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Cracking open the window for strongly interacting massive particles as the halo dark matter

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Abstract. In the early 1990's, an analysis was completed by several theorists of the available mass/cross-section parameter space for unusual particle candidates to solve the dark matter problem, e.g. strongly interacting massive particles (SIMPs). This analysis found several unconstrained windows, such that for SIMP masses and cross-sections within these windows, SIMPs could still be the dominant dark matter in our Galactic halo. Since the early 1990's, some of these windows have been narrowed or closed, and some of these windows have been widened further by more careful analysis. We summarize the present state of the SIMP parameter space, and point to the cosmological salience of SIMPs as dark matter, given some of the present inadequacies of the WIMP solution to the dark matter problem.

1 Cosmological Motivation for Trying to Jar the Window

In the last 10-15 years considerable progress has been made in the understanding of the cosmology of our universe. The original 1960's microwave measurements of the residual background radiation (CMB) from the birth of our universe were followed by precision measurements of this radiation in the 1980's and 1990's. These new CMB measurements point to a flat universe with ($\Omega_{\rm TOT} = 1$). Recent measurements of the absolute luminosities and redshifts of distant supernovae suggest a universe whose expansion is accelerating, pointing to the existence of a repulsive dark energy, accounting to about 70% of the critical density. And at least eight different measurement methods suggest inpendently that the density of matter in the universe (normal matter or otherwise) is more than a quarter *and* less than half of the critical density (N. Bahcall *et al.*, 1999).

On a smaller distance (or redshift) scale than the cosmological scale of the whole universe, we find that the normal baryonic matter found in galaxies amounts to about 4% of the critical density (only about 0.1% in stars), whereas from the total-matter density-measurements mentioned above, we believe that at least 25% of the density of the universe is composed of matter. This suggests that there is a large amount of dark matter on a local galactic scale to be identified and added to the equation at the 20-30% level.

The standard solution to this for the past 20 years has been Cold Dark Matter (CDM), in which the missing dark matter is composed of subatomic collisionless particles (a.k.a. weakly interacting massive particles (WIMPs)). WIMPs can in principle be produced in abundance in the early universe so as to solve the dark matter problem. WIMPs together with dark energy also seem to be a good fit to the recent measurements of the spatial power spectrum of microwave structure at 'large' angular scales of more than 0.2 degrees on the sky.

One possible problem of the WIMP solution to the dark matter problem is that some simulations suggest that WIMPs produce too much structure at very small scales. These simulations have also shown that normal WIMP-like CDM produces dark galactic halos which have density profiles with a divergence at the center of the halo. These divergences have not been observed in the real universe: galaxies tend to have dark halo profiles that are flatter than predicted. Also, these WIMP/CDM simulations predict that there will be roughly 1000 satellite galaxies in the Local Group of galaxies, whereas only about 100 are observed.

Spergel and Steinhardt (2000) have suggested one possible solution: if the CDM has strong self-interactions (SIDM), then the simulated over-abundance of small-scale structure would not be a problem anymore. The strong interactions would cause at least one scattering event between SIDM particles during the history of the universe, which would effectively smooth out the cuspy halos. They even estimate an interaction cross-section of colliding SIDM particles which would alleviate the problems seen in the simulations of WIMPs as CDM:

$$\begin{aligned} \frac{\sigma_{DD}}{m} &= 8\times10^{-25} - 1\times10^{-23}\,{\rm cm^2 GeV^{-1}} \\ &= 0.5 - 6\,{\rm cm^2 g^{-1}}, \end{aligned} \qquad (1)$$

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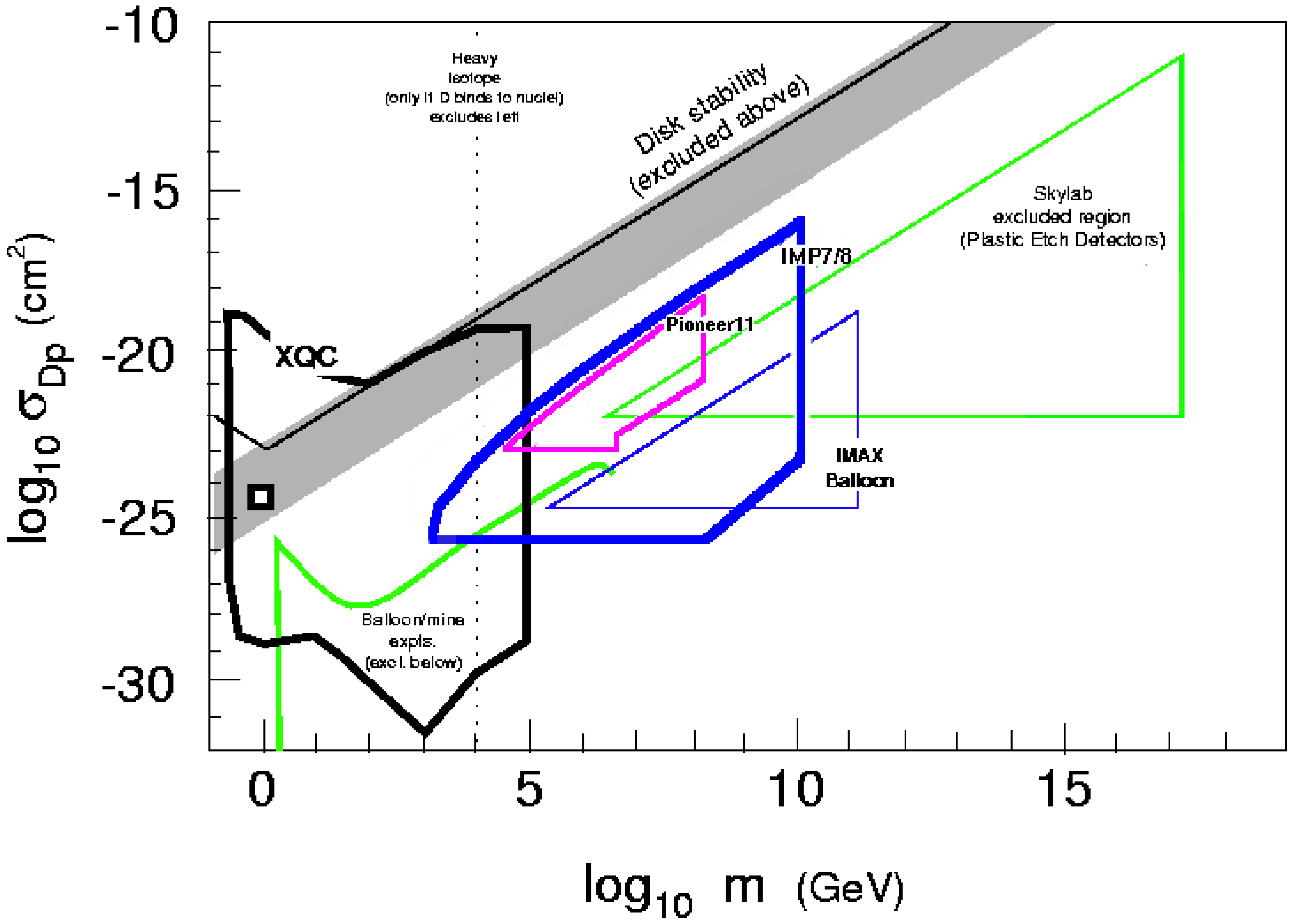

Fig. 1. This plot shows the constraints for dark matter-proton cross-section σ_{Dp} versus mass obtained from a variety of experiments described in the text. We assume here that dark matter (SIMPs) interactions with ordinary matter scale coherently with nucleon number of the scattering agent (the atmosphere or a detector). The excluded regions are labeled as open or closed polygons. The gray region shows the range for the dark matter self-scattering (σ_{DD} in Eq. (1)) to avoid the small-scale structure problem with WIMPs. For some SIMP candidates, σ_{DD} and σ_{Dp} may be comparable, although this is not required generally.

where σ_{DD} is the elastic-scattering cross-section between two SIDM particles, and m is the mass of an SIDM particle. This region of SIDM parameter space is shown as the gray band in Figure 1.

2 The New Crack

But SIDM may also have direct interactions of similar strength with normal matter. Starkman *et al.* (1990) analyzed the observational and theoretical evidence for the possibility that strongly-interacting massive particles (SIMPs) could be the CDM in our galactic halo, and yet remain undetected. These SIMPs were assumed to have interactions with normal baryonic matter. The observational and theoretical evidence analyzed by Starkman *et al.* included a balloon-borne silicon detector (Rich *et al.*, 1987), a silicon detector on Pioneer11 (Simpson *et al.*, 1980), plastic etch detectors on SKYLAB (Shirk and Price, 1978), as well as an analysis of the stability of the Galactic disk and an analysis of heavy water searches.

These SIMPs were studied by Starkman *et al.* under two different scenarios, which had differing interactions with normal baryonic matter. One scenario had an interaction strength which couples to the number of nucleons in a normal nucleus, and the other scenario had an interaction strength which couples with the spin of that nucleus. In both scenarios, they found several open windows in cross-section parameter space. This helped to spur on at least two SIMP search experiments in the early 1990's (McGuire *et al.* (1994), Bacci *et al.* (1994)).

Meanwhile, McGuire (1994) noticed while reviewing Starkman *et al.*'s work that several errors had been made, which opened up a window for SIMPs. The main two errors were:

1. There was a titanium shield of thickness 1.7 mg/cm^2 in front of the Pioneer11 silicon detector which had not been taken into account. The original exclusion plot for Pioneer11 had therefore excluded for SIMPs of arbitrarily large cross-sections.

2. The SKYLAB exclusion region was mis-plotted to exclude upwards from the SKYLAB upper diagonal, whereas it should have excluded downwards from the diago-

nal line, and cut off at $\sigma_{Dp} = 10^{-22}\text{cm}^2$ (as shown in Fig. 1).

This new SIMP/CDM window seems rather important since it overlaps the range of self-scattering cross-sections (σ_{DD} in Eq. (1)) required to solve the small scale structure problem for WIMPs. For some SIMP candidates, σ_{DD} and σ_{Dp} may be comparable, although this is not required generally. In these cases, the self-interacting dark matter particles may be detected directly with suitably-improved space-borne particle detectors.

As first reported in (Wandelt *et al.*, 2000), we have revisited the Starkman SIMP dark matter analysis, by reinterpreting the Pioneer11 experimental data for the SIMP hypothesis, plotting the SKYLAB data correctly, and adding several new exclusion zones to this figure. The new exclusion zones are from:

1. an X-ray quantum calorimeter (XQC) aboard a sounding rocket (McCammon *et al.*, 1996),
2. the IMAX SIMP search experiment using plastic scintillation detectors aboard an antimatter-search balloon-payload (McGuire *et al.*, 1994),
3. the IMP7 and IMP8 satellite-borne silicon detectors (Mewaldt *et al.*, 2001).

In this work, we have carefully checked the analysis of the Pioneer11 and the IMP7/8 detectors for the SIMP-as-DM hypotheses, so we have revised the upper diagonal of the exclusion zones for these two experiments, and in Figure 1, we summarize for the cosmic ray community the complete SIMP parameter space.

3 Can Dark Matter Be Observed Through the Crack?

The area in grey in Figure 1 is the range for the self-scattering cross-section (σ_{DD}) required to solve the small scale structure problem found in WIMP simulations. We might first consider SIMPs for which the cross-section with baryons is similar. This figure shows the comparison of the presently open or closed parameter space for the SIMP-baryon scattering cross-section (σ_{Dp}) and the SIMP-SIMP scattering cross-section from Equation 1, with the assumption that the SIMP-baryon scattering cross-section scales coherently with nucleon number. The revised exclusion plot for an alternative assumption of spin-dependent coupling is not reported here.

The basic results are that the XQC detector has conclusively closed the low-mass area of the gray band in the plot. The reanalysis of the Pioneer11 and SKYLAB event rates and the further analysis of the IMP7/8 event rates has reopened the previously-excluded high-mass area of the gray band in the plot ($M > 10^5$ GeV).

A possible particle candidate that might exist in the remaining gray band are Q-balls (coherent states of squarks and sleptons). Previous Q-ball candidates for dark matter (see Kusenko and Shaposhnikov, 1998) cannot satisfy the σ_{DD}/m constraints for SIDM (see Eq. 1, above). Kusenko and Steinhardt (2001) are proposing a variant which can serve as SIDM. This Q-ball variant can have strong self-interacting cross-sections (corresponding to the gray area) but a very wide range of interactions with protons, spanning most of the unexplored regions (plus some range already excluded by existing measurements). These proposed Q-balls have several unique properties that make them ideally suited for SIDM.

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