Telescope Array bursts and ANITA anomalous events as manifestations of the Dark Matter

Ariel Zhitnitsky

University
of British Columbia,
Vancouver, Canada

"Dark Matter" online workshop, Moscow, June 22-24, 2021

This talk is mostly based on two recent papers on some mysterious events recorded by Telescope Array and ANITA

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

The ANITA Anomalous Events and Axion Quark Nuggets

Xunyu Liang and Ariel Zhitnitsky

Department of Physics and Astronomy, University of British Columbia, Vancouver, V6T 1Z1, BC, Canada

1. The DM and Baryogenesis as two sides of the 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

- Today I specifically focus on two consequences of this construction:
  1. recently observed Mysterious Telescope Array bursts.
  2. recently observed ANITA anomalous events

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 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.

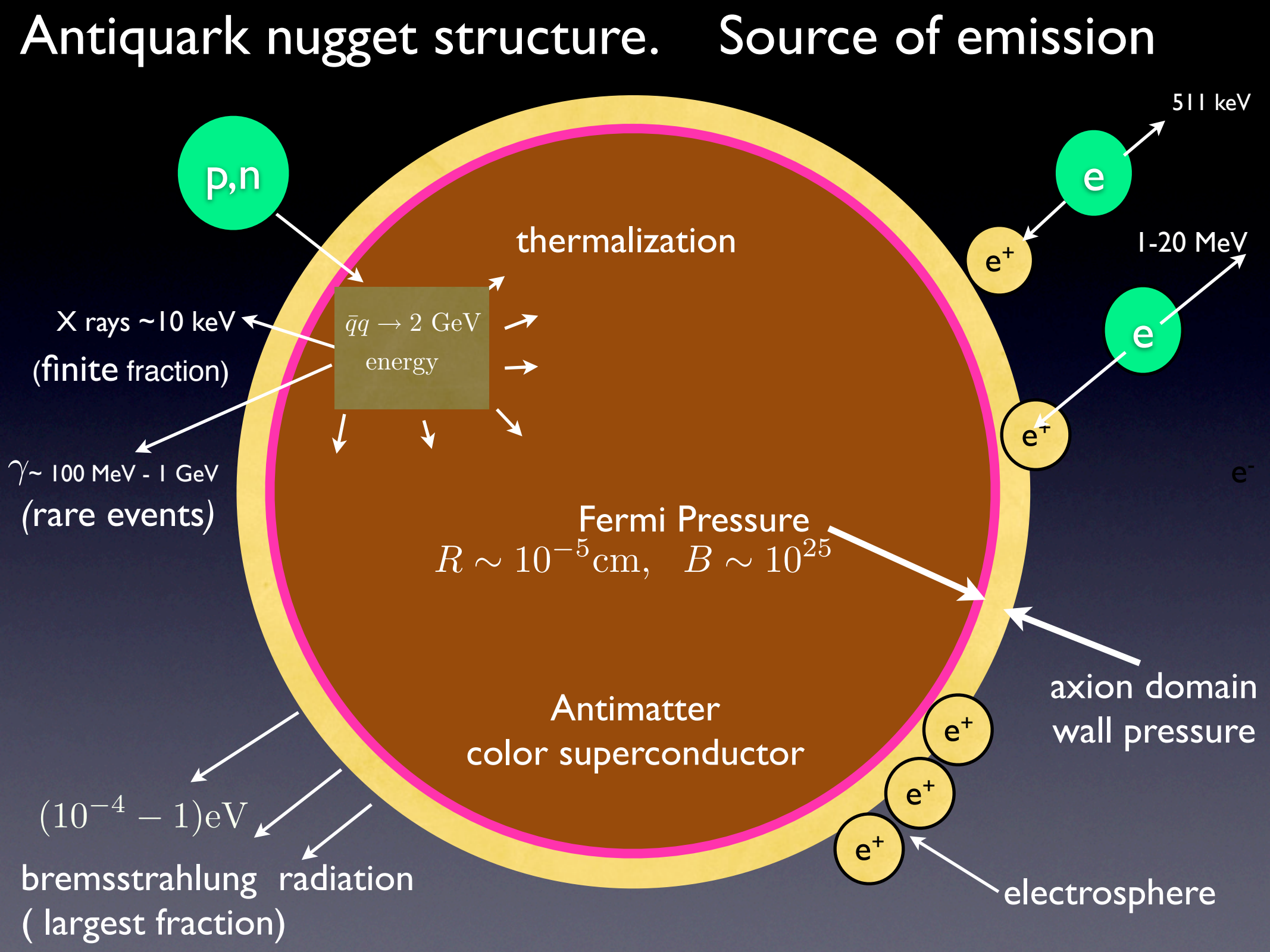
- 2. there are two species, the nuggets and **anti-nuggets**. The size is determined by m_a as $R \sim m_a^{-1}$

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

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

- 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



- There is a **misconception** that the topological defects (such as the domain walls) can only be formed if the **PQ** phase transition occurs after the inflation, i.e. $H_I > f_{PQ}$.

- However: the **N=1** domain wall interpolates between topologically **distinct**, but physically **identical** vacuum states like in sine-Gordon model $V(\theta) \sim \sin\theta$. These distinct topological sectors must be present inside the same horizon such that inflation cannot separate them.

- The **N=1** axion domain walls always exist when θ interpolates between one and the same **physical** vacuum state: $\theta \to \theta + 2\pi n$. Axion strings are irrelevant in formation of the closed bubbles of the axion domain walls which eventually make **AQNs**

3. 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 $10^{19}\mathrm{eV}$;

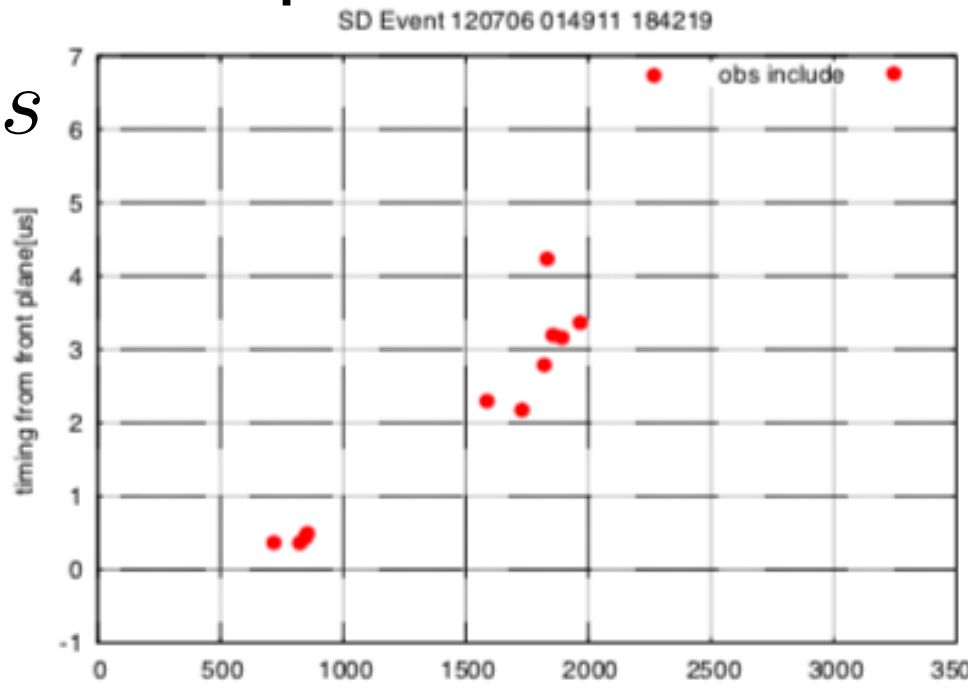
- *"curvature puzzle"*: All burst events are much more curved than usual CR air showers. Also: the edges in waveforms are dramatically different, *"edge puzzle"* (see two next slides);

- *"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;

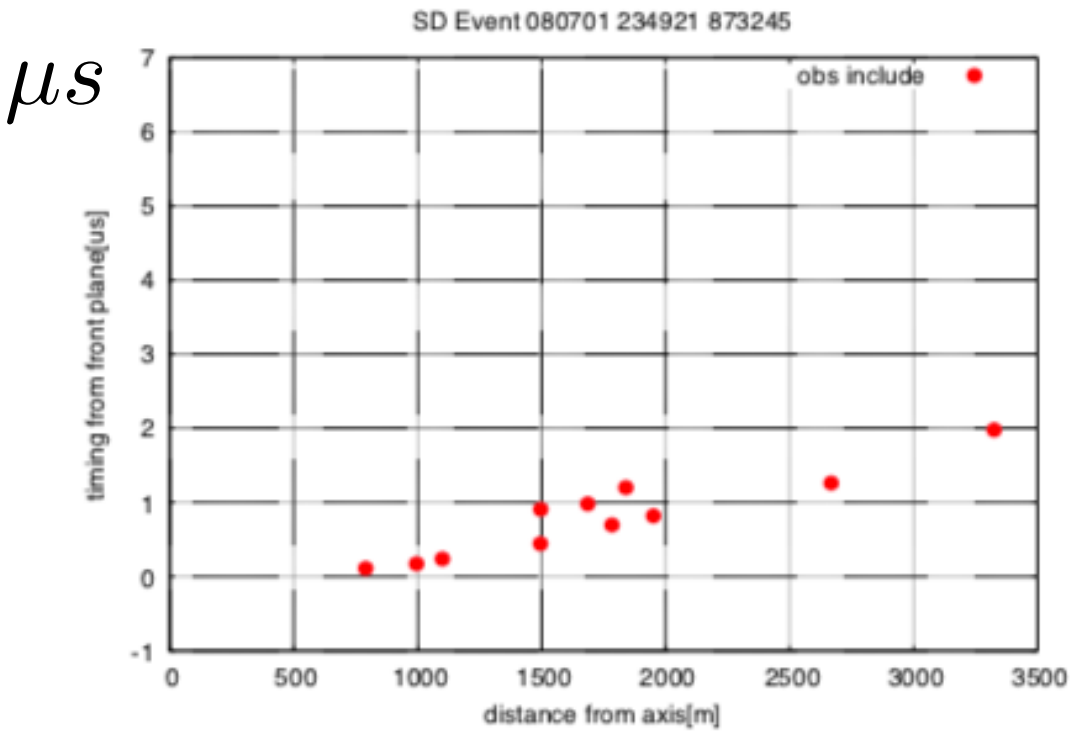
- Reconstructed bursts start at much lower altitude than conventional HECR showers (30km).

adopted from TA collaboration [Abbasi-2017]



typical burst event

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

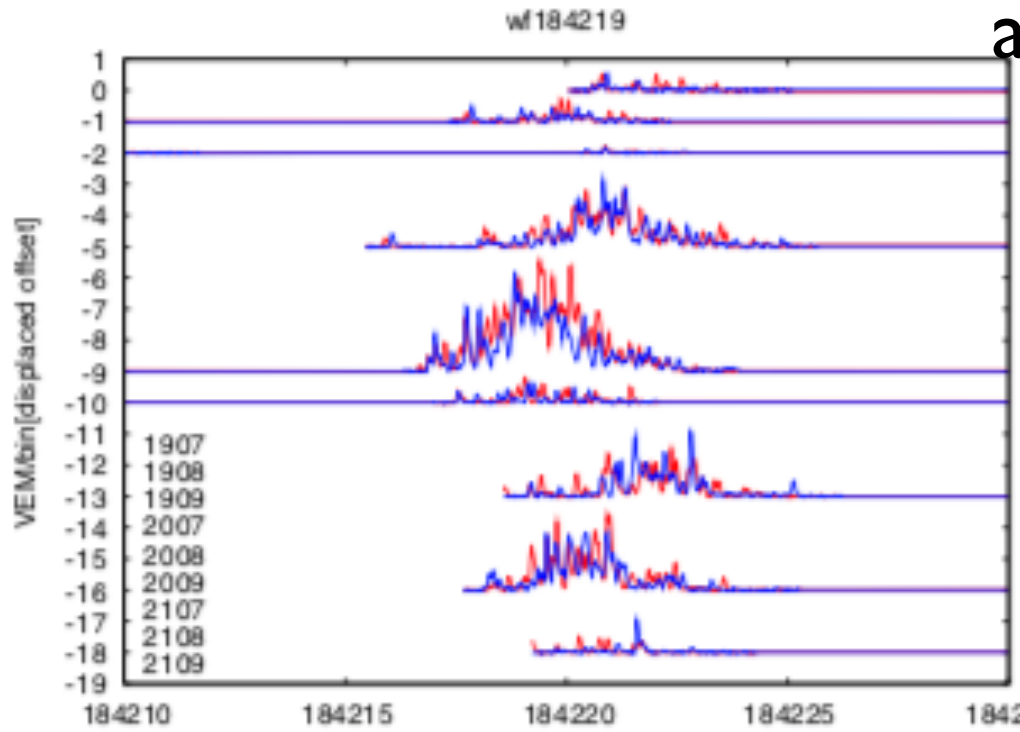


typical CR event

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

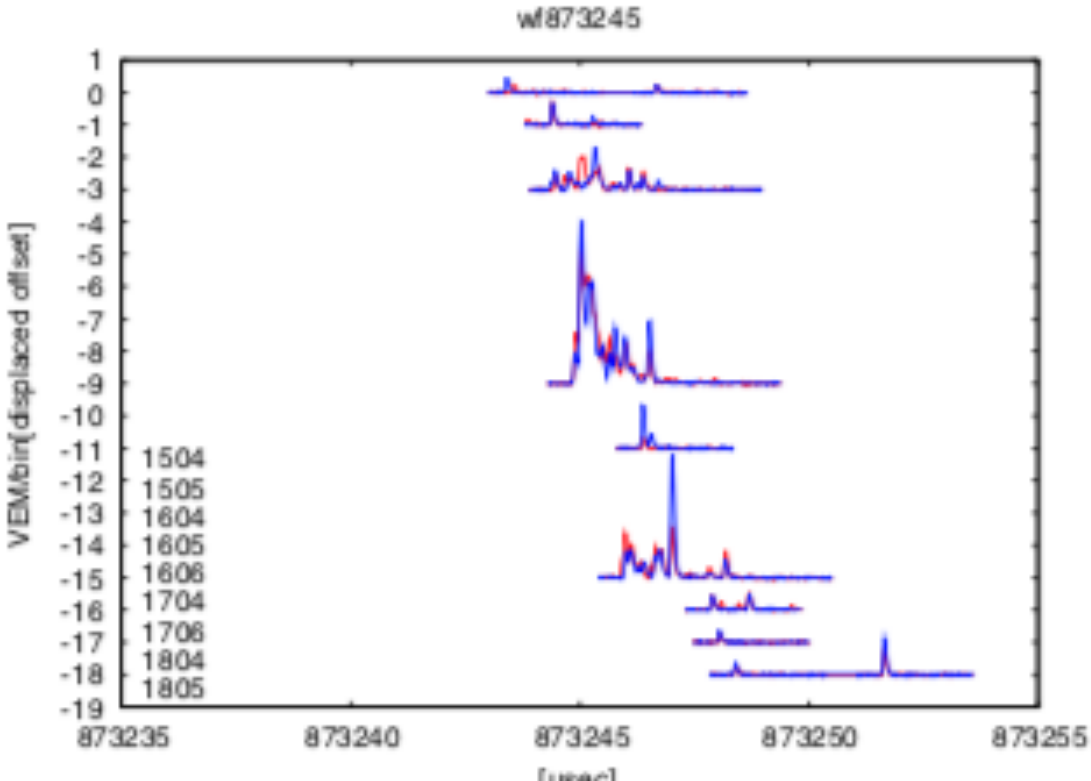
The "curvature puzzle"

adopted from TA [Abbasi-2017]



μs

← - - typical burst event



μs

← - - typical CR event

The "edge puzzle"

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)

4.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: $T \sim 10$ 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 $l_a \sim 100$ 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

- **Typical electric field which must exist in thunderstorms for runaway breakdown (RB):**

$$E_c = (2.16 - 2.84)\frac{\mathrm{kV}}{\mathrm{cm}} \exp\left(-\frac{\mathrm{z}}{\mathrm{h}}\right), \quad \mathrm{h} \simeq 8 \text{ km}.$$

$$\mathrm{l_a} \simeq (50 - 100) \text{ m}, \qquad \tau_\mathrm{a} \simeq \frac{\mathrm{l_a}}{\mathrm{c}} \sim (\text{fraction of}) \ \mu\text{s}.$$

- **The number of weakly bound positrons surrounding the AQN at temperature T is**

$$Q \simeq 4\pi R^2 \int_0^\infty n(z,T)dz \sim \frac{4\pi R^2}{\sqrt{2\pi\alpha}} (m_e T) \left(\frac{T}{m_e}\right)^{1/4},$$

- **Some of these positrons will be localized far away (measured in cm) from the nugget's core**

$$R_{\mathrm{cap}}(T) \simeq \frac{\alpha Q}{T} \sim 2 \text{ cm} \left(\frac{T}{10 \text{ keV}}\right)^{1/4}.$$

- Precisely these weakly bound positrons may be liberated as a result of electric field

$$\Delta E \simeq [eE \cdot R_{\rm cap}] \sim 2 \text{ keV} \gtrsim \text{E}_{\rm bound} \text{ at t} = 0.$$

- These liberated positrons will accelerate:

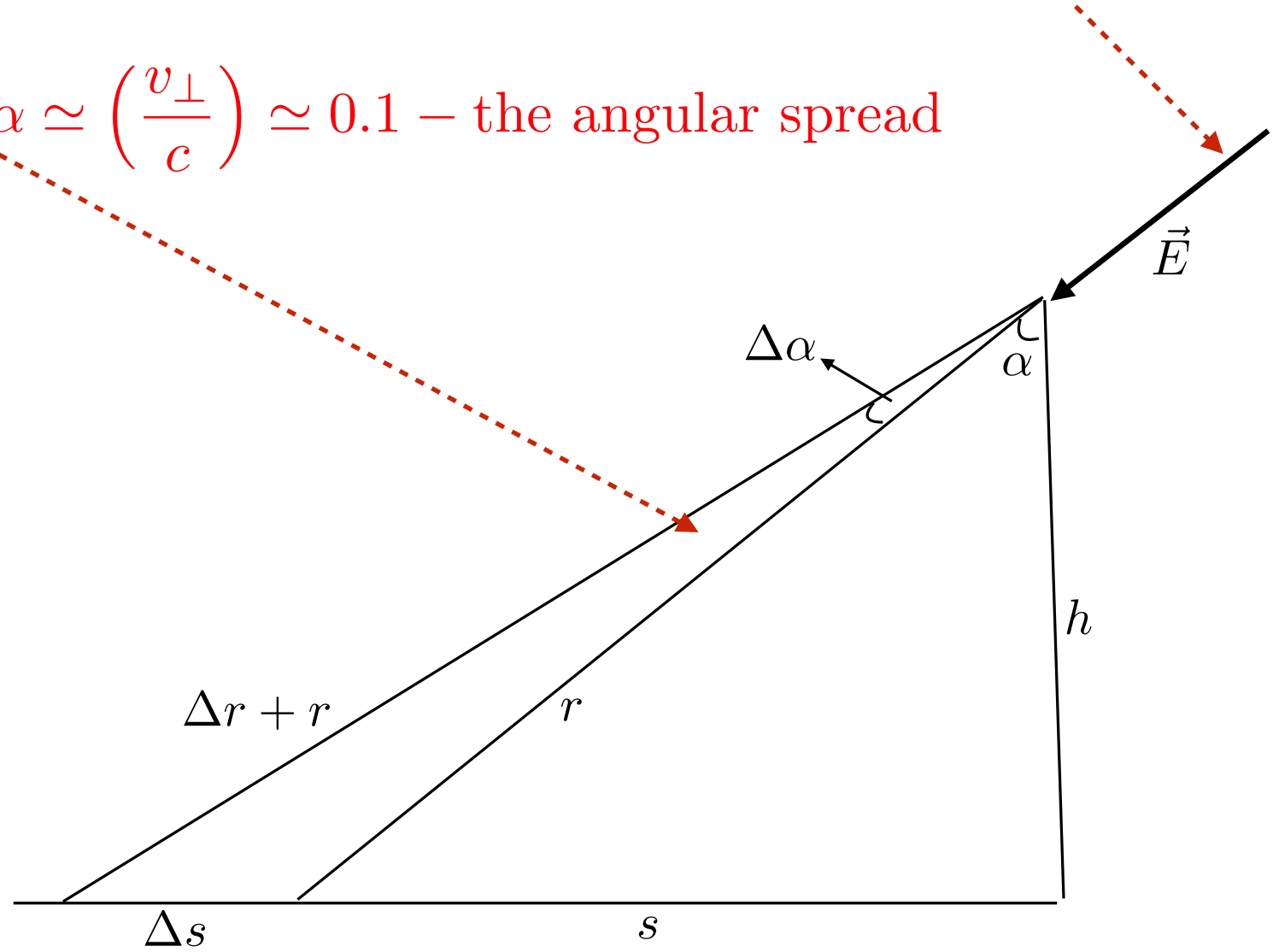
$$E_{\rm exit} \simeq [eE \cdot l_a] \sim 10 \text{ MeV}$$

- These energetic positrons may reach Telescope Array Surface Detector (TASD) which is approximately the number of the observed particles in a given burst:

$$N^{\rm max}_{\rm positrons} \simeq \frac{(\eta \cdot Q)}{4\pi r^2} [507 \cdot 3\text{m}^2] \cdot \langle e^{-\frac{r}{\lambda}} \rangle \approx 10^3,$$

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

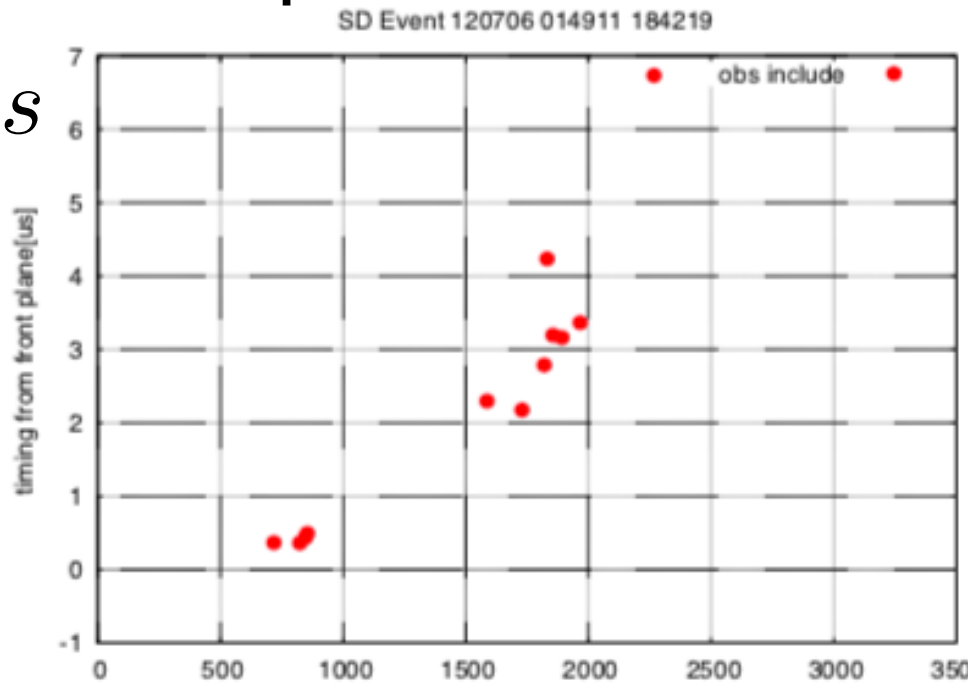
$$\Delta t \simeq \frac{\Delta r}{c} \simeq 3\mu s\cdot(\tan\alpha)\cdot\left(\frac{r}{10\ \mathrm{km}}\right) \text{ where } \Delta r \simeq r\tan\alpha\Delta\alpha$$

- 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]



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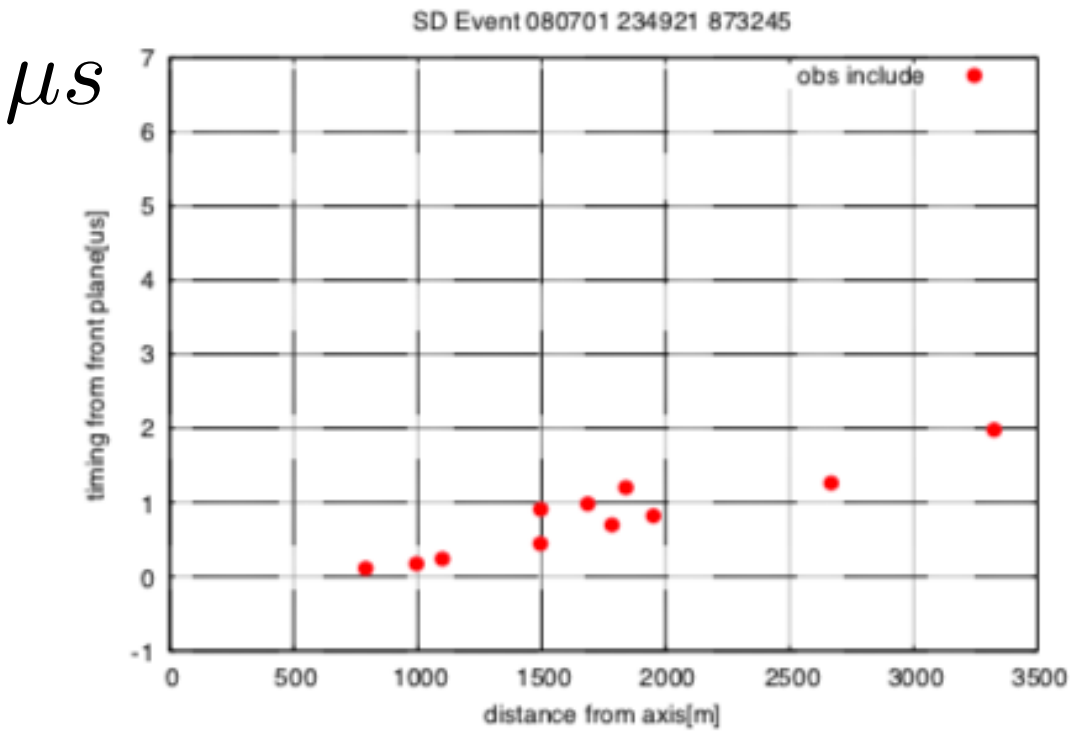


typical CR event

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

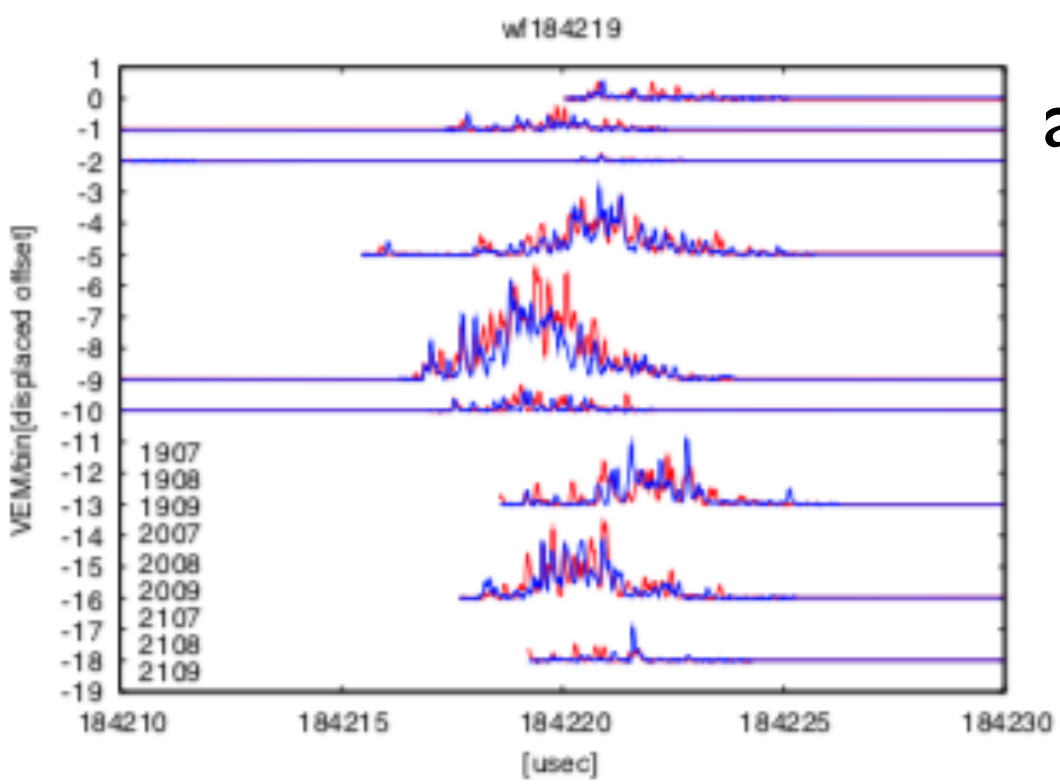
The "curvature puzzle"

- 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*")

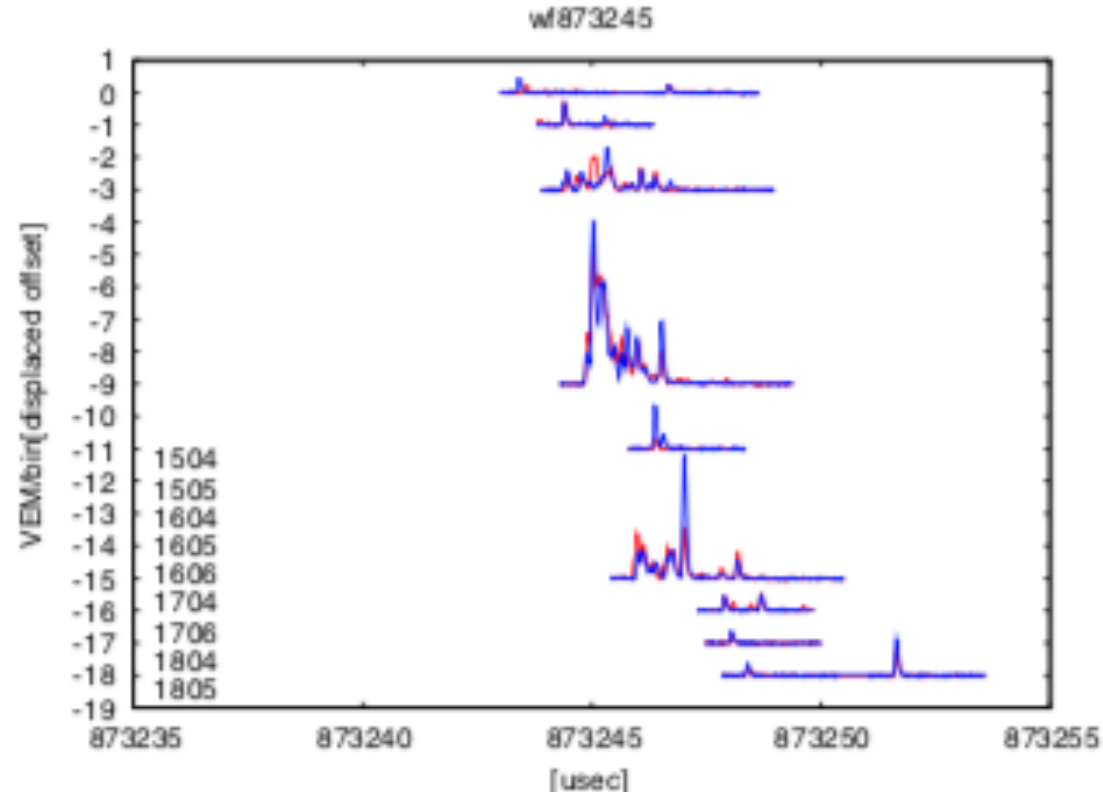
- Conventional CR showers have an ultra relativistic particle (sharp edge in waveforms). Large number of positrons produce non-sharp edge, resolving "*edge puzzle*"



adopted from TA [Abbasi-2017]

← - - typical burst event

μs



← - - typical CR event

μs

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. These parameters are very different from conventional radio pulses due to lightnings.**

5. ANITA anomalous Events

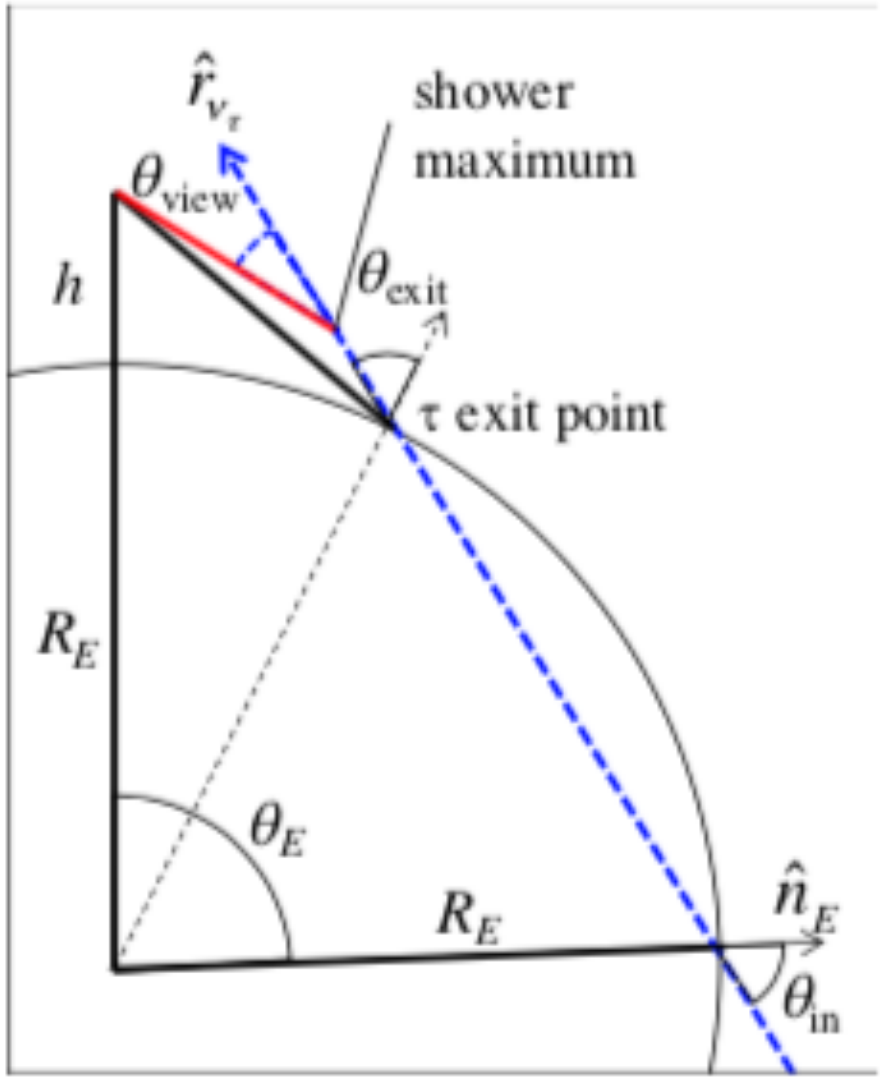
- The Antarctic Impulsive Transient Antenna (ANITA) collaboration observed two anomalous events with non-inverted polarity, see slides below.

- These two events are proven to be very hard to explain in terms of the conventional CR.

- The problem is that the exit angles (relative to the horizon) are large, $(-27^0, -35^0)$, see next slide

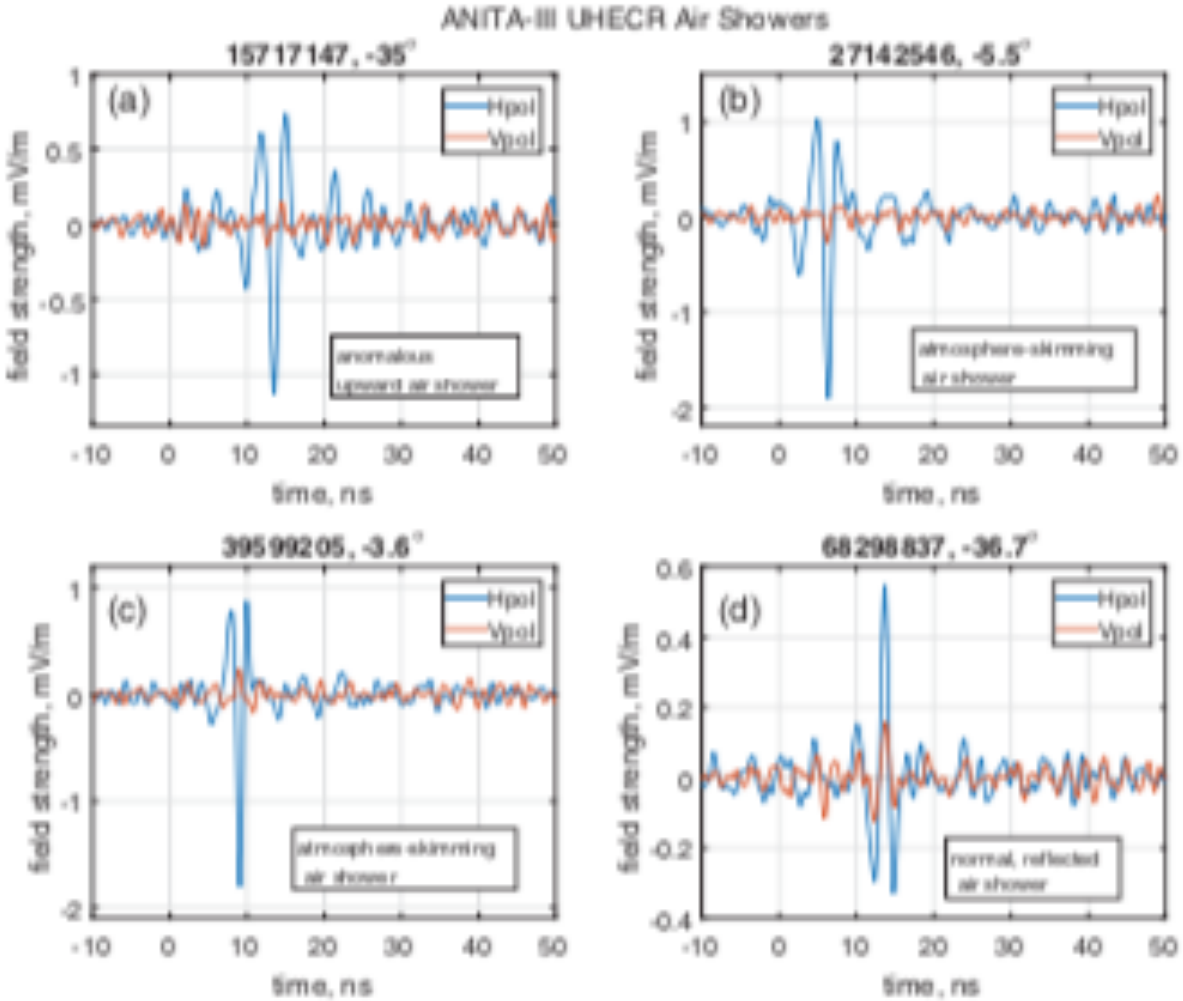
- A neutrino must travel $\gtrsim 5 \cdot 10^3 \mathrm{km}$ with very high energy $E \sim 10^{18} \mathrm{eV}$ to generate such signal

- The SM neutrino is excluded at 5σ CL.



adopted from ANITA
[Gorham-2016]

Large angles $(-27^0, -35^0)$ imply traversing through Earth very large distance (below horizon), considered anomalous. Small angles $\sim (-5^0)$ correspond CR propagation above horizon, and considered normal events.



adopted from ANITA [Gorham-2016]

a) anomalous event, <u>non-inverted</u> polarity (-35^0)

b), c)normal, above horizon CR events with <u>non-inverted</u> polarity. Angles always are very small: (-5.5^0, -3.6^0)

d) normal event with <u>inverted</u> polarity due to the reflection of the conventional CR shower (-36.7^0)

The Antarctic Impulsive Transient Antenna balloon experiment has flown four times over Antarctica and has seen two hard-to-explain particle events. NASA

Oddball particles tunneling through Earth could point to new physics

a journalist's description of the problem.

By **Adrian Cho** | Sep. 27, 2018 , 3:00 PM

next slide is my understanding of the problem

6. ANITA anomalous events as AQN events

- The AQN exits the Earth interior being very hot with the temperature $T \sim 200$ keV
- At such high temperature the e^+e^- production becomes possible as suppression $\exp(-2m/T)$ is not very dramatic
- At such high temperature a very strong AQN's ionization (negative charge -Q) occurs. Consequence: a strong electric field |E| within the electrosphere emerges.
- produced positrons from e^+e^- will experience attraction force and assume location close to the AQN's surface
- Produced electrons from e^+e^- will experience repulsion force and will be accelerated to high energy $\langle E \rangle \sim 10$ MeV by electric field |E| before expel from the system

- Precisely this bunch of electrons emitted at the same instant from the same location with very high energy $\langle E \rangle \sim 10$ MeV produce a coherent radio pulse in the background of geomagnetic B-field

- A typical number of coherent electrons in a bunch is estimated on the level $N \sim 10^9$ to be compared with number $N \sim (10^8 - 10^9)$ in EAS with $E_{\rm CR} \sim (10^{17} - 10^{18})$ eV

- Therefore, the AQN-induced and CR-induced radio signals must be similar in intensity

- The electric field of the radio pulse at distance $\mathcal{R}$ is computed in conventional way:

$$\mathbf{E}(t) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} b(\omega) \mathbf{E}(\omega) e^{-i\omega t} d\omega \approx -\boldsymbol{\epsilon}_{\parallel} \frac{2Ne\rho}{\sqrt{3}\pi c^2 \gamma^2 \mathcal{R}} \, \mathrm{Re} \left[\int_0^{\infty} b(\omega) \, \omega \mathrm{K}_{2/3}(\xi) e^{-i\omega t} d\omega \right]$$

- Typical features of the synchrotron spectrum: it is approximately flat with critical (cutoff) frequency

$$\nu_{\rm c} \equiv \frac{3\gamma^3 c}{4\pi\rho} \approx 0.7\,{\rm GHz}\left(\frac{\gamma}{20}\right)^2 .$$

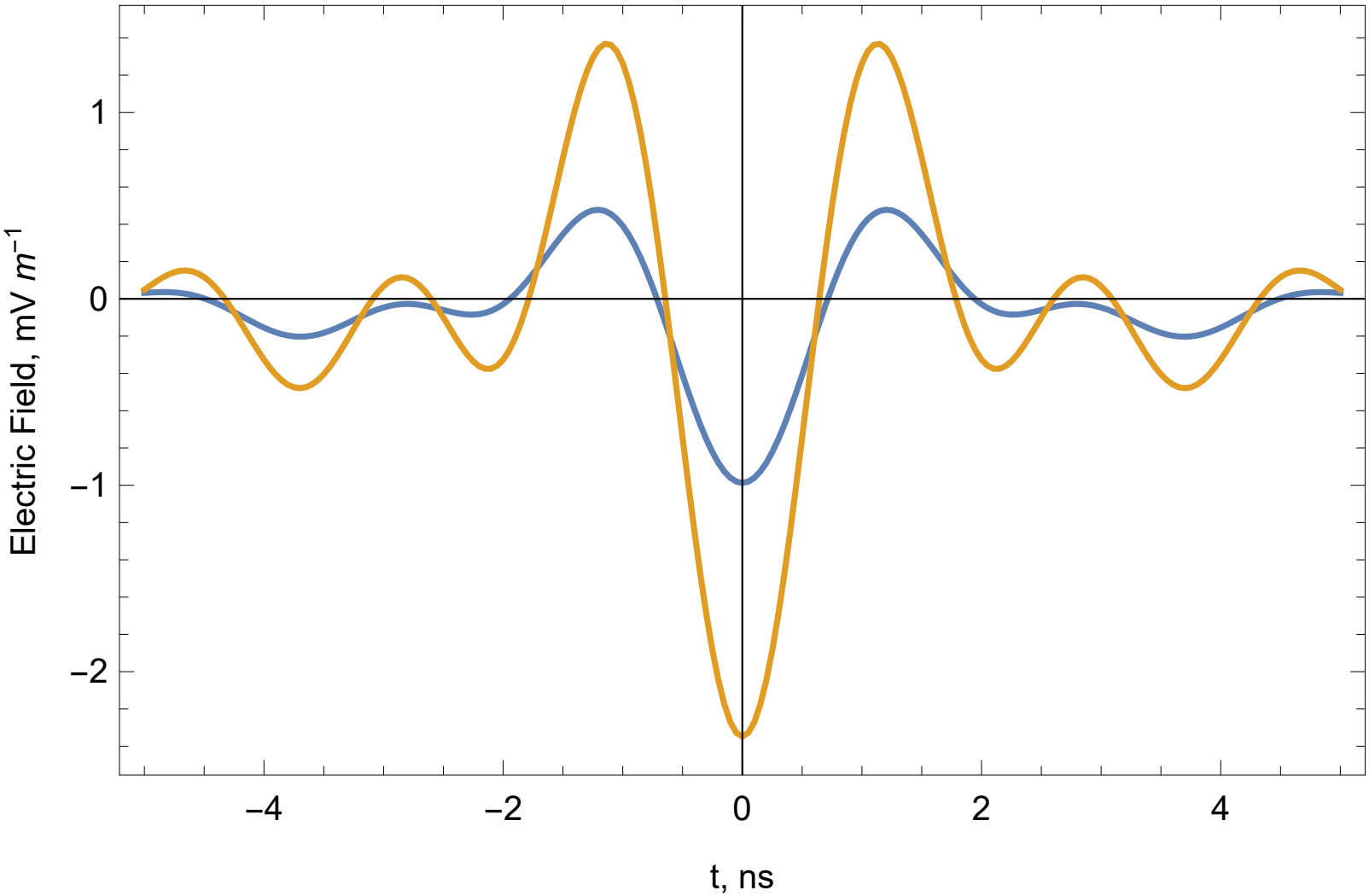
- Typical duration of the signal is $(2-4){\rm ns}$:

$$\tau \approx \frac{1}{\Delta\nu} \approx 2\,{\rm ns}\left(\frac{600\,{\rm MHz}}{\Delta\nu}\right) .$$

- Typical intensity of the pulse is $|\mathbf{E}(\mathbf{t})| \sim {\rm mV/m}$

- Typical power density is $(0.2-0.3)\,{\rm pW\,m^{-2}\,MHz^{-1}}$

- All these values are very close to the observed magnitudes recorded by ANITA and classified as Anomalous events, see slide below



Electric field $|\mathbf{E(t)}|$ in units $\mathbf{mV/m}$

$\theta = 0, N = 5 \cdot 10^8, \gamma = 10(\text{blue}),$ and $\gamma = 20(\text{orange})$

filter $\text{b}(\omega) : (40 - 80)$ & $(200 - 800)$ MHz

- There are dramatic differences with conventional CR radio pulses such that CR-induced and AQN-induced radio pulses can be easily discriminated:

- 1. The extensive air showers (EAS) are characterized by "central axis" and "pancake" geometry. These notions do not exist in the AQN scenario;

- 2. In particular, the width of the "pancake" growth with the distance from central axis in EAS. It dramatically modifies the spectrum and intensity of the emission (when the wavelength becomes shorter than the width) because the coherence diminishes.

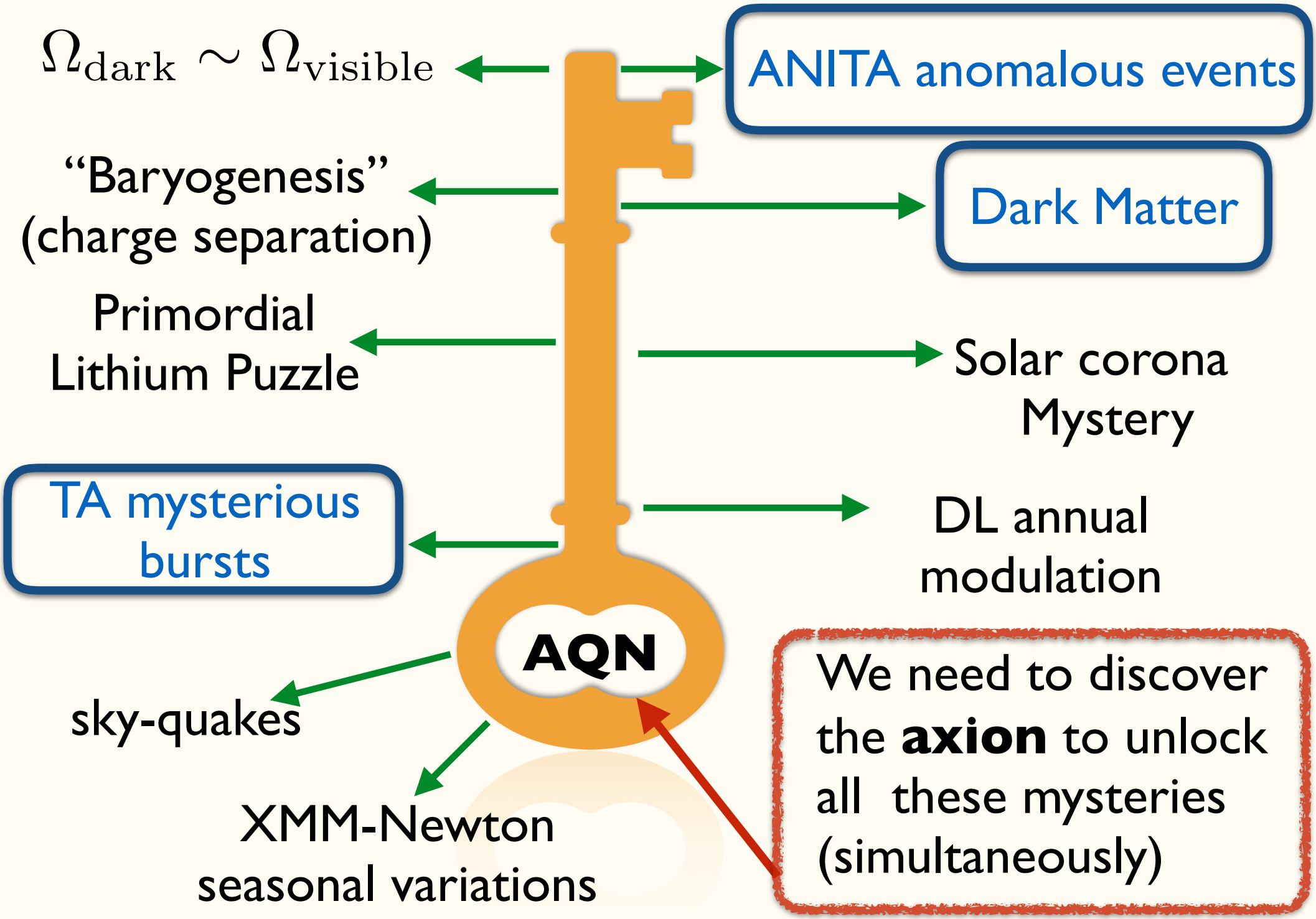
- 3. The cutoff frequency strongly depends on this effect. It should be contrasted with AQN-induced case when particle number density does not depend on distance from central axis.

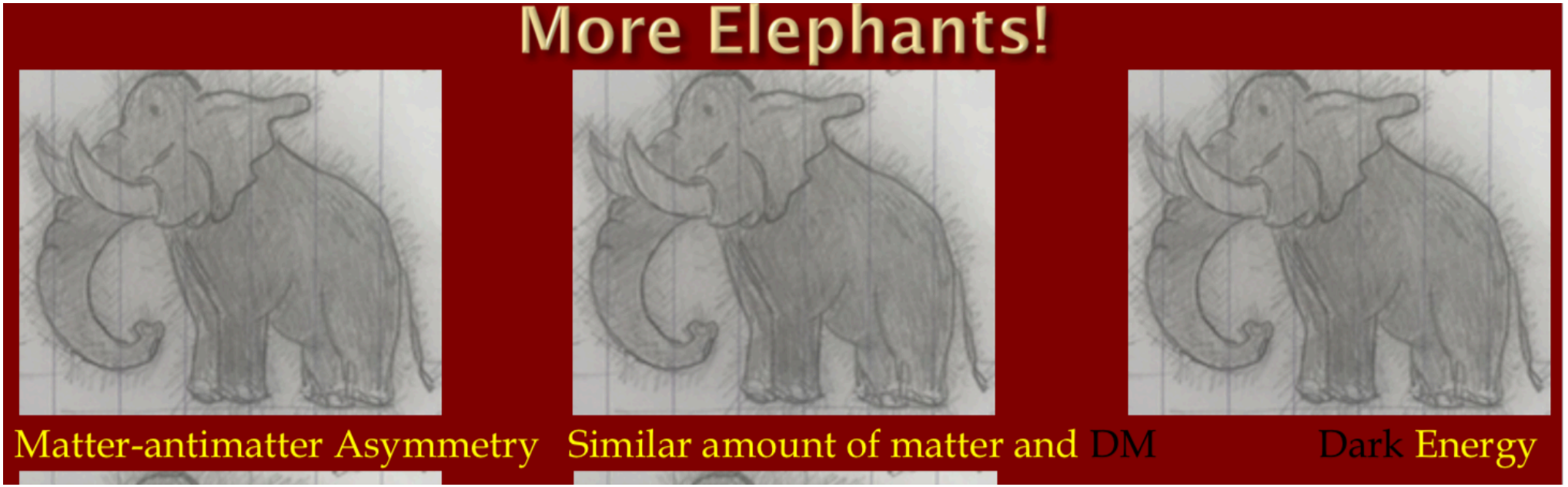
Conclusion

- "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)

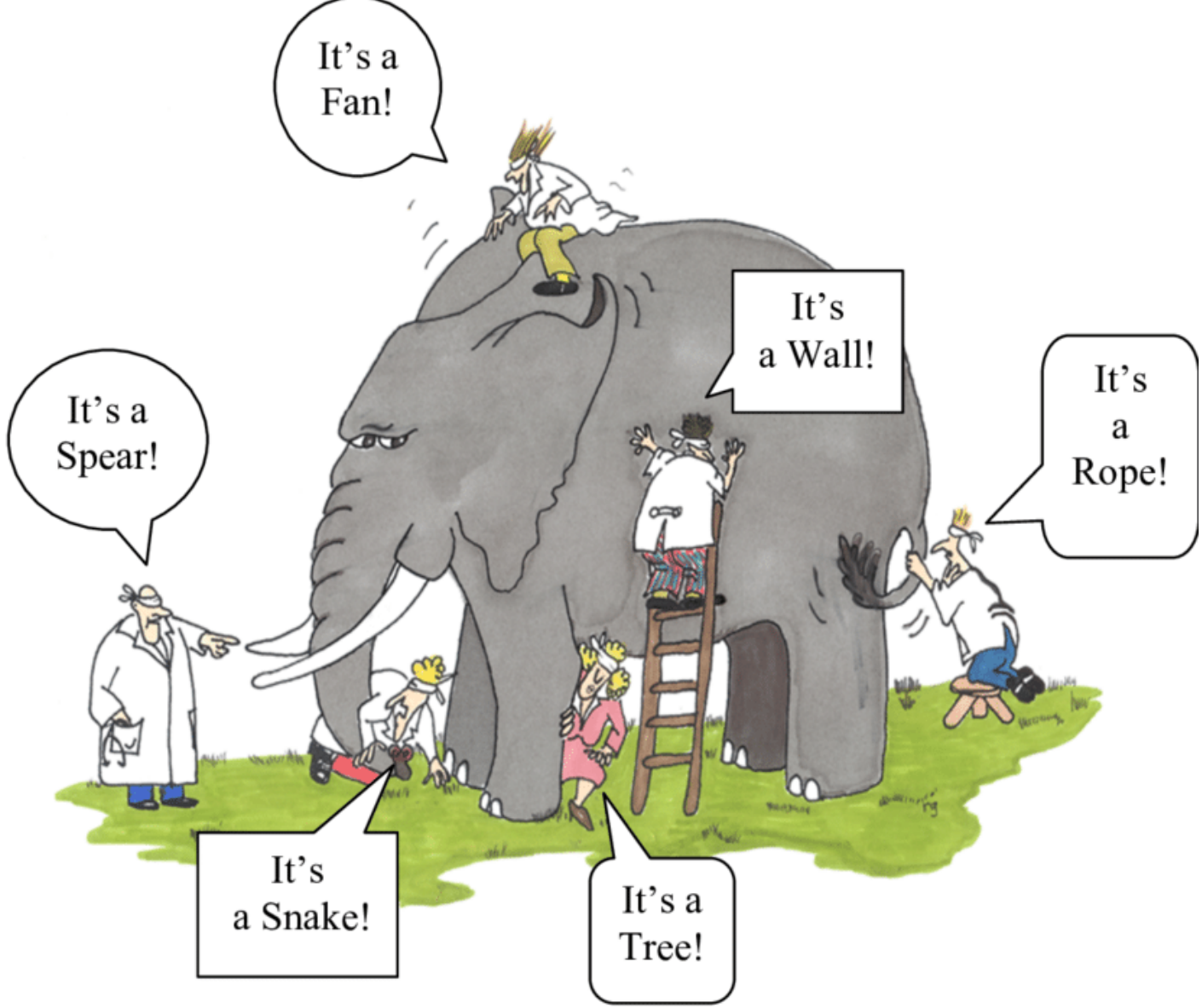
- Ratio: $\Omega_{\rm dark} \sim \Omega_{\rm visible}$ is very generic consequence of this framework (no sensitivity to axion mass m_a, nor to the misalignment angle $\theta_{\rm initial}$). It is the direct consequence of the framework when the dark matter and visible components are proportional to 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, the ANITA anomalous events, 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)



From Dima Budker's talk "More elephants in the room"



The main essence of my talk: different people (from different fields conducting different experiments around the Globe), in fact, observe and study **different** parts of a body of the **same** elephant