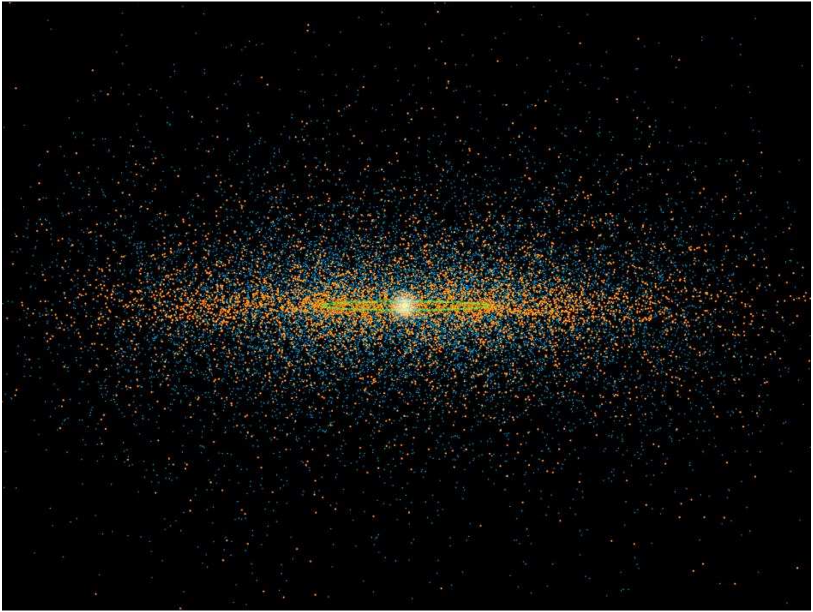
(K)CUDOs for Joe



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

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 surprizing and exceptional character

CUDO: Compact Ultra Dense Object

Solar System Signatures of Impacts by Compact Ultra Dense Objects
JR, Jeremey Birrell, and Lance Labun arXiv:1104.4572, pending

Properties of Dark Compact Ultra Dense Objects
Christopher Dietl, LL, and JR arXiv:1110.0551, PLB 2012

Planetary Impacts by Clustered Quark Matter Strangelets
LL and JR arXiv:1112.5765 APPB 2012

CUDO Example: Strangelets

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 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"

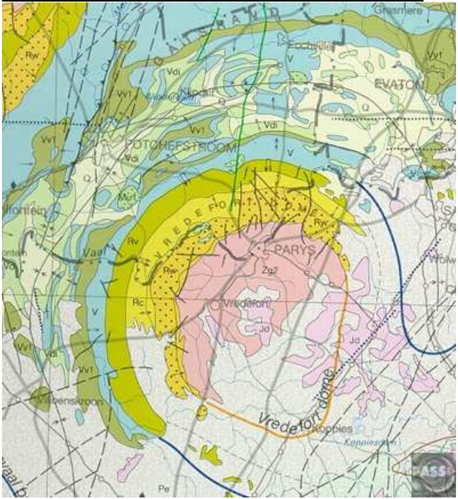
[see e.g. DeRujula/Glashow, Nature,312(1984), Herrin et al,PRD,53(1996) & 73(2006)]

Where is the Meteorite that made the ‘Barringer" Meteor Crater?

This is about 1 mile wide and 570 ft deep recent (50,000y old) crater where many tourists in Arizona visit. 110 years ago Daniel Barringer searched to profit from what he expected to be 2.510^6 tons of iron-nickel content of the meteorite. See what was found. Short of a space ship crash site, of which remains were carefully removed, what is the causes for this gigantic hole in the ground? Counter example: Egypt-Pharaoh Iron came from a recently rediscovered Kamil crater in the South-West Egypt border desert. Impact left a 44.8 m wide and 15.8 m deep hole. The meteorite is estimated to have been 1.3 meters wide and to have weighed 5 to 10 tons. Fragments totaling 800 kilograms were recovered during the geophysical expedition 2010, after 3000y of mining!

Other missing meteorite examples?

[redacted]



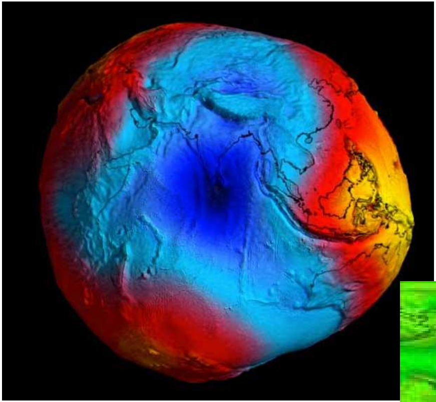
[redacted]

4.2. Where is the Meteorite?

It is generally agreed now that the SIC was generated by a meteorite impact, and yet little evidence has been found of the signature of the impacting body. Highly siderophile elements (primarily PGE and particularly Ir) are a sensitive indicator of meteoritic influx (Peucker-Ehrenbrink and Ravizza, 2000) and impact (Evans et al., 1993). Siderophile element analysis has been outstandingly successful in identification of the worldwide chondritic signature of impact at the Cretaceous–Tertiary boundary (Ganapathy, 1980; Kastner et al., 1984; Evans et al., 1993), but this achievement has distracted attention from puzzling results at impact craters recognized by other criteria. Melt rocks from smaller craters often carry a signature of the impactor as, for example, at the 8.5 km Wanapitei Lake crater (Wolf et al., 1980; Grieve and Ber, 1994). In craters larger than ca. 30 km diam., however, melt rocks often show little or no PGE enrichment as at the 70 km Manicouagan, Quebec crater (Wolf et al., 1980). Nevertheless, the size distinction is not always clearcut since small craters such as the 1.8 km diameter Lonar, India, crater may be found with no meteoritic signature (Morgan, 1978), whereas the ≈70 km Morokweng, South Africa, crater has impact melts containing large amounts of siderophiles (Koeberl et al., 1997; Reimold and Koeberl, 1999).

Citation from Morgan et al 2003

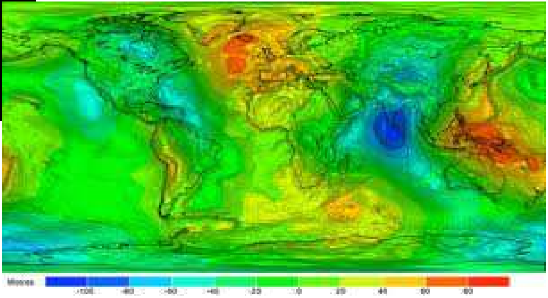
Sudbury, Canada: Vredefort, South Africa; major mining districts of the world, where “something” called an impact seems to have pulled from the depth the Earth siderophile metals we need.



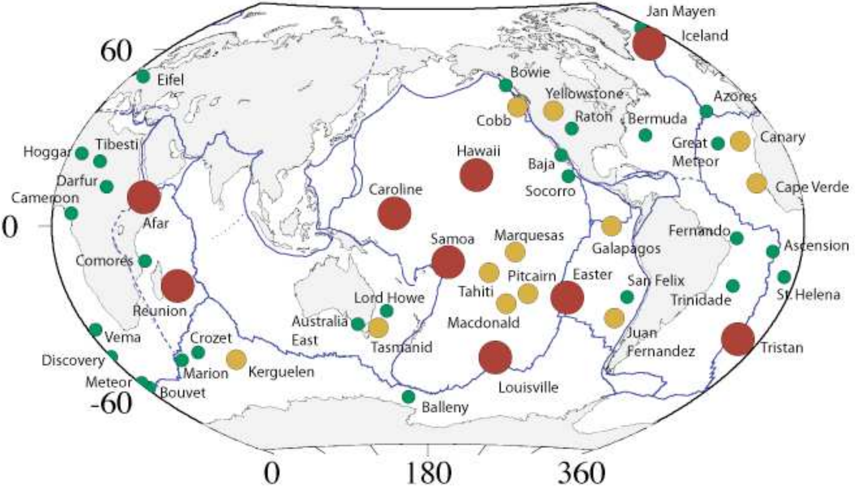
What made this?

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.



Any ‘smaller’ holes? How about ‘hot spots’!



Hotspot map of the Earth: hotspot: hole in Earth's crust with conduit deep into mantle

Do you like diamonds?

Kimberley Open pit mine - made by a 'supersonic gas ejection'

Geologists prefer to look for oil; Challenges for physicists:

- "Evaporated" giant iron-nickel meteorite
- Volcanic hotspots in middle of thick continental crust
- Mantle plumes: deep origin of magma and long-term stability, (some not vertical!)
- Correlation of meteorite impacts and lava flow (crust puncture not possible with normal matter impactor [Ivanov, Geology, 31 (2004)])
- Dual impact/volcanic activity to explain “nuclear winter” events
- Pointlike concentration of heavy elements in Earth’s crust
- Diatremes (punctures in crust by ‘supersonic gas ejection’)

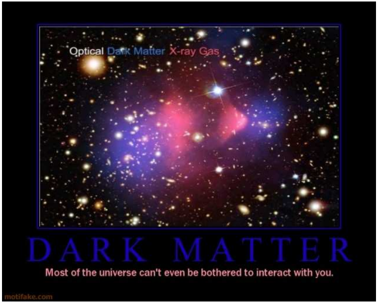
- Young (post-cooling) volcanic activity on Moon
- 100’s of peaks with holes on Mars....

Earth (all rocky bodies) seem to be punctured many times.
Only strangelets??

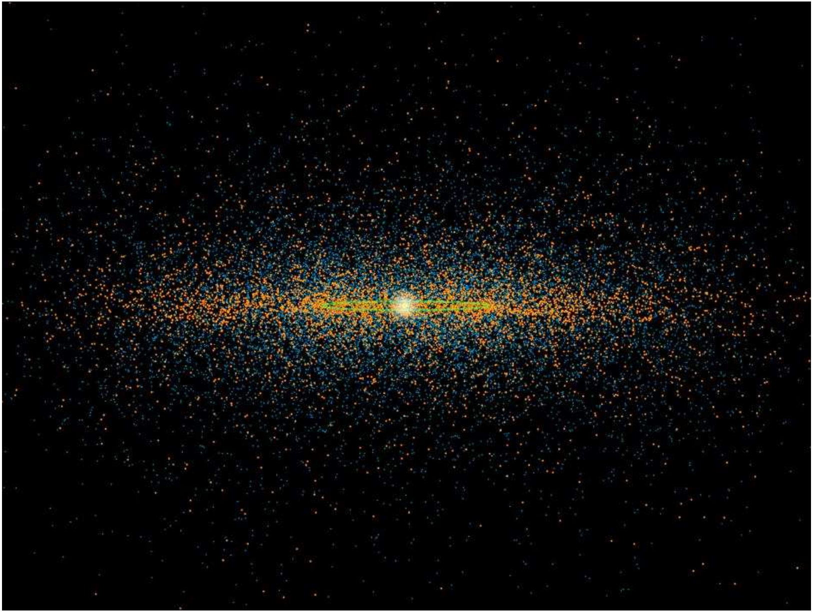
Dark gravitating matter

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



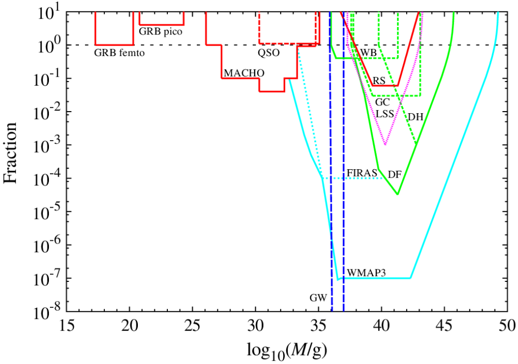
Many candidate particles could mean *many components* of unseen ‘dark’ matter, some could cluster **form a halo of dark matter asteroids?**



CUDO distribution could be just like VISIBLE Asteroids

Any 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

Gravitationally 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

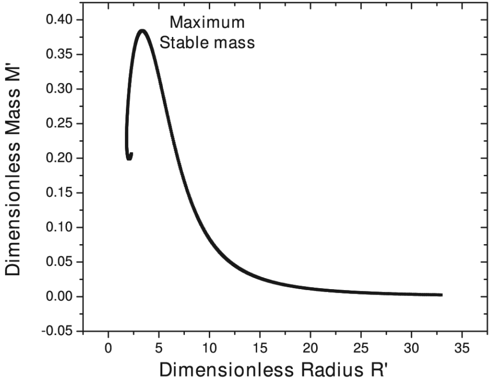
$$\widetilde{p}(\widetilde{\rho}) = m^{-4}\, p\left(\rho m^{-4}\right)$$

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

Two Types of CUDOs

Analogous to compact objects composed of SM matter:

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

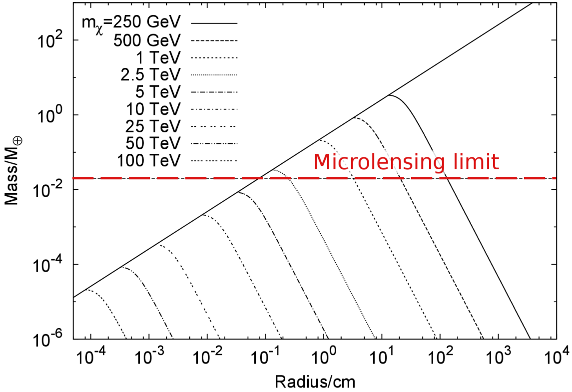
Fundamental fermion	Composite
mass $m_\chi \gtrsim 1\,\mathrm{TeV}$	**B**ag model vacuum pressure $B \gtrsim (1\,\mathrm{TeV})^4$
supported by pressure of degenerate fermi gas	self-bound by interactions
analogy to white dwarf, neutron star	analogy to quark-star, strangelet

Solve for equilibrium configuration in Oppenheimer-Volkoff equations

TeV-scale Fundamental Fermi particle

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

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



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

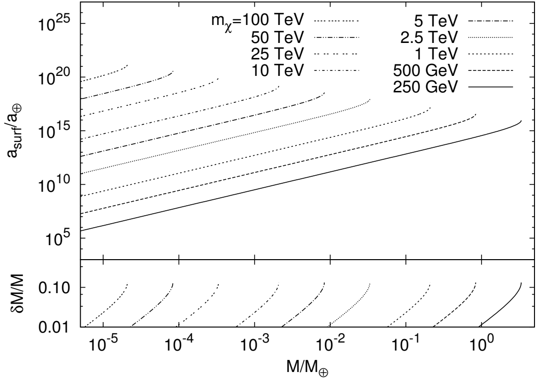
EROS Collaboration, Astron.Astrophys. **469** (2007)

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 $\quad a_{\rm tidal} = \frac{2GM}{r^2}\frac{L}{r} = a_{\rm surf}\frac{R_{\rm surf}^2}{r^2}\frac{2L}{r}$



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

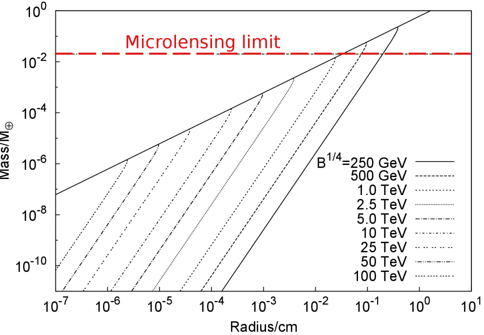
- Tidal acceleration pulls apart atoms in solids: $a_{\rm surf} > 3.5\ 10^{15} a_\oplus$

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

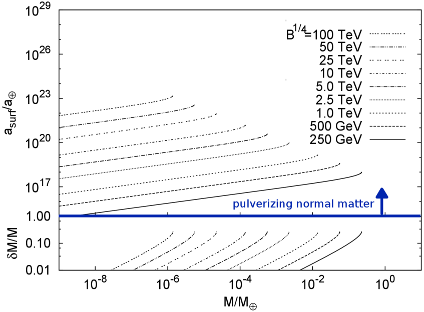
CUDOs not stopped by impact with normal density (visible) matter

Composite with TeV confinement energy

$M_\oplus = 6\,10^{24}\ \mathrm{kg} =$ Earth mass $B =$ 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 $B \gtrsim (1\,\mathrm{TeV})^4$
$M_{\mathrm{max}} = 0.209 \left(\frac{1\,\mathrm{TeV}}{m_\chi}\right)^2 M_\oplus$	$M_{\mathrm{max}} = 0.014 \left(\frac{1\,\mathrm{TeV}}{B^{1/4}}\right)^2 M_\oplus$
$R = 0.809 \left(\frac{1\,\mathrm{TeV}}{m_\chi}\right)^2 \mathrm{cm}$	$R = 0.023 \left(\frac{1\,\mathrm{TeV}}{B^{1/4}}\right)^2 \mathrm{cm}$

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

★ 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

Primordial Origin 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 very stable against gravitational disruption (especially in collisions with normal matter objects)
$\Rightarrow$ persist into present era

If CUDOs exist, many ‘planetary’ collisions!

▶ Study impacts (especially on rocky planets) for characteristic features expected from CUDO compactness

Lessons from prior studies for ‘low’ CUDO masses

- small strangelets [De Rujula & Glashow, Nature (1984)]
- black holes [Khriplovich et al PRD (2008)]
- *Q*-balls [Kusenko & Shoemaker PRD (2009)]

Collisions: a) Tidal Forces

LL,JR and JB, arXiv:1104.4572

Consider CUDO passing through normal density matter

Matter disrupted due to differential acceleration

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

To compromise structural integrity,

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

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

$\Rightarrow$ Material fails somewhere within Fracture length

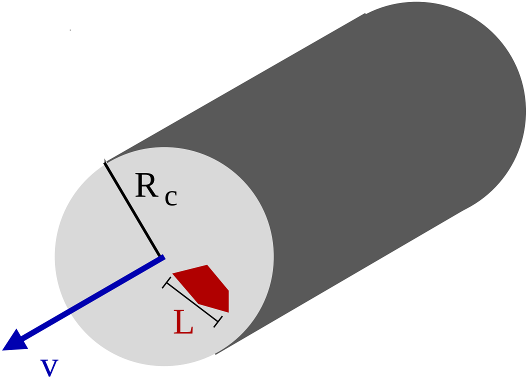
$$\frac{L}{R_c} = \sqrt{2}\frac{c_s}{v}\left(\frac{r}{R_c}\right)^{3/2}$$

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

Collisions: b) Fracture Length and Capture radius

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

$r < R_c$ 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

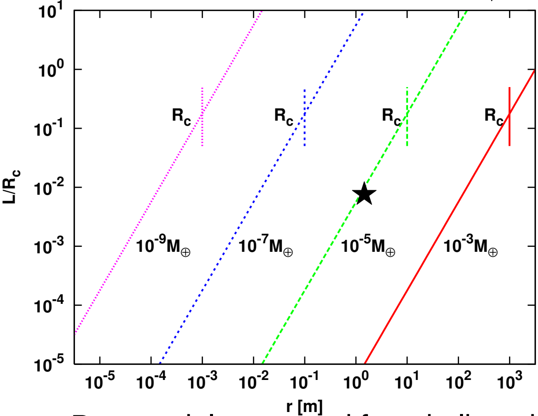
$$\frac{L}{R_c} = \sqrt{2}\frac{c_s}{v}\left(\frac{r}{R_c}\right)^{3/2} < 1$$

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: $M = 10^{-5} M_{\mathrm{Earth}}$
$R = 1\,\mathrm{m}$

$r < R_c$ 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

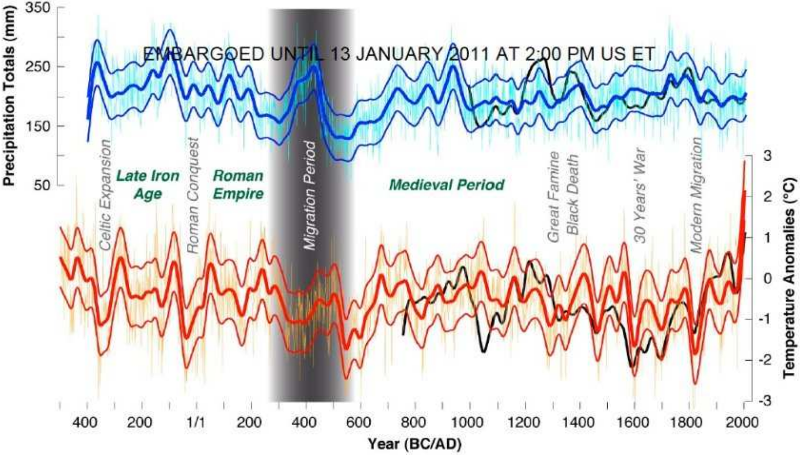
To conclude: a few bits a haps

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
Impact winter (e.g. AD 536[5]) 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 (see GOCE, 21-Lutetia[6], 4-Vesta[7])	*no standard explanation*	CUDO impacts, CUDO core dressed by normal matter envelope

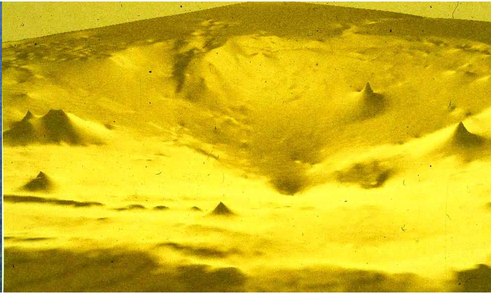
[1]Morgan, et al, EPSL (2004), [2]White & Saunders, Lithos (2005), [3]Abbott & Isley EPSL (2002), [4]Ivanon & Melosh Geology (2003), [5]Ferris, et al, J Geophys. Res.-Atmos (2011), [6]Pätzold, et al, Science (2011), [7]DAWN mission, Science (2012)

AD 536 Event

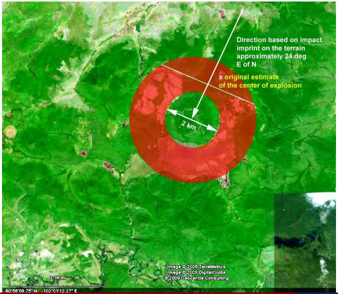
...is hotly contested: a comet or a giant volcano eruption (not found). Is it a '6-month coincidence', probability 10^{-3}? Or, a modest size dressed CUDO puncture and associated transport of material into upper atmosphere. Further milder weather fluctuations are also not well understood.



Tunguska Event: nearby Chako lake not known before

Aerial picture: water level lowered. Acoustic image: ignore 1-byte excursions.



How many CUDO impacts in this picture??