DM as the quark nuggets in a colour superconducting phase

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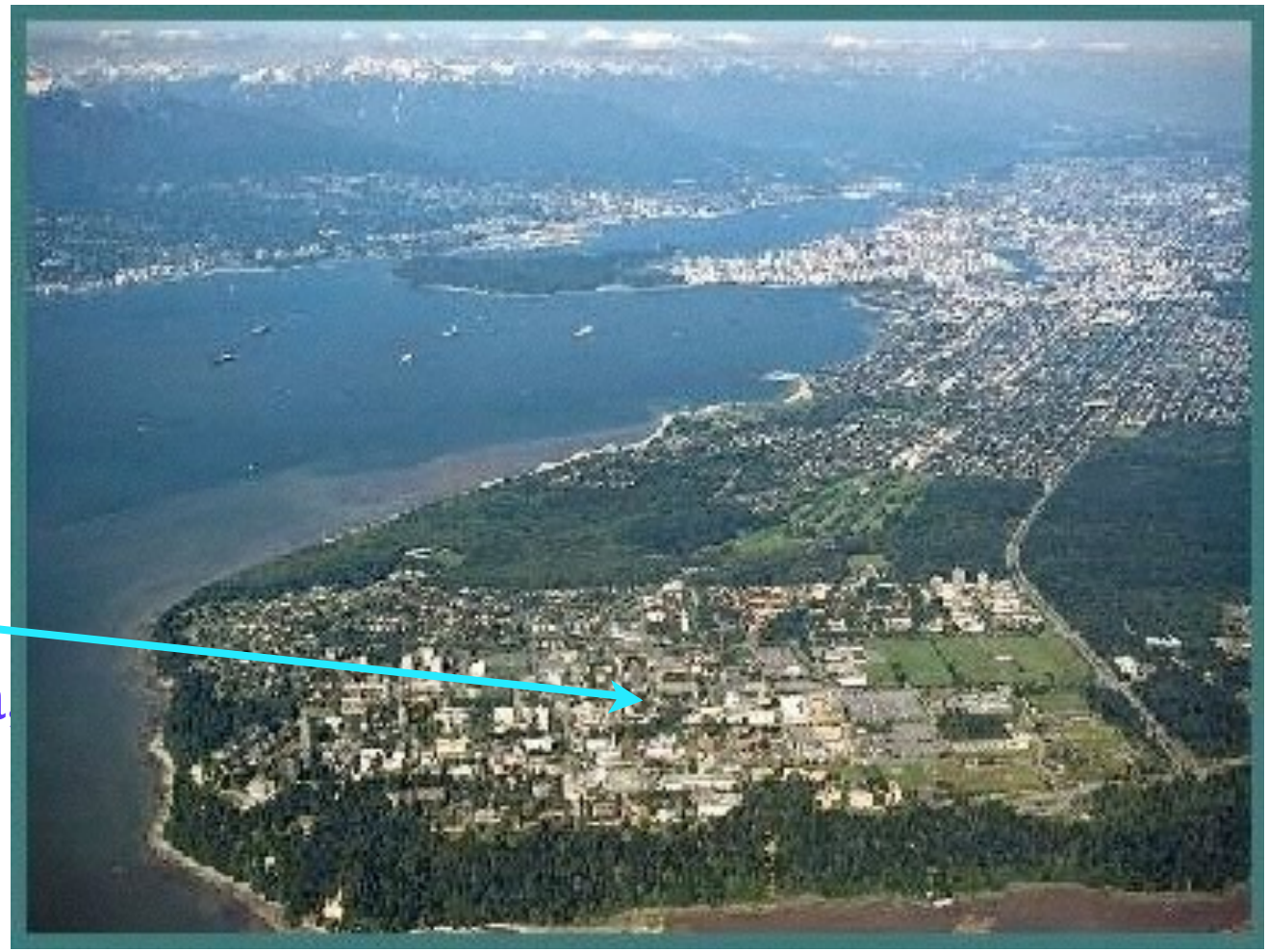

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XII Quark Confinement and the Hadron Spectrum.
Thessaloniki, Greece, 2016

1.Two (naively unrelated) problems: Dark Matter and Baryogenesis.

- 1."Naive" Moral: Dark matter requires New (unknown) Fields
- 2. "Naive" Moral: New Fields must be Nonbaryonic. Arguments come from structure formation requirements, BBN, decoupling DM from radiation, etc
- This proposal: Instead of "New Fields" ⟶ "New phases" (dense colour superconductor) of "Old Fields"
- Instead of "Baryogenesis" ⟶ "separation of charges" of conventional fields (quarks and gluons) at $\theta \neq 0$
- Some elements of this idea have been tested at RHIC and the LHC (thorough the so called Chiral magnetic Effect and Charge separation effect, (*Kharzeev and AZ, 2007*), see a plenary talk by Dima and a number of parallel talks on the subject during this meeting.

- We propose that on the global level the Universe is symmetric. The separation of baryon charges is originated at the QCD scale as a result of the axion domain wall dynamics, see details below

- Some charges are locked in form of large dense quark matter nuggets (and anti-nuggets).

- The nuggets remain stable over cosmological timescales and serve as DM (similar to the Witten's strangelets but with extra pressure due to the N=1 axion domain walls).

- We take the advantage of strong CP violation resulting from $\theta \neq 0$ before the QCD phase transition. It produces the nugget-anti nugget correlated asymmetry in Universe.

- This predicts that the visible (baryonic) and dark matter densities (quark nuggets) are the same order of magnitude today in the Universe: $\Omega_{\rm dark} \approx \Omega_{\rm visible} \sim \Lambda_{\rm QCD}$

- Instead of conventional local fields (such as WIMPs) the DM in our framework is a macroscopical composite object with a typical nuclear density, similar to Witten's strangelets.

- If the nuggets are sufficiently large in size (therefore they are very massive) the observational consequences due to these objects will be suppressed by small number density

$$\text{typical example}: n \sim (\text{fm})^3, \quad B \sim 10^{25}, \quad R \sim 10^{-5}\text{cm}, \quad M \sim 10\text{g},$$

- A small geometrical factor replaces a weak coupling constant (typical for WIMPs) for sufficiently large nuggets

$$\epsilon \sim S/V \sim B^{-1/3} << 1$$

- A fundamental measure is the baryon to entropy ratio is determined by formation temperature $T_{\rm form}$ at which the nuggets and anti-nuggets have completed their formation. This temperature is basically has the QCD scale $T_{\rm form} \simeq 41$ MeV close to the gap $\Delta \sim 100$ MeV and critical $T_{CS} \simeq 0.6\Delta \simeq 60$ MeV when colour superconductor phase sets in inside the nuggets

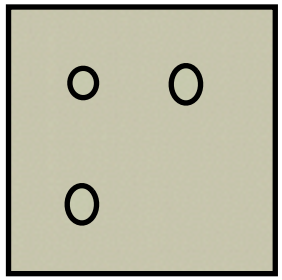
$$T_{\rm form} \simeq 41 \text{ MeV} \qquad \eta \equiv \frac{n_B - n_{\bar{B}}}{n_\gamma} \simeq \frac{n_B}{n_\gamma} \sim 10^{-10}$$

Matter in the Universe

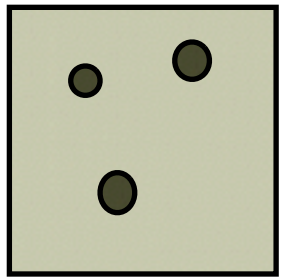
A model which explains both the matter-antimatter asymmetry and the observed ratio of visible matter to DM

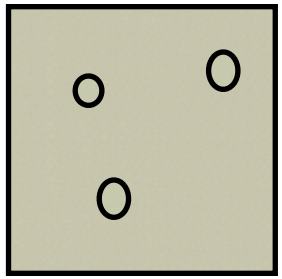
$$B_{tot} = 0 = B_{nugget} + B_{visible} - \bar{B}_{antinugget}$$

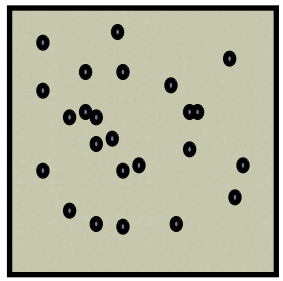
$$B_{DM} = B_{nugget} + \bar{B}_{antinugget} \simeq 5\ B_{visible}$$

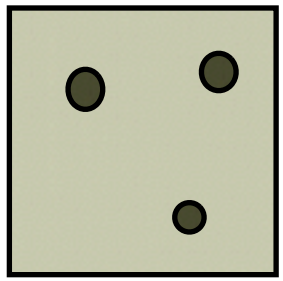


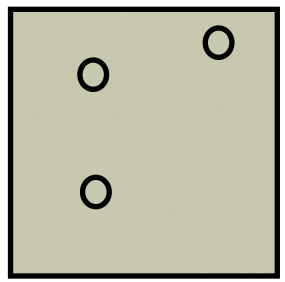
The ratio $B_{nugget}/\bar{B}_{antinaget} \simeq 2/3$ *at the end of formation is determined by the axion CP violating parameter* $\theta \sim 1$











One part: visible matter

Two parts: matter nuggets

Three parts: anti-matter nuggets

2. Observational Cosmological Puzzles

(naively unrelated story)

- Several independent observations of the galactic core suggest unexplained sources of energy:

- The most known case is the 511 keV line (INTEGRAL) which has proven very difficult to explain with conventional astrophysical positron sources.

- A similar, but less known mystery is the excess of gamma-ray photons detected by COMPTEL across a broad energy range 1-20 MeV. Such photons have been found to be very difficult to produce via known astrophysical sources

- Detection by the CHANDRA satellite of diffuse X-ray emission from across the galactic bulge provides a puzzling picture: after subtracting known X-ray sources one finds a residual diffuse thermal X-ray emission consistent with very hot plasma (T= 10 keV). Source of energy fuelling this plasma is a mystery.

- Recent measurements by the ARCADE2 experiment unambiguously show an excess in the isotropic radio background at frequencies around the GHz scale.

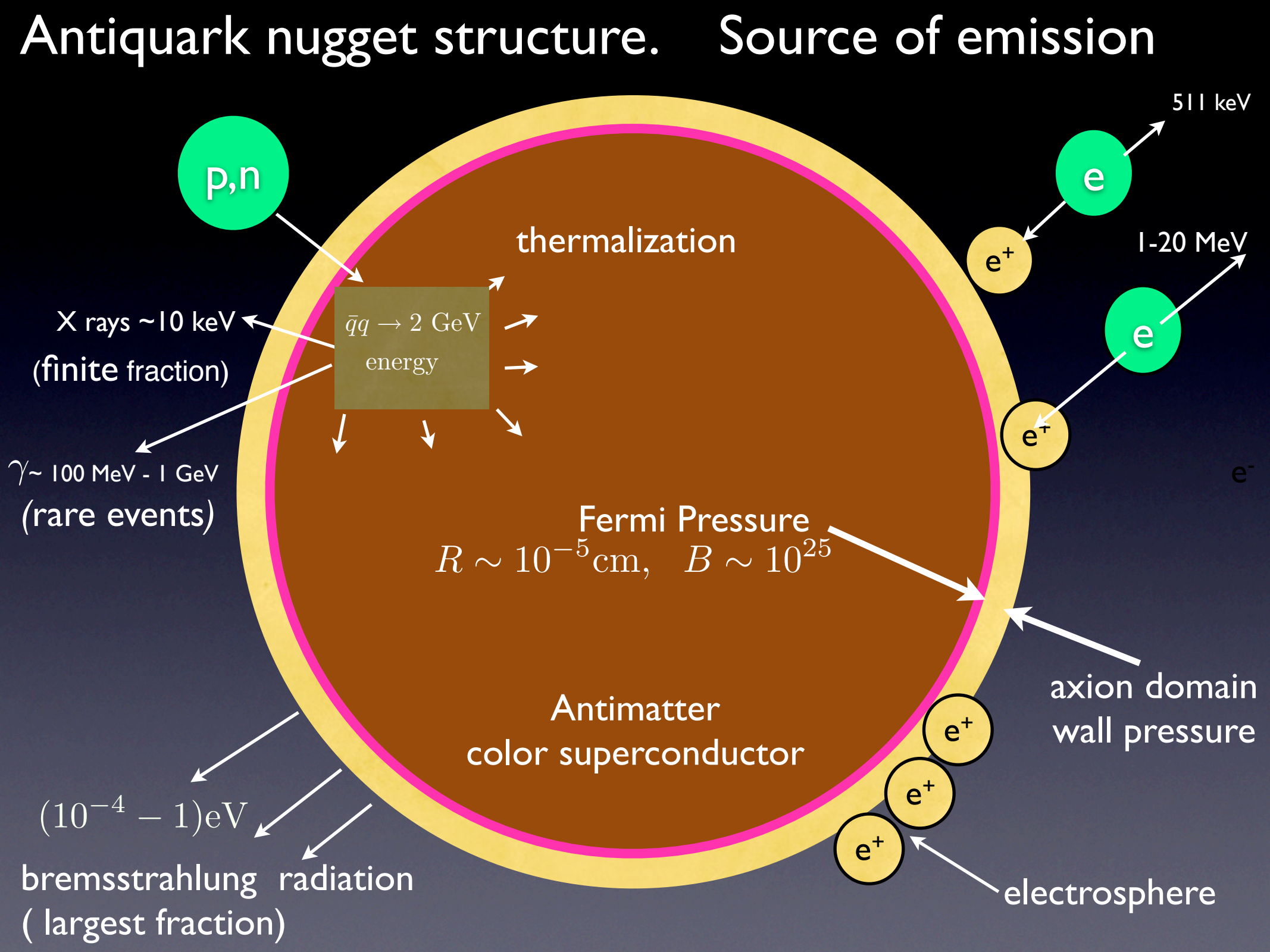
- Origin of these excesses remains a mystery as all conventional sources for these diffuse emissions are not capable to describe the observations.

Relevant Literature

(excesses of radiation at different frequency bands as a result of annihilation of the DM nuggets with visible matter)

- DM-Baryogenesis — JCAP 2003; PRD. 2005; PRD.2006
- 511 keV line (INTEGRAL) — PRL. 2005
- 1-20 MeV excess (COMPTEL) — JCAP 2008; PRD. 2010
- X-ray emission (CHANDRA) — JCAP 2008
- 23 < w < 61 GHz (radio diffuse) — PRD. 2008
- w~ 1 GHz (ARCADE 2) — Phys. Lett. B 2013
- w ~ 1 GHz (nearby galaxies) — Phys. Lett. B 2016
- mini-review prepared for SNOWMASS e-proceedings — arxiv:1305.6318

Antiquark nugget structure. Source of emission



3. Excess of diffuse gamma-rays in 1-20 MeV band. Observations.

- The flux of gamma rays in the 1-20~ MeV range measured by COMPTEL represents a mystery.

- The models (of cosmic rays) for diffuse galactic gamma rays fit the observed spectrum well for a very broad range of energies, 20 MeV- 10 GeV. The models typically also give a good representation of the latitude and the longitudinal distributions. However, the models fail to explain the excess in the 1-20 MeV range observed by COMPTEL.

- Some additional gamma ray sources are required to explain this excess in the 1-20 MeV range (Strong et al, 2004). These data suggest the existence of an energy source beyond currently established astrophysical phenomenon.

- The observed spectrum is extremely difficult to explain by known astrophysical mechanisms.

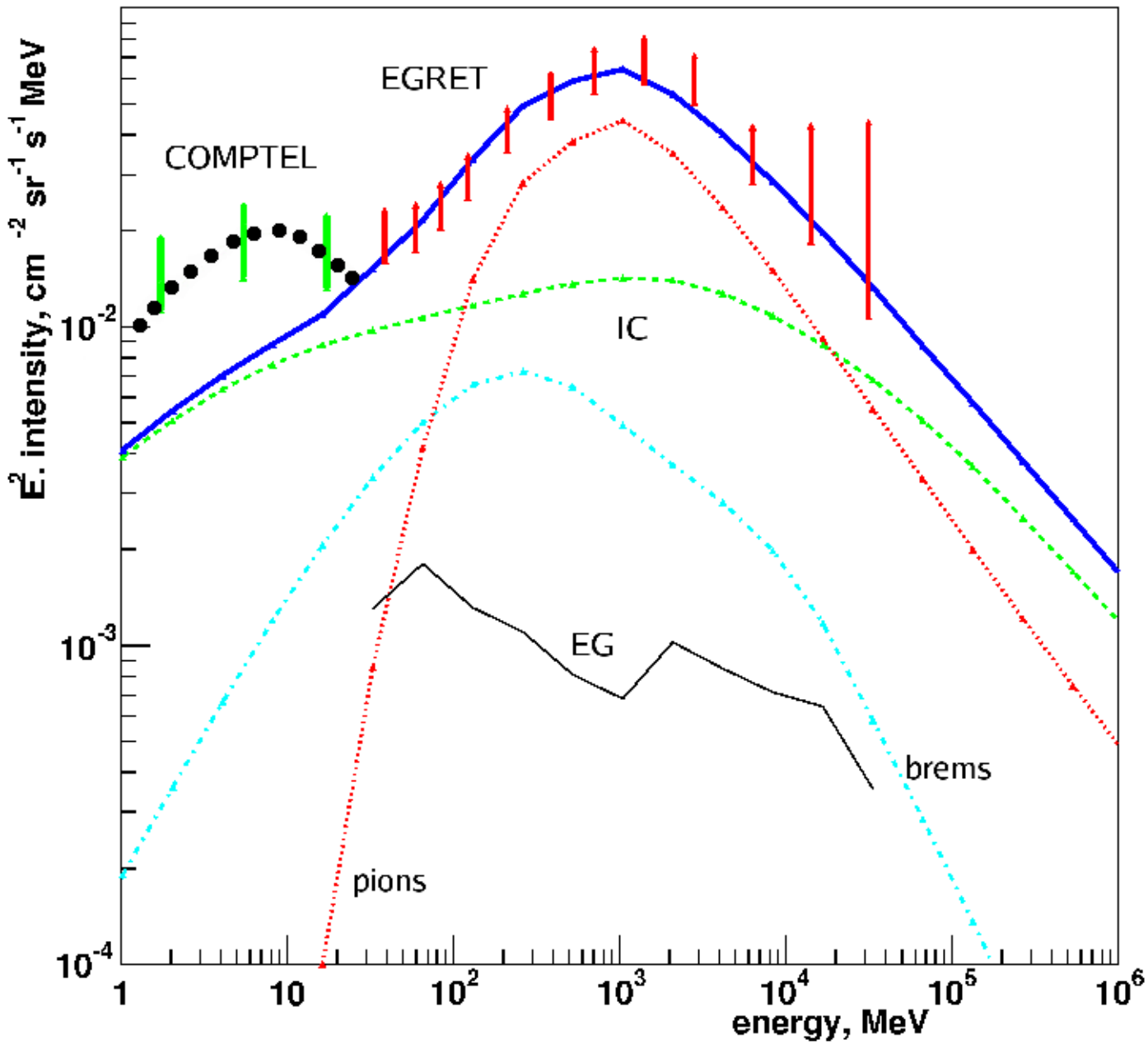
Excess of diffuse gamma-rays in 1-20 MeV band. Computations

(example of a typical computation in this model)

- Non-resonance direct annihilation would produce a broad spectrum at 1~20 MeV which we identify with the excess observed by COMPTEL. This continuum emission must always accompany the 511 keV line and the two must be spatially correlated (prediction).

- The relative ratio of 1-20~ MeV photons and 511 keV line is very sensitive to the profile function of electro-sphere. It was computed using the Thomas-Fermi approximation. There are NO free parameters in computations.

- No new parameters are required to explain the excess in the 1-20~ MeV range -- the normalization and spectrum are fixed by 511 keV flux and known QED and QCD physics.


EGRET
COMPTEL
IC
EG
brems
pions
E². intensity, cm ⁻² sr⁻¹ s⁻¹ MeV
energy, MeV
10⁻²
10⁻³
10⁻⁴
1
10
10²
10³
10⁴
10⁵
10⁶

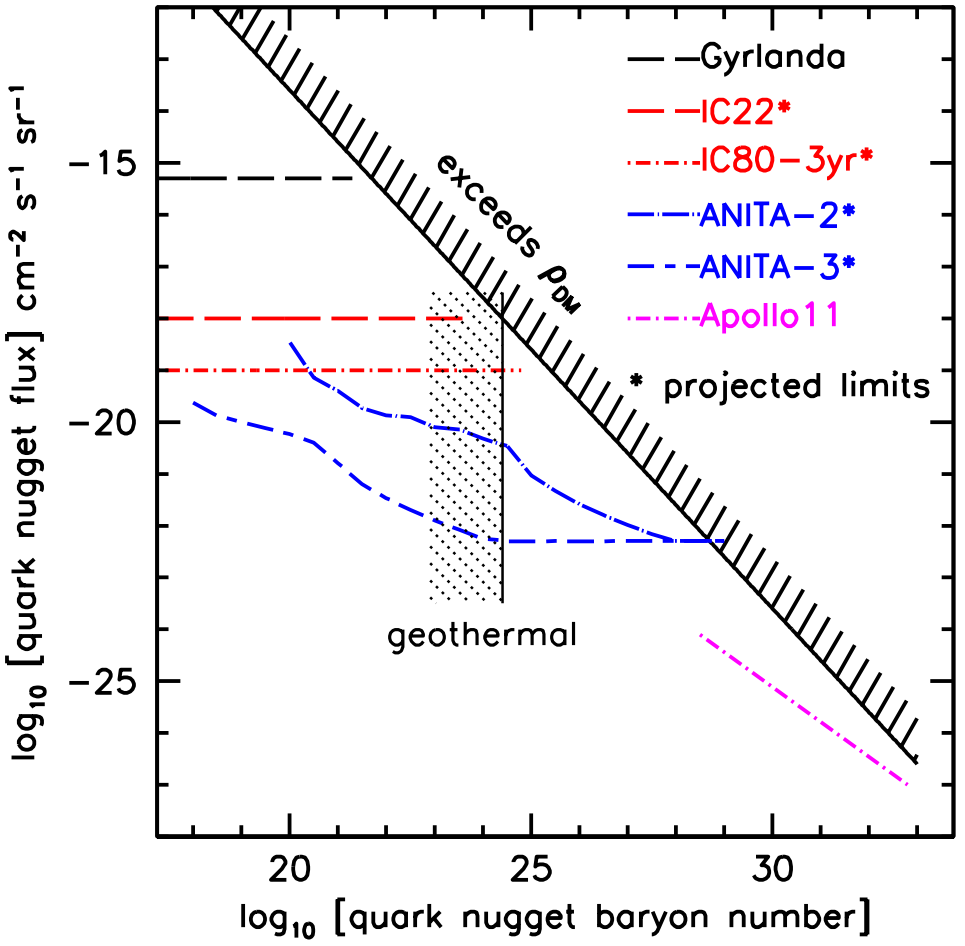
4. Lessons: galactic excess emissions

- "Non- baryonic Dark matter" could be ordinary baryonic matter which is not in the "normal hadronic phase", but rather, in the "exotic" colour superconducting phase.

- In this phase the baryon charge is not available for BBNucleosynthesis

- A small geometrical factor $\epsilon \sim S/V \sim B^{-1/3} << 1$ replaces a weak coupling const.

- Conventional killing problem (for other models) of insufficient CP violation is automatically resolved here: CP violation is large and correlated at the QCD phase transition at the Universe scale; it is <u>diminished</u> by now as a result of the axion dynamics.



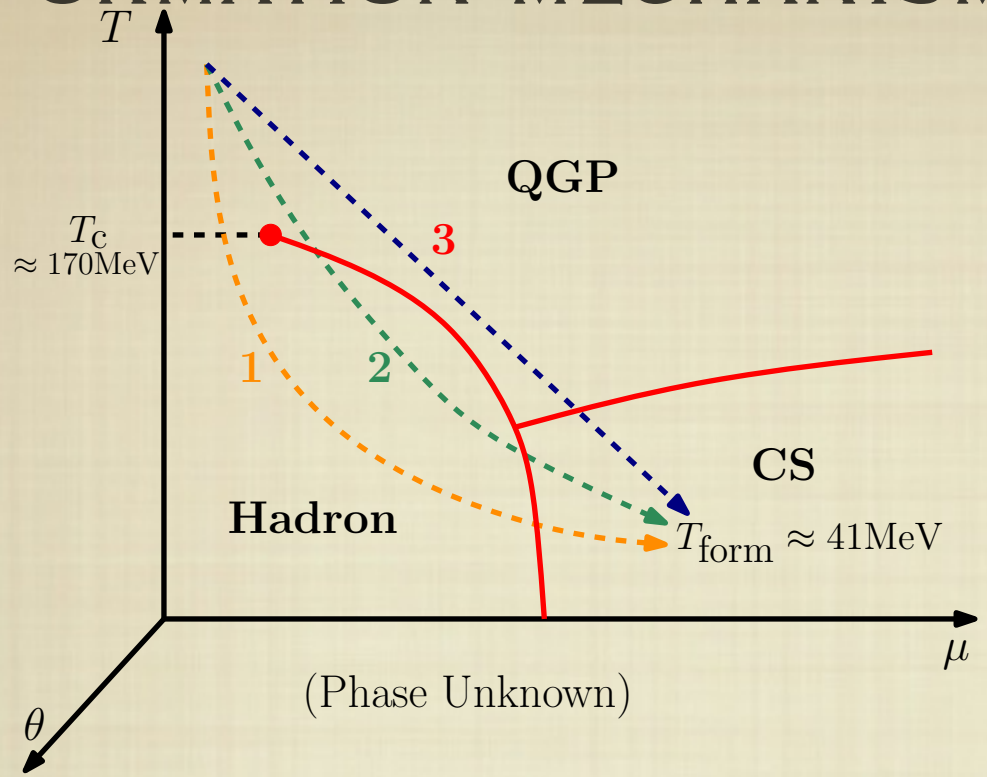
Plot from P. Gorham, PRD 86 (2012) 123005

Existing and projected limits on anti-quark nugget fluxes

CONCLUSION: ground based detection prospects:

1. *Radio emission of anti-quark nuggets with* $B = 10^{24} - 10^{28}$ *can be studied by balloon -borne instruments such as ANITA.*
2. *Analysis of existing ANITA-2 data for these event signatures has begun, and results may be expected within the next few years.*

5.Formation mechanism, arXiv 1606.00435



- Possible cooling paths are denoted as 1, 2, 3. The phase diagram at $\theta \neq 0$ is still unknown. Formation temperature (below the CS phase transition) $T_{\rm form} \simeq 41$ MeV corresponds to the observed value $\eta \equiv \frac{n_B - n_{\bar{B}}}{n_\gamma} \simeq \frac{n_B}{n_\gamma} \sim 10^{-10}$

- Nuggets complete the formation at $T_{\rm form} \simeq 41$ MeV .

- 1 Ingredient: the presence of the axion domain walls N=1 when θ interpolates between one and the same vacuum state: $\theta \to \theta + 2\pi n$. The axion domain walls in general, demonstrate a sandwich-like substructure on the QCD scale Λ_{QCD}^{-1}

- 2 Ingredient: there is another substructure with a similar QCD scale which carries the baryon charge. Local spontaneous symmetry breaking effect. It occurs on the correlation length $\xi \sim m_a^{-1}$

- 3 Ingredient: Kibble-Zurek mechanism which gives a generic picture of formation of the topological defects during a phase transition. After some time the system is dominated by a single, percolated, highly folded and crumpled domain wall of very complicated topology. In addition, there will be a finite portion of the closed walls (bubbles) with typical size of order correlation length $\xi \sim m_a^{-1}$

- 4. Ingredient: There existence of CS phase in QCD. The force which squeezes quarks in neutron stars is gravity; the force which does an analogous job in early universe during the QCD phase transition is a violent collapse of a closed axion domain wall bubble of size $R \sim \xi(T)$

- The bubbles do not completely collapse (as people originally thought). The collapse stops due to internal Fermi pressure.

- 5. If θ vanishes, then equal number of nuggets and anti-nuggets would form. However, the axion field $\theta(t)$ does not vanish at the moment of DW formation. Precisely the dynamics of the coherent axion field $\theta(t)$ leads to preferences in formation of one species of nuggets. This is the charge separation effect on the Universe scale.

6. Accretion of the baryon charge on a single nugget.

- We assume that initial size of the bubble $R \sim \xi(T)$ is sufficiently large such that one can locally treat the surface of the closed bubble being flat, i.e. the problem is effectively reduced to 2D system.

$$\mathcal{L}_4 = \bar{\Psi}\left(i\partial\!\!\!/ - me^{i[\theta(z)-\phi(z)]\gamma_5} - \mu\gamma_0\right)\Psi.$$

- where $\theta(z)$ is axion DW profile, $\phi(z)$ is η' field.

$$\mathcal{L}_2 = \frac{1}{2}(\partial_\mu\theta_1)^2 + \frac{1}{2}(\partial_\mu\theta_2)^2 - U(\theta_1,\theta_2) + \frac{\mu}{\sqrt{\pi}}\frac{\partial(\theta_2+\theta_1)}{\partial z}$$

$$U(\theta_1,\theta_2) = -mm_0\left[\cos(2\sqrt{\pi}\theta_1 - \phi + \theta)\right] - mm_0\left[\cos(2\sqrt{\pi}\theta_2 + \phi - \theta)\right].$$

- θ_1, θ_2 describe the original Ψ fermi field (2 spin states) in effective 2D system in DW background.

- The key point is that some DW may carry the baryon (anti-baryon) charge, depending on the boundary conditions

$$2\sqrt{\pi}\theta_1(z=+\infty) - 2\sqrt{\pi}\theta_1(z=-\infty) = 2\pi n_1$$

$$2\sqrt{\pi}\theta_2(z=+\infty) - 2\sqrt{\pi}\theta_2(z=-\infty) = 2\pi n_2$$

- The baryon charge in general assumes a nonzero value, depending on boundary conditions

$$N = \int d^3x \bar{\Psi}\gamma_0\Psi = -\frac{1}{\sqrt{\pi}}\int_{-\infty}^{+\infty} dz \frac{\partial}{\partial z}(\theta_1+\theta_2) = -(n_1+n_2),$$

- The effect is similar to fractional charge localization on DW. It can be thought as spontaneous Charge Separation Effect during DW formation

- Key point: periodic fields $\theta_1, \theta_2, \phi, \theta$ may assume physically identical, but distinct vacuum values during the QCD phase transition.

7.Formation of the nuggets

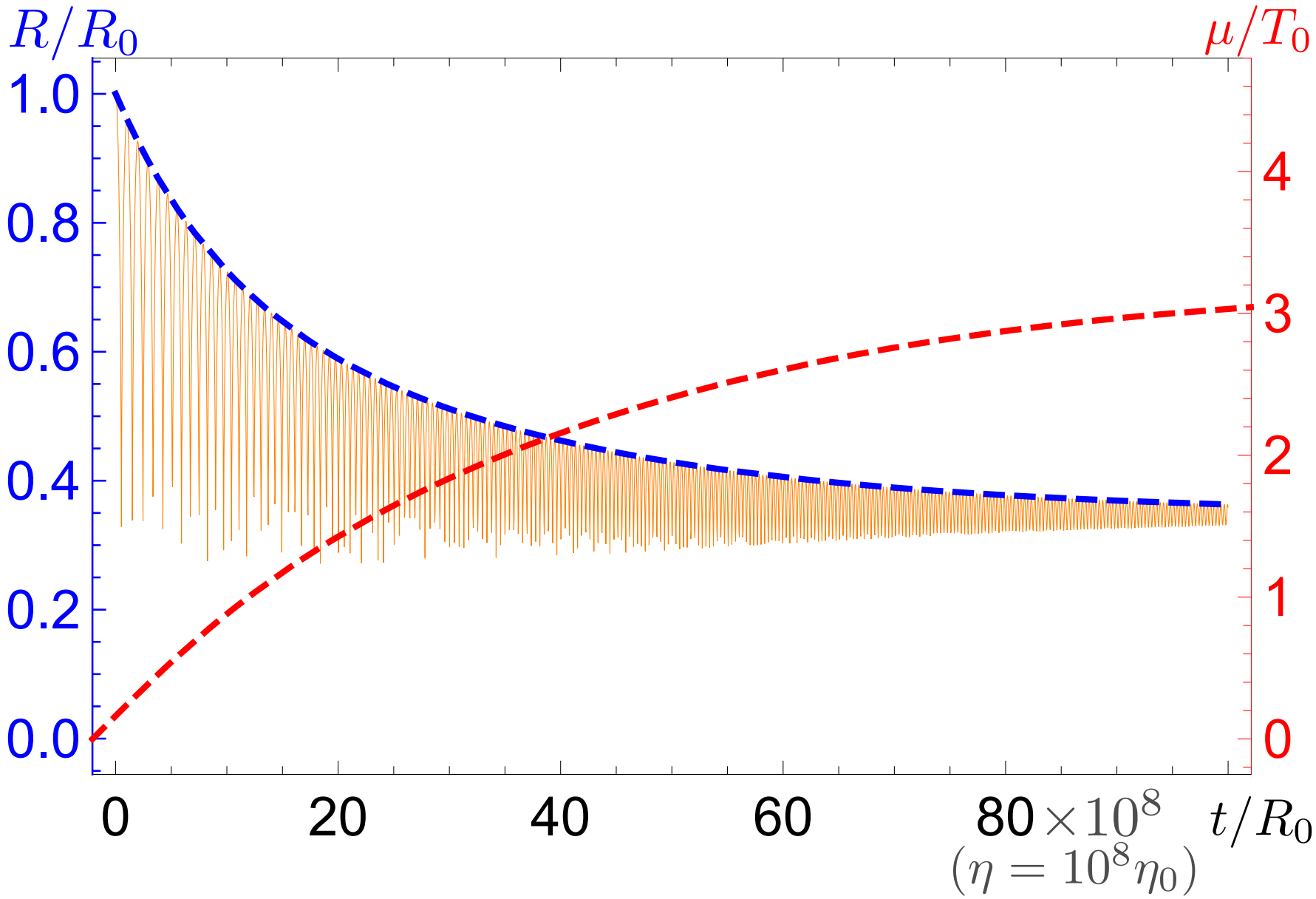
- The equation of motion which determines the time evolution of the nugget $R(t)$ is

$$\sigma\ddot{R}(t) = -\frac{2\sigma}{R(t)} - \frac{\sigma\dot{R}^2(t)}{R(t)} + \Delta P(\mu) - 4\eta\frac{\dot{R}(t)}{R(t)},$$

- σ -DW pressure, $\eta(T)$ -viscosity (which effectively describes the "friction" of the system), while in and out pressures are $\Delta P[\mu(t)] \equiv [P_{\rm in}(\mu) - P_{\rm out}(t)]$

- We also need a relation between $R(t)$ and chemical potential $\mu(t)$ during the evolution

$$\dot{B} = \frac{Ng}{4\pi^2}\dot{S}(t)\int \frac{d^2k_\perp}{\left[\exp(\frac{\epsilon-\mu(t)}{T})+1\right]} + \frac{NgS}{4\pi^2}\frac{\dot{\mu}(t)}{T}\int \frac{d^2k_\perp\left[\exp(\frac{\epsilon-\mu(t)}{T})\right]}{\left[\exp(\frac{\epsilon-\mu(t)}{T})+1\right]^2} + (\text{fluxes}) = 0,$$



numerical results for the evolution of the nugget:

behaviour of the radius with time $R(t)$

behaviour of the chemical potential $\mu(t)$

- These numerical results can be understood analytically

- The system makes a very large number of oscillations before it settles down at $R_{\rm form}$

$$R(t) = R_{\rm form} + (R_0 - R_{\rm form}) e^{-t/\tau} \cos \omega t$$

- Typical frequency and damping time for the observationally allowed window for the axion mass $10^{-6}{\rm eV} \lesssim m_a \lesssim 10^{-3}{\rm eV}$

$$\omega \sim \frac{1}{R_{\rm form}} \sim m_a, \qquad t_{\rm osc} \simeq m_a^{-1}, \quad \tau \sim \frac{\sigma}{2\eta} R_{\rm form} \sim 10^{11} \omega^{-1}$$

- Chemical potential $\mu(t)$ assumes a typical value for Colour Superconducting phase

8. Nuggets vs Anti-nuggets. Correlated formation on a cosmological scale

- If CP violating axion field $\theta(t)$ were zero at the moment of formation than an equal number of nuggets and anti-nuggets would form.

- $\theta \neq 0$ during the formation time implies that the difference between total baryon charge hidden in form of nuggets and anti nuggets is order of one:

$$B_{\rm antinuggets} = c(T) \cdot B_{\rm nuggets}, \quad \text{where} \quad |c(T)| \sim 1,$$

- Baryon charge of the visible matter can be expressed in terms of this parameter $c(T) \sim 1$

$$B_{\rm visible} \equiv (B_{\rm baryons} + B_{\rm antibaryons}) = -\left[1 + c(T)\right] B_{\rm nuggets} = -\left[1 + \frac{1}{c(T)}\right] B_{\rm antinuggets}.$$

- This relation leads to the basic consequence of the proposal

$$\Omega_{\rm dark} \simeq \left(\frac{1+|c(T)|}{|1+c(T)|}\right) \cdot \Omega_{\rm visible} \quad {\rm at} \quad T \leq T_{\rm form}.$$

- This is because both components of matter are proportional to the same scale. There is no any fine tuning in this framework

$$\Omega_{\rm dark} \simeq \Omega_{\rm visible} \sim \Lambda_{\rm QCD}$$

- It is very generic and model-independent result of the entire framework.

- For $c(T_{\rm form}) \simeq -1.5 \quad \Rightarrow \quad \Omega_{\rm dark} \simeq 5 \cdot \Omega_{\rm visible}$ the nuggets saturate the present DM density

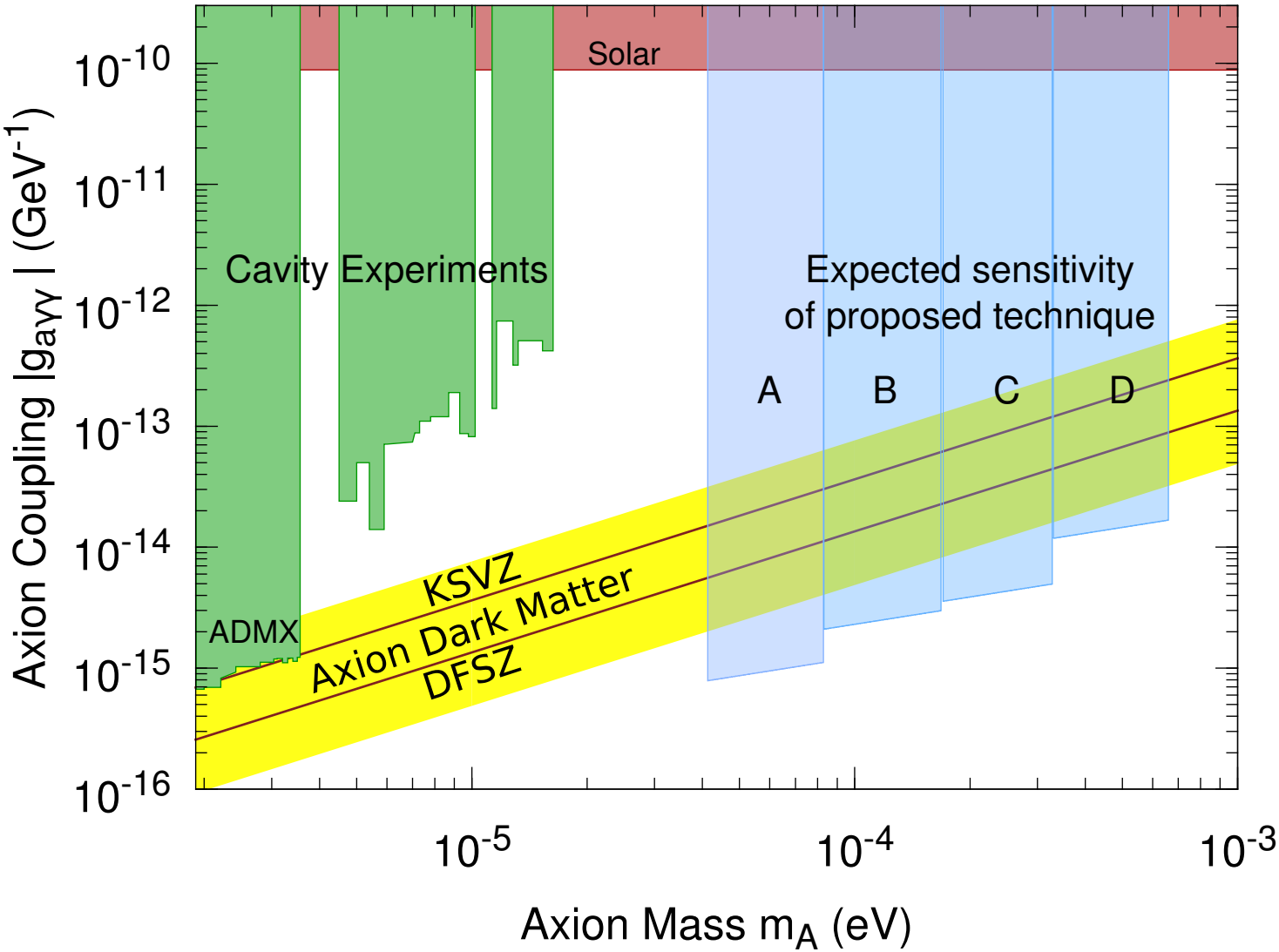
9. Implication for the axion search experiments.

- This model has a single fundamental parameter, a mean baryon number of a nugget $\langle B \rangle \sim 10^{25}$

- It is consistent with all known astrophysical, cosmological, satellite and ground based constraints

- This parameter $\langle B \rangle \sim 10^{25}$ corresponds to the axion mass $m_a \sim 10^{-4}\ eV$. These two parameters are directly related because $\sigma \sim m_a^{-1}$ determines the size of the nuggets $R_{\rm form}$

- Our comment here is that $m_a \sim 10^{-4}\ eV$ contributes very little to $\Omega_{(\rm DM\ axion)}$ but may contribute a lot through the nugget's formation (this proposal)



Cavity / ADMX experimental constraints shown in green. The expected sensitivity for the Orpheus axion search experiment [Rybka, 2014] is shown by blue regions. It covers most interesting region with $m_a \sim 10^{-4} eV$ corresponding to $\langle B \rangle \sim 10^{25}$

Conclusion

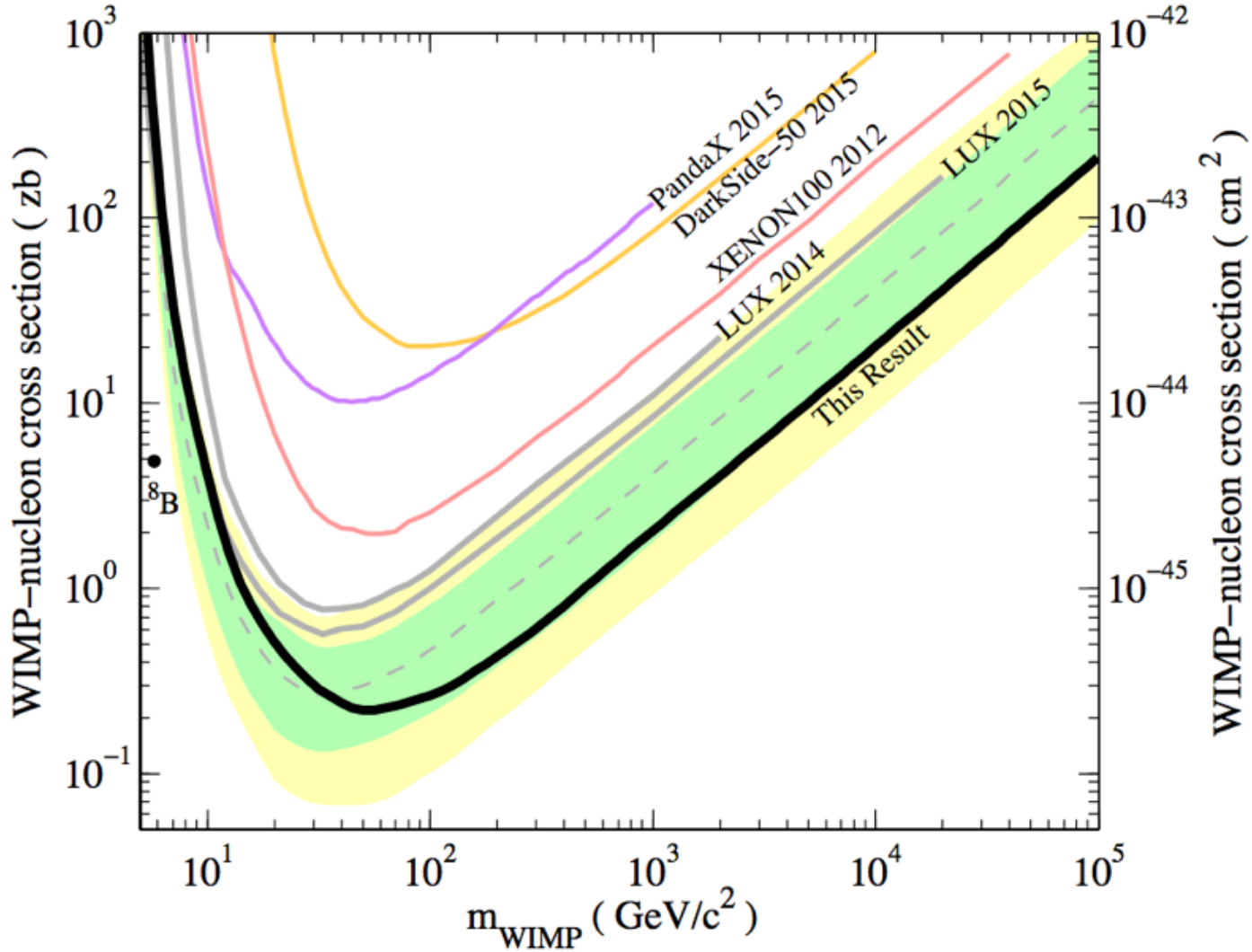
(see arxiv 1606.00435 for the details)

- " Non- baryonic Dark matter" could be ordinary baryonic matter which is in the exotic colour superconducting phase.

- $\Omega_{\rm dark} \simeq \Omega_{\rm visible} \sim \Lambda_{\rm QCD}$ is very generic (model independent) consequence of this framework

- Local separation of the baryon charge (spontaneous) occurs at scales $\xi(T) \sim m_a^{-1}$

- Global separation of the baryon charge occurs on the scale of the visible Universe due to the CP violating coherent dynamics of the axion field $\theta(t)$ during the N=1 domain wall formation.



The exclusion bounds on dark matter-neutron scattering released today, July 21, 2016, by the LUX collaboration. Image credit: LUX collaboration, retrieved from A. Manalaysay's talk.

Latest results from LUX (no WIMPs).

It is a time to change the PARADIGM: from WIMPs to AXION and QUARK NUGGETS