Why PFS is exciting for fundamental physics

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Subaru 20th anniversary symposium, Nov 20, 2019
Dark Matter
Subaru HSC

3D map of dark matter

3D map of galaxies

2D map of galaxies
XENON1t

arXiv:1907.12771

FIG. 4. Upper limits on the SI (upper panel), SD proton-only (middle panel), and SD neutron-only (lower panel) DM-nucleon interaction cross sections from CRESST II, LUX, CDMSLite (proton), EDELWEISS (Migdal), CDEX (BREM), CDMS-Ice (Migdal), NEWS-G, CRESST-III, and DarkSide-50, respectively. The upper limits derived from the S1-S2 data and S2-only data (XENON1T) are shown. Green and yellow shaded regions give the 1 and 2σ constraint on SD couplings.

FIG. 5. Upper limits on the SI-LM DM-nucleon interaction cross section using signal models from the Migdal effect and BREM with masses from 0.1 to 2 GeV/c. The black contour shows a schematic sensitivity versus WIMP mass. The upper limits on the SI and SD (proton-only and neutron-only cases) are due to the long-range nature of the interaction. The background models used in the S2-only data are conservative. The sensitivity contours for the S2-only data is not given since the expected DM signal.

In summary, we performed a search for LDM by using the S1-S2 and S2-only data are inferred using statistics with the optimized event selection derived using the S1-S2 and S2-only data. As in the previous experiments with the S1-S2 data (blue solid lines) and S2-only data (XENON1T), the jumps in the S2-only limits are due to changes in the background models from the Migdal effect and BREM with masses from 0.1 to 2 GeV/c. The upper limits on the SI-LM DM-nucleon interaction cross-section using signal models from the Migdal effect and BREM with masses from 0.1 to 2 GeV/c. The black contour shows a schematic sensitivity versus WIMP mass. The upper limits on the SI and SD (proton-only and neutron-only cases) are due to the long-range nature of the interaction. The background models used in the S2-only data are conservative. The sensitivity contours for the S2-only data is not given since the expected DM signal.

The limit on the SI-LM DM-nucleon interaction cross section is set at 90% C.L. using signal models from the Migdal effect and BREM with masses from 0.1 to 2 GeV/c. The black contour shows a schematic sensitivity versus WIMP mass. The upper limits on the SI and SD (proton-only and neutron-only cases) are due to the long-range nature of the interaction. The background models used in the S2-only data are conservative. The sensitivity contours for the S2-only data is not given since the expected DM signal.

PDG 2018
Miracles

\[ \frac{n_{\text{DM}}}{s} = 4.4 \times 10^{-10} \frac{\text{GeV}}{m_{\text{DM}}} \]

\[ \langle \sigma_{2 \to 2\nu} \rangle \approx \frac{\alpha^2}{m^2} \]
\[ \alpha \approx 10^{-2} \]
\[ m \approx 300 \text{ GeV} \]

WIMP miracle!

\[ \langle \sigma_{3 \to 2\nu^2} \rangle \approx \frac{\alpha^3}{m^5} \]
\[ \alpha \approx 4\pi \]
\[ m \approx 300 \text{ MeV} \]

SIMP miracle!

Hochberg, Kuflik, Volansky, Wacker

arXiv:1402.5143
DDO 154 dwarf galaxy

**FIG. 4:**
Left: Observed rotation curve of dwarf galaxy DDO 154 (black data points) compared to models with an NFW profile (dotted blue) and cored profile (solid red). Stellar (gas) contributions indicated by pink (dot-)dashed lines. Right: Corresponding DM density profiles adopted in the fits. NFW halo parameters are $r_s \approx 3.4 \text{kpc}$ and $c_s \approx 1.5 \times 10^7 \text{M}/\text{kpc}^3$, while the cored density profile is generated using an analytical SIDM halo model developed in [116, 118].

Recent high-resolution surveys of nearby dwarf galaxies have given further weight to this discrepancy. The HI Near Galaxy Survey (THINGS) presented rotation curves for seven nearby dwarfs, finding a mean inner slope $\alpha = 0.29 \pm 0.07$[96], while a similar analysis by LITTLE THINGS for 26 dwarfs found $\alpha = 0.32 \pm 0.24$[167]. These results stand in contrast to $\alpha \ll 1$ predicted for CDM. However, this discrepancy may simply highlight the inadequacy of DM-only simulations to infer the properties of real galaxies containing both DM and baryons. One proposal along these lines is that supernova-driven outflows can potentially impact the DM halo gravitationally, softening cusps [78, 168], which we discuss in further detail in §II E. Alternatively, the inner mass density in dwarf galaxies may be systematically underestimated if gas pressure—due to turbulence in the interstellar medium—provides radial support to the disk [169, 170]. In this case, the observed circular velocity will be smaller than needed to balance the gravitational acceleration, as per Eq. (5), and purported cores may simply be an observational artifact.

In light of these uncertainties, LSB galaxies have become an attractive testing ground for DM halo structure. A variety of observables—low metallicities and star formation rates, high gas fractions and mass-to-light ratios, young stellar populations—all point to these galaxies being highly DM-dominated and having had a quiescent evolution [171]. Moreover, LSBs typically have larger circular velocities and therefore deeper potential wells compared to dwarfs. Hence, the effects of baryon feedback and pressure support are expected to be less pronounced. Rotation curve studies find that cored DM profiles are a better fit for LSBs compared to cuspy profiles [54, 58, 59, 63, 64]. In some cases, NFW profiles can give reasonable fits, but the required halo concentrations are systematically lower than the mean value predicted cosmologically. Although early HI and long-slit HI observations carried concerns that systematic effects—limited resolution (beam-smearing), slit misalignment, halo triaxiality and noncircular motions—may create cores artificially, these issues have largely been put to rest with the advent of high-resolution HI and optical velocity fields (see Ref. [148] and references therein). Whether or not baryonic feedback can provide the solution remains actively debated [67, 172, 173, 174]. Cored DM profiles have been further inferred for more luminous spiral galaxies as well [65, 175, 176].
DDO 154 dwarf galaxy

**FIG. 4:** Left: Observed rotation curve of dwarf galaxy DDO 154 (black data points) [167] compared to models with an NFW profile (dotted blue) and cored profile (solid red). Stellar (gas) contributions indicated by pink (dot-)dashed lines. Right: Corresponding DM density profiles adopted in the fits. NFW halo parameters are \( r_s \approx 3.4 \, \text{kpc} \) and \( \rho_s \approx 1.5 \times 10^7 \, \text{M}_\odot/\text{kpc}^3 \), while the cored density profile is generated using an analytical SIDM halo model developed in [116, 118].

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can be explained if dark matter scatters against itself

\[
\frac{\sigma}{m} \sim 1 \, \text{b} / \text{GeV}
\]

**Need \( \sigma/m \sim 1 \, \text{b} / \text{GeV} \)**

only information on dark matter beyond gravity
Diversity in stellar distribution

Similar outer circular velocity and stellar mass, but different stellar distribution

- compact → redistribute SIDM significantly
- extended → unchanged SIDM distribution

AYuki Kamada

AK, Kaplinghat, Pace, and Yu, PRL, 2017
Wide & deep survey of MW dwarf galaxies w. Subaru/PFS

Blue dots: spectroscopic targets in previous work (Walker+ 2009)

PFS FOV

FoV for pervious survey

Sculptor

nominal boundary \((r_t \sim 76')\), but more member stars actually exist inside/beyond this limit.

Cumulative number of observable stars w. Subaru/PFS

>800 stars observable

Subaru/PFS enables us to measure a large number of stellar spectra over unprecedentedly wide outer areas, where DM largely dominates! ⇒ Best for studying the nature of DM

Masashi Chiba
Dark Matter Detection by Gamma-Ray

Dwarf galaxy

DM \rightarrow \gamma-Rays

Annihilation (or Decay)

\Phi(E, \Delta \Omega) = \left[ \frac{\langle \sigma v \rangle}{8\pi m_{DM}^2} \sum_f \text{Br}(\text{DM DM} \rightarrow f) \left( \frac{dN_\gamma}{dE} \right) \right] \left[ \int_{\Delta \Omega} d\Omega \int_{l.o.s.} dl \rho^2(l, \Omega) \right]

Observed \gamma-Ray Flux

DM Property

Halo Profile

(J-factor)

Determination of J-factor is essential to constrain the DM property

Shigeki Matsumoto
PFS Survey

Precise measurement of DM Halo Profiles

Stellar Velocity Data \iff DM Gravitational Potential

DM Halo: \( \rho(r) = \rho_s (r/r_s)^{-1} (1 + r/r_s)^{-2} \)

Fit

J-factor = \( \left[ \int_{\Delta \Omega} d\Omega \int_{1.0.s} d\rho^2(l, \Omega) \right] \)

Velocity data of \( \sim 800 \) stars enable to determine DM halo profiles very precisely!

J-factor is determined very precisely! \( \Rightarrow \) nature of DM
Visible Matter
After inflation

1,000,000,001

matter

1,000,000,001

anti-matter
10^{-20} seconds later

turned a billionth of anti-matter to matter
Universe Now

This must be how we survived the Big Bang!
Main Paradigm

- neutrinos only electrically neutral elementary matter particle
- could reshuffle matter and anti-matter
- Possible only if neutrino has mass
- Then we owe our existence to neutrinos!

Fukugita Yanagida
Neutrinos saved us from Complete Annihilation?
observe anti-matter turning into matter

\[ m_1^2, m_2^2, m_3^2 \]

\[ \nu_e, \nu_\mu, \nu_\tau \]

atmospheric \( \sim 2.5 \times 10^{-3} \text{eV}^2 \)

solar \( \sim 7.5 \times 10^{-5} \text{eV}^2 \)
Falsifiable?

\[ \langle m \rangle = m_1 + e^{i\alpha} m_2 + e^{i\beta} m_3 \]

\[ \min(m_1, m_2, m_3) \]

\[ m_1 + m_2 + m_3 \]
cosmic string

- neutrino mass likely comes from a new phase transition at very high temperatures
- many of them give cosmic strings
- they lead to gravitational waves we can detect

Dror, Hiramatsu, Kohri, HM, White

http://www.damtp.cam.ac.uk/research/gr/public/cs_evol.html
Dark Energy
\( \Lambda \approx 10^{-120} M_P^4 > 0 \)

You are here

**Anthropic Principle?**  **Multiverse?**
only $\Lambda$ and $w = -1$
nothing interesting with measuring $w$!
Most cited elementary particle theory paper in 2018

String Landscape

\[ |\nabla V| > cV \]

\( \Lambda > 0 \)

(meta)-stable positive vacuum energy

Swampland

\[ w = -1 + \frac{2c^2}{6 + c^2} \]

Obied, Ooguri, Spodyneiko, Vafa, arXiv:1806.08362
Multiverse

NHK Cosmic Front Feb 16, 2017
the conjecture

\[ |\nabla V| > cV \]

no acceleration  no acceleration  \( w=-1 \)  \( w\geq 1 \)

OK  OK  not OK  OK

“It is thus fair to say that these scenarios have not yet been rigorously shown to be realized in string theory.”
too strong?

\[ |\nabla V| > cV \]

- seems to be inconsistent with the slow-roll condition
- also with Higgs, axion, etc with local maxima *Hope for w ≠ -1?*
- perhaps, the constraint is too strong?
- would local maxima be ok?

- Our suggestion:
  - \( |\nabla V| > cV \) or \( \nabla^2 V < 0 \)
  - \( |\nabla V| > cV \) or \( \nabla^2 V < -c'V \)

Ooguri, Palti, Shiu, Vafa, arXiv:1810.05506

HM, Masahito Yamazaki and Tsutomu T. Yanagida, arXiv:1809.00478
Can have $\Delta = 1 + w \neq 0$

- Single-field inflation:
  - $c$ or $c' \sim 0.1$ OK
  - $r$ can be detectable

- Multi-field even better!

**LiteBIRD**

Chien-I Chiang, Jacob Leedom, HM, arXiv:1811.01987
Figure 2.7: Expected accuracy of reconstructing the dark energy density parameter at each redshift, $\Omega_{de}(z)$, from the BAO-measured $D_A(z)$ and $H(z)$ in Fig. 2.6. Here we considered the cosmological constant ($\Omega_{de}(z) = \Omega_{de0}$ = constant) and the flat universe ($\Omega_K = 0$) as the fiducial model. Adding the PFS BAO constraints to the SDSS and BOSS constraints enables reconstruction of the dark energy density to $z' = 2$, and also significantly improves the precision at low redshifts, as the comoving distance at the high redshift arises from an integration of $H(z)$. The solid curve shows the energy density parameter for the fiducial $\Lambda\text{CDM}$ model, while the dashed curve shows the redshift evolution for an early dark energy model in Droan & Robbers (2006), where we employed $w_0 = 1$ and $\Omega_{de0} = 0.05$ for the model parameters (see text for details).

By inverting the sub-matrix of the inverse of the full BAO matrix, $F_{1\nu}$, containing only the parts of the geometrical parameters, $p_a = \{\Omega_m0, \Omega_m0_h, D_A(z_i), H(z_i)\}$, hence the derived constraints on $\tilde{p}_a0$ include marginalization over other parameters such as the galaxy bias and the parameters. Table 2.3 shows the expected accuracies of the dark energy parameters and the curvature parameter for the PFS survey. Here $w_{\text{pivot}}$ is the dark energy equation state at the "pivot" redshift, at which the dark energy equation of state is best constrained for a given survey. The quantity $\text{FoM}_{de}$ is the dark energy figure-of-merit defined in the Dark Energy Task Force Report (Albrecht et al. 2006), which quantifies the ability of a given survey for constraining both $w_0$ and $w_a$; $\text{FoM}_{de} \propto 1/[\{(w_{\text{pivot}})^2 + (w_a)^2\}]$, which is proportional to the area of the marginalized constraint ellipse in a sub-space of $(w_0, w_a)$. Table 2.3 clearly shows that the PFS BAO can significantly tighten the parameter constraints over the SDSS and BOSS surveys. Most interestingly, the PFS has the potential to constrain the curvature parameter to a precision of 0.3%. If we can detect a non-zero curvature, this would represent a fundamental discovery giving a critical constraint on the physics of the early universe, for example insight into different inflation scenarios (Efstathiou 2003; Contaldi et al. 2003; Freivogel et al. 2006; Kleban & Schillo 2012; Guth & Nomura 2012).
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