LII Krakow School of Theoretical Physics, 20 May 2012

The Great Impact of Beyond Standard Model Matter

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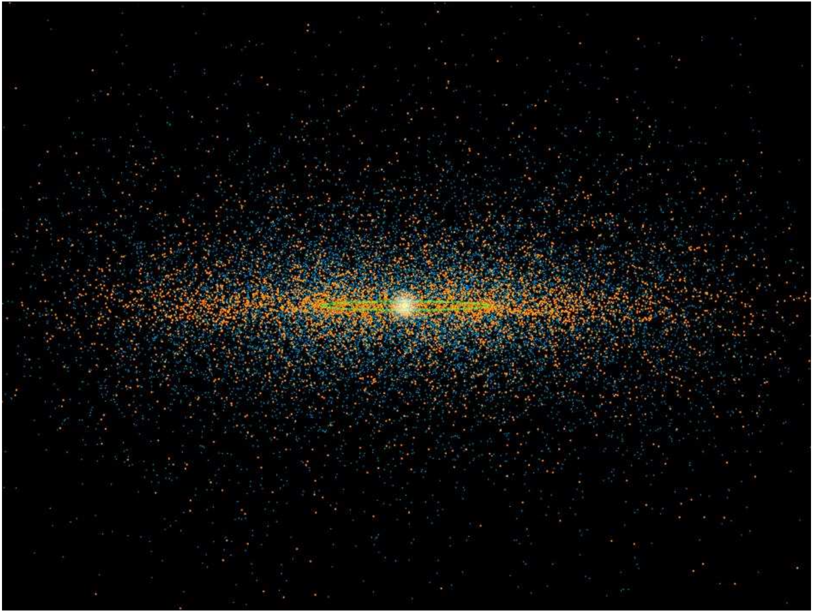
Solar System Signatures of Impacts by Compact Ultra Dense Objects
JR, Jeremey Birrell, and Lance Labun arXiv:1104.4572, pending

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



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

Trouble brews for the common view of particle dark matter:

Kinematical and chemical vertical structure of the Galactic thick disk II. A lack of dark matter in the solar neighborhood
C. Moni Bidin, G. Carraro, R. A. Mendez, R. Smith, arXiv:1204.3924

> “...estimates of the local volume density usually find a much lower quantity of DM (Kuijken & Gilmore 1989; Crézé et al. 1998; Holmberg & Flynn 2000; Korchagin et al. 2003; de Jong et al. 2010)”

and the **closing sentence**:

> “It is clear that the local surface density measured in our work, extrapolated to the rest of the Galaxy, cannot retain the Sun in a circular orbit at a speed of $\sim 220 km/s$. A deep missing mass problem is therefore evidenced by our observations. Indeed, we believe that our results do not solve any problem, but pose important, new ones.”

- Sikora’s talk of earlier today

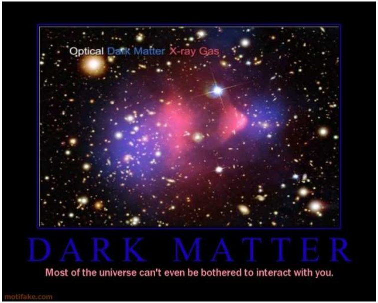
Gravitating matter

From standard cosmology, fractions of **N**on-**B**aryonic and **B**aryonic gravitating matter (h =Hubble constant/100 km s^{-1} Mpc^{-1})

$$\Omega_{\rm nb}h^2 = 0.110 \qquad \Omega_{\rm b}h^2 = 0.0227$$

$\Rightarrow$ 5/6 of gravitating matter not identified

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



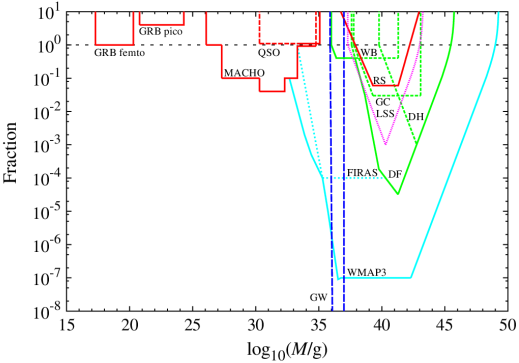
Many, many candidate particles ...
possible to have *many components* of unseen matter
One component a halo of dark matter asteroids?

Constraints on invisible clumps of matter

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

Examples

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



Carr et al PRD **81** 2010

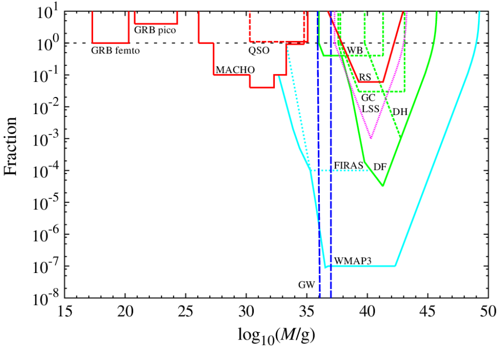
Opportunity in planetary mass range $10^{15}\mathrm{g} < M < 10^{27}\mathrm{g} \simeq$ Earth mass

Constraints on invisible clumps of matter

MACHO subclass: CUDOs = **C**ompact **U**ltra **D**ense **O**bjects
an object with $\geq$ neutron density

Examples

strangelets
micro black holes
self-bound objects made of
Beyond SM fermion(s)



Carr et al PRD **81** 2010

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"
$M \sim 10^{-5} M_{\mathrm{Earth}}$ $R \sim 100\,\mathrm{km}$	$M \sim 10^{-5} M_{\mathrm{Earth}}$ $R \sim 1\,\mathrm{m}$

Compactness and high density mean...

- gravity relevant in interactions: $g_{\mathrm{surf}} = \dfrac{GM}{R^2} = \dfrac{4\pi G}{3}\rho R$
- Normal matter cannot support SQM: a strangelet "falls through"

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

Gravitationally Bound Objects

(Tolman) Oppenheimer Volkoff equations yield solution of self-gravitating matter obeying given equation of state $p(\rho)$

2 scales: m = mass of matter particle (or other characteristic energy)
$M_{\rm Pl}^{-2} = G$ = Newton constant, dimensioned gravity coupling

Compare Newtonian gravitational potential to Fermi energy

$$E = -\frac{GMm}{R} + \epsilon_F \qquad \epsilon_F = \frac{(9\pi N)^{1/3}}{4^{1/3}R}$$

with total object mass M [Landau,Weinberg]

- limiting case $E \to 0$ shows maximum mass $M_{\rm max} \propto m^{-2}$

$$R_{\rm max} \propto GM_{\rm max}$$

- Also applies to objects self-bound by interactions, e.g. quark (bag) stars, characteristic energy from bag constant $B^{1/4}$

[Witten (1984),Narain (2006)]

Gravitationally Bound Objects: Scaling Solution

If we need only 1 equation of state $p(\rho)$ for all relevant ρ

Dimensionless...

1) pressure, density

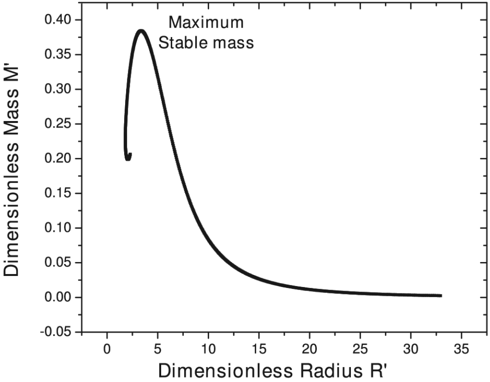
$$\widetilde{p}(\widetilde{\rho}) = m^{-4}\, p\left(\rho m^{-4}\right)$$

2) total mass of solution

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

3) surface radius of solution

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



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

TOV equations now dimensionless – Solve once!

NOT the whole story: check stability against perturbation

Oppenheimer/Serber 1936

CUDOs from TeV-scale particle sector

★ CUDOs composed of $m_\chi \gtrsim$ TeV Beyond SM matter *naturally* have

$$10^{15}\mathrm{g} < M < 10^{27}\mathrm{g} \simeq M_\oplus$$

★ Whether or not found, signatures of CUDOs discuss below help constrain new particles $m_\chi \gtrsim$ TeV

We will consider the above-TeV particle sector to be analogous to SM: same possible interactions and structure just 1000 times higher scale

Two Types of CUDOs

Analogous to compact objects composed of SM matter:

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

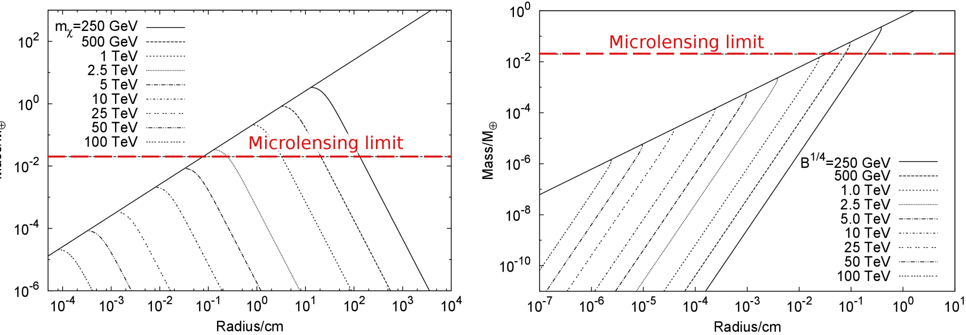
Fundamental fermion	Composite
mass $m_\chi \gtrsim 1\,\mathrm{TeV}$	**B**ag model vacuum pressure $B \gtrsim (1\,\mathrm{TeV})^4$
supported by pressure of degenerate fermi gas	self-bound by interactions
analogy to white dwarf, neutron star	analogy to quark-star, strangelet

Solve for equilibrium configuration in Oppenheimer-Volkoff equations

Size Scales

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

$B = \text{bag model vacuum pressure}$



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

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

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

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

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

Size Scale: Summary

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

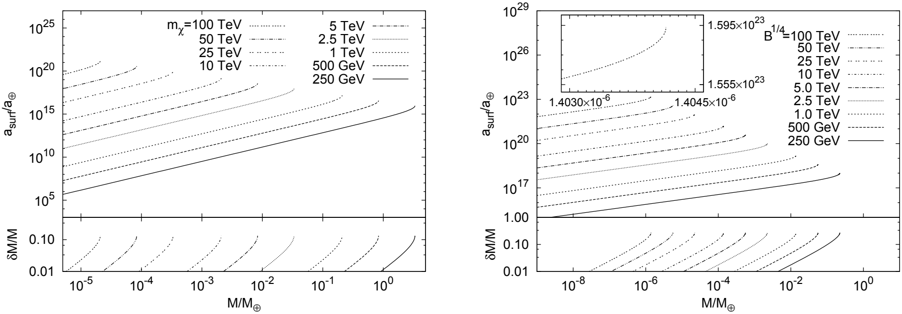
Scaling solution $\Rightarrow$ gravitational binding also scales!

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

Gravitational Properties

Compact: Size of object comparable to gradient of gravitational field

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



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

- Tidal acceleration pulls apart atoms in solids for $a > 3.5\,10^{15} a_\oplus$

$\Rightarrow$ CUDOs not stopped when impacting normal density (visible) matter

Primordial Origin – 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, we must consider collisions!

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

Investigations done for low CUDO masses

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

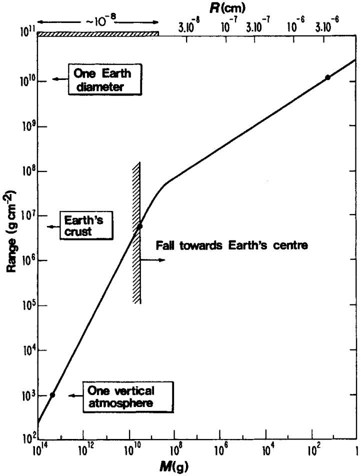
Seeking ‘Nuclearites’=Strangelet meteorites

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?

Collisions and 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

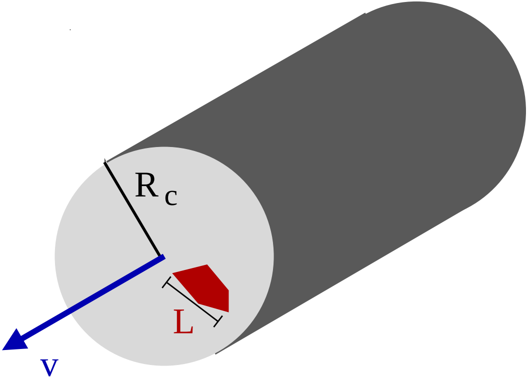
$$\frac{L}{R_c} = \sqrt{2}\frac{c_s}{v}\left(\frac{r}{R_c}\right)^{3/2}$$

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

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

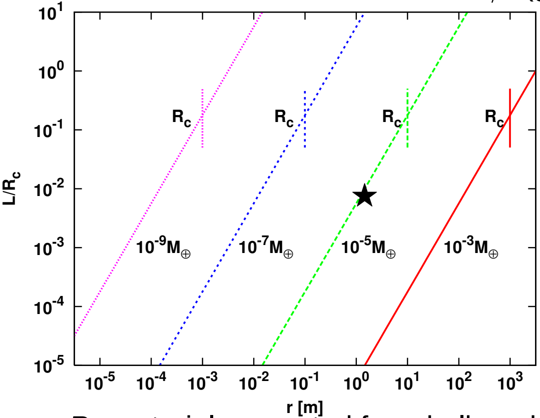
$$\frac{L}{R_c} = \sqrt{2}\frac{c_s}{v}\left(\frac{r}{R_c}\right)^{3/2} < 1$$

sound speed c_s representing bulk modulus (strength) of medium

Fracture Length and 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

(Non)Stopping and Other Characteristics Impacts

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 $M < 10^{-4} M_{\mathrm{Earth}}$ <u>not</u> 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

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 expanation*	CUDO impacts, CUDO core dressed by normal matter envelope

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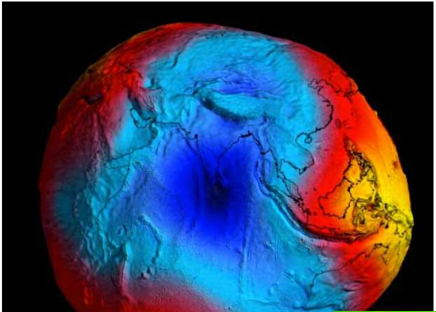
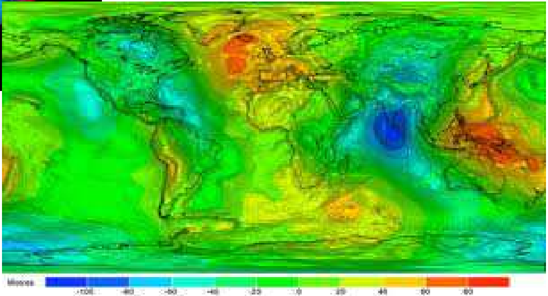
[1] Morgan, et al, EPSL (2004), [2] White & Saunders, Lithos (2005), [3] Abbott & Isley EPSL (2002), [4] Ivanon & Melosh Geology (2003), [5] Ferris, et al, J Geophys. Res.-Atmos (2011), [6] Pätzold, et al, Science (2011), [7] DAWN mission, Science (2012)



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.

Geology: There is a large lava flow called “Deccan Traps” and proposed “Shiva impact” that split Mauritius and India. Large lava flows (Dekan Traps) occured 65 million years ago, about the same time as a Chicxulub impact related to the Cretaceous-Paleogene extinction event.



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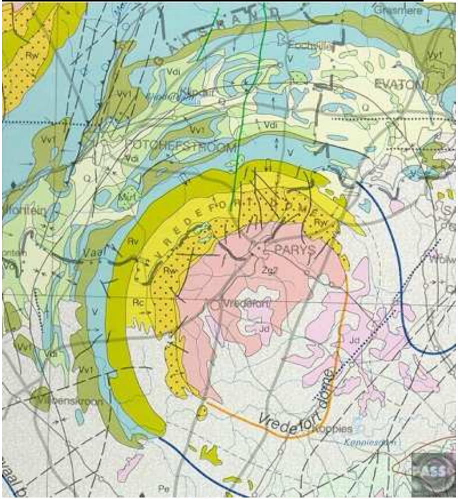

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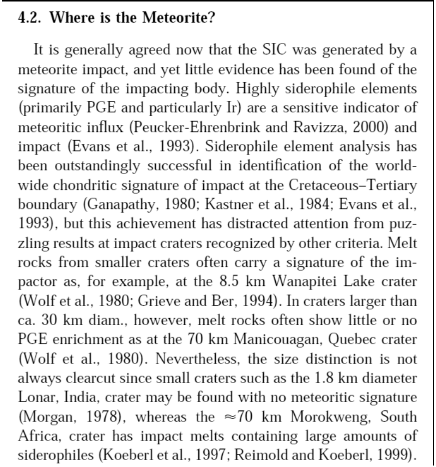


4.2. Where is the Meteorite?

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).

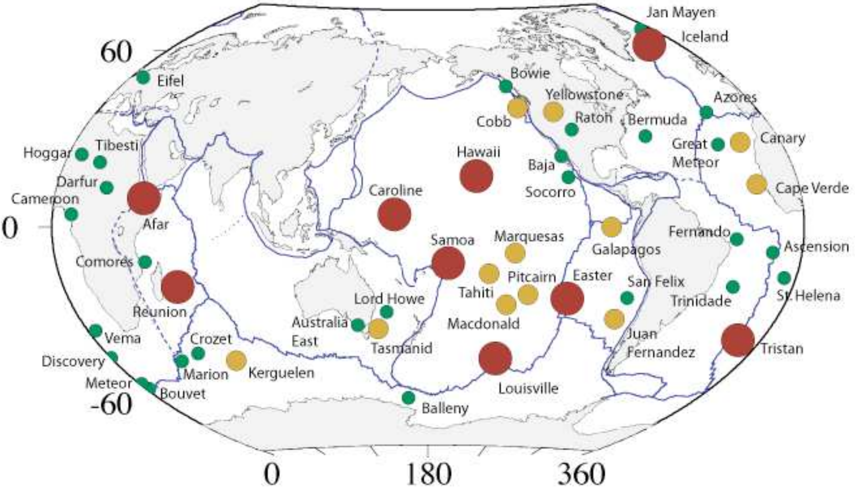
Citation from Morgan et al 2003

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.

Other Geological Riddles

- Volcanic hotspots in middle of thick continental crust
- Mantle plumes: deep origin of magma and long-term stability
- Correlation of meteorite impacts and lava flow
  (not possible with normal matter impactor [Ivanov, Geology, 31 (2004)])
- “Nuclear winter” from meteorite impacts
- Distribution of heavy elements in Earth’s crust
- Unusual impact formations, association with diamonds,
  e.g. Nördlinger Ries crater, Germany
- Diatremes (punctures in crust by ‘supersonic gas ejection’)

- Young (post-cooling) volcanic activity on Moon



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

CUDOs from TeV-scale particle sector

★ CUDOs composed of $m_\chi \gtrsim$ TeV Beyond SM matter *naturally* have

$$10^{15}\mathrm{g} < M < 10^{27}\mathrm{g} \simeq M_\oplus$$

★ Whether or not found, signatures of CUDOs discuss below help constrain new particles $m_\chi \gtrsim$ TeV (difficult for colliders)

Features:

★ Typical Mass and size of compact object scale as m_χ^{-2}

★ Non-relativistic at or before electroweak transition in Early Universe

★ Presence of normal matter to aid early collapse dynamics

Summary of Advantages

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 (6 Gyr)

3. Easy to access signatures: impacts on Earth!

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)]

Where is the Meteorite?

In Arizona there is this a remarkable “Meteor Crater” with even a more remarkable funny history: someone baught it to mine the iron-nickel content of the meteorite but went bancrupt, there is no meteorite. How the hole in the ground came to be without an impactor remains a riddle with even more funny explanations not to be repeated here. There is no local gravitational central impact mountin Counterexample: all Pharaoic Iron came from a recently rediscovered crater in the South-West desert of modern Aegypt. Any other examples?