Topological Defect Dark Matter

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Work in progress with A. Derivyanko …

PRL 2013 + some follow-ups

University of Victoria | British Columbia Canada

PERIMETER INSTITUTE FOR THEORETICAL PHYSICS

Patras workshop, Mainz

Plan

1. Introduction.

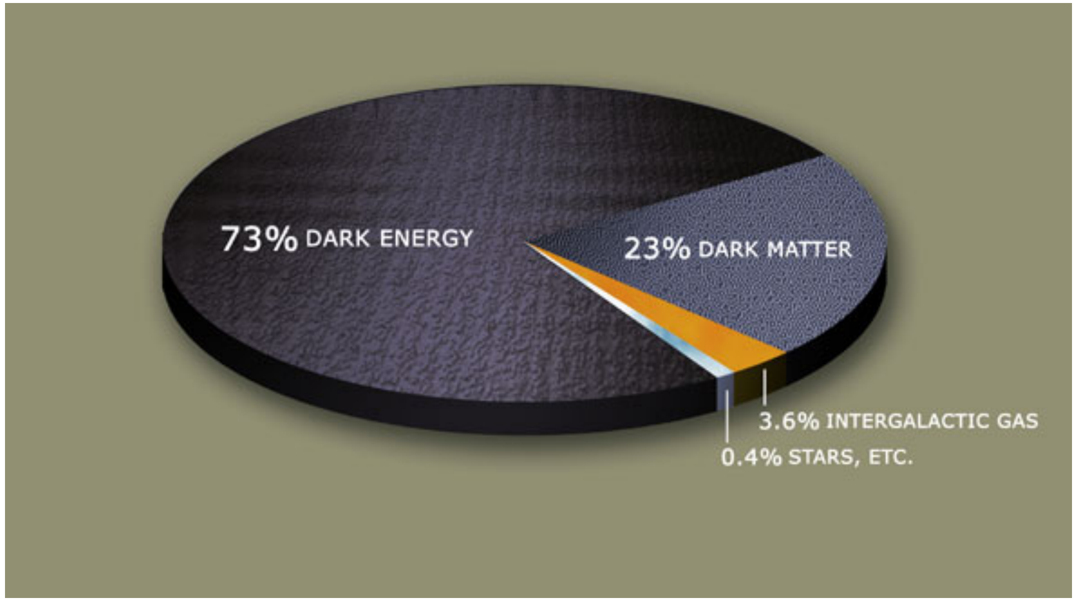
2. **Main idea**: dark matter can be composed of extended is space scalar or vector field configurations. [E.g. made stable for topological reasons] These objects can have elementary interactions with SM particles and fields. One would need a *network of detectors* to see a passing of one such objects through the Earth.

3. Interaction between extended objects and matter can lead to a momentum transfer, change in the frequency of a transition, torque on spin. The signals can be at the detectable level.

4. More detailed example of a domain wall interacting with spins.

5. Future networks of magnetometers, atomic clocks and gravitational wave detectors for transient effects.

Big Questions in Physics



Does dark matter (and also dark energy) have non-gravitational interactions?

The most costly hunt for dark matter (search for WIMPs) have not yet produced a strong positive result. Can we search for other types of dark matter using other techniques?

What is the space of theoretical possibilities for dark matter?

Simple classification of particle DM models

At some early cosmological epoch of hot Universe, with temperature T >> DM mass, the abundance of these particles relative to a species of SM (e.g. photons) was

Normal: Sizable interaction rates ensure thermal equilibrium, $N_{DM}/N_\gamma=1$. Stability of particles on the scale $t_{Universe}$ is required. *Freeze-out* calculation gives the required annihilation cross section for DM -> SM of order ~ 1 pbn, which points towards weak scale. These are **WIMPs**.

Very small: Very tiny interaction rates (e.g. 10^{-10} couplings from WIMPs). Never in thermal equilibrium. Populated by thermal leakage of SM fields with sub-Hubble rate (*freeze-in*) or by decays of parent WIMPs. [Gravitinos, sterile neutrinos, and other "feeble" creatures – call them **super-WIMPs**]

Huge: Almost non-interacting light, m< eV, particles with huge occupation numbers of lowest momentum states, e.g. $N_{DM}/N_\gamma\sim10^{10}$. "Super-cool DM". Must be bosonic. Axions, or other very light scalar fields – call them **super-cold DM**.

But even these broad categories are not exhaustive….

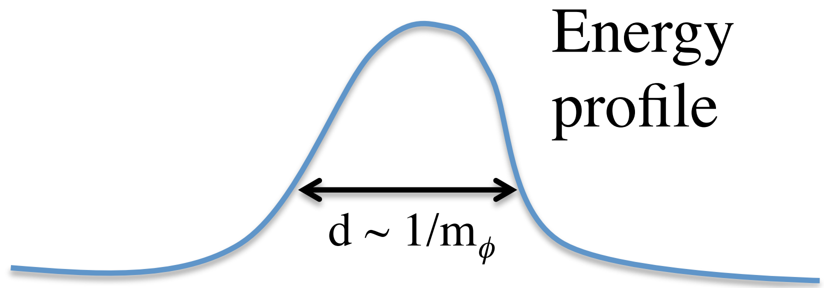
Extended field configurations of light fields

Take a simple scalar field, give it a self-potential e.g. $V(\phi) = \lambda(\phi^2 - v^2)^2$.

If at x = - infinity, ϕ = -v and at x = +infinity, ϕ = +v, then a stable *domain wall* will form in between, e.g. $\phi = v \tanh(x\, m_\phi)$ with $m_\phi = \lambda^{1/2} v$

The characteristic "span" of this object, $d \sim 1/m_\phi$, and it is carrying energy per area $\sim v^2/d \sim v^2 m_\phi$ Network of such *topological defects* (TD) can give contributions to dark matter/dark energy.

0D object – a *Monopole*
1D object – a *String*
2D object – a *Domain wall*



Cosmological problems from stable QCD axion DW – P. Sikivie

Rough comparison with WIMPs and axions

WIMPs DM: EW scale mass. Compton wavelength, $\lambda \sim 1/m_{WIMP}$, deBroglie w.l. $\sim 1/(\text{velocity} \times m_{WIMP}) \sim 1/(10^{-3} \times m_{WIMP}) \sim$ nuclear size.

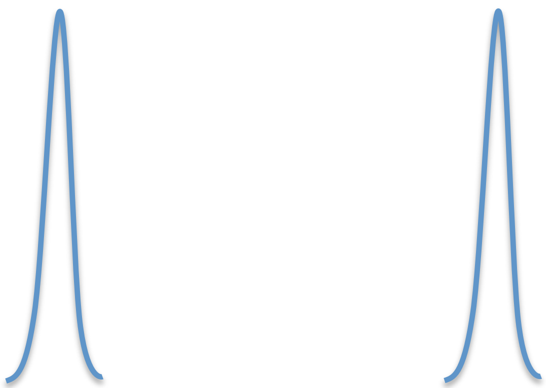
WIMP particles *are widely spaced* compared to their inverse mass with L ~ cm [within our galaxy] in between neighboring particles.

Axion DM: Light particles with huge number of particles per $(\text{w.l.})^3$ → the whole space is filled. Sinusoidal in time waves at $\omega = m_a \sim$ e.g. 10^{-5} eV. Average r.m.s amplitude, a ~ 100 eV, or so << EW scale.

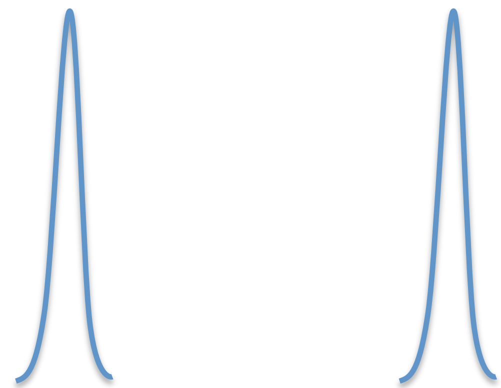
TD DM: A very shallow potential $V(\phi)$ can lead to an amplitude $\phi_{max}=A \sim$ EW scale. A particle-like 0D object is distributed over $1/m_\phi$ distance scales, and so the total mass is $\sim A^2/m_\phi$ >> EW scale. Therefore, necessarily the average distance is $\sim \text{cm} \times (A/m_\phi)^{1/3}$ - very large!

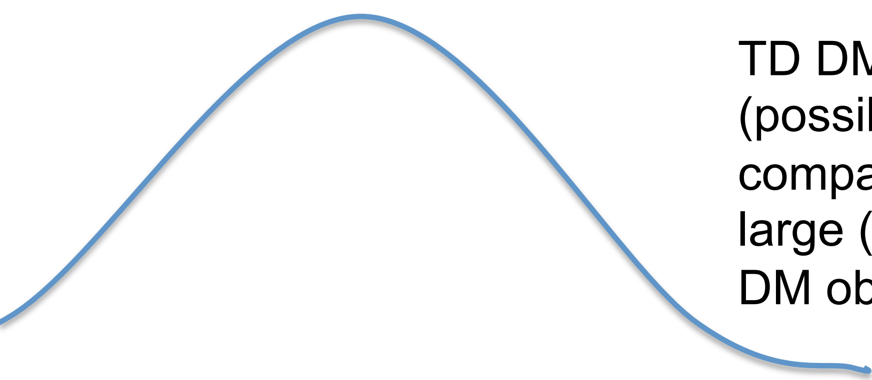
Comparison with WIMPs and axions

Axions – small amplitude but “no space” between particles



WIMPs – EW scale lumps of energy (>> axion amplitude), very concentrated in space And with significant ~ cm gaps between particles





TD DM – large amplitude but also large (possibly macroscopic) spatial extent d. Large compared to WIMPs individual mass, and then large (possibly astronomical) distances between DM objects.

TD DM is a possibility for DM that will have very different signatures in terrestrial experiments.

"Transient" signals from TD DM

Regardless of precise nature of TD-SM particles interaction it is clear that

1. Unlike the case of WIMPs or axions, most of the time with TD DM there is no DM objects around – and only occasionally they pass through. Therefore the DM signal will [by construction] be *transient* and its duration given by $\sim$ size/velocity.

2. If the S/N is not large, then there can be a huge benefit from a network of detectors, searching for a correlated in time signal.

3. There will be a plenty of the constraints on any model of such type with SM-TD interaction, because of additional forces, energy loss mechanisms etc that the additional light fields will provide.

Possible Interactions

Let us call by ϕ, ϕ_1, ϕ_2, … - real scalar fields from TD sector that participate in forming a defect. (More often than not more than 1 field is involved). Let us represent SM field by an electron, and a nucleon. Interactions can be organized as "portals": coeff × $O_{dark}O_{SM}$.

A. $$\frac{\partial_\mu \phi}{f_a} \sum_{\text{SM particles}} c_\psi \bar{\psi}\gamma_\mu\gamma_5\psi \quad \text{axionic portal}$$

B. $$\frac{\phi}{M_*} \sum_{\text{SM particles}} c_\psi^{(s)} m_\psi \bar{\psi}\psi \quad \text{scalar portal}$$

C. $$\frac{\phi_1^2 + \phi_2^2}{M_*^2} \sum_{\text{SM particles}} c_\psi^{(2s)} m_\psi \bar{\psi}\psi \quad \text{quadratic scalar portal}$$

D $$\frac{\phi_1 \partial_\mu \phi_2}{M_*^2} \sum_{\text{SM particles}} g_\psi \bar{\psi}\gamma_\mu\psi \quad \text{current -- current portal}$$

An atom inside a defect will have addt'l contributions to its energy levels

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A. $\frac{\partial_\mu \phi}{f_a} \sum_{\text{SM particles}} c_\psi \bar{\psi} \gamma_\mu \gamma_5 \psi$ axionic portal — Torque on spin

B. $\frac{\phi}{M_*} \sum_{\text{SM particles}} c_\psi^{(s)} m_\psi \bar{\psi} \psi$ scalar portal — Shift of ω + extra gr. force

C. $\frac{\phi_1^2 + \phi_2^2}{M_*^2} \sum_{\text{SM particles}} c_\psi^{(2s)} m_\psi \bar{\psi} \psi$ quadratic scalar portal — Shift of ω + extra gr. force

D $\frac{\phi_1 \partial_\mu \phi_2}{M_*^2} \sum_{\text{SM particles}} g_\psi \bar{\psi} \gamma_\mu \psi$ current – current portal — extra gr. force

The issue of technical naturalness

Any tree level potential

$$V^{tree}(\phi) = c^{tree}{}_0 + c^{tree}{}_1\phi + c^{tree}{}_2\phi^2 + \ldots.$$

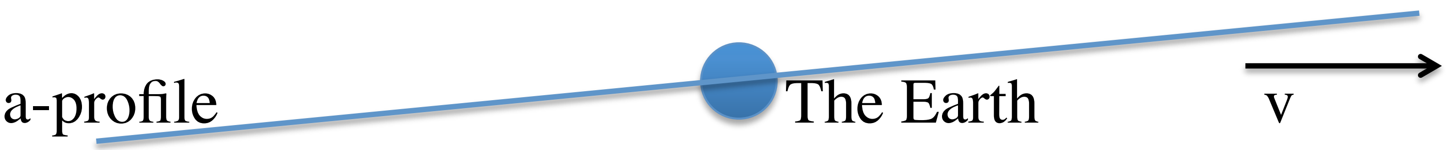
Would have to have coefficients $c^t{}_i$ very small to keep evolution *slow*.
Loops generate *larger* corrections

$$V^{loop}(\phi) = c^{loop}{}_0 + c^{loop}{}_1\phi + c^{loop}{}_2\phi^2 + \ldots.$$

so that $c^{loop}{}_i >> c^{tree}{}_i$, One has to start with large and opposite tree-vs-loop coefficients $c^{loop}{}_i = - c^{tree}{}_i$ to ensure tight cancellation for several terms in the series… Very unnatural! *Standard problem for scalar portals*.
Importantly, same pessimistic argument does not apply to interactions protected by shift symmetry, the axionic portal for example.
(* *But may be the approach idea of having rigid technical naturalness built in a model is not "quite" right, and we would miss out on interesting physics* *)

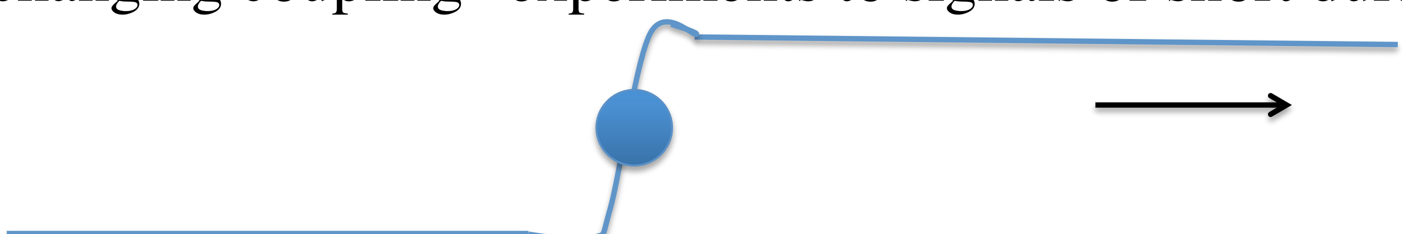
"transient LV" and "transient $\Delta\alpha/\alpha$"

Typical "LV" experiment looks for $b_\mu \bar{\psi}\gamma^\mu\gamma_5\psi$
that one can generalize as interaction os a spin i to with the *fixed* gradient of the scalar field a, $f_i{}^{-1}\partial_\mu a \bar{\psi}_i \gamma_\mu \gamma_5 \psi_i$



Similarly, existing terrestrial checks of ***Δα/α*** etc look for a smooth dα/dt signal, that is a *constant in time*.

And of course TD transient signal can be viewed as generalization of LV and "changing coupling" experiments to signals of short duration.



Setting up a question

1. Take any portal [better still take technically natural ones]. Supply constraints on f_a, M_* etc from the astrophysics, 5th force, etc - anything that does not involve DM

2. Take the DM energy density, *saturate* it with TD DM (this is a big assumption), and require that the average time between crossings T is not much than ~1-10 yr.

3. *Given the strength of some astrophysical constraints and restrictions on energy density of the DM, do the current generation of high precision instruments (atomic magnetometers, atomic clocks, gravitational wave detectors) stand a chance in detecting transient signal from DM?*

If "No" – probably such DM would not be detectable.
If "Yes" – it is worth exploring opportunities for developing a "network"

Proxies and unknowns

The only things **we know** are

$\rho_{DM} \sim 0.4$ GeV/cm^3 - local energy density of Dark Matter

v ~ 10^{-3} c - typical velocity of Milky Way halo objects

Additional "practicality" input $T_{encounter}$ < 1-10 yr

Unknowns : type of portals (I take A and D for now, as the most "safe", and choose baryon current for the vector portal, g=1).

$f_a > 10^9$ GeV, $M_* >$ TeV (astrophysics, colliders etc)

(limit on M_* is in fact quite a bit weaker)

L – average distance between defects. A – amplitude of fields inside TD.

$d \sim 1/m_\phi$ is the "transverse" size of the defects. One can show that

$$\rho_{\rm network} = \frac{A^2 d}{L^3} \quad \text{0D, monopoles}$$

$$= \frac{A^2}{L^2} \quad \text{1D, strings}$$

$$= \frac{A^2}{Ld} \quad \text{2D domain walls}$$

$L^3 \sim d^2 v T$ (for 0D objects)

Equating $\rho_{network} \sim \rho_{DM}$ one can e.g. express A via ρ_{DM}

How do you know if you ran through a wall?

MP, Pustelny, Ledbetter, Jackson-Kimball, Gawlik, Budker, PRL 2013

- It was initiated in discussions with Budker, Pustelny, Ledbetter who had two sensitive atomic magnetometers synchronized via GPS. *What is good for?* Best magnetometers can surpass 1 fT/√Hz! *Are we using these experimental capabilities to the fullest?*
- Domain walls of axion-like field moving with ~ 10^{-3} c, will create a "magnetic" looking perturbation affecting atomic spins.
- Crucially, if such a defect passes through the Earth, how would you know? And will you notice?

You need a time-synchronized network of sensitive probes that can detect the event in different locations. Domain walls will be an especially suitable "target".

Signal of axion-like domain wall

Consider a very light complex scalar field with Z_N symmetry:

$$\mathcal{L}_\phi = |\partial_\mu \phi|^2 - V(\phi); \quad V(\phi) = \frac{\lambda}{S_0^{2N-4}} \left| 2^{N/2}\phi^N - S_0^N \right|^2$$

Theory admits several distinct vacua, $\phi = 2^{-1/2} S \exp(ia/S_0)$

$$S = S_0; \;\; a = S_0 \times \left\{ 0; \; 2\pi \times \frac{1}{N}; \; 2\pi \times \frac{2}{N}; \dots \; 2\pi \times \frac{N-1}{N} \right\}$$

Reducing to the one variable, we have the Lagrangian

$$\mathcal{L}_a = \frac{1}{2}(\partial_\mu a)^2 - V_0 \sin^2\left(\frac{Na}{2S_0}\right)$$

that admits domain wall solutions

$$a(z) = \frac{4S_0}{N} \times \arctan\left[\exp(m_a z)\right]; \quad \frac{da}{dz} = \frac{2S_0 m_a}{N\cosh(m_a z)}$$

$$\rho_{\rm DW} \le \rho_{\rm DM} \Longrightarrow \frac{S_0}{N} \le 0.4 \;\text{TeV} \times \left[\frac{L}{10^{-2}\;\text{ly}} \times \frac{\text{neV}}{m_a}\right]^{1/2}$$

If on top of that *a*-field has the axion-type couplings, there will be a magnetic-type force on the spin inside the wall, $H_{\rm int} = \sum_{i=e,n,p} 2 f_i^{-1} \nabla a \cdot \mathbf{s}_i$

Network of Magnetometers

- For alkali magnetometers, the signal is

$$\mathcal{S} \simeq \frac{0.4\,\mathrm{pT}}{\sqrt{\mathrm{Hz}}} \times \frac{10^9\,\mathrm{GeV}}{f_{\mathrm{eff}}} \times \frac{S_0/N}{0.4\,\mathrm{TeV}} \times \left[\frac{m_a}{\mathrm{neV}}\frac{10^{-3}}{v_\perp/c}\right]^{1/2}$$

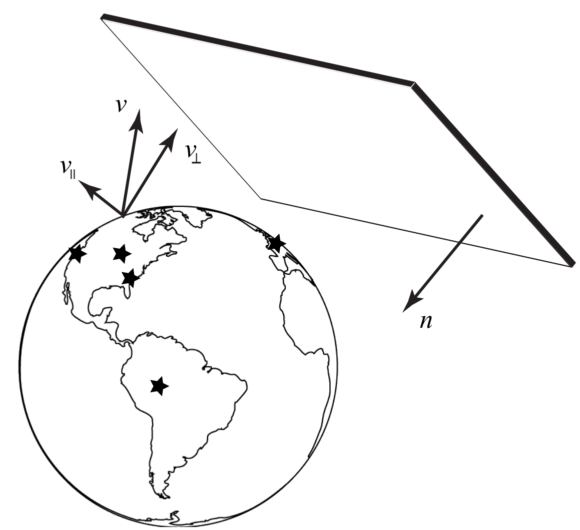
$$\leq \frac{0.4\,\mathrm{pT}}{\sqrt{\mathrm{Hz}}} \times \frac{10^9\,\mathrm{GeV}}{f_{\mathrm{eff}}} \times \left[\frac{L}{10^{-2}\ \mathrm{ly}}\frac{10^{-3}}{v_\perp/c}\right]^{1/2},$$

- For nuclear spin magnetometers, the tipping angle is

$$\Delta\theta = \frac{4\pi S_0}{v_\perp N f_{\mathrm{eff}}} \simeq 5\times 10^{-3}\,\mathrm{rad}\times\frac{10^9\,\mathrm{GeV}}{f_{\mathrm{eff}}}\times\frac{10^{-3}}{v_\perp/c}\times\frac{S_0/N}{0.4\,\mathrm{TeV}}$$

- It is easy to see that one would need >5 stations. 4 events would determine the geometry, and make predictions for the 5th, 6th etc…

* *Nobody has ever attempted this before*



Possible signatures with gravitational wave detectors.

Considering the case of monopoles interacting with an atom via a baryonic portal of $\frac{\phi_1 \partial_\mu \phi_2}{M_*^2}(\bar{n}\gamma_\mu n + \bar{p}\gamma_\mu p)$ type, I have an estimate for an additional acceleration created *during* the TD passing,

$$\Delta a \sim \frac{\rho_{DM} v}{M_*^2 m_p} \left(\frac{L}{d}\right)^3 \sim \frac{\rho_{DM} v}{M_*^2 m_p} \left(\frac{V^2 T}{d}\right)$$

Taking a TeV for the scale of the coupling one arrives to

$\Delta a \sim 10^{-4}$ m/sec^2 × (1m/d)

If d ~ L_{arm} for LIGO ~ 3 km, T ~ 1 yr then

Strain ~ 10^{-16} Hz$^{-1/2}$

and the effective frequency ~ 1/$t_{crossing}$ ~ 100 Hz

This is very realistic, as searches for "grav bursts" reached ~ 10^{-20}Hz$^{-1/2}$

Possible signature with atomic clocks

A. Derevianko, MP (*work in progress*)

Consider an operator $\frac{\phi^2}{M_*^2} m_e \bar{e} e$ that "renormalizes" the mass of an electron once an atom is inside a TD. Because of the quadratic nature of the coupling M_* can be quite low and at a ~ TeV. (There is a huge issue with naturalness of light ϕ, as always]

- The atomic frequencies will shift – temporarily – and in a different way for e.g. clocks on optical and microwave transitions.
- If the $\delta\omega/\omega$ is shifted very briefly, current searches of $d\alpha/dt$ will not catch it as they integrate over a long time.
- Achieving sensitivity to $\delta\omega/\omega$ (1 sec crossing) ~ 10^{-14} seems possible, which will translate to $M_* \sim 10^{12}$ GeV sensitivity.

Take home message:

Current technologies *allow* probing areas of the parameter space of TD DM, that are currently not ruled by astrophysics, collider constraints, or the energy density budget.

By creating a network of magnetometers, and using the existing networks of atomic clocks and GW detectors in a slightly different regime, one can make an interesting step forward in constraining/probing TD DM.

Future direction

- Working out a plausible theoretical framework that creates enough topological defects around us would be a plus.
- Generalization to other types of interaction. Going from spin to frequency, means switching from *magnetometers* to *atomic clocks*.
- Learn from LIGO + friends about strategies of detecting transients. Use existing searches to constrain TD DM (may be not possible to do well – v=1 is always assumed in LIGO type searches)
- Experimental developments: GNOME proposal (Global Network of Magnetometers for studies of Exotic physics).

Conclusion

- We do not know what DM is – it is worth keeping our options open and explore opportunities where significant progress can be made

- Topological defect DM is a suggestion that may be some fraction of the observable "missing energy" comes in form of the extended objects – monopoles, strings or domain walls. At these stage it is not competitive to other theoretical ideas (WIMPs, super-WIMPs, super-cool DM like axions), because we do not have a very good understanding of its abundance.

- The signatures are unusual – transient effects via TD interactions with spin, mass, energy levels. Network of GW detectors, atomic clocks and magnetometers can search for such transient effects.

- Domain walls will have especially unmistakable signature, and we showed that atomic magnetometers can have enough sensitivity for detection.