New gauge forces below the weak scale: a case for the sub-GeV dark boson

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Outline of the talk

1. Why searching for a new gauge groups below the weak scale is important.
2. Energy, Intensity and Precision frontiers in particle physics. Cosmology frontier and dark matter.
3. WIMP paradigm. Secluded WIMPs and mediator forces.
4. A case for dark forces around a GeV – WIMP interpretation of PAMELA data.
5. Novel signatures in particle physics and dark matter searches. Additional cosmological signals.
6. Conclusions

Simplest example of additional U(1) model
(Holdom 1986)

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

This Lagrangian describes an extra U(1)' group (**dark force, hidden photon, secluded gauge boson 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, χ) controls the coupling to the SM.

For the purpose of this talk, I will consider broken U(1)', with the scale of the breaking in a window from MeV-to-GeV. Mixing angle and mass m_V are the only parameters – the model is very minimal.

A much broader scan can be found in the review of J.Jaeckel, A.Ringwald, **arXiv:1002.0329**

Simplest U(1)' Dark Force

Potential between Dark Matter particle and an electron.

$$V_{DM-e}(r) = \frac{\kappa\sqrt{\alpha\alpha'}}{r}\exp(-rm)$$

Potential between two electrons

$$V_{e-e}(r) = \frac{\kappa^2\alpha}{r}\exp(-rm)$$

Potential between DM particle and anti-particle

$$V_{DM-antiDM}(r) = -\frac{\alpha'}{r}\exp(-rm)$$

Why searching for new gauge boson(s) at low and medium energies is important

1. Standard Model is built on SU(3)xSU(2)xU(1) interactions. *Testing for existence of additional gauge groups is needed.*
2. Hints for new sub-GeV gauge bosons might be given to us by *several particle physics anomalies*, most importantly g-2 of the muon.
3. New U(1) groups can serve as mediators of connection between SM and particle dark matter. *Speculative but interesting*.
4. Additional U(1) with kinetic mixing to photons is a very "natural" possibility of new light physics. *It is very simple – even elegant – and extremely predictive.*
5. Significant advances can be achieved using fixed target setups. Only a very small subset of experiments done at low energy can be sensitive to physics beyond SM. Therefore, *it should be done, given a potentially enormous reward in case of a positive result.*

Energy, precision and intensity frontier searches of physics beyond SM

Energy Frontier

(exploring large masses, sizable couplings)

Intensity Frontier

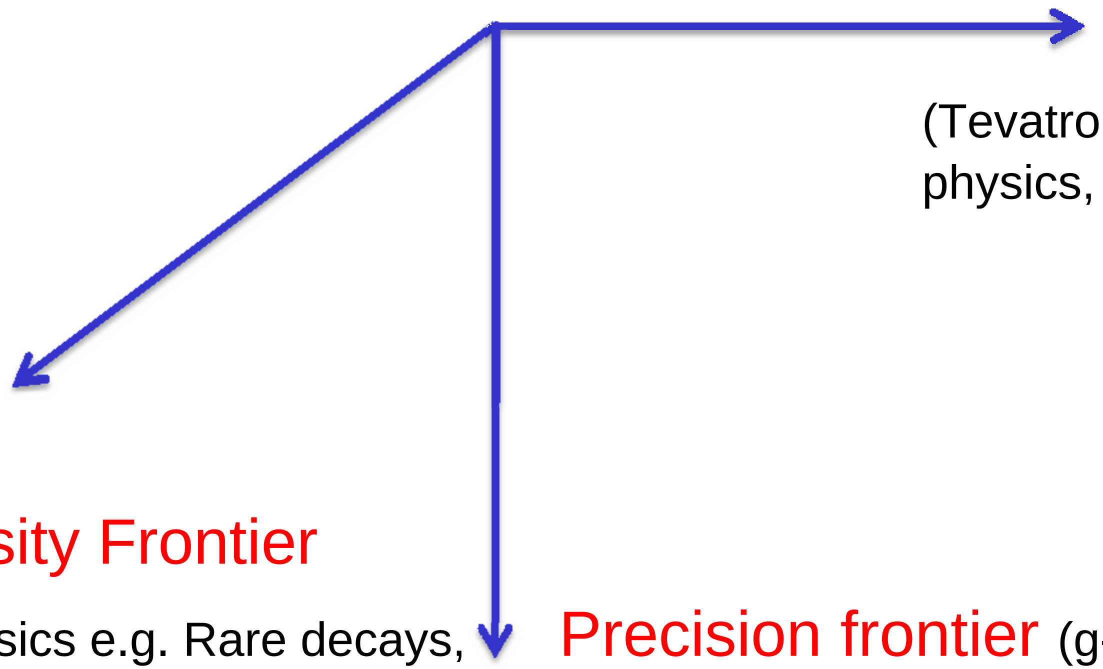
(exploring small masses

and very small couplings)

Precision frontier

Space-time frontier: C o s m o l o g y

Energy, precision and intensity frontier searches of physics beyond SM



Energy Frontier

(Tevatron and LHC: Higgs physics, SUSY searches, Z')

Intensity Frontier

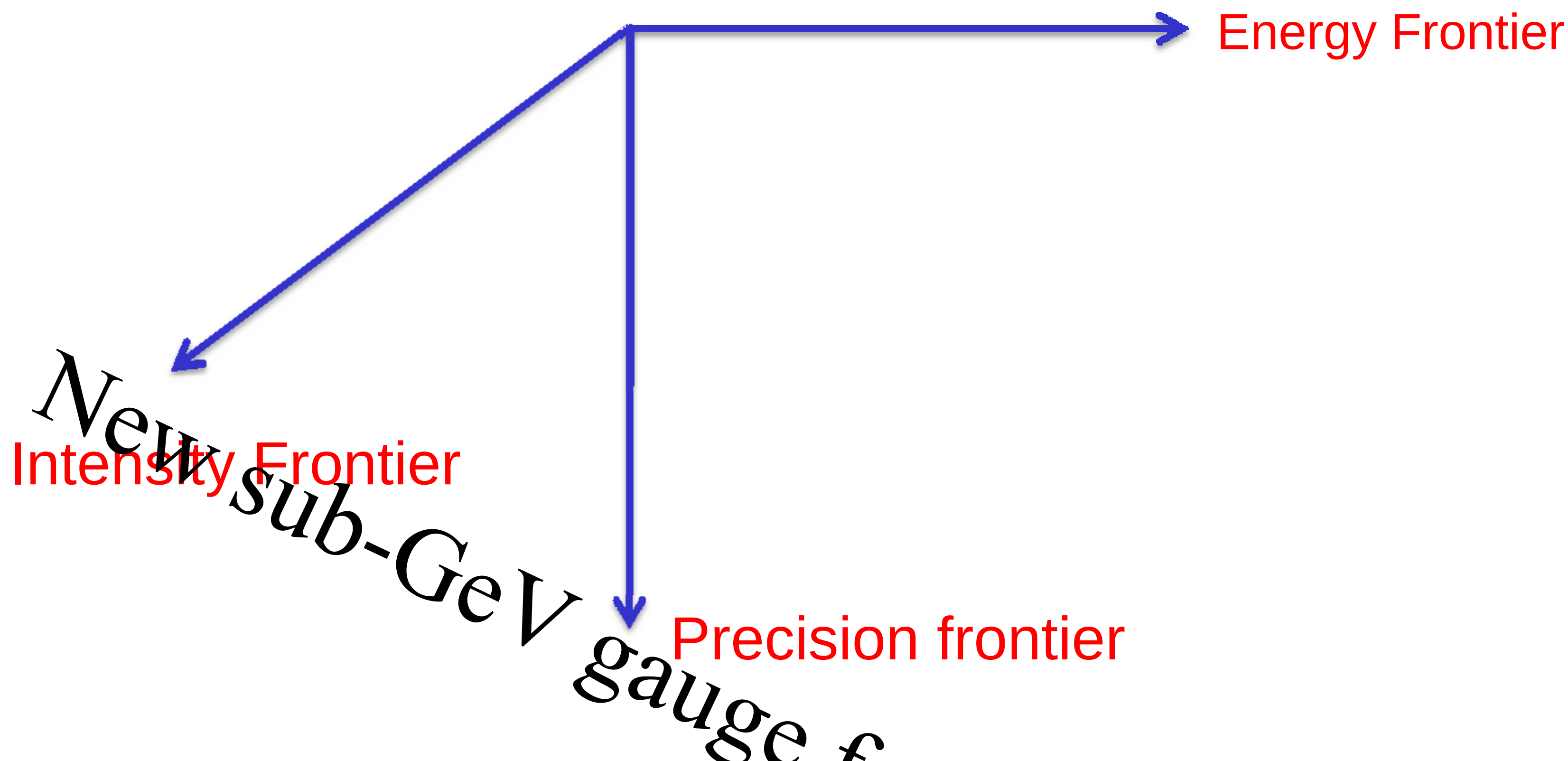
(flavor physics e.g. Rare decays, neutrino beams)

Precision frontier (g-2, precision QED, flavor, EDMs)

Space-time frontier: C o s m o l o g y (CMB, SN, structure..)

Vigorous research programs at all frontiers is required for understanding fundamental physics!!!

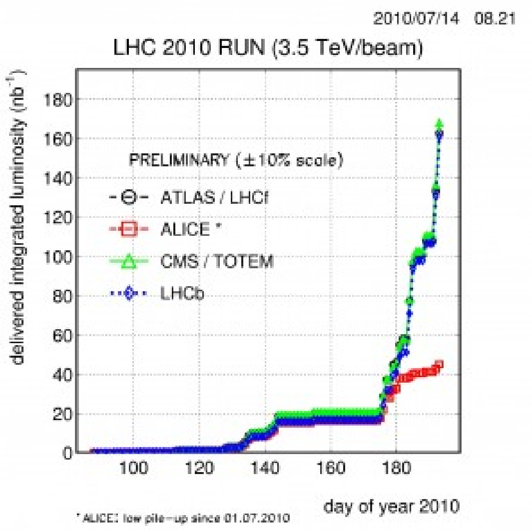
Energy, precision and intensity frontiers
New sub-GeV gauge forces



Space-time frontier: C o s m o l o g y

Energy frontier

Tevatron (with important LEP contribution) pushed our direct understanding of large energies/ small distances to 100-200 GeV benchmark. LHC luminosity is ramping up.



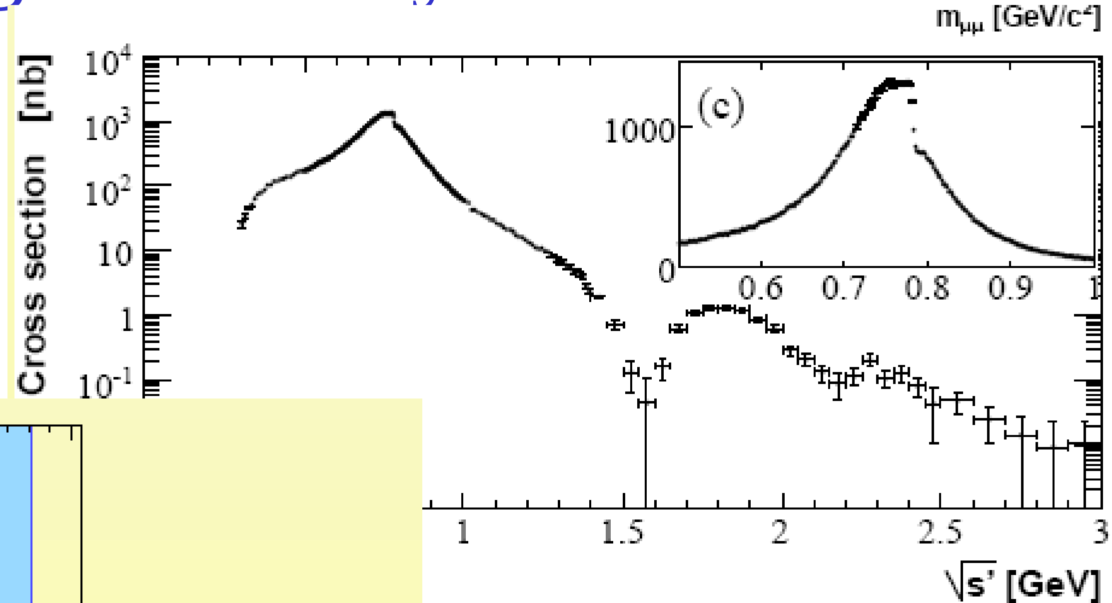
Top-antitop pairs are probably being looked at by hungry experimentalists as we speak. Give it another year and should some new strongly interacting particles (squarks, gluinos) exist in the energy reach, we will see it.

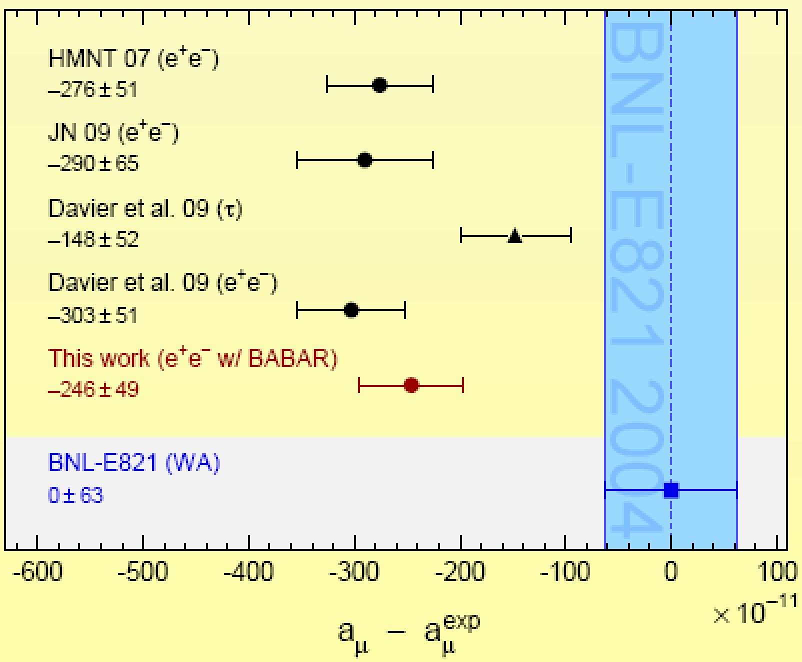
Intensity frontier

B-factories: 1500 inverse fb of integrated luminosity! Confirmation of CP-violation due to the CKM phase. New constraints on physics BSM. Neutrino factories and neutrino telescopes: confirmation of neutrino masses and mixings $\to$ hints on new states (RH neutrinos), and/or new interactions. Future: T2K, Nova, project-X (?).

Precision frontier: Anomaly in g-2 anomaly of muon

Recent BaBar data

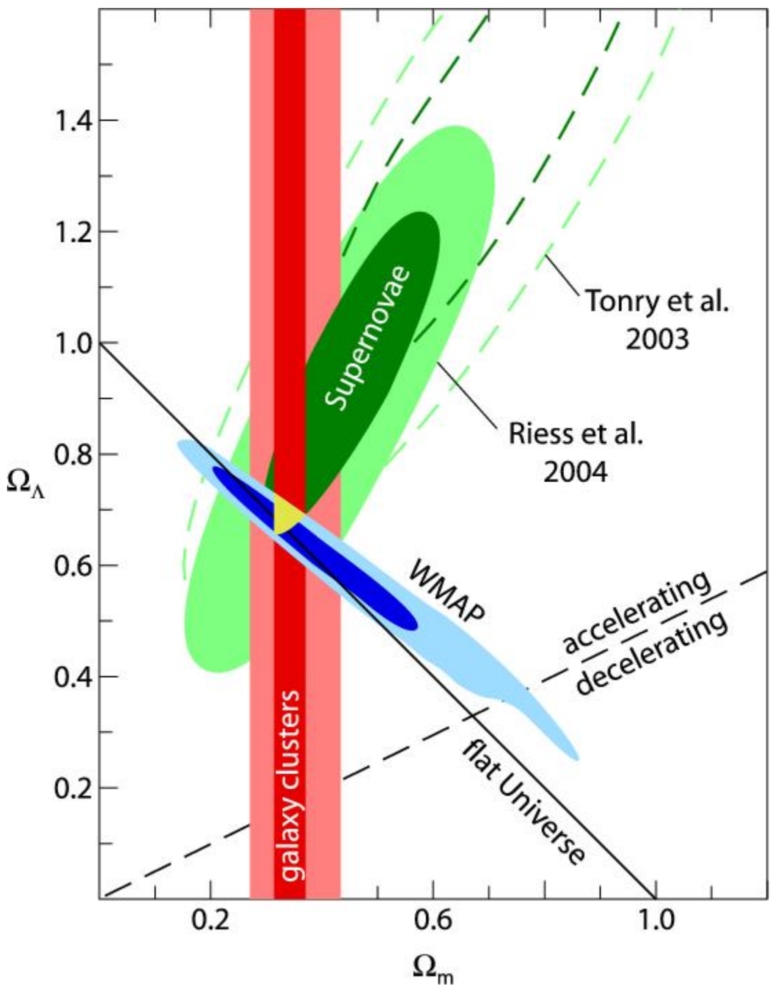




✱ Davier et al. arXiv:0906-5443

The discrepancy of 300×10^{-11} (theoretical value is smaller) is 3.1 sigma away from the measured value. First signs of new physics ?

Cosmology frontier: connecting particle physics and cosmology is a big problem



- The physical nature of DM remains a mystery (particles or something else? What is the mass ? Relation to other SM fields if any?) and is the focal point of many dedicated searches. 1000s of reasonable models of particle DM.
- Why do we live in a seemingly special Universe, with all three components, baryons, DM and DE in more or less comparable amounts?
- Dark energy? No reasonable models except Λ. Problems at quantum level.

WIMP paradigm

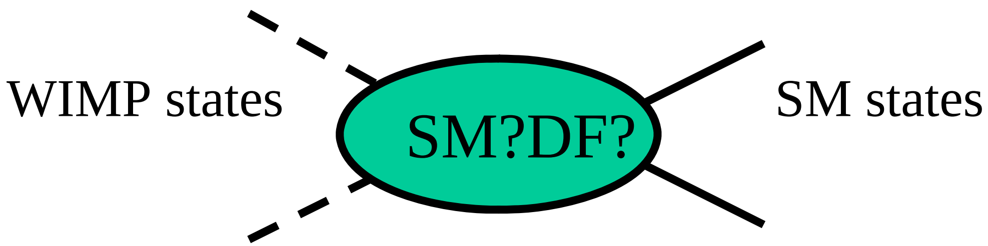
$$\frac{10^{-10} x_f}{\sqrt{g_*(T_f)} \times \langle \sigma v \rangle} \leq \Omega_{\rm DM} h^2 \approx 0.1 \quad \Longrightarrow \quad \langle \sigma v \rangle = 2.5 \times 10^{-26} {\rm cm}^3 {\rm s}^{-1},$$

- Weakly interacting massive particles (neutralinos, KK states etc)

Weak-scale masses, weak-scale couplings,

Large T ($T \gg m_{DM}$): WIMPs are in thermal/chemical equilibrium

$T \sim m_{DM}$: Period of rapid annihilation; $T < 0.05\ m_{DM}$ - freeze-out



The size of the cross section follows from relation

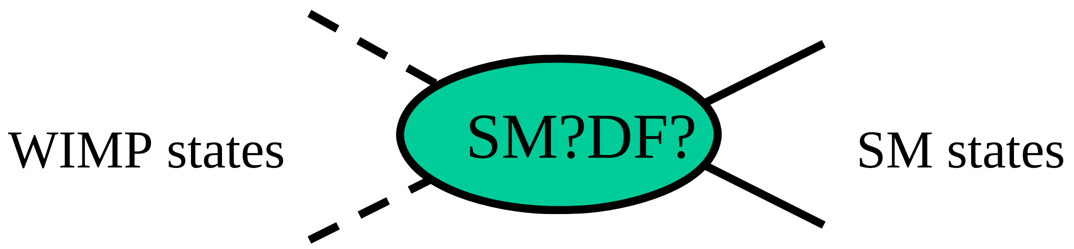
$<\sigma\ v> n_{DM}(T_f)\ \sim$ Hubble Rate (T_f)

"Green blob" – some mediation force, SM force, Higgs boson, new gauge force force, SUSY particle etc. It is model dependent. *It was believed until recently that the weak-scale annihilation rate implies the weak-scale scattering rates as well.* Hence the extensive WIMP direct detection effort.

Lee-Weinberg window and light WIMPs

If annihilation is mediated by the weak-scale force carriers, one should typically expect the following scaling: $\langle \sigma v \rangle \sim 1/(m_{WIMP})^2$ at $m_{WIMP} \gg M_W$ and

$\langle \sigma v \rangle \sim (m_{WIMP} G_F)^2$ at $m_{WIMP} \ll M_W$. **This sets the lower bound on WIMP mass of few GeV, and an upper bound of ~ 10 TeV.**



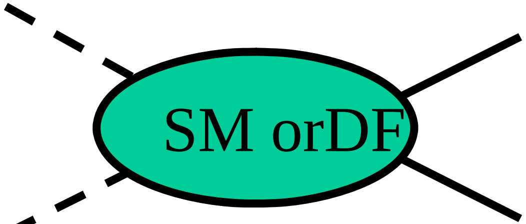
In 2003, after the release of smooth and stronger-than-expected 511 keV line from galactic bulge by SPI on INTEGRAL, Fayet and Boehm suggested to introduce new gauge forces in the sub-GeV range with $g_{SM} \ll g_{DM}$. **U-boson.** Gauged B-L symmetry is a possible example.

Sub-GeV scale U-boson allows for having MeV-scale DM, and speculating that the INTEGRAL signal can be related to the annihilation of light DM.

WIMP paradigm

$$\frac{10^{-10}x_f}{\sqrt{g_*(T_f)}\times\langle\sigma v\rangle} \leq \Omega_{\rm DM}h^2 \approx 0.1 \quad \Longrightarrow \quad \langle\sigma v\rangle = 2.5\times10^{-26}{\rm cm^3 s^{-1}},$$

Main property of WIMPs is the weak-scale annihilation cross section to the SM states. Does the scattering of WIMPs on SM or SM->DM is of the same size?



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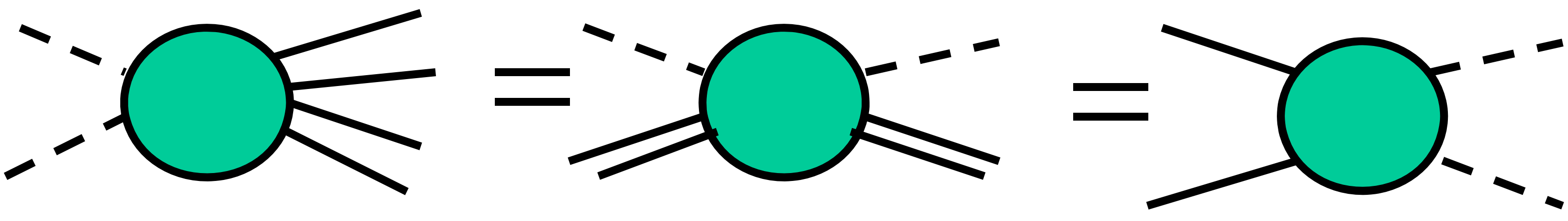


Simplest example of "vector portal" mediation between SM and DM

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

This Lagrangian describes an extra U(1)' group (**dark force**), and some matter charged under it. Mixing angle κ controls the coupling to the SM.

Below the scale of the U(1)' breaking we have

$$\mathcal{L}_{\text{WIMP+mediator}} = -\frac{1}{4}V_{\mu\nu}^2 + \frac{1}{2}m_V^2 V_\mu^2 + \kappa V_\nu \partial_\mu B_{\mu\nu} + \bar{\psi}(iD_\mu\gamma_\mu - m_\psi)\psi + \mathcal{L}_{h'},$$

Now we have 3 parameters, m_V, κ, m_{WIMP}

WIMP model was introduced and partially analyzed in MP, Ritz, Voloshin, 2007. Earlier example with Higgs mediation appeared in Finkbeiner and Weiner, 2007.

The existence of dark forces changes standard WIMP paradigm

$$\mathcal{L}_{\rm WIMP+mediator} = -\frac{1}{4}V_{\mu\nu}^2 + \frac{1}{2}m_V^2 V_\mu^2 + \kappa V_\nu \partial_\mu B_{\mu\nu} + \bar{\psi}(iD_\mu\gamma_\mu - m_\psi)\psi + \mathcal{L}_{h'}$$

ψ – Dirac type WIMP; V_μ – mediator particle.

Two kinematic regimes can be readily identified:

- $m_{mediator} > m_{WIMP}$
  $\psi^+ + \psi^- \to$ virtual $V^* \to$ SM states

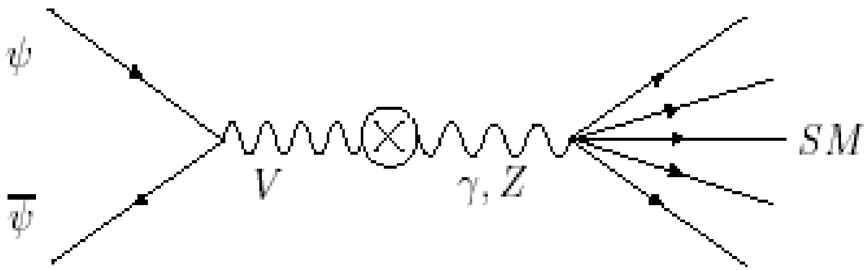
κ has to be sizable to satisfy the constraint on cross section

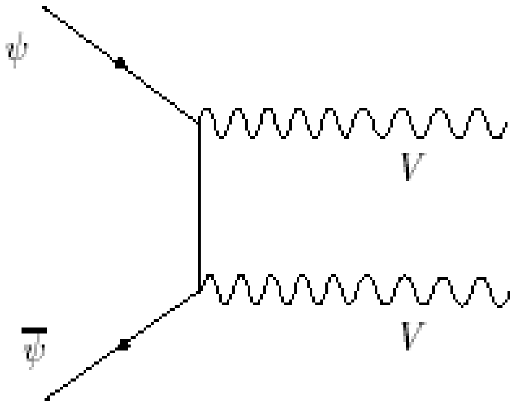
2. $m_{mediator} < m_{WIMP}$
   $\psi^+ + \psi^- \to$ on-shell $V + V$, followed by $V \to$ SM states

There is almost no constraint on κ other than it has to decay before BBN. $\kappa^2 \sim 10^{-20}$ can do the job.

Two types of WIMPs

Un-secluded | Secluded





Secluded regime

Secluded WIMPs: annihilation proceeds to metastable mediators that further decays to SM (e.g. 2 $\to$ 4 processes), and the coupling to SM is not fixed.

$$\sigma v|_{2V}^{+-} = \frac{\pi(\alpha')^2}{m_\psi^2}\sqrt{1-\frac{m_V^2}{m_\psi^2}} \xrightarrow{m_V \ll m_\psi} \frac{\pi(\alpha')^2}{m_\psi^2},$$

$$\alpha' \simeq 10^{-2} \times \left(\frac{m_\psi}{270\ \mathrm{GeV}}\right)$$

Annihilation into pair of V's: no constraint on κ

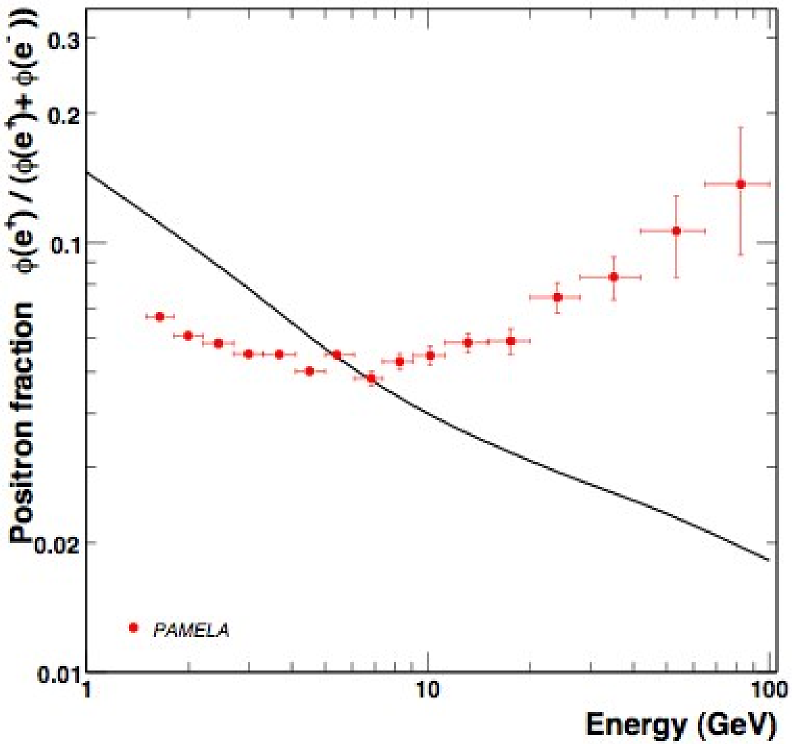
There is a generic class of models – Secluded WIMP models – where WIMP physics could have no signal at colliders and direct detection. There is still an astrophysical signatures from annihilation inside the halo.

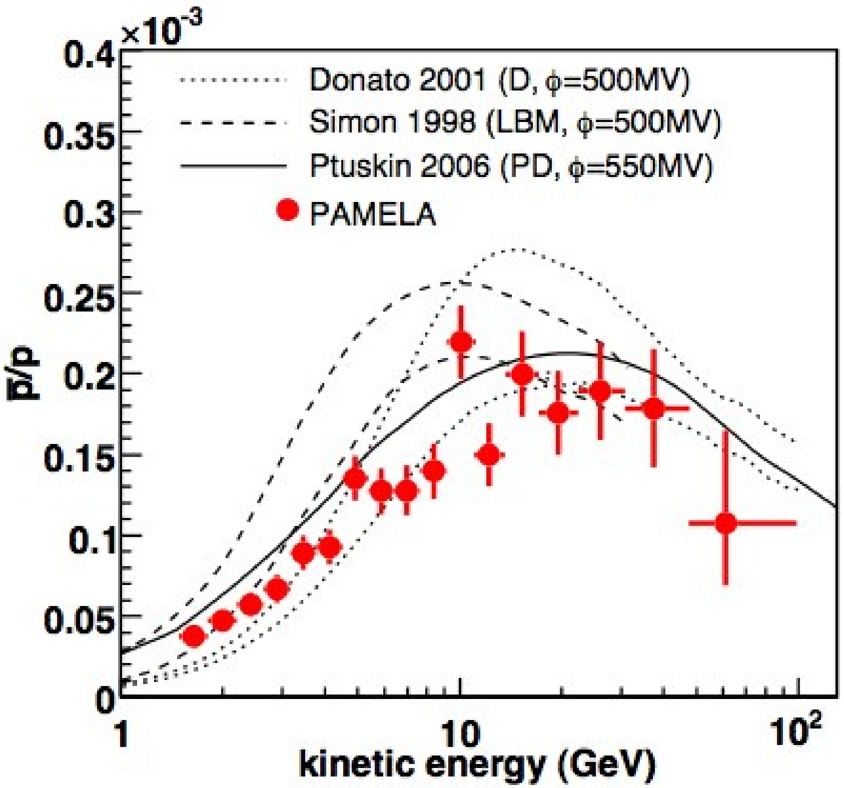
It turns out that the astrophysical signatures can be very interesting if the mediator particle (V-boson) is rather light.

Mediator in action

- HMS Mediator engaging Franco-American convoy in 1782

PAMELA positron fraction (607 citations in SPIRES)

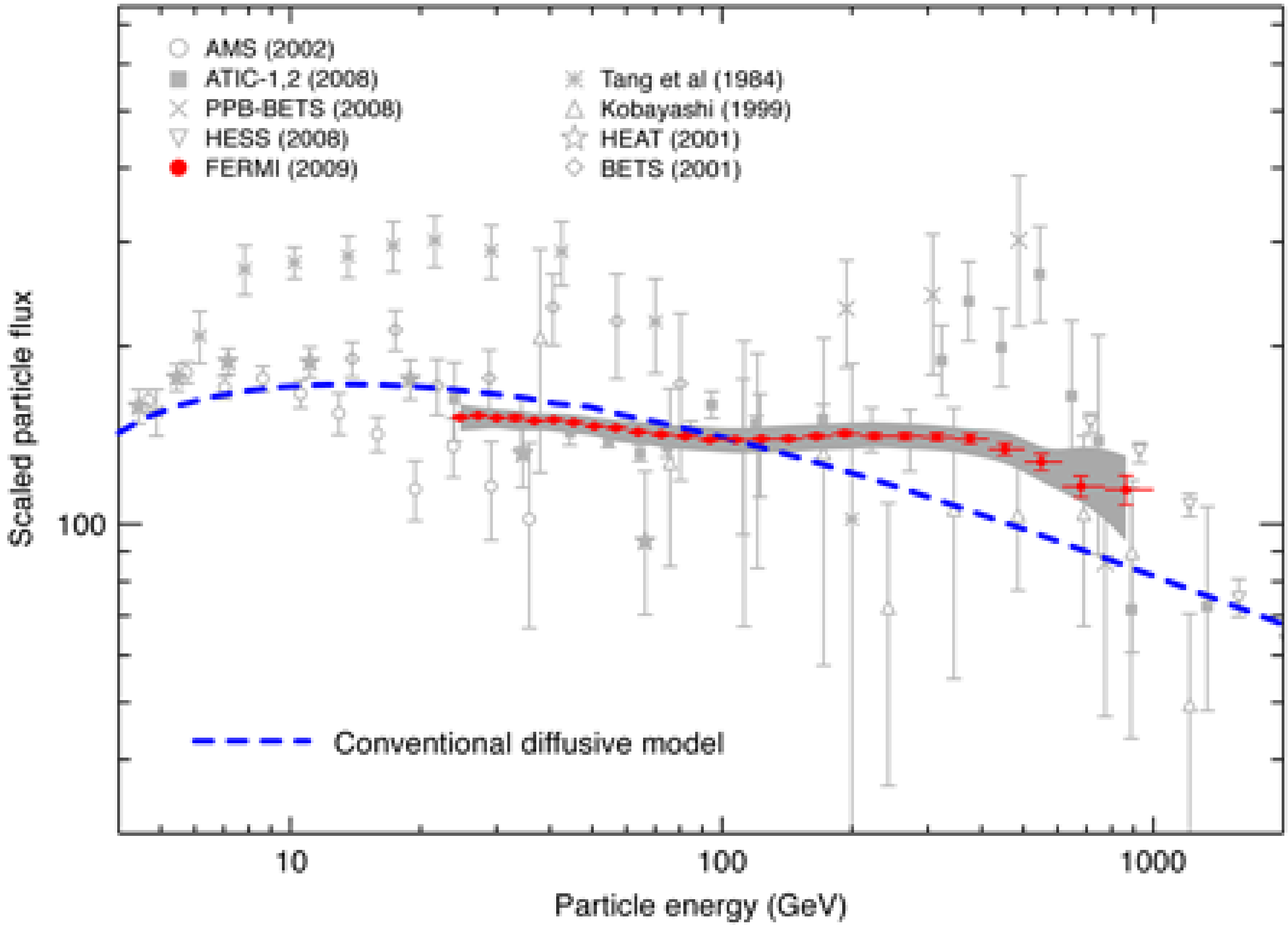




No surprises with antiprotons, but there is seemingly a need for a new source of positrons!

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.

Fermi-LAT result for the e+e- flux (359 cites)



Indirect astrophysical signatures in secluded regime

Annihilation into a pair of V-bosons, followed by decay create boosted decay products.

If m_V is under $m_{DM} v_{DM}$ **~ GeV, the following consequences are generic**

(Arkani-Hamed, Finkbeiner, Slatyer Weiner; MP and Ritz, Oct 2008)

1. Annihilation products are dominated by electrons and positrons
2. Antiprotons are absent and monochromatic photon fraction is suppressed
3. The rate of annihilation in the galaxy, σ_{ann} v, is enhanced relative to the cosmological σ_{ann} v because of the long-range *attractive* V-mediated force in the DM sector.

Fits the PAMELA result.

Possible sources of enhancement of σv over cosmological values (MP and Ritz, 2008)

- Accidental near-threshold resonances
- Sommerfeld factor $\pi\alpha/v$ (if $m_V^{-1} > \lambda_{\text{de Broglie}}$) – (might not be enough e.g. Feng et al, 2010)
- Radiative capture into WIMP-onium, (if $m_V < (\alpha')^2 m_\psi/4$)

Cross section for DM+DM -> (DMDM) + V is given by

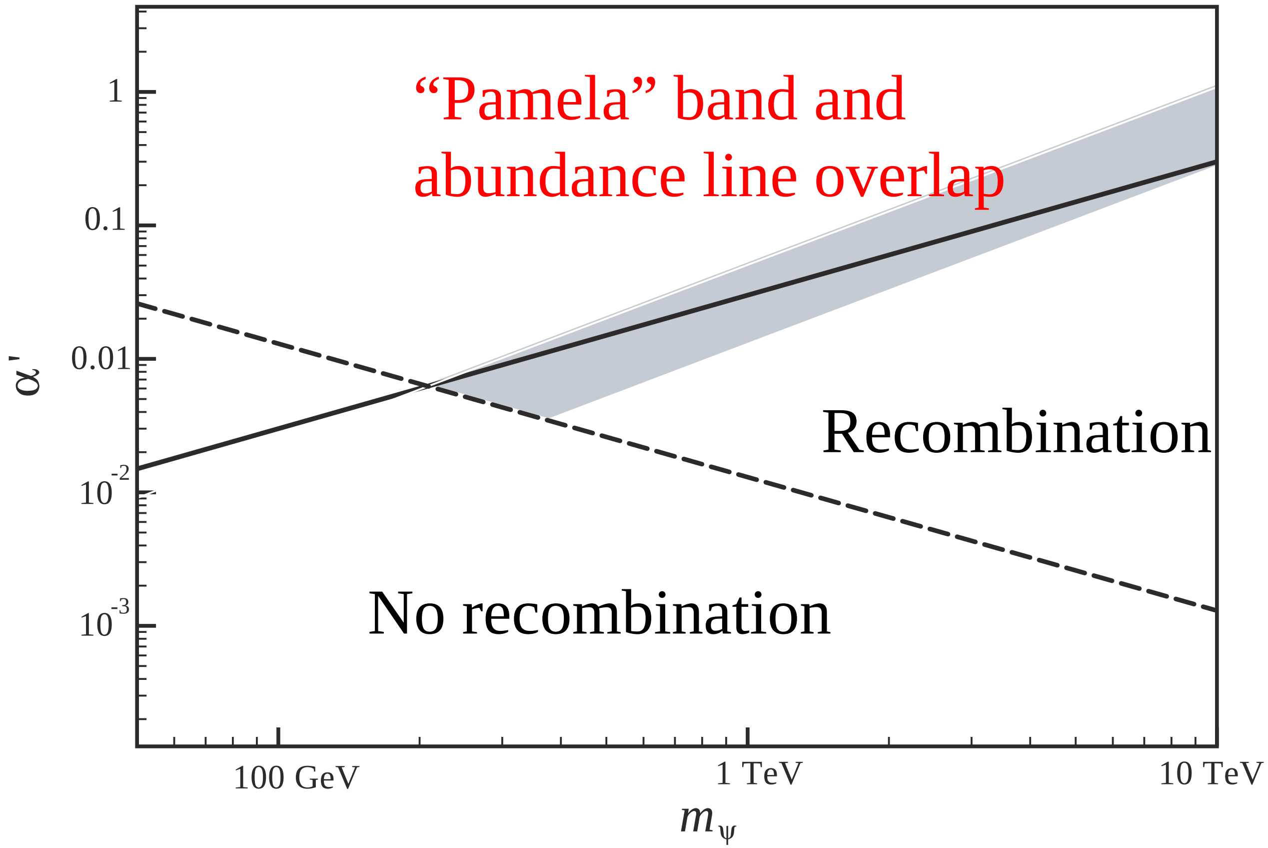
$$\sigma v|^{+-}_{\text{rec}} = \frac{2^{10}\pi^2(\alpha')^2}{3\exp(4)m^2_{\psi(\phi)}}\left(\frac{v_V(3-v_V^2)}{2}\right)\left\langle\frac{\alpha'}{v}\right\rangle_h$$

Enhancement factor constitutes

$$\mathcal{N}^\psi \simeq 20\left\langle\frac{\alpha'}{v}\right\rangle$$

This is exactly a factor of 100-1000 “needed” for WIMP interpretation of Pamela signal for few 100 GeV – TeV WIMP

Mass vs coupling parameter space



With the help of V-mediated attraction in dark sector, there is a broad agreement between secluded WIMPs and Pamela signal over a large range of WIMP masses

Search for the Dark Force

- However suggestive the PAMELA hints may look like, no conclusive proof of the existence of dark force may ever come from indirect astrophysical signatures. Even the 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.*

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)

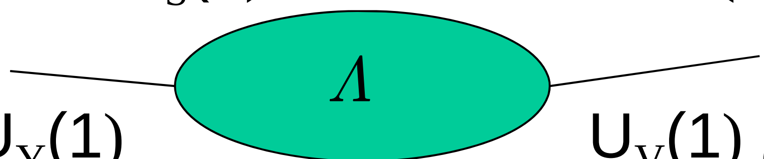


Diagram $U_Y(1)$ $U_V(1)$ does not decouple!

A mixing term is induced, $\kappa F^Y_{\mu\nu} F^S_{\mu\nu}$,

With κ having only the log dependence on Λ,

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

$M_V \sim 1/(4\pi)\, \kappa \times (M_Z$ or TeV$) \sim$ MeV - GeV

In a SUSY version of the model, relation between mixing and mass can be made more precise (C. Cheung et al, 2009)

String-theory inspired predictions for new bosons: Abel et al., 2008.

Most important aspects of extra U(1) phenomenology

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

U-boson$_{\text{Fayet}}$ $\rightarrow$ DM; V-boson$_{\text{our model}}$ $\rightarrow$ SM charged particles.

It seems that chances to detect V-boson are much higher.

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

I shall now go over novel signatures of extra sub-GeV scale U(1)

Precision QED: new force provide correction to anomalous magnetic moments of leptons

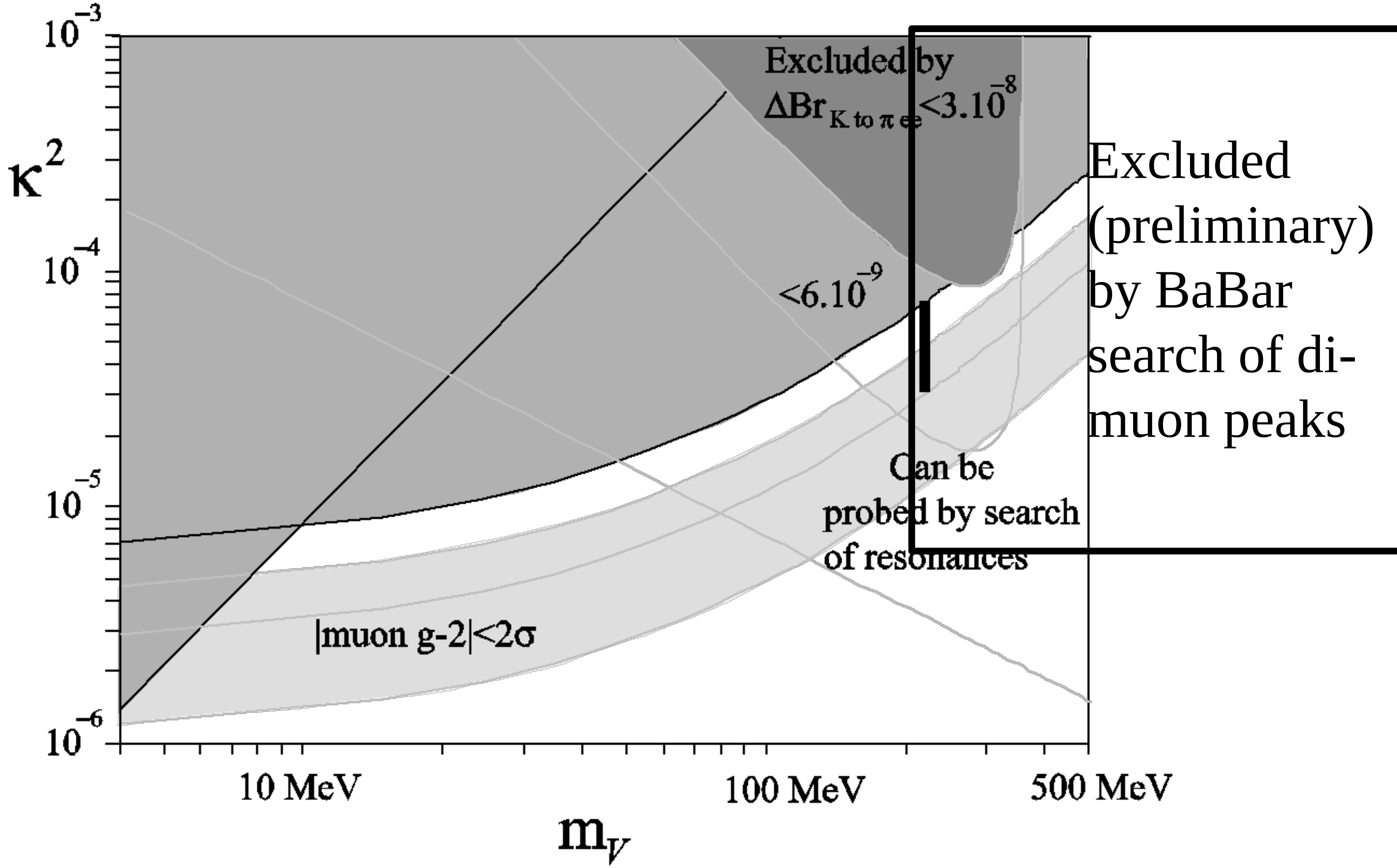
1. Electron g-2 can be used as a constraint on (m_V, κ) only in conjunction with other measurements of α_{EM}.
2. The contribution to the anomaly is *positive*. Opens the door for speculation about the "anomaly" of $(g\text{-}2)_\mu$ anomaly.

$$a_f = \frac{\alpha\kappa^2}{2\pi}\int dz\, \frac{2m_f^2}{m_f^2(1-z)^2 + m_V^2 z} = \frac{\alpha\kappa^2}{2\pi}\begin{cases} 1 & \text{for} \quad m_V << m_f \\ 2m_f^2/3m_V^2 & \text{for} \quad m_V >> m_f \end{cases}$$

For example, $m_V \sim 200$ MeV and $\kappa^2 = 3 \times 10^{-5}$ provide $\Delta a_\mu = 3 \times 10^{-9}$.

κ-m_V parameter space

If g-2 discrepancy taken seriously, mixing of order few 0.001 and mass $m_V \sim m_\mu$ helps to resolve it (MP, 2008)



V-bosons at high-energy colliders

(Arkani-Hamed and Weiner, 2008; Baumgart et al., 2009; Falkowski et al., 2010)

- Once produced, V-bosons have significant energy and decay often/predominantly to lepton producing *lepton jets*.
- Existence of light new states may *modify SUSY signals*, as the SM SUSY LSP would decay to U(1) LSP producing energetic bosons (and lepton jets). This way, one does not pay mixing^2 price.
- Higgs signatures can be modified if it decays often/predominantly into the secluded sector, producing lepton jets

Intensity Frontier: e+e- machines

(Batell, MP, Ritz; Essig, Schuster, Toro; Reece and Wang, 2009)

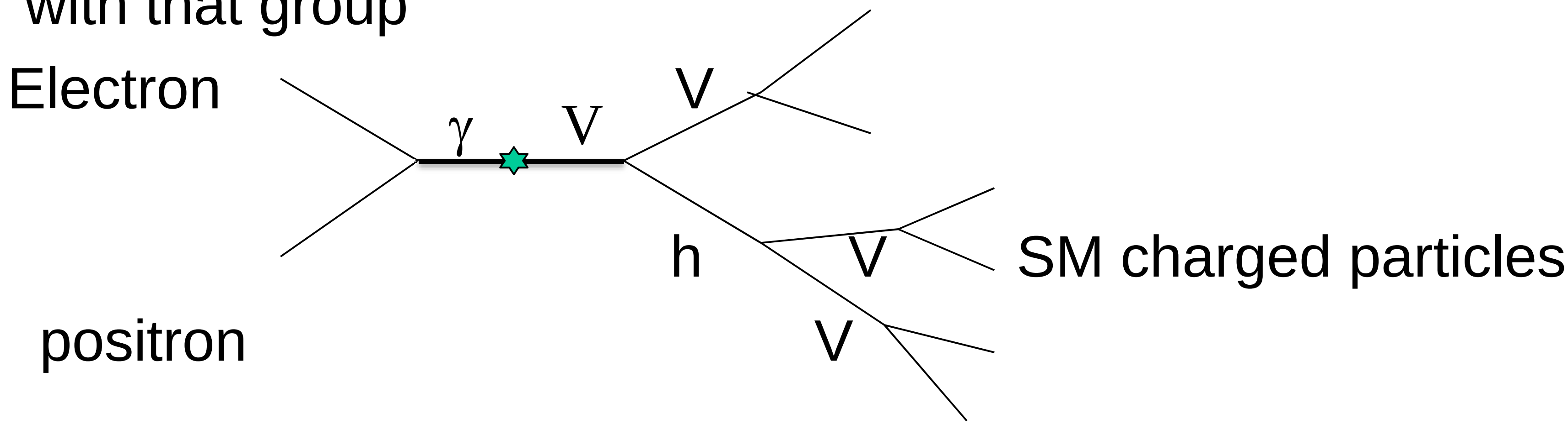
- To search for a milli-coupled GeV-scale particles, one does not need super-powerful machines like Tevatron or LHC.
- It is far more advantageous to use high-luminosity machines at medium energy, that provide clean environments to fish out the small signal.
- B-factories, that collected up to 1500 fmb^{-1} of data seem to be best suited for the search of the secluded gauge groups.
- Leading signatures:

Single vector production: $e^+ + e^- \to \gamma\, V \to \gamma\, l^+ l^-$

Higgs'-strahlung: $e^+ + e^- \to h'\, V \to$ 3 pairs of $l^+ l^-$ or $l^+ l^-$ + missing Energy

Higgs'-strahlung process

- Secluded $U_S(1)$ is spontaneously broken at relatively low scales, therefore there is a not-so-heavy Higgs' associated with that group



- Production of Vh comes at the cost of $(\kappa)^2$ in the cross section. Subsequent decay of V and h back to charged particles comes at no cost, *provided that there are no additional light states in the secluded sector.*
- *Both BaBar and Belle are planning to do a multi-lepton search.*

Probes via Rare Meson Decays

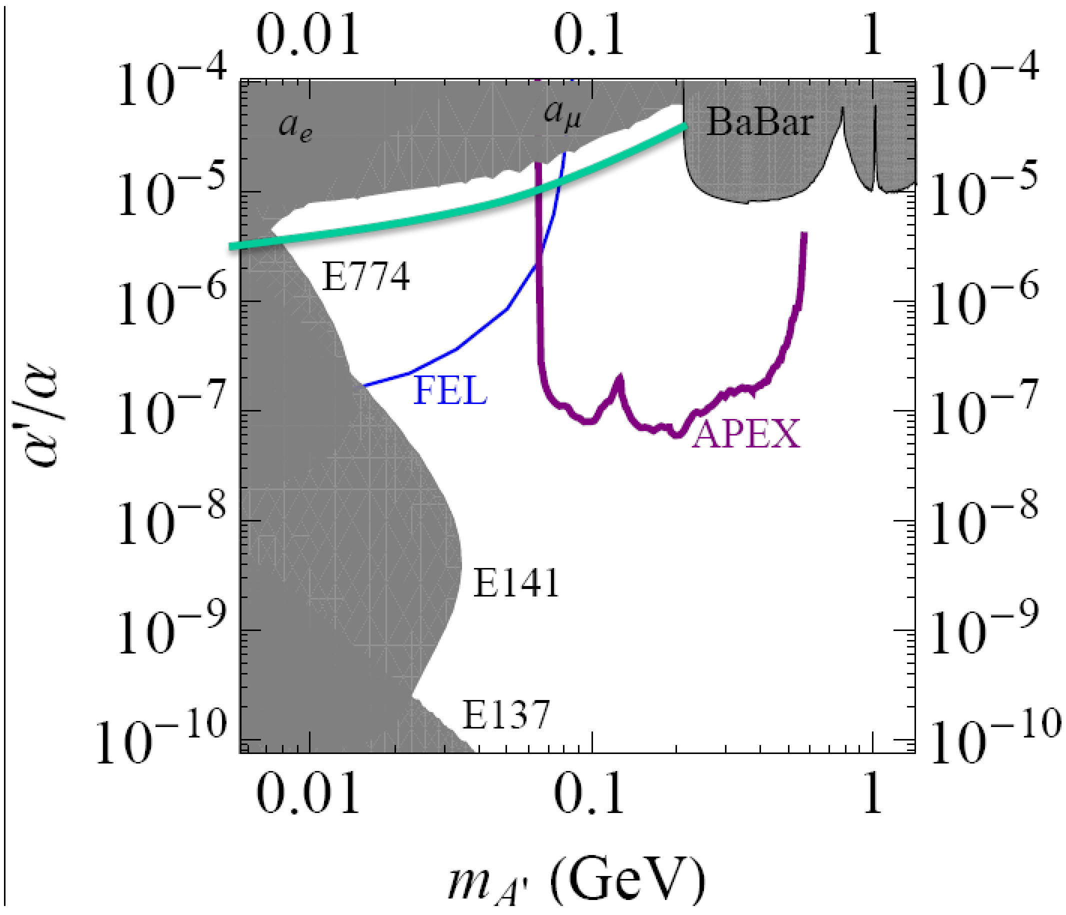
Can also search for resonant structures in rare meson decays witl (low mass) sensitivity κ ~ 10^3 - 10^4

- Kaon decays: $$\mathrm{Br}_{K_L \to V\gamma} \simeq 10^{-3} \times \kappa^2 \times \left(1 - \frac{m_V^2}{m_K^2}\right)^3$$

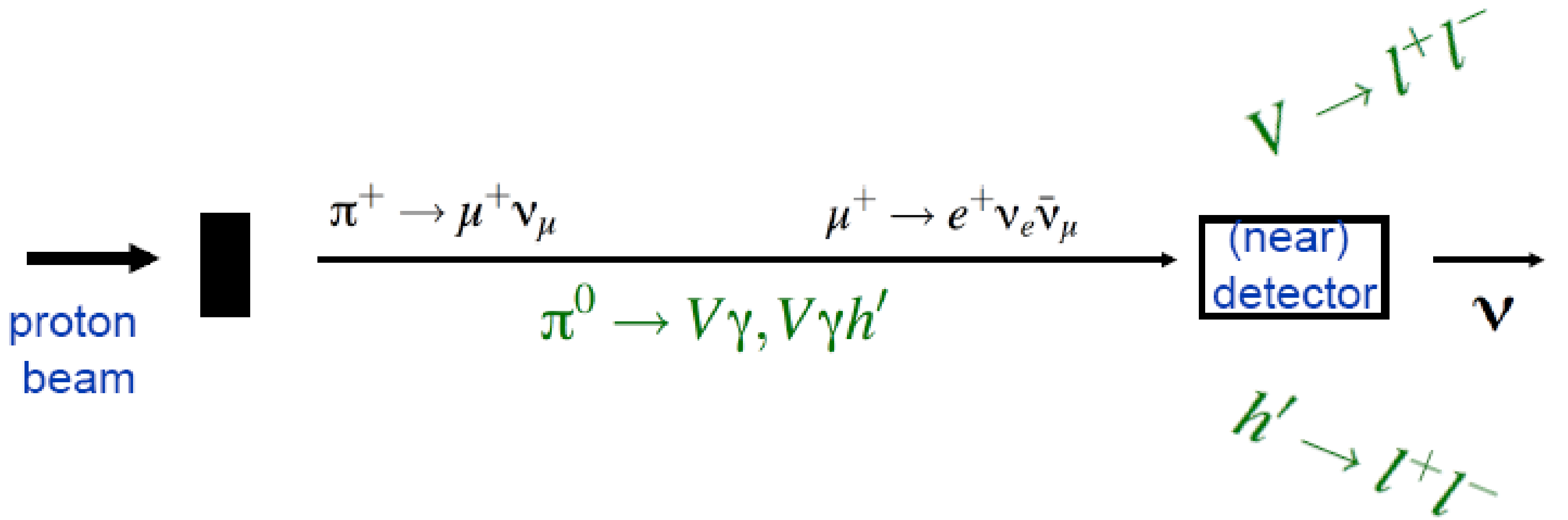
$$\mathrm{Br}_{K_L \to \mu^+\mu^-\gamma} \simeq 3.6 \times 10^{-7}$$ [10^4 events @ KTeV '01]

Intensity Frontier: Electron beam on target

- Bjorken et al., 2009; Fisher and Thaler, 2009; Essig et al. 2010.
- Advance by several orders of magnitude in terms of kappa can be made. Subject of this conference. g-2 region can be fully probed!



Neutrino beam setup can be used for studying long-lived relics (Batell et al., 2009; Harnik et al. 2010)



Neutrino productions are set by strong interactions,

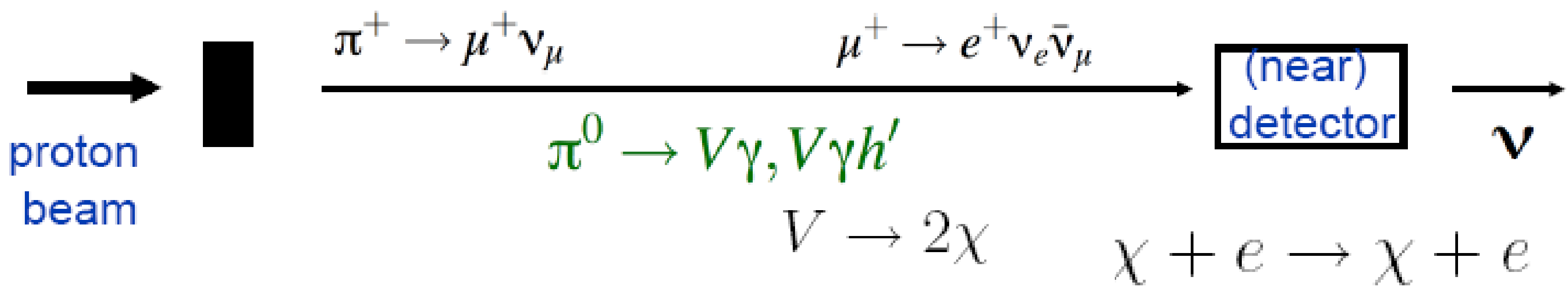
while their detection probabilities are due to weak interactions, 10^(-14)

Exotic particle production may be small, O(kappa^2), but probability of decays inside the detector may be "geometric", as large as 10^(-4). Main

Background may come from neutrinos!

Neutrino beam setup can be accompanied by a beam of *other* light neutral states. "Dark matter beam"

(MeV DM a la Fayet, Boehm)



Probability of prompt decay of V into new dark states χ can be sizable.

Scattering within the detector can look like neutral current events, but being mediated by light vectors could be *larger* than weak scattering rates. E.g. LSND provides best constraints on MeV WIMPs

Beam of MeV-dark matter

LSND provides by far the most precise test of the MeV dark matter idea of Boehm and Fayet; MP, Ritz and Voloshin. This model kills SM modes of V decay – escapes most tests.

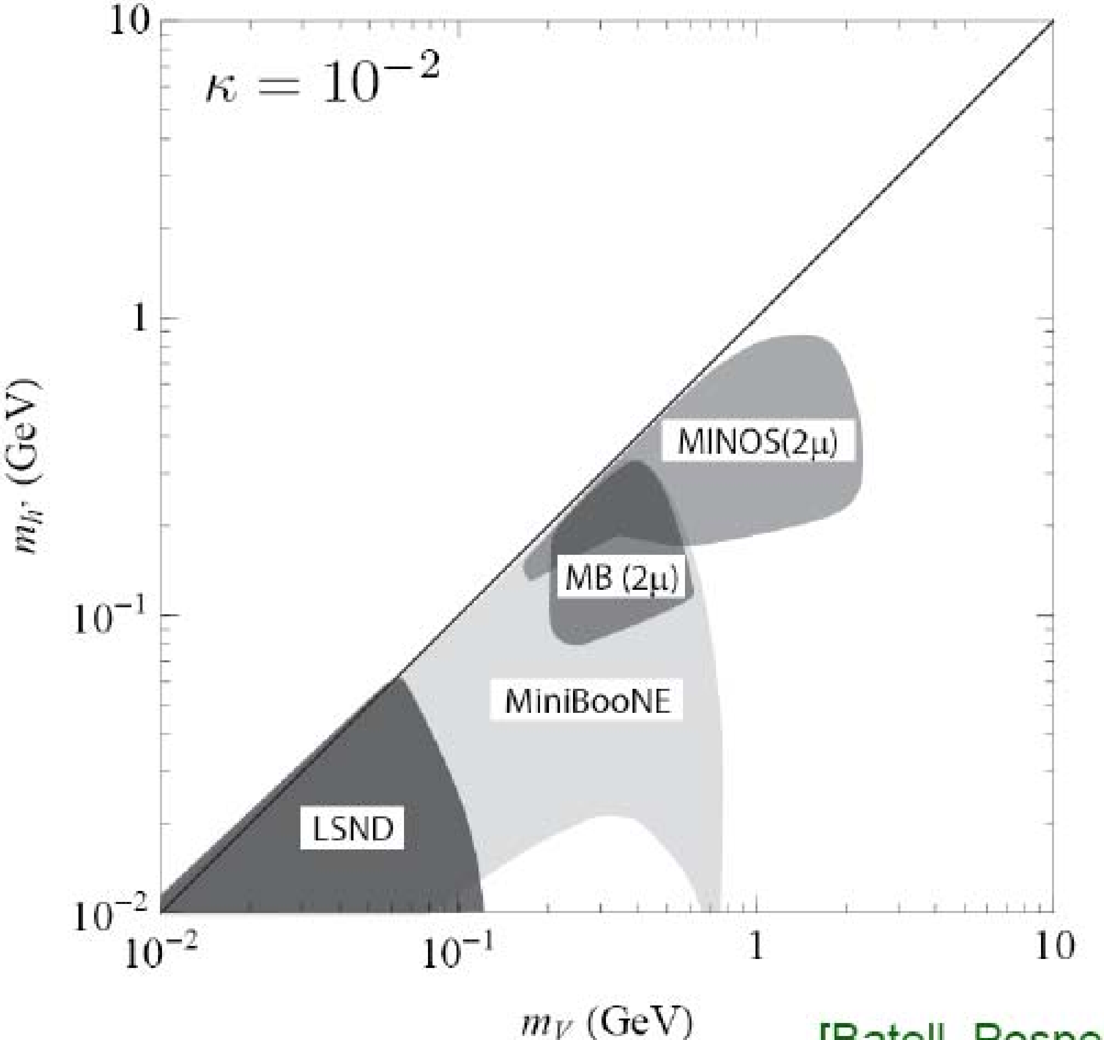
1. $p + p \to X + \pi^0$
2. $\pi^0 \to \gamma V$
3. $V \to 2\chi$
4. $\chi + e \to \chi + e$

$$\frac{\alpha' \kappa^2}{\alpha} \times \left(\frac{10\text{ MeV}}{m_V}\right)^4 \times \left(\frac{m_\chi}{\text{MeV}}\right)^2 \sim 10^{-6}.$$

For a "sweet spot" in parameter space (correct abundance of MeV dark matter, enough positrons for 511 keV line), the total count in the LSND detector **should exceed million events**. These type of searches can be repeated at SNS where the huge beam power at 1GeV is being used. **New proposal (CLEAR) to measure elastic neutrino-N scattering at SNS can be used to kill MeV DM.**

Sensitivity to Higgs'

From LSND, MiniBooNE, NuMI/MINOS, …



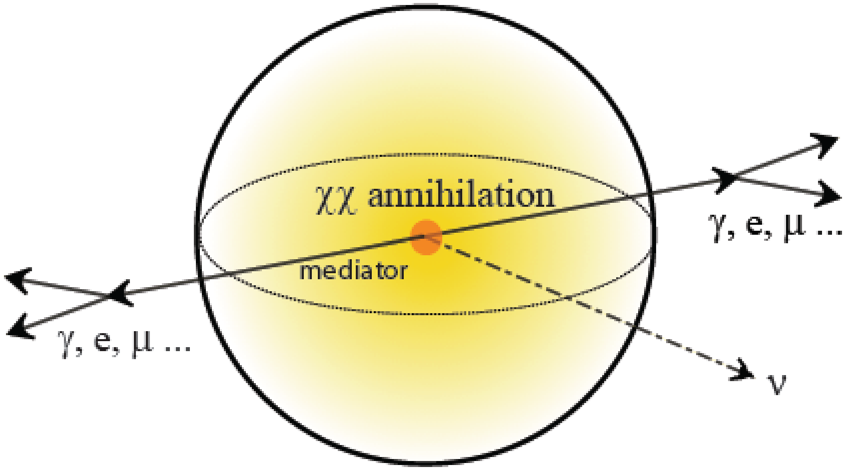
[Batell, Pospelov, AR '09]

Novel signatures for DM physics

- Inelastic processes in direct detection. Instead of pure Dirac fermion, WIMPs can be a quasi-degenerate system of two Majorana fermions which modifies WIMP-nucleus scattering
- Endothermic scattering. O(100 keV) splitting between WIMP components changes the pattern of WIMP-nucleus scattering: WIMPs prefer to scatter off heavier target (Tucker-Smith, Weiner, 2000).
- Exothermic scattering. Excited component of WIMPs may live very long time if $\Delta m < 2 m_e$. WIMP-nucleus scattering may occur with energy release, in excess of what one would naively assume. New signature for direct detection. (Finkbeiner, Slatyer, Weiner, Yavin; Batell, MP, Ritz, 2009).

Novel signatures for DM physics

- DM annihilation inside the Sun/Earth etc may create meta-stable light-ish states that are boosted and decay outside solar radius.
- Decays of metastable mediators create gamma rays from the Sun, collimated with the direction to the central region. Can be searched for with FERMI-GLAST gamma ray telescope.



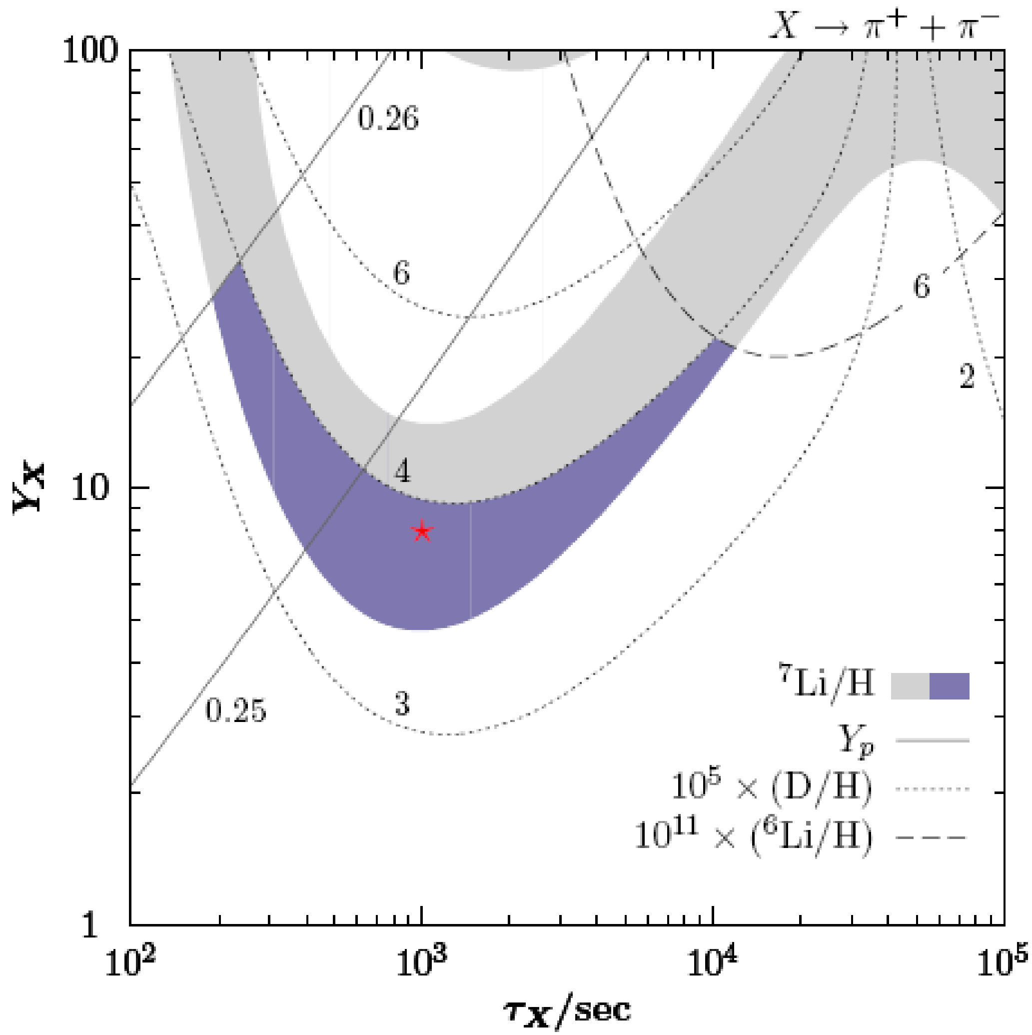
(Batell, MP, Ritz, Shang; Schuster, Toro, Yavin, 2009)

Early Universe and impact on BBN (MP, J. Pradler)

- If "dark force members" live > 1sec, there can be a significant impact on BBN. For lifetimes ~ few 100 – few 1000 seconds, the decay products can interact with protons, producing extra neutrons.
- Extra neutrons are being removed by np$\rightarrow$ dγ reaction, leading to elevated D/H.
- They also convert ^{7}Be to ^{7}Li, followed by ^{7}Li+p$\rightarrow$ 2α. This reduces overall ^{7}Be+^{7}Li abundance (Reno and Seckel, 1987; Jedamzik, 2004), which is intriguing in light of the current cosmological lithium problem (factor of 3 over-production).
- Secluded U(1) models provide perfect candidate with potentially long lifetime, an extra Higgs in the regime m_h < m_V.
- Unrelated to BBN, there is an important modification to the CMB anisotropies due to the extra heating from DM annihilation

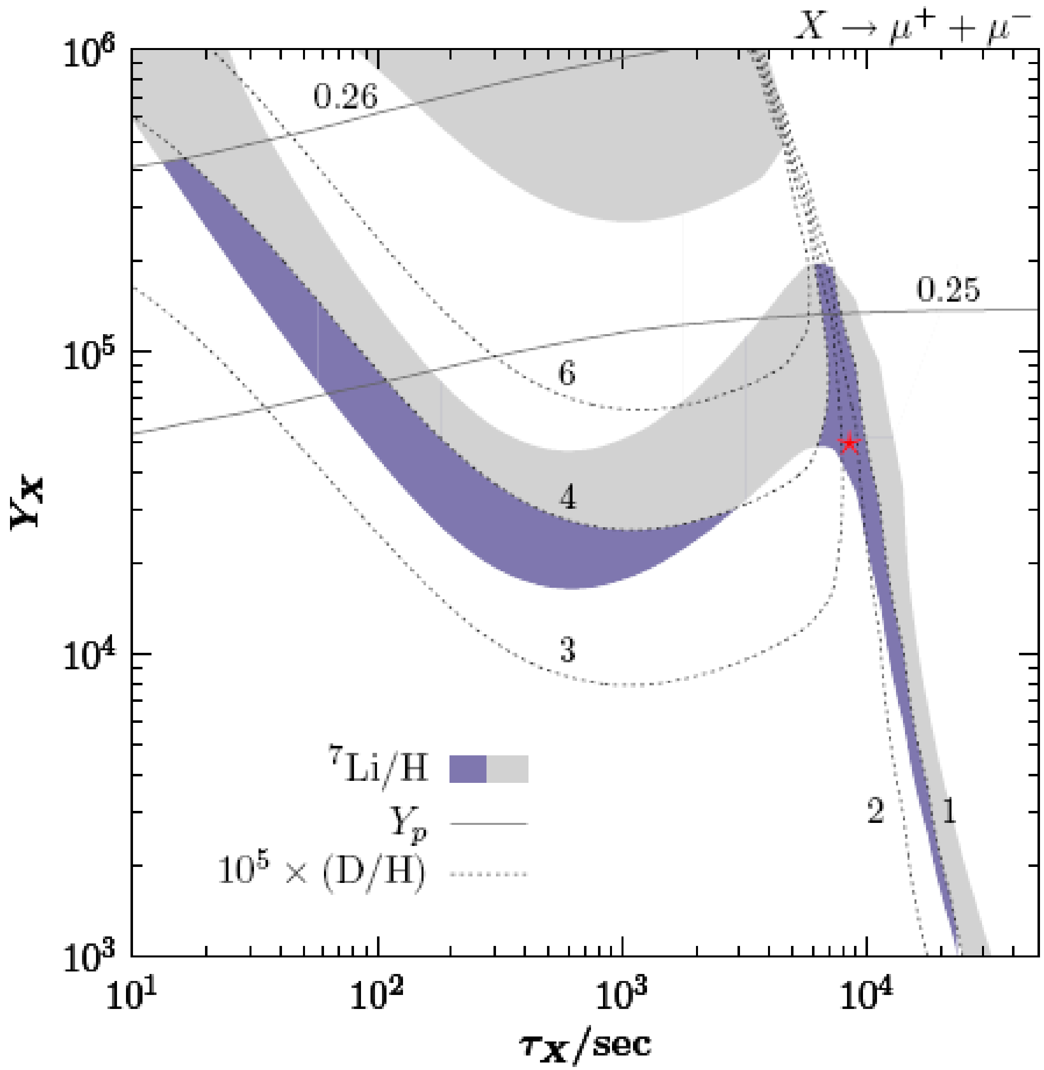
(Slatyer et al., 2009; Galli et al., 2009)

Injection of pions



~ 10 π^- per nucleon are capable of changing neutron abundance by ~ 10^{-5}.

Injection of muons



~ 10^5 μ per nucleon are capable of changing neutron abundance by~ 10^{-5}. Extra neutrons come from additional electron antineutrinos.

Cosmological abundance of secluded Higgses

- Initial abundance of h' is thermal. They live ~ 1000 seconds, and cannot annihilate very efficiently. Naively, they should overclose the Universe at ~ 1 second, and such models are ruled out.
- However, "co-decay" processes save the day:

$$
\begin{aligned}
h' + h' &\to V + V, && \Gamma_1 \propto (\alpha')^2 \kappa^0 \exp(-m_{h'}/T - 2\Delta m/T) \\
h' + V &\to l^+ l^-, && \Gamma_2 \propto \alpha' \alpha \kappa^2 \exp(-m_{h'}/T - \Delta m/T) \\
h' + l^\pm &\to V + l^\pm, && \Gamma_3 \propto \alpha' \alpha \kappa^2 \exp(-\Delta m/T),
\end{aligned}
$$

where $\Delta m = m_V - m_{h'}$. The last process is the most efficient.

- kappa $\sim 3 \times 10^{-5}$ is required for the right lifetimes.

$2\, m_\mu < m_h < 2\, m_\pi$ and $m_V = 1.7\, m_h$ solves lithium problem via injection of muons.

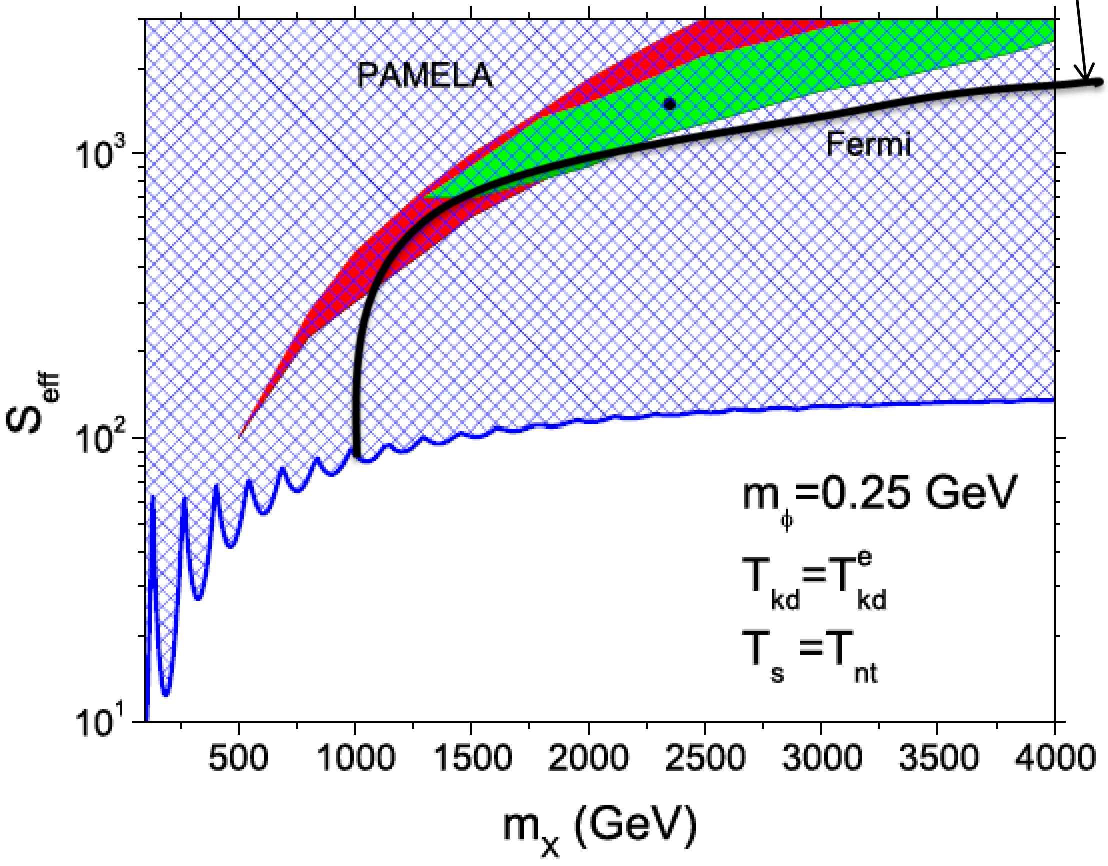
$m_h > 2\, m_\pi$ and $m_V = 1.3\, m_h$ solves lithium problem via injection of pions (kaons).

Conclusions

- Extra U(1) below the weak scale is a natural theoretical possibility. WIMP physics combined with the GeV-scale dark force idea provide nice interpretation to the PAMELA positron anomaly.
- Gauge bosons/Higgses of Dark Forces can be searched for at the precision and intensity frontiers. High-luminosity medium-energy colliders or fixed targets + powerful beams probe a wide range of masses and mixing angles.
- Long-lived (e.g. ~ msec) mediator particles provide novel observational signatures such as annihilation into metastable states inside the Sun, with subsequent decays outside solar radius. Lifetimes of ~1000 sec are not inconsistent with cosmology, and can alleviate lithium problem.
- The model is very simple but is full of surprises!

Recent paper on Sommerfeld enhancement miss the effect of "DM recombination" (MP and Ritz, 2008)

- Feng et al., May 2010



Correctly calculated enhancement factor cuts right through PAMELA and FERMI.

To enhance Sommerfeld, add Bethe and Salpeter.

Hyper-CP anomaly from m_V =214 MeV

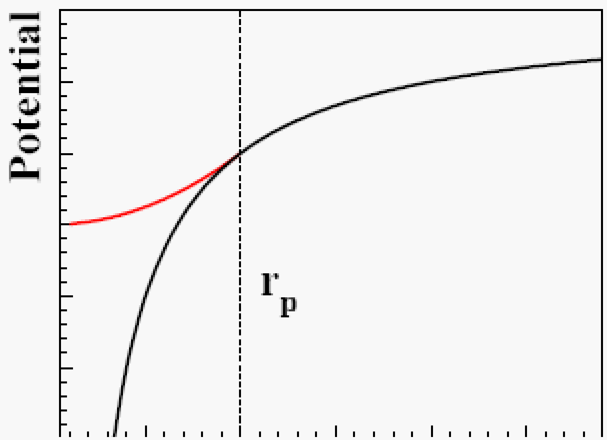
There is a published "anomaly" in the spectrum of muon pair created by the hyperon decay, $\Sigma^+ \to p\, \mu^- \mu^+$. All three events have the same, 214 MeV invariant mass. Branching ~ 10^{-8}.
Can this be caused by secluded V-boson?

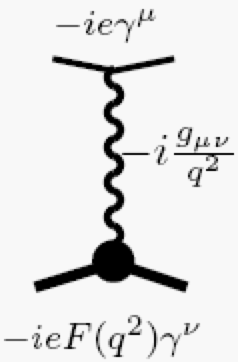
This issue have been looked at by X-G He, Tandean, Valencia, who concluded that vector-like coupled new physics $(s\, \gamma_\mu\, d)\, V_\mu$ cannot fit Hyper CP (process C.) without introducing too large branchings for A. and B. *This conclusion does not apply in this case because all decays are saturated by long-distance contributions.*

My results: Model with secluded U(1)', m_V =214 MeV, $\kappa^2 \sim 10^{-4}$ can contribute to $\Delta\, Br_C$ = few $\times\, 10^{-8}$, while giving $\Delta\, Br_{A,B} \sim 10^{-9}$. Spectrum of lepton pairs in K-decays can show the presence of V-boson.

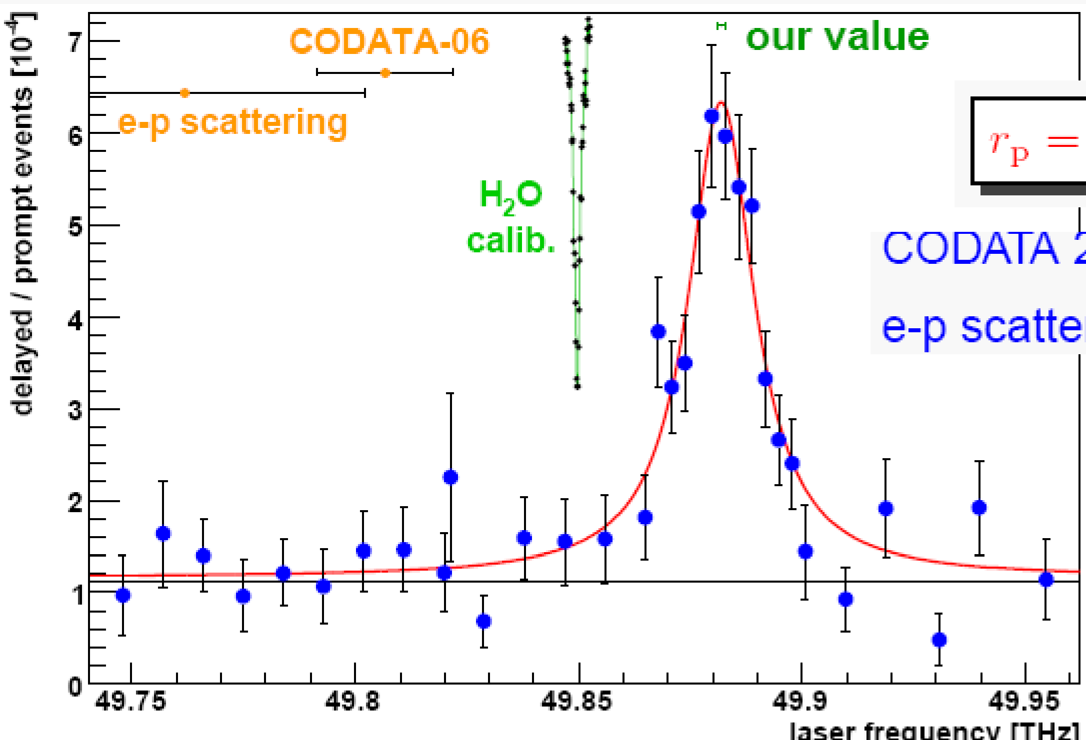
Muonic hydrogen Lamb shift

Fresh of the Nature press!





Contribution of r_p is much larger in μH because the muon is 200 times closer to the nucleus.



$r_{\mathrm{p}} = 0.84184(67)$ fm $\qquad u_r^{\mathrm{th}} = 8 \times 10^{-4}$

CODATA 2006: $r_{\mathrm{p}} = (0.8768 \pm 0.0069)$ fm, from H

e-p scattering: $r_{\mathrm{p}} = (0.895 \pm 0.018)$ fm (2%)

Muonic hydrogen Lamb shift

current discrepancy in r_p – error (possibly in Ry), or new physics?

- New efforts to check Ry constant? μH, new tests with μHe ? Too early to panic.
- Could we blame it on a "dark force"? New vector particle with

effective mass m_V = 2-3 MeV and effective coupling

α = few $\times\ 10^{-9}$ between proton and muon is capable of

A. Giving 300×10^{-11} *positive* correction to muon anomaly
B. Providing extra *negative* contribution to binding energy of μH that is interpreted as proton shrinking by ~ 3.5×10^{-3} fm.

"Dark photon" does not quite "work". Predicts

Radius (scattering) > radius (muonic Hydrogen) > radius (normal H)

Other possibilities with gauged B-3L$_\mu$ (or alike) predict too large effects for muon neutrinos. Gauging RH muon (besides new states for anomaly cancellation) would predict large Parity violation in μ-p interaction. Not clear if viable.