CAP Congress 2019

Cosmological Bounds on Non-Abelian Dark Forces

PRD95, 015032, arXiv:1605.08048
PRD97, 075029, arXiv:1710.06447

TRIUMF & UBC
Collaboration with David Morrissey & Kris Sigurdson

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Outline

1. Motivations
2. Dark Glueballs
3. Cosmological Constraints
Standard Model(s)

\[ SU(3)_c \times SU(2)_L \times U(1)_Y \]
Standard Model(s)

\[ SU(3)_c \times SU(2)_L \times U(1)_Y \]

\[ + \Lambda \times (C)DM \times SM \]
Standard Model(s)

\[ SU(3)_c \times SU(2)_L \times U(1)_Y \]

+ 
\[ \Lambda \times (C)DM \times SM \]

+ 
BSM ???

Missing pieces:

- How does gravity connect with the SM?
- What is dark matter?
- Baryogenesis
- Hierarchy problem
- Strong CP Violation
- ...
BSM in Standard Searches?

**THEORY vs DATA**

**BSM PHYSICS**

*electron channel, and 1.99 TeV in the dimuon channel consistent with the Standard Model prediction. The choice of different models, the data are interpreted...*

ATLAS, arXiv: 1707.02424


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Move to a bigger lab?

Use cosmology and astrophysics to provide limits from the highest energies and earliest epochs in the Universe.

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Dark Forces

- Minimal or non-existent connections with the SM
- Evade current LHC limits
- Evade current direct detection limits
- What can we ask about it?
- **How do we constrain it?**
Focus on dark gauge SU(3)

Evolution of the coupling with energy leads to confinement.

At low energies, gluons confine into glueballs.

\[ \mathcal{L}_{\text{eff}} = -\frac{1}{16\pi \alpha(x(\mu))} X_{\mu \nu}^a X^{a\mu \nu} \]
Focus on dark gauge SU(3)

Evolution of the coupling with energy leads to confinement.

At low energies, gluons confine into glueballs.
Glueball Spectrum

- Come from lattice calculations
- Classified according to $J^{PC}$
- Similar for larger N
- No c-odd states for SU(2)!
- Lightest is generically $0^{++}$, $m \sim 7\Lambda_x$
Although we compute abundances with a large spectrum of glueballs, find only two states matter:

- $0^{++}$: most abundant. Has a unique $3 \text{ to } 2$ interaction that sets the relic yield.
- $1^{+-}$: may have important cosmological consequences if stable.

Can be interesting if stable.
Ruled out by dark matter yield.

Allowed.
Standard Model – Glueball Interactions

\[ \mathcal{O}^{(6)} \sim \frac{1}{M^2} H^\dagger H \text{tr}(X X) \]

\[ \mathcal{O}^{(8a)} \sim \frac{1}{M^4} \text{tr}(F_{SM} F_{SM}) \text{tr}(X X) \]

\[ \mathcal{O}^{(8b)} \sim \frac{1}{M^4} B_{\mu\nu} \text{tr}(X X X)^{\mu\nu} \]

- Non-renormalizable interactions with the SM are possible.
- Integrate out massive fermions charged under both SM and dark gauge groups.
- Couple a darkly charged scalar mediator through a Higgs portal.
Standard Model – Glueball Interactions

\[ \mathcal{O}^{(6)} \sim \frac{1}{M^2} H^\dagger H \text{tr}(XX) \]

\[ \Gamma_6 \sim \frac{m_0^5}{M^4} \]

\[ \mathcal{O}^{(8a)} \sim \frac{1}{M^4} \text{tr}(F_{SM} F_{SM}) \text{tr}(XX) \]

\[ \Gamma_8 \sim \frac{m_0^9}{M^8} \]

\[ \mathcal{O}^{(8b)} \sim \frac{1}{M^4} B_{\mu \nu} \text{tr}(XXX)^{\mu \nu} \]

Only the 0++ can decay through dimension 6.

Dimension 6 decays are parametrically earlier than dimension 8.

If \( C_x \) is a good symmetry, then the 1+- will be stable.

Violates C in the dark sector

\[ \text{tr}(XXX) \rightarrow 1^{+-} \]

\[ \text{tr}(XX) \rightarrow 0^{++} \]
Explicit Decay Scenarios

1. Dimension-8 decays with broken $C_x$
   All glueballs decay with parametrically similar rates.

2. Dimension-8 decays with exact $C_x$
   $1^{+-}$ is stable.

3. Dimension-6 decays with broken $C_x$
   Glueballs decay through the dimension-6 operator except for the C-odd $1^{+-}$ state, making it longer lived.

4. Dimension-6 decays with exact $C_x$
   $1^{+-}$ is stable.
Cosmological Constraints

- As glueballs can decay over many different lifetimes, many various epochs of the Universe can be used to place constraints.

Big Bang? → BBN: ~MeV (3 min.) Light elements form → Recombination: ~eV (380,000 years) CMB forms → Today: ~14 Gyr
Dimension 8, Broken $C_x$

$1^+\text{ entirely subdominant to } 0^{++}$.

Inconsistent with model assumptions.

$R = R_{\text{min}}$

$R = R_{\text{max}}$

1$^+$ makes up all the DM.

Inconsistent with model assumptions.

Ruled out.
Dimension 8, Exact $C_x$ (stable $1^{+-}$)

$R = R_{\text{min}}$

$R = R_{\text{max}}$

$1^{+-}$ makes up all the DM

$0^{+}$ makes up all the DM

Logarithmic scale for $m_0$ (GeV) and $M$ (GeV)

Forestell, Morrissey, Sigurdson, 2018

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Dimension 6, Broken $C_x$

1\(^{++}\) degeneracy lifted.

$R = R_{\text{min}}$

$R = R_{\text{max}}$

Forestell, Morrissey, Sigurdson, 2018
Dimension 6, Exact $C_x$ (stable $1^{+-}$)

$R = R_{\text{min}}$

$R = R_{\text{max}}$

$1^{+-}$ makes up all the DM

Forestell, Morrissey, Sigurdson, 2018
Summary

• Now is a good time to explore new dark gauge forces.

• Rich dynamics in the non-Abelian sector.

• Considered a spectrum of massive glueballs.

• Complicated freeze-out dynamics including a 3→2 cannibalism phase.

• Constrain the gauge based on lifetimes, using various cosmological laboratories.

• Constraints are placed on m, M, R.
Thank You!
Backup Slides...
Dark Forces

- What type of force?
  Abelian – Dark U(1)
  Non-abelian – SU(N), SP(2N), SO(N), etc…

- What mass scale is involved?
  Confinement into massive particles
  Sets relevant energy scales

- Does it connect with the SM?
  Weak connections via particles charged under various light/dark gauge groups.

- Is it stable?
  Dark matter!

- HOW do we constrain it?
From Gluons to Glueballs..

\[ \mathcal{L}_{\text{eff}} = -\frac{1}{16\pi\alpha_x(\mu)} X^a_{\mu\nu} X^{a\mu\nu} \]

\[ \frac{1}{N} X_{\mu\nu} X^{\mu\nu} \rightarrow \text{finite} \]

\[ \frac{1}{N} X_{\mu\nu} X^{\mu\nu} \rightarrow F(\phi, \partial_\mu, m_x) \]

Large N Scaling

NDA
From Gluons to Glueballs..

\[ \mathcal{L}_{\text{eff}} = -\frac{1}{16\pi\alpha_x(\mu)} X^a_{\mu\nu} X^{a\mu\nu} \]

Identify \( m \) with the mass of the lightest scalar field

\[ \mathcal{L}_{\text{eff}} = \frac{1}{2} (\partial\phi)^2 - \frac{1}{2} m^2 \phi^2 - m^4 \sum_{n \geq 3} \frac{a_n}{n!} \left( \frac{4\pi}{N} \right)^{n-2} \left( \frac{\phi}{m} \right)^n \]

Expand function to include all possible interactions
Self-interactions for glueballs today imply that $m > 100$ MeV.

Without SM interactions, only way to change the number of $0^{++}$ glueballs.
Glueball Cosmology

Start simple: single glueball state.

Yield is set by the 3 to 2 interactions.

\[ \dot{n} + 3Hn = -\langle \sigma v^2 \rangle_{32}(n^3 - n^2 \bar{n}) \]

Hubble expansion

3 \rightarrow 2 dilution

\[ \bar{n}_x = g_x \left( \frac{m_x T_x}{2\pi} \right)^{3/2} e^{-m_x/T_x} \]
Glueball Cosmology

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Hubble expansion

3 → 2 dilution

\[ H^2 = \frac{1}{3M_{PL}^2} \rho = g_* \frac{\pi^2}{90} \frac{1}{M_{PL}^2} T^4 \]

\[ \bar{n}_x = g_x \left( \frac{m_x T_x}{2\pi} \right)^{3/2} e^{-m_x/T_x} \]
Assumptions

- Dark sector is thermally decoupled
- Inflation (or something like it) and reheating occurred
  Heats the two sectors independently: $T > T_x > m$
- Glueballs self-thermalize
- Both sectors evolve adiabatically
  Use variable, $R$, as a parameter in the model
- This gives us enough information to solve for the dynamical evolution
  Can determine $T_x(T)$

Entropy Conservation:

\[ R = \frac{s_x(T_x)}{s(T)} = \text{constant} \]

\[ T_x s_x = \rho_x + P_x - \mu_x n_x \]
Multiple Glueball Interactions

Allow any interactions that conserve good symmetries: $J^{PC}$

Limit to 2 to 2 interactions (3 to 2 only affects lightest state considerably).

C conservation implies many C-odd/even interactions will not be allowed

P conservation implies that many more interactions will be velocity suppressed for non-relativistic particles

$$\langle \sigma v \rangle_{ijkl} \sim \frac{(4\pi)^3}{N^4} \frac{\beta_{ijkl}}{s_{ij}} c_L \left( \frac{2}{x_i + x_j} \right)^L$$

Couplings Kinematics Velocity Suppression

$$i + j \rightarrow k + l$$

$$C_i C_j = C_k C_l$$

$$P_i P_j = (-1)^L P_k P_l$$
Temperature Evolution

When 3 to 2 interactions turn off, resumes cooling as normal.

Dark temperature cools slower due to 3 to 2 cannibalism.
Adding More Glueballs: C-Even

\[ \dot{n}_1 + 3Hn_1 = -\langle \sigma_3 v^2 \rangle n_1^2 (n_1 - \bar{n}_1) \]
\[ -\frac{1}{2} \langle \sigma v \rangle_{2111} \left[ \frac{n_2}{n_1} n_1 n_2 - n_2^2 \right] \]
\[ -\langle \sigma v \rangle_{2211} \left[ \frac{n_2^2}{n_1} n_1^2 - n_2^2 \right] \]
\[ -\frac{1}{2} \langle \sigma v \rangle_{2214} \left[ \frac{n_2}{n_1 n_4} n_4 n_2 - n_2 n_4 \right] \]
\[ \dot{n}_2 + 3Hn_2 = +\frac{1}{2} \langle \sigma v \rangle_{2111} \left[ \frac{n_2}{n_1} n_1 n_2 - n_2^2 \right] \]
\[ +\langle \sigma v \rangle_{2211} \left[ \frac{n_2^2}{n_1} n_1^2 - n_2^2 \right] \]
\[ +\langle \sigma v \rangle_{2214} \left[ \frac{n_2}{n_1 n_4} n_4 n_2 - n_2 n_4 \right] \]
\[ +\frac{1}{2} \langle \sigma v \rangle_{2415} \left[ \frac{n_2 n_4}{n_1 n_5} n_5 n_2 - n_2 n_4 \right] \]
\[ -\frac{1}{2} \langle \sigma v \rangle_{1512} \left[ \frac{n_1 n_5}{n_1 n_2} n_2 n_1 - n_1 n_5 \right] \]
\[ \dot{n}_4 + 3Hn_4 = -\frac{1}{2} \langle \sigma v \rangle_{2214} \left[ \frac{n_2}{n_1 n_4} n_4 n_2 - n_2^2 \right] \]
\[ +\frac{1}{2} \langle \sigma v \rangle_{2415} \left[ \frac{n_2 n_4}{n_1 n_5} n_5 n_2 - n_2 n_4 \right] \]
\[ \dot{n}_5 + 3Hn_5 = -\frac{1}{2} \langle \sigma v \rangle_{2415} \left[ \frac{n_2 n_5}{n_1 n_5} n_5 n_2 - n_2 n_5 \right] \]
\[ +\frac{1}{2} \langle \sigma v \rangle_{1512} \left[ \frac{n_1 n_5}{n_1 n_2} n_2 n_1 - n_1 n_5 \right] \]

3→2

Coannihilations

- Can model independently of the c-odd states.
- Get a host of different freeze-out processes at play.

Smaller number changing processes

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0\textsuperscript{++} dominates, and is largely unaffected by underlying states. (Relic density entirely set by 3 $\rightarrow$ 2 process).

2\textsuperscript{++} depletes more efficiently relative to others due to coannihilation effects.