Gravitationally trapped axions and quark nugget dark matter model

Ariel Zhitnitsky

University
of British Columbia,
Vancouver, Canada

This talk is based on two recent papers:

1. **1805.05184** "New mechanism producing axions and how CAST can discover them,"(collaboration with particle physics experimentalists, including **3** members from the organizing committee: **H.Fischer, Y.Semertzidis, K.Zioutas**)

2. **1905.00022** "Gravitationally trapped axions on Earth" (collaboration with astro people)

# Axion and its relation to a number of old (and apparently unrelated) Mysteries

- 1. 80-years old mystery: the nature of **dark matter** (Zwicky 1937)

- 2. another 50-years old mystery: **Baryogenesis** (Sakharov, 1967)

- 3. yet another 80- years old mystery: the so-called "**solar heating puzzle**" (W. Grotrian, 1939)

- 4. yet another old mystery: **Primordial Lithium Puzzle** (problem stays with us for at least two decades)

- 5. many others...

1. Evidence for dark matter

Expected behaviour for the velocities of stars $\longrightarrow$

$$\propto \frac{1}{\sqrt{r}}$$
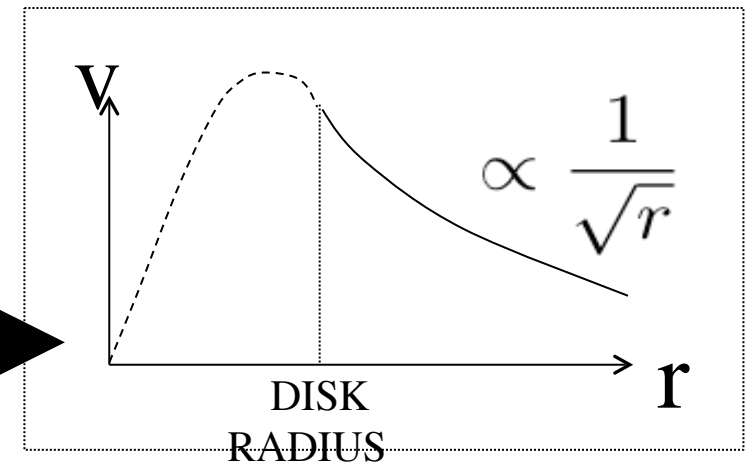
The observed velocity distribution $\longrightarrow$
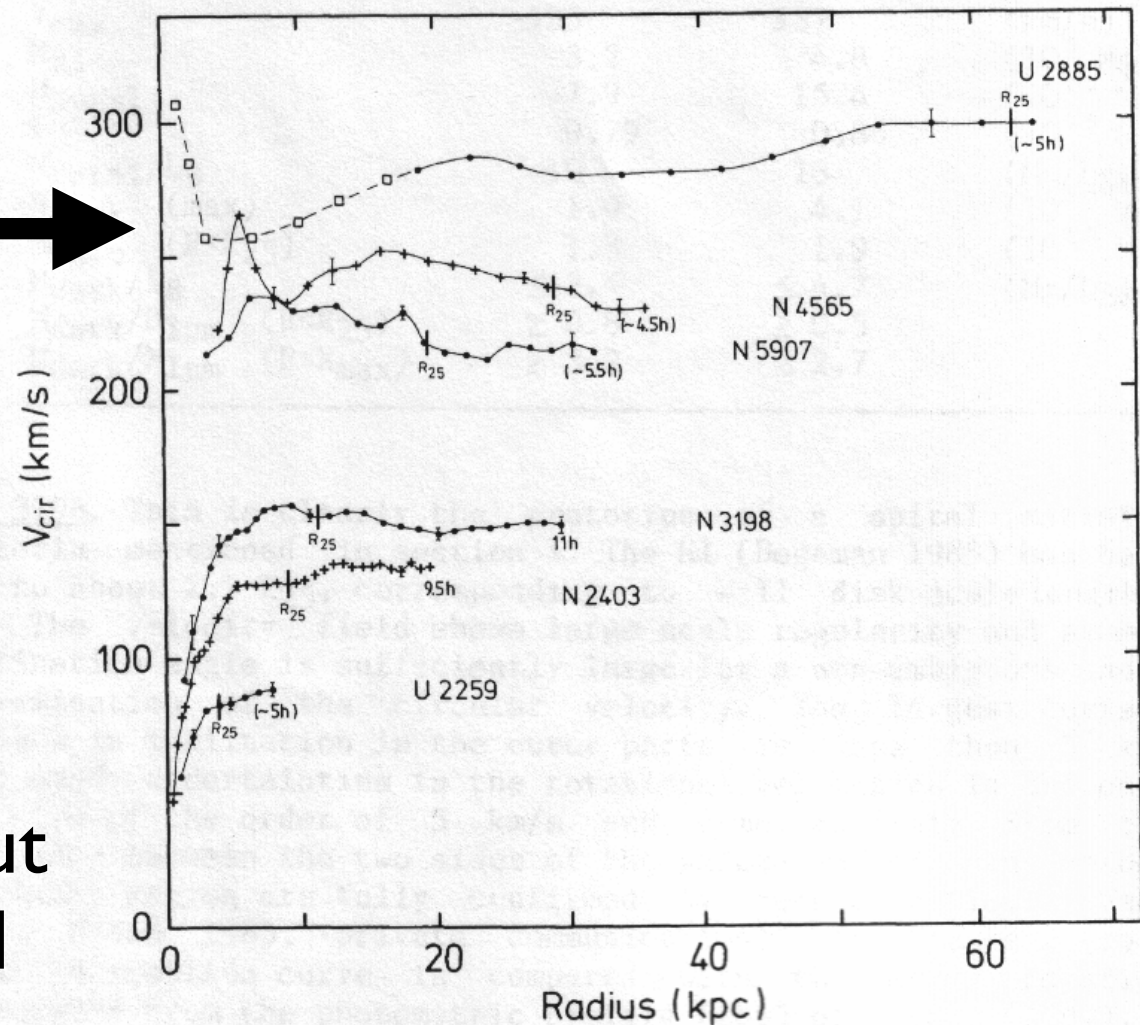
Take home lesson: there is DM in our Universe.
DM knows about gravity, but does not know about E&M
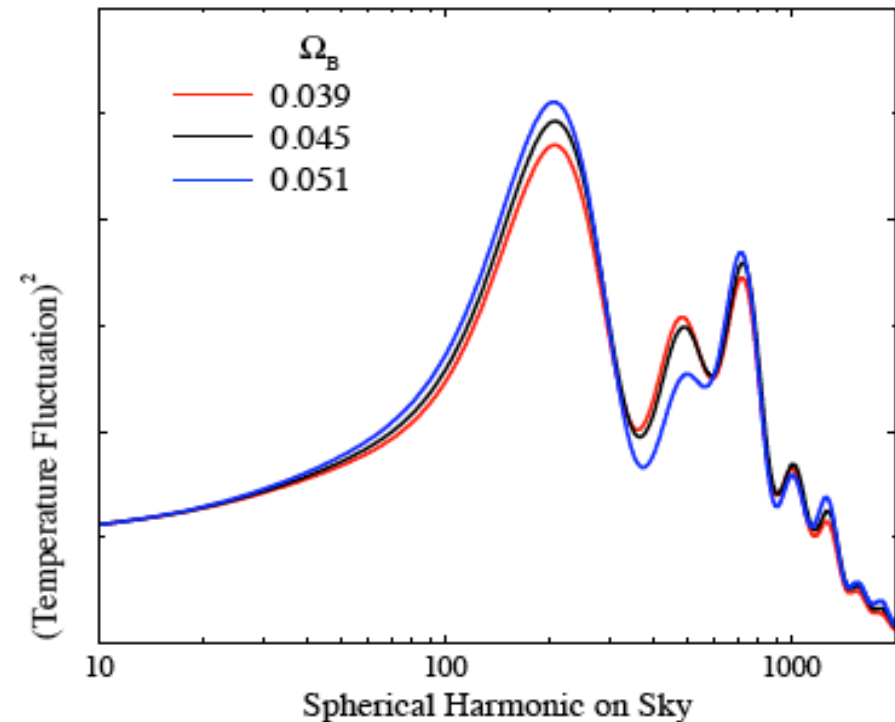
Fritz Zwicky and Vera Rubin

2. Short overview on Baryogenesis

The cosmic microwave background (CMB) and Big Bang Nucleosynthesis (BBN) are highly sensitive to parameter $\eta \equiv n_B / n_\gamma$, the baryon to photon ratio.

$$\eta \equiv \frac{n_B}{n_\gamma} \simeq 6 \cdot 10^{-10}$$

Take home lesson:
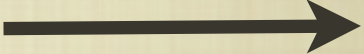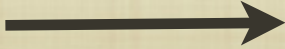the parameter η is known with very high accuracy

Sakharov

Sakharov formulated precise criteria when such baryogenesis is possible:

1. There must be B-violation;
2. There must be C and CP violation;
3. There must be out -of - equilibrium dynamics

1. First two (naively unrelated) Mysteries: Dark Matter and Baryogenesis.

- 1. "Naive" Moral: Dark matter requires New (unknown) Fields such as WIMPs

- 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 $\theta \neq 0$

- THE IDEA THAT THE DM COULD BE IN FORM OF VERY DENSE QUARK NUGGETS (QN) OF STANDARD MODEL FIELDS IS NOT NEW AND HAS BEEN ADVOCATED BY **WITTEN IN 1984**

- THE CRUCIAL (FOR COSMOLOGY) PARAMETER σ/M IS SMALL. THEREFORE, THE NUGGETS ARE QUALIFIED AS DM CANDIDATES

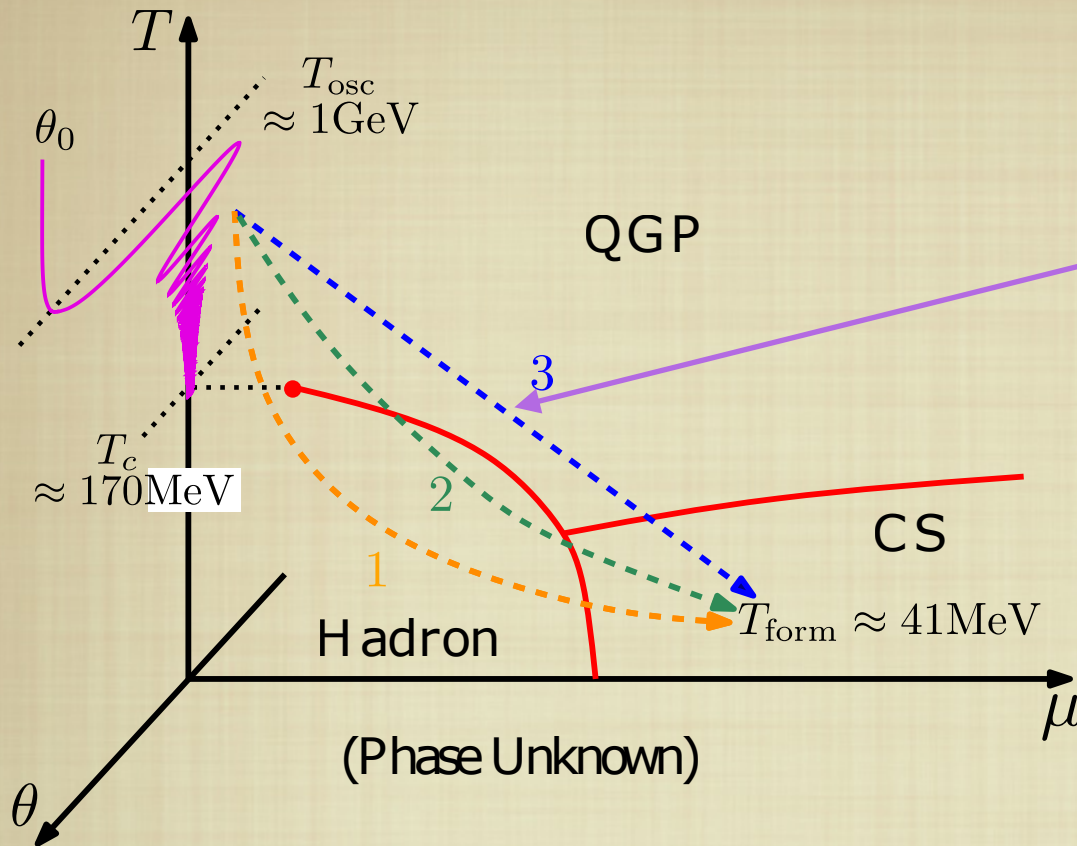$$\frac{\sigma}{M} \ll 1 \left(\frac{\mathrm{cm}^2}{\mathrm{gram}} \right)$$

E. Witten

THERE WERE MANY PROBLEMS WITH THE ORIGINAL 1984-WITTEN'S IDEA:
1. THERE IS NO FIRST ORDER PHASE TRANSITION IN QCD
2. FAST EVAPORATION
3. HARD TO ACHIEVE STABILITY
4. E.T.C.

NEW ELEMENT TO RESCUE THE NUGGET'S IDEA: **THE AXION**

Figure labels: T, θ_0, $T_{\mathrm{osc}} \approx 1\mathrm{GeV}$, QGP, 3, $T_c \approx 170\mathrm{MeV}$, 2, 1, CS, $T_{\mathrm{form}} \approx 41\mathrm{MeV}$, Hadron, μ, (Phase Unknown), θ

This is a novel contribution to DM from the axion field, in addition to conventional misalignment mechanism and DW decay

- Possible cooling paths are denoted as 1, 2, 3. The phase diagram at $\theta \neq 0$ is still unknown. Formation temp. $T = 41 \text{ MeV}$ corresponds to the observed value

$$\eta \equiv \frac{n_B - n_{\bar{B}}}{n_\gamma} \simeq \frac{n_B}{n_\gamma} \sim 10^{-10}$$

- There are 2 new elements (in comparison to Witten's)

1. THERE IS EXTRA **AXION DOMAIN WALL** PRESSURE (ACTING ON THE CLOSED AXION DW BUBBLES). IT MAKES THE NUGGETS STABLE (FIRST ORDER PHASE TRANSITION IS NOT REQUIRED, AS IN THE WITTEN'S CASE). THEY ARE ABSOLUTELY STABLE AND CAN SERVE AS DM PARTICLES.

2. THERE ARE TWO SPECIES, THE NUGGETS AND **ANTI-NUGGETS**. THE SIZE IS DETERMINED BY m_a AS $R \sim m_a^{-1}$

A SMALL GEOMETRICAL FACTOR REPLACES A CONVENTIONAL REQUIREMENT FOR A WEAK COUPLING CONSTANT. NUGGETS ARE **QUALIFIED** AS THE DM CANDIDATES:

$$\epsilon \sim S/V \sim B^{-1/3} << 1 \qquad \sigma/M \ll \ \mathrm{cm}^2/\mathrm{g}$$

COSMOLOGICAL **CP-ODD** AXION FIELD GENERATES THE **DISPARITY** BETWEEN TWO SPECIES AT $\theta \neq 0$ WHICH IMPLIES THE SIMILARITY BETWEEN **DARK AND VISIBLE** SECTORS: $\quad \Omega_{\mathrm{dark}} \approx \Omega_{\mathrm{visible}} \sim \Lambda_{\mathrm{QCD}}$

- 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

- THE AXION FIELD WITH $\theta \neq 0$ DURING THE FORMATION TIME IMPLIES THAT THE DIFFERENCE BETWEEN TOTAL BARYON CHARGE HIDDEN IN FORM OF NUGGETS AND ANTI NUGGETS IS ORDER OF ONE:

$$\Omega_{\text{dark}} \simeq \left(\frac{1+c}{1-c}\right) \Omega_{\text{visible}}, \qquad c \equiv \frac{|B_{\text{nuggets}}|}{|B_{\text{antinuggets}}|}. \quad f_a > \frac{H_I}{2\pi}$$

- BARYON CHARGE OF THE VISIBLE MATTER CAN BE EXPRESSED IN TERMS OF THIS PARAMETER $c(T) \sim 1$. IT IS ASSUMED THAT INFLATION OCCURS AFTER PQ WHEN THE SAME θ_0 OCCUPIES ENTIRE VISIBLE UNIVERSE IN WHICH CASE $c(T) \sim 1$ IS THE SAME IN THE UNIVERSE.

- IT IS VERY GENERIC AND MODEL-INDEPENDENT RESULT OF THE ENTIRE PROPOSAL WHICH HOLDS FOR ANY AXION MASS m_a AND ANY MISALIGNMENT ANGLE θ_0. IT IS THE DIRECT CONSEQUENCE OF THE THERMODYNAMICS (NO ANY FITTINGS INVOLVED!)

- $\Omega_{\text{dark}} \simeq \Omega_{\text{visible}}$ ⟵ as observed

3. The main consequences of the Axion Quark Nugget (AQN) framework

- The relation $\Omega_{\text{dark}} \sim \Omega_{\text{visible}}$ is a very generic and universal outcome of this AQN framework. The claim does not depend on the axion mass m_a nor misalignment angle θ_0.

- The "**baryogenesis**" in this framework is replaced by "**charge separation**" effect when the anti-quarks are hidden in form of the DM nuggets.

- Two (out of three) Sakharov's criteria are present in AQN framework: 1. the $\mathcal{CP}$ symmetry is broken due to the dynamics of the axion field $\theta(t)$ during the QCD time; 2. the disparity between DM nuggets and DM antinuggets is not washed out due to non-equilibrium dynamics of the axion field $\theta(t)$.
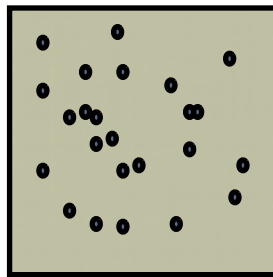
Matter in the Universe
A model which explains both the matter-antimatter asymmetry and the observed ratio of visible matter to DM

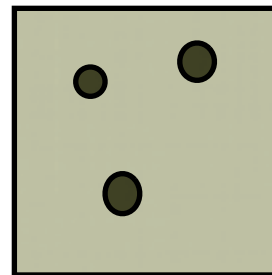$$\Omega_{\text{dark}} \sim \Omega_{\text{visible}}$$

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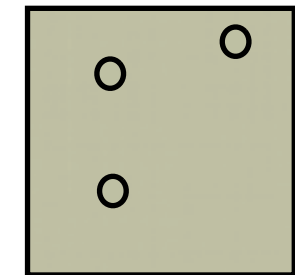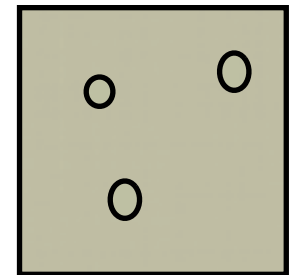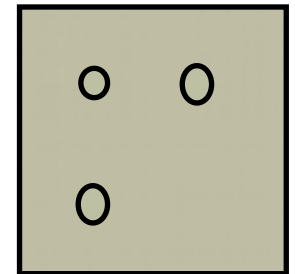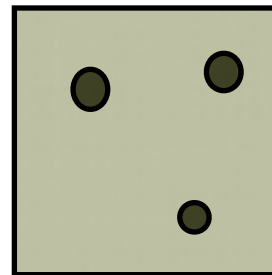
$$B_{DM} = B_{nugget} + \bar{B}_{antinugget} \simeq 5 \, B_{visible}$$

The ratio $B_{nugget}/\bar{B}_{antinaget} \simeq 2/3$ at the end of formation is determined by the sign of axion CP violating parameter θ_0

One part:
visible matter

Two parts:
matter nuggets

Three parts:
anti-matter nuggets

Recent activities on the AQN framework:

- Solar corona heating- PRD 2018 (arxiv 1805.01897) in collaboration with astro-people

- Primordial Lithium Puzzle- PRD 2019 (1811.01965) in collaboration with nuclear physics people

- New mechanism producing axions- PRD 2018 (arxiv 1805.05184), in collaboration with particle physics experimentalists (sitting in this room)

- Gravitationally trapped axions on Earth (arxiv 1905.00022) in collaboration with astro-people

4. Implication for the solar 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 $R_{\mathrm{form}} \sim 10^{-5} \mathrm{cm}$

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

- THESE HIDDEN (IN FORM OF AQNs) AXIONS ARE NOT AVAILABLE UNLESS THE NUGGETS GET DISINTEGRATED, FOR EXAMPLE IN THE SUN, OR THE EARTH'S INTERIOR

- THE AXION DW CONTRIBUTES TO THE TOTAL MASS OF THE NUGGET APPROXIMATELY 1/3 OF AQN MASS. THEREFORE, TOTAL AXION INTENSITY (FROM SUN) IS ESTIMATED AS

$$L_{\odot \text{ (axion)}} \sim \frac{1}{3} L_{\odot \text{ (AQN)}} \simeq \frac{1}{3} \cdot 10^{27} \cdot \frac{\text{erg}}{\text{s}} \qquad \langle v_a \rangle \simeq 0.6 \ c$$

- THE CORRESPONDING AXION FLUX (FROM SOLAR CORONA) MEASURED ON EARTH IS (EXPRESSED IN TERMS OF THE <u>OBSERVED</u> EUV RADIATION FROM CORONA)

$$\Phi_{\text{axions}} \sim \frac{L_{\odot \text{ (axion)}}}{4\pi \langle E_a \rangle D_{\odot}^2} \sim 0.3 \cdot 10^{17} \frac{1}{\text{cm}^2 \ \text{s}} \left(\frac{10^{-5} \text{eV}}{m_a} \right), \qquad D_{\odot} \simeq 1.5 \cdot 10^{13} \ \text{cm},$$

- IT SHOULD BE COMPARED WITH CONVENTIONAL PRIMAKOFF

$$\Phi_a(\text{Primakoff}) \simeq 3.75 \cdot 10^{11} \frac{g_{10}^2}{\text{cm}^2 \ \text{s}}, \quad g_{10} \equiv g_{a\gamma}/10^{-10} \text{GeV}^{-1}, \quad \langle E \rangle = 4.2 \ \text{keV}.$$

5. Implication for the gravitationally trapped axions on Earth.

- Annihilation of AQNs in the earth's interior inevitably produce axions which can be observed on the earth's surface.

- Some of the emitted axions will have the velocities below the escape velocity (11km/s).

- The probability of emission of these low energy axions is tiny. However, they will be accumulated during 4.5 billion of years. So, the density of these axions could be, in principle, observed.

- We use numerical Monte Carlo simulations to the study the gravitationally trapped axions on Earth

THE MAIN RESULT OF THESE SIMULATIONS IS THE ESTIMATE FOR THE AXION DENSITY AS A FUNCTION OF DISTANCE FROM THE EARTH'S CENTRE (INCLUDING $r = R_{\oplus}$)
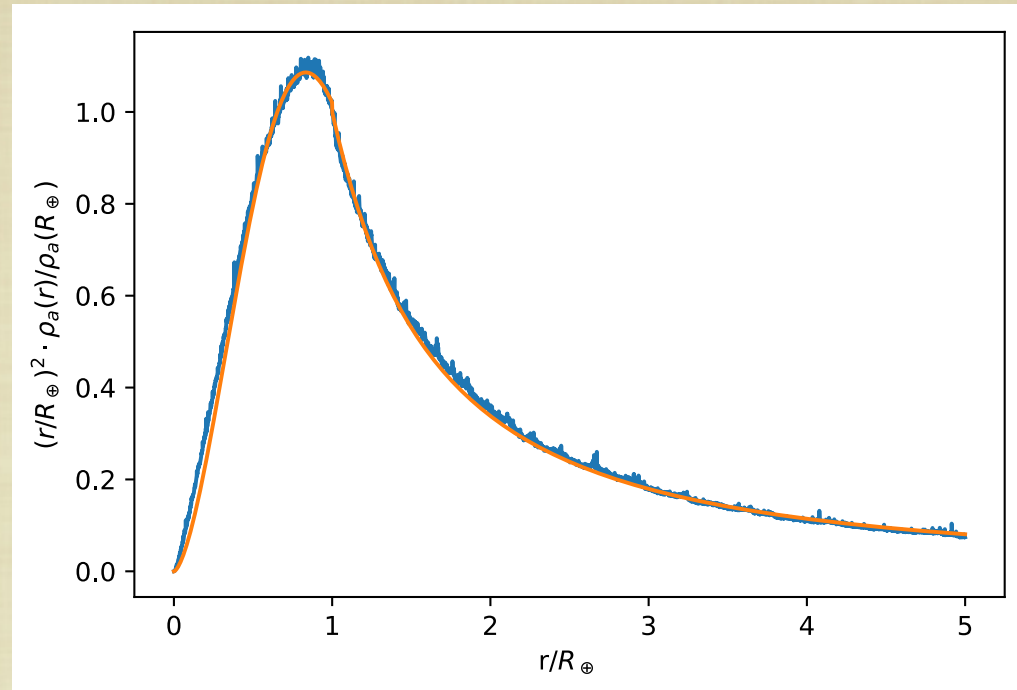
$$\rho_a(R_{\oplus}) \sim 10^{-4} \frac{\text{GeV}}{\text{cm}^3}, \quad \langle v_a(R_{\oplus}) \rangle \simeq 8 \, \frac{\text{km}}{\text{s}}.$$

THIS ESTIMATE IS VERY RIGID AND PREDICTIVE AS THERE IS NO MUCH FREEDOM TO MODIFY THE ESTIMATE WITHIN AQN FRAMEWORK (NO ANY DEPENDENCE ON m_a , OR SIZE DISTRIBUTION FOR AQNS, OR EARTH INTERIOR MODELLING)

The crucial contrast with conventional galactic axions is drastically different spectral features when $\langle v_a \rangle \simeq 8 \ \mathrm{km/s}$ instead of galactic $\langle v_a \rangle \simeq 220 \ \mathrm{km/s}$
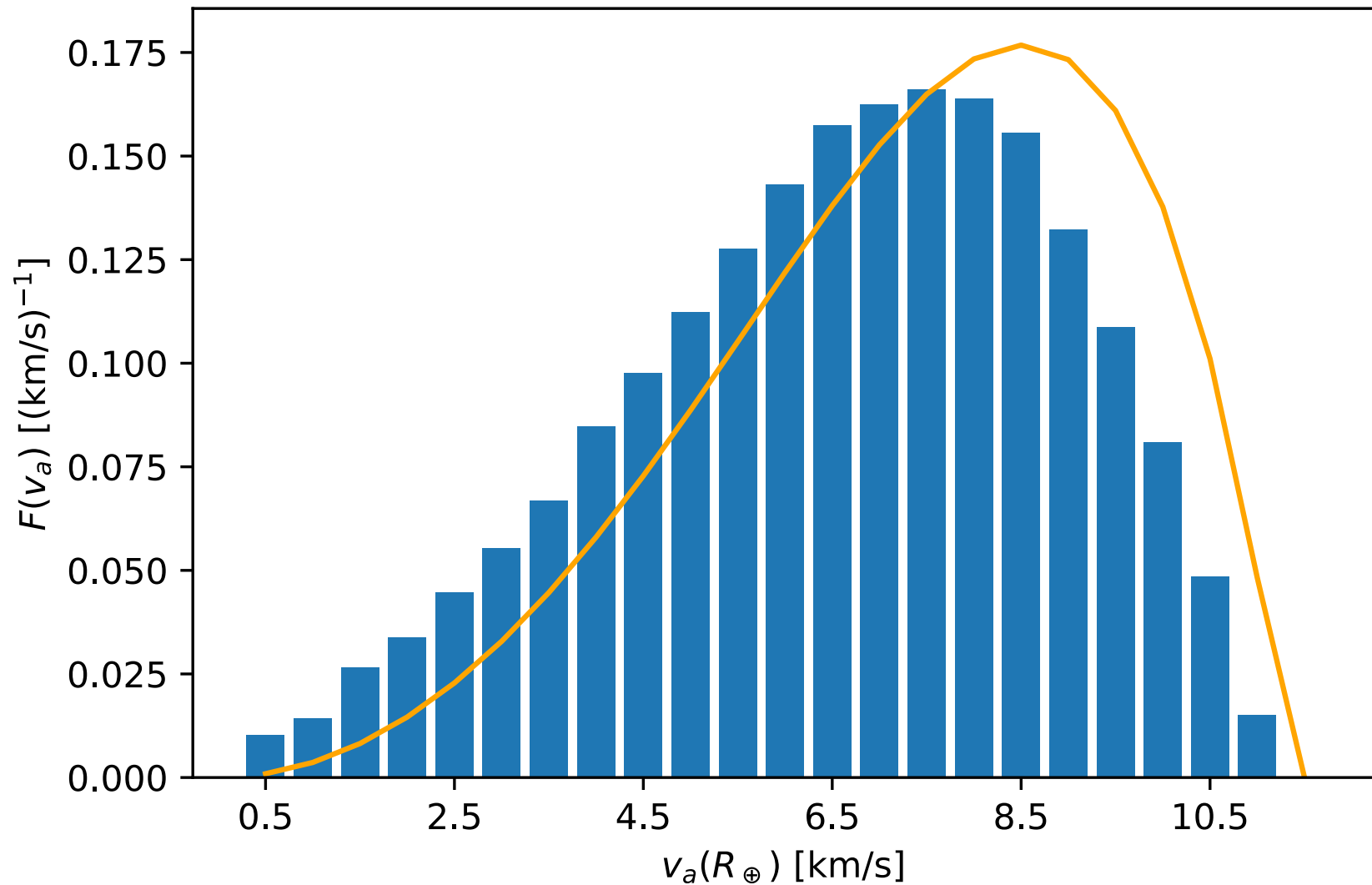
- The key feature of the system is huge the de-Broglie wavelength due to small escape velocity

$$\frac{\lambda_{\mathrm{a}}}{2\pi} \equiv \frac{\hbar}{m_{\mathrm{a}} v_{\mathrm{a}}} \simeq 50\,\mathrm{m} \left(\frac{m_{\mathrm{a}}}{10^{-4}\mathrm{eV}} \right)^{-1} \left(\frac{v_{\mathrm{a}}}{11\ \mathrm{km/s}} \right)^{-1}$$

- This key feature of gravitationally-trapped axions may be a decisive element that may drastically increase the discovery potential for these axions as a result of collecting the signal for a much longer period of time without losing the coherent features of the axion wave.

- In particular, we want to mention few ideas on combination of cavities which may drastically enhance the signal due to coherence:

  1. coupled cavity arrays (*Tobar et al, 1703.07207*),

  2. multiple cell cavity (*Semertzidis et al, 1710.06969*)

axion models :
$0.746 < |C_{a\gamma}| < 1.92$

Plot from Lawson, Millar, et al, 1904.11872
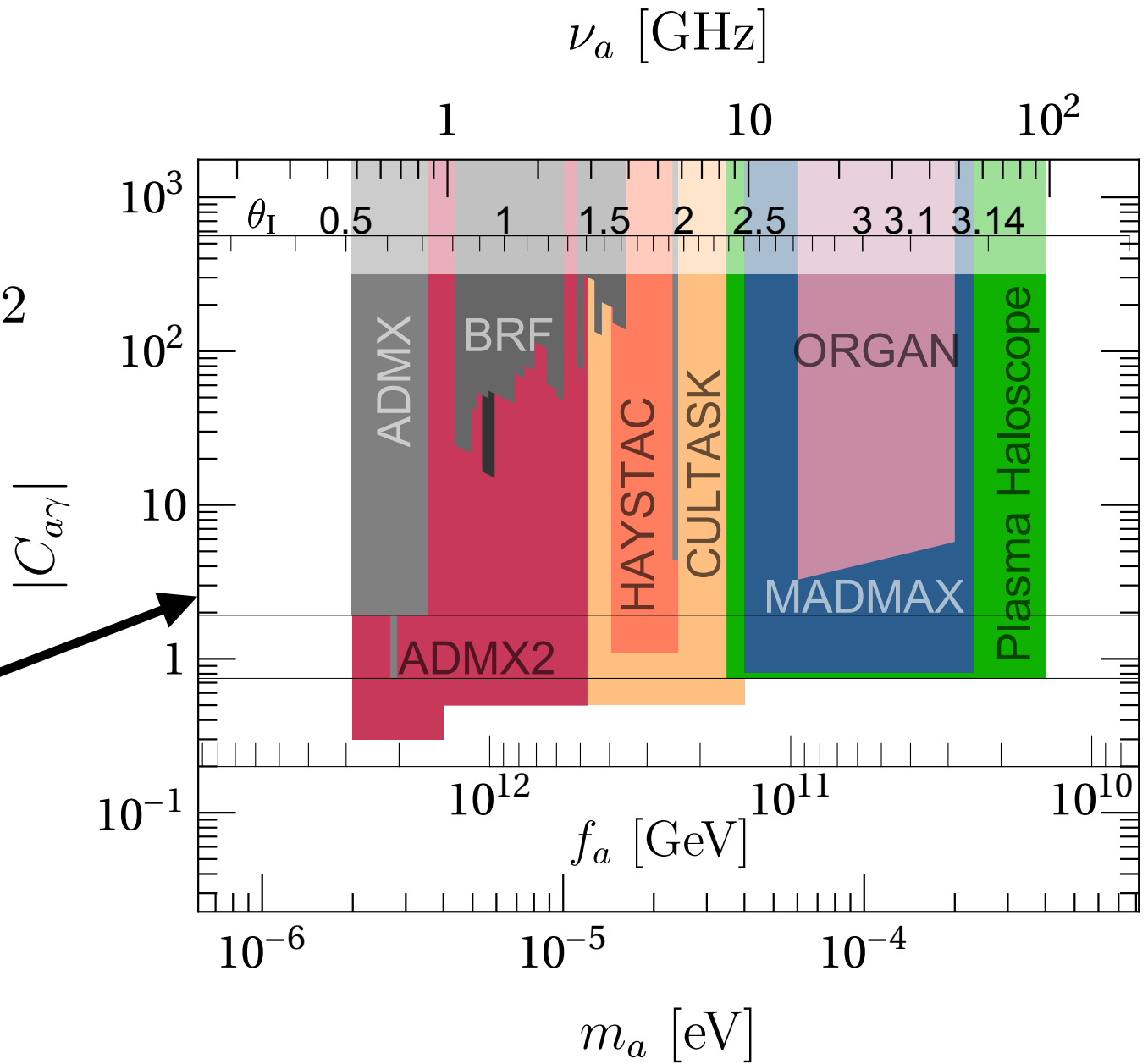
ORGAN, MADMAX, ORPHEUS, Plasma Haloscope (and other instruments) are capable to search axions with mass $m_a \sim 10^{-4} eV$ corresponding to AQNs with $\langle B \rangle \sim 10^{25}$
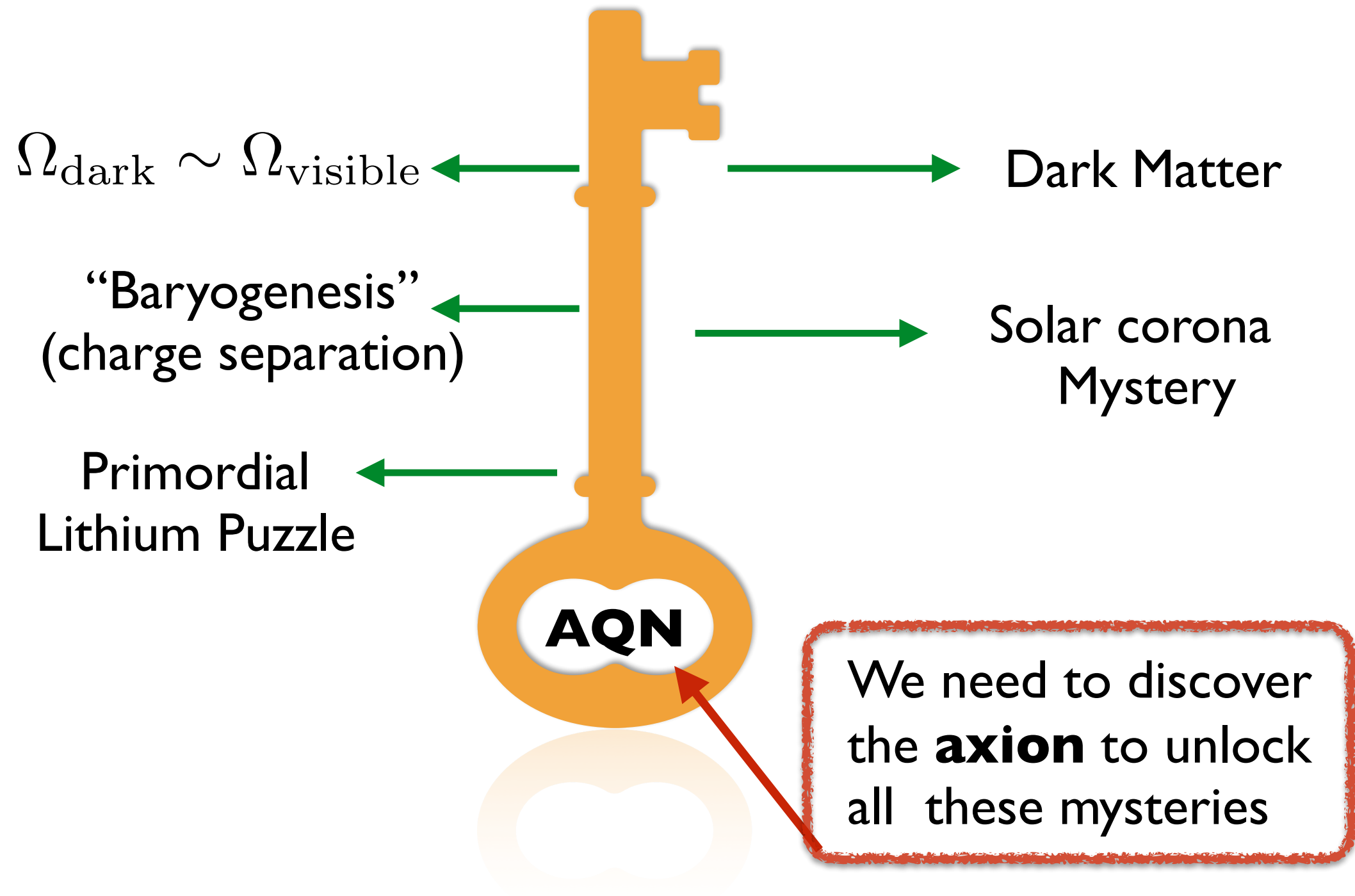
Conclusion

- " Non- baryonic Dark matter" could be ordinary baryonic matter (we know and love) which is in the exotic colour superconducting phase. We coin this model as the axion quark nugget model (AQN)

- $\Omega_{\mathrm{dark}} \sim \Omega_{\mathrm{visible}}$ is very generic consequence of this framework (no sensitivity to axion mass m_a, nor to the misalignment angle $\theta_{\mathrm{initial}}$). It is the direct consequence of the framework when the dark matter and visible components are proportional to one and the same fundamental Λ_{QCD} scale.

- This model offers a simultaneous resolution of a number (naively unrelated) old mysteries: DM, baryogenesis, solar corona mystery, primordial Lithium to name just a few

- The axions will be inevitably produced each time when the annihilation event happens because the axion field plays a key role in construction of the AQNs (plays role of a squeezer). The typical axions have the velocities $v_a \simeq 0.6\,c$.

- However, a tiny portion of the non-relativistic axions can be trapped by the earth gravity. These axions will be accumulated during 4.5 billion years.

- Their discovery will be **DIRECT** manifestation of the AQN framework (in contrast with **INDIRECT** observations such as Baryogenesis, Lithium puzzle, solar corona mystery, diffuse x-rays, galactic 511 keV, etc)

$\Omega_{\text{dark}} \sim \Omega_{\text{visible}}$ $\longleftarrow$ $\longrightarrow$ Dark Matter

"Baryogenesis"
(charge separation) $\longleftarrow$

$\longrightarrow$ Solar corona
Mystery

Primordial
Lithium Puzzle $\longleftarrow$

AQN

We need to discover
the **axion** to unlock
all these mysteries

EXTRA MATERIAL: AQN 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:

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

- BARYON CHARGE OF THE VISIBLE MATTER IS EXPRESSED IN TERMS OF THIS PARAMETER $c(T) \sim 1$ AS THE TOTAL BARYON CHARGE IS ZERO:

$$B_{\text{tot}} = B_{\text{baryons}} + B_{\text{antibaryons}} + B_{\text{nuggets}} + B_{\text{antinuggets}} = 0$$

- This relation leads to the basic consequence of the proposal
$$\Omega_{\mathrm{dark}} \simeq \Omega_{\mathrm{visible}} \sim \Lambda_{\mathrm{QCD}}$$

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

- It is assumed that inflation occurs after PQ when the same θ_0 occupies entire visible Universe in which case $c < 1$ is the same in the Universe.
$$f_a > \frac{H_I}{2\pi}$$

- For $c \simeq 2/3 \Rightarrow \Omega_{\mathrm{dark}} \simeq 5\,\Omega_{\mathrm{visible}}$ the nuggets saturate the present DM density

- **Refs. on the AQN formation mechanism and survival pattern during the evolution:**

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

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

- **Relation between PQ and Inflationary scales; relation between AQNs and conventional axion contributions to DM- PRD 2018 (arxiv 1711.06271)**

- **AQN: size distribution and survival pattern, (arxiv 1903.05090)**