Exploring Dark Matter with Milky Way Substructure

Michael Kuhlen,1,3* Piero Madau,2 Joseph Silk3

The unambiguous detection of dark matter annihilation in our Galaxy would unravel one of the most outstanding puzzles in particle physics and cosmology. Recent observations have motivated models in which the annihilation rate is boosted by the Sommerfeld effect, a nonperturbative enhancement arising from a long-range attractive force. We applied the Sommerfeld correction to the latest calculations, leading to the prediction of gamma-ray fluxes from as many as several hundred dark clumps that should be detectable by the Fermi satellite.

In the standard cold dark matter (CDM) paradigm of structure formation, a weakly interacting massive particle (WIMP) with a mass \( m_\chi \) of 100 GeV to 1 TeV ceases to annihilate when the universe cools to a temperature of \( T_\text{y} \sim m_\chi/20 \), about 1 ns after the Big Bang. A thermally averaged cross section at freeze-out of \( \langle \sigma v \rangle_0 \approx 3 \times 10^{-26} \text{ cm}^3 \text{ s}^{-1} \) results in a relic abundance consistent with observations (1). Perturbations in the dark matter density are amplified by gravity after the universe becomes matter-dominated, around 10,000 years after the Big Bang: the smallest structures (“halos”) collapse early, when the universe is very dense, and merge to form larger and larger systems over time. Today, galaxies like our own Milky Way are embedded in massive, extended halos of dark matter that are very lumpy, teeming with self-bound substructures (“subhalos”) that survived this hierarchical assembly process (2–4). Indirect detection of high-energy antiparticles and gamma rays from dark matter halos provides a potential “smoking gun” signature of WIMP annihilation (5). The usual assumption—that WIMP annihilation proceeds at a rate that does not depend, in the nonrelativistic \( v/c \ll 1 \), on the particle relative velocities—implies that the primary astrophysical quantity determining the annihilation luminosity today is the local density squared. WIMP annihilations still occur in the cores of individual substructures, but with fluxes that are expected to be dauntingly small. The latest calculations show that only a handful of the most massive galactic subhalos may, in the best case, be detectable in gamma rays by the Fermi satellite (6, 7).

The Sommerfeld enhancement, a velocity-dependent mechanism that boosts the dark matter annihilation cross section over the standard \( \langle \sigma v \rangle_0 \) value (8–11), may provide an explanation for the experimental results of the PAMELA satellite reporting an increasing positron fraction in the local cosmic ray flux at energies between 10 and 100 GeV (12), as well as for the surprisingly large total electron and positron flux measured by the ATIC and PPB-BETS balloon-borne experiments (13, 14). Very recent Fermi (15) and HESS (16) data appear to be inconsistent with the ATIC and PPB-BETS measurements, but still exhibit departures with respect to standard expectations from cosmic ray propagation models. Although conventional astrophysical sources of high-energy cosmic rays, such as nearby pulsars or supernova remnants, may provide a viable explanation (17–19), the possibility of galactic dark matter annihilation as a source remains intriguing (20–22). In this case, cross sections a few orders of magnitude above what is expected for a thermal WIMP are required (23).

The Sommerfeld nonperturbative increase in the annihilation cross section at low velocities is the result of a generic attractive force between the incident dark matter particles that effectively focuses incident plane-wave functions. The force carrier may be the W or Z boson of the weak interaction (10), \( m_\chi \approx 80 \) to 90 GeV/c², or a lighter boson, \( m_\chi \sim 1 \text{ GeV/c}^2 \), mediating a new interaction in the dark sector (11, 24). Upon introduction of a force with coupling strength \( \alpha \), the annihilation cross section is shifted to \( \langle \sigma v \rangle \approx S \langle \sigma v \rangle_0 \), where the Sommerfeld correction \( S \) disappears (\( S = 1 \)) in the limit \( v/c \rightarrow 1 \) (thus leaving unchanged the weak-scale annihilation cross section during WIMP freeze-out in the early universe). When \( v/c < \alpha \), \( S \approx \alpha v/c \) ("1/v" enhancement), but \( S \) levels off to \( S_{\text{max}} \approx 6 \alpha m_\chi/v_0 \) at \( v/c \approx 0.5 m_\chi/m_\gamma \) because of the finite range of the interaction. For specific parameter combinations—that is, when \( m_\gamma/m_\chi \approx n^2/\alpha \) (where \( n \) is an integer)—the Yukawa potential develops bound states, and these give rise to large, resonant cross-section enhancements where \( S \) grows approximately as \( 1/v^2 \) before saturating (25).

The Sommerfeld effect connects dynamically the dark sector and the astrophysically observable sector. Because the typical velocities of dark matter particles in the Milky Way today are on the order of \( v/c \sim 10^{-3} \), the resulting boost in the annihilation rate may provide an explanation for the puzzling galactic signals. Relative to particles in the smooth halo component, the Sommerfeld correction preferentially enhances the annihilation luminosity of cold, lower-velocity dispersion substructure, as emphasized in (10, 26, 27). Detailed

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*To whom correspondence should be addressed. E-mail: mkj@ias.edu

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knowledge of the full phase-space density of dark matter particles in the Milky Way is thus necessary to reliably compute the expected signals.

Here, we used the Via Lactea II cosmological simulation—a high-precision calculation of the assembly of the galactic CDM halo—for a systematic investigation of the impact of Sommerfeld-corrected models on present and future indirect dark matter detection efforts. Via Lactea II uses just over 1 billion particles with mass of 4100 solar masses \((M_\odot)\) to follow, with a force resolution of 40 pc, the formation of a \(1.9 \times 10^{12} M_\odot\) Milky Way–sized halo and its substructure from redshift \(z = 104\) to the present \((28-30)\) (Fig. 1A). The smooth halo particles, whose velocity dispersions are set by the global potential, typically have three-dimensional velocity dispersion \(\sigma > 100\) km s\(^{-1}\). Particles in self-bound subhalos dominate at lower-velocity dispersions. The total mass fraction of particles with \(\sigma < 5\) km s\(^{-1}\) is 1%. We calculated the Sommerfeld enhancement factors \(S\) on a particle-by-particle basis by averaging \(S(v)\) over a Maxwell-Boltzmann distribution of relative velocities with one-dimensional velocity dispersion given by \(\sqrt{2/3}\sigma\) (25) (Fig. 1, C and D).

The large Sommerfeld boost expected for \(v/c\) \(\approx 10^{-2}\) to \(10^{-3}\) makes cold subhalos more promising sources of annihilation gamma rays than the higher-density but much hotter region around the galactic center (Fig. 2). In Sommerfeld-enhanced models, substructures are much more clearly visible, and can even outshine the galactic center when the cross section is close to resonance and saturates at low velocities. Furthermore, baryonic processes will tend to heat up the galactic center and dim its Sommerfeld boost, and thereby increase the relative detectability of subhalos. Dark matter halos are not isothermal and have lower-velocity dispersions in the center (25). In addition to an overall increase in the annihilation rate, this “temperature inversion” leads to a relative brightening of the center at the expense of the diffuse flux from the surrounding region (Fig. 3). The subhalo exhibits its own population of subclumps, also Sommerfeld-enhanced.

To address quantitatively the detectability of Sommerfeld-enhanced subhalos by the Fermi Gamma-ray Space Telescope, we converted the annihilation flux calculated from our simulation (31) into a predicted gamma-ray flux and compared it to the expected backgrounds. We investigated two different classes of particle physics models (Table 1):

1) Models motivated by Lattanzi and Silk (LS) (10), in which the force carrier is the conventional weak force gauge boson, the W or Z particle, and the mass of the dark matter particle is \(\gtrsim 4\) TeV. We chose four representative values of \(m_{\gamma}\) and \(\alpha\) that lie increasingly close to a \(S \sim 1/v^2\) resonance. In these models, the main source of gamma rays is the decay of neutral pions that are produced in the hadronization of the annihilation products.

2) Models in which the annihilation is mediated by a new dark sector force carrier \(\phi\) (11). The choice of parameters \((m_{\phi}, m_\gamma, \alpha)\) follows Meade, Papucci, and Volansky (MPV) (32) and...
obtained, and the saturation velocity reaches 90% of $v_{\text{sat}}$. The rightmost columns show $D$, the median distance, and $M_{\text{sub}}$, the mass of the detectable clumps after 5 years in orbit.

| Model | $m_T$ (TeV) | $m_\rho$ (GeV) | $\alpha \times 100$ | $S_{\text{max}}$ | $v_{\text{sat}}$ (km s$^{-1}$) |
|-------|--------------|----------------|-------------------|----------------|------------------|
| LS-1  | 4.30         | 90             | 3.307             | 1,500          | 80               |
| LS-2  | 4.45         | 90             | 3.297             | 12,000         | 28               |
| LS-3  | 4.50         | 90             | 3.288             | 70,000         | 12               |
| LS-4  | 4.55         | 90             | 3.281             | 430,000        | 4.7              |
| MPV-1a| 1.0          | 0.2            | 4.000             | 3,000          | 4.7              |
| MPV-1b| 1.0          | 0.2            | 3.739             | 16,000         | 2.4              |
| MPV-2a| 0.25         | 0.2            | 4.000             | 480            | 4.0              |
| MPV-2b| 0.25         | 0.2            | 4.500             | 40,000         | 3.3              |

The magnitude of the relativistic cross section was fixed to the standard value of $(\sigma v)_0 = 3 \times 10^{-26}$ cm$^2$ s$^{-1}$. Gamma-ray spectra are shown in fig. S2.

We determined the Fermi detection significance by summing the annihilation photons from all the pixels in our all-sky maps covering a given subhalo, and comparing the result to the square root of the number of background photons from the same area. We counted a subhalo as “detectable” if it had a total signal-to-noise ratio greater than 5 (Table 2). The numbers are quite large, implying that individual subhalos should easily be detected by Fermi if Sommerfeld enhancements are important. Even in the most conservative cases (MPV-1a and MPV-2a), around 10 or more subhalos should be discovered after 5 years of observation. Indeed, on the basis of all models considered here, Fermi should be able to accumulate enough flux in its first year of observations to detect several dark matter subhalos at more than 5$\sigma$ significance: if so, this would open the door to studies of nongravitational dark matter interactions. The central brightening discussed above results in a smaller angular extent of a given subhalo’s detectable region: The stronger the Sommerfeld enhancement, the fewer pixels exceed the detection threshold. Nonetheless, for all models considered here, the majority of detectable subhalos would be resolved sources for Fermi.

Another question of interest is whether Sommerfeld-corrected substructure would lead to a strong boost in the local production of high-energy positrons, arising from dark matter annihilation in subhalos within a diffusion region of a few thousand parsecs from Earth, as well as of antiprotons within a correspondingly larger diffusion region. The local dark matter distribution at the Sun’s location appears quite smooth in the highest-resolution numerical simulations to date (28, 30, 35). Tidal forces efficiently strip matter from subhalos passing close to the galactic center and often completely destroy them. Further substructure depletion may be expected from interactions with the stellar disk and bulge. In the Via Lactea II simulation, the mean number of $>10^5$ $M_\odot$ subhalos within 1 kpc of the Sun is only 0.04, and one must reach 3 times this distance to find one clump on average. Without the Sommerfeld effect, this dearth of nearby substructure leads to a local annihilation boost of less than 1%, and at most 20% in the rare case of a nearby clump, as found in a statistical approach (36). The picture changes with Sommerfeld enhancement. The low-velocity dispersion of cold substructure leads to a greatly increased luminosity relative to the hotter smooth component. For typical $1/v$ models, subhalos resolved in our simulation within 2 kpc contribute on average about half as much luminosity as the smooth component, and up to 5 times as much in rare cases. If the Sommerfeld enhancement is resonant ($S \sim 1/v^2$), then these subhalos dominate by a factor of 20 on average and by as much as a factor of 200 in rare cases.
Light-Induced Spontaneous Magnetization in Doped Colloidal Quantum Dots

Rémi Beaulac,1 Lars Schneider,2 Paul I. Archer,1 Gerd Bacher,2 Daniel R. Gamelin1*

An attractive approach to controlling spin effects in semiconductor nanostructures for applications in electronics is the use of light to generate, manipulate, or read out spins. Here, we demonstrate spontaneous photinduced polarization of manganese(II) spins in doped colloidal cadmium selenide quantum dots. Photoexcitation generates large dopant-carrier exchange fields, enhanced by strong spatial confinement, that lead to giant Zeeman splittings of the semiconductor band structure in the absence of applied magnetic fields. These internal exchange fields allow spontaneous magnetic saturation of the manganese(II) spins to be achieved at zero external magnetic field up to ~50 kelvin. Photomagnetic effects are observed all the way up to room temperature.

Future spintronics and spin-photonics technologies will require a portfolio of techniques for manipulating spins in semiconductor nanostructures (1). One approach is to tailor magnetic exchange interactions between charge carriers and embedded magnetic impurity ions within the semiconductor (1–3), which can lead to the formation of a magnetically ordered state, the so-called magnetic polaron (1, 4). Among the most notable phenomena yet discovered in diluted magnetic semiconductors (DMSs) is the so-called exchange Manning state (5–11), which can lead to giant Zeeman splittings of the semiconductor band structure in the absence of applied magnetic fields. These internal exchange fields allow spontaneous magnetic saturation of the manganese(II) spins to be achieved at zero external magnetic field up to ~50 kelvin. Photomagnetic effects are observed all the way up to room temperature.

Studies of photomagnets traditionally associated only with molecular species (20–22). Until very recently, however, available colloidal Mn2+-doped semiconductor nanocrystals suffered from exciton quenching by rapid energy transfer to Mn2+ after nanocrystal photoexcitation (23). This energy transfer is faster than Mn2+ spin reorientation, and it hinders EMP formation (12, 24). Colloidal Mn2+:CdSe QDs can now be prepared so that their excitonic photoluminescence (PL) (Fig. 1D) is not quenched by energy transfer to Mn2+ because their excitonic energy levels can be tuned to lie below all Mn2+ electronic excited states (22, 23). The elimination of QD - Mn2+ energy transfer allows the observation of excitonic PL with 10 K decay times of τ em ~ 100 ns (25). Previous magnetic circular dichroism and magnetic circularly polarized luminescence experiments have already demonstrated that these long-lived excitons coexist with strong Mn2+-exciton magnetic exchange coupling (23).

Here, we demonstrate spontaneous photinduced polarization of Mn2+ spins in colloidal doped CdSe nanocrystals. Very large effective internal magnetic fields were observed that lead to complete magnetization of the nanocrystals in the absence of an external magnetic field at temperatures up to ~50 K, with signatures of photomagnetization observable up to room temperature. These large spin effects can be attributed to the strong zero-dimensional exciton confinement achieved in colloidal doped nanocrystals.

We examined the PL of colloidal Mn2+-CdSe DMS QDs as a function of temperature and time (26). Representative variable-temperature PL results are shown in Fig. 1D for diameter d = 4.3 nm, 4.5% Mn2+-CdSe QDs. Even at room temperature, the excitonic PL maximum shifts to lower energy as the temperature is lowered, in stark contrast with the Varshni-like temperature dependence that is typically observed with colloidal CdSe QDs (27) and other semiconductors, in which the PL energy

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1Department of Chemistry, University of Washington, Seattle, WA 98195–1700, USA. 2Werkstoffe der Elektrotechnik and Center for Nanointegration Duisburg-Essen, Universität Duisburg-Essen, 47057 Duisburg, Germany.

*To whom correspondence should be addressed. E-mail: gamelin@chem.washington.edu

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