Dark Photon and Dark Matter: theoretical motivations

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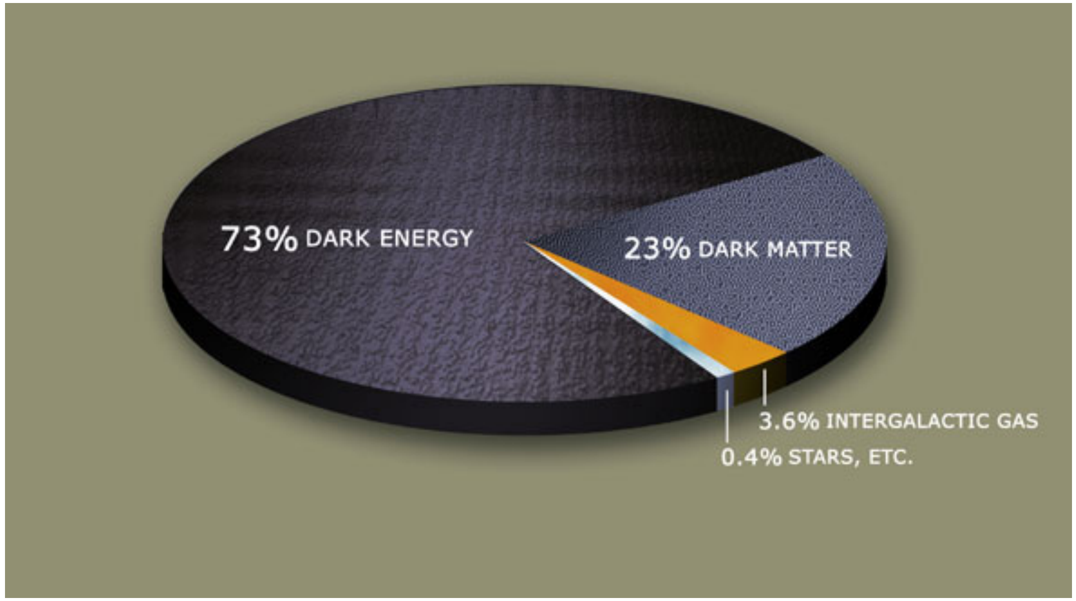
PERIMETER INSTITUTE FOR THEORETICAL PHYSICS

Outline of the talk

1. Introduction. Portals to light new physics.
2. Model of dark photon and “millicharged” particles.
3. Connections to anomalies: Particle physics: g-2, proton charge radius, new anomalies at the LHC ? Astro: 511 keV, Pamela/ Fermi/AMS-2 positron rise, “too-big-to-fail”.
3. Detecting light dark matter in the beam dump experiments and neutrino experiments.
4. Conclusions

Big Questions in Physics

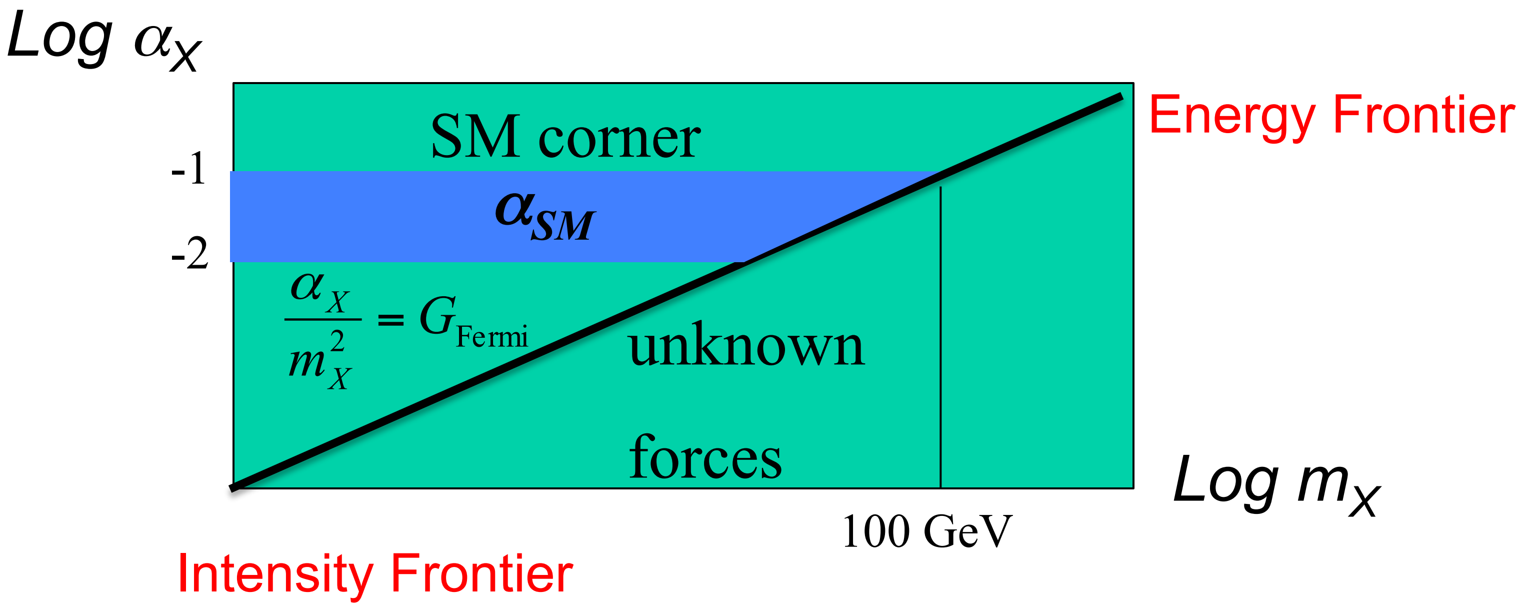


"Missing mass" – what is it?

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

(History lesson: first "dark matter" problem occurred at the nuclear level, and eventually new particles, neutrons, were identified as a source of a "hidden mass" – and of course immediately with the new force of nature, the strong interaction force.)

Intensity and Energy Frontiers



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

Exploring this plot in the downward direction requires large intensities. It also requires a framework of how to describe "progress"

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

……….

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

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*.

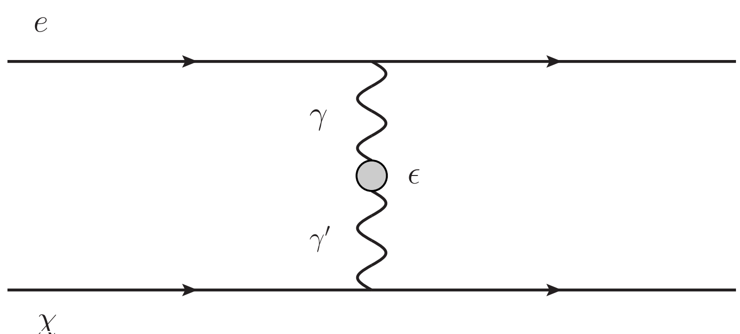
"Simplified model" for dark sector

(Okun', Holdom,…)

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

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

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



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*.

Dark photon

(Holdom 1986; earlier paper by Okun')

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

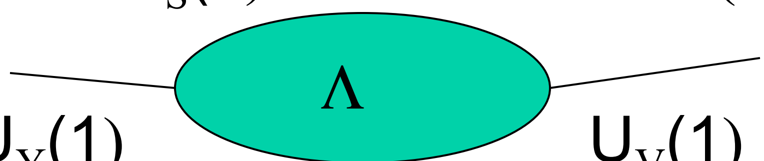
This Lagrangian describes an extra U(1)' group (**dark force, hidden photon, secluded gauge boson, shadow boson etc, also known as U-boson, V-boson, A-prime, gamma-prime etc**), attached to the SM via a vector portal (kinetic mixing). Mixing angle κ (also known as ε, η) controls the coupling to the SM.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

In this talk κ = ε

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

"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) $\sim$ MeV – GeV

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

Variations of vector portal: gauged B - L, L_μ - L_τ ,.. symmetries

- *Anomaly-free, can be UV complete.*
- A non-zero kinetic mixing will be developed out of RG evolution
- Neutrinos get extra interaction – already constrained!
- L_μ - L_τ is the *least constrained* possibility because neither electrons nor nucleons have extra interactions with neutrinos.

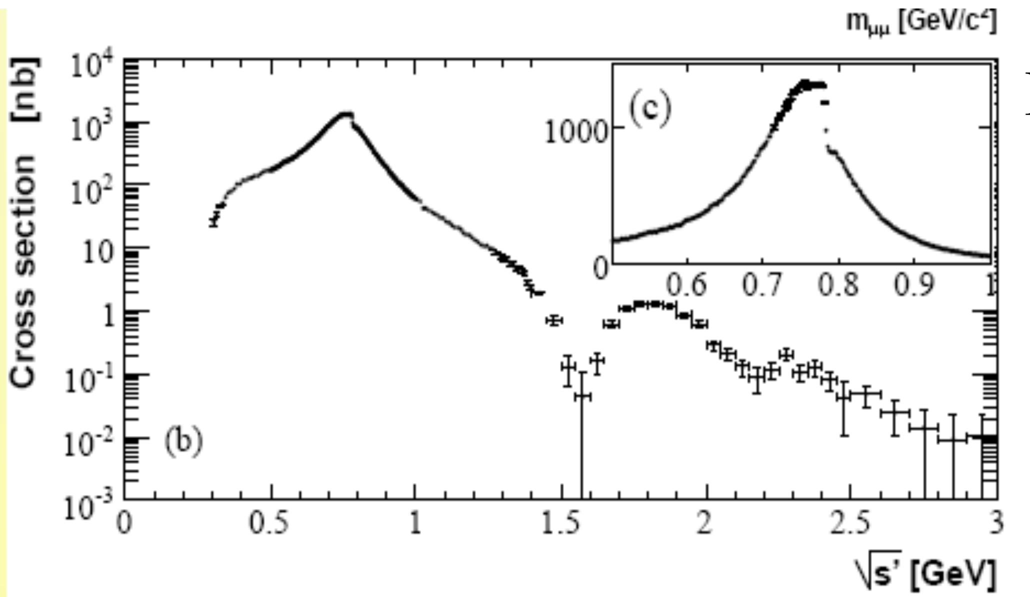
In recent years there has been some increase of experimental activity searching for light particles in MeV-GeV range because of the following speculative motivations.

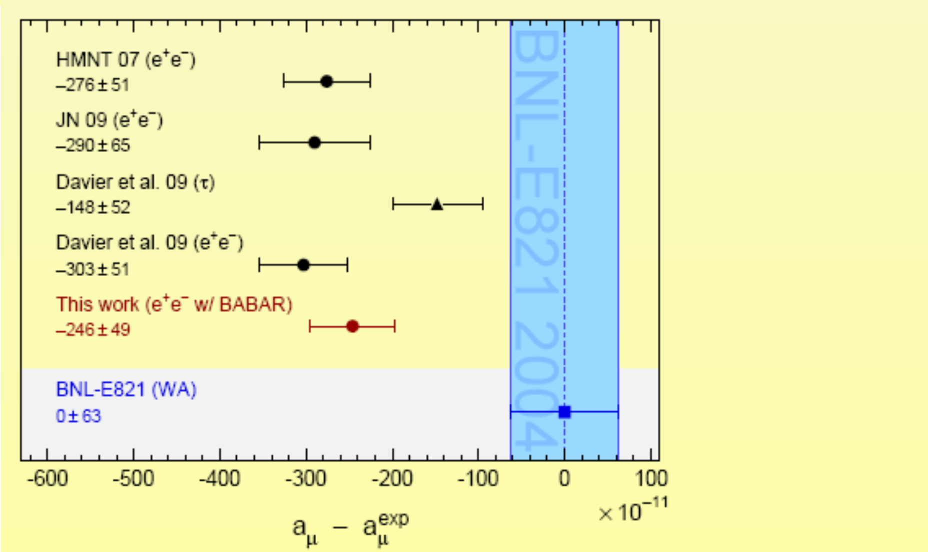
1. Light New Physics helps to solve some particle physics anomalies (muon g-2,…).
2. It helps to tie some astrophysical anomalies (511 keV excess from the bulge, positron excess above 10 GeV etc) with models of dark matter *without large fine tuning.*

Some specific motivations for new states/ new forces below GeV

1. A 1.5 decade old discrepancy of the muon g-2.
2. Discrepancy of the muonic hydrogen Lamb shift.
3. Theoretical motivation to look for an extra U(1) gauge group.
4. Recent intriguing results in astrophysics. 511 keV line, PAMELA positron rise.
5. Too-big-to-fail etc problems of CDM
6. Other motivations.

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.

More discrepancies discovered using muons !

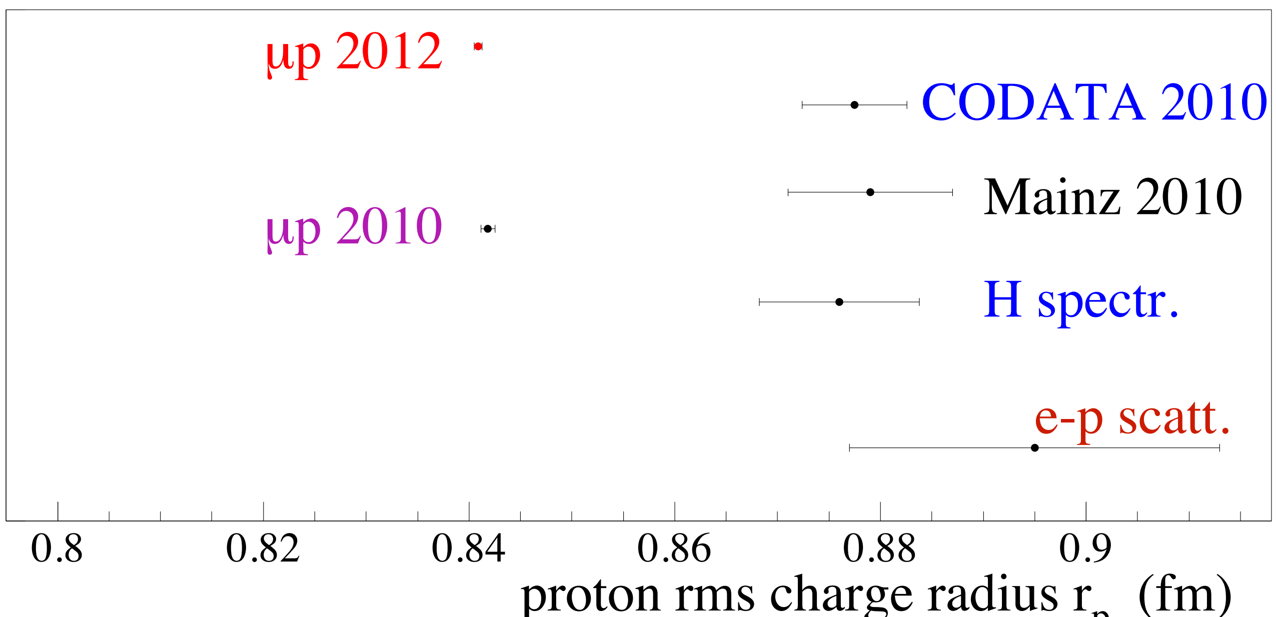
$\nu(2S_{1/2}^{F=1} \to 2P_{3/2}^{F=2})$ = 49881.88(76) GHz R. Pohl *et al.*, Nature 466, 213 (2010)

49881.35(64) GHz preliminary

$\nu(2S_{1/2}^{F=0} \to 2P_{3/2}^{F=1})$ = 54611.16(1.04) GHz preliminary

Proton charge radius: $r_{\rm p} = 0.84089\ (26)_{\rm exp}\ (29)_{\rm th} = 0.84089\ (39)$ fm (prel.)

μp theory: A. Antogini *et al.*, arXiv :1208.2637 (atom-ph)

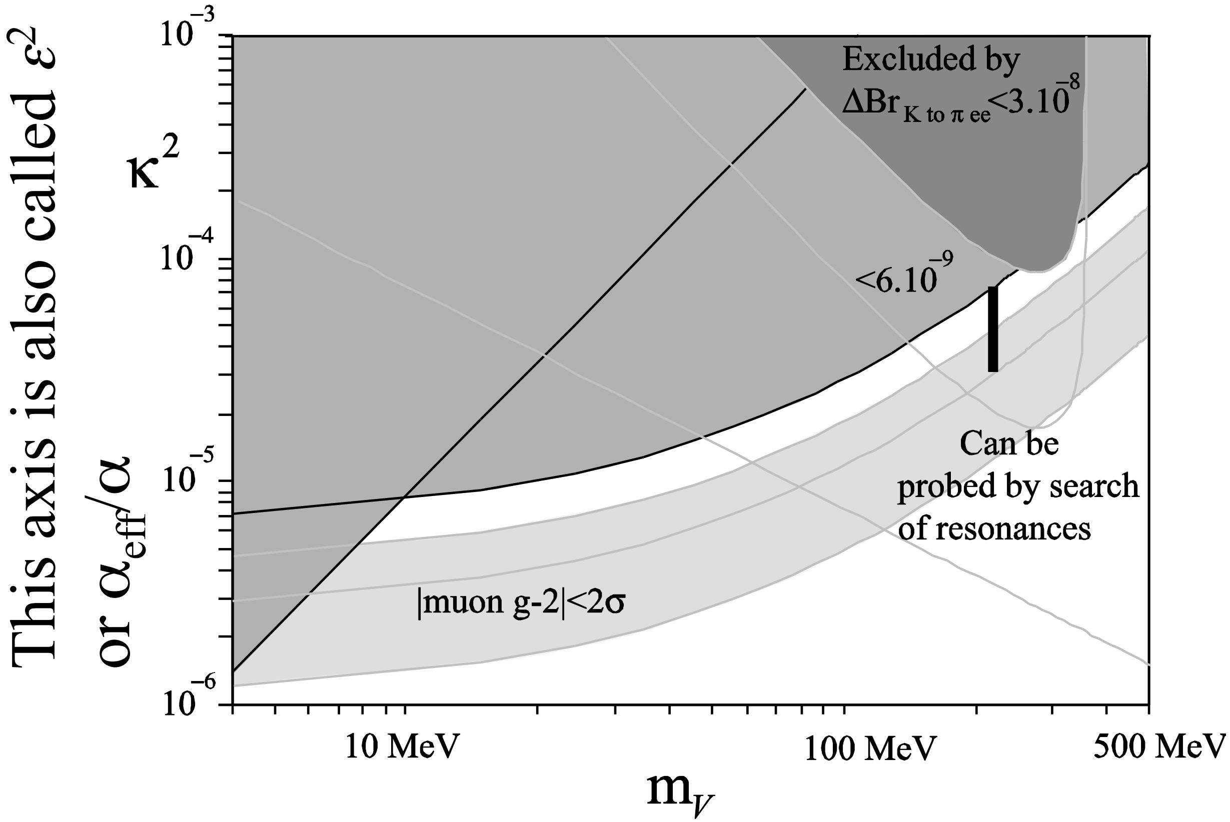


If new physics is responsible for that, it cannot be weak scale, only very light, as r_p will require ~ 10^4 G_F effects… May be some “relative” of dark photon?

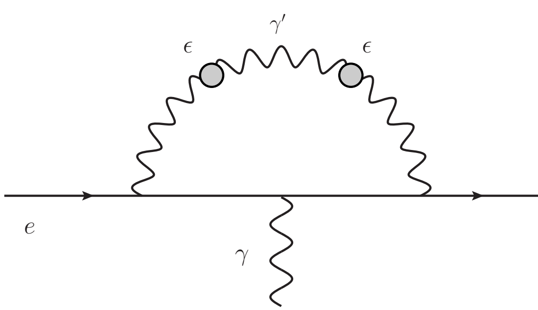
κ-m_V parameter space

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 $m_V \sim m_\mu$

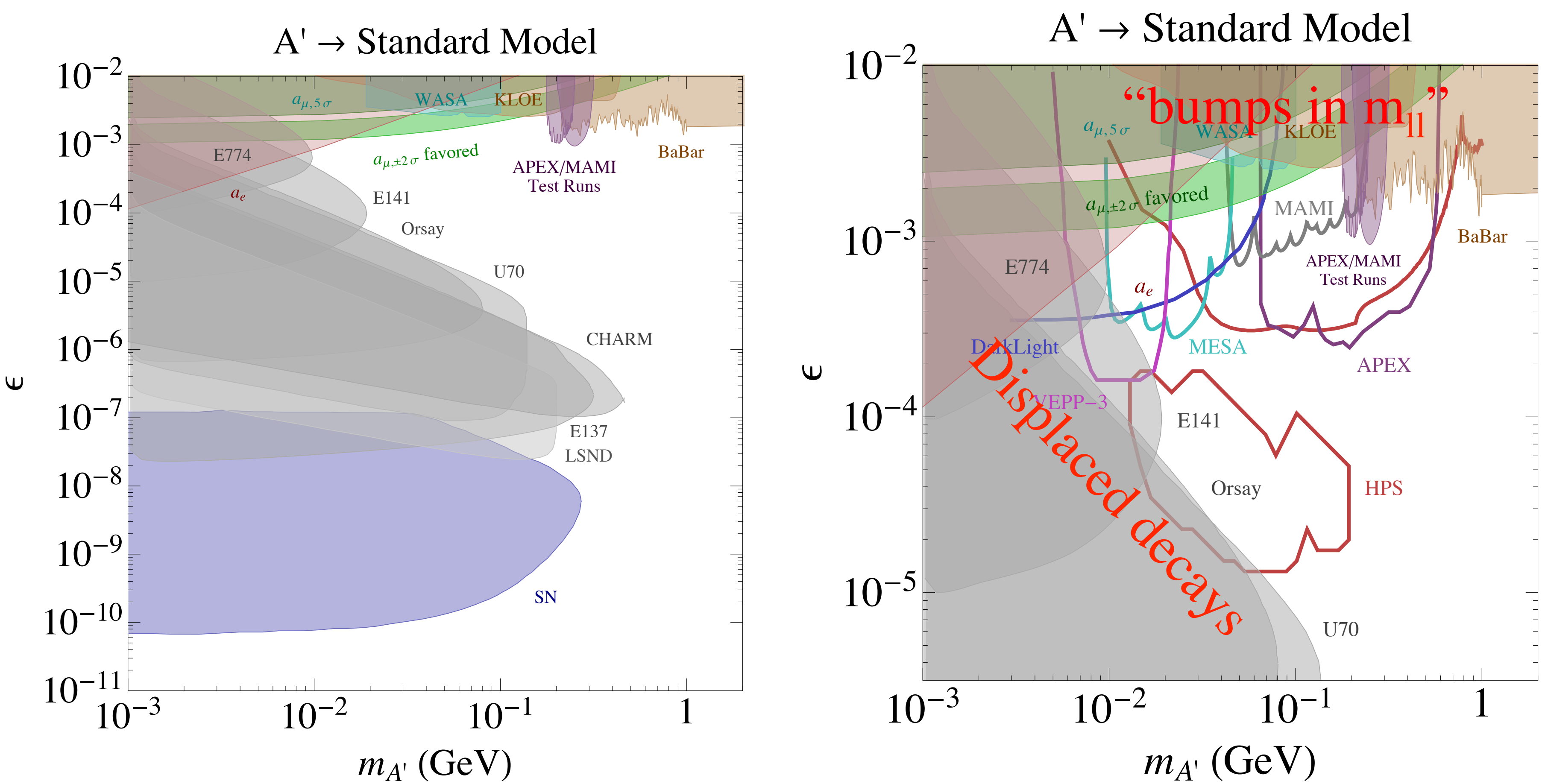


MP, 2008



Since 2008 a lot more of parameter space got constrained

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.

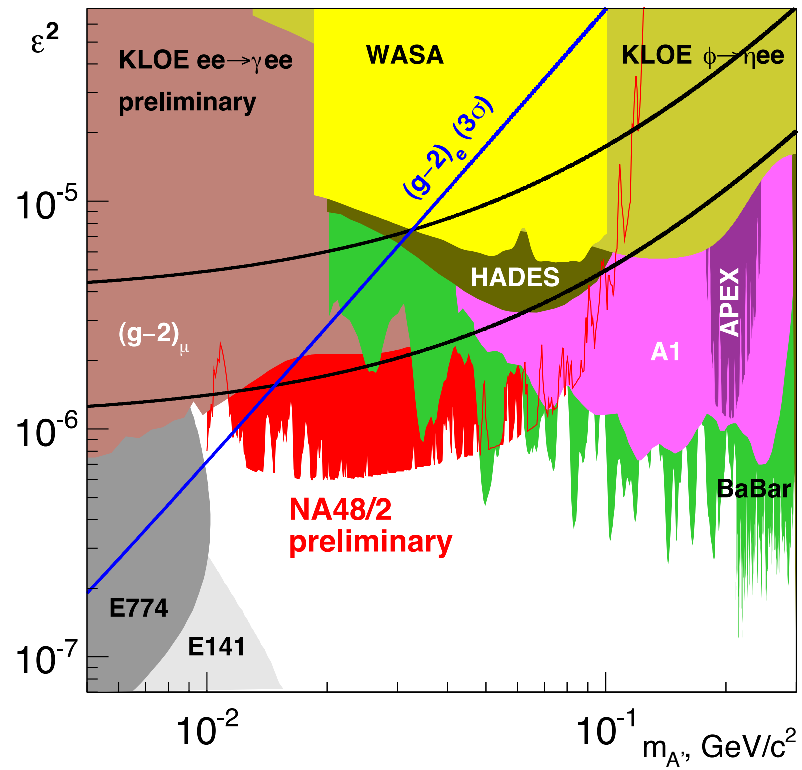
Latest results: A1, Babar, NA48

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.*

Signatures of Z’ of $L_\mu - L_\tau$

Experimental results on “trident”

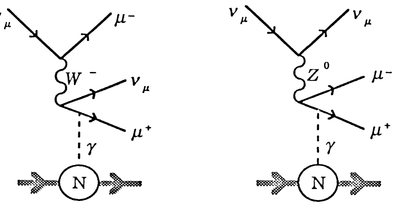
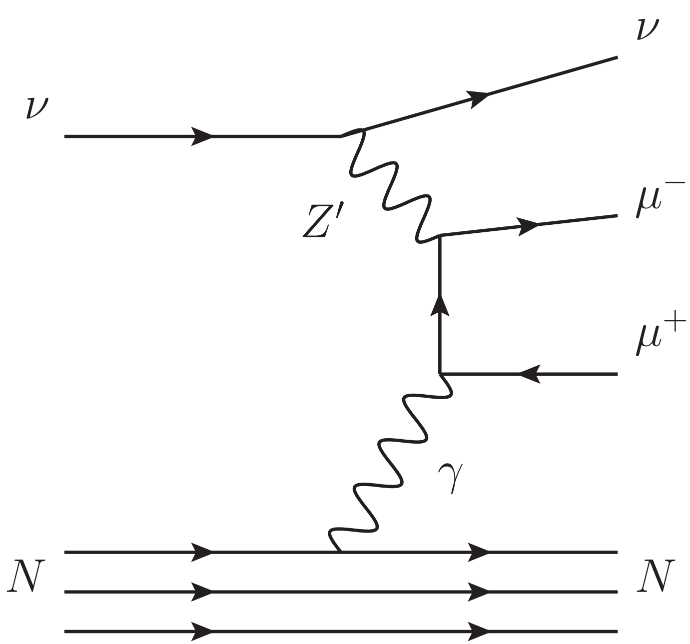
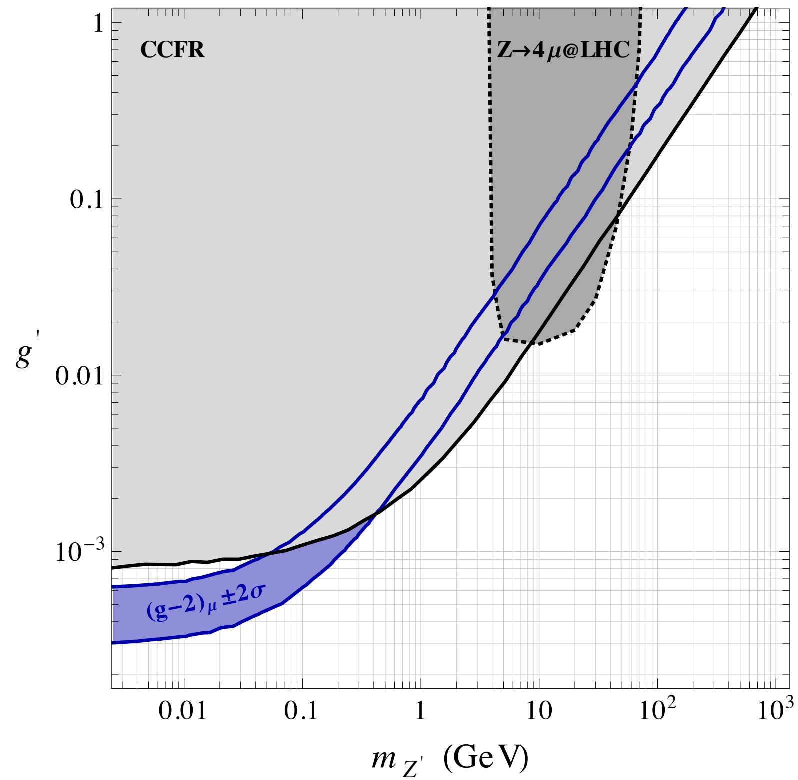


FIG. 1. Feynman diagram showing the neutrino trident production in ν_μ-A scattering via the W and the Z channels.

$$\sigma_{\mathrm{CHARM-II}}/\sigma_{\mathrm{SM}} = 1.58 \pm 0.57\ ,$$
$$\sigma_{\mathrm{CCFR}}/\sigma_{\mathrm{SM}} = 0.82 \pm 0.28\ ,$$
$$\sigma_{\mathrm{NuTeV}}/\sigma_{\mathrm{SM}} = 0.67 \pm 0.27\ .$$

Hypothetical Z’ (any Z’ coupled to L_μ) contributes constructively to cross section. (Almannshofer et al., 2014)





Astrophysical motivations

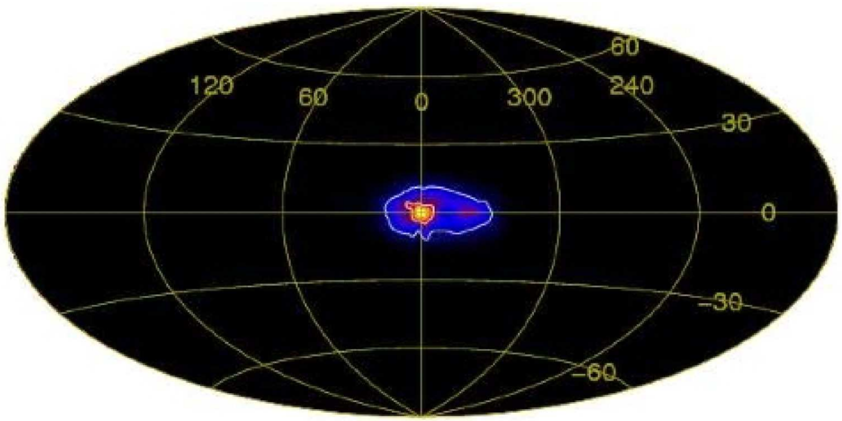


FIG. 4 511 keV line map derived from 5 years of INTEGRAL/SPI data (from Weidenspointner *et al.*, 2008a).

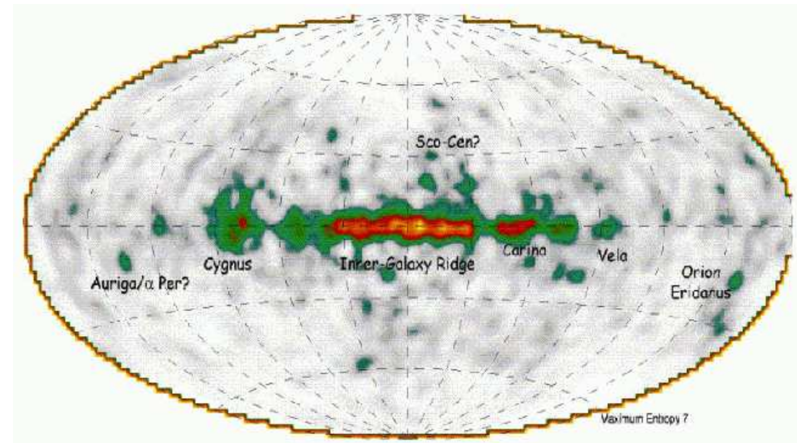
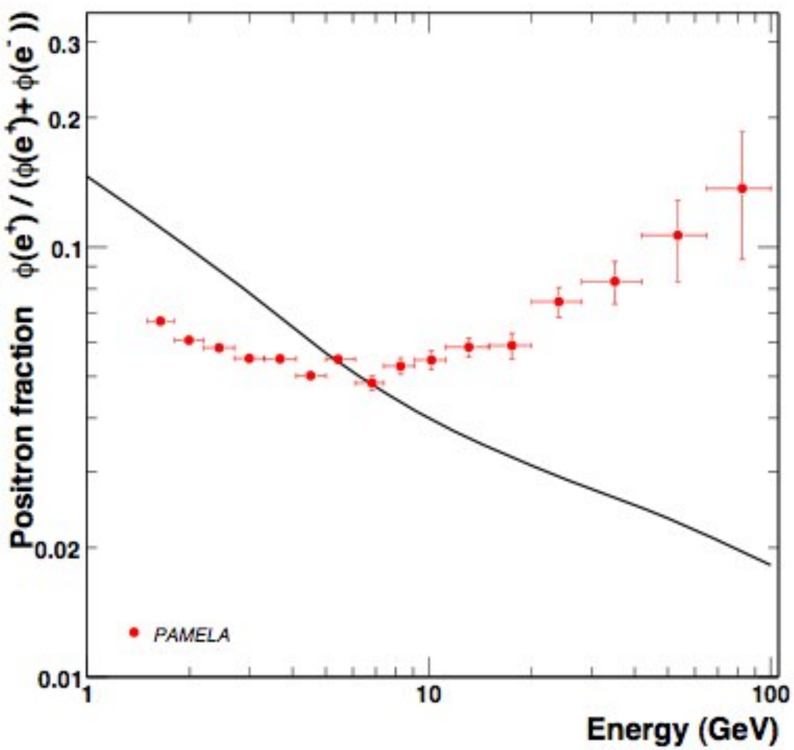


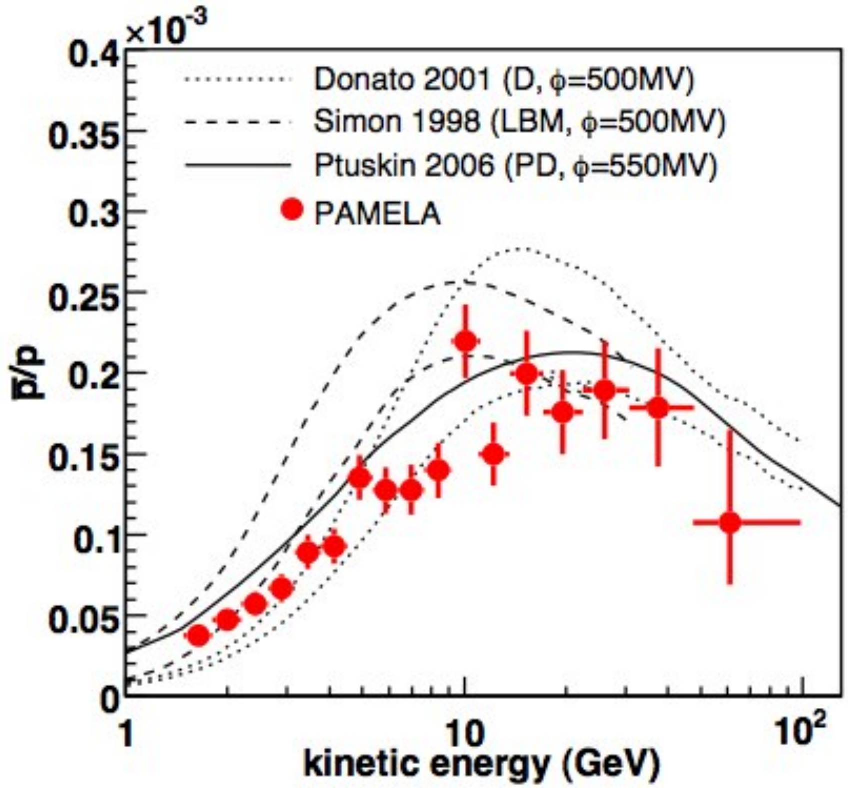
FIG. 7 Map of Galactic ^{26}Al γ-ray emission after 9-year observations with COMPTEL/CGRO (from Plüschke *et al.*, 2001).

There is a lot more positrons coming from the Galactic Center and the bulge that expected. The emission seems to be diffuse.

1. Positrons transported into GC by B-fields?
2. Positrons are created by episodic violent events near central BH?
3. Positrons being produced by DM? Either annihilation or decay?

PAMELA positron fraction





No surprises with antiprotons, but there is seemingly a need for a new source of positrons!

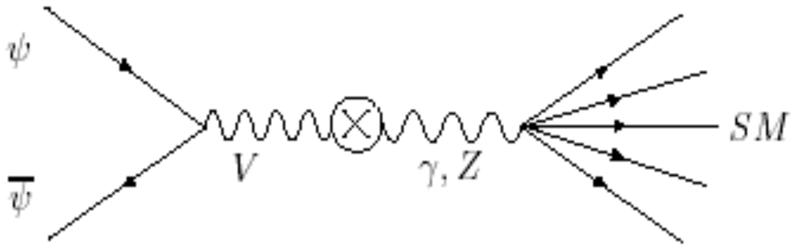
This is a "boost" factor of 100-1000 "needed" for the WIMP interpretation of PAMELA signal. E.g. SUSY neutralinos would not work, because <σv > is too small. Enhancing it "by hand" does not work because WIMP abundance goes down. Dark forces allow bridging this gap due to the late time enhancement by Coulomb (Sommerfeld).

Secluded WIMP idea – heavy WIMPs, light mediators

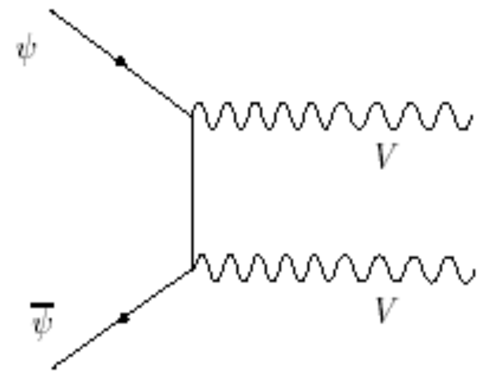
$$\mathcal{L}_{\rm WIMP+mediator} = -\frac{1}{4}V_{\mu\nu}^2 - \frac{\kappa}{2}V_{\mu\nu}B_{\mu\nu} - |D_\mu\phi|^2 - U(\phi\phi^*) + \bar{\psi}(iD_\mu\gamma_\mu - m_\psi)\psi.$$

ψ – weak scale Dark Matter; V –mediator particle.

$m_{mediator} > m_{WIMP}$



$m_{mediator} < m_{WIMP}$

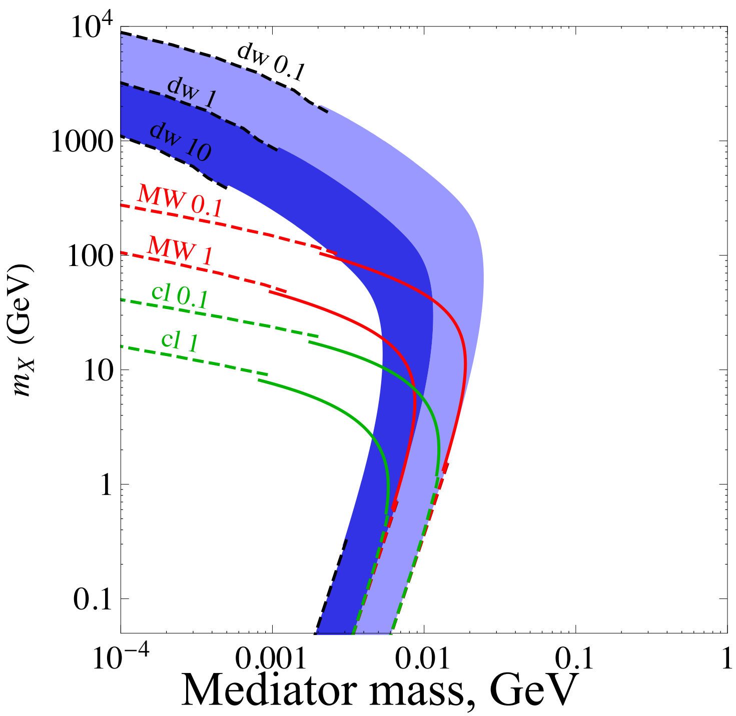


Second regime of annihilation into on-shell mediators (called *secluded*) does not have any restrictions on the size of mixing angle κ.

It turns out $m_{DM} >> m_{mediator}$ regime *helps* to tie PAMELA positron rise and WIMP idea together. (Also explains the lack of enhancement in antiprotons, and photons)

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).



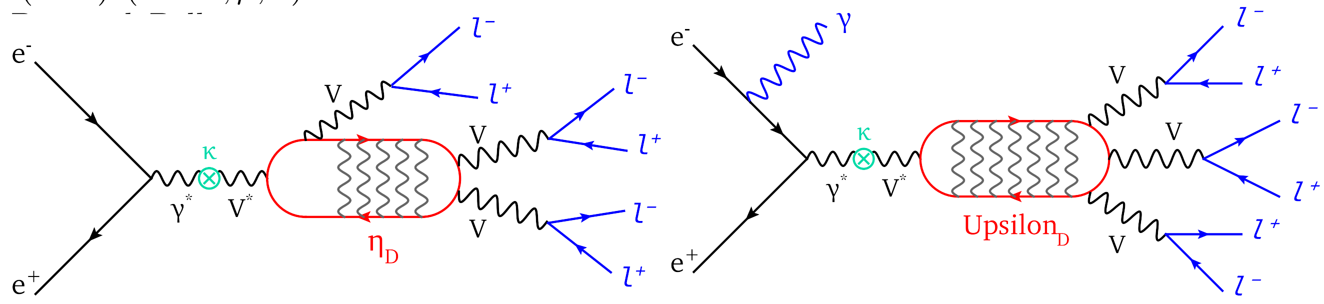
Example of parameter space that creates a core and solves the problem (from Tulin, Yu, Zurek) for $\alpha_d = 0.1$

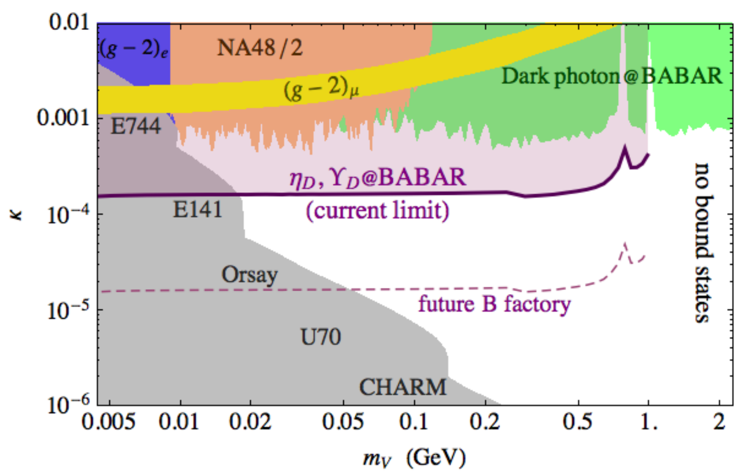
"Discoverable" mass range for the mediators.

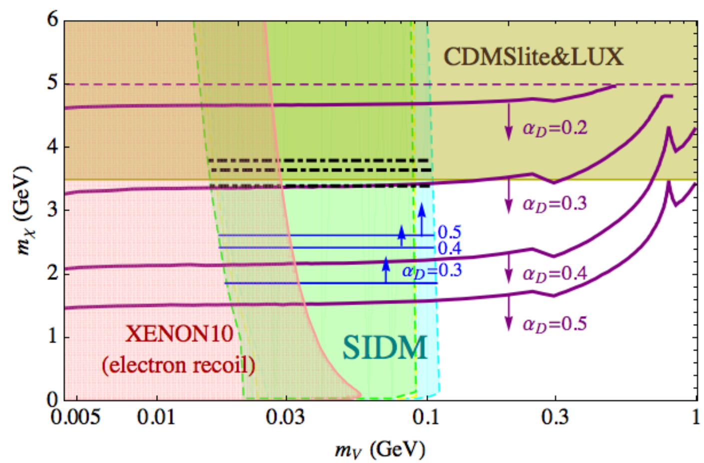
Dark matter bound states at B-factories

- 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

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







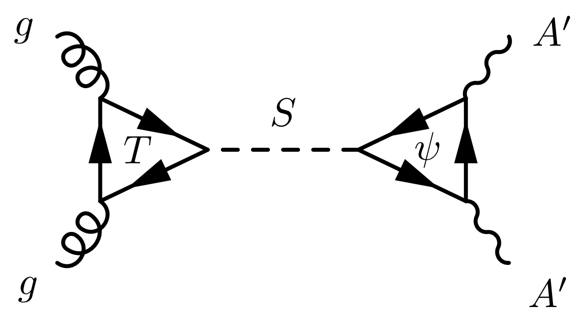
3 pairs of charged particles appear "for free" once Upsilon_dark is produced. This is limited by previous searches of "dark Higgsstrahlung" by BaBar and Belle.

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

“Dark” di-photon resonance

Diphoton events at the LHC are the events that pass the diphoton selection. It can be a pair of dark photons. So, dark photon 750 GeV resonance!

Dark “simplified” model

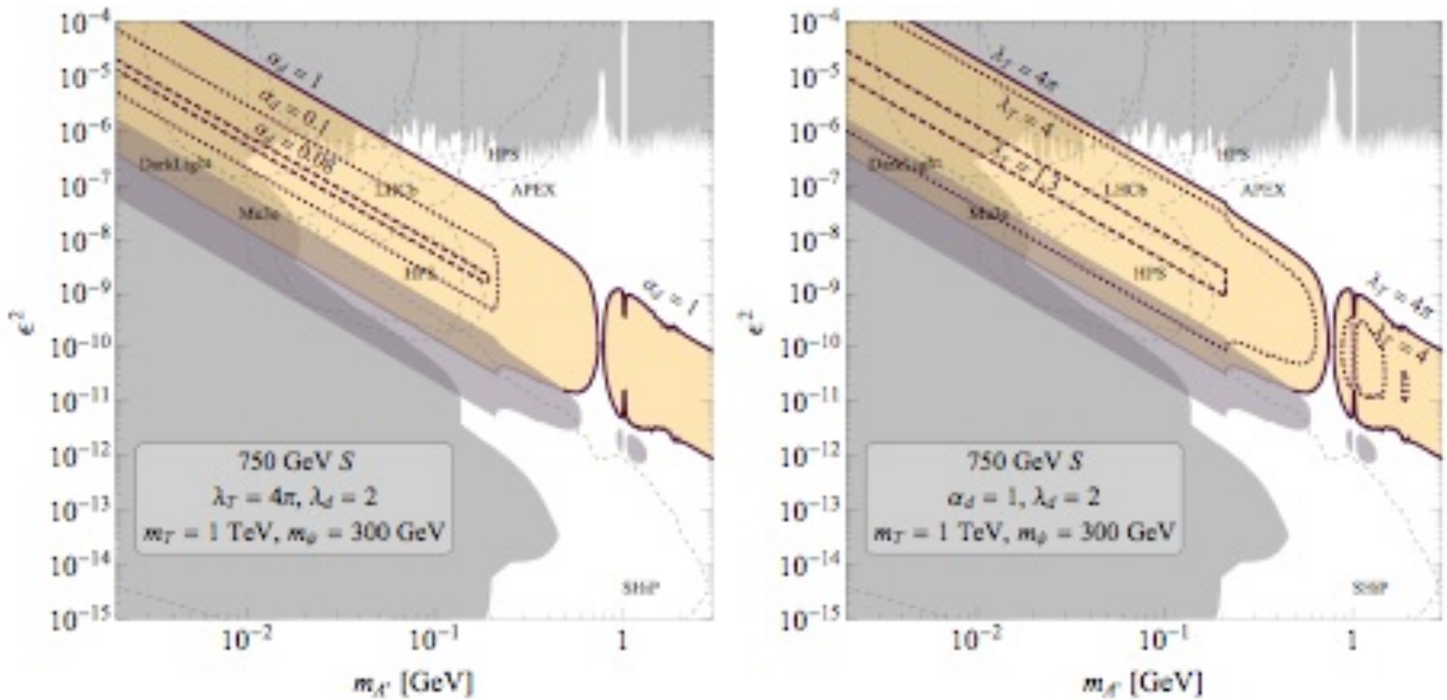


$$gg \to S \to A'A' \to (e^+e^-)(e^+e^-).$$

Marginalizing over properties of S, we get preferred region on $(\varepsilon, m_{A'})$ 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 ~ $\varepsilon^{-2} m_{A'}^{-2}$. Due to large boosts (e.g. ~ 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. This is ROI of parameter space to be explored by experiments discussed here.

Light WIMPs due to light mediators direct production/detection

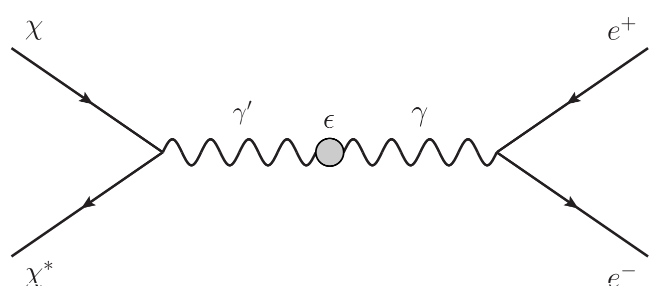
(Boehm, Fayet; MP, Riz, Voloshin …) Light dark matter is not ruled out if one adds a light mediator.

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,

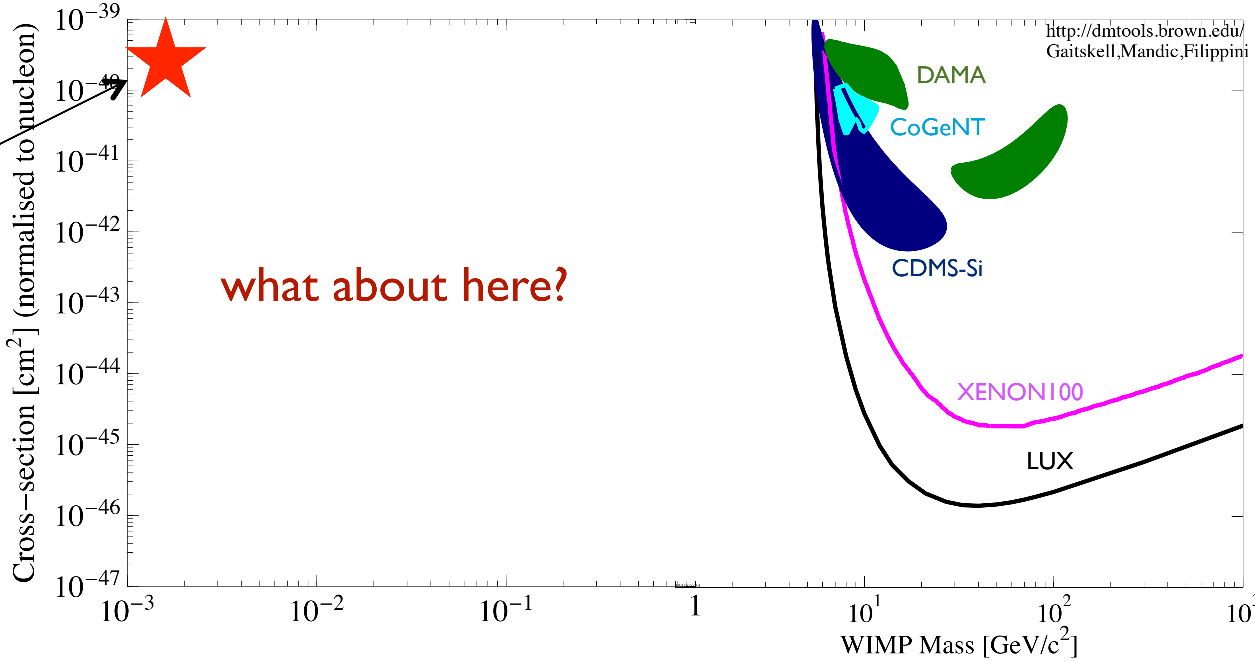
$$\sigma(v/c) \propto \begin{cases} G_F^2 m_\chi^2 & \text{for} \;\; m_\chi \ll m_W, \\ 1/m_\chi^2 & \text{for} \;\; m_\chi \gg m_W. \end{cases} \implies \text{few GeV} < m_\chi < \text{few TeV}$$

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).



Light DM – direct production/detection

511 keV
motivated

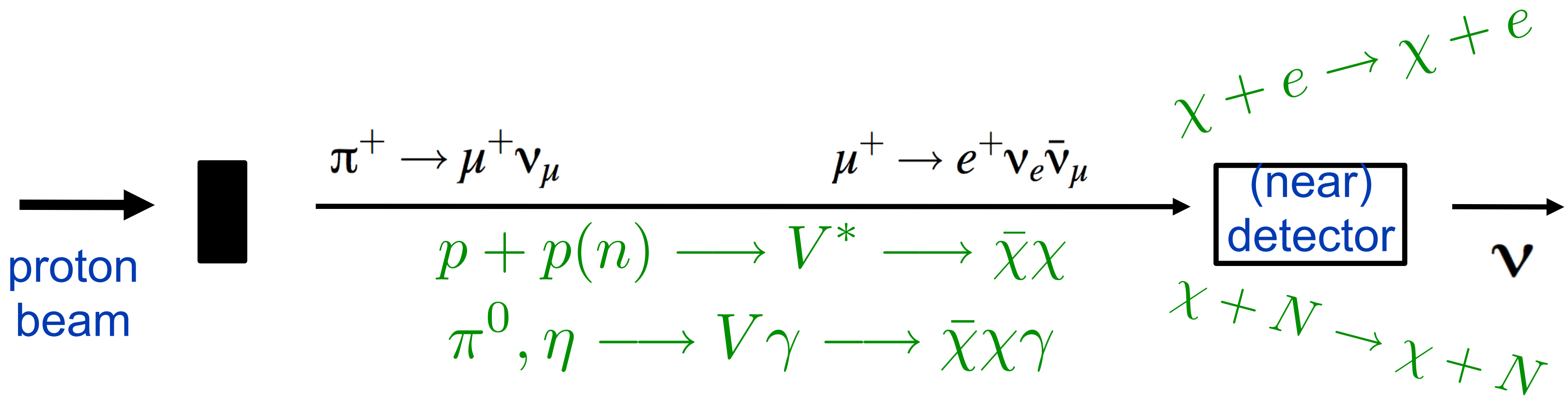


If WIMP dark matter is coupled to light mediators, the WIMP mass scale can be much lighter than nominal Lee-Weinberg bound,

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

Fixed target probes - Neutrino Beams

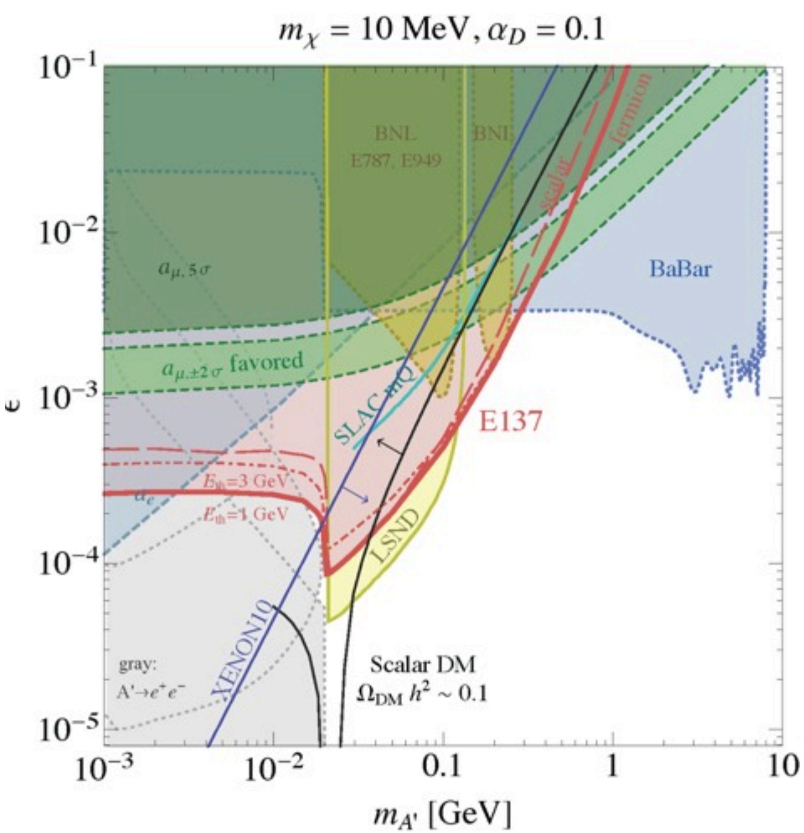
Proposed in Batell, MP, Ritz, 2009. Strongest constraints on MeV DM

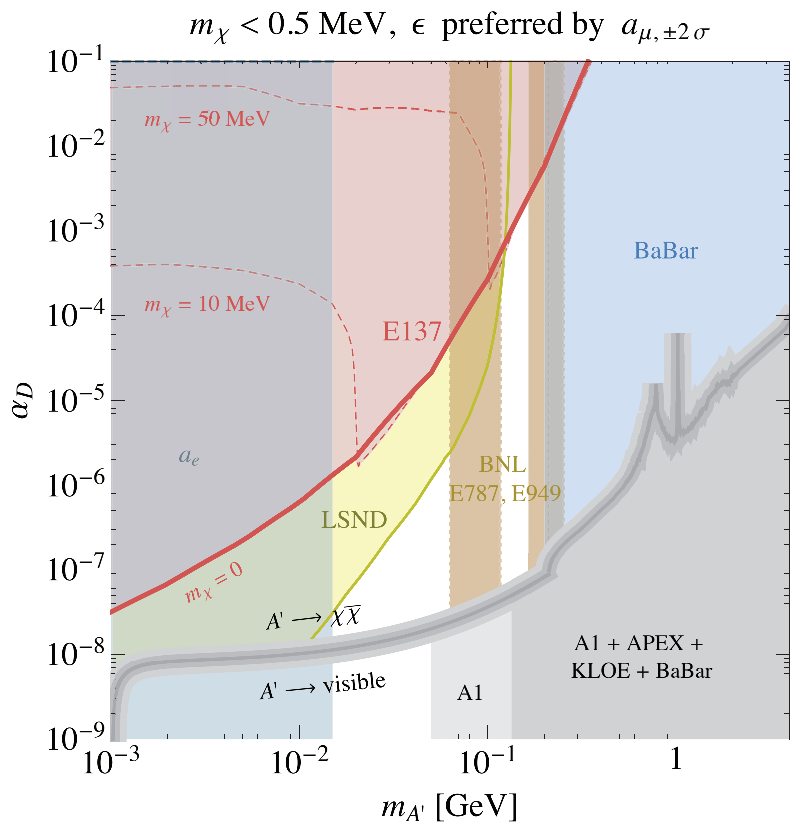


We can use the neutrino (near) detector as a dark matter detector, looking for recoil, but now from a relativistic beam. E.g.

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

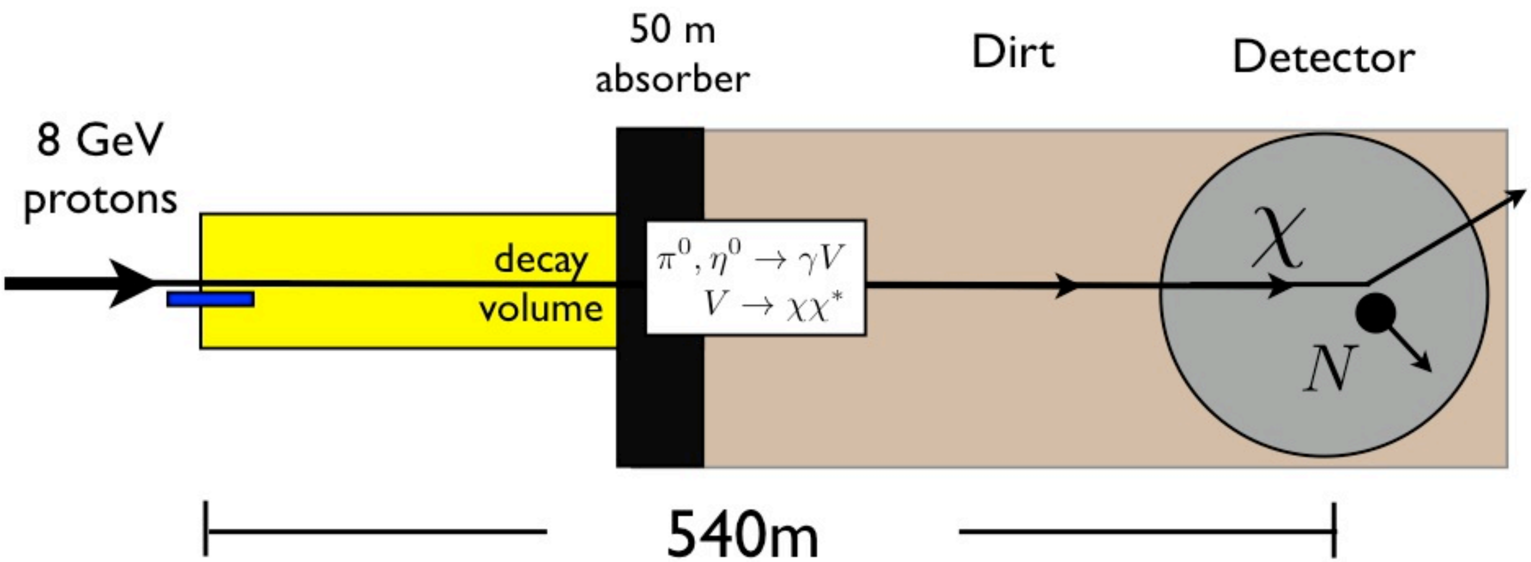
Compilation of current constraints on dark photons decaying to light DM





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.

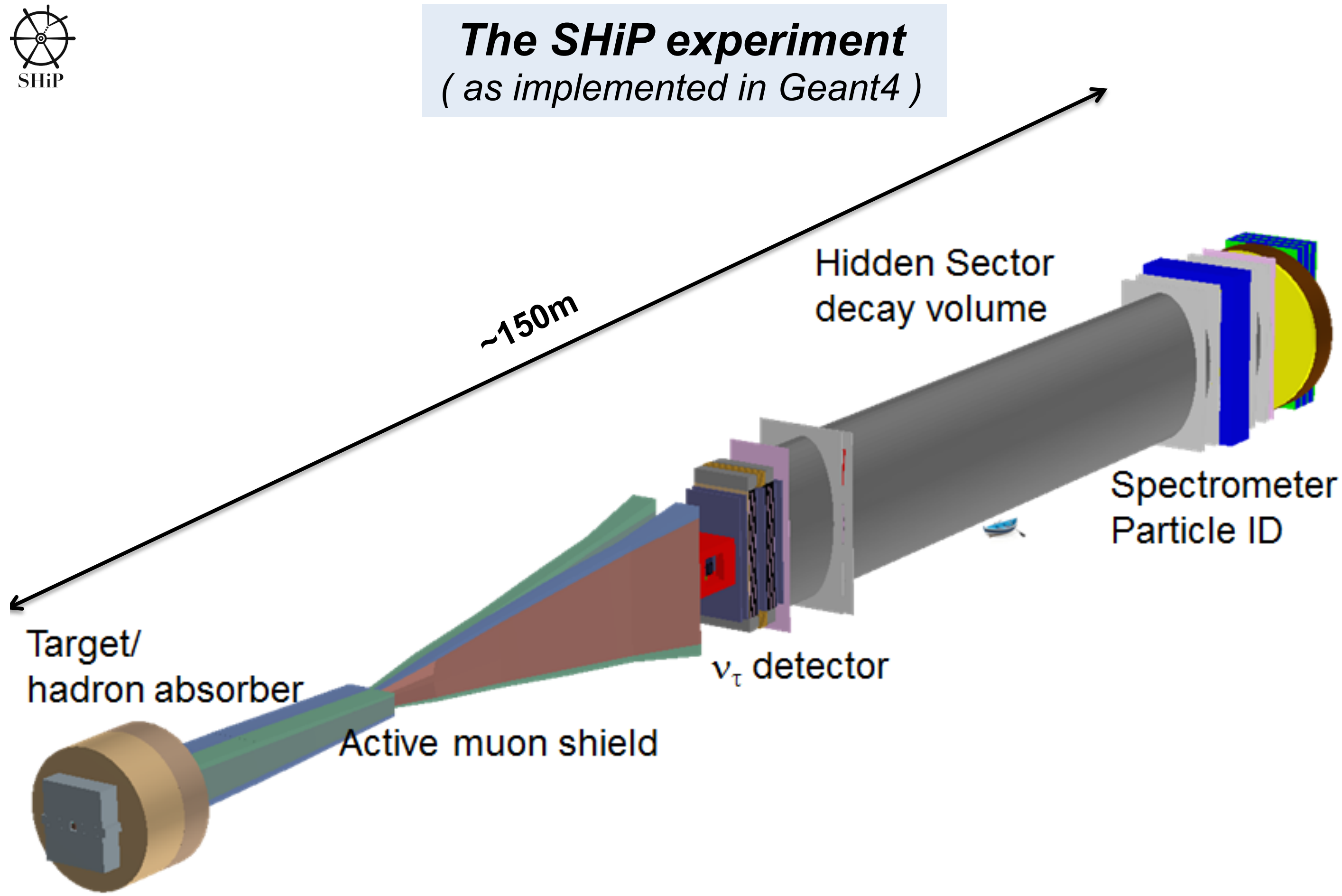
Timing is used (10 MeV dark matter propagates slower than neutrinos) to further reduce backgrounds. First results – this year (2016)

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 (?)

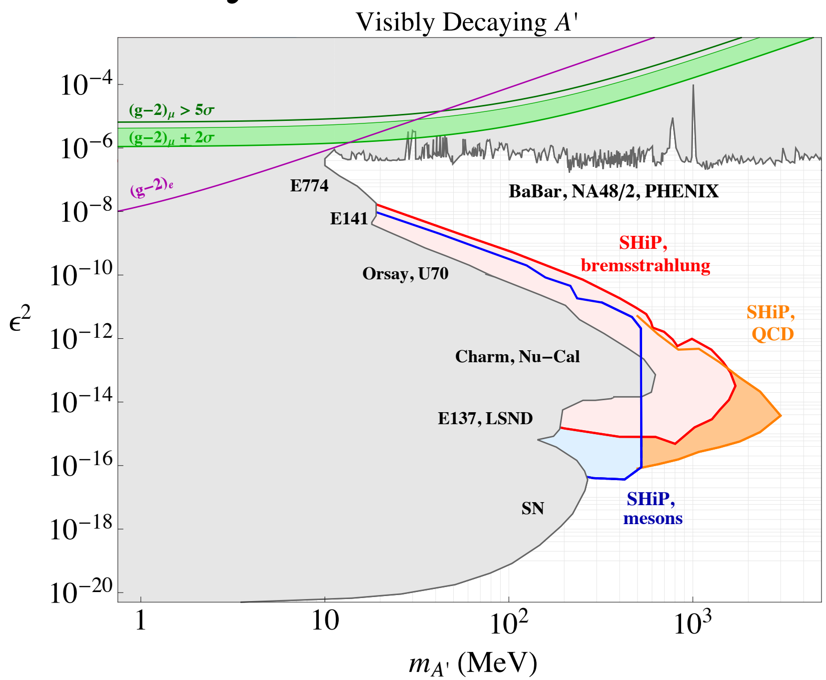
Future: SHiP project at CERN

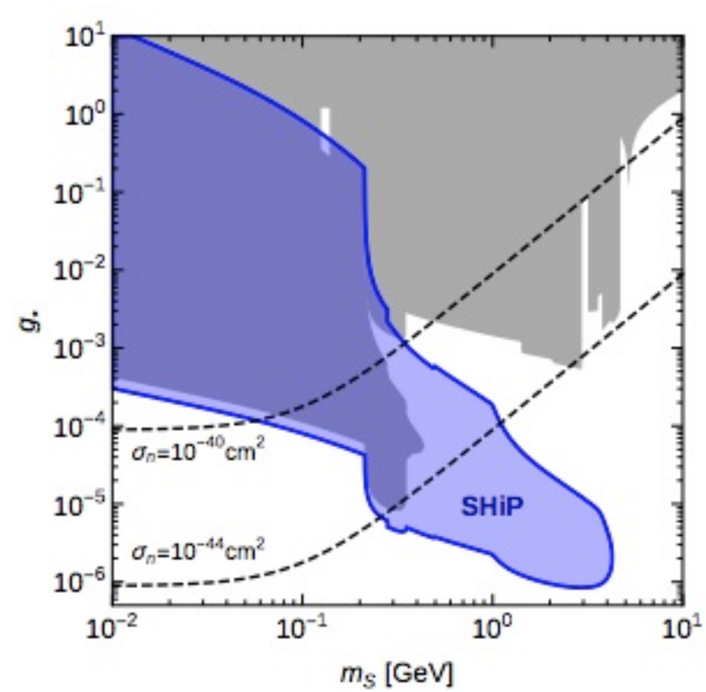


See e.g. A. Golutvin presentation, CERN SHiP symposium, 2015

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 → … $\mu^+\mu^-$



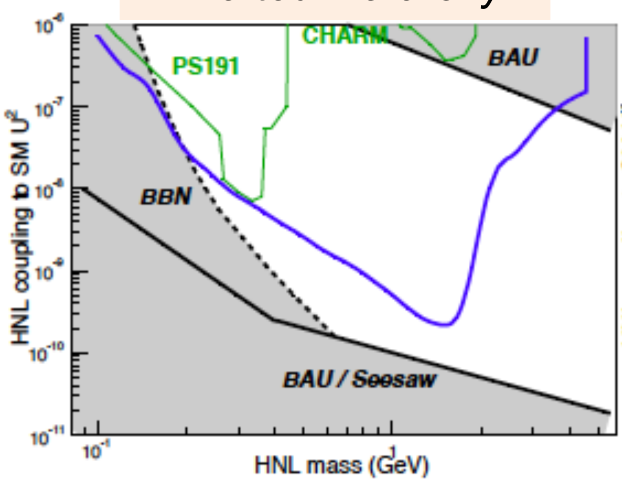


Details can be found in the white paper, 1505.01865, Alekhin et al.

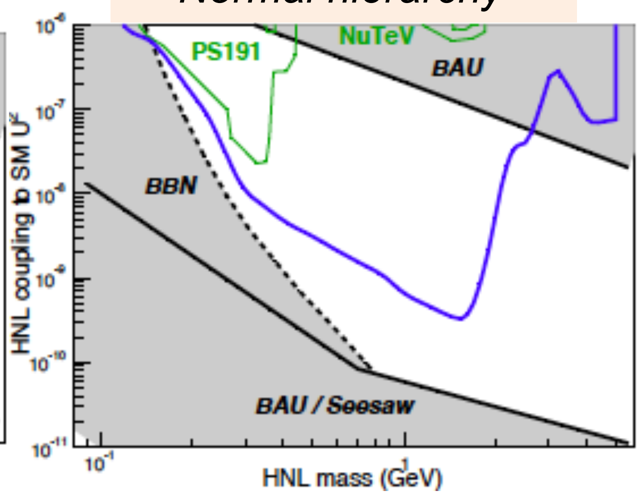
SHiP has unique sensitivity to RH neutrinos

- 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.

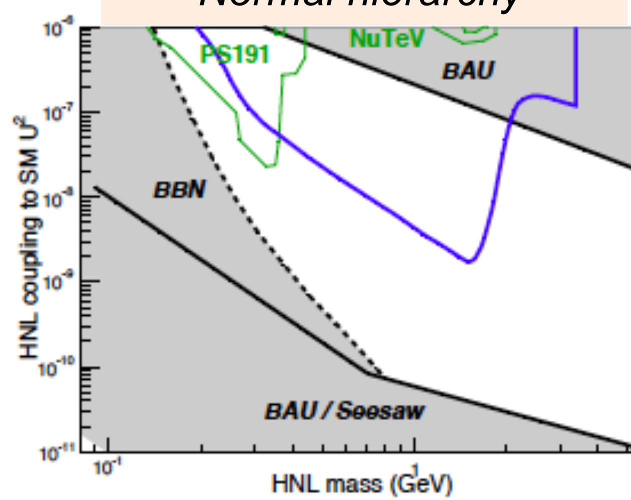
U^2_e: U^2_μ: U^2_τ~52:1:1
Inverted hierarchy



U^2_e: U^2_μ: U^2_τ~1:16:3.8
Normal hierarchy



U^2_e: U^2_μ: U^2_τ~0.061:1:4.3
Normal hierarchy

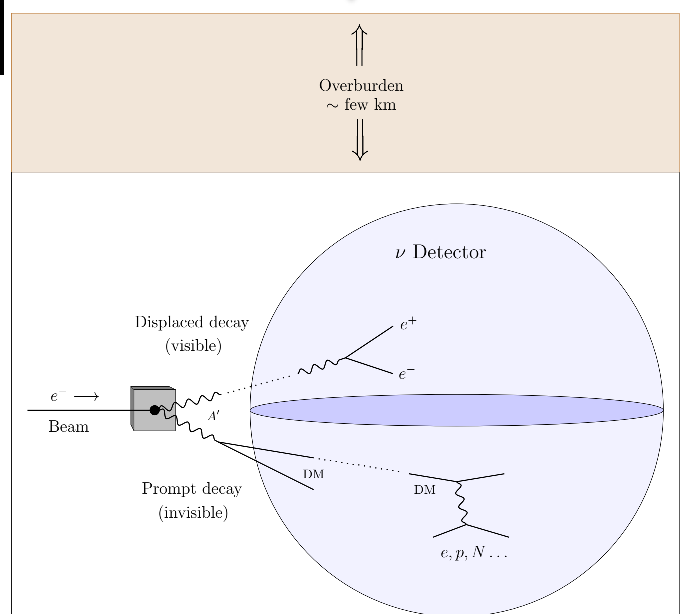


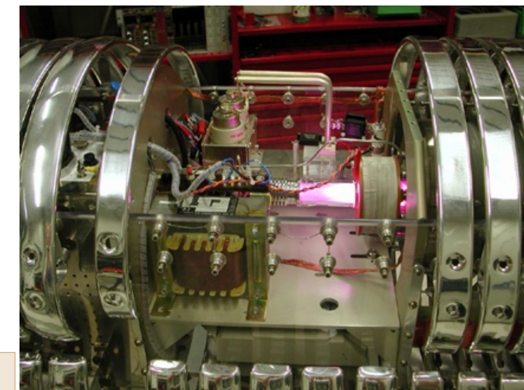
HNL production can be enhanced in non-minimal models, Batell et al.

More coverage of dark sector using underground accelerators and neutrino detectors

with Eder Izaguirre and Gordan Krnjaic, 2014, 2015

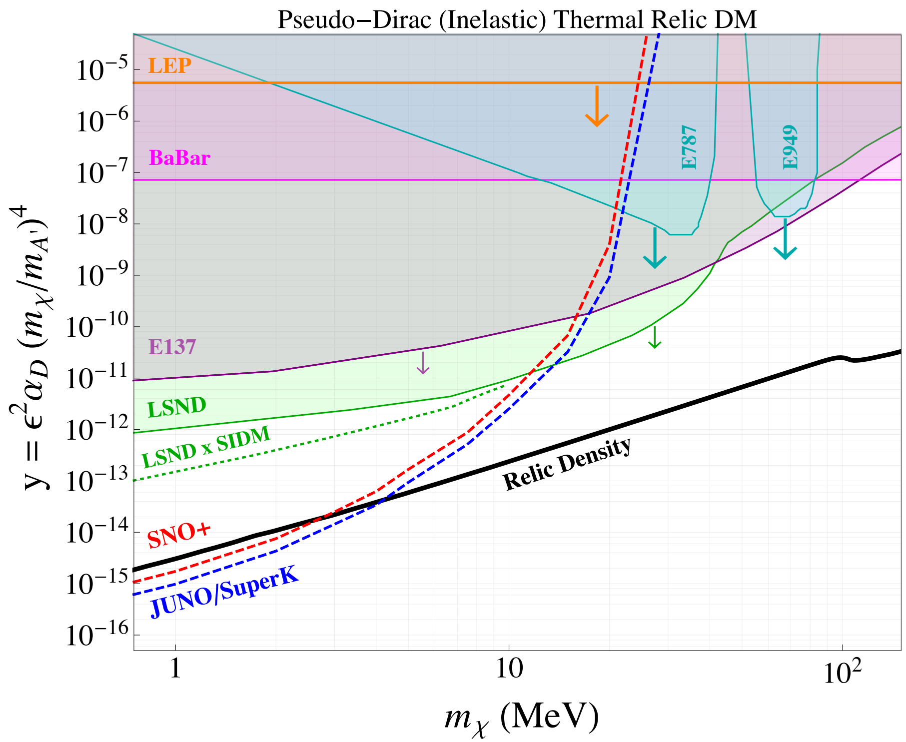
Borexino, Kamland, SNO+, SuperK, Hyper-K (?) …

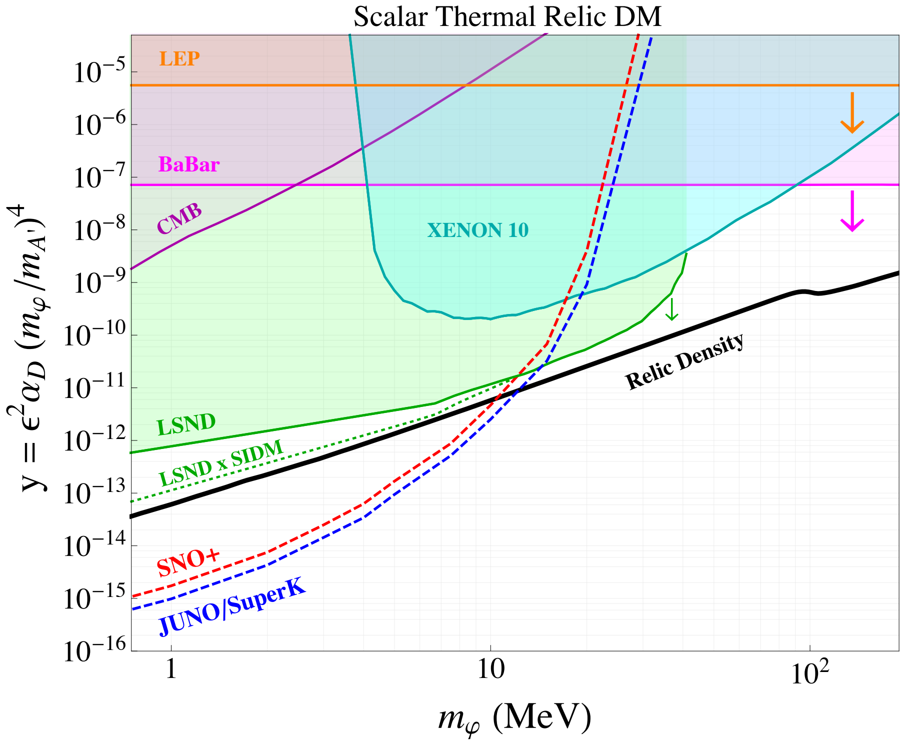




LUNA, DIANA,…, 1 e-linac for calibration

Sensitivity to light DM



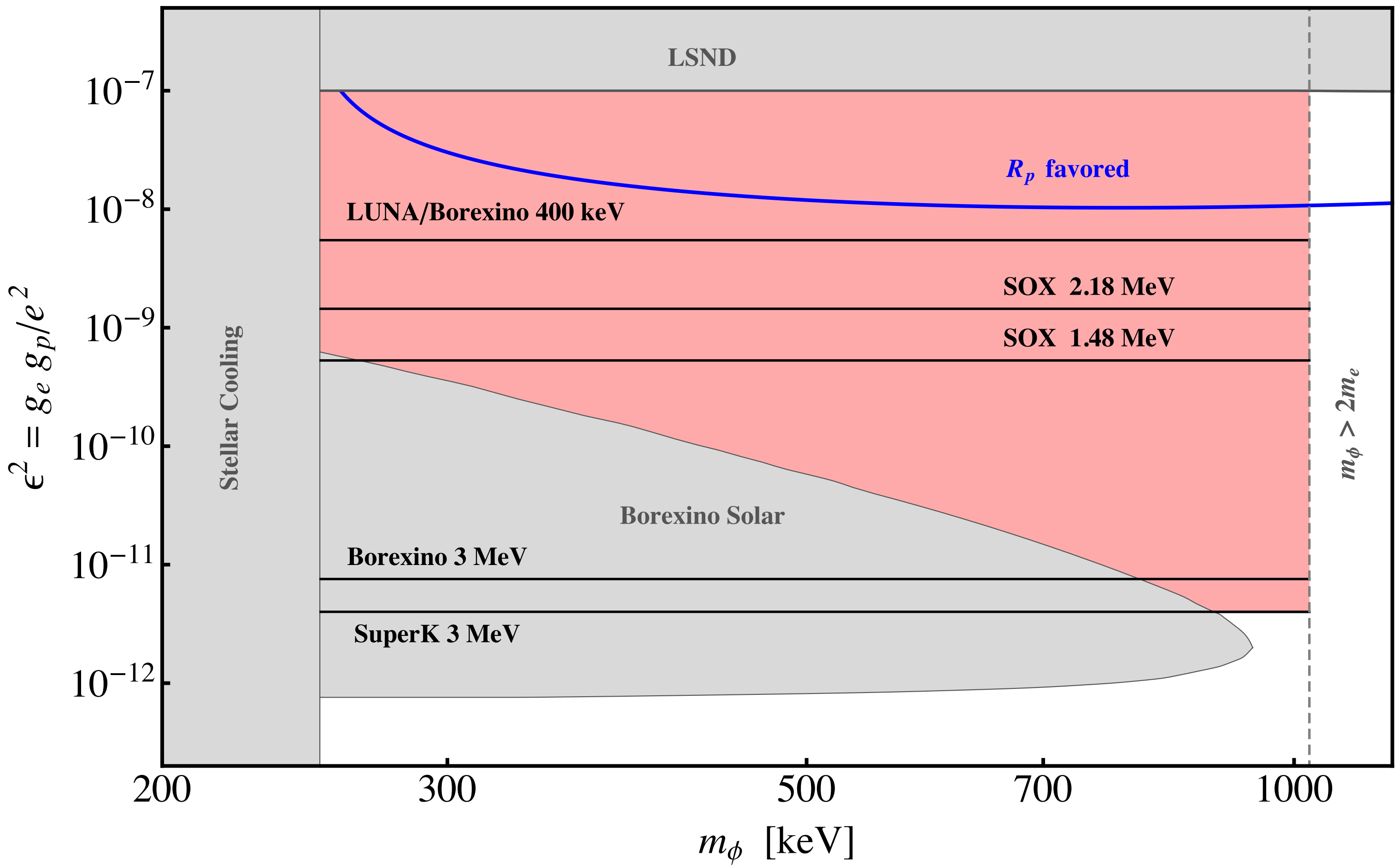


One will significantly advance sensitivity to light DM in the sub-100 MeV mass range. Assuming 10^{24} 100 MeV electrons on target

Izaguirre, Krnjaic, MP, 1507.02681, PRD

Sensitivity to scalar mediator

- ^{16}O de-excitation of 6.05 MeV as a source of scalars, ^{19}F(p,α)^{16}O
- *r_p relevant region can be fully covered.*



Conclusions

1. Light New Physics (not-so-large masses, tiny couplings) is a generic possibility. Some models (dark photon, scalar coupled Higgs portal) are quite natural, and *helpful* in explaining a number of puzzles in particle physics and astrophysics.

2. Some of the original motivations for light dark photons are weakened, but some new ideas (e.g. connection to 750 GeV) appear. Concerted effort in "dark photon" case rules out minimal model as a cause of g-2 discrepancy. Other possibilities remain.

3. Light dark matter via production & scattering is an appealing physics goal. Currently searched at the MiniBoone.

4. Future: more experimental possibilities.