Cosmological Constraints on Hidden Physics

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Summary

New physics may be hidden in a dark sector that minimally interacts with the Standard Model. We investigate one such dark sector, using cosmology to place stringent constraints.

THE HUNT FOR NEW PHYSICS

The Standard Model (SM) of particle physics does a remarkable job of explaining the nongravitational forces of nature. These include the strong, weak, and electromagnetic forces, as well as all of the corresponding particles. These particles include quarks, leptons, and their force carriers: photons, gluons, W bosons and Z bosons. In 2012, the discovery of the Higgs boson at the Large Hadron Collider (LHC) completed the current model of particle physics, and brought all of our theoretical knowledge in line with our experimental observations [1,2].

This was a monumental success, but as successful as the SM is, it still has some weaknesses. For example, neutrinos, the neutral partners to the charged leptons (electrons, muons, and taus), should be massless. However, observations of solar and atmospheric neutrino oscillations between different flavours indicate that they do in fact have mass, in direct contradiction with the SM [3,4]. Further to this, we have measured the mass of many of the other particles, but we do not know *why* everything has the mass that they do (and in fact, some calculations indicate that the 'smallness' of the Higgs boson mass is a real problem in the Standard Model!). These are just a few examples of the need to search for new particles and new physics beyond the Standard Model.

We have a second 'Standard Model' of cosmology that has done the same thing for our understanding of the evolution of the Universe that the regular SM has done for particle physics. Called the ΛCDM model, we require a source of dark energy, (cold) dark matter, and regular matter. These make up the entire energy content of the universe, and together with general relativity explain how the Universe has evolved from the earliest times to produce the extraordinary galaxies and structures that we see today.

Once again, however, we have unresolved questions. What is the nature of dark matter? Is it a particle or something else? How does gravity, which works so well on cosmological scales, interact with the quantum field theories of particle physics? Where did the matter of the Universe actually come from? These are only a few of the questions that are being asked by todays scientific community. The search for these answers drives much of what we explore moving forward, both in theory and experimentally.

DARK FORCES

We have been searching for the answers to these puzzling problems for some time now. While the LHC continues to push the frontiers on precision particle physics, everything we have seen since the discovery of the Higgs boson has been in line with what we would expect from the Standard Model, and does not (yet) hint at the new physics we wish to find. We have also dedicated entire search programs to the hunt for dark matter (typically WIMP-like dark matter, but many other programs have been started as well), with no results so far [5]. Because of this, we have begun to extend our search even further, to look for harder to find physics in more creative places. One such possibility is the search for dark sector forces, which would have minimal connections to the Standard Model. These forces would evade the conventional searches, but could possibly be constrained using the cosmological laboratory. An example of the interactions possible for such a dark force are shown in Fig. 1. The dark sector could be produced by some small interaction with the visible sector, evolve on its own, or decay and create regular particles that then interact with each other and produce a signal for us to detect.

Here we focus on a particular dark sector that consists of self-interacting dark gluons. This force behaves similarly to the strong force that we know and understand very well, with the particle behaviour shown in Fig. 2. At the largest energies, asymptotic freedom leads to free quarks and gluons and a well defined perturbative theory. However, as we move down in energy the coupling constant, α, actually increases to the point that free states are no longer possible, and confinement occurs. This gives us the particles we know and understand, such as hadrons (protons

1. Lindsay Forestell received 2nd place in the CAP Best Student Oral Presentation competition at the 2019 CAP Congress at Simon Fraser University in Burnaby, BC.

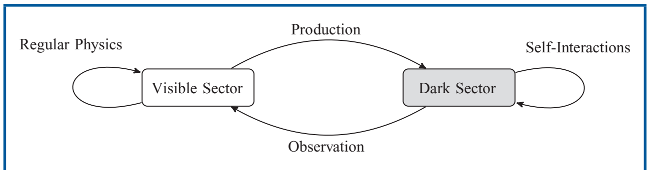

Fig. 1 Visualization of the connections possible between the visible and dark sectors.

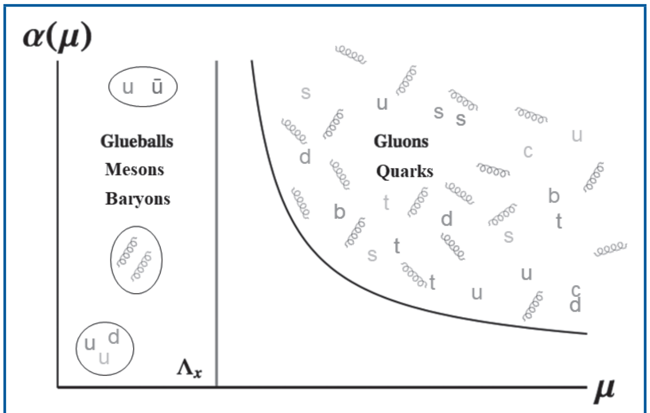

Fig. 2 Schematic depiction of confinement of particles in QCD. At high energies(μ) asymptotic freedom leads to free states of quarks and gluons, while low energies leads to bound states of the particles we are familiar with, the mesons and hadrons. The vertical axis depicts α, the coupling strength between fields in the theory.

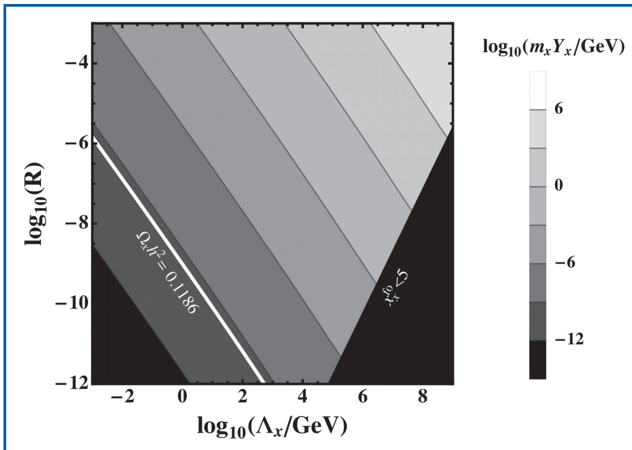

Fig. 3 Abundance of dark glueballs that can be produced in the early Universe as afunction of the mass of the glueballs (horizontal) and temperature of the hidden sector relative to the visible (vertical). Everything above the bold white line is ruled out by overproduction of dark matter.

and neutrons), and mesons (pions). It even predicts bounds states of pure glue, known as glueballs.

In our dark force, we do not include dark quarks, so the only bound state we expect is the glueball. This is what we focused on in our study. We asked and answered questions such as:

- Does it interact with itself?
  - They actually have unique self-interactions that are often termed 'cannibalism' due to the fact that three glueballs can collide and only two come out.
- What would its abundance be?
  - This is heavily dependent on the mass of the dark glueball and temperature of the dark sector. If the correct conditions are met, we can reproduce the dark matter abundance required by ΛCDM. This is shown in Fig. 3.
- Is there more than one type of glueball?
  - There is in fact an entire spectrum of glueball states. However, most of the interesting physics is tied up in the lightest state (where $J^{PC} = 0^{++}$), and so we can keep ourselves focused to only a small subset of the glueballs.

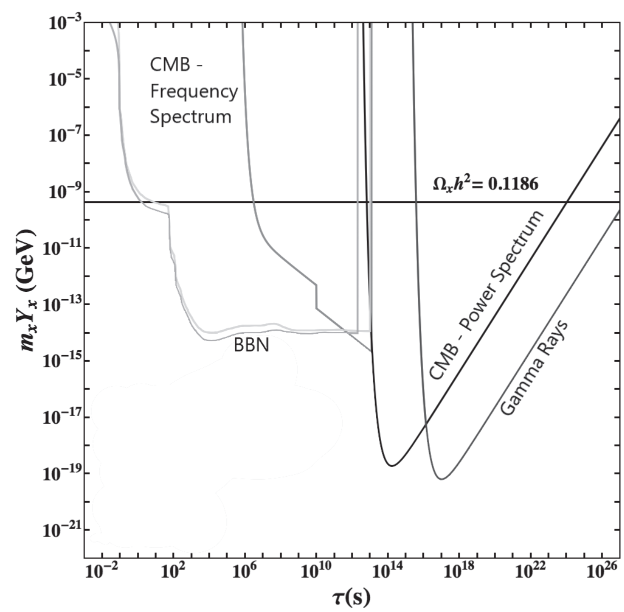

Fig. 4 Cosmological constraints that can be placed on dark glueballs. These span many orders of magnitude in the possible lifetime of the glueball, from seconds to the age of theUniverse. The vertical axis represents the net abundance of glueballs present before they began to decay: the horizontal black line specifically refers to a Universe in which the dark glueball makes up 100% of the measured total dark matter abundance. Any portion of the parameter space above a different constraint curve is ruled out. Over nearly every epoch, a different observation can be used to place constraints on the model.

- Can it interact with regular matter?
  - Yes! The amount of interaction is heavily regulated by various cosmological constraints, which we look at in more detail further on.

COSMOLOGICAL CONSTRAINTS

The final piece of the puzzle is how we can constrain such a dark force. The answer comes from our high precision cosmological observations. We can probe different epochs in the history of the universe using different observations, examples of which are shown in Fig. 4. For example, studies of the lightest elements seen today tell us about Big Bang Nucleosynthesis, which were the few moments responsible for producing the entirety of helium in the early Universe. Moving forward in time, we can actually see the 'last scattering surface' which is the last time the background light of the Universe interacted strongly with free electrons. This light is now what we know to be the Cosmic Microwave Background (CMB), which we have probed extensively with a multitude of experiments. As both of these epochs are very well understood in our current theoretical framework, any disturbance to these models (and subsequent observations) is highly constrained [6,7]. Thus, a new particle such as a dark glueball can only have small interactions (such as a feeble decay to photons or regular gluons). Even further, a glueball that has a lifetime around the age of the Universe would be expected to produce gamma ray signals today, which we could look for with our high energy telescopes. All of these together can be used to put strict limits on not only the possible mass of these dark glueballs, but also how strongly they may interact with the SM. Thus, we can use the cosmological laboratory to provide complementary constraints to those from dark matter and collider searches in our ever evolving hunt for clues to unravel the mysteries we have before us.

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