Global Network, DAMA/LIBRA annual modulation and all that in Axion Quark Nugget (AQN) Model

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This talk is based on three recent papers:

1.1908.04675(collaboration with astro people)

Time Modulations and Amplifications in the Axion Search Experiments.

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2.1909.05320

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

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3.**1909.09475**(collaboration with AMO and Nuclear physics people)

Axion Quark Nuggets and how a Global Network can discover them

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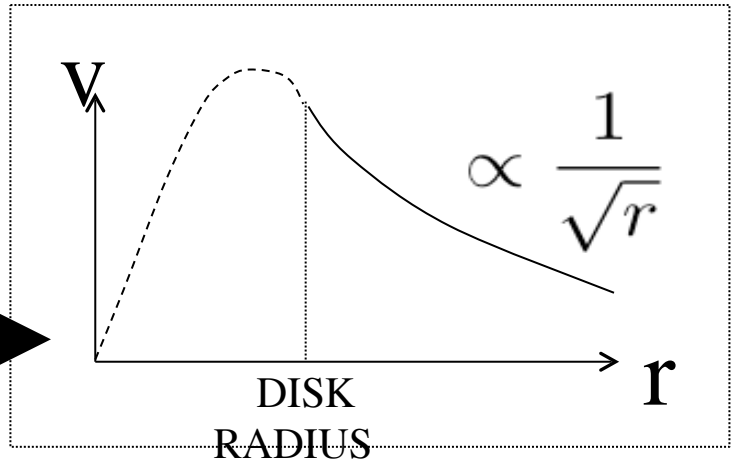
Axion and its relation to a number of old (and apparently unrelated) Mysteries

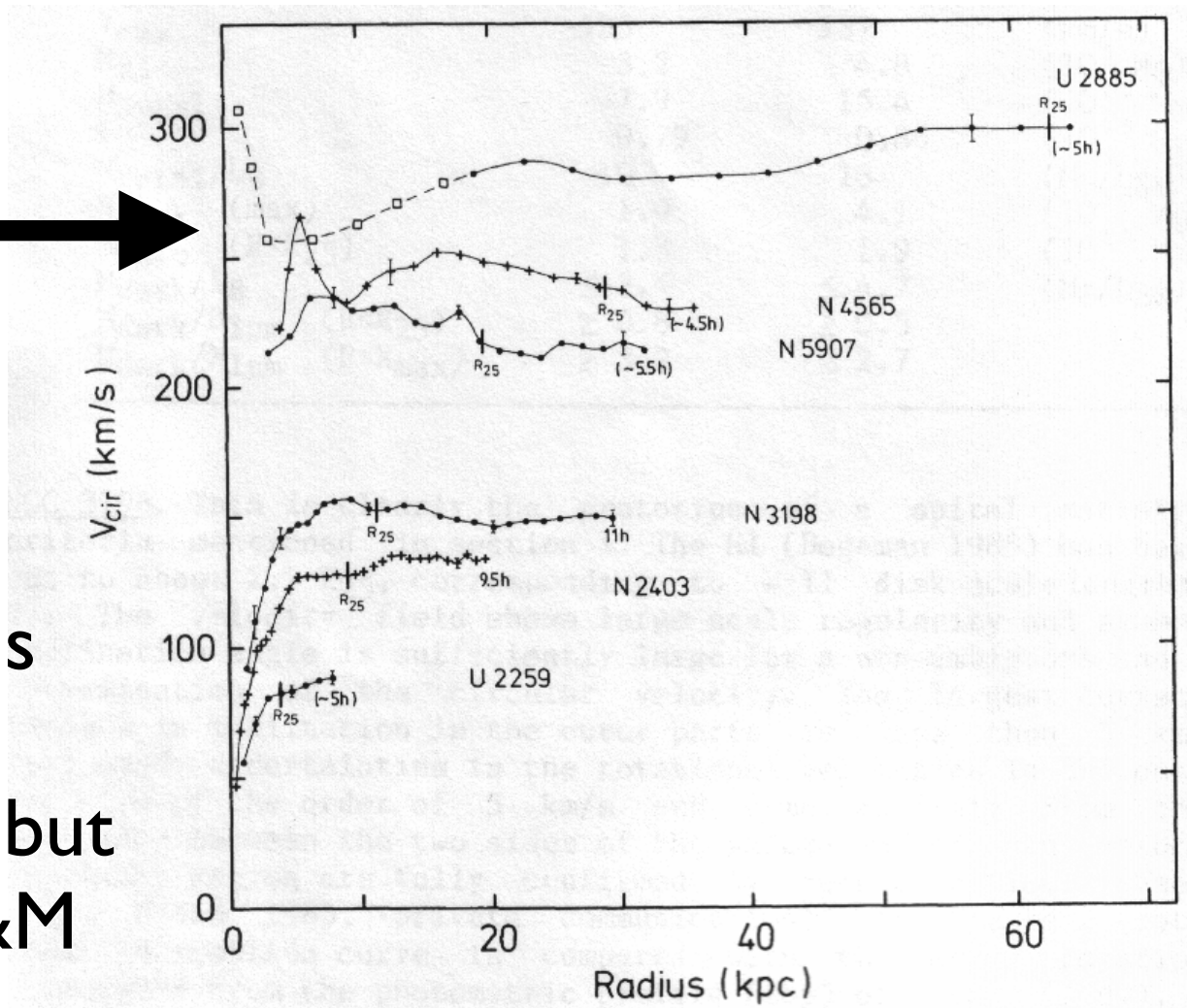
- 1. 80-years old mystery: the nature of **dark matter** (Zwicky 1937)
- 2. another 50-years old mystery: **Baryogenesis** (Sakharov, 1967)
- 3. yet another 80- years old mystery: the so-called "**solar heating puzzle**"
- 4. yet another (few decades old) mystery: **Primordial Lithium Puzzle**
- 5. yet another 20- years old mysterious signal: **DAMA-LIBRA** observation of the annual modulation

1. Evidence for dark matter

Expected behaviour for the velocities of stars



The observed velocity distribution



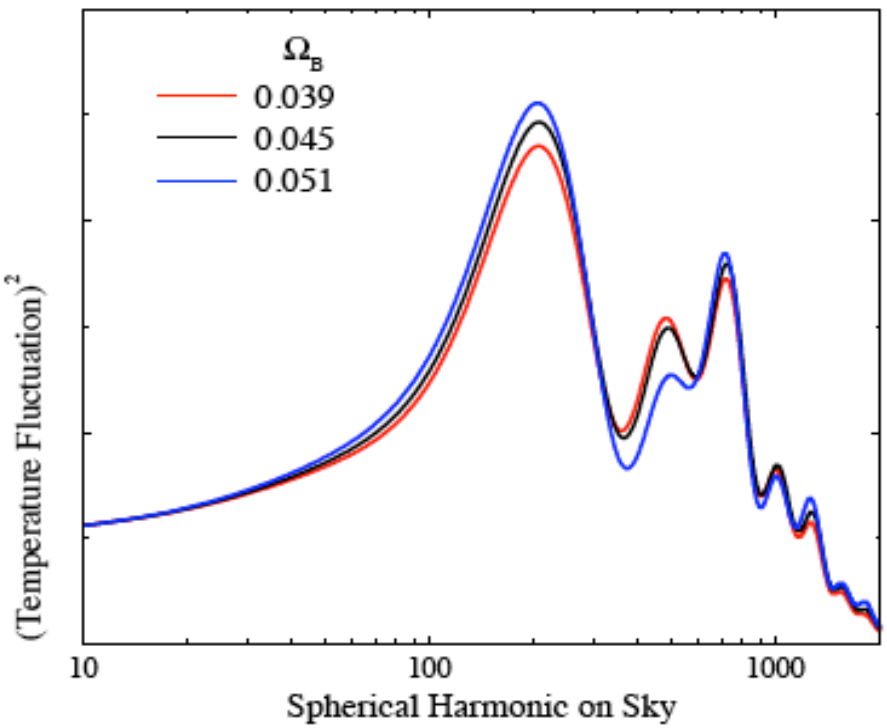
Take home lesson: there is DM in our Universe.
DM knows about gravity, but does not know about E&M

Fritz Zwicky and Vera Rubin

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

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

1.First 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" ⟶ "separation 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

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

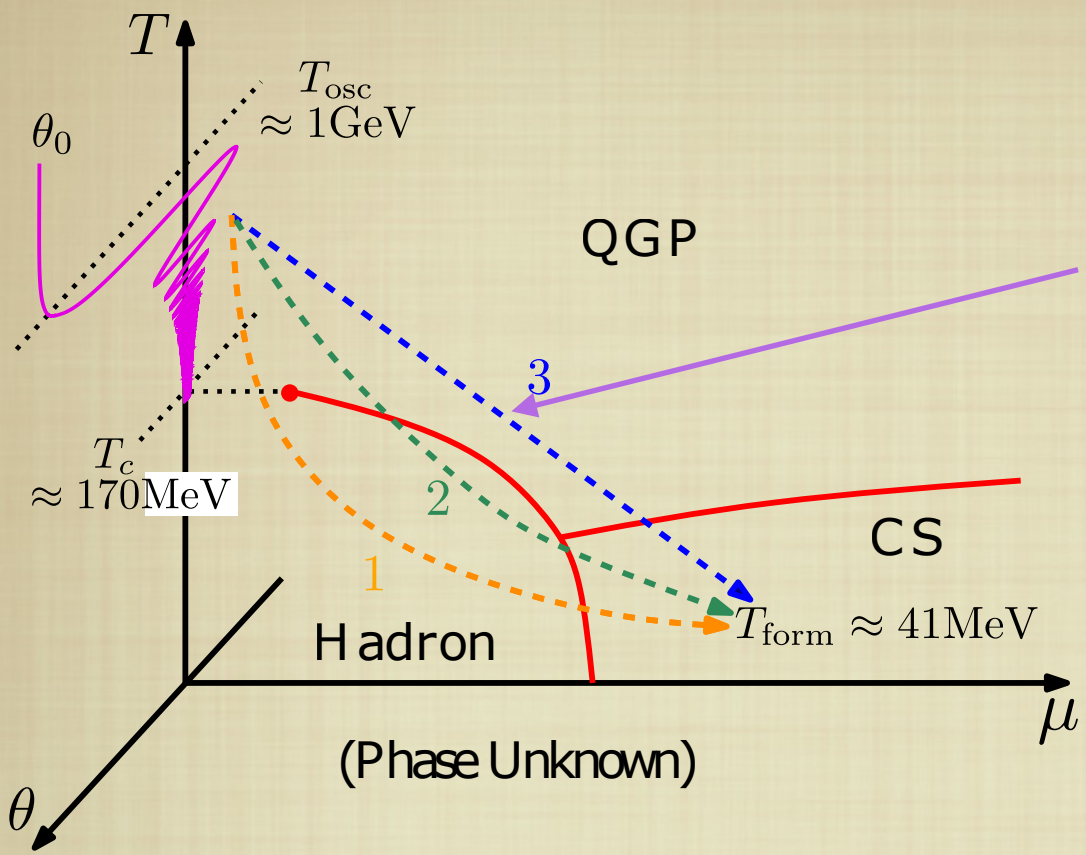
E. Witten

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**

2.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 temp. $T = 41$ MeV corresponds to the observed value $\eta \equiv \frac{n_B - n_{\bar{B}}}{n_\gamma} \simeq \frac{n_B}{n_\gamma} \sim 10^{-10}$
- There are 2 new elements (in comparison to Witten's)

- 1. there is extra **axion domain wall** pressure (acting on the closed axion DW bubbles). It makes the nuggets stable (first order phase transition is not required, as in the Witten's case). 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: $\Omega_{\rm dark} \approx \Omega_{\rm visible} \sim \Lambda_{\rm QCD}$

3. The main consequences of the Axion Quark Nugget (AQN) framework

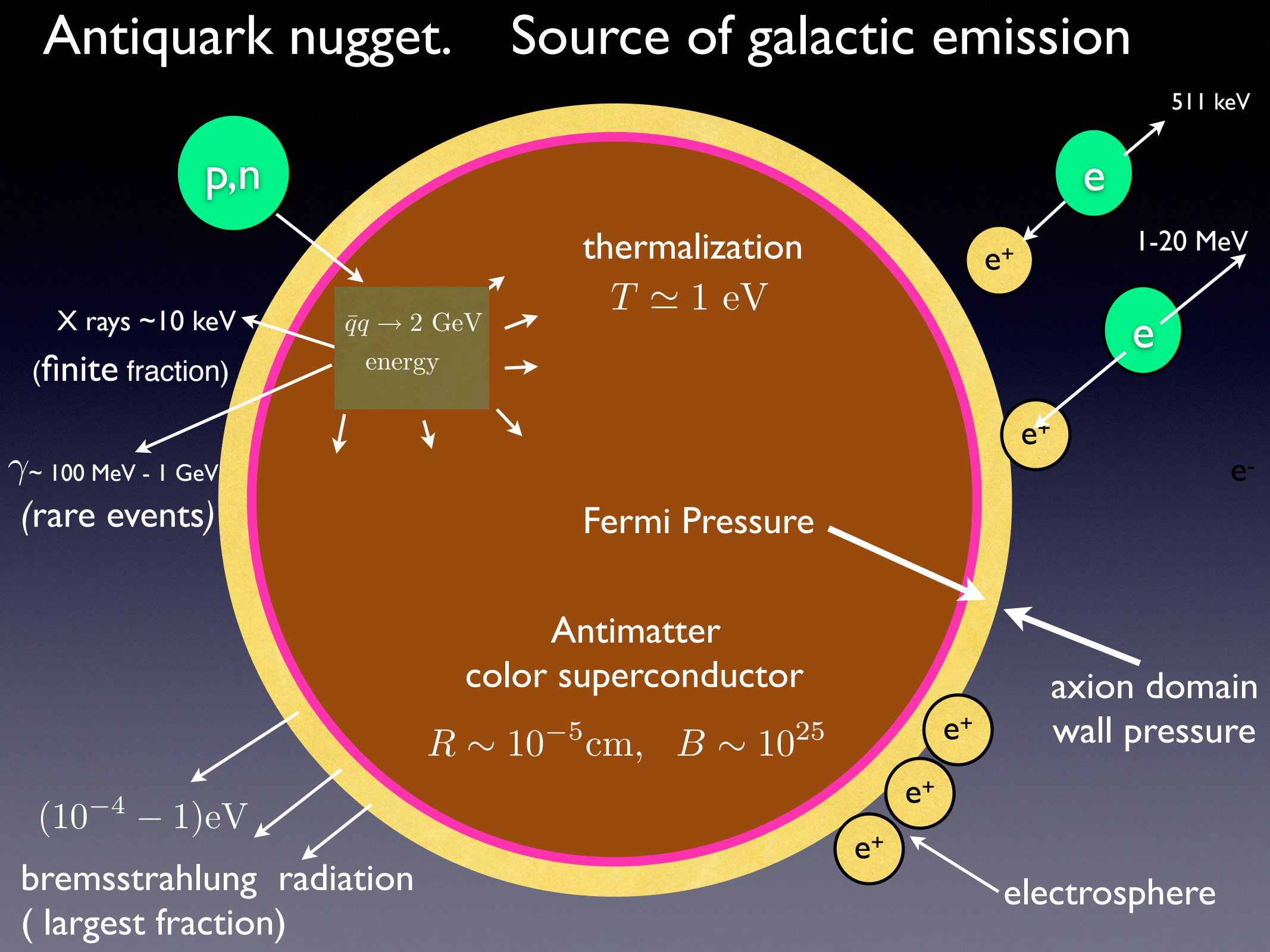
- The relation $\Omega_{\rm dark} \sim \Omega_{\rm visible}$ is a very generic and universal outcome of this AQN framework. The claim does not depend on the axion mass m_a nor misalignment angle θ_0 .

- The "**baryogenesis**" in this framework is replaced by "**charge separation**" effect when the anti-quarks are hidden in form of the DM nuggets.

- The most important consequence for this talk: every annihilation event leads to production of **photons** (in different frequency bands) **axions, neutrinos.**

- The intensity of each emission depends on the environment: 1. emission in galaxy, 2. solar corona, 3. earth's interior (**neutrinos and axions**)

Antiquark nugget. Source of galactic emission



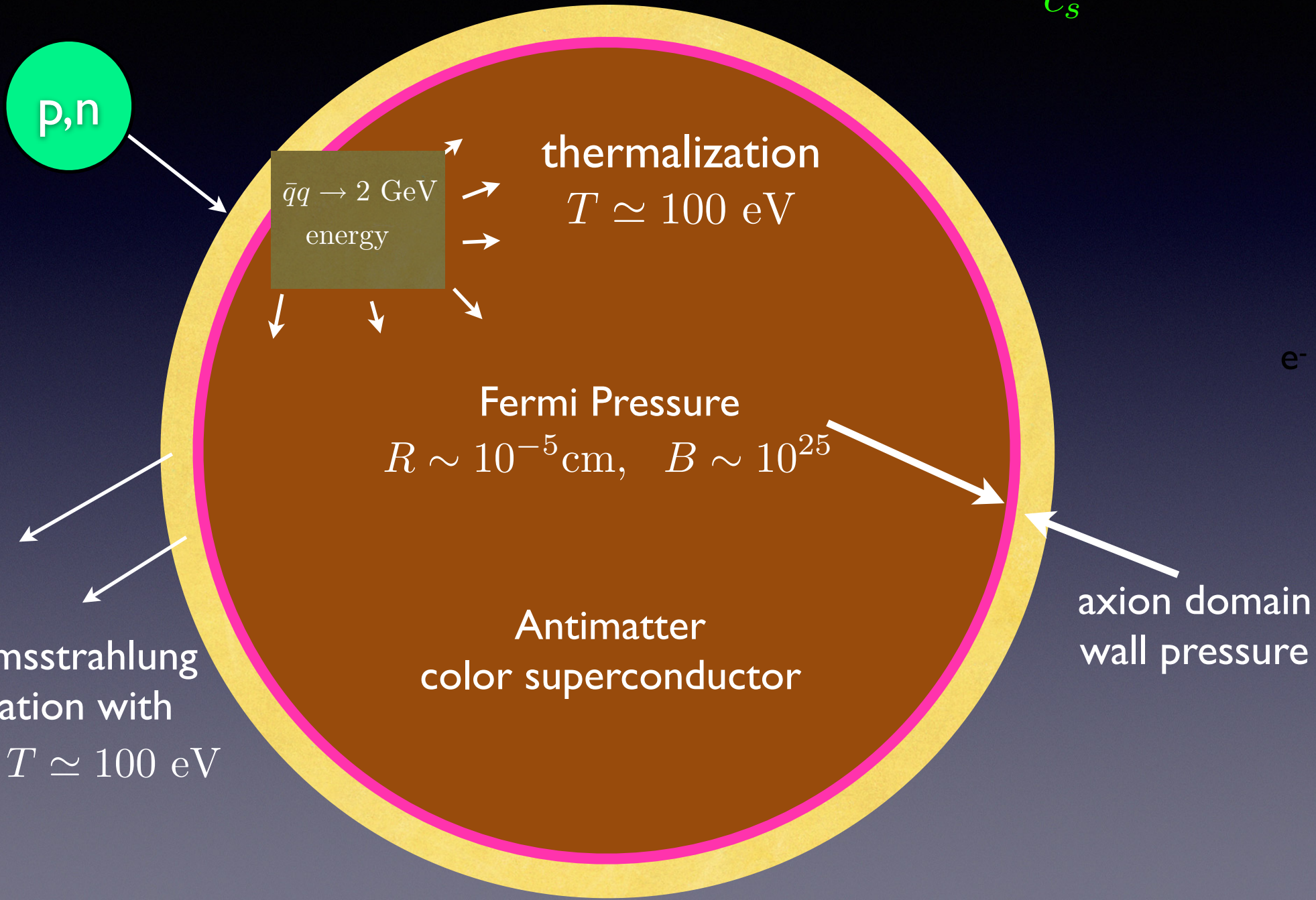
Relevant Literature

(excesses of radiation in different frequency bands as a result of annihilation of the AQNs with visible matter).

All computations are based on **SM** particle physics

- 511 keV line (INTEGRAL) — PRL. (2005)
- 1-20 MeV excess (COMPTEL) — JCAP (2008); PRD. (2010)
- X-ray emission (CHANDRA) — JCAP (2008)
- $23 < w < 61$ GHz (radio diffuse) — PRD. (2008)
- $w \sim 1$ GHz (ARCADE 2) — Phys. Lett. B (2013)
- $w \sim 1$ GHz (nearby galaxies) — Phys. Lett. B (2016)
- mini-review prepared for a conference proceedings — arXiv:1611.05042 (2016)

Source of EUV in solar corona. Supersonic turbulent motion with very large Mach number $M = \frac{v}{c_s} \sim 10$

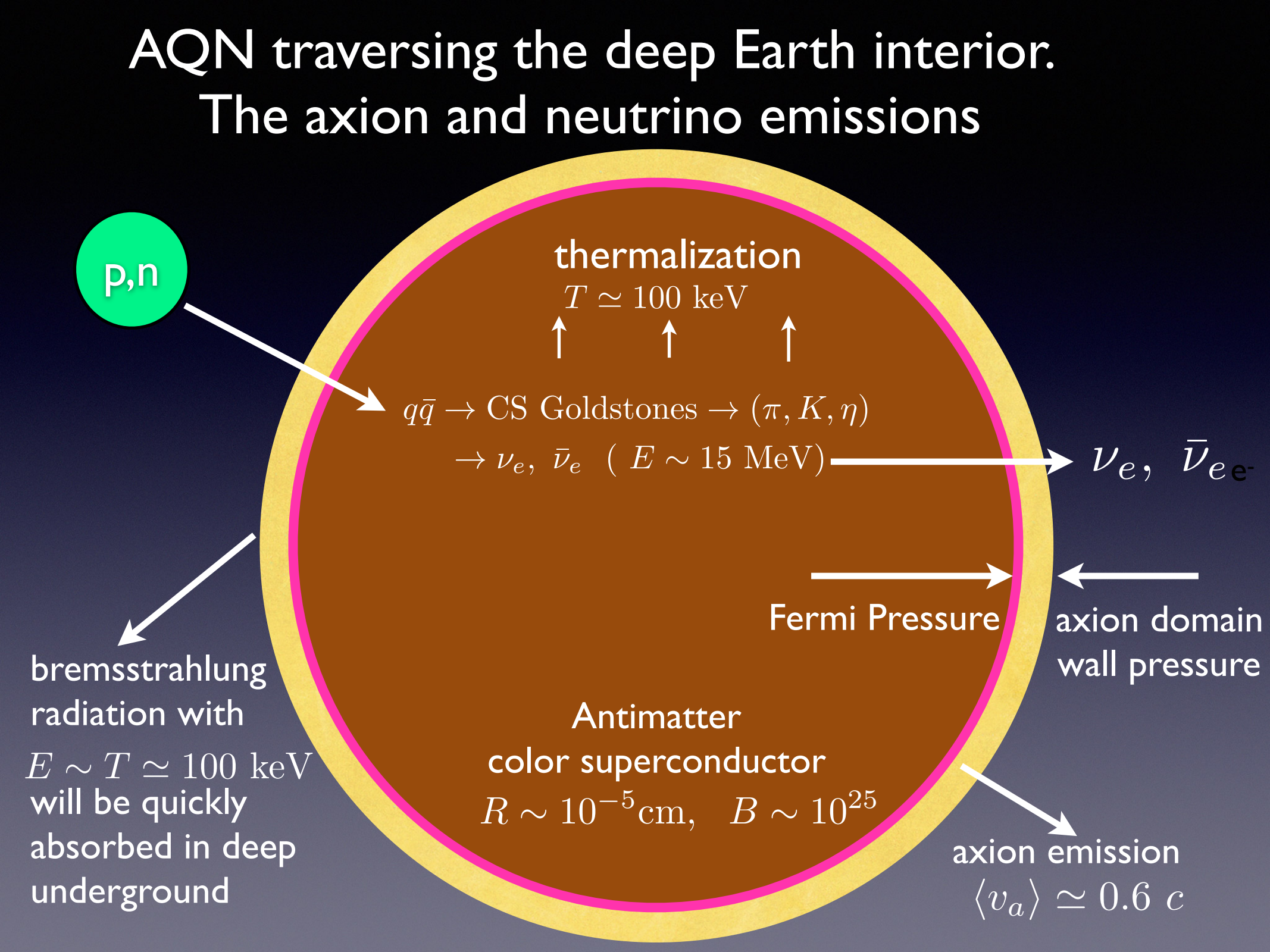


Relevant Literature

(Extreme UV and soft x-ray radiation as a result of annihilation of the AQNs in the solar corona).

- "Solar Extreme UV radiation and quark nugget dark matter model" -JCAP (2017)
- "Solar corona heating by axion quark nugget dark matter" -Phys. Rev. D (2018)
- "Solar Flares and the AQN Dark Matter Model" Phys. Dark Universe (2019)

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



4. The axion emission from the deep Earth interior

- **Flux of the AQNs hitting the earth surface**

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

- **Corresponding axion flux (on Earth surface):**

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

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

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

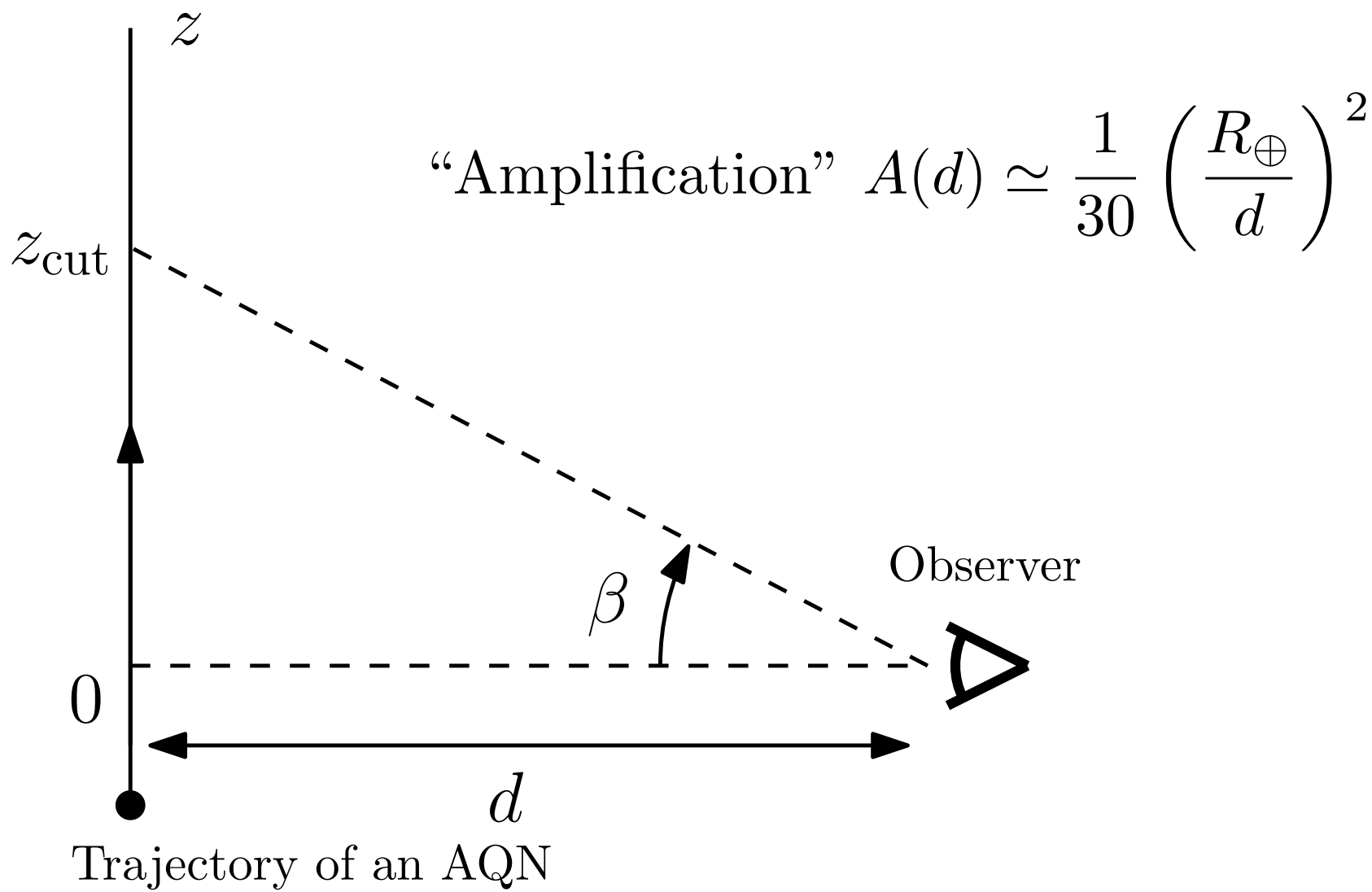
5. Time modulation, amplification, and the Global Network (GN) synchronization

- There are Conventional annual axion modulations due to the velocity difference (June vs December), which is of order $V_\oplus/V_\odot \sim 10\%$

- If a nugget hits the Earth's surface close to the position of an axion detector, a huge numerical amplification will occur as a "local flash" (burst).

- The amplification parameter "A" is defined as the ratio between the intensity due to the "local flash" from a nearby AQN and the average intensity

$$A(d) \equiv \frac{\Delta\Phi_a(d)}{\langle \Phi_a^{\rm AQN} \rangle} \simeq \frac{\beta}{\langle \dot{N} \rangle \langle \Delta t \rangle} \left(\frac{R_\oplus}{d} \right)^2$$



$$\text{“Amplification”}\ A(d) \simeq \frac{1}{30}\left(\frac{R_\oplus}{d}\right)^2$$

Amplification “A” due to the “local flash” becomes numerically large $A \sim 10^2$ when $d \sim 10^2 \mathrm{km}$

A	Time Span	Event rate
1	10 s	0.3 min^{-1}
10	3 s	0.5 hr^{-1}
10^2	1 s	0.4 day^{-1}
10^3	0.3 s	5 yr^{-1}
10^4	0.1 s	0.2 yr^{-1}

10^4-amplification occurs at every single point on Earth every 5 years. It shows up as a flash which lasts 0.1s

- What happens if several axion detectors are synchronized and positioned at distance

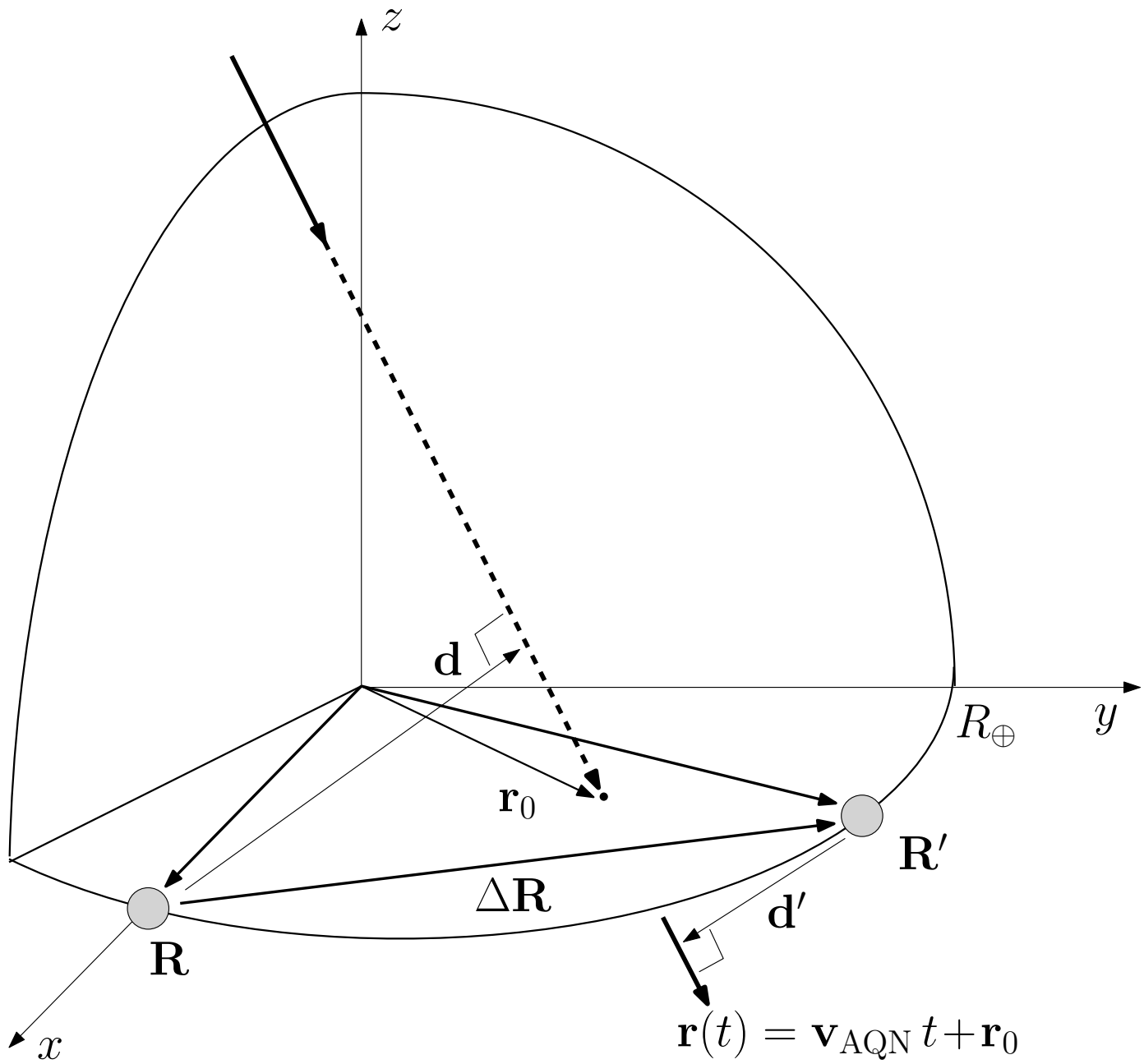
$$d \sim 10^2 \text{ km when } A \sim 10^2$$

- In this case one should expect the **correlated** amplified signals with event rate 0.2/day and with time delay Δt on order of a second $\Delta t \sim 1\text{s}$

$$\Delta t \equiv |t'_* - t_*| = \frac{\Delta R}{v_{\text{AQN}}}\delta \sim 1\text{s}, \quad \delta \equiv |\Delta\hat{\mathbf{R}} \cdot \hat{\mathbf{v}}|.$$

- Synchronized detectors must be close to each other to record the signal from one and the same AQN traversing the Earth

$$\Delta R \simeq 10^2\,\text{km}\left(\frac{10^2}{A}\right)^{1/2}$$



Correlated event rate $\simeq 0.23\ \text{day}^{-1} \left(\frac{10^2}{A}\right)^{3/2}$.

- What is a required Infrastructure for a correlated amplified signal to be properly recorded?

- In fact the required infrastructure has already started to emerge....

- We just need to built the global network of the stations which can detect the axions with

$$\langle v_a \rangle \simeq 0.6c \qquad \nu \simeq 24 \left(\frac{m_a}{10^{-4}\mathrm{eV}} \right) \mathrm{GHz}$$

- Can we do that?

The GNOME Experiment

Collaboration website

Live Data | News | Download | Wiki | Internal

Current date: 2019/09/28 21:54:02 GPS

Show Map Legend

View data of: 2019/09/28 21:54:02 with length 60 seconds View Data and Status

or

View most recent data

Subtract the mean of the data before plotting it

Show datasets to plot selector

Dima Budker and the GNOME

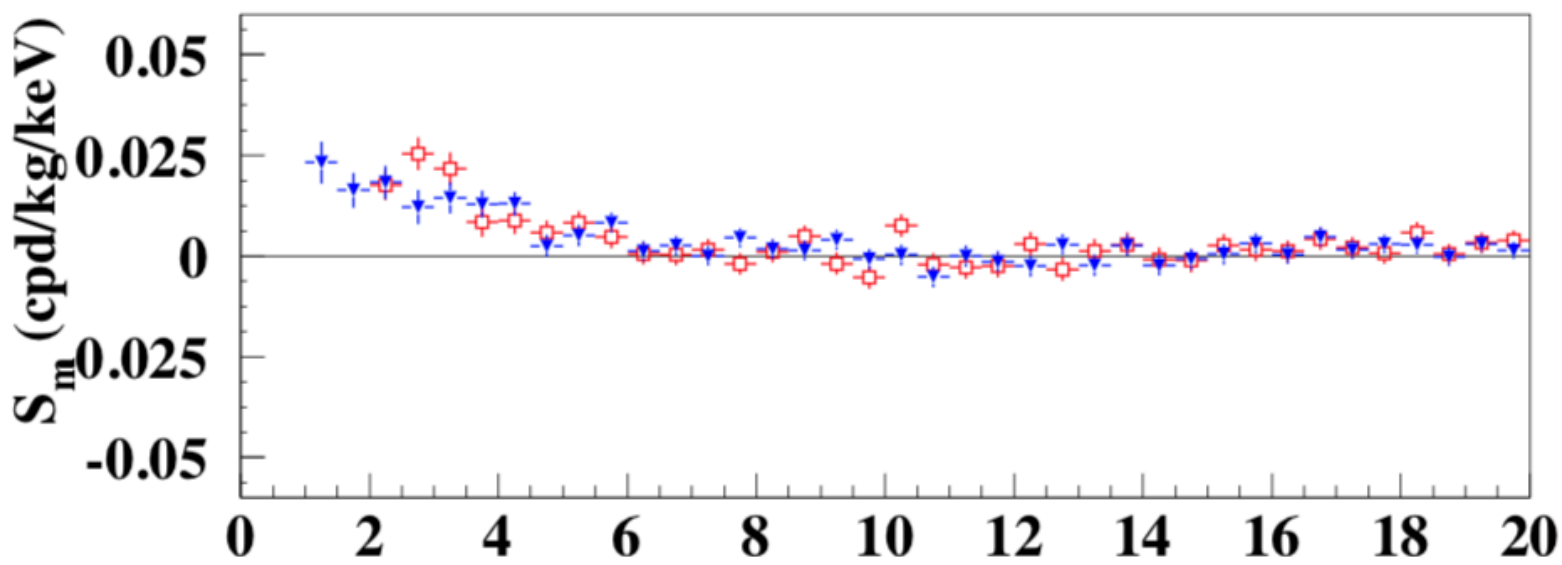
Page will update in: 0

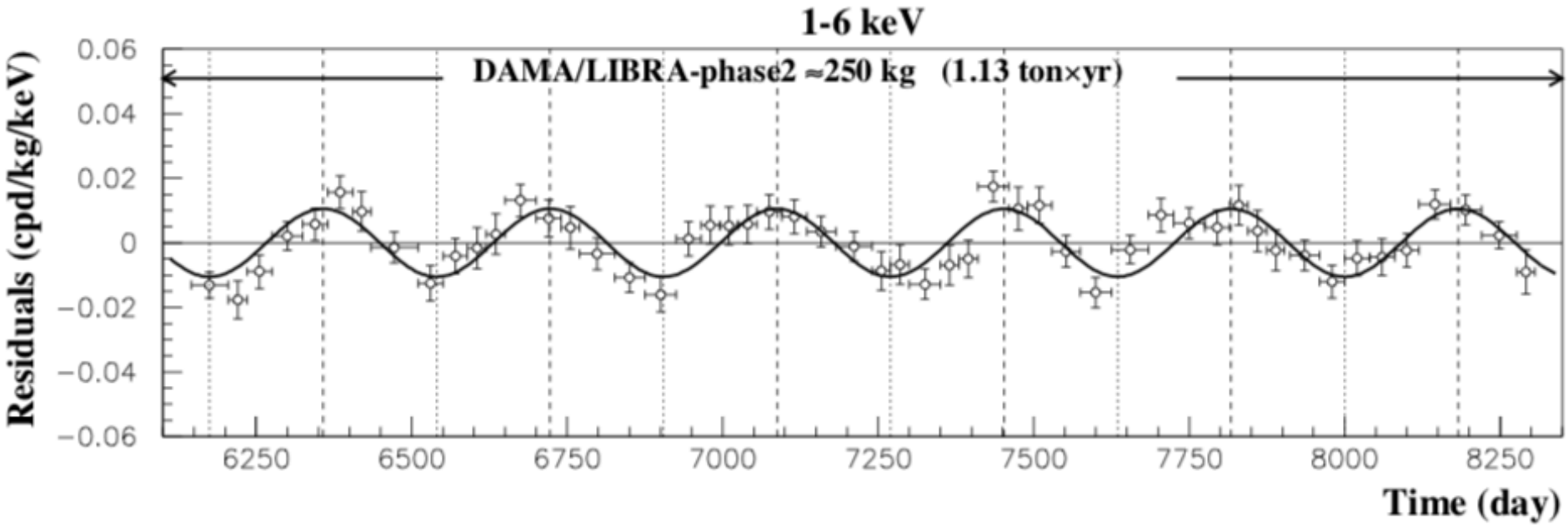
6. DAMA/LIBRA annual modulation. An Overview

- DAMA/LIBRA (DL) experiment claims the observation for an annual modulation in (1-6) keV range at 9.5 sigma;

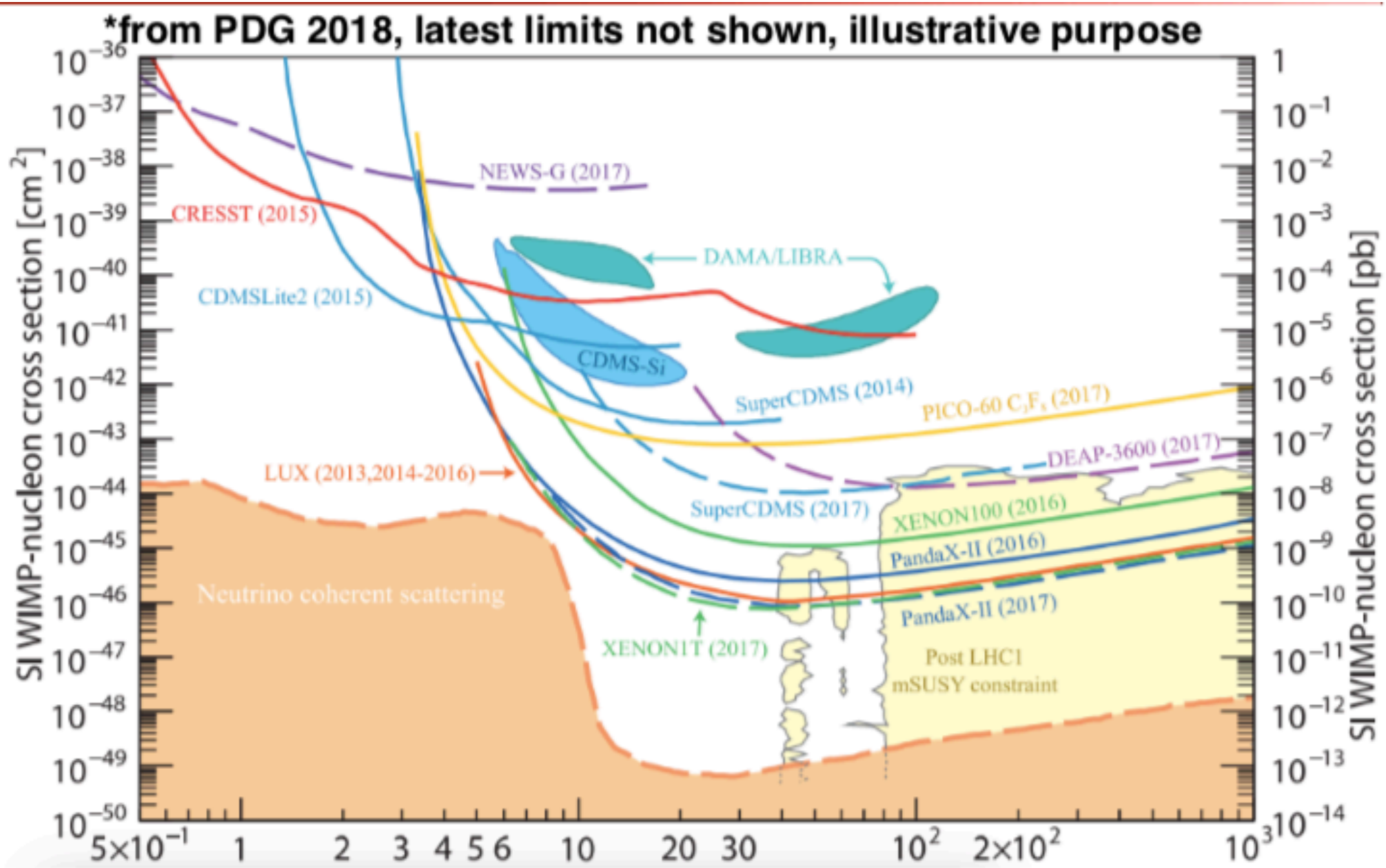
- The measured period (0.999 ± 0.001) and the phases (145 ± 5) strongly indicates the DM origin of the modulation;

- However the annual modulation observed by DL is excluded by other direct detection experiments if interpreted in terms of the WIMP-nuclei interactions





DL recent results. Universe 4 (2018) 116, arxiv: 1805.10486


*from PDG 2018, latest limits not shown, illustrative purpose
SI WIMP-nucleon cross section [cm^2]
SI WIMP-nucleon cross section [pb]
NEWS-G (2017)
CRESST (2015)
CDMSLite2 (2015)
DAMA/LIBRA
CDMS-Si
SuperCDMS (2014)
PICO-60 C_3F_8 (2017)
DEAP-3600 (2017)
LUX (2013,2014-2016)
SuperCDMS (2017)
XENON100 (2016)
PandaX-II (2016)
PandaX-II (2017)
Neutrino coherent scattering
XENON1T (2017)
Post LHC1
mSUSY constraint

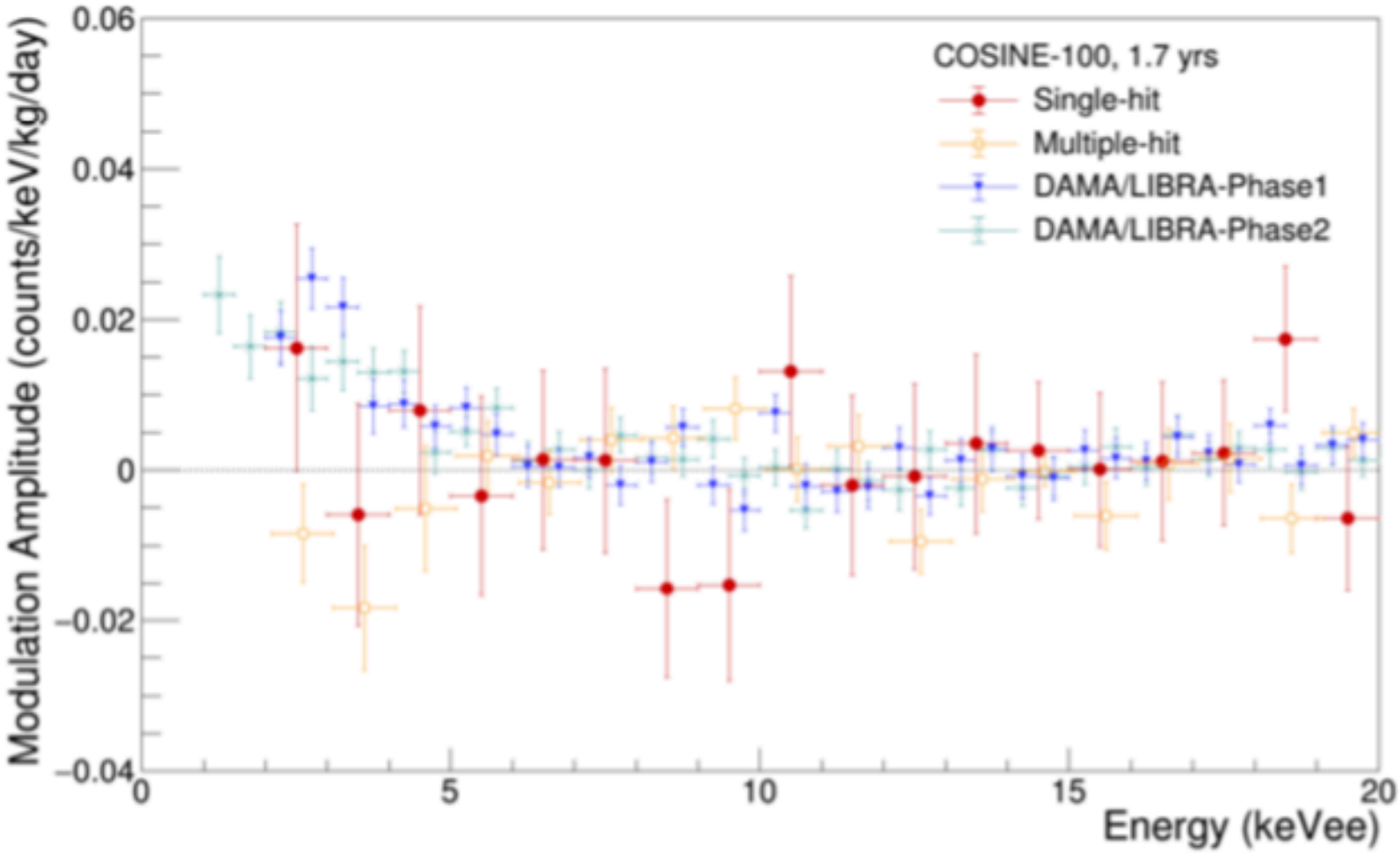
- Several new experiments may soon resolve this controversy related to DL observations.

- 1. The **COSINE-100** collaboration uses the same target medium (sodium iodide) which is the crucial element for the observed DL annual modulations;

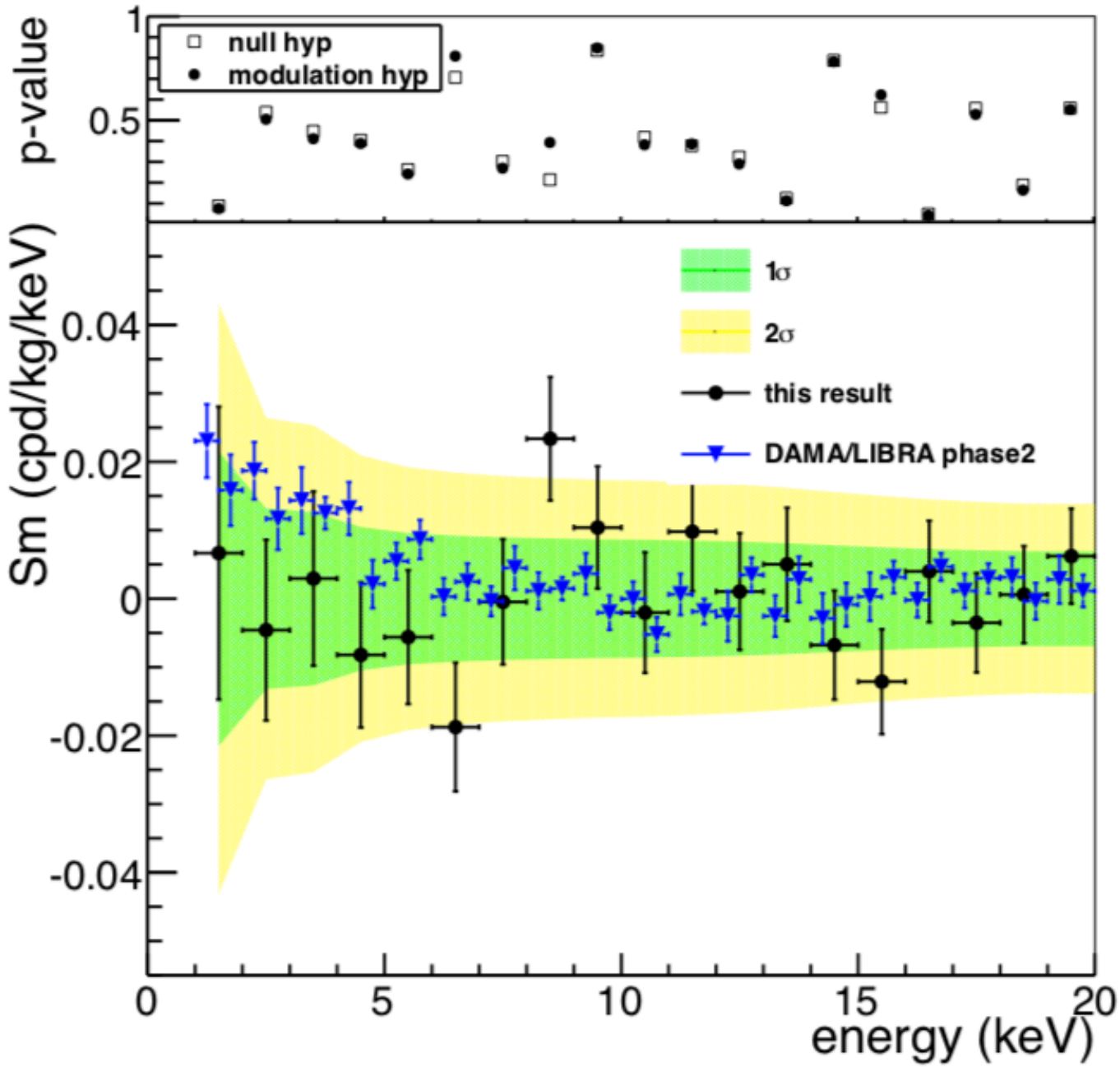
- Presently the COSINE-100 data is consistent with both a null hypothesis and DL (2-6) keV best fit value with 68% confidence level;

- The **ANAIS-112** collaboration also uses the same target medium as DL. The goal is to reach the sensitivity at 3 sigma level in 5 years.

- Moral: more data are needed to confirm or rebut the DL modulation signal



COSINE 100. PRL 123 (2019)031302



ANAIS-112. PRL 123 (2019) 031301

7. DL annual modulation and AQN model

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

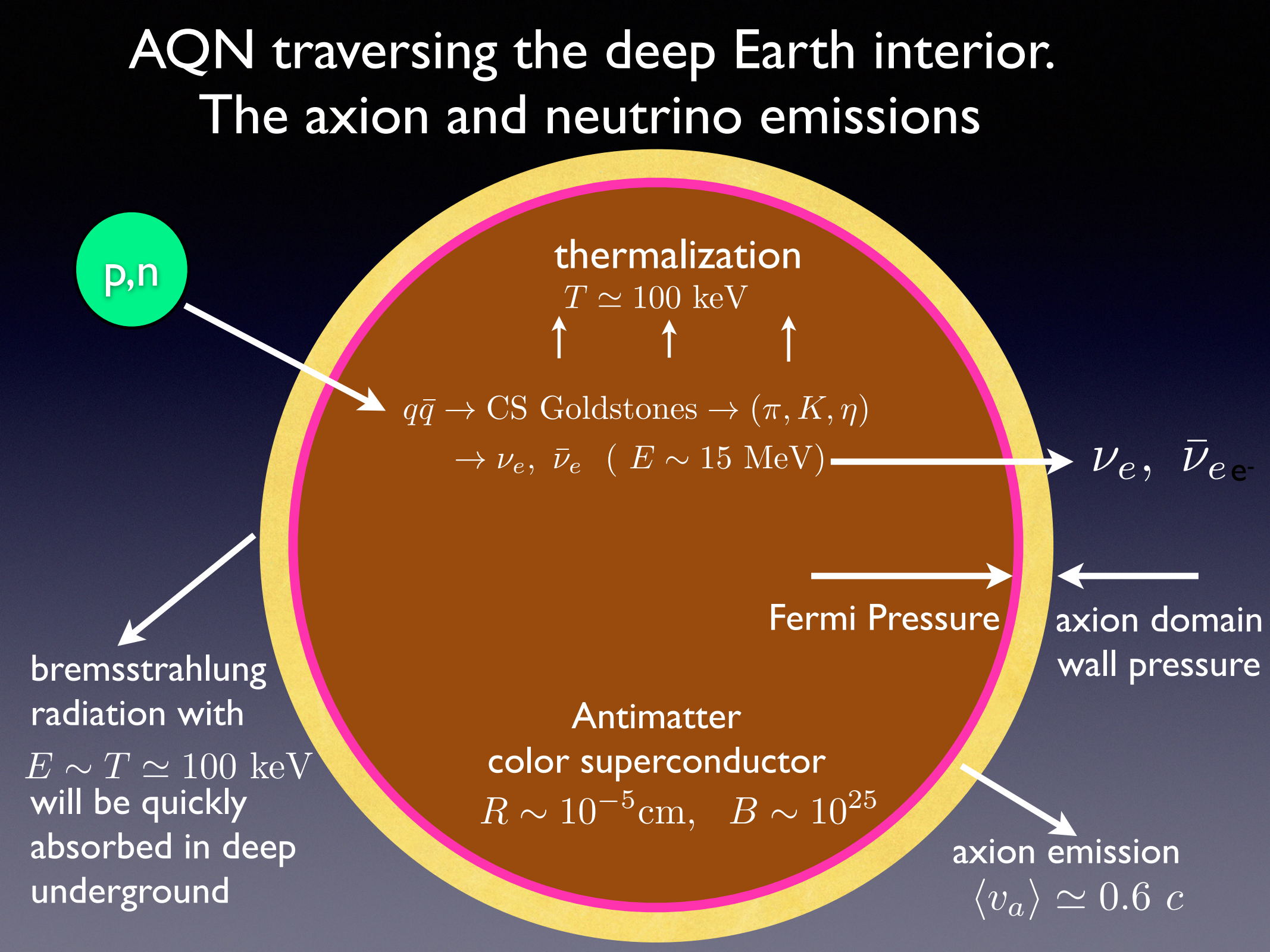
- Our basic claim is that the annual modulation observed by DL has truly genuine DM origin, though it is manifested indirectly through the following chain:

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

- 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

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



- We use the same AQN flux we used for the axion studies:

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

- This normalization determines the neutrino flux produced by AQNs on the Earth's surface

$$\frac{dN_\nu}{dtdA} \simeq 0.6 \cdot 10^6 \cdot \kappa_\nu \cdot \left(\frac{\langle \Delta B \rangle}{\langle B \rangle} \right) \frac{1}{\mathrm{cm}^2 \cdot \mathrm{s}} \sim 10^5 \cdot \kappa_\nu \frac{1}{\mathrm{cm}^2 \cdot \mathrm{s}}$$

- In this formula $\langle \Delta B \rangle / \langle B \rangle \sim (10 - 30)\%$ counts the portion of the annihilated baryon charge in the Earth's interior

- $\kappa_\nu \sim (1 - 10)$ is the number of the ν_e produced due to the annihilation of a single baryon charge (through the Nambu- Goldstone meson production)

- 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):

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

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

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

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

- 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:

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

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

- Intensity: the DL observed modulation

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

- to be compared with

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

- 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.

- In particular, along with **COSINE-100** and **ANAIS-112** collaborations the **CYGNO** proposal may also support or rebut the DL modulation signal.

- The CYGNO will be located at the same site (LNGS) and will be able to measure the directionality, which is the key element to measure the neutron's directions (from solar ν, atmospheric μ, or AQN-induced $\nu \rightarrow n$).

Conclusion

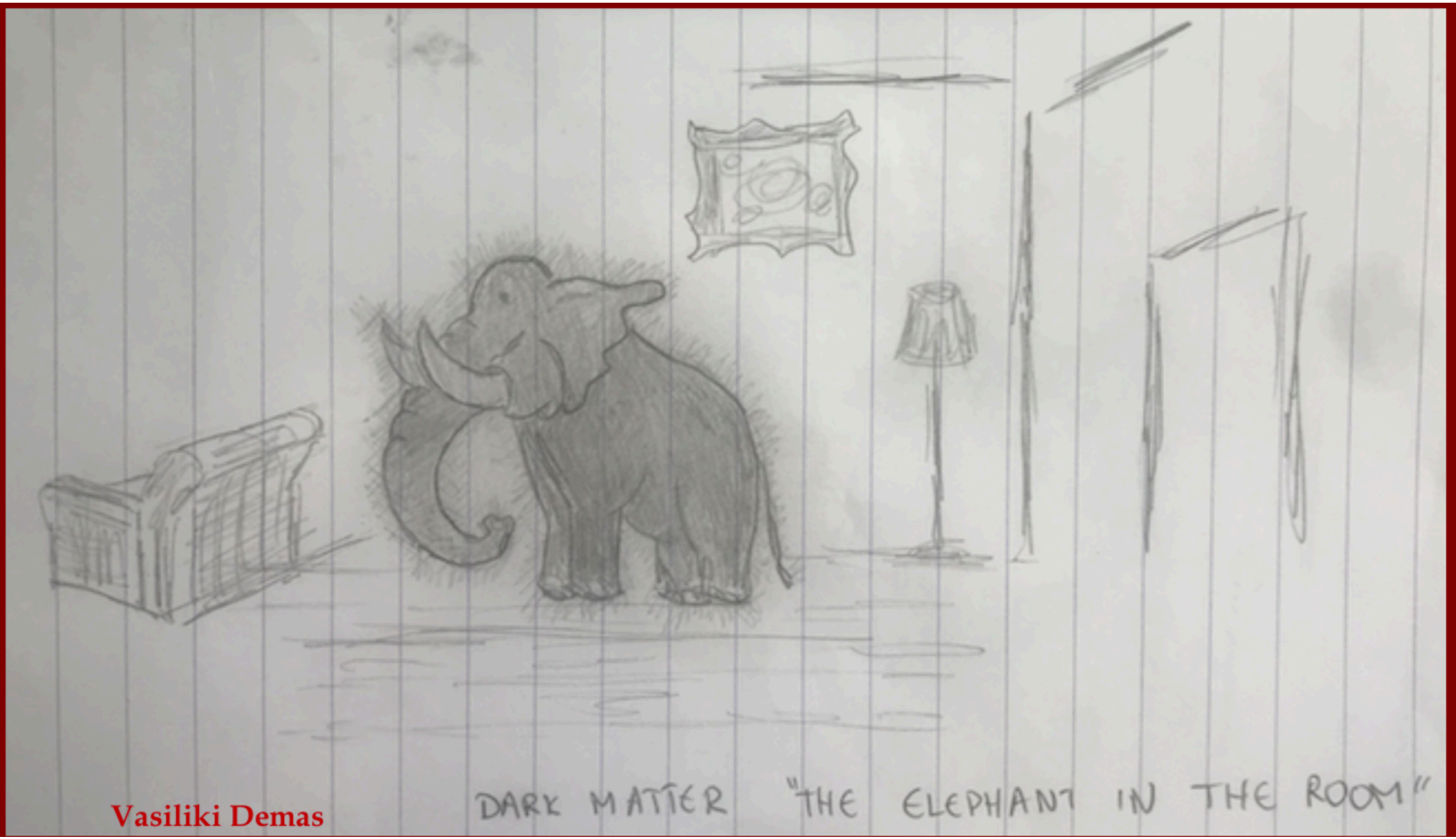
- " Non- baryonic Dark matter" could be ordinary baryonic matter (we know and love). We coin this model as the axion quark nugget model (AQN)
- $\Omega_{\rm dark} \sim \Omega_{\rm visible}$ is very generic consequence of this framework (no sensitivity to axion mass m_a , nor to the misalignment angle $\theta_{\rm initial}$).
- The axions will be inevitably produced each time when the annihilation event happens. The typical axions have the velocities $v_a \sim 0.6c$
- Sudden "local flashes" (bursts) may have enormous amplification up to 10^2 and even more (rare events).

- The noise background may be drastically decreased if one uses the synchronized nearby axion detectors at distance $d \sim 10^2$ km ;

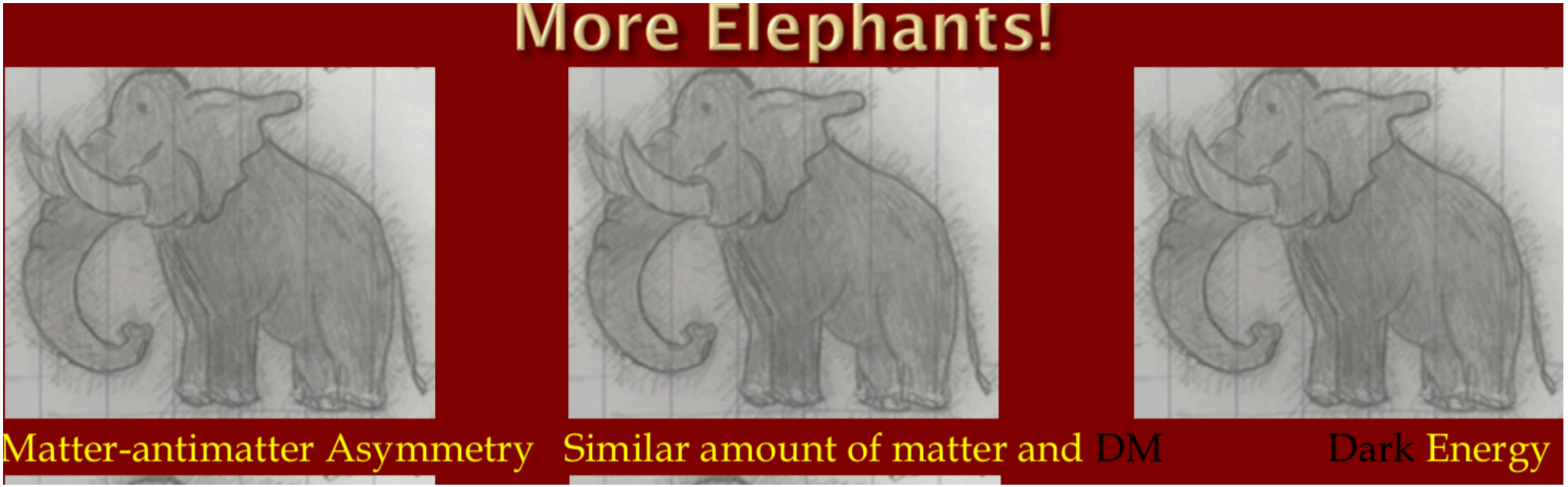
- The time delay typically assumes the value: $\Delta t \sim 1$ s ;

- The long standing puzzle on DL observation of the annual modulation (9.5 sigma CL) may find a natural resolution within the same AQN framework;

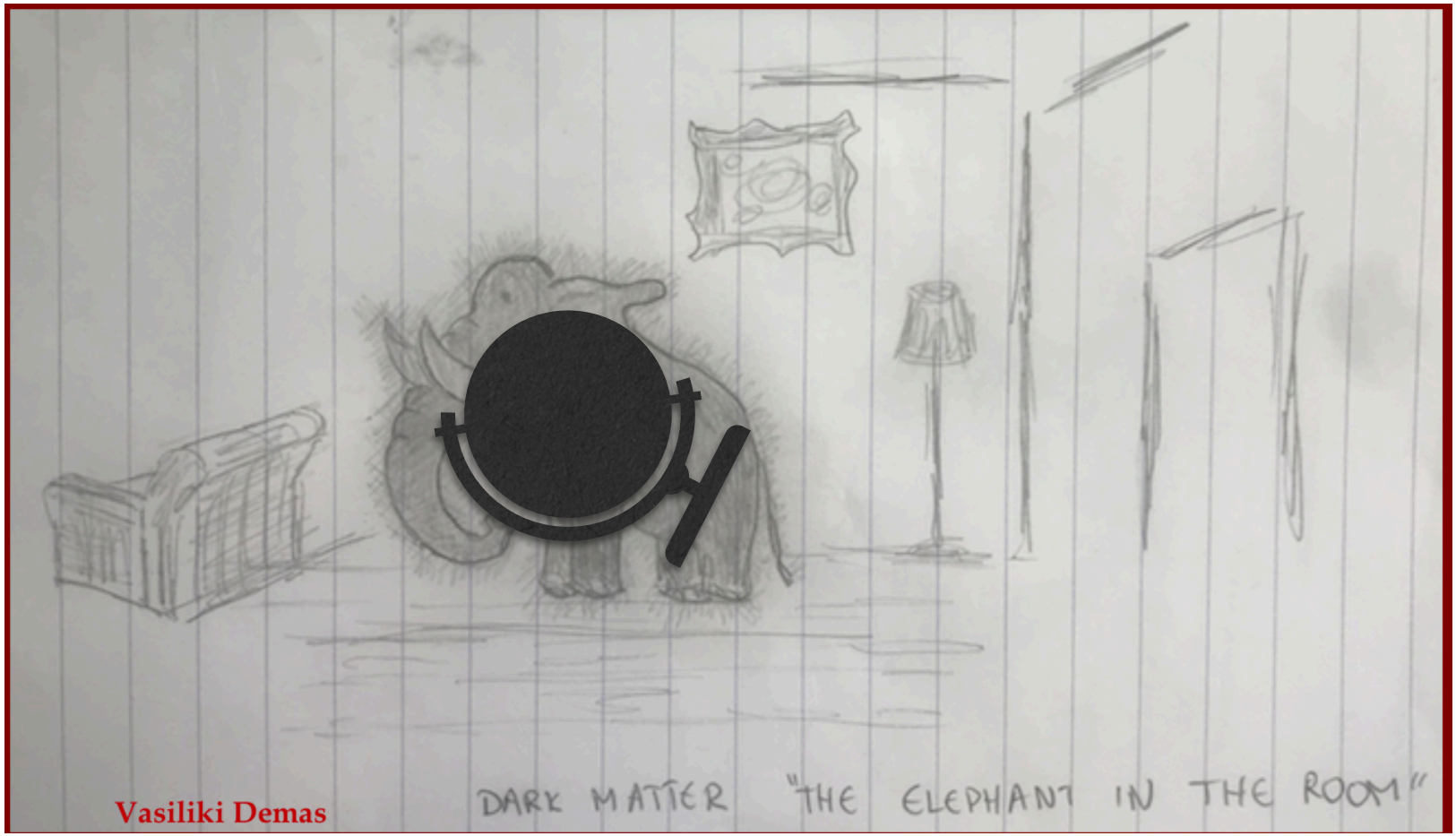
- All energy scales which enter the problem have not been "invented" for explanation of the DL signal. Instead, all the relevant scales [leading e.g. to the observed (1-6) keV recoil energy] have been established long ago in unrelated studies for different purposes in a different context.



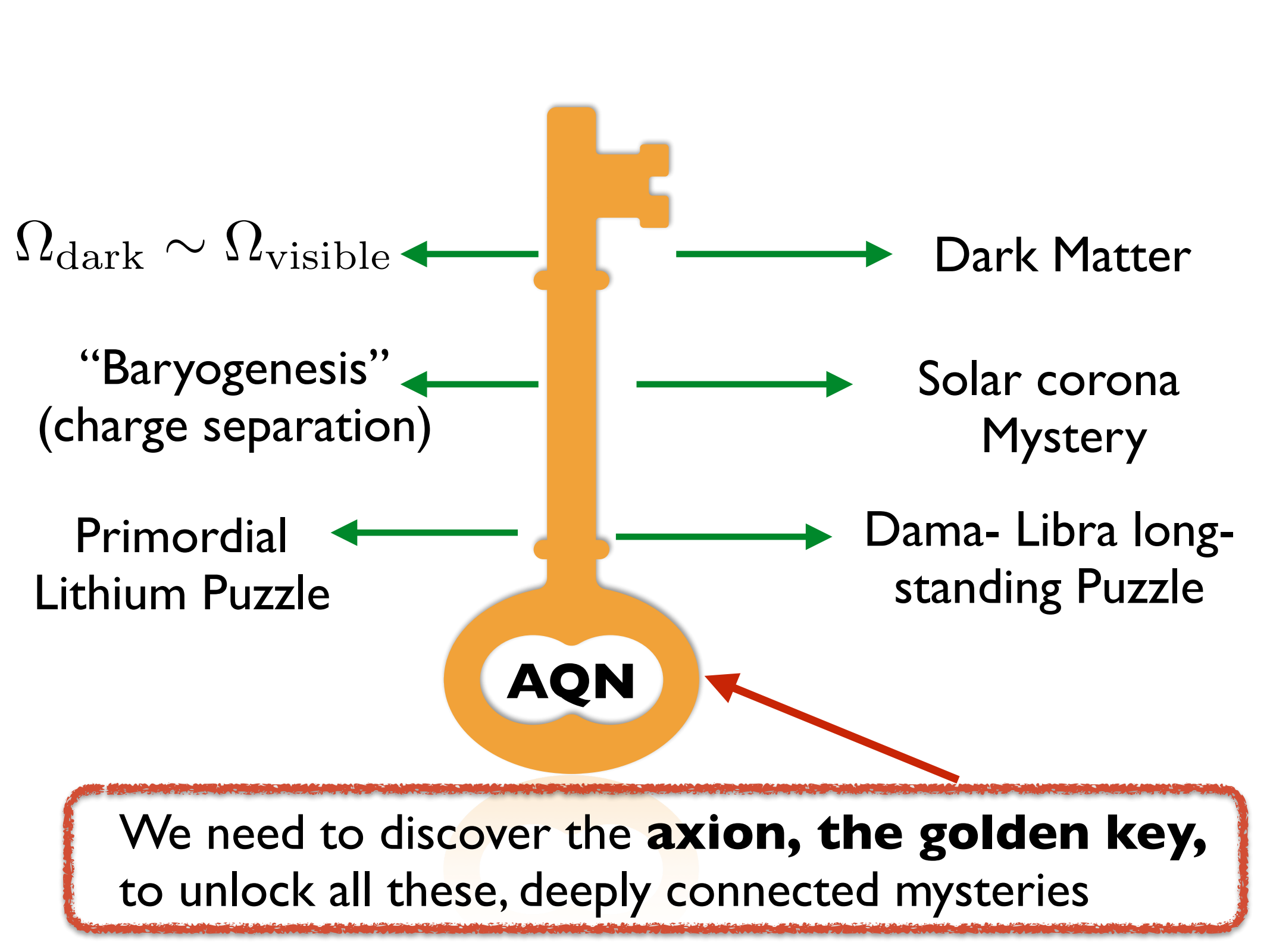
From Dima Budker's talk on DM- "the Elephant in the room"



From Dima Budker's talk with "More elephants…"



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


$\Omega_{\rm dark} \sim \Omega_{\rm visible}$
Dark Matter
"Baryogenesis"
(charge separation)
Solar corona
Mystery
Primordial
Lithium Puzzle
Dama- Libra long-
standing Puzzle
AQN
We need to discover the **axion, the golden key,**
to unlock all these, deeply connected mysteries