Dark Sector at the low energy

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Outline

- Motivation of studying on the dark sector
- Some “hints” for the dark photon
- Searches for the dark photon and dark sector
  - High energy collider
  - Beam dump and fixed target experiments
  - Low energy $e^+e^-$ collider
- Searches for the dark photon at BES
Standard model! What’s the next?

- SM is remarkably successful
- Most of predictions are tested at high precision
- Where is the new physics beyond SM (BSM)?
Standard model! What’s the next?

- SM is remarkably successful
- Most of predictions are tested at high precision
- Where is the new physics beyond SM (BSM)?
- No BSM at all!
  Quite strange… So many problems are unresolved: the origin of mass, flavor, CP-violation, neutrino mass, the dark universe…
- BSM at very high energy scale!
  Commonly believed… But no one knows where is the next scale…
- BSM interacts weakly with SM at low energy scale!
  Low energy experiments in the intensity frontier have capability to discover the new sector;
  Complementary to high energy experiments
**SM, dark sector, and portal**

The interactions between the SM and BSM can be described by effective operators:

\[ L_{\text{eff}} = L_{\text{SM}} + \sum \frac{f_i^{(5)}}{\Lambda} O_i^{(5)} + \sum \frac{f_i^{(6)}}{\Lambda^2} O_i^{(6)} + \ldots \]

They are always suppressed by the energy scale.

- It is difficult to be tested at low energy scale experiments. Only via indirect effects?
- There may be new light particles connecting the dark sector to SM!

**Portal**

- **Energy**
- **Hidden sector (heavy)**
  - SUSY, extra dim...?
  - Unification?
- **Standard model**
- **portal**
- **dark sector (light)**
  - New bosons?
  - Light dark matter?
- **Intensity**

It is also called hidden photon, heavy photon, A', γ', b_μ, Z_D or U boson in the literature.

<table>
<thead>
<tr>
<th>Portal</th>
<th>Particles</th>
<th>Operator(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>“Vector”</td>
<td>Dark photons</td>
<td>(-\frac{\epsilon}{2\cos \theta_W} B_{\mu\nu} F^{\mu\nu})</td>
</tr>
<tr>
<td>“Axion”</td>
<td>Pseudoscalars</td>
<td>(\alpha \frac{q_a}{f_a} F_{\mu\nu} - \frac{\alpha}{f_a} G_{\mu\nu}^{\mu\nu} - \frac{\alpha}{f_a} \bar{\psi} \gamma^{\mu} \gamma^{5} \psi)</td>
</tr>
<tr>
<td>“Higgs”</td>
<td>Dark scalars</td>
<td>((\mu S + \lambda S^2) H^\dagger H)</td>
</tr>
<tr>
<td>“Neutrino”</td>
<td>Sterile neutrinos</td>
<td>(y_N L H N)</td>
</tr>
</tbody>
</table>
The dark universe! The dark sector?

Many results from astrophysical and cosmology observations have confirmed the existence of dark matter (DM).

The particles nature of DM is still unknown.

Only a WIMP?

No! There may exist a dark sector with complicated structure!
Three frontiers for the BSM

- **Energy**
  - Higgs, top, Z
  - New particles: SUSY, extra dimension...

- **Intensity**
  - Flavor
  - Neutrino
  - Hadrons
  - Proton decay
  - Fixed target

- **Cosmology**
  - Dark matter
  - Dark energy
  - CMB, cosmic ray...

- Search for new sub-GeV gauge boson
- Search for new sub-GeV boson
- Search for new dark sector
**Kinetic mixing**

- **Kinetic mixing** between dark photon and photon
- Mixing can be generated by quantum loop mediated by some heavy particles
- Mixing is expected to be small
  \[ \varepsilon \sim \frac{g_D g_Y}{16\pi^2} \log \frac{\Lambda^2}{m_X^2} \sim 10^{-4} \sim 10^{-3} \]
- Induce effective interactions with the SM
  \[ \varepsilon e A' J_{EM} \]
- If the mixing is induced by higher order effects (GUT), it can be very small \( \sim 10^{-7} \)
- Some BSM models (such as SUSY) can also explain the origin of the mass scale
  \( \sim \sqrt{\varepsilon m_z} \sim \text{MeV-GeV} \)
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Dark photons in the SKY?

DM can annihilate/decay into dark photons and produce energetic cosmic rays
CR positron/electron excess

- Observed by PAMELA, Fermi, ATIC and HESS. Recently confirmed by AMS02 with high precision
- DM interpretation requires large DM annihilation cross section. Can be explained by the “Sommefeld” effect mediated by light dark photons ~GeV
- No antiproton excess. If dark photons are light enough, they do not produce antiprotons.
- However, the DM interpretation is severely constrained by high energy gamma-ray observations from Fermi-LAT
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- However, the DM interpretation is severely constrained by high energy gamma-ray observations from Fermi-LAT.
An extended gamma-ray excess with a high significance peaking at a few GeV in the Fermi-LAT data was reported by Hooper and Goodenough in 2009.

This excess is found in the Galactic center and inner galaxy, and is confirmed by many groups in 2013 and 2014.

Can be explained by DM annihilations into $b$ quarks. But constrained by the anti-proton data.

This excess can also be explained by DM annihilations into dark photons.

**GeV gamma-ray excess in the Galactic Center**
Some direct detection experiments claimed the hints of light DM \( \sim \text{GeV} - \text{O}(10) \text{ GeV} \), such as DAMA, CoGeNT, CRESST, and CDMS-Si.

Can be easily explained by the exchange of dark photon.

But the nature of these anomaly is still unclear. Severely constrained by other experiments, such as XENON, LUX, Super-CDMS, CDEX...
Anomalous muon $g-2$

The discrepancy between the theoretical predictions and experimental results is $\sim 3\sigma$.

Hint for BSM, new particles in the loop, SUSY?

Can be explained by the dark photon

$$\varepsilon^2 \frac{\alpha}{2\pi} \sim 10^{-9}$$

But the parameter space is severely constrained.
Current limits from terrestrial experiments ($m_{\gamma^\prime} > \text{MeV}$)

- Dark photon in this mass range can decay into charged leptons and mesons
- Beam dump experiments; Fixed target experiments
- Low energy $e^+e^-$ colliders: direct production, rare meson decay
- High energy colliders
Electron beam dump experiments

- **ep collisions** can produce dark photons. Dark photons travel through the shield, and decay into electron-positron pairs in the detector.
- Very high luminosity
- Constraints are set for particular parameter space
  - large mixing→ small lifetime of dark photon → can not decay in the detector
  - small mixing→ small production of dark photon → no enough statistic
- Experiments with shields of O(cm~100m)

\[ \sigma_{A'} \sim 100 \text{ pb} \left( \frac{\epsilon}{10^{-4}} \right)^2 \left( \frac{100 \text{ MeV}}{m_{A'}} \right)^2 \]

\[ \gamma_{A'} \sim 1 \text{ mm} \left( \frac{\gamma}{10} \right) \left( \frac{10^{-4}}{\epsilon} \right)^2 \left( \frac{100 \text{ MeV}}{m_{A'}} \right) \]

\[ \sigma \sim \frac{\alpha^3 Z^2 \epsilon^2}{m^2} \sim O(10 \text{ pb}) \]
Electron fixed target experiments

The lifetime of dark photon is small (~<O(1) cm)

Need thin target

Produced dark photons are extremely forward

Radioactive and Bethe-Heitler BG

Reconstruct the displaced decay vertex and invariant mass of the dark photon to suppress BG
Research at High energy colliders

- **Direct production (suppressed by small mixing)**

- **Cascade decay, e.g. SUSY particles would decay into dark photon without suppression**

- **Dark higgs strahlung**

The typical signal is highly boosted lepton pair—"lepton jet"
Research at High energy colliders

Exotic higgs decay

Hadron colliders cover the region of heavy dark photon

Curtin et. al, 1412.0018
Dark photon production at $e^+e^-$ colliders

- **Direct production**, $e^+e^- \rightarrow \gamma \ell^+\ell^-$

- **Non-abelian gauge boson**, $e^+e^- \rightarrow V'V' \rightarrow 2\ell^+\ell^-$

- **Higgs strahlung**, $e^+e^- \rightarrow \gamma 'h' \rightarrow 3\ell^+\ell^-$

- **Other complicated decay chains**

......
Production and decay of dark photon

- It is better to produce dark photon at low energy colliders with high luminosity

\[ \sigma \sim \frac{\alpha^2 \varepsilon^2}{E^2} \sim O(10 \, fb) \]

- Large QED background

- Reconstructing invariant mass to suppress the background

- Decay branching ratios can be derived from \( e^+e^- \) collision results

\[
\frac{\sigma(e^+e^- \rightarrow \text{hadrons}, \, s)}{\sigma(e^+e^- \rightarrow \mu^+\mu^-, \, s)} = \frac{BR(b_\mu \rightarrow \text{hadrons})}{BR(b_\mu \rightarrow \mu^+\mu^- (\text{or } e^+e^-))}
\]

Liu et al., 1412.1485
Reach for direct production

\[ \frac{S}{\sqrt{B}} \sim \sqrt{\frac{\sigma_0 L}{\alpha/\pi}} \frac{\epsilon^2}{\sqrt{m_{b\mu}/\delta m}} \times BR(U \rightarrow \ell^+\ell^-) \]

- Assuming luminosity ~100 fb\(^{-1}\)
- Resolution ~MeV
- Rate of \(e^+e^-\rightarrow\gamma\gamma\) ~ 10\(^4\)pb
- Reach for \(\epsilon\) is proportional to \(L^{-1/4}\)

Reece, Wang, 0904.1743
Meson decay

Dark photon can be produced from decays of mesons, $\rho$, $\eta$, $\phi$, $Y$, $J/\psi$, with $BR \sim \varepsilon^2 \cdot BR(\text{meson} \rightarrow \gamma)$

Signal significance can be estimated as

$$S \approx \sqrt{n_X} \cdot \epsilon^2 \cdot \frac{BR(X \rightarrow Y + \gamma) \cdot BR(U \rightarrow \ell^+\ell^-)}{\sqrt{BR(X \rightarrow Y + \gamma^* \rightarrow Y + \ell^+\ell^-)} \cdot \sqrt{BR(X \rightarrow Y + \gamma \rightarrow Y + \ell')}} \cdot \sqrt{m_U \cdot \log \left( \frac{m_X - m_Y}{2m_\ell} \right)}$$

<table>
<thead>
<tr>
<th>$X \rightarrow YU$</th>
<th>$n_X$</th>
<th>$m_X - m_Y$ (MeV)</th>
<th>$BR(X \rightarrow Y + \gamma)$</th>
<th>$BR(X \rightarrow Y + \ell^+\ell^-)$</th>
<th>$\epsilon \leq$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\eta \rightarrow \gamma U$</td>
<td>$n_\eta \sim 10^7$</td>
<td>547</td>
<td>$2 \times 39.8%$</td>
<td>$6 \times 10^{-4}$</td>
<td>$2 \times 10^{-3}$</td>
</tr>
<tr>
<td>$\omega \rightarrow \pi^0 U$</td>
<td>$n_\omega \sim 10^7$</td>
<td>648</td>
<td>$8.9%$</td>
<td>$7.7 \times 10^{-4}$</td>
<td>$5 \times 10^{-3}$</td>
</tr>
<tr>
<td>$\phi \rightarrow \eta U$</td>
<td>$n_\phi \sim 10^{10}$</td>
<td>472</td>
<td>$1.3%$</td>
<td>$1.15 \times 10^{-4}$</td>
<td>$1 \times 10^{-3}$</td>
</tr>
<tr>
<td>$K^0_L \rightarrow \gamma U$</td>
<td>$n_{K^0_L} \sim 10^{11}$</td>
<td>497</td>
<td>$2 \times (5.5 \times 10^{-4})$</td>
<td>$9.5 \times 10^{-6}$</td>
<td>$2 \times 10^{-3}$</td>
</tr>
<tr>
<td>$K^+ \rightarrow \pi^+ U$</td>
<td>$n_{K^+} \sim 10^{10}$</td>
<td>354</td>
<td>-</td>
<td>$2.88 \times 10^{-7}$</td>
<td>$7 \times 10^{-3}$</td>
</tr>
<tr>
<td>$K^+ \rightarrow \mu^+\nu U$</td>
<td>$n_{K^+} \sim 10^{10}$</td>
<td>392</td>
<td>$6.2 \times 10^{-3}$</td>
<td>$7 \times 10^{-8a}$</td>
<td>$2 \times 10^{-3}$</td>
</tr>
<tr>
<td>$K^+ \rightarrow e^+\nu U$</td>
<td>$n_{K^+} \sim 10^{10}$</td>
<td>496</td>
<td>$1.5 \times 10^{-5}$</td>
<td>$2.5 \times 10^{-8}$</td>
<td>$7 \times 10^{-3}$</td>
</tr>
</tbody>
</table>

Reece, Wang, 0904.1743
Some results from $e^+e^-$ colliders

$\Upsilon(2S, 3S) \rightarrow \gamma A^0, A^0 \rightarrow \mu^+\mu^-$

$\phi(1020) \rightarrow \eta A', A' \rightarrow e^+e^-$
Recent result from MAMI

- Results from MAMI have excluded most of parameter space for muon $g-2$
- Only a small window $\sim 10$-$50$ MeV is still alive

A1, 1404.5502
Recent result from BABAR

- The limit on the mixing parameter is $O(10^{-4})$
Sensitivities of future experiments
If the DM particle is light enough, dark photon can decay into a pair of DM.

In this case, visible decay is suppressed by a factor of $e^2$, but invisible decay is not suppressed.

The constraints from previous studies may be changed.
Constraints on the invisible dark photon

The constraints also depend on the DM mass
**Dark sector at BES**

- Large number of $J/\psi$
- $e^+e^- \rightarrow \gamma \gamma' \rightarrow \gamma \ell^+\ell^-$
- $J/\psi \rightarrow \gamma' \ell^+\ell^- \rightarrow 4l$
- $\Psi(2S)\rightarrow \gamma' \chi_{c1,2} \rightarrow e^+e^- \chi_{c1,2}$
- $J/\psi \rightarrow \gamma' h' \rightarrow \ell^+\ell^- + \text{inv}$
- $J/\psi \rightarrow 3\gamma' \rightarrow 6l$

Zhu et al. 0701001, 0904.4644

Li, Luo, 0911.2067
Invisible decay at BESIII

With huge $J/\psi$ and $\psi(2S)$ samples at BESIII, the rare decays is feasible

<table>
<thead>
<tr>
<th>$J/\psi$ decay mode</th>
<th>Number of events /10 billion $J/\psi$ decays</th>
</tr>
</thead>
</table>
| $J/\psi \rightarrow \phi \eta$ | $(31.4 \pm 3.4) \times 10^5$  
| | $(25.7 \pm 2.8) \times 10^5$ |
| $J/\psi \rightarrow \phi \eta'$ | $(16.2 \pm 1.9) \times 10^5$  
| | $(9.6 \pm 1.2) \times 10^5$ |
| $J/\psi \rightarrow \omega \eta$ | $(13.9 \pm 1.4) \times 10^6$  
| | $(6.2 \pm 0.6) \times 10^6$ |
| $J/\psi \rightarrow \omega \eta'$ | $(1.5 \pm 0.2) \times 10^6$  
| | $(0.7 \pm 0.1) \times 10^6$ |
| $J/\psi \rightarrow \rho^0 \eta$ | $(1.9 \pm 0.2) \times 10^6$  
| | $(0.8 \pm 0.09) \times 10^6$ |
| $J/\psi \rightarrow \rho^0 \pi^0$ | $(55.3 \pm 5.8) \times 10^6$  

<table>
<thead>
<tr>
<th>$\psi(2S)$ decay mode</th>
<th>Number of events expected</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\psi(2S) \rightarrow \pi^+ \pi^- J/\psi$</td>
<td>$9.3 \times 10^8$</td>
</tr>
<tr>
<td>$\psi(2S) \rightarrow \pi^0 \pi^0 J/\psi$</td>
<td>$5.6 \times 10^8$</td>
</tr>
<tr>
<td>$\psi(2S) \rightarrow \eta J/\psi$</td>
<td>$9.3 \times 10^7$</td>
</tr>
<tr>
<td>$\psi(2S) \rightarrow \pi^0 J/\psi$</td>
<td>$3.7 \times 10^6$</td>
</tr>
<tr>
<td>$\psi(2S) \rightarrow \gamma \chi_{c0}$</td>
<td>$2.7 \times 10^8$</td>
</tr>
<tr>
<td>$\psi(2S) \rightarrow \gamma \chi_{c1}$</td>
<td>$2.6 \times 10^8$</td>
</tr>
<tr>
<td>$\psi(2S) \rightarrow \gamma \chi_{c2}$</td>
<td>$2.5 \times 10^8$</td>
</tr>
<tr>
<td>$\psi(2S) \rightarrow \gamma \eta_c(1S)$</td>
<td>$7.8 \times 10^6$</td>
</tr>
<tr>
<td>$J/\psi \rightarrow \gamma \eta_c(1S)$</td>
<td>$1.3 \times 10^8$</td>
</tr>
</tbody>
</table>

Li,Zhu, 1202.2955
Some results from BESIII

✿ Invisible decay
  ✿ Search for $J/\psi \rightarrow \phi \eta(\eta') \rightarrow K^+K^-+\text{inv}$
  ✿ Sample $\sim 2.25 \times 10^8 J/\psi$
  ✿ $\text{Br}(\eta\rightarrow\text{inv})/\text{Br}(\eta\rightarrow\gamma\gamma) < 2.6 \times 10^{-4}$
  ✿ $\text{Br}(\eta'\rightarrow\text{inv})/\text{Br}(\eta'\rightarrow\gamma\gamma) < 2.6 \times 10^{-4}$

✿ Visible decay
  ✿ Search for $\psi' \rightarrow \pi^+\pi^- J/\psi, J/\psi \rightarrow \gamma X(\rightarrow \mu^+\mu^-)$
  ✿ Sample $\sim 1.06 \times 10^8 \psi'$
  ✿ Limits on the exotic decay from $4 \times 10^{-7}$ to $2.1 \times 10^{-5}$
Summary

- (sub)GeV dark sector can be tested in three frontiers

- Search for the dark sector in the intensity frontier is well-motivated. This is a very active and attractive topic.

- Some parameter spaces are left for the future low energy high luminosity collider
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Thank you!