MAIN IDEAS / THEMES

- flavor physics could be instrumental in searches for dark sector*/dark matter
  - if light, dark sector particles can be produced in FV rare decays
    - axiflavon
    - heavy neutral leptons
    - light scalar mixing with the higgs
    - dark photon
  - sensitivity to dark sectors through off-shell mediators
    - loops: DM+mediators, example: $(g-2)_\mu$
    - tree: mediators, example: $Z'$ from a gauged flavor group
  - baryogenesis/leptogenesis assisted by dark sectors
  - stability of dark matter could be due to flavor symmetries

*here dark sector: any sector feebly coupled to the SM that can act as a portal to DM
DARK MATTER IN RARE DECAYS
• DM could be produced at tree level, if FV couplings
• for flavor diagonal couplings DM can be produced at 1 loop
• X can be (pseudo-)scalar, (axial-) vector mediator
  • can decay to DM or visible

see, e.g., Bird et al, hep-ph/0401195; Kamenik, Smith, 1111.6402
**AXIFLAVON**

- flavor symmetries that explain Yukawa hierarchies have a QCD anomaly
  - example FN models of flavor

Insertions of VEV $\langle \Phi \rangle \equiv v_\Phi > 0$

$Q_{U(1)_H}(\Phi) = -1$

$\langle H \rangle \equiv v = 174 \text{ GeV}$

- axiflavon mechanism: identify PQ symmetry with FN $U(1)_H$
  - the phase of the flavon is the QCD axion = axiflavon

$$\Phi = \frac{f + \phi(x)}{\sqrt{2}} e^{a(x)} f$$

$\mathcal{L}_{\text{eff}} \sim \left( \frac{\phi}{\Lambda_F} \right)^{x_{ij}} h \tilde{q}_i u_j$

$\epsilon \equiv \frac{\phi}{\Lambda_F}$

Wilczek, PRL 49, 1549 (1982)
Calibbi, Goertz, Redigolo, Ziegler, JZ, 1612.08040
Ema, Hamaguchi, Moroi, Nakayama, 1612.05492
SEARCHING FOR AXIONS/AXIFLAVONS

- axion searches use
  - couplings to photons (haloscopos, helioscopes,...)
  - couplings to gluons (CASPEr)
  - flavor diagonal couplings to electrons, nucleons (astrophysical bounds)

- axiflavon
  - in addition flavor violating couplings to fermions
  - in the minimal FN axiflavon model

\[
\begin{align*}
\bar{d}_j & \rightarrow \cdots \ a \sim \frac{\sqrt{m_i m_j}}{f_a} \\
\bar{d}_i & \rightarrow \cdots \\
\end{align*}
\]

\[
\frac{m_a}{\mu eV} \sim \frac{\sqrt{m_i m_j}}{10^{12} GeV}
\]
SEARCHING FOR AXIONS/
AXIFLAVONS

natural axion
as DM window

minimal axiflavlorn

\[ \theta/\pi \]

\[ 10^{-3} \quad 10^{-2} \quad 10^{-1} \quad 10^{0} \]

\[ 10^{-9} \quad 10^{-11} \quad 10^{-13} \quad 10^{-15} \]

\[ g_{a\gamma} \ (1/\text{GeV}) \]

\[ 10^{-17} \quad 10^{-19} \quad 10^{-21} \]

\[ m_a \ (\text{eV}) \]

E787 & E949:
\[ Br(K^+\rightarrow\pi^+a)<7.3 \cdot 10^{-11} \]

NA62 future:
\[ Br(K^+\rightarrow\pi^+a)<10^{-12} \]

Calibbi, Goertz, Redigolo, Ziegler, JZ, 1612.08040
HEAVY NEUTRAL LEPTONS

• neutrino portal

\[ \mathcal{L}_{\text{vector}} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{DS}} + \sum F_{\alpha I}(\bar{L}_\alpha H)N_I \]

• reach depends on flavor structure, example: tau dominance

Sample diagram for heavy \( N_\tau \)
• a new proposal for long lived particle searches at superKEKB
• stage1: 50ab\(^{-1}\), two walls in Tsukubu Hall instrumented
• stage2: 250ab\(^{-1}\), all the walls and the ceiling instrumented

• scintillating fibers, scintillators or MRPCs

Gazelle
Evans, Tammaro, Trabelsi, JZ, to appear

Sample diagram for heavy \(N_\tau\)
MIXING WITH THE HIGGS

- another example: a mediator is a light scalar mixing with the Higgs
  \[ \mathcal{L}_{\text{int}} = -\mu S H^\dagger H \]
  \[ \theta \simeq \mu \nu / m_h^2 \]

- at 1 loop FCNC transitions: \( B \to K^{(*)} S, D \to \pi S, K \to \pi S, \) etc

- can be searched for
  - as a missing mass peak in \( B \to K^{(*)} \nu \bar{\nu} \)
  - from decays to the SM, e.g., \( S \to \mu^+ \mu^- \)

see, e.g., O'Connell et al, hep-ph/0611014; Battell et al, 0911.4938; Winkler, 1809.01876
MIXING WITH THE HIGGS

mixing with the Higgs

inputs #11, #12, #75, #94

PBC, 1901.09966
MIXING WITH THE HIGGS

mixing with the Higgs

preliminary

GAZELLE
Stage 1: 50 ab$^{-1}$
Stage 2: 250 ab$^{-1}$

J. Zupan  Flavor & CPV in dark sectors  11  ESPP, Granada, May 14 2019
MIXING WITH THE HIGGS

more general light $S \rightarrow \mu \mu$ model

$B \rightarrow K(\phi \rightarrow \mu \mu)$
$B^+ \rightarrow K^+(s \rightarrow \mu \mu)$
$B^0 \rightarrow K^0(s \rightarrow \mu \mu)$ (LHCb)
$B \rightarrow X_s \nu \bar{\nu}$

$\sin^2 \theta$

$\sin \theta$

Belle II $B \rightarrow K^{(*)} \nu \bar{\nu}$

Gligorov et al, 1708.09395

J. Zupan  Flavor & CPV in dark sectors

inputs #11, #12, #75, #94
**DARK PHOTON**

- $U(1)_D$ can have kinetic mixing with hypercharge

\[
\mathcal{L}_{\text{vector}} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{DS}} - \frac{\epsilon}{2 \cos \theta_W} F'_{\mu \nu} B_{\mu \nu},
\]

- induces couplings of dark photon to the SM, prop.to charge
**DARK PHOTON**

- $U(1)_D$ can have kinetic mixing with hypercharge

\[ \mathcal{L}_{\text{vector}} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{DS}} - \frac{\epsilon}{2 \cos \theta_W} F^\mu_{\nu} B_{\mu \nu}, \]

- induces couplings of dark photon to the SM, prop.to charge
DARK MATTER IN LOOP CORRECTIONS
DM IN THE LOOPS

• DM + $Z_2$ odd partner can run in the loop
• e.g., can induce $B(s)$, $D$, $K$ mixing

\[ \begin{array}{c}
 s & \chi_i & d \\
 \phi_d & \chi_i & \phi_d \\
 d & \chi_i & s \\
 \end{array} \]

• another example: $(g-2)_\mu$
  • chirality flip can be on the NP fermion leg
  • NP/DM can be at TeV
• if FV present \( \Rightarrow \) induces $\mu \rightarrow e\gamma$

see, e.g., Blanke, Das, Kast, 1711.10493

Calibbi, Ziegler, JZ, 1804.00009

J. Zupan  Flavor & CPV in dark sectors
DM IN THE LOOPS

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J. Zupan  Flavor & CPV in dark sectors 14
**FLAVORFUL Z'**

- anomaly free formulation of Froggatt-Nielsen $U(1)$ motivated by clockwork
  - in traditional FN: $\lambda = \langle \phi \rangle / m \sim 0.2$
  - in anomaly free FN: $\lambda = m / \langle \phi \rangle \sim 0.2$
- anomaly free FN can be gauged flavorful $Z'$
  - could be light, a portal to dark sector

**anom. free FN: vectorlike**

**chiral**

**vectorlike**

**tradition. FN: chiral**

**vector-like**

**chiral**

---

inputs #8, #25, #38, #123

Smolkovic, Tammaro, JZ, to appear

Alonso, Carmona, Dillon, Kamenik, Camalich, JZ, 1807.09792
An anomaly free formulation of Froggatt-Nielsen $U(1)$ can be gauged flavorful $Z'$. In the traditional FN:

$$\lambda = \langle \phi \rangle / m \approx 0.2$$

In the anomaly free FN:

$$\lambda = m / \langle \phi \rangle \approx 0.2$$

An anomaly free FN can be gauged flavorful $Z'$ which could be light, a portal to a dark sector.

The most stringent constraints on direct $Z'$ production come from SN1987a.
• Anomaly free formulation of Froggatt-Nielsen $U(1)$ motivated by clockwork.

- In traditional FN:
  \[ \lambda = \frac{\langle \phi \rangle}{m} \approx 0.2 \]

- In anomaly free FN:
  \[ \lambda = \frac{m}{\langle \phi \rangle} \approx 0.2 \]

- Anomaly free FN can be gauged flavorful $Z'$.

- Could be light, a portal to dark sector.

- Most stringent constraints from direct $Z'$ production in SN1987a if only couplings to quarks.
DARK MATTER
AND BARYOGENESIS
GENERAL COMMENTS

- electroweak/low scale baryogenesis usually requires
  - extra sources of CPV
  - baryon # violation
  - extra NP particles to generate 1st order phase transition or
    out-of equilibrium decays
- counterexample on the next slide:
  - baryon # need not be violated, if there is dark sector that
    carries away baryon #
  - SM CPV may suffice if there is dark sector
- many other options, e.g., baryogenesis can occur in the dark
  sector, baryon # then transferred to the visible sector
BARYOGENESIS FROM

$B$ MIXING

- viable baryogenesis with only SM CPV
- dark particle $\psi$ carries baryon number
  - search at Belle II, LHCb for $B \rightarrow$ baryon+MET
- needs a colored mediator, $Y$, search for it at ATLAS, CMS

---

Elor, Escudero, Nelson, 1810.00880

Out of equilibrium late time decay

CP violating oscillations

B-mesons decay into Dark Matter and hadrons

\[
\text{Br}(B \rightarrow \xi \phi + \text{Baryon}) \simeq 10^{-3} \left( \frac{m_B - m_\psi}{2 \text{ GeV}} \right)^4 \left( \frac{1 \text{ TeV}}{m_Y} \sqrt{y_{ub}y_{\psi s}} \right)^4.
\]

\[
T_{RH} \sim 20 \text{ MeV}
\]

\[
A_{\ell \ell}^d A_{\ell \ell}^s
\]

\[
\text{BR}(B \rightarrow \phi \xi + \text{Baryon} + ...)
\]
Baryogenesis from $B$ mixing

<table>
<thead>
<tr>
<th>Initial State</th>
<th>Final State</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B_d$</td>
<td>$\psi + \Lambda (usd)$</td>
</tr>
<tr>
<td>$B_s$</td>
<td>$\psi + \Xi^0 (uss)$</td>
</tr>
<tr>
<td>$B^+$</td>
<td>$\psi + \Sigma^+ (uus)$</td>
</tr>
<tr>
<td>$\Lambda_b$</td>
<td>$\bar{\psi} + K^0$</td>
</tr>
<tr>
<td>$B_d$</td>
<td>$\psi + n (udd)$</td>
</tr>
<tr>
<td>$B_s$</td>
<td>$\psi + \Lambda (uds)$</td>
</tr>
<tr>
<td>$B^+$</td>
<td>$\psi + p (duu)$</td>
</tr>
<tr>
<td>$\Lambda_b$</td>
<td>$\bar{\psi} + \pi^0$</td>
</tr>
<tr>
<td>$B_d$</td>
<td>$\psi + \Xi_c^0 (csd)$</td>
</tr>
<tr>
<td>$B_s$</td>
<td>$\psi + \Omega_c (css)$</td>
</tr>
<tr>
<td>$B^+$</td>
<td>$\psi + \Xi_c^+ (csu)$</td>
</tr>
<tr>
<td>$\Lambda_b$</td>
<td>$\bar{\psi} + D^- + K^+$</td>
</tr>
<tr>
<td>$B_d$</td>
<td>$\psi + \Lambda_c + \pi^- (cdd)$</td>
</tr>
<tr>
<td>$B_s$</td>
<td>$\psi + \Xi_c^0 (cqs)$</td>
</tr>
<tr>
<td>$B^+$</td>
<td>$\psi + \Lambda_c (dcu)$</td>
</tr>
<tr>
<td>$\Lambda_b$</td>
<td>$\bar{\psi} + \bar{D}^0$</td>
</tr>
</tbody>
</table>

CP violating oscillations

$\text{Br}(B \to \xi \phi + \text{Baryon}) \simeq 10^{-3} \left( \frac{m_B - m_\psi}{2 \text{ GeV}} \right)^4 \left( \frac{1 \text{ TeV}}{m_Y} \sqrt{y_{ub} y_{\psi s}} \right)^4$. 

B-mesons decay into Dark Matter and hadrons

$\text{BR}(B \to \phi \xi + \text{Baryon} + ...)$
CONCLUSIONS/ RANKING

• rare flavor decays probe dark sector mediators to ~few GeV from on-shell process
• if FV sensitivity to much heavier mediators from off-shell
• ranking of facilities depends on your priors
  • versatility: LHCb Upgrade II +CODEXb, Belle III+Gazelle
  • ultimate reach for light portals : Mathusla, Ship
  • light invisible: NA62 (axiflavon), NA64(dark photon)
  • flavorful mediators: classic flavor probes, mu2e, K-\bar{K} mixing, B-\bar{B} mixing, etc.
FLAVON

- FN mechanism involves
  - vector-like fermions (no QCD anomaly)
  - scalar flavon fields
- effective Yukawas governed by flavon insertions (so that invariant under flavor symm.)

\[ \mathcal{L}_{\text{eff}} \sim \left( \frac{\phi}{\Lambda_F} \right)^{x_{ij}} h \bar{q}_i u_j \]

- hierarchy from powers of small parameter \( \epsilon \)
SOLUTION TO THE FLAVOR PUZZLE

- Large hierarchies in quark + lepton masses and in CKM matrix
  - can be addressed via horizontal $U(1)_H$ symmetry
  - SM LH and RH fermions have different $U(1)_H$ charges
  - hierarchical Higgs Yukawas after $U(1)_H$ broken via vev of scalar field, the flavon $\Phi$

\[ \langle H \rangle \equiv v = 174 \text{ GeV} \]

\[ \langle \Phi \rangle \equiv v_\Phi > 0 \]

\[ Q_{U(1)_H}(\Phi) = -1 \]

figure due to F. Goertz
MIXING WITH THE HIGGS

• assuming also $hSS$ coupling nonzero, giving $BR(h \rightarrow SS) = 10^{-2}$
**DARK PHOTON PORTAL TO DARK MATTER**

- in NA64 a search for $e^\pm Z \rightarrow e^\pm Z A'; A' \rightarrow$ invisible.

### Table: 

<table>
<thead>
<tr>
<th>$\mu^-$ beam</th>
<th>Required number of MOT: $10^{11} - 5 \times 10^{13}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z_\mu \rightarrow \nu \nu$</td>
<td>(g-2)$_\mu$ anomaly: $g^\mu_y &lt; 10^{-4}$, with $\leq 10^{11}$ MOT</td>
</tr>
<tr>
<td>$Z_\mu \rightarrow \chi \bar{\chi}$</td>
<td>$y &lt; 10^{-12}$ for $m_\chi &lt; 300$ MeV with $\approx 10^{13}$ MOT</td>
</tr>
<tr>
<td>$a_\mu \rightarrow$ invisible</td>
<td>$10^{-4} &lt; m Q &lt; 0.1$ e, $10^{-3} &lt; m m Q &lt; 2.5$ GeV</td>
</tr>
<tr>
<td>$\mu - \tau$ conversion</td>
<td>$g_y \lesssim 10^{-2}$, $m_{\mu} \approx 1$ GeV</td>
</tr>
<tr>
<td>Lepton Flavour Violation</td>
<td>$\sigma(\mu - \tau) / \sigma(\mu \rightarrow all) \lesssim 10^{-11}$</td>
</tr>
</tbody>
</table>

### Graph:

- $y = e^2 a_D m_\chi / m_A^4$ for $\alpha_D = 0.1$

- Graph showing the sensitivity of NA64 and other experiments to $\alpha_D$ with $m_\chi = 0.1$ GeV.

- E137, NA64, LSND, Majorana, CP violation, etc.

### Table: 

<table>
<thead>
<tr>
<th>$\pi^-$, $K^-$ beams</th>
<th>Current limits, PDG 2018</th>
<th>Required number of POT(KOT): $5 \times 10^{12}(5 \times 10^{11})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pi^0 \rightarrow$ invisible</td>
<td>$\text{Br}(\pi^0 \rightarrow$ invisible) $&lt; 2.7 \times 10^{-7}$</td>
<td>$\text{Br}(\pi^0 \rightarrow$ invisible) $&lt; 10^{-9}$</td>
</tr>
<tr>
<td>$\eta \rightarrow$ invisible</td>
<td>$\text{Br}(\eta \rightarrow$ invisible) $&lt; 1.0 \times 10^{-4}$</td>
<td>$\text{Br}(\eta \rightarrow$ invisible) $&lt; 10^{-8}$</td>
</tr>
<tr>
<td>$\eta' \rightarrow$ invisible</td>
<td>$\text{Br}(\eta' \rightarrow$ invisible) $&lt; 5 \times 10^{-4}$</td>
<td>$\text{Br}(\eta' \rightarrow$ invisible) $&lt; 10^{-7}$</td>
</tr>
<tr>
<td>$K^0_S \rightarrow$ invisible</td>
<td>no limits</td>
<td>$\text{Br}(K^0_S \rightarrow$ invisible) $&lt; 10^{-9}$</td>
</tr>
<tr>
<td>$K^0_L \rightarrow$ invisible</td>
<td>no limits</td>
<td>$\text{Br}(K^0_L \rightarrow$ invisible) $&lt; 10^{-7}$</td>
</tr>
</tbody>
</table>

- $K^0_S \rightarrow \pi^+ \pi^- \nu \bar{\nu}$ complementary to $K^- \rightarrow \pi^+ \nu \nu$.
MINIMAL AXIFLAVON

- most stringent bounds from kaon sector

\[ \text{BR}(K^+ \rightarrow \pi^+ a) \simeq 1.2 \cdot 10^{-10} \left( \frac{m_a}{0.1 \text{ meV}} \right)^2 \left( \frac{\kappa_{sd}}{N} \right)^2 \]

- 90% CL combined bound from E787 and E949

\[ \text{BR}(K^+ \rightarrow \pi^+ a) < 7.3 \cdot 10^{-11} \]

\[ f_a \gtrsim \frac{\kappa_{sd}}{N} \times 7.5 \cdot 10^{10} \text{ GeV} \]

- note: the weak annihilation where FV from W exchange is always negligible

\[ \frac{\Gamma(K^+ \rightarrow \pi + a)_{\text{w.a.}}}{\Gamma(K^+ \rightarrow \pi + a)} \sim \left( \frac{f_K f_{\pi}}{m_W^2} \right)^2 \left( \frac{\lambda_{11,22}^d}{\lambda_{12,21}^d} \right)^2 \sim 10^{-12} \]
BARYOGENESIS AND VARYING YUKAWAS

- in models of flavor Yukawas have dynamical origin
- viable EWBG if Yukawas change during EW phase transition
  - strong 1st order phase transition
  - large Yukawas at early times, thus enhanced sources of CPV
- models: two flavon FN, RS with Goldberger-Wise, composite Higgs
- searches at LHC: searches for flavons, radion/dilaton, other states part of complete models
- searches at Belle II: all the classic flavor observables - $B$ mixing, etc
  - sometimes model dep. modes, e.g. decay to axiflavon, $a$: $B \rightarrow Ka, D \rightarrow \pi a$, etc

Calibbi, Goertz, Redigolo, Ziegler, JZ, 1612.08040
viable baryogenesis with only SM CPV
• dark particle $\psi$ carries baryon number
  • search at Belle II, LHCb for $B \rightarrow \text{baryon} + \text{MET}$
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Elor, Escudero, Nelson, 1810.00880