A model of light dark baryons and dark radiation

Deog Ki Hong

Pusan National University, Busan, Korea

February 26, 2019

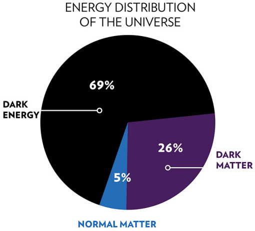
YuCHE 2019, Yonsei Univ., Seoul

arXiv:1808.10149 and work under progress

Dark Matter Paradigms

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

그림: HST



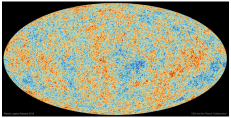


그림: Planck 2018

What we know about dark matter:

- DM has about 5 times the mass density of baryons.
- Dark but massive ($m =$???)
- Can't interact too strongly with QED and QCD.
- Doesn't interact too strongly with itself.

그림: Megering galaxy clusters (Abell 520)

What we know about dark matter:

- DM has about 5 times the mass density of baryons.
- Dark but massive ($m =???$)
- Can't interact too strongly with QED and QCD.
- Doesn't interact too strongly with itself.

그림: Megering galaxy clusters (Abell 520)

What we know about dark matter:

- DM has about 5 times the mass density of baryons.
- Dark but massive ($m =$???)
- Can't interact too strongly with QED and QCD.
- Doesn't interact too strongly with itself.

그림: Megering galaxy clusters (Abell 520)

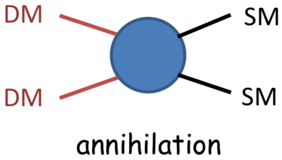
What we know about dark matter:

- DM has about 5 times the mass density of baryons.
- Dark but massive ($m =???$)
- Can't interact too strongly with QED and QCD.
- Doesn't interact too strongly with itself.

그림: Megering galaxy clusters (Abell 520)

WIMP miracle for correct thermal relics

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



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

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

WIMP DM for last 40 years since Lee-Weinberg

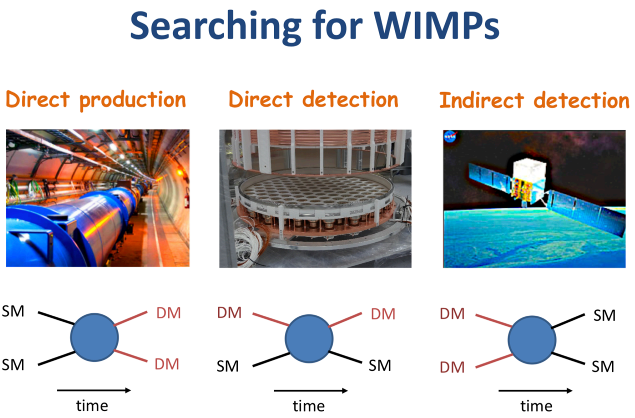
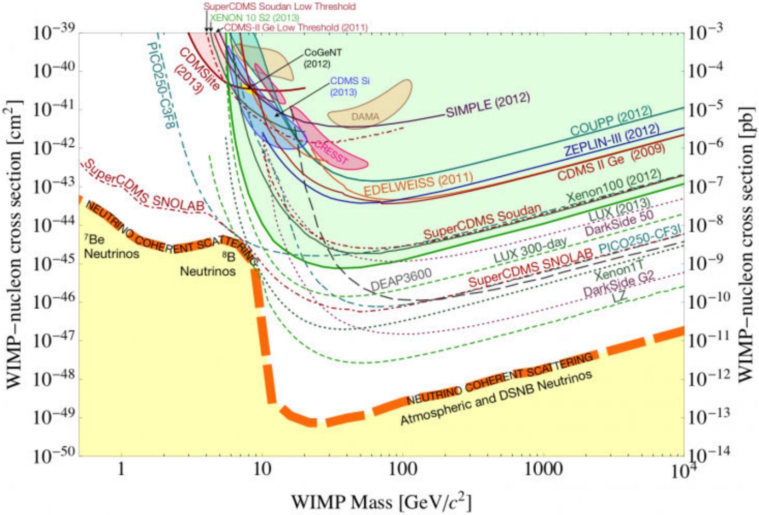
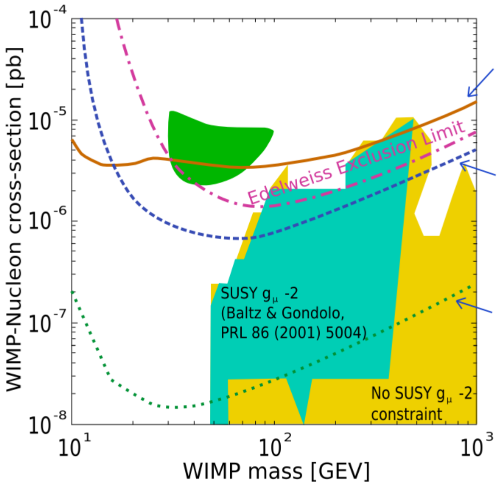


그림: Hochberg at CERN BSM 2018

Search for WIMP DM



Dark Matter Race: CDMS II

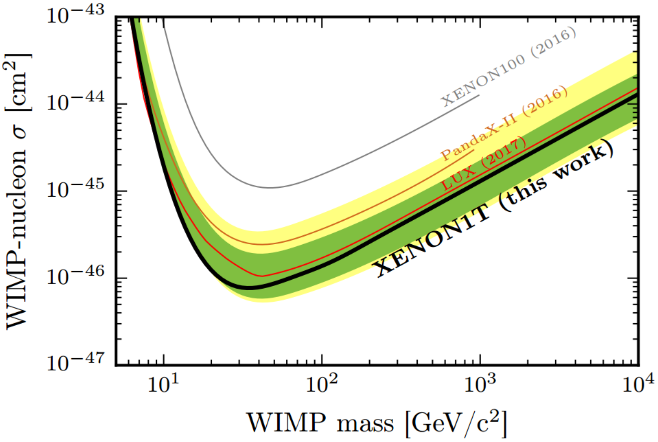


Current CDMS limit

Expected sensitivity of data in hand from first CDMS run at Soudan (5x better than current limit.)

Projected sensitivity for CDMS at Soudan, with 5 towers 4 kg Ge, 1.5 kg Si: 0.1 events/kg/keV/year (100x better than current limit)

Dark Matter Race: XENON1T



Paradigm Shift in DM

Sociology

Dominant paradigm is being challenged.

- Big puzzles
- Great if a solution gives an option for dark matter candidate
- Big ideas: Supersymmetry, extra dimensions...

  Composite Higgs Model

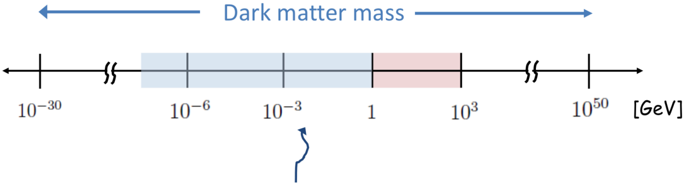
→

- Dark matter exists
- Explain on its own
- Perhaps decoupled from other puzzles
- Think outside the WIMP box

theoretically & experimentally

Openning windows for DM

Beyond the WIMP



Lots of activity in recent years:

Theory & Experiment

Models for naturally light DM

- Particles are light, because of symmetry. ('t Hooft 1979)
- Mass of spinless particle is protected by the shift symmetry:

$$a \to a + constant\,. \quad \text{(axions)}$$

- Mass of spin 1 is protected by gauge symmetry.

$$A_\mu \to A_\mu + \partial_\mu \Lambda\,. \quad \text{(dark photons)}$$

- Spin 1/2 dark baryons? Mass is protected by chiral symmetry, but difficult to realize at low energy.

Models for naturally light DM

- Particles are light, because of symmetry. ('t Hooft 1979)
- Mass of spinless particle is protected by the shift symmetry:

$$a \to a + constant\,. \quad \text{(axions)}$$

- Mass of spin 1 is protected by gauge symmetry.

$$A_\mu \to A_\mu + \partial_\mu \Lambda\,. \quad \text{(dark photons)}$$

- Spin 1/2 dark baryons? Mass is protected by chiral symmetry, but difficult to realize at low energy.

Models for naturally light DM

- Particles are light, because of symmetry. ('t Hooft 1979)
- Mass of spinless particle is protected by the shift symmetry:

$$a \to a + constant\,. \quad \text{(axions)}$$

- Mass of spin 1 is protected by gauge symmetry.

$$A_\mu \to A_\mu + \partial_\mu \Lambda\,. \quad \text{(dark photons)}$$

- Spin 1/2 dark baryons? Mass is protected by chiral symmetry, but difficult to realize at low energy.

Models for naturally light DM

- Particles are light, because of symmetry. ('t Hooft 1979)
- Mass of spinless particle is protected by the shift symmetry:

$$a \to a + constant\,. \quad \text{(axions)}$$

- Mass of spin 1 is protected by gauge symmetry.

$$A_\mu \to A_\mu + \partial_\mu \Lambda\,. \quad \text{(dark photons)}$$

- Spin 1/2 dark baryons? Mass is protected by chiral symmetry, but difficult to realize at low energy.

A model for light DM and DR (DKH 2018)

- We propose a model for spin 1/2 dark baryons based on dark $\mathrm{SU}(5)$ with confining scale $\Lambda = 10\ \mathrm{GeV} \sim 1\ \mathrm{TeV}$:

$$m_\chi = 1\ \mathrm{MeV} \sim 1\ \mathrm{GeV}$$

- The mass is protected by chiral symmetry. The $\mathrm{SU}(5)$ is confined but chiral symmetry is not spontaneously broken.
- The dark-baryons are neutral but have magnetic moment

$$\mu_\chi = g\frac{e}{2m_\chi}, \quad g = \kappa\frac{m_\chi^2}{\Lambda^2}, \quad \kappa = \mathcal{O}(1).$$

A model for light DM and DR (DKH 2018)

- We propose a model for spin 1/2 dark baryons based on dark $\mathrm{SU}(5)$ with confining scale $\Lambda = 10\ \mathrm{GeV} \sim 1\ \mathrm{TeV}$:

$$m_\chi = 1\ \mathrm{MeV} \sim 1\ \mathrm{GeV}$$

- The mass is protected by chiral symmetry. The $\mathrm{SU}(5)$ is confined but chiral symmetry is not spontaneously broken.

- The dark-baryons are neutral but have magnetic moment

$$\mu_\chi = g\frac{e}{2m_\chi}, \quad g = \kappa\frac{m_\chi^2}{\Lambda^2}, \quad \kappa = \mathcal{O}(1)\,.$$

A model for light DM and DR (DKH 2018)

- We propose a model for spin 1/2 dark baryons based on dark $\mathrm{SU}(5)$ with confining scale $\Lambda = 10\ \mathrm{GeV} \sim 1\ \mathrm{TeV}$:

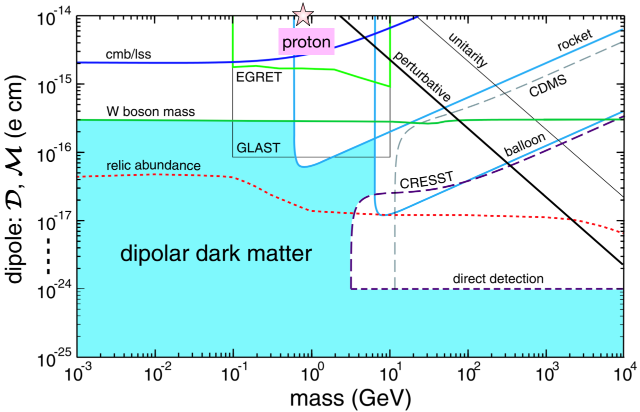
$$m_\chi = 1\ \mathrm{MeV} \sim 1\ \mathrm{GeV}$$

- The mass is protected by chiral symmetry. The $\mathrm{SU}(5)$ is confined but chiral symmetry is not spontaneously broken.
- The dark-baryons are neutral but have magnetic moment

$$\mu_\chi = g\frac{e}{2m_\chi}, \quad g = \kappa\frac{m_\chi^2}{\Lambda^2}, \quad \kappa = \mathcal{O}(1).$$

Dipolar Dark Matter

- Dipolar DM (Sigurdson et al 2004)



Dipolar Dark Matter

- Our model provides a UV complete model for DDM that explains the small MDM naturally.

$$\mu_\chi = g\frac{e}{2m_\chi}, \quad g \sim \frac{m_\chi^2}{\Lambda^2} \sim 10^{-2} - 10^{-12},$$

- Our model has DR and also very light dark axion.

Dipolar Dark Matter

- Our model provides a UV complete model for DDM that explains the small MDM naturally.

$$\mu_\chi = g\frac{e}{2m_\chi}, \quad g \sim \frac{m_\chi^2}{\Lambda^2} \sim 10^{-2} - 10^{-12},$$

- Our model has DR and also very light dark axion.

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

	$\mathrm{SU}(5)$	$\mathrm{SU}(2)^f$	$\mathrm{SU}(2)^{as}$	$\mathrm{U}(1)_B$	$\mathrm{U}(1)_A$	$\mathrm{U}(1)_{\mathrm{em}}$
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:

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

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

	$\mathrm{SU}(5)$	$\mathrm{SU}(2)^f$	$\mathrm{SU}(2)^{as}$	$\mathrm{U}(1)_B$	$\mathrm{U}(1)_A$	$\mathrm{U}(1)_{\mathrm{em}}$
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:

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

A very light dark axion

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

$$\langle Q_\alpha \bar{Q}_\beta \rangle = \Lambda^3 \delta_{\alpha\beta} : \quad \mathrm{SU}(2)_L^{as} \otimes \mathrm{SU}(2)_R^{as} \mapsto \mathrm{SU}(2)_V \,,$$

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

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

A very light dark axion

- The chiral symmetry of decuplet Q^{α}_{ij} is spontaneously broken at $\Lambda \sim \text{confinement scale}$:

$$\langle Q_\alpha \bar{Q}_\beta \rangle = \Lambda^3 \delta_{\alpha\beta} : \quad \mathrm{SU}(2)^{as}_L \otimes \mathrm{SU}(2)^{as}_R \mapsto \mathrm{SU}(2)_V \,,$$

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

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

A very light dark axion

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

$$\langle Q_\alpha \bar{Q}_\beta \rangle = \Lambda^3 \delta_{\alpha\beta} : \quad \mathrm{SU}(2)_L^{as} \otimes \mathrm{SU}(2)_R^{as} \mapsto \mathrm{SU}(2)_V \,,$$

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

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

A very light dark axion

- 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, $g_{a\gamma} = 216\alpha/5\pi f_a$:

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

A very light dark axion

- 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, $g_{a\gamma} = 216\alpha/5\pi f_a$:

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

A very light dark axion

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

$$f_a \sim \Lambda > 3 \times 10^5\ \mathrm{GeV}\,,$$

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:

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

Light dark baryons

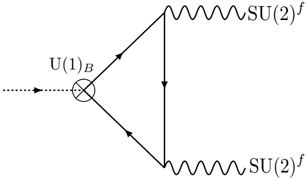
- The chiral symmetry of q_i^α is NOT spontaneously broken, however, by 't Hooft anomaly matching.
- The flavor anomalies of q_i^α is saturated in IR by massless spin 1/2 chimera baryons:

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

Light dark baryons

- The coefficients of the UV and IR anomalies match,

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



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 for $m_q \neq 0$ with $\kappa = \mathcal{O}(1)$:

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

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

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 for $m_q \neq 0$ with $\kappa = \mathcal{O}(1)$:

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

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

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 for $m_q \neq 0$ with $\kappa = \mathcal{O}(1)$:

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

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

Relic abundance of dark baryons

- In the early universe the (electrically charged) dark quarks are in thermal equilibrium with SM particles.
- When the dark SU(5) colors confine, the dark baryons are formed and freeze out at $T_f < \Lambda$:

$$\langle n\sigma v\rangle_{T_f} = H$$

- The freezeout temperature T_f or $x_f \equiv m_\chi / T_f$ is

$$x_f \simeq \ln\left[A/\sqrt{\ln A}\right]$$

where $A = 0.038\sqrt{g_*}\, m_{pl}\, m_\chi\, \langle\sigma v\rangle$.

Relic abundance of dark baryons

- In the early universe the (electrically charged) dark quarks are in thermal equilibrium with SM particles.
- When the dark $\mathrm{SU}(5)$ colors confine, the dark baryons are formed and freeze out at $T_f < \Lambda$:

$$\langle n\sigma v \rangle_{T_f} = H$$

- The freezeout temperature T_f or $x_f \equiv m_\chi / T_f$ is

$$x_f \simeq \ln\left[A/\sqrt{\ln A}\right]$$

where $A = 0.038\sqrt{g_*}\, m_{pl}\, m_\chi \, \langle \sigma v \rangle$.

Relic abundance of dark baryons

- In the early universe the (electrically charged) dark quarks are in thermal equilibrium with SM particles.
- When the dark $\mathrm{SU}(5)$ colors confine, the dark baryons are formed and freeze out at $T_f < \Lambda$:

$$\langle n\sigma v\rangle_{T_f} = H$$

- The freezeout temperature T_f or $x_f \equiv m_\chi/T_f$ is

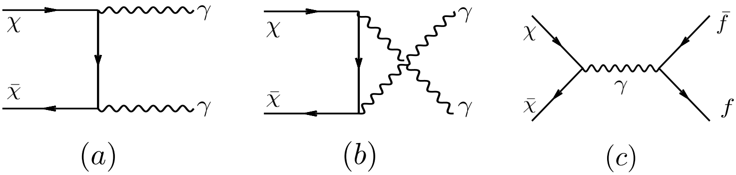
$$x_f \simeq \ln\left[A/\sqrt{\ln A}\right]$$

where $A = 0.038\sqrt{g_*}\, m_{pl}\, m_\chi\, \langle\sigma v\rangle$.

Relic abundance of dark baryons

- The annihilation process (c) of dark baryons to give with $N_{\text{eff}} = \sum_f Q_f^2$

$$\sigma_{\chi\bar{\chi}\to f\bar{f}} v \simeq N_{\text{eff}}\, \alpha\, \mu_\chi^2$$



Relic abundance of dark baryons

- The mass and the confining scale are chosen to give correct thermal relic density ($A = 0.038\sqrt{g_*}\, m_{pl}\, m_\chi \langle \sigma v \rangle$),

$$\Omega_\chi h^2 = 2.1 \times 10^4 \left(\frac{m_\chi}{m_e} \right) \ln \left(A/\sqrt{\ln A} \right) /A = 0.12\,.$$

	$\Lambda = 1$ TeV	$\Lambda = 10$ GeV
m_χ	~ 1 MeV	~ 1 GeV
g-factor	10^{-12}	10^{-2}
$\sigma_{\chi e}$	$10^{-48}\,\mathrm{cm}^2$	$10^{-36}\,\mathrm{cm}^2$

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

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

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

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

Up dark baryon as Dark radiation

- The thermal equilibrium process for dark radiation:

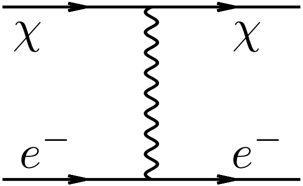


그림: A thermal equilibrium process for $m_\chi < m_e$.

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

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

- The contribution to the radiation energy ($g = 4$)

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

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 to the radiation energy ($g = 4$)

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

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

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

- The contribution to the radiation energy $(g = 4)$

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

Results of light Dark-baryon model

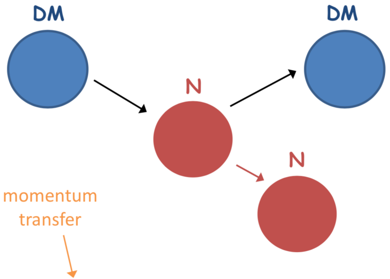
- Our model accommodates DDM, DR and dark-axions with

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

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

Direct detection of light dark baryons

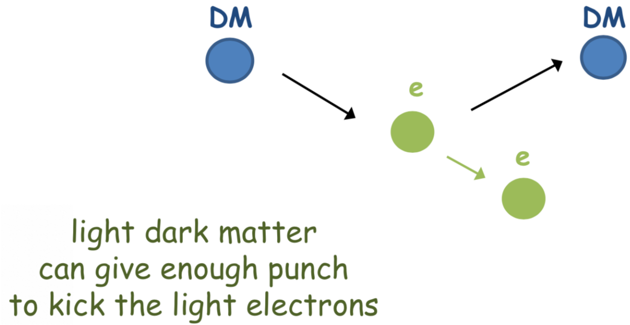
- The sensitivity drops rapidly for nuclear recoil if $m_D < 1\ \mathrm{GeV}$.



$$E_{\mathrm{NR}} = \frac{q^2}{2m_N} = \frac{(m_{\mathrm{DM}}v)^2}{2m_N} \gtrsim E_{\mathrm{threshold}} \sim \mathrm{keV}$$

Direct detection of light dark baryons

- Light DM of $m_D < 1 \text{ GeV}$ do scatter off electrons instead!

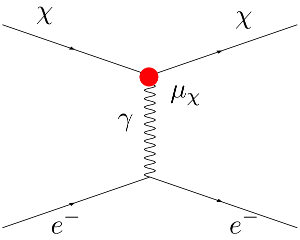


Direct detection of light dark baryons

- Maximum electron kinetic energy

$$E_e \leq \frac{1}{2} m_\chi v_\chi^2 \lesssim 3\,\mathrm{eV} \left(\frac{m_\chi}{\mathrm{MeV}} \right)$$

- Cross sections for light dipolar DM:

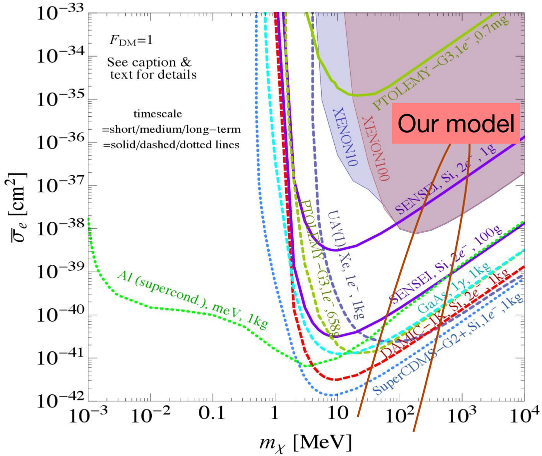


$$\frac{\mathrm{d}\sigma_{\chi e}}{\mathrm{d}\Omega} = \frac{\alpha^2 g^2}{m_\chi^2} F\left(\theta, \frac{m_e}{m_\chi}\right)$$

$$\sigma_{\chi e} \sim 10^{-36} - 10^{-48}\ \mathrm{cm}^2$$

$$(m_\chi = 1\ \mathrm{GeV} - 1\ \mathrm{MeV})$$

Scattering Reach (Community Report 2017)



Conclusion and outlook

- We propose a model for light dipolar DM, based on $\mathrm{SU}(5)$.
- The model supports (almost) massless dark baryons:

$$m_\chi = 1\ \mathrm{MeV} - 1\ \mathrm{GeV}: \quad \Lambda = 1 - 10^{-2}\ \mathrm{TeV}$$

- Dark baryons carry a naturally small magnetic moment

$$\mu_\chi = g\frac{e}{2m_\chi}, \quad g \approx \left(\frac{m_\chi}{\Lambda}\right)^2 = 10^{-2} - 10^{-12}.$$

Conclusion and outlook

- We propose a model for light dipolar DM, based on $\mathrm{SU}(5)$.
- The model supports (almost) massless dark baryons:

$$m_\chi = 1\ \mathrm{MeV} - 1\ \mathrm{GeV}: \quad \Lambda = 1 - 10^{-2}\ \mathrm{TeV}$$

- Dark baryons carry a naturally small magnetic moment

$$\mu_\chi = g\frac{e}{2m_\chi}, \quad g \approx \left(\frac{m_\chi}{\Lambda}\right)^2 = 10^{-2} - 10^{-12}.$$

Conclusion and outlook

- We propose a model for light dipolar DM, based on $\mathrm{SU}(5)$.
- The model supports (almost) massless dark baryons:

$$m_\chi = 1\ \mathrm{MeV} - 1\ \mathrm{GeV}: \quad \Lambda = 1 - 10^{-2}\ \mathrm{TeV}$$

- Dark baryons carry a naturally small magnetic moment

$$\mu_\chi = g \frac{e}{2m_\chi}, \quad g \approx \left(\frac{m_\chi}{\Lambda}\right)^2 = 10^{-2} - 10^{-12}.$$

Conclusion and outlook

- They are within the reach, $\sigma_{\chi e} \sim 10^{-36} - 10^{-48}\,\mathrm{cm}^2$.

	$\Lambda = 1\ \mathrm{TeV}$	$\Lambda = 10\ \mathrm{GeV}$
χ_u	≈ 0	≈ 0
χ_d	$\sim 1\ \mathrm{MeV}$	$\sim 1\ \mathrm{GeV}$
g-factor	10^{-12}	10^{-2}
$\sigma_{\chi e}$	$10^{-48}\,\mathrm{cm}^2$	$10^{-36}\,\mathrm{cm}^2$