Domain Walls and Hubble constant Tension

H.B. Nielsen , Niels Bohr Institut, C.D.Froggatt, Glasgow University

Korfu 11. of September 2023

Solve the Tension in the Hubble Constant fitting in Standard Cosmological Model by Different degenerate Vacua with a Surprisingly Small Domain Wall Energy Density(Tension).

Abstract

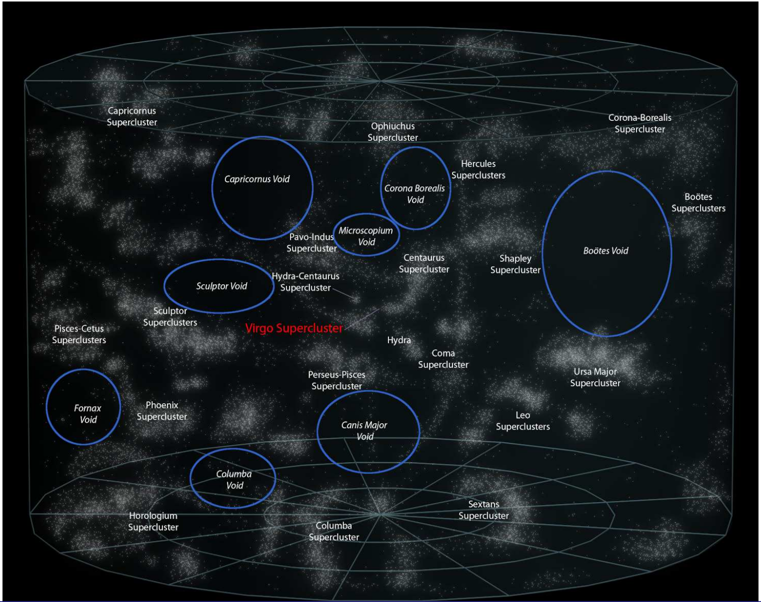
We present the idea that replacing the cosmological constant Λ in the ΛCDM by a distribution of walls with very low tension compared to what one would expect from the "new physics" could help for the tension in the Hubble constant fit in this Standard Cosmological Model. Using parameters from our, since long, model for dark matter as macroscopic pearls, we can get a promising order of magnitude for the correction to the Hubble constant. Our model is on the borderline to fail by predicting too much extra fluctuations as function of direction in the cosmological microwave background radiation, but imagining the bubbles in the voids to have come from more a bit smaller "big bubbles" may help.

Plan of Talk:

- “Big” (meaning 100 Mpc like) domains of new vacuum.
    - Arguments in favour of such “Big” new vacuum domains.
    - May send extra energy into CMB via Suniayev Zamalogikov (SZ) mechanism,
    - Correction to the Back ground temperature needed for Hubble constant tension resolution.
- The small new vacuum bubbles are dark matter pearls. Get parameters: potential difference for a nucleon in the two vacua and energy density of the separating walls betwen the phases of vacuum.
- Dark Matter Underground Experiments.
- Physics behind the difference of the vacua, “hadronic”
- Conclusion.
- Outlook: Dig out dark matter stopped in earth 1400 m down.

Arguments for/ Achievements of Several Vacua (with same energy density):

- There is a 4 σ evidence for the **finestructure constant** α **varying** by about $\frac{\delta\alpha}{\alpha} \sim 10^{-5}$ between different places in the Universe.
- We have long had success with a model for **dark matter as small pieces of a new vacuum phase filled with ordinary matter under pressure.**
- Some lattice simulations of QCD-vacuum with temperature indicates a **phase transition** as function of the **quark masses**.
- We once **pre**dicted the Higgs mass before the Higgs was found in LHC **from this principle of several vacua with same energy density.**


Capricornus Supercluster
Ophiuchus Supercluster
Corona-Borealis Supercluster
Capricornus Void
Corona Borealis Void
Hercules Superclusters
Boötes Superclusters
Pavo-Indus Supercluster
Microscopium Void
Boötes Void
Centaurus Supercluster
Shapley Supercluster
Sculptor Void
Hydra-Centaurus Supercluster
Sculptor Superclusters
Pisces-Cetus Superclusters
Virgo Supercluster
Hydra
Coma Supercluster
Perseus-Pisces Supercluster
Ursa Major Supercluster
Fornax Void
Phoenix Supercluster
Canis Major Void
Leo Superclusters
Columba Void
Sextans Supercluster
Horologium Supercluster
Columba Supercluster

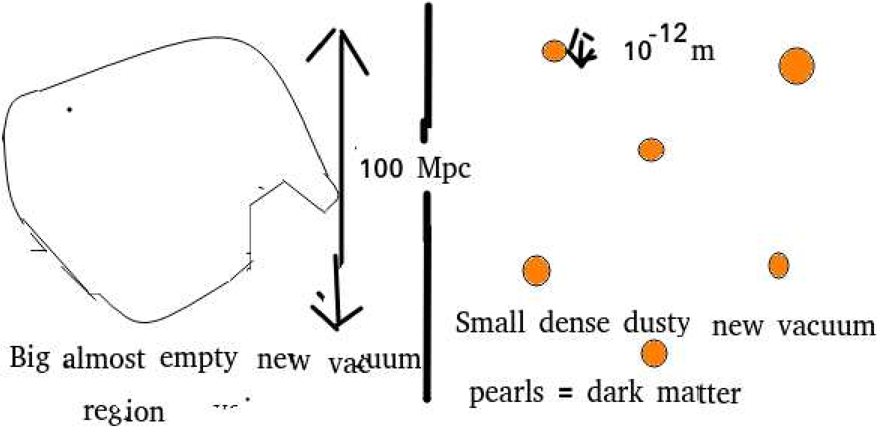
Several Vacua may Replace Some Not-so-wanted Inventions of Physicists

- The Domain Walls have a Negative Pressure Similar to that of the Dark Energy, and can - only effective by a factor 2/3 - **replace the Cosmological Constant.**
- Genericly the coefficient θ in the Lagrange term $\theta F^{\mu\nu} F^{\rho\sigma} \epsilon_{\mu\nu\rho\sigma}$ will be effectively different in the different vacua and thus the extension of such vacua could adjust to minimize energy in much the same way as the axion field is meant to adjust. Thus the several vacua may **replace the axion theory.**

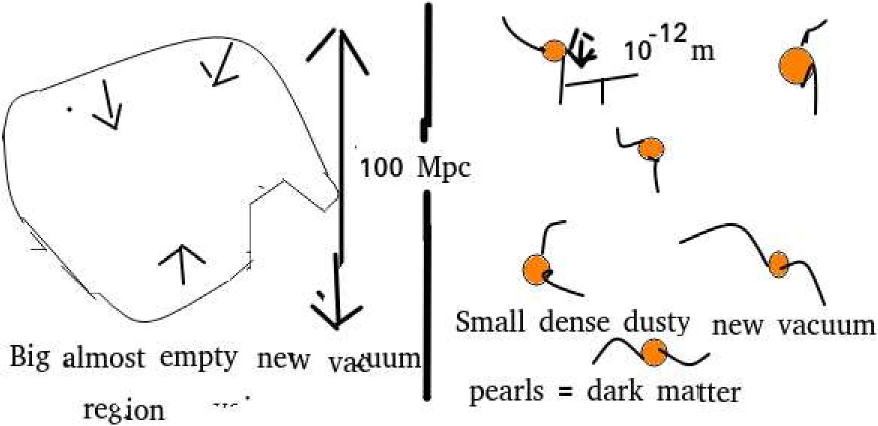
Our Main Story: Solution to Hubble-Lemaitre Constant Tension

- **Energy Released by Nuclei passing from our vacuum to “new” one.**
- This released energy finds by SZ(=Sunyaev-Zeldovich) mechanism way mainly to the cosmic microwave background radiation and brings the temperature up from an original one (say 2.4 K) to the presently observed 2.725 K.
- A lower temperature, as we should have gotten without this SZ-effect from Nuclei passing the walls, would correspond to a larger red shift $z = z_{rec}$ for the (re)combination of of atoms (usually taken to 370000 years) than the usual 1100, and this may **explain the tension.**

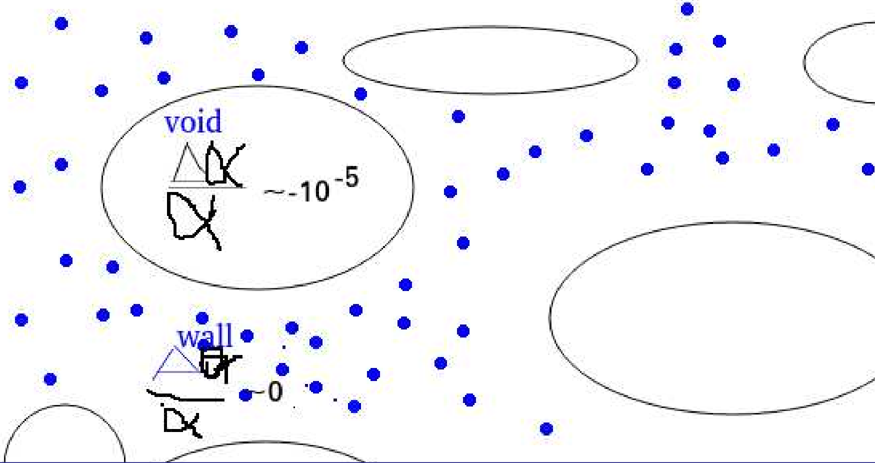
Two kinds of New Vacuum Regions: Big and Small



Small Dirty; Big Shoot Nuclei into themselves with High Energy, several MeV's



“Artist”: Vacua in Universe; Voids one vacuum, clusters of galxies “our” vacuum.



Sound horizon r_s and angular diameter distance d_A

We use the following CMB fit parameters in standard notation:

$$\Omega_b h^2 = 0.02237 \quad (1)$$

$$\Omega_m h^2 = 0.143 \quad (2)$$

$$\Omega_\Lambda = 0.685 \quad (3)$$

$$h = 0.674 \quad (4)$$

$$T = 2.7255K \quad (5)$$

$$\Omega_\gamma h^2 = 2.47 * 10^{-5} \quad (6)$$

$$\Omega_R h^2 = 4.15 * 10^{-5} \quad (7)$$

$$\frac{\Omega_b}{\Omega_\gamma} = 906 \quad (8)$$

$$T = 2.7255 \quad (9)$$

$$z_r = 1100 \quad (10)$$

Calculation

We calculate r_s and d_A using the following expressions

$$r_s = 3000Mpc \int_{z_r}^{\infty} \frac{dz}{H(z)} c(z) \tag{11}$$

$$d_A = 3000Mpc \int_{1}^{z_r} \frac{dz}{H(z)} \tag{12}$$

$$H(z) = \sqrt{\Omega_m h^2 (1+z)^3 + \Omega_R h^2 (1+z)^4 + \Omega_\Lambda h^2} \tag{13}$$

$$c(z)^2 = \frac{1}{3(1+\frac{3\Omega_b}{4\Omega_\gamma(1+z)})} \tag{14}$$

Using the listed parameters we obtain

$$r_s = 143.86Mpc \tag{15}$$

$$d_A = 13949Mpc \tag{16}$$

Now reduce Temperature in Calculation

Now we consider **reducing the temperature and increasing the Hubble constant** to the locally measured value $\mathbf{h = 0.738}$, keeping the "physical" mass densities (measured in units of $\sim 1.9 * 10^{-26} kg/m^3$) $\Omega_m h^2$ and $\Omega_b h^2$ fixed. We note Ω_Λ is negligible in r_s and Ω_R is negligible in d_A. It follows that r_s is unchanged by the change in h and that, apart from the change in z_r, d_A is unaffected by the change in temperature.

Number Possibilities

We now list the results for three different temperatures and give the percentage changes Δr_s and Δd_A in r_s and d_A.

- T $= 2.5$ K $z_r = 1200$ h $= 0.738$
  $r_s = 142.69$ Mpc $\quad \Delta r_s = -0.81\%$
  $d_A = 13721$ Mpc $\quad \Delta d_A = -1.7\%$
- T $= 2.4$ K $z_r = 1250$ h $= 0.738$
  $r_s = 141.75$ Mpc $\quad \Delta r_s = -1.5\%$
  $d_A = 13730$ Mpc $\quad \Delta d_A = -1.6\%$
- T $= 2.3$ K $z_r = 1300$ h $= 0.738$
  $r_s = 140.00$ Mpc $\quad \Delta r_s = -2.7\%$
  $d_A = 13721$ Mpc $\quad \Delta d_A = -1.5\%$

So the **angular size** of the acoustic horizon is **kept fixed** if the drop in temperature to **around T= 2.4 K** is compensated by an increase in the Hubble constant to equal the larger measured value, provided we assume that $\Omega_m h^2$ and $\Omega_b h^2$ are kept fixed.

To get the Hubble constant tension removed we need $T = 2.4K$ as the by SZ unmodified value.

It is not clear what effect this change in T and h would have on the other observables in the complicated CMB fit.
Of course we included in our change, that a change in the temperature prior to the SZ-heating up meant a change in the early Ω_R.
Our fit to make the Hubble constants match needs

Temperature T to use T=2.4 K

How to get Change in Temperature ΔT from Our Dark Matter?

Through long we fitted our dark matter small pearls to obtain **potential difference for nucleons** between the two vacuum phases:

- Using **the very number** $3.5keV$ from the line in the X-ray spectrum, not easily ascribed to the plasmas from which the X-rays were observed, to give us the **potential difference** ΔV for a nucleon in the **two** vacuum **phases.**
- Fitting to getting our dark matter pearls penetrate inot earth before getting **stopped approximately** at the **depth 1400 m of the DAMA/LIBRA** undergraound experiment which alone "sees" dark matter directly, and to getting **enough DM-pearls** down to be able to **recognize seasonal variation.**

A couple of Representative Fermi Energies in Our Bubbles being Dark Matter

- E_f= **3 MeV** Dimensional argument for homolumo-gap identified with the 3.5 keV of the X-ray from DM observed. $\Rightarrow \Delta T \sim$ 0.2 K to 0.35 K
- E_f = **200 MeV** Fitting to stop at and match DAMA/LIBRA, $\Rightarrow \Delta T \sim$ 14 K ... Too much; but if regions of new vacuum smaller or do not anymore expand more than Hubble expansion, then it could be less.

Remember we need

$$\Delta T = \mathbf{0.3\ K} \text{ to go from } 2.725 \rightarrow 2.4 \text{ K}.$$

to get the hoped for shift of the CMB-Hubble constant H_0.

Stories behind Our Estimates of Fermimomentum for the Orinary matter inside our Dark Matter Pearls/Bubbles of New Vacuum

- $E_f \approx p_f$ **= 3 MeV** Derived from the by "demensional argument" (except the $\sqrt{2}$) gotten formula for the homolumo-gap E_H between highest occupied electron level "homo" and lowest unoccupied "lumo"

$$E_H = \sqrt{2}\left(\frac{\alpha}{c}\right)^{3/2} E_f. \qquad (17)$$

Density of the pearl-matter:

$$\rho_B = 5 * 10^{11} kg/m^3. \qquad (18)$$

Story of fitting Pearls to stop at DAMA

- E_f **=200 MeV** Arranging $\frac{\sigma}{M}$ (where σ is the cross section for dark matter pearl hitting a particle, and M is its mass) to be sufficiently small, that a pearl can penetrate the 1400 m down in earth reaching DAMA. Then to get enough particles we need a higher density of the pearl

$$\rho_B \quad = \quad 70^3 * 5 * 10^{11} kg/m^3 = 1.7 * 10^{17} kg/m^3 \qquad (19)$$

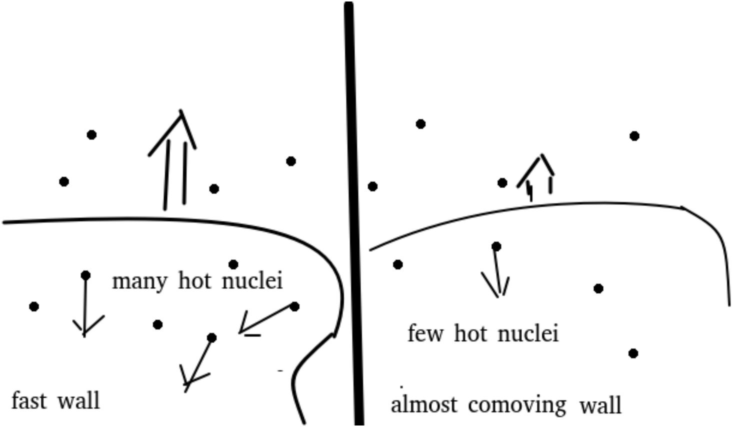
This last value 200MeV for the fermi-momentum in the inside of our pearls would with the same asssumptions as we used for the 3MeV, namely that the Big regions of the new vacuum expanded so as to grow up from being zero size to voids-size with constant velocity relative to comoving, i.e. expanding faster than just Hubble expansion.

There many uncertainties in predicting - even after fitting our dark matter - the change ΔT in the CMb temperature due to the energy input from the by the walls speedeed up nuclei

Especially if in the latest milliard years they have say only 300 km/s speed in excess of the Hubble expansion, then the effect on the change in the CMB temperature could go down by an appreciable factor, say 30, and the $\Delta T = 14K$, could easily be reduced to 0.5K.

But the expected ΔT is NOT many orders of magnitude away from the 0.3 K that would fit the Hubble constant tension

Amount of CMB-temperature Change ΔT Depends on Wall velocity relative to the nuclei it meets



Our dark Matter Fitting with the Same Domain Walls as in the Voids is Crucial for making the Model Trustworthy

There are two numbers that come out of our **dark matter application of the walls**, which are very **encouraging** for the **Big new vacuum regions:**

- The **potential difference** for a nucleon:

$$\Delta V \quad \approx \quad 3MeV \text{ to } 200MeV \tag{20}$$

  so that the change in the microwave background radiation $\Delta T = 0.3K$ is not at all hopeless to get.
- The **Tension or energy density** S gets fitted from the dark matter model to be so small that **walls extended around voids** in the galaxy distribution, would only give energy **densities of order of the cosmological constant.**

The Energy Density in average of walls around voids is of cosmologically Tolerable Order of Magnitude

The energy density of walls with distance R_{void} as a void radius $R_{void} = 100 Mpc$

$$\begin{array}{rcl}
S/R_{void} & \approx & \rho_{vac} \\
\sqrt[3]{S} & = & 70 MeV \text{ to } 360 MeV \text{ see[1]} \\
\text{So: } S & = & 2.4 * 10^5 MeV^3 \text{ to } 4 * 10^7 MeV^3 \\
R_{void} & \approx & 10^8 pc * 3.085 ly/pc * 0.946 * 10^{16} m/ly/(1.97 * 10^{-13} m \\
 & = & 1.48 * 10^{37} MeV^{-1} \\
\text{C.c. } \rho_{vac} & = & (2.24 meV)^4 = 2.5 * 10^{-35} MeV^4 \\
S/R_{void} & = & 2.4 * 10^5 MeV^3/(1.48 * 10^{37} MeV^{-1}) \\
 & = & 1.6 * 10^{-32} MeV^4 \\
\text{to } S/R_{void} & = & 4 * 10^7 MeV^3/(1.48 * 10^{37} MeV^{-1}) = 2.7 * 10^{-30} MeV^4
\end{array}$$

To replace Cosmological constant need $\sim \sqrt[3]{S} = 10$ MeV

To make the domain walls, assuming a distance between them of order of $100 Mpc$ leads to their cubic root of the energy per area be

$$\sqrt[3]{S} = 10 MeV. \tag{30}$$

Within our very crude estimates this 10 MeV is compatible for what we need for getting our pearls penetrate 1 km down to DAMA-depth and having a HOMOLUMO-gap matching the (mysterious) line 3.5 keV presumably originating from dark matter. Also it is of course of the order of the hadron physics scale (or the scale for Nambu Jonalasinio).

Underground Dark Matter Direct Search with NaI Scintillator

Table 3 Annual modulation amplitudes from various experiments. From: An induced annual modulation signature in COSINE-100 data by DAMA/LIBRA's analysis method

Counts/kg/keV/day	1–6 keV	2–6 keV
This work	- 0.0441 ± 0.0057	- 0.0456 ± 0.0056
DAMA/LIBRA	0.0105 ± 0.0011	0.0095 ± 0.0008
COSINE-100	0.0067 ± 0.0042	0.0050 ± 0.0047
ANAIS-112	- 0.0034 ± 0.0042	0.0003 ± 0.0037

The amplitudes of the annual modulation fits using the DAMA-like method to the COSINE-100 3 years data (this work) are compared with results from DAMA/LIBRA15,16, COSINE-1008, and ANAIS-1129 in both 1–6 keV and 2–6 keV regions.

Fluid Xenon Scintillator Experiments Cannot Stop a Heavy Pearl in the Xenon

It is of course impossible to get a very heavy dark matter pearl to stop in the fiducial volume in an underground detector based on **fluid** xenon. It would simply sink to the bottom (at least). Thus with our kind of **stopped** pearls being the main contribution to the observations, the xenon-based experiments (most of the undergraound searches for seeing dark matter directl) will see **nothing**.

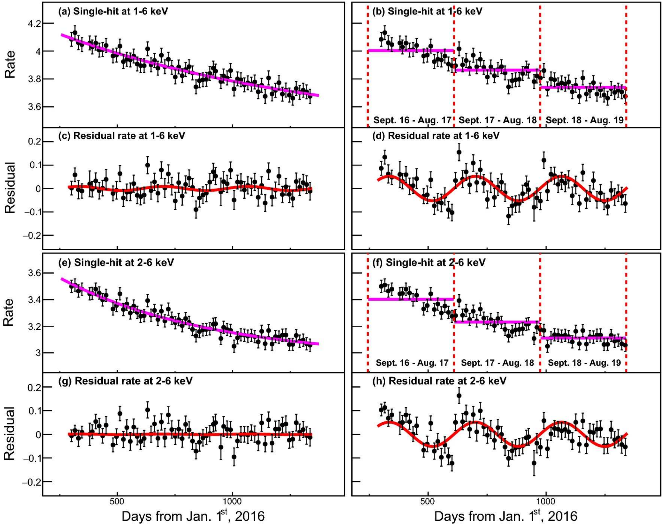

(a) Single-hit at 1-6 keV
(b) Single-hit at 1-6 keV
(c) Residual rate at 1-6 keV
(d) Residual rate at 1-6 keV
(e) Single-hit at 2-6 keV
(f) Single-hit at 2-6 keV
(g) Residual rate at 2-6 keV
(h) Residual rate at 2-6 keV
Rate
Residual
4.2
4
3.8
3.6
0.2
0.1
0
−0.1
−0.2
3.6
3.4
3.2
3
Sept. 16 - Aug. 17
Sept. 17 - Aug. 18
Sept. 18 - Aug. 19
500
1000
Days from Jan. 1st, 2016

Figure text:

Single-hit event rates in the unit of counts/keV/kg/day as a function of time. The top four panels present time-dependent event rates and the residual rates in the single-hit 1–6 keV regions with 15 days bin. Here, the event rates are averaged for the five crystals with weights from uncertainties in each 15-day bin. Purple solid lines present background modeling with the single exponential (a) and the yearly averaged DAMA-like method (b). Residual spectra for the single exponential model (c) and the DAMA-like model (d) are fitted with the sinusoidal function (red solid lines). Same for 2–6 keV in the bottom four panels. Strong annual modulations are observed using the DAMA-like method while the result using the single-exponential models are consistent with no observed modulation.

COSINE-100 mearsurements, methodology dependence

- [2] : When they analyse with the method like the **way of DAMA** the strange **negative amplitude** comes up.
- [1] : When they analyse their own way, the result (which inside uncertainty) is **both cosistent with DAMA and with no oscillation with season** (after three years)

The different Depths of the Experiments Simulating DAMA:

The detector of **Cosine-100** is located underground at a depth of **700m**, approximately **1600m.w.e**, in the Yangyang Underground Laboratory in Yangyang,. South Korea.

DAMA is located **1400 m** ($\sim$ **4200 m.w.e.**) in GranSasso.

The hut housing the **Anais** experiment is placed at the hall B of LSC (under **2450 m.w.e.** ($\sim$ **800 m**) of overburden).

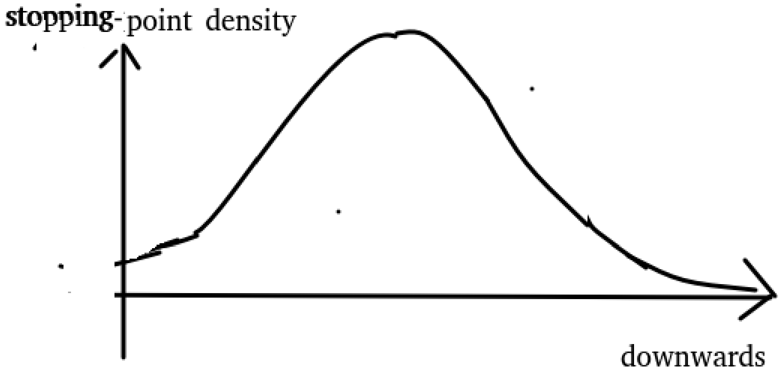
Simple Properties of Our Model:

- The main signal for observation is **radiation** of electrons or photons say
- (Likely) the main observational effect comes thus from dark matter particles, which essentially **stopped**.
- The dark matter particles interact so strongly that they get **slowed down** in the earth shielding.

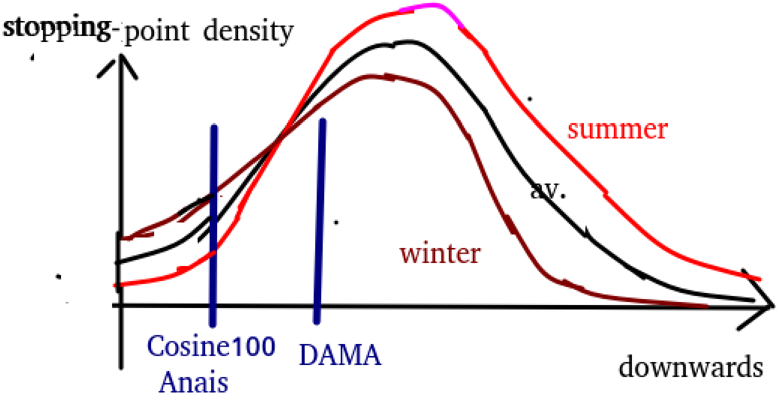
Ignore for simplicity but the moton in one direction down

The depth into which a dark matter particle will penetrate before (effectively) stopping, will be a smooth function of its velocity relative to the Earth. So “topologically” the **distribution of stopping-depths** will repflect the **initially velocity spectrum** in the down direction.

Velocity Distribution gets Transformed to Stopping Position Depth



DAMA is about Twise as Deep Down as Anais and Cosine-100



Properties of Our Pearls of Dark Matter from the DAMA etc. observation or nonobservation

- To get a stopping - just at DAMA crudely - we need a penetration depth of the order of magnitude:

$$\text{Penetration depth } L = \frac{M}{\sigma} * 28/\rho_{stone} \approx 1km \quad (31)$$

$$\Rightarrow \frac{M}{\sigma} \approx 1.1 * 10^5 kg/m^2 \quad (32)$$

$$\Rightarrow \frac{\sigma}{M} \approx 0.9 * 10^{-5} m^2/kg \quad (33)$$

Energy of Impact Consideration

- The density of dark matter in the region of the solar system is

$$\begin{aligned}
D_{sun} &= 0.3 GeV/cm^3 \\
\text{Rate of impact energy ``}Rate'' &= v * D_{sun} \\
&= 300 km/s * 0.3 * 1.79 * 10^{-27} kg/ \\
&= 1.6 * 10^{-16} kg/m^2/s \\
&= 1.4 * 10^{-11} kg/m^2/day
\end{aligned}$$

Getting enough Dama-events

- To get countings like DAMA of the order of at least one hit per 100 days per kg per keV (even taking the variation with season to be bigget than just from the change in infall due to earth motion) and giving each kg NaI say $10^{-2}m^2$ we need

$$\begin{aligned}
\text{number of pearls} & \quad \text{per } m^2 \text{ per day} \\
&= (100kg/m^2)^{-1}\rho_{number\ DM} * v * 86400s/day \\
\text{where } \rho_{number\ DM} &= 0.3GeV/cm^3/M \\
& \quad 86400s/day * (100kg/m^2)^{-1} * \rho_{number\ DM} * \\
&= D_{sun}/M * v * (100kg/m^2)^{-1} * 86400s/day \\
&= 0.3GeV/cm^3/M * 3 * 10^5 m/s * (100kg/m^2) \\
&= \frac{1}{M} 0.3GeV/(10^{-6}m^3) * 1.79 * 10^{-27}kg/GeV
\end{aligned}$$

Domain Walls and Hubble constant Tension

The tension or in $c = 1$ notation also the energy per area S of a domaine wall between different phases of vacuum has dimensionality GeV^3, and if an energy scale of the order of the scales at which we look for " new physics" is used the enrgy density gets so high that domaine walls of cosmological scales of extention would be so heavy as to be totally excuded by the already known energy density (the critical density

$$\begin{aligned}
\rho_c &= \frac{3H^2}{8\pi G} = 1.8788 * 10^{-26} h^2 kg/m^{-3} && (48)\\
&\quad (\text{where } h = H_0/(100 km/Mpc) = 0.674) && (49)\\
&= 2.7754 * 10^{11} h^2 M_{sun} Mpc^{-2}, && (50)\\
\rho_c &= 8.5 * 10^{-27} kg/m^3). && (51)
\end{aligned}$$

"New physics scale" walls excluded.

How High Energy per area possible ?

Say a wall of dimension of the visible universe of length scale

$$R_{visible} = 13 * 10^9 \text{ light years} \tag{52}$$

$$= 1.3 * 10^{10} ly * 9.5 * 10^{15} m/ly = 1.2 * 10^{26} m \tag{53}$$

$$\text{giving} Area \sim 10^{52} m^2 \tag{54}$$

for a domaine wall would allow an energy per area to give the total critical visible energy

$$\text{visible (critical) energy} \sim (1.2 * 10^{26} m)^3 * 8.5 * 10^{-27} kg/m^3 \tag{55}$$

$$= 1.5 * 10^{52} kg \tag{56}$$

being

$$\text{maximal energy per area} \sim \frac{1.5 * 10^{52} kg}{10^{52} m^2} \sim 1.5 kg/m^2. \tag{57}$$

The Tension in the Domain Wall arround the Pearl

$$\begin{aligned} \text{Cubic Root of Tension } S^{1/3} &= 3.9 * 10^6 MeV/m^{1/3}\sqrt[3]{R} \\ &= 3.9 * 10^6 MeV/m^{1/3} * \sqrt[3]{8 * 10^{-15} m} \quad (58) \\ &= 3.6 * 10^2 MeV = 360 MeV \quad (59) \end{aligned}$$

This is the energy scale of **pion or hadron physics** indicating that the **Phases of vacuum we speculate are to be distiguished by some pion or hadron physics!**

What tells the Energy Scale of the Tension S ?

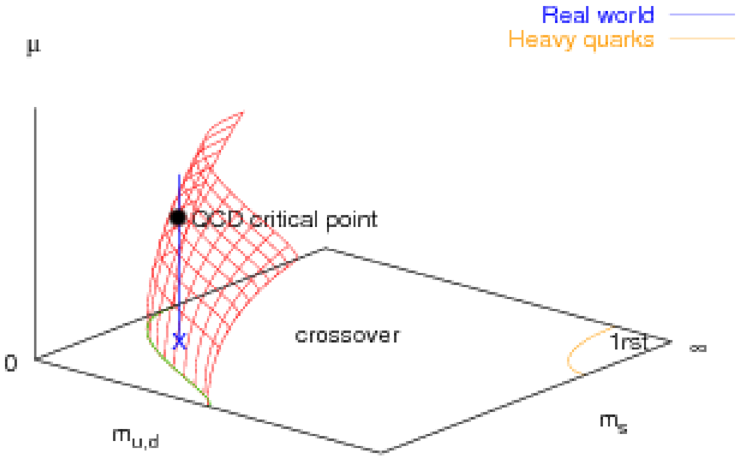
The cubic root of the tension S in the wall surrounding the pearls

$$\sqrt[3]{S} = 360MeV \tag{60}$$

suggests:

- The physics behind should be **Pion or Hadron Physics**: In fact we have found that there is a possibility for there being a phase transition in vacuum, on the one side of which the Nambu Jonalasinio spontaneous breaking is really a spontaneous breaking, while in the other vacuum the quark masses have rather just broken this symmetry.
- If we speculated that the domain walls **surrounded the voids** seen in between the galaxy rich regions with extensions of order of 30 to 300 Mpc, then the **energy density of the walls could replace the dark energy density.**

Phase Diagram, QCD with Quark masses



Columbia plot, just quark masses ($m_u = m_d$)

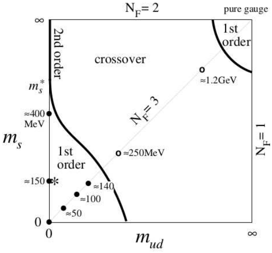


Figure 23: Order of the finite temperature QCD transition in the (m_{ud}, m_s) plane. First order signals are observed at the points marked with filled circle, while no clear two state signals are found at the points with open circle. The second order transition line is suggested [42] to deviate from the vertical axis as $m_{ud} \propto (m_s^* - m_s)^{5/2}$ below m_s^*. The values of quark mass in physical units are computed using a^{-1} determined from m_ρ: $a^{-1} \sim 0.8$ GeV for $\beta \lesssim 4.7$ and $\sim 1.0(1.8)$ GeV for $\beta = 5.0(5.5)$. See Sec. 8 for more detailed discussion on the values of the quark mass in physical units. The real world determined by the value of m_ϕ/m_ρ and m_π/m_ρ corresponds to the point marked with star.

To support us: what side experimental point ?

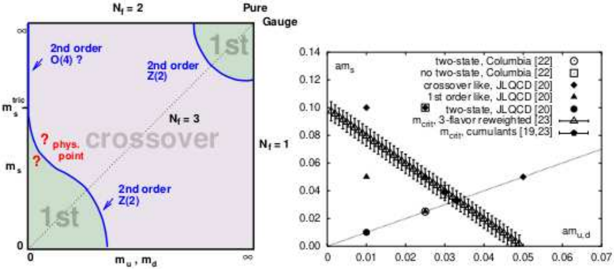


Figure 1: The phase diagram, expected (left) and lattice data (right), in the plane of strange and degenerate u,d quark masses.

“crosover” and “first order” allude to Phase transition as Function of Temperature for the Given Quark masses

If there is a different behavior of a phase transition as function of temperature, it must mean that the regions in quark mass spacee must be indifferent phases.

This is our hope for a phase transition as function of the quark masses of the vacuum itself, even at zero temperature!

A phase transition of this type would be involved with the Nambu Jonalasionio spontaneous breakdown and have an energy scale of the order of say pion masses. We found that our domain wall had a cubic root of its tension i the energy range about 360 MeV.

Remember : We claim a **principle** that there shall be **many vacuum-phases** with energy density finetuned (as a new physics principle) to have the same energy density.

Conclusion, Walls givng Extra Contribution to CMB Radiation Energy helping bringing Hubble constants to agree

We have put forward elements of a theory of dark matter on which we have worked for long, and seen:

- We have long suggested a principle, that there should be **several vaccum phases** with the same energy density(tuned to be just degenerate by some “new physics” finetuning principle “Multipoint criticallity principle”(= MPP)).
- If the energy density $\sim$ tension is as small as suggested by our work on our dark matter model, say of order $S \sim (30 MeV)^3$, then we could have **astronomical size regions of new vacuum**, e.g. filling out the big voids observed with rather few galaxies in them.
- Such astronomically large new vacuum regions are supported

Our own article in the foregoing meeting in Corfu: H. B. Nielsen and C.D. Froggatt, "Our dark matter stopping in earth".

- J. Va'vra "A new possible way to explain the DAMA results" J. Va'vra Physics Letters B 735 (2014) 181–185, Contents lists available at ScienceDirect Physics Letters B www.elsevier.com/locate/physletb

- Govinda Adhikari, Nelson Carlin, JaeJin Choi, Seonho Choi, Anthony Ezeribe, Luis Eduardo França, Chang Hyon Ha, In Sik Hahn, Sophia J. Hollick, Eunju Jeon, Jay Hyun Jo, Han Wool Joo, Woon Gu Kang, Matthew Kauer, Bongho Kim, Hongjoo Kim, Jinyoung Kim, Kyungwon Kim, SungHyun Kim, Sun Kee Kim, Won Kyung Kim, Yeongduk Kim, Yong-Hamb Kim, Young Ju Ko, Doo Hyok Lee, Eun Kyung Lee, Hyunseok Lee, Hyun Su Lee,corresponding author, Hye Young Lee, In Soo Lee,... et al. "An induced annual modulation signature in COSINE-100 data by DAMA/LIBRA's analysis method" Sci Rep. 2023; 13: 4676. Published online 2023 Mar 22. doi: 10.1038/s41598-023-31688-4 PMCID: PMC10033922 PMID:

- Three-year annual modulation search with COSINE-100 G. Adhikari, E. Barbosa de Souza, N. Carlin, J. J. Choi, S. Choi, A. C. Ezeribe, L. E. Fran¸ca, C. Ha, et al. (COSINE-100 Collaboration) "Three-year annual modulation search with COSINE-100" arXiv:2111.08863v2 [hep-ex] 28 Oct 2022
- Gyunho Yu, for the COSINE-100 collaboration "Dark matter search using NaI(TI) at the COSINE-100 experiment" PoS(ICRC2023)1421