Dark Matter from a Hidden Strong Sector

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Model 1: A Baryonic Dark Matter Model

Based on arXiv:1506.06929,
with Shigeki Matsumoto, Yue-Lin Sming Tsai and Tsutomu T. Yanagida.

- Model setup.
- Dark Matter mass.
- Direct detection perspective.
- Annihilation and detection perspective.
- Decay and detection perspective.

A Simple and Promising DM Candidate

- Requirement: DM candidate must be absolutely stable, or sufficiently long lived.

  Answer: the dark baryon is protected by the accidental dark baryon number in the hidden strong sector, even if decay operator is allowed, like proton decay in GUT.

- Requirement: Correct relic abundance is produced.

  Answer: the dark baryon is a thermal relic, its mass is determined by tuning the annihilation cross section to achieve the correct relic abundance.

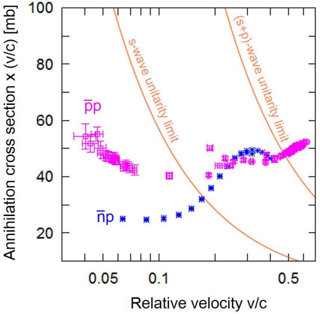
  The constituent dark quark is charged under (part of) the SM gauge group, which guarantees a simple thermal history.
  This setup also opens interesting dark matter phenomenology.

- The unitarity bound of nonrelativistic annihilation cross section is

$$\sigma_a v_{\rm rel} \le \frac{4\pi(2\ell+1)}{m_\chi^2 v_{\rm rel}}$$

  This can be derived by solving a nonrelativistic Schrodinger equation with complex potentials, and using optical theorem.

- At thermal freeze out $v_{\rm rel} \sim 0.2c - 0.4c$, not only s wave but some higher partial wave contribute.



- For $\Omega_\chi h^2 = 0.12$ and Dirac fermion, s wave unitarity bound is 84 TeV of Griest and Kamionkowski (PRL 64, 615), with $v_{\rm rel} \simeq 0.45c$; or 130 TeV of Griest and Seckel (PRD 43, 3191), with $v_{\rm rel}$ averaged.
- Rescaling the annihilation cross section, from the QCD case with $m = 0.938$ GeV to the DM of $\sigma_a v_{\rm rel} = 3 \times 10^{-26}$ cm^{3}s^{-1}, we get

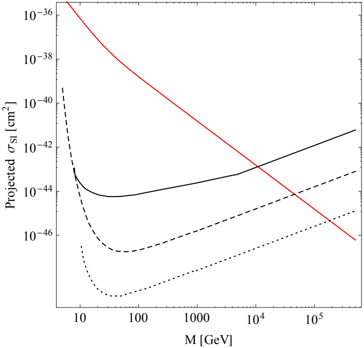
$$m_\chi \simeq 150 \text{ TeV!}$$

- Loop-induced magnetic dipole type interaction with SM photons, determined from NDA

$$\frac{1}{\Lambda}\bar{\psi}\sigma_{\mu\nu}\psi F^{\mu\nu},$$

where $\Lambda \simeq m_\chi$ is the dark QCD scale.

- Differential cross section with $\eta(m_\chi, Q) = \int_{v(Q)} f(\vec{v})\frac{d^3v}{v}$ and $\eta'(m_\chi, Q) = \int_{v(Q)} f(\vec{v}) v d^3 v$ is



$$\frac{d\sigma}{dQ} = \frac{1}{32\pi m_\chi^2 m_N}\frac{1}{4}\frac{Z^2 e^4}{\Lambda^2}\left((16 m_\chi^2 - 32 m_\chi m_N)\eta(m_\chi, Q) + \frac{32 m_\chi^2 m_N}{Q}\eta'(m_\chi, Q)\right)F^2(Q)$$

DM Annihilation in the Galaxy Center

- The dark baryon and anti baryon annihilation is relatively independent with the dark sector model choosing, unlike the following decay phenomenology.

However

- Difficulty in theory: There is no well established way to calculate annihilation cross section in such low velocity region of $v_{\text{rel}} \simeq 10^{-4}c$ at the galaxy center.
  - The first approximation is the s wave unitarity bound, which should be the absolute upper bound.
  - We tried the "boundary potential models" developed by nuclear physicist, which can be regarded as "an expansion around the unitarity bound".
  - However, there is neither experimental proof of the method in such low velocity region, nor validity proof of the potential parameters extracted and rescaled from real QCD in the dark sector.
- Difficulty in detection: Given a DM profile such as the NFW, such high DM scale means low DM number density, so that low annihilation rate.
  - With a reasonable exposure time and aggressive DM profile assumption, the CTA experiment can see upto 90 TeV DM if it is a simple $\chi\chi \to \gamma\gamma$ annihilation.
  - Practically, baryon and antibaryon annihilation will be further suppressed in both the γ branching ratio and its energy.
  - Better experiment such as the LHASSO cannot look into the galaxy center.

We mentioned DM stability but it is not absolute:

- Consider the hidden strong gauge group to be $SU(3)$, then the dark baryon consists of three quarks, and a dark baryon decay operator is a four fermion operator.
- Not assuming any new scale, the suppression scale is the Planck scale

$$\mathcal{O} \supset \frac{1}{M_P^2} QQQL, \qquad \Gamma \simeq \frac{m_\chi^5}{M_P^4} = 2.3 \times 10^{-48}\ \text{GeV}, \qquad \tau \simeq 3 \times 10^{23}\ \text{s}.$$

- Better calculation including the phase space factor $1/(32\pi)$ and the rescaled lattice QCD proton decay matrix elements will increase the decay life time by roughly four orders.

$\tau \simeq 10^{27}$ s is marginal to current experiments!

Gauge	$SU(3)_H$	$SU(3)_c$	$SU(2)_R$	$SU(2)_L$	$U(1)_{B-L}$
Φ	1	1	3	1	$+1$
Q_L	3	1	2	1	$+\frac{1}{6}$
Q_R	3	1	2	1	$+\frac{1}{6}$

- The dark constituent quark is mirror vector-like so that there is no anomaly.
- The SM $U(1)_Y$ is promoted to the $SU(2)_R \times U(1)_{B-L}$ for the dark constituent quark.
- The dark baryon is the "neutron" component of the $SU(2)_R$ doublet, so that it is electromagnetic neutral.
- Dark proton neutron mass splitting should be sufficient, for dark proton decay before the BBN. Such mass splitting can be provided mainly by the dark quark mass splitting induced by the operator $\bar{Q}\Phi^\dagger \Phi Q$.
- The DM decay chain is $N \to \ell_R^+ \Pi^- \to \ell_R^+ W_R^- \to \ell_R^+ \bar{t}_R b_R$,

$$\frac{dN_i}{dE} = \sum_{q=t,b} \int_{E_{q\mathrm{min}}}^{E_{q\mathrm{max}}} \frac{dE_q}{\sqrt{E_\Pi^2 - m_\Pi^2}} \left(\frac{dN_i}{dE}\right)_q' + \frac{1}{3} \sum_{\ell=e,\mu,\tau} \left(\frac{dN_i}{dE}\right)_\ell'.$$

In the following we choose $m_\Pi = 15$ TeV as benchmark.

We use a single parameter (τ) fitting with the recent AMS-02 antiproton data.

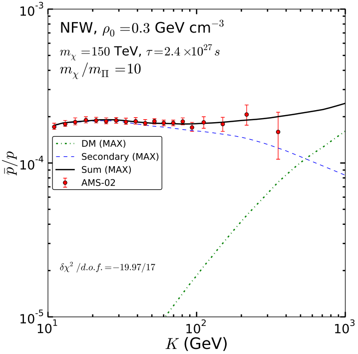


Figure: MAX propagation.

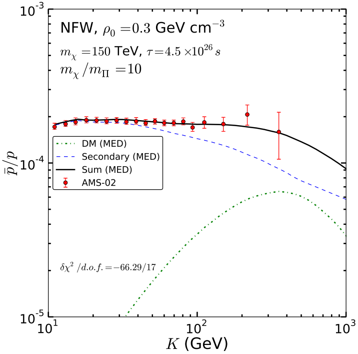


Figure: MED propagation.

We check the fitted life time with the Fermi-LAT EGB and the IceCube neutrino data.

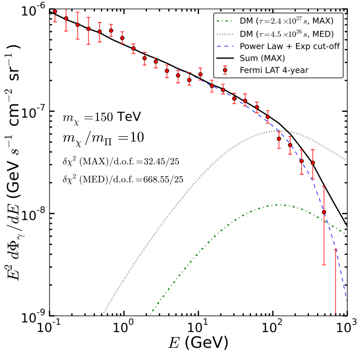


Figure: Fermi-LAT EGB constraints.

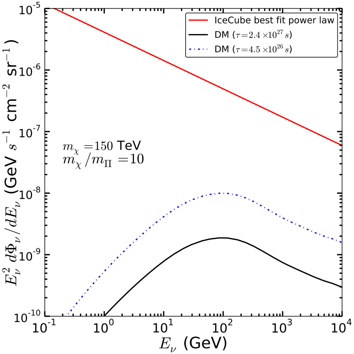


Figure: IceCube neutrino constraints.

The best fit of “MED” is excluded.

Summary of the Baryonic DM Model

- We set up a simple and elegant scenario in which the DM is a hidden baryon of 150 TeV.
- Based on hidden gauge group of $SU(3)$ and BSM gauge $SU(2)_R \times U(1)_{B-L}$ we construct a viable model with phenomenological predictions.
- We studied the direct detection and indirection detect constraints of that model. Much of the parameter space can be probed in the future.

Model 2: The Self Interacting DM Model

The idea is to use the CMB observation to constrain the SIDM.

- The statistical DM last elastic scattering.
- The SIDM Boltzmann equation set.

Based on some preliminary work...

- Assumption of self interaction: nonrelativistic Yukawa potential scattering with mediator of mass μ.
- From Quantum mechanics textbook

$$\frac{d\sigma}{d\Omega} = \frac{C}{(\mu^2 + 2k^2(1-\cos\theta))^2}, \qquad \sigma = \frac{4\pi C}{\mu^2(\mu^2+4k^2)}$$

- In early universe the cross section can be extrapolated with the value determined today

$$\sigma = \sigma_0 \frac{\mu^2 + 4k_0^2}{\mu^2 + 4k^2}$$

  where $k_0 \simeq 10^{-3} m_\chi$.
- In the early universe before the DM virialization, (assuming thermal production) the SIDM has the same temperature with neutrino and subject to redshift. So $k = \frac{2\times10^{-4}\ \text{eV}}{a}$ is very small.
- If μ is also small the cross section is very enhanced.

Is SIDM Elastic Scattering Visible in the Early Universe?

Elastic Scattering Rate ($\sigma v_{\rm rel} n$) vs. Hubble Rate, for $\sigma_0 = 1(m_\chi/\text{GeV})$ barn.

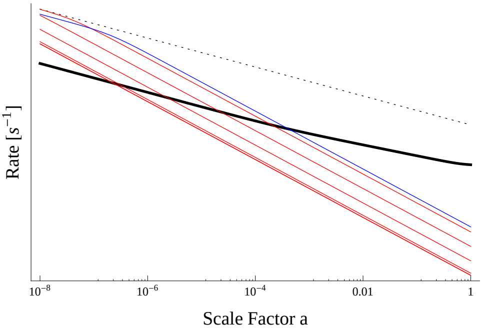


Figure: Red lines from right to left are $\mu/m_\chi = 10^{-6}, 10^{-5}, 10^{-4}, 10^{-3}$ etc for $m_\chi = 5$ GeV; blue line varies m_χ to 1 GeV for $\mu/m_\chi = 10^{-6}$.

I believe even if μ is not very small, it still can affect the CMB.
Because standard CMB initial condition is applied at $a = 10^{-8}$.

The first order Boltzmann Equation for SIDM

- The left hand side is the standard Liouville operator, say in synchronous gauge and comoving coordinate system

$$\mathrm{LHS} = \frac{f(p)}{a}\left(\frac{\partial\Psi}{\partial\tau} + i\frac{\tilde{p}k}{\tilde{E}}(\hat{k}\cdot\hat{n})\Psi + \frac{\partial \ln f(\tilde{p})}{\partial \ln \tilde{p}}\left(\partial_\tau \eta - \frac{\partial_\tau h + 6\partial_\tau \eta}{2}(\hat{k}\cdot\hat{n})^2\right)\right)$$

- The right hand side is the collision term integration

$$\mathrm{RHS} = \frac{1}{2E(p)}\int \frac{d\vec{q}}{(2\pi)^3 2E(q)}\frac{d\vec{p}'}{(2\pi)^3 2E(p')}\frac{d\vec{q}'}{(2\pi)^3 2E(q')}(2\pi)^4\delta^{(4)}(p'+q'-p-q)$$
$$|\mathcal{M}|^2 f(p)f(q)\left(\Psi(\vec{p}')+\Psi(\vec{q}')-\Psi(\vec{p})-\Psi(\vec{q})\right)$$

- The matrix element is

$$|\mathcal{M}|^2 = 64\pi m_\chi^2\sigma_0\frac{\mu^2(\mu^2+4k_0^2)}{(\mu^2+|\vec{p}-\vec{p}'|^2)^2}$$

The first order Boltzmann Equation for SIDM

After some complicated integration, the Boltzmann equation for perturbation looks like

$$
\begin{aligned}
&\frac{\partial\Psi(p)}{\partial\tau}+i\frac{\tilde{p}k}{\tilde{E}}(\hat{k}\cdot\hat{n})\Psi(p)+\frac{\partial\ln f(\tilde{p})}{\partial\ln\tilde{p}}\Big(\partial_\tau\eta-\frac{\partial_\tau h+6\partial_\tau\eta}{2}(\hat{k}\cdot\hat{n})^2\Big)\\
=&\frac{\sigma_0 a}{8\pi^2 m_\chi}\Big(1+\frac{4k_0^2}{\mu^2}\Big)\Big(\Big[2e^{-\frac{p^2}{2m_\chi T}}m_\chi^2T^2+\sqrt{2\pi m_\chi^3T^3}\Big(p+\frac{m_\chi T}{p}\Big)\mathrm{Erf}\big(\frac{p}{\sqrt{2m_\chi T}}\big)\Big](-\Psi(p))\\
&+\Big[\int_0^p q^2dq\Big(2p+\frac{2q^2}{3p}\Big)+\int_p^\infty q^2dq\Big(2q+\frac{2p^2}{3q}\Big)\Big]\Big(-e^{-\frac{q^2}{2mT}}\Psi_0(q)\Big)\\
&+\text{Higher Multipole Terms}\\
&+\Big[\int_0^\infty p'^2dp'\frac{m_\chi T}{\sqrt{p^2+p'^2}}e^{-\frac{p'^4}{2m_\chi(p^2+p'^2)T}}\Big]2\Psi_0(p')\\
&+\text{Higher Multipole Terms}\Big)
\end{aligned}
$$

Still working on it...