Cosmological axion field and quark nugget dark matter model

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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" $\longrightarrow$ "New phases" (dense colour superconductor) of "Old Fields"

- Instead of "Baryogenesis" $\longrightarrow$ "separation of charges" of conventional fields (quarks) at $\theta \neq 0$

- Separation of charges is realized by formation of the nuggets (similar to Witten's nuggets) with 2 extra elements:

- 1. THERE IS EXTRA **AXION DOMAIN WALL** PRESSURE WHICH MAKES THE NUGGETS STABLE (PHASE TRANSITION IS NOT REQUIRED)

- 2. THERE ARE TWO SPECIES, THE NUGGETS AND **ANTI-NUGGETS.**

- THE NUGGETS REMAIN STABLE OVER COSMOLOGICAL TIMESCALES AND SERVE AS DM (SIMILAR TO WITTEN'S NUGGETS)

- A SMALL GEOMETRICAL FACTOR REPLACES A WEAK COUPLING CONSTANT FOR SUFFICIENTLY LARGE NUGGETS
$$\epsilon \sim S/V \sim B^{-1/3} << 1$$

- COSMOLOGICAL CP-ODD AXION FIELD GENERATES THE **DISPARITY** BETWEEN TWO SPECIES AT $\theta \neq 0$ WHICH IMPLIES THE SIMILARITY BETWEEN **DARK AND VISIBLE** SECTORS: $\Omega_{\text{dark}} \approx \Omega_{\text{visible}} \sim \Lambda_{\text{QCD}}$
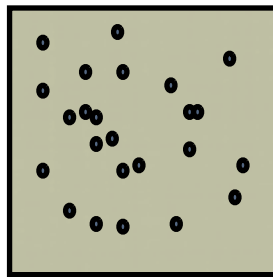
Matter in the Universe
A model which explains both the matter-antimatter asymmetry and the observed ratio of visible matter to DM

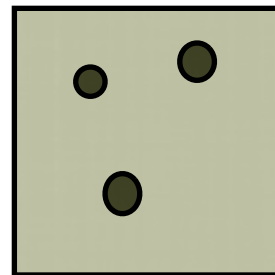$$\Omega_{\text{dark}} \simeq \Omega_{\text{visible}}$$

$$B_{tot} = 0 = B_{nugget} + B_{visible} - \bar{B}_{antinugget}$$
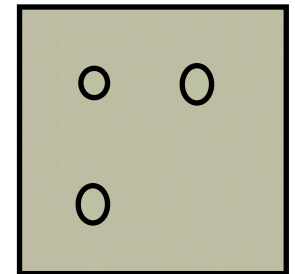
$$B_{DM} = B_{nugget} + \bar{B}_{antinugget} \simeq 5 \, B_{visible}$$

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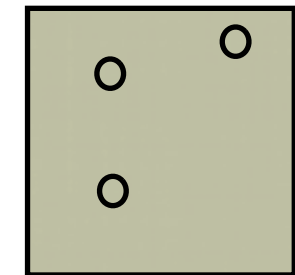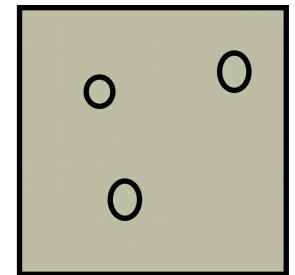
One part:
visible matter

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 (<u>INTEGRAL</u>) 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 <u>COMPTEL</u> 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 <u>CHANDRA</u> 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 <u>ARCADE2</u> experiment unambiguously show an excess in the <u>isotropic radio</u> 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). All computations are based on SM particle physics

- DM-Baryogenesis   JCAP 2003; PRD. 2005; PRD.2006

- 511 keV line (<u>INTEGRAL</u>)   PRL. 2005

- 1-20 MeV excess (<u>COMPTEL</u>)   JCAP 2008; PRD. 2010

- X-ray emission (<u>CHANDRA</u>)   JCAP 2008

- $23 < w < 61$ GHz (<u>radio diffuse</u>)   PRD. 2008

- $w \sim 1$ GHz (<u>ARCADE 2</u>)   Phys. Lett. B 2013

- $w \sim 1$ GHz (nearby galaxies)   Phys. Lett. B 2016
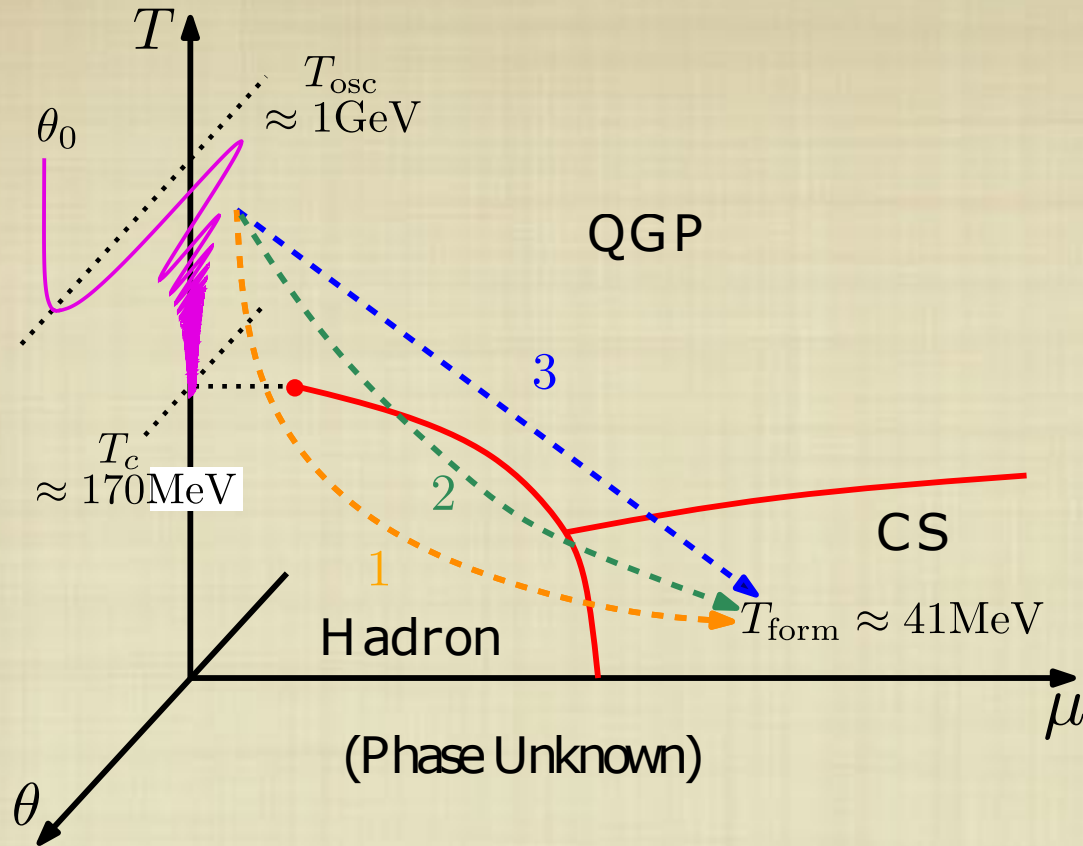
- **Possible cooling paths are denoted as 1, 2, 3. The phase diagram at $\theta \neq 0$ is still unknown. Formation temperature (below the CS phase transition) corresponds to the observed value**

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

- 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 —> no visible matter

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

$$\Omega_{\text{dark}} \simeq \left(\frac{1+c}{1-c}\right) \Omega_{\text{visible}}, \qquad c \equiv \frac{\left|B_{\text{nuggets}}\right|}{\left|B_{\text{antinuggets}}\right|}.$$

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

- It is very generic and model-independent result of the entire proposal. There is no any fine tuning in this framework

$$\Omega_{\text{dark}} \simeq \Omega_{\text{visible}}$$

Relevant Literature on Formation Mechanism :

- Evolution of a single nugget-
PRD 2016 (arxiv 1606.00435)

- Cosmological CP odd axion field and charge separation mechanism
PRD 2017 (1702.04354)

- Cosmological axion and relation to axion search experiments and other constraints
PRD 2018 (arxiv 1711.06271)

4. Solar extreme UV radiation and the axion quark nugget (AQN) dark matter

- The quiet Sun emits EUV radiation with the energy of order 100 eV which cannot be explained in terms of any conventional astro-phenomena (*Solar Corona Mystery, 1939*)
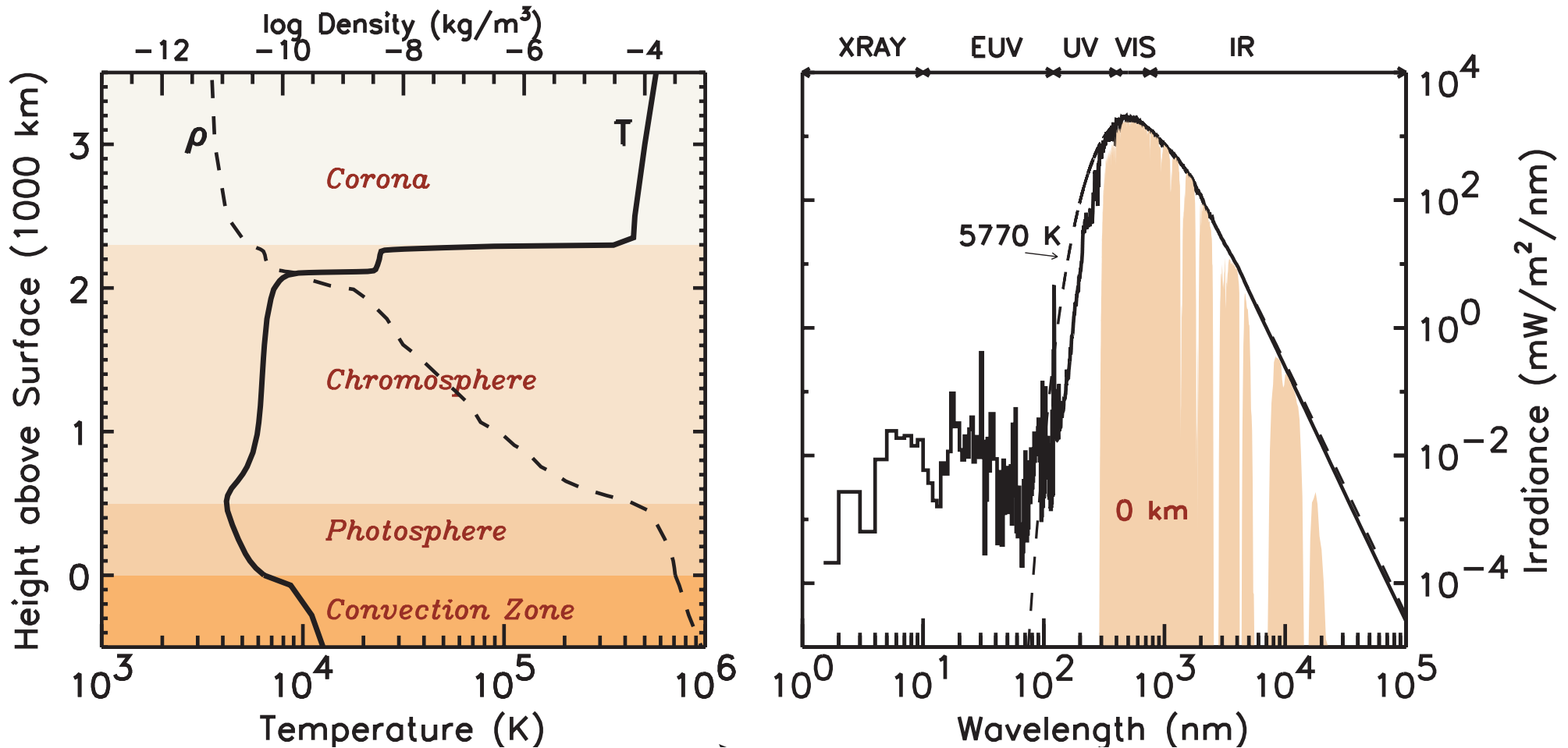
- Total energy output

$$L_\odot \text{ (EUV from Corona)} \sim 10^{30} \cdot \frac{\text{GeV}}{\text{s}} \sim 10^{27} \cdot \frac{\text{erg}}{\text{s}}.$$

- The EUV emission occurs about 2000 km above the surface where the temperature suddenly jumps:

$$T \simeq 10^4 \ K \Rightarrow T \simeq 10^6 \ K$$

- This is famous "Corona heating Puzzle"

Left: the temperature distribution in outer Sun: the drastic changes occur in vicinity of 2000km
Right: the unexpected deviation from the thermal distribution in EUV and soft x rays from corona
From [Zioutas 2016]

- **THIS PROPOSAL:** WE ADVOCATE A SCENARIO WHEN THE ENERGY DEPOSITION IS ORIGINATED FROM OUTSIDE THE SYSTEM (NOT FROM DEEP DENSE REGIONS OF THE SUN)

- THE EXTRA SOURCE OF THE ENERGY IS ASSOCIATED WITH THE **DARK MATTER ANTI-NUGGETS** CONTINUOUSLY ENTERING THE SUN FROM OUTER SPACE.

- THE IMPACT PARAMETER FOR CAPTURE OF THE NUGGETS BY THE SUN

$$b_{\mathrm{cap}} \simeq R_\odot \sqrt{1 + \gamma_\odot}, \qquad \gamma_\odot \equiv \frac{2GM_\odot}{R_\odot v^2},$$

- THE TOTAL ENERGY FLUX DUE TO THE COMPLETE ANNIHILATION OF THE **AQN** (AXION QUARK NUGGETS)

$$L_\odot \ (\mathrm{AQN}) \sim 4\pi b_{\mathrm{cap}}^2 \cdot v \cdot \rho_{\mathrm{DM}} \simeq 4.8 \cdot 10^{27} \cdot \frac{\mathrm{erg}}{\mathrm{s}},$$

- IT AUTOMATICALLY **COINCIDES** WITH THE TOTAL (OBSERVED) EUV ENERGY OUTPUT FROM CORONA WHICH IS HARD TO EXPLAIN IN TERMS OF CONVENTIONAL ASTROPHYSICAL SOURCES (CORONA HEATING PUZZLE)

5. Observation of "nanoflares" as evidence for AQNs (axion quark nugget) in Corona

- Few historical remarks: The term ``nanoflare'' has been introduced (postulated) by Parker in 1983 to advocate the idea that precisely these small events (below the instrumental threshold) might be responsible for the heating of the quiet solar corona.

- It turns out that many properties of these "nanoflares" **postulated** by Solar physics people to run their magnetic hydro- codes, are **automatically satisfied** if one identifies the

$$\text{nanoflares} \equiv \text{AQN annihilation events.}$$

- To reproduce the measured radiation loss in corona, the observed range of nanoflares needs to be in range $(3.7 \cdot 10^{20} - 1.3 \cdot 10^{26}) \text{ erg}$ which largely overlaps with allowed window for AQNs

$$10^{23} \leq |B| \leq 4 \cdot 10^{28}$$

- This is **highly nontrivial consistency check** as the window for |B| comes from astrophysical, cosmological, satellite and ground based constraints. It is also consistent with the axion search experiments as $B \sim R^3$ and $R \sim m_a^{-1}$

$$10^{-6}\text{eV} \leq m_a \leq 10^{-2}\text{eV}$$

- The measured uniform EUV distribution is also consistent with this proposal when nanoflares must be uniformly distributed over the solar surface

- The time measurements of nanoflares demonstrate the Doppler shift 300 km/s, far exceeds thermal velocity 11 km/s. Consistent with AQN DM velocities

- In order to reproduce the observed heating pattern of solar corona the nanoflares must have typical energies and frequency of appearance as follows (magnetic-hydro simulations)

$$\langle W \rangle \simeq 10^{23} \text{ erg}, \qquad \langle \frac{dN}{dt} \rangle \simeq (10^3 - 10^4) \text{ s}^{-1}.$$

- This <u>precisely corresponds</u> to a typical energy of the nugget $\langle B \rangle \sim 10^{25}$ and number of AQNs captured by the Sun per second.

- This proposal also naturally explains a **bizarre observed correlation** (Zioutas et all, 2016) between EUV and the "invisible streaming matter" towards the Sun due to the gravitational lensing

- **Relevant literature on solar EUV and the axion quark nugget (AQN) model:**
 1. JCAP 2017 arxiv:1707.03400, 2. arxiv:1801.01509

6. 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_{form}

- Our comment here is that $m_a \sim 10^{-4} \ eV$ contributes very little to $\Omega_{(\text{DM axion})}$ but may contribute a lot through the nugget's formation (this proposal)
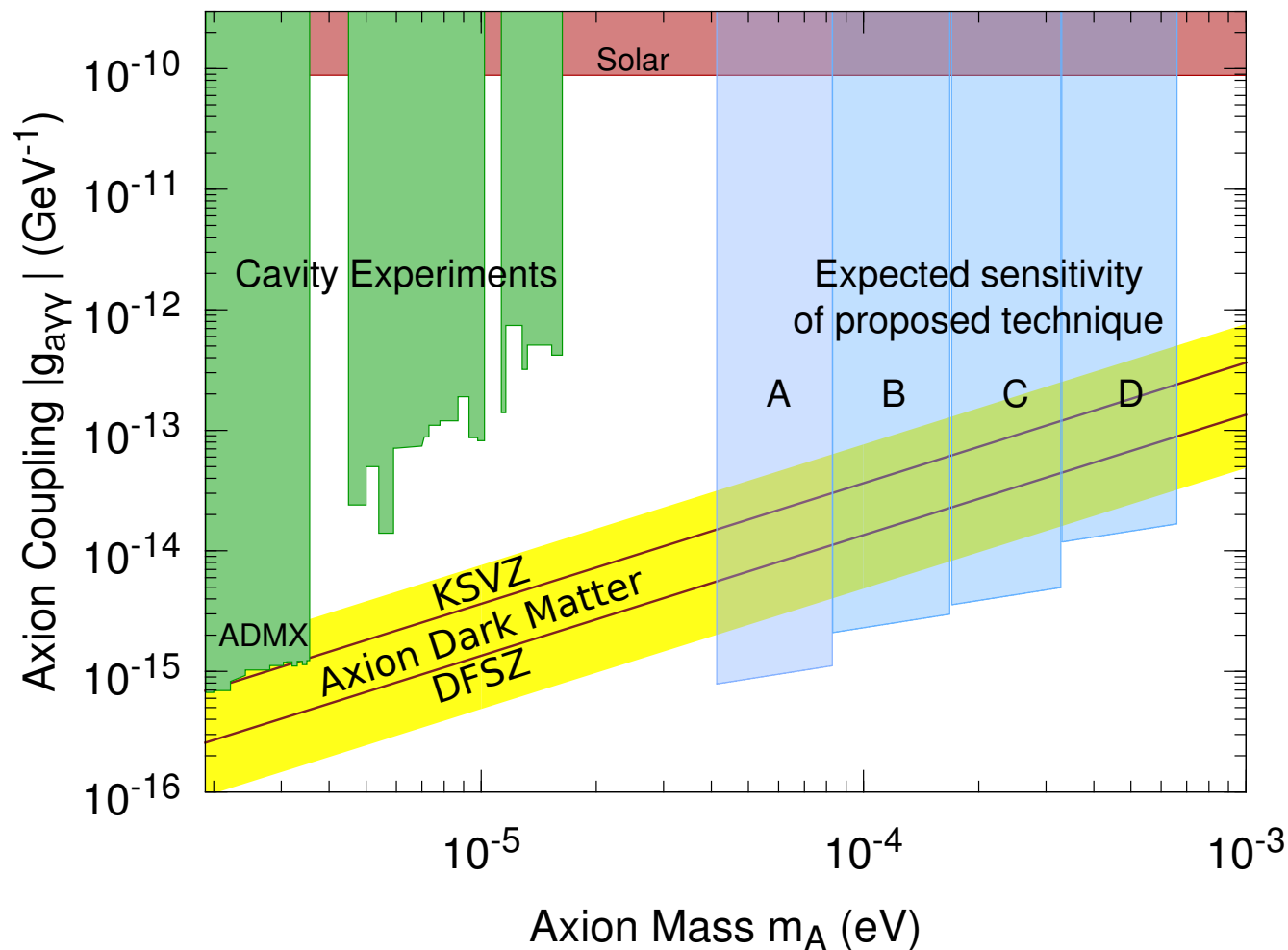
From [Rybka,2014]

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 $\langle B \rangle \sim 10^{25}$. The same region is covered by MADMAX, see [Caldwell, 2017].

Conclusion

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

- We coin this model as the axion quark nugget model (AQN)

- $\Omega_{\text{dark}} \simeq \Omega_{\text{visible}}$ is very generic consequence of this framework (no sensitivity to axion mass m_a, nor to the misalignment angle θ_{initial})

- We suggest that the solar corona heating puzzle might be related to the AQN annihilation events

- We also suggest that nanoflares postulated by Parker long ago can be identified with AQN dark matter annihilation events in the corona