New Directions in dark matter searches

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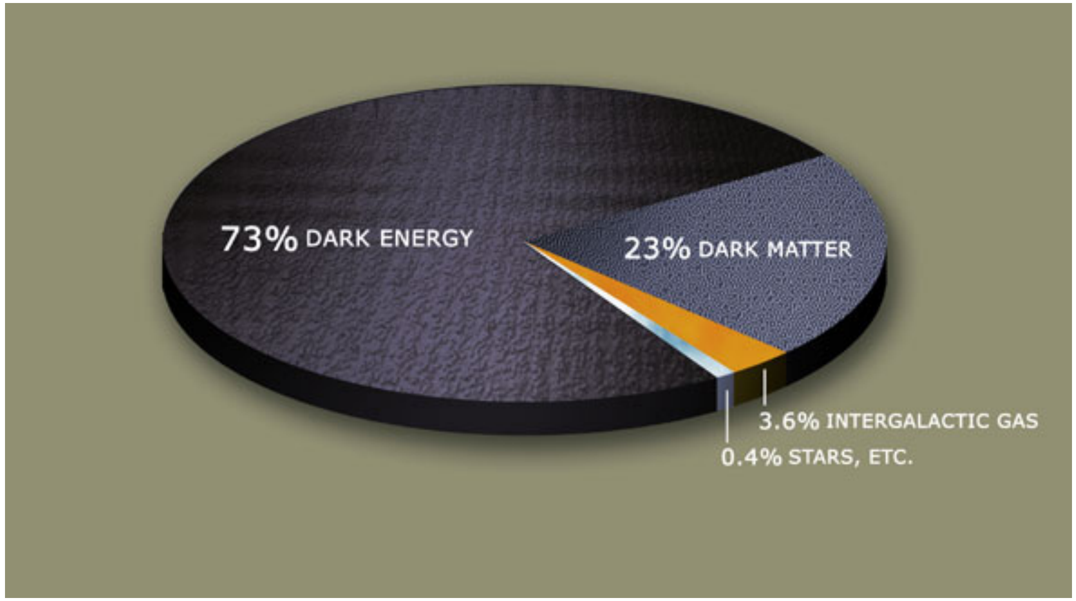
Outline of the talk

1. *Introduction. Many types of dark matter [all good].*
2. Particle dark matter just below the WIMP window (~ MeV DM).
3. Bosonic condensate dark matter.
4. Search for macroscopic size dark matter with advanced Ligo.
5. 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.*

WIMP "lamp post"

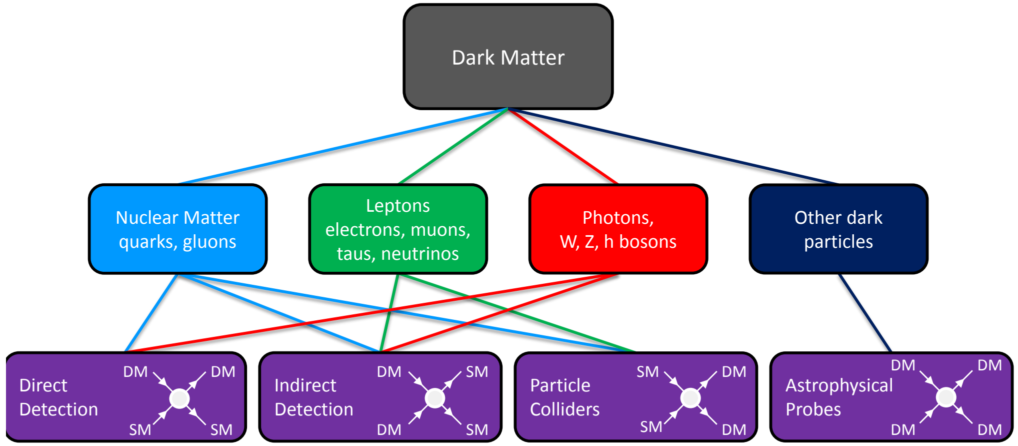
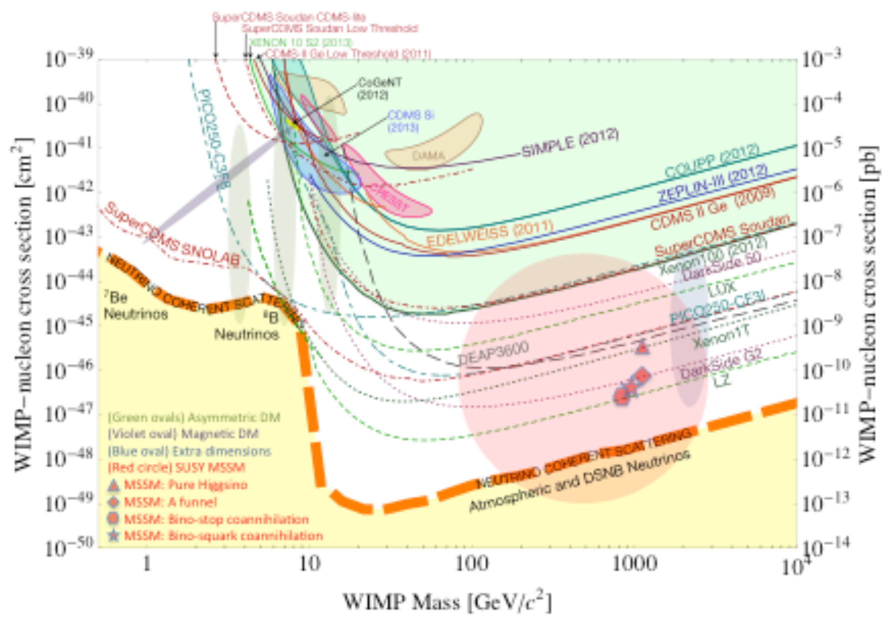


Figure 5. *Dark matter may have non-gravitational interactions with any of the known particles as well as other dark particles, and these interactions can be probed in several different ways.*



From the Snowmass 2013 summary, 1310.8327

New lampposts in DM searches

- WIMP dark matter outside of the "usual" mass range.
- Non-particle Dark Matter with precision measurements.
- Macroscopic dark matter (?)

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

$J_\mu^{\,A}\ \partial_\mu a / f_a$ axionic portal

……….

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

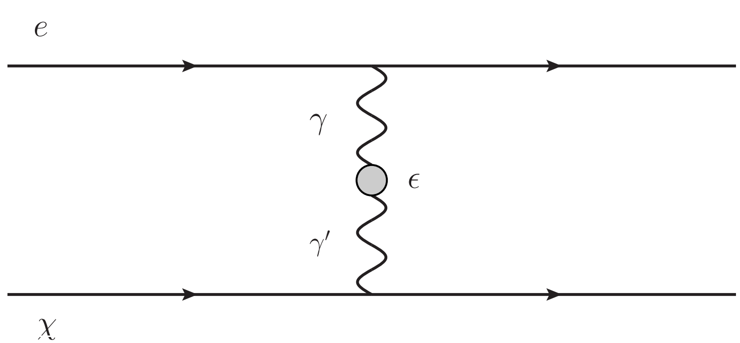
“Simplified model” for dark sector

(Okun’, Holdom,…)

$$\mathcal{L} = \mathcal{L}_{\psi,A} + \mathcal{L}_{\chi,A'} - \frac{\epsilon}{2} F_{\mu\nu} F'_{\mu\nu} + \frac{1}{2} m_{A'}^2 (A'_\mu)^2.$$

$$\mathcal{L}_{\psi,A} = -\frac{1}{4} F_{\mu\nu}^2 + \bar{\psi}[\gamma_\mu(i\partial_\mu - eA_\mu) - m_\psi]\psi$$

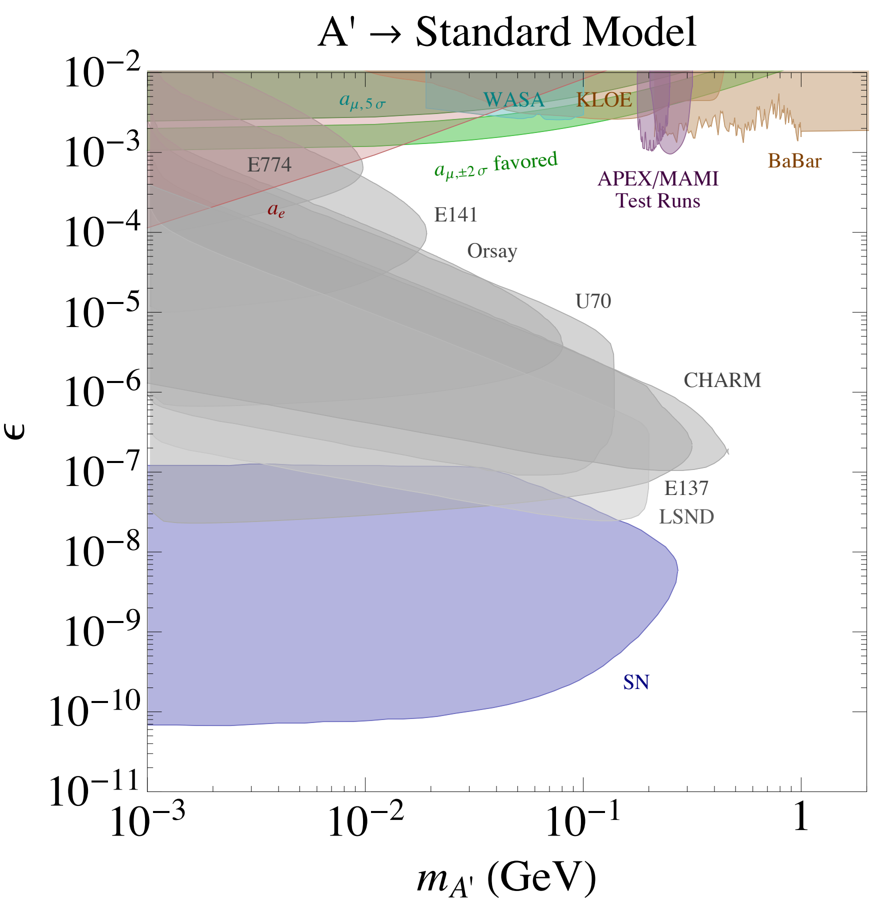
$$\mathcal{L}_{\chi,A'} = -\frac{1}{4}(F'_{\mu\nu})^2 + \bar{\chi}[\gamma_\mu(i\partial_\mu - g'A'_\mu) - m_\chi]\chi,$$

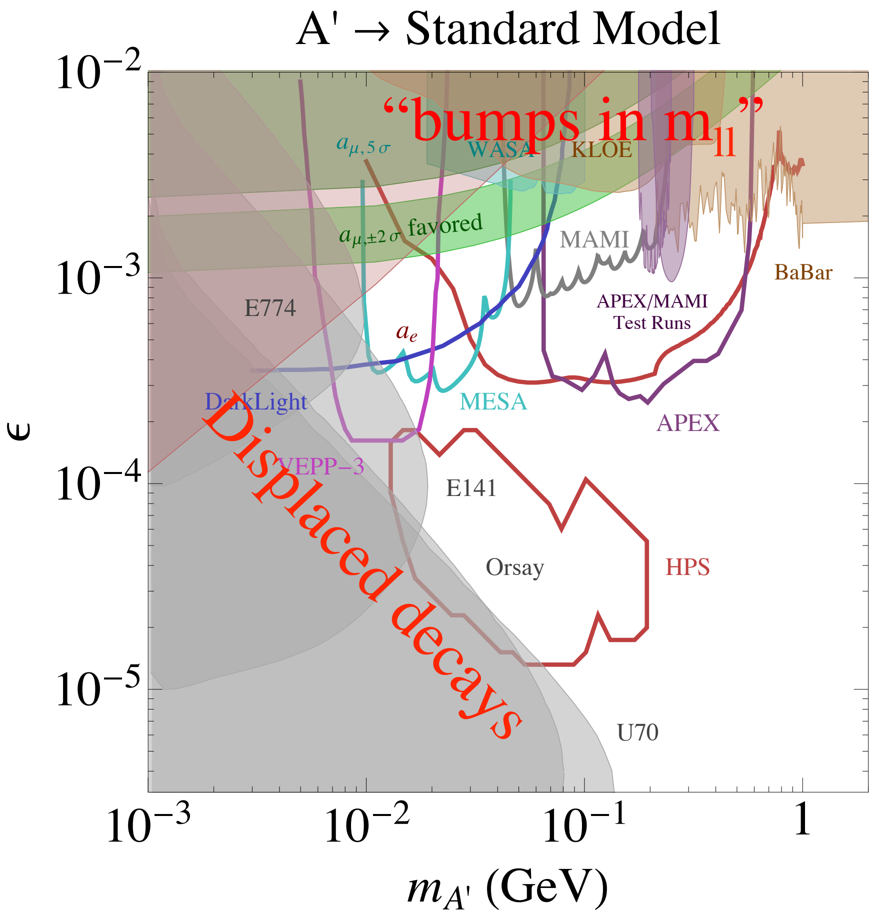


A – photon, *A’* – “dark photon”, ψ - an electron, χ - a DM state, *g’* – a “dark” charge

- “Effective” charge of the “dark sector” particle χ is Q = e × ε (if momentum scale q > m_V). At q < m_V one can say that particle χ has a non-vanishing EM charge radius, $r_\chi^2 \simeq 6\epsilon m_V^{-2}$.
- Dark photon can “communicate” interaction between SM and dark matter. *It represents a simple example of BSM physics*.

Search for dark photons, Snowmass study, 2013





Dark photon models with mass under 1 GeV, and mixing angles ~ 10^{-3} represent a "window of opportunity" for the high-intensity experiments, not least because of the tantalizing positive ~ $(\alpha/\pi)\varepsilon^2$ correction to the muon g - 2.

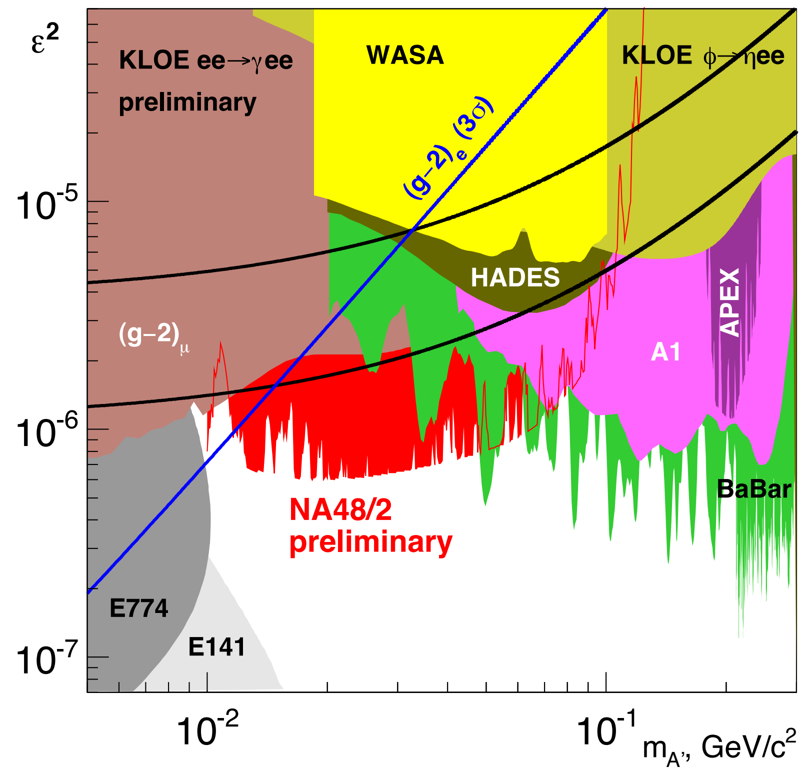
Latest results: A1, Babar, NA48

Signature: "bump" at invariant mass of e^+e^- pairs = $m_{A'}$

Babar: $e^+e^- \rightarrow \gamma V \rightarrow \gamma l^+l^-$

A1(+ APEX): $Z e^- \rightarrow Z e^- V \rightarrow Z e^- e^+e^-$

NA48: $\pi^0 \rightarrow \gamma V \rightarrow \gamma e^+e^-$

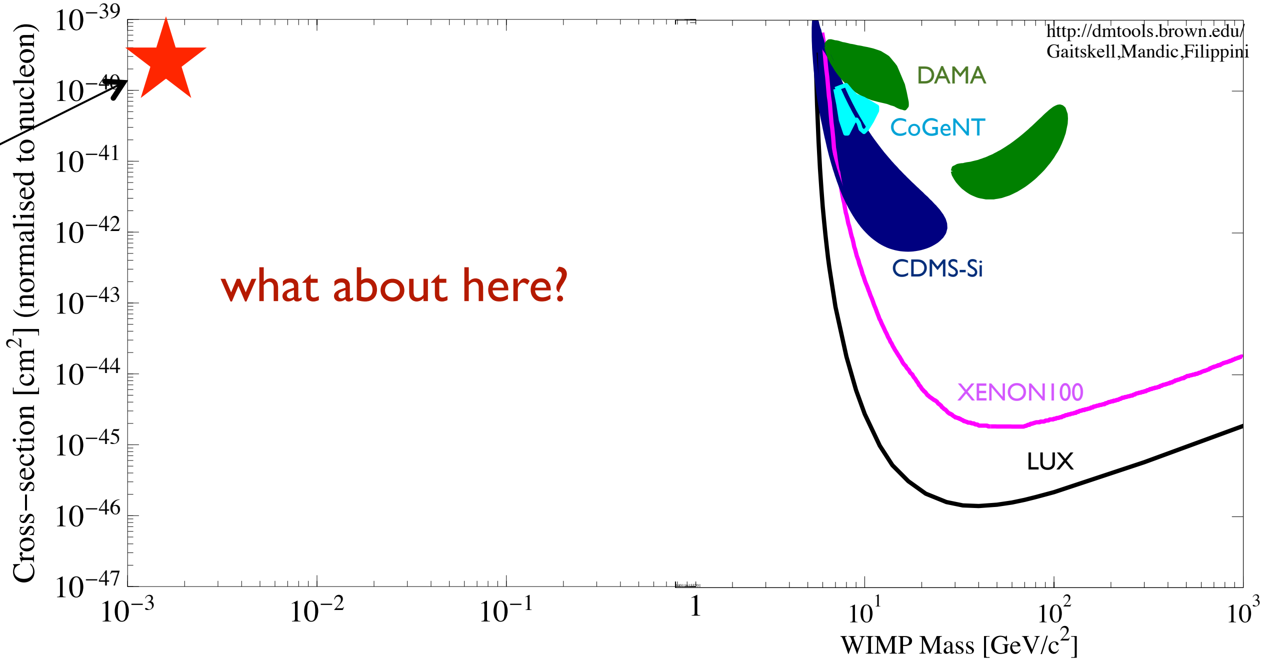


Latest results by NA48 exclude the remainder of parameter space relevant for g-2 discrepancy.

Only more contrived options for muon g-2 explanation remain, e.g. $L_\mu - L_\tau$, or dark photons *decaying to light dark matter.*

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

Light WIMPs due to light mediators direct production/detection

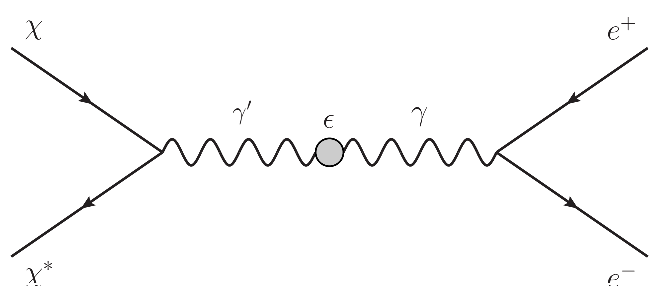
(Boehm, Fayet; MP, Riz, Voloshin …) Light dark matter is not ruled out if one adds a light mediator.

WIMP paradigm: $\sigma_{\rm annih}(v/c) \sim 1\ \text{pbn} \implies \Omega_{\rm DM} \simeq 0.25,$

Electroweak mediators lead to the so-called Lee-Weinberg window,

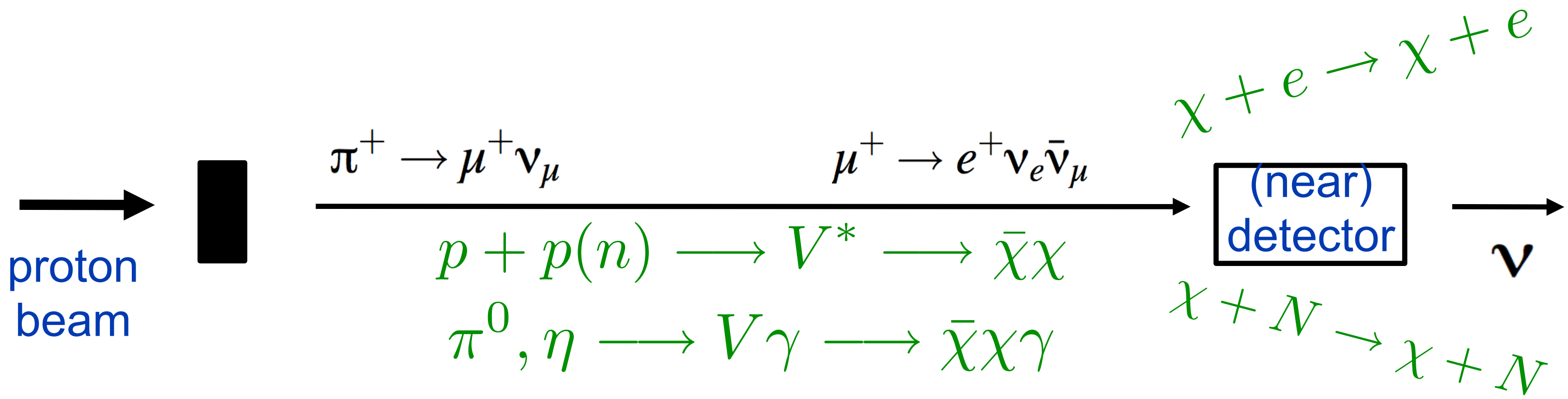
$$\sigma(v/c) \propto \begin{cases} G_F^2 m_\chi^2 & \text{for} \quad m_\chi \ll m_W, \\ 1/m_\chi^2 & \text{for} \quad m_\chi \gg m_W. \end{cases} \implies \text{few GeV} < m_\chi < \text{few TeV}$$

If instead the annihilation occurs via a force carrier with light mass, DM can be as light as ~ MeV (and not ruled out by the CMB if it is a scalar).



Fixed target probes - Neutrino Beams

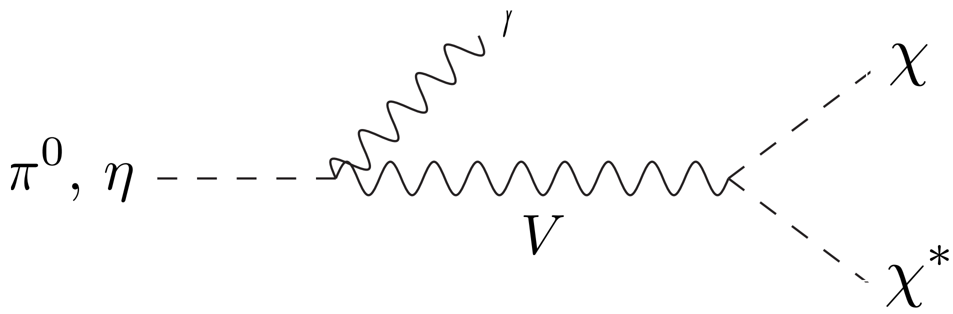
Proposed in Batell, MP, Ritz, 2009. Strongest constraints on MeV DM

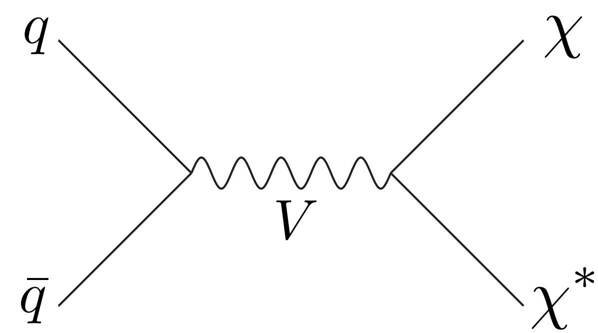


We can use the neutrino (near) detector as a dark matter detector, looking for recoil, but now from a relativistic beam. E.g.

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

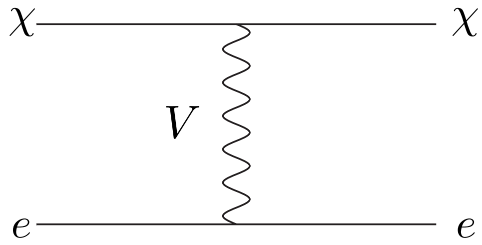
Light DM - trying to force the issue



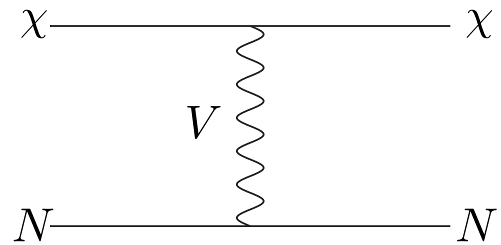


In the detector:

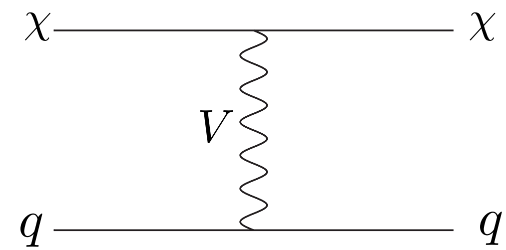
Elastic scattering on electrons



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:

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

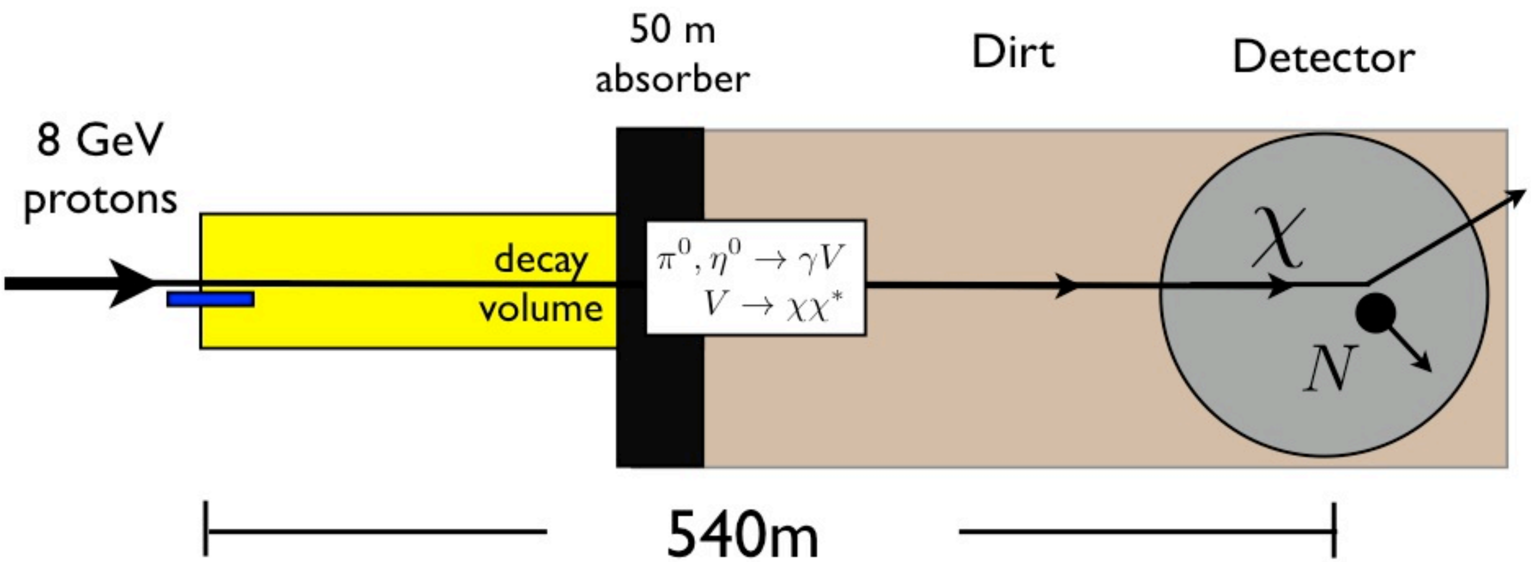
Detection:

Larger than weak scale!

Signals $\sim \sigma_{\text{production}} \times \sigma_{\text{detection}}$ 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

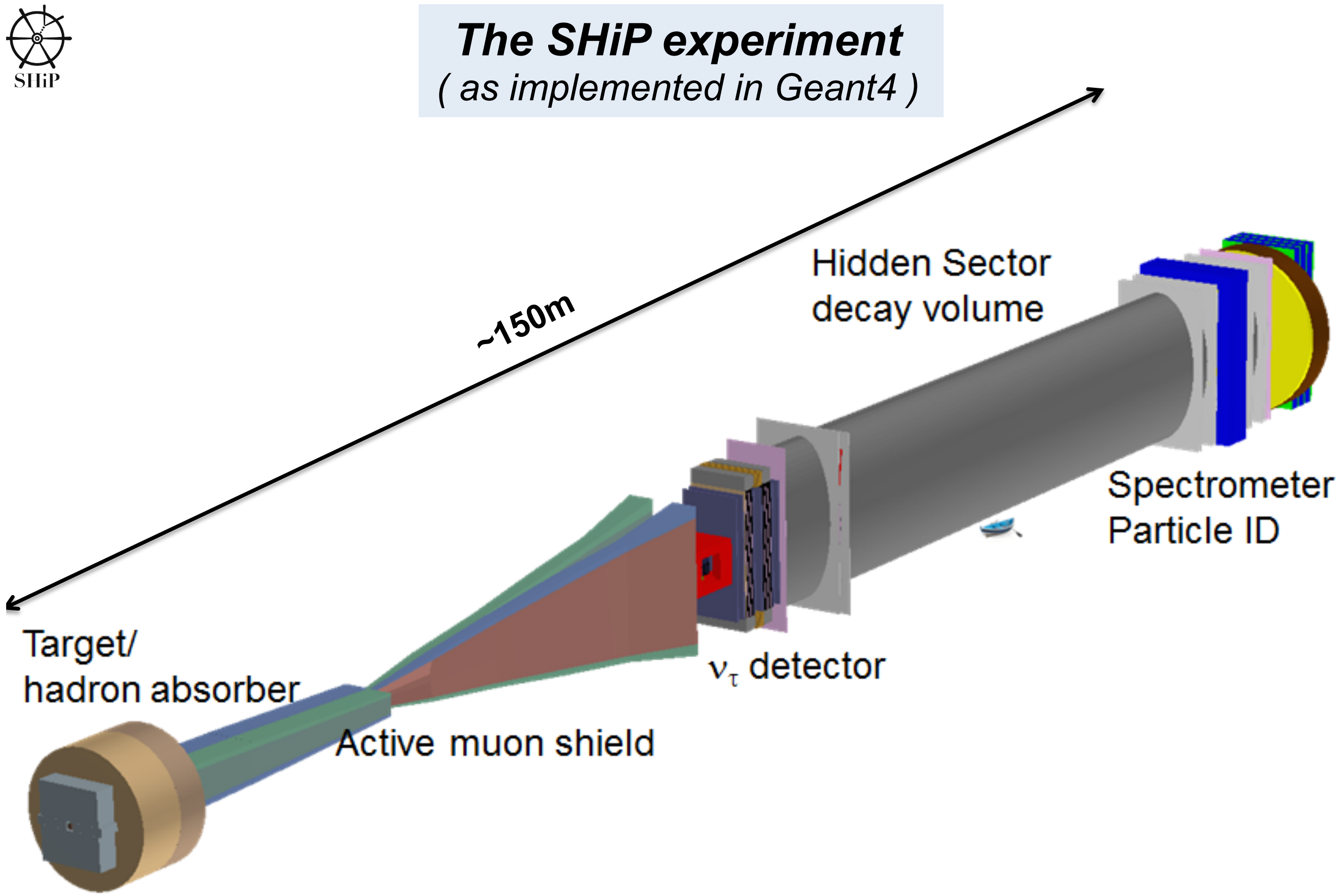


MiniBoone has completed a long run in the beam dump mode, as suggested in [arXiv:1211.2258]

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 big project: SHiP project at CERN



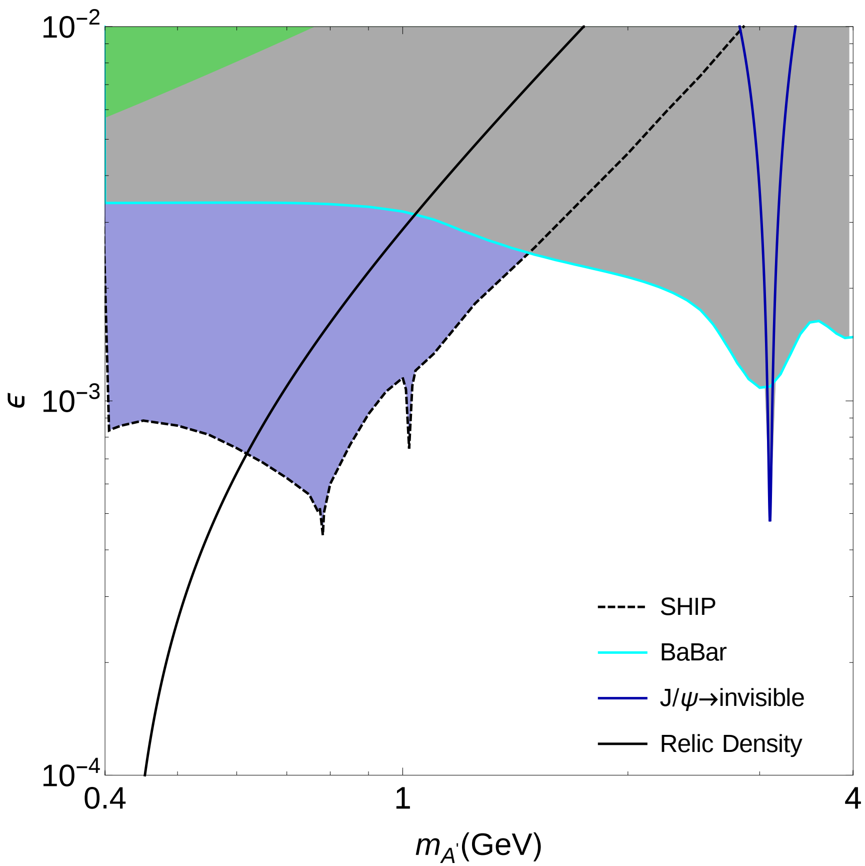
See e.g. A. Golutvin presentation, CERN SHiP symposium, 2015

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)

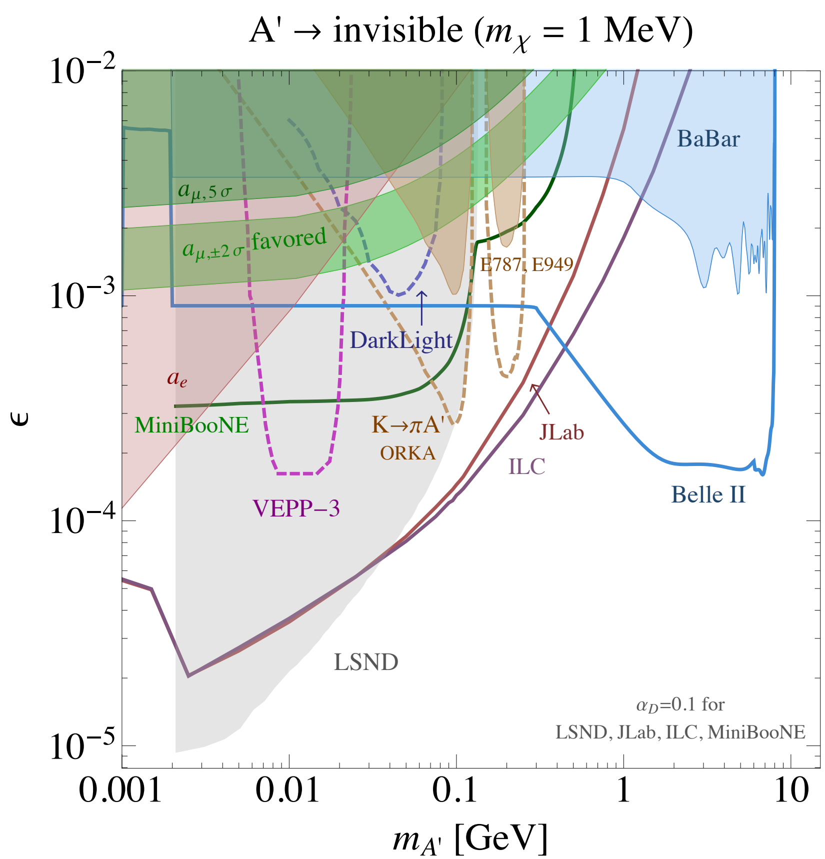
Dark photon mediator,
m_{DM} =200 MeV

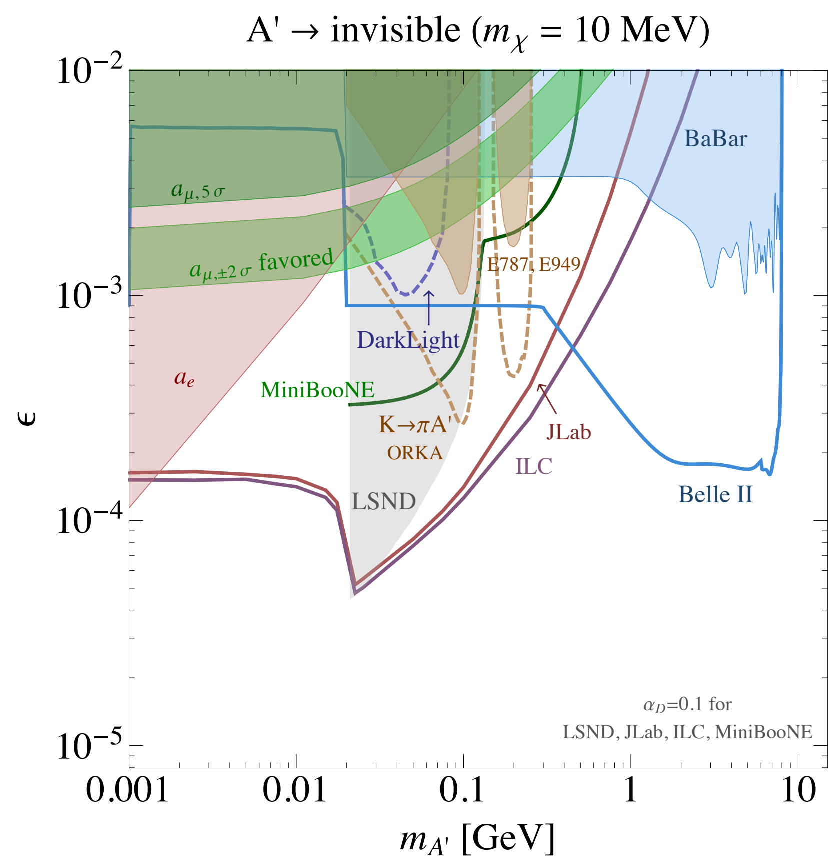
(Figure by P. deNiverville)



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

Compilation of current constraints on dark photons decaying to light DM



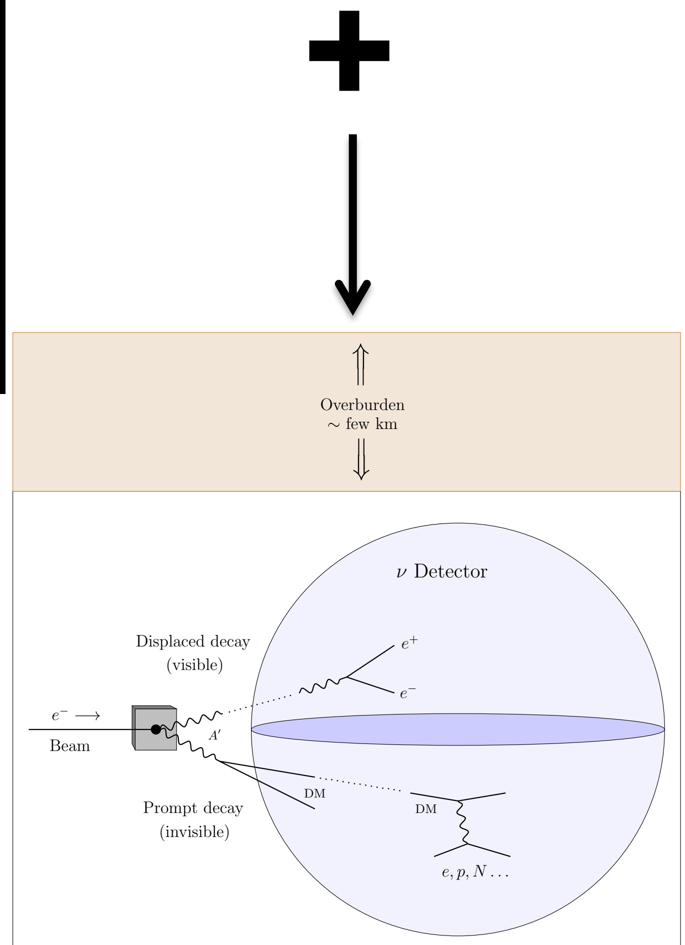


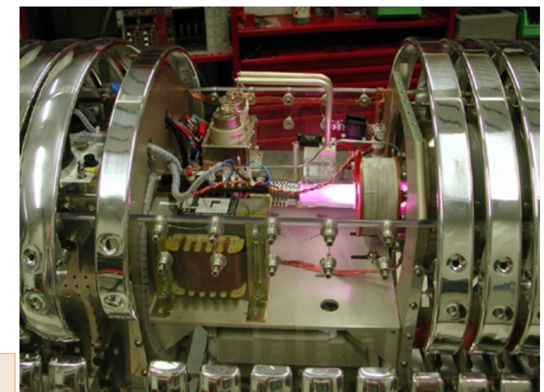
The sensitivity of *electron beam dump experiments* to light DM is investigated in Izaguirre, Krnjaic, Schuster, Toro 2013; Surujon et al. .

New collaboration, BDX

How to improve on the LSND constraints

Eder Izaguirre and Gordan Krnjaic, 2014, 2015





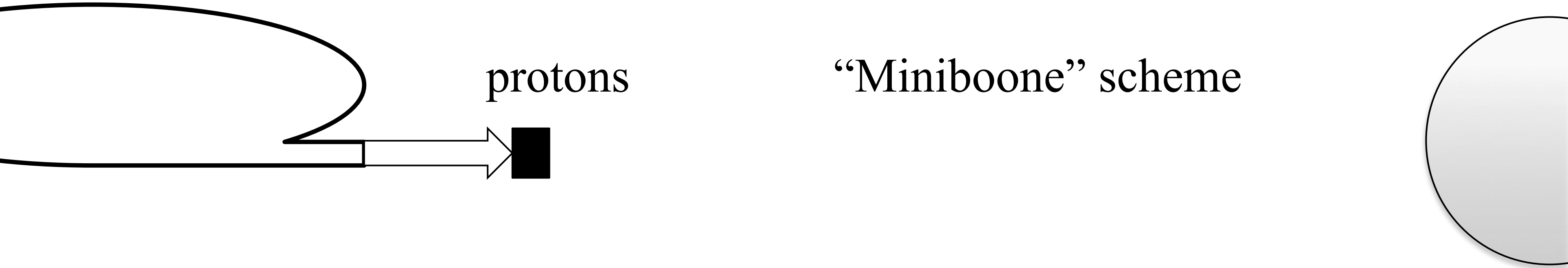
Borexino, Kamland, SNO+, SuperK, Hyper-K (?) …

LUNA, DIANA,…, 1 e-linac for calibration.

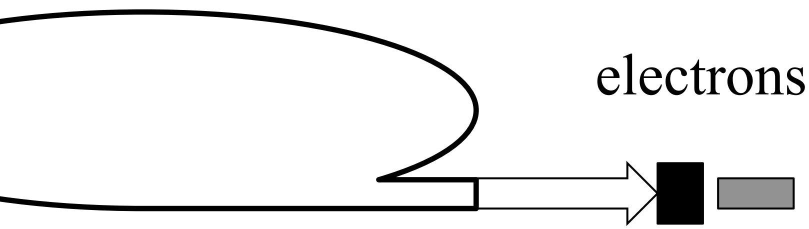
New accelerator ?

Three schemes to search for light DM

1. Proton beam dump, large neutrino detector, near surface, 0.5 km

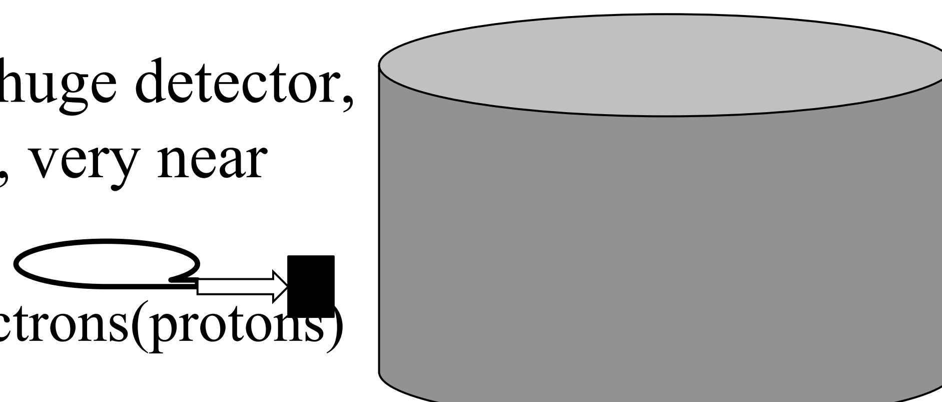


2. Electron beam dump, small-ish detector, very near beam dump



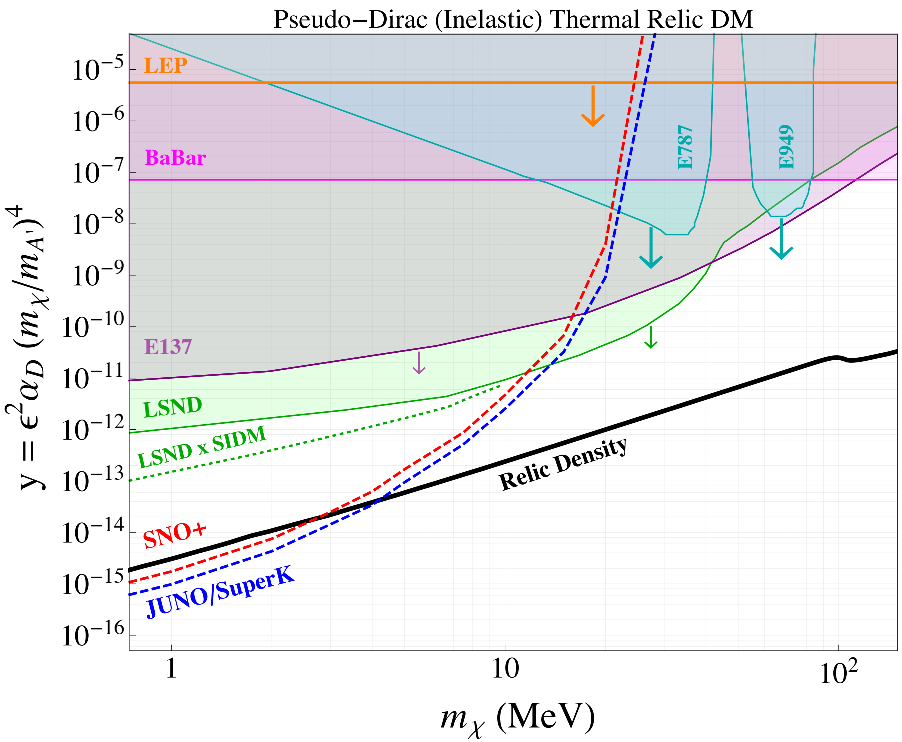
"BDX scheme"

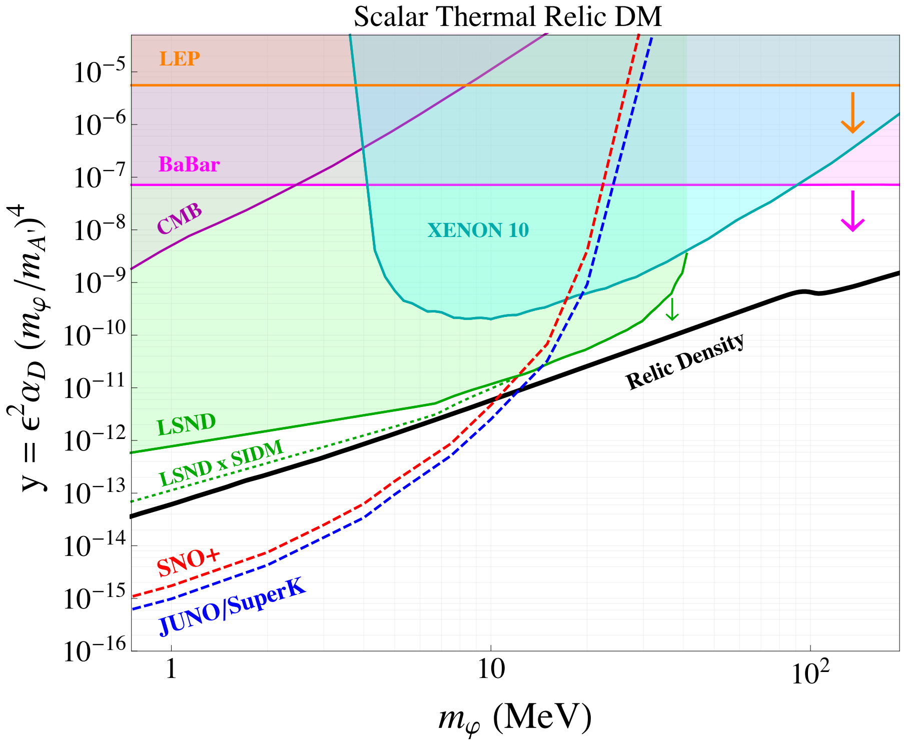
3. Electron beam dump, huge detector, *deep underground*, very near beam dump



"DM-SK"

Sensitivity to light DM





One will significantly advance sensitivity to light DM in the sub-100 MeV mass range. Assuming 10^{24} 100 MeV electrons on target

Izaguirre, Krnjaic, MP, 1507.02681, PRD

Super-cool Dark Matter from misalignment

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

- QCD axion (1981- onwards).

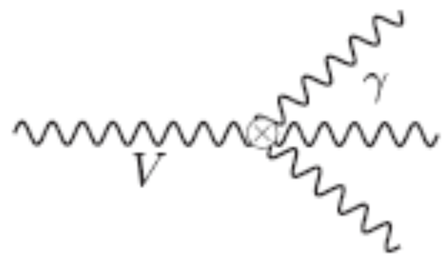
…

- 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*

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:



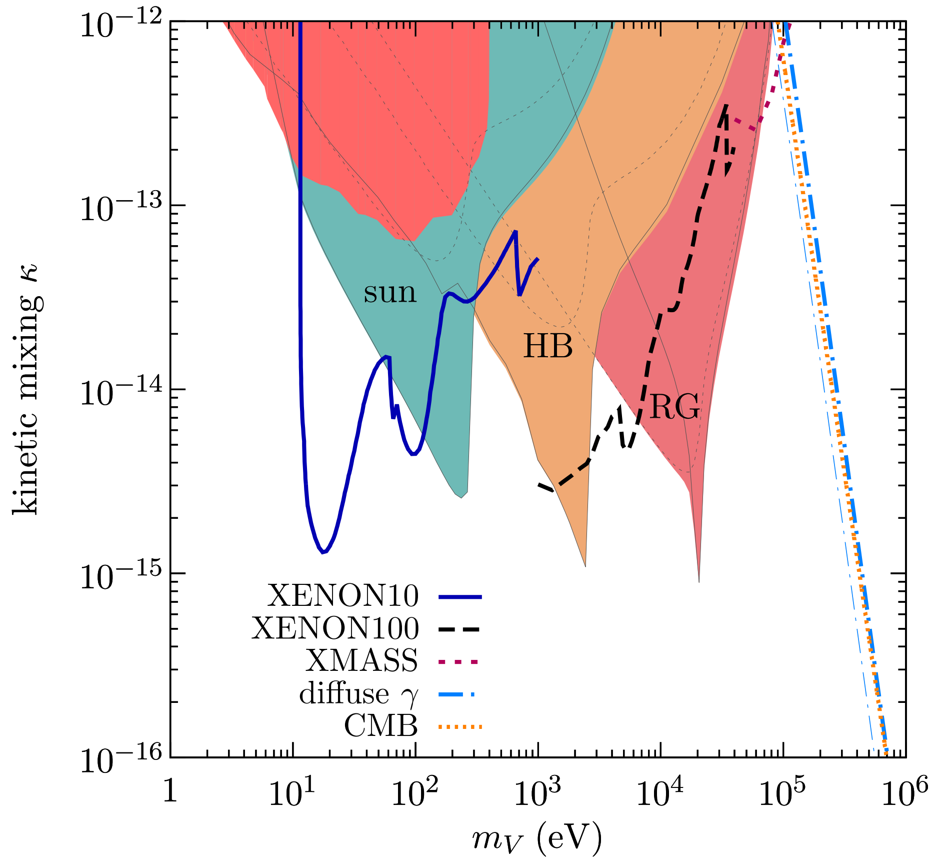
$$\Gamma = \frac{17\,\alpha^3\alpha'}{2^7 3^6 5^3 \pi^3}\,\frac{m_V^9}{m_e^8} \approx \left(4.70\times10^{-8}\right)\,\alpha^3\alpha'\,\frac{m_V^9}{m_e^8}.$$

$$\tau_{\rm U}\Gamma_{V\to3\gamma} \lesssim 1 \quad\Longrightarrow\quad m_V\,(\alpha')^{1/9} \lesssim 1\,\mathrm{keV}\ .$$

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

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

vector DM absorption signal

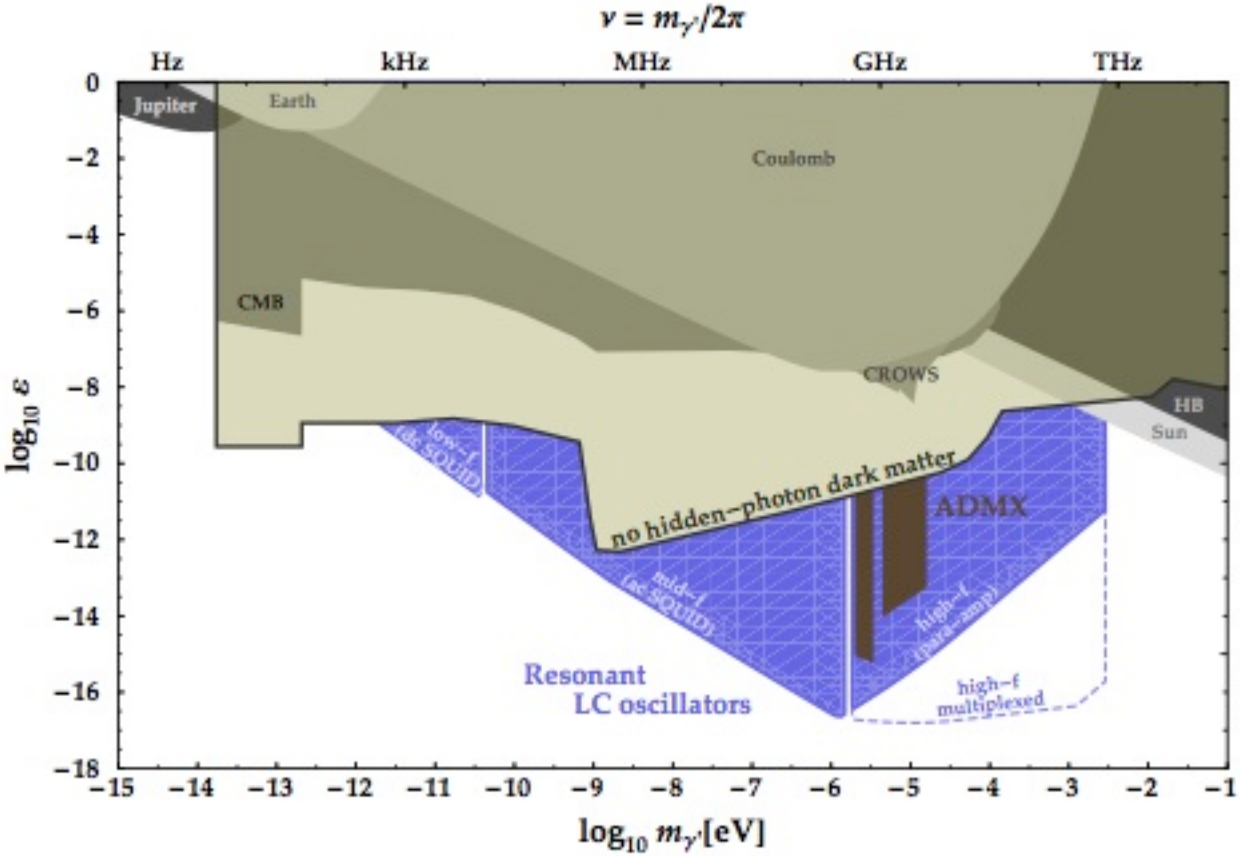


An, MP,
Pradler, Ritz

Large DM experiments can compete with stellar constraints and have sensitivity to mixing angles down to kappa ~10^{-15}.

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

Dark Photon dark matter in the sub-eV range



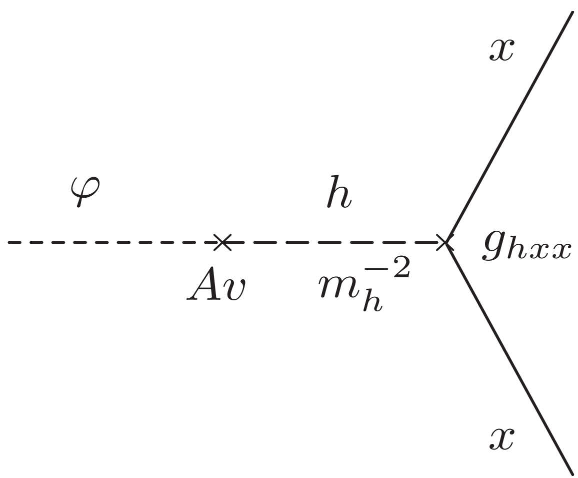
- Misaligned photon dark matter, sub-eV range, from Chaudhuri et al, 2014.

Scalar DM through super-renormalizable portal

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

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

- 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.

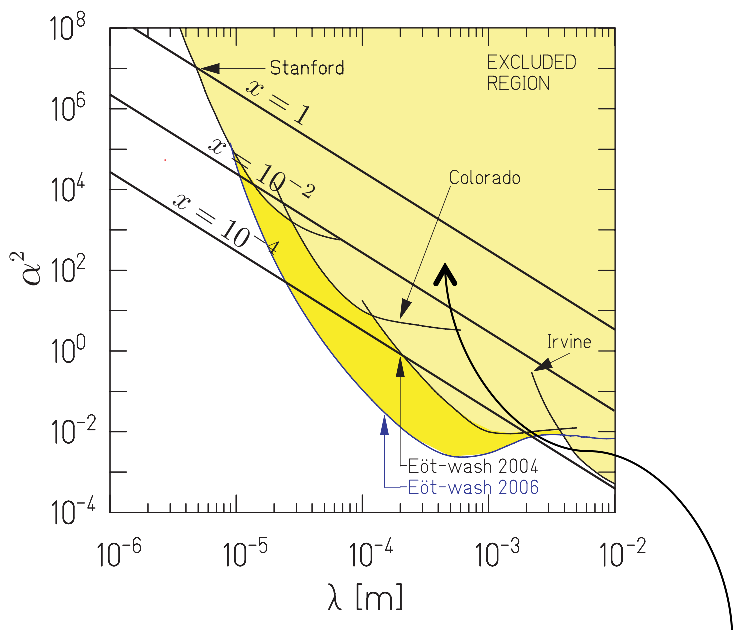
5^{th} force from Dark Matter exchange

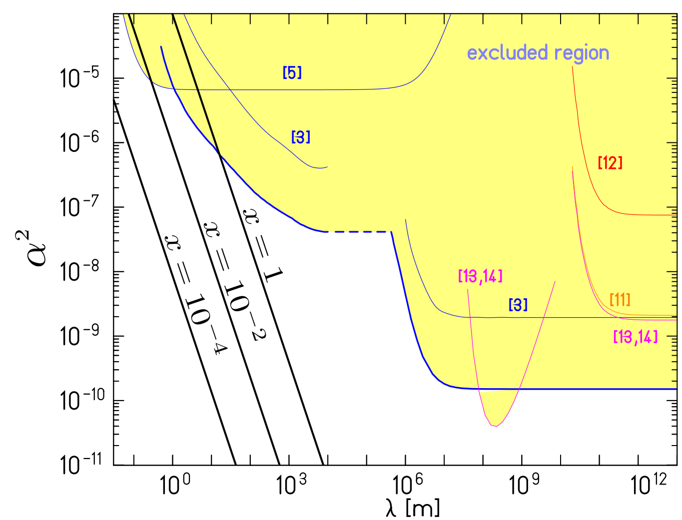
- The main observational consequence of this model: possibility to have an observable 5^{th} force (x= A/mass)
- For the traditional parametrization, $V(r) = -G\frac{m_A m_B}{r}(1+\alpha_A\alpha_B\, e^{-m_\varphi r})\,.$

we can derive the strength of coupling

(! *the second bracket* = 0.83)

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





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

Anomalous spin precession frequency

Easy to see if e.g. "Lorentz violation" searches are sensitive to ALPs dark matter:

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

Let us saturate ρ_{DM} by oscillating *a(t)*.

Let's take the *maximum allowed* f_a from stellar constraints at 10^9 GeV.

Let us take the range of masses 10^{-17} to 10^{-15} eV where e.g. K-He3 magnetometers designed for LV searches are the most sensitive

The energy shift due to DM:

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

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

Right at the edge of current sensitivity! Reanalysis of LV data can constrain dark matter in this mass range.

Macroscopic size DM *other than primordial black holes*

MP et al, 2012; Derevianko and MP, 2013

Laser Interferometers as Dark Matter Detectors

Evan D. Hall,[1] Thomas Callister,[1] Valery V. Frolov,[2] Holger Müller,[3] Maxim Pospelov,[4,5] and Rana X Adhikari[1]

To be submitted

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

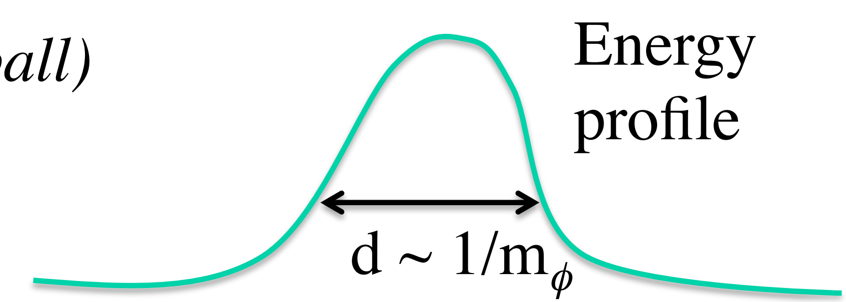
$m_\phi = \lambda^{1/2} v$

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*



Transient signals from macroscopic DM

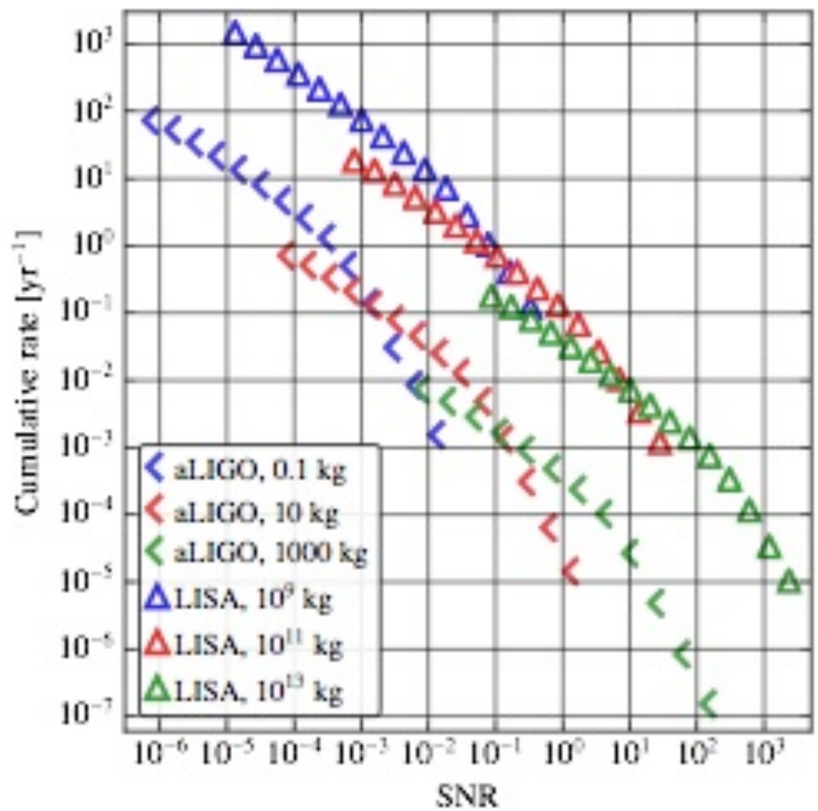
Regardless of precise nature of TD-SM particles interaction it is clear that

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 benefit from a network of detectors, or co-located 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.

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,

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

- 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).

$$\sigma_{\text{DM-DM}} = 16\pi \times \frac{G_{\text{N}}^2 \, M_{\text{DM}}^2 \, \delta_{\text{DM}}^4}{v_{\text{DM}}^4} \times \log\left[\frac{\lambda}{r_{\text{DM}}}\right]. \qquad |\delta_{\text{DM}}| \lesssim 5 \times 10^9 \times \left(\frac{1\ \text{kg}}{M_{\text{DM}}}\right)^{1/4}.$$

Sensitivity to “cat-size” DM

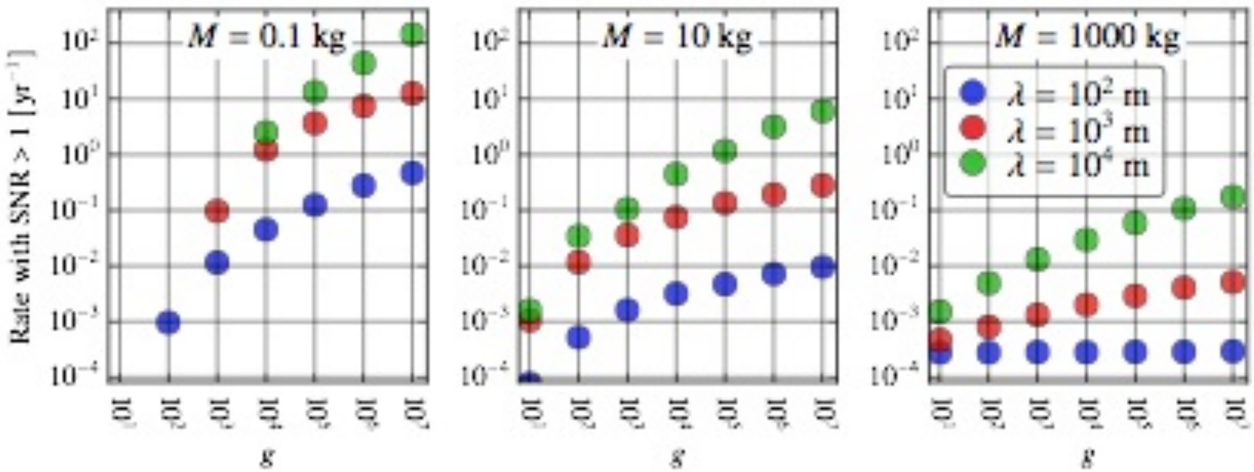


FIG. 2. (color online). Event rate $\dot{\eta}(1)$ for non-SM interactions in a single Advanced LIGO detector, as a function of coupling $g = \delta_{SM}\delta_{DM}$ and screening length λ.

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

Best sensitivity to O(1kg) range.

Simulation by Adhikari, Callister, Frolov, 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. Analysis of precision physics data ("Lorentz violation" searches, 5^{th} force searches) may reveal the presence of new states.

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