Low Energy New Physics

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

Workshop on Hadron Physics in China and Opportunities in US
Huangshan, Anhui, China
July 2013

Low Energy New Physics

(with an example of “Dark Force”)

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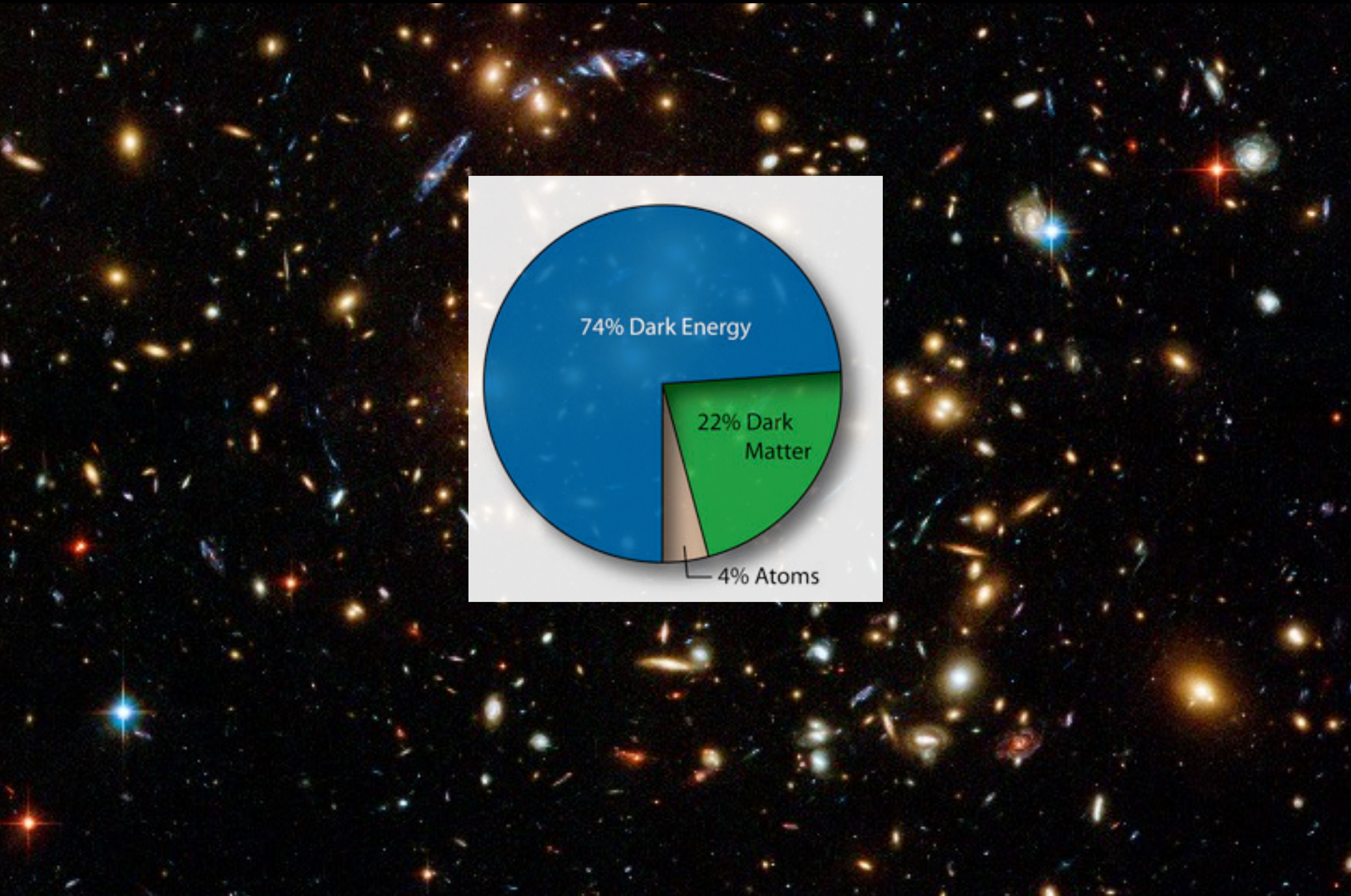
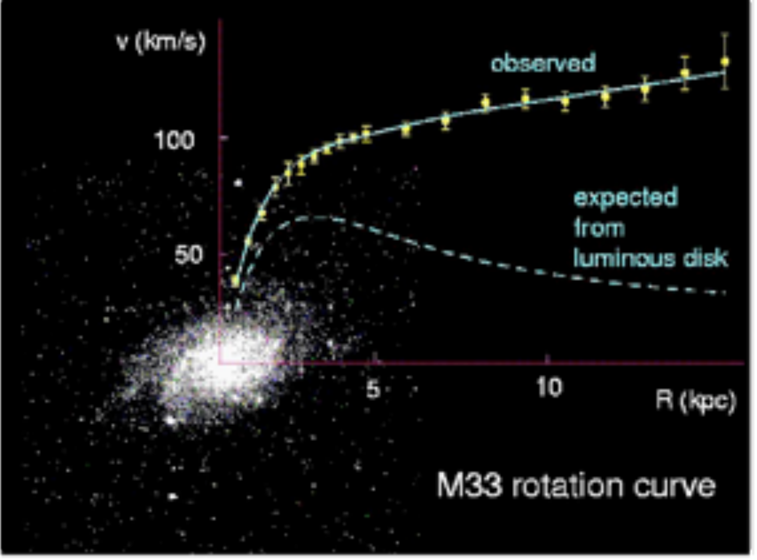
Prelude

We live in a Dark World

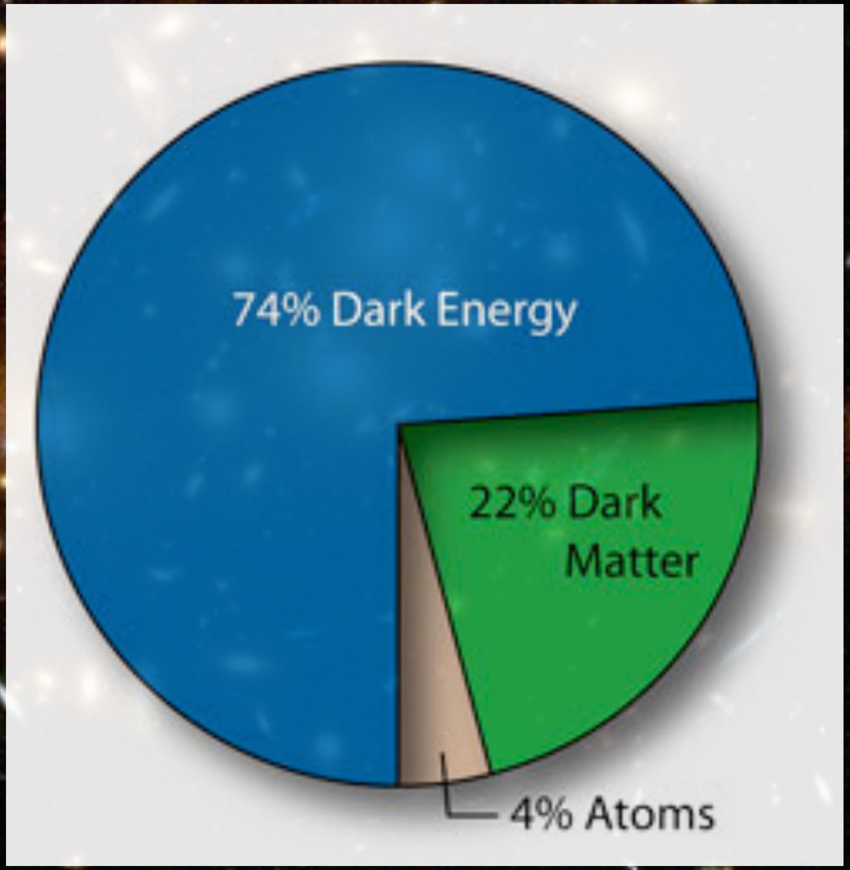


We live in a Dark World

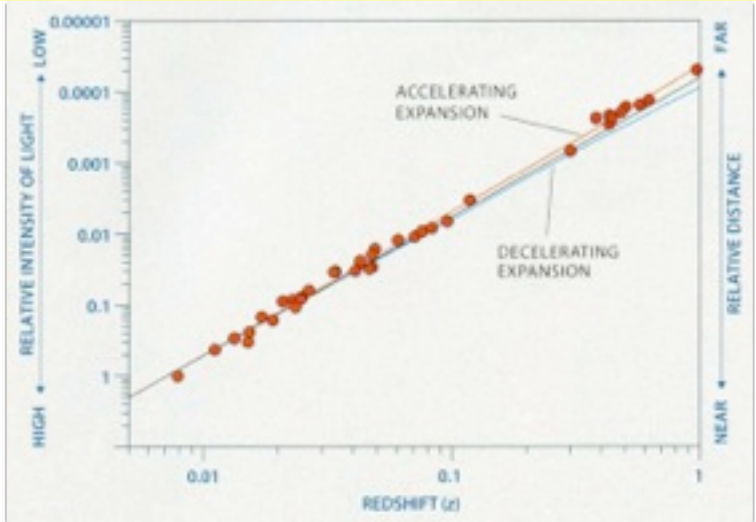


Galaxy rotation curve

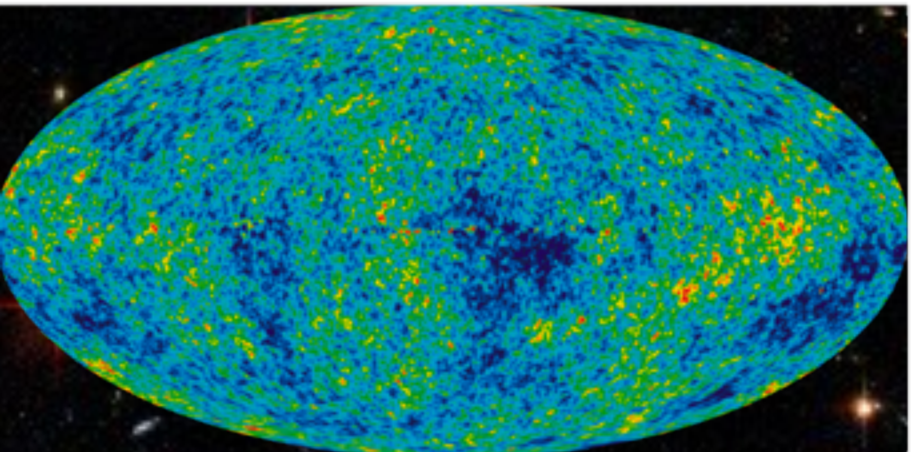
Gravitational lensing



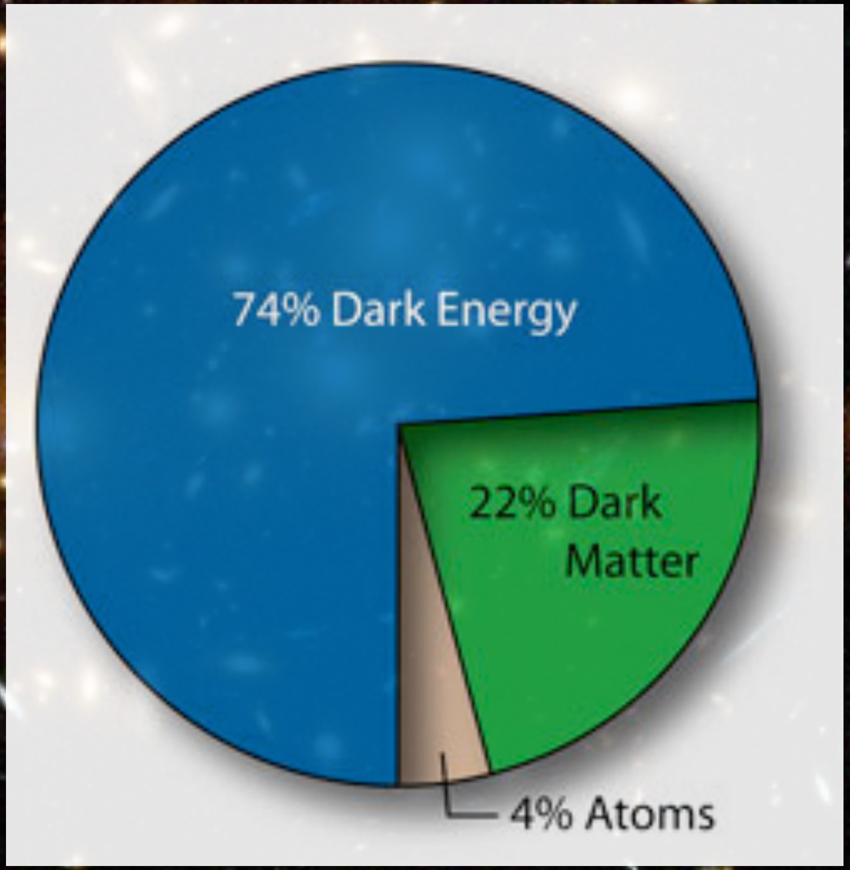
Accelerating Universe
(Supernovae)



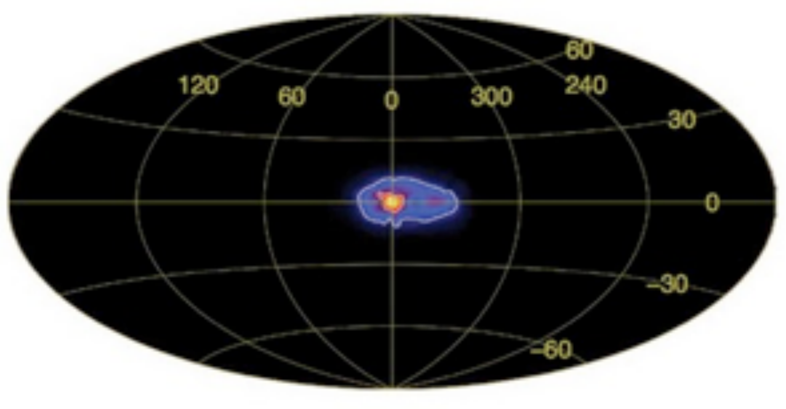
Cosmic Microwave Background



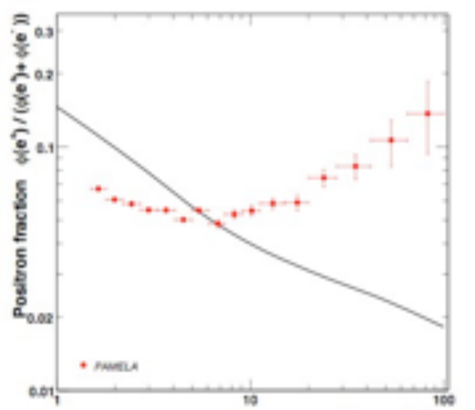
We live in a Dark World



still mystery

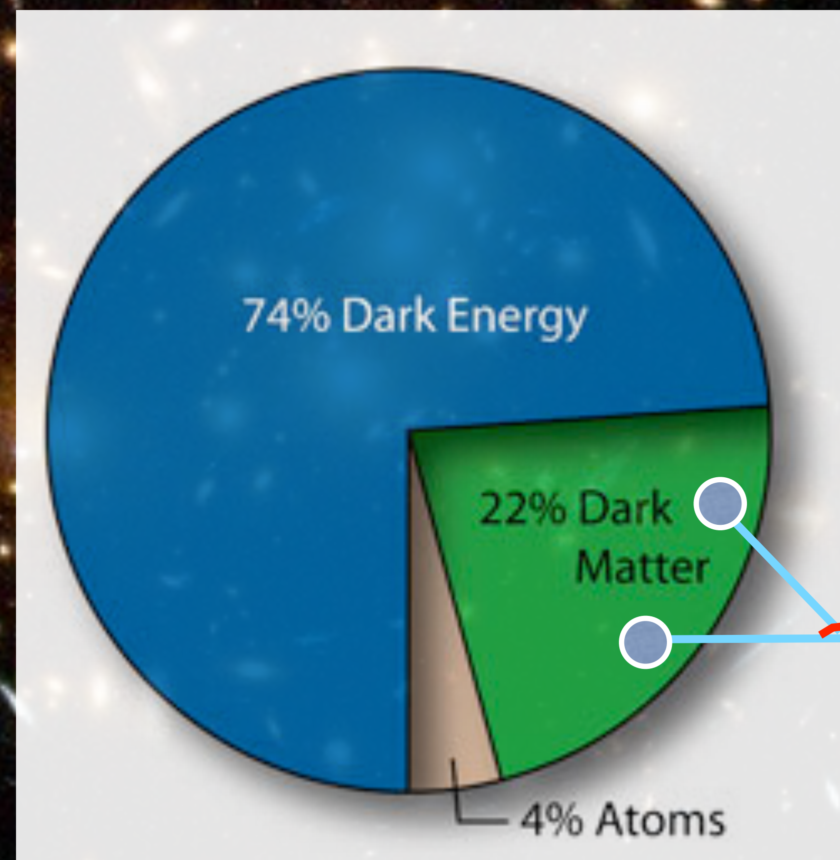


511 keV gamma-ray



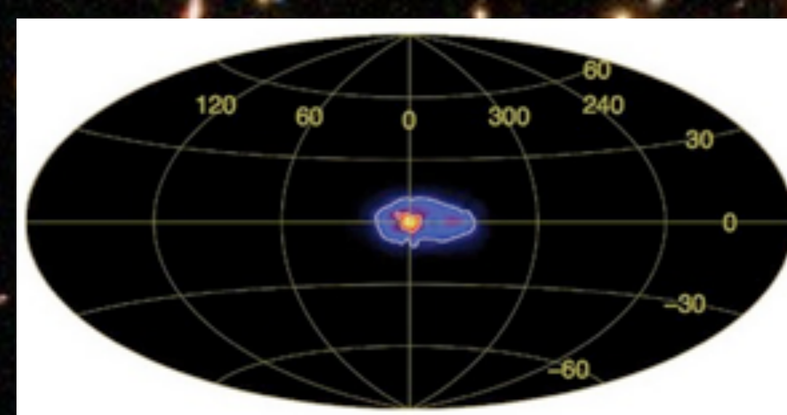
Positron excess

We live in a Dark World

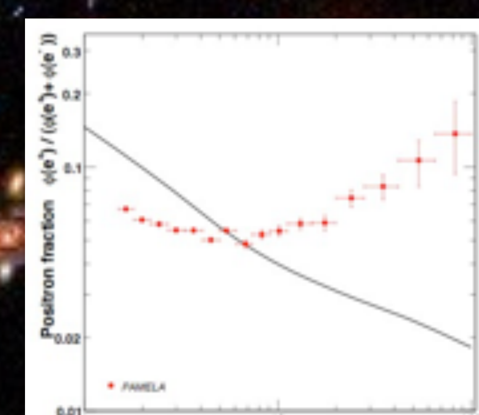


"Dark Force"

(Force among Dark Matters)



511 keV gamma-ray

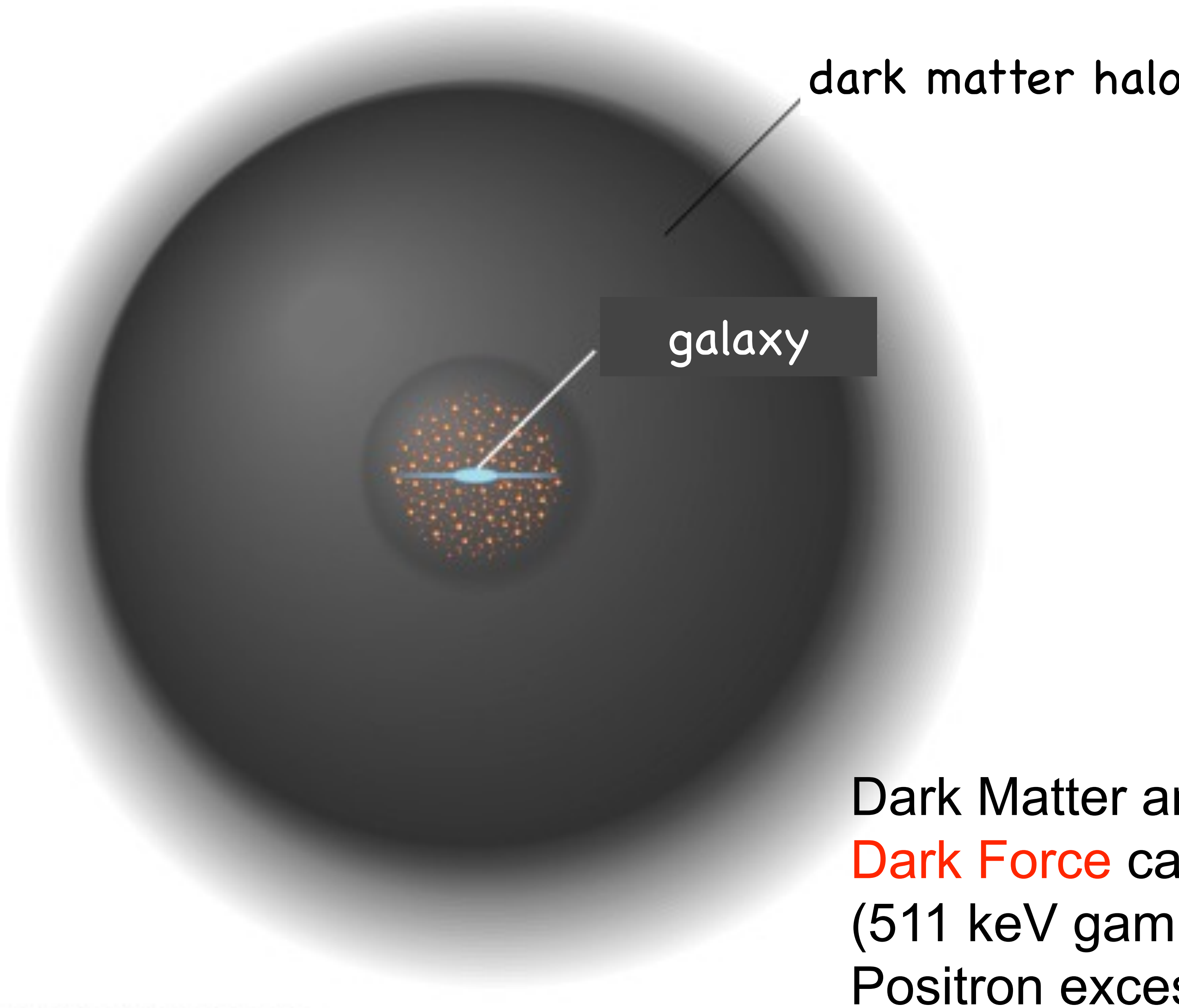


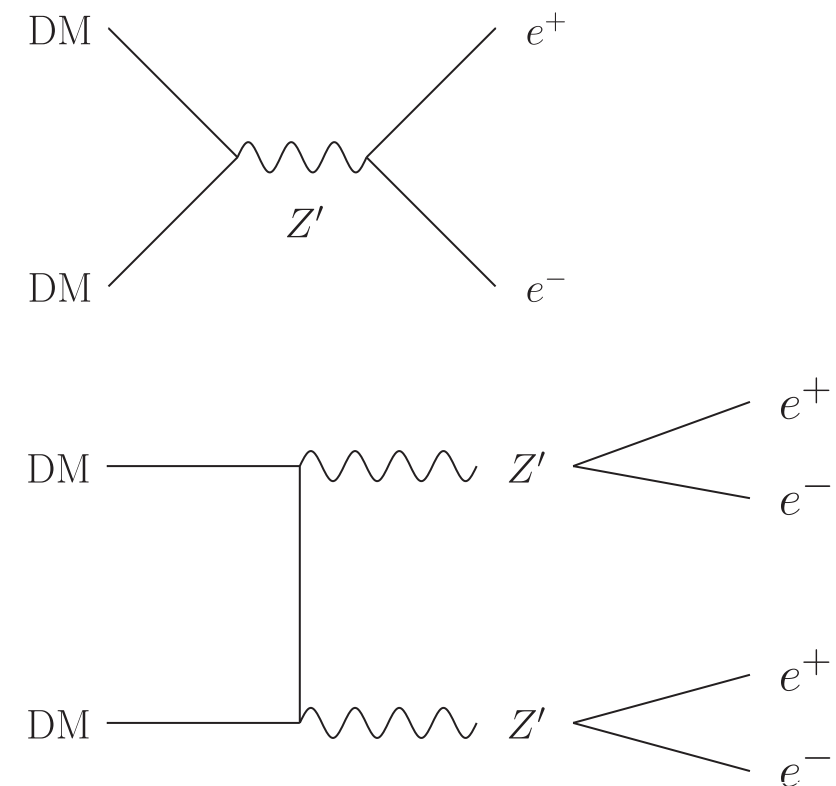
Positron excess

Dark Force (Force among Dark Matters)

Z'
(Dark Force carrier)

- New gauge boson of O(1) GeV scale *(cf. Proton: 1 GeV)*
- Extremely weak couplings to the SM particles





Dark Matter annihilations at Galactic center with Dark Force can address astrophysical anomalies.
(511 keV gamma-ray [Fayet (2004), ...],
Positron excess [Arkani-Hamed, et al (2008), ...])

Dark Trilogy (of Dark World)

1. Dark Energy (Accelerating expansion, CMB, ...)

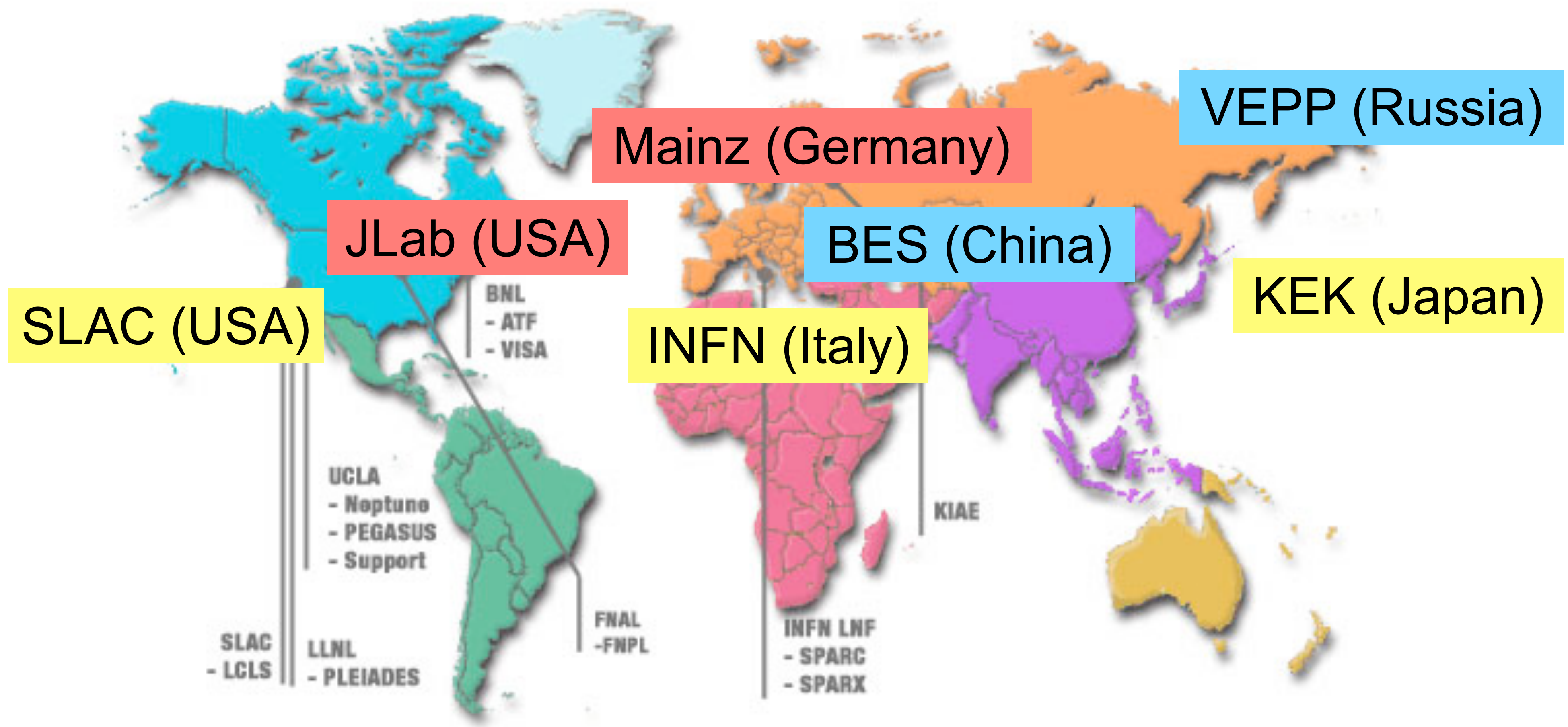
2. Dark Matter (Galaxy rotation curves, Gravitational lensing, ...)

3. Dark Force (511 keV gamma-ray, Positron excess, ...)

Focus of this talk

Dark Force searches in the Labs

Many searches for Dark Force in the Labs around the world (ongoing/proposed).



Particularly interesting: One of the New physics scenarios that can be tested with Low-energy experimental facilities (Nuclear/Hadronic physics labs).

[Dark force carrier Z' scale (GeV) ≈ 1/1000 × Most new physics scale (TeV)]

"various Low-E Labs" "LHC"

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

- Dark Force Models

- Dark Force Searches (Dark Photon)

- Additional Dark Force Searches (Dark Z)

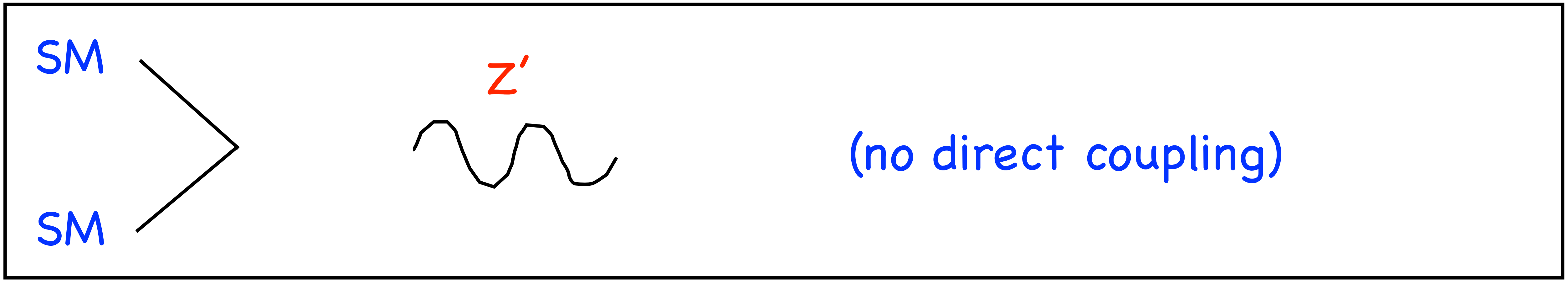
- High-energy experiments

Dark Force Models

Standard Model + Dark Force

Gauge symmetry = $SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_{dark}$

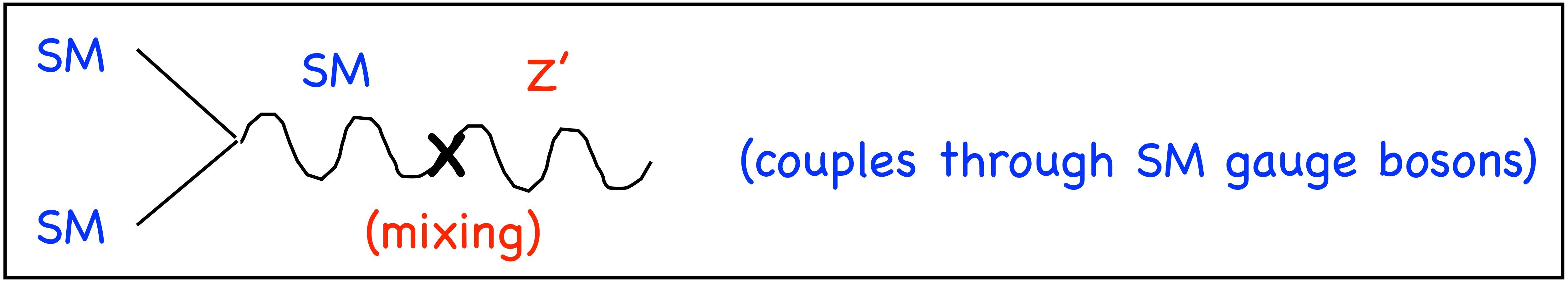
It may interact with DM, but
SM particles have zero charges



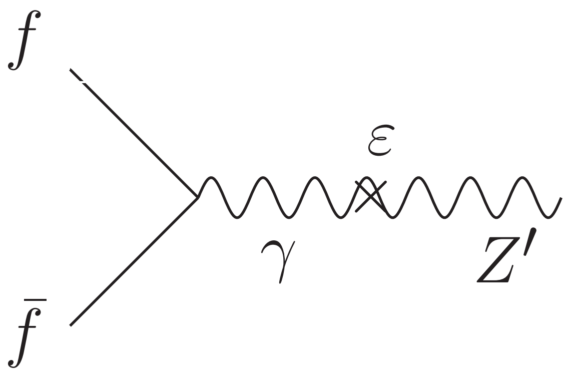
Z' can couple to SM particles through kinetic mixing of $U(1)_Y$ & $U(1)_{dark}$.

[Holdom (1986)]

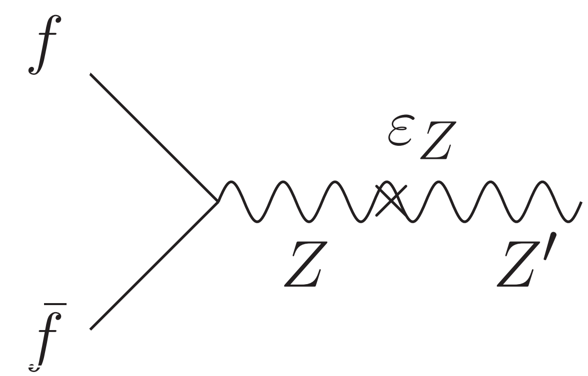
$$\mathcal{L}_{\rm kin} = -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} + \frac{1}{2}\frac{\varepsilon}{\cos\theta_W}B_{\mu\nu}Z'^{\mu\nu} - \frac{1}{4}Z'_{\mu\nu}Z'^{\mu\nu}$$

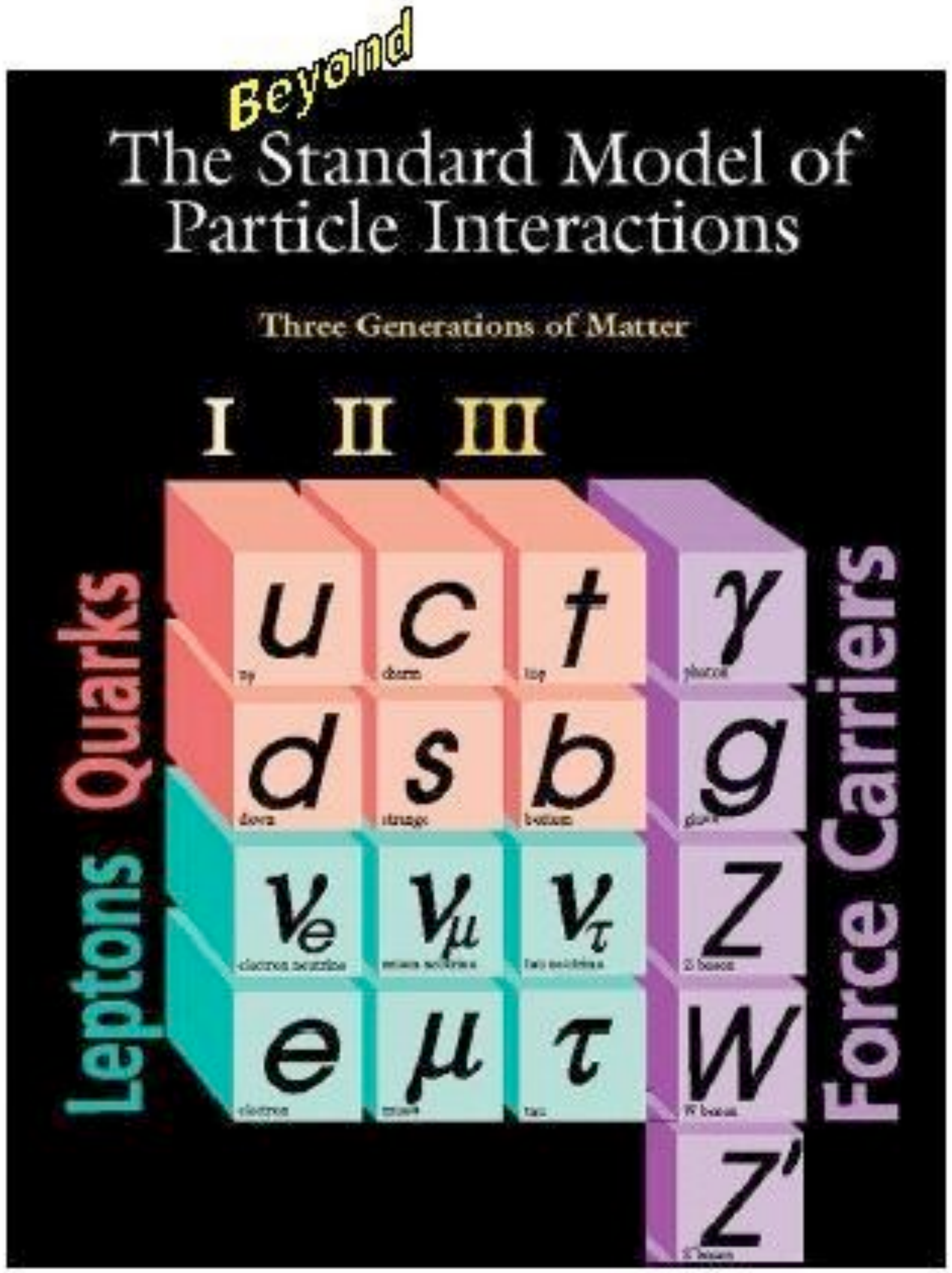


$$B_\mu = \cos\theta_W A_\mu - \sin\theta_W Z_\mu$$



Types of Dark Force





Z' : couplings to the SM particles are suppressed by small <u>mixing</u>.
(model-dependent)

[Arkani-Hamed, et al (2008); and many others]

Popular Model: **Dark Photon**
coupling = ε×(Photon coupling)

[Davoudiasl, Lee, Marciano (2012)]

New Model: **Dark Z**
coupling = ε×(Photon coupling) + ε_Z×(Z coupling)

inherits properties of Z boson like <u>parity violation</u>.
(different couplings for left/right-handed particles)

Higgs structure matters

Model-dependence comes from **how the Z' gets the mass** (i.e. Higgs sector).

- Dark Photon: (ex) additional Higgs singlet gives mass to Z'
- Dark Z: (ex) additional Higgs doublet gives mass to Z'

(Ex) Dark Photon case:
Z-Z' kinetic mixing is cancelled by Z-Z' mass mixing (which is "induced by kinetic mixing") at Leading order.

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

(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

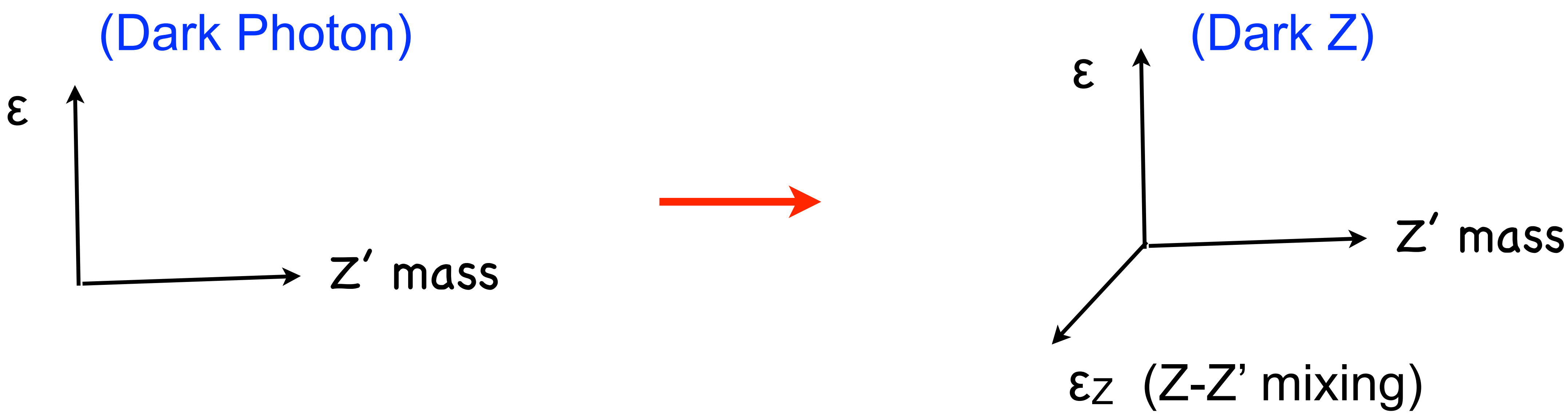
for Higgs singlet

$$J^{NC}_{\mu} = \left(\frac{1}{2}T_{3f} - Q_f \sin^2\theta_W\right)\bar{f}\gamma_{\mu}f - \left(\frac{1}{2}T_{3f}\right)\bar{f}\gamma_{\mu}\gamma_5 f$$

Dark Force couplings depend on Higgs sector.

Effects of New Model (Dark Z)

Parameter space is extended from 2D to 3D.



$$\mathcal{L}_{\rm int} = -\varepsilon\, e J^{\mu}_{em} Z'_{\mu}$$

$$\mathcal{L}_{\rm int} = -\left[\varepsilon\, e J^{\mu}_{em} + \varepsilon_Z\, (g/\cos\theta_W) J^{\mu}_{NC}\right] Z'_{\mu}$$

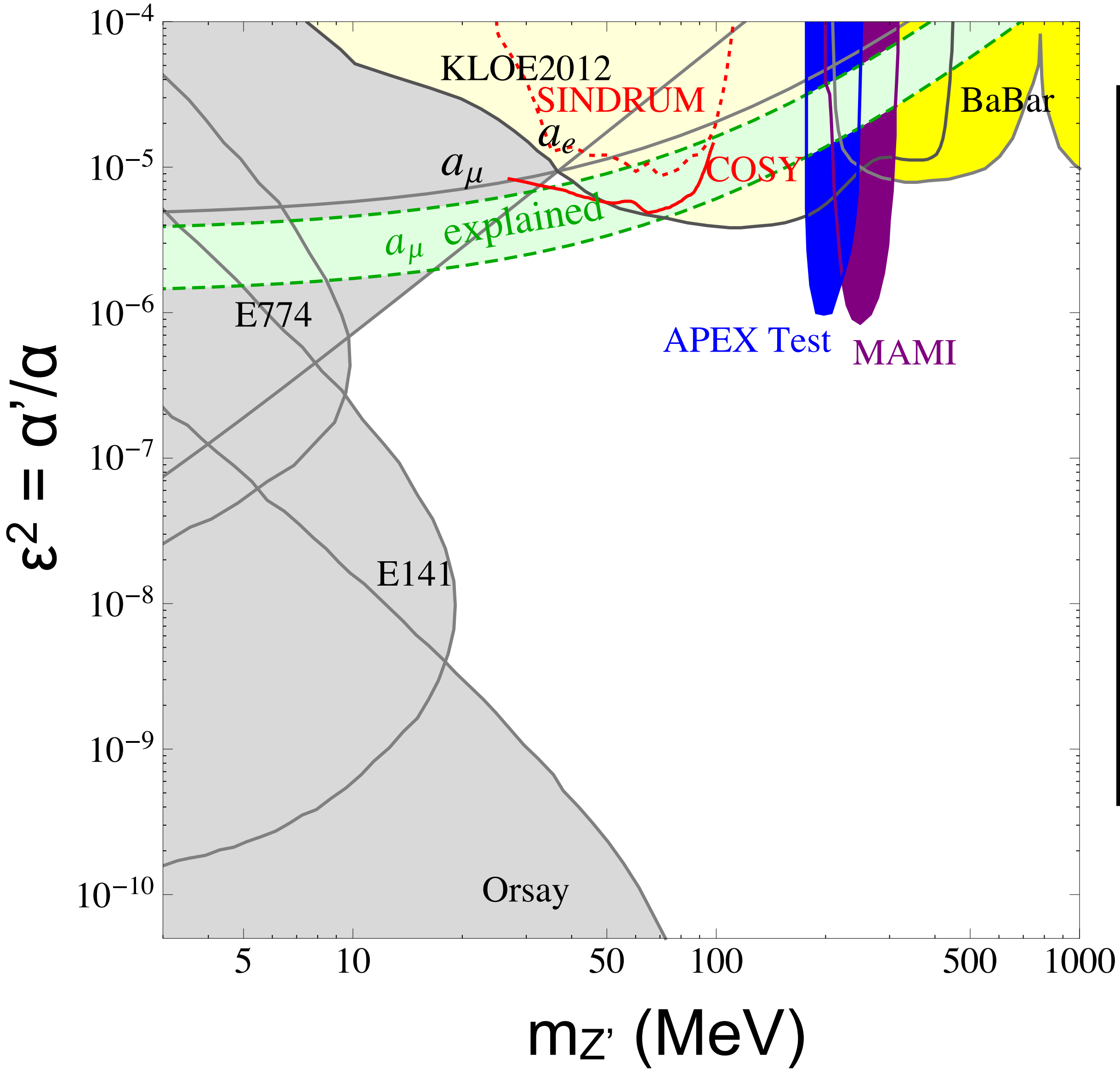
Dark Photon = a special case of Dark Z ($\varepsilon_Z = 0$ limit).

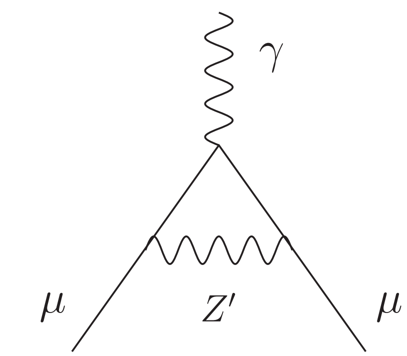
Some experiments irrelevant to Dark Photon searches become relevant to Dark Z searches (Low-E parity test, ... : will be discussed later).

$$\mathcal{L}_{\rm int}({\rm SM}) = -e J^{\mu}_{em} A_{\mu} - (g/\cos\theta_W) J^{\mu}_{NC} Z_{\mu}$$

Dark Force Searches
: relevant to Dark Photon

Dark Photon Searches





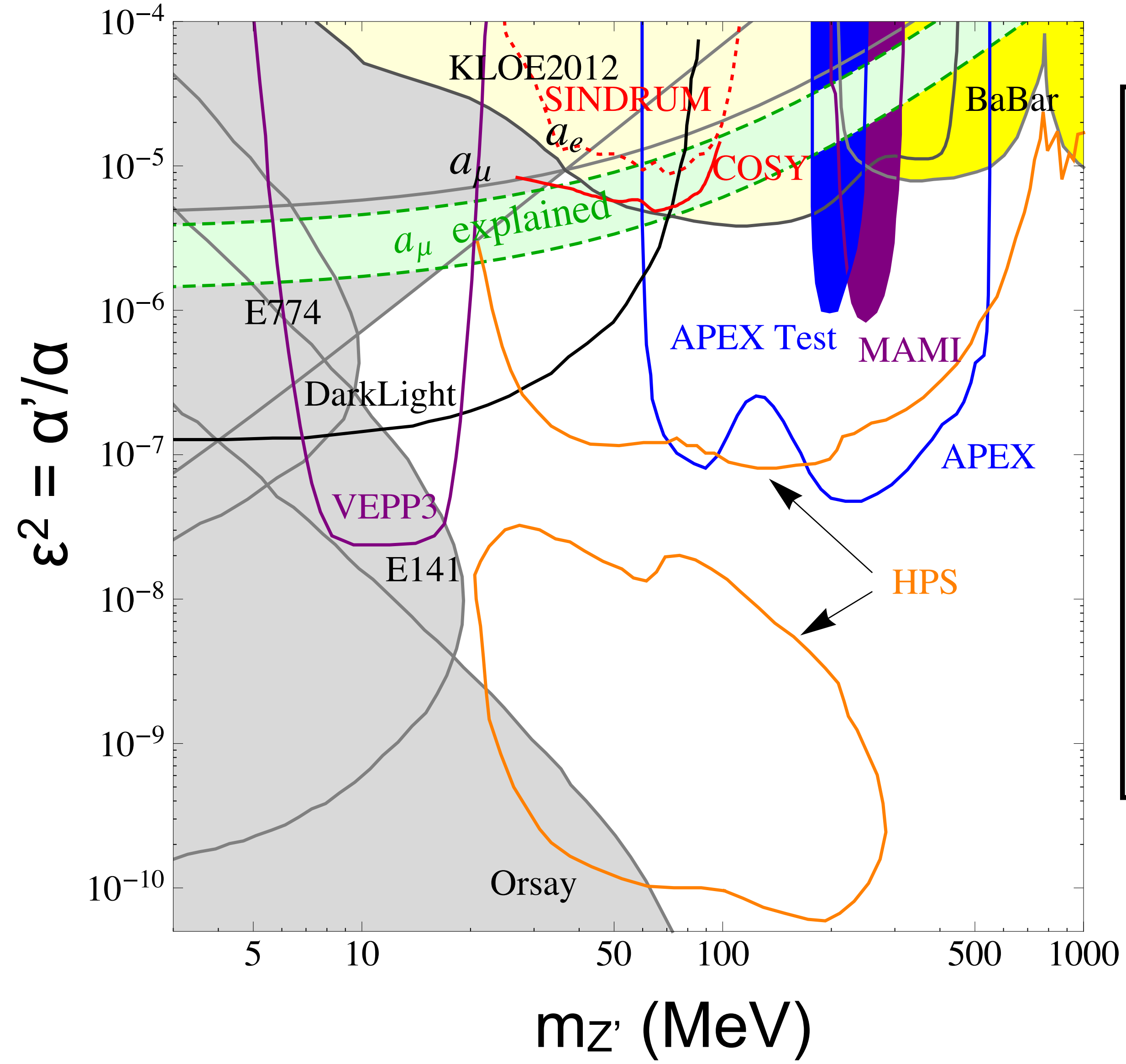
$$(\text{magnetic moment}) = -\frac{g\mu_B S}{\hbar}$$

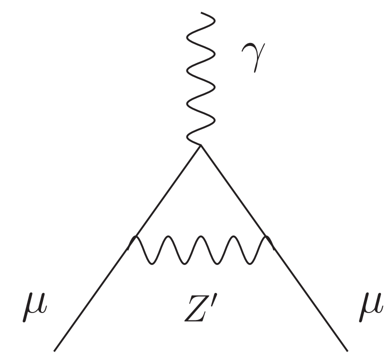
Green band: explains 3.6σ deviation in $g_\mu - 2$ (possibly early hint of Dark Force) [Fayet (2007); Pospelov (2008)]

Current and Future coverage (parts). [Plots from R. McKeown's talk (2011) + subsequent updates]

1. Anomalous magnetic moment (g-2) for e, μ.
2. Beam-dump experiments (E137, E141 at SLAC; E774 at Fermilab)
3. Meson decays: ϒ(bb) → γ Z' (BaBar); ϕ(ss) → η Z' (KLOE); π(dd) → γ Z' (COSY)
4. Fixed target experiments: New experiments designed for direct Dark Photon search (APEX, HPS, DarkLight, MAMI, VEPP3)

Dark Photon Searches





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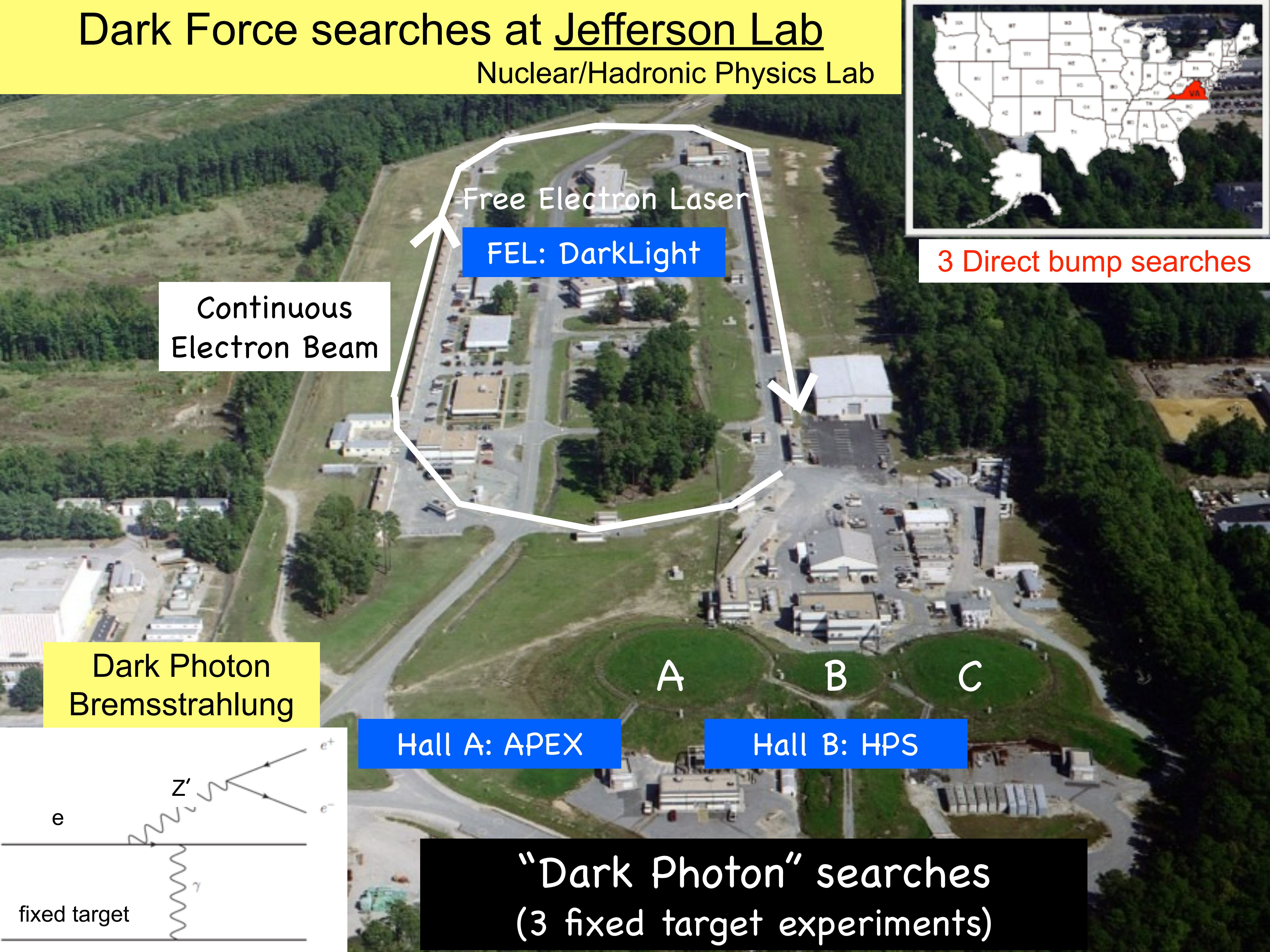
Dark Force searches at Jefferson Lab

Nuclear/Hadronic Physics Lab

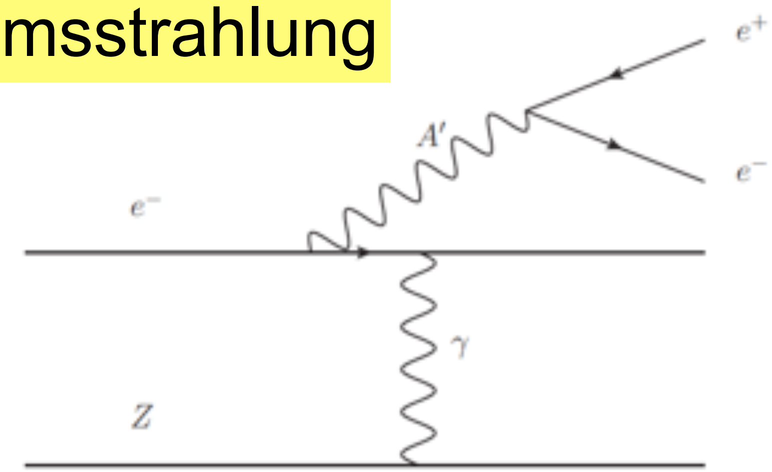


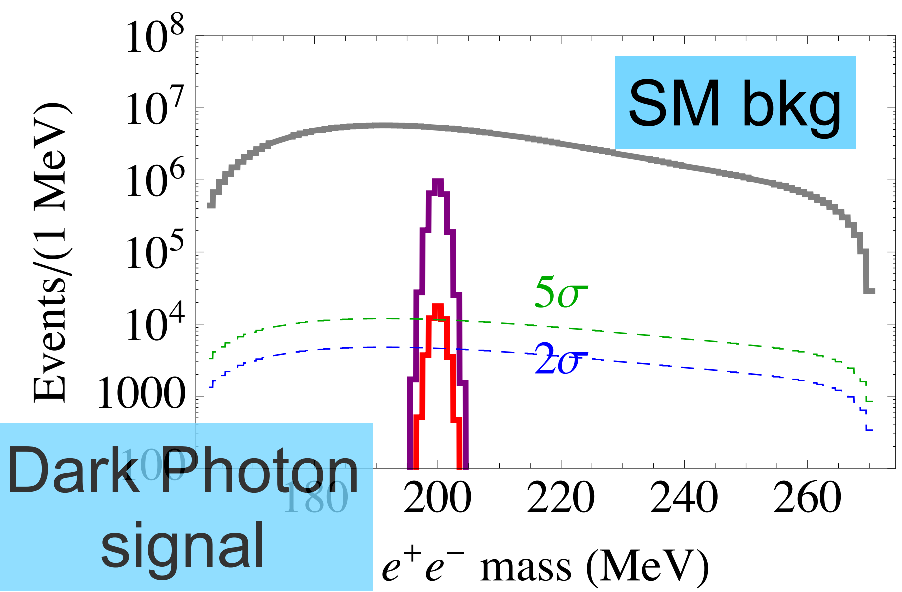
“Dark Photon” searches
(3 fixed target experiments)

Example: A' Experiment (APEX) at JLab - Hall A

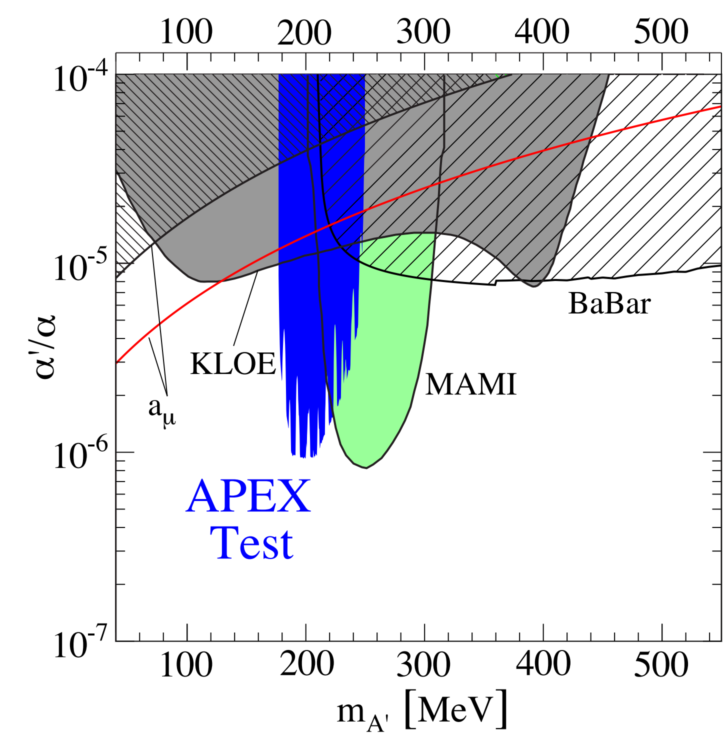
[APEX Collaboration]

Dark Photon Bremsstrahlung





New Fixed target (Tantalium Z=73) experiment designed for direct Dark Photon production/detection. (Z' → e^+e^- narrow resonance search using HRS)



[APEX test-run result (2011)]

Additional Dark Force Searches : relevant to Dark Z

Dark Z effects on Neutral Current phenomenology

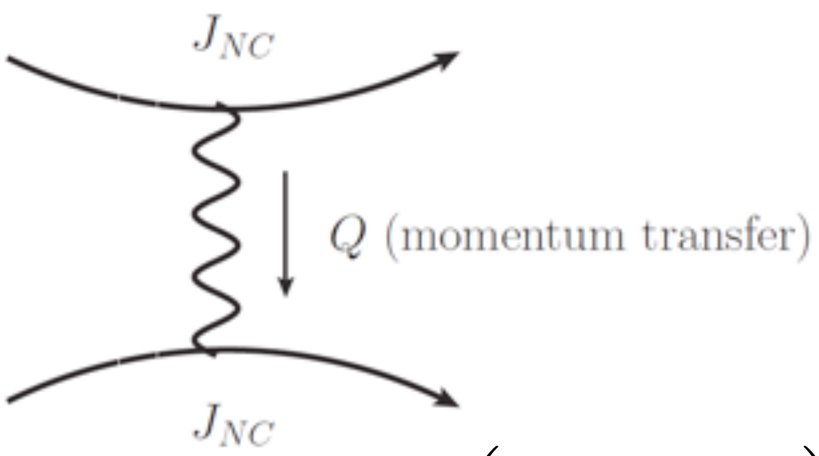
[Davoudiasl, Lee, Marciano (2012)]

Dark Z effect comes as **modification** of eff Lagrangian of Neutral Current scattering.

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

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

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



$$\left(\varepsilon_Z = \frac{m_{Z'}}{m_Z}\delta\right)$$

- Sensitive only to Low-Q^2 (momentum transfer). (Effect negligible for $Q^2 >> m_{Z'}^2$)
- For typical parameter values, $\Delta\sin^2\theta_W$ (Weinberg angle shift) is more sensitive.

"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.

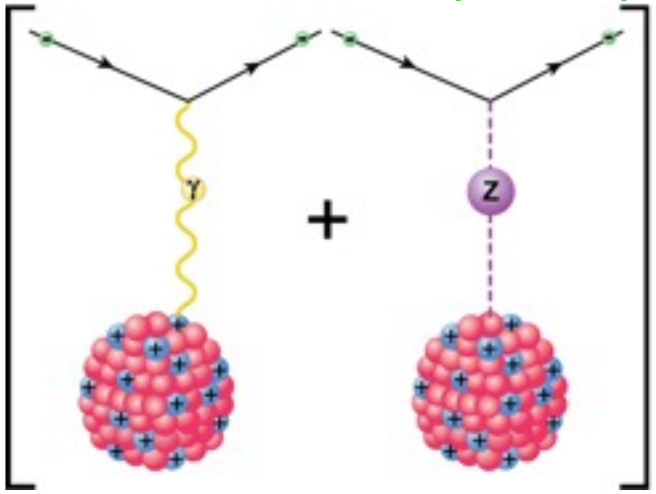
Past Low-Q^2 Parity-Violating Experiments

(i) 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).

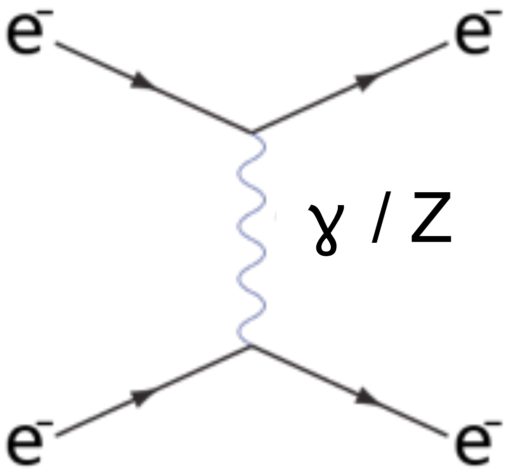


(ii) Polarized Electron Scattering [Left-Right asymmetry $A_{LR} = \sigma_L-\sigma_R / \sigma_L+\sigma_R$]:

$\sin^2\theta_W(m_Z)$=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.



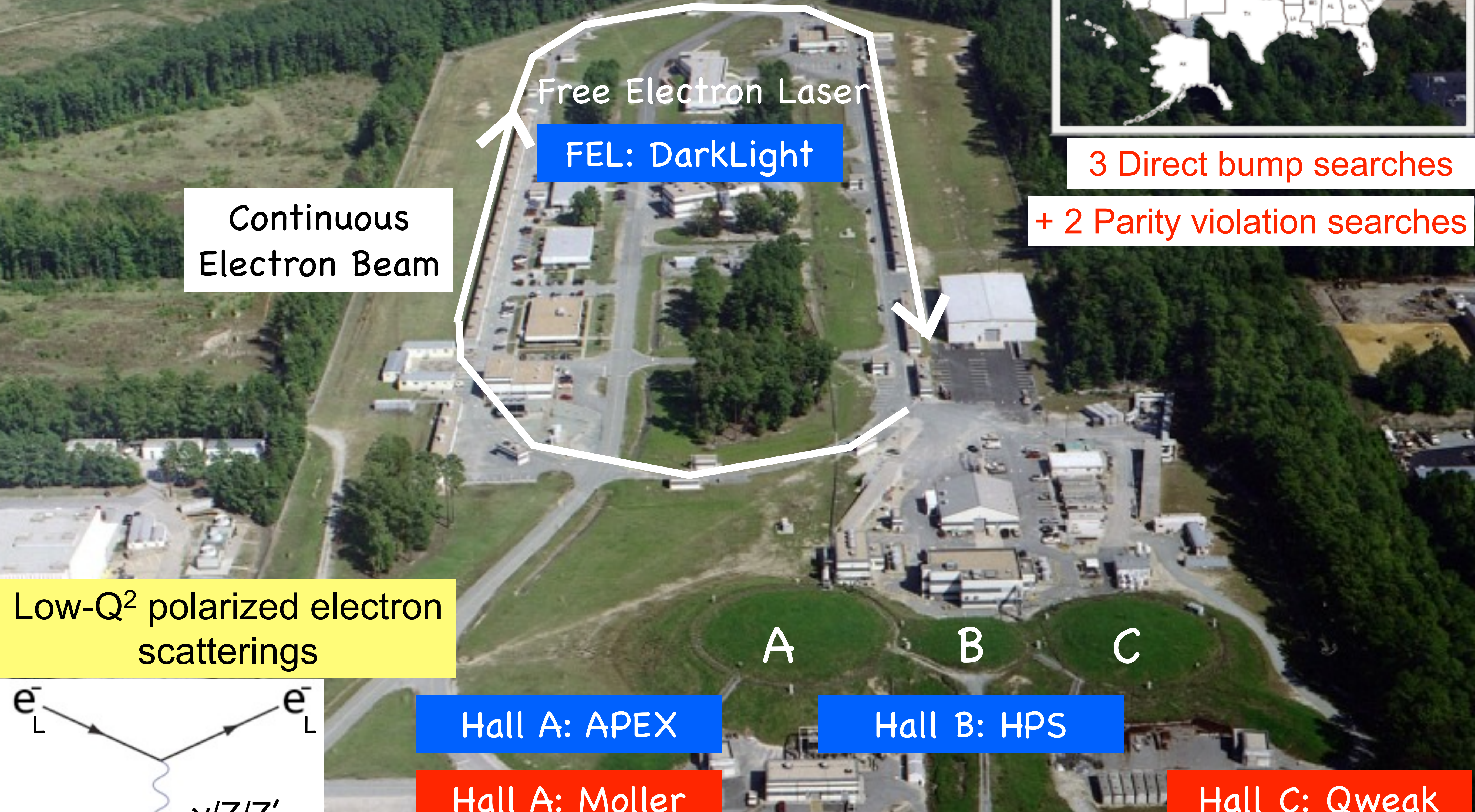
$$\Delta \sin^2\theta_W \simeq -0.42\varepsilon\delta \frac{m_Z}{m_{Z'}} f(Q^2/m_{Z'}^2)$$

Dark Force searches at Jefferson Lab

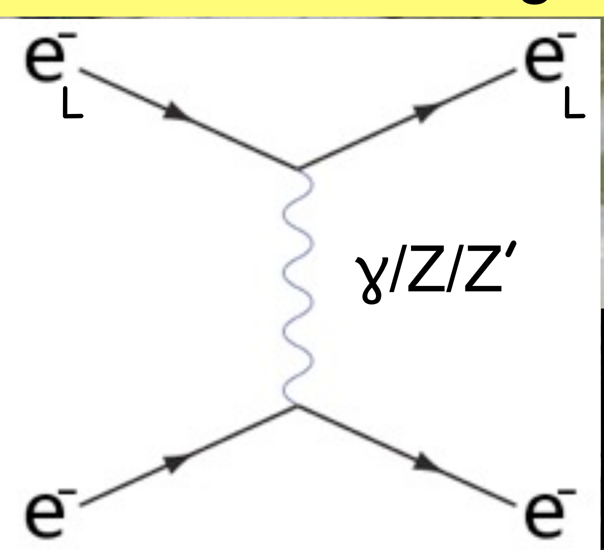
Nuclear/Hadronic Physics Lab

3 Direct bump searches

+ 2 Parity violation searches



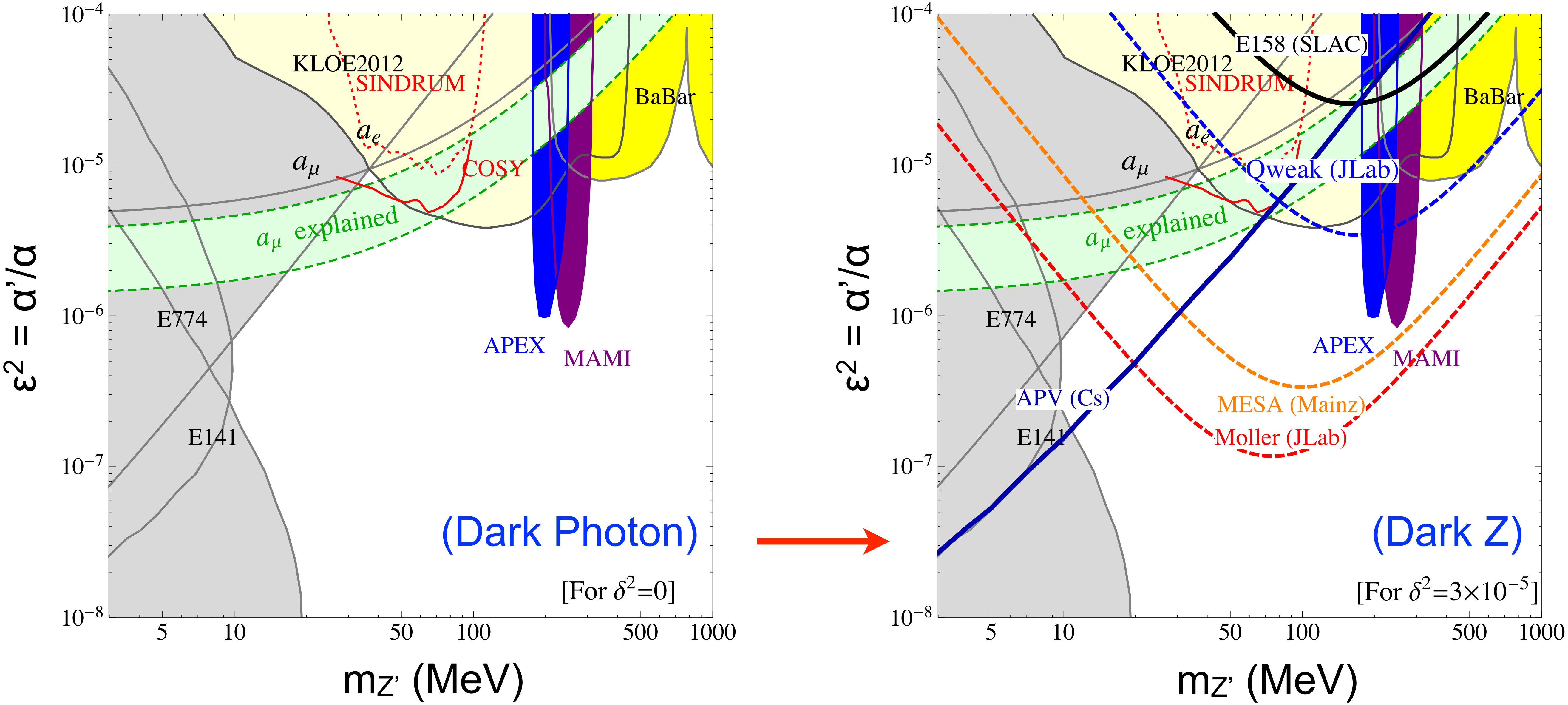
Low-Q^2 polarized electron scatterings



"Dark Z" searches

(2 more experiments relevant to Dark Force searches)

Dark Z Searches



Parameter space is extended by another axis for a new parameter (for Z-Z' mixing).
The new axis is explored by various current/future
Low-energy parity violating experiments.

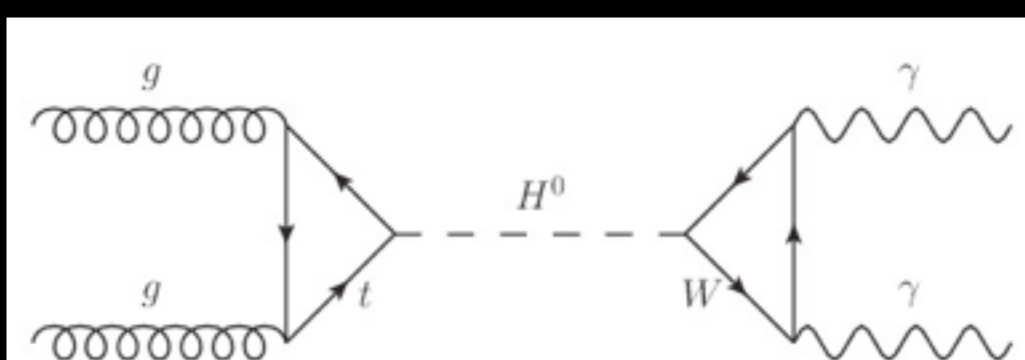
Experiment	Type	$\langle Q \rangle$	$\sin^2\theta_W(m_Z)$
Cesium APV	Cs	2.4 MeV	0.2356(20)
E158 (SLAC)	*ee*	160 MeV	0.2329(13)
Qweak (JLAB)	*ep*	170 MeV	±0.0007
Moller (JLAB)	*ee*	75 MeV	±0.00029
MESA* (Mainz)	*ep*	100 MeV	±0.00037

(*MESA parameters uncertain, but comparable to Moller)

High-energy experiments for Dark Force

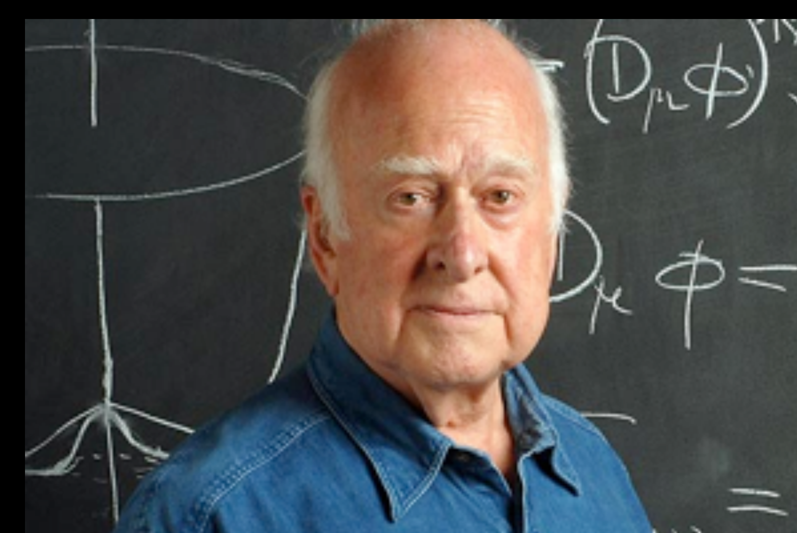
Dark Force at Large Hadron Collider (LHC)?
in Geneva, Switzerland

- Size: 27 km circumference (about 100 m underground)
- Cost: about 6 billion dollars
- Manpower: over 10,000 scientists and engineers



SM-like Higgs boson (mass ~ 125 GeV) was discovered at the LHC experiments (2012).

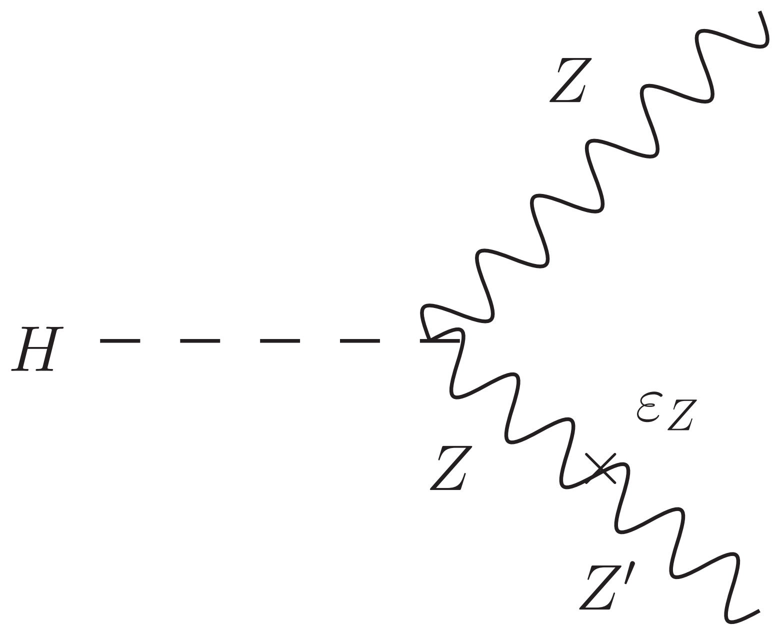
Next step: Precision study (detailed decay modes, ...)



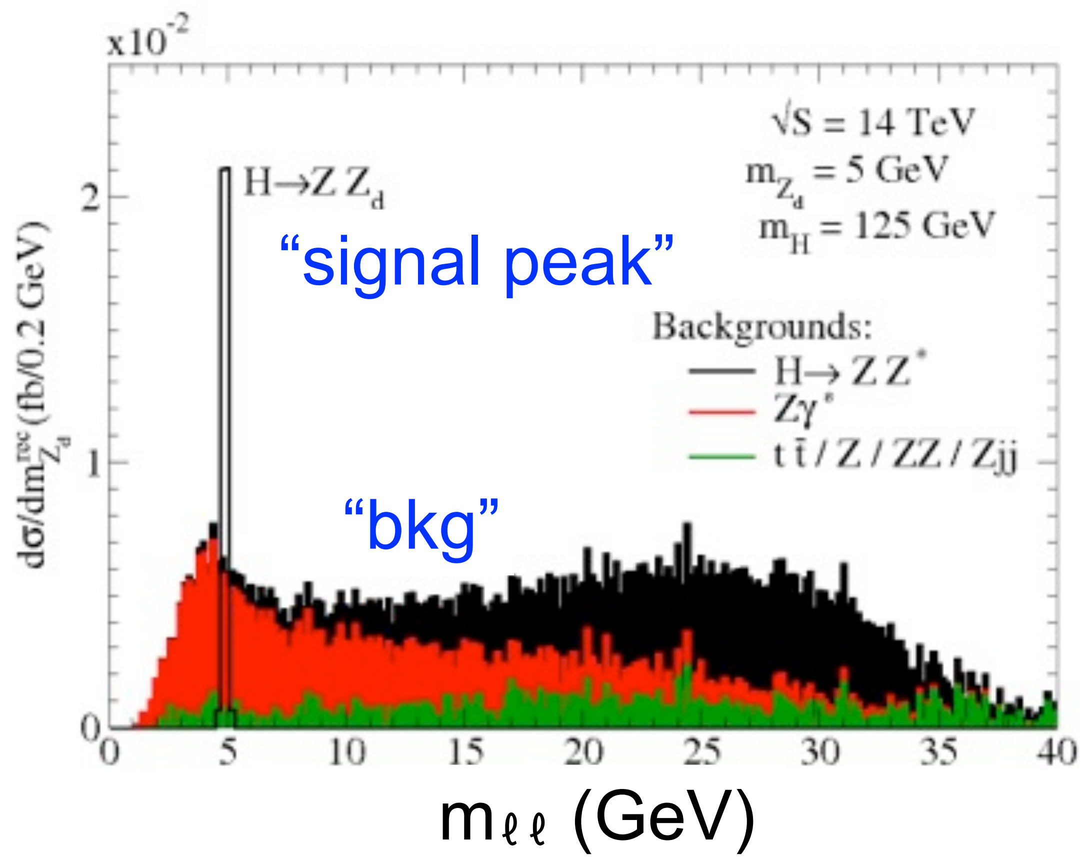
Peter Higgs (UK)

Higgs decay can produce a Dark Force carrier
(Connection of Higgs and Dark Force)

[Davoudiasl, Lee, Lewis, Marciano (2013)]



[Higgs → Z Z' → Z l^+l^-]



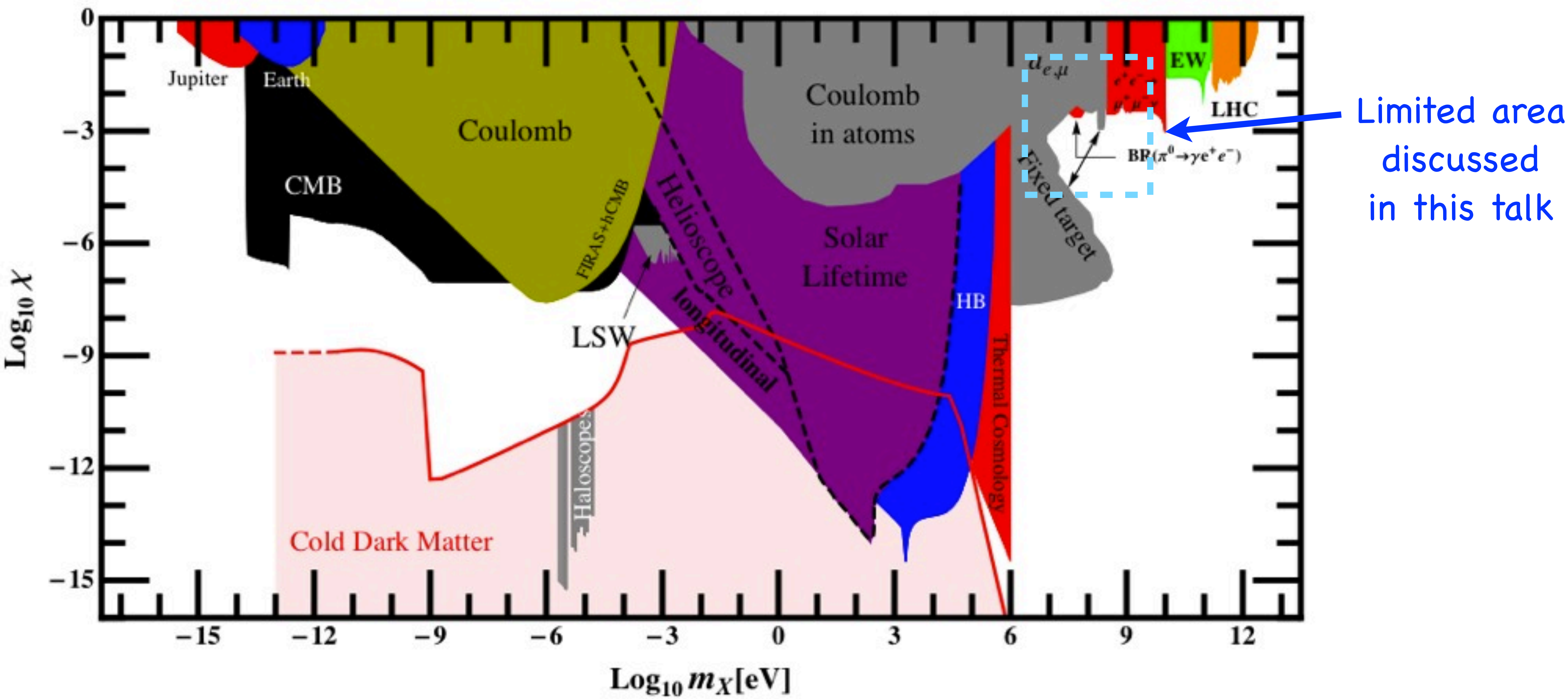
[Reconstructed Z' events (dilepton)]

- LHC can search for Dark Force, too (ex: Higgs decay).
  (It needs L ≈ few × 100 fb^{-1} for 5σ discovery, for typical parameters.)
- Complementary to Low-E experiments (JLab, B factory, ...) in Z' mass coverage.
  (LHC loses sensitivity for $m_{Z'} \lesssim$ several GeV.)

Dark Force can affect the LHC experiments.
(complementary to Low-E experiments in mass coverage)

Extended Range

Extended range of parameters (of Dark Photon)



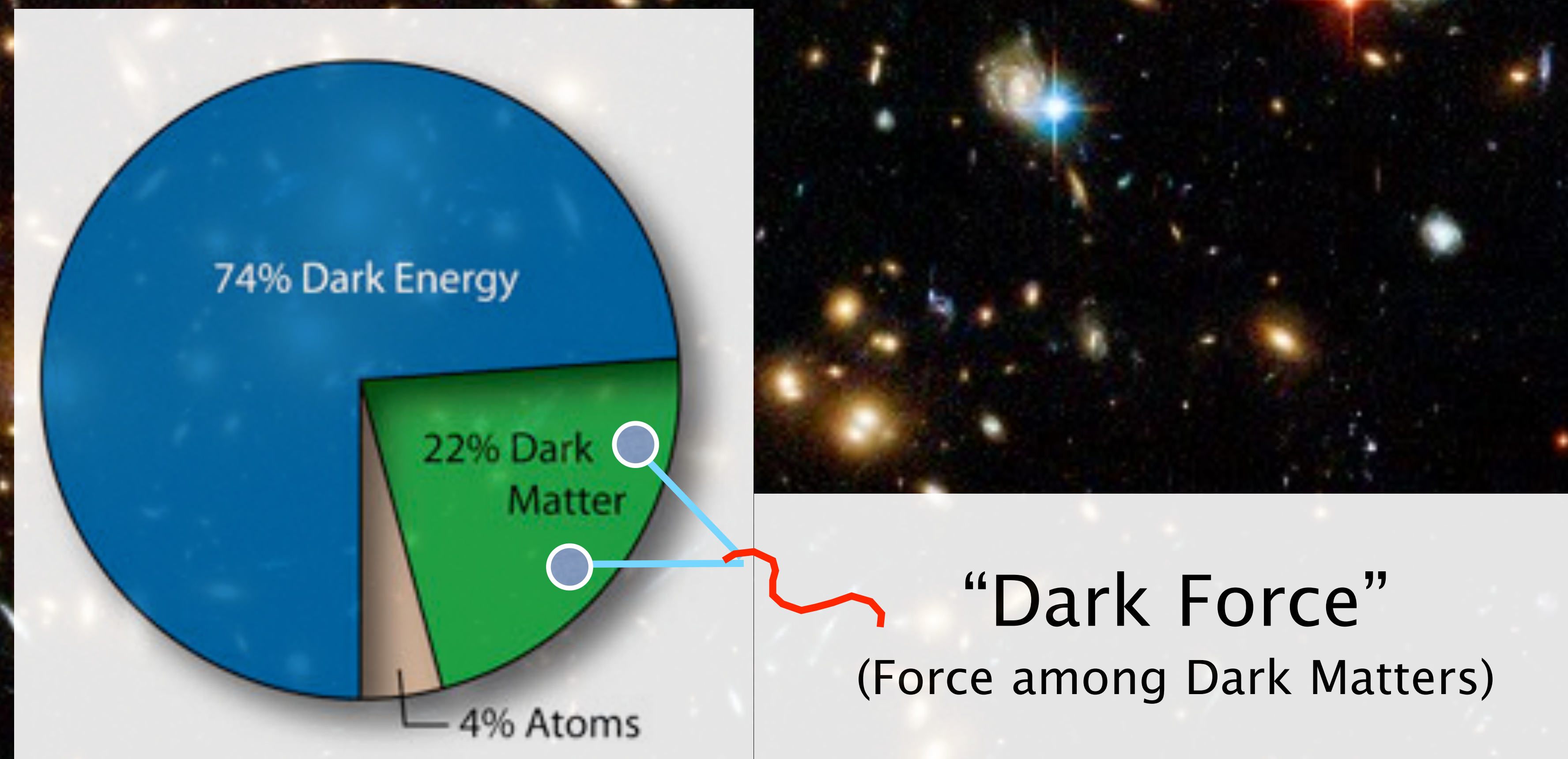
[Jaeckel (2013)]

Not every parameter space related to astrophysical anomalies, but there are vast parameter space unexplored, waiting for us:

(i) Heavier mass or (ii) Smaller coupling

Summary

Dark Force summary



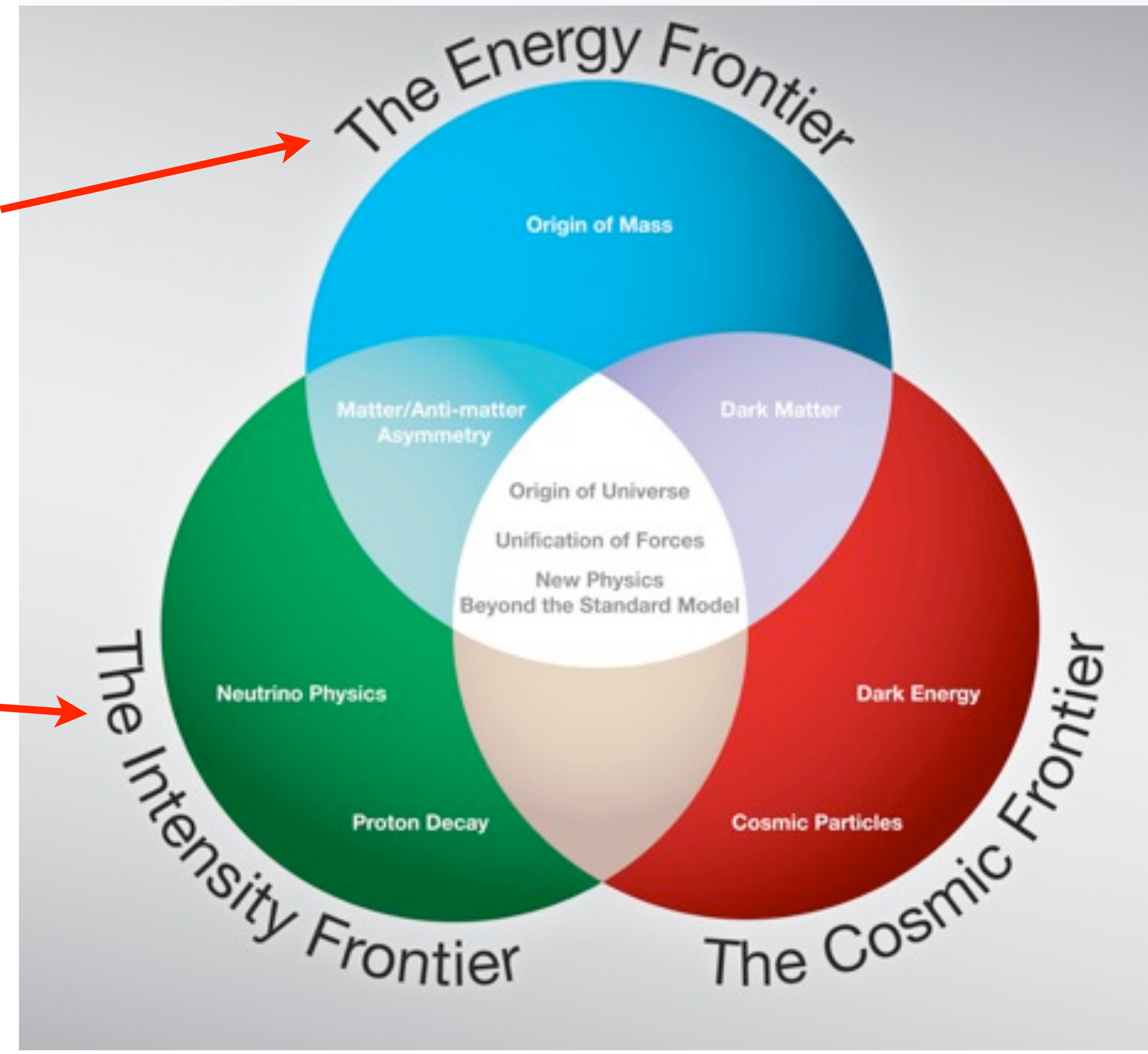
- Originally introduced to explain various astrophysical data.
- Mass ≈ O(1) GeV.
- Coupling ≈ Extremely weak (model-dependent) to the SM particles.
- Searchable at Low-energy Labs. (Fixed target, Low-Q^2 parity test, ...)
- May affect LHC experiments, too. (Rare Higgs decays, ...)

Traditional View

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

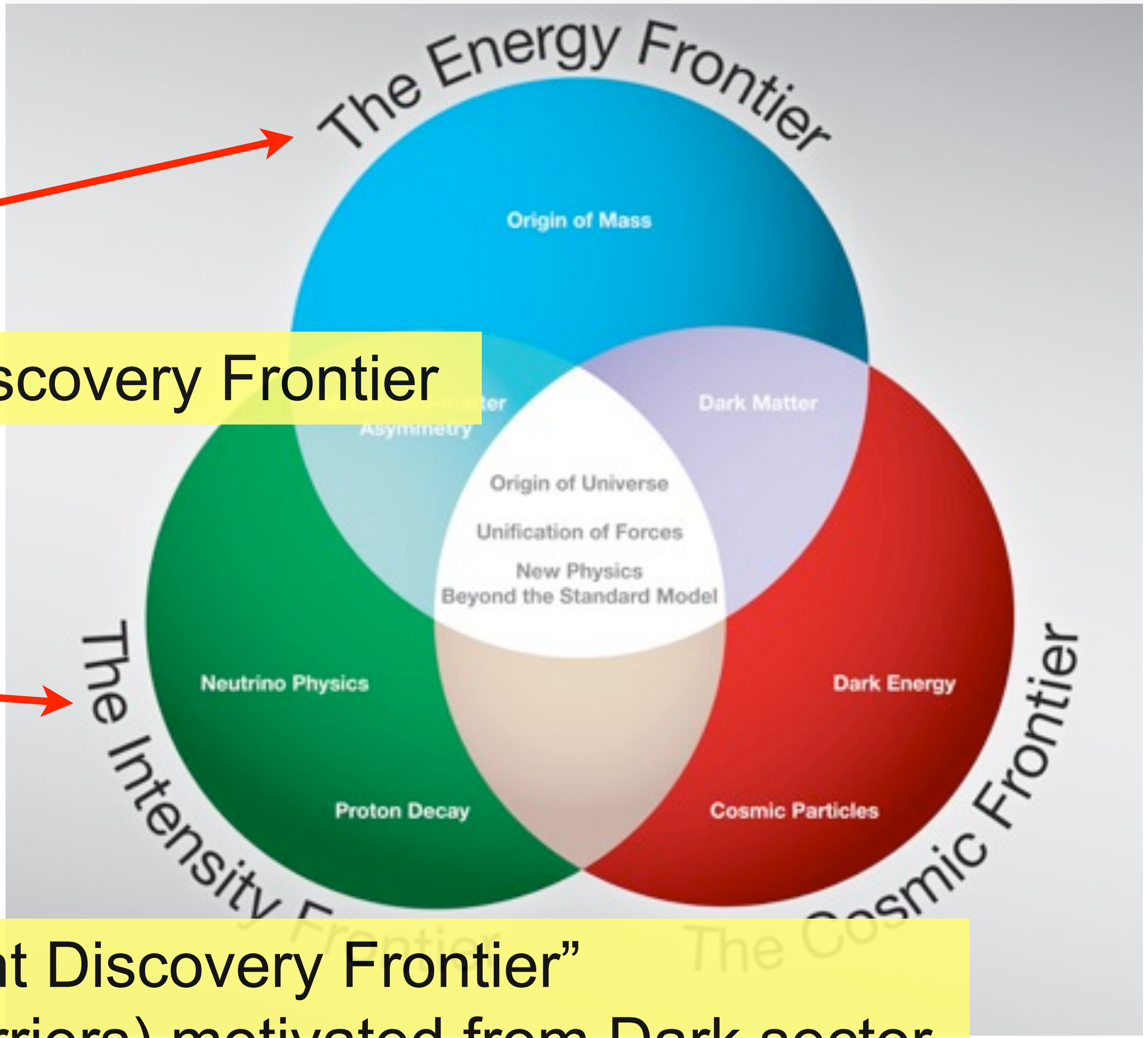
Low-E experiments: Rely on Higher precision to find indirect evidence of New heavy particles (JLab, B-factories, etc).

Particle Physics Frontiers
(by US Department of Energy)



Emerging Alternative View

Particle Physics Frontiers
(by US Department of Energy)



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

Traditionally considered as most important Discovery Frontier

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

Emerging as an "equally important Discovery Frontier"
with New Low-E scale particles (Dark force carriers) motivated from Dark sector.
(Ex) Some Z' bumps and parity violations can be seen only at Low-E experiments.

Low-energy experiments provide unique windows to discover some New physics.

– Thank you –