Searching for Dark Force

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SNU-KAIST-KASI-IBS Joint Journal Club
Institute for Basic Science
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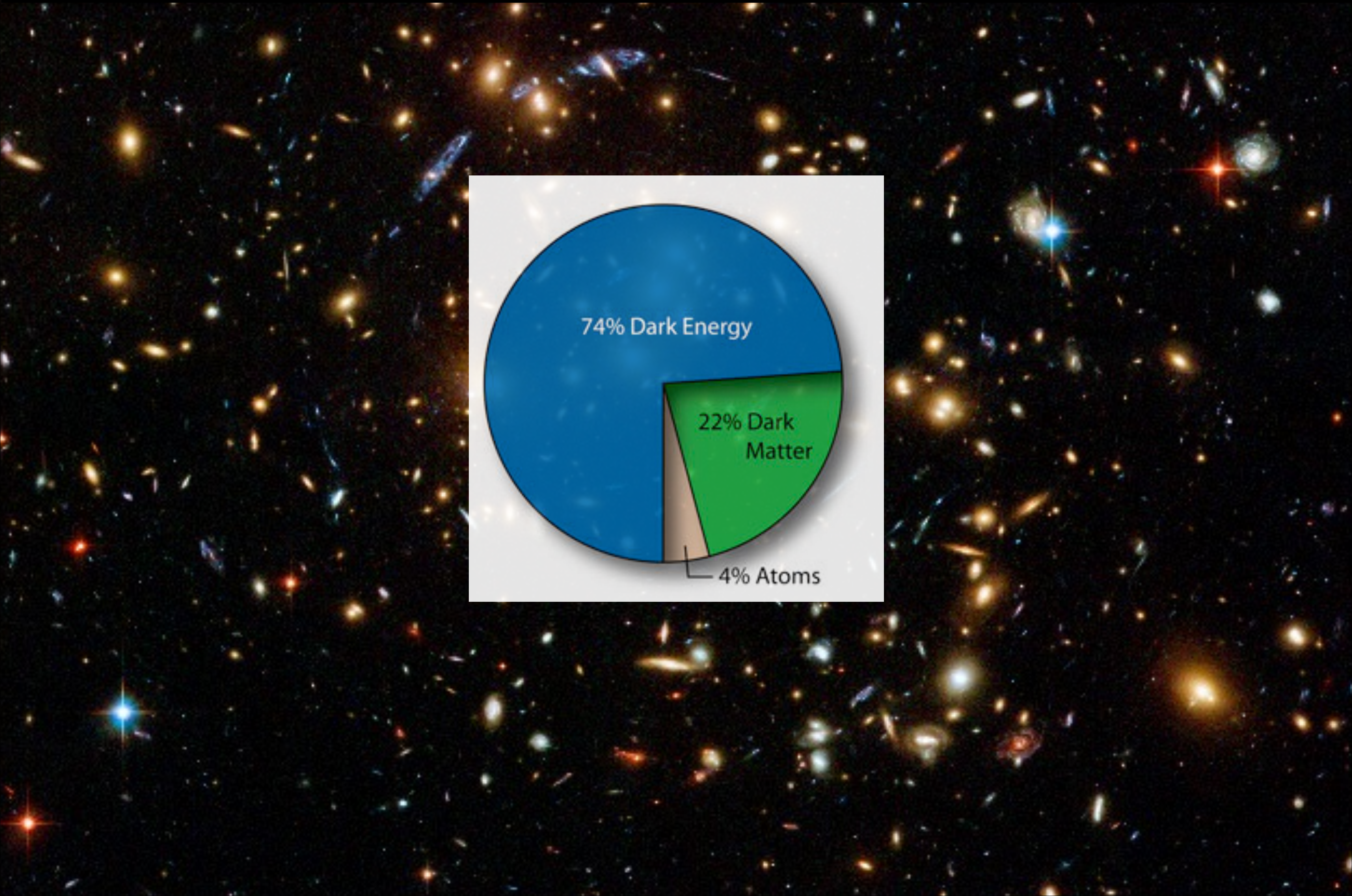
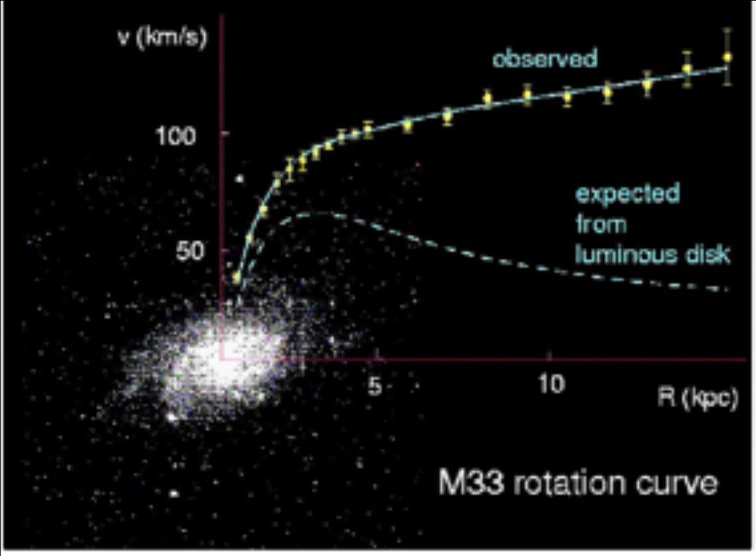
Prelude
(Original Motivation)

We live in a Dark World

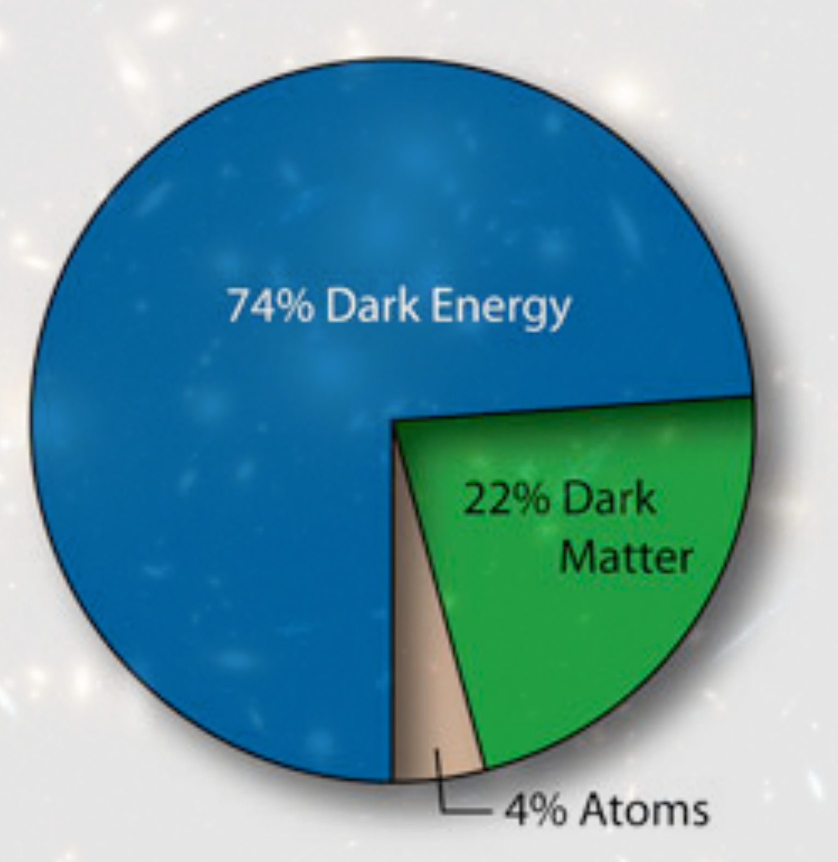


We live in a Dark World

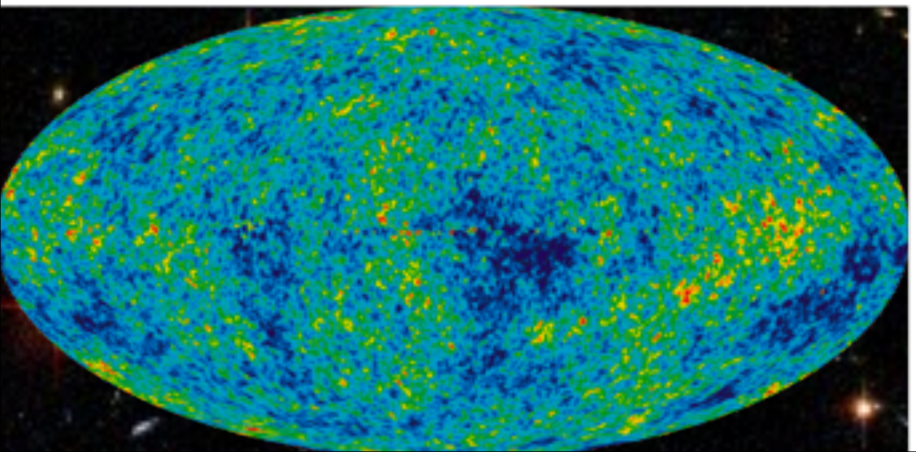


Galaxy rotation curve

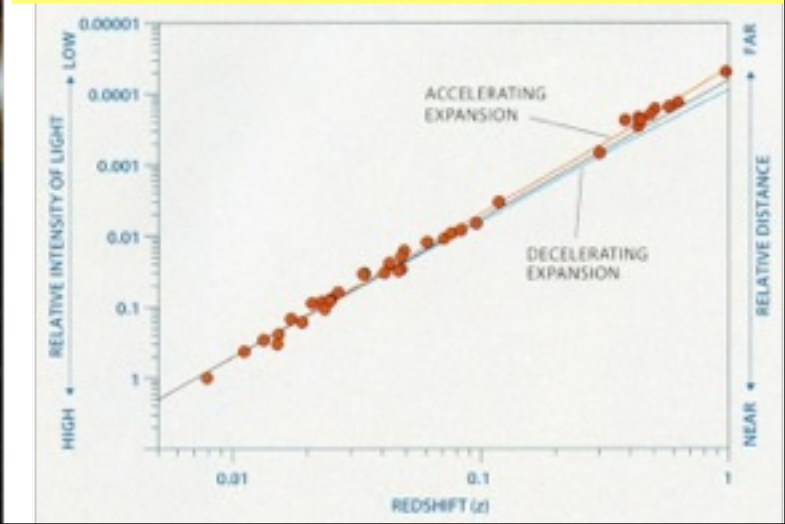
Gravitational lensing



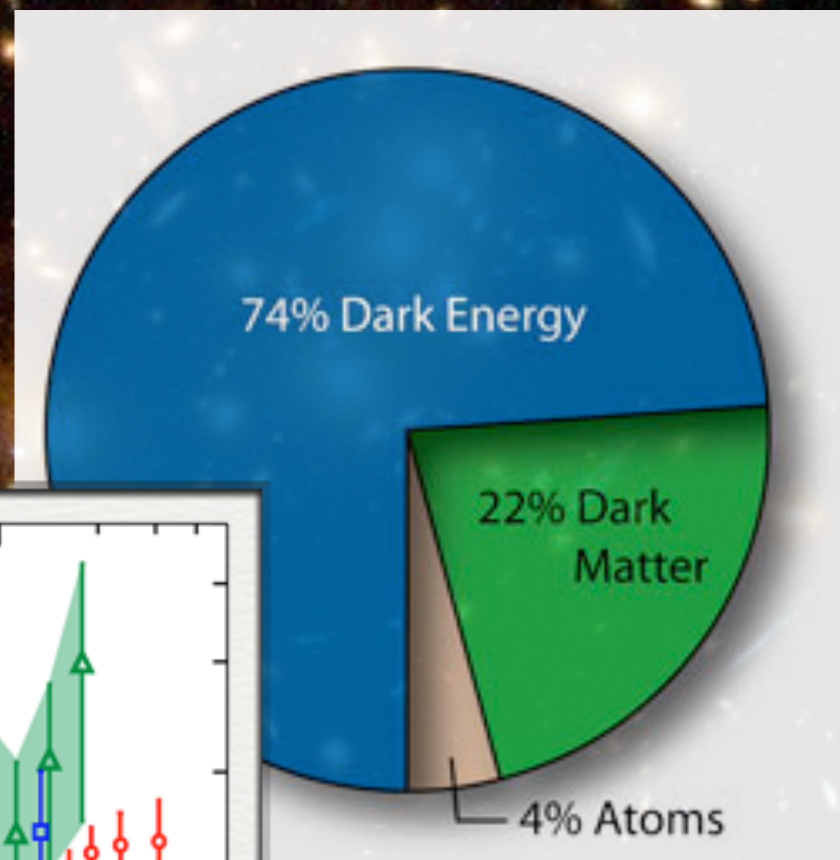
Cosmic Microwave Background



Accelerating Universe
(Supernovae)

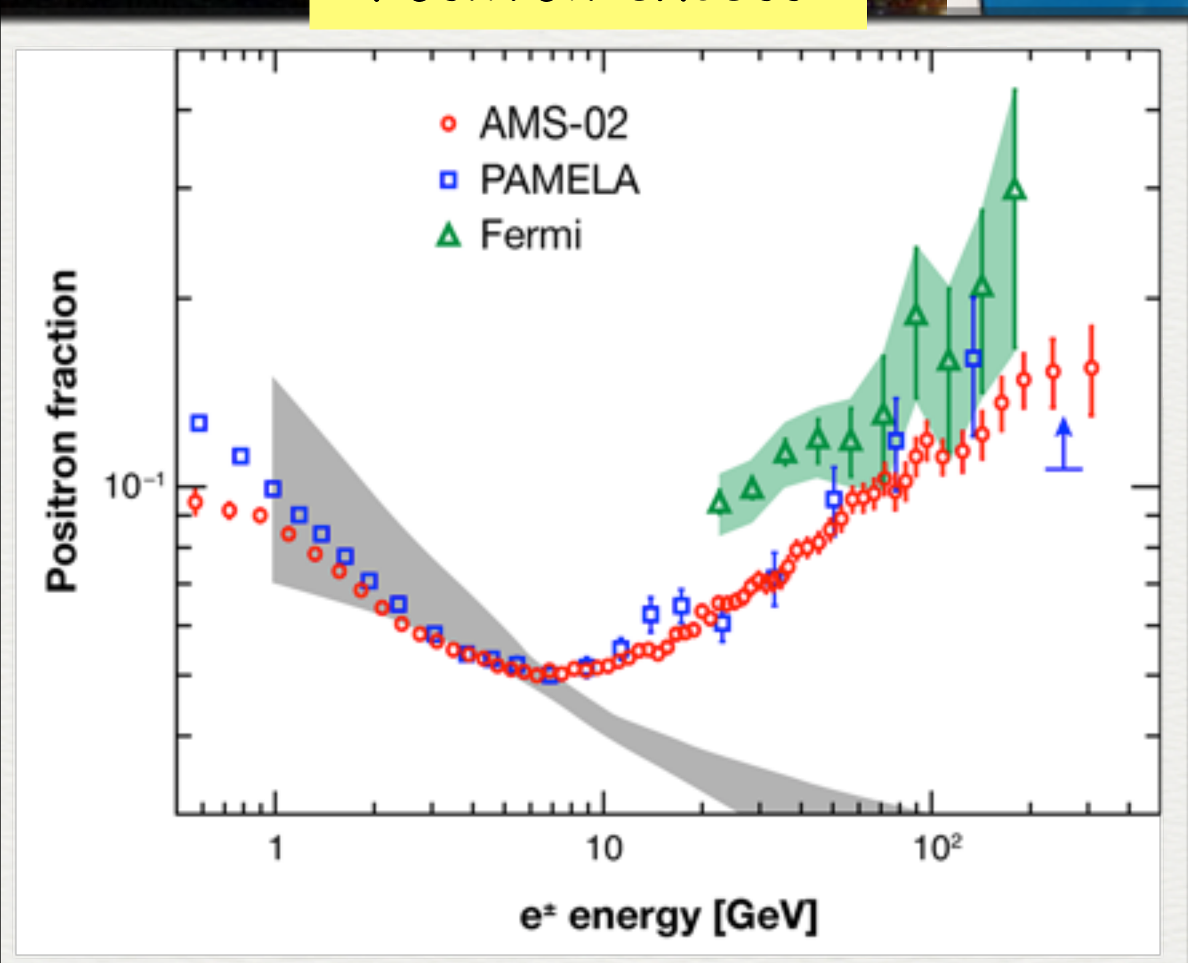


We live in a Dark World



still mystery

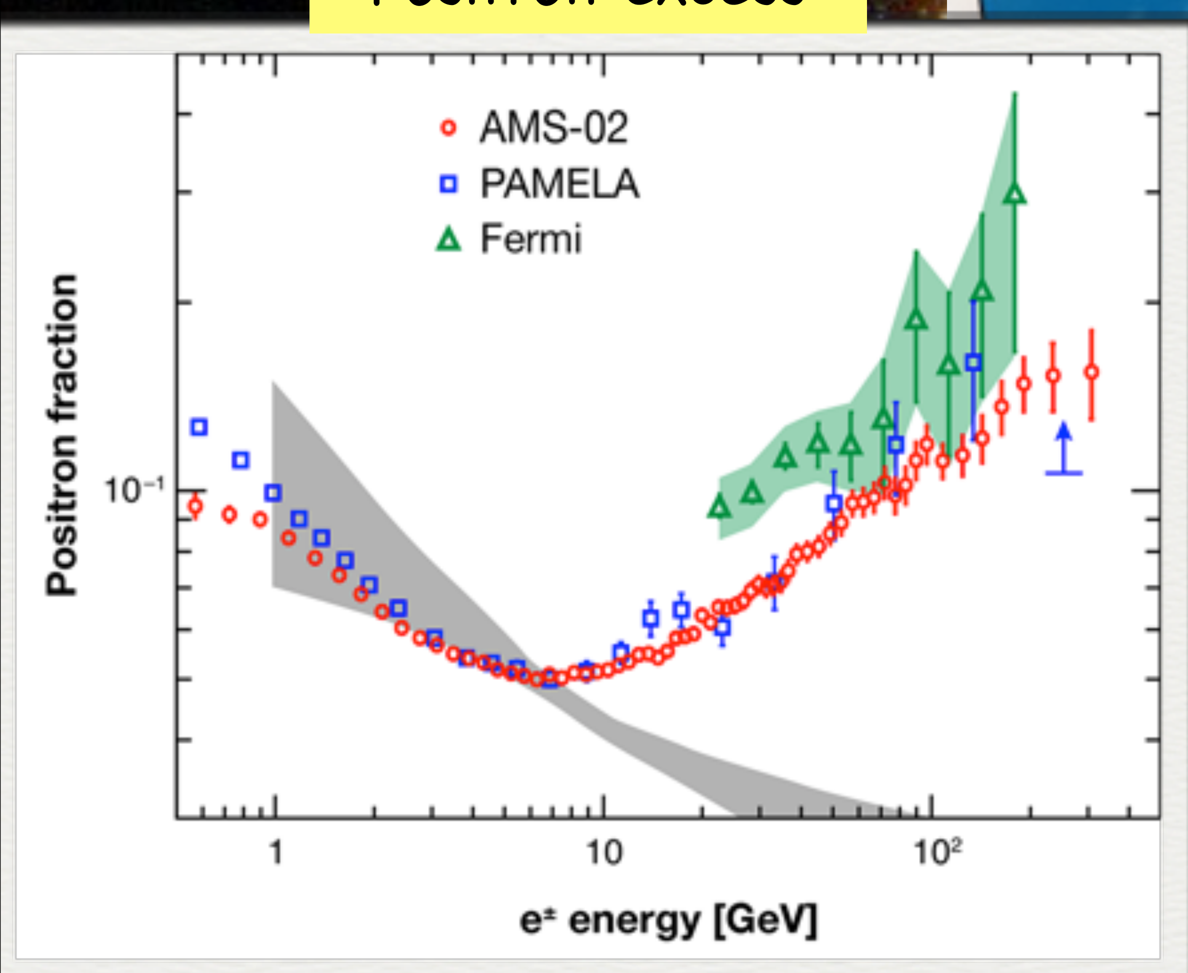
Positron excess

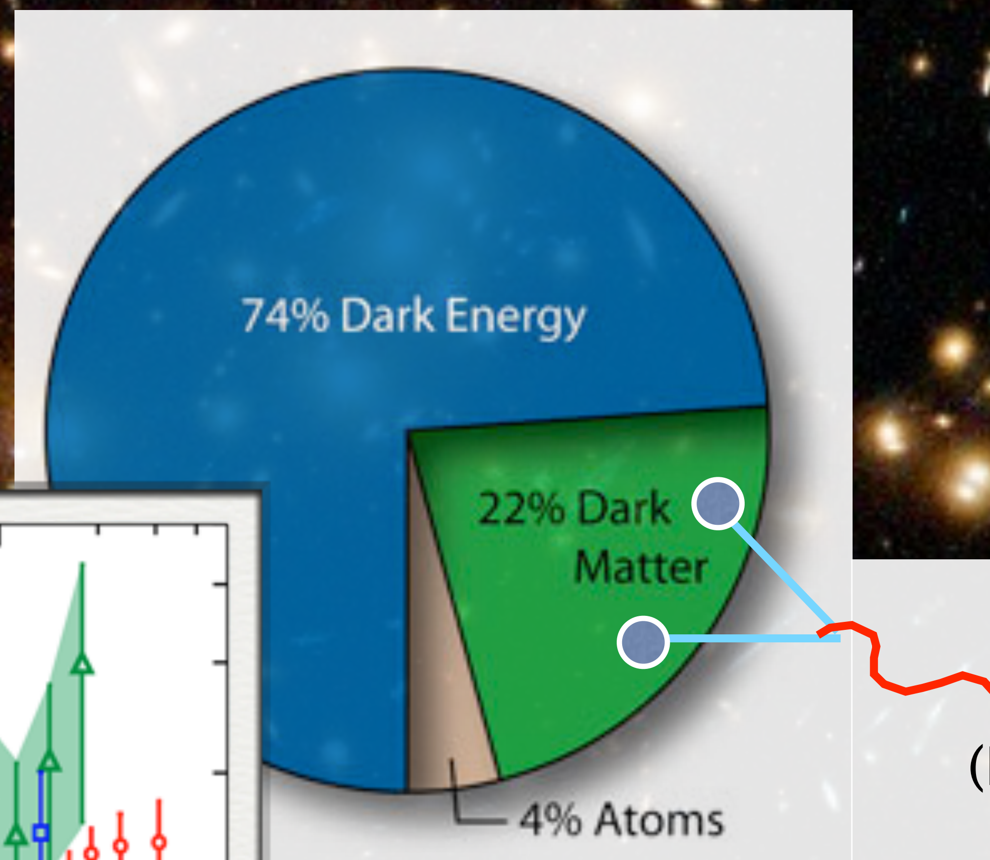


No corresponding antiproton excess
: Typical DM annihilation would produce both e+e- and p+p-

We live in a Dark World

Positron excess





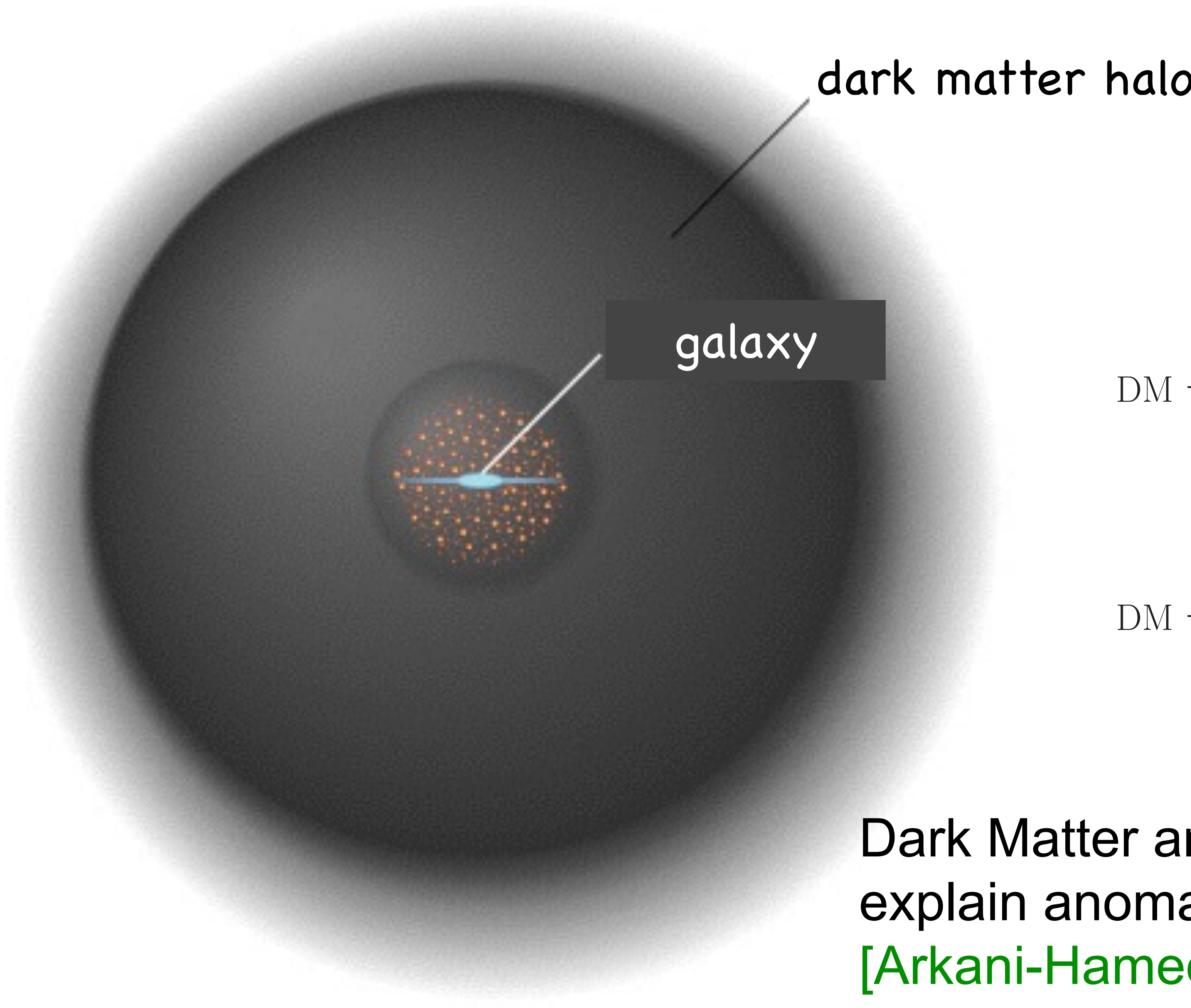
"Dark Force"
(Force among Dark Matters)

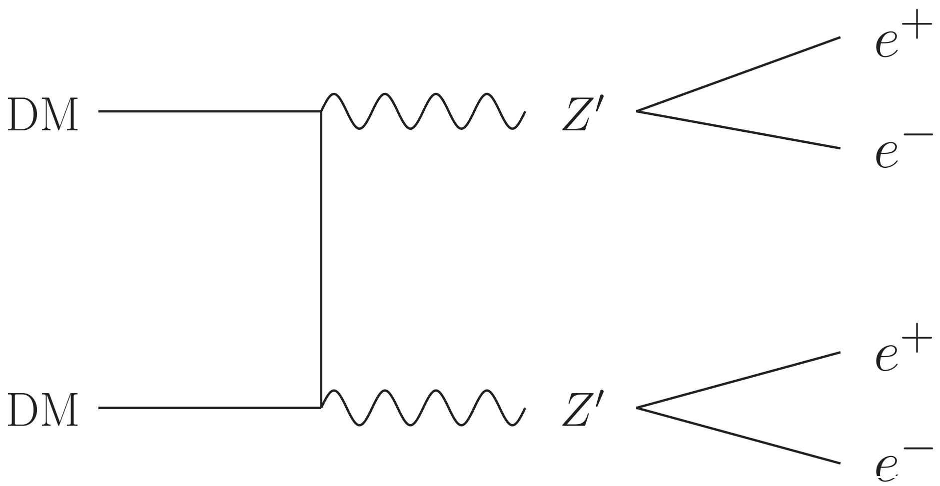
No corresponding antiproton excess
: Typical DM annihilation would produce both e+e- and p+p-

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 with Dark Force can explain anomalies including the positron excess. [Arkani-Hamed *et al* (2008); and others].

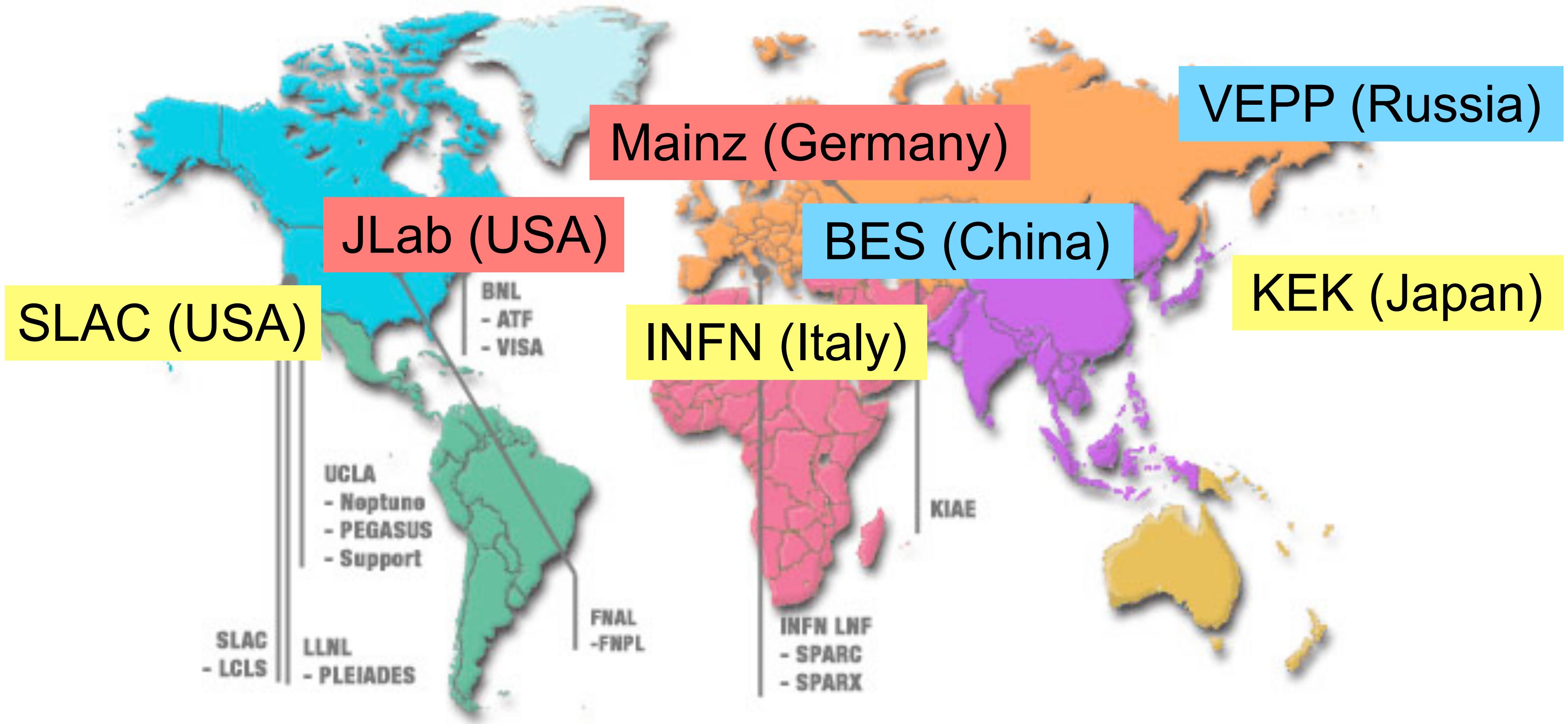
Dark Trilogy (of Dark World)

1. Dark Energy (Accelerating expansion, ...)
2. Dark Matter (Galaxy rotation curve, ...)
3. Dark Force (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).

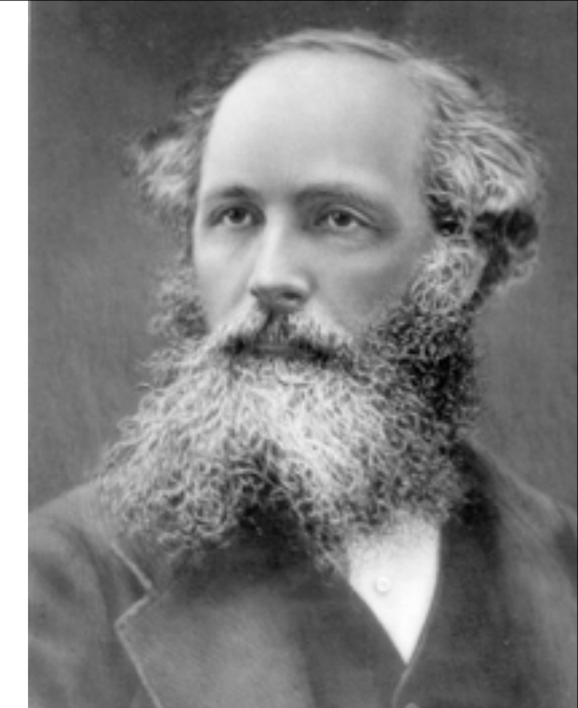


Particularly attractive: One of the New physics scenarios that can be tested with Low-energy experimental facilities (Nuclear/Hadronic physics labs).

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

"various Low-E Labs" "LHC"

Hunting for New fundamental force



Fundamental forces (interactions) in nature:
(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, and bring the **revolutionary effects** in our life.

Outline

- Dark Force Models

- Dark Force Searches (in Low-energy experiments)

- Implications for the LHC (connecting Low-E & High-E physics)

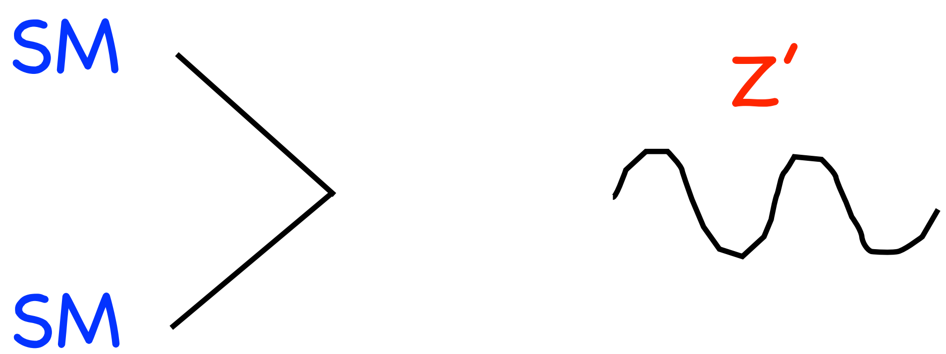
- …

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

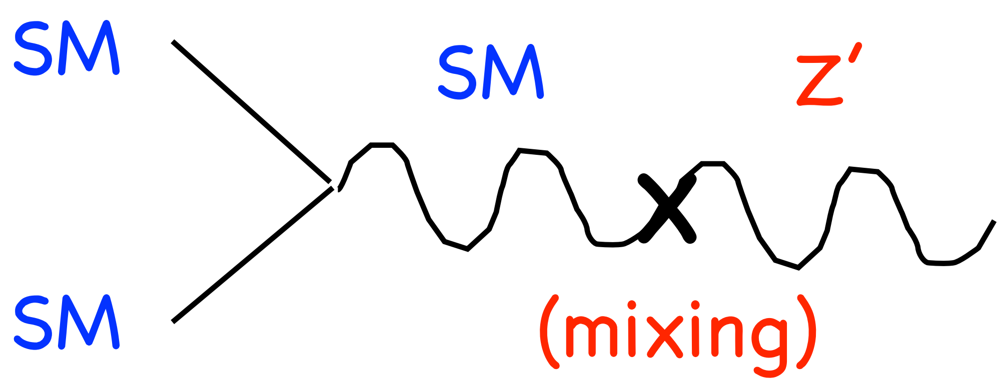


(no direct coupling)

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

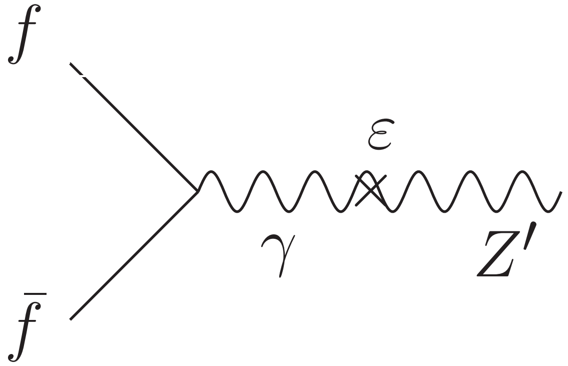
[Holdom (1986)]

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

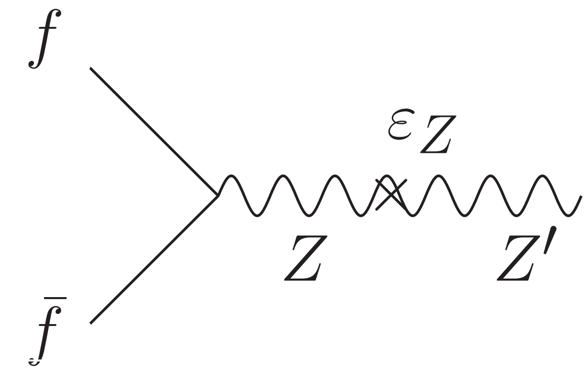


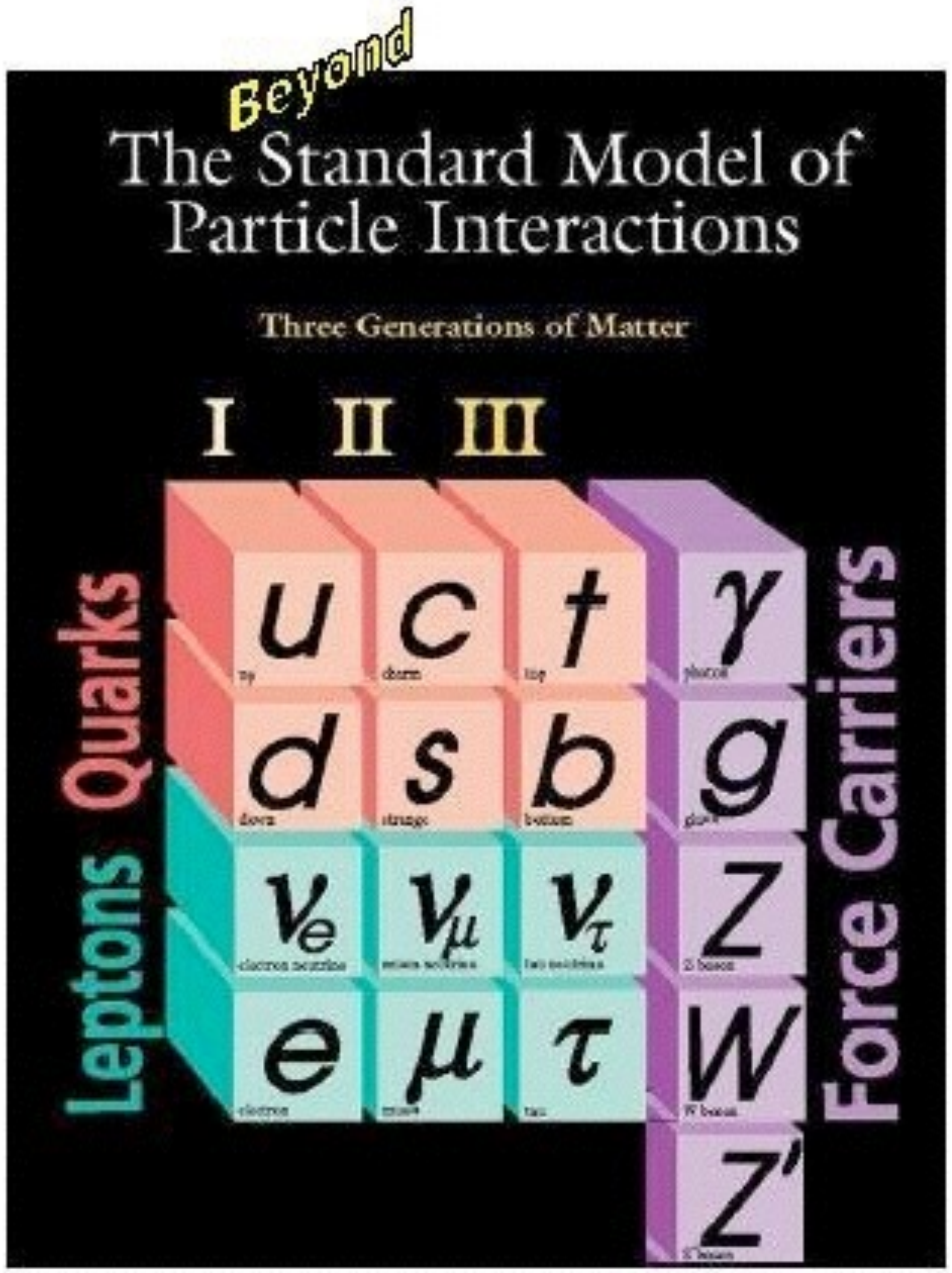
(couples through SM gauge bosons)

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



Types of Dark Force





Z' : <u>couplings</u> to the SM particles are suppressed by small <u>mixing</u>.

(model-dependent)

(i) Popular Model: **"Dark Photon"**

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

mass = O(1) GeV

coupling = ε×(Photon coupling)

(ii) New Model: **"Dark Z"**

[Davoudiasl, LEE, Marciano (2012)]

mass = O(1) GeV *(cf. Z mass = 91 GeV)*

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 in coupling comes from **how Z' gets mass** (or Higgs sector).

- Dark Photon: (ex) additional Higgs singlet gives mass to Z'
  coupling = ε×(Photon coupling)
- Dark Z: (ex) additional Higgs doublet (+ singlet) gives mass to Z'
  coupling = ε×(Photon coupling) + ε_Z×(Z coupling)

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

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

(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 Higgs singlet)*

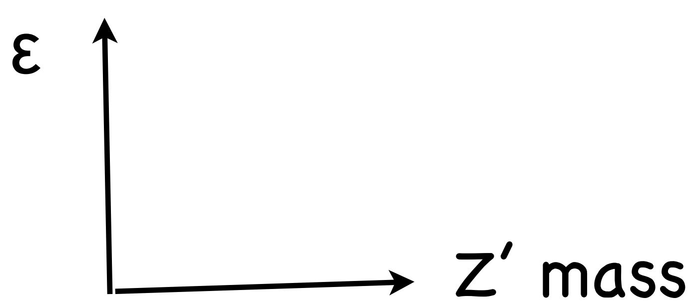
$$J^{NC}_{\mu} = \left(\frac{1}{2}T_{3f} - Q_f \sin^2\theta_W\right)\bar{f}\gamma_{\mu}f - \left(\frac{1}{2}T_{3f}\right)\bar{f}\gamma_{\mu}\gamma_5 f$$

Dark Force couplings depend on Higgs sector.

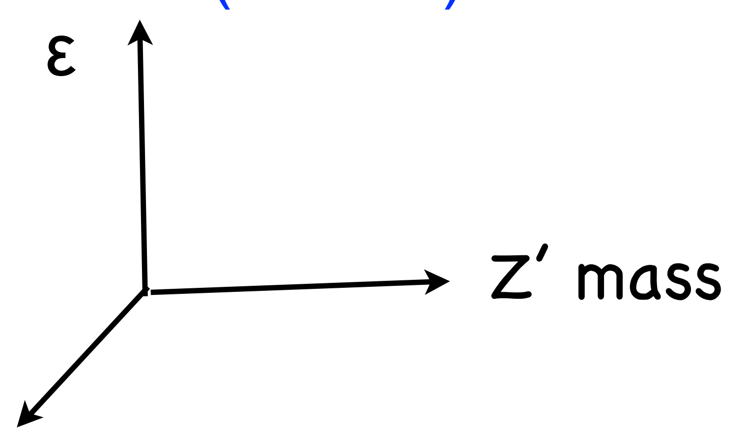
Effects of New Model (Dark Z)

Parameter space (Z' mass and coupling to the SM) is extended from 2D to 3D.

(Dark Photon)



(Dark Z)



ε_Z (Z-Z′ mixing) : parity violating

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

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

- Dark Z = Dark Photon with a more general coupling.
- Dark Photon = a special case of Dark Z (ε_Z = 0 limit).

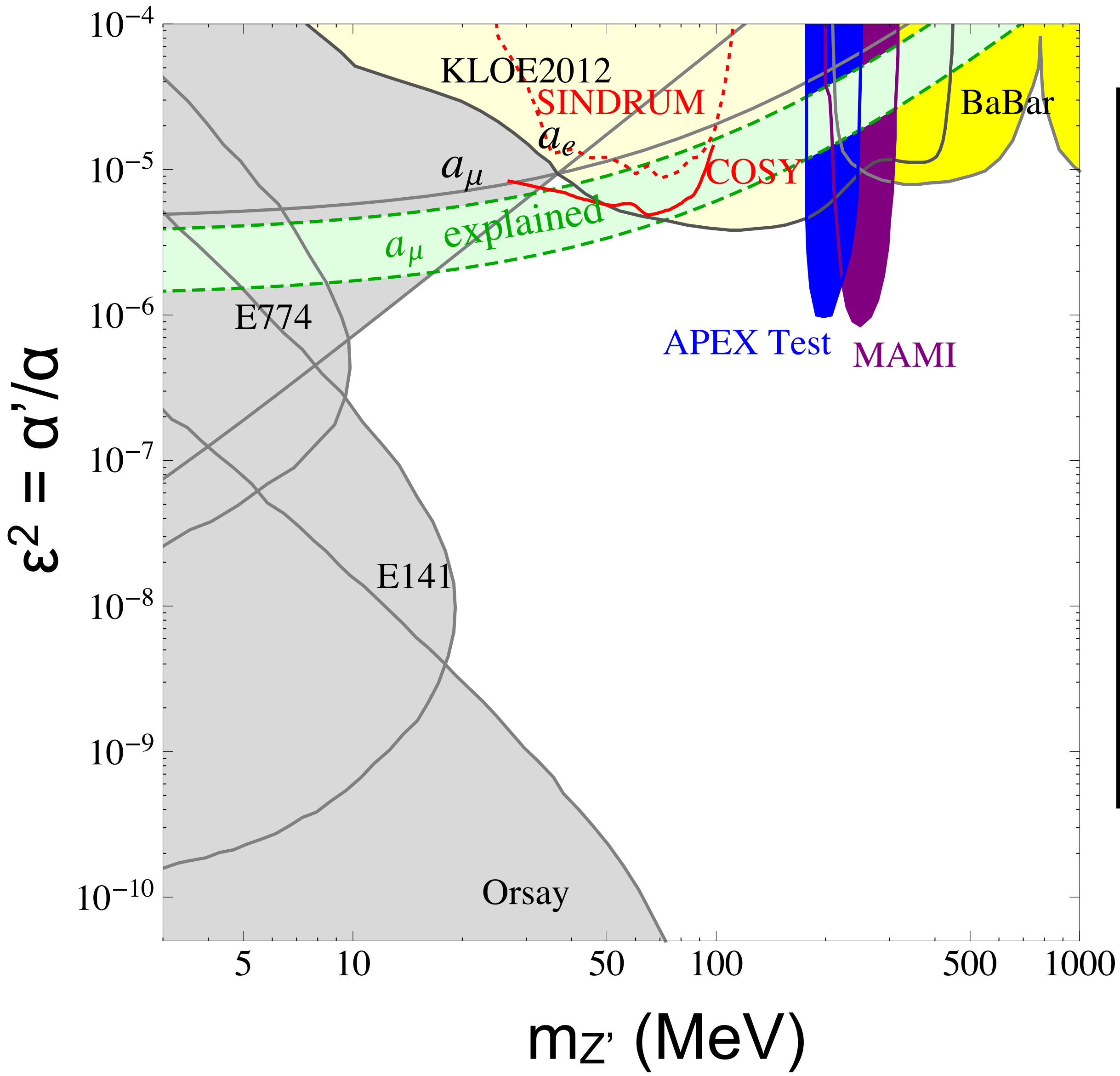
Some experiments irrelevant to Dark Photon searches become relevant to Dark Z searches.

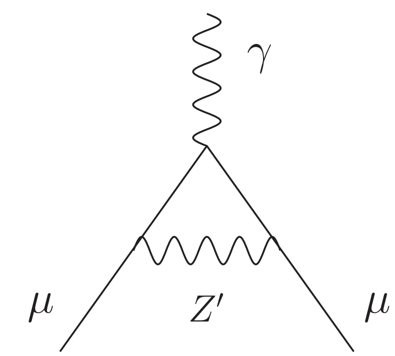
(Ex) Low-E parity test, enhanced favor-changing meson decays, rare Higgs/Top decays, ... : will be discussed later

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

Dark Force Searches
(in Low-energy experiments)

Dark Photon Searches





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

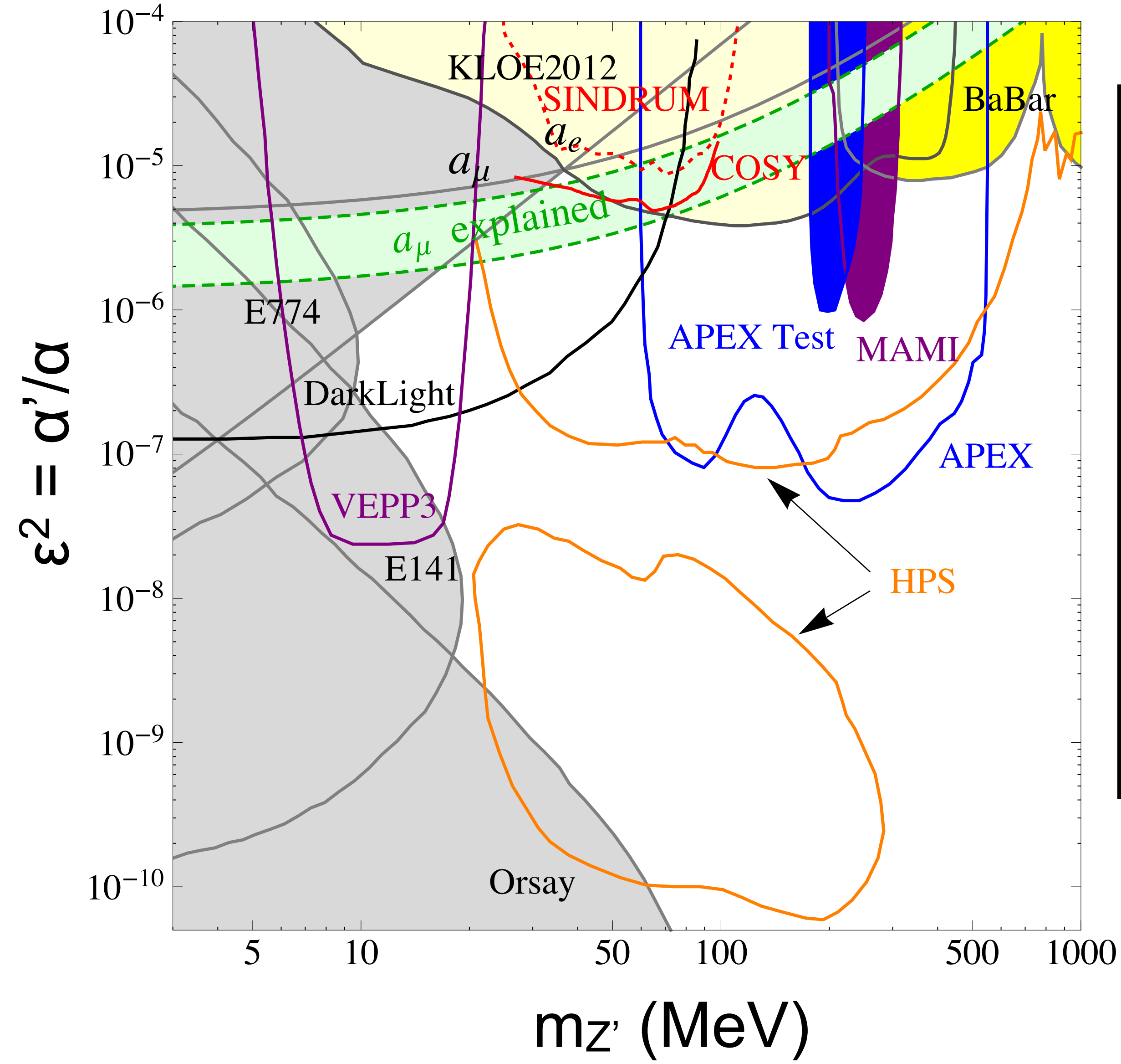
Green band: explains <u>3.6σ deviation</u> in g_μ - 2 (possibly early hint of Dark Force)

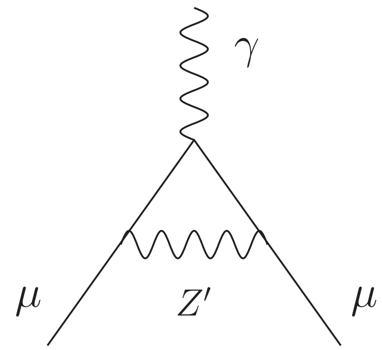
[Fayet (2007); Pospelov (2008)]

Current and Future coverage (parts) [as of 2013 summer]

1. Anomalous magnetic moments (g-2) for e, μ.
2. Beam-dump experiments: 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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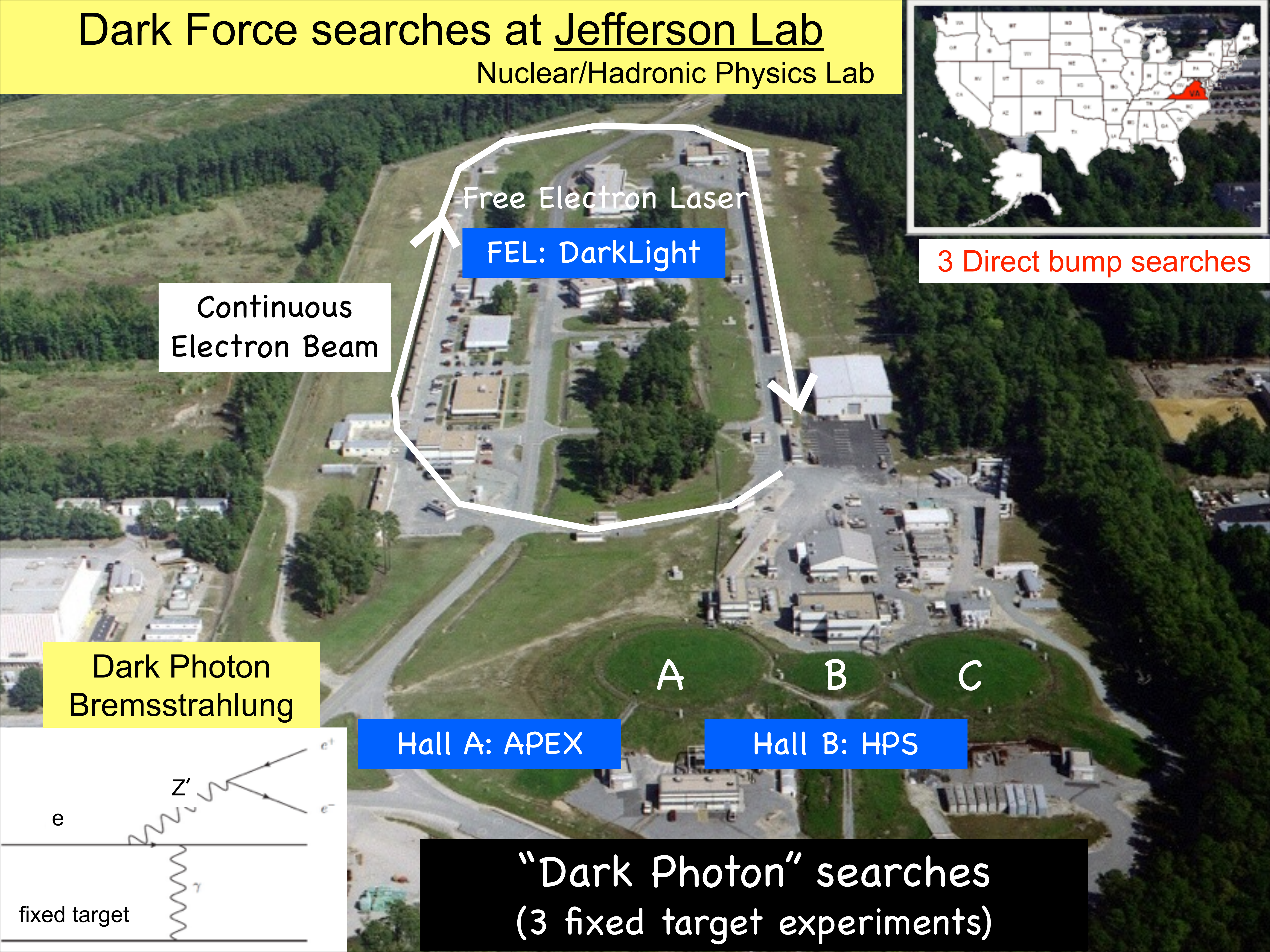
Dark Force searches at Jefferson Lab

Nuclear/Hadronic Physics Lab



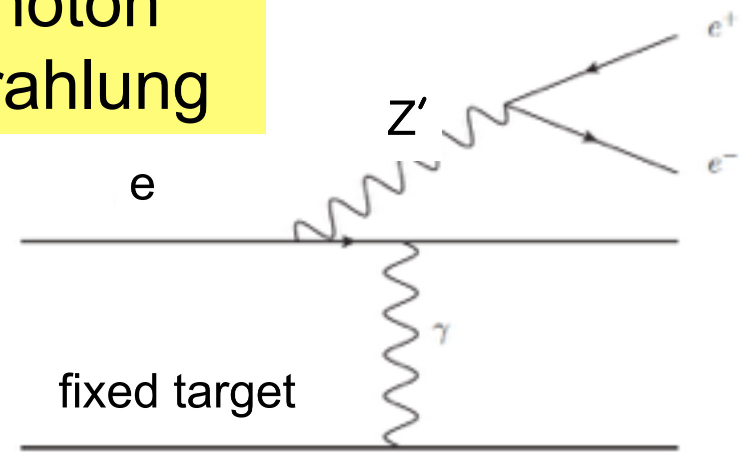
"Dark Photon" searches

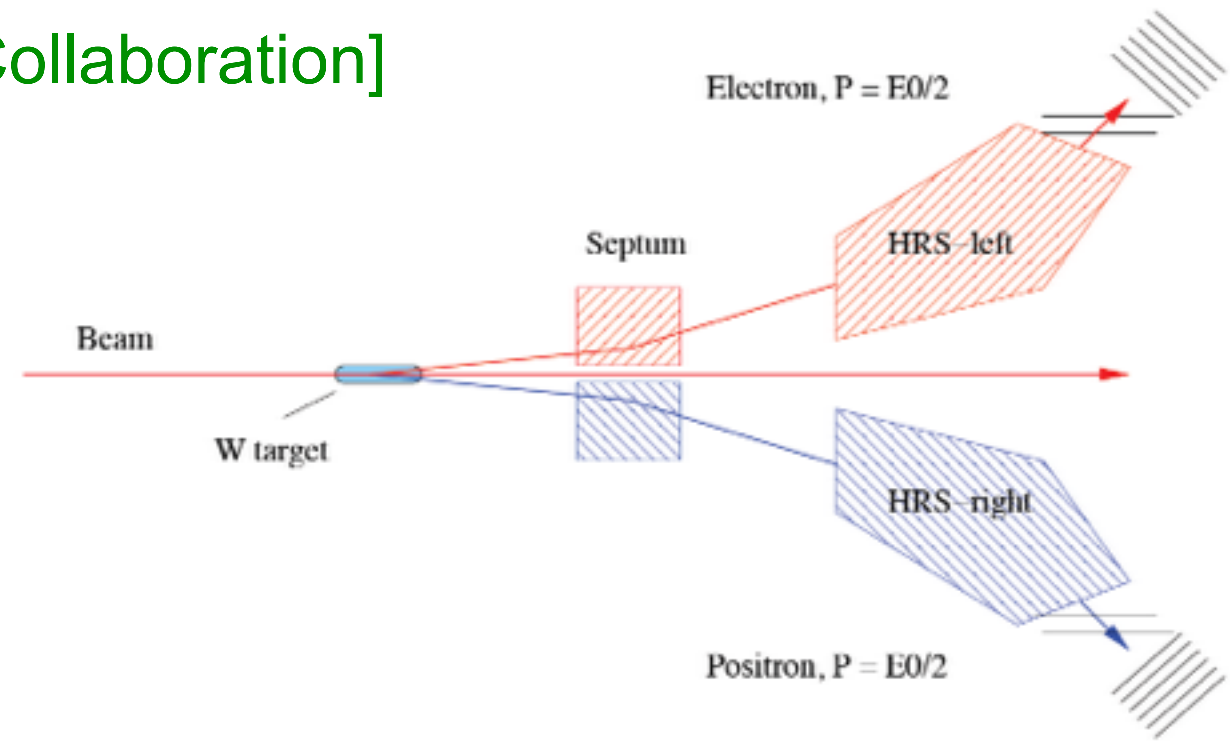
(3 fixed target experiments)

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

[APEX Collaboration]

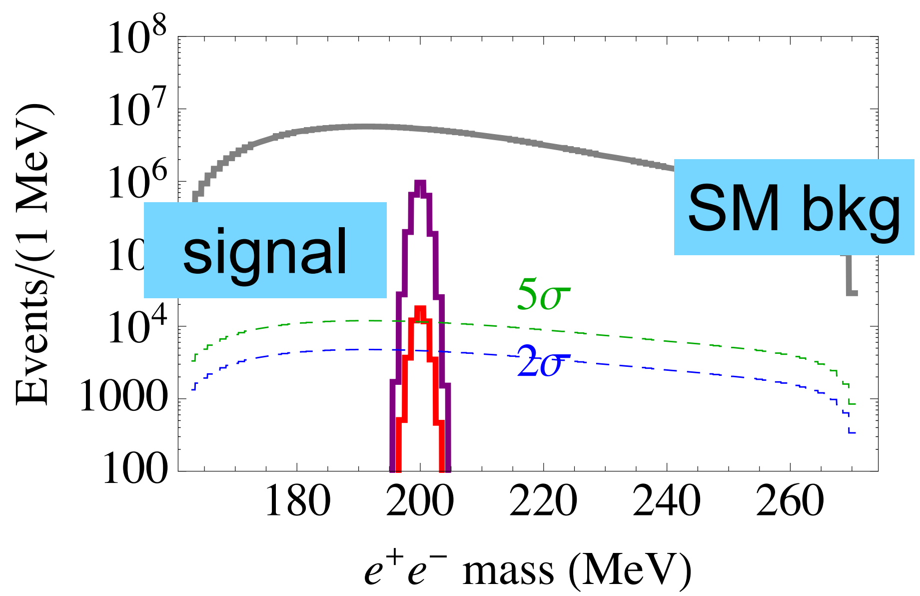
Dark Photon Bremsstrahlung

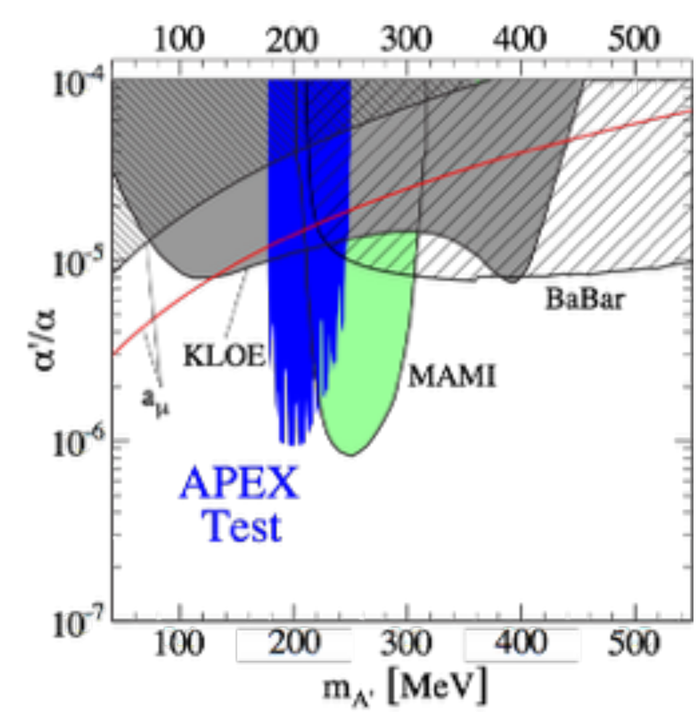




New Fixed target (Tantalium Z=73) experiment designed for direct Dark Photon production/detection.

Z' → e^+e^- narrow resonance search using High Resolution Spectrometer.





One of the Fastest-developing New fields

In 2009,
New experiments suggested by theorists

New Fixed-Target Experiments to Search for Dark Gauge Forces.
James D. Bjorken, Rouven Essig, Philip Schuster (SLAC), Natalia Toro (Stanford U., ITP). Jun 2009. 20 pp.
Published in **Phys.Rev. D80 (2009) 075018**
SLAC-PUB-13650, SU-ITP-09-22
DOI: 10.1103/PhysRevD.80.075018
e-Print: **arXiv:0906.0580 [hep-ph] PDF**
1. References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
2. Journal Server; ADS Abstract Service; SLAC Document Server

Detailed record - Cited by 193 records

In 2010,
APEX experiment proposal (JLab)

An Electron Fixed Target Experiment to Search for a New Vector Boson A' Decaying to e+e-.
Rouven Essig, Philip Schuster (SLAC), Natalia Toro (Stanford U., Phys. Dept.), Bogdan Wojtsekhowski (Jefferson Lab). Jan 2010. 19 pp.
Published in **JHEP 1102 (2011) 009**
SLAC-PUB-13882, SU-ITP-10-01
DOI: 10.1007/JHEP02(2011)009
e-Print: **arXiv:1001.2557 [hep-ph] PDF**
1. References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
2. Journal Server; ADS Abstract Service; SLAC Document Server

Detailed record - Cited by 61 records

In 2011,
First results published

Search for a New Gauge Boson in Electron-Nucleus Fixed-Target Scattering by the APEX Experiment.
APEX Collaboration (S. Abrahamyan (Yerevan Phys. Inst.) *et al.*). Aug 2011. 5 pp.
Published in **Phys.Rev.Lett. 107 (2011) 191804**
JLAB-PHY-11-1406-SLAC-PUB-14491
DOI: 10.1103/PhysRevLett.107.191804
e-Print: **arXiv:1108.2750 [hep-ex] PDF**
1. References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
2. Journal Server; ADS Abstract Service; JLab Document Server

Detailed record - Cited by 76 records

Amazing speed for a modern New Physics search experiment!
(using existing Low-Energy facility built for nuclear/hadronic physics)

"Dark Z" effects on Weak Neutral Current phenomenology

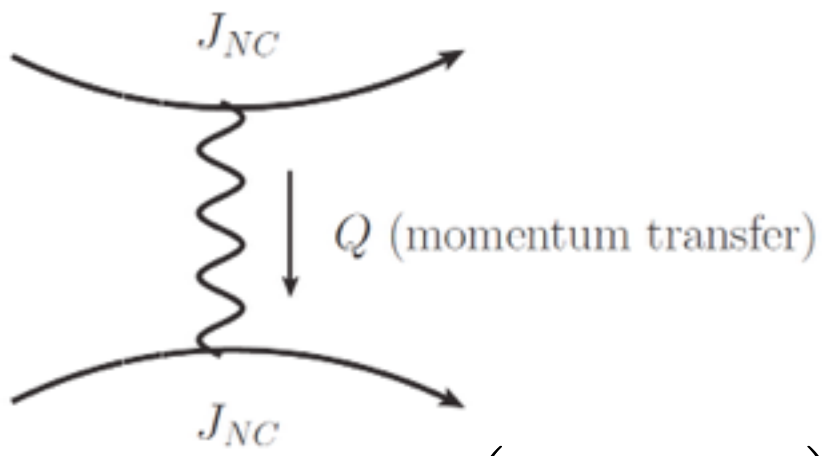
[Davoudiasl, LEE, Marciano (2012)]

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

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

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

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



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

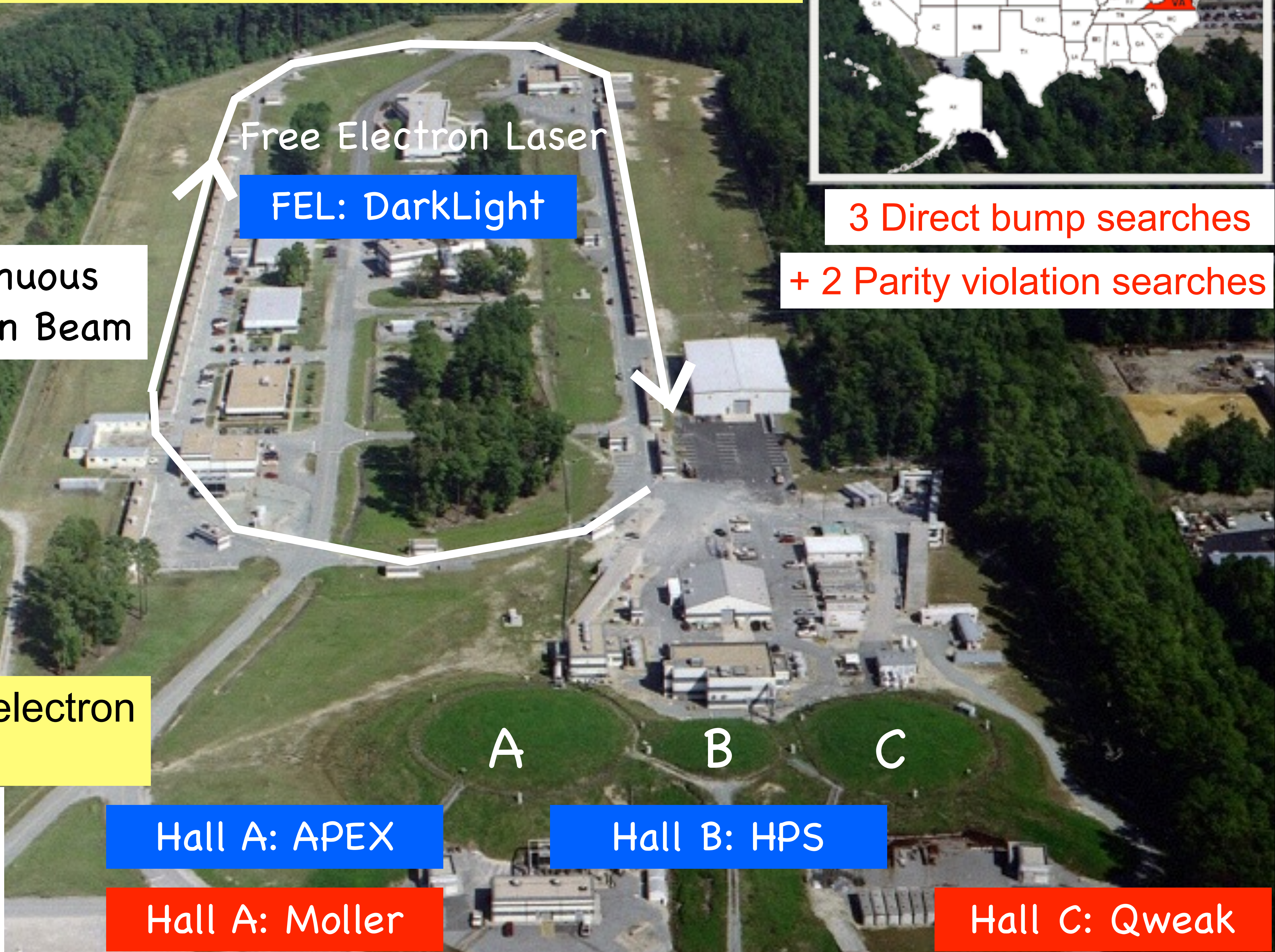
- Sensitive only to Low-Q^2 (momentum transfer). (Effect negligible for Q^2 >> mZ'^{2})
- For typical parameter values, $\Delta\sin^2\theta_W$ (Weinberg angle shift) is more sensitive.

"Low-Q^2 Parity-Violating experiments (measuring Weinberg angle)" seem to be a right place to look.

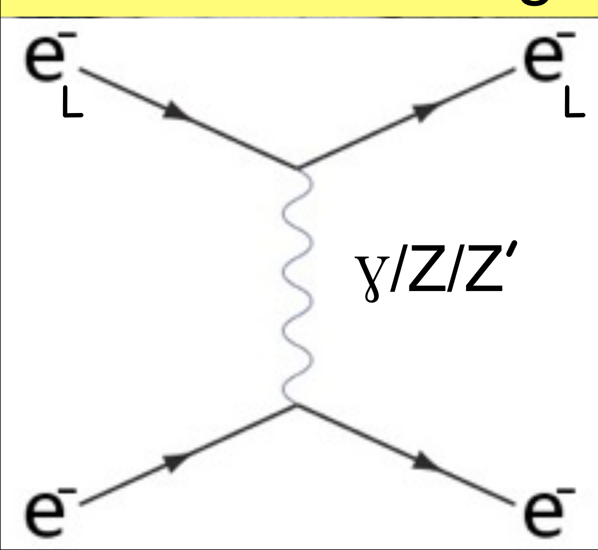
Dark Z effectively changes the weak neutral current scattering (including parity), but only for the "Low" momentum transfer (Q).

Dark Force searches at Jefferson Lab

Nuclear/Hadronic Physics Lab



Low-Q^2 polarized electron scatterings



"Dark Z" searches

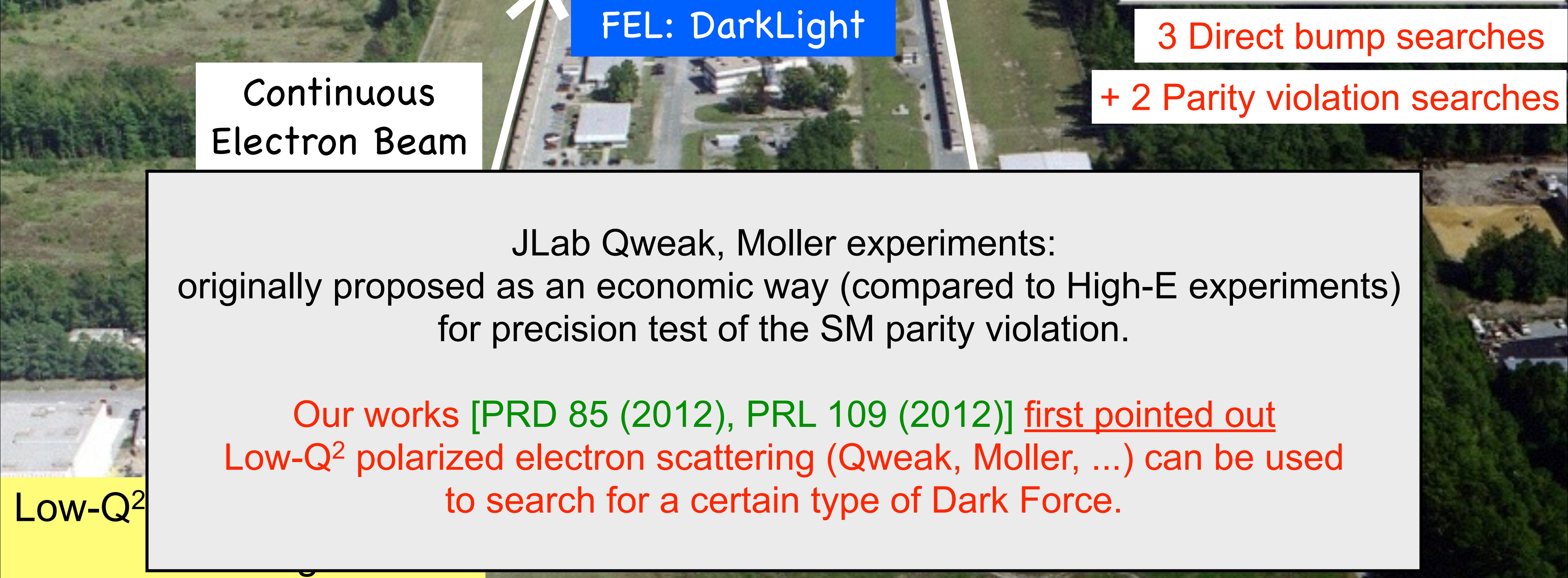
(2 more experiments relevant to Dark Force searches)

Dark Force searches at Jefferson Lab

Nuclear/Hadronic Physics Lab

3 Direct bump searches

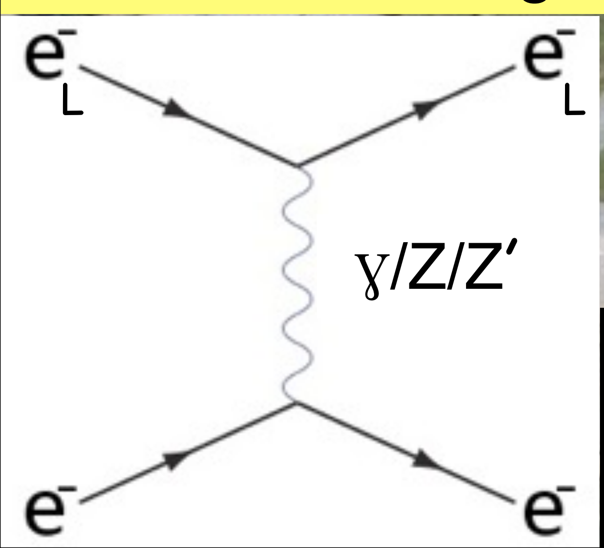
+ 2 Parity violation searches



JLab Qweak, Moller experiments:
originally proposed as an economic way (compared to High-E experiments) for precision test of the SM parity violation.

Our works [PRD 85 (2012), PRL 109 (2012)] first pointed out Low-Q^2 polarized electron scattering (Qweak, Moller, ...) can be used to search for a certain type of Dark Force.

Low-Q^2



"Dark Z" searches

(2 more experiments relevant to Dark Force searches)

Major Item of Equipment proposal of JLab Moller experiment (2013)

would be the first to reach the required level), such measurements probe S and T well below ± 0.1. They are about twice as sensitive to $X(Q^2)$ as S, and probe $m_{...}$ ~ 2 TeV.

2.5 The Dark Z'

Some recent BSM models have relatively light new degrees of freedom which cannot be incorporated into the contact interaction formalism. Absence of such BSM-induced deviations in high energy measurements implies that such light particles must couple very weakly. In certain regions of parameter space, low Q^2 measurements can have unique or enhanced sensitivity. In this context, the possibility of a "dark" Z boson [33, 34], denoted as Z_d and of mass m_{Z_d}, stemming from a spontaneously broken $U(1)_d$ gauge symmetry associated with a secluded "dark" particle sector was recently investigated. The Z_d boson can couple to SM particles through a combination of kinetic and mass mixing with photon and the Z^0-boson, with couplings ε and $\varepsilon_Z = \frac{m_{Z_d}}{m_Z}\delta$ respectively.

With our work (Dark Z), Moller (Low-E parity test) argued their "unique sensitivity" to a certain kind of New Physics.

[Davoudiasl, LEE, Marciano]

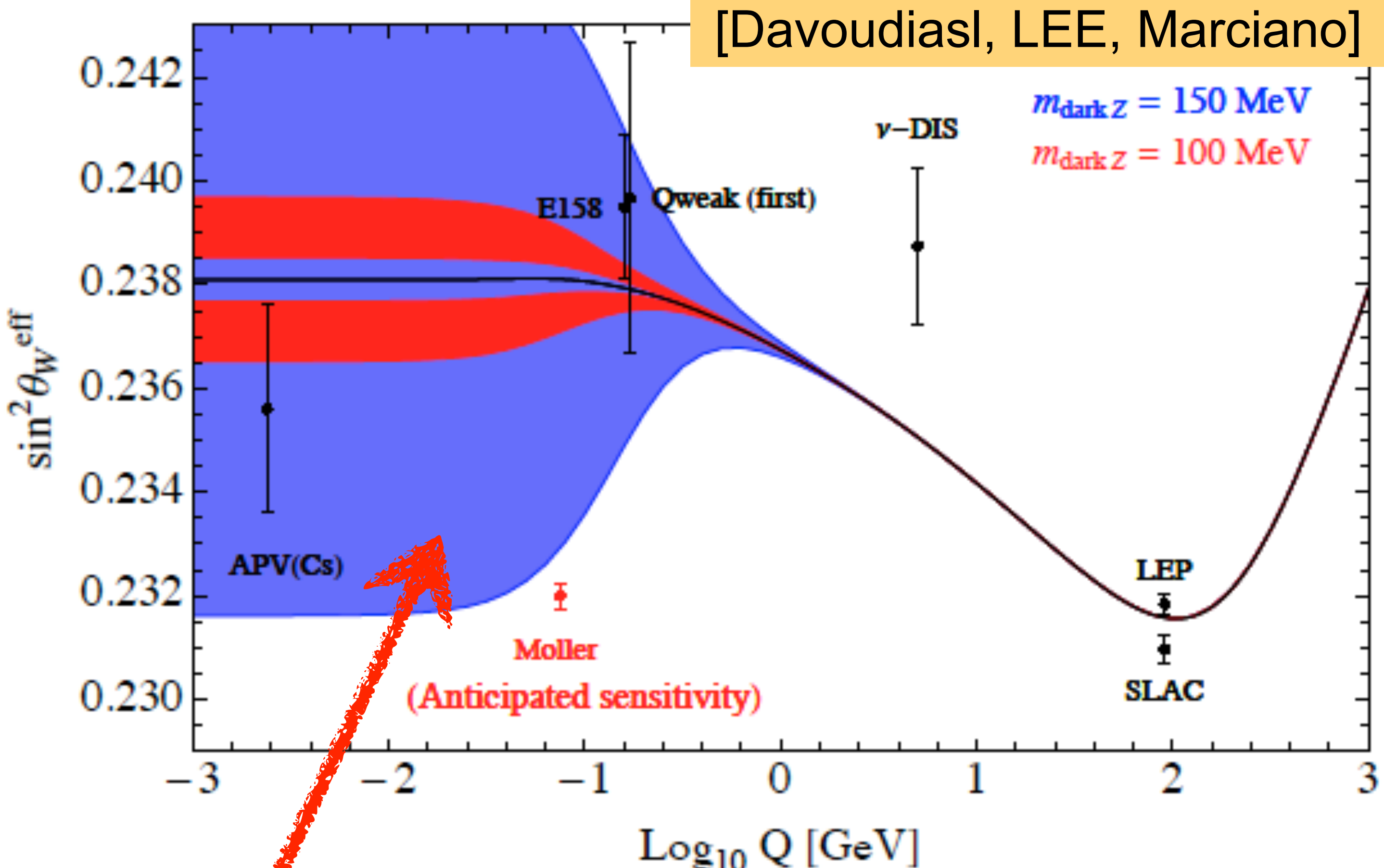


Figure 6: *The ... a light Z_d to ... decay constr... The proposed ... with an arbitrary central value.*

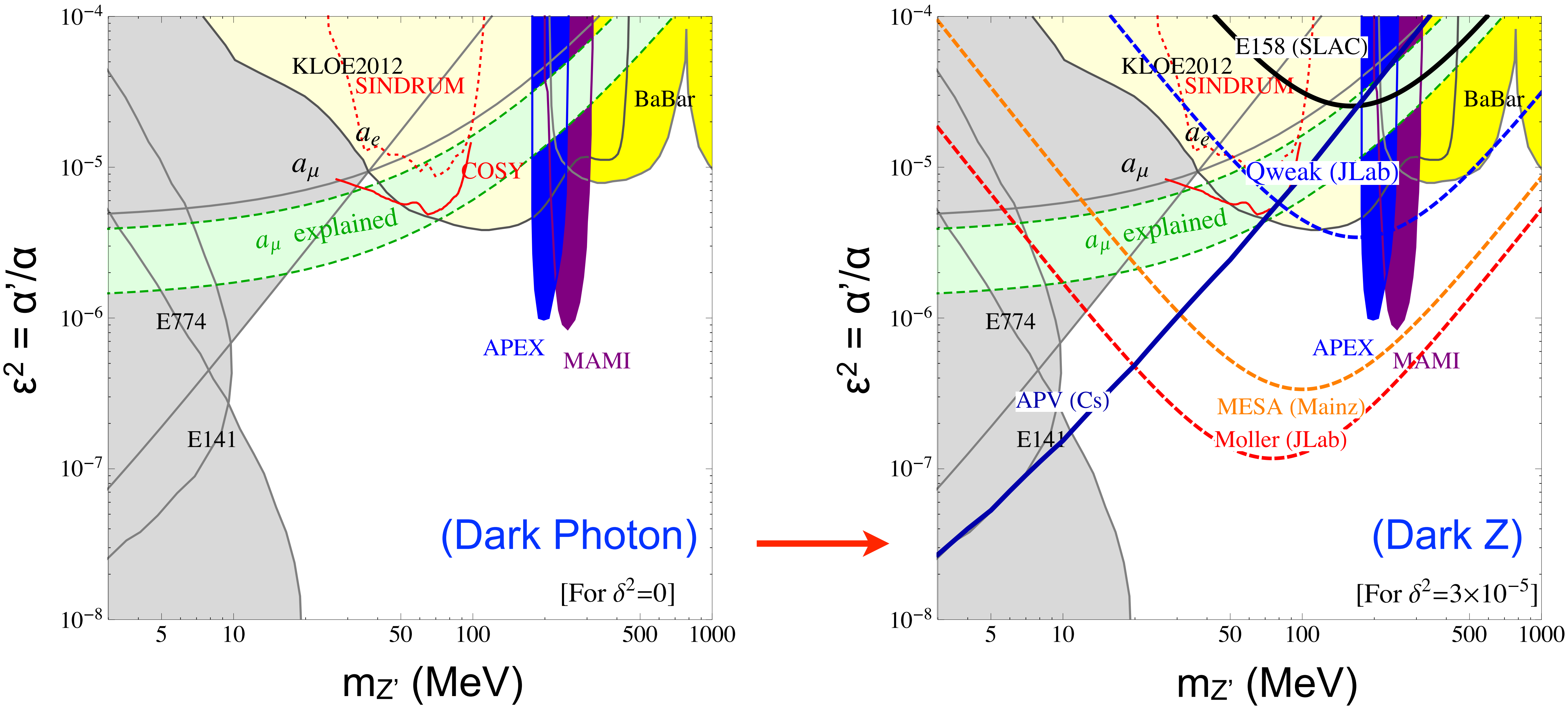
Deviations from the SM prediction (due to Dark Z) can appear only in the Low-E experiments.

...of mass mixing ($\delta \neq 0$), a new source of "dark" parity violation arises [33] such that it ... on other precision electroweak observables at high energy, but is quite discernable at ...ift in the weak mixing angle [34]:

$$\Delta \sin^2\theta_W(Q^2) \simeq -0.42\varepsilon\delta\frac{m_Z}{m_{Z_d}}\left(\frac{m_{Z_d}^2}{Q^2+m_{Z_d}^2}\right). \quad (10)$$

...small (1.5σ) APV deviation, $\Delta\sin^2\theta_W(0) \simeq -0.003(2)$ suggests $\delta \simeq \pm 1 - 4\times 10^{-3}$ ...esting region that can be explored by future APV or A_{PV} measurements. ...this to the discussion in the previous section by inspecting the sensitivity of $X(Q^2)$ ...$\theta_W)/\alpha$) to $m_{Z_d} \sim 20-50$ MeV. APV measurements where Q^2 is naturally small ...cellent probes because they do not have the $m_{Z_d}^2/(Q^2+m_{Z_d}^2)$ suppression. However, ...ctionally far more sensitive to $X(Q^2)$. For example, the $-0.9\pm 0.6\%$ shift in the APV ...l to a 27% shift in Q_W^e if measured at the same Q. For $m_{Z_d} \sim 50$ MeV, the MOLLER ...MeV, would see an 8.4% shift ($\sim 3.7\sigma$). ...been pointed out [41] that the constraints in Eqn. 9 are considerably weakened if the ...other dark matter particles, rendering the branching ratio $Z_d \to e^+e^- \ll 1$. In such a ...nstraints on Z_d masses in the range between 50 and 200 MeV would come from neutral ...ents (sensitive to $X(Q^2)$) and rare kaon decay experiments ($K\to\pi+X$). ...ible deviations to $\sin^2\theta_W(Q)$ for Z_d mass of 100 and 150 MeV, under the ...s the $(g-2)_\mu$ anomaly, but taking into account constraints from the K decay ...n be seen that the proposed MOLLER A_{PV} measurement has significant ...under this scenario.

Dark Z Searches



Parameter space is extended from 2D to 3D.

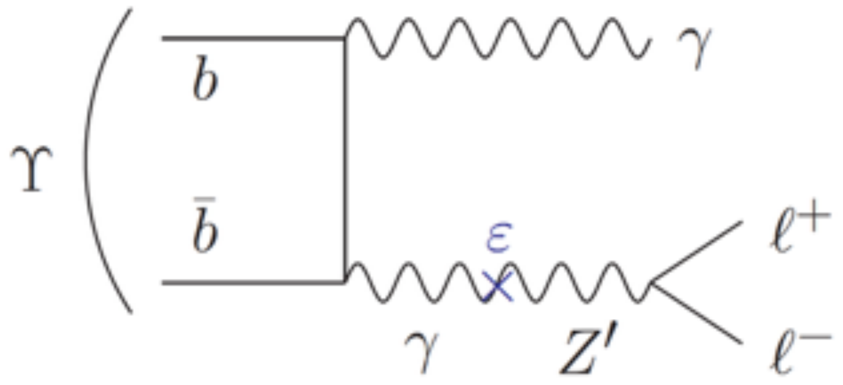
Parameter space is extended by another axis for a new parameter (for Z-Z' mixing).
The new axis is explored by various current/future Low-energy parity violating experiments.

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)

Meson decays into Light Z’

Typical Dark Force searches in meson decays are performed in flavor-conserving ones [with quarkonium (qqbar meson)].

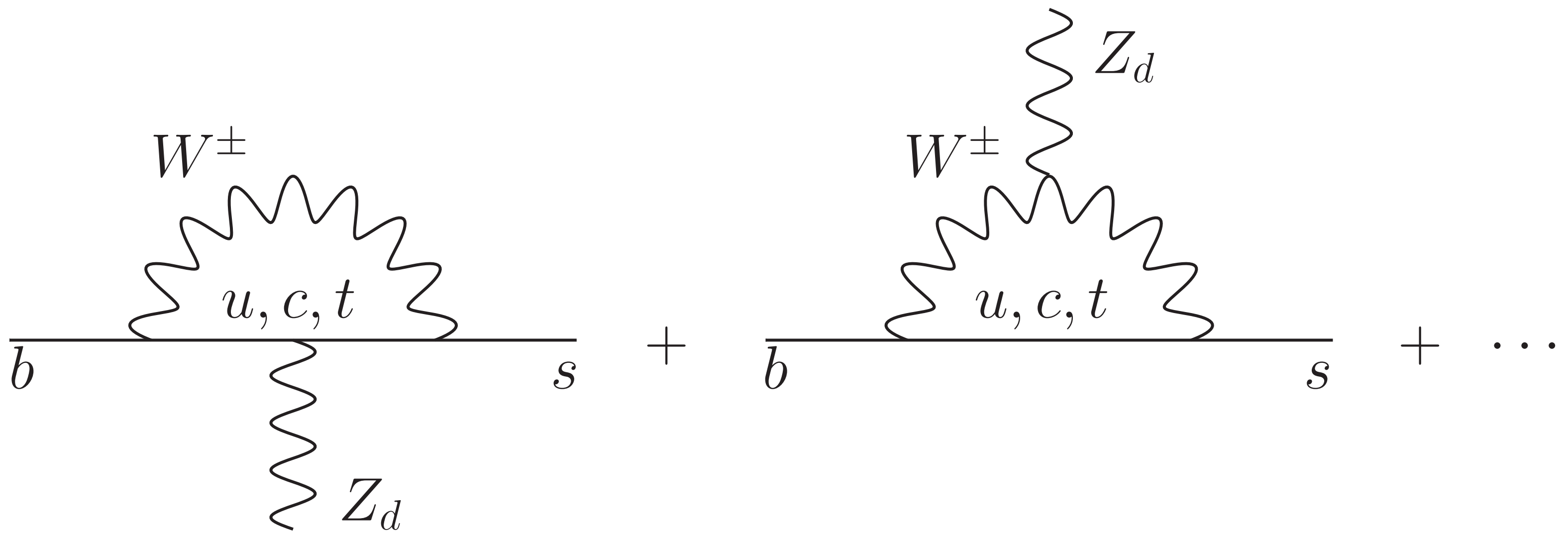


Υ(3S) → γ Z’ → γ + dilepton-resonance

Flavor-conserving meson decays
Υ(bb) → γ Z’ (BaBar), ϕ(ss) → η Z’ (KLOE), π(dd) → γ Z’ (COSY)
: Important searches for the Dark Force

Flavor-changing Meson decays into Light Z'
(B → K Z', K → π Z')

Flavor-changing decays:
(B → K Z', K → π Z')



- Dark Photon:
(loop-suppression)×(small ε) → rather small Branching ratio.

- Dark Z: [Davoudiasl, LEE, Marciano (2012)]
(loop-suppression)×(small ε_Z)×(enhancement factor) → **much bigger Branching ratio !**
for boosted Z'

(enhancement factor) = E / mZ' , at amplitude level, applies to the longitudinally polarized Z', which happens when mZ' << mB, mK.
Longitudinally polarized Z' behaves as an "axion" (for production), which couples strongly to heavy particles (Top-quark). [Goldstone Boson Equivalence Theorem]

Flavor-changing Meson decays into Light Z'
($B \to K Z'$, $K \to \pi Z'$)

For boosted Z' (ex: mZ' = 1 GeV << mB),

[Dark Photon] $\mathrm{BR}(B \to K Z') \simeq 6 \times 10^{-7}\, \varepsilon^2$

[Dark Z] $\mathrm{BR}(B \to K Z')|_{\mathrm{longitudinal}} \simeq 0.1\, \delta^2$ $\left(\varepsilon_Z = \frac{m_{Z'}}{m_Z}\delta\right)$

(typically, $\varepsilon^2 < 10^{-5}$, $\delta^2 < 10^{-4}$)

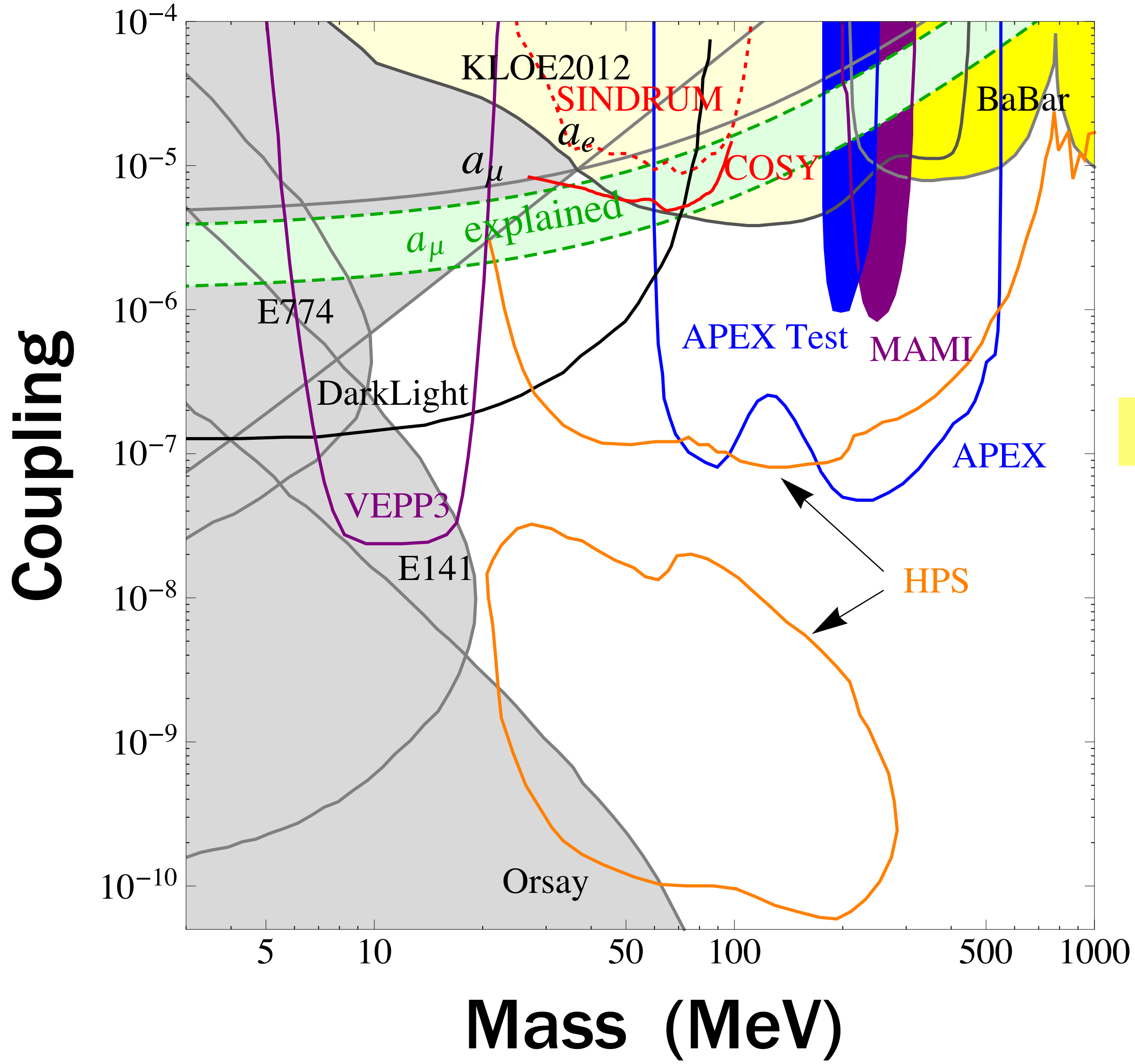
(No GBET enhancement in Dark Photon because its longitudinal mode does not contain SM Higgs. → Difficult to expect realistic level of observation.)

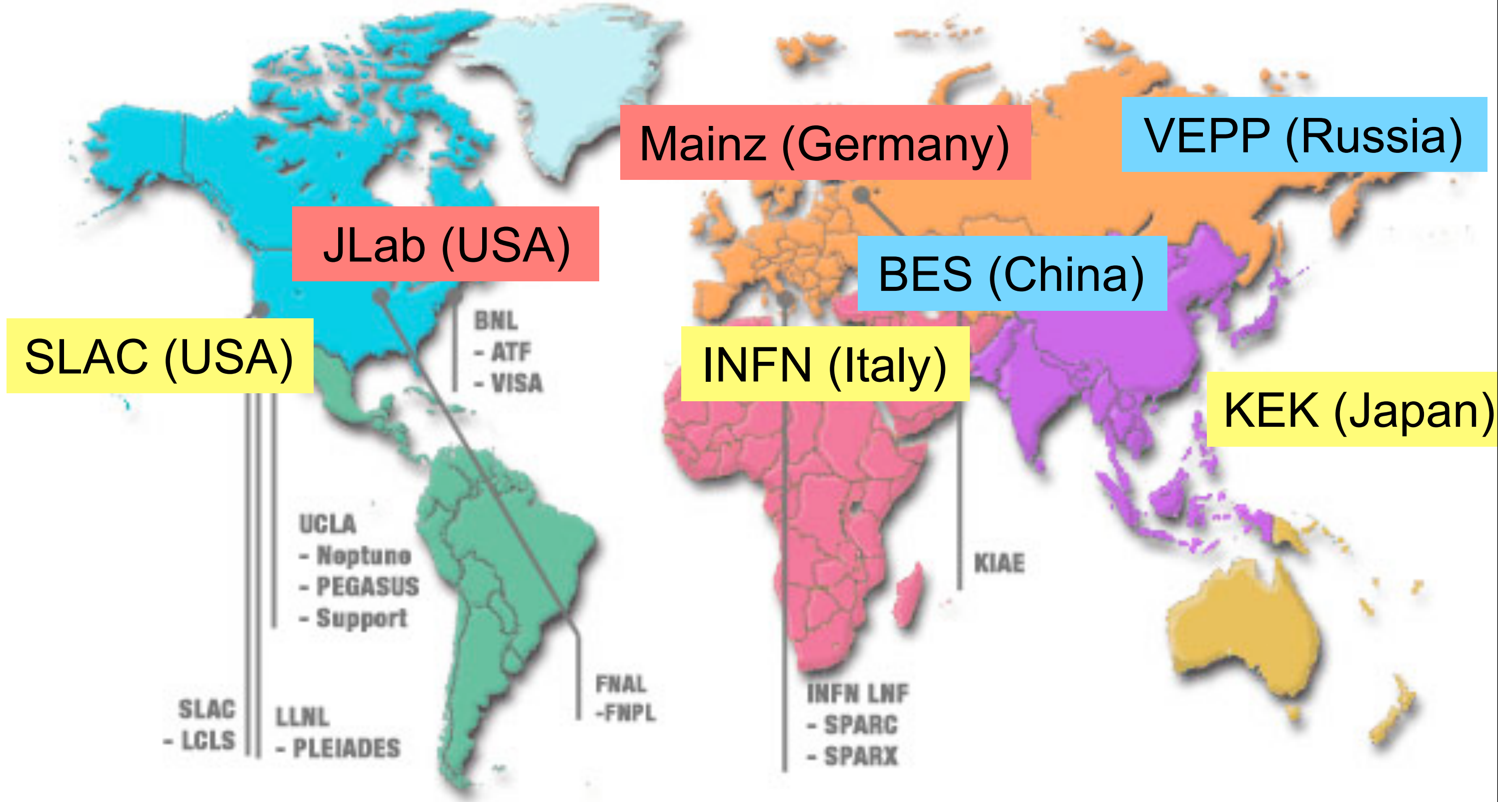
(Unlike Dark Photon) Dark Z predicts potentially Large Branching ratios.

→ **Fine bin search [$Z' \to \ell^+\ell^-$ can give a bump] in "flavor-changing" meson decays have a good potential to discover the Z' ($B \to K Z'$, $K \to \pi Z'$).**

Enhancement from Goldstone boson equivalence theorem allows big effects in flavor-changing meson decays for Dark Z.

Dark Force searches at Low-E Labs





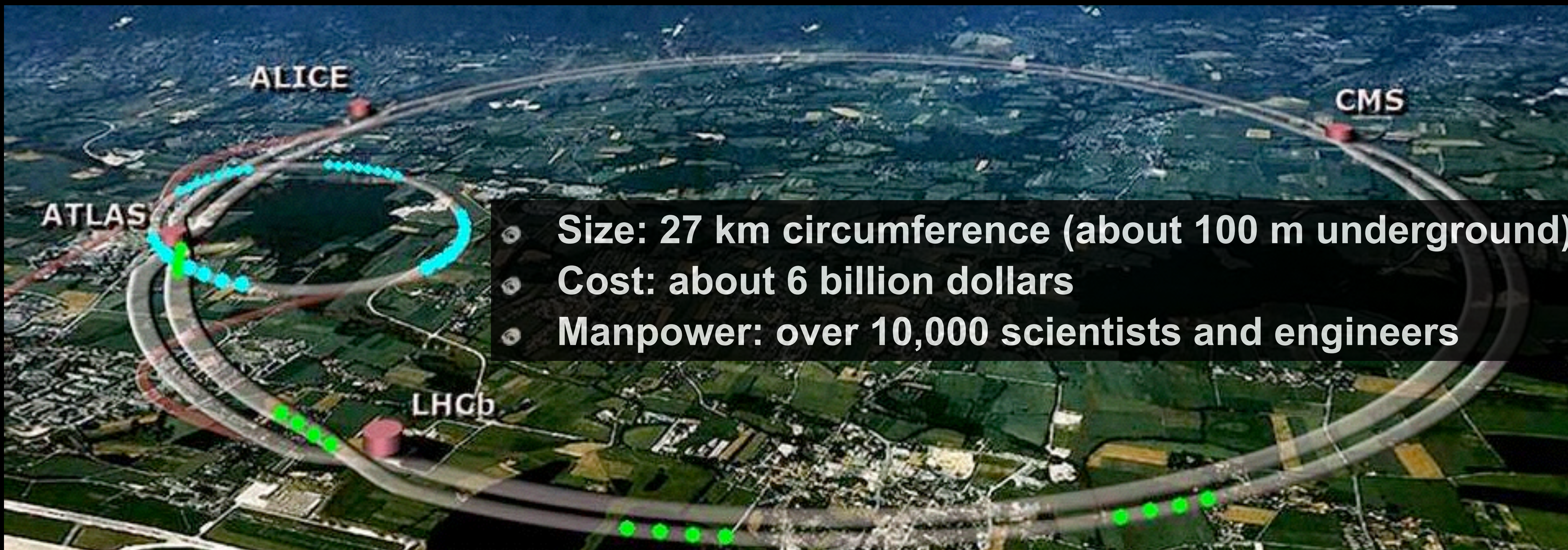
1. Anomalous magnetic moments
2. Beam-dump experiments
3. Meson decays [Y(bb) → γ Z', ...]
4. Fixed target experiments (Bremsstrahlung)
5. Polarized electron scattering
6. Flavor-changing meson decays [B → K Z', ...]
...

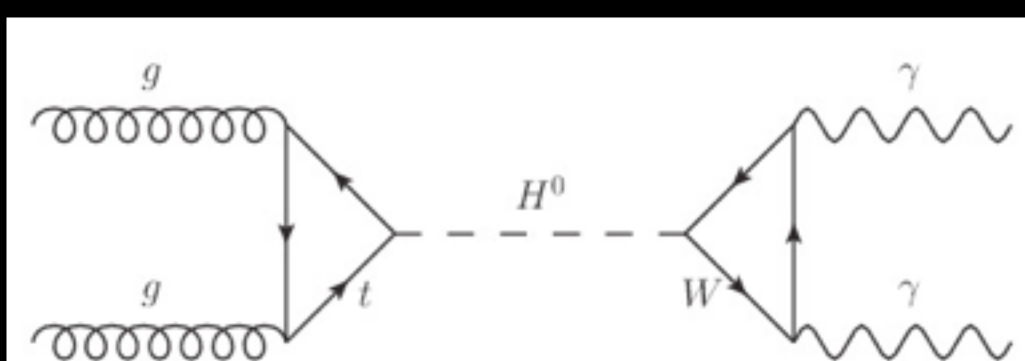
Dark Force: one of rare New physics that can be searched for in the Low-E experiments. *(Similar to Axion physics.)*

With attentions from Low-energy Labs, **Dark Force search is becoming a big industry.**

Implications for the LHC
(connecting Low-E & High-E physics)

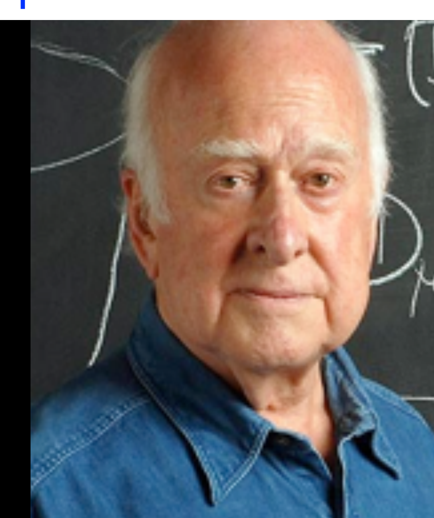
Dark Force at Large Hadron Collider (LHC)?
in Geneva, Switzerland





2013 Nobel prize winners

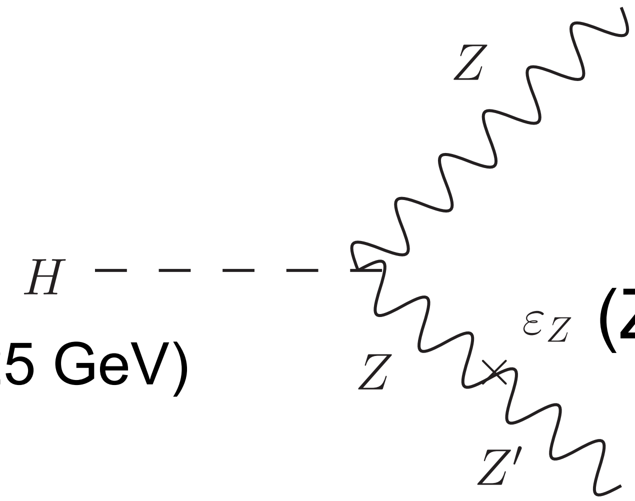

F. Englert (Belgium)


P. Higgs (UK)

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

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

Higgs-to-Dark decay at the LHC

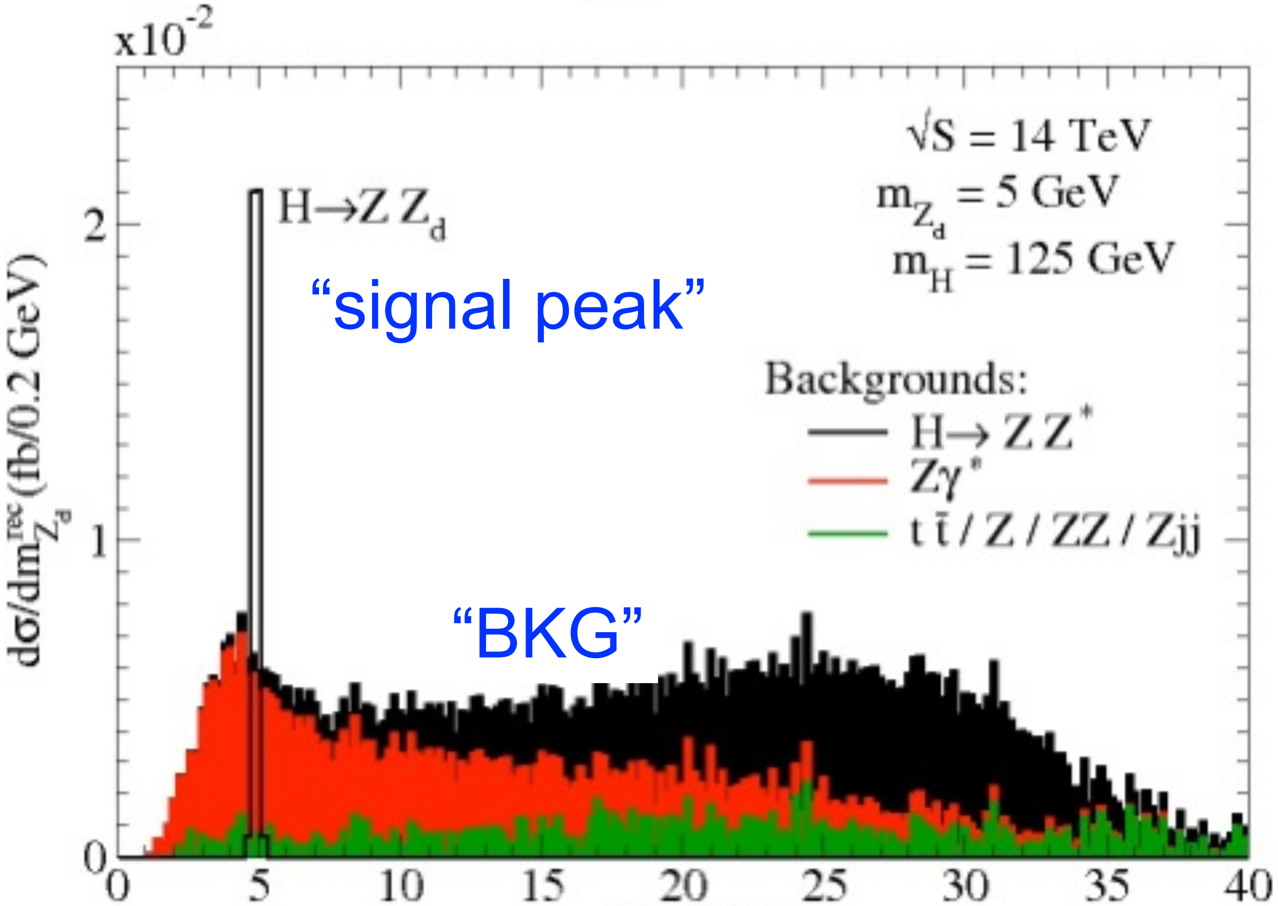


(125 GeV)

(Z-Z' mixing)

[Higgs ➞ Z Z'   in Dark Z model]

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



"signal peak"

"BKG"

$m_{\ell\ell}$ (GeV)

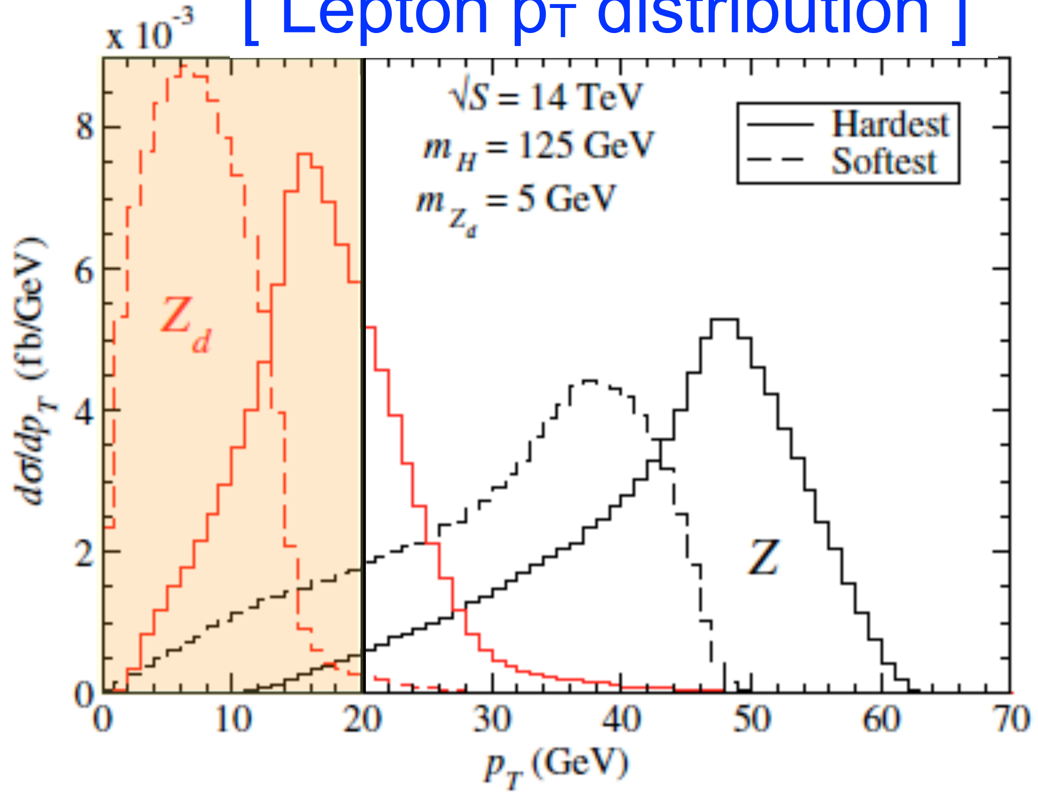
[Reconstructed Z' (dilepton) events after some cuts]

- Signal: H ➞ Z Z' ➞ 4-leptons
- Major BKG: Z ɣ*, H ➞ Z Z*

The LHC can search for Dark Force too (even without producing Dark Matter).

Higgs-to-Dark decay at the LHC

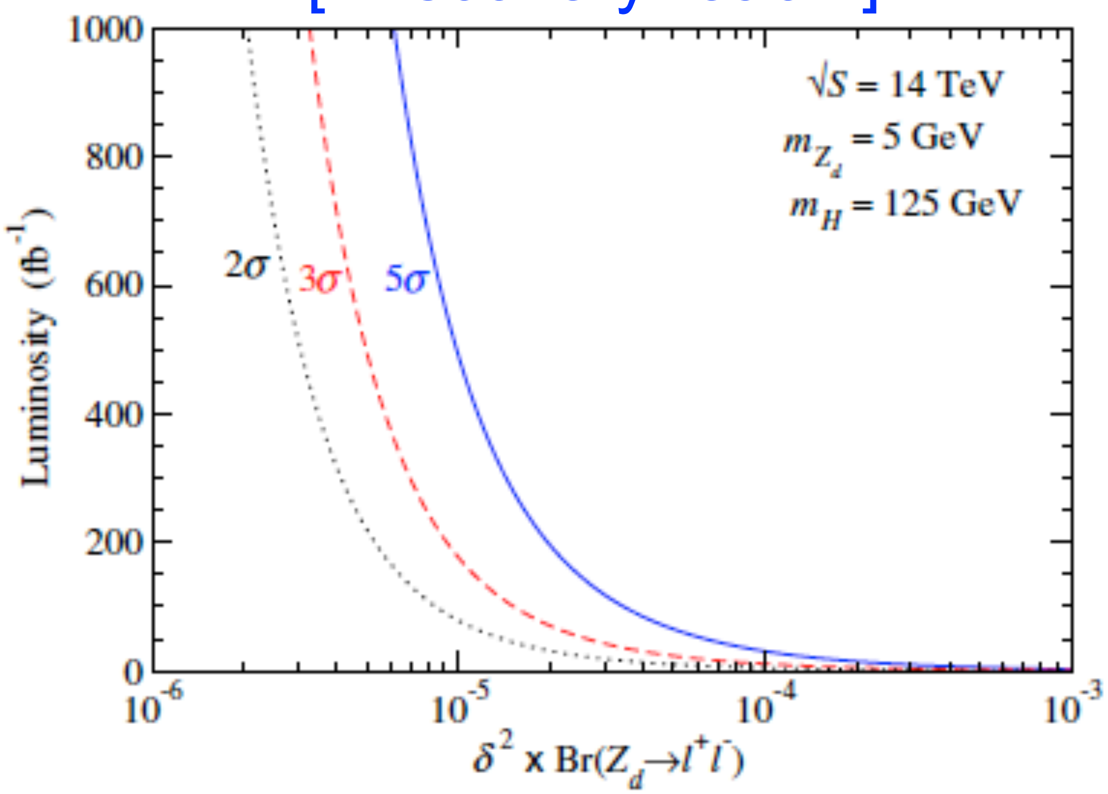
[Lepton p_T distribution]



Typical searches may miss our signal.
(Lepton p_T > 20 GeV, for SM Higgs search $H \to Z Z^* \to 4L$ to avoid $Z \gamma^*$ BKG.)

We suggest lower p_T > 4 GeV,
with invariant mass windows (4L-resonance at mH, 2L-resonance at mZ, 2L-resonance at mZ'.)

[Discovery reach]



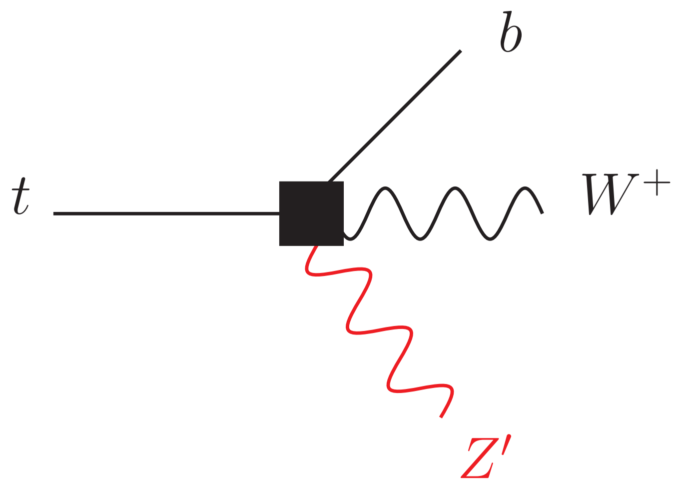
Signal is not very large [$Br(H \to Z Z') \approx 20\ \delta^2$],
but mass windows cut out most BKG
(S/B ~ 1.5).

Luminosity ≈ (a few) × 100 fb^{-1} can make 5σ discovery (LHC 14 TeV).

[~ a few years of time]

Top-to-Dark decay at the LHC

[K Kong, LEE, M Park (2014)]

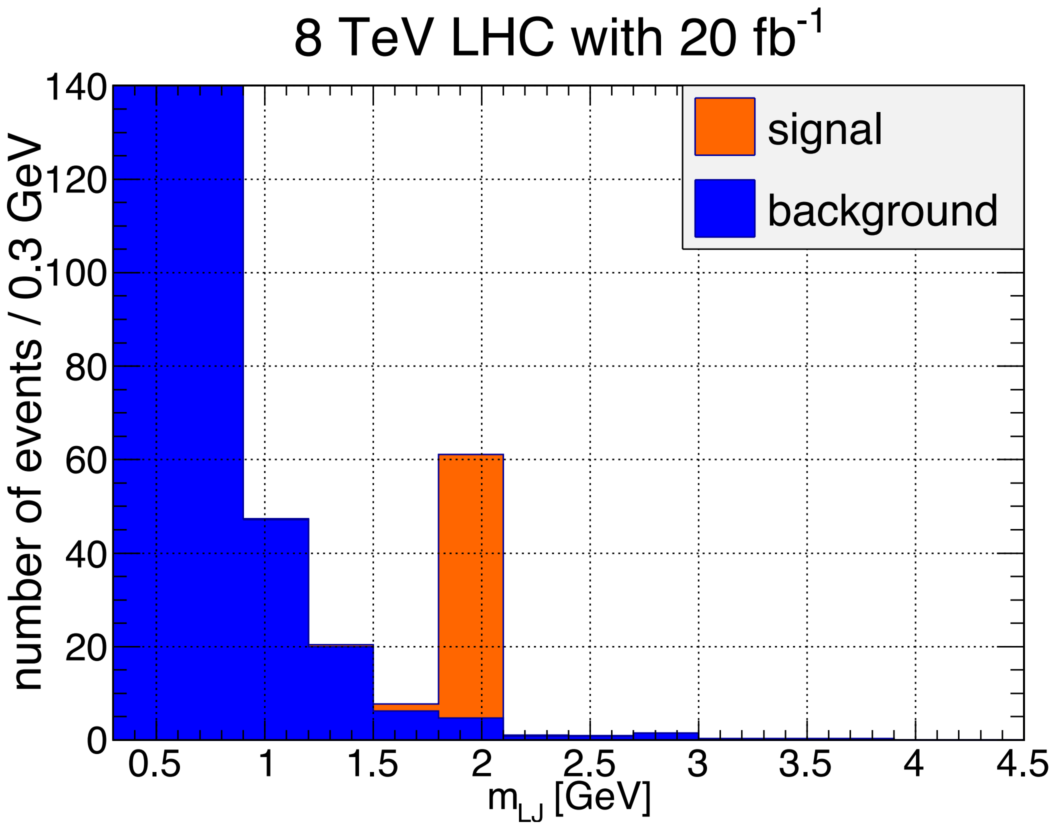


Good chance of New physics in Top (173 GeV) decay.
[Current top decay BR have O(10%) uncertainty.]

Top may decay into Z' (through a light charged Higgs)
$t \to bH^+ \to bW + Z$'s (on-shell decay)
: dominant top decay products (bW) + elusive Z's
[easily mis-identifiable as $t \to bW$]

(Ex) With Lepton-jet analysis
for $BR(t \to bW + Z') = 10^{-3}$ and
$BR(Z' \to \ell\ \ell) = 0.2$

We suggest re-analysis of the existing 8 TeV t tbar data ($L_{tot} = 20\ fb^{-1}$) may give you a discovery (at 15σ level) now!

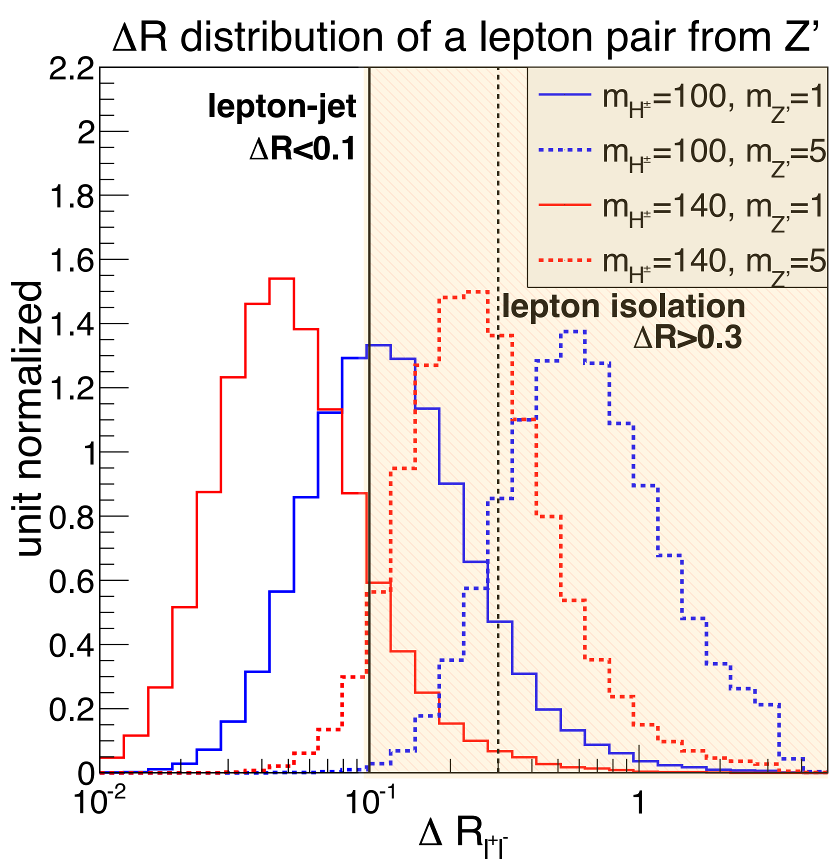


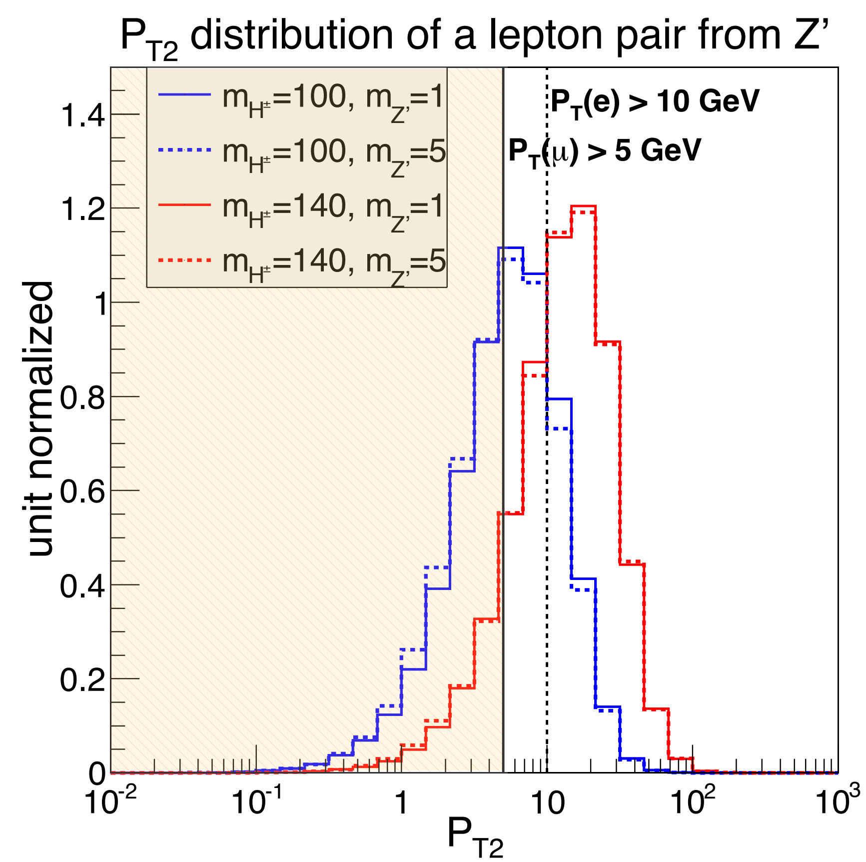
Lepton-jet

Lepton-jet (highly collimated leptons) is a good object for analyzing highly boosted Z' decaying into a lepton pair [Arkani-Hamed, Weiner (2008); Cheung, et al (2009)].

We take

1. At least 2 same flavor leptons (e, μ) with $p_T > 10$ (e), 5 (μ) [in a cone of $\Delta R < 0.1$]
2. Hadronic and leptonic isolation of $p_T < 3$ [in $0.1 < \Delta R < 0.3$]
3. $|mLJ - mZ'| < 0.2 \times mZ'$

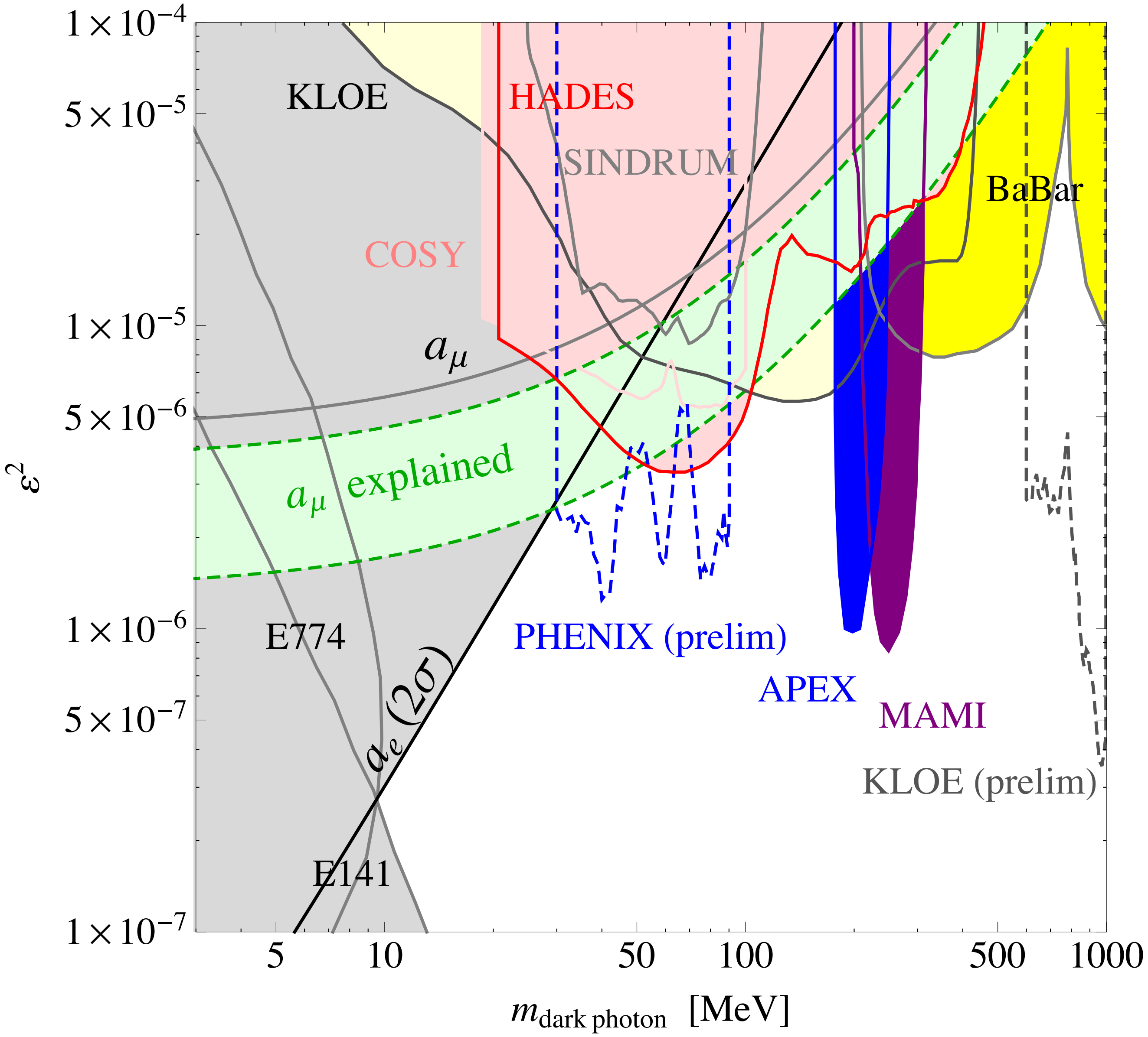




Lepton-jet tagging efficiency: Higher for lighter Z', heavier $H^\pm$.
(Ex) 45% [mZ' = 1 GeV, $mH^\pm$ = 140 GeV], 0.03% [mZ' = 5 GeV, $mH^\pm$ = 100 GeV].

Recent Developments
(Variants)

Invisibly-decaying Dark Photon



[Most up-to-dated constraints on Dark Photon parameter space (HADES, PHENIX, KLOE, …)]

Whole green band (muon g-2 favored) is almost ruled out !

mZ' > 2 m_{DM}

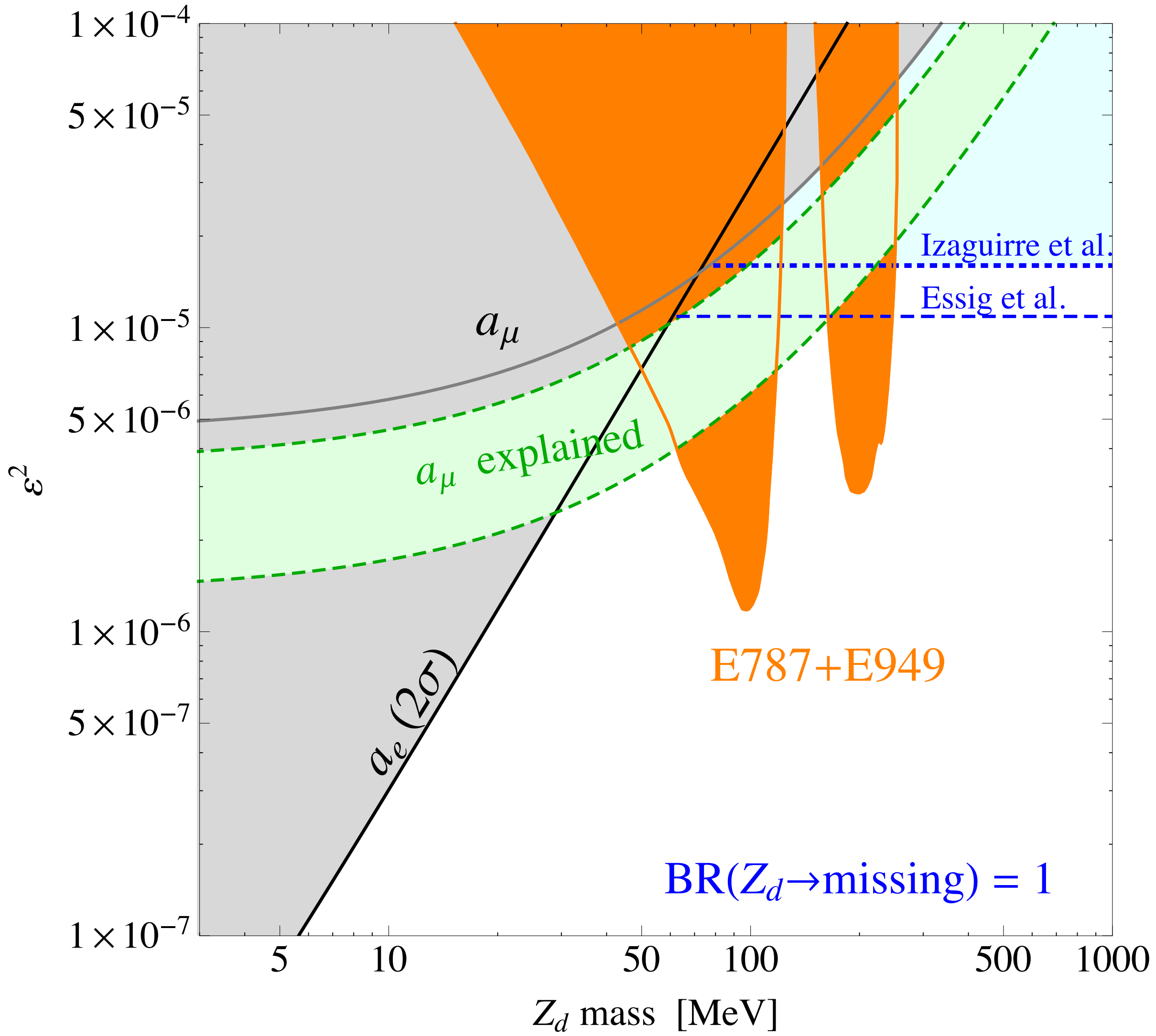
What if the Dark force carrier Z' decays into Light DM (LDM) dominantly?

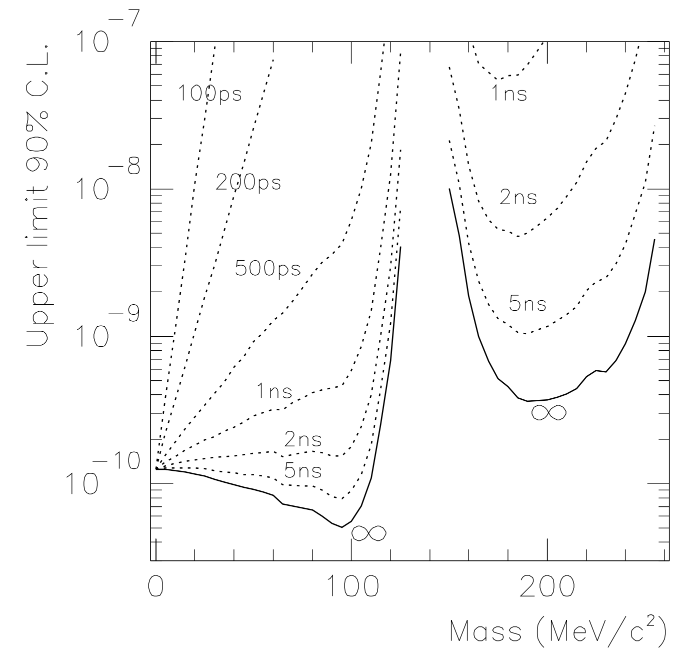
(far from original motivation, but intriguing direction)

It can save the Dark Force solution to the muon g-2, but how do we test it?

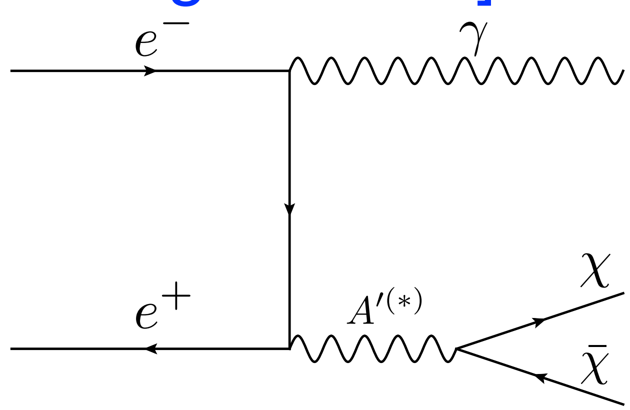
(Partly because of this,) Invisibly-decaying Z' is one of the very recent focuses.

Invisibly-decaying Dark Photon





[BNL "K → π + nothing" search]

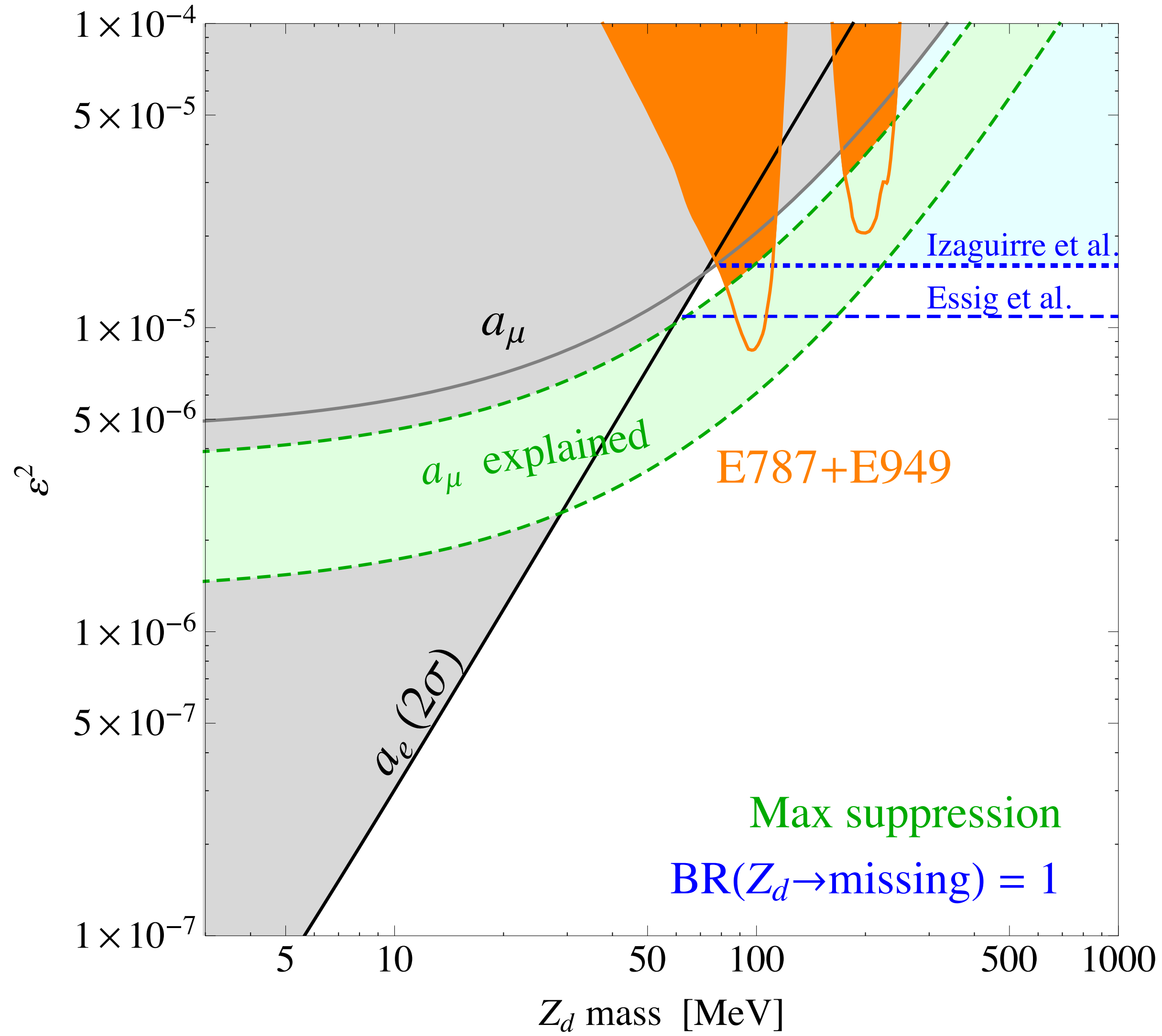


[e+e- → γ + nothing]

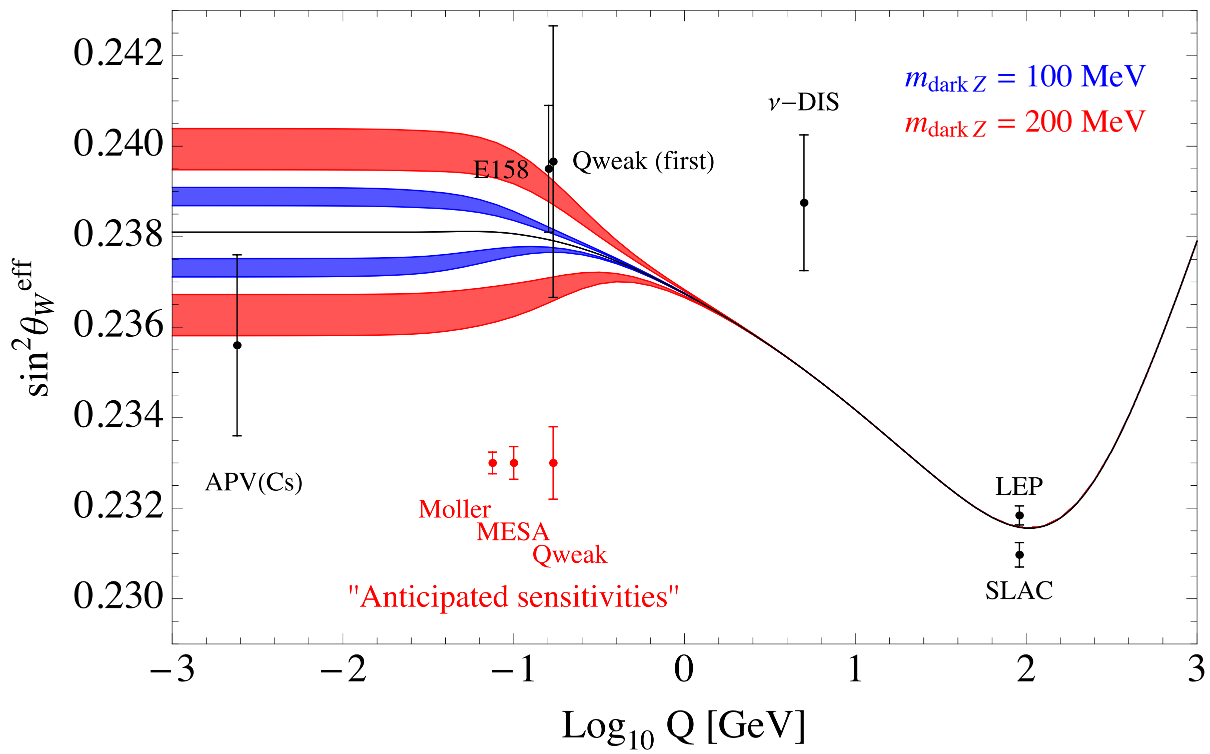
Current constraints on invisibly-decaying Z' come from
(i) BNL "K → π + nothing" search results
(ii) BABAR "e+e- → γ + nothing" search results

Large part of the green band is constrained again even for the invisibly-decaying Z'.

Invisibly-decaying Dark Z boson



[Davoudiasl, LEE, Marciano (2014)]



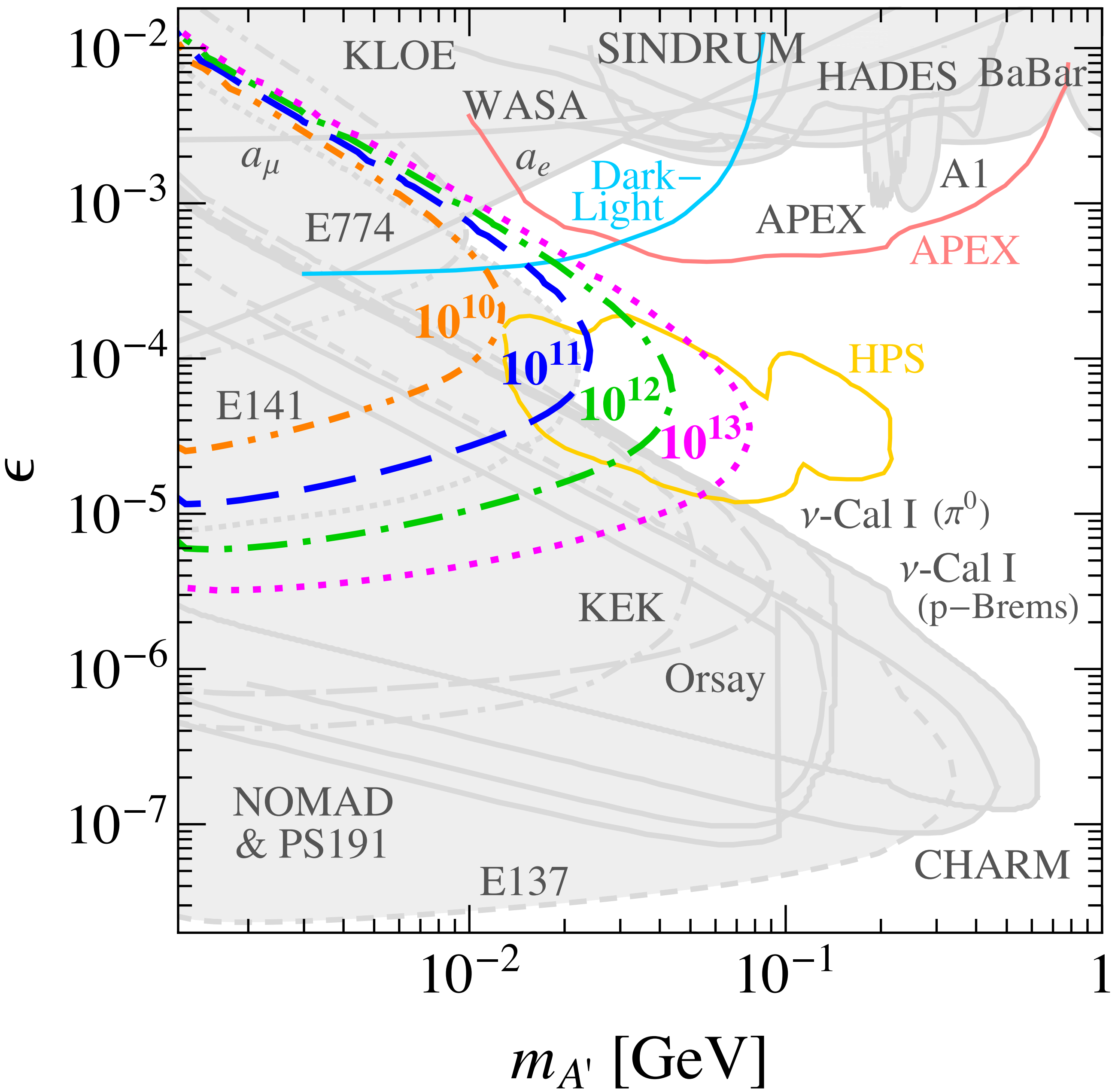
$$\mathcal{L}_{\text{int}} = -\left[\varepsilon\, e J^{\mu}_{em} + \varepsilon_Z\, (g/\cos\theta_W) J^{\mu}_{NC}\right] Z'_{\mu}$$

In Dark Z model, because of the additional term (ε_Z term), there can be a difference. For example, “K → π + nothing” constraints can become much weaker.

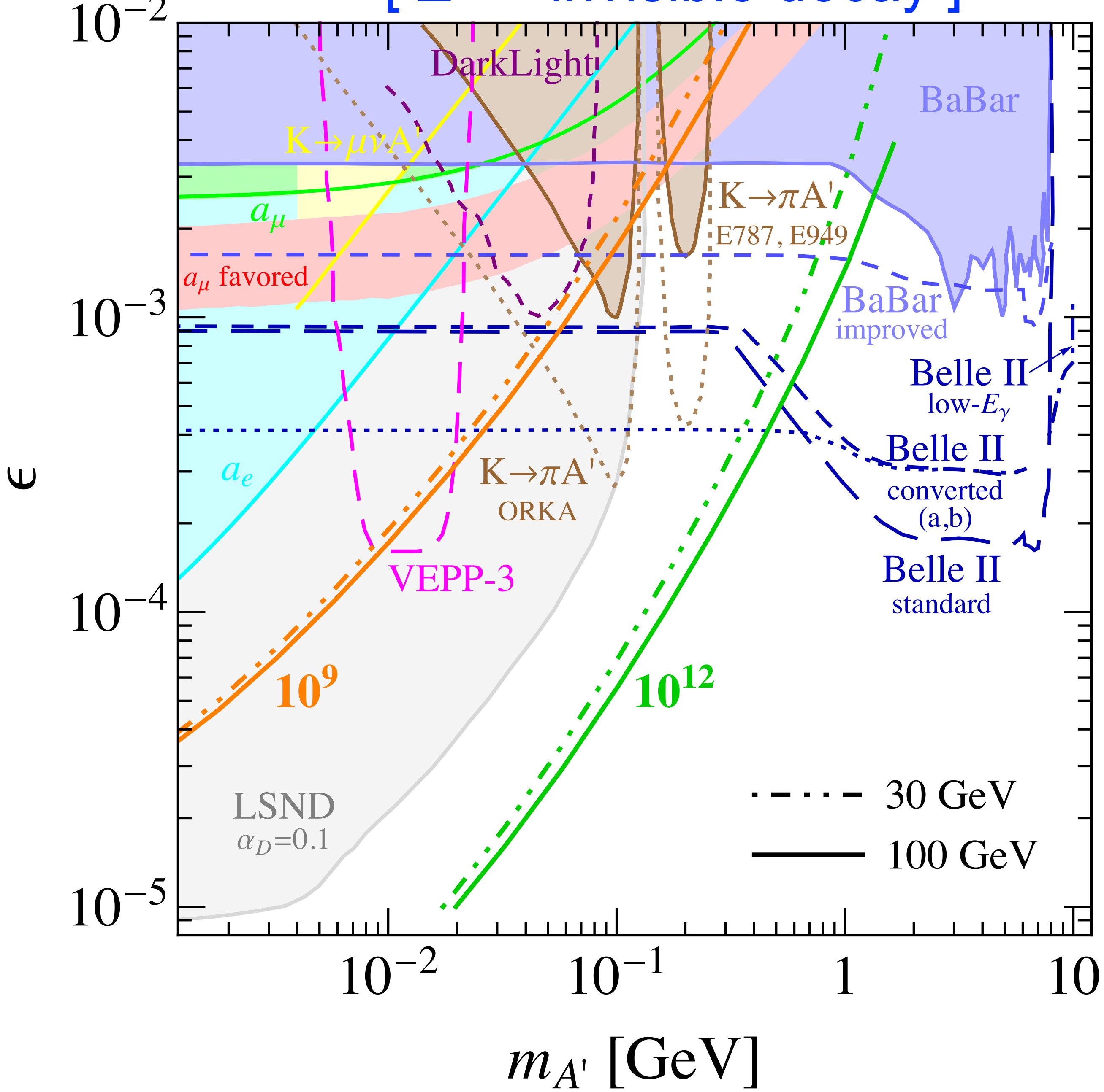
Low-E parity test (Moller, Qweak, …) is excellent for the invisibly-decaying Z’ as well, as is independent of Z’ decay BR.

Recently proposed experiments (including SPS)

[Z’ → e^+e^- decay]



[Z’ → invisible decay]



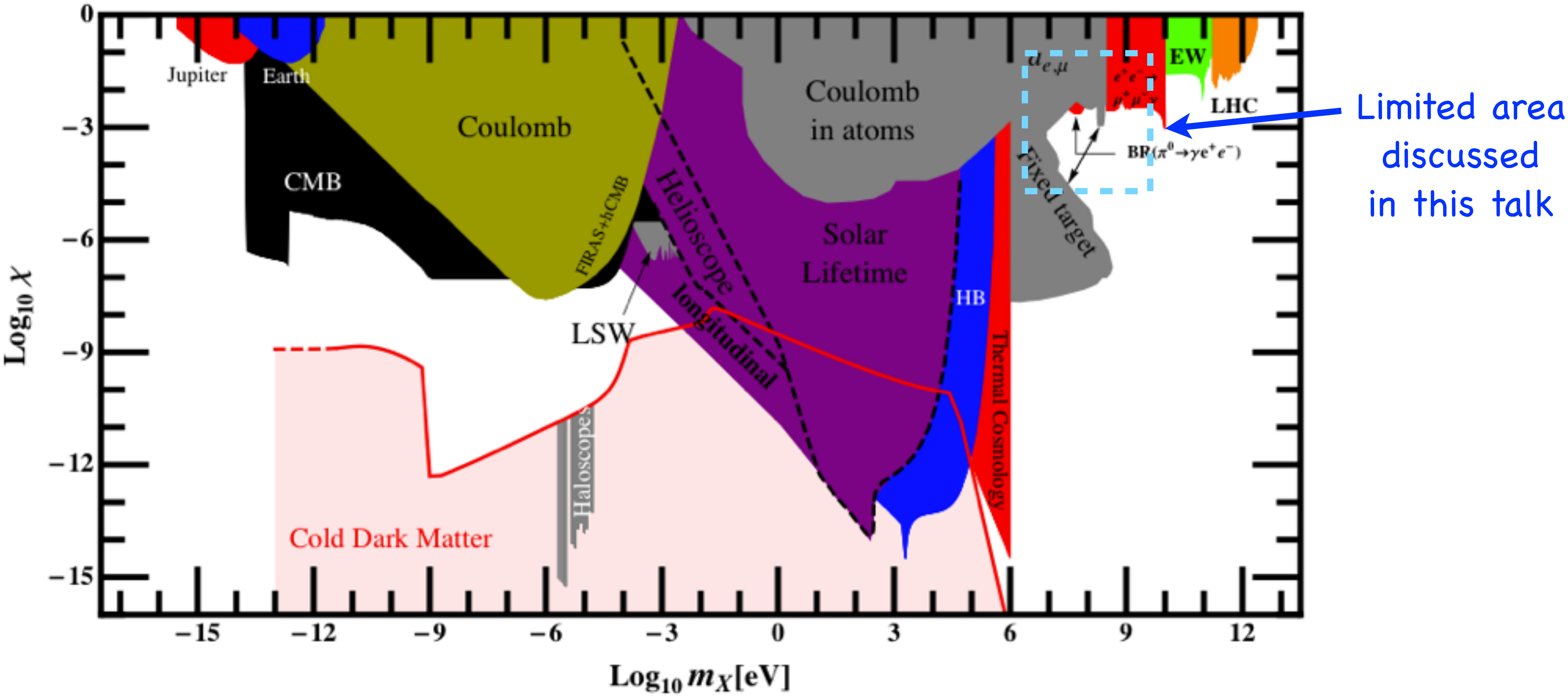
[Andreas, …, Semertzidis, … (2013)]

Many ideas to search for the Z’ (visible or invisible) !

Great interest in Dark Force.

Extended Range

Extended range of parameters (of Dark Photon)



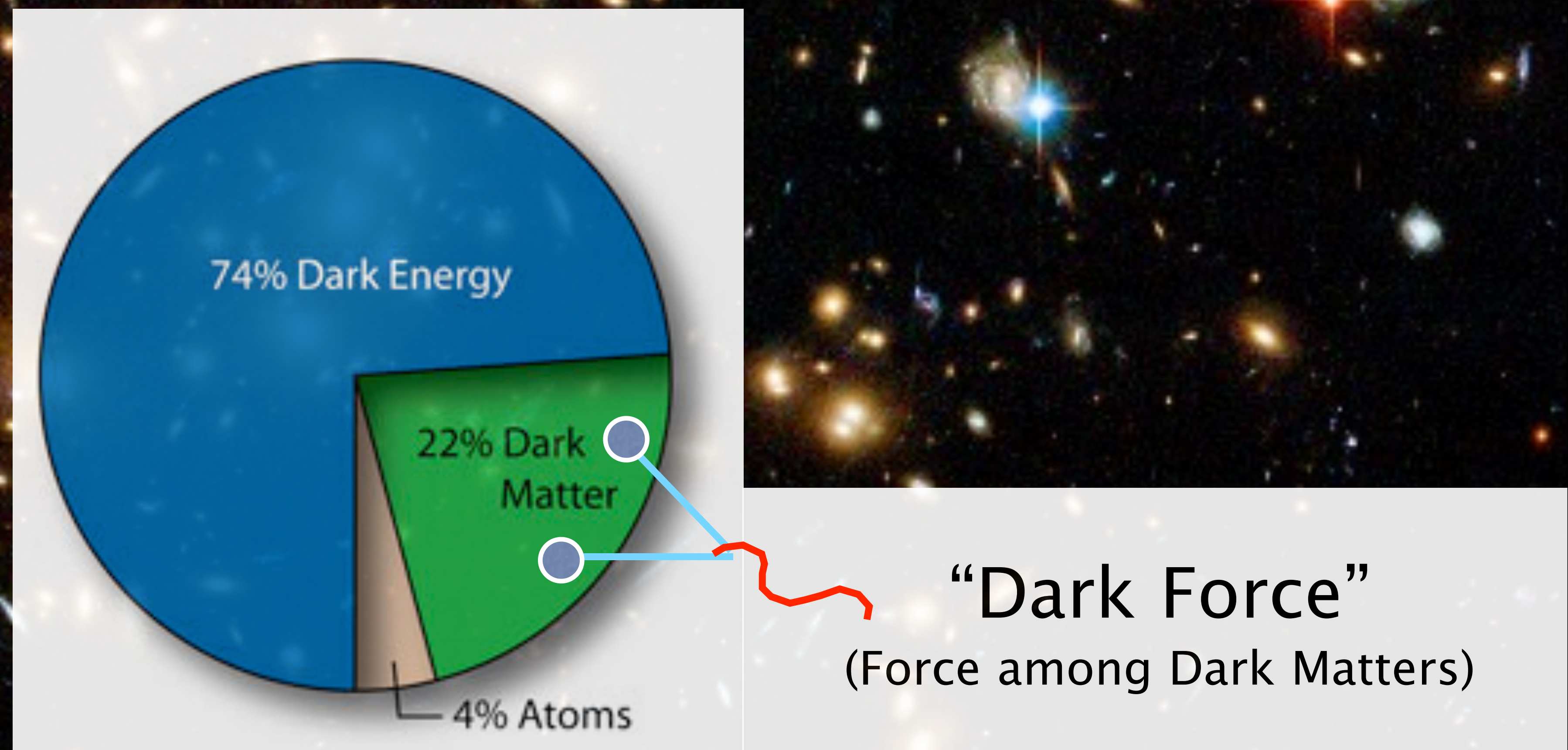
[Jaeckel (2013)]

Not entire parameter space is necessarily related to astrophysical anomalies (original motivation of Dark Force), but there are **vast unexplored space** waiting for us.

(Its exploration requires new ideas and experimental innovations.)

Summary

Dark Force summary



- Originally introduced to explain some astrophysical data.
- Potentially a solution to other puzzles too [ex: muon g-2 deviation]
- Mass ≈ O(1) GeV.
- Coupling ≈ Extremely weak (model-dependent) to the SM particles.
- Searchable at Low-energy Labs (Jefferson Lab, B-factory, ...).
- May affect the LHC experiments, too.

Dark Force summary

Overview of my contributions in Dark Force

[7 papers + 1 community study report + several invited talks]

- Presented a New type of Dark Force model **[Modeling]**
  (Ex: Dark Z = Dark Photon with generalized couplings)

- Suggested New experiments for Dark Force search **[New Prediction]**
  (Ex: Low-E parity test, Flavor-changing meson decay, Higgs/Top decay, ...)

- Performed Feasibility study using Monte Carlo **[Simulation]**
  (Ex: Required luminosities for discovery in Higgs/Top decay, …)

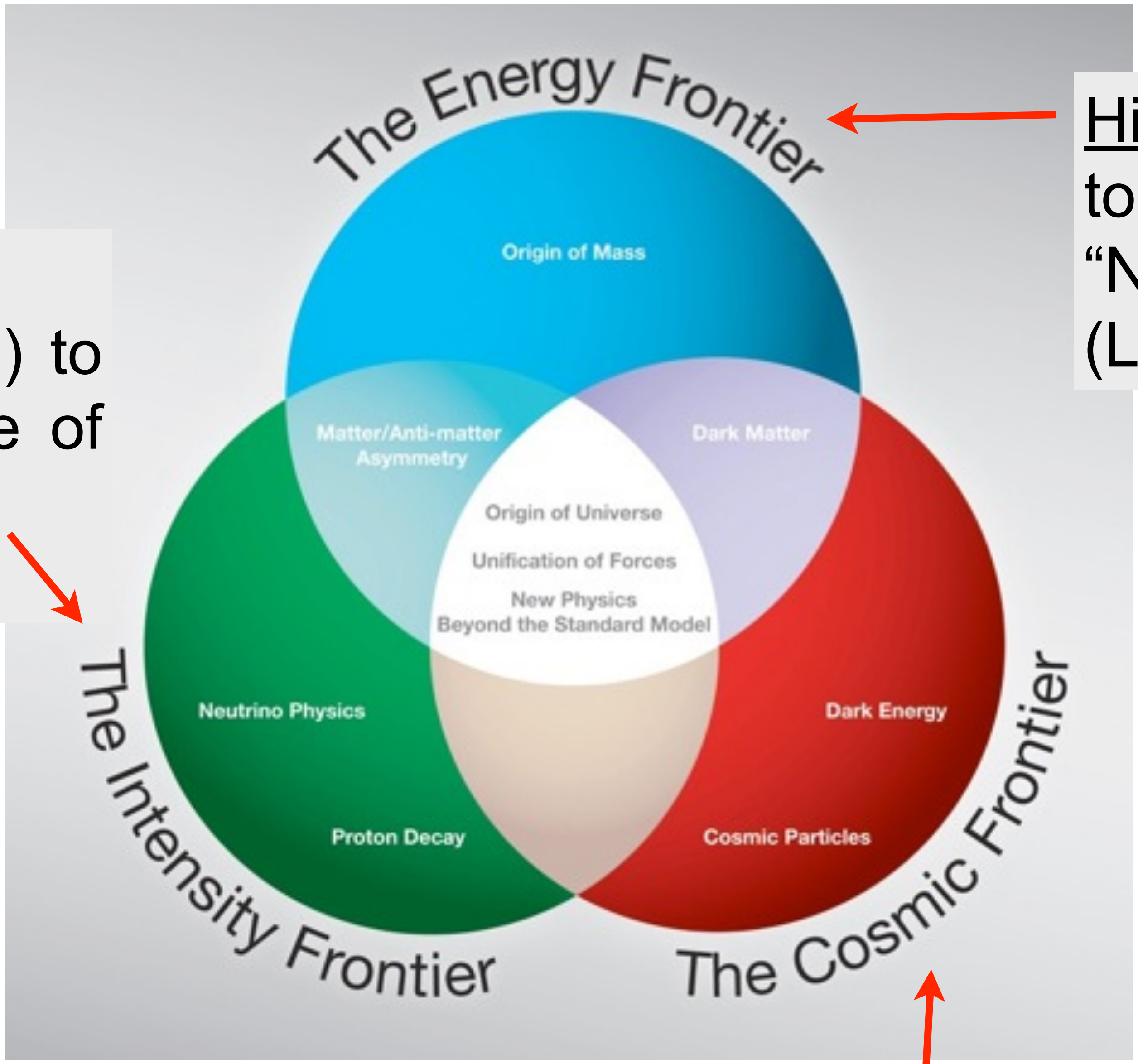
- Interacted with experimentalists **[Dissemination]**
  (Convincing people for real data analysis [by talks and discussions])

In short, "a whole package of New Dark Force study"

Still working on Dark Force as well as other New physics scenarios.

Position of Dark Force research

Particle Physics Frontiers
(by US Department of Energy)



<u>High-E experiments</u>:
to find direct evidence of "New heavy particles" (LHC, etc).

<u>Low-E experiments</u>:
(with enough statistics) to find "indirect" evidence of New heavy particles (JLab, B-factory, etc).

Traditional View

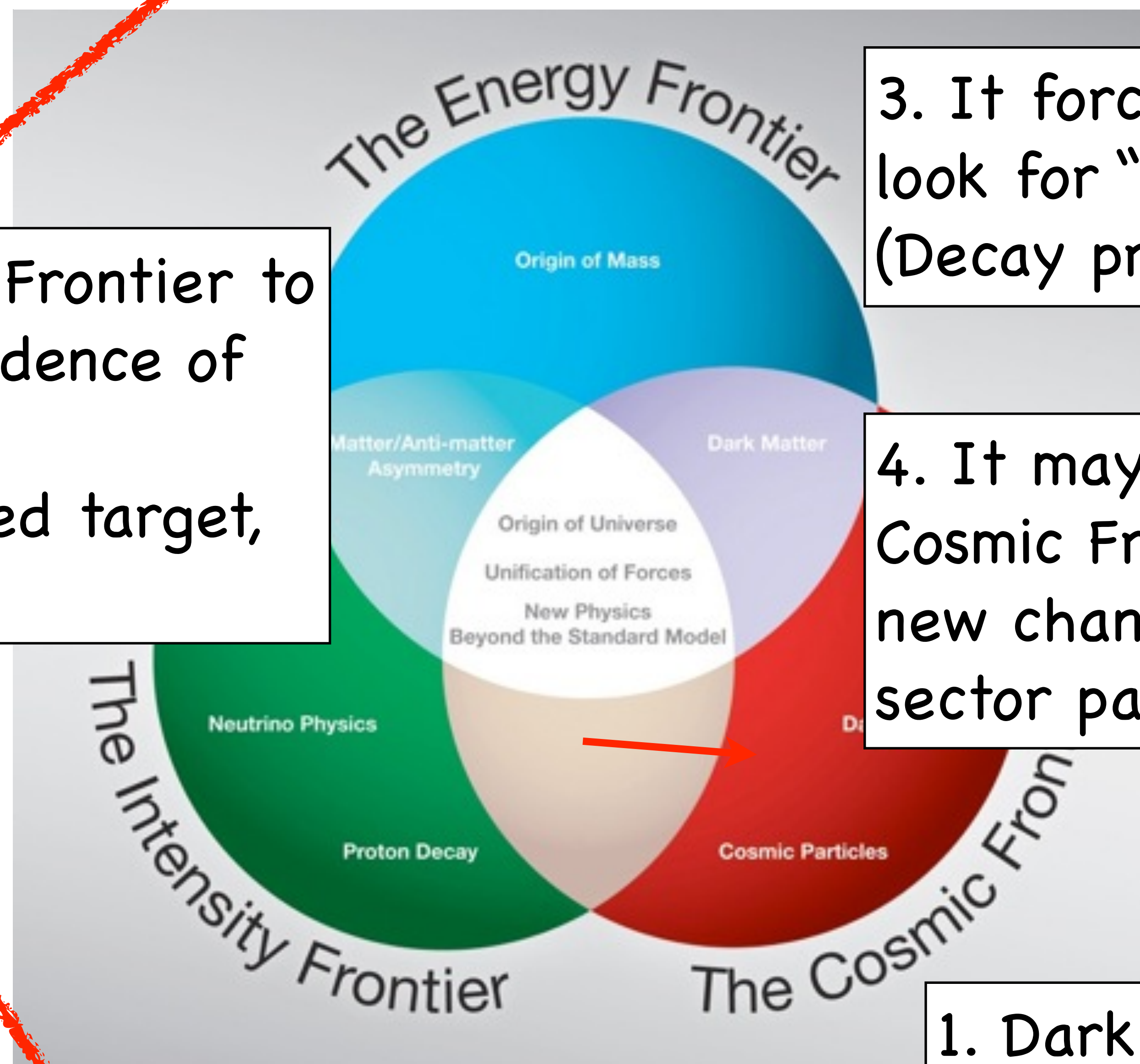
<u>Underground / Satellite experiments:</u>
to find new signals from the sky
(Direct dark matter detection, Cosmic rays, etc).

Position of Dark Force research

Particle Physics Frontiers
(by US Department of Energy)

2. It forces Intensity Frontier to search for "direct" evidence of New physics
(Bump searches in fixed target, meson decay, ...)

3. It forces Energy Frontier to look for "New light particles"
(Decay product of Higgs, top, ...)



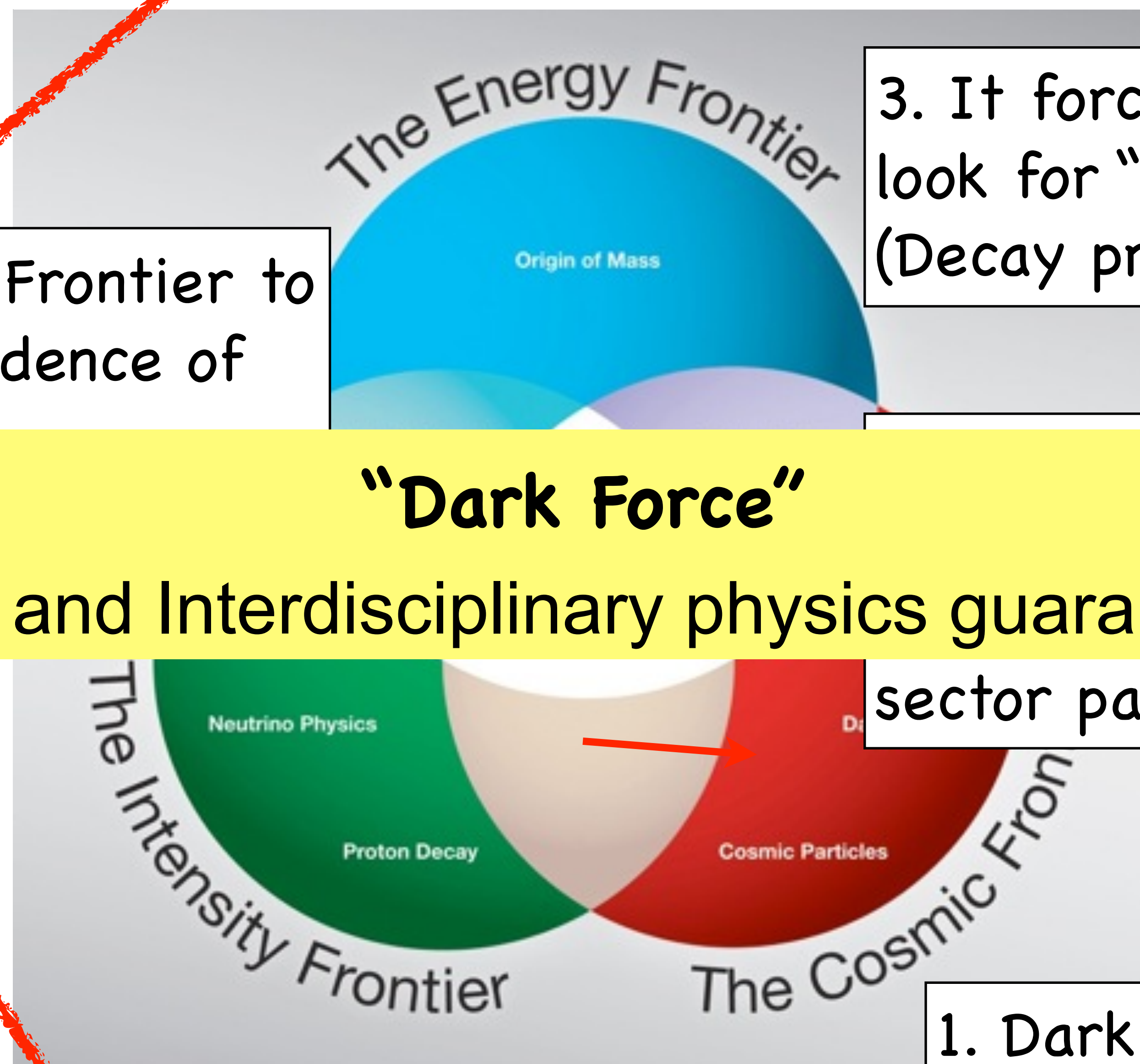
4. It may force changes in Cosmic Frontier too, providing new channels to search for Dark sector particles.

1. Dark Force (DM's force) was originally introduced in Cosmic Frontier
(Astrophysical anomalies)

Unconventional View
(somewhat similar to Axion)

Position of Dark Force research

Particle Physics Frontiers
(by US Department of Energy)



3. It forces Energy Frontier to look for "New light particles" (Decay product of Higgs, top, ...)

2. It forces Intensity Frontier to search for "direct" evidence of New physics
(Bump searche… meson decay, …

"Dark Force"

Rich and Interdisciplinary physics guaranteed

…anges in …o, providing …earch for Dark sector particles.

1. Dark Force (DM's force) was originally introduced in Cosmic Frontier
(Astrophysical anomalies)

Unconventional View
(somewhat similar to Axion)

- Thank you -