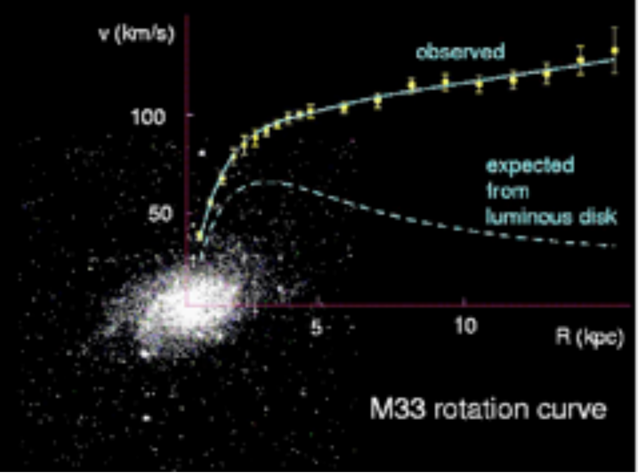
Dark Z boson and Parity Violation

based on the works with H. Davoudiasl and W. Marciano at BNL
[PRD85 (2012), PRL109 (2012), PRD86 (2012)]

Hye-Sung Lee
(William and Mary / Jefferson Lab)

JLab Hall A Collaboration Meeting
Jefferson Lab, December 2012

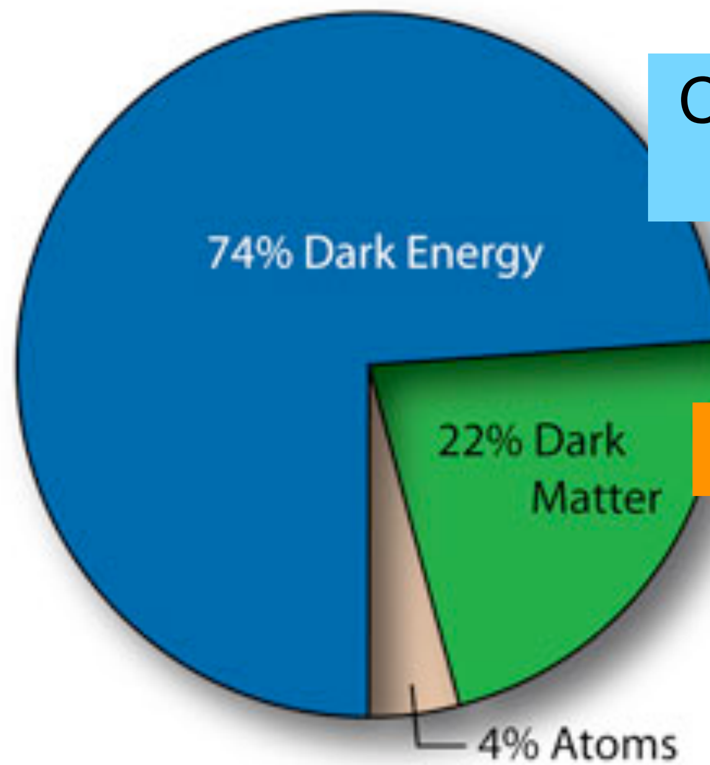
Prelude



We live in a Dark World

Established fact by now: there is a Dark sector (Dark matter, Dark energy, ...).
Too many evidences to deny it. (Galaxy rotation curve, Gravitational lensing, Cosmic Microwave Background, ...)

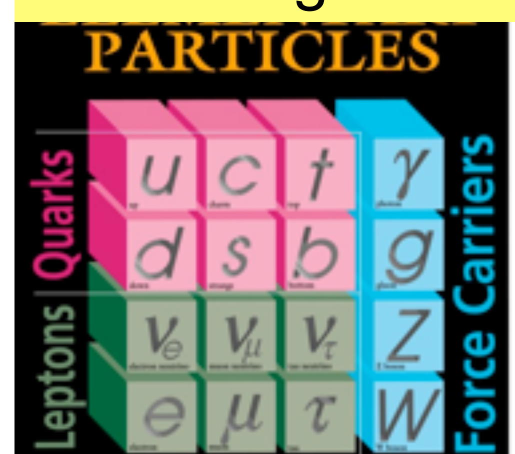
Cosmological constant Λ of Einstein's GR?

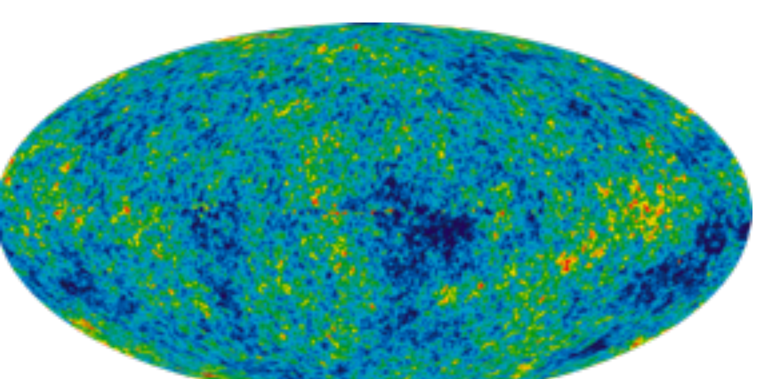


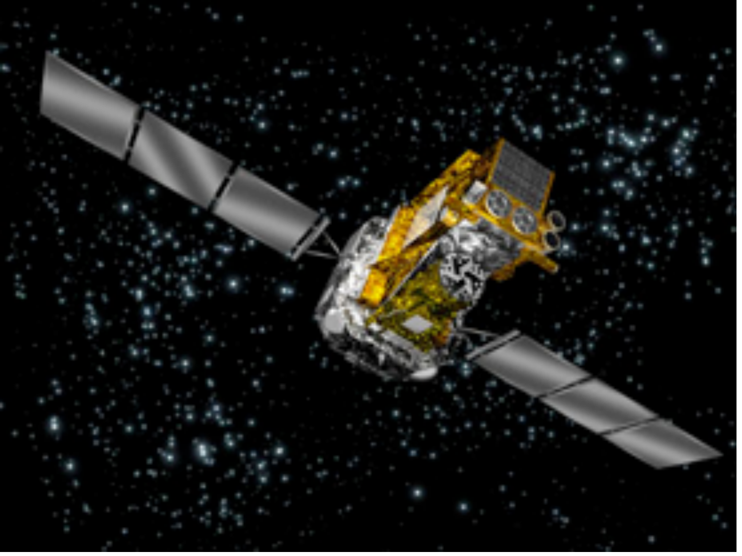
One New particle?

Q: What does it look like though?
Cosmological constant + One particle?
(Minimal picture)

"Rich" Bright sector (SM)



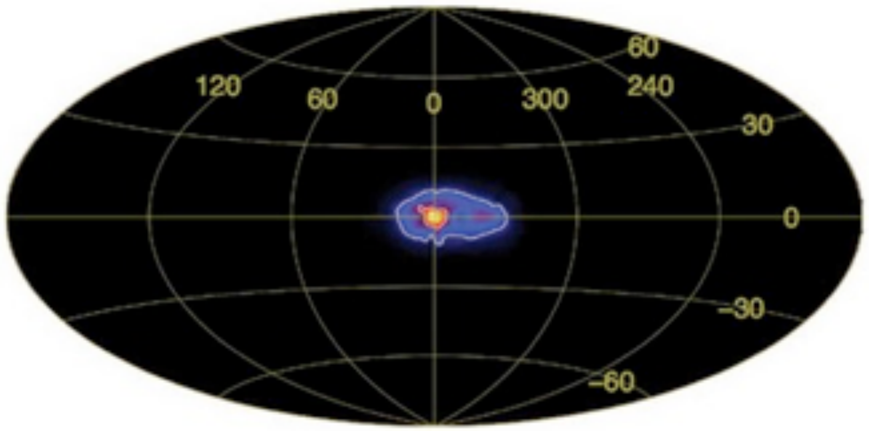




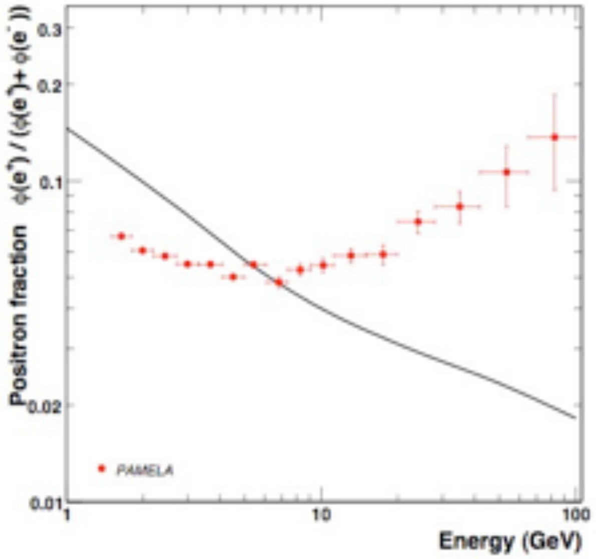
Hints for "Rich" Dark Sector

(Many Dark Particles)

Hint for Rich Dark sector: Excess in the astrophysical signals from our galaxy.



[511 keV gamma-ray (INTEGRAL)]



[Positron excess (ATIC, PAMELA)]

These are hard to explain with a Minimal picture (Λ + 1 particle) for Dark Sector.
→ It implies the Dark sector may be Rich (with other particles interacting with DM).

Natural. Bright sector (only 4% of Universe energy) has rich structure.

Among the candidates are a so-called **"Dark Force"** carrier.

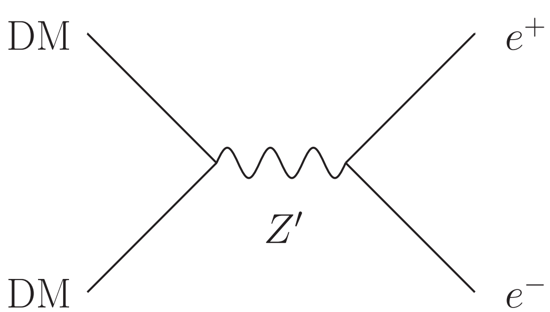
Dark Force (New gauge interaction in Dark sector)

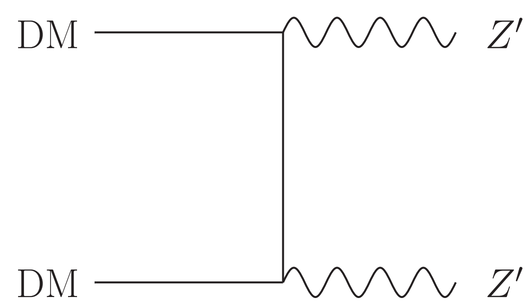
Dark Force carrier: Light Z' [a new gauge boson of $m_{Z'}$ ~ O(1) GeV]

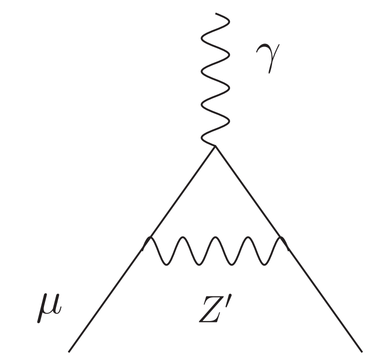
($m_{proton} \approx 1$ GeV)

DM annihilation at Galactic center with "GeV-scale gauge boson" can explain

(1) 511 keV gamma-ray (INTEGRAL) [Fayet (2004)]
(2) Positron excess (ATIC, PAMELA) [Arkani-Hamed,Finkbeiner,Slatyer,Weiner (2008)]







$$(\text{magnetic moment}) = -\frac{g\mu_B S}{\hbar}$$

g_μ : muon magnetic moment factor
$(g-2)_\mu=0$ (at tree-level)

Also, $(g-2)_\mu$ anomaly, (3.6σ deviation), can be explained [Fayet (2007); Pospelov (2008)].

Cf. Many pioneering works on Light Z' (called "U boson") in a rather general setup were done by [P. Fayet (since 1980)].

Dark Force carrier (Light Z') searches

The Rich Dark sector picture (DM + more particles) motivates the search for Dark Force carrier (Light gauge boson).

Particularly interesting: One of the New Physics scenarios that can be tested with existing/upcoming Low-Energy experimental facilities (JLab in US, Mainz facility in Germany, etc).

Many searches based on the "Dark Photon" model (well-established Dark Force scenario) are actively going on.

What I will present today:
(i) We generalize the "Dark Photon" to "Dark Z" (New Dark Force model).
(ii) We expand the types of the relevant Dark Force search experiments.

Hunting for New fundamental force

Fundamental forces (interactions) known to us:
(1) Gravity [I. Newton, ... in 17C]
(2) Electromagnetic force [J. Maxwell, ... in 19C]
(3) Weak nuclear force [E. Fermi, ... in 20C]
(4) Strong nuclear force [M. Gell-Mann, ... in 20C]

Each and every fundamental force made huge impact in understanding physical world.

Discovery of another fundamental force will do the same.

Outline

1. Dark Photon overview (well-established model)

2. Dark Z (New model by Davoudiasl, HSL, Marciano)

3. Dark Z Implications for Parity-Violating Experiments

"New" search for Dark Force

1. Dark Photon (overview)

Dark U(1)

Consider a U(1)' gauge symmetry -- Dark U(1) -- which may interact with DM and Hidden sector particles (particles unknown to us). SM particles have zero charges.

Gauge boson kinetic term (QED example):

[QED] $$\mathcal{L}_{\rm kin}^{\rm QED} = -\frac{1}{4} A_{\mu\nu} A^{\mu\nu} \qquad (\text{with } A_{\mu\nu} \equiv \partial_\mu A_\nu - \partial_\nu A_\mu)$$

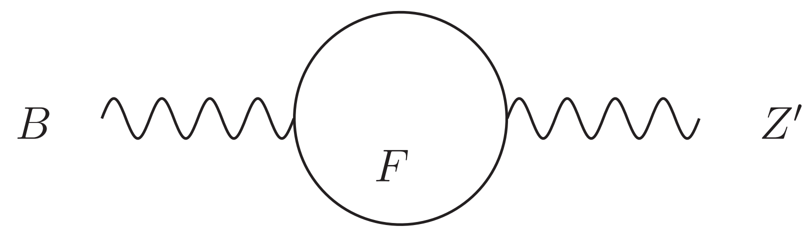
Z' couples to SM particles through kinetic mixing of $U(1)_Y$ & U(1)'. [Holdom (1986)]

[SM+U(1)'] $$\mathcal{L}_{\rm kin} = -\frac{1}{4} B_{\mu\nu} B^{\mu\nu} + \frac{1}{2} \frac{\varepsilon}{\cos\theta_W} B_{\mu\nu} Z'^{\mu\nu} - \frac{1}{4} Z'_{\mu\nu} Z'^{\mu\nu}$$

$$B_\mu = \cos\theta_W A_\mu - \sin\theta_W Z_\mu$$

(Hypercharge gauge boson = Photon & Z boson)

Expected size of kinetic mixing from loops of heavy fermions: $\varepsilon \sim (g_Y g_{Z'})/(16\pi^2) \lesssim 10^{-3}$



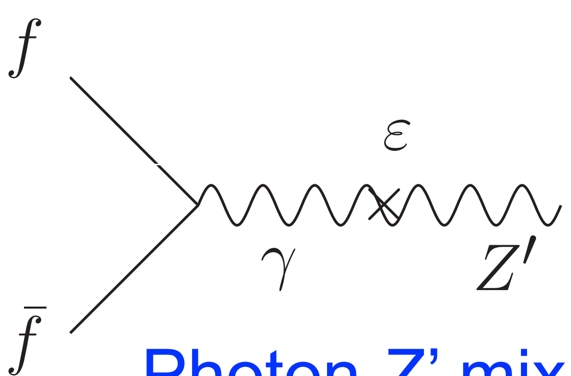
Dark Photon

Typical phenomenology of the $U(1)_Y$ & U(1)’ kinetic mixing is carried out in the setup that Z’ couples only to Electromagnetic (EM) Current just like Photon.

[QED] $\mathcal{L}_{\rm int}^{\rm QED} = -eJ^{\mu}_{em}A_{\mu}$ $\quad (J^{\mu}_{em} = Q_f \bar{f}\gamma^{\mu} f)$

(EM current) ~ flow of fermions with electric charge

[SM+U(1)’] $\mathcal{L}_{\rm int} = -\varepsilon\, eJ^{\mu}_{em}Z'_{\mu}$



$: \ \varepsilon\, eQ_f$

Photon-Z’ mixing

(coupling) = ε (Photon coupling)
Thus, named as “Dark Photon”

Puzzling at first glance since $B_{\mu} = \cos\theta_W A_{\mu} - \sin\theta_W Z_{\mu}$

$SU(2)_L \times U(1)_Y \rightarrow U(1)_{em}$

$\{W_1, W_2, W_3, B\} \rightarrow \{W^+, W^-, Z, \gamma\}$

(What happened to Z-Z’ mixing?)

Higgs structure matters

Dark Photon is justified **in the simplest Higgs structure**

"SM Higgs doublet + Higgs singlet"

(Higgs doublet: to break $SU(2)_L \times U(1)_Y$ and give mass to SM gauge bosons),
(Higgs singlet: to break U(1)' and give mass to Z').

Z-Z' kinetic mixing part is cancelled by Z-Z' mass mixing (which is "induced by kinetic mixing") at Leading order.

$$\mathcal{L}_{\text{int}} \sim -eJ^{\mu}_{em}A_{\mu} - (g/\cos\theta_W)J^{\mu}_{NC}Z_{\mu}$$

(Kinetic mixing diagonalization) $\rightarrow -eJ^{\mu}_{em}[A_{\mu} + \varepsilon Z'_{\mu}] - (g/\cos\theta_W)J^{\mu}_{NC}[Z_{\mu} + O(\varepsilon)Z'_{\mu}]$

(Z-Z' mass matrix diagonalization) $\rightarrow -eJ^{\mu}_{em}[A_{\mu} + \varepsilon Z'_{\mu}] - (g/\cos\theta_W)J^{\mu}_{NC}Z_{\mu}$

depends on Higgs sector

for 1 Higgs doublet + singlet

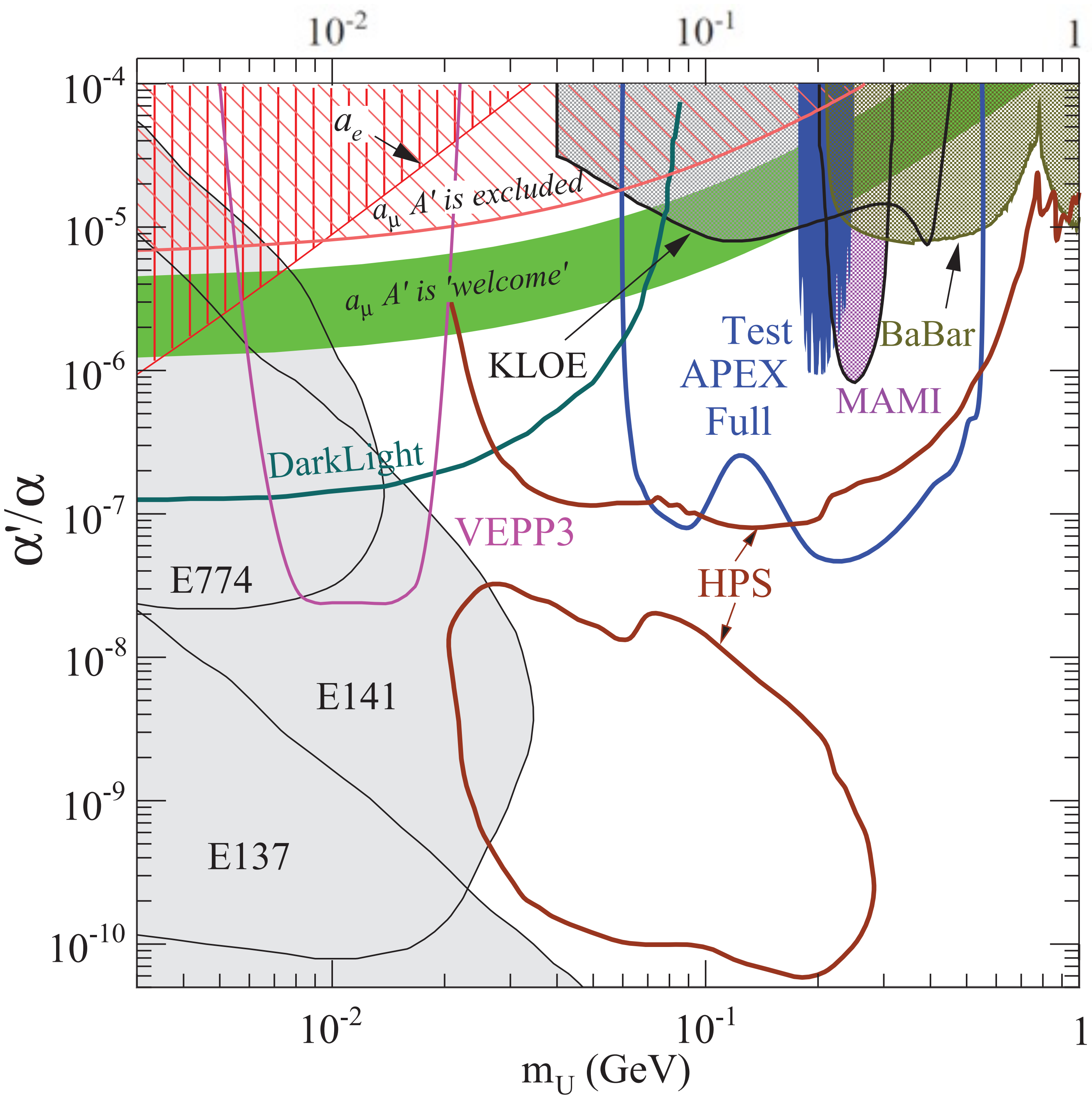
* SM Z boson couples to weak Neutral Current: $J^{NC}_{\mu} = \left(\frac{1}{2}T_{3f} - Q_f \sin^2\theta_W\right)\bar{f}\gamma_{\mu}f - \left(\frac{1}{2}T_{3f}\right)\bar{f}\gamma_{\mu}\gamma_5 f$

(weak Neutral Current) ~ flow of fermions with Z boson charge

Dark Force couplings depend on Higgs sector.

(Later, we use this observation to introduce "Dark Z" which couples to NC.)

Typical implications for Dark Photon



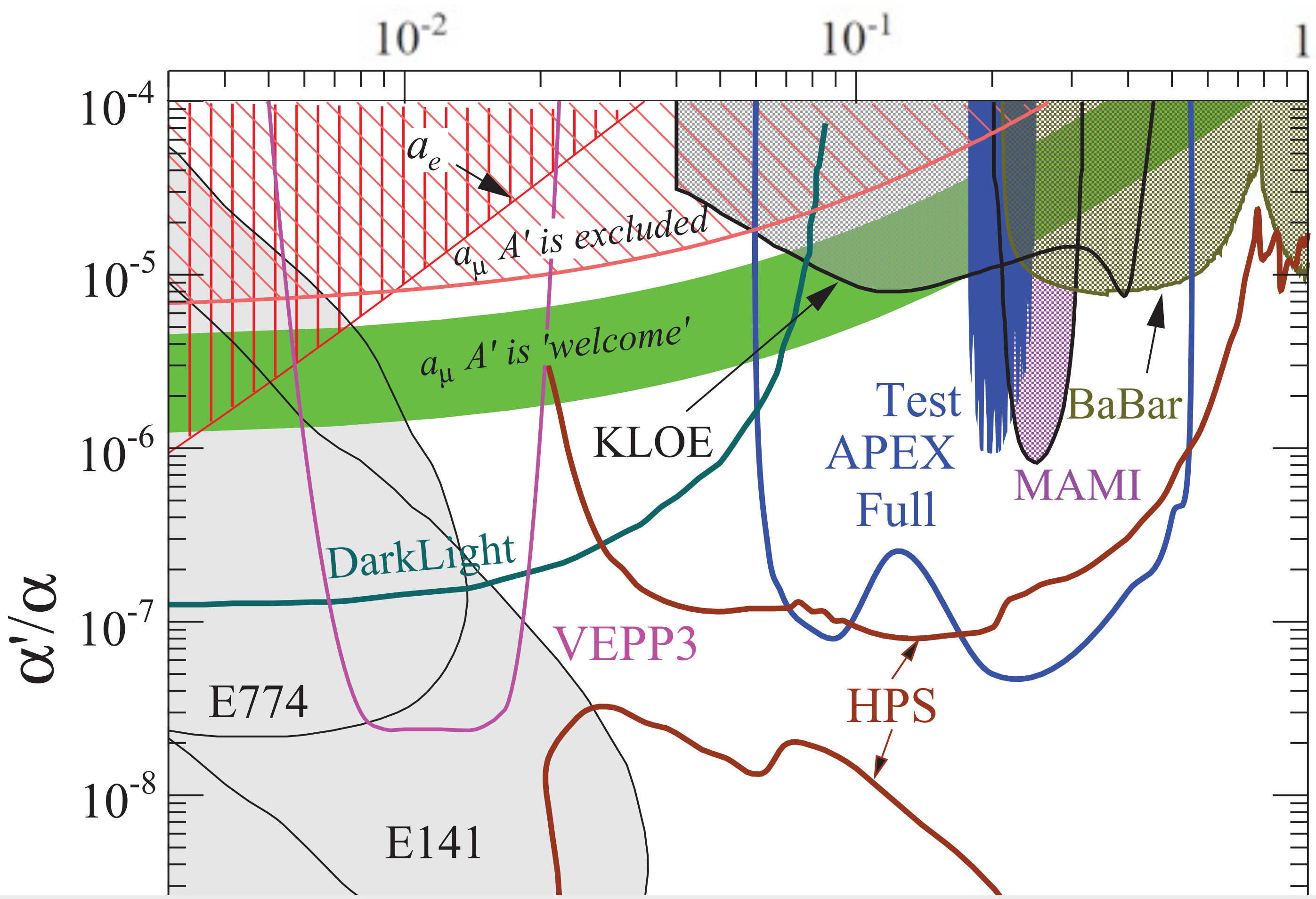
Numerous studies of Dark Photon phenomenology

[Pospelov,Ritz (2008)]
[Reece,Wang (2009)]
[Bjorken,Essig,Schuster,Toro (2009)]
[Freytsis,Ovanesyan,Thaler (2009)]
and many more ...

Constraints/Sensitivity in the ($m_{Z'}$, ε^2) plane [from R. McKeown's talk (Sep 2011)]

$$\varepsilon^2 = \alpha'/\alpha$$

Typical implications for Dark Photon



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and many more ...

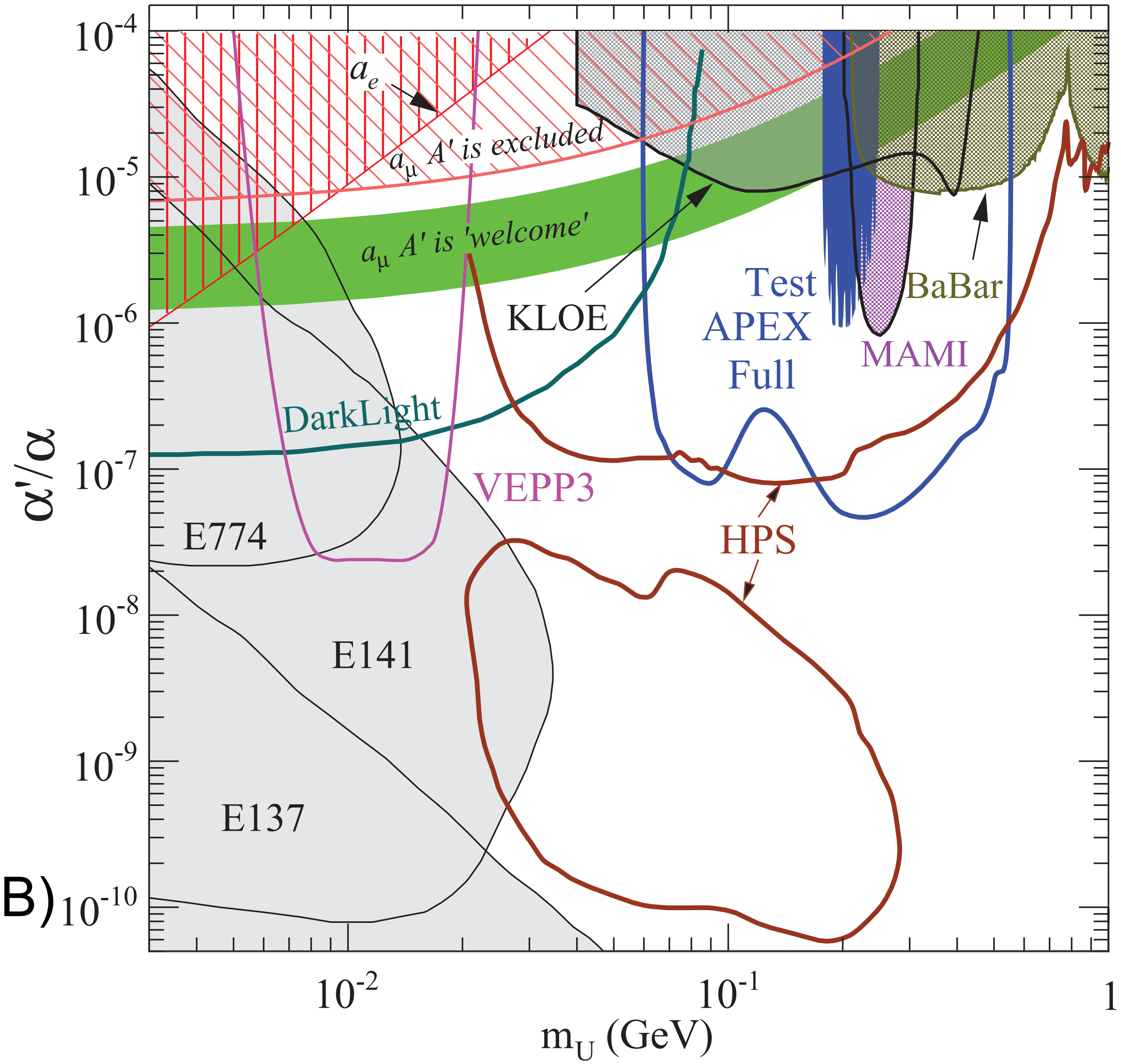
1. g-2 (for electron, muon)
   (Deviation in muon g-2 [green band] can be an early hint of Dark Photon.)

2. Electron beam-dump experiments (E137, E141 at SLAC; E774 at Fermilab)

3. $\Upsilon(bb) \rightarrow \gamma\, Z' \rightarrow \gamma\, \mu^+\mu^-$ (BaBar at SLAC); $\phi(ss) \rightarrow \eta\, Z' \rightarrow \eta\, \ell^+\ell^-$ (KLOE in Italy)

5. Fixed target experiments: New experiments designed for direct Dark Photon search
   (APEX at JLab; MAMI in Mainz; ...) **See next talk (B. Wojtsekhowski).**

Dark Force searches at Jefferson Lab (JLab)



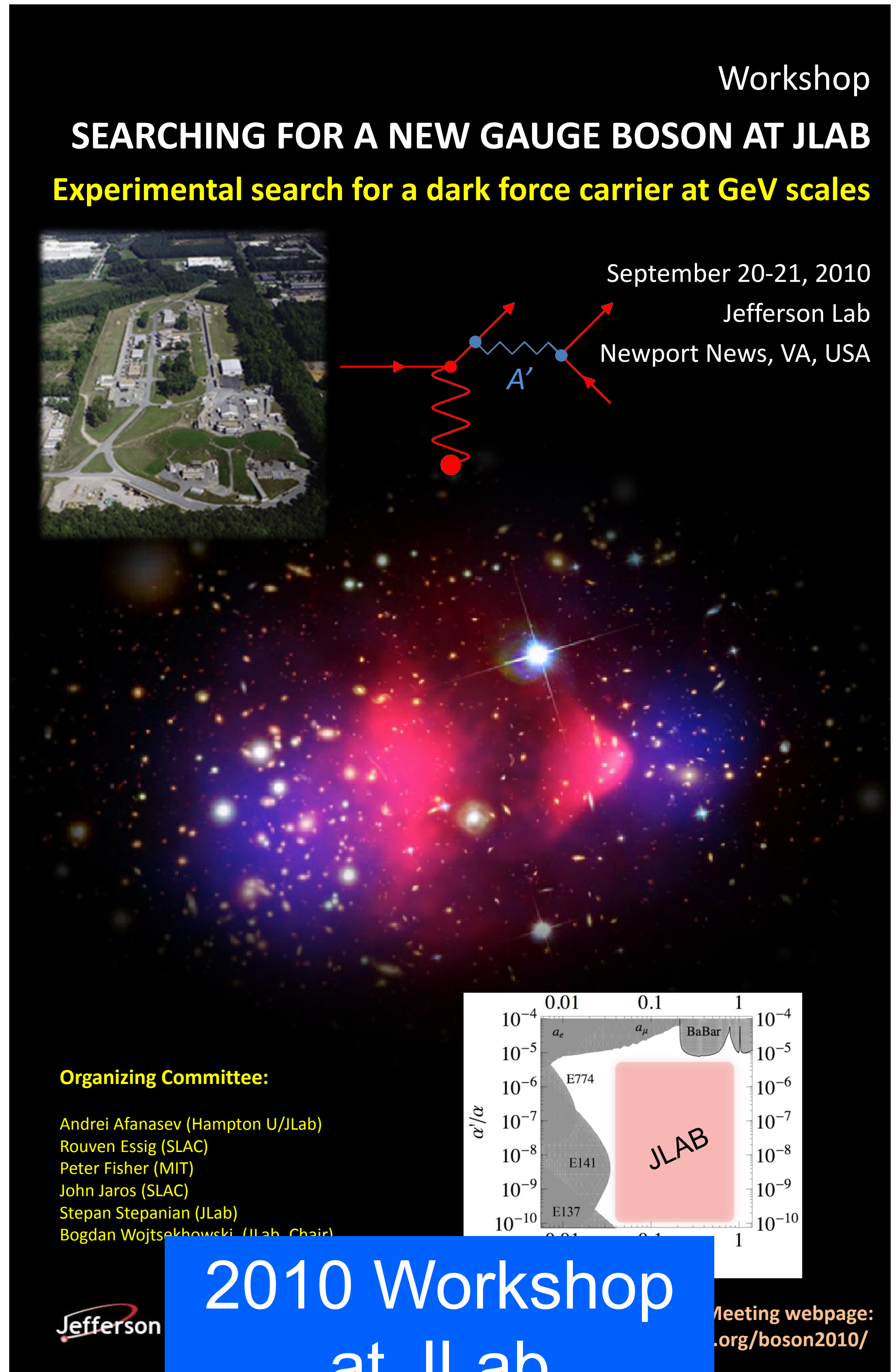
Ongoing/Proposed experiments for "direct" Dark Photon search:

(1) APEX (JLab - Hall A)
(2) Heavy Photon Search (JLab - Hall B)
(3) DarkLight (JLab - FEL)
(4) MAMI (Mainz Microtron, Germany)
(5) VEPP3 (Budker in Russia)

Hunting for **Dark Force (very weakly interacting Light Z')** is becoming a Big industry. Especially, with attentions from Low-Energy experimental facilities (Traditional role: Hadronic/Nuclear physics by precision measurement).

Dark Force Workshops

2009 Workshop
at SLAC

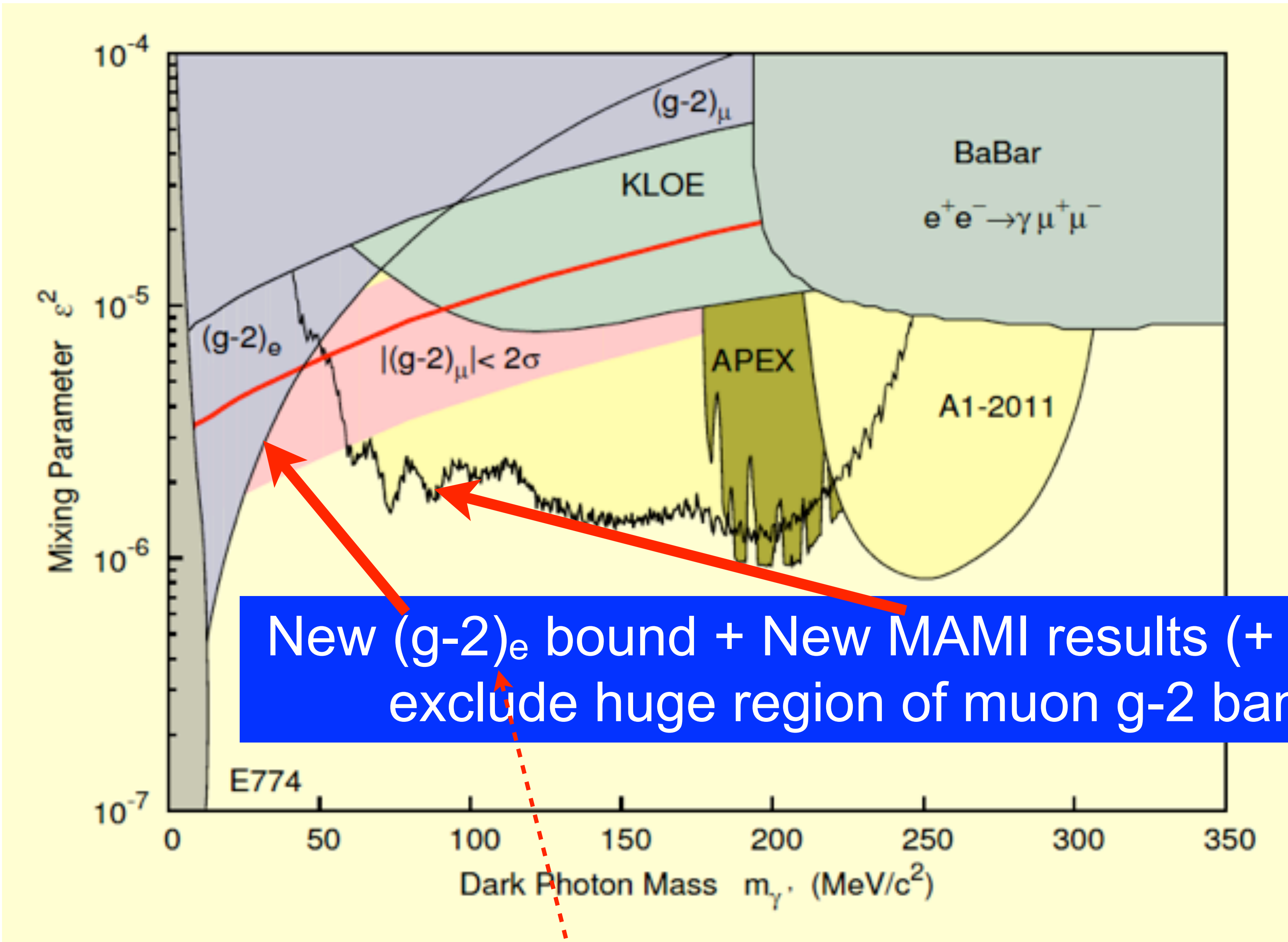


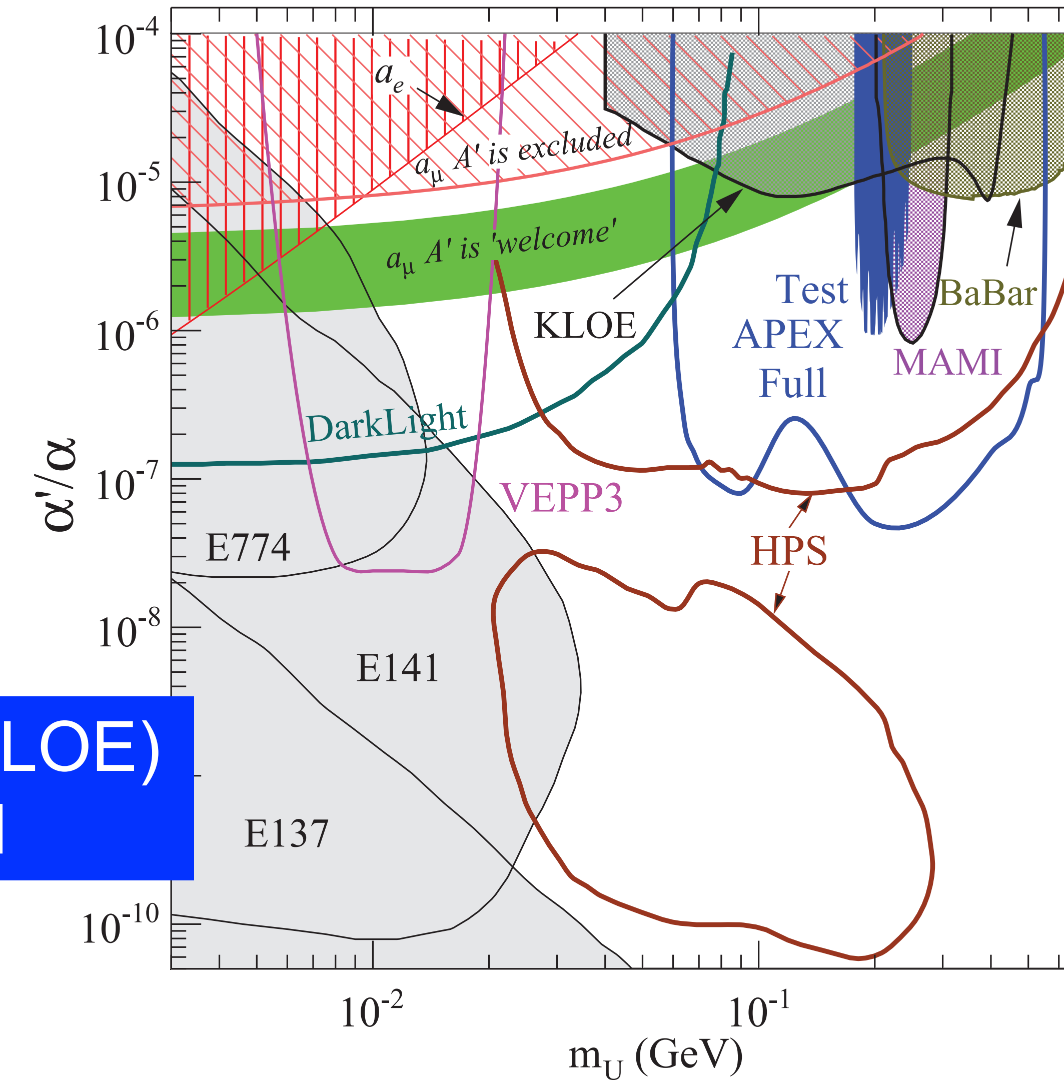
2010 Workshop
at JLab

2012 Workshop
at INFN (Rome)

October 16-19, 2012
(Many new results!)

New results presented at October Workshop (Rome)





New $(g\text{-}2)_e$ bound + New MAMI results (+ KLOE) exclude huge region of muon g-2 band

[MAMI 2012 preliminary (Oct 2012)]

[Sep 2011]

New $(g\text{-}2)_e$ bound [Davoudiasl, HSL, Marciano (Aug 2012)]
: based on recent α measurement (with ^{87}Rubidium) [Bouchendira et al (2011)]
and improved calculation on $(g\text{-}2)_e$ [Kinoshita et al (May 2012)].

2. Dark Z

: a variant of Dark Photon with “different couplings”

[Davoudiasl, HSL, Marciano (2012)]

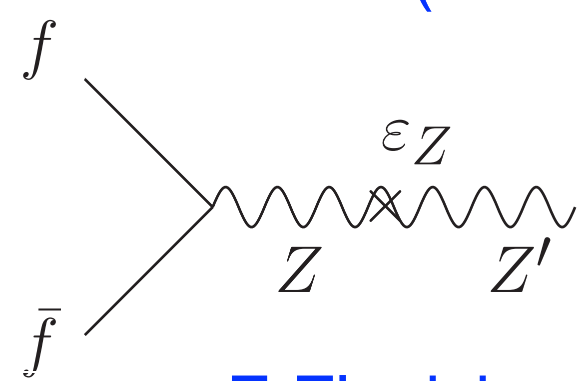
General Higgs sector

Dark Photon model: Z-Z' mixing (from $U(1)_Y$ & U(1)' kinetic mixing) vanishes due to the simplest Higgs sector (1 doublet + singlet).

Dark Z model: Consider the same setup as Dark Photon case (kinetic mixing), but with a more general Higgs sector.

Now, Z-Z' mixing angle $\varepsilon_Z = \frac{m_{Z'}}{m_Z}\delta$ does not vanish in general.

(δ : small model-dependent quantity)



Z-Z' mixing

We do not specify the Higgs sector, but it can be realized with, for example, Two Higgs Doublet Model (2HDM) type-I:

H_1 with zero U(1)' charge → Similar to SM Higgs doublet,
H_2 with nonzero U(1)' charge → Second doublet breaks U(1)' and gives mass to Z'
(+ optional Higgs singlet H_d)

$$\delta = \sin\beta \sin\beta_d \quad (\text{with } \tan\beta \equiv v_2/v_1 \ , \quad \tan\beta_d \equiv v_2/v_d)$$

(δ is a function of vacuum expectation values of scalars.)

Dark Z

The Z' couples to EM Current (∝ ε: Photon-Z' mixing) as well as the weak Neutral Current (∝ ε_Z: Z-Z' mixing).

$$\mathcal{L}_{\text{int}}^{\text{SM}} = -eJ_{em}^{\mu}A_{\mu} - (g/\cos\theta_W)J_{NC}^{\mu}Z_{\mu}$$

$$\mathcal{L}_{\text{int}}^{Z'} = -\left[\varepsilon\, eJ_{em}^{\mu} + \varepsilon_Z\,(g/\cos\theta_W)J_{NC}^{\mu}\right]Z'_{\mu} \qquad (\varepsilon_Z = \delta\; m_{Z'}/m_Z)$$

(coupling) = ε (Photon coupling) + ε_Z (Z coupling)
: a combination of Photon and Z couplings

To emphasize the difference from Dark Photon (with only Photon coupling), we refer our Z' to "**Dark Z boson**". (In ε→0 limit, only Z coupling)

In a rough sense, (Dark Photon) ≈ Heavy-version Photon,
(Dark Z boson) ≈ Light-version Z boson.

New features due to Different Couplings of Dark Z

Dark Photon bounds (APEX, MAMI, etc) apply to Dark Z as well, in most parameter space of interest.
(Around the bounds, $|\varepsilon| >> |\varepsilon_Z|$, where [Dark Z coupling] ≈ [Dark Photon coupling].)

In addition, since Dark Z has "axial coupling", it implies new features that Dark Photon does not show.

(i) Parity Violation [LH and RH fermions couple differently to Dark Z]

(ii) Enhancement from Goldstone Boson Equivalence Theorem [in Boosted case]

(iii) Coupling to electrically neutral particles [such as neutrinos]

These properties are basically inherited from Z boson, but show up in more interesting ways because Dark Z is light (~ O(1) GeV).

As an example, in this talk, we explore Dark Z implications for Parity Violation experiments.

3. Dark Z Implications for Parity-Violating Experiments

[Davoudiasl, HSL, Marciano (2012)]

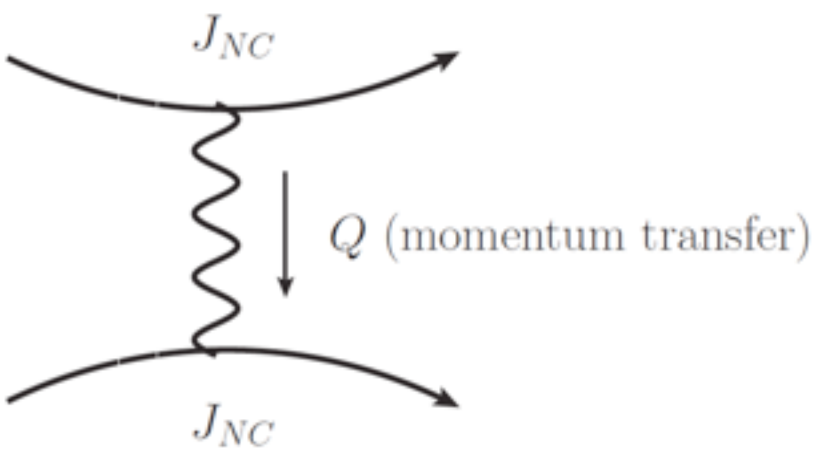
Dark Z effects on Neutral Current phenomenology

Dark Z effect comes as **modification** of effective Lagrangian of Z-mediated scattering.

$$\mathcal{L}_{\rm eff} = -\frac{4G_F}{\sqrt{2}} J^{\mu}_{NC}(\sin^2\theta_W) J^{NC}_{\mu}(\sin^2\theta_W)$$

$$G_F \to \left(1 + \delta^2 \frac{1}{1 + Q^2/m^2_{Z'}}\right) G_F$$

$$\sin^2\theta_W \to \left(1 - \varepsilon\delta \frac{m_Z}{m_{Z'}} \frac{\cos\theta_W}{\sin\theta_W} \frac{1}{1 + Q^2/m^2_{Z'}}\right) \sin^2\theta_W$$



1. Sensitive only to Low-Q^2 (momentum transfer). (Effect negligible for $Q^2 \gg m_{Z'}^2$)
2. Unless ε is extremely small, $\Delta\sin^2\theta_W$ (Weinberg angle shift) is more sensitive.

(SM Z boson: $1/(m_Z^2 + Q^2) \approx 1/m_Z^2$ in Low-E effective theory, because $m_Z^2 \gg Q^2$)

"Low-Q^2 Parity-Violating experiments (measuring Weinberg angle)" seem to be a right place to look: (i) Atomic parity violation, (ii) Polarized electron scattering.

Scattering mediated by Dark Force (Light Z') can be observed only in Low-Energy experiments.

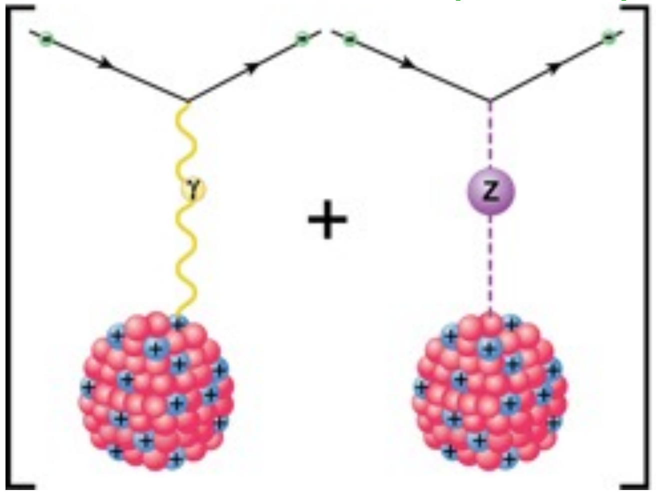
Past Low-Q^2 Parity-Violating Experiments

Atomic Parity Violation [Weak nuclear charge $Q_W(Z,N) \simeq -N+Z(1-4\sin^2\theta_W)$]:

$Q_W(^{133}Cs) = -72.58(43)$ in Cesium Experiment [C. Wieman et al (1985-1988)]

$Q_W(^{133}Cs) = -73.23(2)$ in SM [reflecting new result by Flambaum et al (2012)]

in reasonable agreement (1.5σ).



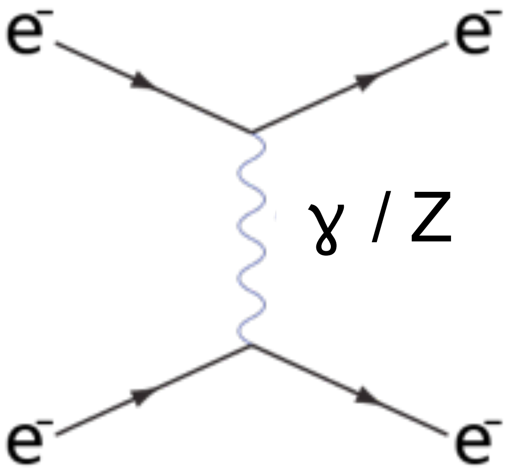
Polarized Electron Scattering [Left-Right asymmetry $A_{LR} = \sigma_L-\sigma_R / \sigma_L+\sigma_R$]:

$\sin^2\theta_W(m_Z)=0.2329(13)$ in Moller scattering; <Q>≈160 MeV) [SLAC E158 (2005)]

$\sin^2\theta_W(m_Z)=0.23125(16)$ directly measured at Z-pole [LEP, SLC average]

in good agreement.

$$\Delta \sin^2\theta_W \simeq -0.42\varepsilon\delta \frac{m_Z}{m_{Z'}} f(Q^2/m_{Z'}^2)$$



Low-Q^2 Parity-Violating Experiments

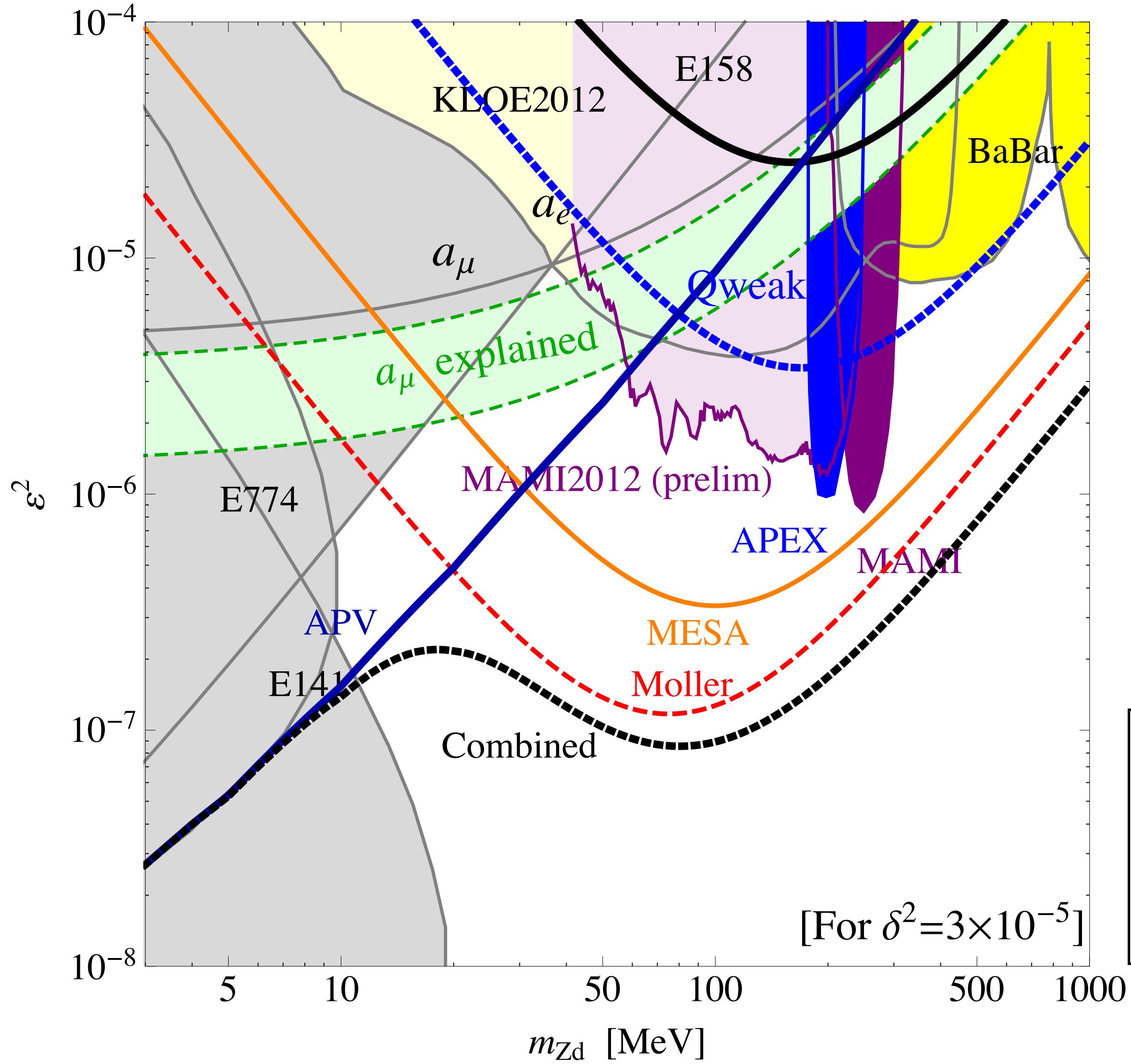
	Experiment	Type	$\langle Q \rangle$	$\sin^2\theta_W(m_Z)$	Bound on dark Z (90% CL)
Past	Cesium APV	Cs	2.4 MeV	0.2356(20)	$\varepsilon^2 < \frac{21\times10^{-5}}{\delta^2}\left(\frac{m_{Z_d}}{m_Z}\right)^2 \frac{1}{K(m_{Z_d})^2}$
	E158 (SLAC)	ee	160 MeV	0.2329(13)	$\varepsilon^2 < \frac{62\times10^{-6}}{\delta^2}\left(\frac{(160\text{ MeV})^2+m_{Z_d}^2}{m_Z m_{Z_d}}\right)^2$
Upcoming	Qweak (JLAB)	ep	170 MeV	±0.0007	$\varepsilon^2 < \frac{7.4\times10^{-6}}{\delta^2}\left(\frac{(170\text{ MeV})^2+m_{Z_d}^2}{m_Z m_{Z_d}}\right)^2$
Future	Moller (JLAB)	ee	75 MeV	±0.00029	$\varepsilon^2 < \frac{1.3\times10^{-6}}{\delta^2}\left(\frac{(75\text{ MeV})^2+m_{Z_d}^2}{m_Z m_{Z_d}}\right)^2$
	MESA* (Mainz)	ep	100 MeV	±0.00037	$\varepsilon^2 < \frac{2.1\times10^{-6}}{\delta^2}\left(\frac{(100\text{ MeV})^2+m_{Z_d}^2}{m_Z m_{Z_d}}\right)^2$
	Combined			±0.00021	$\varepsilon^2_{\text{comb}} < \frac{1}{\sum_i(1/\varepsilon_i^2)}$

TABLE I: Existing and possible future constraints on dark Z from various parity violating experiments

*MESA parameters uncertain.
(Largely, comparable to Moller)

Qweak (JLab): Present Low-Q^2 PV experiment

(Run completed in May 2012; Analysis ongoing)



**Updated from the publication (PRL, Jul 2012) to include New APV calculation [Flambaum et al (Jul 2012)], New (g-2)$_e$ bound [Davoudiasl, HSL, Marciano (Aug 2012)], and New MAMI, KLOE bounds [Oct 2012].*

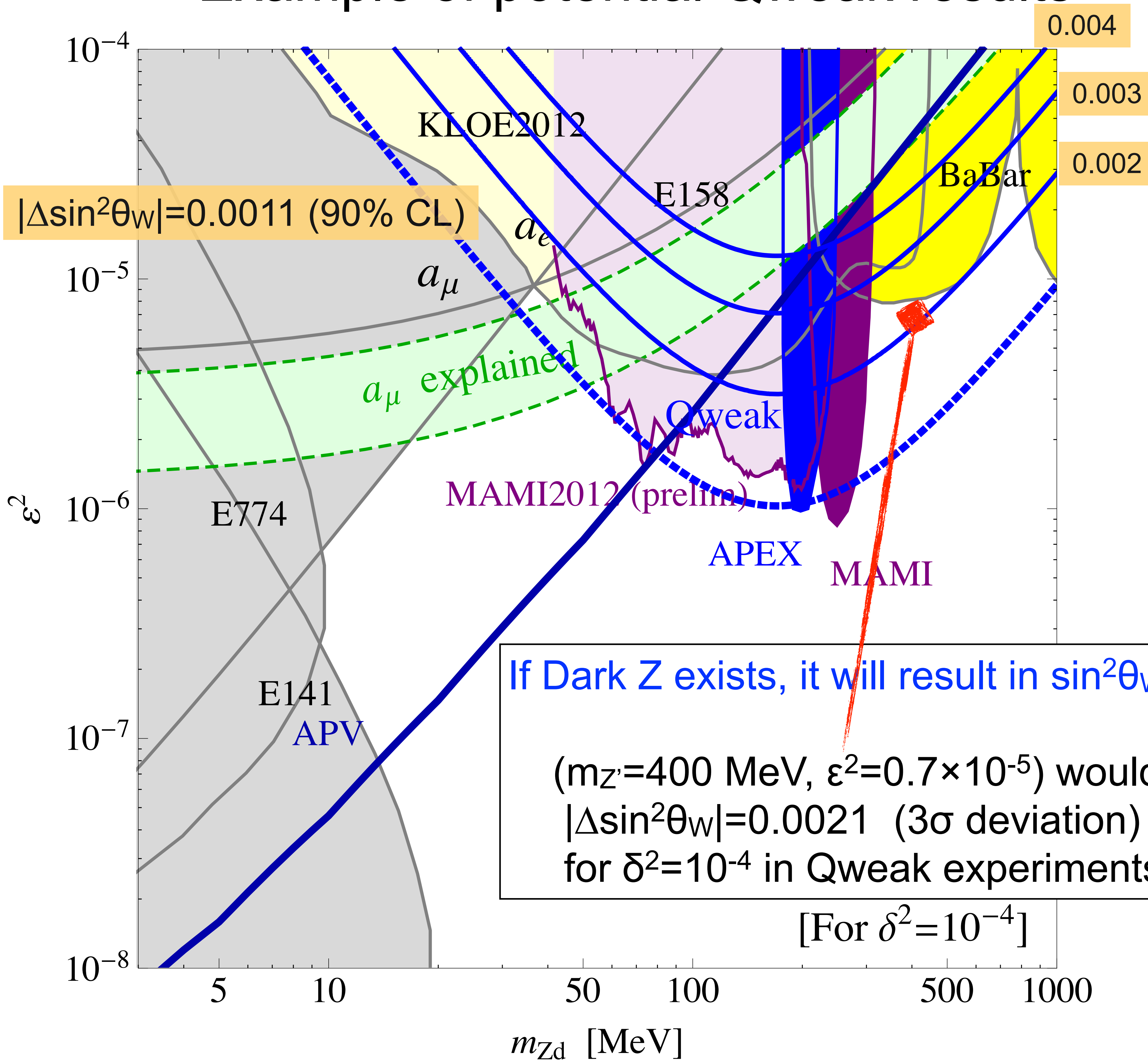
Larger δ^2 increases PV experiments sensitivity. (Curves in 90% CL)

$$\varepsilon_Z = \frac{m_{Z'}}{m_Z}\delta$$

If Dark Z causes muon g-2 anomaly, Qweak $\sin^2\theta_W$ should be in good agreement with the SM prediction. (APV closes the green band at $\delta^2 = 3\times10^{-5}$.)

In other words, if Qweak sees a significant deviation, it can "rule out" the Dark Z explanation of muon g-2 anomaly!

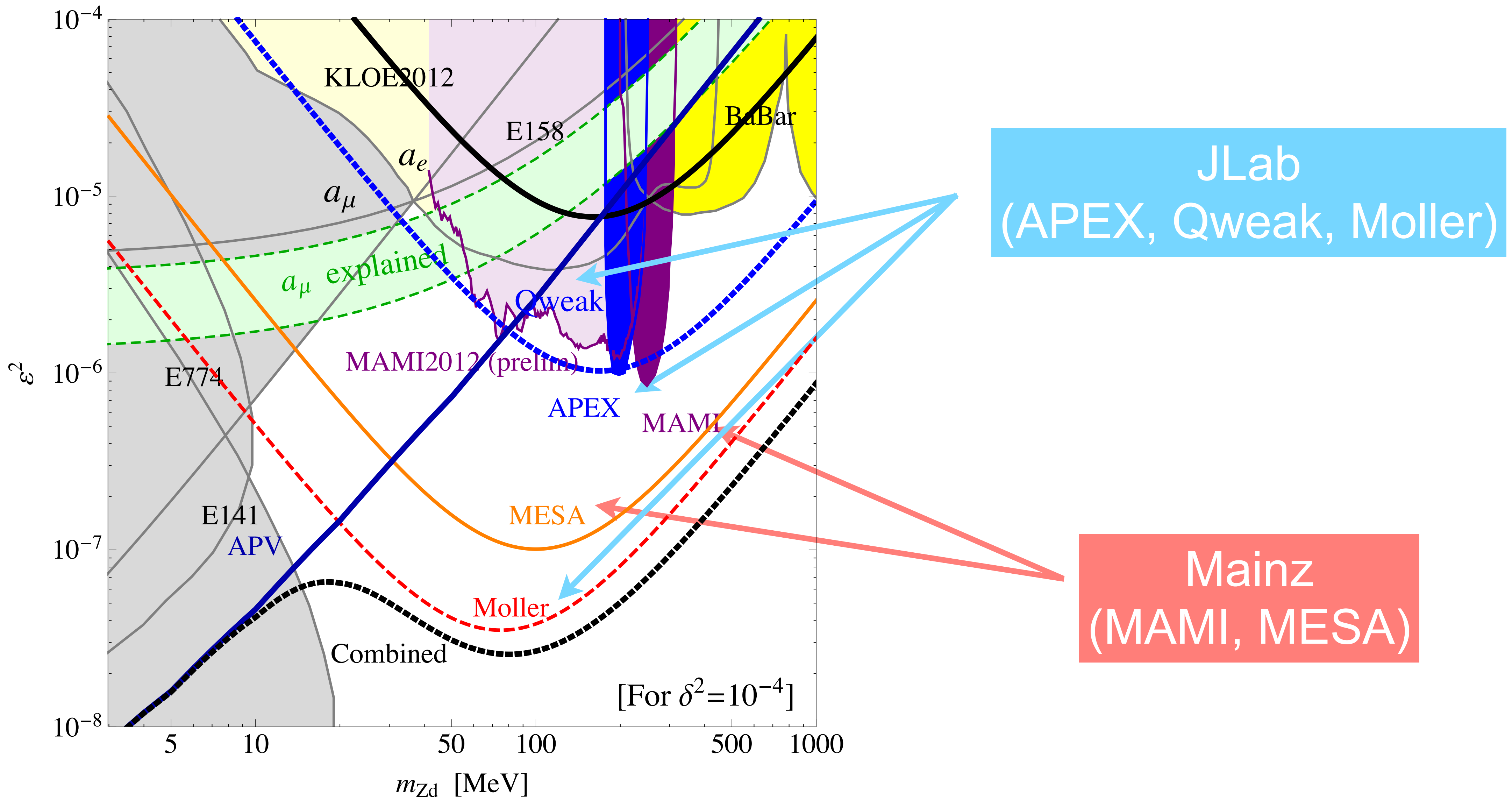
Example of potential Qweak results



If Dark Z exists, it will result in $\sin^2\theta_W$ shift.

($m_{Z'}$=400 MeV, $\varepsilon^2=0.7\times10^{-5}$) would give $|\Delta\sin^2\theta_W|=0.0021$ (3σ deviation) for $\delta^2=10^{-4}$ in Qweak experiments.

Moller (JLab), MESA (Mainz) : Future experiments

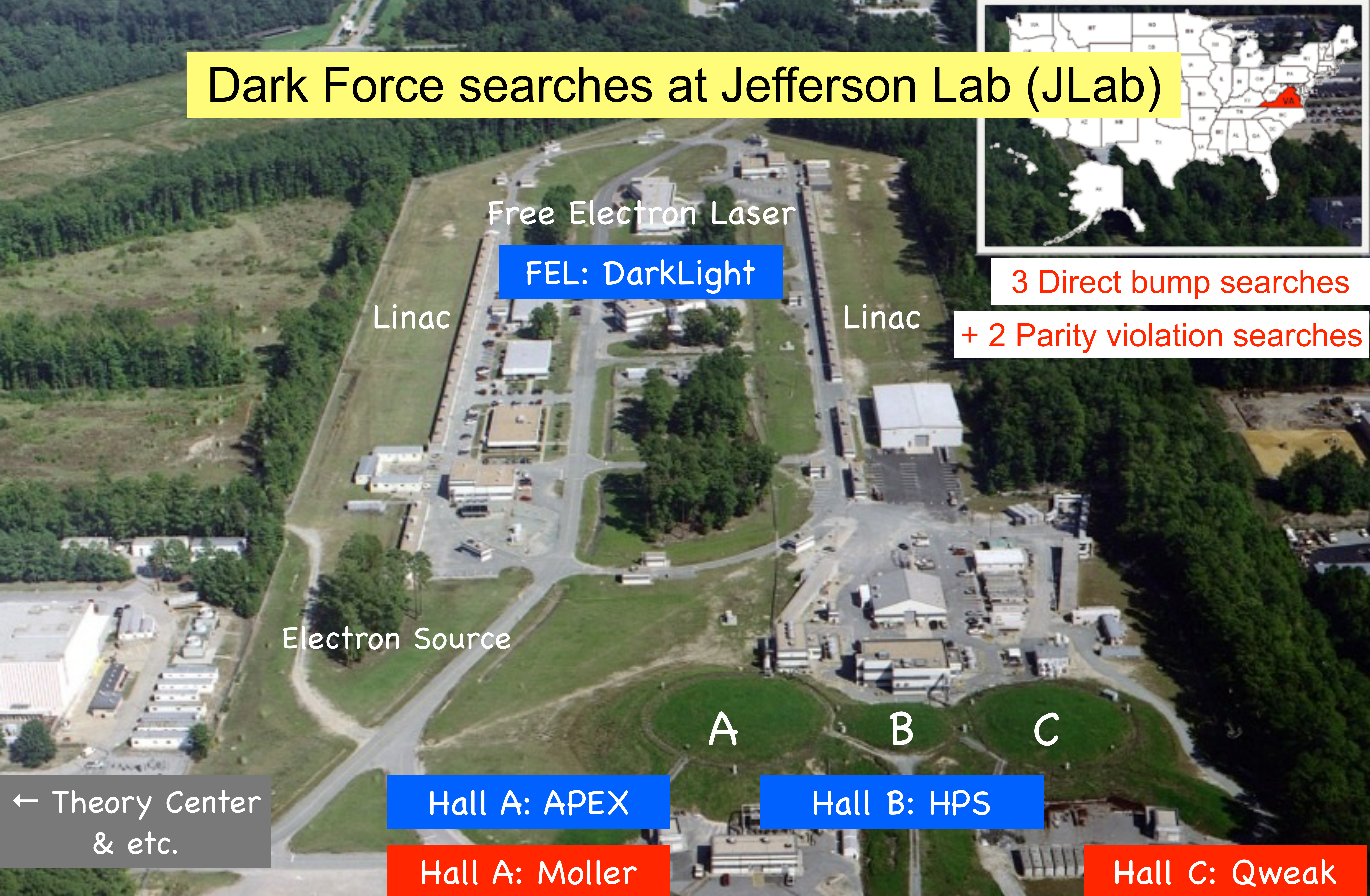


Muon g-2 anomaly is Not the only motivation for Light Z'. Much Larger parameter space is motivated by DM-related phenomena (though model-dependent).

"It is worth to cover as much parameter space as possible."

Future Low-Q^2 polarized electron scattering experiments [Moller at JLab, MESA in Mainz] can test Dark Z in wide parameter space.

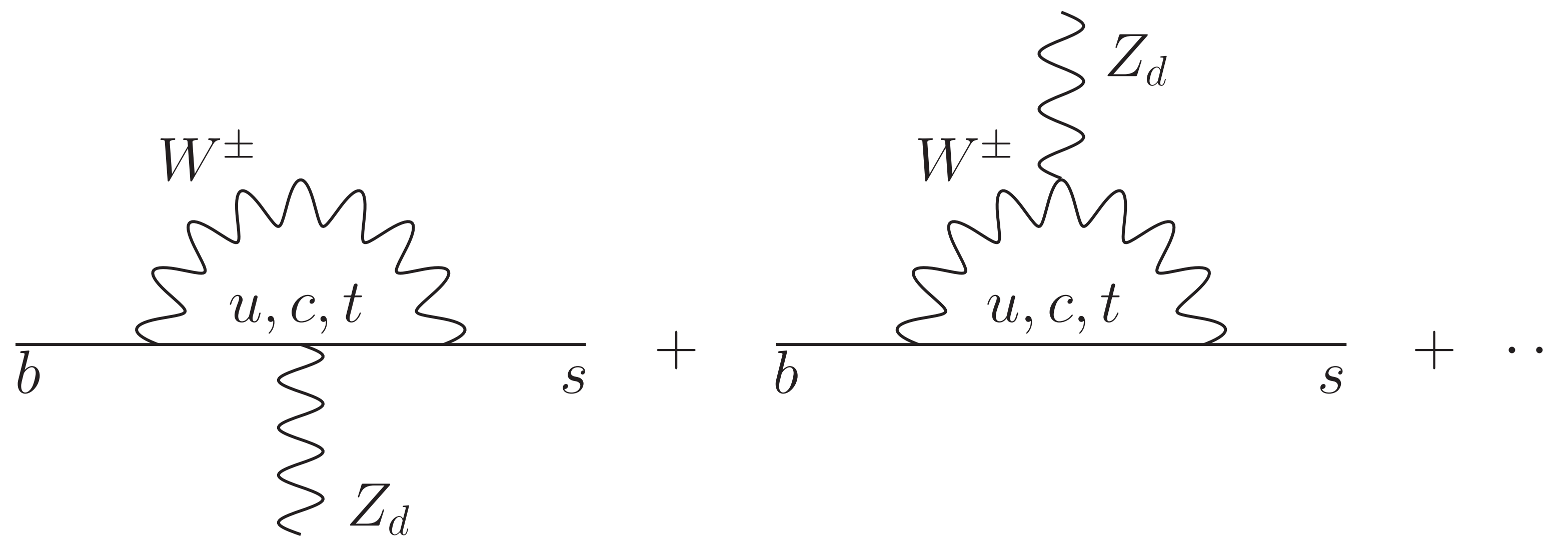
Dark Force searches at Jefferson Lab (JLab)



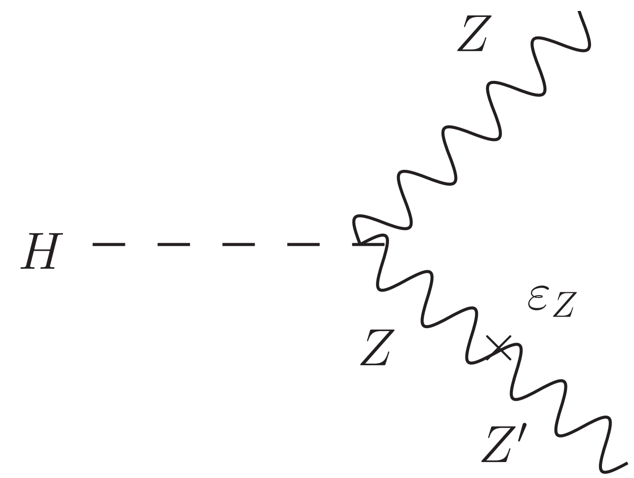
Low-Q^2 Parity-Violating experiments are Complementary "Dark Force" (with axial couplings) searches!

Other Implications of Dark Z
(Flavor-changing Meson decays & Higgs decays)

B → K Z' : 2-body decays
(for $m_{Z'} << m_B$)



H → Z Z' decay
(for $m_{Z'}$ = several GeV)



(HZZ' coupling) =
ε_Z (HZZ coupling)

- We can expect sizable FCNC meson decays (B → K Z', K → π Z') (for $m_{Z'} << m_B$).
[Goldstone Boson Equivalence Theorem: Boosted gauge boson behaves as Imaginary part of Higgs. --> It couples strongly to heavy particles.]
- Similarly, H → Z Z' is sizable and observable at the LHC (for $m_{Z'}$ = several GeV).

Enhancement from Goldstone Boson Equivalence Theorem allows sizable effects in rare decays to Dark Z.

Summary

“Dark Z” model expands the Dark Force searches

In the Dark U(1) gauge interaction picture (SM particles have zero charges), the Dark sector can still communicate with the SM through kinetic mixing $U(1)_Y$ & U(1)’.

Z’ coupling depends on details of Higgs sector.

(i) **Dark Photon**: couples to EM Current ... (simplest Higgs sector case)

(coupling) = ε (Photon coupling)

(ii) **Dark Z**: couples to Neutral Current as well ... (more general Higgs sector)

(coupling) = ε (Photon coupling) + ε_Z (Z coupling)

Dark Z is a natural way to introduce axial couplings to “Dark Photon”-like study.

→ It brings many **other** experiments to Dark Force searches:

(i) Low-Q^2 parity violating experiments [Qweak, Moller, etc]

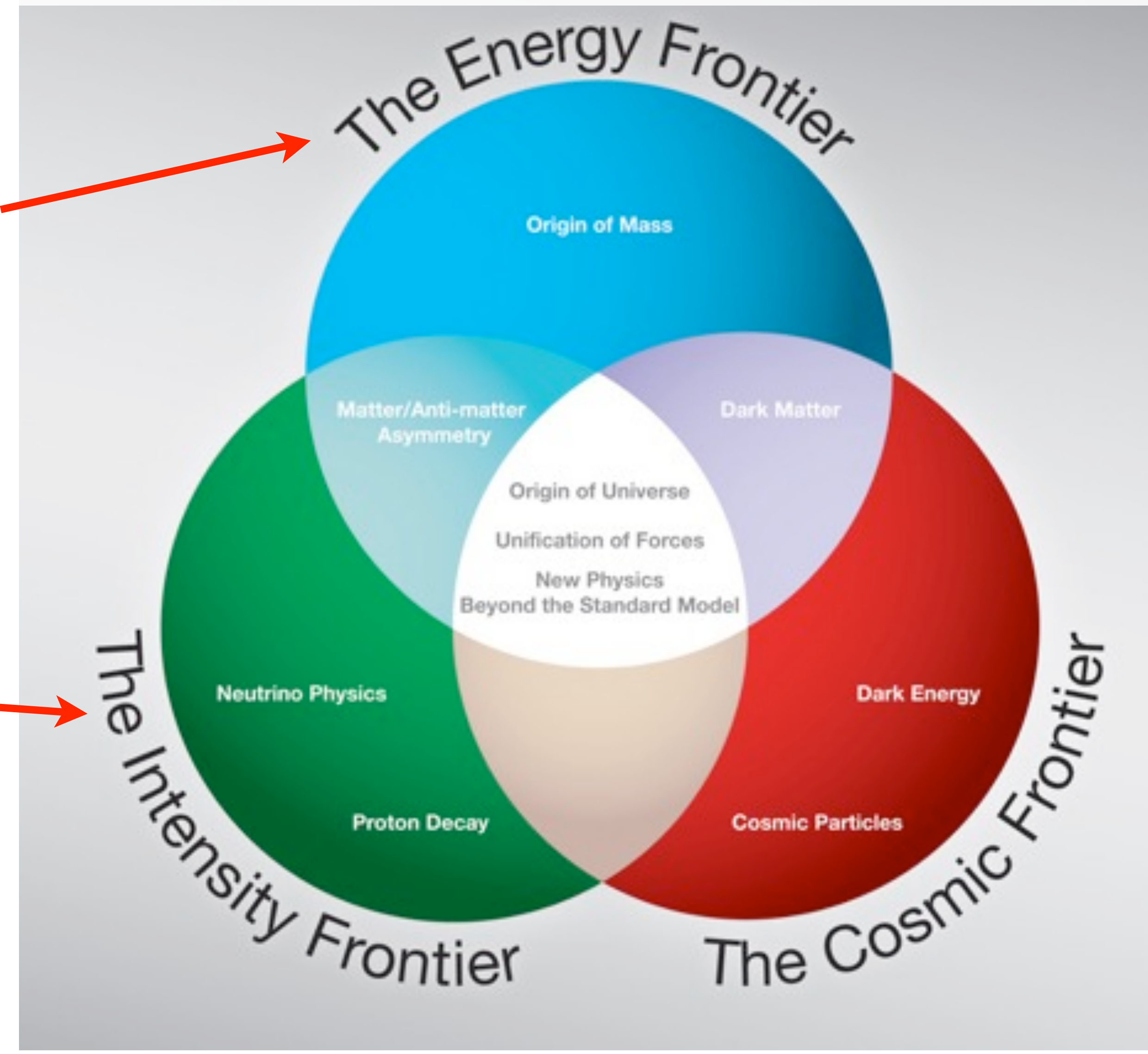
(ii) Flavor-changing rare meson decays [B → K Z’, K → π Z’]

. . .

What I presented today:
(i) We generalized the “Dark Photon” to “Dark Z” (New Dark Force model).
(ii) We expanded the types of the relevant Dark Force search experiments.

Traditional View

Particle Physics Frontiers
(by US Department of Energy)

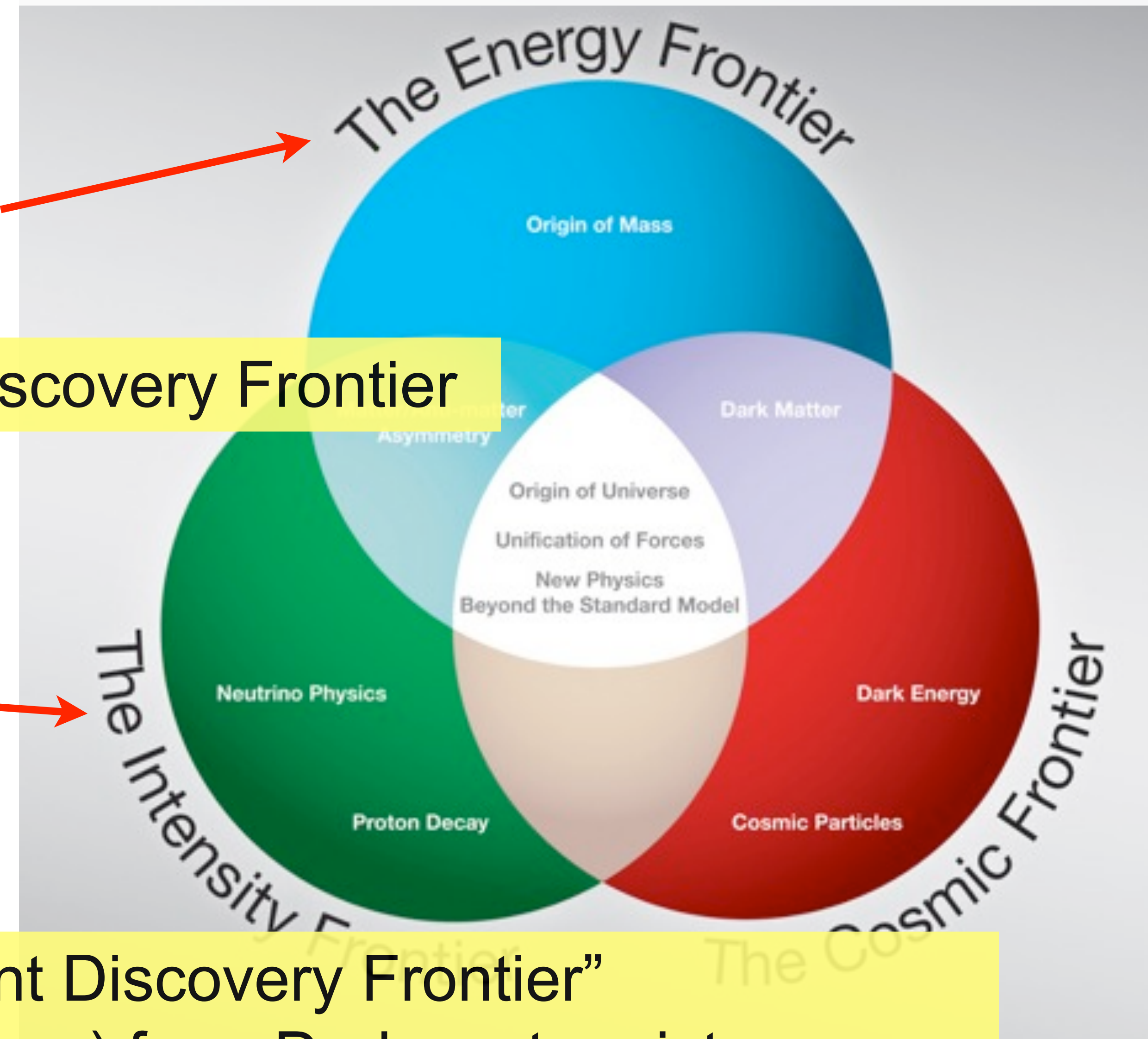


<u>High-E experiments</u>: Rely on Higher energy facility to find direct evidence of New heavy particles (LHC, Tevatron, etc).

<u>Low-E experiments</u>: Rely on Higher precision to find indirect evidence of New heavy particles (JLab, B-factories, Neutrino oscillations, etc).

Emerging Alternative View

Particle Physics Frontiers
(by US Department of Energy)



<u>High-E experiments</u>: Rely on Higher energy facility to find direct evidence of New heavy particles (LHC, Tevatron, etc).

Traditionally considered as most important Discovery Frontier

<u>Low-E experiments</u>: Rely on Higher precision to find indirect evidence of New heavy particles (JLab, B-factories, Neutrino oscillations, etc).

Emerging as an "equally important Discovery Frontier"
with New light particles (Dark gauge bosons) from Dark sector picture.
(Dark Example: Only Low-E can see the bump and parity violation deviation)

Next New Physics discovery might take place in Low-E experiments rather than in High-E experiments.

Thank you!