ibs 기초과학연구원 Institute for Basic Science

The Dark Matter – Baryon Coincidence

problem, solutions, and signatures

based on arXiv: 2411.16860, 2411.18725, 2506.10928

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Identification of Dark Matter 2026, Zaragoza, Spain

What do we know about Dark Matter?

- Dark Matter need to be

(1) Cold (non-relativistic)

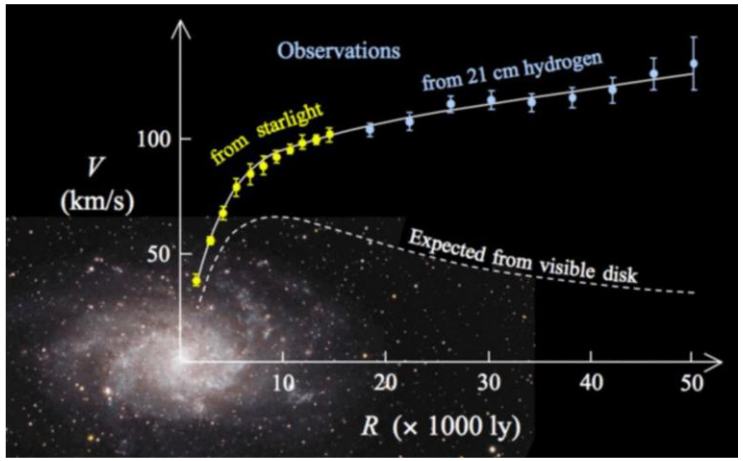
(2) Dark (not interact with photons)

(3) Collision-less

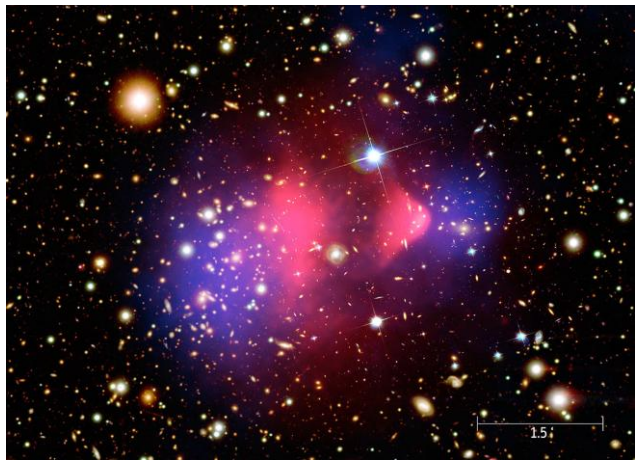
(4) Stable / Long-lived

$+$ $\rho_D \approx 2.3 \times 10^{-30}\ \mathrm{g/cm^3}$

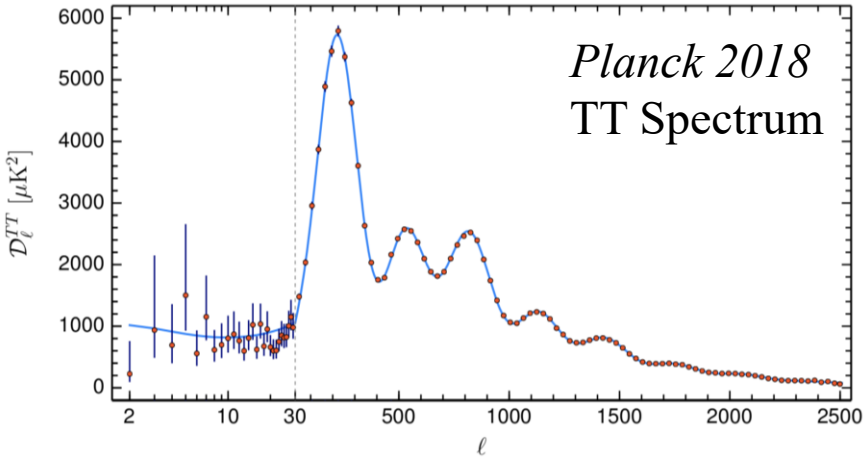
(percent-level precision !!)



Galaxy rotation curves

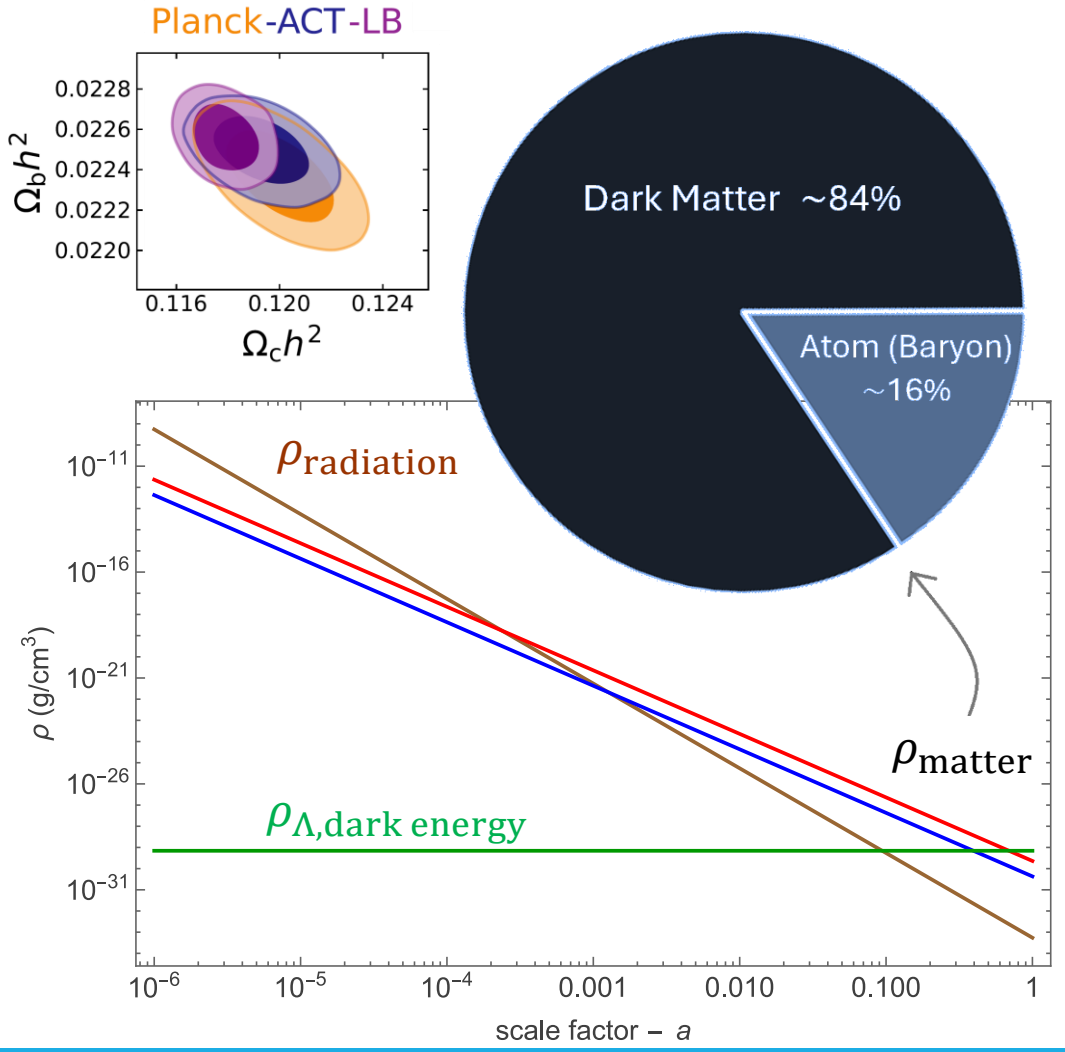


Merging galaxy clusters



Cosmic Microwave Background

The Dark Matter – Baryon Coincidence



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

For comparison,

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

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

These ratios have been **fixed** since the early universe !!

More about the DM – Baryon Coincidence

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

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

- For comparison,

$$\rho_p/\rho_n = n_p/n_n \times m_p/m_n = 7$$

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

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

More about the DM – Baryon Coincidence

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(Symmetry!!)

$n_p/n_n \sim 7 \because SU(2)$ $\quad$ $m_p/m_n \sim 1 \because SU(2)$

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

$n_p/n_e \sim 1 \because U(1)_{EM}$ $\quad$ $m_p/m_e \sim 1800$

More about the DM – Baryon 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!!)

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

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

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

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

$m_p/m_e \sim 1800$

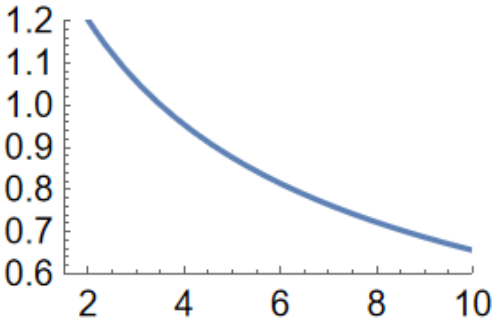
Solutions to the DM – Baryon Coincidence

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

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

from unknown Baryogenesis but determined by **Asymmetry**

from QCD confinement with a mass $m_B \sim \Lambda_{\rm QCD}$



Solutions to the DM – Baryon Coincidence

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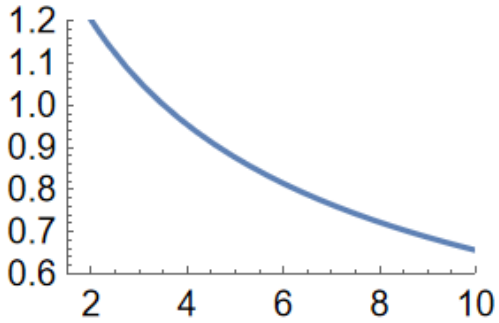

DM number density is also determined by Asymmetry?

DM mass should arise from similar dynamics as QCD Baryons?

(Part of) Solution: Asymmetric Dark Matter

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

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

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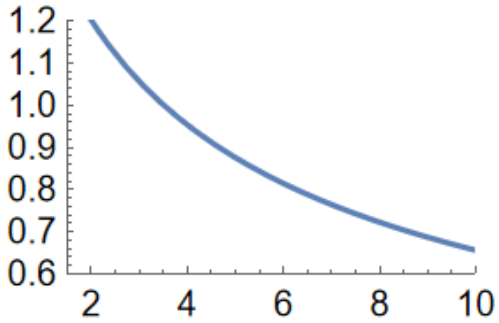


Asymmetric DM where $n_D - n_{\bar{D}} \neq 0$ $U(1)_{D-B}$ symmetry

DM mass should arise from similar dynamics as QCD Baryons?

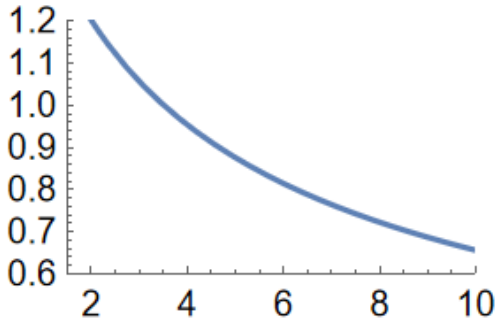
(Part of) Solution: Dark Baryon Dark Matter

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

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

from unknown Baryogenesis but determined by **Asymmetry**

from QCD confinement with a mass $m_B \sim \Lambda_{\rm QCD}$



Asymmetric DM where $n_D - n_{\bar{D}} \neq 0$ $U(1)_{D-B}$ symmetry

Dark Baryon DM where $m_D \sim \Lambda_{\rm dQCD}$ with $\Lambda_{\rm dQCD} \sim \Lambda_{\rm QCD}$

Complete Solutions of Coincidence Problem

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

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

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

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

Solution $\Rightarrow$ **Asymmetric Dark Baryon @ $\mathcal{O}(1)$ GeV**

Complete Solutions of Coincidence Problem

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$\sim\mathcal{O}(1) \because U(1)_{D-B}$ [Petraki, Volkas '13; Zurek '13]

$\sim\mathcal{O}(1) \because \Lambda_{\mathrm{dQCD}} \sim \Lambda_{\mathrm{QCD}}$ [Symmetry, Dynamics, or others]

Solution $\Rightarrow$ **Asymmetric Dark Baryon @ $\mathcal{O}(1)$ GeV**

How to detect it?

direct detection, ~~indirect detection~~, ~~collider searches~~

Complete Solutions of Coincidence Problem

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

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

$n_D/n_B \sim \mathcal{O}(1) \because U(1)_{D-B}$ [Petraki, Volkas '13; Zurek '13]

$m_D/m_B \sim \mathcal{O}(1) \because \Lambda_{\rm DC} \sim \Lambda_{\rm QCD}$ [Symmetry, Dynamics, or others]

Solution $\Rightarrow$ **Asymmetric Dark Baryon @ $\mathcal{O}(1)$ GeV**

direct detection

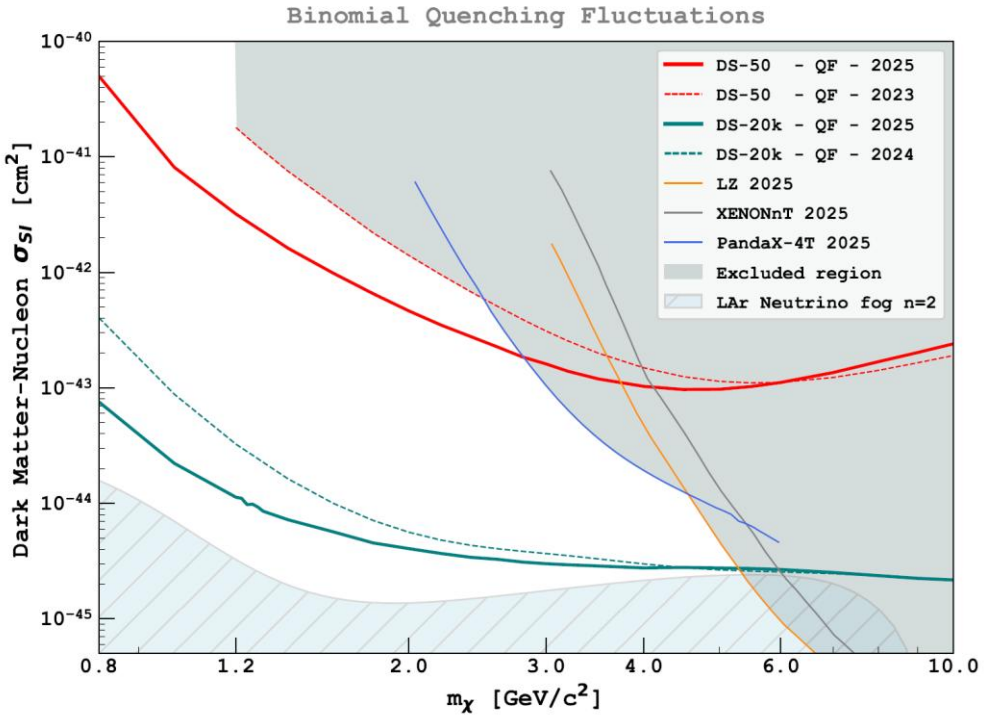
+

Dark Mesons!!

collider searches

Complementary searches of Dark QCD Sector

- $\mathcal{O}(1)$-GeV Dark Baryon D
- Direct Detection experiments



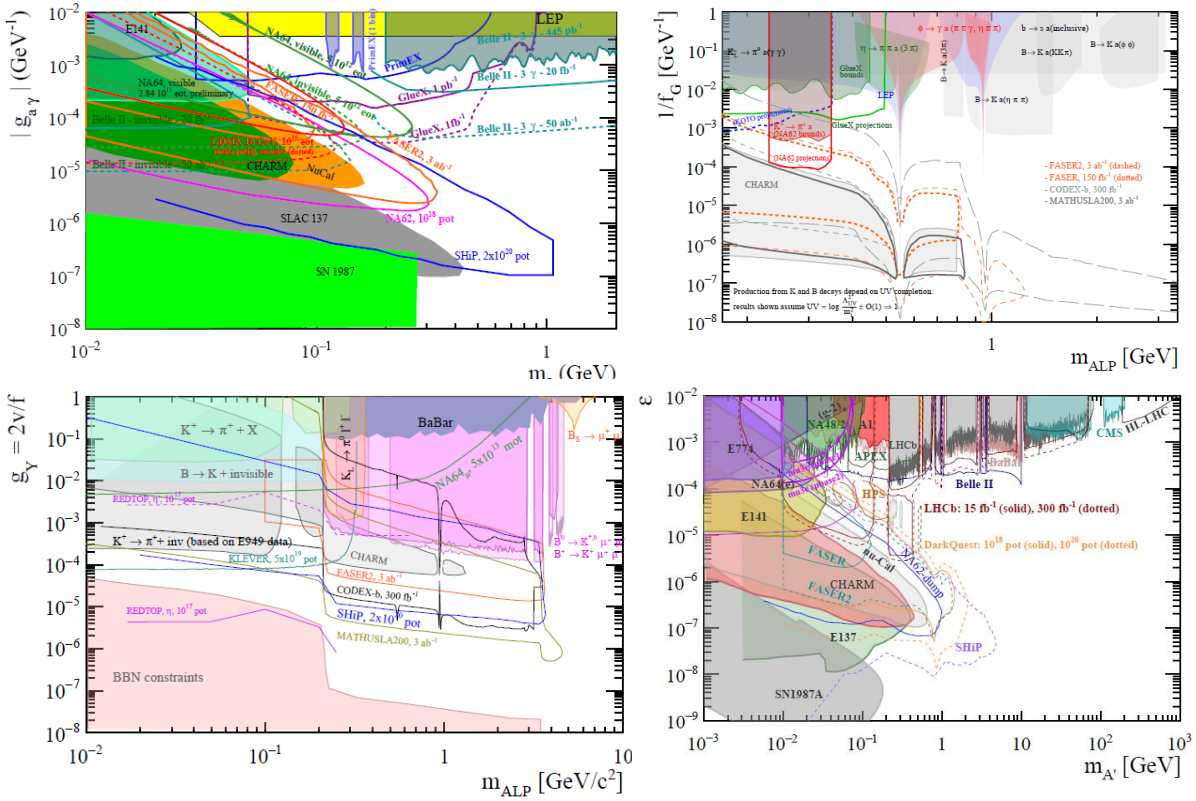
2511.13629 by DarkSide Collaboration

Mass
Coupling
Decay const.

$\Leftrightarrow$

Dark QCD
$(\Lambda_{\mathrm{dQCD}}, m_\chi)$

- (Sub-)GeV Dark Meson : π', ρ', η'
- Collider-based and beam-dump experiments



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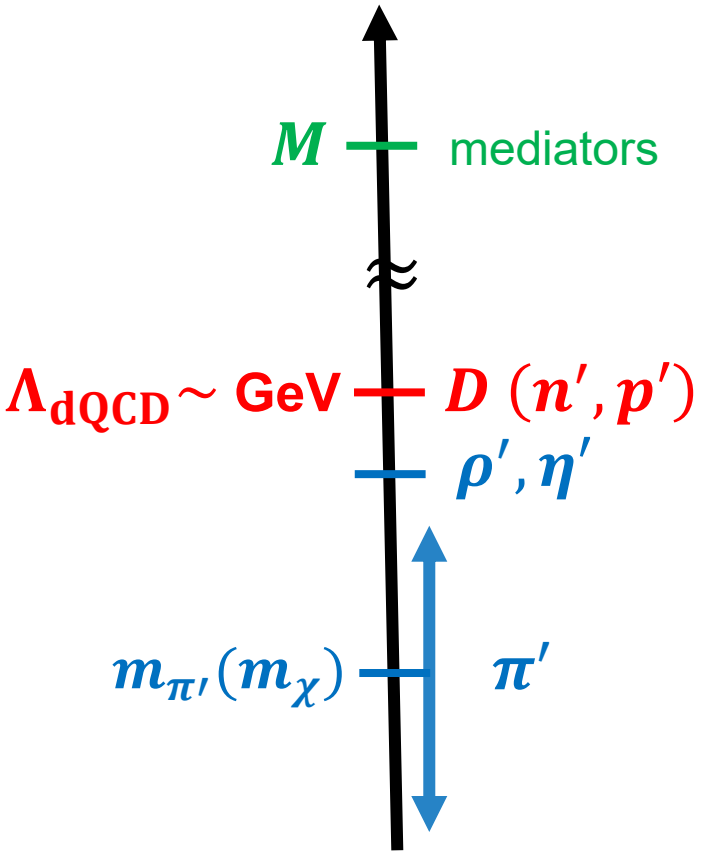
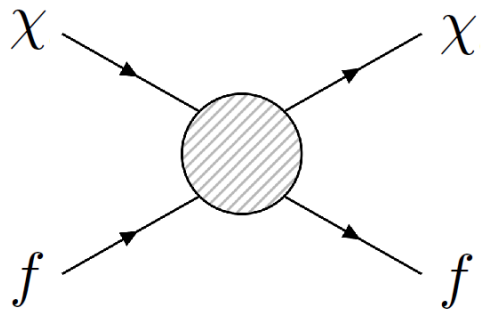
$SU(3)_D$ with $N_F = 2$ via the fermion portal

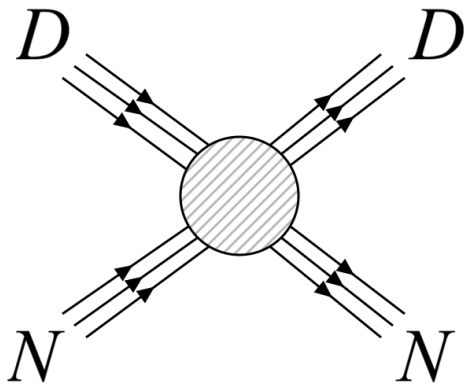
- Dark QCD Spectrum + Fermion Portal $\Longrightarrow$ (1) Direct Detection of $D\ (n', p')$



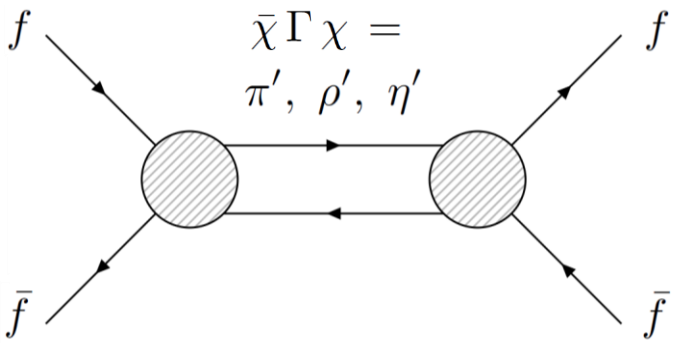


in this talk, we consider

$$\frac{1}{M^2}\left(\bar{\chi}_L\gamma_\mu\chi_L\right)\left(\bar{f}_R\gamma^\mu f_R\right)$$

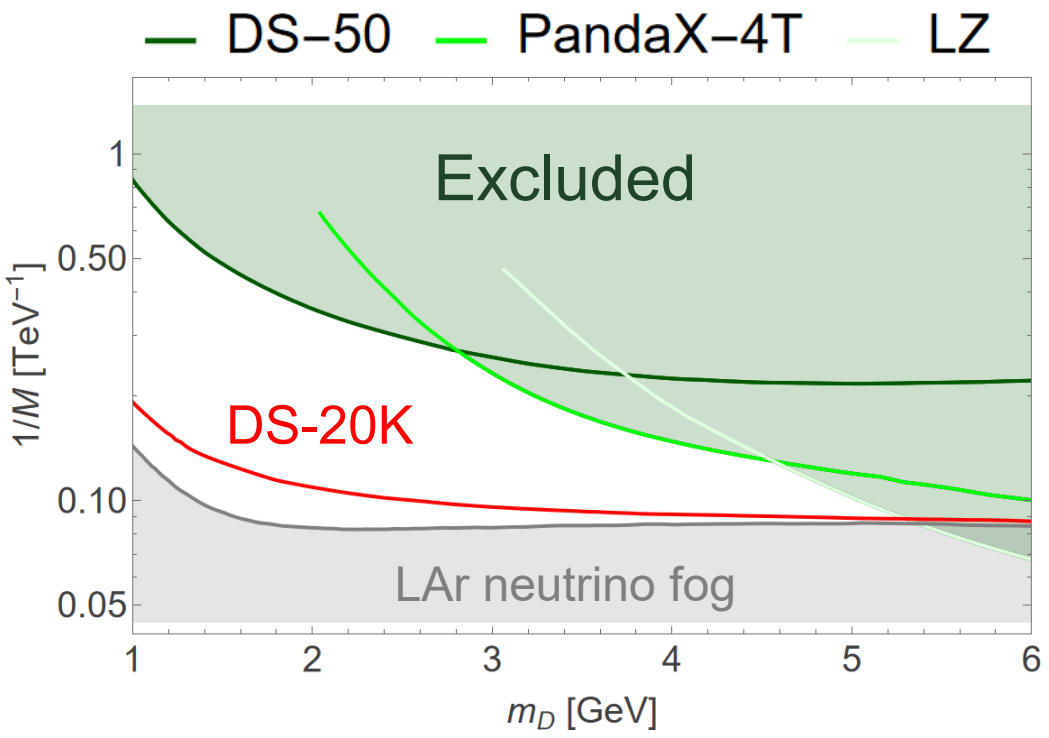


(2) Collider Searches of π', ρ', η'

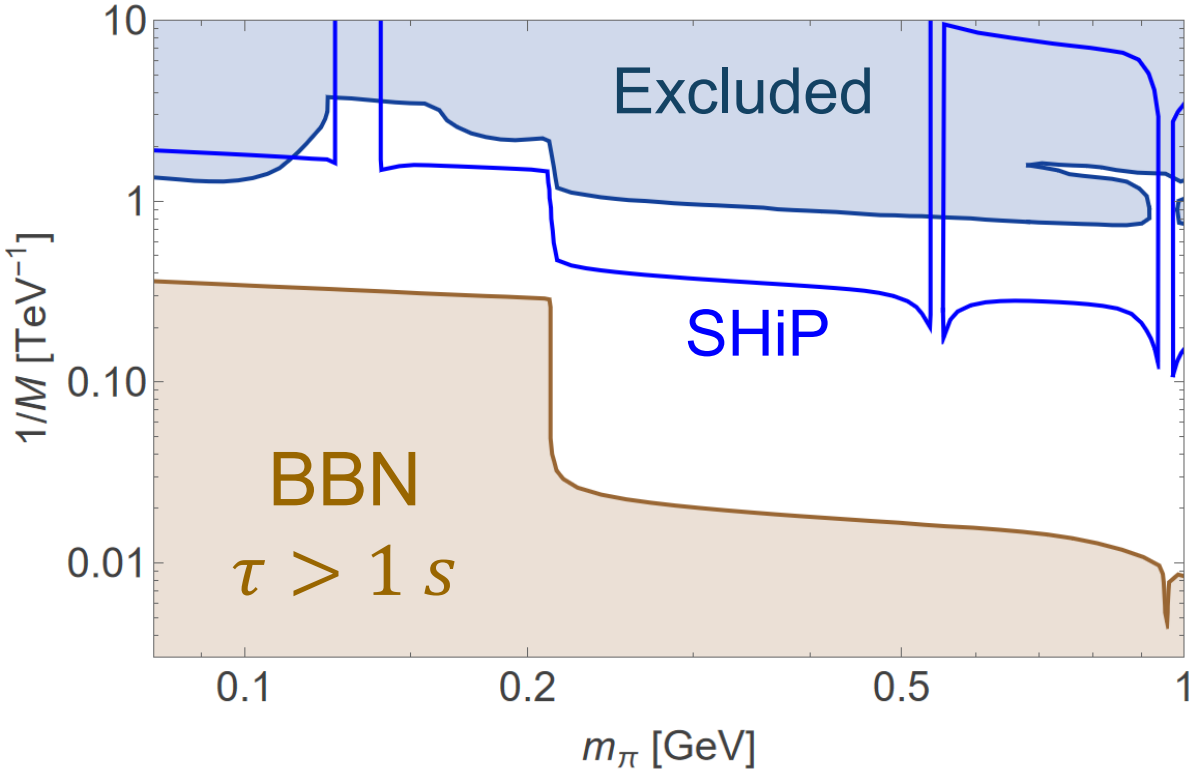


Constraint on the scale of mediator M

- $\mathcal{O}(1)$-GeV Dark Baryon D
- Direct Detection experiments

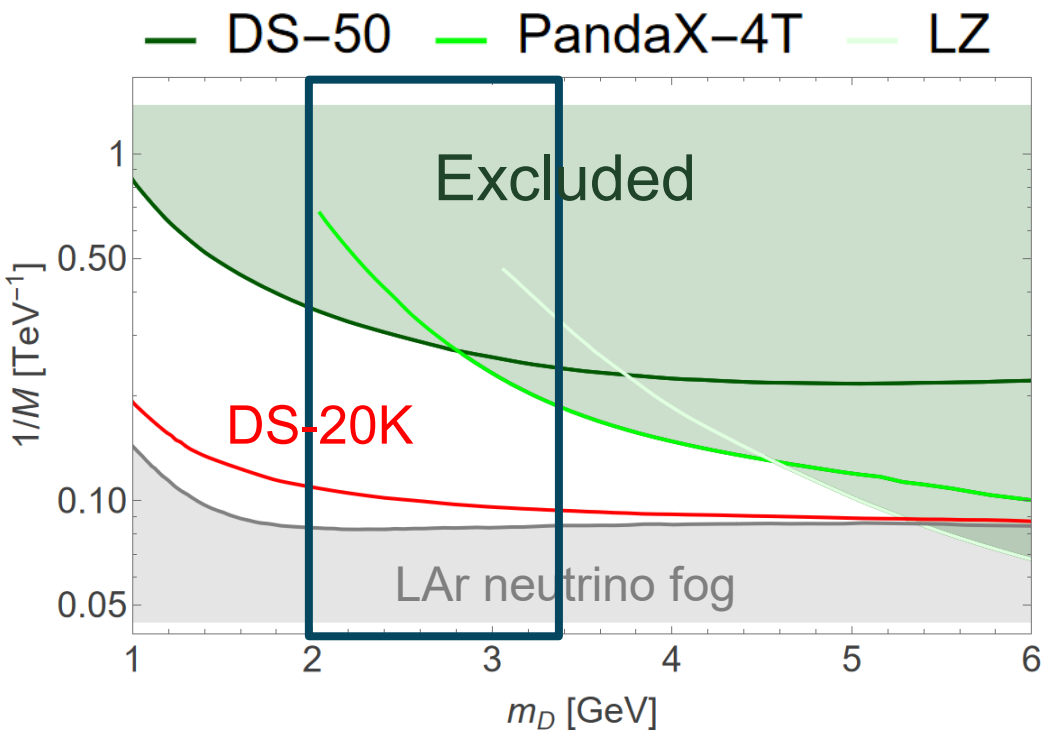


- Sub-GeV Dark Pion π'
- Collider-based and beam-dump experiments



Complementary searches of Dark QCD Sector

- $\mathcal{O}(1)$-GeV Dark Baryon D
- Direct Detection experiments



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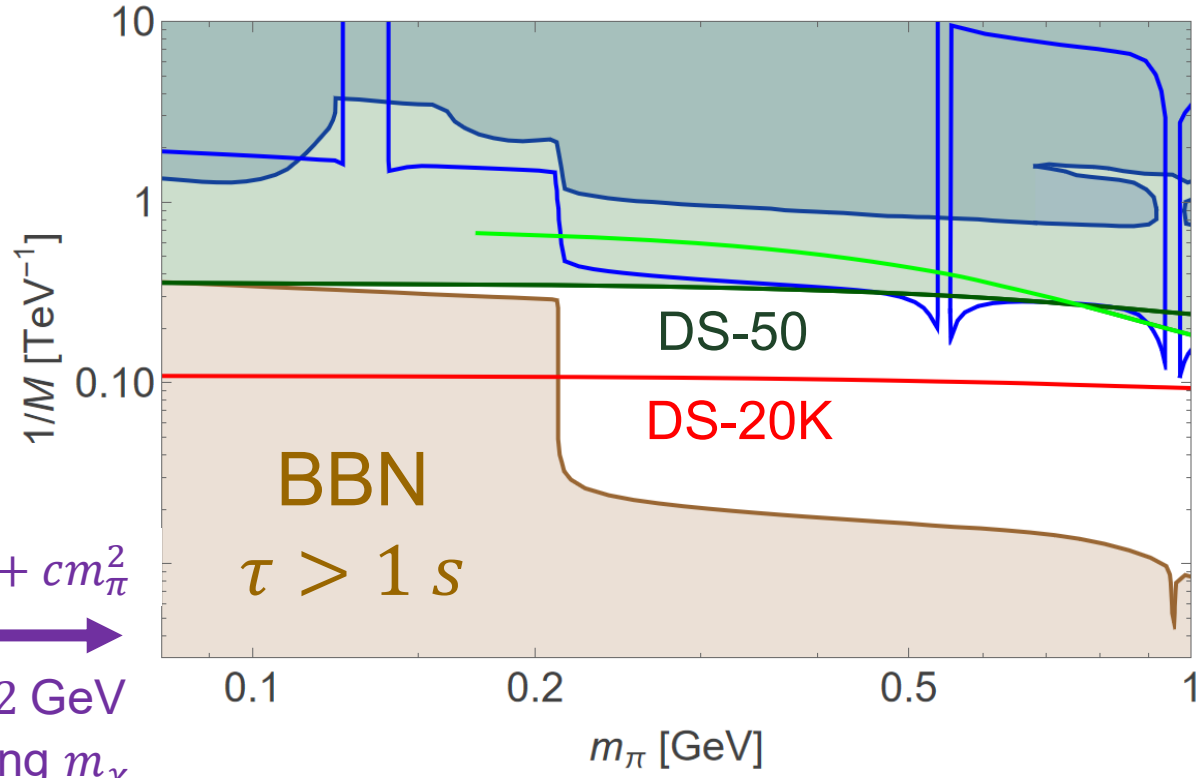


$m_D = m_0 + cm_\pi^2$

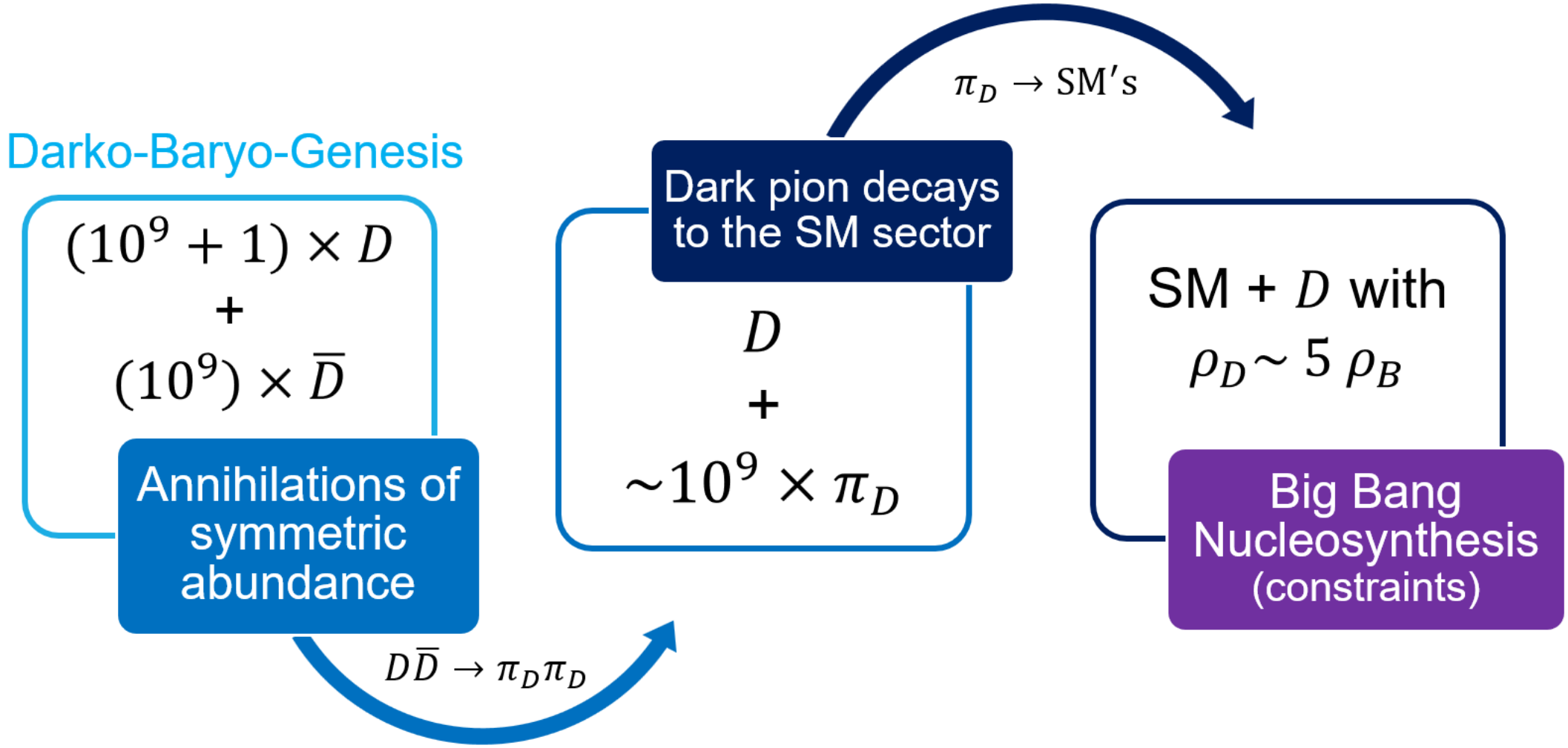
$\Lambda_{\mathrm{dQCD}} = 2$ GeV with varying m_χ

Summary

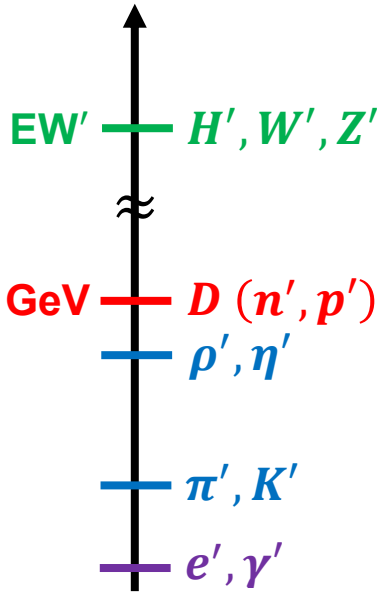
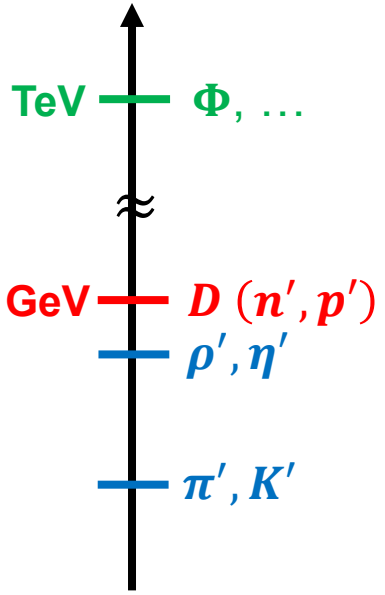
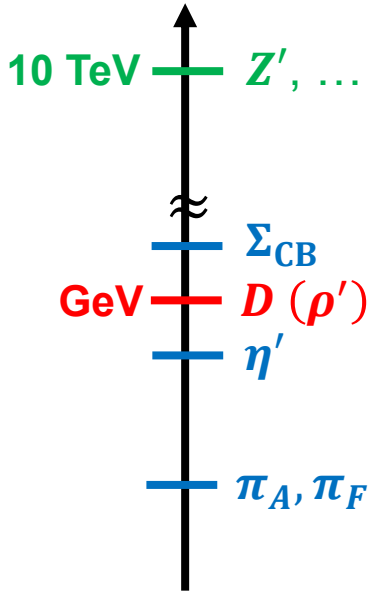
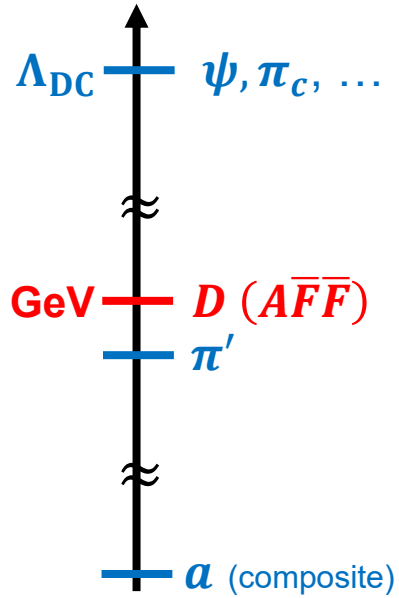
- **Problem**
  - The **Dark Matter – Baryon Coincidence** is a nontrivial condition
  - This $\mathcal{O}(1)$ ratio might not a coincidence but a hint to probe the nature of Dark Matter
- **Solution & Signature**
  - The typical solutions requires **$\mathcal{O}(1)$-GeV Asymmetric Dark Baryon as Dark Matter**
  - It also implies an existence of a complete dark QCD sector including Dark Mesons
  - **Direct detection** and **collider searches** provide complementary searches
- **Future prospect**
  - There are also other resonances that can be look for, such as **dark vector meson ρ'**
  - It also predicts sizable **dark matter self-interaction** that might explain small-scale structure

Back up

Cosmology of Asymmetric Dark Matter



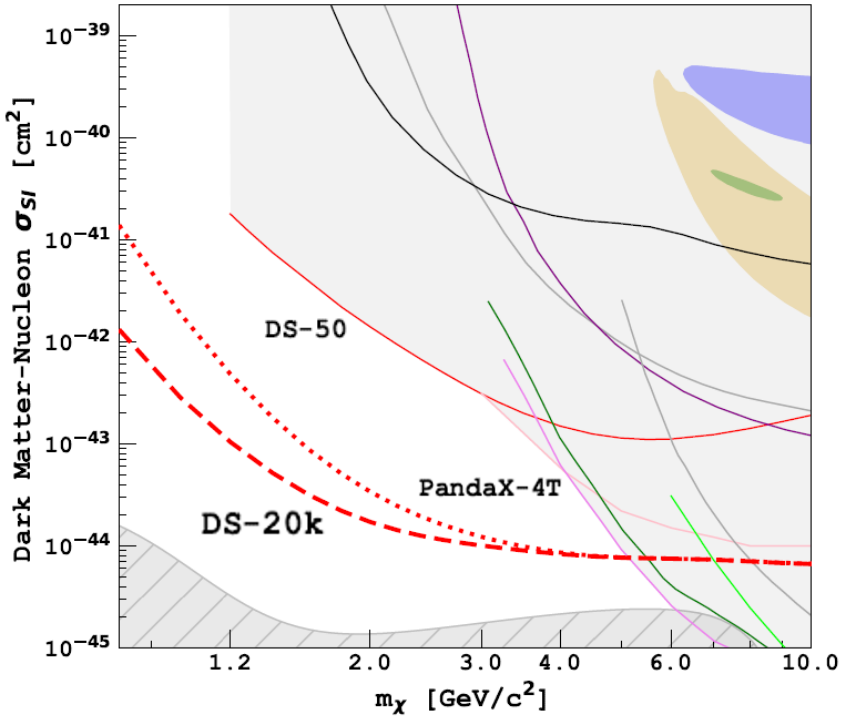
Strongly Coupled Dark Sectors from DMBC

	Mirror Dark Sector	IR Fixed Point	Dark GUT	Chiral Dark Sector
Dark Color	SU(3)	SU(3)	Sp(4)	SU(5)
Dark Quarks	u', d', c', s', t', b'	$6 \times (F, \bar{F})$	$3 \times (A, F, \bar{F})$	$A, F, \bar{F}$
additional	+ leptons, photon...	bi-fund. fields	heavy Z' boson	composite axion
Spectrum other heavy states (mediate SM-DS) **Dark Baryon** other resonances from dark color other light states				

Different Ex.: Dark Baryon + Dark Photon (A)

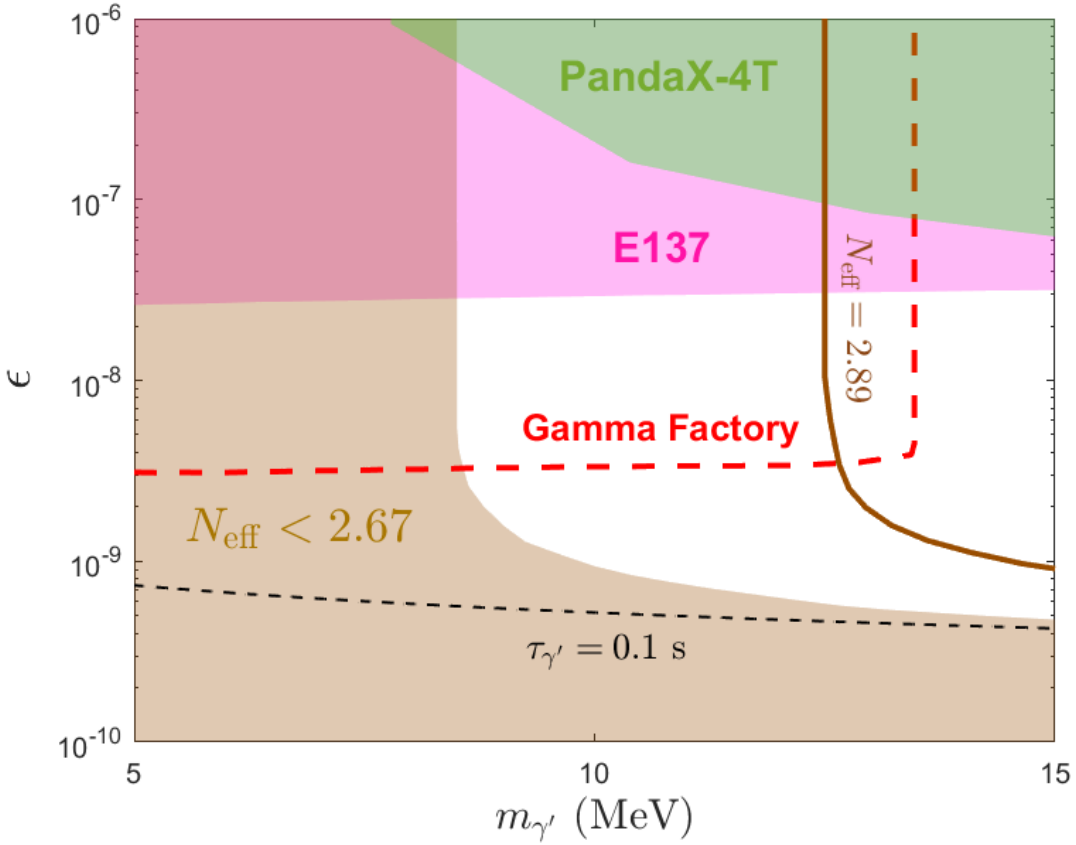
- Solution to the coincidence problem =

$\mathcal{O}$(1)-GeV Asymmetric Dark Baryon Dark Matter + **Dark photon γ' (axial-vectorial)**



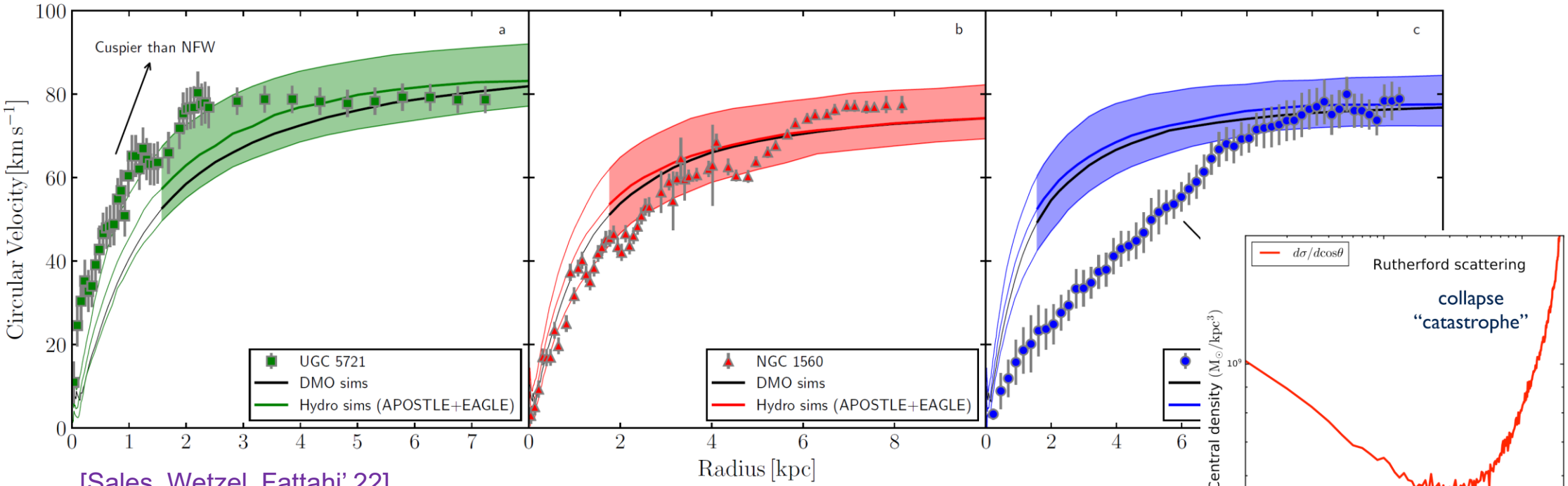
[DarkSide 2407.05813]

SIDM fitting



Diversity problem and Collapsed SIDM Halo

- Diversity of rotation curves are observed from more steeply raising than NFW (UGC 5721), to well described by an NFW profile (NGC 1560), to showing a very extended core (IC 2574).



[Sales, Wetzel, Fattahi' 22]

- Can be explained by core collapsed Self-interacting Dark Matter halo??