Missing Matter: Evidence

- Cluster Kinematics
- Interacting Clusters
- Gravitational lensing
- Galaxy rotation curves
- Cosmic microwave background (CMB)
- Supernovae Ia
- Large scale structure (LSS)
- Big bang nucleosynthesis (BBN)
Dark Matter: Evidence

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Disclaimer:

We could “just” modify the theory of gravity!
(if only it was that easy)
Cosmological energy budget

Obligatory Pie Chart
Image: Jeff Filippini
Dark Matter: Candidates

**WIMPs**

**Motivations:**
- “The WIMP miracle”
- Beyond the Standard Model ambitions:
  - esp. SUSY

The non-discovery of WIMP-DM and especially of any BSM physics at the LHC should de-privilege WIMPs as the premiere DM candidate.
Other non-SM Dark-matter candidates

- Axions
- Exotica
What do we really know about Dark Matter?

Matter:

- \( n \propto (1+z)^{-3} \)

at least approximately, over a wide range of \( z \)
What do we really know about DM?

Dark:

- Does not automatically mean $\sigma$ is small!
- $n \propto 1/m \Rightarrow$
  - traditional limits on $\sigma$ fail when $m$ is large!
How could this be?

Interaction rates go as $\Gamma \sim n_x \sigma_x v \sim (\sigma_x/m_x) \rho_x v$

Gravitational observations fix $\rho_x$

What matters is $(\sigma_x/m_x)$ -- the “reduced cross-section”

DM can be low-mass-very-low-\(\sigma\), or high-mass-not-so-low-\(\sigma\)!

MACROscopic Dark Matter
Average local dark matter density?

$10^{16}$ g of dark matter expected within the Earth’s orbital radius

Here, a smooth distribution

Could this be the wrong picture?
Average local dark matter density?

$10^{16}$ g of dark matter expected within the Earth’s orbital radius

Could this be the right picture?
What do we know about DM $\sigma$?
What do we know about DM $\sigma$?

- Strongly-interacting dark matter: Starkman et al. (1990), ..., Mack et al. (2007)
- More or less constrained up to $\sim 10^{17}$ GeV
What about macroscopic stuff – $m > \sim 1$g?
Macros – what are they?

Ordinary Standard Model matter:

- Stellar remnants – WD, NS, BH
- Planets and other smaller
Big Bang Nucleosynthesis (BBN)

Burles, et al. (1999)
Macros – what are they?

Ordinary Standard Model matter:
- Stellar remnants – WD, NS, BH
- Planets and other smaller objects

Lesson: if DM is baryons it must be “hidden” before BBN
Macros – what are they?

In the Standard Model

- Strange Quark Nuggets, Witten (1984)
Dark matter in the Standard Model?
Quark nuggets, Witten (1984)

- Considered a (1st order) QCD phase transition in the early universe
- Different stable phases of nuclear matter may exist (hadronic vs. quark)
- Hadrons plausibly produced alongside nuclear objects with masses $10^9$ to $10^{18}$g

FIG. 3. Isolated shrinking bubbles of the high-temperature phase.

Witten (1984)
Macros – what are they?

In the Standard Model

- Strange Quark Nuggets, Witten (1984)
- Strange Baryon Matter (Lynn et al., 1990)
- Strange Chiral Liquid Drops (Lynn, 2010)
- Other names: nuclearites, strangelets, CUDOs

Primordial Black Holes
Macros – what are they?

Almost (?) Standard Model

- Compact Composite Objects/
  Baryonic Color Superconductors (+ axion) (Zhitnitsky, 2003)
- Crypto-baryonic DM (Frooghat & Nielsen, 2005)

(Well) Beyond the Standard Model

e.g. SUSY Q-balls, topological defect DM, ...
Macros – what are they?

In the Standard Model

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Dark Matter may be a Standard Model phenomenon!
Why should we want Standard Model Dark Matter?

• SM is the most successful scientific theory ever
• Every past claim of an experimental contradiction has eventually been proved false
• All “problems” with it are aesthetic or experimentally inaccessible
• SM+ GR ($w \Lambda$) explains all cosmology “except”:
  • perhaps complicated non-linear systems like galaxies
  • Initial conditions (inflation)
  • Large angle/low-l CMB
  • need for dark matter
So... what’s allowed for Macros?

- A systematic probe of “macroscopic” dark matter candidates that scatter classically (geometrically) with matter

- Basic parameters: mass, cross section, charge, and some model-specific (e.g. elastic vs. inelastic scattering):

  \[ M_x, \; \sigma_X = \pi R_X^2, \; V(R_X) \sim eQ_x/R_X \]
Model-independent constraints

- Gravitational effects (lensing)
- Elastic and inelastic coupling of
  - Macros to baryons
  - Macros to other Macros
  - Macros to photons
Model-independent constraints

Gravitational effects
Gravitational Lensing

- Flux amplification

Image: GFDL
Gravitational Lensing

Microlensing

\[ A = \frac{u^2 + 2}{u\sqrt{u^2 + 4}} \]

\[ u \equiv \frac{r_0}{R_E} \]

Paczynski (1986)
Gravitational Lensing

Microlensing

- Griest et al. (2013) used sources in the local solar neighborhood

Combined, they exclude

\[ 4 \times 10^{24} \text{ g} < M_X < 6 \times 10^{34} \text{ g} \]
Gravitational Lensing

Femtolensing


\[
A = \frac{2 + u^2 + 2 \cos \Delta \phi}{u \sqrt{4 + u^2}}
\]

\[
u \equiv \frac{r_0}{R_E}
\]

\[
\Delta \phi = E \Delta r
\]

Barnacka et al. (2012)
Gravitational Lensing

Femtolensing


- Marani et al. (1998), used data the BATSE GRB experiment

- Barnacka et al. (2012) used GRB data from Fermi Combined, and exclude

\[ 10^{17} g < M_X < 10^{20} g \]
Model-independent Macro Constraints
(including DM-photon coupling & lensing)

Jacobs, Starkman, Lynn (2014)
Model-independent constraints

Records left on earth

\[ \Phi = 5 \times 10^{-3} \frac{g}{M_x} \text{ km}^{-2} \text{ yr}^{-1} \]

\[ \Phi_{\text{Earth}} = 7 \times 10^8 \frac{g}{M_x} \text{ yr}^{-1} \]
Macros-baryon Interactions

Ancient Mica

- Chemical etching reveals lattice defects in muscovite mica

- Old samples buried deep (~3 km) underground make good monopole detectors

- Used by de Rujula and Glashow (1984), Price (1988) to rule out nuclearite dark matter < 55g

- Generalizable to Macros

**FIG. 2.** Geometry of collinear etch pits along the trajectory of a hypothetical monopole-nucleus bound state in three sheets of mica that had been cleaved, etched, and superimposed for scanning.

Price and Salamon (1986)
Macro Constraints
(on elastic scattering w/ baryons and other Macros)

Jacobs, Starkman, Lynn (2014); Jacobs, Starkman, Weltman (2014)
Macro-baryon Interactions

Skylab

- Carried plastic track cosmic ray detectors
- Same idea – much less exposure (Shirk and Price)
- But no overburden, so good to higher $\sigma_x/m_x$
Macro Constraints
(on elastic scattering w/ baryons and other Macros)

Jacobs, Starkman, Lynn (2014); Jacobs, Starkman, Weltman (2014)
Macro-baryon Interactions
Resonant-bar Gravitational Wave Detectors

- Gravitational waves might be detected by looking for excitation of normal modes of aluminum cylinders
- If cold (~2K), these are also sensitive to cosmic rays ... because of the thermo-acoustic effect

Joseph Weber (~1960’s)
Image: AIP Emilio Segrè Visual Archives
Resonant-bar Gravitational Wave Detectors

- More exposure than Skylab, less than mica
- More overburden than Skylab, less than mica
- Liu and Barish, 1988: Constraint on "nuclearite" dark matter
- NAUTILUS & EXPLORER experiments rule out nuclearite dark matter candidates below $10^{-4}g$
- Can be generalized for macro dark matter. We find: $m < 10^{-5}g$ for $(\sigma_x/m_x) < 0.001$ cm$^2$/g
Macro Constraints
(on elastic scattering w/ baryons and other macros)

Jacobs, Starkman, Lynn (2014); Jacobs, Starkman, Weltman (2014)
Macro-baryon Interactions
Seismology

- Macros hit the Earth or Moon and excite seismic waves
- Seismographs can detect them
Seismic search for strange quark nuggets

Eugene T. Herrin, Doris C. Rosenbaum, and Vigdor L. Teplitz
Phys. Rev. D 73, 043511 – Published 17 February 2006

ABSTRACT

Bounds on masses and abundances of Strange Quark Nuggets (SQNs) are inferred from a seismic search on Earth. Potential SQN bounds from a possible seismic search on the Moon are reviewed and compared with Earth capabilities. Bounds are derived from the data taken by seismometers implanted on the Moon by the Apollo astronauts. We show that the Apollo data implies that the abundance of SQNs in the region of 10 kg to 1 ton must be at least an order of magnitude less than would saturate the dark matter in the solar neighborhood.
Reconsidering seismological constraints on the available parameter space of macroscopic dark matter

David Cyncynates, Joshua Chiel, Jagjit Sidhu, and Glenn D. Starkman
Phys. Rev. D 95, 063006 – Published 7 March 2017

ABSTRACT

Using lunar seismological data, constraints are proposed on the available parameter space of macroscopic dark matter (macros). We show that actual limits are considerably weaker by considering in greater detail the mechanism through which macro impacts generate detectable seismic waves, which have wavelengths considerably longer than the diameter of the macro. We show that the portion of the macro parameter space that can be ruled out by current seismological evidence is considerably smaller than previously reported, and specifically that candidates with greater than or equal to nuclear density are not excluded by lunar seismology.
Seismological signals

- Only long wavelength seismic waves propagate
- Small macros produce mostly short wavelength acoustic modes
- Huge spectral mismatch
Model-independent Macro Constraints

Cyncynates et al. (2016)
Model-independent constraints

Records left on the sky
Macro-baryon Interactions
Effects on large-scale structure

- DM-SM interactions would have caused extra collisional damping of acoustic oscillations of the baryon-photon plasma (Boehm et al. 2001)

- Baryons scattering off Macros: exert a force: \( <F> \sim n_B \sigma_{XB} v_B m_B v_x \), which will change the DM dynamics if \( <F>/p_x > H \)

\[ \Rightarrow \left( \frac{\sigma_X}{m_X} \right) < 3 \text{ cm}^2/\text{g} \]
Macro-baryon Interactions
Effects on large-scale structure (more details)

- Chen et al. (2002) used CMB and LSS observations to constrain interaction
- Dvorkin et al. (2014) added Lyman-alpha observations (z~3) and found

\[
\left(\frac{\sigma_X}{m_X}\right) < 0.003 \text{ cm}^2/\text{g}
\]
Macro-baryon Interactions
Cluster gas heating

- Virial theorem implies DM particles and baryons will have similar velocities
- High mass of Macros means energy transfer to baryons in a collision, implying gas heating
- Gas would be hottest at center. Lack of this observation implies

\[ \sigma_{\chi}/m_\chi < 0.06 \text{ cm}^2/\text{g} \]

Chuzhoy and Nusser (2006)
Macro-Macro Coupling
Self-interacting dark matter (SIDM)

- Spergel and Steinhardt (2000) (cusp-core issue)
- Simulations vs. obs: e.g., Davé et al. (2000), Randall et al. (2007), Rocha et al. (2012)

$(\sigma_X/m_X) < 0.25 \text{ cm}^2/\text{g}$

Wilkinson et al. (2014) used Planck CMB data to constrain DM-photon interactions to

\[(\sigma_X / m_X) < 4.5 \times 10^{-7} \text{ cm}^2 / \text{g}\]

Applies to Macros, assuming thermal equilibrium with the plasma

Wilkinson et al. (2014)
Model-dependent constraints
Model-dependent constraints: Continued solar existence

If the macro would “convert” ordinary matter, then solar stability requires $M_X > 10^{18}g$
Model-dependent constraints
Effects on BBN?

- Helium mass fraction, \( X_4 \approx 0.25 \pm 0.01 \) (Aver et al. 2013)

\[
X_4 = \frac{4 \times \frac{1}{2} n_n}{n_n + n_p} = \frac{2n_n}{n_n + n_p}
\]

- If \( n \) and/or \( p \) can be absorbed by macros – change \( X_4 \)

- Theoretical uncertainties on Standard Model predications are relatively tiny so we must ensure

\[-0.006 < \Delta X_4 < 0.002\]
Model-dependent BBN constraints

Jacobs, Allwright, Mafune, Manikumar, and Weltman (2016)
Other considerations

- **Production**: if baryonic must incorporate ~80% of baryons
- **Stability**: must survive in hot dense “slowly” cooling plasma
  \[ t(T) \sim 1\text{s} \ (\text{MeV}/T)^2 \]
- **But not too stable (unless very large)**
Conclusions

- Dark matter doesn’t have to interact weakly if it’s very massive. **It might even arise within the Standard Model.**
- Regardless of its nature, there are unconstrained regions of size vs. mass.
- There are other potential probes: seismological (terrestrial and lunar), atmospheric and marine observations (light, sound)
- Such “strongly”-interacting dark matter candidates may be relevant to several outstanding issues in the current CDM paradigm (cusp vs. core, missing satellites, …)
- We need to keep looking