Statistical challenges in substructure lensing

DM-Stat, Banff International Research Station
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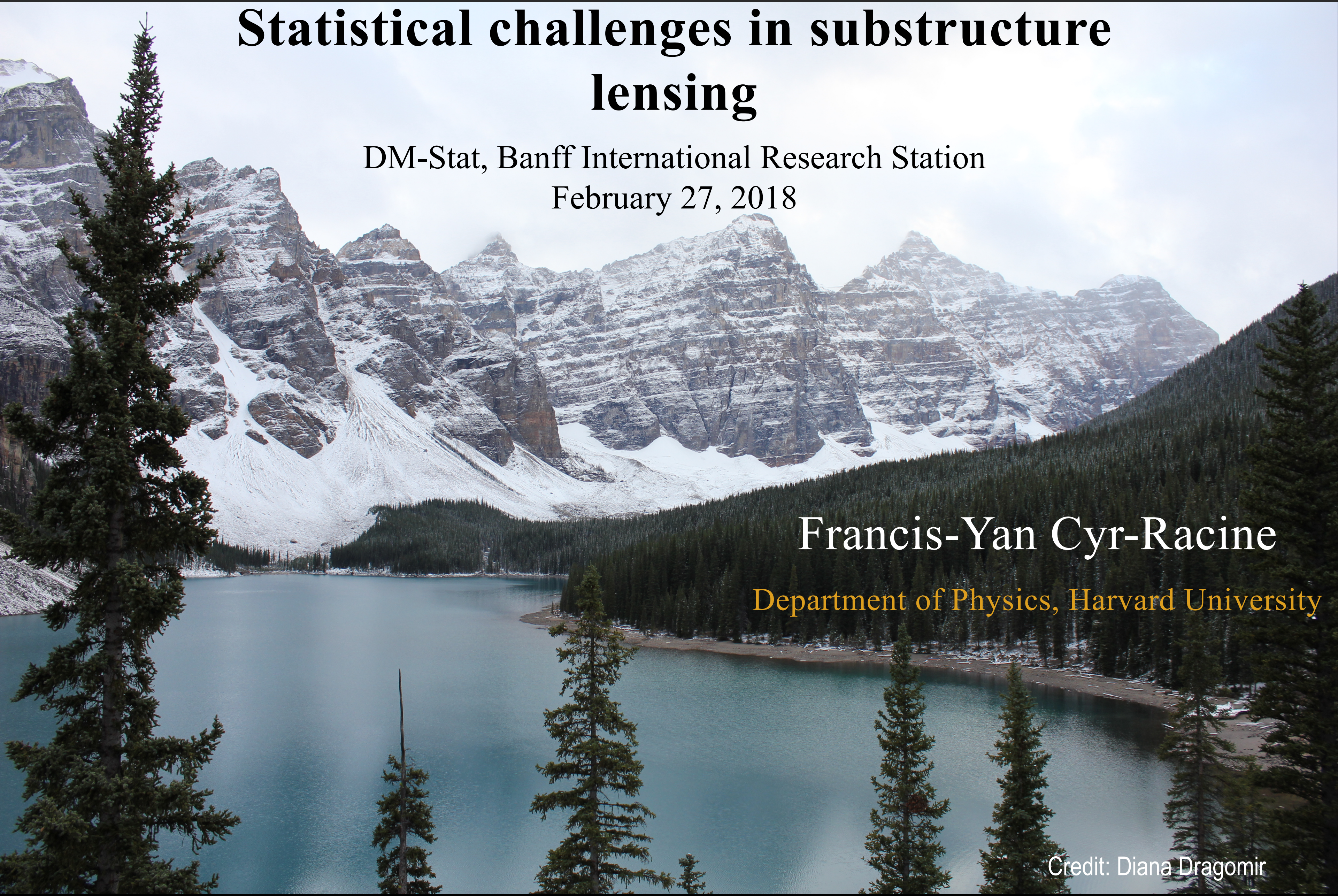
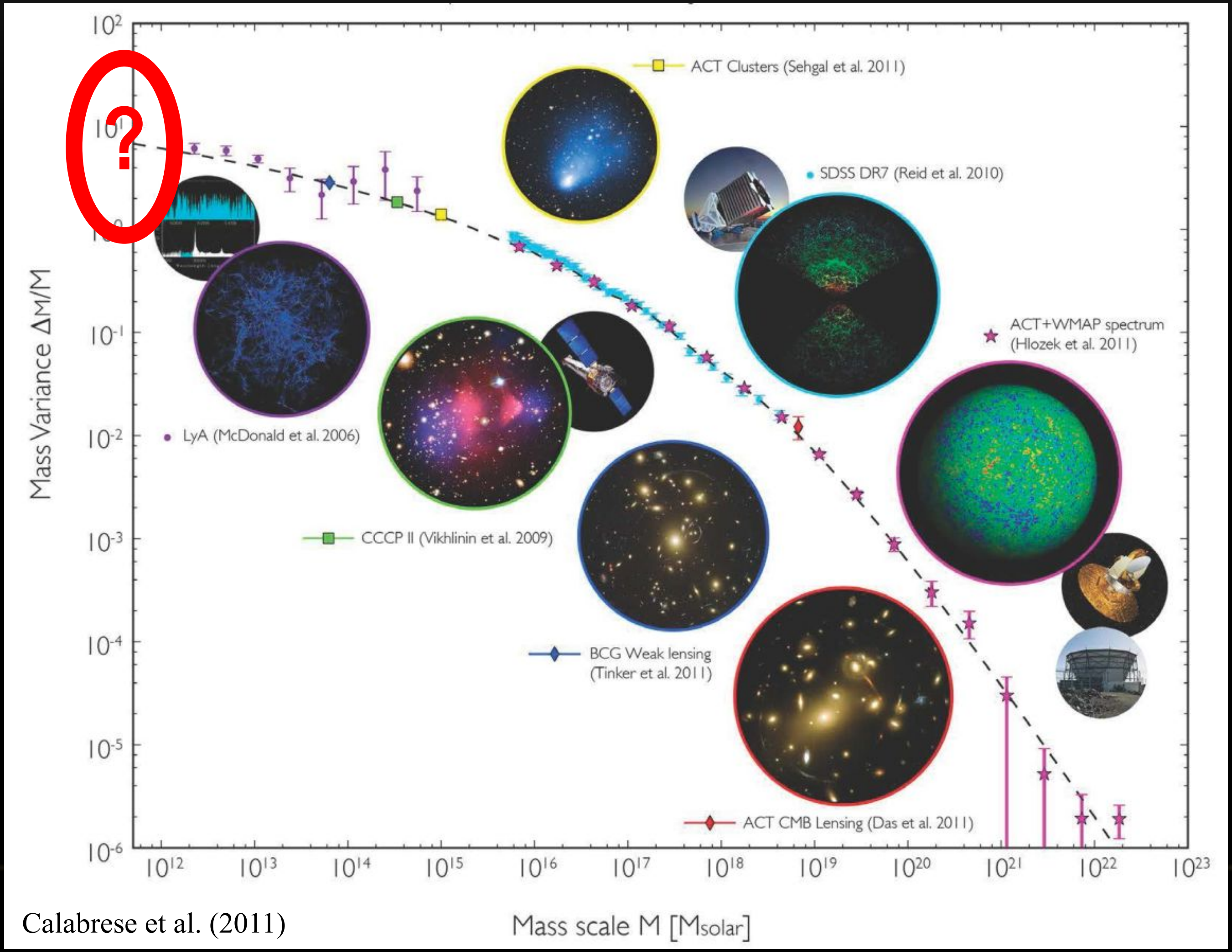


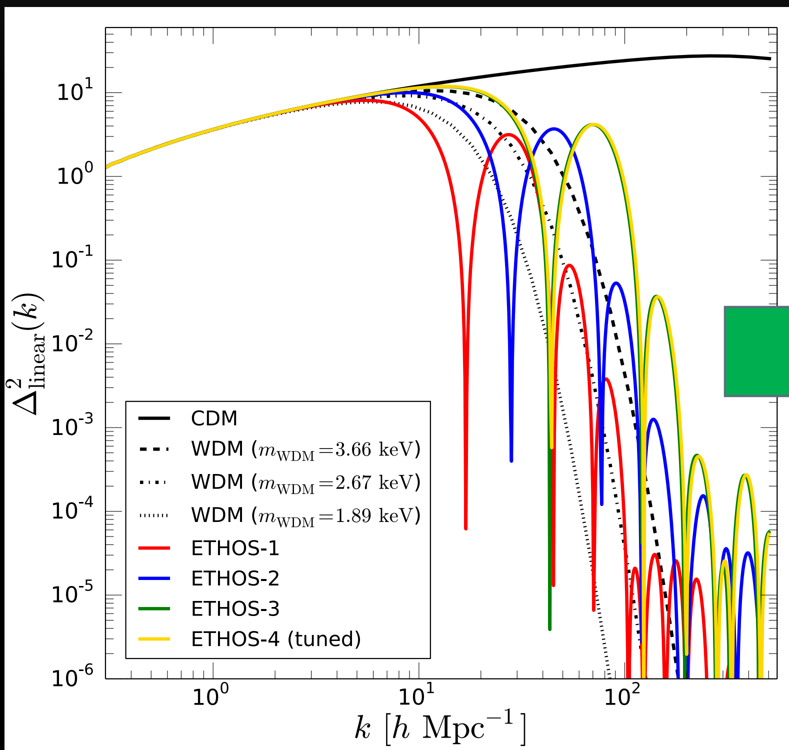
Credit: Diana Dragomir

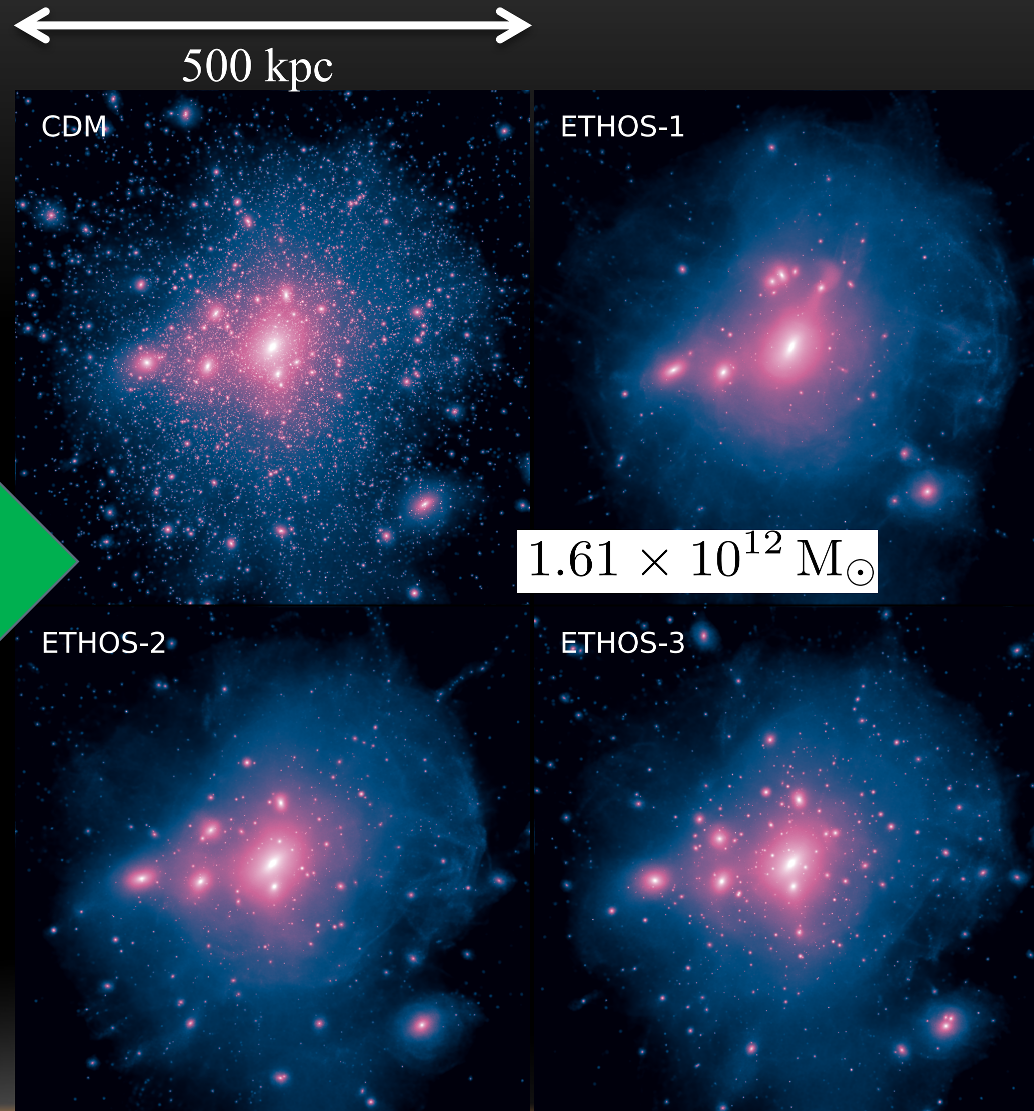
Probing small mass/length scales is key to determine the particle properties of DM



Calabrese et al. (2011)

Dark matter physics affects small-scale structure





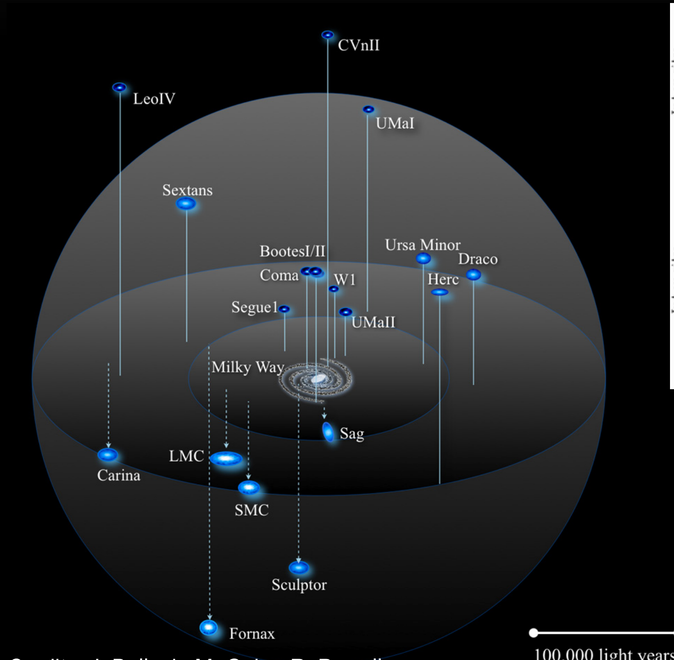
Vogelsberger, Zavala, Cyr-Racine +, arXiv:1512.05349

Many possible ways to probe small-scale structure

Gravitational Lensing

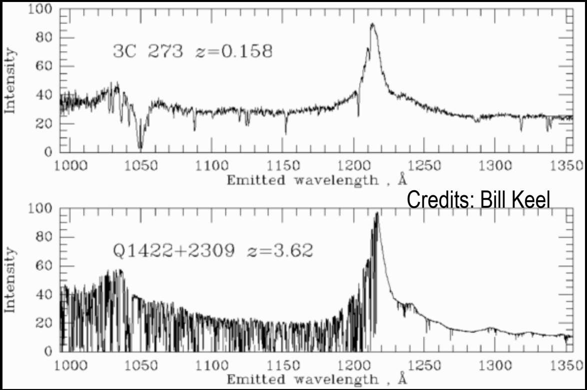
RXJ 1131-1231 (HST/NASA)

Local dwarf galaxies



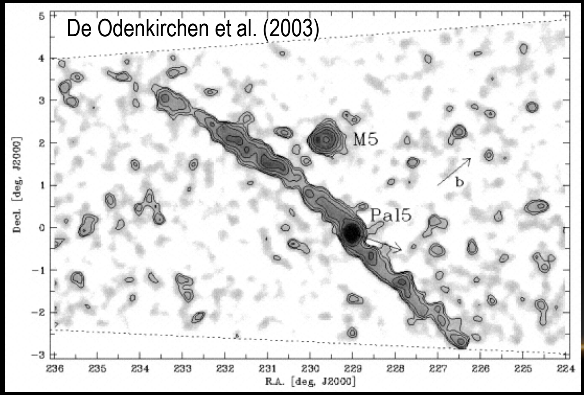
Credits: J. Bullock, M. Geha, R. Powell

Lyman-alpha forest

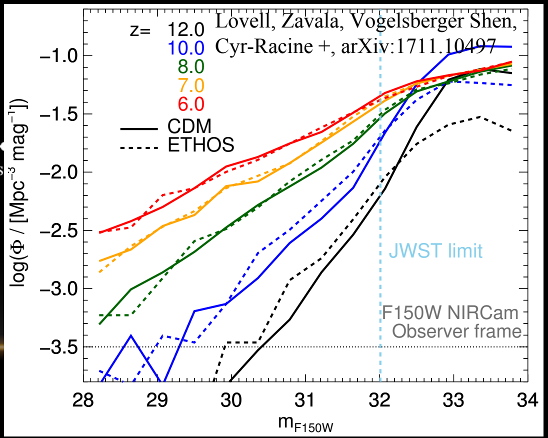


Credits: Bill Keel

Stellar Streams

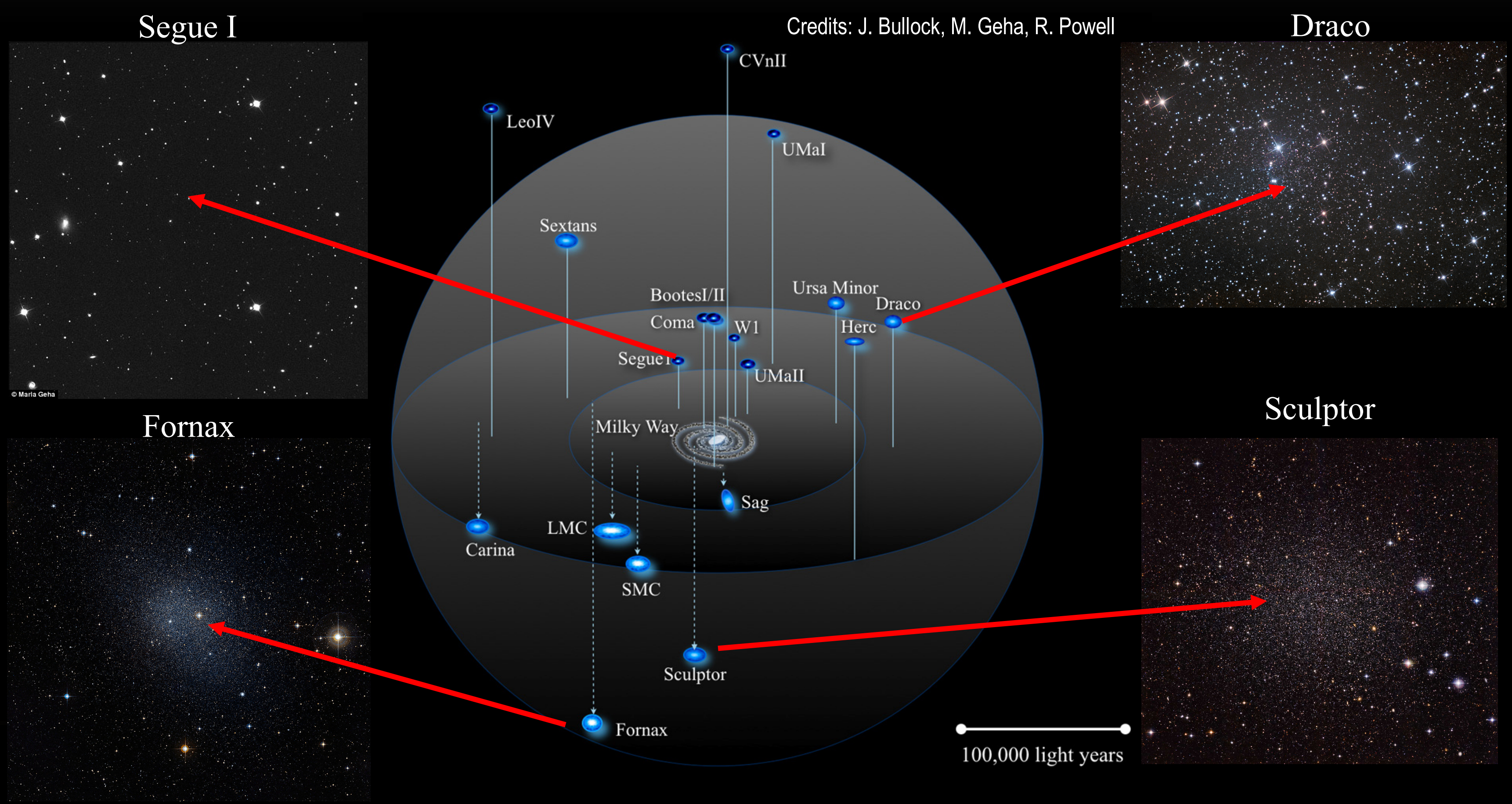


UV Luminosity Function

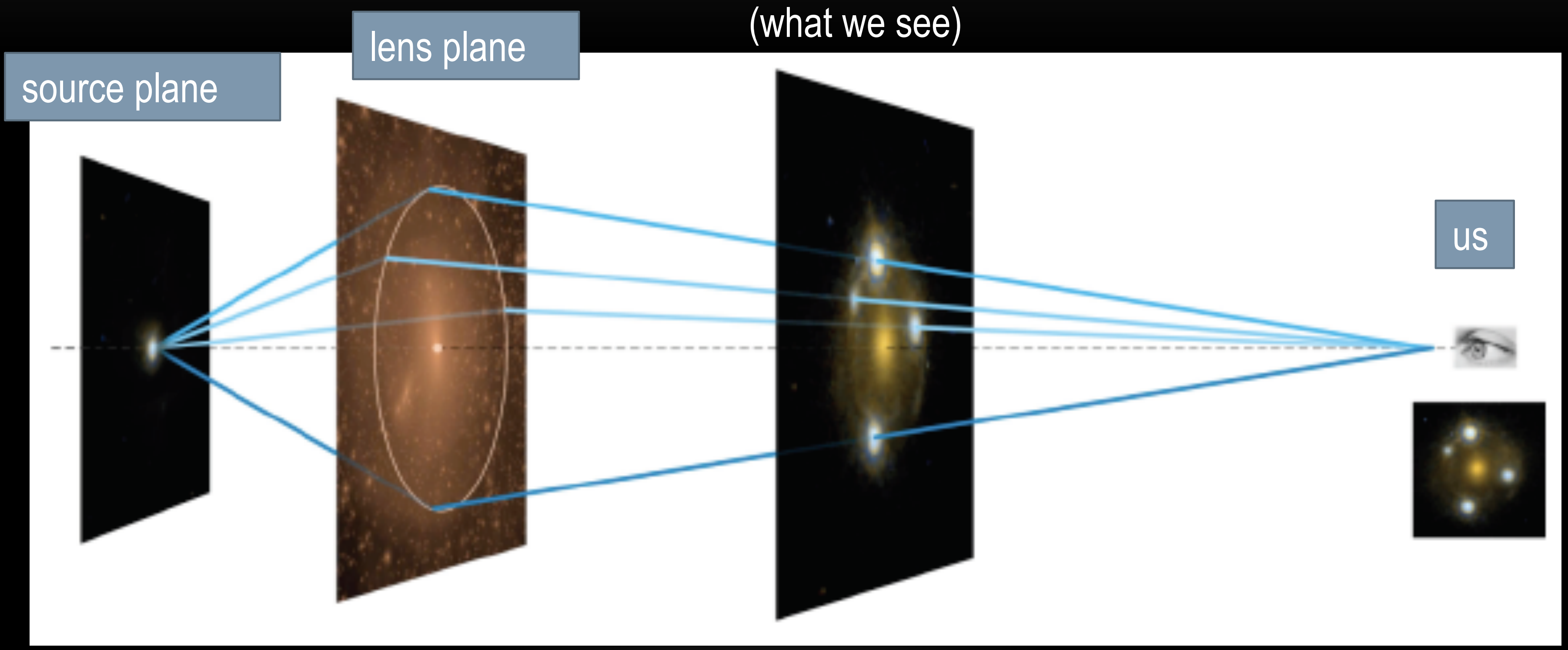


Example: Mapping the Milky Way satellites

- We are approaching the limit of visible small-scale structure!

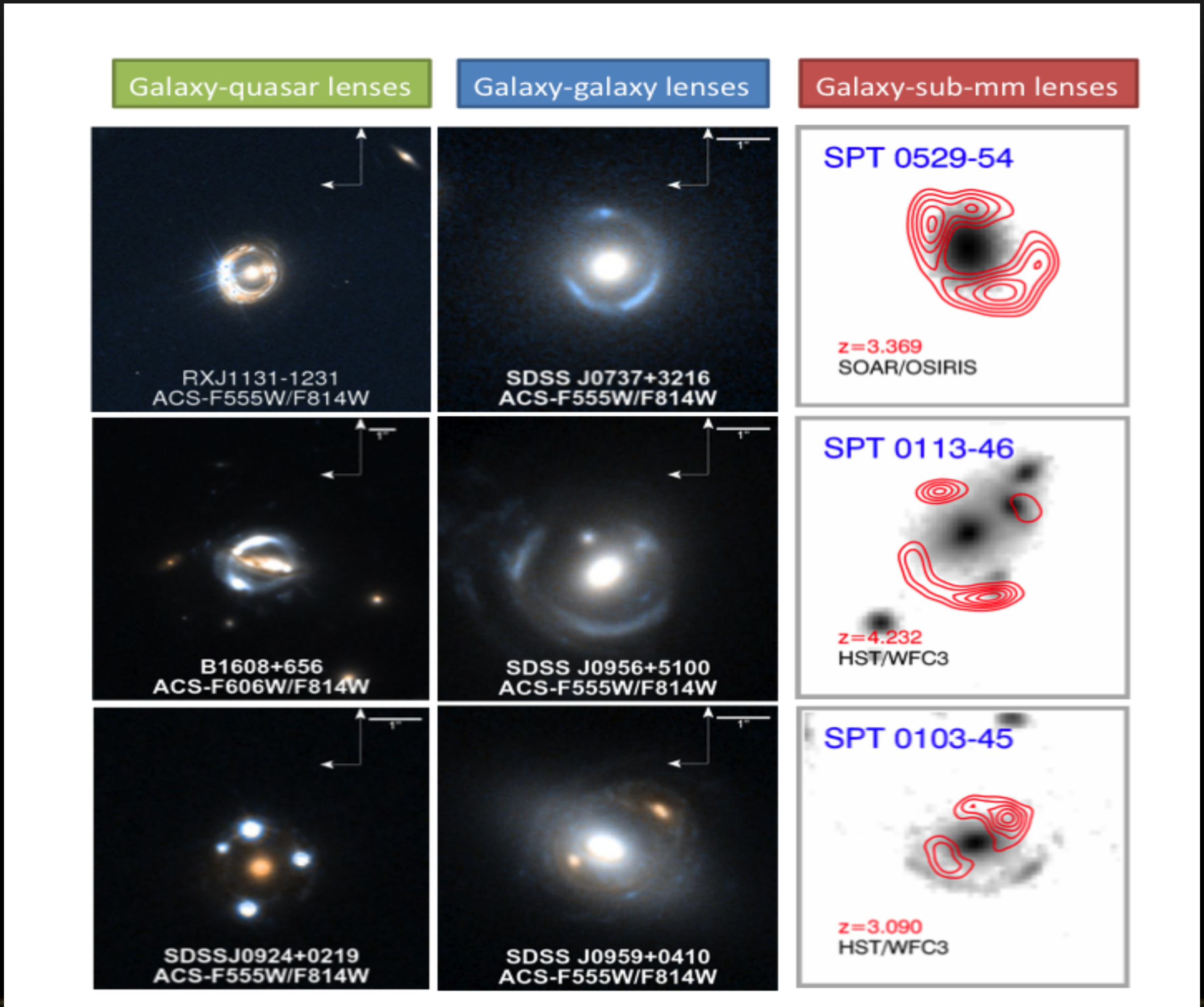


One possible solution: Strong Gravitational Lensing



Credits: Leonidas Moustakas

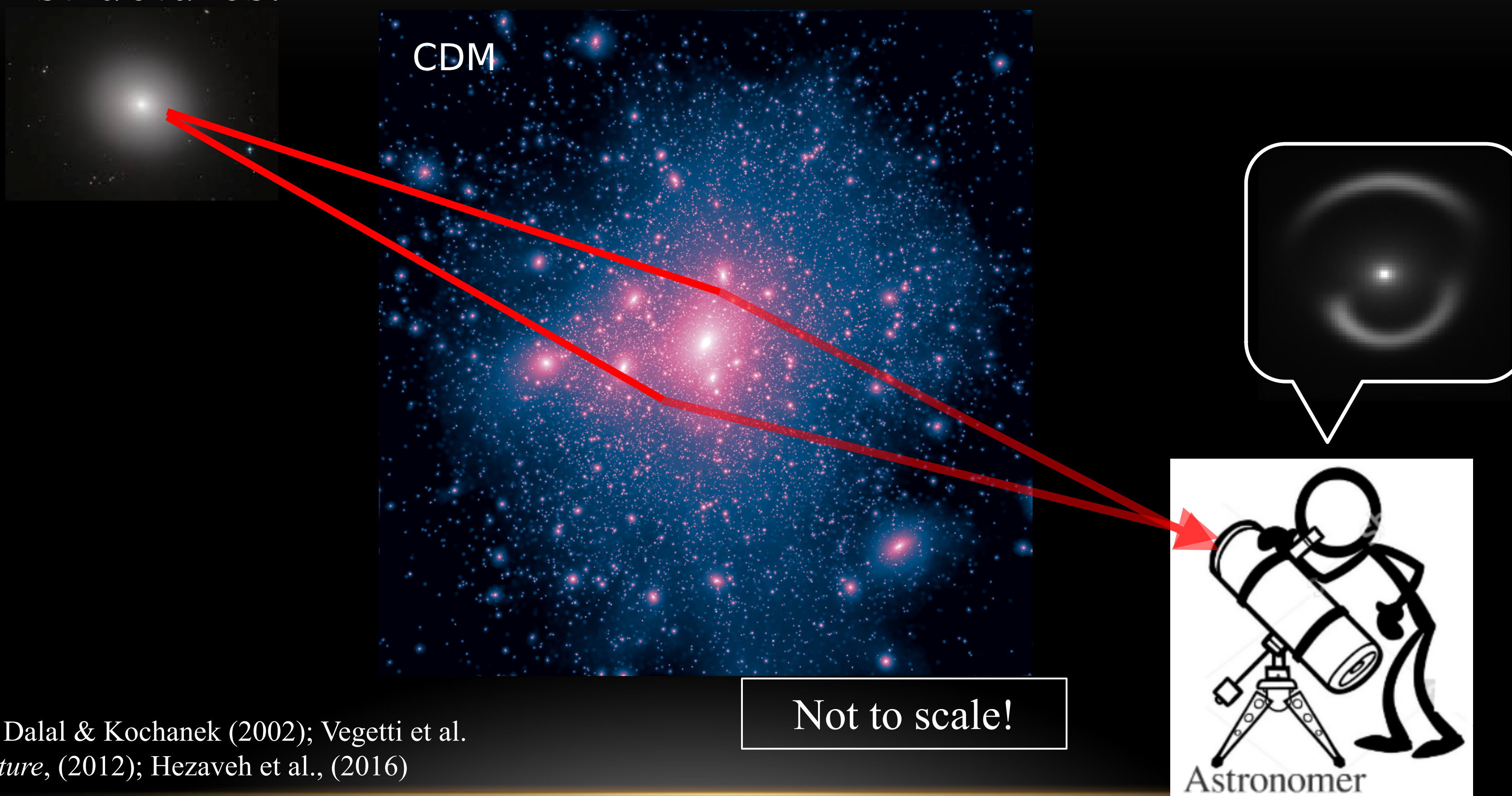
Galaxy-scale Gravitational Lenses



Credits: Leonidas Moustakas

Probing substructure through gravitational lensing

- Use universality of gravity to probe smallest dark matter structures.



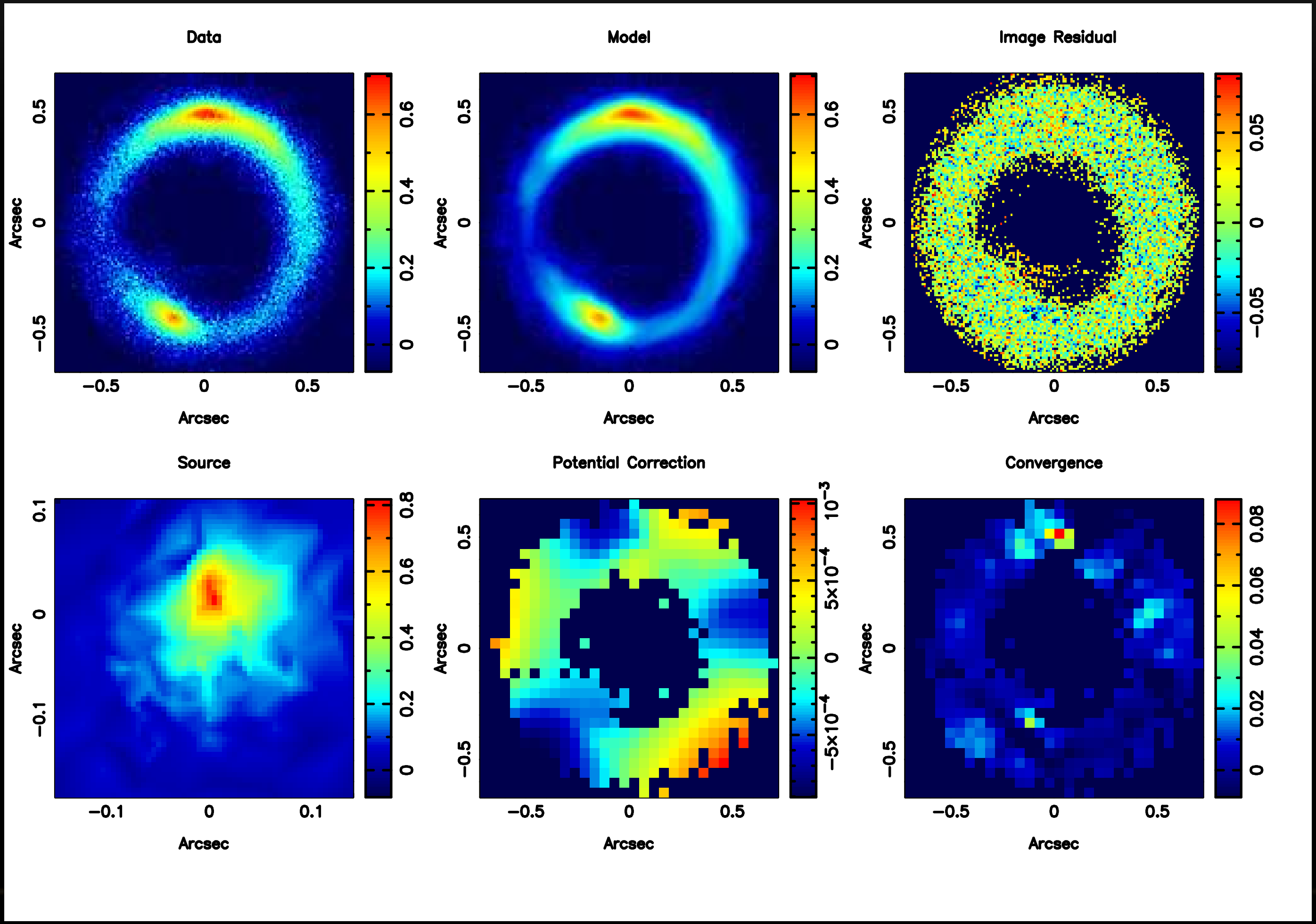
See e.g. Dalal & Kochanek (2002); Vegetti et al. *Nature*, (2012); Hezaveh et al., (2016)

Probing substructure through gravitational lensing

- Compact sources (quasars):
  - Flux-ratio anomalies (Dalal & Kochanek 2002)
  - Time-delay lensing (Keeton & Moustakas 2009, Cyr-Racine et al. 2016)
- Extended sources (galaxies):
  - Gravitational imaging of subhalos (Koopmans 2005; Vegetti et al. 2009, 2012, 2014; Hezaveh et al. 2016)
  - Transdimensional inference of subhalos (Brewer et al. 2015; Daylan et al. 2018)
  - Power spectrum analysis of substructure field (Hezaveh et al. 2016; Cyr-Racine, Keeton & Moustakas, 2018)

Direct Subhalo Detection

- "Gravitational Imaging" of Perturbed Einstein Rings



Vegetti et al. *Nature*, (2012). See also Hezaveh et al. (2016)

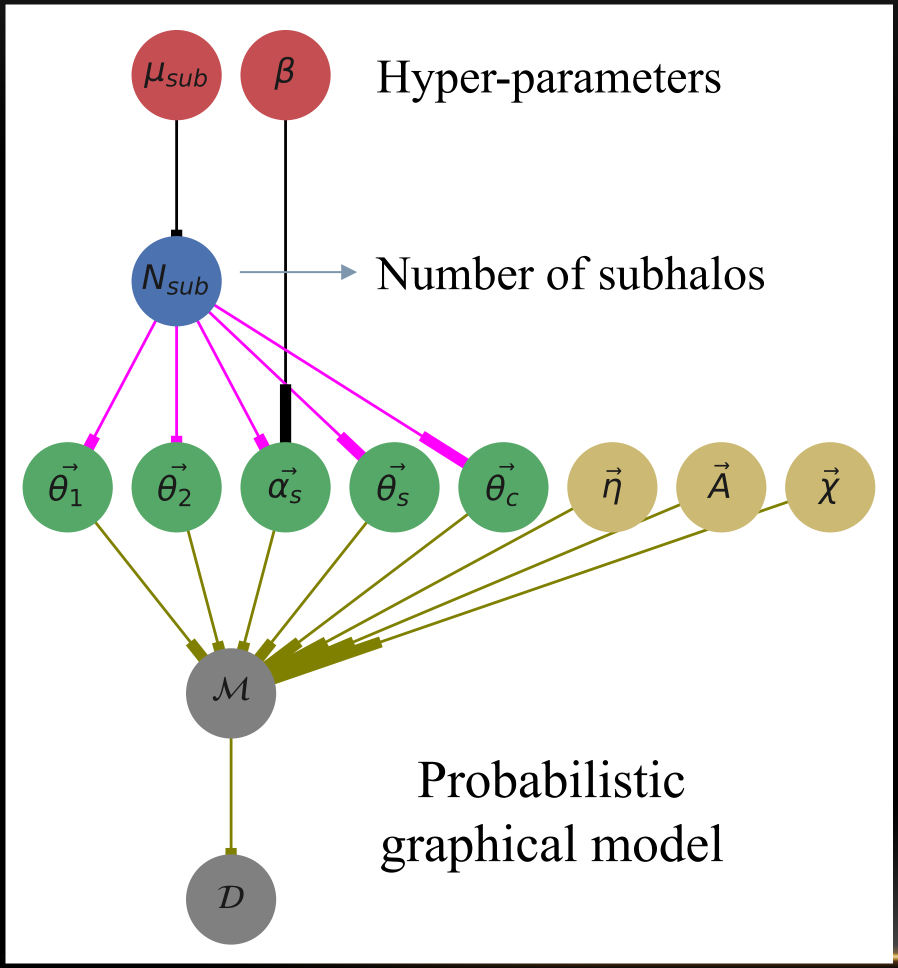
Direct Subhalo Detection: Challenges

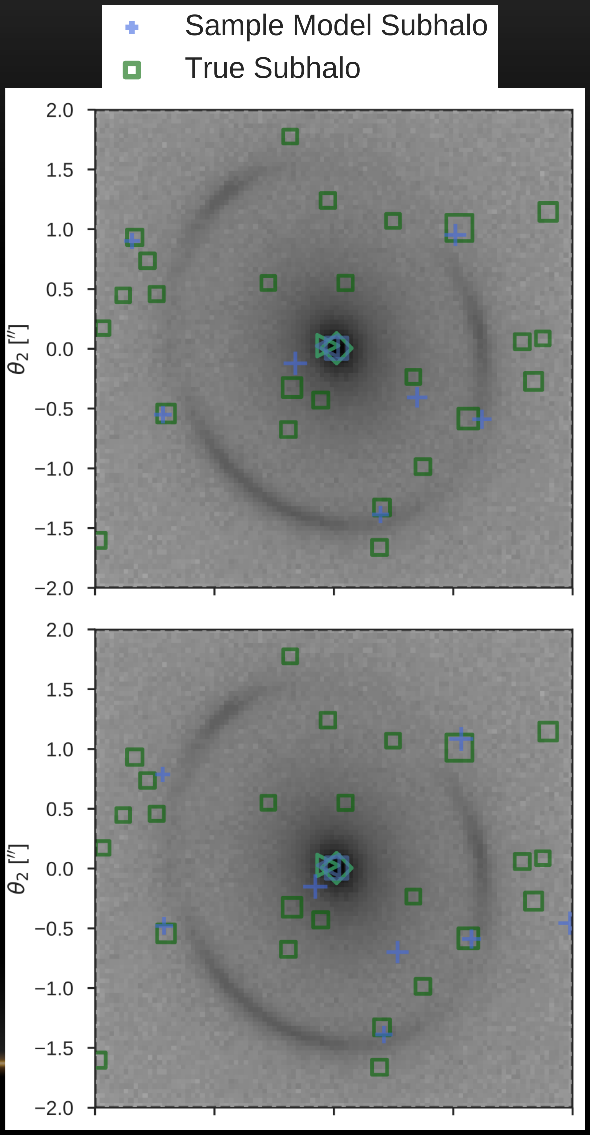
- What is actually detected?
- Unclear what the measured mass actually mean (Minor & Kaplinghat, 2017).
- Throw away all lensing data to infer dark matter subhalo statistics (subhalo mass function).
- Number of subhalo is fixed (Degeneracies with main lens model).

Can we improve on this?

Transdimensional subhalo Inference

- Let the data drive the model complexity





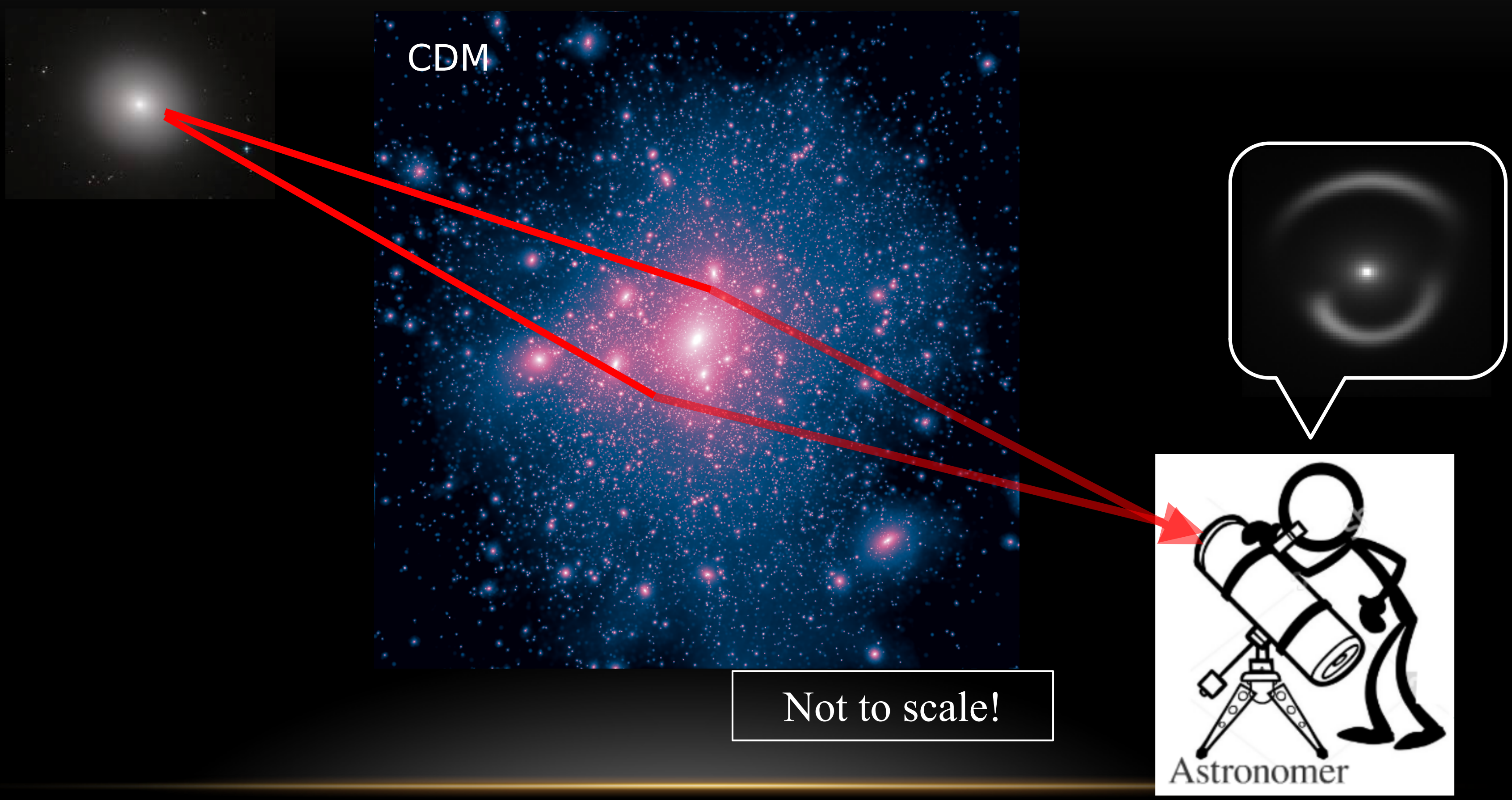
Daylan, Cyr-Racine et al. (2018). See also Brewer et al. (2015)

Transdimensional subhalo inference: Pros and Cons

- Pros:
  - Allows covariances between models with different number of subhalos to be taken into account.
  - Lead to direct constraints on the mass function (hyper-parameters) that are (in my opinion) more believable.
- Cons:
  - Might need to impose bound on model complexity (parsimony prior).

Power spectrum analysis of substructure field

- Move away from the subhalo language

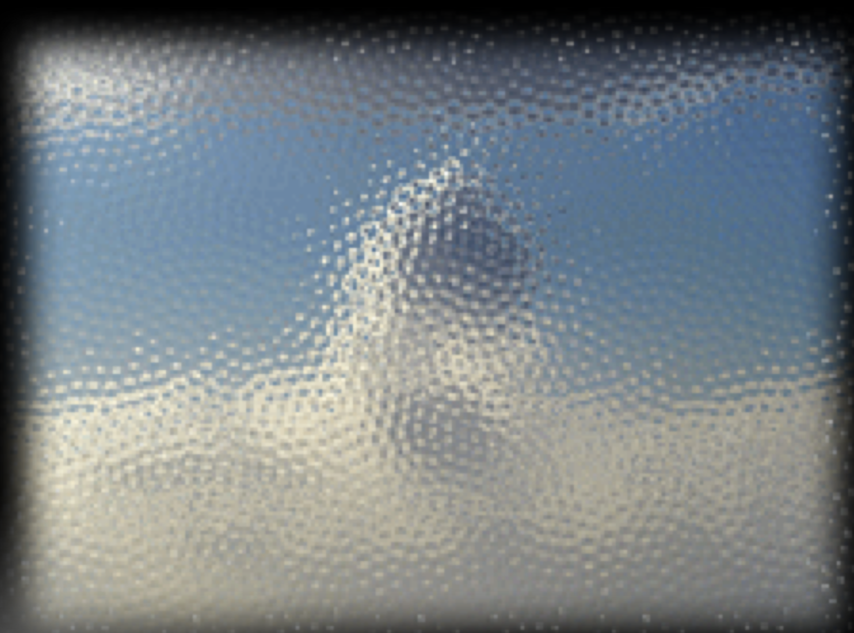


Substructure field analogy: Looking through a textured window

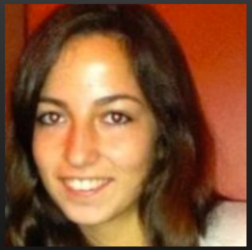
- The textured window introduces perturbation on a given scale.

1) Unperturbed image

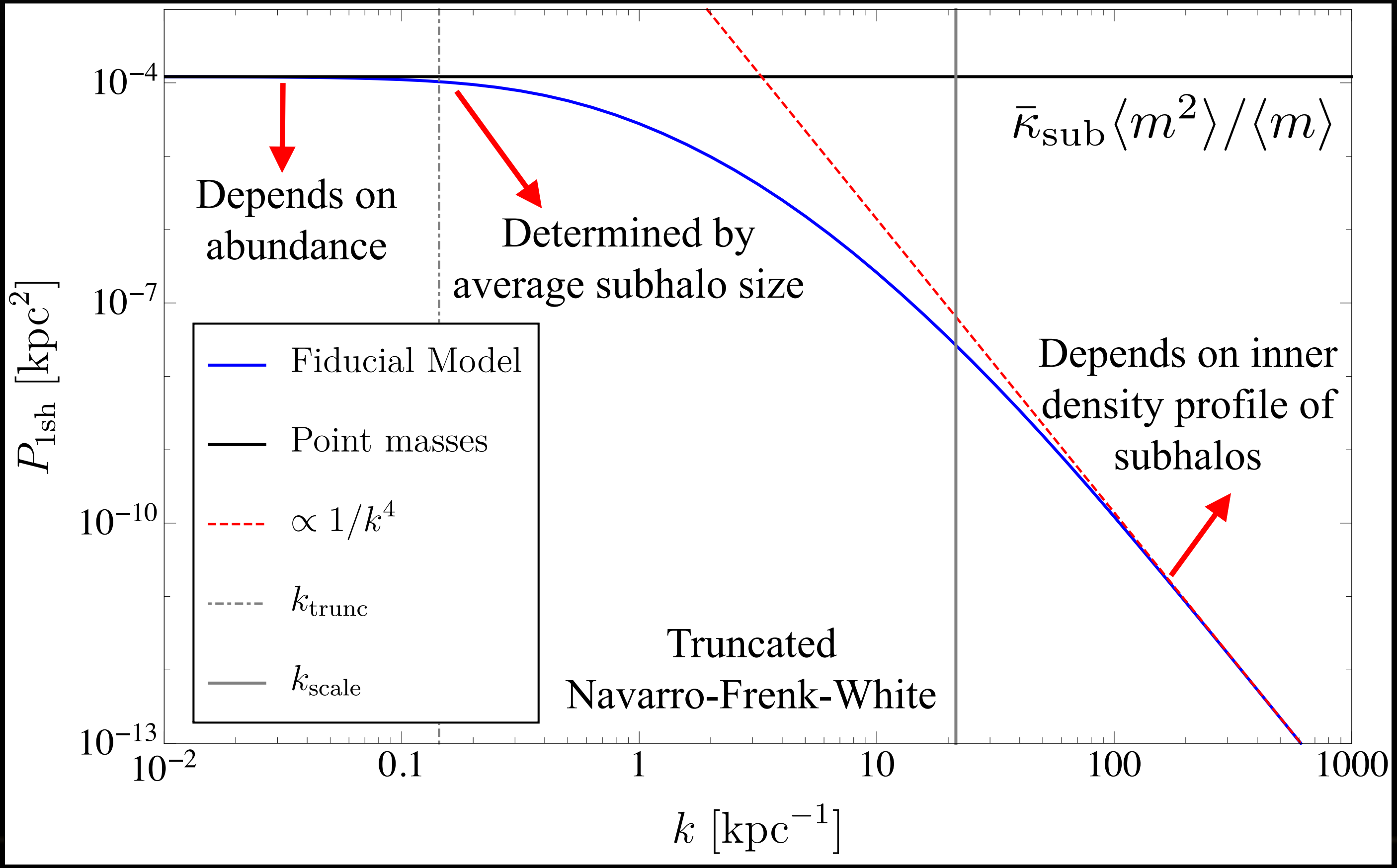
2) Image seen through textured glass



Substructure power spectrum



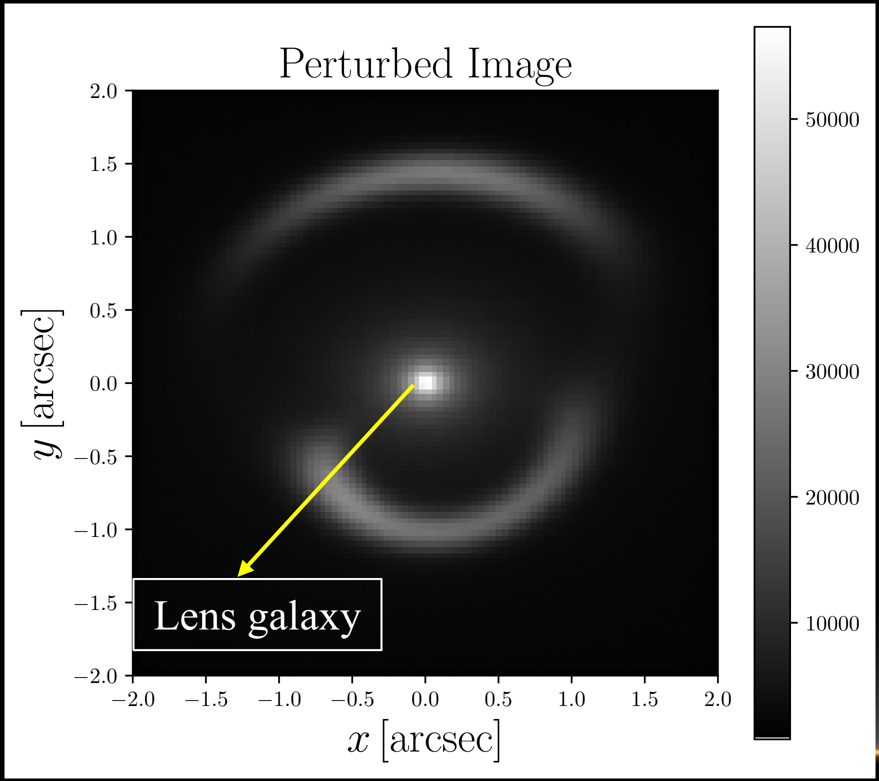
- The power spectrum has three main features:

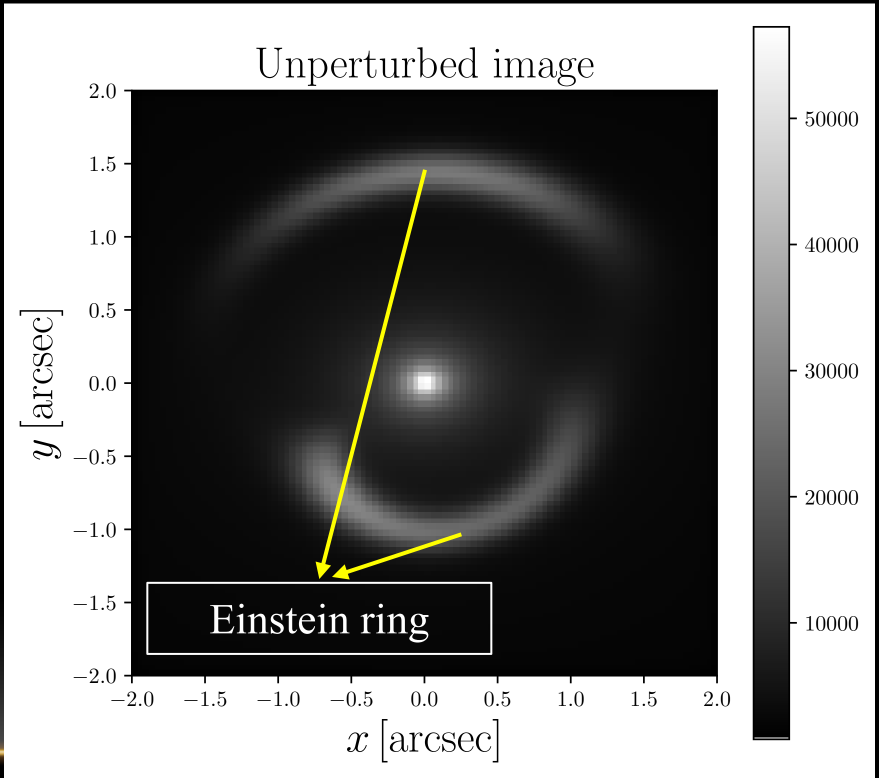


Díaz Rivero, Cyr-Racine, & Dvorkin, arXiv:1707.04590

Effect of substructures on lensed images

- The substructure deflection field, leads to subtle surface brightness variations along the Einstein ring





Cyr-Racine, Keeton & Moustakas, in prep.

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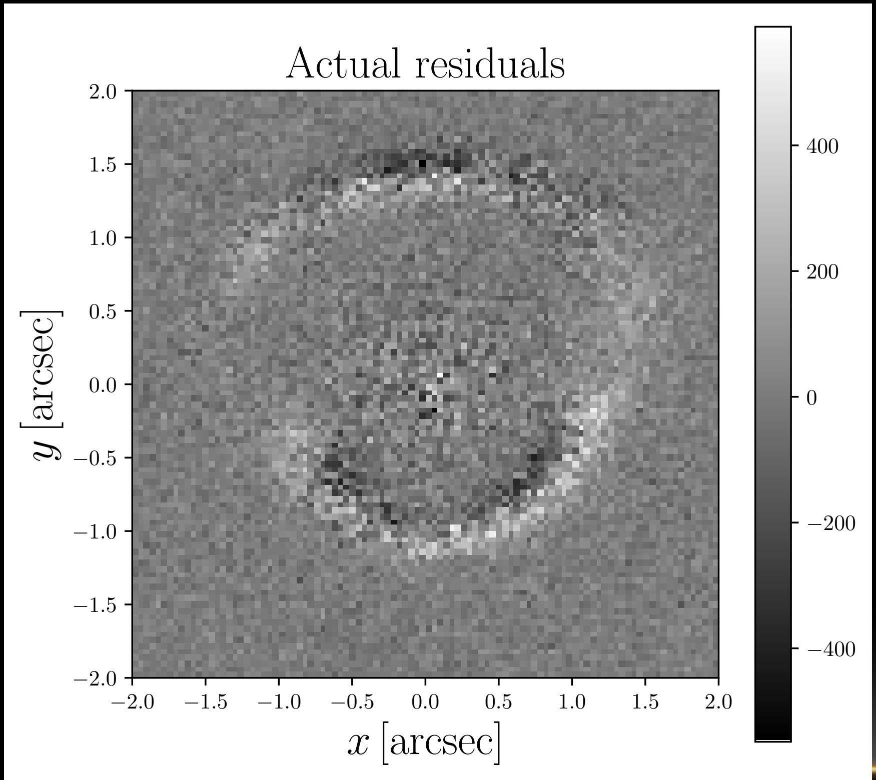
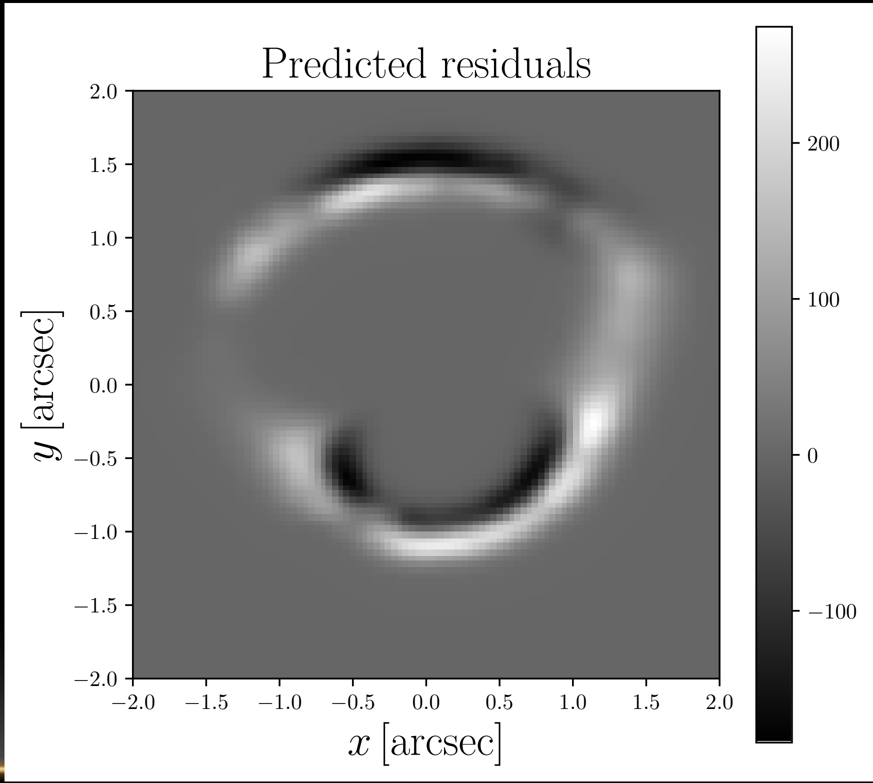
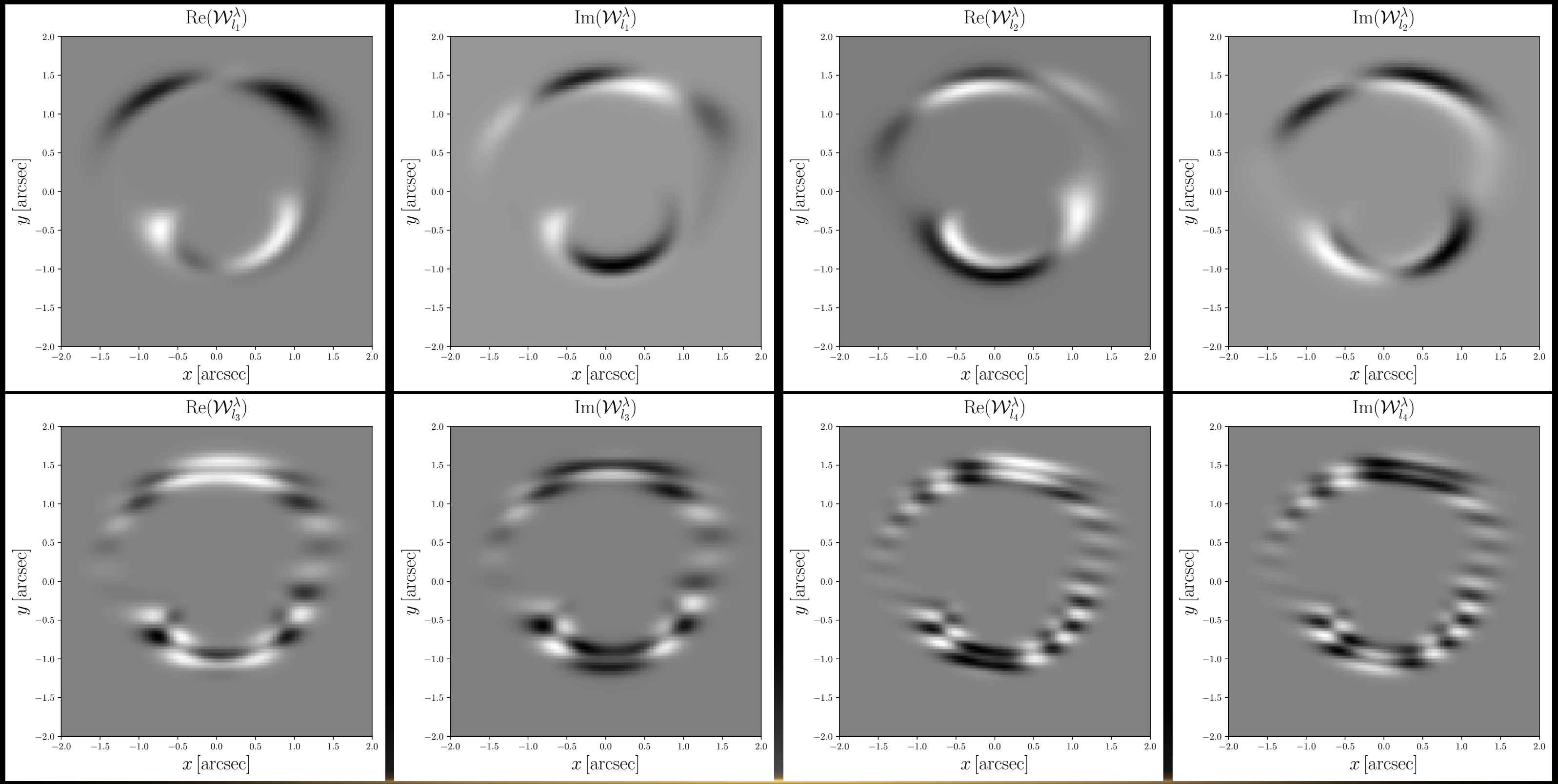




Cyr-Racine, Keeton & Moustakas, in prep.

From image residuals to substructure power spectrum

- We can decompose the image residuals in a Fourier-like basis to determine which modes are present in the data.

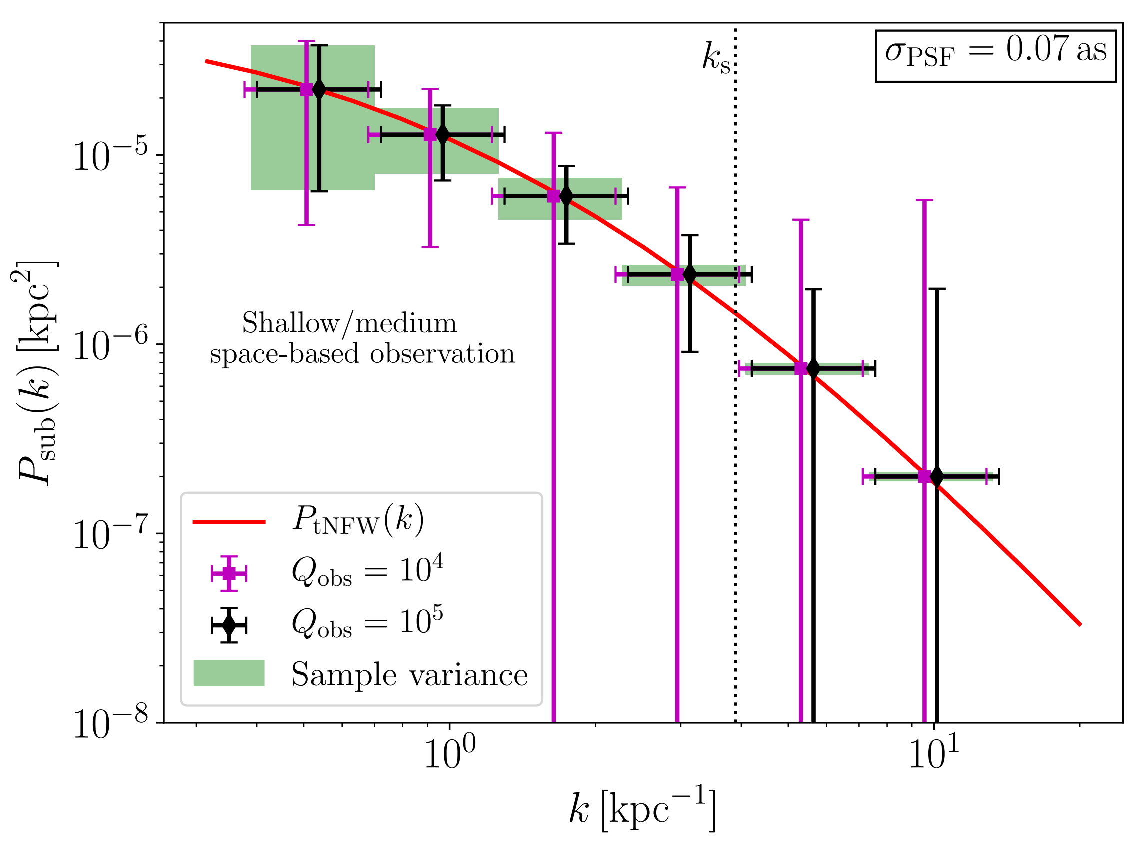


Cyr-Racine, Keeton & Moustakas, in prep.

Use *Hubble Space Telescope* mock images to assess sensitivity

- We show a significant detection of the power spectrum:

$$Q^{\lambda}_{\rm obs} \equiv N^{\lambda}_{\rm obs} \frac{T_{\rm exp}\mathcal{F}_{\lambda}}{\sigma_1 \mathcal{S}^{(\lambda)}_{\rm inv}}$$



WFC3 UVIS
F555W

Cyr-Racine, Keeton & Moustakas, in prep.

The next decade of substructure lensing

- With LSST and WFIRST(??), the number of known galaxy-scale gravitational lenses will grow dramatically (from ~100 to ~10000).
- This will open the "statistical era" of strong lensing.
- Need to compare "direct" subhalo detection with more general probe of the density field.
- Several challenges to tackle, including how to jointly analyze a large number of lenses.

Thanks!