# Quark Matter in the Solar System : Evidence for a Game-Changing Space Resource

T. Marshall Eubanks[a]

[a] *Asteroid Initiatives LLC, Clifton, Virginia*

*Paper for presentation at the IAA Space Exploration Conference, January 09, 2014, and for publication in Acta Astronautica.*

**Abstract**

Macroscopic quark matter nuggets are an alternative explanation for Dark Matter (DM) consistent with the observational constraints on this mysterious cosmological component. Such quark matter theories have strong implications in the formation, development and current behavior of the Solar System, as primordial quark nuggets orbiting the Galaxy would be subject to capture during planetary formation, leading to the retention of condensed quark matter in the centers of the Sun, planets and asteroids today, a possibility that needs to be taken seriously in Solar System Research.

As quark nuggets are expected to have a minimum mass set by their physics of their formation, any sufficiently small asteroid with a quark matter core would be a strange asteroid, with a high bulk density and strong gravitational binding. Small strange asteroids would be the easiest nugget hosts to detect observationally, and the most accessible source of quark matter once detected. Solar System observations of small Very Fast Rotating (VFR) asteroids (those with rotation periods $\leq$ 1/2 hour) support the quark matter nugget hypothesis. If VFR asteroids are assumed to be bound by quark matter cores, the inferred core mass range peaks at $\sim 10^{10}$ kg, consistent with the stable quark matter mass range predicted by the detailed theory of Zhitnitsky and his colleagues [1, 2].

As there is a prospect that quark nuggets could be used to produce large amounts of antimatter, the economic benefit from even a single ultra-dense strange asteroid could be little short of astounding. If some of the Near-Earth Objects (NEO) are indeed strange asteroids they would truly constitute a game-change resource for space exploration. It is likely that the quark nugget theory will either be rapidly refuted using Solar System observations, or become a focus of space exploration and development in the remainder of this century.

*Keywords:* Quark Matter, Asteroids, Dark Matter, Space Exploration

## 1. Introduction

Attractive forces of unknown origin have been shown to be necessary on a wide range of astronomical scales, from galactic satellites, disks and halos to the largest cosmological structures, which has led to a wide variety of proposed solutions, mostly invoking some sort of particulate DM. Modern cosmological data show that CDM makes up about 26.8% of the total energy density of the universe [3], roughly five times the energy density of ordinary matter, and also that any DM particles must have been relatively cold (i.e., with low velocity dispersion) in the early universe). Solutions with these properties are referred to as Cold Dark Matter (CDM).

While many candidates for CDM are microscopic, such as Weakly Interactive Massive Particles (WIMPs), the DM need not be either microscopic, or non-interacting. Astrophysical data limit the ratio of the cross-section, $\sigma_c$, and mass, $m_c$, of any CDM particles; the best current limit coming from observations of the "Bullet Cluster" (1E 065756), where two colliding galaxy clusters show the CDM (observable with gravitational lensing) decoupled from the cluster gas [4], with the cross section limit being [5]

$$\frac{\sigma_c}{m_c} \leq 0.1 \text{ m}^2 \text{ kg}^{-1}. \quad (1)$$

(Observational cross section limits for specific particles in specific mass ranges may of course be significantly lower.) If CDM is assumed to consist of macroscopic spherical objects, with mass $M_Q$, radius $R_Q$ and density $\rho_Q$, the scattering cross section is $4\pi R_Q^2$ and Equation 1 yelds

$$\rho_Q R_Q \geq 30 \text{ kg m}^{-2} \quad (2)$$

While Equations 1 and 2 are powerful constraints on particle CDM models, they are consistent, by many orders of magnitude, with any macroscopic compact object with densities at or above the nuclear density ($\rho_N \sim 4 \times 10^{17}$ kg m$^{-3}$).

Section 2 describes some of the features of quark nuggets as DM, focusing on one particular macroscopic quark nugget DM solution, Compact Composite Objects (CCOs), condensations of Color-Flavor-Locked (CFL) superfluid quark matter dating from the Quantum ChromoDynamics (QCD) phase transition in the early universe [1, 2]. Section 3 describes the current observational constraints on quark nuggets; CCOs are a viable CDM candidate and pass the currently available observational tests. Section 4 describes how DM (of almost any sort) would be captured in the early Solar System, and how the CCO theory thus predicts that CCOs should be present today in the Solar System, buried inside of most large and many small bodies, including some of the small NEO. Section 5 briefly describes the current asteroid data, which not only support of the existence of a set of small, ultra-dense "strange asteroids" but are consistent with the predictions of the CCO theory. This consistency between theory and observation should motivate more attention and resources being applied tests of the CCO hypothesis; with adequate resources it should be possible to confirm or refute the CCO hypothesis in the Solar System in a relatively short period of time. Section 6 describes my conclusions and mentions a means of extracting energy from a quark nugget. Even a single exploitable quark nugget would truly be a game-changing space resource, able to serve as a source of antimatter, and thus an entirely new energy resource for the exploration and development of the Solar System [6].

## 2. Quark Nuggets as Dark Matter

The idea that condensed quark matter could form in the early universe and persist until the present has a considerable history, first proposed as strangelets [7] and nuclearites [8] almost 3 decades ago, with more recent proposals for CCOs [2] and Compact Ultra-Dense Objects (CUDOs) [9, 10, 11]; this paper will focus on CCOs, a specific proposed quark nugget / CUDO, as the associated theory provides testable predictions for Solar System observations. Most of its findings would apply to any type of nugget (such as the gravitationally bound CUDO's proposed by Dietl *et al.* [12]), should they be present in sufficient numbers in the relevant mass range.

In the theory developed by Zhitnitsky and his colleagues [2, 13, 14, 15] CCOs are created by compression from the collapse of axion domain walls at an epoch near the QCD phase transition, a few microseconds after the Big Bang at a temperature of $\sim$ 160 MeV ($2 \times 10^{12}$ K). The theory predicts that with stable CCOs, at least, formed in a fairly narrow range of masses. (In the theory the lower mass limit is set by the stability of the CCO against decay; some lower CCO masses could potentially be metastable and survive until the present [16].) The stable CCO mass range is primarily determined by the value of $f_a$, the axion decay constant, with the current uncertainty in $f_a$ [17] creating an uncertainty of the stable CCO mass, $M_Q$ of over five orders of magnitude, $10^5$ kg $\lesssim M_Q \lesssim 4 \times 10^{10}$ kg. The actual range of stable CCO masses would be less than two orders of magnitude within that range, depending on the precise value of $f_a$. An improved determination of $f_a$, or a direct determination of the primordial $M_Q$, thus holds the potential for either improving the limit on the other quantity, or ruling out the current CCO theory entirely. (Zhitnitsky has proposed that a majority of cosmological CCOs would actually be antimatter, to allow for a universal symmetry between matter and antimatter in the universe; antimatter nuggets captured in the formation of the Solar System should have annihilated very early and will not be considered further in this paper.)

## 3. Existing Experimental Limits on Condensed Objects

Figure 1 displays the current observational constraints on quark nugget DM assuming a monochromatic mass spectrum, i.e., that all of the DM is contained at a single $M_Q$. The limits on large nugget masses are set by gravitational lensing, while smaller nugget mass constraints are derived from the failure to detect passage of nuggets through a detector, either passage through a laboratory mass (for the smallest mass range) or (in the middle of the mass spectrum) passage completely through the Earth or the Moon [19]. The lensing constraints and the planetary passage constraints are most relevant to the CCO theory.

Limits on the largest nugget masses are set by the failure to detect an anomalously large number of gravitational microlensing events, either in data from the *Kepler* satellite [20] or from a variety of ground-based campaigns [21]. An even more relevant constraint from gravitational lensing was recently set by the search for gravitational femtolensing of Gamma Ray Bursts (GRB) observed by the *Fermi* telescope [22]. Femtolensing is caused by the time delay between different paths across a gravitational lens, which is approximately the period of a 100 KeV gamma ray for a $10^{15}$ kg

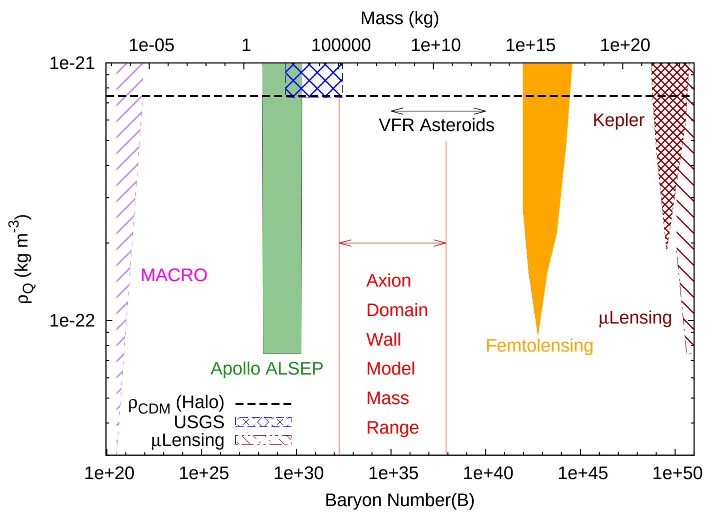


Figure 1: Limits on CUDOs assuming a monochromatic mass spectrum. Shaded regions are excluded by various observational constraints, while "$\rho_{CDM}$(Halo)" is the Galactic DM density estimated using stellar kinematics [18]. The limits on this plot apply to any type of condensed matter DM, although specific DM candidates may have more stringent specific limits depending on the theory of their creation, evolution and observability.

condensed mass at cosmological distances [23]. (These constraints are converted to a constraint in the CUDO Halo density by assuming that the Galaxy shares the cosmological proportion of dark and ordinary matter.)

The various quark nugget mass constraints do not overlap, creating three "windows" in the mass spectrum where a population sufficient to account for Halo DM would not violate current observational constraints. The middle mass window allows nugget masses in the range $1.5 \times 10^5$ kg $\leq M_Q \leq 10^{15}$ kg, which includes almost the entire theoretically predicted range for stable CCO masses (except for the very lowest CCO masses below $1.5 \times 10^5$ kg), as well as the entire nugget mass range suggested by astronomical observations of the asteroids. The best near-term prospect for an improvement in these constraints could possibly be through data from the *Insight* spacecraft seismometer on Mars [24], if that planet proves to be sufficiently seismically quiet. Seismological bounds are flux limited for larger masses, with the bound after a decade of observations being limited to $M_Q \lesssim 4 \times 10^7$ kg, not sufficient to fully constrain the theoretically predicted range of CCO masses.

## 4. Primordial Capture of Dark Matter in the Solar System

Most Solar System DM would result from "primordial capture" by gravitational potential changes during the collapse of the proto-Solar nebula (three-body capture after the formation of the Solar System is relatively much less efficient). This process, which has been shown to be important for the primordial capture of interstellar comets [25, 26] and for DM capture in stars [27], should insert a significant amount of any CDM into the early Solar System, much of which would still be present in the Solar System today.

A molecular cloud the size of the Orion-A nebula (one of the nearest star-formation regions, with a post-collapse radius $\sim$ 85 ly and mass $\sim 1.3 \times 10^5$ $M_\odot$) [28] would, if collapse started at twice the background disk gas density [29], have a pre-collapse radius of $\sim$ 200 ly and a gravitational collapse time $\sim 2 \times 10^7$ yr. A DM particle with a typical Halo velocity of 300 km s$^{-1}$ would pass through the entire pre-collapse cloud in $\sim$ 200,000 yr, much less than the gravitational collapse time and even faster than the pre-collapse supersonic turbulence (with Mach numbers up to $\sim$ 50, i.e., velocities up to $\sim$ 130 km s$^{-1}$) [30]. Such DM particles would be unlikely to be captured. On the other hand, a DM particle that happened to be inside the cloud at the start of its collapse with a relative velocity comparable to the local speed of sound (a few km s$^{-1}$) would be almost stationary relative to the cloud's shock waves and would experience a large change in the local gravitational potential as the gas flowed around it, rendering it subject to capture.

The amount of primordially captured Solar System DM depends sensitively on the conditions of the birth of the Solar System, and particularly on the size of the parent molecular cloud (larger clouds are more effective in capturing DM during collapse). In this paper, a "top-hat" capture probability is assumed, where any particle with a relative kinetic energy ≤ the change in the cloud binding energy during collapse (corresponding to relative velocities $\lesssim 5$ km s$^{-1}$ for the Orion-A cloud model) is assumed to be captured; particles with a higher relative velocity are assumed to evade capture. This capture probability, although crude, provides a conservative estimate of the amount of captured material.

At least two galactic DM populations would contribute significantly to the primordially captured DM, the "dark disk" [31] and the galactic dark Halo [32]. The dark disk is a thin disk of DM with relatively small peculiar velocities ($\sim$ 50 km s$^{-1}$) relative nearby ordinary matter in the Galactic thin disk [33, 34], while the galactic Halo is a much thicker cloud of DM containing most of the mass in the Galaxy. While the Halo is more massive, Halo DM has a nearly random virial velocity of $\sim$ 200 km s$^{-1}$, and thus large velocities relative to any molecular clouds in the Galactic plane, which significantly reduces its capture efficiency compared to the lower relative velocities of DM in the dark disk.

This paper assumes that the Sun formed in the galactic plane at its present galactic radius, and uses the disc DM density estimate of Just & Jahreiß [29] ($9.5 \times 10^{-22}$ kg m$^{-3}$), assuming that the dark disk and Halo DM densities were locally equal at the time of formation [34]. If the parent cloud is assumed to be the size and mass of the Orion-A Nebula the total amount of primordially captured DM from both sources would be $\sim 2 \times 10^{-6}$ $M_\odot$ ($\sim 3 \times 10^{24}$ kg), with $\sim$ 98% of the captured material coming from the dark disk. If the Sun was not in the Dark Disk at the time of its formation, then the total primordially captured DM would be $\sim 3 \times 10^{-8}$ $M_\odot$ ($\sim$ $6 \times 10^{22}$ kg).

## 5. Ultra-Dense Asteroids in the Solar System Today

Most primordially captured quark nuggets would now be either in the Oort cloud or at the centers of the Sun, planets and larger asteroids, where they would be difficult to detect with current technology. Some primordial nuggets would, however, reside today in the smaller asteroids, where the prospects for their detection are considerably better. "Small" asteroids (defined as those with radii $\lesssim$ 200 m) have masses comparable to the theoretical predictions for the largest stable CCOs ($\lesssim 4 \times 10^{10}$ kg) [1]. The existence of small hyper-dense strange asteroids is a direct prediction of the CCO DM hypothesis and leads to direct tests for the theory in the Solar System. Any small body with a majority of its mass in a strange matter quark nugget core will be denoted a "strange asteroid," such bodies, with mantle radii $\lesssim$ 100 m ($M_Q$ / $10^{10}$ kg)$^{1/3}$, would be gravitationally bound by their CCO cores and would have unusually small surface-area to mass ratios, but, as a CCO core would be physically very small (≤ 1 mm radius) and thus contribute negligibly to the moments of inertia, strange asteroids would have surface-area to moment of inertia ratios comparable to ordinary matter asteroids of the same size.

Radiation forcing is important for small asteroids in the inner Solar System, causing both changes in semi-major axis (the Yarkovsky effect, which scales with the surface-area to mass ratio), and rotational torques (the Yarkovsky-OKeefe-Radzievskii-Paddack, or YORP, effect, which scales roughly with the surface area to moment of inertia ratio) [36]. The Yarkovsky effect is thought to be responsible both for delivering Main Belt asteroids, via resonances, into near-Earth orbits [37], and also for sweeping such objects out of near-Earth orbits, limiting their lifetime as NEO. YORP torquing of small bodies is thought to be responsible for the large number of rapidly rotating small asteroids.

The CCO theory makes several firm predictions about strange asteroids, based on the difference in mass and gravitational binding, but not in moments of inertia, between these bodies and comparably sized ordinary matter asteroids. The CCO theory predicts that there should be a population of small strange asteroids, that these bodies, once placed in a near-Earth orbit, should have longer residence times than ordinary matter asteroids (due to the smaller sensitivity to Yarkovsky accelerations), that some of these bodies should be be spun-up by YORP toques, and that (due to the higher gravitational binding), these bodies could be spun up to substantially faster rotational periods before disruption. As longer residence times in near Earth orbits imply that a relatively high fraction of the small NEO could be strange asteroids, and as the rotational period is one of the few dynamical variables known for a large set of small asteroids, the first Solar System test of the CCO theory resides in comparing these predictions with the observed rotation of the asteroids.

### 5.1. *Quark Matter Effects in the Rotation of Small Asteroids*

Figure 2 reveals something of the complicated relationships [39, 40] between asteroid radii and rotation periods, using the complete set of rotation data available as of December, 2013 [35, 41]. YORP apparently accelerates the rotation of many asteroids, with a sizable fraction of the medium sized NEO and Main Belt objects being spun up to rotate at or near their limit rotation [40], the so-called "Rubble Pile Limit" (RPL)

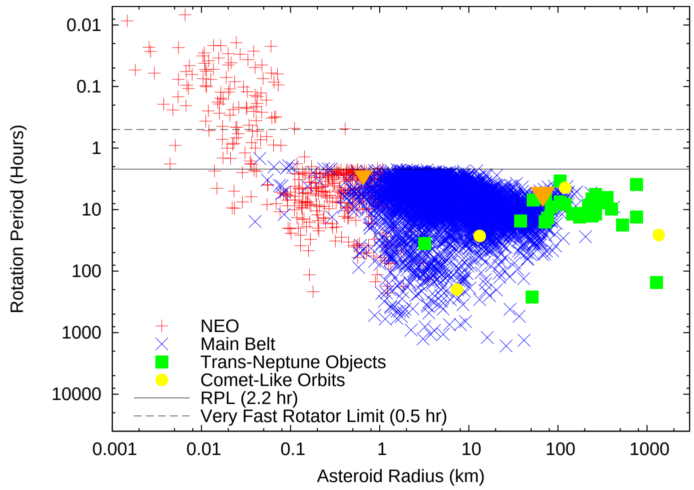


Figure 2: The asteroid rotation period-radius relation for all 4598 bodies with unflagged rotation data, based on the December, 2013, Asteroid Light Curve Database [35], after the removal of any flagged data. The Hungaria and Mars Crossing asteroids are included in the MB asteroid category in this image. The change in the character of asteroid rotation rates at R ~ 200 m is obvious to the eye, with many asteroids with R < 200 m having rotation periods < 1 hour while almost all asteroids with R > 200 m have periods ≥ 2 hours. The horizontal lines show the 2.2 hour Rubble Pile limit and the 0.5 hour VFR limit.

at which the rotational acceleration cancels the gravitational acceleration on the body's equator, implying the beginning of surface rotational disruption. A spherical ordinary matter asteroid (denoted by subscript "A") with uniform density $\rho_A$, is subject to mass loss at a rotational frequency, $\Omega_{RPL}$, where the equatorial rotational acceleration matches the acceleration due to gravity, with

$$\Omega_{RPL}^2 = \frac{GM_A}{R_A^3} = \frac{4\pi G\rho_A}{3}. \tag{3}$$

Equation 3 shows that for a spherical body the RPL rotation depends only on the bulk density of the object; apparent rotation limits can thus be used to directly infer density, under the assumption that the RPL holds.

The situation is, however, very different for small NEO, those with $R_A < 200$ m, where there is little or no evidence for the 2.2 hour RPL and the rotational distribution peaks at periods $\ll 1$ hour. The VFR period limit corresponds to a rubble pile density > 40,000 kg m$^{-3}$, well above that expected from any ordinary matter. Of the 185 NEO with a radius estimate < 200 m, 107 (58%) are FR and almost half (81 objects, or 44%) are VFR. It is noteworthy that, for the asteroid size range and location for which ultra-dense core-dominated asteroids are expected in the CCO hypothesis, there is a substantial population possessing the very fast rotation rates that are indicative of high densities.

In the CCO hypothesis, assuming a lack of internal cohesion, it is straightforward to take the observed radius and rotation frequency and estimate the mass of the CCO core, $M_Q$, (further assuming a uniform density, $\rho_A$, for a spherical ordinary matter mantle), yielding

$$M_Q = R_A^3\left(\frac{\Omega^2}{G} - \frac{4\pi\rho_A}{3}\right). \tag{4}$$

Figure 3 shows a histogram of the number of CCO candidates as a function of the CCO mass inferred using Equation 4, assuming $\rho_A = 2300$ kg m$^3$, for two independent sets of asteroids, those ≤ 50 m and > 50 m in radius. Gaussians are fit to each histogram to estimate the center and spread of the distribution, with estimated centroid masses of 1 and 16 × $10^{10}$ kg for the smaller and larger bodies, respectively. It is striking that these independently inferred mass ranges both overlap the mass range predicted by the axion domain wall model for CCO formation. The agreement between these quantities is striking, especially given the uncertainties in both the rotational mass estimates and quark matter cosmology. These results suggest that, if the CCO theory is valid, the axion decay constant, $f_a$, should be found near the upper end of its predicted range (i.e., $f_a \sim 3 \times 10^{11}$ GeV).

## 6. Conclusions: Applications of Solar System Quark Nuggets

It is certainly possible that the use of asteroid rotation rates to infer the existence of condensed matter cores could be misleading. The agreement between theory and observations visible in Figure 3 is not in itself

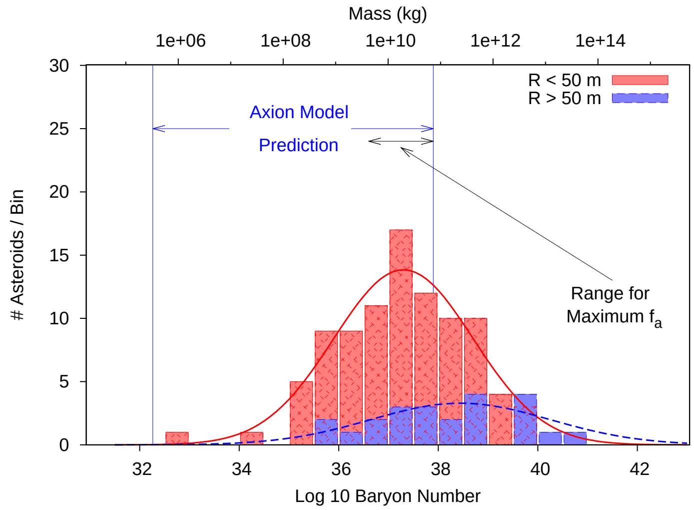


Figure 3: Histogram of the CCO core mass required to prevent rotational disruption assuming gravitational binding and no internal tensile strength, for two independent sets of asteroids. These core mass estimates are based on a rubble pile model with a default $\rho$ = 2300 kg m$^{-3}$ for all asteroid mantles. Also shown (as vertical lines) is the CCO mass range allowed by the axion domain wall theory given current experimental constraints on the axion delay constant $f_a$ and, as marked, the narrower range consistent with the maximum allowed value [38] for $f_a$ ($2.8 \times 10^{11}$ GeV). The displayed Gaussians are fit to determine the histogram centroids; note that these centroids are both close to the upper range of the CCO mass region predicted (completely independently) by the axion domain wall theory.

proof of the existence of strange asteroids, as small bodies could have internal cohesion or tensile strength, and a sufficiently high tensile strength would explain any observed rotation period [42]. However, the striking agreement between theory and experiment, as seen that Figure, does suggest that this theory is worthy of further research.

Should the CCO hypothesis be confirmed, there would be condensed quark matter, and possibly also condensed antimatter, available in the solar system for research and exploitation, in quantities vastly larger than what could be created in any foreseeable particle accelerator. Even a single CCO could provide a very large amount of energy, sufficient to power our civilization for many centuries once it was mined from its ordinary matter mantle. A possible means of energy production from CFL superconductors is provided by Andreev reflection [43], where a high energy ($\geq$ the superconducting gap energy of ~ 100 MeV) beam of baryons directed at the CCO surface would be absorbed by the nugget, generating (through baryon number conservation) free antiparticles.

Even a single ultra-dense asteroid in the Solar System would be truly a game changing discovery worthy of direct exploration by spacecraft. It seems likely that this theory will either be rapidly disproven (by further research into the small asteroids) or will become a major focus of the future exploration of space and economic development of the Solar System.



## References


[1] A. Zhitnitsky, 'Nonbaryonic' dark matter as baryonic colour superconductor, J. Cosmology and Astroparticle Physics 10 (2003) 010. doi:10.1088/1475-7516/2003/10/010. `arXiv:arXiv:hep-ph/0202161`.

[2] A. Zhitnitsky, Cold dark matter as compact composite objects, Phys. Rev. D 74 (2006) 043515. doi:10.1103/PhysRevD.74.043515. `arXiv:arXiv:astro-ph/0603064`.

[3] P. Collaboration, Planck 2013 results. XVI. Cosmological parameters, 2013. `arXiv:arXiv:1303.5076`, Submitted to Astronomy & Astrophysics.

[4] D. Clowe, M. Bradač, A. H. Gonzalez, M. Markevitch, S. W. Randall, C. Jones, D. Zaritsky, A Direct Empirical Proof of the Existence of Dark Matter, Ap. J. 648 (2006) L109–L113. doi:10.1086/508162. `arXiv:arXiv:astro-ph/0608407`.

[5] M. Markevitch, A. H. Gonzalez, D. Clowe, A. Vikhlinin, W. Forman, C. Jones, S. Murray, W. Tucker, Direct Constraints on the Dark Matter Self-Interaction Cross Section from the Merging Galaxy Cluster 1E 0657-56, Ap. J. 606 (2004) 819–824.

[6] T. M. Eubanks, Powering Starships with Compact Condensed Quark Matter, in: Proceedings of the 2013 100-Year Star Ship Symposium, 2013. `arXiv:http://bit.ly/1gQz1Bd`.

[7] E. Witten, Cosmic separation of phases, Phys. Rev. D 30 (1984) 272–285. doi:10.1103/PhysRevD.30.272.

[8] A. de Rújula, S. L. Glashow, Nuclearites - A novel form of cosmic radiation, Nature 312 (1984) 734–737.

[9] J.-E. Alam, S. Raha, B. Sinha, Quark Nuggets as Baryonic Dark Matter, Ap. J. 513 (1999) 572–575. doi:10.1086/306905. arXiv:arXiv:astro-ph/9704226.

[10] B. J. Carr, M. Sakellariadou, Dynamical Constraints on Dark Matter in Compact Objects, Ap. J. 516 (1999) 195–220. doi:10.1086/307071.

[11] J. Rafelski, C. Dietl, L. Labun, Compact Ultradense Objects in the Solar System, Acta Physica Polonica B (2012) 2251. arXiv:1303.4506.

[12] C. Dietl, L. Labun, J. Rafelski, Properties of gravitationally bound dark compact ultra dense objects, Phys. Let. B. 709 (2012) 123–127. arXiv:1110.0551.

[13] M. M. Forbes, A. R. Zhitnitsky, Domain walls in QCD, J. High Energy Phys. (2001) 013. doi:10.1088/1126-6708/2001/10/013. arXiv:arXiv:hep-ph/0008315.

[14] D. T. Son, M. A. Stephanov, A. R. Zhitnitsky, Domain Walls of High-Density QCD, Phys. Rev. Lett. 86 (2001) 3955–3958. doi:10.1103/PhysRevLett.86.3955. arXiv:arXiv:hep-ph/0012041.

[15] D. H. Oaknin, A. R. Zhitnitsky, Baryon asymmetry, dark matter, and quantum chromodynamics, Phys. Rev. D 71 (2005) 023519. doi:10.1103/PhysRevD.71.023519. arXiv:arXiv:hep-ph/0309086.

[16] K. Lawson, A. R. Zhitnitsky, Quark (Anti) Nugget Dark Matter, in: Cosmic Frontier Workshop (CF3 and CF6 groups), SLAC 2013. Snowmass 2013 e-Proceedings, 2013. arXiv:arXiv:1305.6318.

[17] A. Kusenko, L. J. Rosenberg, Snowmass-2013 Cosmic Frontier 3 (CF3) Working Group Summary: Non-WIMP dark matter, ArXiv e-prints (2013). arXiv:1310.8642, report of the CF-3 Working Group at Community Planning Study ”Snowmass-2013”.

[18] J. Bovy, S. Tremaine, On the Local Dark Matter Density, Ap. J. 756 (2012) 89. doi:10.1088/0004-637X/756/1/89. arXiv:1205.4033.

[19] E. T. Herrin, V. L. Teplitz, Whole Earth Seismic Telescope, in: V. Trimble, A. Reisenegger (Eds.), Clusters, Lensing, and the Future of the Universe, volume 88 of *Astronomical Society of the Pacific Conference Series*, 1996, p. 282.

[20] K. Griest, A. M. Cieplak, M. J. Lehner, New Limits on Primordial Black Hole Dark Matter from an Analysis of Kepler Source Microlensing Data, Physical Review Letters 111 (2013) 181302. doi:10.1103/PhysRevLett.111.181302.

[21] P. Tisserand, EROS-2 Collaboration, Limits on the Macho content of the Galactic Halo from the EROS-2 Survey of the Magellanic Clouds, Astron. Astrophys. 469 (2007) 387–404. doi:10.1051/0004-6361:20066017. arXiv:arXiv:astro-ph/0607207.

[22] A. Barnacka, J.-F. Glicenstein, R. Moderski, New constraints on primordial black holes abundance from femtolensing of gamma-ray bursts, Phys. Rev. D 86 (2012) 043001. doi:10.1103/PhysRevD.86.043001. arXiv:1204.2056.

[23] A. Gould, Femtolensing of gamma-ray bursters, Ap. J. Lett. 386 (1992) L5–L7. doi:10.1086/186279.

[24] O. Robert, J. Gagnepain-Beyneix, T. Nebut, S. Tillier, S. Deraucourt, K. Hurst, T. Gabsi, P. Lognonne, W. B. Banerdt, D. Mimoun, M. Bierwirth, S. Calcutt, U. Christenssen, D. Giardini, L. Kerjean, P. Laudet, D. Mance, R. Perez, T. Pike, R. Roll, P. Zweifel, Seis Team, The InSight Very Broad Band (VBB) Seismometer Payload, in: Lunar and Planetary Institute Science Conference Abstracts, volume 43 of *Lunar and Planetary Inst. Technical Report*, 2012, p. 2025.

[25] L. Neslušan, The Oort cloud as a remnant of the protosolar nebula, Astron. Astrophys. 361 (2000) 369–378.

[26] H. F. Levison, M. J. Duncan, R. Brasser, D. E. Kaufmann, Capture of the Sun’s Oort Cloud from Stars in Its Birth Cluster, Science 329 (2010) 187–. doi:10.1126/science.1187535.

[27] F. Capela, M. Pshirkov, P. Tinyakov, Constraints on primordial black holes as dark matter candidates from star formation, Phys. Rev. D 87 (2013) 023507. doi:10.1103/PhysRevD.87.023507. arXiv:1209.6021.

[28] R.-z. Yang, E. de Oña Wilhelmi, F. Aharonian, Probing Cosmic Rays in Nearby Giant Molecular Clouds with the Fermi Large Area Telescope, 2013. arXiv:1303.7323, submitted to A & A.

[29] A. Just, H. Jahreiß, Towards a fully consistent Milky Way disc model - I. The local model based on kinematic and photometric data, Mon. Not. R.A.S. 402 (2010) 461–478. doi:10.1111/j.1365-2966.2009.15893.x. arXiv:0910.3481.

[30] R. S. Klessen, Star Formation in Molecular Clouds, in: C. Charbonnel, T. Montmerle (Eds.), EAS Publications Series, volume 51 of *EAS Publications Series*, 2011, pp. 133–167. doi:10.1051/eas/1151009. arXiv:1109.0467.

[31] C. W. Purcell, J. S. Bullock, M. Kaplinghat, The Dark Disk of the Milky Way, Ap. J. 703 (2009) 2275–2284. doi:10.1088/0004-637X/703/2/2275. arXiv:arXiv:0906.5348.

[32] F. Nesti, P. Salucci, The Dark Matter Halo of the Milky Way, AD 2013, J. Cosmology and Astroparticle Physics 7 (2013) 16. doi:10.1088/1475-7516/2013/07/016. arXiv:1304.5127.

[33] J. I. Read, L. Mayer, A. M. Brooks, F. Governato, G. Lake, A dark matter disc in three cosmological simulations of Milky Way mass galaxies, Mon. Not. R.A.S. 397 (2009) 44–51. doi:10.1111/j.1365-2966.2009.14757.x. arXiv:0902.0009.

[34] T. Bruch, A. H. G. Peter, J. Read, L. Baudis, G. Lake, Dark matter disc enhanced neutrino fluxes from the Sun and Earth, Physics Letters B 674 (2009) 250–256. doi:10.1016/j.physletb.2009.03.042. arXiv:0902.4001.

[35] B. D. Warner, A. W. Harris, P. Pravec, The asteroid lightcurve database, Icarus 202 (2009) 134–146. doi:10.1016/j.icarus.2009.02.003.

[36] W. F. Bottke, Jr., D. Vokrouhlický, D. P. Rubincam, D. Nesvorný, The Yarkovsky and Yorp Effects: Implications for Asteroid Dynamics, Annual Review of Earth and Planetary Sciences 34 (2006) 157–191. doi:10.1146/annurev.earth.34.031405.125154.

[37] A. Morbidelli, D. Vokrouhlický, The Yarkovsky-driven origin of near-Earth asteroids, Icarus 163 (2003) 120–134. doi:10.1016/S0019-1035(03)00047-2.

[38] O. Wantz, E. P. S. Shellard, Axion cosmology revisited, Phys. Rev. D 82 (2010) 123508. doi:10.1103/PhysRevD.82.123508.

[39] P. Pravec, A. W. Harris, T. Michalowski, Asteroid Rotations, in: W. F. Bottke Jr., A. Cellino, P. Paolicchi, and R. P. Binze (Ed.), Asteroids III, University of Arizona Press, 2002, pp. 113–122.

[40] A. W. Harris, P. Pravec, Rotational properties of asteroids, comets and TNOs, in: L. Daniela, M. Sylvio Ferraz, F. J. Angel (Eds.), Asteroids, Comets, Meteors, volume 229 of *IAU Symposium*, 2006, pp. 439–447. doi:10.1017/S1743921305006903.

[41] E. Bowell, Orbits of Minor Planets (Bowell+ 2013), 2012. URL: http://www.naic.edu/ nolan/astorb.html, the research and computing needed to generate astorb.dat were funded principally by NASA grant NAG5-4741, and in part by the Lowell Observatory endowment.

[42] D. J. Scheeres, C. M. Hartzell, P. Sánchez, M. Swift, Scaling forces to asteroid surfaces: The role of cohesion, Icarus 210 (2010) 968–984. doi:10.1016/j.icarus.2010.07.009. arXiv:1002.2478.

[43] M. Sadzikowski, M. Tachibana, Andreev Reflection in Superconducting QCD, Acta Physica Polonica B 33 (2002) 4141–4164. arXiv:arXiv:hep-ph/0208037.