New Directions in Searches for Dark Matter beyond WIMPs

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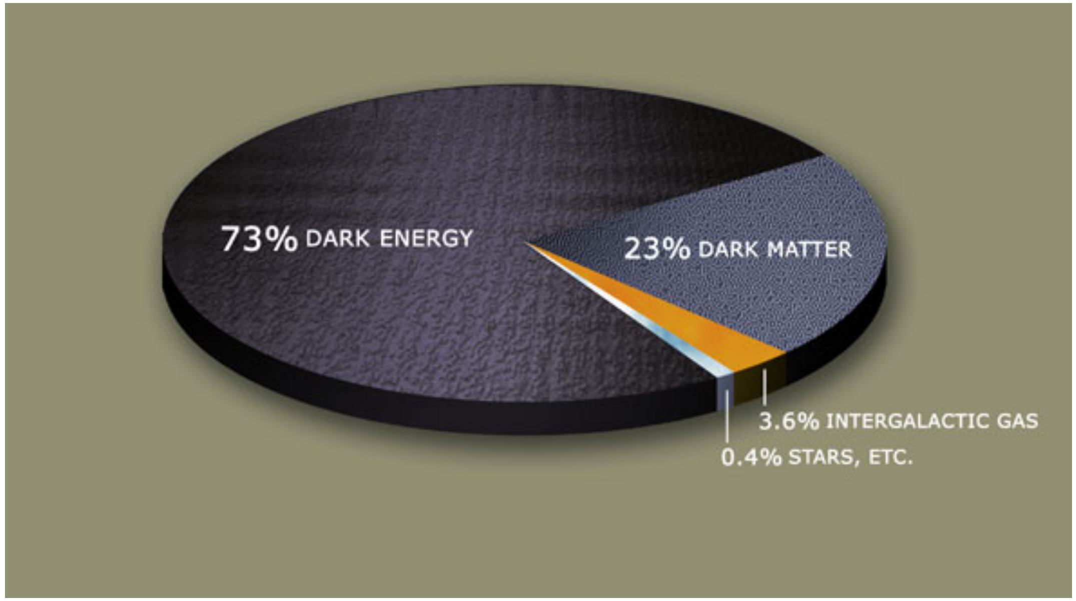
Outline of the talk

1. *Introduction. Many classes of dark matter.*
2. Particle dark matter just below the WIMP window (~ MeV DM).
3. Super-WIMP dark matter absorption signals.
4. Bosonic condensate dark matter.
5. Search for macroscopic size dark matter.
6. Conclusions.

Big Questions in Physics



"Missing mass" – what is it?

New particle, new force, …? *Both*? How to find out?

Challenges ?? Too many options for DM. In "direct detection" there is an extrapolations from ~ kpc scale (~ 10^{21} cm) down to 10^2 cm scale.

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**. (asymmetric WIMPs are a variation.)

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. $N_{DM}/N_{\gamma}\sim 10^{10}$. "Super-cool DM". Must be bosonic. Axions, or other very light scalar fields – call them **super-cold DM**.

Many reasonable options. *Signatures can be completely different.*

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.

↓

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.

↓

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

WIMP "lamp post"

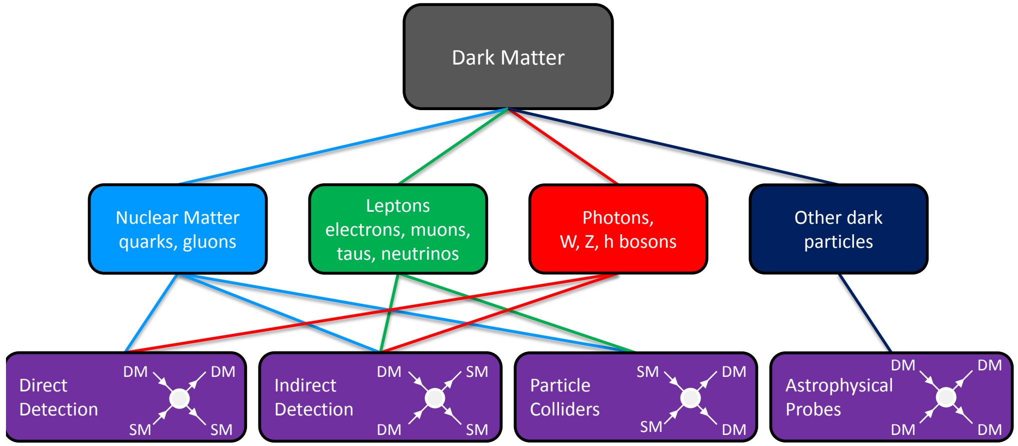
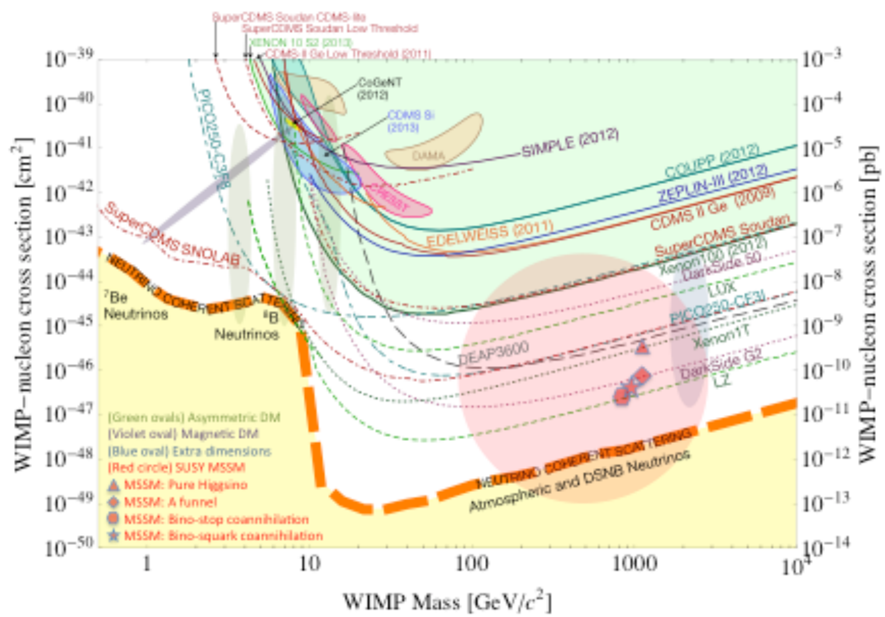
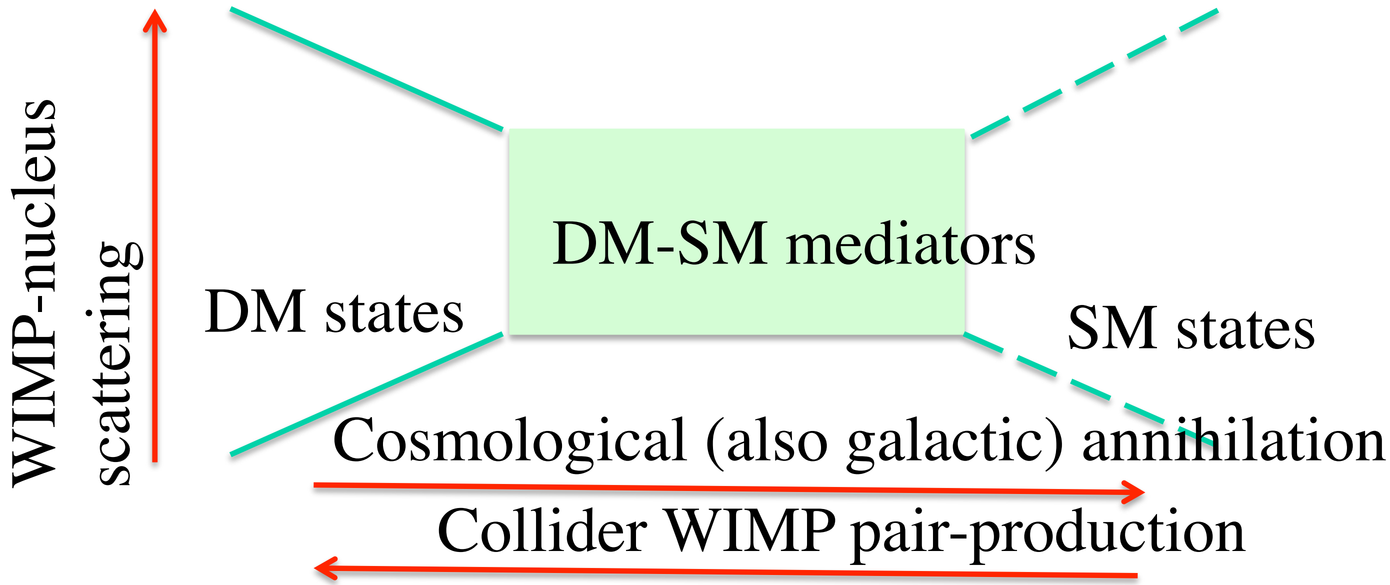


Figure 5. *Dark matter may have non-gravitational interactions with any of the known particles as well as other dark particles, and these interactions can be probed in several different ways.*



From the Snowmass 2013 summary, 1310.8327

WIMP paradigm



$$\langle \sigma_{ann} v \rangle \approx 1\text{pbn} \times c$$

1. What is inside this green box? I.e. what forces mediate WIMP-SM interaction?

2. Do sizable annihilation cross section always imply sizable scattering rate and collider DM production?

Are WIMP models predictive?

- The most "economical" WIMP models, e.g. new *"inert" EW multiplet*, *Higgs-mediated neutral scalar DM* etc, tend to be very predictive: $m_{WIMP} \rightarrow \sigma_{WIMP\text{-}atom}$
- Small enlargement of parameter space of models leads to the enormous range of possibilities for $\sigma_{WIMP\text{-}atom}$, including immeasurably small values (while maintaining correct abundance via annihilation)
- Consequently, there is no "no-loose theorem" when it comes to WIMPs, and even experimentalists' best efforts (e.g. reaching "neutrino floor") will not lead to "ruling out WIMPs as DM".
- So, let's try to get as much physics output as possible from our investment in the DM searches

Simplest models of Higgs mediation

Silveira, Zee (1985); McDonald (1993); Burgess, MP, ter Veldhuis(2000)

DM through the Higgs portal – *minimal model of DM*

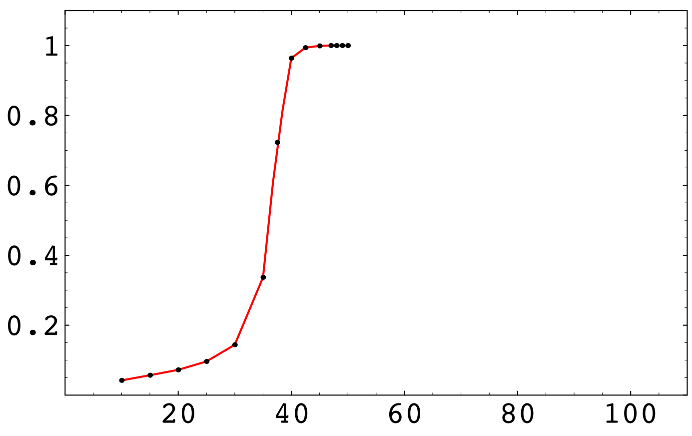
$$-\mathcal{L}_S = \frac{\lambda_S}{4}S^4 + \frac{m_0^2}{2}S^2 + \lambda S^2 H^\dagger H$$

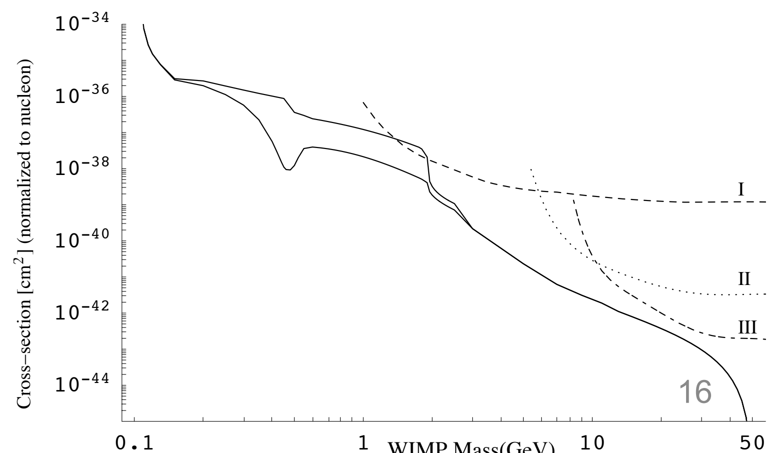
$$= \frac{\lambda_S}{4}S^4 + \frac{1}{2}(m_0^2 + \lambda v_{EW}^2)S^2 + \lambda v_{EW} S^2 h + \frac{\lambda}{2}S^2 h^2.$$

125 GeV Higgs is "very fragile" because its with is ~ y_b^2 – very small

$R = \Gamma_{\text{SM modes}}/(\Gamma_{\text{SM modes}}+\Gamma_{\text{DM modes}})$. Light DM can kill Higgs boson easily

(missing Higgs Γ: van der Bij et al., 1990s, Eboli, Zeppenfeld,2000)





Simple variations on the WIMP Higgs portal model

Post-minimal models = lots of possibilities

- Higgs-mediated fermionic dark matter λ and mediator ϕ:

$$\mathcal{L}_{\text{WIMP+mediator}} = y\,\phi\,\lambda\,[1\cos(\theta) + i\,\gamma_5\sin(\theta)]\,\lambda + A\,\phi\,(H^+H)$$

By taking angle from θ from 0 to $\pi/2$, the elastic scattering cross section goes down by ~ 6 orders of magnitude (MP, Ritz, 2011)

- *Secluded dark matter*:

$$\mathcal{L}_{\text{WIMP+mediator}} = y\,\phi\,\lambda\,\lambda + A\,\phi\,(H^+H)$$

What is the prediction for WIMP-nucleus direct detection scattering if $m_\phi < m_\lambda$ and $\lambda\lambda \rightarrow \phi\phi$ followed by ϕ decays?

Annihilation cross section is set by y coupling alone, and scattering is set by yA. **There is no prediction.** Can be as small as $10^{-60}\,\text{cm}^2$.
MP, Ritz, Voloshin, 2007

New lampposts in DM searches

- Producing and detecting MeV-scale DM particles in proton-on-target and electron-on-target experiments
- Searching for electron recoil (not nuclear) – extending the mass range of direct WIMP detection
- Non-particle Dark Matter with precision measurements.
- ….

With 50 orders of magnitude mass span just for particle DM, there got to be additional "windows of opportunity" for DM searches

MeV-scale WIMP Dark Matter

Neutral "portals" to the SM – an organizing principle

Let us *classify* possible connections between Dark sector and SM

$H^+H\ (\lambda\, S^2 + A\, S)$ Higgs-singlet scalar interactions

$B_{\mu\nu} V_{\mu\nu}$ "Kinetic mixing" with additional U(1)' group

(becomes a specific example of $J_\mu^i A_\mu$ extension)

$LH\, N$ neutrino Yukawa coupling, N – RH neutrino

$J_\mu^i A_\mu$ requires gauge invariance and anomaly cancellation

It is very likely that the observed neutrino masses indicate that Nature may have used the *LHN* portal…

Dim>4

$J_\mu^A\ \partial_\mu a\,/f$ axionic portal

……….

$$\mathcal{L}_{\rm mediation} = \sum_{k,l,n}^{k+l=n+4} \frac{\mathcal{O}_{\rm med}^{(k)} \mathcal{O}_{\rm SM}^{(l)}}{\Lambda^n},$$

Dark photon model (as possible DM-SM mediator)

(Holdom 1986; earlier paper by Okun')

$$\mathcal{L} = -\frac{1}{4}V_{\mu\nu}^2 - \frac{\kappa}{2}V_{\mu\nu}F^{\mu\nu} + |D_\mu \phi|^2 - V(\phi),$$

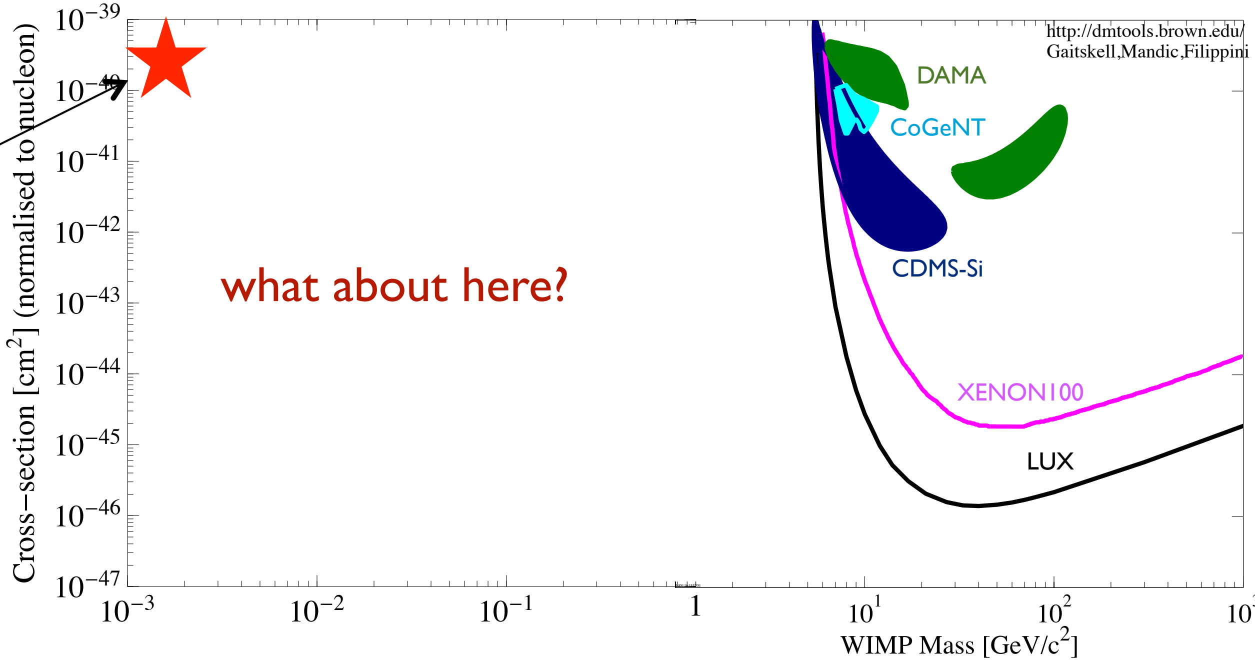
This Lagrangian describes an extra U(1)' group (**dark force, hidden photon, secluded gauge boson, shadow boson etc, also known as U-boson, V-boson, A-prime, gamma-prime etc**), attached to the SM via a vector portal (kinetic mixing). Mixing angle κ (also known as ε, η) controls the coupling to the SM. New gauge bosons can be light if the mixing angle is small.

Low-energy content: Additional massive photon-like vector V, and a new light Higgs h', both with small couplings.

Well over several hundred theory papers have been written with the use of this model in some form in the last six years

Light DM – direct production/detection

511 keV motivated



If WIMP dark matter is coupled to light mediators, the WIMP mass can be much lighter than Lee-Weinberg range, (Boehm, Fayet)

$$\mathcal{L} \supset |D_\mu \chi|^2 - m_\chi^2 |\chi|^2 - \frac{1}{4}(V_{\mu\nu})^2 + + \frac{1}{2} m_V^2 (V_\mu)^2 - \frac{\kappa}{2} V_{\mu\nu} F^{\mu\nu} + \dots$$

DM

mediation

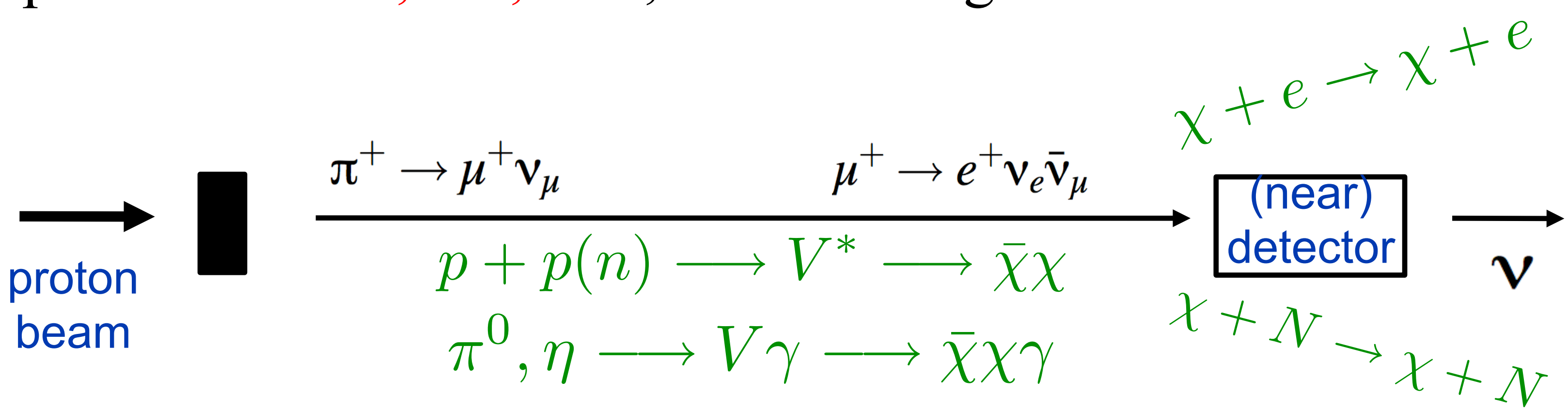
New efforts in Direct Detection with low energy deposition

- Experimental developments (e.g. DAMIC, NEWS,…)
- Xenon10 analysis of O(1) ionization electrons (Essig et al., PRL2012). Energy deposition > 13 eV.
- Theoretical/experimental ideas about extending sensitivity to 1 eV range and below (e.g. Graham et al, Hochberg et al., …)

On-going work, expect lots to discuss during this workshop.

Fixed target probes - Neutrino Beams

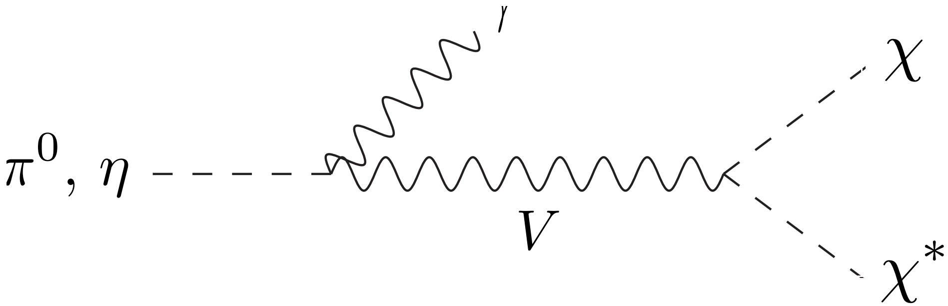
Proposed in Batell, MP, Ritz, 2009. Strongest constraints on MeV DM

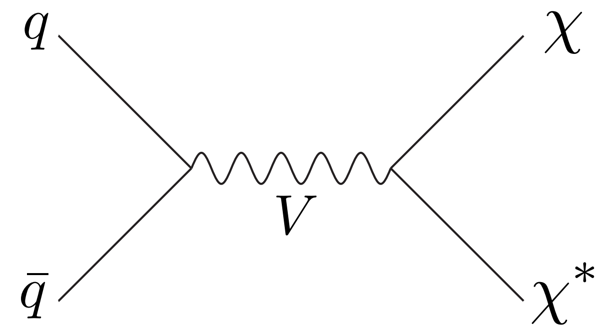


We can use the neutrino (near) detector as a dark matter detector, looking for recoil, but now from a relativistic beam. E.g.

T2K	MINOS	MiniBooNE
30 GeV protons	120 GeV protons	8.9 GeV protons
(➠ ~5x10^{21} POT)	10^{21} POT	10^{21} POT
280m to on- and off-axis detectors	1km to (~27ton) segmented detector	540m to (~650ton) mineral oil detector

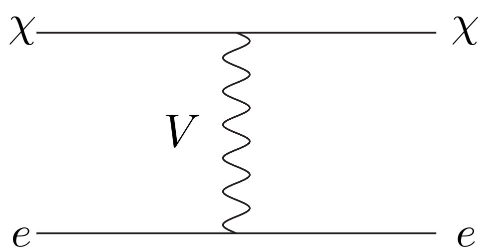
Light DM - trying to force the issue



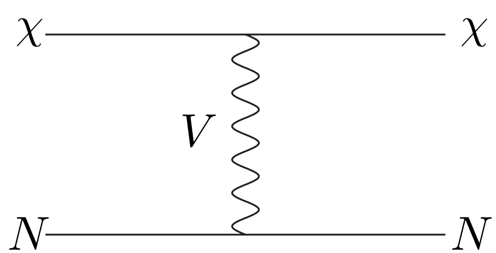


In the detector:

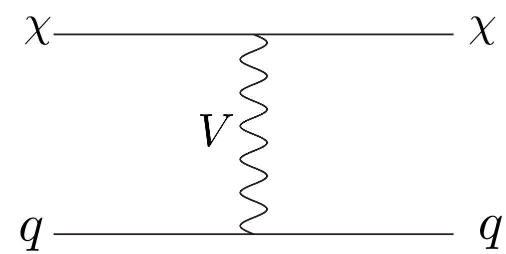
Elastic scattering on electrons



Elastic scattering on nucleons



Deep inelastic scattering



Same force that is responsible for depletion of χ to acceptable levels in the early Universe will be responsible for it production at the collision point and subsequent scattering in the detector.

Comparison of Neutrino and light DM

Neutrinos:

Production:

Strong scale $\sigma \sim 100$ mbn

Detection:

Weak scale $\sigma \sim G_F^2 E_{cm}^2$

Light WIMPs:

Production:

$\sigma \sim \sigma_{\mathrm{strong}} \times \varepsilon^2$

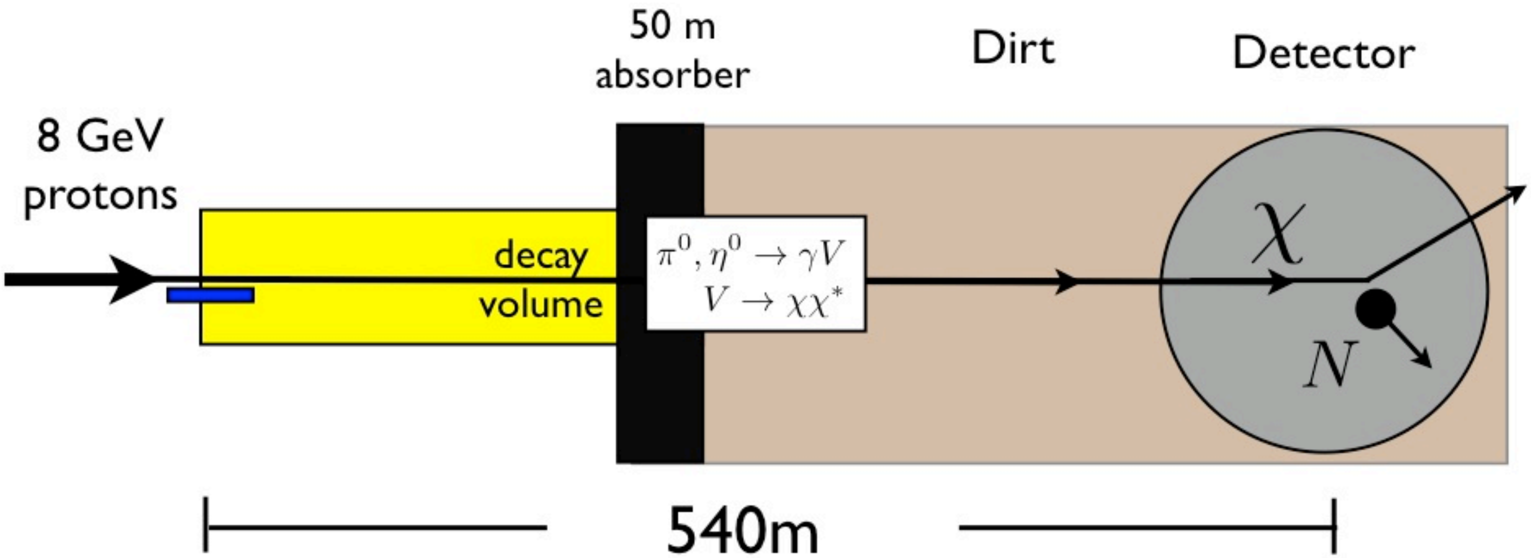
Detection:

Larger than weak scale!

Signals $\sim \sigma_{\mathrm{production}} \times \sigma_{\mathrm{detection}}$ can be of comparable strength

The reason for "stronger-than-weak" force for light dark matter comes from the Lee-Weinberg argument. (The weak-scale force will be *insufficient* in depleting WIMP DM abundance to observable levels if m_{DM}< few GeV. Therefore, stronger-than-weak force and therefore relatively light mediator is needed for sub-GeV WIMP dark matter).

Prospects in improving sensitivity: protons



MiniBoone has completed a long run in the beam dump mode, as suggested in [arXiv:1211.2258]

By-passing Be target is crucial for reducing the background (R. van de Water +…)

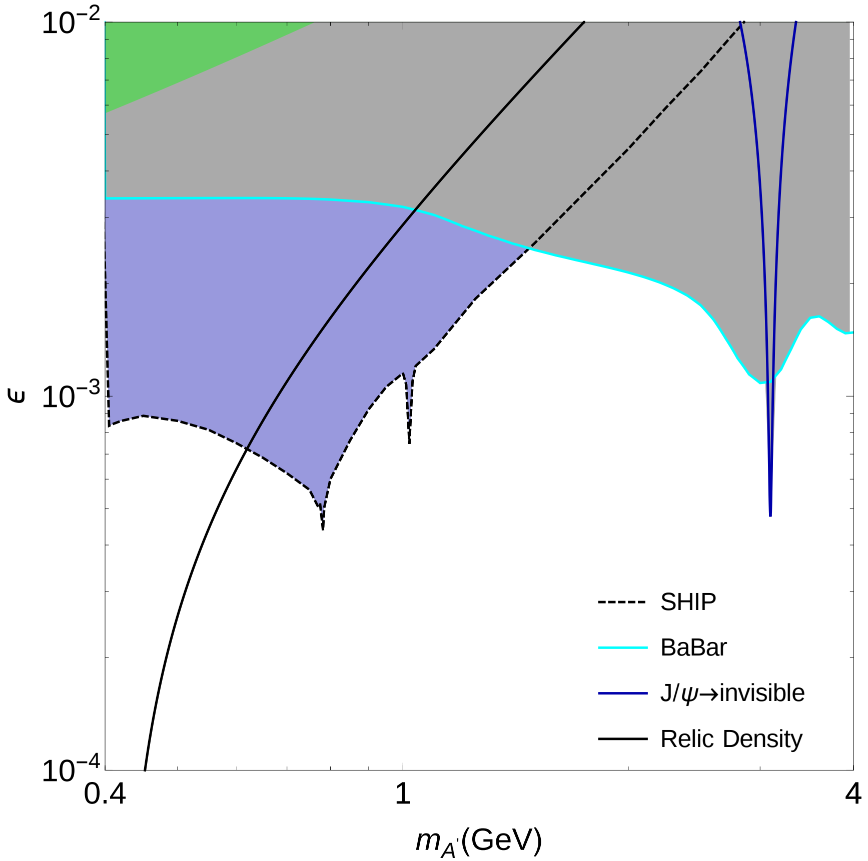
Timing is used (10 MeV dark matter propagates slower than neutrinos) to further reduce backgrounds

Future?? SHiP proposal at CERN

The sensitivity of SHiP tau neutrino detector to light DM scattering (400 GeV beam dump; >10^{20} protons on target)

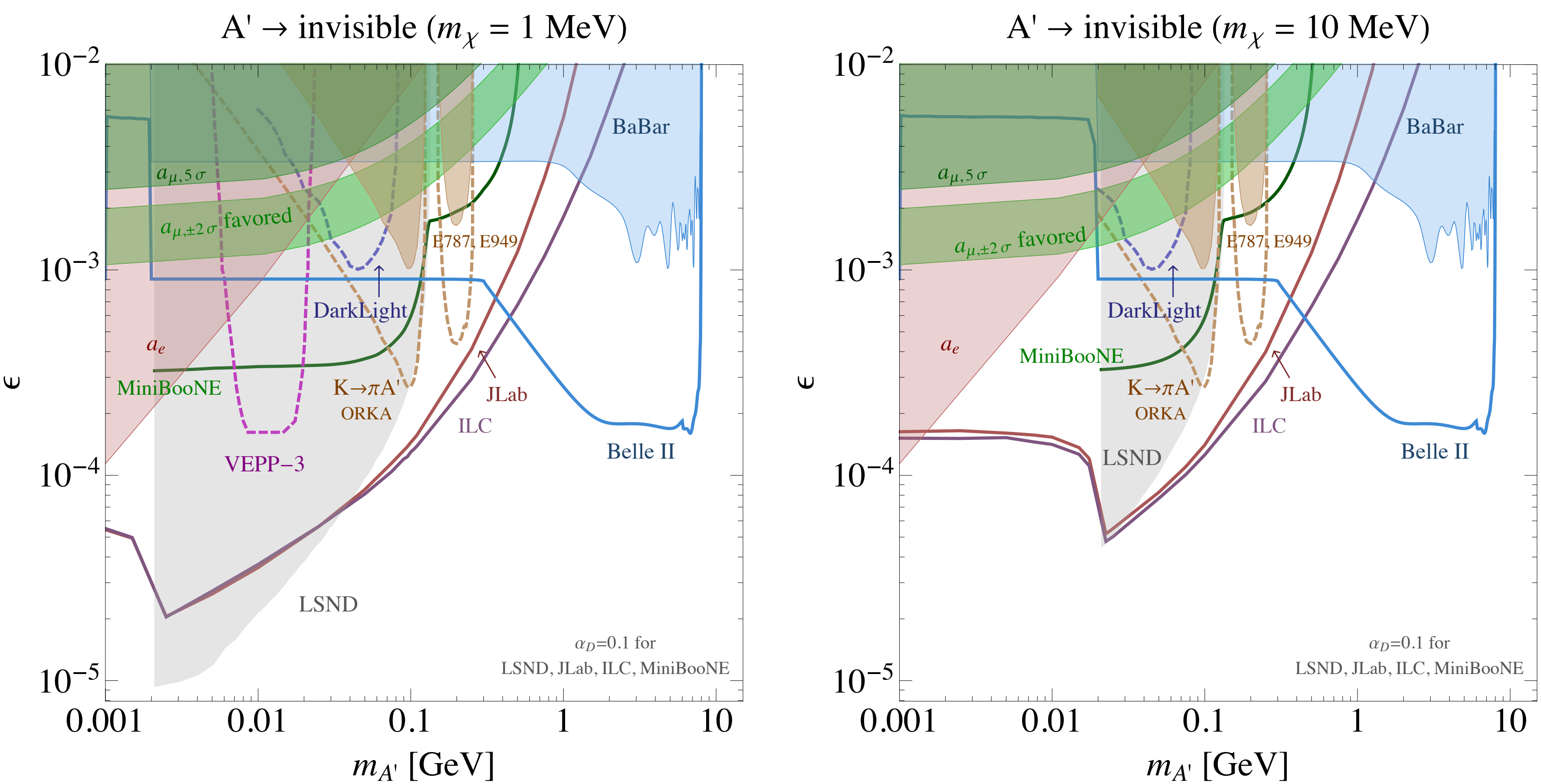
Dark photon mediator,
m_{DM} =200 MeV

(Figure by P. deNiverville)



The sensitivity of SHiP tau neutrino detector to *light mediators* will be improved.

Compilation of current constraints on dark photons decaying to light DM

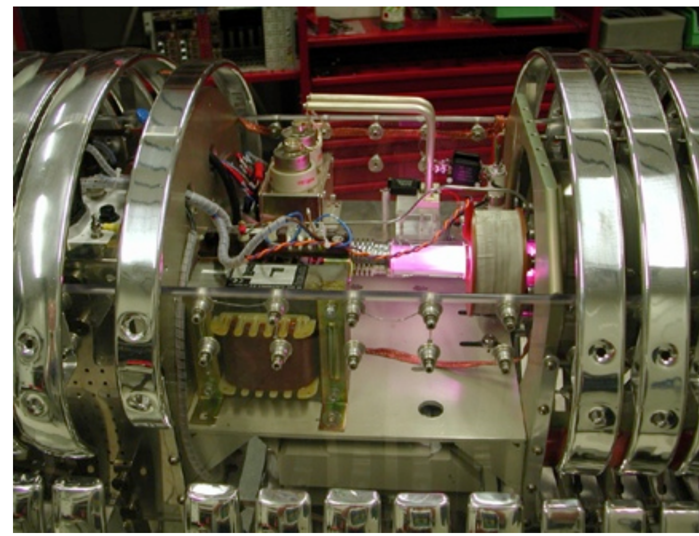


The sensitivity of *electron beam dump experiments* to light DM is investigated in Izaguirre, Krnjaic, Schuster, Toro 2013; Surujon et al. . New collaboration, BDX

More coverage of parameter space using underground accelerators and neutrino detectors

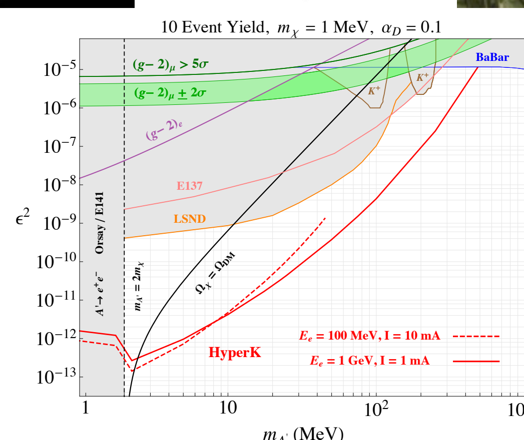
with Eder Izaguirre and Gordan Krnjaic, 2014, 2015

+



Borexino, Kamland, SNO+, SuperK, HyperK…

Krnjaic's talk



LUNA, DIANA,…+ new accelerators

Absorption signatures of super-WIMPs

“Simplified” models of super-WIMPs

- New light bosonic states V, A, S, P, T etc below 1 MeV with small couplings [no worries about stability] can be very long-lived and can constitute the DM.
- The interaction with electrons and photons can be used for their detection

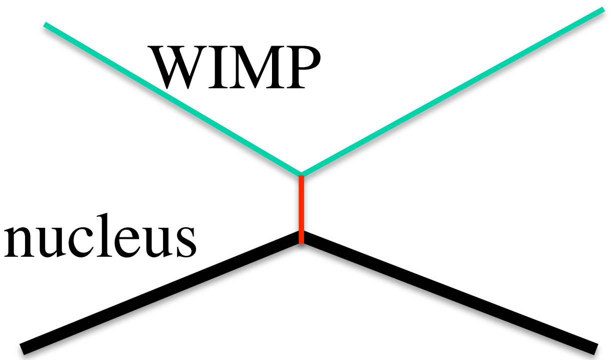
$$\begin{array}{l} \text{(pseudo)scalar} \quad g_S S\bar{\psi}\psi, \quad g_P P\bar{\psi}\gamma_5\psi, \\ \text{(pseudo)vector} \quad g_V V_\mu\bar{\psi}\gamma_\mu\psi, \quad g_A \mathcal{A}_\mu\bar{\psi}\gamma_\mu\gamma_5\psi, \\ \text{tensor} \quad g_T T_{\mu\nu}\bar{\psi}\sigma_{\mu\nu}\psi, \quad \cdots \end{array}$$

- *S* and *P* decays will give 2 photon signature – monochromatic lines – and will in general better constrained by astrophysics. [3.55 keV line can be fit by *S* or *P* without any problems]
- There is no issues with naturalness [conservatively understood]:

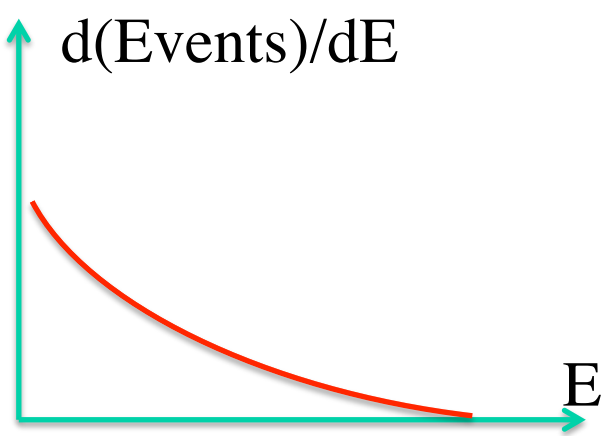
  e.g. $m_S > 10^{-1}\, g_S \times \text{Cutoff} \sim 10^{-11}\, (g_S/10^{-10})\ \text{TeV} \sim 10\ \text{eV}$
- Why bosonic? Sterile neutrinos can also do N + e → ν + e, but rates are tiny, and energy deposition is miniscule.

New DM signal: absorption of super-WIMPs

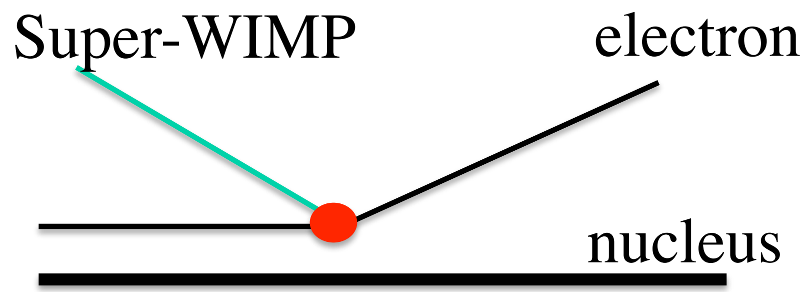
WIMP-nucleus scattering



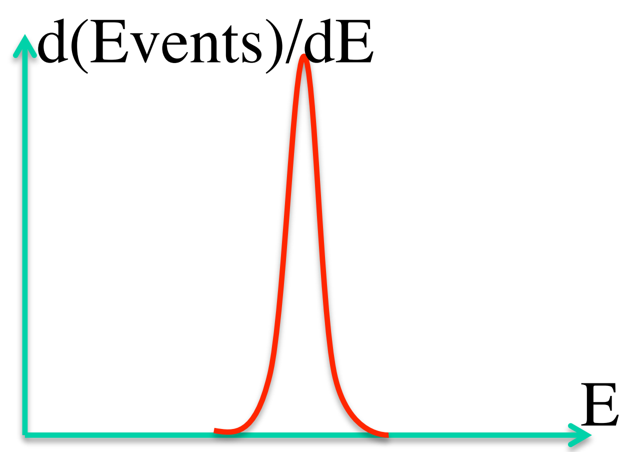
Signal: ionization + phonons/light



Atomic absorption of super-WIMPs



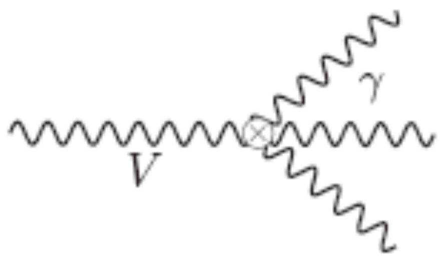
Ionization at $E=m_{superWIMP}$



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:



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

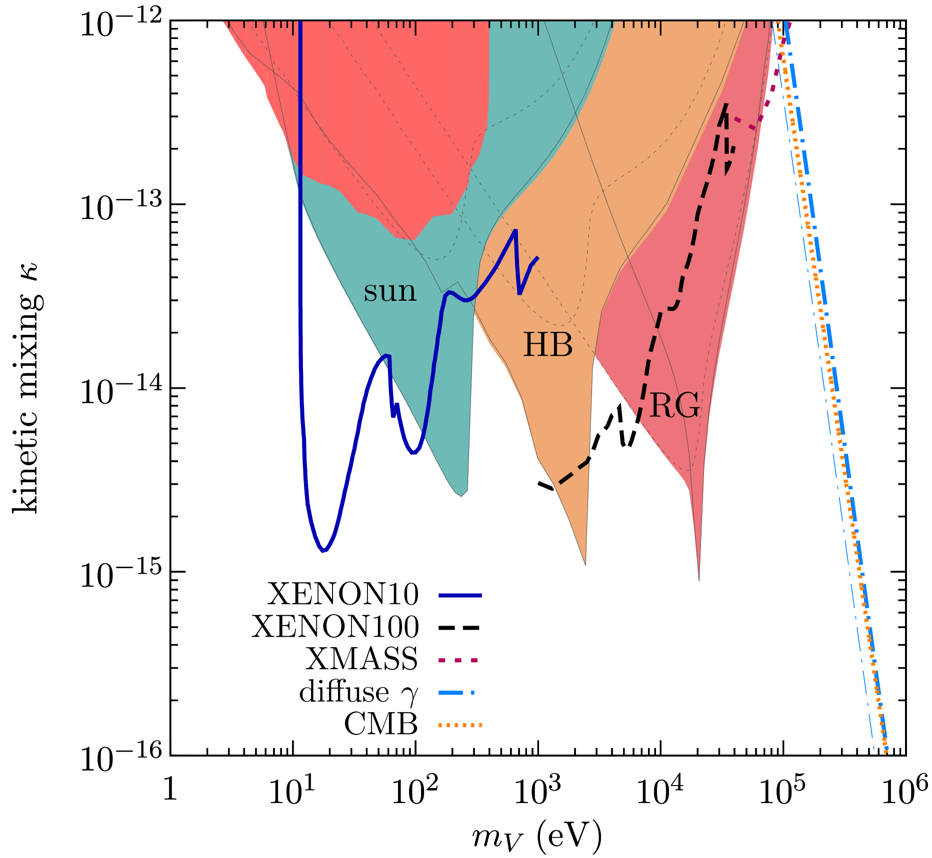
$$\tau_U \Gamma_{V\to 3\gamma} \lesssim 1 \quad\Longrightarrow\quad m_V\,(\alpha')^{1/9} \lesssim 1\,\mathrm{keV}\ .$$

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

Can be viable DM model: MP, Ritz, Voloshin; Redondo, Postma

vector DM absorption signal

An, MP, Pradler, Ritz (Dec. 2014)



Large DM experiments can compete with stellar constraints and have sensitivity to mixing angles down to kappa ~10^{-15}. *See J. Pradler's talk.*

Many experiments now (Xenon100, CDMS, Malbec, Xmas, Edelweiss, CoGeNT, and soon LUX) report their sensitivity to the keV-scale super-WIMPs

Super-cool Dark Matter from misalignment

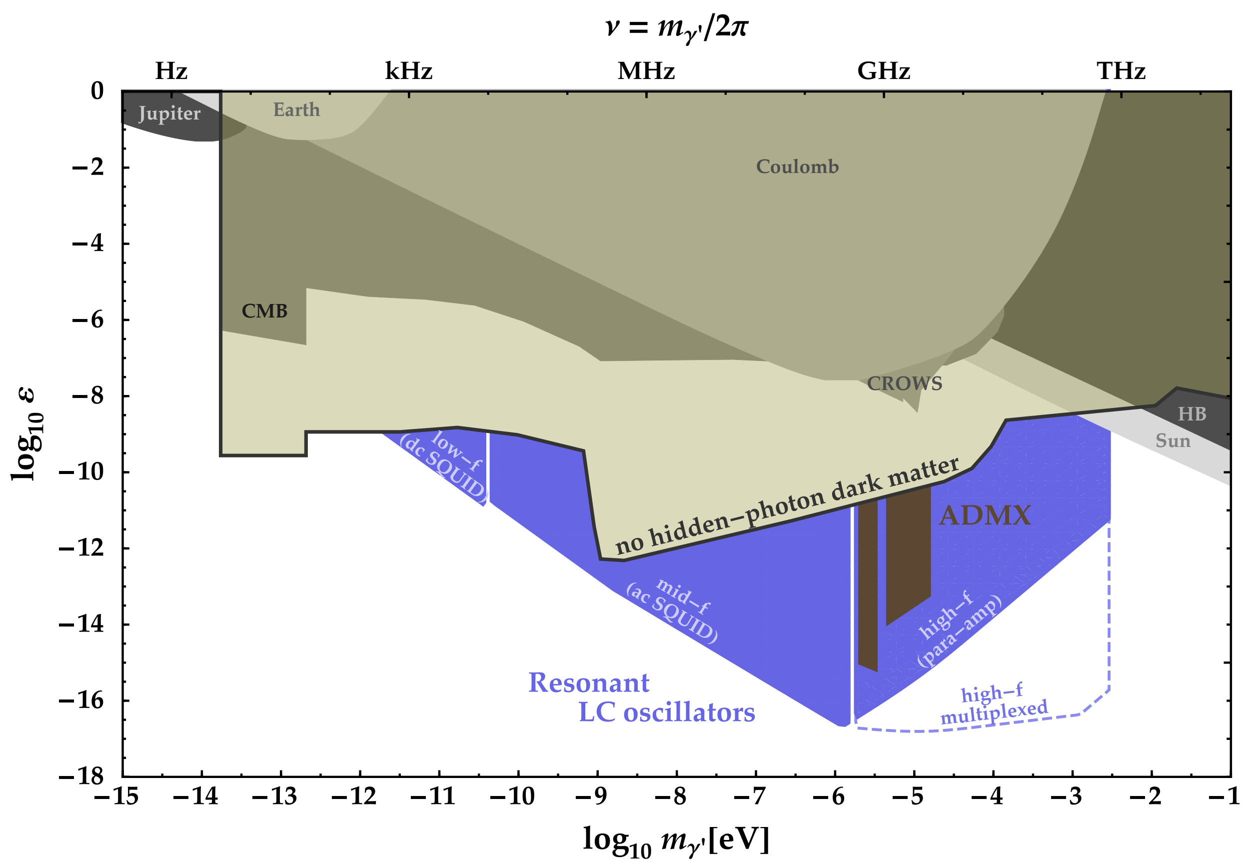
Sub-eV mass ranges – has to be non-thermal.

- QCD axion (1981- onwards).

…

- Scalar DM through the super-renormalizable Higgs portal (Piazza, MP, 2010) Also, pointed out dark photon DM possibility.
- Nelson, Scholtz (2011); Arias et al (2012); Jaeckel, Redondo, (2013); … J Mardon et al, (2014).
- Most models are subject to uncertainty related to the "initial displacement" of the field from minimum (and possible isocurvature perturbation constraints.)
- Sad part*: for non-QCD axion models, signals are not guaranteed, because nothing requires this DM to be coupled to the SM*

Dark Photon dark matter in the sub-eV range



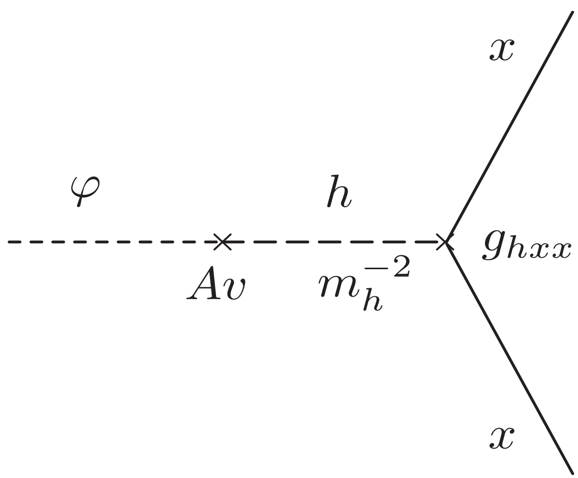
- Misaligned photon dark matter, sub-eV range, from Chaudhuri et al, 2014.

Scalar DM through super-renormalizable portal

- Piazza, MP, 2010: *There is a unique portal in the SM*

$$V = -\frac{m_h^2}{2} H^\dagger H + \lambda (H^\dagger H)^2 + A H^\dagger H \phi + \frac{m_\varphi^2}{2}\phi^2 \,.$$

- There is no runaway direction if $A^2/m_\varphi^2 < 2\lambda$
- After integrating out the Higgs, the theory becomes very similar to Brans-Dicke – but *better* because of UV completeness our theory.



$$g_{\varphi xx} = \frac{Av}{m_h^2} g_{hxx}$$

$$g_{hNN} \simeq \frac{200 - 500\,\mathrm{MeV}}{v} \sim O(10^{-3})$$

- Main consequence of such model is a new scalar force mediated by dark matter.

5^{th} force from Dark Matter exchange

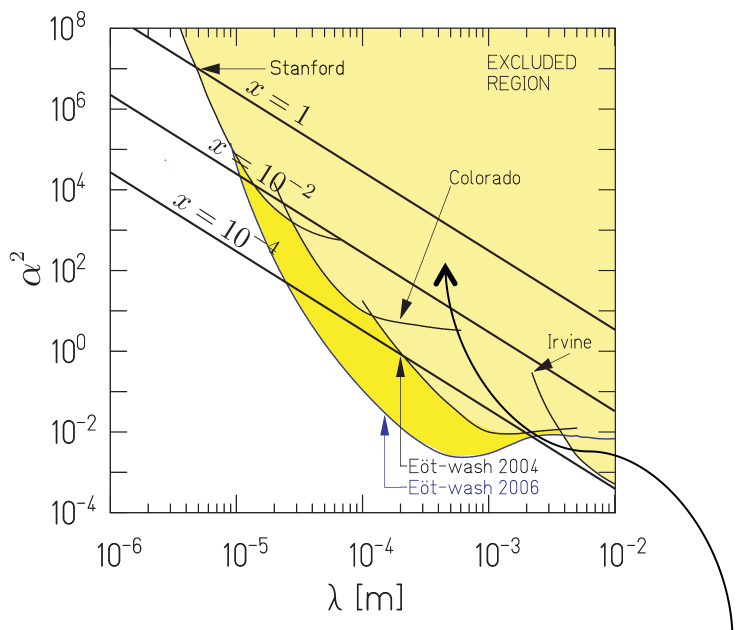
- The main observational consequence of this model: possibility to have an observable 5^{th} force   (x= A/mass)

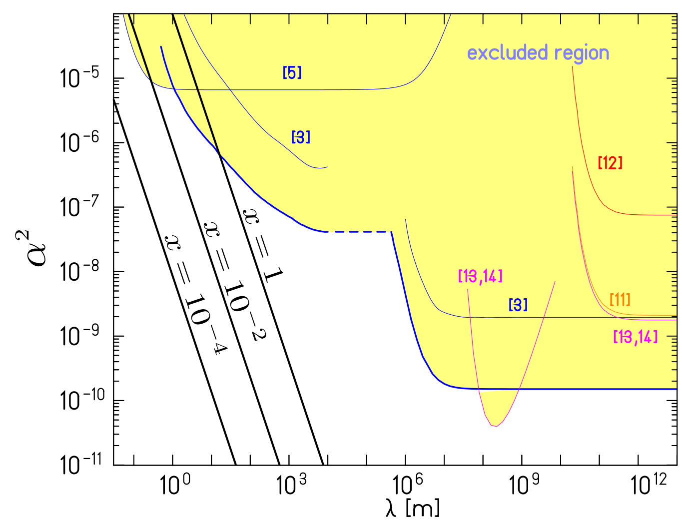
- For the traditional parametrization, $V(r) = -G\dfrac{m_A m_B}{r}\left(1+\alpha_A\alpha_B\, e^{-m_\varphi r}\right).$

we can derive the strength of coupling

$$\alpha \;=\; g_{hNN}\frac{\sqrt{2}M_P}{m_{\rm nuc}}\frac{Av}{m_h^2}$$
$$\simeq\; 10^{-3}\left(\frac{m_h}{115\,{\rm GeV}}\right)^{-2}\frac{A}{10^{-8}{\rm eV}}.$$

(! *the second bracket* = 0.83)





One can expect a "natural" 5^{th} force from DM in 10 micron – 100 m range

Macroscopic size DM other than primordial black holes

MP et al, 2012; Derevianko and MP, 2013;

Adhikari et al, work in progress

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

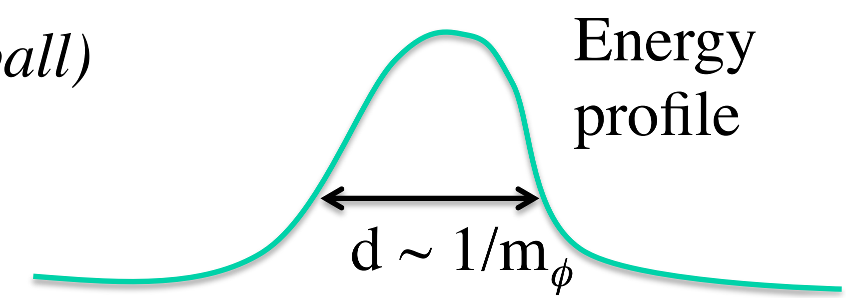
$m_\phi = \lambda^{1/2} v$

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 (also a Q-ball)*

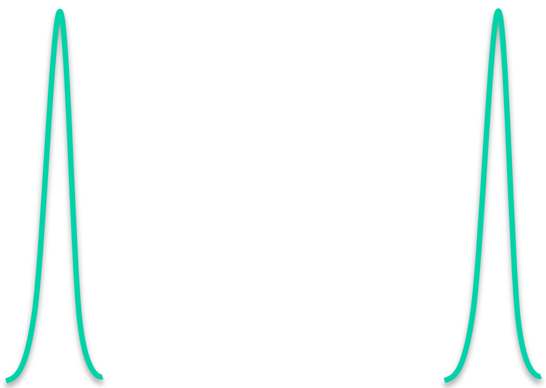
1D object – a *String*

2D object – a *Domain wall*

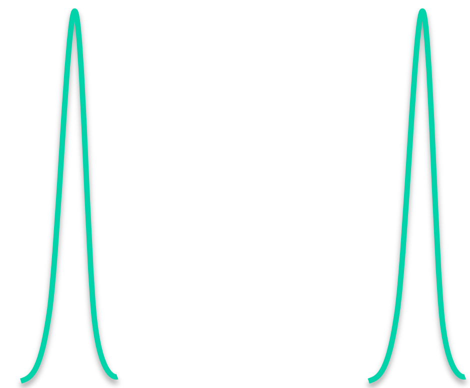


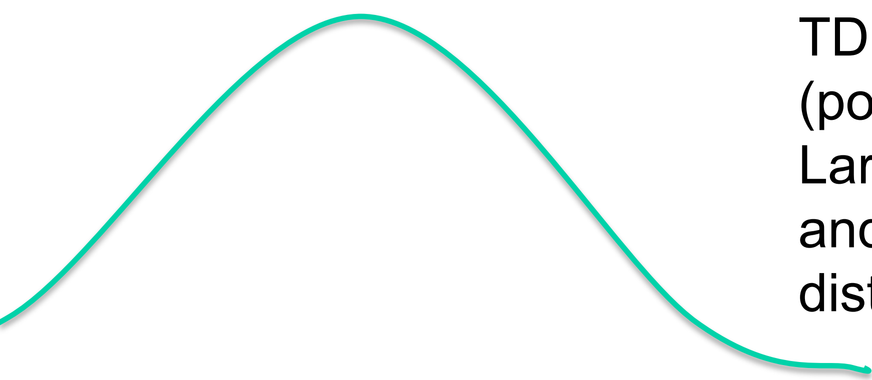
Comparison with WIMPs and axions

Axions – small amplitude but “no space” between particles

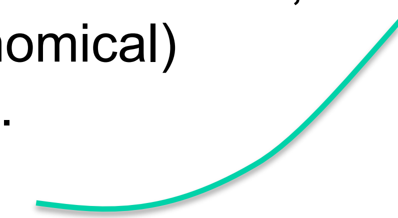


WIMPs – EW scale lumps of energy (>> axion amplitude), very concentrated in space. And with significant ~ cm gaps between particles





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

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

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

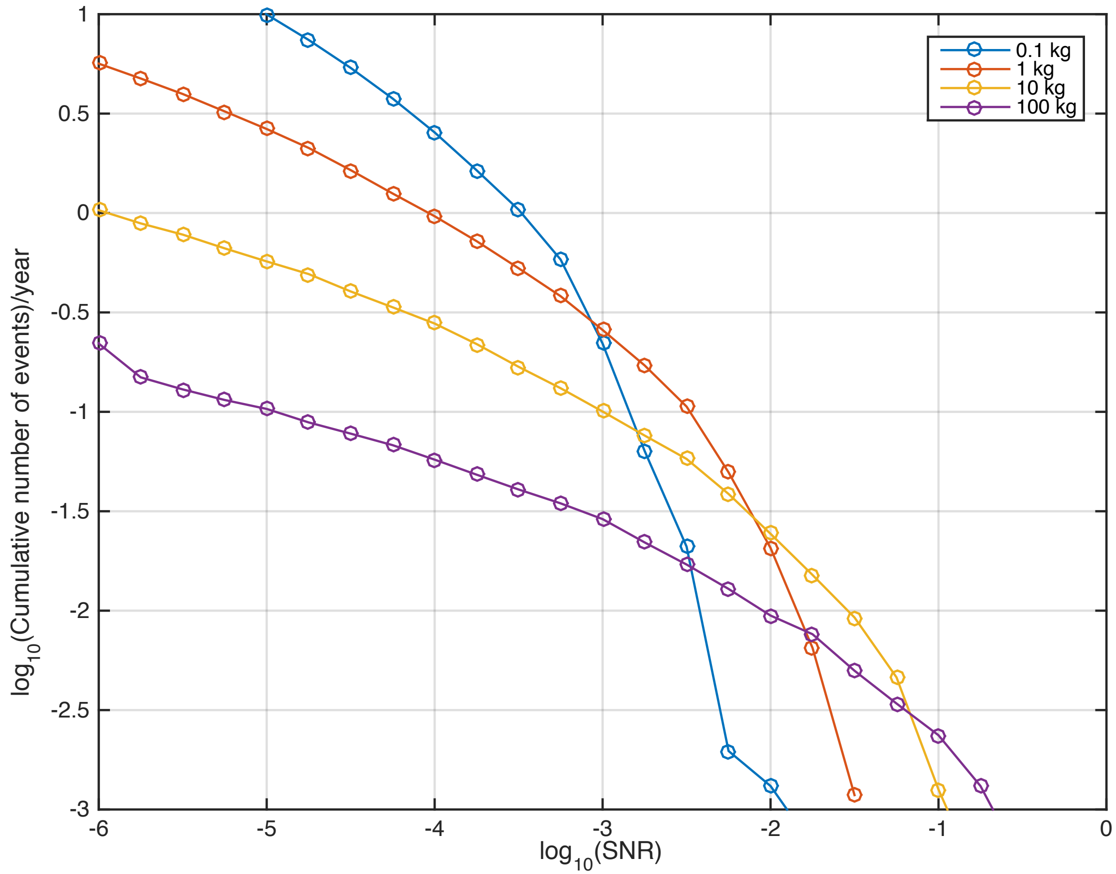
D $$\frac{\phi_1 \partial_\mu \phi_2}{M_*^2} \sum_{\text{SM particles}} g_\psi \bar{\psi} \gamma_\mu \psi \quad \text{current} - \text{current portal}$$ extra gr. force

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

Experimental developments

- First steps towards creating the network of correlated atomic magnetometers have been made with potential nods at Berkeley, Mainz, Cal State East Bay, Krakow… (Budker, Jackson Kimball, Gawlik, Pustelny and others). A multi-node magnetometer network is called **GNOME** collaboration.
- Atomic clock networks already exist (e.g. GPS, GLONASS etc). However, their sensitivity to a possible transient signal is not quantified properly. Blewitt, Derevianko (UNR) will address that and investigate the best possible clocks for a specialized network.
- An investigation of **Advanced Ligo** sensitivity to the macroscopic size dark matter has been performed, Adhikari, Cllister, Hall, Frolov, Muller, MP.

Simulation of sensitivity to grav interaction



A passage of 0-dim objects (e.g. “monopoles”) gives a disturbance signal with characteristic w ~ v/L ~ 100 Hz (a good range for Ligo!). Average energy density is fixed to galactic ρ_{DM}.

A few orders of magnitude short from being able to detect gravitational-size interaction with macroscopic DM.

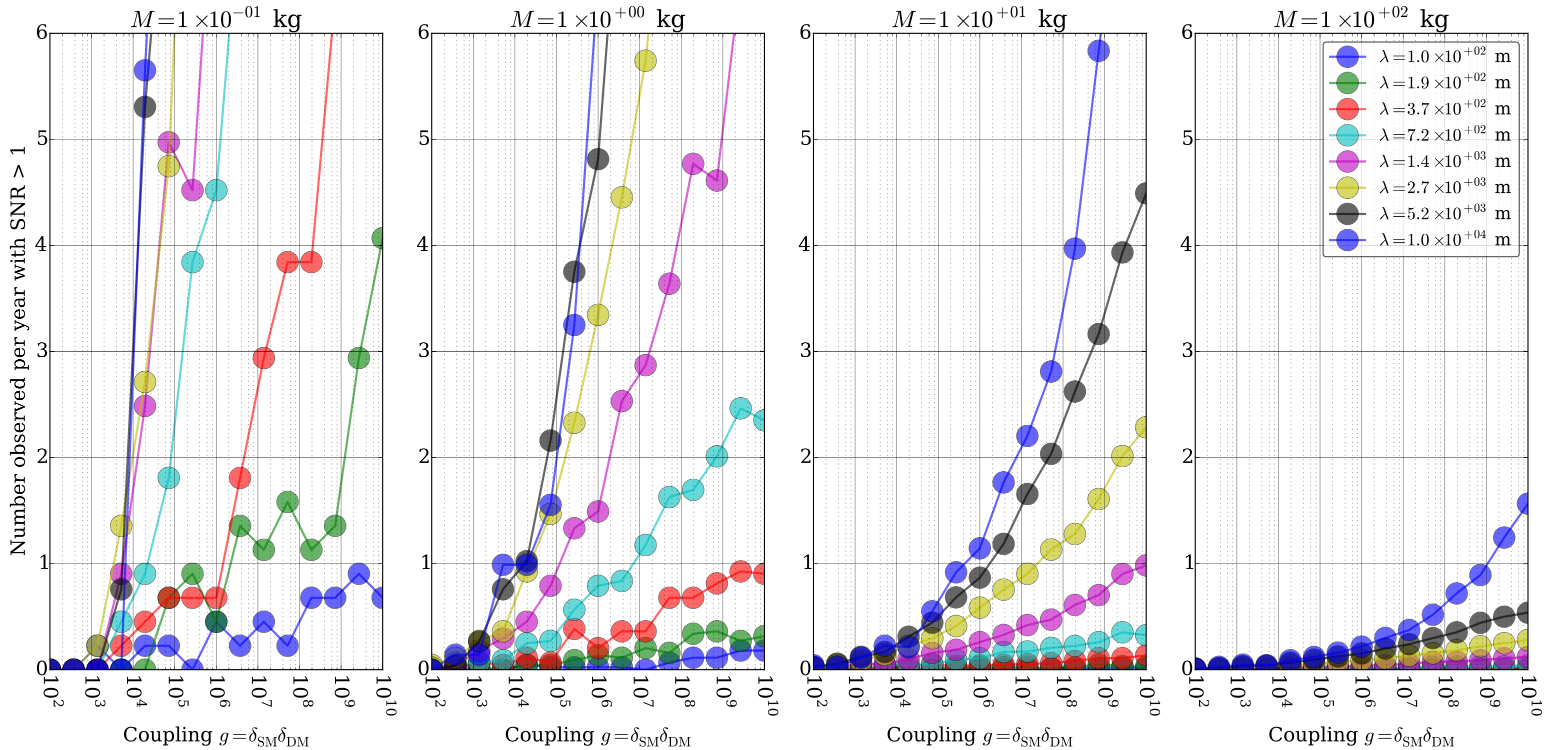
Sensitivity to new Yukawa interaction

- A non-gravitational interaction between DM and SM could be parametrized by a Yukawa force,

- $V_{atom1\text{-}atom2} = -G_N m_1 m_2 / r \ (1 + \delta_{SM}^2 \, \mathrm{Exp}[-r/\lambda])$
- $V_{atom\text{-}DM} = -G_N m_{atom} m_{DM} / r \ (1 + \delta_{SM}\delta_{DM} \, \mathrm{Exp}[-r/\lambda])$

- From the 5th force measurements we will know that the extra SM couplings are small, $\delta_{SM}^2 < 10^{-5}$. In contrast, the coupling to the dark sector can be large, $\delta_{DM} >> 1$ if the range of the force is much smaller than the galactic size (e.g. $\lambda \sim$ few km).

Sensitivity to “cat-size” DM



One could have good sensitivity to extra force between DM-SM, that is not constrained by other means.

Simulation by Adhikari, Cllister, Hall

(picture by Vasya Lozhkin)

Conclusions

1. Dark matter takes 25% of the Universe's energy budget. Its identity is not known. Many theoretical possibilities for the CDM exist: WIMPs, super-WIMPs, super-cold DM

2. **It is important to cast as wide an experimental net as possible*, as we continue our investments in WIMP searches*

3. New signals of MeV dark matter can be investigated in the beam dump experiments from production and scattering.

4. New ionization signatures from absorption of super-WIMP dark matter are constrained by direct detection experiments.

5. *Altogether different possibility*: macroscopic dark matter inducing transient signal. Advanced Ligo will have strong sensitivity.

Oscillating force on He3 spin

Recent suggestions to search for ALP dark matter by Graham, Rajendran

Easy to see if e.g. M. Romalis' "Lorentz violation" search is sensitive to ALPs dark matter:

$$\mathcal{L} = \frac{\partial_\mu a}{f_a} \overline{n} \gamma_\mu \gamma_5 n$$

As everyone else in this game, I will saturate ρ_{DM} by oscillating a(t).

If I take the *maximum allowed* f_a from stellar constraints, the range of masses 10^{-17} to 10^{-15} eV where the K-He3 magnetometer is the most sensitive and can probe ALP dark matter.

The energy shift due to DM:

$$\Delta E = \frac{m_a a}{f_a} \frac{v}{c} = \frac{\sqrt{\rho_{DM}}}{f_a} \frac{v}{c}$$

$$= 1.5 \times 10^{-33} \text{GeV} \times \frac{10^9 \text{ GeV}}{f_a} \times \left(\frac{\rho_{DM}}{0.3 \text{GeVcm}^{-3}} \right)^{1/2} \times \frac{v/c}{10^{-3}}$$

Right at the edge of current sensitivity!!

Brief history of the subject

- *DAMA collaboration* (2008) has claimed that their modulation signal may come from absorption of ~ 3 keV ALPs.
- They made *multiple errors*, including the fatal one: in fact *there is no modulation*. Absorption cross section ~ 1/velocity, σ v = const. Corrected in MP, Ritz, Voloshin (PRV), 2008.
- In keV mass range X-ray limits from decays + stellar energy loss constraints are much more sensitive to ALPs than direct detection (Gondolo, Raffelt, PRV, Postma Redondo, 2008)
- Vector dark matter (where decays to photons is inhibited is a perfect candidate for direct detection search via absorption), PRV.
- Many experiments now (Xenon100, CDMS, Malbec, Xmas, Edelweiss, CoGeNT, and soon LUX) report their sensitivity to the keV-scale ALPs. [Better use vectors, as ALPs are more constrained by astro]
- Below keV only a select few has sensitivity via the signature that T. Volansky discussed in the scattering channel yesterday.

Q1: 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?

Q2: 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?