Novel Probes of Dark Matter

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What is the particle nature of Dark Matter?

- Cosmological observables as a probe of dark matter interactions at large/intermediate scales.

- Strong gravitational lensing as a model-independent probe of dark matter at small scales.

- Conclusions and future directions.
Looking for Dark Matter off the beaten track

Where do Dark Matter interactions matter?

Some well known avenues:

Excess high energy cosmic/gamma rays;
Missing energy at colliders;
Nucleon recoil deep underground;
...

Important to look for new avenues
Going Beyond the WIMP Paradigm

- The WIMP parameter space is being actively explored.

- A wealth of knowledge is and will soon be available from cosmological surveys, which will reveal new information about the dark sector.

We should look beyond the WIMP scenario, exploiting these data sets as much as we can!
Probing Dark Matter Interactions through the CMB and the large-scale structure of the Universe.

Case study: Dark Matter – baryon strong interactions

C. Dvorkin, K. Blum and M. Kamionkowski, PRD (2014)
Boehm et al. (2014), Bucklet et al. (2014), Ali-Haimoud et al. (2015),..., Muñoz et al. (2015),...,Aloni et al.(2016), Poulin et al. (2017),Gluscevic et al.(2018), Slatyer et al. (2018), Chang, Essig, and McDermott, etc, etc...
Probing sub-GeV Dark Matter-Baryon Scattering with Cosmological Observables

Effective Interaction
\[ m_\chi, \sigma \propto v^n \]

Observable Signatures
CMB temperature and polarization + Lyman-alpha forest

Constraints
Planck 2015 + Sloan Digital Sky Survey (SDSS)
Limits will get much (order of magnitude) better with CMB-S4: **main science driver** for the Dark Matter science case in the **CMB-S4 Decadal Survey Report**.

Cosmological observables provide an extremely complementary probe to that of direct detection and other indirect searches!
Going beyond the freeze-out mechanism

Freeze-out

Freeze-in

WIMPs

\[ n_\chi \sim e^{-m_\chi/T_d} \]

\((\sigma v)\)
New channel for Freeze-in

Probing Dark Matter scattering with current/future cosmological probes

C. Dvorkin, T. Lin, K. Schutz, in prep.
Probing Dark Matter fluctuations at smaller scales

Probing Dark Matter substructure at small scales via strong gravitational lensing
Strong Gravitational Lensing
Looking for Dark Subhalos

*Idea*: subhalos can locally perturb lensed images, so by looking at the residual between the images predicted by modeling the lens as a smooth mass and what is actually observed we can infer the presence of subhalos.

The *advantage* relative to other methods for detecting dark matter is that we *do not need to assume a coupling* between the Standard Model and Dark Matter (in contrast to direct/indirect detection and colliders): *model-independent method*.

Another main advantage is that by focusing on the lowest mass subhalos present in galaxies (largely devoid of stars) we can minimize baryonic feedback.
The numerous population of low mass subhalos (< $10^7$ M$_\odot$) may be statistically detected by their collective perturbations on images.

*Hezaveh, Dalal, et al. (2016)*
A different approach to substructure lensing: statistical detection of dark subhalos

Key Question:
What can we learn about low-mass subhalos from measuring the substructure convergence power spectrum?
• We developed a general formalism to study the N-point function of the convergence field from first principles, which can be easily applied to subhalo populations with different properties.

• We model the convergence field as a fluctuation field superimposed on the smoothly varying background density profile of the host:

\[ \kappa_{\text{tot}}(r) = \kappa_0(r) + \kappa_{\text{sub}}(r) \]

\[ \kappa_{\text{sub}}(r) = \sum_{i=1}^{N_{\text{sub}}} \kappa_i(r - r_i, m_i, q_i) \]

\[ \kappa = \frac{\Sigma}{\Sigma_{\text{crit}}} \] (Surface mass density)

\[ \Sigma_{\text{crit}} = \frac{c^2 D_{os}}{4\pi G D_{ol} D_{ls}} \]

\[ q_i \] are a set of parameters that represent the intrinsic properties of a subhalo.

A. Diaz Rivero, F. Cyr-Racine, and C. Dvorkin, PRD (2017)
A General Formalism

**Change of language:** instead of talking about lensing perturbations in terms of individual subhalos, look at the correlation function of the projected density field.

- Start from first principles to derive the lens plane-averaged convergence correlation function.

\[ P_{\text{sub}}(k) = \int d^2r \, e^{-i k \cdot r} \xi_{\text{sub}}(r) \quad ; \quad P_{\text{sub}}(k) = P_{1\text{sh}}(k) + P_{2\text{sh}}(k) \]

- 1-subhalo term: arises from ensemble-averaging over the spatial distribution of a single subhalo.

\[ P_{1\text{sh}}(k) = \frac{(2\pi)^2 \bar{\kappa}_{\text{sub}}}{\langle m \rangle \Sigma_{\text{crit}}} \int dm \, dq \, m^2 \, \mathcal{P}_m(m) \, \mathcal{P}_q(q|m) \times \left[ \int dr \, r J_0(k \, r) \bar{\kappa}(r, q) \right]^2 \]

- 2-subhalo term: arises from averaging over pairs of distinct subhalos.

\[ P_{2\text{sh}}(k) = \frac{(2\pi)^2 \bar{\kappa}_{\text{sub}}^2}{\langle m \rangle^2} P_{ss}(k) \left[ \int dm \, dq \, m \, \mathcal{P}_m(m) \, \mathcal{P}_q(q|m) \times \int dr \, r J_0(k \, r) \bar{\kappa}(r, q) \right]^2 \]

*A. Diaz Rivero, F. Cyr-Racine, and C. Dvorkin, PRD (2017)*
Substructure Power Spectrum: Truncated NFW Subhalo Population

The Power Spectrum can be described mainly by three quantities:

A. Diaz Rivero, F. Cyr-Racine, and C. Dvorkin, PRD (2017)
Substructure Power Spectrum: Truncated Cored Profile

Key probe of the inner subhalo density profile: asymptotic slope.

A. Diaz Rivero, F. Cyr-Racine, and C. Dvorkin, PRD (2017)
Simulations from Vogelsberger et al.
- Effect on substructure due to a cutoff in the initial power spectrum + Dark Matter self-interactions.

Comparing the amplitude and slope of the power spectrum on scales $0.1 \text{kpc}^{-1} < k < 10 \text{kpc}^{-1}$ from lenses at different redshifts can help us distinguish between CDM and other DM scenarios.

The effective mass is reduced between $z = 0.5$ and $z = 0$ due to higher susceptibility to tidal stripping.

Comparing the amplitude and slope of the power spectrum on scales $0.1 \text{kpc}^{-1} < k < 10 \text{kpc}^{-1}$ from lenses at different redshifts can help us distinguish between CDM and other DM scenarios.

Change in the slope at $k \gtrsim 2 \text{kpc}^{-1}$ due to tidal stripping transferring power from larger to smaller scales.

In the next decade, we will discover tens of thousands of lensed galaxies. This vast increase in sample sizes (in coordination with other facilities, e.g. HST, ALMA) will provide much stronger statistical constraints on dark matter models than what is currently possible.

“Probing the Fundamental Nature of Dark Matter with the Large Synoptic Survey Telescope”, 2019
arXiv:1902.01055
Convolutional Neural Networks (CNNs) to find Dark Matter Substructure

**Classification**: binary output - is an image likely to contain substructure or not? Can help identify promising images for further (expensive) traditional analysis.

*Our simulation pipeline for the training and validations sets:*

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A. Diaz Rivero and C. Dvorkin (2019)
Conclusions and the Road Ahead

• The CMB and the large-scale structure of the universe (Lyman-alpha forest, future 21 cm observations, galaxy surveys, weak lensing measurements, etc) encode a wealth of information about the interactions of the dark sector.

• Important clues about Dark Matter physics lie on small scales: detection of dark subhalos via strong gravitational lensing has great potential for revealing the particle nature of dark matter.

This coming decade will bring a wealth of new and complementary cosmological data.

We should continue to look off the beaten track, and hopefully we will shed light on the dark sector soon.