Stable Sexaquark as Dark Matter

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S as DM

• **S == stable, 6-quark state**
  - works well as dark matter
  - would not (yet) have been found in lab searches

• **SDM direct detection:**
  - Underground detectors are insensitive: DM loses energy in Earth => energy deposit << threshold
  - Co-rotation => XQC (sounding rocket) insensitive to individual events; can they use integrated heating?

• **DM-baryon interaction may help with astro/cosmo puzzles:**
  - DM in inner galaxy ~co-rotates with Sun
  - structure in rotation curves, core-cusp problem, $H_0$ & $\sigma_8$

• **A baryon asymmetry of the universe is generic**

• **H naturally has the correct relic abundance**
  - $S$ and baryon abundances are natural for expected cross section.
  - $T_{f.o.}$ in 10-50 MeV range => scenario is self-consistent:
    - Freezeout occurs below QCD phase transition: treatment in terms of hadrons is legit.
    - Freezeout occurs before nucleosynthesis: $S$ impact is almost negligible, maybe interesting.
Stable Sexaquark Dark Matter

Same quark content as H-dibaryon (Jaffe 1977), but different physics: not a loosely bound di-Λ!

Deeply bound \( \Rightarrow m_S \sim 2 m_p \) and stable (or \( \tau > \tau_{\text{Univ}} \))

**Crucial feature:**

S is much smaller than usual hadrons
(proton, pion)

6-quark, \( Q=0, B=2 \)

Spin-0, scalar

Flavor singlet

\( m \sim 1.2-1.9 \) GeV

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Nucleon

pion cloud

Compton wavelength: 0.3 fm

Radius: 0.9 fm

\( f_0 / \omega + \Phi / \text{glueball cloud} \)

\[ \leftarrow 0.15 \text{ fm} \]

\[ \rightarrow 0.15-0.4 \text{ fm} \]
S is elusive

- **Many negative searches, but all are inapplicable.** They either:
  - looked for H-dibaryon through decays (but S is stable)
  - restricted to mass > 2 GeV (but \(m_S < 2 \text{ GeV}\))
  - required fast production in S=-2 hypernuclei (but small overlap with baryons)

- **Wavefunction overlap with baryons is very small.** Extremely rare fluctuation required for S ↔ \(\Lambda \Lambda\); S↔NN is \(G_F^2\) smaller =>
  - nuclei are stable (\(\tau > 10^{29} \text{ yr}\))
  - hard to produce in fixed target experiments

- **S is similar to** (much more copious) neutrons

- **Promising accelerator detection strategies**
  - Apparent lack of baryon number and strangeness conservation:
    - \(\Delta B = \pm 2\) with \(\Delta S = \mp 2\)
  - Reconstruct missing mass, e.g.:
    - \(\gamma \rightarrow \Lambda \Lambda \bar{S} (+\text{ pions})\)
    - \(M_S^2 = (p_\gamma - p_{\Lambda 1} - p_{\Lambda 2} - \sum p_\pi)^2\)
Conditions on Dark Matter:

✓ $\tau_{DM} > \tau_{Univ}$, cold, neutral
✓ primordial nucleosynthesis
✓ Particle must not be already excluded
  – accelerator searches [but try missing mass $\Upsilon \to S + 2$ anti-Lambdas ]
  – exotic isotopes

⇒ DM searches
  – indirect impacts (heating planets, helioseismology,...) [n.b., non-annihilating!]
  – stability of nuclei [small wavefunction overlap]
  – neutron stars equation of state of and stability

⇒ Co-rotation scenario
⇒ Relic density & Baryon Asymmetry
⇒ Structure formation & cosmology constraints
Co-rotation and Direct Detection

- Light, *slow-moving* DM is not visible in current detectors
  
  - $\text{KE}_{\text{DM}} = 500 \text{ eV} \left(\frac{m_{\text{DM}}}{2 m_p}\right) \frac{v^2}{(220 \text{ km/s})^2}$
  
  - $\frac{\langle E_{\text{deposit}}\rangle}{\text{KE}_{\text{DM}}} = 0.12$ for Si target
    - $= 0.02$ for Hg target
    - $= 0.44$ for H or He target
  
  - Energy-loss length in Earth crust: $\lambda = 2 \text{ cm} / \sigma_{10\text{mb}}$

  - CRESST, Xenon1T, LUX, DAMIC

- XQC above atmosphere is best; $E_{\text{thresh}} = 30 \text{ eV}$
  (McCammon+02, Wandelt+02, GF+Zaharijas05, Erickcek+07, Mahdawi+GRF 2017)

  - Mahdawi+GRF 2017: $\sigma_{\text{DM}} < 10^{-29} \text{ cm}^2$ for standard velocity dispersion — SDM has $\sigma_{\text{DM}} \sim 10$-100 mb

- Co-rotation rescues SDM
Dark Matter-Gas Scattering

$v_f \sim (2/3)^N$ \(v_i \Rightarrow\) only a few interactions are enough for co-rotation scenario to work

**Integrated Column Density for NFW orbits 10 Gyr**

\[ \chi = \int_{l}^0 dl' \rho_{\text{gas}}(r) \]

- Only inner parts of the halo interact
- Extended halo is NOT affected

(D. Wadekar & GRF in prep)
Highly idealized analysis:
- static potential & gas
- actually grows by accretion
- c.f. Bruch-Read+
- proof of concept, shows cross-section needed is reasonable.

Co-rotation!
in realistic galaxies, gas is inhomogeneous ⇒

test with extra torus
S-Dark Matter in solar neighborhood conforms to & co-rotates with the gaseous disk, AS SEEN IN EXTERNAL GALAXIES!

Swaters+12

Figure 1. Mass models based on scaling the stellar disc and the H I component for the late-type dwarf galaxies in our sample. The filled circles represent the derived rotation curves. The thin full lines represent the contribution of the stellar discs to the rotation curves and the dotted lines that of the gas. The solid lines represent the best-fitting model based on scaling the contributions of the stars and the gas. The arrows at the bottom of each panel indicate a radii of two optical disc scale lengths. In the top left corner of each panel, the UGC number and the inclination are given.

Non-conforming galaxies had recent mergers!
Systematic analysis needed…
Example Rotation Curves

Sharp increases in overall RC $\leftrightarrow$ amplifying structure in gas

But not always… Exceptions $\leftrightarrow$ galaxy experienced recent merger, as predicted by SDM!
Cosmology & structure formation

- DM-baryon interaction: momentum transfer => *slight drag on structure formation*
  - Dvorkin, Blum, Kamionkowski (2014):
    - Ly-alpha forest: $\sigma < \sim 10$ mb if $v$-indept
    - momentum transfer helps reconcile $H_0$ & $\sigma_8$
  - Problem or opportunity? To be Determined…

- S-S self interactions + S-baryon interactions: *may provide benefits of Self Interacting DM*
  - core-cusp problem, etc.
Baryon Asymmetry of the Universe

- S described by complex scalar field, like the Higgs
  - may have VEV in early Univ
  - phase rotates at no cost in energy ⇒
  - **Non-zero baryon number density is generic**

\[ n_B \sim \langle \phi_S^\dagger \partial_t \phi_S \rangle \]

_Baryon number is non-zero. After reheating it looks like it was just an initial condition._
Dark Matter Relic Abundance

- **Reheating:** production of photons & fragmentation of $\langle \phi_S \rangle$ into particles

- **Breakup:** $\gamma + S \rightarrow \Lambda \Lambda$

\[
\frac{d n_S}{n_S \, dT} = -\Gamma(\gamma + S \rightarrow \Lambda \Lambda) \frac{dt}{dT}
\]

\[
\Gamma(\gamma + S \rightarrow \Lambda \Lambda)(T) = \langle n_\gamma(T) \sigma_{\gamma + S \rightarrow \Lambda \Lambda}(T) v(T) \rangle
\]

- $\sim 16\%$ of $S$'s are broken up before freeze out $\Rightarrow$

\[
\frac{\Omega_{DM}}{\Omega_b} = 5 \text{ is Natural!}
\]
Sexaquark as DM

- S == stable, 6-quark state
  - works well as dark matter
  - would not (yet) have been found in lab searches
  - MUST SEARCH in Belle, BABAR data: $\gamma \rightarrow \Lambda \Lambda \bar{S}$ (+ pions) (missing mass peak !)
    strangeness-Baryon number imbalance in central events LHC?

- SDM direct detection:
  - Underground detectors are insensitive: DM loses energy in Earth $\Rightarrow$ energy deposit $\ll$ threshold
  - Co-rotation $\Rightarrow$ XQC (sounding rocket) insensitive to individual events; can they use integrated heating?
  - NEED DM DETECTOR SENSITIVE to 10-100 mb cross section and eV energy deposits!

- DM-baryon interaction may help with astro/cosmo puzzles:
  - DM in inner galaxy $\sim$co-rotates with Sun
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- A baryon asymmetry of the universe is generic

- H naturally has the correct relic abundance
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  - $T_{i.o.}$ in 10-50 MeV range $\Rightarrow$ scenario is self-consistent:
Backup Slides
Sexa vs Hexa...


- If sexaquark is DM it, should be renamed R for Rubin!

<table>
<thead>
<tr>
<th>Number</th>
<th>Latin prefixes</th>
<th>Greek prefixes**</th>
<th>Sanskrit[^1]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cardinal</td>
<td>Multiple</td>
<td>Distributive</td>
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</tbody>
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[^1]: Sometimes Greek *hexa-* is used in Latin compounds, such as *hexadecimal*, due to taboo avoidance with the English word *sex*.
Viability of Co-Rotation Scenario

Schwarzschild Modelling

1. Choose a potential (NFW)
2. Follow an orbit in this potential

Simulations of DM interacting with gas in the Milky Way

(Jay) Digvijay Wadekar (NYU) in collaboration with G. R. Farrar
Schwarzschild

1. Choose a potential (NFW)
2. Follow an orbit in this potential
3. Generate a library of orbits
Schwarzschild

1. Choose a potential (NFW)
2. Follow an orbit in this potential
3. Generate a library of orbits
4. Weighted sum of orbits gives density corresponding to NFW
Sensitivity to gas density structure

Galpy Baryons

Olling-Merrifield

Density for Miyamoto-Nagai Potential

Surface Number density within (-1<z<1 kpc)

Surface Number density within (-1<z<1 kpc)