

Cosmological axion field and quark nugget dark matter model

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

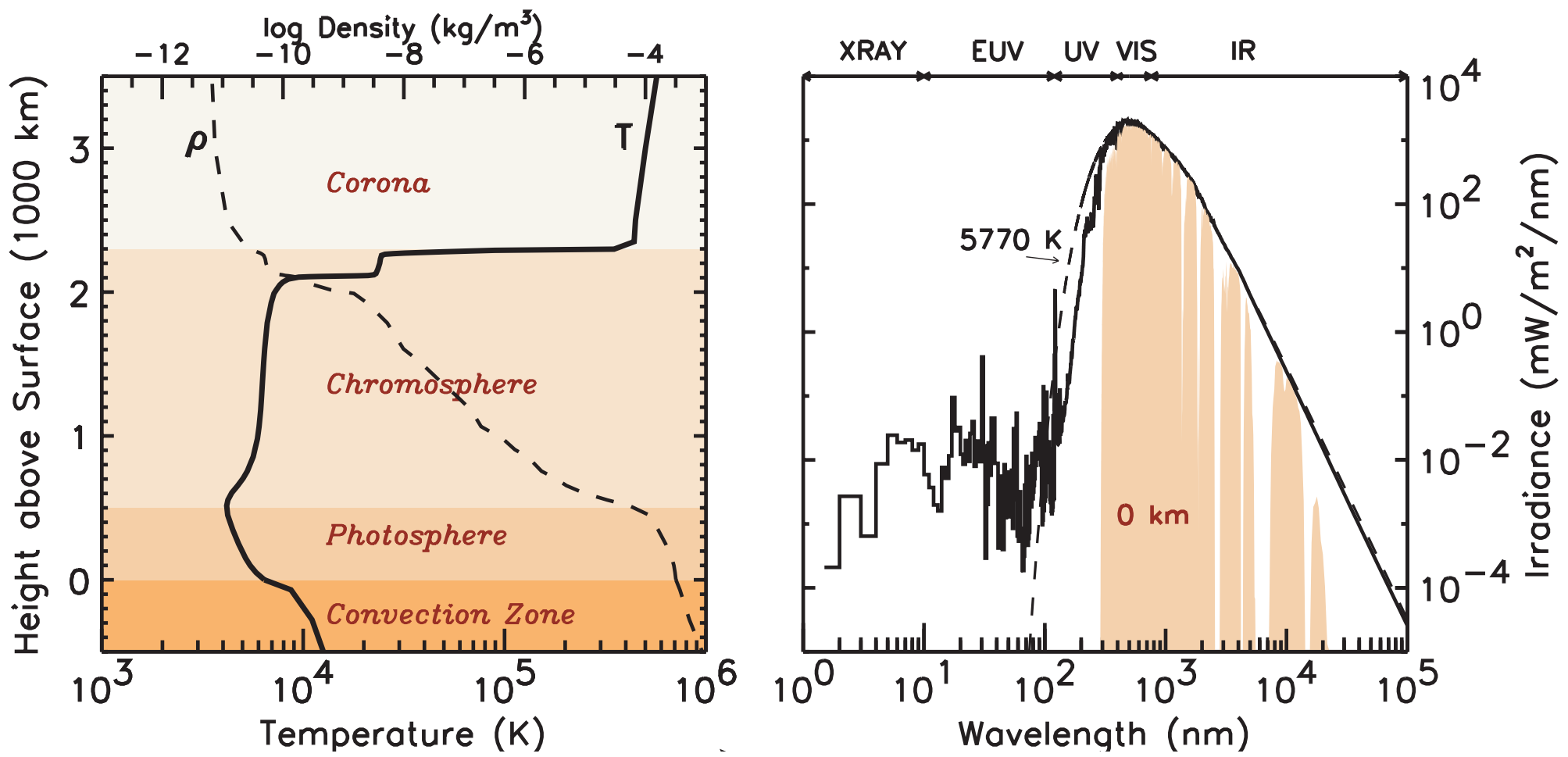
1. **N.Raza, L.van Waerbeke and AZ**, 1805.01897
"Solar Corona Heating by the Axion Quark Nugget
Dark Matter," (collaboration with astronomers)

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)**



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:

$$T \simeq 10^4 \text{ K} \Rightarrow T \simeq 10^6 \text{ K}$$

■ “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
- 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 (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)

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

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

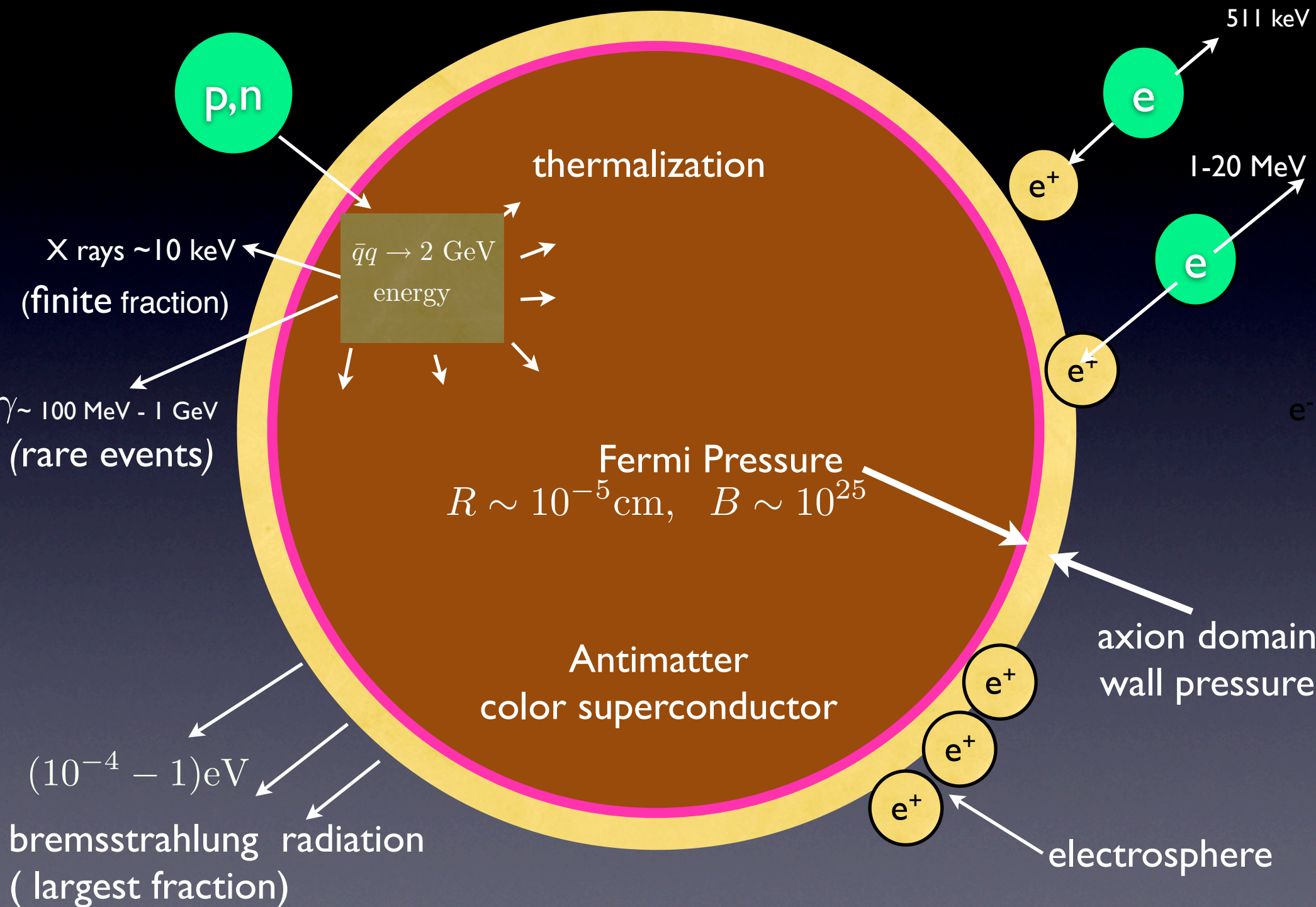
■ A SMALL GEOMETRICAL FACTOR REPLACES A WEAK COUPLING CONSTANT. NUGGETS ARE QUALIFIED AS THE DM CANDIDATES:

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

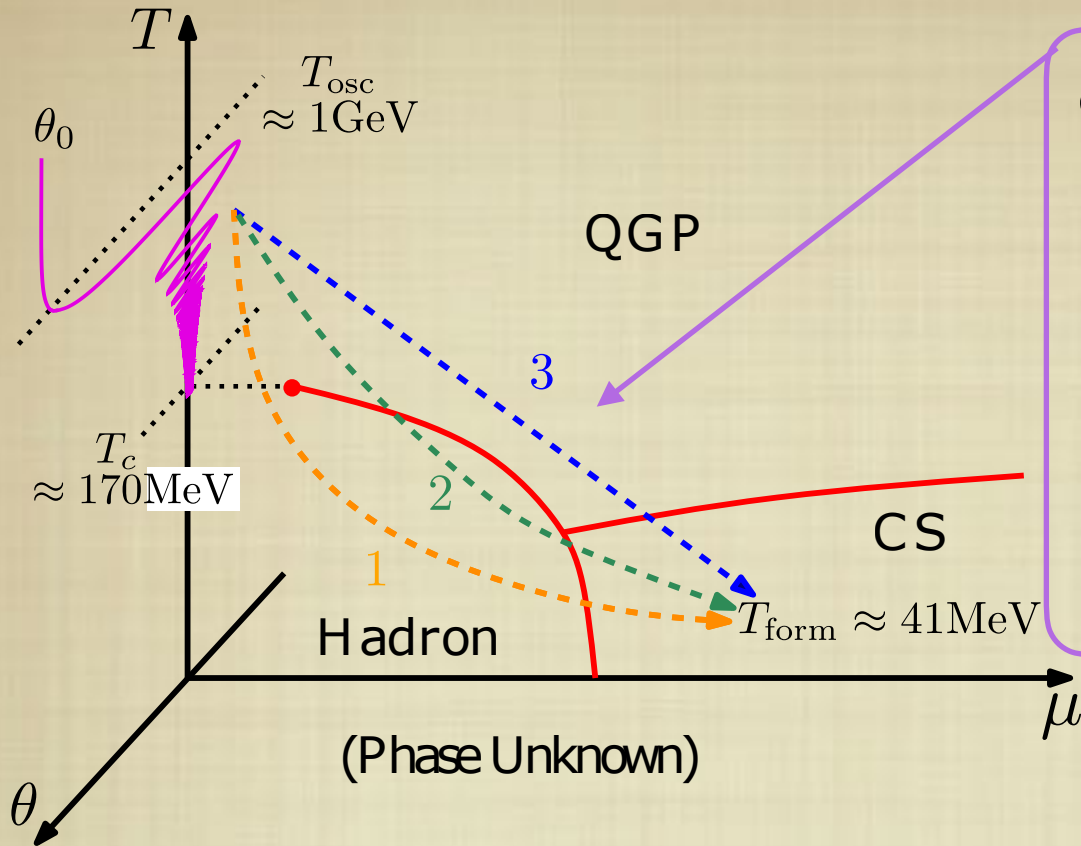
■ COSMOLOGICAL CP-ODD AXION FIELD GENERATES THE DISPARITY BETWEEN TWO SPECIES AT $\theta \neq 0$ WHICH IMPLIES THE SIMILARITY BETWEEN DARK AND VISIBLE

SECTORS: $\Omega_{\text{dark}} \approx \Omega_{\text{visible}} \sim \Lambda_{\text{QCD}}$

Antiquark nugget structure. Source of emission



2. FORMATION MECHANISM



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 TEMPERATURE (BELOW THE CS PHASE TRANSITION) CORRESPONDS TO THE OBSERVED VALUE

■ NUGGETS COMPLETE THE FORMATION AT $T_{\text{form}} \simeq 41 \text{ MeV}$.

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)**

■ THERE ARE MANY NONTRIVIAL SETTLE POINTS RELATED TO THE FORMATION MECHANISM. I WANT TO MENTION JUST TWO KEY INGREDIENTS WHICH ARE IMPORTANT FOR THIS PRESENTATION

■ **1- INGREDIENT:** THE PRESENCE OF THE AXION DOMAIN WALLS $N=1$ WHEN θ INTERPOLATES BETWEEN ONE AND THE SAME VACUUM STATE: $\theta \rightarrow \theta + 2\pi n$. THE AXION DOMAIN WALLS IN GENERAL, DEMONSTRATE A SANDWICH-LIKE SUBSTRUCTURE ON THE QCD SCALE Λ_{QCD}^{-1}

■ IT IS NORMALLY ASSUMED THAT THE TOPOLOGICAL DEFECTS (SUCH AS THE DOMAIN WALLS) CAN ONLY BE FORMED IF THE PQ PHASE TRANSITION OCCURS AFTER THE INFLATION, I.E. $H_I > f_{PQ}$.

■ THIS CONVENTIONAL ARGUMENT IS CORRECT FOR $N \neq 1$, AND IT IS INCORRECT FOR $N = 1$.

■ WE ALWAYS ASSUME THAT $H_I < f_{PQ}$. HOWEVER N=1 AXION DOMAIN WALLS STILL WILL BE FORMED.

■ THE POINT IS THAT THE N=1 DOMAIN WALL INTERPOLATES BETWEEN TOPOLOGICALLY DISTINCT, BUT PHYSICALLY IDENTICAL VACUUM STATES. THESE DISTINCT TOPOLOGICAL SECTORS MUST BE PRESENT INSIDE THE SAME HORIZON (FOR SELF CONSISTENCY OF THE THEORY) SUCH THAT INFLATION CANNOT REMOVE THEM.

■ THERE ARE FEW FORMAL ARGUMENTS SUPPORTING THIS CLAIM: THE 2π PERIODICITY IN θ CAN BE RESTORED IF ALL $|k\rangle$ TOPOLOGICAL SECTORS ARE PRESENT IN THE SYSTEM (WITTEN, 1980)

$$E_{\text{vac}}(\theta) \sim \min_k (\theta + 2\pi k)^2 + \mathcal{O}\left(\frac{1}{N_c}\right)$$

- THE $N=1$ AXION DOMAIN WALL CORRESPONDS TO THE INTERPOLATION $|k = 0\rangle \rightarrow |k = 1\rangle$ WHEN BOTH STATES ARE PHYSICALLY IDENTICAL STATES. THESE STATES OBVIOUSLY PRESENT IN THE SYSTEM IRRESPECTIVELY TO THE INFLATIONARY SCALE $H_I < f_{PQ}$ or $H_I > f_{PQ}$.
- ANOTHER ARGUMENT SUPPORTING THE SAME CLAIM IS BASED ON THE DUALITY WHEN THE DOMAIN WALL SOLUTION IN SINE GORDON AXION POTENTIAL $V(\theta) \sim \cos \theta$ WITH $\theta \rightarrow \theta + 2\pi n$ IS FORMULATED IN TERMS OF THE DUAL LOCAL ψ FIELD.
- LOCALITY OBVIOUSLY IMPLIES THAT THIS ψ FIELD CANNOT BE REMOVED OUTSIDE THE HORIZON DURING THE INFLATIONARY EPOCH BECAUSE IT WOULD VIOLATE THE FUNDAMENTAL PROPERTY OF THE THEORY.

■ **2-INGREDIENT.** 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 \rightarrow 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:

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

■ 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

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

MATTER IN THE UNIVERSE

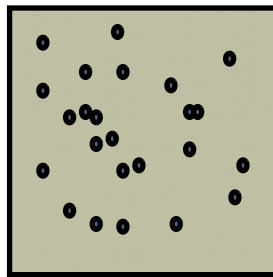
A model which explains both the matter-antimatter asymmetry and the observed ratio of visible matter to DM

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

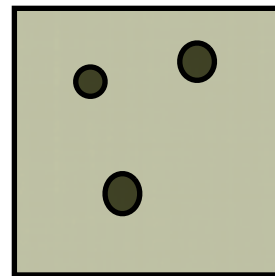
$$B_{\text{tot}} = 0 = B_{\text{nugget}} + B_{\text{visible}} - \bar{B}_{\text{antinugget}}$$

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

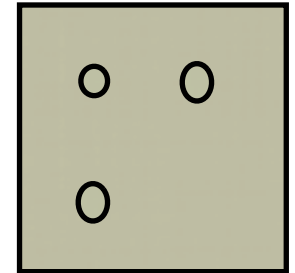
The ratio $B_{\text{nugget}}/\bar{B}_{\text{antinugget}} \simeq 2/3$ at the end of formation is determined by the sign of axion CP violating parameter θ_0



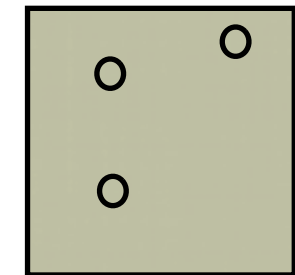
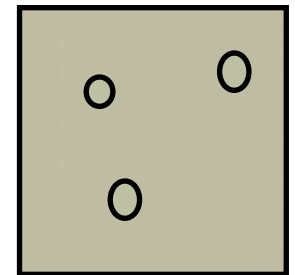
One part:
visible matter



Two parts:
matter nuggets



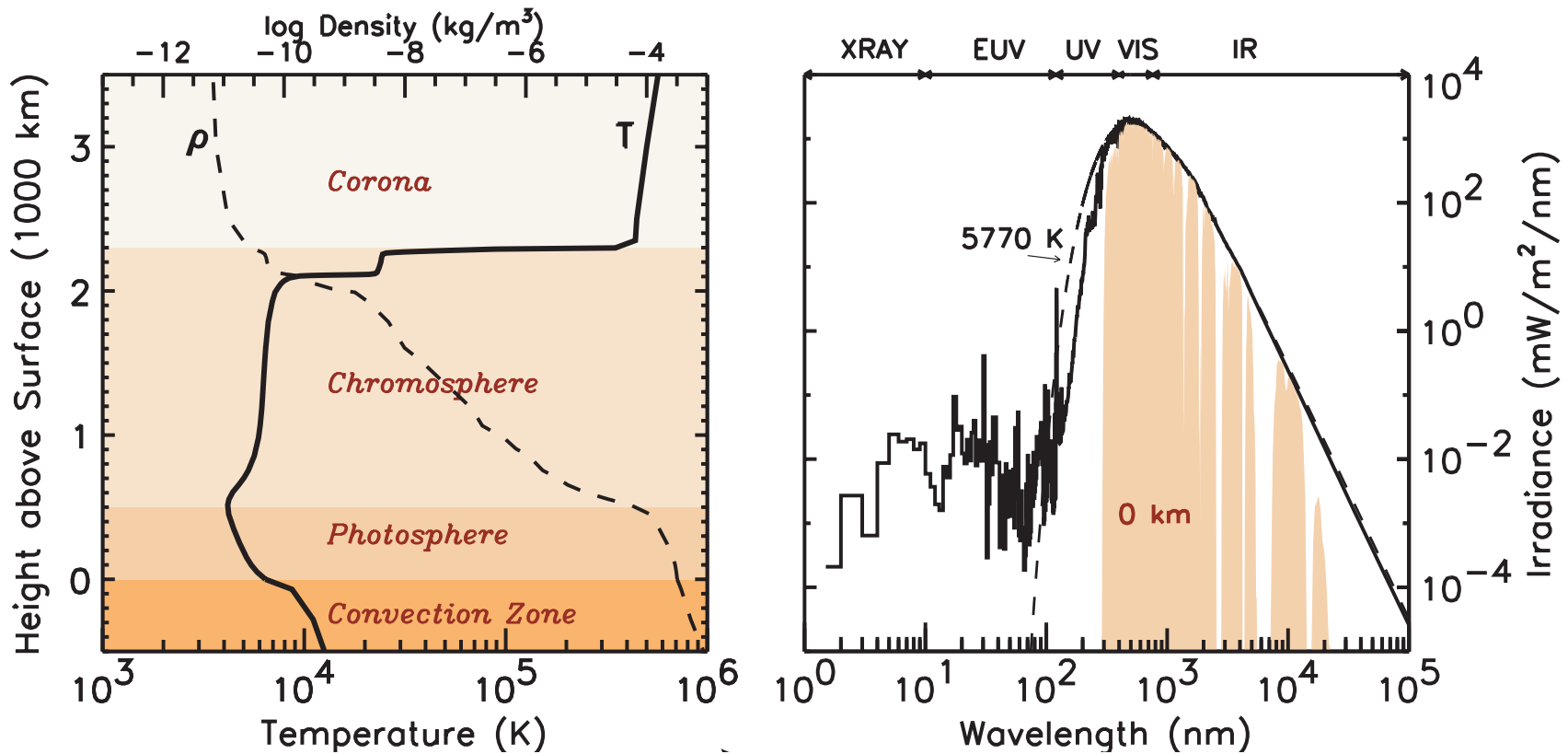
Three parts:
anti-matter nuggets



3. THE MAIN LESSONS OF THE FRAMEWORK

- THE RELATION $\Omega_{\text{dark}} \simeq \Omega_{\text{visible}}$ 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
- 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 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 $\theta(t)$.

4. Application to the “solar corona mystery”



Left: the temperature distribution in outer Sun

Right: the unexpected deviation from the thermal distribution with EUV luminosity from corona:

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

- **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

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

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

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

- 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

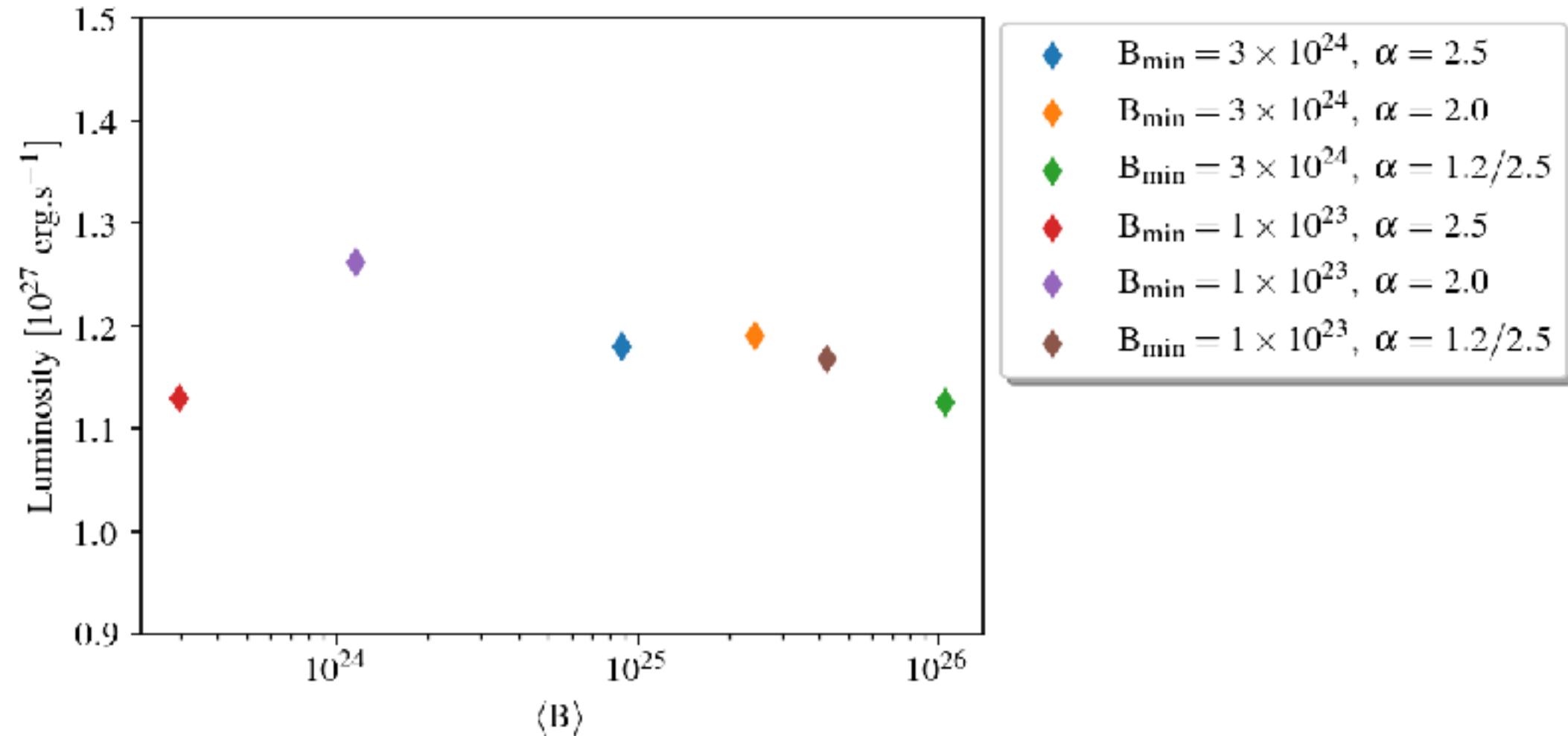
■ IT WAS GENERATED 10^{10} SAMPLE PARTICLES DISTRIBUTED OVER 10 AU IN DISTANCE

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

■ ONLY 3.6×10^4 PARTICLES ARE CAPTURED BY THE SUN. THIS RATE IS DETERMINED BY NEWTON GRAVITY AND DM DENSITY ρ_{DM}

■ THE TYPICAL TIME FOR IMPACT ~ 1 MONTH

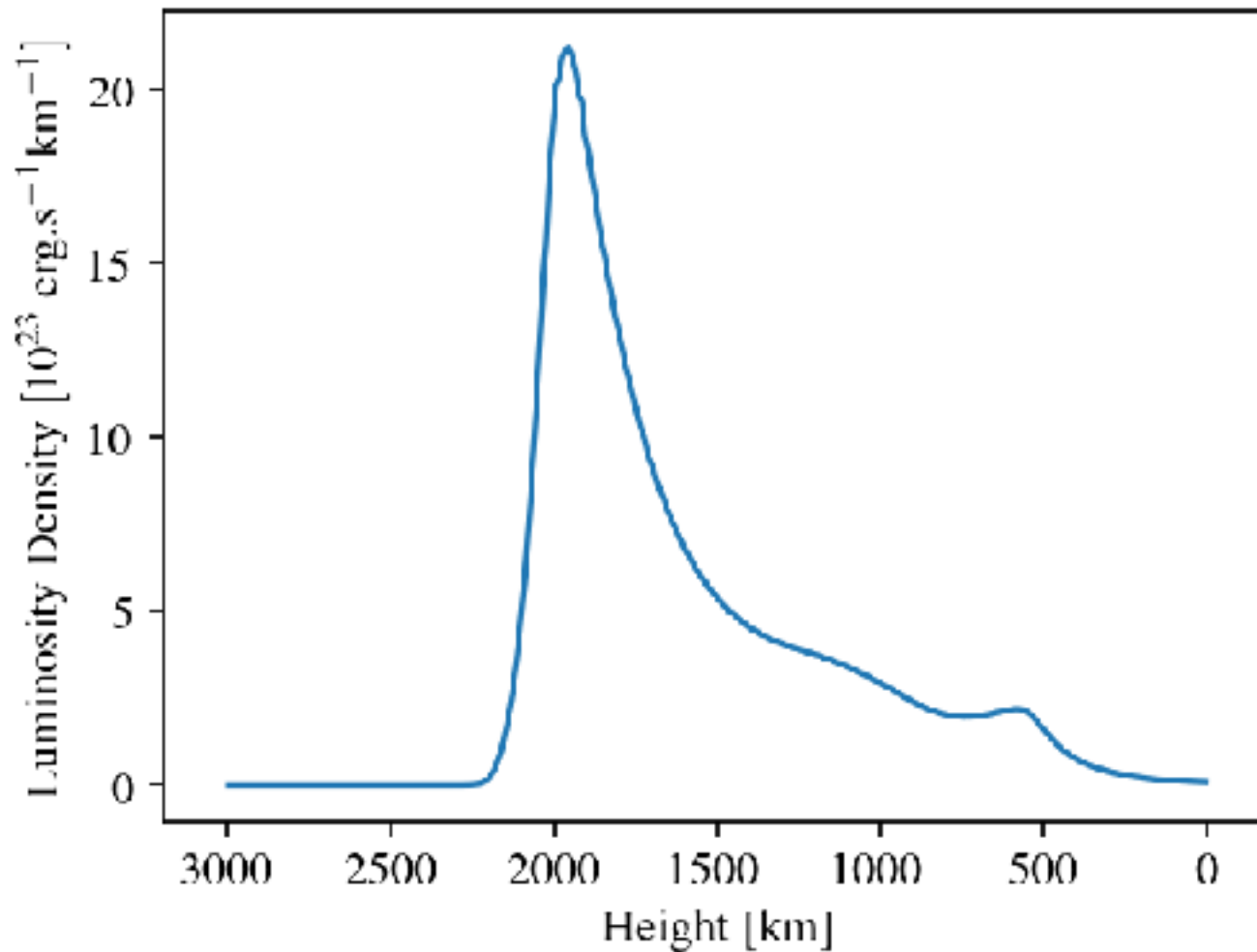
Extrapolated Total Annihilation Luminosity



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

Total Annihilation Luminosity Profile

$$(B_{\min} = 3 \times 10^{24}, \alpha = 2.0)$$



The AQNs start to annihilate at the altitude $\sim 2000\text{km}$, where the drastic changes are known to occur in vicinity of the Transition Region

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.

■ ORIGINALLY, PEOPLE THOUGHT THAT “NANOFLARE” IS A MINIATURE IMAGE OF A FLARE AND MAY OCCUR DUE TO THE MAGNETIC RECONNECTION PHENOMENON(MANY PROBLEMS). NOWADAYS THE NANOFLARES ARE INTRODUCED TO MHD CODES WITHOUT SPECIFYING THEIR NATURE.

■ IT TURNS OUT THAT MANY PROPERTIES OF THESE “NANOFLARES” POSTULATED BY SOLAR PHYSICS PEOPLE TO RUN THEIR MHD- CODES, ARE AUTOMATICALLY SATISFIED FOR AQN ANNIHILATION EVENTS IN THE SUN

THEREFORE WE IDENTIFY

nanoflares \equiv AQN annihilation events.

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)

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

THIS PRECISELY CORRESPONDS TO A TYPICAL ENERGY OF THE NUGGET $\langle B \rangle \sim 10^{25}$ AND NUMBER OF AQNS CAPTURED BY THE SUN PER SECOND (DETERMINED BY THE DM DENSITY AND NEWTON GRAVITY, NOT SOLAR PHYSICS).

$$\langle W \rangle \cdot \left\langle \frac{dN}{dt} \right\rangle \sim 10^{27} \text{ erg} \cdot \text{s}^{-1}$$

■ TO REPRODUCE THE MEASURED RADIATION LOSS IN CORONA, THE OBSERVED RANGE OF NANOFLARES NEEDS TO BE IN RANGE $(3.7 \cdot 10^{20} - 1.3 \cdot 10^{26})$ 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

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 $m_a \sim 10^{-4} \text{ eV}$. 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 $m_a \sim 10^{-4} \text{ eV}$ CONTRIBUTES VERY LITTLE TO $\Omega_{(\text{DM axion})}$ 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 IS ESTIMATED AS

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

■ THE CORRESPONDING AXION FLUX MEASURED ON EARTH IS

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

■ IT SHOULD BE COMPARE WITH CONVENTIONAL PRIMAKOFF MECHANISM

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

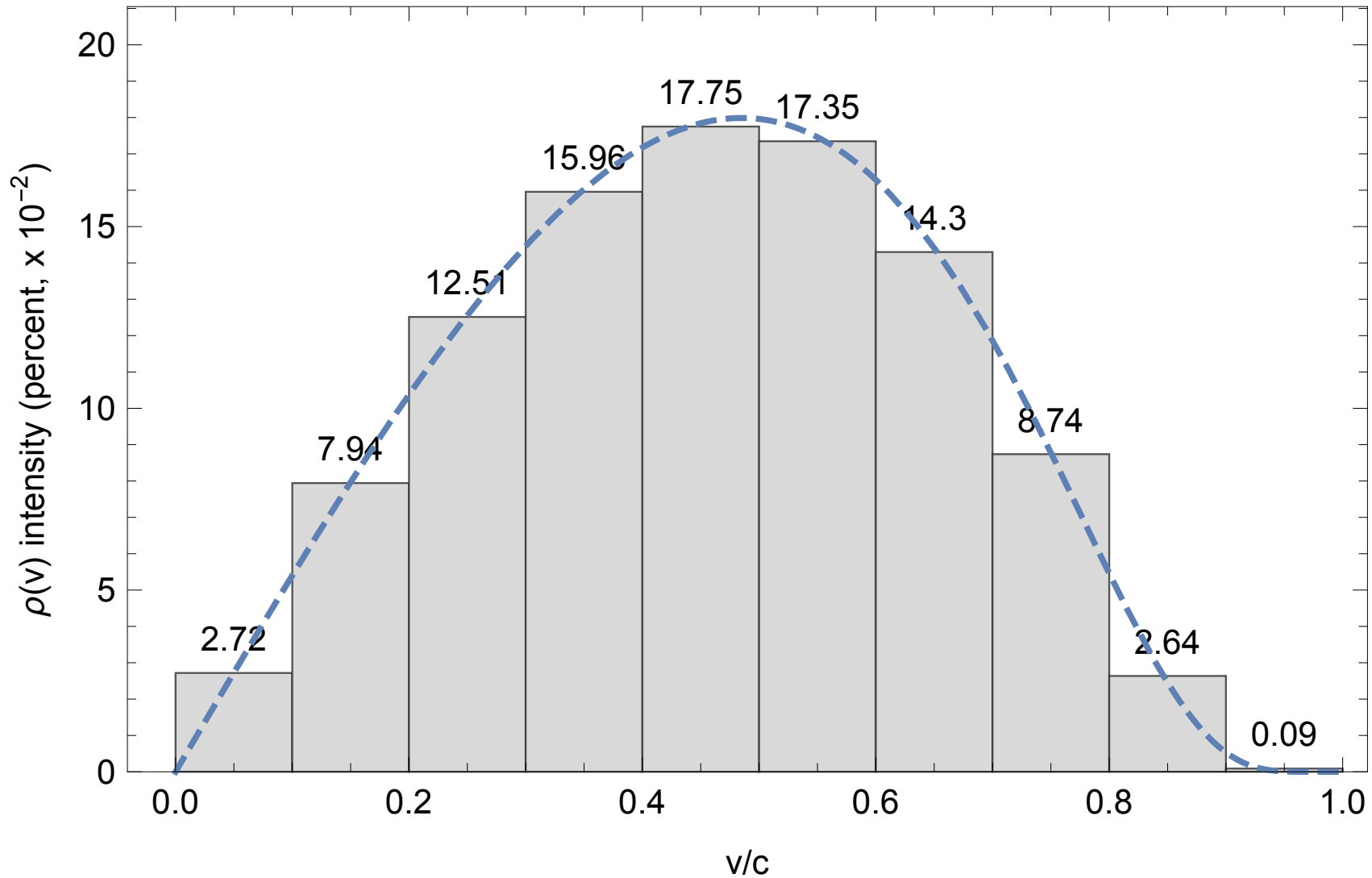
■ THE DIFFERENCE WITH CONVENTIONAL CASE IS THAT THE AXIONS EMITTED FROM AQNS HAVE TYPICAL RELATIVISTIC VELOCITIES WITH $\langle E \rangle = 1.1 m_a$, NOT THE KEV ENERGIES

■ THEREFORE, THE ENERGY FLUXES ARE DIFFERENT

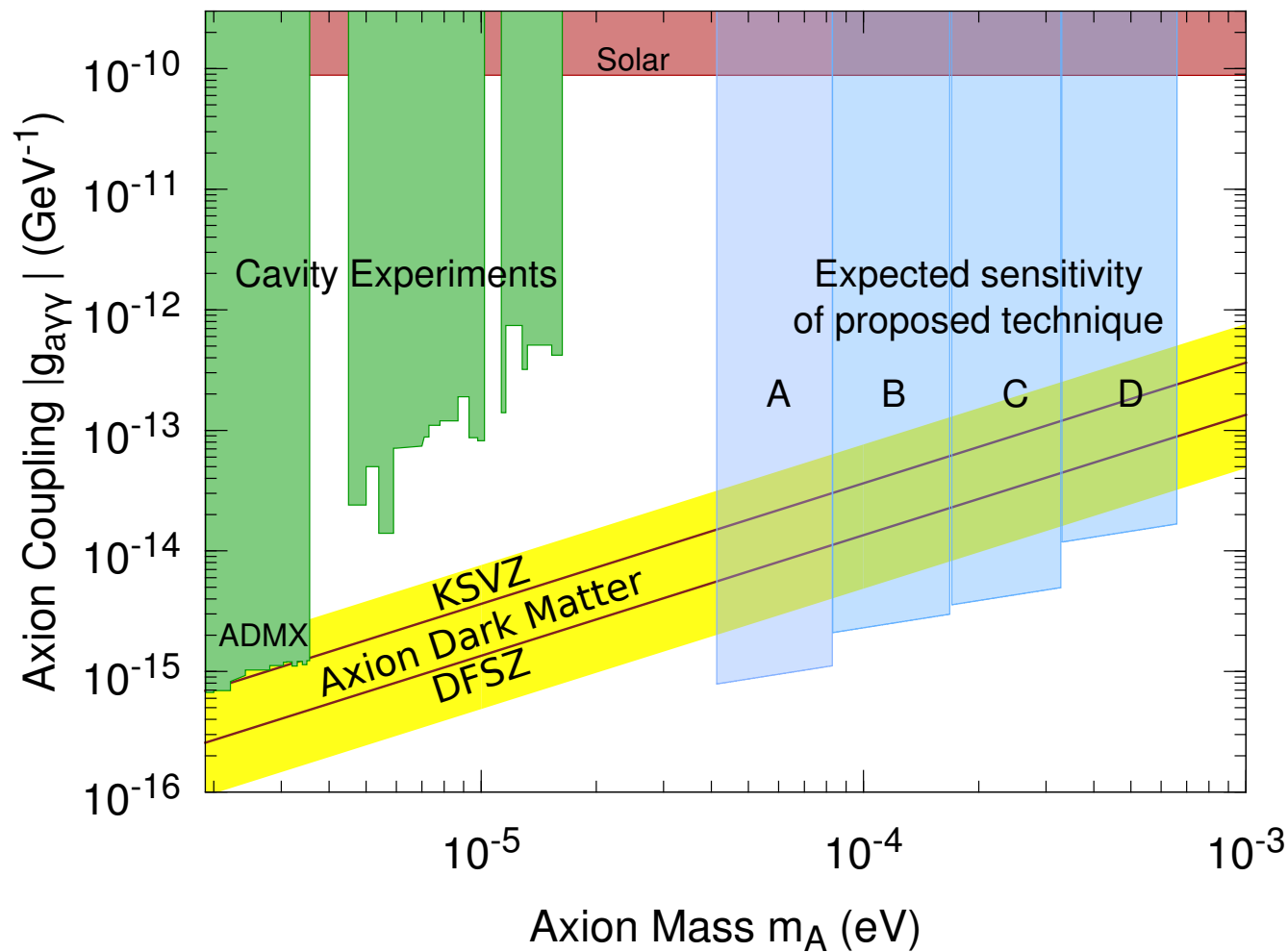
$$m_a \Phi_{\text{axions}} \sim 0.3 \cdot 10^{12} \frac{\text{eV}}{\text{cm}^2 \text{ s}}, \quad \langle E \rangle \Phi_a(\text{Primakoff}) \sim g_{10}^2 \cdot 10^{15} \frac{\text{eV}}{\text{cm}^2 \text{ s}}.$$

■ NORMALIZED AXION SPECTRUM IS DEFINED AS

$$\rho(v_a) \equiv \frac{1}{\Phi_{\text{axions}}^{\text{tot}}} \frac{d}{dv_a} \Phi_{\text{axions}}(v_a), \quad \int_0^1 dv_a \rho(v_a) = 1$$



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 $m_a \sim 10^{-4} \text{ eV}$ 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)

■ $\Omega_{\text{dark}} \simeq \Omega_{\text{visible}}$ 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 NANOFIARES POSTULATED BY PARKER LONG AGO CAN BE IDENTIFIED WITH AQN DARK MATTER ANNIHILATION EVENTS IN THE CORONA

- **THIS MODEL OFFERS A SIMULTANEOUS RESOLUTION OF THREE (NAIVELY UNRELATED) OLD MYSTERIES: DM, BARYOGENESIS, SOLAR CORONA MYSTERY**
- **CONCLUSION FROM MY FRIENDS (PARTICLE PHYSICS EXPERIMENT)- THE UPGRADED **CAST** HAS A POTENTIAL TO DISCOVER DM AXIONS FROM AQNs WHICH ARE PRODUCED IN THE SOLAR CORONA**
- **CONCLUSION FROM MY FRIENDS (ASTRO-PEOPLE)- THE **PARKER SOLAR PROBE** (LAUNCH WINDOW: JULY 31- AUGUST 19, 2018) WILL BE CAPABLE TO ADDRESS AND STUDY MANY QUESTIONS RELATED TO THIS PROPOSAL, INCLUDING THE SOLAR CORONA MYSTERY**

Part-2:

**New ideas on the axion search
experiments via Topological
Casimir Effect**

**PRD-2017, arxiv: 1702.00012,
in collaboration with Charles
Cao, Caltech**

1. TERMINOLOGY AND DEFINITIONS

1. THE TITLE INCLUDES TWO TERMS: AXION, RELATED TO THE θ PARAMETER, AND THE TOPOLOGICAL CASIMIR EFFECT (TCE).

2. THE θ ENTERS THE QCD- LAGRANGIAN AS THE TOTAL DIVERGENCE. IT DOES NOT CHANGE EQUATION OF MOTION.

$$L_\theta = \theta \int d^4x q(x), \quad q(\mathbf{x}) = \frac{1}{16\pi^2} \text{tr} [F_{\mu\nu} \tilde{F}^{\mu\nu}] \sim \partial_\mu K^\mu$$

NEVERTHELESS, IT IS KNOWN THAT θ IS THE PHYSICAL PARAMETER OF THE THEORY. IT IS DUE TO THE PRESENCE OF THE INSTANTONS AND TOPOLOGICAL SECTORS IN QCD.

EXAMPLE: PARTICLE ON A CIRCLE: FOR UNDERGRADS: $\theta\dot{q}$ -IS IRRELEVANT, WHILE FOR GRADS: $\theta\dot{q}$ - TERM IS CRUCIAL

$$L = \int dt \left[\frac{\dot{q}^2}{2} + \theta\dot{q} \right], \quad E_n = \frac{1}{2} \left(n - \frac{\theta}{2\pi} \right)^2, \quad \theta \equiv \oint_s \vec{A} \cdot d\vec{l}, \quad \vec{A} = \vec{\nabla} \frac{\theta}{2\pi} \phi$$

Aharonov -Bohm
type effect

$\theta = \text{const}$ IS PROMOTED TO THE AXION FIELD $\theta \rightarrow \theta(x)$

■ THE TIME-DEPENDENT AXION FIELD $\theta(x)$ OBVIOUSLY MODIFIES THE QED MAXWELL EQUATIONS

$$\vec{\nabla} \times \vec{B} = \vec{j} + \frac{\partial \vec{E}}{\partial t} - g_{a\gamma\gamma} \vec{B} \frac{\partial a}{\partial t}, \quad \vec{j}_a = -\dot{\theta} \frac{K_{a\gamma\gamma} \alpha}{2\pi} \vec{B}, \quad g_{a\gamma\gamma} = \frac{K_{a\gamma\gamma} \alpha}{2\pi f_a},$$

$$a(t) = f_a \theta(t), \quad \alpha \equiv \frac{e^2}{4\pi}, \quad K_{a\gamma\gamma}(DFSZ) \simeq 0.75, \quad K_{a\gamma\gamma}(KSVZ) \simeq -1.92$$

■ THE ANOMALOUS CURRENT $\vec{j}_a \sim \dot{\theta} \vec{B}$ IS VERY UNUSUAL: IT POINTS ALONG \vec{B} , IN CONTRAST WITH ORDINARY E&M WHEN

$$\vec{j}_{EM} = \sigma \vec{E} \quad ; \quad \vec{j}_{EM} \perp \vec{B} \quad \longleftrightarrow \quad \vec{j}_a \sim \dot{\theta} \vec{B}$$

■ MOST OF THE PROPOSALS TO DETECT DM AXIONS IN VACUUM ARE BASED ON THIS EXTRA CURRENT $\vec{j}_a \sim \dot{\theta} \vec{B}$

■ SIMILAR NON-DISSIPATING CURRENT $\vec{j}_\theta \sim \dot{\theta} \vec{B}$ HAS BEEN VERY ACTIVE AREA OF RESEARCH IN RECENT YEARS WITH DRASTICALLY DIFFERENT SCALES $\dot{\theta} \sim \Lambda_{\text{QCD}}$ IN HEAVY IONS AT RHIC/ LHC INSTEAD OF $\dot{\theta} \sim m_a$ IN AXION PHYSICS. SOME CP-ODD EFFECTS (CHIRAL MAGNETIC, CHARGE SEPARATION,...) APPARENTLY HAVE BEEN OBSERVED.

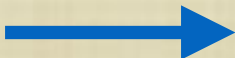
2. AXION FIELD AND ITS COUPLING

- AXION FIELD IS THE NAMBU-GOLDSTONE FIELD. IT NORMALLY COUPLES THROUGH THE DERIVATIVES $\sim \partial_\mu \theta$
- IN PARTICULAR, MOST EXPERIMENTS/PROPOSALS ARE BASED ON GENERATION OF THE EXTRA ANOMALOUS COUPLING $\vec{j}_a \sim \dot{\theta} \vec{B}$ IN MAXWELL SYSTEM ($\vec{j}_a = 0$ for $\theta = \text{const}$)
- ADMX, MM (MAGNETOMETER, SIKIVIE, 1985, 2014); ORPHEUS RYBKA 2014); RC (RE-ENTRANT CAVITIES, TOBAR, 2015); MADMAX (RAFFELT, REDONDO, 2016); BROADBAND/RESONANT EFFECTS... $\sim \dot{\theta}^2$
- CASPER (BUDKER, 2014, GRAHAM, 2013); “AXION-WIND” (FLAMBAUM, 2013); QUAX (BARBIERI, 2016) ... EXPERIMENTS ARE ALL PROPORTIONAL TO $\sim (\nabla \theta)$

■ MORAL: IN USUAL CIRCUMSTANCES THE EFFECTS RELATED TO THE AXION FIELD ARE ALWAYS PROPORTIONAL TO $\partial_\mu \theta$ WHEN θ COUPLES TO E&M FIELD.

■ IT IS NORMALLY EXPLAINED BY AN ARGUMENT THAT $\theta = \text{const}$ IS UNPHYSICAL IN $L_\theta \sim \theta \vec{E} \cdot \vec{B} \sim \theta \partial_\mu [\epsilon^{\mu\nu\lambda\sigma} A_\nu F_{\lambda\sigma}]$ BECAUSE IT IS A TOTAL DERIVATIVE AND DOES NOT CHANGE THE EOM. THE DIFFERENCE WITH QCD- NO INSTANTONS IN E&M

■ NEVERTHELESS, I WANT TO ARGUE THAT θ ITSELF BECOMES A PHYSICAL PARAMETER IN E&M.

■ FIRST: I EXPLAIN A THEORETICAL IDEA. SECOND: I PRESENT SOME NUMERICAL ESTIMATES. BASICALLY, INSTEAD OF THE “INTENSITY”-TYPE EXP.  “INTERFERENCE” TYPE EXP.

3. TERMINOLOGY: TOPOLOGICAL CASIMIR EFFECT (TCE)

THE GOAL NOW IS TO EXPLAIN THE KEY ELEMENT OF THE CONSTRUCTION, THE TCE, WHEN THE MAXWELL SYSTEM BECOMES SENSITIVE TO θ ITSELF AND NOT $\partial_\mu \theta$

CONSIDER A NON-SIMPLY CONNECTED MANIFOLD (FOR EXAMPLE, A RING WITH AREA $L_1 \times L_2$ AND WIDTH L_3), THEN THERE WILL BE THE “INSTANTON FLUXES” IN E&M DESCRIBING THE TUNNELLING TRANSITIONS IN QED BETWEEN DISTINCT TOPOLOGICAL $|k\rangle$ SECTORS SIMILAR TO THE QCD INSTANTONS (NON-PERTURBATIVE EFFECTS).

ANALOGY: PARTICLE ON A RING, SENSITIVE TO THE θ TERM, OR AHARONOV -BOHM EFFECT WHEN A PARTICLE IS SENSITIVE TO A PURE GAUGE POTENTIAL $A_\mu \sim \partial_\mu f$ WITH $F_{\mu\nu} = 0$ AS A RESULT OF THE PHASE INTERFERENCE.

■ THE MAXWELL ACTION IS QUADRATIC IN NATURE, SUCH THAT PARTITION FUNCTION DECOUPLES: $\mathcal{Z} = \mathcal{Z}_{\text{pert}} \times \mathcal{Z}_{\text{top}}(\theta)$. TUNNELLING EVENTS EXPLICITLY CONTRIBUTE TO $\mathcal{Z}_{\text{top}}(\theta)$.

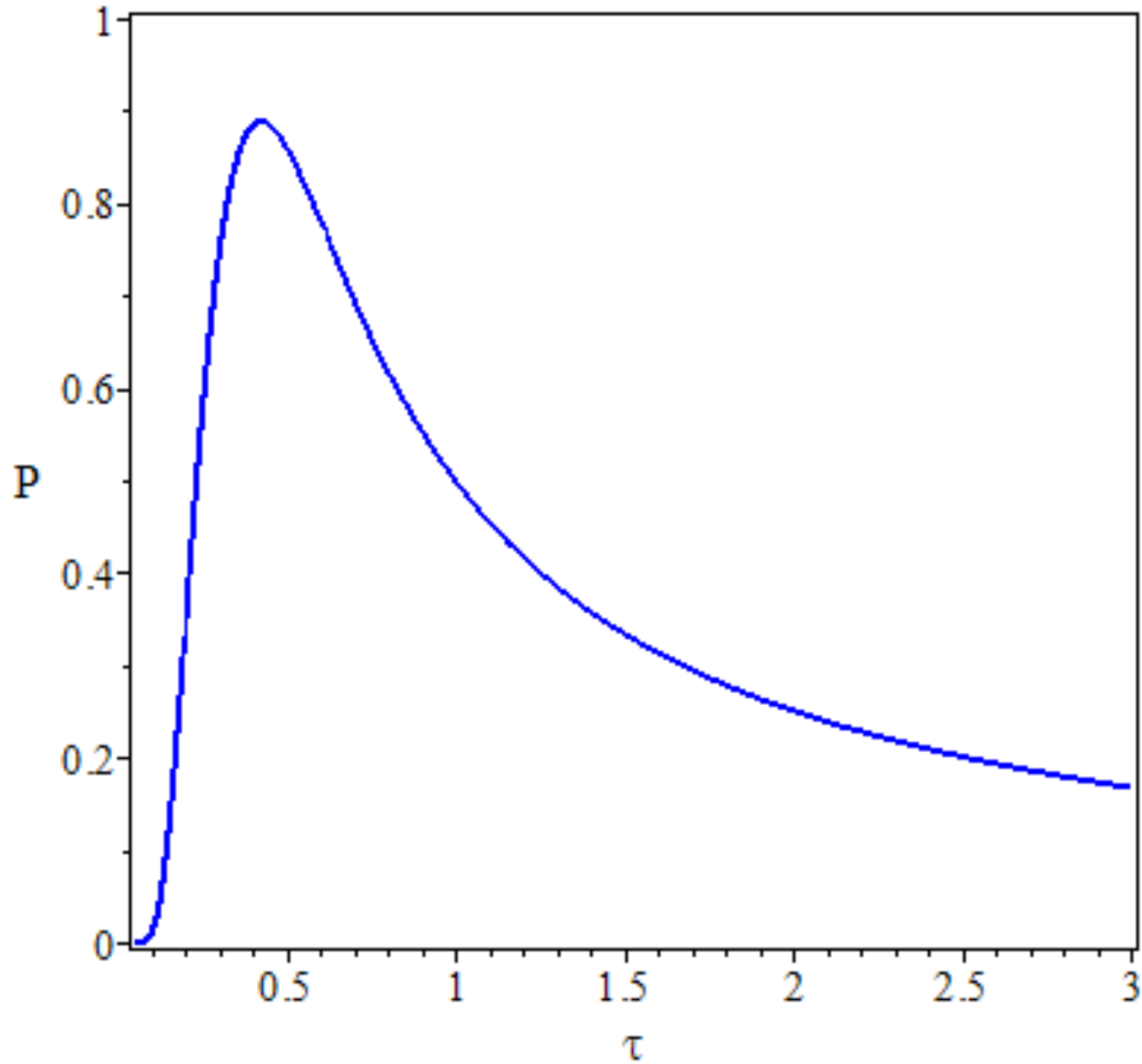
■ THE TOPOLOGICAL PARTITION FUNCTION $\mathcal{Z}_{\text{top}}(\theta)$ IS NON-ANALYTICAL IN COUPLING $\exp(-1/e^2)$. THEREFORE, ALL EFFECTS ARE NON-PERTURBATIVE IN NATURE AND CANNOT BE SEEN IN PERTURBATION THEORY FROM E&M EQUATIONS

$$\mathcal{Z}_{\text{top}} = \sqrt{\frac{2\pi\beta L_3}{e^2 L_1 L_2}} \sum_{k \in \mathbb{Z}} e^{-\frac{2\pi^2 k^2 \beta L_3}{e^2 L_1 L_2}} = \sqrt{\pi\tau} \sum_{k \in \mathbb{Z}} e^{-\pi^2 \tau k^2} \quad \tau \equiv 2\beta L_3 / e^2 L_1 L_2.$$

■ MORAL: THERE IS AN ADDITIONAL CONTRIBUTION TO THE CASIMIR PRESSURE (THE SO CALLED TCE) WHICH IS NOT RELATED TO THE PROPAGATING VIRTUAL PHOTONS. IT IS ORIGINATED FROM THE TUNNELLING TRANSITIONS IN QED

$$P_{\text{top}} = \frac{1}{\beta L_1 L_2} \frac{\partial}{\partial L_3} \ln \mathcal{Z}_{\text{top}}. \quad P = -\frac{\pi^2}{240 L_3^4} \quad \frac{P_{\text{top}}}{P} \sim \frac{1}{\alpha} \frac{L_3^4}{L_1^2 L_2^2}$$

Topological Casimir Pressure



Extra Topological Casimir Pressure measured in units $\frac{2}{L_1^2 L_2^2 e^2}$
as a function of $\tau \equiv \frac{2\beta L_3}{e^2 L_1 L_2}$

4. EXTERNAL MAGNETIC FIELD AS θ_{eff} PARAMETER

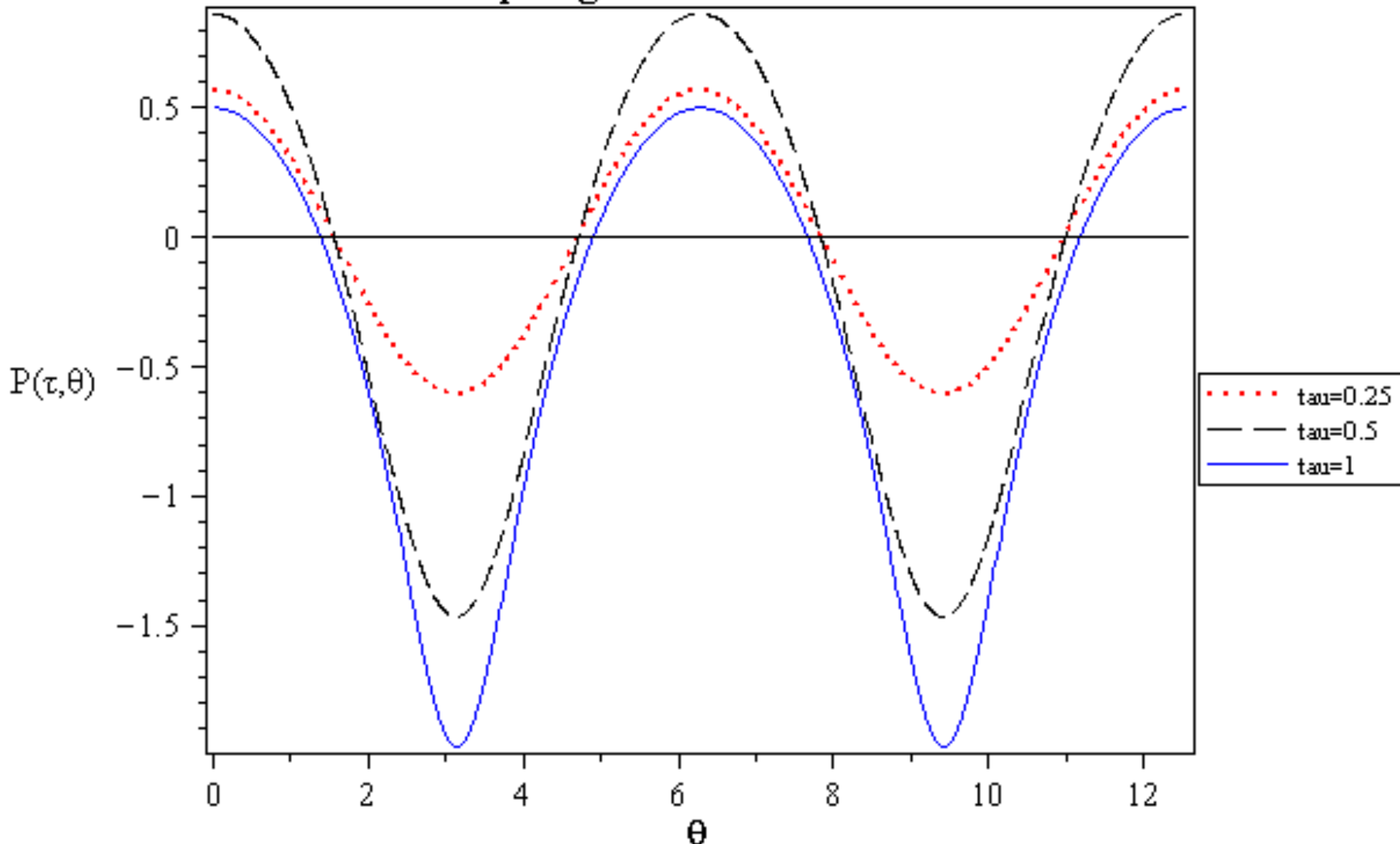
■ NORMALLY, IN CONVENTIONAL CIRCUMSTANCES AN EXTERNAL MAGNETIC FIELD DOES NOT AFFECT THE CASIMIR VACUUM ENERGY AS THE LOOP VACUUM EFFECT IS NEGLIGIBLE $\sim \alpha^2 B_{\text{ext}}^2 / m_e^4$ (EULER-HEISENBERG TERM)

■ FOR THE TOPOLOGICAL CASIMIR EFFECT THE SITUATION DRASTICALLY CHANGES DUE TO QUANTUM INTERFERENCE OF “INSTANTON-FLUXES” AND EXTERNAL FIELD. EFFECT BECOMES OF ORDER OF ONE. INDEED,

$$\mathcal{Z}_{\text{top}}(\tau, \theta_{\text{eff}}) = \sqrt{\pi\tau} \sum_{k \in \mathbb{Z}} \exp \left[-\pi^2 \tau \left(k + \frac{\theta_{\text{eff}}}{2\pi} \right)^2 \right] \quad \theta_{\text{eff}} = e B_z^{\text{ext}} L_1 L_2$$

■ WHEN $\theta \neq 0$ THE TOPOLOGICAL PORTION OF THE PARTITION FUNCTION $\mathcal{Z}_{\text{top}}(\theta, \theta_{\text{eff}}, \tau)$ EXPLICITLY DEPENDS ON θ THIS IMPLIES THAT PHYSICS OBVIOUSLY DEPENDS ON θ AS A RESULT OF TUNNELLING EVENTS $\sim \exp(-1/e^2)$.

Topological Casimir Pressure



The Topological Casimir Pressure drastically changes when external magnetic field $\theta_{\text{eff}} = eB_z^{\text{ext}} L_1 L_2$ varies, in huge contrast with conventional Casimir effect determined by the conventional fluctuating photons

5. RELATION TO WITTEN'S EFFECT

- THE θ TERM IN THE BACKGROUND OF THE MAGNETIC FIELD IN THE GIVEN TOPOLOGICAL SECTOR $|\kappa\rangle$ CAN BE REPRESENTED AS

$$S_\theta \sim \theta e^2 \int d^4x \vec{E} \cdot \vec{B} = \theta \left[e \int d^2x_\perp B_z \right] \cdot \left[e \int dzdt E_z \right] = 2\pi\kappa \theta \cdot \left[e \int dzdt E_z \right].$$

- NON-TRIVIAL TOPOLOGICAL SECTOR $\oint_\Gamma A_\mu dx_\mu = 2\pi\kappa$ IS ENFORCED BY EXTERNAL FIELD SIMILAR TO AB PHASE.

- 4D FORMULA FOR θ -TERM IS REDUCED TO 2D SCHWINGER MODEL WHERE θ IS KNOWN TO BE A PHYSICAL PARAMETER OF THE SYSTEM DUE TO THE NONTRIVIAL TOPOLOGY

- THE EFFECT IS SIMILAR TO WITTEN EFFECT WHEN θ BECOMES A PHYSICAL PARAMETER IN THE MONOPOLE SECTOR AND THE MONOPOLE BECOMES THE DYON WITH ELECTRIC CHARGE $e' = -(e\theta/2\pi)$

■ IN BOTH CASES THE θ PARAMETER BECOMES A PHYSICALLY OBSERVABLE PARAMETER NOT IN VACUUM BUT IN A HEAVY TOPOLOGICAL SECTOR (MONOPOLE'S CHARGE IN WITTEN'S CASE, MAGNETIC FLUX IN OUR CASE)

■ IN BOTH CASES THE TOPOLOGY IS ENFORCED BY SOME EXTERNAL MAGNETIC OR ELECTRIC FIELD

■ IN THIS CASE THE EFFECT IS PROPORTIONAL TO θ EVEN WITHOUT TUNNELLING SUPPRESSION FACTOR $\exp(-1/e^2)$

■ IT OPENS UP A NEW PERSPECTIVE WITH AXION SEARCHES BECAUSE THE EFFECTS ARE PROPORTIONAL TO STATIC θ , IT IS LINEAR IN $\theta \sim 1/f_a$, AND IT IS PROPORTIONAL TO THE STRENGTH OF THE MAGNETIC OR ELECTRIC EXTERNAL FIELD CORRESPONDING TO A SPECIFIC TOPOLOGICAL SECTOR $|\kappa\rangle$

6. NUMERICAL ESTIMATES

■ IN PARTICULAR, IF WE TAKE A CYLINDER IN THE BACKGROUND OF THE MAGNETIC FIELD, THEN IN THE PRESENCE OF A PASSING AXION $\theta(x)$ THE ELECTRIC FIELD WILL BE INDUCED ALONG THE MAGNETIC FIELD

$$\langle \vec{E} \rangle_{\text{ind}} = -\frac{K_{a\gamma\gamma}\alpha}{\pi} \theta \vec{B}_{\text{ext}},$$

■ IF WE PLACE THE PLATES AT THE ENDS OF THE CYLINDER THIS INDUCED $\langle \vec{E} \rangle_{\text{ind}}$ FIELD WILL INDUCE THE CHARGES ON PLATES

$$\langle Q \rangle \sim \frac{e\theta(t)}{2\pi} K_{a\gamma\gamma} \cdot \left[\frac{eB_{\text{ext}}L_1L_2}{2\pi} \right].$$

■ THIS CHARGE SEPARATION EFFECT DUE TO $\theta \neq 0$ GENERATES THE POTENTIAL DIFFERENCE $\langle \Delta V \rangle$

$$\langle \Delta V \rangle \simeq \frac{e\theta K_{a\gamma\gamma}L_3}{2\pi L_1L_2} \cdot \left[\frac{eB_{\text{ext}}L_1L_2}{2\pi} \right] \sim 0.2K_{a\gamma\gamma}\theta \cdot \left(\frac{L_3}{\text{mm}} \right) \cdot \left(\frac{B_{\text{ext}}}{\text{Gauss}} \right) (\text{volt}).$$

- IF WE CONNECT TWO PLATES WITH A WIRE THERE WILL BE INDUCED CURRENT DUE TO INDUCED CHARGES

$$\langle J \rangle \sim \frac{\langle Q \rangle c}{L_3} \left(\frac{v}{c} \right) \approx 10^{-6} \cdot \left(\frac{\theta K_{a\gamma\gamma}}{10^{-14}} \right) \cdot \left(\frac{L_1 L_2 / L_3}{\text{mm}} \right) \cdot \left(\frac{B_{\text{ext}}}{1\text{T}} \right) \cdot \left(\frac{v}{c} \right) \text{nA}$$

- THE DUAL PICTURE WITH ELECTRIC EXTERNAL FIELD SUGGESTS THAT THE MAGNETIC FIELD WILL BE INDUCED IN THE PRESENCE OF E_{ext} ,

$$\langle B \rangle_{\text{ind}} = \frac{\theta K_{a\gamma\gamma} \alpha}{\pi} E_{\text{ext}},$$

- THE INDUCED MAGNETIC FIELD CAN BE INTERPRETED AS THE SURFACE PERSISTENT CURRENT ON THE RING

$$\langle J \rangle \simeq \frac{\theta K_{a\gamma\gamma} \alpha}{\pi} L_3 E_{\text{ext}} \sim 10^{-6} \cdot \left(\frac{\theta K_{a\gamma\gamma}}{10^{-14}} \right) \cdot \left(\frac{E_{\text{ext}}}{10^5 \frac{\text{V}}{\text{cm}}} \right) \cdot \left(\frac{L_3}{\text{mm}} \right) \text{nA}.$$

CONCLUSION FOR PART-2 ON TCE

- PHYSICS COULD BE SENSITIVE TO θ ITSELF RATHER THAN TO $\partial_\mu \theta$ AS A RESULT OF NON-PERTURBATIVE QED PHYSICS. IT IS LINEAR IN $\theta \sim 1/f_a$ BUT PARAMETRICALLY SUPPRESSED $\exp(-1/e^2)$. IT COULD BE NUMERICALLY LARGE FOR A SPECIFIC GEOMETRICAL DESIGN OF A RING.
- PHYSICS COULD BE ALSO SENSITIVE TO θ EVEN WITHOUT SUPPRESSION ~~$\exp(-1/e^2)$~~ IN TOPOLOGICAL SECTOR $|\kappa\rangle$. ALL NEW OBSERVABLES (INDUCED CHARGE $\langle Q \rangle$, INDUCED CURRENT $\langle J \rangle$, INDUCED POTENTIAL $\langle V \rangle$) ARE LINEAR IN θ EFFECTS AS A RESULT OF QUANTUM INTERFERENCE.
- ADVANCED-KWISP DESIGN (G. CANTATORE, 1803.07685) HAS A POTENTIAL FOR OBSERVING THE TCE USING DMIM (DOUBLE MEMBRANE INTERACTION MONITOR)