Broadening the scope of Dark Matter searches

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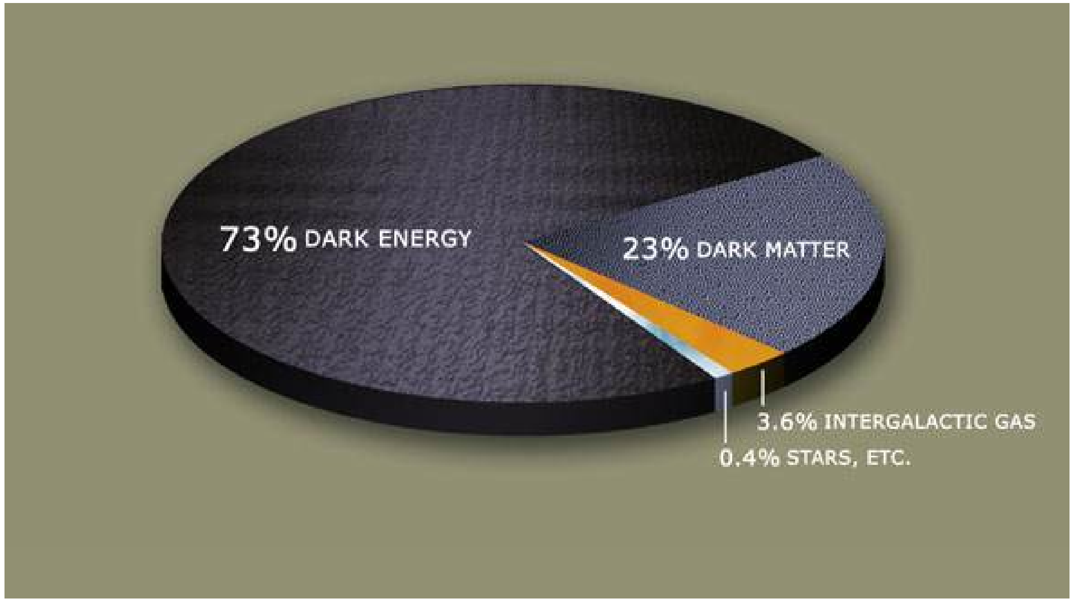
Big Questions in Physics



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

Can we detect it?

What is the space of theoretical possibilities for dark matter?

Outline of the talk

1. Intro.
2. Using the dark matter experiments to search for other things:
   i. Solar exotics
   ii. Absorption of bosonic super-WIMPs
   iii. Elastic scattering of non-standard neutrinos.
3. Producing and detecting MeV-scale DM.
4. Expanding the search for dark matter beyond particle candidates:
   i. Macroscopic size dark matter objects
   ii. Transient effects due to dark matter. Networks of atomic clocks and magnetometers.
5. Conclusions

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**.

Signatures can be completely different. WIMPs are most realistic for discovery

Evolution of theoretical interest to DM

Mid 90's: In the 0^{th} approximation: SUSY neutralino as WIMPs and axion models as "super-cold" DM.

$\downarrow$

Last ~15 years – O(few 100) or more models of WIMPs (sometimes much simpler than MSSM neutralino), super-WIMPs, and super-cold DM are developed. Some models have a much *broader* observational consequences than "neutralinos and/or axions". Some have no *observable properties* other than gravitational interactions.

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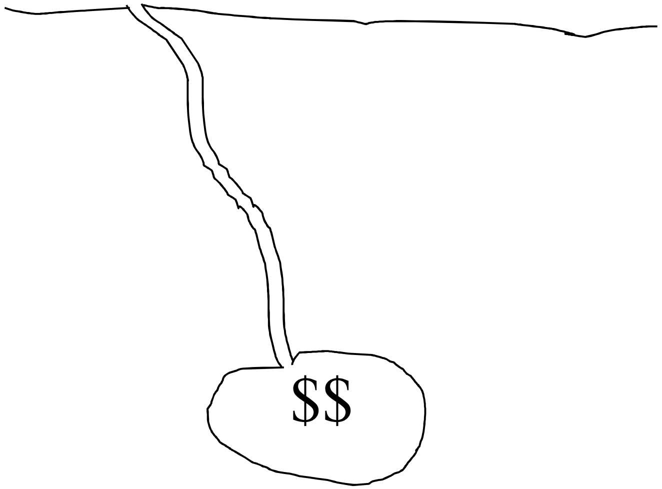
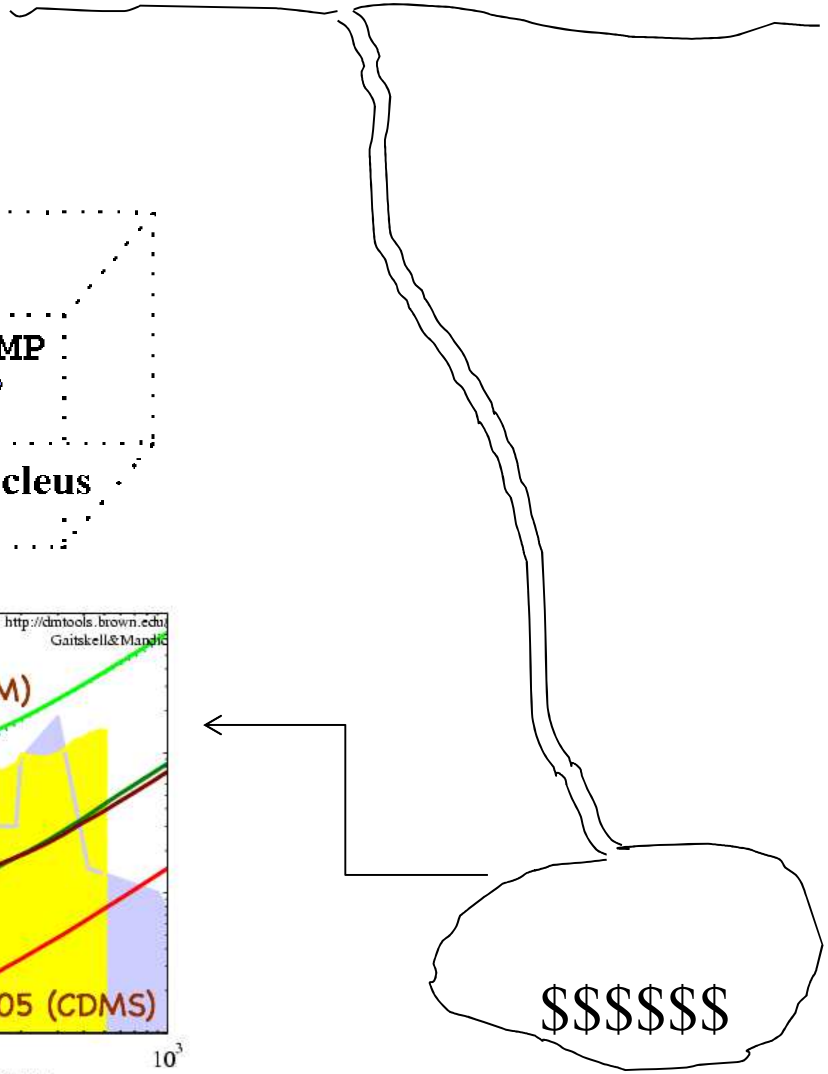
Future? Any model of DM that has a chance of satisfying abundance (+may be some theory priors of "technical naturalness") is worth searching for.

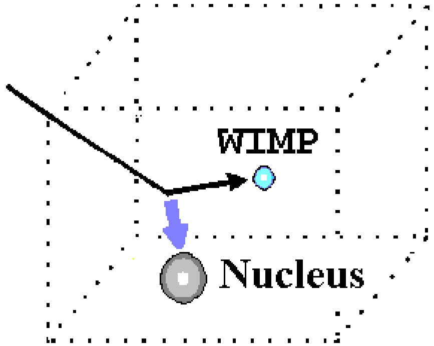
Currently all "direct DM detection" experiments search for the same thing

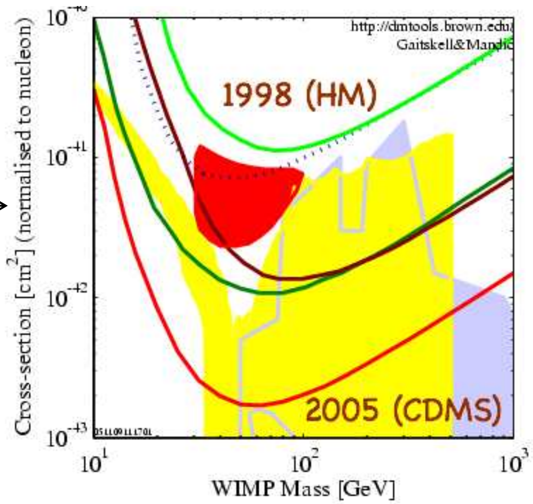
An average Dark Matter experiment



A more advanced DM







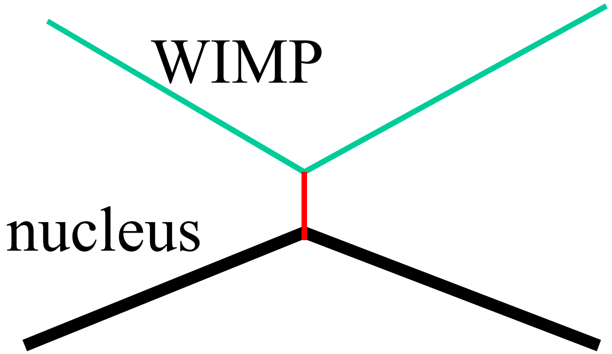
Diversifying physics output of direct detection exp's is needed !!!

Q1: High-energy physics experiments searching for BSM, search for wide classes of New Physics models. Could direct dark matter detection can [given considerable $ invested] also search for wider class of signatures covering not exclusively WIMP searches?

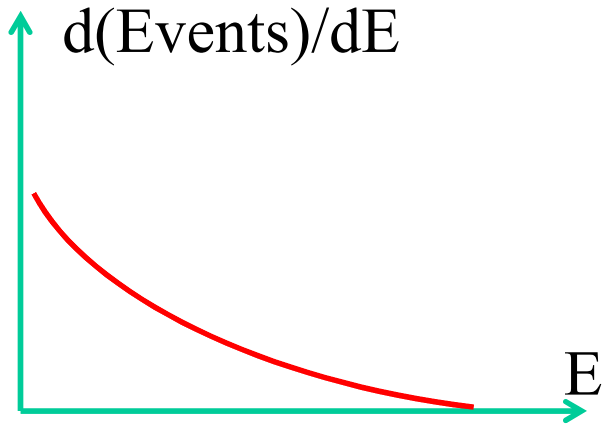
Q2: We are attracted to existing particle models of DM because of their relative simplicity. But it may not be what nature choses. Do we make enough efforts to search for DM with non-conventional experimental methods?

Example 1: New signal: absorption of super-WIMPs

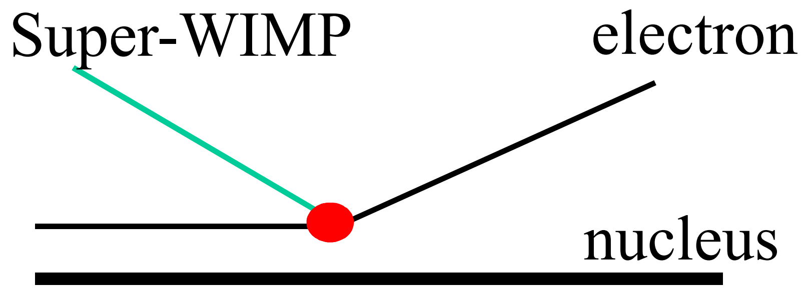
WIMP-nucleus scattering



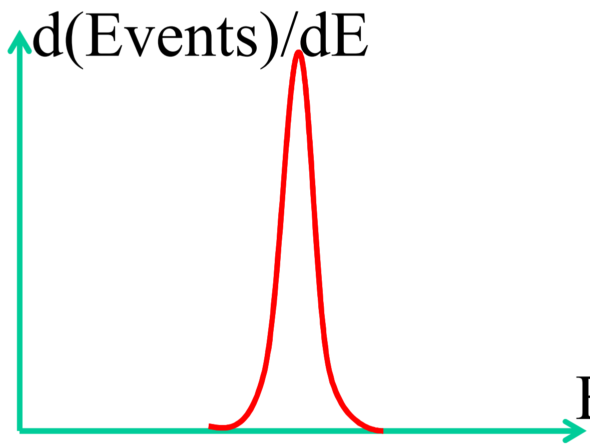
Signal: ionization + phonons/light



Atomic absorption of super-WIMPs



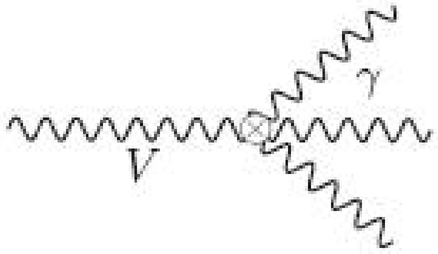
Ionization at $E=m_{superWIMP}$



(superweakly interacting)Vector Dark Matter

$$\mathcal{L} = -\frac{1}{4}V_{\mu\nu}^2 - \frac{\kappa}{2}V_{\mu\nu}F_{\mu\nu} + \mathcal{L}_{h'} + \mathcal{L}_{\dim>4},$$

- Vectors are long-lived if $m_V < 2\, m_e$. V has to decay to 3 photon via the light-by-light loop diagram:



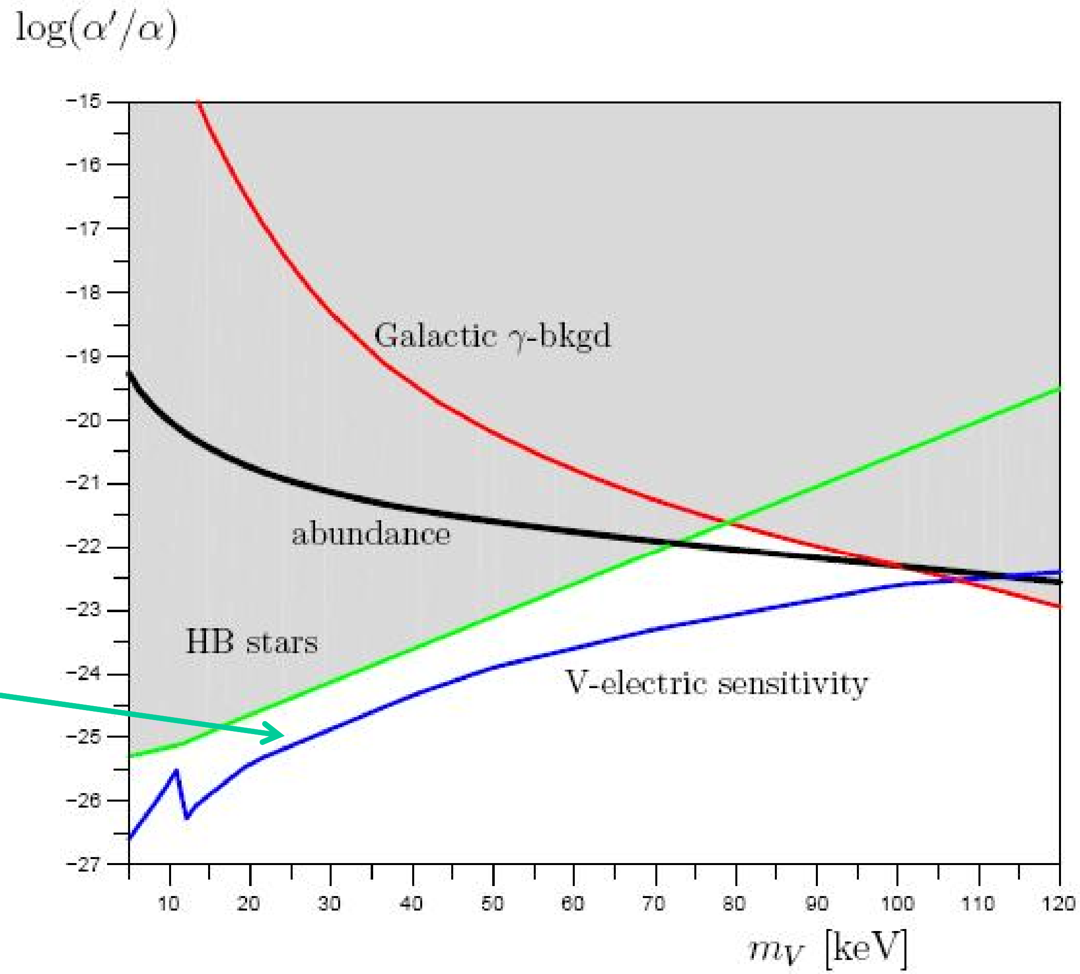
$$\Gamma = \frac{17\,\alpha^3\alpha'}{2^7 3^6 5^3 \pi^3}\,\frac{m_V^9}{m_e^8} \approx \left(4.70\times 10^{-8}\right)\,\alpha^3\alpha'\,\frac{m_V^9}{m_e^8}.$$

$$\tau_{\mathrm{U}}\Gamma_{V\to 3\gamma} \lesssim 1 \quad\Longrightarrow\quad m_V\,(\alpha')^{1/9} \lesssim 1\,\mathrm{keV}\ .$$

The γ-background constraints are weak. (No monochromatic lines)

Absorbing Dark Photon DM

Very “approximate”, proper Experimental analysis is needed



Direct detection search of Vector super-WIMP is competitive with other constraints. MP, Ritz, Voloshin, 2008. See also Postma, Redondo, 2008 + 1 more recent paper by the UCLA group.

- Searches for “odd lines” in electron recoil was performed by e.g. CDMS, EDELWEISS, CoGeNT (but only in the limited range of energies up to ~ 10 keV)

- It would be nice to extend the analysis to a wider range
  (e.g. 0-1 MeV range).

Example 2: dark photons from the Sun

- Should very light particles other than neutrino exist (axions; sub-keV dark photons etc) they can be produced by the Sun, and searched for with various types of "helioscopes"

- Recently, we (An, Pradler, MP) have re-derived the production of the light dark photons in stars (previous analyses have miscalculated it by (many!) orders of magnitude).

- We have shown that *low-threshold dark matter detectors are world's most sensitive dark photon helioscopes*.

In-medium emission of light dark vectors

A "Stuckelberg" mass vector decouples in the limit $m_V \rightarrow 0$

$$\mathcal{L}_{\rm int} = -\frac{\kappa}{2} F_{\mu\nu} V^{\mu\nu} + e J^\mu_{\rm em} A_\mu \xrightarrow{\text{on-shell V}} \mathcal{L}_{\rm int} = -\kappa m_V^2 A_\mu V^\mu + e J^\mu_{\rm em} A_\mu .$$

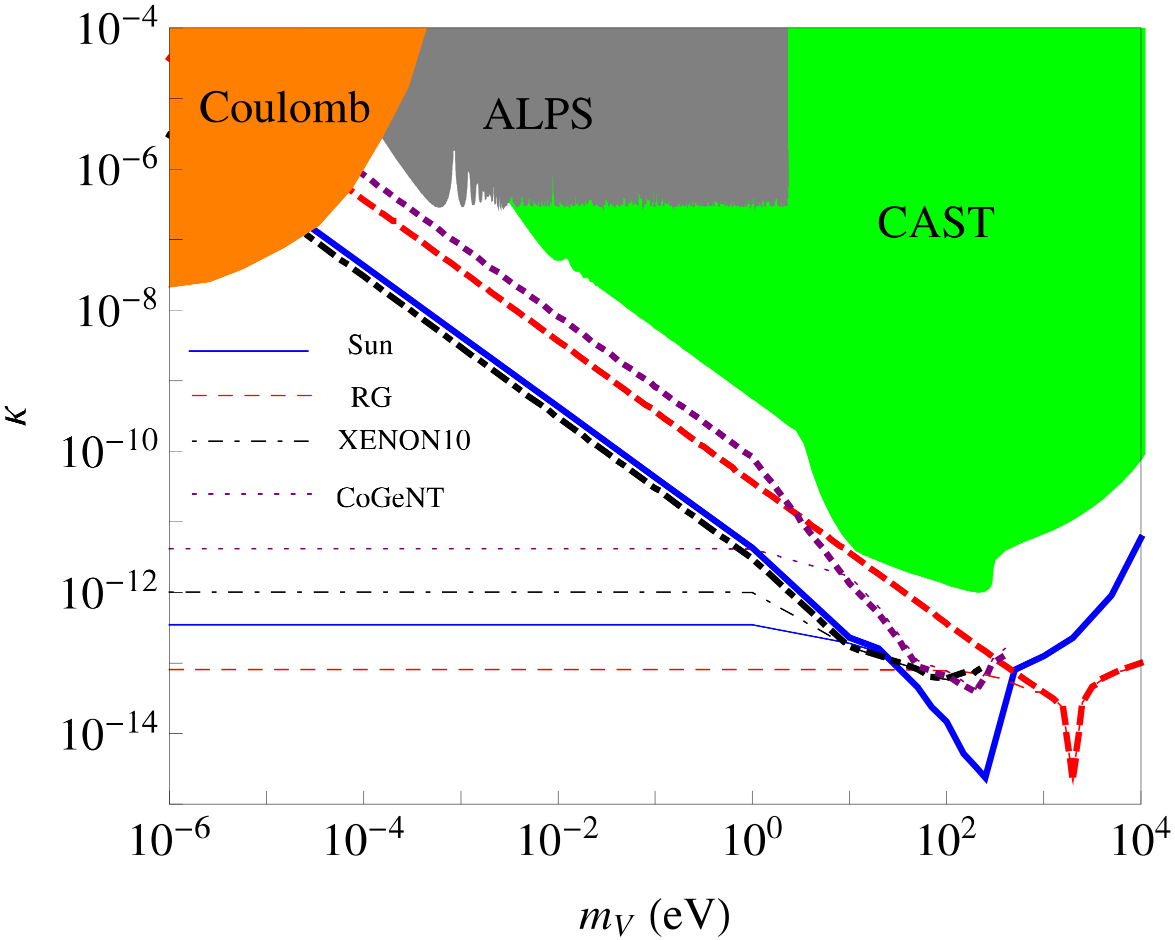
It is clear that the emission will be suppressed if the plasma frequency ω_p is much larger than m_V. This has lead to an incorrect statement in the literature that the Emission Rate is suppressed by $(m_V/\omega_p)^4$.

We have shown that for the transverse modes

Γ_T scales as $(m_V/\omega_p)^4$ in medium and as $(m_V/\omega_p)^0$ in vacuum

For the Longitudinal modes $\Gamma_L \sim (m_V/\omega_p)^2$, *both in medium and vacuum*! A whole experimental program of so-called light-shining-through-walls (LSW) was using stellar limits that were incorrectly relaxed by 10 orders of magnitude at $m_V \sim 10^{-3}$ eV…

Limits on Dark Photons



Constraint from the ionization at Xenon10 surpasses even very strong constraints from stellar cooling (also derived by our group)

An, MP, Pradler, PRL 2013

Example 3:

Detecting non-standard solar neutrino oscillations using WIMP detectors

MP 2011

Harnik, Kopp, Machado 2012

Pospelov, Pradler 2012

Pospelov, Pradler *to appear*

Probing non-standard ν physics with DM detectors

In recent years a lot of *man*hours* was spent on the discussion of possible signals (keV-scale energy deposition) observed by some "direct DM detection" experiments. 99% of these discussions is inevitably centered around: *is it WIMP or is it background*? Could it be *anything else* that leads to O(keV) scale energy deposition? My answer: it could be different *new physics*, including solar neutrinos

Scattering of ^{8}B neutrinos is very similar in shape to many "DM signals"… but about 10^{-4} from what is "needed". But a new state with stronger-than-weak elastic scattering rate can appear:

Sun

^{8}B: $\nu_{SM} \rightarrow \nu_{\text{"Baryonic"}}$

Earth

The model will be interesting for "direct detection" if one can

1. Enhance the coherent scattering rate by $\sim 10^3$-10^4
2. Hide this enhancement from the solar ν experiments.

The “baryonic neutrino” model

- Consider a new “neutrino-like” particle coupled to baryonic currents:

$$\mathcal{L} = -\frac{1}{4}V_{\mu\nu}^2 + \frac{1}{2}m_V^2 V_\mu^2 + \bar{\nu}_b\gamma_\mu(i\partial_\mu + g_l V_\mu)\ \nu_b + \sum_q \bar{q}(i\not{D}_{SM} + \frac{1}{3}g_b\gamma_\mu V_\mu)q + \mathcal{L}_m.$$

At the nucleon level we have a isosinglet vector current:

$$\frac{1}{3}V_\mu g_b \sum_q \bar{q}\gamma_\mu q \ \rightarrow\ g_b V_\mu(\bar{p}\gamma_\mu p + \bar{n}\gamma_\mu n) + \ldots$$

These properties *suppress* standard neutrino signals and *enhance* the elastic recoil. Let us introduce an analogue of Fermi constant:

$$\mathcal{L}_{NCB} = G_B \times \bar{\nu}_b\gamma_\mu\nu_b J_\mu^{(0)};\quad G_B = \frac{g_l g_b}{m_V^2} \equiv \mathcal{N} \times \frac{10^{-5}}{\mathrm{GeV}^2}.$$

Comments on the model

- "Stronger-than-weak" force, $N \sim 100$, implies $M_{mediator} << M_Z$. The most safe place to hide it is below 100 MeV, where one can have $g_B \sim (10^{-2}\text{-}10^{-3})$ e. This is not ruled out by any of the existing experiments.
- Anomaly can be cancelled by new matter at the weak scale.
- Neutrino mass is not a problem: one could use the same set of RH neutrinos to [economically] introduce the mass in both sectors,

$$\mathcal{L} = LH\mathbf{Y}N + \nu_{bL}\phi\mathbf{b}N + (h.c.) + \frac{1}{2}N\mathbf{M}_R N.$$

- Kinetic mixing will be developed radiatively, but $\kappa \sim$ loop factor, hence ok with recent constraints.
- The model has gauge anomaly (it is *B*, not *B-L*), but I can cancel it at the weak scale. I can leave it a-la Stuckelberg, and given a ~ 10 TeV cutoff, the tuning of m_V will be less than in the Higgs_{SM}

Oscillation of Solar neutrinos into ν_b

- Suppose the mass matrix is such that some part of the solar neutrinos oscillate into neutrino$_b$.

$$\Phi_{^8B} = (5.69^{+0.173}_{-0.147}) \times 10^6\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}, \quad E_{max,^8B} = 16.36\,\mathrm{MeV},$$

$$\Phi_{hep} = (7.93 \pm 0.155) \times 10^3\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}, \quad E_{max,hep} = 18.8\,\mathrm{MeV}.$$

At the Sun location we have ("+" is an appropriate mu-tau neutrino combination that participates in solar neutrino oscillations)

$$P_e(\mathrm{Sun}) \simeq \frac{1}{3}; \quad P_+(\mathrm{Sun}) \simeq \frac{2}{3}; \quad P_b(\mathrm{Sun}) = 0.$$

- At Earth's location one can easily have a more complicated mix:

$$P_b(\mathrm{Earth}) \simeq \sin^2(2\theta_b)\sin^2\left[\frac{\Delta m_b^2 L(t)}{4E}\right]$$

$$P_e(\mathrm{Earth}) \simeq \frac{1}{3}\left(1 - \sin^2(2\theta_b)\sin^2\left[\frac{\Delta m_b^2 L(t)}{4E}\right]\right)$$

$$P_+(\mathrm{Earth}) \simeq \frac{2}{3}\left(1 - \sin^2(2\theta_b)\sin^2\left[\frac{\Delta m_b^2 L(t)}{4E}\right]\right),$$

Effective interaction and enhancement of elastic channels

How much signal you would have is given by

Probability of oscillation * interaction strength

$$\mathcal{N}_{\text{eff}}^2 = \mathcal{N}^2 \times \frac{1}{2} \times \sin^2(2\theta_b),$$

Despite N being very large, say a 100 or a 1000, standard neutrino detectors will have hard time detecting neutrino$_b$ because

$$\frac{\sigma_{\nu_b-\text{Nucl}}(\text{elastic})}{\sigma_{\nu_b-\text{Nucl}}(\text{inelastic})} \sim \frac{A^2}{E_\nu^4 R_N^4} \sim 10^8,$$

The last formula is especially important because it allows to "hide" the enhancement of the elastic scattering from the dedicated neutrino experiments.

Signals of ν_b in "conventional" neutrino detectors

- Consider for example the deuteron breakup reaction, or Carbon excitation with subsequent energy release:

$$
\begin{aligned}
d + \nu_b &\rightarrow \nu_b + n + p \\
{}^{12}\mathrm{C} + \nu_b &\rightarrow \nu_b +{}^{12}\mathrm{C}^*(4.44\ \mathrm{MeV}) \rightarrow \nu_b +{}^{12}\mathrm{C} + \gamma
\end{aligned}
$$

Because of the properties of baryonic currents the hadronic amplitude is quadratic in neutrino energy, and the signal is quartic:

$$
\langle d|\exp(i\mathbf{q}\mathbf{r}^{(n)}) + \exp(i\mathbf{q}\mathbf{r}^{(p)})|np\rangle
$$

$$
= 2\langle d|np\rangle + i\mathbf{q}\cdot\langle d|\mathbf{r}^{(n)} + \mathbf{r}^{(p)}|np\rangle - \frac{q_k q_l}{2}\langle d|r_k^{(n)}r_l^{(n)} + r_k^{(p)}r_l^{(p)}|np\rangle = -\frac{q_k q_l}{4}\langle d|r_k r_l|np\rangle
$$

Elastic scattering signal

- There can be a considerable recoil signal from neutrino_b due to the coherent enhancement, and interaction strength that I took stronger-than-weak:

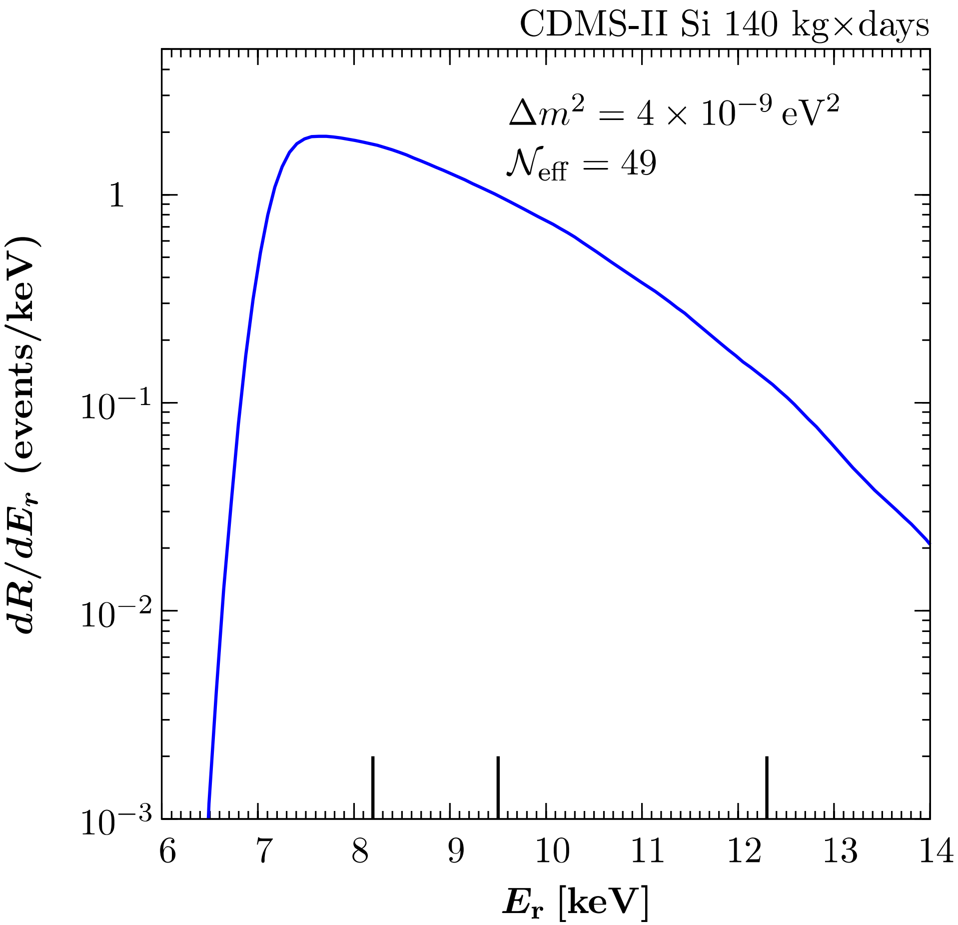
$$\frac{dR}{dE_r} \simeq \frac{A^2 m_N}{2\pi} \times \frac{1}{2}\sin^2(2\theta_b) G_B^2 \Phi_{s\mathrm{B}} \times I(E_r, E_0)$$

$$\simeq 85\, \frac{\text{recoils}}{\text{day} \times \text{kg} \times \text{KeV}} \times \left(\frac{A}{70}\right)^3 \times \frac{N_{\text{eff}}^2}{10^4} \times I(E_r, E_0).$$

Here $I(E_r)$ is the recoil integral given by

$$I(E_r, E_0) = \int_{E^{\min}(E_r)}^{\infty} dE \left(1 - \frac{(E^{\min})^2}{E^2}\right) \times f_{s\mathrm{B}}(E) \times 2\sin^2\left[\frac{\pi E_0}{E}\right]$$

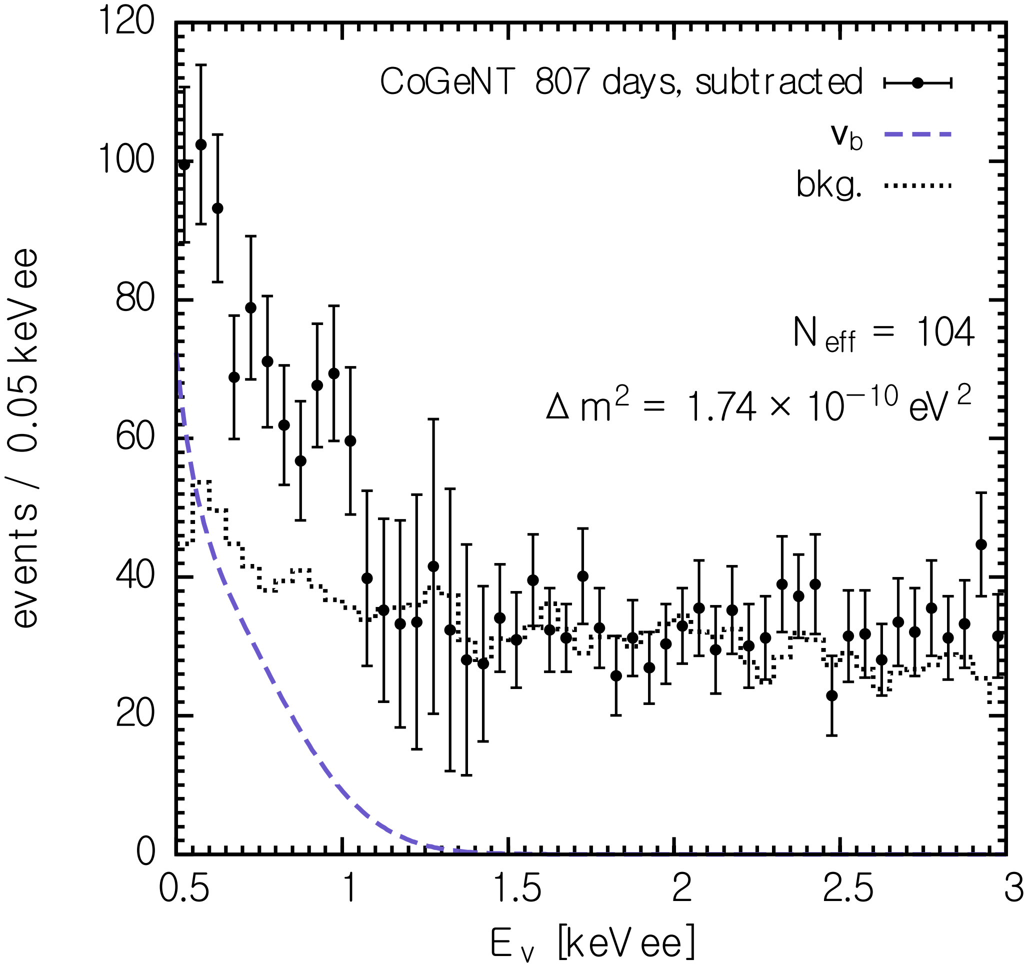
Fit to recent CDMS event



(MP, Pradler, to appear) Recent CDMS Si events fit into the story OK, just as they would for light DM models.

Recoil in Germanium detectors: CoGeNT, CDMS

MP, J. Pradler, 2012

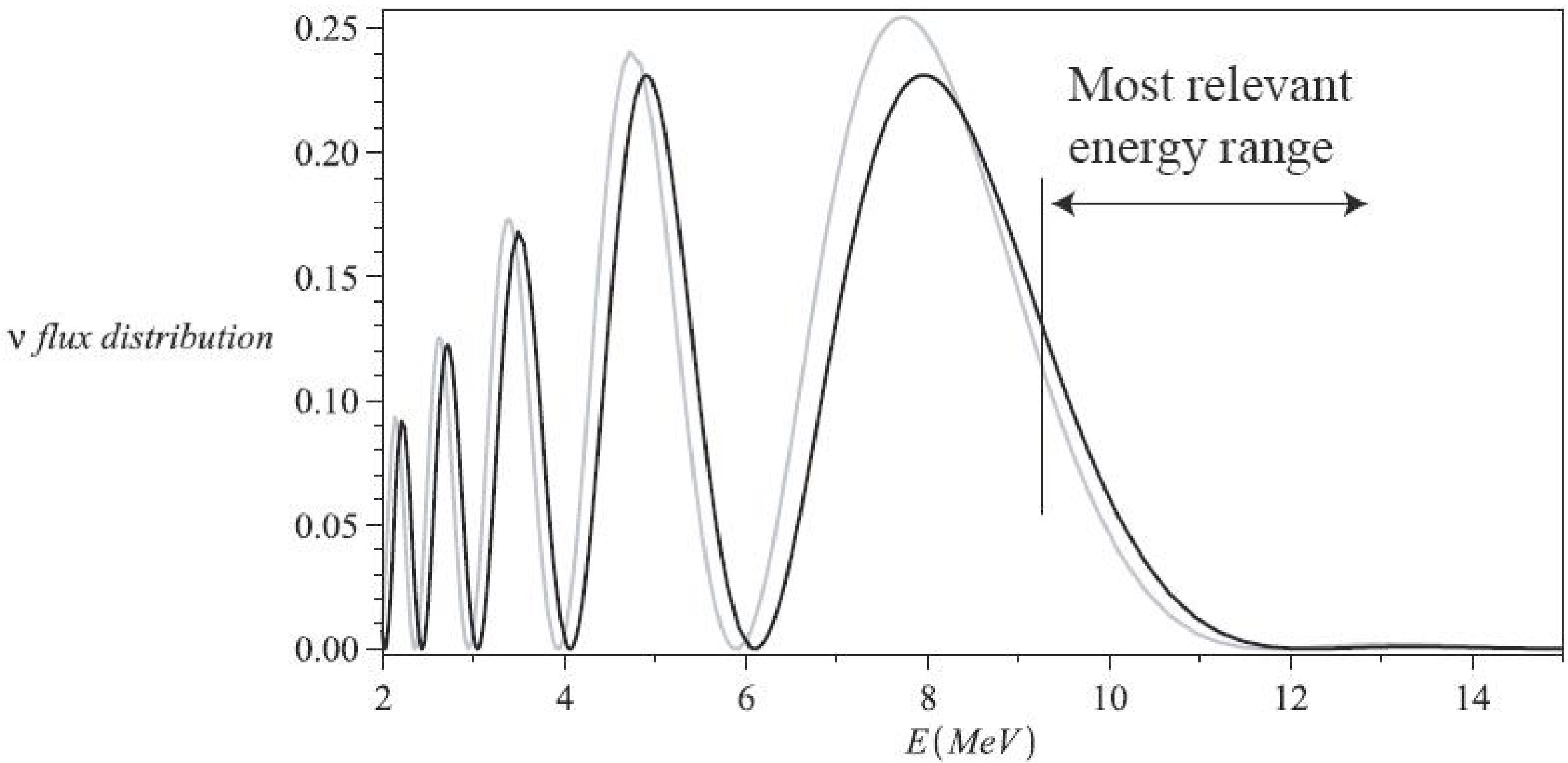


1. *You can put the model line through CoGeNT dots*. Probably not advisable as we learn that most of it [all of it?] is likely background

2. CDMS does not kill the "ν_b explanation" of CoGeNT

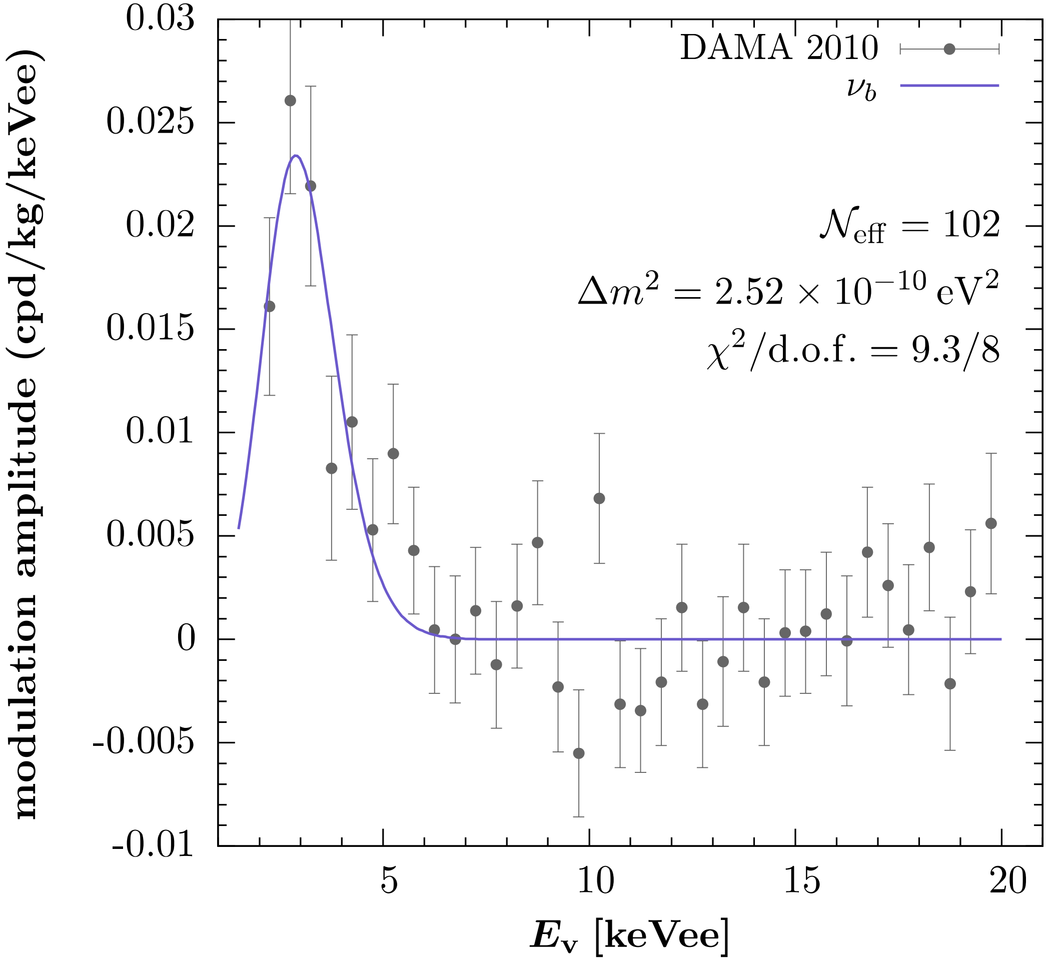
DAMA and "Just-So" phase reversal

- If oscillation length is comparable to the Earth-Sun distance, the phase can be reversed, and more neutrinos will arrive in July

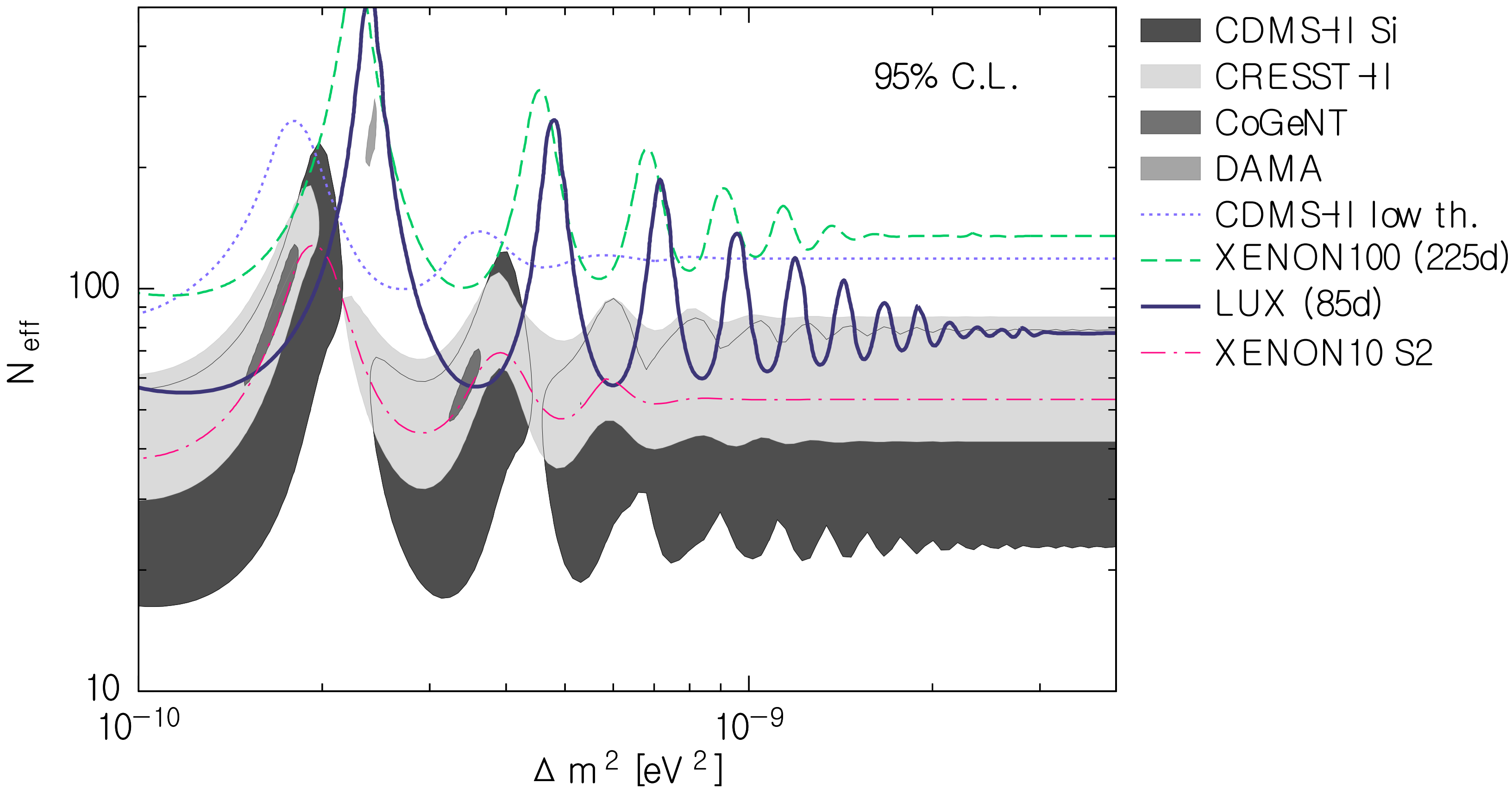


Fitting DAMA modulation amplitude

- Neglecting the phase offset of ~ 1 month, the fit of the ν_b model to DAMA modulation amplitude can be pretty decent. Fit to the phase has 1 month discrepancy.

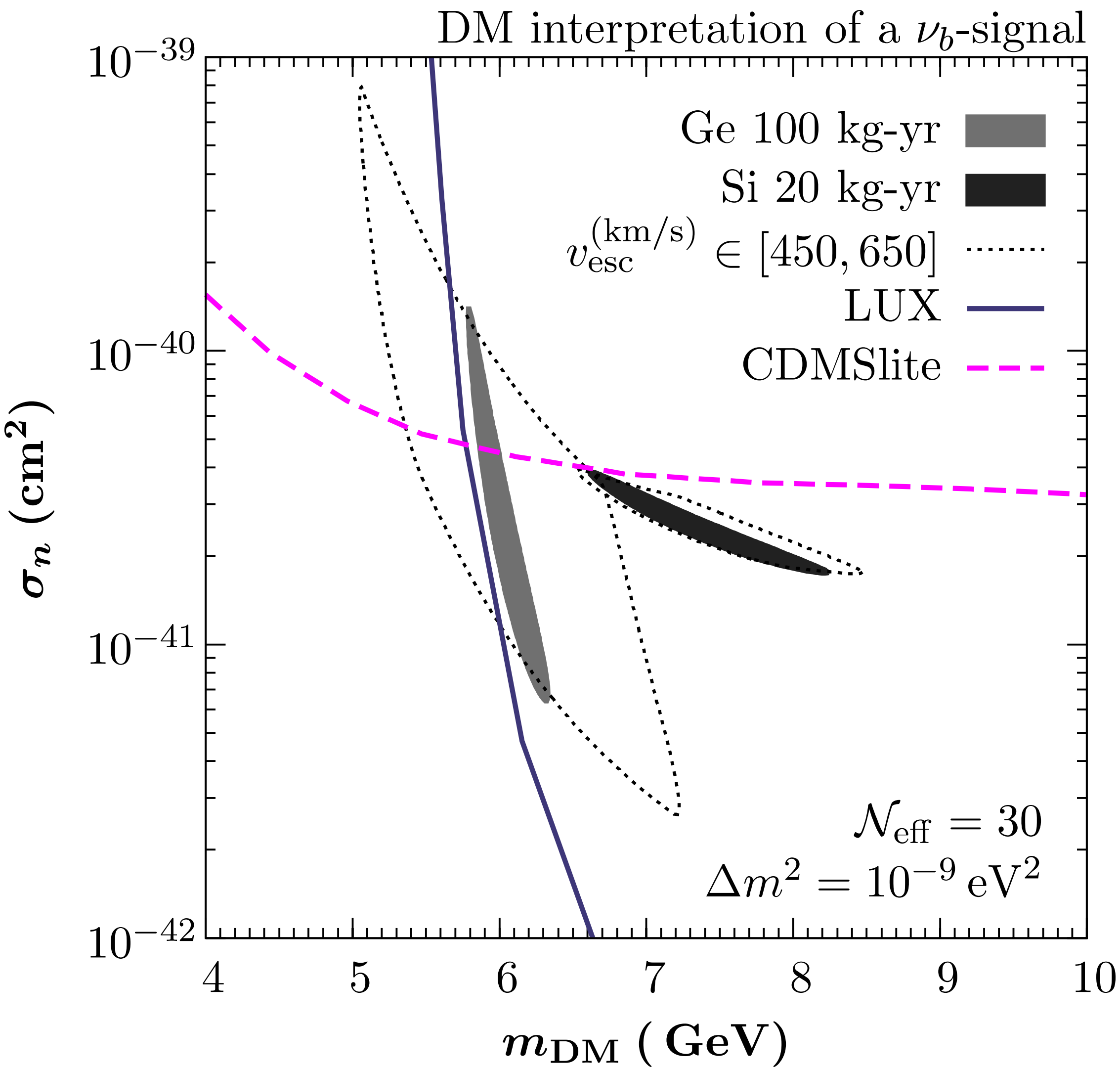


Putting things together on N_{eff}-Δm^2 plot



Strongest constraints on N_{eff} are from Xenon-10 ionization-only analysis – but it is the most uncertain as well. CRESST and CDMS excess events can be interpreted in this model without conflict Xe

"Baryonic" neutrino and "light" DM are hard to tell apart



Conclusions to Part I

1. There exists classes of new physics models – other than WIMPs – where [so-called] direct detection can make a decisive contribution. For example, very dark vectors as super-WIMP Dark Matter, dark photon flux from the Sun can be stringently limited by null results of ionization search.

2. Oscillation to "semi-sterile" neutrinos with enhanced interaction via baryonic current gives nuclear recoil that is very difficult to distinguish from ~5-7 GeV WIMP recoil. The model escapes other constraints, and speculatively, can be entertained as the origin of the excess events in CDMS Si, and CRESST without contradicting Xe-type experiments.

With lots of $$$ being funneled into the direct DM detection, it is important to broaden the scope of the program and start analyzing/constraining cases other than a "conventional" WIMP.

New ideas in DM searches

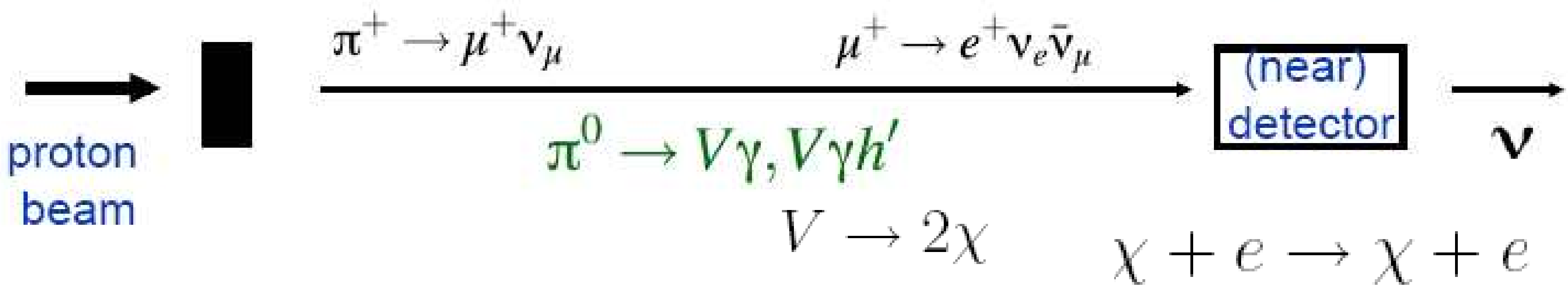
1. Producing and detecting MeV-scale DM particles in proton-on-target and electron-on-target experiments

2. Non-particle Dark Matter with atomic physics tools.

MeV dark matter in collisions

1. MeV DM models (and the whole concept of how make WIMPs light) are introduced by Boehm, Fayet
2. Unlike many 10-GeV-and-up WIMP models that can be studied via direct detection, O(MeV) scale DM models are difficult for direct detection as they carry no appreciable energy to deposit.
3. Solution: *make energetic DM particles* in the collisions of protons with a target and subsequent decay of mesons to DM, and *detect produced DM particles* via the (quasi)elastic NC scattering signature.
4. Realistic goal for many short-base line neutrino experiments like LSND, MiniBoone etc. Neutrino beams can be accompanied by the MeV DM beam. (Batell, MP, Ritz).
5. Strong constraints can be obtained that way, owing to the huge number of produced hadrons ($N_{\text{LSND pions}} \sim 10^{21}$).

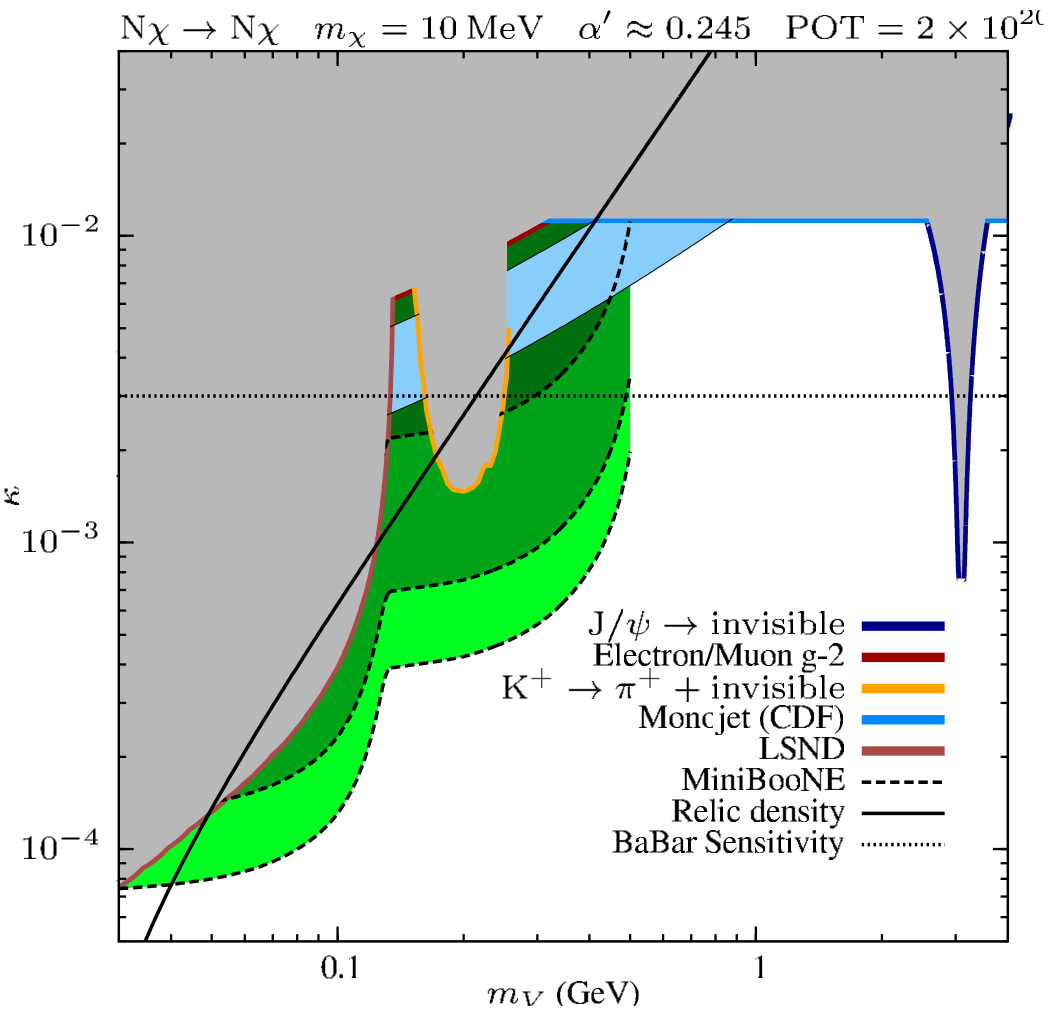
Neutrino beam set up can be accompanied by beam of *other* light neutral states. “Dark matter beam”



Probability of prompt decay of mediator-V into new dark states χ can be sizable.

Scattering within the detector can look like neutral current events, but being mediated by light vectors could be *larger* than weak scattering rates. E.g. LSND provides best constraints on MeV WIMPs

Existing constraints + possible reach of MiniBoone



DeNiverville et al., 2013. *New MiniBooNE (mini)-run will happen later this year to search for light dark matter !!!*

Electron beams + extra “near detector”

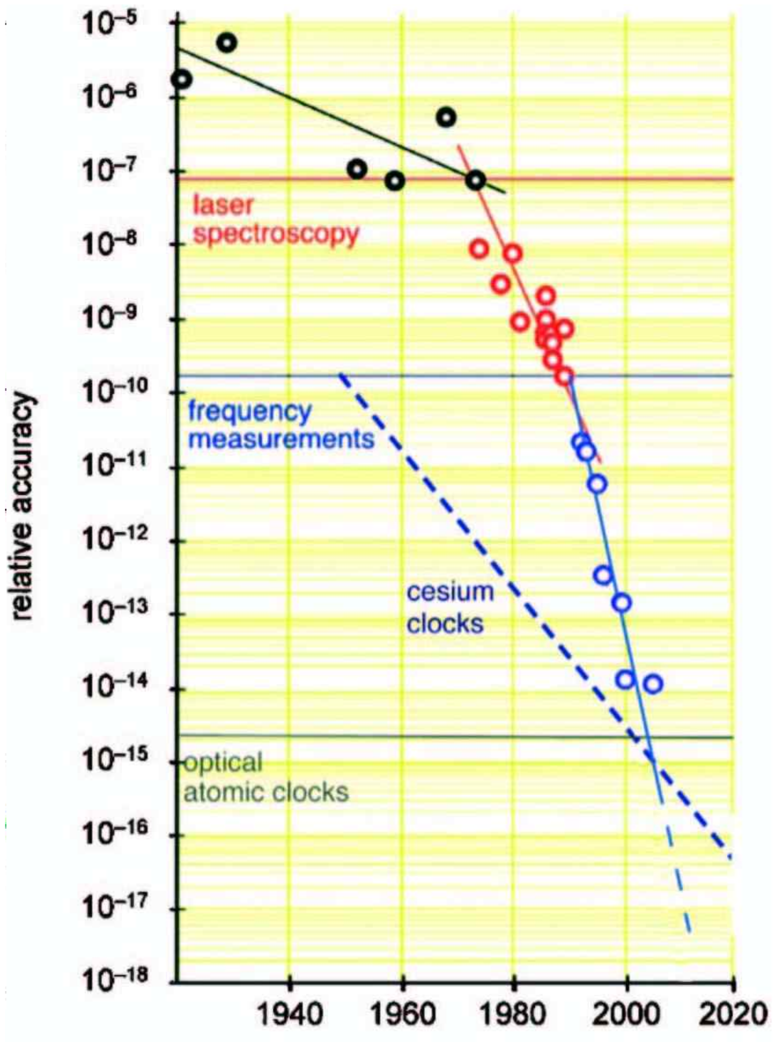
Electron beams have huge potential: no neutrino background. Needs a dedicated detector behind the beam dump. Sensitivity plot for 12 GeV beam + 10^{22} EOT Izaguirre, Krnjaic, Schuster, Toro 2013

Conclusion for Part II

Proton-on-target and electron-on-target appear to be the most promising way of searching for MeV-scale WIMP dark matter.

There will be dedicated searches done in the near future

Can the progress in AMO translate to new sensitive DM experiments?



Hansch's Nobel lecture 2005

There have been tremendous advances in the last ~15 yr in AMO physics. There is a lot of appetite for fundamental [cosmological] applications. So far being limited to search of "changing couplings", and to "Lorentz violation".

We propose to utilize it for searches of new types of dark matter that have macroscopic (e.g. 1 km) spatial extent.

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, $\phi = -v$ and at x = +infinity, $\phi = +v$, then a stable *domain wall* will form in between, e.g. $\phi = v \tanh(x\, m_\phi)$ with

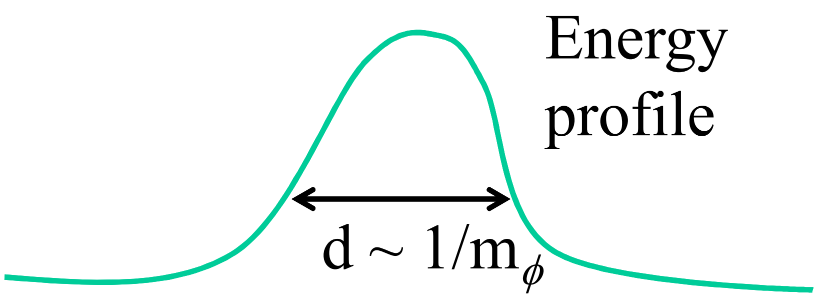
$m_\phi = \lambda^{1/2} v$

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.

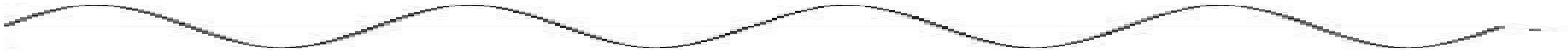
Axion DM: Light particles with huge number of particles per $(\text{w.l.})^3$ → the whole space is filled. Sinusoidal in time waves at $\omega = m_a \sim$ e.g. 10^{-5} eV. Average r.m.s amplitude, a ~ 100 eV, or so << EW scale.

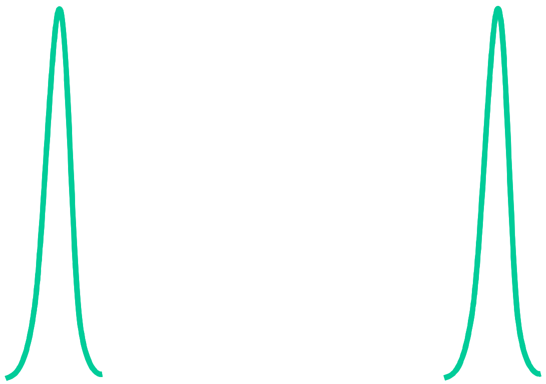
TD DM: A very shallow potential $V(\phi)$ can lead to an amplitude

$\phi_{max} = A \sim$ 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!

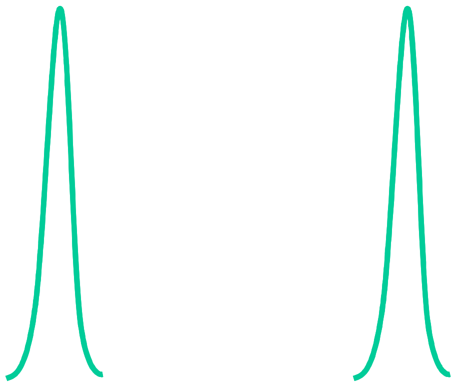
Comparison with WIMPs and axions

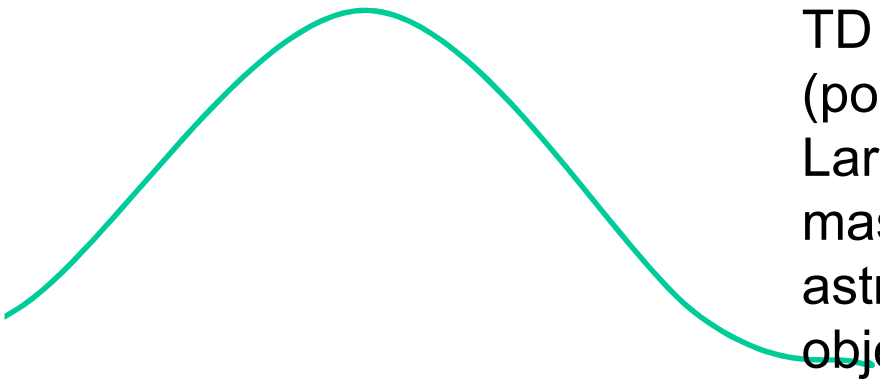
Axions – small amplitude but “no space” between particles





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

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

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

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

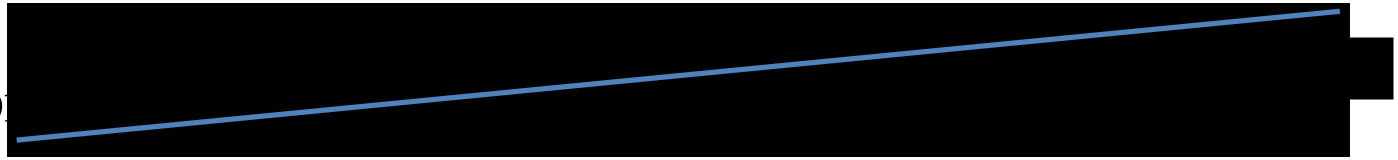
$$V^{loop}(\phi) = c^{loop}{}_0 + c^{loop}{}_1\phi + c^{loop}{}_2\phi^2 + \ldots.$$

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.

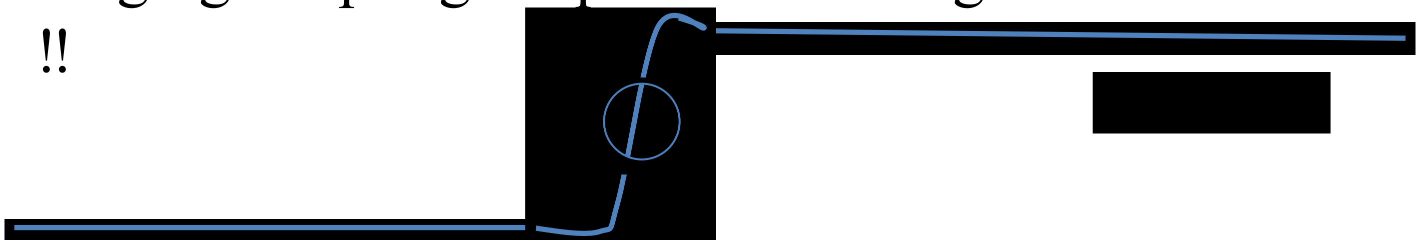
(* *But may be the approach idea of having rigid technical naturalness built in a model is not "quite" right, and we would miss out on interesting physics* *)

“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*, ! $f_i^{-1}\partial_\mu a\bar{\psi}_i\gamma_\mu\gamma_5\psi_i$
!
!
a-p



!
Similarly, existing terrestrial checks of $\Delta\alpha/\alpha$ 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

$v \sim 10^{-3}$ 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

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

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

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

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

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

Network of Magnetometers

- For alkali magnetometers, the signal is !

Exper. Sensitiv.
!
S ~ below fT/Hz

MP et al, PRL 2013

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

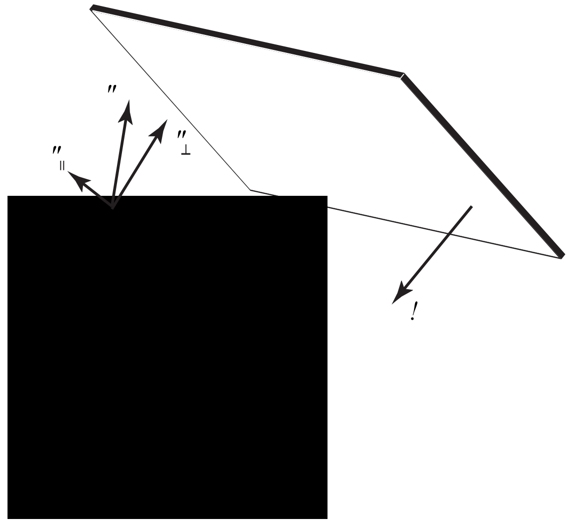
$$\leq \frac{0.4\,\mathrm{pT}}{\sqrt{\mathrm{Hz}}} \times \frac{10^9\,\mathrm{GeV}}{f_{\mathrm{eff}}} \times \left[\frac{L}{10^{-2}\,\mathrm{ly}}\,\frac{10^{-3}}{v_\perp/c}\right]^{1/2},$$

- 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 signature with atomic clocks

A. Derevianko, MP ~~(*work in progress*)~~ arXiv:1311.1244

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_* ~ 10^{12} GeV sensitivity.

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

Δa ~ 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$^{-1/2}$

Take home message for Part III

Current technologies *allow* probing areas of the parameter space of transient effects due to 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 DM composed of extended in space objects.