

Novel Probes of Dark Matter

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Outline

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!

Going beyond the WIMP scenario

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



Linda Xu



Andrew Chael

Effective
Interaction

$$m_\chi, \sigma \propto v^n$$

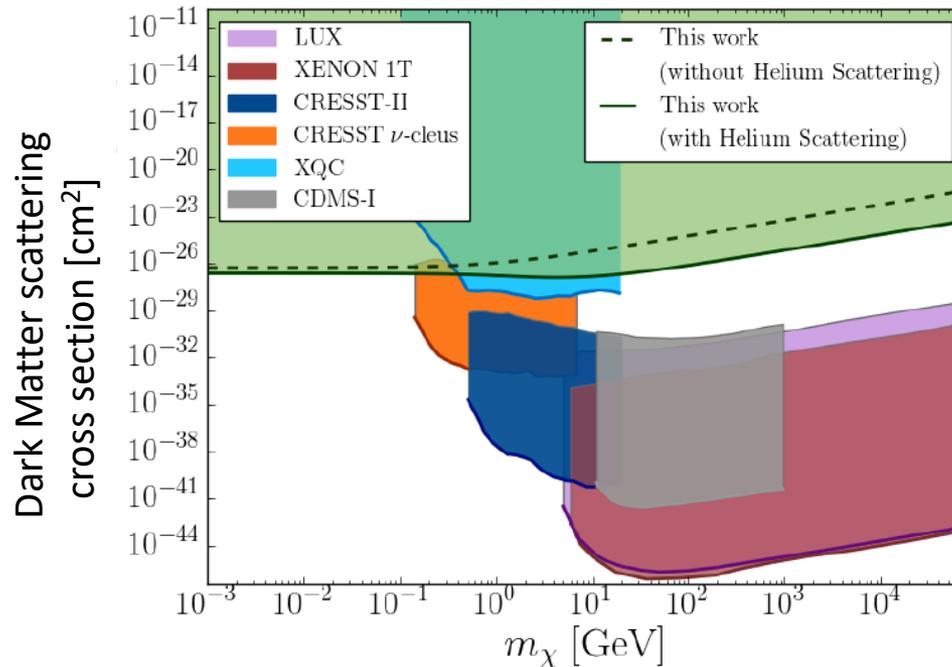
Observable
Signatures

CMB temperature
and polarization +
Lyman-alpha forest

Constraints

Planck 2015 +
Sloan Digital Sky
Survey (SDSS)

Velocity-Independent Scattering



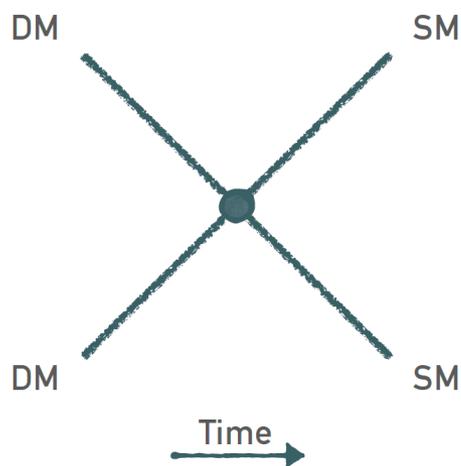
Linda Xu, C. Dvorkin and Andrew Chael, PRD (2018)

- 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***.

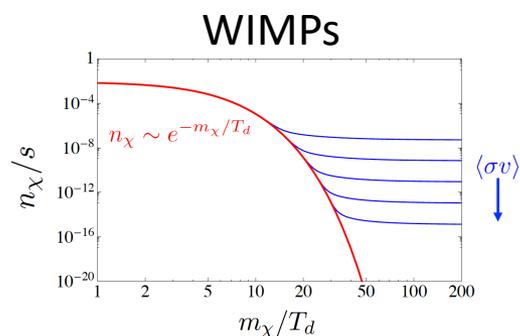
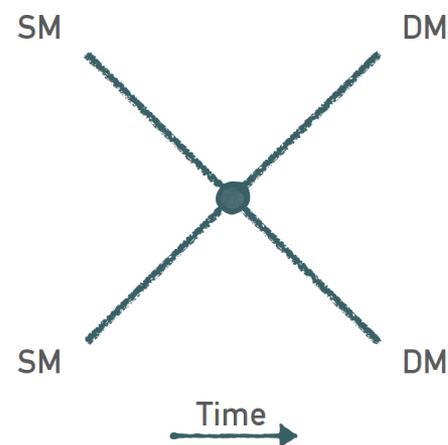
Cosmological observables provide an extremely complementary probe to that of direct detection and other indirect searches!

Going beyond the freeze-out mechanism

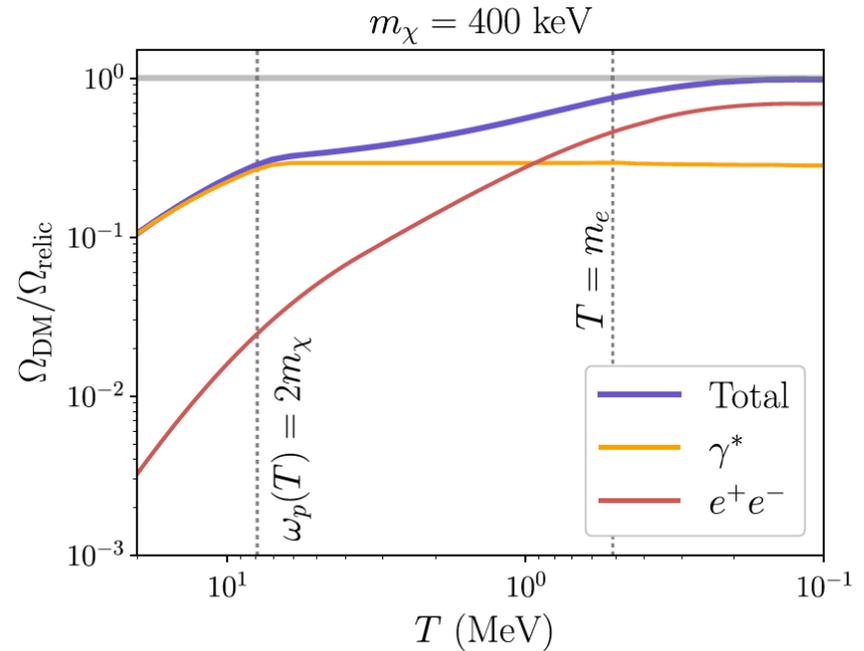
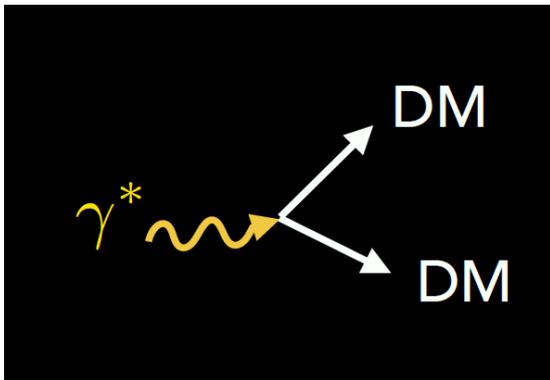
Freeze-out



Freeze-in



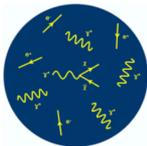
New channel for Freeze-in



Editors' Suggestion

Making dark matter out of light: Freeze-in from plasma effects

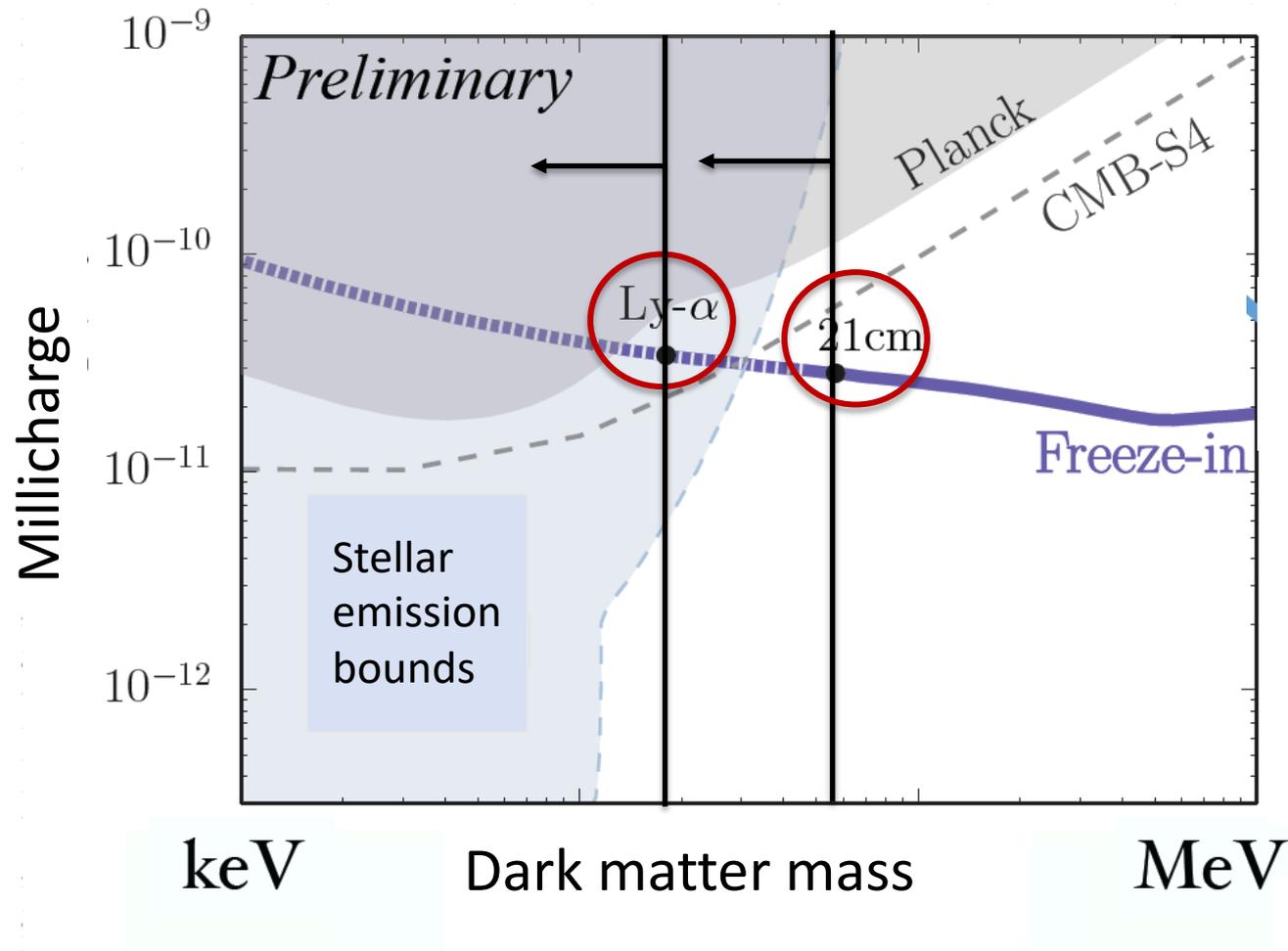
Cora Dvorkin, Tongyan Lin, and Katelin Schutz
Phys. Rev. D **99**, 115009 (2019) – Published 11 June 2019



Dark matter (DM) could couple to Standard Model (SM) particles through a light mediator and this could be responsible for the observed DM abundances through *freeze-in*. Here, the authors identify an additional production channel through the decay of photons that have acquired an in-medium plasma mass. They contribute to the relic abundance, lowering by an order of magnitude the target cross-section for the lowest dark matter masses.

C. Dvorkin, T. Lin, K. Schutz, PRD (2019)

Probing Dark Matter scattering with current/future cosmological probes

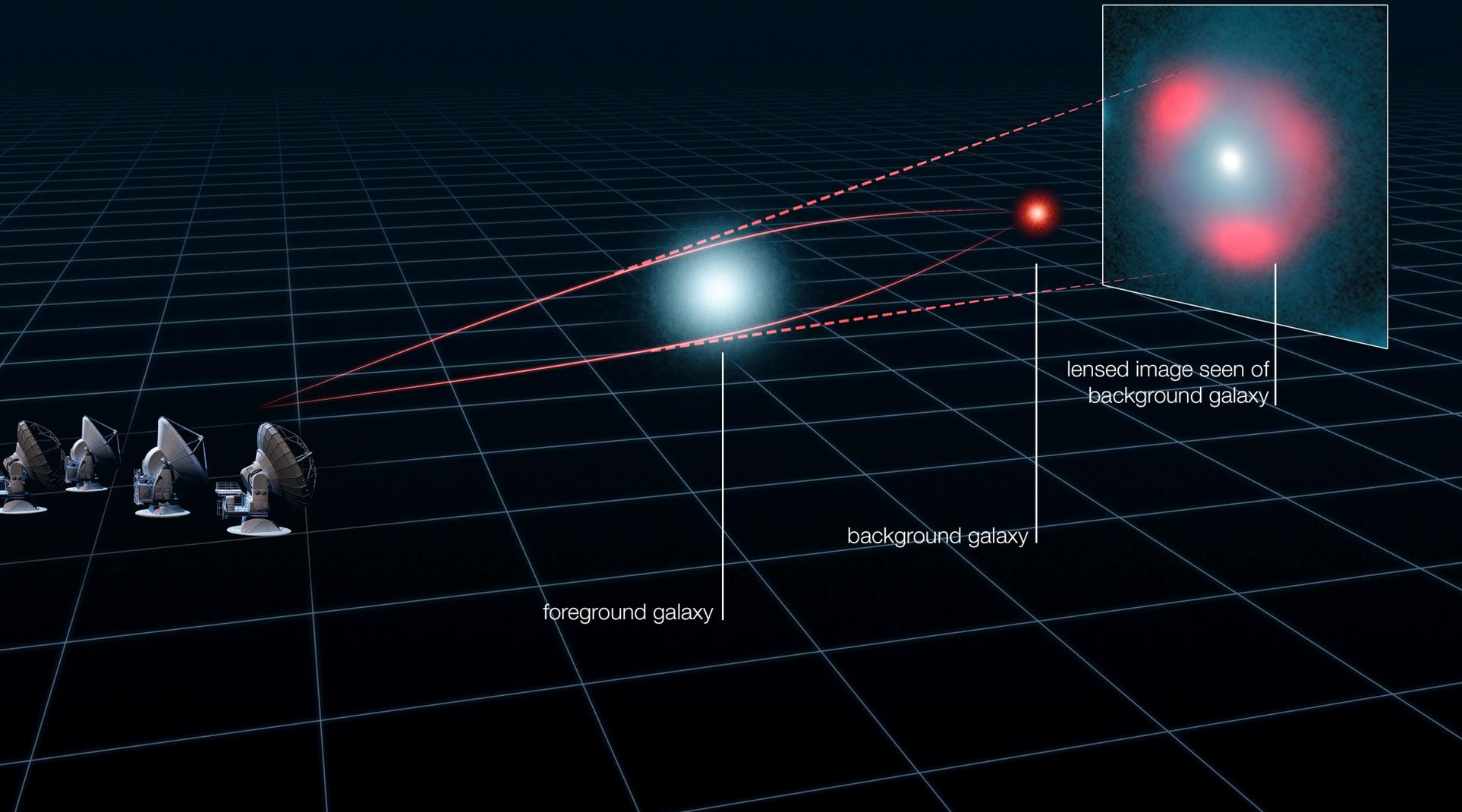


C. Dvorkin, T. Lin, K. Schutz, in prep.

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?***

A General Formalism

Ana Diaz
Rivero



- 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:

$$\kappa_{\text{tot}}(\mathbf{r}) = \kappa_0(\mathbf{r}) + \kappa_{\text{sub}}(\mathbf{r}), \text{ where } \kappa = \frac{\Sigma}{\Sigma_{\text{crit}}} \text{ (Surface mass density)}$$

$$\kappa_{\text{sub}}(\mathbf{r}) = \sum_{i=1}^{N_{\text{sub}}} \kappa_i(\mathbf{r} - \mathbf{r}_i, m_i, \mathbf{q}_i) \quad \left(\Sigma_{\text{crit}} = \frac{c^2 D_{os}}{4\pi G D_{ol} D_{ls}} \right)$$

\mathbf{q}_i are a set of parameters that represent the intrinsic properties of a subhalo.

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.

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

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

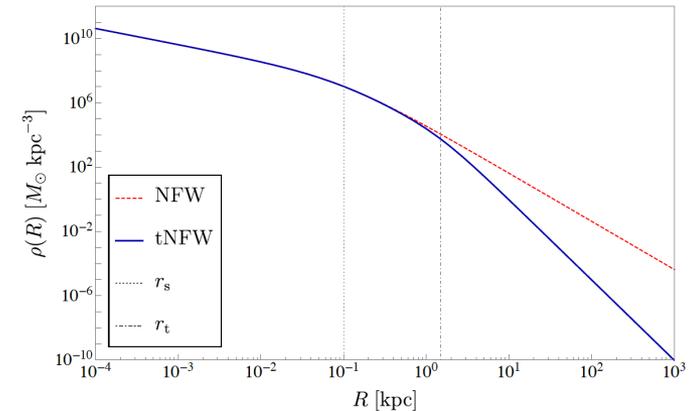
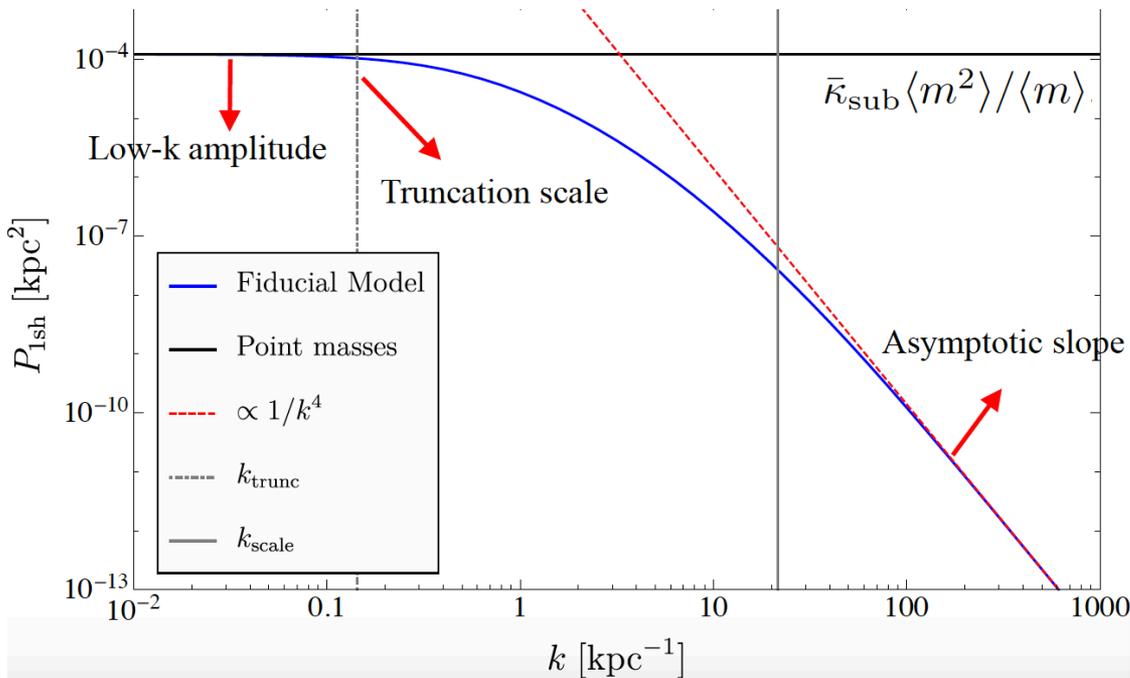
$$P_{1\text{sh}}(k) = \frac{(2\pi)^2 \bar{\kappa}_{\text{sub}}}{\langle m \rangle \Sigma_{\text{crit}}} \int dm d\mathbf{q} m^2 \mathcal{P}_m(m) \mathcal{P}_q(\mathbf{q}|m) \times \left[\int dr r J_0(kr) \hat{\kappa}(r, \mathbf{q}) \right]^2$$

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

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

Substructure Power Spectrum: Truncated NFW Subhalo Population

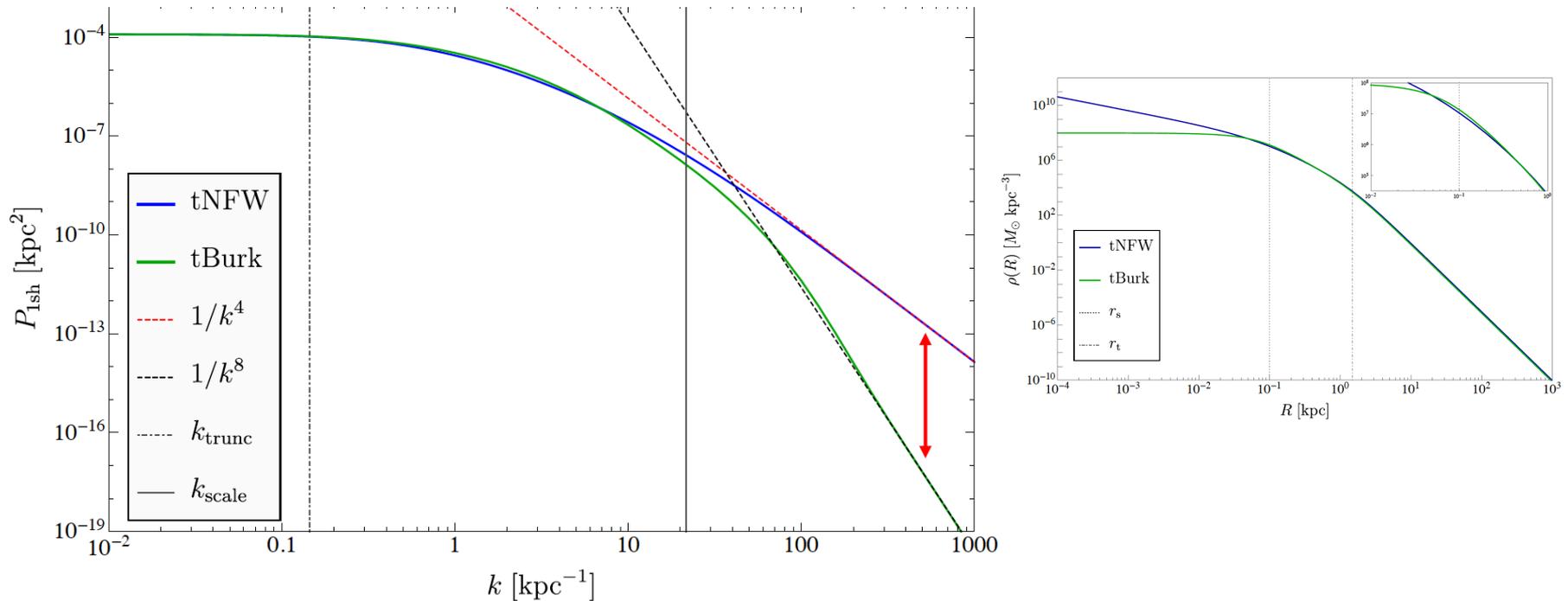
The **Power Spectrum** can be described mainly by **three quantities**:



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**.

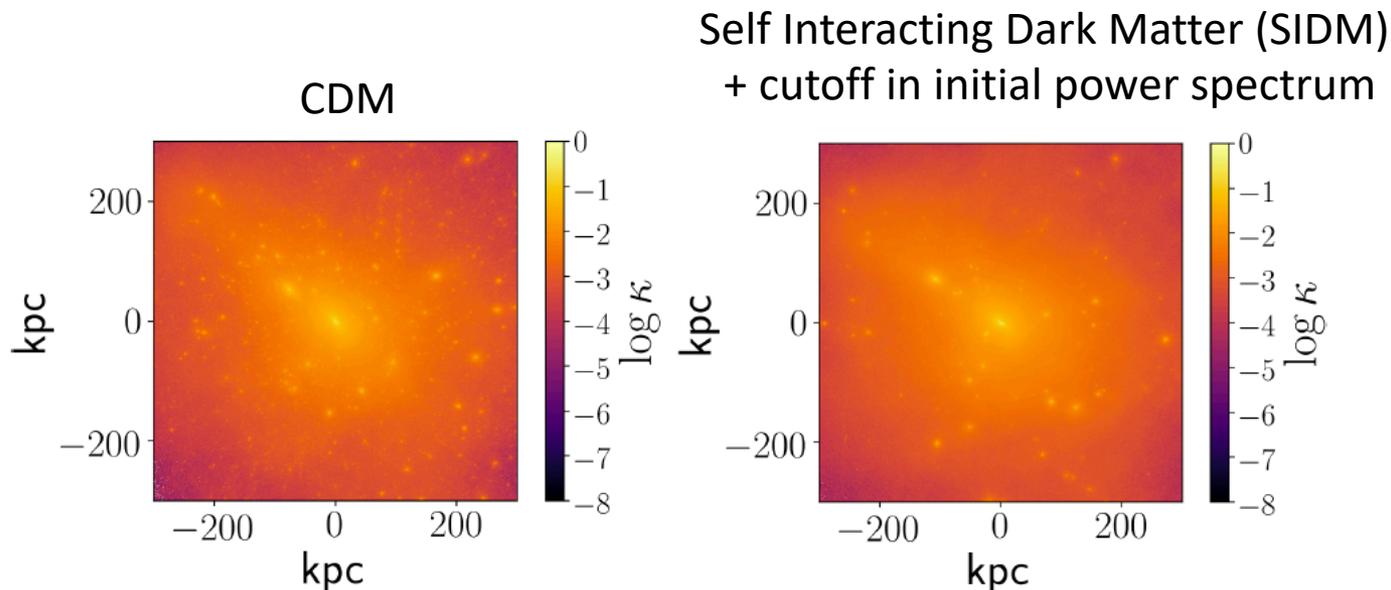


A. Diaz Rivero, F. Cyr-Racine, and C. Dvorkin, PRD (2017)

The Convergence Power Spectrum: Insights from Simulations

Simulations from Vogelsberger et al.

- Effect on substructure due to a cutoff in the initial power spectrum + Dark Matter self-interactions.

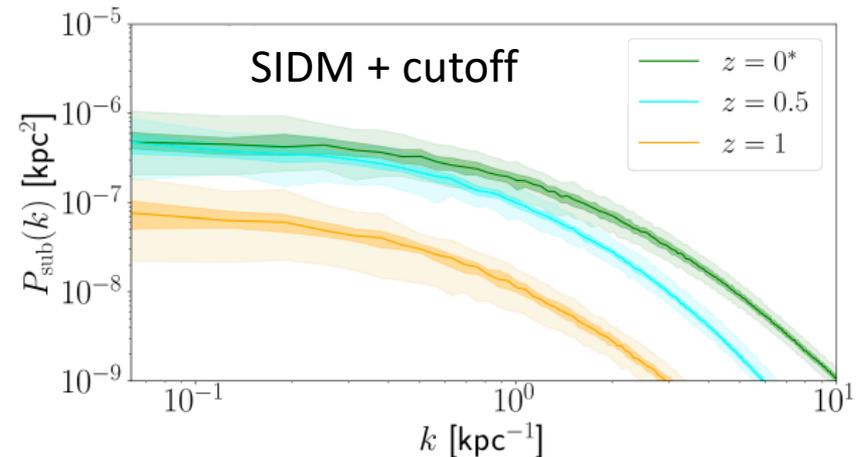
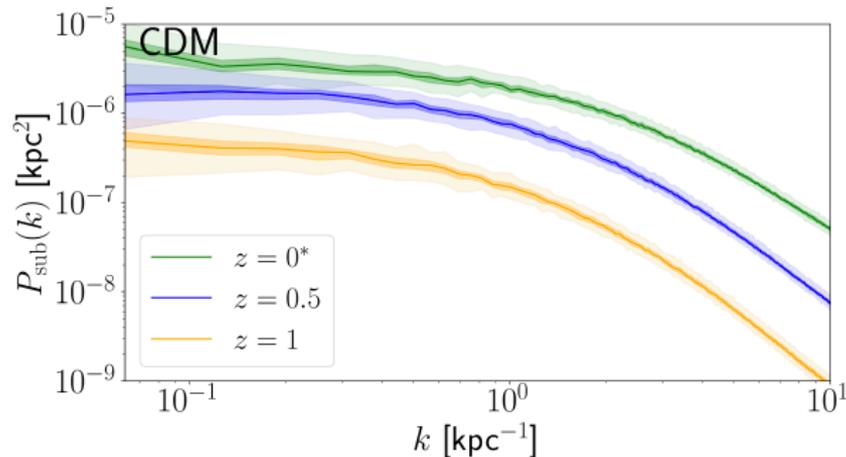


A. Diaz Rivero, C. Dvorkin, F. Cyr-Racine, et al., PRD (2018)

Redshift and Scale-Dependence

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.

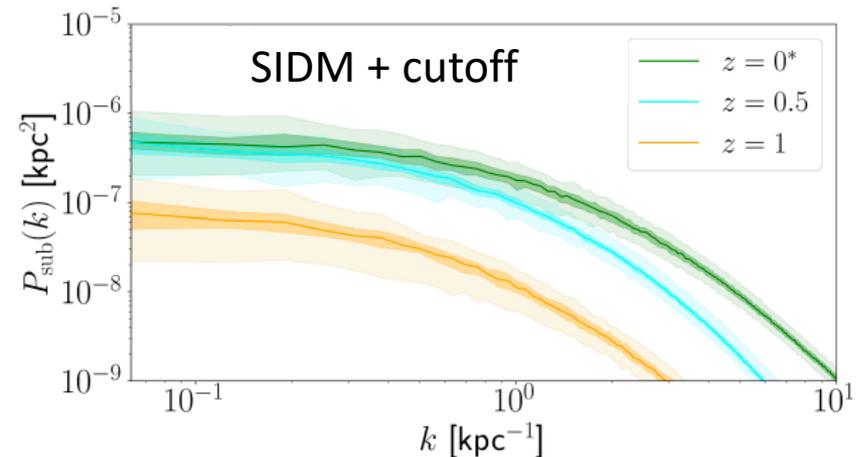
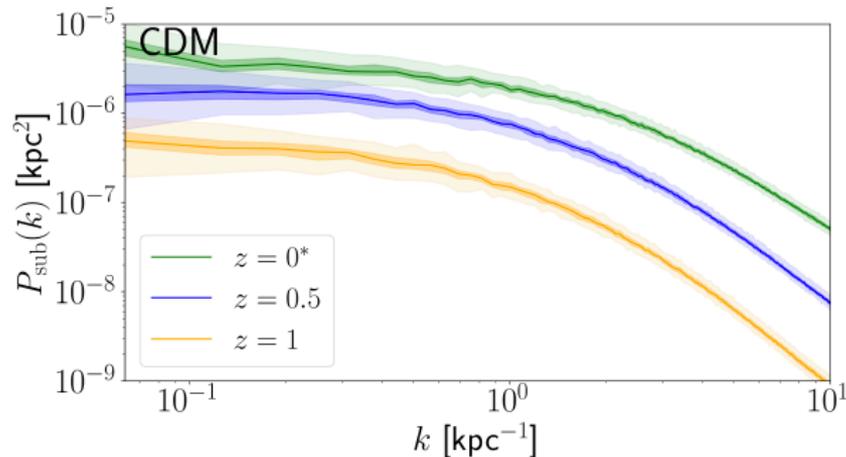


A. Diaz Rivero, C. Dvorkin, F. Cyr-Racine, et al., PRD (2018)

Redshift and Scale-Dependence

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.



A. Diaz Rivero, C. Dvorkin, F. Cyr-Racine, et al., PRD (2018)

The Road Ahead

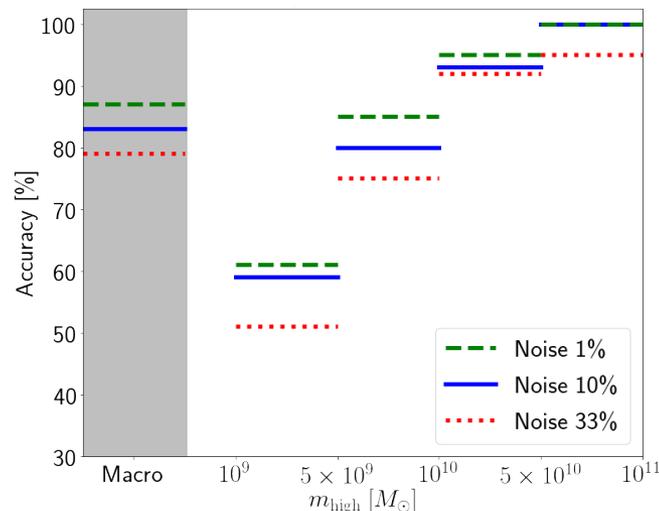
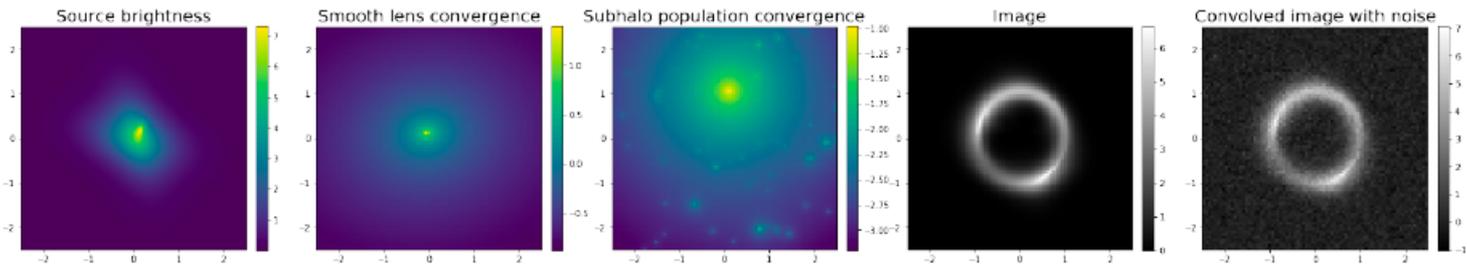
In the next decade, we will discover tens of thousands of lensed galaxies. This vast increase in sample sizes (in coordination with other facilities, e.g. HST, ALMA) will provide **much stronger statistical constraints on dark matter models** than what is currently possible.

*“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:



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.**