

Axion Quark Nuggets and Matter-Antimatter asymmetry: theory, observations and future searches

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Mega Dark Matter workshop, May 2-20, 2022

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 AND MYSTERIOUS EVENTS ... TO BE MENTIONED TODAY...
- WHY THE BARYONIC MATTER DENSITY Ω_{visible} AND THE DARK MATTER DENSITY Ω_{dark} ARE SIMILAR IN VALUES AS OBSERVATIONS SUGGEST, $\Omega_{\text{dark}} \simeq 5 \Omega_{\text{visible}}$? THEY COULD ASSUME DRAMATICALLY DIFFERENT SCALES IF THEY ARE ORIGINATED FROM DIFFERENT PHYSICS.

Fritz Zwicky and Vera Rubin



The DM side of the coin



Sakharov

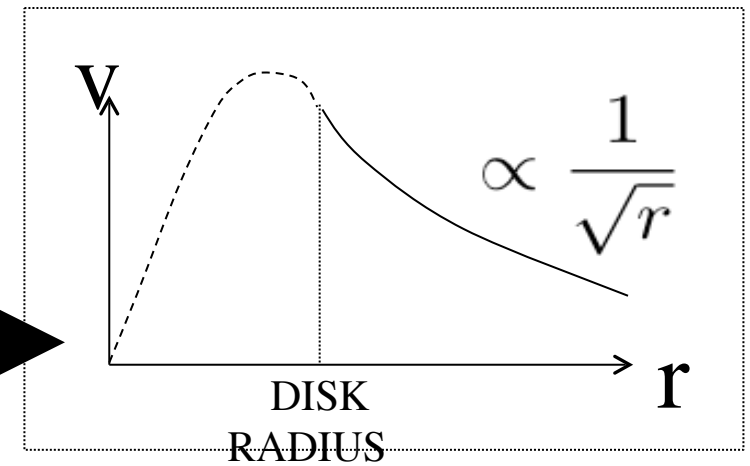
Sakharov formulated precise criteria when such baryogenesis is possible:

1. There must be B-violation;
2. There must be C and CP violation;
3. There must be out-of-equilibrium dynamics

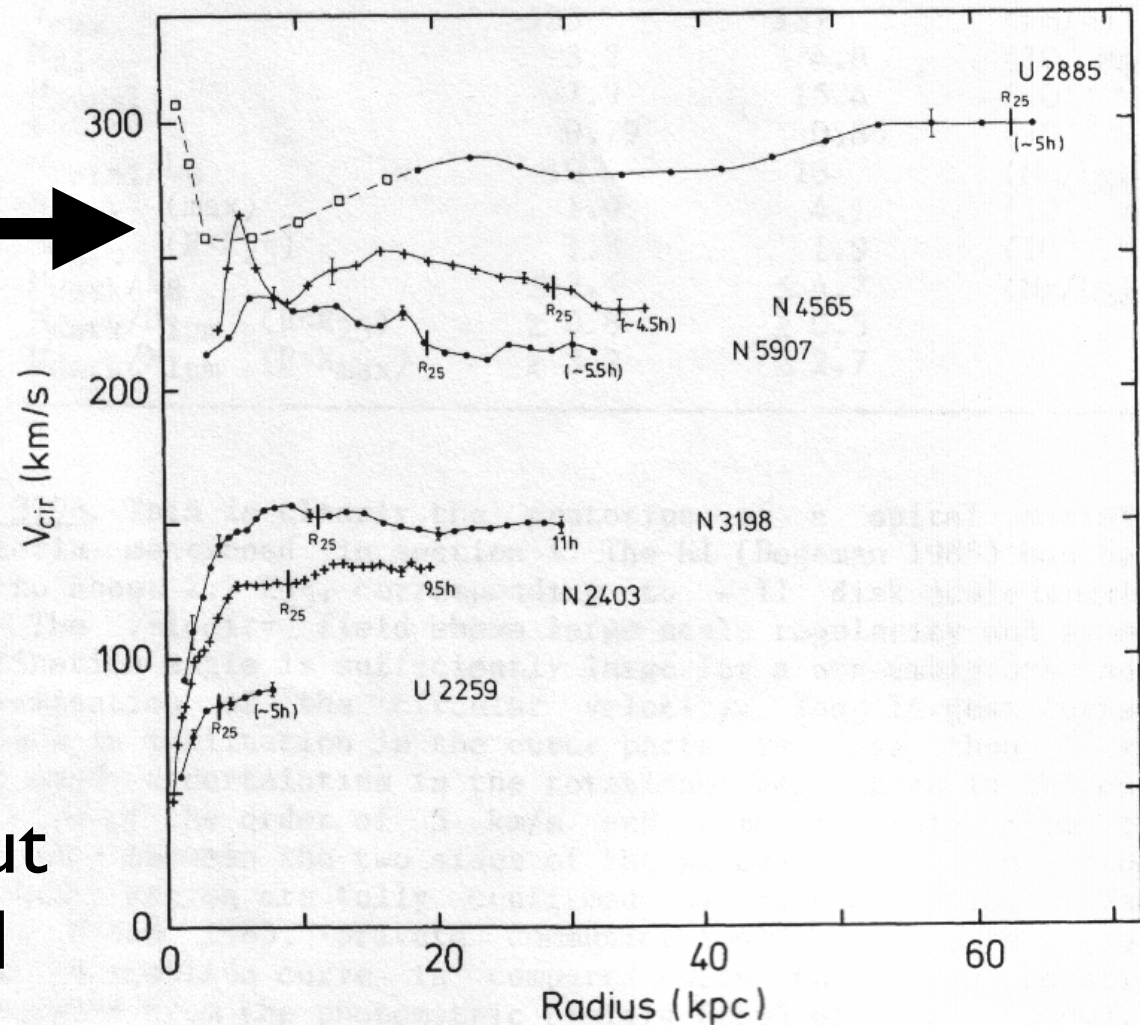
The Baryogenesis side of the coin

I. Evidence for dark matter

Expected behaviour for the velocities of stars



The observed velocity distribution



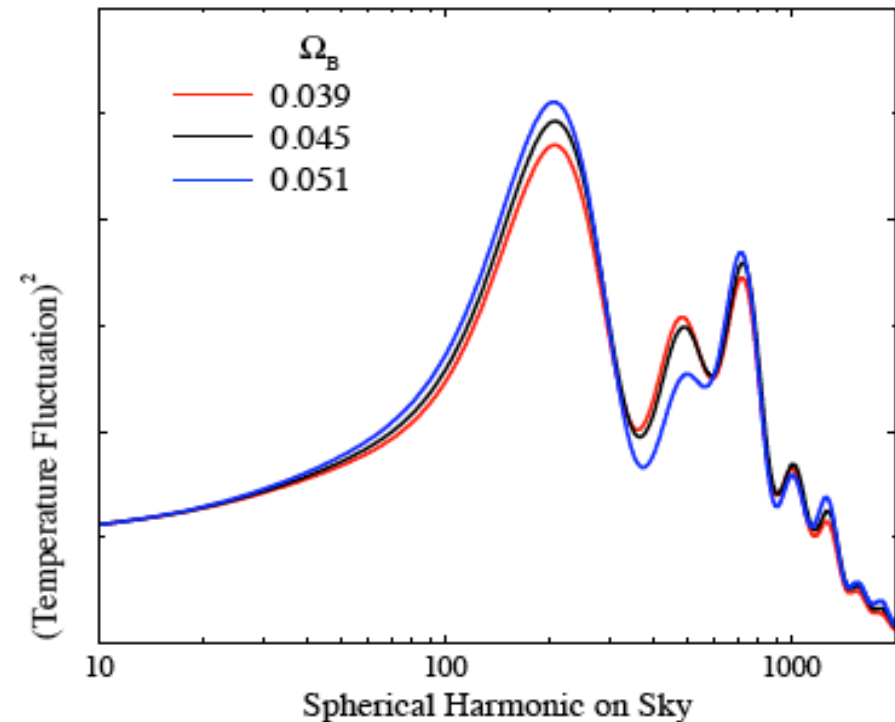
Take home lesson: there is DM in our Universe.
DM knows about gravity, but does not know about E&M

2. Short overview on Baryogenesis

The cosmic microwave background (CMB) and Big Bang Nucleosynthesis (BBN) are highly sensitive to parameter $\eta \equiv n_B/n_\gamma$, the baryon to photon ratio.

$$\eta \equiv \frac{n_B}{n_\gamma} \simeq 6 \cdot 10^{-10}$$

Take home lesson:
the parameter η is known
with very high accuracy



- On other hand: our fundamental equations predict that the matter and antimatter should have equal number densities, i.e. $n_B = n_{\bar{B}}$
- In this case the protons and antiprotons annihilate each other until the temperature drops to $T \simeq 20 \text{ MeV}$
- For such low temperature the parameter η is many orders of magnitude smaller than observed value:

$$\eta \text{ (naive)} \equiv \frac{n_B}{n_\gamma} \sim 10^{-19} \quad \text{for} \quad T = 20 \text{ MeV}$$

- Conventional resolution: one should have one extra baryon per $\sim 10^{10}$ particles such that the annihilation stops at $T = 40 \text{ MeV}$ when no antimatter remains

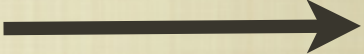
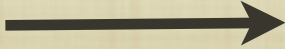
■ THESE TWO (NAIVELY UNRELATED) PHENOMENA, THE DM AND BARYOGENESIS ARE NORMALLY CONSIDERED TO BE TWO DIFFERENT STORIES... WE WANT TO ARGUE THAT THESE TWO PHENOMENA ARE, IN FACT, INTIMATELY CONNECTED.

■ FURTHERMORE, OUR CLAIM IS THAT WE HAVE BEEN WITNESSING (INDIRECTLY) THE MANIFESTATIONS OF THE DM (BEYOND GRAVITY) FOR YEARS WITH MANY PUZZLING OBSERVATIONS ON ALL SCALES (GALACTIC, SUN, EARTH)

■ TODAY I SPECIFICALLY FOCUS ON SEVERAL OBSERVED PUZZLES AND ANOMALIES WHICH COULD BE THE MANIFESTATIONS OF THIS FRAMEWORK :

1. MYSTERIOUS DIFFUSE GALACTIC UV RADIATION;
2. SOLAR CORONA HEATING MYSTERY (SINCE 1939)
3. RECENTLY OBSERVED BY HORIZON 10T THE MULTI MODAL MYSTERIOUS CR-LIKE EVENTS
4. RECENTLY OBSERVED THE ANOMALOUS ANITA CR-LIKE EVENTS WITH NON-INVERTED POLARITY.

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

$$\frac{\sigma}{M} \ll 1 \left(\frac{\text{cm}^2}{\text{gram}} \right)$$

E. Witten

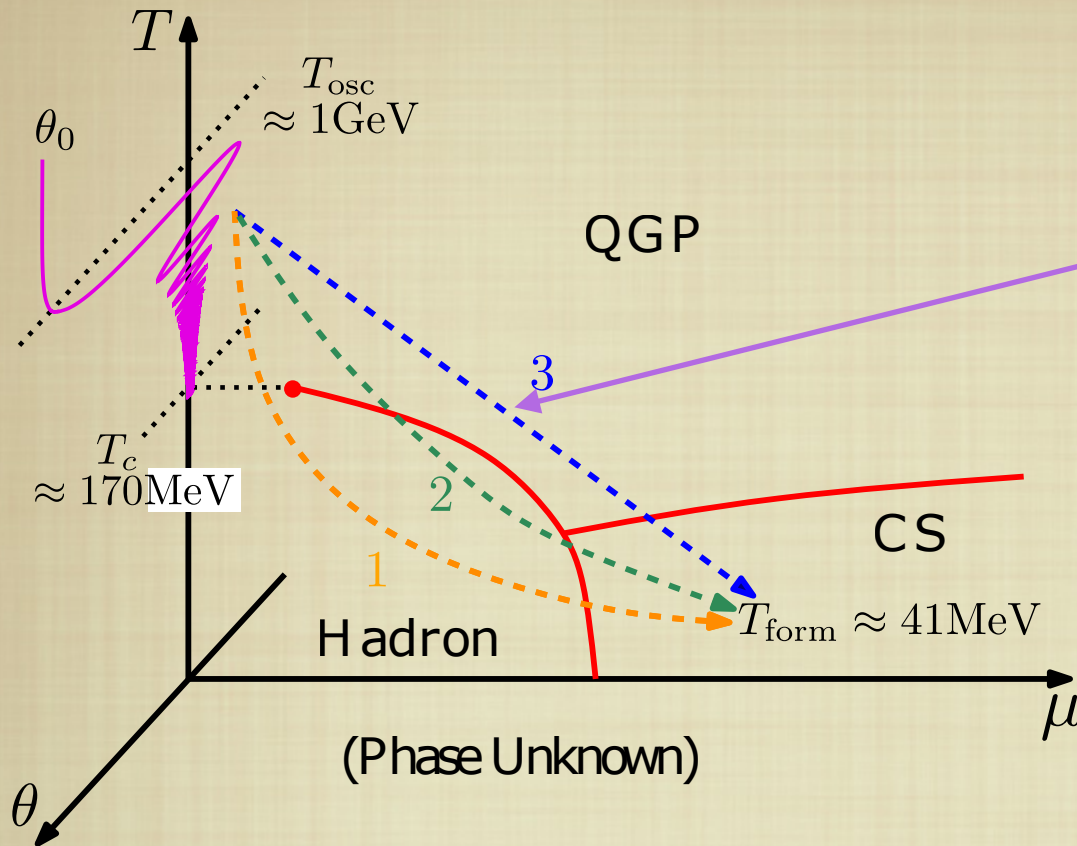


THERE WERE MANY PROBLEMS WITH THE ORIGINAL 1984-WITTEN'S IDEA:

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**).

AXION QUARK NUGGET'S (AQN) FORMATION



This is a novel contribution to DM from the axion field, in addition to conventional misalignment mechanism and DW decay

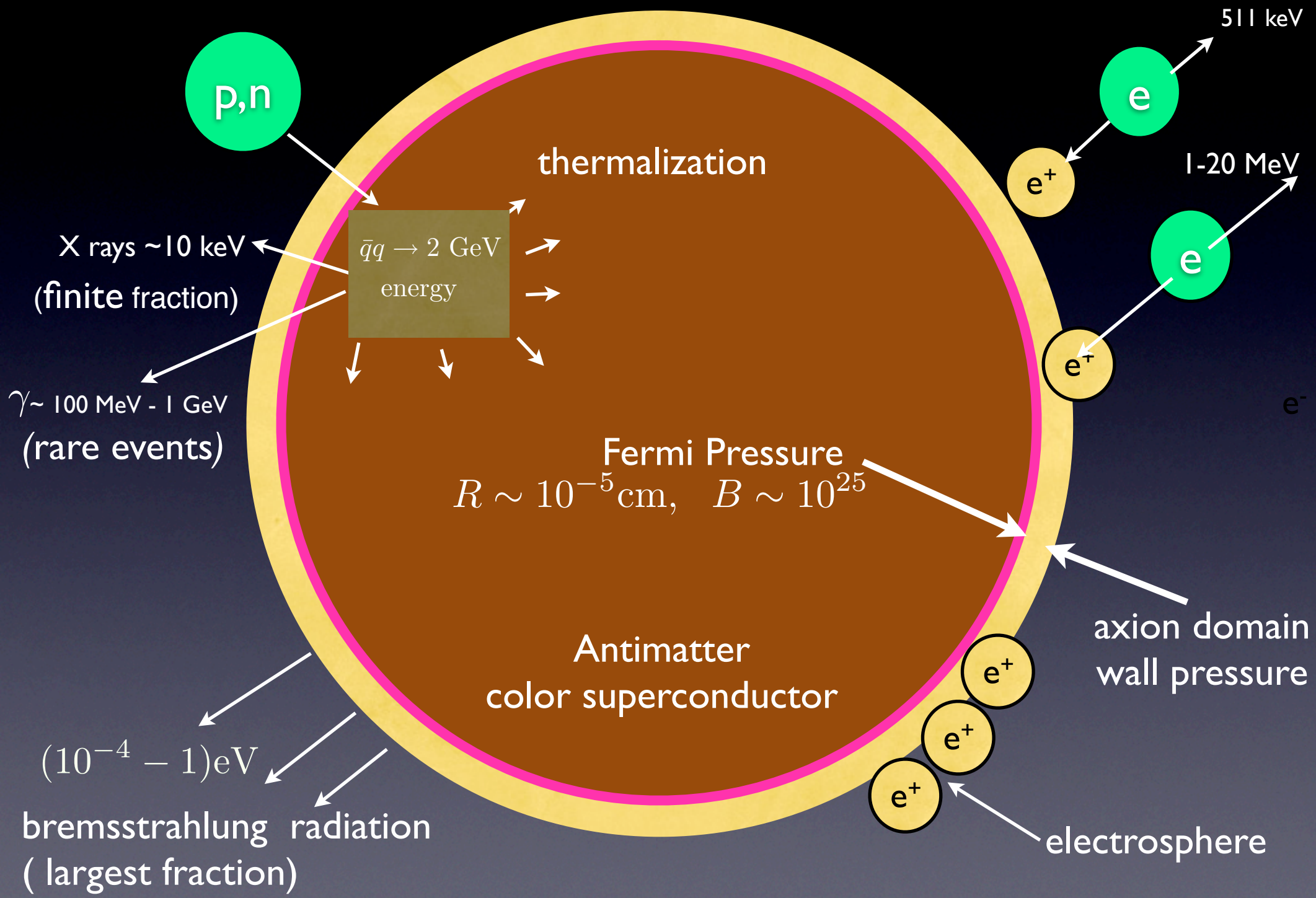
■ POSSIBLE COOLING PATHS ARE DENOTED AS 1, 2, 3. THE PHASE DIAGRAM AT $\theta \neq 0$ IS STILL UNKNOWN. FORMATION TEMPERATURE $T = 41 \text{ MeV}$ CORRESPONDS TO THE OBSERVED VALUE

$$\eta \equiv \frac{n_B - n_{\bar{B}}}{n_\gamma} \simeq \frac{n_B}{n_\gamma} \sim e^{-\left(\frac{m_p}{T_{\text{form}}}\right)} \sim 10^{-10}$$

■ THERE ARE 2 NEW ELEMENTS (IN COMPARISON TO WITTEN'S)

- 1. THERE IS EXTRA CP ODD AXION FIELD. PRECISELY THIS CP ODD FIELD $\theta \neq 0$ IS RESPONSIBLE FOR CHARGE SEGREGATION OF THE CHARGE (REPLACING BARYOGENESIS)
- 2. AS A CONSEQUENCE: THERE ARE TWO SPECIES, THE NUGGETS AND ANTI-NUGGETS (REPRESENTING THE DM). THE CONSTRUCTION LEADS TO THE SIMILARITY BETWEEN DARK AND VISIBLE SECTORS: $\Omega_{\text{dark}} \approx \Omega_{\text{visible}} \sim \Lambda_{\text{QCD}}$
- THE NUGGETS AND ANTI-NUGGETS ARE ABSOLUTELY STABLE OBJECTS ON THE COSMOLOGICAL TIME SCALE. ONLY SMALL PORTION OF THE BARYON CHARGE GET ANNIHILATED DURING BBN, CMB, POST-RECOMBINATION EPOCHS.
- THEREFORE, THE AQNS SURVIVE THE LONG EVOLUTION IN UNFRIENDLY ENVIRONMENT UNTIL PRESENT DAYS IF
$$\langle B \rangle \geq 3 \cdot 10^{24} \quad [\text{direct IceCub constraint}]$$

Antiquark nugget structure. Source of emission



■ **INSTEAD OF CONVENTIONAL LOCAL FIELDS (SUCH AS WIMPS) THE DM IN OUR FRAMEWORK IS A MACROSCOPICAL COMPOSITE OBJECT WITH A TYPICAL NUCLEAR DENSITY, SIMILAR TO WITTEN'S STRANGELETS.**

■ **THE OBSERVATIONAL ASTROPHYSICAL CONSEQUENCES WILL BE SUPPRESSED BY VERY TINY NUMBER DENSITY n_{AQN}**

$$n_{\text{AQN}} \sim \frac{\rho_{\text{DM}}}{M} \sim 10^{-25} \text{cm}^{-3}, \quad \frac{d\Phi}{dA d\Omega} \approx 4 \cdot 10^{-2} \left(\frac{10^{25}}{\langle B \rangle} \right) \left(\frac{\rho_{\text{DM}}}{0.3 \text{ GeV cm}^{-3}} \right) \frac{\text{events}}{\text{yr} \cdot \text{km}^2}$$

$$\text{internal : } M \sim m_p B \sim 10 \text{g}, \quad n_B \sim (\text{fm})^3 \sim 10^{40} \text{cm}^{-3}, \quad B \sim 10^{25}, \quad R \sim 10^{-5} \text{cm}$$

■ **A SMALL CROSS SECTION TO MASS RATIO REPLACES A WEAK COUPLING CONSTANT (TYPICAL FOR WIMPS) FOR SUFFICIENTLY LARGE NUGGETS AS $\epsilon \sim \pi R^2/M \sim B^{-1/3} \ll 1$**

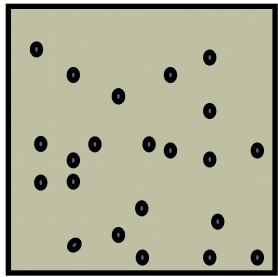
■ **A FUNDAMENTAL RATIO $\eta \sim \exp(-m_p/T_{\text{form}}) \sim 10^{-10}$ IS DETERMINED BY FORMATION TEMPERATURE $T_{\text{form}} \lesssim T_c \simeq 60 \text{ MeV}$ AND ITS QCD NATURE (NO BARYOGENESIS NEEDED)**

MATTER IN THE UNIVERSE

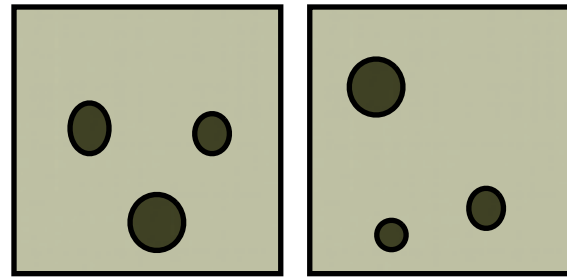
1. CP violating parameter $\theta \sim 1$ generates the difference between number of nuggets and antinuggets which must be order of one effect (observations: $B_{nugget}/\bar{B}_{antinugget} \simeq 2/3$)
2. The annihilation processes continue until visible anti-baryons get annihilated and baryons remain;
3. The final result: $\Omega_{\text{dark}} \approx \Omega_{\text{visible}}$ as observed irrespective to any parameters of the model

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

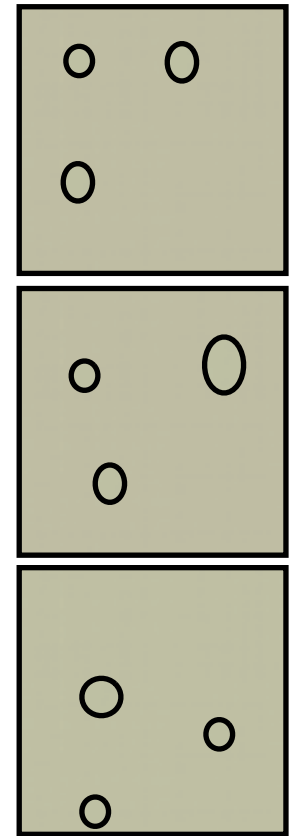
$$B_{DM} = B_{nugget} + \bar{B}_{antinugget} \simeq 5 B_{visible}$$



One part:
visible matter
(hadronic phase)



Two parts:
matter nuggets
(CS phase)



Three parts:
anti-matter nuggets
(CS phase)

Applications. Observed mysterious emissions: from the galaxy to the Sun to the Earth

- galaxy



Physics Letters B
Volume 828, 10 May 2022, 137015



The mysterious diffuse UV radiation and axion quark nugget dark matter model

Ariel Zhitnitsky 

- Sun: Solar corona heating by axion quark nugget dark matter

Nayyer Raza, Ludovic Van Waerbeke, and Ariel Zhitnitsky
Phys. Rev. D **98**, 103527 – Published 26 November 2018

- Earth: **Multi-Modal Clustering Events Observed by Horizon-10T and Axion Quark Nuggets**

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Universe **2021**, 7(10), 384; <https://doi.org/10.3390/universe7100384>

- In the applications to be discussed below I take agnostic viewpoint regarding the formation mechanism- I assume that such antimatter nuggets exist. It is consistent with all cosmological, astrophysical, satellite, and terrestrial observations as long as

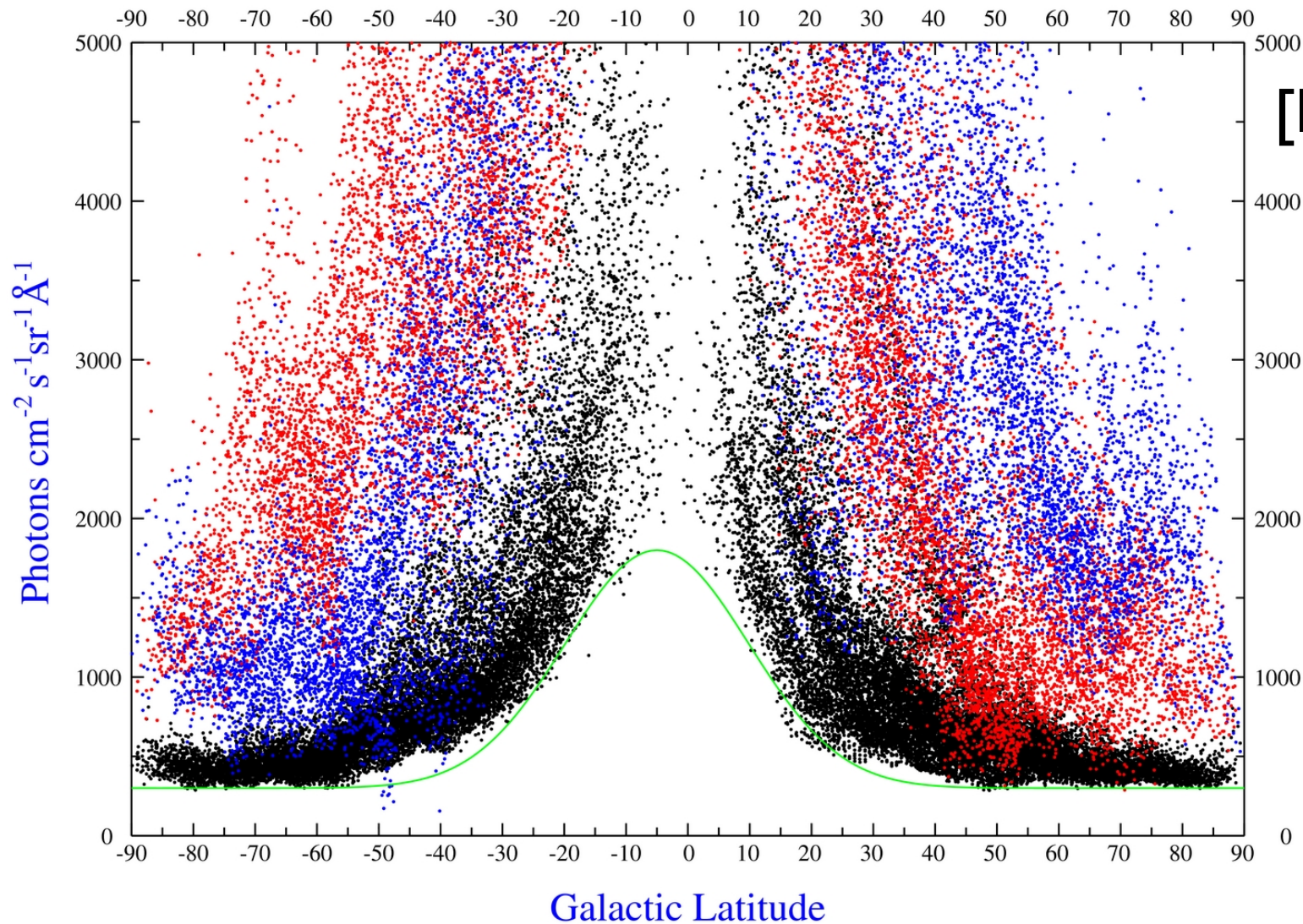
$$\langle B \rangle \geq 3 \cdot 10^{24} \quad [\text{direct IceCub constraint}]$$

- I'll mention about some subtle elements and many misconceptions on the formation mechanism and survival pattern at the very end of this talk

3. MYSTERIOUS COSMIC DIFFUSE UV RADIATION

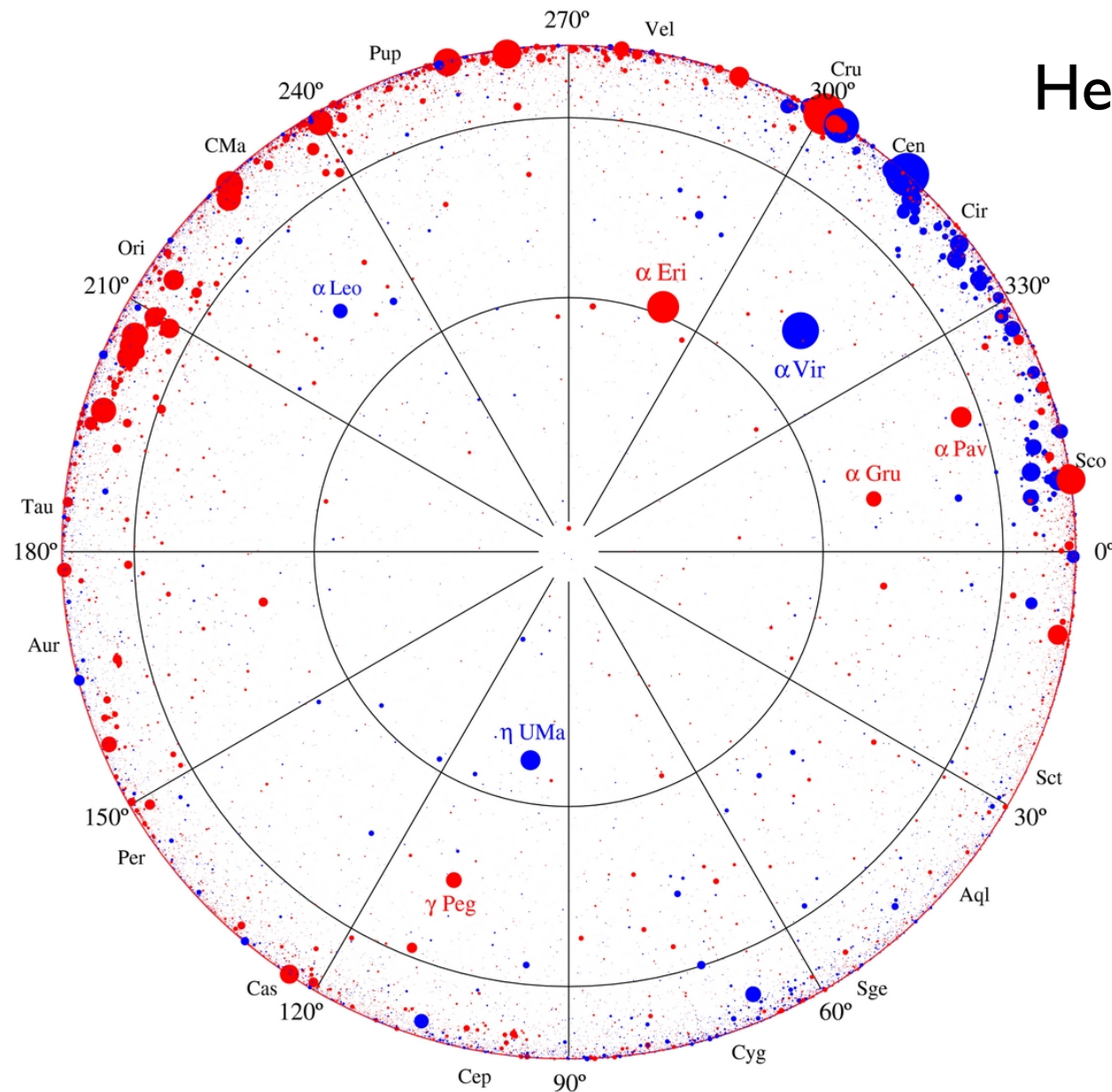
- RECENT STUDIES OF THE DIFFUSE FAR UV BACKGROUND BY GALEX (GALAXY EVOLUTION EXPLORER) SHOW HUGE INCONSISTENCY OF THE CONVENTIONAL PICTURE WHEN UV BACKGROUND IS A RESULT OF DUST SCATTER FROM THE UV EMITTING STARS, [HENRY ET AL, 2015]:
 - 1. “*uniformity puzzle*” -THE DIFFUSE FUV $[(1300 - 1700)\text{\AA}]$ RADIATION IS VERY UNIFORM IN BOTH HEMISPHERES, IN CONTRAST WITH STRONG NON-UNIFORMITY IN DISTRIBUTION OF THE UV EMITTING STARS (SEE NEXT SLIDE);
 - 2. “*galactic longitude puzzle*” - THE DIFFUSE FUV RADIATION IS ALMOST INDEPENDENT OF GALACTIC LONGITUDE. IT MUST BE CONTRASTED WITH LOCALIZATION OF THE UV EMITTING STARS WHICH ARE MOSTLY CONFINED TO THE LONGITUDE RANGE $(180^0 - 360^0)$ (SEE NEXT SLIDE);

- 3. “*galactic latitude puzzle*”- THE DIFFUSE RADIATION INCREASES IN BRIGHTNESS TOWARD LOWER GALACTIC LATITUDE. THIS SHOULD BE CONTRASTED WITH CONVENTIONAL MODELLING WHICH PREDICTS VERY LOW BRIGHTNESS AT LOW GALACTIC LATITUDES $\in (-20^0, +20^0)$
- 4. “*non-correlation puzzle*” CONVENTIONAL PICTURE FOR THE FUV SUGGESTS THAT IT MUST BE CORRELATED WITH THE THERMAL ($100\mu m$) EMISSION AS BOTH RADIATIONS ARE ASSUMED TO BE RELATED TO THE DUST AND ITS DISTRIBUTION IN THE GALAXY.
- THIS PICTURE DRAMATICALLY FAILS AS THERMAL ($100\mu m$) EMISSION IS HIGHLY ASYMMETRIC AND STRONGLY CORRELATED WITH LOCATIONS OF THE UV EMITTING STARS, WHILE FUV DIFFUSE EMISSION IS HIGHLY SYMMETRIC AND UNIFORM, SEE SLIDES BELOW. IT ALSO SUGGESTS THAT FUV HAS GALACTIC (NOT EXTRA GALACTIC, NOR TERRESTRIAL) ORIGIN.



[Henry et al, 2015]

FUV (black), thermal ($100 \mu\text{m}$) emission at different longitudes (red-southern, and blue-northern). Dramatic difference between the thermal and FUV emissions, which must have independent origin. There is no connection between thermal (asymmetric) and FUV (symmetric) emissions,



Locations of the UV bright stars are shown (blue-northern, red-southern galactic latitudes). The sky is dramatically different in FUV as most of the bright stars concentrated on galactic plane and half of the galactic longitudes ($180^0 - 360^0$)

4. MYSTERIOUS FUV RADIATION AS THE AQN ANNIHILATION EVENTS IN GALAXY

- A TYPICAL INTERNAL TEMPERATURE OF THE AQNS IS DETERMINED BY CONDITION THAT THE RADIATION OUTPUT IS BALANCED BY THE ENERGY DUE TO ANNIHILATIONS

$$4\pi R^2 \cdot F_{\text{tot}}(T) \approx \kappa \cdot (\pi R^2) \cdot (2 \text{ GeV}) \cdot n \cdot v_{\text{AQN}}$$

- THE TOTAL SURFACE EMISSIVITY IS MOSTLY DETERMINED BY THE PHYSICS OF THE ELECTROSPHERE (BREMSSTRAHLUNG)

$$F_{\text{tot}}(T) = \int_0^\infty d\omega \frac{dF}{d\omega}(\omega) \approx \frac{16}{3} \frac{T^4 \alpha^{5/2}}{\pi} \sqrt[4]{\frac{T}{m}}$$

- TYPICAL INTERNAL TEMPERATURE IN THE CENTRAL REGIONS OF GALAXY COULD BE VERY HIGH $T_{\text{eff}} \geq (2.5 - 5) \text{ eV}$ WHICH IMPLIES THAT THE AQNS COULD BE VERY STRONG UV EMITTERS

■ **TOTAL LUMINOSITY L_{AQN} FROM A SINGLE AQN IS**

$$L_{\text{AQN}} \approx 4\pi R^2 \cdot F_{\text{tot}}(T) \approx 4.7 \left(\frac{T}{5 \text{ eV}} \right)^{\frac{17}{4}} \frac{\text{erg}}{\text{s}}$$

■ **TO ESTIMATE TOTAL FUV INTENSITY $\Phi_{\text{AQN}}^{\text{FUV}}$ PRODUCED BY ALL NUGGETS ALONG THE LINE OF SIGHT ONE SHOULD MULTIPLY L_{AQN} TO THE AQN'S DENSITY AND MEAN FREE PATH $\mathcal{R} \sim 0.6 \text{ kpc}$ AND FRACTION $\chi \simeq 0.2$ TO FUV EMISSION**

$$\Phi_{\text{AQN}}^{\text{FUV}} \sim L_{\text{AQN}} n_{\text{AQN}} \mathcal{R} \chi \sim 5 \cdot 10^{-5} \left(\frac{T}{5 \text{ eV}} \right)^{\frac{17}{4}} \frac{\text{erg}}{\text{s} \cdot \text{cm}^2}$$

■ **THIS ESTIMATE SHOULD BE COMPARED WITH INTENSITY OF EXCESS FUV DETECTED BY GALEX OVER ITS BANDPASS**

$$10^{-5} \text{ erg cm}^{-2} \text{ s}^{-1} \quad \text{in band } (1380 - 2500) \text{ \AA}$$

- IT SHOULD BE ALSO COMPARED WITH FUV INTENSITY PRODUCED BY WIMP-LIKE MODELS $< 10^{-17} \text{erg}/(\text{s} \cdot \text{cm}^2)$ THIS MECHANISM NATURALLY EXPLAINS 1-4 PUZZLES MENTIONED ABOVE:
- “*uniformity puzzle*” IS RESOLVED AS DM IN FORM OF THE AQN UNIFORMLY DISTRIBUTED IN THE GALAXY;
- “*galactic longitude puzzle*” IS RESOLVED AS DM PARTICLES ARE NOT SENSITIVE TO GALACTIC LONGITUDE;
- “*galactic latitude puzzle*” IS RESOLVED AS THE INTENSITY MUST INCREASE TOWARD LOWER LATITUDES BECAUSE IT IS PROPORTIONAL TO VISIBLE DENSITY $\Phi_{\Gamma} \propto \int_{\Gamma} dl n(l) n_{\text{DM}}(l)$
- “*non-correlation puzzle*” WITH IS THERMAL EMISSION IS ALSO RESOLVED AS DM DOES NOT FOLLOW THE LOCATIONS OF STARS.

- I WANT TO FINISH THIS PART OF MY TALK (ABOUT FUV) WITH SEVERAL QUOTAS FROM OBSERVATIONAL PAPER [HENRY 2015] WHO ANTICIPATED/REQUIRED SUCH KIND OF DM:
- “THE SOURCE OF THE DIFFUSE FUV EMISSION IS UNKNOWN - THAT IS THE MYSTERY THAT IS REFERRED TO IN THE TITLE”
- THIS “EXOTIC” MYSTERIOUS COMPONENT OF EMISSION IS UNKNOWN BUT MUST BE GALACTIC ORIGIN, AND COULD BE DUE TO STRONG INTERACTION OF DM WITH THE NUCLEI OF INTERSTELLAR MEDIUM
- THE AUTHORS [HENRY 2015] ALSO SUGGEST THAT DM IN FORM OF A “COMPOSITE” SYSTEM MAY CONTRIBUTE TO THE EXOTIC FUV COMPONENT
- OUR COMMENT- ALL THESE COMPONENTS ARE AUTOMATICALLY PRESENT IN THE AQN CONSTRUCTION

5. SOLAR EXTREME UV (EUV) RADIATION

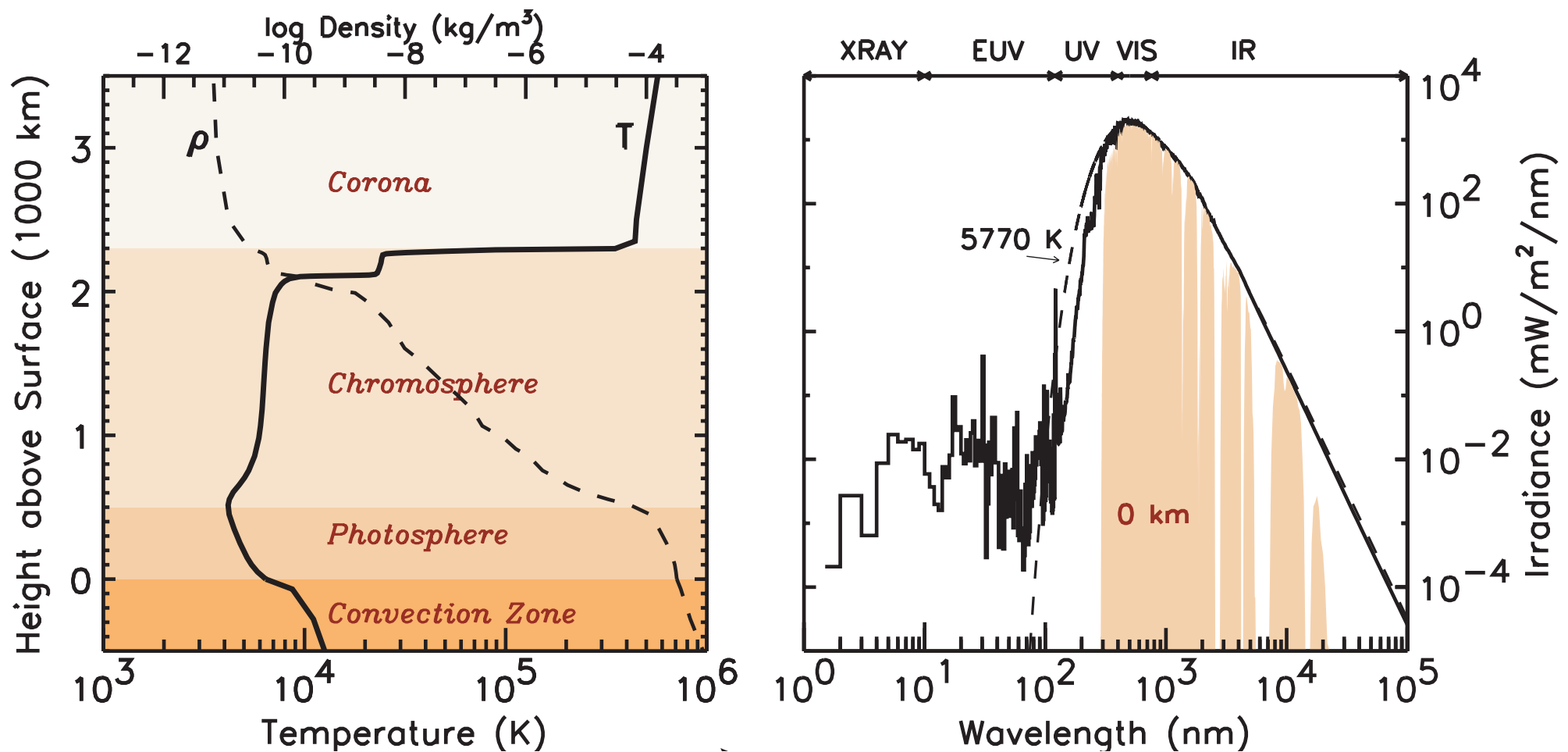
■ THE QUIET SUN EMITS EUV RADIATION WITH THE ENERGY OF ORDER 100 eV WHICH CANNOT BE EXPLAINED IN TERMS OF ANY CONVENTIONAL ASTRO-PHENOMENA.

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

■ 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*, W.Grotrian, 1939)



Left: the temperature distribution in outer Sun: the drastic changes occur in vicinity of 2000km. The transition region is about 200 km wide.

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

- PUZZLES: THE TRANSITION HAPPENS ON SCALE 200 KM, WHILE TYPICAL SCALES (MEAN FREE PATHS) ARE $(10^3 - 10^4)$ km
- THIS APPARENT VIOLATION OF THE SECOND LAW OF THERMODYNAMICS (TEMPERATURE INCREASES WHEN DENSITY DECREASES) CAN ONLY BE RESOLVED IF THERE IS SOME UNKNOWN NON-THERMAL SOURCE OF ENERGY
- THE SOURCE SHOULD SUSTAIN POWER OF ORDER 10^{27} erg/s WHICH REPRESENTS $(10^{-6} - 10^{-7})$ OF THE TOTAL LUMINOSITY
- THIS EMISSION IS VERY UNIFORM OVER SURFACE, AND OCCURS EVEN IN THE QUIET SUN WHERE MAGNETIC FIELD IS SMALL ~ 1 G
- THIS EUV EMISSION IS ALMOST INSENSITIVE TO SOLAR CYCLES
- THE OBSERVED DOPPLER SHIFTS OF EMITTING IONS: ~ 300 KM/S, FAR EXCEED THERMAL VELOCITY 11 KM/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, WHICH IS A CONVENTIONAL EXPLANATION, SEE COMMENTS BELOW)

■ 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)

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 BY SOLAR PHYSICS PEOPLE)

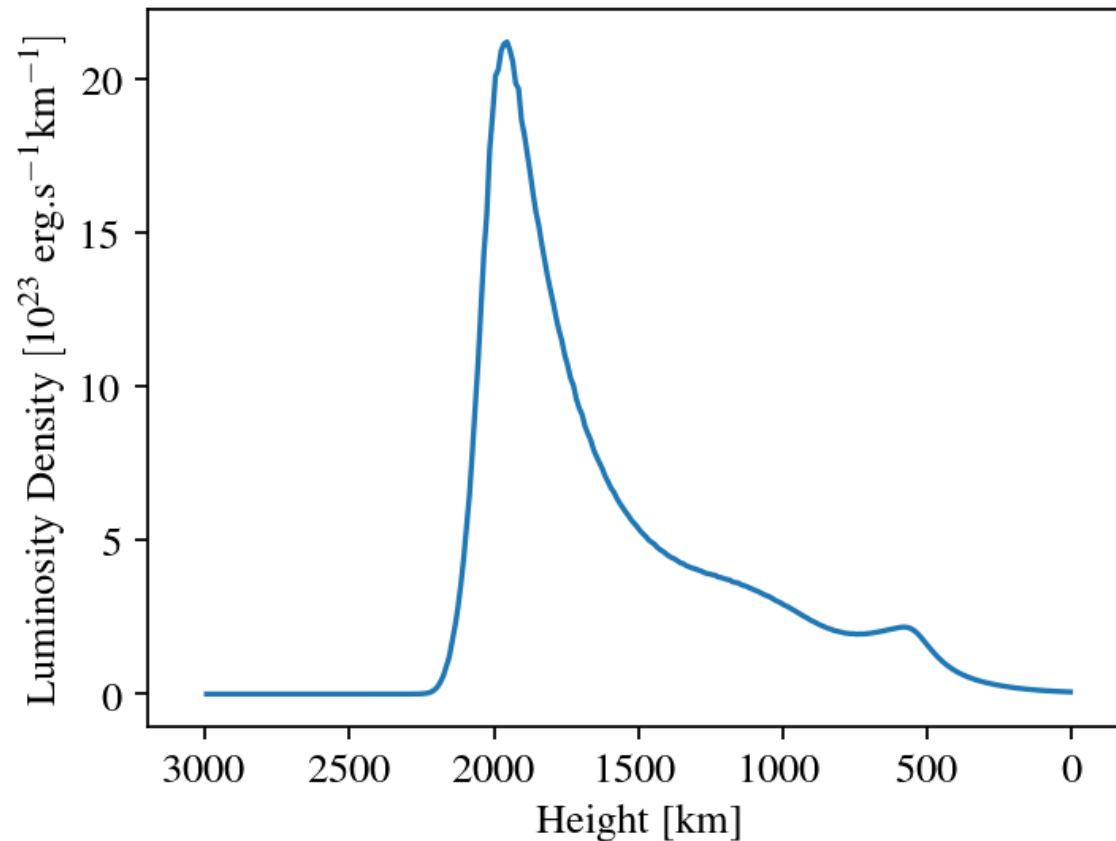
$$\langle W \rangle \simeq 10^{23} \text{ erg}, \quad \left\langle \frac{dN}{dt} \right\rangle \simeq (10^3 - 10^4) \text{ s}^{-1}.$$

■ 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).

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

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 (TR). The size, 200 km of the TR is a highly nontrivial feature of this proposal (determined by annihilation pattern of the AQNs).

■ 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 DIFFERENT CONSTRAINTS.

■ THE MEASURED UNIFORM EUV DISTRIBUTION IS ALSO CONSISTENT WITH THIS PROPOSAL WHEN AQNs ARE UNIFORMLY DISTRIBUTED OVER THE SOLAR SURFACE

■ CONVENTIONAL APPROACHES FAIL TO EXPLAIN A SMALL TRANSITION REGION SIZE (200 km).

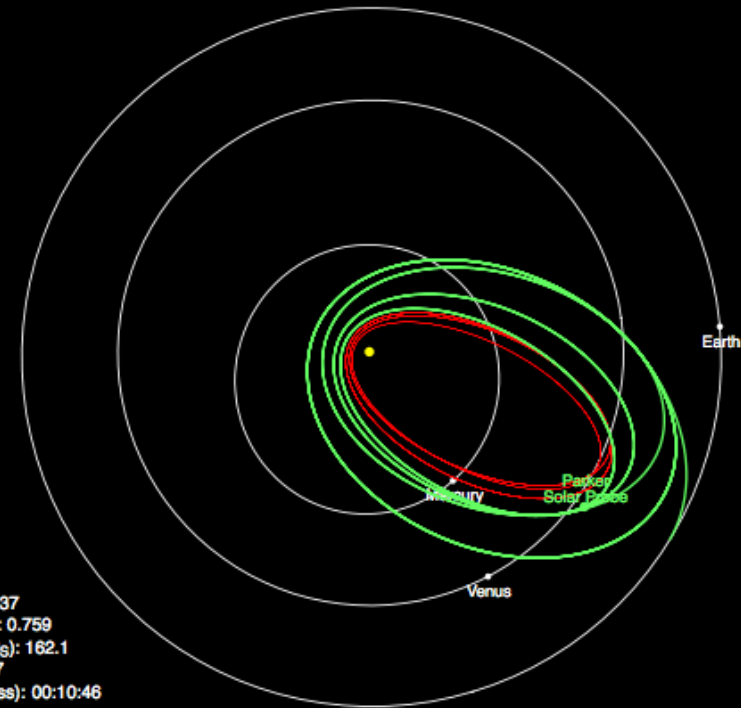
■ THE TIME MEASUREMENTS OF NANOFLARES DEMONSTRATE THE DOPPLER SHIFT 300 km/s, FAR EXCEEDS THERMAL VELOCITY 11 km/s. CONSISTENT WITH AQN DM VELOCITIES



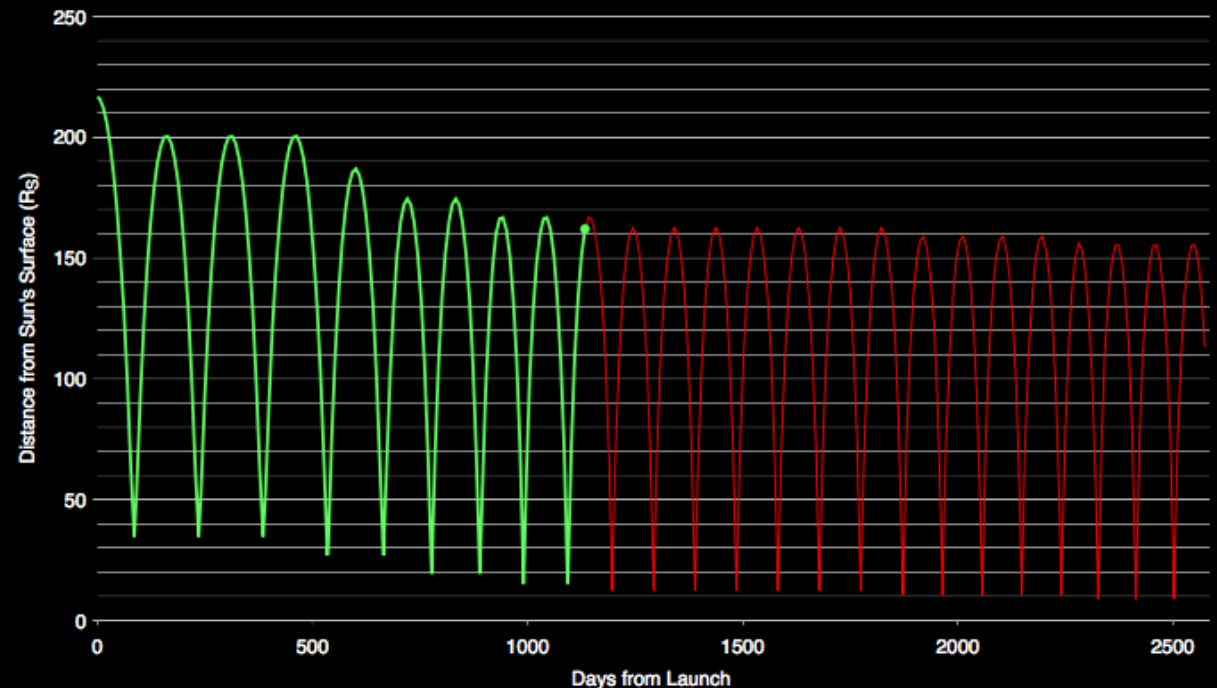
CONCLUSION
FROM MY
COLLABORATORS
(ASTRO-PEOPLE)-
THE **PARKER**
SOLAR PROBE
(LAUNCH ON
AUGUST 12.
2018) WILL HAVE
SUFFICIENT
RESOLUTION IN
FEW YEARS TO
RESOLVE THE
SOLAR CORONA
MYSTERY

Parker Solar Probe Mission Trajectory and Current Position

Helio-centric Velocity (km/s): 16.37
Distance from Sun Center (AU): 0.759
Distance from Sun's Surface (R_{\odot}): 162.1
Distance from Earth (AU): 0.647
Round-Trip Light Time (hh:mm:ss): 00:10:46
19 Sep 2021 03:00:00 UTC



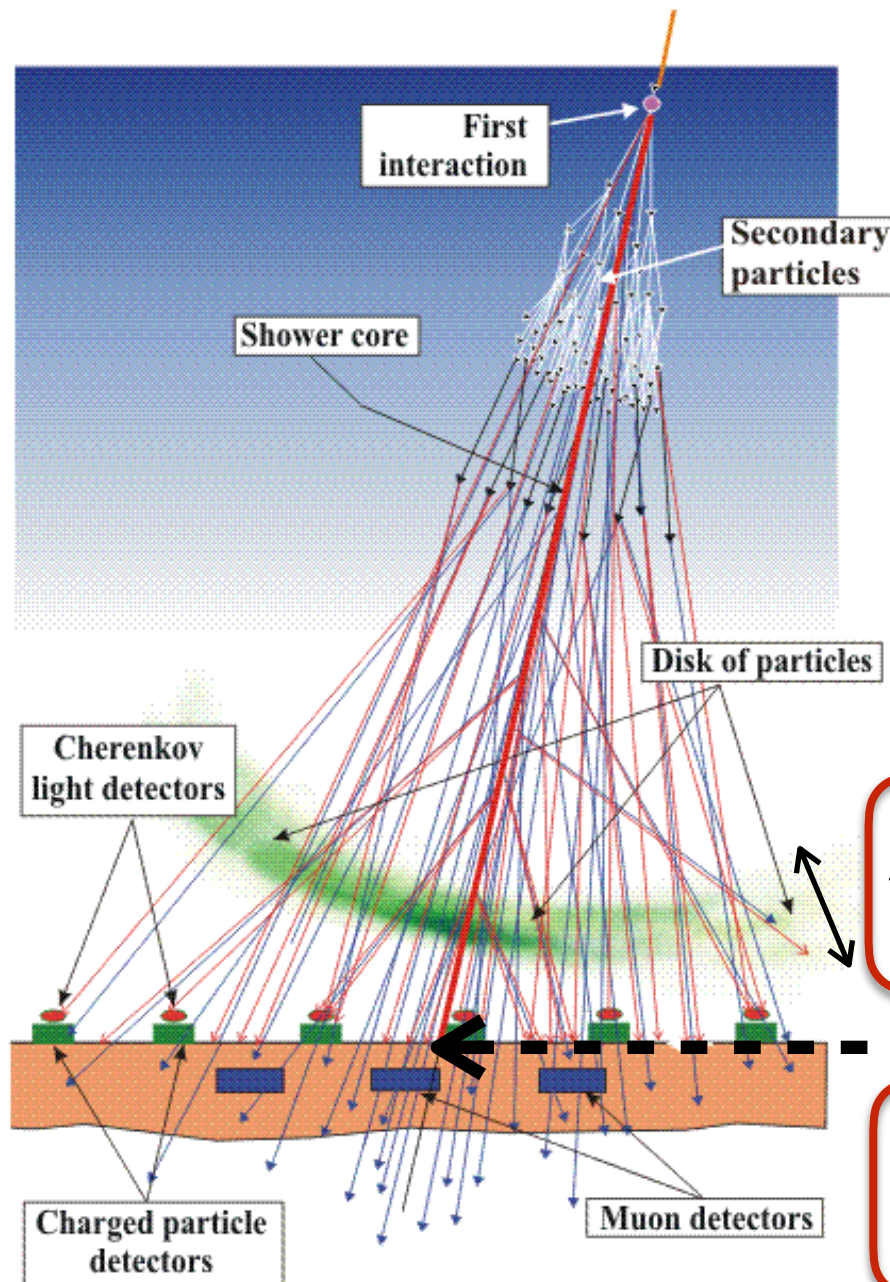
Parker Solar Probe Distance from Sun



6. MULTI-MODAL CLUSTERING EVENTS OBSERVED BY HORIZON 10T COSMIC-RAY LABORATORY

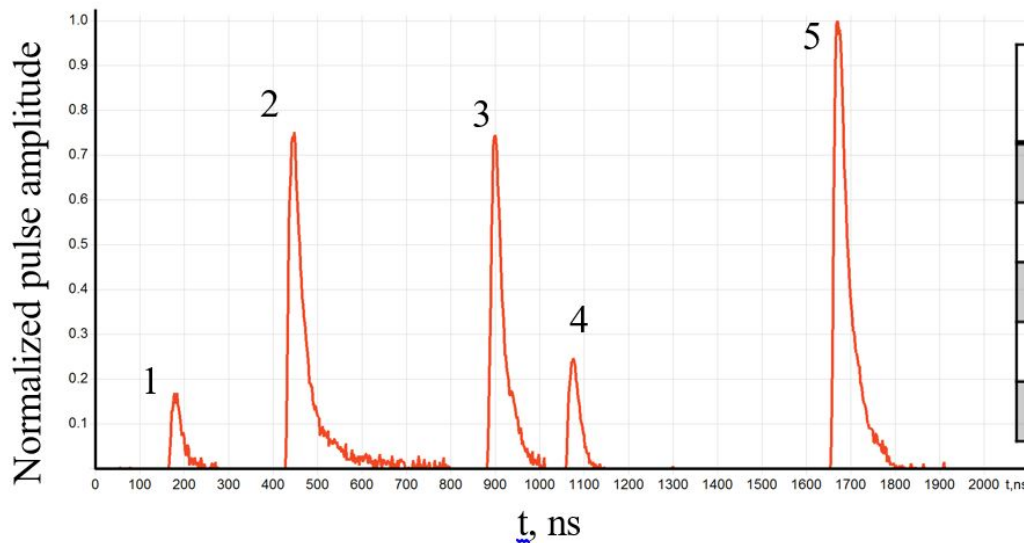
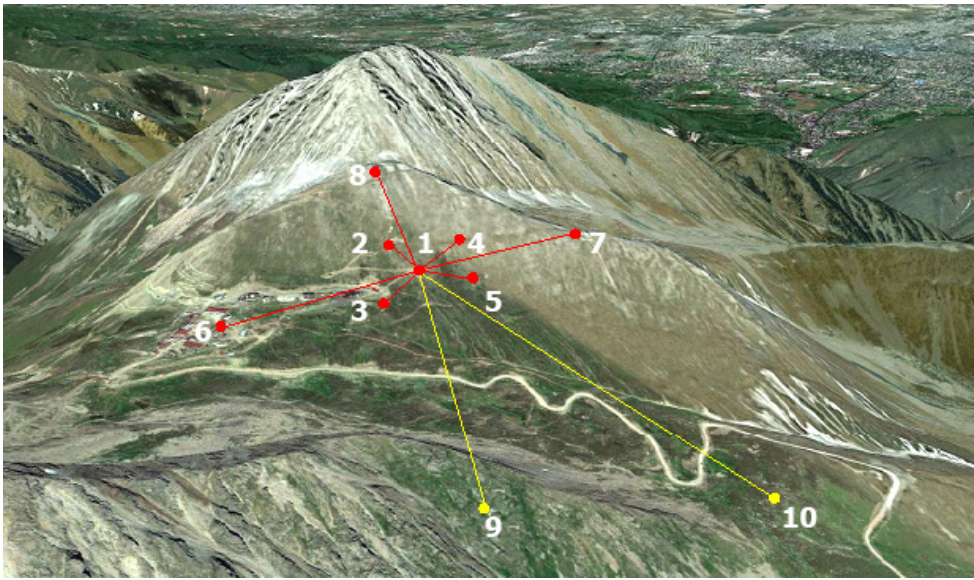
- THE HORIZON 10T COLLABORATION HAS OBSERVED RECENTLY MYSTERIOUS MULTI-MODAL EVENTS (MME).
- THE OBSERVED EVENTS ARE DRAMATICALLY DIFFERENT FROM CONVENTIONAL EXTENSIVE AIR SHOWERS (EAS).
 - 1. NORMAL EAS CAN BE THOUGHT AS A DISK-PANCAKE WITH WELL DEFINED CORE OF THE SHOWER, THE EAS AXIS
 - 2. EAS REPRESENTS AN UNIFORM DISTRIBUTION OF PARTICLES CHARACTERIZED BY $\rho(R)$ -NUMBER OF PARTICLES PER UNIT AREA, WHICH DROPS WITH DISTANCE R
 - 3. EAS THICKNESS τ IS MEASURED IN NANOSECONDS INSTEAD OF METERS $\tau = \Delta d/c$

EAS of cosmic rays in atmosphere



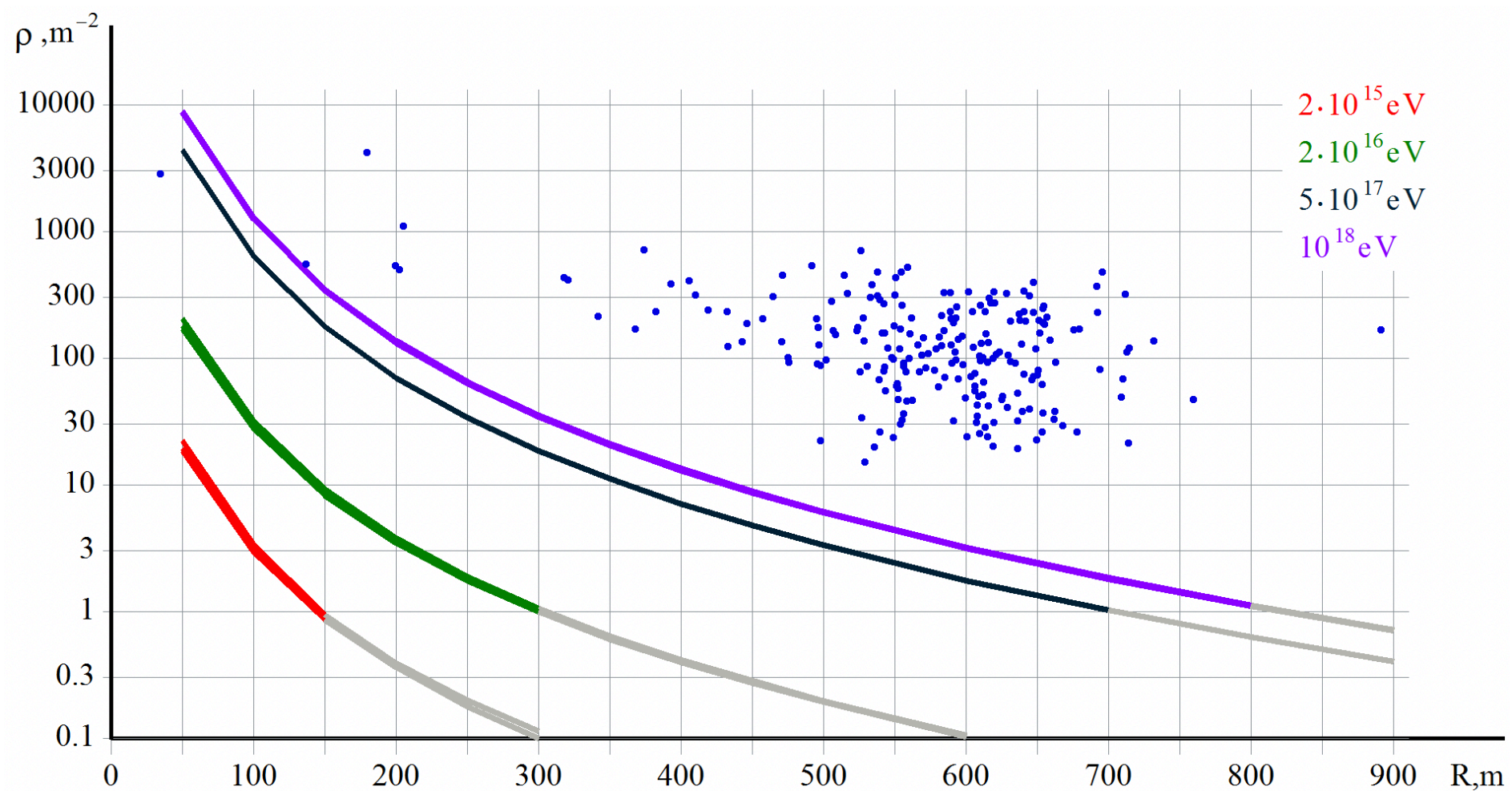
$$\tau = \Delta d / c \quad \text{width } \tau(R) \text{ as a function of } R$$

R : distance from the core

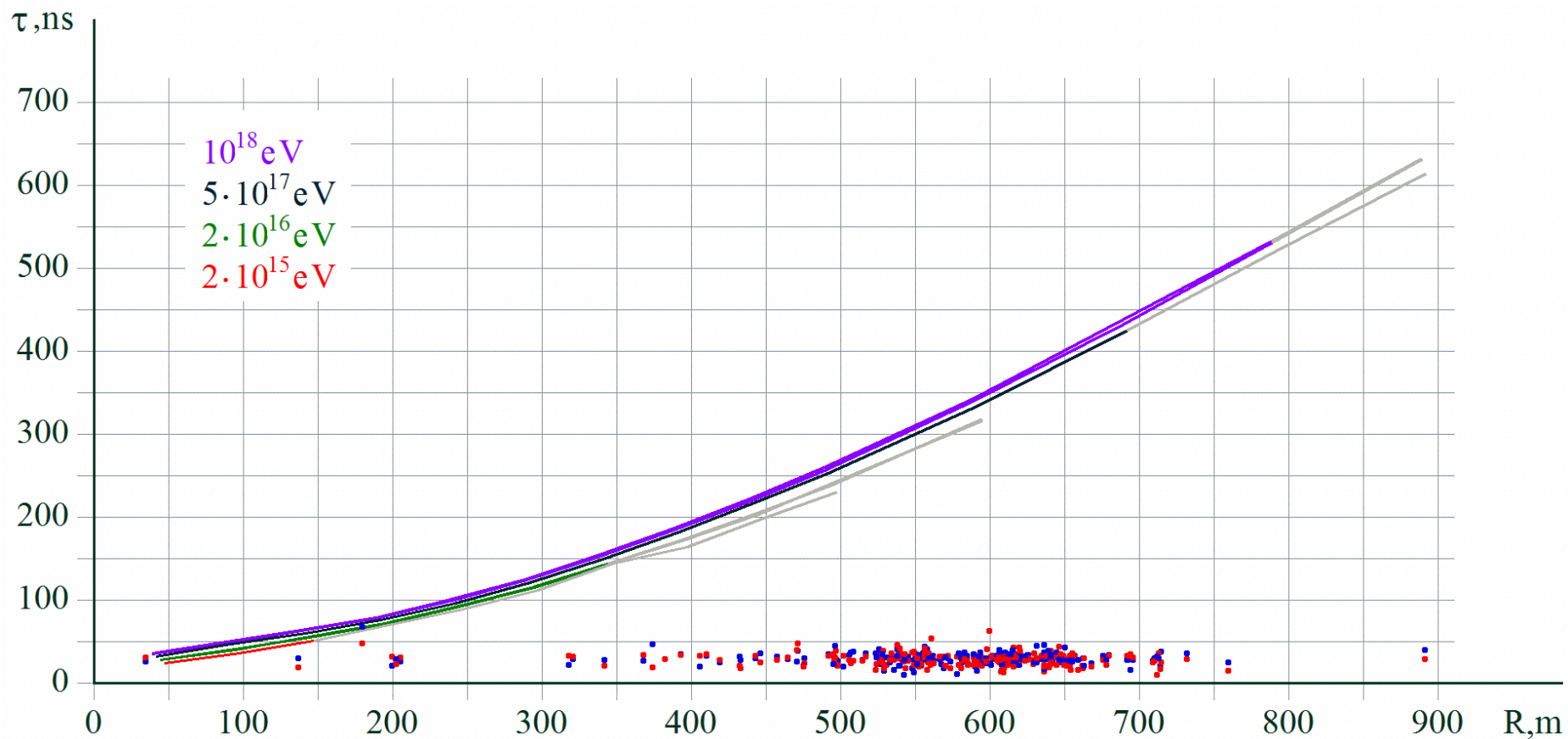


| Peak # | Delay ns | $\tau_{0.8}$ ns | $\rho_{0.8}$ #/m ² |
|--------|----------|-----------------|-------------------------------|
| 1 | 0 | 28 | 32 |
| 2 | 265 | 34 | 256 |
| 3 | 720 | 31 | 187 |
| 4 | 894 | 31 | 52 |
| 5 | 1493 | 35 | 339 |

Normally, in a given detector one should see a single event characterized by width $\tau(R)$ as a probability to have two or more consecutive EAS events in a small area within μs is tiny. *It is not what observed: 5 events separated by μs*



Particle density $\rho(R)$ must dramatically decrease as a function of R , at least by factor 10^3 for $R \in (100 - 700) \text{ m}$. *It is not what actually observed.* Furthermore, the observed magnitude is much higher than expected for $E \sim (10^{17} - 10^{18}) \text{ eV}$



The width $\tau(R)$ must increase with R and should be on the level $\tau(R) \sim (400 - 600) \text{ ns}$ at $R \sim 700 \text{ m}$. *It is not what actually observed: the pulse width remains the same on the level $\tau(R) \approx (20 - 35) \text{ ns}$ irrespective to distance R .*

7. AQN INTERPRETATION OF THE MYSTERIOUS COSMIC RAY-LIKE EVENTS

■ THE NUGGETS MADE OF MATTER OR ANTIMATTER CAN CROSS THE EARTH WITHOUT LOOSING MUCH MASS AND MOMENTUM $\pi R^2 R_{\oplus} n_{\text{rock}} \ll B$ for $n_{\text{rock}} \sim 10^{24} \text{cm}^{-3}$

■ WHEN THE ANTIMATTER AQN HITS THE MATERIAL THE INTERNAL TEMPERATURE T STARTS TO RISE. IT CAN BE ESTIMATED FROM THE CONDITION THAT THE ANNIHILATION ENERGY RATE EQUALS TO THE EMISSIVITY FROM ELECTROSPHERE DUE TO BREMSSTRAHLUNG RADIATION

$$F_{\text{tot}}(4\pi R^2) \approx \kappa \cdot (\pi R^2) \cdot (2 \text{ GeV}) \cdot n \cdot v_{\text{AQN}} \quad \text{where} \quad F_{\text{tot}} \approx \frac{16}{3} \frac{T^4 \alpha^{5/2}}{\pi} \sqrt[4]{\frac{T}{m}},$$

■ THE TEMPERATURE FOR THE AQN TRAVERSING THE EARTH COULD BE AS HIGH AS $T \approx (100 - 200) \text{ keV}$ AT THE MOMENT OF EXIT WHEN IT CONTINUES TO PROPAGATE IN ATMOSPHERE

■ AT SUCH HIGH TEMPERATURE THREE NEW EFFECTS WILL OCCUR:

■ 1. THE AQNS WILL ACQUIRE A NEGATIVE CHARGE Q AS SOME POSITRONS FROM ELECTROSPHERE WILL LEAVE THE SYSTEM

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

■ 2. A STRONG INTERNAL ELECTRIC FIELD EMERGES

■ 3. AS A RESULT A e^+e^- PAIR PRODUCTION IS POSSIBLE AS A SUPPRESSION FACTOR $\exp(-2m/T) \sim 0.01$ IS NOT HUGE FOR HIGH $T \simeq 200$ keV. SIMILAR EFFECT HAD BEEN STUDIED PREVIOUSLY FOR QUARK STARS (DOMINANT COOLING PATTERN).

■ RESULTING POSITRONS WILL PARTIALLY SCREEN THE ELECTRIC FIELD WHILE THE ELECTRONS WILL LEAVE THE SYSTEM WITH HIGH ENERGY $\langle E \rangle \sim 10$ MeV. THE MEAN FREE PATH FOR SUCH ELECTRONS IS SEVERAL KILOMETRES

■ WHAT IS THE EMISSION PATTERN OF THE AQNS WHILE THEY ARE TRAVELLING IN ATMOSPHERE?

■ THERE ARE TWO LIMITING CASES: IF A TYPICAL TIME SCALE DUE TO THE ANNIHILATION $\tau_{deposit}$ IS LONGER THAN THE TIME SCALE τ_{cool} DUE TO EMISSION I.E. $\tau_{deposit} \gg \tau_{cool}$ THAN A CONTINUOUS COOLING PROCESS TAKES PLACE

■ IF A TYPICAL TIME SCALE DUE TO THE ANNIHILATION IS MUCH SHORTER THAN THE COOLING TIME THAN (IT IS EXACTLY OUR CASE WITH OUR PARAMETERS):

$$\tau_{deposit} \ll \tau_{cool} \Rightarrow (\text{short eruptions occur})$$

■ A NICE ANALOGY FOR SUCH ERUPTION LIKE EVENTS IS THE LIGHTNING FLASH UNDER THUNDERCLOUDS. CLOUDS GET IONIZED VERY EFFICIENTLY. THE NEUTRALIZATION OF THE IONS IS LESS EFFICIENT. IF SOME CONDITION ARE MET THE DISCHARGE OCCURS (LIGHTNING STRIKE IN OUR ANALOGY)

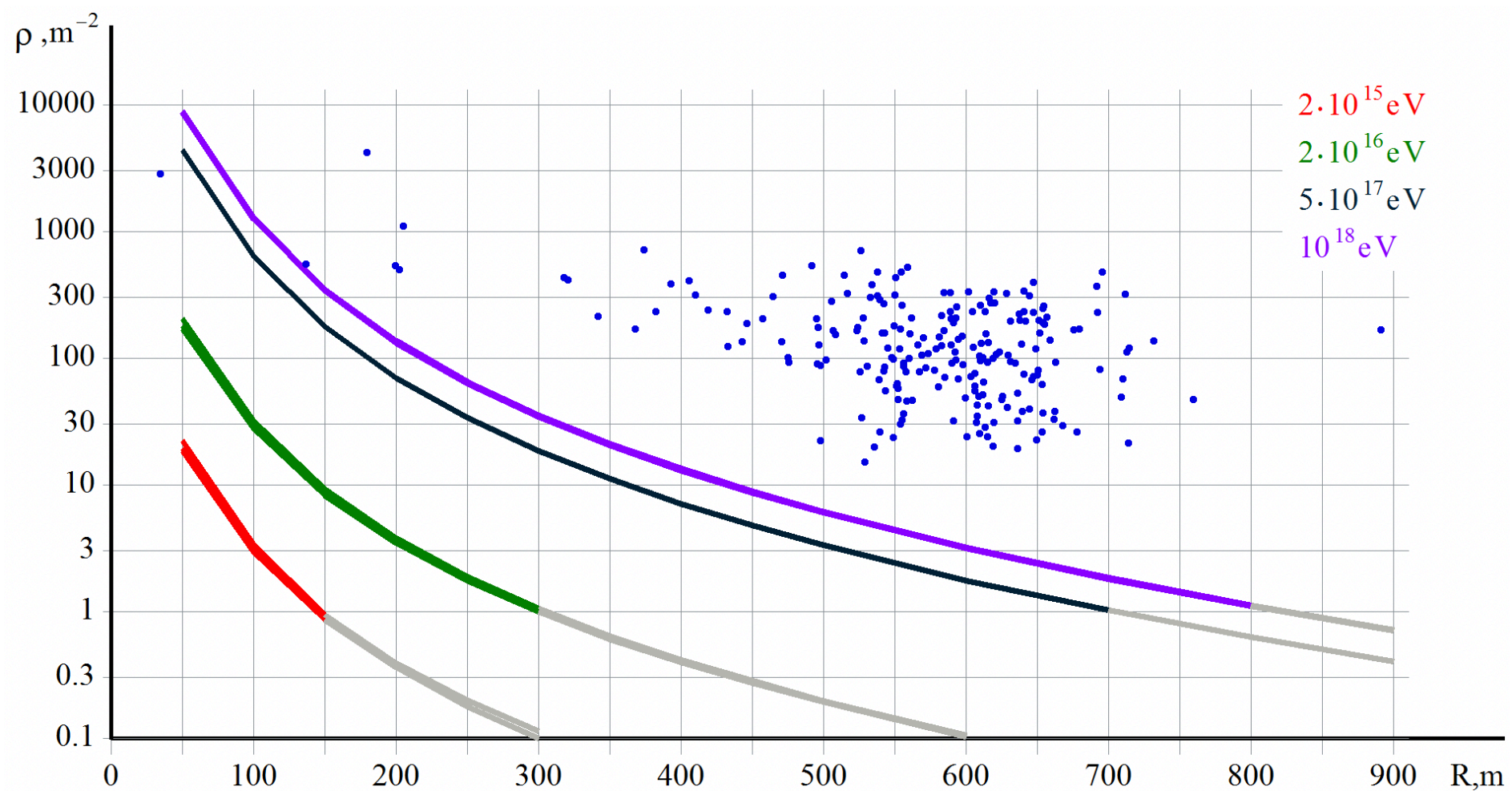
8. AQN PROPOSAL CONFRONTS OBSERVATIONS

- EACH ERUPTION PRODUCES $N \approx (10^8 - 10^9)$ WHICH ARE ACCELERATED BY INTERNAL FIELD TO ENERGY $\langle E \rangle \sim 10$ MeV
- THESE ELECTRONS MOVE IN THE BACKGROUND OF THE GEOMAGNETIC FIELD $\mathcal{B}_{\text{down}} \simeq 0.49$ G, $\mathcal{B}_{\text{north}} \simeq 0.24$ G SUCH THAT INSTANTANEOUS RADIUS OF CURVATURE IS

$$\rho \approx \frac{\gamma m c}{e \mathcal{B} \sin \theta_{\mathcal{B}}} \approx 2.8 \text{ km} \left(\frac{\gamma}{20} \right), \quad \gamma \equiv \frac{\langle E \rangle}{m}$$

- THE ELECTRONS CHANGE THE UPWARD TO DOWNWARD DIRECTION ON THIS SCALE AND CAN MIMIC THE CR
- PARTICLE NUMBER DENSITY $\rho(R)$ AT THE HORIZON-10T SITE IS

$$\rho(R) \sim \frac{(10^8 - 10^9)}{(2.5 \text{ km})^2} \sim \frac{(20 - 200)}{\text{m}^2}$$



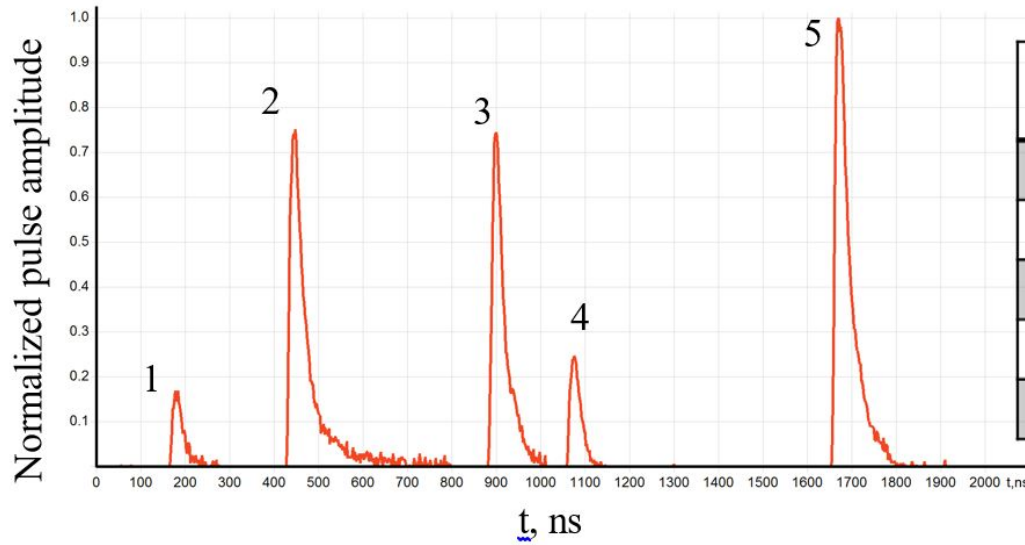
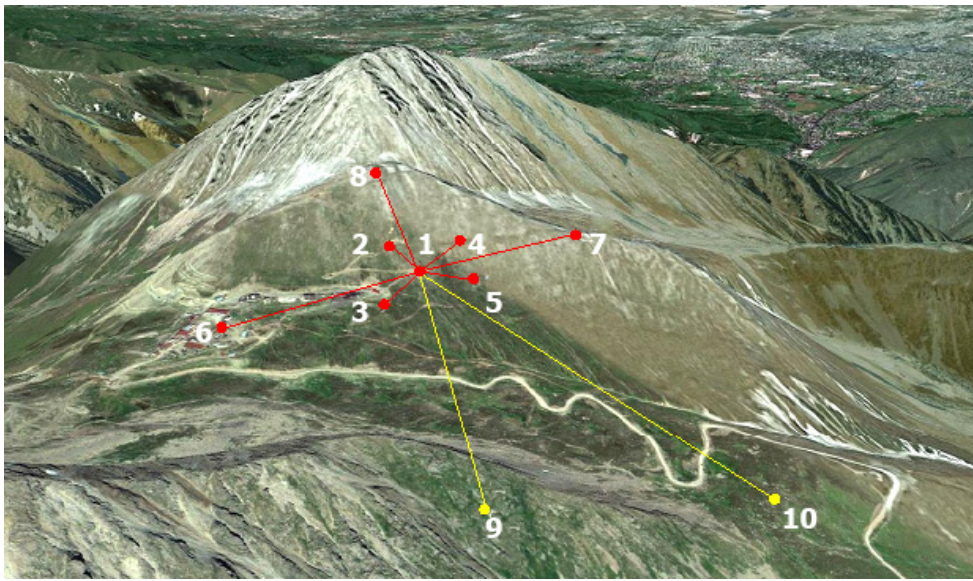
Particle density $\rho(R)$ does not depend on R as mere notion the “shower core” does not exist in the AQN framework

■ THE MYSTERIOUS CLUSTERING FEATURE IS ALSO CAN BE UNDERSTOOD IN THE AQN FRAMEWORK: THERE ARE MULTIPLE EMISSIONS FROM THE AQN WITH TIME DELAYS BETWEEN PULSES $\tau_{\text{delay}} \sim (10^2 - 10^3) \text{ ns}$, SEE NEXT SLIDE

■ THE TIME DURATION OF A SINGLE PULSE MUST BE CONSTANT AS IT IS ENTIRELY DETERMINED BY INTERNAL AQN DYNAMICS (HARD TO COMPUTE). OBSERVATIONS SUGGEST $\tau_{\text{pulse}} \approx (20 - 35) \text{ ns}$. INDEED, NO DEPENDS ON R

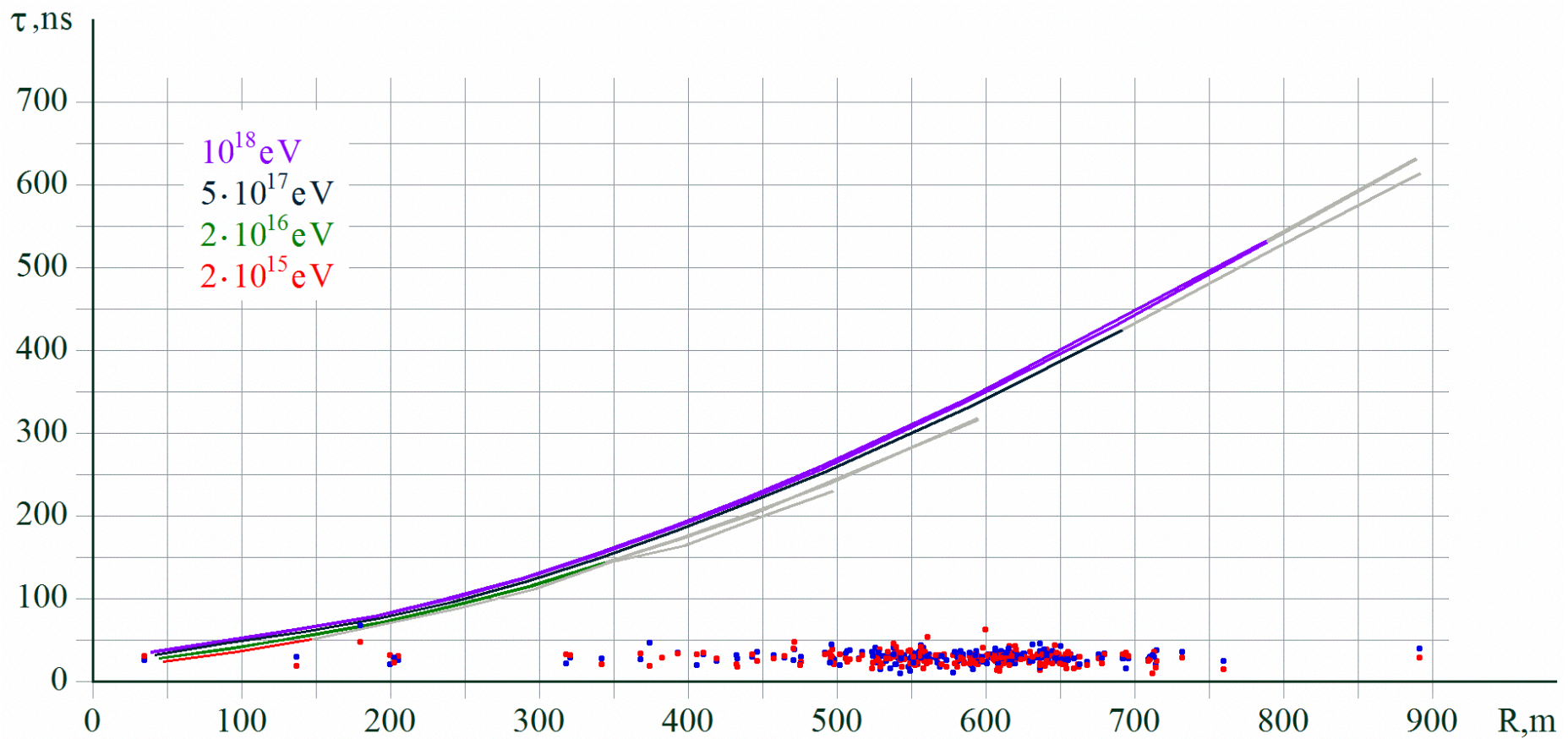
■ THE NUMBER OF ELECTRONS $N \gtrsim 10^9$ IN A BUNCH DURING A GIVEN ERUPTION CAN BE PRODUCED BY A CR PARTICLE WITH ENERGY $E_{\text{CR}} \gtrsim 10^{19} \text{ eV}$, SEE PREVIOUS SLIDE. IT OCCURS ONLY ONCE EVERY FEW YEARS. THE OBSERVED EVENT RATE $\sim 10^3/\text{year}$, CONSISTENT WITH AQN PROPOSAL

■ WE SUGGEST TO TEST THIS PROPOSAL BY STUDYING THE SYNCHRONIZED RADIO PULSES WITH $\nu \sim (200 - 800) \text{ MHz}$.



| Peak # | Delay ns | $\tau_{0.8}$ ns | $\rho_{0.8}$ #/m ² |
|--------|----------|-----------------|-------------------------------|
| 1 | 0 | 28 | 32 |
| 2 | 265 | 34 | 256 |
| 3 | 720 | 31 | 187 |
| 4 | 894 | 31 | 52 |
| 5 | 1493 | 35 | 339 |

time delay between pulses $\tau_{\text{delay}} \sim (10^2 - 10^3) \text{ ns}$ while the width for each individual pulse $\tau(R)$ is approximately const.

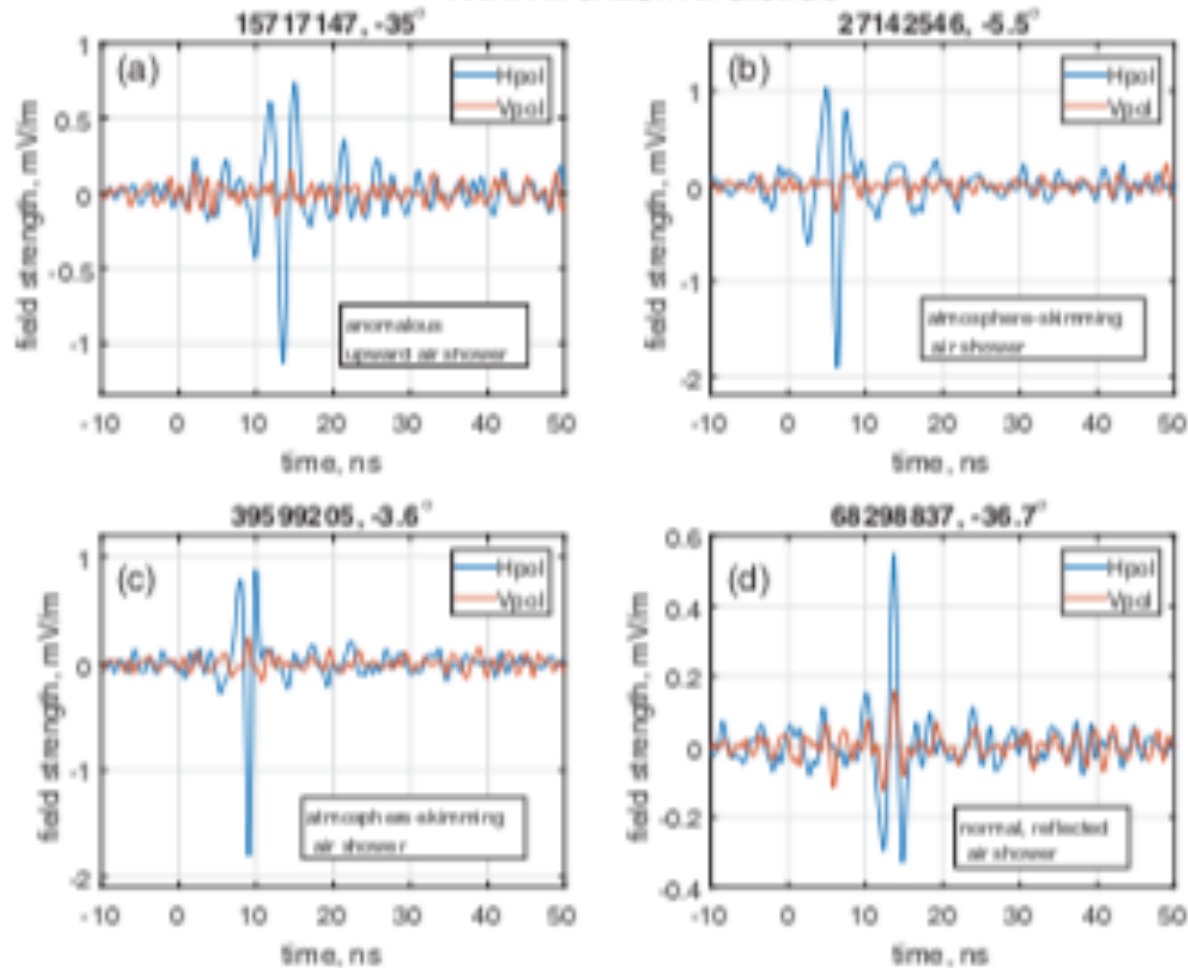


The time duration of a single pulse $\tau_{\text{pulse}} \approx (20 - 35) \text{ ns}$ should not depend on R as mere notions “disk width” nor “central axis” of EAS do not exist in this framework.

Snowmass-2021 (CF7) proposal “Probing Fundamental Physics with Multi-Modal CR events”, arXiv:2204.04045

9. 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 $\gtrsim 5 \cdot 10^3 \text{km}$ WITH VERY HIGH ENERGY $E \sim 10^{18} \text{eV}$ TO GENERATE SUCH SIGNAL
- THE SM NEUTRINO IS EXCLUDED AT 5σ CL.



adopted from ANITA
[Gorham-2016]

- a) anomalous event, non-inverted polarity (-35°)
- b), c) normal, above horizon CR events with non-inverted polarity. Angles always are very small: (-5.5° , -3.6°)
- d) normal event with inverted polarity due to the reflection of the conventional CR shower (-36.7°)



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

10. ANITA ANOMALOUS EVENTS AS AQN EVENTS

- THE AQN EXITS THE EARTH INTERIOR BEING VERY HOT WITH THE TEMPERATURE $T \sim 200 \text{ keV}$
- 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 $\langle E \rangle \sim 10 \text{ MeV}$ 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 $E_{CR} \sim (10^{17} - 10^{18})$ 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:**

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

■ **TYPICAL FEATURES OF THE SYNCHROTRON SPECTRUM: IT IS APPROXIMATELY FLAT WITH CRITICAL (CUTOFF) FREQUENCY**

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

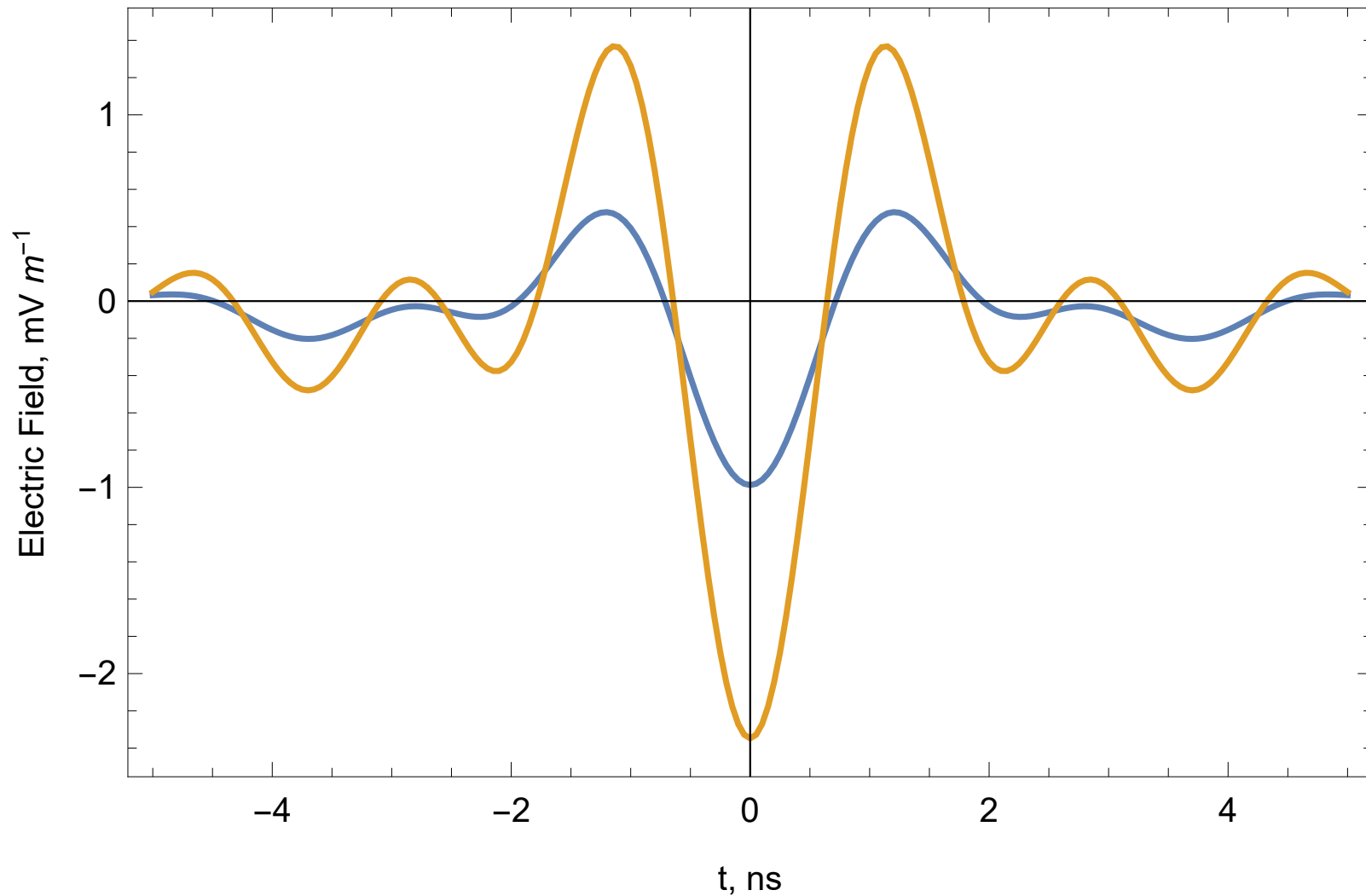
■ **TYPICAL DURATION OF THE SIGNAL IS $(2 - 4)\text{ns}$**

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

■ **TYPICAL INTENSITY OF THE PULSE IS $|\mathbf{E}(\mathbf{t})| \sim \text{mV/m}$**

■ **TYPICAL POWER DENSITY IS $(0.2 - 0.3) \text{ pW m}^{-2} \text{ MHz}^{-1}$**

■ **ALL THESE VALUES (INCLUDING THE EVENT RATE) ARE VERY CLOSE TO THE OBSERVED MAGNITUDES RECORDED BY ANITA AND CLASSIFIED AS ANOMALOUS EVENTS, SEE SLIDE BELOW**



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

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

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

■ THERE ARE DRAMATIC DIFFERENCES WITH CONVENTIONAL CR RADIO PULSES SUCH THAT CR-INDUCED AND AQN-INDUCED RADIO PULSES CAN BE EASILY DISCRIMINATED:

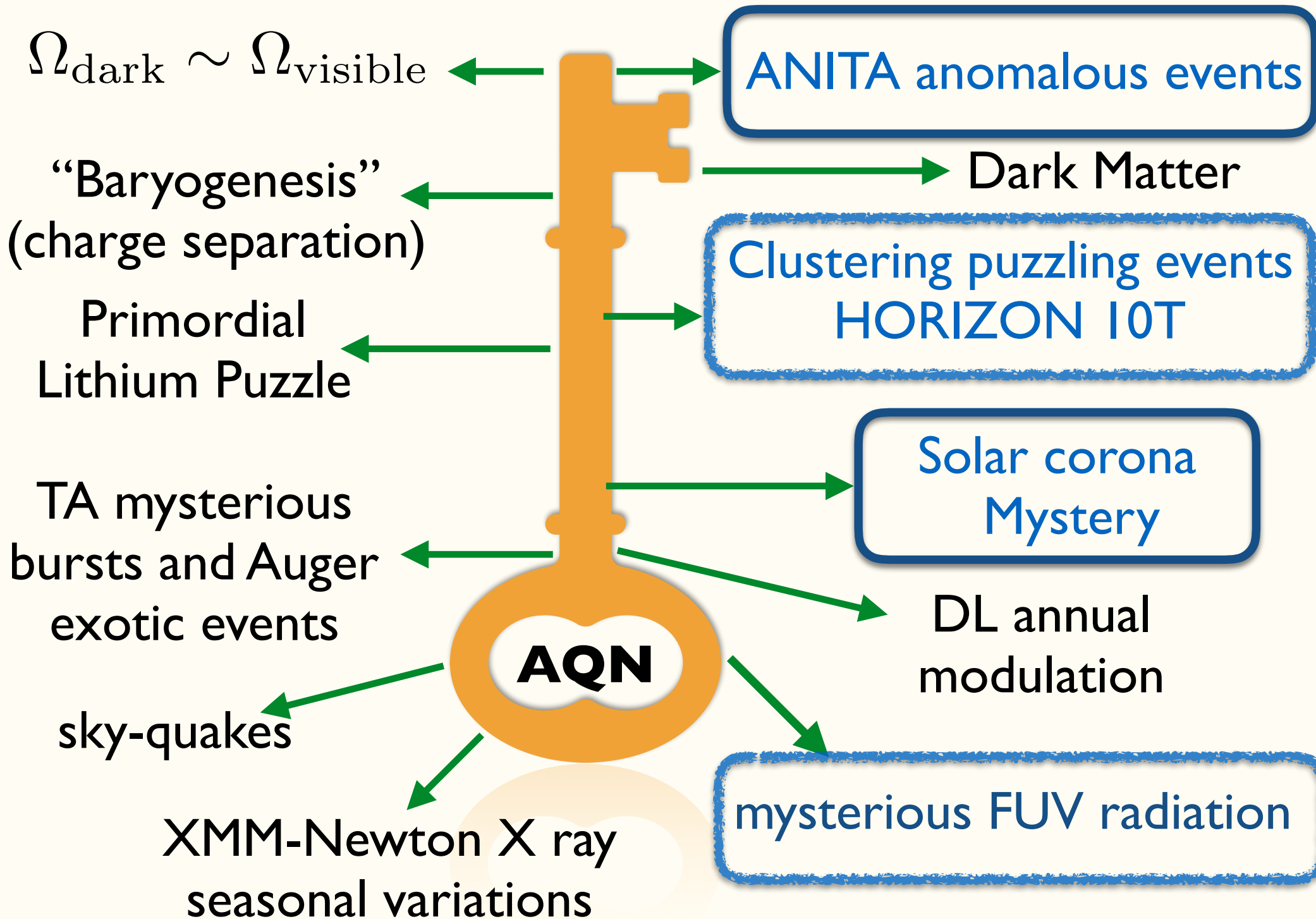
■ 1. THE EXTENSIVE AIR SHOWERS (EAS) ARE CHARACTERIZED BY “CENTRAL AXIS” AND “PANCAKE” GEOMETRY. THESE NOTIONS DO NOT EXIST IN THE AQN SCENARIO;

■ 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 NON-HADRONIC COLOUR SUPERCONDUCTING PHASE, THE AQN
- RATIO: $\Omega_{\text{dark}} \sim \Omega_{\text{visible}}$ IS VERY GENERIC CONSEQUENCE OF THIS FRAMEWORK (NO SENSITIVITY TO AXION MASS m_a , NOR TO THE MISALIGNMENT ANGLE θ_{initial}). IT IS THE DIRECT CONSEQUENCE OF THE FRAMEWORK WHEN BOTH COMPONENTS ARE PROPORTIONAL TO ONE AND THE SAME FUNDAMENTAL Λ_{QCD} SCALE.
- THIS MODEL OFFERS A SIMULTANEOUS RESOLUTION OF A NUMBER (NAIVELY UNRELATED) OLD MYSTERIES: DM, BARYOGENESIS, FUV EXOTIC RADIATION +MANY MORE PUZZLING AND UNEXPLAINED YET PHENOMENA



More Elephants!



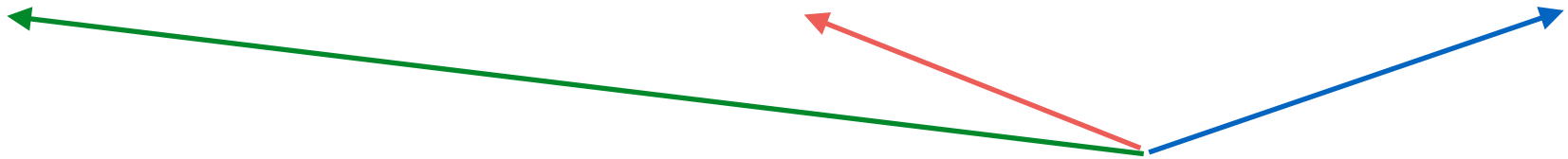
Matter-antimatter Asymmetry



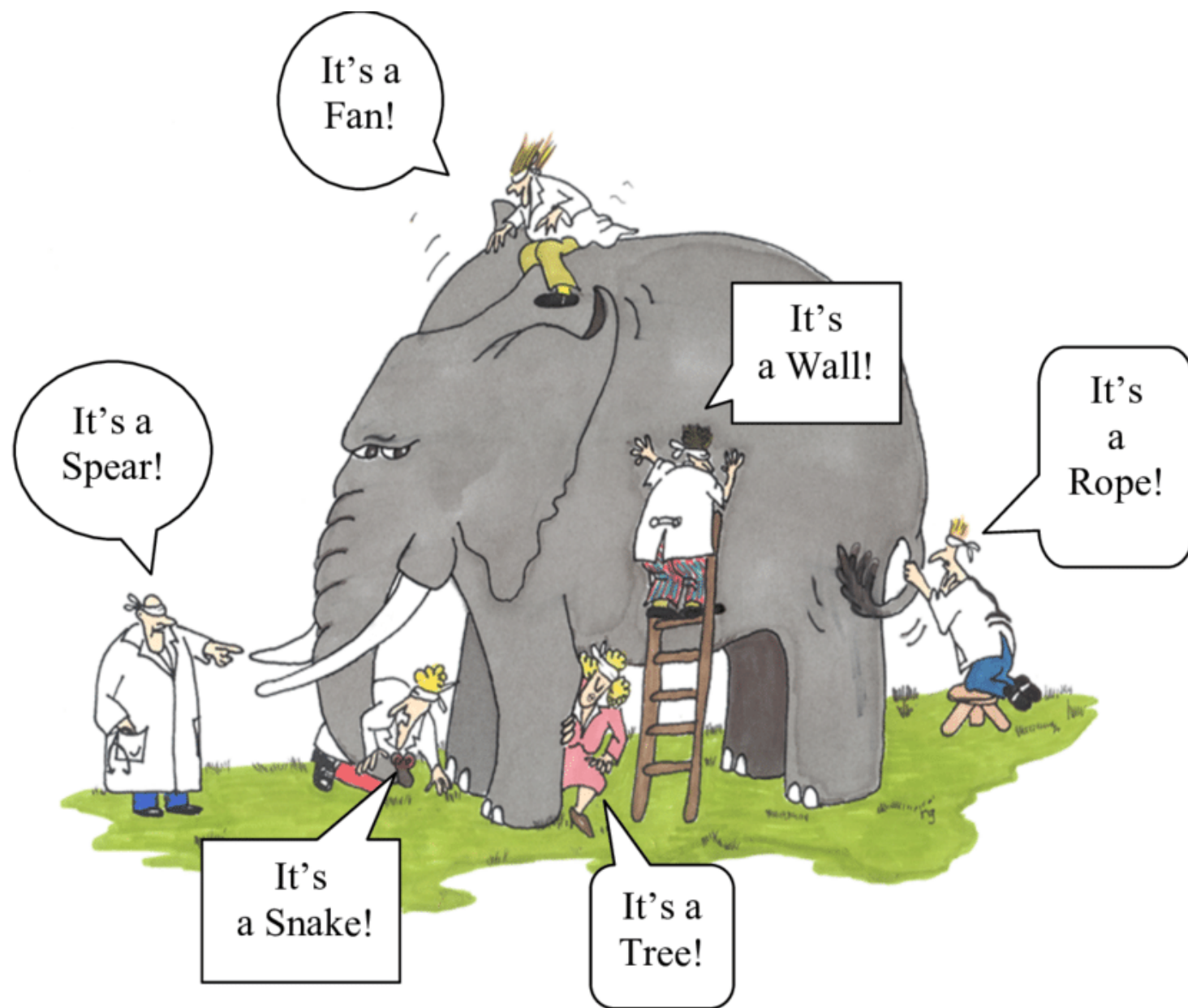
Similar amount of matter and DM



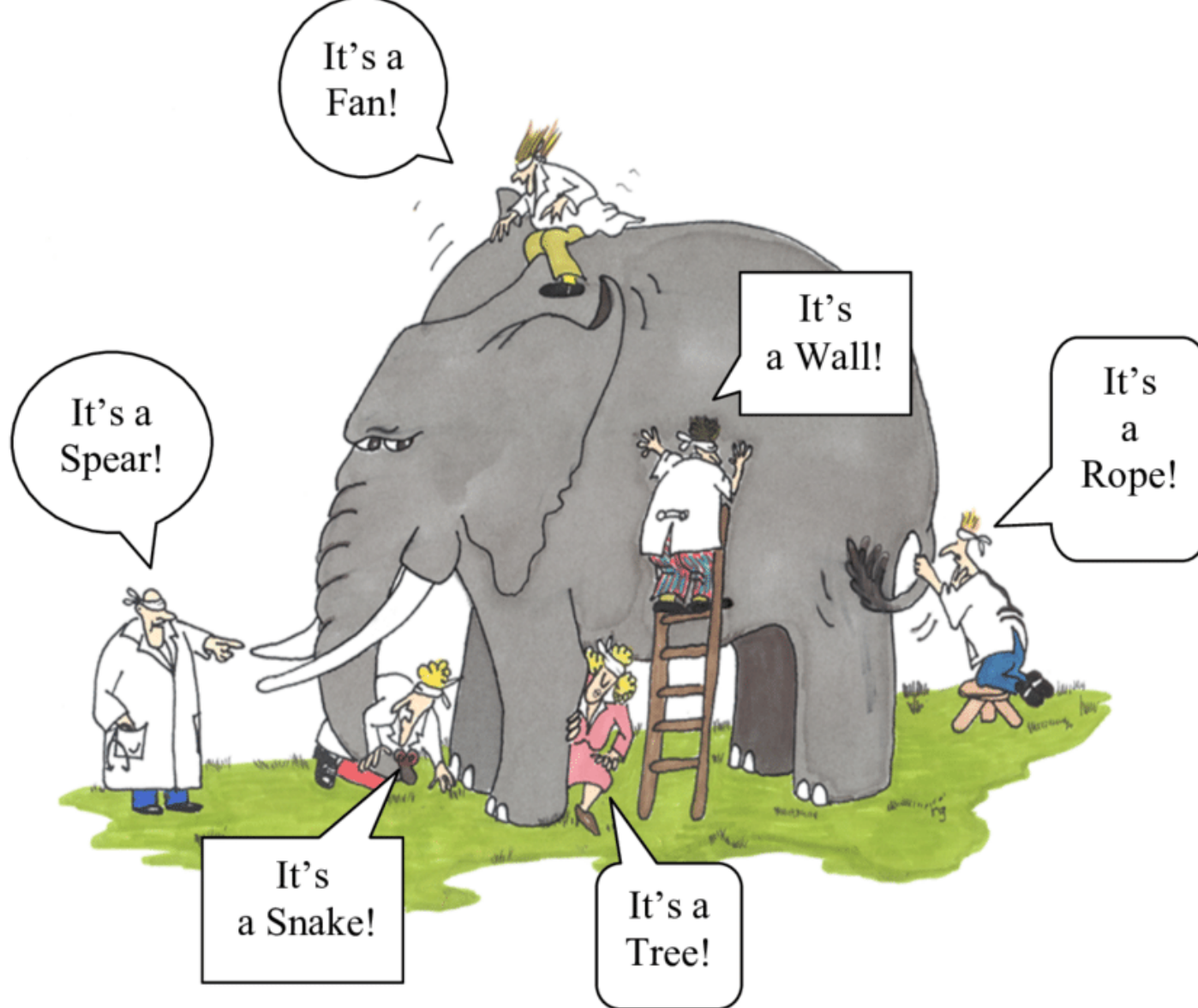
Dark Energy



From Dima Budker's talk "More elephants in the room". He discussed numerous problems on DM, matter-antimatter asymmetry, similarity between DM and visible matter, etc



My vision of the elephant in the room: we are the heroes from the poem of John Godfrey Saxe “Blind men and the elephant”



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

■ DO WE HAVE AN EXTRAORDINARY EVIDENCE TO MAKE OUR
EXTRAORDINARY CLAIM?

■ TIME WILL TELL...



In Other Words...



“Extraordinary claims
require
extraordinary
evidence.”

-Carl Sagan

**Backup slides. Few comments
on formation mechanism and
survival pattern**

1. COMMON MISCONCEPTIONS ON FORMATION

- 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.
- 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: $\theta \rightarrow \theta + 2\pi n$. AXION STRINGS ARE IRRELEVANT IN FORMATION OF THE CLOSED BUBBLES OF THE AXION DOMAIN WALLS WHICH EVENTUALLY MAKE AQNs

- WE ALWAYS ASSUME THAT $H_I < f_{PQ}$. HOWEVER N=1 AXION CLOSED DOMAIN WALLS STILL WILL BE FORMED.
- IN FACT, THE NUMERICAL SIMULATIONS [VILENKIN ET AL, 1994] SUGGEST THAT APPROXIMATELY 87% OF TOTAL WALL AREA OF N=1 DW BELONG TO PERCOLATED CLUSTER (13% ARE SMALL CLOSED BUBBLES OF DIFFERENT TOPOLOGY)
- THE FERMI PRESSURE PREVENTS THE SMALL CLOSED BUBBLES FROM COLLAPSE AND DECAYING TO THE AXIONS. THE AXION STRINGS ARE IRRELEVANT ELEMENTS HERE.
- THE CONVENTIONAL PICTURE OF THE EVOLUTION OF THE NETWORK (DW+STRINGS) APPLIES TO THE PERCOLATED CLUSTER. IT DOES NOT APPLY TO CLOSED BUBBLES.
- THE PROPER CLASSIFICATION IS $|\theta, k\rangle$ WHERE $|k\rangle$ CAN BE THOUGHT AS THE BRILLOUIN ZONE NUMBER IN CM PHYSICS. THE 2π PERIODICITY IN θ CAN BE RESTORED IF ALL $|k\rangle$ TOPOLOGICAL SECTORS ARE PRESENT IN THE SYSTEM

- 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. AQN FORMATION: ACCRETION OF THE BARYON CHARGE ON A SINGLE CLOSED BUBBLE.

- WE ASSUME THAT INITIAL SIZE OF THE BUBBLE $R \sim \xi(T)$ IS SUFFICIENTLY LARGE SUCH THAT ONE CAN LOCALLY TREAT THE SURFACE OF THE CLOSED BUBBLE BEING FLAT, I.E. THE PROBLEM IS EFFECTIVELY REDUCED TO 2D SYSTEM.

$$\mathcal{L}_4 = \bar{\Psi} \left(i \not{\partial} - m e^{i[\theta(z) - \phi(z)]\gamma_5} - \mu \gamma_0 \right) \Psi.$$

- WHERE $\theta(z)$ IS AXION DW PROFILE, $\phi(z)$ IS η' FIELD.

$$\mathcal{L}_2 = \frac{1}{2}(\partial_\mu \theta_1)^2 + \frac{1}{2}(\partial_\mu \theta_2)^2 - U(\theta_1, \theta_2) + \frac{\mu}{\sqrt{\pi}} \frac{\partial(\theta_2 + \theta_1)}{\partial z}$$

$$U(\theta_1, \theta_2) = -mm_0 [\cos(2\sqrt{\pi}\theta_1 - \phi + \theta)] - mm_0 [\cos(2\sqrt{\pi}\theta_2 + \phi - \theta)].$$

- θ_1, θ_2 DESCRIBE THE ORIGINAL Ψ FERMION FIELD (2 SPIN STATES) IN EFFECTIVE 2D SYSTEM IN DW BACKGROUND.

- THE KEY POINT IS THAT SOME DW MAY CARRY THE BARYON (ANTI-BARYON) CHARGE, DEPENDING ON THE BOUNDARY CONDITIONS

$$2\sqrt{\pi}\theta_1(z = +\infty) - 2\sqrt{\pi}\theta_1(z = -\infty) = 2\pi n_1$$

$$2\sqrt{\pi}\theta_2(z = +\infty) - 2\sqrt{\pi}\theta_2(z = -\infty) = 2\pi n_2$$

- THE BARYON CHARGE IN GENERAL ASSUMES A NONZERO VALUE, DEPENDING ON BOUNDARY CONDITIONS

$$N = \int d^3x \bar{\Psi} \gamma_0 \Psi = -\frac{1}{\sqrt{\pi}} \int_{-\infty}^{+\infty} dz \frac{\partial}{\partial z} (\theta_1 + \theta_2) = -(n_1 + n_2),$$

- THE EFFECT IS SIMILAR TO FRACTIONAL CHARGE LOCALIZATION ON DW. IT CAN BE THOUGHT AS SPONTANEOUS CHARGE SEPARATION EFFECT DURING DW FORMATION

- KEY POINT: PERIODIC FIELDS $\theta_1, \theta_2, \phi, \theta$ MAY ASSUME PHYSICALLY IDENTICAL, BUT DISTINCT VACUUM VALUES DURING THE QCD PHASE TRANSITION.

■ ANOTHER CONCEPTUAL QUESTION: WHY THE BARYONS CANNOT EASILY LEAK THROUGH VERY WIDE AXION DW?

■ THERE IS QCD SUBSTRUCTURE IN FORM OF THE η' FLAVOUR-SINGLET FIELD. THIS FIELD IS KNOTTED WITH THE AXION FIELD BY CONSTRUCTION. IT IMPLIES THAT η' AND AXION FIELDS CANNOT BE UNKNOTTED SEPARATELY AS THEY ARE TOPOLOGICALLY LINKED.

■ THE AXION FIELD IS LOCALIZED WELL OUTSIDE THE NUGGET AND STRONGLY OVERLAPS WITH ITSELF. HOWEVER, IT CANNOT BE UNKNOTTED BECAUSE IT IS LINKED TO THE η' PORTION OF THE DW.

■ AS THE $R \gg m_{\eta'}^{-1}$ THE CONFIGURATION BECOMES ENERGETICALLY STABLE AS A RESULT OF EQUILIBRATION, BETWEEN FERMI PRESSURE AND DW PRESSURE (WITH η')

3. AQN FORMATION: TIME EVOLUTION

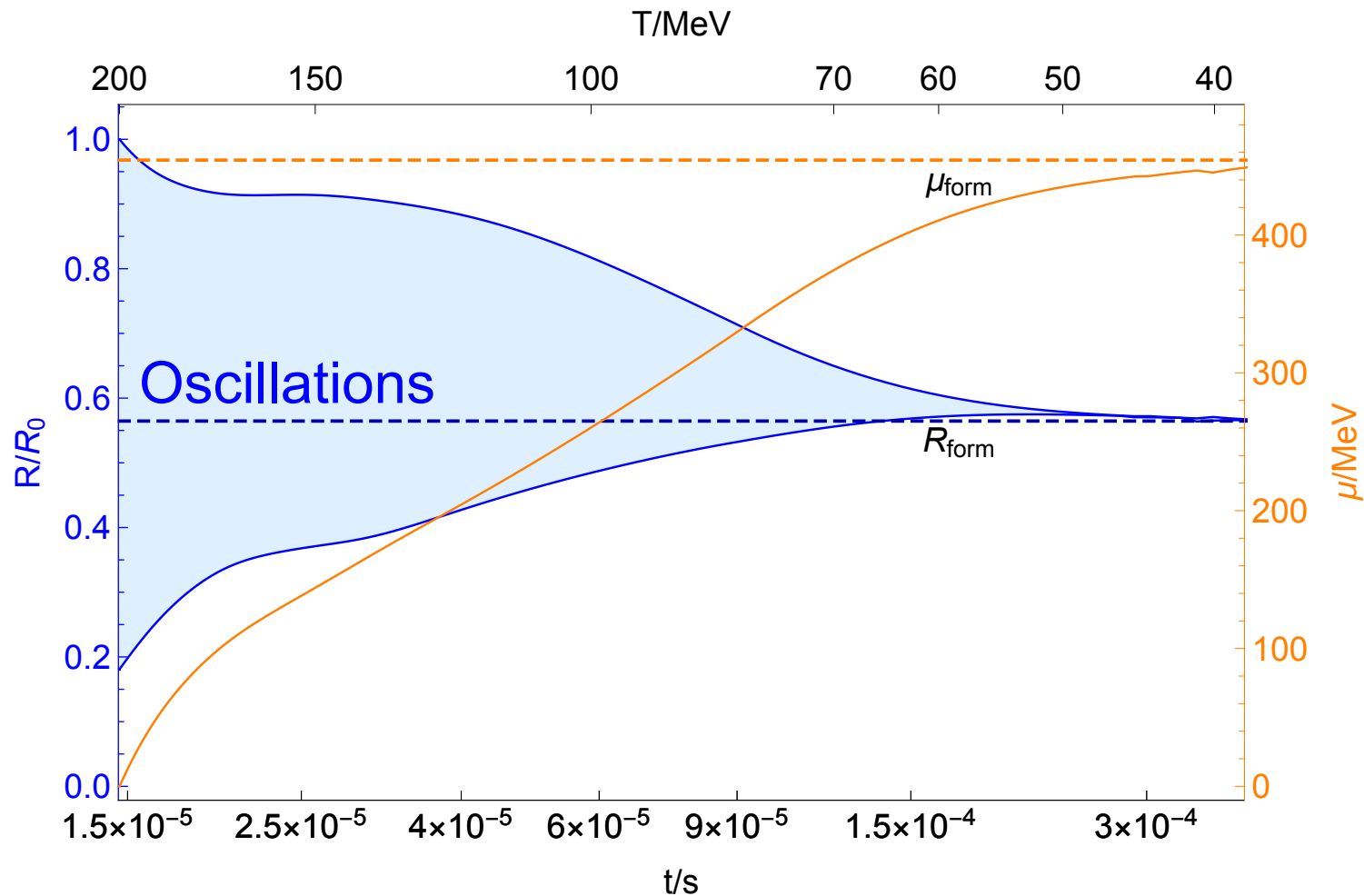
■ THE EQUATION OF MOTION WHICH DETERMINES THE TIME EVOLUTION OF THE NUGGET $R(t)$ IS

$$\sigma \ddot{R}(t) = -\frac{2\sigma}{R(t)} - \frac{\sigma \dot{R}^2(t)}{R(t)} + \Delta P(\mu) - 4\eta \frac{\dot{R}(t)}{R(t)},$$

■ σ -DW PRESSURE, $\eta(T)$ -VISCOSITY (WHICH EFFECTIVELY DESCRIBES THE “FRICTION” OF THE SYSTEM), WHILE IN AND OUT PRESSURES ARE $\Delta P[\mu(t)] \equiv [P_{\text{in}}(\mu) - P_{\text{out}}(t)]$

■ WE ALSO NEED A RELATION BETWEEN $R(t)$ AND CHEMICAL POTENTIAL $\mu(t)$ DURING THE EVOLUTION

$$\dot{B} = \frac{Ng}{4\pi^2} \dot{S}(t) \int \frac{d^2 k_{\perp}}{\left[\exp\left(\frac{\epsilon - \mu(t)}{T}\right) + 1 \right]} + \frac{NgS}{4\pi^2} \frac{\dot{\mu}(t)}{T} \int \frac{d^2 k_{\perp} \left[\exp\left(\frac{\epsilon - \mu(t)}{T}\right) \right]}{\left[\exp\left(\frac{\epsilon - \mu(t)}{T}\right) + 1 \right]^2} + (\text{fluxes}) = 0,$$



Time evolution of the AQN after the formation. The shaded light blue region represents the numerous oscillations. The solid orange line represents the evolution of the chemical potential μ .

1. Formation ends at proper temperature $T \simeq 40 \text{ MeV}$
2. Chemical potential $\mu \simeq 400 \text{ MeV}$ where CS sets in

■ THE SYSTEM MAKES A VERY LARGE NUMBER OF OSCILLATIONS BEFORE IT SETTLES DOWN AT R_{form} . EVERY SINGLE OSCILLATION GENERATES SMALL ASYMMETRY $\Delta\mu \sim \theta_0$. HOWEVER, THE ACCUMULATION EFFECT BECOMES PROFOUND AS A RESULT OF LARGE NUMBER OF COHERENT OSCILLATIONS:

$$R(t) = R_{\text{form}} + (R_0 - R_{\text{form}})e^{-t/\tau} \cos \omega t$$

■ TYPICAL FREQUENCY AND DAMPING TIME FOR $m_a \in (10^{-6} - 10^{-3})\text{eV}$ OBSERVATIONALLY ALLOWED WINDOW FOR THE AXION MASS

$$\omega \sim \frac{1}{R_{\text{form}}} \sim m_a, \quad t_{\text{osc}} \simeq m_a^{-1}, \quad \tau \sim \frac{\sigma}{2\eta} R_{\text{form}} \sim 10^{11} \omega^{-1}$$

■ CHEMICAL POTENTIAL $\mu(t)$ ASSUMES A TYPICAL VALUE FOR COLOUR SUPERCONDUCTING PHASE $\mu \simeq 400 \text{ MeV}$

■ “CONSPIRACY” OF SCALES: \mathcal{T} (EXPRESSED IN TERMS OF THE AXION AND QCD PHYSICS) PRECISELY ASSUMES THE VALUE OF THE UNIVERSE EXPANSION $t_0 \sim 3 \cdot 10^{-4} \text{ s}$

4. AQN FORMATION: COHERENCE ON A COSMOLOGICAL SCALE. ABUNDANCE.

■ 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.

■ $\theta \neq 0$ 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 IS EXPRESSED IN TERMS OF THIS PARAMETER $c(T) \sim 1$ AS THE TOTAL BARYON CHARGE IS ZERO:

$$B_{\text{tot}} = B_{\text{baryons}} + B_{\text{antibaryons}} + B_{\text{nuggets}} + B_{\text{antinuggets}} = 0$$

■ THE SAME RELATION CAN BE WRITTEN AS FOLLOWS

$$[\Omega_{\text{dark}} = \Omega_{\bar{N}} + \Omega_N] \quad , \quad [\Omega_{\text{visible}} = \Omega_{\bar{N}} - \Omega_N] \quad \rightarrow \quad \Omega_{\text{dark}} \approx \Omega_{\text{visible}} \sim \Lambda_{\text{QCD}}$$

■ THERMODYNAMICS DOES THE JOB. THE ABUNDANCE OF AQNS IS ALWAYS EFFECT OF ORDER OF ONE AS A RESULT OF LONG ACCUMULATION OF THE BARYON CHARGE LEADING TO $c(T) \sim 1$

■ THE THERMO-EQUILIBRATION (DURING OSCILLATIONS) BETWEEN VISIBLE BARYONS AND AQNS WASHES OUT ANY SENSITIVITY TO INITIAL PARAMETERS OF THE SYSTEM, SUCH AS m_a, θ_0

■ PARAMETER $\eta \sim 10^{-10}$ HERE IS DETERMINED BY THE TEMPERATURE WHEN FORMATION ENDS $T_{\text{form}} \approx 40 \text{ MeV} \lesssim T_{\text{CS}} \approx 60 \text{ MeV}$. THERE IS NO FINE TUNING (IN TERMS OF T) IN THIS FRAMEWORK

■ IT IS ASSUMED THAT INFLATION OCCURS AFTER PQ WHEN THE SAME θ_0 OCCUPIES ENTIRE VISIBLE UNIVERSE

■ FOR $c \simeq 2/3 \quad \Rightarrow \quad \Omega_{\text{dark}} \simeq 5 \Omega_{\text{visible}} \quad \text{THE}$
NUGGETS SATURATE THE PRESENT DM DENSITY TODAY.

5. SURVIVAL PATTERN

■ PRE- BBN EVOLUTION. THE COLLISION RATE CAN BE ESTIMATED AS

$$\Gamma_{\text{col}} = 4\pi R^2 n_B v_B = 4\pi R^2 \frac{2\zeta(3)}{\pi^2} \eta \left(\frac{T}{\hbar c} \right)^3 \sqrt{\frac{2T}{m_p}} c$$

■ THE TOTAL NUMBER OF ANNIHILATED BARYONS DURING THIS TIME PERIOD IS ESTIMATED AS (WHERE $\kappa(T)$ IS THE FRACTION OF SUCCESSFULLY ANNIHILATED BARYONS)

$$\Delta B = \int_0^{T_{\text{form}}} dT \frac{dt}{dT} \Gamma_{\text{col}} \kappa(T) \approx 3 \times 10^{25} \kappa(T) \ll B, \quad \kappa(T) \ll 10^{-3}$$

■ MOST OF THE ANTI-NUGGETS SURVIVE THE PRE-BBN EVOLUTION, I.E. $\Delta B \ll B$ AS MOST OF THE BARYONS FROM VISIBLE COMPONENT GET REFLECTED RATHER THAN ANNIHILATED $\kappa(T) \ll 10^{-3}$

■ POST-BBN EVOLUTION. THE COLLISION RATE IS DETERMINED BY THE CAPTURE DISTANCE R_{cap} RATHER THAN SIZE OF THE NUGGET DUE TO IONIZATION OF THE SYSTEM:

$$\Gamma_{\text{col}}(T) = 4\pi R_{\text{cap}}^2(T) n_B(T) v_B(T), \quad R_{\text{cap}} \simeq 10^2 R.$$

■ THE TOTAL ANNIHILATED BARYON CHARGE DURING THIS EPOCH IS VERY SMALL:

$$\Delta B = \int_0^{T_*} dT \frac{dt}{dT} \kappa(T) \Gamma_{\text{col}}(T) \sim \kappa(T) 10^{24} \ll B$$

■ THE NUMBER OF ANNIHILATION EVENTS IS SUFFICIENTLY SMALL SUCH THAT ALL NUGGETS WITH $B \geq 10^{24}$ SURVIVE THE EVOLUTION.

■ NUCLEI WITH $Z \geq 3$ INTERACT WITH NEGATIVELY CHARGED AQNS MUCH STRONGER THAN THE PROTONS. IN FACT, IT MIGHT BE A RESOLUTION OF FAMED PRIMORDIAL ${}^7\text{Li}$ PROBLEM [PRD 2019]

- **REFS. ON THE AQN FORMATION MECHANISM AND SURVIVAL PATTERN DURING THE EVOLUTION:**
- **EVOLUTION OF A SINGLE NUGGET- PRD 2016 (ARXIV 1606.00435)**
- **COSMOLOGICAL CP ODD AXION FIELD AND CHARGE SEPARATION (BARYOGENESIS) MECHANISM - PRD 2017 (1702.04354)**
- **RELATION BETWEEN PQ AND INFLATIONARY SCALES; RELATION BETWEEN AQNs AND CONVENTIONAL AXION CONTRIBUTIONS TO DM- PRD 2018 (ARXIV 1711.06271)**
- **AQN: SIZE DISTRIBUTION AND SURVIVAL PATTERN (INCLUDING PRE-BBN, POST-BBN AND POST-RECOMBINATION EPOCHS). IT ALSO INCLUDES VIOLENT EVENTS SUCH AS GALAXY AND STAR FORMATIONS - PRD 2019 (ARXIV 1903.05090)**