Portals to the Dark Sector

Brian Batell
University of Pittsburgh

GGI Tea Breaks Theory Colloquium
March 24, 2021
The Energy Budget of the Universe

- Dark Energy: 69%
- Dark Matter: 26%
- Normal Matter: 5%
We’ve made progress in our understanding...
Dark Matter

- Dark Energy: 69%
- Dark Matter: 26%
- Normal Matter: 5%
Gravitational Evidence for Dark Matter
The search for non-gravitational dark matter interactions is a top priority today.
Is there any good reason to expect dark matter to have non-gravitational interactions?
Cosmological Genesis of Dark Matter

Dark matter may have been produced from particle reactions in the hot plasma during the Big Bang.

Suggests non-gravitational interactions with normal matter.
At early times, \( T \gg m_\chi \), both DM annihilation and production (inverse annihilation) are efficient.

As temperature drops, \( T \lesssim m_\chi \), DM production is kinematically disfavored, and DM begins to annihilate away.

Eventually, DM freeze-out occurs when annihilation rate becomes smaller than the Hubble rate.

Relic abundance of DM controlled by the annihilation cross section \( \langle \sigma v \rangle \)

\[
\Omega_\chi h^2 \sim 0.1 \left( \frac{p_b}{\langle \sigma v \rangle} \right)
\]
What’s here?

\[
\chi, \bar{\chi}, \text{SM}
\]
Weakly Interacting Massive Particle (WIMP)

- Dark matter may be charged under the electroweak interaction (e.g., neutralino in the MSSM)

\[ \langle \sigma v \rangle \sim \frac{\pi \alpha_W^2}{m^2_\chi} \sim 1 \text{ pb } \times \left( \frac{\alpha_W}{(1/30)} \right)^2 \left( \frac{\text{TeV}}{m_\chi} \right)^2 \]

- Dark matter with weak interactions and weak scale mass is produced with the observed relic abundance

“WIMP Miracle”
WIMP Phenomenology

Production at Colliders

\[ \chi \rightarrow \text{SM} \]

\[ \bar{\chi} \rightarrow \text{SM} \]

Direct Detection

Indirect Detection
So far, there are no signs of WIMPs

The WIMP framework is well-motivated and we should continue searching for WIMPs

It’s also time to open our minds and consider other possibilities for dark matter
What if dark matter does not experience the known forces of nature?
The Dark Sector Paradigm

Standard Model

Dark Sector
The Dark Sector Paradigm

- Dark matter
- Dark forces
- Other dark particles
The Dark Sector Paradigm

Standard Model ➔ Portal ➔ Dark Sector

- Non-gravitational interaction with ordinary matter

- Dark matter
- Dark forces
- Other dark particles
Portals may mediate non-gravitational interactions between dark matter and ordinary matter.
History lesson - 1930s:

• Back then, the “Standard Model” was photon, electron, nucleons

• Beta decay: \( n \rightarrow p + e^- \)

  Continuous spectrum!

• Pauli proposes a radical solution - the neutrino!

  \( n \rightarrow p + e^- + \bar{\nu} \)

• Perfect example of a “dark sector”
  • neutrino is electrically neutral
  • very weakly interacting and light
  • interacts with “Standard Model” through “portal” -  
    \[ (\bar{p} \gamma^\mu n)(e \gamma_\mu \nu) \]
Lee-Weinberg Bound

Light thermal DM interacting via weak interactions generically overproduced

\[ \langle \sigma v \rangle \sim \frac{G_F^2 m_{\chi}^2}{\pi} \approx 1 \text{ pb} \times \left( \frac{m_{\chi}}{5 \text{ GeV}} \right)^2 \]

\[ m_{\chi} \gtrsim \mathcal{O} \left( \text{GeV} \right) \]

Lee-Weinberg bound evaded with new light mediators

[Boehm, Fayet]
[Boehm, Fayet]

\[ \langle \sigma v \rangle \sim \frac{g_X^2 g_f^2 m_{\chi}^2}{m_{Z'}^4} \sim 1 \text{ pb} \times \left( \frac{g_X}{0.5} \right)^2 \left( \frac{g_f}{0.001} \right)^2 \left( \frac{m_{\chi}}{100 \text{ MeV}} \right)^2 \left( \frac{1 \text{ GeV}}{m_{Z'}} \right)^4 \]

Light DM

WIMPs

\sim 10^{-22} \text{ eV}

\sim 100 \text{ TeV}

\sim 30 M_{\odot}
Benchmark model: Vector Portal Dark Matter

\[ \mathcal{L} \supset |D_\mu \chi|^2 - m_\chi^2 |\chi|^2 - \frac{1}{4} (F'_{\mu \nu})^2 + \frac{1}{2} m_{A'}^2 (A'_{\mu})^2 - \frac{\epsilon}{2} F'_{\mu \nu} F^{\mu \nu} + \ldots \]

- Dark photon mediates interaction between DM and SM
- 4 new parameters: \( m_\chi, m_{A'}, \alpha_D, \epsilon \)
- Thermal target:

\[ \langle \sigma v \rangle \sim \frac{\epsilon^2 \alpha_D \alpha m_\chi^2}{m_V^4} \sim \frac{y}{m_\chi^2} \]

\[ y \equiv \epsilon^2 \alpha_D (m_\chi / m_{A'})^4 \]

Observed DM relic abundance predicted along this line

[Holdom]
[Hooper, Zurek]
[Arkani-Hamed, et al]
Proton Beam Dump Dark Matter Searches

- Can be done with existing and near future accelerator neutrino experiments, e.g., MiniBooNE, NOvA, T2K, MicroBooNE, SBN, ICARUS, DUNE…

Dark matter production in proton-target collisions

Dark Matter scattering in detector

[BB, Pospelov Ritz]
[deNiverville, Pospelov Ritz]
[McKeen, deNiverville, Ritz]
[Coloma, Dobrescu, Frugiuele, Harnik]
[Kahn, Krnjaic, Thaler, Toups]
… many others
Dark matter production mechanisms:

- Neutral mesons decays
- Bremsstrahlung + vector meson mixing
- Direct production

Dark matter detection via scattering:

- Elastic electron, nucleon, nucleus (coherent) scattering
- Inelastic neutral pion production
- Deep inelastic scattering

BdNMC
[deNiverville, Chen, Pospelov, Ritz]
https://github.com/pgdeniverville/BdNMC/releases

- Publicly available proton beam fixed target DM simulation tool developed by P. deNiverville (LANL)
MiniBooNE-DM @ FNAL

- Dedicated off target / beam dump run mode, collected 1.9E20 POT
- Leading limits on vector portal dark matter model for ~ 100 MeV mass range
- Demonstrates proton beam dump as an effective search method for light dark matter

- 8 GeV protons on iron dump; 800 ton mineral oil detector

[MiniBooNE-DM
**DUNE-PRISM @ FNAL**

- 120 GeV protons on graphite target
- DUNE-PRISM movable near detector allows sensitive search to light dark matter
- DM-to-neutrino flux increases as detector is moved off axis
  - Neutrinos produced through decay of charged mesons, which are focused by magnetic horn
  - DM produced through decay of unfocused neutral mesons

---

[De Romeri, Kelly, Machado]
[Breitbach, Buonocore, Frugiuele Kopp, Mittnacht]
Dark Matter in the far-forward region at the LHC

- Total LHC pp cross section is \(\sim 100 \text{ mb}\), and mainly directed in the forward region
- Energetic, low \(p_T\), light particles, e.g., \(\sim 10^{17}\) pions, TeV energies, mrad angles
- The FASER experiment will exploit this to search for long-lived, light, weakly interacting particles [Feng, Galon, Kling, Trojanowski]

- There is a proposal to construct a larger Forward Physics Facility for the HL-LHC era - see the kickoff workshop for physics opportunities: [https://indico.cern.ch/event/955956](https://indico.cern.ch/event/955956)

- Can also use this approach to search for light dark matter [BB, Feng, Trojanowski]
Dark Matter in the far-forward region at the LHC

- Two detector options considered:
  - FASERν2: Emulsion Detector 10-ton scale
  - FLArE: LArTPC 10, 100- ton scale

- Kinematic, topological cuts can mitigate neutrino backgrounds

- FASERν2, FLArE can probe a significant region of cosmologically motivated parameter space
Missing energy / momentum searches for dark matter

$E_e^f \ll E_B$

[Andreas. et al]
[Izaguirre, Krnjaic, Schuster, Toro]
[Kahn, Krnjaic, Tran, Whitbeck]
• 100 GeV electron beam incident on ECAL

• Dark matter produced in ECAL and carries most of the beam energy

• Large missing energy signature (small energy deposition in ECAL, no energy deposition in HCAL)

• $2.84 \times 10^{11}$ EOT - best limits on invisibly decaying dark photon below 300 MeV

• Future datasets with electron and muon beams can probe a significant parts of the thermal relic targets
LDMX @ SLAC

- Proposed electron beam experiment utilizing missing momentum technique

- More kinematic handles to reject backgrounds, discriminate final state electrons from photons

- Can cover most thermal targets, irrespective of dark matter particle nature

Initial design study, 1808.05219
Electron-positron colliders

- Large cross sections, high luminosities, hermetic detectors; complementary to fixed target experiments

- Invisible dark photon: mono-photon signature - peak in recoil mass spectrum
  
  
  [Izaguirre, Krnjaic, Schuster, Toro]
  
  [Essig, Mardon, Papucci, Volansky, Zhong]

- BABAR places strongest limits for dark photon masses between 100 MeV - 10 GeV  [BABAR, 1702.03327]

- Belle II will collect O(50/ab), and will be able to probe new parameter space with early data.

- Searches also being done at other flavor factories, e.g. BESIII, KLOE

[Belle II Physics Book, 1808.10567]
**Direct Detection of sub-GeV Dark Matter**

- Traditional direct detection through nuclear recoils loses sensitivity to dark matter lighter than about 1 GeV

- A number of novel approaches to sub-GeV dark matter direct detection are being pursued, including

  - Dark matter-electron scattering (e.g., in noble liquids, semiconductors, …)
  - Dark matter-nuclear scattering (e.g., via Migdal effect and bremsstrahlung)
  - Dark matter scattering off collective modes in molecules and in crystals (e.g., phonons, plasmons and magnons)

[see work by e.g., Caputo, Esposito, Geoffray, Graham, Griffin, Hochberg, Ibe, Kaplan, Kahn, Knapen, Krnjaic, Griffin, Lin, Lisanti, Melia, Mitridate, Nakano, Polosa, Pradler, Pyle, Rajendran, Schutz, Shoji, Sun, Suzuki, Trickle, Walters, Yu, Zhang, Zhao, Zurek, …]
DM-nuclei scattering

\[ E_R = \frac{q^2}{2m_N} \sim \frac{\mu_{\chi N}^2 v^2_\chi}{m_N} \approx 1 \text{keV} \left( \frac{m_\chi}{\text{GeV}} \right)^2 \left( \frac{130 \text{ GeV}}{m_N} \right) \]

DM-electron scattering

\[ \frac{1}{2} m_\chi v^2_\chi > \Delta E_{\text{binding}} \rightarrow m_\chi \gtrsim 1 \text{MeV} \left( \frac{\Delta E_{\text{binding}}}{1 \text{eV}} \right) \]

\[ E_R \sim qv \sim (m_e \alpha) v \approx 4 \text{eV} \]
SENSEI

- Silicon Skipper-CCD detector sensitive to DM-electron scattering

- Repeated sampling allows for precise measurement of pixel charge — ultra-low noise and low threshold

- First results using 2 gram x 24 day exposure sets leading limits in 1-10 MeV mass range

- Projections for future Si-Skipper CCD experiments

[SENSEI Collaboration PRL, 125, 171802]

Figure from T.T.Yu
Neutrino Portal and Seesaw Mechanism

- Neutrinos have a tiny non-zero mass ($10^{-10}$ smaller than the proton mass!)

Seesaw mechanism for neutrino mass:

$$y L H N + \frac{1}{2} M N^2 + \text{h.c.}$$

Mass mixing:

$$\begin{pmatrix} \nu \\ N \end{pmatrix} \begin{pmatrix} 0 & y \nu \\ y \nu & M \end{pmatrix} \begin{pmatrix} \nu \\ N \end{pmatrix} \implies m_\nu \sim \frac{y^2 \nu^2}{M}, \quad m_N \sim M$$

- Heavy neutrino inherits weak interaction of light neutrino
- Interaction strength suppressed by mixing angle $U$

[Minkowski; Yanagida; Mohapatra, Senjanovic; Gell-Mann, Ramond, Slansky; Schechter, Valle]

[2015 Nobel Prize to T. Kajita and A. McDonald]

From Khalil, Moretti
Neutrino Portal Dark Matter

\[ -\mathcal{L} \supset m_\phi^2 |\phi|^2 + m_\chi \bar{\chi}\chi + m_N \bar{N}N + \left[ \lambda_\ell \bar{L}_\ell \hat{H} N_R + \phi \bar{\chi} (y_L N_L + y_R N_R) + \text{h.c.} \right] \]

- Approximate lepton number symmetry allows for light SM neutrinos even if the Yukawa coupling $\lambda_\ell$ (and active sterile mixing) is large

\[ \nu_4 = \left( U_{N4}^* N_L + \sum_\ell U_{\ell4}^* \nu_\ell L \right) U_{\ell4} = \frac{\lambda_\ell \nu}{m_4}, \quad |U_{N4}| = \frac{m_N}{m_4} = \sqrt{1 - \sum_\ell |U_{\ell4}|^2}. \]

- Large mixing allows for a sizable DM - SM neutrino coupling

\[ y_L \phi \bar{\chi}_R N_L + \text{h.c.} \]

\[ \rightarrow y_L |U_{N4}| \phi \bar{\chi}_R \nu_4 L - y_L \sqrt{1 - |U_{N4}|^2} \phi \bar{\chi}_R \nu_4 L + \text{h.c.} \]

- Important implications for cosmology and phenomenology
“Invisible” Sterile Neutrino

\[ m_N > m_\phi, m_\chi \]

\[ \nu_4 \rightarrow \chi \]

\[ \phi \rightarrow \chi \]

\[ \bar{\chi} \rightarrow \nu \]

Phenomenology

- Fermi constant (muon lifetime); PMNS non-unitarity; EW precision; CKM unitarity
- Muon, tau, Meson decays (peak searches); lepton universality tests;
- Invisible Z, Higgs decays; Drell-Yan (W decays)
- Atmospheric oscillations (relevant for \( \nu_\tau \))
Direct annihilation to light SM neutrinos

\[ \vec{\chi} \rightarrow \bar{\nu}_l \]

\[ \chi \rightarrow \nu_l \]

\[ \propto U^2 \]

\[ \langle \sigma v \rangle \simeq \frac{Y}{32\pi m_\chi^2} \]

\[ Y \equiv y_L^4 \left( \sum_i |U_{4i}|^2 \right)^2 \frac{m_\chi}{m_\phi} \]

- Represent conservative constraints on the thermal hypothesis
- New ideas to probe remaining open parameter space are welcome!
Visible Decays of Portal Mediators

[Physics Beyond Colliders Report, 1901.09966]

Dark photon, vector portal

Heavy neutral lepton, neutrino portal

Dark scalar, Higgs portal
Higgs Portal to the Dark Sector

• Dark scalar couples just like Higgs, but with couplings suppressed by mixing angle

\[ -\mathcal{L} \supset (\mathcal{A}S + \mathcal{S}^2)H^\dagger H \rightarrow \sin \theta \frac{m_f}{v} S \bar{\psi} \psi + \ldots \]

• Past experiments strongly constrain dark matter annihilating to SM through the Higgs portal [Krnjaic ’15]

• Expect dark matter is heavier than scalar and scalars decay to visible particles

Scalar may be long-lived!
Higgs Portal at Fermilab
DarkQuest Experiment

- DarkQuest is a proposed upgrade of the Fermilab SeaQuest nuclear physics experiment
- 120 GeV protons from the Fermilab Main Injector impinge on ~ 5m iron beam dump
- Magnetic field (KMAG), 4 tracking stations, muon ID system, Electromagnetic calorimeter
Higgs Portal at Fermilab
DarkQuest Experiment

- Dark scalar production:
  - Proton Bremsstrahlung
  - Gluon fusion
  - Meson decay

- DarkQuest will have excellent sensitivity to GeV scale Higgs portal scalars
  - Phase I: $10^{18}$ POT, 5-6m decay region
  - Phase II: $10^{20}$ POT, 7-12m decay region
Dark sectors may play a role in addressing other puzzles in nature
Dark Sectors and the Hierarchy Problem

Twin Higgs

\[ |H_A|^2 |H_B|^2 \]

\[ Z_2 : A \leftrightarrow B \]

[Chacko, Harnik, Goh]
[Barbieri, Gregoire, Hall]

NNaturalness

\[ \Lambda_H^2 \]

\[ m_H^2 \]

\[ v = 0 \]

\[ v > v_{us} \]

\[ v_{us} = 246 \text{ GeV} \]

[Arkani-Hamed, D’Agnolo, Cohen, Hook, Kim, Pinner]

Relaxation

[V(\phi)]
The Twin Higgs

Scalar potential has approximate SU(4) symmetry

\[ \mathcal{H} = \begin{pmatrix} H_A \\ H_B \end{pmatrix} \]

forces radiative correction to scalar mass to be SU(4) symmetric

No correction to pNGB Higgs mass

Neutral fermionic top partners

Note: small \( Z_2 \) breaking is required to obtain desired vacuum alignment
Mirror Symmetric Twin Higgs

- Exact copy of the SM in the mirror sector

- Phenomenology:
  - Higgs portal $|H_A|^2|H_B|^2$
  - Reduced Higgs coupling to SM states
  - $h_A \rightarrow b_B \bar{b}_B \rightarrow \text{invisible}$

[Image of tuning graph]

[Image of diagram showing SM and Twin with UV states 5-10 TeV, $t_B$, $W_B, Z_B$, $t_A$, $h_A$, $W_A, Z_A$, $b_B$, $b_A$]

[Burdman, Chacko, Harnik, de Lima, Verhaaren]
Dynamical Breaking of Twin Gauge and $Z_2$ Symmetries

[BB, Verhaaren]
[see also Liu, Weiner]

- Add hypercharged or colored scalars in both sectors. Assume $Z_2$ is “exact”

\[
\begin{align*}
\text{SM}_A & \quad + \quad \Phi_A \sim (1, 1, Y)_A \\
\text{SM}_B & \quad + \quad \Phi_B \sim (1, 1, Y)_B
\end{align*}
\]

- Vacuum spontaneously breaks twin hypercharge and $Z_2$:
  \[
  \langle \Phi_A \rangle = 0 \quad \langle \Phi_B \rangle = f_\Phi
  \]

- An effective $Z_2$-breaking mass term causes $\langle H_A \rangle \ll \langle H_B \rangle$:
  \[
  V \supset \delta_{H\Phi}(|\Phi_A|^2 - |\Phi_B|^2)(|H_A|^2 - |H_B|^2) \rightarrow -\delta_{H\Phi} f_\Phi^2 (|H_A|^2 - |H_B|^2)
  \]

- New dynamical fermion mass terms are allowed in the twin sector
  \[
  \lambda \Phi_B \psi_B \psi_B' \rightarrow \lambda f_\Phi \psi_B \psi_B'
  \]
Couplings of $\Phi_B$ and Twin Fermion Masses ($Y = 1$)

$$-\mathcal{L}_{Y=1} \supset \frac{1}{2} \lambda_1 \Phi_B^+ L_B L_B + \frac{c_1}{\Lambda} \Phi_B^- L_B H_B \bar{\ell}_B + \frac{c_2}{\Lambda} \Phi_B^+ Q_B H_B^\dagger \bar{u}_B + \frac{c_3}{\Lambda} \Phi_B^- Q_B H_B \bar{d}_B + \text{h.c.}$$

$$\supset \lambda_1 f_\Phi \nu_B \ell_B + \frac{v_B f_\Phi}{\sqrt{2\Lambda}} \nu_B \ell_B + \frac{c_2 v_B f_\Phi}{\sqrt{2\Lambda}} d_B \bar{u}_B + \frac{c_3 v_B f_\Phi}{\sqrt{2\Lambda}} u_B \bar{d}_B + \text{h.c.},$$

- Twin neutrinos married to charged leptons,
- Twin up quarks married to down quarks
- Maximum size of twin mass between 10 GeV - 1 TeV

Can potentially realize Fraternal Twin Higgs dynamically [Craig,Katz,Strassler, Sundrum]

Interplay between twin fermion masses and precision tests:

- E.g. Lepton Flavor Violation

$$\lambda \Phi_A L_A L_A + \lambda \Phi_B L_B L_B$$

$$\Br(\mu \rightarrow e\gamma) = \tau_\mu \frac{\alpha |\lambda_{13}^* \lambda_{23}|^2 |m_\mu^5}{2^{14} 3^2 \pi^4 m_\phi^4} \approx 4.2 \times 10^{-13} \left(\frac{300 \text{ GeV}}{m_\phi}\right)^4 \left(\frac{\sqrt{|\lambda_{13}^* \lambda_{23}|}}{0.02}\right)^4$$
A vibrant experimental program to search for dark sectors is emerging!

Resources:

• Dark Sectors 2016 Workshop: Community Report

  https://arxiv.org/abs/1707.04591

• Physics Beyond Colliders at CERN: Beyond the Standard Model Working Group Report

• Basic Research Needs for Dark Matter Small Projects New Initiatives
Outlook

• Dark matter provides strong empirical evidence for physics beyond the Standard Model.

• Cosmological origin of dark matter provides motivation for non-gravitational interactions with normal matter.

• The dark sector paradigm is well-motivated and leads to a rich variety of phenomena associated with dark matter, with potential connections to other fundamental puzzles in nature.

• Testing these scenarios requires new experimental strategies; many exciting ideas are being explored

• The dark sector could be much richer than the scenarios I’ve discussed. We’ve only scratched the surface on this subject!