WHAT IS DM AGAIN?

1. Stable, cold, (almost) collisionless, dissipationless substance
2. Interacts (only?) gravitationally
3. Makes up ~25% of the energy density of the universe
4. Mass?

Galaxy formation
\[ \lambda_{dB} = \frac{2\pi}{mv} \lesssim 100 \text{ kpc} \]
\[ m \gtrsim 10^{-24} \text{ eV} \]

[Viitikainen et al., PRD 91 (2015)]

microlensing searches of PBHs
\[ m \lesssim 10^{46} \text{ GeV} \]
THE FUZZY DM PARADIGM

Dwarf galaxies

• Standard CDM typically produces too much small scale structure
• Can be suppressed if DM de Broglie wavelength prohibits small scale structures:

\[ m_{\text{DM}} \approx 10^{-22} \text{ eV} \quad \Rightarrow \quad \lambda_{\text{dB}} \gtrsim 1 \text{kpc} \]

[Hu, Barkana, Gruzinov, PRL 85 (2000)]

Better fit to small scale structure!

THE FUZZY DM PARADIGM

- Small scale is set by a balance of gravity and quantum pressure:
  
  No self-interactions!

- Self-interactions may drastically alter situation:
  
  repulsive $\lambda > 0$

  attractive $\lambda < 0$

Relaxed mass range: [Ferreira, 2005.03254]

$m_{\text{DM}} \approx 10^{-22} - 1 \text{ eV}$

Instabilities!

[Guth et al. PRD 92, 2015]

Focus of this talk!
Most economic way to couple fuzzy DM to SM via Higgs Portal:

\[ \mathcal{L} = \frac{1}{2} \partial_\mu s \partial^\mu s - \frac{1}{2} m_s^2 s^2 - \frac{1}{4!} \lambda_s s^4 - \frac{1}{2} \lambda_{h.s} s^2 H^\dagger H \]

DM is protected by a \( \mathbb{Z}_2 \) symmetry and has positively bounded potential \( \lambda_s > 0 \Rightarrow \) a priori wide range of FDM masses allowed!

In the FDM regime the occupation numbers are huge

\[ n \lambda_{dB}^3 \approx 6.35 \cdot 10^5 \left( \frac{\text{eV}}{m} \right)^4 \]

\( \Rightarrow \) can be treated as a classical wave!

How do we search for wave DM?
At low momenta Higgs portal mediates an effective DM-nucleon coupling
\[ \mathcal{L} \supset -\frac{1}{2} \lambda_h s^2 H^+ H \rightarrow c_{sNN} s^2 \bar{N}N \]
where now
\[ s^2 = s_0^2 \cos^2(m_s t) \rightarrow \frac{s_0^2}{2} (1 + \cos(2m_s t)) \]

LIGHT DM – HIGGGS PORTAL

<table>
<thead>
<tr>
<th>Fifth force</th>
<th>Premordial helium abundance</th>
</tr>
</thead>
<tbody>
<tr>
<td>[ m_N = m_P \propto c_{sNN} s_0^2 ]</td>
<td>[ c_{sNN} = \lambda_h \frac{m_N}{m_h^2} \frac{2n_H}{3(11 - \frac{2}{3} n_L)} ]</td>
</tr>
</tbody>
</table>

[Brax et al., PRD 97, 2018]
[Hees et al., PRD 98, 2018]
[Bauer, PF, Reimitz, Plehn, 2005.13551]
Light DM – Higgs Portal

- At low momenta, the Higgs portal mediates an effective DM-nucleon coupling

\[ \mathcal{L} \supset -\frac{1}{2} \lambda_{hs} s^2 H^\dagger H \rightarrow c_{sNN} s^2 \bar{N}N \]

where now

\[ s^2 = s_0^2 \cos^2(m_s t) \rightarrow \frac{s_0^2}{2} \left( 1 + \cos(2m_s t) \right) \]

[Bauer, PF, Reimitz, Plehn, 2005.13551]
• Consider model with new weak scale mediator $\phi$

\[
\mathcal{L} \supset \frac{1}{2} m_\phi^2 \phi^2 - \frac{\mu_{\phi s}}{2} \phi s^2 - \frac{\alpha_s}{\Lambda_\phi} \phi \, \text{Tr}[G_{\mu \nu} G^{\mu \nu}] \quad \rightarrow \quad c_{s NN} \, s^2 \, \bar{N} N
\]

• High mass window rather unconstrained!

[Bauer, PF, Reimitz, Plehn, 2005.13551]
LIGHT DM – ALPS

• Maybe best motivated candidate for FDM is an axion-like particle. It has a reason to be very light.

• Axions are Nambu-Goldstone particles, protected by shift symmetry:

\[ \Phi = (f + s)e^{ia/f} \quad \text{and} \quad e^{ia/f} \to e^{i(a+c)/f} = e^{ia/f}e^{ic/f} \]

• Mass is generated by small explicit breaking:

\[ V(a) = \Lambda^4 \left[ 1 - \cos \left( \frac{a}{f} \right) \right] = \frac{\Lambda^4}{2f^2} a^2 + \ldots \]

with the heavy axion scale \( f = \mathcal{O}(f_{\text{GUT}}) \)
LIGHT DM – ALPS

- Consider model with new weak scale mediator $\phi$ and ALP DM candidate $a$. Only shift-symmetric couplings allowed:

\[
\mathcal{L} \supset -\frac{1}{2} m_\phi \phi^2 - \frac{\partial_\mu a \partial^\mu a}{2 \Lambda_{\phi a}} \phi - \frac{\alpha_S}{\Lambda_\phi} \phi \text{ Tr}[G_{\mu\nu} G^{\mu\nu}] \rightarrow c_{aNN} \partial_\mu a \partial^\mu a \bar{N}N
\]

- Almost unconstrained at low masses because of momentum suppression:

\[
\propto q^4
\]

[Bauer, PF, Reimitz, Plehn, 2005.13551]
NEW SEARCH STRATEGIES AT LHC

• Conventional direct and indirect DM search strategies hopeless due to low momenta of (U)LDM

• But production at LHC enhances momenta:

Direct detection @ LHC
(Deep inelastic scattering)

Indirect detection @ LHC
(Background annihilation)

[Bauer, PF, Reimitz, Plehn, 2005.13551]
DIRECT DETECTION

- Boosted DM can undergo DIS in detector material and produce jets.

1. E.g. Higgs Portal:

\[ N_{\text{DIS}} = \mathcal{L}_{\text{HL}} \sigma_h \text{BR}_{h \rightarrow ss} P_{\text{DIS}} \]

with \( P_{\text{DIS}} = 1 - e^{L_{\text{det}} n_x \sigma_x} \)

Distinguishable from LLPs:

\[ n_{Pb} \gg n_{Xe} \]

But unfortunately for HP:

\[ \frac{d^2 \hat{\sigma}_{\text{DIS}}}{dx \, dy} = \frac{\lambda_{h,s}^2 g_{hgg}^2}{4\pi \hat{s}} \frac{Q^4}{(Q^2 + m_h^2)^2} \]

\[ P_{\text{DIS}} = 1 - e^{L_{\text{L}} n_{Pb} \sigma_{Pb} e^{L_{\text{H}} n_{Fe} \sigma_{Fe}}} \approx 7.5 \cdot 10^{-21} \]

[But unfortunately for HP:]

[2005.13551]
2. Scalar DM with scalar mediator

\[
\frac{d^2 \hat{\sigma}_{\text{DIS}}}{dx \, dy} = \frac{\alpha_s^2}{4 \pi \, \hat{s}} \left( \frac{\mu_{\phi s}}{\Lambda_\phi} \right)^2 \frac{Q^4}{(Q^2 + m_{\phi}^2)^2}
\]

LHC
\[
m_{\phi} = 100 \, \text{GeV}
\]
\[
\langle E_s \rangle = 39. \, \text{GeV}
\]

Dijet + ISR

\[
\frac{1}{\Lambda_\phi} \quad \text{[GeV]}^{-1}
\]
\[
\mu_{\phi s} \quad \text{[GeV]}
\]

Supernova Cooling

3. ALP DM with scalar mediator

$$\frac{d^2 \sigma_{\text{DIS}}}{dx \, dy} = \frac{\alpha_s^2}{16 \pi} \frac{Q^4}{s} \frac{\Lambda_{\phi_a}^2 \Lambda_{\phi}^2}{Q^2 + m_{\phi}^2} \left( \frac{Q^2 + 2m_a^2}{Q^2 + m_{\phi}^2} \right)^2$$

\[N_{\text{DIS}}\]

**LHC**

- $m_\phi = 100$ GeV
- $\langle E_a \rangle = 50$ GeV

Disappearance Domains:
- Dijet + ISR
- Subnuclear Cooling

**DIS @ HL-LHC**

- $m_\phi = 100$ GeV
- $\Lambda_{\phi_a} = 10$ GeV

**DIS @ FCC**

[14]

[Bauer, PF, Reimitz, Plehn, 2005.13551]
WHAT ABOUT BOOSTED FLAVOR

- Axion couplings to weak gauge bosons
  \[ \mathcal{L} \supset (\partial_\mu a)^2 - \frac{m_a^2}{2}a^2 - \frac{g_a WW}{4} a \text{ Tr}[W_{\mu\nu} \tilde{W}^{\mu\nu}] \]
  induces flavor decays
  \[ B \rightarrow K^{(*)} a \]
  \[ K \rightarrow \pi a \]

- Tagged flavor decay plus recoil jet as emerging signature for Belle-II or LHCb?

- E.g. LHCb produces large numbers of boosted B’s:
  median \( p_a \sim 40 \text{ GeV} \)
  and 20% \( p_a > 90 \text{ GeV} \)

[thanks to Martino Borsato for these numbers]

[Izaguirre, Lin, Shuve, PRL118 (2017)]
SUMMARY

- (U)LDM can be produced at the LHC with large boost and then be detected by recoil jets produced in DIS

- Complementary to existing direct detection or ULDM probes! Promising for momentum-suppressed interactions!

- Potentially interesting signature for flavor in LHCb, Belle-II, …

- Many more improvements and generalizations:
  - quark couplings
  - SM neutrinos, steriles
  - meson decays
  - new detectors
  - …
BACKUP
INDIRECT DETECTION @ LHC

- ULDM has huge occupation numbers, so can it annihilate with the halo background field if produced at LHC?

\[ n_{\text{DM}} = \frac{\rho_{\text{DM}}}{m_s} \approx 3 \times 10^{30} \left( \frac{10^{-22} \text{ eV}}{m_s} \right) \]

- But cross section scales with mass \( \sigma_{\langle s \rangle s \rightarrow \gamma \gamma} \approx \frac{\lambda_{h s}^2 \sigma_{h s}}{4\pi} \frac{m_s}{m_h^3} \)

- Mean free path independent of mass and very large

\[ \lambda = \frac{1}{n_{\text{DM}} \sigma_{\langle s \rangle s \rightarrow \gamma \gamma}} = \frac{4\pi}{\lambda_{h s}^2 \sigma_{h s}} \frac{m_h^3}{\rho_{\text{DM}}} \geq 10^{43} \text{ m} \]

- Larger cross section above electron threshold, but also much lower densities!
VARIATION OF CONSTANTS

- Fundamental constants like $m_f, \alpha$ or $m_V$ are described by SM operators

$$\mathcal{L}_{\text{SM}} \supset - \sum_f m_f \bar{f} f - \frac{F_{\mu \nu} F^{\mu \nu}}{4} + \sum_V \delta_V m_V^2 V_\mu V^\mu$$

- In the presence of ULDM these operators modified, e.g. in the Higgs portal

$$\mathcal{L} \supset \frac{\lambda_{hs} m_f}{2 m_h^2} s^2 \bar{f} f - \frac{\lambda_{hs} g h_{\gamma \gamma}}{2 m_h^2} \frac{1}{s^2} F_{\mu \nu} F^{\mu \nu} - \lambda_{hs} \delta_V \frac{m_V^2}{m_h^2} s^2 V_\mu V^\mu$$

where the DM field is described by the classical wave

$$s^2 = s_0^2 \cos^2(m_s t) \rightarrow \frac{s_0^2}{2} (1 + \cos(2m_s t))$$