# Review of Dark Sectors

**Maxim Pospelov**

Perimeter Institute, Waterloo/University of Victoria, Victoria

*With **Jeff Dror** (Cornell), **Robert Lasenby** (Perimeter)*

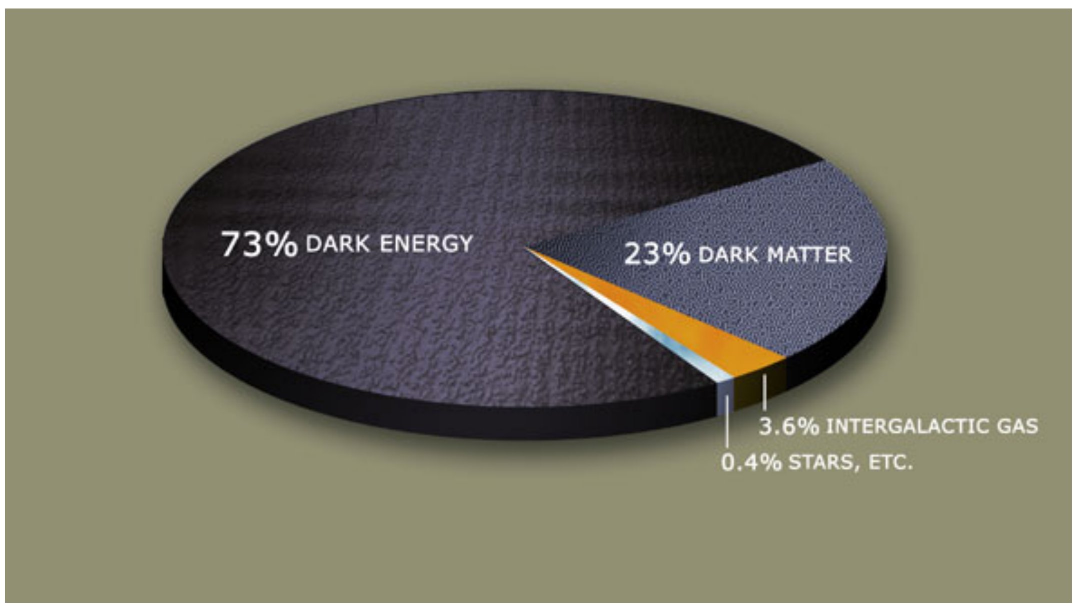
*1705.06726, + in preparation.*

University of Victoria | British Columbia Canada

PERIMETER INSTITUTE FOR THEORETICAL PHYSICS

# Outline of the talk

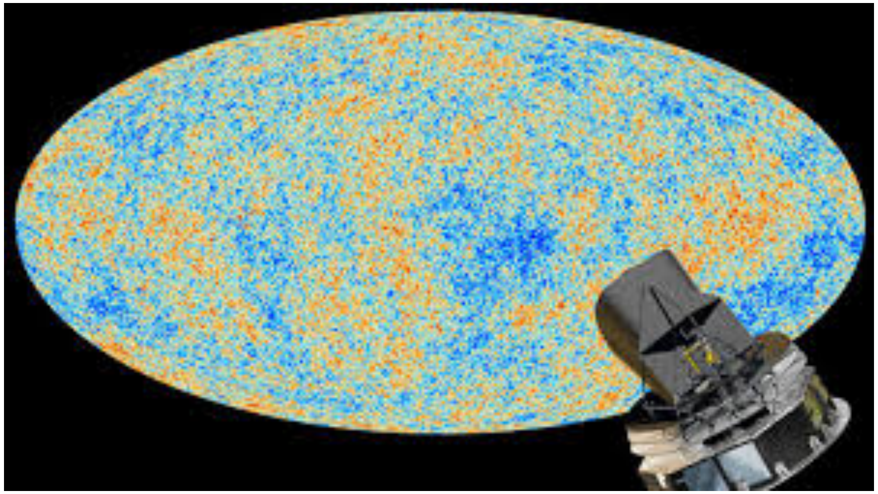
- Part I. Review of dark sectors.
- Part II. New constraints on light vectors coupled to non-conserved currents.



# What are we looking for?

- Dark matter particles.
- New forces that could mediate interaction between SM and dark matter states.
- Explore generic extensions of SM by [singlet] weakly interacting states, including new gauge groups.
- Have a meaningful beyond-SM-applications of the existing experiments. Think of new experiments/measurements. [It is pretty much an open subject].

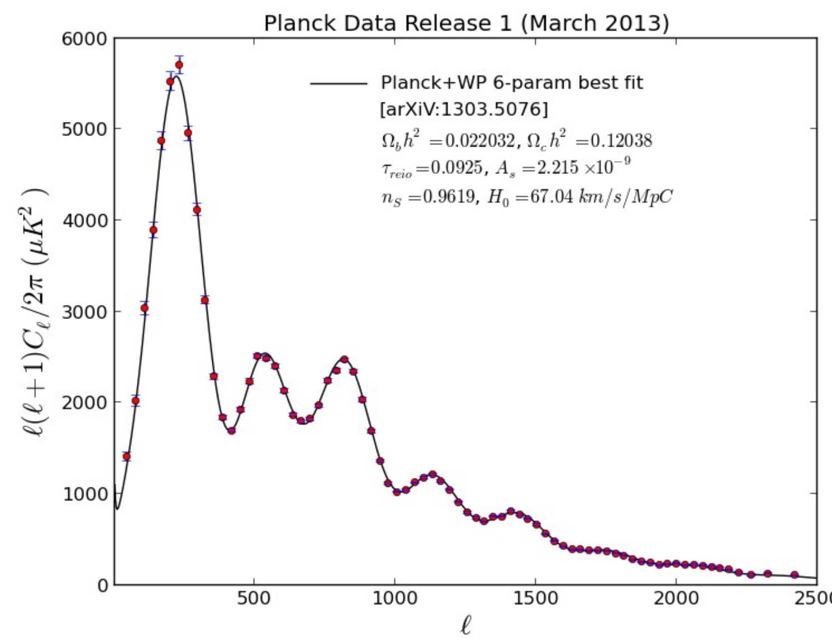
# State-of-the-art CMB results



Due to the growth of c/H(t) which determines horizon size, many CMB Universes "fit" into todays sky.

The temperature of these patches is not exactly the same, but differs by $\sim 10^{-5}\, T_{CMB}$ from spot to spot.

Statistics of this fluctuations encodes information about physical conditions during the CMB Universe, and geometrical information about the propagation from the surface of last scattering to us.



# Implications of early cosmology

1. Universe was relatively *simple* at T ~ 0.3 eV.

2. The dark matter was already "*in place*" at the time of the matter-radiation equality, when the potential wells created by DM started to grow. We see statistical evidence of H and He falling (and rebounding) into the DM gravitational wells.

3. DM is not "made of ordinary atoms" – and there is 6 times more of it than of ordinary H and He. $\Omega_{\text{dark matter}} / \Omega_{\text{baryons}} = 5.4$

4. What is it? These are *not* known neutrinos : they would have to weigh ~ 50 eV (excluded), and would have a hard time making smaller scale structure (too hot to cluster on small scales).

5. Simplicity of the early Universe, makes many of us suspect that the DM might be in the form of unknown (= e.g. beyond-SM particles).

# 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

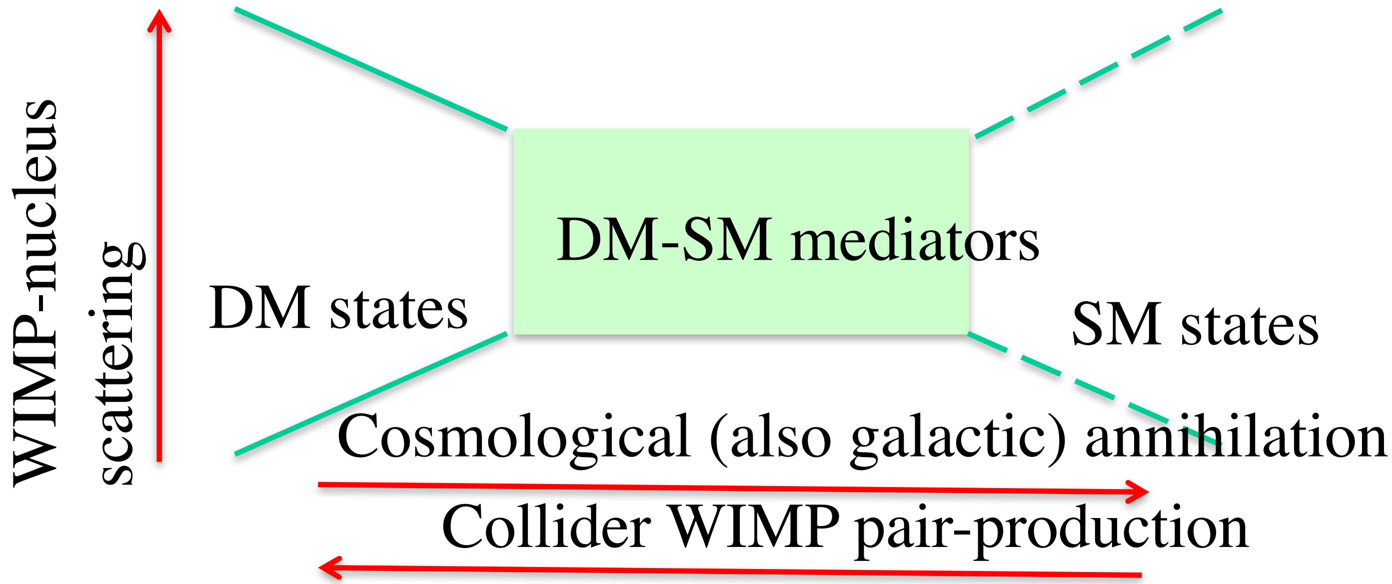
*Normal:* Sizable interaction rates ensure thermal equilibrium, $N_{DM}/N_{\gamma}=1$. Stability of particles on the scale $t_{Universe}$ is required. *Freeze-out* calculation gives the required annihilation cross section for DM -> SM of order ~ 1 pbn, which points towards weak scale. These are **WIMPs**. (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. $N_{DM}/N_{\gamma}\sim10^{10}$. "Super-cool DM". Must be bosonic. Axions, or other very light scalar fields – call them **super-cold DM**.

Many reasonable options. *Signatures can be completely different.*

# WIMP paradigm, some highlights

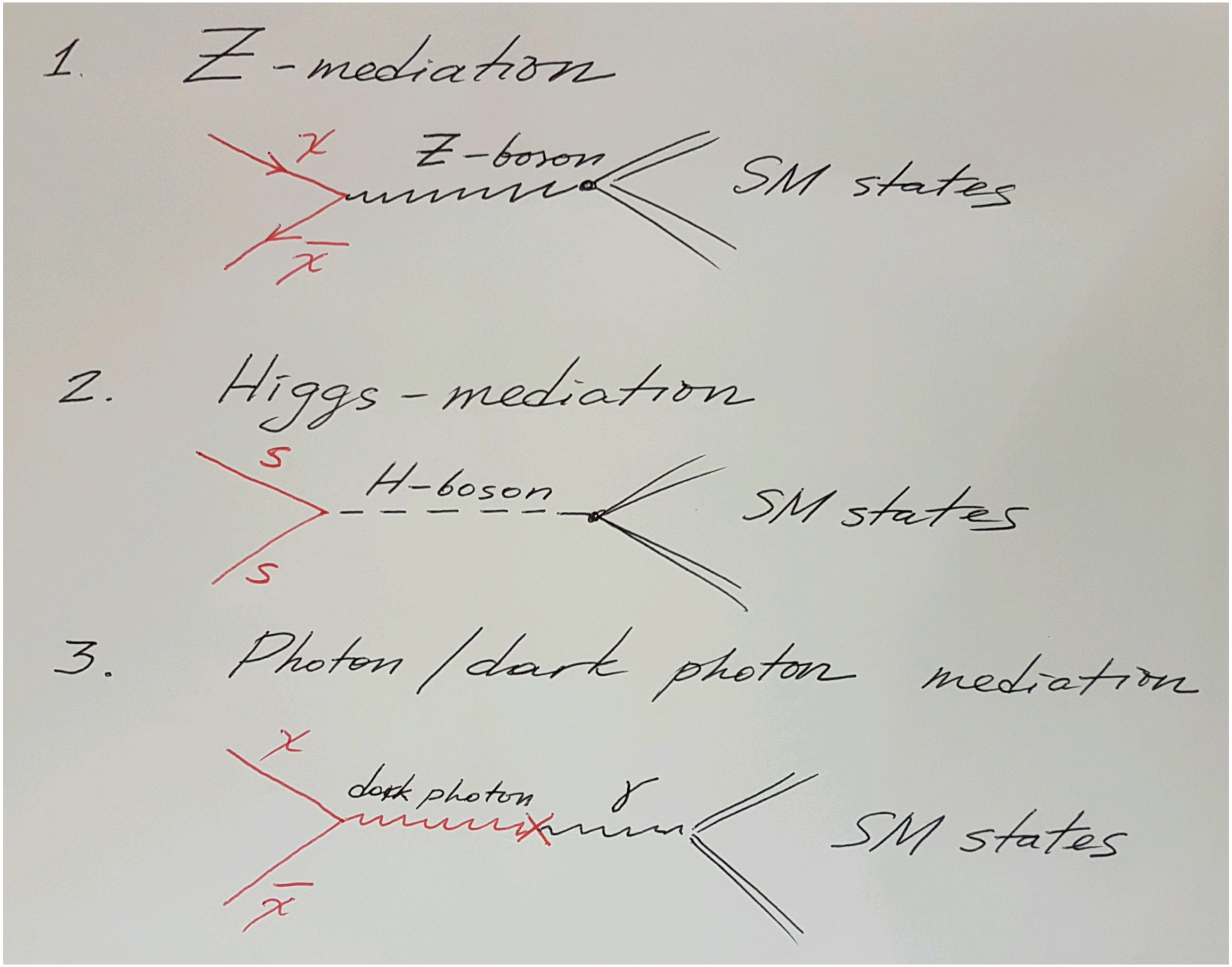



$$\langle \sigma_{ann} v \rangle \approx 1\text{pbn} \times c$$

*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 $\sigma_{DM-N}$

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

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

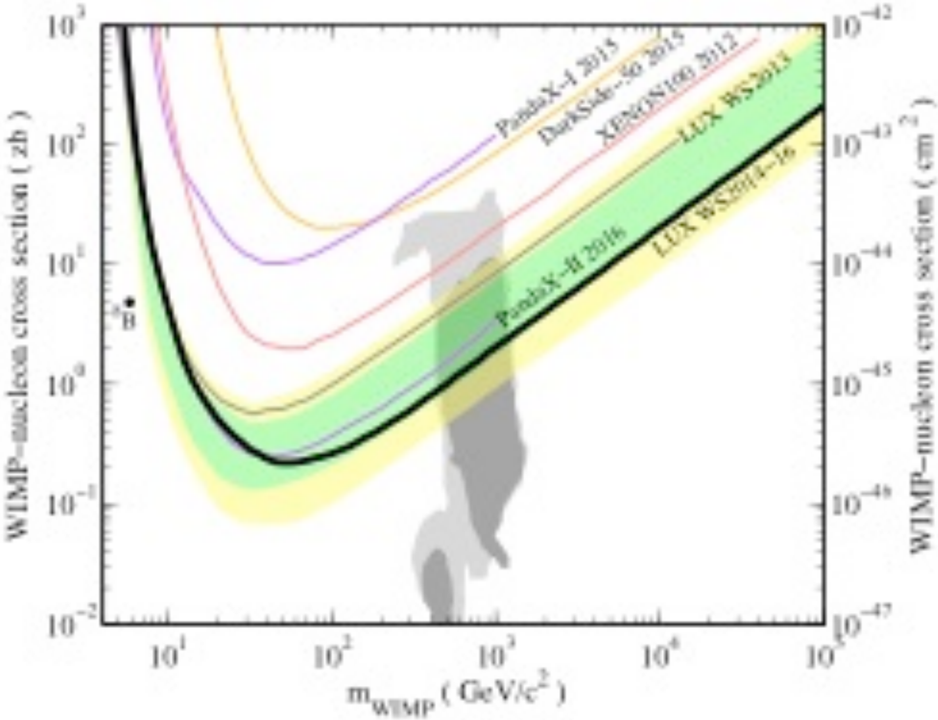
$\sigma_{DM-Nucleon}$ (Higgs-mediated) ~ $(10^{-4}\text{-}10^{-5}) \times \sigma_{DM-Nucleon}$ (Z-mediated)

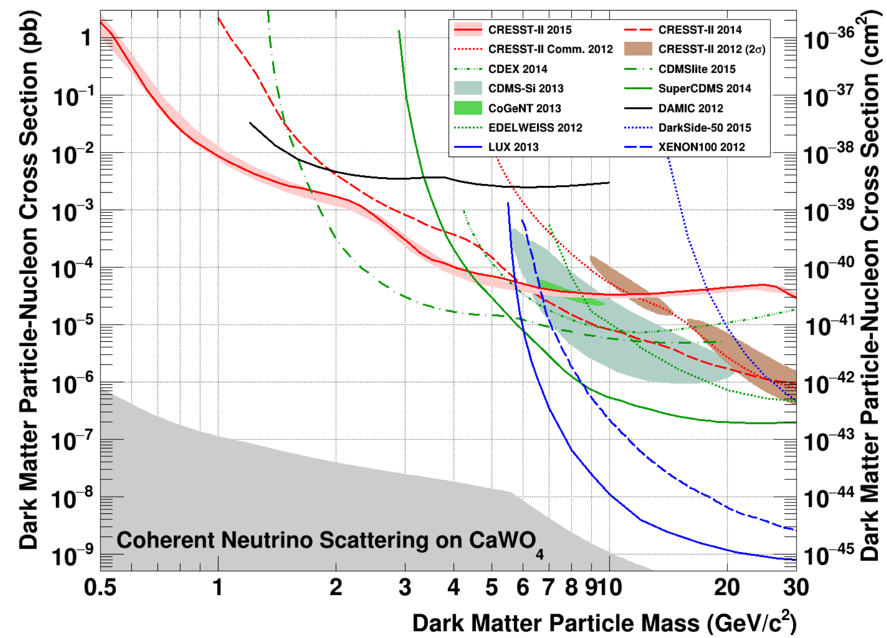
$\sigma_{DM-Nucleon}$ (EW loop) ~ $10^{-9} \times \sigma_{DM-Nucleon}$ (Z-mediated)

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

# Progress in direct detection of WIMPs

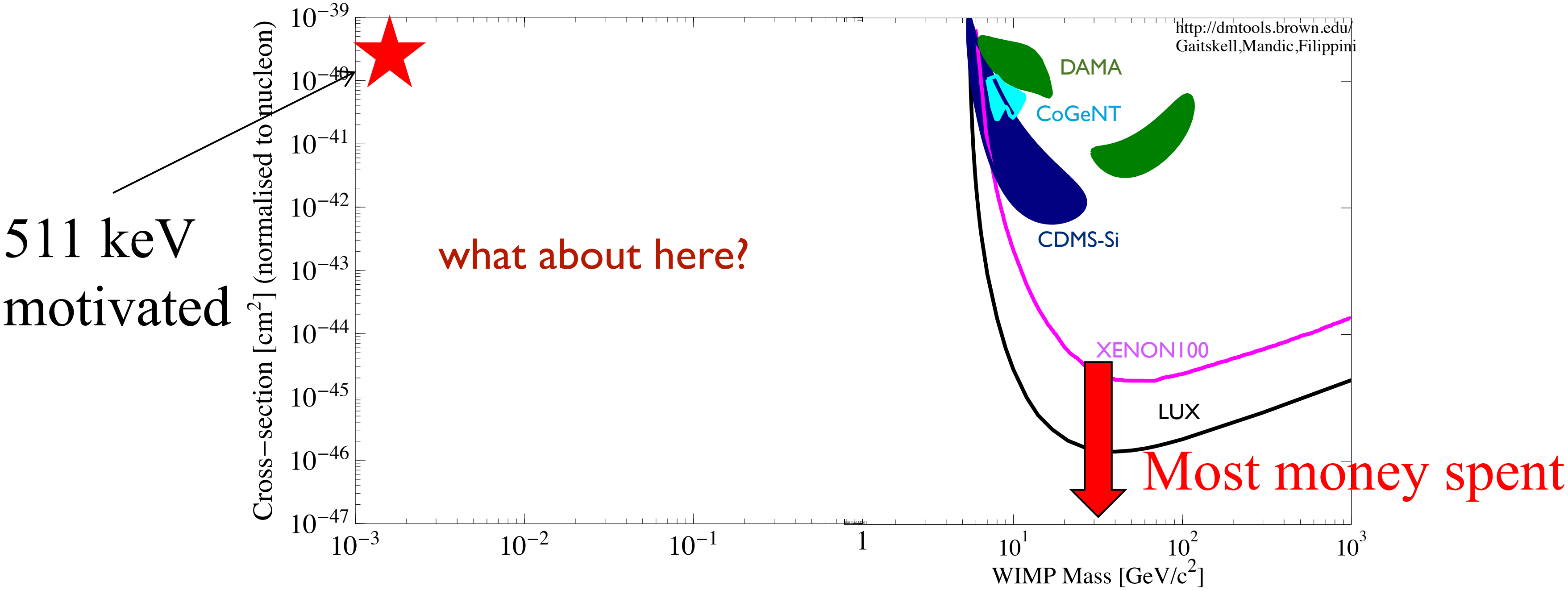
## (latest 2016 LUX and CRESST results)




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

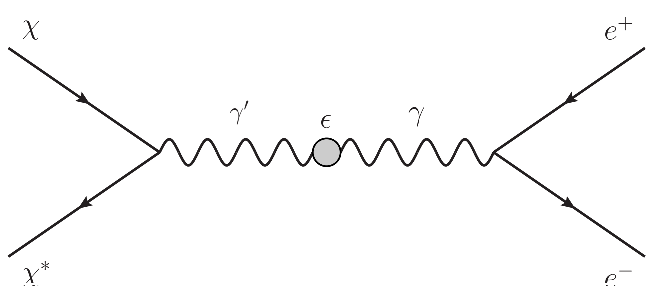
(Boehm, Fayet; MP, Riz, Voloshin …) Light dark matter is not ruled out if one adds a light mediator.

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,

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

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).




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

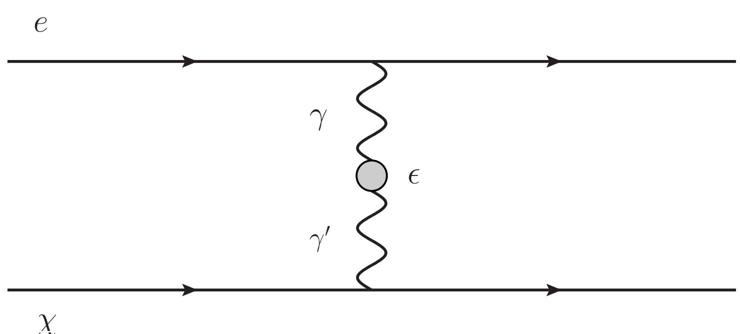
# "Simplified model" for dark sector

**(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", $\psi$ - an electron, $\chi$ - a DM state, *g'* – a "dark" charge

- "Effective" charge of the "dark sector" particle $\chi$ is Q = e × ε (if momentum scale q > $m_V$ ). At q < $m_V$ one can say that particle $\chi$ 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*.

# 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.
4. ….

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

# 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…

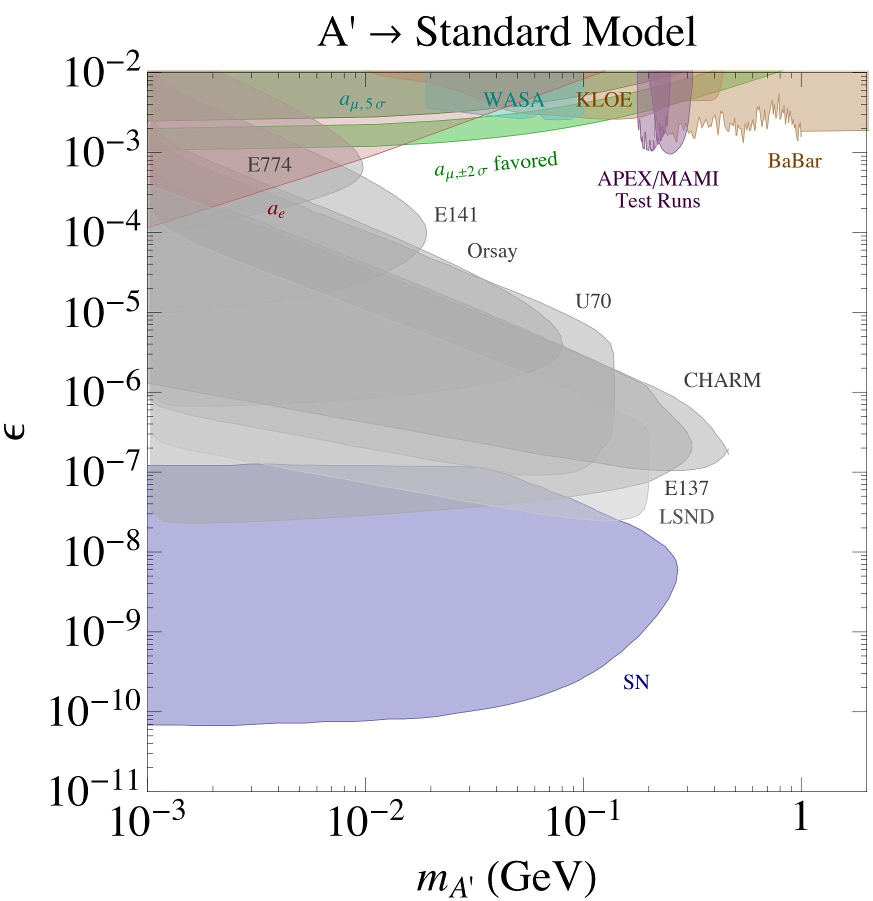
Dim>4

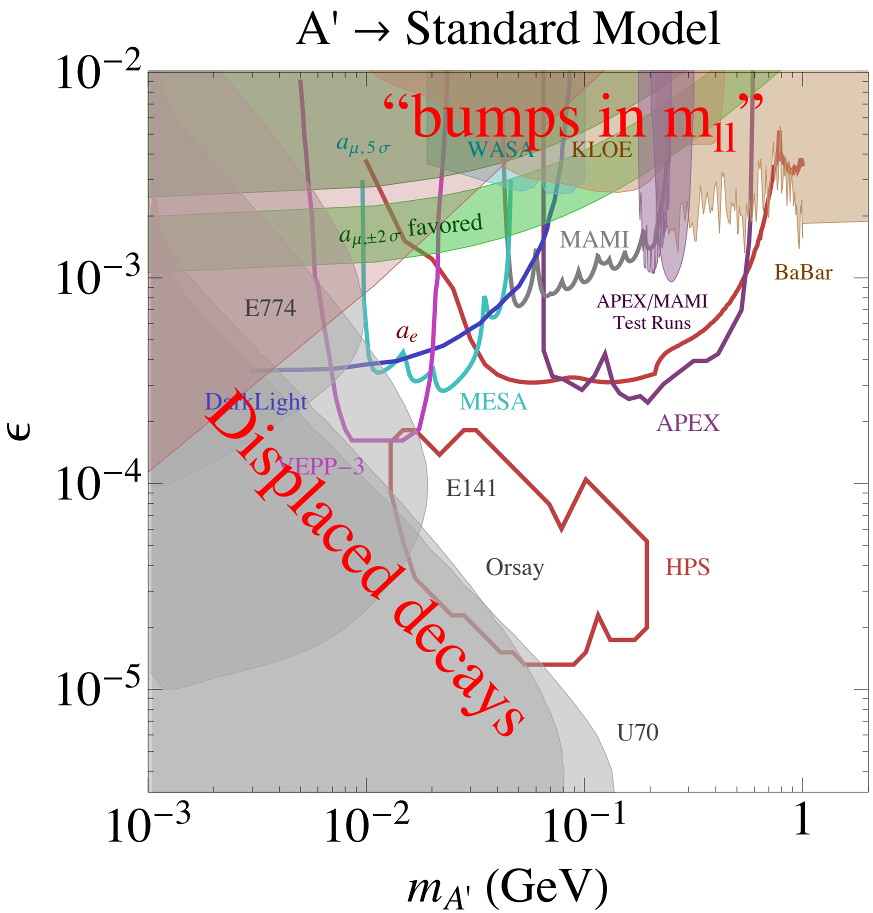
$J_\mu^A\ \partial_\mu a\,/f$ axionic portal

……….

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

# 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.

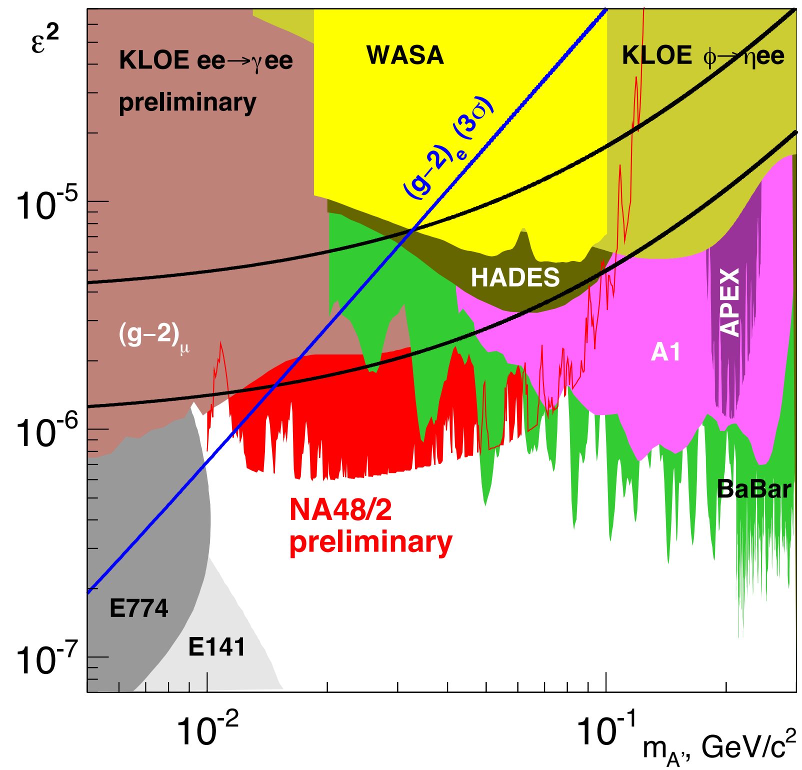
# Zooming in: A1, Babar, NA48

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

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

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

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




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

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

# "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.

# 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.*

# Missing energy/momentum searches

NA64 has recent results (great sensitivity after $3\times10^9$ e on target). Plot from Banerjee et al, 1610.02988. Much more data expected in future

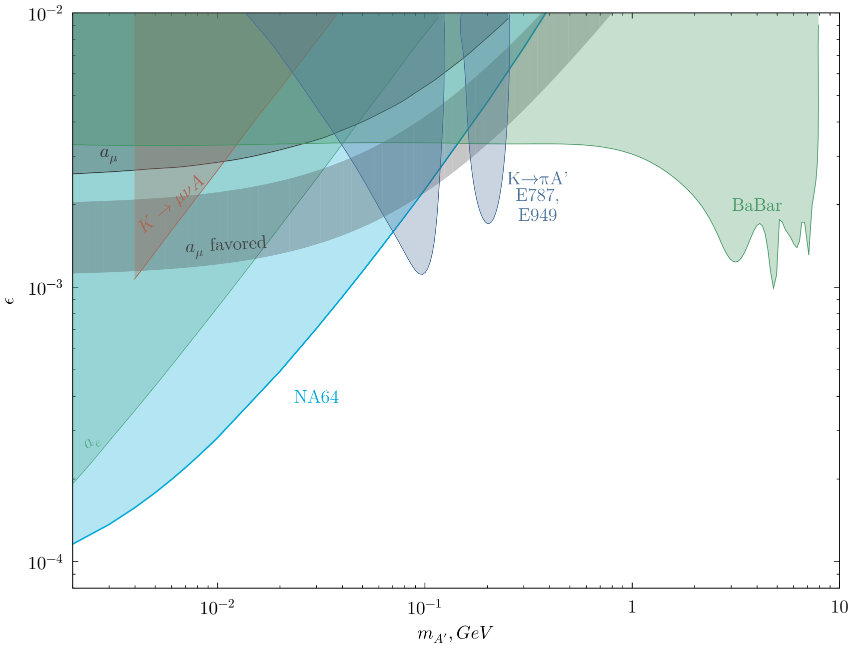



FIG. 3: The NA64 90 % C.L. exclusion region in the $(m_{A'}, \epsilon)$ plane. Constraints from the BaBar [48, 55], and E787+ E949 experiments [47, 56], as well as muon $\alpha_\mu$ favored area are also shown. Here, $\alpha_\mu = \frac{g_\mu - 2}{2}$. For more limits obtained from indirect searches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

Search of a process

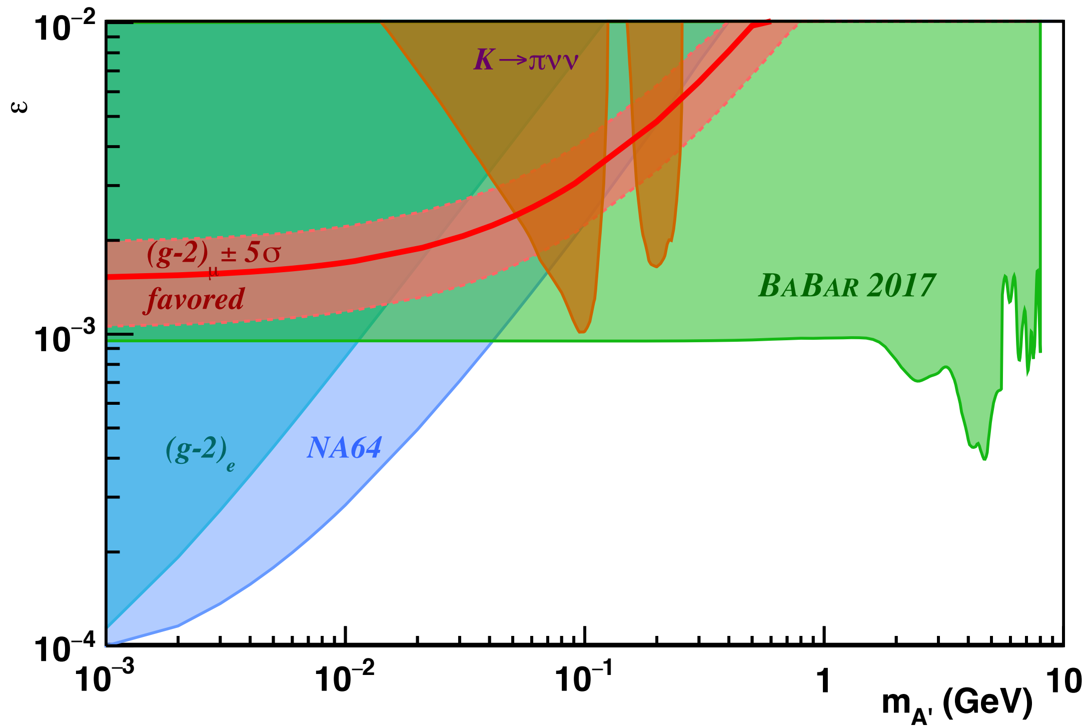
$$e + Z \rightarrow e + Z + V \rightarrow e + Z + \chi\chi$$

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 in1702.03327. Search of $e^+e^- \rightarrow \gamma + V \rightarrow \gamma + \chi\chi$

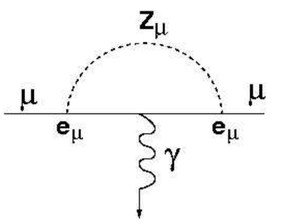



- Complementary to NA64
- Covers all of the dark photon parameter space, decaying invisibly, consistent with alleviating the muon g-2 discrepancy

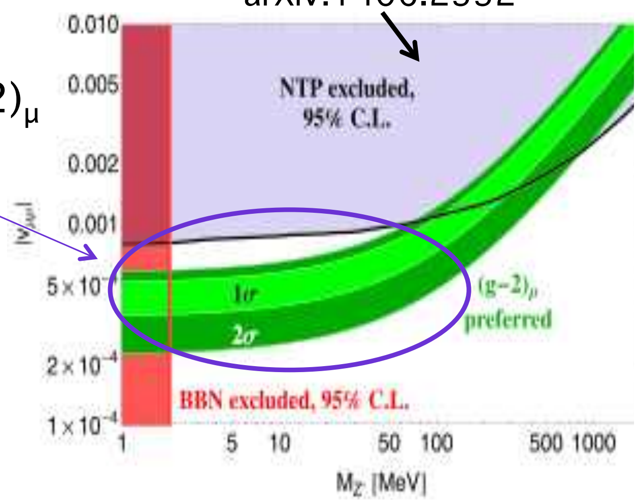
# Running NA64 in the muon mode?

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



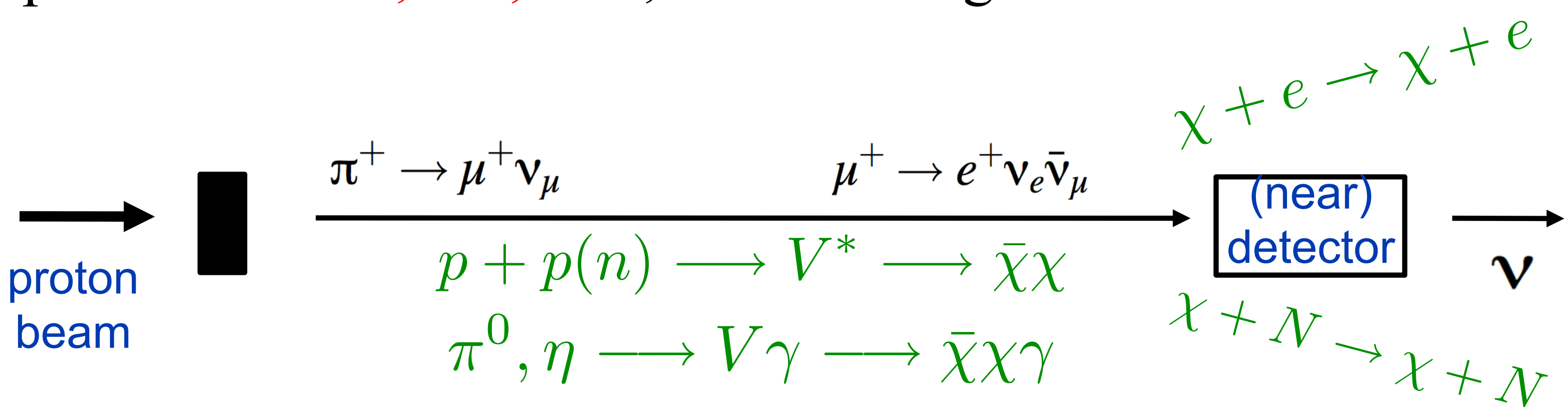

Strong motivation for a sensitive search for Z´->νν, μ⁺μ⁻ in a near future experiment by using (unique) high intensity muon beam at CERN.

The upgraded muon beam at the SPS

Invisibly decaying $L_\mu$-$L_\tau$ gauge boson and dark scalar below the d-muon threshold can be probed this way.

# Fixed target probes - Neutrino Beams

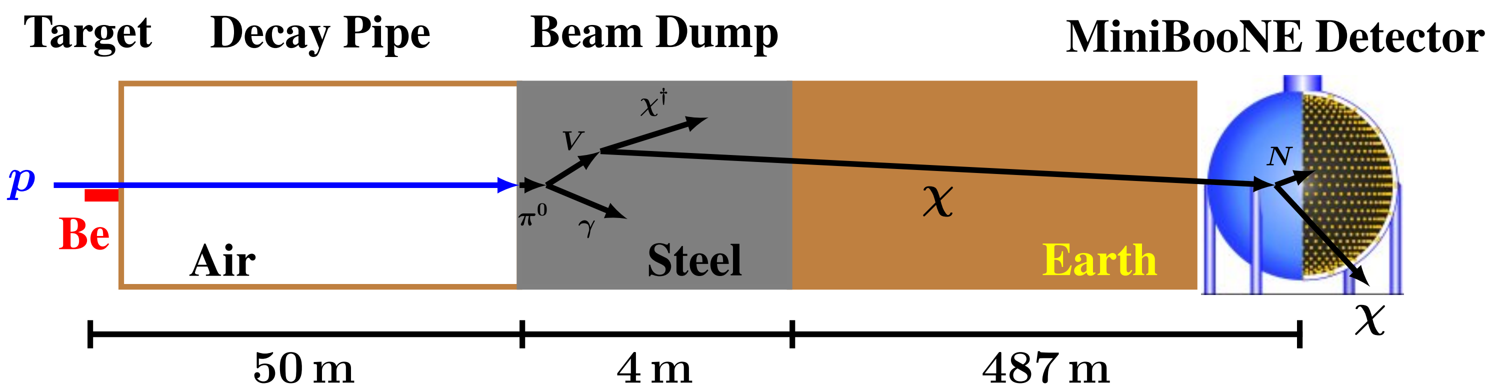
Proposed in Batell, MP, Ritz, 2009. Strongest constraints on MeV DM




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 |
| (➠ ~5x$10^{21}$ 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 |

# MiniBooNE search for light DM



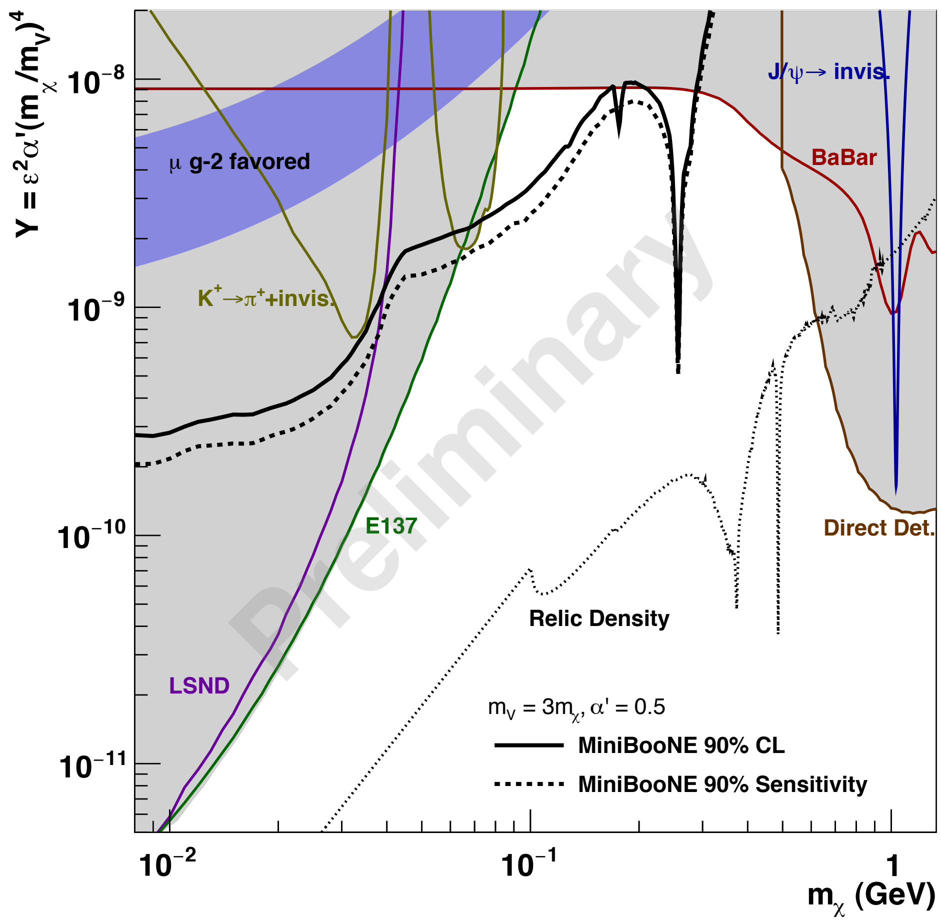

MiniBoone has completed a long run in the beam dump mode, as suggested in [arXiv:1211.2258]

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.

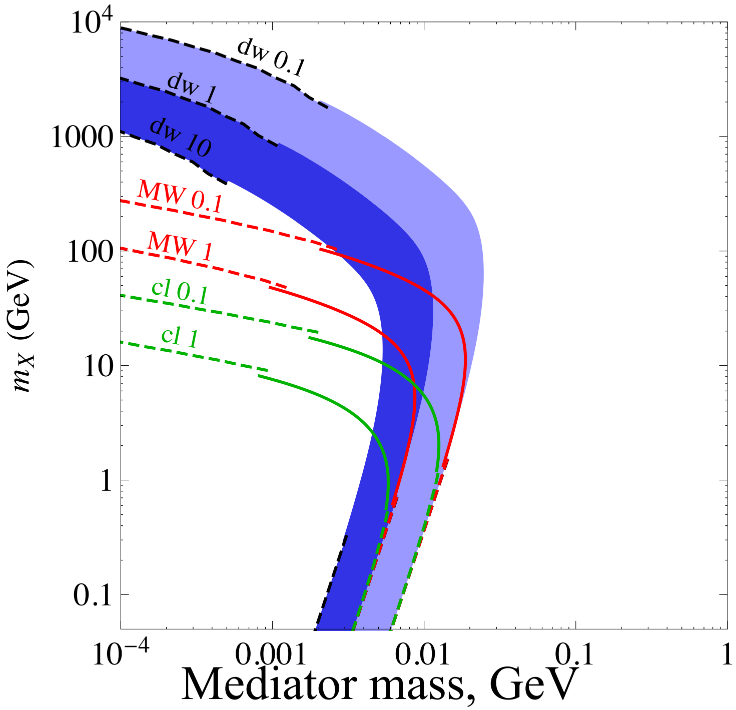
# New parts of the parameter space get excluded




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. There is a possibility to improve sensitivity using BDX

# 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).



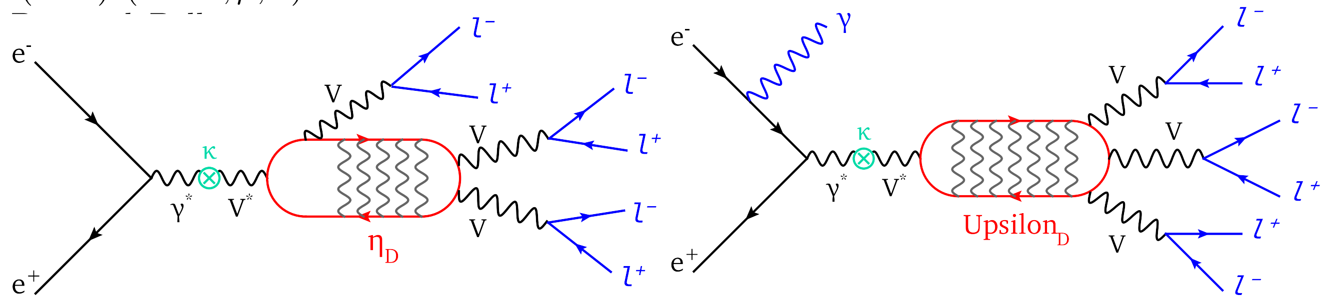

Example of parameter space that creates a core and solves the problem (from Tulin, Yu, Zurek) for $\alpha_d = 0.1$

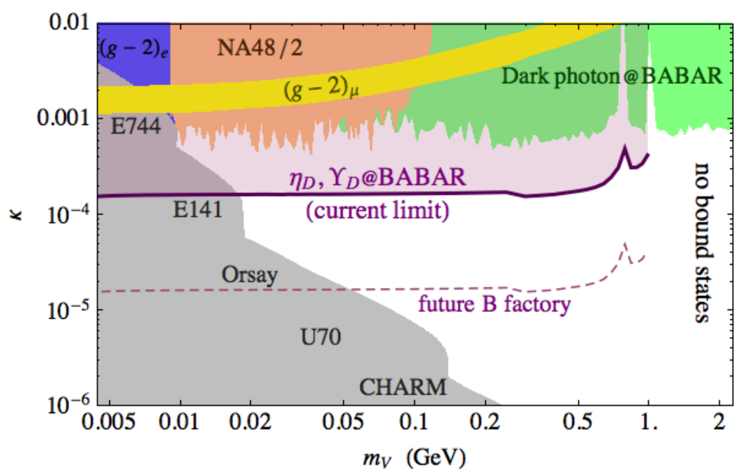
Some of the parameter space is within reach of B-factories.

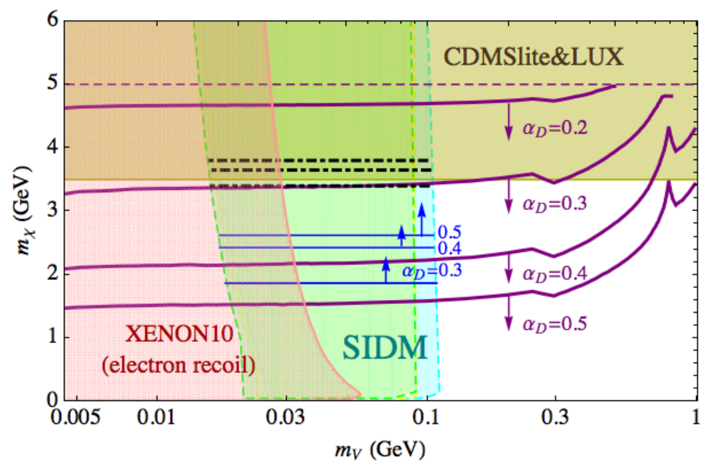
# Dark matter bound states at B-factories

- 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

# Part II: A classification of light U(1) models

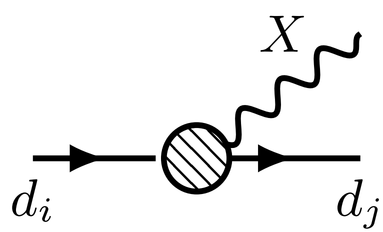
Let's classify them into 3 cartegories

1. *Dark photon: technically natural, UV complete, couple to a conserved current.*
2. *B-L, $L_\mu$-$L_\tau$, and other anomaly free combinations: all of the above, but coupling constant $g_X$ is small – somewhat unusual. Strong constraints from neutrino physics.*
3. *Models coupled to the tree-level conserved current broken by anomalies. E.g. gauged baryon number, or lepton number. Presumes cancellation of anomalies at high-energy. Nice low energy behaviour, weak constraints on gauged baryon number?*
4. *Models coupled to a non-conserved current. (e.g. vector particle coupled to an axial-vector current)*

- Phenomenology-driven demand often force speculators to consider 3 and 4. (proton charge radius, $^8$Be decay anomaly)

# Non-conserved currents will be sensitive to high-mass scales through loops

- A  well know example are enhancement of non-conserved currents inside loops leading to FCNC. The key – access to momenta ~ $m_W$ and $m_t$.




- For a fully conserved current, like couplings of dark photon,

Amplitude ~ $G_F\, m^2_{meson}$

For a non-conserved current,

Amplitude ~ $G_F\, m^2_{top}$

Application to an axial-vector coupling leads to

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

# Gauge symmetry broken by anomalies

- Consider $L = g_X X_\mu \, \Sigma \, (\bar{q} \, \gamma_\mu \, q)$ which is the coupling of a vector particle "X" to a baryon current. If we stay at the tree level, then the current is exactly conserved, and nothing would be wrong with such a $U(1)_{\text{baryon}}$.

- However [and famously], this symmetry is broken by the triangle chiral anomaly (Adler++):

$$\partial^\mu J_\mu^{\text{baryon}} = \frac{\mathcal{A}}{16\pi^2} \left( g^2 W^a_{\mu\nu} (\tilde{W}^a)^{\mu\nu} - g'^2 B_{\mu\nu} \tilde{B}^{\mu\nu} \right)$$

- The vector $X$ cannot stay massless, and a strong interaction will develop at scales $\lesssim \frac{4\pi m_X}{g_X} / \left( \frac{3g^2}{16\pi^2} \right)$ (Preskill) unless such theory is UV completed, and anomaly is cancelled in full theory

# Cancellation of anomalies for a baryonic U(1)

Anomaly of the baryon current can be cancelled by a new sector that is *heavier* than the SM. There are two main ways of doing it (and possibilities in between)

**Option 1**

Anomaly is cancelled by a non-chiral sector charged under SM gauge group. "Vector-like fermions"

$m_{anomalon}$ stays finite as SM vev → 0

Chiral under $U(1)_X$, get their masses due to $v_X$. This is a preferred option so far.

**Option 2**

Anomaly is cancelled by new fermions that are SM-like. Their mass is due to SM vev.

Big implications to EW precision, huge modifications to Higgs physics. Are these models still alive?

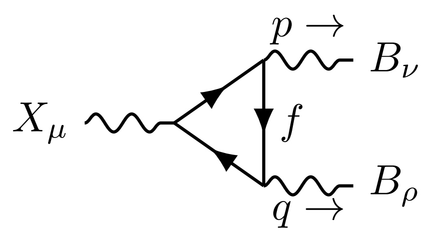
# Wess-Zumino term and low-energy EFT

- I stick to Option 1, and cancel the anomaly using heavy VL under SM fermions.

Longitudinal amplitude generated by the anomaly

$$-(p+q)_\mu \mathcal{M}^{\mu\nu\rho}_{\rm SM} = \frac{\mathcal{A}_{XBB}}{12\pi^2} g_X g'^2 \epsilon^{\nu\rho\lambda\sigma} p_\lambda q_\sigma \,,$$

$$\mathcal{M}^{\mu\nu\rho}_{\rm SM} \equiv \sum_f$$




,

is modified by the inclusion of the WZ term that restores the SM gauge invariance (eliminates longitudinal SM amplitudes).

$$\mathcal{L} \supset \frac{\mathcal{A}_{BBX}}{12\pi^2} g_X g'^2 \epsilon^{\mu\nu\rho\sigma} X_\mu B_\nu \partial_\rho B_\sigma \,,$$

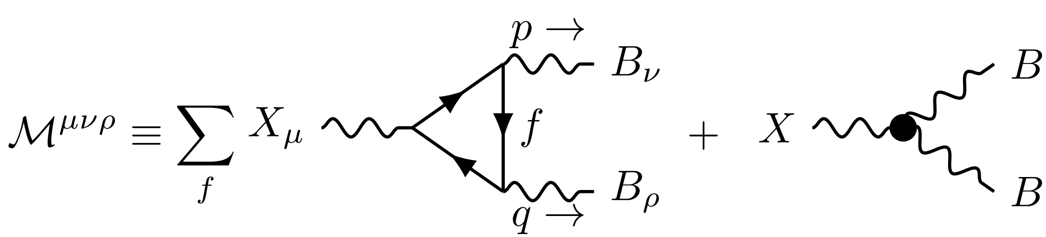
$$-(p+q)_\mu \mathcal{M}^{\mu\nu\rho}_{\rm WZ} = \frac{\mathcal{A}_{XBB}}{6\pi^2} g_X g'^2 \epsilon^{\nu\rho\lambda\sigma} p_\lambda q_\sigma \,.$$

Note that exact form of the WZ terms depends on regularization chosen for the triangular diagrams.

# Wess-Zumino term and low-energy EFT

Combining the anomalous contributions and WZ term, we get full longitudinal $X$ amplitude for such theory. Its form is independent on exact composition of the sector that cancels anomaly – only on the fact that anomaly-cancelling sector preserves SM gauge invariance.

$$-(p+q)_\mu \mathcal{M}^{\mu\nu\rho} = \frac{\mathcal{A}_{BBX}}{4\pi^2} g_X g'^2 \epsilon^{\nu\rho\lambda\sigma} p_\lambda q_\sigma \,,$$
$$p_\nu \mathcal{M}^{\mu\nu\rho} = q_\rho \mathcal{M}^{\mu\nu\rho} = 0 \qquad (5)$$




One can confirm this by repeating the calculation with UV complete theory, where the result ( $M^{\mu\nu\rho}$ ) emerges from the dependence of triangular diagrams on masses of anomaly-cancelling fermions.

# Non-decoupling of the longitudinal mode

- In equivalent language, one can use a Stuckelberg substitution, $X_\mu \rightarrow \partial_\mu\varphi \times (g_X/m_X)$.

Previously obtained results are equivalent to the pseudoscalar coupled to SM gauge bosons in the following way:

$$
\begin{aligned}
&\frac{\mathcal{A}}{16\pi^2}\frac{g_X\varphi}{m_X}(g^2W^a\tilde{W}^a - g'^2B\tilde{B}) = \\
&\frac{\mathcal{A}}{16\pi^2}\frac{g_X\varphi}{m_X}\Big(g^2(W^+\tilde{W}^- + W^-\tilde{W}^+) \\
&\quad +gg'(\cot\theta_w - \tan\theta_w)Z\tilde{Z} + 2gg'Z\tilde{F}) \\
&\quad -ieg^2\tilde{F}^{\mu\nu}(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) + \dots\Big)
\end{aligned}
$$

There is no coupling to γγ, but there are couplings to WW and Zγ, which will result in serious phenomenological consequences

# Z → γ X decay

- At one loop, Z boson will decay to γ X final state, and the emission of longitudinal scalar is $m_Z^2/m_X^2$ enhanced. (A=3/2 for the baryonic X).

$$\Gamma_{Z\to\gamma X} \simeq \frac{\mathcal{A}^2}{384\pi^5} g_X^2 g^2 g'^2 \frac{m_Z^3}{m_X^2}$$

This corresponds to
$$\frac{\Gamma_{Z\to\gamma X}}{\Gamma_Z} \simeq 10^{-7}\mathcal{A}^2 \left(\frac{\mathrm{TeV}}{m_X/g_X}\right)^2$$

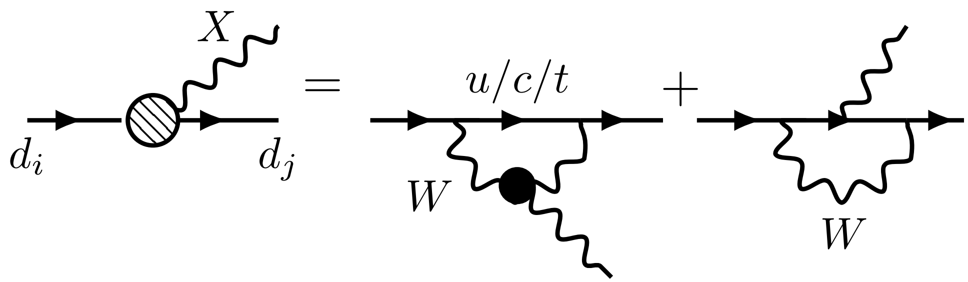
- One can use previous LEP measurements for Z→ gamma + invisible, as well as Tevatron Z→ gamma + pi0.

- LHC will have huge sensitivity through studies of $l^- l^+ \gamma$ final states.

# FCNC amplitudes at two loop

- Anomalous [two-loop] contributions to FCNC amplitudes are important

$$\mathcal{L} \supset g_{X d_i d_j} X_\mu \bar{d}_j \gamma^\mu \mathcal{P}_L d_i + \text{h.c.} + \ldots$$




$$g_{X d_i d_j} = -\frac{3g^4\mathcal{A}}{(16\pi^2)^2} g_X \sum_{\alpha\in\{u,c,t\}} V_{\alpha i} V^*_{\alpha j} F\left(\frac{m_\alpha^2}{m_W^2}\right)$$

$$\simeq -\frac{3g^4\mathcal{A}}{(16\pi^2)^2} g_X V_{ti} V^*_{tj} F\left(\frac{m_t^2}{m_W^2}\right) + \ldots ,$$

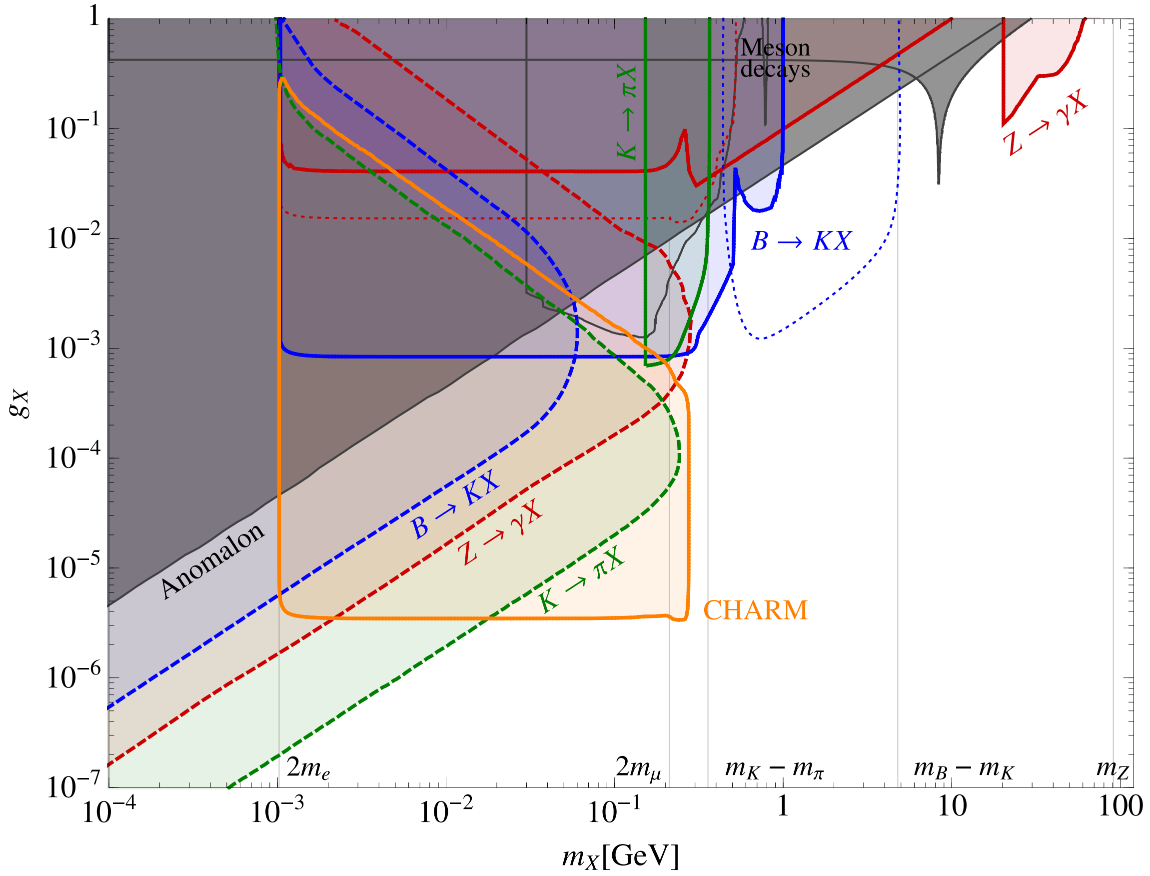
where

$$F(x) \equiv \frac{x(1 + x(\log x - 1))}{(1-x)^2} \simeq x \quad (\text{for } x \ll 1)$$

- As anticipated, $m^2_{\text{top}}$ enhancement is there.

# Resulting constraints on gauged baryon number

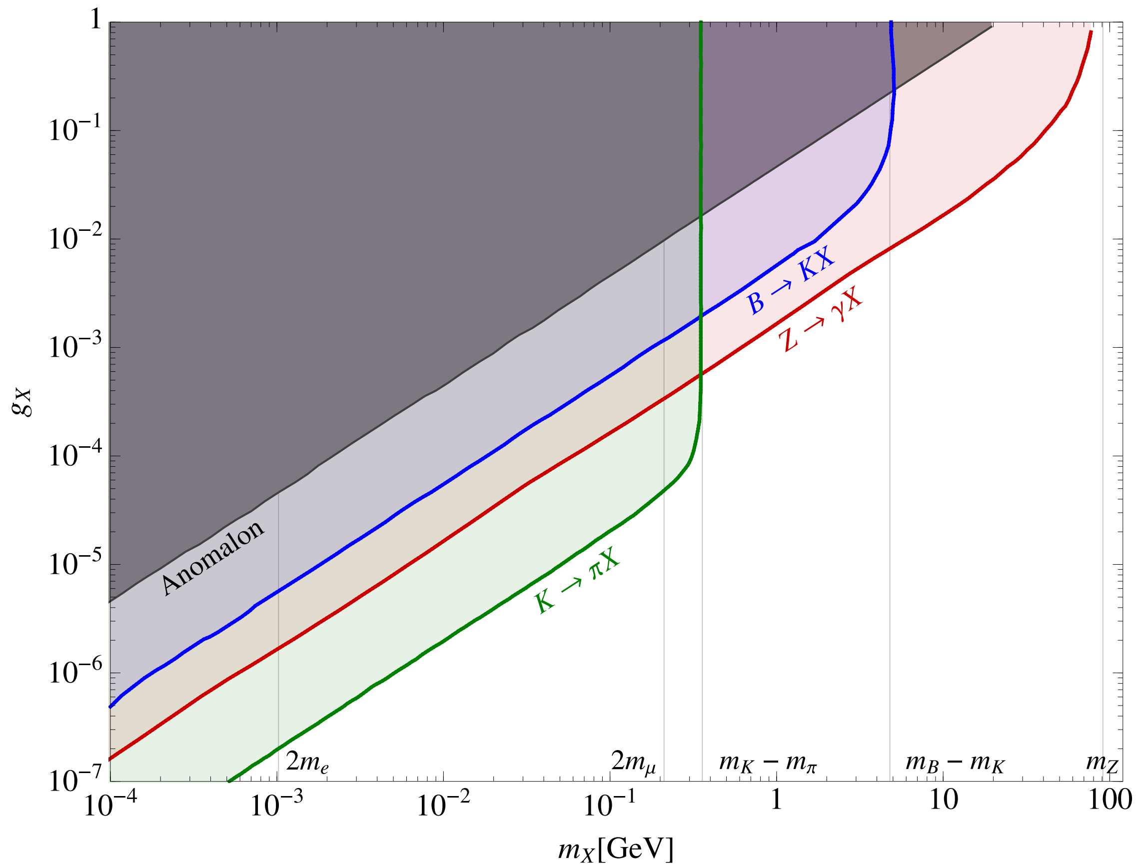
- No additional X→ invisible channels.




- Constraints can be improved via additional studies at LHC and B-factories.

# Resulting constraints on gauged baryon number

- With additional X→ invisible channels.




- The baryonic force in this case is limited to be below weak interaction strength, $(g_X^2/m_X^2) < G_F$.

# Conclusions

- Light weakly coupled sectors is a generic possibility. Can easily accommodate dark matter.

- Particles comprising dark sector can easily be within reach of the medium energy high intensity experiments.

- Among the most interesting dark sector candidates are dark photons and dark Higgses, as well as more exotic possibilities ($L_\mu$-$L_\tau$, $U(1)_{B\text{-}L}$ gauge bosons).

- In case of anomalous currents coupled to new vector states, new constraints are derived from the enhanced production of the longitudinal modes for new vector states.