Dark matter from hidden sectors

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Perimeter Institute, Waterloo/University of Victoria, Victoria

Moriond EWK meeting, 2016

University of Victoria | British Columbia Canada

PERIMETER INSTITUTE FOR THEORETICAL PHYSICS

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"The hardest thing of all is to find a black cat in a dark room, especially if there is no cat." — Confucius

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New physics: UV or IR? (let's say IR/UV boundary ~ EW scale)

Neutrino oscillations: We know that new phenomenon exists, and if interpreted as neutrino masses and mixing, is it coming from deep UV, via e. .g Weinberg's operator

$$\mathcal{L}_{\rm NP} \propto (HL)(HL)/\Lambda_{\rm UV} \text{ with } \Lambda_{\rm UV} \gg \langle H \rangle$$

or it is generated by *new IR field*, such as RH component of Dirac neutrinos?

Dark matter: 25% of Universe's energy balance is in dark matter: we can set constraints on both. If it is embedded in particle physics, then e.g. neutralinos or axions imply new UV scales.

However, *there are models of DM where NP lives completely in the IR, and no new scales are necessary*.

Both options deserve a close look. In particular, *light and very weakly coupled states are often overlooked, but deserve attention*.

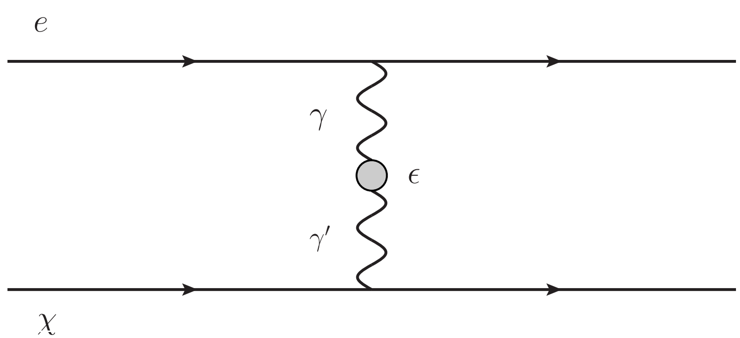
"Simplified model" for dark sector

(Okun', Holdom,…)

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

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

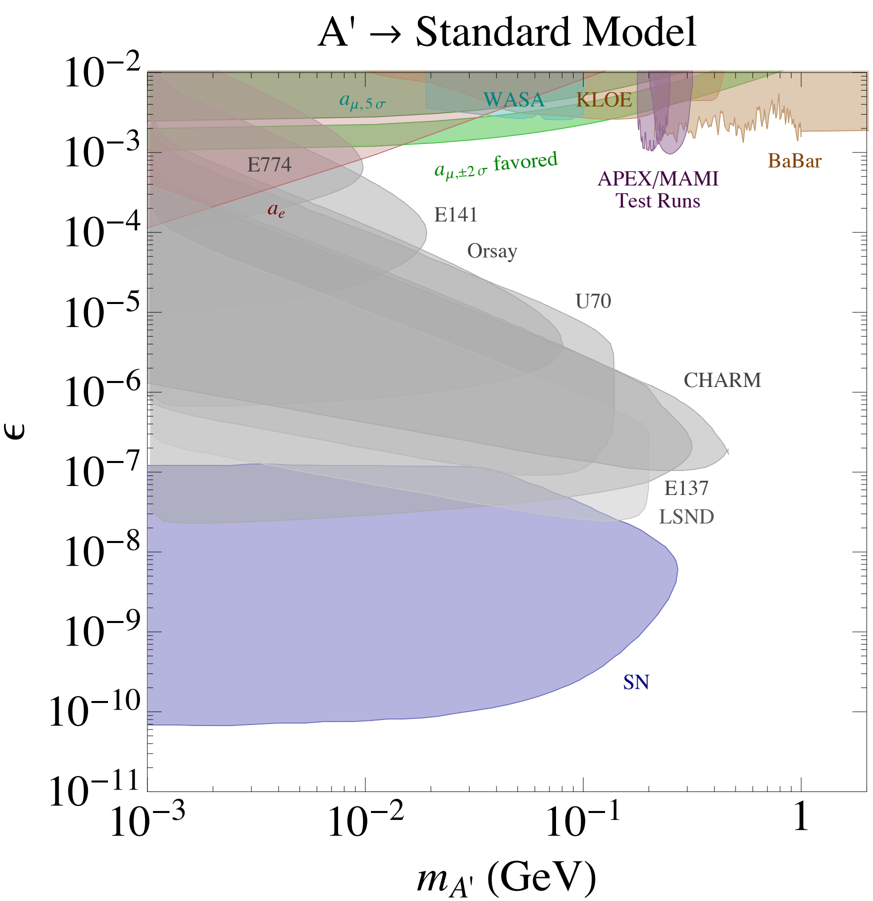
$$\mathcal{L}_{\chi,A'} = -\frac{1}{4} (F'_{\mu\nu})^2 + \bar{\chi}[\gamma_\mu(i\partial_\mu - g'A'_\mu) - m_\chi]\chi,$$

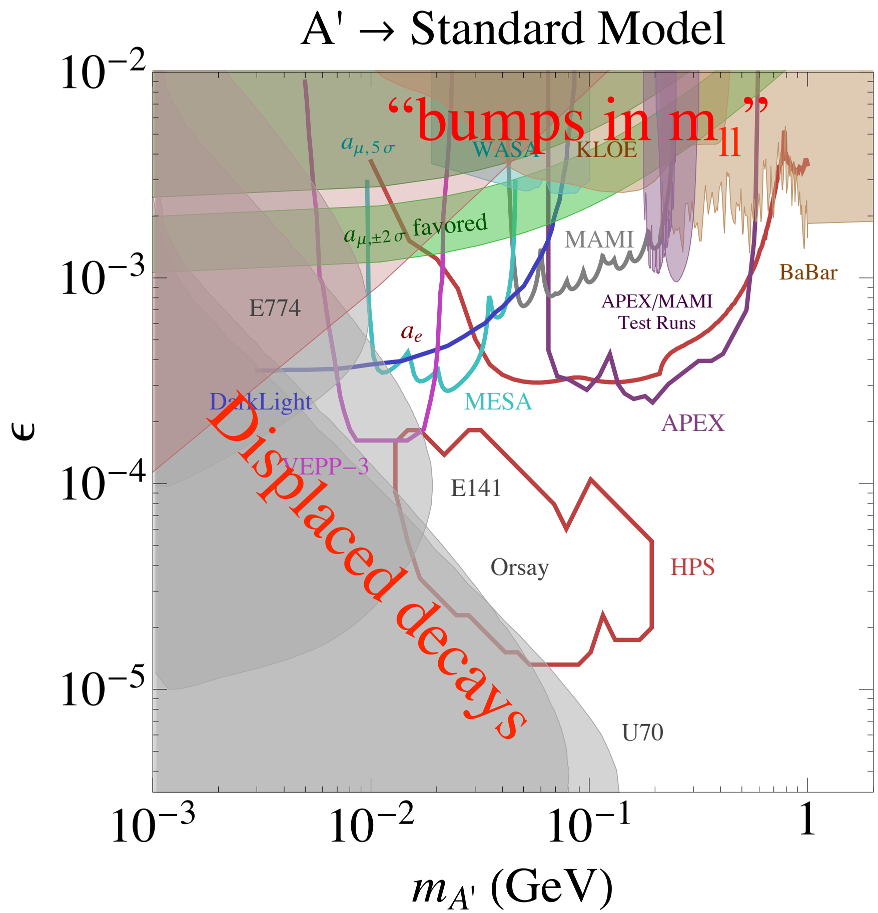


A – photon, *A'* – "dark photon", ψ - an electron, χ - a DM state, *g'* – a "dark" charge

- "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, $r^2_\chi \simeq 6\epsilon m_V^{-2}$.
- 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.

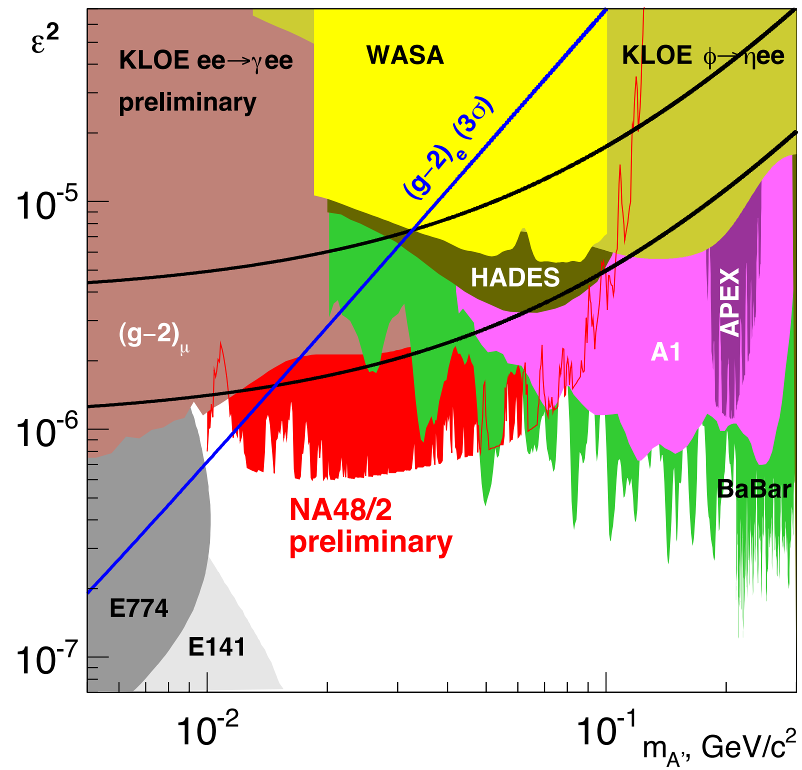
Latest results: A1, Babar, NA48

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

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

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

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



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.*

DM classification

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 DM is also in this category.

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**.

The DM via dark U(1):

Depending on the choice of $\{\alpha_d, \varepsilon, m_\chi, m_{A'}\}$ dark matter can be in very different regimes. For example:

- Normal WIMP regime ($\chi\chi \to$ off-shell A'$\to$ SM annihilation, weak scale DM)
- Secluded WIMP regime ($\chi\chi \to$ A'A' annihilation. Almost no requirement on ε)
- Dark Coulomb enhanced annihilation, $(\sigma v)_{galaxy} \gg (\sigma v)_{Early\ Universe}$, $\pi\alpha_d/v \gg 1$
- WIMP-type DM outside Lee-Weinberg window, m_χ, $m_{A'} \ll$ GeV
- Self-interaction of DM and dark bound states, $\sigma_{DM\text{-}DM} \gg \sigma_{DM\text{-}SM}$, $\varepsilon \ll 1$, $\alpha_d \sim \alpha_{SM}$
- Super-weakly interacting dark matter, either χ or A', ε is tiny, $m_{A'} < m_e$
- Super-cold dark matter from A', is in e.g. ~ sub-eV regime.

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in today's talk

1:"Very Dark Photon" dark matter

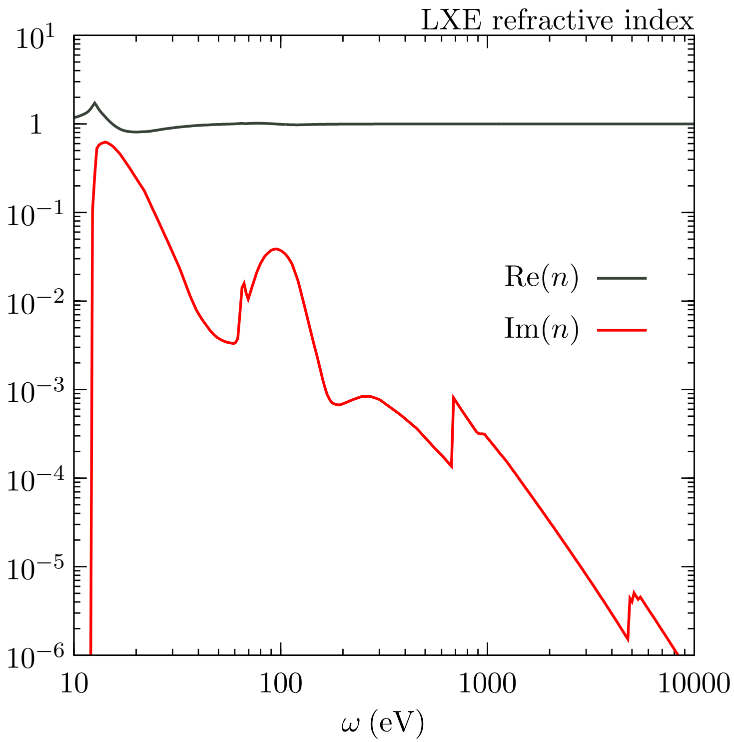
- Very weakly coupled dark photons (e.g. $\varepsilon \sim 10^{-13}$) can be dark matter in sub-eV regime due to misalignment mechanism or in the keV regime due to misalignment + thermal emission. If couplings are small, it is not going to be re-thermalized.

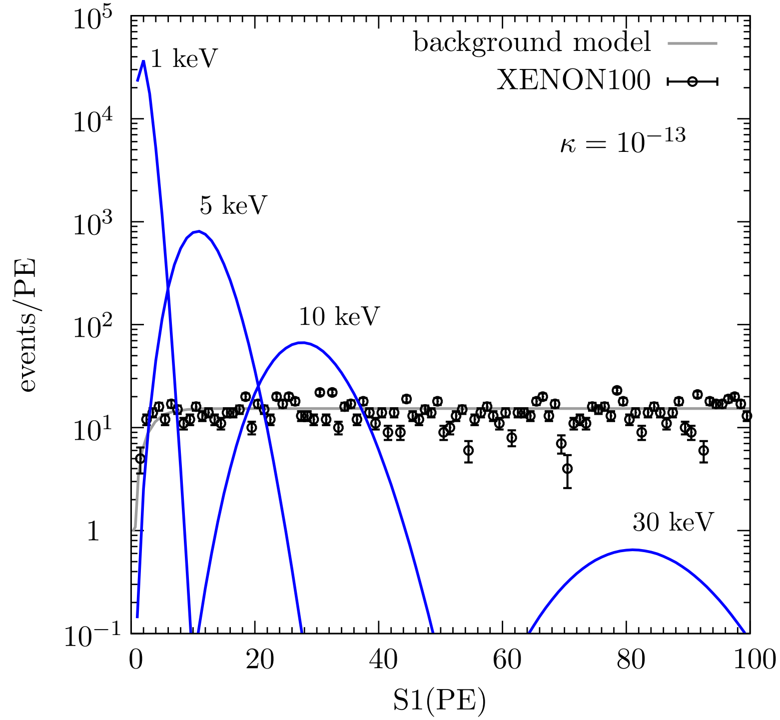
$$\Omega_V h^2 \approx 0.4 \frac{g_*(T_{\rm osc})^{3/4}}{g_{*S}(T_{\rm osc})} \sqrt{\frac{m_V}{1\,{\rm keV}}} \left(\frac{\widetilde{V}_{I,i}}{10^{11}\,{\rm GeV}} \right)^2 .$$

- If $m_V < 2\ m_e$ then only $V \rightarrow 3\ \gamma$ is possible. It is a delayed decay – larger couplings will be consistent with bounds. No monochromatic photons = weaker limits from x- and gamma-rays.

- Basis for detection: non-zero coupling to electrons, that lead to atomic ionization, $Xe + V \rightarrow Xe^+ + e^-$

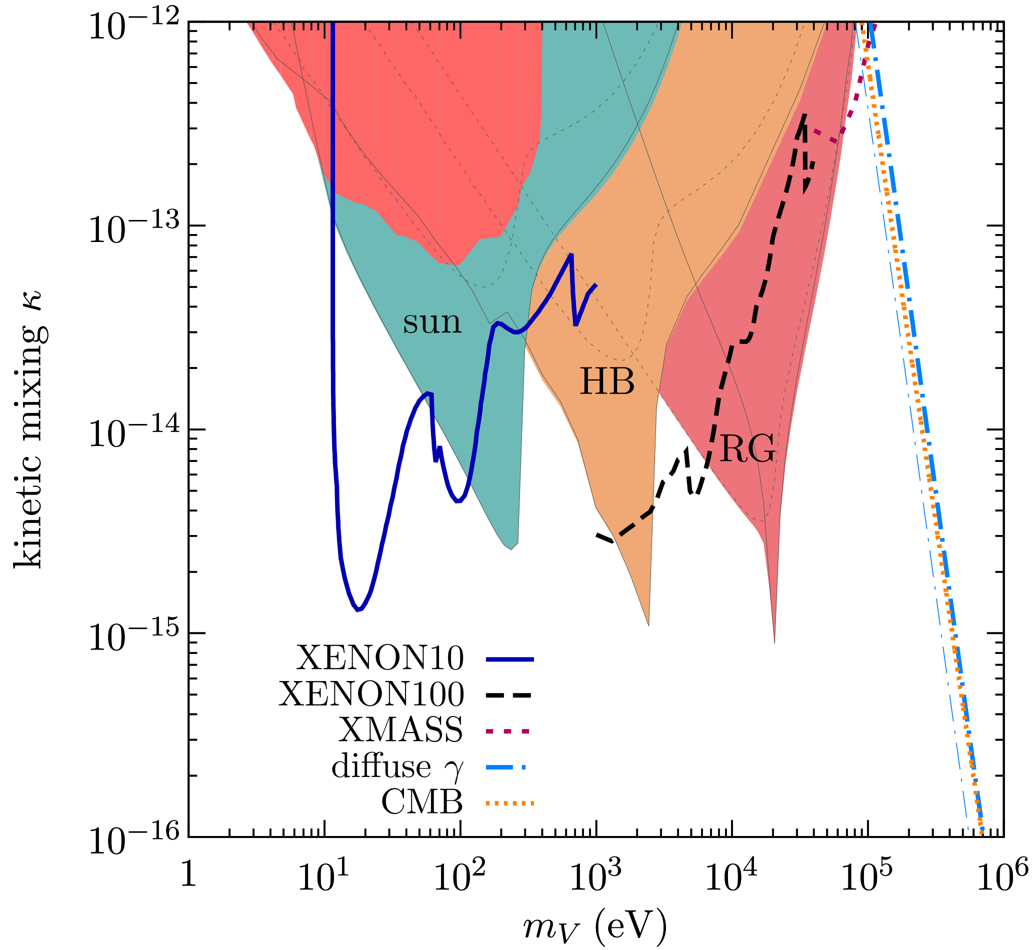
Absorption of [dark] photons in Xe





- The absorption cross section is strongly enhanced for small values of m_V.
- Constrained by "ionization only" signals.

"Super-WIMP" DM absorption signal

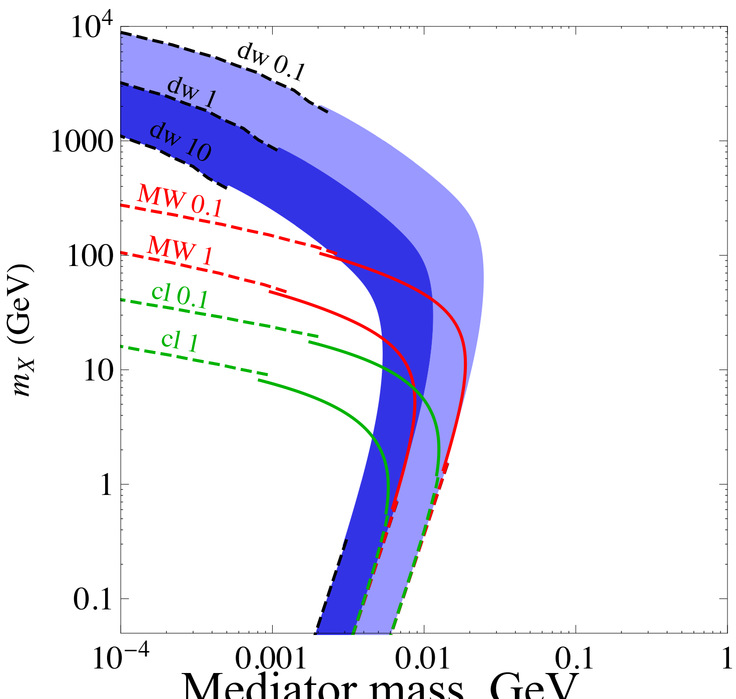


An, MP, Pradler, Ritz, PRD 2015

Large DM experiments can compete with stellar constraints and have sensitivity to mixing angles down to $\varepsilon \sim 10^{-15}$. (unfortunately, $\varepsilon = 0$ is also ok)

2: DM with a hint on self-interaction?

- Comparison of observations and simulations seem to point to problems with dwarf galaxy substructures (also known as "too-big-to-fail" problem).
- It may or may not be a real problem (it is an astrophycist-dependent problem).
- Self-scattering due to a dark force, at 1 cm^2/g level, seems to help, as it flattens out central spikes of DM (which is a reported problem).



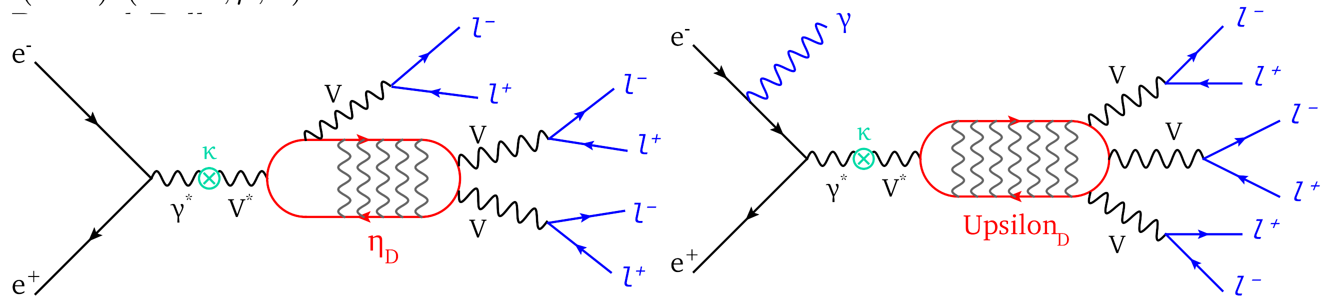
Example of parameter space that creates a core and solves the problem (from Tulin, Yu, Zurek) for $\alpha_d = 0.1$

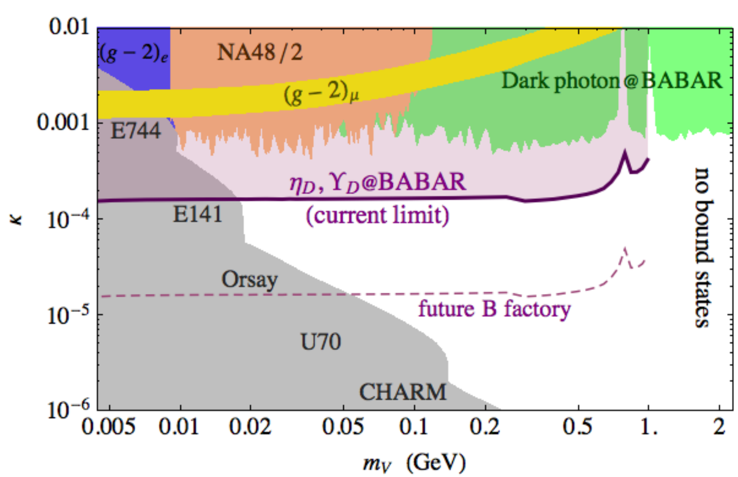
Some of the parameter space is within reach of B-factories.

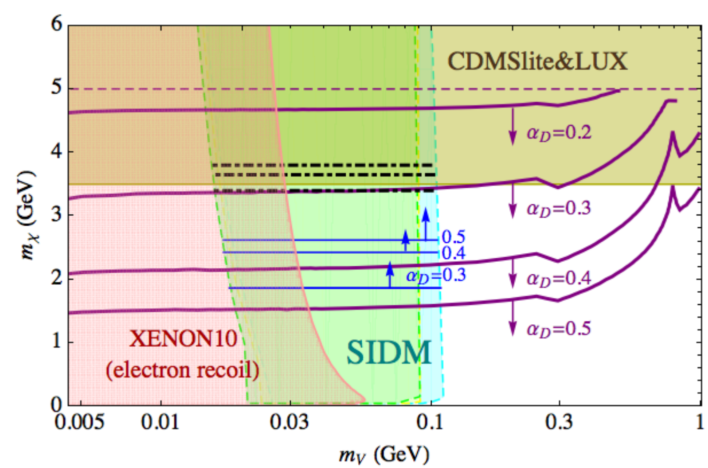
Dark matter bound states at B-factories

- If $\alpha_d > 0.2$, the sub-5 GeV Dark matter *can increase the sensitivity to dark force* via production of "dark Upsilon" that decays producing multiple charged particles

$\Upsilon_D \to 3V \to 3(l^+l^-)\ (l = e, \mu, \pi)$







3 pairs of charged particles appear "for free" once Upsilon_dark is produced. This is limited by previous searches of "dark Higgsstrahlung" by BaBar and Belle.

An,Echenard, MP, Zhang, PRL, to appear

3: Light WIMPs due to light mediators direct production/detection

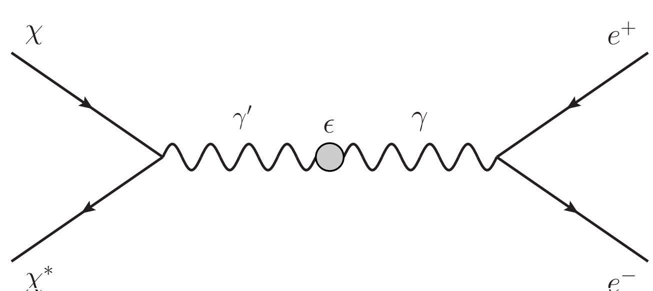
(Boehm, Fayet; MP, Riz, Voloshin …) Light dark matter is not ruled out if one adds a light mediator.

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

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

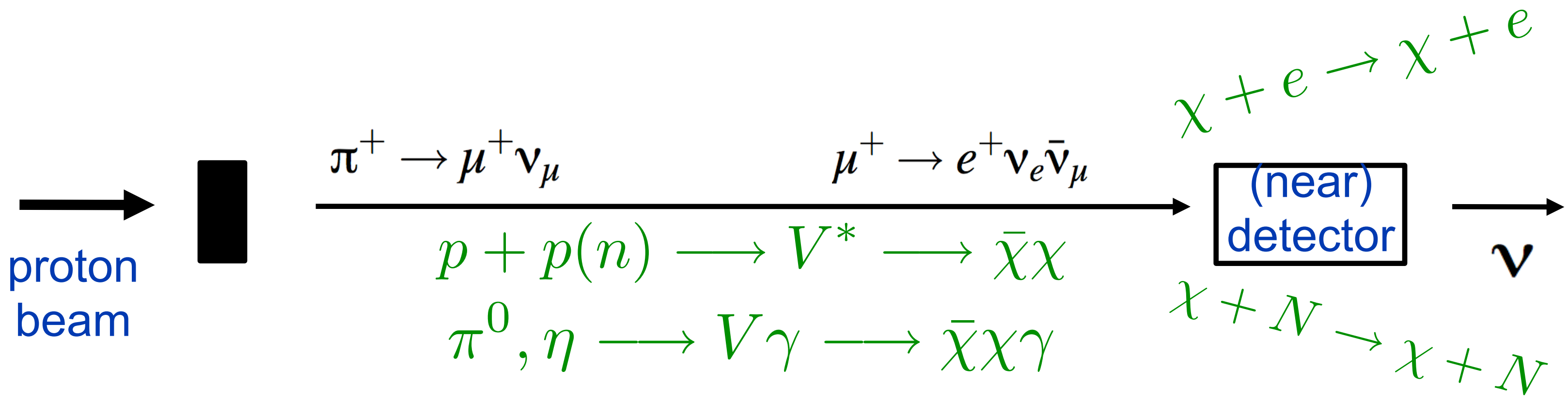
$$\sigma(v/c) \propto \begin{cases} G_F^2 m_\chi^2 & \text{for} \quad m_\chi \ll m_W, \\ 1/m_\chi^2 & \text{for} \quad m_\chi \gg m_W. \end{cases} \implies \text{few GeV} < m_\chi < \text{few TeV}$$

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

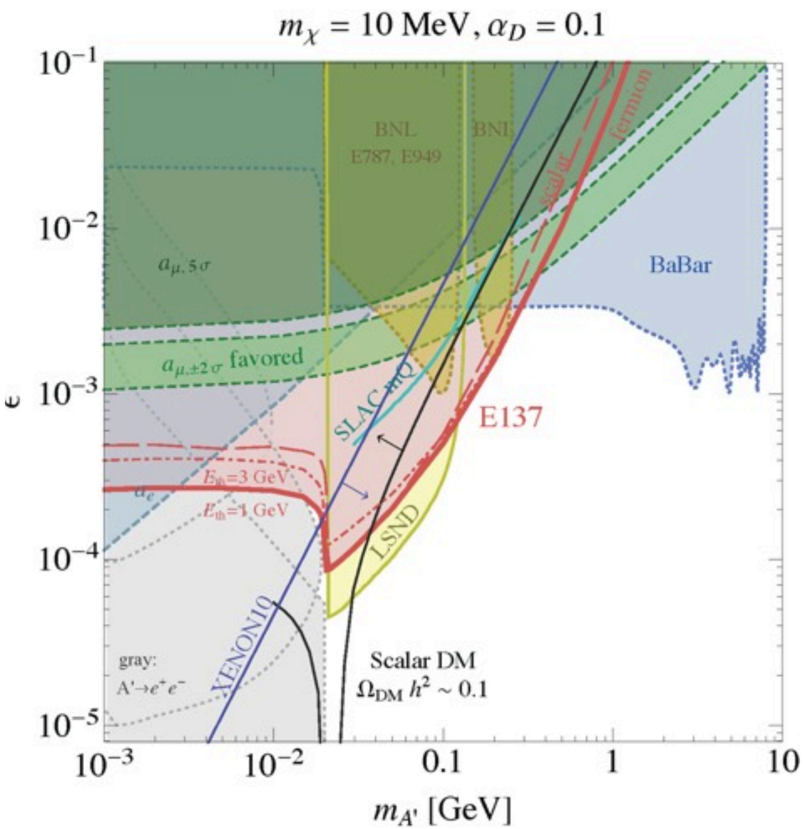
Proposed in Batell, MP, Ritz, 2009. Strongest constraints on MeV DM

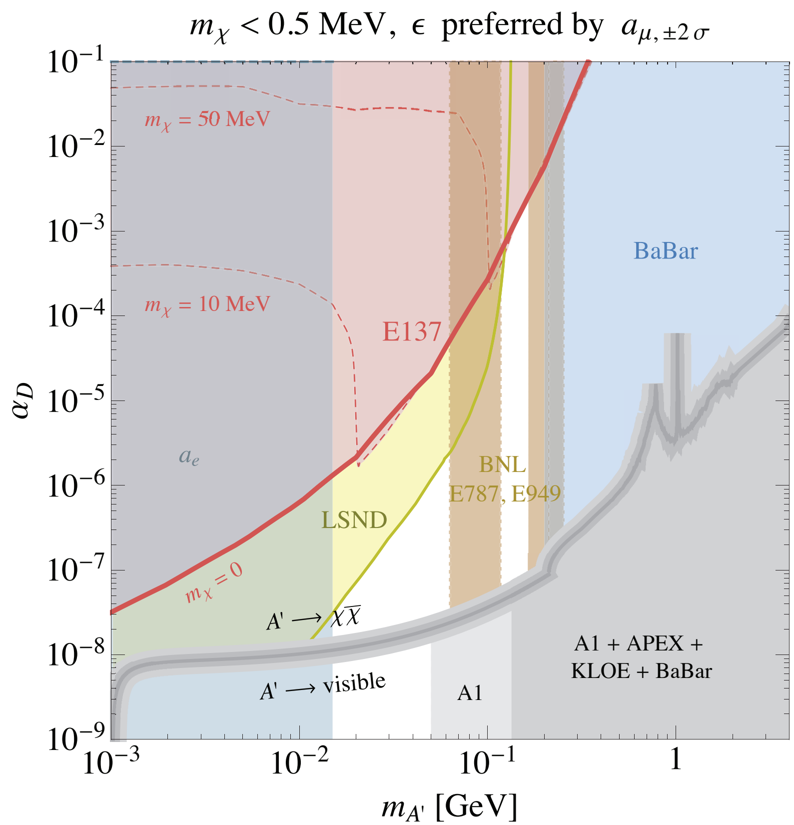


We can use the neutrino (near) detector as a dark matter detector, looking for recoil, but now from a relativistic beam. E.g. One can use results of old (LSND) and current neutrino experiments to look for light DM

Neutrinos are produced with strong cross sections but scatter due to weak force. Light WIMPs will be produced and scattered out of interactions that are much weaker then strong & EM force but much stronger than weak force. A trade-off.

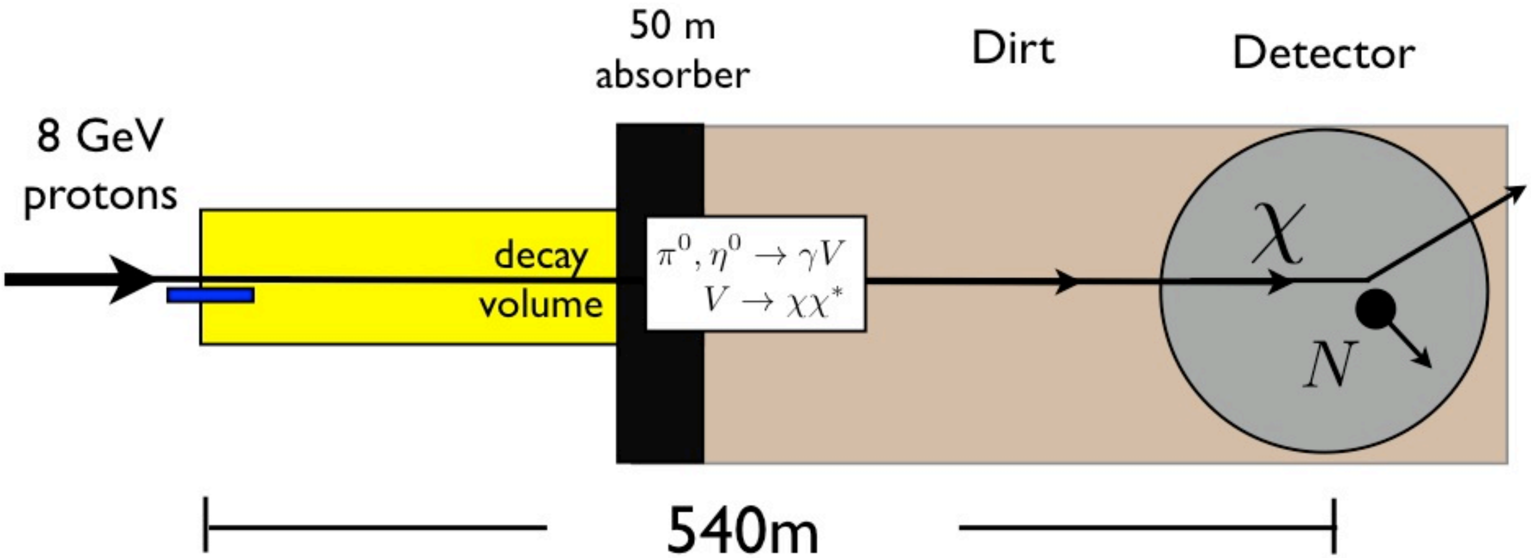
Compilation of current constraints on dark photons decaying to light DM





The sensitivity of electron beam dump experiments to light DM is investigated in Izaguirre et al, 2013; Batell, Essig, Surujon, 2014.

MiniBooNE search for light DM



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

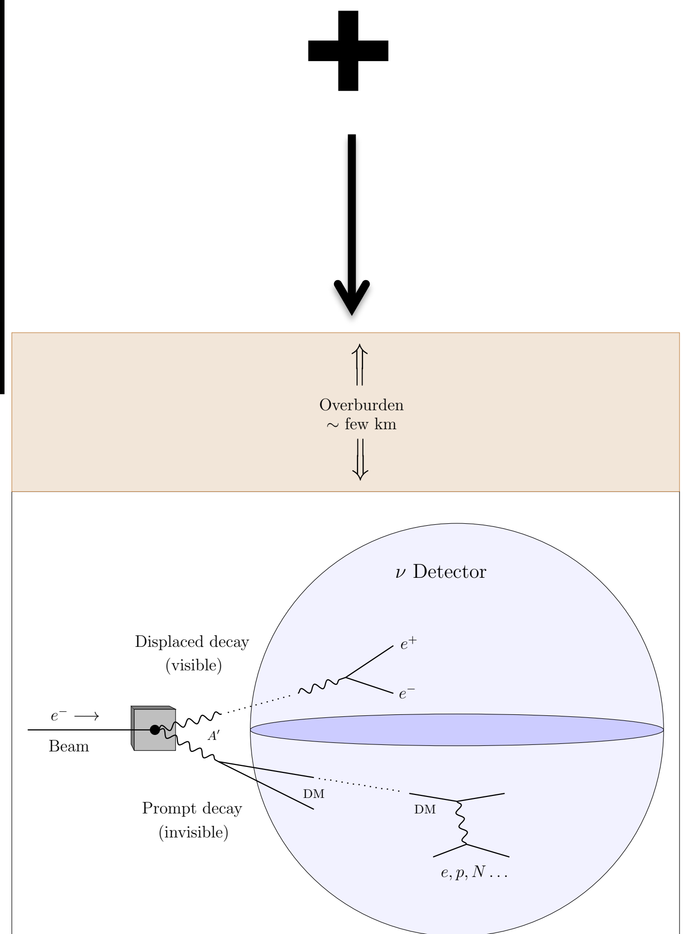
By-passing Be target is crucial for reducing the neutrino background (R. van de Water et al. …) . Currently, suppression of ν flux ~50.

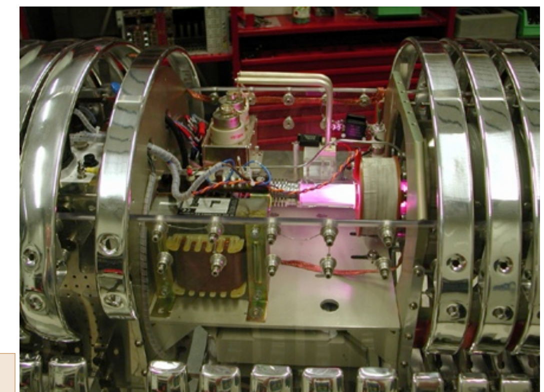
Timing is used (10 MeV dark matter propagates slower than neutrinos) to further reduce backgrounds. First results – this year (2016)

More coverage of dark sector using underground accelerators and neutrino detectors

with Eder Izaguirre and Gordan Krnjaic, 2015, 2016

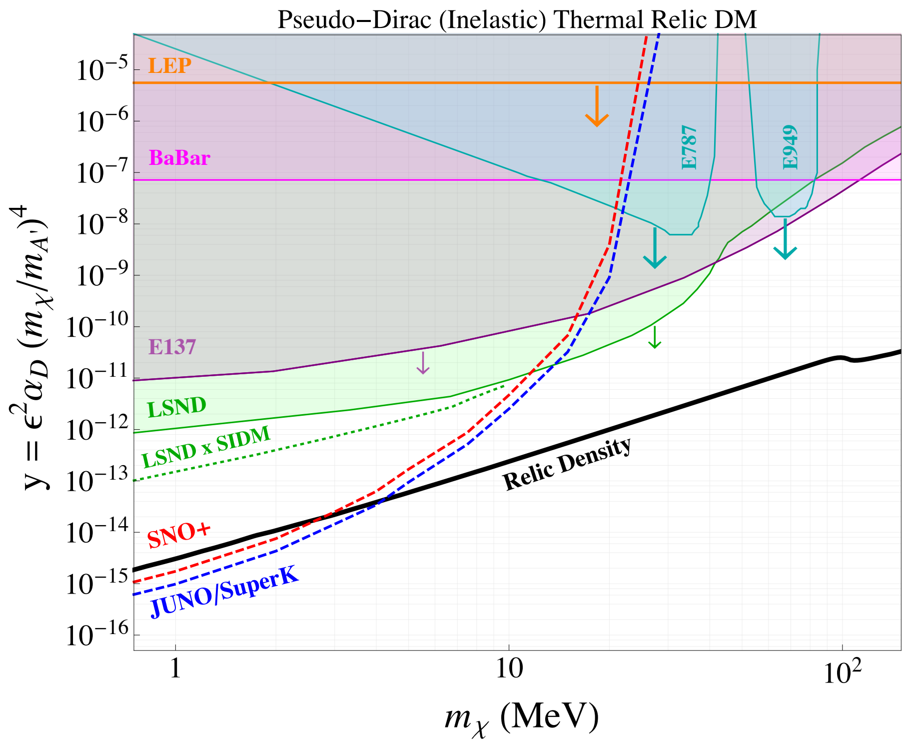
Borexino, Kamland, SNO+, SuperK, Hyper-K (?) …

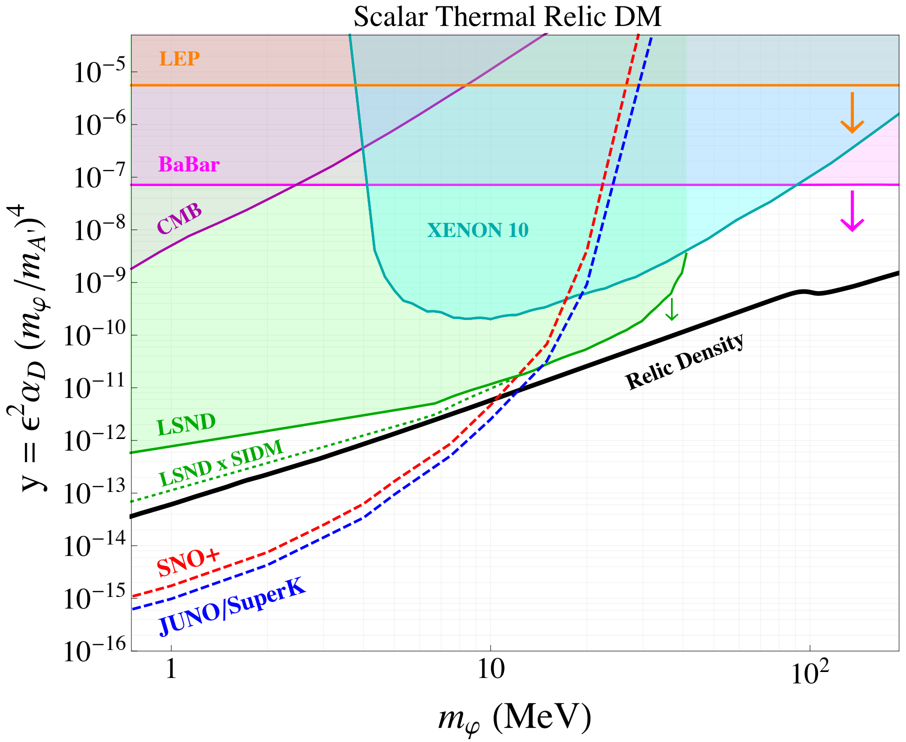




LUNA, DIANA,…, 1 e-linac for calibration

Sensitivity to light DM





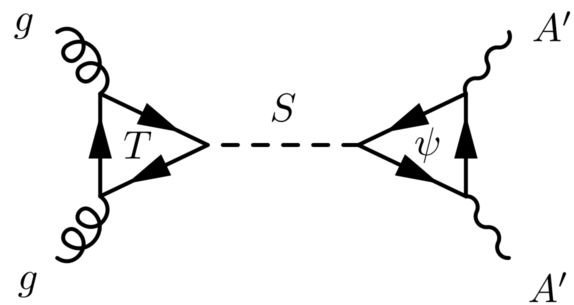
One will significantly advance sensitivity to light DM in the sub-100 MeV mass range. Assuming 10^{24} 100 MeV electrons on target

Izaguirre, Krnjaic, MP, 1507.02681, PRD

"Dark" di-photon resonance

By now you must be familiar with the main rule of the game: stick "dark" in front of everything. So, dark photon 750 GeV resonance!

Dark volks model

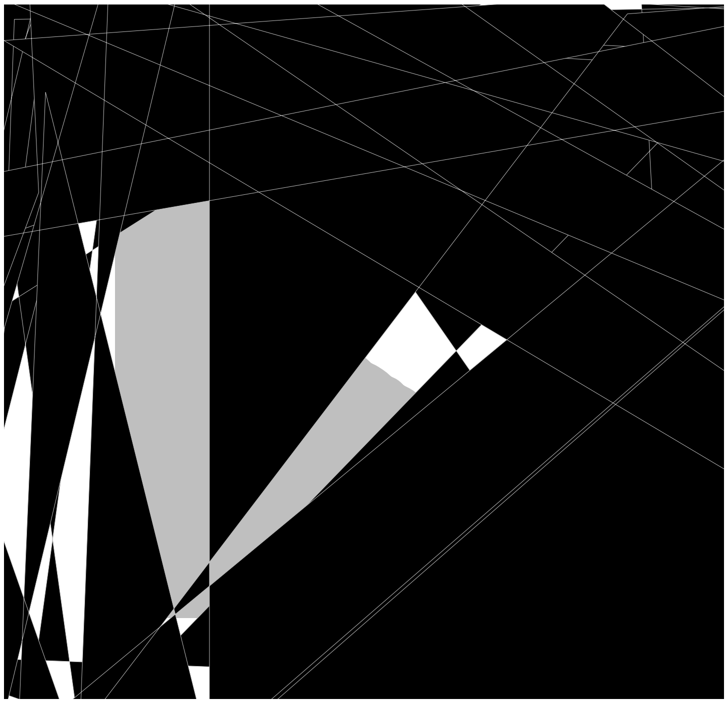


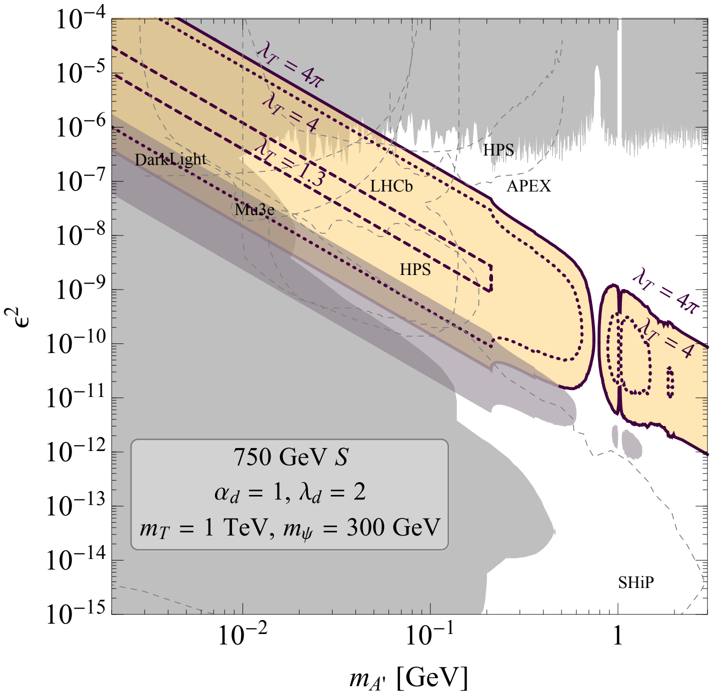
$$gg \to S \to A'A' \to (e^+e^-)(e^+e^-).$$

Marginalizing over properties of S, we get preferred region on (ε, $m_{A'}$) plane, that give A' decays within ~ meter scale that may "fake" real photon conversion.

Dark 750 GeV continued

Chen, Zhong, Lefebvre, MP, 1603.01256





Decay length scales as $\sim \varepsilon^{-2} m_{A'}^{-2}$. Due to large boosts (e.g. $\sim 10^4$) at the LHC, the preferred parameter space is in the allowed gap. Of course, decays of A' *can be* differentiated from regular γ conversion – something better done by experimentalists.

Conclusions

1. Light New Physics (not-so-large masses, tiny couplings) is a generic possibility. Some models (e.g. dark photon-mediated models) are quite minimal yet UV complete, and have diverse DM phenomenology.

2. If mixing angles are tiny dark photon itself with $m_{A'} < 2m_e$ can be dark matter. "Ionization-only" signature in DM direct detection constrain it stronger than astrophysics.

3. Self-interaction of DM [motivated by astrophysics] opens new opportunities to search for dark sectors via dark $Y_D \rightarrow 3A' \rightarrow 6e$

4. Sub-GeV WIMP dark matter can be searched for via production & scattering. (MiniBoone results should be available this year). To improve on LSND constraints one would need new experimental ideas implemented (BDX, ν detectors + accelerators, etc).

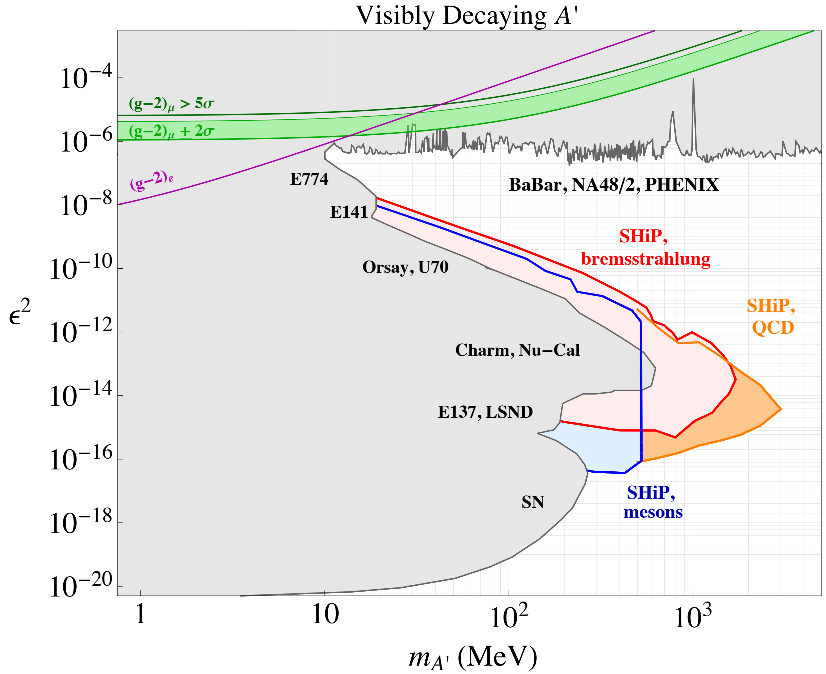
On-going and future projects

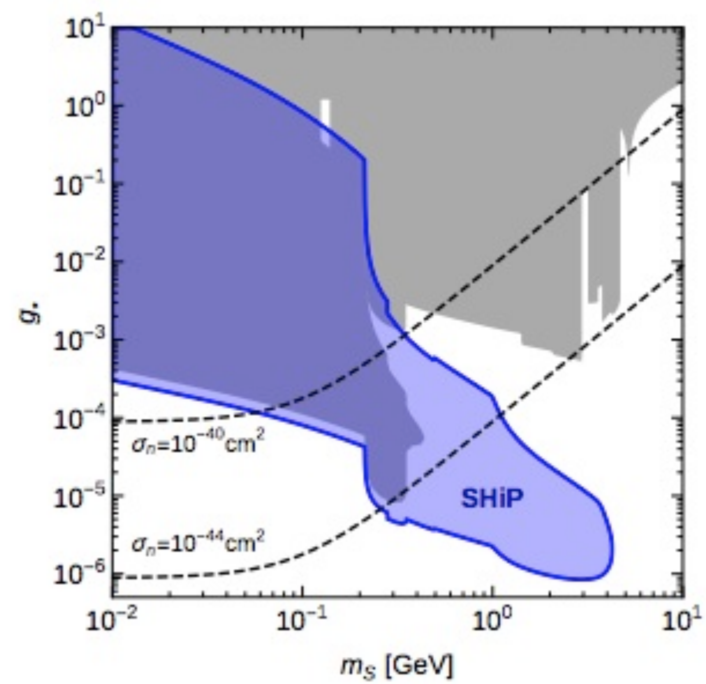
Fixed Target/beam dump experiments sensitive to

- Dark Photons: HPS, DarkLight, APEX, Mainz, SHiP…
- Light dark matter production + scattering: MiniBoNE, BDX, SHiP…
- Right-handed neutrinos: SHiP
- Missing energy via DM production: NA62 ($K \rightarrow \pi\nu\nu$ mode), positron beam dumps…
- Extra Z' in neutrino scattering: DUNE near detector (?)

SHiP sensitivity to vector and scalar portals

- SHiP will collect 2×10^{20} protons of 400 GeV dumped on target
- Sensitivity to dark vectors is via the unflavored meson decays, and through direct production, pp → … V → …… l^+l^-
- Sensitivity to light scalar mixed with Higgs is via B-meson decays, b → s + Scalar → … $\mu^+\mu^-$





Details can be found in the white paper, 1505.01865, Alekhin et al.