Unveiling the Nature of Dark Matter with Cosmological Observables

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Harvard University

"Understanding Cosmological observations" workshop
Benasque, Spain
July, 2019

Outline

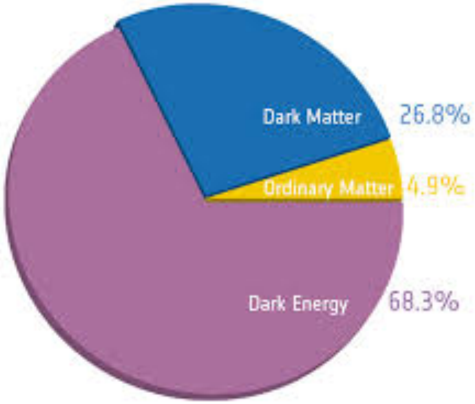
What is the **particle nature of Dark Matter**?

- 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.

What is the particle nature of Dark Matter?



Looking for Dark Matter off the beaten track

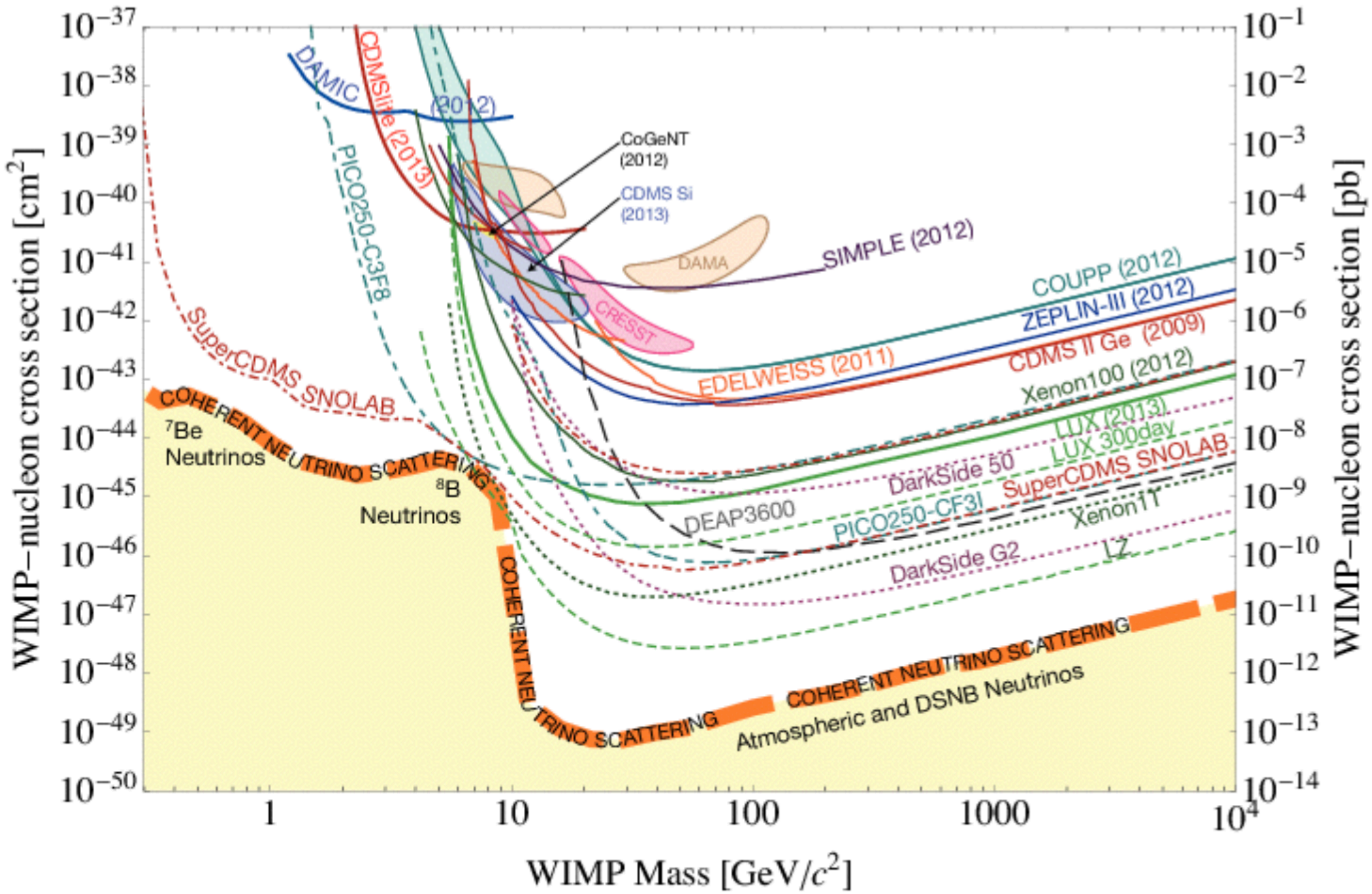
Where do Dark Matter interactions matter?

<u>Some well known avenues</u>:

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

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

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

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

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

Dark Matter-baryon momentum exchange rate:

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

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_χ, $\sigma \propto v^n$

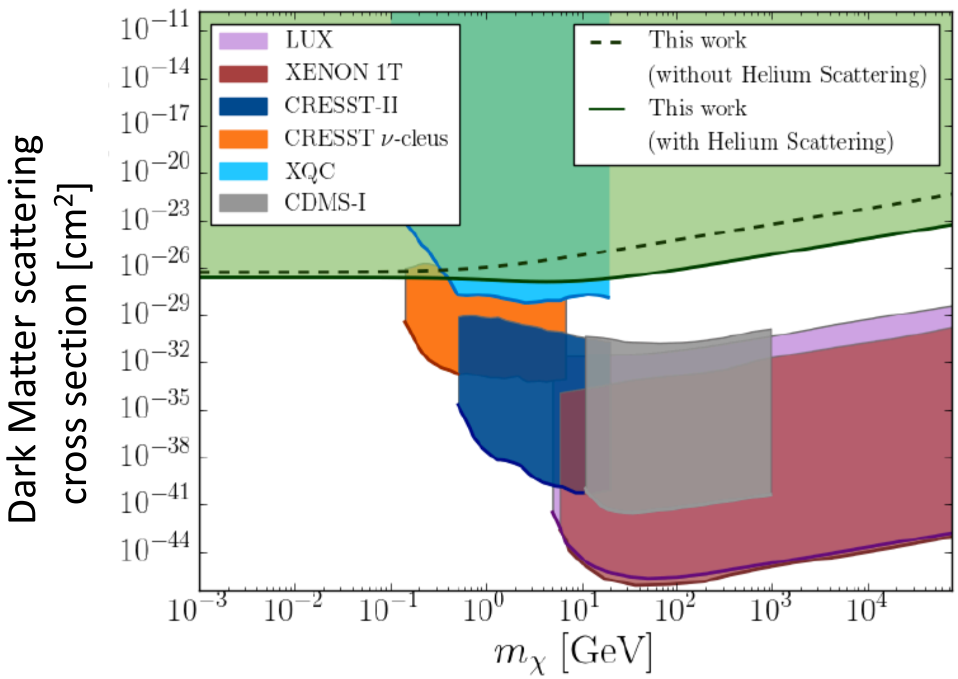
Observable Signatures

CMB temperature and polarization + Lyman-alpha forest

Constraints

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

Velocity-Independent Scattering

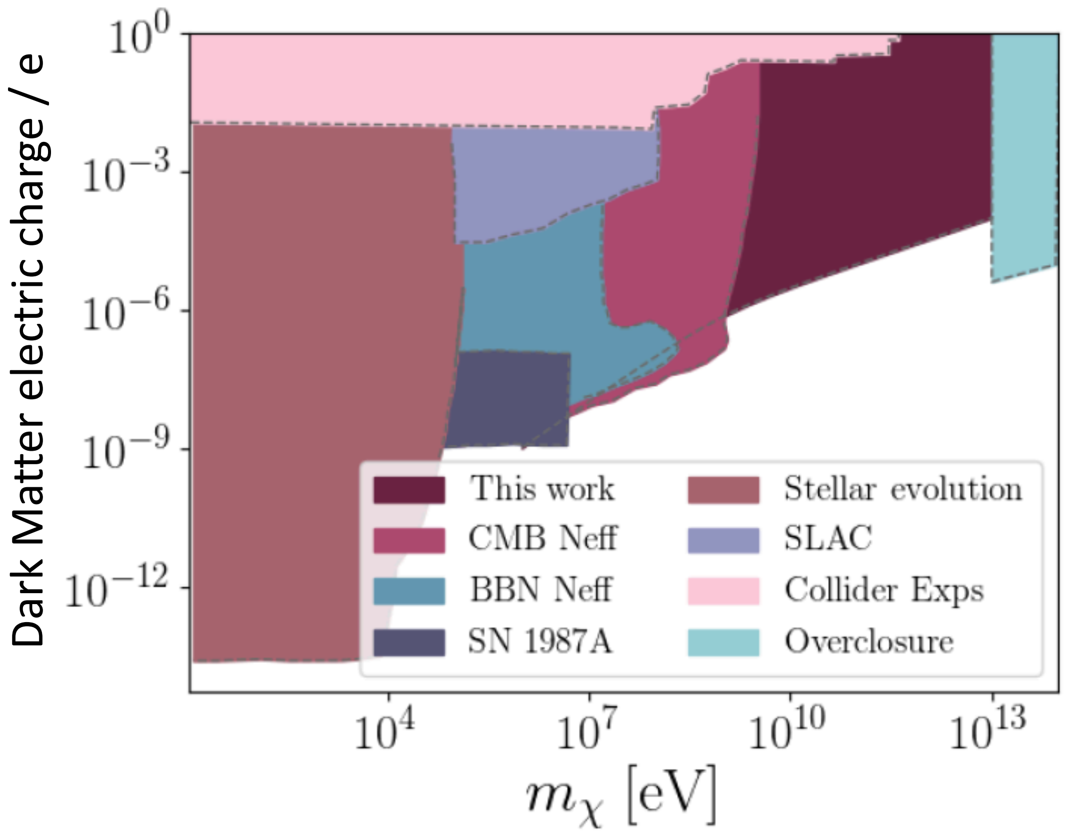


Linda Xu, C. Dvorkin and Andrew Chael, PRD (2018)

- 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!

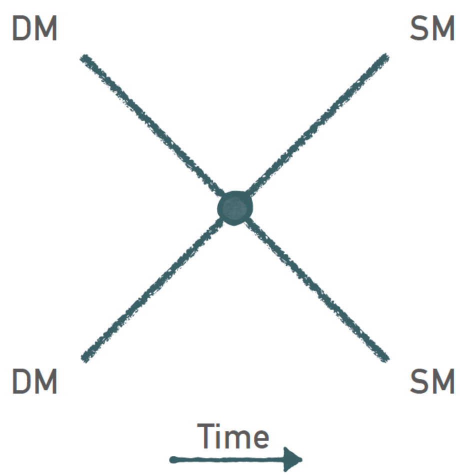
Millicharged Dark Matter



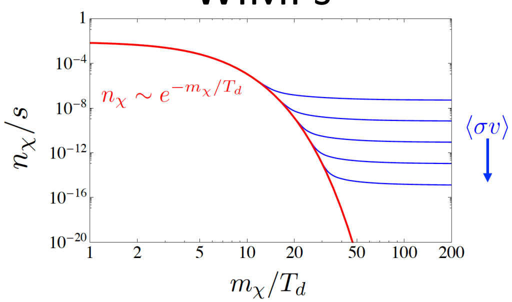
Linda Xu, C. Dvorkin and Andrew Chael, PRD (2018)

Going beyond the freeze-out mechanism

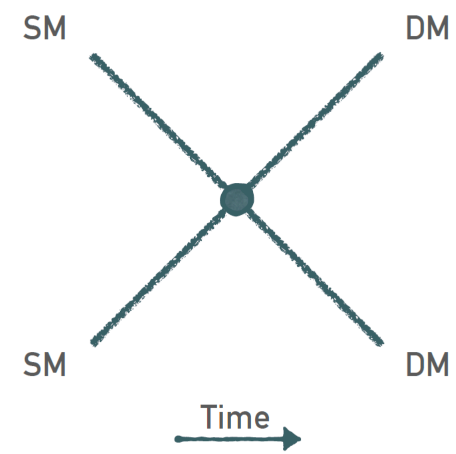
Freeze-out



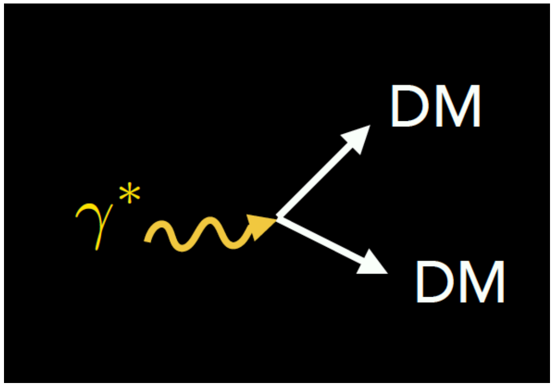
WIMPs

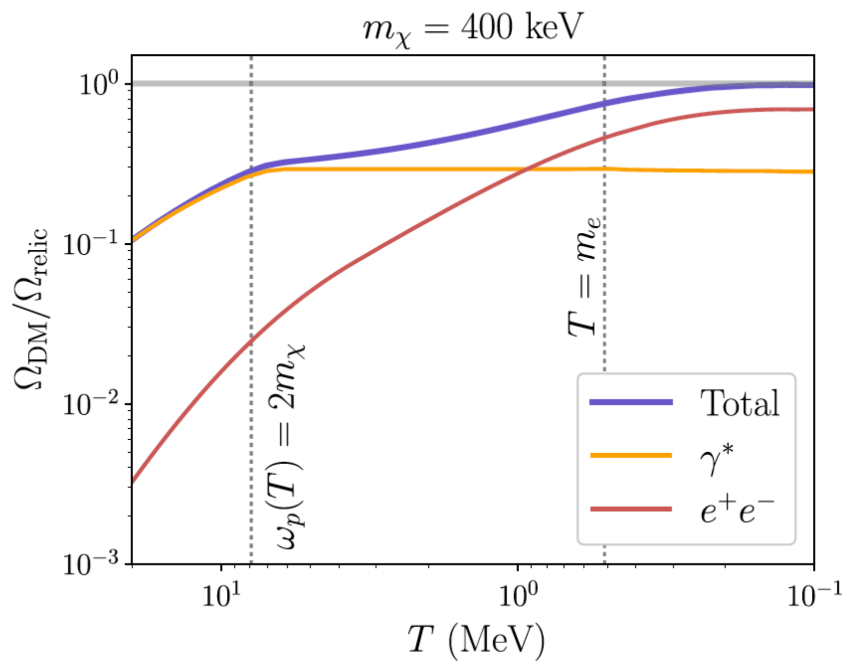


Freeze-in



New channel for Freeze-in



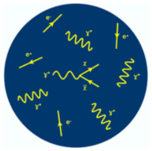


Editors' Suggestion

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

Cora Dvorkin, Tongyan Lin, and Katelin Schutz

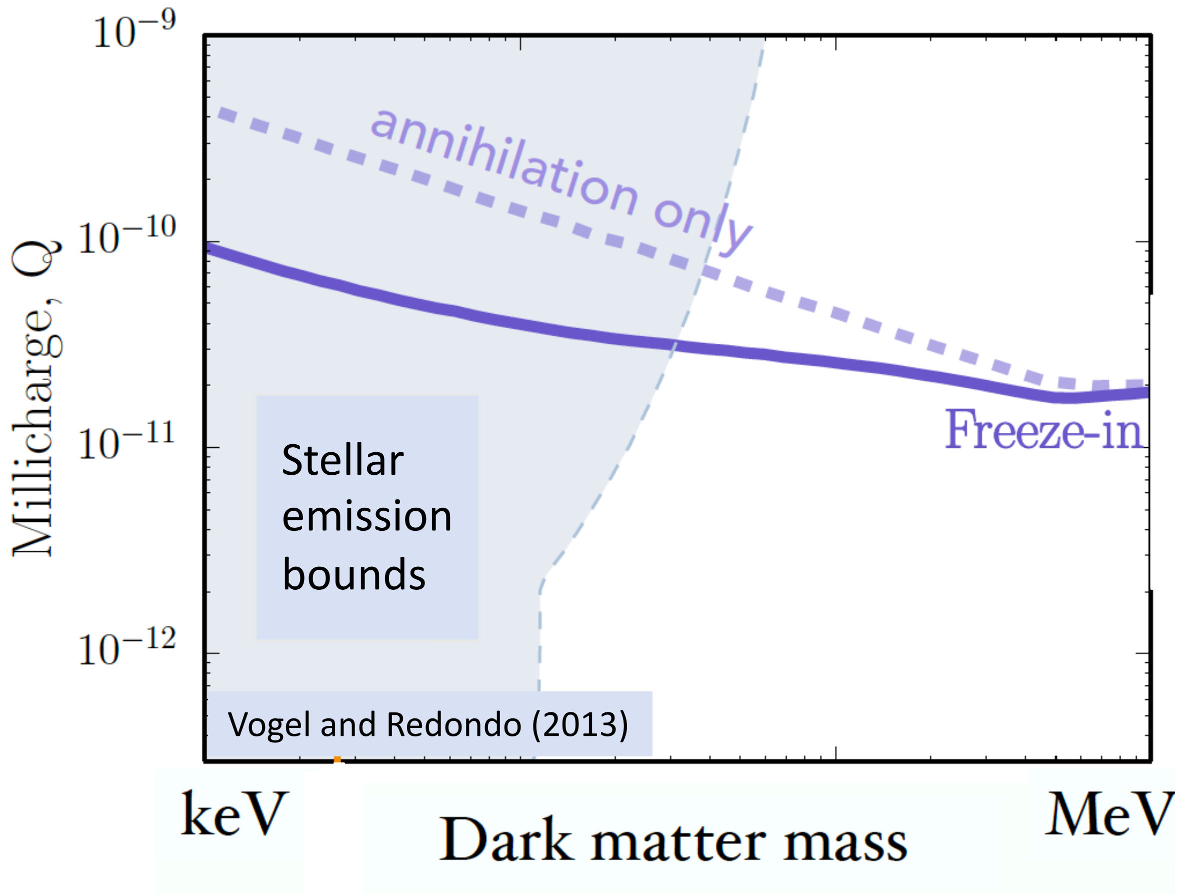
Phys. Rev. D **99**, 115009 (2019) – Published 11 June 2019



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.

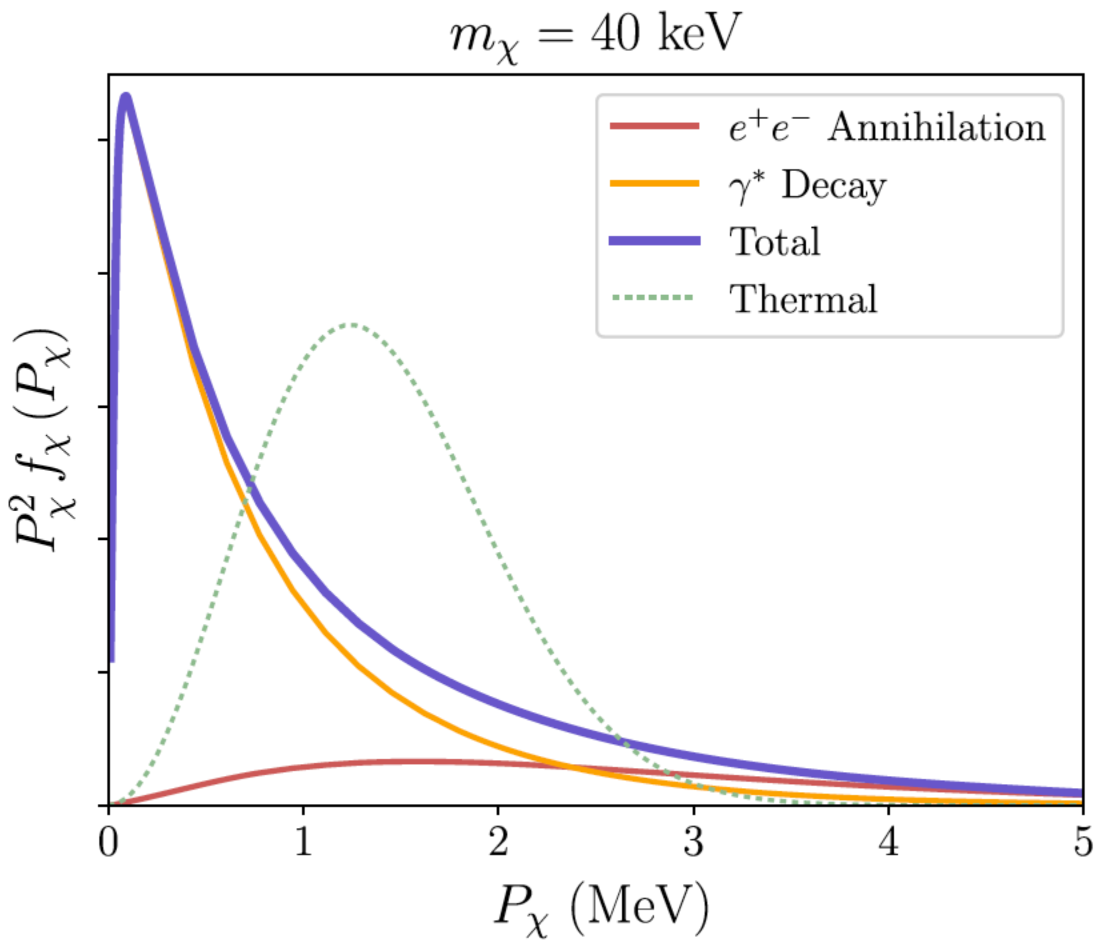
C. Dvorkin, T. Lin, K. Schutz, PRD (2019)

New channel for Freeze-in



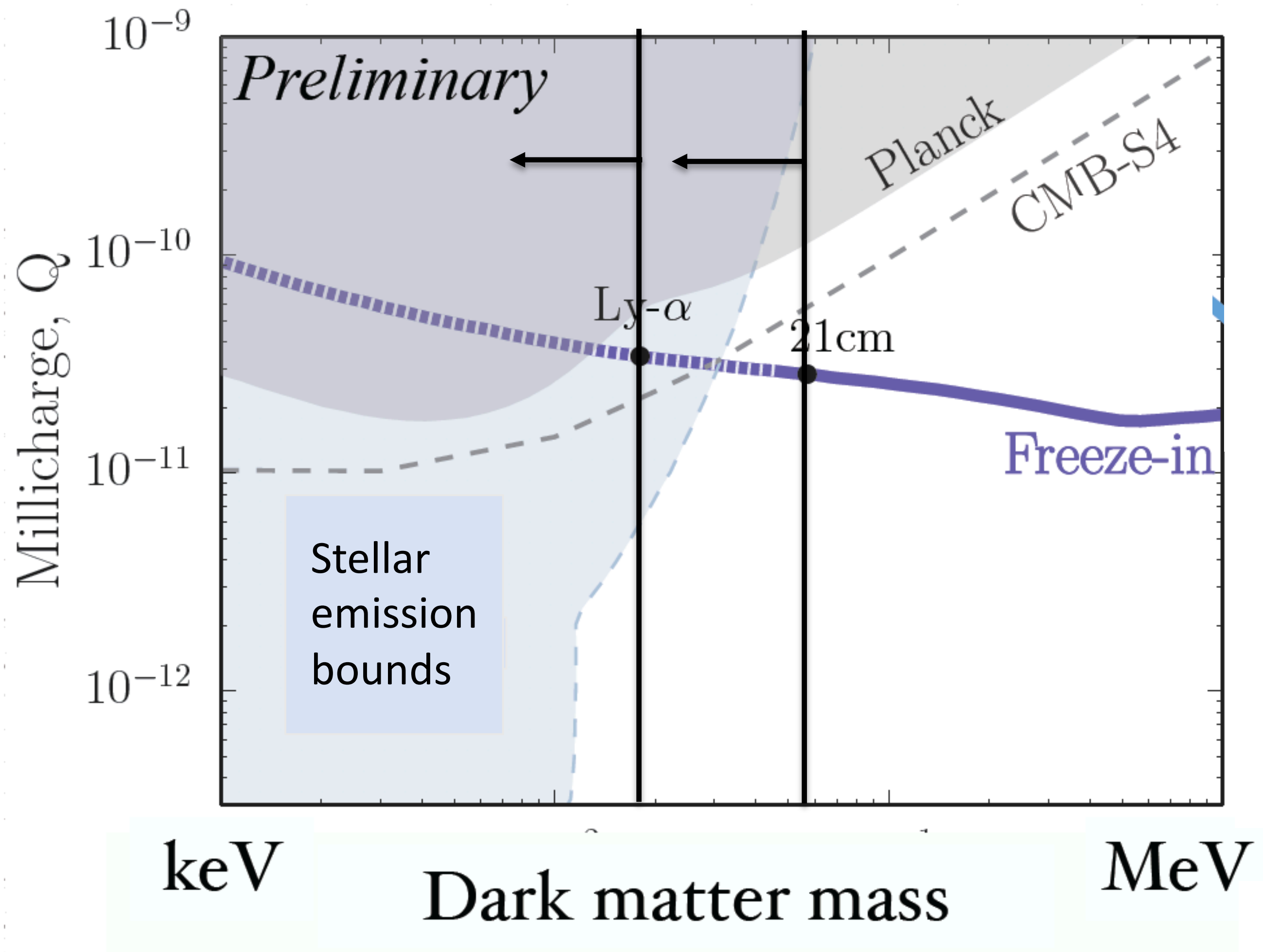
C. Dvorkin, T. Lin, K. Schutz, PRD (2019)

Dark Matter phase space



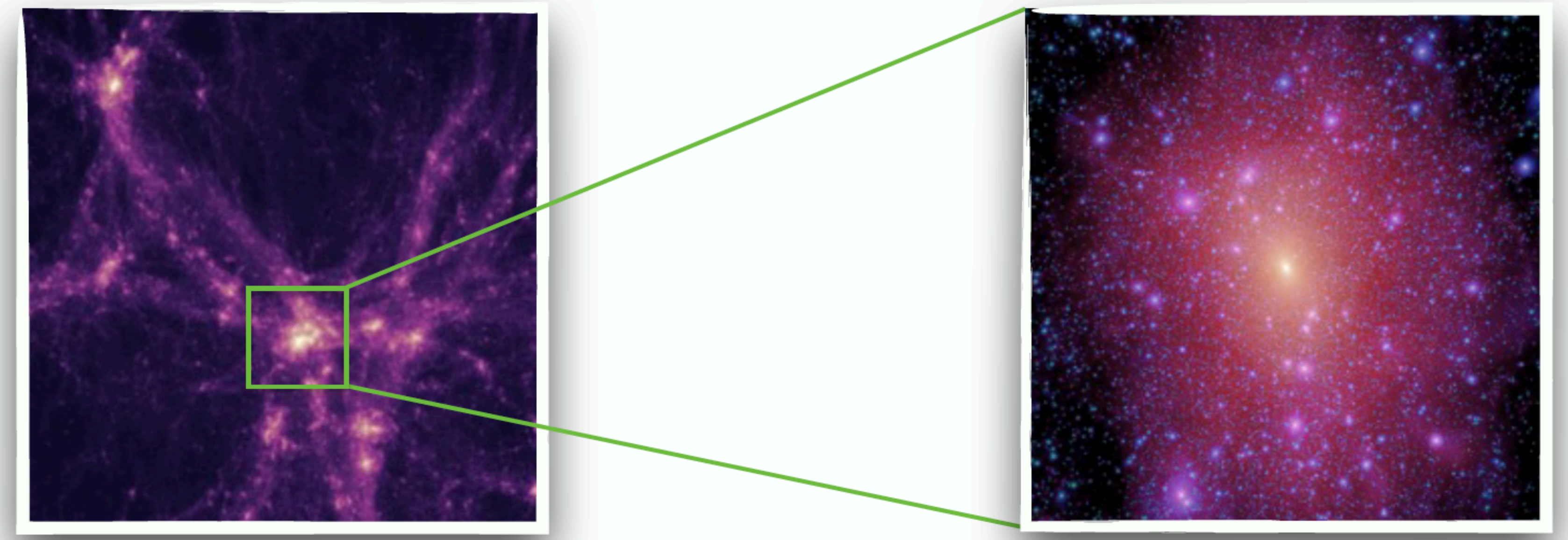
C. Dvorkin, T. Lin, K. Schutz, PRD (2019)

Probing Dark Matter scattering with current/future cosmological probes



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

Small-scale structure of Dark Matter

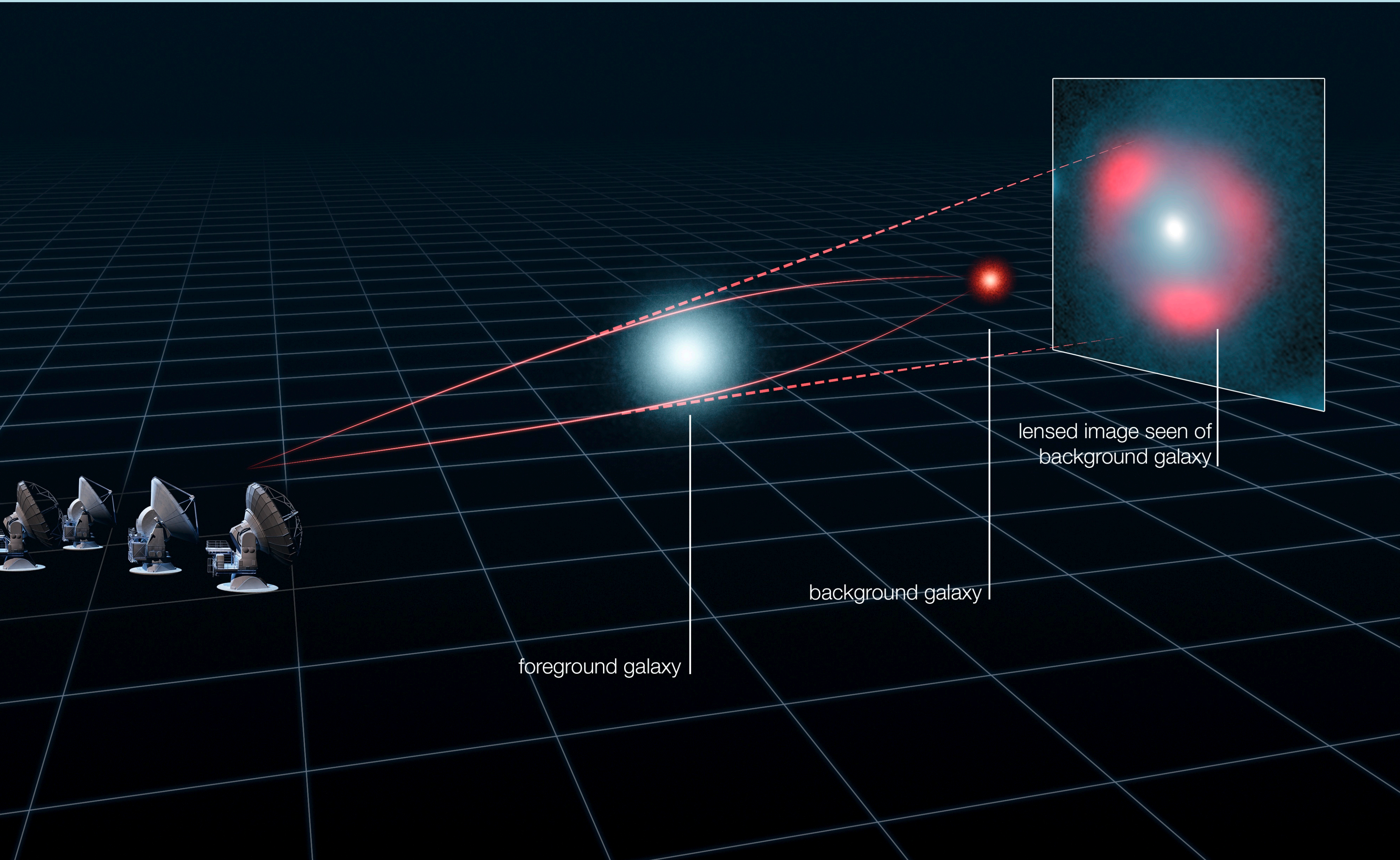


Large-scale structure is very well measured.

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

Probing Dark Matter substructure at small scales via strong gravitational lensing

Strong Gravitational Lensing



Looking for Dark Subhalos

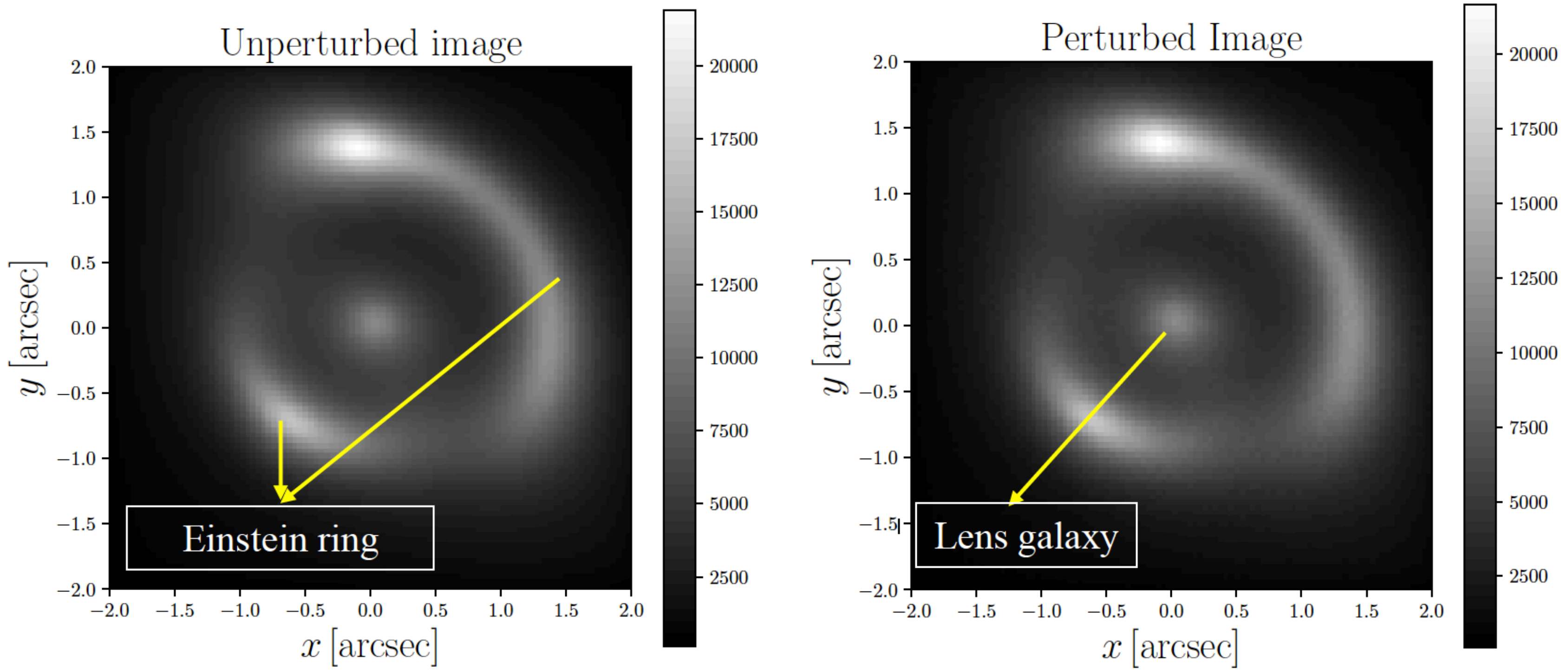
***Idea*: subhalos can locally perturb lensed images, so by looking at the residual between the images predicted by modeling the lens as a smooth mass and what is actually observed we can infer the presence of subhalos.**

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.

Looking for Dark Subhalos

In a CDM halo, many subhalos can be encountered along any given line of sight. The substructure deflection field leads to subtle surface brightness variations along the Einstein ring.



Looking for Dark Subhalos

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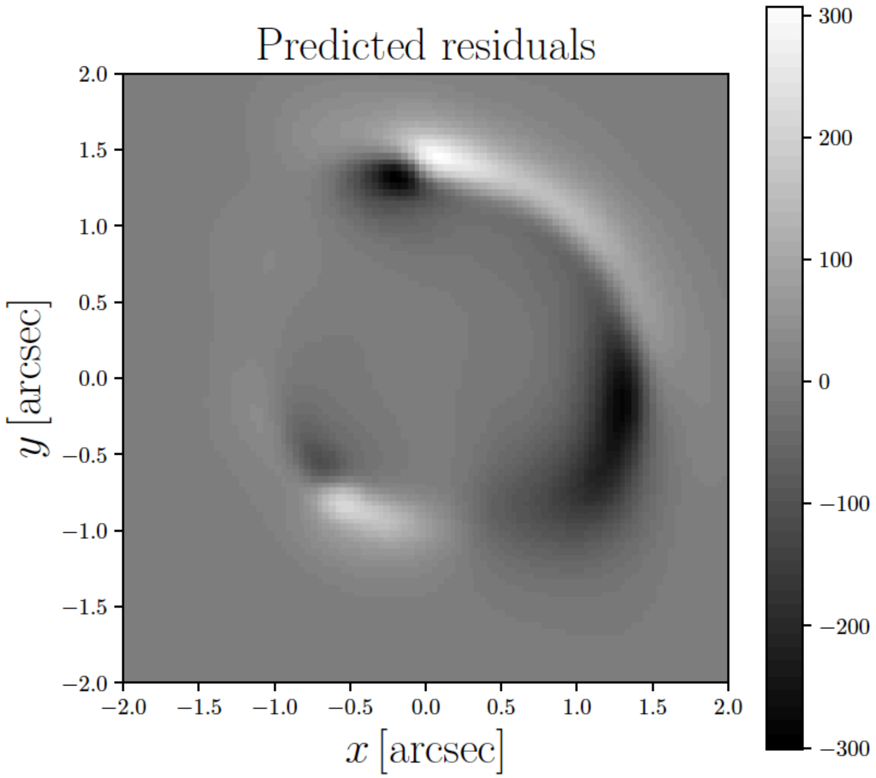


The numerous population of low mass subhalos ($< 10^7$ $M_\odot$) may be ***statistically detected*** by their collective perturbations on images.

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:

$\kappa_{\rm tot}(\mathbf{r}) = \kappa_0(\mathbf{r}) + \kappa_{\rm sub}(\mathbf{r})$, 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

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

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.

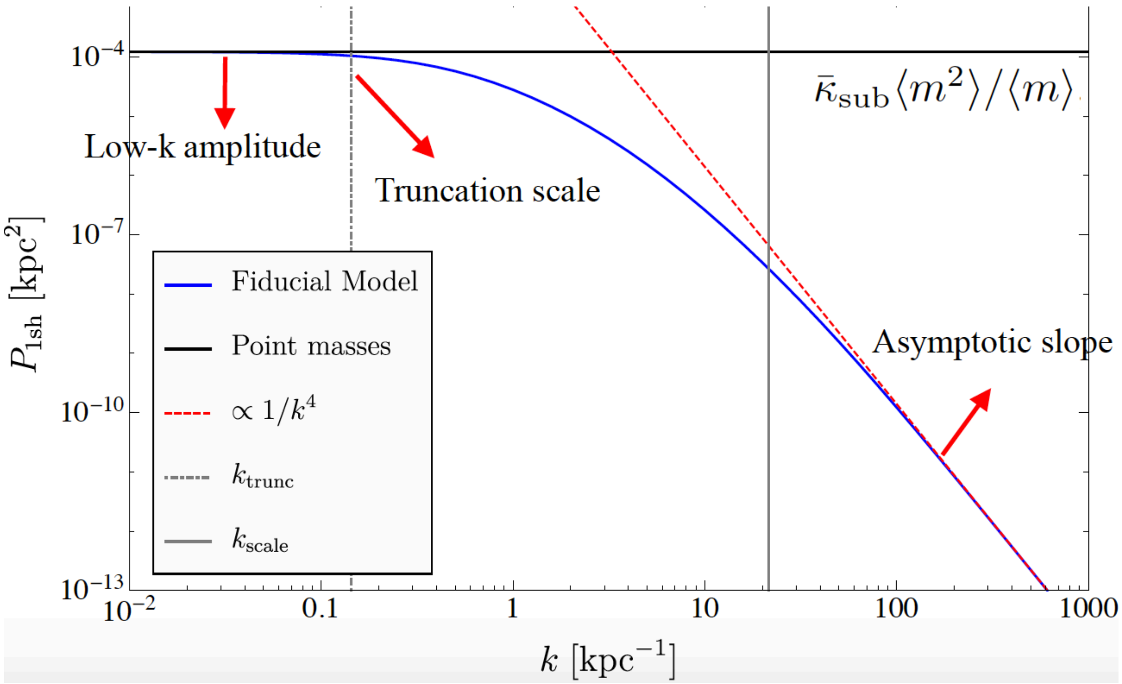
$$P_{\rm 1sh}(k) = \frac{(2\pi)^2 \bar{\kappa}_{\rm sub}}{\langle m \rangle \Sigma_{\rm crit}} \int dm\, d\mathbf{q}\, m^2\, \mathcal{P}_{\rm m}(m)\, \mathcal{P}_{\rm q}(\mathbf{q}|m) \times \left[\int dr\, r J_0(k\,r) \hat{\kappa}(r, \mathbf{q})\right]^2$$

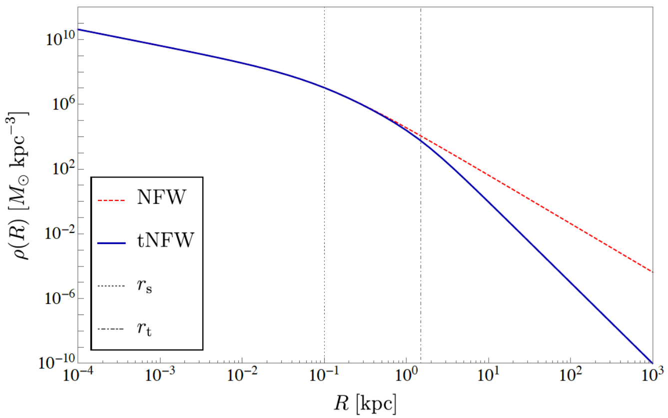
- 2-subhalo term: arises from averaging over pairs of distinct subhalos.

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

Substructure Power Spectrum: Truncated NFW Subhalo Population

The Power Spectrum can be described mainly by three quantities:

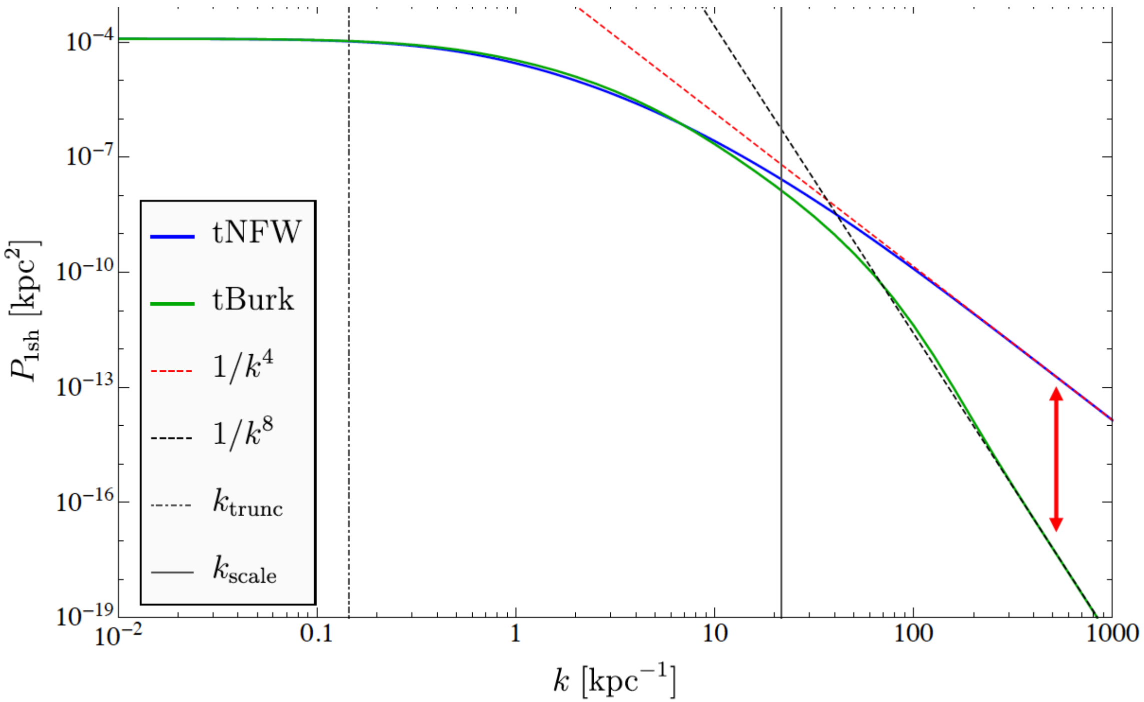


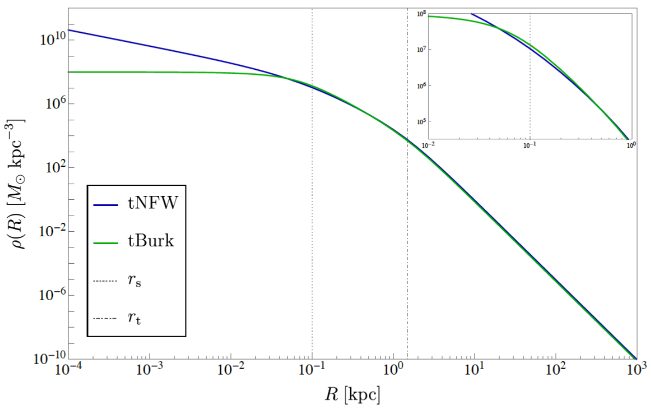


A. Diaz Rivero, F. Cyr-Racine, and C. Dvorkin, PRD (2017)

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)

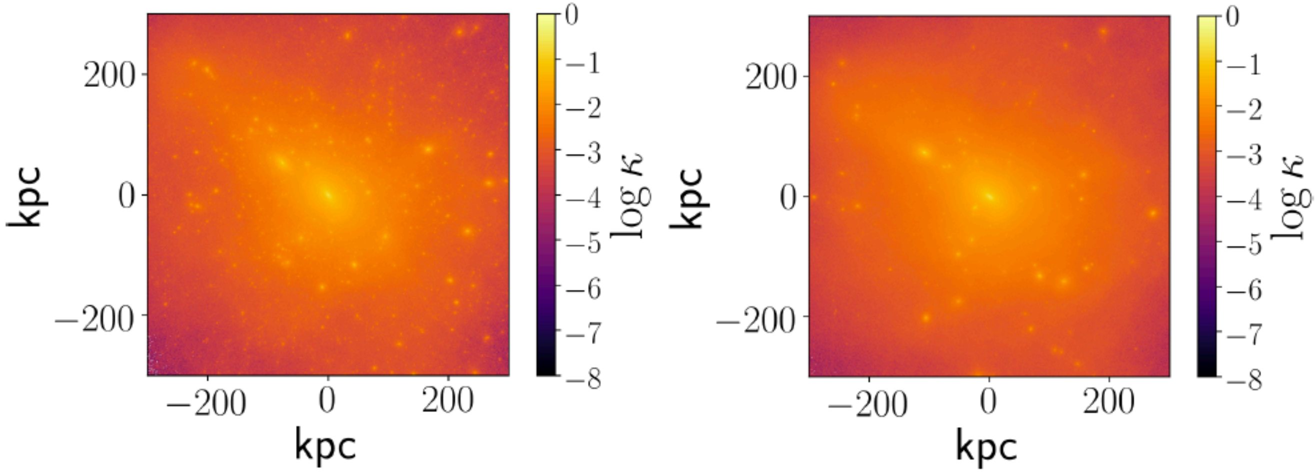
The Convergence Power Spectrum: Insights from Simulations

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

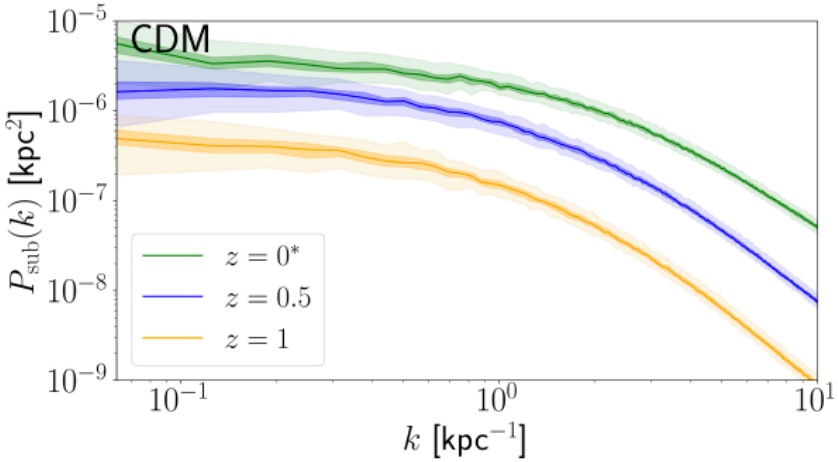


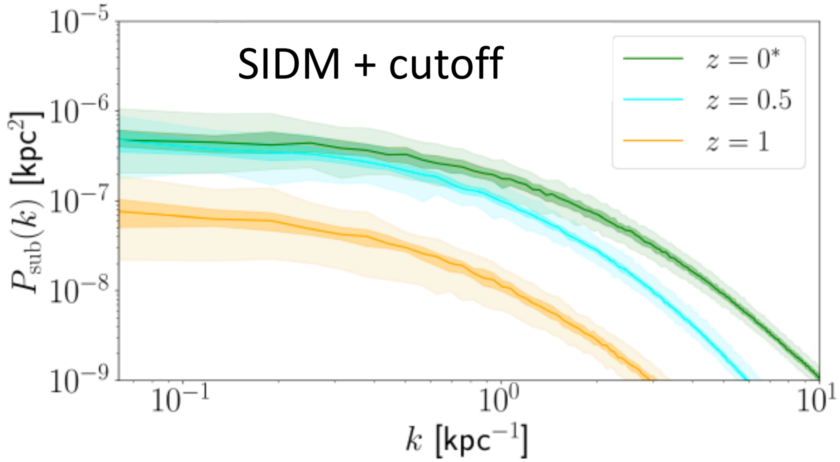
Diaz Rivero, C. Dvorkin, et al. , PRD (2018)

Redshift and Scale-Dependence

Comparing the amplitude and slope of the power spectrum on scales $0.1\ \mathrm{kpc}^{-1} < k < 10\ \mathrm{kpc}^{-1}$ 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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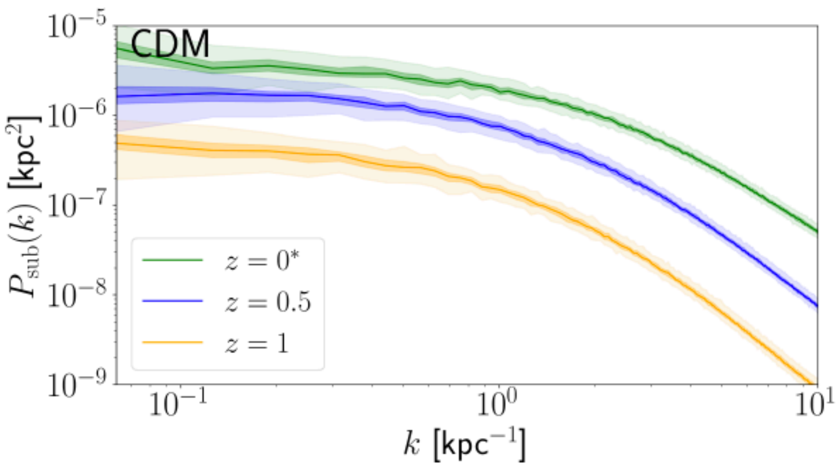
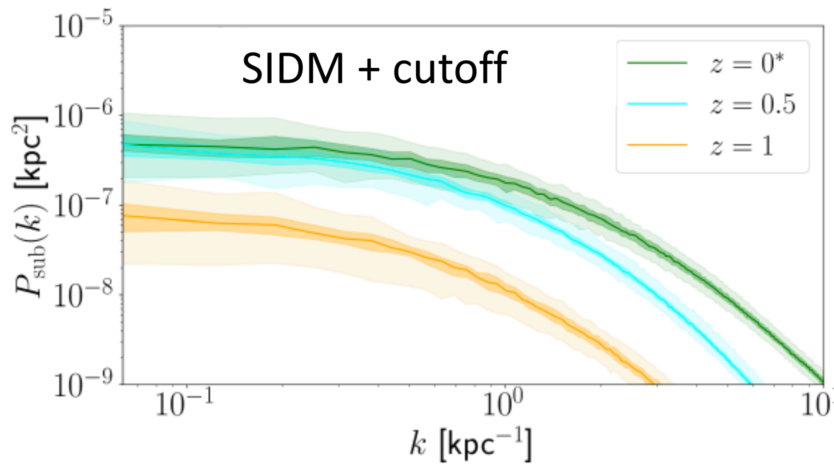
Change in the slope at $k \gtrsim 2\ \mathrm{kpc}^{-1}$ due to tidal stripping transferring power from larger to smaller scales.





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

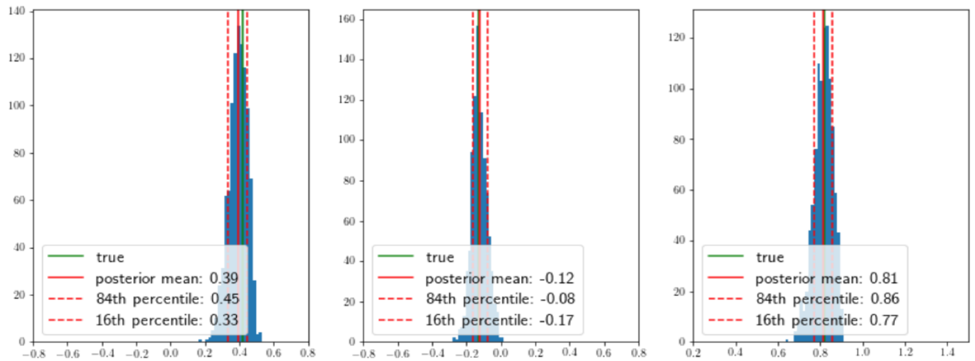
The Road Ahead

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
arXiv:1902.01055

Convolutional Neural Networks (CNNs) and Dark Matter Substructure

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



x [arcsec] y [arcsec] $b_{Einstein}$ [arcsec]

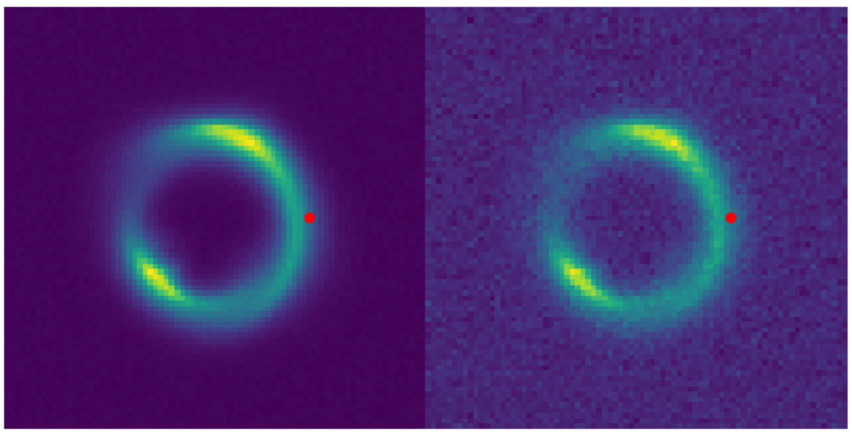
Previous work on related topic:
L. Perrault Levasseur et al. (2017)

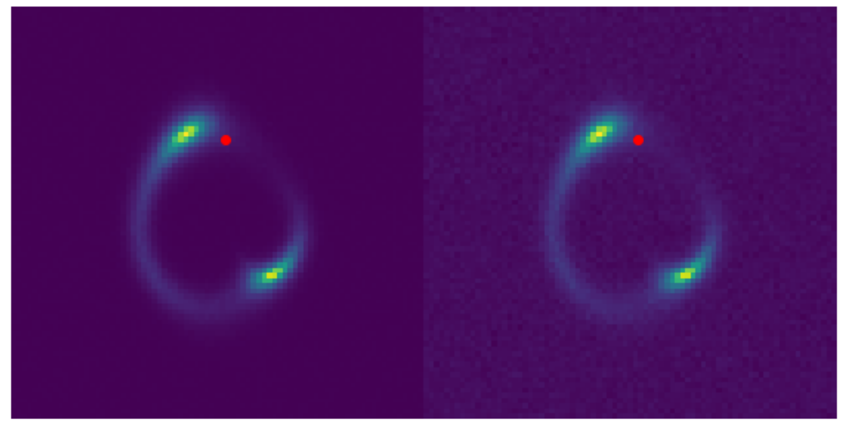
Using CNNs to find substructure:

Classification: binary output - is an image likely to contain substructure or not?
Can help identify promising images for further (expensive) traditional analysis.
Expensive and long training - parallelizing over many GPUs needed.

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

Convolutional Neural Networks (CNNs) and Dark Matter Substructure





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

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 major 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.