Cosmological axion field and quark nugget dark matter model

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This talk is based on two very recent (May 2018) preprints:

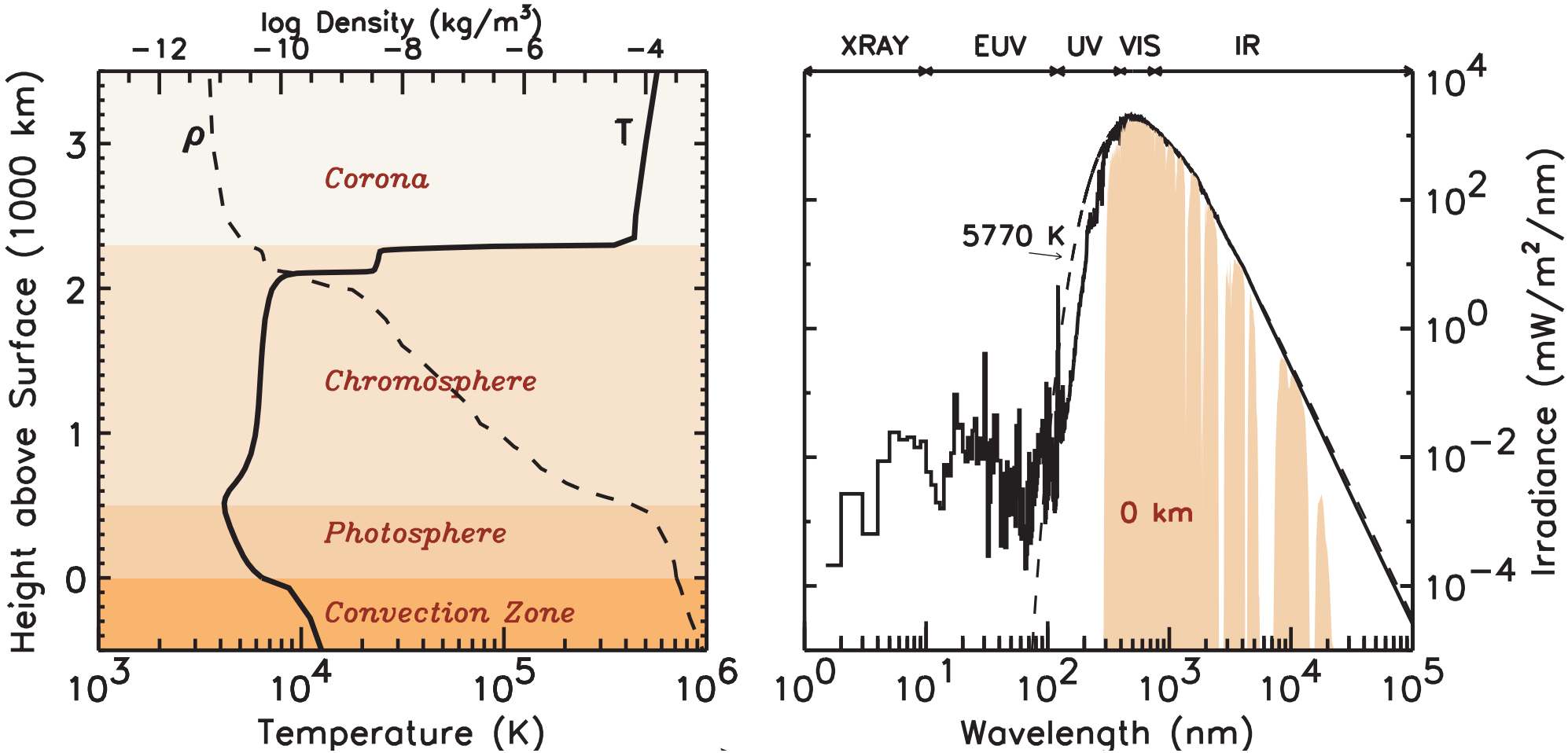
1. **N.Raza, L.van Waerbeke and AZ,**1805.01897 "Solar Corona Heating by the Axion Quark Nugget Dark Matter,"(collaboration with astronomers)

2.**H.Fischer, X.Liang, Y.Semertzidis, AZ and K.Zioutas,** 1805.05184
"New mechanism producing axions and how CAST can discover them,"(collaboration with particle physics experimentalists)

There is one term in common, the "**axion**" which is key element in both preprints and the subject of this talk.

Axion and its relation to three very 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)
- I want to offer a new unified (unorthodox) framework where all these, naively unrelated, phenomena could be intimately connected and originated from one and the same physics. **Axion** will play the key role in linking these phenomena.



Left: the temperature distribution in outer Sun: the drastic changes occur in vicinity of 2000km. The transition region is about 100 km wide.

Right: the unexpected deviation from the thermal distribution in EUV and soft x rays from corona

Solar extreme UV (EUV) radiation

- The quiet Sun emits EUV radiation with the energy of order 100 eV which cannot be explained in terms of any conventional astro-phenomena.

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

- Apparent violation of thermodynamics. Can be only resolved with non-thermal injection of energy that heats up the corona. The EUV emission occurs about 2000 km above the surface where the temperature suddenly jumps: $T \simeq 10^4\ K \Rightarrow T \simeq 10^6\ K$

- "everything above the photosphere (about 10^{-6} of the total solar luminosity) is not supposed to be there at all" (*Solar Corona Mystery, 1939*)

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" ⟶ "New phases" (dense colour superconductor) of "Old Fields"

- Instead of "Baryogenesis" ⟶ "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

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

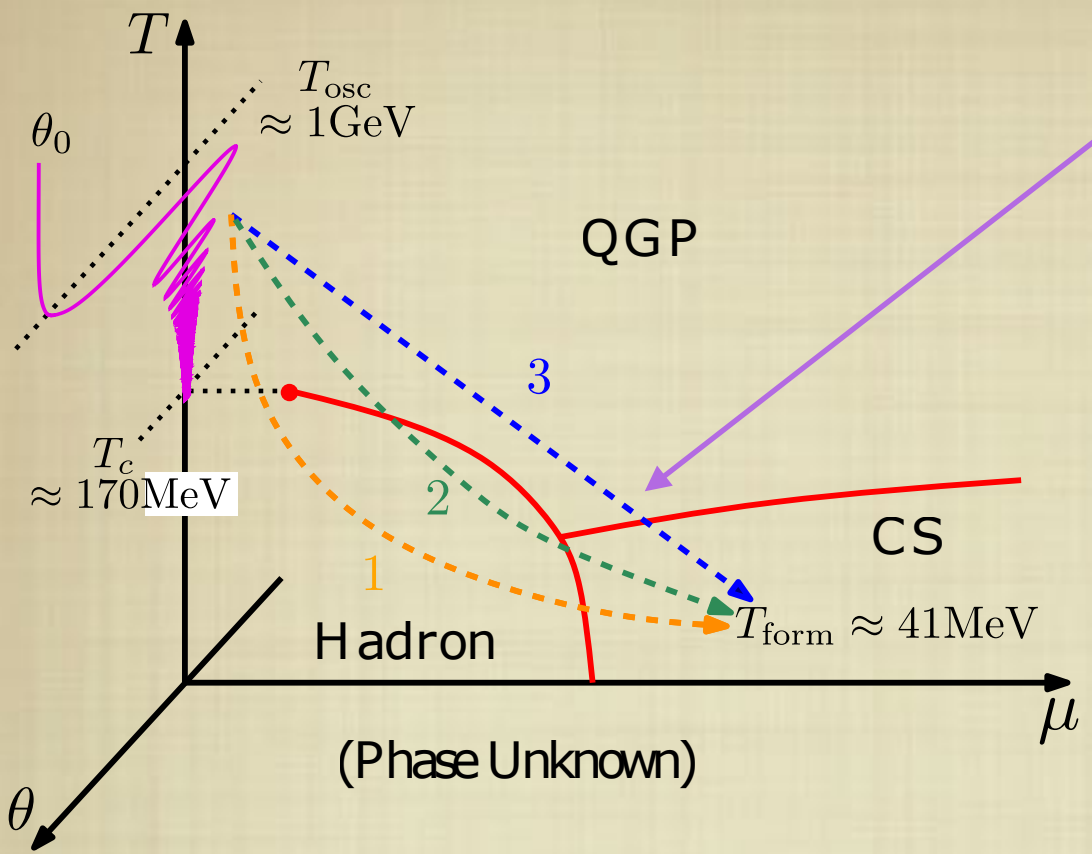
E. Witten

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**

2.Axion field stabilizes the quark nuggets



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. $T = 41$ MeV corresponds to the observed value

- There are 2 new elements (in comparison with 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: $\Omega_{\mathrm{dark}} \approx \Omega_{\mathrm{visible}} \sim \Lambda_{\mathrm{QCD}}$

- 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:

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

- 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 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!)

- $\Omega_{\rm dark} \simeq \Omega_{\rm visible}$ ← as observed

3. The main lessons of the framework

- The relation $\Omega_{\rm dark} \simeq \Omega_{\rm visible}$ is a very natural and universal outcome of this framework. This claim holds in entire visible Universe as inflation occurs after PQ: $H_I < f_{PQ}$. The claim is not sensitive to specific details of the system (thermodynamics does the job)

- 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 our 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

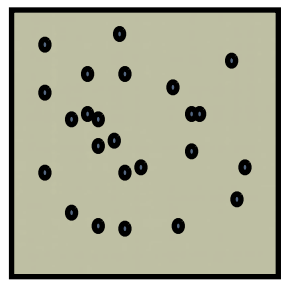
A model which explains both the matter-antimatter asymmetry and the observed ratio of visible matter to DM

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

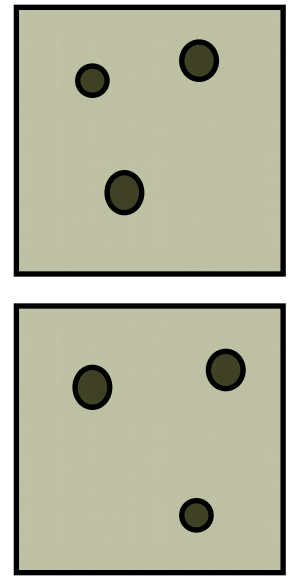
$$B_{tot} = 0 = B_{nugget} + B_{visible} - \bar{B}_{antinugget}$$

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

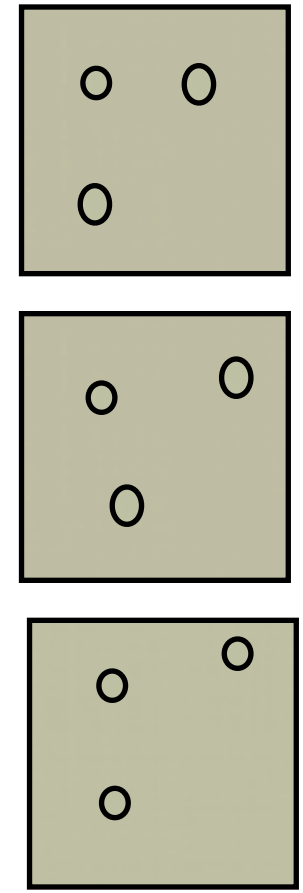
The ratio $B_{nugget}/\bar{B}_{antinaget} \simeq 2/3$ *at the end of formation is determined by the sign of axion CP violating parameter* θ_0



One part: visible matter



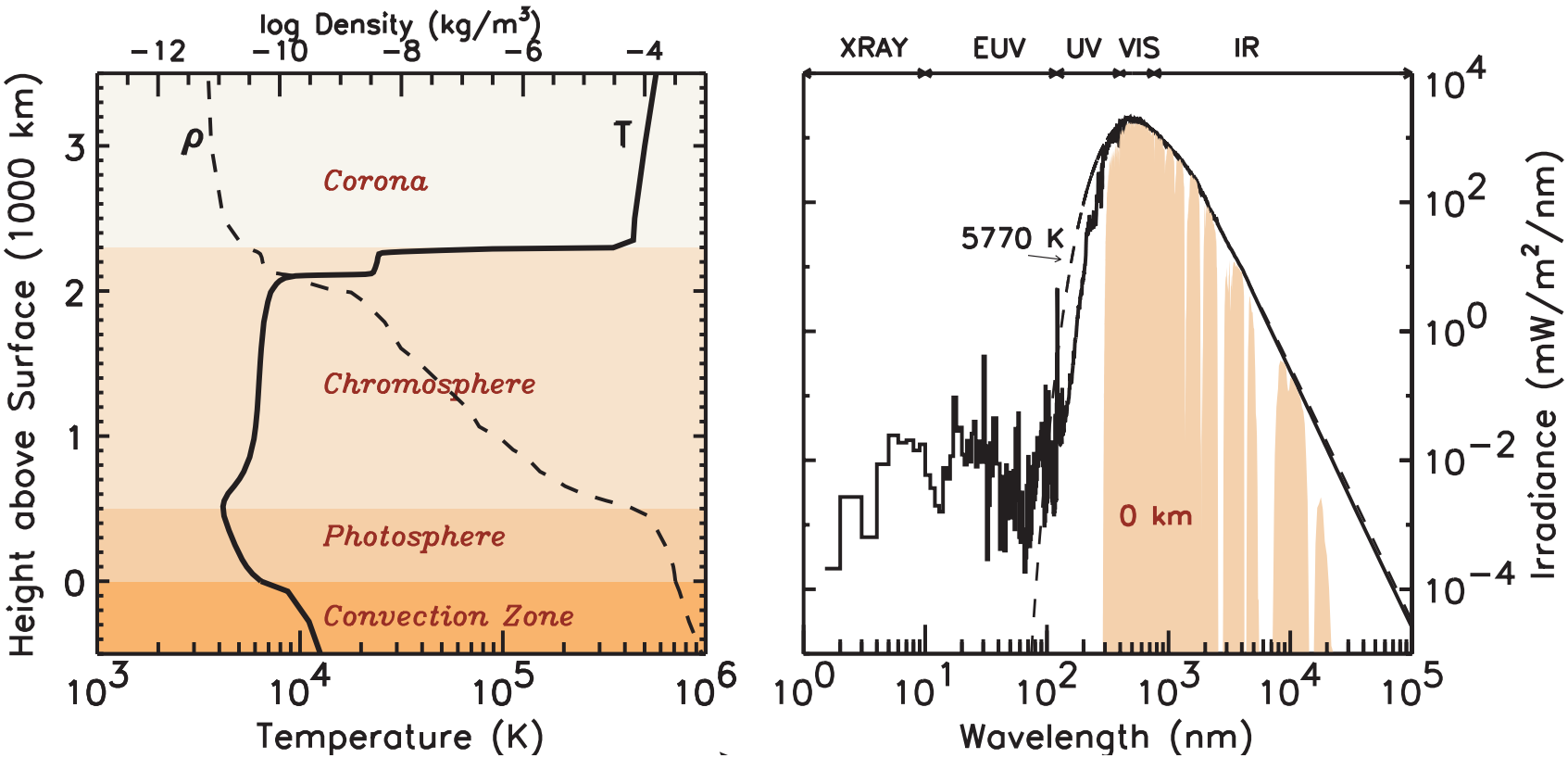
Two parts: matter nuggets



Three parts: anti-matter nuggets

4. Application to the " solar corona mystery"

(project started at PATRAS-2017 motivated by discussions with Konstantin Z.)



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

- **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

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

- the total energy flux due to the complete annihilation of the **AQN** (axion quark nuggets) is estimated as

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

- It nicely **coincides** with the total (observed) EUV energy output from corona which is hard to explain in terms of conventional astrophysical sources (corona heating puzzle)

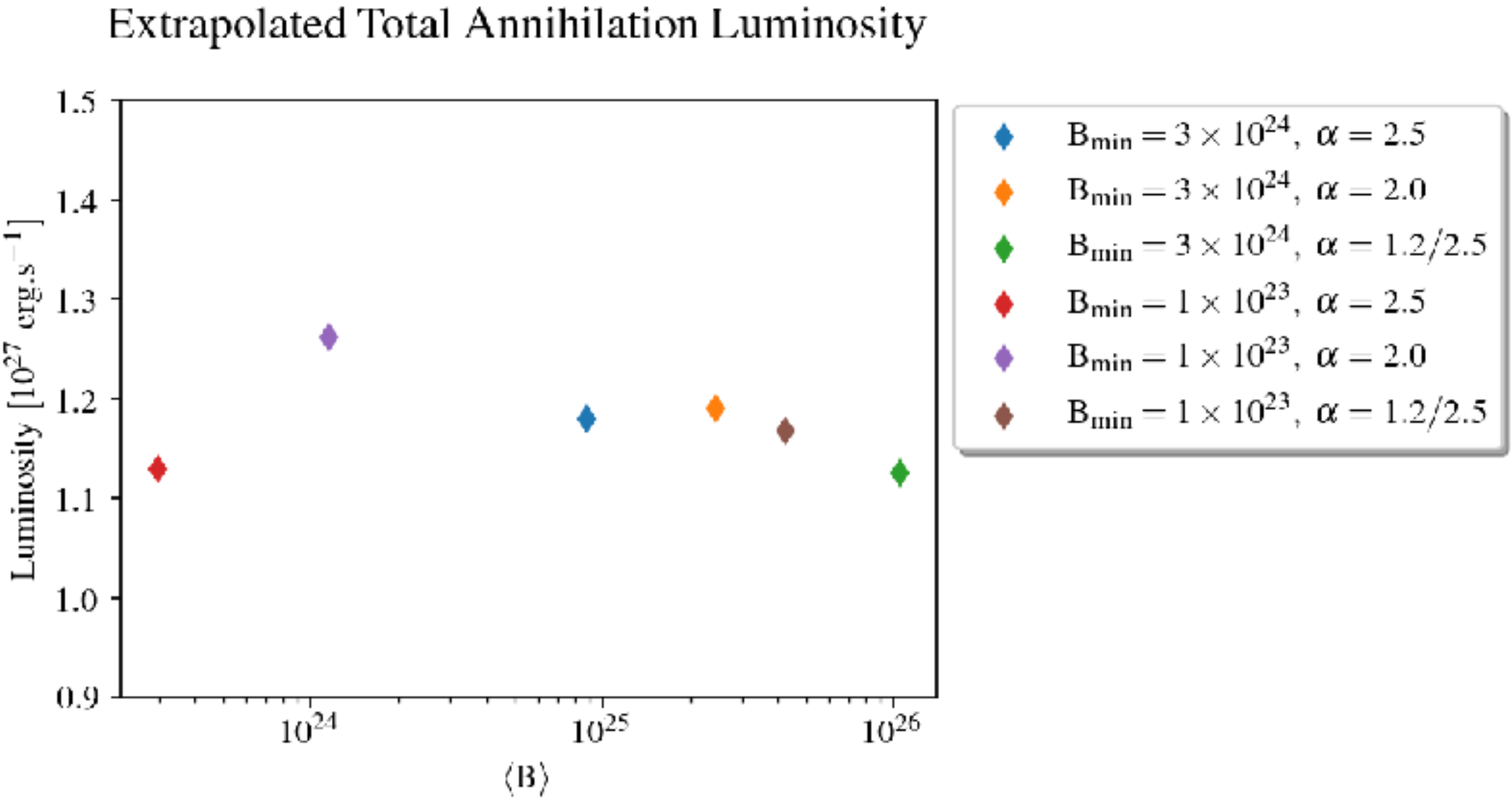
- These order of magnitude estimates have been confirmed by recent Monte Carlo (MC) simulations, see arxiv:1805.01897

- It was generated 10^{10} sample particles distributed over 10 AU in distance

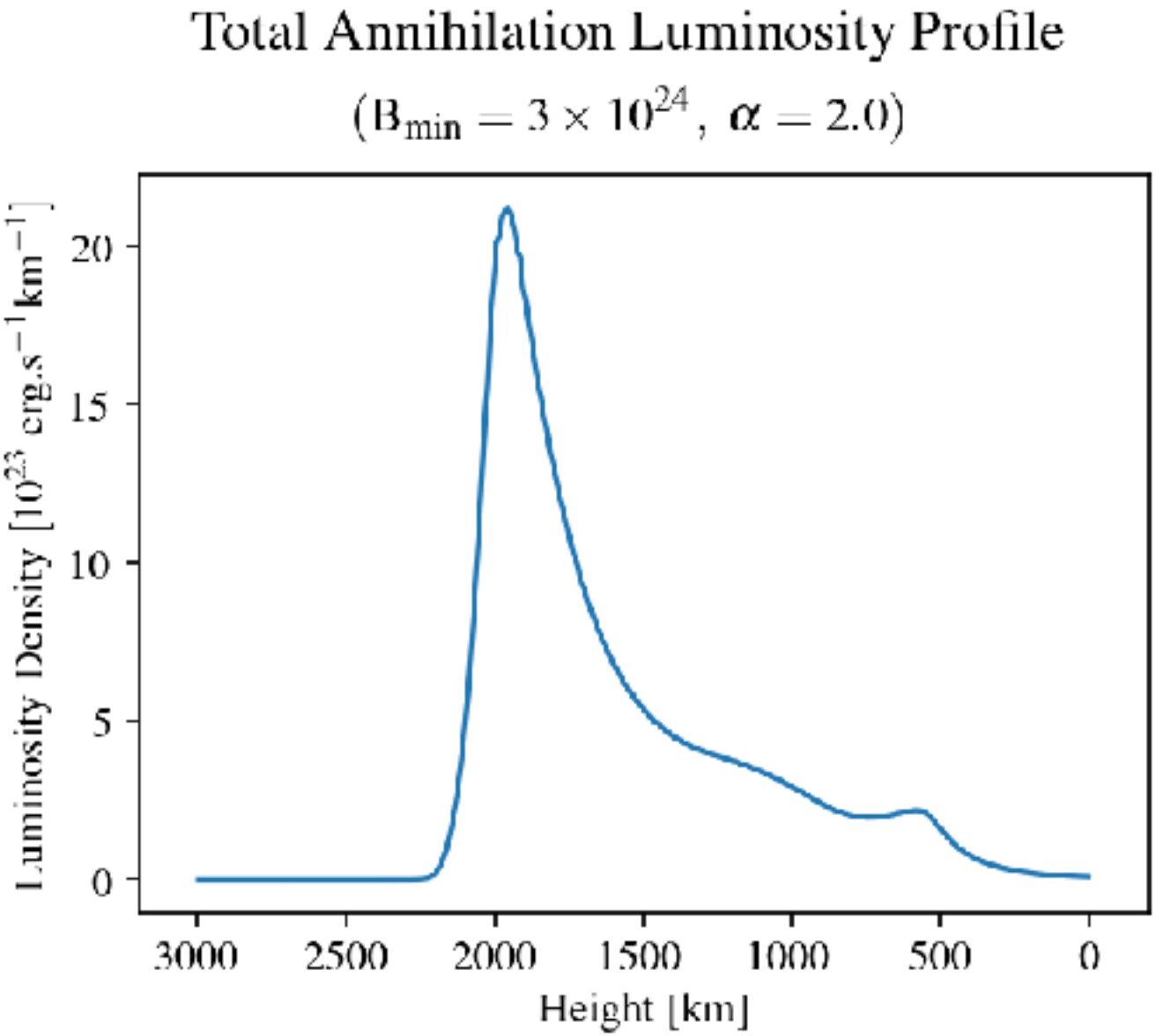
$$f_{\mathbf{v}}(v_x, v_y, v_z) \sim \exp\left[-\frac{(v_x - v_\odot)^2 + v_y^2 + v_z^2}{2\sigma_{v_i}^2}\right], \quad V_\odot \simeq 220 \text{ km/s}$$

- Only 3.6×10^4 particles are captured by the Sun. This rate is determined by Newton Gravity and DM density $\rho_{\rm DM}$

- The typical time for impact ~ 1 month



The total luminosity due to the annihilation events of the AQNs with the solar material is precisely $\sim 10^{27}\mathrm{erg/s}$. This intensity is determined by the DM density ρ_{DM} , and it is not sensitive to any other parameters of the model.



The AQNs start to annihilate at the altitude ~2000km, where the drastic changes are known to occur in vicinity of the Transition Region

5. 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)

- These hidden (in form of AQNs) axions are not available unless the nuggets completely disintegrated, for example in the Sun

- 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

$$L_{\odot\ (\mathrm{axion})} \sim \frac{1}{3} L_{\odot\ (\mathrm{AQN})} \simeq \frac{1}{3} \cdot 10^{27} \cdot \frac{\mathrm{erg}}{\mathrm{s}}$$

- The corresponding axion flux (from solar axions) measured on Earth is

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

- It should be compared with conventional Primakoff

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

- The difference with conventional case is that the axions emitted from AQNs have typical relativistic velocities with $\langle E \rangle = 1.1\, m_a$, not $E \sim 4$ keV

- Therefore, the energy fluxes are different

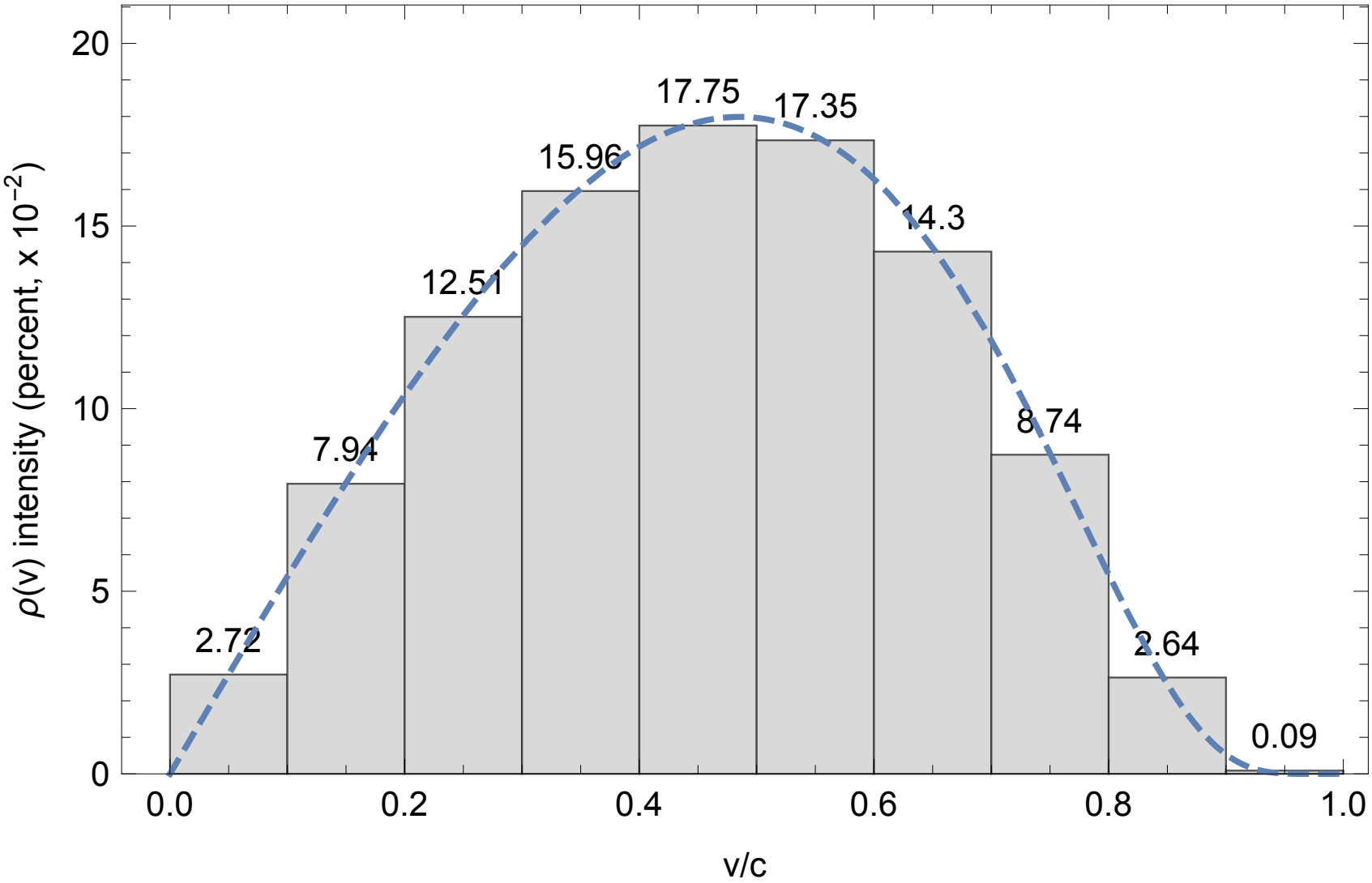
$$m_a \Phi_{\rm axions} \sim 0.3 \cdot 10^{12} \frac{eV}{\rm cm^2\ s}, \qquad \langle E \rangle \Phi_a({\rm Primakoff}) \sim {\rm g}_{10}^2 \cdot 10^{15} \frac{\rm eV}{\rm cm^2\ s}.$$

- The emission of the axions from AQNs from deep Earth's underground is

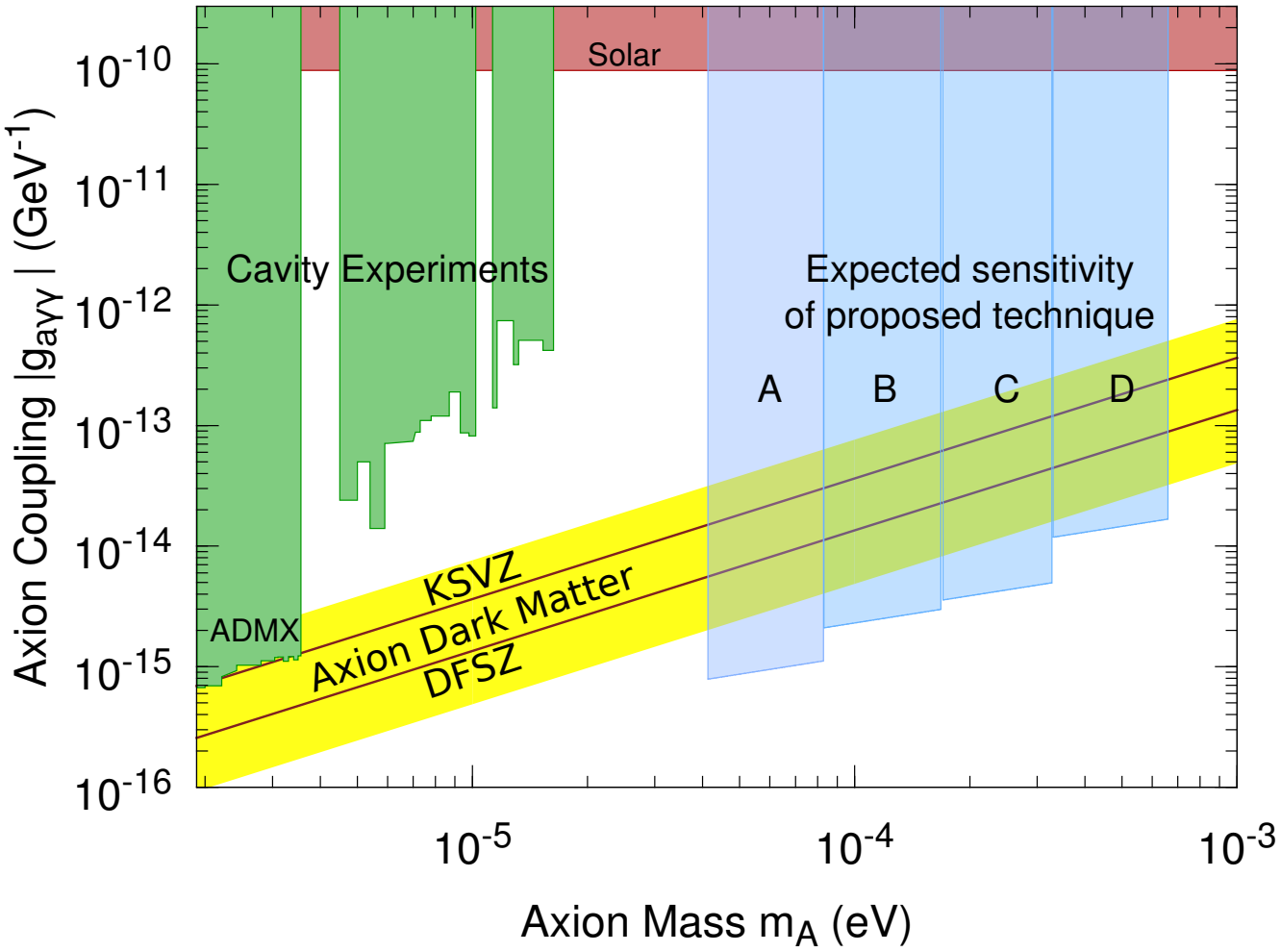
$$m_a \Phi({\rm Earth\ axions}) \sim 10^{16} \cdot \left(\frac{\Delta B}{B} \right) \frac{\rm eV}{\rm cm^2\ s} \quad \text{where} \quad \frac{\Delta B}{B} \sim (0.1 - 1)$$

- it should be compared with galactic axion flux

$$m_a \Phi({\rm galactic\ axions}) \sim \rho_{\rm DM} \cdot v_{\rm DM} \simeq \frac{0.3\ {\rm GeV}}{\rm cm^3} v_{\rm DM} \simeq 10^{16} \frac{eV}{\rm cm^2\ s}.$$



The axion velocity distribution emitted by the nuggets during the AQN annihilation events in the Sun. The velocities are relativistic, but not ultra-relativistic.



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 [Caldwell, 2017] .

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)

- $\Omega_{\rm dark} \simeq \Omega_{\rm visible}$ is very generic consequence of this framework (no sensitivity to axion mass m_a , nor to the misalignment angle $\theta_{\rm initial}$). It is the direct consequence of the thermodynamics.

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

- We also suggest that the axions from AQNs can be studied by conventional instruments as $v \sim 0.5\ c$ in contrast with DM galactic axions with $v \sim 10^{-3} c$