Discovering New Physics with Cosmological Data Sets

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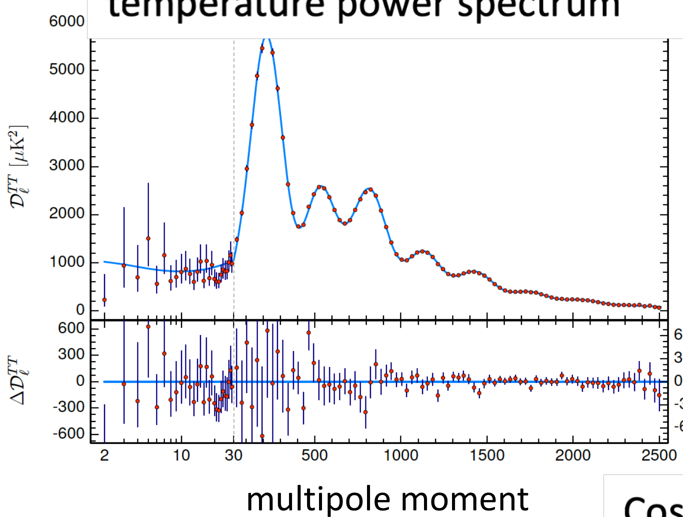
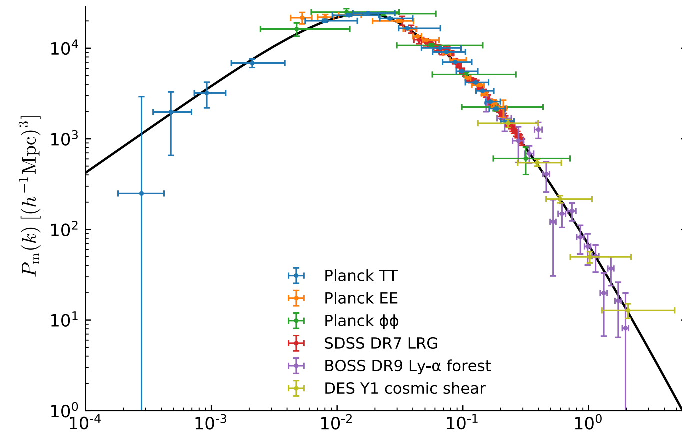
ΛCDM: our Standard Model of Cosmology

A simple model that is extremely successful on large cosmological scales.

Cosmic Microwave Background temperature power spectrum

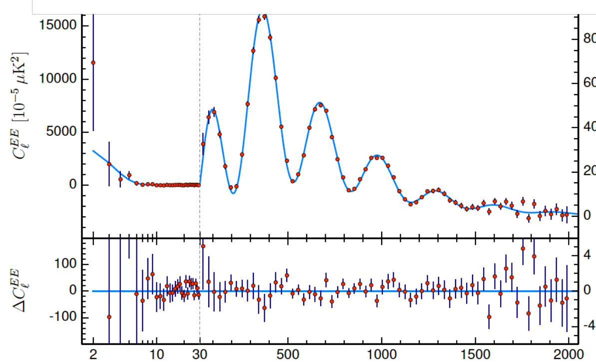


Matter power spectrum



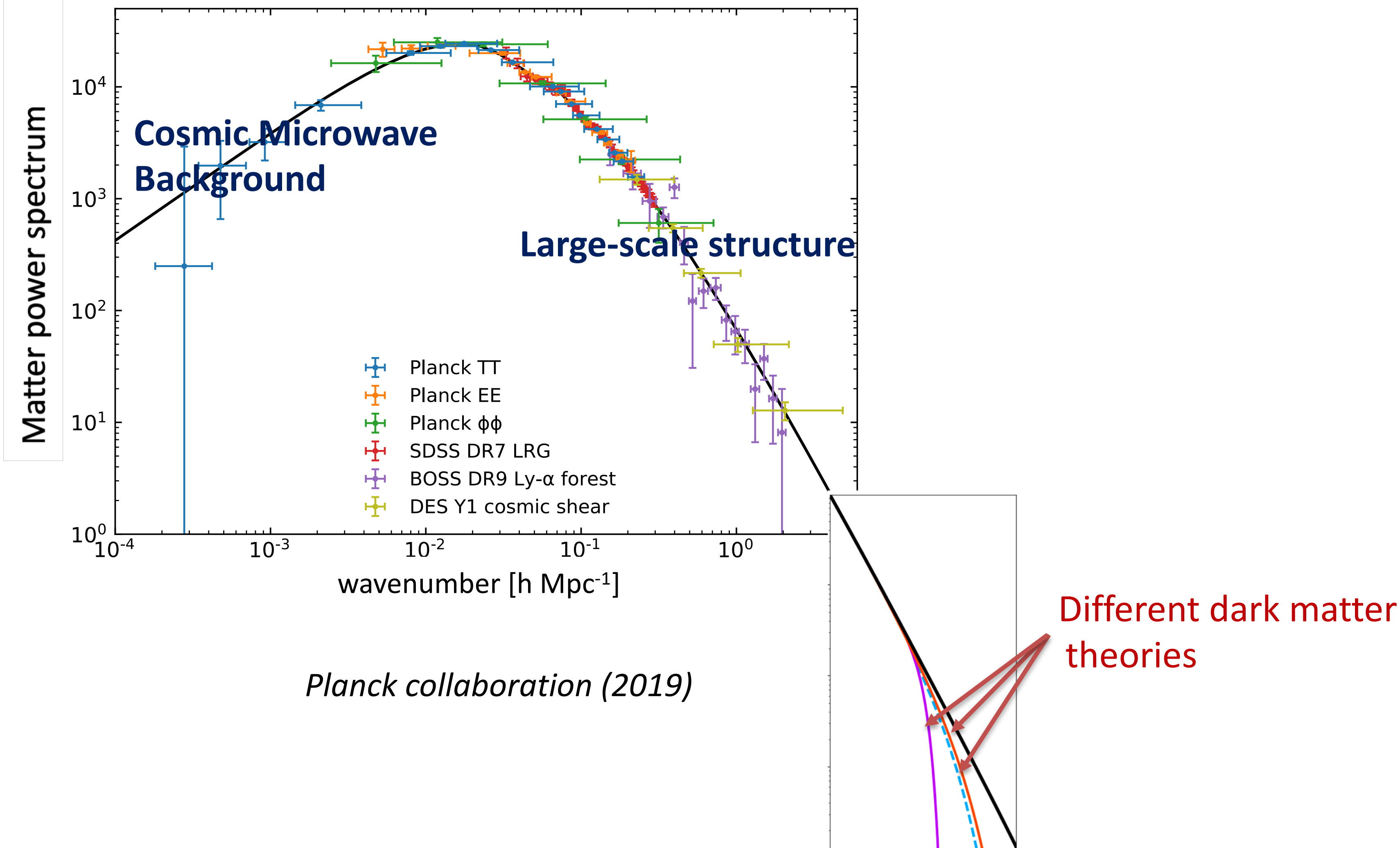
wavenumber [h Mpc^{-1}]

Cosmic Microwave Background polarization power spectrum



multipole moment

Planck collaboration (2019)



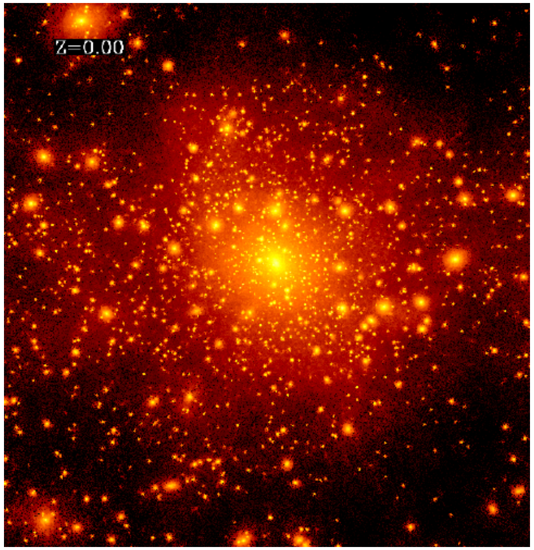
Planck collaboration (2019)

Small-scale structure: provides fertile grounds for testing different dark matter theories.

Dark Matter on sub-galactic scales

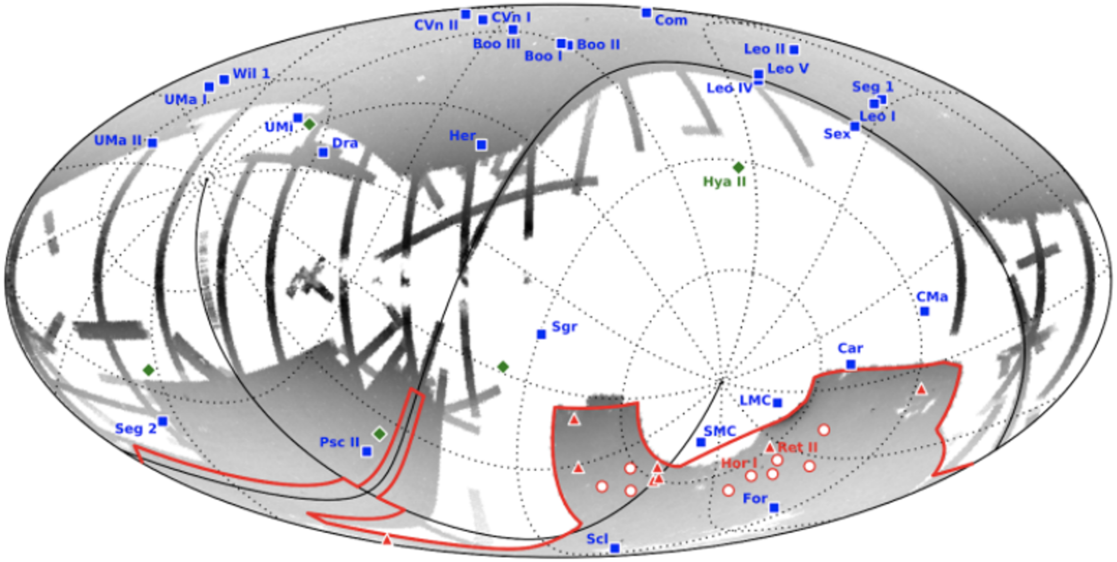
We expect an abundance of structure within dark matter halos.

Projected dark matter density for a Milky-Way sized halo



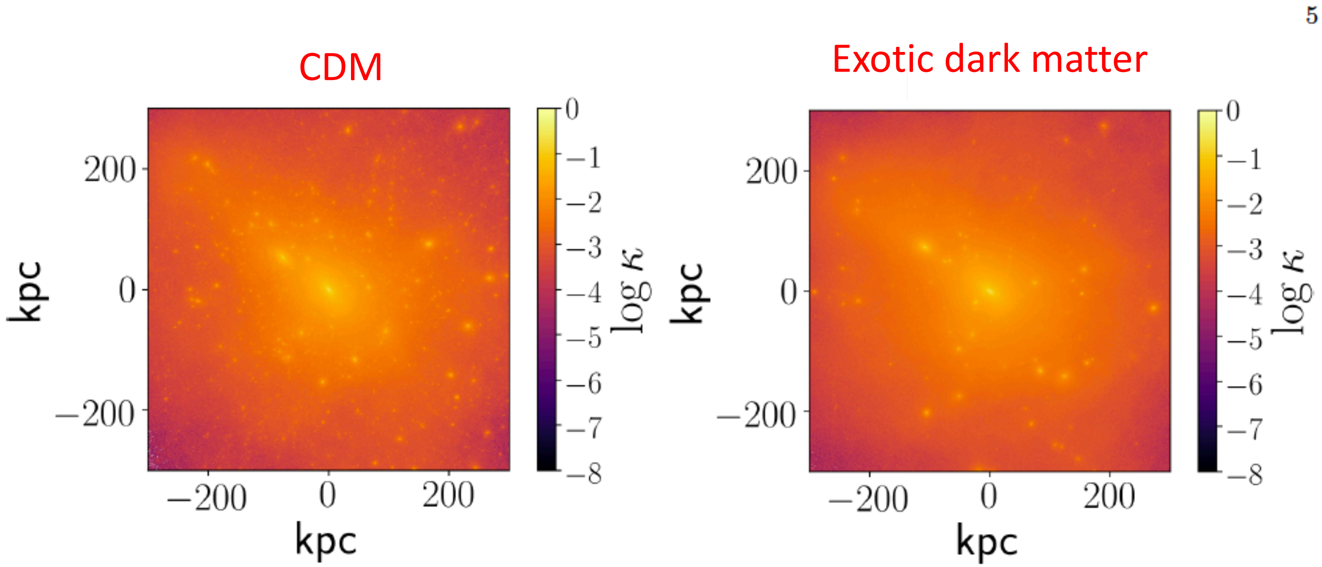
A. Kravtsov, Adv. in Ast. (2009)

Observed Milky Way satellite galaxies



DES Collaboration (2015)

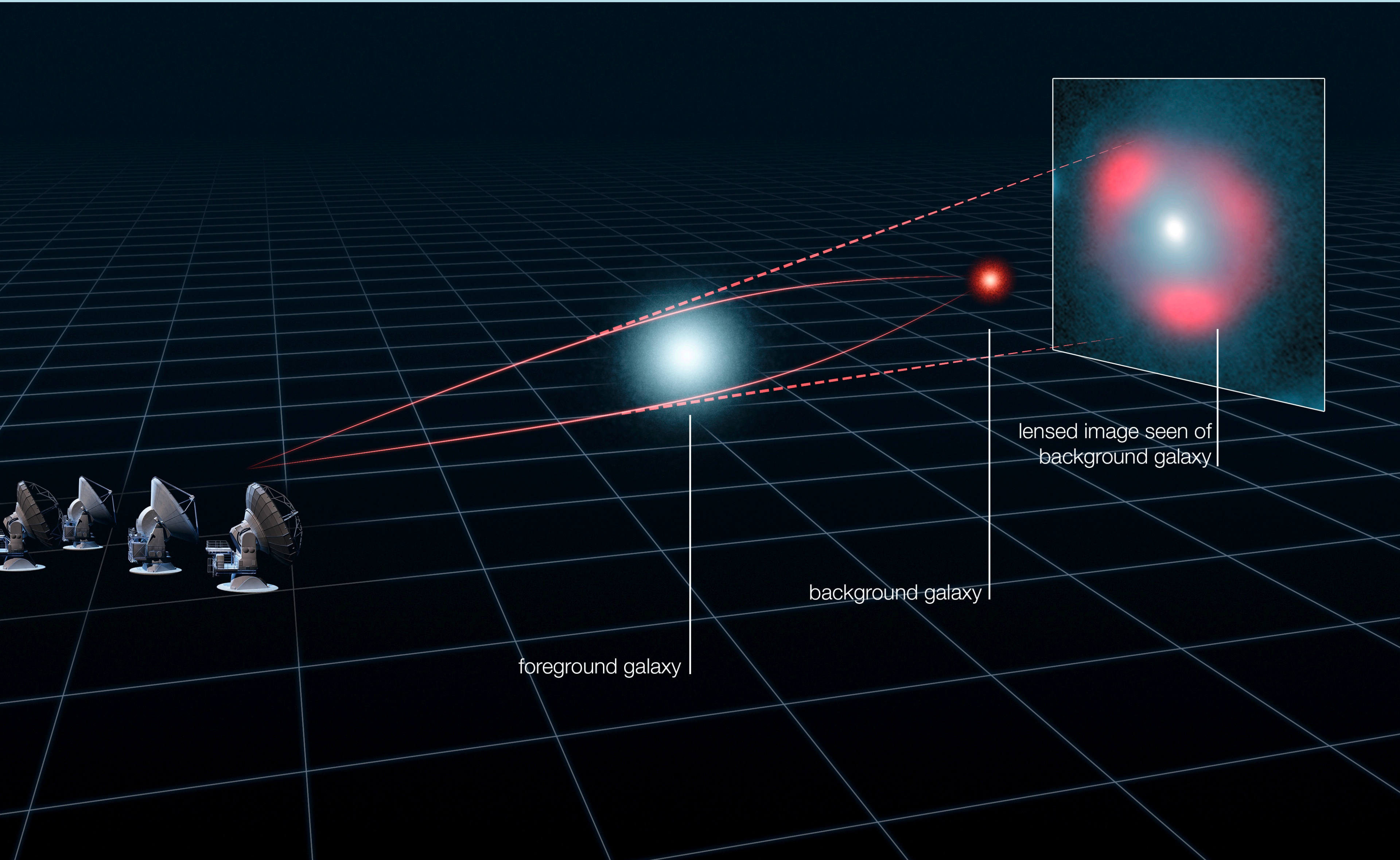
Dark Matter models: effects on sub-galactic scales



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

Let’s use these small scales to falsify/corroborate the CDM paradigm.

Strong gravitational lensing



Looking for dark subhalos

***Idea (Mao and Schneider, 1998)*: 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 the lowest mass subhalos are largely devoid of stars: a gravitational technique is needed to detect them.

Strong gravitational lensing as a small-scale probe

Direct detection: resolve individual, more massive perturbers and infer properties (mass, position). Requires postprocessing and combining many images to convert detections into dark matter constraints.

A. Diaz Rivero and C. Dvorkin, PRD (2019)
B. Ostdiek, A. Diaz Rivero, and C. Dvorkin (2020a, 2020b)

Indirect/statistical detection: statistically detect the collective perturbations on images of a large number of unresolved low-mass structures (marginalizing over individual subhalo properties).

A. Diaz Rivero, F. Cyr-Racine, and C. Dvorkin, PRD (2017)
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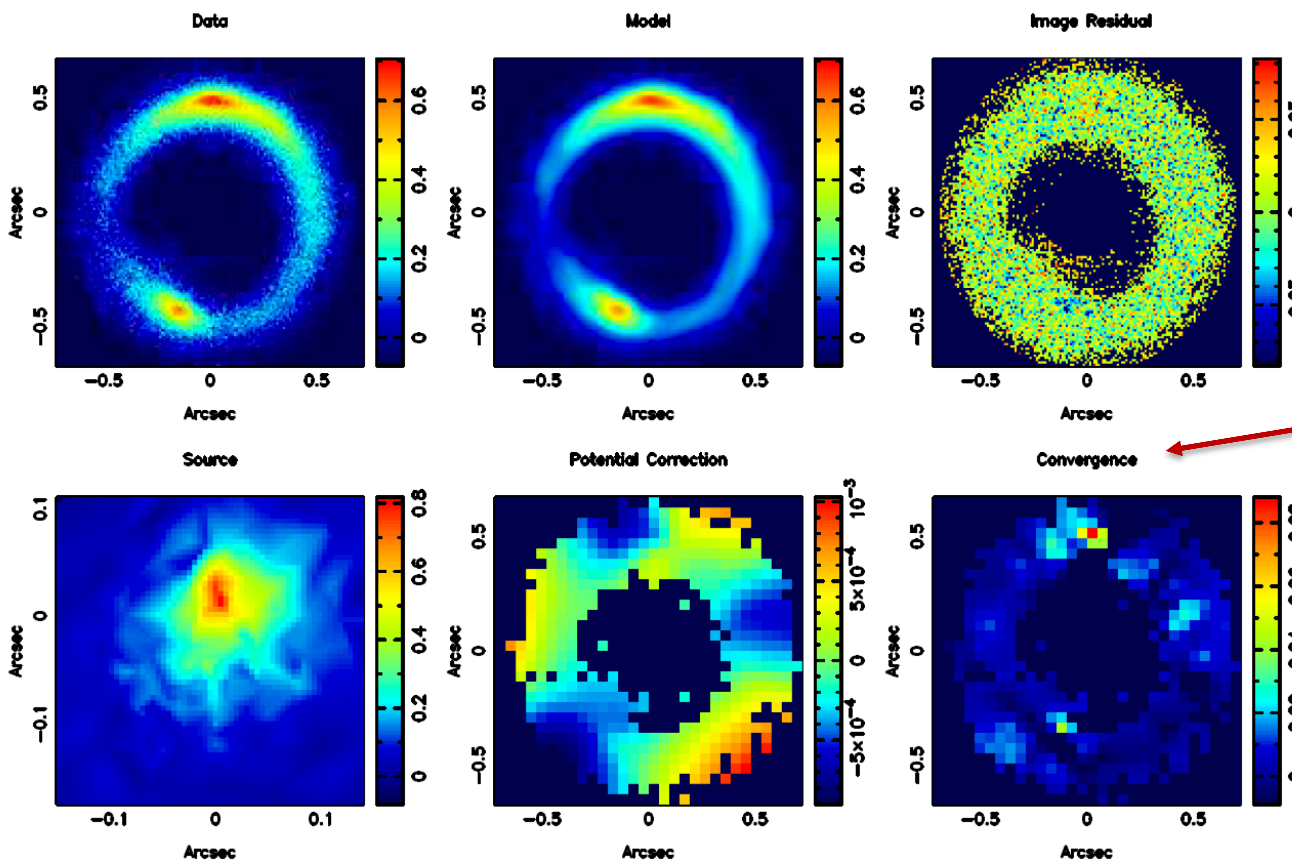
Direct detection: gravitational imaging



Reconstructed surface mass density

Vegetti et al., Nature (2012)

The road ahead

The Vera Rubin Observatory will discover tens of thousands of lensed galaxies in the coming decade.

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

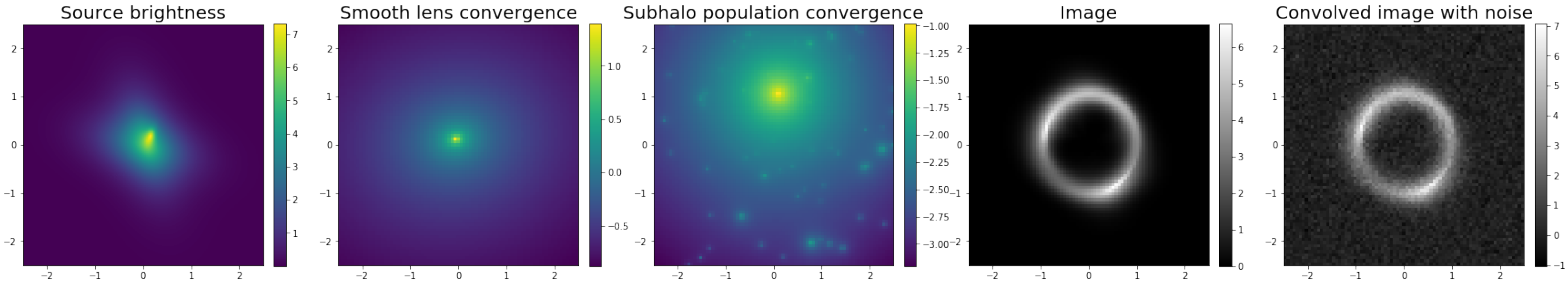
The road ahead: machine learning to the rescue

Direct detection of substructure is computationally very expensive.

Can we speed up the process of analyzing the huge number of lensed galaxies expected with near-future surveys?

Our simulation pipeline:

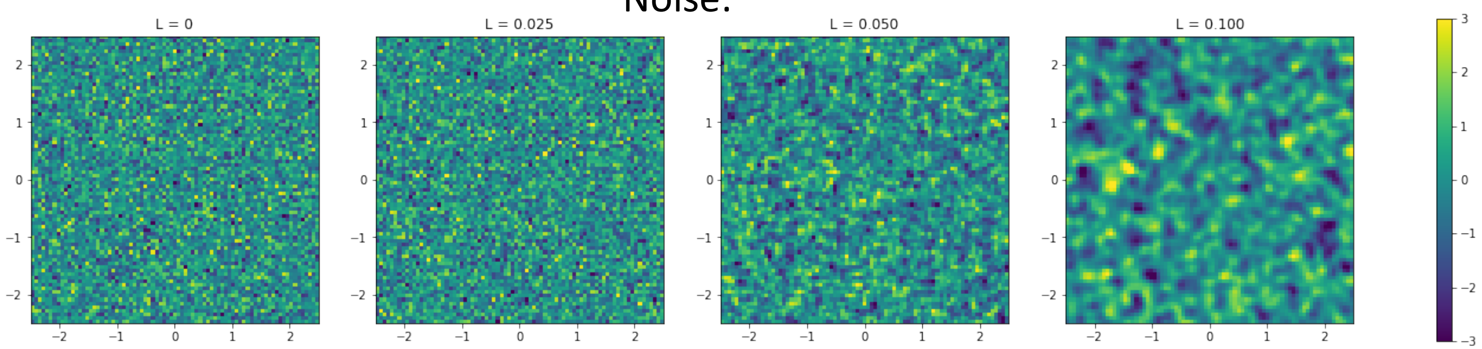
Ana Diaz Rivero



(with *Lenstronomy*, Birrer et al., 2015)

We varied the macro model, the source, and the subhalo-population from image to image + different levels of (correlated) noise.

Noise:



A. Diaz Rivero and C. Dvorkin, PRD (2019)

Direct detection of substructure with CNNs

Classification: binary output - is an image likely to contain substructure or not?

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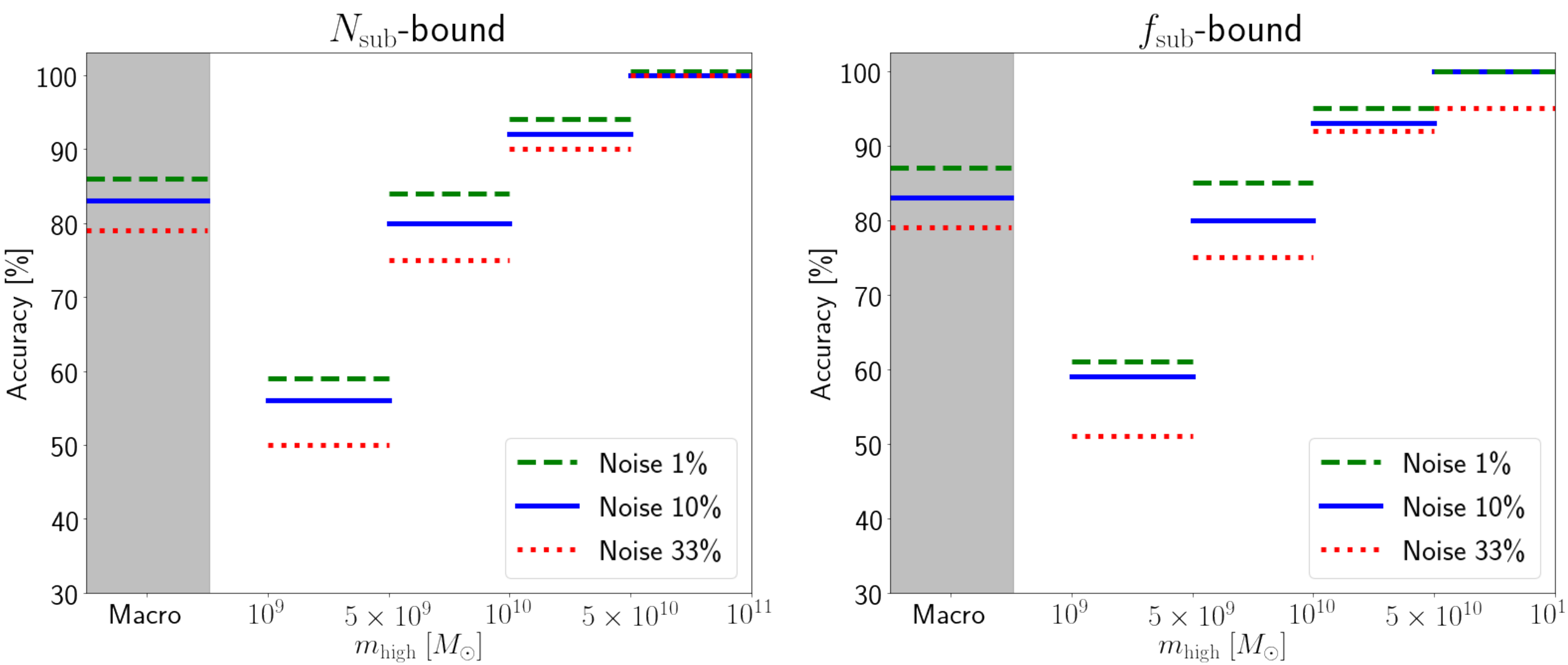
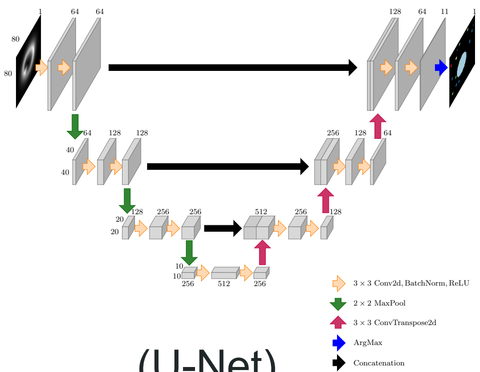


A. Diaz Rivero and C. Dvorkin, PRD (2019)

Direct detection of substructure with image segmentation

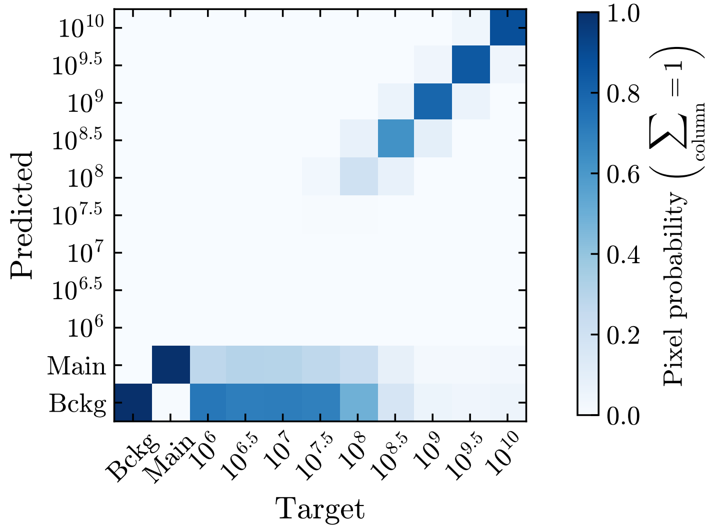


(U-Net)

Bryan Ostdiek

Ana Diaz Rivero

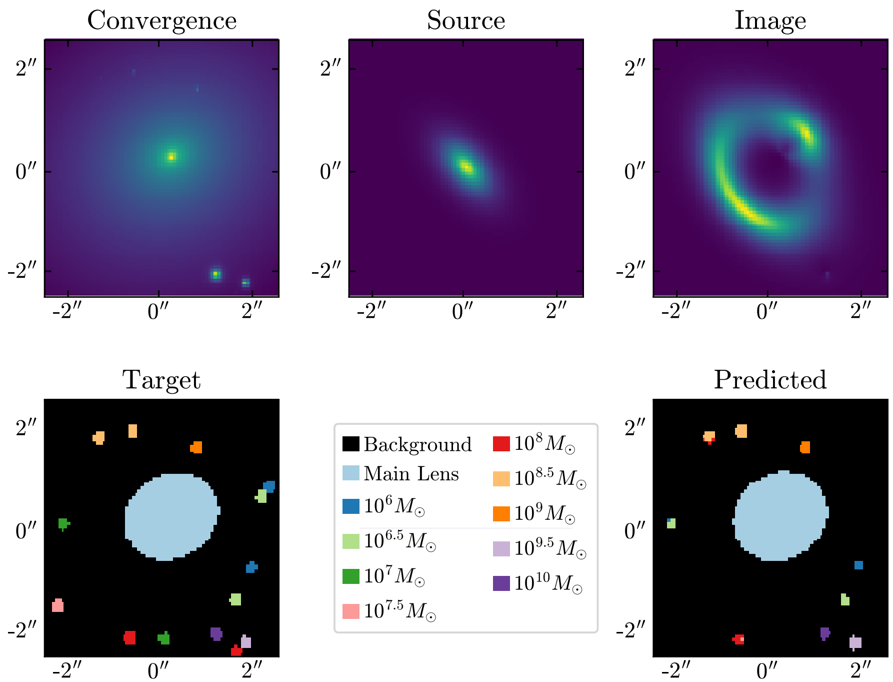
With HST-like noise

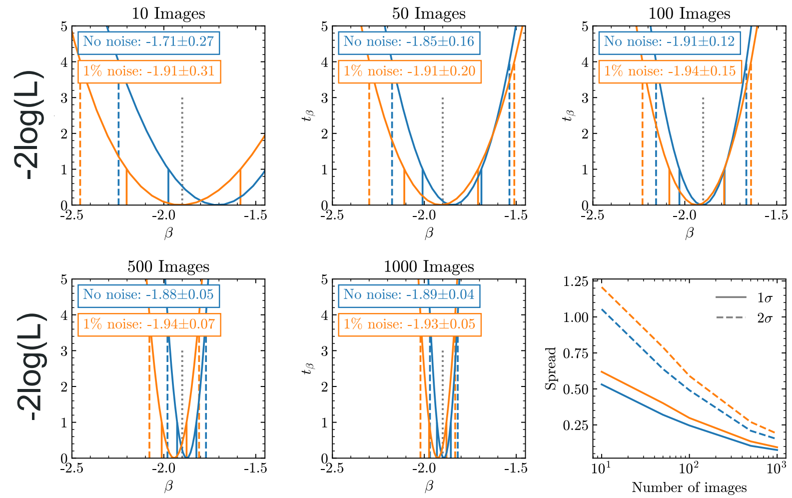


B. Ostdiek, A. Diaz Rivero and C. Dvorkin (2020)

arXiv: 2009.06639
arXiv: 2009.06663

Constraints on the subhalo mass function with image segmentation





subhalo mass function slope

B. Ostdiek, A. Diaz Rivero and C. Dvorkin (2020)

The NSF AI Institute for Artificial Intelligence and Fundamental Interactions (IAIFI)

http://iaifi.org

Advance physics knowledge – from the smallest building blocks of nature to the largest structures in the universe – and galvanize AI research innovation

Strong gravitational lensing as a small-scale probe

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Statistical detection: convergence power spectrum

Convergence = surface mass density in units of critical density for lensing

Dark matter theories

Strong lens images

What we want

(Sub)halo MF

Deflection vectors on the lens plane

Convergence Power Spectrum

Slide from Ana Diaz Rivero

A general framework for substructure statistics

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 $\kappa = \dfrac{\Sigma}{\Sigma_{crit}}$ (Surface mass density)

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

$\mathbf{q}_i$ 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 framework for substructure statistics

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.

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

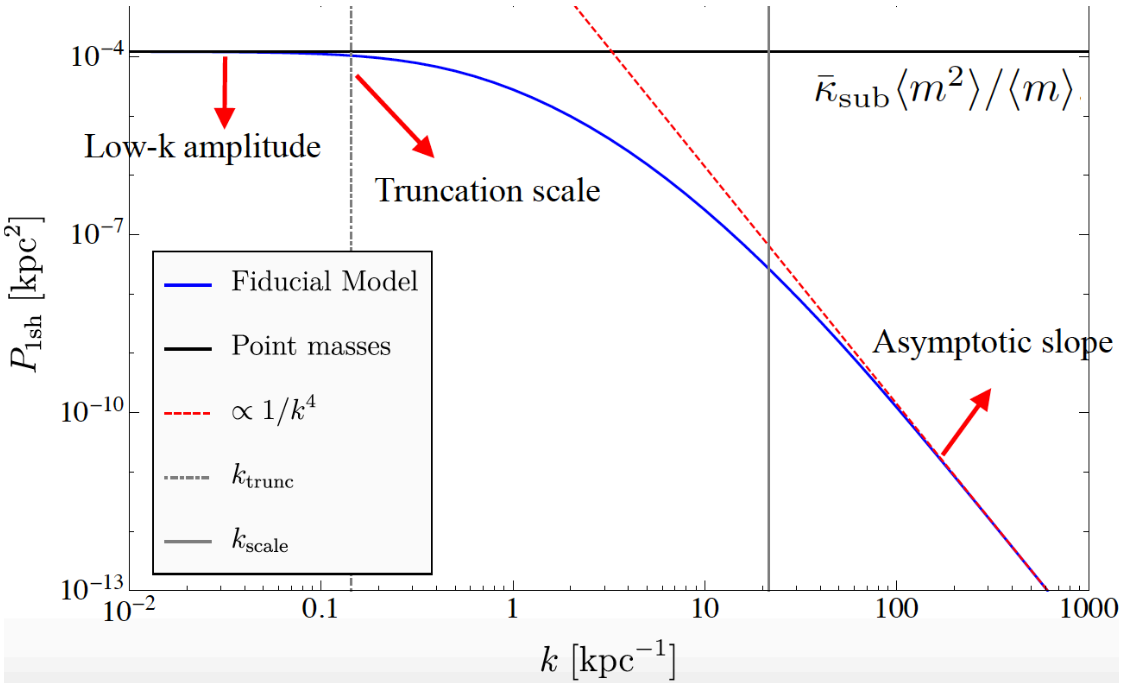
- 2-subhalo term: arises from averaging over pairs of distinct subhalos.

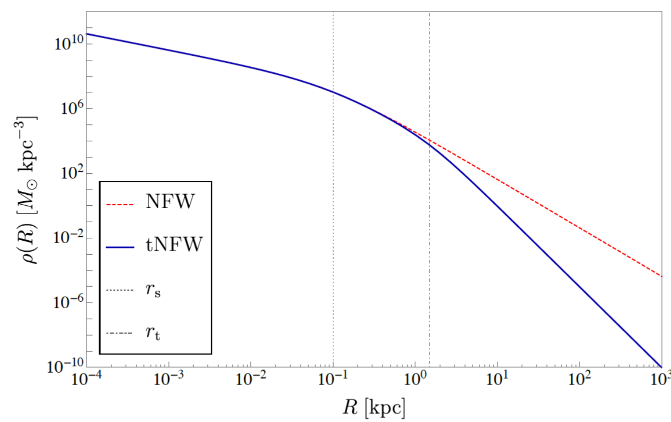
$$P_{\rm 2sh}(k) = \frac{(2\pi)^2 \bar{\kappa}_{\rm sub}^2}{\langle m\rangle^2} P_{\rm ss}(k) \left[\int dm\, d\mathbf{q}\, m\, \mathcal{P}_{\rm m}(m)\, \mathcal{P}_{\rm q}(\mathbf{q}|m) \times \int dr\, r J_0(k\,r)\hat{\kappa}(r,\mathbf{q})\right]^2$$

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

Substructure convergence power spectrum

The Power Spectrum can be described mainly by three quantities:

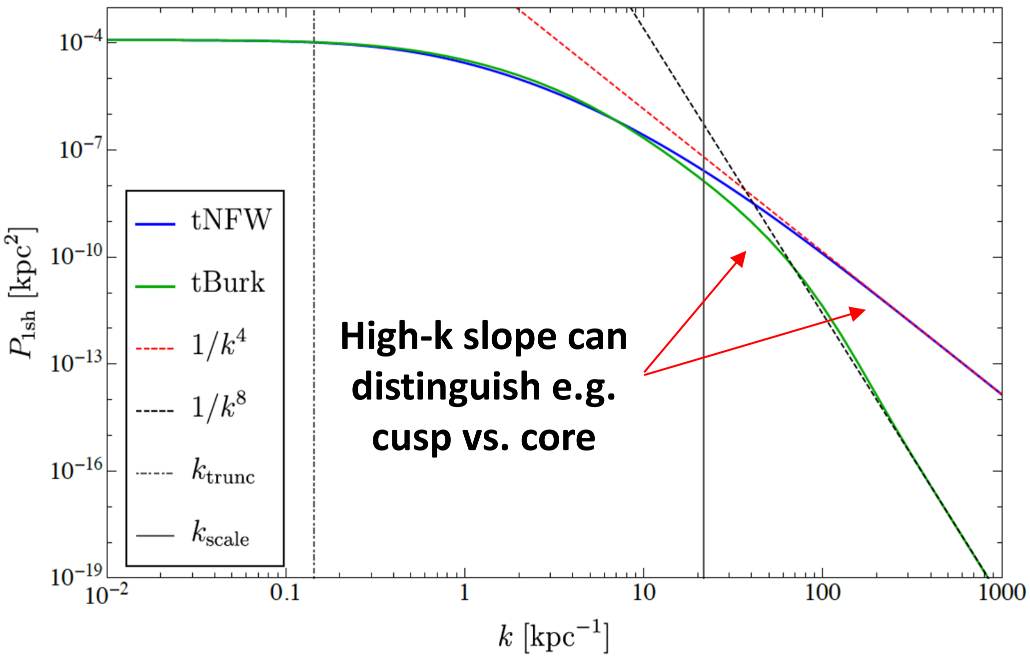


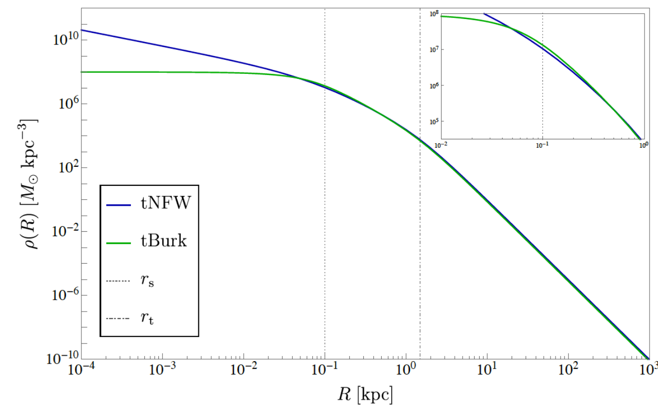


A. Diaz Rivero, F. Cyr-Racine, and C. Dvorkin, PRD (2017)

Substructure convergence power spectrum

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

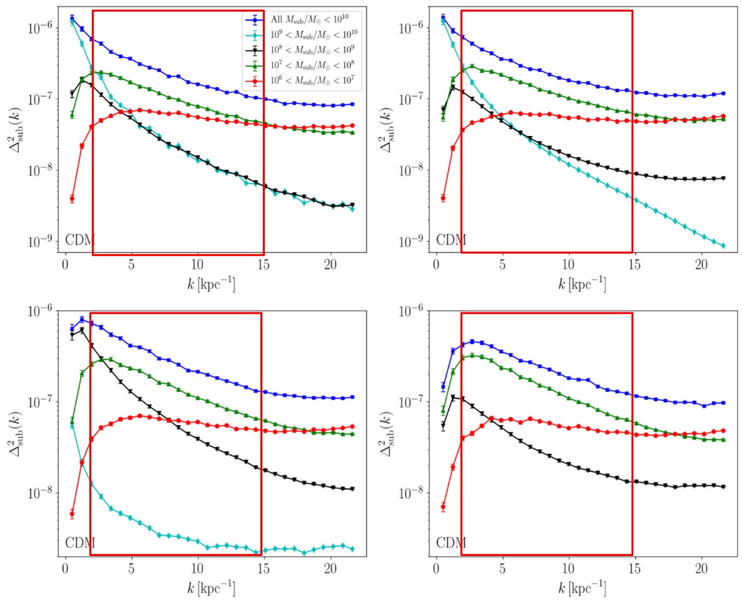




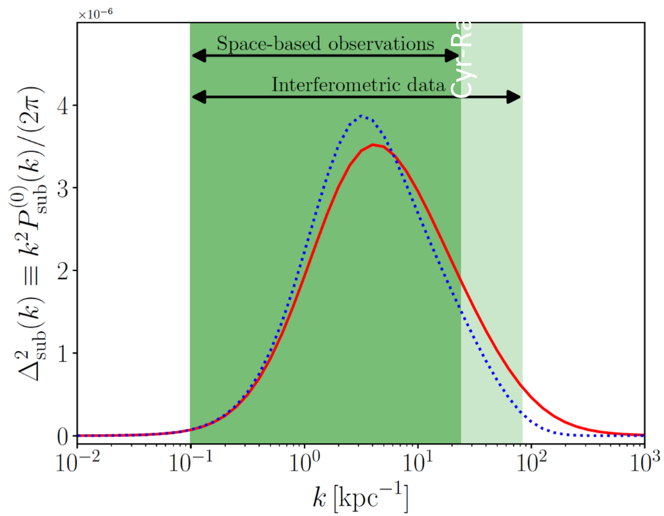
A. Diaz Rivero, F. Cyr-Racine, and C. Dvorkin, PRD (2017)

Substructure convergence power spectrum: sensitivity

Sensitivity



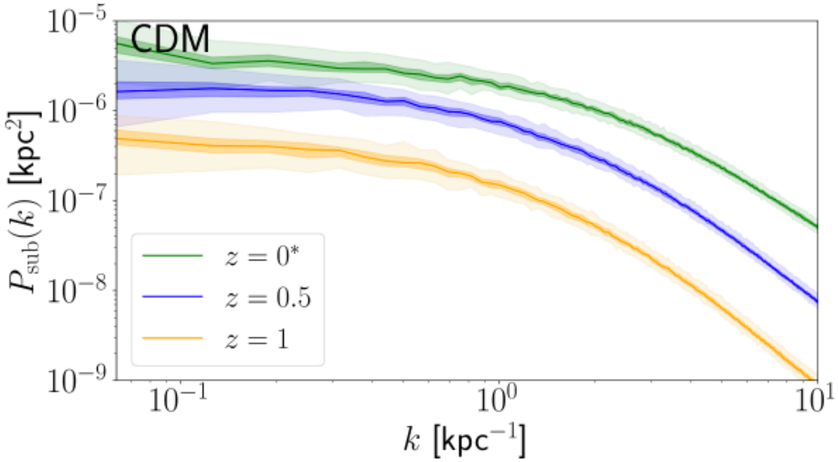
A. Diaz Rivero, C. Dvorkin, F. Cyr-Racine, J. Zavala, and M. Vogelsberger, PRD (2018)



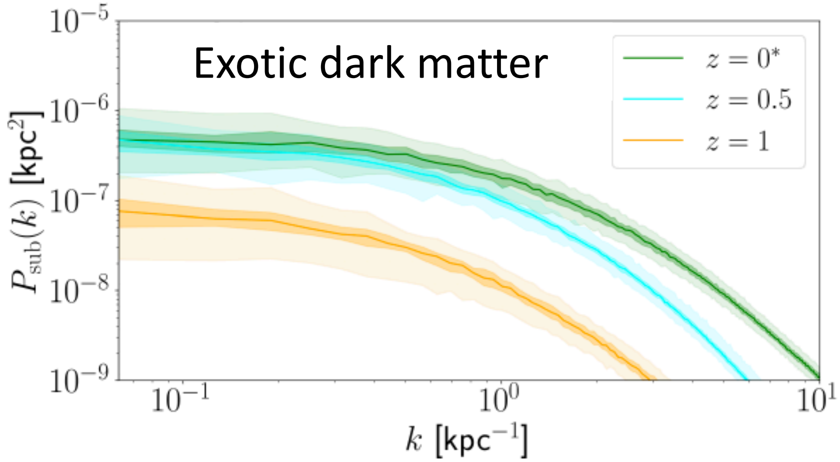
Cyr-Racine+ (2018)

Substructure convergence power spectrum: redshift 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.



Exotic DM: low-mass cutoff+self-interactions

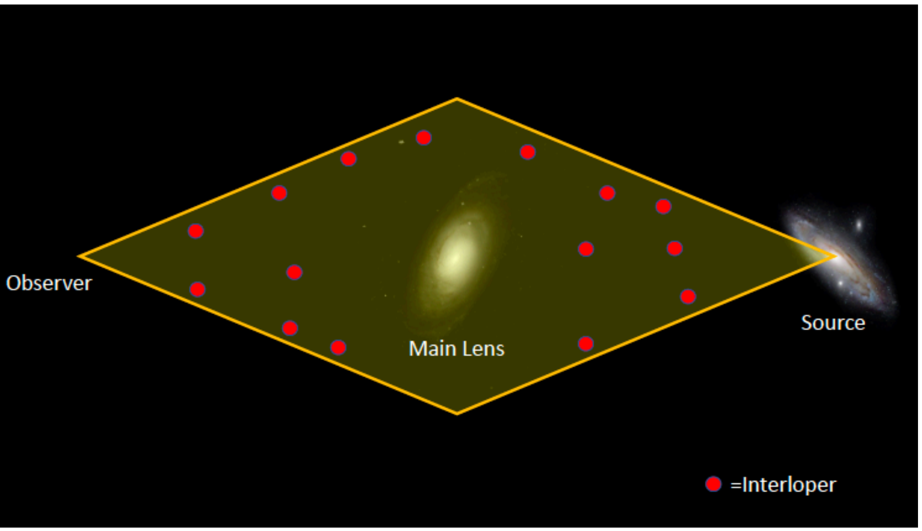


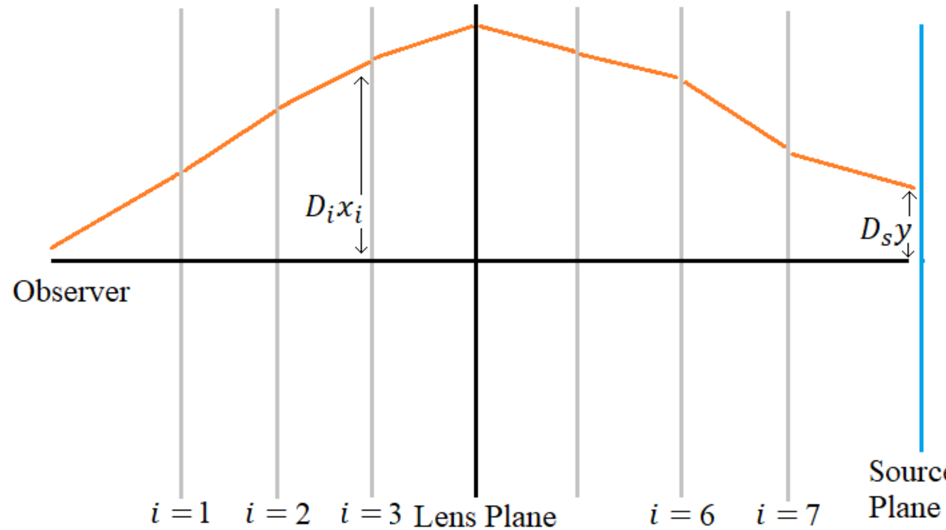
A. Diaz Rivero, C. Dvorkin, F. Cyr-Racine, J. Zavala, and M. Vogelsberger, PRD (2018)

Line-of-sight (LOS) halos

Cagan Sengul

Arthur Tsang





$$\vec{y} = \vec{x}_1 - \sum_{i=1}^{N} \vec{\alpha}_i(\vec{x}_i)$$

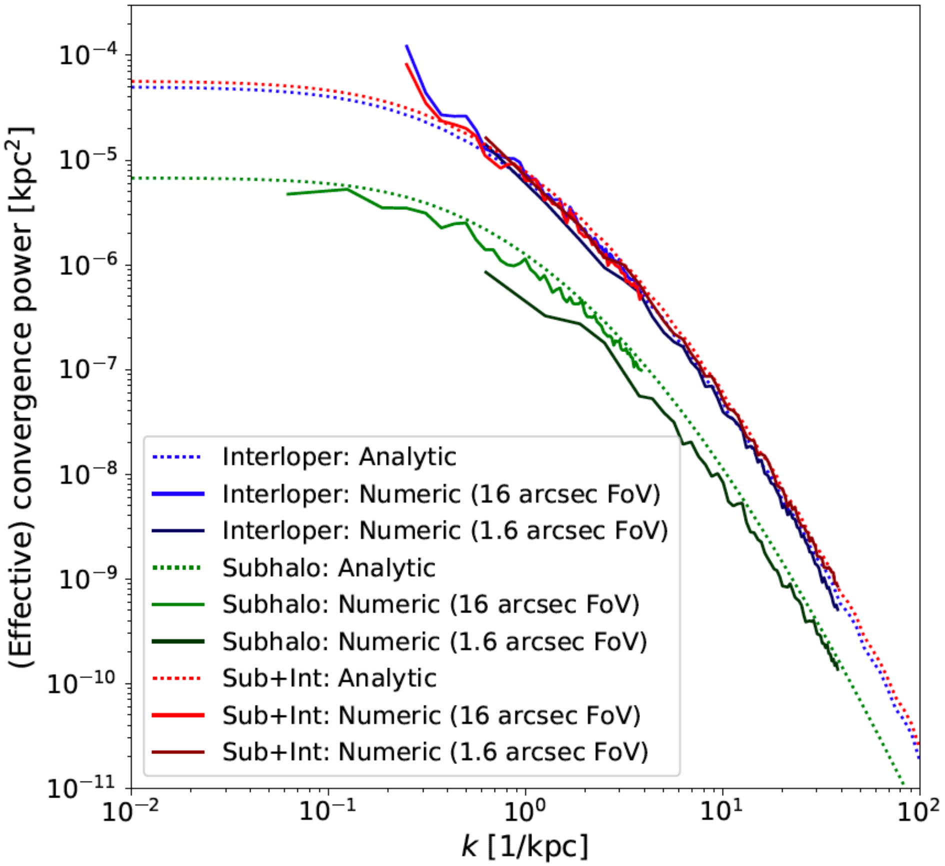
$$\vec{x}_j = \vec{x}_1 - \sum_{i=1}^{j-1} \beta_{ij} \vec{\alpha}_i(\vec{x}_i), \quad \text{where} \quad \beta_{ij} \equiv \frac{D_{ij} D_s}{D_j D_{is}}$$

C. Sengul, A. Tsang, A. Diaz Rivero, C. Dvorkin, H. Zhu and U. Seljak, PRD (2020)

Line-of-sight convergence power spectrum

$$P_{\rm I}(k) = \left(\frac{4\pi G}{c^2}\right)^2 D_l^2 \int_0^{\chi_s} d\chi \, \frac{W_{\rm I}^2(\chi)}{g^2(\chi)\chi^2}$$
$$\times \int dm \, n(m,\chi)\, m^2$$
$$\times \int d^2\vec{q}\,\mathcal{P}(\vec{q}\,|\,m,\chi) \left|\tilde{\phi}\left(\frac{D_l r_{\rm s}}{g(\chi)D_\chi}k;\,\tau\right)\right|^2$$

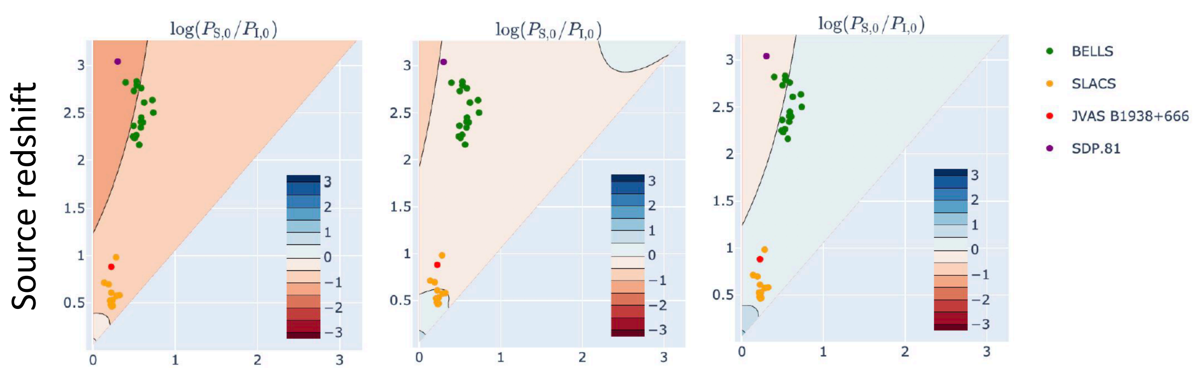
$$W_{\rm I} \equiv W_{\rm fg} + W_{\rm cp} + W_{\rm bg} = \frac{f(\chi)D_{\chi s}\chi^2}{D_\chi D_s}$$



C. Sengul, A. Tsang, A. Diaz Rivero, C. Dvorkin, H. Zhu and U. Seljak, PRD (2020)

Line-of-sight (LOS) halos vs. subhalos

Ratio of substructure to LOS halos power spectrum amplitude:



Lens redshift f_{sub}= 0.4%

Lens redshift f_{sub}= 2 %

Lens redshift f_{sub}= 4 %

Fraction of dark matter halo mass in substructure (f_{sub}) →

C. Sengul, A. Tsang, A. Diaz Rivero, C. Dvorkin, H. Zhu and U. Seljak, PRD (2020)

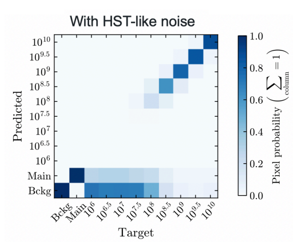
- In order to translate a measured power spectrum amplitude to a dark matter theory, it is paramount to understand the relevant mass function involved (halos along the line of sight or subhalos in the lens galaxy?).

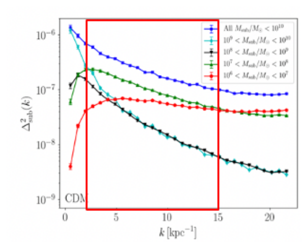
- Work in progress: re-analyzing systems previously claimed as subhalos in the literature.

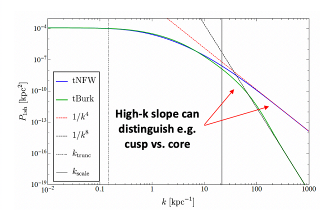
Concluding thoughts

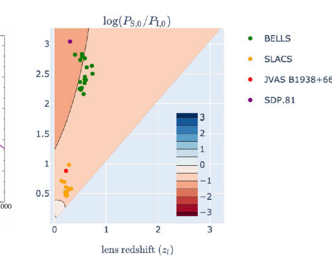
Important clues about the physics of the dark sector lie on astrophysical data sets:

- Enhancing direct detection with machine learning
  - Comparable sensitivity to traditional methods
  - Orders of magnitude faster
- The convergence power spectrum: a statistical probe
  - Sensitive to lower masses than direct detection
  - Direct link to dark matter theories
  - Interlopers likely dominate for the SLACS and BELLS lenses









Unveiling the nature of the dark sector using cosmology at large and small scales