Dark Sector in High-Intensity Experiments

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The relevant literatures are growing fast. Let me know if I have not included your important works. I will include them to the slides.

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Outline

- Why study “dark sector” theories?
  Why sub-MeV to GeV+ region?
  Why accelerator (intensity) probes?
- Intro to dark sector “portals”, dark matter, and anomaly motivated models
- Search overview: accelerator experiments
- Search overview: large (neutrino) observatories
Exploration of Dark Matter & Dark Sector

- **Astrophysical/cosmological observations** are important to reveal the actual story of dark matter (DM).
- **Why accelerator experiments? And why Sub-MeV – GeV+?**
Thermal Dark Matter & The Rise of Dark Sector

• The Lee-Weinberg bound (1977'): below $\sim 2 \text{ GeV}$, DM freeze-out through weak-Interaction (e.g. through $Z$-boson) would overclose the Universe (not strong enough!!).

• Could consider ways to get around this but generally light DM needs light mediators to freeze-out to proper relic abundance.

• Mediator is needed for a proper freeze-out: the rise of “dark sector” (DM + mediators + stuffs).

• Neutrino experiments can probe both mediators & dark matter
“Portal” Particles

- Renormalizable interactions.
  
  \[ \mathcal{L} = \left\{ \begin{array}{l}
  \frac{\varepsilon}{2 \cos \theta_W} B_{\mu\nu} F'^{\mu\nu}, \quad \text{vector portal} \\
  (\mu \phi + \lambda \phi^2) H^\dagger H, \quad \text{Higgs portal} \\
  y_n LHN, \quad \text{neutrino portal}
  \end{array} \right. \]

- High-Dim. axion portal is also popular
Why study sub-MeV – GeV+ region?

Signals of discoveries grow from anomalies
Maybe nature is telling us something so we don’t have to search in the dark? (or probably systematics?)
Some anomalies involving sub-MeV - GeV+ Explanations

- Muon g-2 anomaly
- LSND & MiniBooNE anomaly
- EDGES result
- KOTO anomaly
- Beryllium anomaly

Below ~ MeV there are also strong astrophysical/cosmological bounds that are hard to avoid even with very relaxed assumptions
Advantage of Accelerator (Intensity) Searches: Robust Probes & Constraints

Also consider ambient dark matter

Produce dark particles in collisions

Same mass and interaction strength.

Different assumptions

Some details of these figures will be explained later

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Energy vs Intensity Frontier

High energy frontier

Intensity frontier

https://indico.fnal.gov/event/18430/session/8/contribution/17
redesigned from Roni Harnik’s slide

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## Benchmark Models for Dark-Sector Searches

### Snowmass RF06 Classification

**Benchmarks in Final State x Portal Organization**

<table>
<thead>
<tr>
<th>Vector</th>
<th>DM Production</th>
<th>Mediator Decay Via Portal</th>
<th>Structure of Dark Sector</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_\chi$ vs. $y$ $[m_\chi/m_s=3,a_\rho=0.5]$</td>
<td>$m_A^\ast$ vs. $\epsilon$ [decay-mode agnostic]</td>
<td>$iDM$ $m_\chi$ vs. $y$ $[m_\chi/m_s=3,a_\rho=0.5]$ (anom connection)</td>
<td></td>
</tr>
<tr>
<td>$m_A^\ast$ vs. $y$ $[m_\chi/m_s=3,y=y_\rho]$</td>
<td>$m_A^\ast$ vs. $\epsilon$ [decays]</td>
<td>SIMP-motivated cascades [slices TBD]</td>
<td></td>
</tr>
<tr>
<td>$m_\chi$ vs. $q$</td>
<td>U(1)$_{B-L}/\mu-\tau/B-3\tau$ (DM or SM decays)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$m_\chi$ vs. $\sin\theta$ $[\chi=0$, fix $m_\chi/m_s,g_\rho]$ (thermal target excluded 1512.04119, should still include)</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Note excluded DM relevance of $S\to SM$ of mediator searches</td>
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<table>
<thead>
<tr>
<th>Scalar</th>
<th>Mediator Decay Via Portal</th>
<th>Structure of Dark Sector</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_S$ vs. $\sin\theta$ $[\chi=0]$</td>
<td></td>
<td></td>
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<tr>
<td>$m_S$ vs. $\sin\theta$ $[\chi=s.t. Br(H\to ss \sim 10^{-2})]$</td>
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<tr>
<td></td>
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<td>Dark Higgsstrahlung (w/vector)</td>
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<td></td>
<td></td>
<td>scalar SIMP models</td>
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<td></td>
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<td>Leptophilic/leptophobic dark Higgs</td>
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</tbody>
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<tr>
<th>Neutrino</th>
<th>Mediator Decay Via Portal</th>
</tr>
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<tbody>
<tr>
<td>$e/\mu/\tau$ a la 1709.07001</td>
<td>Sterile neutrinos with new forces</td>
</tr>
</tbody>
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<thead>
<tr>
<th>ALP</th>
<th>Mediator Decay Via Portal</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_\chi$ vs. $f_q/l$ $[\chi=0$, fix $m_\chi/m_s,g_\rho]$ (thermal target excluded)</td>
<td>FV axion couplings</td>
</tr>
<tr>
<td>What about $f_\tau,f_\rho$?</td>
<td></td>
</tr>
</tbody>
</table>

**Bold = BRN benchmark, italic= PBC benchmark.** others are new suggestions. **Underline=CV benchmarks that were not used in BRN**

### PBC: The Physics Beyond Colliders initiative at CERN

Krnjaic, Toro, ... Tsai, arXiv:2207.00597
YT is charge of the millicharged section, if you have any questions/suggestions regarding that section, (e.g., BDX, see Smith’ talk tomorrow)

Overview of benchmark models

Interesting models include:

1. Deep Theoretical Motivations
2. Thermal Dark Matter
3. Explain Anomalies
4. Connect to Cosmological or Astrophysical Measurements
Portal Particles, Dark Matter, & Anomalies

**Vector Portal** \[ \mathcal{L} \supset \frac{\epsilon}{2 \cos \theta_W} F'_{\mu\nu} B^{\mu\nu}. \]

- Massless dark photon can lead to millicharged particles

**Neutrino Portal** \[ \mathcal{L} \supset -y^\alpha L_\alpha H N + h.c., \]

- Other neutrino coupling to new particles interesting for anomalies

**Higgs Portal** \[ \mathcal{L} \supset -(AS + \lambda S^2) H^\dagger H, \]

**ALP Portal** \[ \mathcal{L}_{\text{ALP}} \supset \frac{1}{4} g_{\alpha\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu} + ig_{ee} \bar{a} e \gamma^5 e + ia \bar{\psi}_N \gamma^5 (g^{(0)}_{an} + g^{(1)}_{an}) \psi_N, \]

- I will discuss cosmogenic ALP in large neutrino observatories
Vector Portal

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Vector Portal: Dark Photon

Dark photon $A'$: mass basis

$$\mathcal{L}_{A'} = -\frac{\varepsilon}{2\cos\theta_W} A'_{\mu\nu} B^{\mu\nu} - \frac{1}{2} m_{A'} A'_{\mu} A'^{\nu}$$

- Batell, Blinov, Hearty, McGehee, 2207.06905
- See also Tsai, deNiverville, Liu, 1908.07525, PRL 21, for the LongQuest projections & CHARM / NuCal Updates
Vector Portal Dark Matter

From Krnjaic

\[ L_\chi = i g_A A'^\mu J'_\mu + \partial^\mu \chi^\dagger \partial_\mu \chi - m_{\chi}^2 \chi^\dagger \chi, \]

\[ J'_\mu = (\partial_\mu \chi^\dagger) \chi^\dagger - \chi^\dagger \partial_\mu \chi \]

\[ \alpha_D \equiv g_D^2 / 4\pi \]

Batell et al, arXiv:2207.06898
Inelastic Dark Matter & Muon g-2 explainer

\[ \Delta a_\mu \equiv a_\mu^{exp} - a_\mu^{th} = (274 \pm 73) \times 10^{-11}, \]
See, e.g., Fayet, 2007 (hep-ph/0702176)

\[ \Delta \equiv \frac{m_2 - m_1}{m_1}. \]

- See also Mohlabeng PRD 20, arXiv:1902.05075

(a) iDM: \( \Delta = 0.4, \alpha_D = 0.1 \). With muon \( g - 2 \) and DM regimes. 
   \( m_{A^i}/m_{\chi_1} = 3 \), with preliminary DUNE results
Millicharged Dark Sector

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Motivations of Millicharged Particle & Dark Matter

- Is electric charge quantized and why? A long-standing question!

- SM U(1) allows arbitrarily small (any real number) charges. Why don’t we see them? Motivates Dirac quantization, Grand Unified Theory (GUT), to explain such quantization (anomaly cancellations fix some SM $U(1)_Y$ charge assignments)

- MCP (not confined) is predicted by some Superstring theories: Wen, Witten, Nucl. Phys. B 261 (1985) 651-677
  [https://www.youtube.com/watch?v=AmUI2qf9uyo](https://www.youtube.com/watch?v=AmUI2qf9uyo) (watch 15:50 to 17:28)

- Link to string compactification and quantum gravity (Shiu, Soler, Ye, PRL ’13)

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Kinetic Mixing and Millicharge Phase

- Coupled to new dark fermion $\chi$

See, Holdom, 1985

$$\mathcal{L} = \mathcal{L}_\text{SM} - \frac{1}{4} B'_{\mu\nu} B'^{\mu\nu} - \frac{\kappa}{2} B'_{\mu\nu} B^{\mu\nu} + i\bar{\chi}(\not{\phi} + ie^' B^' + iM_{\text{MCP}})\chi$$

- New fermion $\chi$ charged under new gauge boson $B'$.

- Millicharged particle (MCP) can be a low-energy consequence of massless dark photon (a new U(1) gauge boson) coupled to a new fermion (become MCP in a convenient basis.)

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Millicharge Particles & Dark Matter

- Simply a search for particles with \( \{\text{mass, electric charge}\} = \{m_x, e\epsilon\} \)
  \[ \epsilon = Q_x/e \]

- Probes include our works on Neutrino Experiments: Magill, Plestid, Pospelov, Tsai, arXiv:1806.03310, PRL19;
  FLArE: Kling, Kuo, Trojanowski, Tsai: arXiv:2205.09137
Dark Sector with other EM Form Factors

\[ \mathcal{L}_\chi \supsetee e \bar{\chi} \gamma^\mu \chi A_\mu + \frac{1}{2} \mu \chi \bar{\chi} \sigma^{\mu\nu} \chi F_{\mu\nu} + \frac{i}{2} d \chi \bar{\chi} \sigma^{\mu\nu} \gamma^5 \chi F_{\mu\nu} - a \chi \bar{\chi} \gamma^\mu \gamma^5 \chi \partial^\nu F_{\mu\nu} + b \chi \bar{\chi} \gamma^\mu \chi \partial^\nu F_{\mu\nu}, \]

Kling, Kuo, Trojanowski, and Tsai, \textit{arXiv:2205.09137}
Neutrino Portal
Heavy Neutral Lepton

\[ \mathcal{L} \supset -y^{\alpha} L_{\alpha} H N + \text{h.c.}, \]

where \( y^\alpha \) is a Yukawa coupling with \( \alpha = e, \mu, \tau \).

- After EW symmetry breaking, the HNLs mix with the SM neutrinos.
- Follow the convention of considering a single HNL that dominantly mixes with a specific neutrino flavor, i.e., dominant electron-, muon-, or tau- flavor mixing.
- Phenomenology characterized by the HNL mass, \( m_N \), and mixing angle:
  \[ |U_{eN}|^2, |U_{\mu N}|^2, |U_{\tau N}|^2 \]

See, e.g., Snowmass Whitepaper, Batell et al, arXiv:2207.06905
Heavy Neutral Lepton

$|U_{eN}|^2 = |U_{\tau N}|^2 = 0$, Dirac $N$
Electron Collider Beam-Dump Searches for HNL

Can be designed for other $e^+e^-$ colliders as ILC, C3, CLIC, FCC-ee, and CEPC.

- Giffin, Gori, Tsai, Tuckler, arXiv:2206.13745
- Nojiri, Sakaki, Tobioka, Ueda, arXiv:2206.13523
Dipole Portal Heavy Neutral Lepton

Magill, Plestid, Pospelov, Tsai, PRD 18, arXiv:1803.03262

New Fig from Kamp; Ref: Batell, ..., Tsai, arXiv:2207.06898;

\[ L \supset \bar{N}(i\dot{\phi} - m_N)N + (d\bar{\nu}_L\sigma_{\mu\nu}F^{\mu\nu}N + h.c). \]
Searches in Large Neutrino Observatories

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Millicharge Searches at Neutrino Observatories

by Chantelauze, Staffi, and Bret

https://www.futurelearn.com/info/courses/learn-about-weather/0/steps/39415

1111.5031, Super-K Collaboration, PRD12
Supernova Relic Neutrino Search at Super–K

Super-K,
http://www-sk.icrr.u-tokyo.ac.jp/sk/index-e.html

(Plestid, Takhistov, Tsai, Bringmann, Kusenko, Pospelov, PRD 20)
Cosmogenic Axion-Like Particles (ALP) at Neutrino Observatories

For DUNE and JUNO,
Solid: $N_{\text{sig}}^{\text{ALP}} / \text{yr} = 1$
Dashed: $N_{\text{sig}}^{\text{ALP}} / \text{yr} = 3$

$$\mathcal{L}_{\text{ALP}} \supset \frac{1}{4} g_{\alpha \gamma \gamma} a F_{\mu \nu} \tilde{F}^{\mu \nu}$$

Cui, Kuo, Pradler, and Tsai, arXiv:2207.13107
Interesting models include

1. Deep Theoretical Motivations
2. Thermal Dark Matter
3. Explain Anomalies
4. Connect to Cosmological or Astrophysical Measurements
Summary & Outlook

• **Intensity searches** provide strong probes of rich dark sector motivated by **dark matter** and **experimental anomalies**

• One of the **main efforts for our community** in the next 5 to 10 years.

• Explore other models with other **theory motivations & beyond the simplified models**: connecting to **string theory, grand unification theory**, etc.

• Models with also signatures in **cosmological measurements, direct detection, and astrophysical observations**, are prime targets for the future

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Higgs & ALP Portal:
Both have very interesting dark matter phenomenology; only show minimal models here
Higgs Portal

Batell et al, arXiv:2207.06898

\[ \mathcal{L} \supset \sin \theta S \left( \frac{2m_W^2}{v} W_\mu^+ W_\mu^- + \frac{m_Z^2}{v} Z_\mu Z^\mu - \sum_f \frac{m_f}{v} \bar{f} f \right), \]
\[ \mathcal{L}_{\text{ALP}} \supset \frac{1}{4} g_{\gamma\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu} + ig_{aee} a e^{-\gamma} e + \ldots \]

Batell et al, arXiv:2207.06898
Thank you!

Yu-Dai Tsai, UC Irvine, 22