Limits on quark nugget dark matter from cosmic ray detectors

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Outline

- Baryogenesis and dark matter
- Quark nugget dark matter
- Present constraints
- Consequences for cosmic ray observatories

Baryogenesis

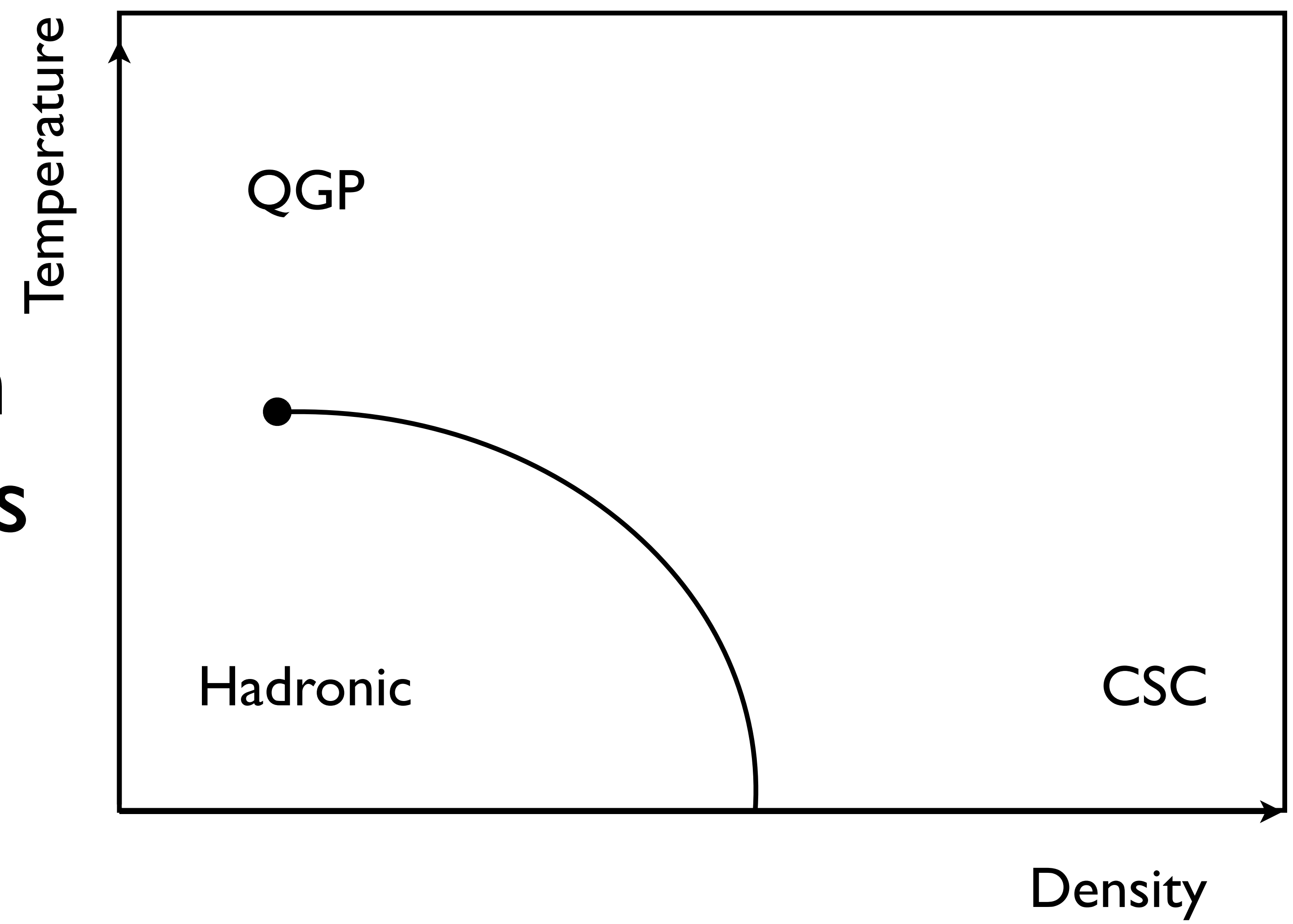
- The universe is strongly dominated by matter while antimatter is present in only trace amounts
- The laws of physics as we know them are matter-antimatter symmetric so there is no obvious mechanism by which to generate this cosmological asymmetry
- Any such mechanism must involve CP violation and non-equilibrium processes

Baryogenesis as separation of charges

- It is generally assumed that baryogenesis must also involve baryon number violation
- Alternatively it is possible to generate an *apparent* baryon excess even in a universe with no net baryonic charge
- Any such ‘baryogenesis’ mechanism must preferentially act on antiquarks rather than quarks
- But how do we hide the antibaryons?

The phases of QCD

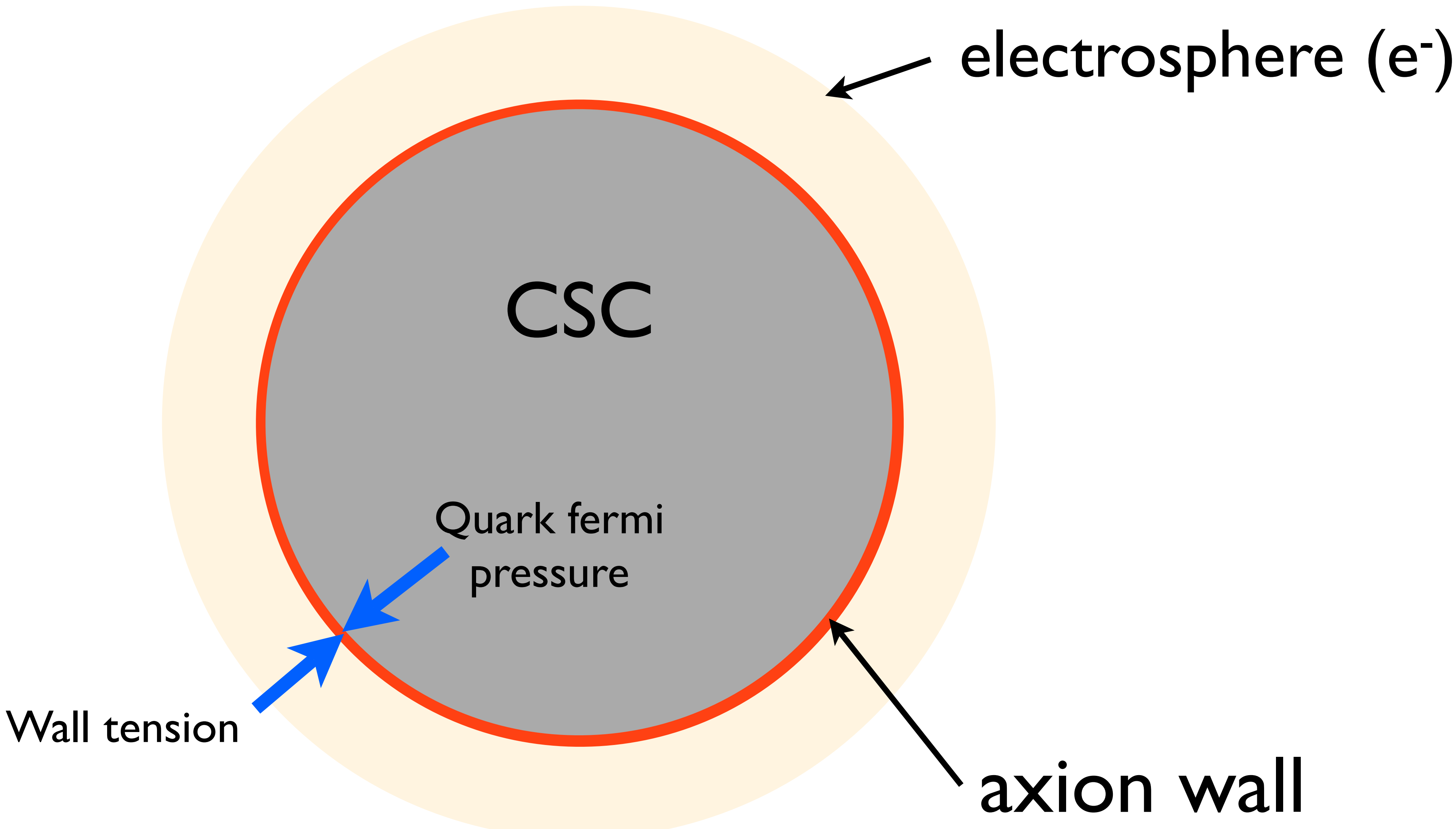
- We live in the low density low temperature phase of QCD
- At larger densities the ground state is a colour superconductor in which quarks form cooper pairs
- If hadronic matter in the can be squeezed to sufficient density it can form stable nuggets of CSC



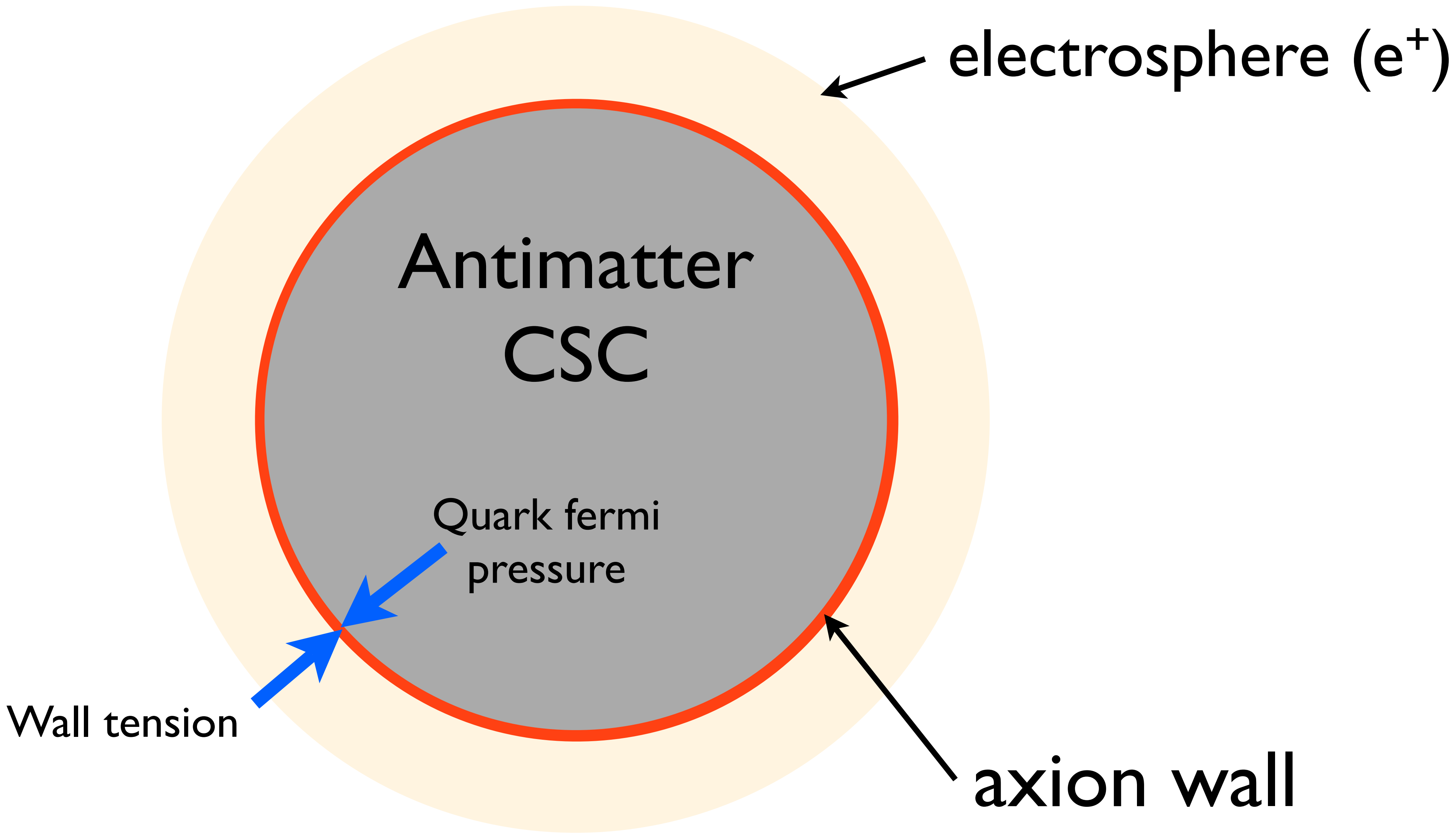
A nugget formation model

- The QCD phase transition may be accompanied by the formation of a network of axion domain walls which quickly decay as the axion field relaxes, the walls have a typical scale $\sim m_a^{-1} << H^{-1}$
- As the walls collapse they interact with the QGP in a CP violating way so that they preferentially sweep up either matter or antimatter
- If sufficient material is trapped in the wall its collapse may be halted by the fermi pressure

Quark nuggets

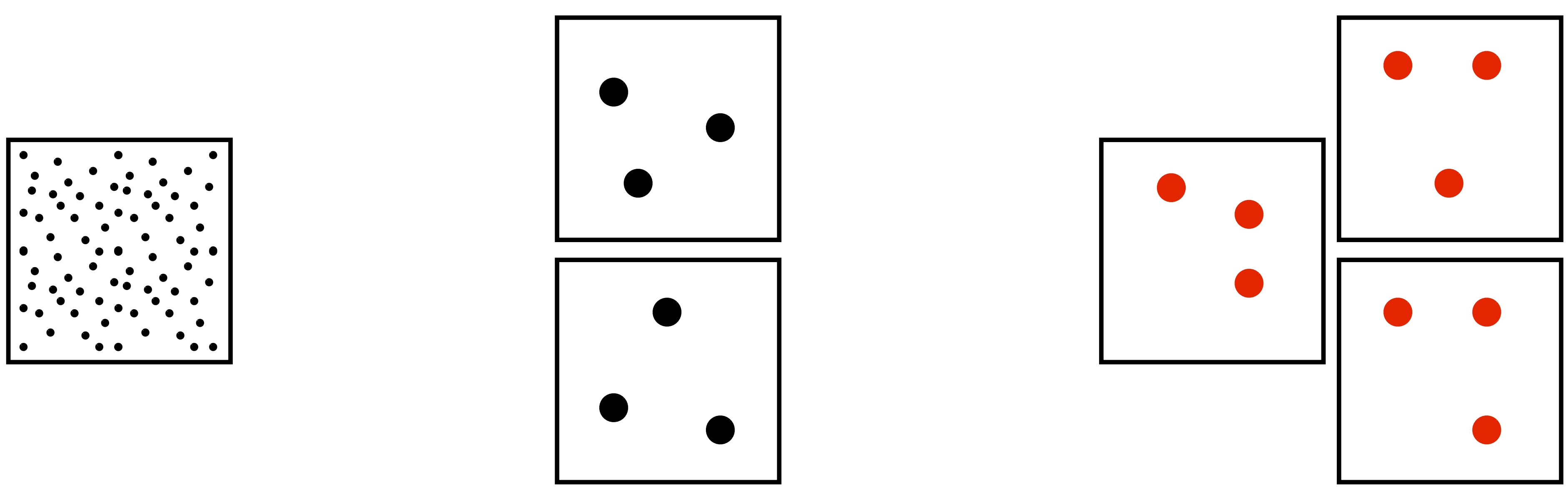


Antiquark nuggets



A baryon neutral dark matter model

- Quark nuggets of large mass have a small number density and may serve as the dark matter
- This would explain the similar scales $\Omega_{DM} \approx 5\Omega_{vis}$



One part visible matter | Two parts matter nuggets | Three parts antimatter nuggets

Nugget Parameters

- The size of the nuggets formed in this process will be largely determined by the tension of the domain walls, this is set by the axion mass scale which must fall in the range 10^{-2}eV > m_a >10^{-6}eV
- Estimating the wall tension and equating it with the fermi pressure inside we find that the nuggets must have a mass in the range 10^{-3}g > M_N >10^9g and a radius 10^{-6} cm>R>10^{-3} cm
- Outside this range there is no known mechanism for compressing the baryons to a sufficient density

Present constraints

- The nuggets are 'dark' because of their low number density not the weakness of their interactions

- Astrophysical consequences are scaled by the matter/dark matter interaction rate which depends on both size and mass

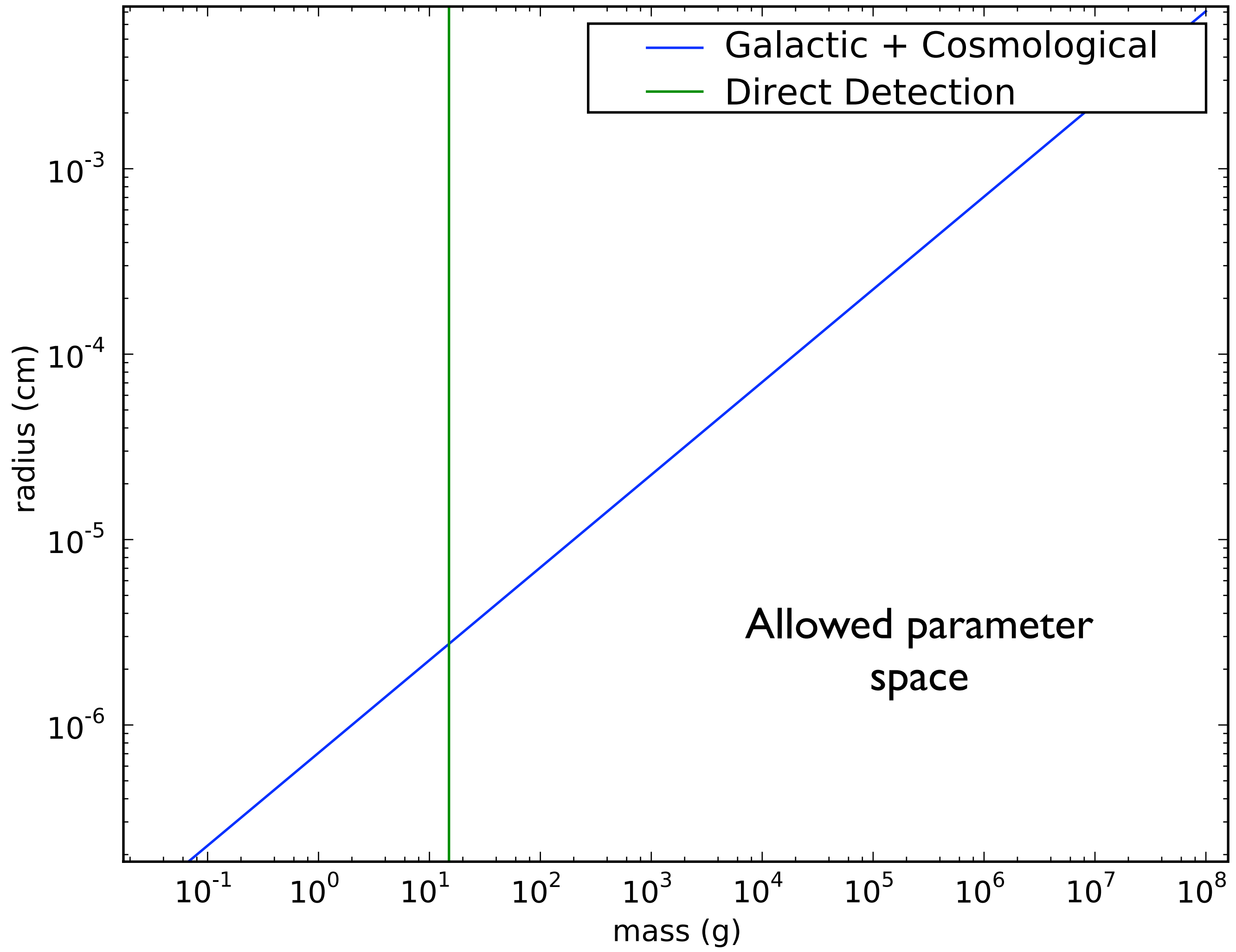
$$\int dr\, n_{DM}\, v\sigma_N\, n_{vis} = (\pi R_N^2/M_N) \int dr\, \rho_{DM}\, v\, n_{vis}$$

- Direct searches are purely flux limited and thus constrain only the nugget mass

$$\Phi = \rho_{DM}\, v/M_N$$

Present constraints

- Direct detection limits are dominated by monopole searches
- Indirect limits come from lack of detection in both galactic diffuse emission and the isotropic cosmological background



Quark nugget induced air showers

- An antiquark nugget crossing the atmosphere will be heated by nuclear annihilations and emit both thermal radiation and charged particles
- The charged particle emission is dominated by muons with typical nuclear scale energies
- Can these showers be detected by large scale cosmic ray detectors?

Basic scales

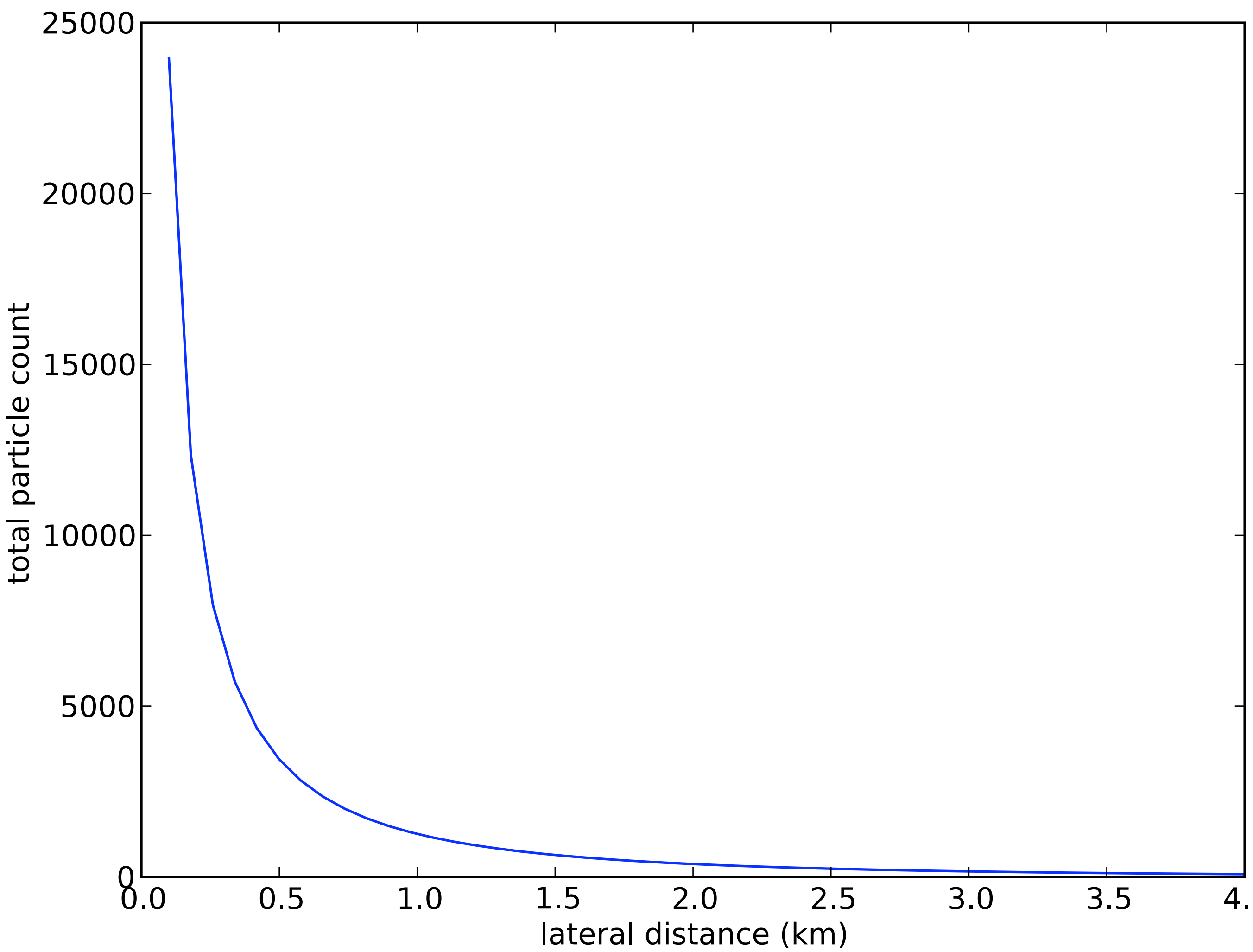
- The flux of nuggets of a given baryon number is $\approx (1\ km^{-2}yr^{-1})(10^{25}/B)$
- The nuggets carry typical galactic scale velocities $v \approx 200km/s$ so the associated shower will evolve on a scale of ~10ms
- Full annihilation of the atmospheric column would release ~MJ of energy most energy will thermalize within the nugget or as low energy thermal radiation

Fluorescence detection

- Fluorescence yield scales with atmospheric density rather than with depth
- High in the atmosphere conventional fluorescence dominates but at higher densities thermal emission may become dominant
- The total event will last for a few ms with the bright thermal emission dominating only very near the surface

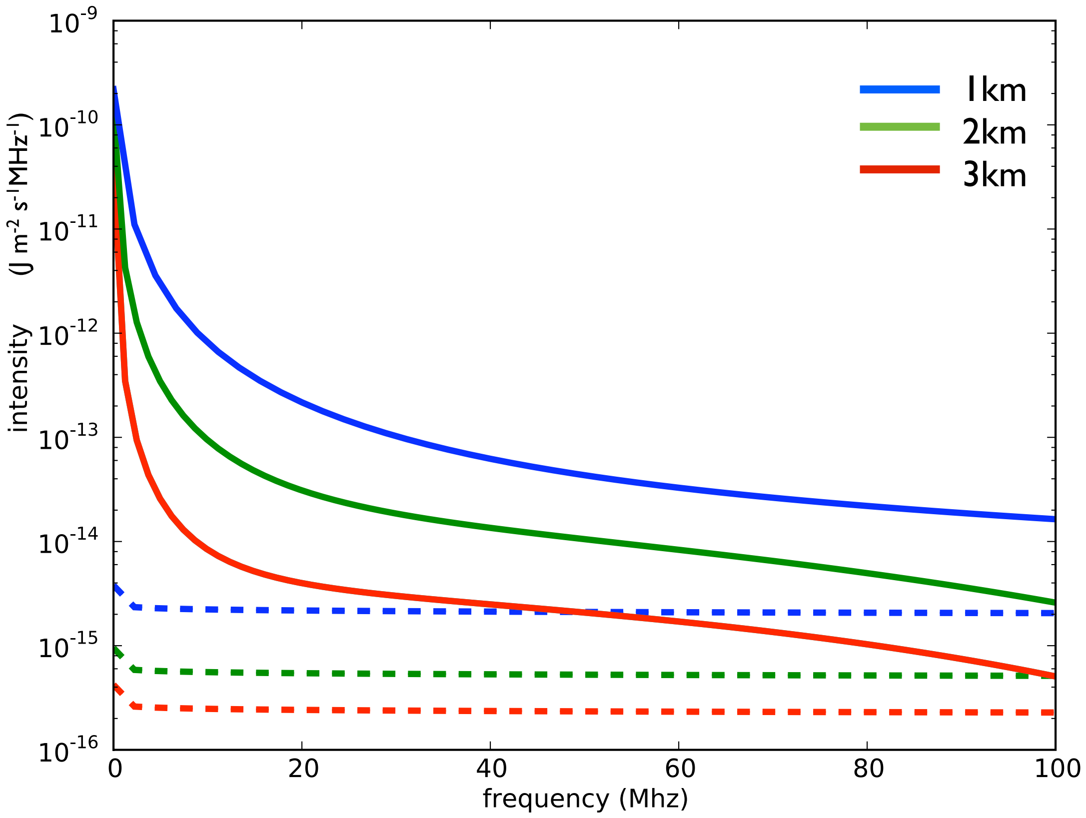
Surface particle counts

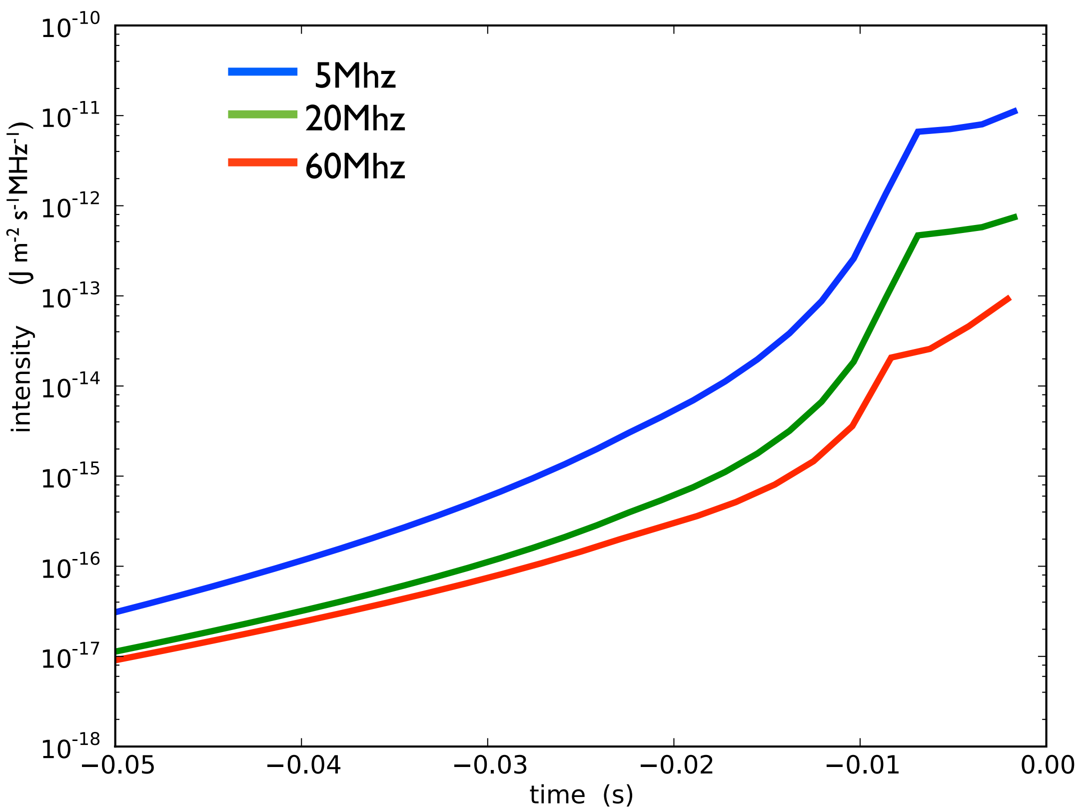
- The nuggets continue to produce charged particles all the way to the surface
- The shower front will cross the surface over ms timescales and extend over km distances
- May produce clustered lightning-like events



Radio detection

- Radio emission is produced by both geosynchrotron (forward directed) and thermal (isotropic) emission
- The total emission intensity is similar to that of an UHECR shower
- Constraints based on radio emission have been extracted from the ANITA data





Potential cosmic ray detector constraints

- Very high mass (>kg) dark matter models can only be constrained by experiments sensitive to very low flux
- Unfortunately this also requires sensitivity to long duration events
- Surface detection and radar searches seem more promising than fluorescence