DM and Matter-Antimatter asymmetry as two sides of the coin: theory, observations and future experimental searches.

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16th Patras Workshop, Trieste, June 14-18, 2021

This talk is mostly based on two recent papers

PHYSICAL REVIEW D **101,** 043012 (2020)

Axion quark nuggets and how a global network can discover them

Dmitry Budker*

Johannes Gutenberg-Universität Mainz (JGU)—Helmholtz-Institut, 55128 Mainz, Germany and Department of Physics, University of California, Berkeley, California 94720-7300, USA

speaking on Thursday.

Victor V. Flambaum†

School of Physics, University of New South Wales, Sydney 2052, Australia and Johannes Gutenberg-Universität Mainz (JGU)—Helmholtz-Institut, 55128 Mainz, Germany

speaking on Tuesday

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The mysterious bursts observed by telescope array and axion quark nuggets

Ariel Zhitnitsky[1]

Published 29 April 2021 • © 2021 IOP Publishing Ltd

Journal of Physics G: Nuclear and Particle Physics, Volume 48, Number 6

Citation Ariel Zhitnitsky 2021 *J. Phys. G: Nucl. Part. Phys.* **48** 065201

1. The DM and Baryogenesis as two sides of the same coin

- There are two (apparently unrelated) stories:

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

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

- There are many other **observed** (naively unrelated) puzzles ... to be mentioned today

Fritz Zwicky and Vera Rubin

The DM side of the coin

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

The Baryogenesis side of the coin

- These two (naively unrelated) phenomena, the **DM** and **baryogenesis** are normally considered to be two different stories... We want to argue that these two phenomena are, in fact, intimately connected

- **CP-odd Axion** Field plays the key role in linking these two phenomena.

- Furthermore, our claim is that we have been witnessing (indirectly) the manifestation of the DM (beyond gravity) for years with many puzzling observations, including "solar heating puzzle", "Primordial Lithium Puzzle" + many more

- Today I specifically focus on two consequences of this construction:
  1. broadband axion searches;
  2. recently observed Mysterious Telescope Array bursts.

2. 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" ⟶ "segregation 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**. We call the objects the <u>axion quark nugget (**AQN**)</u>.

- 1. there is extra N=1 **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.

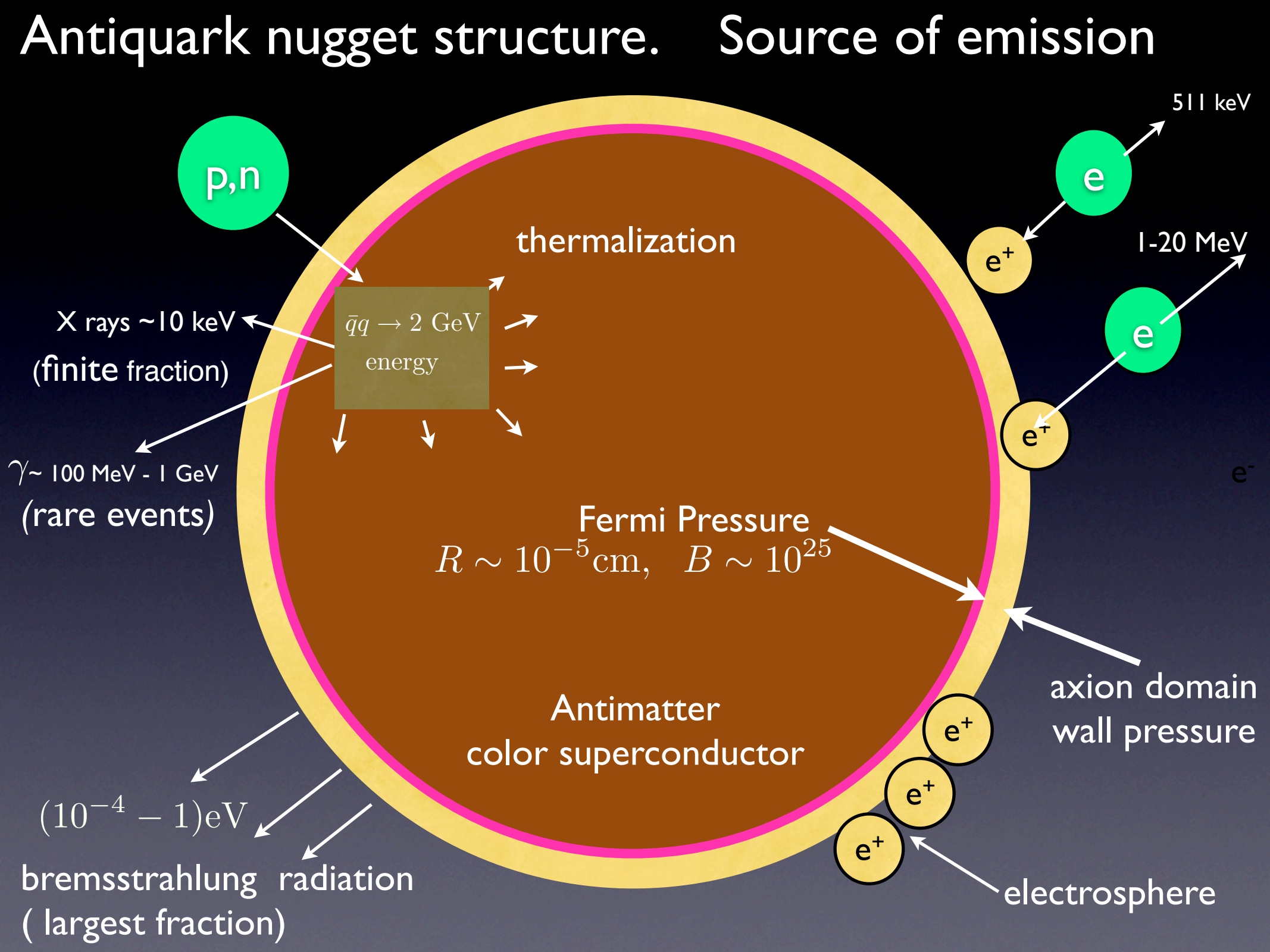
- 2. there are two species, the nuggets and **anti-nuggets**. The size is determined by m_a as $R \sim m_a^{-1}$

- A small geometrical factor replaces a conventional requirement for a weak coupling constant. Nuggets are **qualified** as the DM candidates:

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

- Cosmological **CP-odd** axion field generates the **disparity** between two species at $\theta \neq 0$ which implies the similarity between **dark and visible** sectors: $\Omega_{\rm dark} \approx \Omega_{\rm visible} \sim \Lambda_{\rm QCD}$

Antiquark nugget structure. Source of emission



3. When the AQN hits the Earth...

- Number of AQNs hitting the earth surface is tiny. It is very rare event in comparison with WIMPs:

$$\frac{\langle \dot{N} \rangle}{4\pi R_\oplus^2} = \frac{0.4}{\mathrm{km^2 yr}} \left(\frac{10^{24}}{\langle B \rangle} \right) \left(\frac{\rho_{\mathrm{DM}}}{0.3 \frac{\mathrm{GeV}}{\mathrm{cm^3}}} \right) \left(\frac{\langle v_{\mathrm{AQN}} \rangle}{220 \mathrm{km/s}} \right).$$

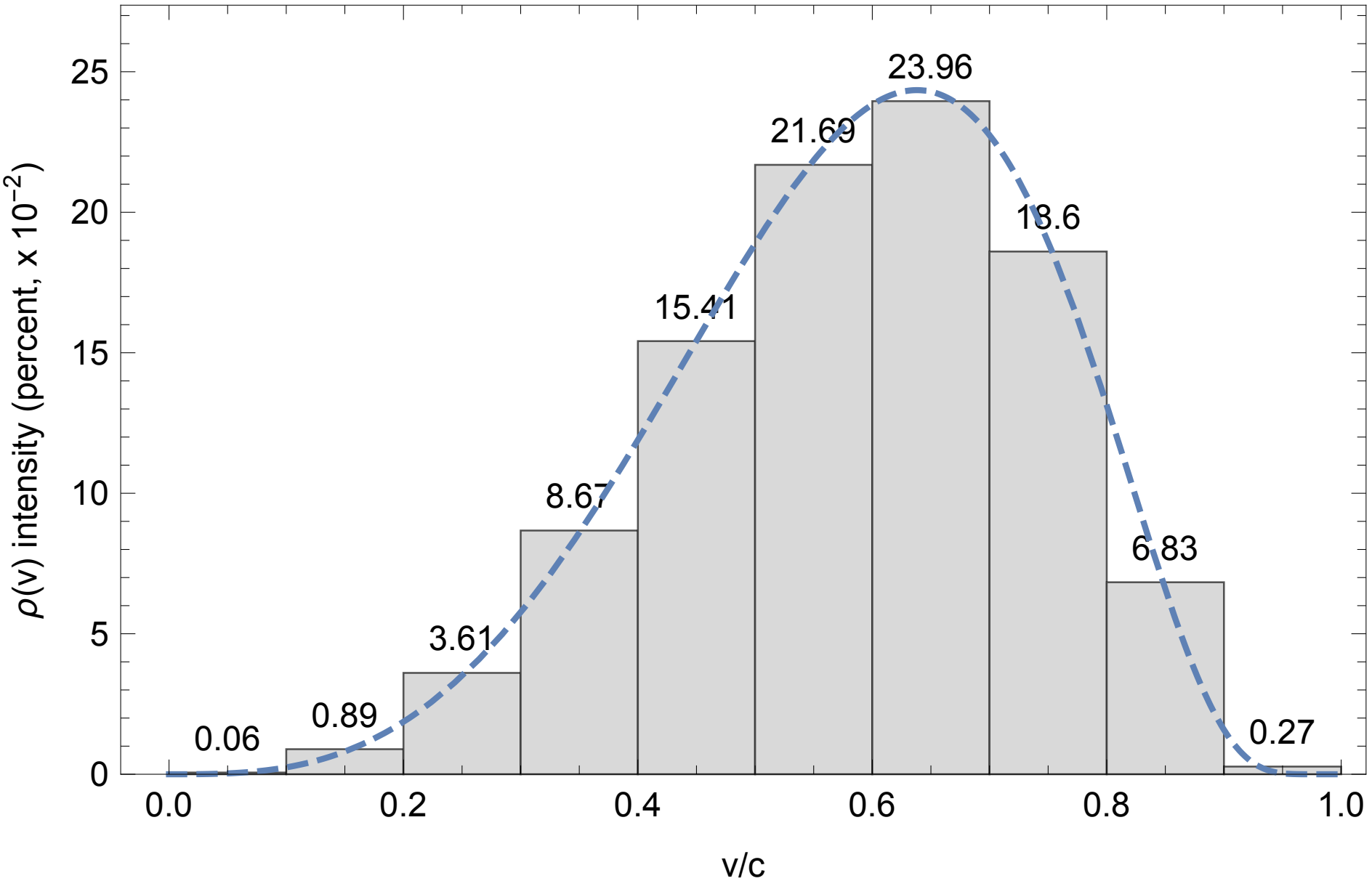
- Corresponding axion flux (as a result of annihilation)

$$m_a \langle \Phi_a^{\mathrm{AQN}} \rangle \sim 10^{14} \frac{\mathrm{eV}}{\mathrm{cm^2 s}}, \quad \mathrm{v_a} \simeq 0.6\mathrm{c}.$$

- It should be compared with conventional galactic axions (misalignment mechanism, DW decays)

$$m_a \Phi_a^{(\mathrm{galactic})} \sim \rho_{\mathrm{DM}} v_{\mathrm{DM}} \simeq 10^{16} \left(\frac{\rho_{\mathrm{DM}}}{0.3\,\mathrm{GeV}} \right) \frac{\mathrm{eV}}{\mathrm{cm^2 s}}, \quad v_a \simeq 10^{-3} c$$

- The flux is two orders of magnitude smaller... One should study separately: relativistic AQN-induced axions and gravitationally trapped AQN-induced axions



The main result of these computations is that the typical velocity is very large $\langle v_a \rangle \approx 0.6c$ which should be contrasted with galactic axions $\langle v_a \rangle \approx 10^{-3}c$

4. Broadband Detection strategy

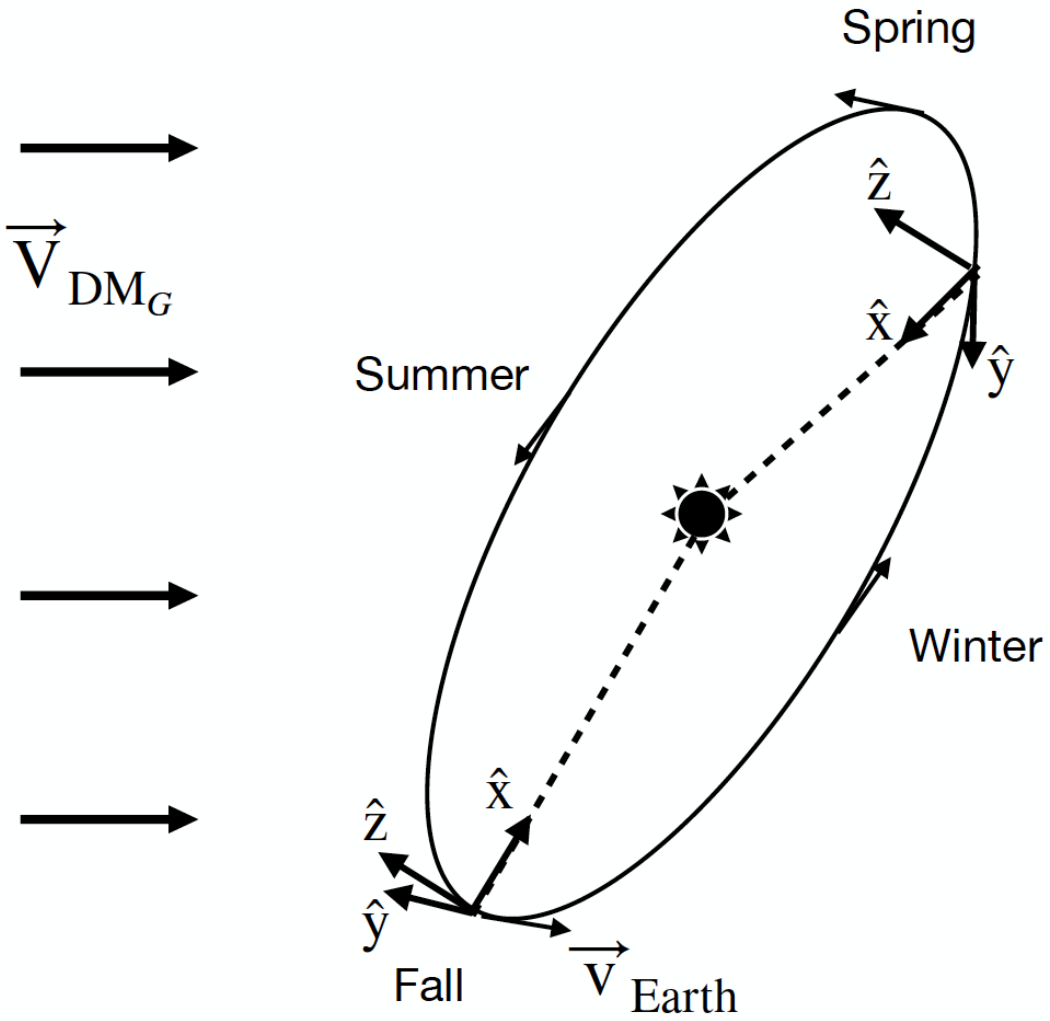
- Average velocity of the AQN-induced axions is very large $\langle v_a \rangle \simeq 0.6c$. The corresponding EM signal is expected to be very broad with $\Delta\nu \sim \nu$.

- For example: if $m_a \approx 1.25 \cdot 10^{-5}\text{eV} \approx 3\ \text{GHz}$ the EM band corresponds to $\nu \in (3 - 5.4)\text{GHz}$. It should be contrasted with conventional case $\Delta\nu/\nu \sim 10^{-6}$.

- It is obvious: a new broadband detection strategy must be implemented in one way or another.

- The DM flux shows the annual (and daily) modulations due to the presence of relative orientation of the Earth's velocity and axis of rotation and DM galactic wind (effect~ 10%):

$$\langle E_a \rangle \Phi_a^{\text{AQN}}(t) \simeq 10^{14} A(t) \left[\frac{\text{eV}}{\text{cm}^2\text{s}}\right] \qquad A_{(\text{a})}(t) \equiv [1 + \kappa_{(\text{a})} \cos\Omega_a(t - t_0)],$$



The annual modulations have been known for a long -long time. The source of the annual modulation is the difference in relative (with respect to the galactic wind) velocities during the summer and winter. It leads to difference in fluxes. The effect is estimated on the level of 10%

- 1. The idea is to separate entire frequency band into a number of smaller frequency bins $\Delta\nu_i$

- 2. The time dependent signal in each frequency bin has to be fitted according to the daily or annual modulation to extract fitting parameters $\kappa^i_{(\mathrm{a})}, \kappa^i_{(\mathrm{d})}$

$$A_{(\mathrm{a})}(t) \equiv [1 + \kappa_{(\mathrm{a})} \cos\Omega_a(t - t_0)], \qquad A_{(\mathrm{d})}(t) \equiv [1 + \kappa_{(\mathrm{d})} \cos(\Omega_d t - \phi_0)]$$

- 3.Let us assume that the modulation is recorded in some bin, say $\bar{i}$: such that $\kappa^{\bar{i}}_{(\mathrm{d})} \neq 0$ or/and $\kappa^{\bar{i}}_{(\mathrm{a})} \neq 0$

- 4. One should check that no modulation appears in other bins $i \neq \bar{i}$, no modulations appear for zero magnetic field B=0. One should also check a proper drift of the phase ϕ_0 with the seasons (to exclude any spurious signals)

- 5. There are few others (more sophisticated consistency checks) that the signal is not a spurious signal

5. $a \rightarrow \gamma$ conversion: galactic axions with $v_a \sim 10^{-3}\ c$ versus AQN-induced axions with $v_a \sim 0.6\ c$

- The standard rate of conversion is given by

$$P_{a\to\gamma} = \frac{1}{v_a}\left(\frac{gB}{q}\right)^2 \sin^2\left(\frac{qL}{2}\right), \quad q = \omega - \sqrt{\omega^2 - m_a^2}, \quad g \simeq \frac{g_\gamma \alpha}{f_a \pi}$$

- Resonant conversion corresponds to the case when $(qL) \ll 1$ and we arrive to usual form $P_{a\to\gamma} = v_a^{-1}(gBL/2)^2$

- For non relativistic axions one should multiply $P_{a\to\gamma}$ to the axion flux to arrive to

$$\Phi_\gamma = \frac{(\rho_a v_a)}{m_a} P_{a\to\gamma} \approx \frac{\rho_a}{m_a}\left[\frac{gB}{m_a}\sin\left(\frac{m_a L}{2}\right)\right]^2 .$$

- Φ_γ counts the number of microwave photons emitted per unit time from unit area. It does not depend on v_a at small v_a .

❖ Now consider the AQN-induced axions with $v_a \sim c$. There are several crucial elements which lead to dramatically different treatment of the relativistic axions:

❖ 1. The conventional treatment assumes the coherent conversion such that $P_{a\to\gamma} \propto L^2$. This scaling holds as long as $L \ll \lambda$ where $\lambda \sim (m_a v_a)^{-1}$ is De Broglie wave length where conversion occurs. If coherence persists up to scale $l < L$ the coherence enhancement is $L^2 \to Ll$

❖2. It should be contrasted with $v_a \sim c$ case when one should average over many cycles, i.e. $\sin^2(\frac{qL}{2}) \to 1/2$

❖3. The conversion is a result of a single elementary process when formation length is the Compton length $l \sim m_a^{-1}$. One should sum over effective "layers" along the axion path which produces factor $Ll \sim Lm_a^{-1} \gg 1$ for $v_a \sim c$.

- Therefore, conventional resonance formula for Φ_γ is replaced by

$$\Phi_\gamma^{\rm AQN}({\rm tot.}) \approx \frac{A}{2}\Phi_a^{\rm AQN} \cdot \left[\frac{gB}{m_a}\right]^2 \cdot (m_a L).$$

- Numerically, it can be represented as follows

$$\Phi_\gamma^{\rm AQN}({\rm tot.}) \approx 0.1A \left(\frac{g_\gamma}{0.97}\right)^2 \left(\frac{B}{10T}\right)^2 \left(\frac{L}{m}\right) \frac{\rm ph.}{\rm m^2 day},$$

- To detect such low rate requires single photon counters.

- Important point here is that the enhancement factor A(t) could be very large for a short period of time. For example, once a day one should expect $A(t) \sim 10^2$ lasting for 1 second as a result of a nearby passing AQN (at distance about 100 km).

- The power excess in unit volume is determined by

$$P_\gamma^{\rm AQN}({\rm tot.}) \approx A(t) \left(\frac{\langle \rho_a^{\rm AQN}\rangle m_a}{2}\right) \left(\frac{gB}{m_a}\right)^2 (m_a L).$$

- In conventional units it assumes the form

$$P_\gamma^{\rm AQN}({\rm tot}) \approx 10^{-26} A(t) \left(\frac{\rm Watt}{\rm m^3}\right) \left(\frac{g_\gamma}{0.97}\right)^2 \times \left(\frac{B}{10\ {\rm Tesla}}\right)^2 \left(\frac{L}{m}\right) \left(\frac{m_a}{10^{-4}{\rm eV}}\right)^2.$$

- It is instructive to compare this estimate with conventional formula for the power excess

$$P_a \propto 10^{-26} Q_\alpha ({\rm W/m^3}), \quad \frac{\Delta\nu}{\nu} \ll 1, \ \ {\rm cavity\ type\ exp.}$$

- The quality factor $Q_\alpha \sim 10^6$ in resonance cavities is absent in our case with $v_a \sim c$ (no narrow resonances).

- However, entire logic of collecting the signal and discriminating it from the noise and spurious signals is dramatically different from conventional treatment of the cavity type experiments.

- Broadband instruments could be a revolutionary step to implement this search strategy as it effectively removes or diminishes most of the spurious signals

- In particular, see talk by S.Knirck at "Patras-2021" or talk by A. Sonnenschein at "axions beyond Gen2- 2021" workshop (on instruments such as "BREAD", "dish antenna", "single photon counter" etc)

- Furthermore: the conventional analysis assumes that the galactic axions with any mass saturates the DM density. It obviously cannot be the case for large m_a when $\rho_{\rm DM} \sim m_a^{-7/6}$ to be contrasted with the AQN model when $\rho_{\rm DM} \sim \rho_{\rm B}$ for any m_a

Few key comments on daily modulations

- The daily modulations for WIMPs or any other fundamental particles (including galactic axions) are very tiny. Indeed, additional velocity is 0.5 km/s to be compared with velocity of galactic wind 220 km/s

- This is the main reason why the daily modulations were largely ignored in the past.

- It should be contrasted with the AQN prediction when the difference in sizes (AQN is a composite object) at the moment of **entry** and **exit** of the Earth's surface alters this conclusion.

- <u>Work in progress</u>: We are trying to incorporate these ideas on <u>daily modulations</u> by using the CAST-CAPP data

6. Telescope Array mysterious bursts

- Telescope Array (TA) experiment [Abbasi-2017] has recorded several bursts of air shower-like events. This bursts are very distinct from conventional single showers, and are found to be 100% correlated with thunderstorm. The unusual features are:

- *"clustering puzzle"*: Burst is defined as 3+ consecutive events within 1ms, which would be a highly unlikely occurrence for 3+ consecutive hits in the same area ~ 1km if interpreted as CR events

- If one tries to fit the observed bursts with conventional code for HECR events one should expect $10^{13}\mathrm{eV}$ energy range (based on frequency of appearance), while intensity suggests $10^{19}\mathrm{eV}$;

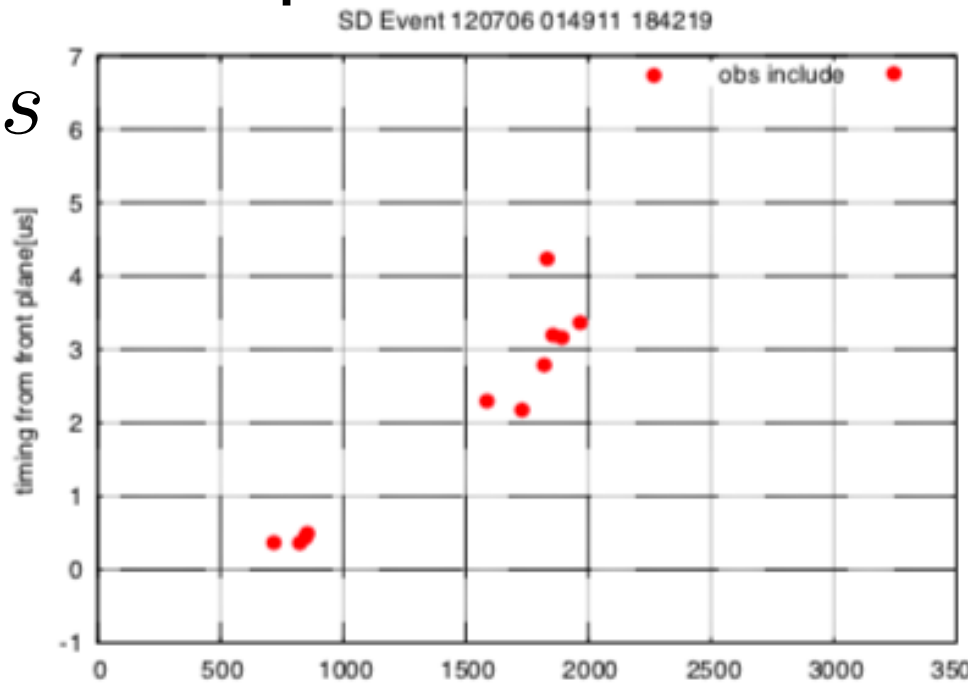
- *"curvature puzzle"*: All burst events are much more curved than usual CR air showers. Also: the edges in waveforms are dramatically different, *"edge puzzle"* (see two next slides);

- *"synchronization (with thunderstorm) puzzle"*: Most of the bursts are synchronized (less than 1 ms) or related (less than 200 ms) with the lightnings/flashes

- Some bursts are not related to lightings → they cannot be outcome of flashes. All of them observed under thunderstorm. The total 10 burst events have been observed during 5 years of observations;

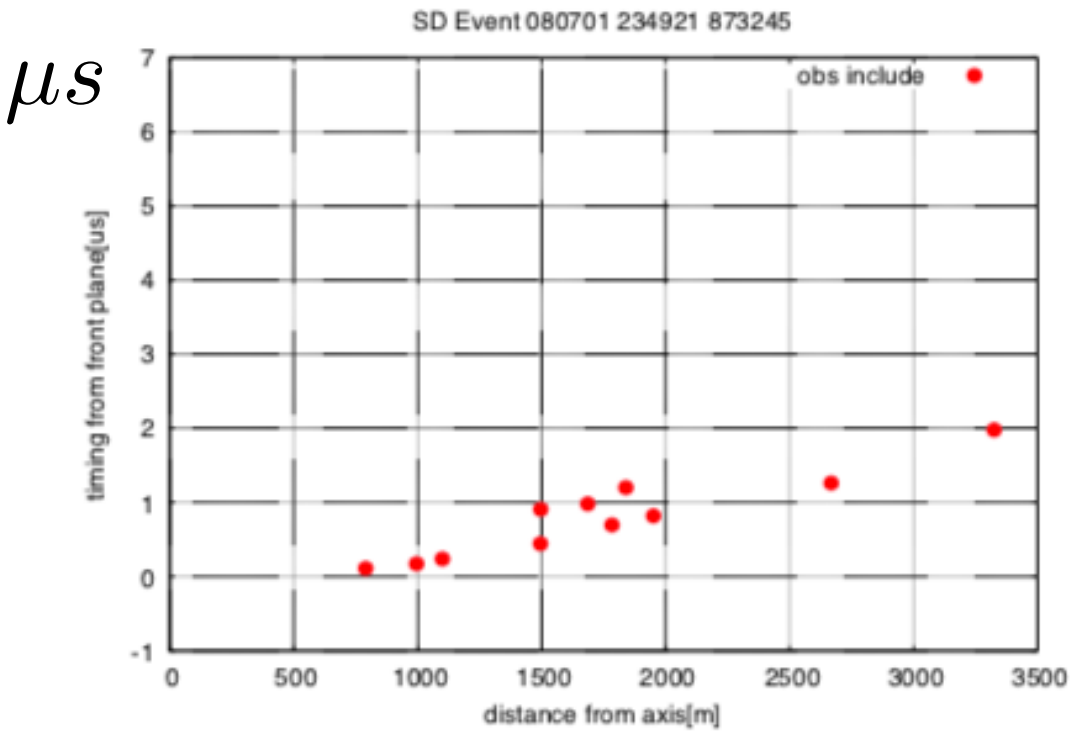
- Reconstructed bursts start at much lower altitude than conventional HECR showers (30km).

adopted from TA collaboration [Abbasi-2017]



typical burst event

$$\Delta s \in (0, 5 - 2)\mathrm{km},$$
$$\Delta \mathrm{t} \in (0 - 8)\mu\mathrm{s}$$

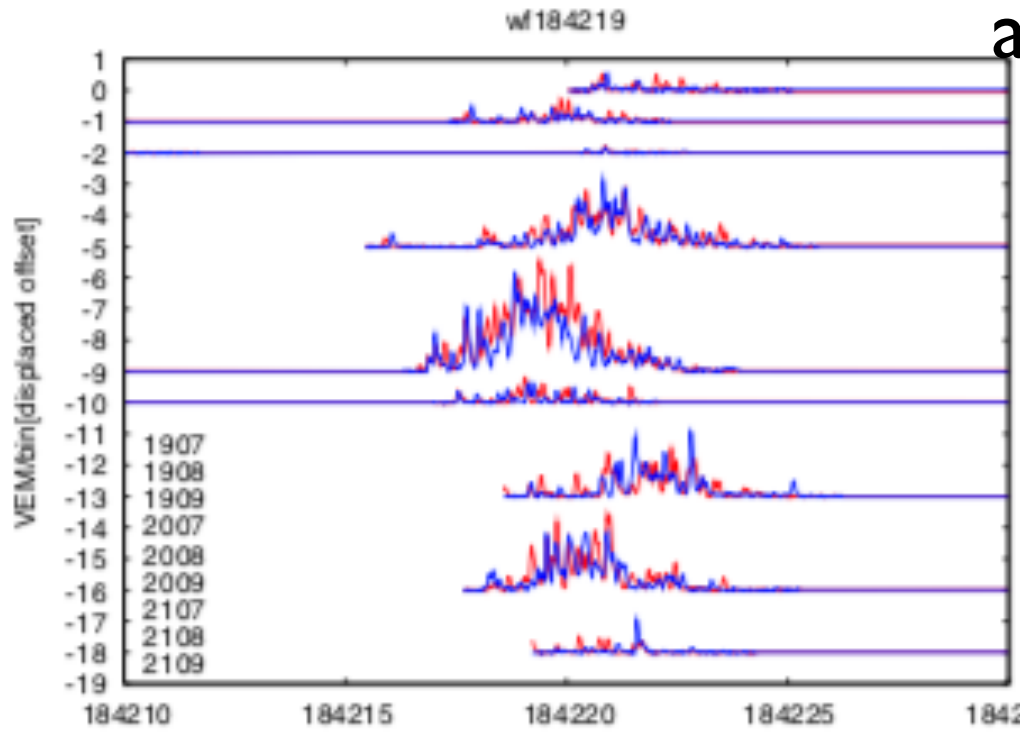


typical CR event

$$\Delta s \in (0, 5 - 3.5)\mathrm{km},$$
$$\Delta \mathrm{t} \in (0 - 2)\mu\mathrm{s}$$

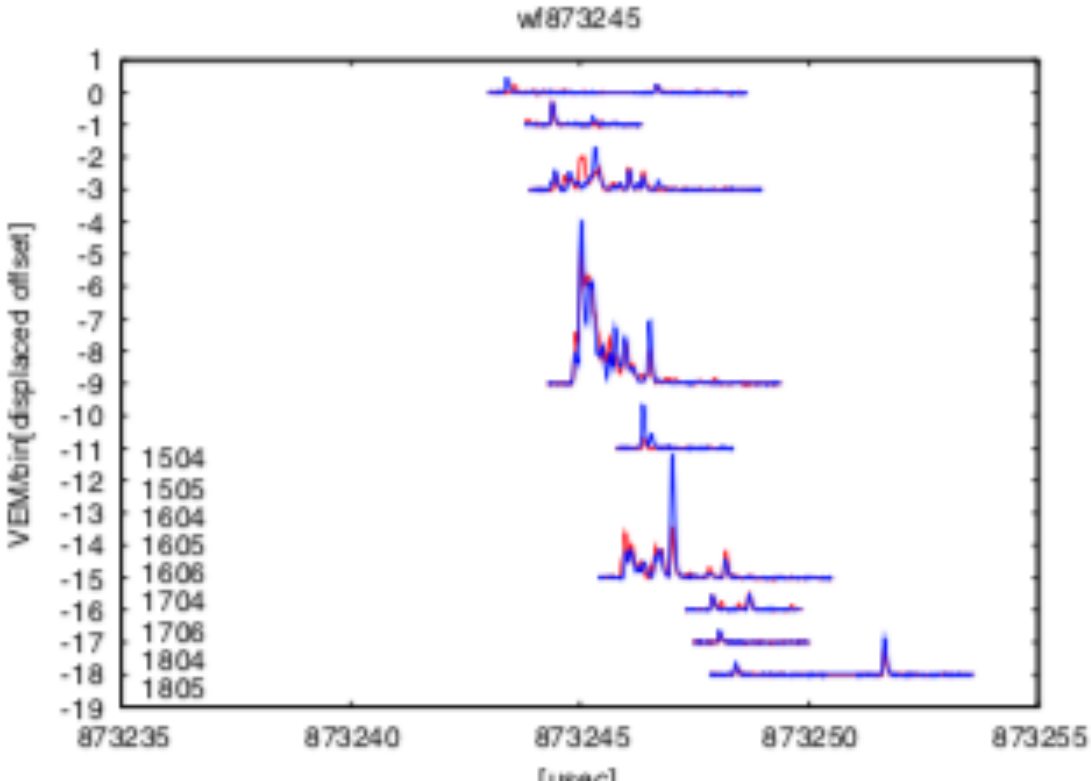
The "curvature puzzle"

adopted from TA [Abbasi-2017]



μs

← - - typical burst event



μs

← - - typical CR event

The "edge puzzle"

7. Mysterious bursts as the AQN annihilation events under thunderstorm

- When the AQN propagates in atmosphere it experience a large number of annihilation events with surrounding material

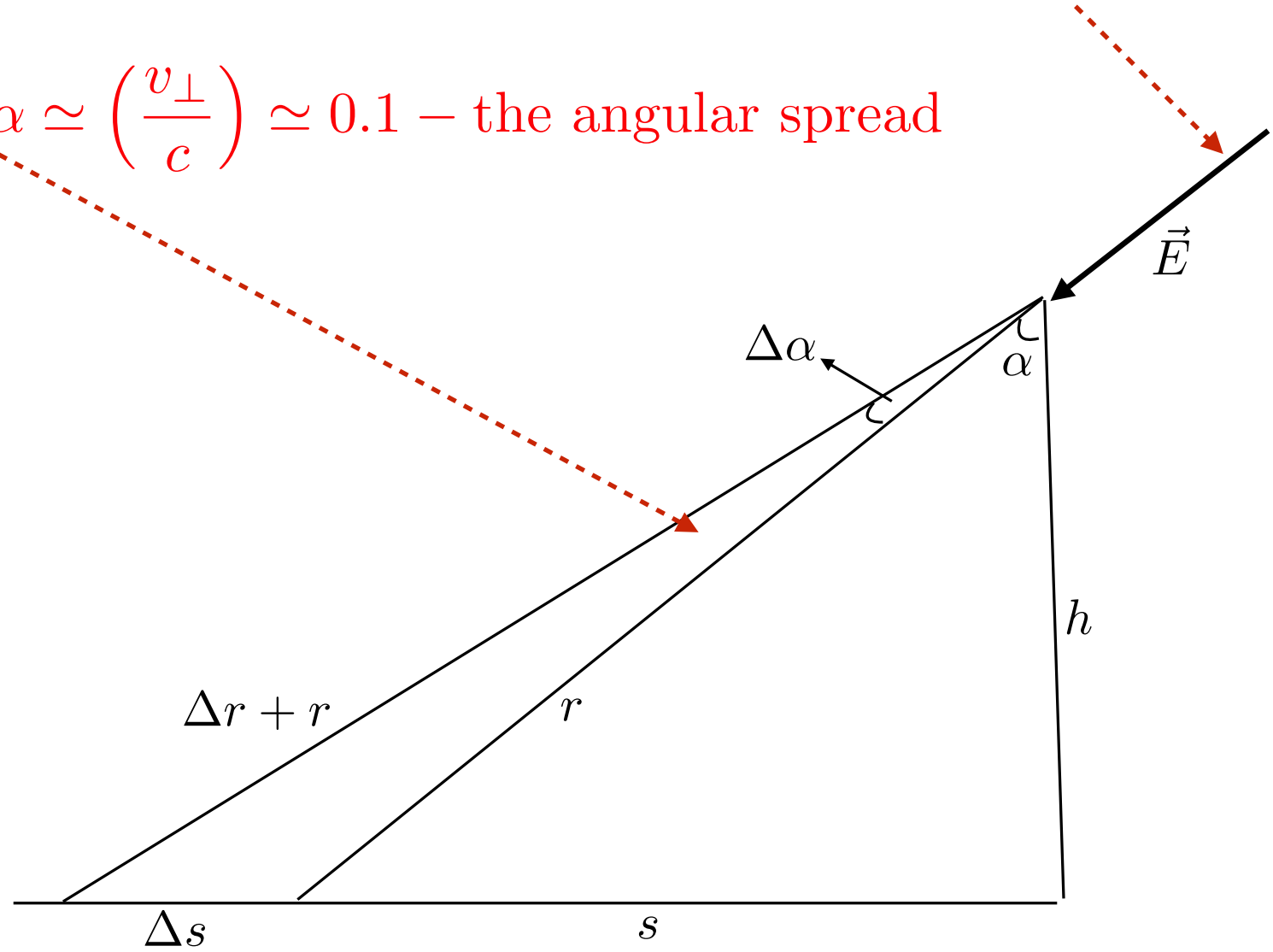
- If the AQN hits the region under thundercloud the weakly bound positrons localized away from the nugget's core may be liberated by pre-existing electric field **E~kV/cm** which is known to exist

- As a result of strong electric field the positrons will accelerate to energies ~ 10 MeV on scales of order $l_a \sim 100$ m (so called avalanche scale)

- The mean free path for such energetic positrons is of order several km, so they can reach the TA detector

Instant direction of the electric field at the moment of exit

$\Delta\alpha \simeq \left(\frac{v_\perp}{c}\right) \simeq 0.1$ – the angular spread



Δs - Spatial spread on the surface, observed by TASD

- The positrons travelling the distance r the spatial spread Δs is estimated as

$$\Delta s \simeq r\left(\frac{\Delta\alpha}{\cos\alpha}\right) \simeq \frac{1\ \mathrm{km}}{\cos\alpha}\left(\frac{r}{10\ \mathrm{km}}\right)$$

- The time spread of the arriving particles is determined by Δr and estimated as follows

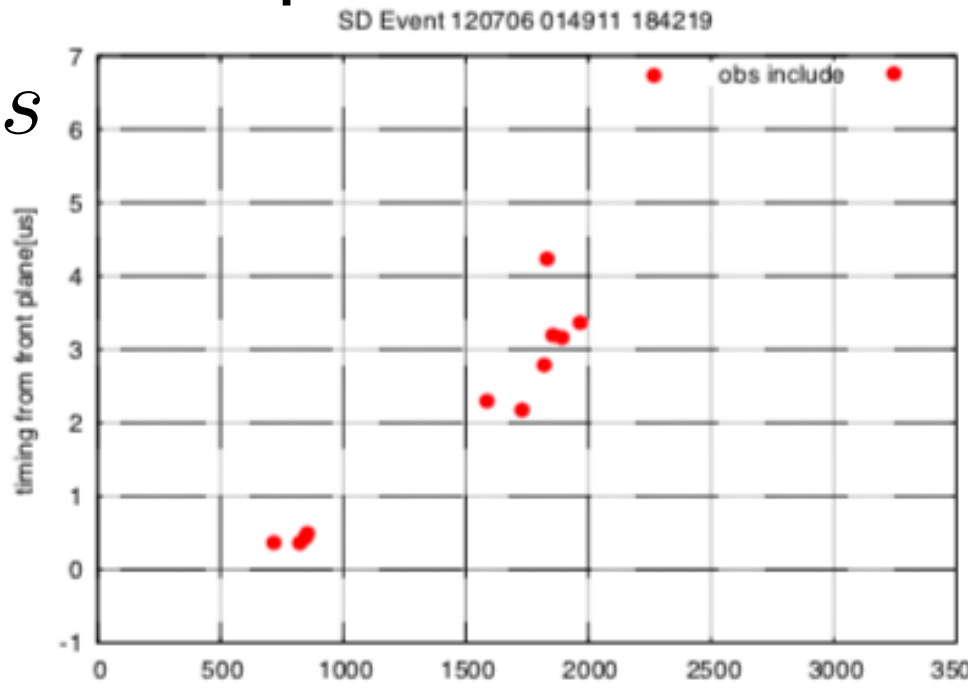
$$\Delta t \simeq \frac{\Delta r}{c} \simeq 3\mu s\cdot(\tan\alpha)\cdot\left(\frac{r}{10\ \mathrm{km}}\right) \text{ where } \Delta r \simeq r\tan\alpha\Delta\alpha$$

- Important: the basic scale is $v_\perp \simeq 0.1c$ which is not present in conventional CR analysis

$(2\Delta t)$ varies $(0-8)\mu$s when $(2\Delta$s$)$ changes between $(0.5-2)$ km

- It is consistent with observations. It represents resolution of "*the curvature puzzle*" within AQN model

adopted from TA collaboration [Abbasi-2017]



typical burst event

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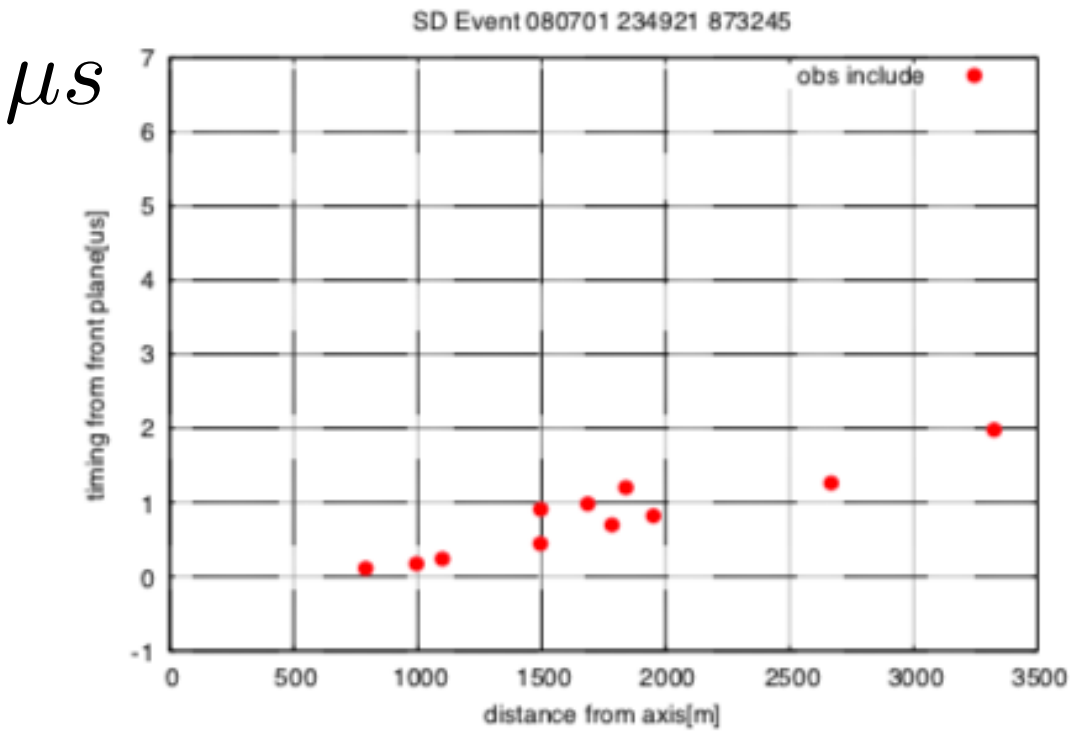


typical CR event

$$\Delta s \in (0, 5 - 3.5)\mathrm{km},$$
$$\Delta \mathrm{t} \in (0 - 2)\mu\mathrm{s}$$

The "curvature puzzle"

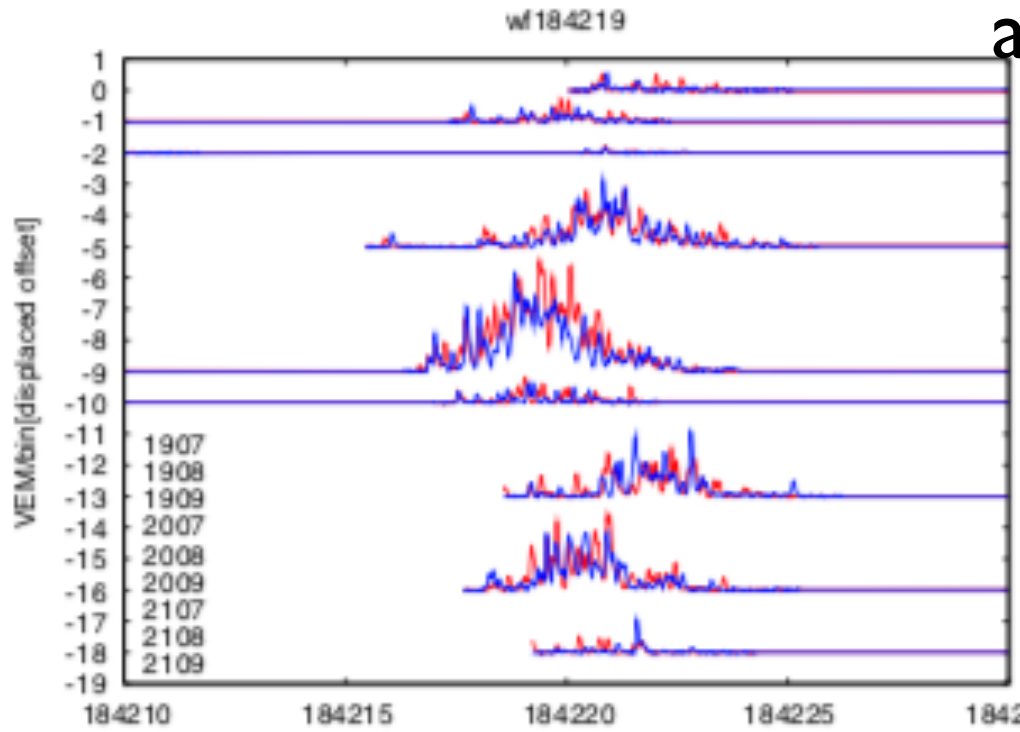
- All bursts are observed under the thunderstorm. It is hard to understand how CR may "know" about the thunderstorms. In AQN framework the electric field plays the key role by liberating the positrons which mimic the CR events (this resolves "*synchronization puzzle*".

- The AQN traverses a short distance ~0.25km during the burst $10^{-3}s$ which is treated as a cluster of events when the electric field fluctuates on the scale of along the AQN's path $10^{-6}s$ (it resolves "*clustering puzzle*")

- Occurrence of 3+ intense events during $10^{-3}s$ in 1km area is hard to explain with conventional CR assumption (it resolves "*clustering puzzle*")

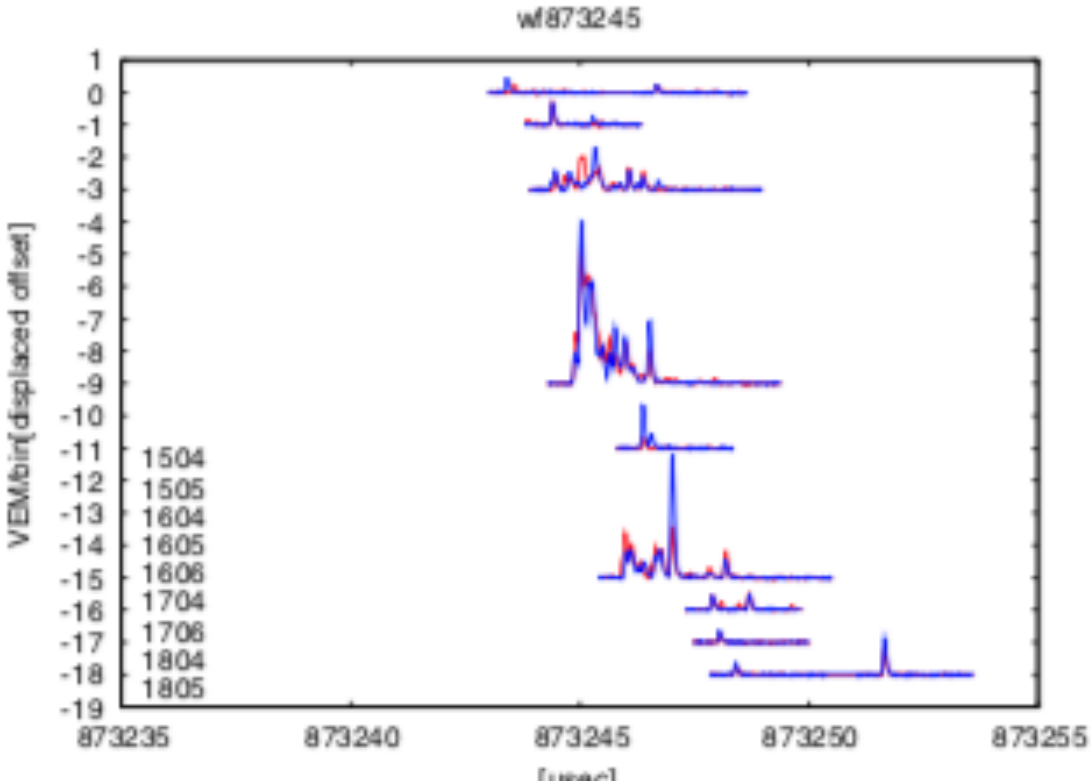
- Conventional CR showers have an ultra relativistic particle (sharp edge in waveforms). Large number of positrons produce non-sharp edge, resolving "*edge puzzle*"

adopted from TA [Abbasi-2017]



μs

← - - typical burst event



μs

← - - typical CR event

The "edge puzzle"

- Possible Tests of this AQN based proposal:

- 1. We suggest to reanalyze existing data by extending the cutoff time scale for the definition of the burst $\Delta t_{\rm burst} = 1$ ms. One should expect more events within the bursts when $\Delta t_{\rm burst}$ is longer

- 2. We predict a unique radio signal **synchronized** with the mysterious bursts. This is because TA burst and radio emission are originated from the same location emitted at the same time and propagate with the same speed of light.

- This signal should be in the bandwidth $\nu \in (0.5 - 200)$MHz with amplitude $|E| \sim 20$ (mV/m) of the corresponding electric field and its duration $\tau \sim 0.3 \mu s$ at distance $R \sim 10$ km

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)

- $\Omega_{\rm dark} \sim \Omega_{\rm visible}$ 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 framework when the dark matter and visible components are proportional to one and the same fundamental $\Lambda_{\rm QCD}$ scale.

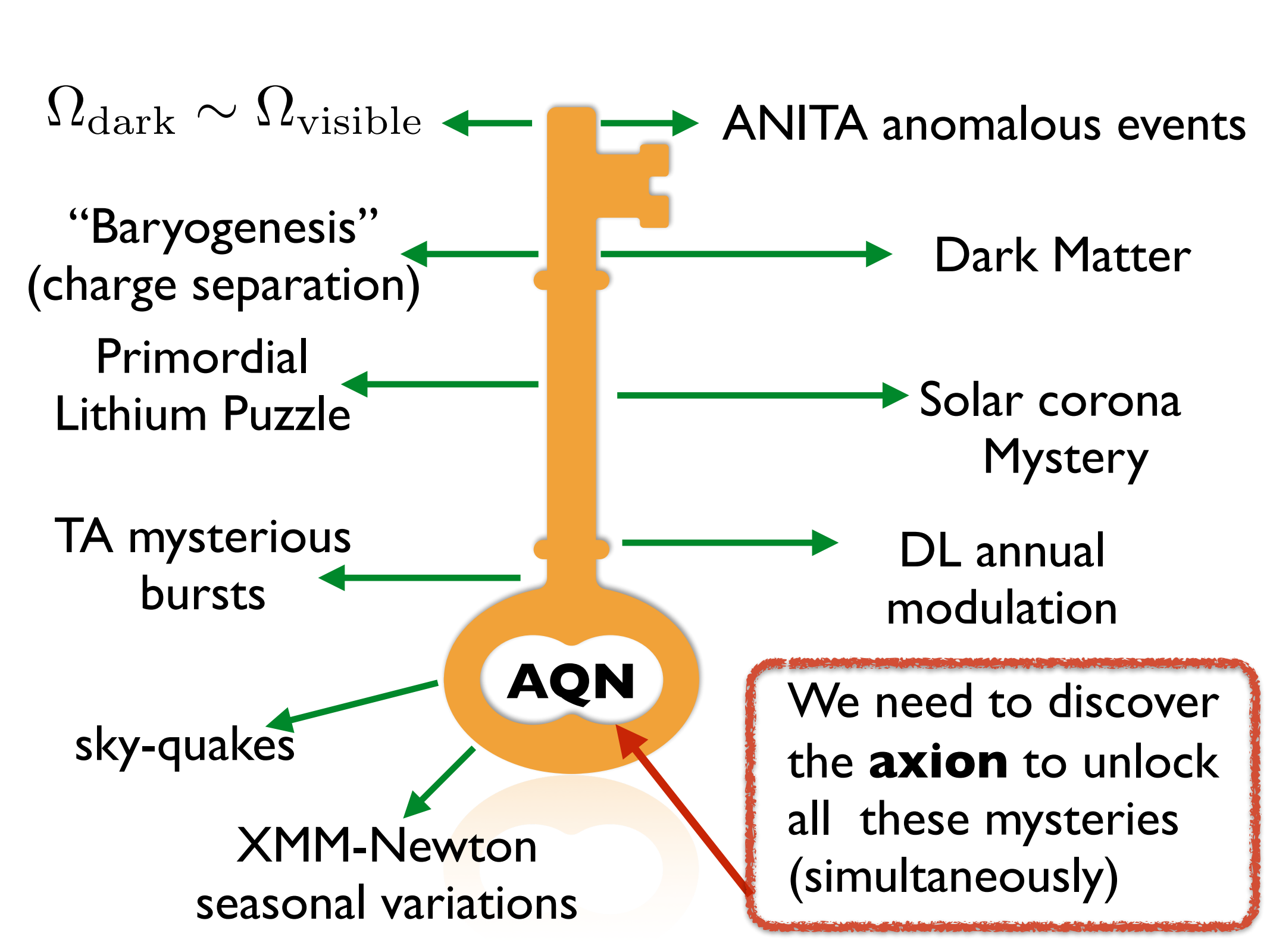
- This model offers a simultaneous resolution of a number (naively unrelated) old mysteries: DM, baryogenesis, solar corona mystery, primordial Lithium, Telescope Array mysterious bursts, etc

- 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 $v_a \simeq 0.6\ c$.

- **Broadband** detection technique must be implemented to search for such axions.

- **Daily modulation** is a powerful tool to analyze the data to remove spurious and noise signals (work in progress with CAST-CAPP data).

- The discovery of the axions with $v_a \simeq 0.6\ c$ will be **direct** manifestation of the AQN framework (in contrast with **indirect** observations such as Baryogenesis, Lithium puzzle, solar corona mystery, galactic 511 keV, XMM -Newton seasonal variations, etc)


$\Omega_{\rm dark} \sim \Omega_{\rm visible}$
ANITA anomalous events
"Baryogenesis"
(charge separation)
Dark Matter
Primordial
Lithium Puzzle
Solar corona
Mystery
TA mysterious
bursts
DL annual
modulation
AQN
sky-quakes
XMM-Newton
seasonal variations
We need to discover the **axion** to unlock all these mysteries (simultaneously)