From 10^{-20} to 10^{60} eV: looking for dark matter over a broad range of possibilities

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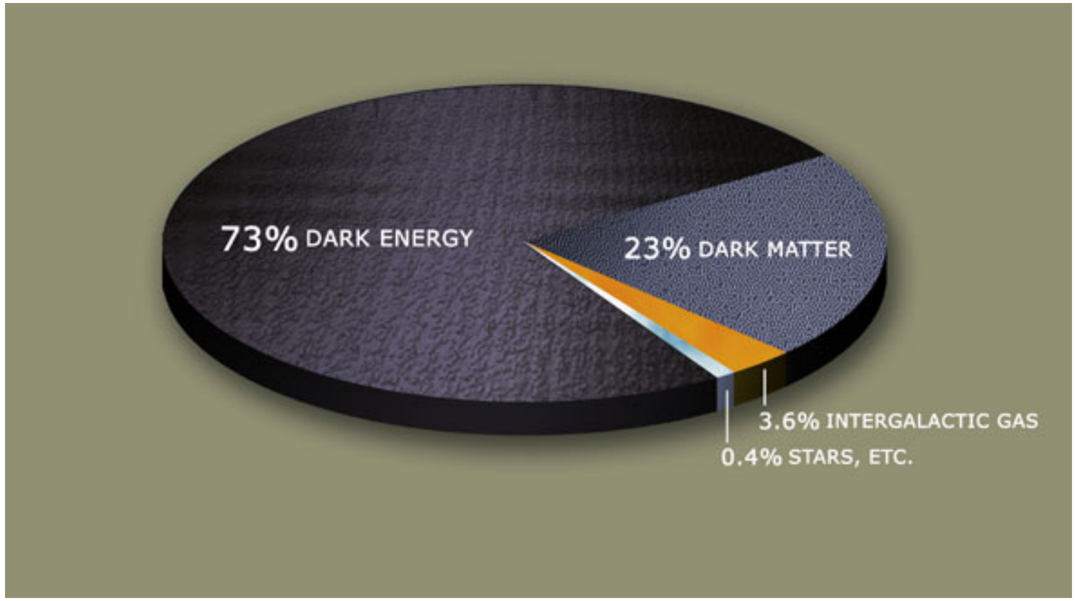
Outline of the talk

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

“Macroscopic” DM possiblities

- Primordial black holes ($M_{BH} > 10^{15}$ g)
- MACHOs
- Non-topological solitons (Q-balls)
- Topological defects (e.g. monopoles etc)
- ……..

[Cosmological history for most part is not worked out…]

WIMP “lamp post”

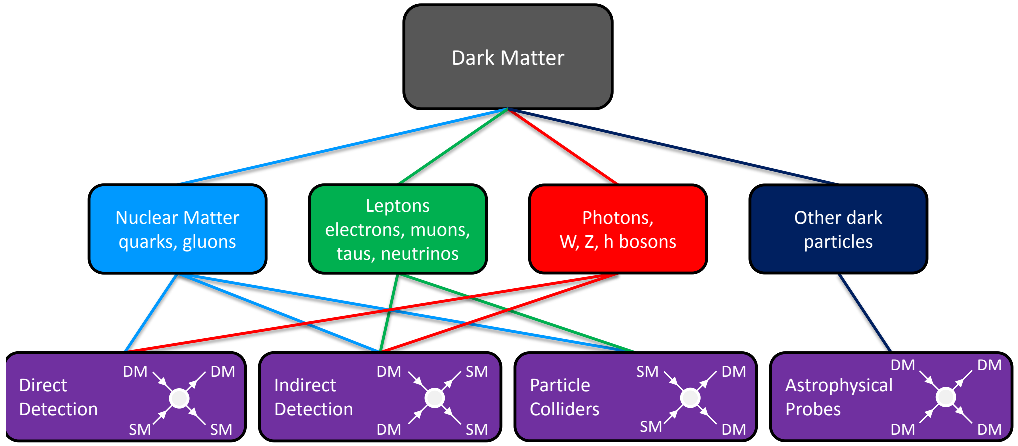
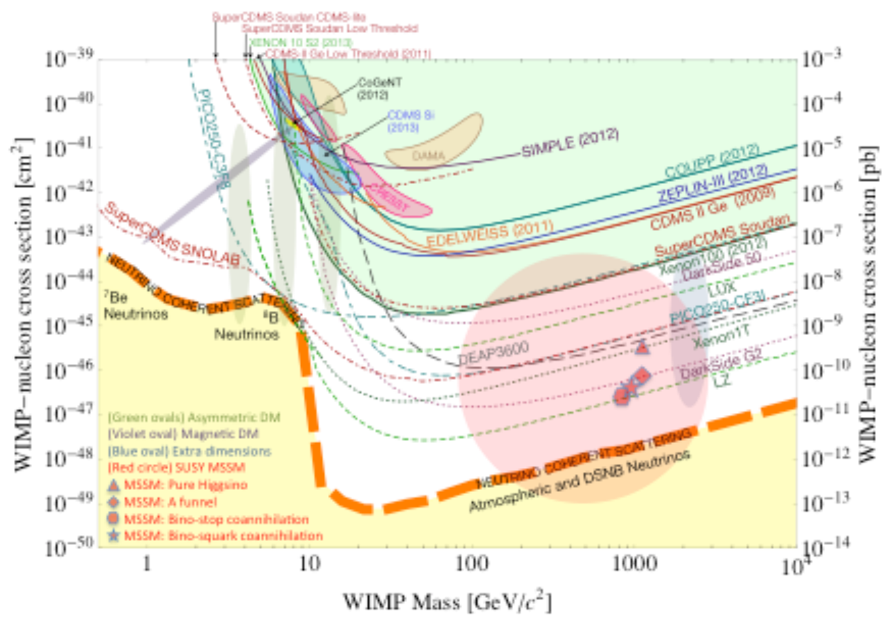
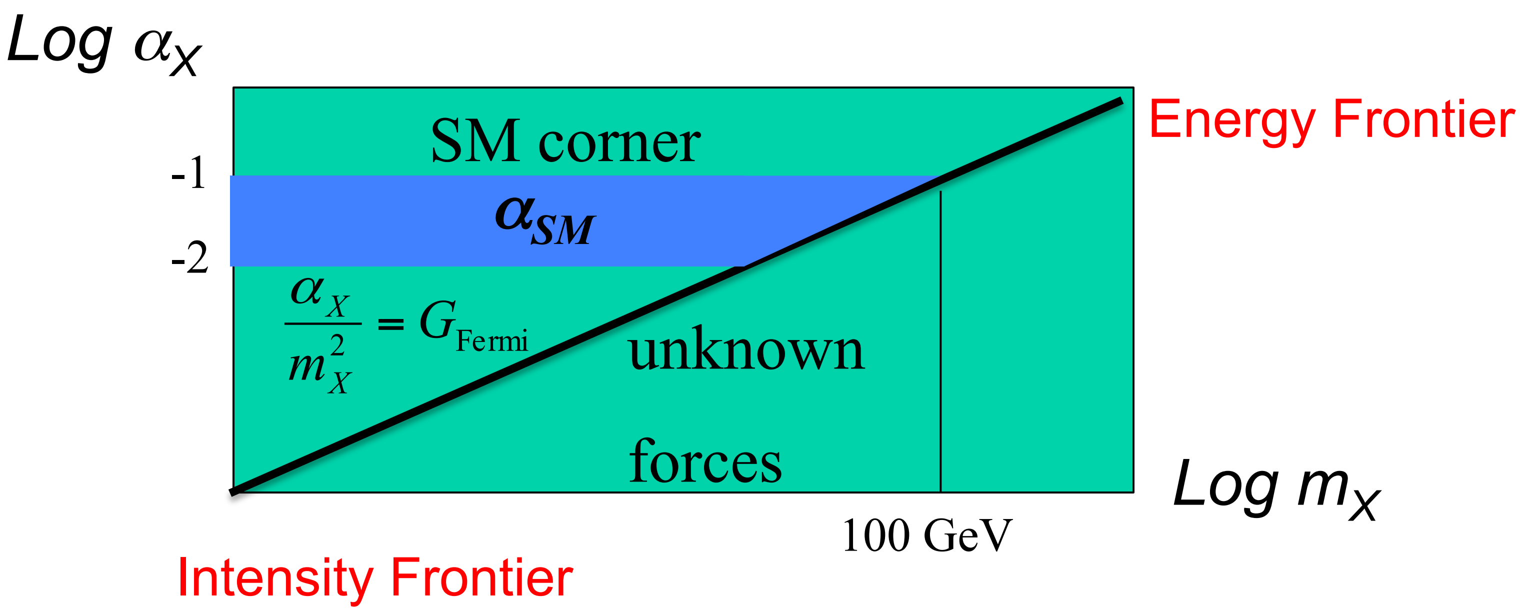


Figure 5. *Dark matter may have non-gravitational interactions with any of the known particles as well as other dark particles, and these interactions can be probed in several different ways.*



From the Snowmass 2013 summary, 1310.8327

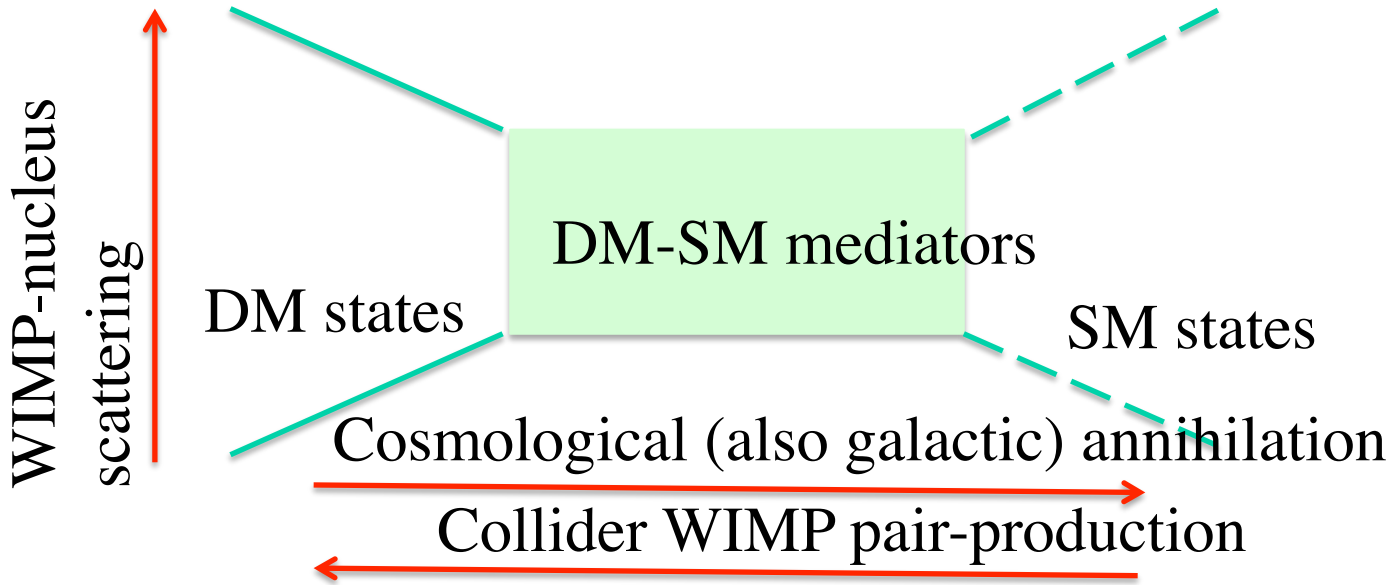
Intensity and Energy Frontiers



$$V(r) = \frac{\alpha_X}{r}\exp(-r/\lambda_X) = \frac{\alpha_X}{r}\exp(-rm_X) \longrightarrow \text{Amplitude} \approx \frac{\alpha_X}{q^2 + m_X^2}$$

LHC can realistically pick up New Physics with $\alpha_X \sim \alpha_{SM}$, and $m_X \sim$ 1TeV, while having no success with $\alpha_X \sim 10^{-6}$, and $m_X \sim$ GeV.

WIMP paradigm



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

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

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 80 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 and dark photons

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.

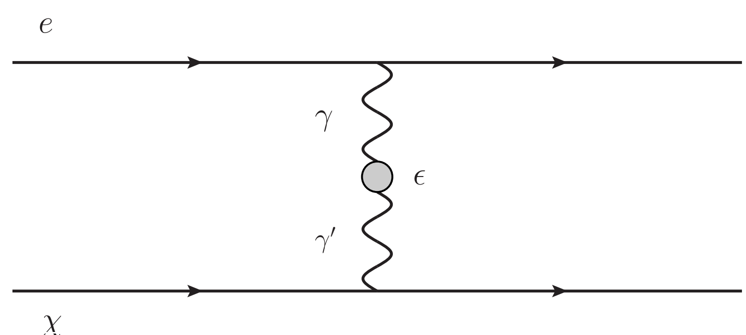
Well over several hundred theory papers have been written with the use of this model in some form in the last six years

Model for "mini-charged" particles

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

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

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



- "Effective" charge of the "dark sector" particle χ is $Q = e \times \varepsilon$ (if momentum scale $q > m_V$). At $q < m_V$ one can say that particle χ has a non-vanishing *EM charge radius*, $r_\chi^2 \simeq 6\epsilon m_V^{-2}$.

“Non-decoupling” of secluded U(1) Theoretical expectations for masses and mixing

Suppose that the SM particles are not charged under new $U_S(1)$, and communicate with it only via extremely heavy particles of mass scale Λ (however heavy!, e.g. 100000 TeV) charged under the SM $U_Y(1)$ and $U_S(1)$ (B. Holdom, 1986)

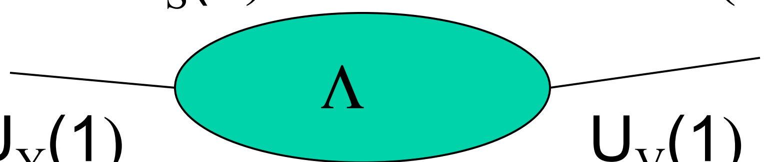


Diagram $U_Y(1)$ $U_V(1)$ does not decouple!

A mixing term is induced, $\kappa\, F^Y_{\mu\nu} F^S_{\mu\nu}$,

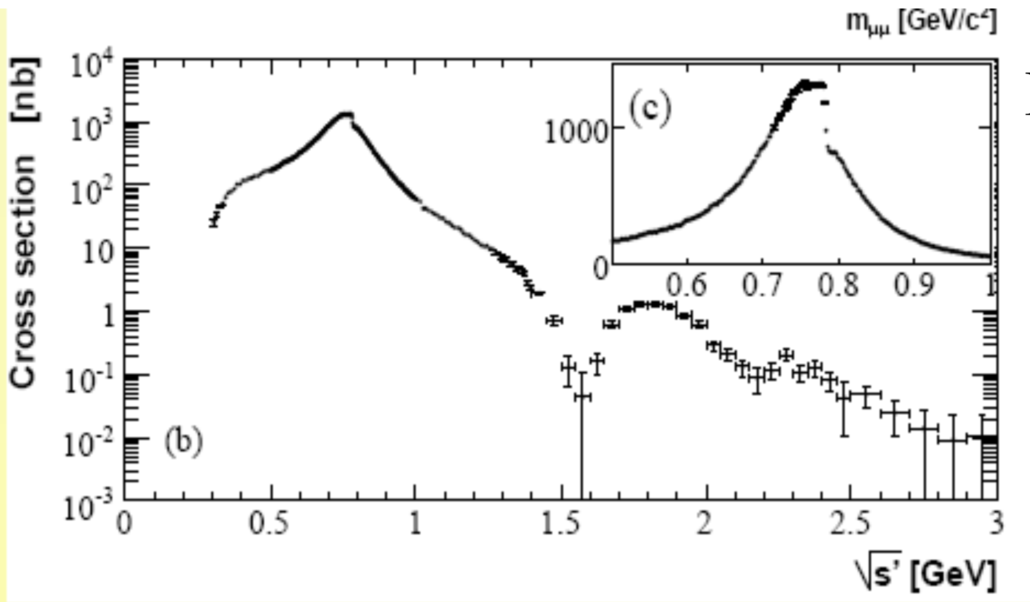
With κ having only the log dependence on mass scale Λ

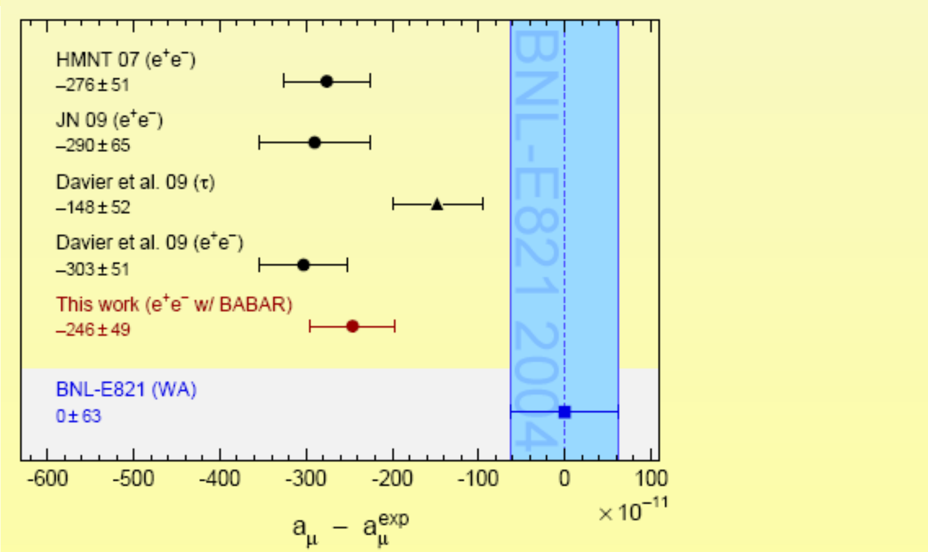
$\kappa \sim (\alpha\alpha')^{1/2} (3\pi)^{-1} \log(\Lambda_{UV}/\Lambda) \sim 10^{-3}$

$M_V \sim e'\kappa M_{EW}$ (M_Z or TeV) ~ MeV – GeV

This is very “realistic” in terms of experimental sensitivity range of parameters.

g-2 of muon





✱ Davier et al. arXiv:0906-5443

More than 3 sigma discrepancy for most of the analyses. Possibly a sign of new physics, but some complicated strong interaction dynamics could still be at play.

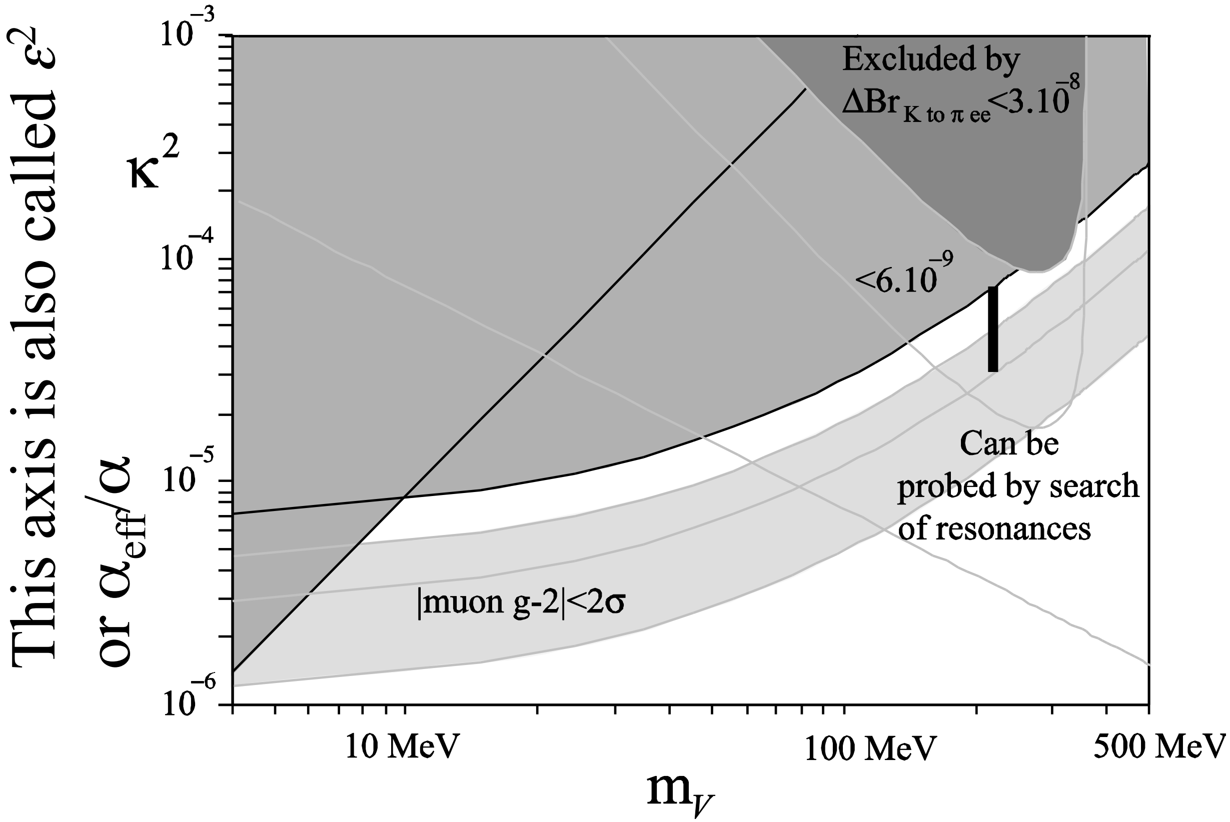
Supersymmetric models with large-ish $\tan\beta$; light-ish sleptons, and right sign of μ parameter can account for the discrepancy.

Sub-GeV scale vectors/scalars can also be at play.

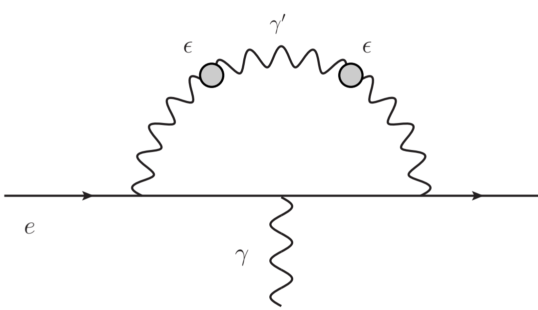
κ-m_V parameter space

If g-2 discrepancy taken seriously, a new vector force can account for deficit. (Krasnikov, Gninenko; Fayet; Pospelov)

E.g. mixing of order few 0.001 and mass $m_V \sim m_\mu$

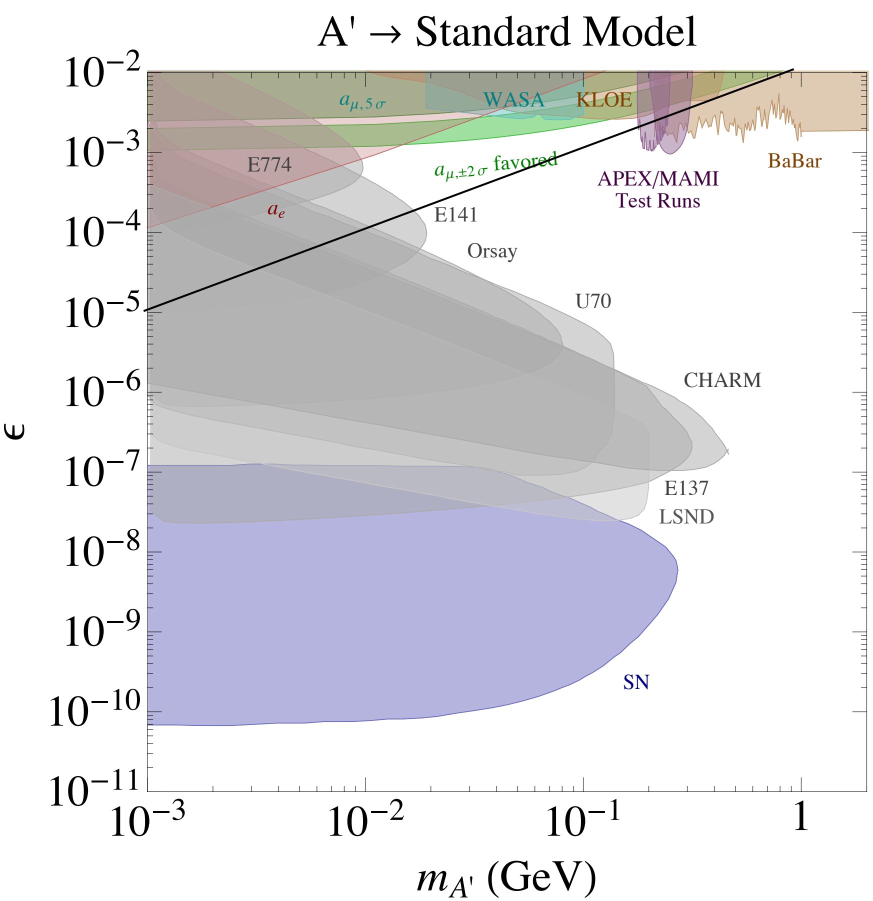


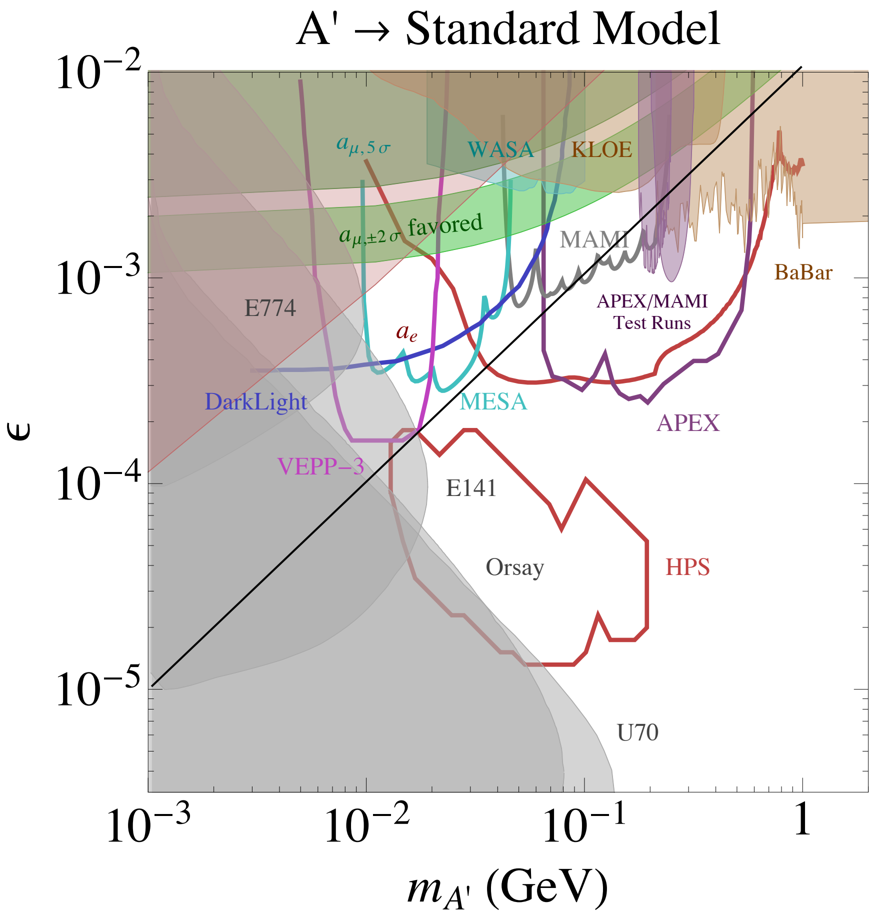
MP, 2008



Since 2008 a lot more of parameter space got constrained

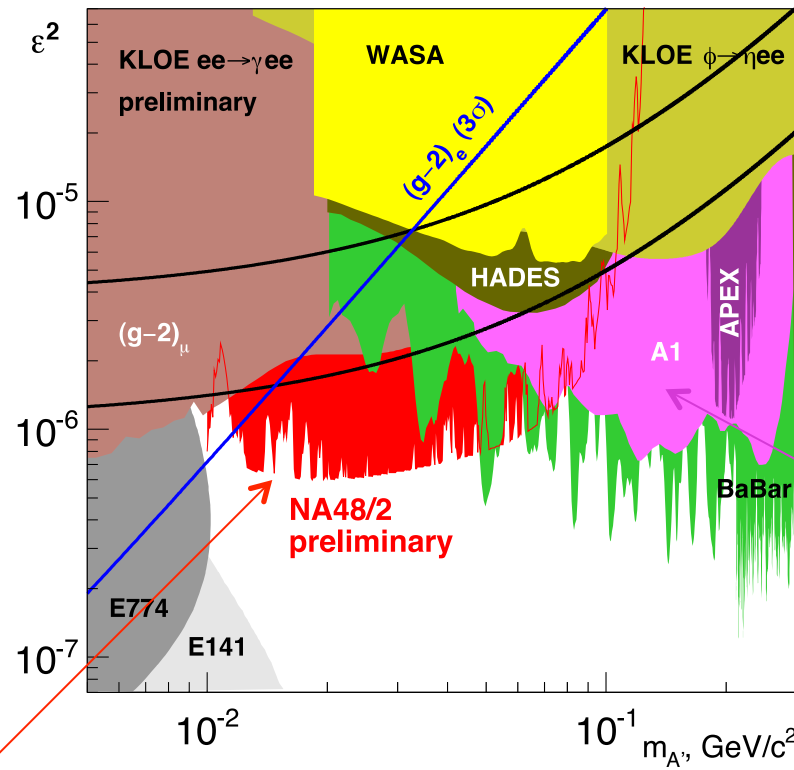
ε-m_V parameter space, Essig et al 2013





Dark photon models with mass under 1 GeV, and mixing angles ~ 10^{-3} represent a "window of opportunity" for the high-intensity experiments, and soon the g - 2 ROI will be completely covered. *Gradually, all parameter space in the "SM corner" gets probed/excluded.*

Latest result from NA48



B. Echenard et al, BabarB.

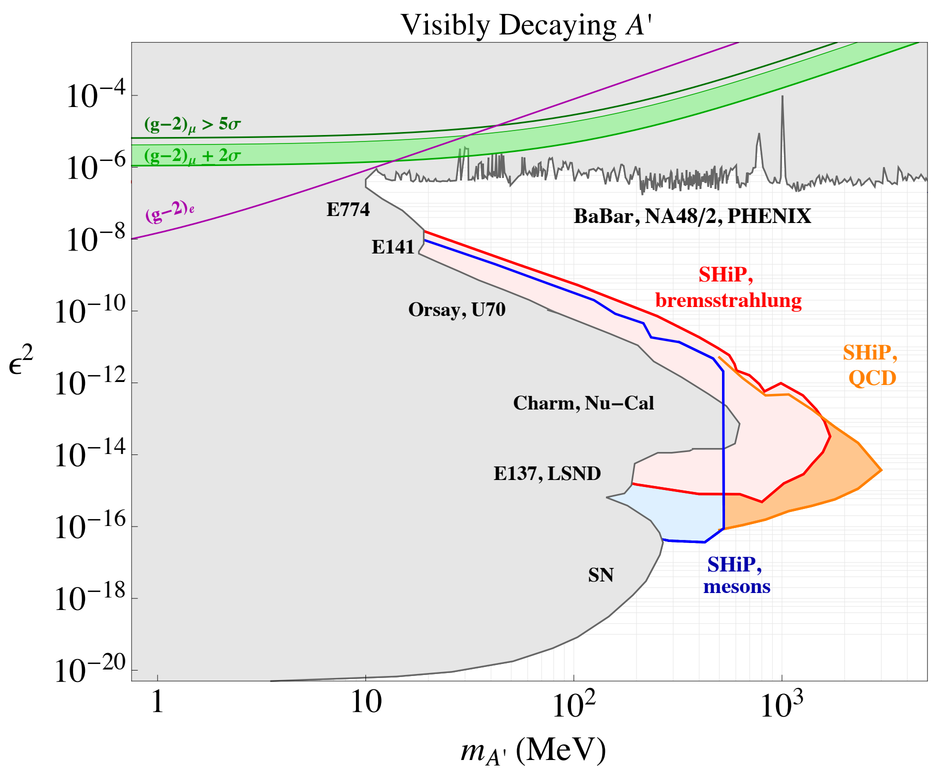
H. Merkel et al, Mainz

E. Goudzovski et al (NA48) 2014 – excludes the remainder of parameter space relevant for g-2 discrepancy.

Only more contrived options for g-2 remain (e.g. $L_\mu - L_\tau$)

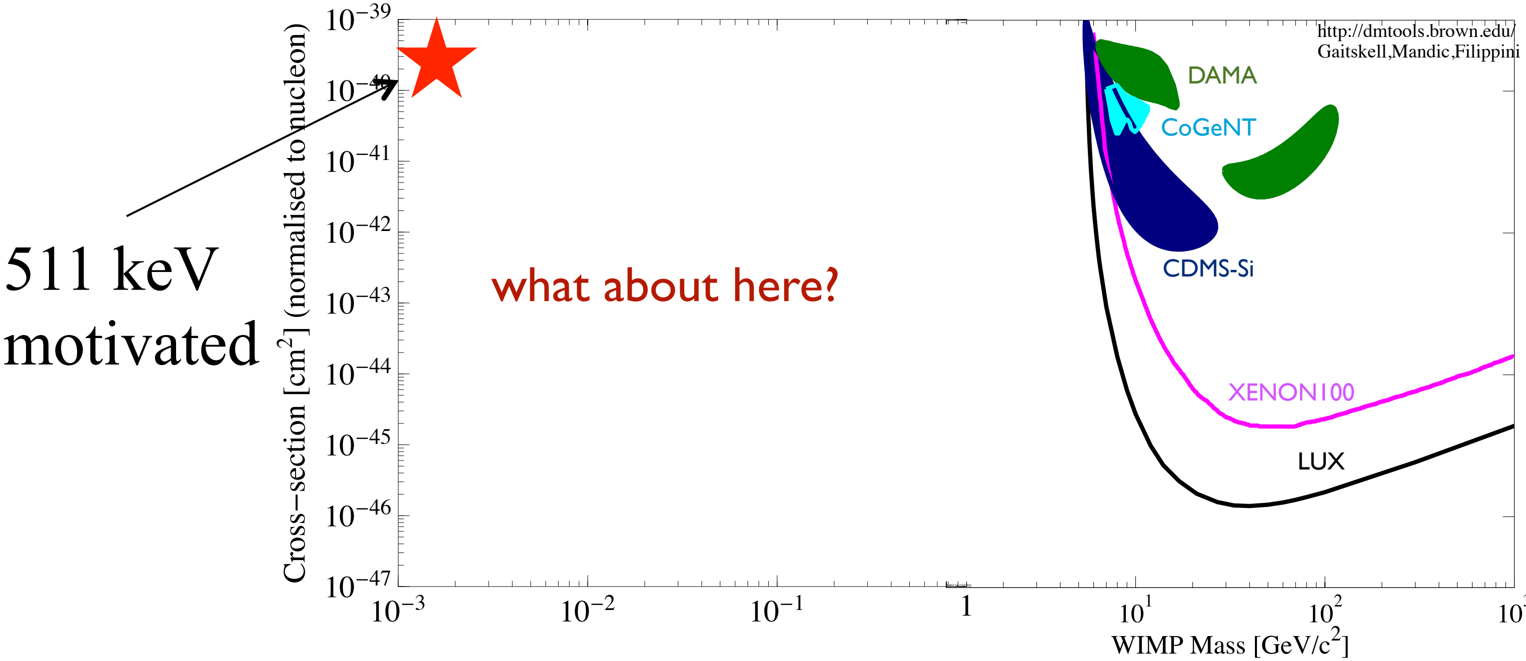
Future: SHiP project at CERN

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



What if dark photon decays to light dark matter? (epicycle #2)

Light DM – direct production/detection



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

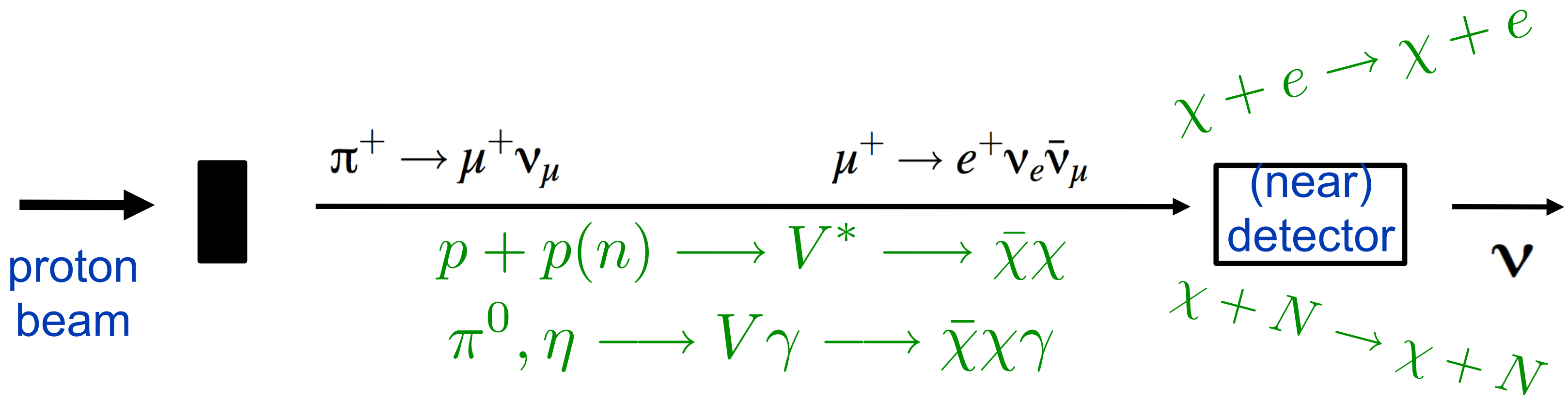
$$\mathcal{L} \supset |D_\mu \chi|^2 - m_\chi^2 |\chi|^2 - \frac{1}{4}(V_{\mu\nu})^2 + + \frac{1}{2} m_V^2 (V_\mu)^2 - \frac{\kappa}{2} V_{\mu\nu} F^{\mu\nu} + \ldots$$

DM

mediation

Fixed target probes - Neutrino Beams

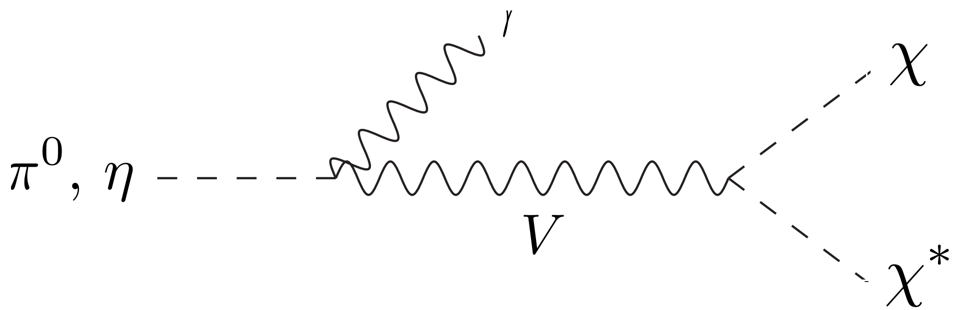
Proposed in Batell, MP, Ritz, 2009. Strongest constraints on MeV DM

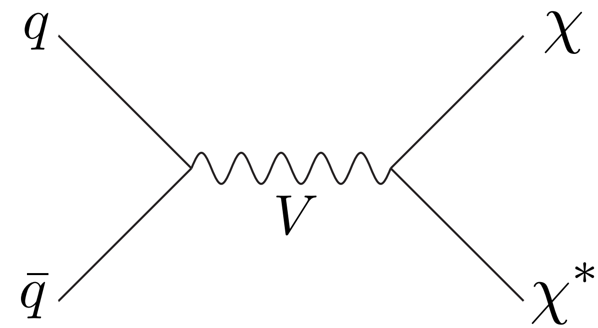


We can use the neutrino (near) detector as a dark matter detector, looking for recoil, but now from a relativistic beam. E.g.

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

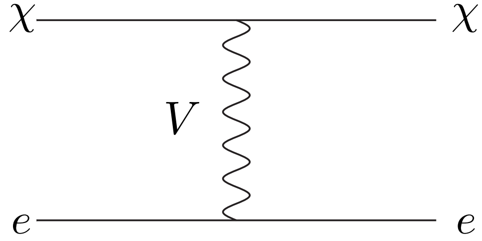
Light DM - trying to force the issue



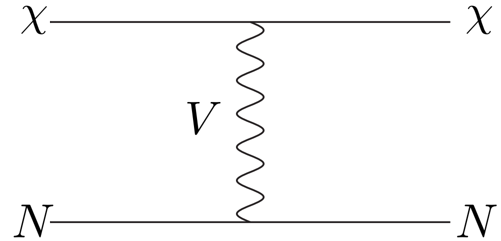


In the detector:

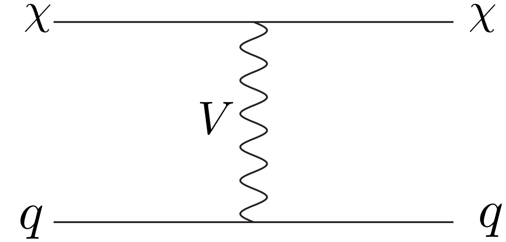
Elastic scattering on electrons



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:

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

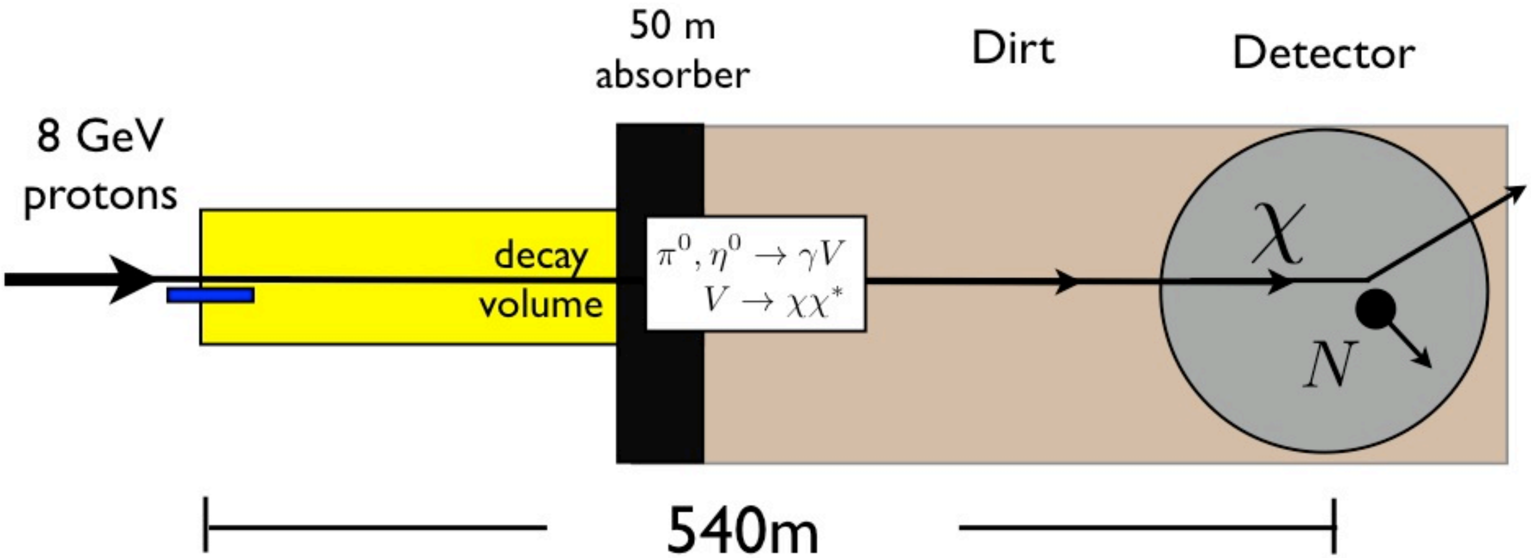
Detection:

Larger than weak scale x-section!

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 +…)

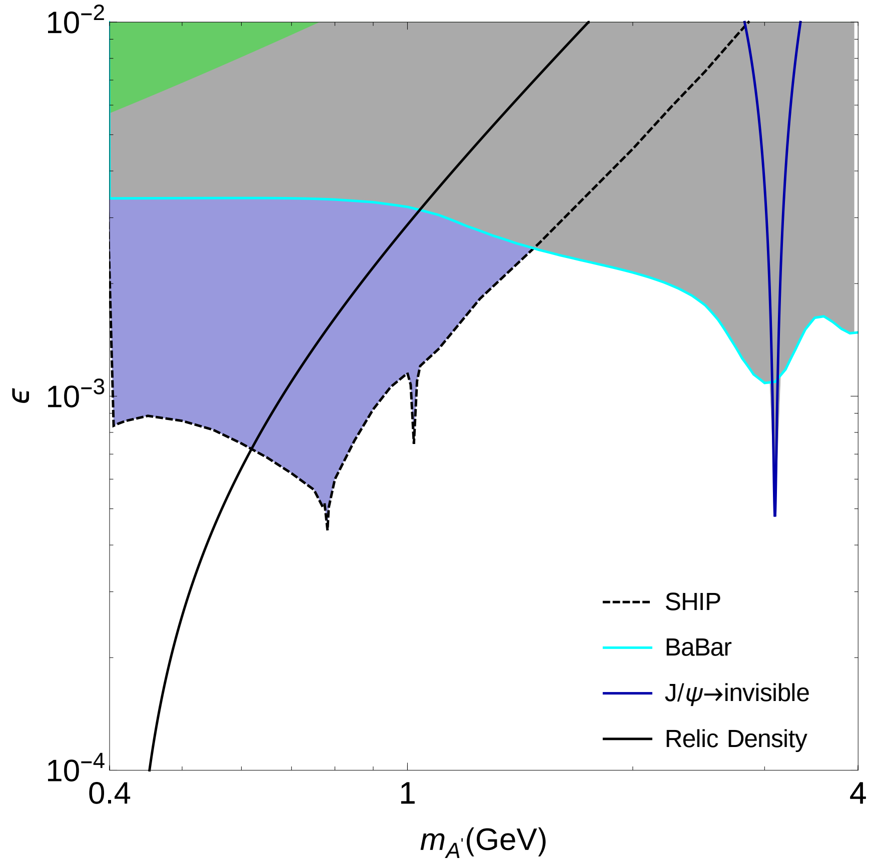
Timing is used (10 MeV dark matter propagates slower than neutrinos) to further reduce backgrounds

Future?? SHiP proposal at CERN

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

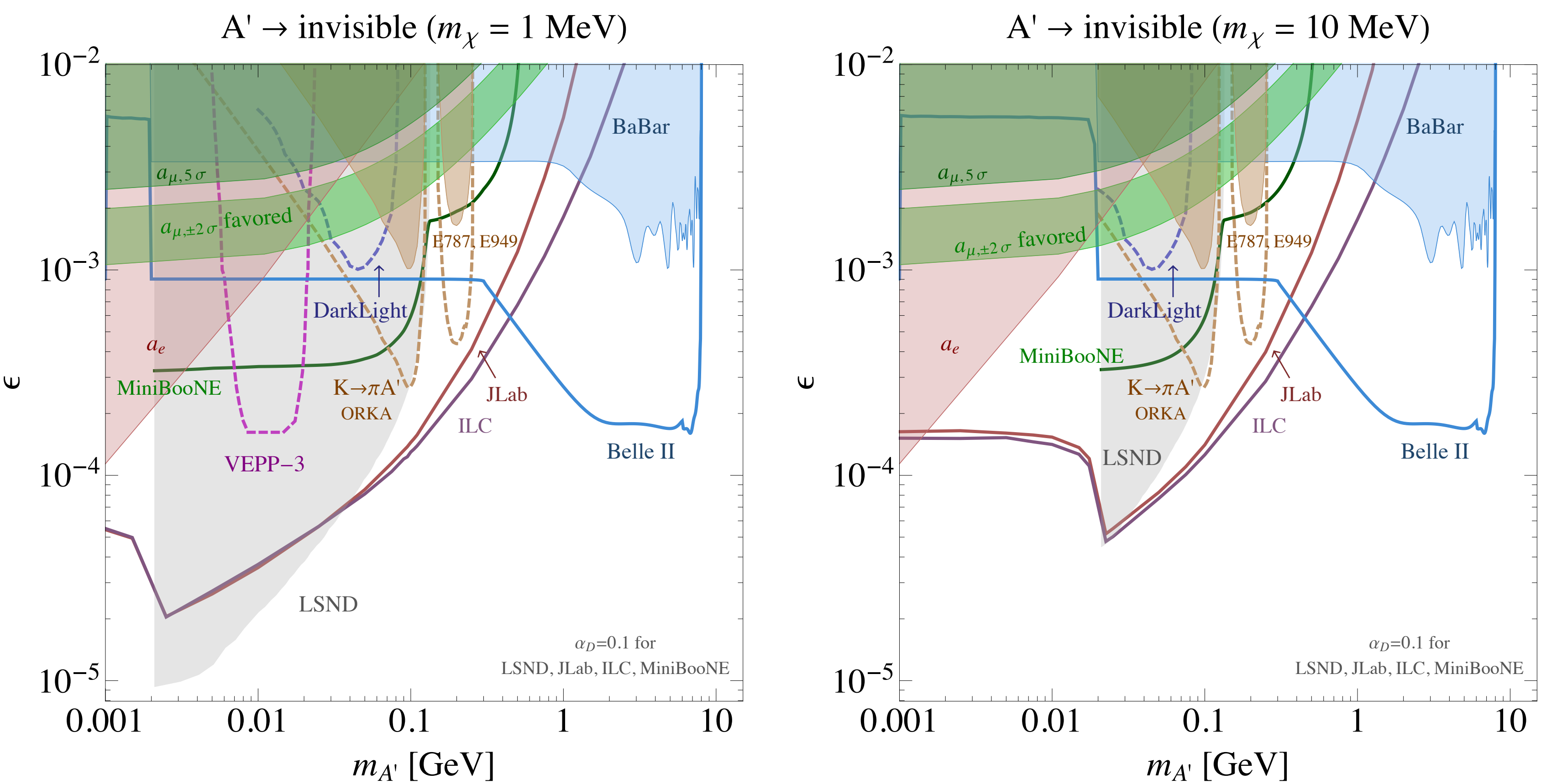
Dark photon mediator, m_{DM} =200 MeV

(Figure by P. deNiverville)



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

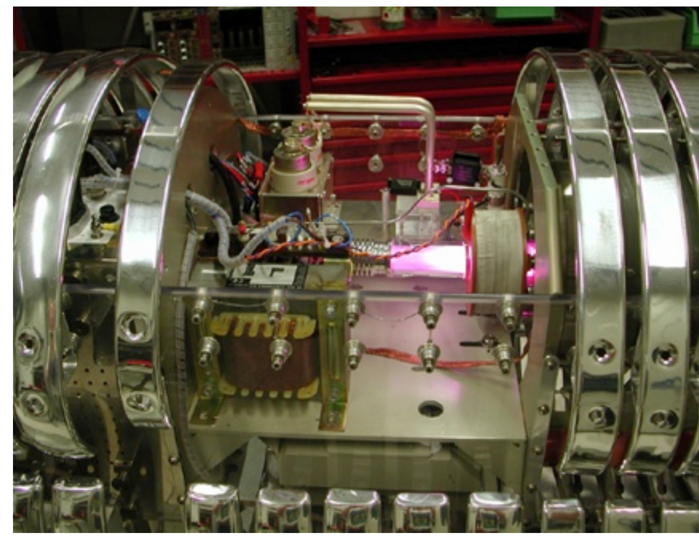
Compilation of current constraints on dark photons decaying to light DM



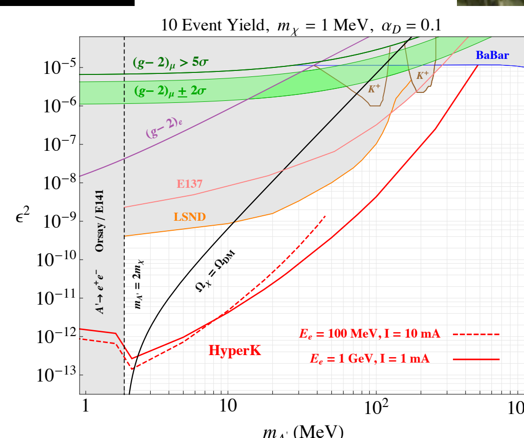
The sensitivity of *electron beam dump experiments* to light DM is investigated in Izaguirre, Krnjaic, Schuster, Toro 2013; Surujon et al. . New collaboration, BDX

More coverage of parameter space using underground accelerators and neutrino detectors

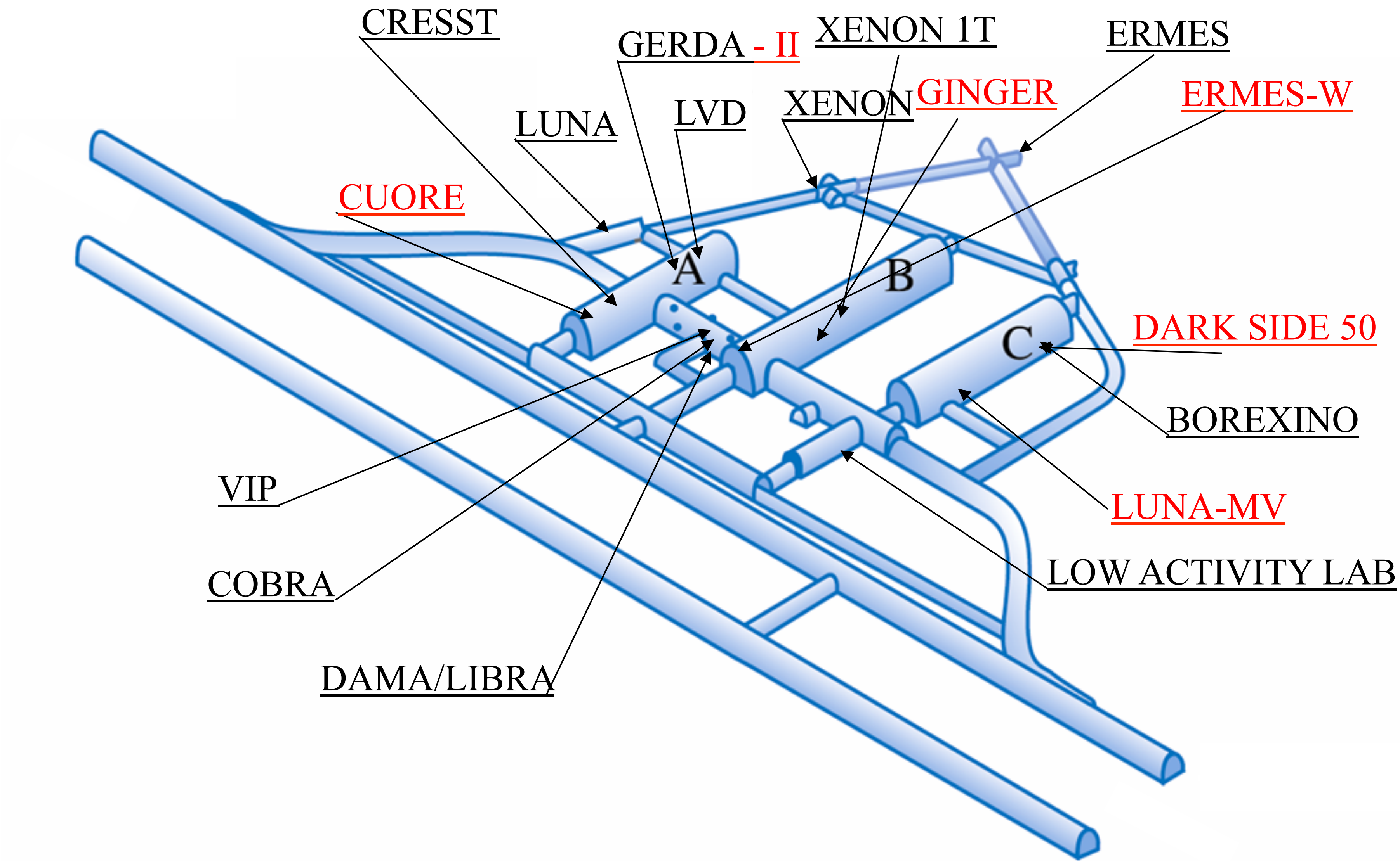
with Eder Izaguirre and Gordan Krnjaic, 2014, 2015



Borexino, Kamland, SNO+, SuperK, HyperK…

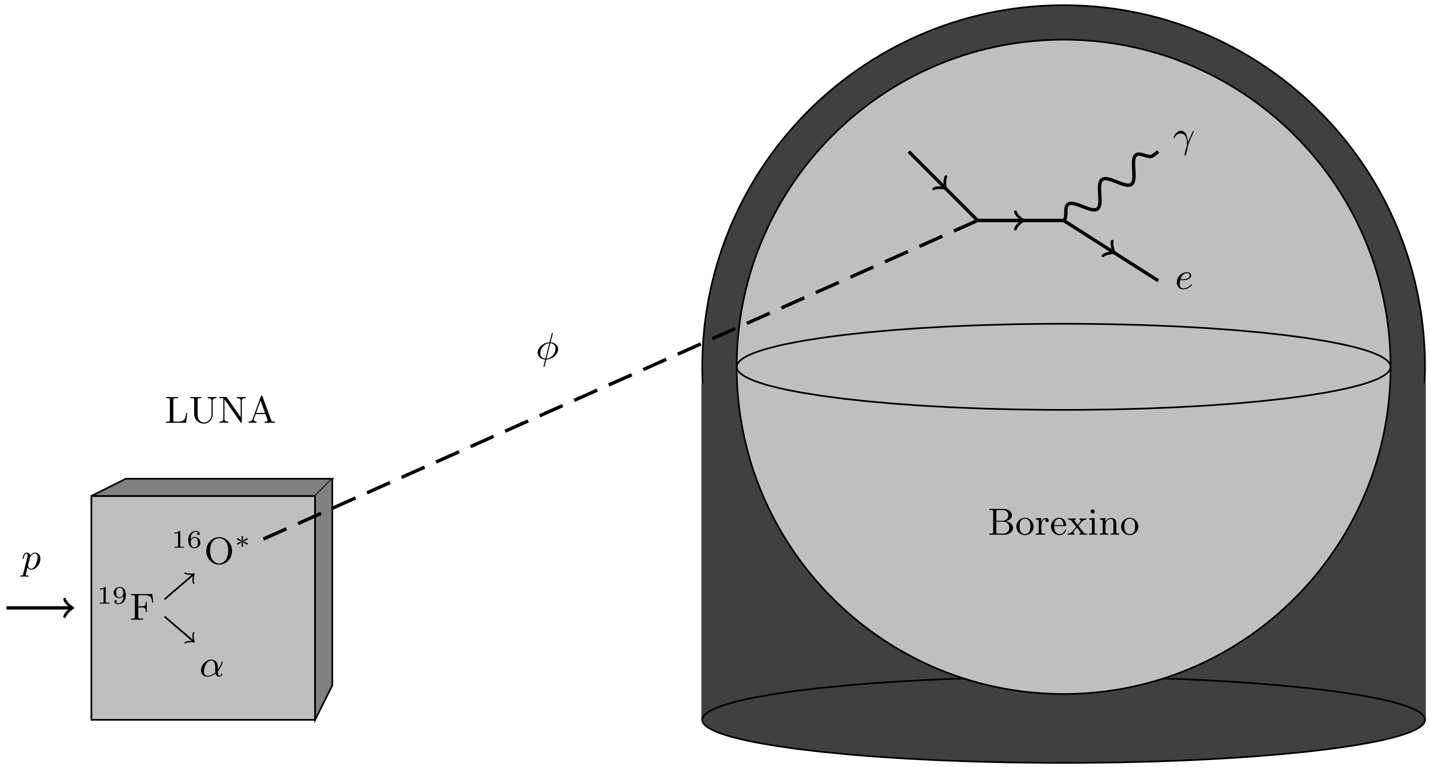


LUNA, DIANA,…+ new accelerators



Planned location of LUNA-MV is in direct proximity of Borexino

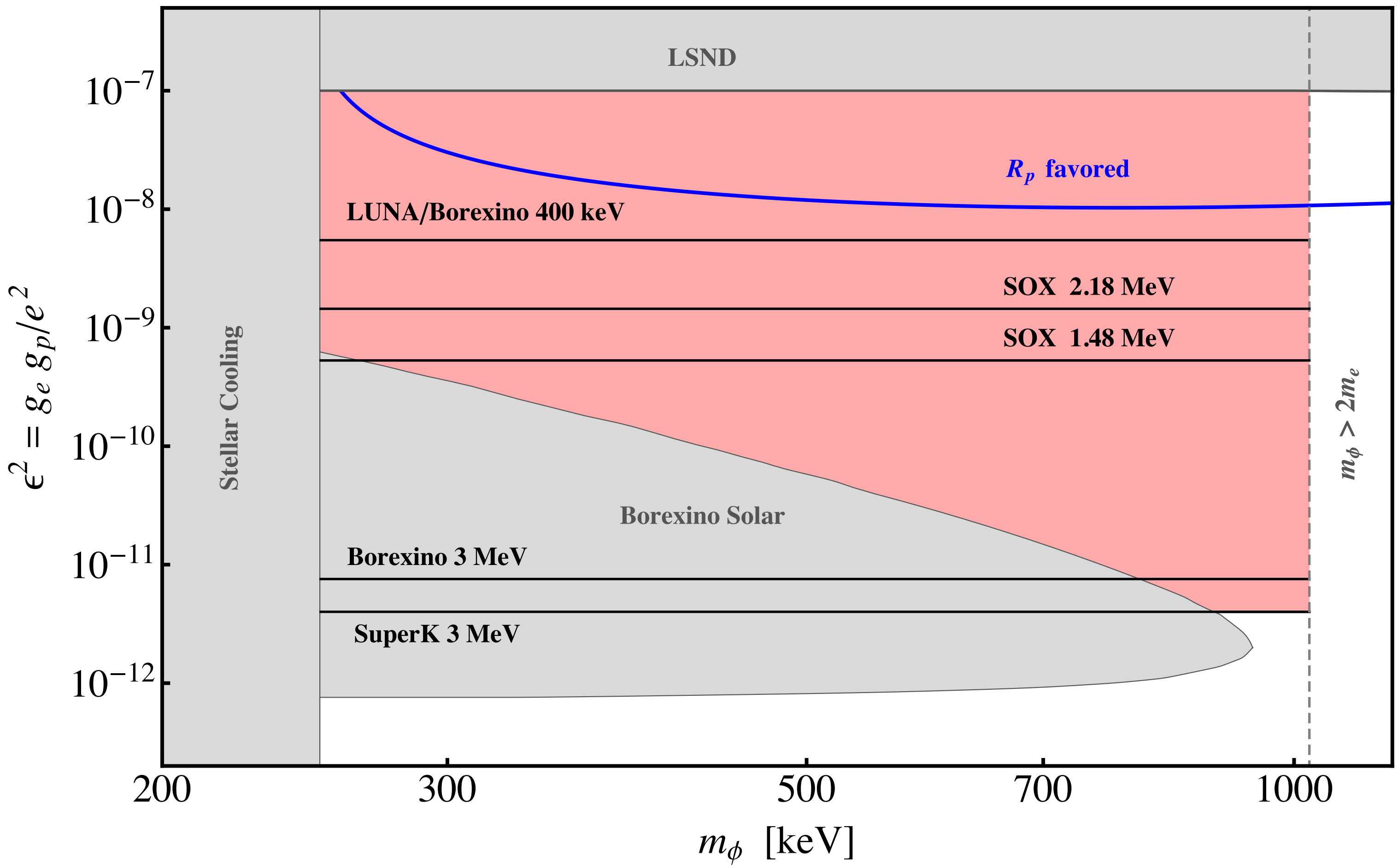
“Coupling” LUNA and Borexino



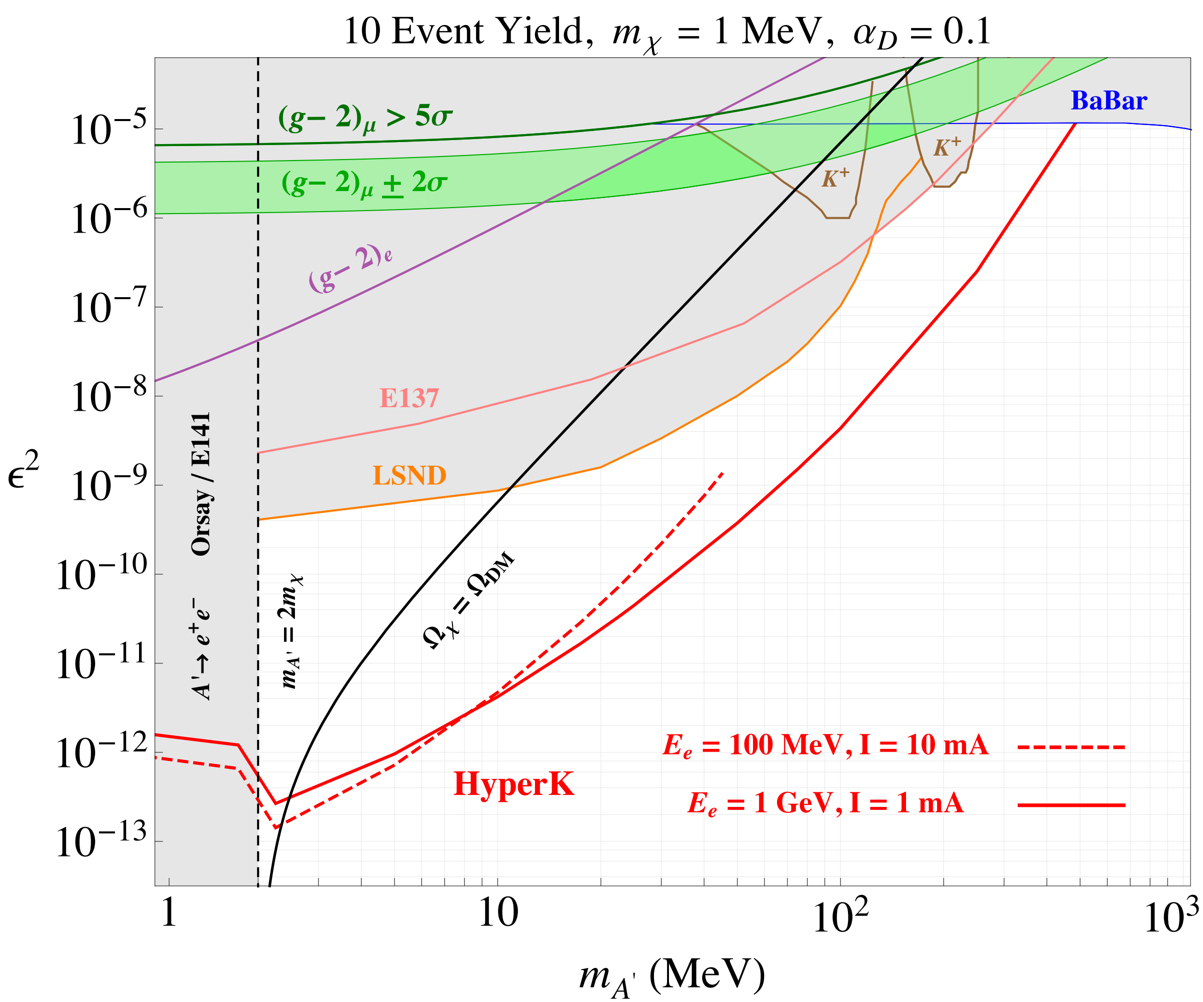
Potential problem: nuclear reactions can liberate some neutrons (e.g. via ^{19}F +α → ^{22}Na +n), and there are stringent requirements on not increasing *n* background at the location of DM experiments.

Sensitivity plot

- 6.05 MeV is in the “cleanest” region of Borexino.
- *r_p relevant region can be fully covered.*



Sensitivity to light DM



$$\mathcal{L} = \mathcal{L}_\chi - \frac{1}{4}V_{\mu\nu}V^{\mu\nu} + \frac{1}{2}m_V^2 V_\mu V^\mu - \frac{\kappa}{2}V^{\mu\nu}F_{\mu\nu} + \cdots$$

with

$$\mathcal{L}_\chi = \begin{cases} i\bar{\chi}\not{D}\chi - m_\chi\bar{\chi}\chi, & \text{(Dirac fermion DM)} \\ |D_\mu\chi|^2 - m_\chi^2|\chi|^2, & \text{(Complex scalar DM)} \end{cases}$$

One can have a chance on improving sensitivity to very light DM, and e.g. decisively test models that aim at explaining 511 keV bulge excess via DM annihilation.

One will advance sensitivity to ALPs in 200 keV < m_a <100 MeV range

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

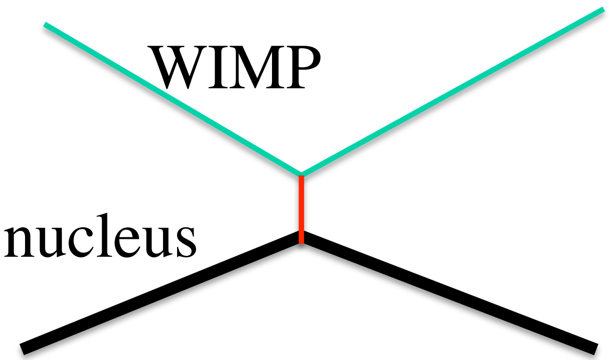
$$\text{(pseudo)scalar} \quad g_S S\bar{\psi}\psi, \quad g_P P\bar{\psi}\gamma_5\psi,$$
$$\text{(pseudo)vector} \quad g_V V_\mu\bar{\psi}\gamma_\mu\psi, \quad g_A \mathcal{A}_\mu\bar{\psi}\gamma_\mu\gamma_5\psi,$$
$$\text{tensor} \quad g_T T_{\mu\nu}\bar{\psi}\sigma_{\mu\nu}\psi, \quad \cdots$$

- *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]:

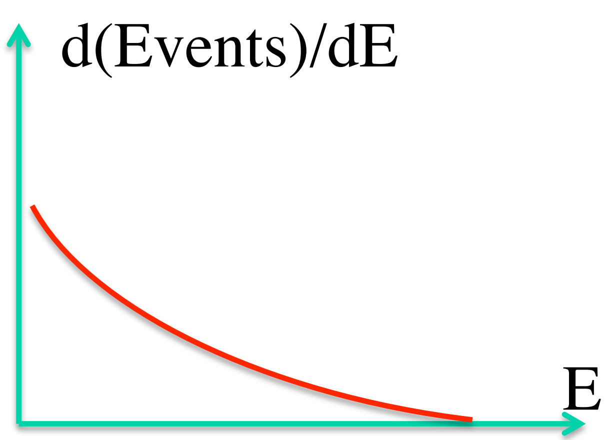
  e.g. $m_S > 10^{-1}\, g_S \times \text{Cutoff} \sim 10^{-11}\, (g_S/10^{-10})\ \text{TeV} \sim 10\ \text{eV}$
- Why bosonic? Sterile neutrinos can also do N + e → ν + e, but rates are tiny, and energy deposition is miniscule.

New DM signal: absorption of super-WIMPs

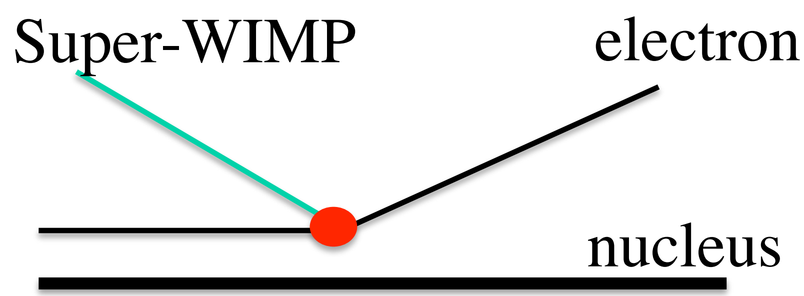
WIMP-nucleus scattering



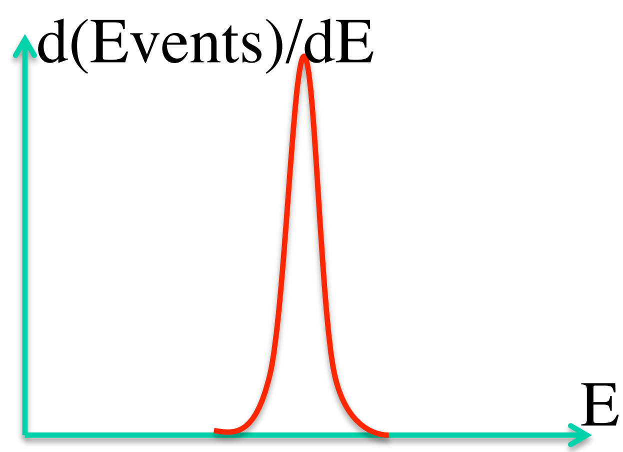
Signal: ionization + phonons/light



Atomic absorption of super-WIMPs



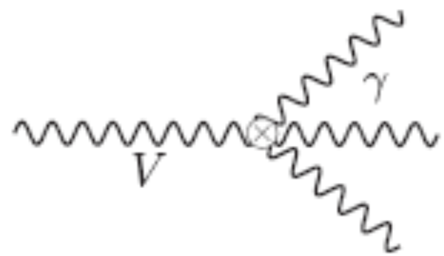
Ionization at $E = m_{superWIMP}$



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:



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

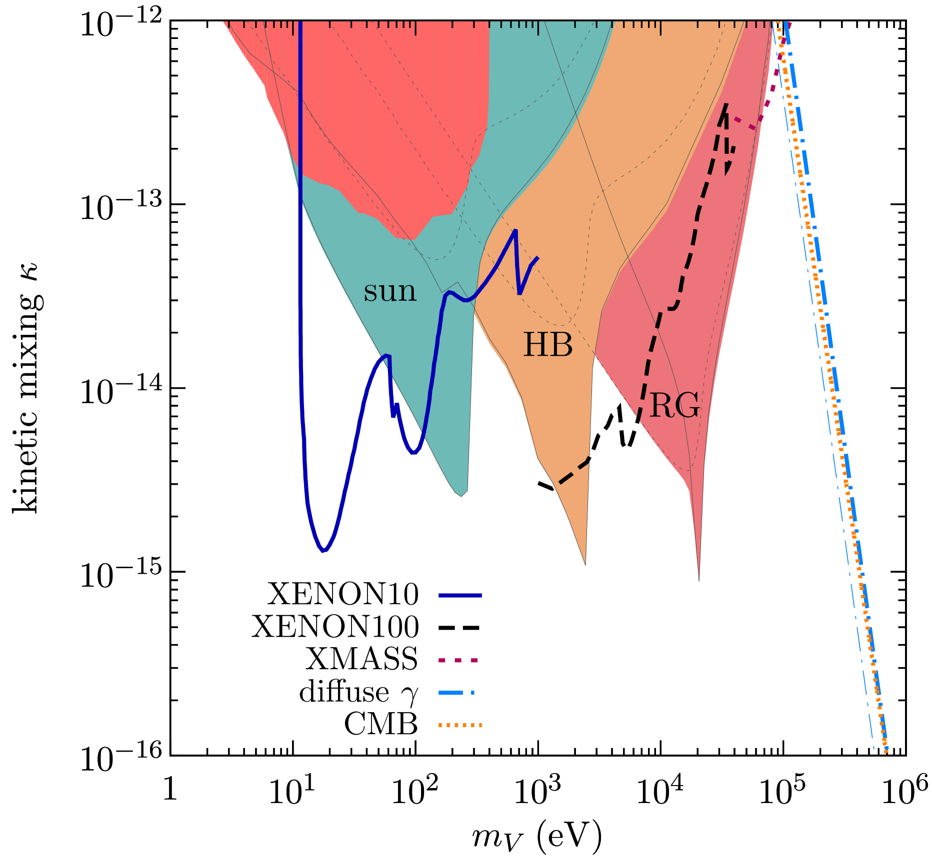
$$\tau_U \Gamma_{V\to3\gamma} \lesssim 1 \implies m_V\,(\alpha')^{1/9} \lesssim 1\,\mathrm{keV}\ .$$

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

Super-cool Dark Matter from misalignment

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

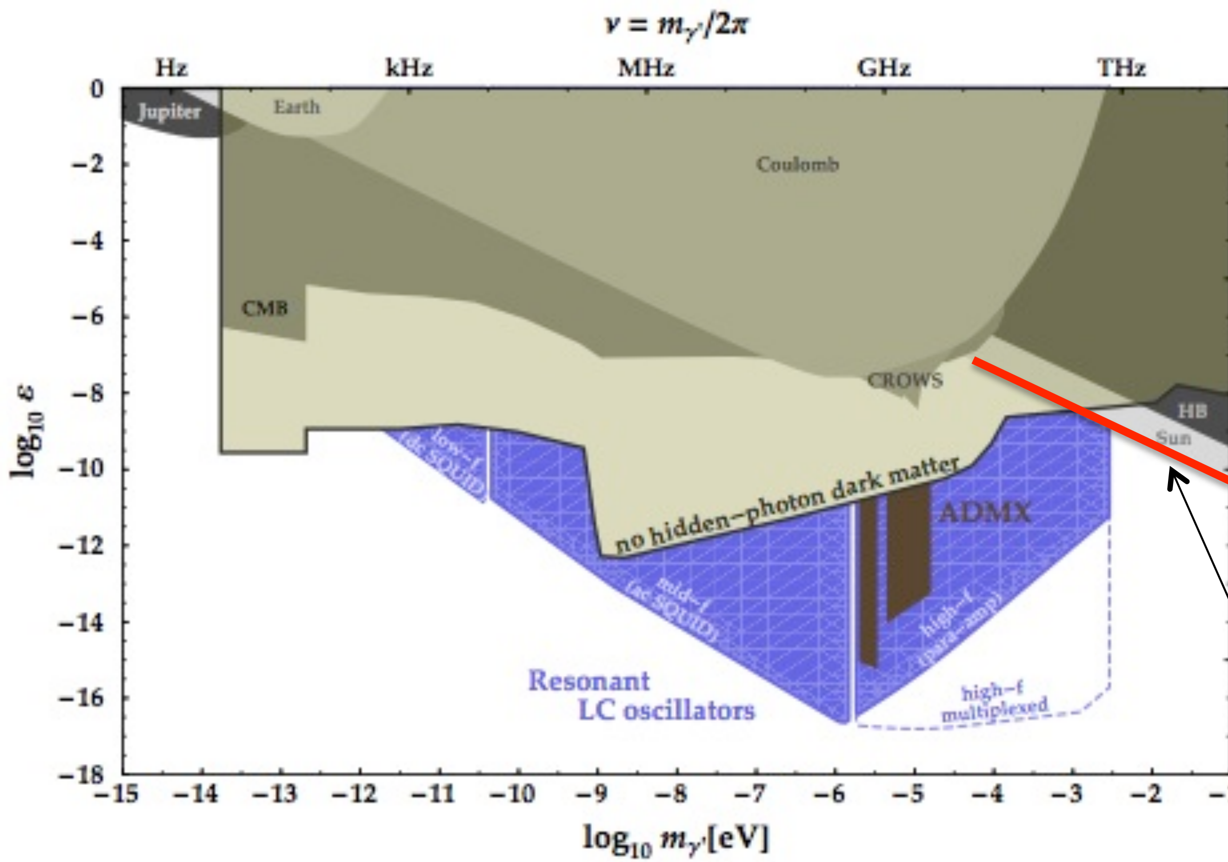
- QCD axion (1981- onwards).

…

- 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. [See also Joerg, Andreas and Javier's work.]



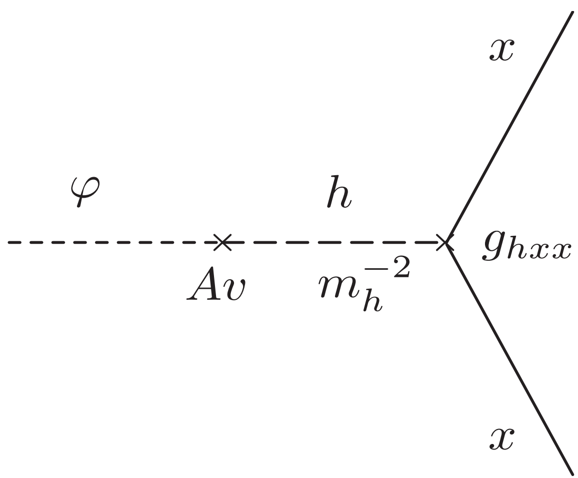
Xenon10 limit

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.

5th force from Dark Matter exchange

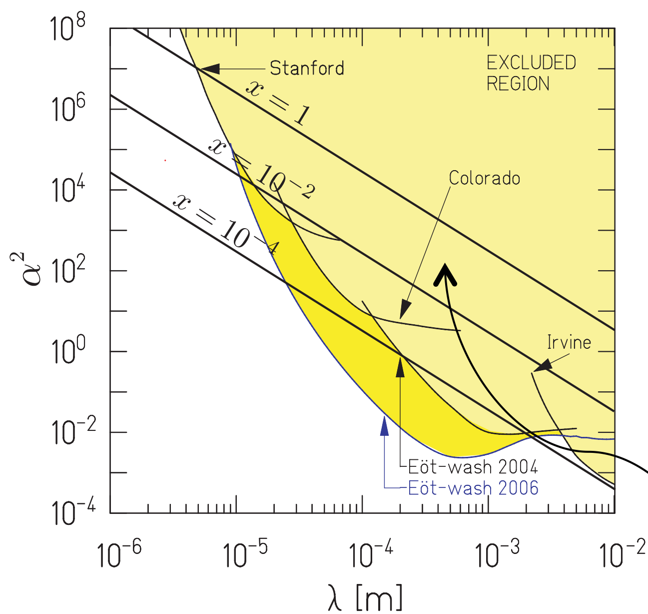
- The main observational consequence of this model: possibility to have an observable 5th force (x= A/mass)
- For the traditional parametrization,

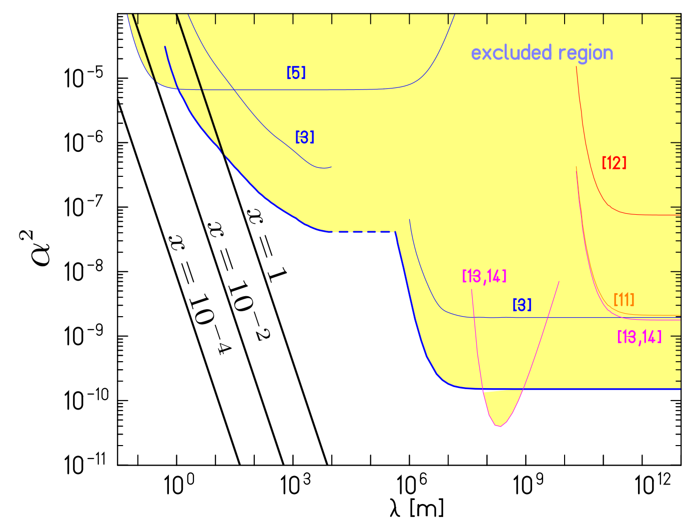
$$V(r) = -G\frac{m_A m_B}{r}\left(1+\alpha_A\alpha_B\, e^{-m_\varphi r}\right).$$

we can derive the strength of coupling

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

(! *the second bracket* = 0.83)





One can expect a “natural” 5th 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

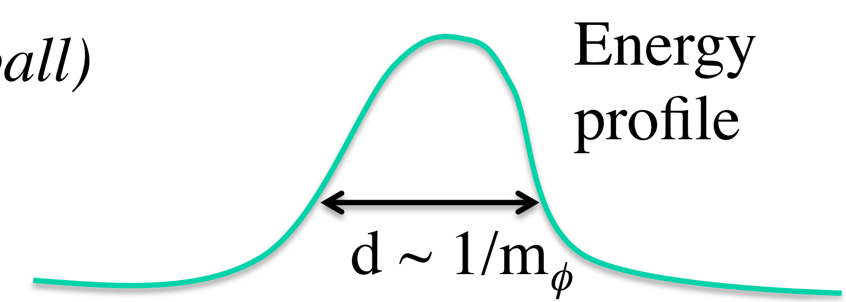
$m_\phi = \lambda^{1/2} v$

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)*

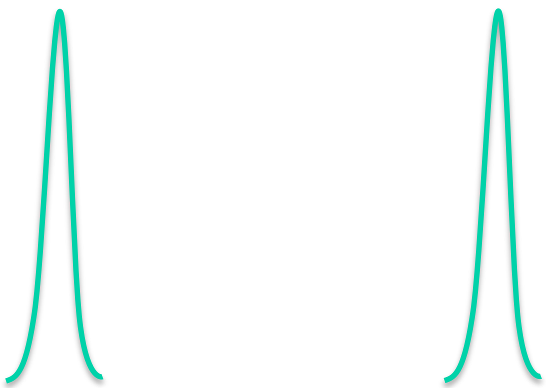
1D object – a *String*

2D object – a *Domain wall*

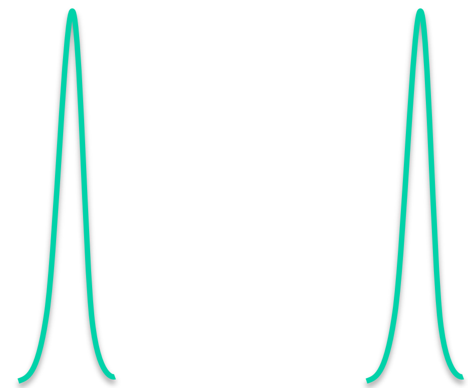


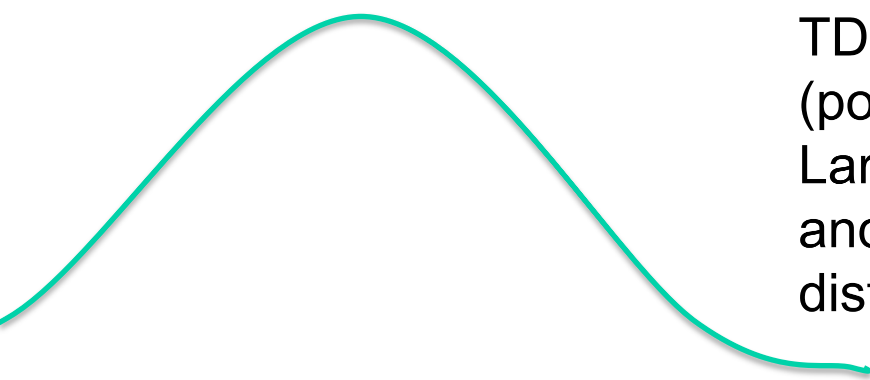
Comparison with WIMPs and axions

Axions – small amplitude but “no space” between particles

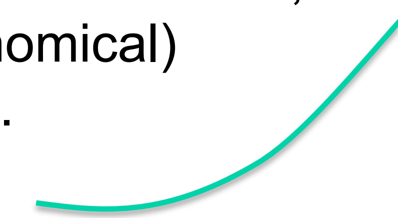


WIMPs – EW scale lumps of energy (>> axion amplitude), very concentrated in space. And with significant ~ cm gaps between particles





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

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

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

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

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

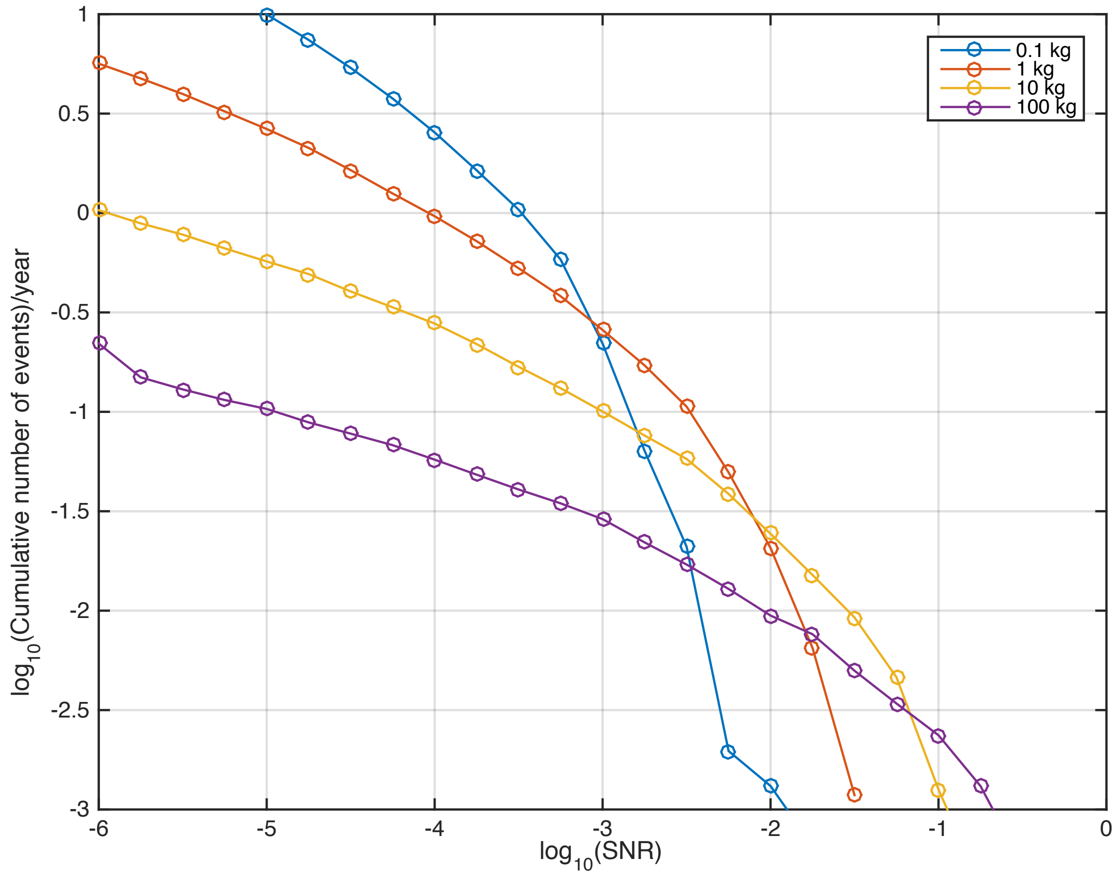
Experimental developments [old slide]

- 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, Callister, 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

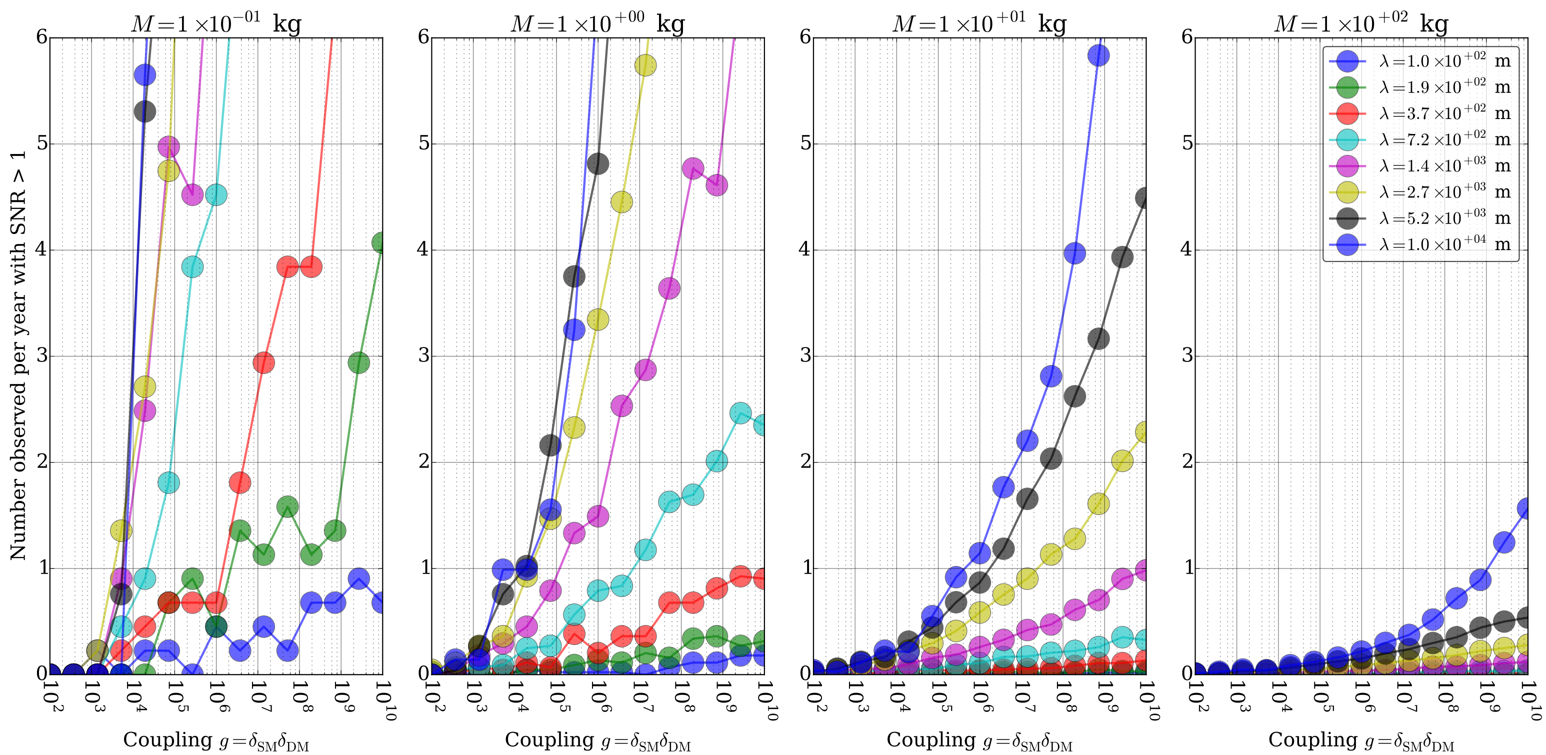
- A non-gravitational interaction between DM and SM could be parametrized by a Yukawa force,

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

- From the 5^{th} 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).

- $\sigma_{DM}/m_{DM} < 1\ \mathrm{cm}^2/\mathrm{g} \;\rightarrow\; \delta_{DM} < 10^{10} \;\rightarrow\; \delta_{SM}\delta_{DM} < 10^7$

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, Callister, 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.