Dark Forces and New Physics at the Intensity Frontier

Maxim Pospelov

University of Victoria, Victoria/Perimeter Institute, Waterloo

Theory collaborators: B. Batell, P. Deniverville, D. McKeen, J. Pradler, A. Ritz, M. Voloshin.

University of Victoria | British Columbia Canada

PERIMETER INSTITUTE FOR THEORETICAL PHYSICS

Outline of the talk

1. Energy and Intensity Frontiers. Portals to SM.
2. *In case you did not notice*: implications of the LHC results.
3. "Anomalies" and various rationales for dark forces at low energy. Secluded U(1) (= dark photon) model. Possible connection to dark matter. Main features and signatures.
4. *New results/ideas for secluded sectors:*

    4a. p-on-target and MiniBooNE + friends proposal

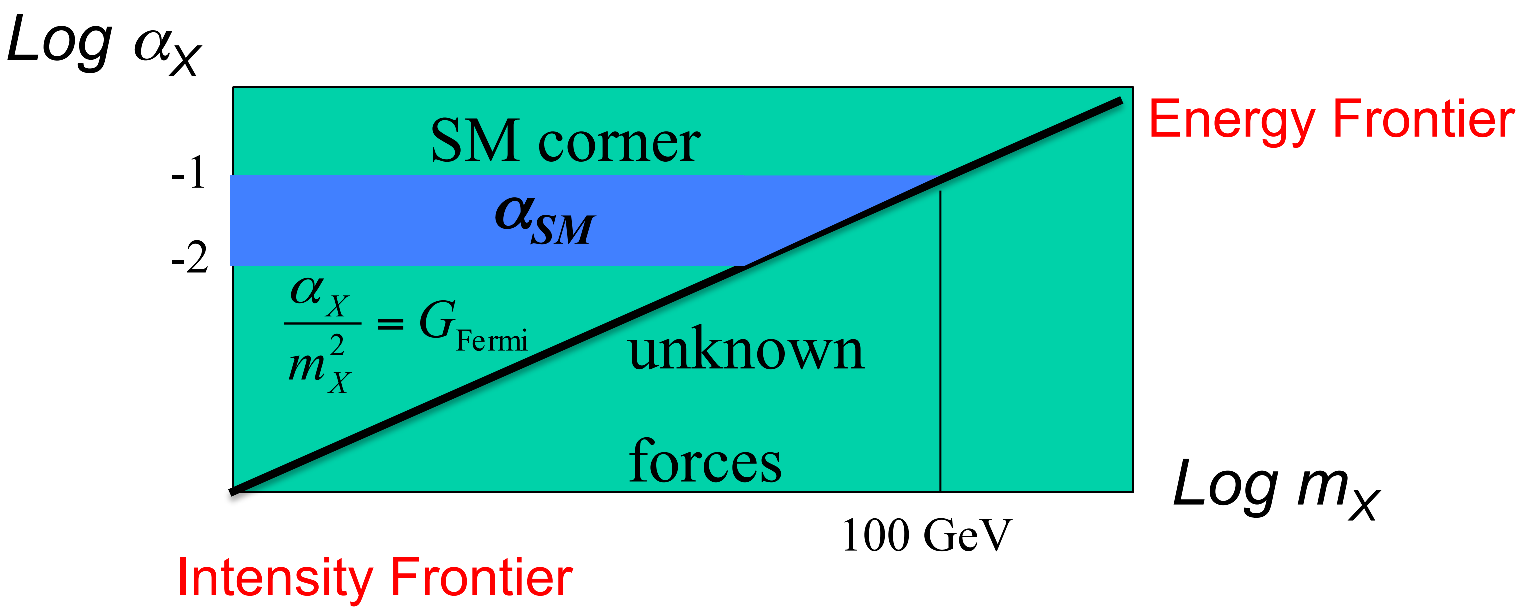
    4b. Very very dark photons. Implication for CMB/BBN

    4c. DM detectors as powerful probe of "solar dark photons"

    4d. Lepto-specific Higgs at low energy

1. Looking ahead. *Wish list of new measurements and experiments.*
2. 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.

Two ways ahead after establishing SM

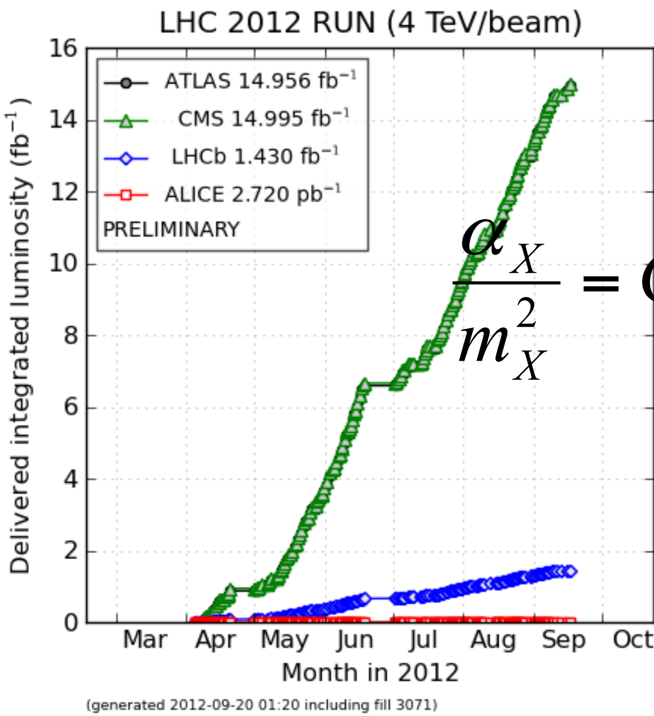
L-way (Low-energy way)

Let's settle down, explore in detail what we already know, and if opportunity comes along we strike.

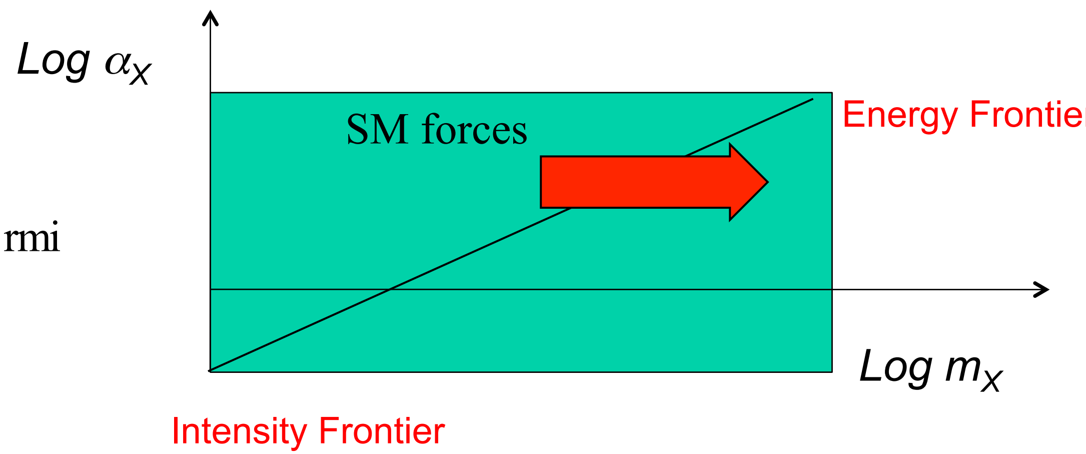
T-way (TeV way)

Let's run across the TeV frontier with sabres in our hands. Crossing the energy frontier will lead to new discoveries.

LHC – it was worth the wait!



$$\frac{\alpha_X}{m_X^2} = G_{\mathrm{Fermi}}$$



Both ATLAS and CMS enjoy record-breaking 2012 data taking run providing direct probe of TeV-scale world.

LHC and its implications

1. There is a new, [most likely] scalar resonance with high significance at about ~ 125 GeV that *on average* fits 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. Photon rate for Higgs candidate $R_{\gamma\gamma}$ seems large. *No evidence for coupling to leptons*. Low $R_{\tau\tau}$ may have important implications for the intensity frontier.

4. No "superpartners" at TeV pushes many theorists rethink naturalness. No naturalness = no strong argument for TeV NP. Why not GeV?

5. Important non-LHC news (advances in neutrino physics, DM detection sensitivity, precision frontier measurements)

Neutral doors ["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

$J_\mu^i A_\mu$ 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

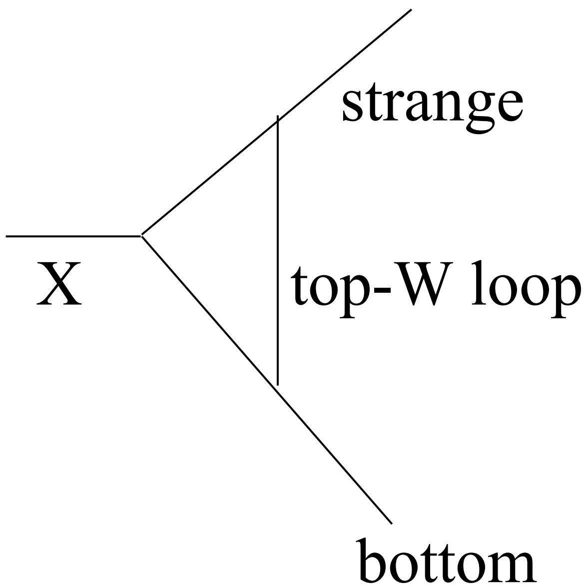
$J_\mu^A\ \partial a\,/f$ axionic portal

……….

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

Why baryonic or EM currents are “safe” from flavor constraints

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.

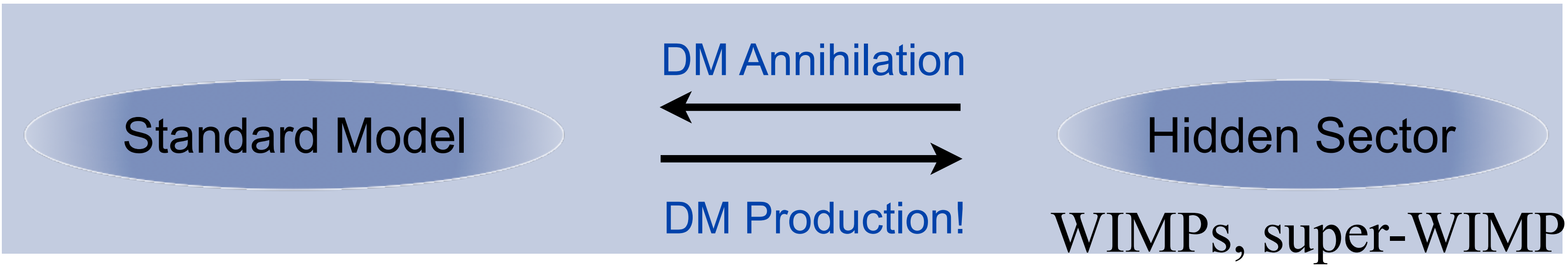


For a conserved vector current, $G_F\, q^2$

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')

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

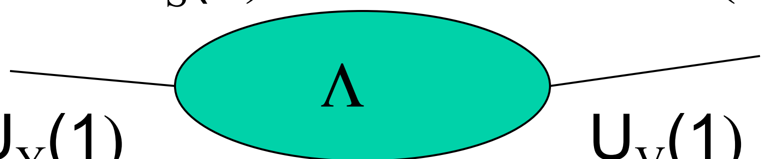
This Lagrangian describes an extra U(1)' group (**dark force, hidden photon, secluded gauge boson, shadow boson etc, also known as U-boson, V-boson, A-prime, gamma-prime etc**), attached to the SM via a vector portal (kinetic mixing). Mixing angle κ (also known as ε, η) controls the coupling to the SM.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

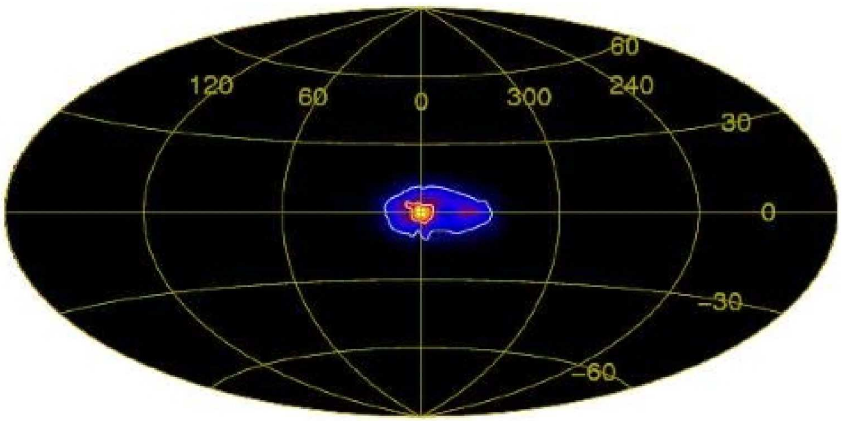


FIG. 4 511 keV line map derived from 5 years of INTEGRAL/SPI data (from Weidenspointner *et al.*, 2008a).

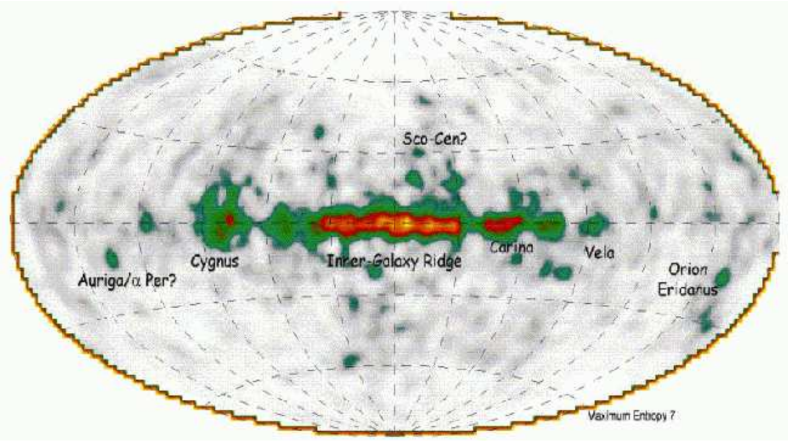
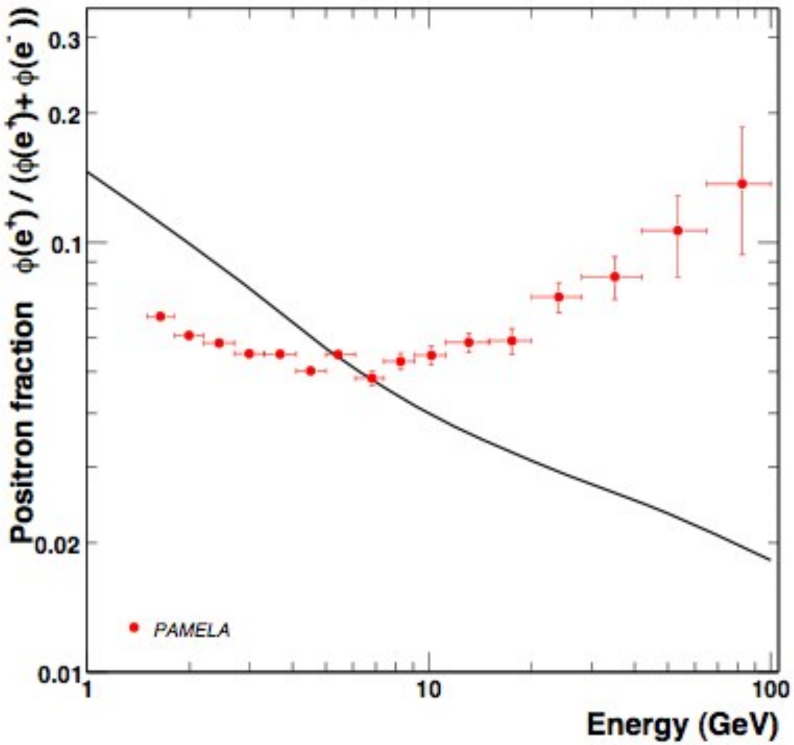


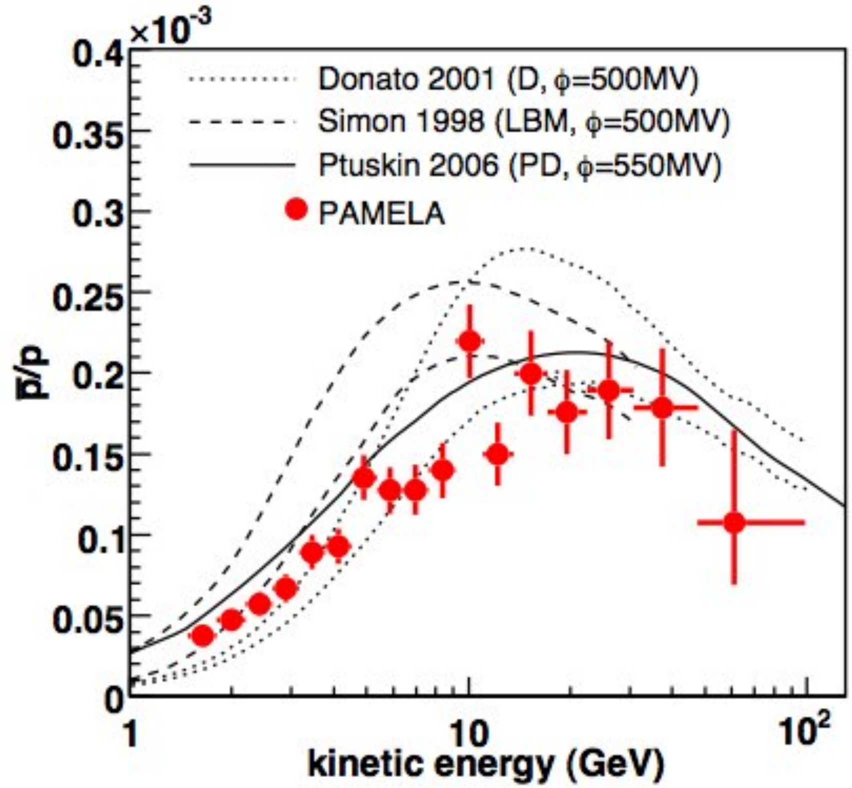
FIG. 7 Map of Galactic ^{26}Al γ-ray emission after 9-year observations with COMPTEL/CGRO (from Plüschke *et al.*, 2001).

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!

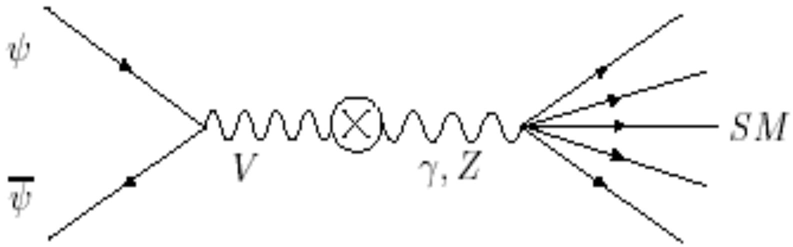
This is a "boost" factor of 100-1000 "needed" for the WIMP interpretation of PAMELA signal. E.g. SUSY neutralinos would not work, because <σv > is too small. Enhancing it "by hand" does not work because WIMP abundance goes down. Dark forces allow bridging this gap due to the late time enhancement by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

Secluded WIMP idea – heavy WIMPs, light mediators

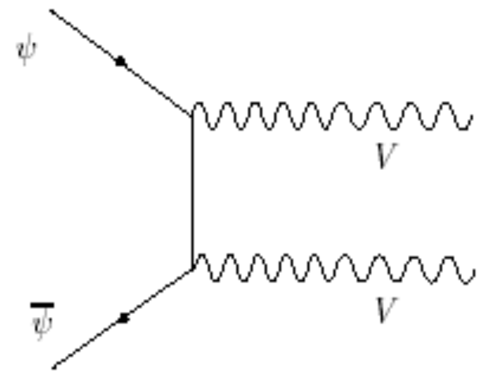
$$\mathcal{L}_{\mathrm{WIMP+mediator}} = -\frac{1}{4}V_{\mu\nu}^2 - \frac{\kappa}{2}V_{\mu\nu}B_{\mu\nu} - |D_\mu\phi|^2 - U(\phi\phi^*) + \bar{\psi}(iD_\mu\gamma_\mu - m_\psi)\psi.$$

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

$m_{mediator} > m_{WIMP}$



$m_{mediator} < m_{WIMP}$

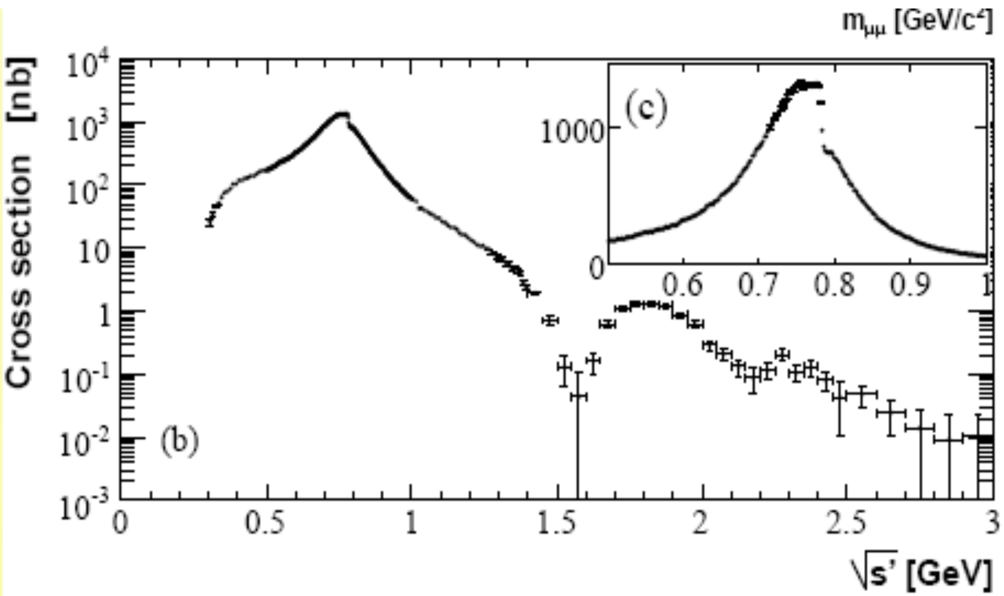


Second regime of annihilation into on-shell mediators (called *secluded*) does not have any restrictions on the size of mixing angle κ.

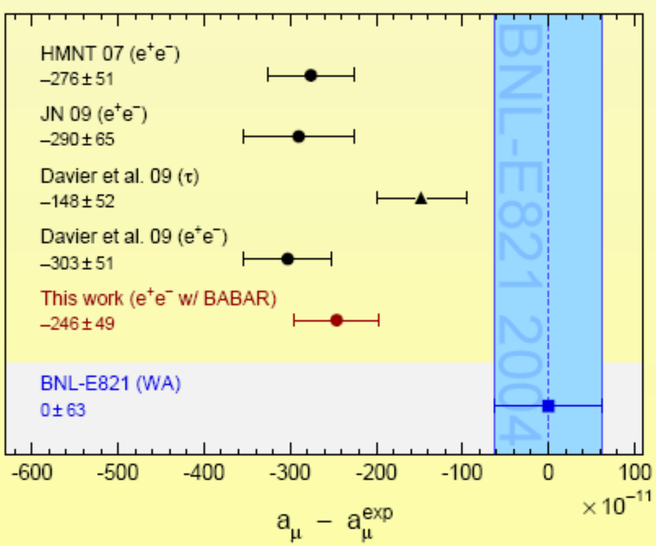
It turns out *this helps* to tie PAMELA positron rise and WIMP idea together.

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

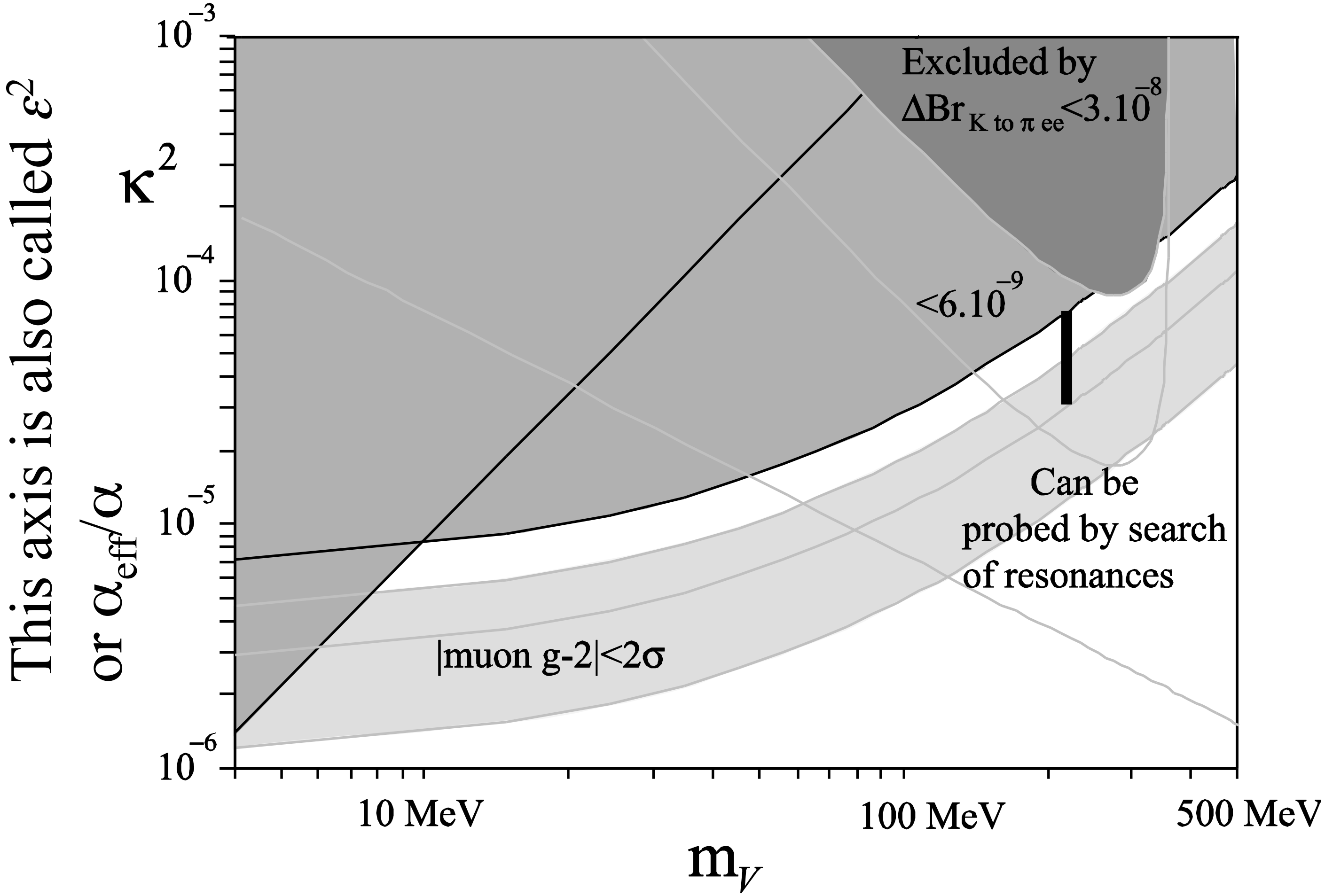
Supersymmetric models with large-ish *tanβ*; light-ish sleptons, and right sign of μ parameter can account for the discrepancy.

Sub-GeV scale vectors can also be at play.

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 $m_V \sim m_\mu$

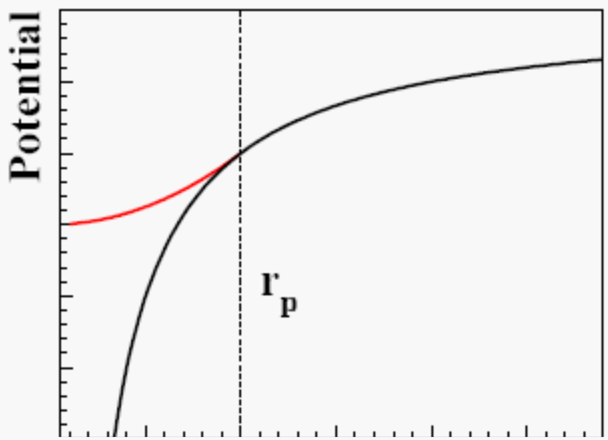


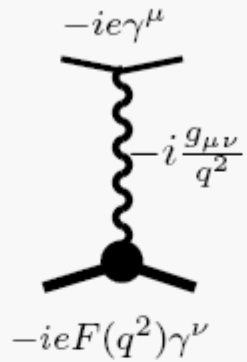
MP, 2008

Since 2008 a lot more of parameter space got constrained, and many new results will be reported here.

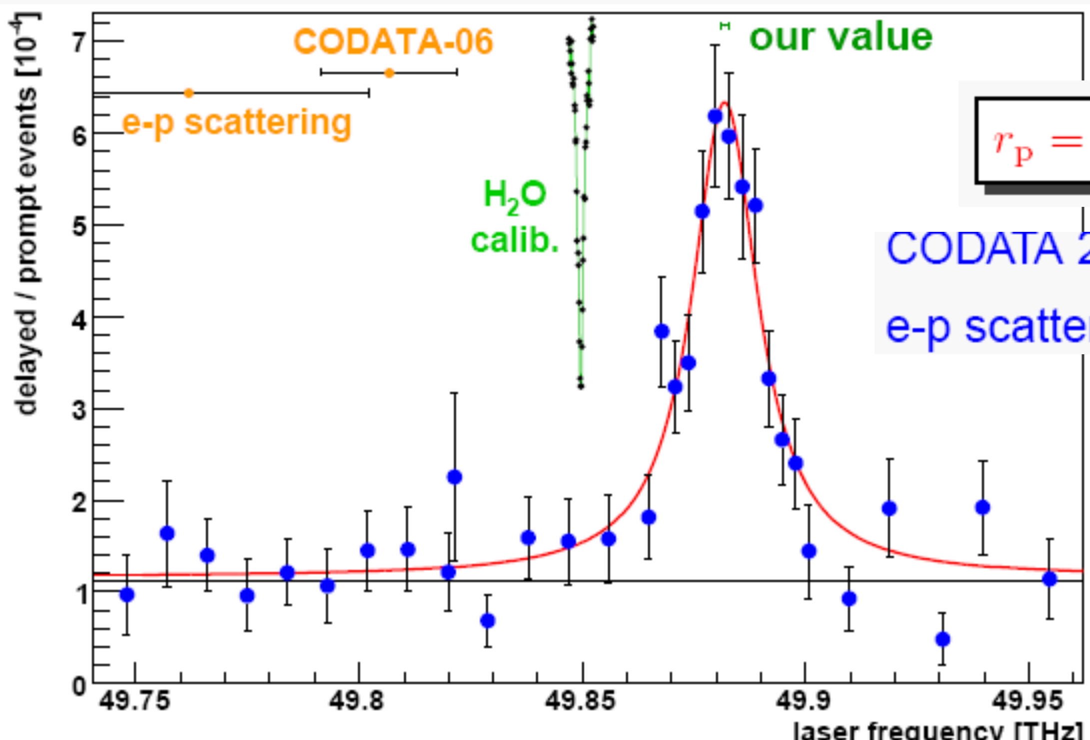
Muonic hydrogen Lamb shift

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.



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

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.***

Most important aspects of hidden U(1) phenomenology

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

$U_{Fayet} \rightarrow$ light DM; V(A')-boson $\rightarrow$ 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

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

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

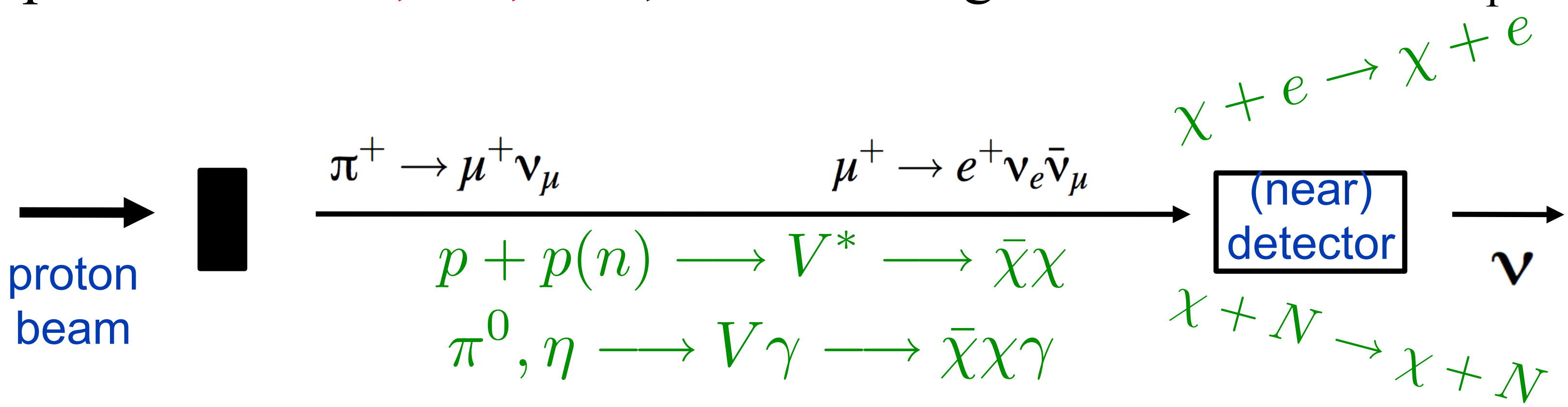
1. Production in association with γ, $ee^+ \rightarrow V\gamma \rightarrow \mu\mu^+\gamma$ (Search for a peak in μ-spectrum: BaBar, Belle, KLOE). $\kappa \sim 10^{-3}$ is reachable. Limiting U_F is more difficult.
2. Meson decays: π^0, η, η', ω, ϕ ...$\rightarrow V\gamma \rightarrow \gamma\, ll^+$. (KLOE,BESSIII,WASA-COSY…) $K \rightarrow \pi V \rightarrow \pi ll^+$ or π+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": $e + Z \rightarrow Z + V \rightarrow Zll^+$. (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 all looking forward to hearing about new results at this meeting!

But enough ideology/motivation. New results from our group!

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
(➠ ~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

Submitted to PAC,

Fermilab in Sep 2012

First presentation to PAC by R. Van de Water yesterday, Oct 15, 2012.

Main idea is to replace Be target with higher Z absorber and cut on ν background for WIMP search

Light Mass WIMP Searches with a Neutrino Experiment: A Request for Further MiniBooNE Running

September 19, 2012

The MiniBooNE Collaboration

R. Dharmapalan, S. Habib, C. Jiang, & I. Stancu
University of Alabama, Tuscaloosa, AL 35487

R. A. Johnson & D.A. Wickremasinghe
University of Cincinnati, Cincinnati, OH 45221

F.G. Garcia , R. Ford, T. Kobilarcik, W. Marsh,
C. D. Moore, D. Perevalov, & C. C. Polly
Fermi National Accelerator Laboratory, Batavia, IL 60510

J. Grange & H. Ray
University of Florida, Gainesville, FL 32611

R. Cooper & R. Tayloe
Indiana University, Bloomington, IN 47405

G. T. Garvey, W. Huelsnitz, W. Ketchum, W. C. Louis, G. B. Mills,
J. Mirabal, Z. Pavlovic, & R. Van de Water,
Los Alamos National Laboratory, Los Alamos, NM 87545

B. P. Roe
University of Michigan, Ann Arbor, MI 48109

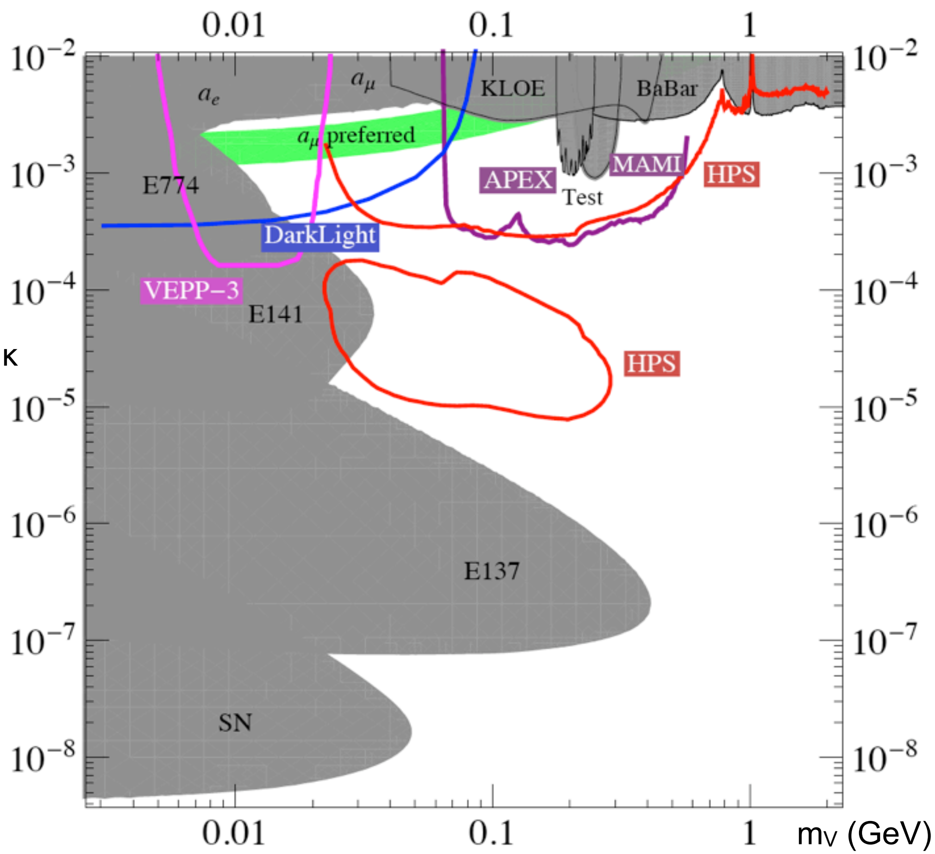
A. A. Aguilar-Arevalo
Instituto de Ciencias Nucleares, Universidad Nacional Autónoma de México, D.F. México

P. Nienaber
Saint Mary's University of Minnesota, Winona, MN 55987

The Theory Collaboration

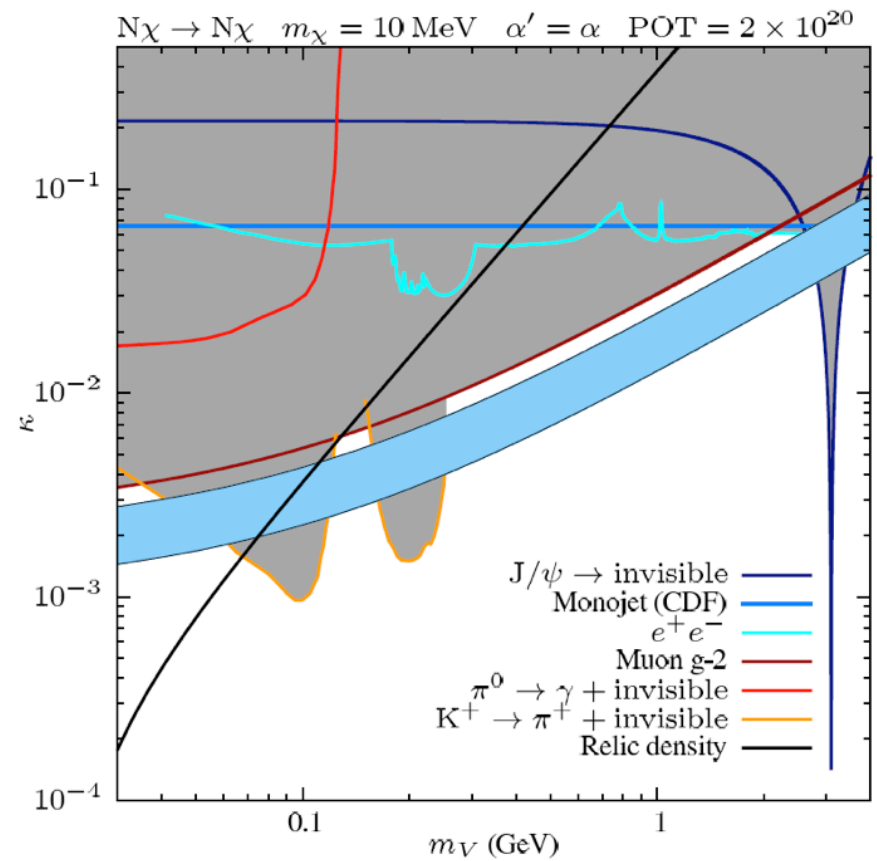
B. Batell
University of Chicago, IL 60615

P. deNiverville , D. McKeen, M. Pospelov, & A. Ritz
University of Victoria, Victoria, BC, V8N-1M5



$m_V < 2m_\chi$

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

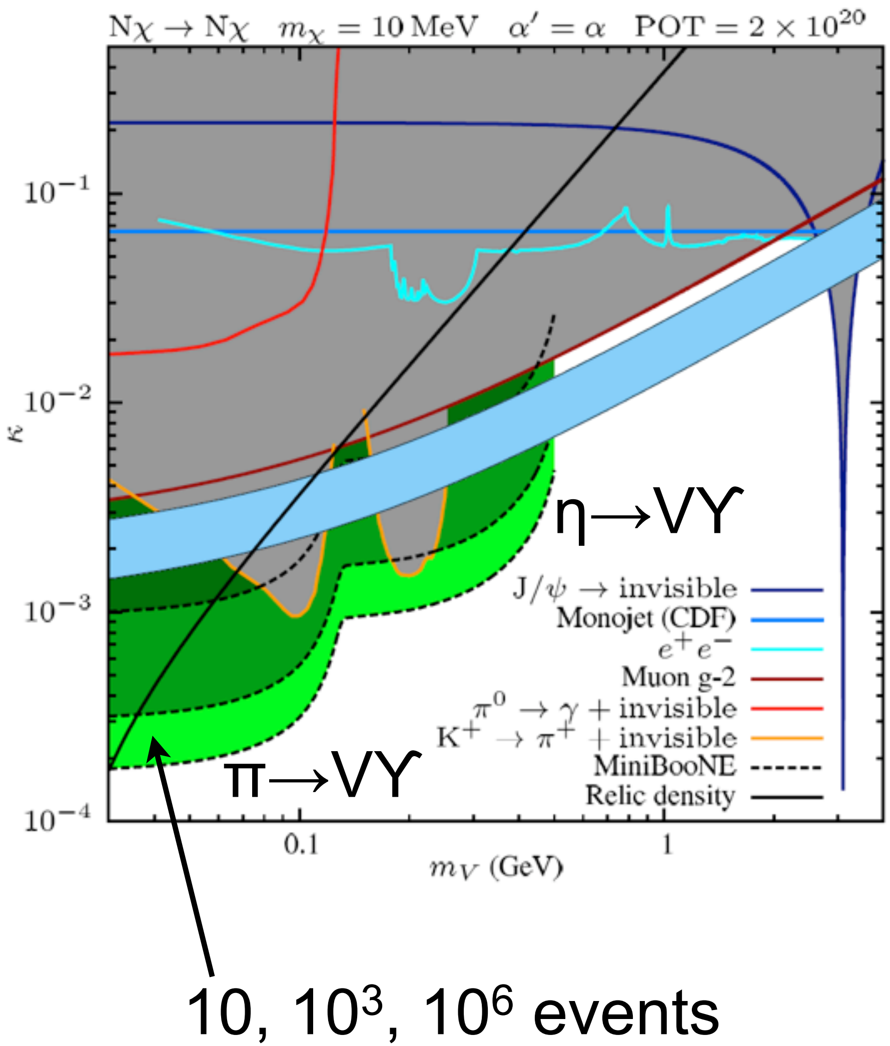


$m_V > 2m_\chi$

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

Batell, deNiverville, McKeen, Pospelov, Ritz, in progress

MiniBooNE sensitivity



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, $ee \to V$, and then decay much later affecting the outcome of the BBN and/or ionization history for the CMB.

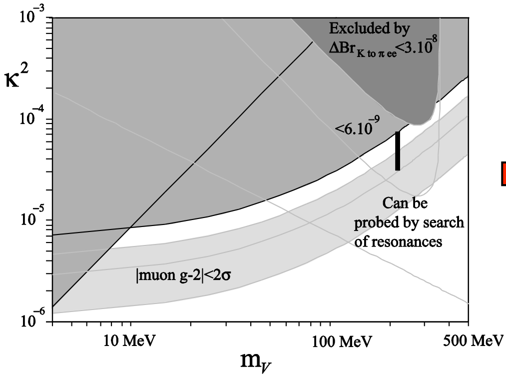
$$Y_{V,f} = 2.3 \times 10^{-3} \times \frac{\Gamma_V}{1\ \mathrm{Hz}} \times \left(\frac{10\ \mathrm{MeV}}{m_V}\right)^2$$ vectors per entropy (γ,ν) is produced.

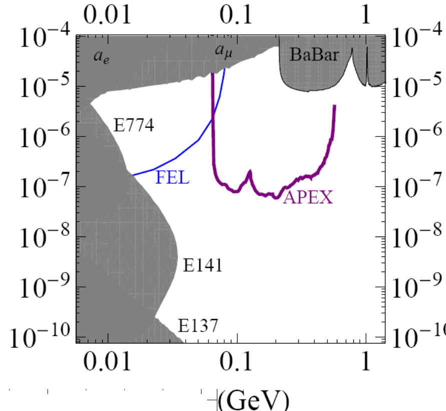
Late decay produce $$E_{\mathrm{p.b.}} = 2.6\ \mathrm{eV} \times \frac{\Gamma_V}{10^{-14}\ \mathrm{Hz}} \times \frac{10\ \mathrm{MeV}}{m_V}$$

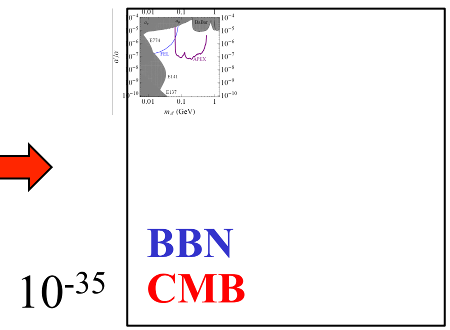
per baryon. $\Delta X_e \sim$ *up to 0.1. Huge!* $\leftarrow$ *strong constraints from CMB*

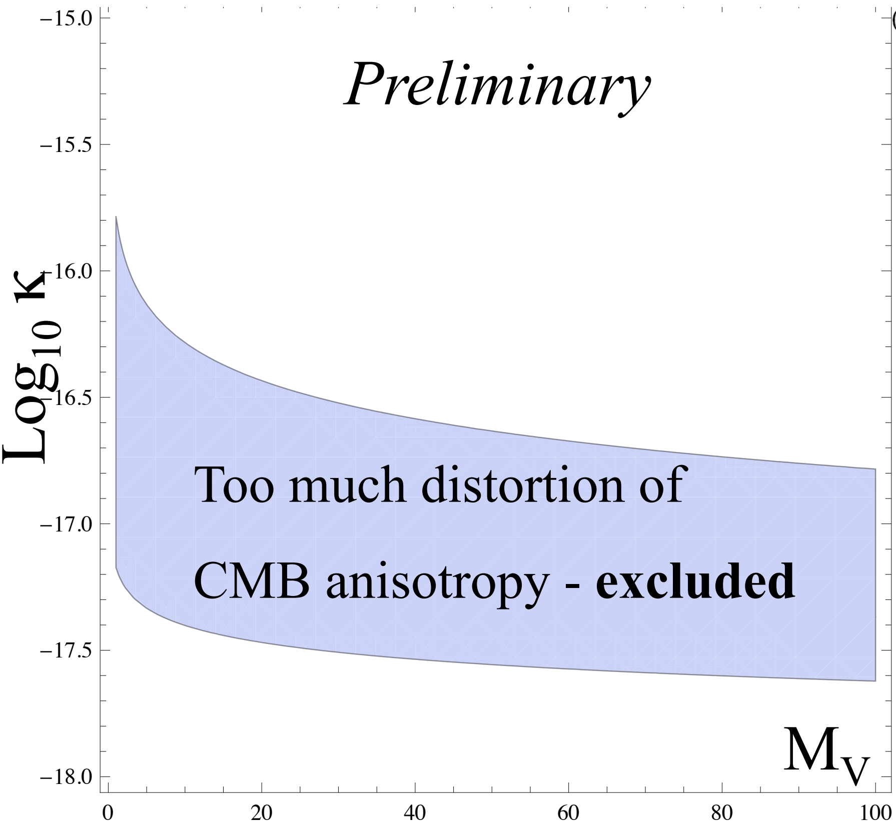
Fradette, MP, Pradler, Ritz, *work in progress.*

Effect on BBN and CMB









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

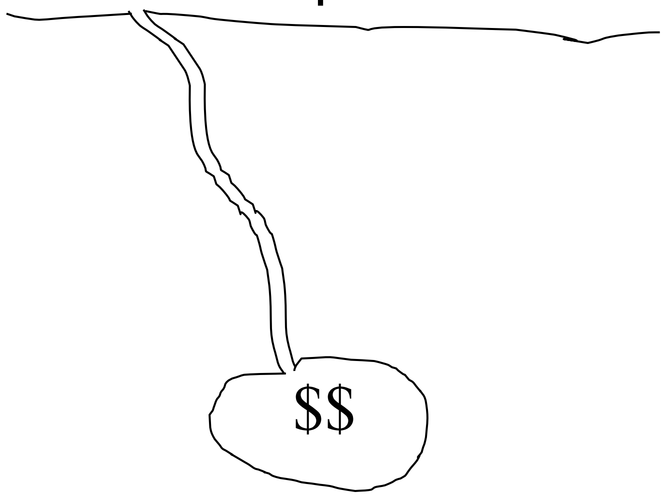
In some fraction of the parameter space the only effect is the reduction of $^7Li/H$ (which you can argue is a good thing).

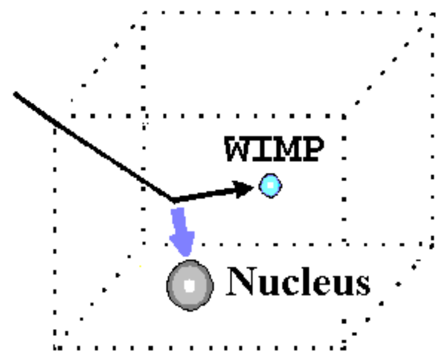
Earlier discussions can be found in published works of Postma, Redondo; Pospelov, Pradler

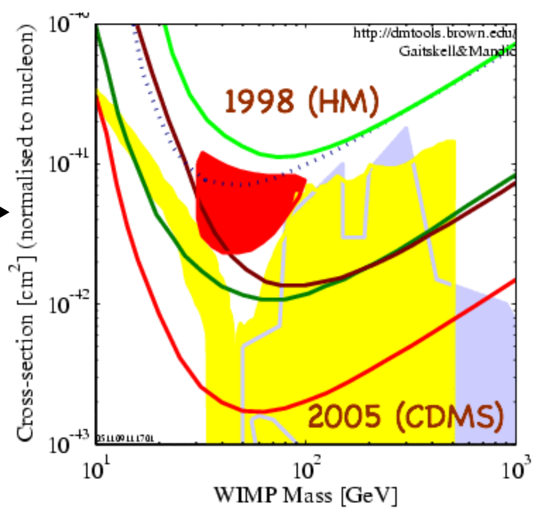
Currently all “direct DM detection” experiments search for the same thing

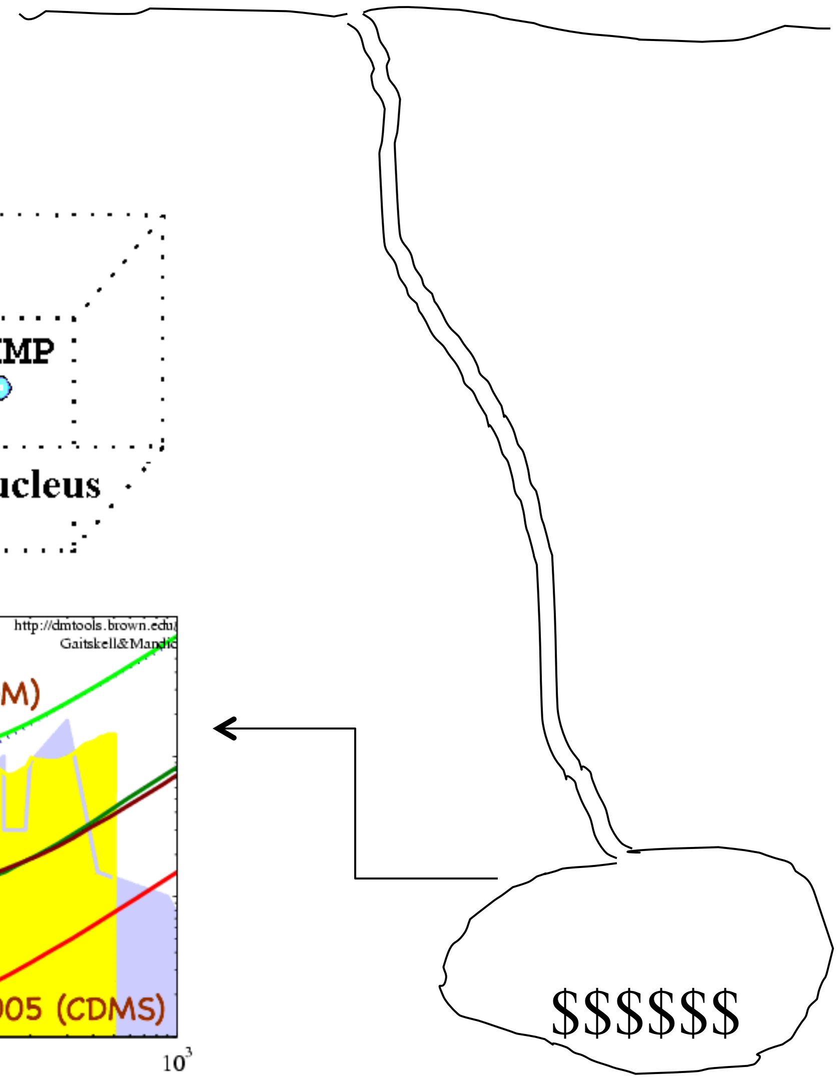
An average Dark Matter detection experiment

A more expensive DM experiment









Diversifying physics output of direct detection exp’s is needed **!!!** (Take a cue from HEP exp’s See also R. Essig’s talk)

Using DM detectors you can study:

1. "Solar axions" (Avignone, 1980s) and other light exotics.
2. Super-WIMP dark matter absorbed by atoms (DAMA col, MP, Ritz, Voloshin, 2008)
3. Non-standard properties of solar neutrinos (MP, 2011; Harnik et al, MP, Pradler, 2012)
4. Signal from sub-GeV DM giving atomic excitations (Essig et al; Graham et al.; 2011-2012)
5. …

New constraint on "Solar Dark Photons"

New constraints in Horvat et al, Oct 2012, from HPGe (Germanium detector on the surface.)

MP, Pradler: *constraints from CoGeNT and Xenon10 are much stronger, because both are sensitive to sub-keV energy release, where dark photons are peaked.*

At $\mathbf{m_V = 1eV}$, the ionization rate at CoGeNT provides a strong bound of **kappa < $\mathbf{10^{-10}}$** *(preliminary)*

The analysis of constraints on the whole mV-kappa parameter space is on-going.

Lepton-specific Higgs:

Evidence for **Higgs boson** (125 GeV state) coupling to

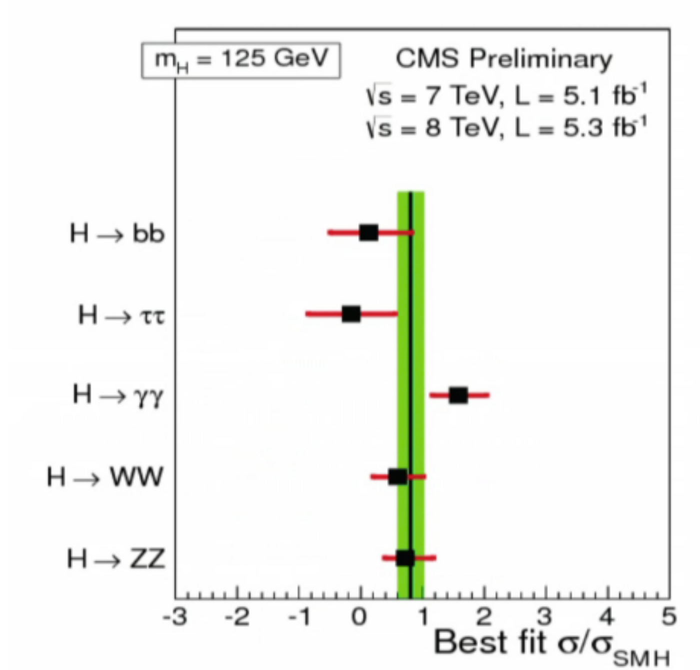
Top quark:

Bottom quark:

W/Z:

Leptons:

?



May be we have a separate Higgs giving mass to leptons? [Not a new idea]

$$\langle H_q \rangle = v_q \simeq v_{SM}; \quad \langle H_l \rangle = v_l = v_q/\tan\beta \ll v_{SM}.$$

$$H_q \supset h(125);\ \text{longit}\ W, Z; \qquad H_q \supset h_l;\ A;\ H^{\pm}$$

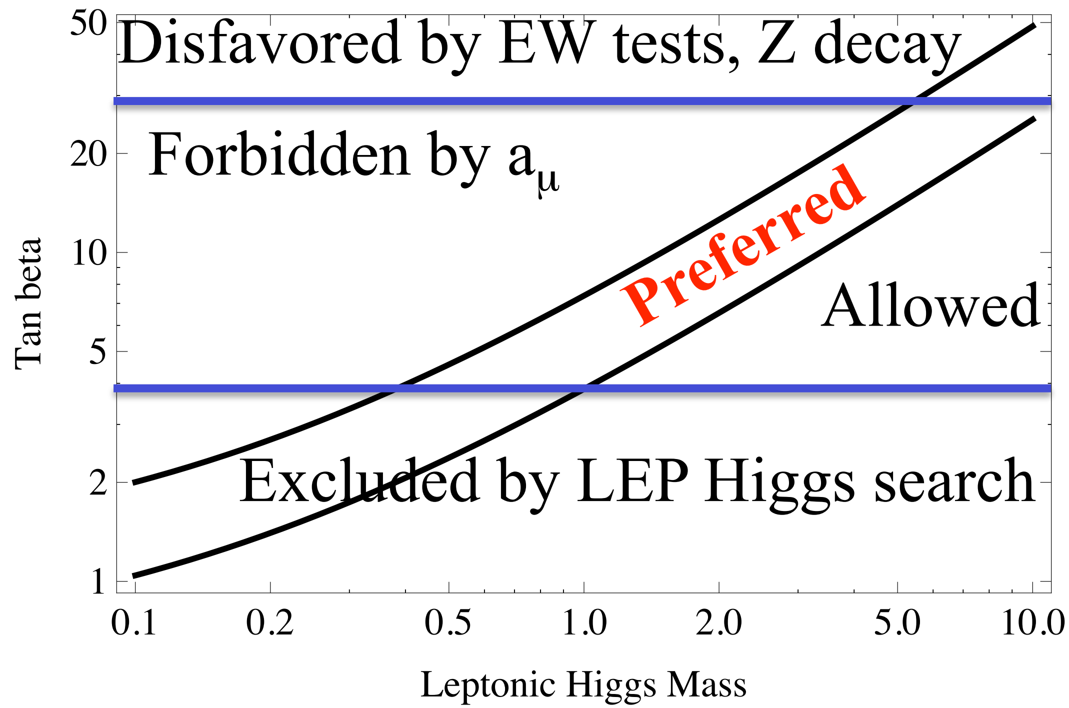
LEP requires $m_l + M_A; \quad 2M_{H^\pm} > E_{c.m.LEPII}$ Apparent $\boldsymbol{\tau\tau}$ rate will be suppressed if in addition:

$$R_{\tau\tau} \ll 1 \quad if\ m_l^2 \ll m_h^2. \qquad\qquad R_{\tau\tau} = (y_\tau/y_{\tau,SM})^2 \times \theta_{lq}^2 = \left(\frac{m_l^2}{m_l^2 - m_h^2}\right)^2$$

Signatures of h_l at low energy

Batell, McKeen, MP, Ritz, work in progress

Absence of h → taus motivates one light state from H_l, h_l, *below* weak scale. Moreover, possible connection to $(g-2)_\mu$ pushes m_l (leptonic Higgs mass) under 10 GeV. *Schematic plot* (blue lines are very approximate)



Main signatures: $e^+e^- \rightarrow \tau\tau\, h_l \rightarrow$ 4 taus or $2\tau 2\mu$ *This is not unlike multilepton signatures from Dark Force searches (now with miss E)*

My wish list for the future (on top of things that are on-track):

1. **B-factories**: Search for associated production of "X" with tau-pairs. Important because of the possibly of light lepton-specific Higgs
2. **Fixed targets**: OK, θ_{13} is known. Now what? All "p-on-t" experiments *can and must* include the Dark Force/light WIMP program. *Cover g-2 region of interest*.
3. **LHC**: Addt'l sensitivity to dark forces in EW processes and DY.
4. **DM/underground ν exp**: broaden your physics goals to other exotics
5. **Theory-experiment link**: *dark photons are nice but* there are equally meritorious portals (baryonic current, B-L, L_μ-L_τ) etc, that needs to be thought about and analyzed. Higgs and axionic portals.
6. **[Parts] of exp community**: Rethink your motivations in line with recent LHC results; TeV is not the only game in town.
7. **[Parts] of theory community**: I am also sad that squarks and gluinos are not 300 GeV, but you can do a lot better than model-building at 10-100 TeV. Do something useful already.

Conclusions

- Search for new physics at the intensity frontier is not driven *only* by the desire to learn about the TeV scale. New Physics at a GeV and below is a legitimate search target.

- A lot of progress, both in theory and experiment, is achieved already, in limiting light Dark Forces and WIMP DM. Many exciting physics searches to do still.

- How soon are we going to see the Dark Force?

38 years rule = new forces of nature are discovered every 38 years

1. 2011/2012 Discovery of the Higgs, i.e. Yukawa force.
2. 1973 – Gargamelle experiment sees the evidence for weak neutral currents in nu-N scattering
3. 1935 – Chadwick gets NP for his discovery of neutron with subsequent checks that there exists strong n-p interaction. Strong force is established.
4. 1897 – Becquerel discovers radioactivity – first evidence of weak charged currents (in retrospect).
5. 1860s – first papers of Maxwell on EM. Light is EM excitation. E & M unification.

(+/- 2 years or so).

Bad news: This puts the discovery of dark force to a round but uncomfortable date of 2050. ***Good news: we'll meet again***