



Strongly Coupled Dark Sectors from the Dark Matter–Baryon Coincidence

based on arXiv: 2411.16860, 2411.18725

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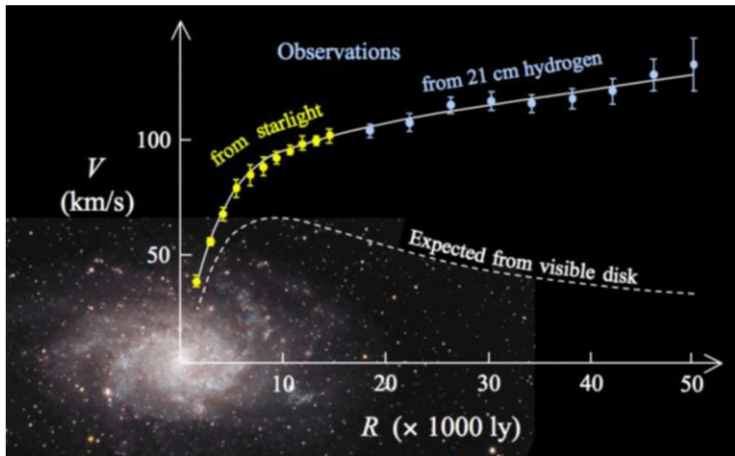
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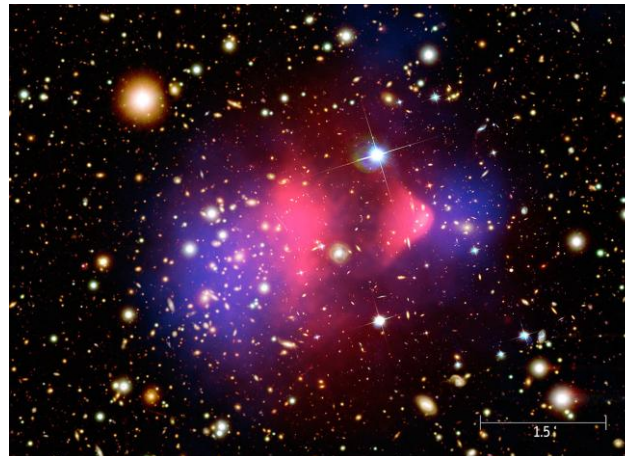
What do we know about Dark Matter?

- Dark Matter need to be
 - (1) Cold (non-relativistic)
 - (2) Dark (not interact with photons)
 - (3) Collision-less
 - (4) Stable / Long-lived

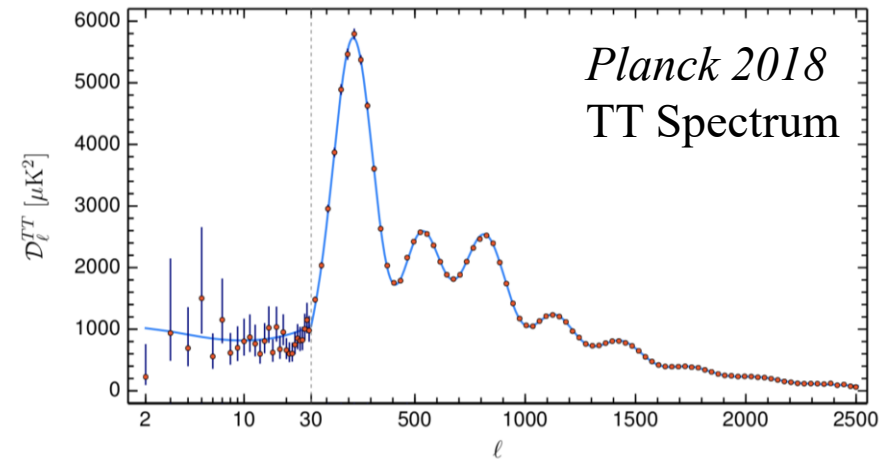
$$+ \quad \rho_D \approx 2.3 \times 10^{-30} \text{ g/cm}^3$$



Galaxy rotation curves

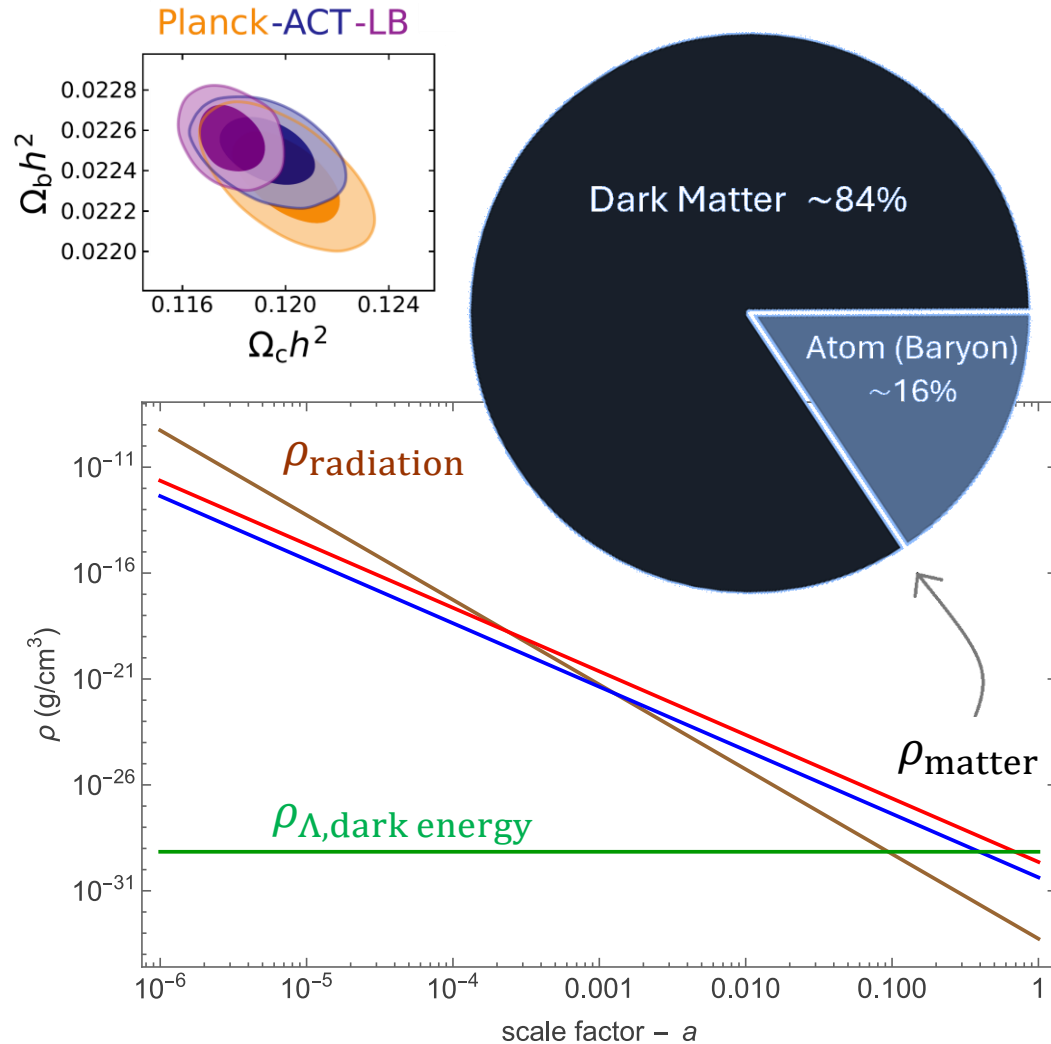


Merging galaxy clusters



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

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

More about the DM – Baryon Coincidence

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

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

- For comparison,

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

$\sim 7 \because SU(2)_F$ $\sim 1 \because SU(2)_F$

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

$\sim 1 \because U(1)_{EM}$ ~ 1800

More about the DM – Baryon Coincidence

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

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

from unknown Baryogenesis from QCD confinement

- For comparison,

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

$\sim 7 \because SU(2)_F$ $\sim 1 \because SU(2)_F$

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

$\sim 1 \because U(1)_{EM}$ ~ 1800

Previous attempts: Asymmetric Dark Matter

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

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

- For comparison,

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

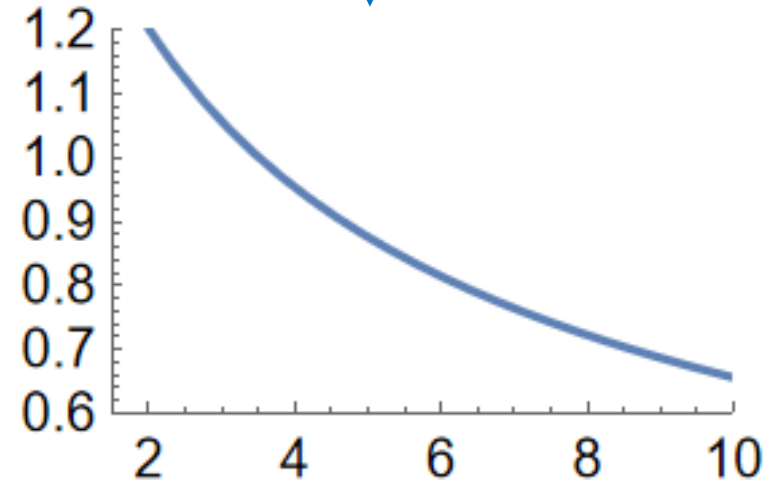
$$\rho_p / \rho_e = \underbrace{n_p / n_e}_{\sim 1 \because U(1)_{EM}} \times \underbrace{m_p / m_e}_{\sim 1800} = 1800$$

Previous attempts: Asymmetric Dark Matter

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

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

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



$$m_B \sim \Lambda_{\text{QCD}} = 4\pi \times v_{\text{QCD}} \quad (f_\pi = 92 \text{ MeV})$$

Toward Comparable DM and Baryon Masses

- A complete solution to the problem should also predict $m_D = Y_D v_D \sim m_B = 4\pi v_{\text{QCD}}$

$$\frac{\rho_D}{\rho_B} = \frac{n_D}{n_B} \times \frac{m_D}{m_B} = \frac{n_D}{n_B} \times \left(\frac{Y_D}{4\pi} \times \frac{v_D}{v_{\text{QCD}}} \right) = 5 \text{ !?}$$

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

A complete solution = Asymmetric

Previous attempts: Dark Baryon Dark Matter

- Dark Baryon DM from strongly coupled dark sectors is another necessary condition.

$Y_D \sim \mathcal{O}(4\pi)$
 if Dark Matter is a Baryon of
Strongly Coupled Dark Sectors

$$\frac{\rho_D}{\rho_B} = \frac{n_D}{n_B} \times \frac{m_D}{m_B} = \frac{n_D}{n_B} \times \left(\frac{Y_D}{4\pi} \times \frac{v_D}{v_{\text{QCD}}} \right) = 5 \text{ !?}$$

$\sim \mathcal{O}(1)$ $\sim \mathcal{O}(1)$ $\sim \mathcal{O}(1)$
 $\because U(1)_{D-B}$ $\because Y_D \sim \mathcal{O}(4\pi)$

A complete solution = Asymmetric Dark Baryon

Toward Comparable DC and QCD VEVs

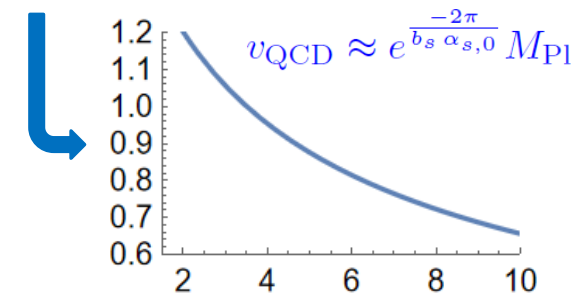
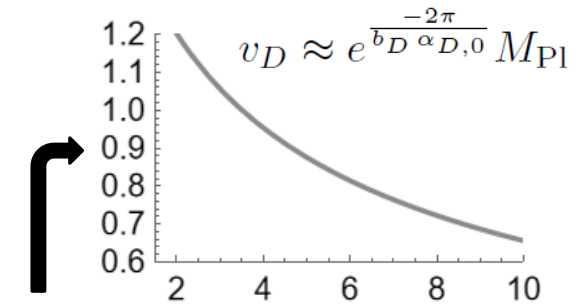
- The last piece of a complete solution is to achieve comparable VEVs, $v_D \sim v_{\text{QCD}}$

How to get $\frac{v_D}{v_{\text{QCD}}} \approx e^{\left(\frac{-2\pi}{b_D \alpha_{D,0}} - \frac{-2\pi}{b_s \alpha_{s,0}}\right)} \approx 535 \left(\frac{\alpha_{s,0}^{-1}}{b_s} - \frac{\alpha_{D,0}^{-1}}{b_D}\right) \rightarrow \mathcal{O}(1)$?

$$\frac{\rho_D}{\rho_B} = \frac{n_D}{n_B} \times \frac{m_D}{m_B} = \frac{n_D}{n_B} \times \left(\frac{Y_D}{4\pi} \times \frac{v_D}{v_{\text{QCD}}} \right) = 5 !?$$

$\sim \mathcal{O}(1)$ $\sim \mathcal{O}(1)$
 $\because U(1)_{D-B}$ $\because Y_D \sim \mathcal{O}(4\pi)$

A complete solution = Asymmetric Dark Baryon



Toward Comparable DC and QCD VEVs

- The last piece of a complete solution is to achieve comparable VEVs, $v_D \sim v_{\text{QCD}}$

How to get $\frac{v_D}{v_{\text{QCD}}} \approx e^{\left(\frac{-2\pi}{b_D \alpha_{D,0}} - \frac{-2\pi}{b_s \alpha_{s,0}}\right)} \approx 535 \left\{ \frac{\alpha_{s,0}^{-1}}{b_s} - \frac{\alpha_{D,0}^{-1}}{b_D} \right\} \rightarrow \mathcal{O}(1)$?

$\sim \mathcal{O}(0.1)$

But $\sim \mathcal{O}(1)$

Ex: $b_s = 7, g_{s,0}: 0.8 \rightarrow 0.7 \Rightarrow 200$

It is essentially a fine-tuning problem!!

$$\frac{\rho_D}{\rho_B} = \frac{n_D}{n_B} \times \frac{m_D}{m_B} = \frac{n_D}{n_B} \times \left(\frac{Y_D}{4\pi} \times \frac{v_D}{v_{\text{QCD}}} \right) = 5 !?$$

$\sim \mathcal{O}(1)$ $\sim \mathcal{O}(1)$

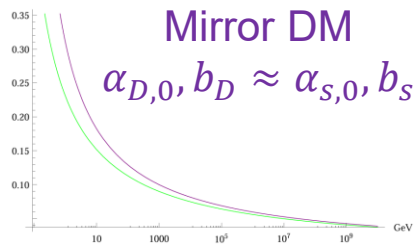
$\because U(1)_{D-B}$ $\because Y_D \sim \mathcal{O}(4\pi)$

A complete solution = Asymmetric Dark Baryon

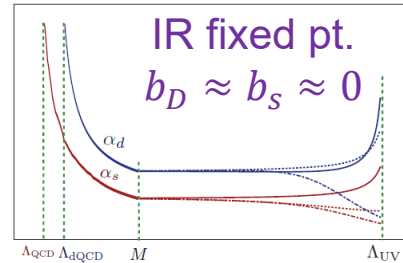
Attempts: Mirror / IRFP / Dark GUT / Chiral DS

- Many attempts have been made to achieve $v_D \sim v_{\text{QCD}}$ with mechanisms

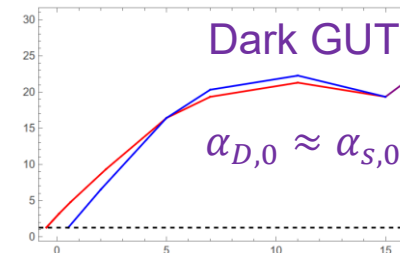
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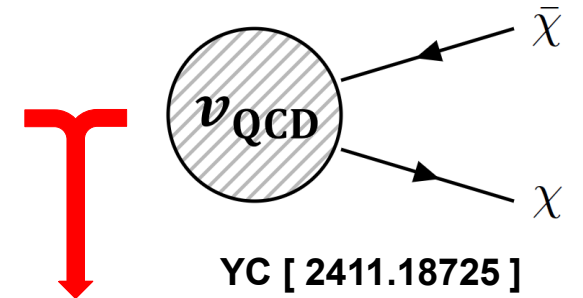
Volkas, Foot, ... '03...



Bai, Schwaller '13



YC [2411.16860]



$$\frac{\rho_D}{\rho_B} = \frac{n_D}{n_B} \times \frac{m_D}{m_B} = \frac{n_D}{n_B} \times \left(\frac{Y_D}{4\pi} \times \frac{v_D}{v_{\text{QCD}}} \right) = 5 !?$$

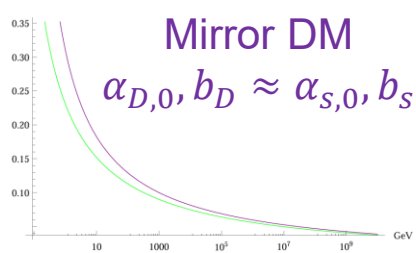
$\sim \mathcal{O}(1)$ $\sim \mathcal{O}(1)$ $\sim \mathcal{O}(1) \because v_D \sim v_{\text{QCD}}$
 $\because U(1)_{D-B}$ $\because Y_D \sim \mathcal{O}(4\pi)$ from Sym. or Dynamics

A complete solution = Asymmetric Dark Baryon + $v_D \sim v_{\text{QCD}}$ mech.

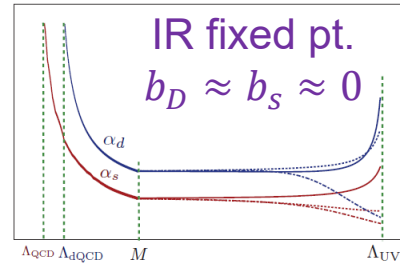
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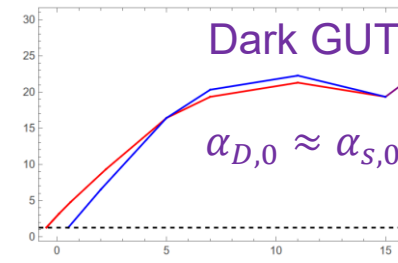
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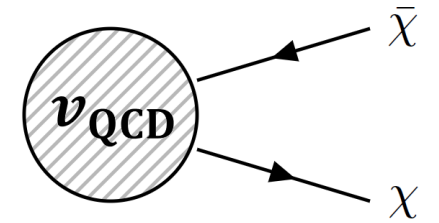
Volkas, Foot, ... '03...



Bai, Schwaller '13



YC [2411.16860]



YC [2411.18725]

QCD-like (Vector-like) Strongly Coupled Dark Sector
Dark Baryons with $m_D = 4\pi v_D$. For $v_D \sim v_{\text{QCD}} \Rightarrow m_D \sim m_B$

Chiral SCDS
Light Dark Baryon
with $m_D = 4\pi \epsilon$
 $\epsilon \sim v_{\text{QCD}} \Rightarrow m_D \sim m_B$

The requirement of a mechanism to achieve $v_D \sim v_{\text{QCD}}$ points toward different classes of Strongly Coupled Dark Sectors

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	<p>other heavy states (mediate SM-DS)</p> <p>Dark Baryon other resonances from dark color</p> <p>other light states</p>			