The Future of Particle Cosmology (after LHC Run II)

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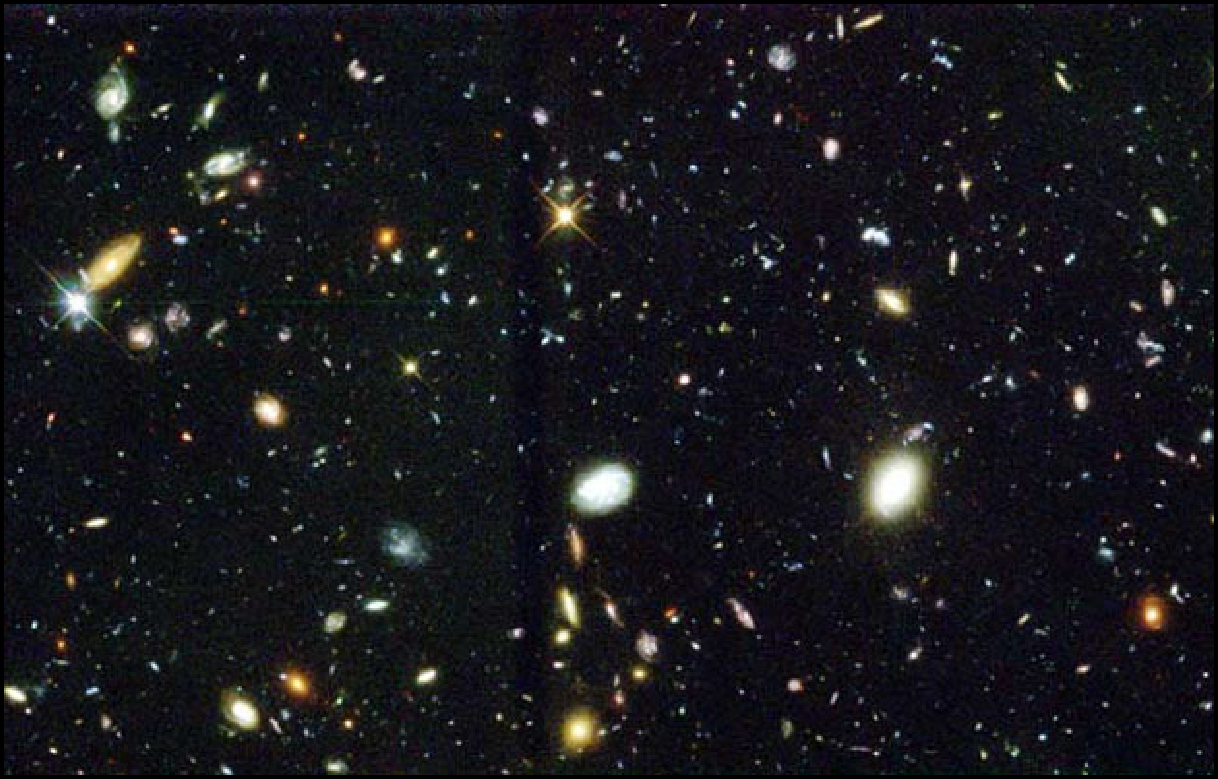

NExT PhD Workshop 2017, Abingdon, UK

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Lecture 4: Light States from "Dark Sectors"

- DM may reside in a separate sector with its own forces
- Analogy with SM, a multicomponent sector

- Simple example: a "dark" sector $U(1)_d$
- Mediated by vector boson Z_d of mass m_{Z_d} coupling g_d
- Interaction with SM: dim-4 operator (portal) via *mixing*

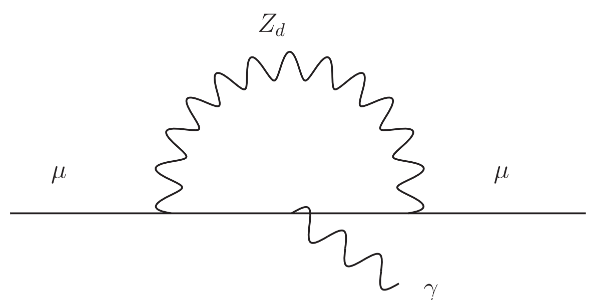
- $m_{Z_d} \lesssim 1$ GeV has been invoked in various contexts
- DM interpretation of astrophysical data

Arkani-Hamed, Finkbeiner, Slatyer, Weiner, 2008

- Explaining 3.5σ $g_\mu - 2$ anomaly: $\Delta a_\mu = a_\mu^{\text{exp}} - a_\mu^{\text{SM}} = 276(80) \times 10^{-11}$

Fayet, 2007 (direct coupling)

Pospelov, 2008 (kinetic mixing)



- DM matter sector may be light ($\lesssim 1$ GeV), weakly coupled to SM

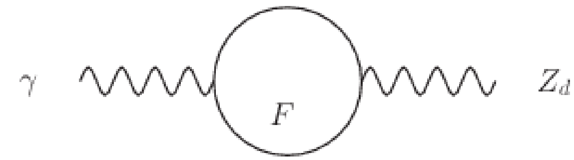
Dark Photon

- Kinetic mixing: Z_d of $U(1)_d$ and B of SM $U(1)_Y$ Holdom, 1986

$$\mathcal{L}_{\text{gauge}} = -\frac{1}{4}\mathbf{B}_{\mu\nu}\mathbf{B}^{\mu\nu} + \frac{1}{2}\frac{\varepsilon}{\cos\theta_{\mathbf{W}}}\mathbf{B}_{\mu\nu}\mathbf{Z}_{\mathbf{d}}^{\mu\nu} - \frac{1}{4}\mathbf{Z}_{\mathbf{d}\mu\nu}\mathbf{Z}_{\mathbf{d}}^{\mu\nu}$$

$X_{\mu\nu} = \partial_\mu X_\nu - \partial_\nu X_\mu$

  - $\varepsilon \ll 1$ may be loop induced: $\varepsilon \sim e g_d/(4\pi)^2 \lesssim 10^{-3}$



- Remove cross term, via field redefinition
  - $Z_d \to Z_d/\sqrt{1-\varepsilon^2/\cos^2\theta_W}$ and $B_\mu \to B_\mu + (\varepsilon/\cos\theta_W)Z_{d\mu}$
  - $A_\mu \to A_\mu + \varepsilon Z_{d\mu}$ and $Z_\mu \to Z_\mu - \varepsilon \tan\theta_W Z_{d\mu}$
  - Z-Z_d mass matrix digonalization

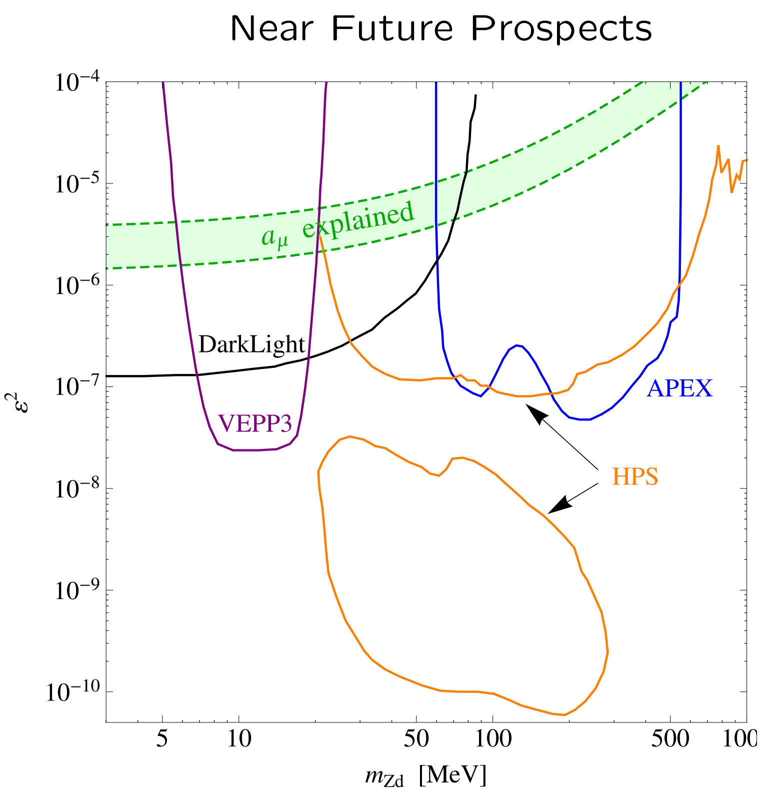
$\Rightarrow Z_d$ couples to EM current: $\boxed{\mathcal{L}_{\text{int}} = -e\,\varepsilon\, J^\mu_{em} Z_{d\mu}}$ $J^\mu_{em} = \sum_f Q_f \bar{f}\gamma^\mu f + \cdots$

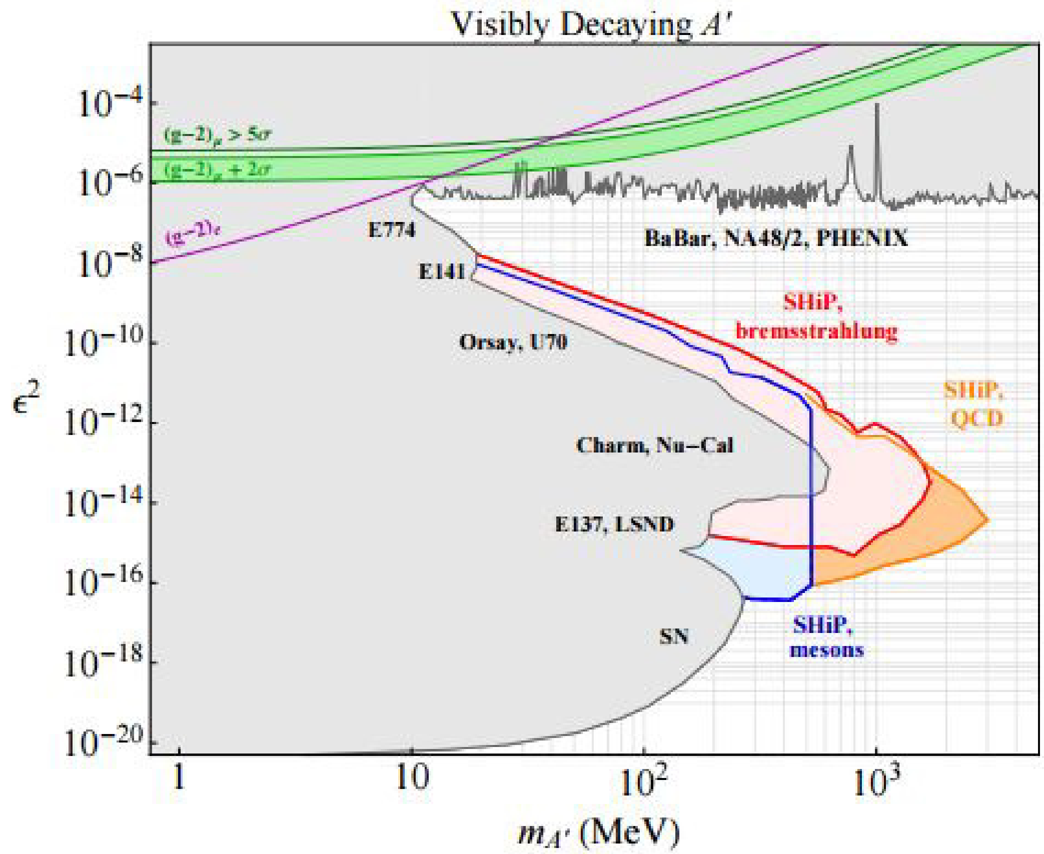
  - Like a photon, but ε-suppressed couplings: "dark" photon
  - Neutral current coupling suppressed by $m^2_{Z_d}/m^2_Z \ll 1$

- Active experimental program to search for dark photon

Pioneering work by Bjorken, Essig, Schuster, Toro, 2009

- An early experimental target: $g_\mu - 2$ parameter space



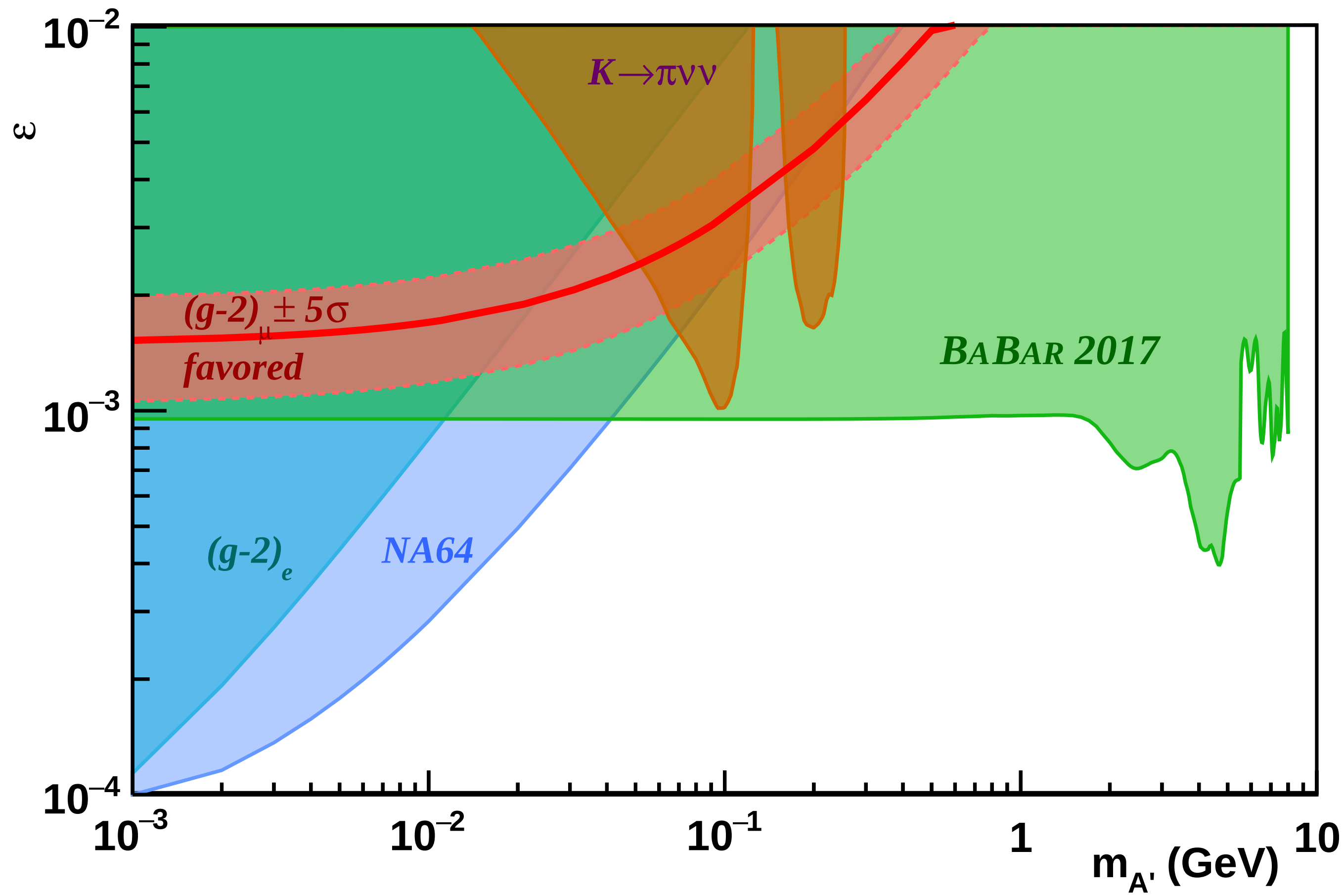


S. Alekhin *et al.*, arXiv:1504.04855 [hep-ph]

GeV-scale visibly decaying Z_d basically excluded as $g_\mu - 2$ explanation

“Invisible” Dark Photon

- $\exists$ **dark** X**:** $m_X < m_{Z_d}/2$ **and** $Q_d g_d \gg e\varepsilon \Rightarrow$ **Br**$(Z_d \to X\bar{X}) \simeq 1$



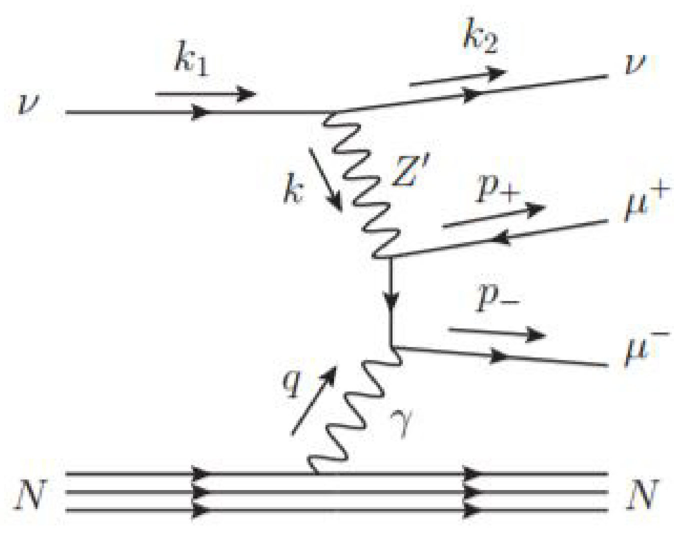
Recent 90% CL bound from Babar Collaboration, arXiv:1702.03327 [hep-ex]

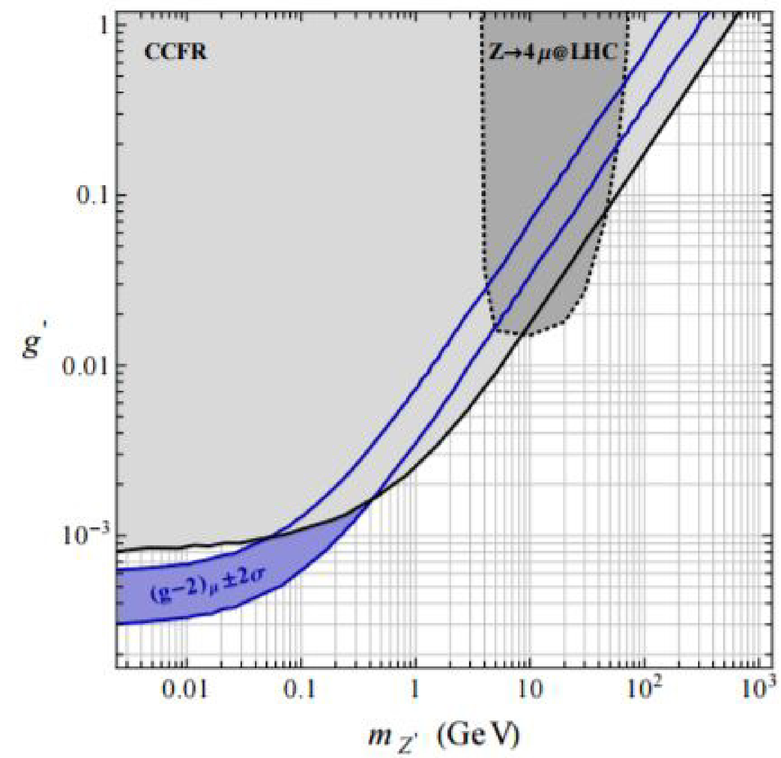
GeV-scale “invisible” dark photon $g_\mu - 2$ solution ruled out

Some Alternative Possibilities for $g_\mu - 2$

• Gauged $L_\mu - L_\tau$: anomaly free
Altmannshofer, Gori, Pospelov, Yavin, 1403.1269, 1406.2332

• Constrained by "trident processes" for low vector masses





Figures from 1406.2332

• Dark Higgs scalar ϕ coupled to μ Chen, HD, Marciano, Zhang 1511.04715; Batell, Lange, McKeen, Pospelov, Ritz, 1606.04943

• CP violating ϕ couplings also possible: potentially observable muon EDM 1511.04715

• Other signals, for example from muon decay: $\mu \to e\nu\bar{\nu}\phi$

Invisible Z_d and Low Mass DM Production

- Possible production and detection of *DM beams* in experiments

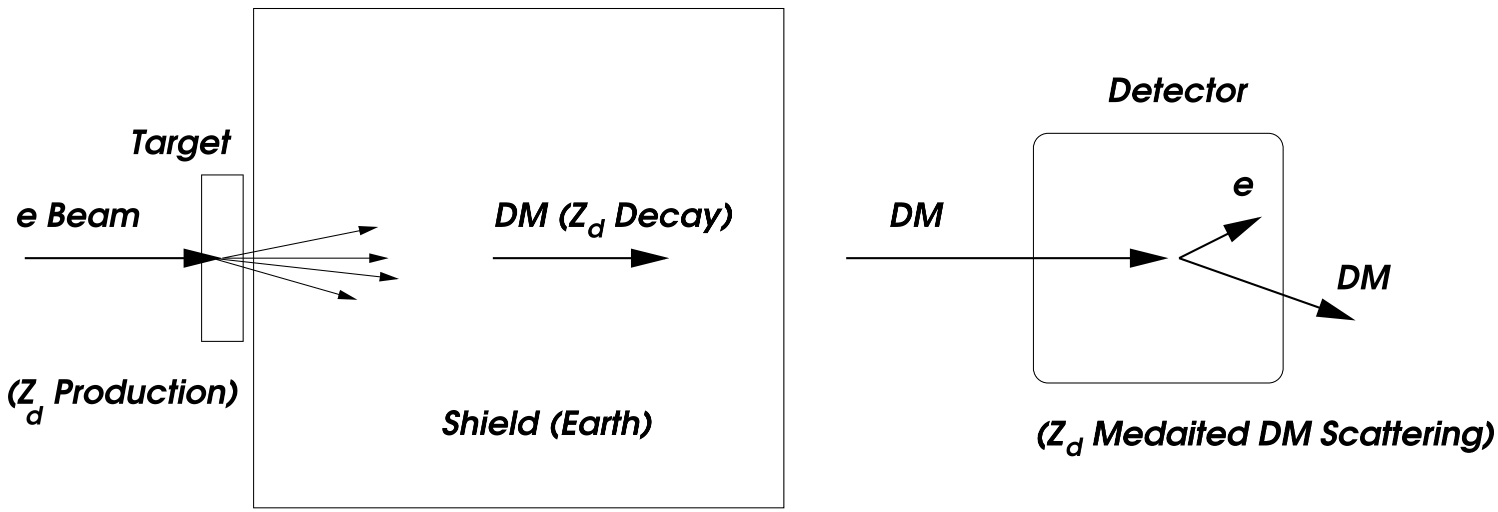
- p or e on fixed target $\Rightarrow$ production of boosted Z_d (meson decays, bremsstrahlung,. . .)

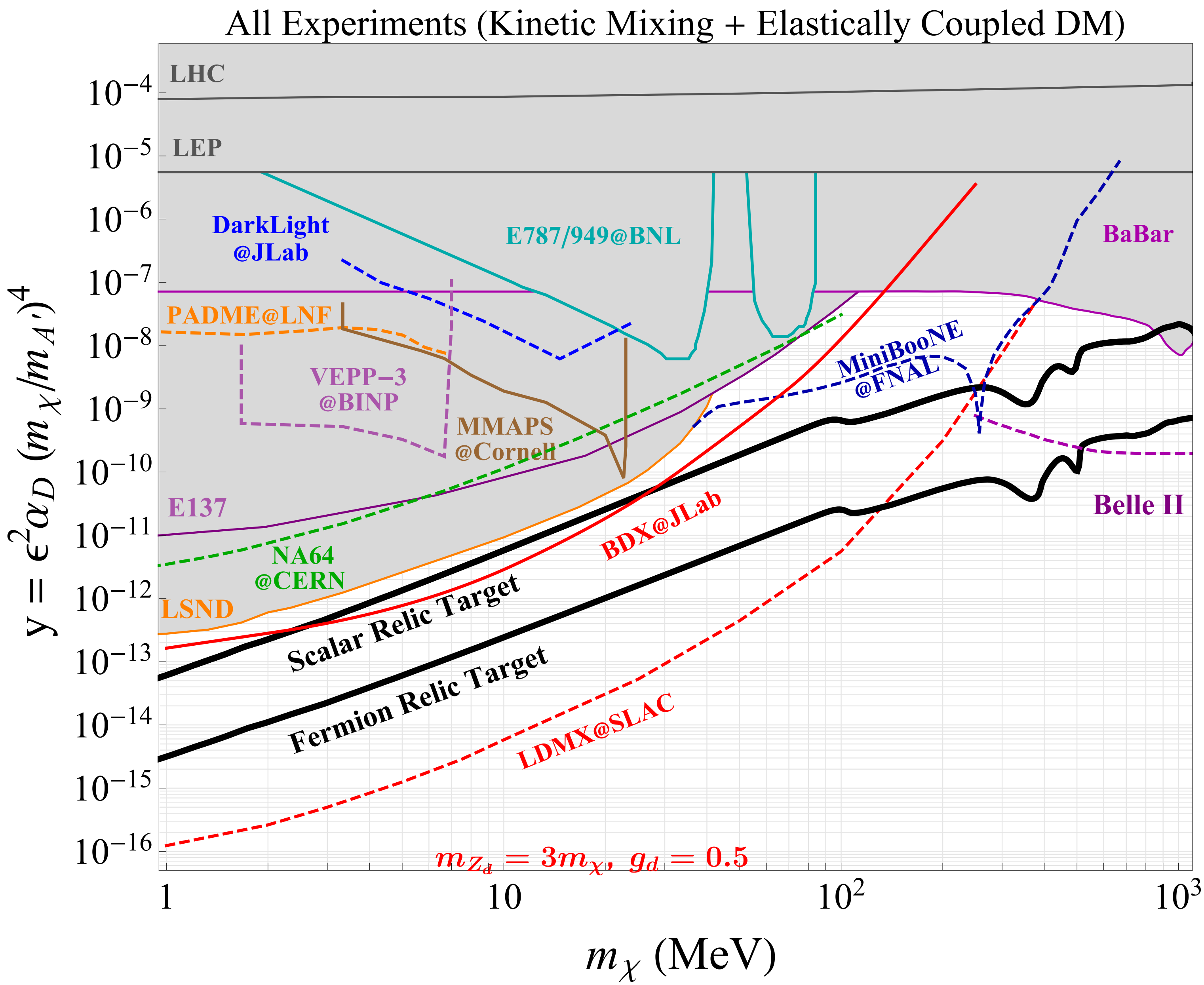
- Z_d beam decays into DM which can be detected via Z_d exchange

- Event rate depends on $\alpha_d \equiv g_d^2/(4\pi)$ and ε^2

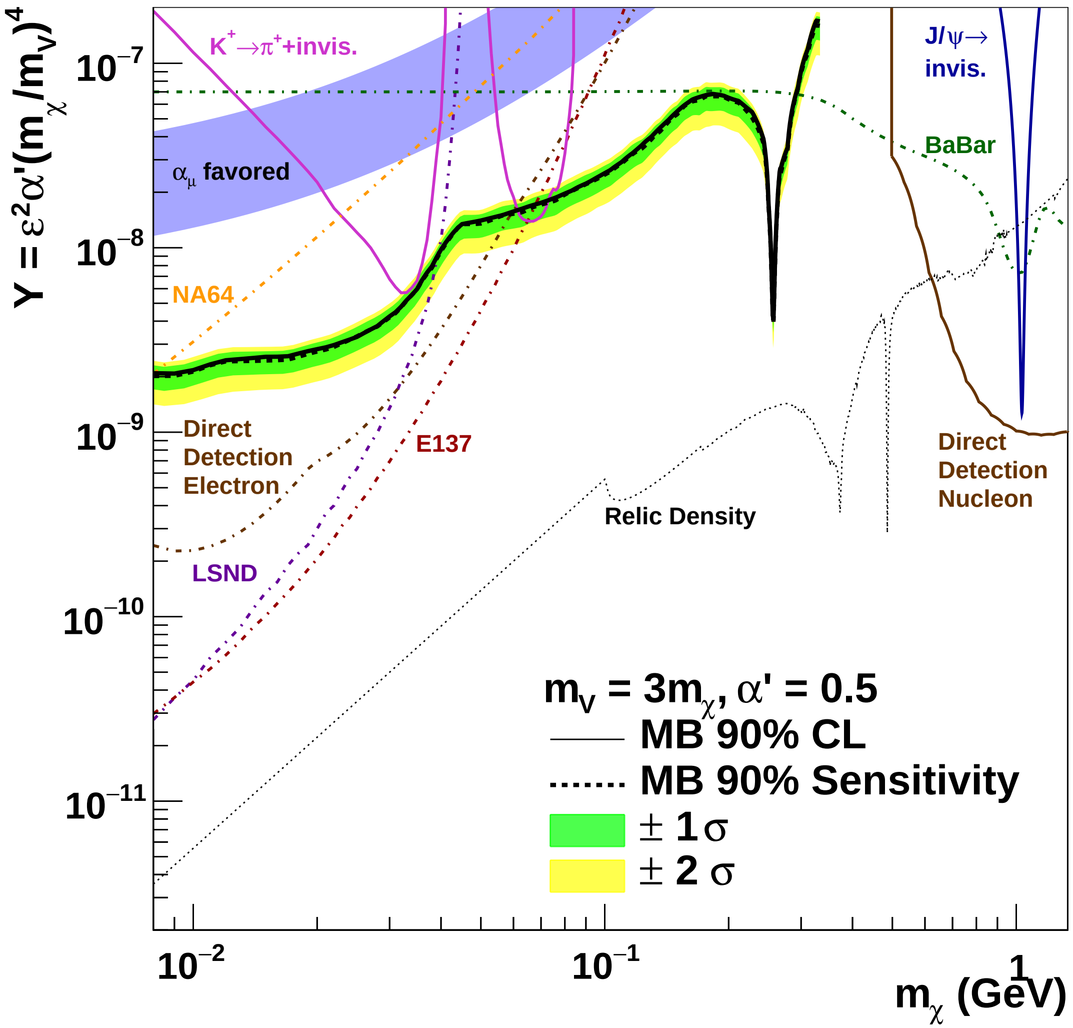
Batell, Pospelov, Ritz, 2009 (p beam); Izaguirre, Krnjaic, Schuster, Toro, 2013 (e beam dump)

- Interesting probe of GeV-scale DM (challenge for direct detection)





J. Alexander *et al.*, arXiv:1608.08632 [hep-ph]



From arXiv:1702.02688 [hep-ex] (MiniBooNE Collaboration)

"Dark Matter Search in a Proton Beam Dump with MiniBooNE"

Solid line: quark/nucleon coupling; Dot-dashed: electron coupling; χ: scalar DM

- For $q^2 \gg m^2_{Z_d}$, *running* of $\alpha_d(q^2) \gtrsim$ few $\times$ 0.1 (and $\varepsilon^2 \propto \alpha_d$) could be significant, sensitive to dark sector spectrum below q^2 HD, Marciano, 2015

See also Zhang, Li, Cao, Li, 2009; Sannino, Shoemaker, 2014 (non-Abelian gauge groups)

Dark Z

HD, Lee, Marciano, 1203.2947

- Z_d may also have mass mixing with SM Z

$$M_0^2 = m_Z^2 \begin{pmatrix} 1 & -\varepsilon_Z \\ -\varepsilon_Z & m_{Z_d}^2/m_Z^2 \end{pmatrix}$$

$$\boxed{\varepsilon_Z = \frac{m_{Z_d}}{m_Z}\delta}$$

$\delta \ll 1$ a model-dependent parameter

- M_0 leads to Z-Z_d mixing angle ξ given by: $\tan 2\xi \simeq 2\frac{m_{Z_d}}{m_Z}\delta = 2\varepsilon_Z$

- Induced interactions with kinetic and mass mixing

$$\mathcal{L}_{\text{int}} = \left(-e\varepsilon J_\mu^{em} - \frac{g}{2\cos\theta_W}\varepsilon_Z J_\mu^{NC}\right) Z_d^\mu$$

$J_\mu^{NC} = \sum_f (T_{3f} - 2Q_f \sin^2\theta_W)\bar{f}\gamma_\mu f - T_{3f}\bar{f}\gamma_\mu\gamma_5 f$; $T_{3f} = \pm 1/2$ and $\sin^2\theta_W \simeq 0.23$

- Neutral current coupling of Z_d like a Z, suppressed by ε_Z: "dark" Z

Notation: Z_d dark photon or dark Z, depending on the context

A Concrete Dark Z Model

- Mass mixing can naturally occur in a 2HDM

- Type I 2HDM: H_1 and H_2, where only H_1 has $Q_d \neq 0$
  - $U(1)_d$ as protective symmetry for FCNCs instead of the usual $\mathbb{Z}_2$
  - SM fermions only couple to H_2 (SM-like); $\langle H_i \rangle = v_i$
  - Generally, also a dark sector Higgs particle ϕ with $\langle \phi \rangle = v_d$

$$m_Z \simeq \frac{g}{2\cos\theta_W}\sqrt{v_1^2 + v_2^2} \quad \text{and} \quad m_{Z_d} \simeq g_d\, Q_d\, \sqrt{v_d^2 + v_1^2}$$

- With $\tan\beta = v_2/v_1$ and $\tan\beta_d = v_d/v_1$ we get

$$\varepsilon_Z \simeq (m_{Z_d}/m_Z)\cos\beta\cos\beta_d \Rightarrow \delta \simeq \cos\beta\cos\beta_d$$

- H_1 has $Q_Y Q_d \neq 0$ $\rightarrow$ generally also expect kinetic mixing

Dark Z Phenomenology

HD, Lee, Marciano, 2012

- "Dark" parity violation [independent of BR($Z_d \to$ visible)]

Polarized electron scattering, atomic parity violation, . . .

- Flavor physics ($m_{Z_d} < m_{\text{meson}}$)

- Longitudinal Z_d enhancement $\sim E/m_{Z_d}$

$\{\text{BR}(K^+ \to \pi^+ Z_d)_{\text{long}} \simeq 4 \times 10^{-4}\delta^2 \quad ; \quad \text{BR}(B \to K Z_d)_{\text{long}} \simeq 0.1\delta^2\} \to |\delta| \lesssim 10^{-3}$

- Rare Higgs decays, *e.g.* $H \to Z Z_d$ ($m_{Z_d} \ll m_Z$, on-shell Z_d)

ATLAS Collaboration, 2015

- In 2HDM realization there could be other signals

- Dominant $H^\pm \to W^\pm Z_d$ (tree-level) for $m_{H^\pm} \lesssim m_t$

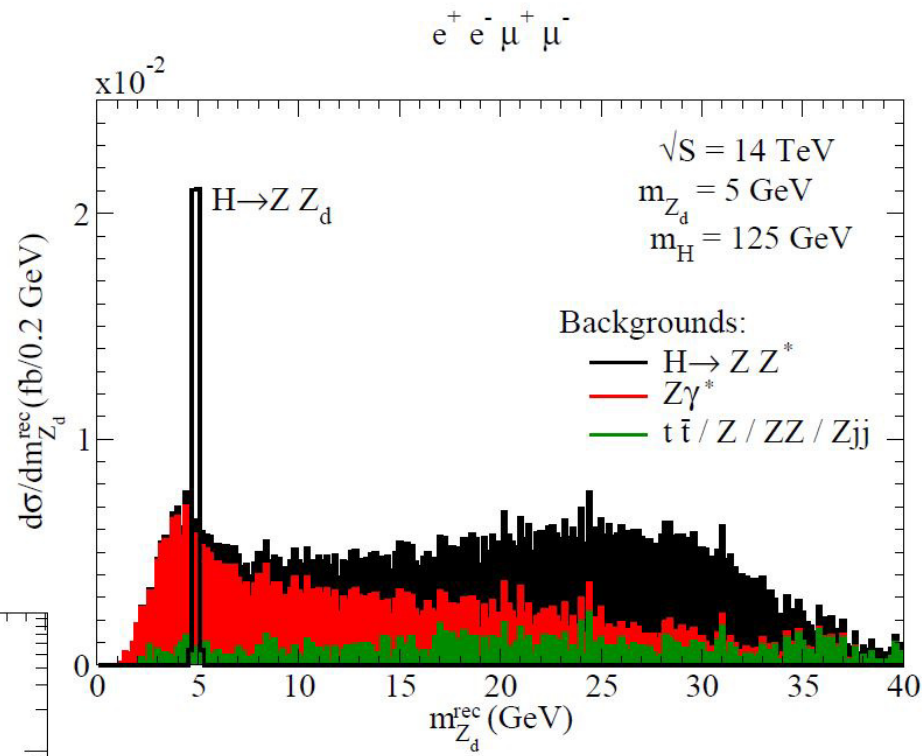
HD, Marciano, Ramos, Sher, 2014
Lee, Kong, Park, 2014

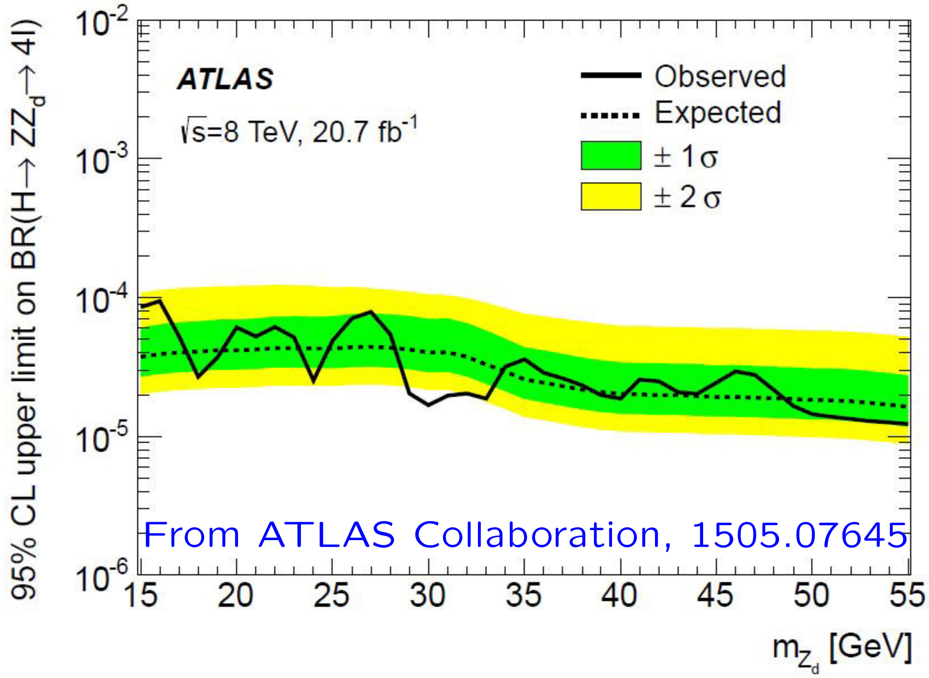
For other signals of dark sectors in rare Higgs decays, see also D. Curtin *et al.*, 1312.4992; Curtin, Essig, Gori, Shelton, 1412.0018

- Assuming $\delta^2 \times \text{Br}(Z_d \to \ell^+\ell^-) = 10^{-5}$ From HD, Lee, Lewis, Marciano 1304.4935
- If kinetic mixing dominated:

$\text{Br}(Z_d \to \ell^+\ell^-) \simeq 0.15$

For each $\ell = e, \mu$; $m_{Z_d} \sim 5 - 10$ GeV





Dark Z and Parity Violation

- Low Q^2 ($\lesssim m_{Z_d}^2$) parity violation from $Z - Z_d$ mixing

- Both mass and kinetic mixing

- Z_d effects can be parameterized by HD, Lee, Marciano, 2012

$$G_F \to \rho_d G_F \quad \text{and} \quad \sin^2\theta_W \to \kappa_d \sin^2\theta_W$$

$$\text{with } \rho_d = 1 + \delta^2 \frac{m_{Z_d}^2}{Q^2 + m_{Z_d}^2} \quad \text{and} \quad \kappa_d = 1 - \varepsilon \frac{m_Z}{m_{Z_d}} \delta \frac{\cos\theta_W}{\sin\theta_W} \frac{m_{Z_d}^2}{Q^2 + m_{Z_d}^2}$$

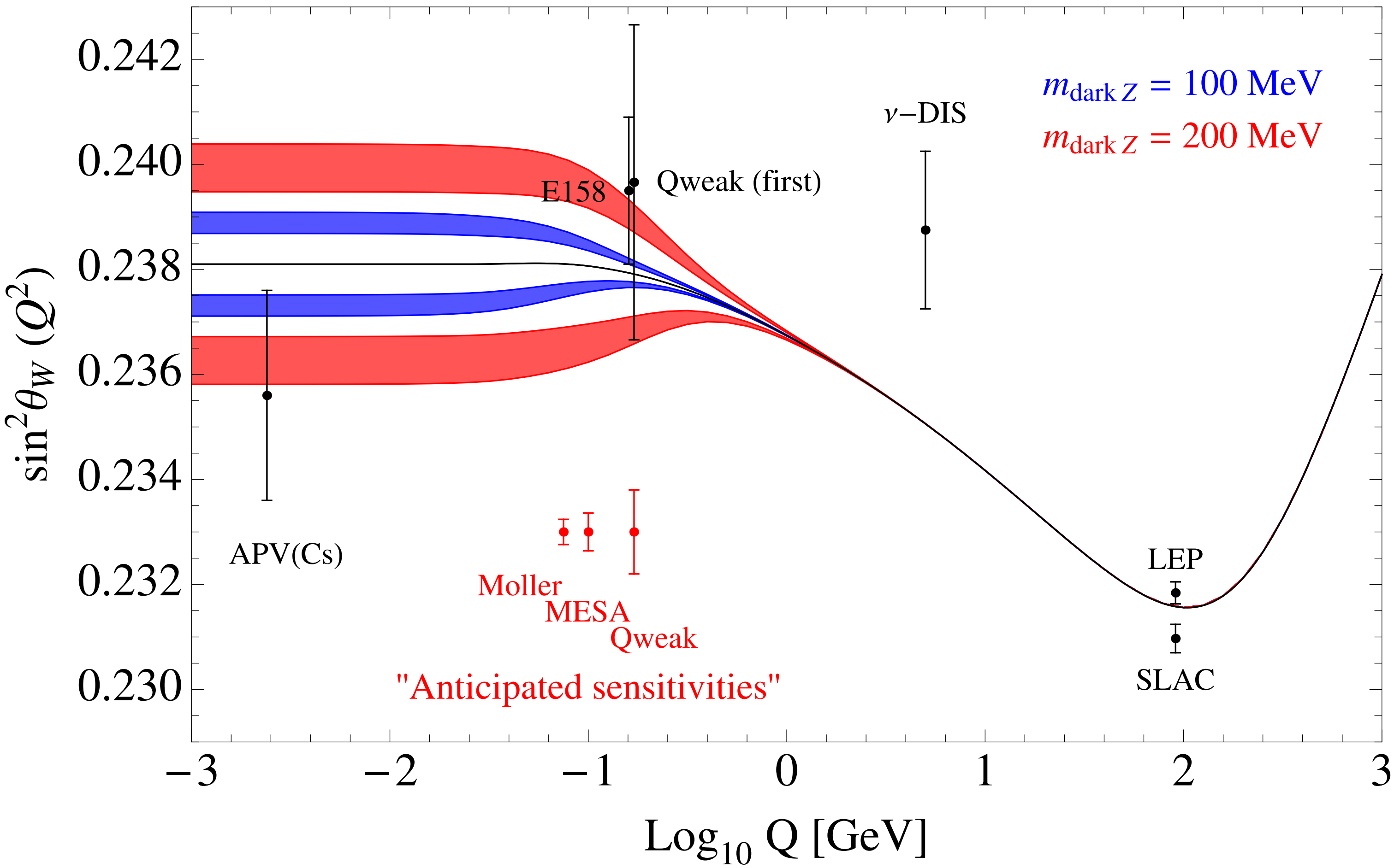
- Leads to variation of $\sin^2\theta_W$ with Q^2:

$$\boxed{\Delta \sin^2\theta_W(Q^2) = -\varepsilon\delta \frac{m_Z}{m_{Z_d}} \sin\theta_W \cos\theta_W f\left(Q^2/m_{Z_d}^2\right)}$$

$$f\left(Q^2/m_{Z_d}^2\right) = 1/(1 + Q^2/m_{Z_d}^2)$$

Running of $\sin^2\theta_W$ with Q^2

From HD, Lee, Marciano, Phys. Rev. D **89**, no. 9, 095006 (2014)



- Black curve: SM running   Marciano, Sirlin, 1981; Czarnecki, Marciano, 1996
- Z_d parameters: $|\varepsilon| \sim |\delta| \sim$ few $\times\, 10^{-3}$ (for $g_\mu - 2$)
- Two branches corresponding to $\varepsilon\delta$ sign ambiguity ($\Delta \sin^2\theta_W \propto \varepsilon\delta$)

Other Probes of Light Dark Matter

• In recent years, electron scattering has been examined as a means of probing $\sim$ MeV-GeV scale Galactic DM

See, for example, Essig, Manalaysay, Mardon, Sorensen, Volansky, 2012; Essig, Fernandez-Serra, Mardon, Soto, Volansky, Yu, 2015

• This includes scattering in liquid noble gases as well solid states targets

• The energy could lead to ionization or excitation

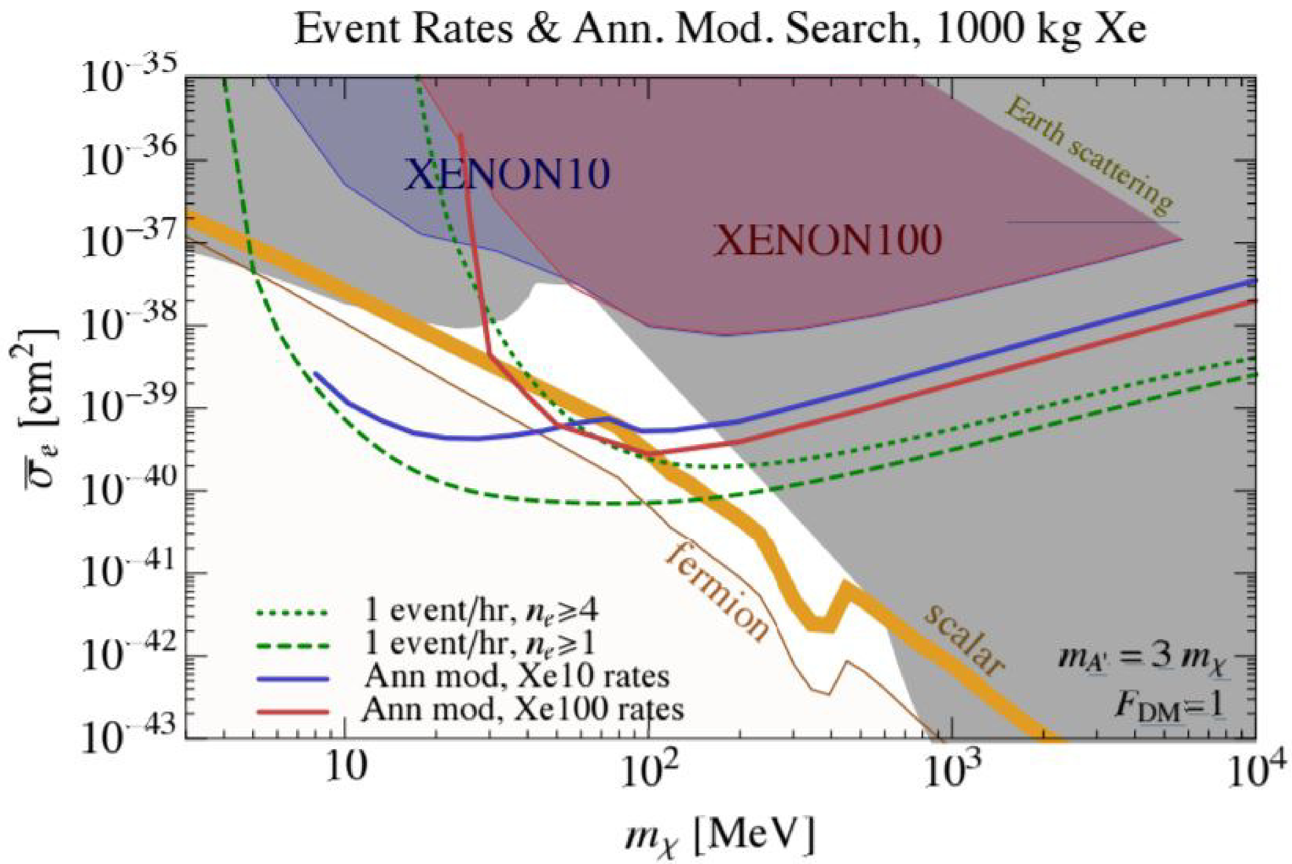
• $\Delta E \sim 10$ eV (ionization) ; $\Delta E \sim 1$ eV (valence-conduction band gap)

• The smaller mass of the electron makes energy transfer from the Galactic dark matter, moving at $v_{\rm DM} \sim 10^{-3}$, more efficient

Example:

• $m_N \sim 100$ GeV, $m_{\rm DM} \sim 10$ MeV $\rightarrow E^N_{\rm recoil} \sim 10^{-3}$ eV

• $m_e \sim 0.5$ MeV, $v_e \sim \alpha$ ($\gg v_{\rm DM}$), $m_{\rm DM} \sim 10$ MeV $\rightarrow E^e_{\rm recoil} \sim 10$ eV



From Essig, Volnasky, Yu, 1703.00910

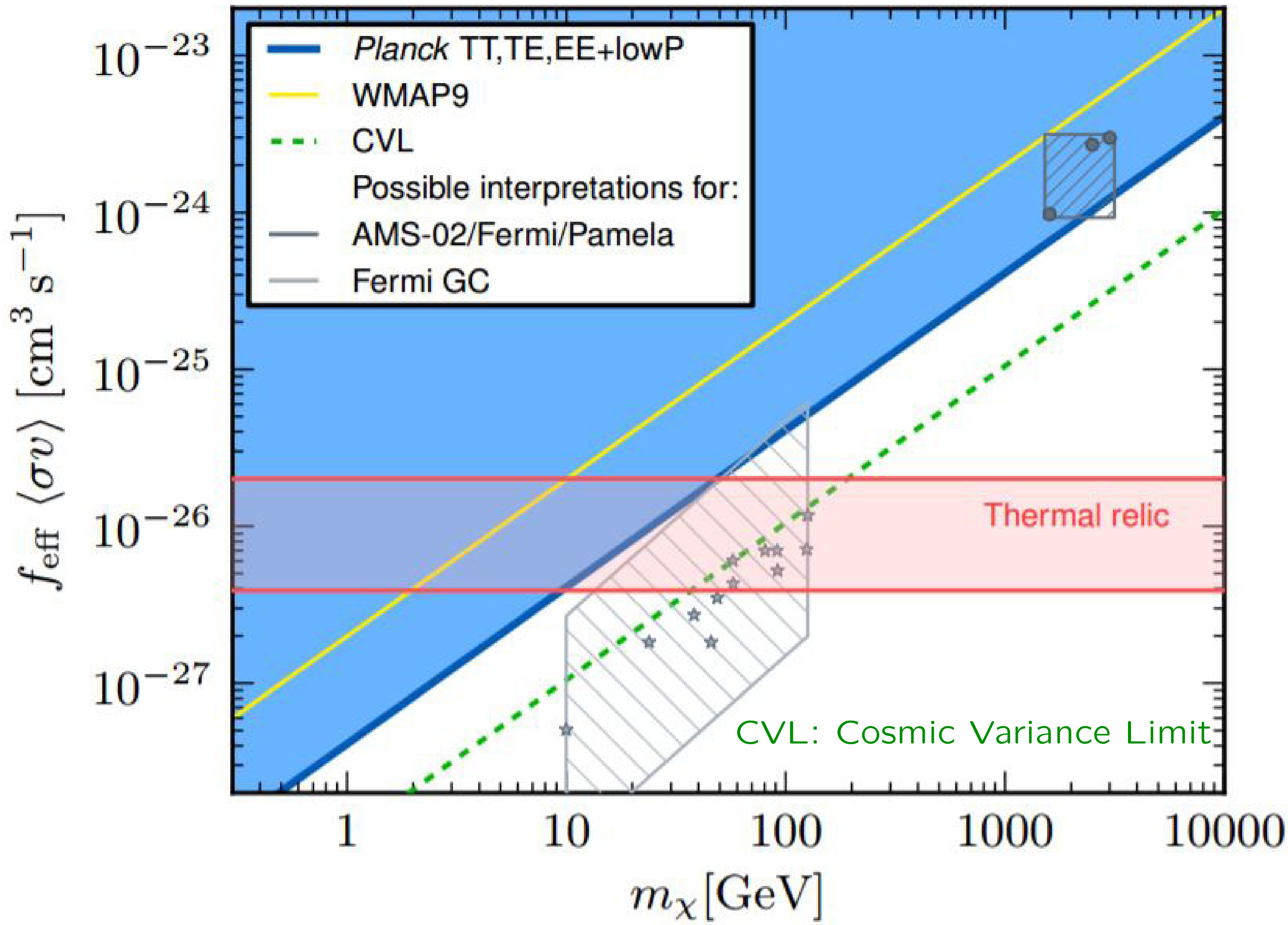
• Thermal relic DM lighter than ~ 10 GeV disfavored by CMB observations (modifications to temperature and polarization power spectra from annihilations): DM annihilations distorting the spectrum, unless

Chen, Kamionkoswski, 2003; Padmanabhan, Finkbeiner,2005; Madhavacheril, Sehgal, Slatyer, 2013

• p-wave, suppressed at late times : scalar DM via dark photon

• Asymmetric DM: no late time annihilation (consistent above "fermion" line)

CMB Constraints on DM Annihilation



From Planck Collaboration, 1502.01589

Concluding Remarks

- Open cosmological questions (beyond SM): DM, baryogenesis, inflation,. . .
- DM and baryognesis: physics may be available to laboratory experiments
- Many ideas and proposals remain viable to address either puzzle
- No firm signal of physics beyond SM at LHC yet, but this could change in the next few years
- A discovery at the LHC may shed light on cosmology and motivate weak scale explanations of DM, baryogenesis,. . .
- If LHC does not uncover new states, alternative models (to EW baryogenesis, WIMPs,...) may warrant more attention
- Some alternatives may be accessible to experiments, but require new methods
- Vast possible parameter space: plenty of room for new ideas in theory and experiment
- Perhaps the next big break through will come from one or a few of the attendees of the NExT2017 lectures!

Coda

We end these lectures with words from an extra ordinary intellect, foreshadowing what was to come centuries later. This vision describes our understanding of fundamental phenomena today, and will perhaps hold far into the future:

> *...I am induced by many reasons to suspect that they [phenomena of nature] may all depend upon certain forces by which the particles of bodies, by some causes hitherto unknown, are either mutually impelled towards each other, and cohere in regular figures, or are repelled and recede from each other; which forces being unknown, philosophers have hitherto attempted the search of nature in vain; but I hope the principles here laid down will afford some light either to this or some truer method of philosophy.*
>
> *Sir Isaac Newton*
>
> *(Preface to Principia)*