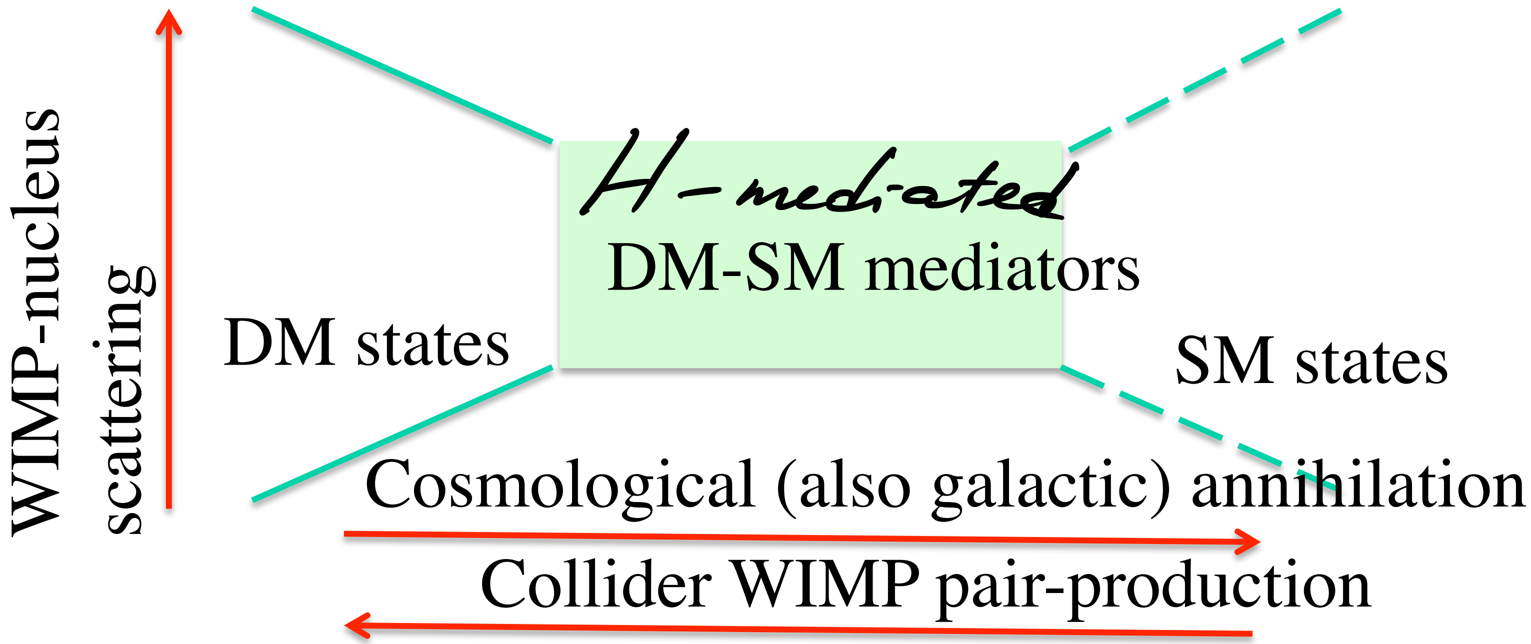
# Lecture 3

- WIMPs as dark matter
- WIMPs with a new mediating force
- Dark photon as a mediator of a dark force
- Chasing anomalies with light new particles: galactic positrons, muon g-2, charge radius problem, etc
- Strategies to search for dark photons, with light dark matter and without. A few results.

# WIMP paradigm, some highlights



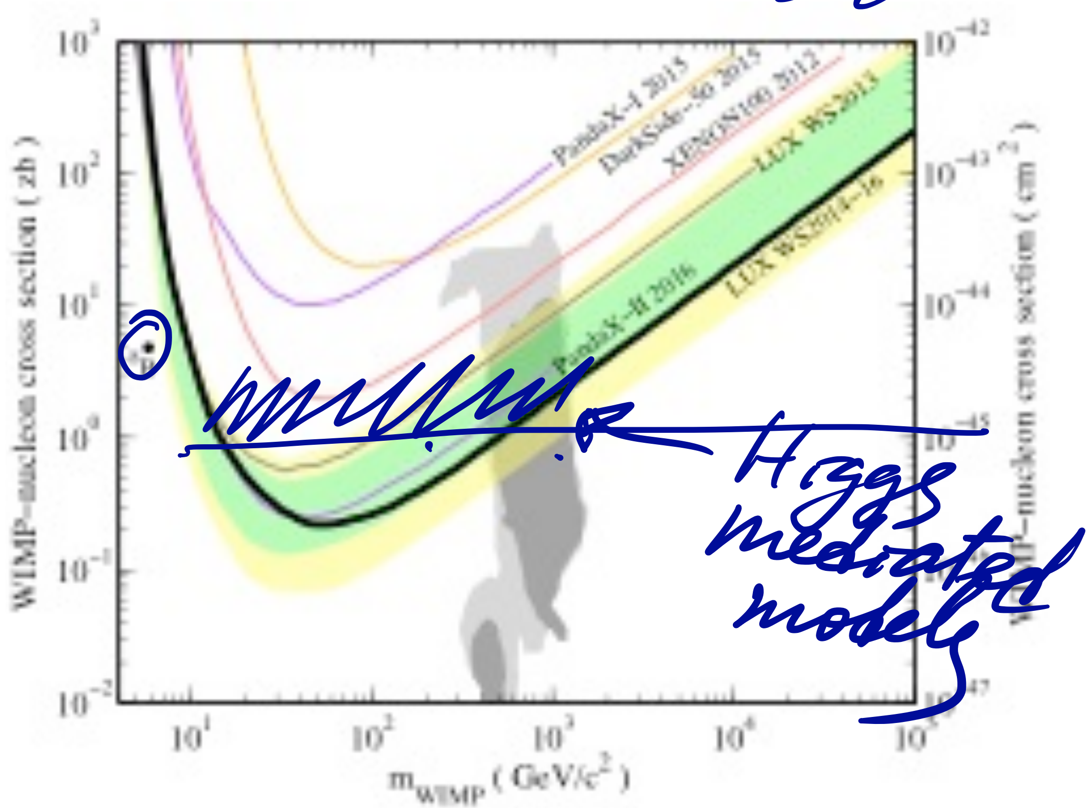

$$\langle \sigma_{ann} v \rangle \approx 1\mathrm{pbn} \times c$$

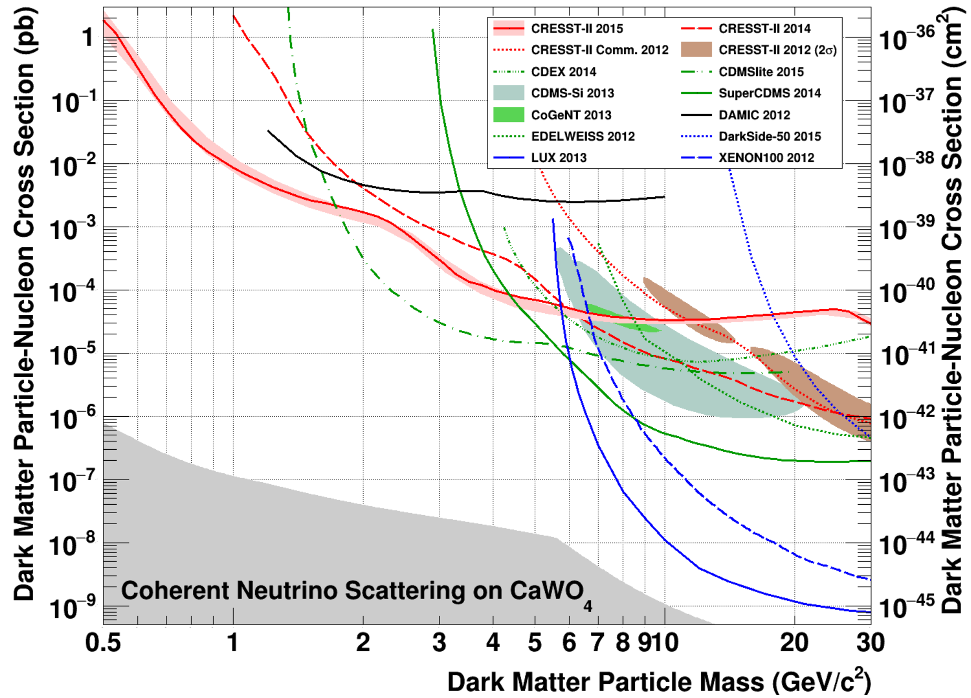
*1. What is inside this green box? I.e. what forces mediate WIMP-SM interaction?*

*2. Do sizable annihilation cross section always imply sizable scattering rate and collider DM production?*

# Progress in direct detection of WIMPs

Z-mediated exchange



# Summary of main features of WIMPs

- Regulates its abundance via self-annihilation with $\sigma$ v ~ $10^{-36}$ cm$^2$

- The mass of WIMPs is in a several GeV – several TeV window (Lee-Weinberg) *if* the interaction is mediated by weak-scale forces.

- Direct detection experiments surpass sensitivity of $10^{-45}$ cm$^2$ without seeing a signal – worrying sign for many models, including models with Z boson mediators. Probes the tree-level Higgs exchange

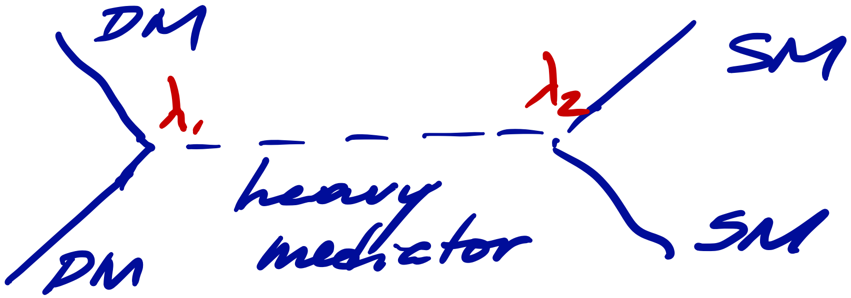
- Sensitivity of direct detection will be ultimately limited by elastic recoil of solar and atmospheric neutrinos

- Low mass WIMPs do not carry much energy, and are less constrained

# What changes if we add a mediator?

Coupling to SM is no longer dictated by size of annilation $\sigma$.

(A)

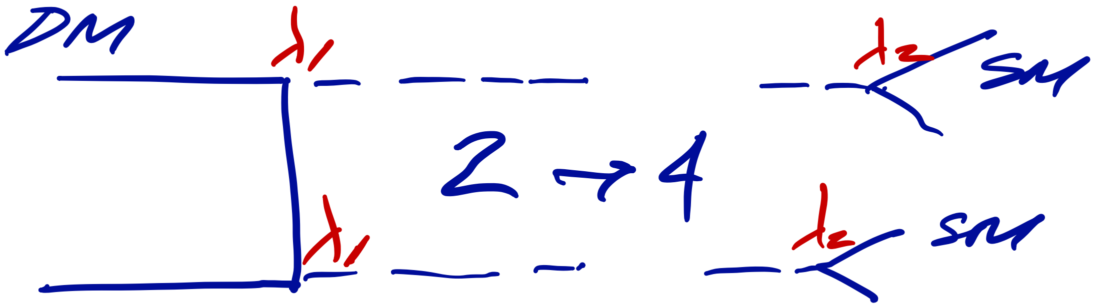



$$(v\sigma)_{ann} \sim \frac{(\lambda_1 \lambda_2)^2 m_{DM}^2}{(M_{mediator})^4}$$

Both $\lambda_1$ and $\lambda_2$ have to be sizeable

(B) "Staged" annihilation:

"DM → mediators → decay to SM.




$$(\sigma v)_{ann} \sim \frac{\lambda_1^4}{m_{DM}^2}$$

The size of $\lambda_2$ coupling can be almost arbitrarily small

# What changes if we add a mediator?

We can lower the mass scale of DM

Lee-Weinberg: $(\sigma v)_{ann} \sim G_F^2 m_{DM}^2 \gtrsim 10^{-36}\,cm^2 \Rightarrow m_{DM} \gtrsim 6\,GeV$

Now, if $M_{mediator}$ is <u>smaller</u> than $m_W$, much lighter WIMP Dark matter is allowed.

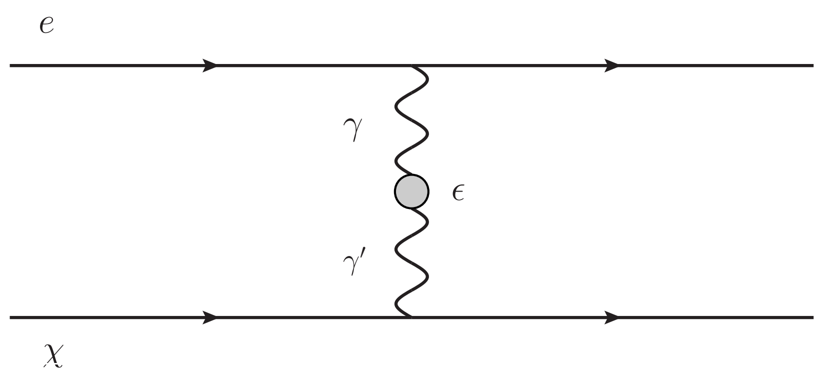
# "Simplified model" for dark sector

**(Okun', Holdom,…)**

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

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

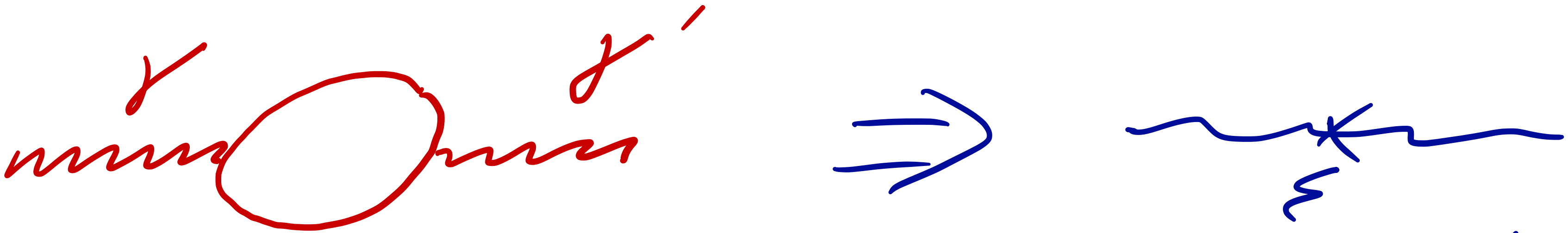
$$\mathcal{L}_{\chi,A'} = -\frac{1}{4}(F'_{\mu\nu})^2 + \bar{\chi}[\gamma_\mu(i\partial_\mu - g'A'_\mu) - m_\chi]\chi,$$




$A$ – photon, $A'$ – "dark photon", $\psi$ - 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, $r_\chi^2 \simeq 6\epsilon m_V^{-2}$.
- Dark photon can "communicate" interaction between SM and dark matter. *It represents a simple example of BSM physics*.

# A reasonable top down model?



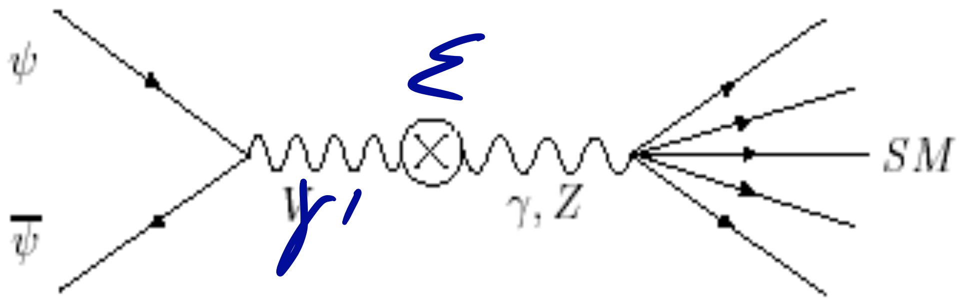

heavy particles charged under both groups

$$\varepsilon \simeq \text{couplings} \times \log\left(\frac{\Lambda_{UV}}{\mu}\right)$$

Loops of heavy particles can give $\varepsilon \lesssim 10^{-2}$ (depends on the number of loops).

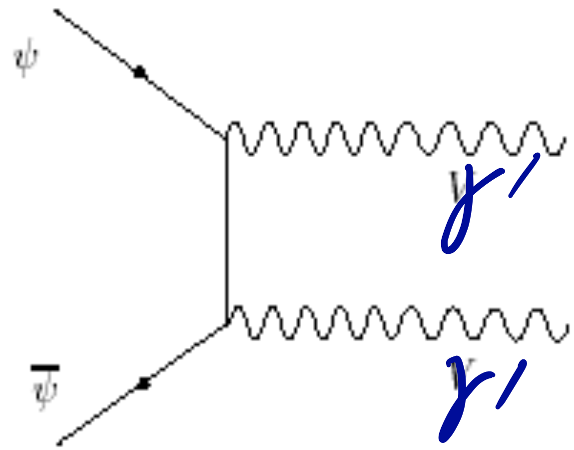
# Two types of WIMPs

## Un-secluded




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

## Secluded

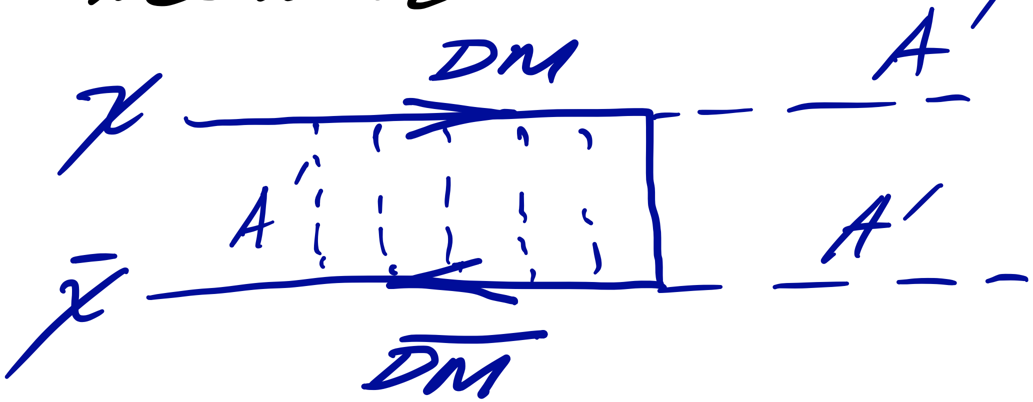


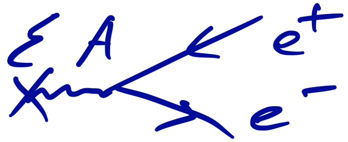

*Potentially well-hidden*
Mixing angle can be $10^{-10}$ or so. It is not fixed by DM annihilation

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

# Consequences of light mediator

Coulomb (aka Sommerfeld) enhancement.




$m_{A'} < 2m_\chi$

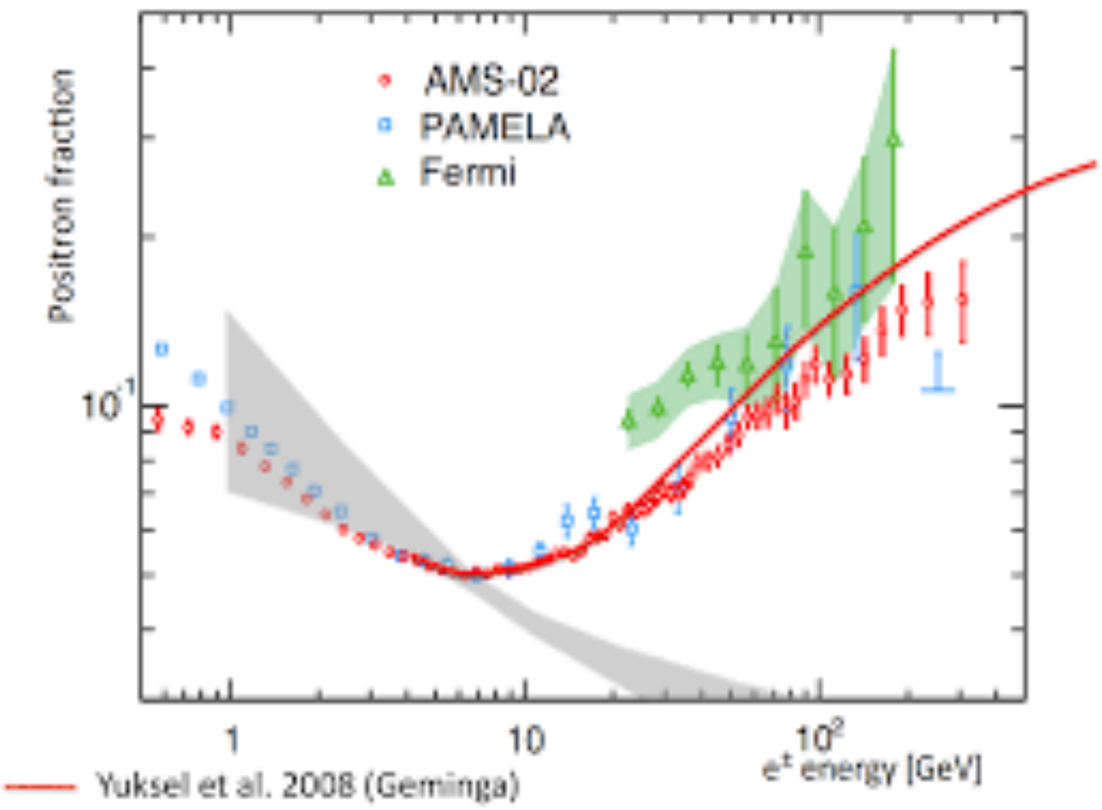
For heavy nonrelativistic DM

$$(v\cdot\sigma_{ann})(v\ll c) \simeq \frac{2\pi\alpha'}{v}\times(\sigma_{ann}\cdot v)_{v\sim c}$$

Notice that at freeze-out $v\sim 0.3c$; and inside the galaxy $v\sim 10^{-3}c$.

$$\frac{(\sigma v)_{galaxy}}{(\sigma v)_{f.o.}} \text{ can be } \gg 1.$$

# Consequences of light mediator




- Galactic positron excess can be modelled via the annihilation of DM into light mediators.
- Need the enhancement of cross section at low galactic velocities
- Increasingly under pressure from the absence of the excesss in γ

# Astrophysical motivations for very MeV-scale DM: 511 keV line

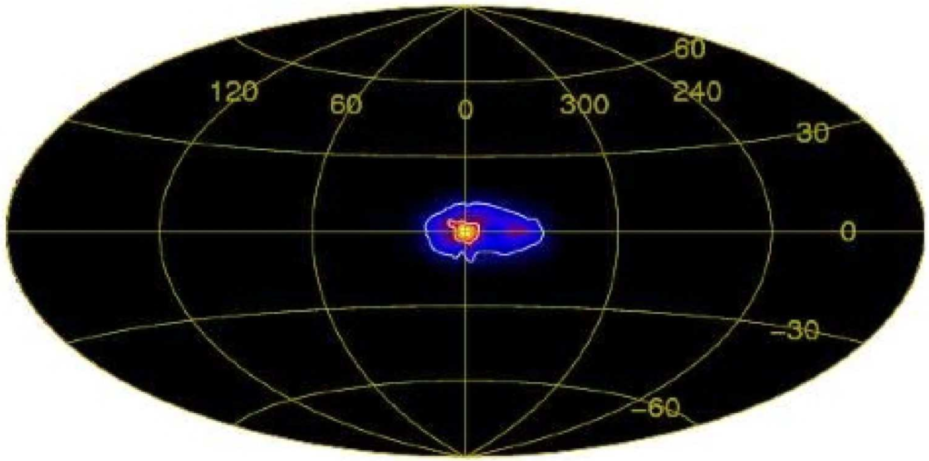



FIG. 4  511 keV line map derived from 5 years of INTEGRAL/SPI data (from Weidenspointner *et al.*, 2008a).

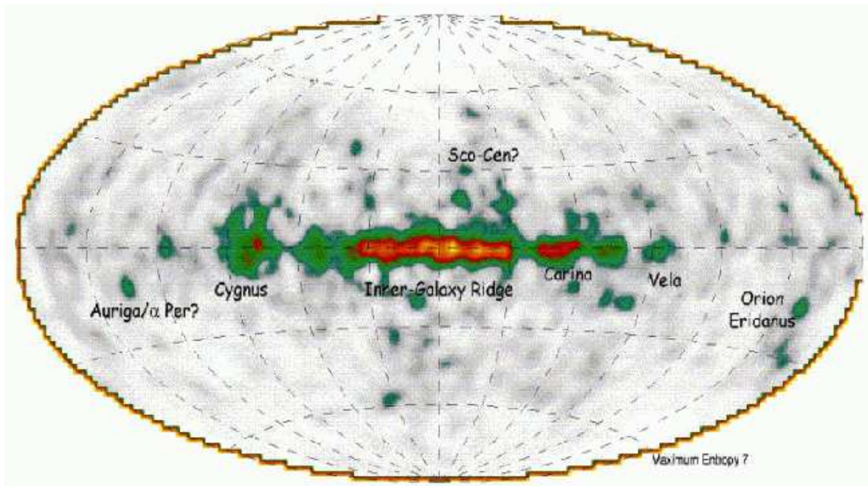
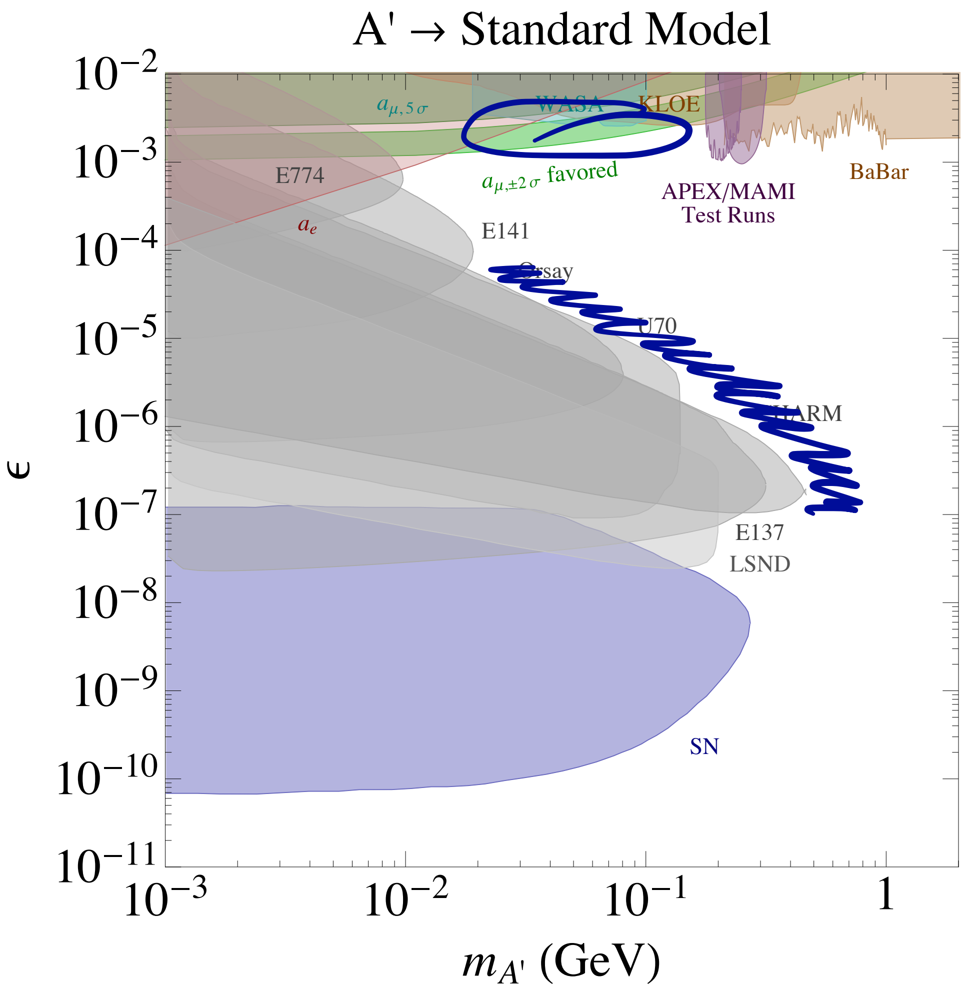


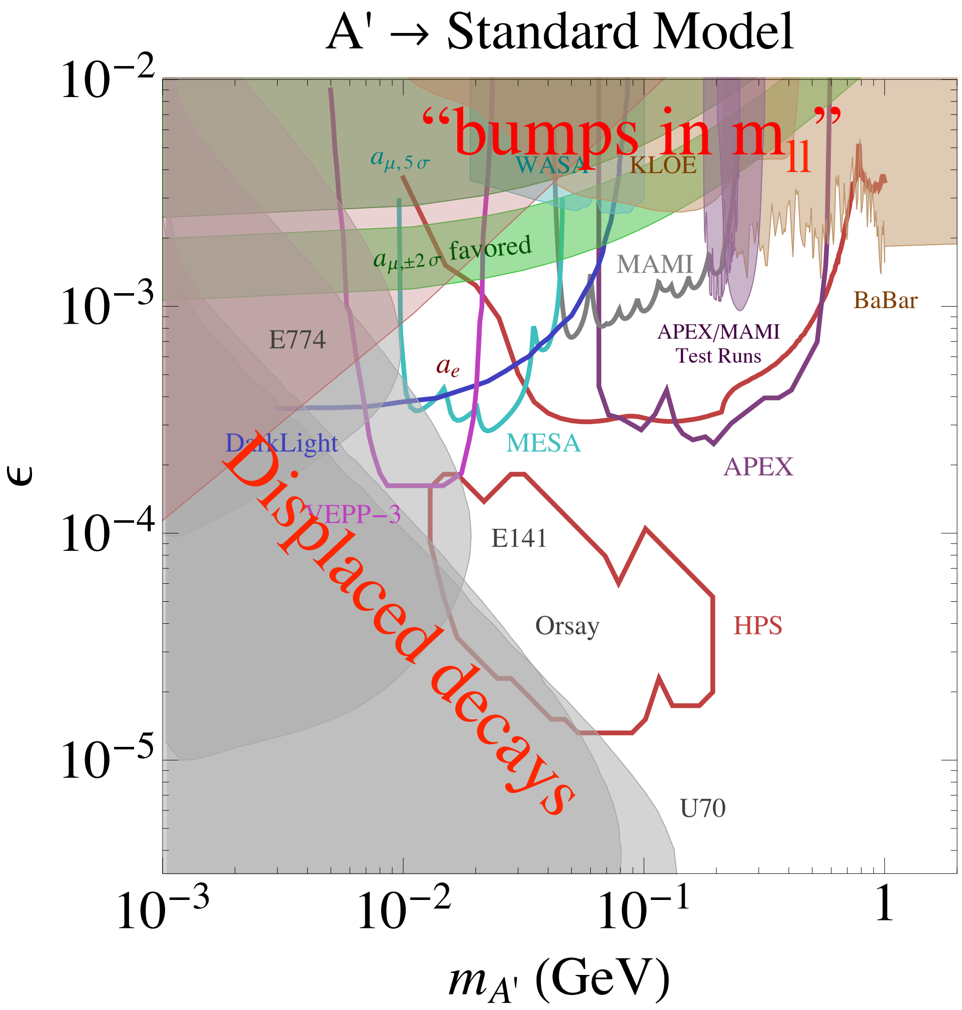

FIG. 7  Map of Galactic $^{26}$Al $\gamma$-ray emission after 9-year observations with COMPTEL/CGRO (from Plüschke *et al.*, 2001).

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?

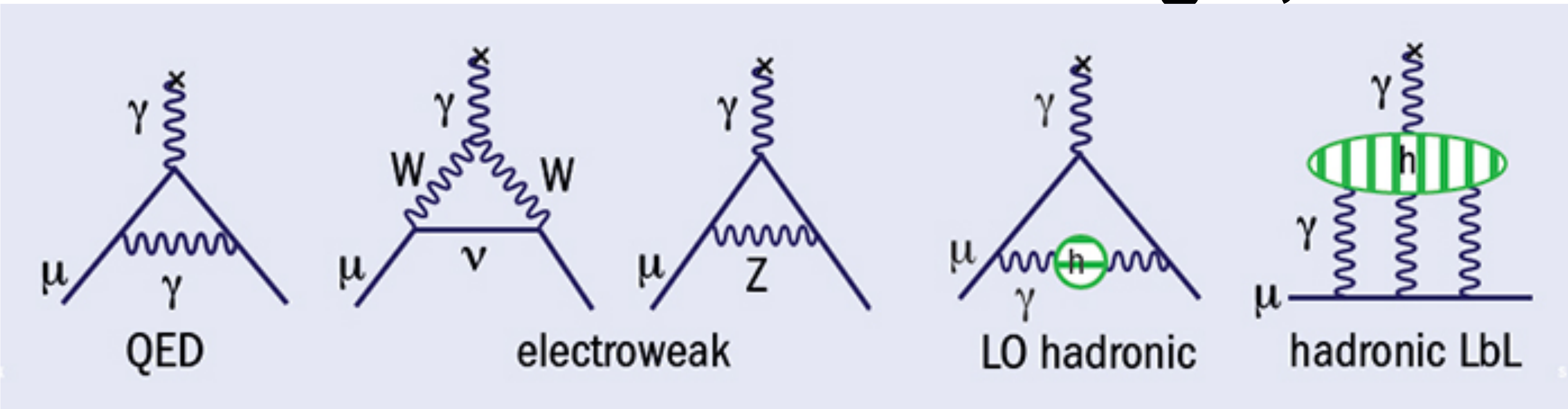
# Search for dark photons, Snowmass study, 2013




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.

# Theoretical status of muon g-2, SM

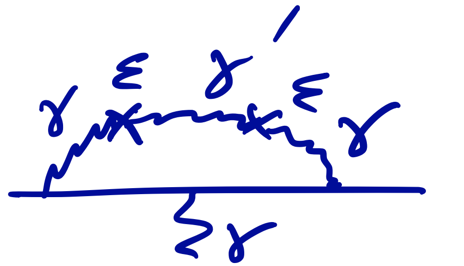



The history of theoretical calculations goes very far in the past. Back to Schwinger's result, $a_\mu^{\text{1-loop QED}} = \alpha / (2\,\pi)$

Currently, the QED, Strong and Weak contributions are under control

$$a_\mu^{\text{SM theory}} = 116591828 \pm 49 \times 10^{-11}$$

$$a_\mu^{\text{experiment}} = 116592089(63) \times 10^{-11}$$




$$a_\mu^{\text{Deficit}} = (26.1 \pm 8) \times 10^{-10}$$

$m_{\gamma'} \ll m_\ell$


Even larger than EW contribution !

$\frac{\alpha}{2\pi}\varepsilon^2$

$$a_\mu^{\text{EW}} = (154 \pm 2) \cdot 10^{-11}$$

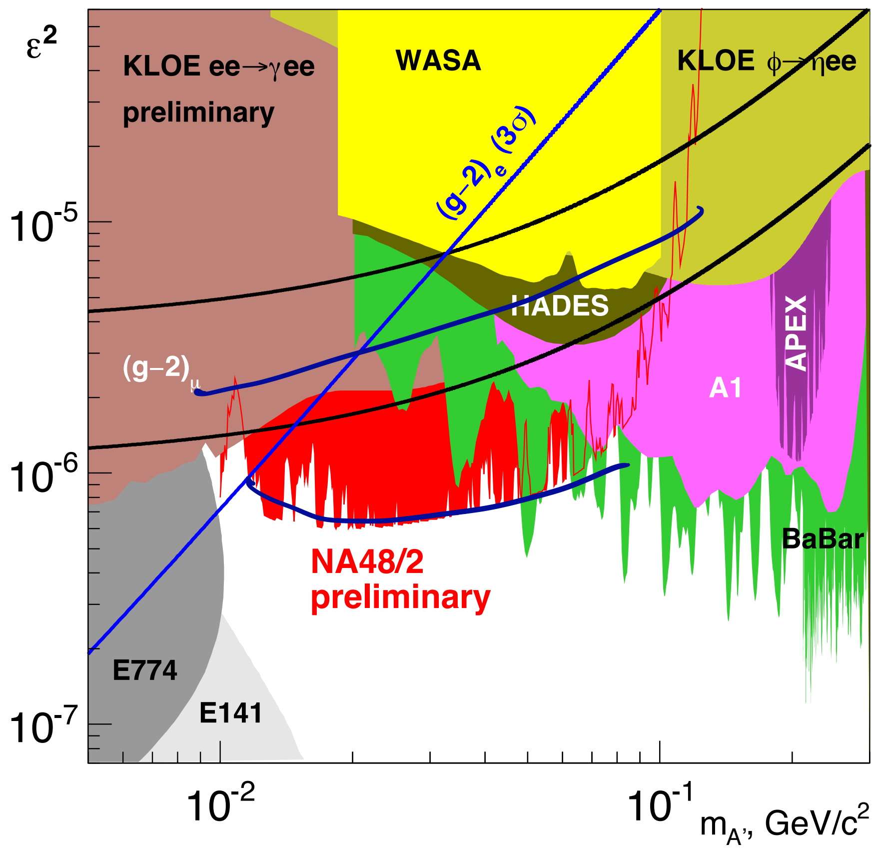
# Latest results: A1, Babar, NA48

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.*

# Muon pair-production by neutrinos

VOLUME 66, NUMBER 24 PHYSICAL REVIEW LETTERS 17 JUNE 1991

**Neutrino Tridents and *W*-*Z* Interference**

S. R. Mishra,[a] S. A. Rabinowitz, C. Arroyo, K. T. Bachmann,[b] R. E. Blair,[c] C. Foudas,[d] B. J. King,

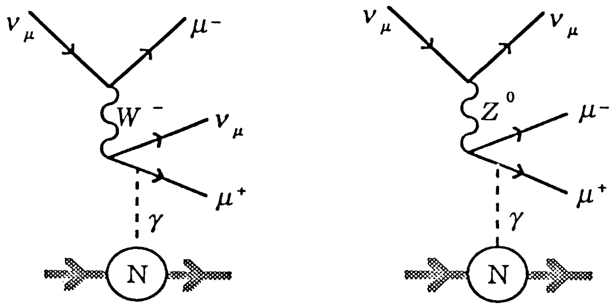


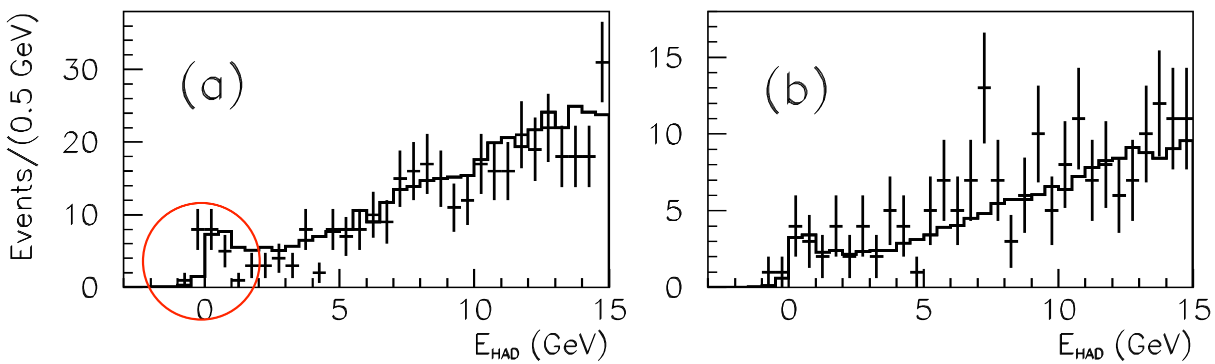

FIG. 1. Feynman diagram showing the neutrino trident production in $\nu_\mu$-$A$ scattering via the $W$ and the $Z$ channels.

$$\sigma_{\nu N}(\mathrm{CC}) = (0.680 \pm 0.015) E_\nu \times 10^{-38}\ \mathrm{cm}^2/\mathrm{GeV}\,,$$

$$\sigma(\nu\ \mathrm{trident}) = (4.7 \pm 1.6) E_\nu \times 10^{-42}\ \frac{\mathrm{cm}^2}{\mathrm{Fe\ nucleus}}$$

$$\text{at } \langle E_\nu \rangle = 160\ \mathrm{GeV}\,.$$

- NuTeV results:



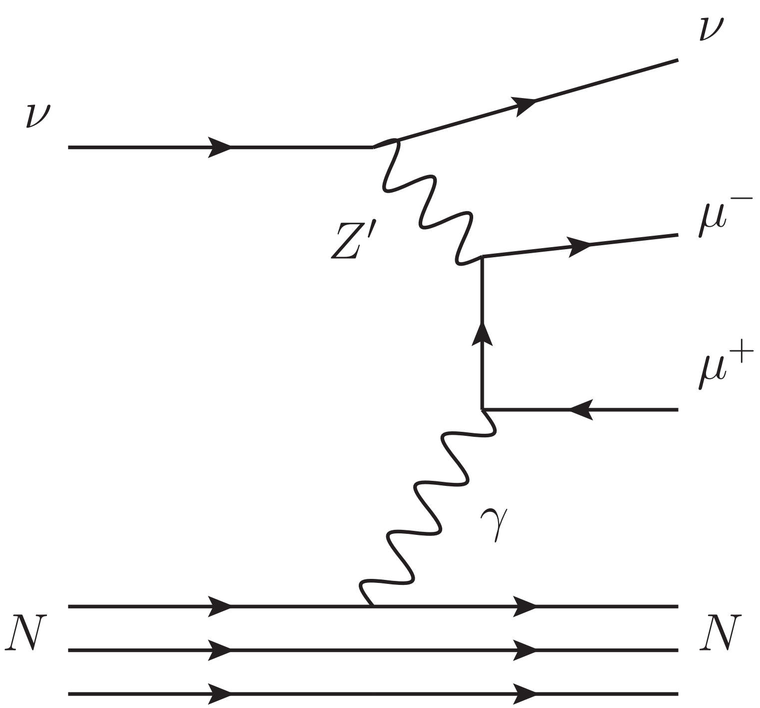

Trident production was seeing with O(20) events, and is fully consistent with the SM destructive W-Z interference.

# Additional contribution from Z' of $L_\mu$ - $L_\tau$

Experimental results

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

Hypothetical Z' (any Z' coupled to $L_\mu$) contributes constructively to cross section.

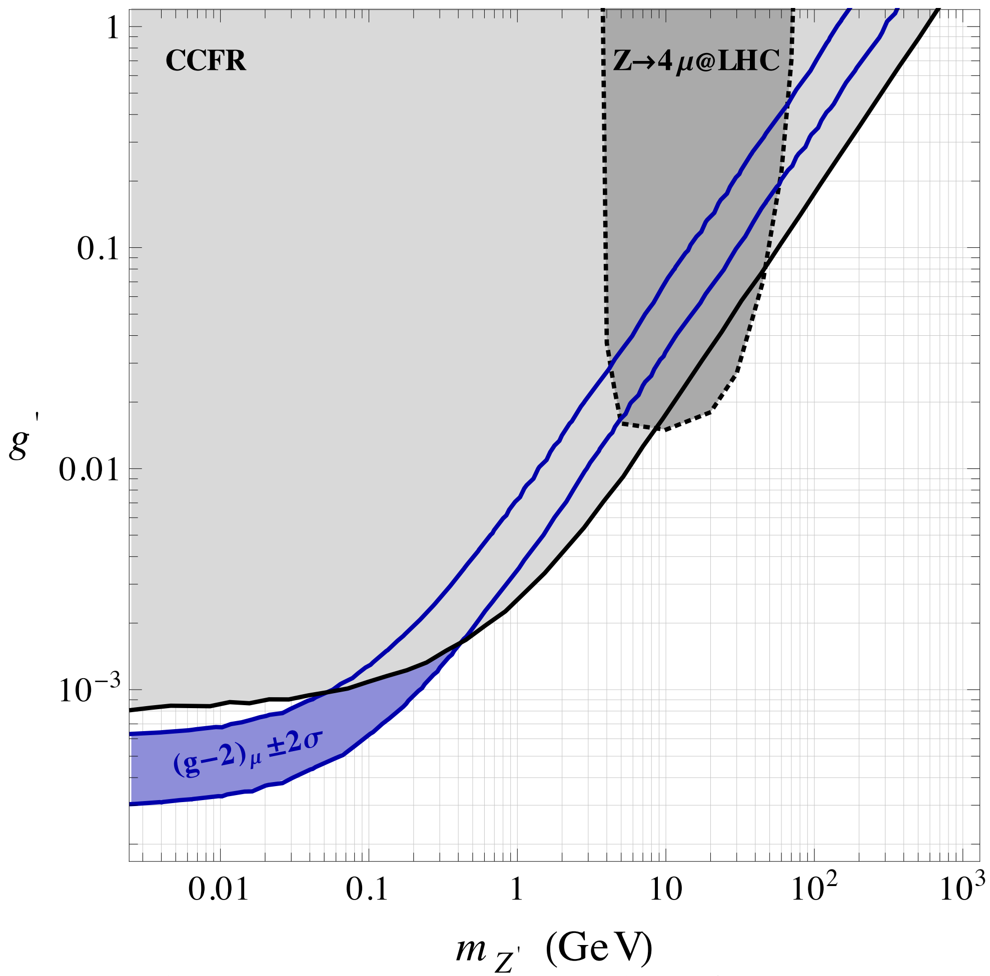



In the heavy Z' limit the effect simply renormalizes SM answer:

$$\frac{\sigma}{\sigma_{\text{SM}}} \simeq \frac{1 + \left(1 + 4s_W^2 + \underbrace{2v^2/v_\phi^2}_{\approx 4}\right)^2}{1 + \left(1 + 4s_W^2\right)^2}$$

~8-fold enhancement of cross section

# Full result on $M_{Z'}$ - g' parameter space




Muon pair production process excludes solutions to muon g-2 discrepancy via gauged muon number in the whole range of

$M_{Z'} > 400$ MeV

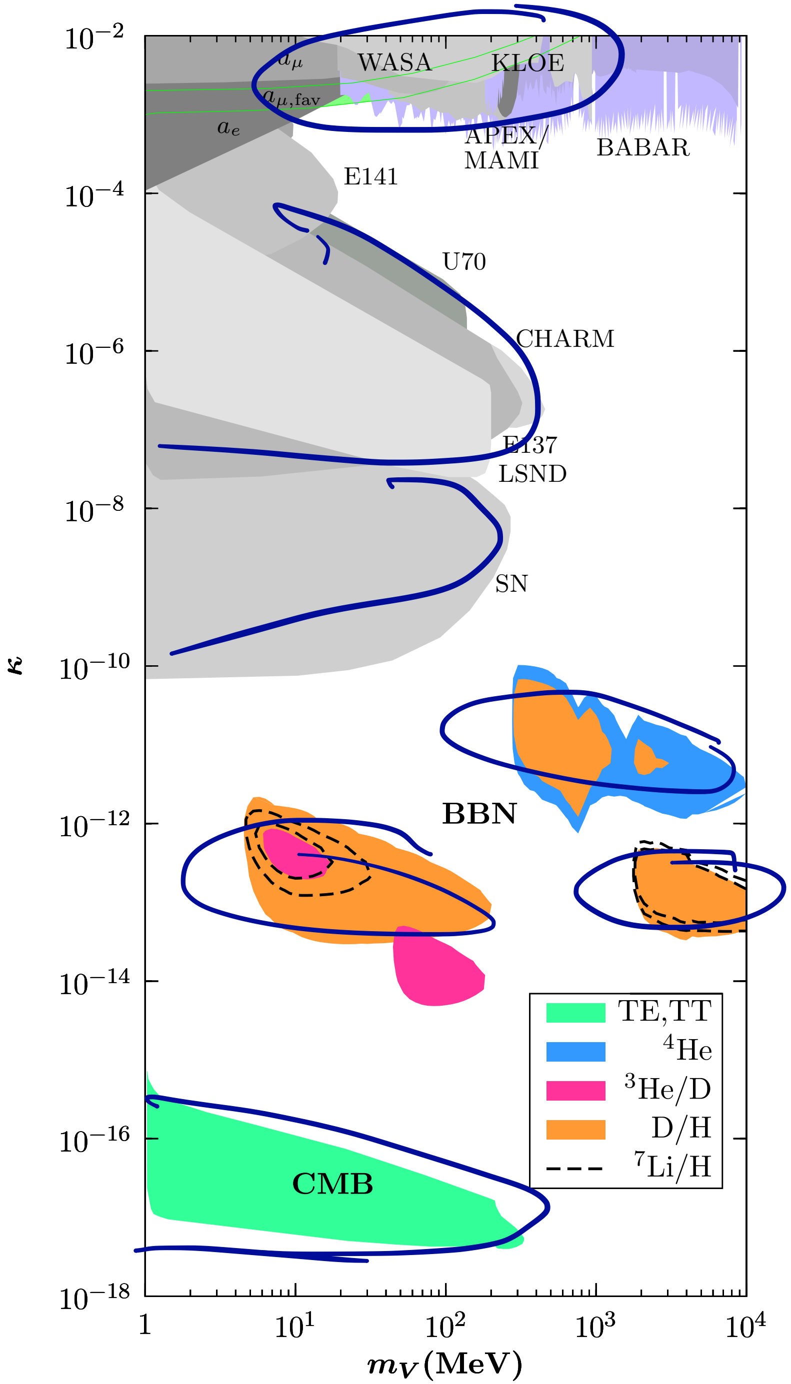
In the "contact" regime of heavy Z'>5 GeV, the best resolution to g-2 overpredicts muon trident cross section by a factor of ~ 8.

*Can it be improved in the future at LBNE (O(50) events /yr ) ???*

Altmannshofer, Gori, MP, Yavin, PRL, 2014

Also, watch out for the future missing momentum searches, e.g. NA64

# CMB and BBN constraints




- Thermal production of "very dark photons" at T ~ 0.4 m_V
- If couplings are very small, decays happen much later,

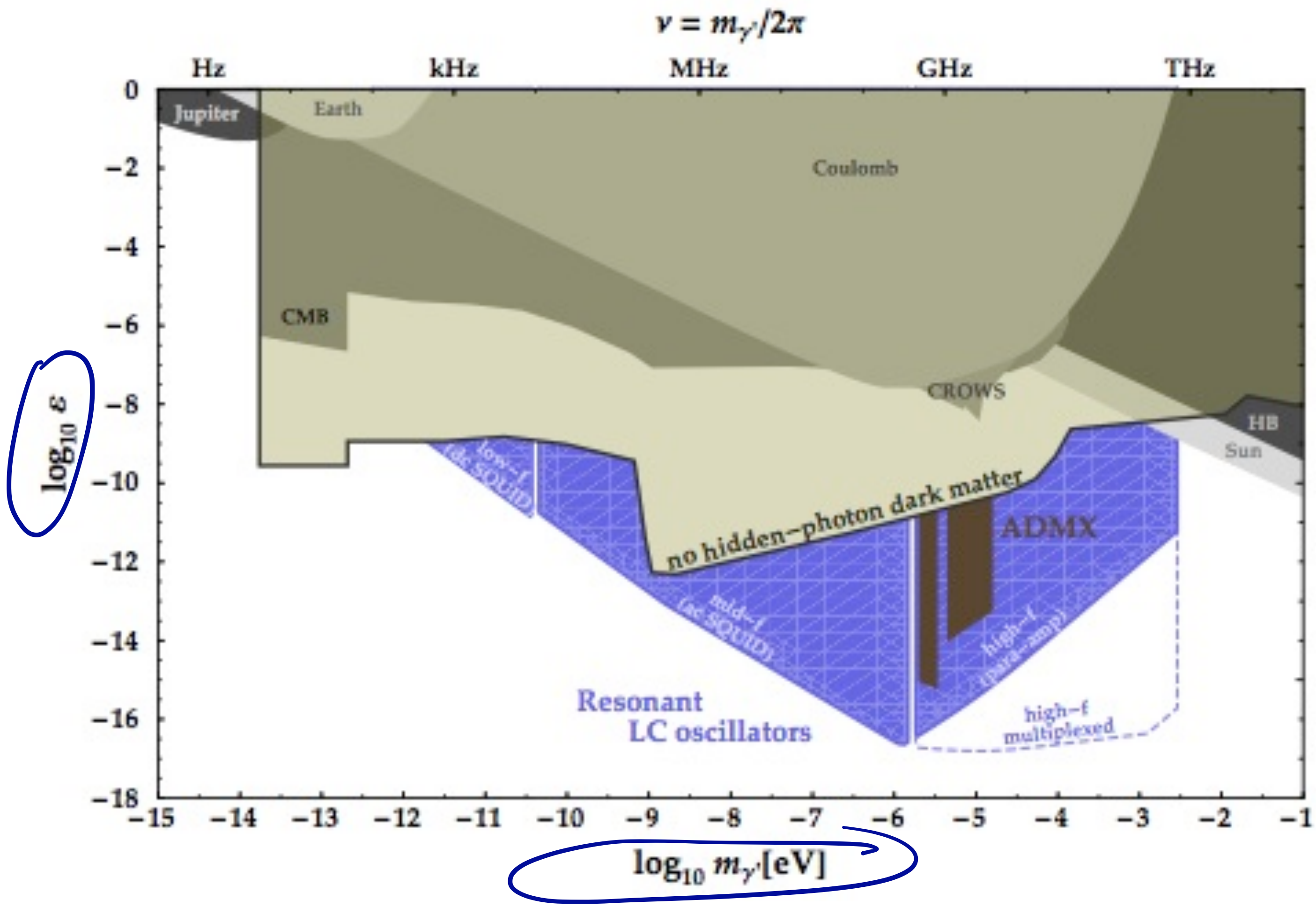
$$\tau_V \simeq \frac{3}{\alpha_{\rm eff} m_V} = 0.6 \text{ mln yr} \times \frac{10\,\text{MeV}}{m_V} \times \frac{10^{-35}}{\alpha_{\rm eff}}$$

- Disrupt BBN outcome or CMB angular anisotropies
- Energy release per baryon can be significant,

$$E_{\rm p.b.} \sim \frac{m_V \Gamma_{\rm prod} H^{-1}_{T=m_V}}{n_{b,T=m_V}} \sim \frac{0.1\alpha_{\rm eff} M_{\rm Pl}}{\eta_b} \sim \alpha_{\rm eff} \times 10^{36}\,\text{eV}$$

Strong constraints on mixing angle as amall as $10^{-17}$.

# Probing dark photon over range of masses




- Misaligned photon dark matter, sub-eV range, from Chaudhuri et al, 2014.

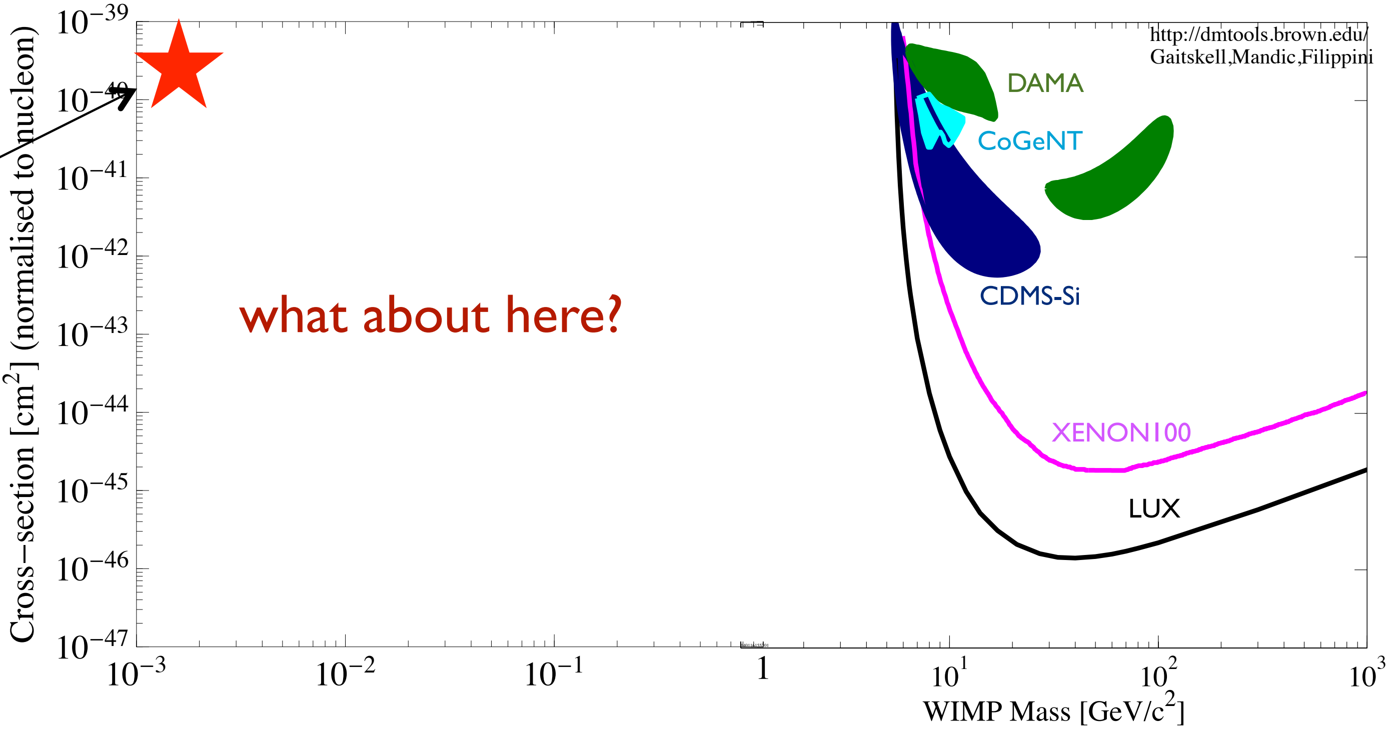
# On-going and future projects

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, NA64…
- Extra Z' in neutrino scattering: DUNE near detector (?)

# 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,

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

DM

mediation

# Light WIMPs due to light mediators direct production/detection

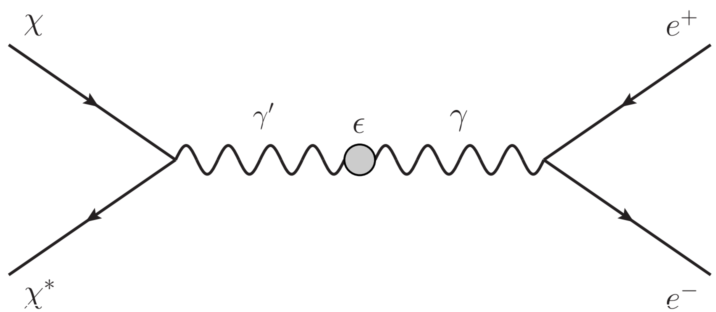
Light dark matter is not ruled out if one adds a light mediator.

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,

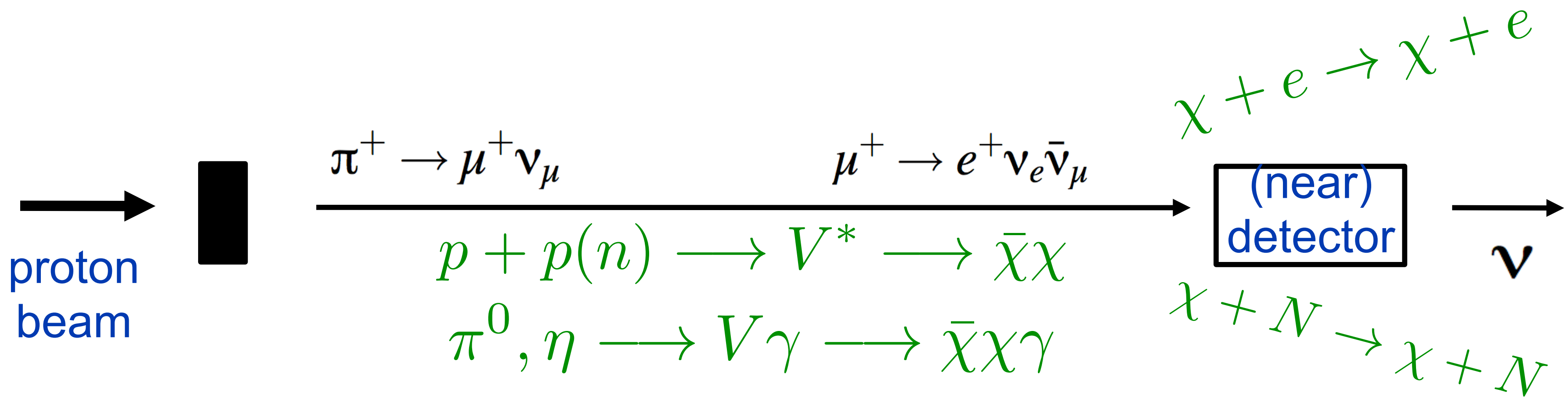
$$\sigma(v/c) \propto \begin{cases} G_F^2 m_\chi^2 & \text{for} \quad m_\chi \ll m_W, \\ 1/m_\chi^2 & \text{for} \quad m_\chi \gg m_W. \end{cases} \quad \implies \quad \text{few GeV} < m_\chi < \text{few TeV}$$

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.

| 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 |

# Comparison of Neutrino and light DM

**Neutrinos**:

*Production*:

Strong scale $\sigma \sim 100$ mbn

*Detection*:

Weak scale $\sigma \sim G_F^{\,2} E_{cm}^{\;\;2}$

**Light WIMPs**:

*Production*:

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

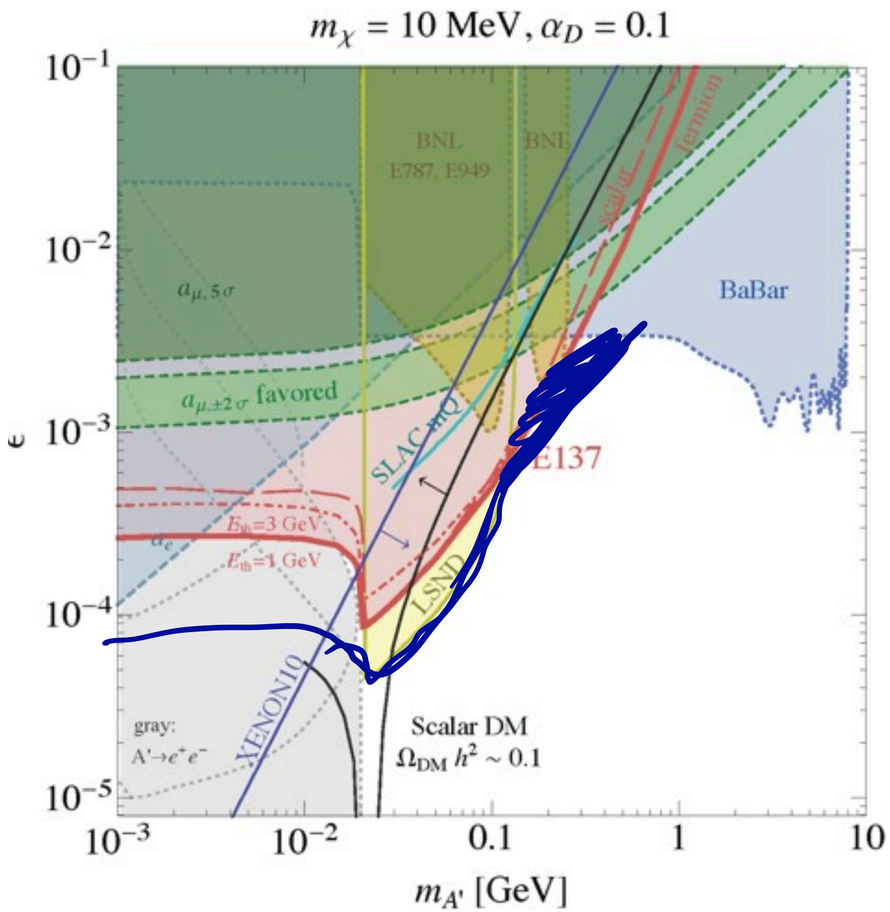
*Detection*:

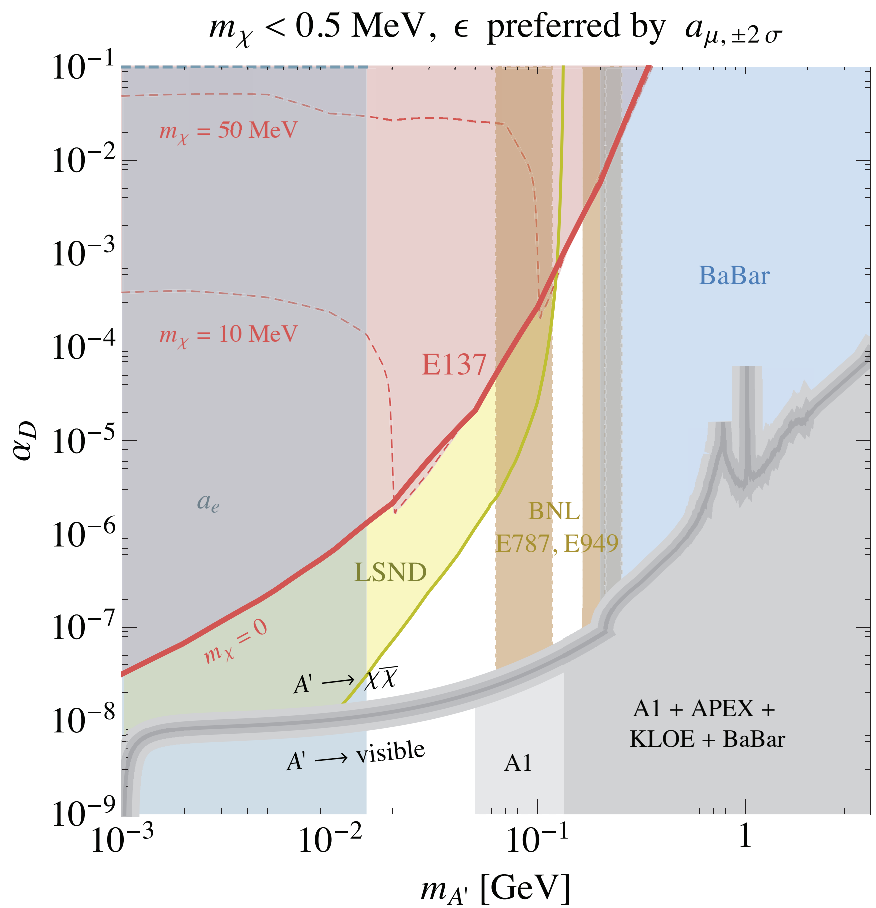
Larger than weak scale!

Signals $\sim \sigma_{\text{production}} \times \sigma_{\text{detection}}$ can be of comparable strength

The reason for "stronger-than-weak" force for light dark matter comes from the Lee-Weinberg argument. (The weak-scale force will be *insufficient* in depleting WIMP DM abundance to observable levels if $m_{DM}$< few GeV. Therefore, stronger-than-weak force and therefore relatively light mediator is needed for sub-GeV WIMP dark matter).

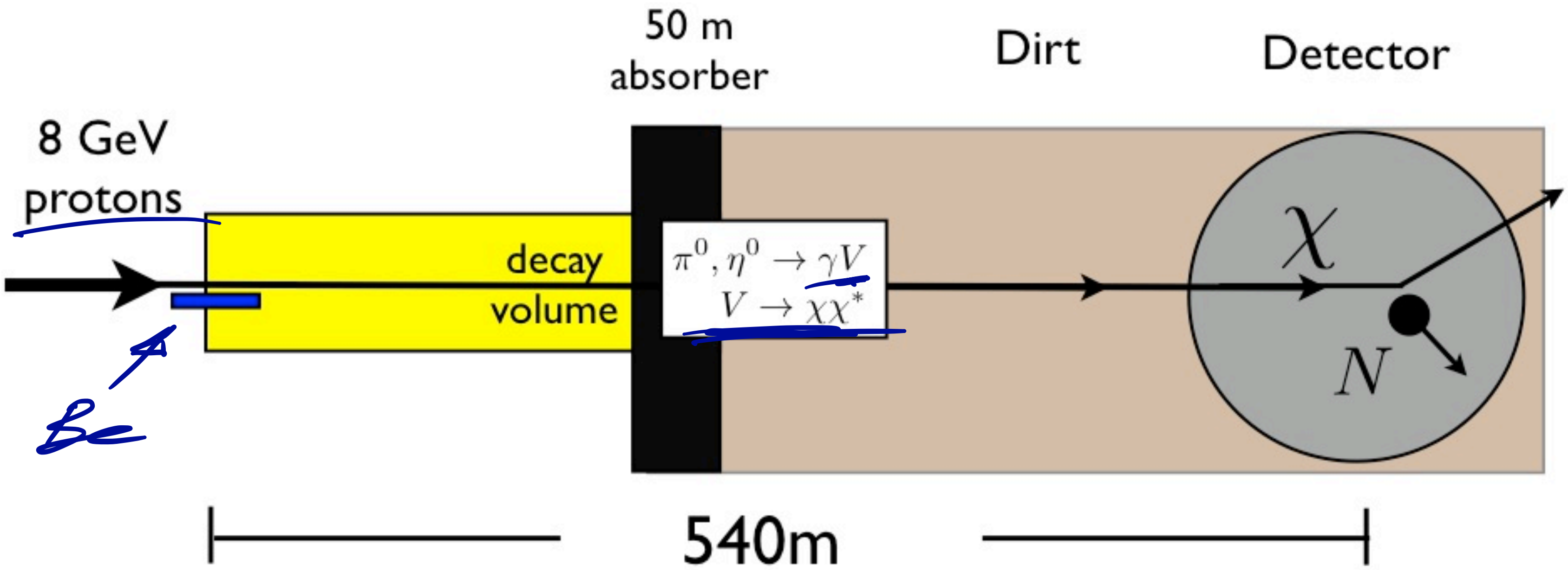
# Compilation of current constraints on dark photons decaying to light DM




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.

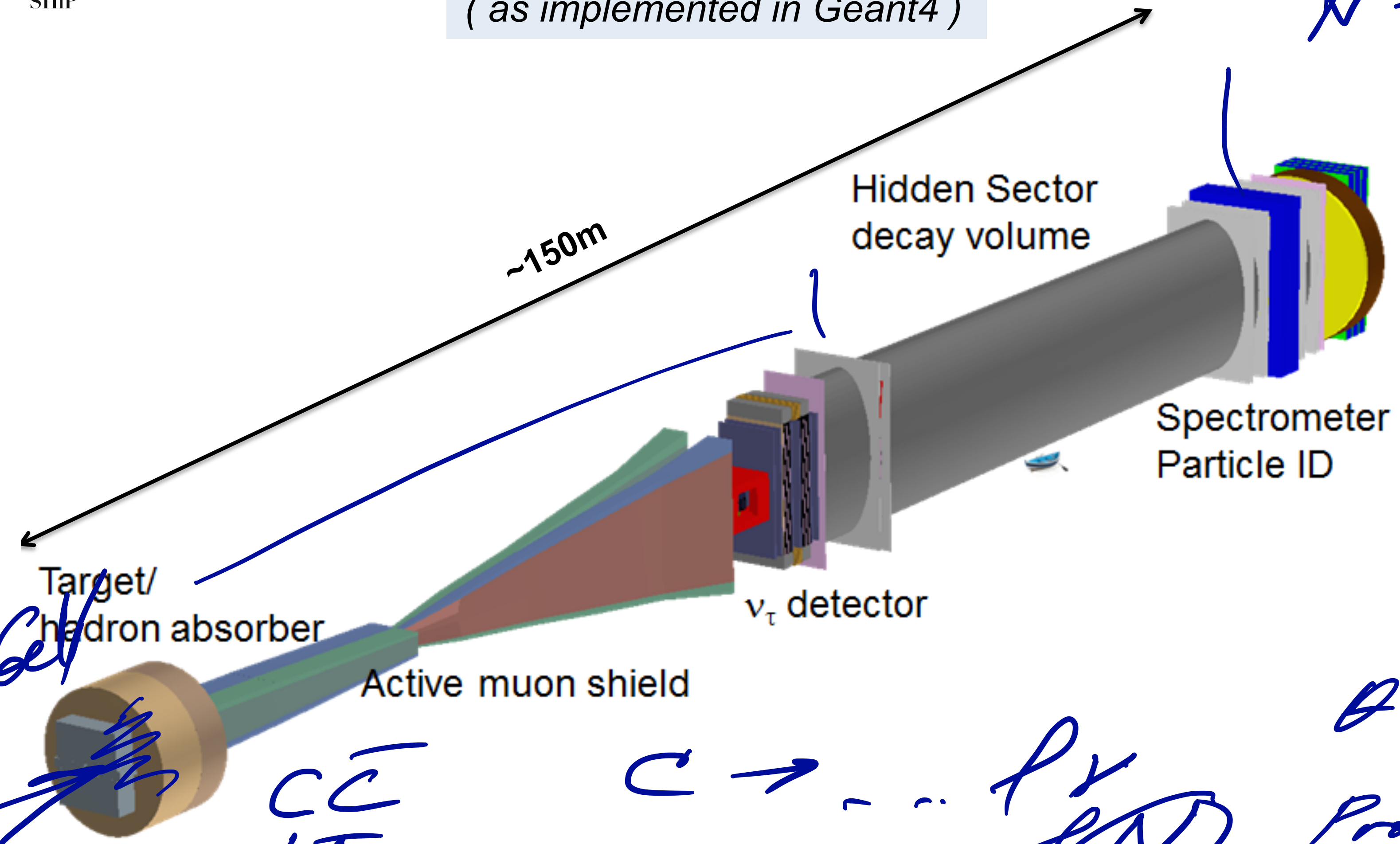
Timing is used (10 MeV dark matter propagates slower than neutrinos) to further reduce backgrounds. First results – this year (2016)

# Future big project: SHiP project at CERN

SHiP

***The SHiP experiment***
*( as implemented in Geant4 )*

$N \to \pi^+ \mu^-$




400 GeV
SPS

$c\bar{c}$
$b\bar{b}$

$c \to \dots D_s \to \ell N$

$\theta \sim \frac{m_\ell}{m_N}$

$\mathrm{Prob} \sim \theta^2$

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

$2 \times 10^{21}$ pot

# More anomalies driving new experiments?

- LSND etc hint on light sterile neutrino ← new developments at Fermilab
- Proton charge radius problem?
- Recently reported anomalous signal in $^{8}$Be(18.15) decay.
- BBN abundance of $^{7}$Li is off by a factor of 3 from observations
- A hint on DM self-interaction mediated by light particle exchange?

good spot to search for light DM.

# More discrepancies discovered using muons !

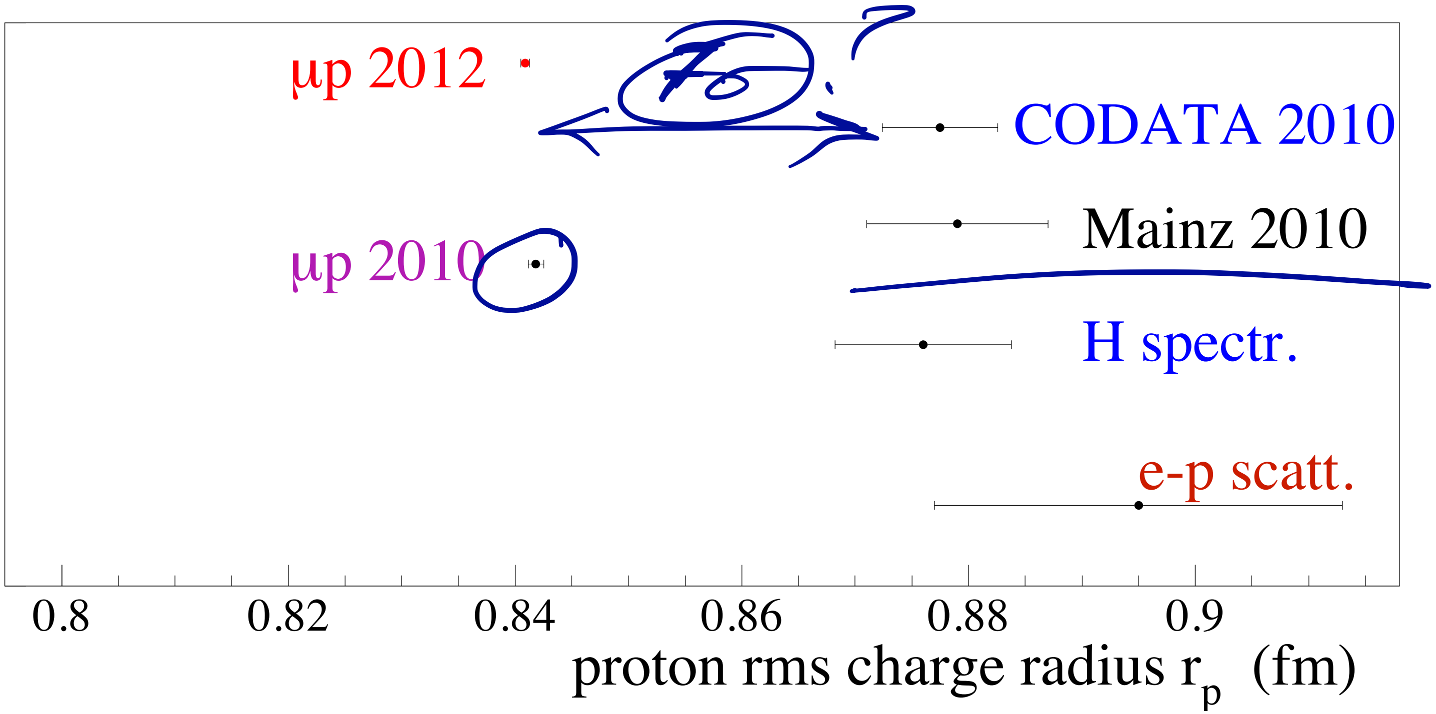
$\nu(2S_{1/2}^{F=1} \to 2P_{3/2}^{F=2})$ = 49881.88(76) GHz — R. Pohl *et al.*, Nature 466, 213 (2010)

49881.35(64) GHz — preliminary

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

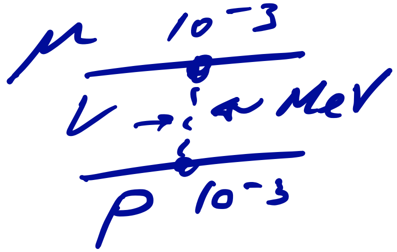
Proton charge radius: $r_{\rm p}$ = 0.84089 $(26)_{\rm exp}$ $(29)_{\rm th}$ = 0.84089 (39) fm (prel.)

$\mu$p theory: A. Antogini *et al.*, arXiv :1208.2637 (atom-ph)

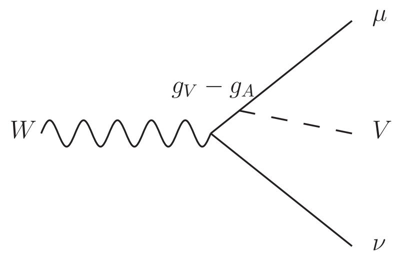



If new physics is responsible for that, it cannot be weak scale, only very light, as $r_p$ will require $\sim 10^4\ G_F$ effects…

# Muon-specific vector forces




$$\mathcal{L}_{\rm int} = -V_\nu \left[\kappa J_\nu^{\rm em} - \bar\psi_\mu (g_V\gamma_\nu + g_A\gamma_\nu\gamma_5)\psi_\mu\right] \\ = -V_\nu \left[e\kappa\bar\psi_p\gamma_\nu\psi_p - e\kappa\bar\psi_e\gamma_\nu\psi_e \\ -\bar\psi_\mu((e\kappa+g_V)\gamma_\nu + g_A\gamma_\nu\gamma_5)\psi_\mu + \ldots\right],$$




The problem with this is that it is not SM gauge invariant – sensitivity at high energy ~ $(\Lambda_{UV}/m_V)^2$. Decay of W is one issue, but there will be lots of trouble with EWP observables, off-shell W-exchange etc. (~ O(1 GeV) mass shifts)

*Putting it in the SM representation is the only model solution.*

$$\mathcal{L} = -\frac{1}{4}V_{\alpha\beta}^2 + |D_\alpha\phi|^2 + \bar\mu_R i \not{D}\mu_R - \frac{\kappa}{2}V_{\alpha\beta}F^{\alpha\beta} - \mathcal{L}_m$$

Implication: a new parity NC-like parity-violating force for muons, that is *stronger than weak.*

# Other possibilities??

$\bar{\mu}\mu\varphi$

$\mu_L \mu_R H \varphi \frac{1}{\Lambda}$

- How about the scalar force – call it *S* – that provides e-p repulsion and fixes $r_p$ discrepancies at least between normal H and $\mu$H (Tucker-Smith, Yavin proposal)?

$$\mathcal{L}_\phi = \frac{1}{2}(\partial_\mu \phi)^2 - \frac{1}{2} m_\phi^2 \phi^2 + (g_p \bar{p} p + g_e \bar{e} e + g_\mu \bar{\mu}\mu)\phi$$

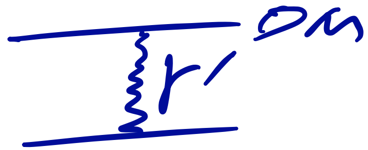
- Couplings will be very small, and the mass will be small, O(200 keV- 1MeV), $y_e y_p / e^2 \sim - 10^{-8}$.
- This turns out to be somewhat of a blind spot in terms of astro and cosmo constraints. *Issues with UV completion, n scattering*
- Izaguirre, Krnjaic, MP: use small *underground accelerators* coupled with large scale detectors such as *Borexino, Super-K* etc… Up to ~ 20 MeV kinematic reach is available due to nuclear binding. Use $^{19}$F+p → $^{16}$O(*) + $^{4}$He reaction

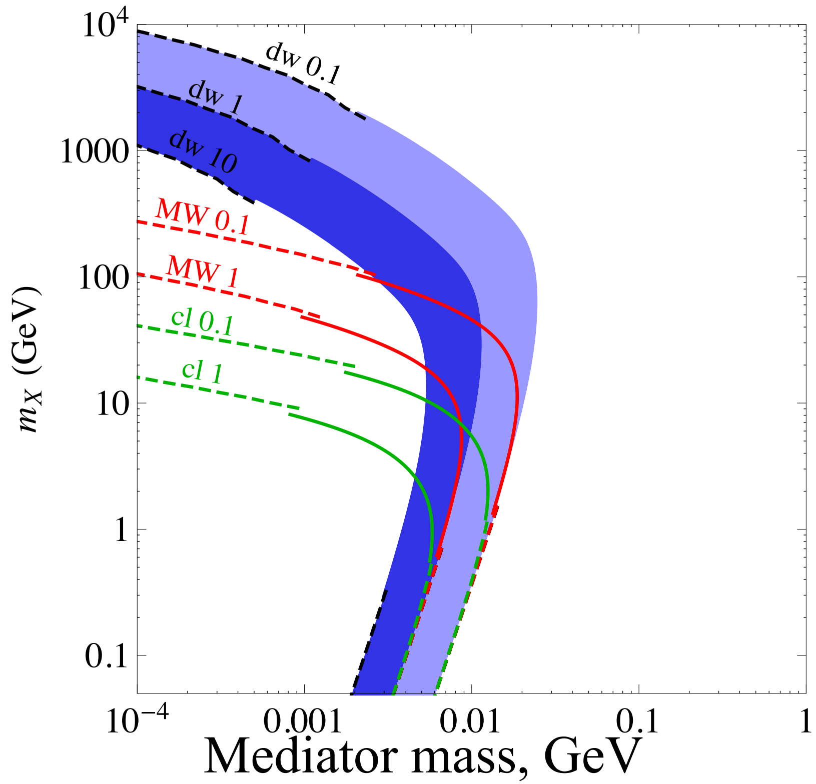
# DM with a hint on self-interaction?

- 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).

$\sim 10^{-24}\,\mathrm{cm}^2/\mathrm{GeV}$

- Self-scattering due to a dark force, at 1 cm²/g level, seems to help, as it flattens out central spikes of DM (which is a reported problem).



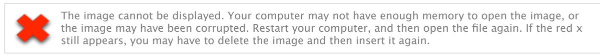



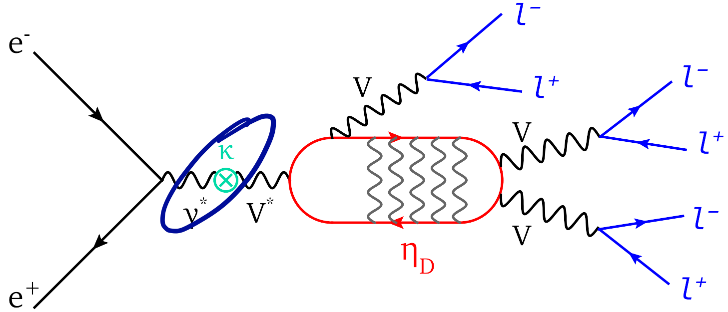

Example of parameter space that creates a core and solves the problem (from Tulin, Yu, Zurek) for $\alpha_d = 0.1$

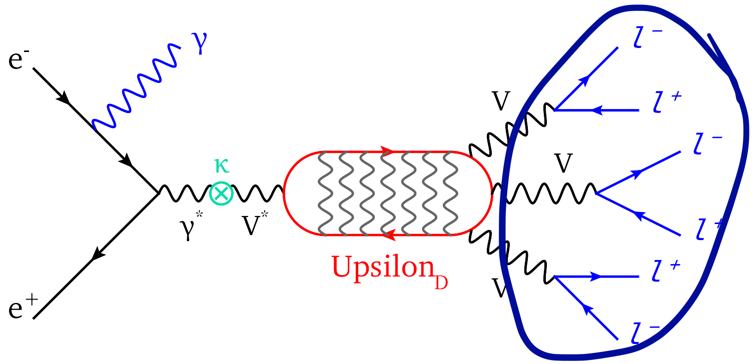
"Discoverable" mass range for the mediators.

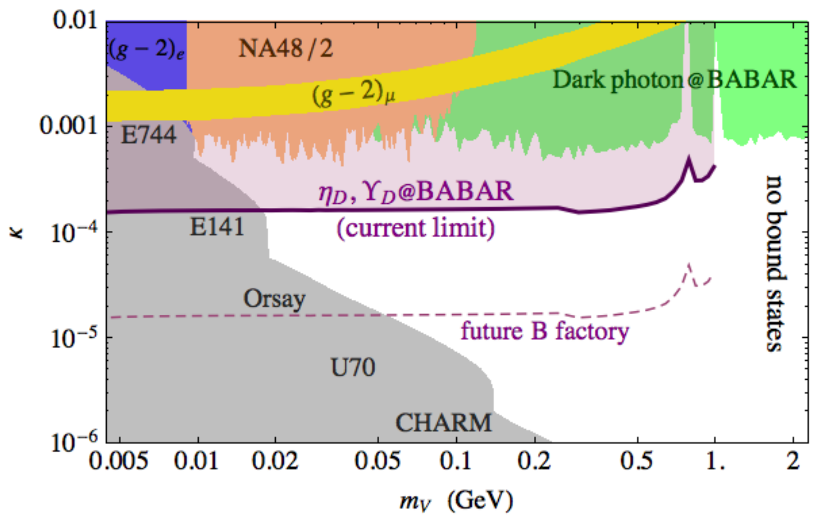
# Dark matter bound states at B-factories

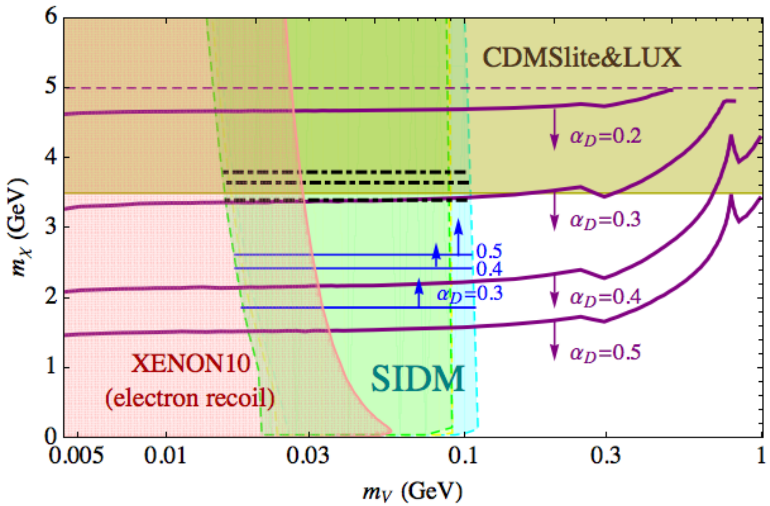
- If $\alpha_d > 0.2$, the sub-5 GeV Dark matter *can increase the sensitivity to dark force* via production of "dark Upsilon" that decays producing multiple charged particles




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

# Conclusions

- Many motivations for dark sectors, but which one describes the observed dark matter is not clear
- Progress in WIMP detection is enormous.
- Light force between Dark matter and SM expands phenomenological possibilities
- Light weakly coupled particles (e.g. mediators of DM interaction) can be responsible for a number of different phenomena and anomalies (starting from muon g-2). Direct searches of such light particles haven't turn up a positive detection yet, but the progress in recent years in sensitivity has been substantial.