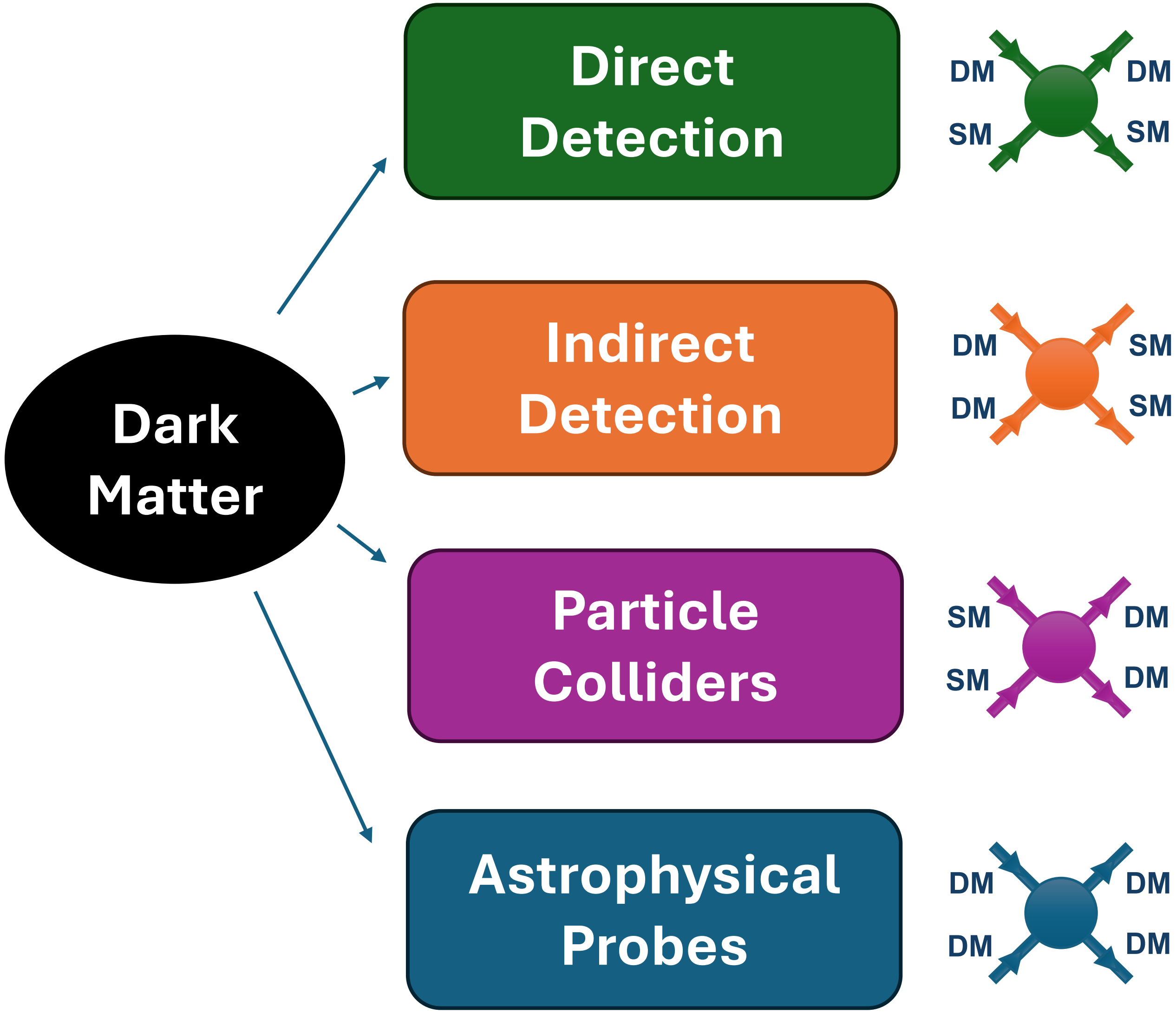
4. Cosmic Microwave Background (CMB)



ESA and the Planck Collaboration.

Dark Matter Detection

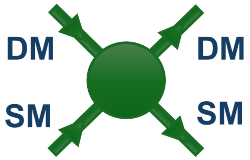
Experiments Techniques

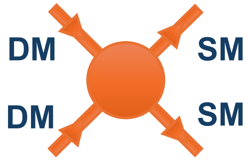


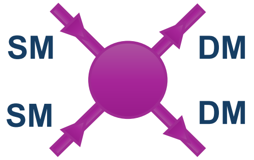
Dark Matter Detection

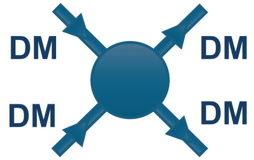
Dark Matter

	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

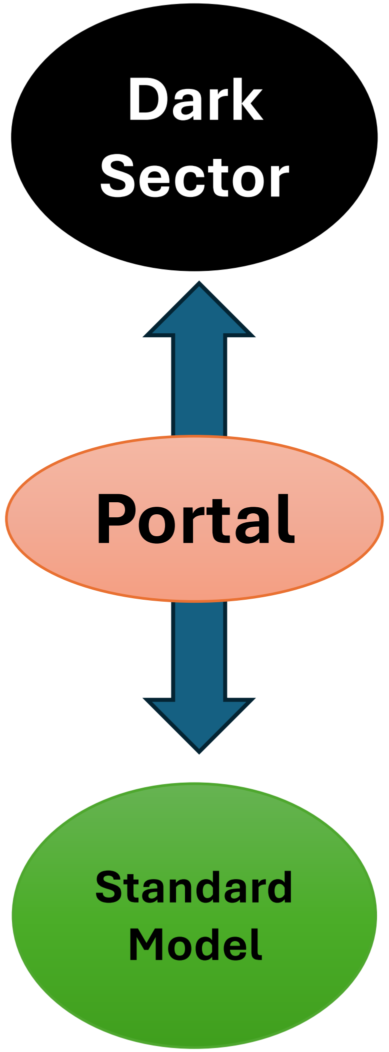




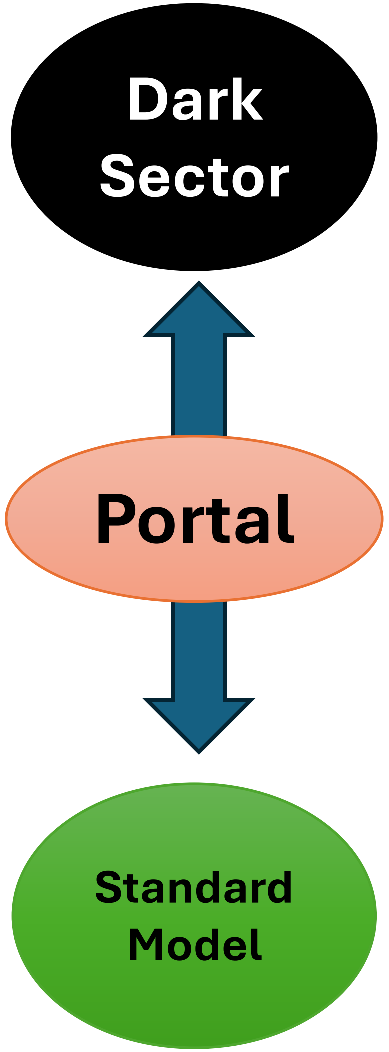




Dark Matter Detection

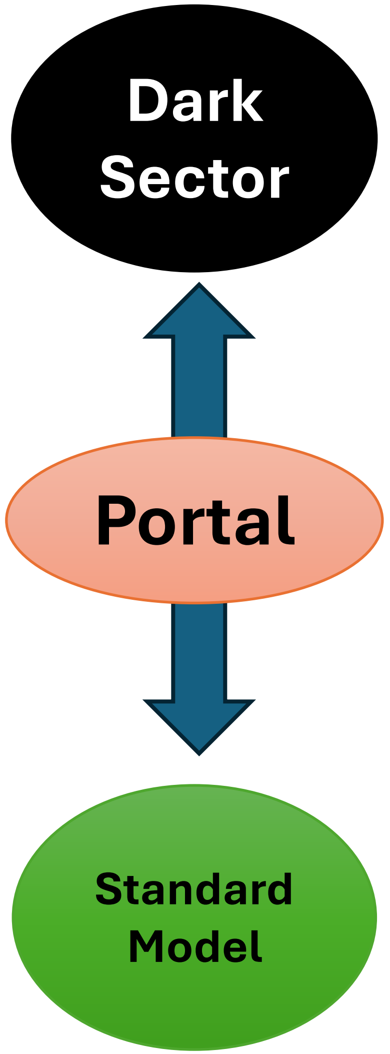


Dark Matter Portals



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



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Dark Photon Model with Dark Matter

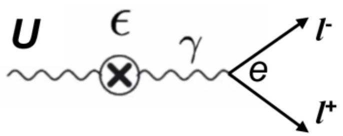
* for the 'dark photon' or ' U- boson': A', V, U, ϕ

Arxiv.1411.1404

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

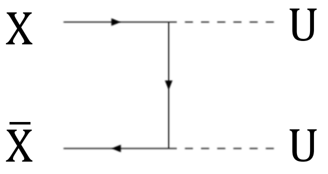
Mediator Particle U | Interaction U-SM | Interaction U-DM | DM particle

- ε ➡ Kinetic mixing parameter
- M_U ➡ Dark photon mass
- g_χ ➡ Dark coupling constant
- m_χ ➡ Dark matter mass



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

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



DM Annihilation

- Dirac case
  $-m_\chi \bar{X} X$

Due to the kinetic mixing the dark photon (U-boson) couples to the electromagnetic current with strength εe

4-free parameters (ε, m_U) (α_X, m_X)

SM hypercharge field strength:

$$B_{\mu\nu} \equiv \partial_\mu B_\nu - \partial_\nu B_\mu$$

Dark photon field strength:

$$F'_{\mu\nu} \equiv \partial_\mu A'_\nu - \partial_\nu A'_\mu$$

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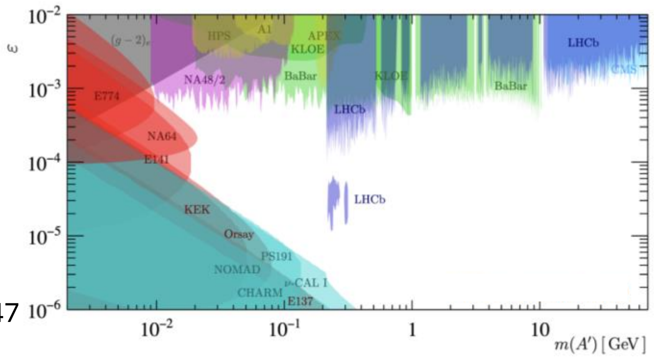
4-free parameters

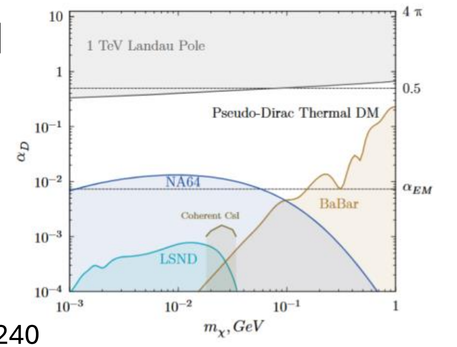
(ε, m_U) (α_X, m_X)

$\varepsilon^2(M_U)$



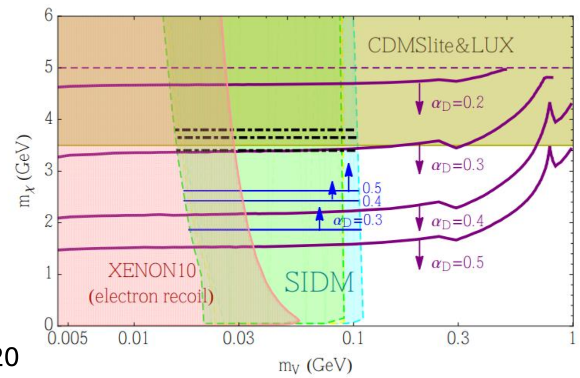
Arxiv.1801.04847

$\alpha_\chi(m_\chi)$



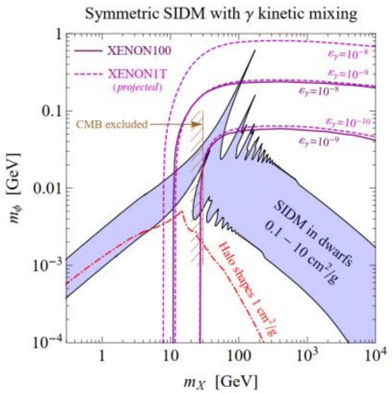
Arxiv:2307.0240

$m_\chi(M_U)$



Arxiv.1510.05020

$M_U(m_\chi)$



Arxiv.1308.0618

Dark Photon Model. Minimal

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

- ε → Kinetic mixing parameter
- M_U → Dark photon mass
- g_χ → Dark coupling constant
- m_χ → Dark matter mass

(ε, m_U)

(α_X, m_X)

$$Br(U \to l^+ l^-) = \frac{\Gamma_{l^+l^-}}{\Gamma_{l^+l^-} + \Gamma_{\mu^+\mu^-} + \Gamma_{hadrons} + \Gamma_{DM}}$$

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

$$Br(U \to l^+ l^-) < Br(U \to DM)$$

Invisible Decay

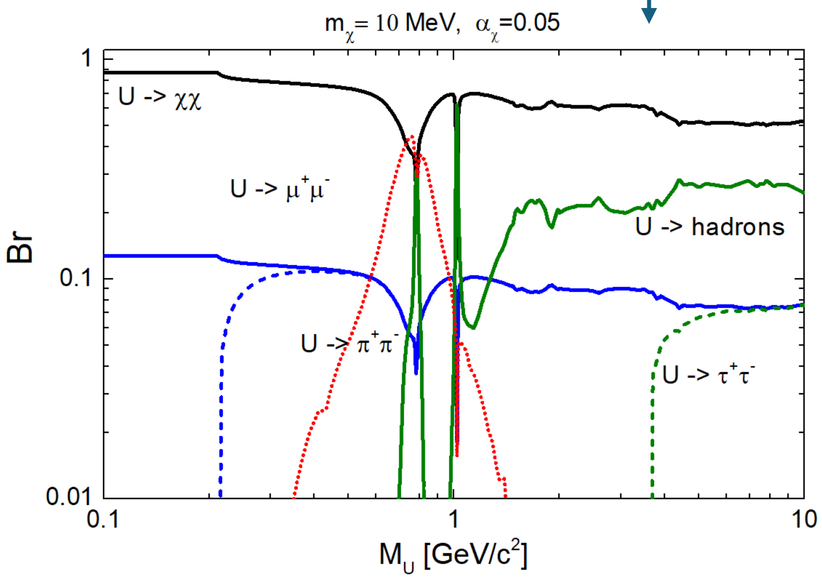
$m_U > 2\, m_\chi$

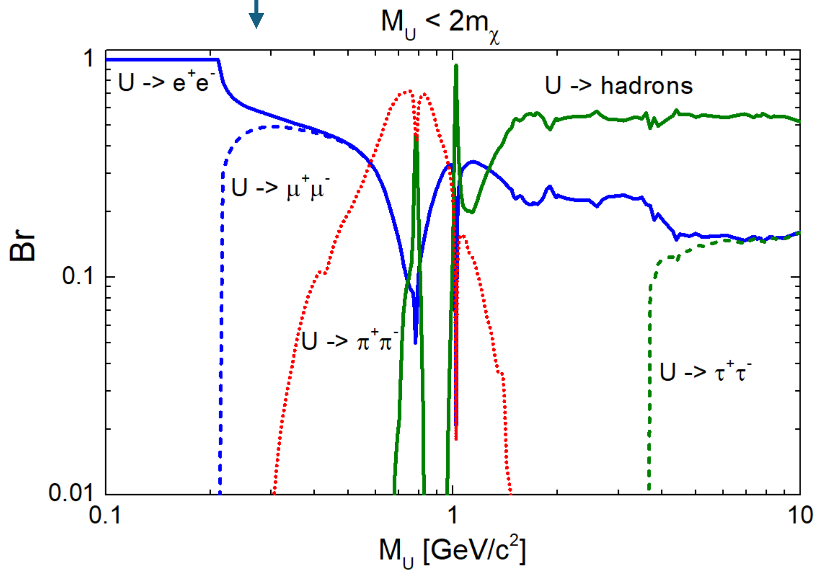
$U \to \chi\bar{\chi}$

Visible Decay

$m_U < 2\, m_\chi$

$U \to SM$





A. Fradette et al. (2015), arXiv:1501.00459, B. Batell et al. (2009), arXiv:0903.0363

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$\boldsymbol{\varepsilon}$ → **Kinetic mixing parameter**

$\boldsymbol{M}_{\boldsymbol{U}}$ → **Dark photon mass**

$(\boldsymbol{\varepsilon}, \boldsymbol{m}_{\boldsymbol{U}})$

Invisible Decay

$m_U > 2\, m_\chi$

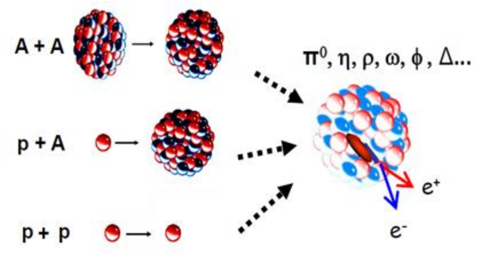
$U \rightarrow \chi\bar{\chi}$

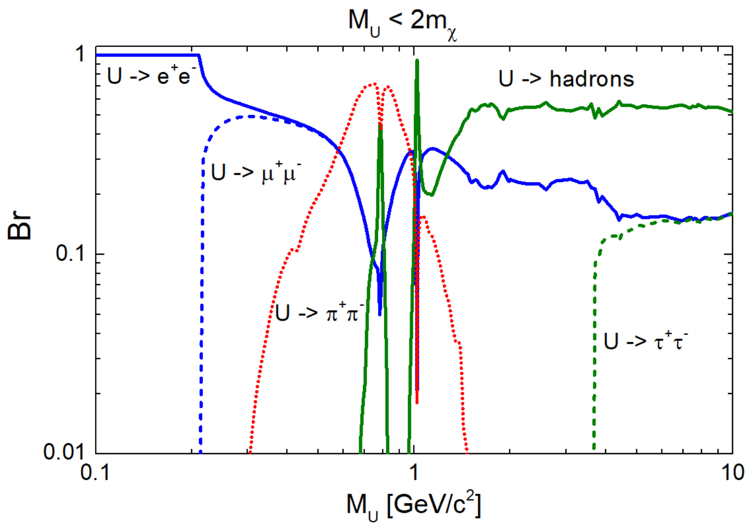
Visible Decay

$m_U < 2\, m_\chi$

$U \rightarrow SM$

Possible dark photon observation by dilepton experiments and how to produce them?



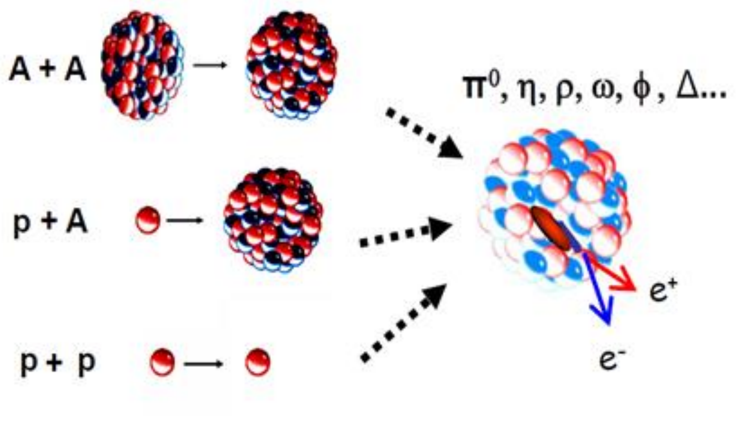


Minimal Model

Only U in Dark Sector

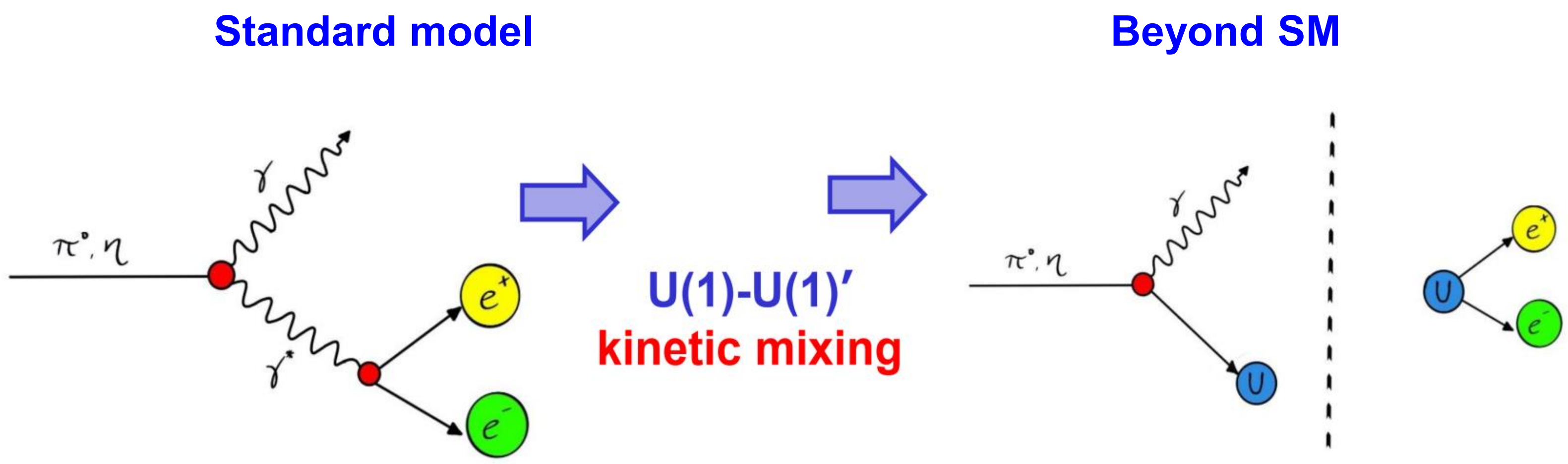
- $U \rightarrow SM$

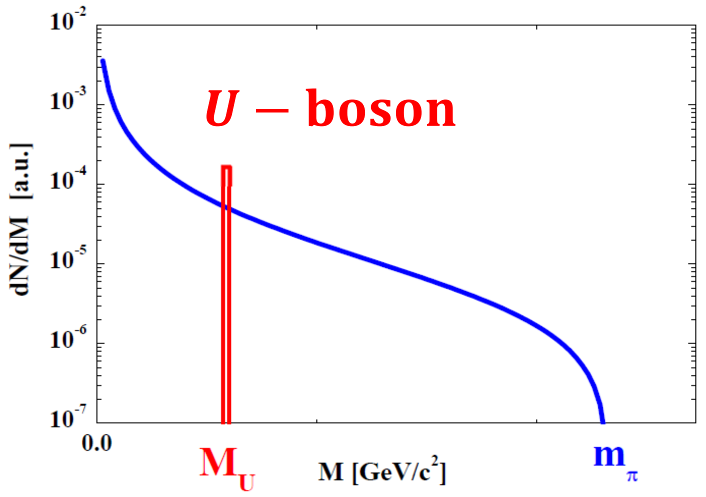
Possible dark photon observation by dilepton experiments



- Dilepton spectra from SM sources are well studied by dilepton experiments from SIS to LHC energies (HADES, STAR,…)
- Hadron production by p+p, p+A, A+A
- Dark photon production in hadronic decays by $\pi, \eta, \Delta, \omega, \phi, \rho, K, \ldots$ decays
- Dalitz π^0,η and Δ decays are the dominant dilepton sources at low M

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



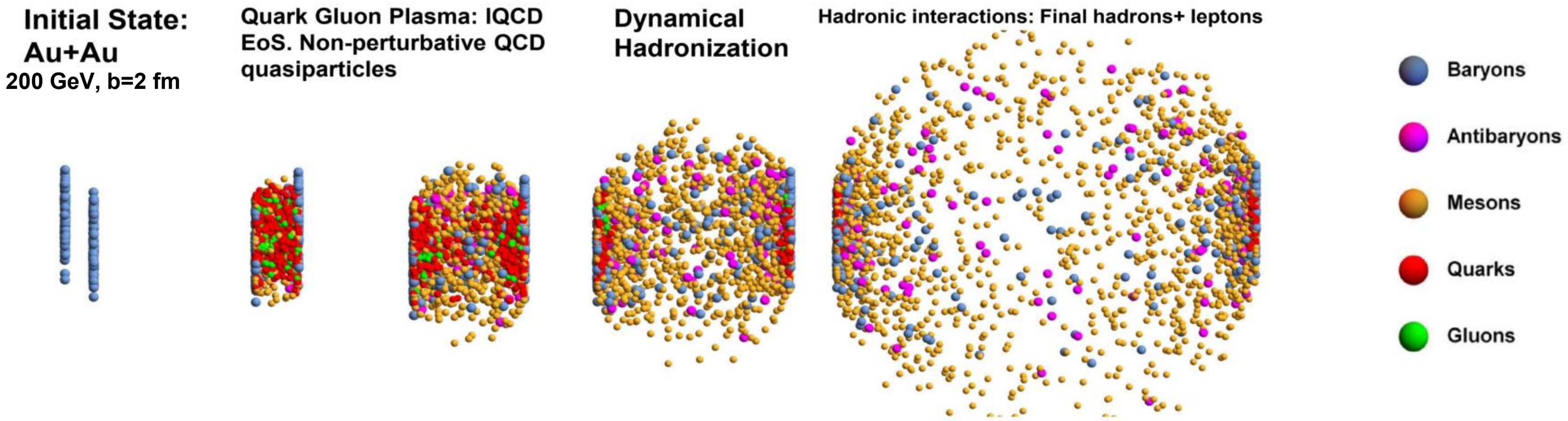


Theoretical modeling of U-boson production

Goal: estimate the upper limit for the kinetic mixing parameter $\varepsilon^2(m_U)$ of the U-boson from the theoretical calculation of the dilepton spectra using the microscopic PHSD transport approach

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

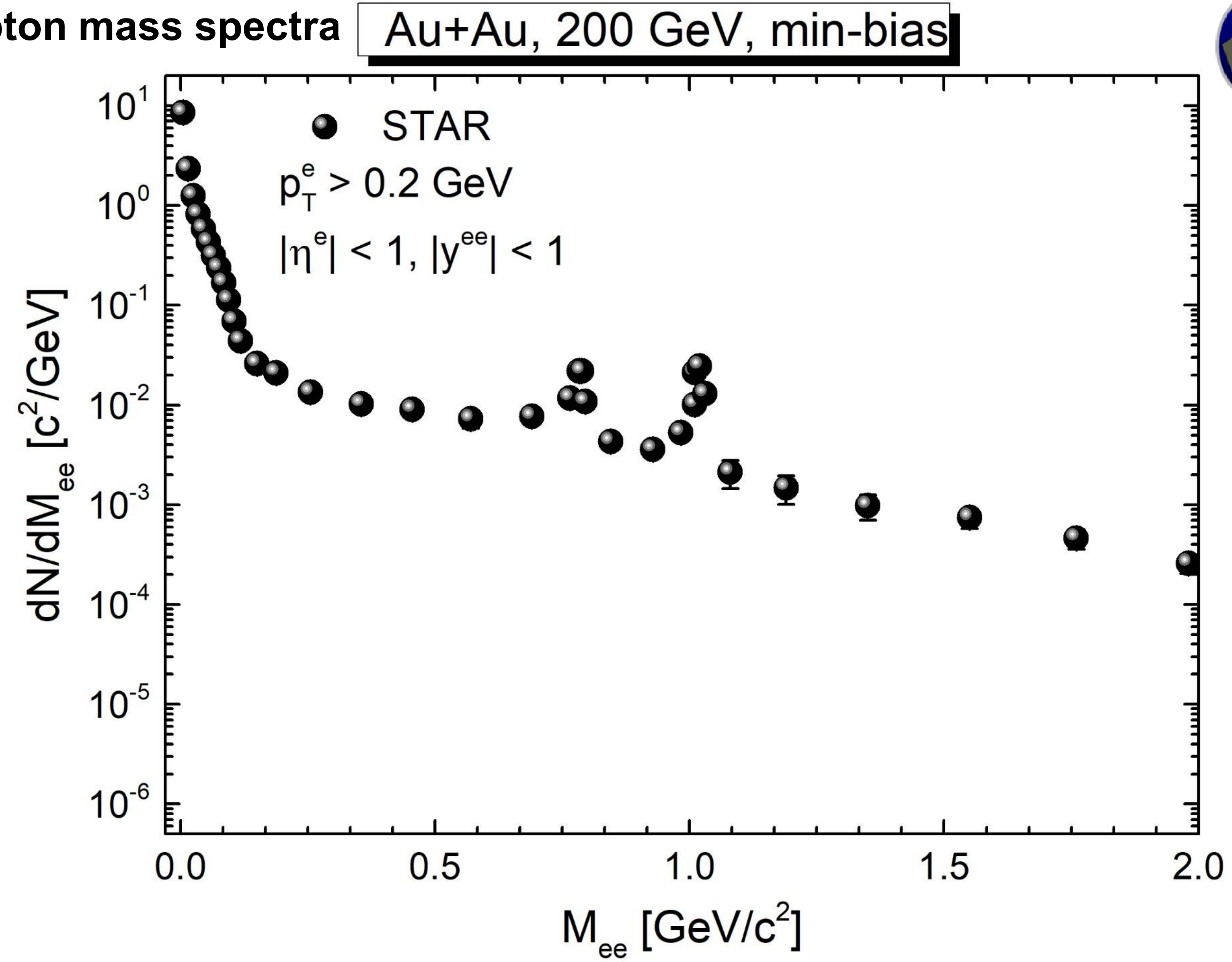
Dynamics: based on the solution of generalized off-shell transport equations derived from Kadanoff-Baym many-body theory



➔ 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



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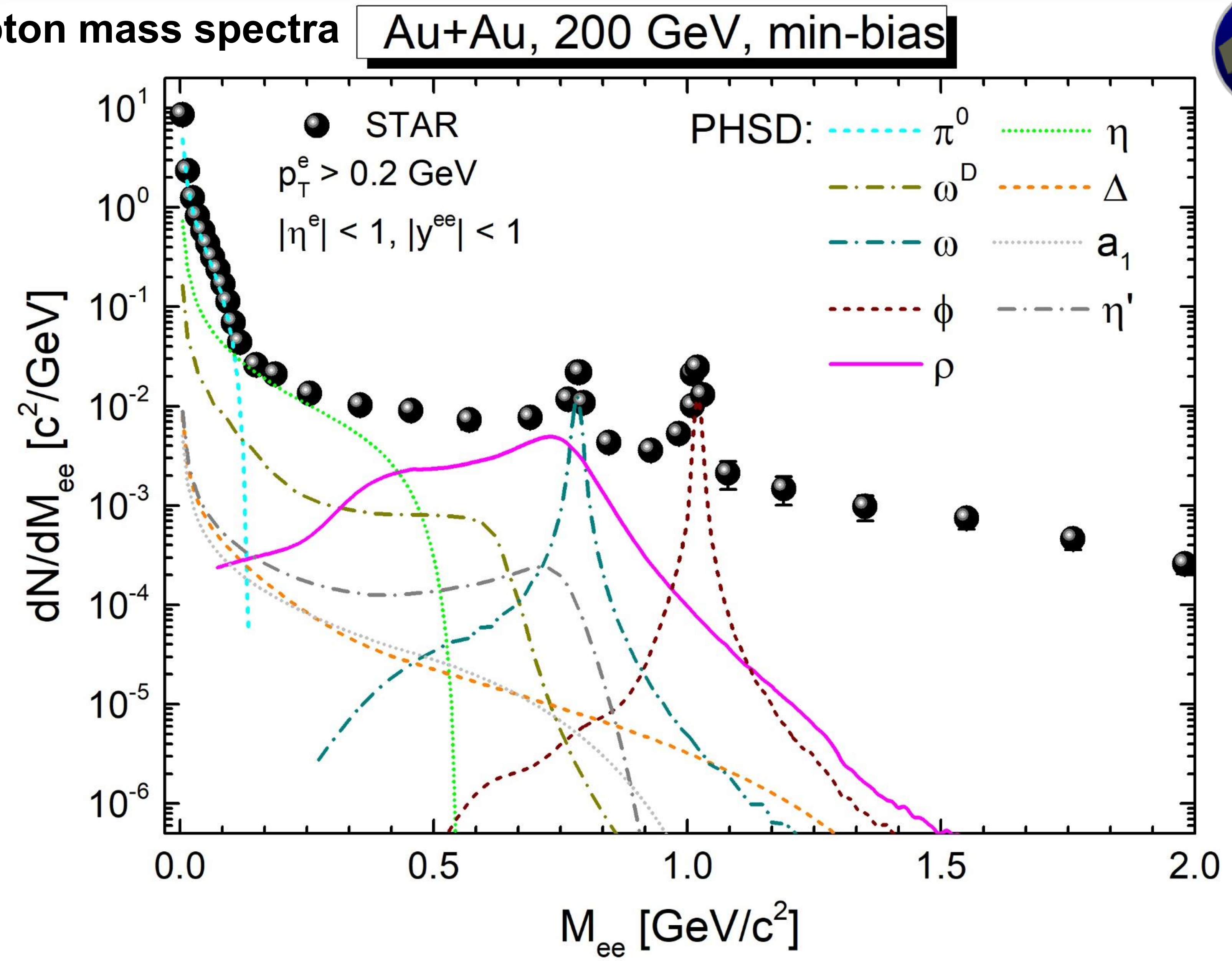

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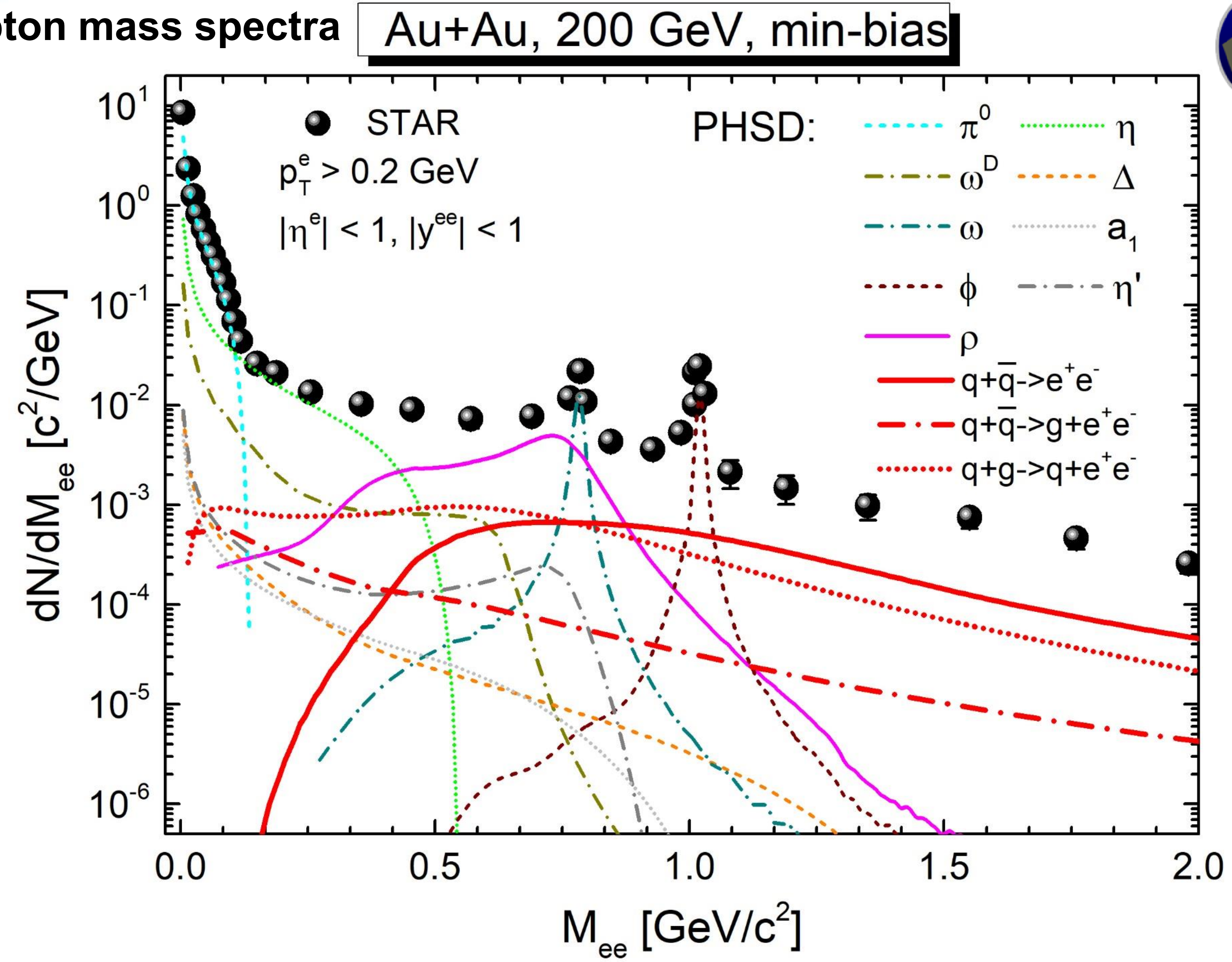

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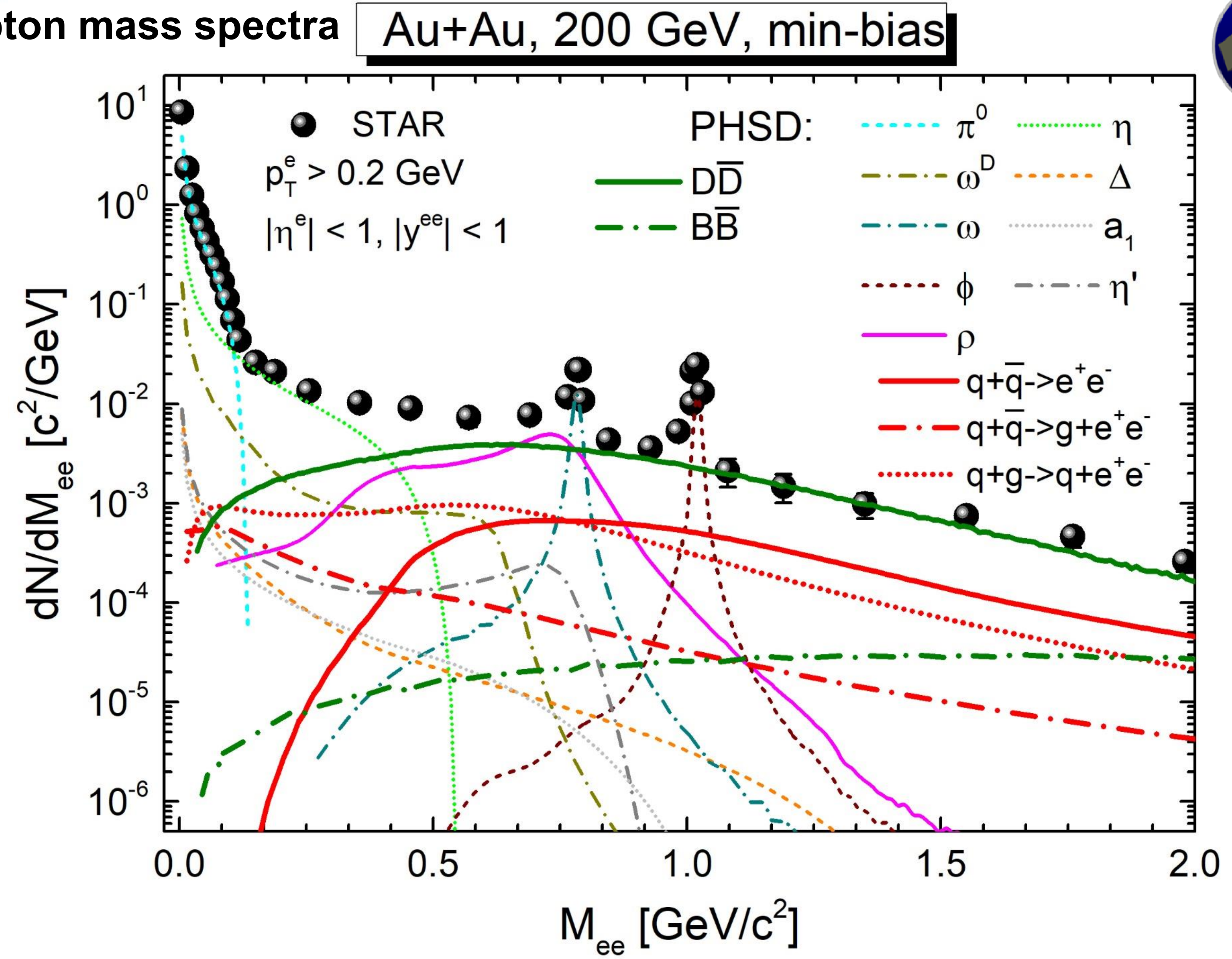
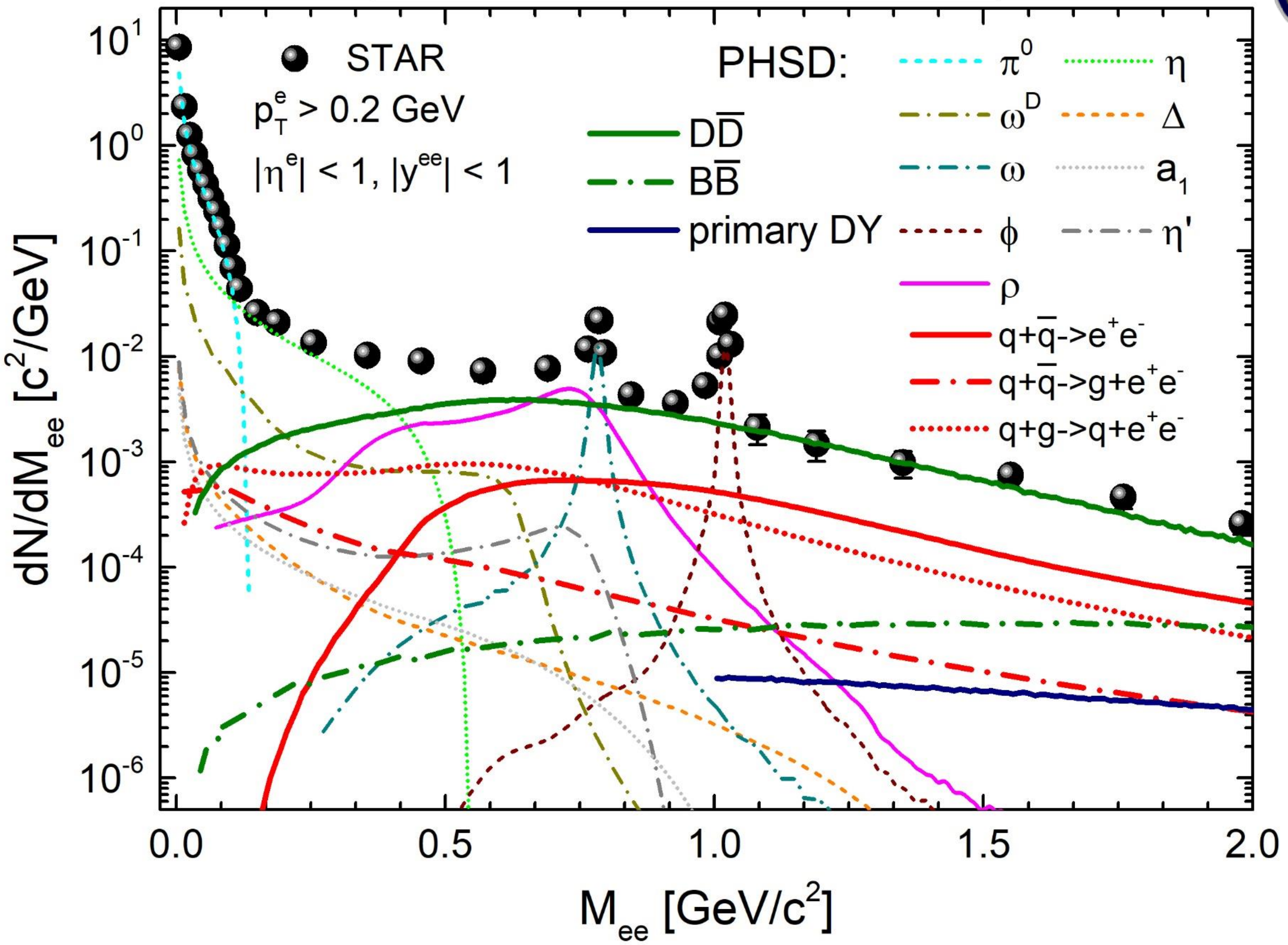


Dilepton mass spectra

Au+Au, 200 GeV, min-bias



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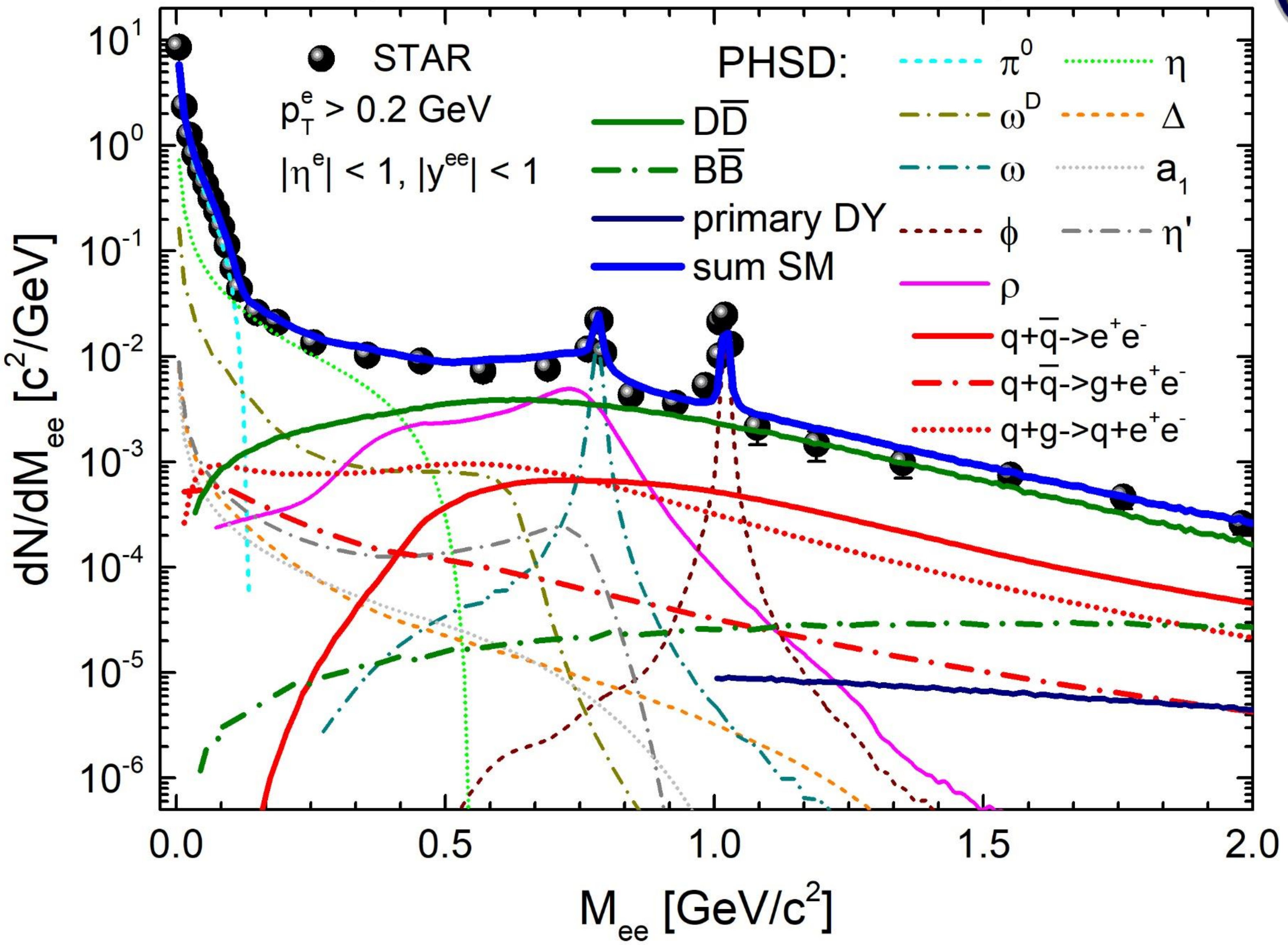
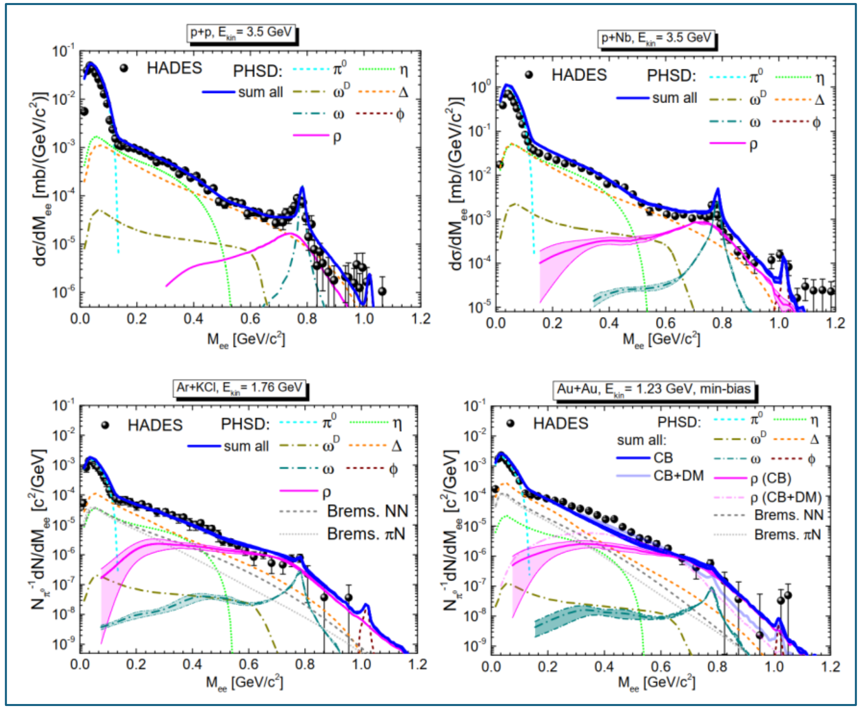
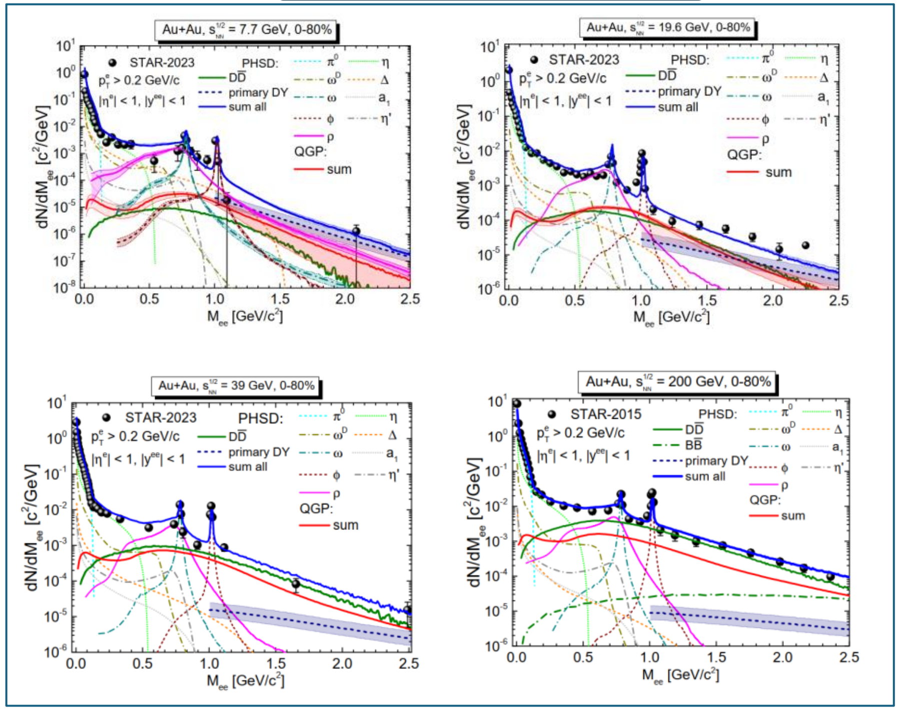


Dilepton spectra from PHSD from SIS to RHIC energies

SIS-HADES

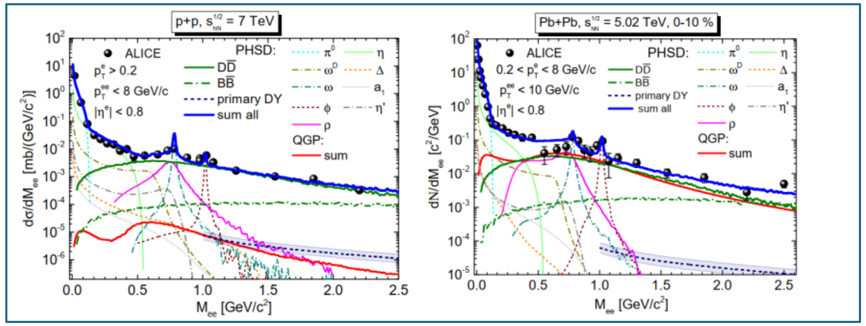


BES-RHIC-STAR



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

LHC-ALICE



See **ArXiv:2503.05253**

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

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

$$U \to e^+ e^-$$

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

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

$$h \to X + U$$

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

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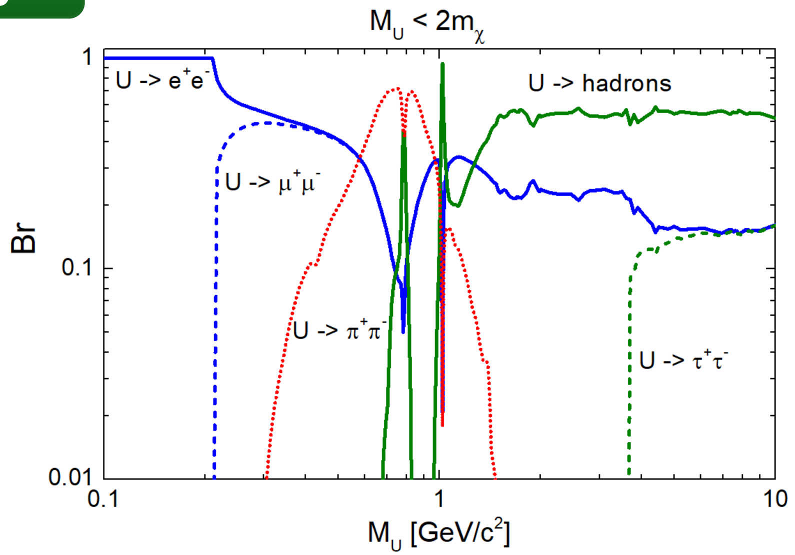

A. Fradette et al. (2015), arXiv:1501.00459
B. Batell et al. (2009), arXiv:0903.0363

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

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

Based on the model
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

$$Br(\omega \rightarrow \pi^0 U) = \varepsilon^2 Br(\omega \rightarrow \pi^0\gamma) \frac{\left[(m_\omega^2 - (m_U + m_\pi))(m_\omega^2 - (m_U - m_\pi))\right]^{3/2}}{(m_\omega^2 - m_\pi^2)^3}$$
→ D. Gorbunov et al. (2024) PLB, 852, 138599

$$Br(K^+ \rightarrow \pi^+ U) = \frac{\alpha\varepsilon^2}{\pi^2\, \Gamma_T(K)} \frac{m_U}{m_K} W'(m_U) \lambda^{1/2}(m_U, m_k, m_\pi)$$
→ M. Pospelov (2009) PRD 80, 095002

$$Br(V \rightarrow U) = \frac{\alpha\varepsilon^2 m_U}{3\Gamma_T(V)} \qquad V = \rho, \phi, \omega$$
→ B. Battel , et al. (2009) PRD 79, 115008

$$Br(q\,\bar{q} \rightarrow U) = \varepsilon^2 \frac{\Gamma^{PHSD}_{q\,\bar{q}\rightarrow e^+e^-}}{\Gamma_T(V)}$$
→ Arxiv: 2507.11163 C. Ahdida et al. (2021) EPJ 81 C, 451

new channels in PHSD

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.

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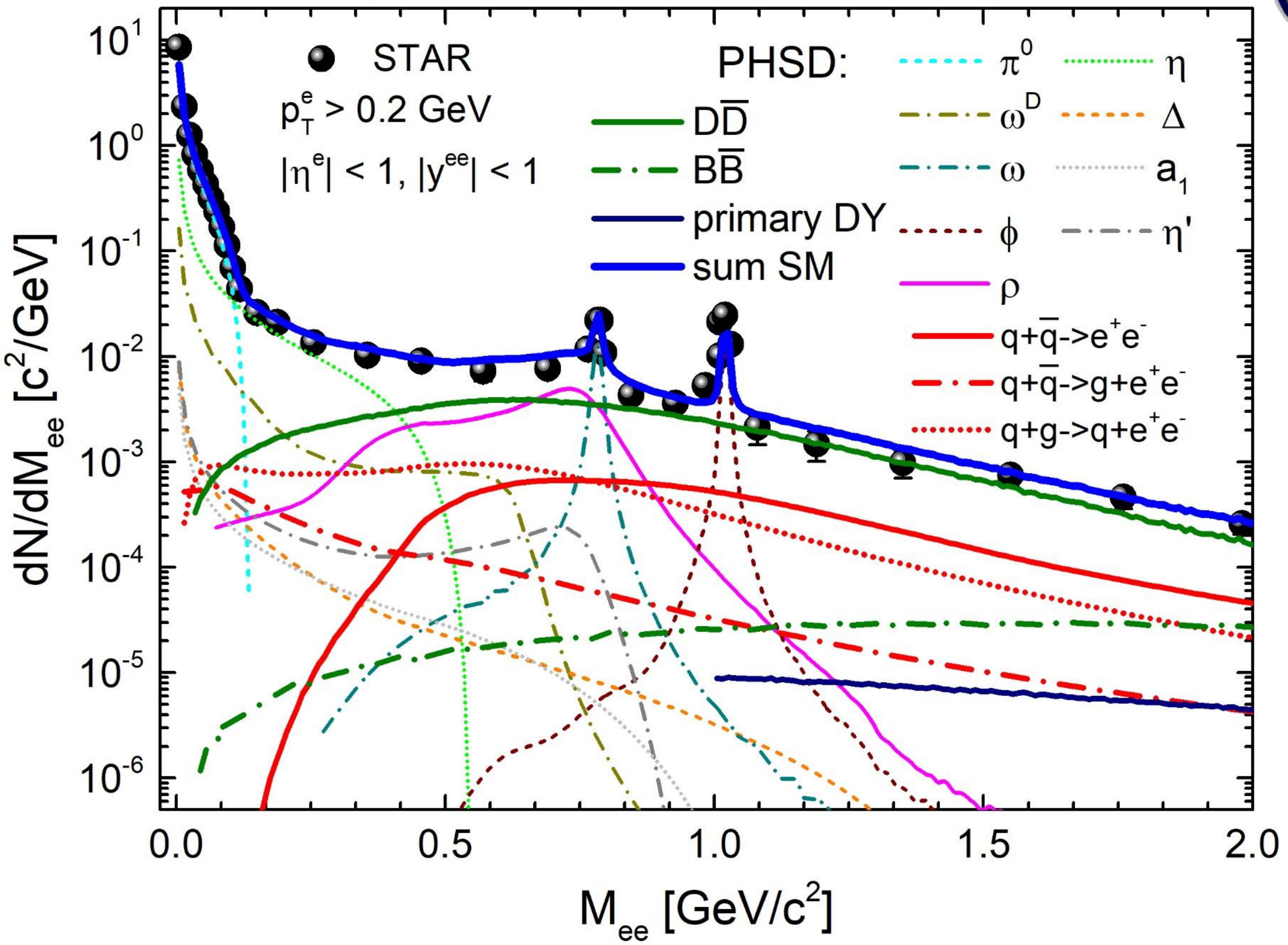
$$\varepsilon^2(M_U) = C_U \cdot \left(\frac{dN^{sumSM}}{dM}\right) \Big/ \left(\frac{dN^{sumU}_{\varepsilon^2=1}}{dM}\right)$$

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

Dilepton mass spectra

Au+Au, 200 GeV, min-bias



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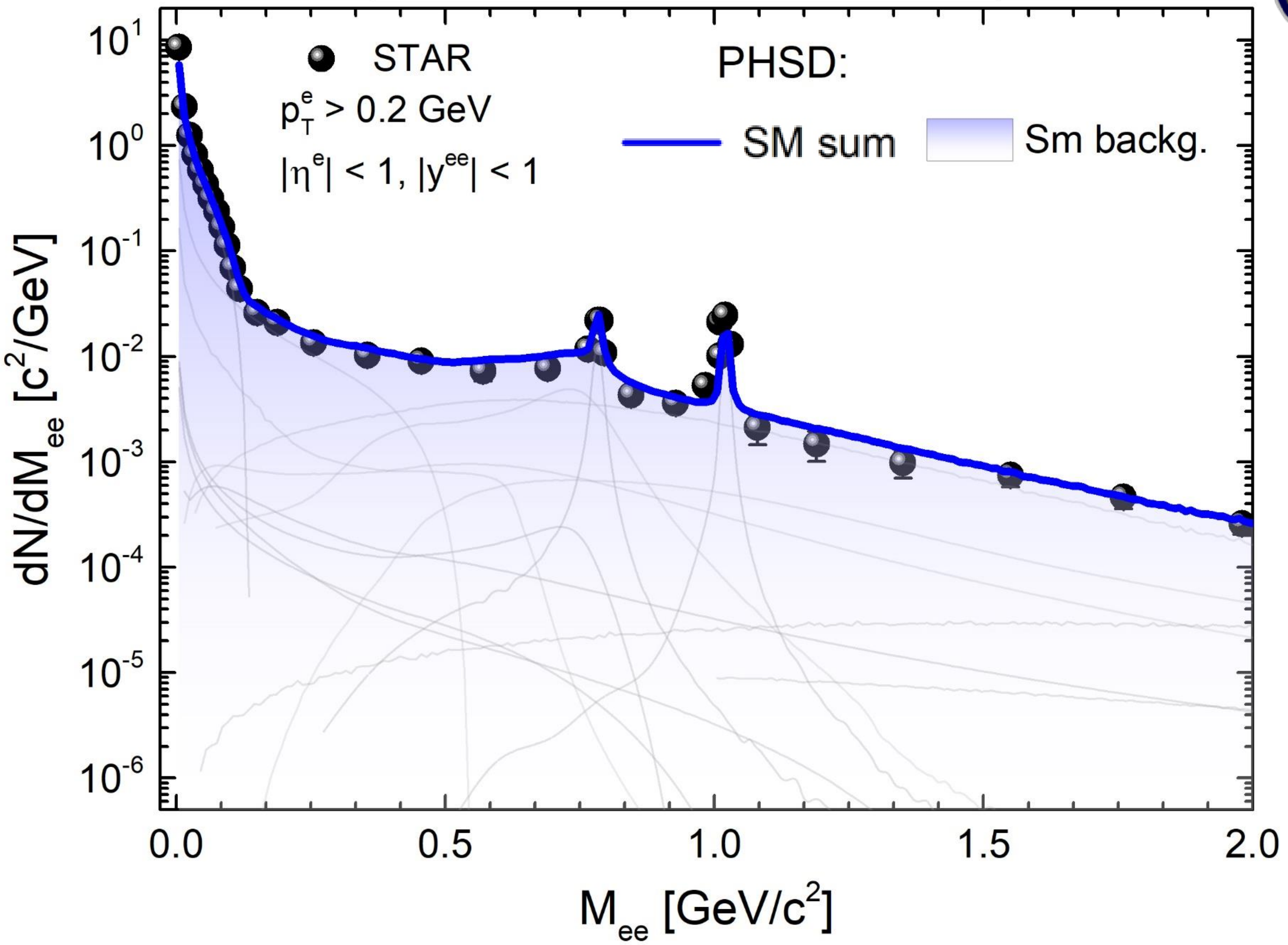

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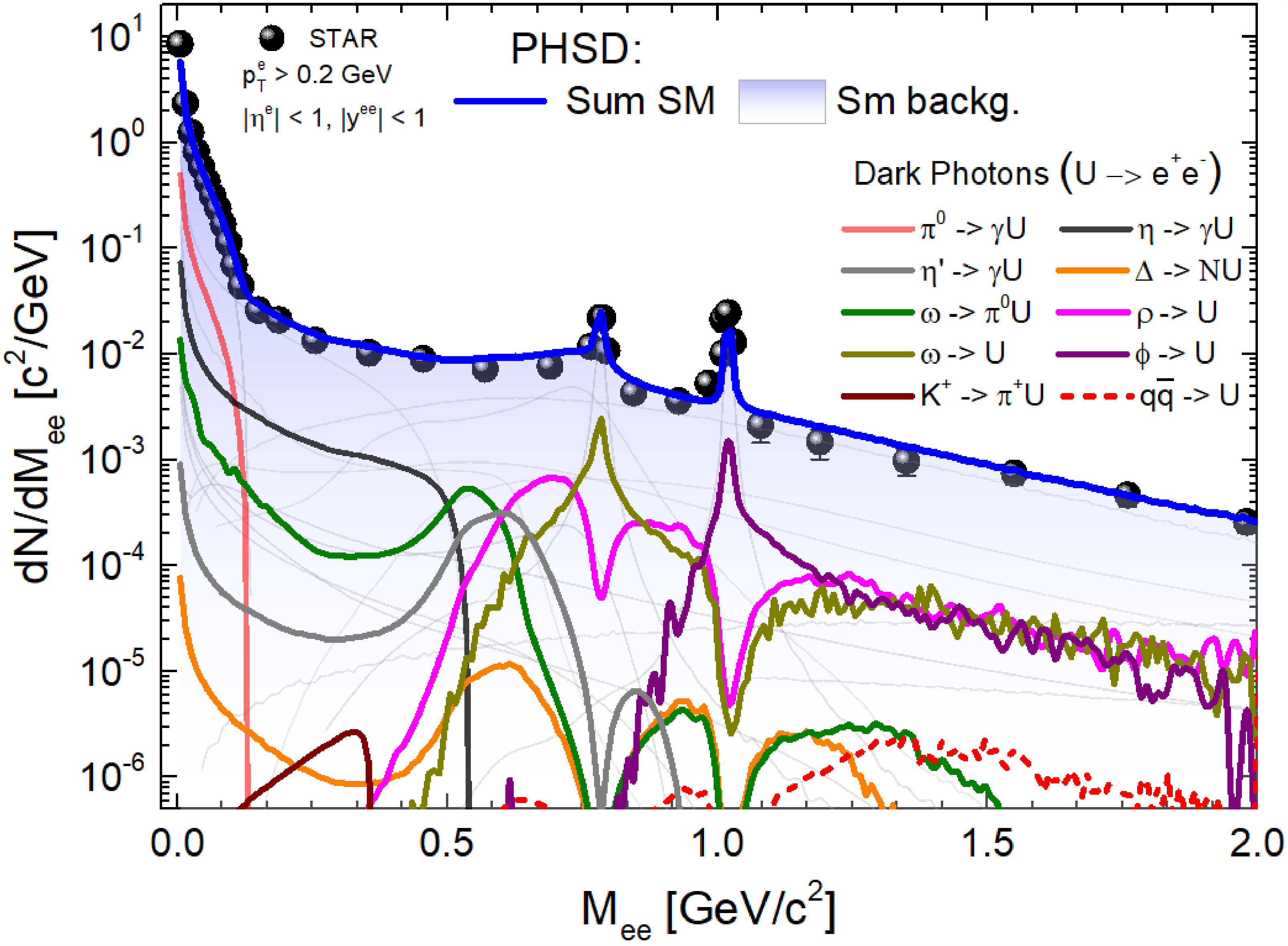

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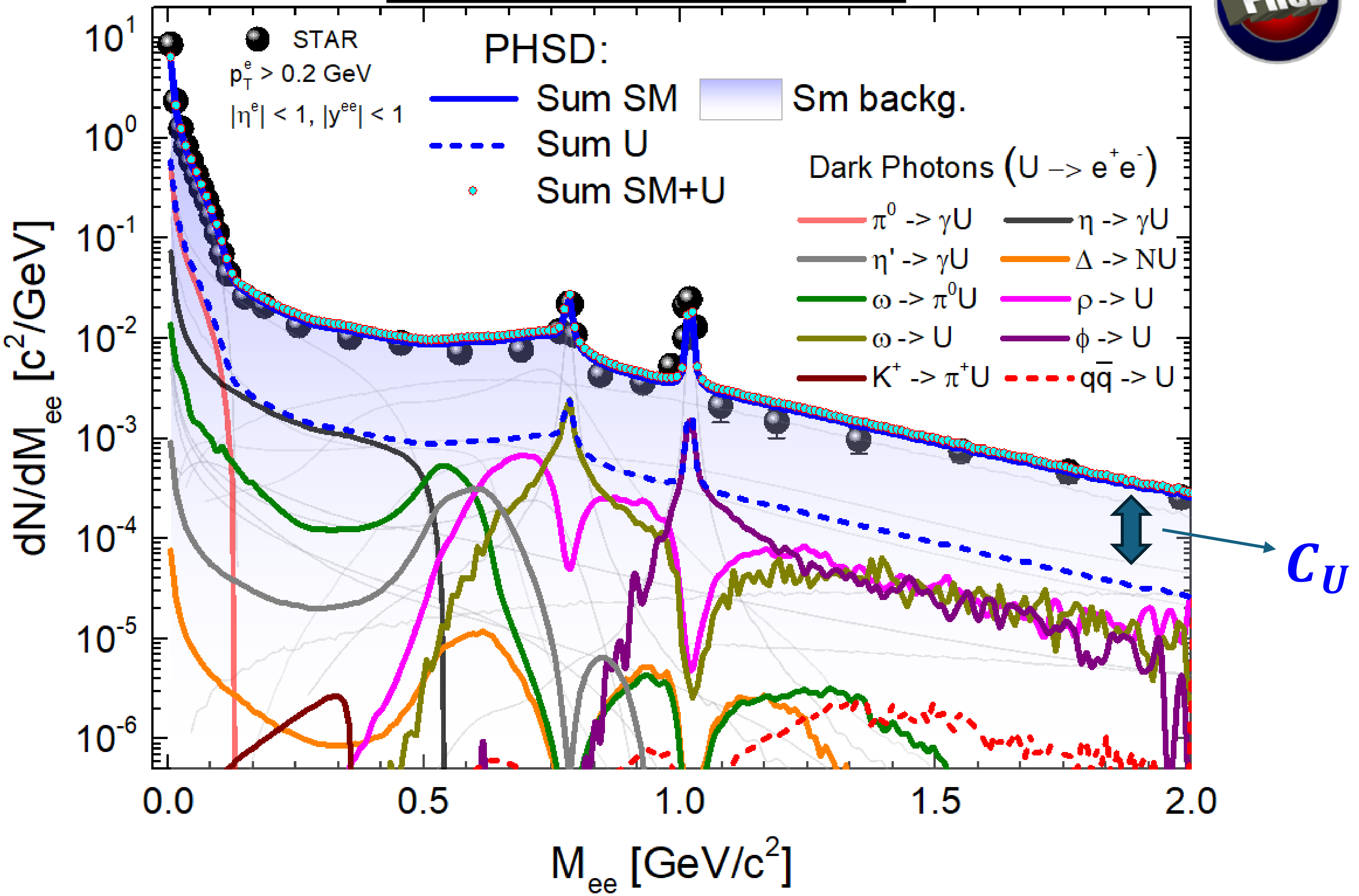
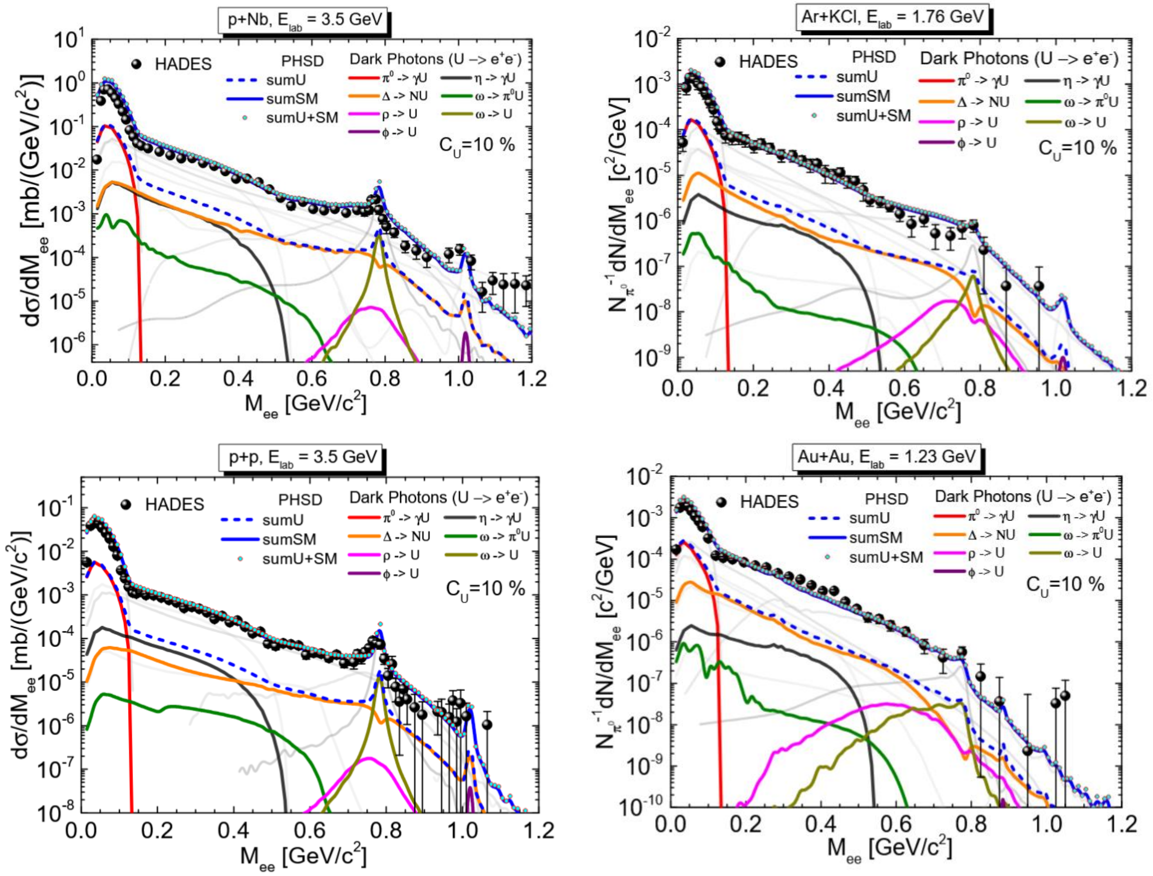
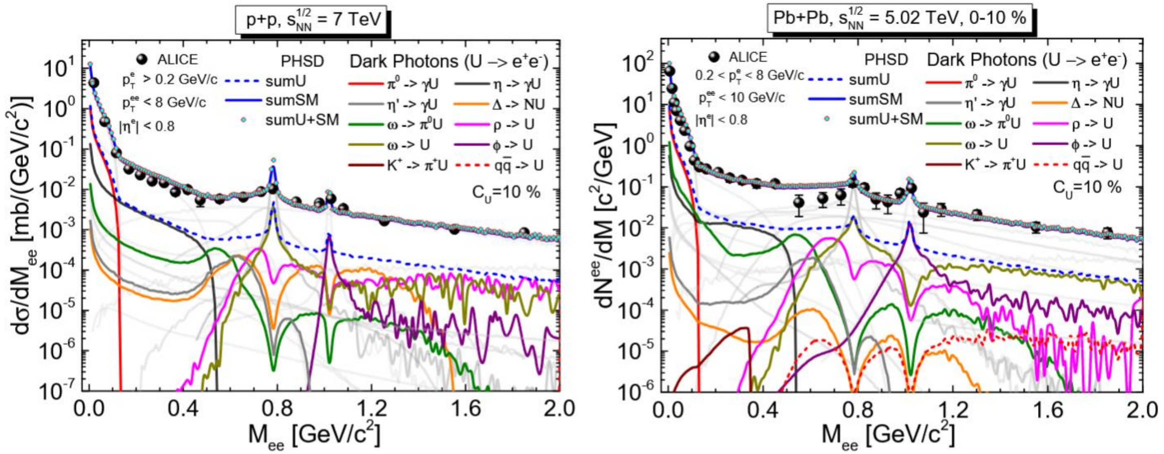


Dilepton spectra from U-boson decays

SIS-HADES



BES-RHIC-STAR



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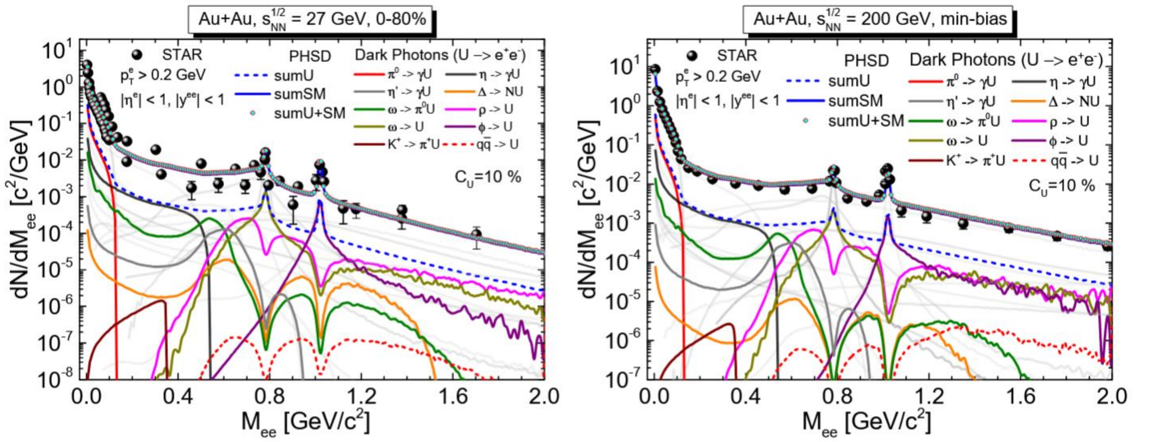


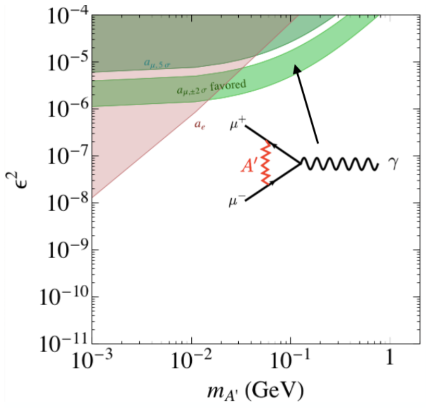
See **arXiv:2507.11163**

- **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**

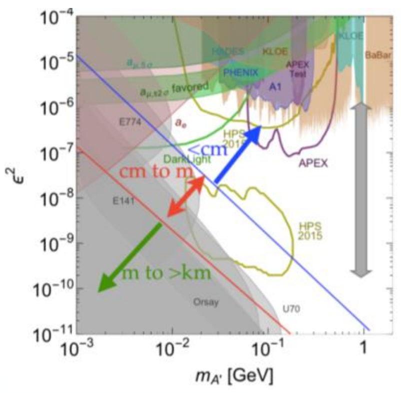
Dark Photons $\varepsilon^2(M_U)$ Constraints

time

2008

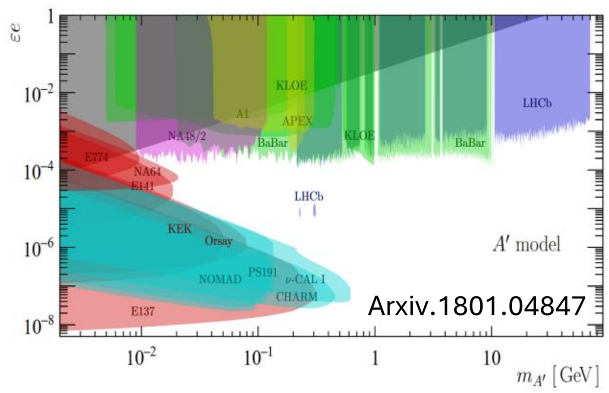


2014

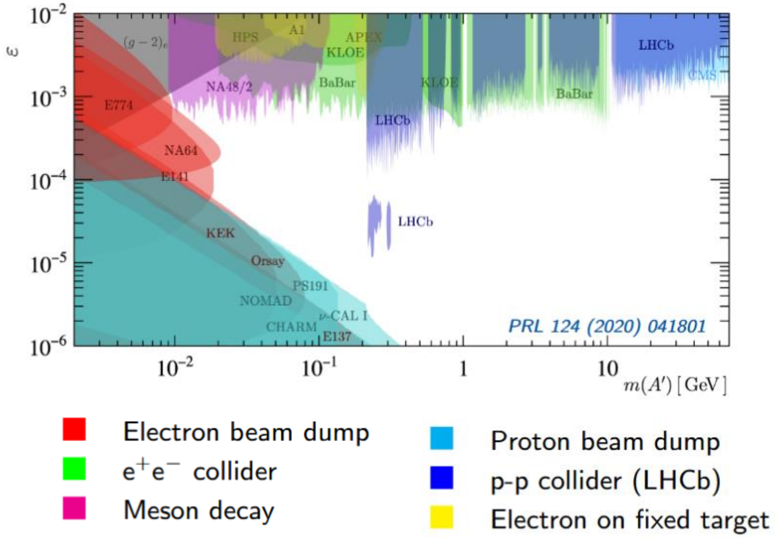


plot illustrations from N.Toro

2018



2020



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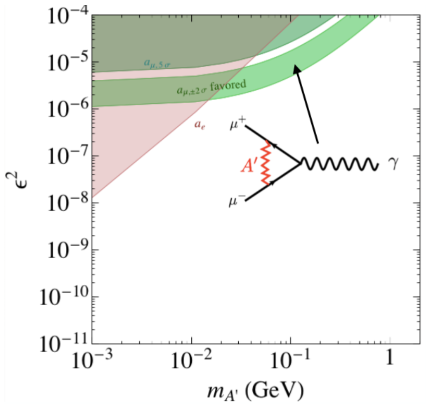

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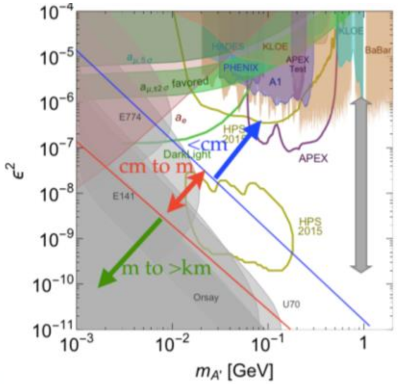

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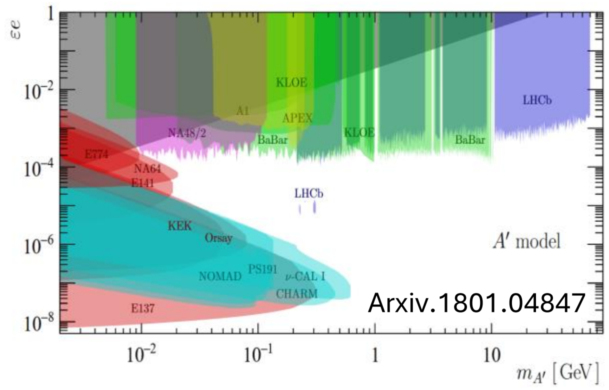

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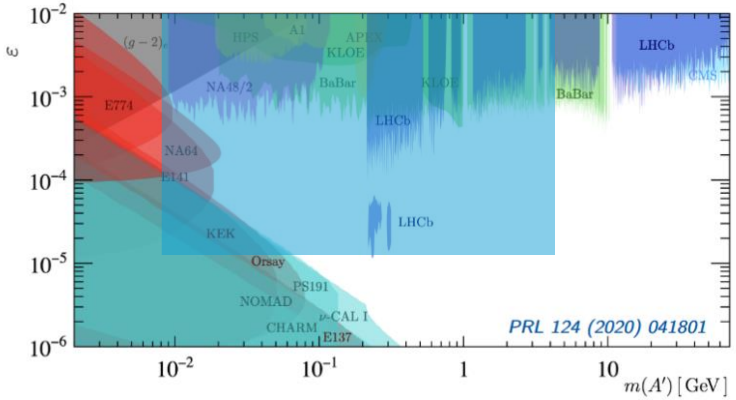
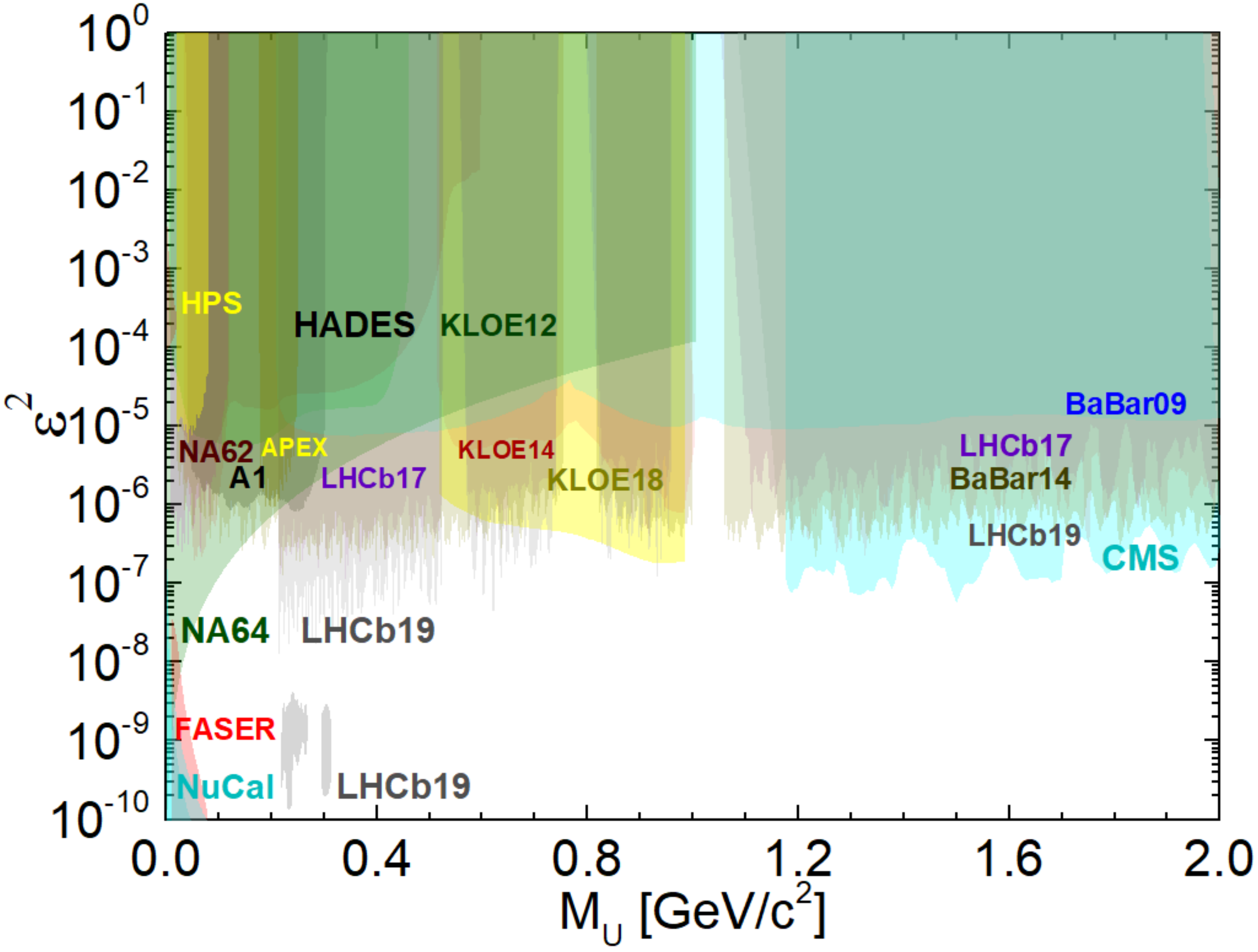
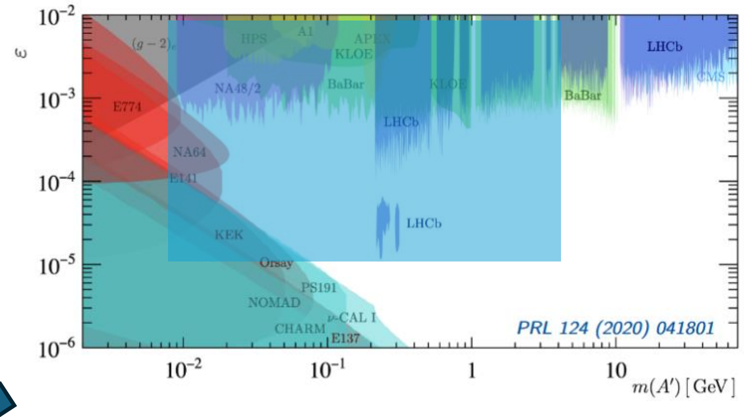


- Electron beam dump
- e^+e^- collider
- Meson decay
- Proton beam dump
- p-p collider (LHCb)
- Electron on fixed target

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





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

The **upper limit for the kinetic mixing parameter $\varepsilon^2(M_U)$** of dark photons extracted from the PHSD dilepton spectra - with C_U **allowed surplus** of the total SM yield

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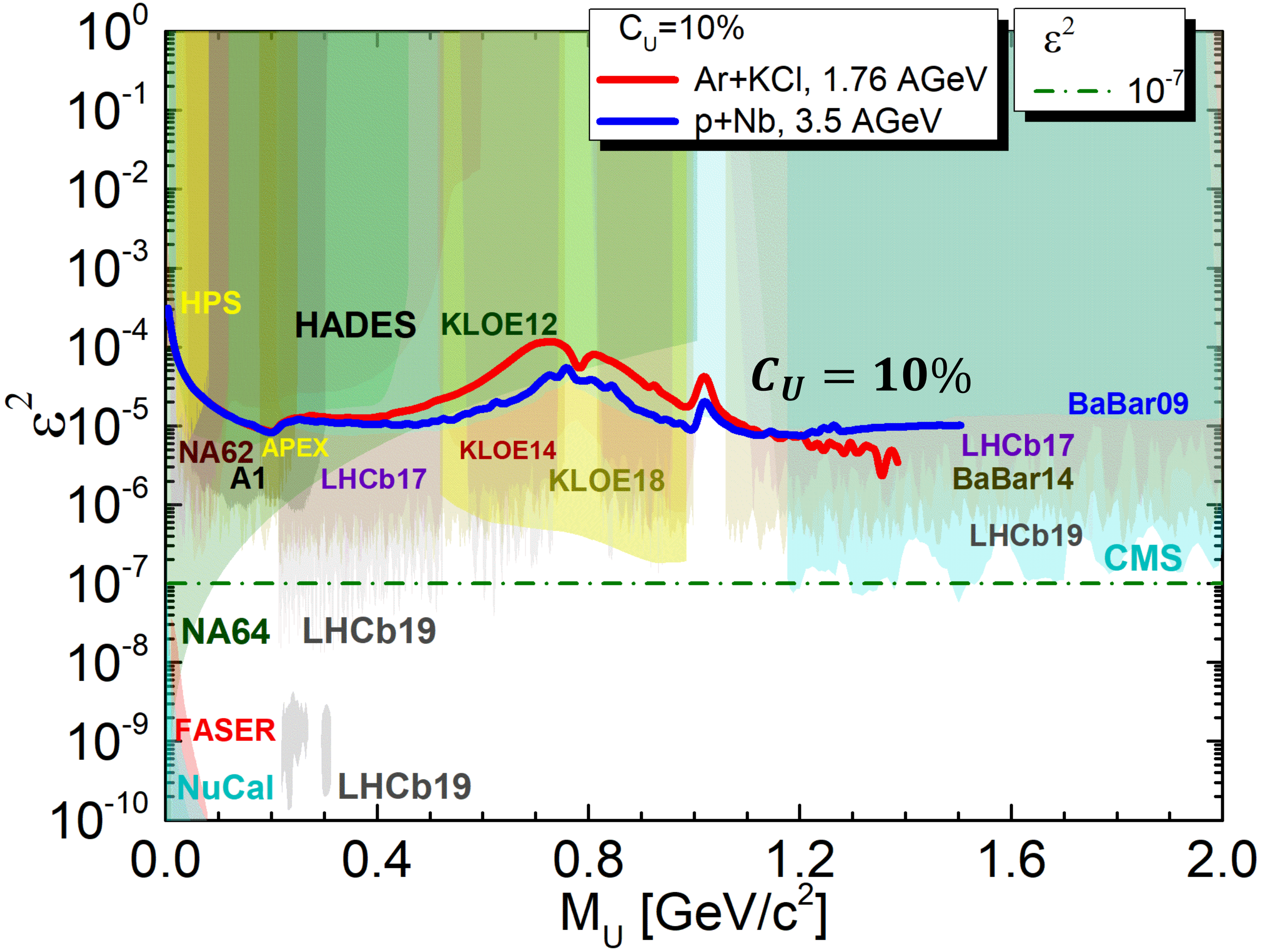

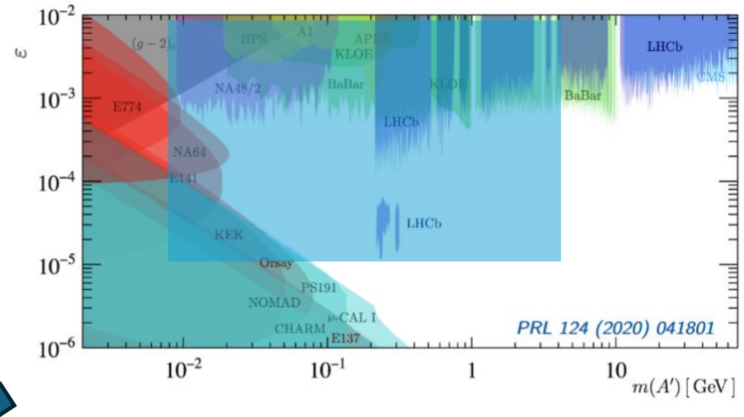

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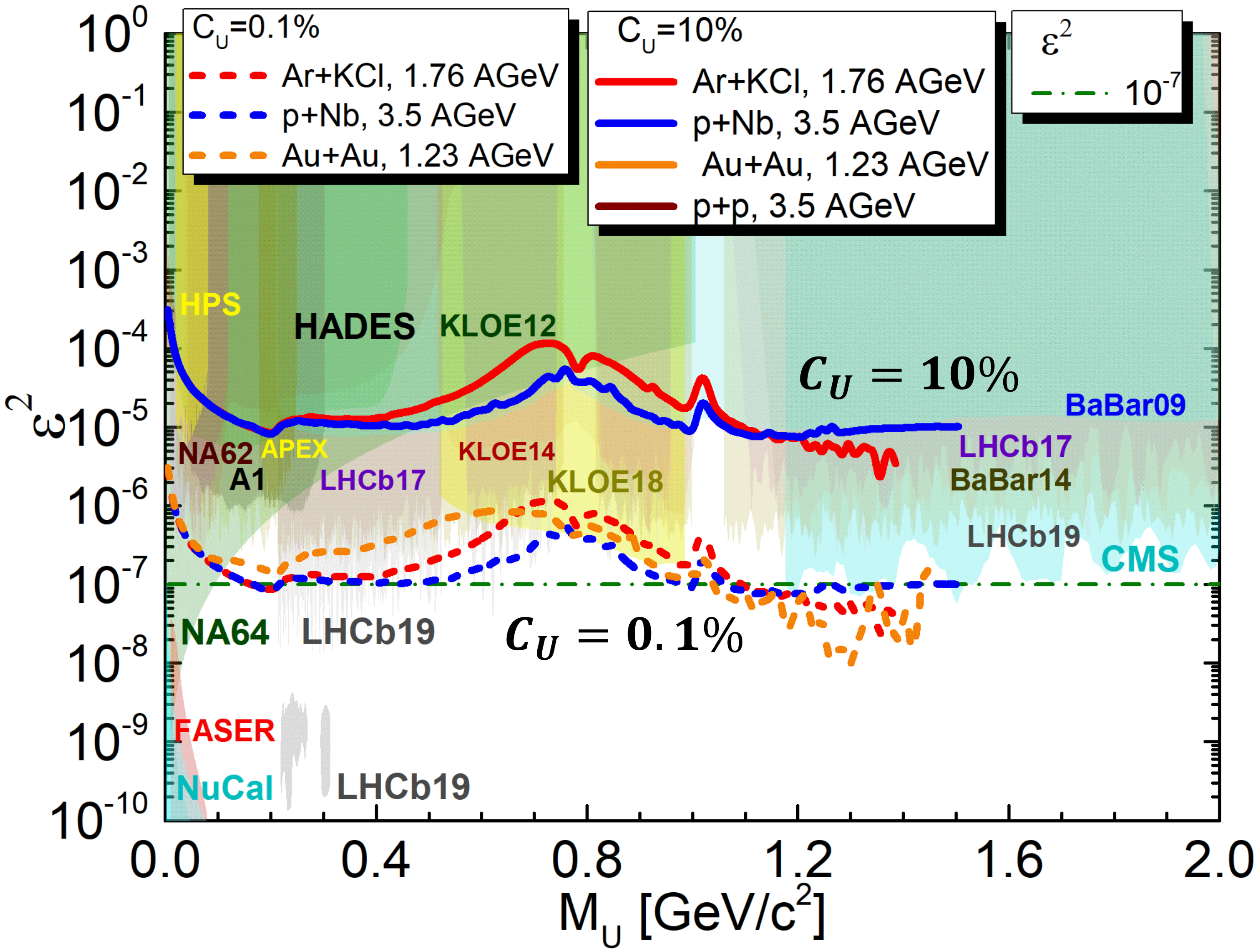

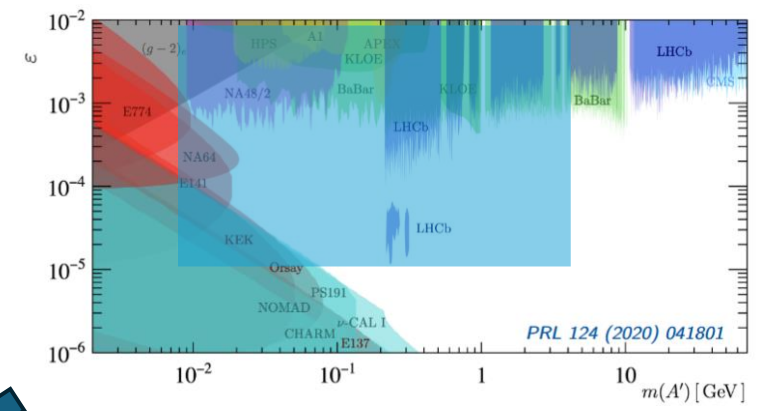

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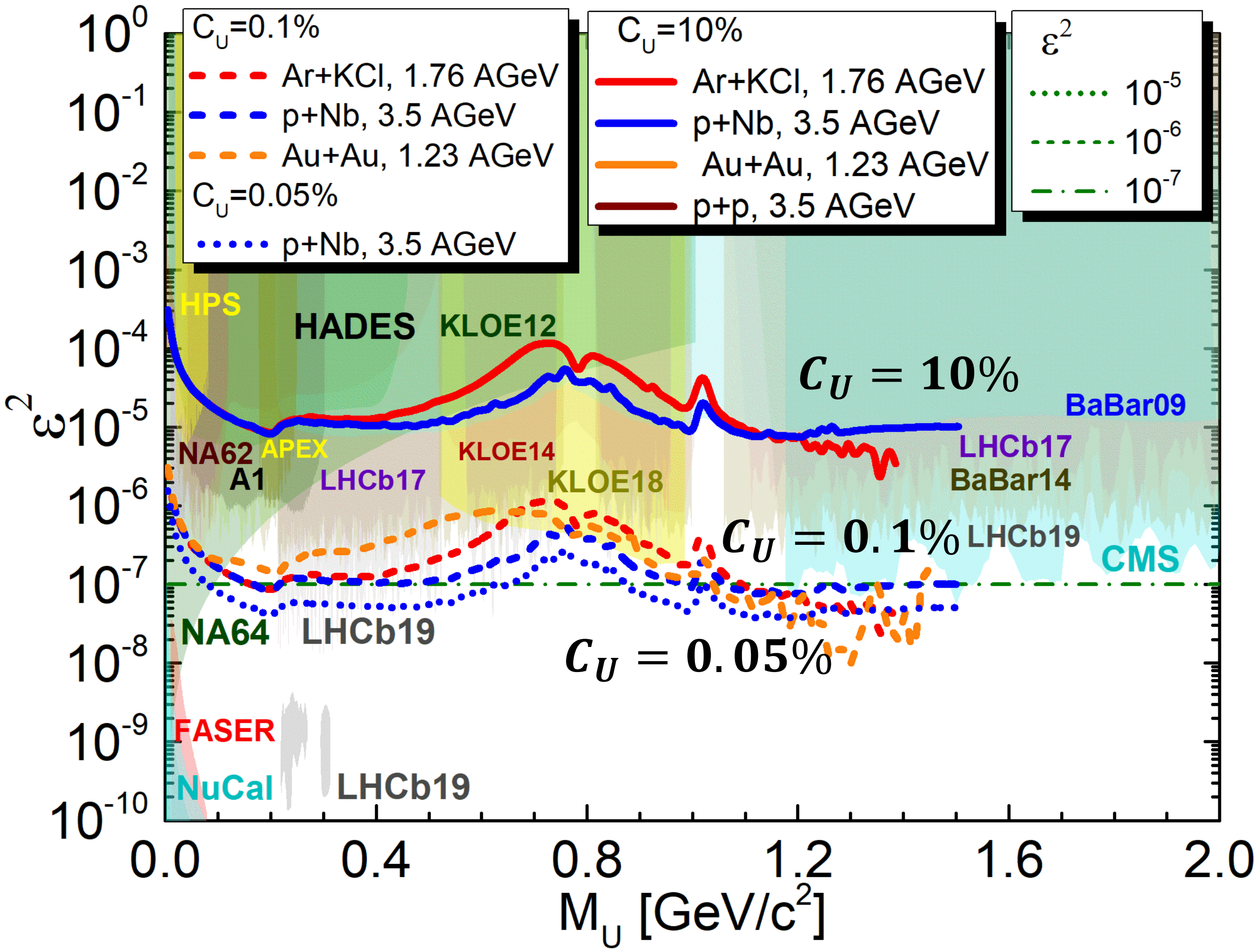

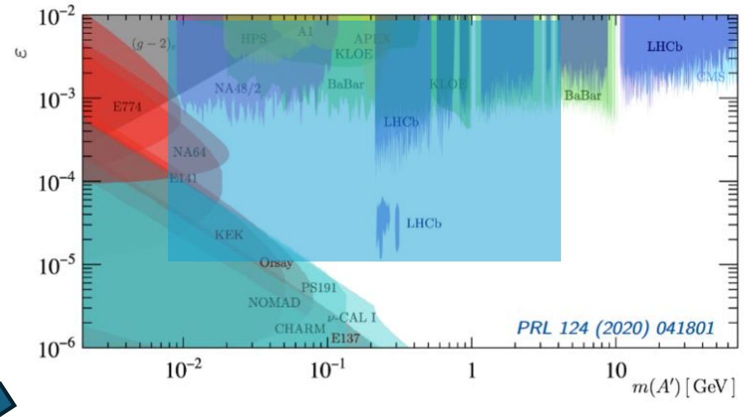

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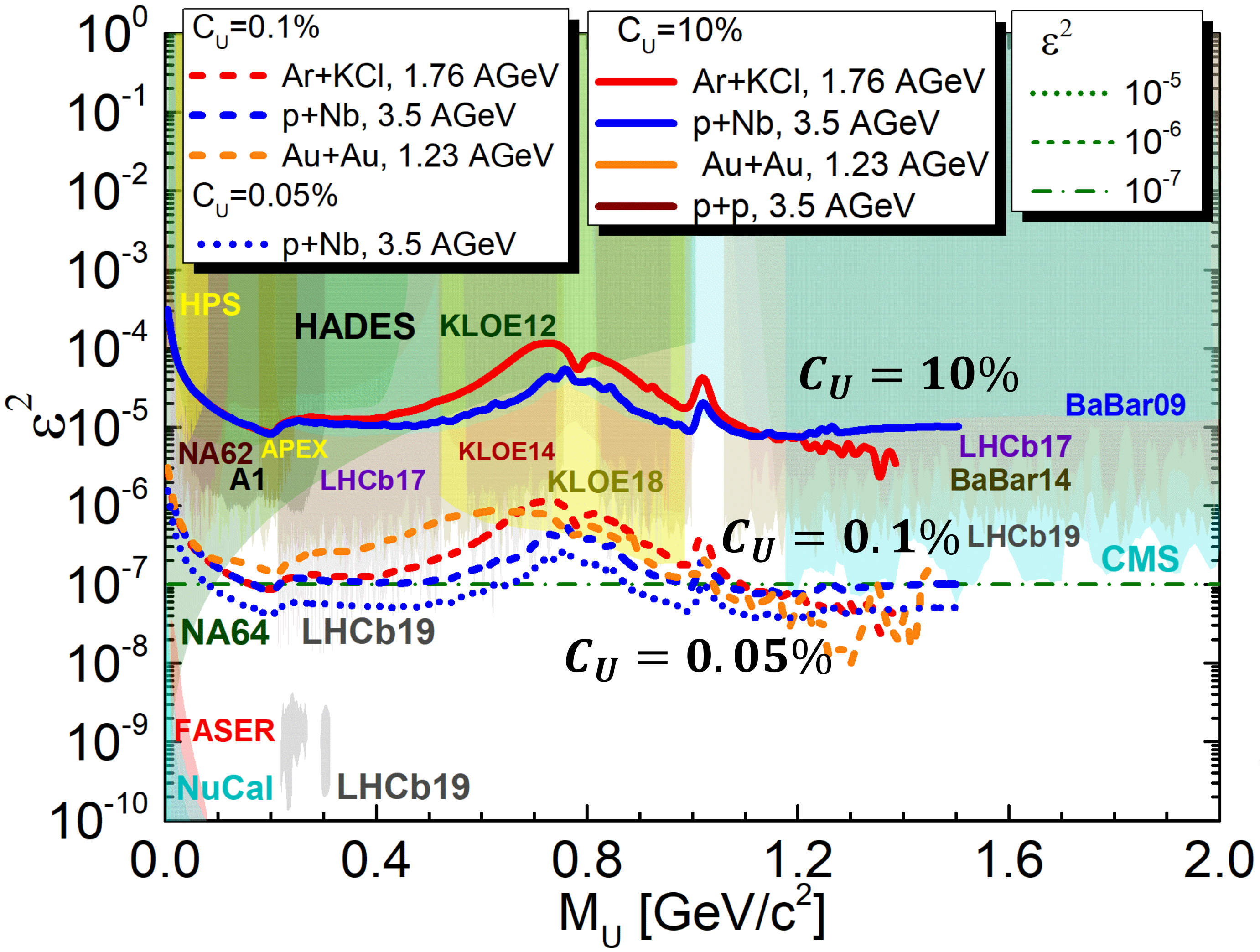
SIS-HADES



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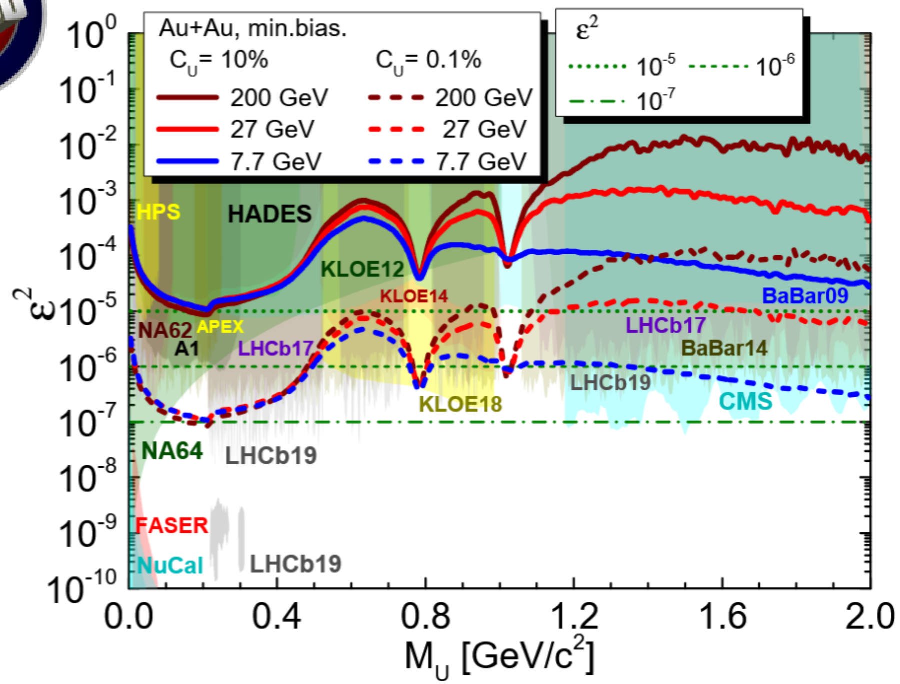

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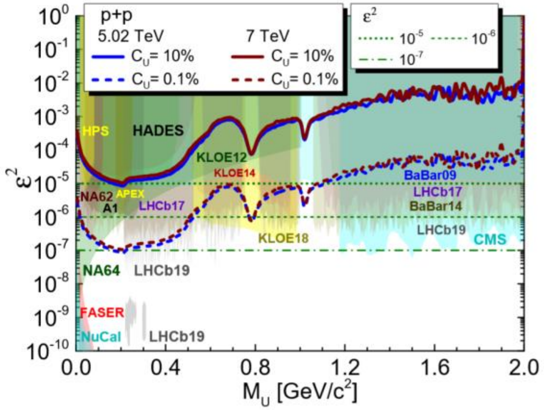

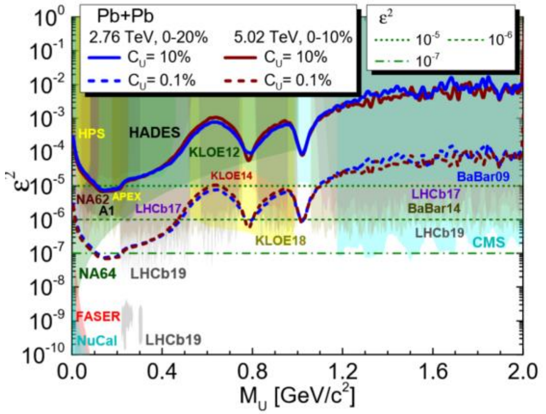

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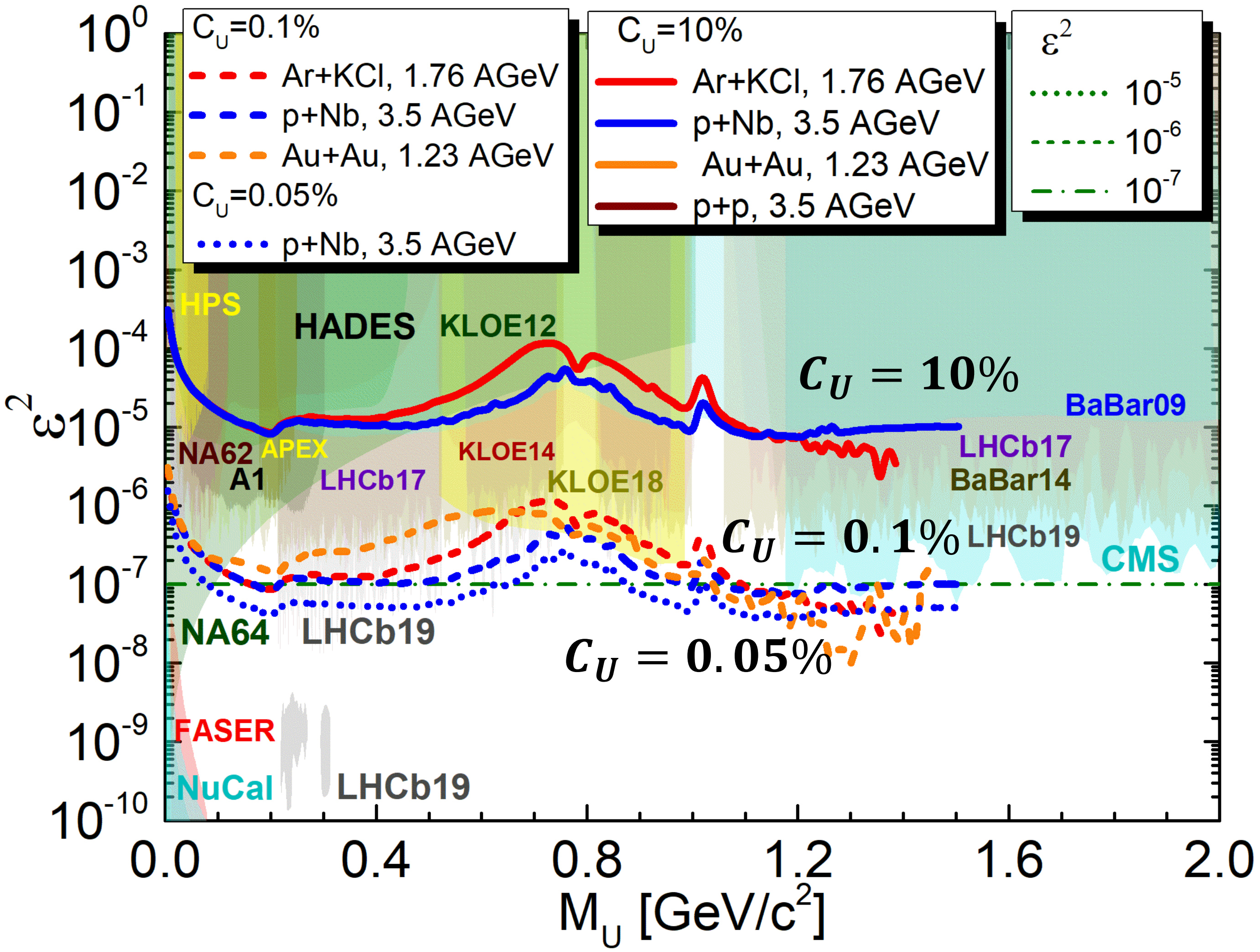

- More recent data from LHCb17, KLOE18, and CMS demand tighter constraints, compatible only if the possible dark photon contribution is reduced to $C_U = 0.05 - 0.1\%$
- These findings are consistent with global experimental exclusion limits, confirming that dilepton measurements are highly sensitive probes for testing dark photon scenarios.

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

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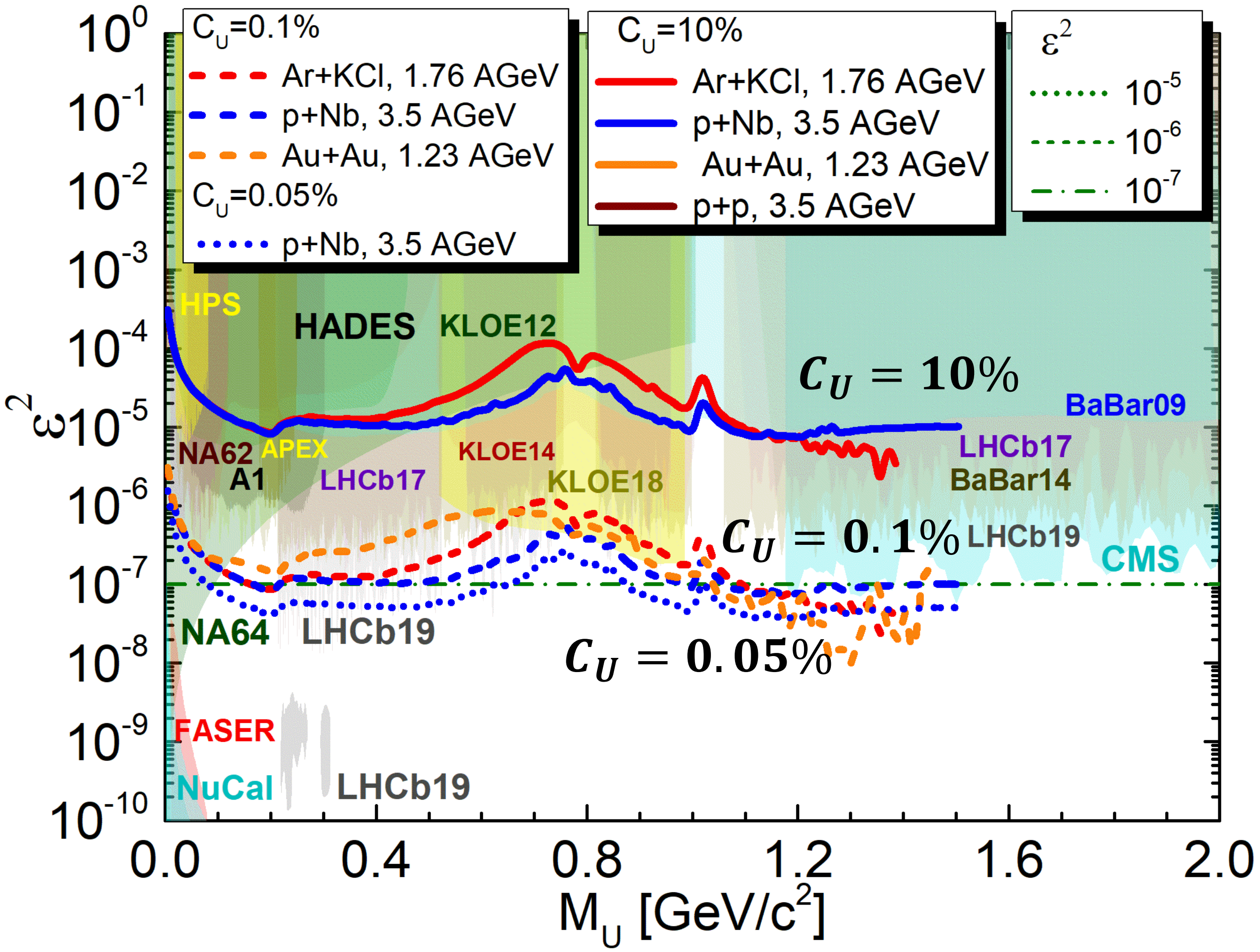

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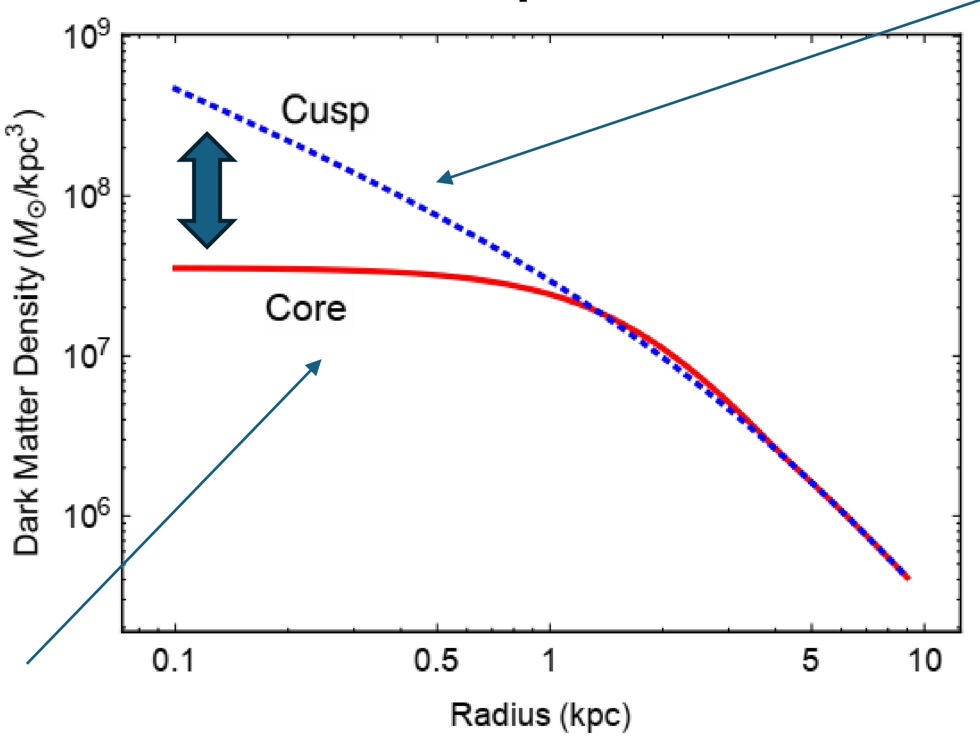
Cosmological Constraints
- Thermal Relic Abundance

Astrophysical Constraints
- SIDM constraints (Core-Cusp P.)

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

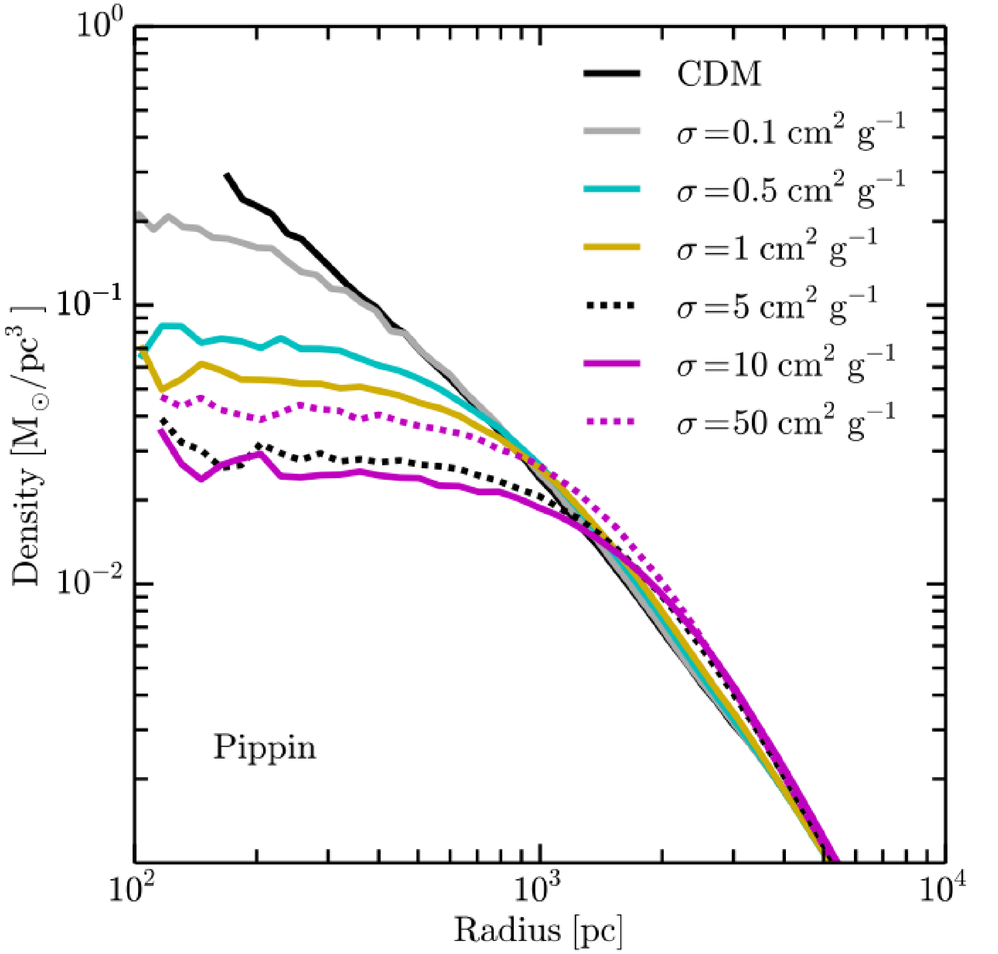
Based on Λ_{CDM} model, describe well Large scales (Galaxy clusters)

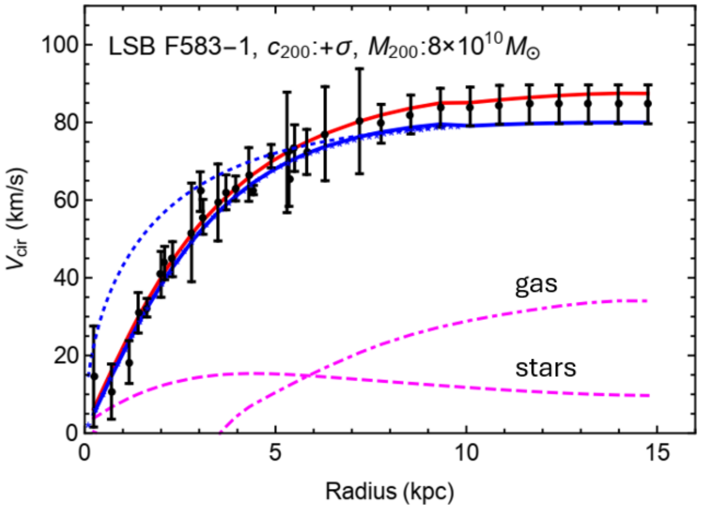
Core-Cusp Problem

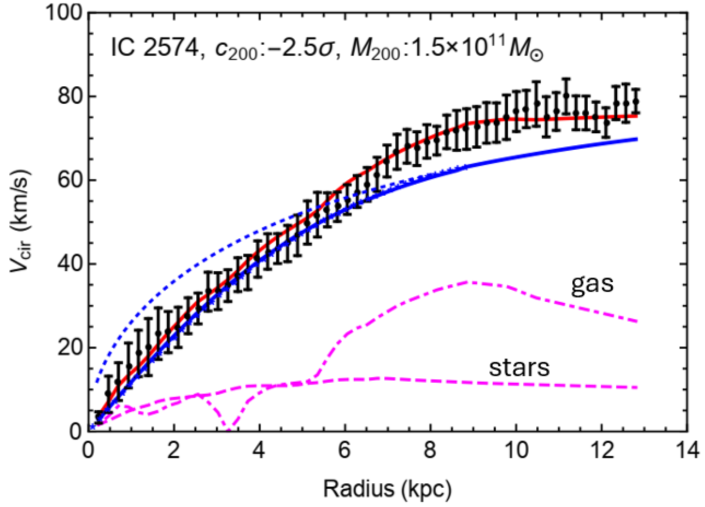


Other observations, small scales (dwarf galaxies)

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







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→ *CDM halos* No interactions

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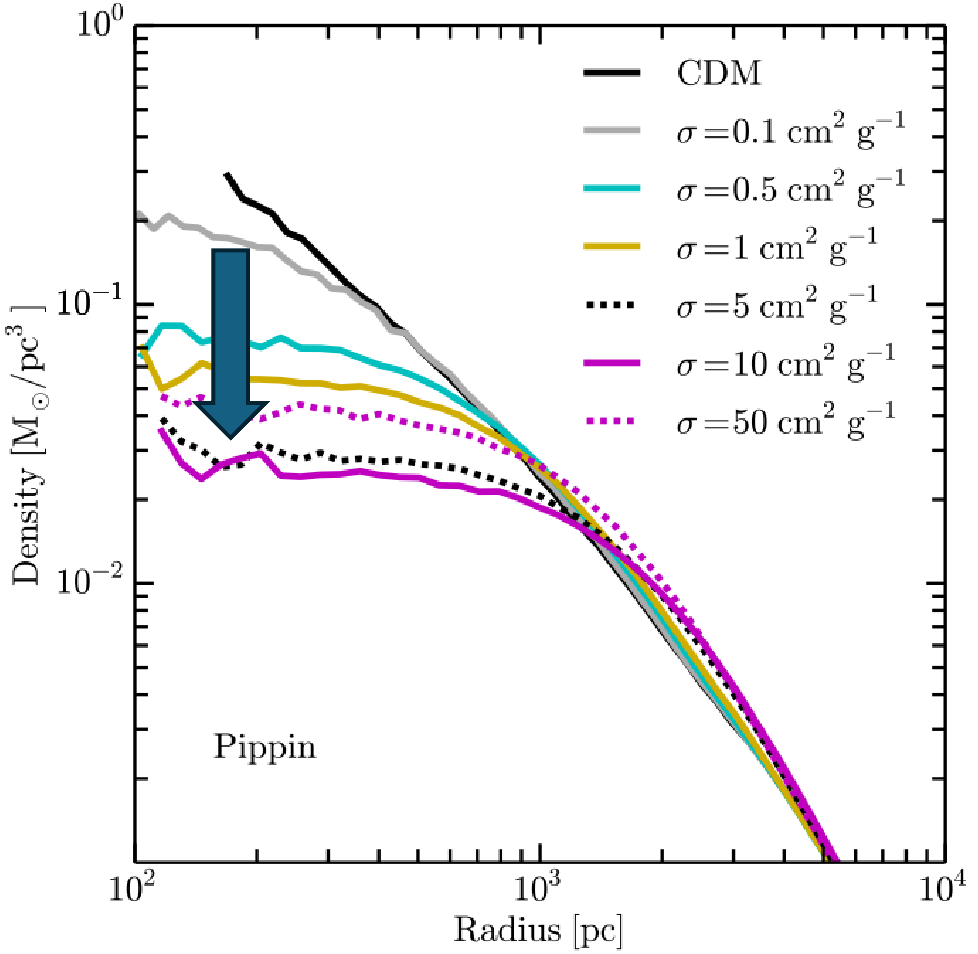

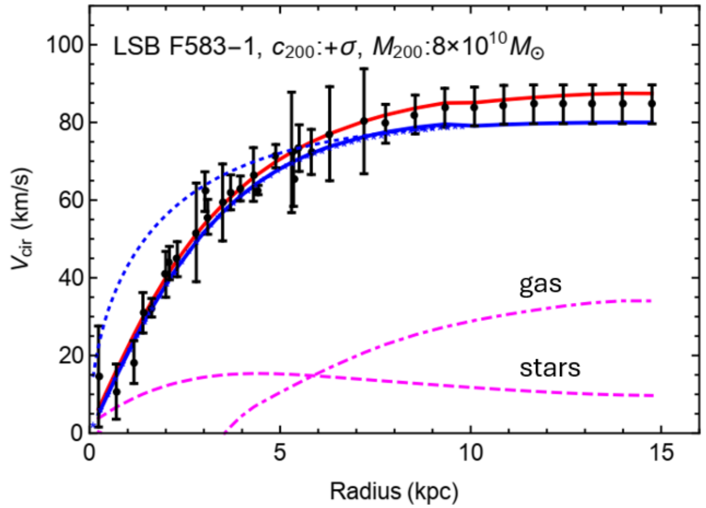

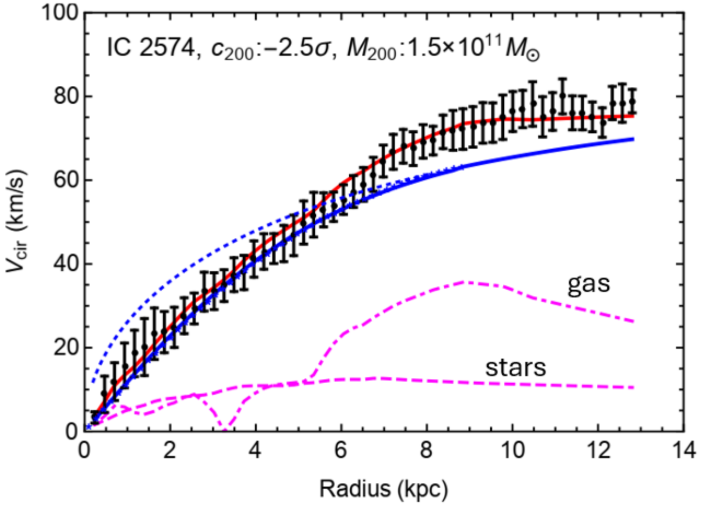

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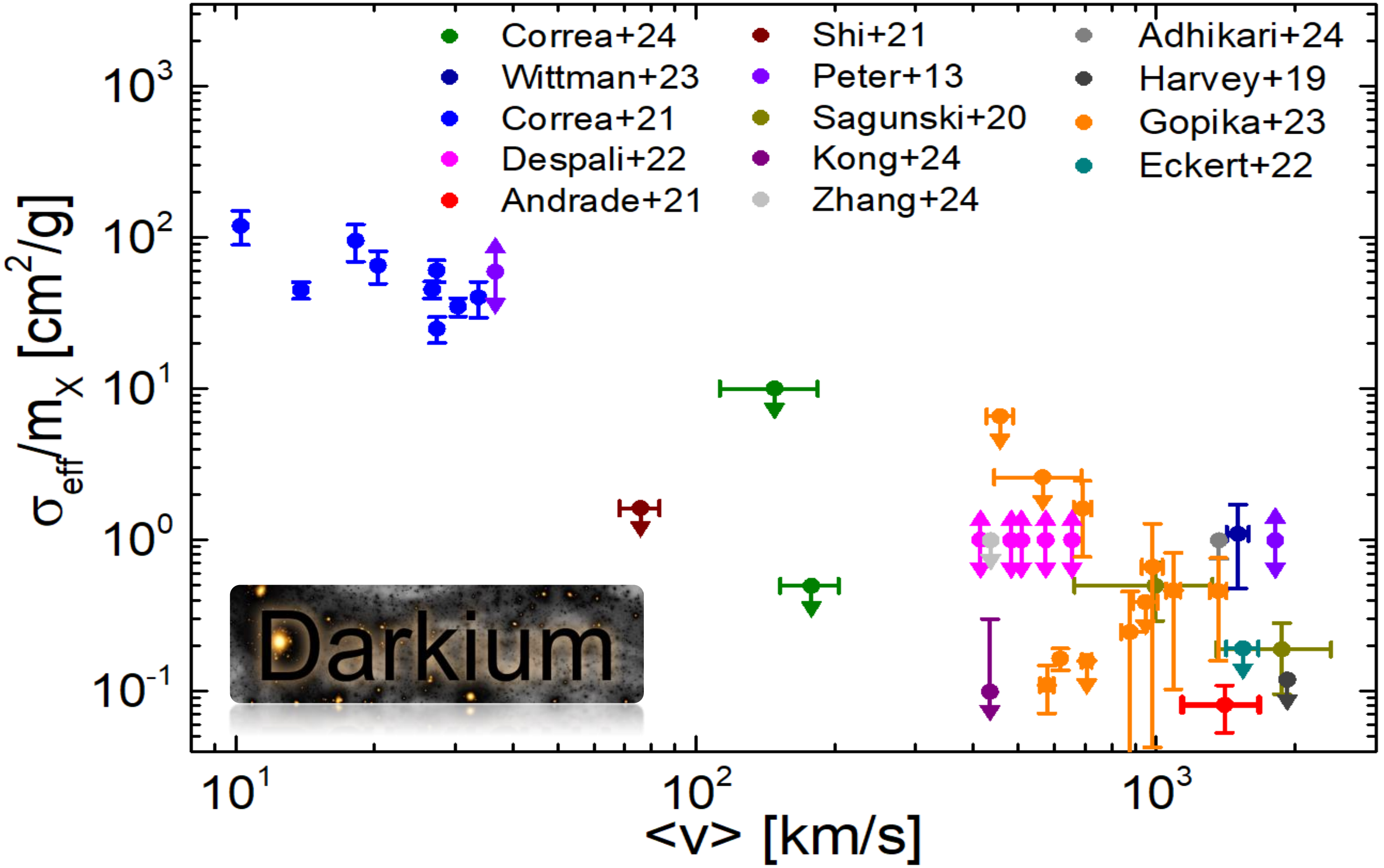
$$V(r) = \pm \frac{\alpha_X}{r} e^{-m_U r}$$

+ repulsive
- attractive

Arxiv.1308.0618



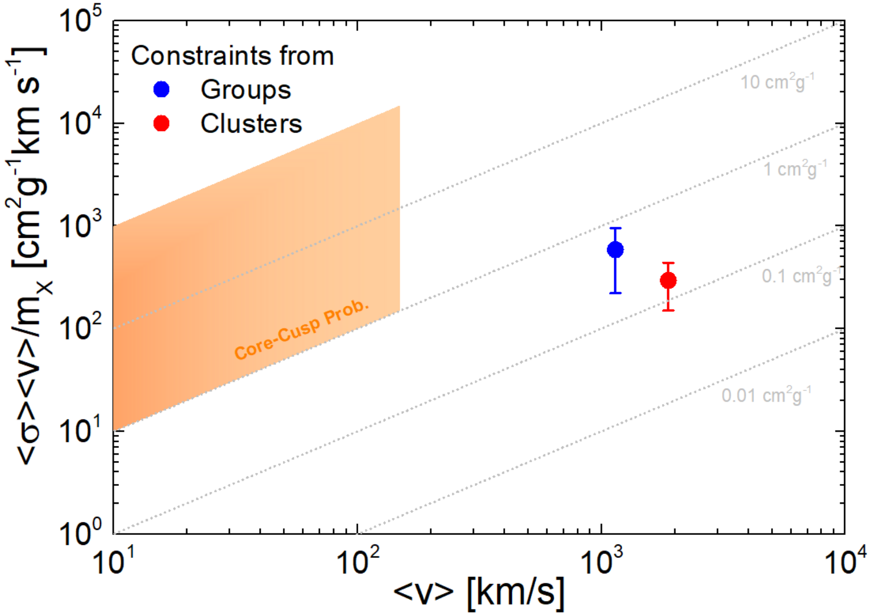
Arxiv: 2310.07750

Effective cross-section Constraints

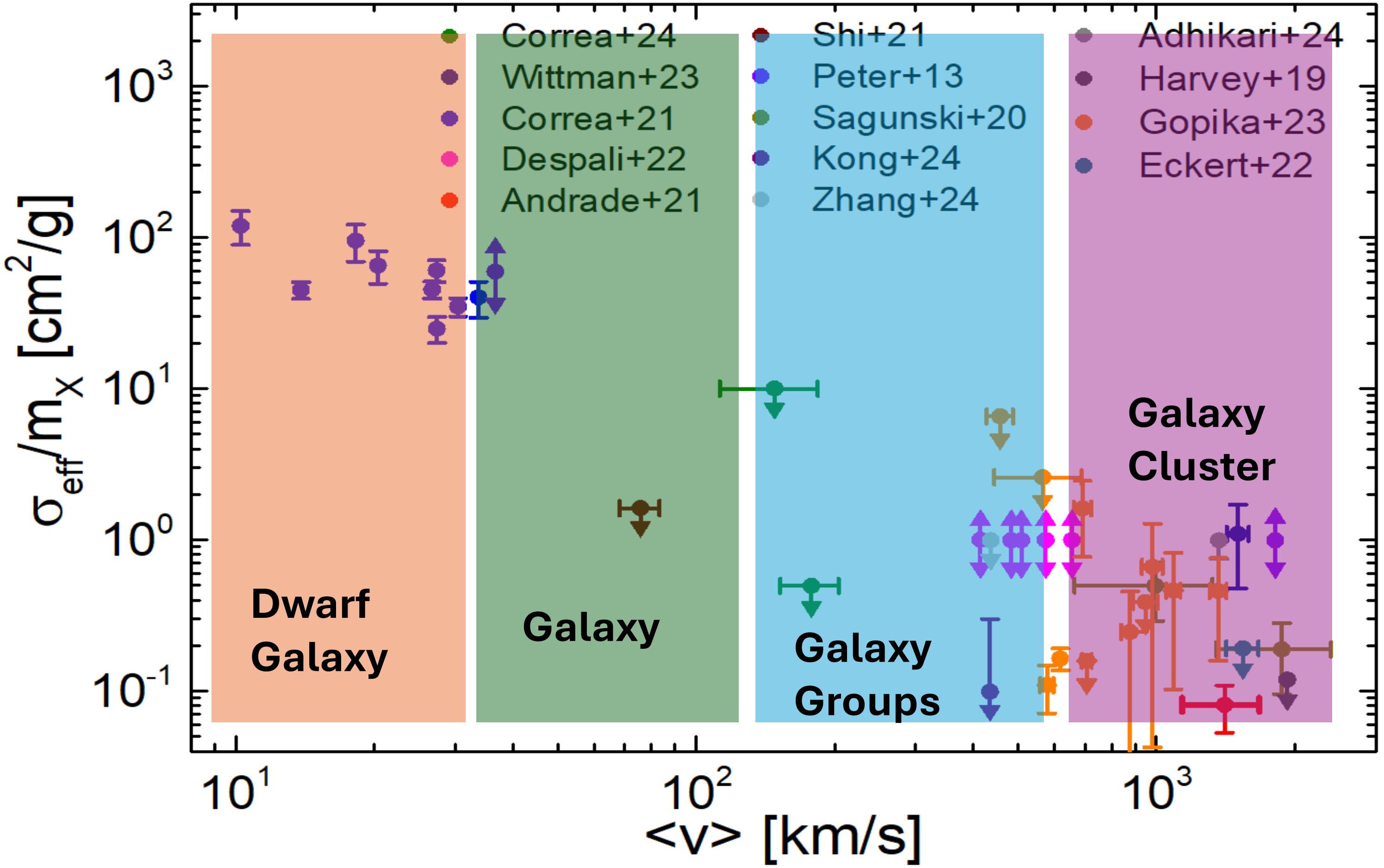
$$\sigma_{eff} = \frac{3}{2}\frac{\langle \sigma(v)\, v^5 \rangle}{\langle v^5 \rangle}$$

ArXiv: 2205.03392

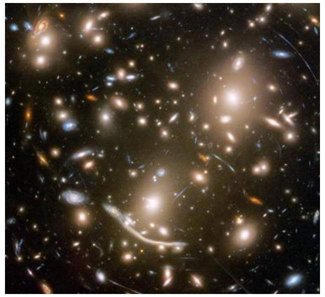
Groups and Clusters Constraints



Arxiv: 2011.04679





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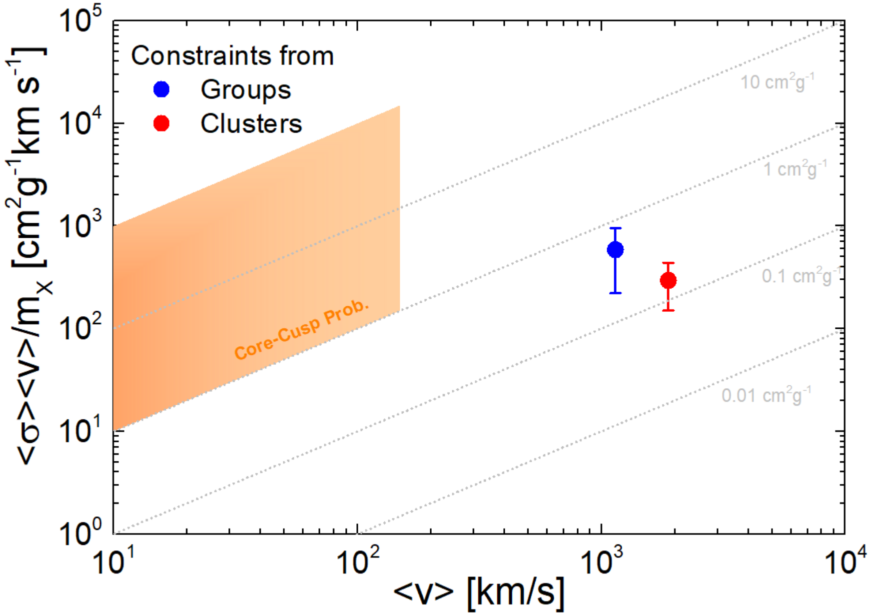

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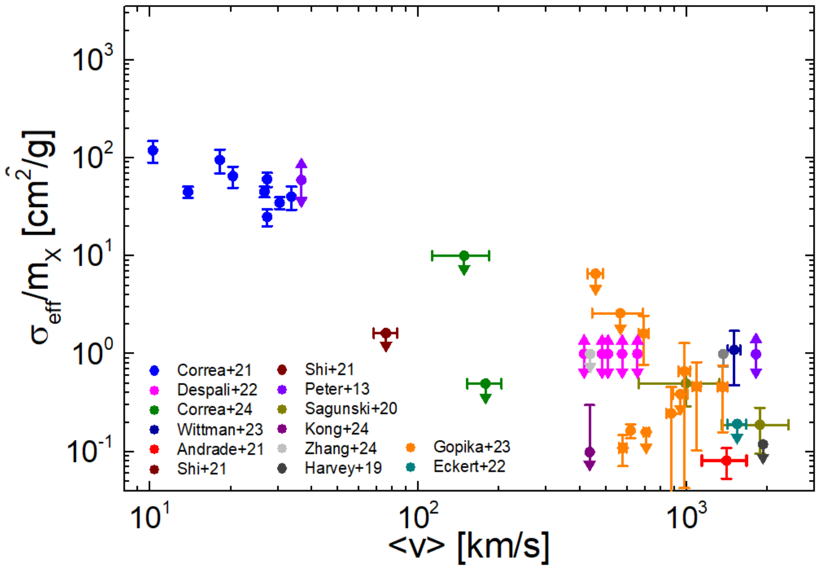
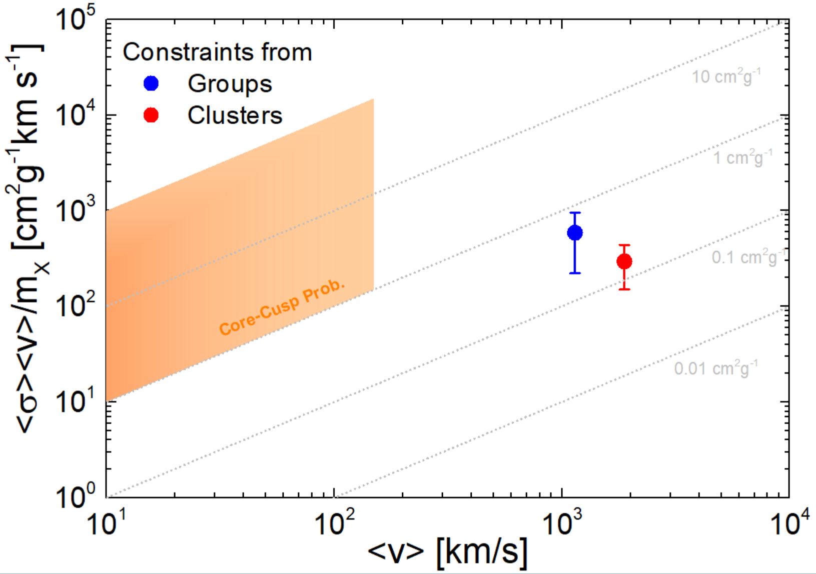




CLASSICS

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

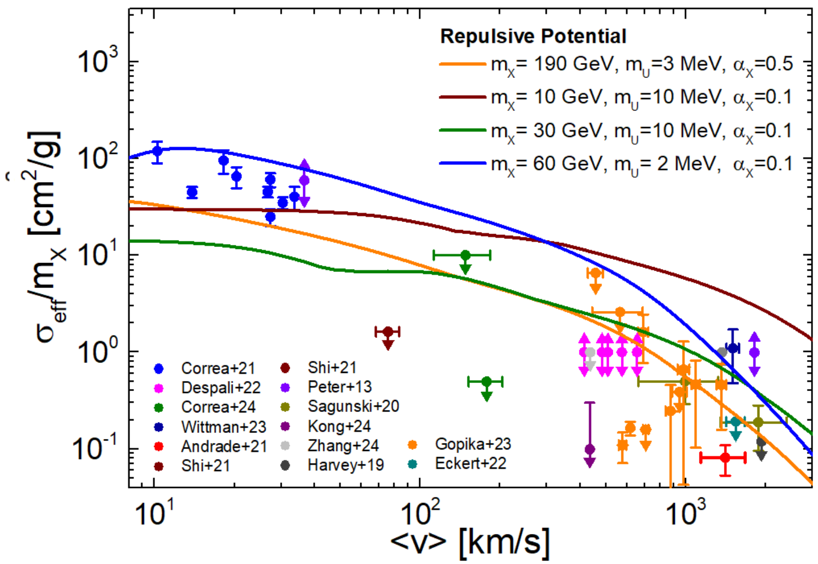
$$\sigma_V = \int d\Omega\,\sin^2\theta\,\frac{d\sigma}{d\Omega}.$$

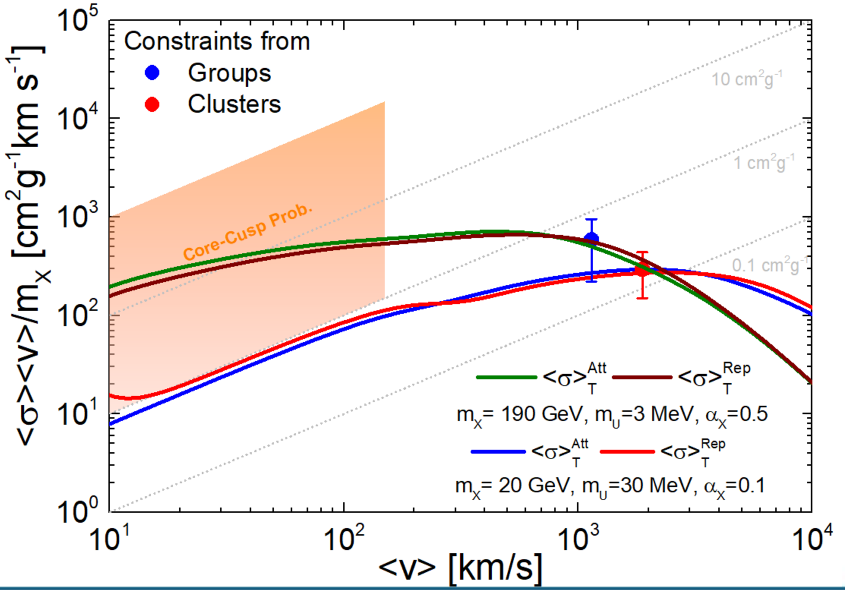
Maxwell–Boltzmann distribution to compute velocity-averaged cross sections

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

- $\frac{m_\chi v}{m_U} > 1$ Classical trajectory methods
- $\frac{m_\chi v}{m_U} < 1$ Hulthén potential approximation, but uses **analytic approximations** from *Tulin, Yu & Zurek (arXiv:1302.3898)*.

Effective cross-section Constraints





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

- Momentum-transfer cross section

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

- Viscosity cross section

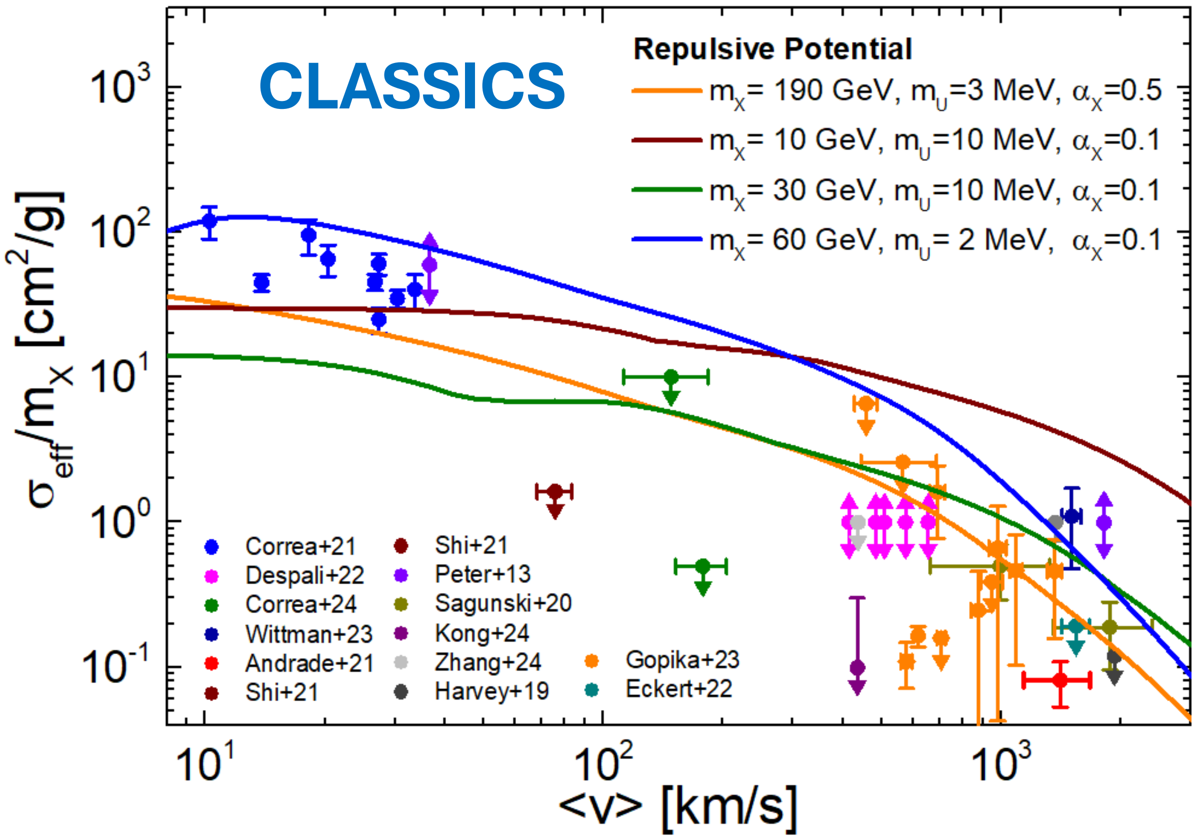
$$\sigma_V = \int d\Omega \, \sin^2\theta \, \frac{d\sigma}{d\Omega}.$$

Maxwell–Boltzmann distribution to compute velocity-averaged cross sections

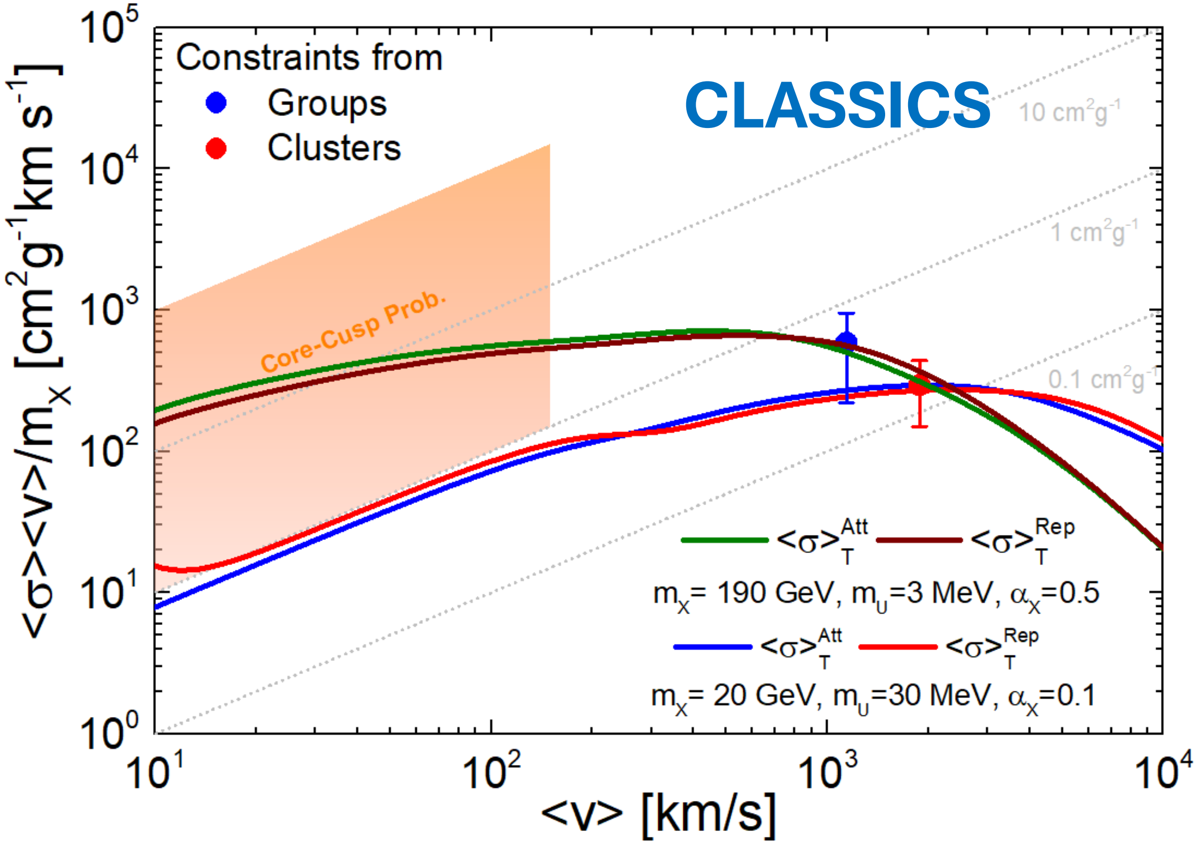
$$f(v) = 4\pi \left(\frac{m_\chi}{2\pi k_B T} \right)^{3/2} v^2 \, e^{-\frac{m_\chi v^2}{2k_B T}}$$

- $\frac{m_\chi v}{m_U} > 1$ Classical trajectory methods
- $\frac{m_\chi v}{m_U} < 1$ Hulthén potential approximation, but uses **analytic approximations** from *Tulin, Yu & Zurek (arXiv:1302.3898)*.

Effective cross-section Constraints



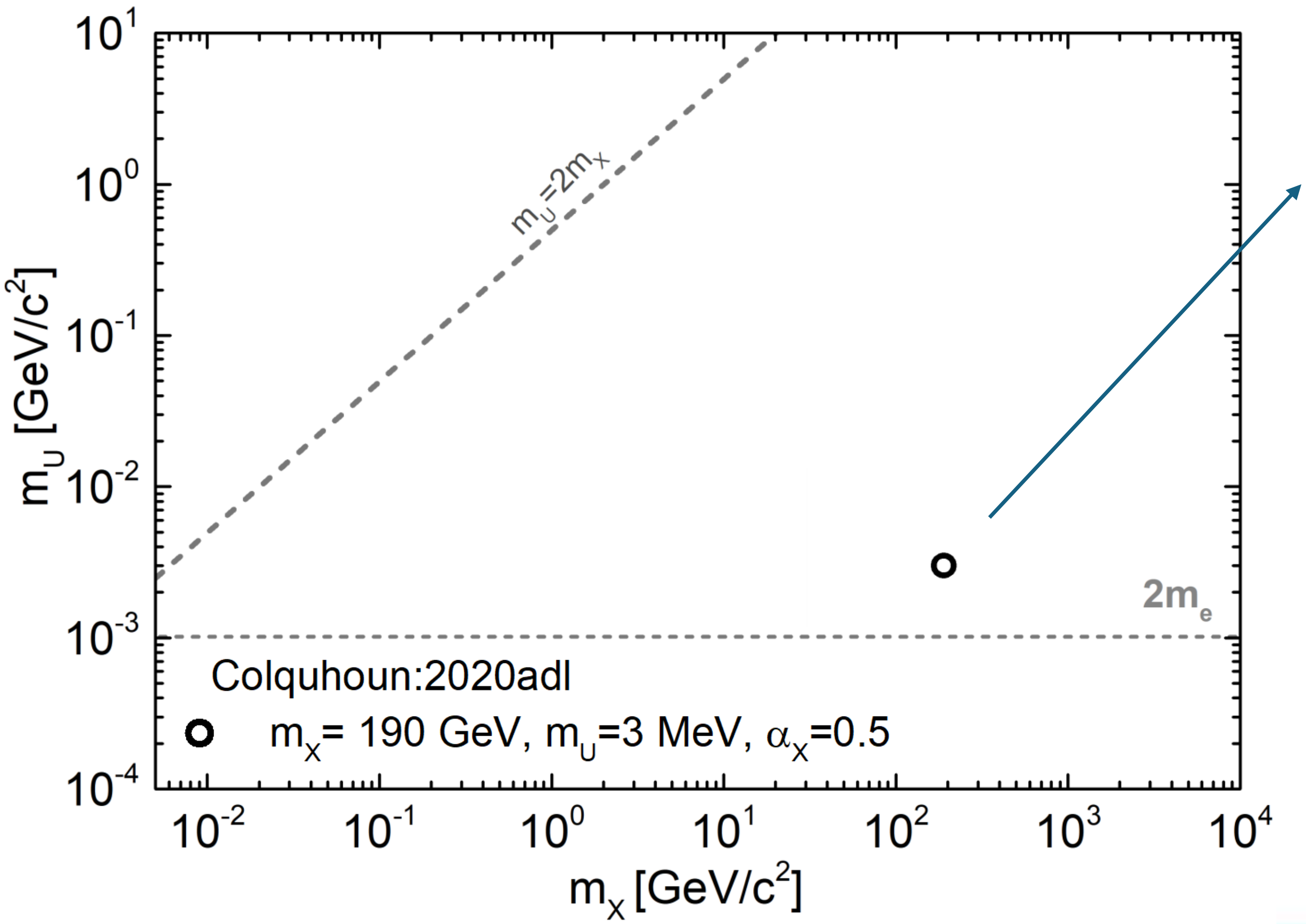
Groups and Clusters Constraints



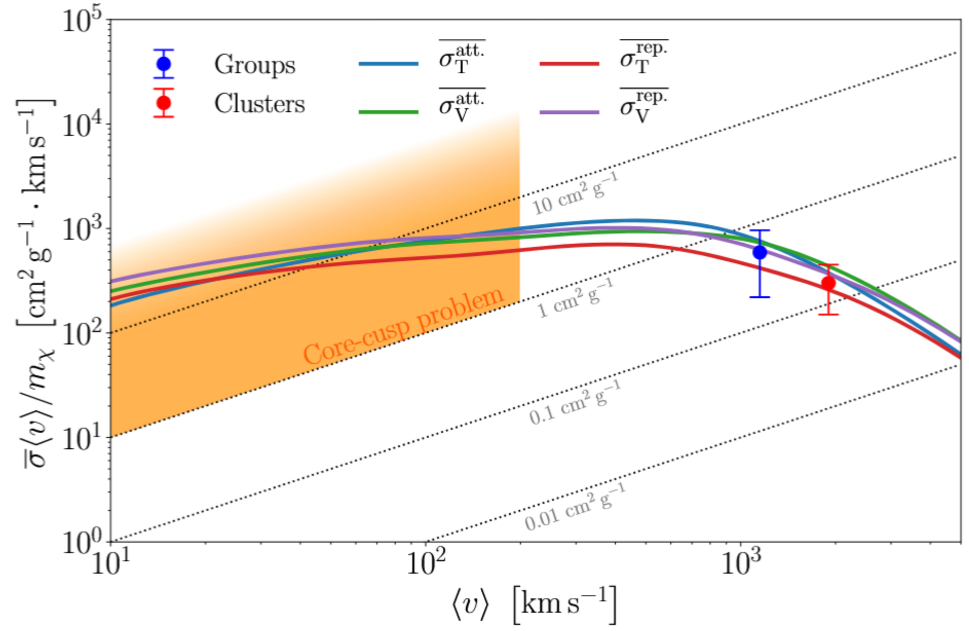
$$\{m_U, m_X, \alpha_X\} \longrightarrow$$ **fulfill both constraints**

Dark Photon Mass vs Dark Matter Mass

$$m_U(m_X)$$



CLASSICS



Benchmark point Arxiv: 2011.04679

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

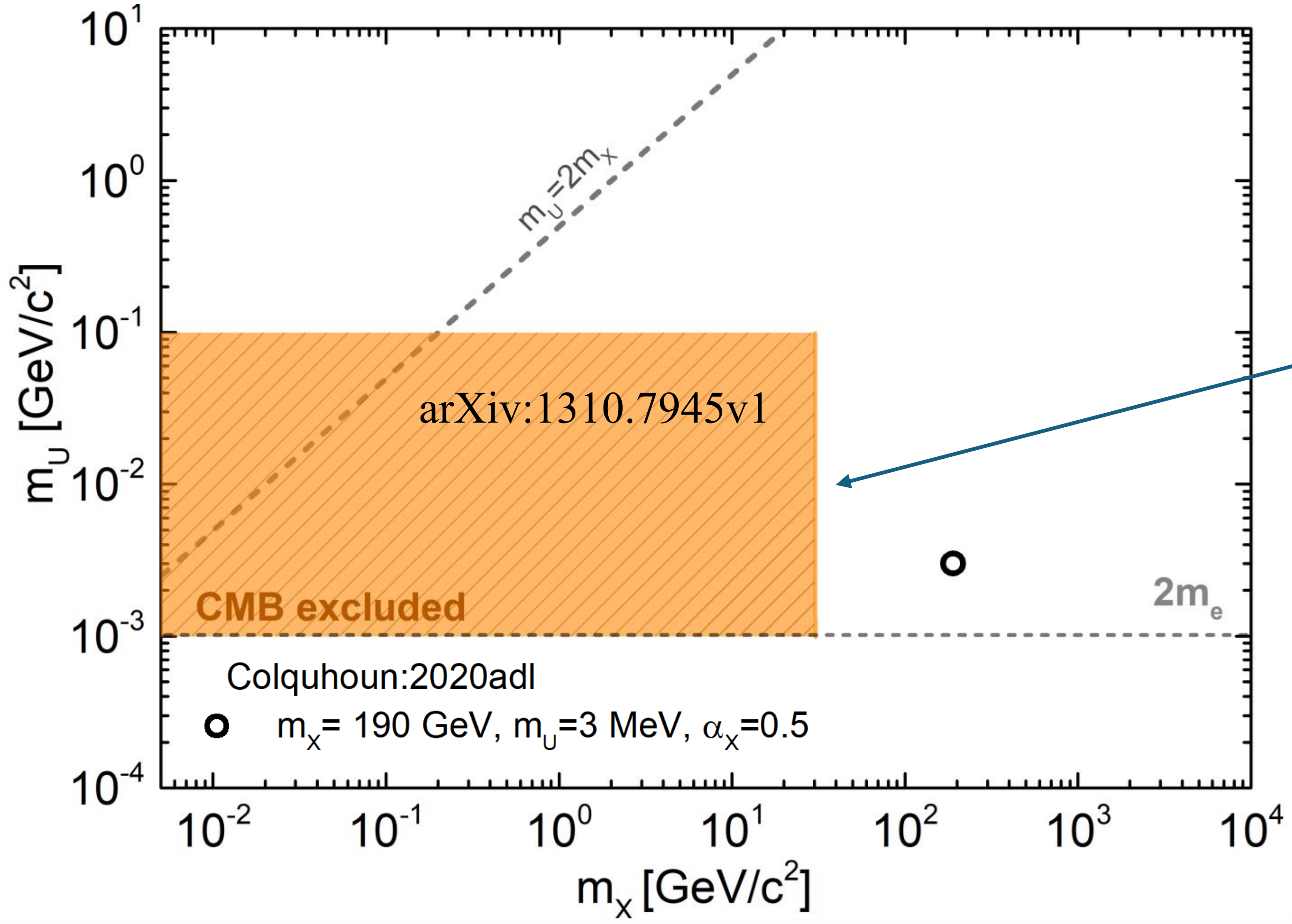
Dark Photon Mass vs Dark Matter Mass

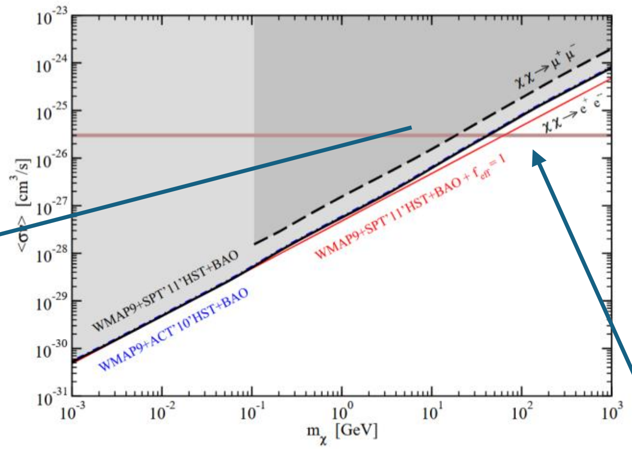
$$m_U(m_X)$$

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

arXiv:1512.08015 -> Plack Measurements

arXiv: 2105.08334



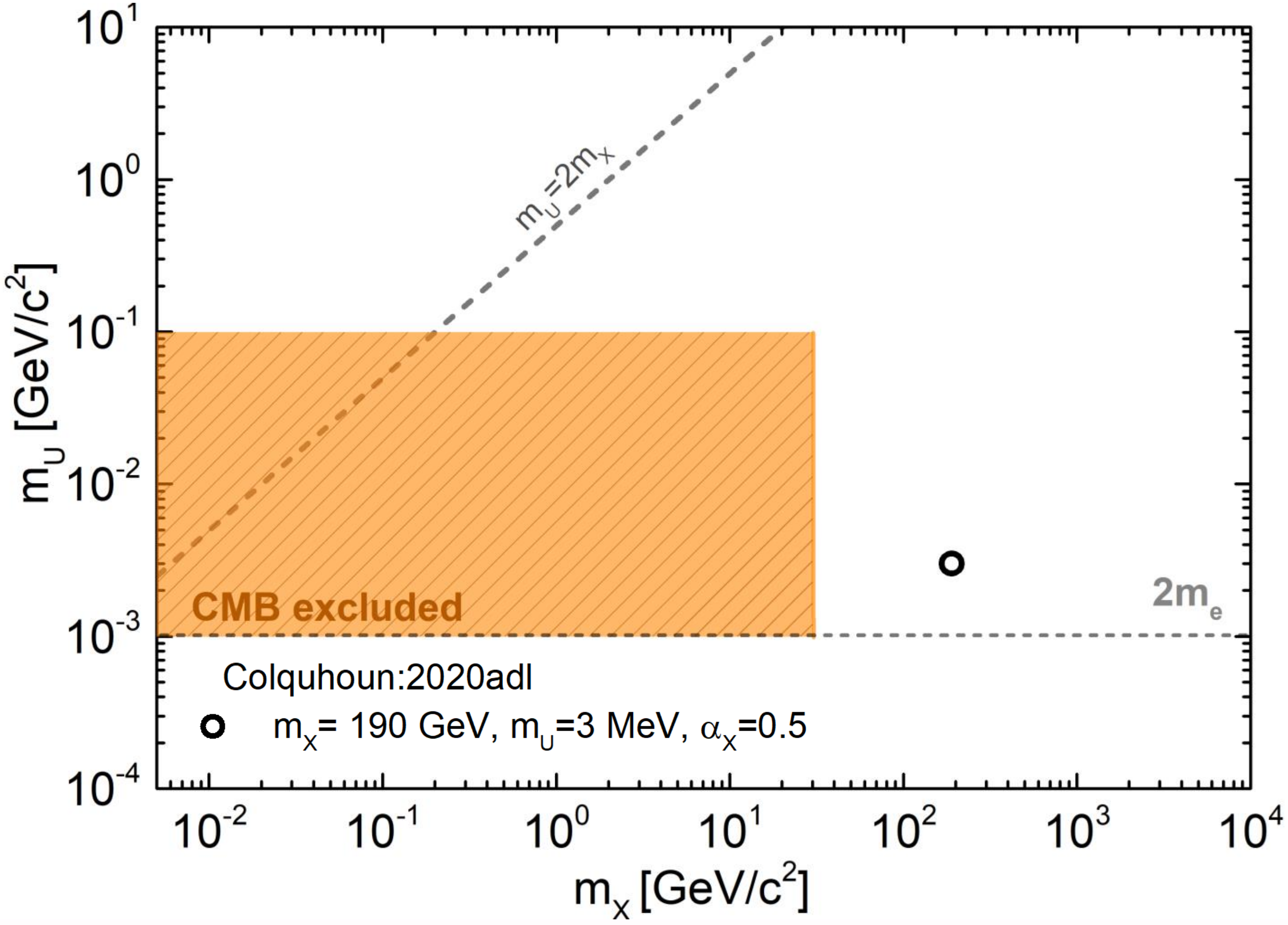


$\langle \sigma v \rangle \approx 3 \times 10^{-26}\ cm^3 s^{-1}$ arXiv:1303.5094

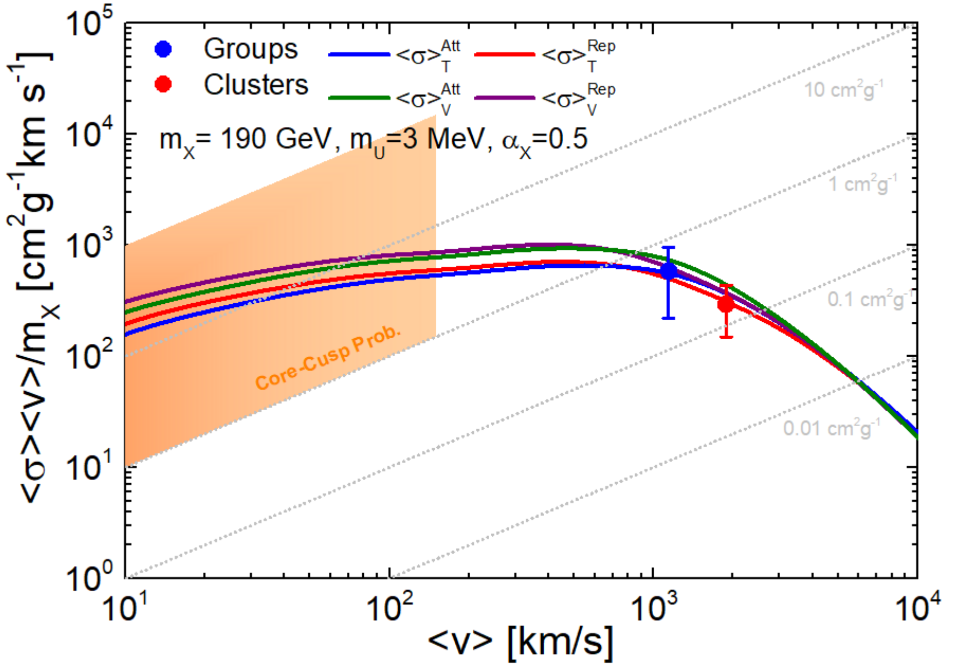
$$\boldsymbol{\Omega_{DM} h^2 \sim 0.120 \pm 0.001}$$

Dark Photon Mass vs Dark Matter Mass

$$m_U(m_X)$$

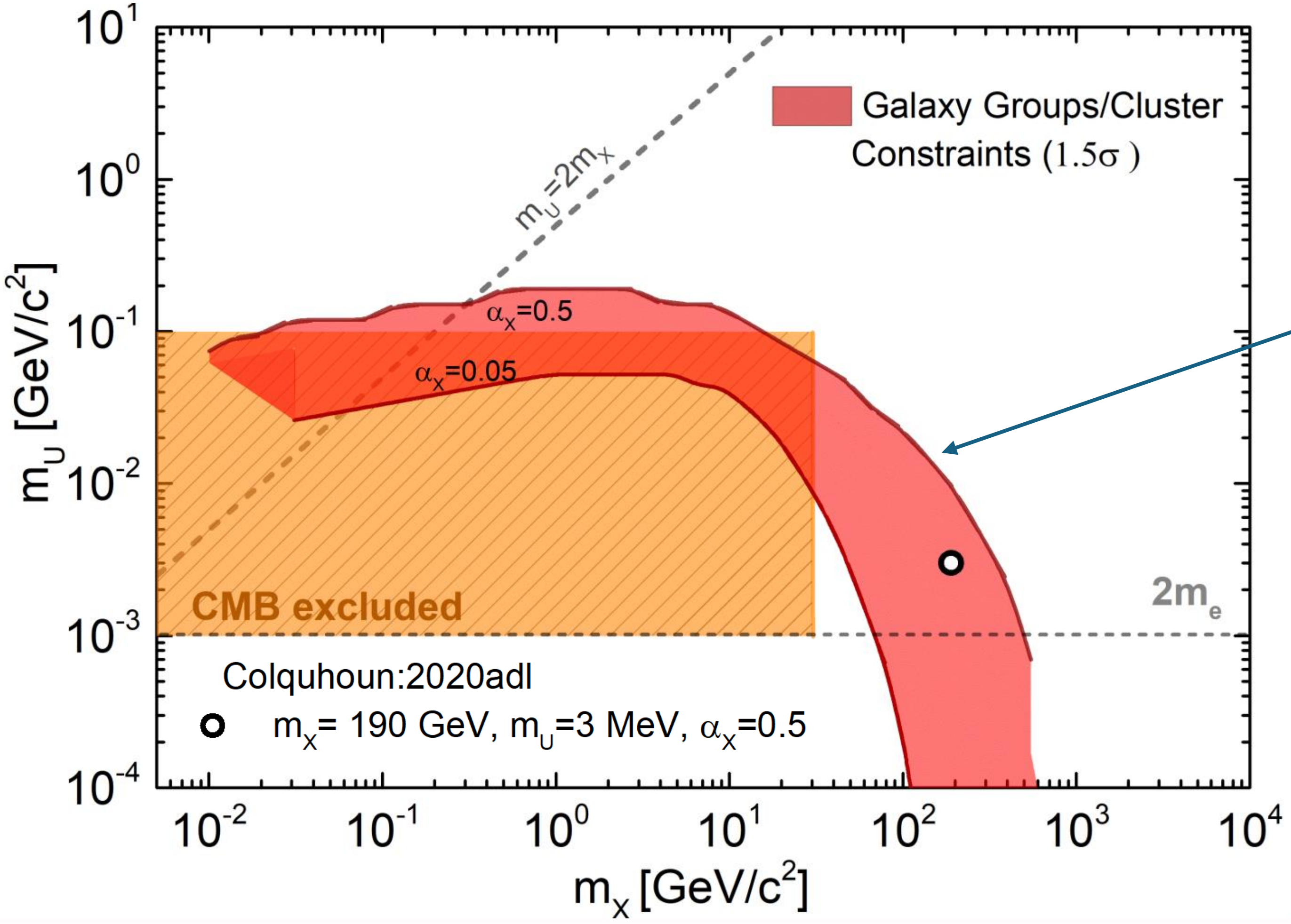


Groups and Clusters Constraints

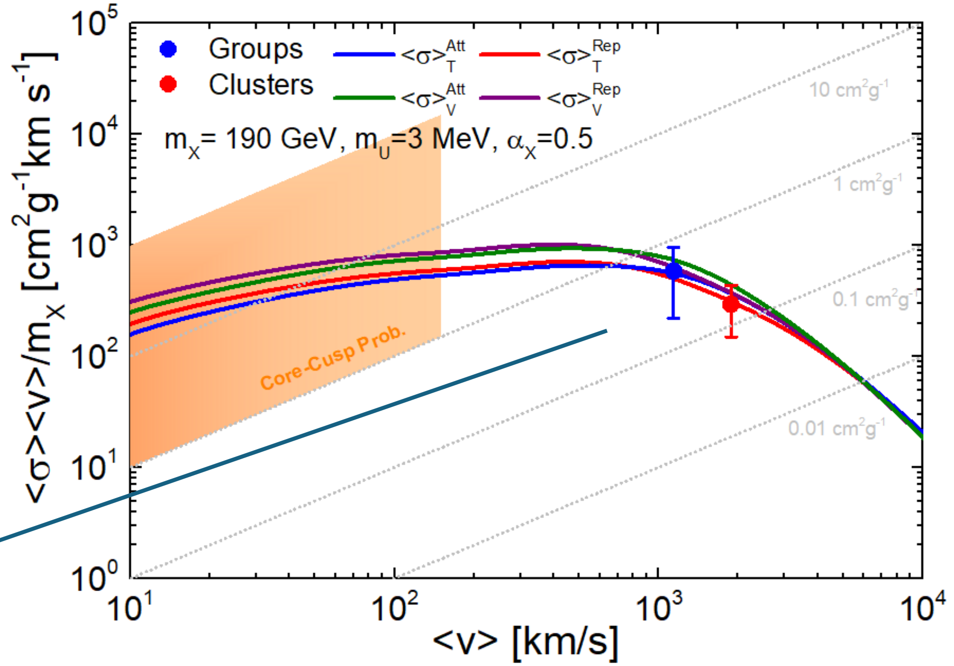


Dark Photon Mass vs Dark Matter Mass

$$m_U(m_X)$$

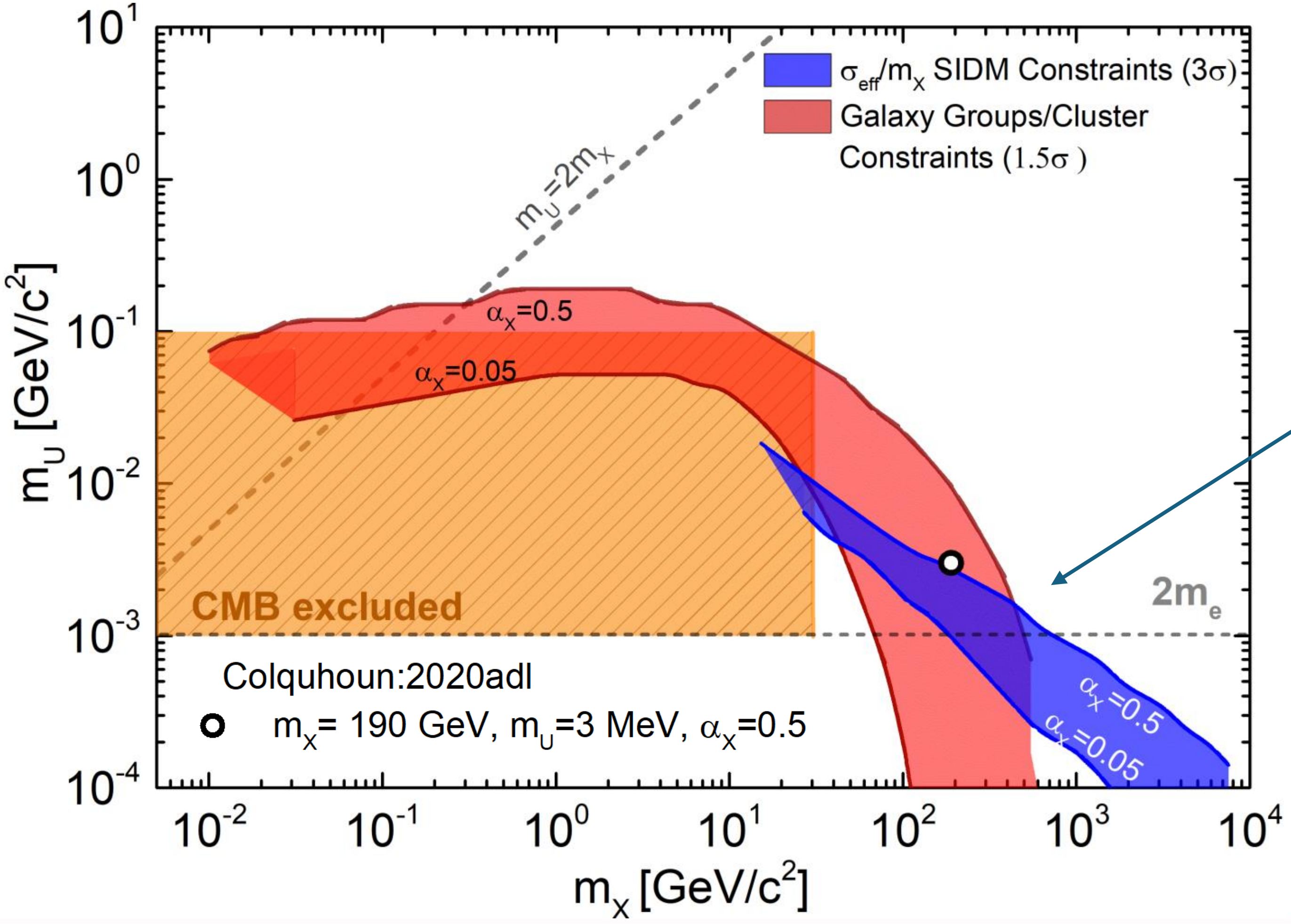


Groups and Clusters Constraints

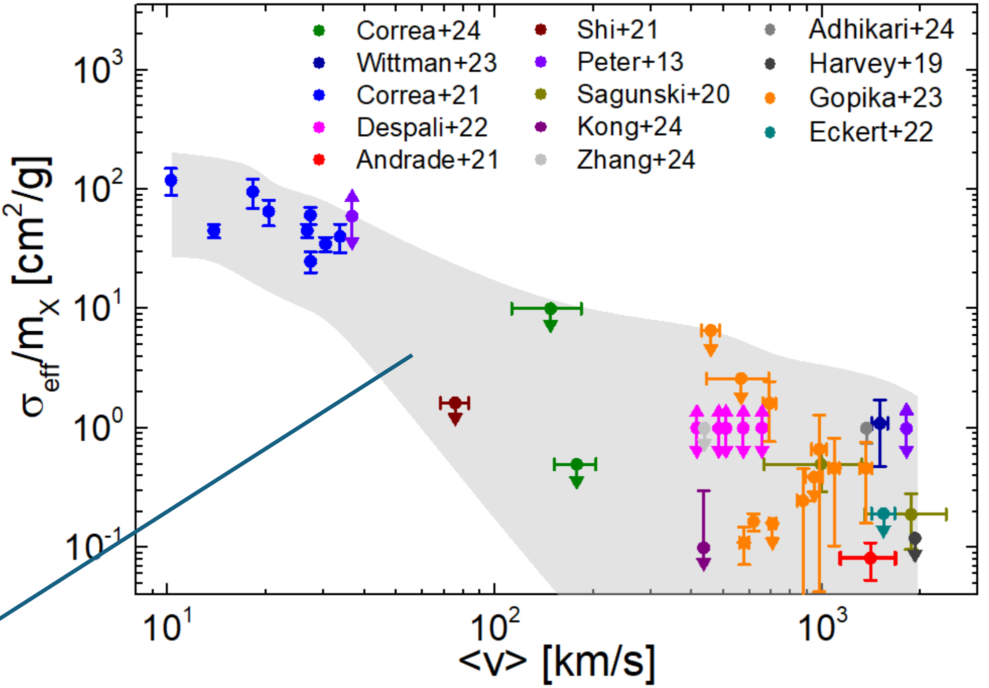


Dark Photon Mass vs Dark Matter Mass

$$m_U(m_X)$$



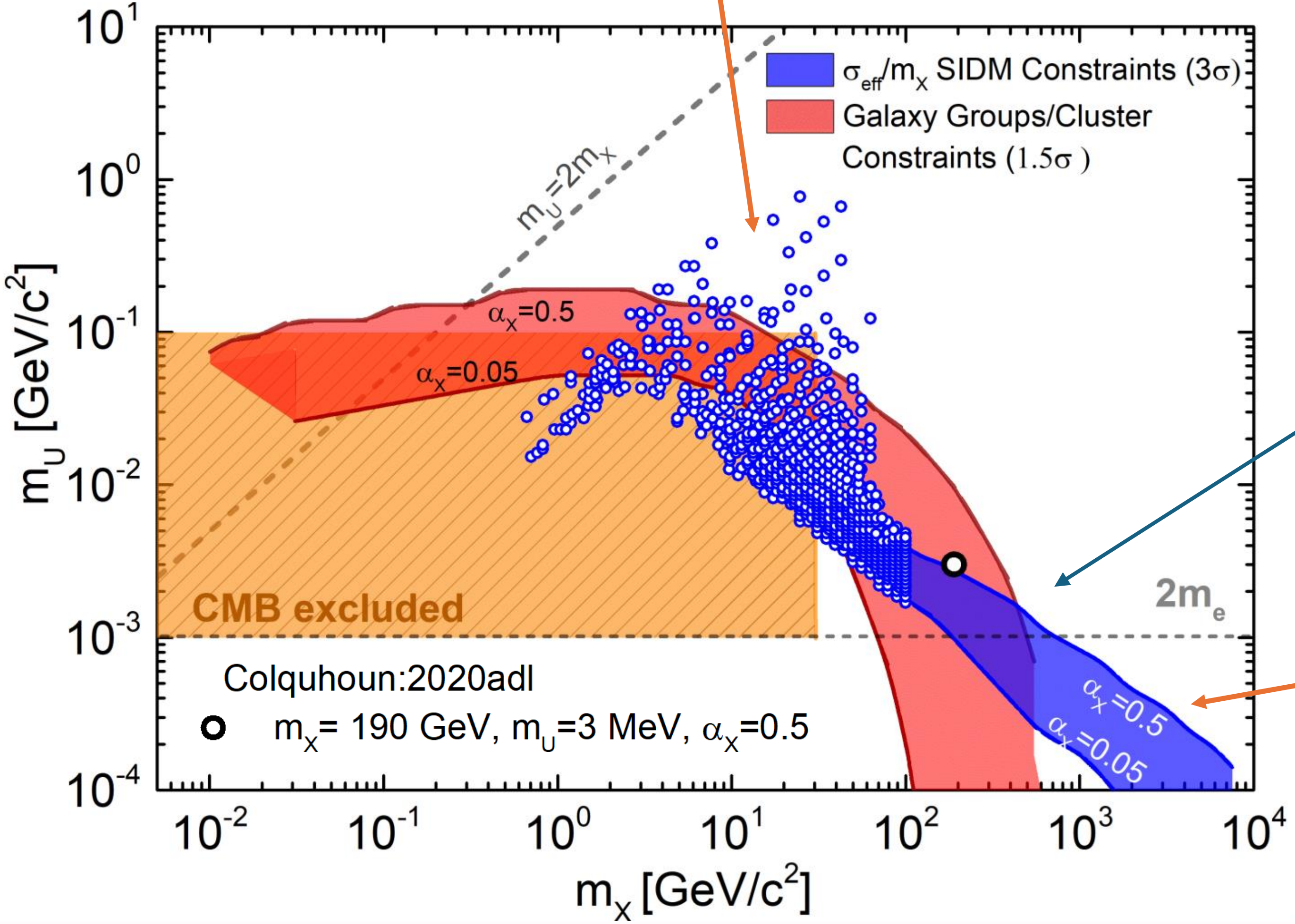
Effective cross-section Constraints



Dark Photon Mass vs Dark Matter Mass

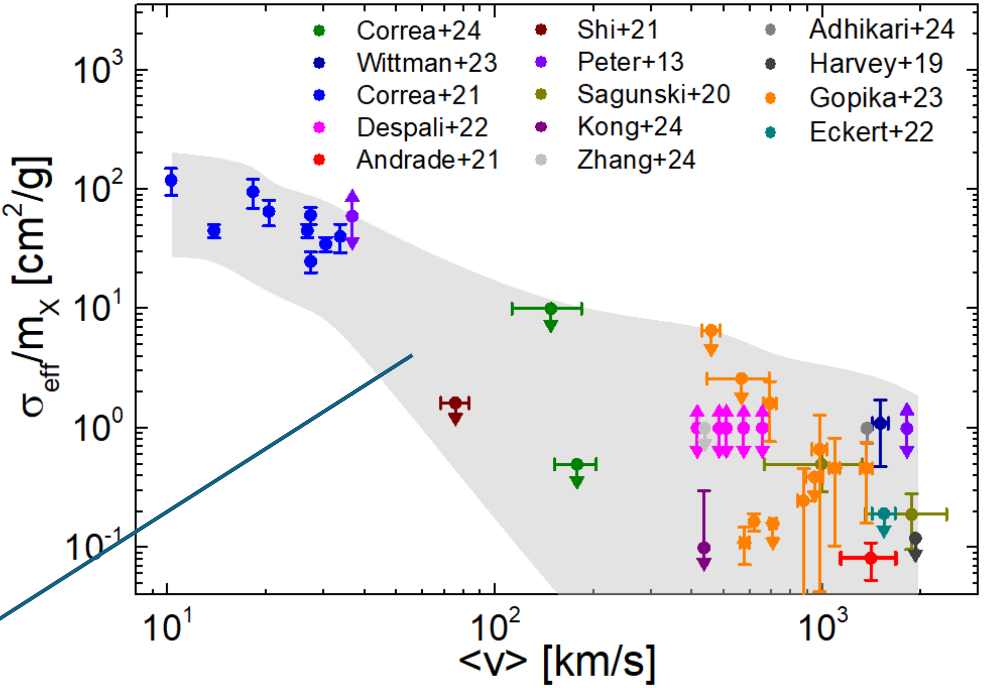
$m_U(m_X)$

Attractive Potencial



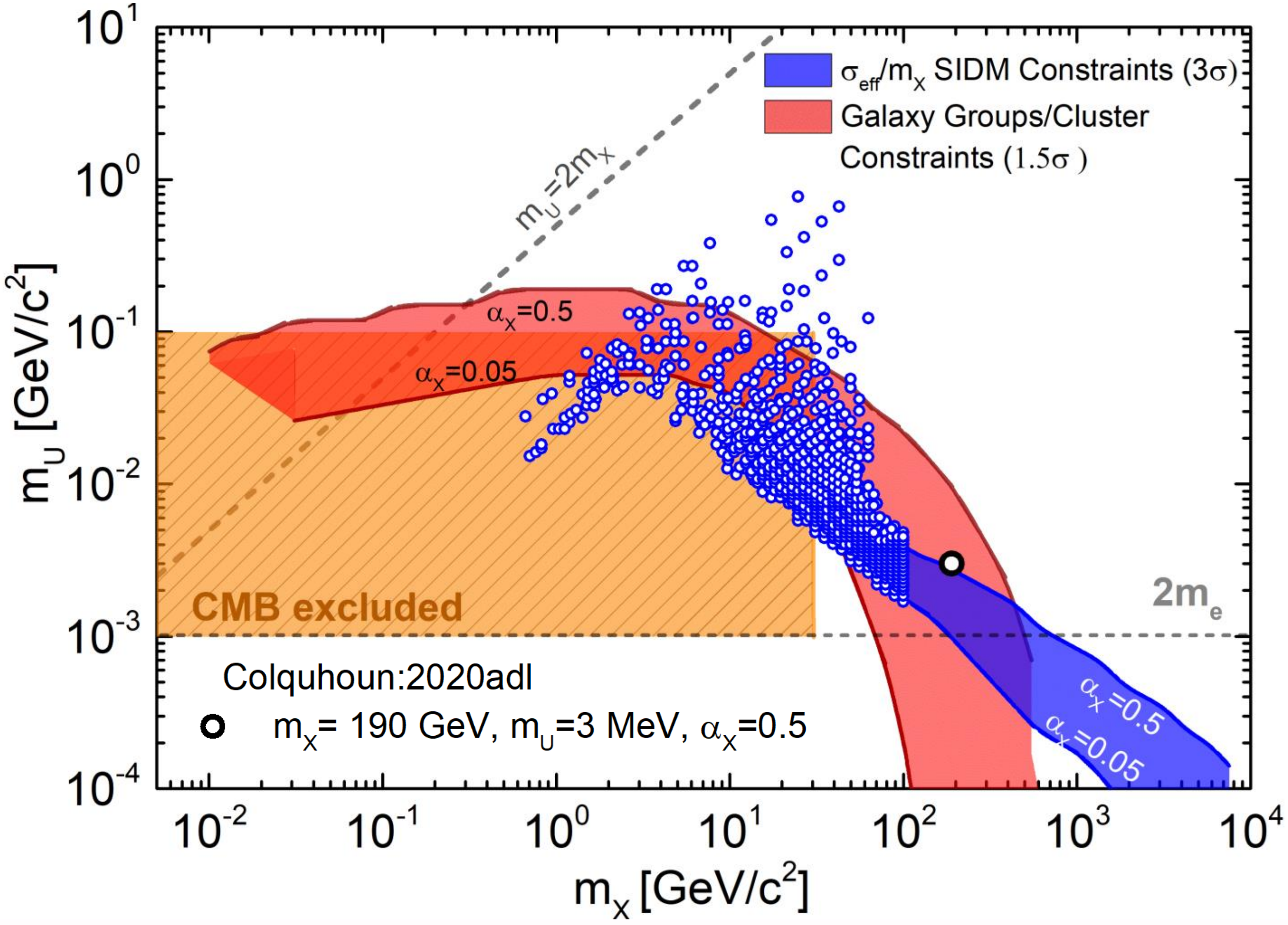
Repulsive Potencial

Effective cross-section Constraints



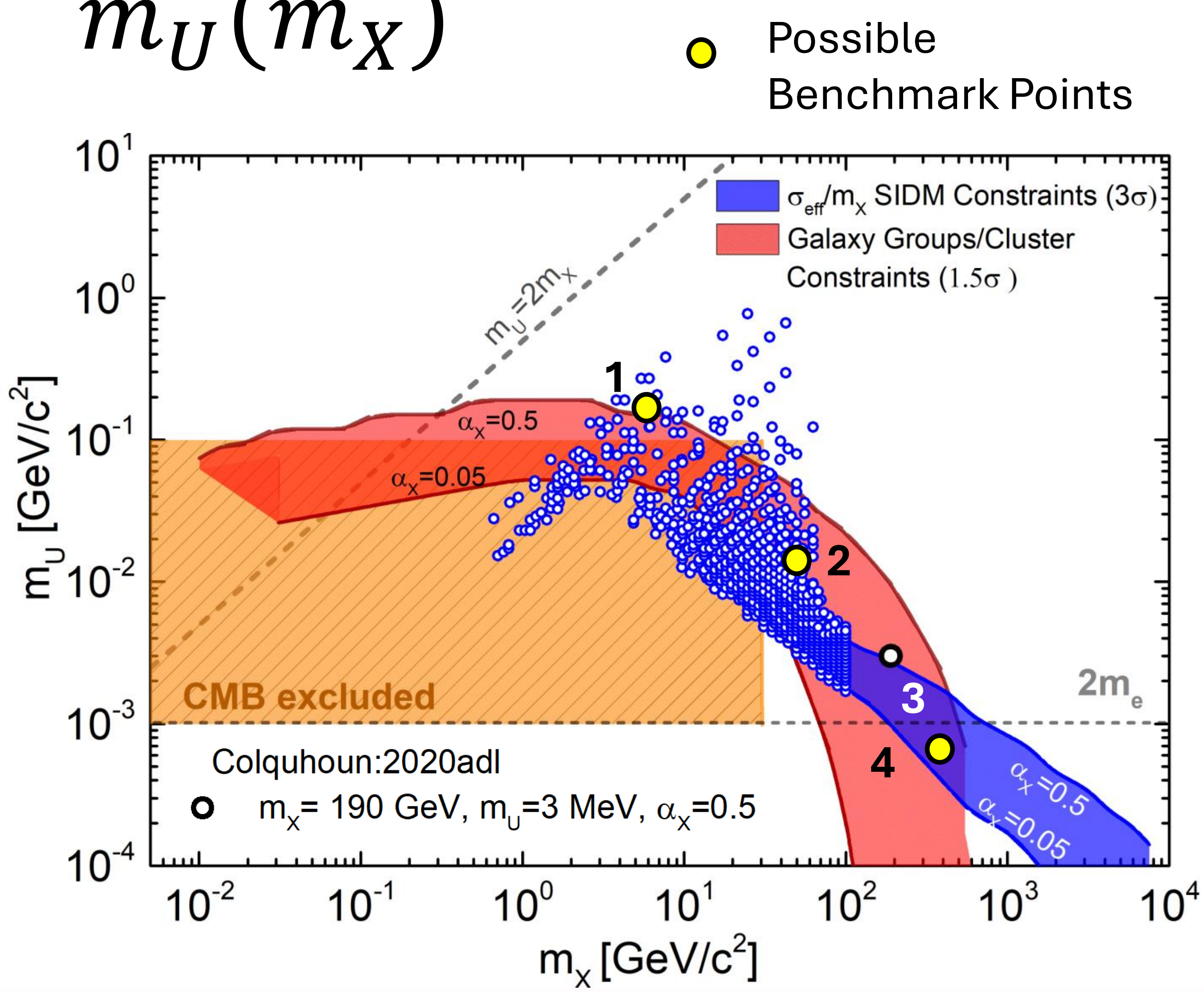
Dark Photon Mass vs Dark Matter Mass

$$m_U(m_X)$$



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
2. $m_U \sim 10\ MeV$
   $m_X \sim 50 - 80$ GeV
3. $m_U = 3\ MeV$
   $m_X \sim 190$ GeV
4. $m_U < 2m_2$
   $m_X \sim 200 - 800$ GeV

Thermal Relic Abundance

$$\Omega_{DM} = \frac{\rho_{DM}}{\rho_{cr}} \sim 26.41\ \%$$

$h = 0.674$

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

Dark Matter: Inelastic

Mediator: Dark Photon

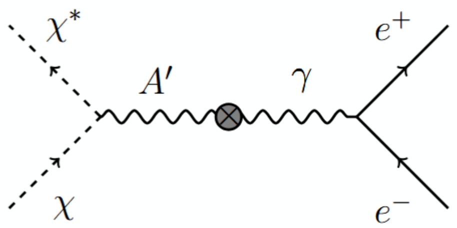
- $m_U > 2\, m_X$ Cross-Section is dependent of ε^2

$(\varepsilon, m_U, \alpha_X, m_X)$

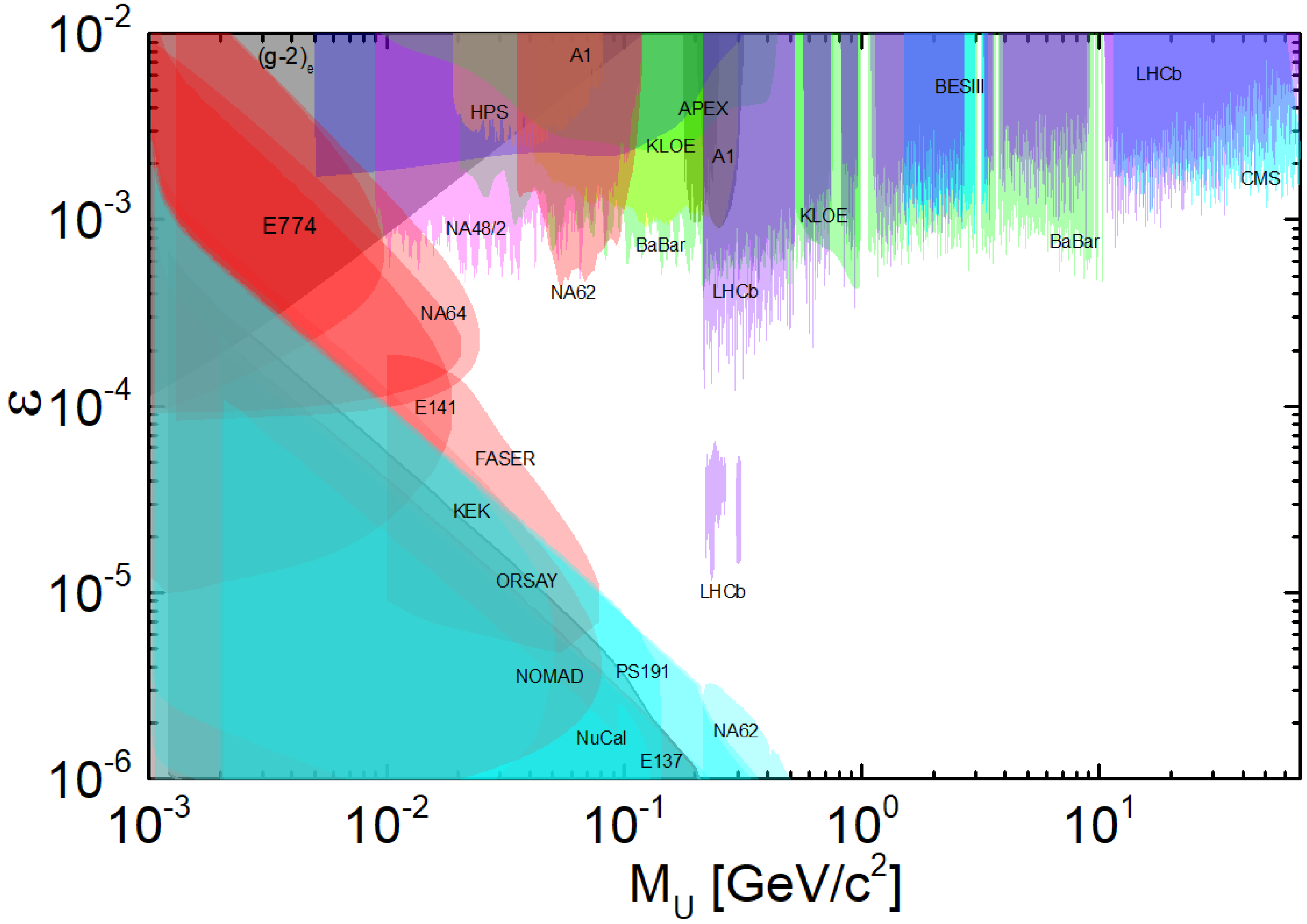
$\chi\bar{\chi} \to U^* \to f\bar{f}$ Direct Annihilation

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

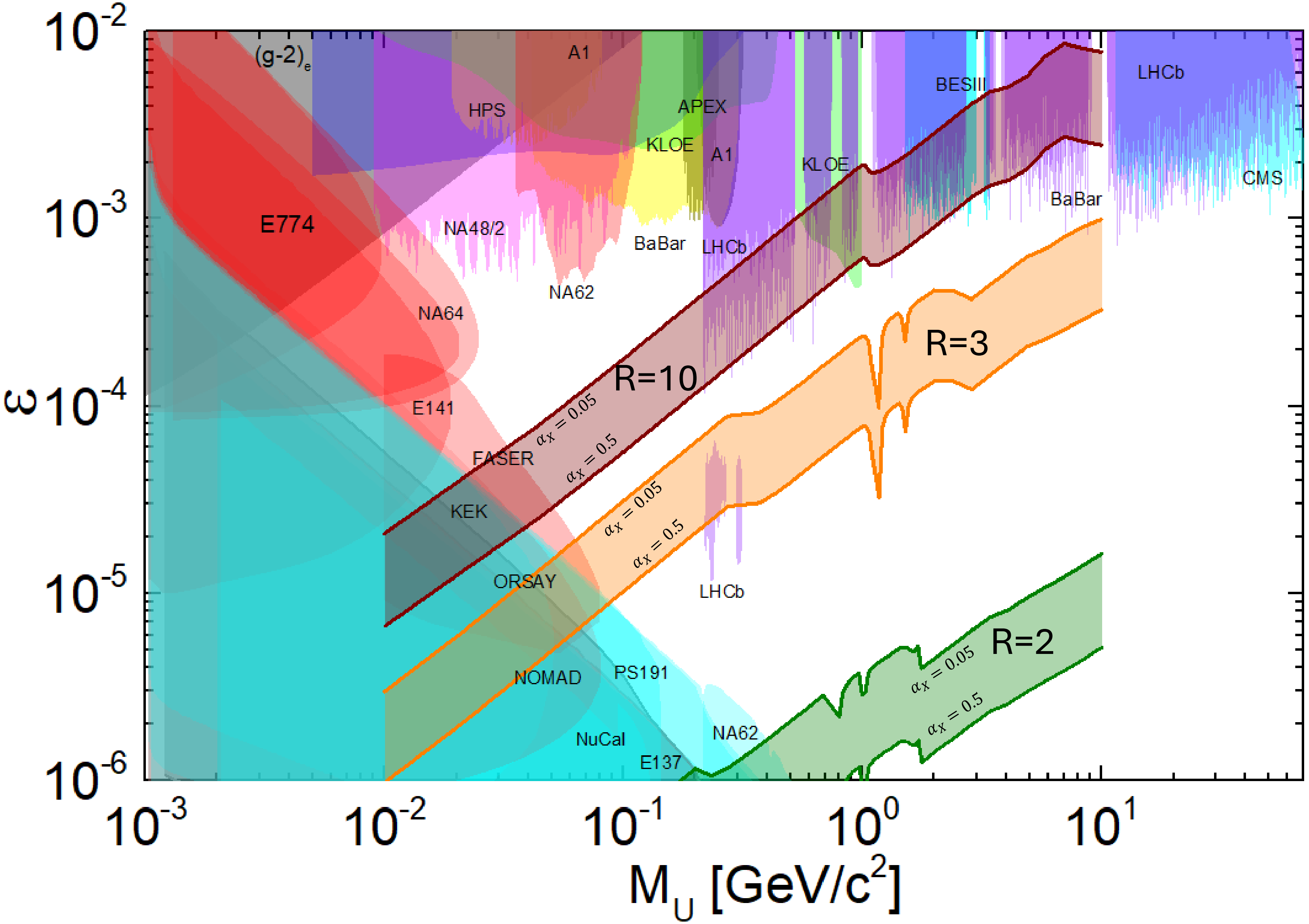
s − channel



Kinetic Mixing parameter $\varepsilon^2(M_U)$ and DM thermal Relic Abundance



Kinetic Mixing parameter $\varepsilon^2(M_U)$ and DM thermal Relic Abundance



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

Red DeliVeR

$\alpha_X = \{0.05, 0.5\}$

- $M_U = 2\ m_X$
- $M_U = 3\ m_X$
- $M_U = 10\ m_X$

Work in Progress

Summary

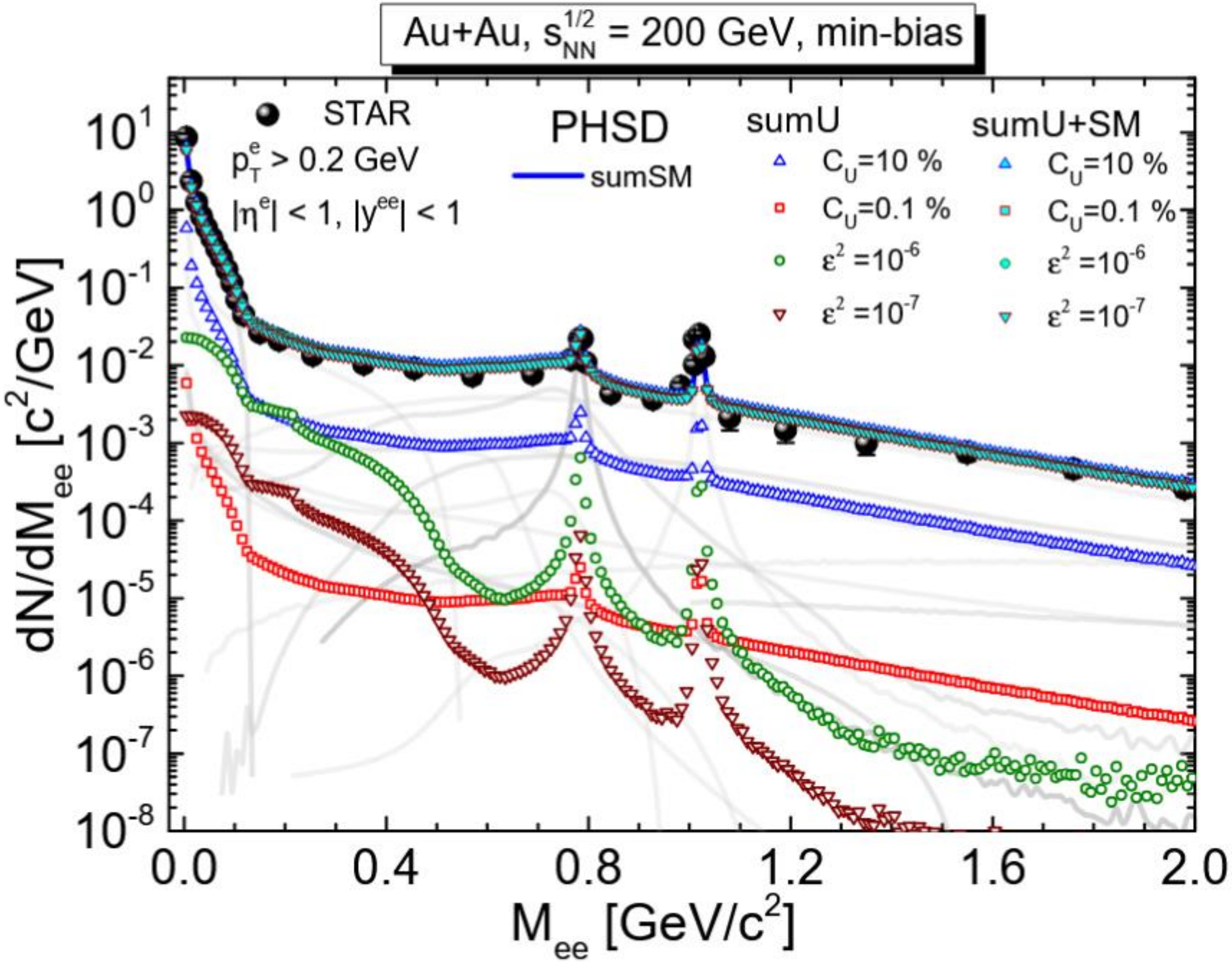
- Dilepton spectra from heavy-ion collisions provide a **sensitive probe of dark photon scenarios**, consistent with global experimental bounds.
- Recent results from **LHCb**, **KLOE**, and **CMS** impose even tighter bounds, which can only be satisfied if the possible dark photon contribution is reduced to $\boldsymbol{C_U = 0.05 - 0.1\%}$
- 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.

➔Perspectives:

- Explore dark alpha space phase $\alpha_X(m_X)$ with SIDM and Thermal Relic Abundance constraints
- Combine SIDM constraints with Thermal relic abundance constraints in $m_U(m_X)$ phase space.
- Explore the axion portal with dilepton decays

Thank you for your attention

Backup Slides


Au+Au, $s_{NN}^{1/2}$ = 200 GeV, min-bias
STAR
p_T^e > 0.2 GeV
$|\eta^e|$ < 1, $|y^{ee}|$ < 1
PHSD
sumSM
sumU
sumU+SM
C_U=10 %
C_U=0.1 %
ε^2 =10^{-6}
ε^2 =10^{-7}
dN/dM_{ee} [c^2/GeV]
M_{ee} [GeV/c^2]

Dark photon production in PHSD

Dalitz Decay

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

$\Delta \to NU$

$\omega \to \pi^0 U$

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

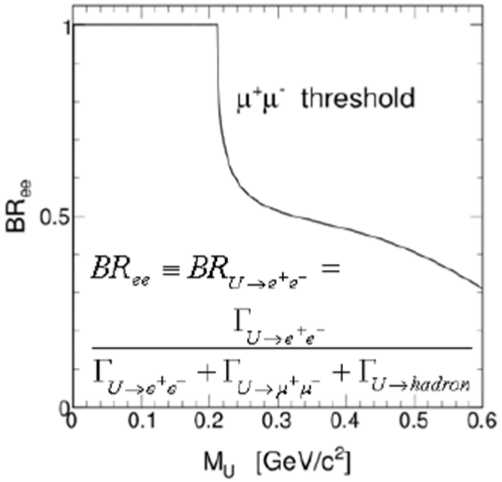
Direct Decay

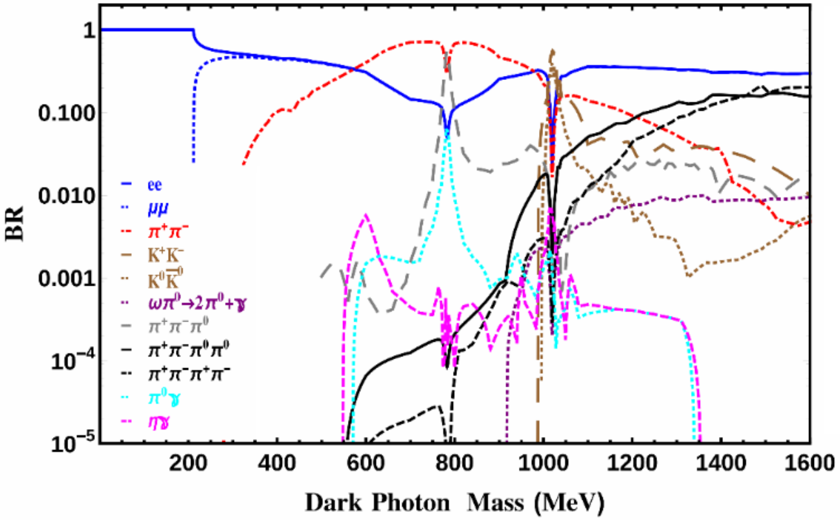
$\rho, \phi, \omega \to U$

$U \to e^+e^-$

Branching ratio for the decay of U-bosons to e^+e^-

$$Br^{U\to e^+e^-} = \frac{\Gamma_{U\to e^+e^-}}{\Gamma_T(U)} = \frac{\Gamma_{U\to e^+e^-}}{\Gamma_{U\to e^+e^-} + \Gamma_{U\to \mu^+\mu^-} + \Gamma_{U\to hadrons}}$$





J. Liu et al. JHEP 08, 050 (2015)

B. Batel, et al. (2009) PRD 80, 095024   I. Schmidt et al., PRD 104 (2021) 015008

Dark photon production in PHSD

Dalitz Decay

$\pi^0, \eta \rightarrow \gamma U$

$\Delta \rightarrow NU$

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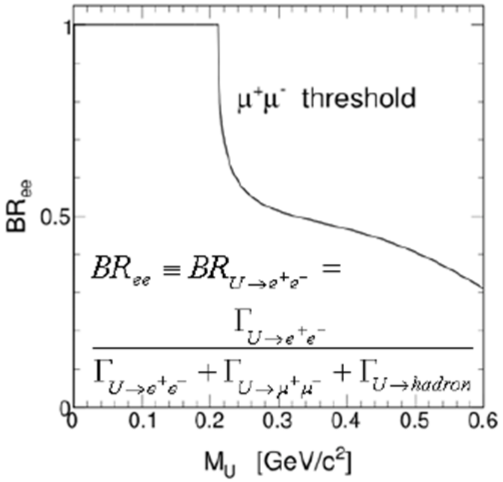
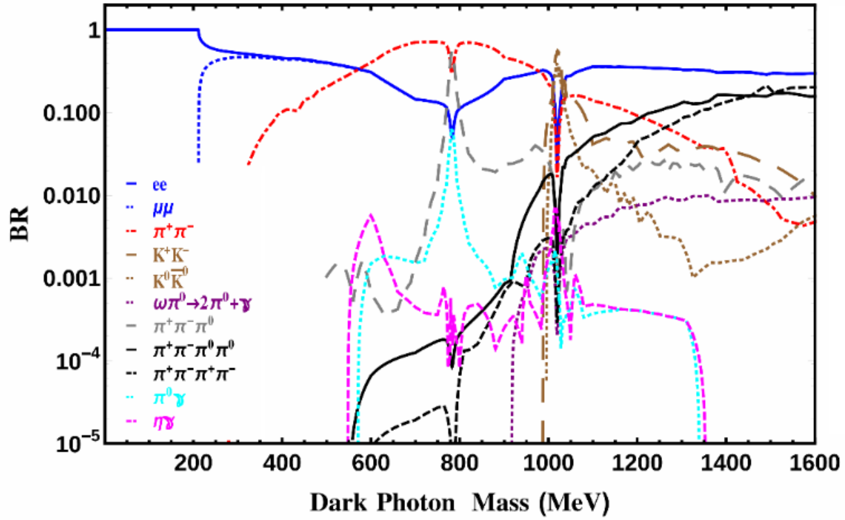




J. Liu et al. JHEP 08, 050 (2015)

$$Br^{U\rightarrow e^+e^-} = \frac{1}{1 + \sqrt{1 - \frac{4m_\mu^2}{m_U^2}}\left(1 + \frac{2m_\mu^2}{m_U}\right)(1 + R(m_U))}$$

$$R(\sqrt{s}) = \sigma_{e^+e^-\rightarrow hadrons} / \sigma_{e^+e^-\rightarrow \mu^+\mu^-}$$

B. Batel, et al. (2009) PRD 80, 095024 I. Schmidt et al., PRD 104 (2021) 015008

Navarro-Frenk-White (NFW) profile

$$\rho_{\mathrm{NFW}}(r) = \frac{\rho_s}{(r/r_s)(1+r/r_s)^2}$$

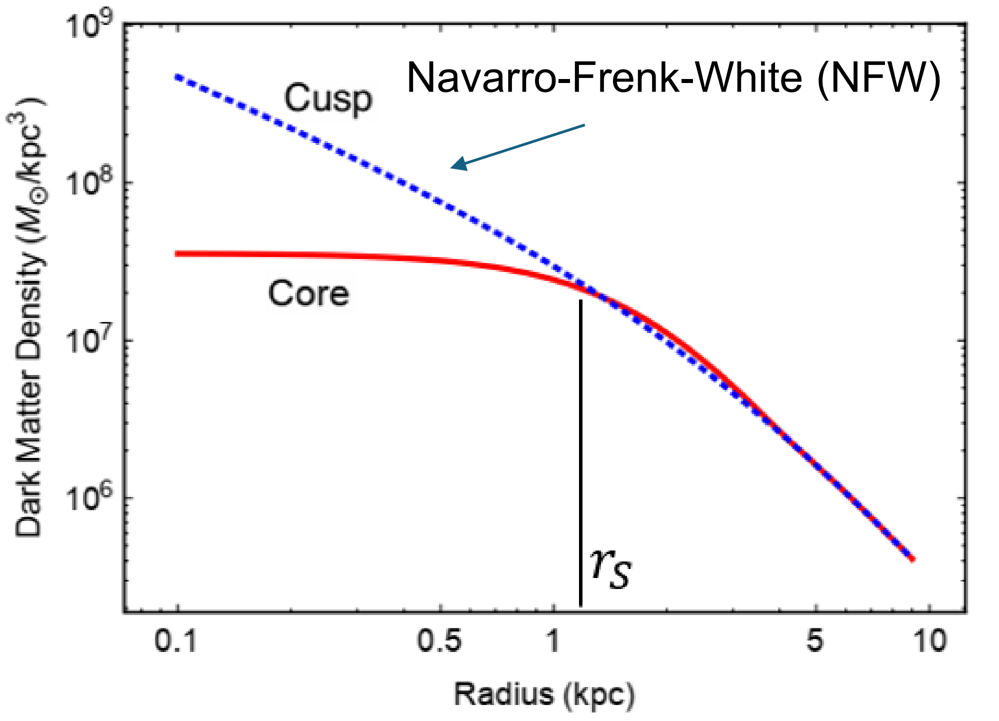
Dark Matter Density profiles (depends on each galaxy)
2 free parameters:

r_S → Core radius of the dark matter halo.
ρ_S → Central density of the dark matter halo.

For a spherical halo, the DM contribution to the rotation curve is

$$V_{halo}(r) = \left(\frac{G\, M_{halo}(r)}{r}\right)^{1/2}$$

$$M(r) = \int_0^r 4\pi r'^2 \rho(r')\, dr'$$



Navarro, Frenk & White (1995b)

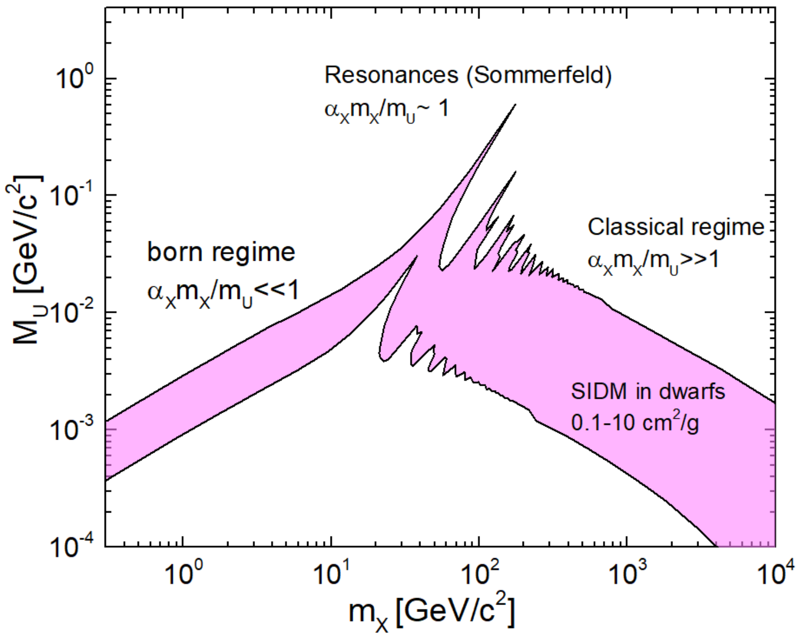
Elastic DM self-scattering

Born limit $\boldsymbol{\alpha_X m_X \ll m_\phi}$

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

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

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

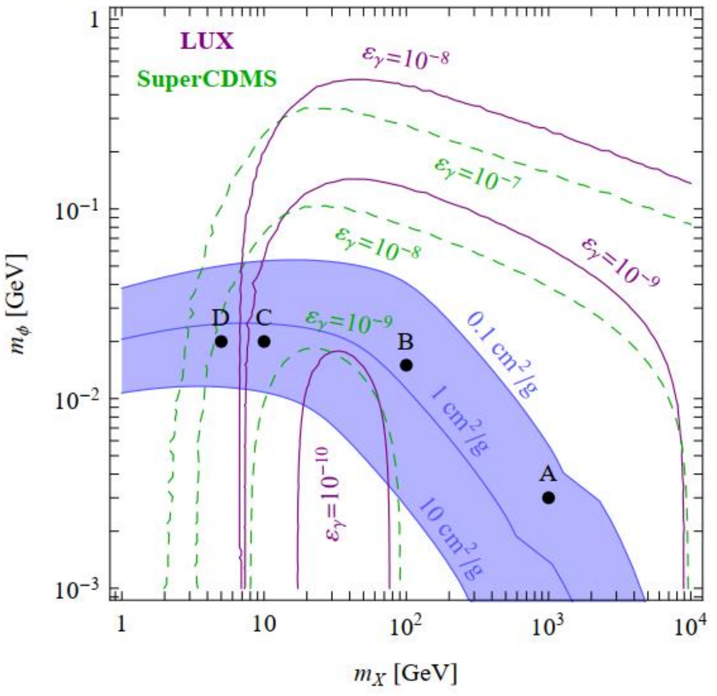


$$\frac{\sigma}{m_X} = \left(\frac{\alpha_X}{10^{-2}}\right)^2 \left(\frac{m_X}{10\ GeV}\right)^1 \left(\frac{m_\phi}{40\ MeV}\right)^{-4}$$

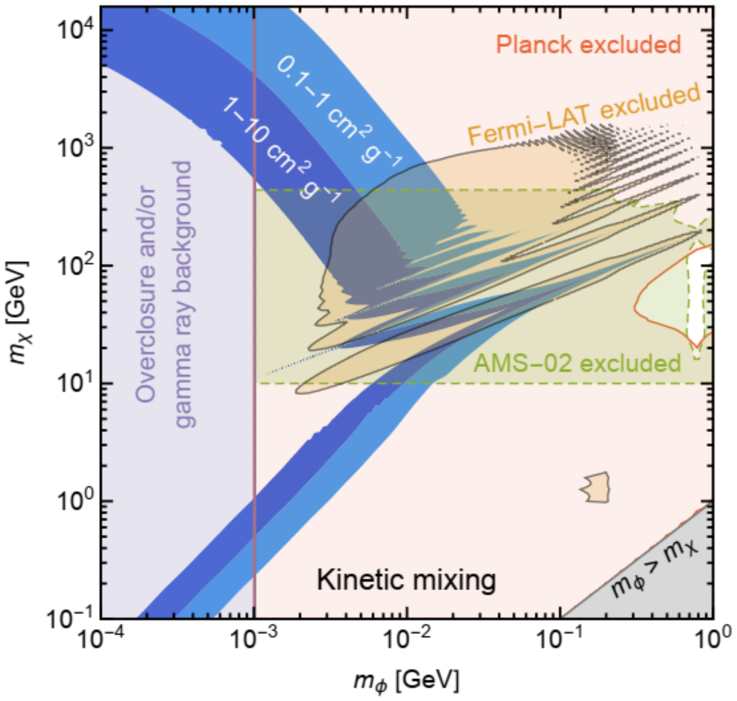
$$0.1 < \sigma/m < 10\ cm^2/g$$

Cosmological Constraint

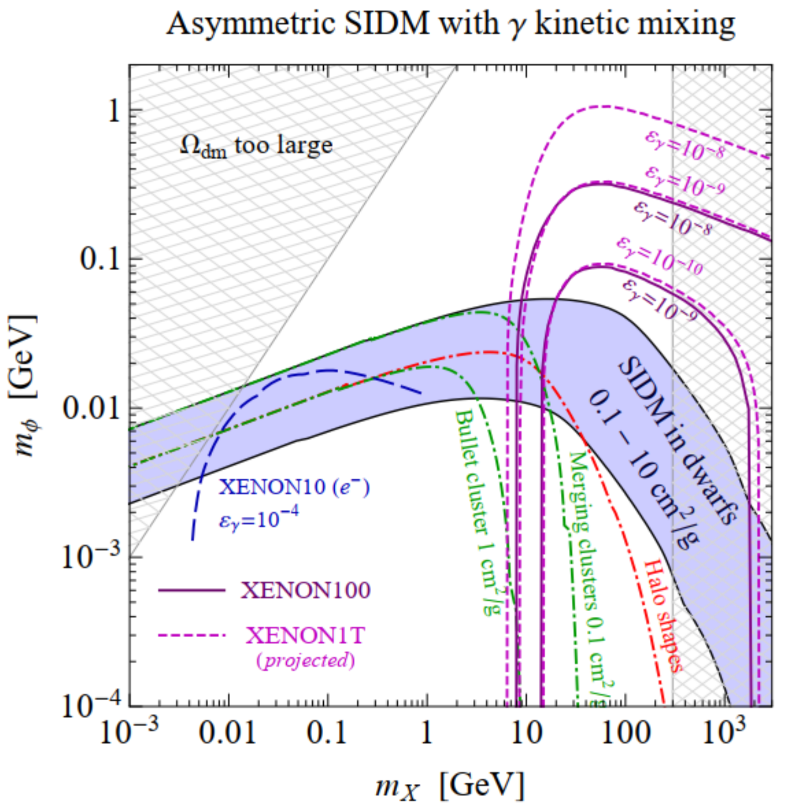
S. Tulin, H.-B. Yu, and K. M. Zurek, Phys. Rev. **D87**, 115007 (2013), 1302.3898



Tulin 2017



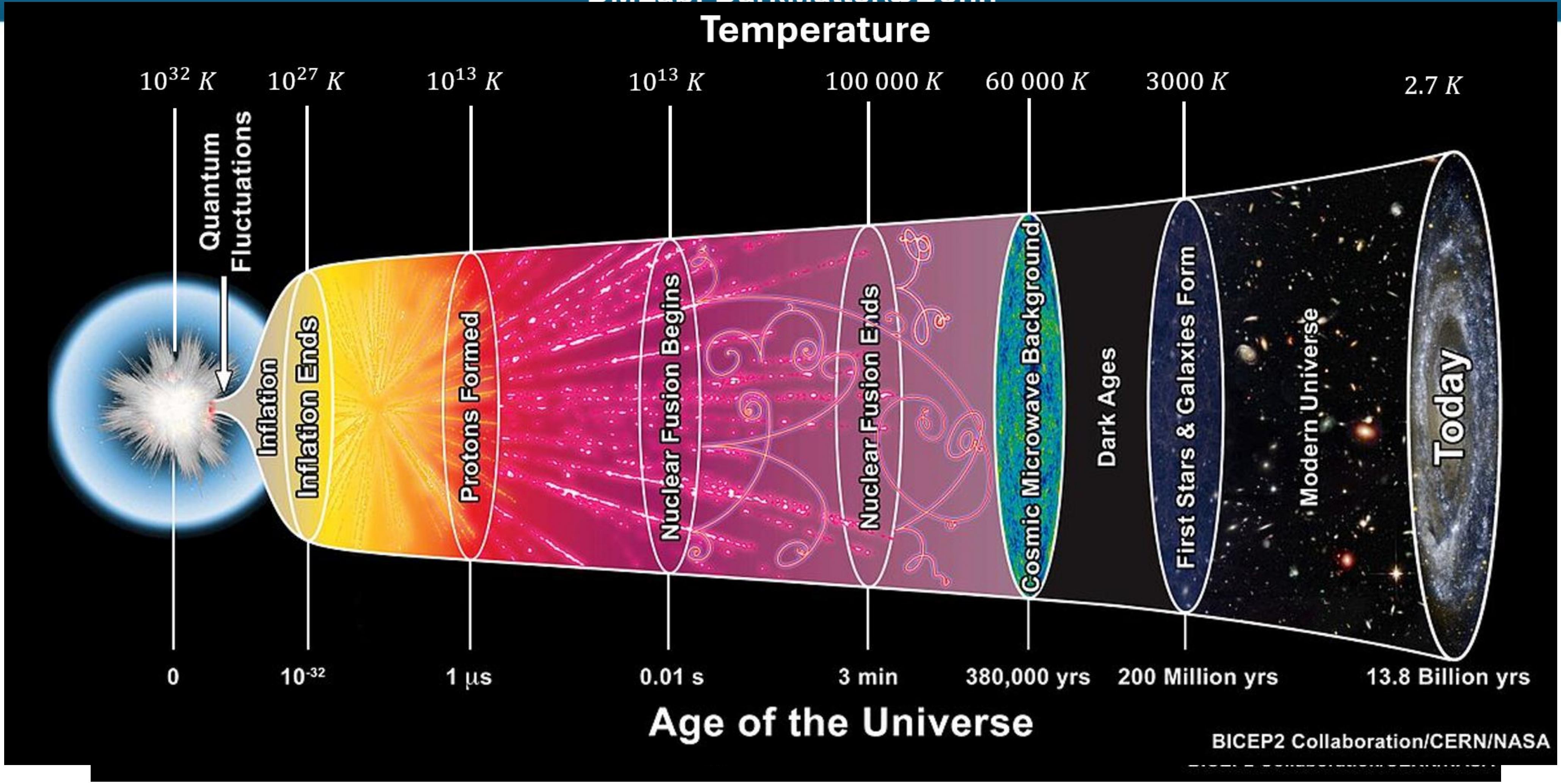
Bringmann 2017



Kaplinghat 2013

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

Cosmological Constraint



$T \ll m_\chi$

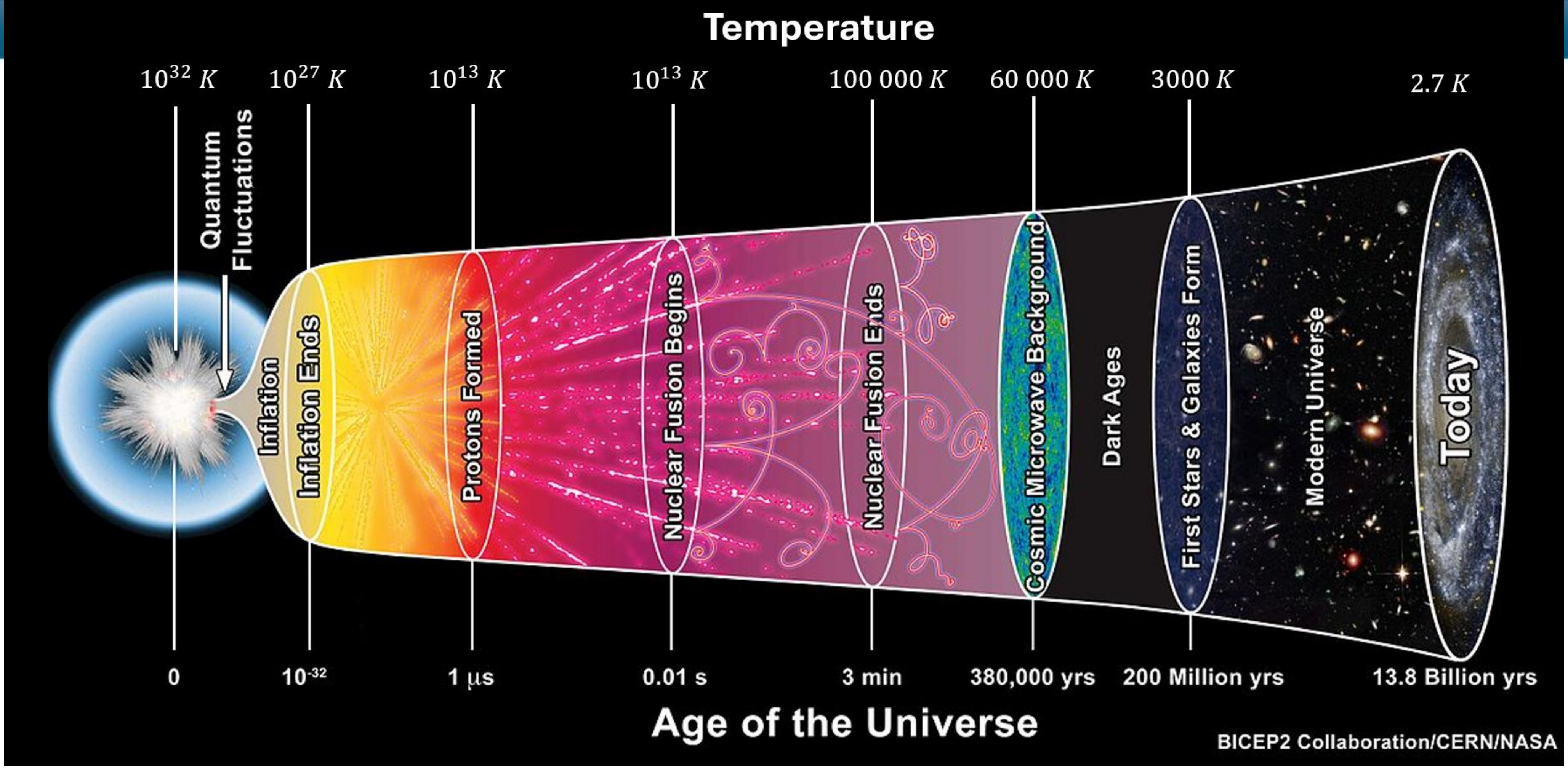
$n_\chi \approx n_\chi^{eq}$

Equilbrium with the plasma

$n_\chi^{eq} \sim e^{-m_\chi/T}$

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

$T \gg m_\chi$
freeze − out



$$\frac{dn_\chi}{dt} + 3Hn_\chi \approx 0$$

$$T \gg m_\chi$$

$$n_\chi \approx n_\chi^{eq}$$

Equilbrium with the plasma

$$n_\chi^{eq} \sim e^{-m_\chi/T}$$

$$n_\chi^{eq} \sim g\left(\frac{m_\chi T}{2\pi}\right)^{3/2} e^{-m_\chi/T}$$

$$\frac{dn_\chi}{dt} + 3Hn_\chi \approx -\sigma v\, n_\chi^2$$

$$T \ll m_\chi$$

$$\Gamma = n_\chi\, \sigma v \sim H \quad \text{freeze} - \text{out}$$

$$Y_\infty = \frac{H}{s\,\sigma v}$$

Thermal Relic Abundance

$$\chi\bar{\chi} \to U^* \to f\bar{f}$$

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

$$\sigma_{\rm ann}(s) = \kappa\,\frac{16\pi}{s\beta_\chi^2}\,\frac{(2s_V+1)}{(2s_\chi+1)^2}\,\frac{s\,\Gamma_{\chi\chi^*}(s)\,\Gamma_{\rm SM}(s)}{(s-m_V^2)^2+m_V^2\Gamma_V^2}$$

$$\Gamma_{\chi\bar{\chi}} = \varepsilon^2\,\frac{\alpha_\chi m_U}{12}\left(1-\frac{4m_\chi^2}{m_U^2}\right)^{3/2}$$

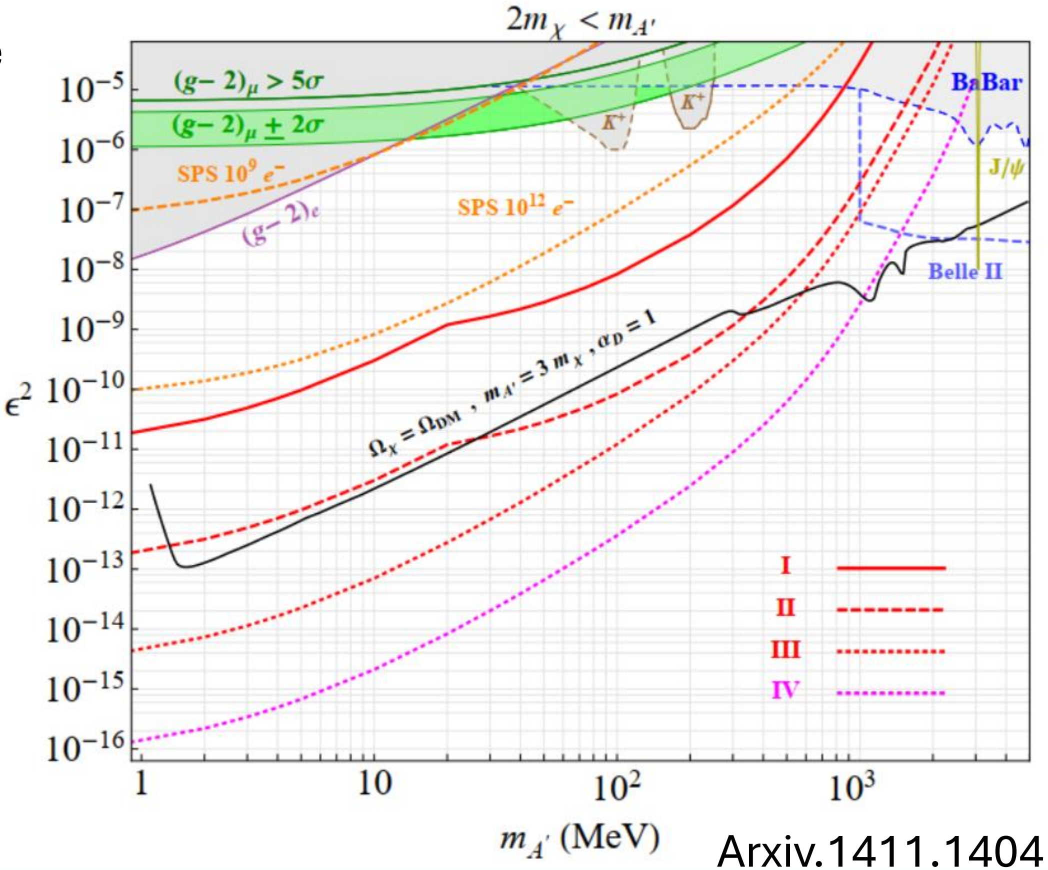
$$m_U \gg m_\chi$$

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

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

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

Black Line



Arxiv.1411.1404

Arxiv.1411.1404

PhysRevD.99.075001

Arxiv.1801.05447

Arxiv.1307.6554

Red DeliVeR

https://arxiv.org/abs/2410.00881

Plack mission CMB: arxiv.1807.06209

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

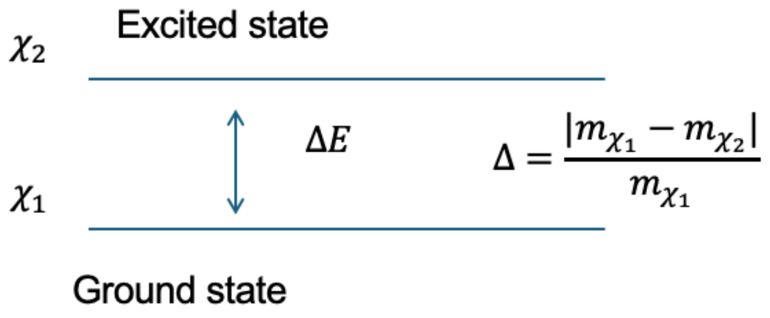
$\Omega_{DM}h^2 > 0.12$ Overproduction

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

Solve the Boltzmann Eq. for the DM relic density at freeze-out

DM: χ_1, χ_2

1. Inelastic
2. Majorana
3. Majorana Fermion
4. Dirac Fermion
5. Dirac
6. Complex Scalar
7. No DM



Mediator:

Vector

1. Dark Photon U,A'
2. B-L
3. B-3L
4. B
5. $L_\mu - L_\tau$

$$Q = y_B B - y_e L_e - y_\mu L_\mu - y_\tau L_\tau$$

y_B	y_e	y_μ	y_τ	Q	q_Q^f			
					quarks	e/ν_e	μ/ν_μ	τ/ν_τ
1	1	1	1	$B-L$	$\frac{1}{3}$	-1	-1	-1
1	0	0	3	$B-3L_\tau$	$\frac{1}{3}$	0	0	-3
1	0	0	0	B	$\frac{1}{3}$	0	0	0
0	0	-1	1	$L_\mu - L_\tau$	0	0	1	-1

Table 1. Couplings to SM fermions for the models studied in Sec. 3.

Coupling	A'	$B-L$	B	Protophol
g_X	εe	g_{B-L}	g_B	g_p
$x_{u,c,t}$	$\frac{2}{3}$	$\frac{1}{3}$	$\frac{1}{3}$	$-\frac{1}{3}$
$x_{d,s,b}$	$-\frac{1}{3}$	$\frac{1}{3}$	$\frac{1}{3}$	$\frac{2}{3}$
$x_{e,\mu,\tau}$	-1	-1	$-\frac{e^2}{(4\pi)^2}$	-1
$x_{\nu_e,\nu_\mu,\nu_\tau}$	0	-1	0	0

Red DeliVeR

https://arxiv.org/abs/2410.00881

Boltzmann Eq.

$$\frac{\mathrm{d}Y_{1,2}}{\mathrm{d}x} = \frac{s}{Hx}\Bigg[-\langle\sigma v\rangle_{12\to ff}\left(Y_1Y_2 - Y_1^{\rm eq}Y_2^{\rm eq}\right) \pm 2\,\langle\sigma v\rangle_{22\to 11}\left((Y_2)^2 - \left(Y_1\frac{Y_2^{\rm eq}}{Y_1^{\rm eq}}\right)^2\right) \pm \frac{1}{s}\left(\Gamma_{2f\to 1f} + \langle\Gamma\rangle_{2\to 1ff}\right)\left(Y_2 - Y_1\frac{Y_2^{\rm eq}}{Y_1^{\rm eq}}\right)\Bigg],$$

$$Y_i^{\rm eq} \equiv \frac{n_i^{\rm eq}}{s}, \text{ with } \begin{cases} n_i^{\rm eq} = \dfrac{3\zeta(3)}{4\pi^2}\, g_i\, T^3 & \text{for } \quad T \gg m_i\,, \\ n_i^{\rm eq} = g_i\left(\dfrac{m_i T}{2\pi}\right)^{3/2} \exp\left(-\dfrac{m_i}{T}\right) & \text{for } \quad T \ll m_i\,, \end{cases}$$

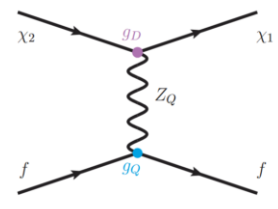
- Gondolo–Gelmini Integral for the thermal average

$$\langle\sigma v\rangle(T) = \frac{T}{64\pi^4 n_i^{\rm eq} n_j^{\rm eq}} \int_{s_{\rm min}}^{\infty} ds\, \sqrt{s}\,\hat{\sigma}(s)\, K_1(\sqrt{s}/T).$$

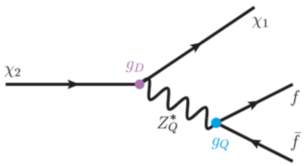
$$\Gamma(Z_Q \to f\bar{f}) = C^f\frac{\alpha_Q (q_Q^f)^2}{3} m_{Z_Q}\left(1 + 2\frac{m_f^2}{m_{Z_Q}^2}\right)\sqrt{1 - \frac{4\,m_f^2}{m_{Z_Q}^2}}\,,$$

$$\Gamma(Z_Q \to \chi_1\chi_2) = \frac{\alpha_D}{3} m_{Z_Q}\left(1 - \frac{\Delta^2}{R^2}\right)^{3/2}\left(1 + \frac{(\Delta+2)^2}{2R^2}\right)\sqrt{1 - \frac{(\Delta+2)^2}{R^2}}$$

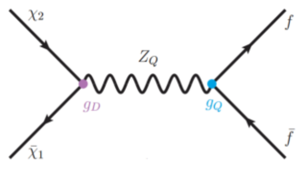
$$\Gamma(\chi_2 \to \chi_1 \bar{f} f) \simeq \frac{4\,\alpha_Q\,\alpha_D\,\Delta^5\, m_{Z_Q}}{15\pi R^5}$$



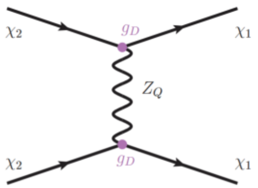
c) $\chi_2 f \to \chi_1 f$



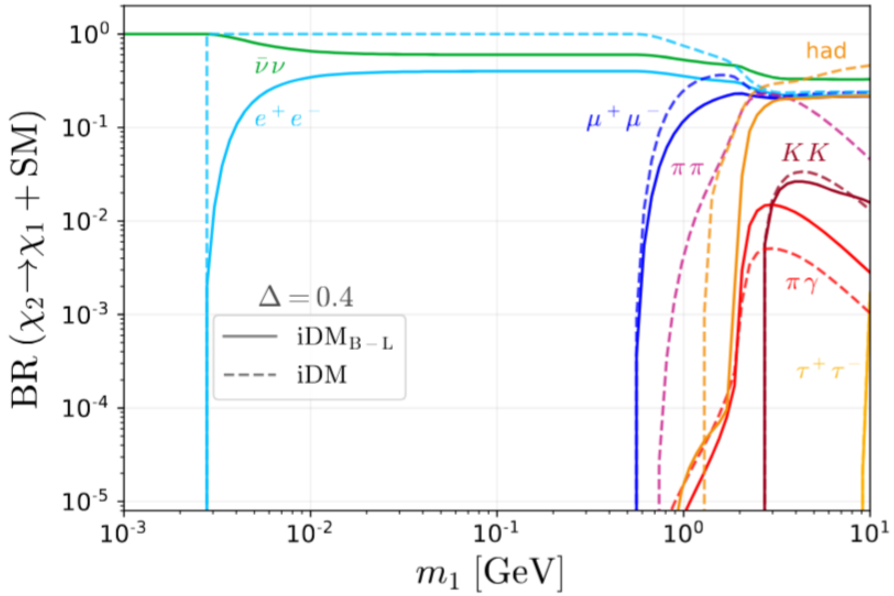
d) $\chi_2 \to \chi_1 + \mathrm{SM}$



a) $\chi_1\chi_2 \to \mathrm{SM}$

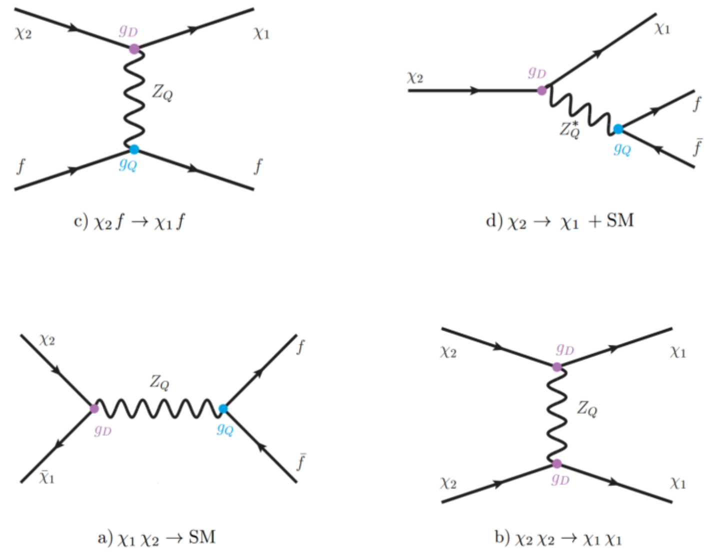


b) $\chi_2\chi_2 \to \chi_1\chi_1$



Red DeliVeR

https://arxiv.org/abs/2410.00881



DM relic density at freeze-out

$$Y_{1,2} = \frac{n_{1,2}}{s}$$

$$\frac{\mathrm{d}Y_{1,2}}{\mathrm{d}x} = \frac{s}{Hx}\Bigg[-\langle\sigma v\rangle_{12\to ff}\left(Y_1Y_2 - Y_1^{\rm eq}Y_2^{\rm eq}\right) \pm 2\,\langle\sigma v\rangle_{22\to 11}\left((Y_2)^2 - \left(Y_1\frac{Y_2^{\rm eq}}{Y_1^{\rm eq}}\right)^2\right) \pm \frac{1}{s}\left(\Gamma_{2f\to 1f} + \langle\Gamma\rangle_{2\to 1ff}\right)\left(Y_2 - Y_1\frac{Y_2^{\rm eq}}{Y_1^{\rm eq}}\right)\Bigg],$$

Since scatterings and decays conserve the total number of X_1 and X_2, the only process that survives is the coannihilation channel

$$n = n_1 + n_2 \qquad Y^{eff} = \frac{n}{s}$$

$$x = m/T \ll 1 \qquad \Gamma \ll H \to Y_\infty$$

$$\frac{\mathrm{d}Y^{\rm eff}}{\mathrm{d}x} = \frac{s}{Hx}\left[-2\,\langle\sigma v\rangle_{\rm eff}\left((Y^{\rm eff})^2 - (Y^{\rm eq})^2\right)\right],$$

$$\Omega_\chi h^2 = \frac{m_\chi\, s_0}{\rho_c/h^2}\,Y_\infty,$$

$$\langle\sigma v\rangle_{\rm eff} = \langle\sigma v\rangle_{12\to ff}\frac{n_1^{\rm eq}n_2^{\rm eq}}{(n^{\rm eq})^2},$$

we evaluate the full thermal average numerically using Bessel functions.

$$\sigma_{12ff}(s) = \frac{12\pi s^2}{(s-m_{Z_Q}^2)^2 + m_{Z_Q}^2\Gamma_{Z_Q}^2}\,\frac{\Gamma_{Z_Q\to \mathrm{SM}}(s)\,\Gamma_{Z_Q\to\chi_1\chi_2}(s)}{\lambda(s, m_1^2, m_2^2)}$$

$$\chi\bar{\chi} \to U^* \to f\bar{f}$$

- NRL

$$s \approx (m_1+m_2)^2 + \mu(m_1+m_2)\,v_{\rm rel}^2,$$

- Maxwell-Boltzmann Dist.

$$n_i^{\rm eq} \simeq g_i\left(\frac{m_iT}{2\pi}\right)^{3/2} e^{-m_i/T}$$

Arxiv.1411.1404 Arxiv.1801.05447

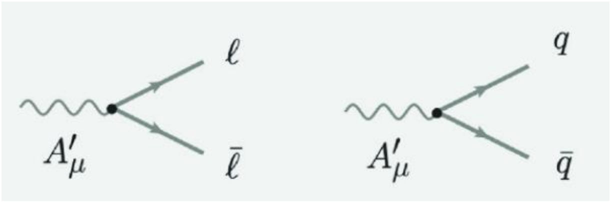
PhysRevD.99.075001 Arxiv.1307.6554

$U \to f\bar{f}$

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

Visible decay

$$m_U > 2m_f$$

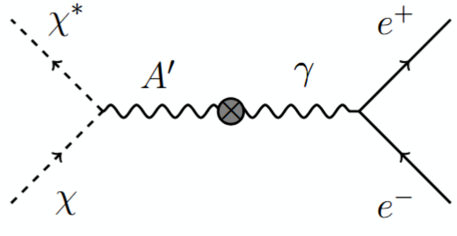


$\chi\bar{\chi} \to U^* \to f\bar{f}$ Direct Annihilation

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

s – channel

$$m_U > 2m_X$$



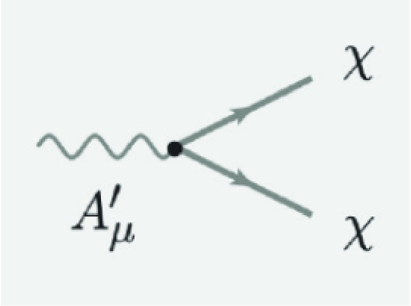
$U \to X_1X_2$ Direct Annihilation

$$\Gamma(U \to X_1X_2) = \frac{\alpha_\chi m_U}{3}\left(1 - \Delta^2\frac{m_X^2}{m_U^2}\right)^{\frac{3}{2}}\left(1 + \frac{(\Delta+2)^2}{2m_U^2} m_X^2\right)\left(1 - \frac{(\Delta+2)^2}{m_U^2} m_X^2\right)^{1/2}$$

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

$$m_U > 2m_X$$

Invisible decay

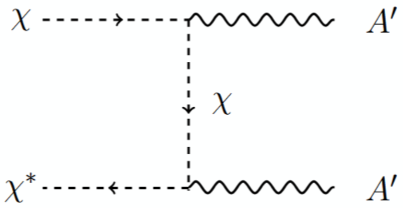


$X_1X_2 \to UU$ "secluded“ regime

$$\sigma v\,(XX \to UU) \sim \frac{\pi\alpha_X^2}{m_X^2}\left(1 - \frac{m_X^2}{m_X^2}\right)^{1/2}$$

t – channel

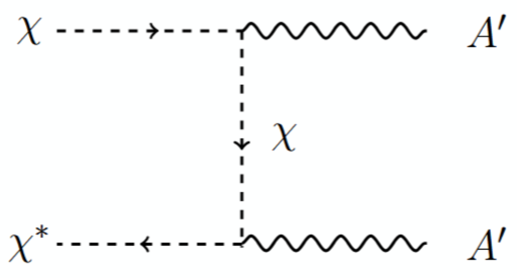
$$m_U < 2m_X$$



Dominant Channels

$R < 2$ 2 $R > 2$ $R = m_U/m_X$

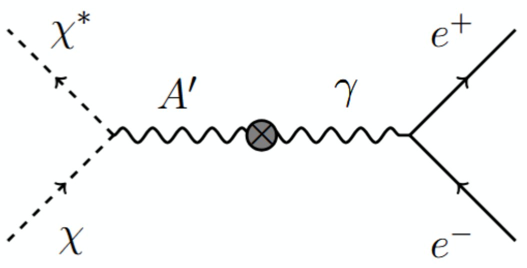
t − channel



$m_U < 2m_X$

- Cross-Section is independent of ε^2

s − channel annihilation



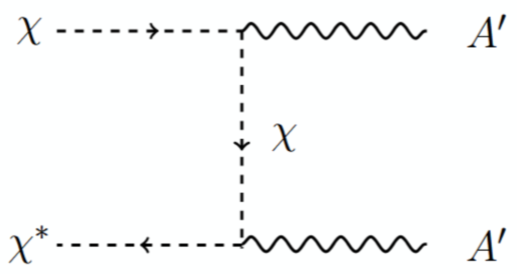
$m_U > 2m_X$

- Cross-Section is dependent of ε^2

Dominant Channels

$R < 2$ 2 $R > 2$ $R = m_U/m_X$

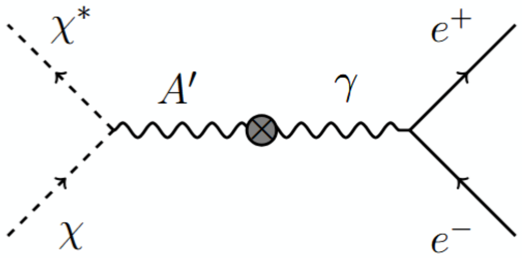
t − channel



$m_U < 2m_X$

- Cross-Section is independent of ε^2

s − channel annihilation



$m_U > 2m_X$

- Cross-Section is dependent of ε^2

Red DeliVeR

https://arxiv.org/pdf/2011.04679

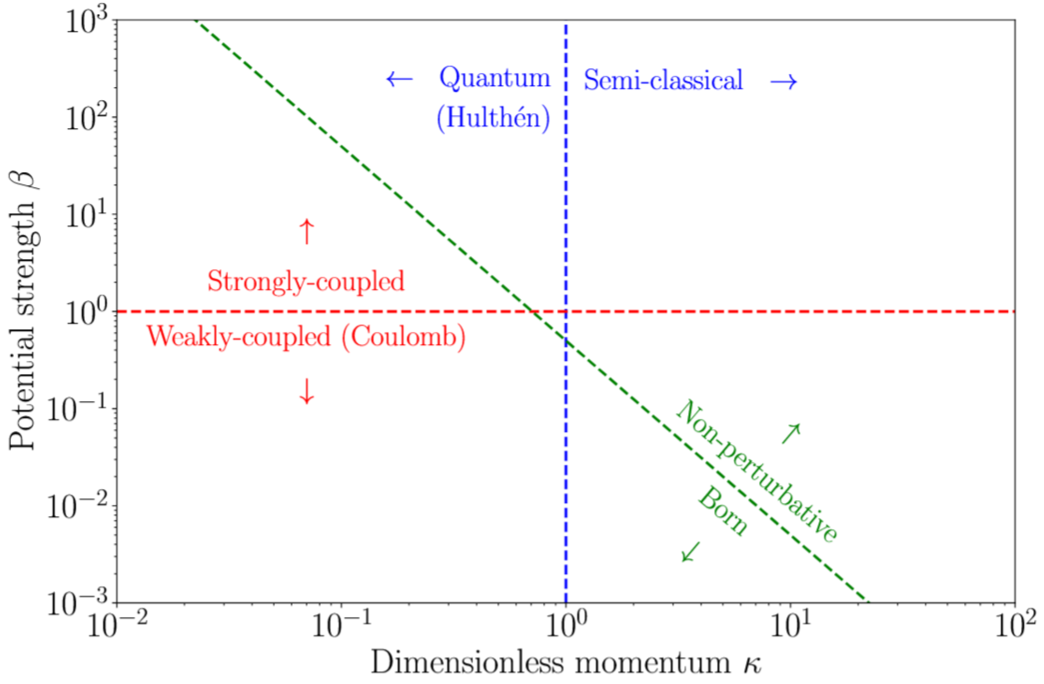
CLASSICS

CalcuLAtionS of Self Interaction Cross Sections

The Semi-Classical Regime for Dark Matter Self-Interactions

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

$$\kappa = \frac{m_\chi\, v}{2\, m_\phi} \qquad \beta = \frac{2\, \alpha_\chi\, m_\phi}{m_\chi\, v\text{^}2}$$



System	$\langle v \rangle$	β_0	κ_0	$\overline{\sigma_T^{att.}}/m_\chi$ [cm^2 g^{-1}]	$\overline{\sigma_T^{rep.}}/m_\chi$ [cm^2 g^{-1}]	$\overline{\sigma_V^{att.}}/m_\chi$ [cm^2 g^{-1}]	$\overline{\sigma_V^{rep.}}/m_\chi$ [cm^2 g^{-1}]
Dwarf galaxy	50	2890	2.34	10.9	9.0	11.7	13.6
Galaxy	250	116	11.7	4.3	2.6	3.5	3.8
Galaxy group	1150	5.46	53.8	0.66	0.36	0.64	0.54
Galaxy cluster	1900	2.00	88.9	0.20	0.14	0.23	0.19

TABLE I. Velocity averaged self-interaction cross sections for $m_\chi = 190\,\text{GeV}$, $m_\phi = 3\,\text{MeV}$, $\alpha_\chi = 0.5$ at different astrophysical scales.

CLASSICS

https://arxiv.org/pdf/2011.04679

The Semi-Classical Regime for Dark Matter Self-Interactions

Potential

1. Attractive (Resonances)
1. Repulsive (Soft)

DM Particle

1. Scalar
2. Fermion
3. Vector
4. Distinguishable particles

$$\sigma_T^{\text{att.}} = \frac{\pi}{m_\phi^2} \times \begin{cases} 2\beta^2 \zeta_{1/2}(\kappa, \beta) & \beta \leq 0.2\,, \\ 2\beta^2 \zeta_{1/2}(\kappa, \beta)\, e^{0.64(\beta - 0.2)} & 0.2 < \beta \leq 1\,, \\ 4.7 \log(\beta + 0.82) & 1 < \beta < 50\,, \\ 2 \log \beta (\log \log \beta + 1) & \beta \geq 50\,, \end{cases}$$

$$\sigma_T^{\text{rep.}} = \frac{\pi}{m_\phi^2} \times \begin{cases} 2\beta^2 \zeta_{1/2}(\kappa, \beta) & \beta \leq 0.2\,, \\ 2\beta^2 \zeta_{1/2}(\kappa, \beta)\, e^{-0.53(\beta - 0.2)} & 0.2 < \beta \leq 1\,, \\ 2.9 \log(\beta + 0.47) & 1 < \beta < 50\,, \\ \lambda_T (\log 2\beta - \log \log 2\beta)^2 & \beta \geq 50\,, \end{cases}$$

$$\sigma_V \to \begin{cases} \sigma_V^{\text{even}} & \text{scalar DM}\,, \\ \frac{1}{4}\sigma_V^{\text{even}} + \frac{3}{4}\sigma_V^{\text{odd}} & \text{fermion DM}\,, \\ \frac{2}{3}\sigma_V^{\text{even}} + \frac{1}{3}\sigma_V^{\text{odd}} & \text{vector DM}\,. \end{cases}$$

$$\kappa = \frac{m_\chi\, v}{2\, m_\phi} \qquad \beta = \frac{2\, \alpha_\chi\, m_\phi}{m_\chi\, v\text{^}2}$$

https://arxiv.org/pdf/2011.04679

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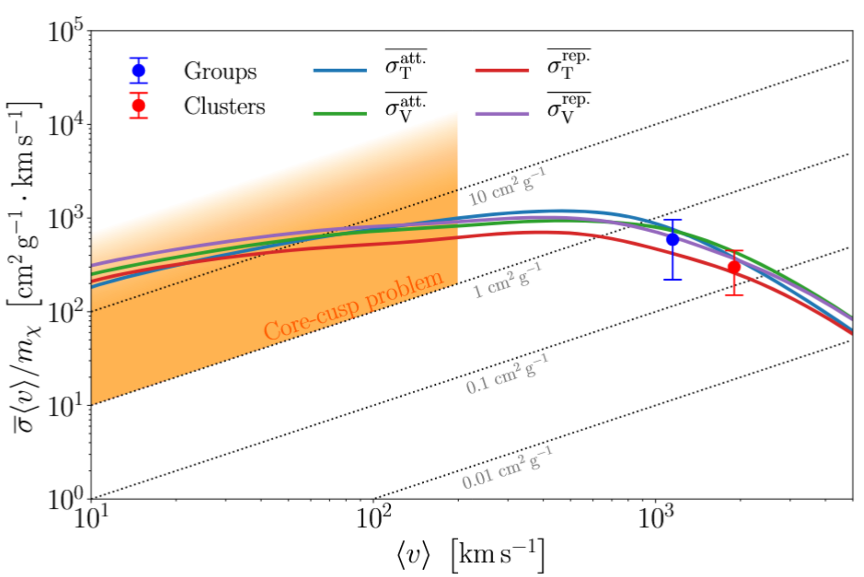
$$\langle v \rangle = \frac{4}{\sqrt{\pi}} v_0$$

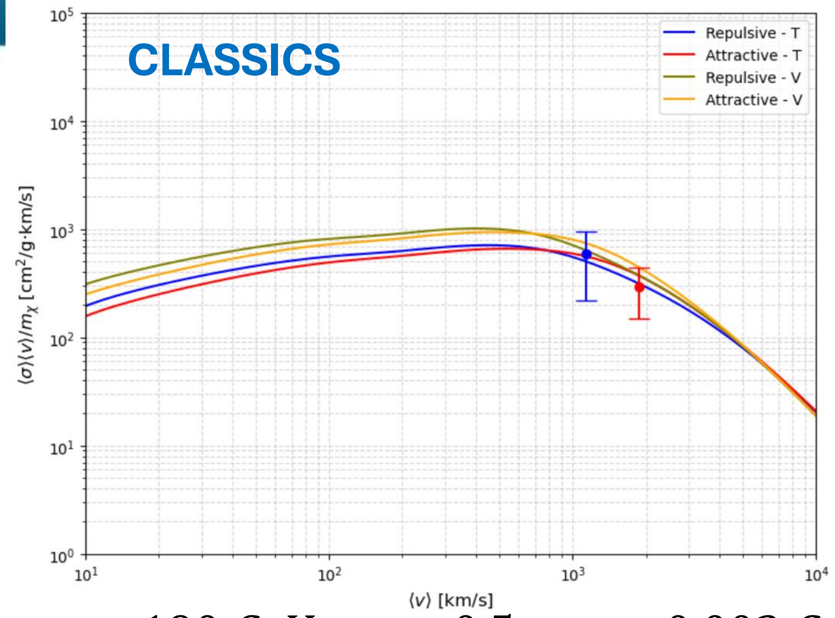
$$\overline{\sigma_T} = \frac{\langle \sigma(v)\, v^2 \rangle}{16\sqrt{2}\, v_o^2/\pi}$$

$$\overline{\sigma_T} = \frac{1}{\sqrt{2}} \frac{\langle \sigma(v)\, v^2 \rangle}{\langle v \rangle^2}$$

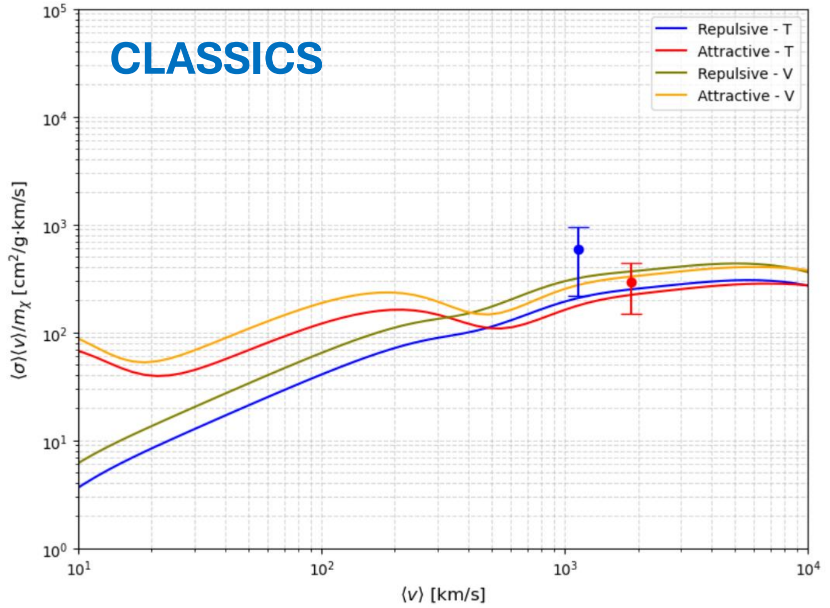
$$\overline{\sigma_V} = \frac{\langle \sigma(v)\, v^3 \rangle}{24\ v_0^3/\sqrt{\pi}}$$

$$\overline{\sigma_V} = \frac{8}{3\pi} \frac{\langle \sigma(v)\, v^2 \rangle}{\langle v \rangle^3}$$

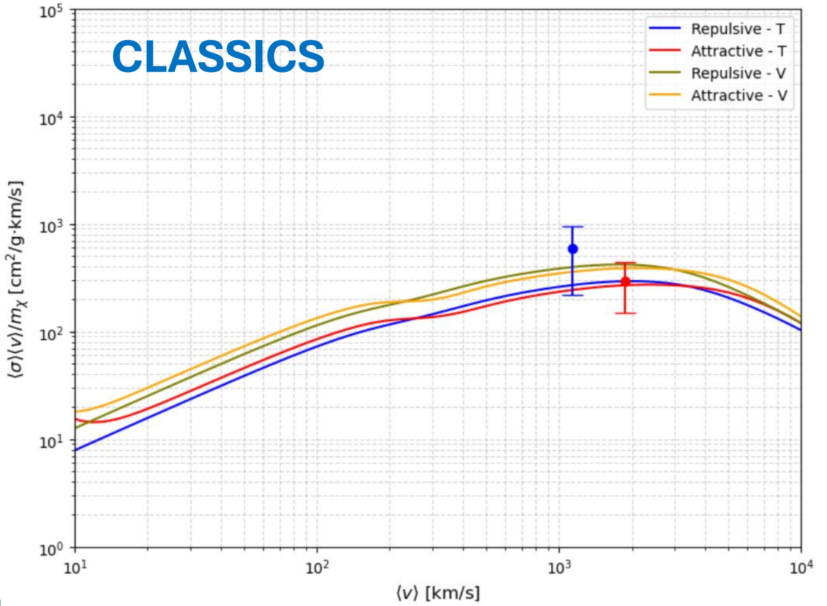




$m_\chi = 190\ GeV, \alpha_\chi = 0.5, m_U = 0.003\ GeV$



$m_\chi = 20\ GeV, \alpha_\chi = 0.5, m_U = 0.05 GeV$



$m_\chi = 20\ GeV, \alpha_\chi = 0.1, m_U = 0.03 GeV$

https://arxiv.org/pdf/2011.04679

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

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

$$\frac{dN^{sumU}}{dM} = \sum_{h=1}^{8} \frac{dN_h^{U\to e^+e^-}}{dM}$$

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

2) Calculate the sum of all SM contributions and 'dark matter' (DM) contributions :

$$\frac{dN^{total}}{dM} = \frac{dN^{sumSM}}{dM} + \frac{dN^{sumU}}{dM} = \frac{dN^{sumSM}}{dM} + \varepsilon^2 \frac{dN^{sumU}_{\varepsilon^2=1}}{dM} \quad (2)$$

3) Obtain constraints by requesting that dN^{total}/dM (SM+DM) cannot exceed the sum of SM channels (i.e. exp. data!) by more than a factor C_U in each bin dm, i.e.

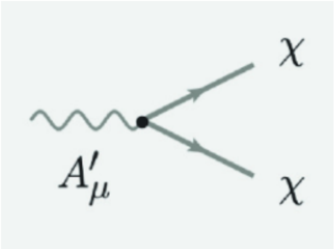
$$\frac{dN^{total}}{dM} = (1 + C_U) \frac{dN^{sumSM}}{dM}$$

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

4) Calculate $\varepsilon^2(m_U)$ by assuming C_U : e.g. C_U =0.1 → 10% DM extra yield to the SM yield

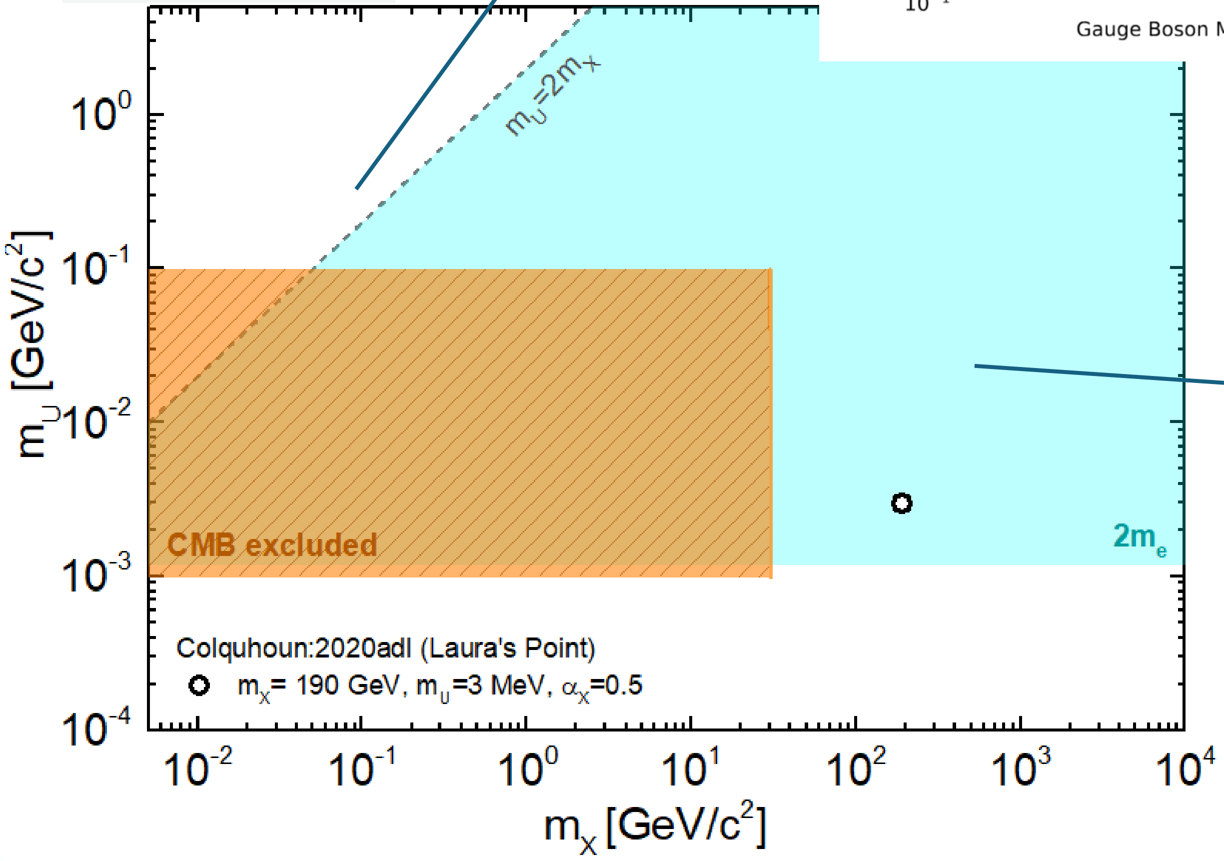
$$\varepsilon^2(m_U) = C_U \cdot \left(\frac{dN^{sumSM}}{dM}\right) \Big/ \left(\frac{dN^{sumU}_{\varepsilon^2=1}}{dM}\right)$$

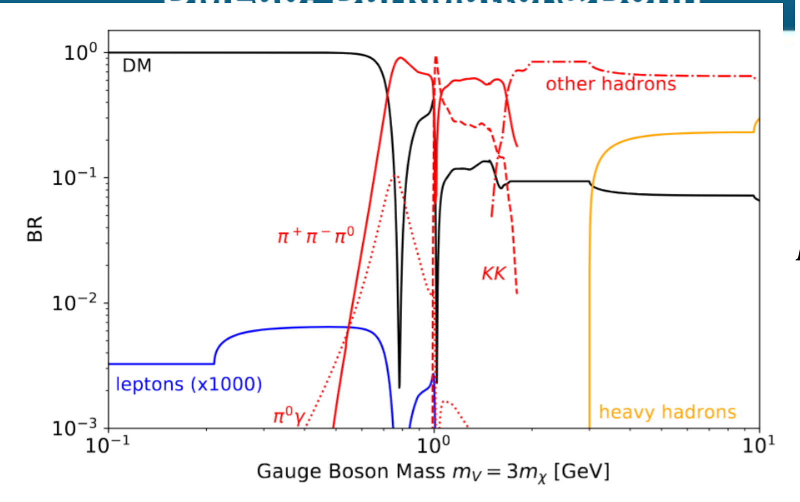
$m_U(m_X)$



$m_U > 2m_X$

Invisible decay





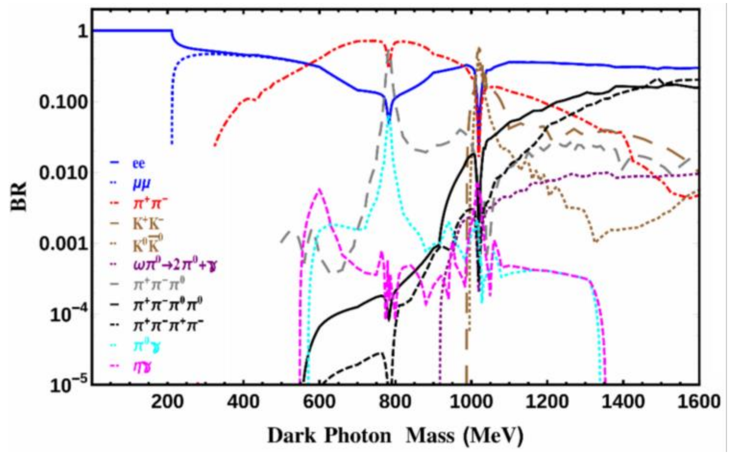
$$\Gamma_{\chi\chi^*} = \kappa \frac{\alpha_\chi m_V}{12}\left(1 - \frac{4m_\chi^2}{m_V^2}\right)^{3/2}$$

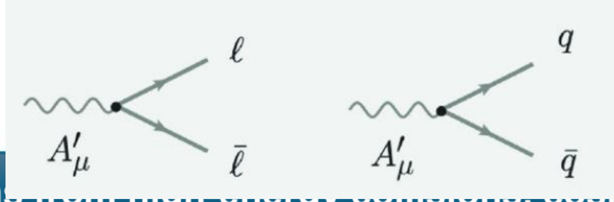
$$Br(U \to l^+l^-) \ll Br(U \to DM)$$

$$Br(U \to l^+l^-) = \frac{\Gamma_{l^+l^-}}{\Gamma_{l^+l^-} + \Gamma_{\mu^+\mu^-} + \Gamma_{hadrons} + \boldsymbol{\Gamma_{DM}}}$$

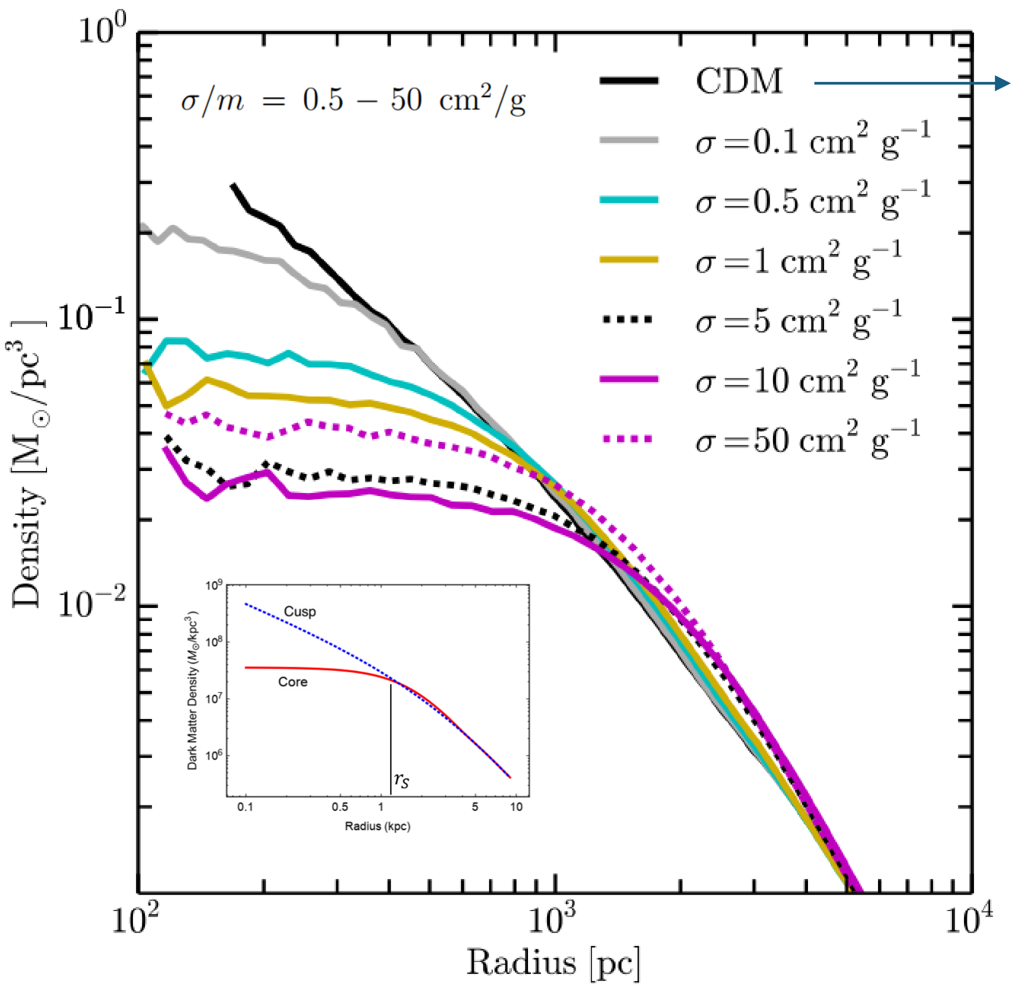
$m_U > 2m_f$

Visible decay





Density profiles for halo (N-body simulations)



No interactions

SIDM resolves dwarf-scale anomalies

Positive observations	σ/m	v_{rel}	Observation	Refs.
Cores in spiral galaxies (dwarf/LSB galaxies)	$\gtrsim 1\ cm^2/g$	$30 - 200\ km/s$	Rotation curves	[102, 116]
Too-big-to-fail problem				
Milky Way	$\gtrsim 0.6\ cm^2/g$	$50\ km/s$	Stellar dispersion	[110]
Local Group	$\gtrsim 0.5\ cm^2/g$	$50\ km/s$	Stellar dispersion	[111]
Cores in clusters	$\sim 0.1\ cm^2/g$	$1500\ km/s$	Stellar dispersion, lensing	[116, 126]
Abell 3827 subhalo merger	$\sim 1.5\ cm^2/g$	$1500\ km/s$	DM-galaxy offset	[127]
Abell 520 cluster merger	$\sim 1\ cm^2/g$	$2000 - 3000\ km/s$	DM-galaxy offset	[128, 129, 130]
Constraints				
Halo shapes/ellipticity	$\lesssim 1\ cm^2/g$	$1300\ km/s$	Cluster lensing surveys	[95]
Substructure mergers	$\lesssim 2\ cm^2/g$	$\sim 500 - 4000\ km/s$	DM-galaxy offset	[115, 131]
Merging clusters	$\lesssim$ few cm^2/g	$2000 - 4000\ km/s$	Post-merger halo survival (Scattering depth $\tau < 1$)	Table II
Bullet Cluster	$\lesssim 0.7\ cm^2/g$	$4000\ km/s$	Mass-to-light ratio	[106]

TABLE I: Summary of positive observations and constraints on self-interaction cross section per DM mass.

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

Cosmological Constraint

$$\frac{\sigma}{m_X} \sim 2\ barns/GeV$$

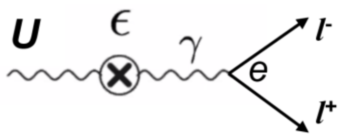
Self-Interacting Dark Matter (U, V, A', ϕ)

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

Dark Mediator U | Interaction U-SM | Interaction U-DM | DM particle

$\boldsymbol{\varepsilon}$ ➡ **Kinetic mixing parameter**

$\boldsymbol{m_U}$ ➡ **Dark photon mass**



ε²=α'/α

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

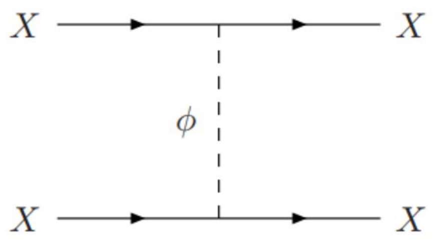
Arxiv.1308.0618

$$+\, V(r) = \pm \frac{\alpha_X}{r} e^{-m_U r}$$

+ → repulsive

- → attractive

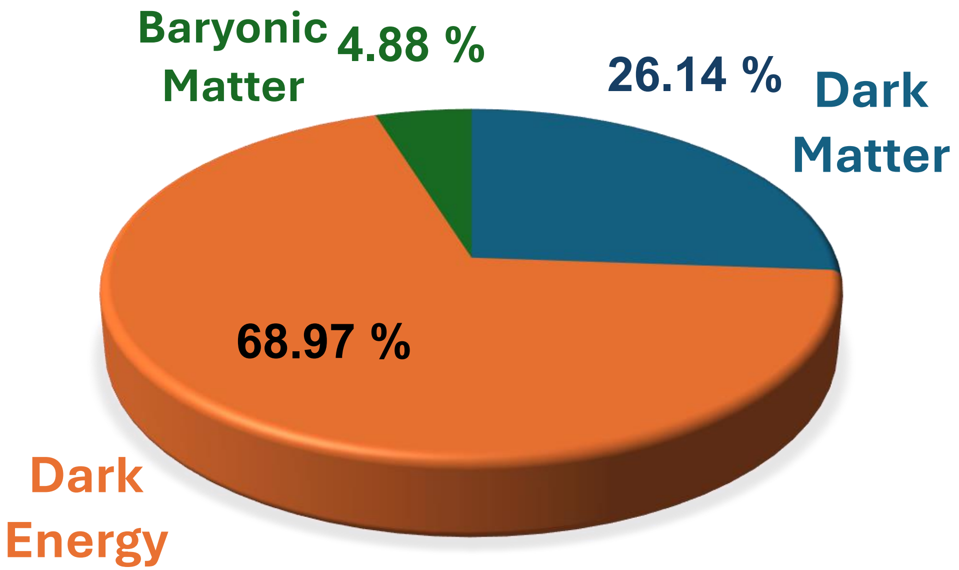
scalar φ case, DM scattering is purely attractive.
vector φ case, *XX* or *X¯X¯* scattering is repulsive, while *XX¯* is attractive



DM self-interactions

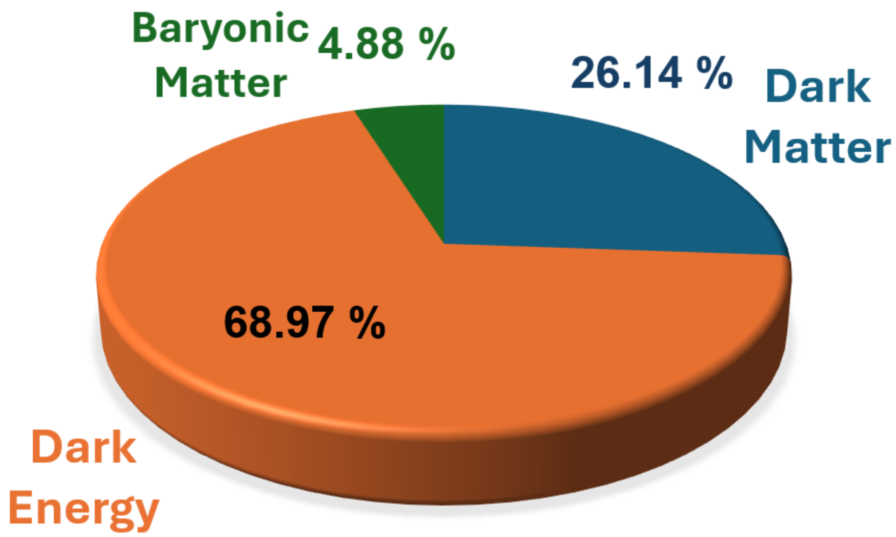
Structure of the Universe

Data from Planck 2028 results (Arxiv: 1807.06209)

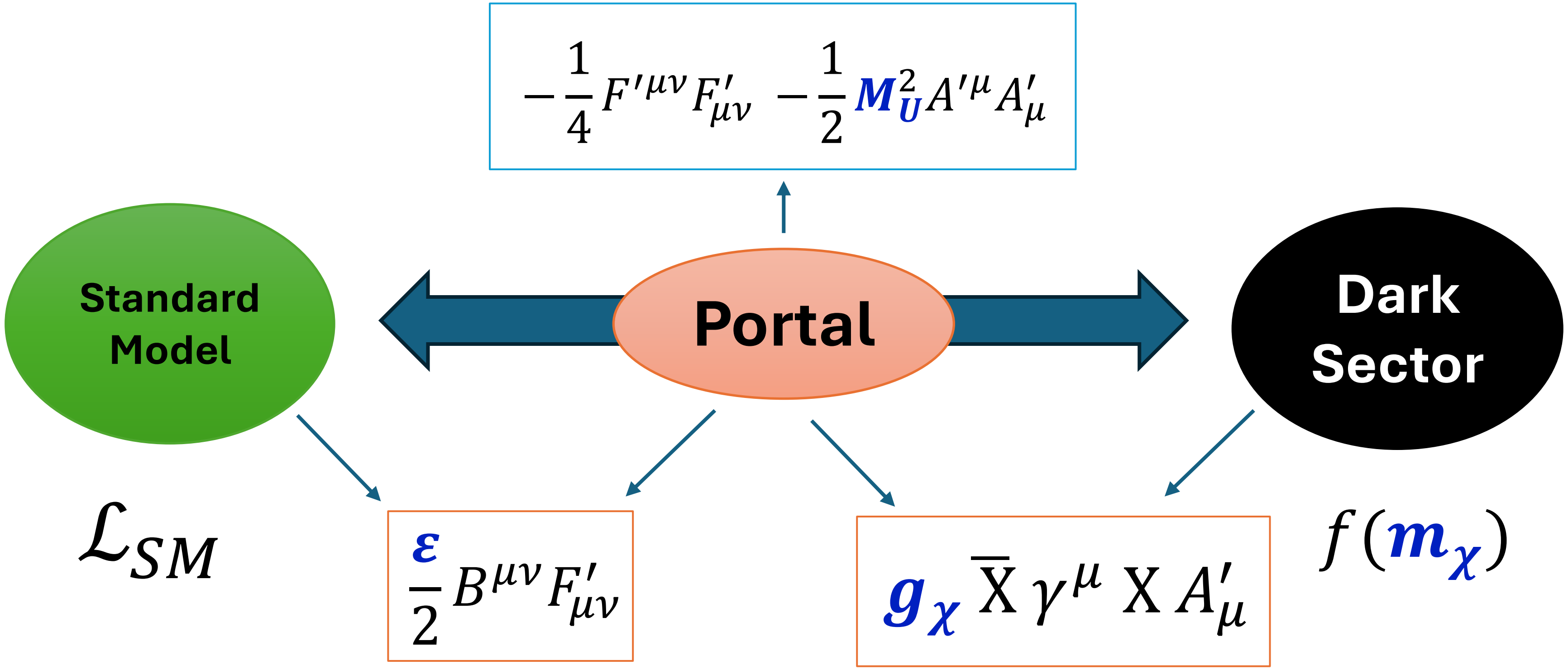


1933: F. Zwicky: observation of the Coma galaxy cluster -> Extra mass

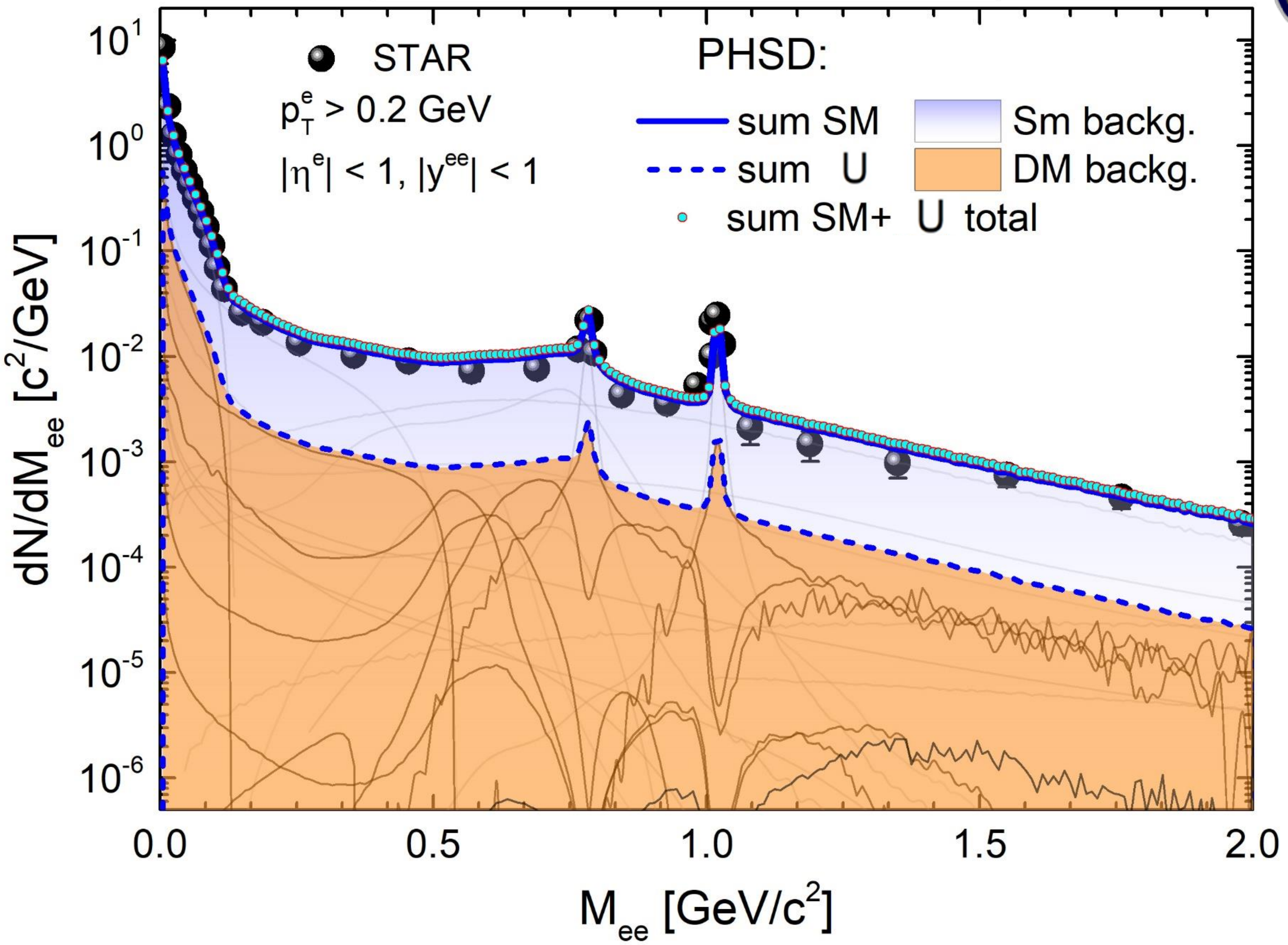
- Dark matter (DM) ~26%
- DM detected by astrophysical observations based on gravitational effects:



Dark Matter Detection

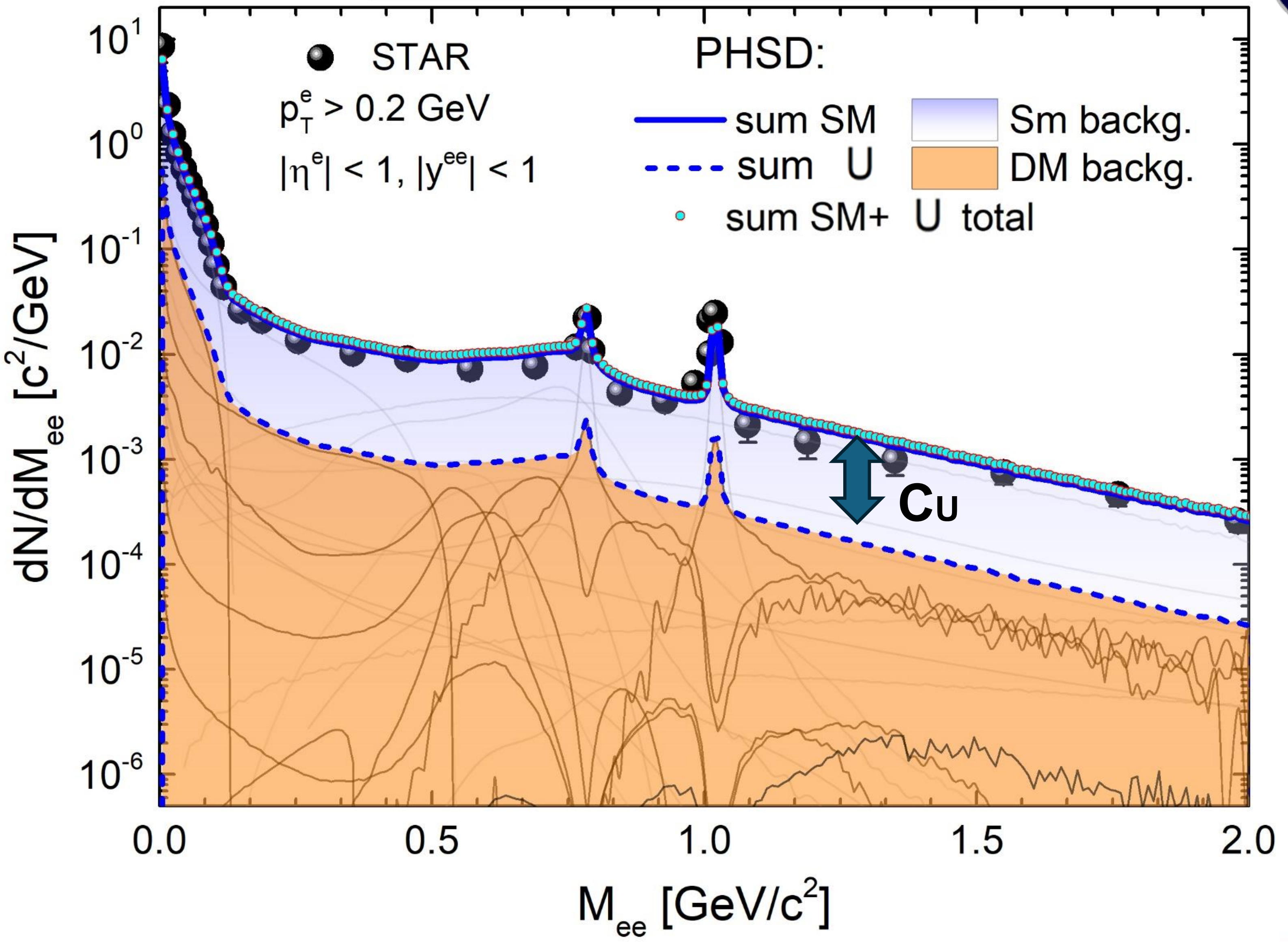


Dilepton mass spectra Au+Au, 200 GeV, min-bias



Dilepton mass spectra

Au+Au, 200 GeV, min-bias



PHSD
$\varepsilon^2(m_U)$

Cosmological Constraints

$\{\alpha_X, m_X, \varepsilon^2, m_U\}$

- Thermal Relic Abundance

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

Arxiv.1411.1404

$s - \text{channel}$

Astrophysical Constraints

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

- SIDM constraints (Core-Cusp P.)

Arxiv.1302.3898

Red DeliVeR

https://arxiv.org/abs/2410.00881

Boltzmann Eq.

$$\frac{\mathrm{d}Y_{1,2}}{\mathrm{d}x} = \frac{s}{Hx}\Big[-\langle\sigma v\rangle_{12\to ff}\left(Y_1Y_2 - Y_1^{\rm eq}Y_2^{\rm eq}\right) \pm 2\,\langle\sigma v\rangle_{22\to 11}\left((Y_2)^2 - \left(Y_1\frac{Y_2^{\rm eq}}{Y_1^{\rm eq}}\right)^2\right) \pm \frac{1}{s}\left(\Gamma_{2f\to 1f} + \langle\Gamma\rangle_{2\to 1ff}\right)\left(Y_2 - Y_1\frac{Y_2^{\rm eq}}{Y_1^{\rm eq}}\right)\Big],$$

$$Y_i^{\rm eq} \equiv \frac{n_i^{\rm eq}}{s}\,,\ \text{with}\ \begin{cases} n_i^{\rm eq} = \dfrac{3\zeta(3)}{4\pi^2}\,g_i\,T^3 & \text{for}\quad T \gg m_i\,,\\[2mm] n_i^{\rm eq} = g_i\left(\dfrac{m_i T}{2\pi}\right)^{3/2}\exp\left(-\dfrac{m_i}{T}\right) & \text{for}\quad T \ll m_i\,,\end{cases}$$

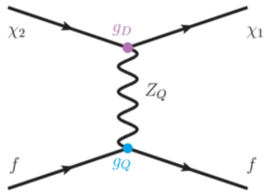
- Gondolo–Gelmini Integral for the thermal average

$$\langle\sigma v\rangle(T) = \frac{T}{64\pi^4 n_i^{\rm eq} n_j^{\rm eq}}\int_{s_{\rm min}}^{\infty} ds\,\sqrt{s}\,\hat\sigma(s)\,K_1(\sqrt{s}/T).$$

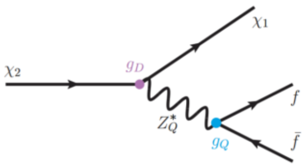
$$\Gamma(Z_Q\to f\bar f) = C^f\frac{\alpha_Q (q_Q^f)^2}{3} m_{Z_Q}\left(1 + 2\frac{m_f^2}{m_{Z_Q}^2}\right)\sqrt{1 - \frac{4\,m_f^2}{m_{Z_Q}^2}}\,,$$

$$\Gamma(Z_Q\to\chi_1\chi_2) = \frac{\alpha_D}{3} m_{Z_Q}\left(1 - \frac{\Delta^2}{R^2}\right)^{3/2}\left(1 + \frac{(\Delta+2)^2}{2R^2}\right)\sqrt{1 - \frac{(\Delta+2)^2}{R^2}}$$

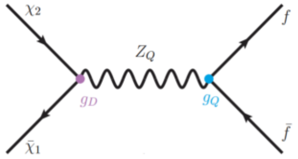
$$\Gamma(\chi_2\to\chi_1\bar f f) \simeq \frac{4\,\alpha_Q\,\alpha_D\,\Delta^5\,m_{Z_Q}}{15\pi R^5}$$



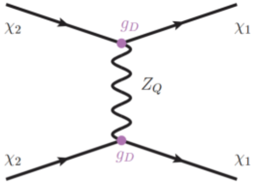
c) $\chi_2 f \to \chi_1 f$



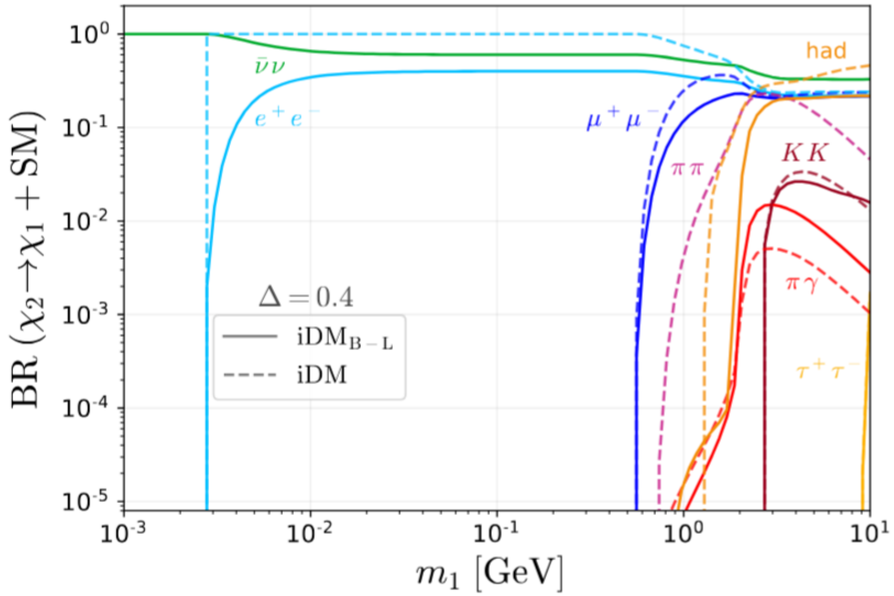
d) $\chi_2 \to \chi_1 + \mathrm{SM}$



a) $\chi_1\chi_2 \to \mathrm{SM}$



b) $\chi_2\chi_2 \to \chi_1\chi_1$



Red DeliVeR

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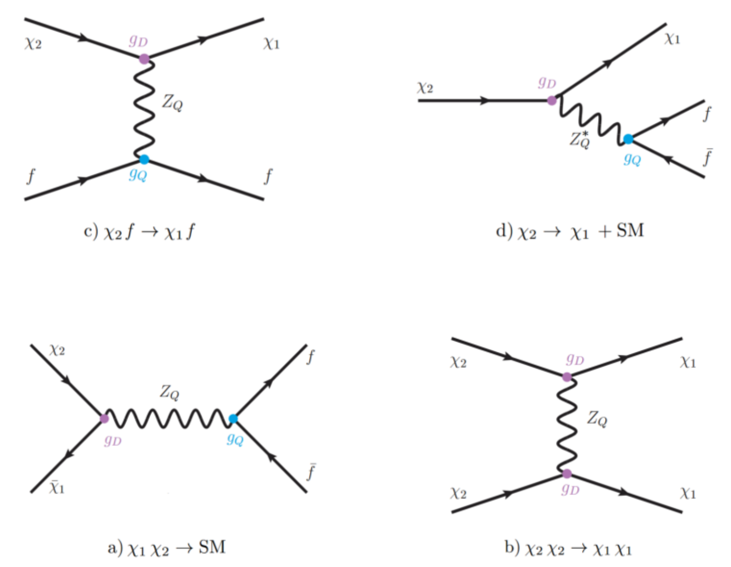


DM relic density at freeze-out

$$Y_{1,2} = \frac{n_{1,2}}{s}$$

$$\frac{\mathrm{d}Y_{1,2}}{\mathrm{d}x} = \frac{s}{Hx}\Bigg[-\langle\sigma v\rangle_{12\to ff}\left(Y_1Y_2 - Y_1^{\mathrm{eq}}Y_2^{\mathrm{eq}}\right) \pm 2\langle\sigma v\rangle_{22\to 11}\left((Y_2)^2 - \left(Y_1\frac{Y_2^{\mathrm{eq}}}{Y_1^{\mathrm{eq}}}\right)^2\right) \pm \frac{1}{s}\left(\Gamma_{2f\to 1f} + \langle\Gamma\rangle_{2\to 1ff}\right)\left(Y_2 - Y_1\frac{Y_2^{\mathrm{eq}}}{Y_1^{\mathrm{eq}}}\right)\Bigg],$$

Since scatterings and decays conserve the total number of X_1 and X_2, the only process that survives is the coannihilation channel

$$n = n_1 + n_2 \qquad Y^{eff} = \frac{n}{s}$$

$$x = m/T \ll 1 \qquad \Gamma \ll H \;\to Y_\infty$$

$$\frac{\mathrm{d}Y^{\mathrm{eff}}}{\mathrm{d}x} = \frac{s}{Hx}\left[-2\langle\sigma v\rangle_{\mathrm{eff}}\left((Y^{\mathrm{eff}})^2 - (Y^{\mathrm{eq}})^2\right)\right],$$

$$\Omega_\chi h^2 = \frac{m_\chi\, s_0}{\rho_c/h^2}\, Y_\infty,$$

$$\langle\sigma v\rangle_{\mathrm{eff}} = \langle\sigma v\rangle_{12\to ff}\frac{n_1^{\mathrm{eq}} n_2^{\mathrm{eq}}}{(n^{\mathrm{eq}})^2},$$

we evaluate the full thermal average numerically using Bessel functions.

$$\sigma_{12ff}(s) = \frac{12\pi s^2}{(s - m_{Z_Q}^2)^2 + m_{Z_Q}^2\Gamma_{Z_Q}^2}\,\frac{\Gamma_{Z_Q\to\mathrm{SM}}(s)\,\Gamma_{Z_Q\to\chi_1\chi_2}(s)}{\lambda(s, m_1^2, m_2^2)}$$

$$\chi\bar{\chi} \to U^* \to f\bar{f}$$

- NRL

$$s \approx (m_1 + m_2)^2 + \mu(m_1 + m_2)\, v_{\mathrm{rel}}^2,$$

- Maxwell-Boltzmann Dist.

$$n_i^{\mathrm{eq}} \simeq g_i\left(\frac{m_i T}{2\pi}\right)^{3/2} e^{-m_i/T}$$

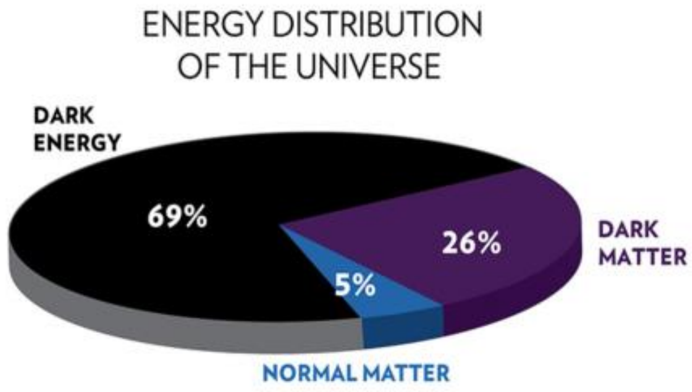
Arxiv.1411.1404 Arxiv.1801.05447

PhysRevD.99.075001 Arxiv.1307.6554

Thermal Relic Abundance

$h = 0.674$

Plack mission CMB: arxiv.1807.06209



$$\Omega_{DM} = \frac{\rho_{DM}}{\rho_{cr}} \sim 26.41\ \%$$ → $\boldsymbol{\Omega_{DM} h^2 \sim 0.120 \pm 0.001}$

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

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

$m_U > m_\chi$

Boltzmann Eq. production and Annihilation of X

$$\frac{dn}{dt} + 3Hn = -\langle \sigma v \rangle \left(n^2 - (n^{eq})^2 \right)$$

H → Hubble Constant
n^{eq} → number density at thermal eq.
σv → total annihilation cross section multiplied by velocity

For massive particles, i.e. in the non-relativistic limit, and in the Maxwell-Boltzmann approximation,

Arxiv.0404175

$$n^{eq} = g \left(\frac{mT}{2\pi} \right)^{3/2} e^{-m/T}$$

$$\Omega_X h^2 \approx \frac{3 \times 10^{-27} \mathrm{cm}^3 \mathrm{s}^{-1}}{\langle \sigma v \rangle}$$

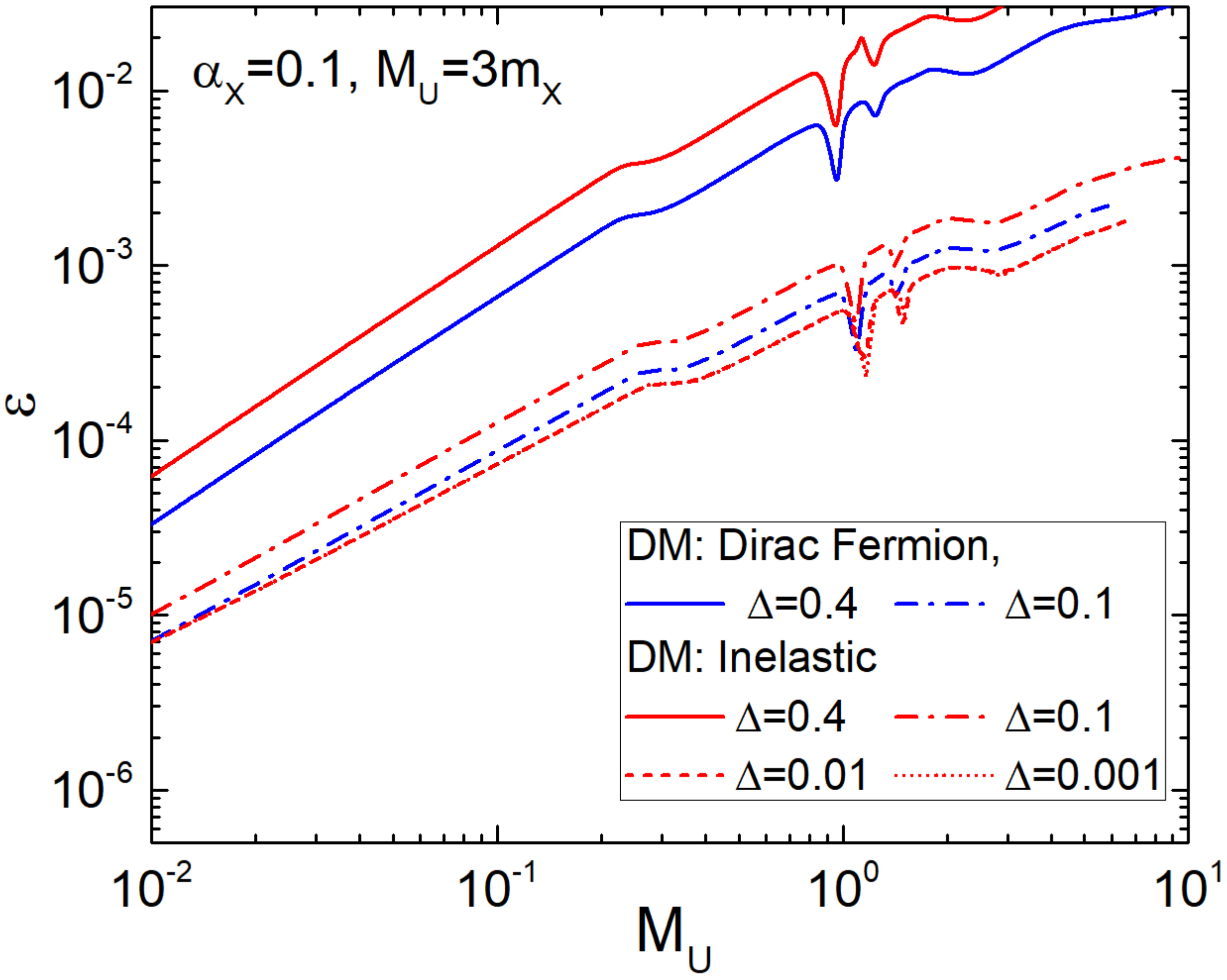
$$\langle \sigma_{\rm ann} v \rangle = \frac{\kappa}{2} \frac{\int_{4m_\chi^2}^{\infty} \sqrt{s}(s - 4m_\chi^2)\, \sigma_{\rm ann}(s)\, K_1(\sqrt{s}/T)\, ds}{8 m_\chi^4 T K_2^2(m_\chi/T)}$$

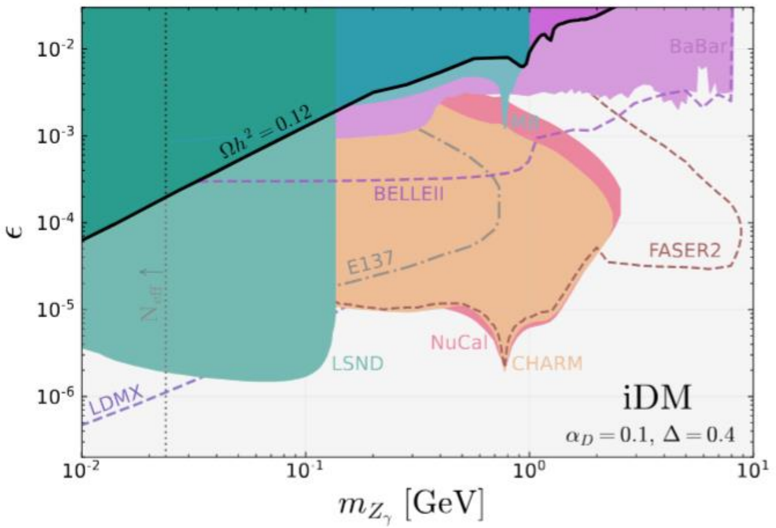
$$\langle \sigma v \rangle \approx 3 \times 10^{-26}\ cm^3 s^{-1}$$ Arxiv.1204.3622

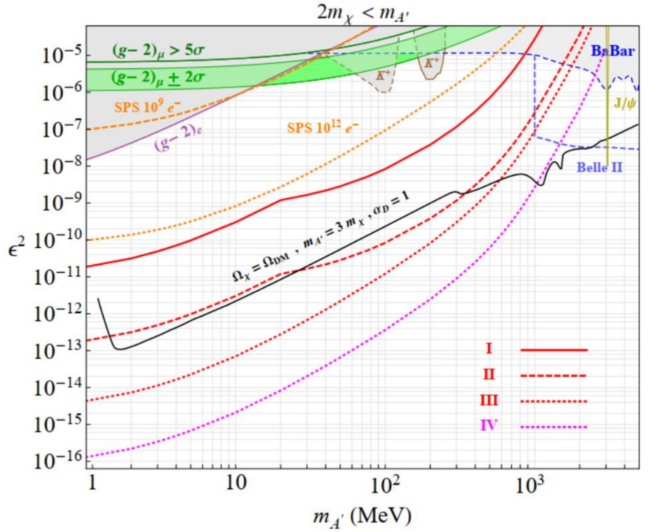
Red DeliVeR

https://arxiv.org/abs/2410.00881

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



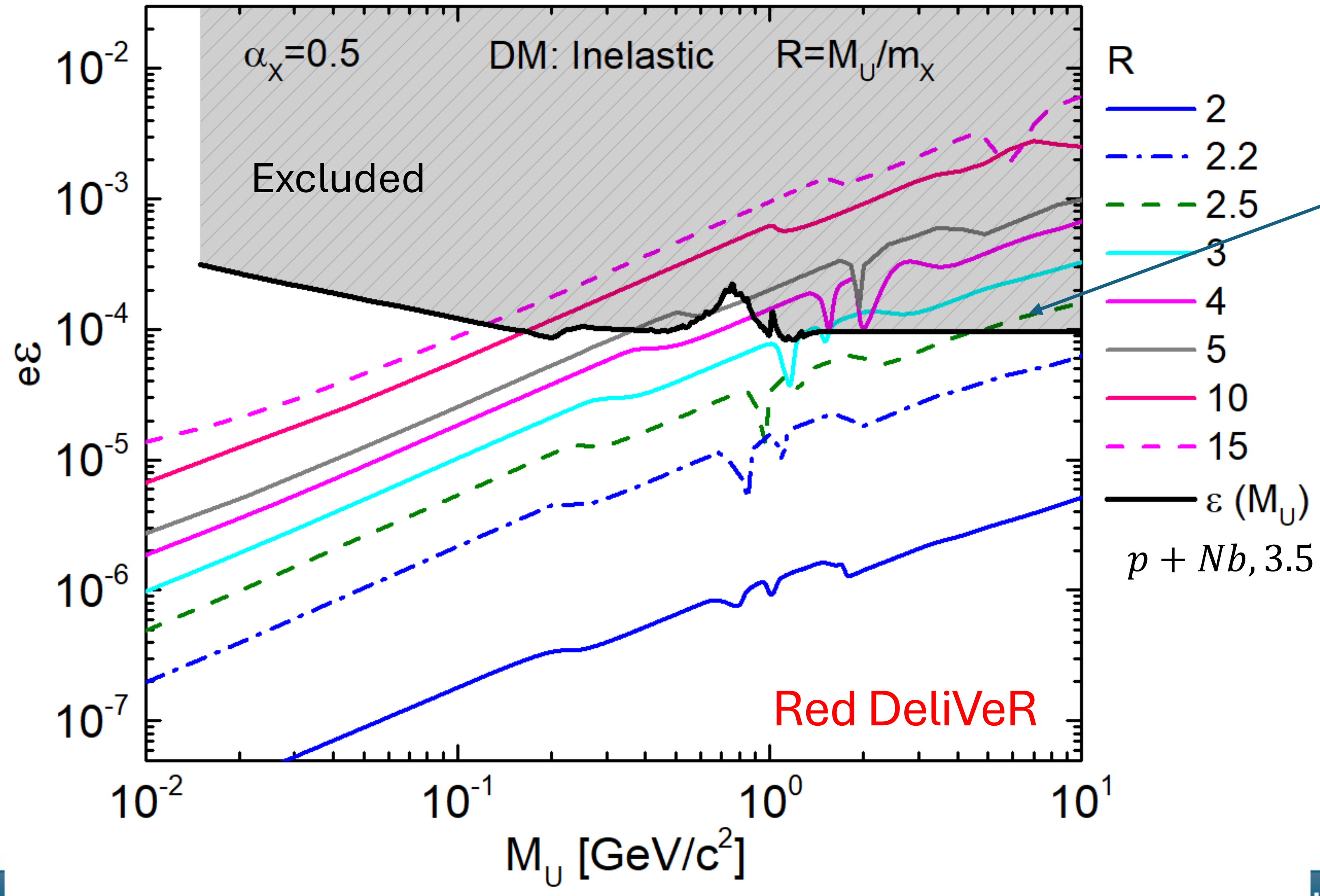


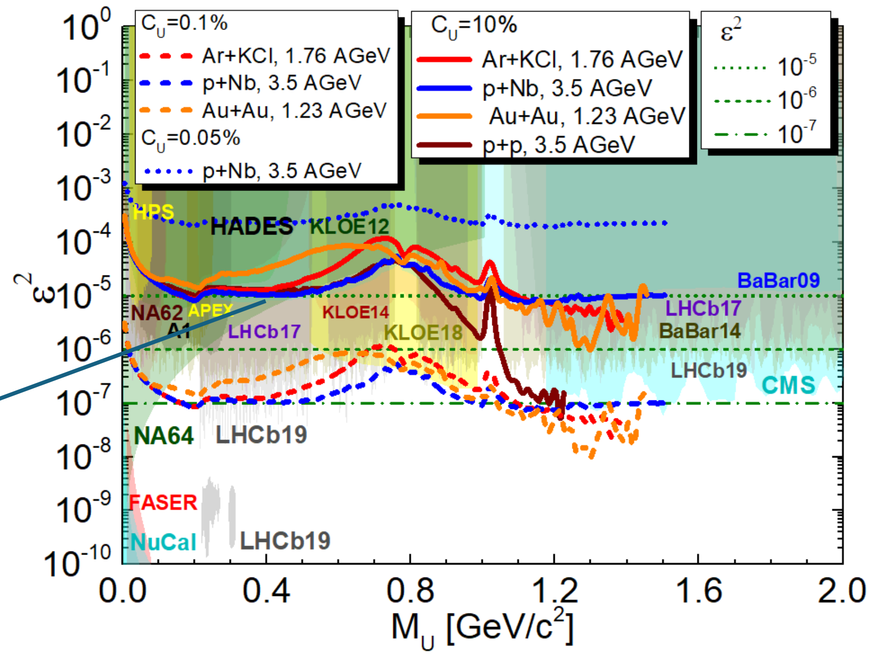


$$\Delta = \frac{|m_{\chi_1} - m_{\chi_2}|}{m_{\chi_1}}$$

Arxiv.1411.1404

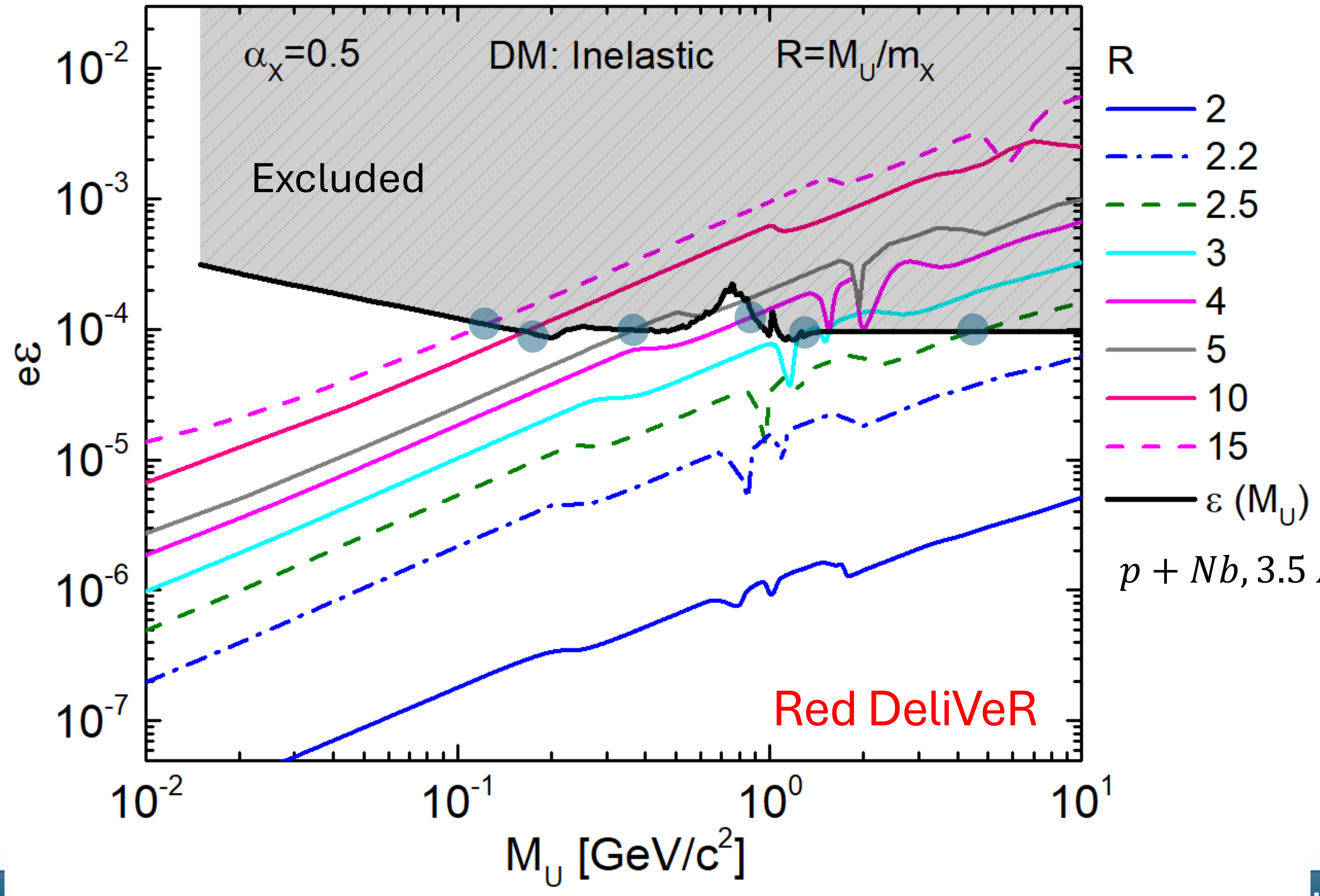
Thermal Relic Abundance





$p + Nb, 3.5\ AGeV, C_U = 0.05\%$

Thermal Relic Abundance



$p + Nb, 3.5\ AGeV, C_U = 0.05\%$