The State of Particle Physics

The success of the Standard Model is a triumph

It is the result of several decades of theoretical & experimental exploration, of pushing at the boundaries of what we knew

But we are not done!

Standard Model is not satisfactory

Several sharp pieces of evidence for New Physics exist
Dark Matter: powerful evidence for New Physics

It doesn’t have to be a WIMP at the Weak-scale!

LHC results challenge connection between dark matter and Weak-scale naturalness

Dark matter suggests the presence of a dark sector, neutral under all Standard Model forces
Many, rich Dark Sectors?

Why should **Standard Model** sector be special?

Rich, intricate structure!
Many, rich Dark Sectors?

Why should Standard Model sector be special?

What if Dark Sector is equally intricate?

Rich, intricate structure!
Many, rich Dark Sectors?

Why should Standard Model sector be special?

What if Dark Sector is equally intricate?

What if there are many Dark Sectors?

How could we know?

Rich, intricate structure!
Dark Sectors

• motivated by dark matter, but also by theory, strong CP, data (e.g. muon g-2 & astrophysics)

• several well-motivated possibilities exist

• probe with a rich, diverse, and relatively inexpensive experimental program, going beyond standard searches

• a discovery would be a game-changer
A dark sector consists of particles that do not interact with known forces.

Dark Sectors

Standard Model

\[ g, W^\pm, Z, \gamma \]

Known Forces

strong, weak, EM

Dark Sector

forces + particles
dark matter?

unlike matter that interacts with known forces, dark sector particles can be well below Weak-scale
only a few important interactions exist that are allowed by Standard Model symmetries
Portals

- **“Axion”**
  \[ \frac{1}{f_a} F_{\mu\nu} \tilde{F}^{\mu\nu} a \]
  axions & axion-like particles (ALPs)

- **“Vector”**
  \[ \epsilon F'_{Y,\mu\nu} F'_{\mu\nu} \]
  dark photon $A'$

- **“Higgs”**
  \[ \lambda H^2 S^2 + \mu H^2 S \]
  exotic Higgs decays?
  see e.g. review 1312.4992

- **“Neutrino”**
  \[ \kappa (HL)N \]
  sterile neutrinos?
Portals

our focus today

(very brief, since several other talks)

- **“Axion”**
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Axion

explains why CP violation in strong force is so small i.e. solves strong CP problem

axion is associated with spontaneous breaking at a scale $f_a$ of an approximate global Peccei-Quinn (PQ) symmetry

$$m_a \sim \frac{\Lambda_{QCD}^2}{f_a} \sim 0.6 \text{ meV} \frac{10^{10} \text{ GeV}}{f_a}$$

naturally light

can be generalized to axion-like particles or “ALPs”

axions & ALPs are excellent dark matter candidates
If Axions are all of Dark Matter...

If $f_a > H_I$, then get large isocurvature perturbations (disfavored by WMAP/Planck)

Visinelli, Gondolo

(Turner & Wilczek; see also Marsh et.al., Higaki et.al.)
If Axions are all of Dark Matter…

- If $f_a > H_I$, then get large isocurvature perturbations (disfavored by WMAP/Planck).

  $\implies$ BICEP2 disfavors axion DM for large $f_a$

Visinelli, Gondolo
(Turner & Wilczek; see also Marsh et.al., Higaki et.al.)

(assuming standard $\Lambda$CDM cosmology
(but caveats exist!!)
Portals

“Axion” \( \frac{1}{f_a} F_{\mu\nu} \tilde{F}^{\mu\nu} a \) axions & axion-like particles (ALPs)

“Vector” \( \epsilon F^{Y,\mu\nu} F'_{\mu\nu} \) dark photon A'

“Higgs” \( \lambda H^2 S^2 + \mu H^2 S \) exotic Higgs decays?

“Neutrino” \( \kappa (HL) N \) sterile neutrinos?

see e.g. review 1312.4992
Standard Model
\[ g, \ W^\pm, \ Z, \ \gamma \]

Known Forces

Dark Sector
\[ A' \text{ (massive)} \]

New force: \( U(1) \)

dark matter?
Dark Photons

ordinary photon & $A'$ can mix

Standard Model

$g \ W^\pm, Z, \gamma$

Dark Sector

$A'$ (massive)

$\Delta L = \frac{\epsilon}{2} \epsilon_{\mu
u} F_{\mu
u}'$

“Kinetic Mixing”

simplest Dark Sector consists of just an $A'$
Generating Kinetic Mixing

e.g. loops of heavy particles charged under photon and $A'$

$\gamma \cdots \cdots \cdots \cdots \cdots \cdots \cdots A'$

$\epsilon \sim 10^{-5} - 10^{-2}$

a motivated target
Mixing with photon allows:

A’ coupling to quarks and charged leptons:

$q, \ell^+$

$q, \ell^-$

$\gamma^*$

$\epsilon$

$A'$

and

for low $A'$ masses, can also get

$A' \leftrightarrow \gamma$ “oscillation” (like $\nu$'s)
low-mass (< MeV) $A'$ parameter space

Experimental techniques often similar to axion/ALP searches

Jaeckel, Redondo, Ringwald, …
Another well-motivated target: $m_{A'} \sim \text{MeV-GeV}$

- mass scale appears naturally in some models
e.g. Arkani-Hamed & Weiner; Cheung et.al.; Morrissey et.al.

- much excitement generated in 2008 from various cosmic-ray and terrestrial “anomalies” suggesting dark matter interacts with $A'$

   Arkani-Hamed et.al.; Cholis et.al.; Pospelov & Ritz

while speculative, it made us realize amazing possibilities at GeV-scale!
Hints for A’ with MeV-GeV mass?

anomalous muon g-2?

A’ may explain observed \((g_s - 2)_\mu\)
Known constraints ~2008

\[ m_{\ell} = 10^{-11} \text{ to } 10^{-3} \text{ GeV} \]

\[ m_{A'} = 10^{-3} \text{ to } 10^{-1} \text{ GeV} \]

\[ a_{\mu, 5\sigma} \]

\[ a_{\mu, \pm 2\sigma \text{ favored}} \]

\[ a_{e} \]
How to look for $A'$ with MeV-GeV mass?

$e^+e^-$ colliders

Rare meson decays

$\phi \rightarrow \eta A'$

$\pi^0 \rightarrow \gamma A'$

$A' \rightarrow e^+e^-, \mu^+\mu^-, \pi^+\pi^-, \ldots$

or $A' \rightarrow$ Dark Matter (see later)

B-factories, Phi-factories

searches completed/ongoing/planned
How to look for $A'$ with MeV-GeV mass?

New & old $e^-$ fixed target experiments

look for $A' \rightarrow e^+e^-$ resonance or displaced vertex

e.g. SLAC, JLab, MAMI, …
How to look for $A'$ with MeV-GeV mass?

*Proton-beam fixed target experiments*

**Example: produce $A'$ from pion decays**

Proton-beam fixed target experiments

LSND, OscSNS, MiniBooNE, MicroBooNE, MINOS, NOvA, LBNE, Project X, …
Current constraints

past

electron + proton
beam dumps

supernova

Pospelov; Fayet;
Bjorken, RE, Schuster, Toro
Andreas, Niebuhr, Ringwald
Batell, Pospelov, Ritz;
RE, Harnik, Kaplan, Toro
Blumlein, Brunner;
Dent, Ferrer, Krauss
RE, Schuster, Toro, Wojtsekowski
KLOE, APEX, MAMI/A1 Collaborations
Davoudiasl, Lee, Marciano;
Endo, Hamaguchi, Mishima
Current constraints (zoomed in)

B/Phi-factory searches
Current constraints (zoomed in)

B/Phi-factory searches

Test runs of new e^-FT experiments @ JLab/Mainz
Constraints expected this year

Phenix @ RHIC
(preliminary)

MAMI?
Beranek et.al.

BaBar?

most of g-2 region
covered soon, assuming
$Br(A' \rightarrow \text{visible}) = 100\%$

for invisible decay see later
New searches (~few years)

2015:
HPS
(vertexing!)
New searches (~few years)

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~2016/17:
APEX
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Mu3e  (Echenard, RE, Zhong)
New searches (~few years)

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- HPS (vertexing!)

~2016/17:
- APEX
- Mu3e (Echenard, RE, Zhong)
- DarkLight
New searches (~few years)

2015:
HPS
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~2016/17:
APEX
Mu3e (Echenard, RE, Zhong)
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VEPP-3
New searches (~few years)

2015:
HPS
(vertexing!)

~2016/17:
APEX
Mu3e (Echenard, RE, Zhong)
DarkLight
VEPP-3
HPS w/ possible True Muonium discovery
New searches (~few years)

2015:
HPS
(vertexing!)

~2016/17:
APEX
Mu3e  (Echenard, RE, Zhong)
DarkLight
VEPP-3
HPS  w/ possible True Muonium discovery

+MAMI, Phenix, WASA, HPS2019, … (not shown)
sub-GeV DM & Dark Photons

Standard Model
$g\ W^{\pm},\ Z\ \gamma$

Dark Sector
DM + $A'$

Examples

$\chi\ A'\ q,\ \ell^-,\ \bar{q},\ \ell^+$

$e^-\ A'(*)\ \chi\ \gamma$

$e^+\ A'(*)\ \chi\ \bar{\chi}$
Direct Detection

probe DM in our halo scattering off
e.g. *electrons* in detector

lots of potential for current & new experiments!

(XENON100, LUX, Darkside, Super-CDMS, …)
Invisible $A'$ decays

Hidden Photon $\rightarrow$ invisible ($m_{A'} > 2 m_{\chi}$)
Invisible $A'$ decays

Hidden Photon $\rightarrow$ invisible ($m_{A'} > 2 m_\chi$)
Invisible $A'$ decays

Hidden Photon → invisible ($m_{A'} > 2 m_\chi$)

- $a_\mu, 5\sigma$
- $a_\mu, \pm 2\sigma$ favored
- $e$

$K \rightarrow \pi A'$
E787, E949

BaBar

$Pospelov$
RE, Mardon, Papucci, Volansky, Zhong; Izaguirre, Krnjaic, Schuster, Toro
deNiverville, Pospelov, Ritz
Invisible $A'$ decays

Hidden Photon $\rightarrow$ invisible ($m_{A'} > 2 m_\chi$)
Proton-beam fixed target experiments

e.g. neutrino facilities

\[ P \rightarrow \pi^0 \rightarrow \gamma A' \rightarrow XX \rightarrow X \rightarrow e^-/N \]

Target \quad \text{Decay pipe} \quad \text{Shield} \quad \text{Detector}

LSND, OscSNS, MiniBooNE, MicroBooNE, MINOS, NOvA, LBNE, Project X, …
**LSND sets powerful constraints**

Hidden Photon $\rightarrow$ invisible ($m_{A'} > 2m_\chi$)

**MiniBooNE currently taking data**

Note: Constraints are model-dependent!
Electron-beam fixed target experiments

Krnjaic, Izaguirre, Schuster, Toro
Diamond, Schuster

new parasitic experiments possible at
e.g. JLab, Mainz, SLAC, SuperKEK, ILC, …
Constraints from past beam dumps

Hidden Photon → invisible ($m_{A'} > 2 m_\chi$)

$\epsilon$

$m_{A'}$ [GeV]

Batell, RE, Surujon (to appear)

Diamond, Schuster

E137

SLAC mQ

E137

MiniBooNE

VEPP-3

LSND

BaBar

Belle II

Standard

DarkLight

K$\rightarrow$\pi A'

ORKA
Constraints from past beam dumps

Hidden Photon → invisible ($m_{A'} > 2 m_\chi$)

- $\alpha_\mu$, 5$\sigma$
- $\alpha_\mu$, 2$\sigma$
- $\alpha_\mu$, favored
- $\alpha_e$
- MiniBooNE
- VEPP-3
- E137
- BaBar
- SLAC mQ
- JLab
- ILC
- Belle II
- Standard

$\epsilon$

$m_{A'}$ [GeV]

Note: $g$-2 region is strongly constrained for simplest invisible decays

+ exciting prospects for future experiments!

E137

Batell, RE, Surujon (to appear)

SLAC mQ

Diamond, Schuster

LSND, JLab, ILC, MiniBooNE
Conclusions

- Dark sectors are well-motivated by theory, DM, strong CP, muon g-2, astrophysics, …
- Experiments use intense beams & sensitive detectors
- Small-scale, inexpensive, uses existing facilities/technologies

We don’t know which guiding principle for finding new physics is reliable; must explore all motivated possibilities.