

“Dark Physics” and Dipole Moments

*Based on work by:
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Outline

1. **Dark Matter & $U(1)_d$ Gauge Symmetry**

i) **Underground Detection vs Positron & γ -ray Excesses**

*ii) **(Very) Light Dark Matter ($\leq 100\text{MeV}$?)**

iii) **Dark Bosons (Dark Photon (γ_d), Dark Z (Z_d), U , ..)**

2. **Kinetic $U(1)_Y \times U(1)_d$ Mixing $\frac{1}{2}\epsilon/\cos\theta_W B_{\mu\nu} D^{\mu\nu}$**

i) $\Delta a_\mu = a_\mu^{\text{exp}} - a_\mu^{\text{SM}} = 276(80) \times 10^{-11}$ (3.5σ discrepancy!)

$\Delta a_e = a_e^{\text{exp}} - a_e^{\text{SM}} = -92(81) \times 10^{-14}$ (1000x more precise)

ii) The Dark Photon Solution: $\epsilon e \gamma_d^\mu J_\mu^{\text{em}}$

iii) γ_d Searches ($\gamma_d \rightarrow e^+e^-$) (m_{γ_d}, ϵ parameter space)

$m_{\gamma_d} \approx 40\text{MeV}, \epsilon \approx 2 \times 10^{-3}$

(being cornered or ruled out?)

3. Z - γ_d mass mixing (General Discussion)

Non-Conserved Currents $\epsilon_Z g/2 \cos \theta_W Z_d^\mu J_\mu^{NC}$

. *i) Atomic PV & Polarized Electron Scattering

Dark Parity Violation & Running $\sin^2 \theta_W(Q)$

*ii) Rare K & B Decays (eg. $K \rightarrow \pi Z_d$, $B \rightarrow K Z_d$)

$K \rightarrow \pi Z_d \rightarrow \pi e^+ e^-$ or $\pi +$ "missing energy"

iii) Higgs Decay $H \rightarrow Z Z_d \rightarrow 4$ charged leptons

*4. $K \rightarrow \pi Z_d \rightarrow \pi +$ "missing energy"

Kinetic Mixing (Pospelov) vs Mass Mixing (DLM)

(Implications for dark photon searches)

5. Outlook

1. *Dark Matter & $U(1)_d$ Symmetry*

The Existence of Dark Matter throughout the Universe is well Established by Astrophysics, particularly gravitational lensing

New Stable Particle? Properties? An entire new sector?

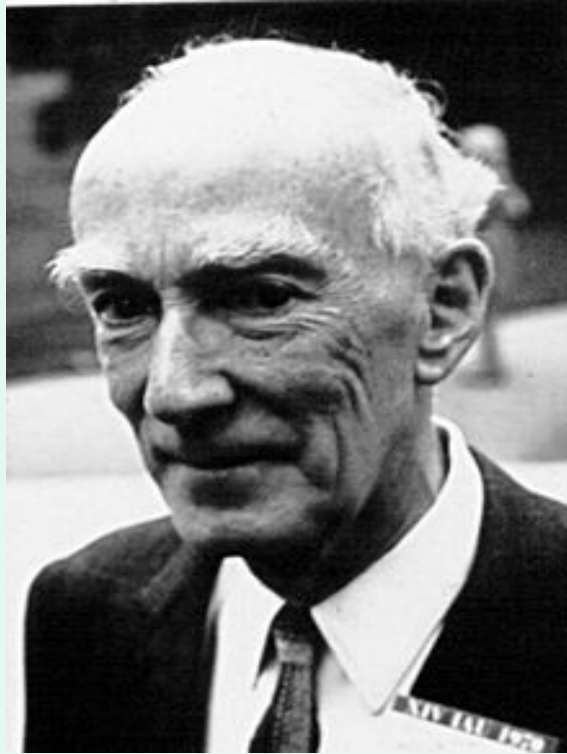
i) Underground Detection & H.E. Positron & γ -ray Excesses

The Hunt For Dark Particles ($\geq 80\%$ of all Matter!)

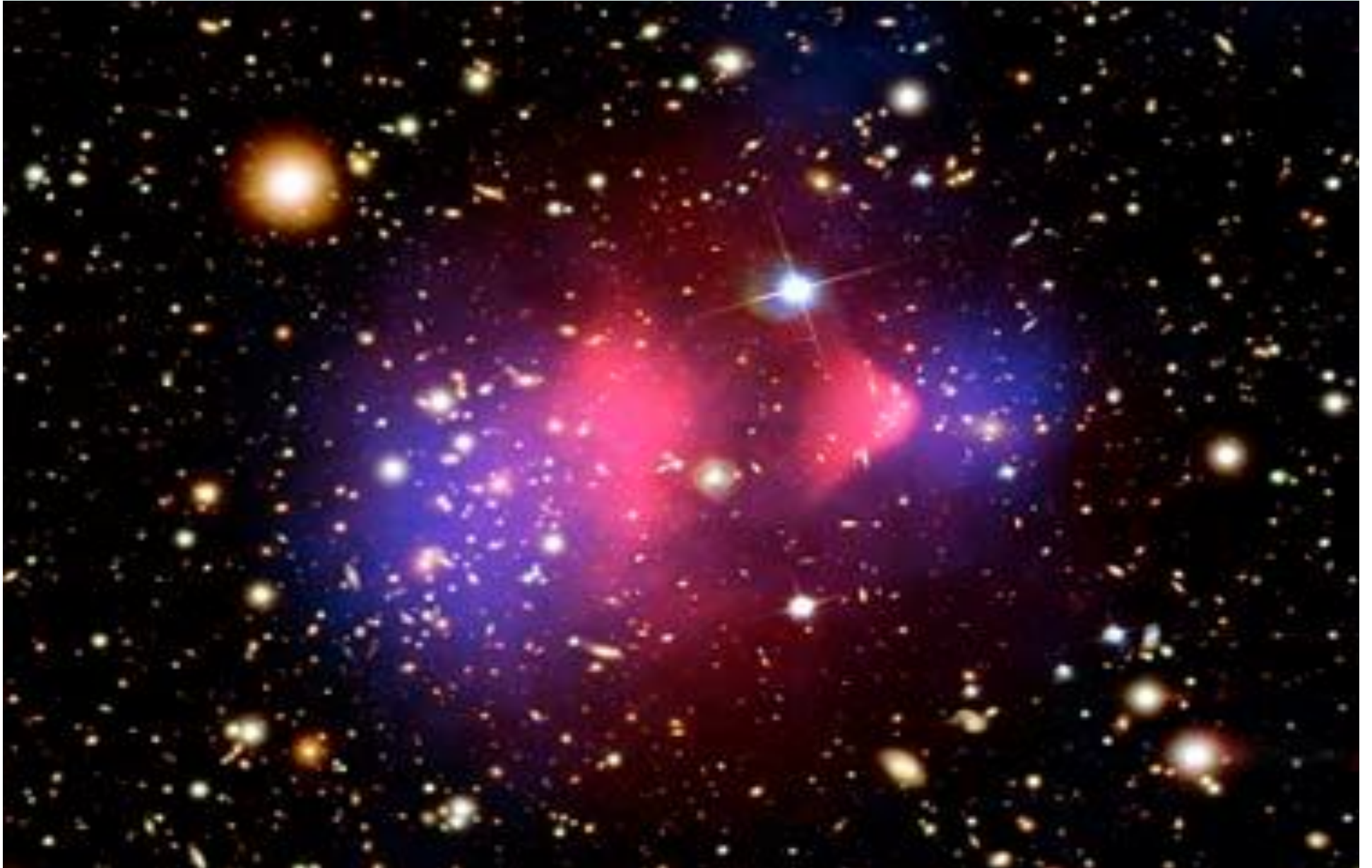
- **Underground Searches** for Dark Matter Particles (WIMPS) $m_\chi \sim 100 \text{ GeV}$
Search via coherent elastic scattering off nuclei (Z exchange?) **Recoil**
(Interactions may be spin/isospin dependent)
CDMSII(Si) 3 events $m_\chi \sim 8.6 \text{ GeV}$, $\sigma \sim 2 \times 10^{-41} \text{ cm}^2$
Consistent with Dama & CoGent but XENON100 & LUX Tension

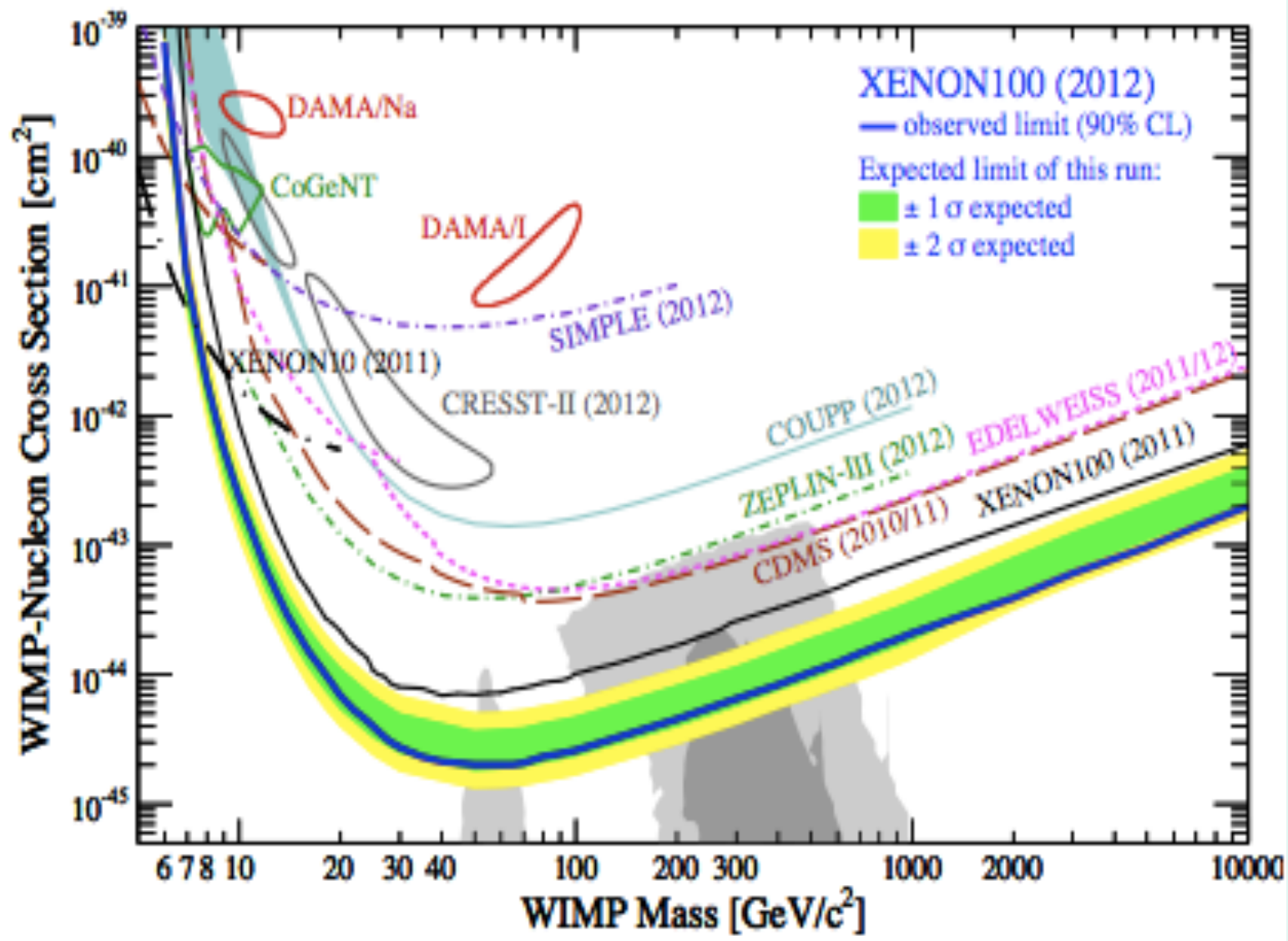
(About the same time Dirac antiparticles were being discovered)
1932-33's Astronomers start to see
"Dark Matter" Evidence!

Jan Oort & Fritz Zwicky

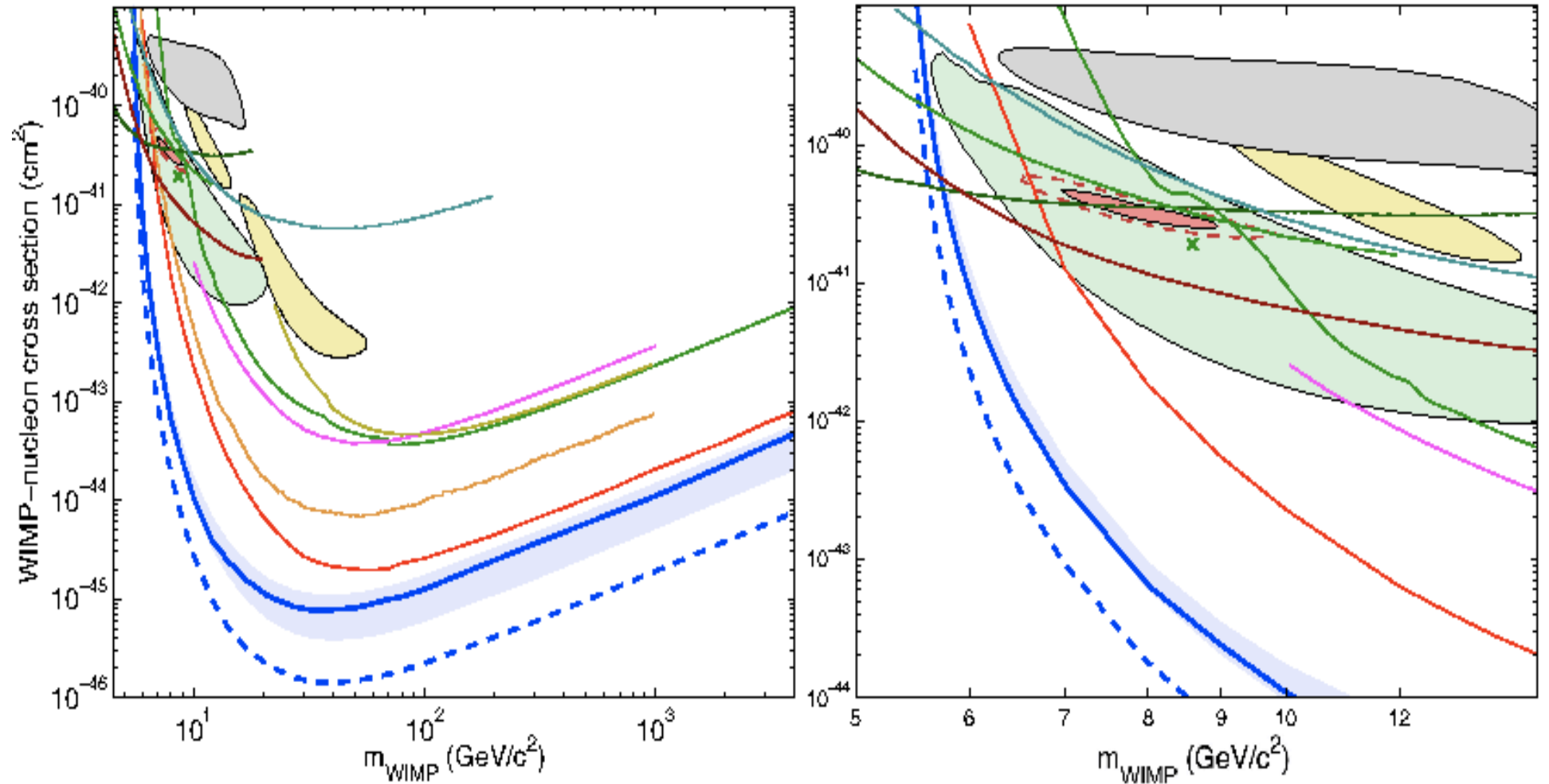


Bullet Galaxy Cluster Dark Matter Poster





LUX Update



Why don't we see dark matter underground?

- ***Possibilities***
- Majorana States – Only spin dependent incoherent
Too Light for recoil searches

Astrophysics: Hints of Dark Particle Annihilations

Light or Heavy Dark Matter Particles?

Positron (e^+) Excesses at high energies(?)

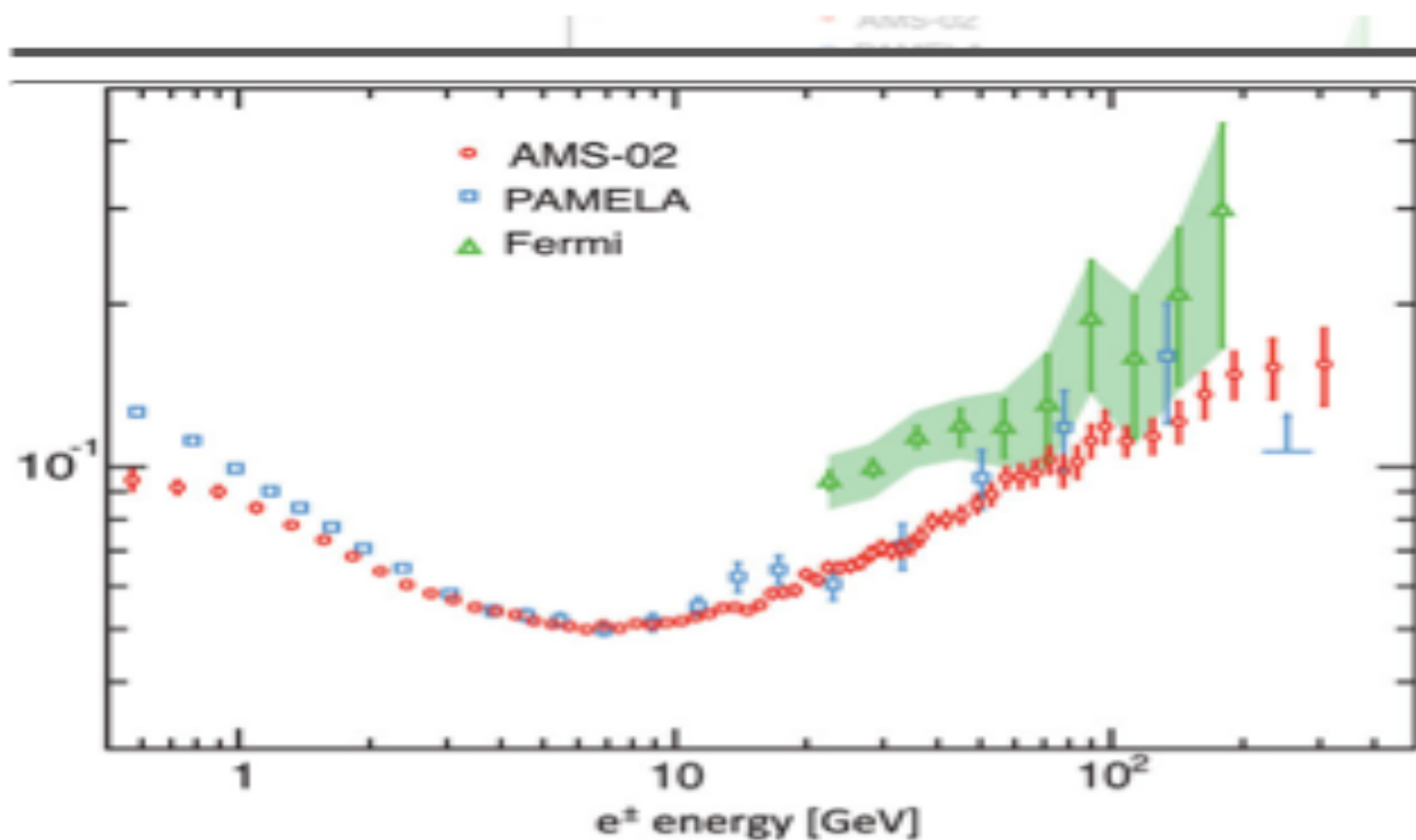
Pamela, Fermi, AMS (Heavy Dark Matter) > TeV? (Unlikely Interpretation?)

Fermi γ -ray Excess from Galactic Center

Light ~ 10 GeV Dark matter annihilations ($\rightarrow e^+e^-, \mu^+\mu^-, \tau^+\tau^-$)

Both Interesting Effects

Interpretations?



positron fraction as measured by the AMS (red circles) from 1 to 350 GeV. (Courtesy: *Phys. Rev. Lett.* **110** 141102)

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The Dark Boson – A Portal to Dark Matter

What if some dark **sector** particles interact with one another via a new massive but relatively “light” γ_d **or** Z_d (Dark Boson)?
U(1)_d local gauge symmetry of the Dark Sector

Introduced for 1) Sommerfeld Enhancement

2) $\gamma_d \rightarrow e^+e^-$ (source of positrons, ***γ -rays***)

3) Cosmic Stability of dark matter U(1)_d
eg Wimp Number (S. Weinberg)

*4) Muon Anomalous Magnetic Moment

5) *Light (< GeV) Dark Matter Abundance

Can we find direct evidence for such a particle (boson)?

Dark Symmetry & Our World Mix?

*1. Kinetic $U(1)_Y \times U(1)_d$ Mixing (B. Holdom): $B_{\mu\nu} D^{\mu\nu}$

*2. Z - γ_d mass mixing (DLM)

3. $U(1)_d = B-L, L_\mu-L_\tau, L_e-L_\mu, L_e-L_\tau \dots$

(All or some ordinary particles have dark charge)

$U(1)_d$ Vector Like Small or Large Unquantized Couplings

2. Kinetic $U(1)_Y \times U(1)_d$ Mixing (Holdom)

$$L_{U(1)_Y \times U(1)_d} = -\frac{1}{4} (B_{\mu\nu} B^{\mu\nu} - 2\varepsilon/\cos\theta_W B_{\mu\nu} D^{\mu\nu} + D_{\mu\nu} D^{\mu\nu})$$

$$B_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu \quad D_{\mu\nu} = \partial_\mu \gamma_{d\nu} - \partial_\nu \gamma_{d\mu}$$

$\varepsilon = O(\text{few} \times 10^{-3})$ or smaller loop effect

Remove Mixing by field redefinitions

$$B_\mu \rightarrow B_\mu + \varepsilon/\cos\theta_W \gamma_{d\mu} \text{ or in terms of } \gamma \text{ \& } Z$$

$$A_\mu \rightarrow A_\mu + \varepsilon \gamma_{d\mu} \quad Z_\mu \rightarrow Z_\mu + \varepsilon \tan\theta_W \gamma_{d\mu}$$

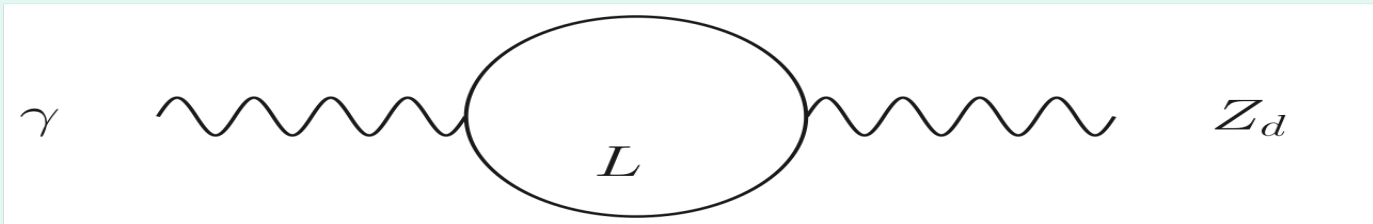
$$L_{\text{int}} = -e\varepsilon (J_\mu^{\text{em}} - 1/2 \cos^2\theta_W J_\mu^{\text{NC}}) \gamma_d^\mu$$

Second term largely cancelled by Z - γ_d mass matrix diagonalization! (Suppressed at low Q^2)

Remaining Z - γ_d mixing $O(\varepsilon m_{Z_d}^2/m_Z^2)$ very small $\sim 10^{-7}$ - 10^{-9} !

Example

**One Loop gamma- γ_d Kinetic Mixing
(Through Heavy Charged Leptons)
That also carry $U(1)_d$ charge
Expect $\epsilon \sim eg_d/8\pi^2 \approx O(10^{-3})$**



The Muon Anomalous Magnetic Moment

$$\Delta a_\mu = a_\mu^{\text{exp}} - a_\mu^{\text{SM}} = 276(63)(49) \times 10^{-11} \quad (2015)$$

$$276(80) \times 10^{-11} \quad (3.5\sigma \text{ discrepancy!})$$

Includes Recent *(Aoyama, Hayakawa, Kinoshita & Nio)

Note? $\Delta a_e = a_e^{\text{exp}} - a_e^{\text{SM}} = -92(81) \times 10^{-14}$ (1000x more precise)

Interpretations

Generic 1 loop SUSY Contribution:

$$a_\mu^{\text{SUSY}} = (\text{sgn}\mu) 130 \times 10^{-11} (100 \text{ GeV} / m_{\text{susy}})^2 \tan\beta$$

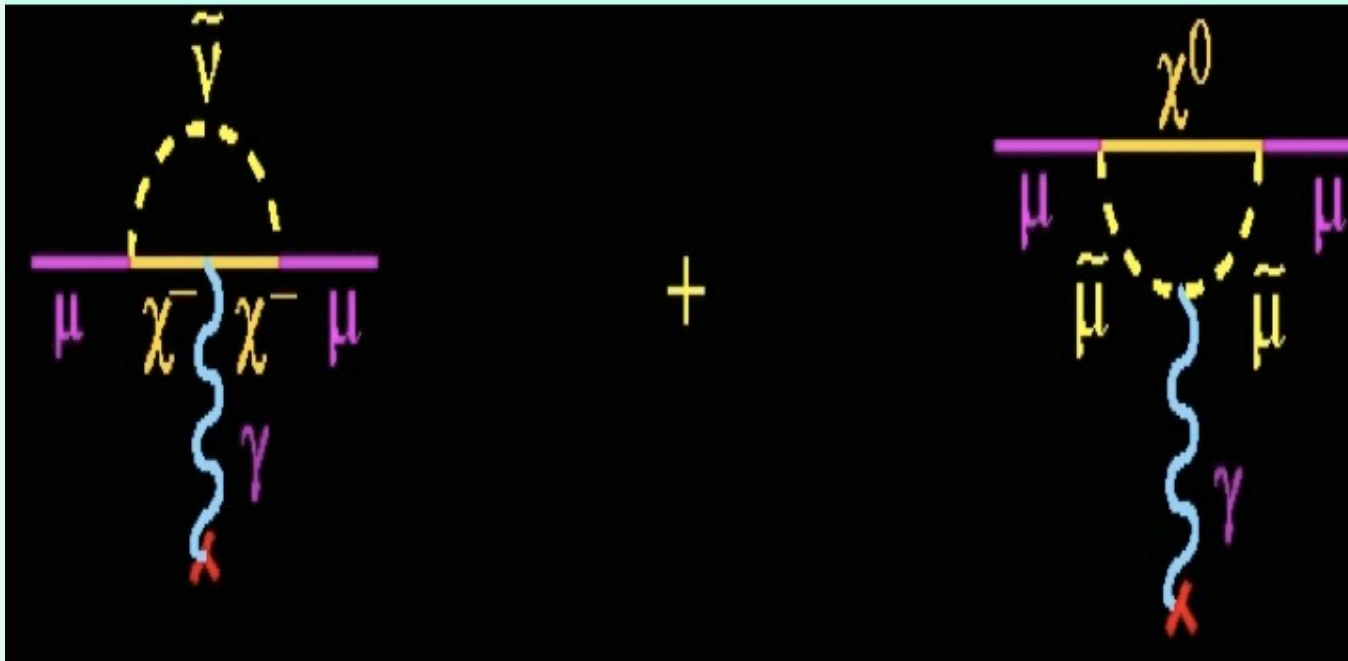
$$\tan\beta \approx 3-40, m_{\text{susy}} \approx 100-500 \text{ GeV} \quad Some LHC Tension$$

Fermilab a_μ^{exp} Exp. Factor 4 Improvement

BNL to FNAL: The Last Mile



3.2 “New Physics” Effects
_SUSY 1 loop a_μ Corrections
(Most Likely Scenario)



Other Explanations: ***Hadronic e^+e^- Data? HLBL (3loop)?***

Multi-Higgs Models (2 loop)

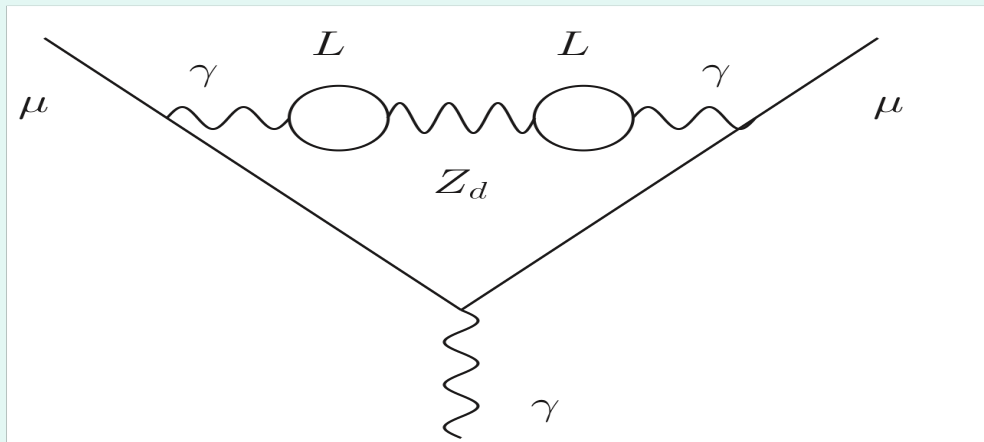
Extra Dimensions < 2TeV, Heavy Z' , Dynamics...

Light Higgs Like Scalar < 10MeV?

*** *Dark Photons (Fayet, Pospelov...)***

**$a_\mu^{Z_d} = \alpha/2\pi\epsilon^2 F(m_{Z_d}/m_\mu)$, $F(0)=1$ solves g-2 discrepancy
for $\epsilon^2 \approx 10^{-6}-10^{-4}$ & $m_{Z_d} \approx 10-500\text{MeV}$ (see figure)**

Dilbert Diagram



Z_d contribution to a_e

- $a_e^{Z_d} = \alpha/2\pi\epsilon^2 F(m_{Z_d}/m_e) > 0$ (Vector Interaction)

$a_e(\text{exp}) - a_e(\text{theory}) = -0.92 (0.81) \times 10^{-12}$ (sign!) $< 1.5 \times 10^{-12}$
2-3 sigma CONSTRAINS “NEW PHYSICS” (eg Dark Photon)

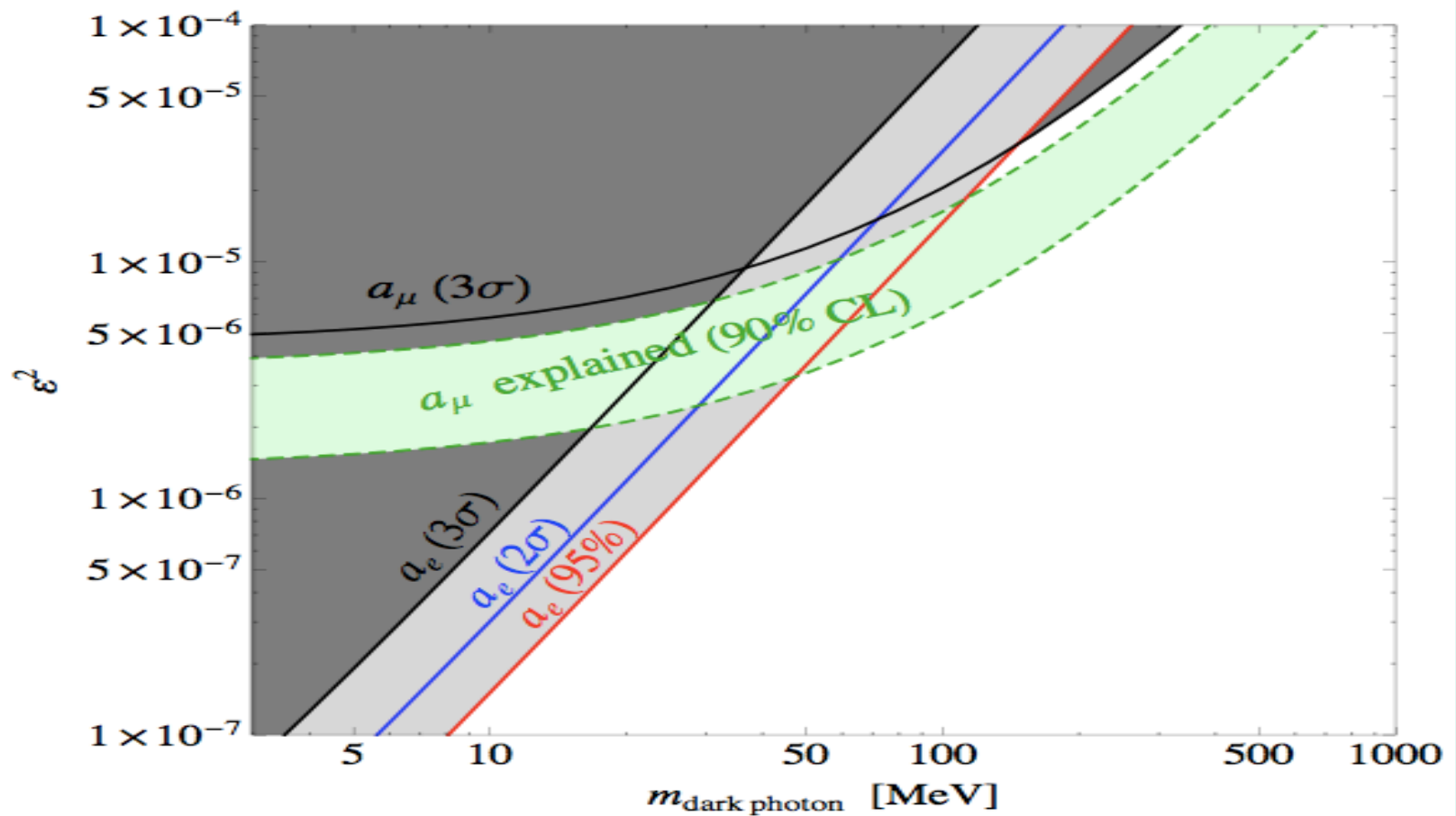
Important Improvement:

$\alpha^{-1}(^{87}\text{Rb}) = 137.035999049(90)$ [R. Bouchendira et al. \(2011\)](#)

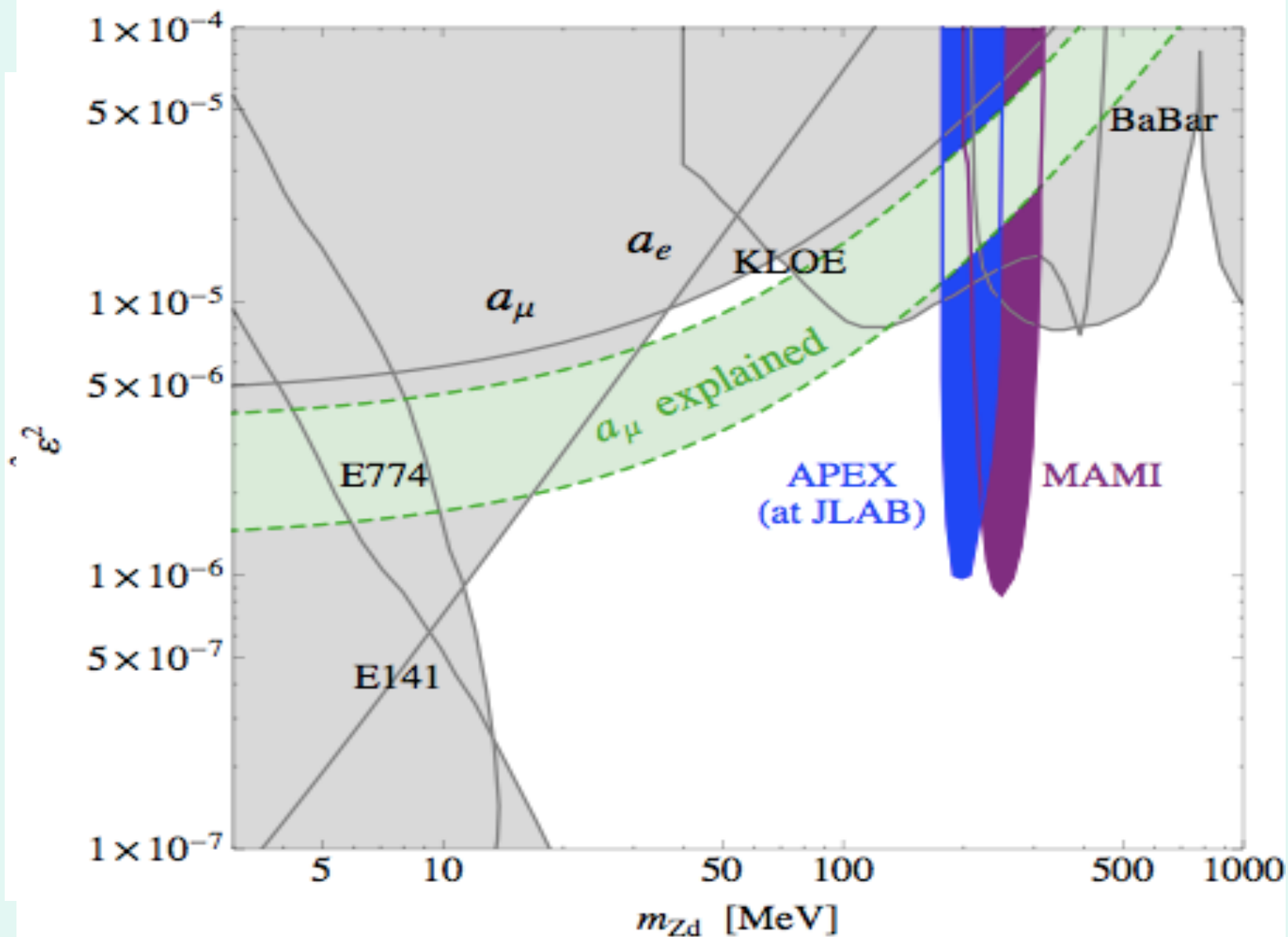
Future Improvement? (factor 7!)

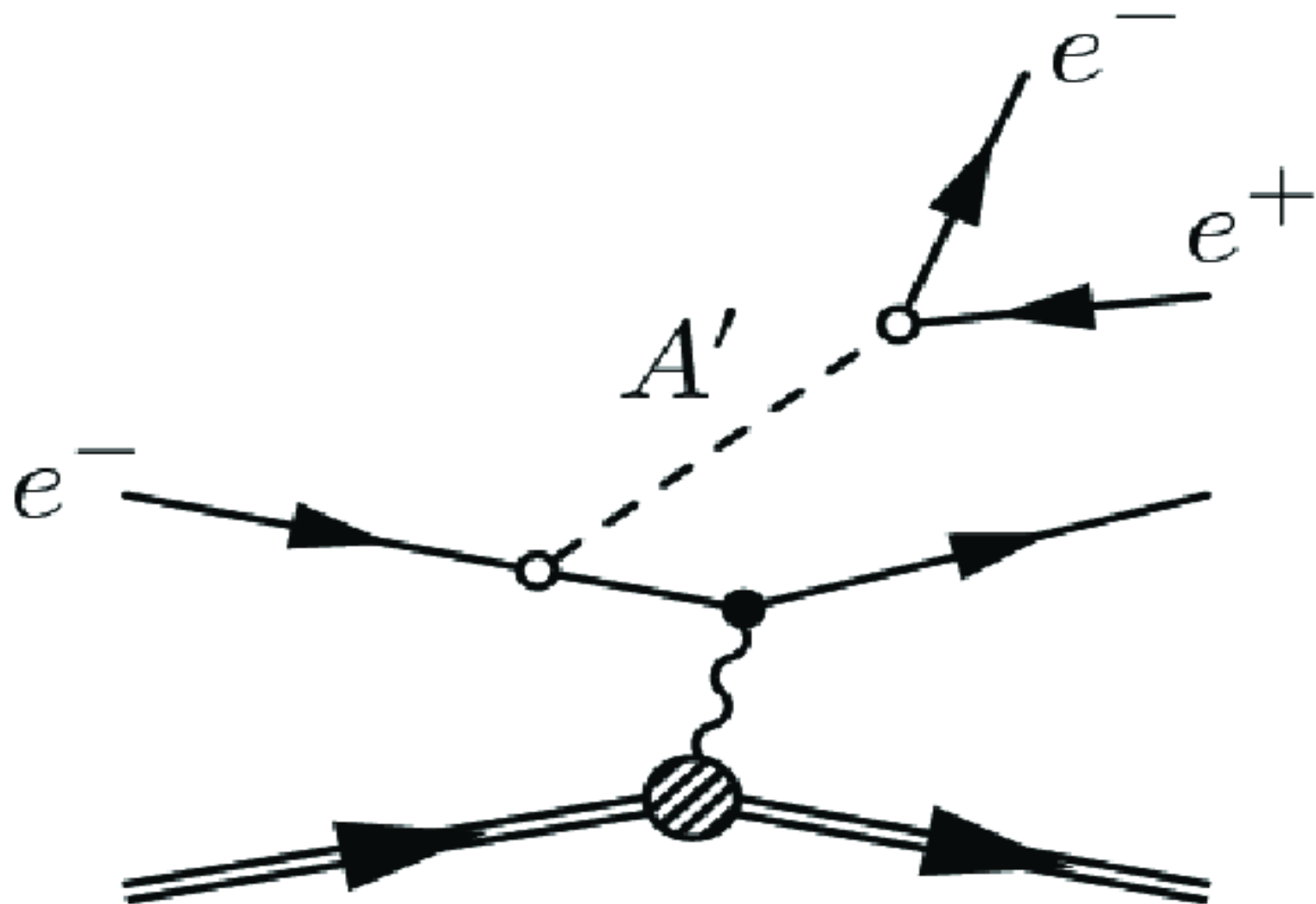
Lepton Magnetic Moment Constraints on the Dark Photon

(Green Band Corresponds to $a_\mu^{\text{exp}} - a_\mu^{\text{SM}} = 276(63)(49) \times 10^{-11}$ 90% CL)

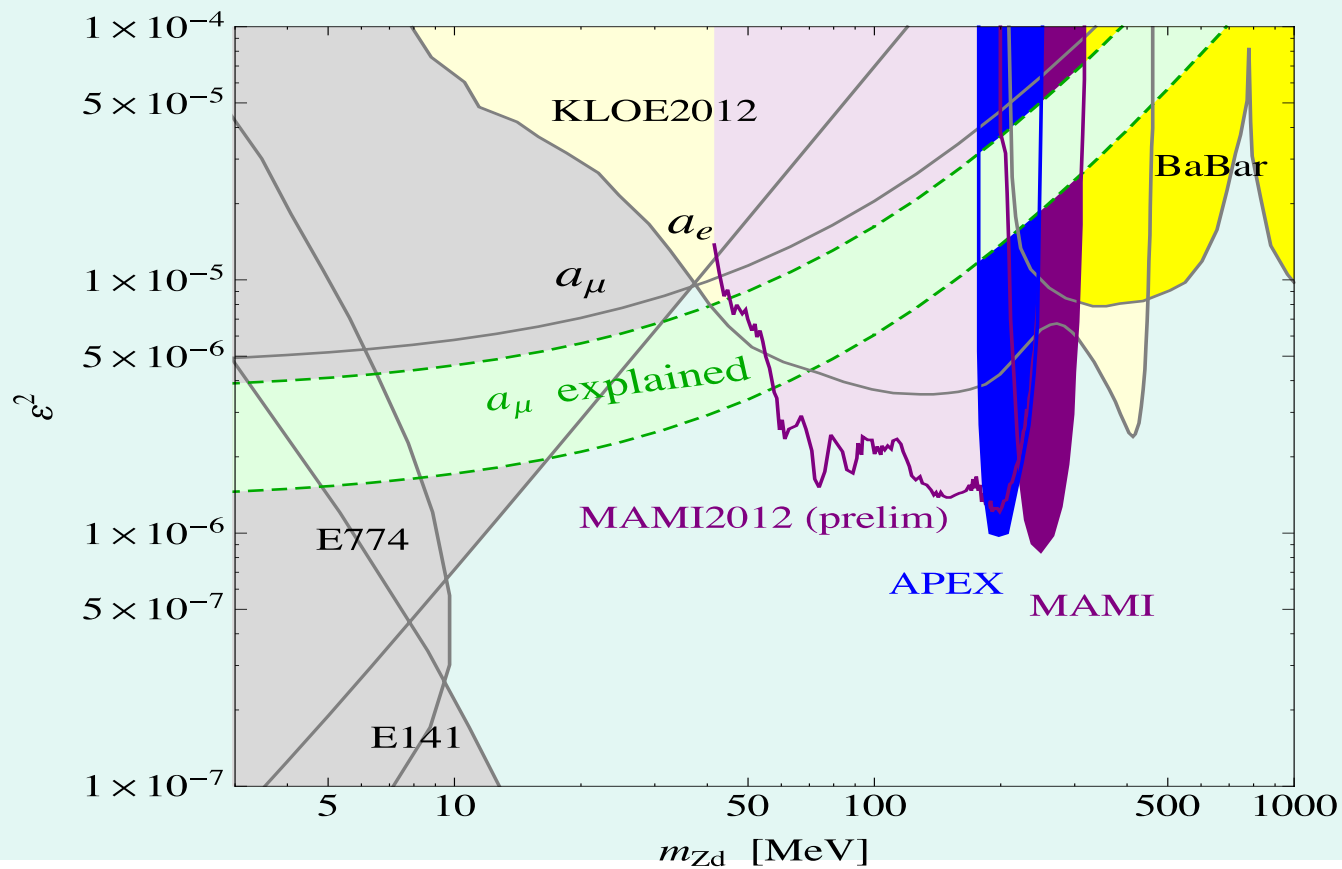


Dark Photon Exclusion Early 2012
(Some assume $BR(Z_d \rightarrow e^+e^-) \sim 1$)

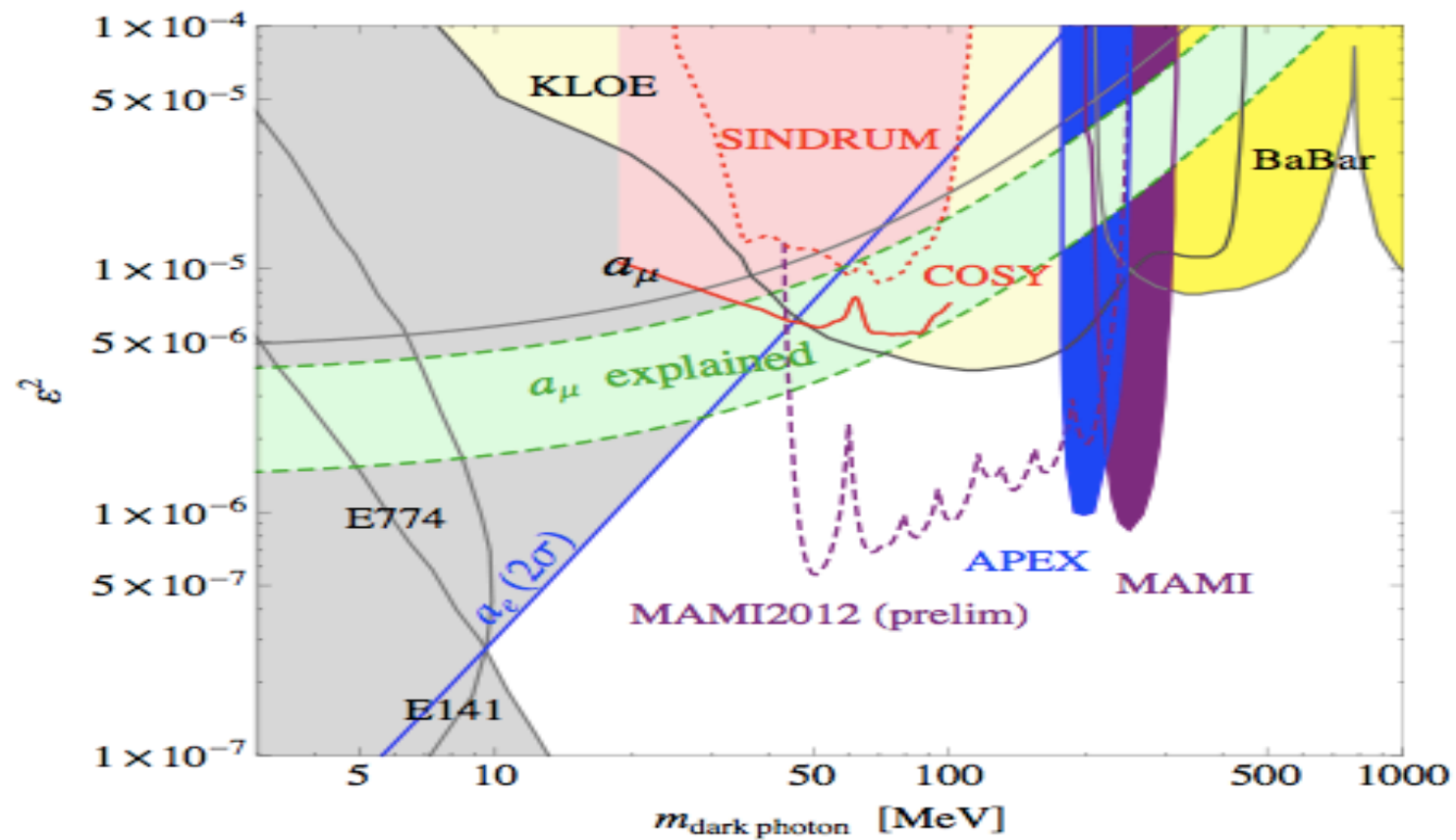




2013 Updates \rightarrow 20MeV-50MeV Left

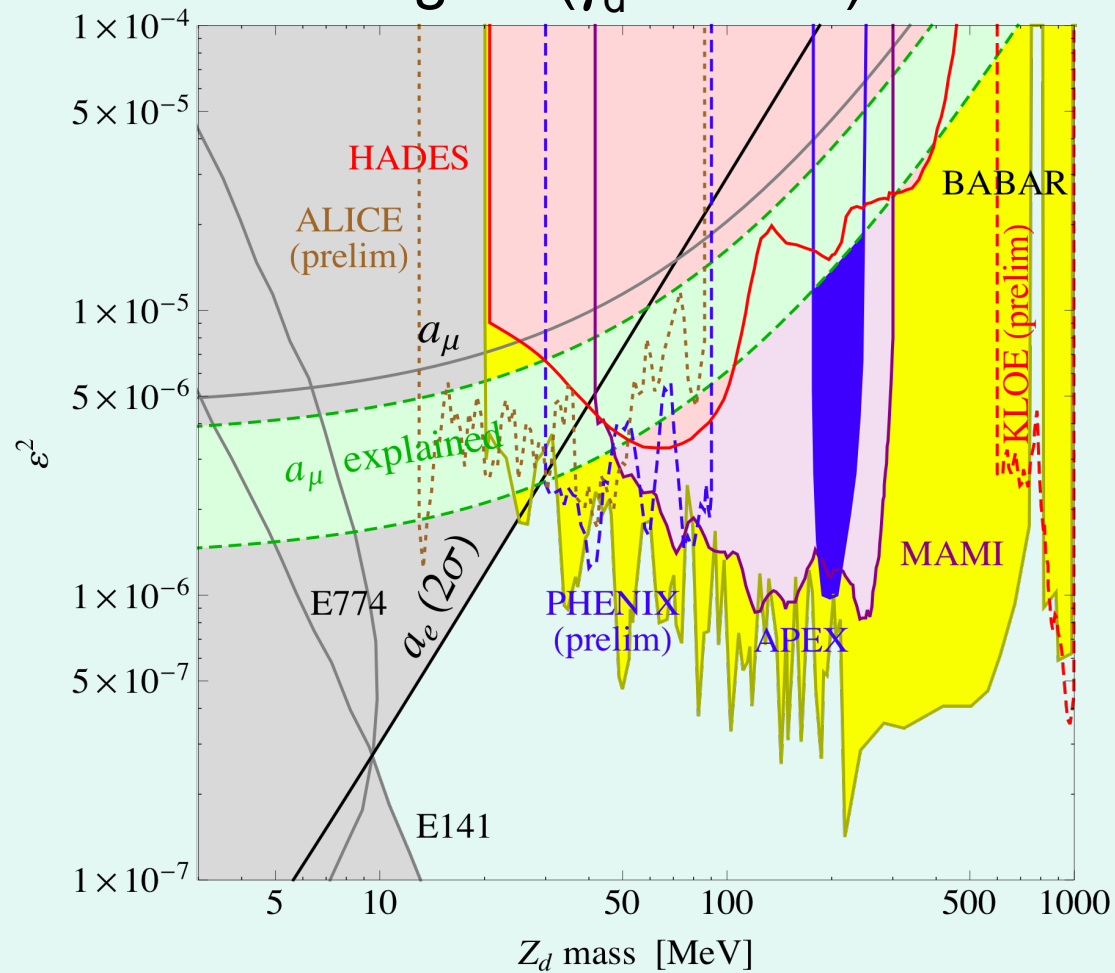


Updated Dark Photon Constraints including $\pi^0 \rightarrow \gamma\gamma_d$
(assume $BR(\gamma_d \rightarrow e^+e^-) \sim 1$)



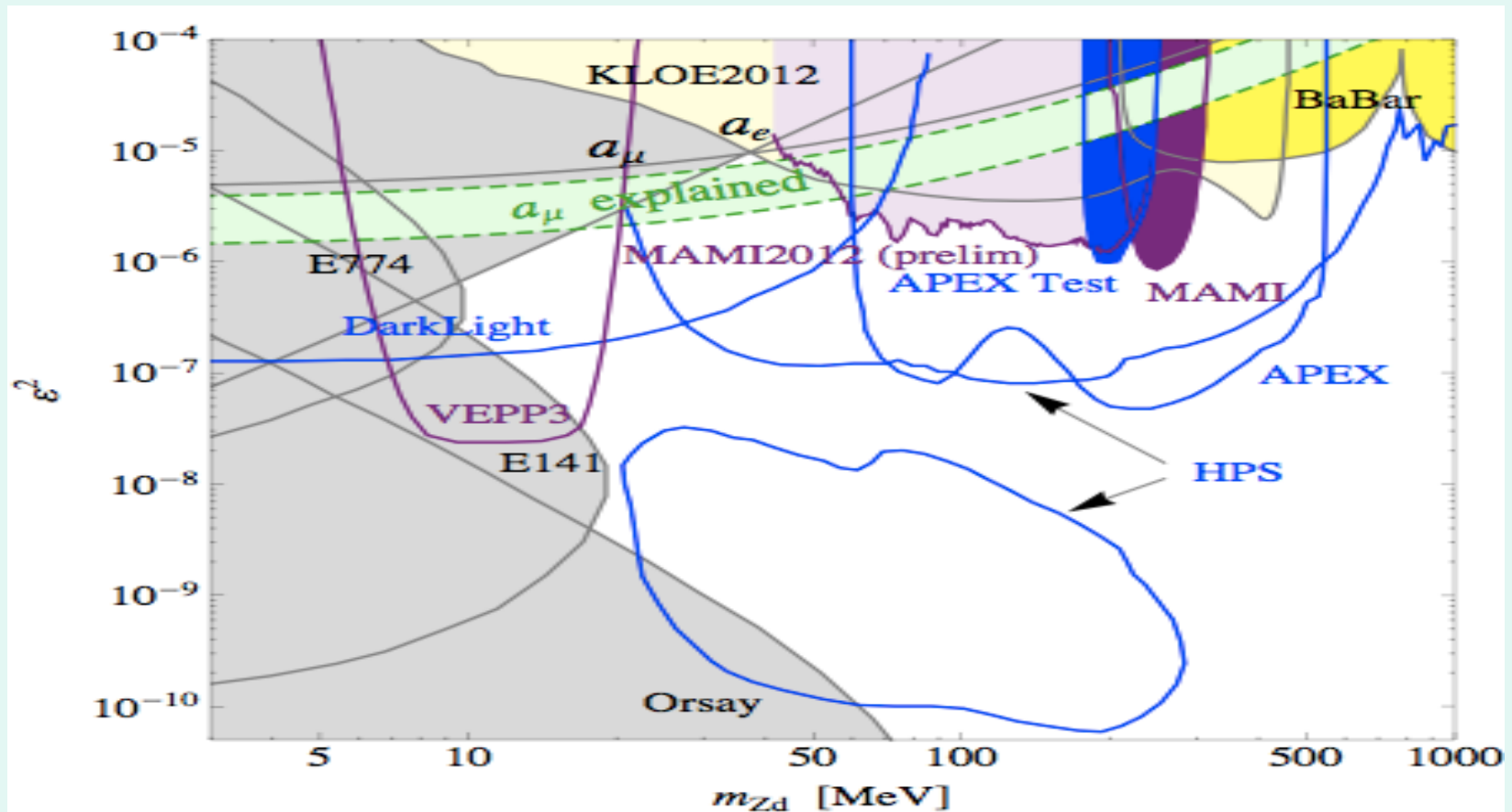
2014 Dark Photon Constraints including Phenix $\pi^0 \rightarrow \gamma\gamma_d$ (Ruled Out?)

Assuming $\text{BR}(\gamma_d \rightarrow e^+e^-) \sim 1$



Some Future Dark Photon Sensitivity

Assumes $\text{Br}(\gamma_d \rightarrow e^+e^-)=1$ What if $\gamma_d \rightarrow$ missing energy?



Light Dark Matter Alternative

Very light Dark Matter χ (10-100-few hundred MeV) can be a viable scenario (Fayet, Pospelov ...)

Needs Dark Photon! For viable density

Requires strong dark coupling $g_d \sim 3-10e!$ Note g_d & ϵ Run!

Strong Dynamics? (*H. Davoudiasl & WJM 2015*)

Consequences of $BR(\gamma_d \rightarrow \chi\chi) \sim 1$ light dark matter

Invisible (Missing Energy) Decays Dominate

Pospelov et al: Light Dark Matter may be part of accelerator produced neutrino beams.

$BR(\pi^0 \rightarrow \gamma + \gamma_d) \sim O(10^{-5}-10^{-6})$ $\gamma_d \rightarrow$ light Dark matter

MiniBoone Proposal, Beam Dumps... $\sigma \sim \epsilon^2 \alpha \alpha_d / Q^2$

3. Z - Z_d mass mixing

$$\epsilon_Z = m_{Z_d}/m_Z \delta \rightarrow \epsilon_Z g/2\cos\theta_W Z_d^\mu J_\mu^{NC}$$

Neglecting Kinetic Mixing ϵ

$$M^2 = \begin{bmatrix} m_Z^2 & -m_{Z_d}m_Z\delta \\ -m_{Z_d}m_Z\delta & m_{Z_d}^2 \end{bmatrix} \quad \begin{array}{l} 0 \leq |\delta| < 1 \\ \delta \approx (m_{Z_d}/m_Z) \ll 1 \end{array}$$

Mixing angle $\approx \epsilon_Z = m_{Z_d}/m_Z \delta \sim (m_{Z_d}/m_Z)^2 \sim 10^{-6}$

Gives rise to: $g/2\cos\theta_W (m_{Z_d}/m_Z \delta) J_\mu^{NC}$

Like a Z with smaller mass and couplings

$$J_\mu^{NC} = (T_{3f} - 2Q_f \sin^2\theta_W) f \gamma_\mu f - T_{3f} f \gamma_\mu \gamma_5 f$$

Extended Higgs Example

1st Higgs Doublet $\langle\phi_1\rangle=v_1 \rightarrow W^\pm, Z, \text{ fermion masses}$

2nd Higgs Doublet $\langle\Phi_2\rangle=v_2$ dark charge (Portal) W^\pm, Z, Z_d masses

3rd Higgs Singlet $\langle\phi_d\rangle=v_d$ carries dark charge: Z_d mass

$$\tan \beta = v_2/v_1 \quad \tan \beta_d = v_2/v_d$$

$$\varepsilon_Z = m_{Z_d}/m_Z \sin\beta \sin\beta_d \approx m_{Z_d}/m_Z v_2^2/v_1 v_d = m_{Z_d}/m_Z \delta$$

\rightarrow parity violation (like ordinary Z but suppressed by ε_Z)

longitudinal Z_d like an axion E/m_{Z_d} coupling!

At High Energies Z_d Axion Like but spin 1!

Dark Parity Violation

Effect of ε & δ together: (at low $Q^2 \ll m_Z^2$)

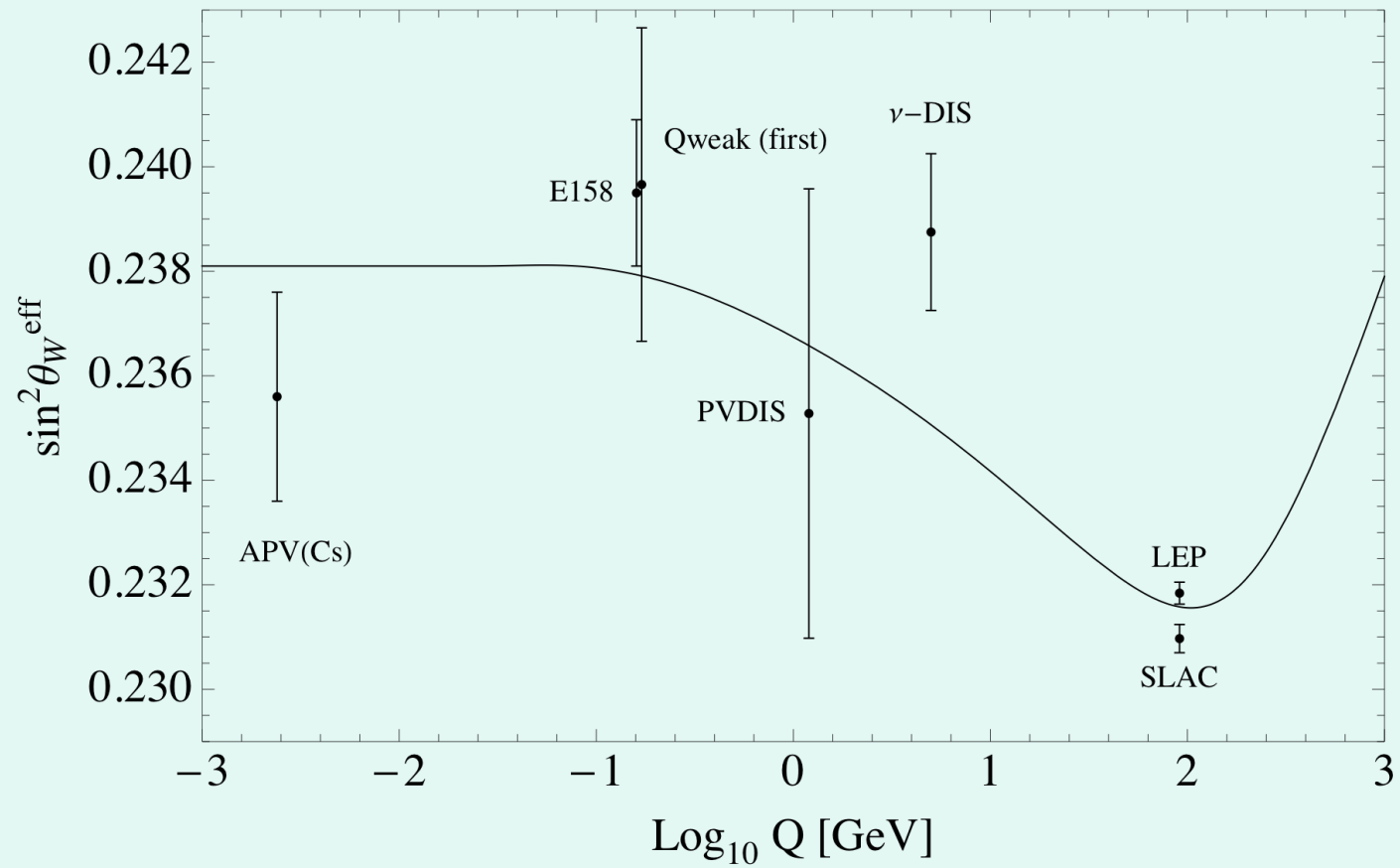
$$\Delta \sin^2 \theta_W(Q^2) = 0.42 \varepsilon \delta m_Z m_{Z_d} / (Q^2 + m_{Z_d}^2) \approx 0.42 \varepsilon m_{Z_d}^2 / (Q^2 + m_{Z_d}^2)$$

Shift largest at small $Q^2 < m_{Z_d}^2$

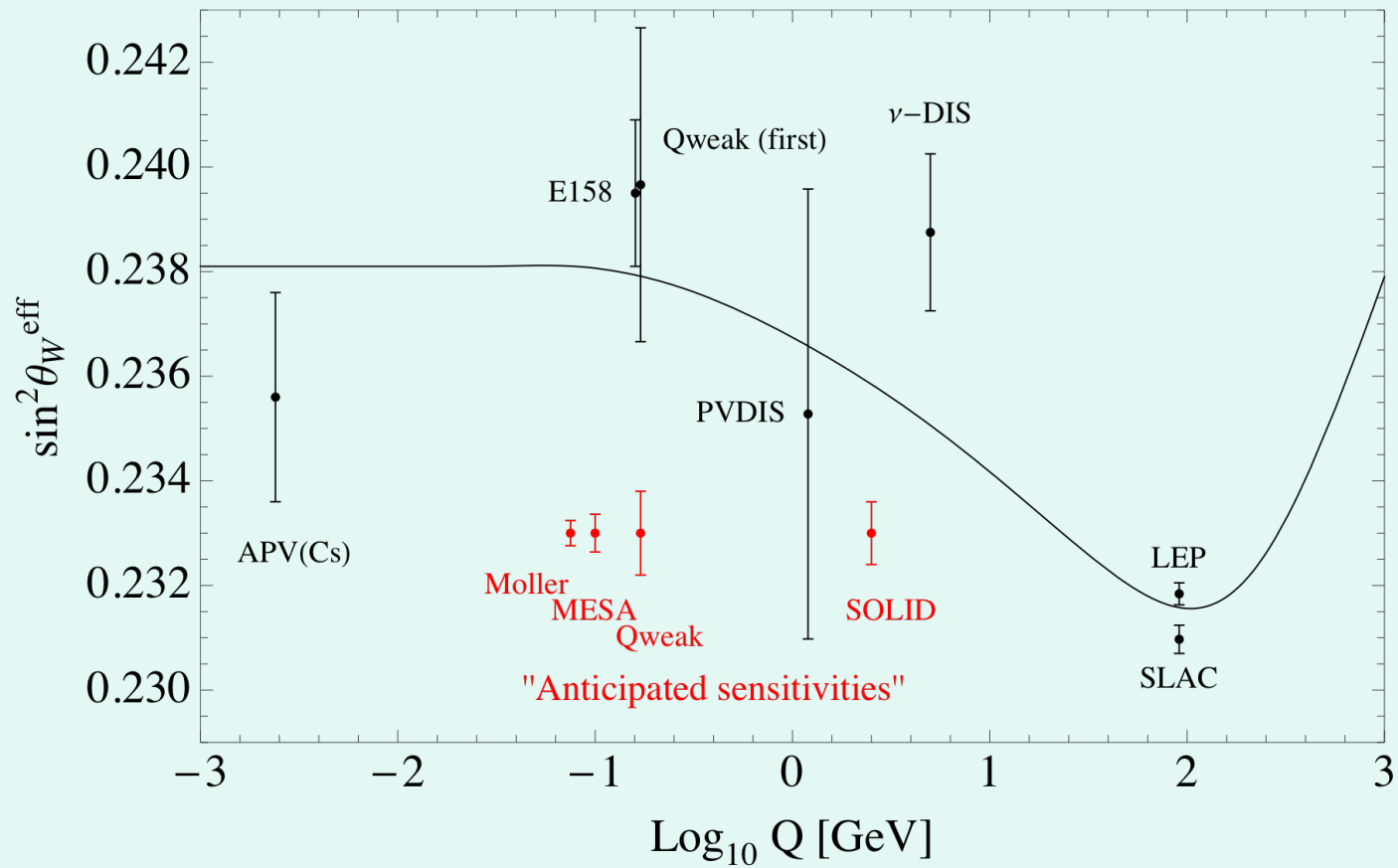
APV & $m_{Z_d} = 50 \text{ MeV} \rightarrow \sin^2 \theta_W(Q \approx 75 \text{ MeV})$ shift by 0.0010!

Negligible effect at the Z Pole!

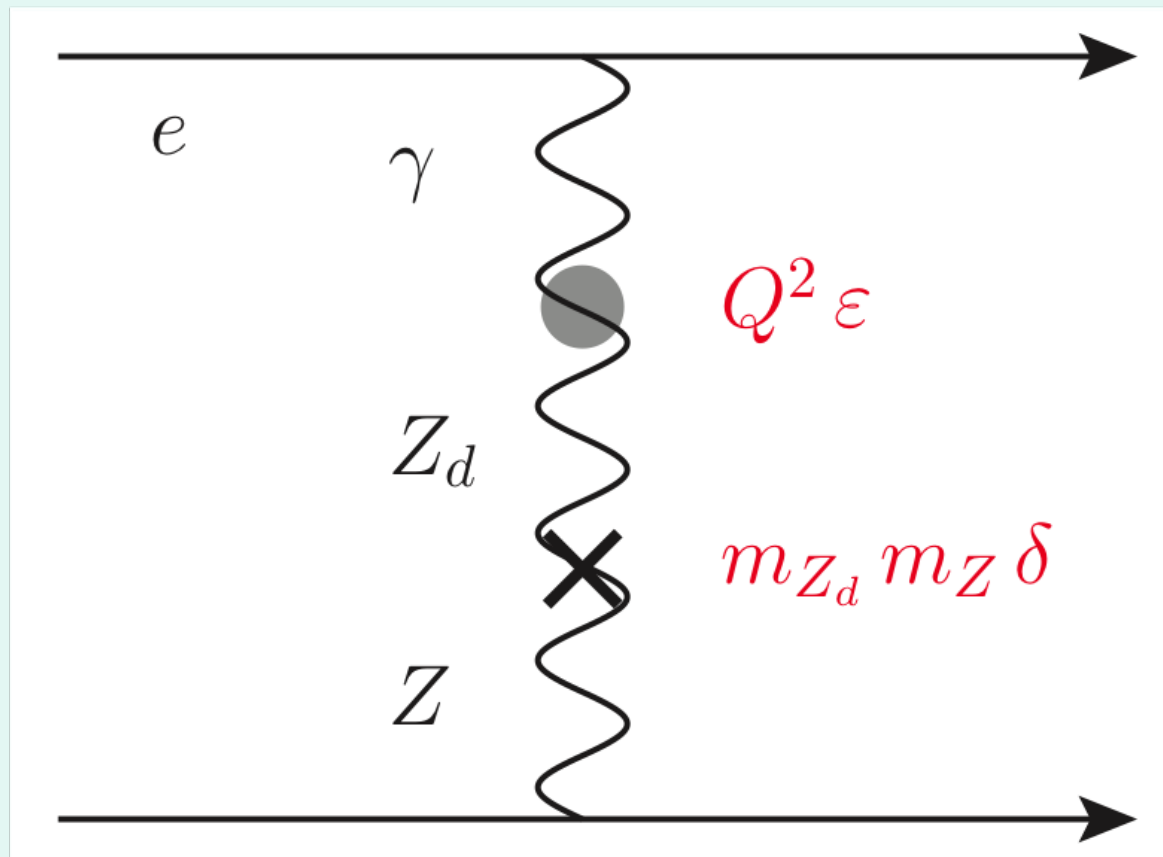
Measurements of running $\sin^2\theta_W(Q^2)$



$\sin^2\theta_W(Q^2)$ Measurements & expected Future Sensitivities

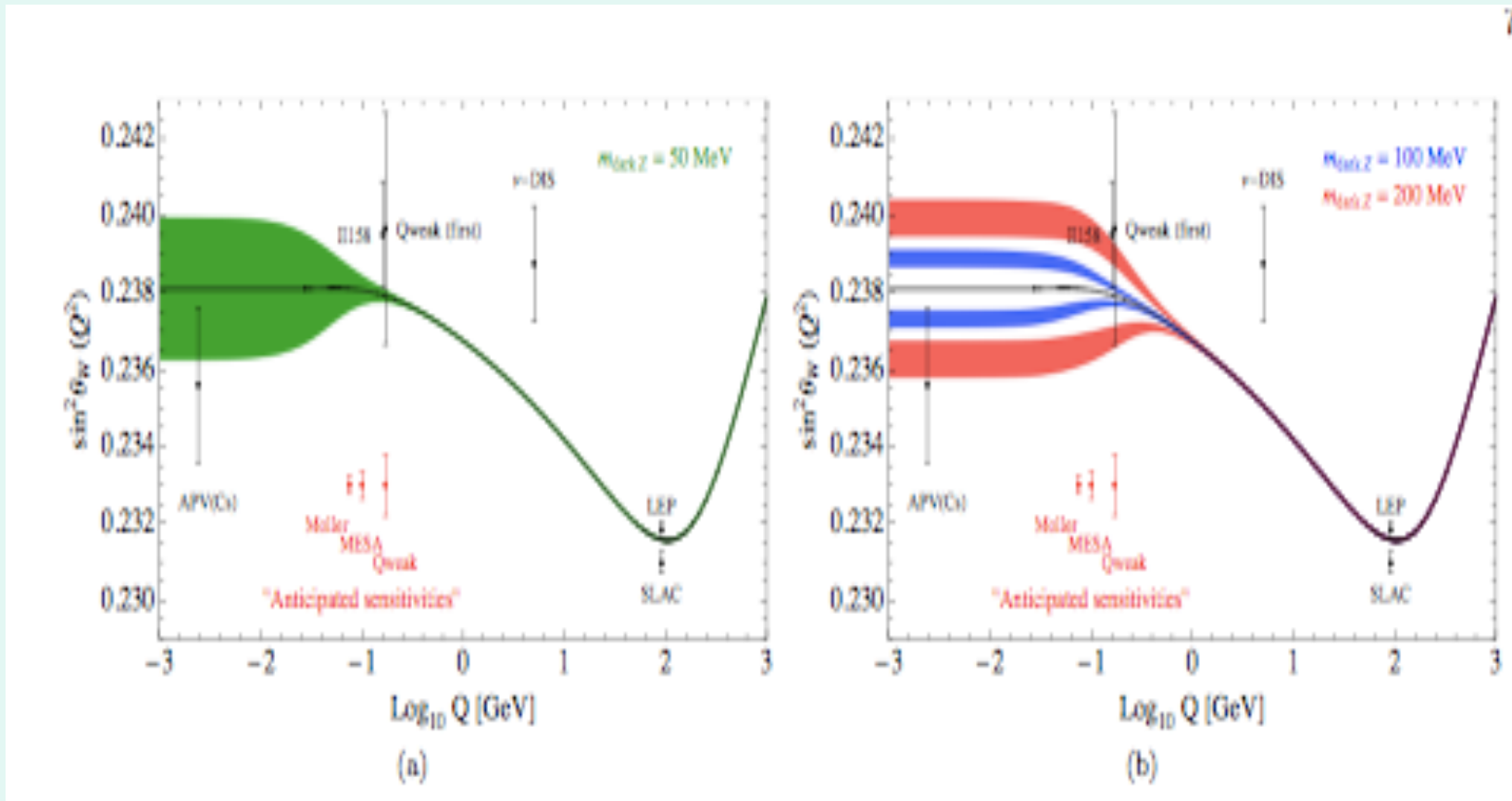


Dark Z Effect on electron scattering
Photon-Z Mixing through Z_d
from H-S Lee



Potential Effect of “Light” Z_d on Running

H. DAVOUDIASL, H-S LEE, W. MARCIANO



3ii) **Rare K & B Decays (eg. $K \rightarrow \pi Z_d$) $\delta^2 \rightarrow 10^{-6}$!**

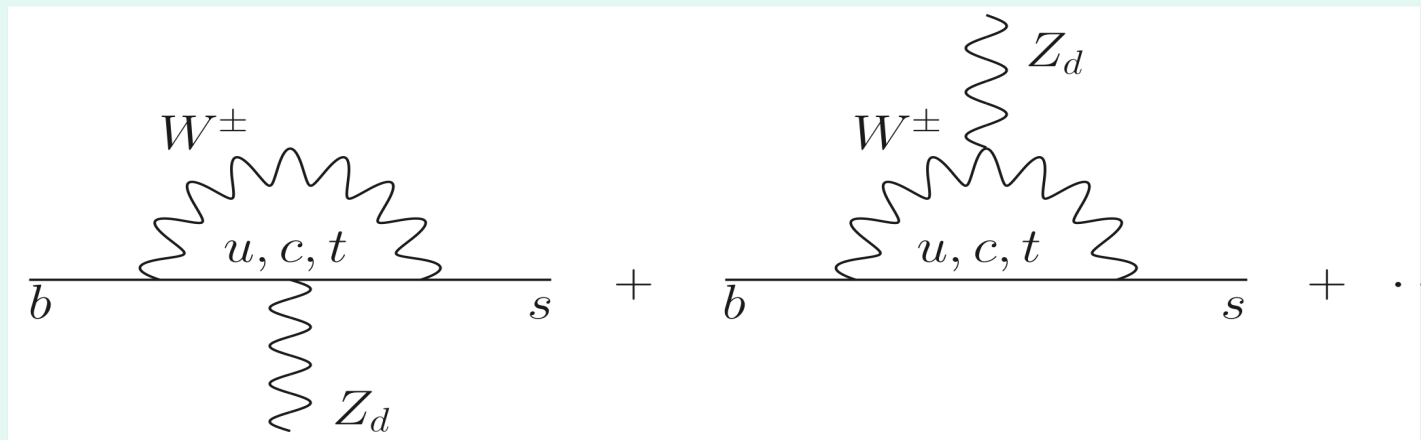
- With Z-Z_d mixing $\rightarrow Z_d^{\mu f} \gamma_{\mu} \gamma_5 f$ coupling non-conserved
Loop Induced Effects: eg Zsd or Zbs $Z \rightarrow \epsilon_Z Z_d$
Longitudinal Z_d couples strongest to heavy particles eg t, b...
Flavor Changing Neutral Currents: Z_dsd & Z_dbs
Proportional to $g^2(m_t/m_W)^2 \times |V_{ts} V_{td}^*|$ or $|V_{tb} V_{ts}^*|$

$BR(K \rightarrow \pi Z_d) \approx 4 \times 10^{-4} \delta^2$ $Z_d \rightarrow e^+e^-, \mu^+\mu^-,$ or neutrinos
light dark matter?

$BR(B \rightarrow K Z_d) \approx 0.1 \delta^2$

Some Model Dependence

Flavor Changing neutral current decays and ε_Z



K & B Decay Bounds

$$\text{BR}(K^+ \rightarrow \pi^+ e^+ e^-)_{\text{exp}} = 3.00(9) \times 10^{-7} \quad \text{probes } \delta^2 \approx 10^{-4}$$

$$\text{BR}(K^+ \rightarrow \pi^+ \mu^+ \mu^-)_{\text{exp}} = 9.4(6) \times 10^{-8} \quad \text{probes } \delta^2 \approx 10^{-4}$$

$$\text{BR}(K^+ \rightarrow \pi^+ \nu \nu)_{\text{exp}} = 1.7(1.1) \times 10^{-10} \quad \text{probes } \delta^2 \approx 10^{-6}$$

SM Expectation $\sim 0.8 \times 10^{-10}$

Depends on m_{Z_d} and Z_d Branching Ratios

K_L potentially better $\text{BR}(K_L \rightarrow \pi^0 e^+ e^-) < 2.8 \times 10^{-10}$ KTeV!

$\text{BR}(B^+ \rightarrow K Z_d) < 10^{-7}$ probes $\delta^2 \approx 10^{-6}$ Can do even better!

B decays – Look for $e^+ e^-$ pairs at m_{Z_d} Super B Factories

4. $K \rightarrow \pi Z_d \rightarrow \pi e^+ e^-$ or π^+ "missing energy"

M. Pospelov(2009) Kinetic γ - Z_d Mixing $\rightarrow K \rightarrow \pi Z_d$

$$BR(K \rightarrow \pi Z_d) = 1.6 \times 10^{-3} |V_{cd} V_{cs}^*|^2 \epsilon^2 (m_{Z_d}/100 \text{MeV})^2 \\ \approx 8 \times 10^{-5} \epsilon^2 (m_{Z_d}/100 \text{MeV})^2$$

$$BR(K \rightarrow \pi Z_d) \approx 2 \times 10^3 |V_{td} V_{ts}^*|^2 \delta^2 \quad (\mathbf{Z-Z_d \text{ mixing}}) \quad \mathbf{DLM} \\ \approx 4 \times 10^{-4} \delta^2 \quad \text{similar magnitudes for } \delta \approx m_{Z_d}/m_Z$$

Amplitudes could interfere constructively or destructively

Can be searched for in $K \rightarrow \pi e^+ e^-$ or π^+ "missing energy"

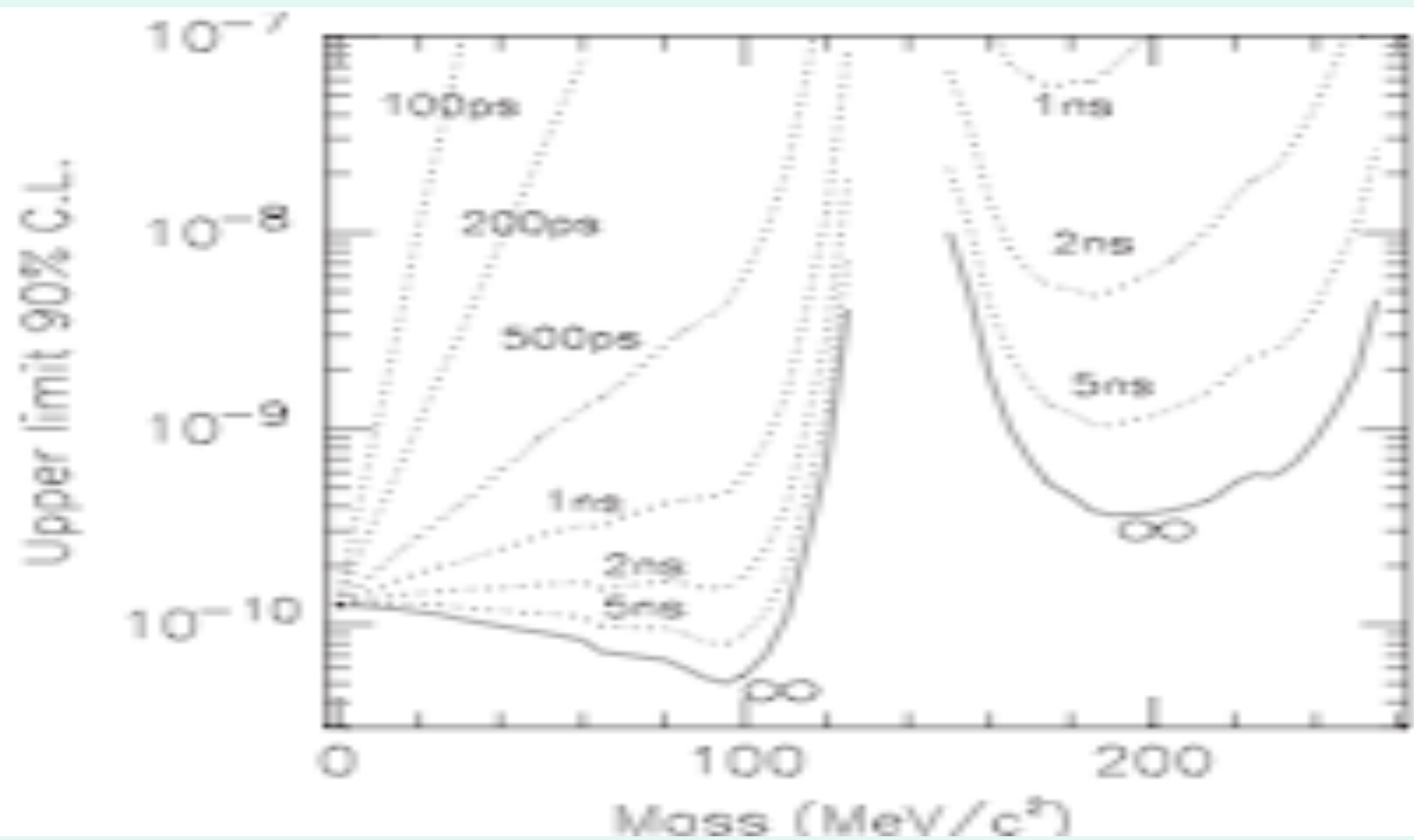
What if $\text{Br}(Z_d \rightarrow e^+e^-) \ll 1$?
 , $\text{Br}(Z_d \rightarrow e^+e^-) \ll \text{Br}(Z_d \rightarrow \text{missing energy}) = 1$
 For $m_{Z_d} < 200 \text{ MeV}$
Solves muon g-2 discrepancy

- **Pospelov:** Kinetic Mixing and $K^+ \rightarrow \pi^+ Z_d$

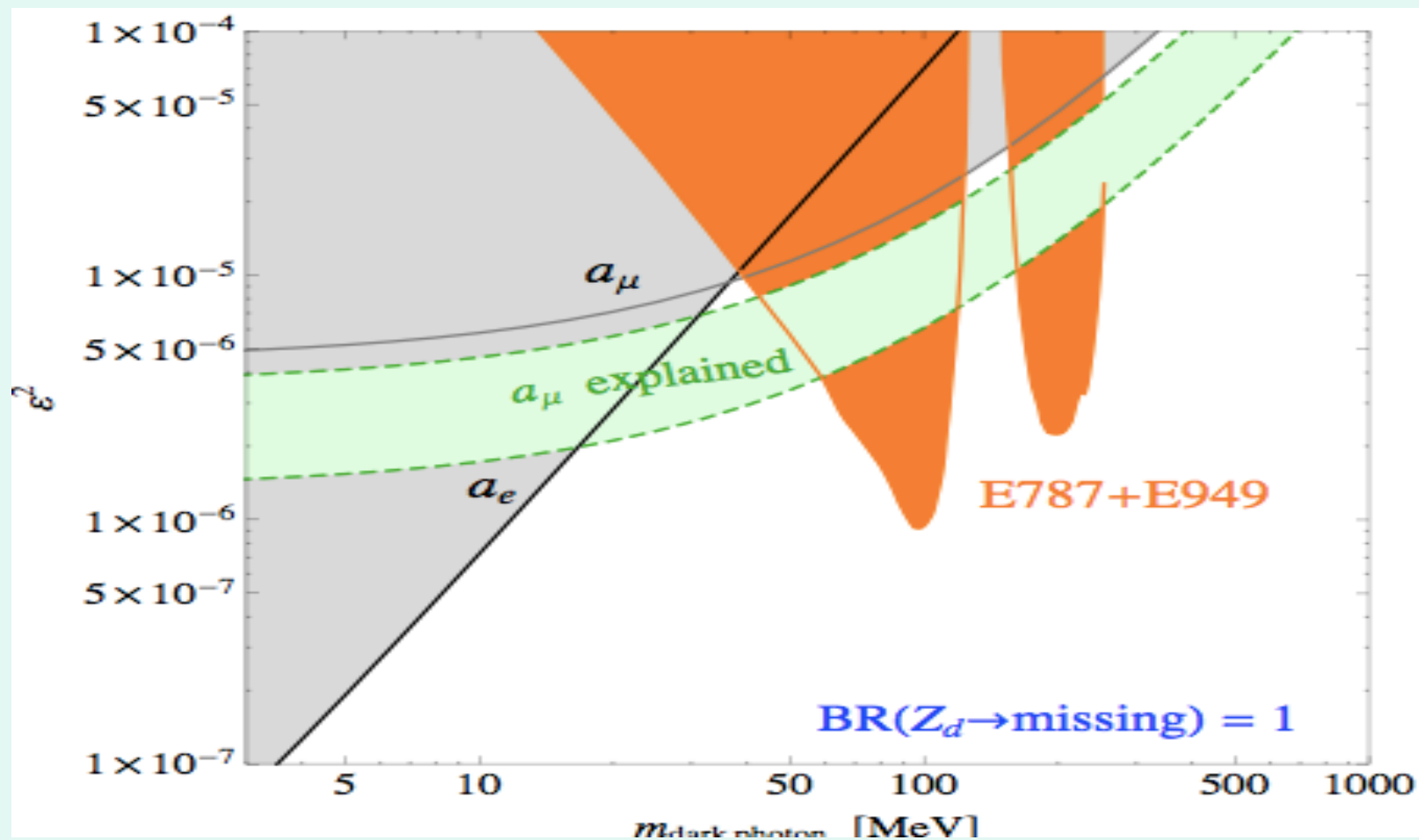
$$\text{BR}(K^+ \rightarrow \pi^+ Z_d) = 8 \times 10^{-5} \epsilon^2 (m_{Z_d} / 100 \text{ MeV})^2$$

E787/949 at BNL sensitive to $\text{BR}(K^+ \rightarrow \pi^+ + \text{missing energy})$
 down to 5×10^{-11} at $m_{Z_d} = 100 \text{ MeV} \rightarrow \epsilon < 8 \times 10^{-4}$!

For $\text{BR}(Z_d \rightarrow \text{missing energy}) = 1$ leaves mainly
 $20 \text{ MeV} < m_{Z_d} < 50 \text{ MeV}$ & $m_{Z_d} \sim m_\pi$



Dark Photon Constraints for $\text{BR}(\gamma_d \rightarrow \chi\chi)$
 $m_{\gamma_d} = 100, 200 \text{ MeV}$ ruled out



Z-Z_d Mass Mixing $\rightarrow \epsilon_Z = \delta m_{Z_d} / m_Z \approx (m_{Z_d} / m_Z)^2$

- Potentially Observable Effects (for $\delta \geq 10^{-3}$)
APV & Polarized Electron Scattering at low $\langle Q \rangle$
 $BR(K \rightarrow \pi Z_d) \approx 4 \times 10^{-4} \delta^2$ $BR(B \rightarrow K Z_d) \approx 0.1 \delta^2$

δ^2 roughly probed to 10^{-6}

$K \rightarrow \pi Z_d \rightarrow \pi^+$ "missing energy"

ϵ and δ effects could partially cancel!

Suppression by $\sim 1/6$ allows $Z_d \sim 100$ MeV

Combined with muon $g-2 \rightarrow$ observable dark PV Band

6. Outlook

- Light Dark Photon & $g_\mu - 2$ – tension (if e^+e^- decay dominate)
- Light Dark Boson + Light Dark Matter (avoid e^+e^- constraints)
- $(K \rightarrow \pi Z_d)$ $Z_d \rightarrow$ light dark matter constraint tension for
 $m_{Z_d} \sim 100$ & 200 MeV (kinetic - mass mixing suppression)
NA62 started running in 2014: $\sim 20x$ more K^+ sensitivity
 $\sim 100x$ more $\pi \rightarrow \gamma Z_d$ sensitivity

Predictive Bands for dark parity violation in Moller & P2

Z_d Evidence would revolutionize particle physics

The End or “New Beginning”!!