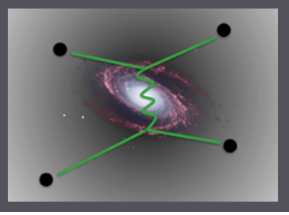

MAX-PLANCK-INSTITUT FÜR KERNPHYSIK HEIDELBERG

Two Coincidences are a Clue

probing a GeV-scale dark QCD sector

based on arXiv:2506.10928

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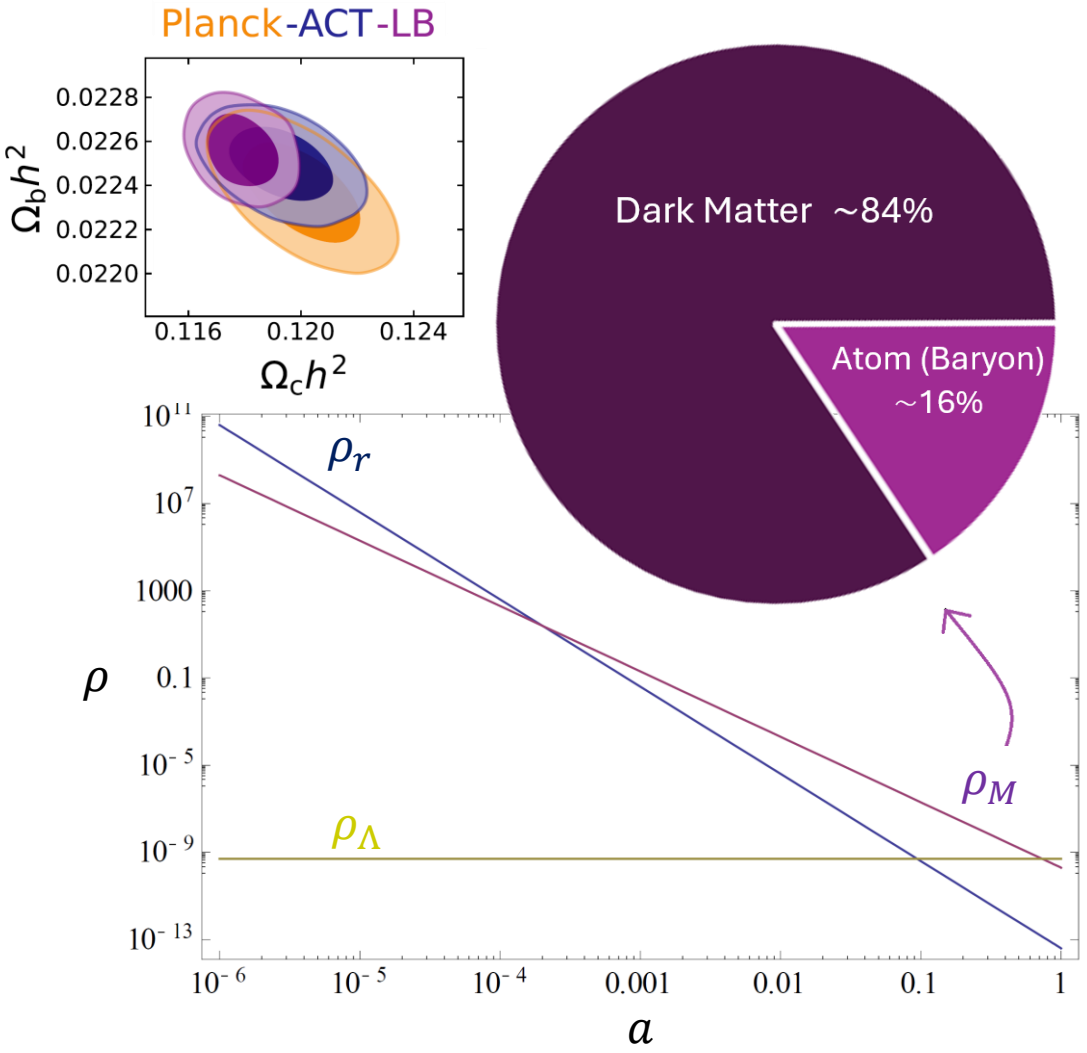
June 13th, 2025

2025 SIDM Workshop, IFIC Valencia

The First Coincidence: Energy Density



$\Rightarrow$ Why $\rho_D / \rho_B \approx 5$?

For comparison,

$\rho_{\text{proton}} / \rho_{\text{neutron}} \approx 7$

$\rho_{\text{proton}} / \rho_{\text{electron}} \approx 1800$

More about the Energy Density Coincidence

- For non-relativistic particles, the energy density = number density × mass

$$\rho_D/\rho_B = n_D/n_B \times m_D/m_B = 5\ !?$$

n_D/n_B: from unknown Baryogenesis

m_D/m_B: from QCD confinement

- For comparison,

$$\rho_p/\rho_n = n_p/n_n \times m_p/m_n = 7$$ (Symmetry!!)

$n_p/n_n \sim 7 \because SU(2)_F$

$m_p/m_n \sim 1 \because SU(2)_F$

$$\rho_p/\rho_e = n_p/n_e \times m_p/m_e = 1800$$

$n_p/n_e \sim 1 \because U(1)_{EM}$

$m_p/m_e \sim 1800$

(Part of) Solution: Asymmetric Dark Matter

- The problem is partly solved in *Asymmetric DM models* [Petraki, Volkas '13; Zurek '13]

$$\rho_D/\rho_B = \underbrace{n_D/n_B}_{\sim\mathcal{O}(1)\ \because\ U(1)_{D-B}} \times \underbrace{m_D/m_B}_{\text{from QCD confinement}} = 5\ !?$$

- For comparison,

$$\rho_p/\rho_n = \underbrace{n_p/n_n}_{\sim 7\ \because\ SU(2)_F} \times \underbrace{m_p/m_n}_{\sim 1\ \because\ SU(2)_F} = 7 \quad \text{(Symmetry!!)}$$

$$\rho_p/\rho_e = \underbrace{n_p/n_e}_{\sim 1\ \because\ U(1)_{EM}} \times \underbrace{m_p/m_e}_{\sim 1800} = 1800$$

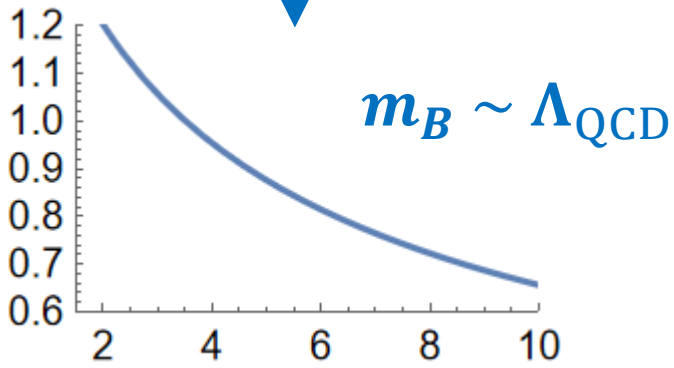
(Part of) Solution: Dark Baryon as Dark Matter

- A complete solution should also explain the comparable masses

$$\rho_D/\rho_B = n_D/n_B \times m_D/m_B = 5\ !?$$

$n_D/n_B \sim \mathcal{O}(1) \because U(1)_{D-B}$

[Petraki, Volkas '13; Zurek '13]



$m_B \sim \Lambda_{\mathrm{QCD}}$

Dark QCD sector with $m_D \sim \Lambda_{\mathrm{DC}} \sim \Lambda_{\mathrm{QCD}}$

(Symmetry, Dynamics, or…)

Complete Solutions of Coincidence Problem

- The coincidence problem can be solved by combining the two solutions

$$\rho_D/\rho_B \;=\; n_D/n_B \;\times\; m_D/m_B \;=\; 5\ !?$$

$$\sim\mathcal{O}(1) \because U(1)_{D-B} \qquad \sim\mathcal{O}(1) \because \Lambda_{\rm DC} \sim \Lambda_{\rm QCD}$$

[Petraki, Volkas '13; Zurek '13] [Symmetry, Dynamics, or others]

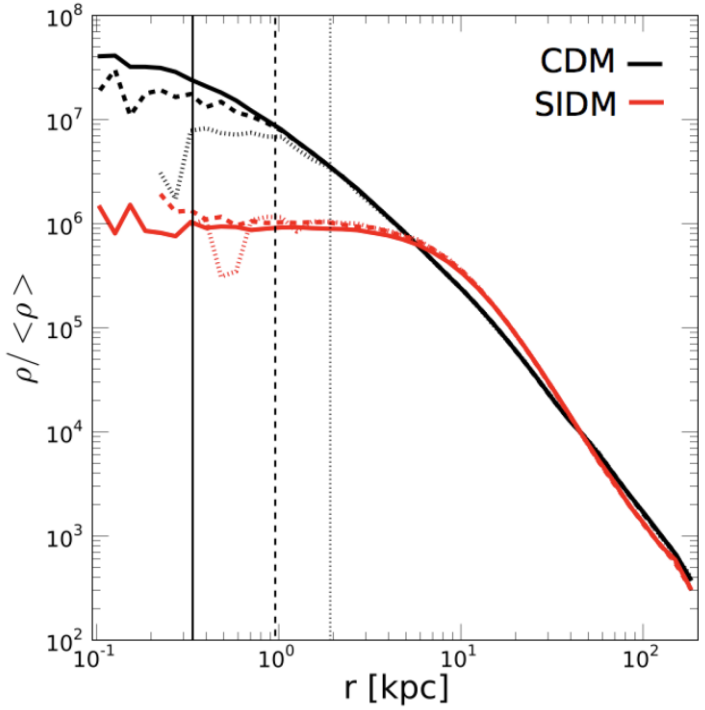
$\Rightarrow$ **Asymmetric + Dark Baryon**

with dark matter mass $m_D = 1 - 5$ GeV

which implies a new VEV $f \approx \mathcal{O}(100)$ MeV

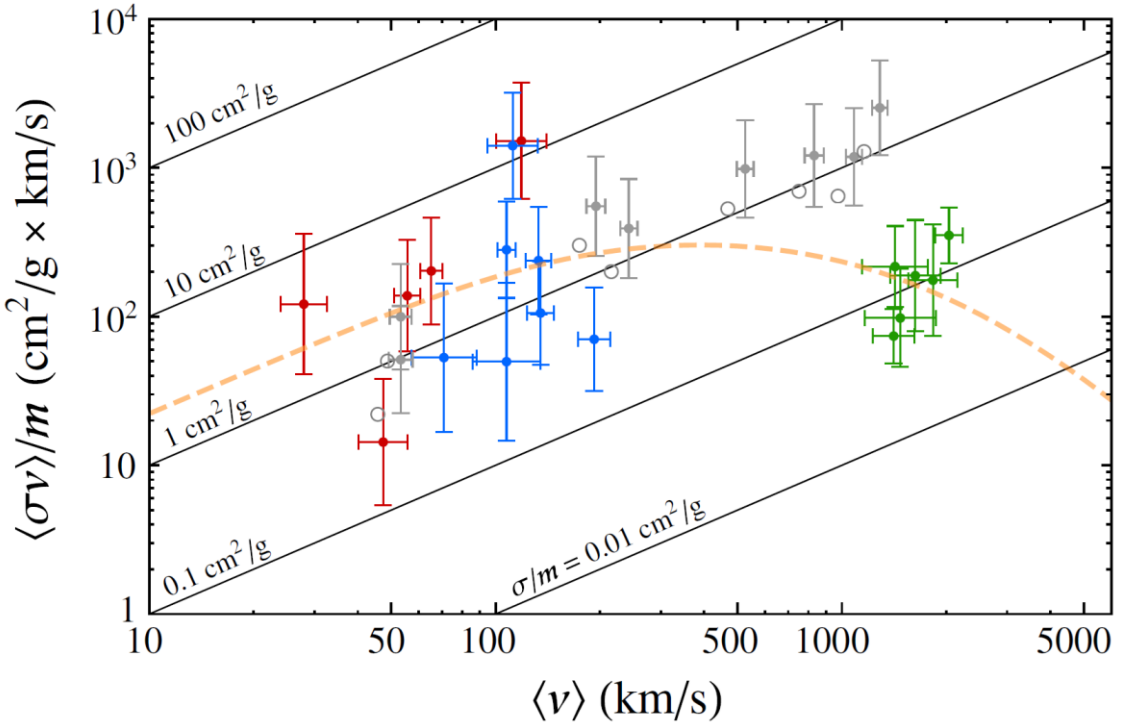
and comes with **large self-interactions!!**

Small-Scale Structure and Self-Interacting DM



[Vogelsberger, Zavala, Loeb' 12]

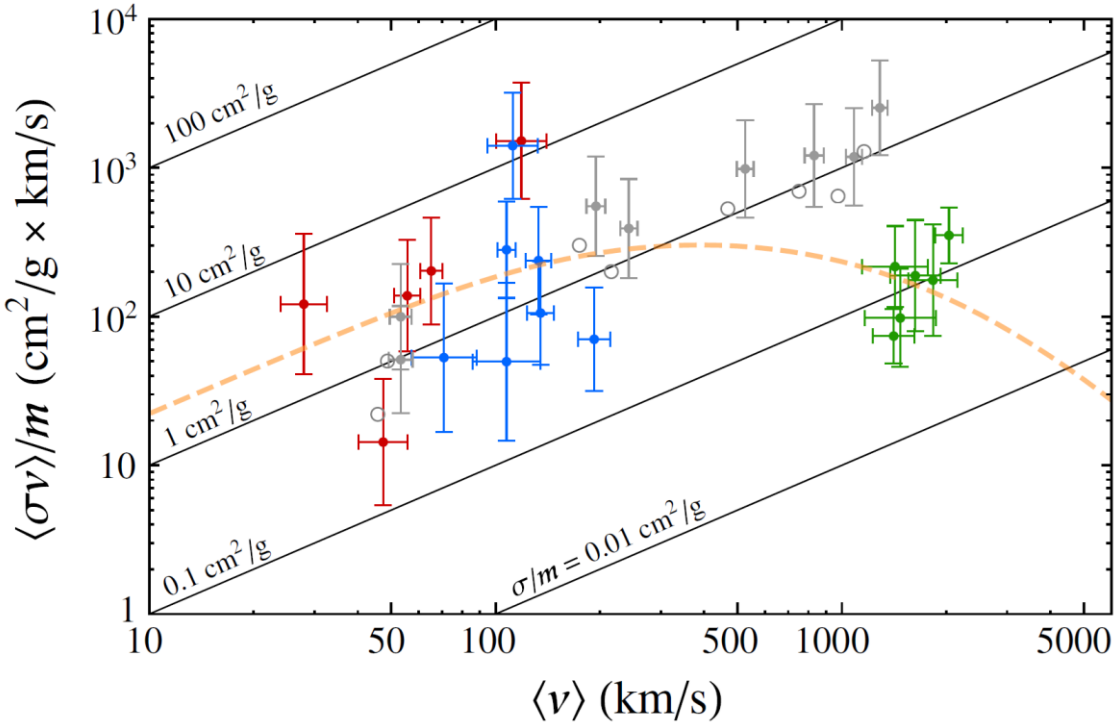
⇒



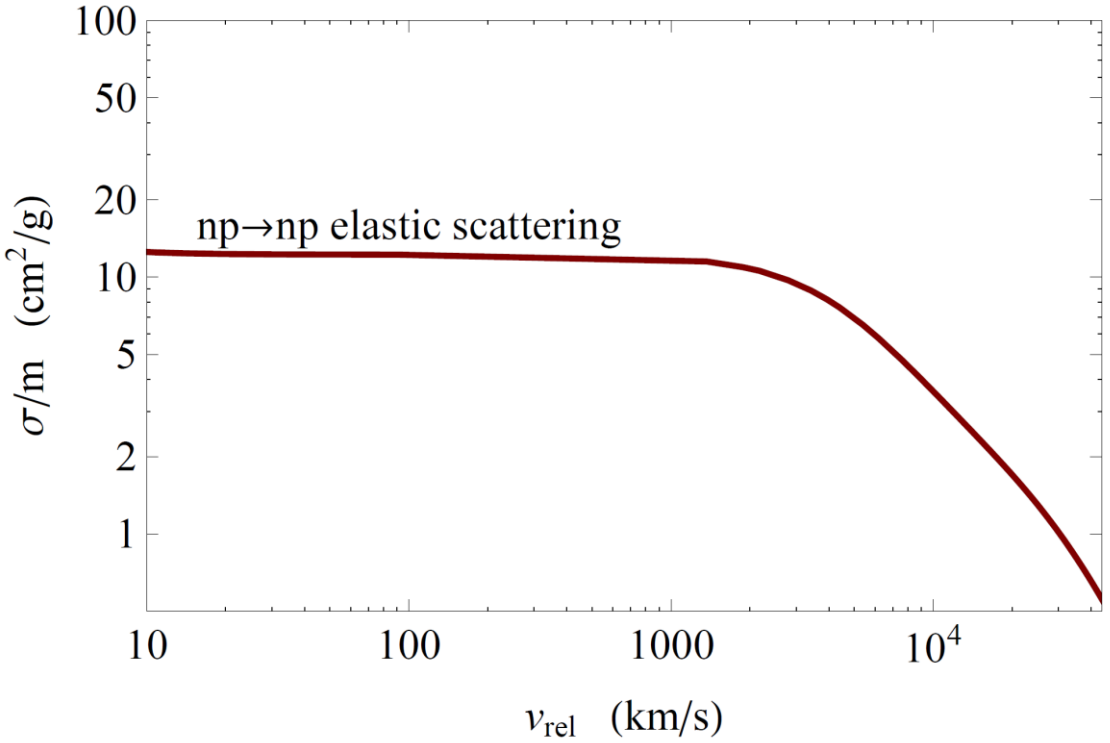
[Kaplinghat, Tulin, Yu' 15]

- The core-cusp problem can be explained by dark matter self-interactions
- A cross section $\sigma/m = 1 - 10\ cm^2/g$ can address the tension on galaxy scales

The Second Coincidence : Self-interaction

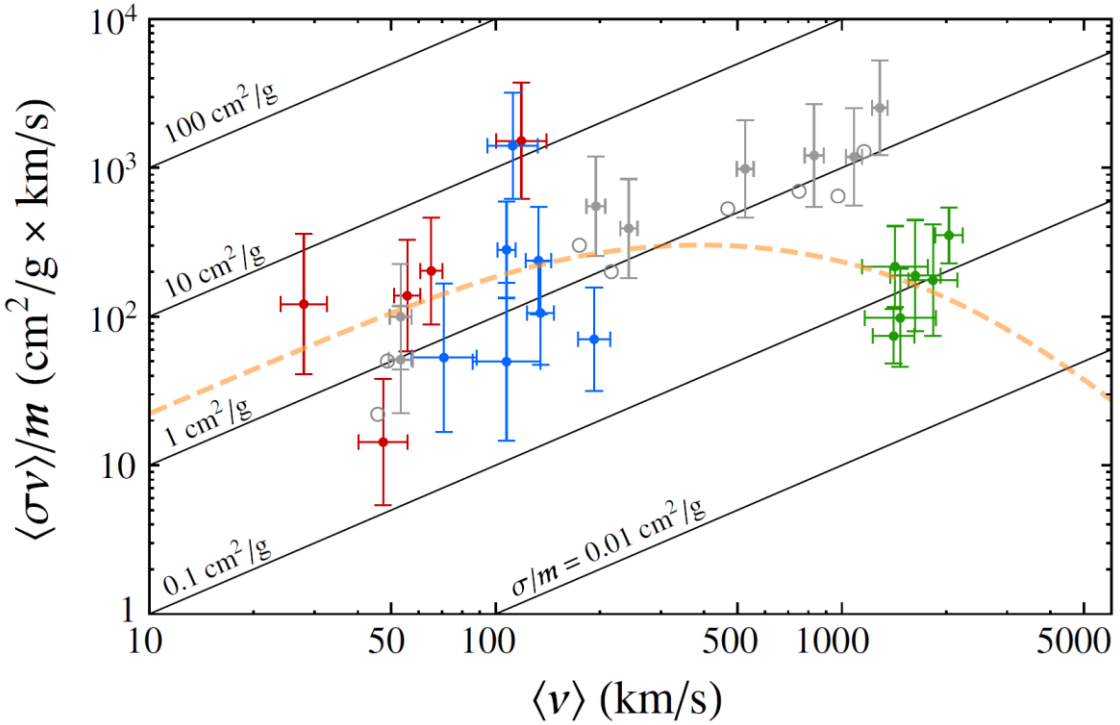


[Kaplinghat, Tulin, Yu' 15]



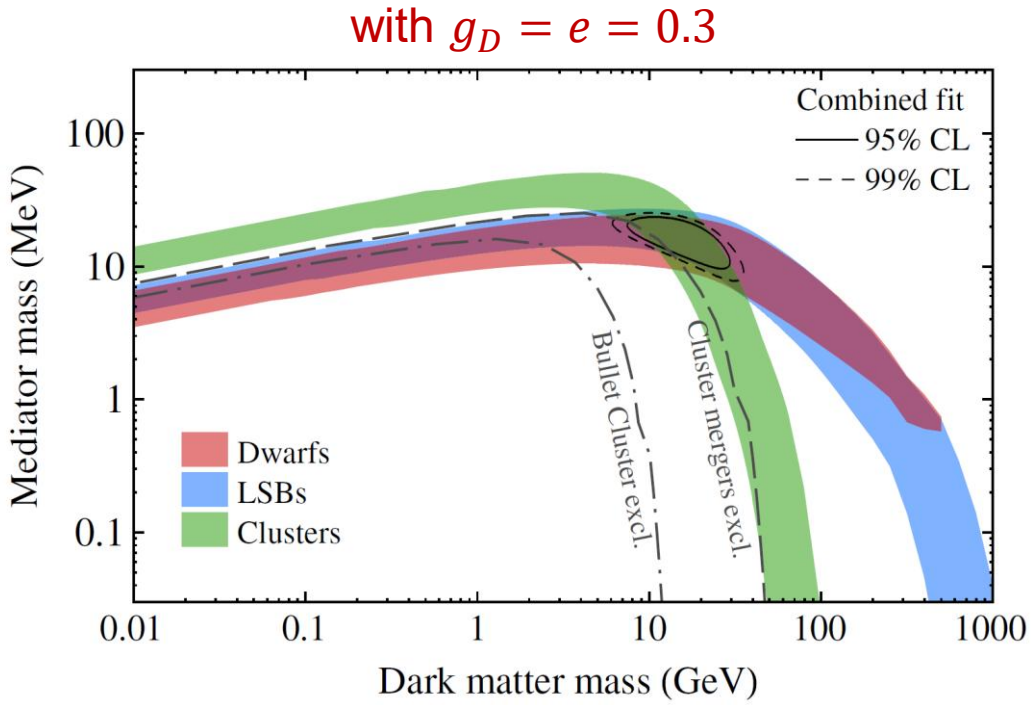
- The required cross section of dark matter is similar with the nucleon self-scattering of QCD.
- The comparable cross section at low velocity implies a similar scale of interaction $f \approx 100$ MeV

Hint at Dark Baryon + Dark Photon model?



[Kaplinghat, Tulin, Yu' 15]

⇒



- The velocity-dependence can be explained by a light mediator (dark photon) with $m_{\gamma'} \approx 10\ \mathrm{MeV}$
- The fact that $m_{\gamma'} \approx 10\ \mathrm{MeV} \approx g_D f$ hints at a common origin of dark baryon and dark photon

A simplified model of Chiral Dark QCD sector

UV: 2411.18725

- Gauge group: Dark Color $\boldsymbol{SU(N)_D}$ × Dark $\boldsymbol{U(1)_D}$ with gauge coupling g_D
- Matter content: $\boldsymbol{\psi_L = (N, 1/2),\ \psi_R = (N, -1/2)}$ (with other fermions to cancel anomaly)

- Once the dark color $SU(N)_D$ becomes strongly coupled at the confinement scale $\Lambda_{\rm DC}$, the two Weyl fermions form a condensate $\Phi = \overline{\psi_R}\psi_L = (1,1)$ with a lagrangian given by

$$\mathcal{L}_{\rm DS} = -\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + |D_\mu\Phi|^2 + \mu^2|\Phi|^2 - \lambda|\Phi|^4 + i\bar{\psi}_{L,R}\not{D}\,\psi_{L,R} + Y_\psi\,\bar{\psi}_L\,\Phi\,\psi_R + \text{h.c.}$$

  where the real part ϕ acquires a VEV $\langle\phi\rangle = f$, giving $m_\psi = Y_\psi f$ and $m_{\gamma'} = g_D f$

- The dark baryon composed of N dark quarks has $m_D = N\,Y_\psi f = Y_D f$ and $Q_D = N/2$

- We consider the kinetic mixing portal with parameter ϵ as $-\frac{\epsilon}{2}F'_{\mu\nu}F^{\mu\nu} \implies \epsilon e A'_\mu J^\mu_{\rm QED}$

Free Parameters of Chiral Dark QCD sector

UV: 2411.18725

- Gauge group: Dark Color $\boldsymbol{SU(N)_D}$ × Dark $\boldsymbol{U(1)_D}$ with gauge coupling g_D
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dark QCD scale

dark photon mass

where the real part ϕ acquires a VEV $\langle\phi\rangle = f$, giving $m_\psi = Y_\psi f$ and $m_{\gamma'} = g_D f$

- The dark baryon composed of N dark quarks has $m_D = N\,Y_\psi f = Y_D f$ and $Q_D = N/2$

dark matter mass

Fix $N = 3$

portal

- We consider the kinetic mixing portal with parameter ϵ as $-\frac{\epsilon}{2}F'_{\mu\nu}F^{\mu\nu} \implies \epsilon e A'_\mu J^\mu_{\rm QED}$

Factorization of Born approximation

- With a simplified model, we can derive SIDM cross section using Born approximation

$$\sigma_D \approx \sigma_T^{\text{Born}} = \frac{1}{2\pi}\frac{Q_D^4 g_D^4}{m_D^2 v^4}\left(\ln(1+R^2) - \frac{R^2}{1+R^2}\right) \text{ with } R \equiv \frac{m_D v}{m_{\gamma'}} \quad (\text{ to check } \frac{\alpha_D m_D}{m_{\gamma'}} \ll 1)$$

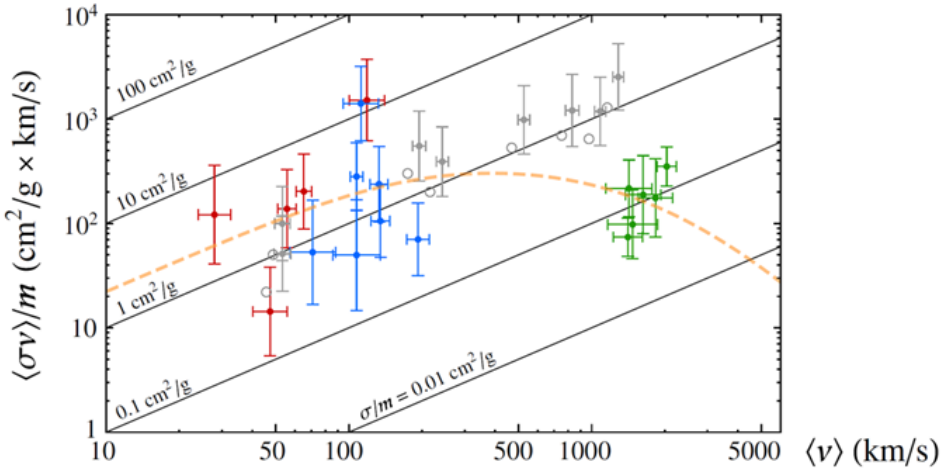
- Under our parameterization, we get an expression that can be factorized

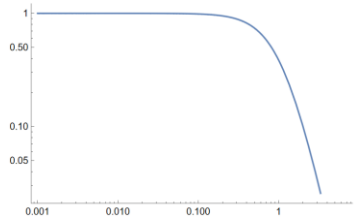
$$\frac{\sigma_D}{m_D} \approx \frac{Q_D^4}{4\pi}\frac{m_D}{f^4}\left[\frac{2}{R^4}\left(\ln(1+R^2) - \frac{R^2}{1+R^2}\right)\right]$$

$= \sigma/m$ at zero-velocity as a function of (m_D, f)

$$\left(\frac{\sigma_D}{m_D}\right)_{\text{low}} = [1.1, 3.2]\frac{\text{cm}^2}{\text{g}}$$

[Kaplinghat, Tulin, Yu' 15]





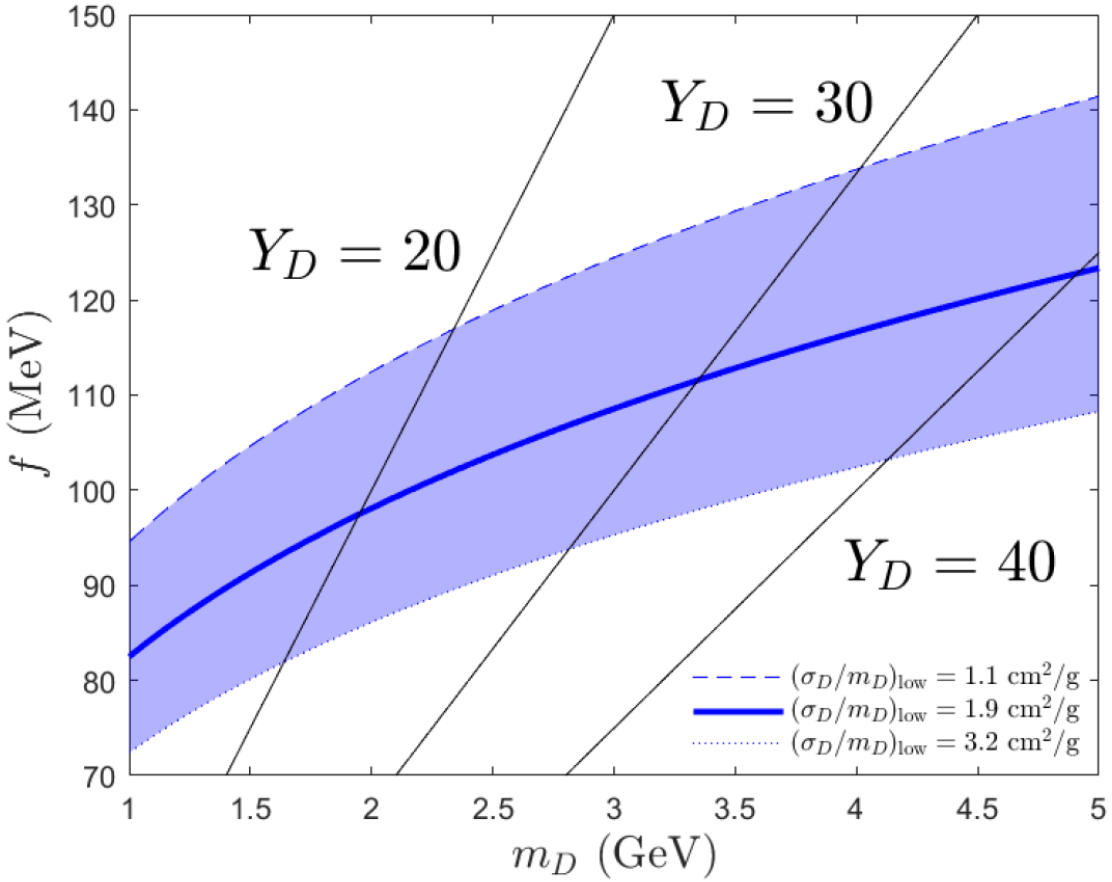
The velocity dependence as a function of $(m_D, m_{\gamma'})$

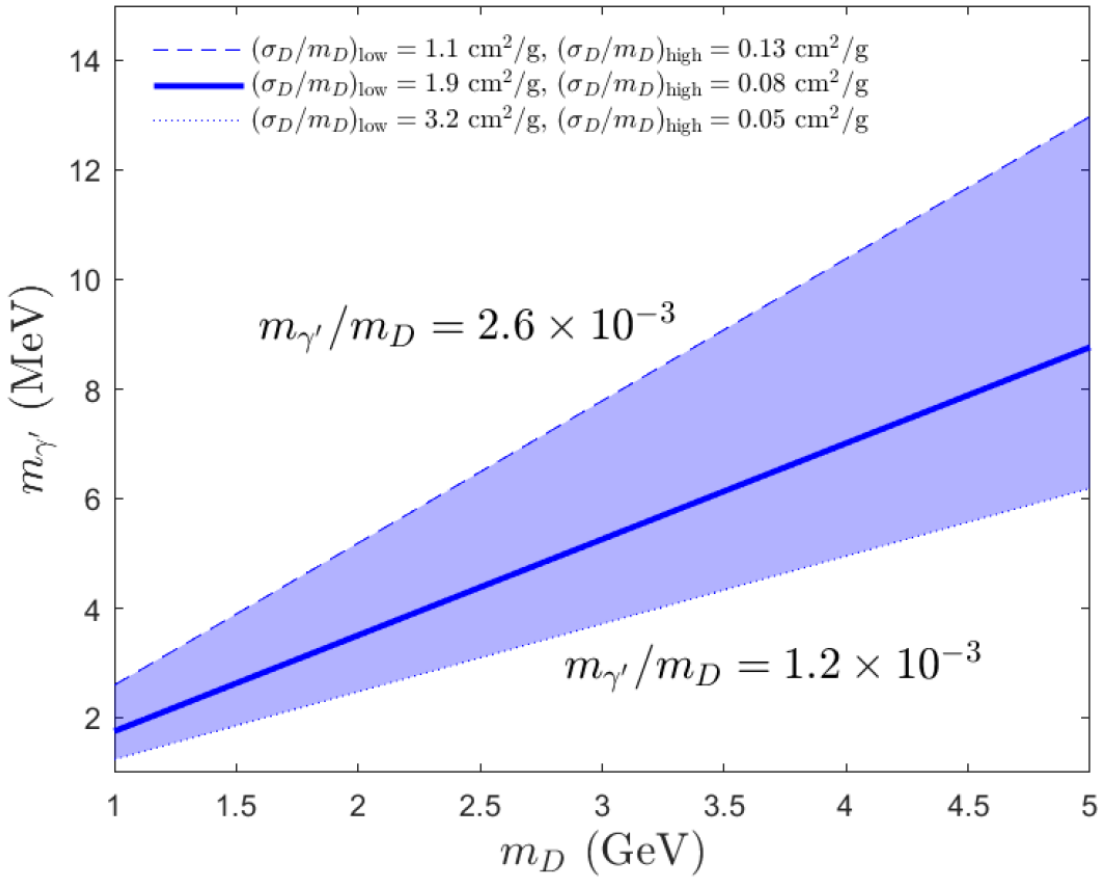
$$\left(\frac{\sigma_D}{m_D}\right)_{\text{high}} = [0.05, 0.13]\frac{\text{cm}^2}{\text{g}}$$

[Kaplinghat et al' 21]

Resulting Parameter space of $(f, m_D, m_{\gamma'})$

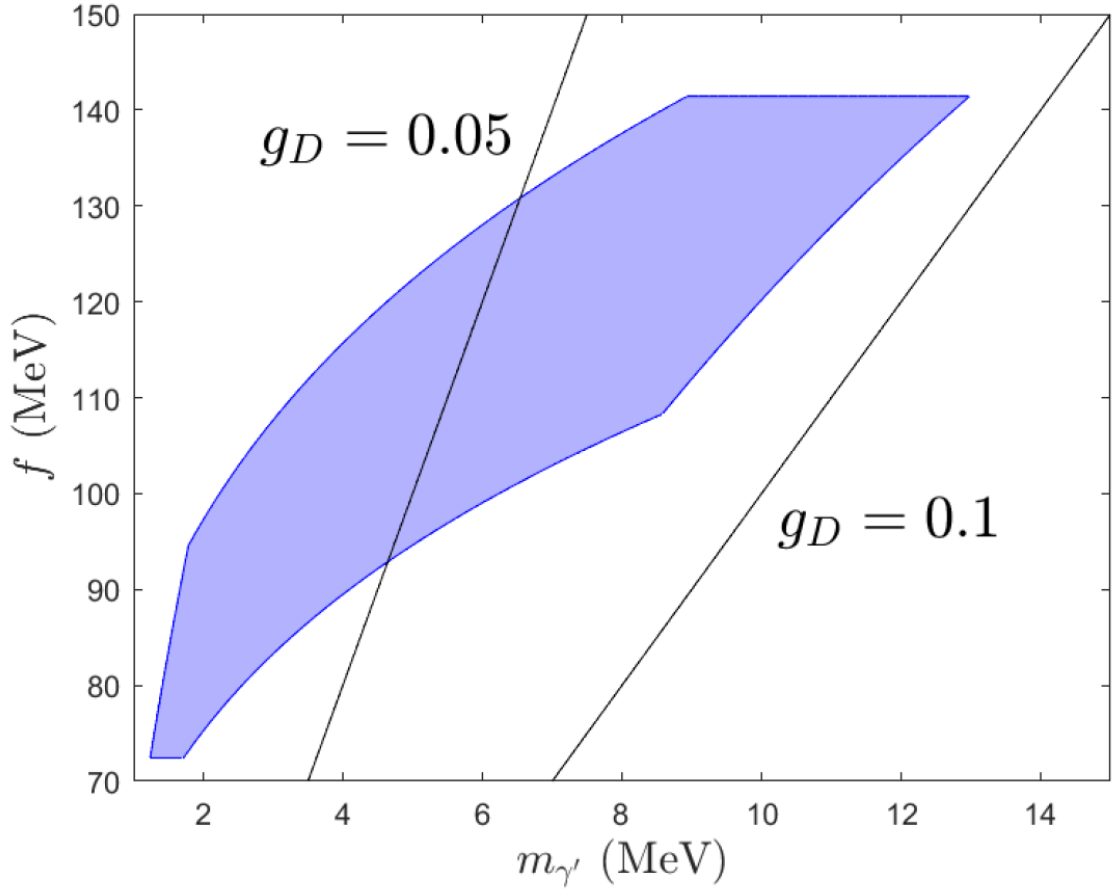
- We focus on a narrow parameter space with $m_D = 1-5$ GeV motivated by the first coincidence





Resulting Parameter space of $(f, m_D, m_{\gamma'})$

- Combining the two plots, we can get a plot for $(f, m_{\gamma'})$ and derive the gauge coupling g_D



$$f = [70, 140] \text{ (MeV)}$$

$$m_{\gamma'} = [1, 13] \text{ (MeV)}$$

$$\Rightarrow \alpha_D < 7 \times 10^{-4}$$

Velocity dependence is NATURAL!

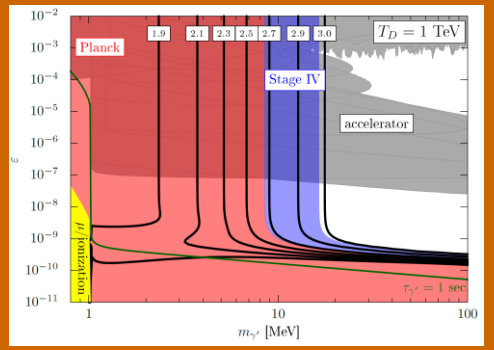
It is a consequence of hierarchy between weak and strong coupling

$$\frac{m_{\gamma'}}{m_D} = \frac{g_D}{Y_D} = \mathcal{O}(10^{-3})$$

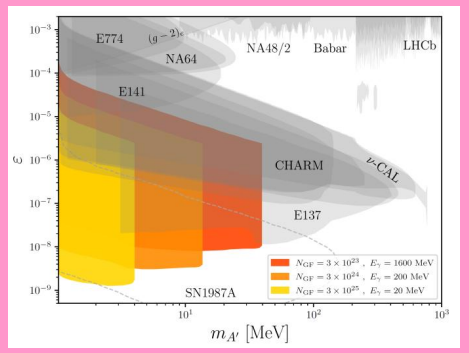
Complementary searches and Constraints

If the mixing parameter ϵ is nonzero, we get

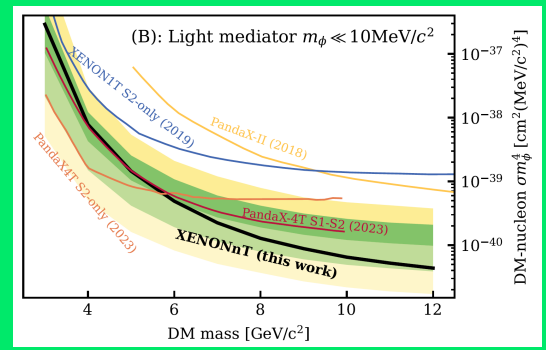
Cosmology
CMB & BBN



Dark Photon
Searches

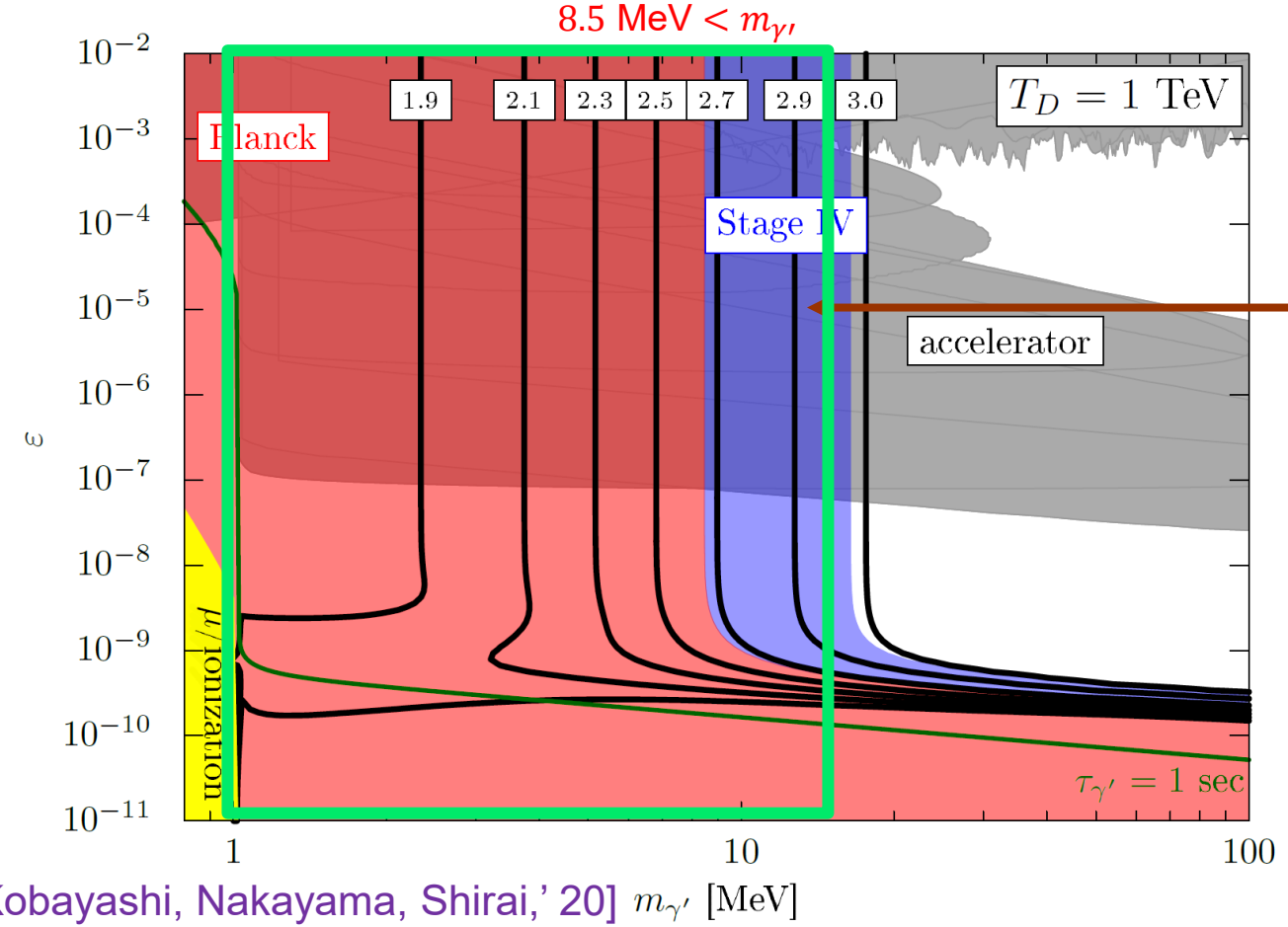


Dark Matter
Direct detection



Cosmology – MeV dark photon and $N_{\rm eff}$

- The dark photon with masses of few MeV will lower down the $N_{\rm eff}$



[Ibe, Kobayashi, Nakayama, Shirai,' 20]

$$N_{\rm eff}^{\rm SM} = 3.0440 \pm 0.0002$$

[Drewes, Georis, Klasen, Wiggering, Wong' 24]

$$N_{\rm eff} = 2.89 \pm 0.11$$

$$(68\%, \text{P-ACT-LB-D-He})$$

[ACT DR6 2503.14454]

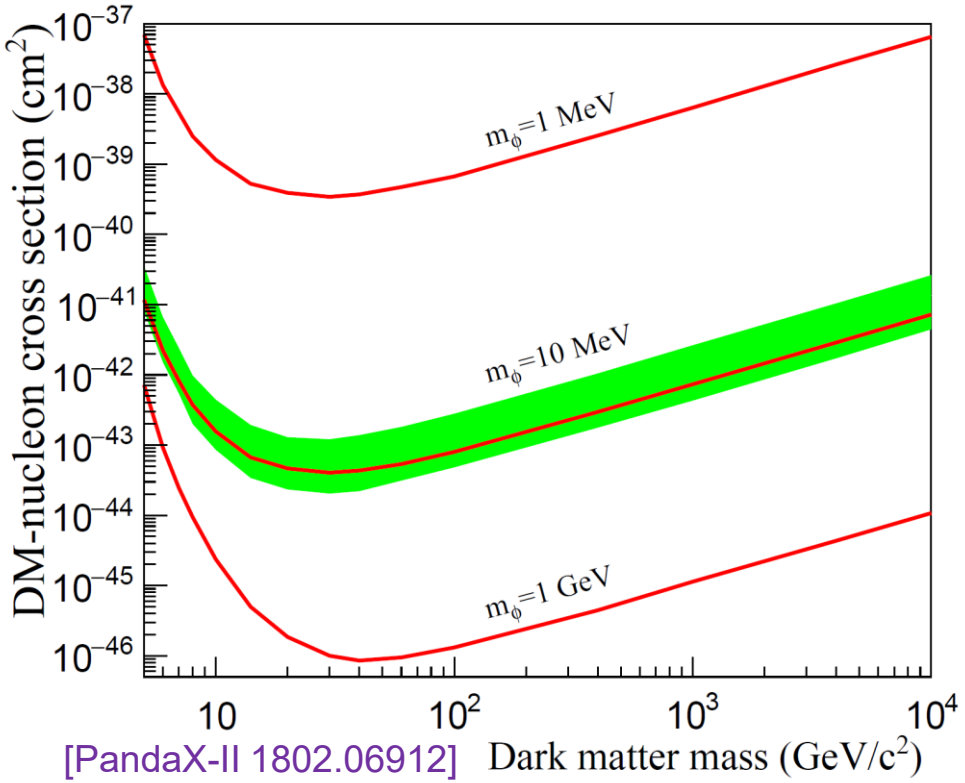
which corresponds to

$$m_{\gamma'} = 12.5 \text{ MeV}$$

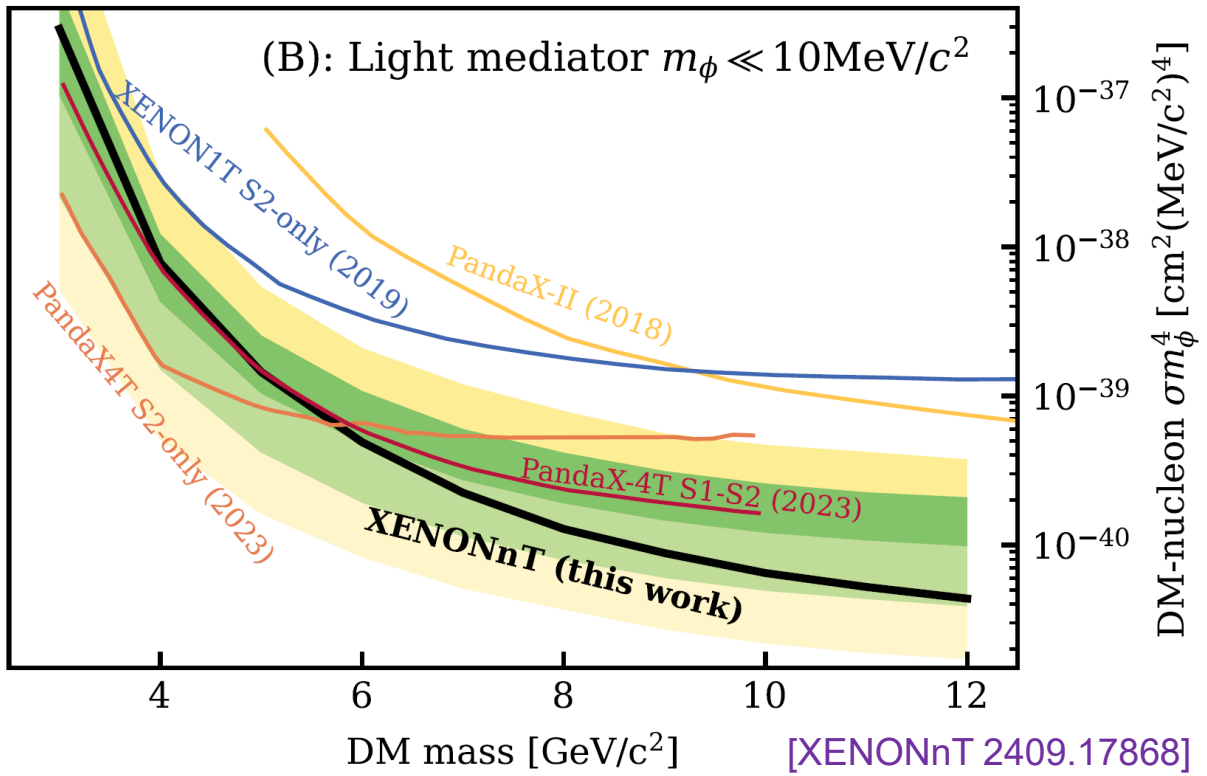
The third coincidence? CMB-S4 with sensitivity of 0.027 can check it !!

Dark Matter Searches – Direct Detection

- Direct detection for interactions through a light mediator with a mass smaller than the critical momentum is no longer sensitive to the mediator's mass. Instead, it can put a constraint on $\sigma m_{\gamma'}^4$, (it still works ok for $m_{\gamma'} \approx 10$ MeV)



[PandaX-II 1802.06912]



[XENONnT 2409.17868]

Combined analysis: N_{eff} + Direct Detection

- Using the relation we got, we can derive it in our model, which is given by

$$\sigma m_{\gamma'}^4 = \frac{1}{\pi} e^2 \epsilon^2 (Q_D g_D)^2 \left(\frac{Z}{A}\right)^2 \mu_n^2 v_0^2$$

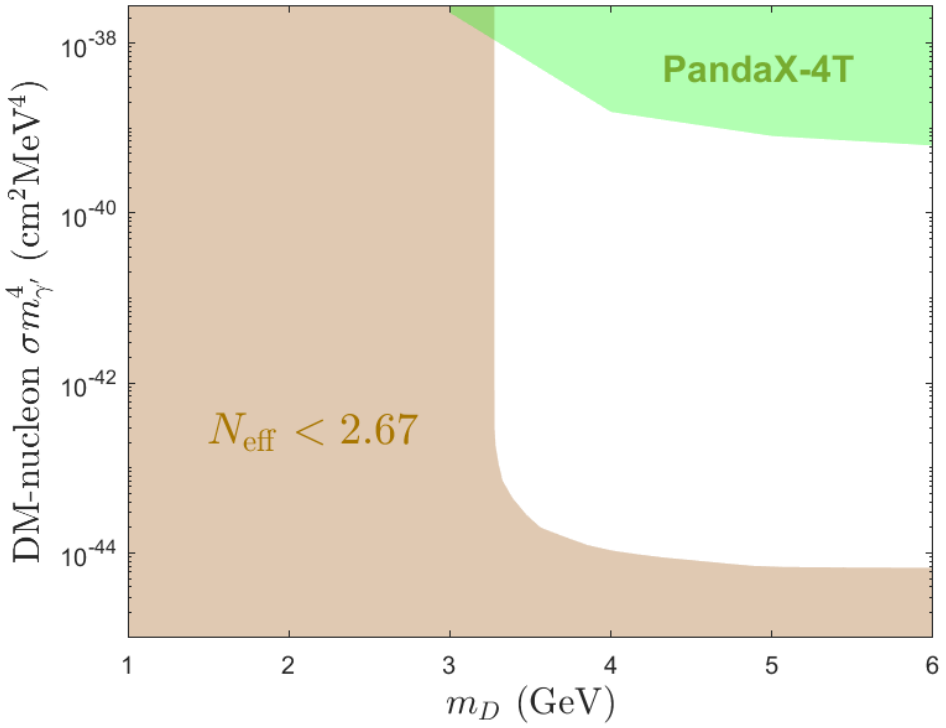
Velocity-suppression comes from $\bar{\psi}\gamma^\mu\gamma^5\psi$ axial-vector current that couples to dark photon in a chiral theory!

Must be nonzero for dark photon decay

Must be nonzero for DM Self-interaction

$$= 3.4 \times 10^{-45}\ \mathrm{cm}^2\,\mathrm{MeV}^4 \times m_D^{\frac{1}{2}} \mu_n^2 \times \left(\frac{v_0}{10^{-3}}\right)^2 \times \left(\frac{m_{\gamma'}/m_D}{2.6 \times 10^{-3}}\right) \left(\frac{0.1\ \mathrm{s}}{\tau_{\gamma'}}\right) \left(\frac{(\sigma_D/m_D)_{\mathrm{low}}}{1.1\ \mathrm{cm}^2/\mathrm{g}}\right)^{\frac{1}{2}}$$

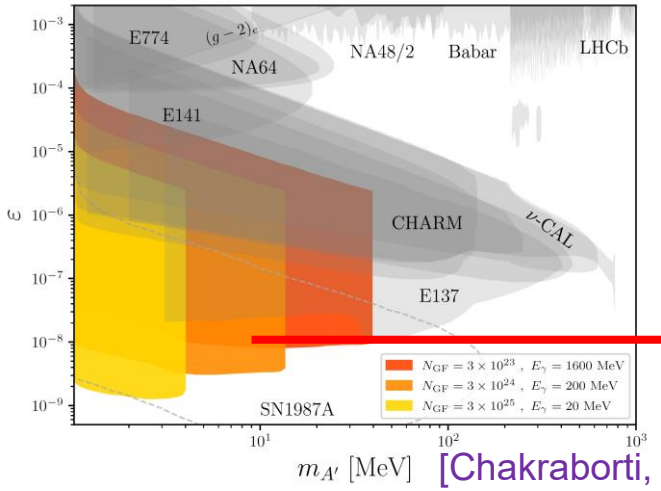
1. $m_D < 3.3$ GeV is ruled out by N_{eff}
2. $\approx 10^5$ space is still left for the rest mass range



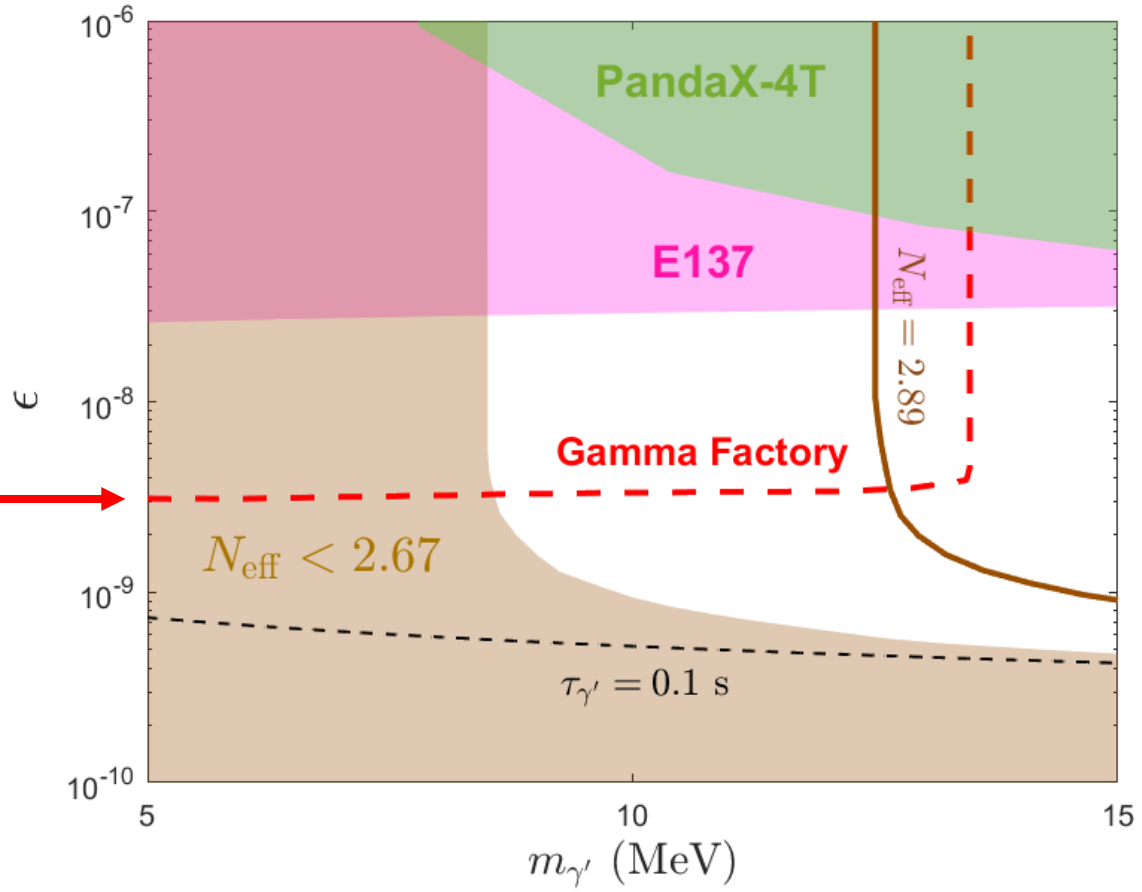
Combined analysis: dark photon parameters

- The relation also allows us to turn direct detection into constraint on mixing parameter ϵ

1. Beam dump experiment E137 is stronger
2. Supernova bounds do not apply to SIDM
3. A finite window is left to be tested in future
4. Gamma Factory can cover part of space



[Chakraborti, Feng, Koga, Valli' 21]



Summary

- Two (Three?) coincidences from the cosmological/astrophysical measurements

1. Energy density – Solid and hint at Asymmetric Dark Baryon model (dynamical solution?)
2. Self-interaction – To be confirmed (see a lot of nice talks during the workshop!)
3. $\mathbf{N_{eff}} < \mathbf{N_{eff,SM}}$? – Will reach required precision (but could also be other BSM physics?)

- A simplified model of a Chiral Dark QCD sector

1. Feature only 4 parameters (fix N=3) -

   dark QCD scale $\boldsymbol{f}$, dark matter mass $\boldsymbol{m_D}$, dark photon mass $\boldsymbol{m_{\gamma'}}$, mixing parameter $\boldsymbol{\epsilon}$
2. This parameterization allows us to factorize the Born approximation
3. Axial-vector current introduces a velocity suppression which avoids strong constraints
4. A finite parameter space is left and can be probed in future (CMB-S4, γ-factory, Xenon…)