# Light and Dark: survey of theoretical ideas for new physics in O(1-100 MeV)

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*New results shown: in collaboration with H. An, B. Batell, P. Deniverville, A. Fradette, D. McKeen, J. Pradler, A. Ritz.*

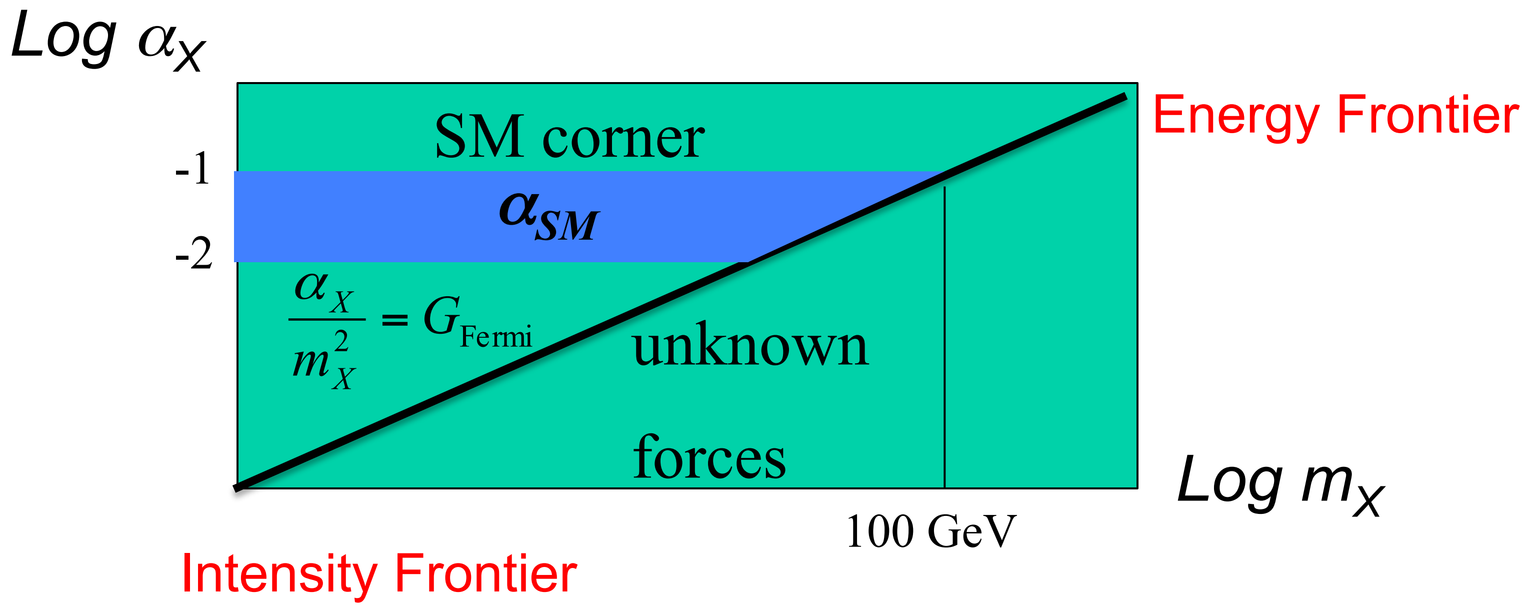
University of Victoria | British Columbia Canada

PERIMETER INSTITUTE FOR THEORETICAL PHYSICS

# Outline of the talk

1. Energy and Intensity Frontiers. Portals to SM.
2. Implications of the LHC results.
3. “Anomalies” and various rationales for dark forces at low energy.
4. Simplest vector portal: secluded U(1) (= dark photon) model. Possible connection to dark matter. Main features and signatures.
5. *Selected new results for dark photons.*
6. Higgs portals: a possibility for light scalars. Leptonic Higgs portal – new interesting search target for low-energy experiments.
7. “Stuckelberg” vector portals: new sources for parity violation at low energy.
8. Conclusions.

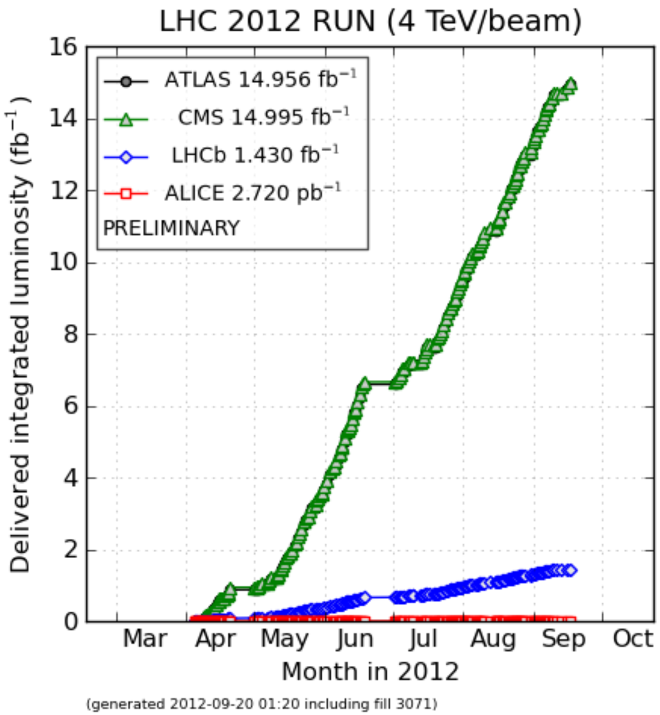
# Intensity and Energy Frontiers

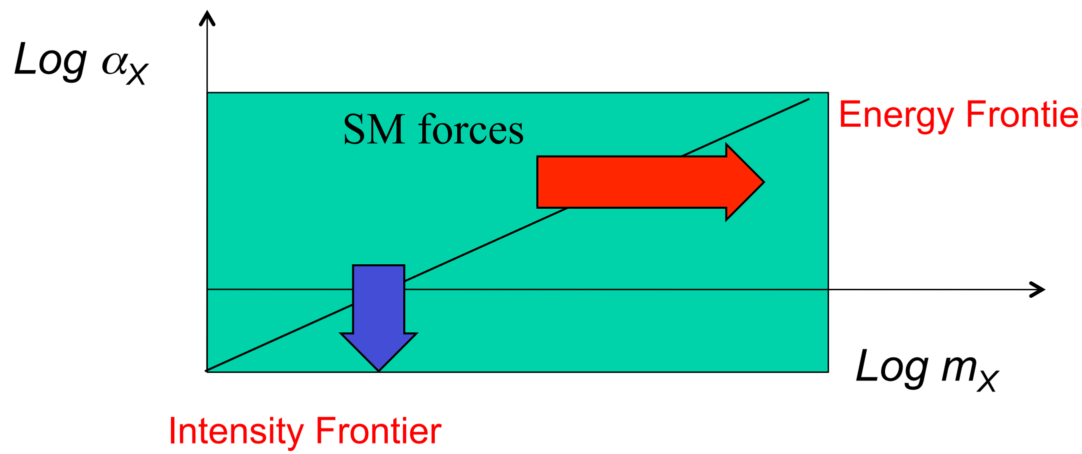



$$V(r) = \frac{\alpha_X}{r}\exp(-r/\lambda_X) = \frac{\alpha_X}{r}\exp(-rm_X) \longrightarrow \text{Amplitude} \approx \frac{\alpha_X}{q^2 + m_X^2}$$

**LHC can realistically pick up New Physics with $\alpha_X \sim \alpha_{SM}$, and $m_X \sim$ 1TeV, while having no success with $\alpha_X < 10^{-6}$, and $m_X \sim$ GeV.**

# LHC – it was worth the wait!
# Higgs [SM-like scalar] particle is discovered




One implication of the LHC at the moment is that [so far] there is no new physics at TeV. [e.g. Moriond 2013: new sequential Z' are limited to **2.9TeV** – you may reconsider some motivations for PNC exp]

Why not GeV scale or below? *Follow the blue arrow!*

# LHC and its implications

1. There is a new, [most likely] scalar resonance with high significance at about ~ 125 GeV that *so far* fits rather wel the **SM Higgs boson** description.
2. Some exotic physics (new strongly-interacting states with advantageous decay channels, new heavy EW boson like resonances etc) is pushed to above 1-3 TeV. Difficult news for many experiments that were motivated to look for ~ 1 TeV Z'. [Now you have to be 10 times more precise to compete – or else *welcome to the dark side*.]
3. No "superpartners" at TeV pushes many theorists rethink naturalness. No naturalness argument = no very strong arguments for TeV NP. **Why not GeV and sub-GeV?**

# Neutral "portals" to the SM

Let us *use* these doors, and attach the Dark Matter to the SM

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

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

$J_{\mu}^{i} A_{\mu}$ Stuckelberg or new U(1) portals.

It is very likely that the observed neutrino masses indicate that Nature may have used the *LHN* portal…

Dim>4

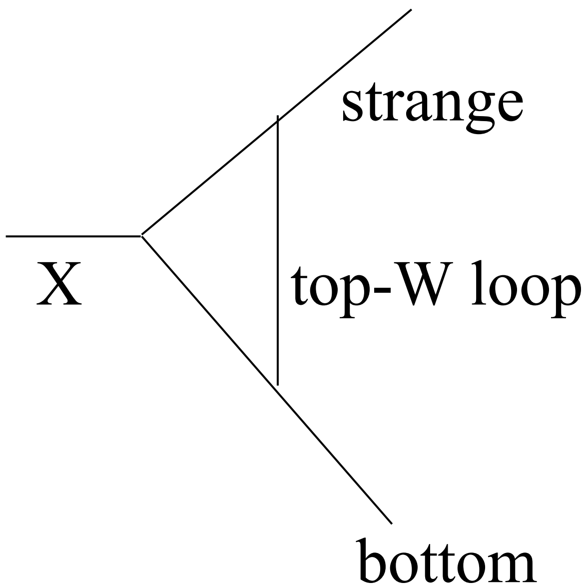
$J_{\mu}^{A}\ \partial a_{\mu} / f$ axionic portal

……….

$$\mathcal{L}_{\mathrm{mediator-SM}} = \sum_{k,l,n}^{k+l=n+4} \frac{O^{(k)}_{\mathrm{med}} O^{(l)}_{\mathrm{SM}}}{\Lambda^n}; \quad \mathcal{L}_{\mathrm{mediator-DM}} = \sum_{k,l,n}^{k+l=n+4} \frac{O^{(k)}_{\mathrm{med}} O^{(l)}_{\mathrm{DM}}}{\Lambda^n}$$

# Some portals are better searched with flavor physics rather than directly

Conserved vector currents are uniquely positioned to avoid very strong flavor constraints. Axial vector portals, Higgs portals are potentially liable to very strong flavor constraints. Consider generic FCNC penguin-type loop correction.

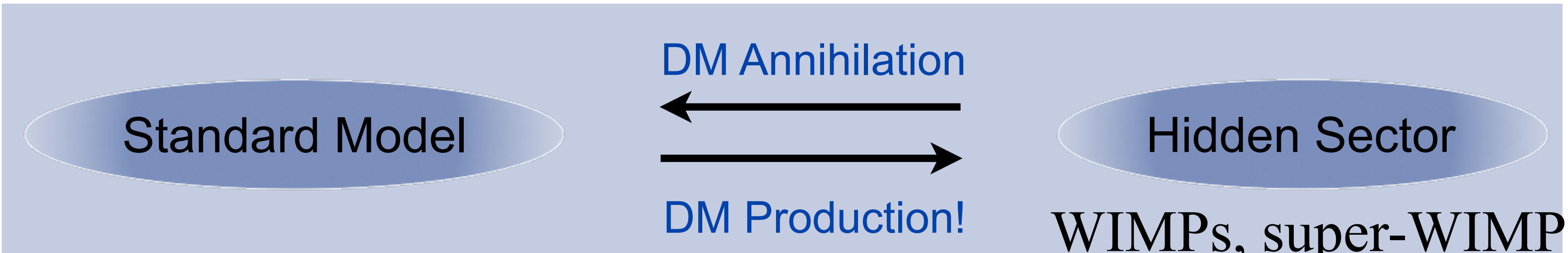



**For a conserved vector current, $G_F\ q^2$**

**For axial vector current, $G_F\ m_t^2$**

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

# Possible connection to WIMP-y dark matter




WIMPs, super-WIMPs

**Mediators (SM Z, h etc or dark force)**

**Heavy WIMP/heavy mediators:** - "mainstream" literature

**Light WIMPs/light mediators:** Boehm et al; Fayet; MP, Ritz, Voloshin; Hooper, Zurek; others

**Heavy WIMPs/light mediators:** Finkbeiner, Weiner; Pospelov, Ritz, Voloshin (secluded DM); Arkani-Hamed et al., many others

**Light WIMPs/heavy mediators:** does not work. (Except for super-WIMPs; or non-standard thermal history)

# Simplest example of a mediator sector

(Holdom 1986; earlier paper by Okun')

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

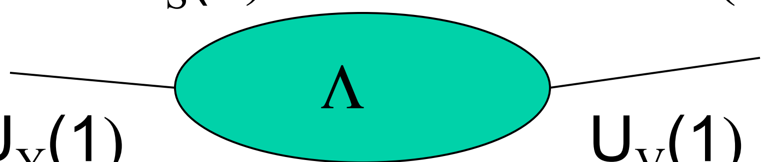
This Lagrangian describes an extra U(1)' group (**dark force, hidden photon, secluded gauge boson, shadow boson etc, also known as U-boson, V-boson, A-prime, gamma-prime etc**), attached to the SM via a hypercharge vector portal (kinetic mixing). Mixing angle κ (also known as ε, η) controls the coupling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

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

*Well over 100 theory papers have been written with the use of this model in some form in the last four years.*

# 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 $\Lambda$ (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 $\kappa$ having only the log dependence on scale,

$\kappa \sim (\alpha\alpha')^{1/2} (3\pi)^{-1} \log(\Lambda_{UV}/\Lambda) \sim 10^{-3}$

$M_V \sim e'\kappa M_{EW}$ ($M_Z$ or TeV) ~ MeV – GeV

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

# Some specific motivations for new states/new forces below GeV

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

# Astrophysical motivations: 511 keV line

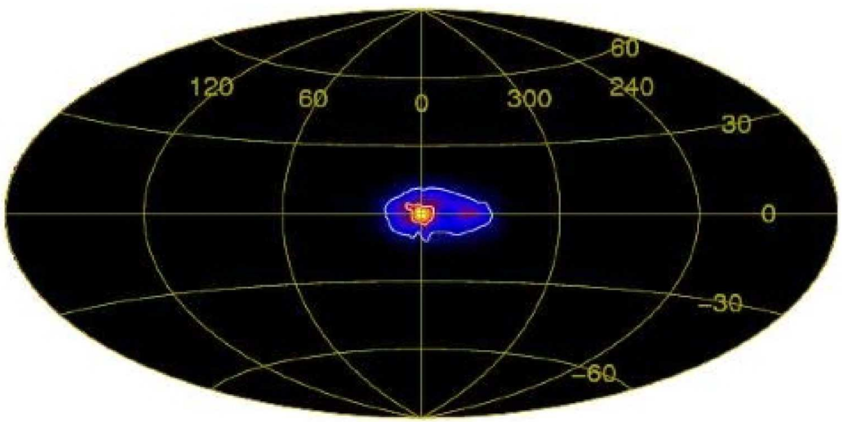



FIG. 4 511 keV line map derived from 5 years of INTEGRAL/SPI data (from Weidenspointner *et al.*, 2008a).

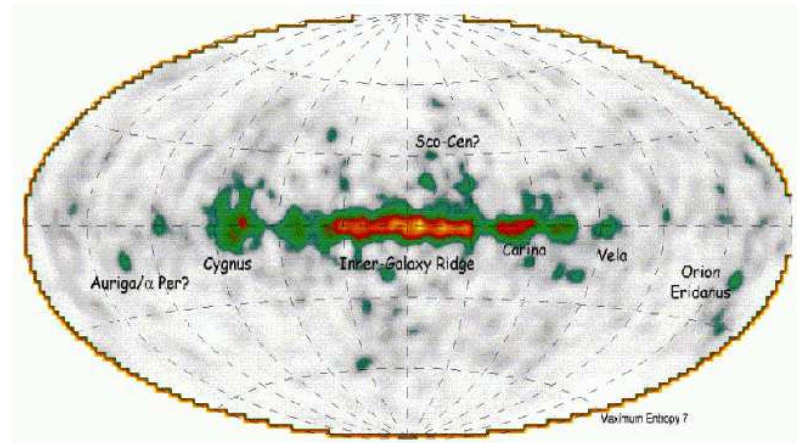
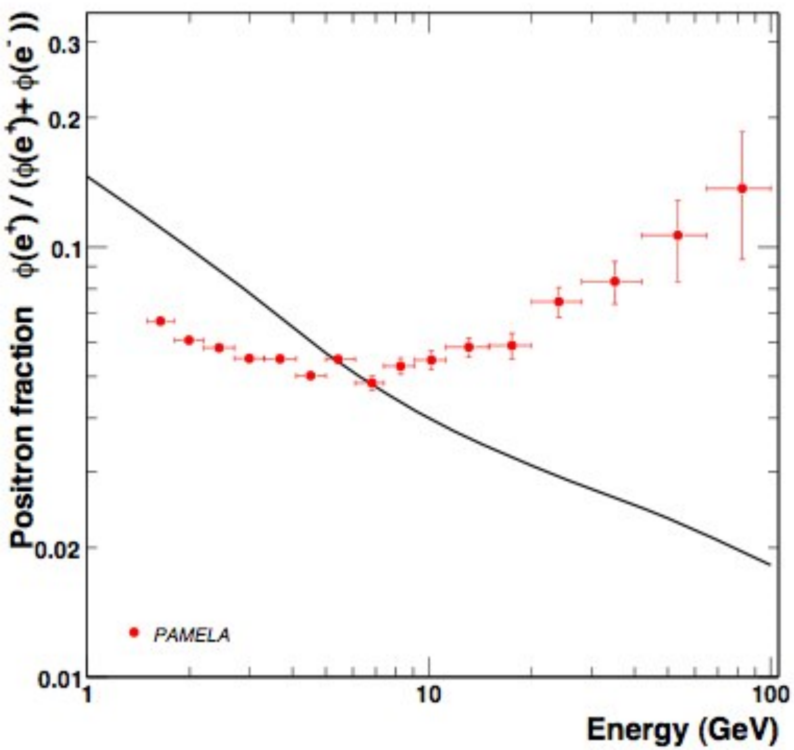


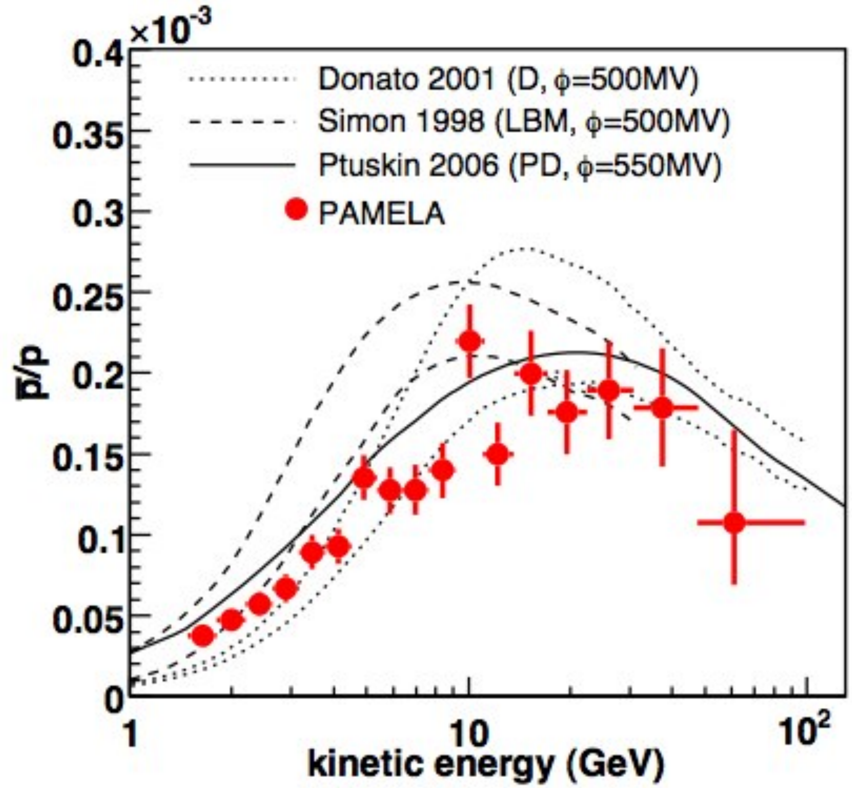

FIG. 7 Map of Galactic $^{26}$Al $\gamma$-ray emission after 9-year observations with COMPTEL/CGRO (from Plüschke *et al.*, 2001).

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?

# PAMELA positron fraction




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

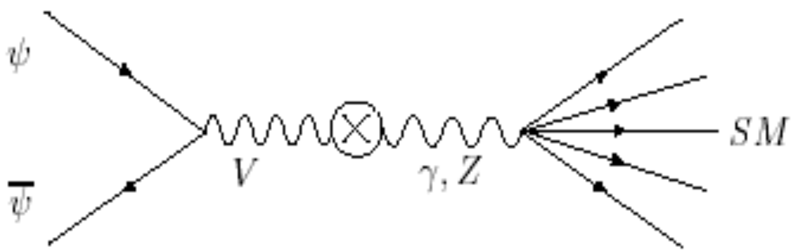
This is a "boost" factor of 100-1000 "needed" for the WIMP interpretation of PAMELA signal. E.g. SUSY neutralinos would not work, because $<\sigma v>$ is too small. Enhancing it "by hand" does not work because WIMP abundance goes down. Dark forces allow bridging this gap due to the late time enhancement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

# Secluded WIMP idea – heavy WIMPs, light mediators

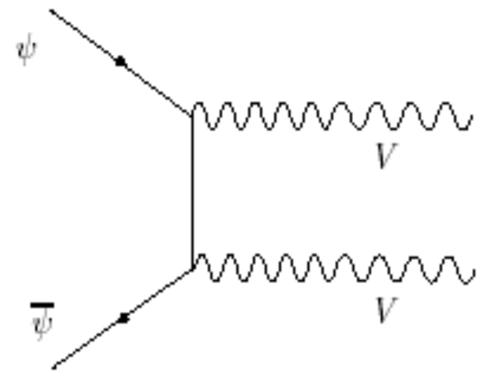
$$\mathcal{L}_{\rm WIMP+mediator} = -\frac{1}{4}V_{\mu\nu}^2 - \frac{\kappa}{2}V_{\mu\nu}B_{\mu\nu} - |D_\mu\phi|^2 - U(\phi\phi^*) + \bar{\psi}(iD_\mu\gamma_\mu - m_\psi)\psi.$$

$\psi$ – weak scale Dark Matter; $V$ –mediator particle.

$m_{mediator} > m_{WIMP}$




$m_{mediator} < m_{WIMP}$

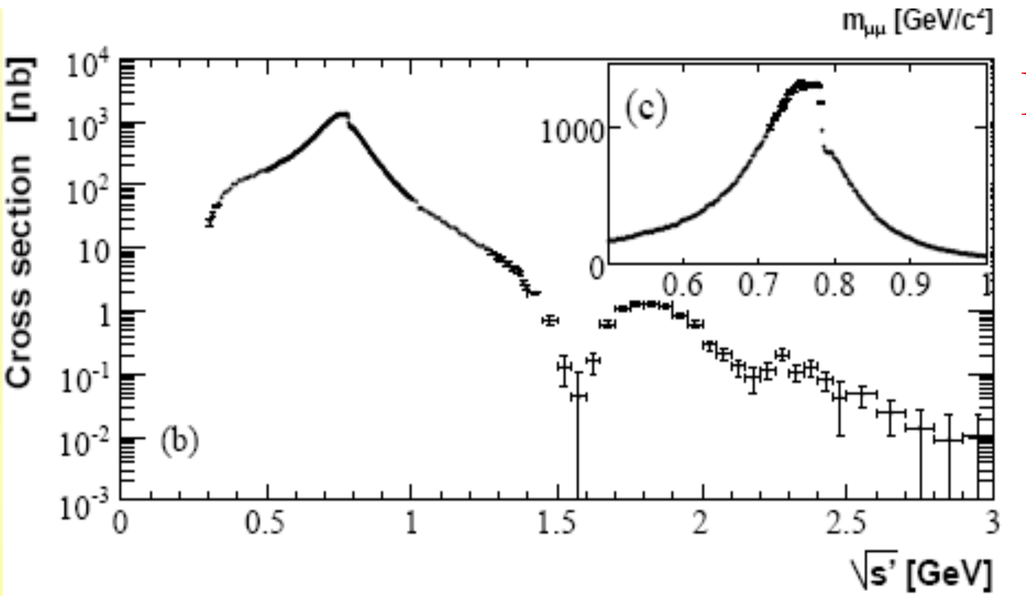



Second regime of annihilation into on-shell mediators (called *secluded*) does not have any restrictions on the size of mixing angle κ.

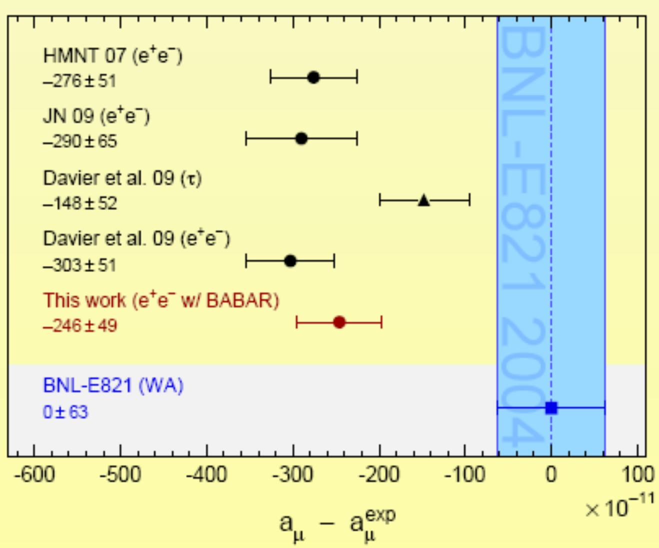
It turns out *this helps* to tie PAMELA positron rise and WIMP idea together. Since 08 this explanation is challenged by the new FERMI-LAT limits. *And of course everyone awaits AMS-2 results*.

# g-2 of muon

## BaBar contribution to the “hadronic piece” of VP diagram




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.



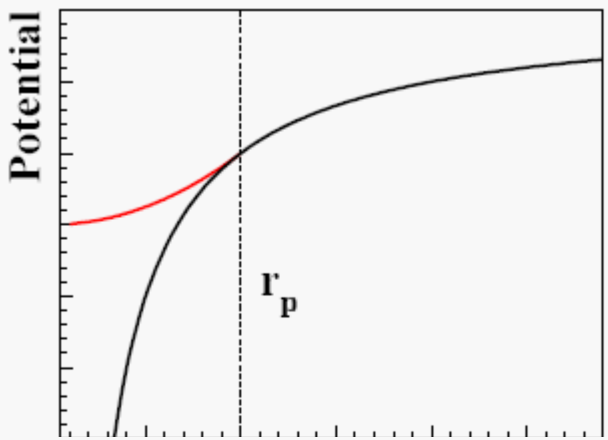

✱ Davier et al. arXiv:0906-5443

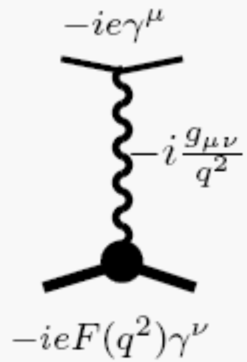
Supersymmetric models with large-ish *tanβ*; light-ish sleptons, and right sign of μ parameter can account for the discrepancy.

Sub-GeV scale vectors can also be at play.

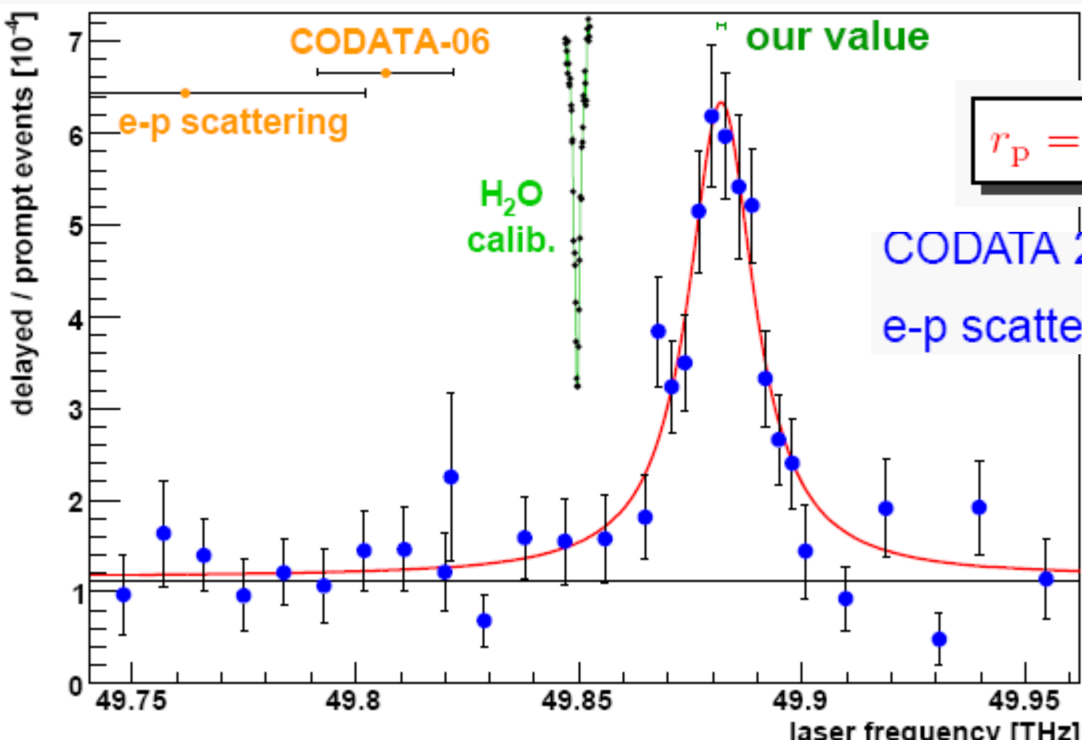
# Muonic hydrogen Lamb shift

so different from what was expected! New force for muons?




Contribution of $r_p$ is much larger in $^1$H because the muon is 200 times closer to the nucleus.




$r_p = 0.84184(67)$ fm $\quad u_r^{th} = 8 \times 10^{-4}$

CODATA 2006: $r_p = (0.8768 \pm 0.0069)$ fm, from H

e-p scattering: $r_p = (0.895 \pm 0.018)$ fm (2%)

Now more precise due to Mainz, JLab

# Other interesting anomalies where new light particles may play some role

- Hyper-CP anomaly: close clustering of [all] 3 muon events around 214 MeV in $\Sigma \rightarrow p\mu\mu$
- Light mediators might be required if indeed DAMA, CoGeNT and CRESST "signals" are a consequence of ~10 GeV WIMP.
- Tension in $\pi^0 \rightarrow ee$ between theory and observations. Light "axial vector" force

*However suggestive of a "new force" different experimental and observational anomalies may look like, no conclusive proof of the existence of dark force may ever come from indirect astrophysical signatures.* ***Connection to DM may be a wishful thinking...***

- Only reproducible terrestrial experiments might convince anyone in the existence of dark forces.

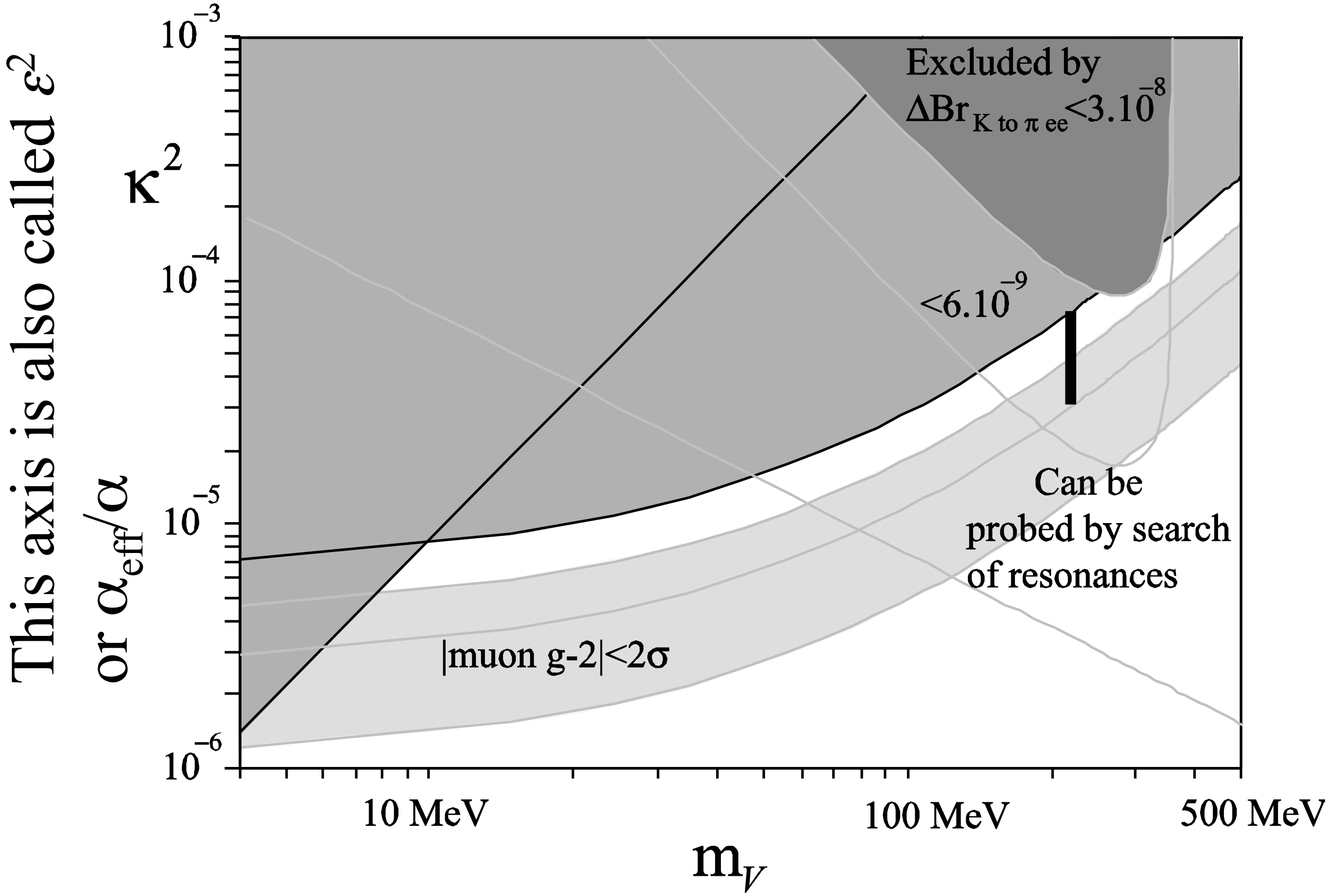
- We come back to the "intensity frontier" picture. ***Huge luminosities are required.***

# Signatures of DP: 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, and many new limits have been obtained.

# Most important aspects of hidden U(1) phenomenology

1. *Whether or not there are new light states* (other than SM) charged under U(1):

$U_{Fayet}$ → light DM; V(A')-boson → SM charged particles.

It has serious consequences for signatures. ($U_F$ has lots of missing E)

2. *Possibility of long-lived states*. Vectors are long-lived if mixing angles are small $\kappa \lesssim 10^{-7} - 10^{-6}$. Higgs' particles are very long-lived even if the mixing angles are sizable, provided that

   $\kappa \sim 10^{-4} - 10^{-2}$ and $m_V > m_{h'}$

3. *Possibility of increased lepton multiplicities at no cost* (e.g. in the decay chain of Higgs')

4. *New vector states couple to the SM via a conserved current* (EM current). No $(m_t/m_K)^2$ enhancement of FCNC as it would have been for (pseudo)scalar or axial-vector portals. Moderate flavor constraints

# Particle physics signatures of V and $U_F$

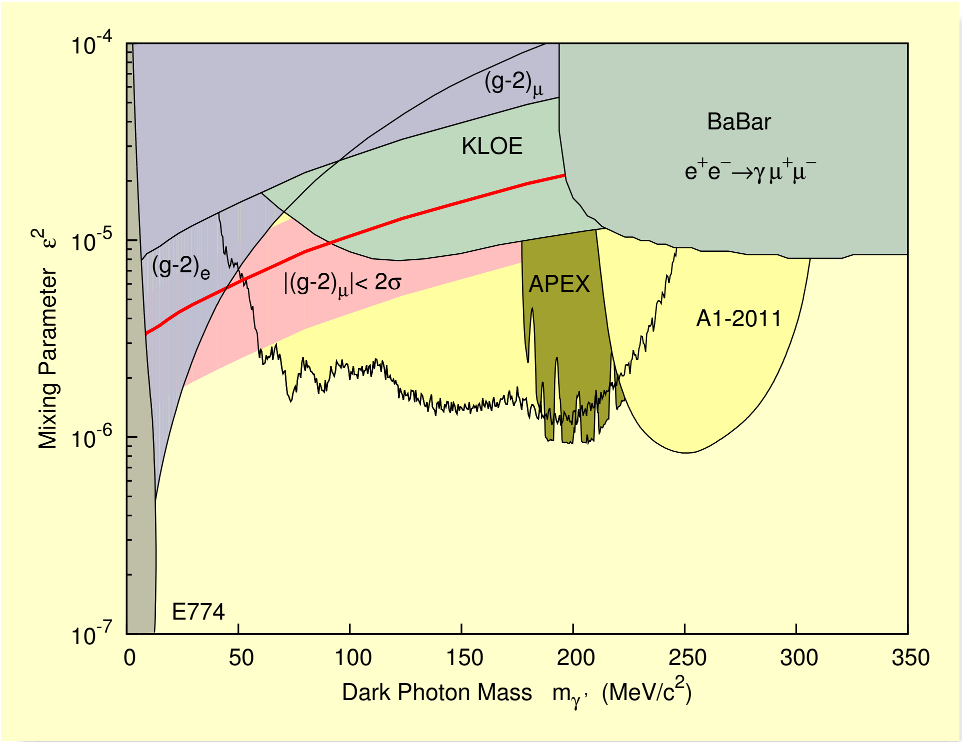
1. Production in association with $\gamma$, $ee^+ \to V\gamma \to \mu\mu^+\gamma$ (Search for a peak in $\mu$-spectrum: BaBar, Belle, KLOE). $\kappa \sim 10^{-3}$ is reachable. Limiting $U_F$ is more difficult.
2. Meson decays: $\pi^0$, $\eta$, $\eta'$, $\omega$, $\phi$ …$\to V\gamma \to \gamma\, ll^+$. (KLOE,BESSIII,WASA-COSY…) $K \to \pi V \to \pi ll^+$ or $\pi$+missing E (more sensitivity to $U_F$). NA62…
3. Dark higgs-strahlung (BaBar, Belle, KLOE) = multileptons or missing energy. (Generic signature if U(1) is not "Stuckelberg"). Probing as low as $\kappa \sim 10^{-4}$ is possible.
4. e-on-target. "Bump hunt": e + Z $\to$ Z + V $\to$ $Zll^+$. (APEX, Mainz, HPS, DarkLight…) $U_F$ is difficult.
5. p-on-target. Search for longish-lived mediators. Search for $U_F$ to light DM (new dedicated proposal of MiniBooNE+theorists, submitted to PAC, Fermilab).

*We are going to hear about some new results at this meeting.*

# *Huge progress in the last few yrs (Jlab, Mainz, BaBar, KLOE )*

Extended mass range (data taking 2012, preliminary)

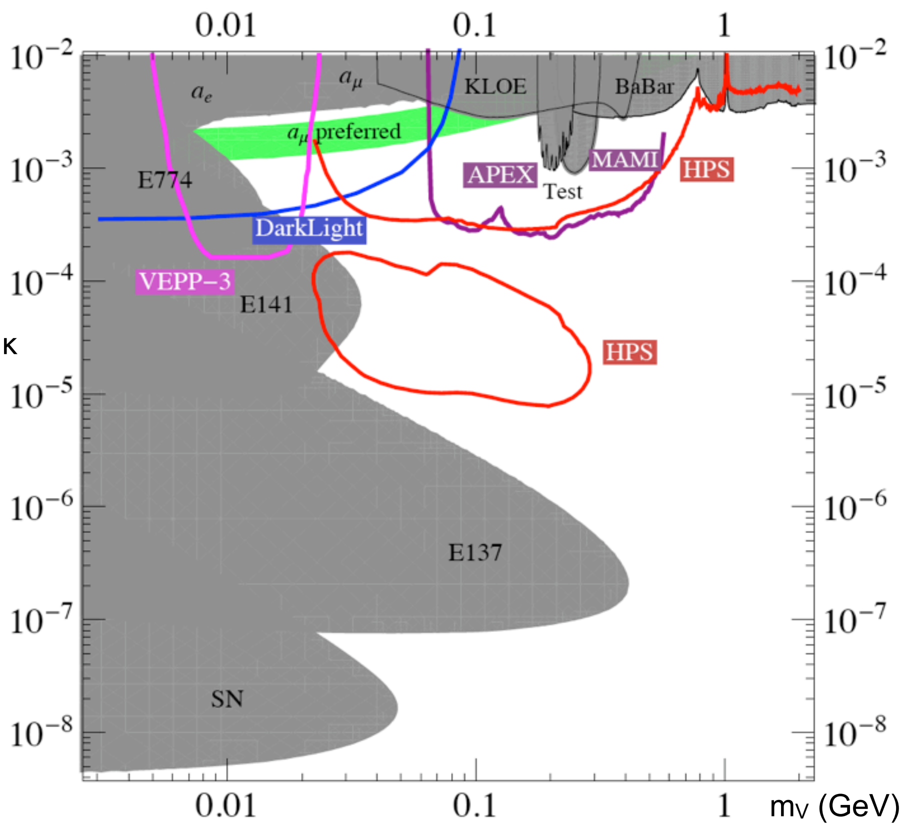
- Extension to lower mass region
- Several beam energy settings
- Lower mass limit: minimum angle between spectrometers




Almost all g-2 band is covered now – but there is an island left at ~30 MeV. Relevant region for the proposals discussed in this meeting.

H. Merkel et al (Mainz), Dark2012, also this meeting

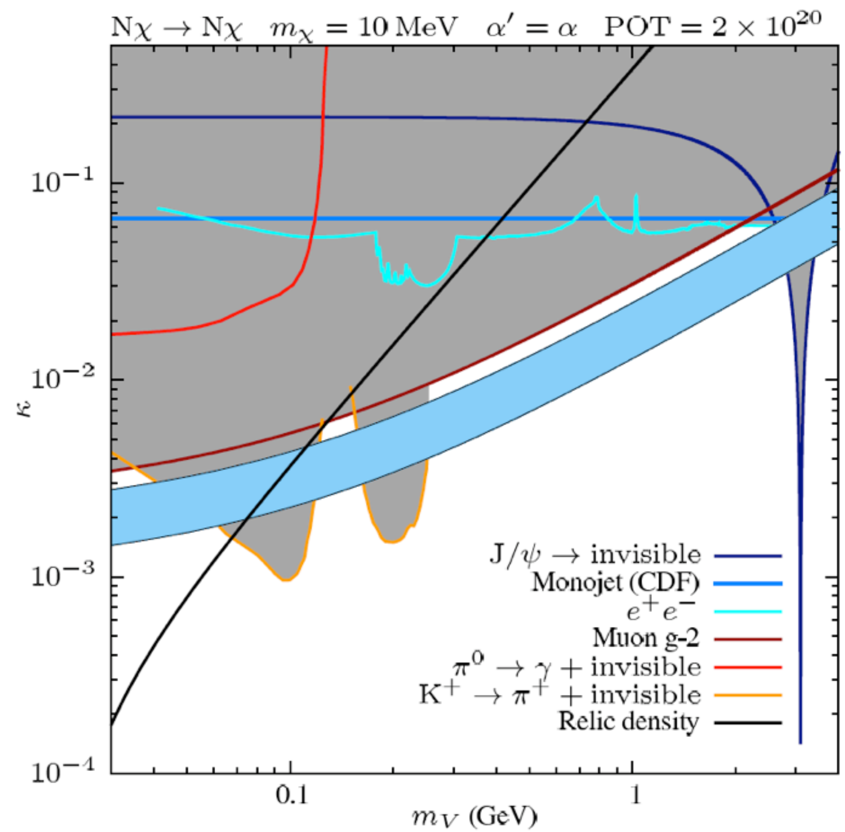
## No invisible channels




$m_V < 2m_\chi$

[Intensity Frontier Worskhop, Hewett, Weerts et al '12]

## Invisible decay dominates

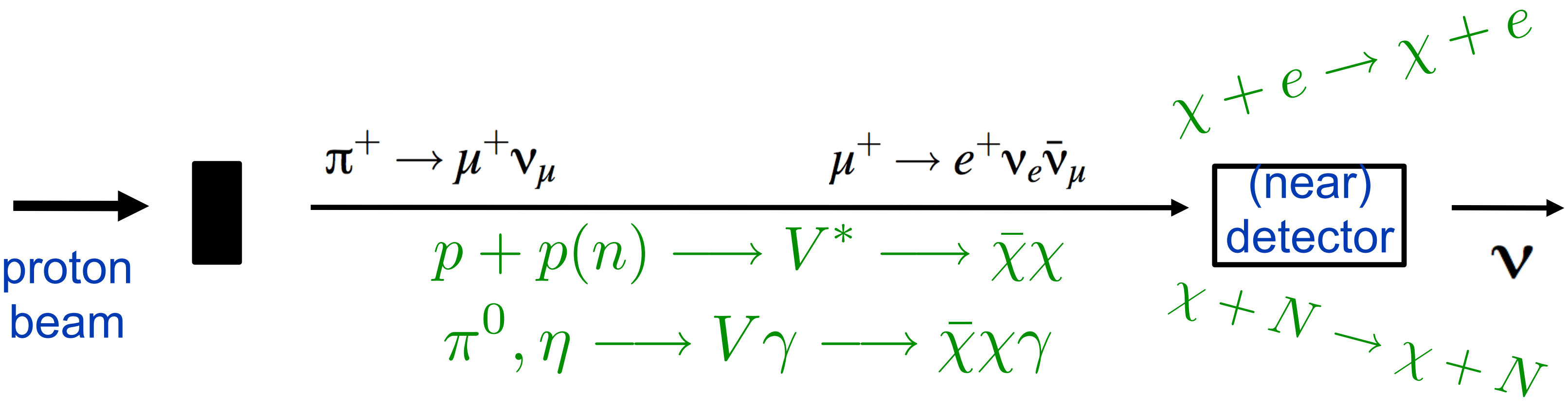



$m_V > 2m_\chi$

Some limits removed due to short V-lifetime, while others weakened by $Br(V \to 2l) \sim \alpha\kappa^2/\alpha'$

# Fixed target probes - Neutrino Beams

Proposed in Batell, MP, Ritz, 2009. Strongest constraints on $U_F$

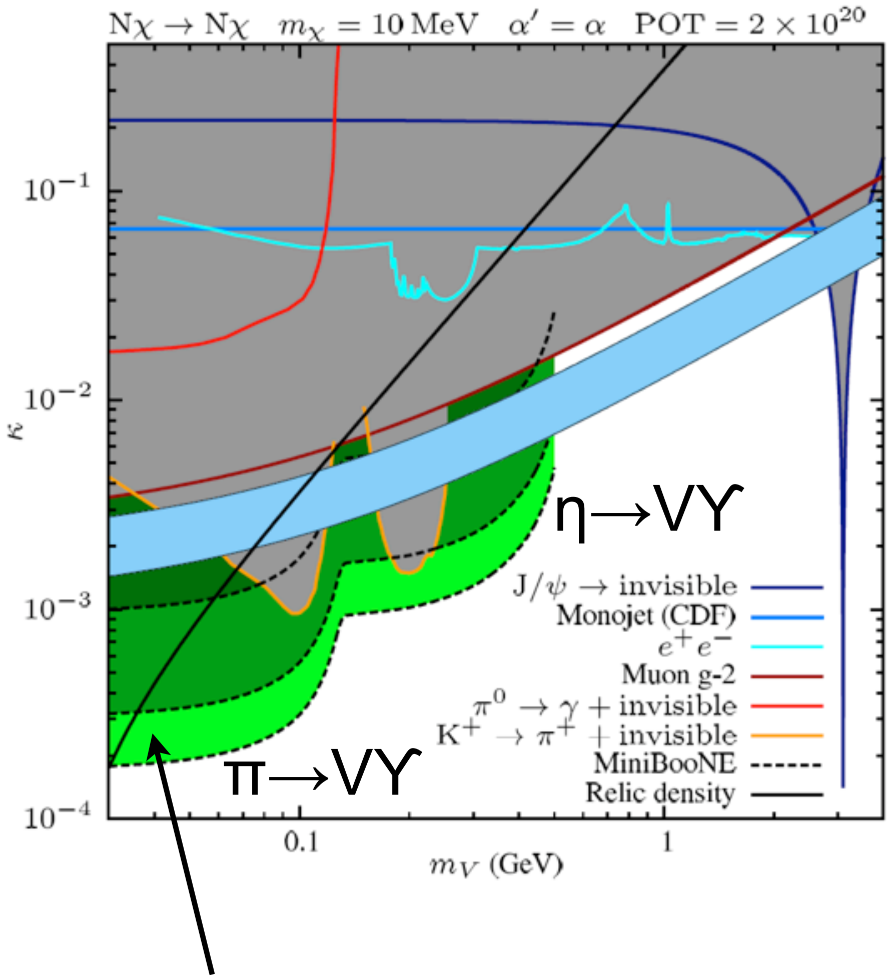



We can use the neutrino (near) detector as a dark matter detector, looking for recoil, but now from a relativistic beam. E.g.

| 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 |

Batell, deNiverville, McKeen, Pospelov, Ritz, + MiniBooNE col

# MiniBooNE sensitivity




10, $10^3$, $10^6$ events

*Dark Light* can also be sensitive to invisible final states, Kahn, Thaler

# Very [very] dark photons

**The Universe itself is an *active detector***! Unlike astrophysics which presents challenging backgrounds, pre-galactic cosmology is relatively *simple*, and thanks to recent advances, allows for precision tests.

Take a dark photon with $M_V \sim$ MeV, $\kappa \sim 10^{-18}$, or $\boldsymbol{\alpha_{eff} = 10^{-38}}$. Cross section for producing such a particle is $\sigma \sim 10^{-65}$ cm$^2$ or so.

Even a "Project XXX" would not help… Yet we have evidence of $T \sim$ MeV (through BBN) in the early Universe.

MeV scale particles are produced, $ee \rightarrow V$, and then decay much later affecting the outcome of the BBN and/or ionization history for the CMB.

$$Y_{V,f} = 2.3 \times 10^{-3} \times \frac{\Gamma_V}{1\ \text{Hz}} \times \left(\frac{10\ \text{MeV}}{m_V}\right)^2$$

vectors per entropy ($\gamma,\nu$) is produced.

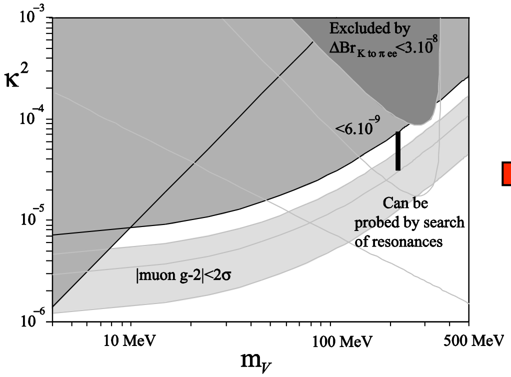
*Late decay produce*

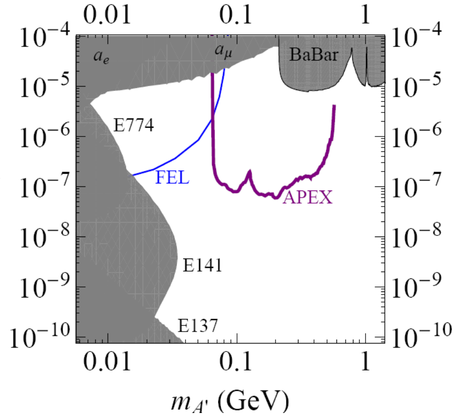
$$E_{\text{p.b.}} = 2.6\ \text{eV} \times \frac{\Gamma_V}{10^{-14}\ \text{Hz}} \times \frac{10\ \text{MeV}}{m_V}$$

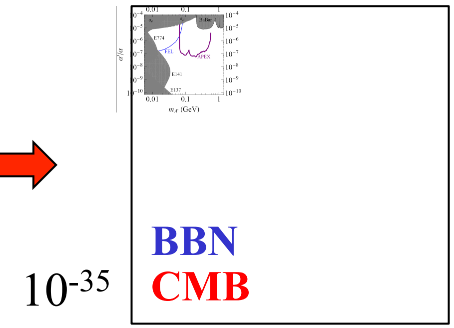
*per baryon. $\Delta X_e \sim$ up to 0.1. Huge! ← strong constraints from CMB*

Fradette, MP, Pradler, Ritz, *work in progress.*

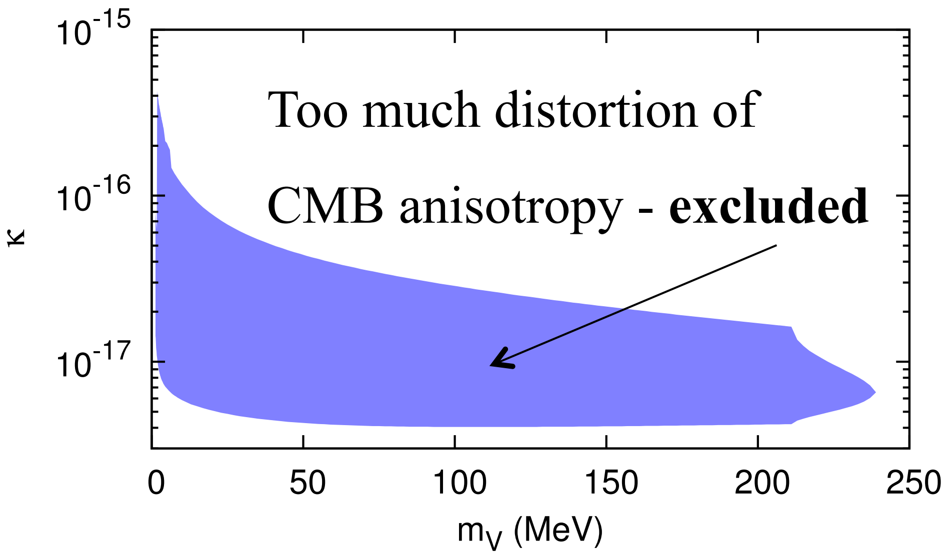
# Effect on BBN and CMB




*New results (Fradette et al.)*



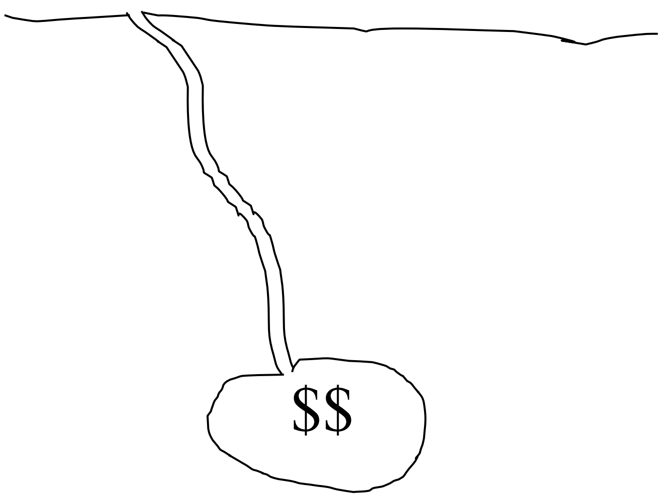

BBN is affected for $\kappa \sim 10^{-12}$

In some fraction of the parameter space the only effect is the reduction of $^7$Li/H (which you can argue is a good thing). Earlier discussions can be found in published works of Postma, Redondo; Pospelov, Pradler

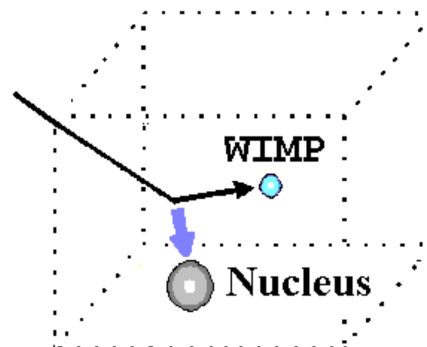
Planck data are coming in soon!

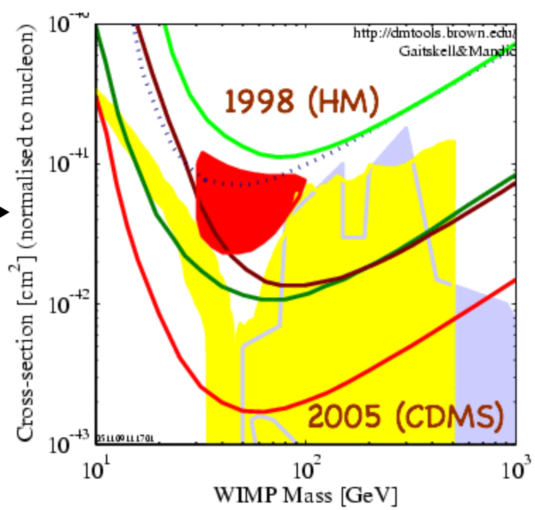
# DM experiments are the best Dark Photon helioscopes

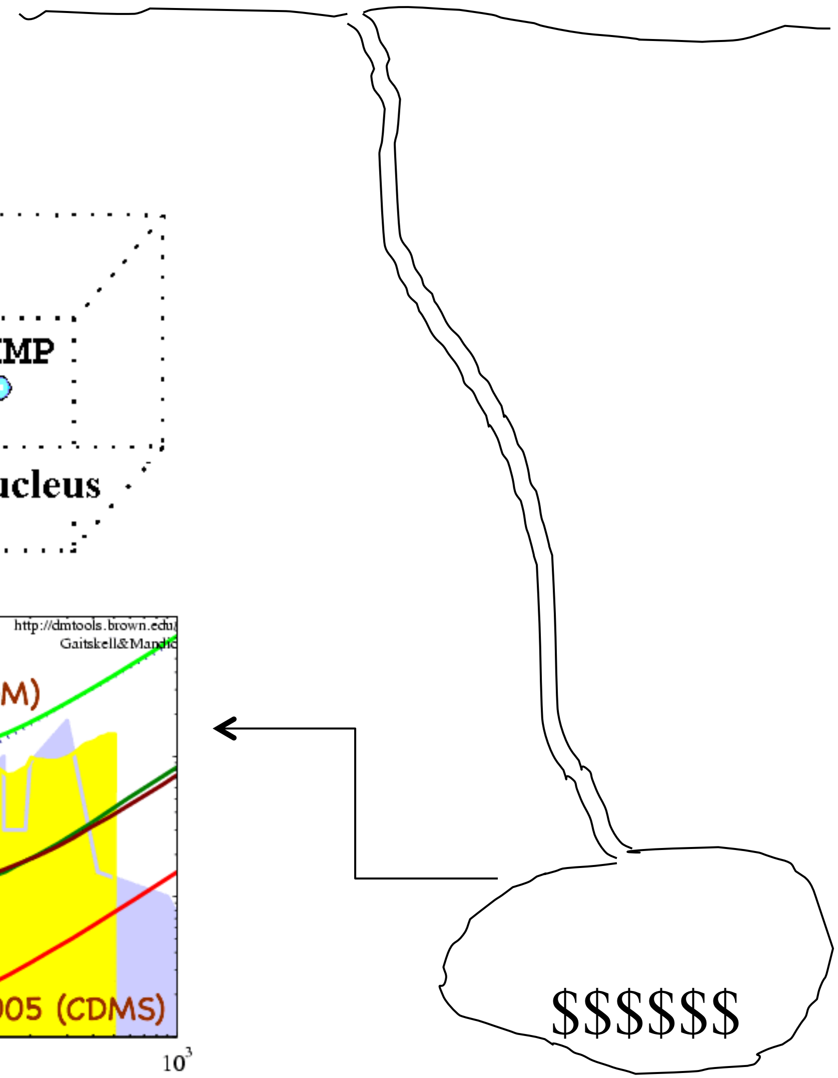
An average Dark Matter detection experiment




A more expensive DM experiment



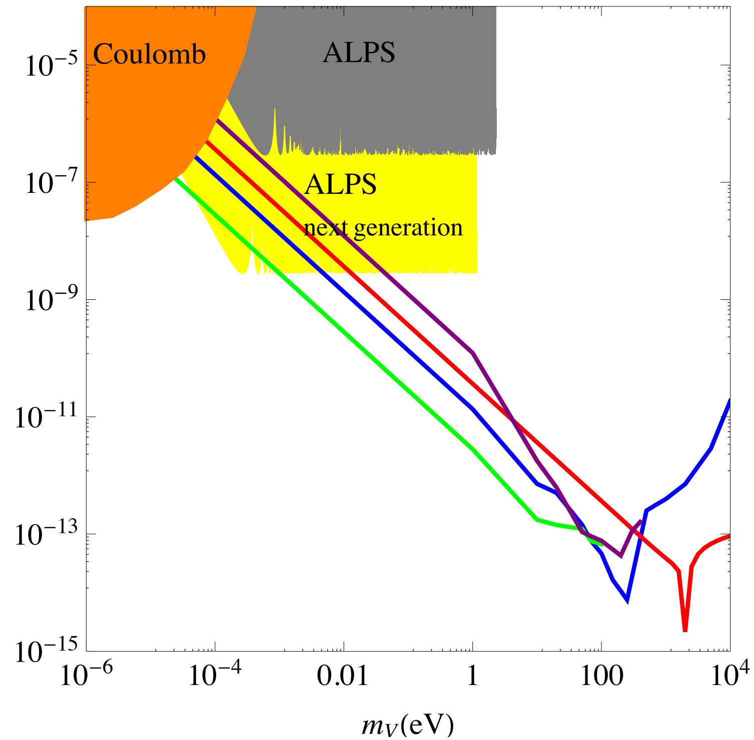




Currently all "direct DM detection" experiments search for the same thing
*Diversifying physics output of direct detection exp's is needed*

# New constraint on "Solar Dark Photons"

H. An, J. Pradler, MP, Feb 2013. We have derived correct stellar constraints on dark photons is sub-keV regime. Showed (paper in preparation) that Xenon10 (ionization only) provides the strongest probe ever of dark photons in the mV ~ $10^{-5}$ – 1 keV range.




At $m_V \sim 10^{-3}$ eV the existing constraints (signal ~ $(\text{kappa})^4$) are improved by ~ 10 orders of magnitude.

# New physics via Higgs portals

Recent discovery of the Higgs[-sure like] particle gives new legitimacy to the Higgs portals. Simplest *super-renormalizable* SM portal:

$$\mathcal{L}_{\text{s.r. Higgs portal}} = ASH^\dagger H$$

2HDM portals:

$$\mathcal{L}_{\text{s.r. 2HDM portal}} = A_1 SH_1^\dagger H_1 + A_2 H_2^\dagger H_2 + (A_{12} SH_1^\dagger H_2 + h.c.)$$

$A_i$ parameters are ~ mass1 – this is why they are unique. A chance to maintain naturalness for [reasonably] light S. Flavor constraints such as B→K ll (Batell, MP, Ritz; Freytsis, Ligeti,Thaler, 2009) are usually prohibitive e.g. for any additional non-flavor tests at ~ few 100 MeV.

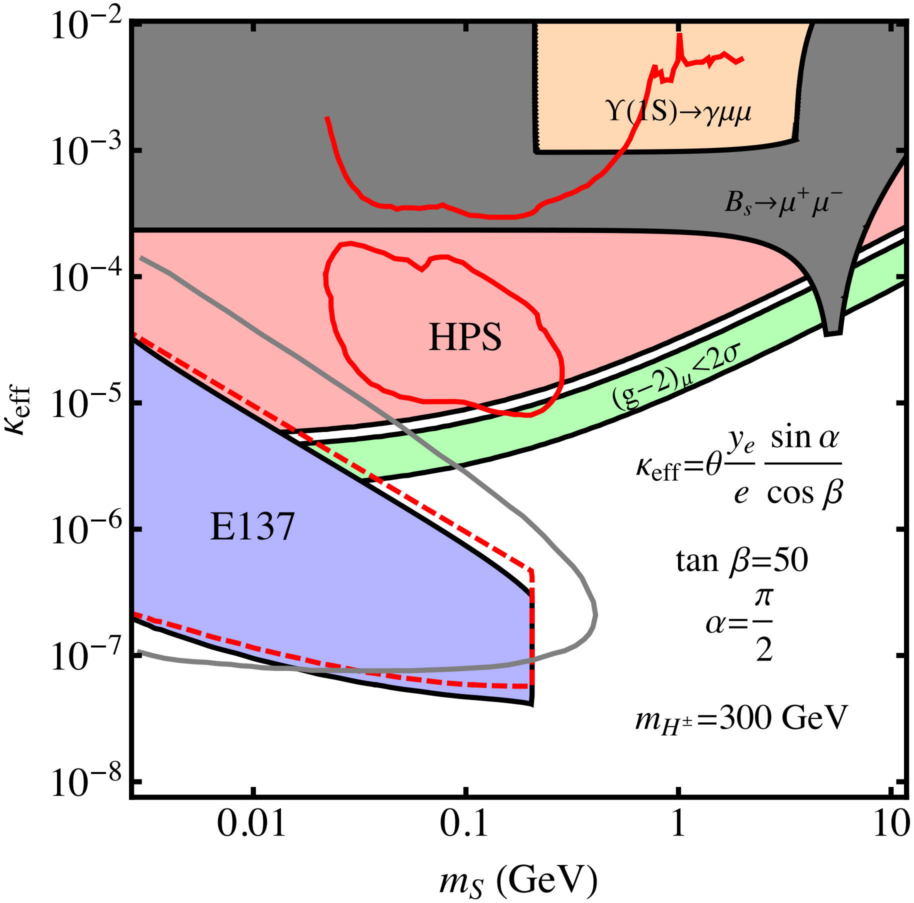
*Exception* is the Leptonic Higgs portal. $H_1$ gives masses to leptons, $H_2$ to quarks and weak bosons, and $\langle H_1 \rangle / \langle H_2 \rangle \ll 1$ . $S$ mixes mostly with leptonic Higgs. This model minimizes flavor constraints and opens some interesting possibilities for $S$ at low energies,

$$\mathcal{L}_{\text{eff}} = \theta \tan\beta \; S(Y_e^{\text{SM}} \bar{e}e + Y_\mu^{\text{SM}} \bar{\mu}\mu + Y_\tau^{\text{SM}} \bar{\tau}\tau)$$

Unlike Dark Photon model, couplings to leptons are not universal.

# Signatures of leptonic Higgs portal

Batell, McKeen, MP, Ritz, work in progress




*A new light scalar boson with couplings to leptons ~ $m_{lepton}$ .*

Calling scalar coupling to electrons

$Y_e = e\,\kappa_{eff}$, we recast existing constraints, and of course the "g-2" band is shifted down because of the enhancement of muon coupling by $m_\mu/m_e$.

**A new interesting signature**: $e^+e^- \to \tau\tau\, h_l \to 2\tau 2\mu$ *This is not unlike multilepton signatures from Dark Force searches (now with miss E)*

# Motivation for extra P-odd effects mediated by light particles

Batell, McKeen, MP, New "muonic" vector forces – if entertained as the origin of the muonic hydrogen Lamb shift discrepancy – almost invariably requires new large sources of parity violation for muons.

1. Try to imbed this within SM – particles (muons, electrons etc) come in chiral representations and left-handed is paired with neutrinos.
2. "r_p" discrepancy requires new force $\sim 10^4 G_F$, for muon neutrinos interactions are known at least at $10^{-1} G_F$. You cannot involve LH muon (without breaking the SM gauge group).
3. You can still have large effect via interaction of RH muon,

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

4. Two-loop effects will transfer muonic parity violation to the electron sector.

# Stuckelberg portals

New vector forces beyond "dark photon"?

$$\mathcal{L}_{\text{Stuckelberg portal}} = V^\mu \overline{Q}\gamma_\mu G_Q Q + V^\mu \overline{D}\gamma_\mu G_D D + V^\mu \overline{U}\gamma_\mu G_U U + V^\mu \overline{L}\gamma_\mu G_L L + V^\mu \overline{E}\gamma_\mu G_E E$$

New couplings that can have MFV representation,

$G_i = g_i \mathbf{1} + g_i'$ Yukawa$^2$ +…

Because the of the chiral nature of SM fields, Q = $(1-\gamma_5)/2$Q, etc, the parity will be broken as long as e.g. $g_L \neq g_E$. [Possible anomalous triangles will give sensitivity of $m_V$ to the UV cutoff. This sensitivity is pushed to 3 loops – ok, if we keep the cutoff around TeV and mass of m_V in the 1 MeV – 100 MeV window. ]

This type of parity violation (similar to Davoudiasl, Marciano, Lee model) can be probed in parity experiments (but not at LHC). Flavor signatures discussed in Kamenik, Smith.

# Conclusions

- Search for new physics at the intensity frontier is not driven *only* by the desire to learn about the TeV scale. New Physics in the 1-100 MeV window, with $O(10^{-3})$ couplings is a legitimate search target. If possible dark matter related speculations are met with skepticism, the $g\text{-}2_{\mu}$ – anomaly in the anomaly – still motivates to look for new particles and their unusual interactions at low energies.
- A lot of progress, both in theory and experiment, is achieved already, in limiting light Dark Forces. Many exciting physics searches to do still.
- New facilities – such as those discussed at this meeting – will help explore (i.e. constrain/discover) sub-100 MeV mass range, and unusual decay signatures.