Small but mighty: Dark matter substructure

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With
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In dark matter science, hope for the best…

- Let’s hope we can find dark matter in the lab…

And many, many more…
…but prepare for the worst!

- Gravitational signatures might be all we can observe!
What dark matter physics can we probe through astronomy?

1) Interactions affecting the DM transfer function (initial conditions)

2) Interaction affecting the dynamics of structure formation (self-interaction)

Vogelsberger, Zavala, Cyr-Racine +, arXiv:1512.05349
Physical impacts of modified matter power spectrum and dark matter self-interaction.

1) Change to the abundance of small-scale substructure

2) Change to the inner structure of subhalos

See also: Schewtschenko et al. (2015, 2016), Boehm et al. (2014), Buckley et al. (2014), Elbert et al. (2017).

Vogelsberger, Zavala, Cyr-Racine+, arXiv:1512.05349

Francis-Yan Cyr-Racine, Harvard
Galaxy-scale Gravitational Lenses

Credits: Leonidas Moustakas
Direct Substructure Detection

• “Gravitational Imaging” of Perturbed Einstein Rings

Direct Substructure Detection

• “Gravitational Imaging” of Perturbed Einstein Rings

Hezaveh et al., (2016)
Direct Substructure Detection: A transdimensional approach

- A more accurate way to capture model covariances

See also Brewer at al. (2015)
A different approach to substructure lensing: 2-point correlation function

- Instead of describing lensing perturbations in terms of individual subhalo, look at the correlation function of the projected density field.

![Graph showing the power spectrum of subhalos](image)

Hezaveh et al., (2016)

Fisher Forecast
Substructure lensing: 2-point function

- Philosophy: in a CDM halo, many subhalos are encountered along any given line of sight.

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Vogelsberger, Zavala, Cyr-Racine+, arXiv:1512.05349
Substructure lensing: 2-point function

- My philosophy: even if the convergence field is not entirely Gaussian, looking at the substructure power spectrum is interesting.
- Key Question:

What will we learn about low-mass subhalos from measuring the substructure convergence power spectrum?
Substructure Convergence Power Spectrum

Diaz Rivero, Cyr-Racine, & Dvorkin, arXiv:1707.04590

• Goal: Use the halo model to compute from first principle the substructure convergence power spectrum.

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

\[ \xi_{\text{sub}}(\mathbf{r}) \equiv \frac{1}{A} \int d^2 \mathbf{s} \int \prod_{i} d^2 \mathbf{r}_i \mathcal{P}_r(\mathbf{r}_i) \times (\kappa_{\text{sub}}(\mathbf{s}) - \bar{\kappa}_{\text{sub}})(\kappa_{\text{sub}}(\mathbf{s} + \mathbf{r}) - \bar{\kappa}_{\text{sub}}) \]

\[ P_{\text{sub}}(\mathbf{k}) = \int d^2 \mathbf{r} \, e^{-i\mathbf{k} \cdot \mathbf{r}} \xi_{\text{sub}}(\mathbf{r}) \]
Substructure Power Spectrum: tNFW

- As a warm up, let’s consider a population of truncated NFW subhalos.

Díaz Rivero, Cyr-Racine, & Dvorkin, arXiv:1707.04590
Substructure Power Spectrum: tNFW

- The power spectrum depends mostly on three quantities:

![Graph showing the substructure power spectrum with labeled axes: k [kpc^{-1}], P_{1sh} [kpc^2], and κ_{sub} \langle m^2 \rangle / \langle m \rangle. The graph includes labels for Low-k amplitude, Truncation scale, Asymptotic slope, Fiducial Model, Point masses, \propto 1/k^4, k_{trunc}, k_{scale}, and κ_{sub} \langle m^2 \rangle / \langle m \rangle.](attachment:image.png)

Díaz Rivero, Cyr-Racine, & Dvorkin, arXiv:1707.04590
Substructure Power Spectrum: truncated cored profile

- Let’s now consider an SIDM-inspired truncated cored profile:

Diaz Rivero, Cyr-Racine, & Dvorkin, arXiv:1707.04590
Substructure Power Spectrum: truncated cored profile

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

Díaz Rivero, Cyr-Racine, & Dvorkin, arXiv:1707.04590
Measuring the substructure power spectrum: cartoon
Cyr-Racine, Keeton & Moustakas, in prep.
Measuring the substructure power spectrum: cartoon

Fiducial image

Image residuals
Measuring the substructure power spectrum: cartoon

- There is definitely signal in the lensing residual!

![Graph showing the power spectrum](image)
Substructure Lensing: Conclusions

• Substructure lensing allows the study of small-scale dark matter structures that may hold key information about dark matter physics.
• The n-point functions of the projected density field allow for a more general description of dark matter substructure.
• The substructure power spectrum mostly depends on the abundance of substructure, their truncation, and their inner density profile.
• In principle, it appears possible to measure the substructure convergence power spectrum. A thorough study is on the way.