Light dark matter

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Light dark matter

- What does ”light DM” mean ? Gravity does not care whether these are 10^{-30}, 1 or 10^{30} kg objects as long as they have same velocity distribution.

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Light dark matter

- **What does ”light DM” mean ? Gravity does not care whether these are 10^{-30}, 1 or 10^{30} kg objects as long as they have same velocity distribution.**
- ***Working definition:*** *light dark matter is some form of particle dark matter with mass lighter than the range where most search efforts and $ are currently being spent.*

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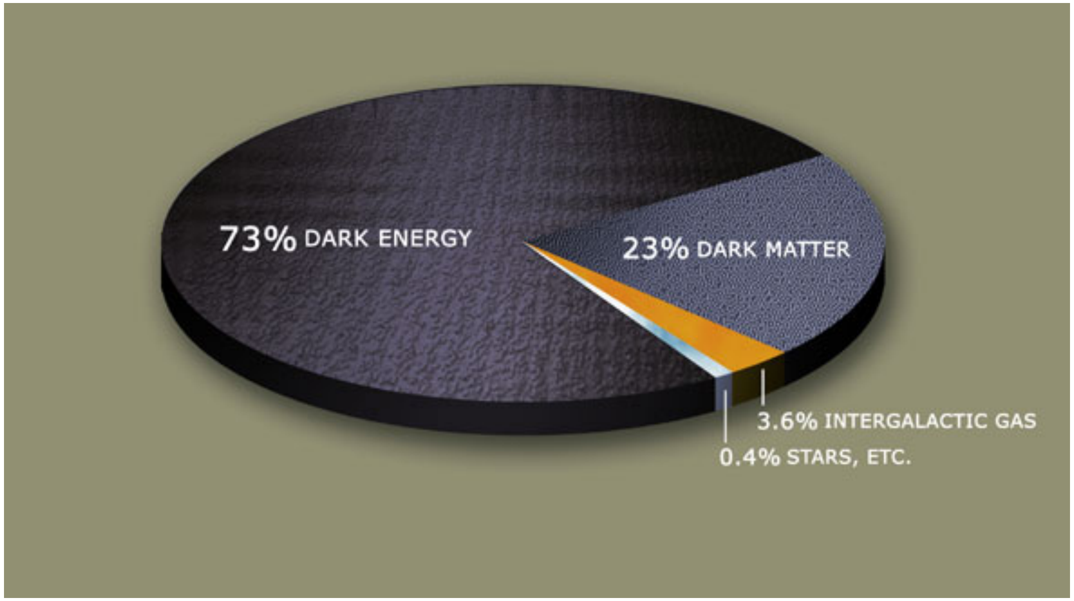
Big Questions in Physics



"Missing mass" – what is it?

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

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

Outline of the talk

1. *Introduction. Types of dark matter.* Weakly interacting massive particles (WIMPs).
2. Light dark matter and light mediators. Examples of models that pass current experimental constraints.
3. Searches at short baseline neutrino experiments and missing energy searches. Searches of mediators.
4. Ways to improve sensitivity: SHiP, electron beam experiments, underground experiments.
5. Direct detection of light dark matter using the electron recoil – bridge to detecting super-weakly interacting DM.
6. Conclusions.

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 **superweakly interacting MPs**]

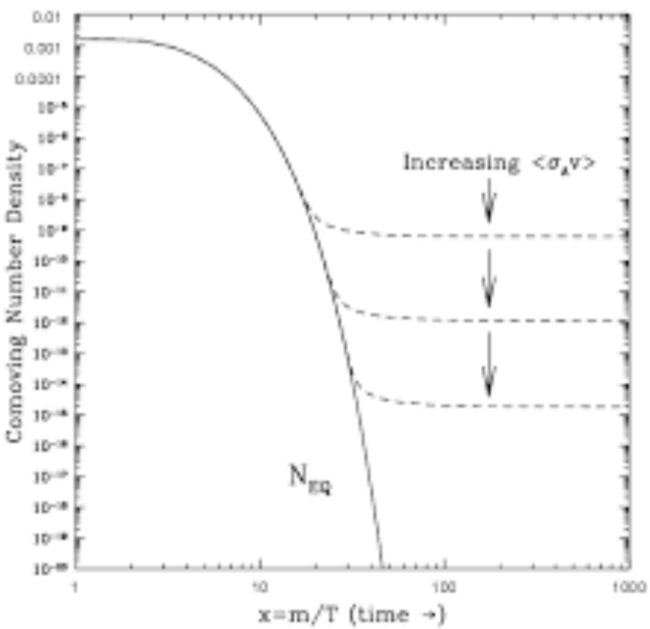
Huge: Almost non-interacting light, m< eV, particles with huge occupation numbers of lowest momentum states, e.g. $N_{DM}/N_\gamma \sim 10^{10}$. "Super-cool DM". Must be bosonic. Axions, or other very light scalar fields – call them **super-cold DM**.

Weakly interacting massive particles

In case of electrons and positrons (when the particle asymmetry = 0), the end point is $n_e/n_{gamma} \sim 10^{-17}$. It is easy to see that this is a consequence of a large annihilation cross section ($\sim \alpha^2/m_e^2$).

We need a particle "X" with smaller annihilation cross section,

$X + X \rightarrow$ SM states.

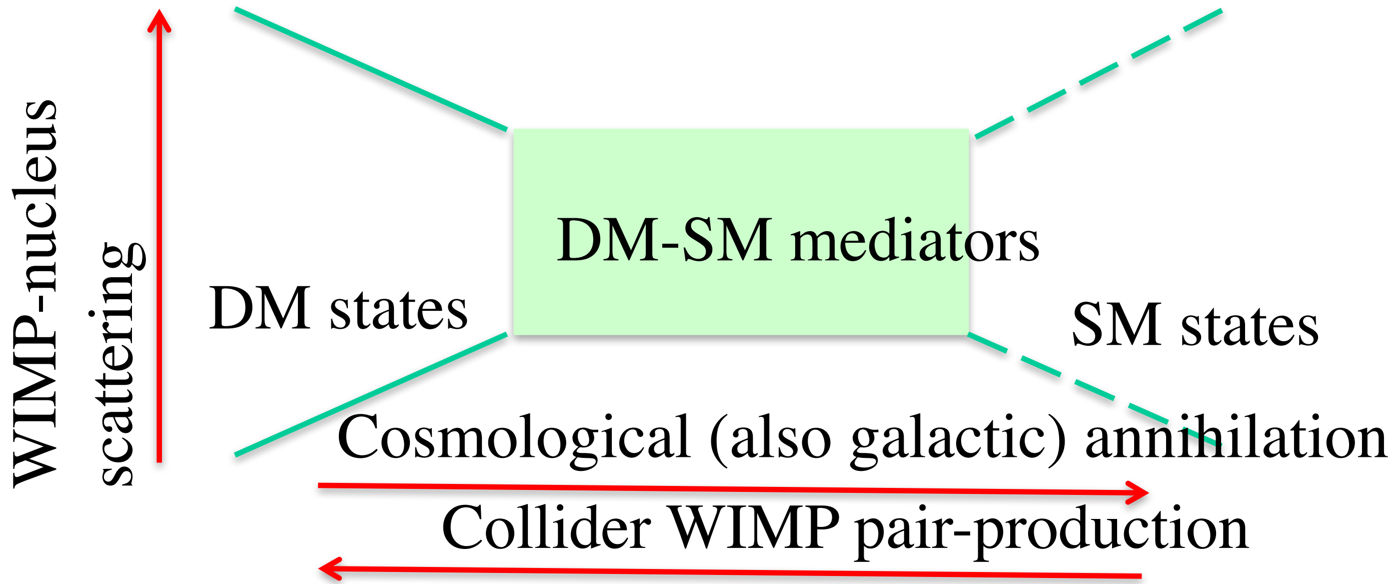


Honest solution of Boltzmann equation gives a remarkably simple result. $\Omega_X = \Omega_{DM}$, observed if the annihilation rate is

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

$10^{-36}\ \text{cm}^2 = \alpha^2/\Lambda^2 \rightarrow \Lambda = 140$ GeV. **Λ ~ weak scale (!)** First implementations by (Lee, Weinberg; Dolgov, Zeldovich,….)

WIMP paradigm, some highlights

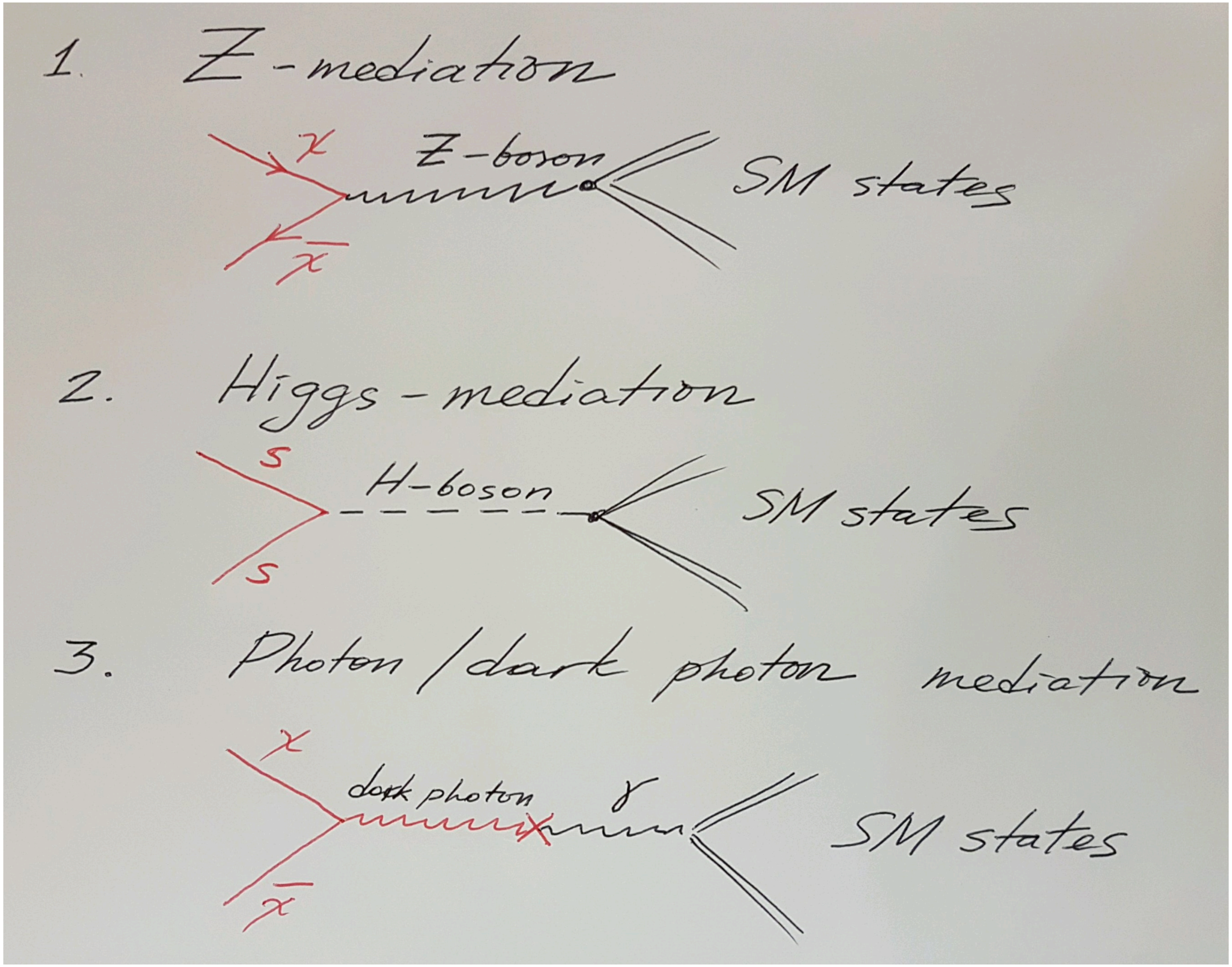


$$\langle \sigma_{ann} v \rangle \approx 1\text{pbn} \times c$$

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? (What is the mass range?)

Examples of DM-SM mediation



Very economical extensions of the SM.

DM particles themselves + may be extra mediator force. Can be very predictive.

Theoretical predictions for $\sigma_{DM\text{-}N}$

- Unlike annihilation of WIMP DM (whose inferred cross section is quite model independent), the scattering cross section $\sigma_{DM\text{-}N}$ does depend on the model.

- Take an "original" WIMP model with a ~ 10 GeV Dirac fermion annihilating into SM particles via an intermediate Z-boson.

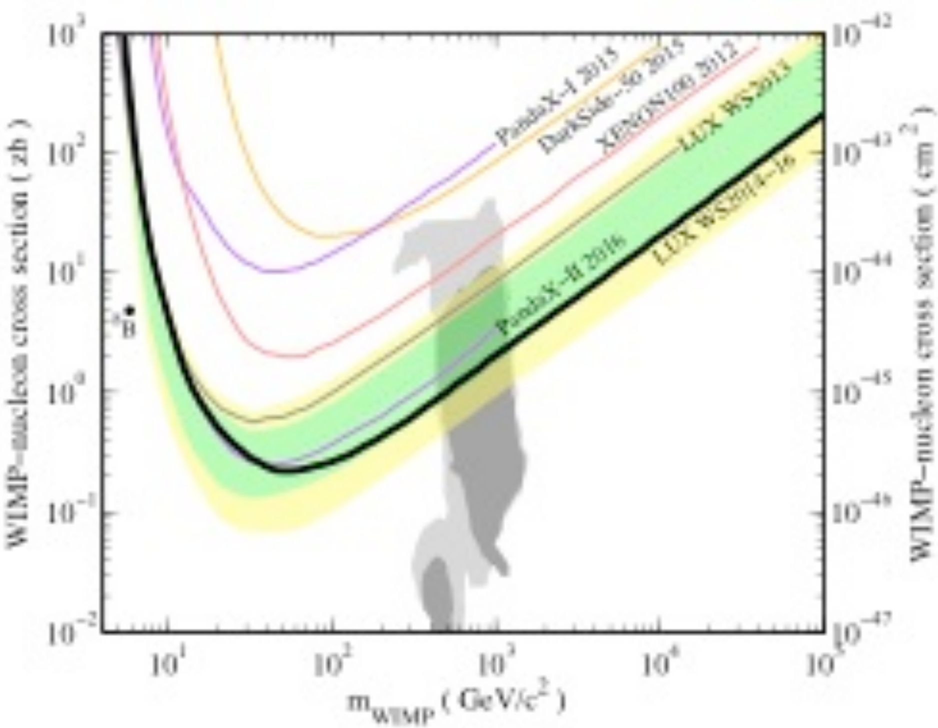
$\sigma_{DM\text{-}Nucleon}$ (Z-mediated) ~ $(1/8\pi)\, m_p^2 (G_F)^2 \sim (10^{-39}\text{-}10^{-38})\ \mathrm{cm}^2$ range.

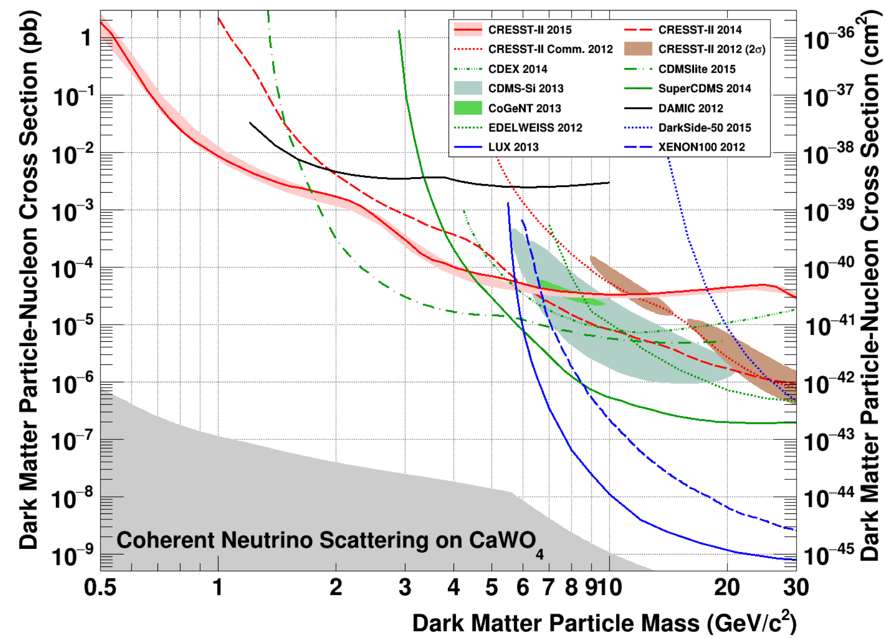
$\sigma_{DM\text{-}Nucleon}$ (Higgs-mediated) ~ $(10^{-4}\text{-}10^{-5}) \times \sigma_{DM\text{-}Nucleon}$ (Z-mediated)

$\sigma_{DM\text{-}Nucleon}$ (EW loop) ~ $10^{-9} \times \sigma_{DM\text{-}Nucleon}$ (Z-mediated)

Looks tiny, but how does it compare with the today's limits?

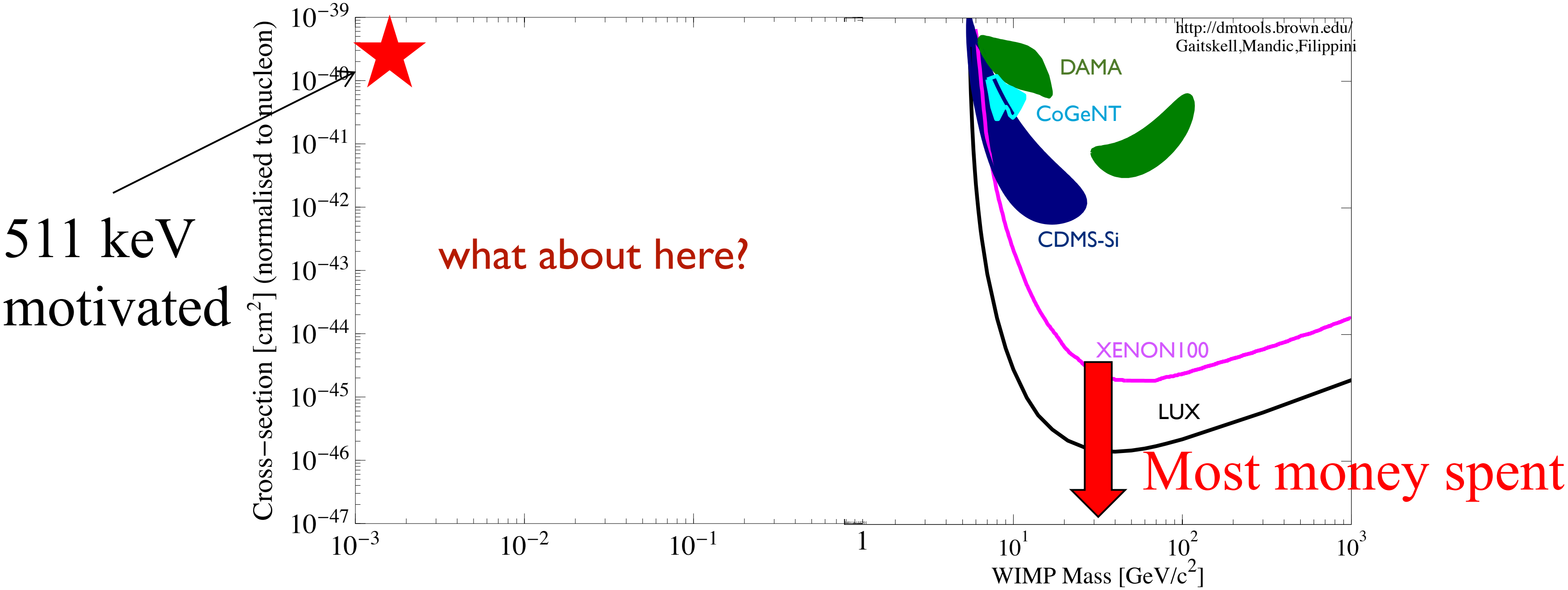
Progress in direct detection of WIMPs
(latest 2016 LUX and CRESST results)





Spin-independent Z-boson mediated scattering of a Dirac WIMP is excluded from ~ 1 GeV to 100 TeV – i.e. over the entire WIMP mass range. EW scale Higgs mediated models are heavily constrained (but there are exceptions). Next generation noble-liquid-based experiments will begin probing EW loop level cross sections.

Light DM – difficult to detect via nuclear recoil



- There is a large, potentially interesting part of WIMP DM parameter space that escapes constraints from DM-nuclear scattering, but is potentially within reach of other probes

- Viable models imply *the dark sector*, or accompanying particles facilitating the DM → SM annihilation. Can create additional signatures worth exploring.

Light WIMPs are facilitated by light mediators

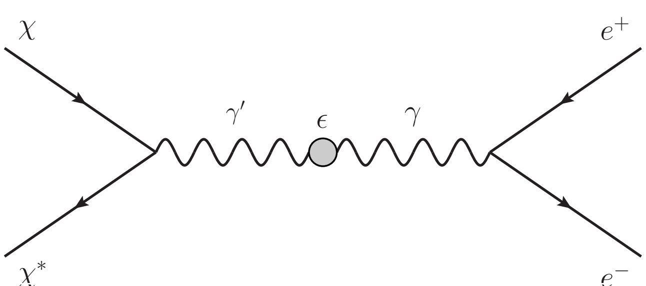
(Boehm, Fayet; MP, Riz, Voloshin …) Light dark matter is not ruled out if one adds a light mediator.

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,

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

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).



$$\sigma_{\rm annih}(v/c) \simeq \frac{8\pi\alpha\alpha_D\epsilon^2(m_\chi^2 + 2m_e^2)v^2}{3(m_{A'}^2 - 4m_\chi^2)^2}\sqrt{1 - m_e^2/m_\chi^2}.$$

Neutral "portals" to the SM

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

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

$B_{\mu\nu} V_{\mu\nu}$ "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

……….

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

“Simplified models” for light DM

some examples

- Scalar dark matter talking to the SM via a dark photon (variants: L_{mu}-L_{tau} etc gauge bosons). With $2m_{DM} < m_{mediator}$.

$$\mathcal{L} = |D_\mu \chi|^2 - m_\chi^2 |\chi|^2 - \frac{1}{4} V_{\mu\nu}^2 + \frac{1}{2} m_V^2 V_\mu^2 - \frac{\epsilon}{2} V_{\mu\nu} F_{\mu\nu}$$

- Fermionic dark matter talking to the SM via a “dark scalar” that mixes with the Higgs. With $m_{DM} > m_{mediator}$.

$$\mathcal{L} = \overline{\chi}(i\partial_\mu \gamma_\mu - m_\chi)\chi + \lambda \overline{\chi}\chi S + \frac{1}{2}(\partial_\mu S)^2 - \frac{1}{2} m_S^2 S^2 - AS(H^\dagger H)$$

After EW symmetry breaking *S* mixes with physical *h*, and can be light and weakly coupled provided that coupling A is small. (recall G Krnjaic’s talk). Let’s call it dark Higgs (P Ko’s talk).

Two different types of annihilation

- Model 1: one step process:

$$\chi\chi^* \;\rightarrow\; \text{off shell dark photon} \;\rightarrow\; e^+e^-$$

- Model 2: two-step process: annihilation to mediators with subsequent decay

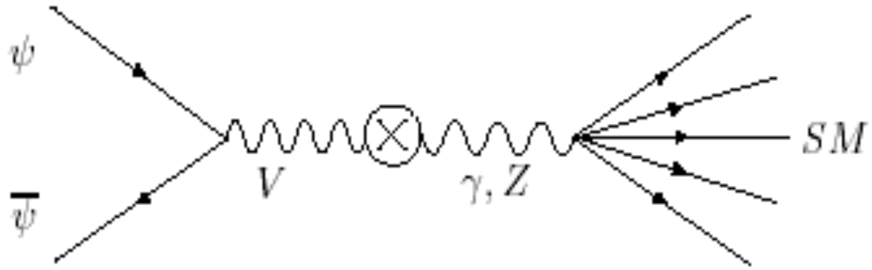
$$\chi\overline{\chi} \;\rightarrow\; S + S \;\rightarrow\; \ldots \;\rightarrow\; (e^+e^-) + (e^+e^-)$$

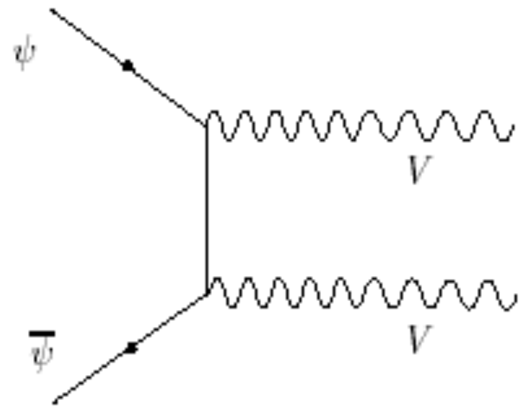
In both cases, the annihilation proceed in *p-wave*, and is very suppressed at the recombination time → no CMB constraints.

Thus, (few MeV – to – GeV) range is not excluded by cosmology.

Two types of WIMPs

Un-secluded — Secluded





Ultimately discoverable
Size of mixing*coupling is set by annihilation. Cannot be too small.

Potentially well-hidden
Mixing angle can be 10^{-10} or so. It is not fixed by DM annihilation

You think gravitino DM is depressing, but so can be WIMPs

How to look for light WIMP DM ?

1. Detect missing energy associated with DM produced in collisions of ordinary particles

2. Produce light dark matter in a beam dump experiment, and detect its subsequent scattering in a large [neutrino] detector

3. Detect scattering of light ambient DM on electrons, and keep lowering the thresholds in energy deposition.

All three strategies are being actively worked on, and pursued by several ongoing and planned experiments.

Anomalies? A simple concept of dark matter + mediator allows [speculatively] connecting DM to some on-going puzzles

1. Unexpectedly strong and uniform 511 keV emission from galactic bulge could be fit by annihilation of a few MeV galactic WIMPs.
2. If DM is heavy and mediator is light, one can fit its annihilation to the famous positron-to-electron ratio rise (thanks to Sommerfeld enhancement at low velocity, bound states effects, as well as lepto-phylic composition of the final states)
3. Inner density profiles of galaxies can smoothed out by the self-scattering WIMPs with 10^{-24}cm^2/GeV. For EW scale WIMPs, light mediators can easily provide such cross section. (S Tulin's talk).
4. ….

These connections are all rather interesting but not necessarily compelling. We'd like a laboratory probe (Exclusion or confirmation).

Missing energy/momentum searches

NA64 has recent results (great sensitivity after 3×10^9 e on target). Plot from Banerjee et al, 1610.02988. Much more data expected in future

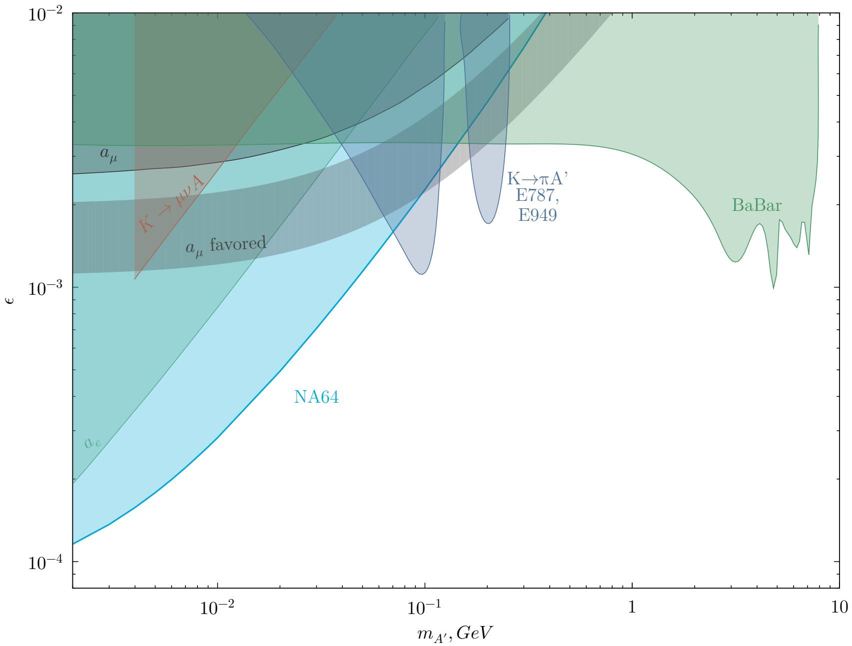


FIG. 3: The NA64 90 % C.L. exclusion region in the $(m_{A'}, \epsilon)$ plane. Constraints from the BaBar [48, 55], and E787+ E949 experiments [47, 56], as well as muon α_μ favored area are also shown. Here, $\alpha_\mu = \frac{g_\mu - 2}{2}$. For more limits obtained from indirect searches and planned measurements see e.g. Refs. [5].

Search of a process

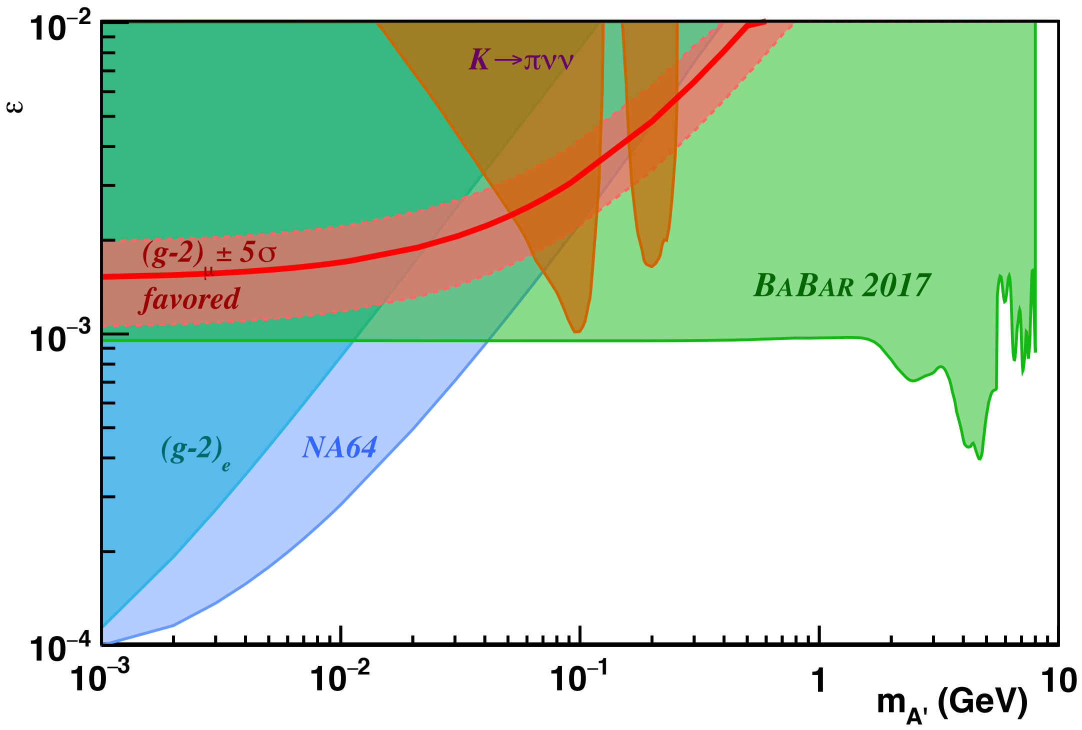
$$e + Z \rightarrow e + Z + V \rightarrow e + Z + \chi\chi$$

Significant new constraints on dark mediator parameter space. Complements visible decay searches

There is a parallel effort in the US, called LDMX, possibly at SLAC

Most recent BaBar results

BaBar collaboration has published new results two weeks ago, 1702.03327. Search of $e^+e^- \rightarrow \gamma + V \rightarrow \gamma + \chi\chi$

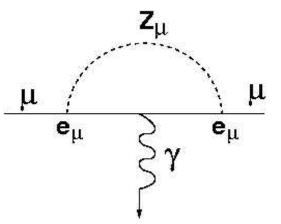


- Complementary to NA64
- Covers all of the dark photon parameter space, decaying invisibly, consistent with alleviating the muon g-2 discrepancy

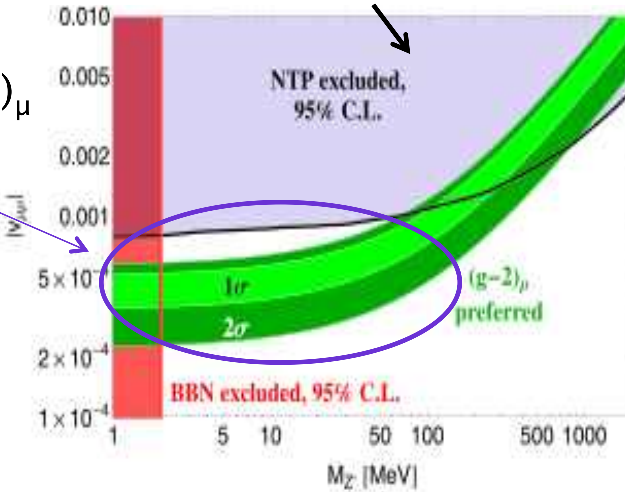
Running NA64 in the muon mode?

In connection with g-2 of the muon discrepancy, and in order to diversify from dark photons, *one could run the NA64 in muon mode with up to 10^7 muons/second*. S. Gninenko idea/slide:

- Class of U(1)´models: in SM it's possible to gauge one of $L_e - L_\mu$, $L_e - L_\tau$, $L_\mu - L_\tau$ LN differences. No anomaly.
- Extra (broken) U(1)´, new massive boson Z´ coupled predominantly to μ and τ through the $L_\mu - L_\tau$ current (leptonic dark photon)
- $M_{Z'}$ could be in sub-GeV range
  $Z' \to \mu^+\mu^-$ or $Z' \to \nu\nu$ if $M_{Z'} < 2\, m_\mu$
- Impact on: ν–physics, explanation of $(g-2)_\mu$



Altmannshofer et al., arXiv:1406.2332



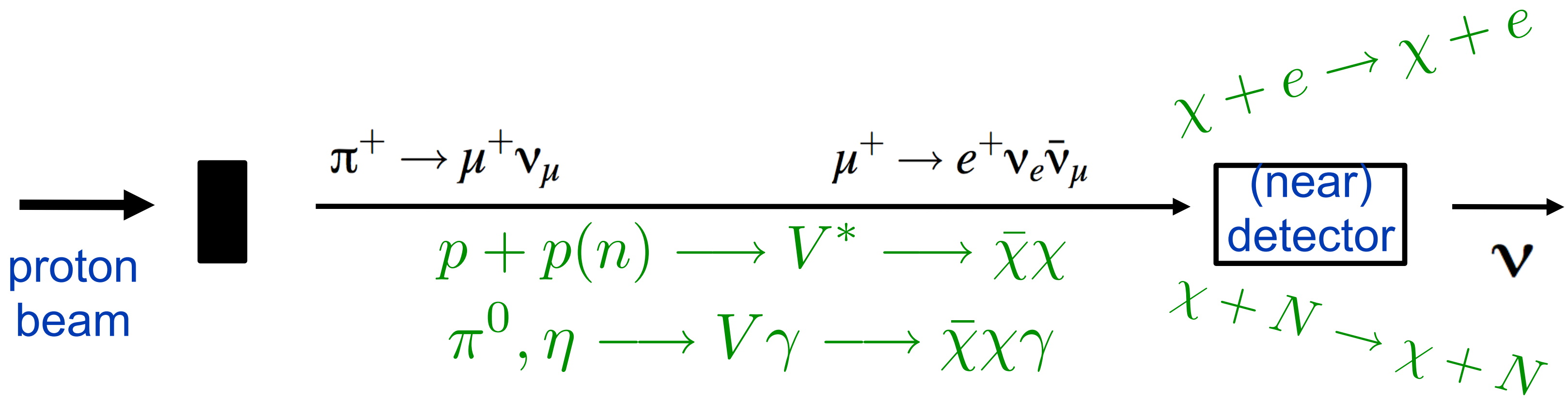
Strong motivation for a sensitive search for Z´->νν, μ⁺μ⁻ in a near future experiment by using (unique) high intensity muon beam at CERN.

The upgraded muon beam at the SPS

Invisibly decaying L_μ-L_τ gauge boson and dark scalar below the d-muon threshold can be probed this way.

Fixed target probes - Neutrino Beams

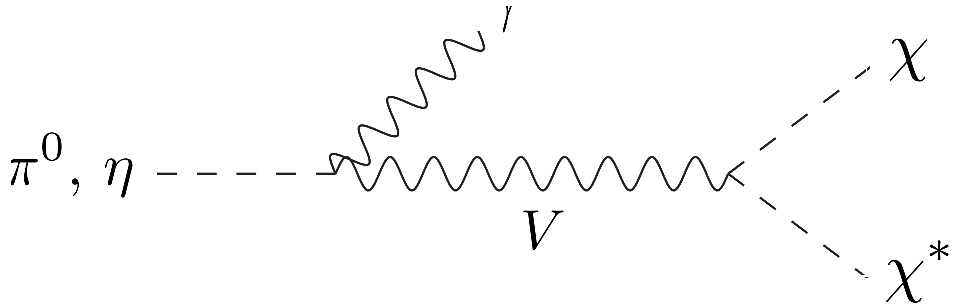
Proposed in Batell, MP, Ritz, 2009. Strongest constraints on MeV DM

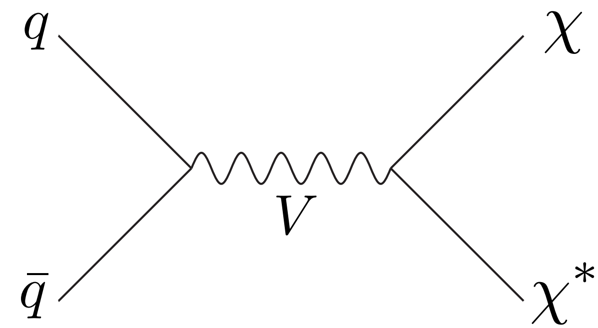


We can use the neutrino (near) detector as a dark matter detector, looking for recoil, but now from a relativistic beam. E.g.

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

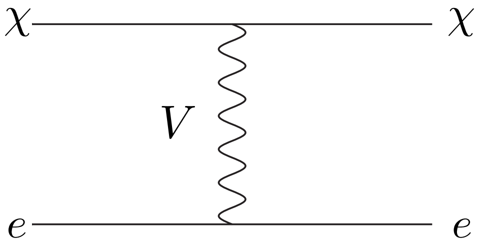
Light DM - trying to see production + scattering



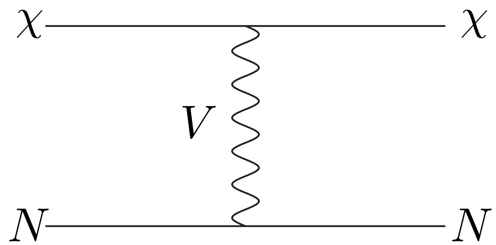


In the detector:

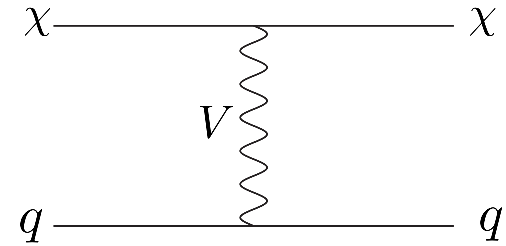
Elastic scattering on electrons



Elastic scattering on nucleons



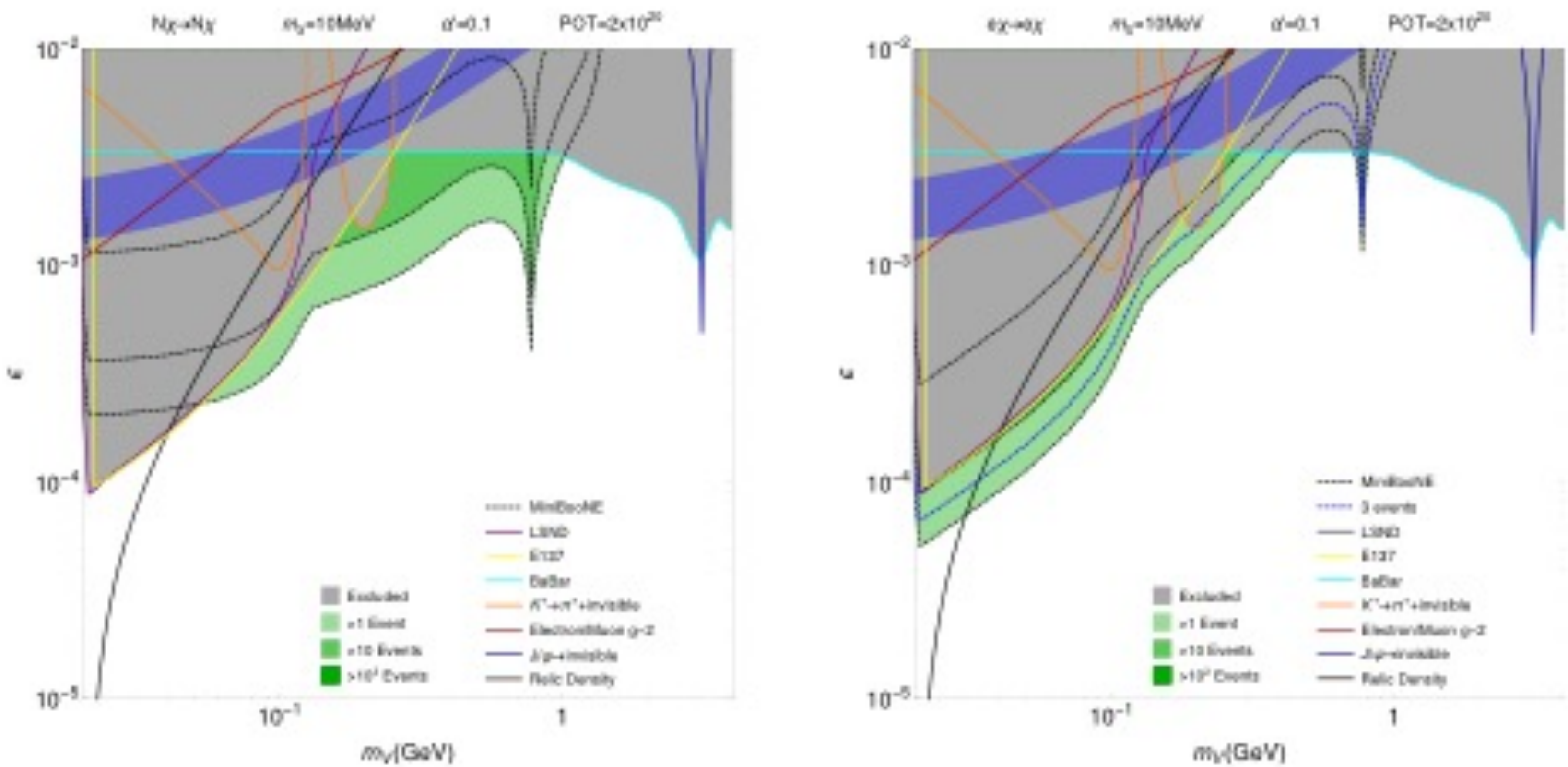
Deep inelastic scattering



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.

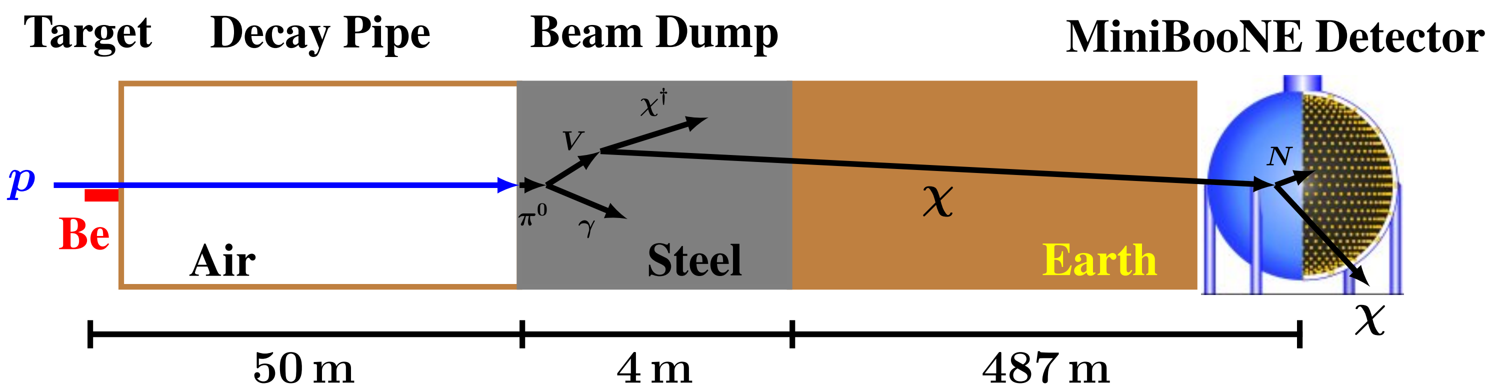
Signal scales as (mixing angle)^4.

Constraints on dark matter particles produced in beam dump collisions



Best constraints are provided by the LSND and E137 (electron beam dump) experiments. deNiverville et al., 1609.01770.

MiniBooNE search for light DM



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

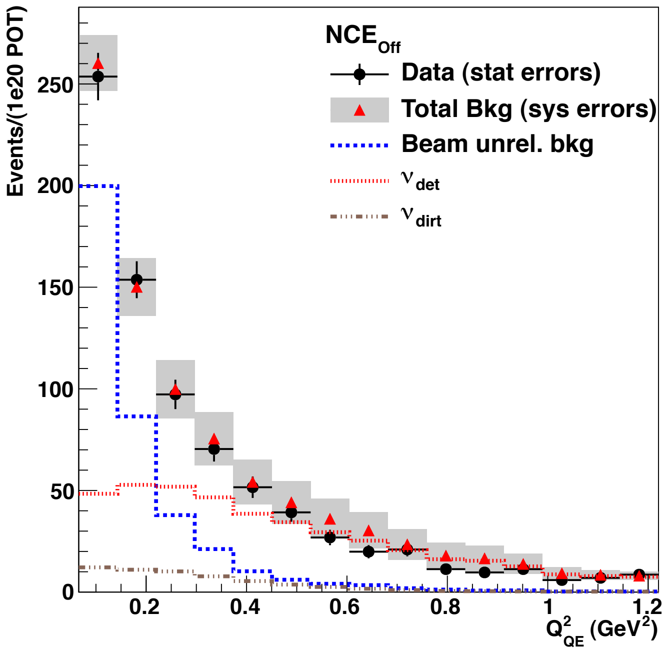
By-passing Be target is crucial for reducing the neutrino background (Richard van de Water et al. …) . Currently, suppression of ν flux ~50.

Timing is used (10 MeV dark matter propagates slower than neutrinos) to further reduce backgrounds. First results – 2016, 2017

Important contribution from P deNiverville, B Batell.

On-going and future projects

From the W & C talk by Thornton, and a new paper

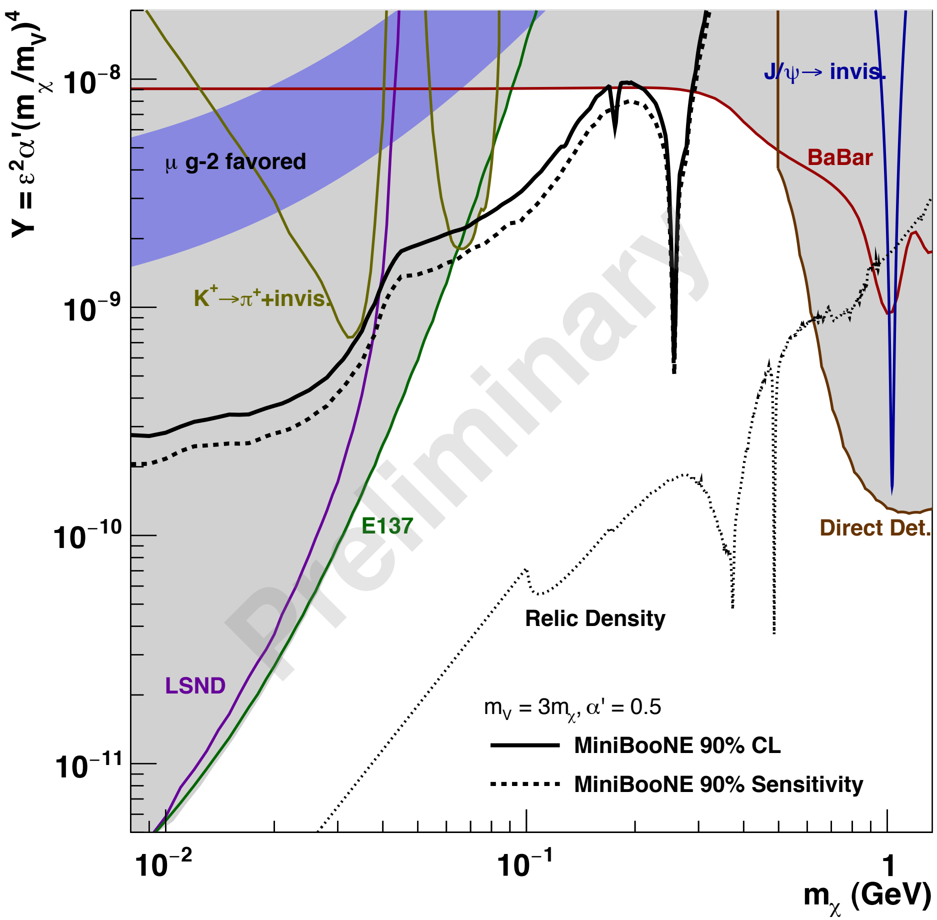


	#events	uncertainty
BUB	697	
ν_{det} bkg	775	
ν_{dirt} bkg	107	
Total Bkg	1579	14.3% (pred. sys.)
Data	1465	2.6% (stat.)

The off-target run of MiniBoone is a success (despite the absence of DM signal!):

- Neutrino background from the beam is brought down to be comparable from cosmics
- Data are well described by MC

New parts of the parameter space get excluded



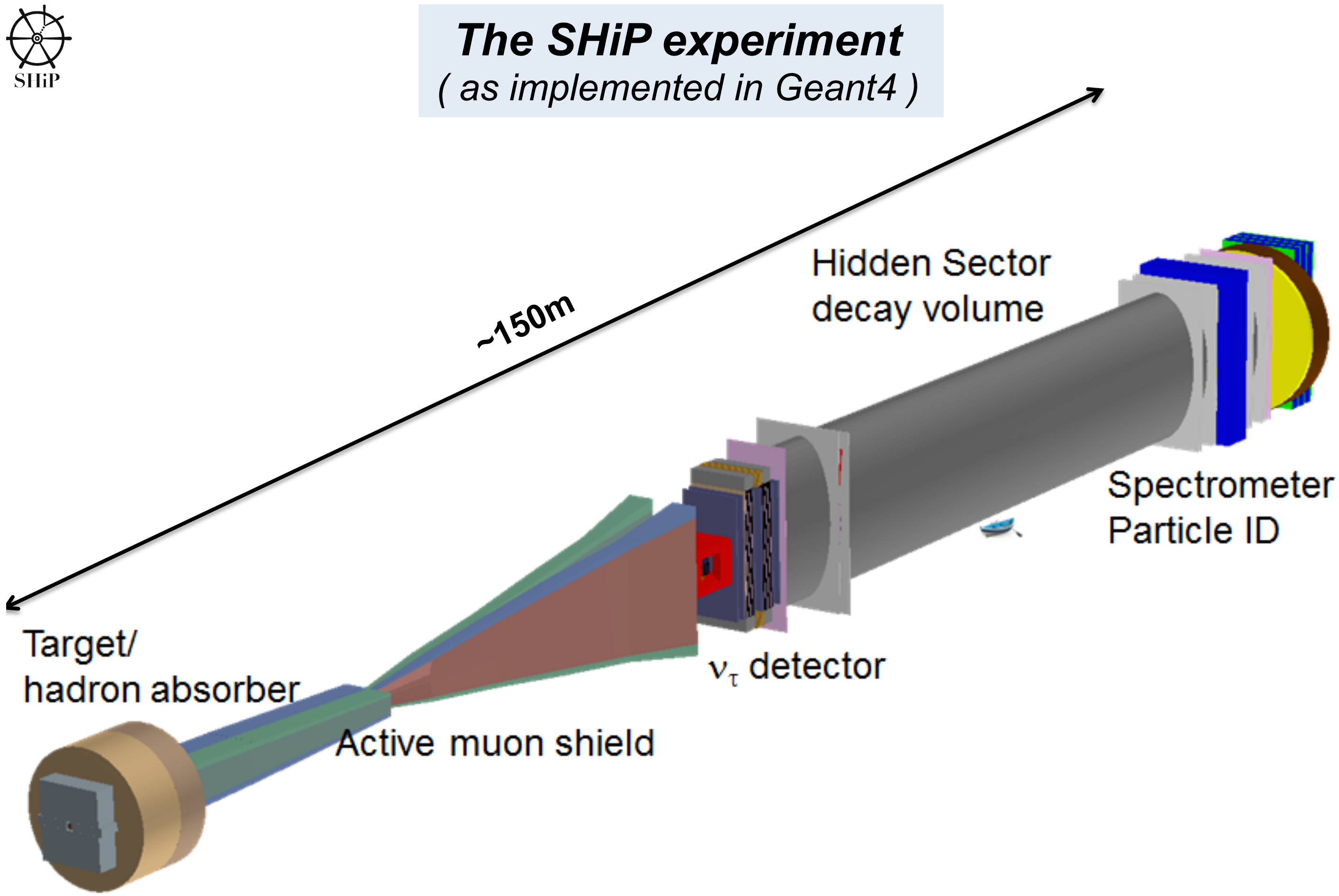
Improves over LSND, SLAC experiments, and Kaon decays in the range of the mediator mass from ~ 100 to few 100 MeV. Details can be found in 1702.02688.

Future directions

To improve on sensitivity to light dark matter in beam dump/fixed target experiments:

- **SHiP**
- NA64 with more intensity (LDMX)
- More experiments at short neutrino baseline program and DUNE near detector (C. Frugiuele and collaborators)
- ….
- Ultimate beam dump experiment looking for light DM in scattering = powerful accelerator next to large neutrino detectors deep underground for least background.

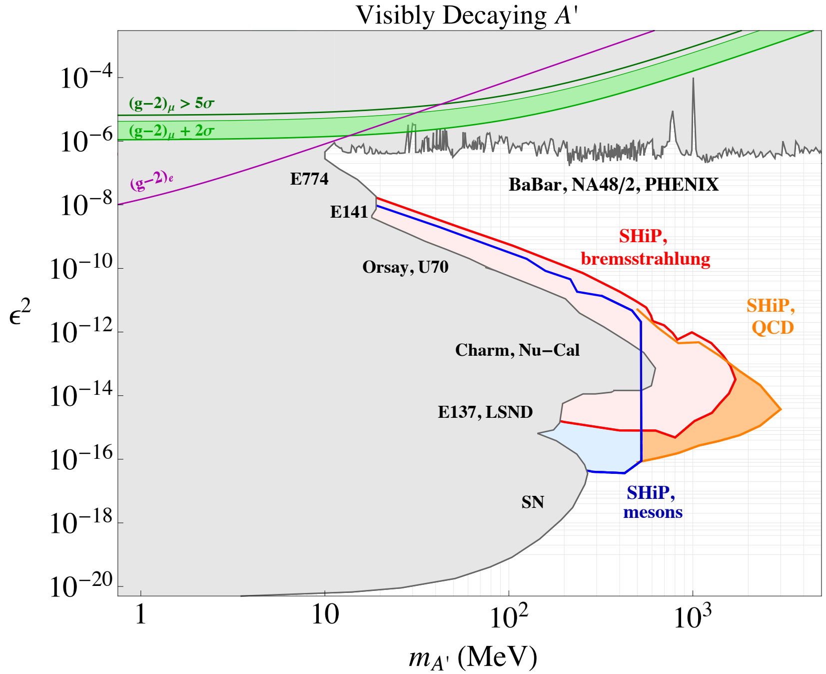
Future: SHiP project at CERN

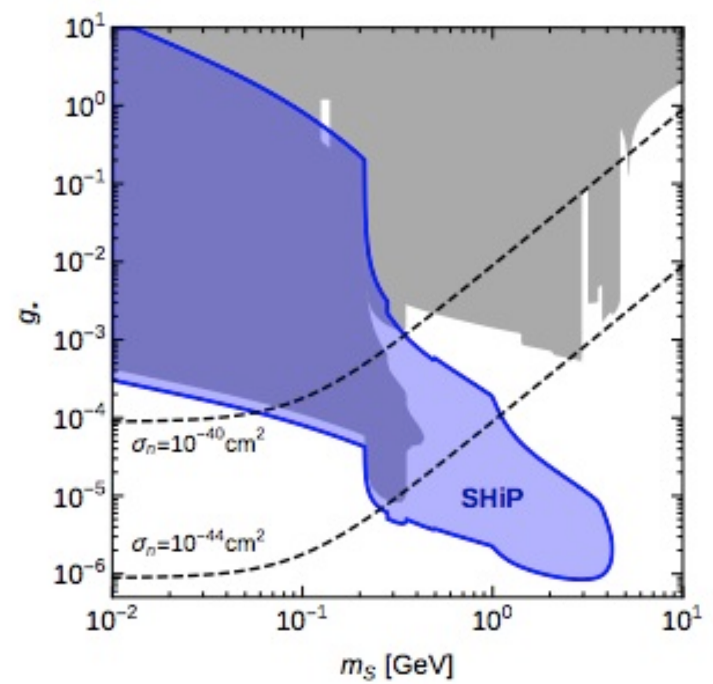


A proposal for a large experiment at CERN SPS to look for all types of hidden particles: sterile neutrinos, axion-like particles, dark photons, dark Higgses. Can also be used to study scattering signature of light DM

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 → … $\mu^+\mu^-$



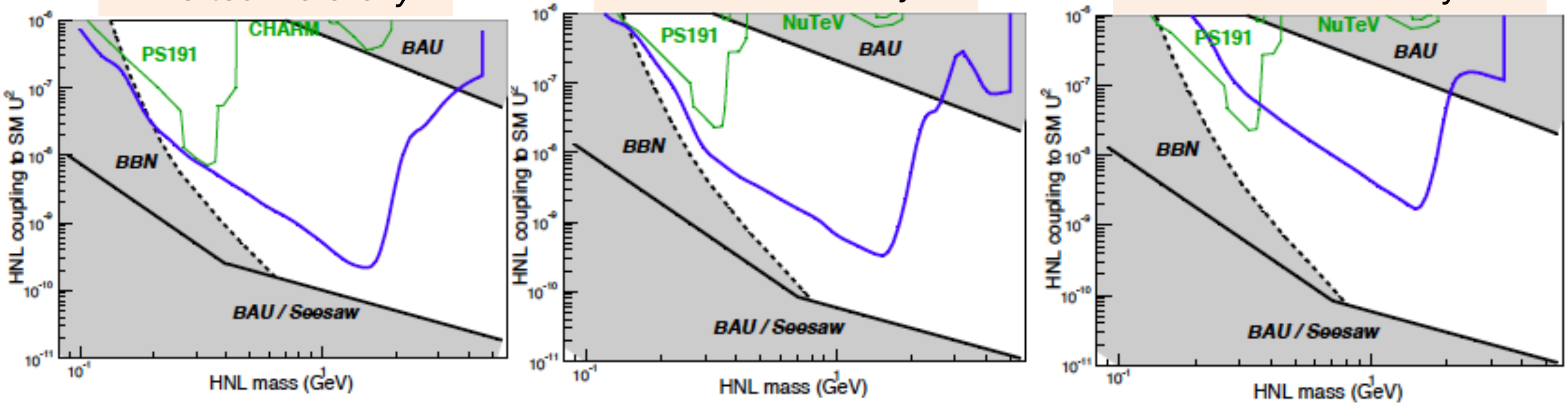


Details can be found in the white paper, 1505.01865, Alekhin et al.

SHiP has unique sensitivity to RH neutrinos

- Production channel is through charm pp → c cbar → N_R. (N_R are often called Heavy Neutral Leptons, or HNL)
- Detection is through their occasional decay via small mixing angle *U*, with charged states in the final state, e.g. $\pi^+\mu^-$, $\pi^-\mu^+$, etc.
- Decays are slow, so that the sensitivity is proportional to (Mixing angle)^4.

$U^2_e : U^2_\mu : U^2_\tau \sim 52:1:1$ *Inverted hierarchy* | $U^2_e : U^2_\mu : U^2_\tau \sim 1:16:3.8$ *Normal hierarchy* | $U^2_e : U^2_\mu : U^2_\tau \sim 0.061:1:4.3$ *Normal hierarchy*



HNL production can be enhanced in non-minimal models, Batell et al.

SHiP sensitivity to light DM

- Estimated in deNiverville et al.

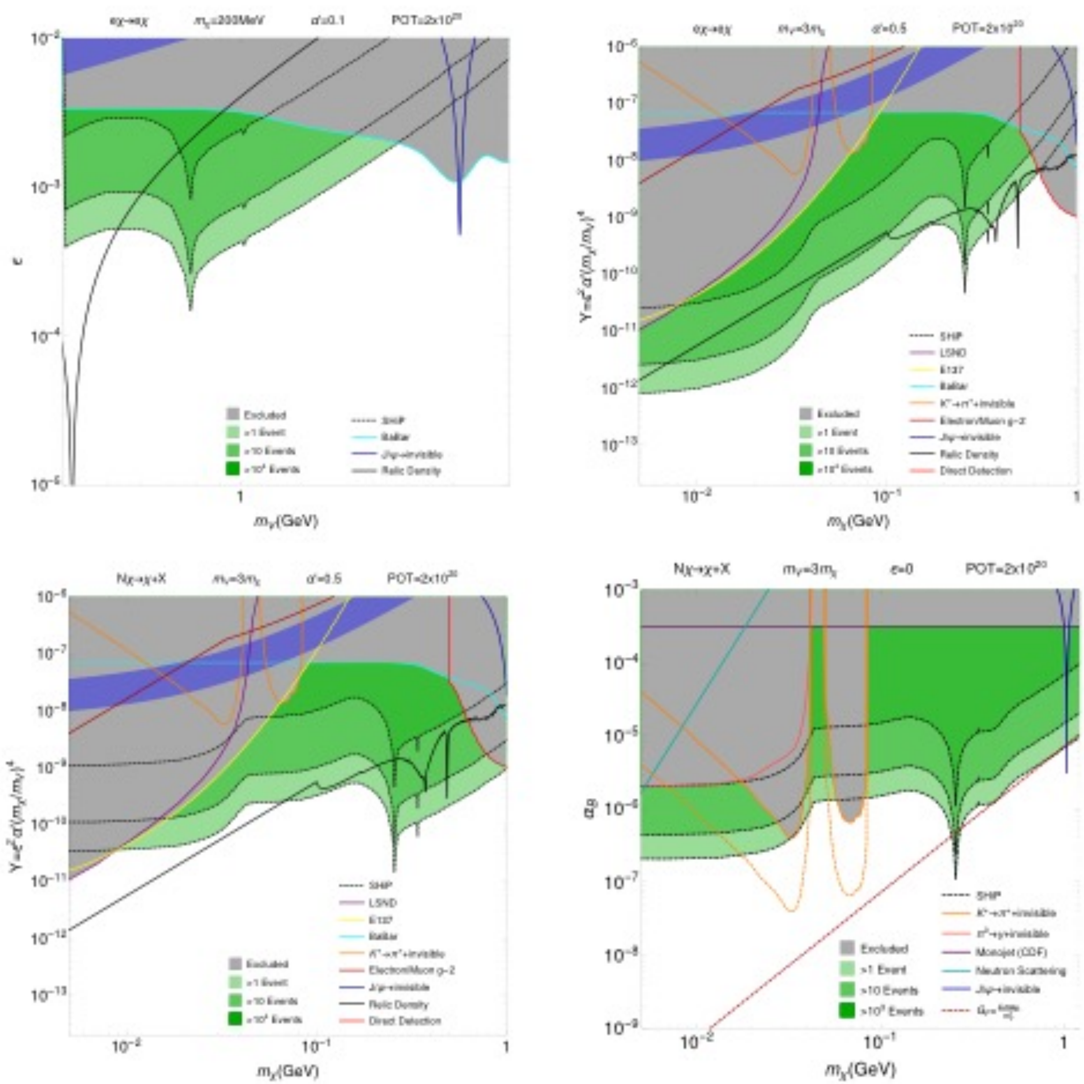


FIG. 11. Plots showing the SHiP yield of light dark matter scattering events in various channels.

A comment on SHiP

Details of physics motivation can be found in the

white paper, 1505.01865, Alekhin et al.

SHiP is not just a proton beam dump, it is beam dump of "everything"

- Protons produce enormous amount of EM decaying particles (pi0, eta), that all cascade to photons, and EM showers. **It is an enormous electron and photon beam dump!**
- Muons are also copiously produced and go through the tens of meters of material before being diverted/slowed down. **It is a muon beam dump as well.**

So far the sensitivity studies to NP were mostly limited to the primary productions inside the target, but there is a lot to explore with these secondary "beams", and sensitivty to many exotic candidates will improve

More coverage of dark sector using underground accelerators and neutrino detectors

with Eder Izaguirre and Gordan Krnjaic, 2014, 2015

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

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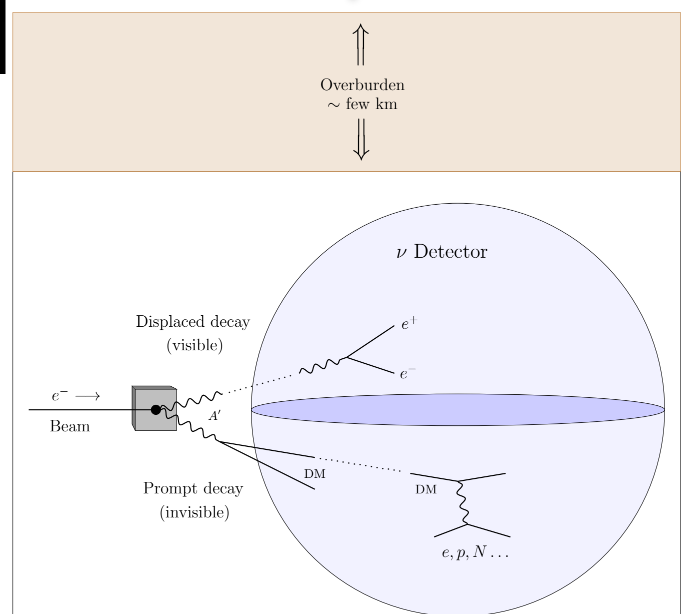
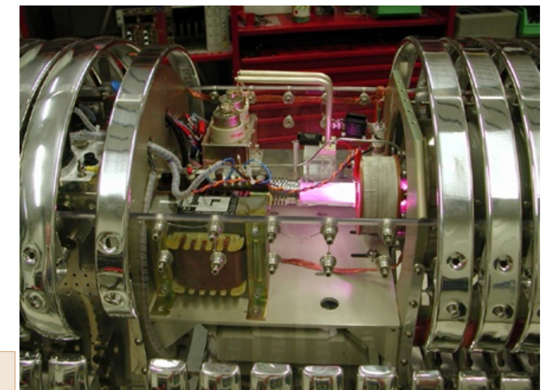
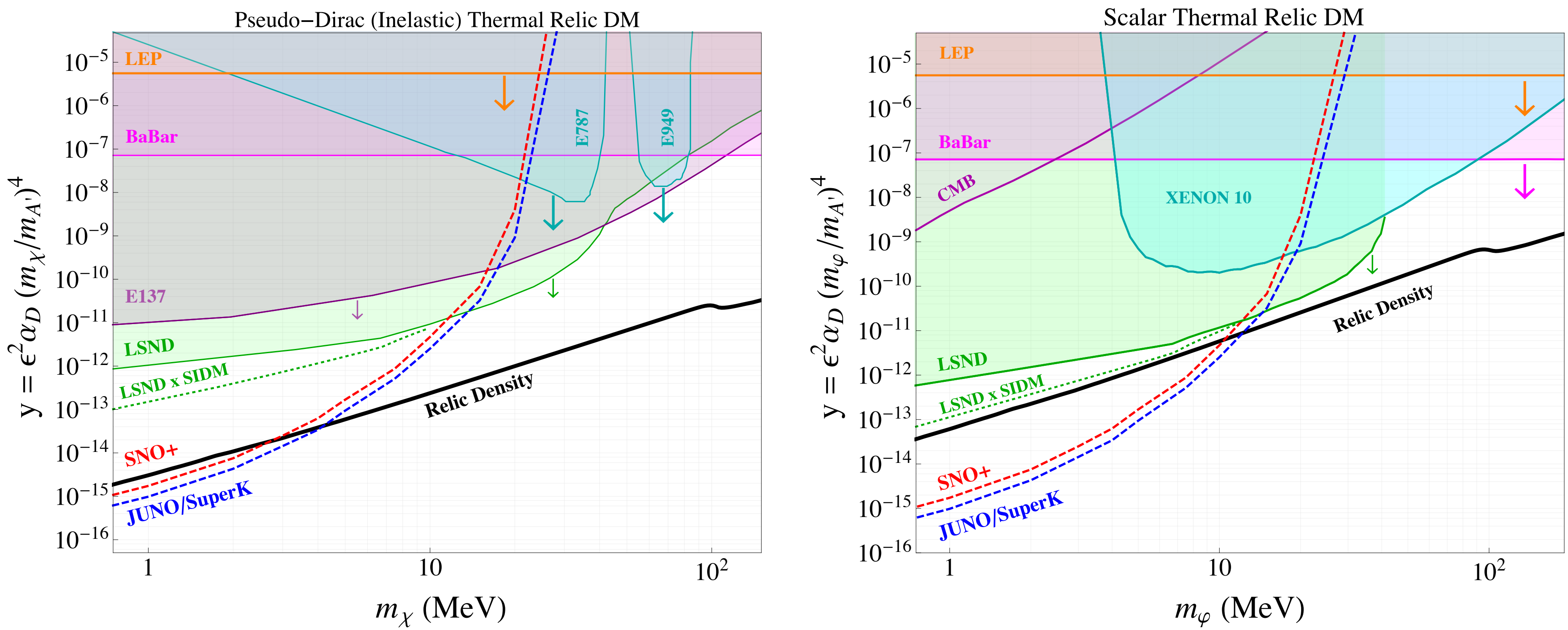




LUNA, DIANA,…, 1 e-linac for calibration

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

One of the topics to be discussed at a pre-TAUP meeting at PI, Jul20-22

Search for small mass mediators

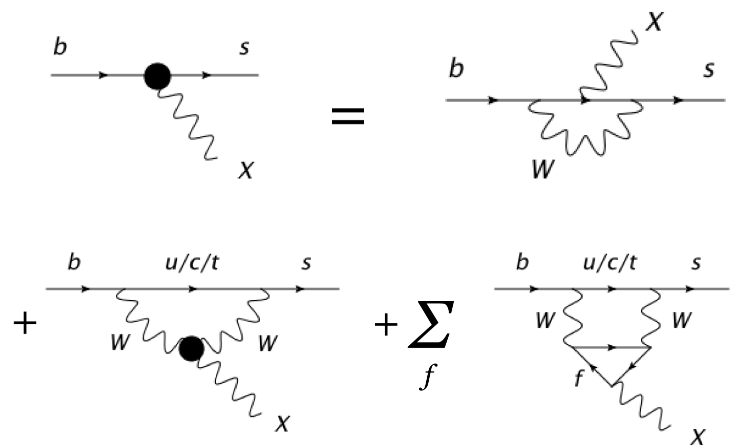
$$\mathcal{L} = \overline{\chi}(i\partial_\mu\gamma_\mu - m_\chi)\chi + \lambda\overline{\chi}\chi S + \frac{1}{2}(\partial_\mu S)^2 - \frac{1}{2}m_S^2 S^2 - AS(H^\dagger H)$$

$$\to \ldots.\frac{1}{2}(\partial_\mu S)^2 - \frac{1}{2}m_S^2 S^2 + S\theta(y_f\overline{f}f + \ldots) \qquad \theta = \frac{Av}{m_h^2}$$

- If $m_{\mathrm{mediator}} < m_{\mathrm{DM}}$ the best strategy is to look for the mediator itself directly.
- Dark photon portal search (and any conserved vector current portal) does not induce large FCNC
- Other portals (axial vectors, dark Higgses and scalars in general, ALPs, baryonic vector) are severely constrained by flavor physics.

Scalar currents are very different from conserved vector currents

Conserved vector currents are uniquely positioned to avoid very strong flavor constraints.



$$\simeq \left[C V_{tb} V_{tc}^* \frac{m_t^2}{m_W^2} \right] X_\mu \bar{s} \gamma^\mu \mathcal{P}_L b + \frac{1}{m_W^2} \ldots$$

For a conserved vector current, $G_F\, q^2$ For scalar current, $G_F\, m_t^2$

There is extremely strong sensitivity to new scalars, pseudoscalars axial-vectors in rare K and B decays.

Generalization of this argument/constraints: R Lasenby et al (in prep)

Top-W loop and light mediators

- Calculations of the "Higgs penguin" are especially neat:

$$\mathcal{M}_S = \frac{S}{v} m_b \bar{s}_L b_R \times \frac{3}{2}\theta \frac{(y_t^{\rm SM})^2 V_{tb} V_{ts}^*}{16\pi^2}$$

- Notice the absence of any complicated function of m_t/m_W. The reason being is that the effect is similar to scale anomaly:

$$m_t \bar{t}t \to \left(1 + \frac{h}{S}\right) m_t \bar{t}t \quad \to \quad \text{H.peng.} \ \sim (\gamma \cdot p) \frac{\partial}{\partial v} \text{SelfEnergy}(m_t/m_W)$$

$$\frac{\partial}{\partial v} \text{SelfEnergy}(m_t/m_W) = \frac{\partial}{\partial v} \text{SelfEnergy}(y_t/g_W) = 0?$$

- The result is not 0 because of the scale dependence,

  Self-Energy ~ $\text{Log}(\Lambda_{UV}/v)$

$$\Gamma_{K\to\pi+\phi-\text{mediator}} \simeq \left(\ \theta \ \ \right)^2 \left(\frac{3m_t^2 V_{td} V_{ts}^*}{16\pi^2 v^2}\right)^2 \frac{m_K^3}{64\pi v^2}.$$

Constraints from flavor decay

- Best constraints come from the K→ π νν (low mass, Brookhaven exp, to be superseded by NA62), and from search of di-muons peaks in B → K μμ at the LHCb.
- Currently (Higgs mixing angle)$^2 < 2\times10^{-7}$ from Kaons and similarly and even better from LHCb.

- *To be topical*, constraints on the axial vector couplings of light vectors is very strong = longitudinal mode does not decouple, and you are looking at the emission of a Goldstone enhanced by $(m_B/m_X)^2$.

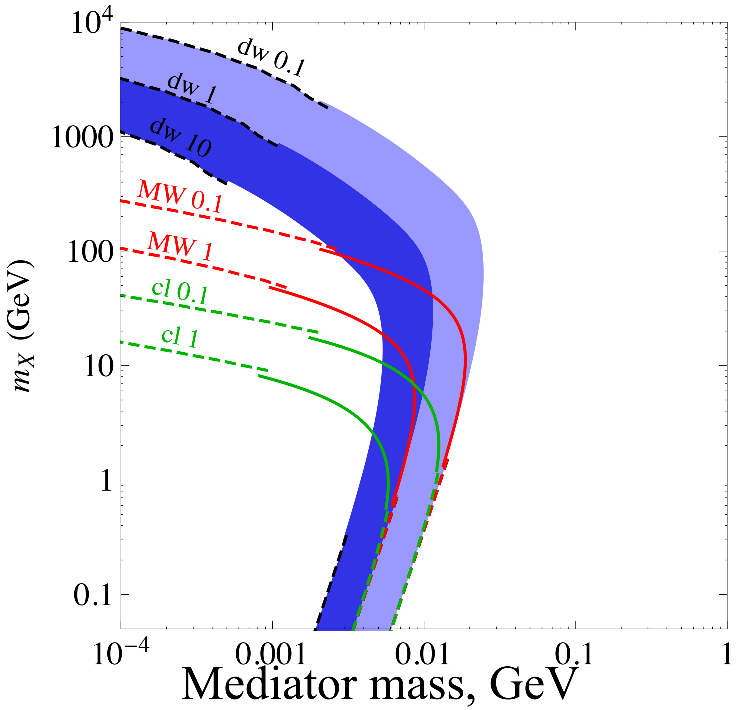
$$\frac{g_{\text{axial}}}{10^{-6}} \times \left(\frac{17\text{ MeV}}{m_X}\right) < 0.1 - 1$$

Normalization on 17 MeV is purely coincidental

SHiP can improve many of the scalar/axial/Alps etc portal sensitivities

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).



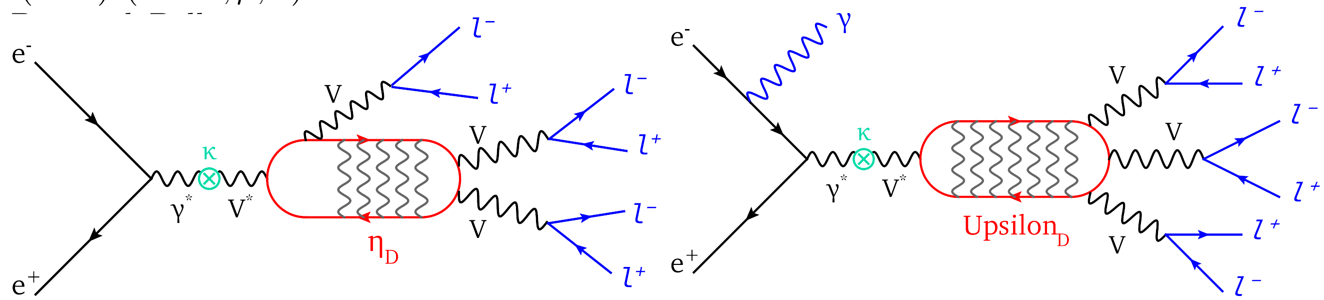
Example of parameter space that creates a core and solves the problem (from Tulin, Yu, Zurek) for $\alpha_d = 0.1$

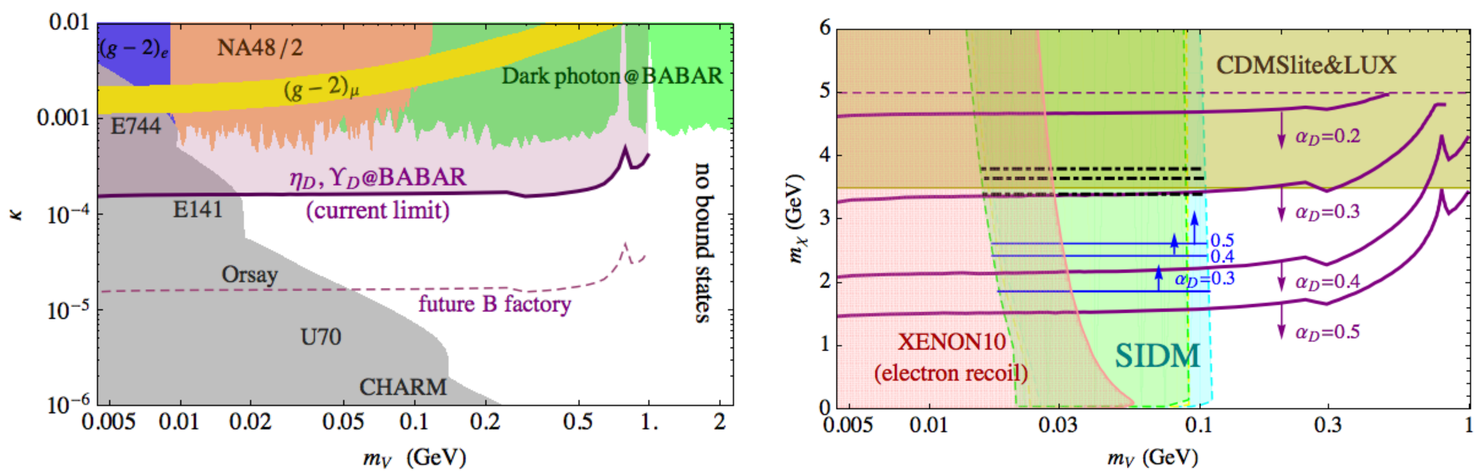
Some of the parameter space is within reach of B-factories.

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, 2016

Pushing down the sensitivity to energy deposition in direct detection

- In the last few years there has been a push to extend the sensitivity of direct detection to very light dark matter, and go below the 1 keV energy deposition scale

Ionization,
E_{th} > few eV,
10^2/kg/day/keV

Large direct detection experiments

E_{th} >1keV counting rates ~ 10^{-2}/kg/day/keV for E ~ few keV

Large neutrino experiments E_{th} >200 keV counting rates at ~ 10^{-2}/ton/day/MeV for E ~ few MeV

Active field of exploration, starting from

Essig, Mardon, Sorensen, Volansky …

“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.

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

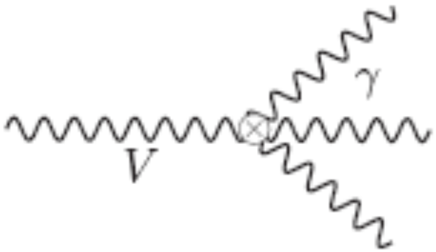
- If $m_V < 2\ m_e$ then only $V \rightarrow 3\ \gamma$ is possible. It is a delayed decay – larger couplings will be consistent with bounds. No monochromatic photons = weaker limits from x- and gamma-rays.

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

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:



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

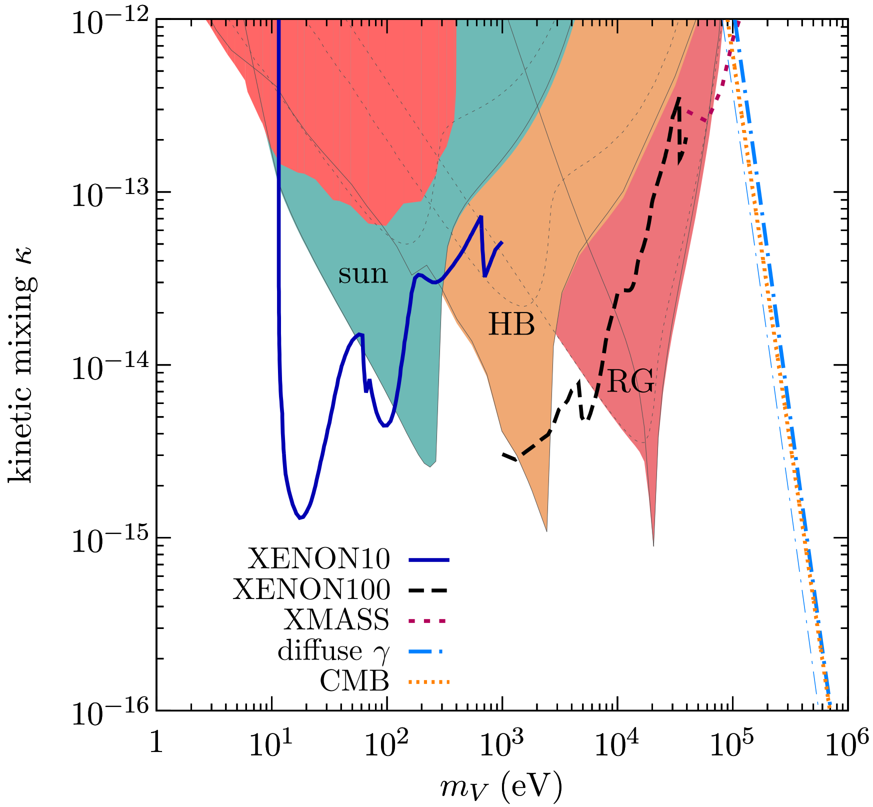
$$\tau_U \Gamma_{V\to 3\gamma} \lesssim 1 \quad \Longrightarrow \quad m_V\,(\alpha')^{1/9} \lesssim 1\,\mathrm{keV}\ .$$

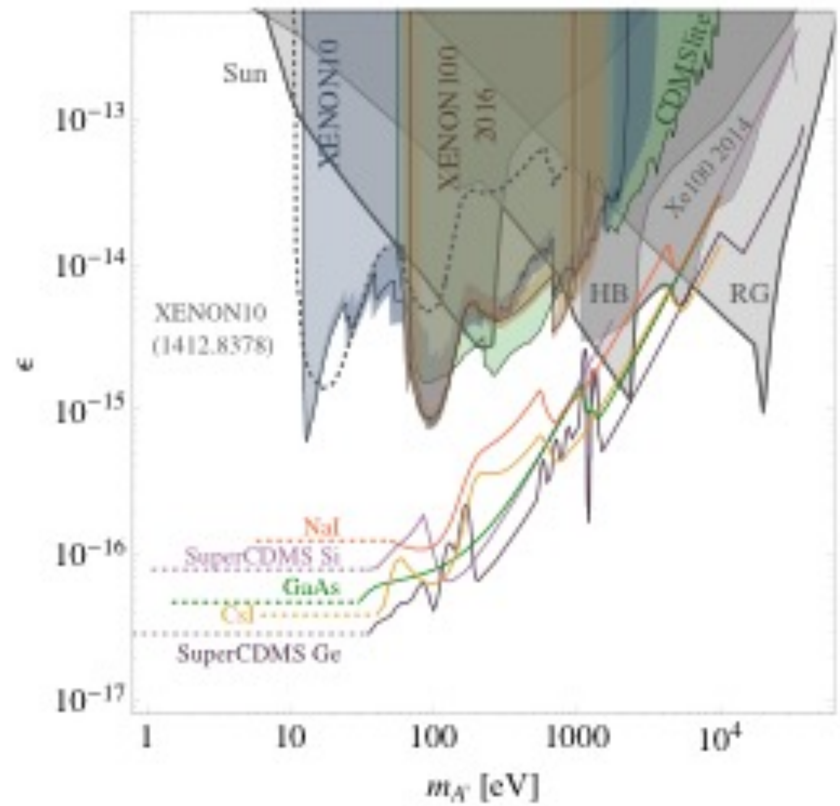
The γ-background constraints are weak. (No monochromatic lines)

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

“Super-WIMP” DM absorption signal

An, MP,Pradler, Ritz, PRD 2014,   Bloch et al (Tian-Tian Yu)





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)

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*.

Conclusions

1. Light New Physics (not-so-large masses, tiny couplings) is a generic possibility. Some models (e.g. dark photon or dark Higgs-mediated models) are quite minimal yet UV complete, and have diverse DM phenomenology.
2. Sub-GeV WIMP dark matter can be searched for via production & scattering or missing energy. New results from NA64, BaBar, MiniBoone are all less than few months/weeks old. *No signal, improved constraints*. SHiP will improve on that.
3. Search for mediators (diversifying away from dark photon) benefit significantly from flavor searches. In some cases, bound states of DM enhance sensitivity reach to mediators. CERN plays important role in these searches!
4. Taking direct detection below keV energy thresholds seriously allows probing sub-GeV masses of WIMPs *and* break into the super-weakly interacting DM territory probing freeze-in dark matter, absorption of DM particles etc.

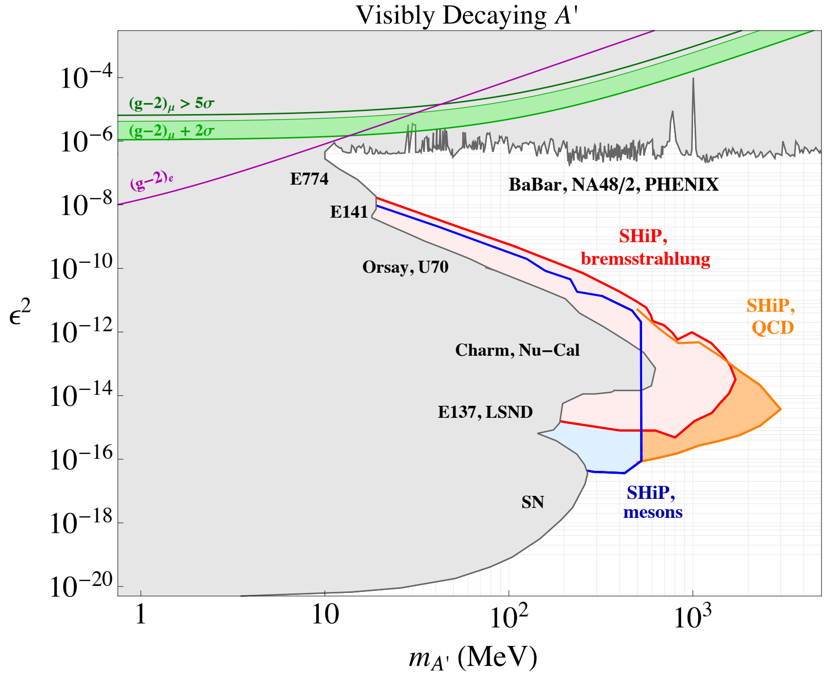
On-going and future projects

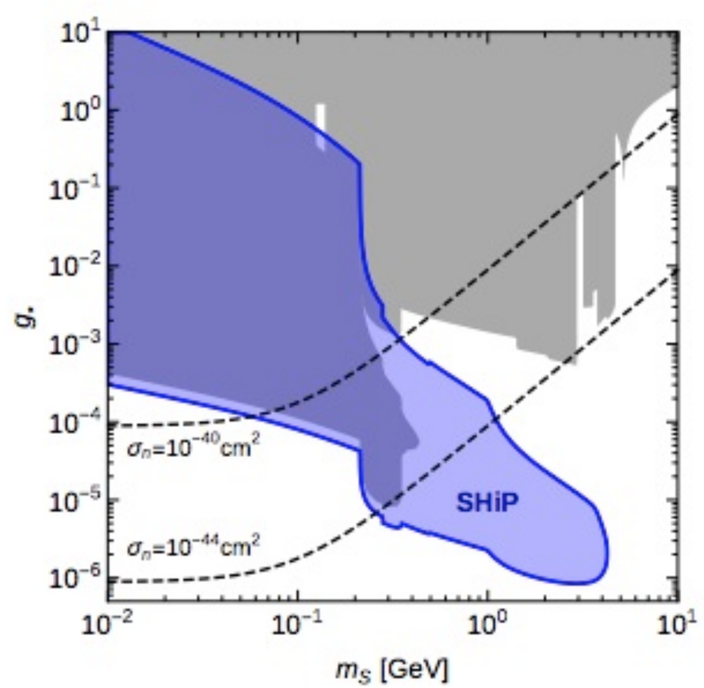
Fixed Target/beam dump experiments sensitive to

- 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.