DAMA/LIBRA annual modulation and Axion Quark Nugget (AQN) Dark Matter Model

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“Marcel Grossmann -16”, DM6—session, July 7, 2021

This talk is mostly based on two my recent papers on DAMA-LIBRA results and some mysterious events recorded by Telescope Array

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The mysterious bursts observed by telescope array and axion quark nuggets

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

- There are two (apparently unrelated) phenomena:

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

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

- many other **observed** 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

- I specifically focus today on two consequences of this model:
  1. Observed DAMA-LIBRA annual modulation
  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" $\longrightarrow$ "New phases" (dense colour superconductor) of "Old Fields"

- Instead of "Baryogenesis" $\longrightarrow$ "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

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

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.

E. Witten

New element to rescue the nugget's idea: **the axion**. We call the objects the axion quark nugget (**AQN**).

- 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.

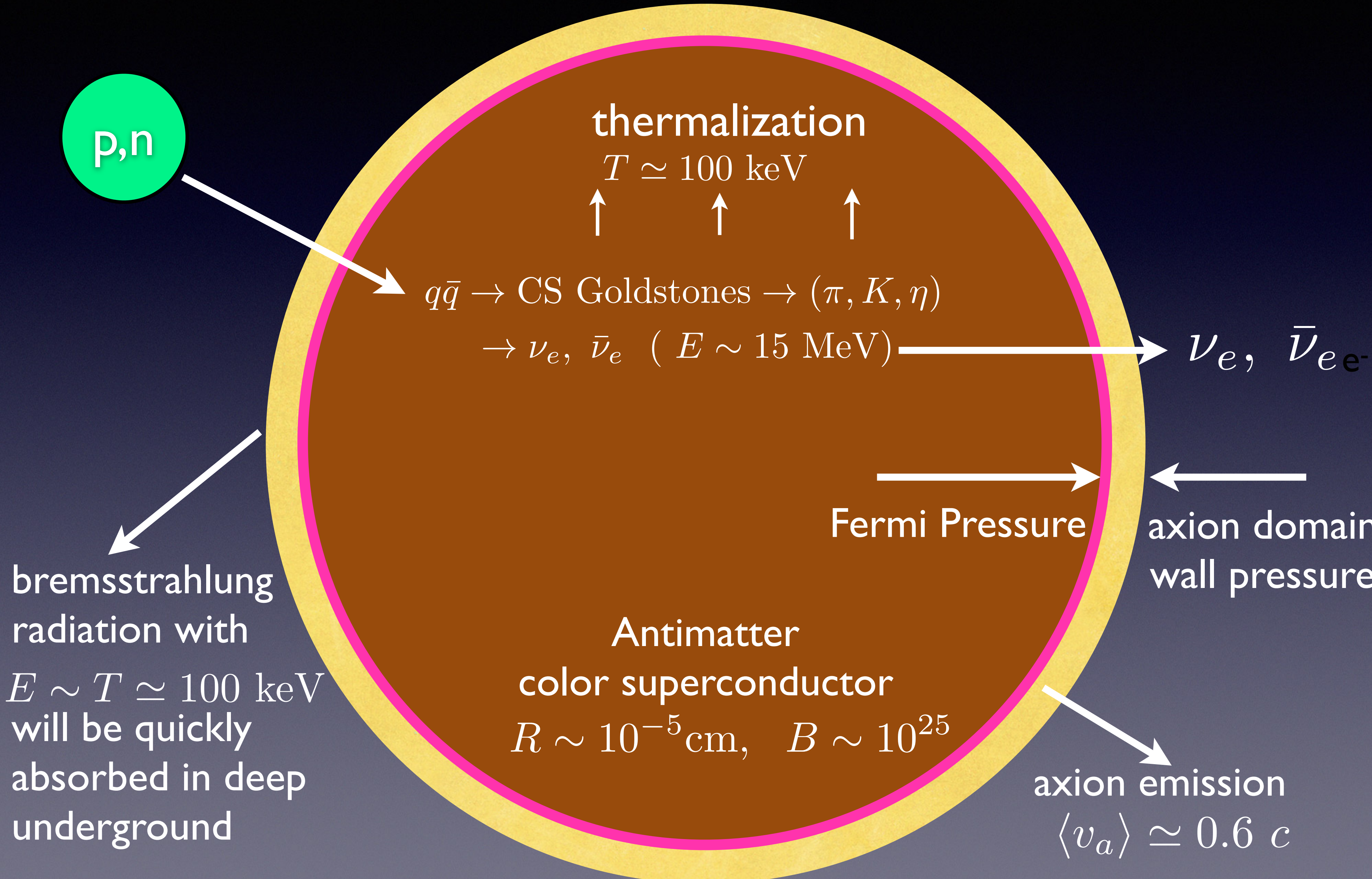
- 2. there are two species, the nuggets and **anti-nuggets**. The size is determined by m_a as $R \sim m_a^{-1}$

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

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

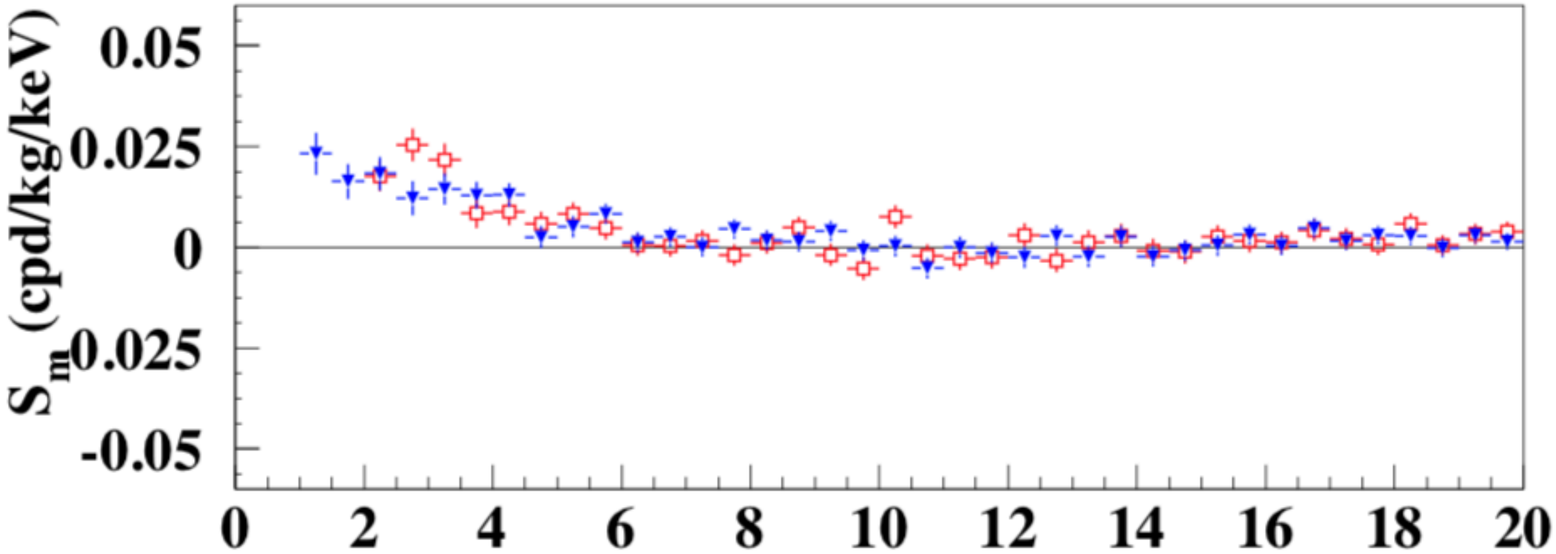
- Cosmological **CP-odd** axion field generates the **disparity** between two species at $\theta \neq 0$ which implies the similarity between **dark and visible** sectors: $\Omega_{\rm dark} \approx \Omega_{\rm visible} \sim \Lambda_{\rm QCD}$

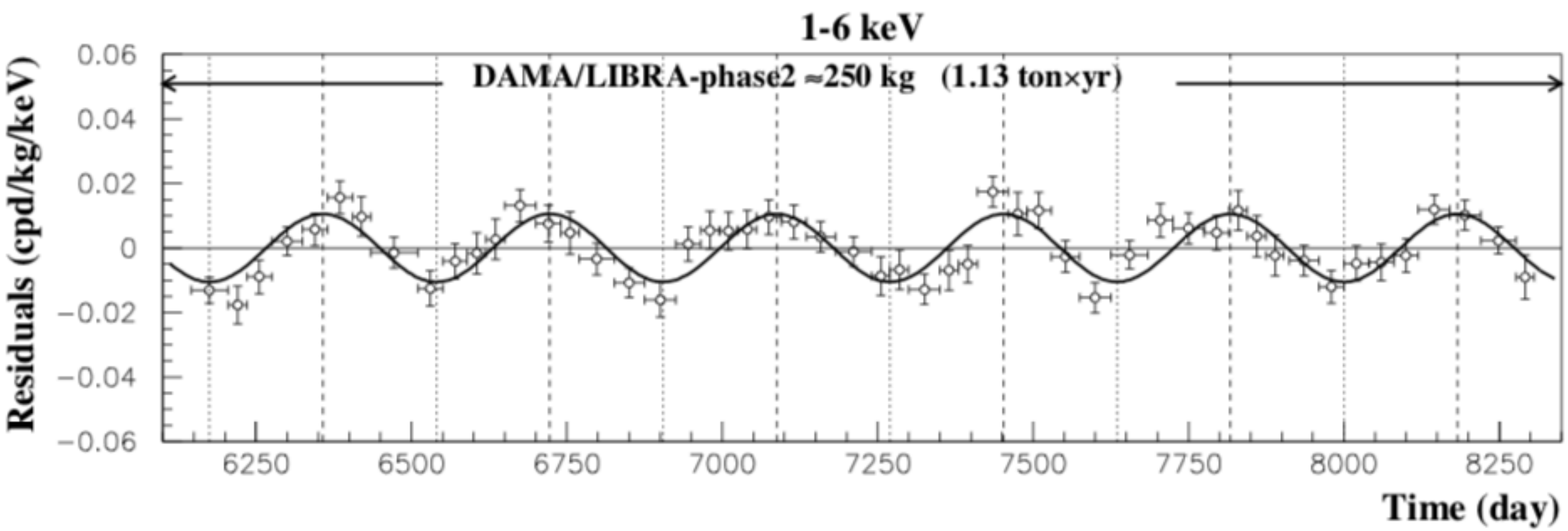
AQN traversing the deep Earth interior. The axion and neutrino emissions



3. DAMA/LIBRA annual modulation. An Overview

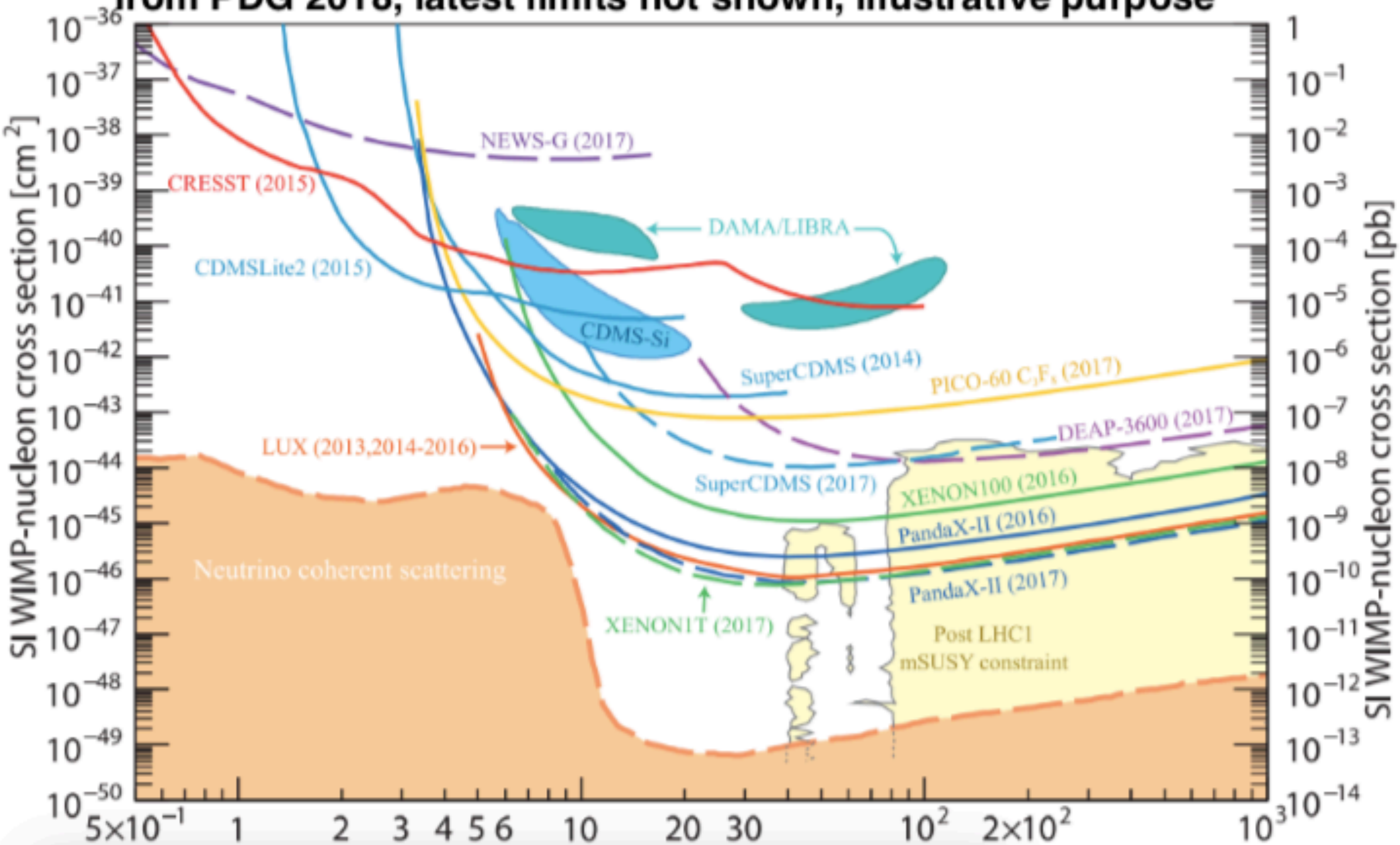
- DAMA/LIBRA (DL) experiment claims the observation for an annual modulation in (2-6) keV range at 12.9 sigma;
- The measured period (0.999 ± 0.001) and the phases (145 ± 5) strongly indicates the DM origin of the modulation;
- However the annual modulation observed by DL is excluded by other direct detection experiments if interpreted in terms of the WIMP-nuclei interactions





Significance : $> 11.9\sigma$ Universe 4 (2018) 116

***from PDG 2018, latest limits not shown, illustrative purpose**



4. DL annual modulation and AQN model

- The goal here is to offer a resolution (within AQN framework) of the DL controversy.

- Our basic claim is that the annual modulation observed by DL has <u>truly genuine DM origin</u>, though it is manifested <u>indirectly</u> through the following chain:

$$\boxed{\mathrm{AQN} \rightarrow (\text{neutrinos}) \rightarrow (\text{surrounding neutrons}) \rightarrow \mathrm{DL}.}$$

- Important: we shall not modify any parameters from our previous studies (excess of galactic emission, primordial lithium, solar corona heating) to fit DL

- In particular, the neutrino spectrum and intensity emitted by AQNs (which eventually determine $(1-6)$ keV energy recoil) have been computed long ago for completely different purposes

- Total hit rate for entire Earth's surface is:

$$\langle \dot{N} \rangle \simeq 0.67 \ \mathrm{s}^{-1} \left(\frac{\rho_{\mathrm{DM}}}{0.3 \frac{\mathrm{GeV}}{\mathrm{cm}^3}} \right) \left(\frac{\langle v_{\mathrm{AQN}} \rangle}{220 \ \frac{\mathrm{km}}{\mathrm{s}}} \right) \left(\frac{10^{25}}{\langle B \rangle} \right).$$

- The corresponding neutrino flux is estimated as

$$\frac{dN_\nu}{dt dA} \simeq 0.6 \cdot 10^6 \cdot \kappa_\nu \cdot \left(\frac{\langle \Delta B \rangle}{\langle B \rangle} \right) \frac{1}{\mathrm{cm}^2 \cdot \mathrm{s}}, \qquad \left(\frac{\langle \Delta B \rangle}{\langle B \rangle} \right) \sim 0.3$$

- Parameter κ_ν describes the number of produced neutrinos per single annihilation event (with B=1)

- It is instructive to compare the AQN-induced flux with the (solar) flux in this $E_{\nu,\bar{\nu}} \lesssim 15 \mathrm{MeV}$ energy band. The largest flux comes from ^8B which is about

$$\Phi_{\nu_e} \simeq 5 \cdot 10^6 (\mathrm{cm}^{-2} \mathrm{s}^{-1})$$

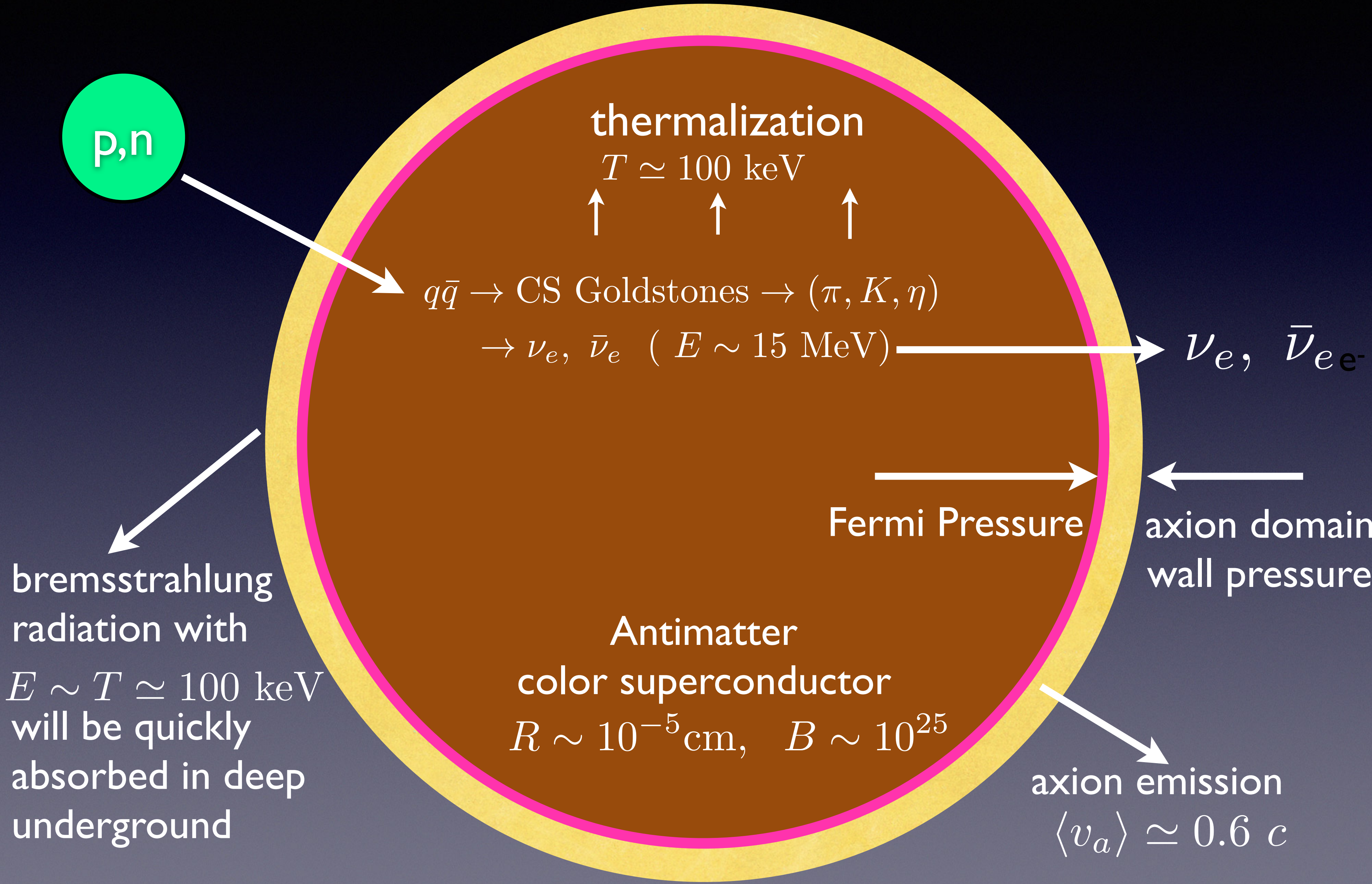
- The neutrino spectrum $E_{\nu,\bar{\nu}} \lesssim 15\text{MeV}$ is basically determined by the masses of the Nambu-Goldstone bosons in CS phase (computed long ago), see slide:

$$m_{\pi,K,\eta}(CS) \sim 20 \text{ MeV to be contrasted with } m_{\pi} \sim 140 \text{ MeV}$$

- The neutrino AQN-induced flux could be only slightly below than ^8B dominant ν_e solar flux in this energy band even at $\kappa_\nu \sim 10$. It is not ruled out by any experiment.

- The key point is as follows: the AQN-induced ν_e subdominant flux is the subject to the annual modulation as it has inherent DM origin. It can be discriminated from the solar ^8B-generated ν_e flux

AQN traversing the deep Earth interior.
The axion and neutrino emissions



- The AQN-induced neutrinos will liberate the neutrons from surrounding rocks with the rate:

$$r_\nu^{AQN} \simeq 10^{-2} \cdot \kappa_\nu \left[\frac{\text{neutron}}{\text{day} \cdot \text{m}^3}\right].$$

- The typical energy distribution (with a sharp cutoff) of these neutrons will be

$$E_n \simeq \frac{\mathbf{p}_n^2}{2m_n} \sim 10^2 \text{ keV}, \qquad \mathbf{p}_n \simeq (\mathbf{p}'_\nu - \mathbf{p}_\nu)$$

- The sharp cutoff $\sim 10^2$ keV is determined by the ν_e energy (which itself is determined by NG) ~ 15 MeV

- We emphasize again: all these scales have not been "invented" to fit the recoil energy observed by DM modulation signal $\Delta E_{\text{recoil}} \simeq (1-6)$ keV

- We estimate the energy transfer ΔE as a result of elastic scattering when $m_2 \simeq 23\ m_1$ is sodium mass for the lightest Na nucleon from DL detector:

$$\Delta E = 2E_n \frac{m_1 m_2}{(m_1+m_2)^2}\left(1-\cos\theta_{\mathrm{CM}}\right) \simeq 8.6\ \mathrm{keV}\left(1-\cos\theta_{\mathrm{CM}}\right).$$

- The recoil energy cannot exceed this value, which is amazingly close to 6 keV cutoff **observed** by DL.

- Intensity: the DL **observed** modulation

$$\mathrm{DL\ total\ modulation} \simeq 10\left[\frac{\mathrm{counts}}{\mathrm{day}}\right].$$

- to be compared with

$$\mathrm{AQN-\ \ induced\ modulation} \simeq \kappa_\nu\left[\frac{\mathrm{neutrons}}{\mathrm{day}}\right]\left(\frac{L}{10\ \mathrm{m}}\right)^3$$

- The parameter L in this formula describes the effective volume from surrounding rocks when the neutrons may affect the DL detector's count.

- It is very hard nuclear physics problem to compute the L (due to the resonances). The parameter L must be measured.

- The prediction is consistent with DL counting for parameter $\kappa_\nu \sim 10$ (number of neutrinos from a single event of the AQN-annihilation)

- The AQN-induced neutrino flux is by factor (5-10) lower in comparison with solar ^8B. However, the key point is that this subdominant neutron AQN-induced component is subject to annual modulation

- Several new experiments may soon resolve this controversy related to DL observations.

- 1. The **COSINE-100** collaboration uses the same target medium (sodium iodide). It is inconsistent with DL results if interpreted in terms of the WIMP-nuclei interactions

- 2.**CYGNO** is capable to measure the directionality. It is expected to be installed at LNGS by fall 2021. They will measure environmental neutron flux (including directionality, and time modulation)

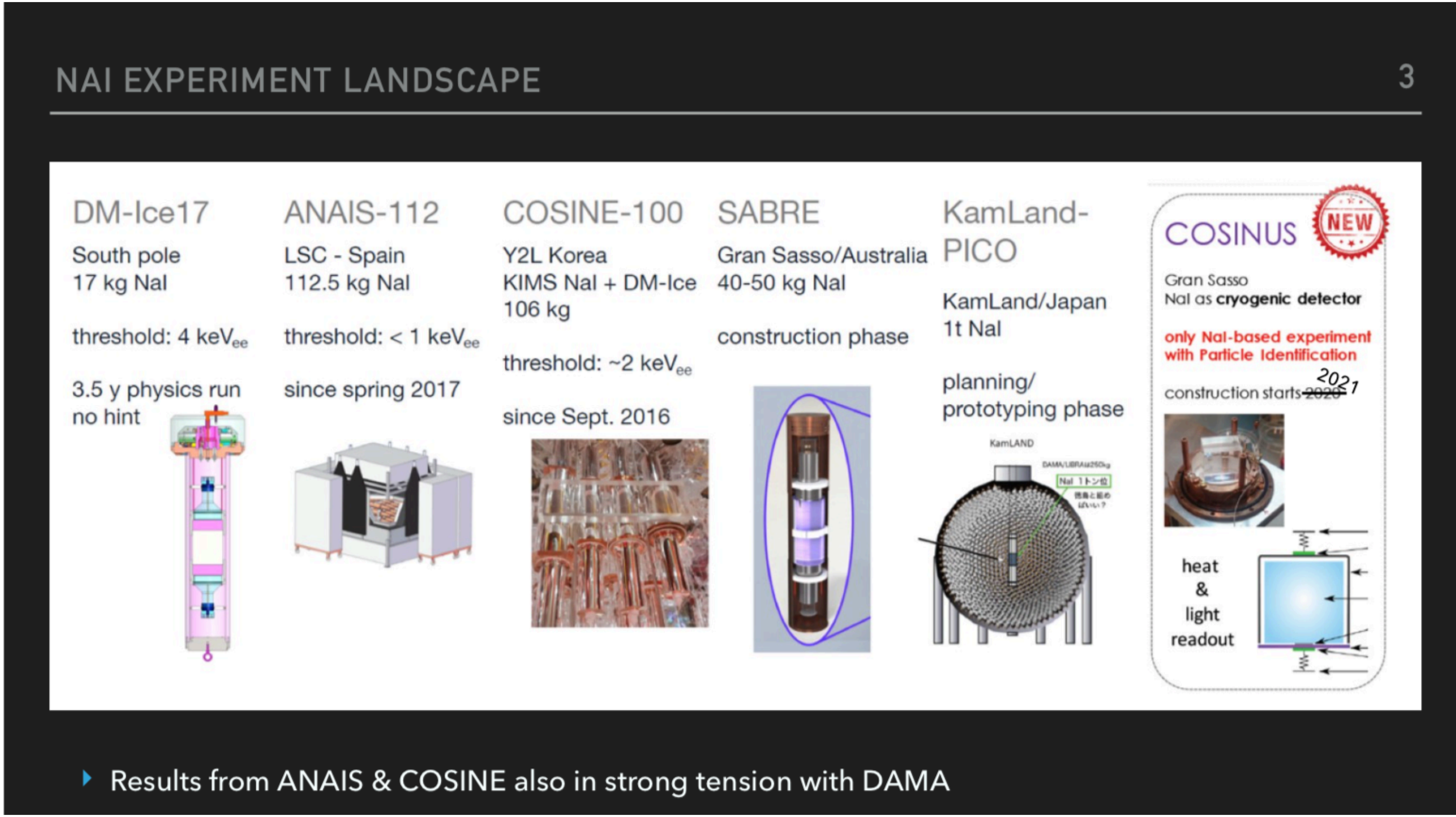
- 3.The **ANAIS-112** collaboration also uses the same target material. The goal is to reach the sensitivity at level 3σ for 5 years of data. Present sensitivity:

$$2.5\ (2.7)\sigma \text{ for } 1-6\ (2-6)\ \text{keV}$$

I specifically requested (and was promised) to collect some data without neutron shielding, which may prevent the AQN-induced neutrons (generating the annual modulation) to enter the detectors

ACKNOWLEDGMENTS *(from my PRD paper)*

I am thankful to G. Adhikari for answering my questions on the present status and future plans for the COSINE-100 Collaboration (see footnote 10) and Elisabetta Baracchini for elaboration on future plans for the CYGNO Collaboration (see footnote 11) during the PATRAS-2019 axion meeting in Freiburg. I am thankful to Maria Martinez [ANAIS-112] and Elisabetta Baracchini [CYGNO] for correspondence. I am also thankful to Hyunsu Lee [COSINE] and Maria Luisa Sarsa [ANAIS-112] for discussions



Other NaI experiments. Slide from a COSINUS presentation at the PATRAS-2021 meeting

5. Comments on DL and other experiments

- The most other existing experiments exclude DL signal **if interpreted** in terms of **WIMP** models;
- Very different neutron shieldings are used in different experiments;
- Recoil energy for heavier targets (such as xenon) could be below threshold;
- New experiments such as COSINE-100, CYGNO, ANAIS-112 may confirm this proposal on annual modulations **if** the neutron shielding is removed
- It can be tested by measuring the directionality, modulation and intensity of the surrounding neutrons

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 $10^{19}\mathrm{eV}$;

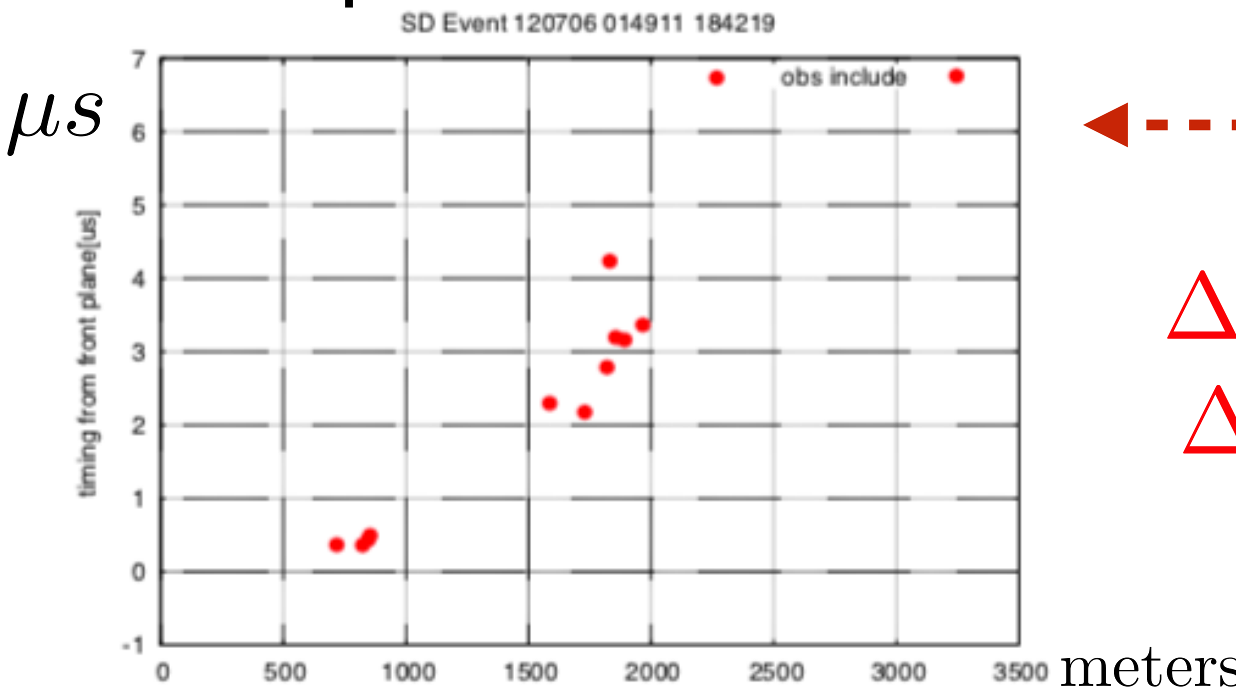
- *"curvature puzzle"*: All burst events are much more curved than usual CR air showers. Also: the edges in waveforms are dramatically different, *"edge puzzle"* (see two next slides);

- *"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 lightnings→ 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;

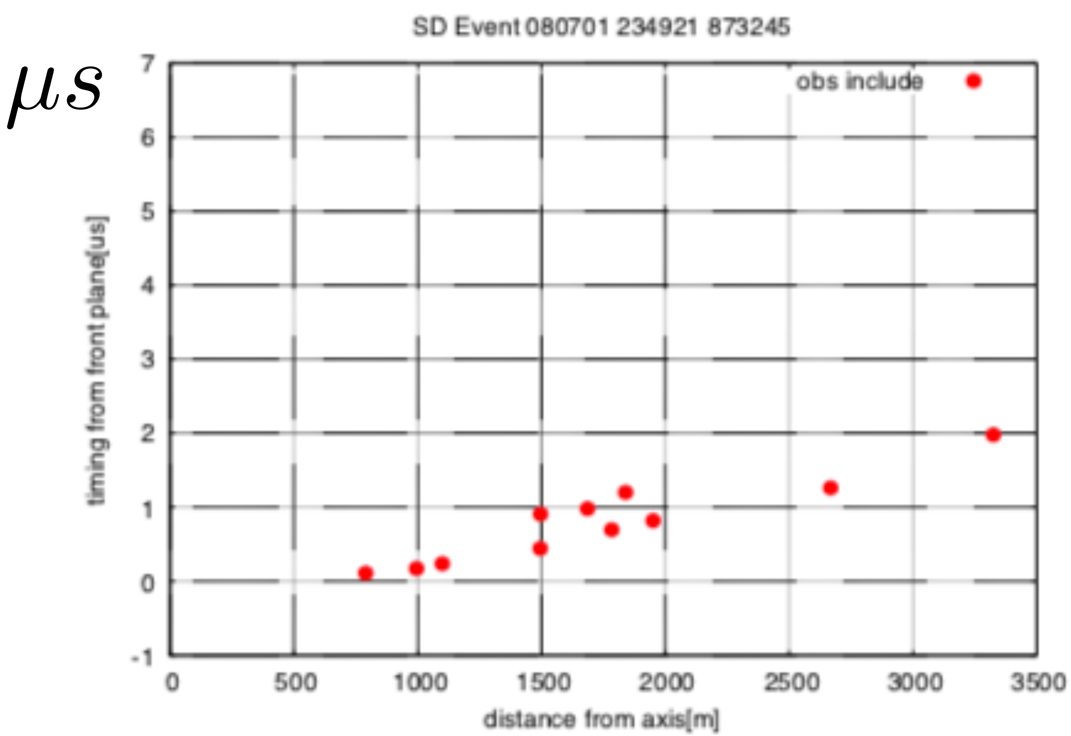
- Reconstructed bursts start at much lower altitude than conventional HECR showers (30km).

adopted from TA collaboration [Abbasi-2017]



◀- - - - - typical burst event

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

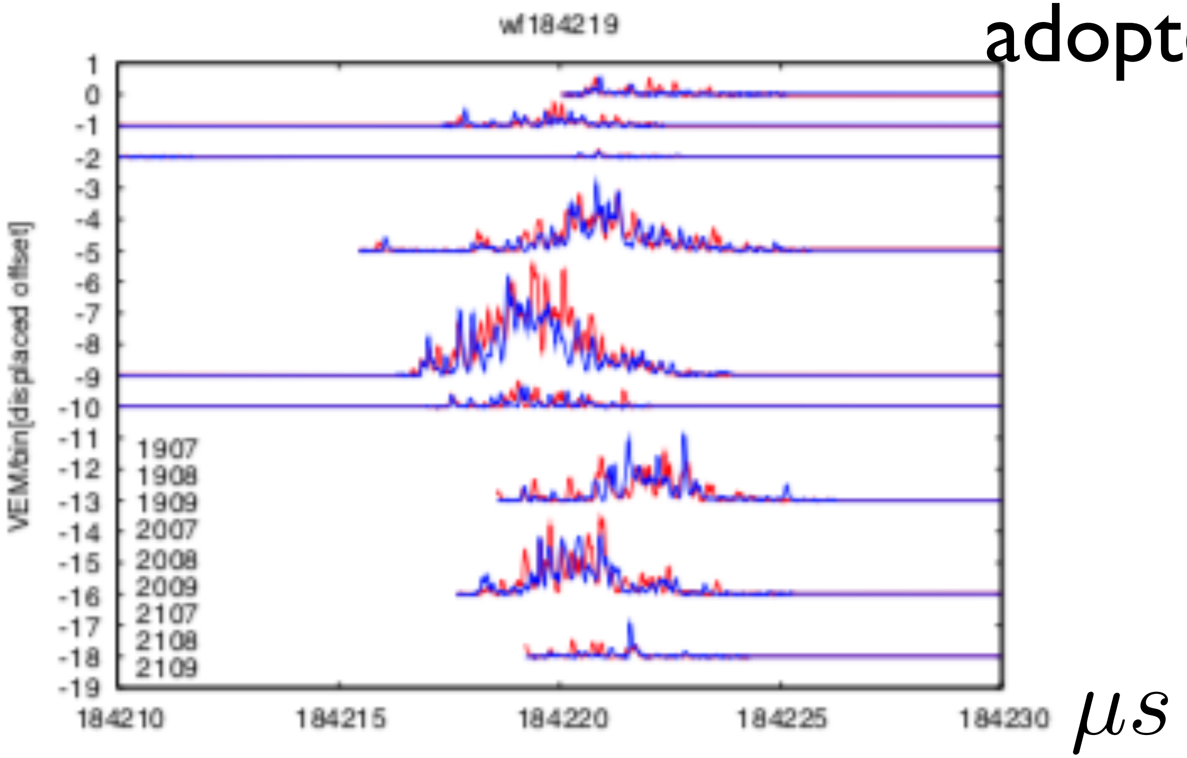


◀- - - - - typical CR event

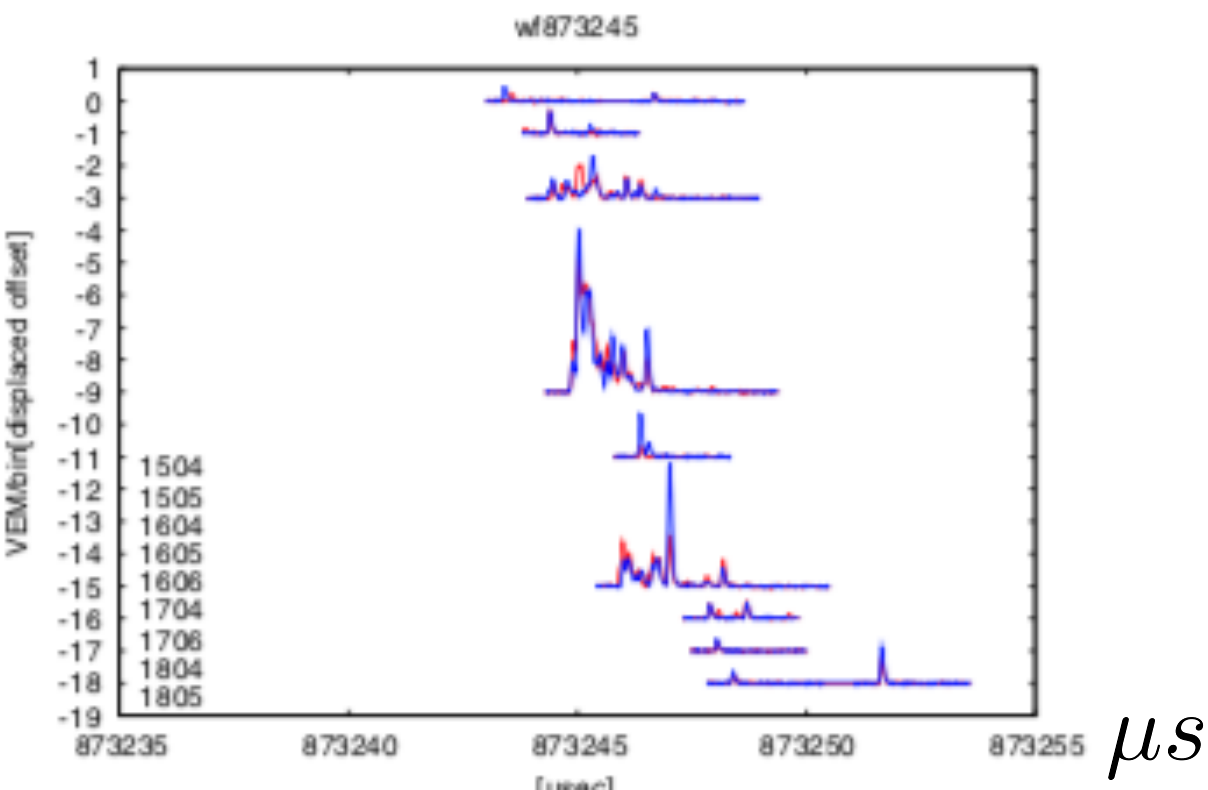
$$\Delta s \in (0, 5 - 3.5)\mathrm{km},$$
$$\Delta \mathrm{t} \in (0 - 2)\mu\mathrm{s}$$

The "curvature puzzle"

adopted from TA [Abbasi-2017]



typical burst event



typical CR event

The “edge puzzle”

a journalist published a story about my paper .
I better show few slides by myself

physicsworld

DARK MATTER AND ENERGY RESEARCH UPDATE

Cosmic-ray detector might have spotted nuggets of dark matter

21 Jan 2021

Scanning the sky: the Middle Drum facility of the Telescope Array observatory in the Utah desert. Could anomalous signals seen by the observatory be evidence for axion quark nuggets? (Courtesy: Ben Stokes/University of Utah)

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. Internal temperature: $T \sim 10 \text{ keV}$

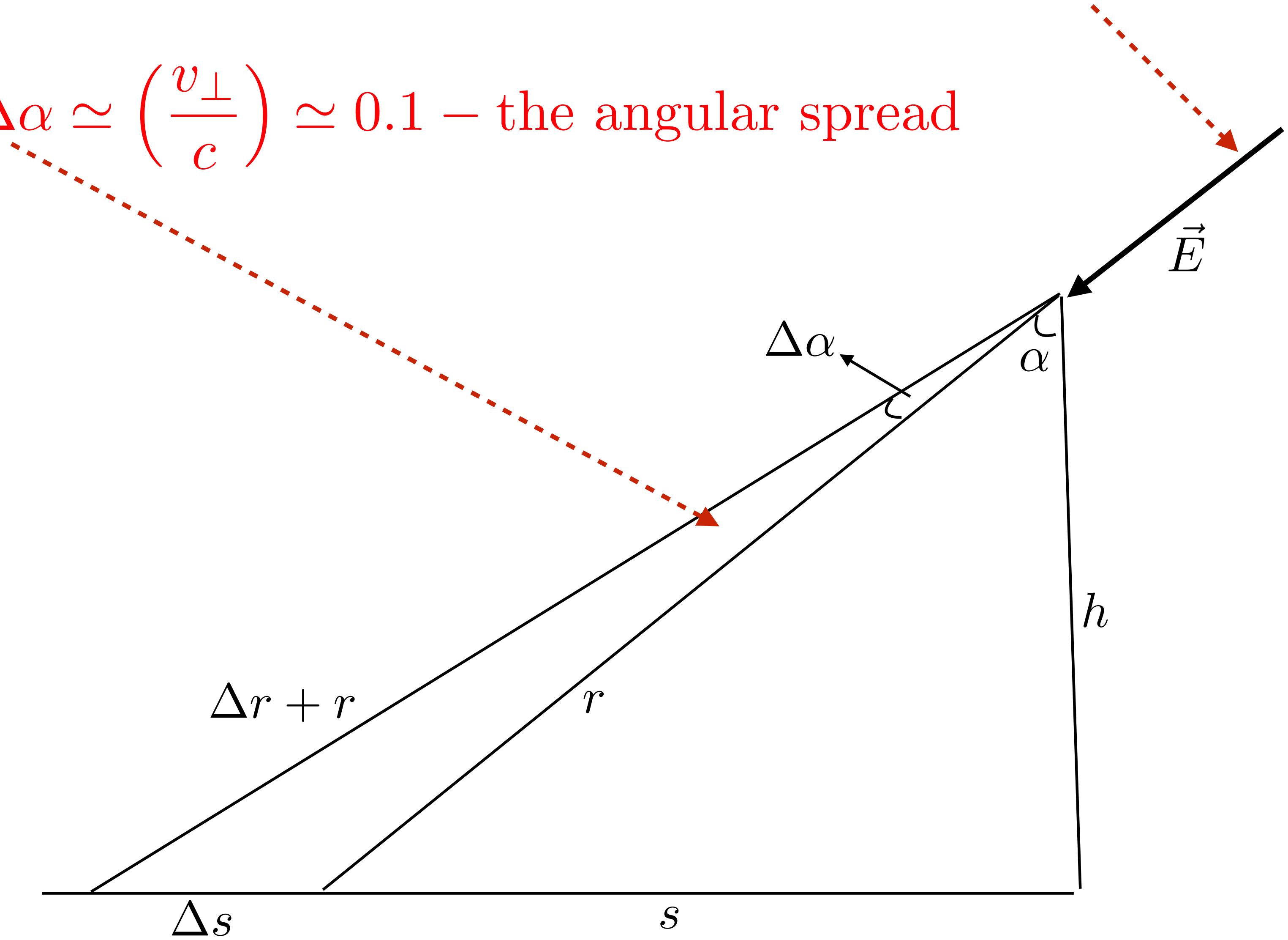
- If the AQN hits the region under thundercloud the weakly bound positrons localized away from the nugget's core may be liberated by pre-existing electric field **E~kV/cm** which is known to exist

- As a result of strong electric field the positrons will accelerate to energies ~ 10 MeV on scales of order $l_a \sim 100 \text{ m}$ (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

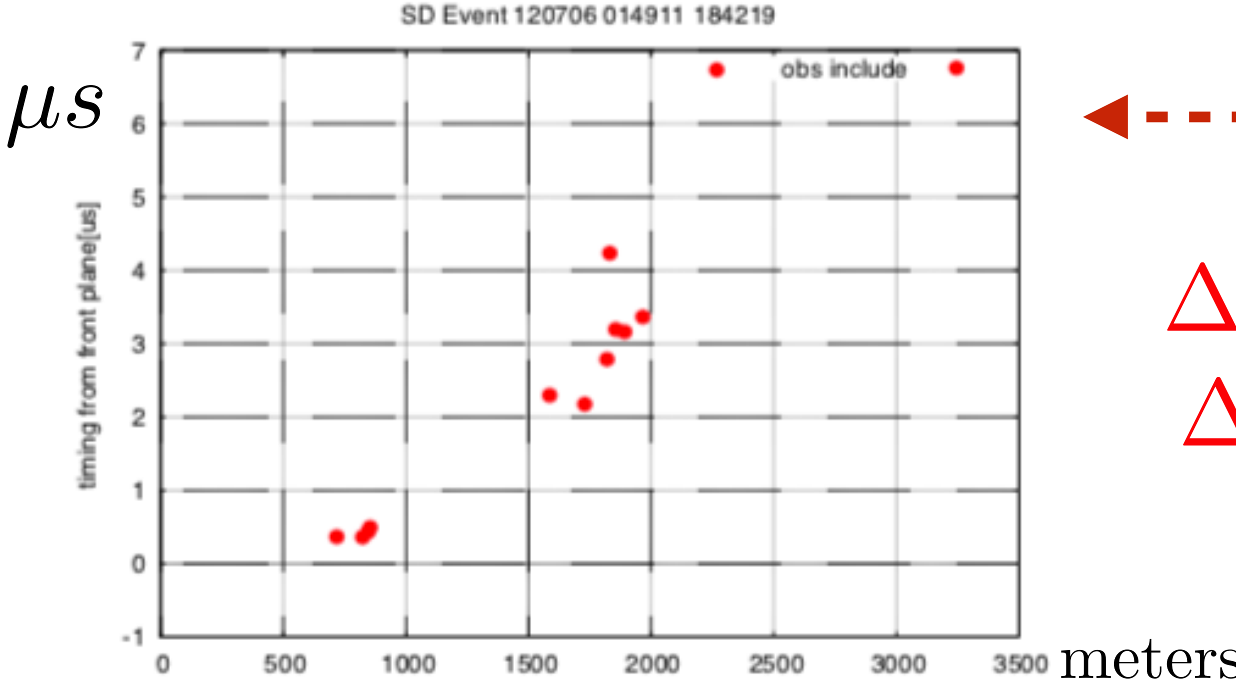
$$\Delta t \simeq \frac{\Delta r}{c} \simeq 3\mu s\cdot(\tan\alpha)\cdot\left(\frac{r}{10\ \mathrm{km}}\right) \text{ where } \Delta r \simeq r\tan\alpha\Delta\alpha$$

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

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

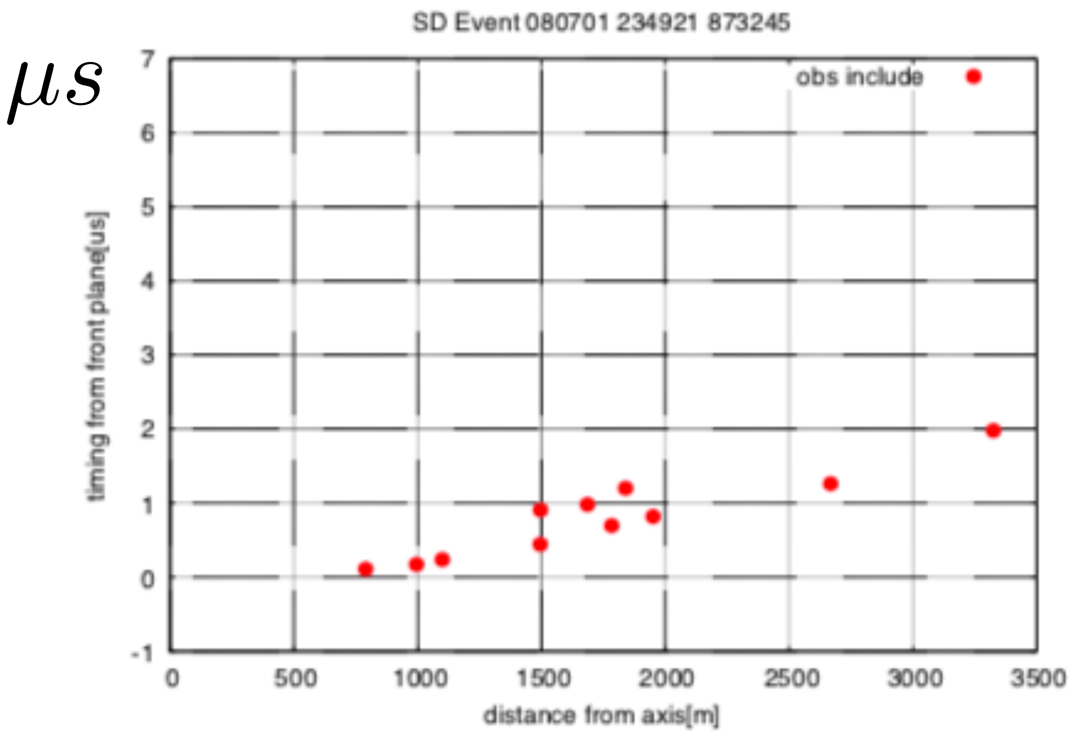
- It is consistent with observations. It represents resolution of *"the curvature puzzle"* within AQN model

adopted from TA collaboration [Abbasi-2017]



typical burst event

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



typical CR event

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

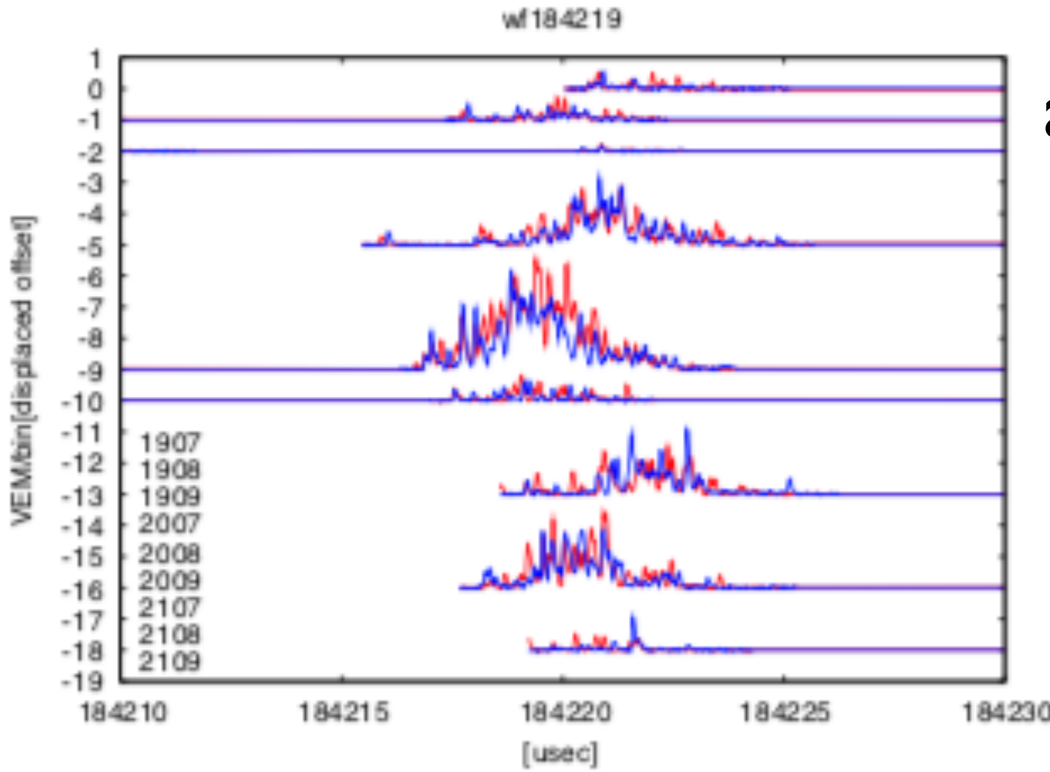
The "curvature puzzle"

- 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*")

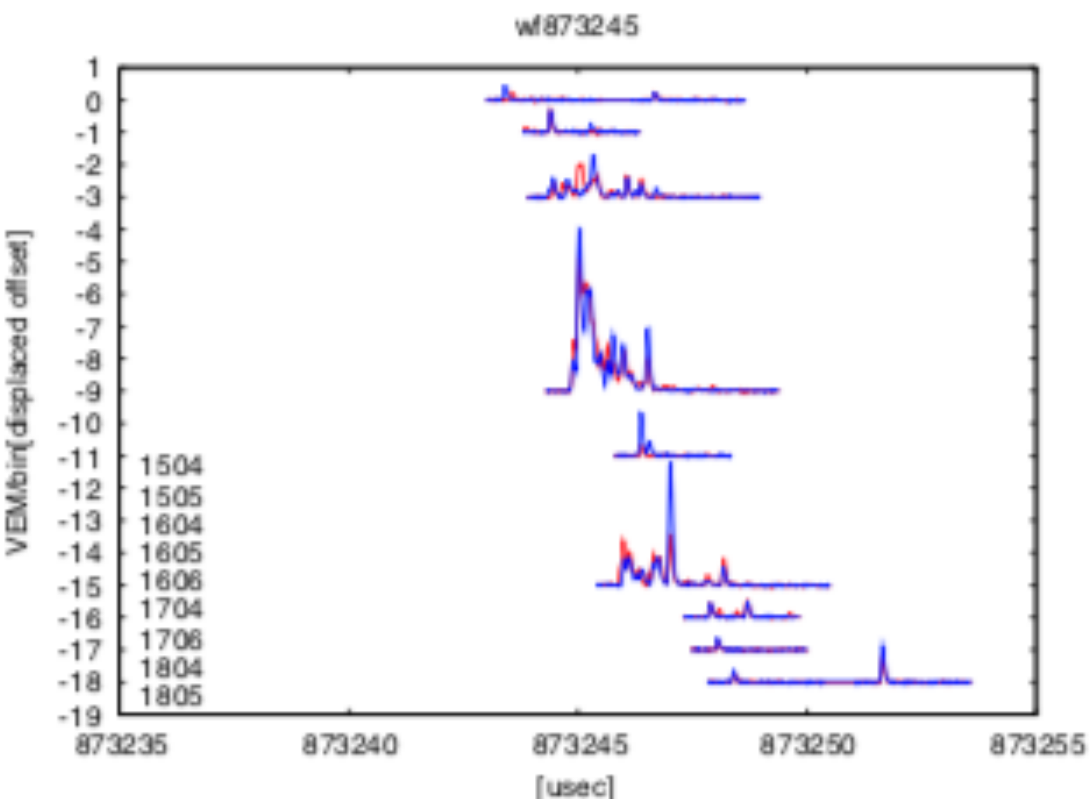
- Conventional CR showers have an ultra relativistic particle (sharp edge in waveforms). Large number of positrons produce non-sharp edge, resolving "*edge puzzle*"



adopted from TA [Abbasi-2017]

μs

typical burst event



μs

typical CR event

The “edge puzzle”

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)

- Ratio: $\Omega_{\rm dark} \sim \Omega_{\rm visible}$ 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.

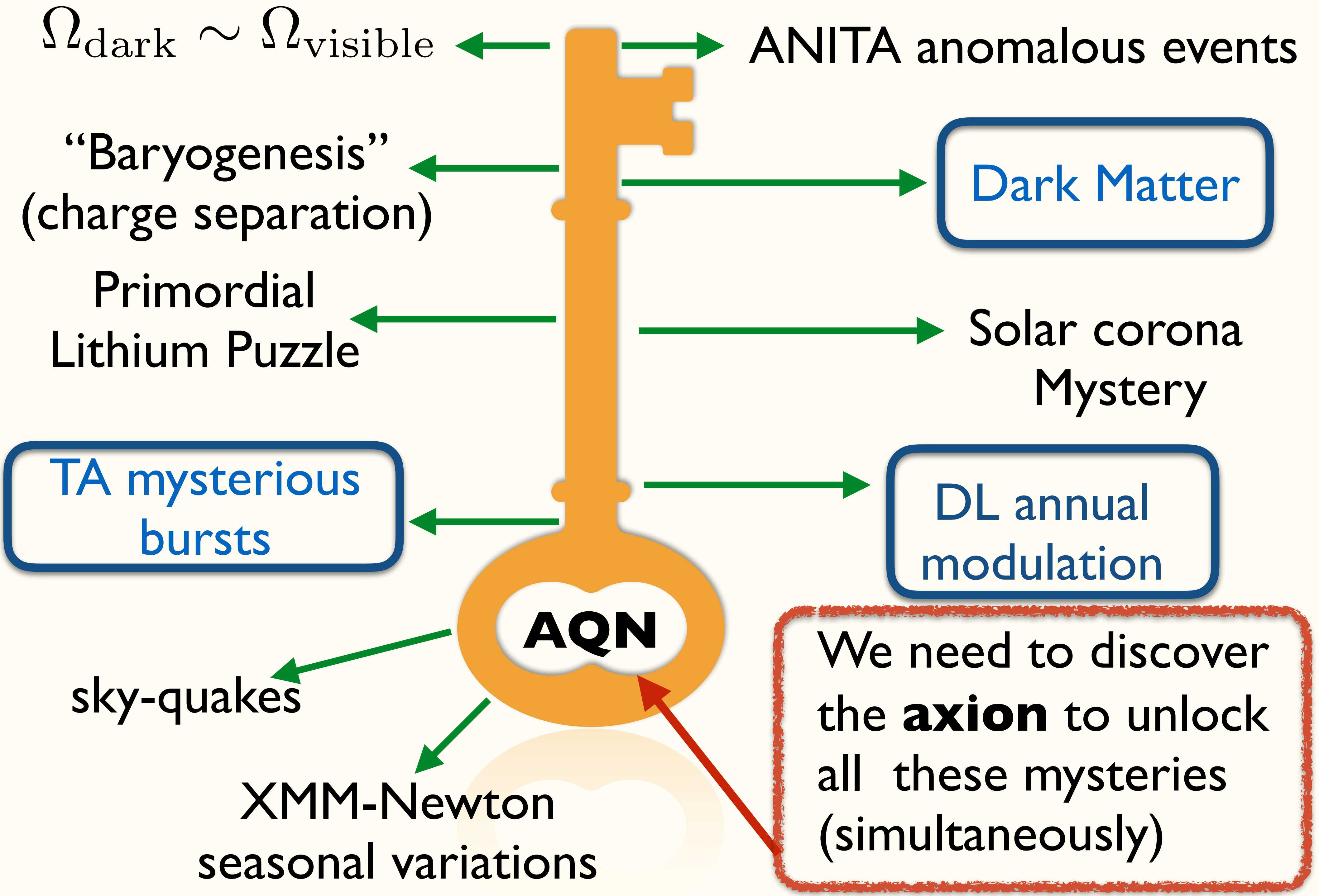
- This model offers a simultaneous resolution of a number (naively unrelated) old mysteries: DM, baryogenesis, solar corona mystery, primordial Lithium puzzle, the Telescope Array mysterious bursts, DL annual modulations, etc

- The long standing puzzle on DL observation of the annual modulation (12.9 sigma CL) may find a natural resolution within the same AQN framework;

- All energy scales which enter the problem have not been "invented" for explanation of the DL signal. Instead, all the relevant scales [leading e.g. to the observed (1-6) keV recoil energy] have been established long ago in unrelated studies for different purposes in a different context.

- This model also predicts large (~20%) **daily** modulations. This prediction is presently analyzed by the CAST-CAPP collaboration with axions.

- CAST-CAPP uses the axions emitted by AQN instead of ν which is relevant for the DL studies: $\nu \rightarrow n$



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