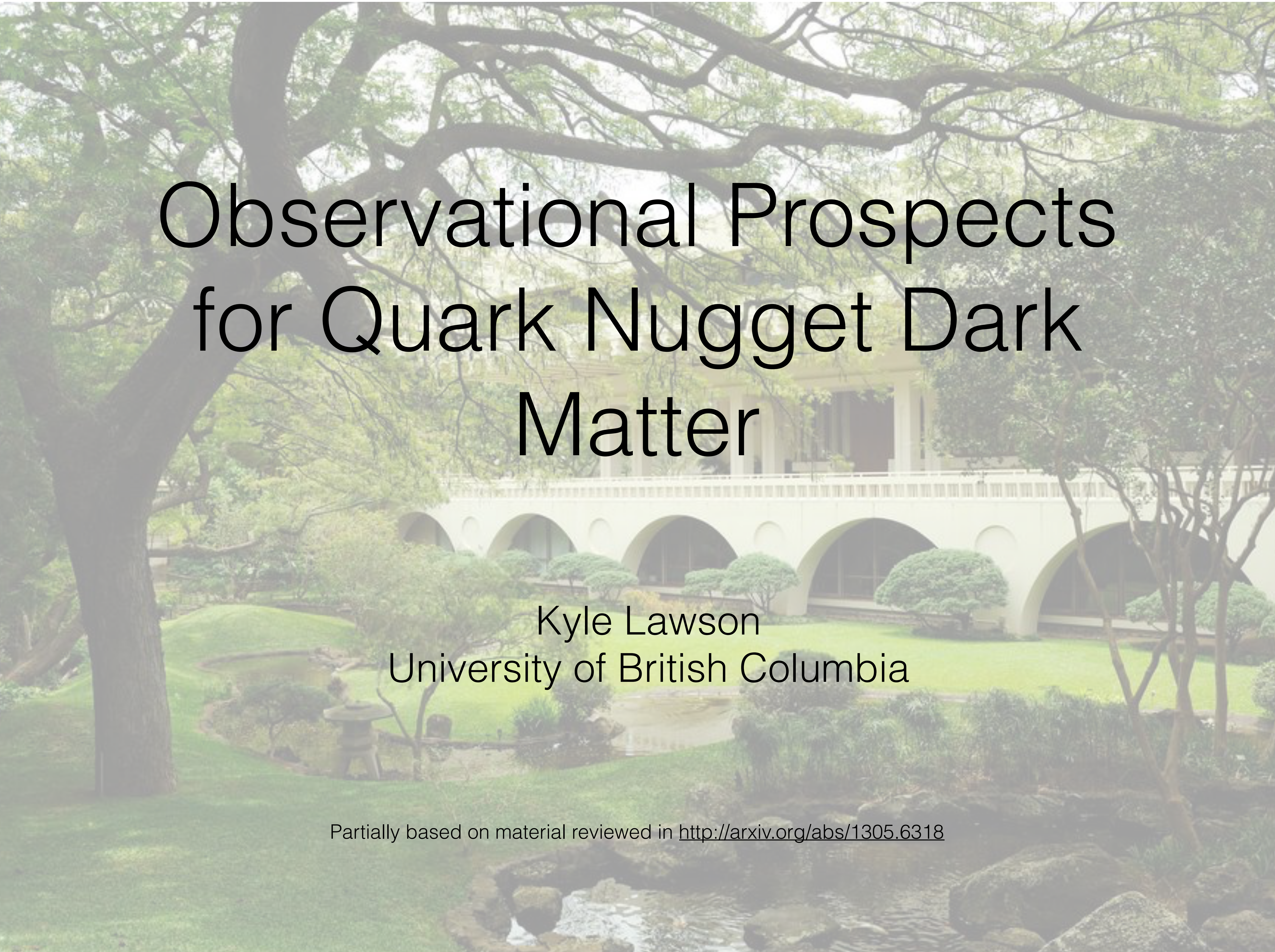

Observational Prospects for Quark Nugget Dark Matter

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Partially based on material reviewed in http://arxiv.org/abs/1305.6318

Outline

- Baryogenesis (matter/antimatter asymmetry)
- Quark nugget dark matter
- Astrophysical constraints
- Direct detection constraints

Baryogenesis

- The observable universe is dominated by matter rather than antimatter
- The process by which this asymmetry arises despite the CPT symmetry of the fundamental laws is called baryogenesis
- The degree of baryogenesis determines the matter to photon ratio (ie. the amount of baryonic matter in the universe)

- Matter and dark matter exist at similar densities ($\Omega_{DM} = 5\Omega_{Vis}$) but there is no established reason for this similarity
- This may suggest a connection between baryogenesis and the origin of the dark matter
- Can we build models in which baryogengesis and dark matter are fundamentally connected?

Quark Nugget Dark Matter

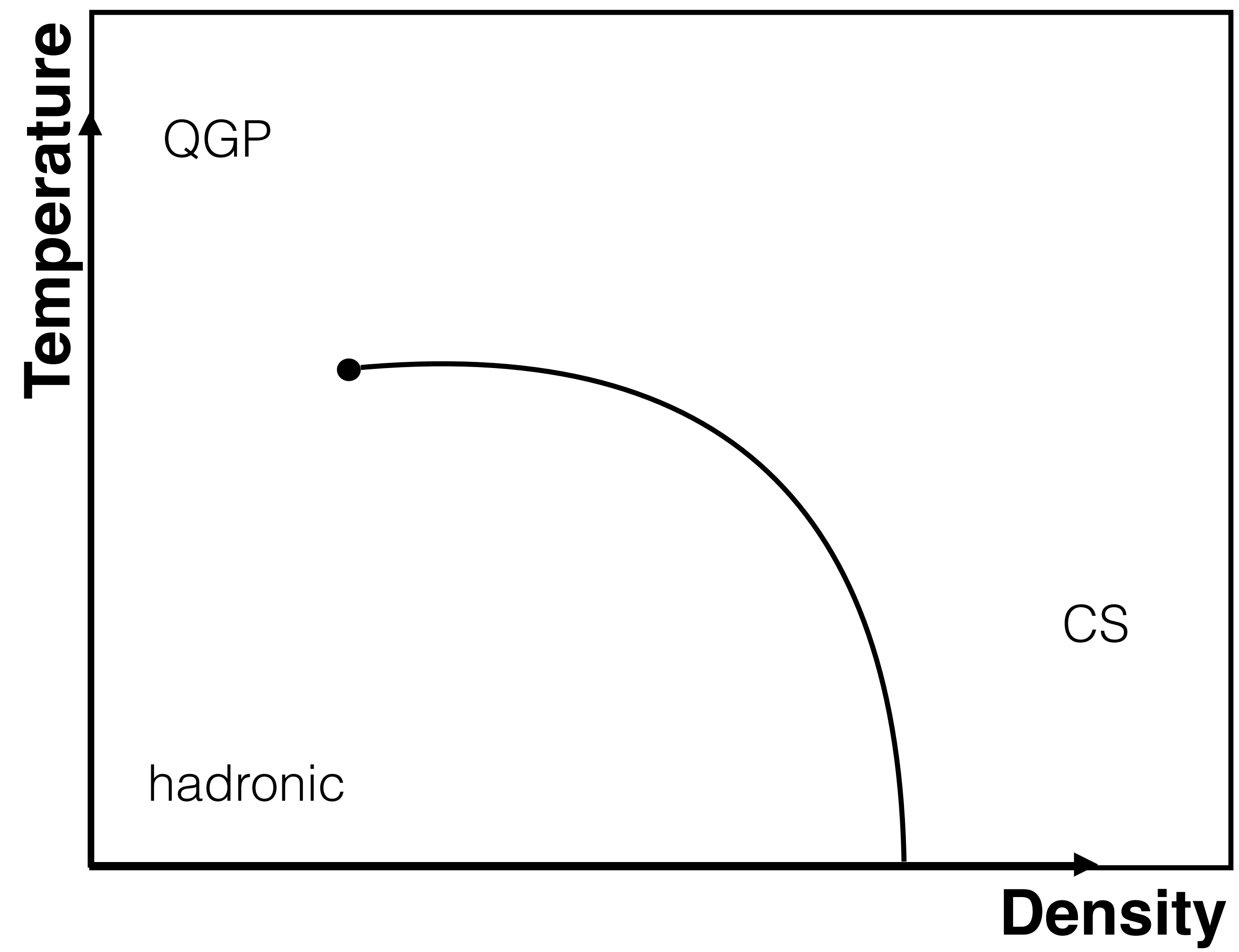
- Rather than introducing a new fundamental particle we can explain the dark matter with standard model quarks and antiquarks in a novel phase

- Dark matter interactions scale with the cross-section to mass ratio so sufficiently dense and massive composite objects may avoid detection

Quark Matter

- At high densities the properties of QCD change dramatically

- The ground state in the relevant regime is a colour superconductor in which quarks form cooper pairs analogous to those of a conventional superconductor



Colour Superconductivity

- The specific pairing channel determines the ground state and the elementary excitations and many such channels are possible

- Nugget properties are largely independent of the specific phase of quark matter realized in the core

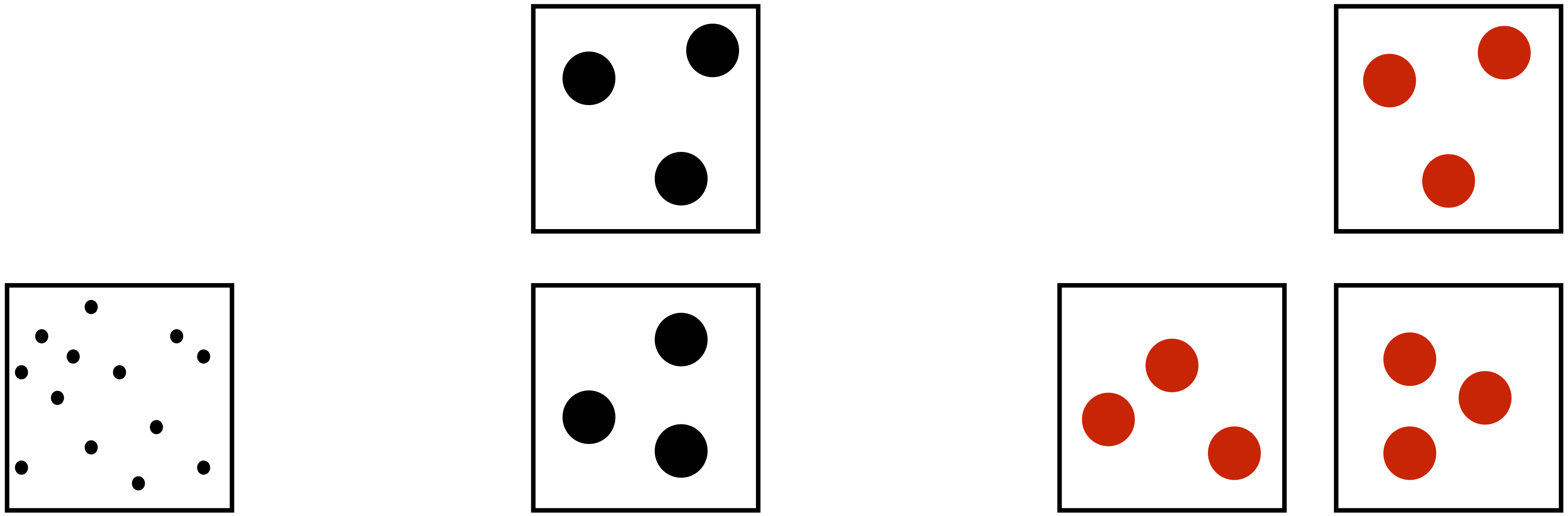
Nugget Formation

- The required compression may be provided by the collapse of domain walls at the QCD phase transition
- In this model “baryogenesis” proceeds through charge separation with antimatter preferentially locked into dense nuggets of quark matter
- An analysis of these dynamics involves strongly coupled interactions far from equilibrium and calculations are highly model dependent
- Once formed the nuggets essentially decouple from the surrounding plasma and will remain stable over cosmological time scales

Matter Content

- This model can account for matter and dark matter in the appropriate ratio within a universe with no net baryon number

- All antimatter not bound into nugget form then annihilates away



One part hadronic matter

Two parts quark nuggets

Three parts antiquark nuggets

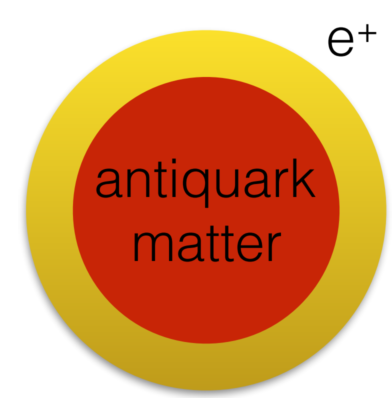
Physical Properties

- The resulting quark nuggets will be slightly above nuclear density
- A combination of theoretical and experimental considerations suggests $10^{25}<B<10^{33}$ (ie. $1g<M<1000$ tons, $10^{-5}<R<10^{-2}$)
- The interactions of the nuggets are primarily determined by their surface layer

The Electrosphere

- The central quark matter will carry a net charge due to the quark mass splitting

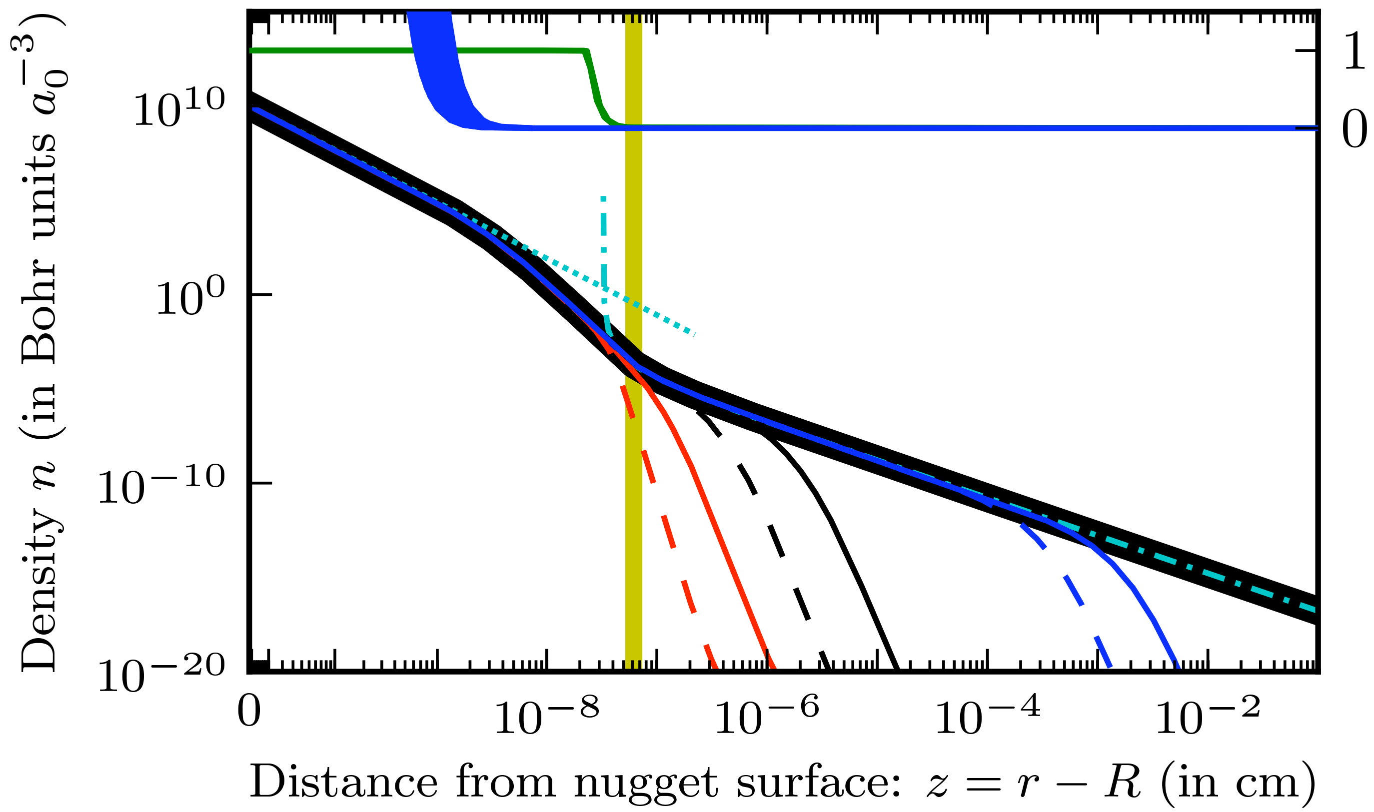
- This charge is shielded by a layer of electrons (or positrons in the case of an antiquark nugget)



- Emission from the nuggets is primarily from the outer layer of the electrosphere

- Near the quark matter surface the positrons are strongly bound with energies E~10MeV

- Further from the nugget the central charge is screened and the electrosphere smoothly extrapolates to vacuum with the outer positrons being only weakly bound



Indirect Detection

- Interactions between the nuggets and surrounding matter are suppressed by the geometric factor σ/M but are not inherently weak
- In regions of sufficient visible matter density the nuggets may have observable consequences
- These consequences will be determined by the radiative properties of the nuggets
- In most of the following I will focus on antiquark nuggets as they have the most pronounced observational consequences

Electron Annihilation

- Far from the nugget the average positron momentum and incoming electrons annihilate mainly through an intermediate Ps bound state
- This process results in a narrow 511 keV line and and associated three photon continuum
- Ps formation is a resonance process and is responsible for the majority (~90%) of annihilations

- The few (~10%) incident electrons which survive into the high density regime of the electrosphere annihilate with tightly bound positrons producing a broad continuum across the 1-20 MeV range

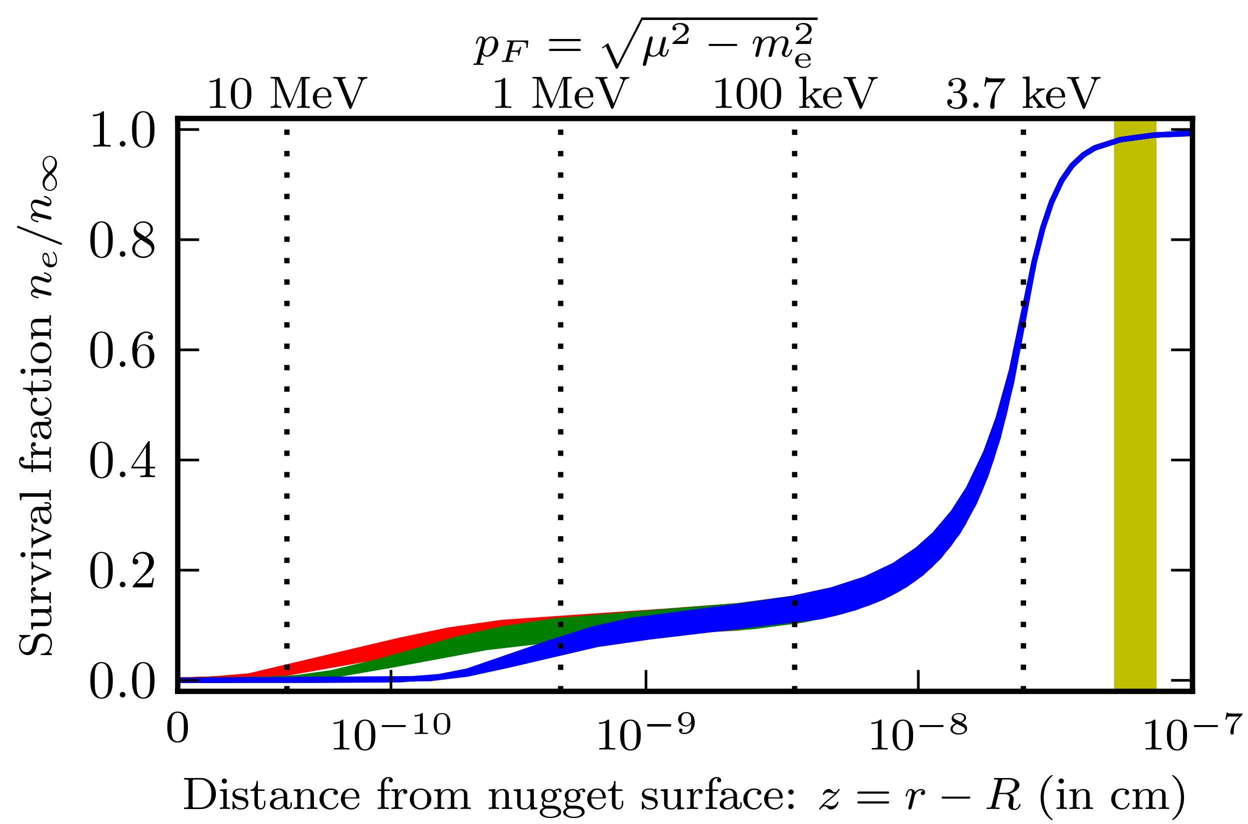


Figure from Forbes, Lawson & Zhitnisky 2010
http://arxiv.org/abs/0910.4541

Galactic Observations

- A stronger than expected 511 keV line is observed in the diffuse emission from the galactic centre
- The unknown origin of this line makes it difficult to constrain any contribution from quark nuggets
- A nugget population with $B \sim 10^{24}$ would saturate the observed 511 line strength imposing a lower limit on baryon number
- Uncertainty in cosmic ray propagation models prevents us from improving this constrain significantly with higher energy MeV data in the 1-20MeV range

Proton Annihilation

- Protons annihilate within the quark matter and the energy released is rapidly thermalized within the nuggets
- This is the primary mechanism heating the antiquark nuggets and the thermal energy is emitted as low energy photons from the outer layers of the electrosphere
- x-ray emission may be generated by annihilations very near the surface but is strongly suppressed relative to low energy thermal emission diffuse emission measurements of galactic x-rays do not improve on the electron annihilation bounds

Thermal Emission

- As the emitted photons are not in equilibrium with the positrons the spectrum differs from a typical black body spectrum

- At typical galactic densities the nuggets will have an emission spectrum that extends from the infrared down to microwave frequencies

- Below ~1GHz the spectrum is cut off by many body effects resulting in very little radio emission

Galactic Microwave Emission

- Across most of the spectrum diffuse emission from the nuggets is easily lost in the galactic background but it becomes potentially observable at microwave frequencies ~50GHz
- A nugget population with $B \sim 10^{25}$ would saturate galactic microwave “haze”emission near the galactic centre (assuming a cusped DM profile)

Early Universe

- Nugget thermal emission from z~1100 can make a significant contribution to the isotropic radio background potentially exceeding CMB emission at low frequencies

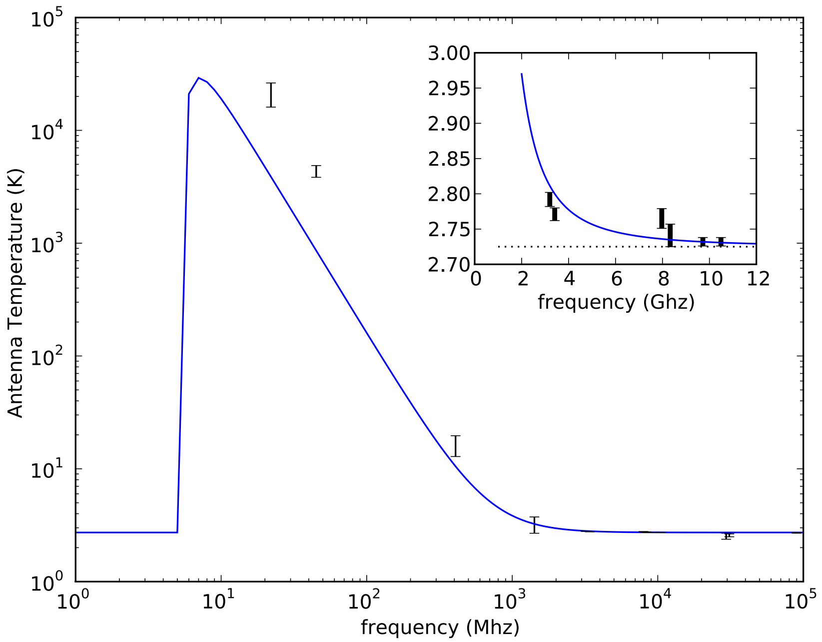


Figure from Lawson & Zhitnisky 2013
http://arxiv.org/abs/1210.2400
data points from Arcade 2 (Fixsen et.al 2011)

- Again the constraints on the order of B~10^{25} but in this case there is large uncertainty related to late time structure formation

Direct Detection

- Large uncertainties remain in the astrophysical backgrounds making a clear dark matter signal difficult to separate from conventional astrophysics
- Astrophysical observations are strongly complemented by ground based direct detection
- We may estimate the nugget flux based on the local dark matter density:

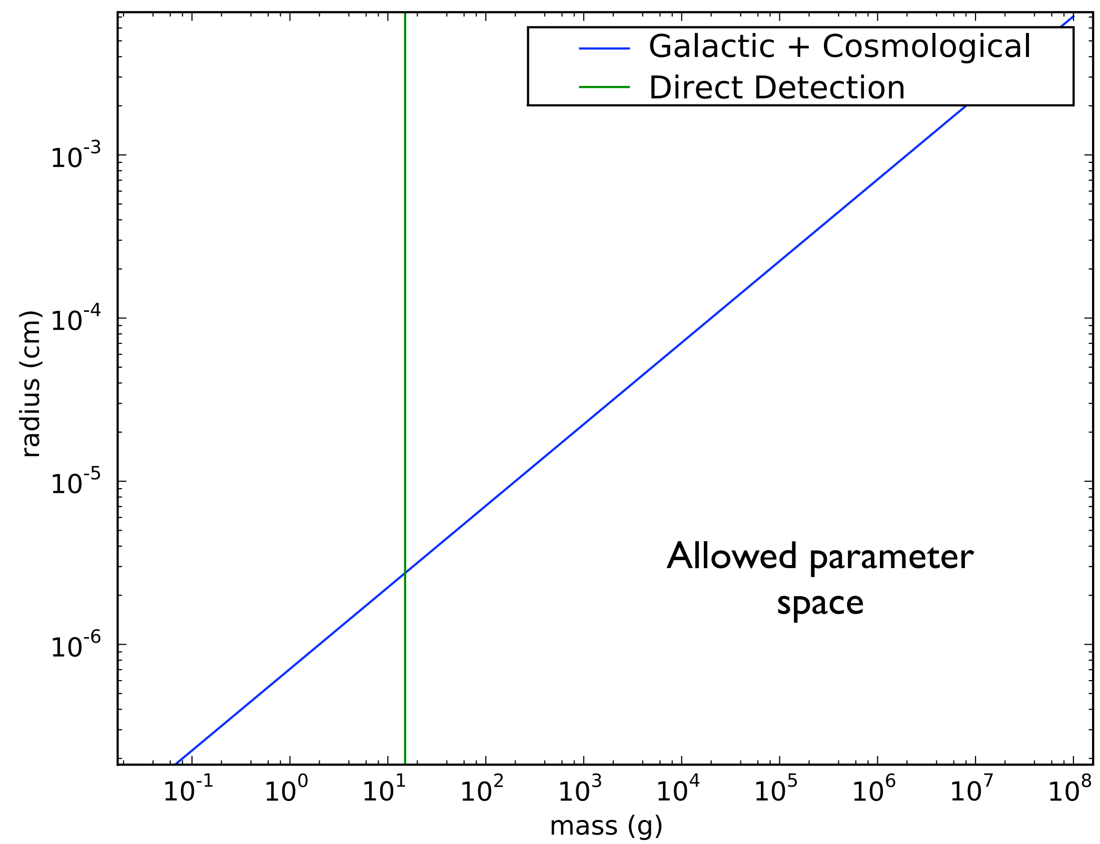
$$\Phi = n_{DM}\, v \approx (10^{24}/B)\ \mathrm{km}^{-2}\ \mathrm{yr}^{-1}$$

- Astrophysical constraints scale with the interaction rate:

$$\int dr\, n_{DM}\, \sigma_N\, v\, n_{vis} = (\sigma/M) \int dr\, \rho_{DM}\, v\, n_{vis} \sim B^{-1/3}$$

- Direct detection experiments scale directly with the nugget flux:

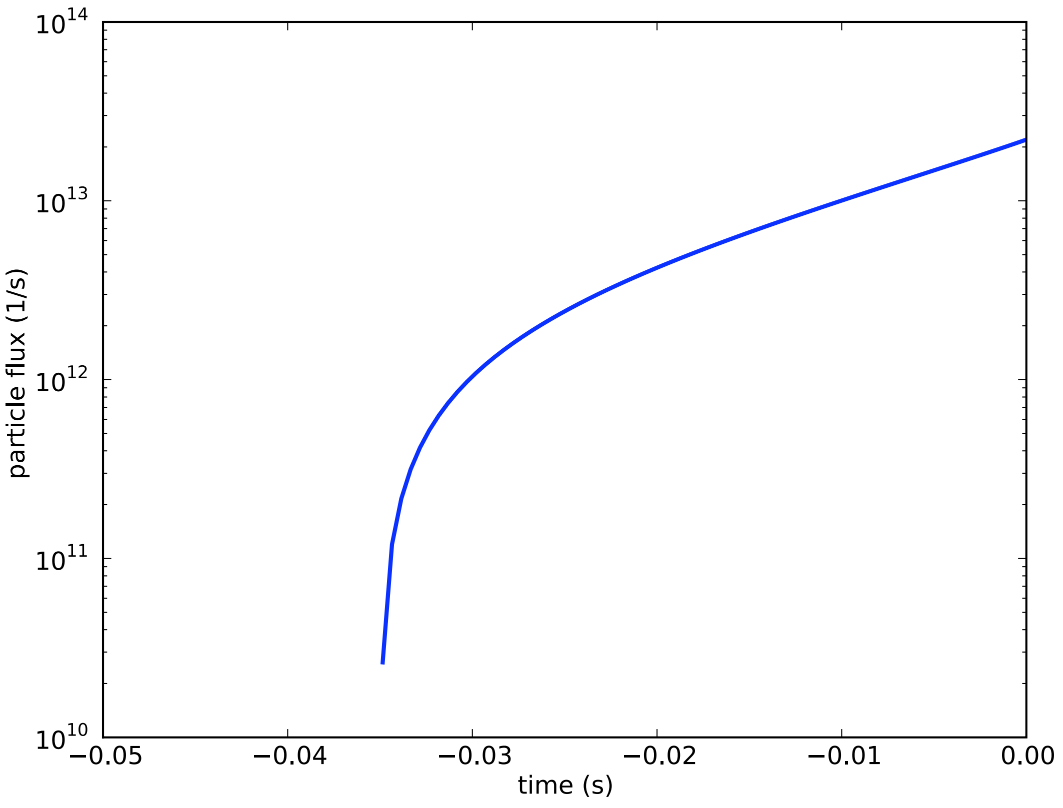
$$\Phi = \rho_{DM}\, v/M \sim B^{-1}$$



Current Constraints

- The most unambiguous limits come from non-relativistic monopole searches (MACRO, Lake Baikal, IceCube)

- The nuggets travel at galactic velocities v~200km/s making them a difficult target for large scale detectors which typically use timing cuts to focus on objects moving at the speed of light



Nugget Induced Air Showers

- An antiquark nugget crossing the atmosphere will be heated to a surface temperature at the keV scale and emit substantial amounts of ionizing radiation

- These showers evolve with atmospheric density rather than depth and thus develop very near the earth's surface

Neutrino Production

- The annihilation of a proton or neutron within the quark matter releases ~2GeV of energy mostly in the form of light "mesons"
- The energy of mesons within a colour super conductor is an order of magnitude below their vacuum value
- These mesons rapidly undergo multiple scatterings becoming non-relativistic before they decay producing a neutrino
- Some small fraction of very near surface annihilations may produce higher energy neutrinos

Neutrino Spectrum

- Unlike all other possible detection channels neutrino emission is sensitive to the phase of quark matter realized in the core (through the light meson spectrum and the average proton penetration depth)
- As the mesons decay essentially at rest we expect relatively narrow neutrino emission lines from two body weak decays

Neutrino Constraints

- SuperK strongly constrains the solar neutrino flux above 20MeV which sets an effective limit of the lightest modes of any allowed quark matter phase

- At lower energies neutrino production by conventional solar processes dominates over any possible nugget contribution

- Solar processes do not produce antineutrinos so experiments which independently tag neutrinos and antineutrinos can place important limits of both the total solar capture rate and the meson masses with in the nugget core

- The strongest neutrino constraints will actually come from improved statistics at lower energies

Conclusions

- Dark matter does not have to fall within the WIMP paradigm
- There are a number of high mass composite models (including the one presented here) not accessible to conventional dark matter searches or collider search programs
- Large scale astroparticle physics experiments offer the strongest potential to test this class of models