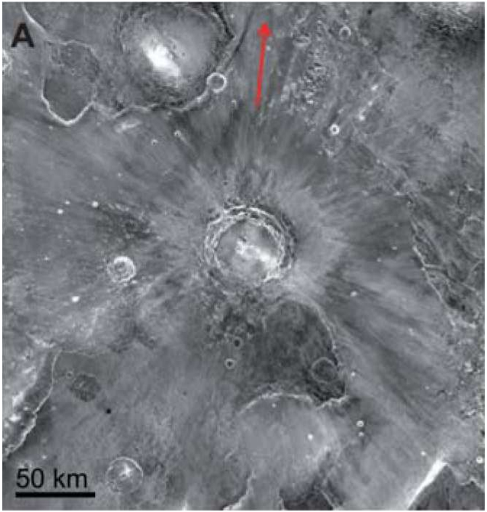
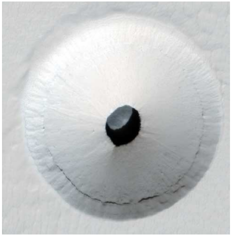
(K)CUDOs at Ψ_{Tucson}



Work based on collaborative effort with present/former AZ students: Jeremiah Birrell and Lance Labun with contributions from exchange student from Germany Ch. Dietl.

1. Introduction
2. Dark Matter (CDM) Generalities
3. Strangeletts
4. Dark Matter (DM) CUDOs
5. CUDO impacts



kudos (from Greek kyddos, singular) = honor; glory; acclaim; praise

kudo = back formation from kudos construed as a plural

cud (Polish, pronounced c-ood) = miracle

cudo (colloq. Polish) = of surprising and exceptional character

CUDO=Compact UltraDense Object:

A new opportunity to search for dark matter. Not dark matter in form of elementary particles (all present day searches) but (self) bound dark matter. Either an ultra-compact impactor or/and condensation seed for comets. There is a lot of dark matter around, cosmological abundance limit shown below.

A new type of meteors

What if there are ‘dark’ matter meteor and asteroid-like bodies in the Universe?

Could some of them have collided with solar system bodies and the Earth?

Are they dressed in visible matter from prior impacts and as condensation seeds?

CUDOs’ high density of gravitating matter provides the distinct observable, the surface-penetrating puncture: shot through

Only a fraction of the kinetic energy damaging the solid surface.

Asteroids of high density

Planetary and Space Science 73 (2012) 98–118

Contents lists available at SciVerse ScienceDirect

Planetary and Space Science

journal homepage: www.elsevier.com/locate/pss

ELSEVIER

Density of asteroids

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ARTICLE INFO

Article history:
Received 23 August 2011
Received in revised form
1 March 2012
Accepted 6 March 2012
Available online 3 April 2012

ABSTRACT

The small bodies of our solar system are the remnants of the early stages of planetary formation. A considerable amount of information regarding the processes that occurred during the accretion of the early planetesimals is still present among this population. A review of our current knowledge of the density of small bodies is presented here. Density is indeed a fundamental property for the understanding of their composition and internal structure. Intrinsic physical properties of small bodies are

29	Amphitrite	MBA	S	OC	1.29	$\pm$ 0.20 $\times 10^{19}$	A.28	217.59	$\pm$ 10.71	B.29	2.38	$\pm$0.51	28	$\pm$ 21	C
30	Urania	MBA	S	OC	1.74	$\pm$ 0.49 $\times 10^{18}$	A.29	94.48	$\pm$ 5.37	B.30	3.92	$\pm$1.29	0	$\pm$ 32	C
31	Euphrosyne	MBA	C	CM	1.27	$\pm$ 0.65 $\times 10^{19}$	A.30	272.92	$\pm$ 8.85	B.31	1.18	$\pm$0.61	47	$\pm$ 52	D
33	Polyhymnia	MBA	S	OC	6.20	$\pm$ 0.74 $\times 10^{18}$		53.98	$\pm$ 0.91		75.28	$\pm$9.71	0	$\pm$ 12	✗
34	Circe	MBA	Ch	CM	3.66	$\pm$ 0.03 $\times 10^{18}$	A.31	113.02	$\pm$ 4.90	B.32	4.83	$\pm$0.63	0	$\pm$ 13	✗
36	Atalante	MBA	C	CM	4.32	$\pm$ 3.80 $\times 10^{18}$		110.14	$\pm$ 4.38	B.33	6.17	$\pm$5.48	0	$\pm$ 88	E
38	Leda	MBA	Cgh	CM	5.71	$\pm$ 5.47 $\times 10^{18}$		115.41	$\pm$ 1.33	B.34	7.09	$\pm$6.79	0	$\pm$ 95	E
39	Laetitia	MBA	S	OC	4.72	$\pm$ 1.14 $\times 10^{18}$	A.32	153.80	$\pm$ 4.14	B.35	2.47	$\pm$0.63	25	$\pm$ 25	C

Fruitful Discussions with Marshall Eubanks lead to these data.

Asteroids of high density

Quite a few more suspects: List of anomalies/CUDO candidates:

		M [10^{18}kg]	Diameter [km]	ρ [g /cm^3]
33	Polyhymnia	6.20 ± 0.74	53.98 ± 0.91	75.28 ± 9.71
152	Atala	5.43 ± 1.24	60.03 ± 3.01	47.92 ± 13.10
675	Ludmilla	12.0 ± 2.4	67.66 ± 0.95	73.99 ± 15.05
1686	DeSitter	6.76 ± 3.18	30.60 ± 1.41	450.51 ± 220.9
57	Mnemosyne	12.6 ± 2.4	113.01 ± 4.46	16.62 ± 3.73
72	Feronia	3.32 ± 8.49	83.95 ± 4.02	10.71 ± 27.44
112	Iphigenia	1.97 ± 6.78	71.07 ± 0.52	10.48 ± 36.06
126	Velleda	0.47 ± 5.79	44.79 ± 1.33	10.00 ± 123.00
132	Aethra	0.41 ± 2.71	35.83 ± 6.59	17.09 ± 112.83
148	Galia	4.89 ± 1.67	83.45 ± 5.07	16.06 ± 6.22
204	Kallisto	0.60 ± 1.81	50.36 ± 1.69	8.98 ± 27.07
210	Isabella	3.41 ± 1.09	73.70 ± 8.47	16.26 ± 7.65
234	Barbara	0.44 ± 1.45	45.62 ± 1.93	8.84 ± 29.17
485	Genua	1.36 ± 0.44	56.31 ± 4.15	14.53 ± 5.68
582	Olympia	0.43 ± 1.17	43.39 ± 1.49	10.00 ± 27.35

THE EARTH, ALL ROCKY PLANETS ARE DETECTORS

1. All objects in solar system are detectors for impacts

   (rate enhanced by gravitational focusing)

2. On rocky planets impact signatures are long-lived

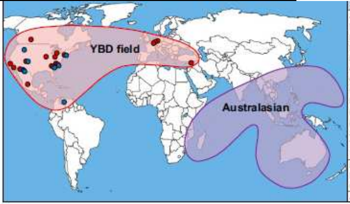
   $\Rightarrow$ Detectors integrate over geologic timescales (Gyr)

   EXAMPLE: The enigmatic spherules (next slide)

3. Easy to access signatures: impacts on Earth! However, these impacts are also geologically unstable and subject to weathering. Only recent events carry clear signatures and can be discussed. May offer guidance what to look for at a distance

4. New sensitivity to compact high-density objects (MACHOs): planetary mass objects below present resolution of direct astronomical observation, e.g. by gravitational microlensing, [Carr,PRD,81(2010)]

Fig. 1. YDB impact field, based on data from 27 locations. In the YDB strewnfield (red), there are 18 YDB sites in this study (red dots; see table on *Right*). Eight independent studies have found spherules and/or scoria-like objects at nine additional sites (blue dots) located in Arizona, Montana, New Mexico, Maryland, South Carolina, Pennsylvania, Mexico, and Venezuela. The largest accepted impact strewnfield, the Australasian (purple), is shown for comparison with each strewnfield covering ~50 million square kilometers or ~10% of the planet. Table shows location of sites and lists site details (A, archeological material; B, black mat; C, charcoal; M, megafaunal remains, present either at the sampling location or in the vicinity). Also given are stratigraphic settings (Strat: A, alluvial; C, colluvial; E, eolian; G, glacial; and L, lacustrine) and relative physical stability of depositional paleoenvironments (Env: A, active, e.g., riverine, lacustrine, or eolian; I, inactive).



Site/Location	Details	Strat	Env	Setting
Arlington Cyn, CA	B,C,A,M	A	A	Coastal cyn
Barber Crk, NC	A	A,E	A	Relict dune
Big Eddy, MO	A	A	A	Flood-plain
Blackville, SC	–	A,E	I	Carolina bay
Blackwater, NM	B,C,A,M	A,L	A	Streambed
Chobot, ALB	B,C,A,M	A,L	A	Lakeshore
Cuitzeo, MEX	B,C,M	L	A	Lake bed
Gainey, MI	B,C,A,M	A,G	I	End-glacial
Kimbel Bay, NC	–	C,E	A	Carolina bay
Melrose, PA	–	C,G	I	End-glacial
Murray Spgs AZ	B,C,A,M	C,L	A	Streambed
Sheriden Cv, OH	B,C,A,M	C	A	Karst-cave
Talega, CA	B,A	A,C	I	Streambed
Topper, SC	A	A,C	I	River bank
Lingen, GER	B,C	E	A	Paleo-dunes
Lommel, BEL	B,CA	E	A	Paleo-dunes
Ommen, NED	B,C	E	A	Paleo-dunes
Abu Hureyra, SYR	B,C,A	A,E	I	Mound (tell)

Evidence for deposition of 10 million tonnes of impact spherules across four continents 12,800 y ago

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doi: 10.1073/pnas.1301760110, Proceedings of National Academy of Sciences (US) PNAS June 4, 2013 vol. 110 no. 23 E2088-E2097

How did an impact distribute these spherules, that is the question here!

Significance

We present detailed geochemical and morphological analyses of nearly 700 spherules from 18 sites in support of a major cosmic impact at the onset of the Younger Dryas episode (12.8 ka). The impact distributed ~10 million tonnes of melted spherules over 50 million square kilometers on four continents. Origins of the spherules by volcanism, anthropogenesis, authigenesis, lightning, and meteoritic ablation are rejected on geochemical and morphological grounds. The spherules closely resemble known impact materials derived from surficial sediments melted at temperatures >2,200 °C. The spherules correlate with abundances of associated melt-glass, nanodiamonds, carbon spherules, aciniform carbon, charcoal, and iridium.

Example: Comet stability

THE ASTROPHYSICAL JOURNAL, 757:127 (33pp), 2012 October 1 doi:10.1088/0004-637X/757/2/127

COMET C/2011 W3 (LOVEJOY): ORBIT DETERMINATION, OUTBURSTS, DISINTEGRATION OF NUCLEUS, DUST-TAIL MORPHOLOGY, AND RELATIONSHIP TO NEW CLUSTER OF BRIGHT SUNGRAZERS

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Received 2012 May 12; accepted 2012 July 30; published 2012 September 11

ABSTRACT

We describe the physical and orbital properties of C/2011 W3. After surviving perihelion passage, the comet was observed to undergo major physical changes. The permanent loss of the nuclear condensation and the formation of a narrow spine tail were observed first at Malargue, Argentina, on December 20 and then systematically at Siding Spring, Australia. The process of disintegration culminated with a terminal fragmentation event on December 17.6 UT. The postperihelion dust tail, observed for ~3 months, was the product of activity over <2 days. The

THE ASTROPHYSICAL JOURNAL LETTERS, 784:L22 (4pp), 2014 April 1 doi:10.1088/2041-8205/784/2/L22

IMAGING COMET ISON C/2012 S1 IN THE INNER CORONA AT PERIHELION

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Received 2014 January 2; accepted 2014 February 16; published 2014 March 12

ABSTRACT

Much anticipation and speculation were building around comet ISON, or C/2012 S1, discovered on 2012 September 21 by the International Scientific Optical Network telescope in Russia, and bound for the Sun on 2013 November 28, with a closest heliocentric approach distance of 2.7 $R_\odot$. Here we present the first white light

Primordial DM Meteor Possible – Qualitative Consideration

High mass/energy scale help with early-universe formation:

a)Becoming non-relativistic at an earlier time, dark matter has a density proportionally higher at the time when gravity can begin to work on local density fluctuations

b)CUDO comprises $10^{11} - 10^{19}$ fewer particles $\Rightarrow$ requires smaller correlation volume contributing

c)Dark particle-particle gravitational interaction $10^{6} - 10^{10}$ times larger.

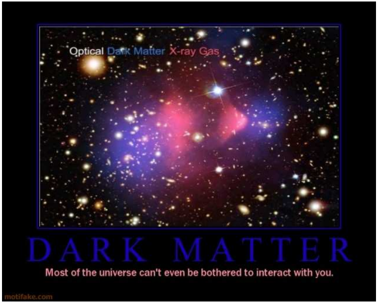
d)Normal (SM) matter in same correlation volume easily ejected carrying away energy and angular momentum (Auger process)

High surface acceleration CUDOs stable against gravitational disruption (especially in collisions with normal matter objects)
$\Rightarrow$ persist into present era

Dark Matter is Matter

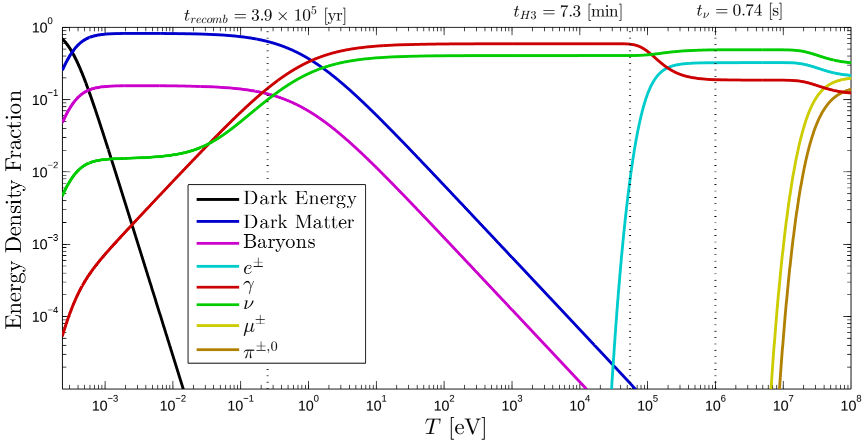
From standard cosmology, fractions of **N**on-**B**aryonic and **B**aryonic gravitating matter show $4/5$ of gravitating matter not identified: ‘dark’

Bullet Cluster, Abell 520, etc show
– Separation of luminous matter and gravity source
$\Rightarrow$ evidence of independent dynamics
$\Rightarrow$ small self-interaction



Many candidate particles could mean *many components* of unseen ‘dark’ matter, some could cluster **form a halo of dark matter asteroids?**

DARK UNIVERSE: $\rho_c = 10.5\mathrm{keV}h^2/\mathrm{cm}^3$, $h|_{\mathrm{today}} = 0.7$



PLANCK satellite measures CMB which froze out at $T = 0.25$ eV. Universe structure red shifted by $z \simeq 1000$ analyzed within ΛCDM model. In current era: 69% dark energy, 26% dark matter, 5% baryons, $<$ 1% photons and neutrinos; of 3 neutrinos ν one is $m_\nu = 0$ and two $m_\nu = 0.1$ eV

Brief overview of ΛCDM

Friedmann−Lemaitre−Robertson−Walker (FRW) homogeneous and isotropic Universe metric:

$$ds^2 = dt^2 - a^2(t)\left[\frac{dr^2}{1-kr^2} + r^2(d\theta^2 + \sin^2(\theta)d\phi^2)\right].$$

Standard ΛCDM model is spatially flat ($k = 0$); Scaling factor $a(t)$ determines the distance between objects at rest in the Universe frame. The resultant Einstein equations for a perfect fluid source:

$$G^{\mu\nu} = R^{\mu\nu} - \left(\frac{R}{2} + \Lambda\right) g^{\mu\nu} = 8\pi G_N T^{\mu\nu}, \quad T^{\mu}_{\nu} = \mathrm{diag}(\rho, -P, -P, -P),$$

We absorb the dark energy into $\rho \to \rho + \Lambda M_p^2$, $P \to P - \Lambda M_p^2$, $M_p \equiv 1/\sqrt{8\pi G_N} = 2.435 \times 10^{18}$ GeV and obtain for the Hubble parameter $H \equiv \dot{a}/a$, and deceleration parameter $q = (1 + 3\rho/P)/2$

$$3M_p^2 H^2 = \rho, \;\; 6M_p^2 q H^2 = \rho + 3P, \;\; \dot{\rho} = -3(\rho + P)H.$$

Given equation of state $P(\rho)$ one can solve for the large scale dynamics of the Universe.

LIMITS ON DARK MATTER PARTICLE MASS

Beyond the standard model particles: mass limit pushed up by CERN-LHC and now electron dipole moment to 1000's of proton mass:

In most suggested extensions of the standard model, a measurable d_e implies the existence of heavy new particles with masses roughly proportional to $1/\sqrt{|d_e|}$. Their *CP*-violating interactions with electrons and other leptons could also account for the cosmological matter–antimatter asymmetry.

A d_e of 10^{-26} *e*·cm would have suggested that the new particles have masses of a few hundred GeV. That's precisely the energy scale of electroweak symmetry breaking, where SUSY models originally anticipated the appearance of "sleptons," supersymmetric boson partners of the leptons.

But now we learn that d_e is even smaller than 10^{-28} *e*·cm. "That's a very significant tightening of constraints on the new physics," says theorist Maxim Pospelov (University of Victoria, British Columbia). "It seems to disengage the anticipated *CP*-violating leptonic interactions from the electroweak scale. It pushes the new particles firmly into multi-TeV territory inaccessible to the next generation of sub-TeV electron–positron colliders." Their discovery at CERN's Large Hadron Collider remains an open question.

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GO TO SECTION...

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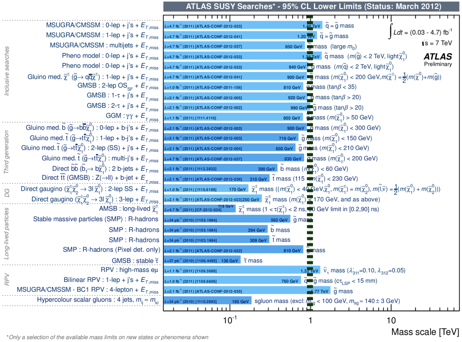
2. J. Baron *et al.* (ACME collaboration), *Science* **343**, 269 (2014). http://dx.doi.org/10.1126/science.1248213

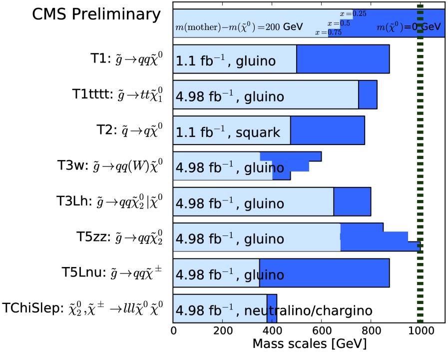
DOI: http://dx.doi.org/10.1063/PT.3.2334

Collider constraints: Supersymmetry



ATLAS, March 2012

95% confidence level Lower Limits



CMS

Components of unseen matter

	mass range	constraints (if any)	interactions
baryon			
▶ MACHOs	$10^{15} - 10^{36}$ g	standard cosmology, microlensing	gravity, small EM
▶ quark nuggets	$10^{-23} - 10^{32}$ g	BBN, direct search, stellar physics	gravity, small EM
neutrino			
▶ relic SM νs	< a few eV	cosmology $\Omega_\nu h^2 \leq 0.0067$	weak
▶ sterile	keV		–
black holes	$10^{15} - 10^{50}$ g	microlensing	gravity
WIMPs (various)	GeV-TeV	collider, direct searches	weak gauge coupling
Q-balls (various)	GeV-TeV	collider, direct searches	–
axions	μeV-meV	direct searches	anomaly
Hidden sector	>GeV	standard cosmology (BBN)	unknown non-SM
extra-dim (KK)	>TeV	collider	various SM, non-SM

PDG 2010, Madsen astro-ph/9809032,astro-ph/0612740, Bergstrom arXiv:0903.4849, Feng arXiv:1003.0904

Example: Strangelets: *uds*-symmetric matter in bulk

Strangelet = piece of $n_u \simeq n_d \simeq n_s$ matter, large baryon number A

Simple argument for (meta)stability

Chemical equilibrium:

$$\mu_d = \mu_u = \mu_s$$

Charge neutrality:

$$\frac{2}{3}n_u - \frac{1}{3}n_d - \frac{1}{3}n_s = 0$$

Compute thermodynamic potentials $\Omega_{u,d} = -\frac{\mu_{u,d}^4}{4\pi^2}$

with massive strange quark $m_s > 0$

$$\Omega_s = -\frac{\mu_s^4}{4\pi^2}\left(\sqrt{1-x^2}(1-\frac{5}{2}x^2) + \frac{3}{2}x^4 \ln(x^{-1} + \sqrt{x^{-2}-1})\right) \quad x = m_s/\mu_s$$

Third fermi sea reduces Energy/baryon: $\frac{E/A(3\text{ flavors})}{E/A(2\text{ flavors})} < 1$

Example of Strangelett Mass and Size Scales

Strangelet = piece of $n_u \simeq n_d \simeq n_s$ matter, large baryon number A

Madsen astro-ph/9809032, astro-ph/0612740

$$10^{30} < A < 10^{56} \quad \Leftrightarrow \quad \begin{cases} 10^4\ \mathrm{kg} < M < 10^{29}\ \mathrm{kg} \\ 10^{-20} < M/M_{\mathrm{Earth}} < 10^5 \end{cases}$$

- Constant density: $M \sim R^3$
- Density scale set by nuclear length $R_{\mathrm{nuc}} \sim 1\ \mathrm{fm}$
  (10^5 reduction relative to normal matter atomic length $R_{\mathrm{atom}} \sim 1$Å)

Normal matter asteroid	SQM "asteroid"
$M \sim 10^{-5} M_{\mathrm{Earth}}$	$M \sim 10^{-5} M_{\mathrm{Earth}}$
$R \sim 100\ \mathrm{km}$	$R \sim 1\ \mathrm{m}$

Compactness and high density $\rho_{\mathrm{nuc}} \sim 10^{15} \rho_{\mathrm{atomic}}$ mean...

- ▶ gravity relevant in interactions: $g_{\mathrm{surf}} = \dfrac{GM}{R^2} = \dfrac{4\pi G}{3}\rho R$
- ▶ Matter cannot support a strangelet: "punctures the Earth"

[see e.g. DeRujula/Glashow, Nature,312(1984), Herrin et al,PRD,53(1996) & 73(2006)]

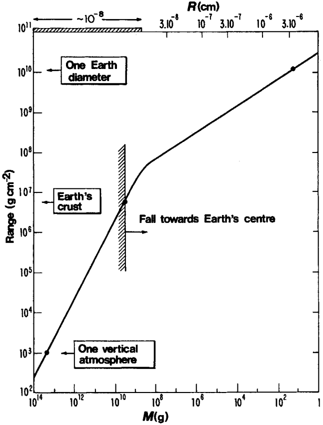
Strangelet meteorites= ‘Nuclearites’ considered before:

CUDO impacts on Earth have been considered before:

de Rujula & Glashow, Nature (1984)
Proposed searching for

1. tracks preserved in mica
2. visible light emission
3. large scale scintillators
4. Seismic waves

continued: Herrin et al, PRD, **53** (1996) & **73** (2006), AMS (ongoing), Lunar Soil Search, PRL (2009)



- all but (1) above require *real time* observation of impact

What happens for heavier impactors?

Sources of Strangelets

1. Cosmological

First order phase transition to hadronic vacuum [Witten,PRD,30(1984)]

Objects $A < 10^{55}$ evaporate at $T \simeq 50\,\mathrm{MeV}$ [Alcock & Farhi,PRD,32(1985)]

Strangeness enriched at surface $\rightarrow$ reduced emissivity of nucleons

$$** \text{ Quasi-equilibrium } A \sim 10^{46} \Leftrightarrow M \simeq 10^{19}\,\mathrm{kg} = 10^{-5} M_{\mathrm{Earth}} \; **$$

[Madsen,PRD,34(1986) & 43(1991)]

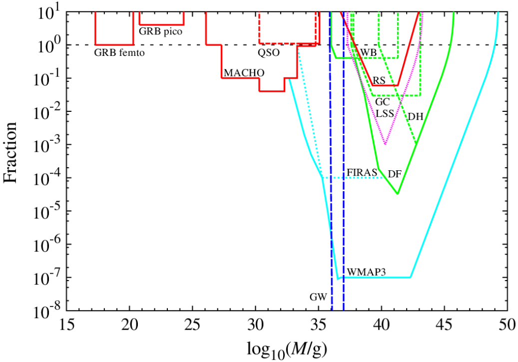
- Large objects $A \gtrsim 10^{23}\Omega_{\mathrm{nug}}^3 h^6 f_N^3$ consistent with BBN
- Quark matter in nuggets does <u>not</u> contribute to BBN limit on Ω_b

2. Strange stars

Collisions eject fragments [Madsen,JPG,28(2002) & Bauswein,PRL,103(2009)]

Microlensing constraints on invisible clumps of matter

MACHOs = **M**assive **C**ompact **H**alo **O**bjects
sought by gravitational microlensing surveys (MACHO, EROS, OGLE)



Carr et al PRD **81** 2010

Examples

failed stars (brown dwarfs)
supermassive planets
neutrino stars
Bose stars
black holes

YES: SUB-planetary mass range $10^{15}\mathrm{g} < M < 10^{27}\mathrm{g} \simeq$ Earth mass

Character of Gravi Bound Objects: Scaling Solution

If we have only $m, M_{\rm Pl}$ and need only 1 equation of state $p(\rho)$

Dimensionless...

1) pressure, density

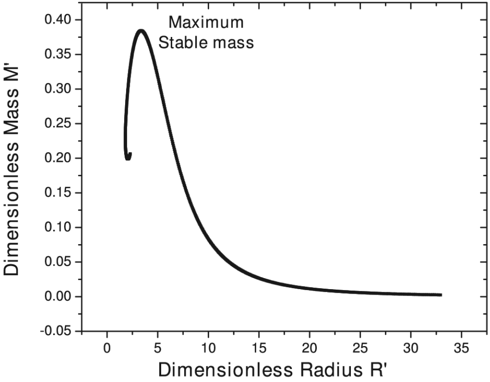
$$\widetilde{p}(\widetilde{\rho}) = m^{-4}\, p\left(\rho m^{-4}\right)$$

2) total mass of solution

$$\widetilde{M} = M \frac{m^2}{M_{\rm Pl}^3}$$

3) surface radius of solution

$$\widetilde{R} = R \frac{m^2}{M_{\rm Pl}}$$



[Narain, Schaffner-Bielich, Mishutsin, PRD **74** (2006)]

TOV equations now dimensionless – Solve once!

NOT the whole story: check stability against perturbation

Oppenheimer/Serber 1936

We consider two types of DM CUDOs

Analogous to compact objects composed of SM matter:

Narain et al, PRD **74** (2006), Dietl et al, PLB **709** (2012)

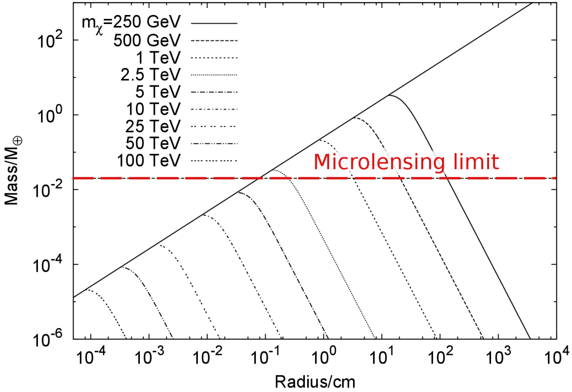
Fundamental fermion	Composite
mass $m_\chi \gtrsim 1\,\mathrm{TeV}$	**B**ag model vacuum pressure $B \gtrsim (1\,\mathrm{TeV})^4$
supported by pressure of degenerate fermi gas	self-bound by interactions
analogy to white dwarf, neutron star	analogy to quark-star, strangelet

Solve for equilibrium configuration in Oppenheimer-Volkoff equations

TeV-scale Fundamental Fermi particle

$M_\oplus = 6\ 10^{24}$ kg
$= \text{Earth mass}$

$M_{\max} \propto m_\chi{}^{-2}$



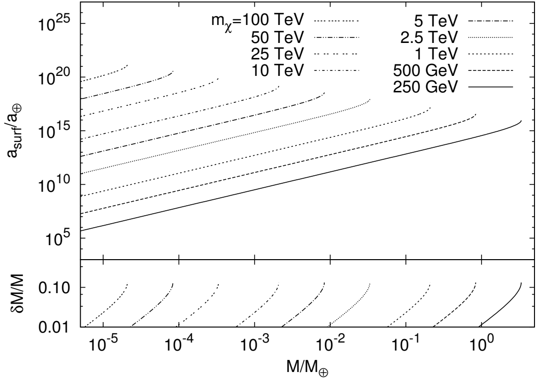
★ upper end of curve are objects stable and robust in collisions

EROS Collaboration, Astron.Astrophys. **469** (2007) Dietl et al, PLB **709** (2012)

Gravitational Stability and Tidal Force

Compact: Size of object comparable to gradient of gravitational field

$\Rightarrow$ Tidal force important $\quad a_{\rm tidal} = \frac{2GM}{r^2}\frac{L}{r} = a_{\rm surf}\frac{R^2_{\rm surf}}{r^2}\frac{2L}{r}$



$a_\oplus = 9.8 \mathrm{m/s}^2$
$= $ Earth surface

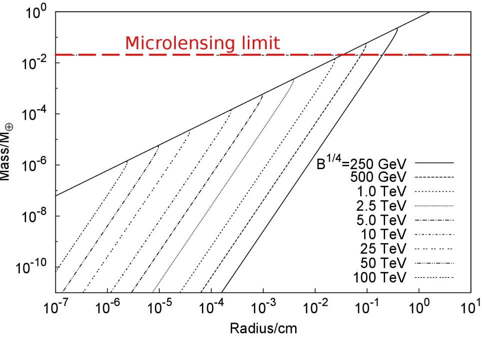
- Tidal acceleration pulls apart atoms in solids: $a_{\rm surf} > 3.5\ 10^{15} a_\oplus$

Dietl et al, PLB **709** (2012)

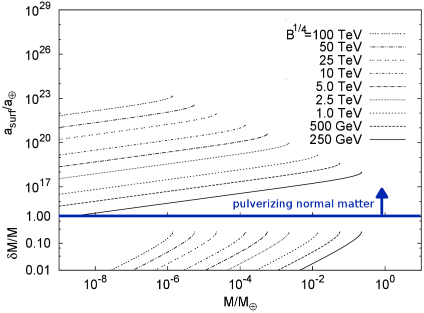
CUDOs not stopped by impact with normal density (visible) matter

Composite with TeV confinement energy

$M_\oplus = 6\,10^{24}\,\mathrm{kg} =$ Earth mass $\quad B =$ bag model vacuum pressure



Dietl et al, PLB **709** (2012)



$$M_{\max} \propto (B^{1/4})^{-2}$$

EROS Collaboration, Astron.Astrophys. **469** (2007)

Tidal force destructive for
$a_{\rm surf} > 3.5\,10^{15} a_\oplus$

Summary: Fundamental Fermi vs. Composite/Bag

Fundamental fermion	Composite particle
mass $m_\chi \gtrsim 1\,\mathrm{TeV}$	vacuum pressure $B \gtrsim (1\,\mathrm{TeV})^4$
$M_{\max} = 0.209 \left(\frac{1\,\mathrm{TeV}}{m_\chi}\right)^2 M_\oplus$	$M_{\max} = 0.014 \left(\frac{1\,\mathrm{TeV}}{B^{1/4}}\right)^2 M_\oplus$
$R = 0.809 \left(\frac{1\,\mathrm{TeV}}{m_\chi}\right)^2 \mathrm{cm}$	$R = 0.023 \left(\frac{1\,\mathrm{TeV}}{B^{1/4}}\right)^2 \mathrm{cm}$

$$M_\oplus = 6\,10^{24}\,\mathrm{kg} = \text{Earth's mass}$$

★ Due to high mass scale, common $M <$ Earth mass, $R < 1$ cm

$\Rightarrow$ Highly compact and not too heavy

Scaling solution $\Rightarrow$ gravitational binding also scales!

$\Rightarrow$ as stable as white dwarf/neutron star solutions with SM particles

Collisions: a) Tidal Forces

in PRL

Consider CUDO passing through normal density matter

Matter disrupted due to differential acceleration

$$a(r - L/2) - a(r + L/2) = a_{\rm tidal} = \frac{2GML}{r^3}$$

To compromise structural integrity,

$$\text{gravitational pressure} > \text{compressional strength}$$

$$\frac{F_{\rm tidal}}{\rm area} = \rho\, L\, a_{\rm tidal} > \rho\, c_s^2 \quad \text{(bulk modulus)}$$

$\Rightarrow$ Material fails somewhere within Fracture length

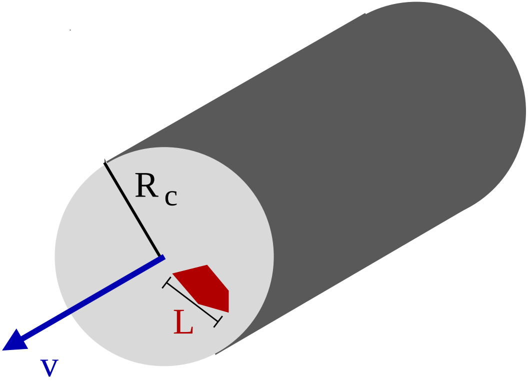
$$\frac{L}{R_c} = \sqrt{2}\frac{c_s}{v}\left(\frac{r}{R_c}\right)^{3/2}$$

$c_s =$ Bulk sound speed   Gravitational Capture radius $R_c := \frac{2GM}{v^2}$

Collisions: b) Fracture Length and Capture radius

Length scale: Gravitational capture radius $R_c = \dfrac{2GM}{v^2}$

$r < R_c$ material accreted to passing CUDO
$r > R_c$ material pulled in direction of motion, but left behind



In solid medium, material must be broken into pieces small enough to accrete

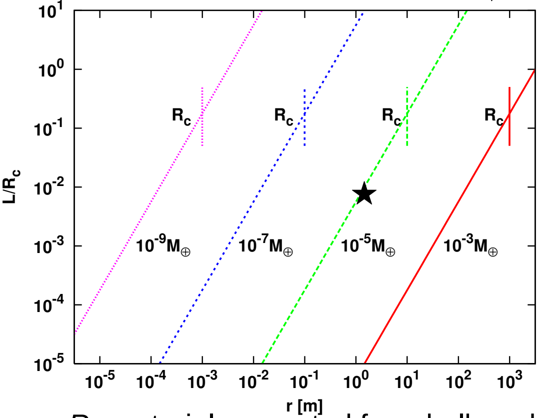
$$\frac{L}{R_c} = \sqrt{2}\frac{c_s}{v}\left(\frac{r}{R_c}\right)^{3/2} < 1$$

sound speed c_s representing bulk modulus (strength) of medium

Collisions: c) Accretion

CUDO velocity

- $v \sim 40\,\mathrm{km/s}$ (co-moving near solar system)
- $v \sim 200\,\mathrm{km/s}$ (galactic halo population)



Strip material from target:

$$\frac{L}{R_c} = \sqrt{2}\frac{c_s}{v}\left(\frac{r}{R_c}\right)^{3/2} < 1$$

Earth mantle: $c_s \simeq 8\,\mathrm{km/s}$

Example: $10^{-5} M_{\mathrm{Earth}}$

$R = 1\,\mathrm{m}$

$r < R_c$ material separated from bulk and accreted to CUDO

$r > R_c$ material pulled in direction of motion, but left behind

Collisions: d) Stopping, Other Characteristics

Entrainment of Material

Captured matter acquires CUDO velocity $\Rightarrow$ reduces kinetic energy

$\frac{\Delta E}{E} = 0.01 \left(\frac{40\ \mathrm{km/s}}{v}\right)^4 \frac{M}{M_{\mathrm{Earth}}}$ Objects $M < 10^{-4} M_{\mathrm{Earth}}$ not stopped

$\Rightarrow$ Two surface punctures! Entry and Exit signatures

Drag from Normal matter interactions

- Molten $T \sim 10^5\ \mathrm{K}$ shocked material
- Mixing of nearby entrained and nearly-entrained material

Pulling debris stream along behind CUDO

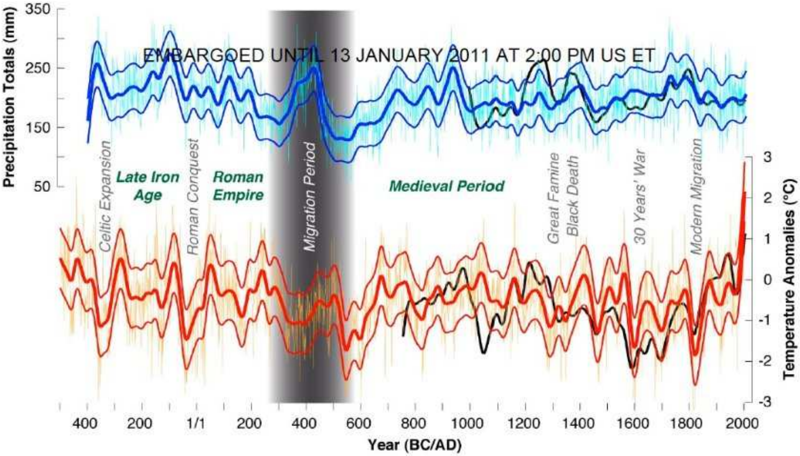
- Matter from previous collisions can "dress" CUDO,
  giving appearance of normal (but overdense) meteor
- Fraction remains bound to impacted planet,
  but re-distributed inside and above surface

Needs Explanation

1. Comet Ison survives (2013) grazing collision
2. Comet Lovejoy (2011/2) C/2011 W3 grazes within Roche limit the solar corona and survives the passage only to explode later
3. 10 million tons of spherules 12.8kyears ago altered climate and are not of ‘conventional origin
4. Climatic excursion 536-545A.D. Ice Cores indicate ‘explosive’ volcanic origin, no impact wound and upper atmosphere material needed was initially interpreted as a 500m cometary impact.
5. Moon MASCONS
6. GOCE Earth

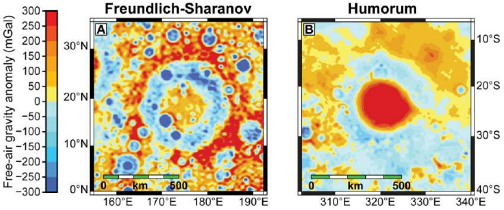
AD 536 Event

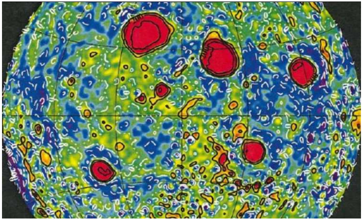
...is hotly contested: a comet or a giant volcano eruption (not found). Is it a '6-month coincidence', probability 10^{-3}? Or, a modest size dressed CUDO puncture and associated transport of material into upper atmosphere. Further milder weather fluctuations are also not well understood.

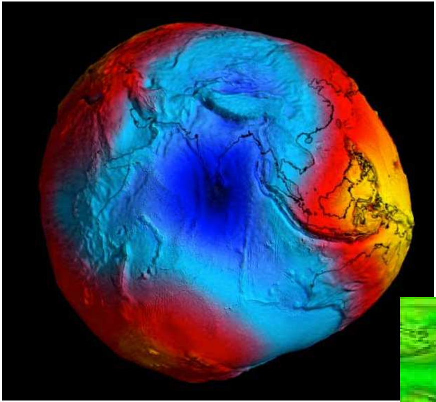


Remote Sensing: MASCONS

MASCONs (mass concentration): Lunar mascons appear due to old impacts, but how such strong anomalies were created/preserved is debated. Is excess mass due to denser lava material filling the crater or due to upwelling of denser iron-rich mantle material to the crust? Mascons make the Moon the most gravitationally lumpy body known in the solar system, anomaly is 0.5%. Mascons also exist on Mars, none have been found on Venus or Earth – as of 2001; those two larger planets, however, have had an active tectonic (geological) past that has drawn their crusts down into their interiors several times in the past few billion years, homogenizing the distribution of mass. Forward to 2012/2013: High-resolution gravity GRAIL mission show that gravitational fields resembling a bull's-eye pattern: a center of strong, or positive, gravity surrounded by alternating rings of negative and positive gravity.
http://web.mit.edu/newsoffice/2013/an-answer-to-why-lunar-gravity-is-so-uneven-0530.html



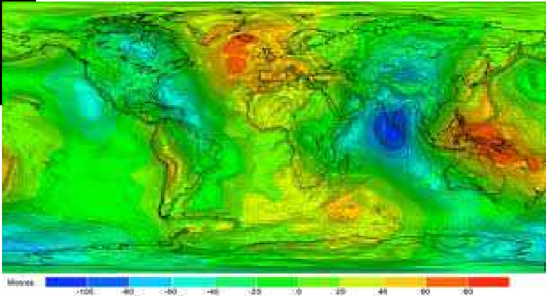




What made this?

The **G**ravity Field and Steady-State **O**cean **C**irculation **E**xplorer (GOCE) produced geoid view of Earth showing a spherical impact-like depression South-West off the India coast.

In India there is a large lava flow region called “Deccan Traps” dating to 65 million years ago - was this the Dinosaur killer? Geologists argue about that.



More Puzzles	Seen in Lit.	CUDO as cause
Impact correlation with volcanic[1,2] & mantle plume[3] activity on Earth	Models of normal matter impacts do not puncture Earth's crust[4]	CUDO passage melts and pulls material to surface at exit
Climatic excursions related to 'impacts' leading also to mass extinctions	1) comet impact deposits material in upper atmosphere, 2) very large eruption, 3) multiple impacts	CUDO creates impact and exit features, pulls debris from surface, deposited at all altitudes in atmosphere
Gravity anomalies e.g. odd morphology and/or density anomalies		CUDO impacts, CUDO core dressed by normal matter envelope

Not entirely science-fiction

Compact ultradense matter impactors
JR, Lance Labun, and Jeremiah Birrell, Phys.Rev.Lett. 110 (2013) 111102
http://prl.aps.org/abstract/PRL/v110/i11/e111102

Compact Ultradense Objects in the Solar System
JR, Christopher Dietl, LL; Acta Phys.Polon. B43 (2012) 12, 2251-2260
http://th-www.if.uj.edu.pl/acta/vol43/abs/v43p2251.htm

Properties of Dark Compact Ultra Dense Objects
Christopher Dietl, LL, and JR, Phys.Lett. B709 (2012) 123-127
http://dx.doi.org/10.1016/j.physletb.2012.02.015

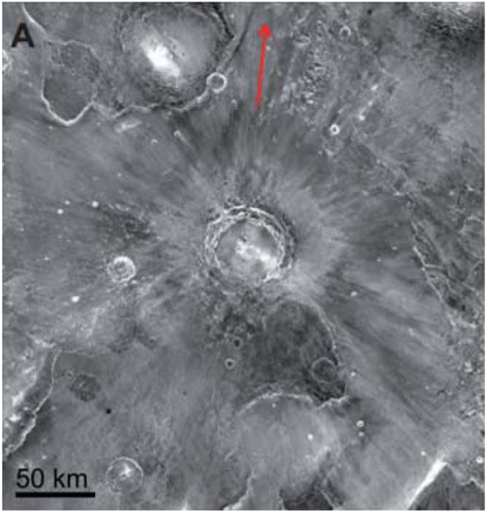
Planetary Impacts by Clustered Quark Matter Strangelets
LL and JR, Acta Phys.Polon.Supp. 5 (2012) 381-386
http://dx.doi.org/10.5506/APhysPolBSupp.5.381

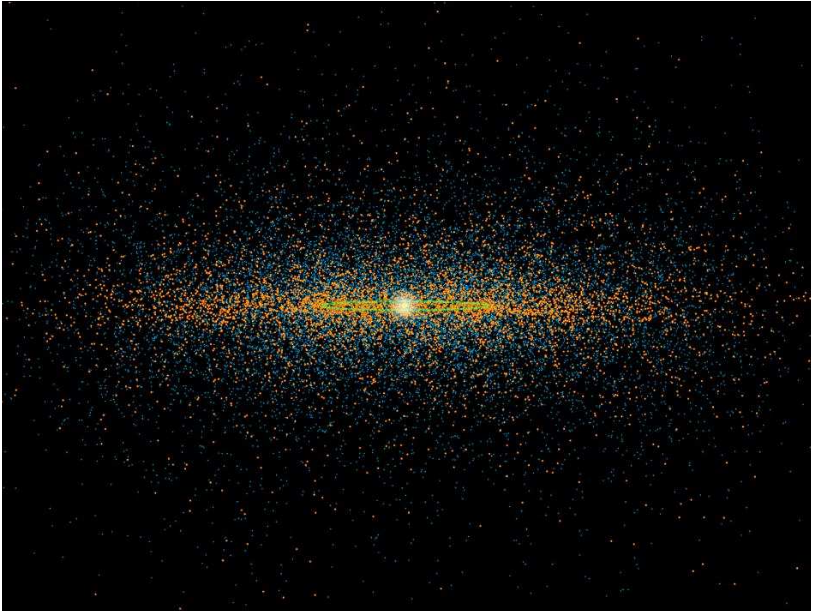
Traveling Through the Universe: Back in Time to the Quark-Gluon Plasma Era
JRi and Jeremiah Birrell, J. Phys. G in press.
http://arxiv.org/abs/arXiv:1311.0075 [nucl-th]

Supported by US DoE Grant: DE-FG02-04ER41318

Opening Figure:

Mojave Crater on Mars, surce of all Mars impactors on Earth.
Candidate for CUDO exit





Edge-on View of Near-Earth Asteroids by NEOWISE: the asteroid-hunting portion of NASA's Wide-field Infrared Survey Explorer, or WISE, mission