Composite dark axions and light dark baryons

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Based on arXiv:1808.xxxxx

Introduction
Introduction

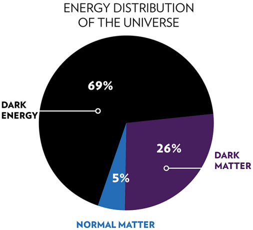
A model for light DM and DR

Conclusion and outlook

Dark Matter Paradigms

- Most stuffs in the universe are dark. (Planck 2018)

Figure: HST



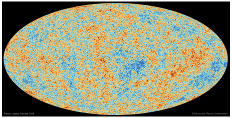


Figure: Planck 2018

What we know about dark matter:

- DM has about 5 times the mass density of baryons.
- Dark but massive ($m =???$)

Figure: Megering galaxy clusters (Abell 520)

- Can't interact too strongly with QED and QCD.
- Doesn't interact too strongly with itself.

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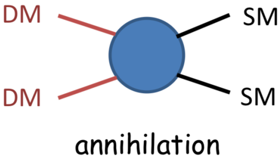
WIMP miracle

- Weakly interacting massive particles (Lee+Weinberg, 1977)



$$\langle \sigma v \rangle = \frac{\alpha^2}{m_{\rm DM}^2}$$

$$m_{\rm DM} \sim 100 \text{ GeV}$$

WIMP DM for last 40 years

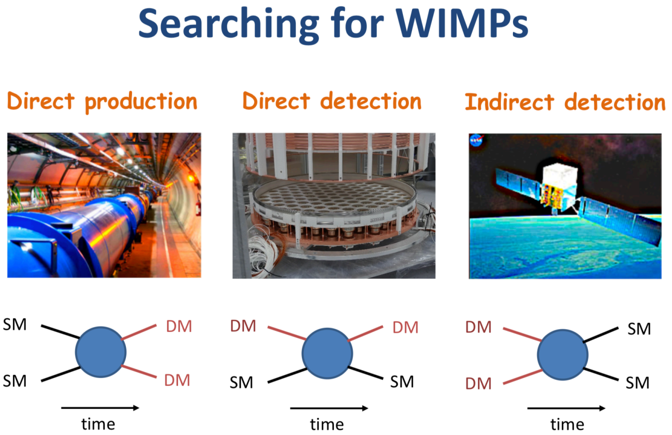
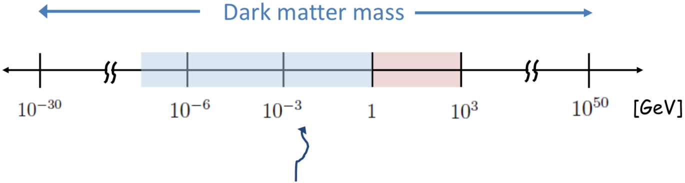


Figure: Hochberg at CERN BSM 2018

Openning windows for DM

Beyond the WIMP



Lots of activity in recent years:

Theory & Experiment

A model for Multi-component DM and DR (DKH 2018)

- Consider $\mathrm{SU}(5)$ gauge theory with dark quarks in mixed representations.

	$\mathrm{SU}(5)$	$\mathrm{SU}(2)^f$	$\mathrm{SU}(2)^{as}$	$\mathrm{U}(1)_B$	$\mathrm{U}(1)_A$	$\mathrm{U}(1)_{\mathrm{em}}$
q_i^a	$\square$	$\square$	1	$1/5$	q_f	$2/5$
Q_{ij}^α	$\begin{smallmatrix}\square\\\square\end{smallmatrix}$	1	$\square$	$2/5$	q_{as}	$-1/5$
χ^a	1	$\square$	1	1	$q_f + 2q_{as}$	0

- The model has $G_f \otimes G_{as}$ chiral symmetries:

$$G_f = \mathrm{SU}(2)_L^f \otimes \mathrm{SU}(2)_R^f, \quad G_{as} = \mathrm{SU}(2)_L^{as} \otimes \mathrm{SU}(2)_R^{as}$$

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A very light dark axion

- The chiral symmetry of decuplet Q_{ij}^{α} is spontaneously broken at $\Lambda \sim \mathrm{confinement\,scale}$:

$$\left\langle Q_\alpha \bar{Q}_\beta \right\rangle = \Lambda^3 \delta_{\alpha\beta}$$

$$\mathrm{SU}(2)_L^{as} \otimes \mathrm{SU}(2)_R^{as} \mapsto \mathrm{SU}(2)_V \,,$$

- $\mathrm{U}(1)_A$ is non-anomalous by construction and is spontaneously broken together with G_{as}.
- There are 4 Nambu-Goldstone bosons: π^A $(A = 1, 2, 3)$ and dark-axion a with mass, assuming $m_U \ll m_D$

$$m_a = \frac{f_\pi m_\pi}{f_a/6} \cdot \frac{\sqrt{m_U m_D}}{m_U + m_D} \ll m_\pi \,.$$

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- Dark axion decays into two photons:

$$\mathcal{L}_{a\gamma\gamma} = \frac{c_\gamma}{32\pi^2} \cdot \frac{6a}{f_a} F_{\mu\nu}\tilde{F}^{\mu\nu} \,,$$

- Life time of dark axions, $g_{a\gamma} = 216\alpha/5\pi f_a$:

$$\Gamma_{a\to\gamma\gamma} = \frac{g_{a\gamma}^2 m_a^3}{64\pi} \simeq 5\times 10^{-22}\,\mathrm{s}^{-1}\left(\frac{m_a}{10^{-3}\ \mathrm{eV}}\right)^3 \cdot \left(\frac{1\ \mathrm{TeV}}{f_a}\right)^2 ,$$

- The dark-axions with $m_a < 1.6\times 10^{-2}$ eV live longer than the age of the universe for $f_a = 1$ TeV .
- Since they couple to SM particles at one-loop, unless $m_a > \mathcal{O}(1)$ keV, from the stellar cooling constraints

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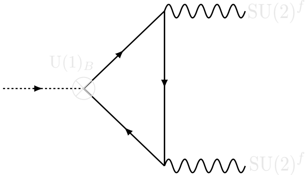
Light dark baryons

- The chiral symmetry of q_i^α is NOT spontaneously broken, however, by 't Hooft anomaly matching.
- The flavor anomalies of q_i^α is saturated in IR by massless spin 1/2 chimera baryons:

$$\chi^a \sim \epsilon_{\alpha\beta} q_i^a Q_{jk}^\alpha Q_{lm}^\beta \epsilon^{ijklm} ,$$

- The coefficients of the UV and IR anomalies match,

$$A_{\rm UV}^{ab} = \frac{1}{5} \cdot 5\,{\rm Tr}\left(\tau^a \tau^b\right), \quad A_{\rm IR}^{ab} = 1 \cdot {\rm Tr}\left(\tau^a \tau^b\right) ,$$



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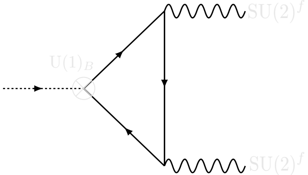

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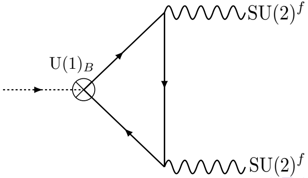

Mass and magnetic moment of chimera baryons

- Dark (chimera) baryons are massless in the chiral limit:

$$m_\chi \sim m_q \ll \Lambda$$

- The dark-baryons are neutral but have magnetic dipole moment, μ_χ, when chiral symmetry is broken, $m_q \neq 0$:

$$\mu_\chi = g\frac{e}{2m_\chi}, \quad g = \kappa\frac{m_\chi^2}{\Lambda^2},$$

where $\kappa = \mathcal{O}(1)$.

- Dark-baryons in our model belongs to dipolar DM but with **naturally** small magnetic moments.

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Dark baryons as Dark radiation

- Up dark-baryon can be made very light or massless by taking $m_q = (m_u \approx 0, m_d)$.
- In the chiral limit the Pauli form factor $F_2(q^2) = 0$ and thus the magnetic dipole moment $\mu_\chi = F_2(0)$ vanishes:

$$\bar{u}_\chi(p') \left[\gamma^\mu F_1(q^2) + \frac{i\sigma^{\mu\nu} q_\nu}{2m_\chi} F_2(q^2) \right] u_\chi(p) \, .$$

- Very light dark-baryons still couple to SM particles, since the Dirac form factors $F_1(q^2) \neq 0$ though $F_1(0) = 0$:

$$\frac{e\, c_d}{\Lambda^2} \bar{\chi} \gamma_\mu \chi \partial_\nu F^{\mu\nu} \, ; \quad \frac{e^2 c_d}{\Lambda^2} \bar{\chi} \gamma^\mu \chi \, \bar{\psi}_e \gamma_\mu \psi_e$$

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Dark radiation

- The ratio of the interaction rate to the expansion rate

$$\frac{\Gamma_{int}}{H} \sim \frac{e^4 c_d^2 T^5/\Lambda^2}{T^2/m_{pl}} = \left(\frac{T}{T_\chi}\right)^3 ,$$

where the decoupling temperature of massless dark-baryons

$$T_\chi \simeq 0.06 \text{ GeV} \left(\frac{\sqrt{c_d}\,\Lambda}{1 \text{ GeV}}\right)^{4/3} .$$

- The contribution from the massless dark-baryons to the radiation energy ($g = 4$)

$$\Delta N_{\text{eff}} = \frac{13.56}{g_*^s(T_\chi)^{4/3}} \cdot g \lesssim 0.12 \quad \text{for} \quad \Lambda \gtrsim 3 \text{ GeV} .$$

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Results of light Dark-baryon model

- Our model accommodates dark radiation, light dark-baryons or very light dark-axions, which contribute significantly to relic density, depending on the confinement scale, Λ:

$$\Omega_m h^2 \sim 0.12, \quad \Delta N_{\rm eff} \sim 0.1$$

	$\Lambda = 1 - 10^{-2}$ TeV	$\Lambda = 200$ MeV	$\Lambda \gtrsim 10^7$ GeV
χ_u	≈ 0	≈ 0	≈ 0
χ_d	$\sim 1 - 10^3$ MeV	10 eV	$\times$
a	$\times (> \text{keV})$	$\times (> \text{keV})$	$\lesssim 10$ eV

Dark axion ad QCD axion

- If we identify $\mathrm{U}(1)_A$ as the $\mathrm{U}(1)_{\mathrm{PQ}}$ Peccei-Quinn symmetry, the electroweak single PQ field of DFSZ model is then a composite field of decuplet dark-quarks:

$$\phi_{\mathrm{PQ}} \sim \bar{Q}Q\,,.$$

- The confining scale is then

$$\Lambda \sim f_{\mathrm{PQ}} \sim 10^9 - 10^{12}\ \mathrm{GeV}\,.$$

- The dark baryons are too weakly interacting, $g \sim m_\chi^2/\Lambda^2 \ll 1$.

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Conclusion and outlook

- We propose a model for light DM and dark radiation, which has a light dark-baryons, very light dark-axions, and almost massless dark-baryon.
- The model supports massless spin 1/2 chimera baryons that saturate the flavor anomaly:

$$\chi^a \sim \epsilon_{\alpha\beta} q_i^a Q_{jk}^{\alpha} Q_{lm}^{\beta} \epsilon^{ijklm} ,$$

- Dark baryons are light or almost massless because of unbroken chiral symmetry.
- Dark baryons are neutral but carry a magnetic moment,

$$\mu_\chi = g \frac{e}{2m_\chi}, \quad g \approx \left(\frac{m_\chi}{\Lambda}\right)^2 .$$

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$$m_a \lesssim 10 \text{ eV} \quad \text{for} \quad \Lambda \gtrsim 10^7 \text{ GeV} .$$

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