Small but mighty: Dark matter substructure

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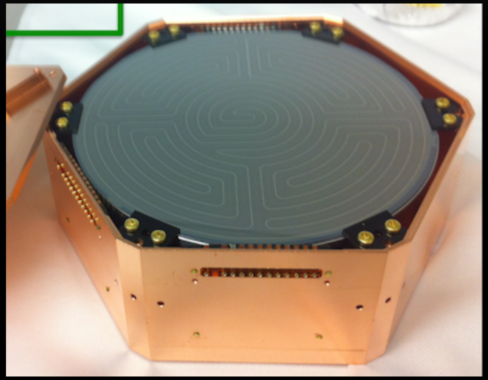
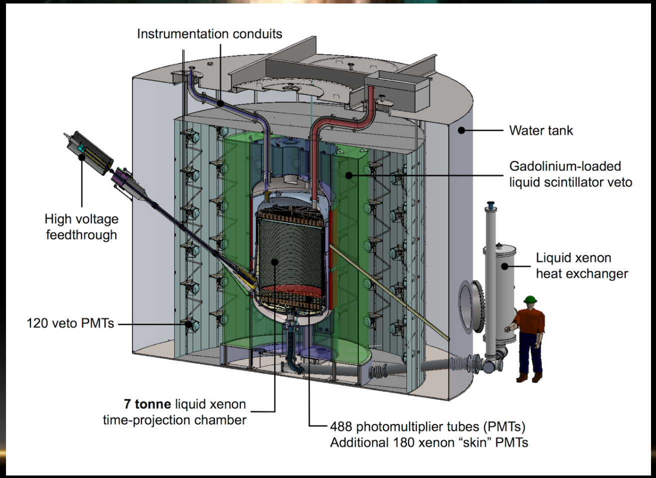
In dark matter science, hope for the best…

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



And many, many more…

Xe
XENON
Dark Matter Project



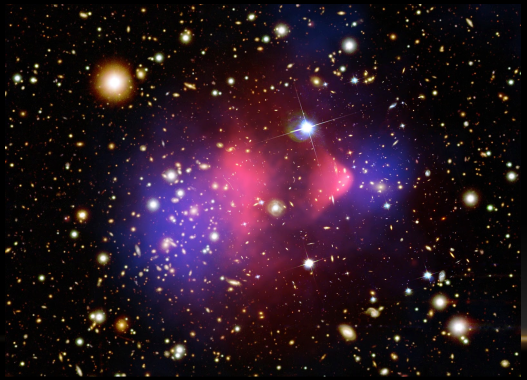
…but prepare for the worst!

- Gravitational signatures might be all we can observe!

Gravitational Lensing

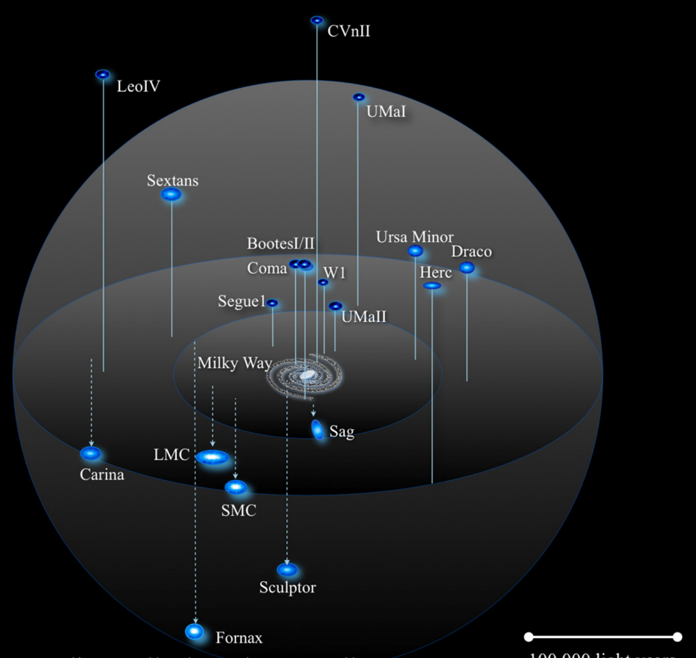
Suyu et al. (2013)

Merging Clusters



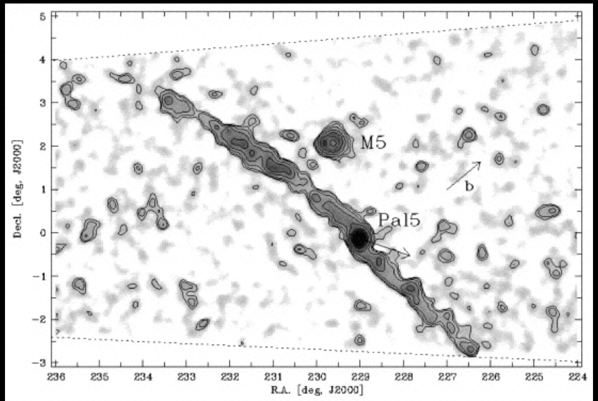
Markevitch et al., Clowe et al.

Dwarf galaxies



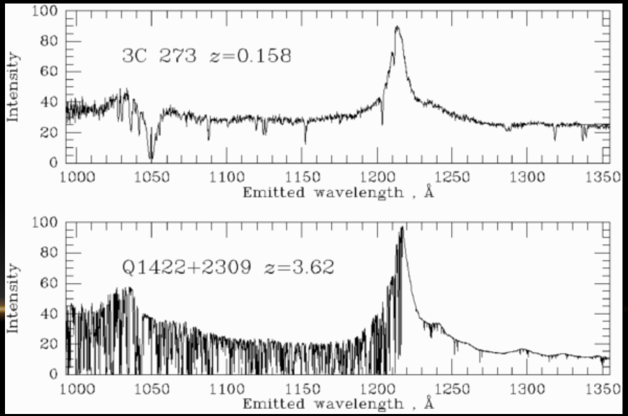
Credits: Bullock, Geha, Powell

Stellar Streams



de Odenkirchen et al. (2003)

Lyman-alpha forest

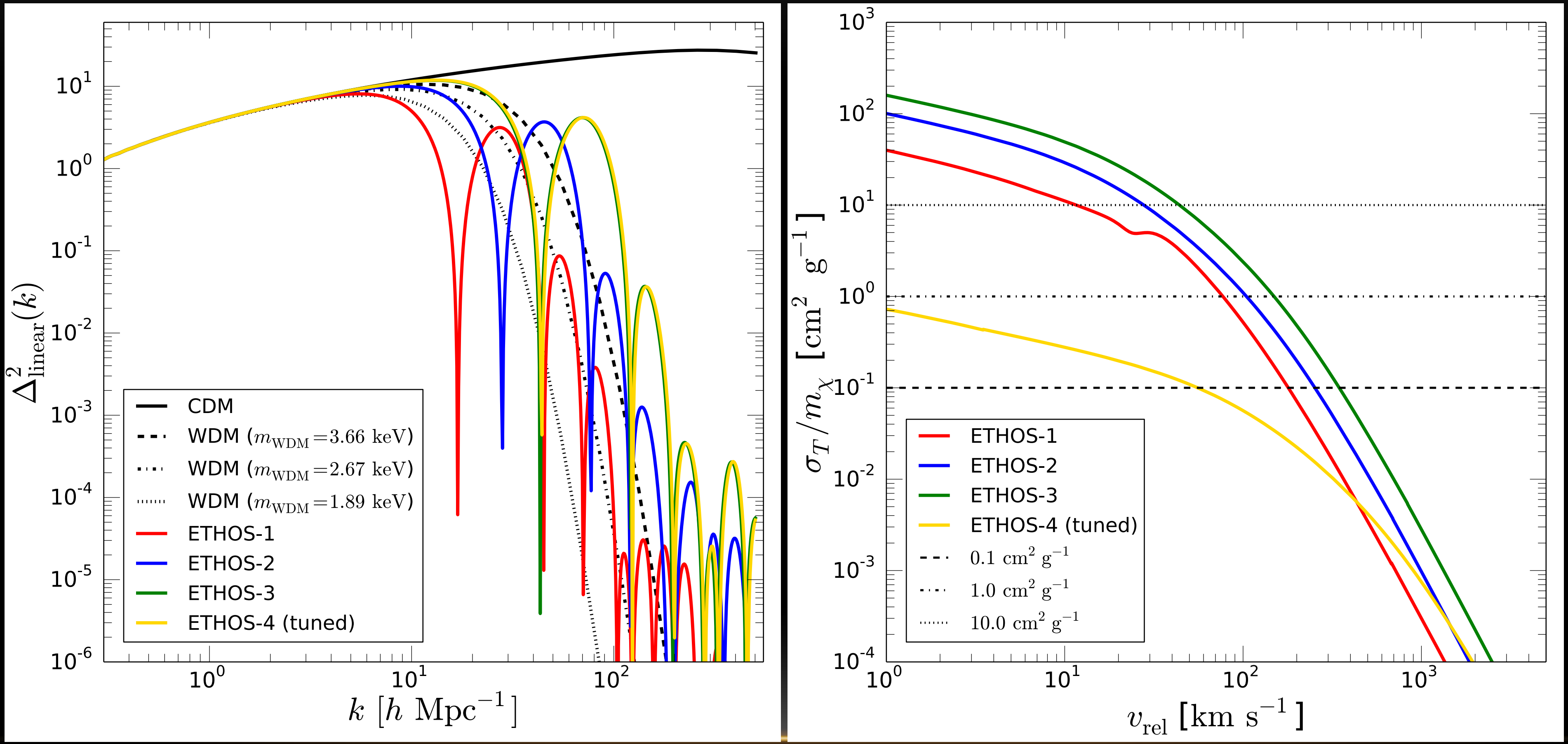


Credits: Bill Keel

What dark matter physics can we probe through astronomy ?

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

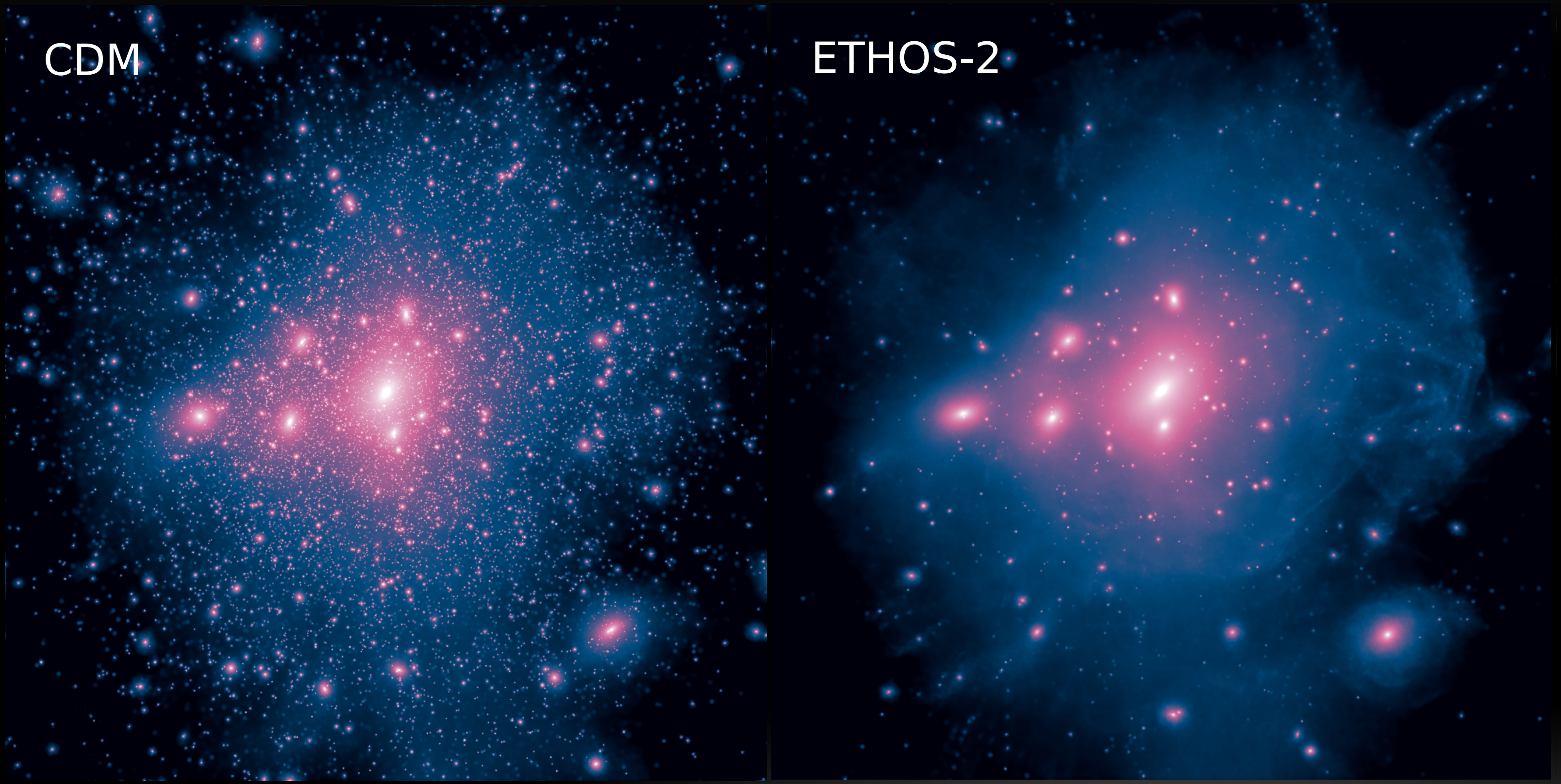
2) Interaction affecting the dynamics of structure formation (self-interaction)



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

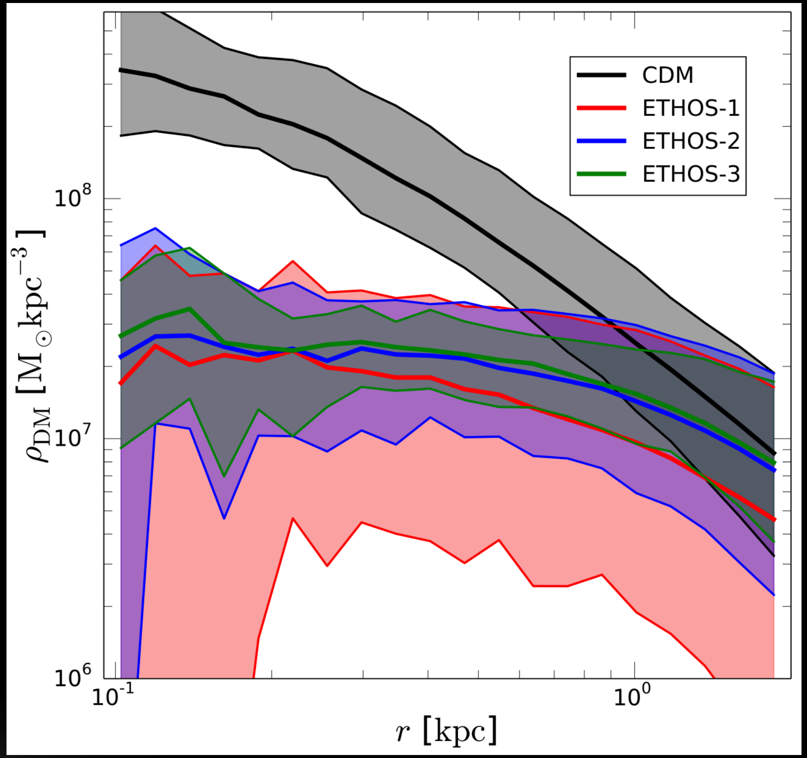
Physical impacts of modified matter power spectrum and dark matter self-interaction.

1) Change to the abundance of small-scale substructure



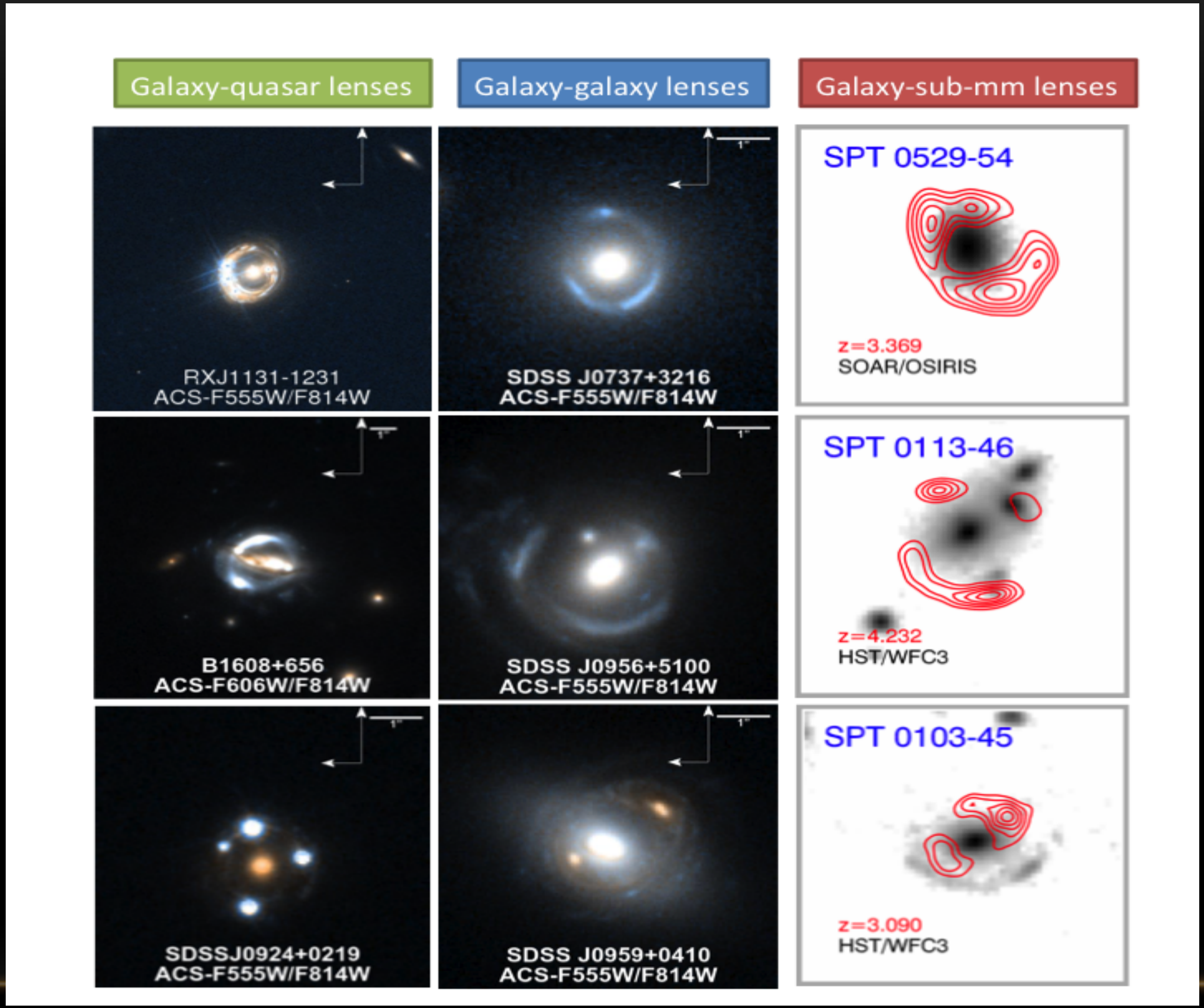
See also: Schewtschenko et al. (2015, 2016), Boehm et al. (2014), Buckley et al. (2014), Elbert et al. (2017).

2) Change to the inner structure of subhalos



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

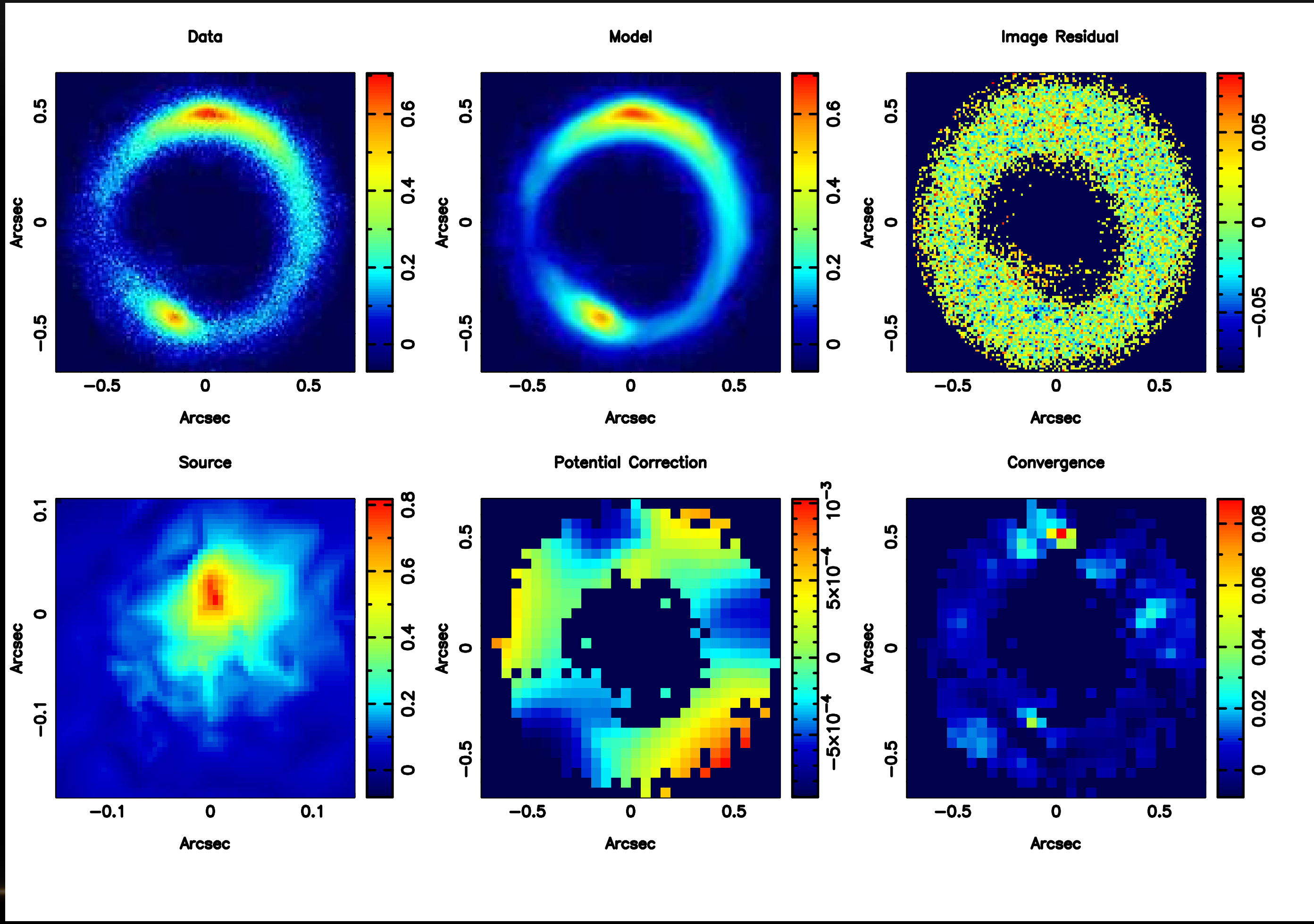
Galaxy-scale Gravitational Lenses



Credits: Leonidas Moustakas

Direct Substructure Detection

- “Gravitational Imaging” of Perturbed Einstein Rings



Vegetti et al. *Nature*, (2012)

Direct Substructure Detection

- "Gravitational Imaging" of Perturbed Einstein Rings

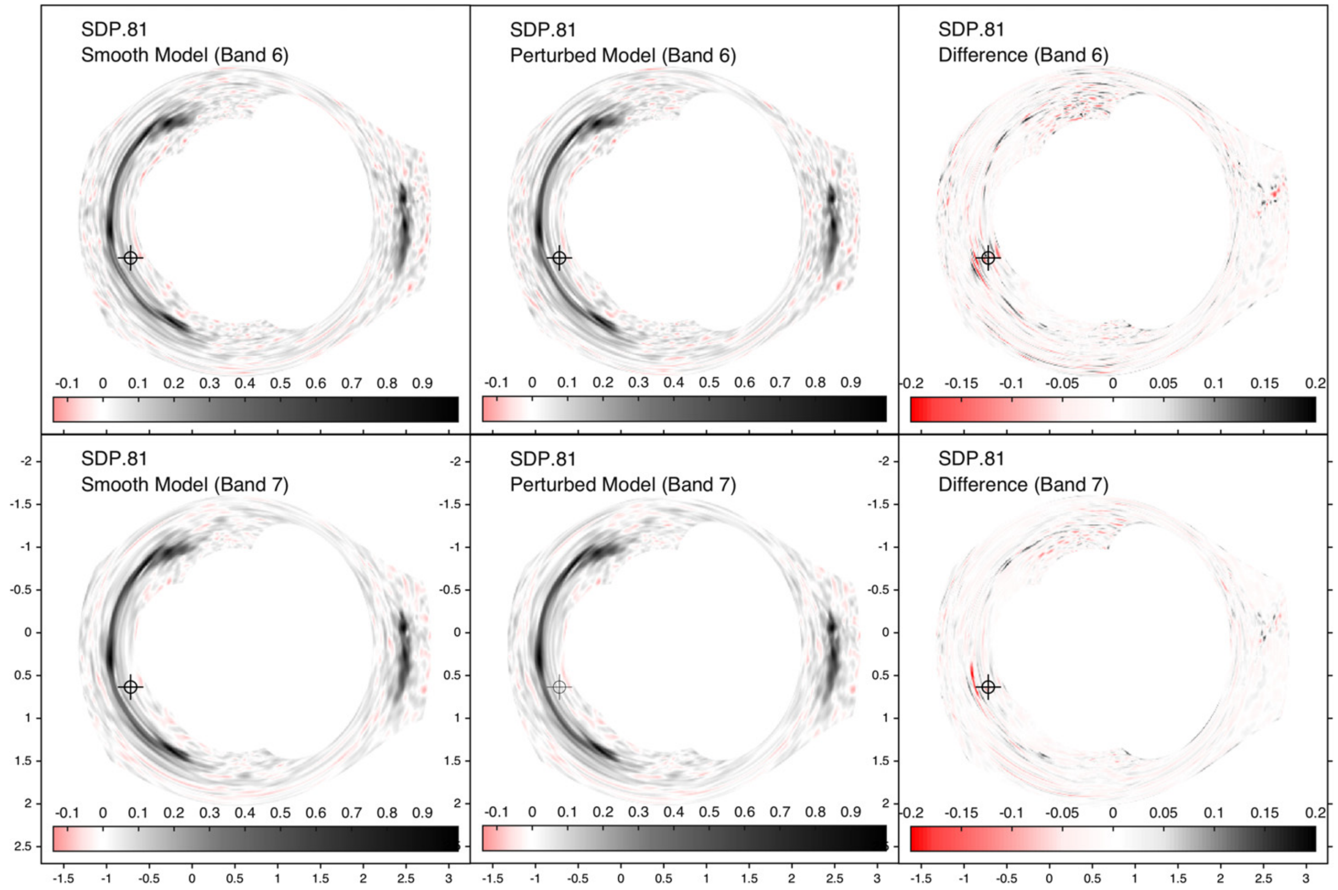


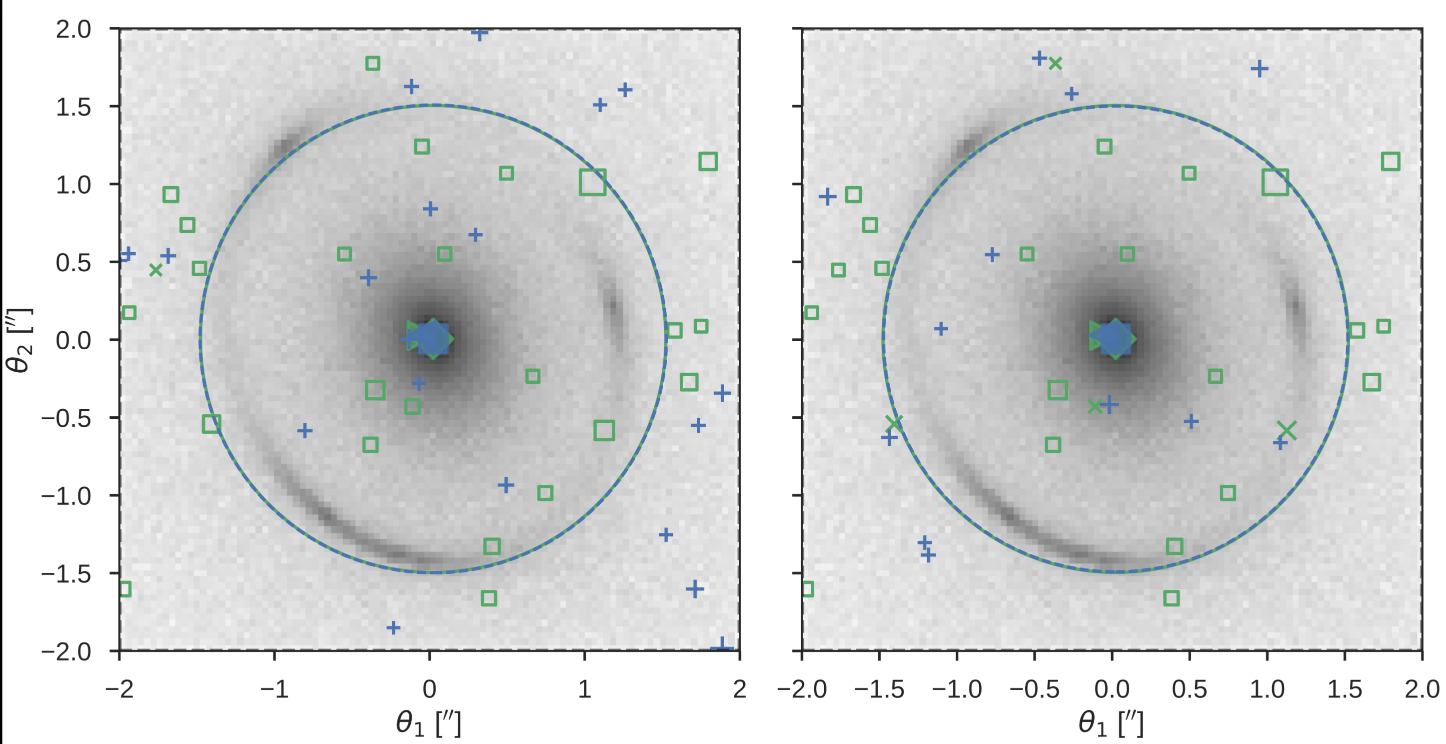
Figure 6. Top left: the sky emission model in band 6 for the best-fit smooth lens parameters for the SDP.81 data. Top middle: the same for the perturbed model. Top right: the difference between the two models. The bottom panels show the same for band 7. The bright feature in the difference plots is mainly caused by the astrometric anomaly of the arc. In each row, the images have been scaled to the peak flux of the smooth model.

Hezaveh et al., (2016)

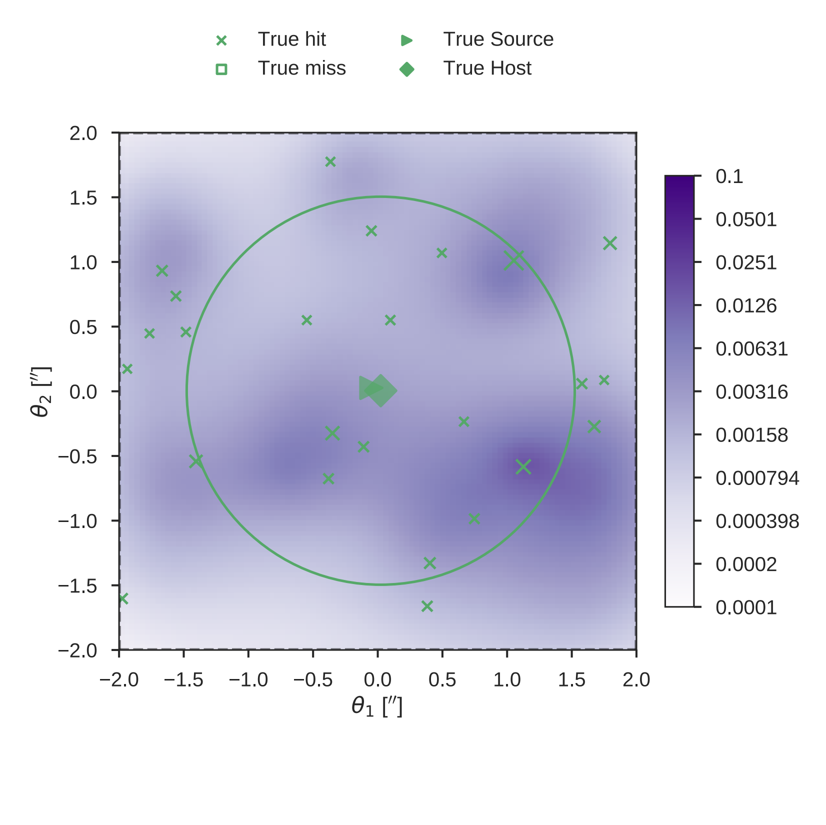
Direct Substructure Detection: A transdimensional approach

Daylan, Cyr-Racine, et al., arXiv:1706.06111

- A more accurate way to capture model covariances

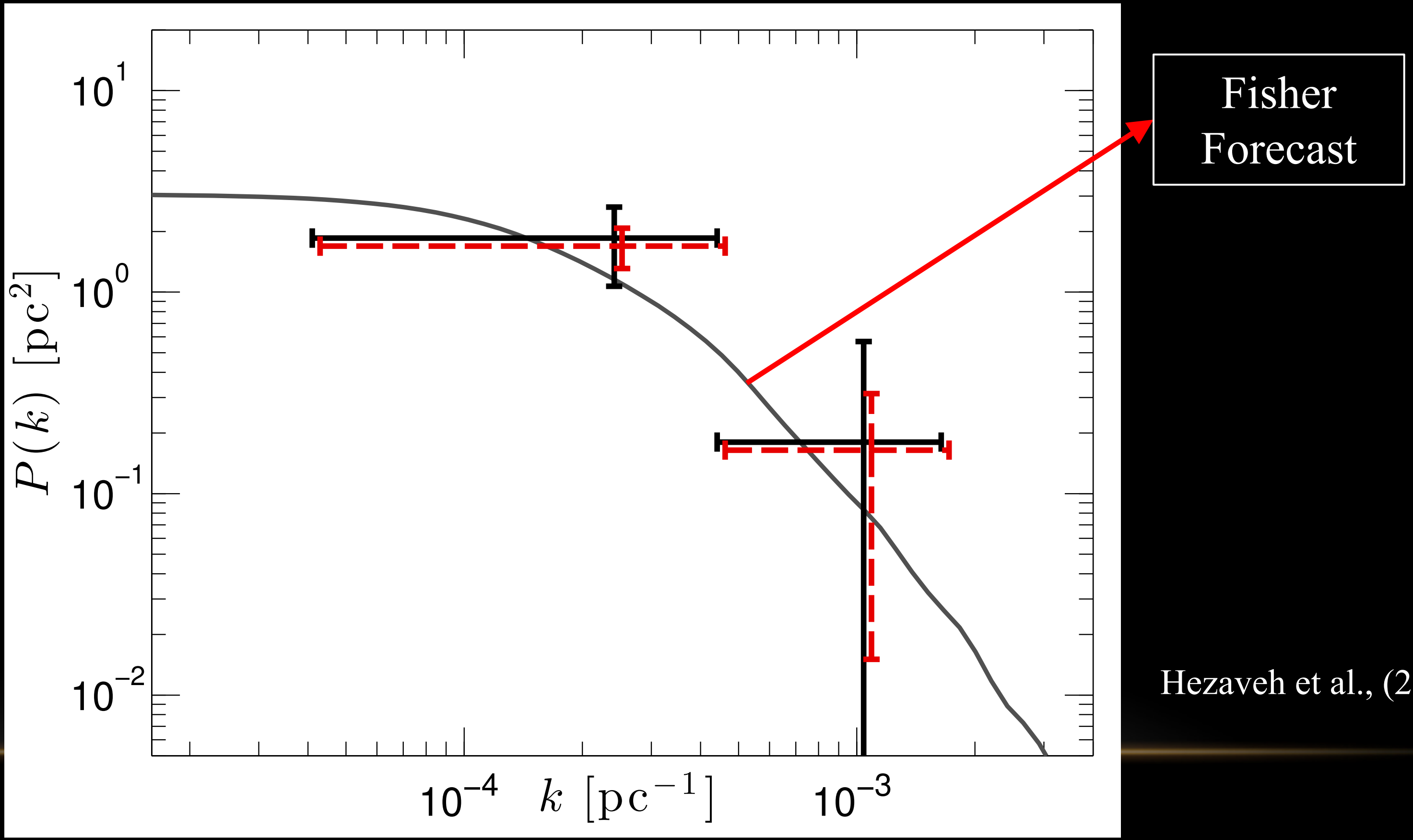


See also Brewer at al. (2015)



A different approach to substructure lensing: 2-point correlation function

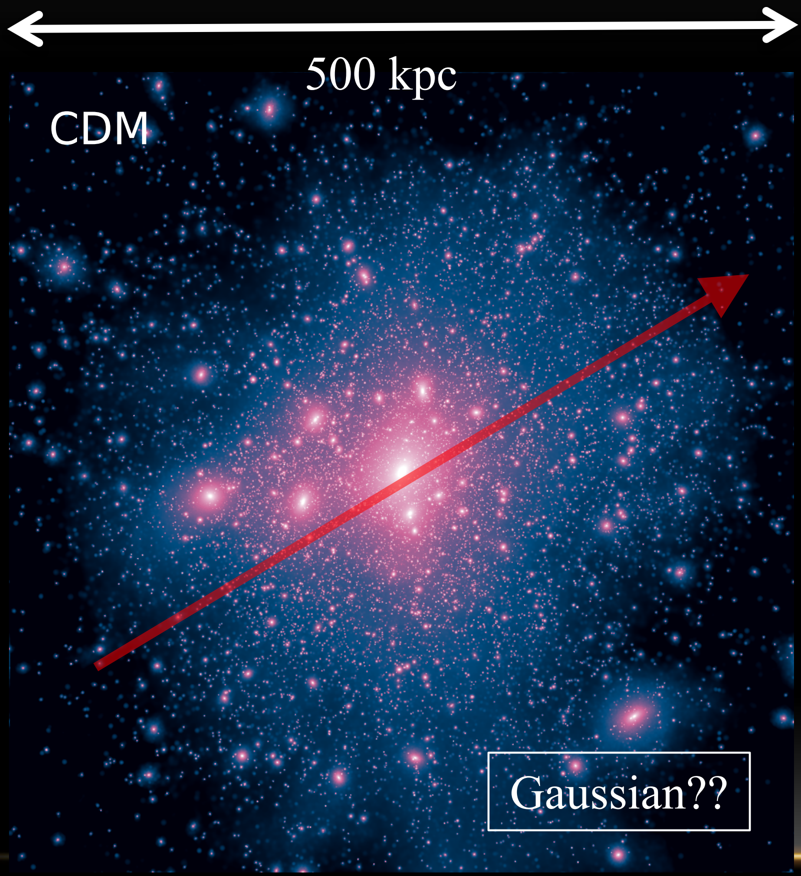
- Instead of describing lensing perturbations in terms of individual subhalo, look at the correlation function of the projected density field.

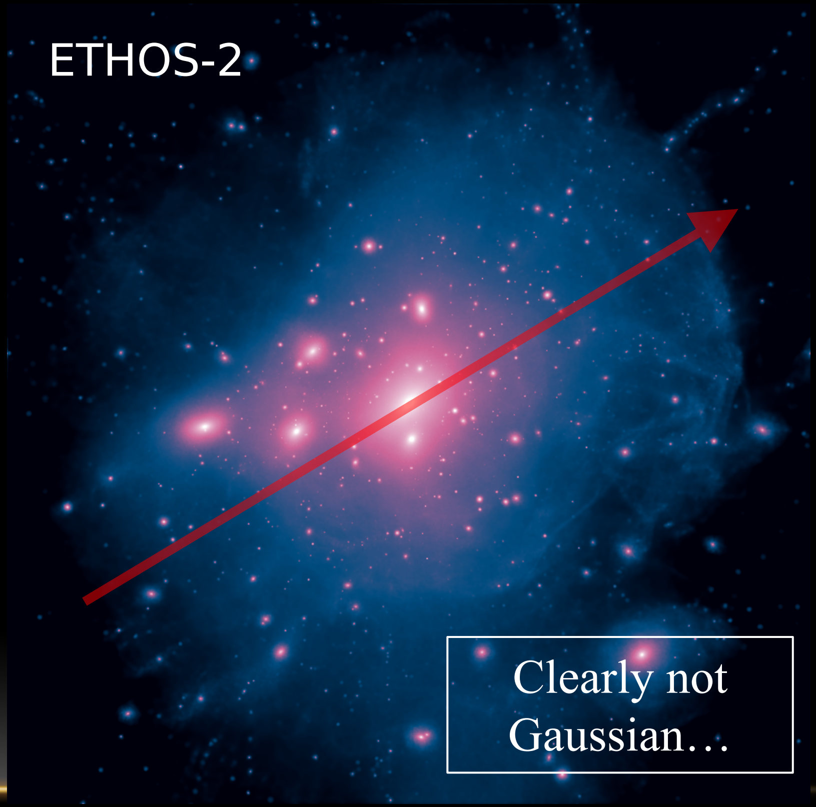


Hezaveh et al., (2016)

Substructure lensing: 2-point function

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





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

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

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

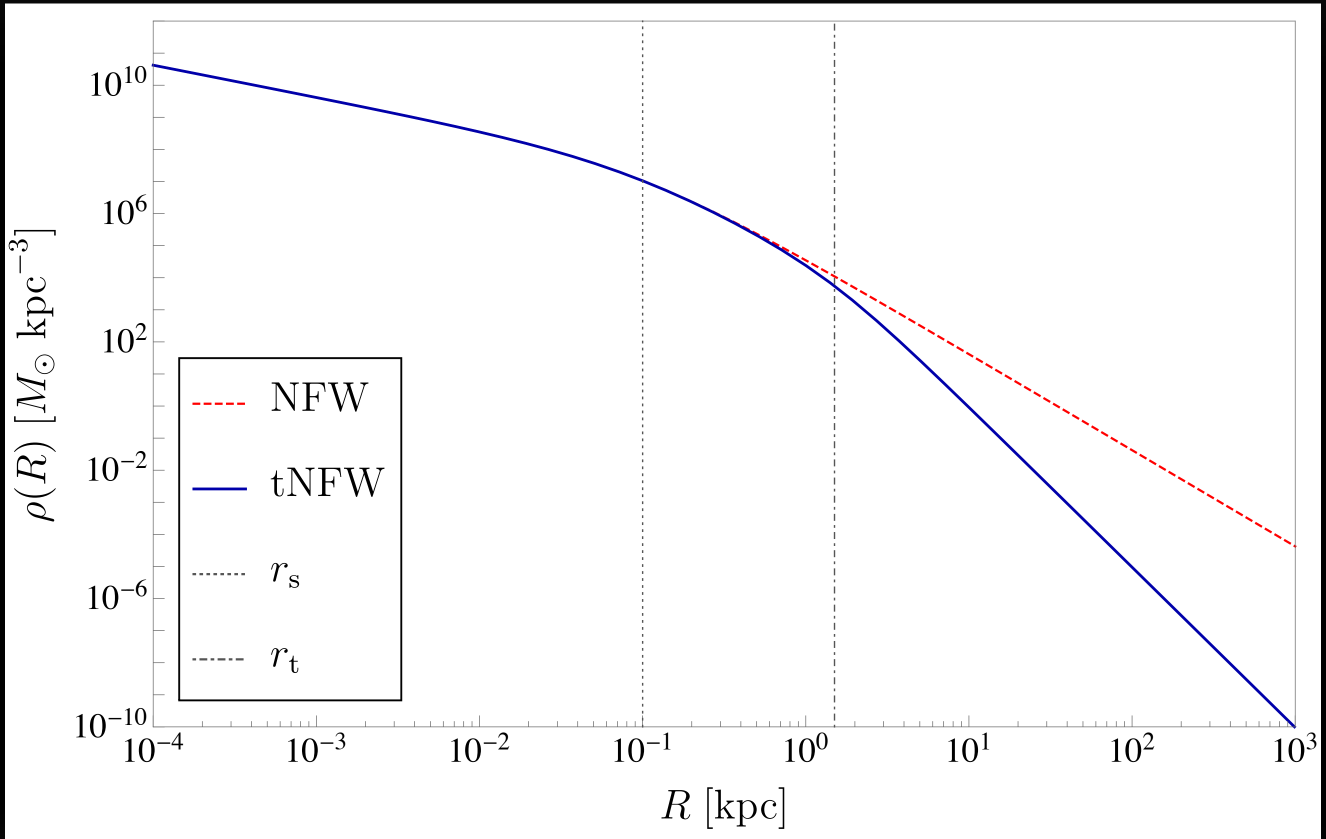
$$\kappa_{\rm sub}(\mathbf{r}) = \sum_{i=1}^{N_{\rm sub}} \kappa_i(\mathbf{r}-\mathbf{r}_i, m_i, \mathbf{q}_i),$$

$$\xi_{\rm sub}(\mathbf{r}) \equiv \frac{1}{A}\int d^2\mathbf{s} \int \prod_i d^2\mathbf{r}_i \mathcal{P}_{\rm r}(\mathbf{r}_i) \times (\kappa_{\rm sub}(\mathbf{s}) - \bar{\kappa}_{\rm sub})(\kappa_{\rm sub}(\mathbf{s}+\mathbf{r}) - \bar{\kappa}_{\rm sub})$$

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

Substructure Power Spectrum: tNFW

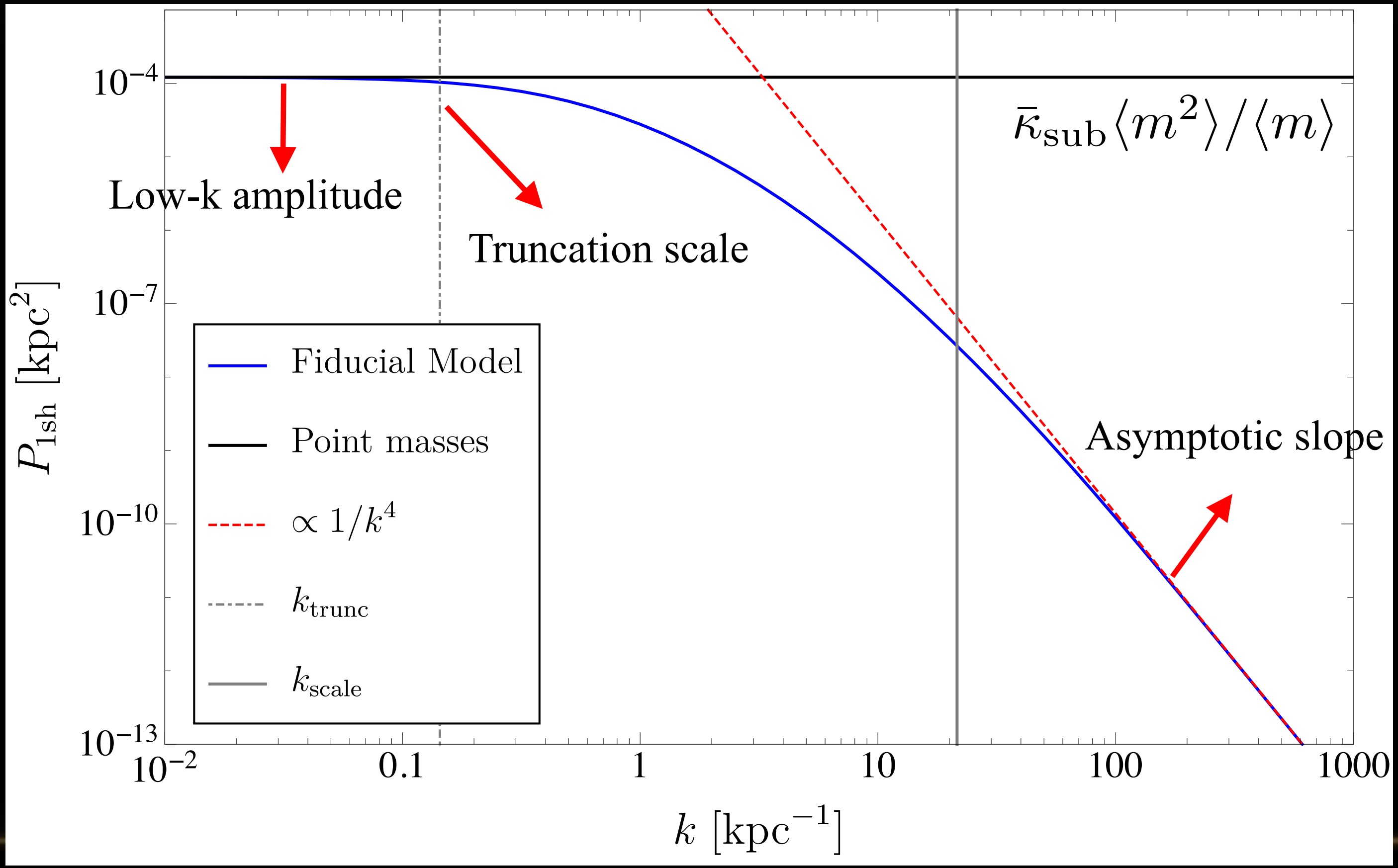
- As a warm up, let's consider a population of truncated NFW subhalos.



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

Substructure Power Spectrum: tNFW

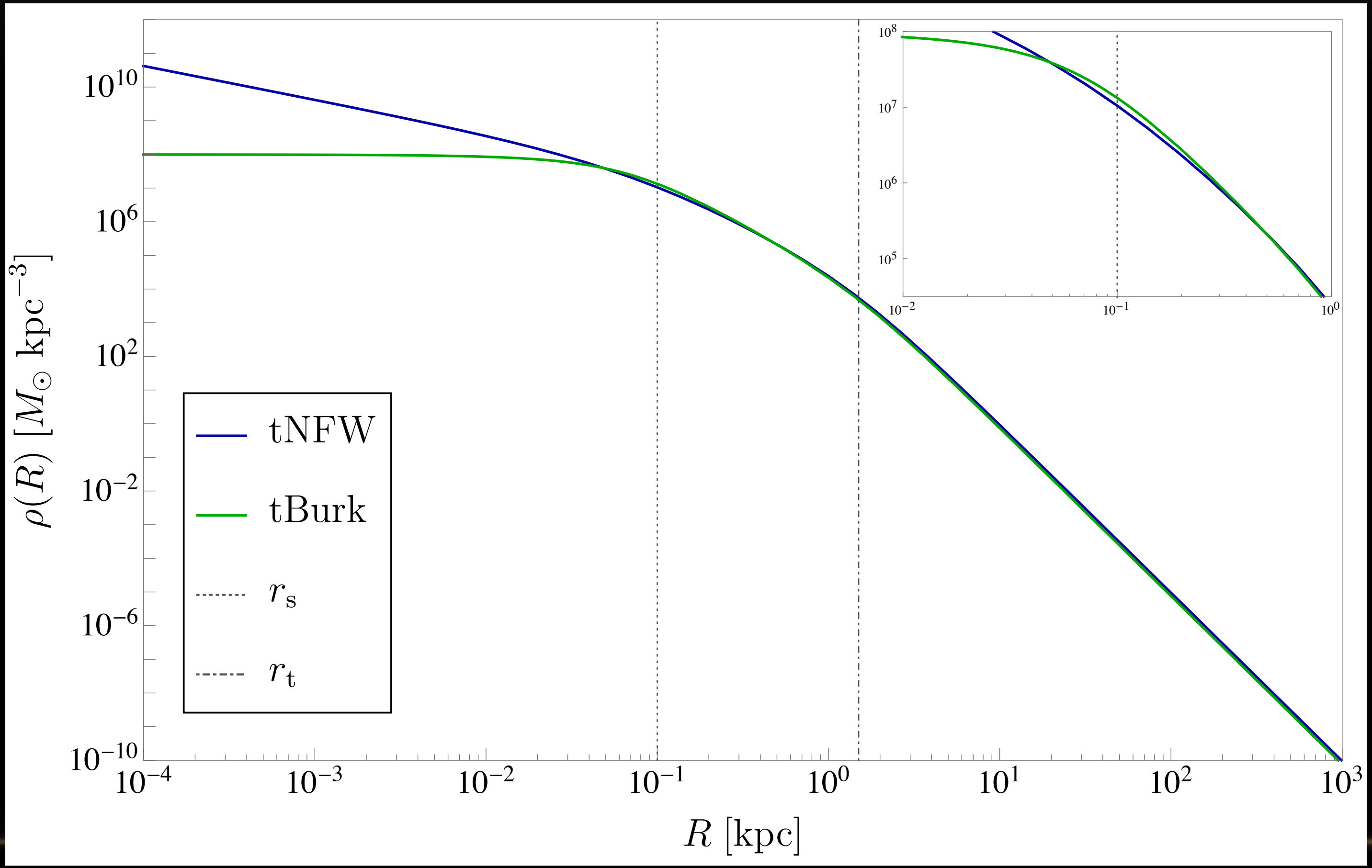
- The power spectrum depends mostly on three quantities:



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

Substructure Power Spectrum: truncated cored profile

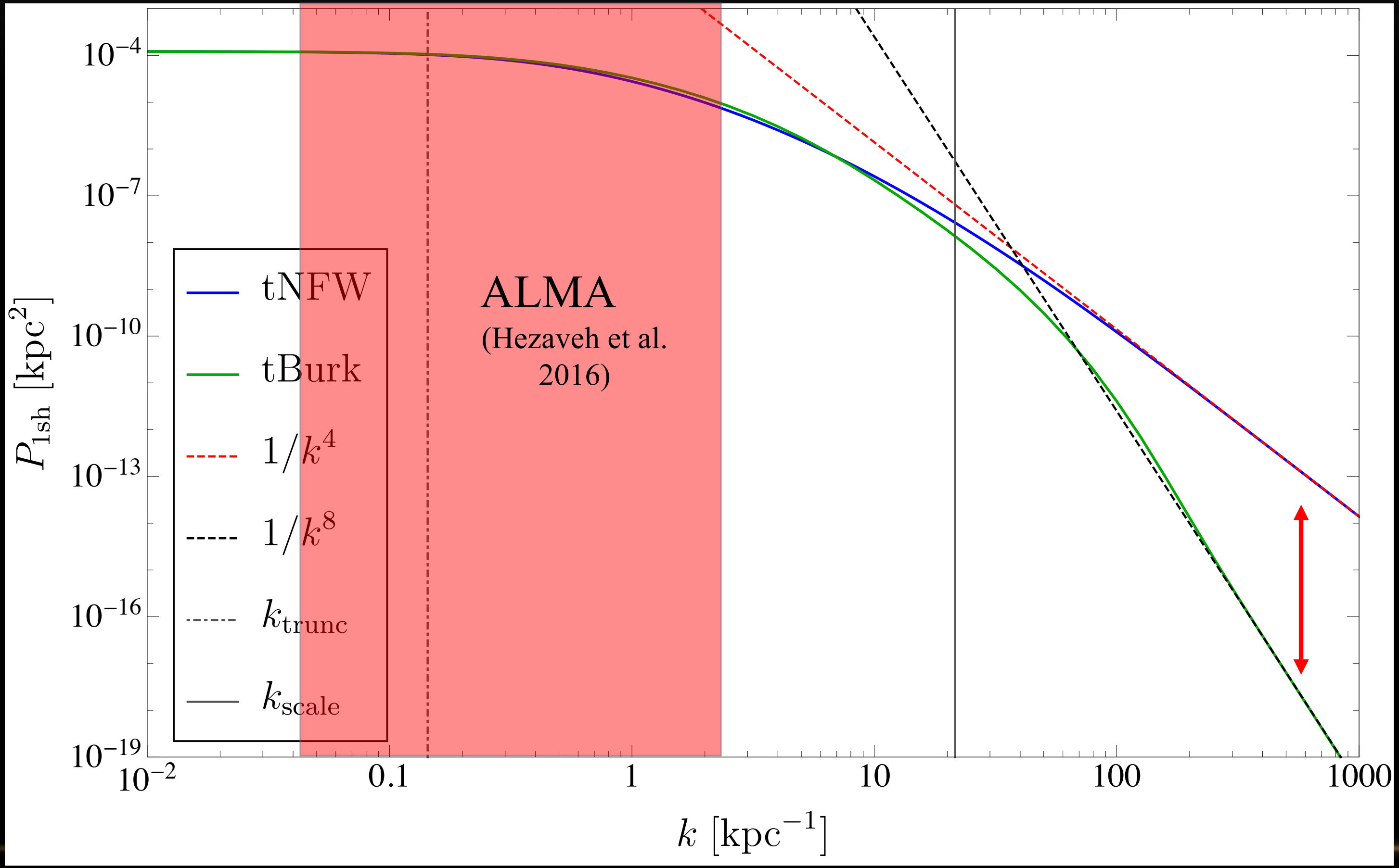
- Let's now consider an SIDM-inspired truncated cored profile:



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

Substructure Power Spectrum: truncated cored profile

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

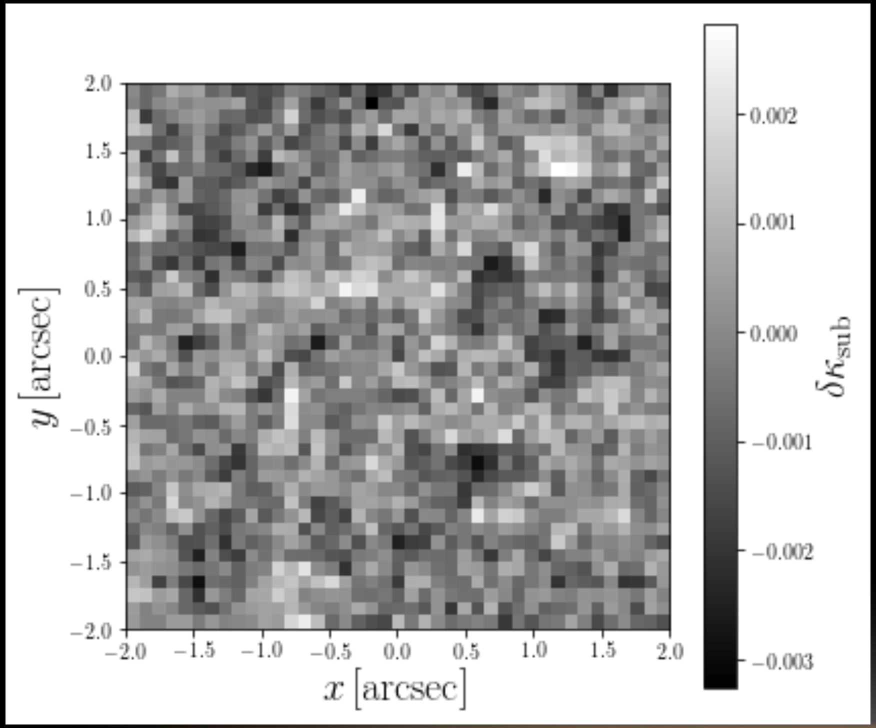


Díaz Rivero, Cyr-Racine, & Dvorkin, arXiv:1707.04590

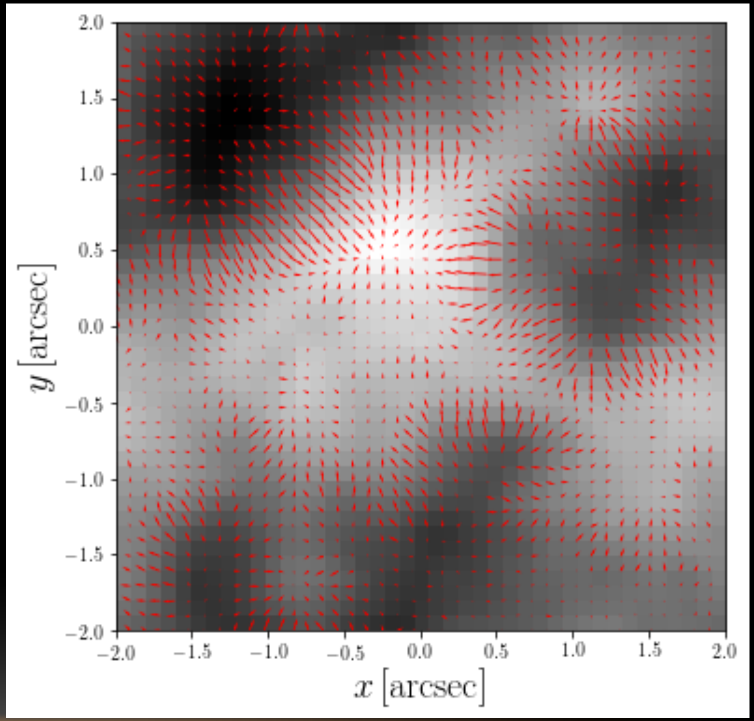
Measuring the substructure power spectrum: cartoon

Cyr-Racine, Keeton & Moustakas, in prep.

Substructure convergence perturbation



Lensing potential and deflection field



Measuring the substructure power spectrum: cartoon

Fiducial image

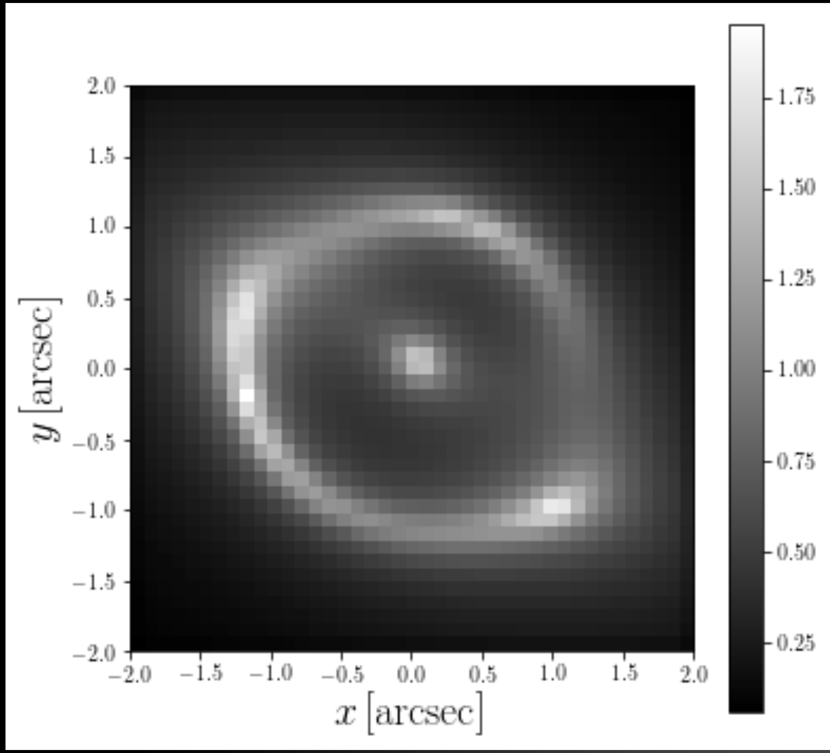
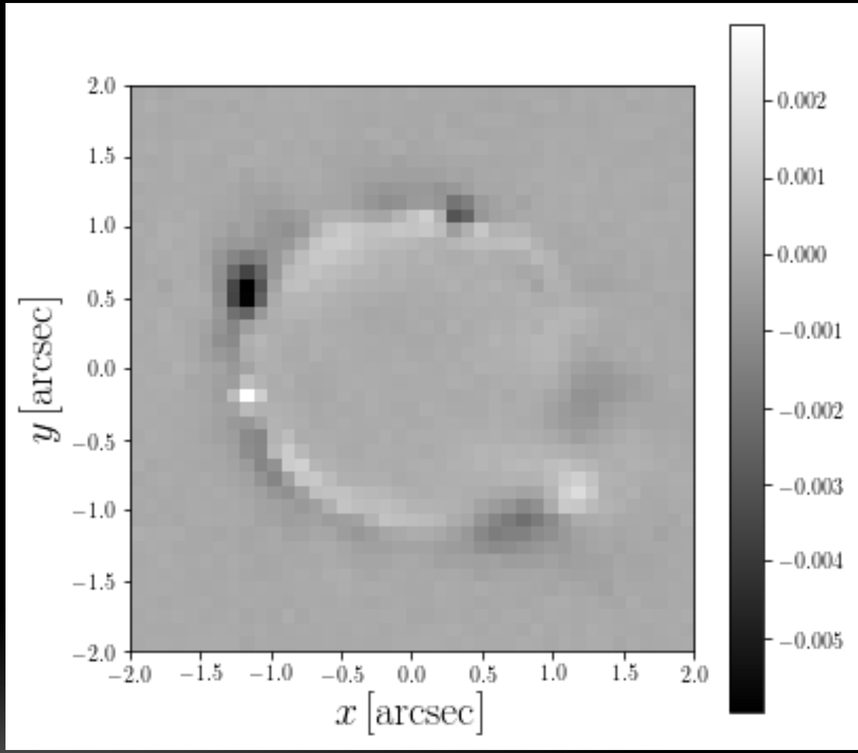
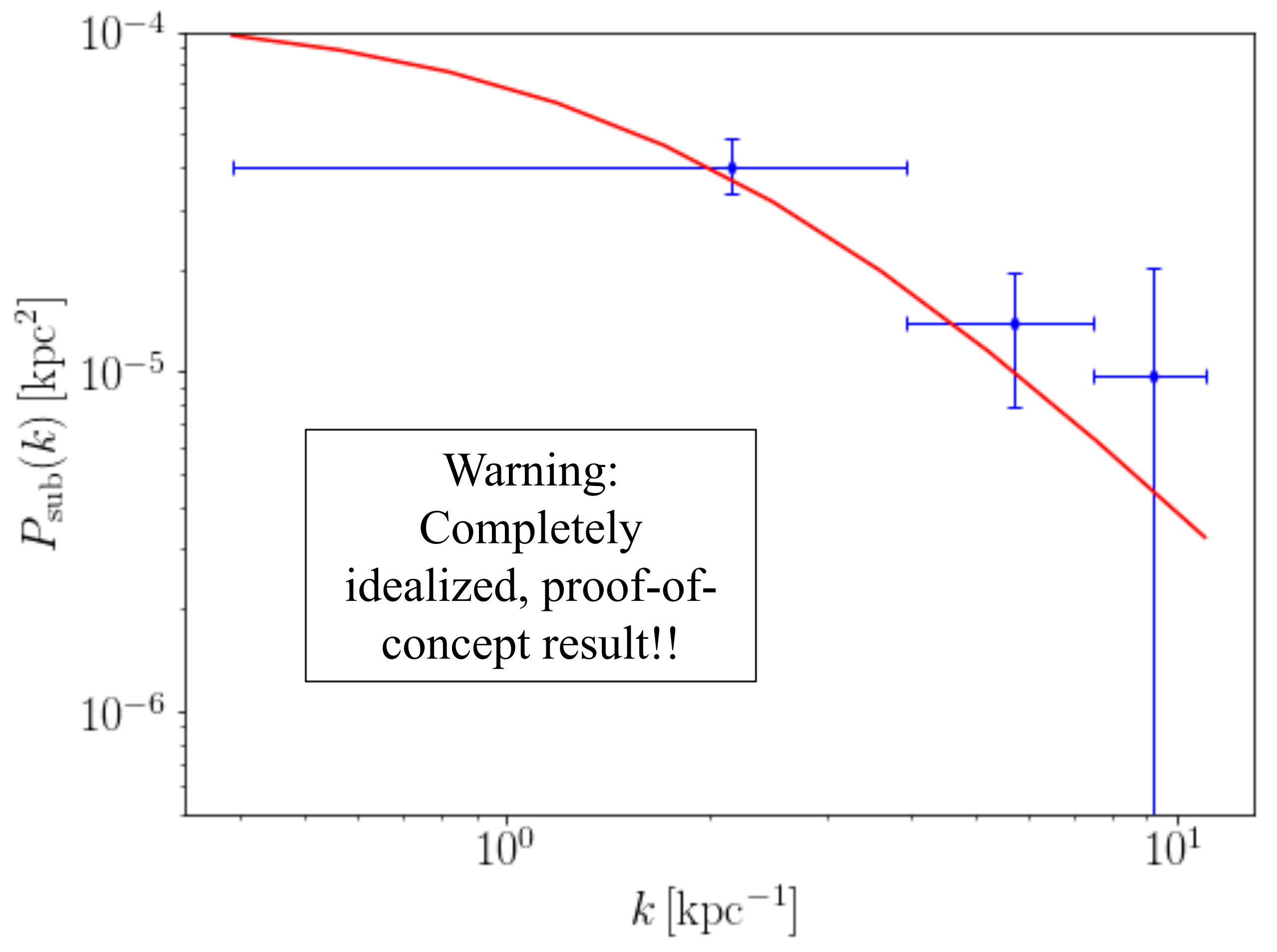


Image residuals



Measuring the substructure power spectrum: cartoon

- There is definitely signal in the lensing residual!



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.