Deciphering the Dark Side of Structure Formation with Cosmological Data

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Outline

What is the **particle nature of Dark Matter**?

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

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

- Conclusions and future directions.

Looking for Dark Matter off the beaten track

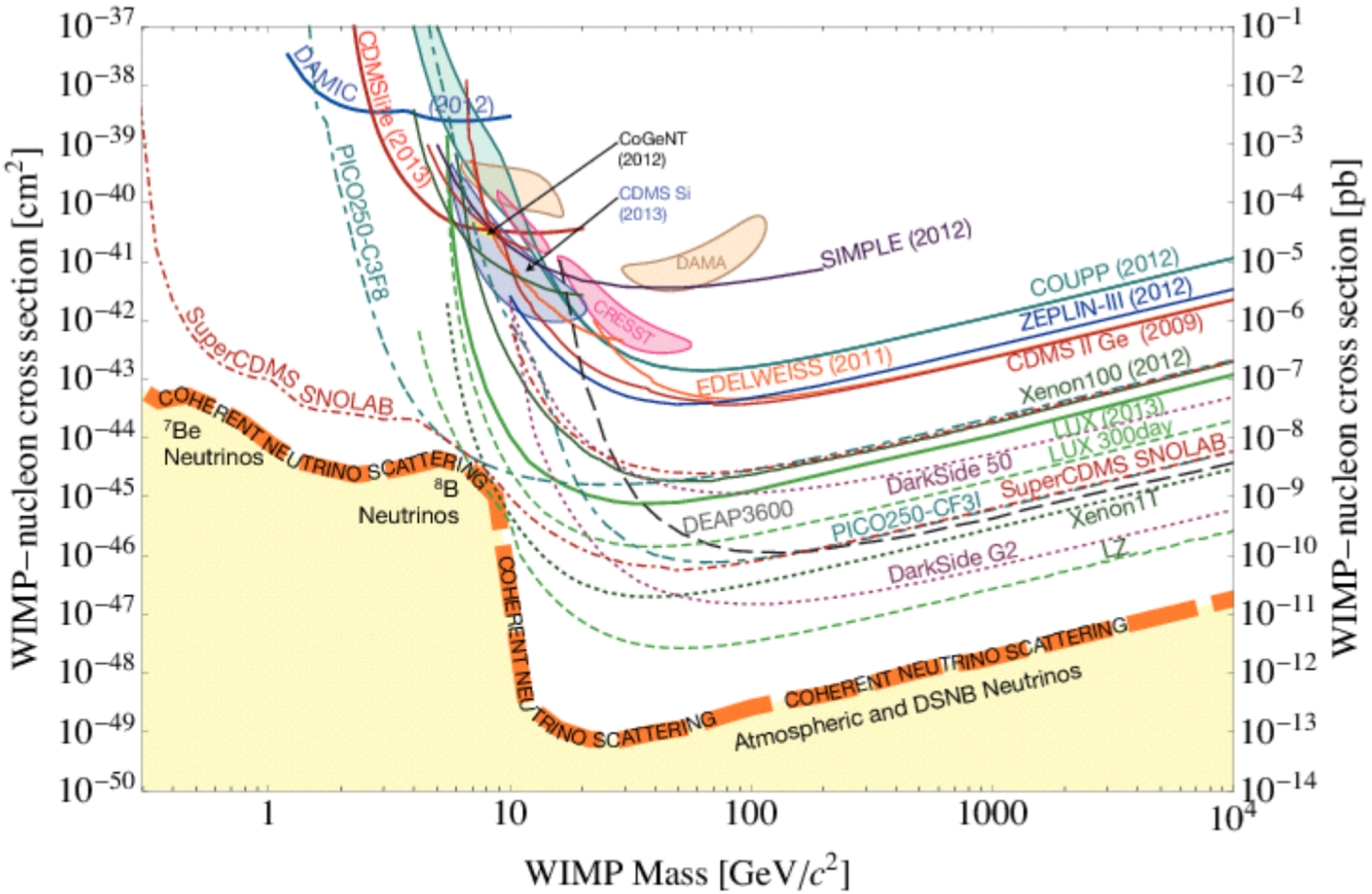
Where do Dark Matter interactions matter?

Some well known avenues:

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

Important to look for new avenues

Well-motivated Dark Matter Candidate: WIMP



Snowmass 2013

Going Beyond the WIMP Paradigm

- The WIMP parameter space is getting more and more constrained.

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

We should exploit 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

Dark Matter-Baryon Interactions

C. Dvorkin, K. Blum and M. Kamionkowski, PRD (2014)

density fluctuations ← $\dot{\delta}_\chi = -\theta_\chi - \frac{1}{2}\dot{h}$

velocity divergence ← $\dot{\theta}_\chi = -\frac{\dot{a}}{a}\theta_\chi + c_\chi^2 k^2 \delta_\chi + \boxed{R_\chi \left(\theta_b - \theta_\chi\right)}$

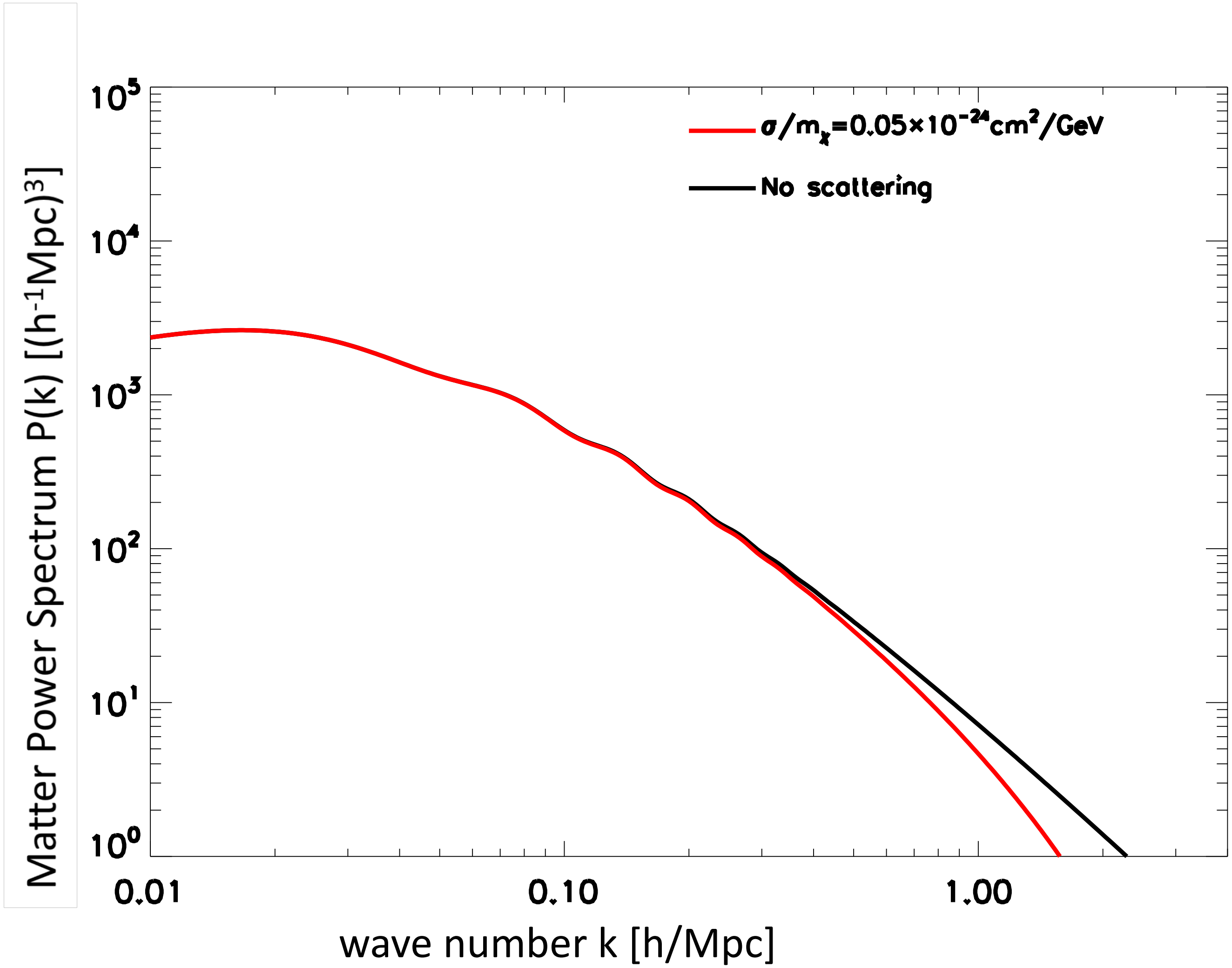
$$\dot{\delta}_b = -\theta_b - \frac{1}{2}\dot{h}$$

$$\dot{\theta}_b = -\frac{\dot{a}}{a}\theta_b + c_b^2 k^2 \delta_b + \boxed{\frac{\rho_\chi}{\rho_b} R_\chi \left(\theta_\chi - \theta_b\right)} + R_\gamma \left(\theta_\gamma - \theta_b\right)$$

Dark Matter-baryon momentum exchange rate:

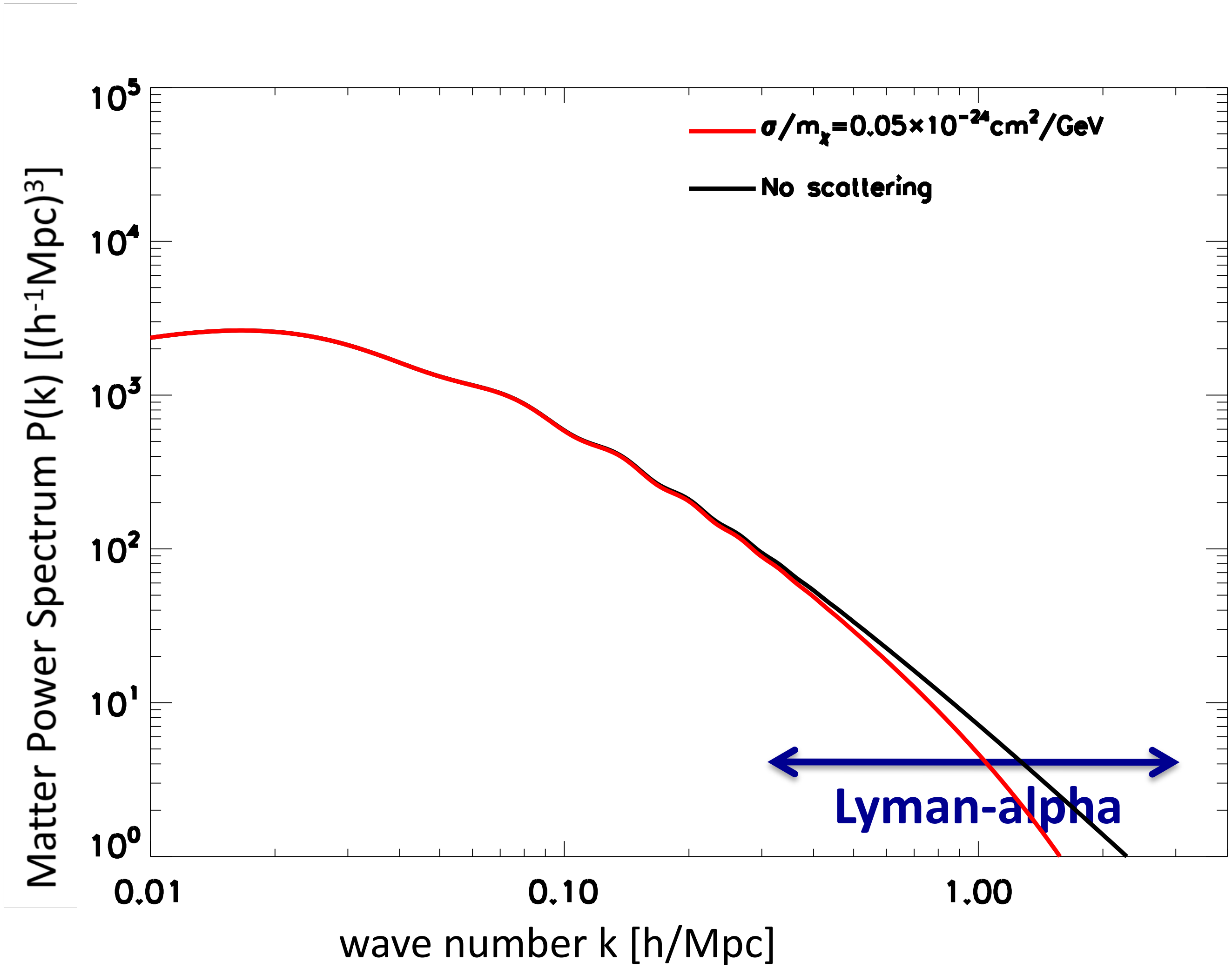
$$R_\chi = \frac{a\rho_b\sigma_0}{m_\chi + m_H} c_n \left(\frac{T_b}{m_H} + \frac{T_\chi}{m_\chi} + \frac{V_{\rm RMS}^2}{3}\right)^{\frac{n+1}{2}} \text{ with } \sigma(v) = \sigma_0 v^n$$

Effect on the Matter Power Spectrum



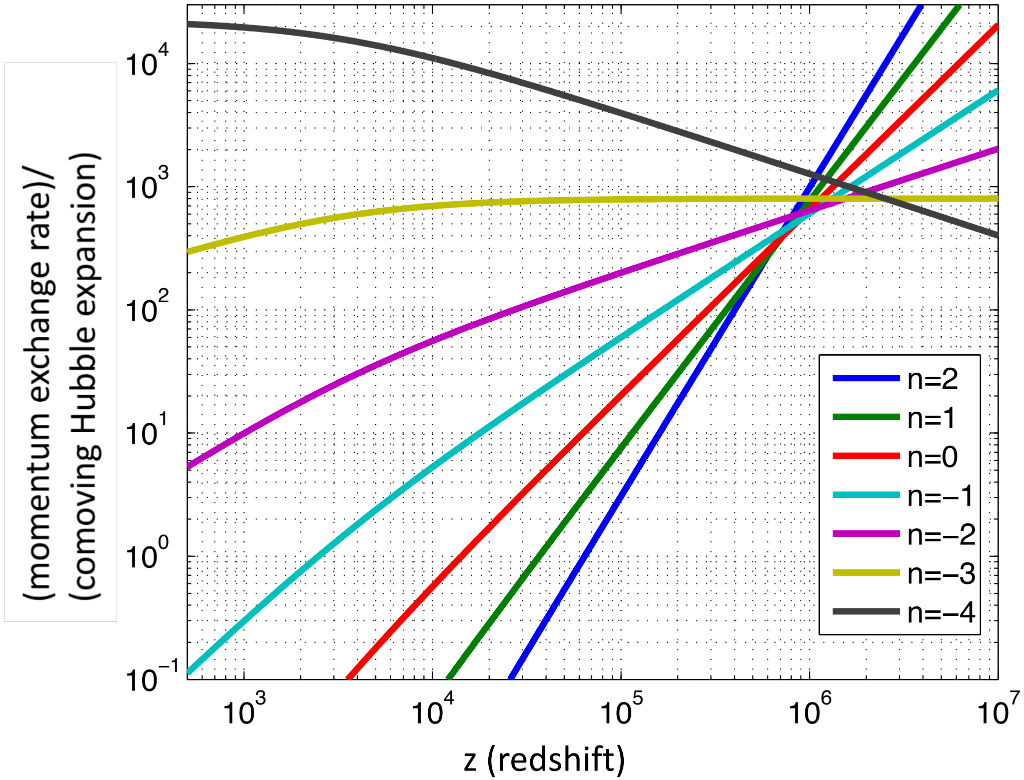
C. Dvorkin, K. Blum and M. Kamionkowski, Phys. Rev. D (2014)

Effect on the Matter Power Spectrum



C. Dvorkin, K. Blum and M. Kamionkowski, Phys. Rev. D (2014)

Probing Dark Matter-Baryon Scattering with Cosmology



All the curves ($\sigma(v) = \sigma_0 v^n$) are normalized to satisfy a mean free path of $\sim$ 1 Mpc in a system like the Milky Way, with $\rho_\chi \simeq 0.4\ GeV/cm^3$, and $v \approx 220\ km/s$.

C. Dvorkin, K. Blum and M. Kamionkowski, PRD (2014)

Minimal mean free path for baryons scattering on Dark Matter

Mean free path: $\lambda = \left(\frac{\rho_\chi \sigma}{m_\chi}\right)^{-1}$ $(\text{with} \ \ \rho_\chi \approx 0.4\,\text{GeV}/\text{cm}^3)$

MCMC likelihood analysis with **CMB data** from the **Planck** satellite and **Lyman-alpha data** from the **Sloan Digital Sky Survey** (SDSS):

The minimal mean free path of a dark matter particle scattering with baryons at the virial velocity and in a system with $\rho_\chi \simeq 0.4\ GeV/cm^3$ is always larger than the distance a particle travels in such a system in the history of the universe (~3 Mpc).

A baryon in the halo of a galaxy like our Milky Way does not scatter with Dark Matter particles during the age of the Universe.

C. Dvorkin, K. Blum and M. Kamionkowski, PRD (2014)

Probing sub-GeV Dark Matter-Baryon Scattering with Cosmological Observables

Linda Xu   Andrew Chael

Effective Interaction

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

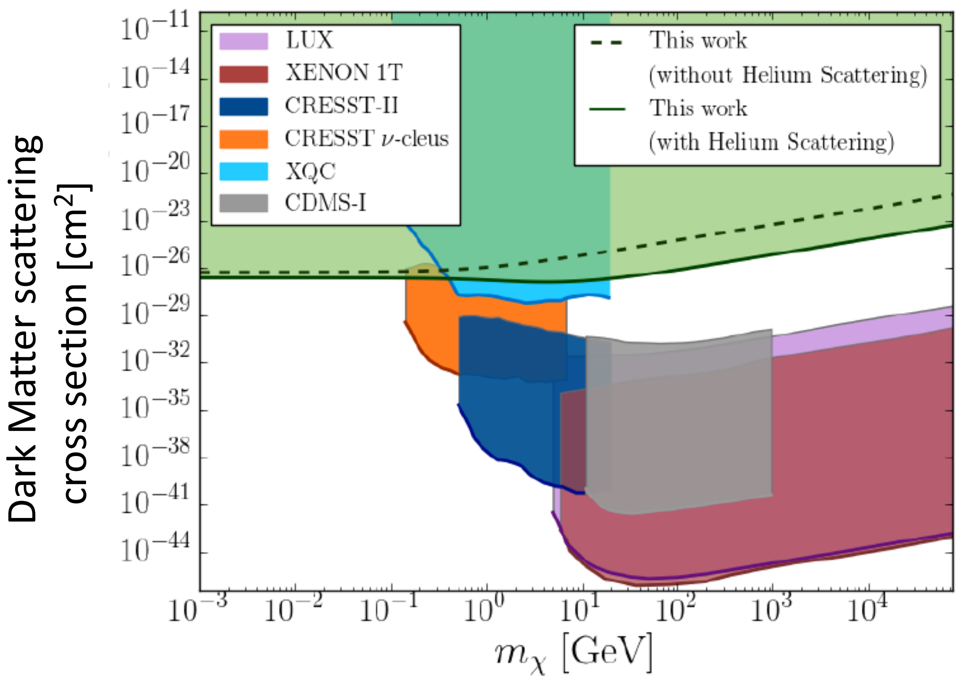
Observable Signatures

CMB temperature and polarization + Lyman-alpha forest

Constraints

MCMC on Planck 2015 + Sloan Digital Sky Survey (SDSS)

Velocity-Independent Scattering

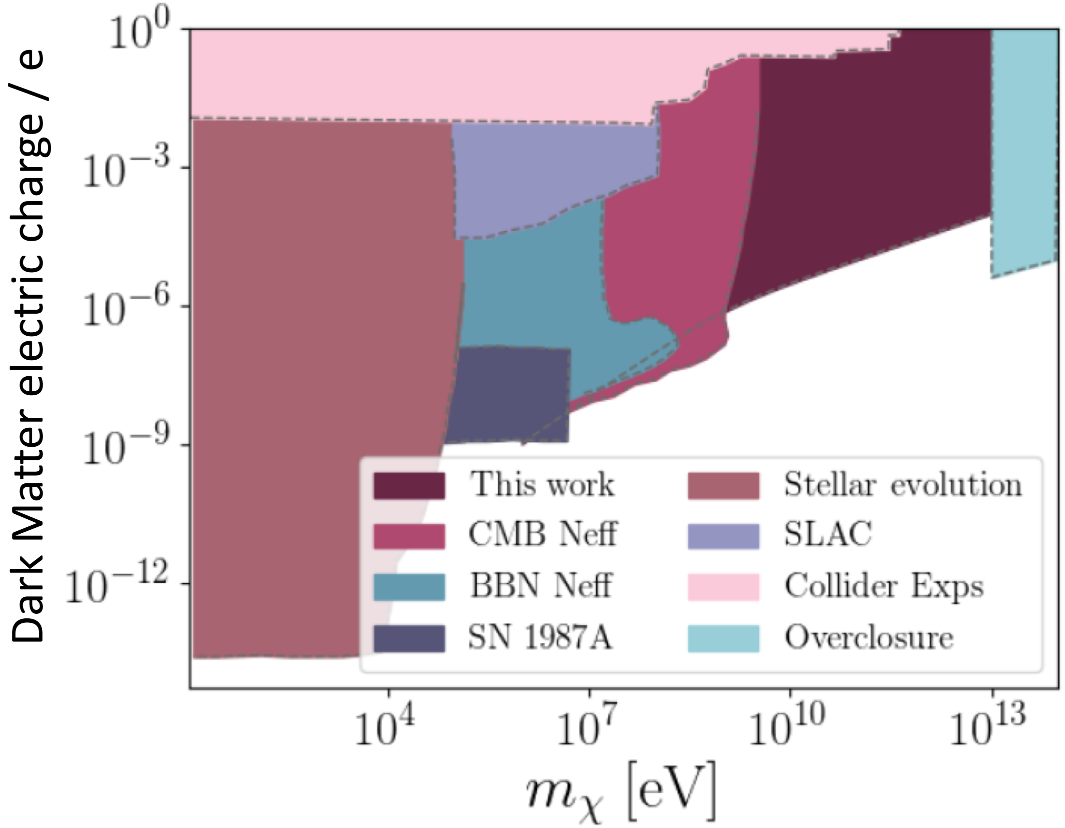


Linda Xu, C. Dvorkin and Andrew Chael, PRD (2018)

- 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.***

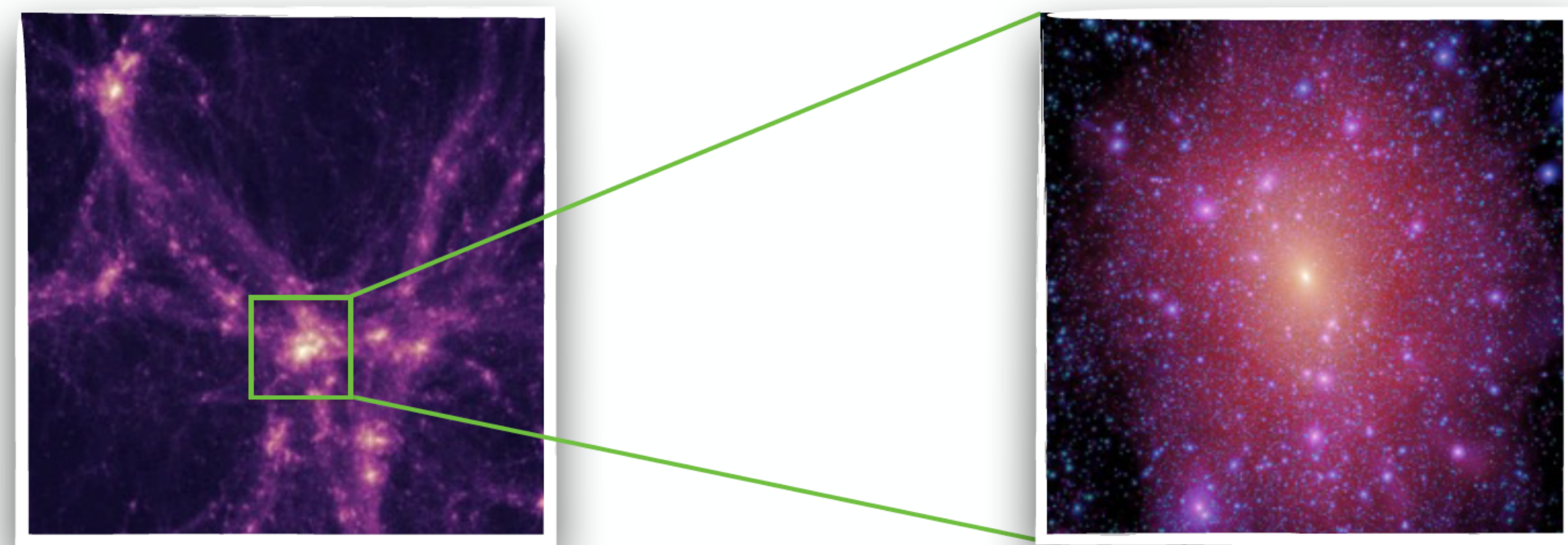
Cosmological observables provide an extremely complementary probe to that of direct detection and other indirect searches!

Millicharged Dark Matter



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

Small-scale structure of Dark Matter



Large-scale structure is very well measured.

Small-scale structure of Dark Matter is not as well understood.

Probing Dark Matter substructure at small scales via strong gravitational lensing

Looking for Dark Subhalos

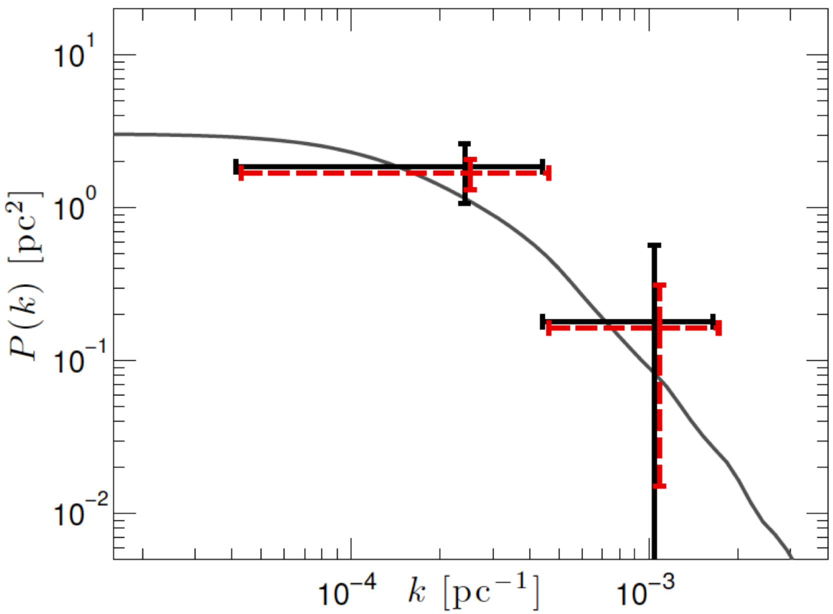
***Idea*: subhalos can locally perturb lensed images, so by looking at the residual between the images predicted by modeling the lens as a smooth mass and what is actually observed we can infer the presence of subhalos.**

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.

A different approach to substructure lensing: statistical detection of dark subhalos

The numerous population of low mass subhalos ($< 10^7\ M_\odot$) may be ***statistically detected*** by their collective perturbations on images.



Error bars based on mock ALMA observations.
Black = 10 hr long. Red = 40 hr long.

Hezaveh, Dalal, et al. (2016)

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:

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

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

$\mathbf{q}_i$ 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.

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

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

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

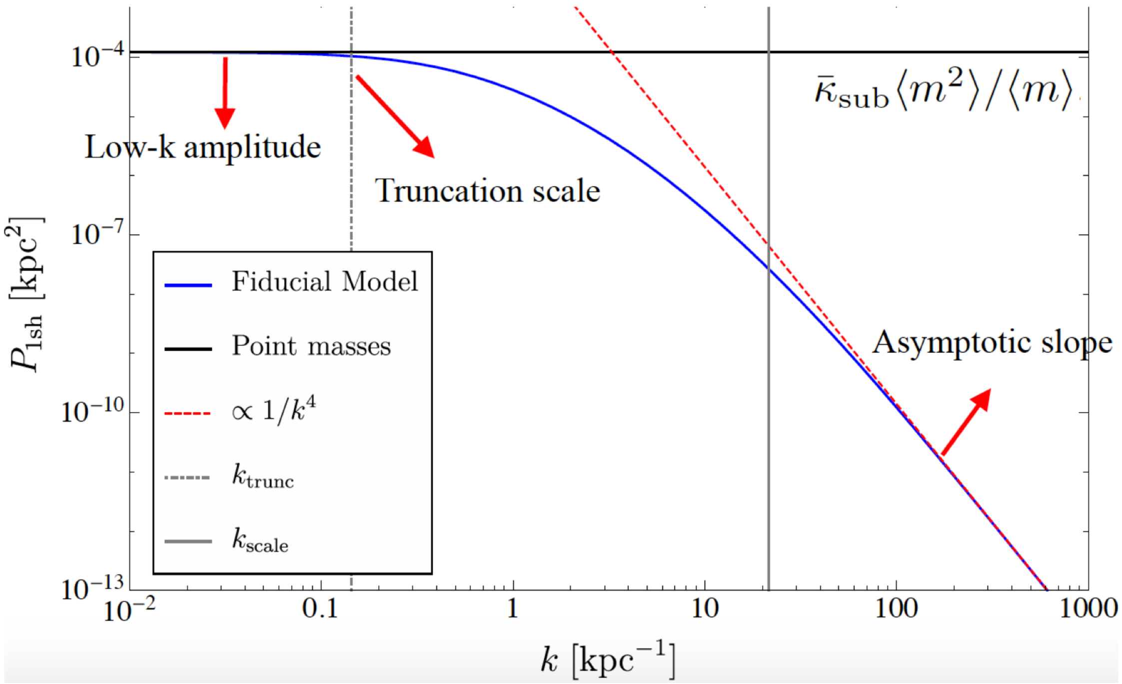
- 2-subhalo term: arises from averaging over pairs of distinct subhalos.

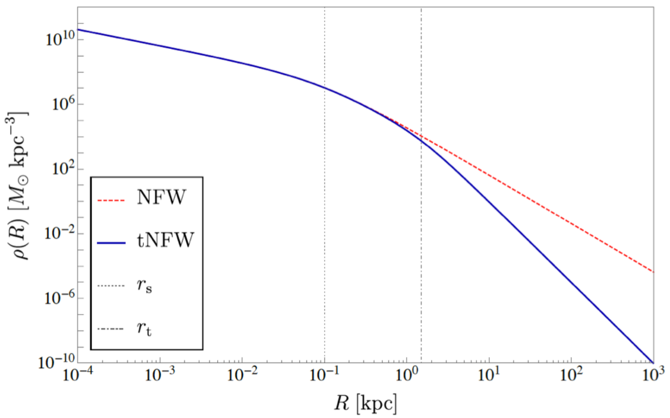
$$P_{\rm 2sh}(k) = \frac{(2\pi)^2 \bar{\kappa}_{\rm sub}^2}{\langle m \rangle^2} P_{\rm ss}(k) \left[\int dm\, d\mathbf{q}\, m\, \mathcal{P}_{\rm m}(m)\, \mathcal{P}_{\rm q}(\mathbf{q}|m) \times \int dr\, r J_0(k\, r) \hat{\kappa}(r, \mathbf{q}) \right]^2$$

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:

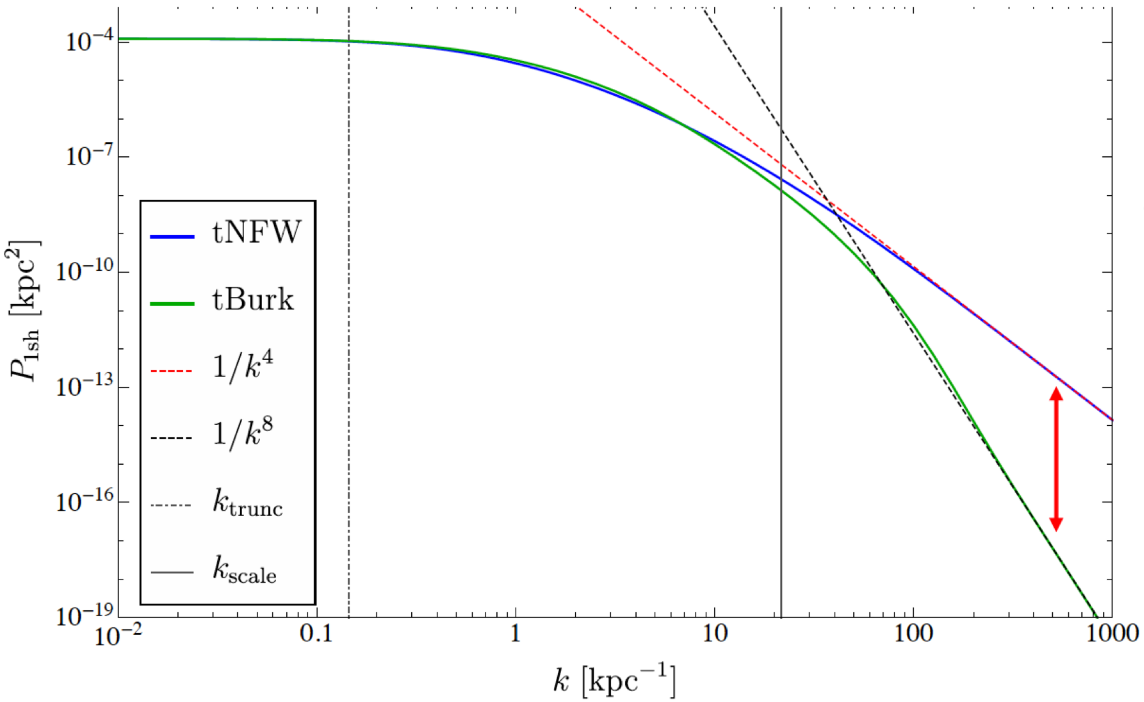


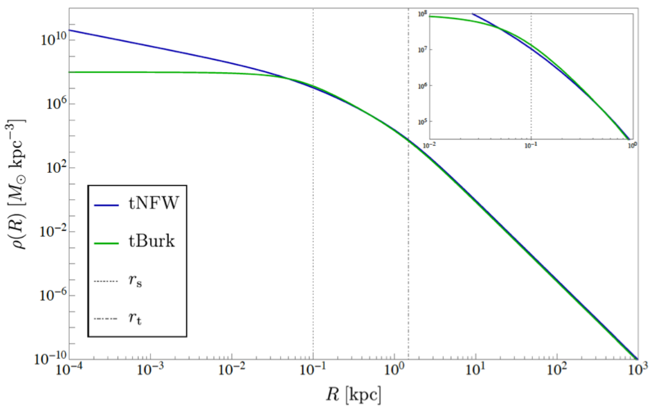


A. Diaz Rivero, F. Cyr-Racine, and C. Dvorkin, PRD (2017)

Substructure Power Spectrum: Truncated Cored Profile

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





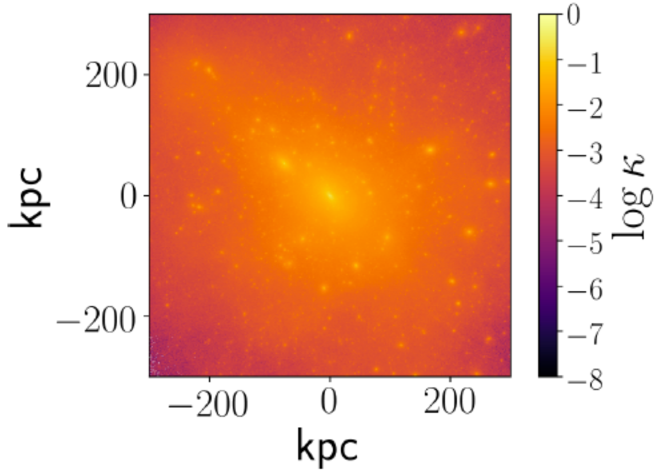
A. Diaz Rivero, F. Cyr-Racine, and C. Dvorkin, PRD (2017)

The Convergence Power Spectrum: Insights from Simulations

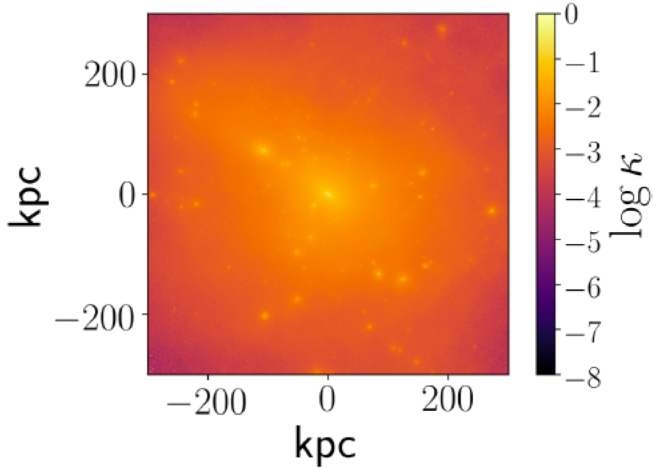
Simulations from Vogelsberger et al.

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

CDM



Self Interacting Dark Matter (SIDM)
+ cutoff in initial power spectrum

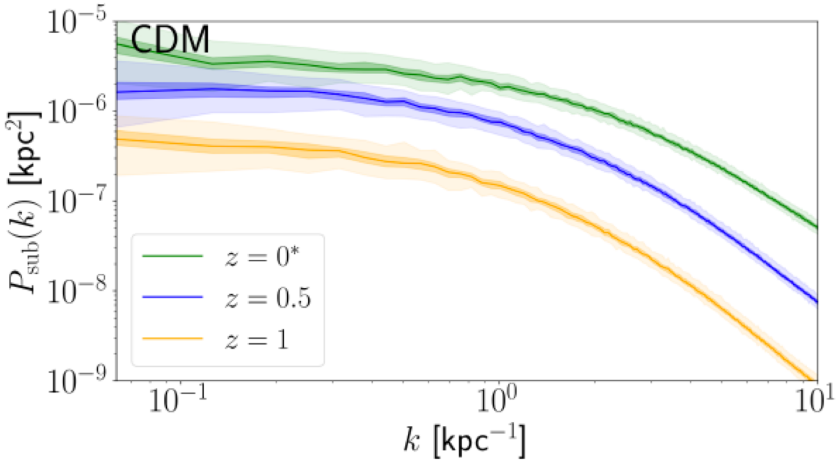


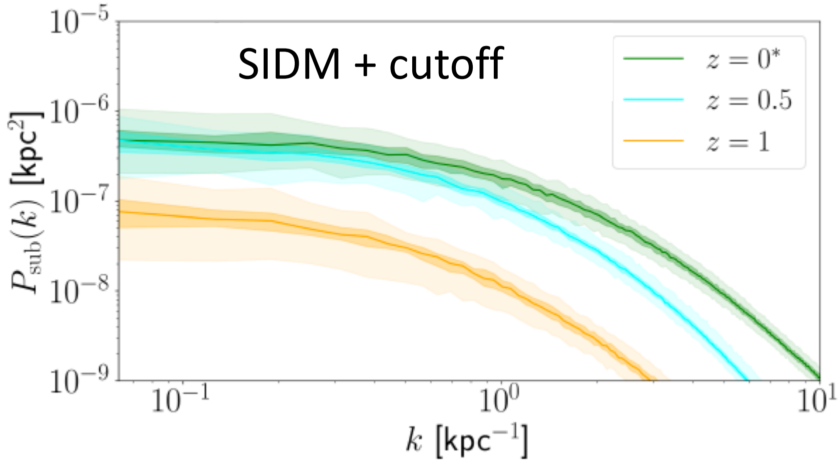
Diaz Rivero, C. Dvorkin, et al. , PRD (2018)

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.





Diaz Rivero, C. Dvorkin, et al. , PRD (2018)

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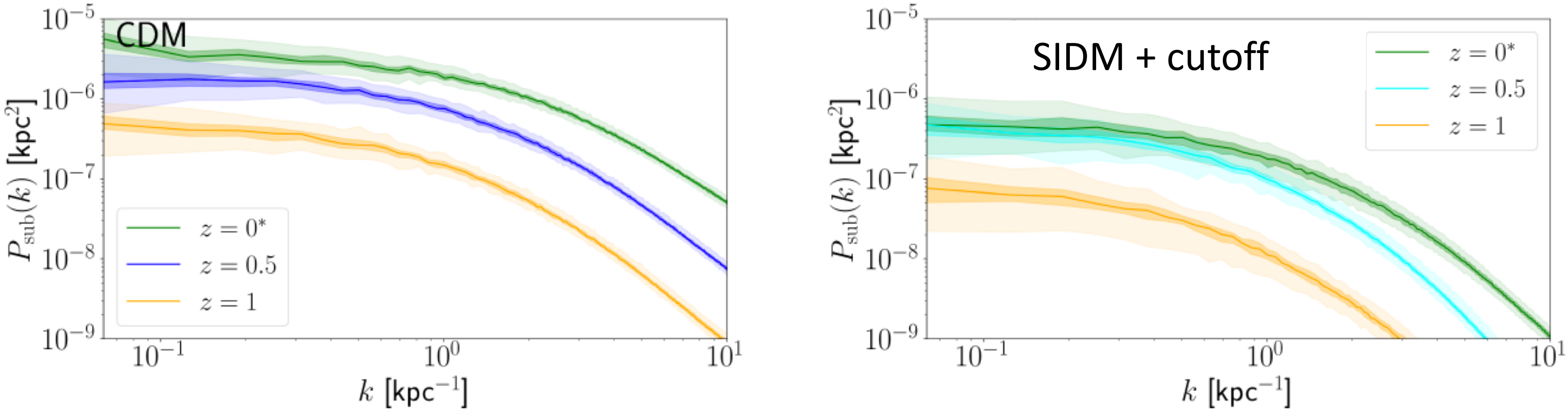
Change in the slope at $k \gtrsim 2\ \mathrm{kpc}^{-1}$ due to tidal stripping transferring power from larger to smaller scales.



Diaz Rivero, C. Dvorkin, et al. , PRD (2018)

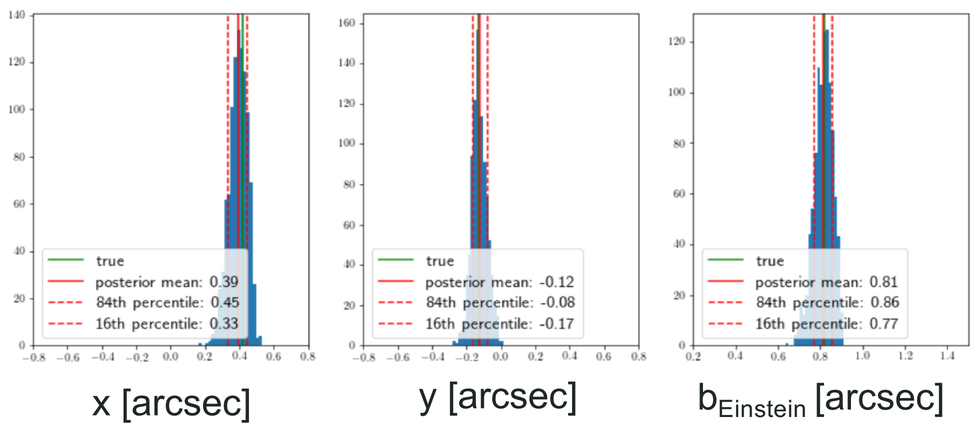
The Road Ahead

LSST 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 (LSST Dark Matter group)

Convolutional Neural Networks (CNNs) and Dark Matter Substructure

Illustrating posteriors with a simple simulated image (Neural Network with 2 hidden layers):



Previous work on related topics:
L. Perrault Levasseur et al. (2017)

Using CNNs to find substructure:

1. **Classification**: binary output - is an image likely to contain substructure or not? Can help identify promising images for further (expensive) traditional analysis.
2. **Regression**: estimate macro parameters + properties of a single subhalo - bypass traditional analysis.

Expensive and long training - parallelizing over many GPUs needed.

A. Diaz Rivero and C. Dvorkin, work in progress

Conclusions and the Road Ahead

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- 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.

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, promising spectacular advances in our yet very incomplete understanding of the universe.

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