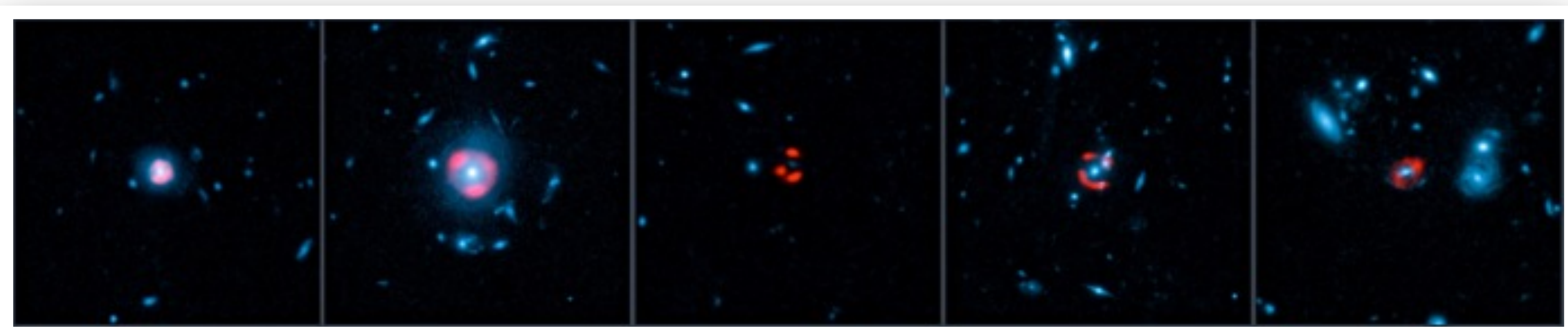
Measuring the Power Spectrum of Dark Matter Subhalos with Strong Lensing

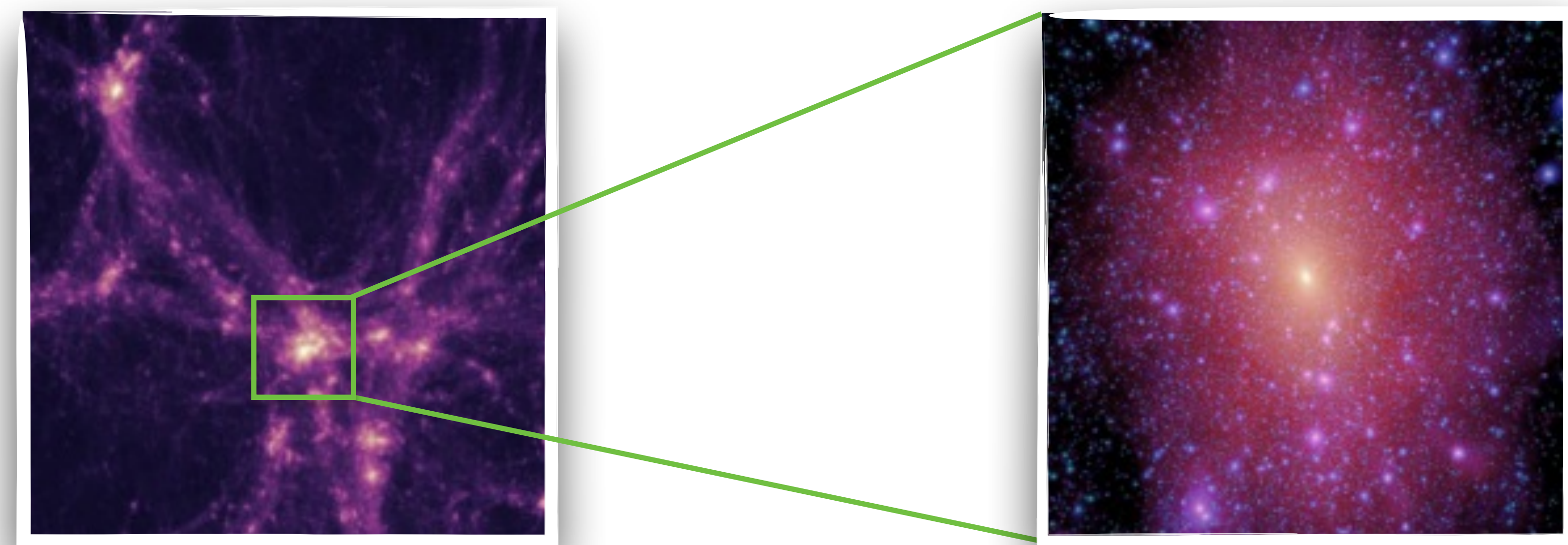


Yashar Hezaveh
KIPAC - Stanford University

IPMU - Nov 2014

Neal Dalal, N. Murray, P. Marshall, T. Kisner, R. Blandford
Gil Holder, C. Fassnacht, D. Marrone, J. Vieira
and the South Pole Telescope team

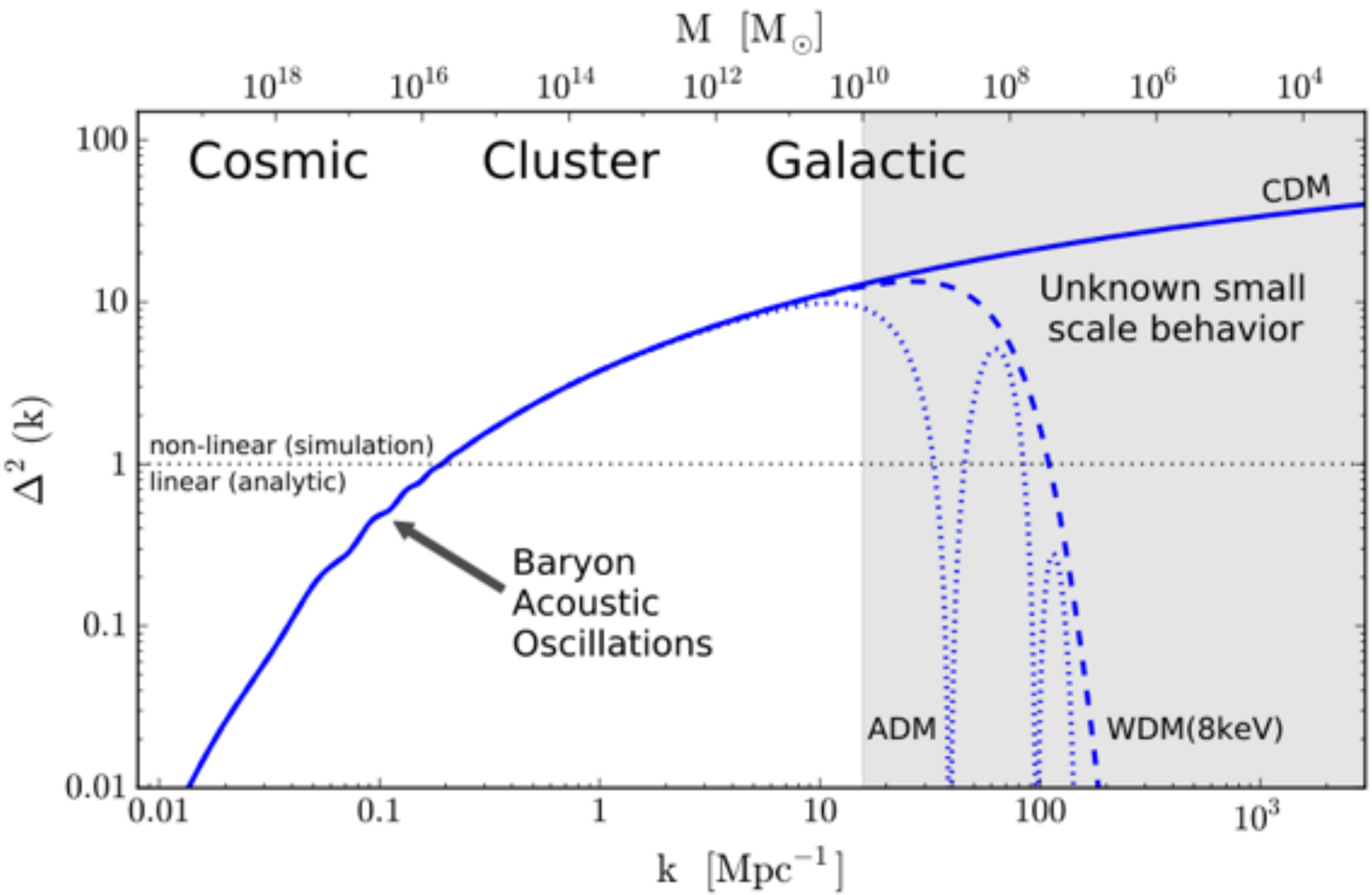
Small-Scale Structure of Dark Matter



Large scale structure is very well constrained

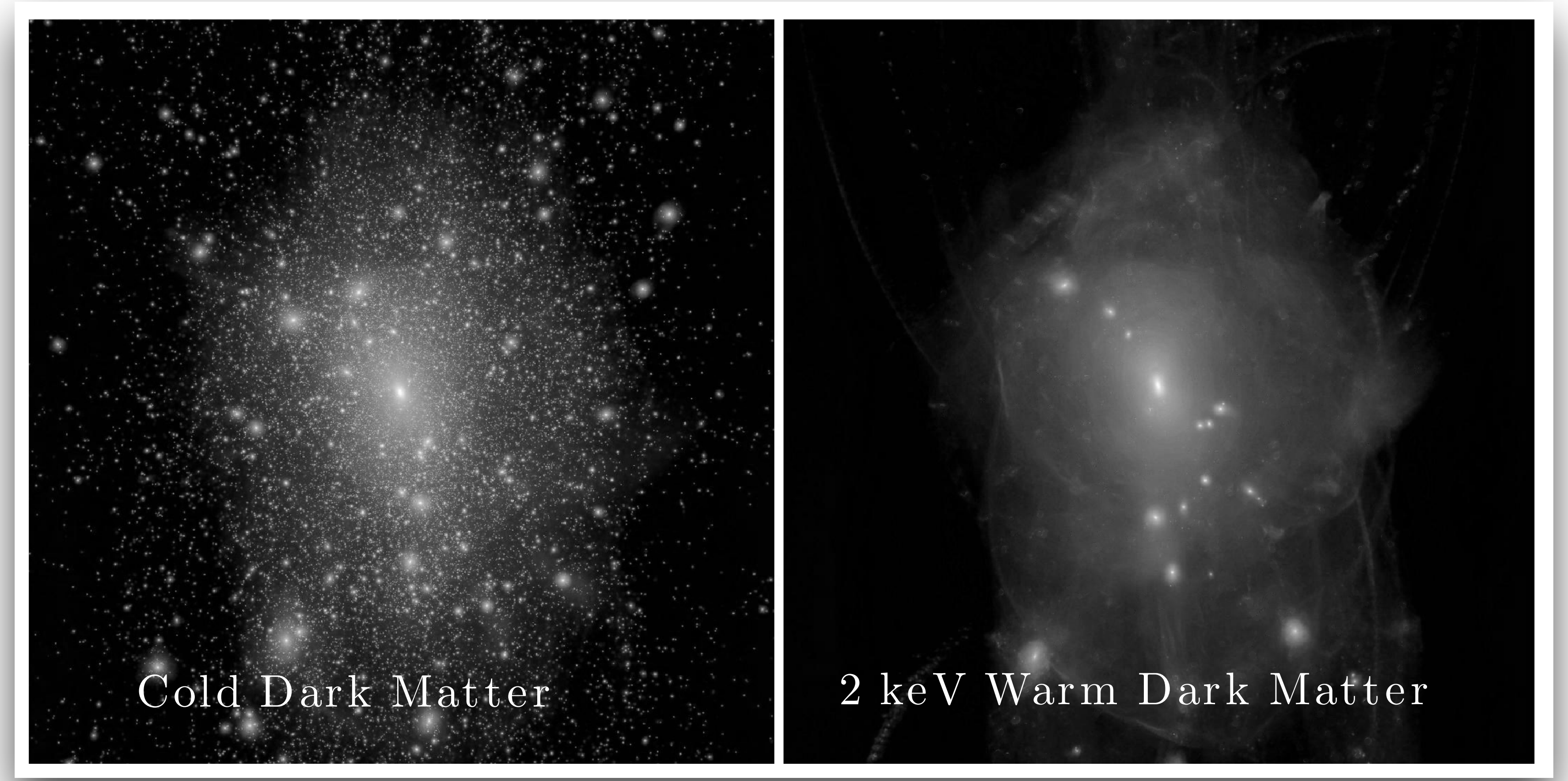
What do halos look like on small scales?

Dark Matter Power Spectrum



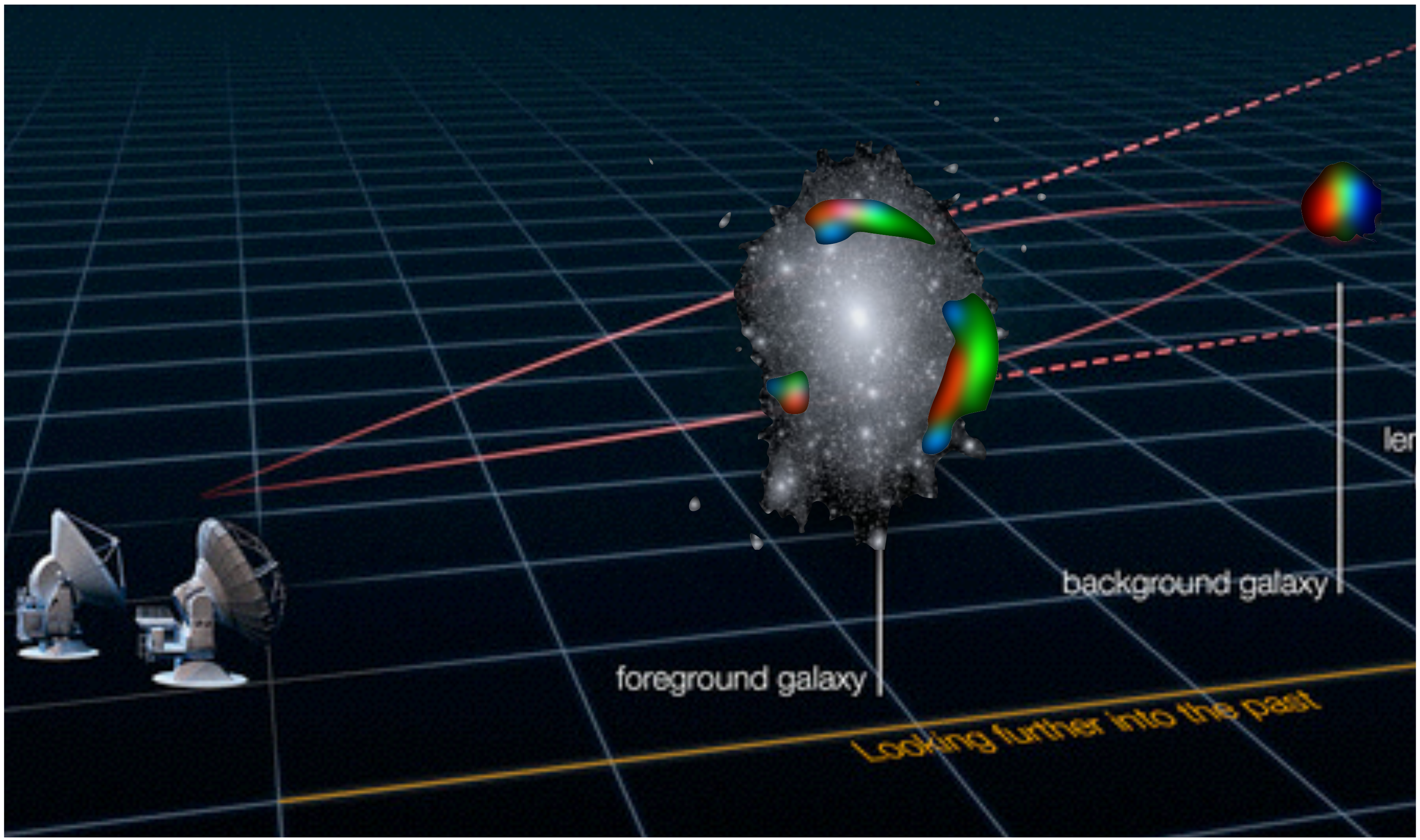
Kuhlen

What Do Dark Matter Halos Look Like?

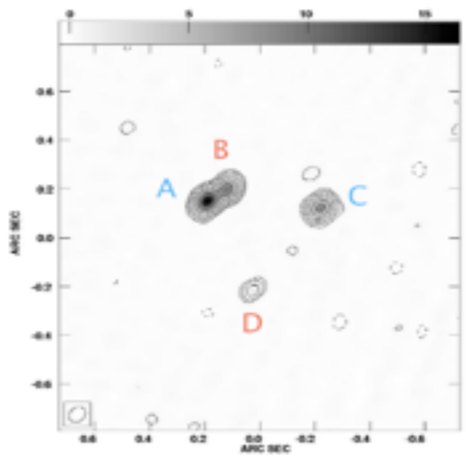


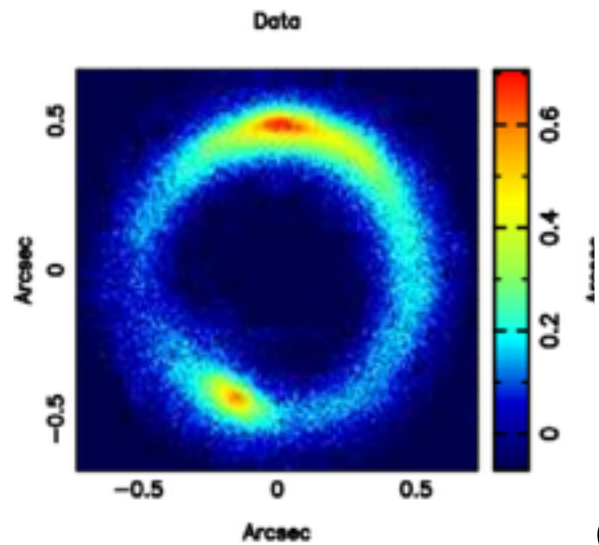
Lovell

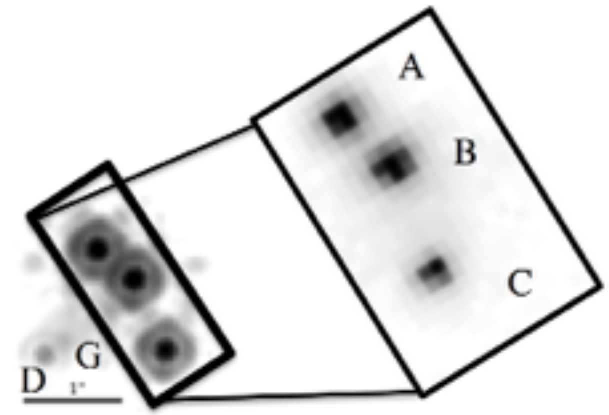
Strong Gravitational Lensing



Probing Subhalos with Different Classes of Lenses

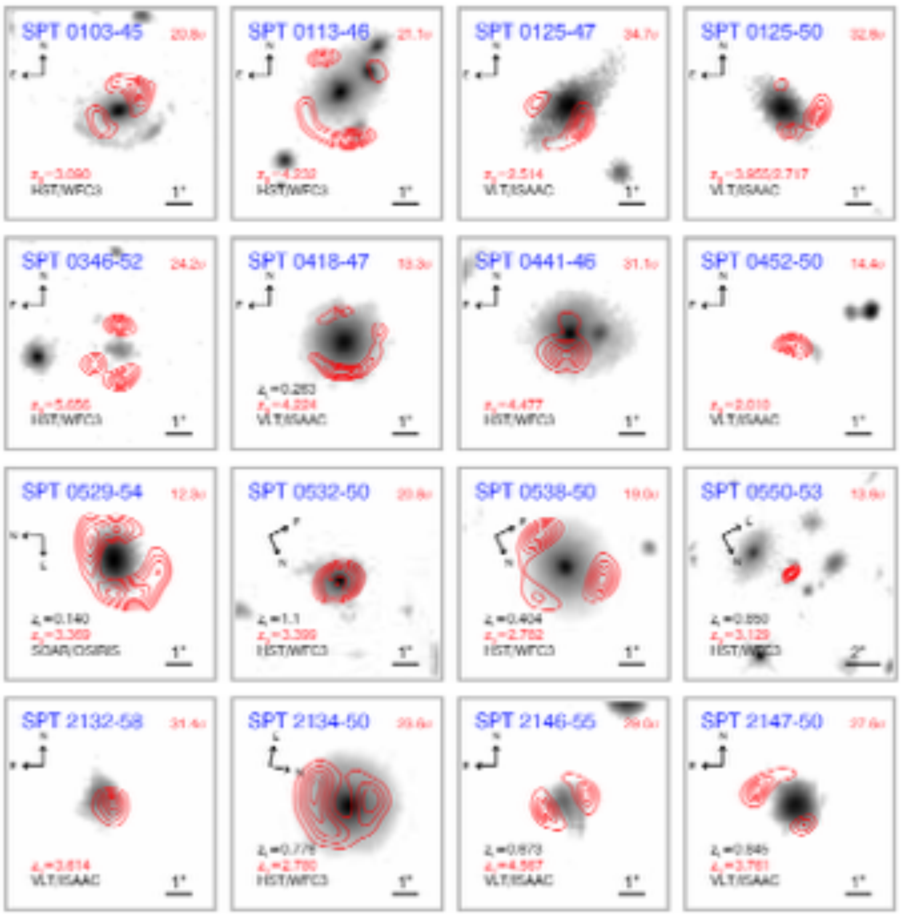


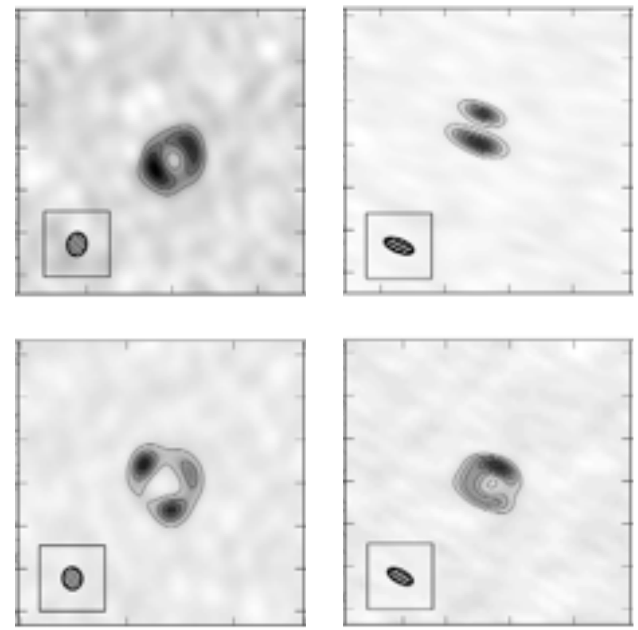




(see Anna Nierenberg's talk)

Strong Lenses in mm-wave

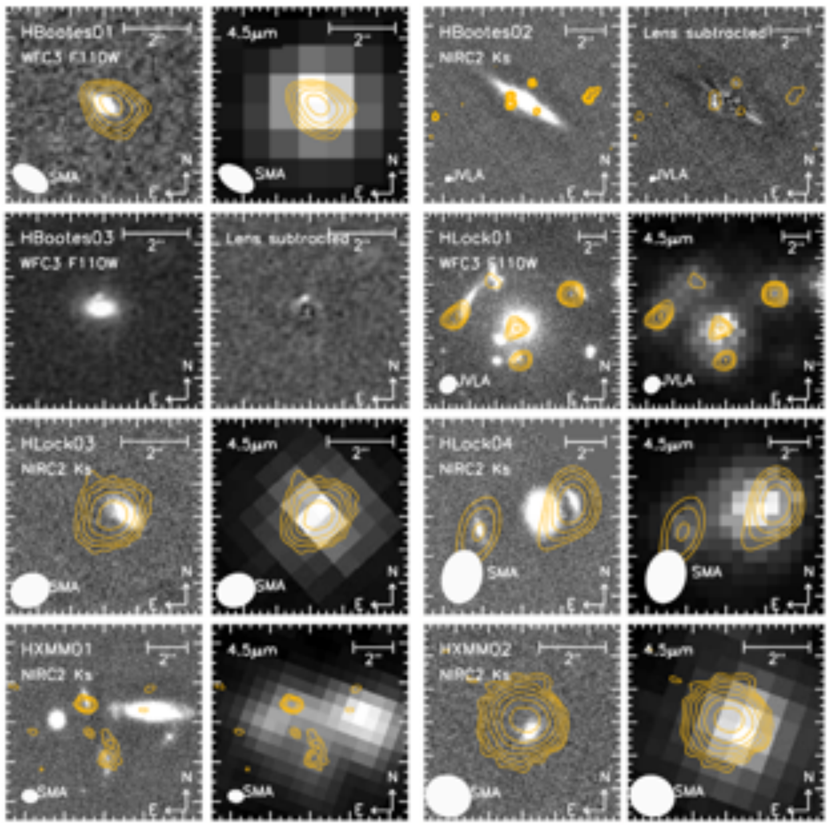


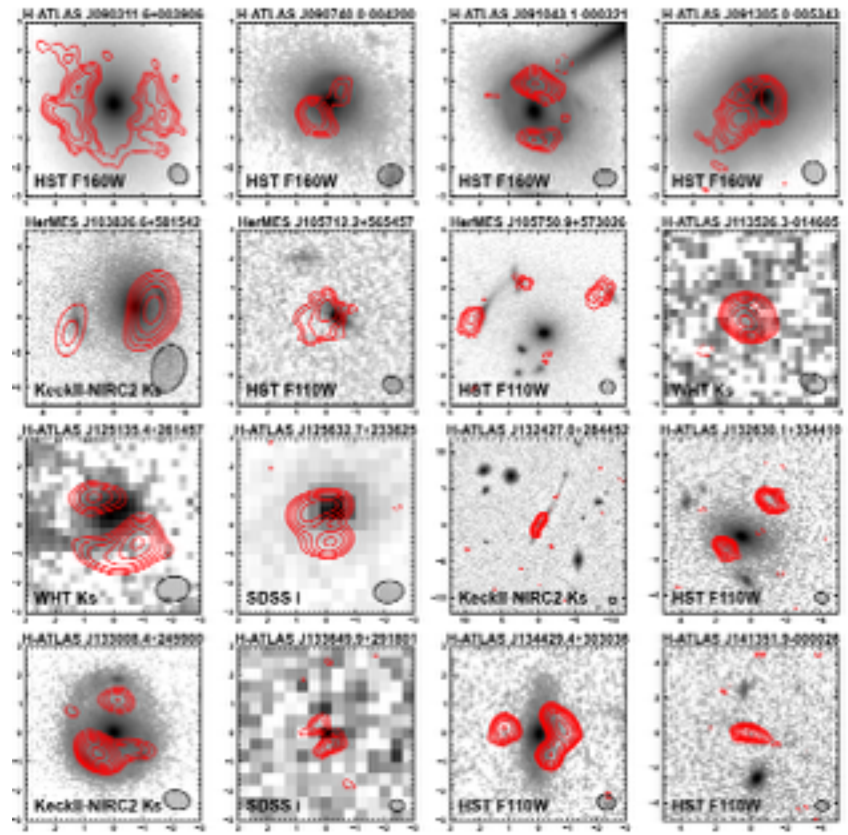


Vieira et al. Nature 2013

Hezaveh et al. ApJ. 2013

Strong Lenses in mm-wave





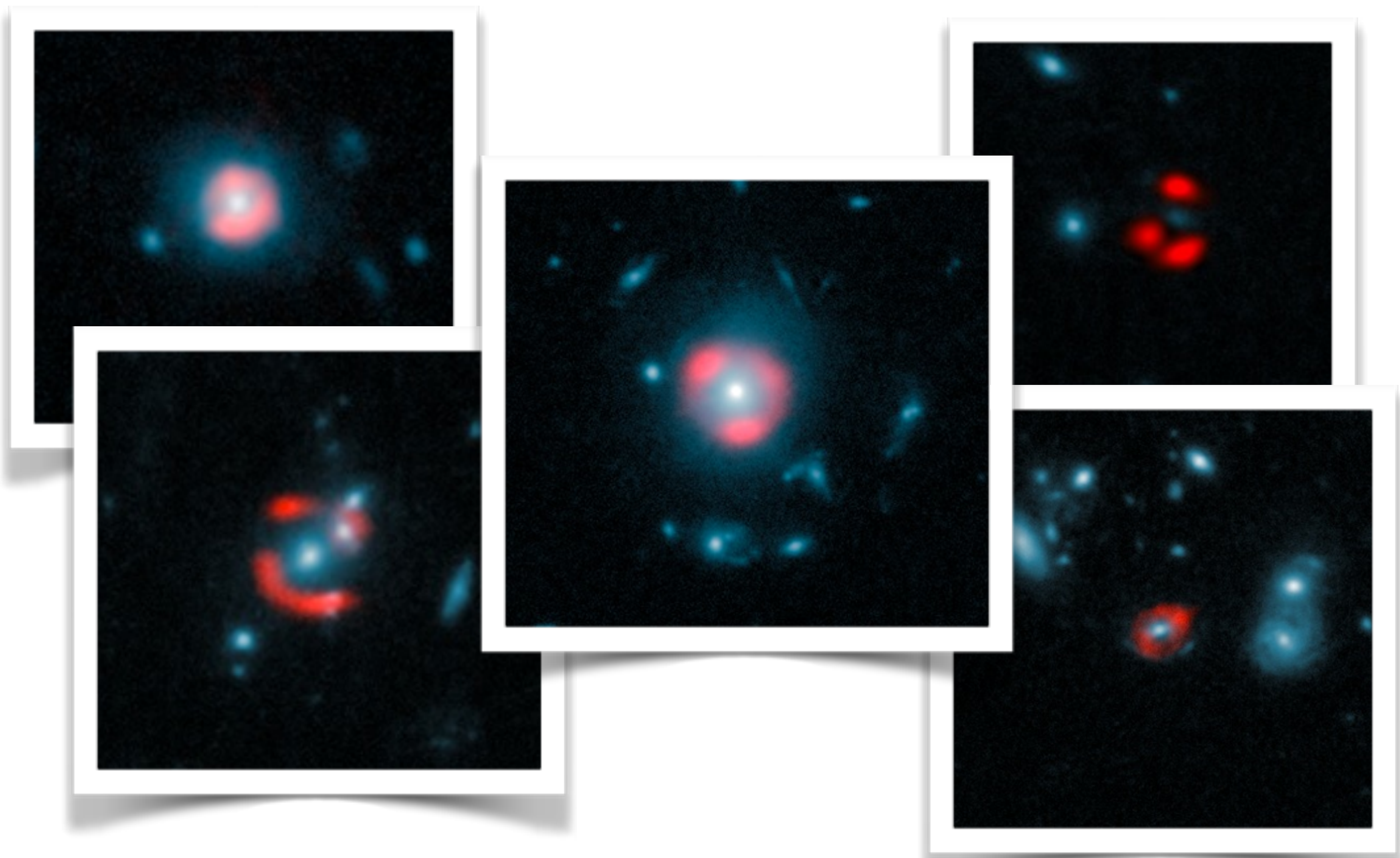
(see Julie Wardlow's talk!)

Wardlow et al. ApJ 2013

Bussmann et al. ApJ 2013

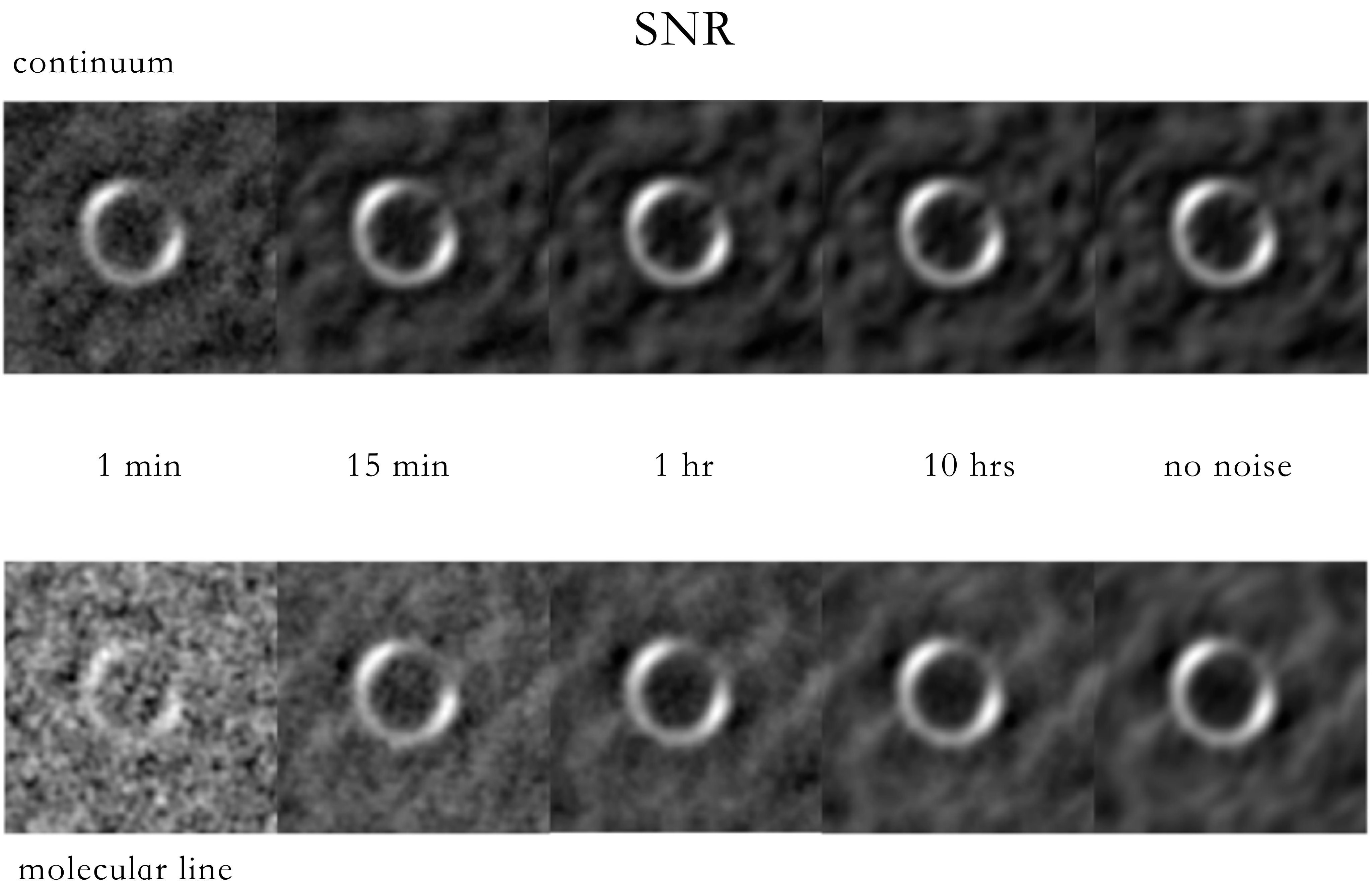
ALMA observations of SPT-discovered sources

Blue: HST (optical), Red: ALMA



Vieira et al. Nature 2013

Hezaveh et al. ApJ. 2013


SNR
continuum
1 min
15 min
1 hr
10 hrs
no noise
molecular line

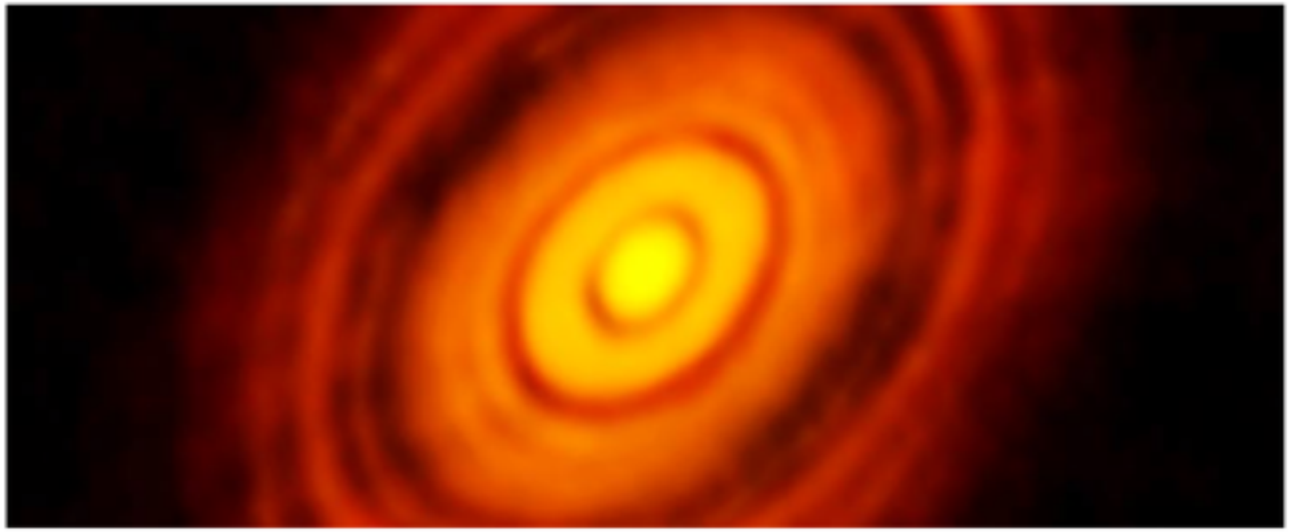
European Southern Observatory

eso1436 — Photo Release

SPACE SCOOP

Revolutionary ALMA Image Reveals Planetary Genesis

6 November 2014



This new image from ALMA, the Atacama Large Millimeter/submillimeter Array, reveals extraordinarily fine detail that has never been seen before in the planet-forming disc around a young star. These are the first observations that have used ALMA in its near-final configuration and the sharpest pictures ever made at submillimetre wavelengths. The new results are an enormous step forward in the observation of how protoplanetary discs develop and how planets form.

For ALMA's first observations in its new and most powerful mode, researchers pointed the antennas at HL Tauri — a young star, about 450 light-years away, which is surrounded by a dusty disc [1]. The resulting image exceeds all expectations and reveals unexpectedly fine detail in the disc of material left over from star birth. It shows a series of concentric bright rings, separated by gaps [2].

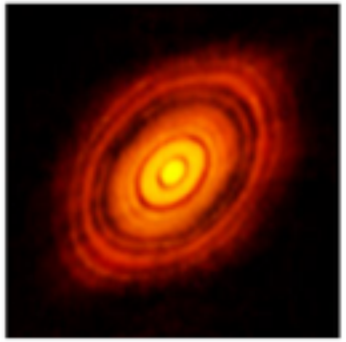
"These features are almost certainly the result of young planet-like bodies that are being formed in the disc. This is surprising since such young stars are not expected to have large planetary bodies capable of producing the structures we see in this image," said Stuartt Corder, ALMA Deputy Director.

Search Press Releases...

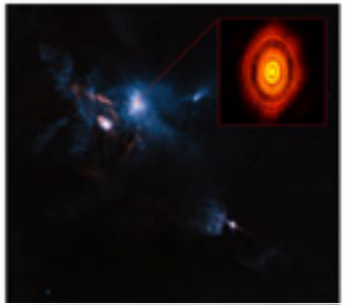
About the Release

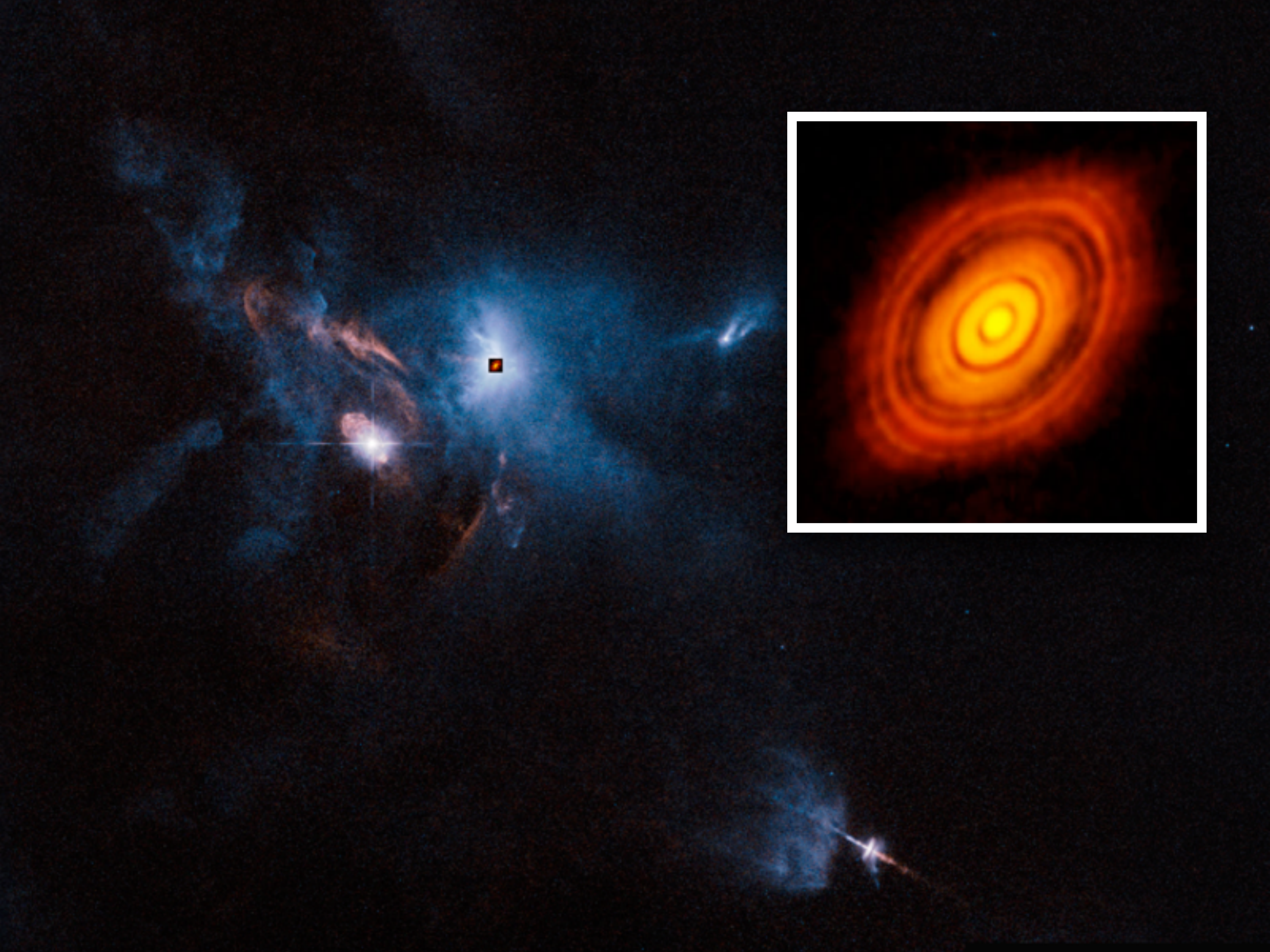
Release No.:	eso1436
Name:	HL Tauri
Type:	• Milky Way : Star : Circumstellar Material : Disk : Protoplanetary
Facility:	Atacama Large Millimeter/submillimeter Array

Images

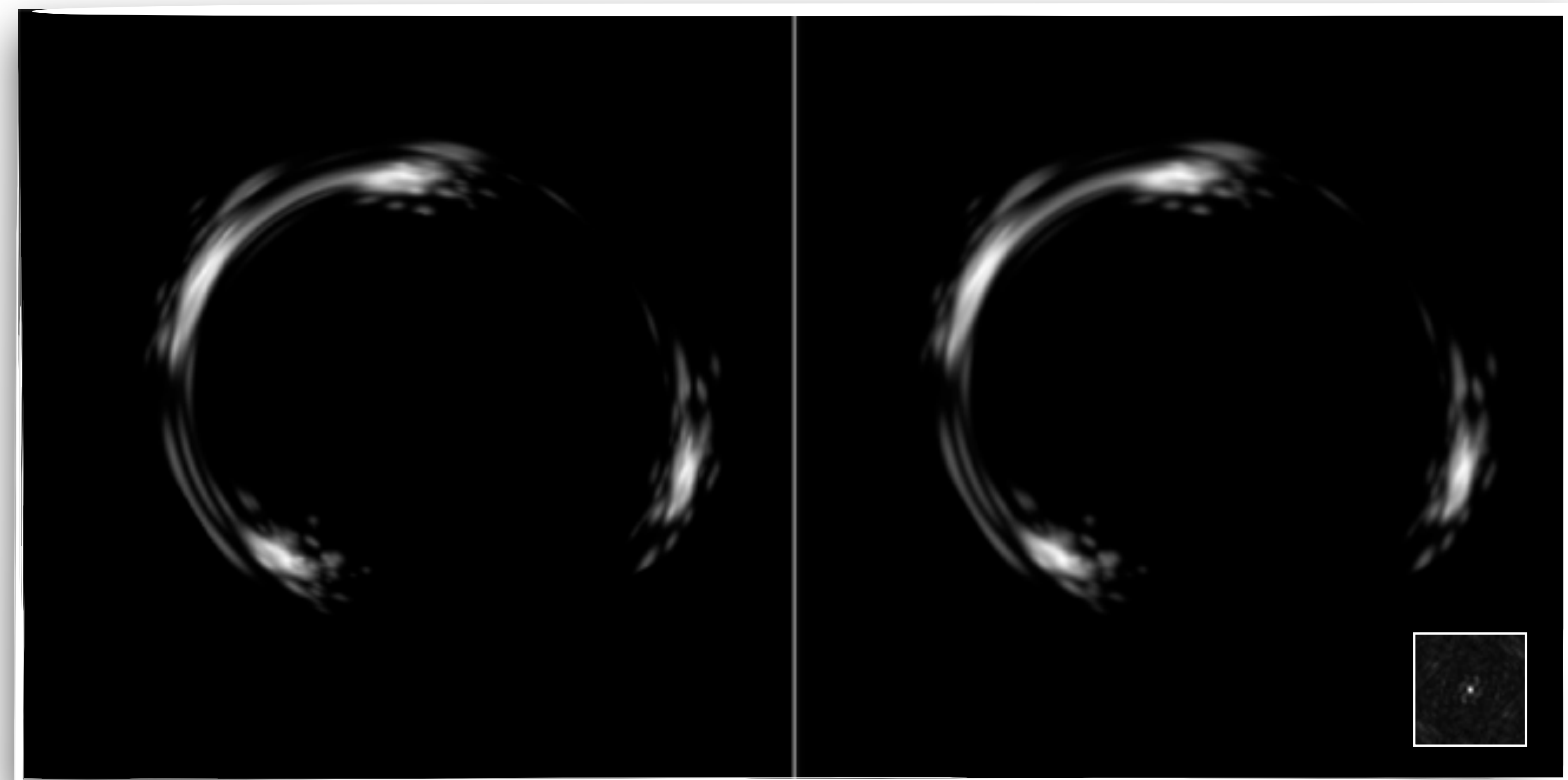


PR Image eso1436a
ALMA image of the protoplanetary disc around HL Tauri

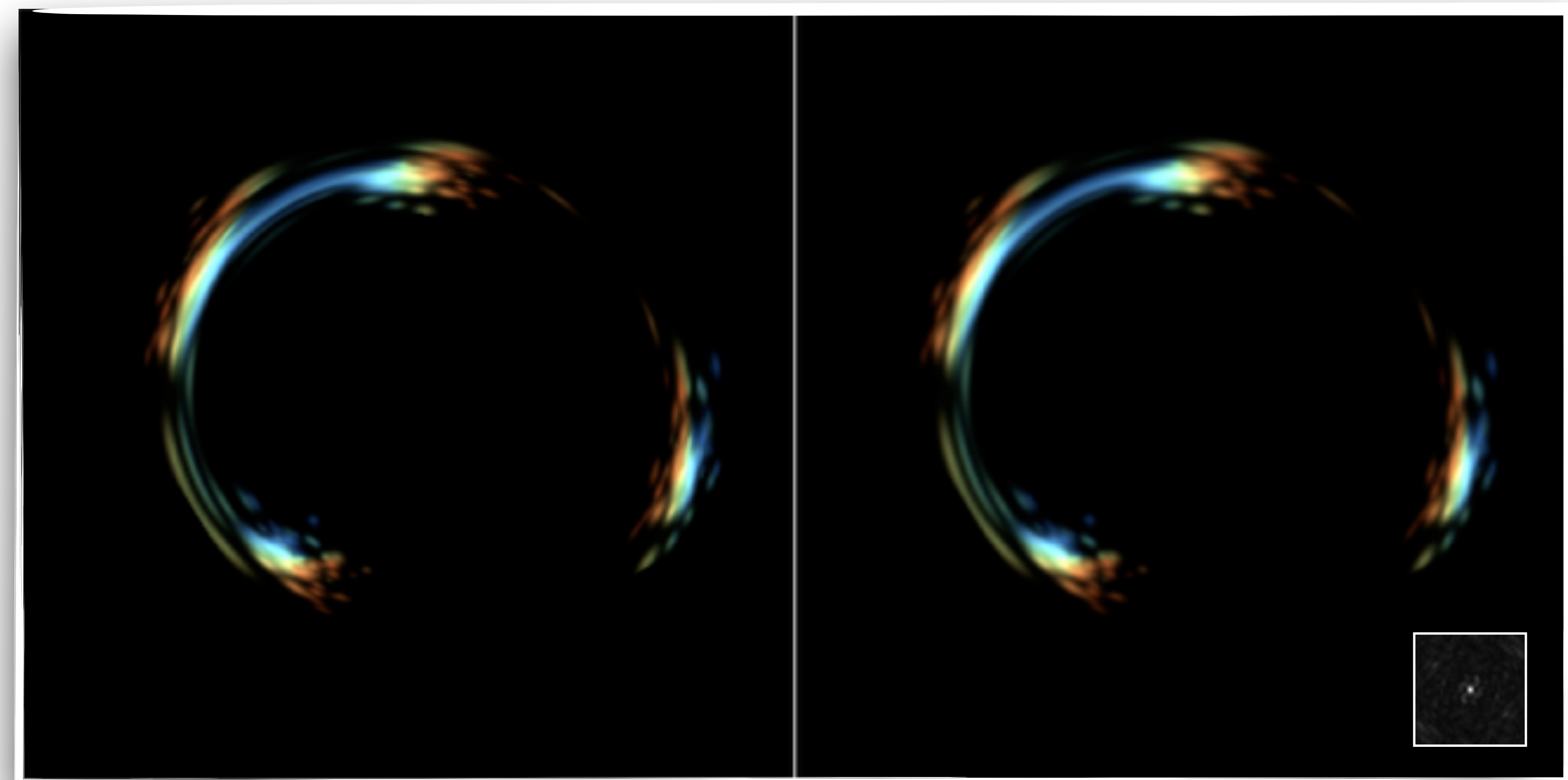




Strong Lenses with ALMA in Extended config.

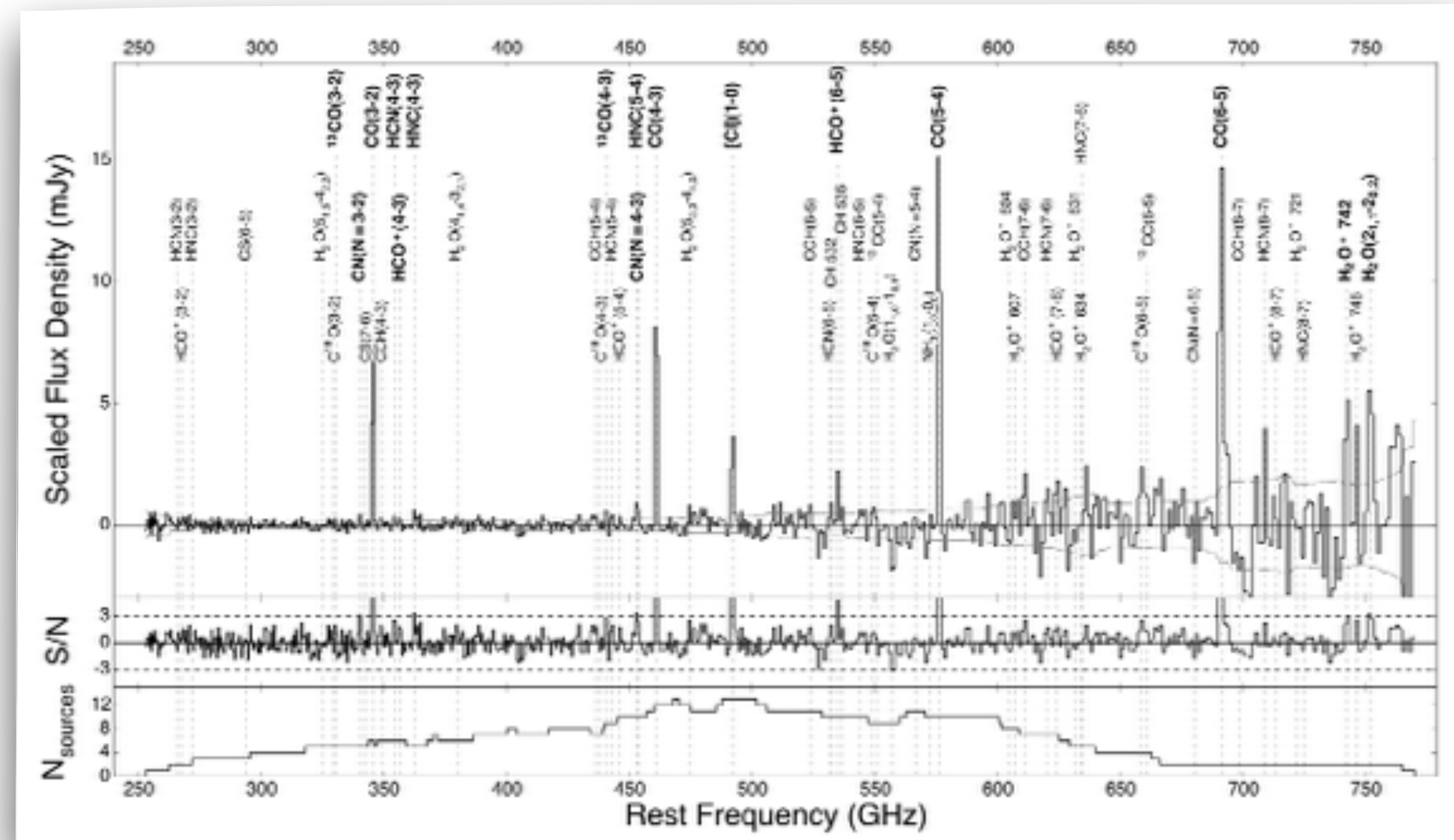


Strong Lenses with ALMA in Extended config.



THE FUTURE IS HERE

A Wealth of Molecular Lines

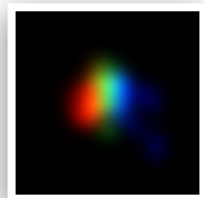


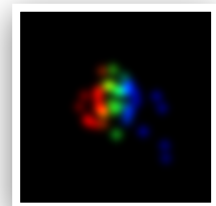
Spilker

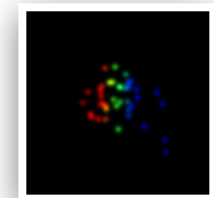
A Wealth of Molecular Lines

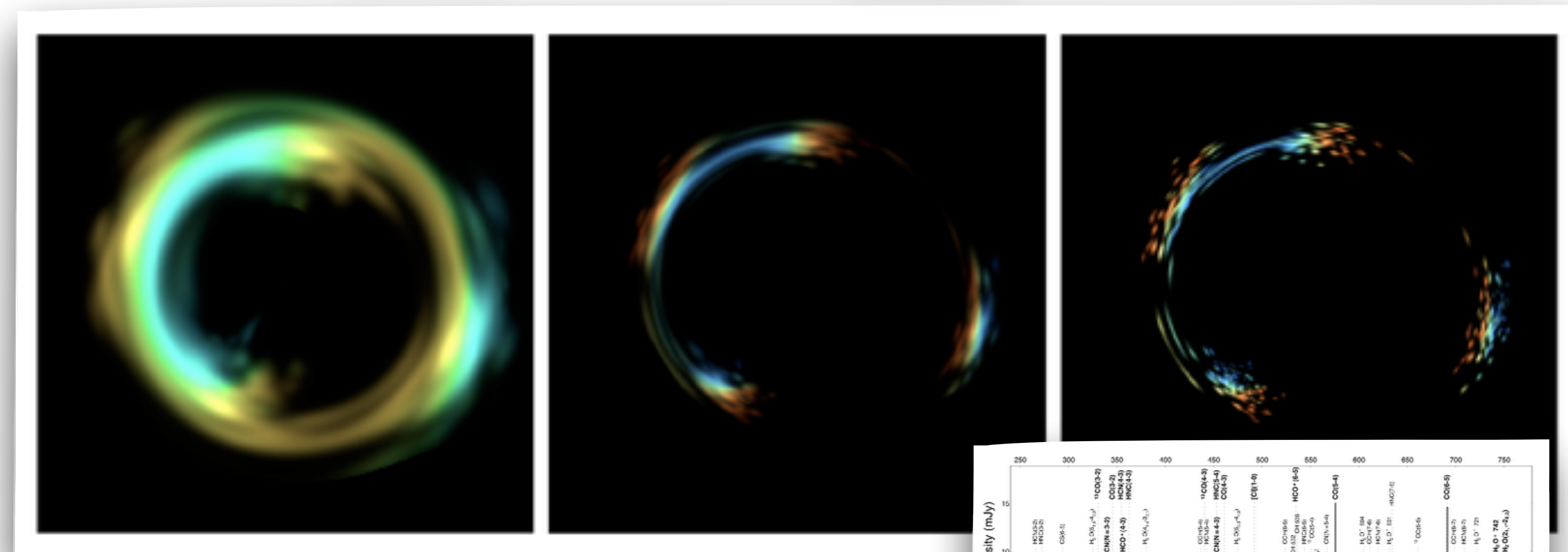
LOW EXCITATION GAS

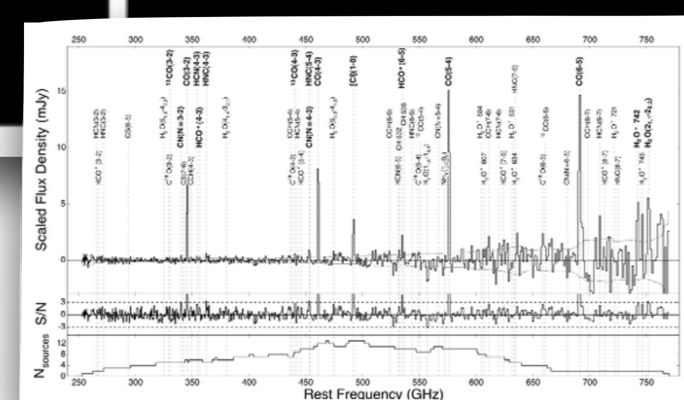
HIGH EXCITATION GAS



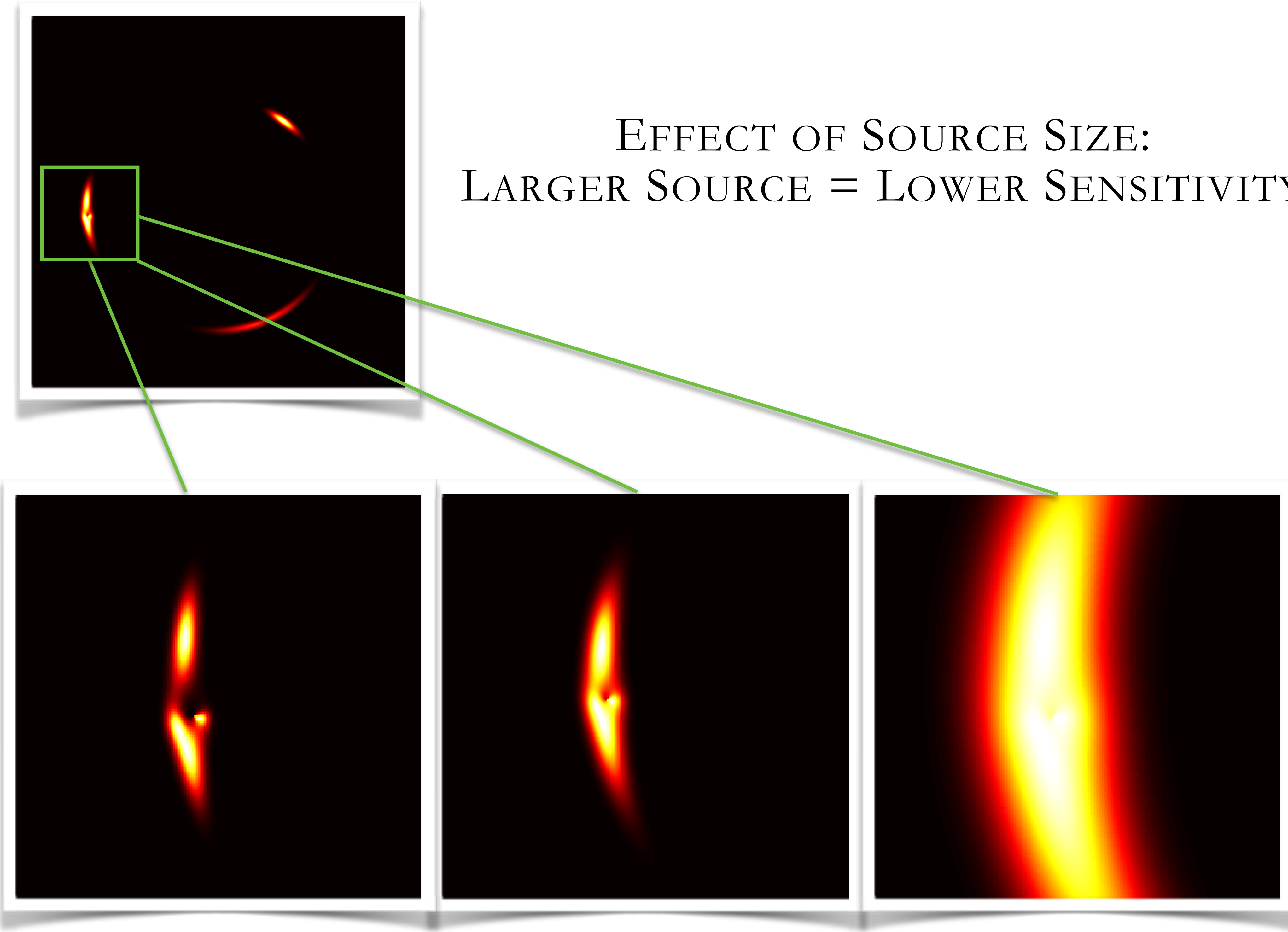




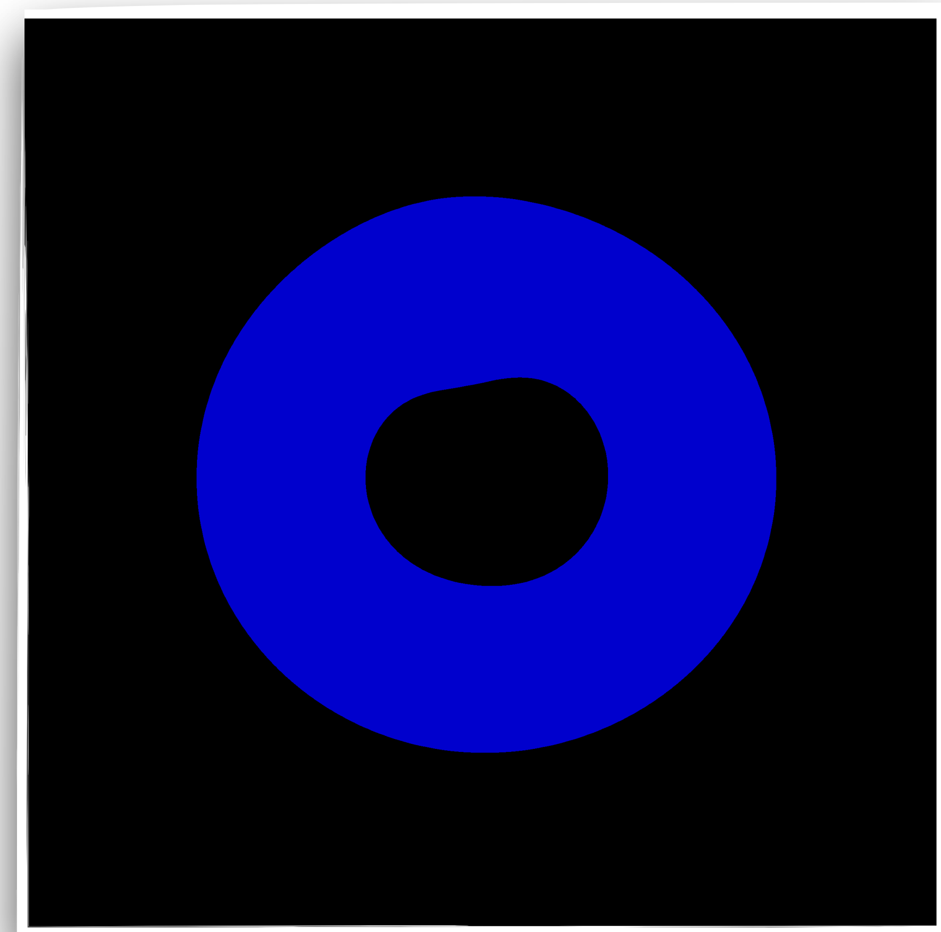




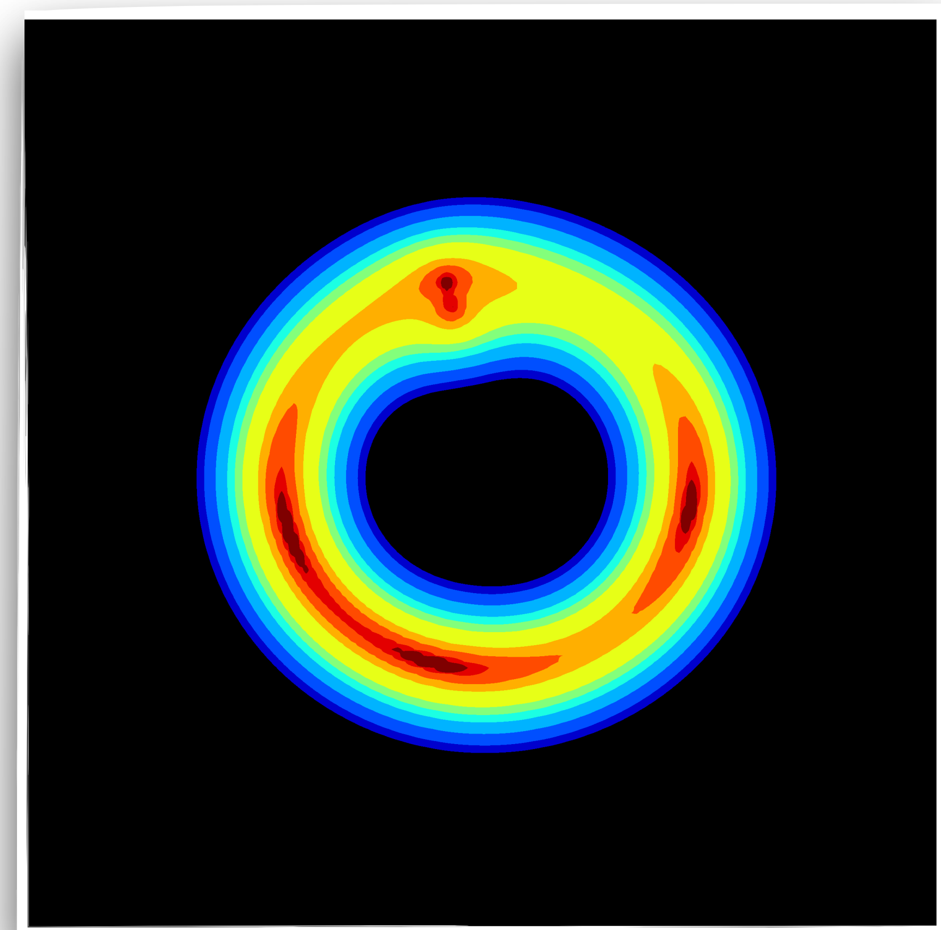
Effect of Source Size: Larger Source = Lower Sensitivity



SMGs are extended
How can we improve sensitivity?

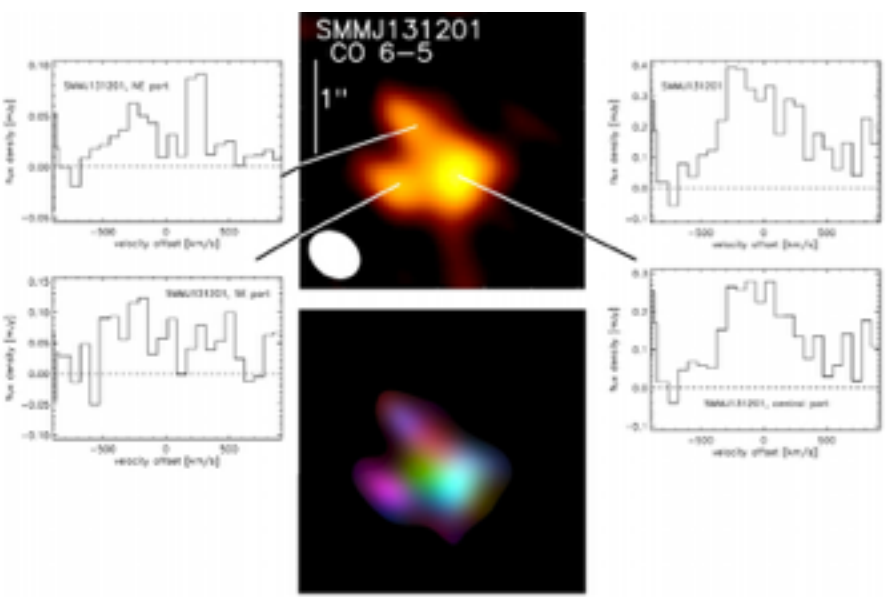


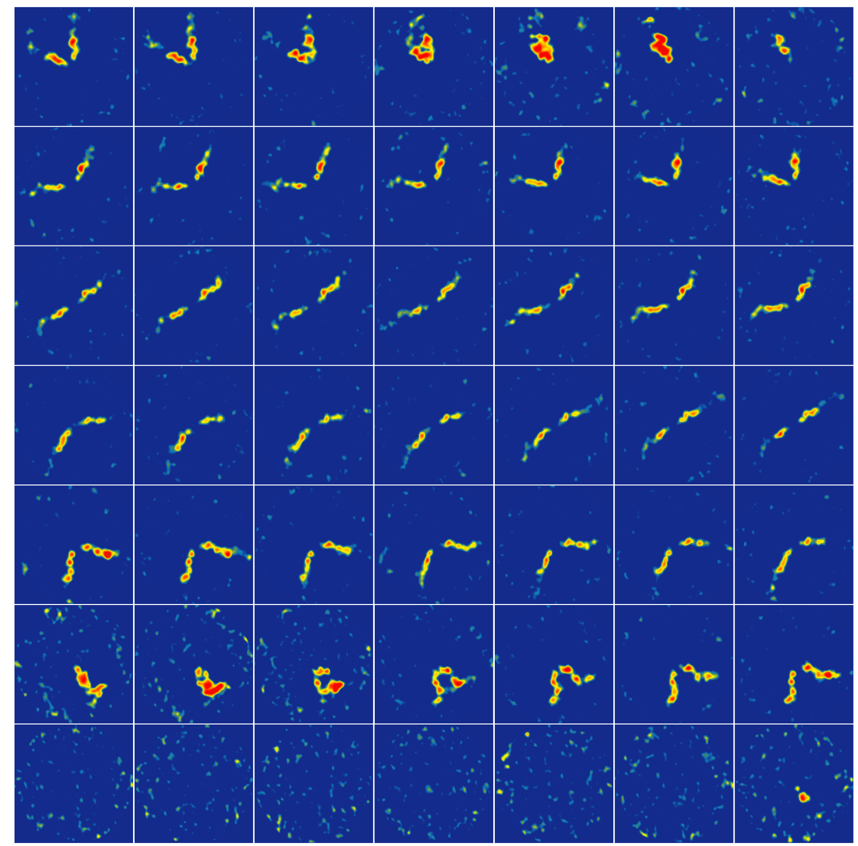
SMGs are extended
How can we improve sensitivity?



We need a small source, or a source with small features...

Velocity Structure

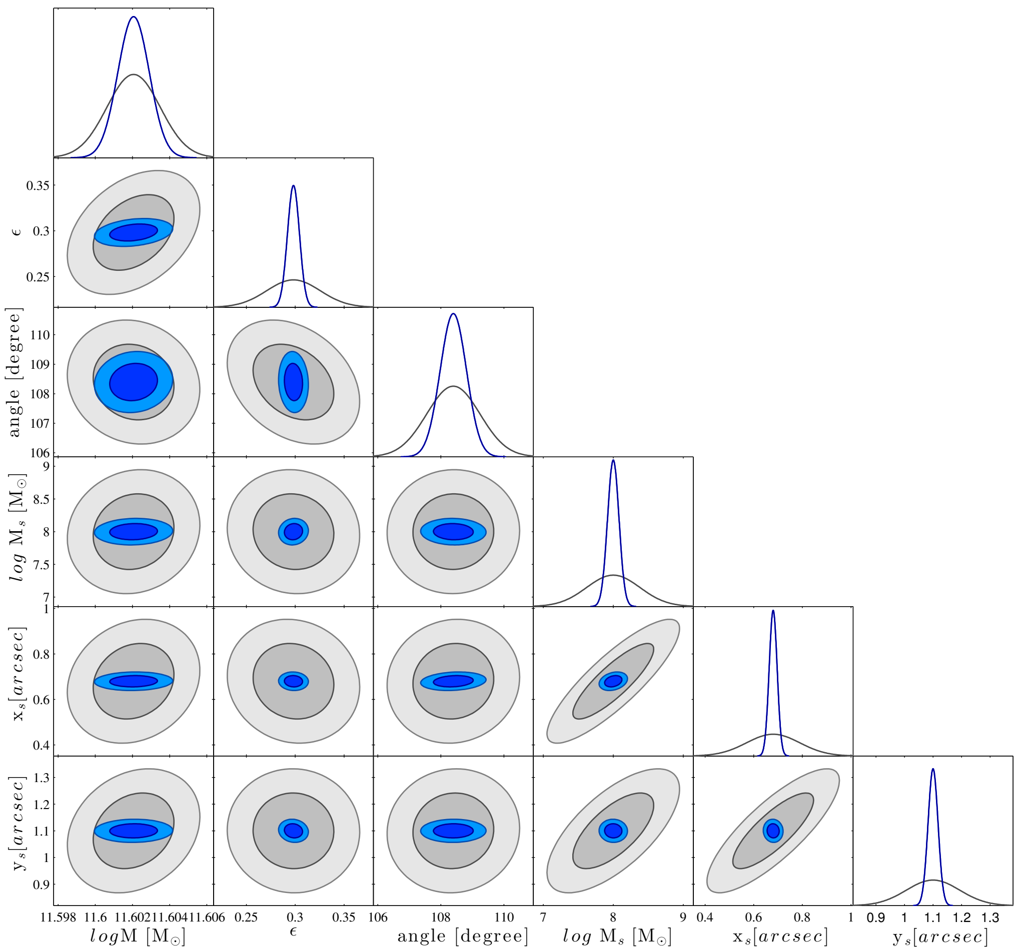




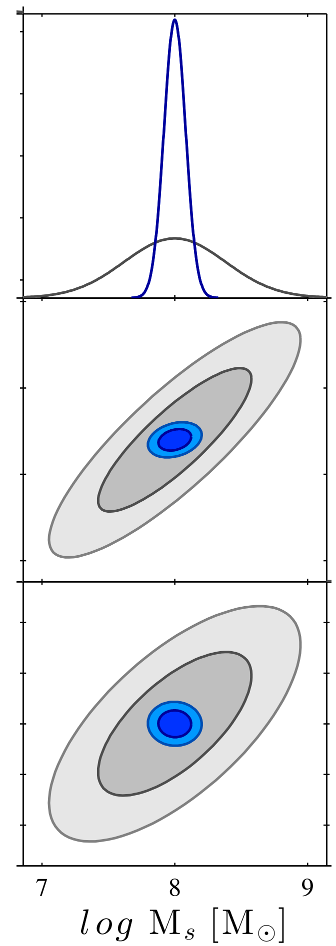
Engel

C

Sensitivity Analysis of Detecting DM Subhalos

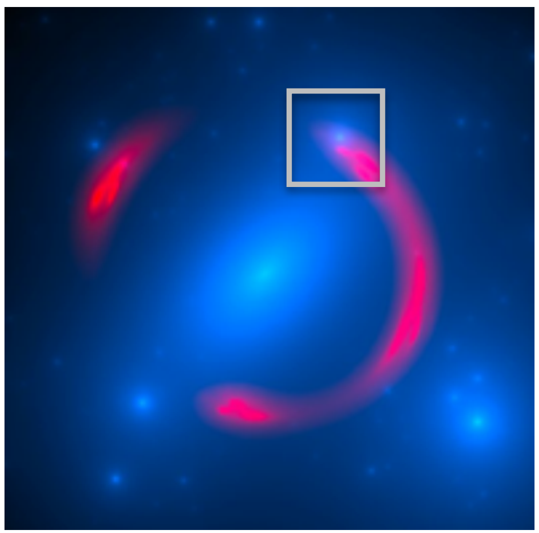


After marginalizing over ~60 source parameters



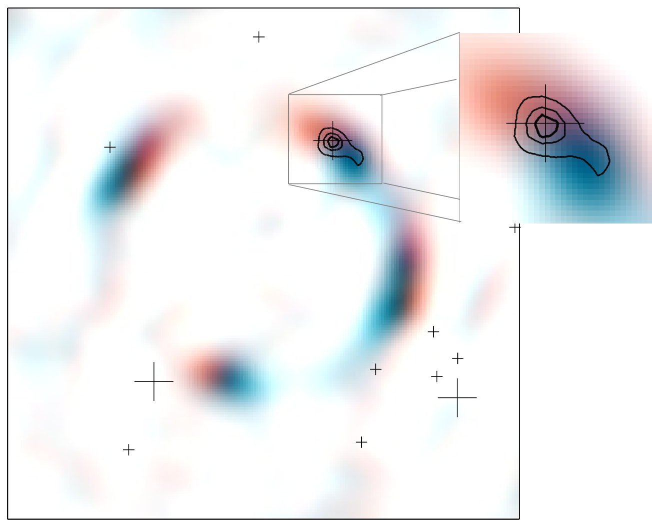
Hezaveh

Simulations indicate that with ALMA, we can Detect DM subhalos in these systems

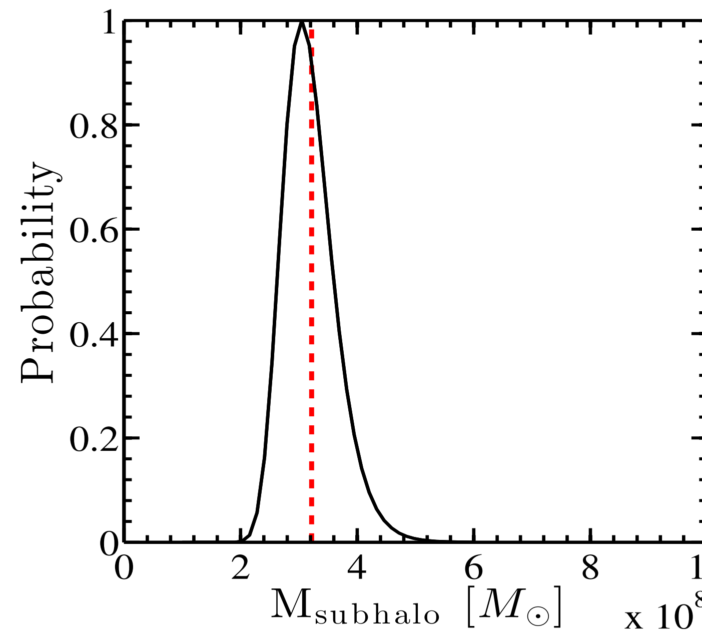


Nbody + ray tracing simulation

Detected subhalo



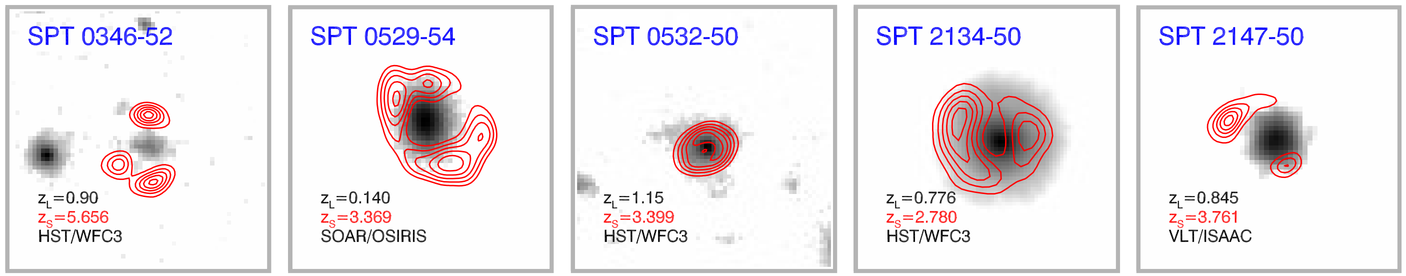
Mock ALMA observation



Recovered subhalo mass

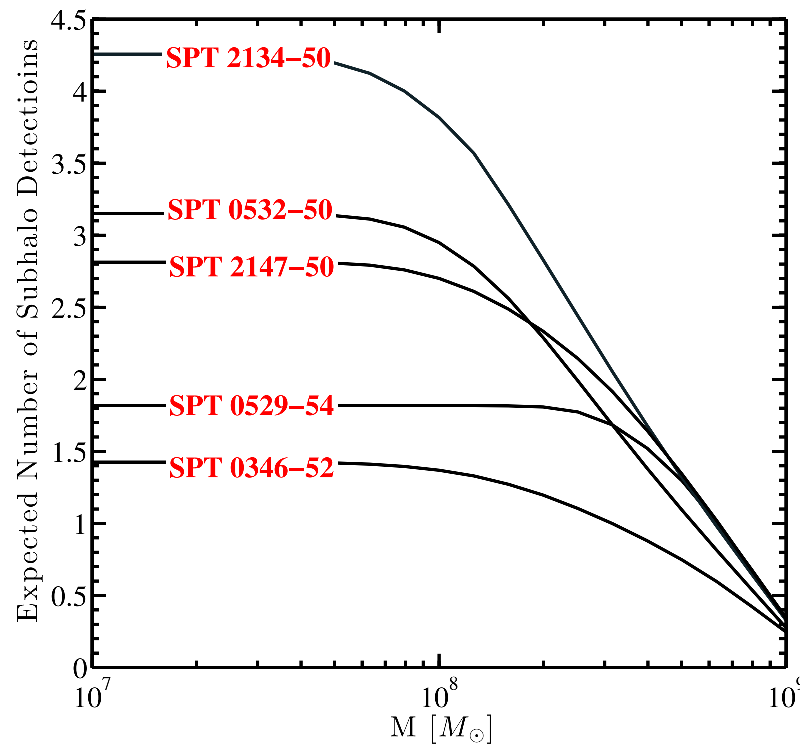
Evil team now lead by W. Morningstar and P. Marshall

SPT-DMS



ALMA Cycle II Plan

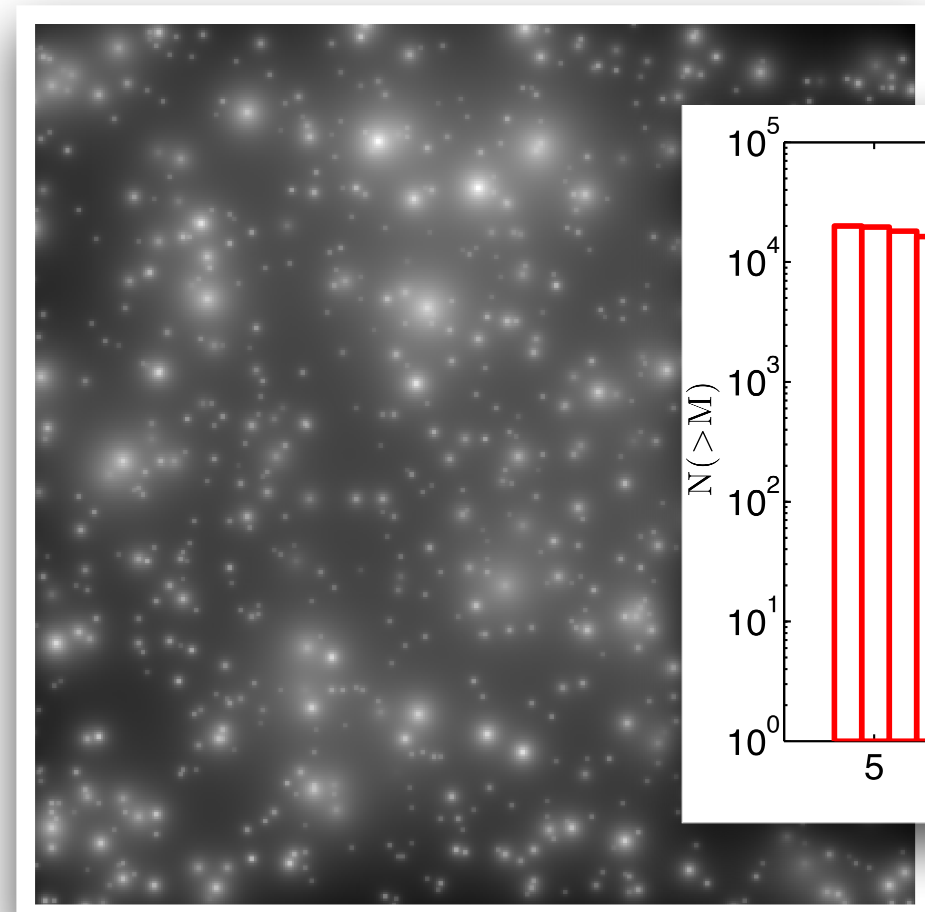
CO 7-6 molecular lines
5 Targets
Predictions for:
One hour observation
Cycle 2:
 32 antennas
 max baselines ~ 1.5 km

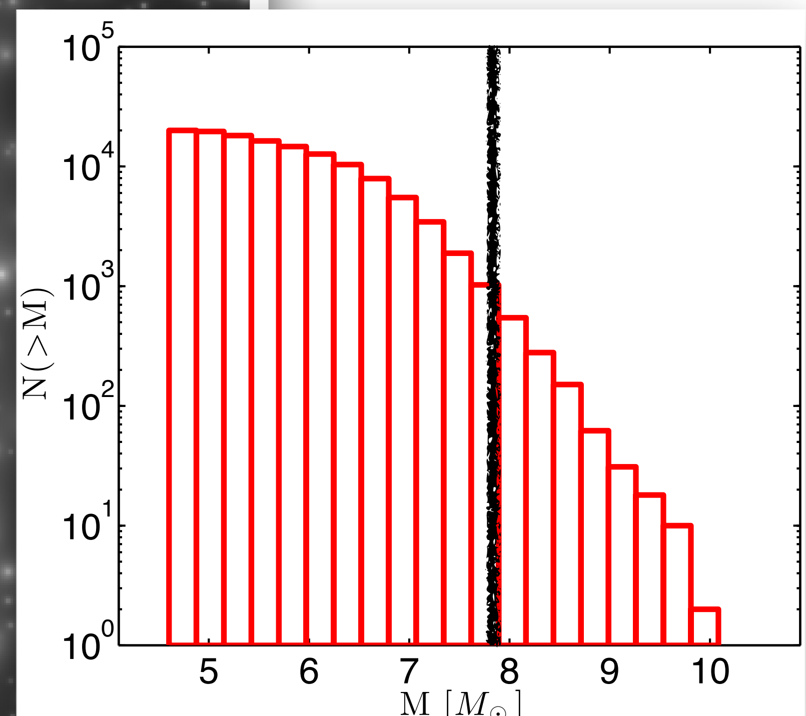


Full
 max

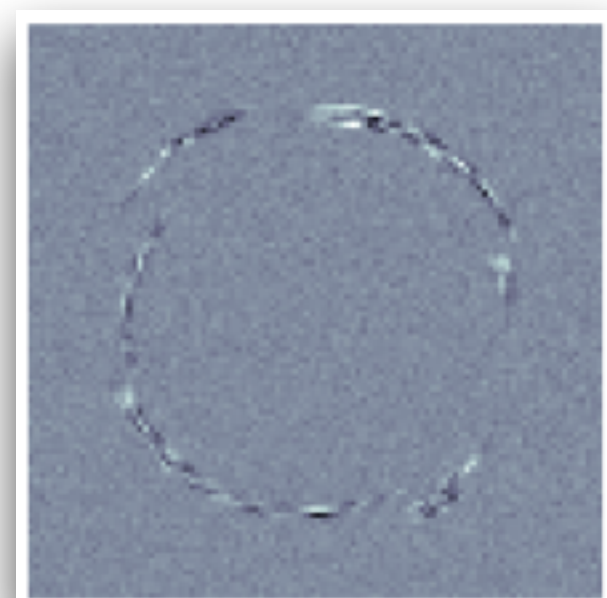
We can detect and model massive subhalos

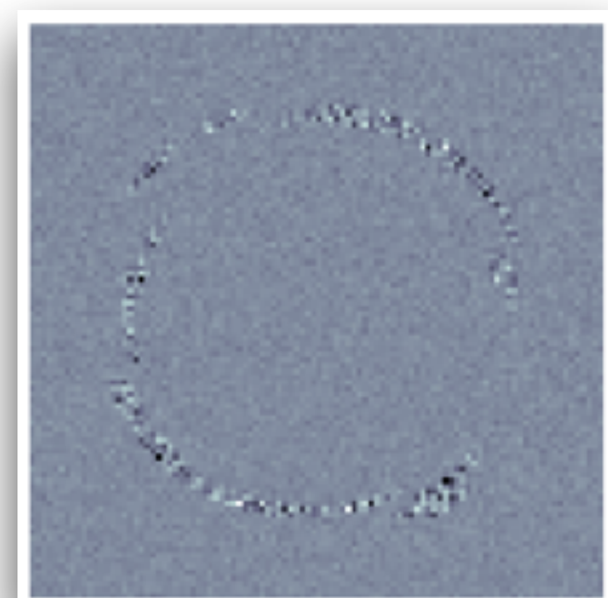
What about the thousands of lower mass ones?
Can we detect them as a whole?



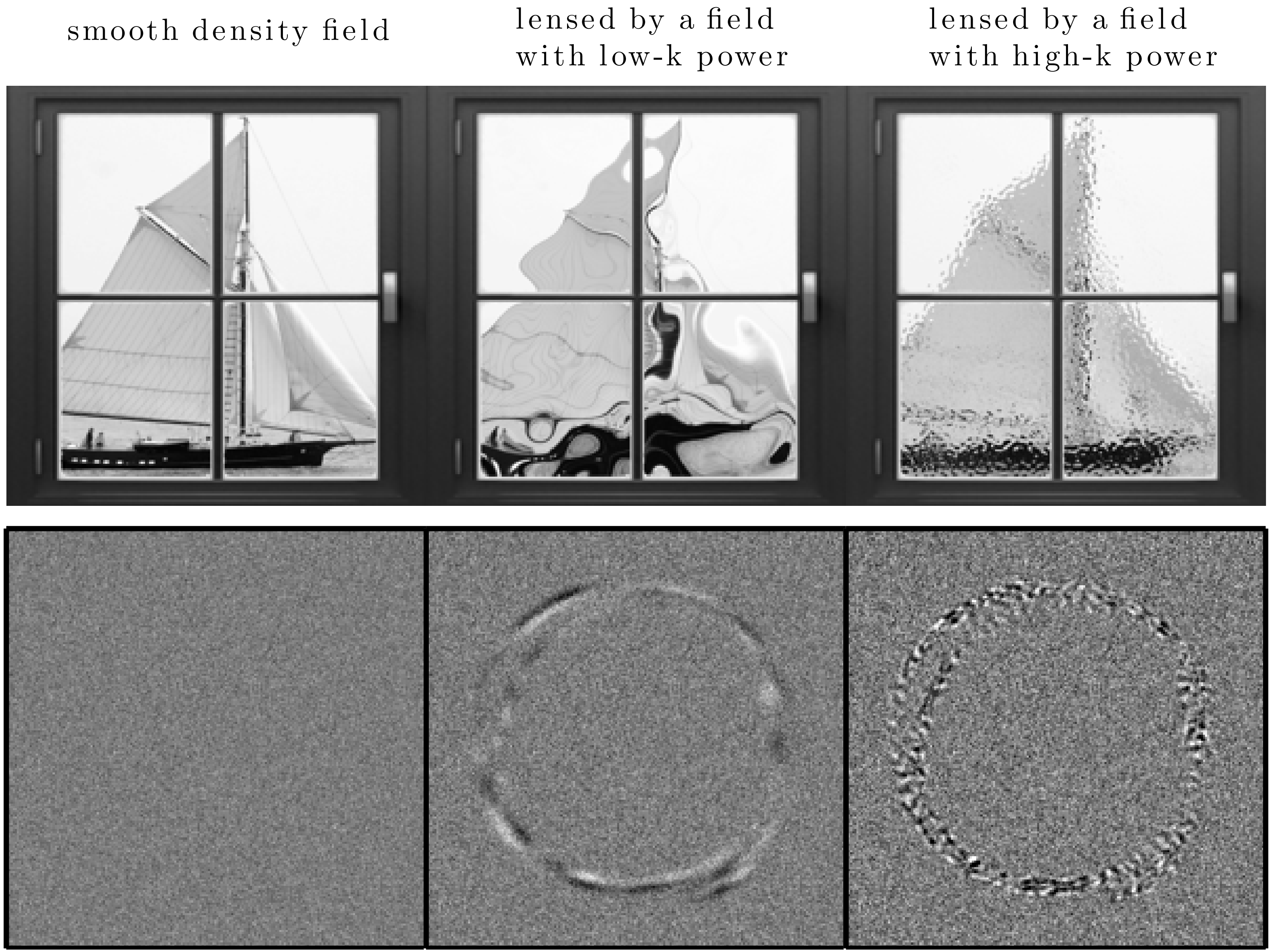


Residuals from Modeling with a Smooth Lens:





Residuals from Modeling with a Smooth Lens:

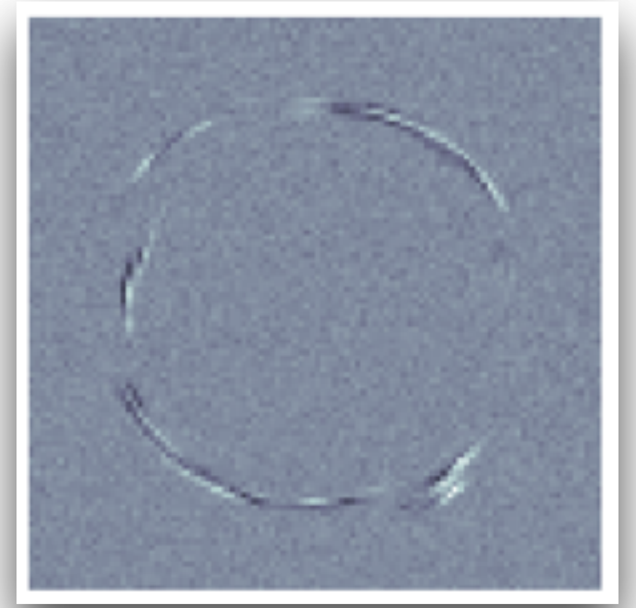
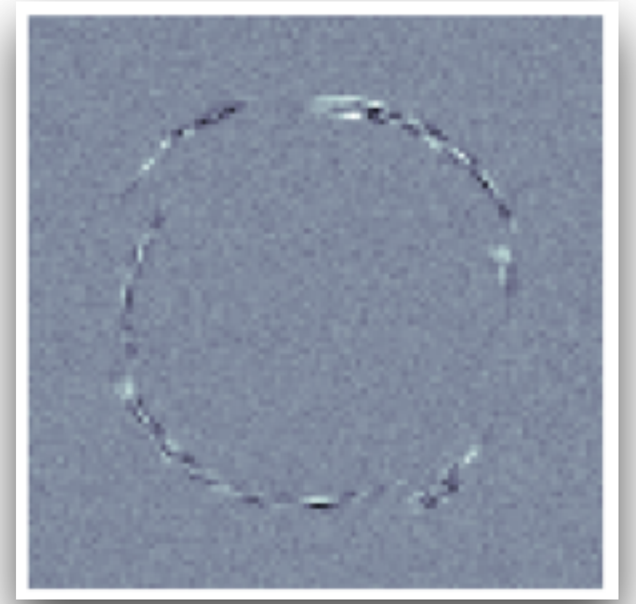
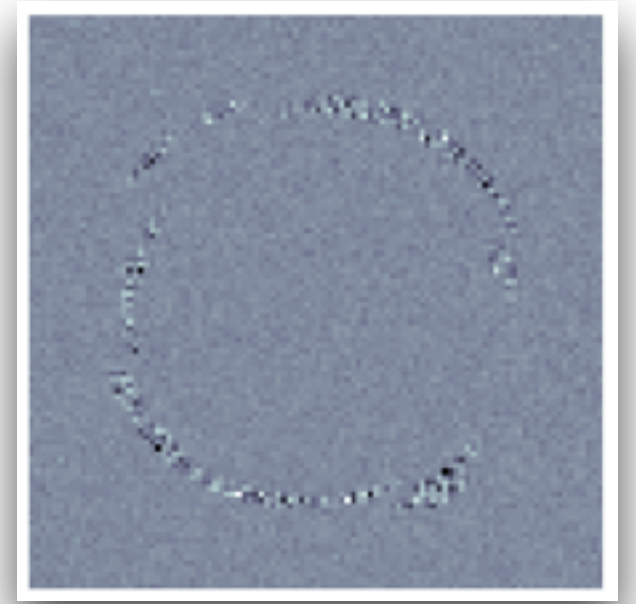


COVARIANCE OF DEFLECTIONS

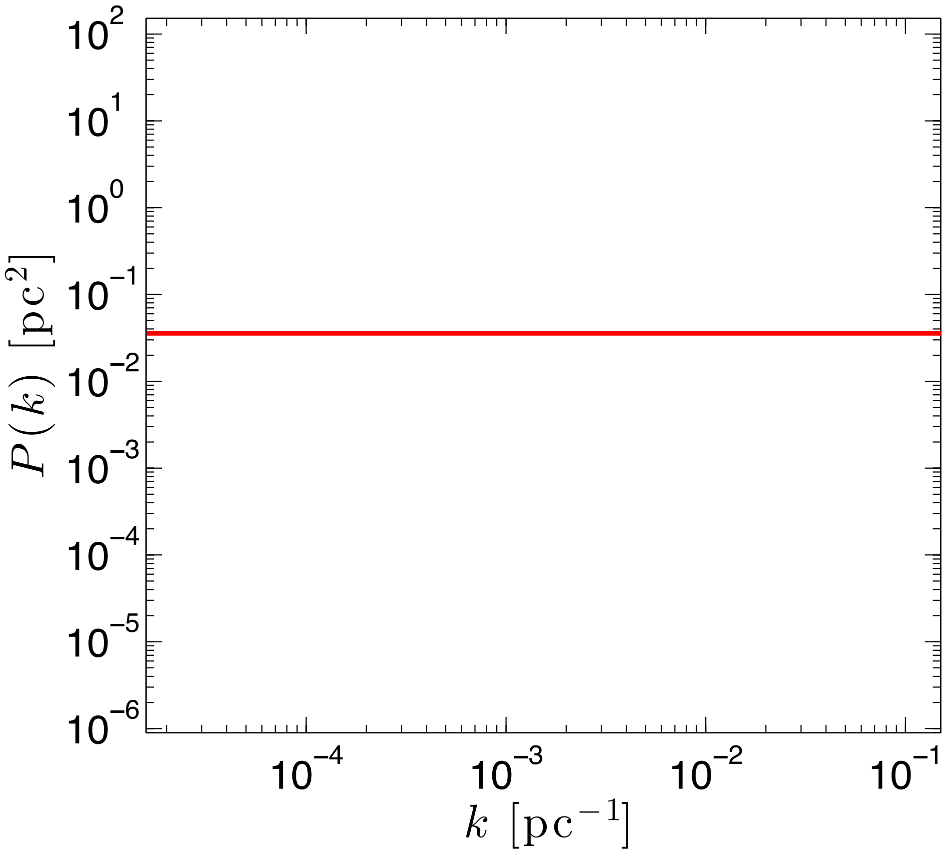
DENSITY POWER SPECTRUM

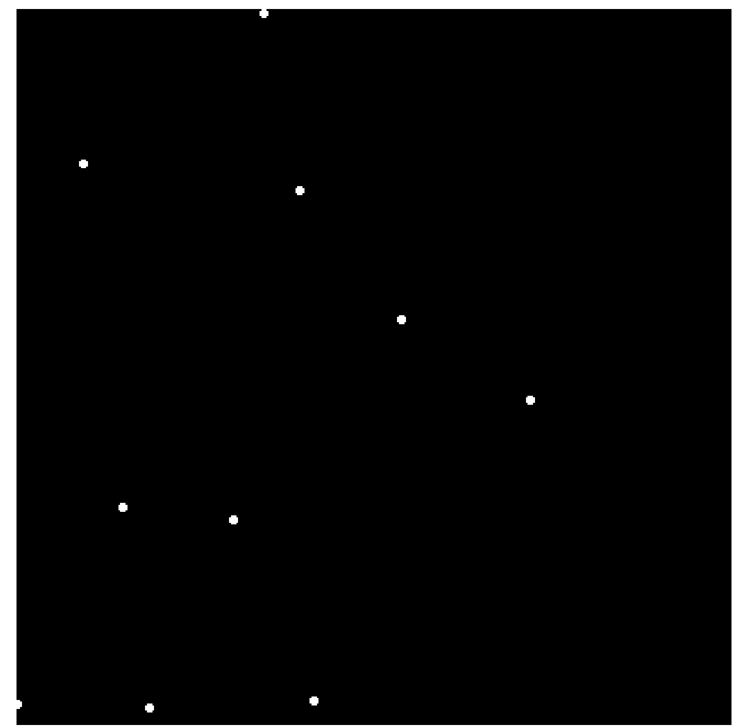
$$\mathbf{C}_\alpha = \langle \alpha_i(\vec{x})\, \alpha_j(\vec{x}+\vec{r})\rangle = 4\int P(k)\left(\frac{\delta_{ij}}{k^2 r} J_1(kr) - \frac{r_i r_j}{k r^2} J_2(kr)\right) dk$$

$$\mathcal{L}(C_\alpha) = (|C_N|\,|C_\alpha|\,|C_p||M|)^{-1/2} e^{\frac{1}{2}B^T M B} \quad e^{-\frac{1}{2}(\Delta \boldsymbol{O}^T C_N^{-1} \Delta \boldsymbol{O} + \mathbf{p}_0 C_p^{-1} \mathbf{p}_0)}$$

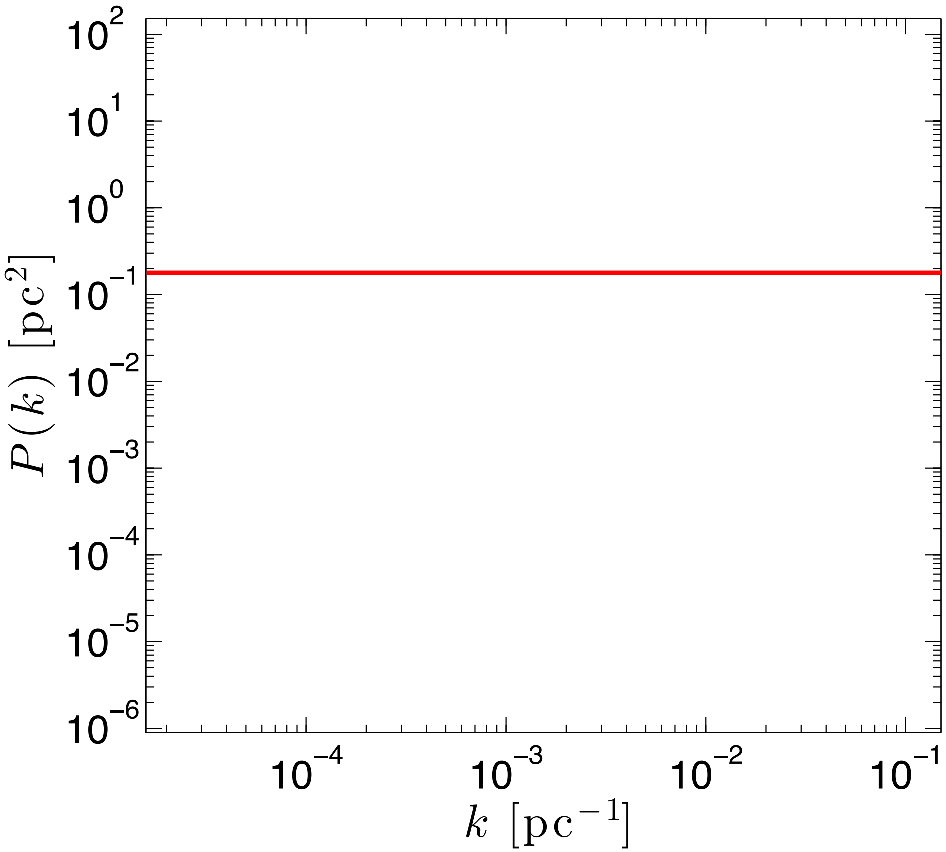




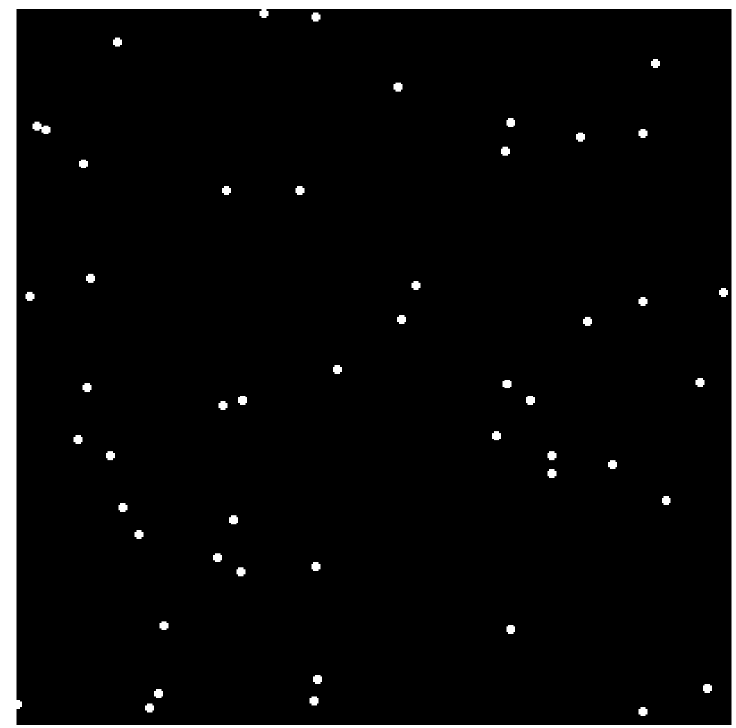
DM subhalo density Power Spectrum



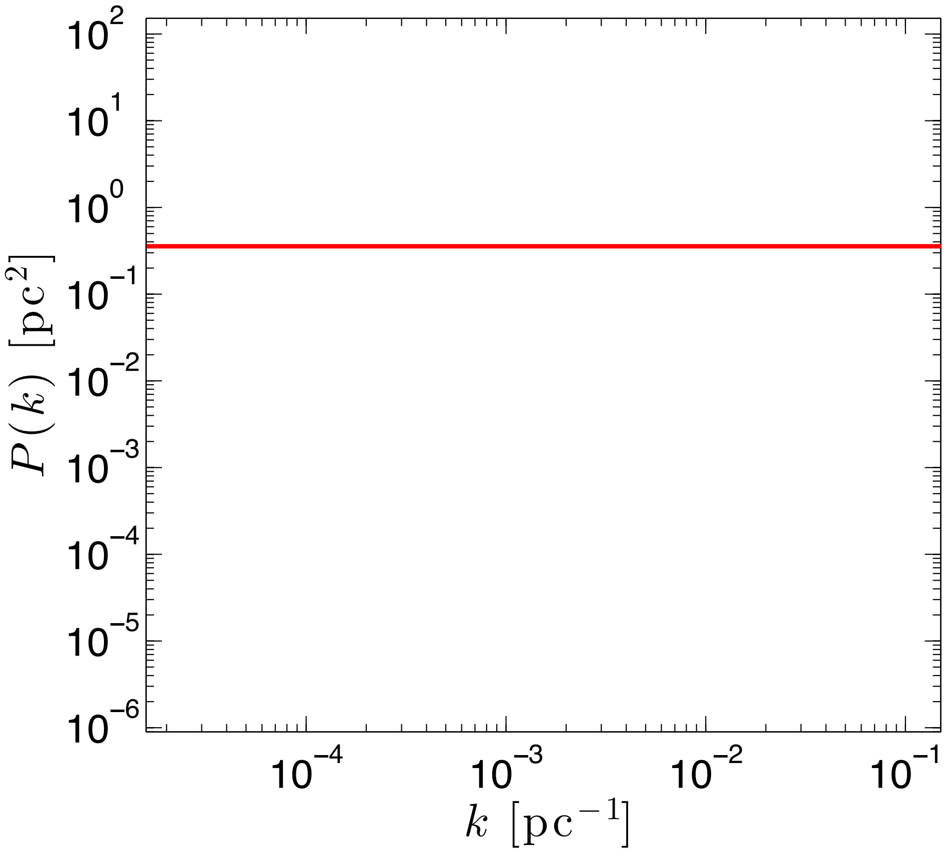


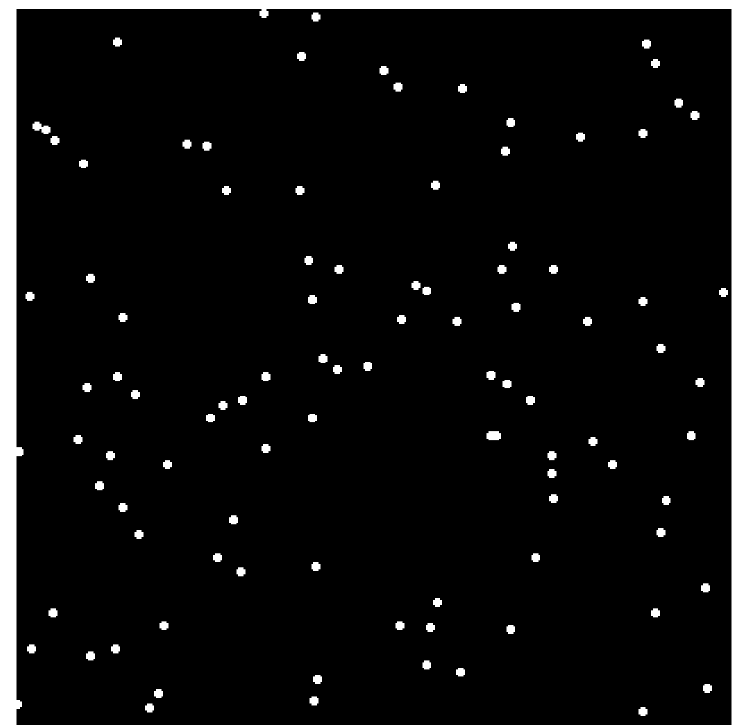
DM subhalo density Power Spectrum



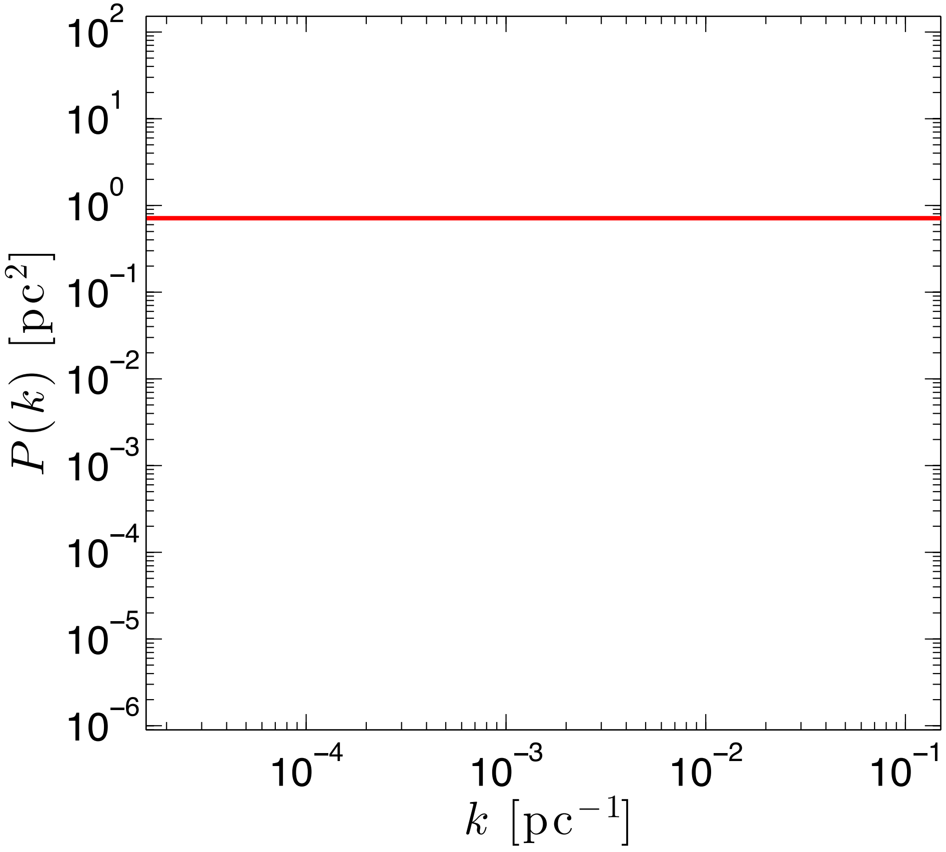


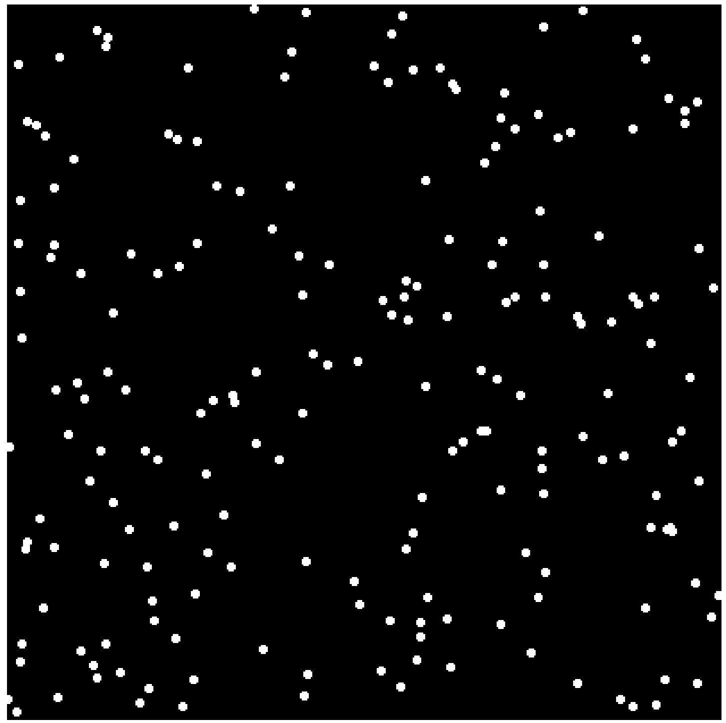
DM subhalo density Power Spectrum



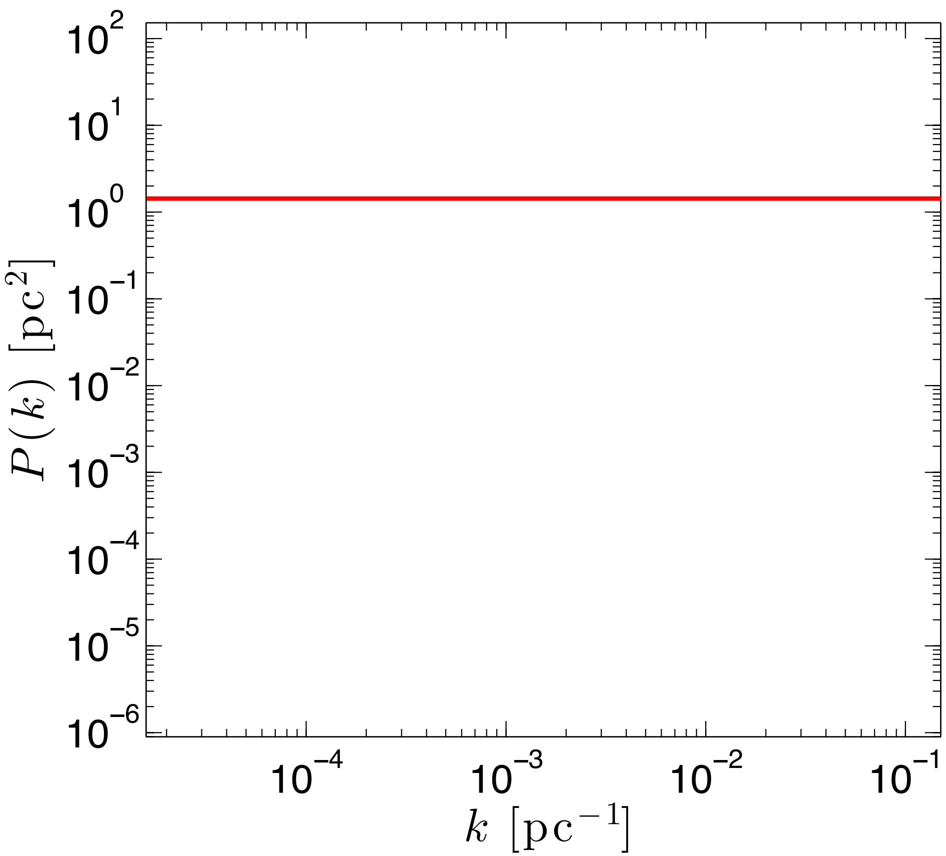


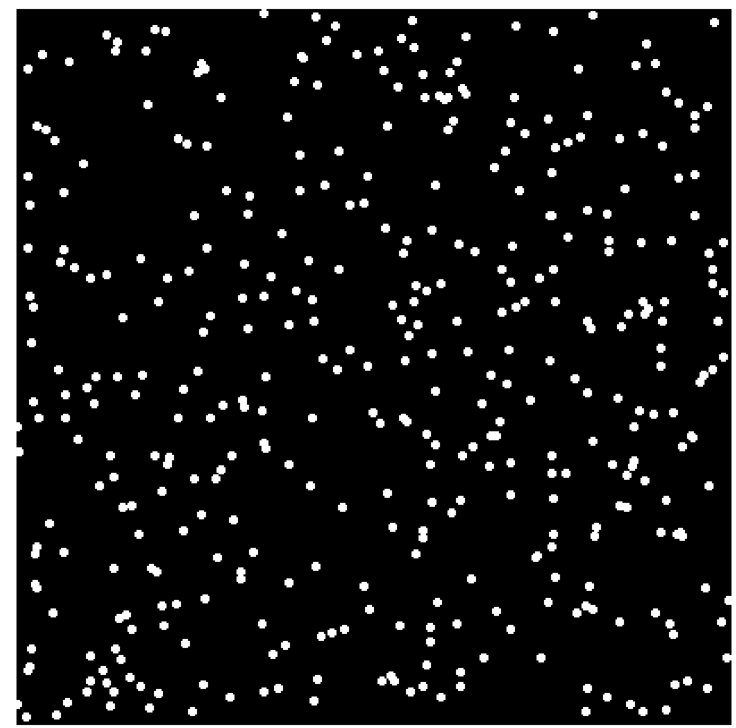
DM subhalo density Power Spectrum



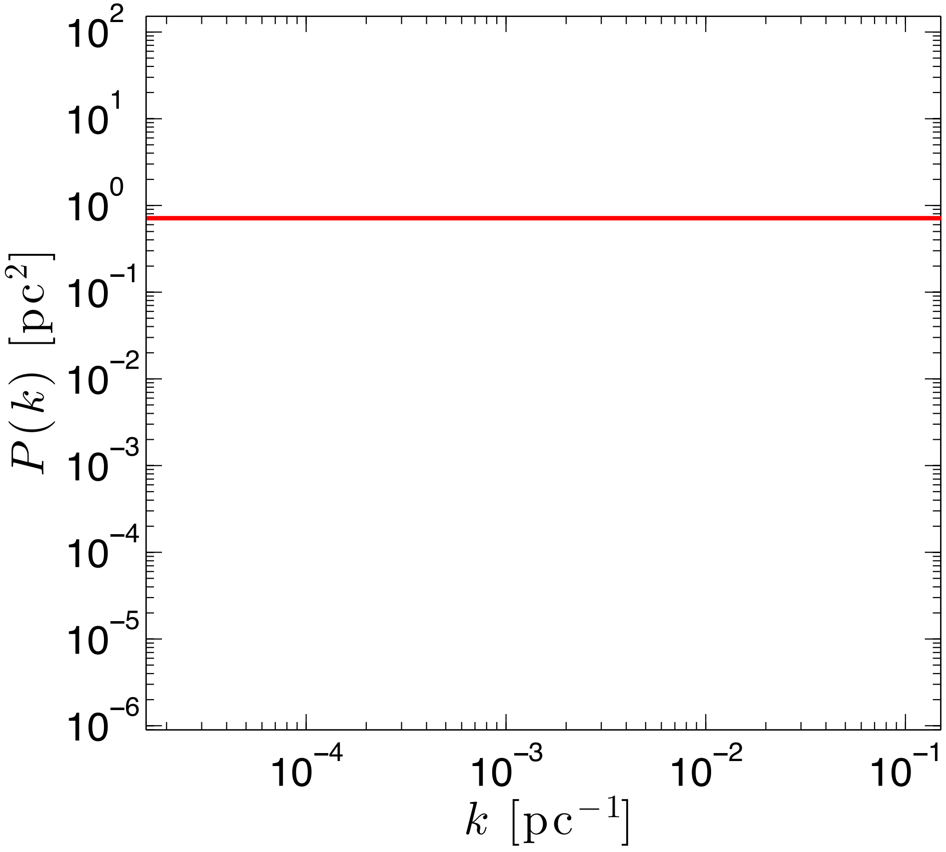


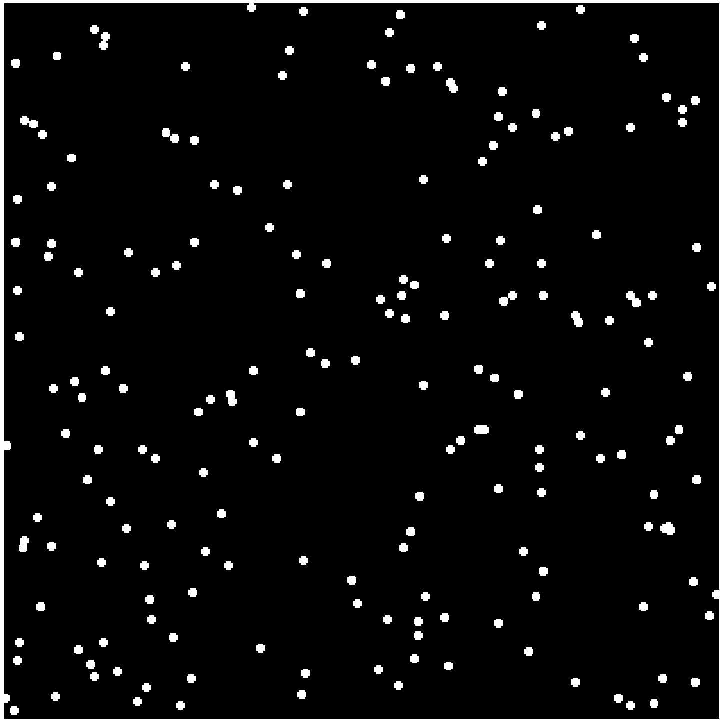
DM subhalo density Power Spectrum



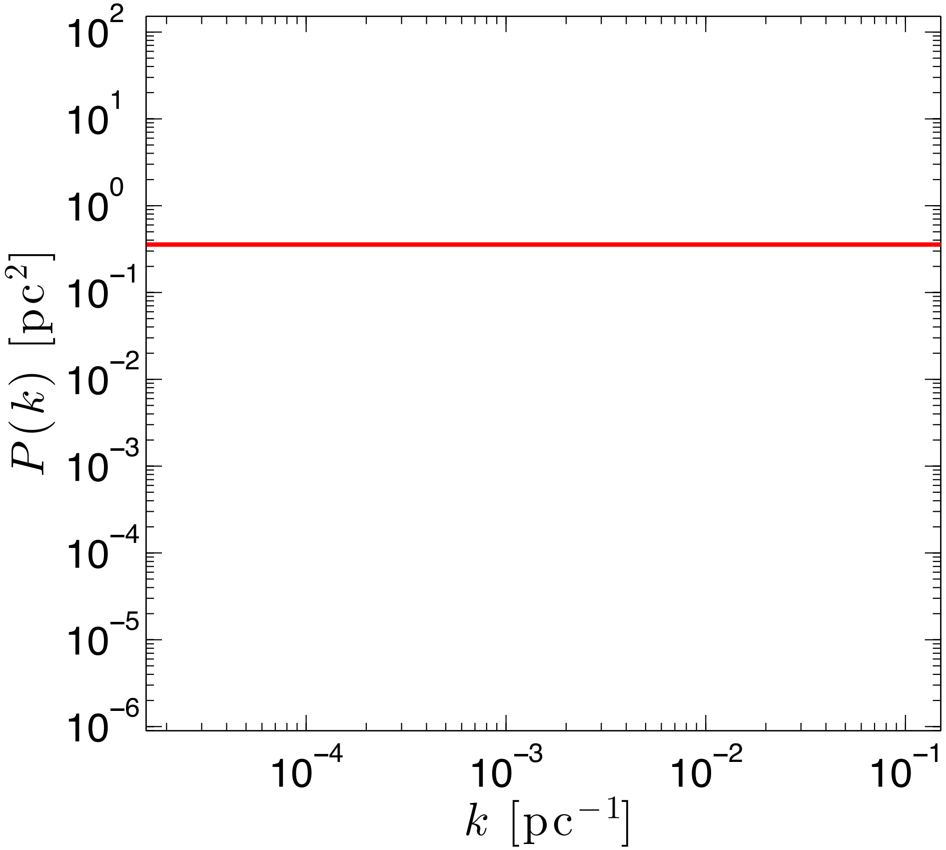


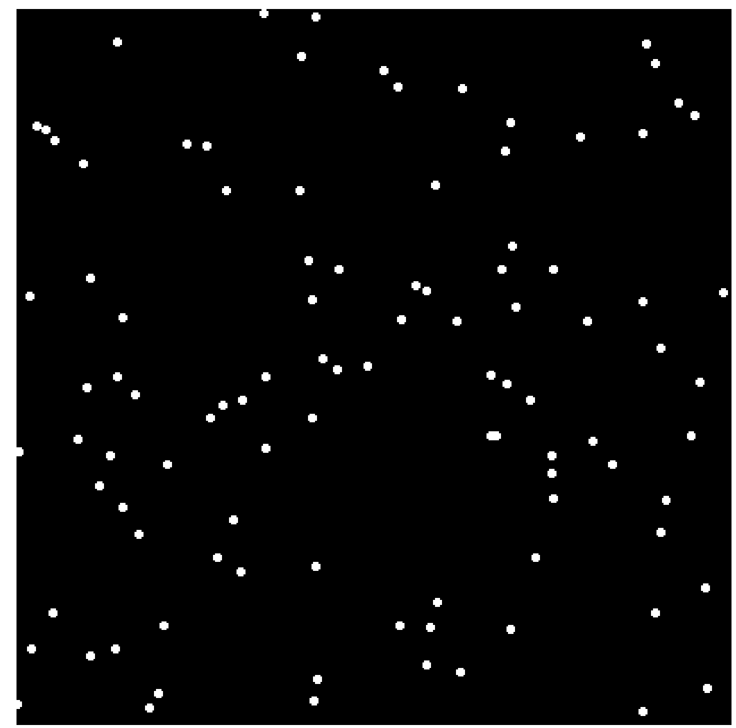
DM subhalo density Power Spectrum



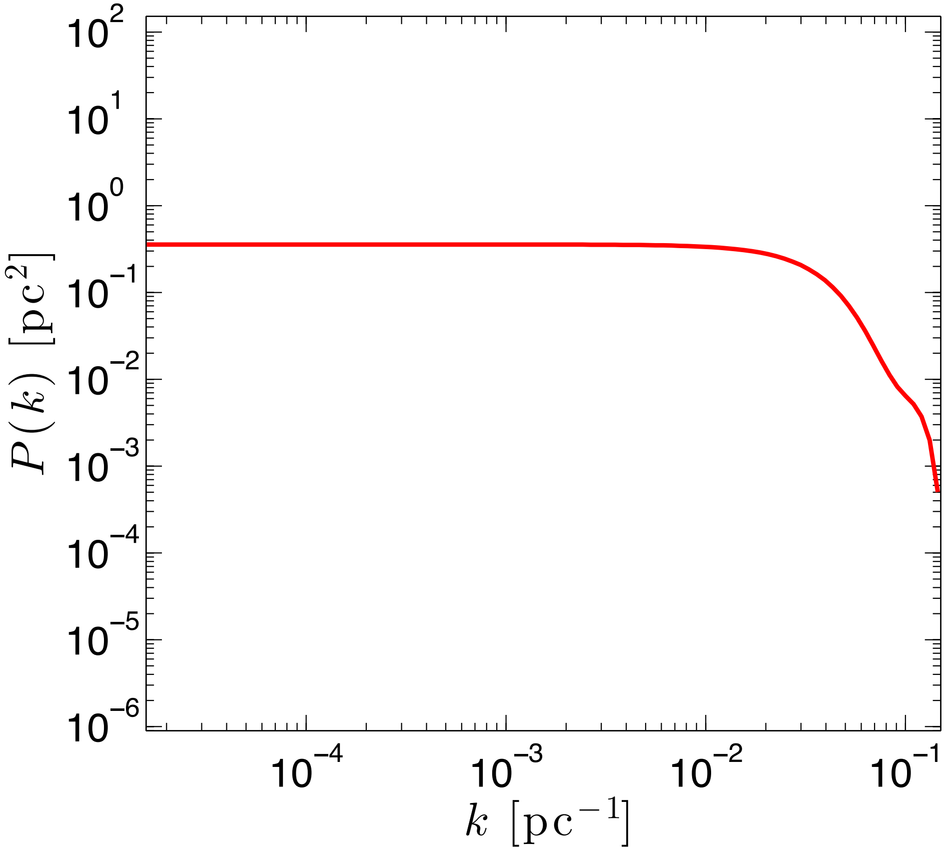


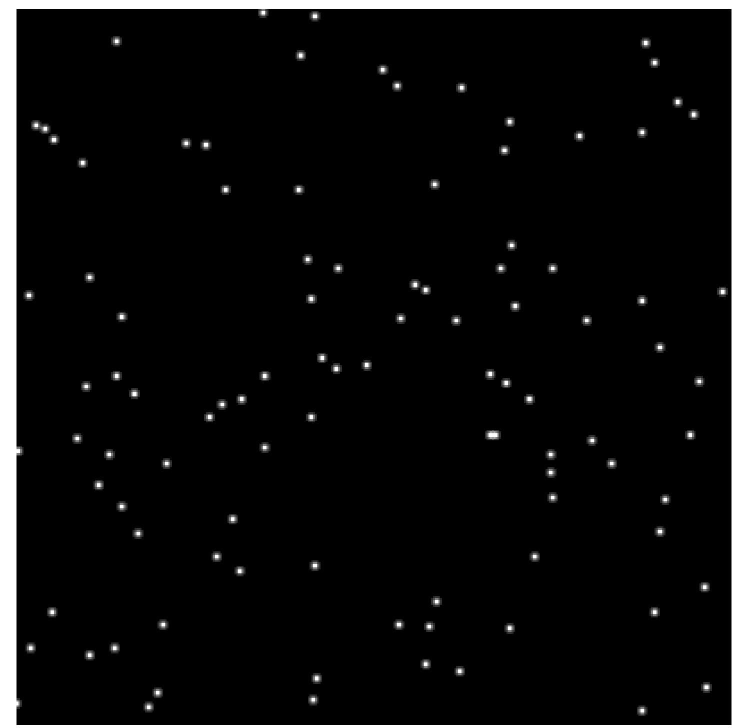
DM subhalo density Power Spectrum



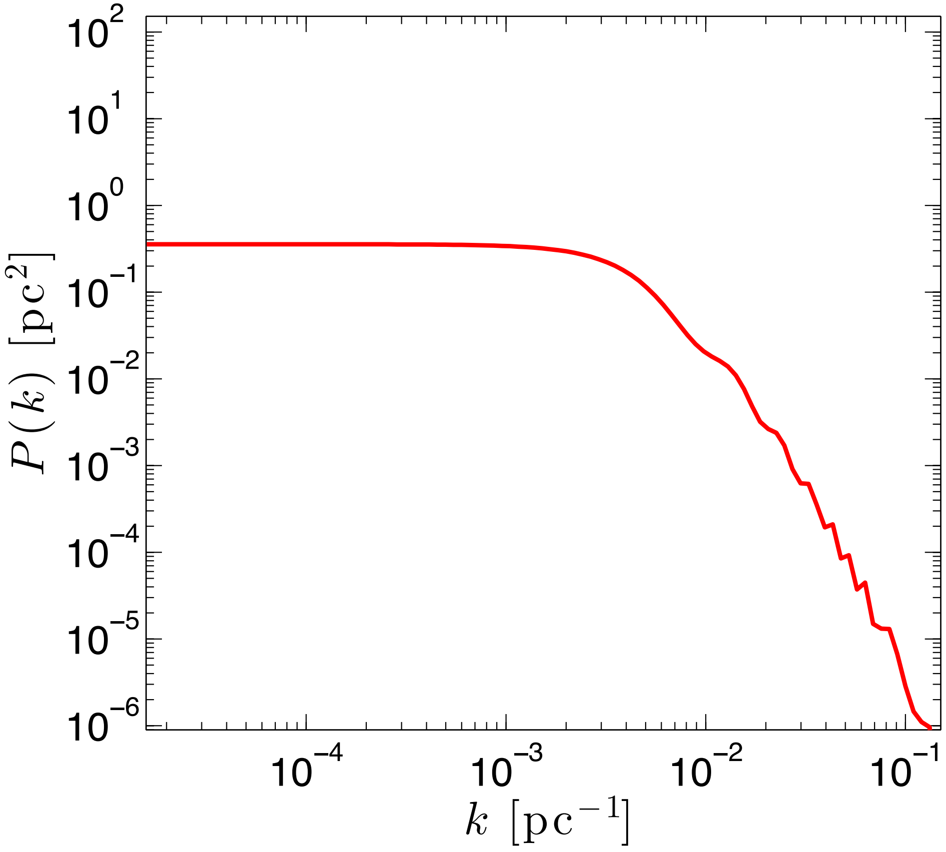


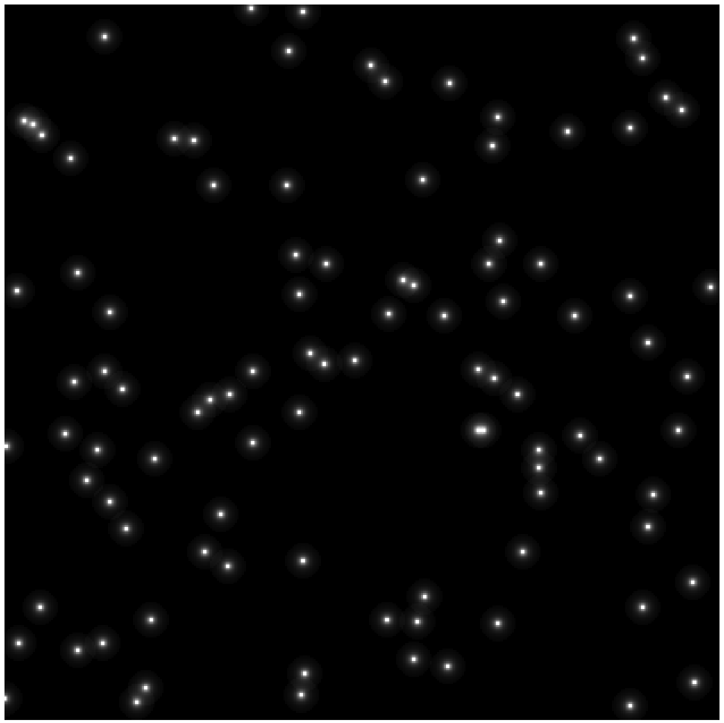
DM subhalo density Power Spectrum



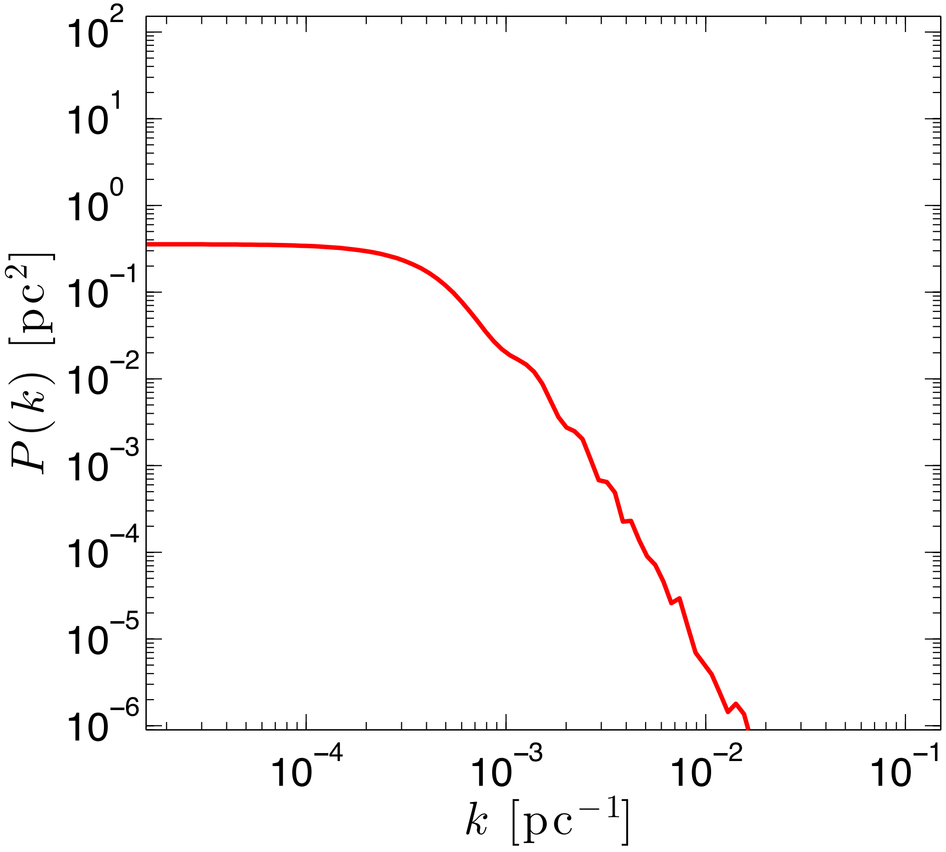


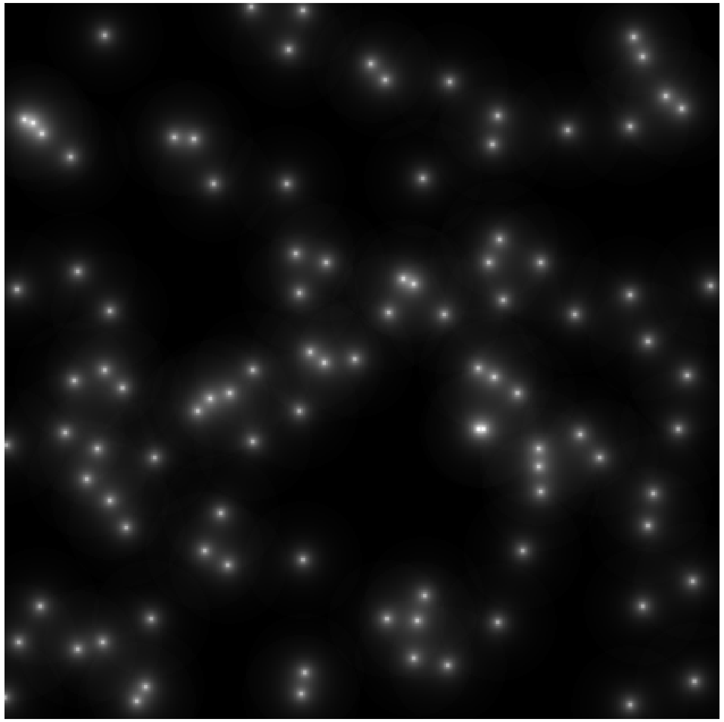
DM subhalo density Power Spectrum



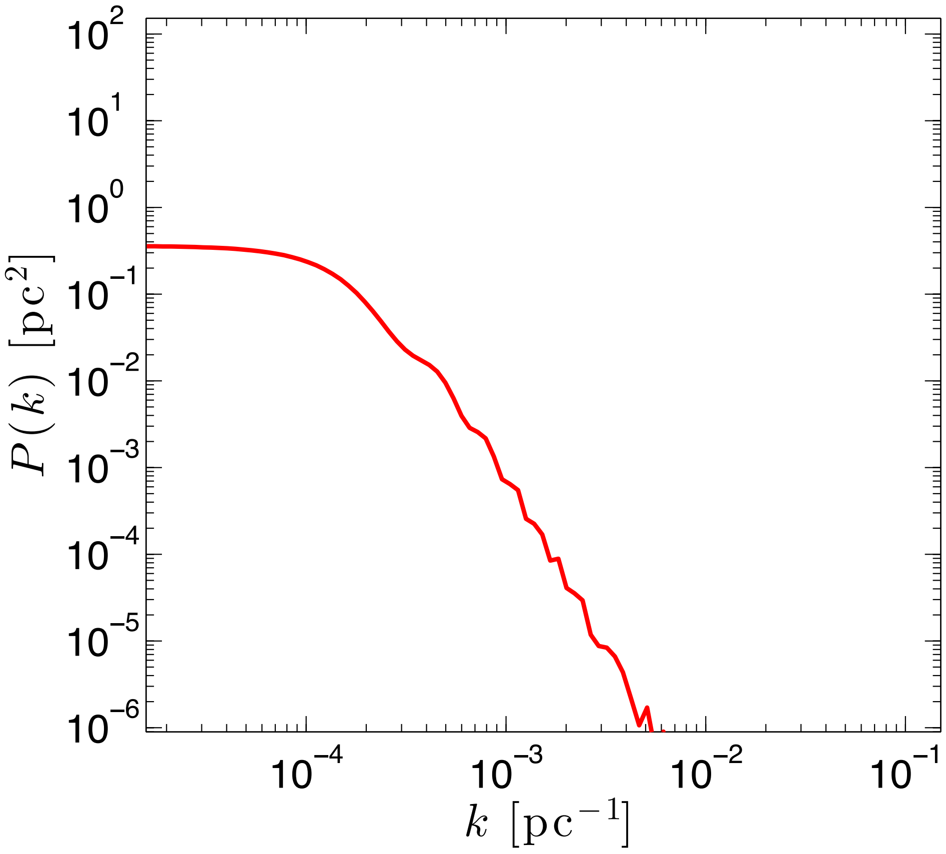


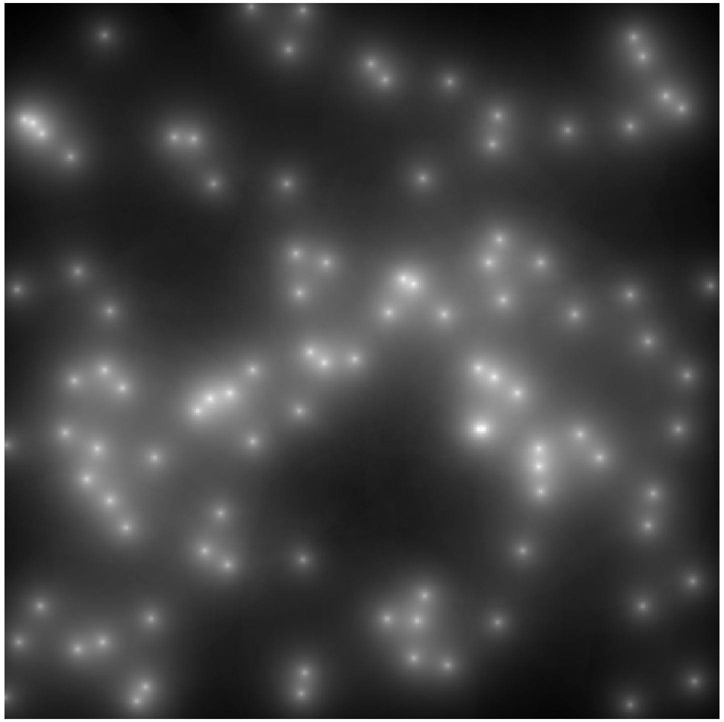
DM subhalo density Power Spectrum



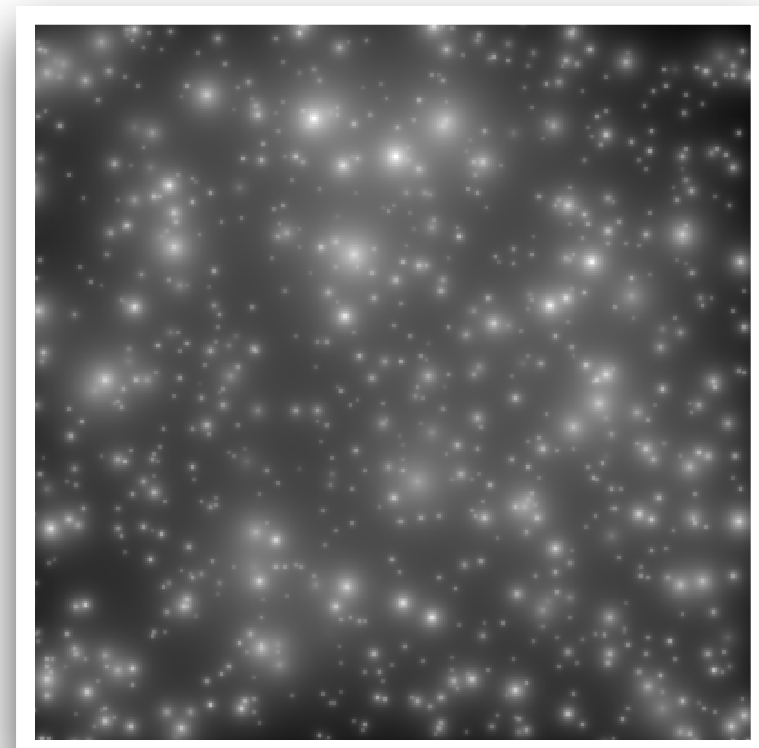


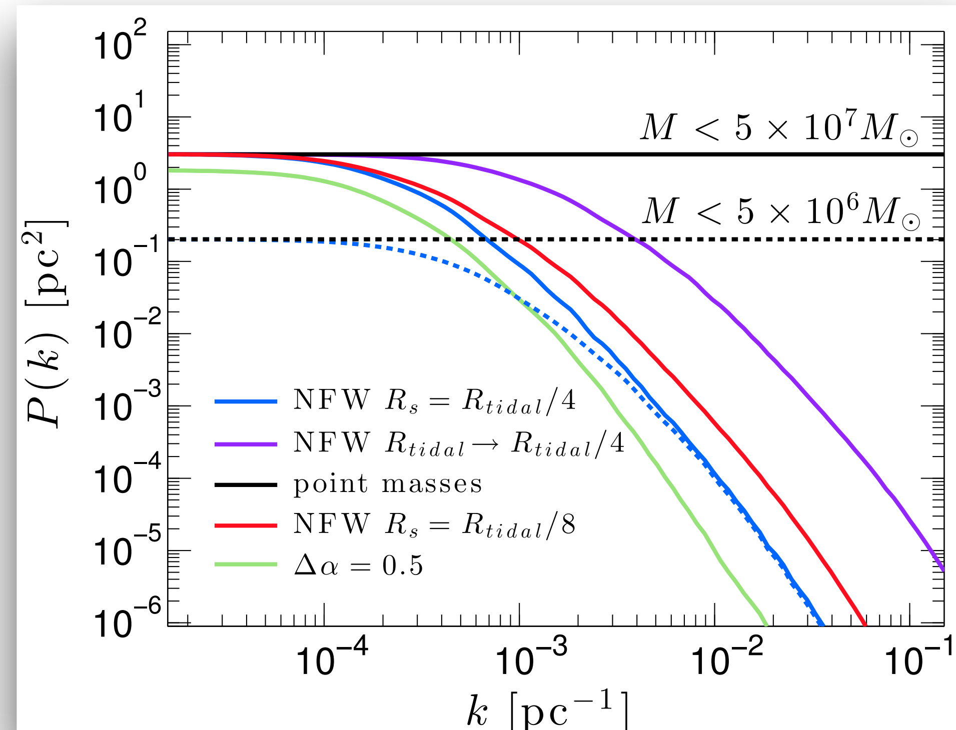
DM subhalo density Power Spectrum





Power Spectrum of subhalo density field

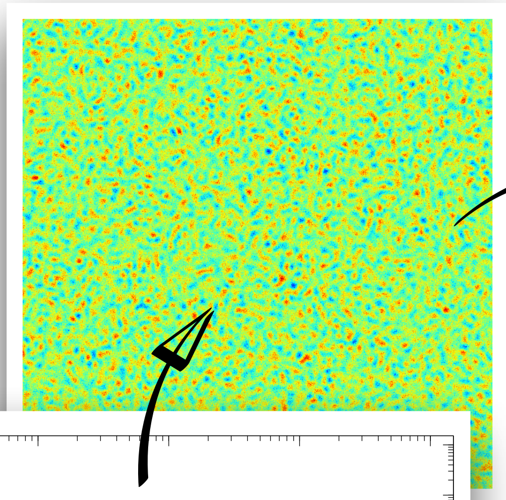


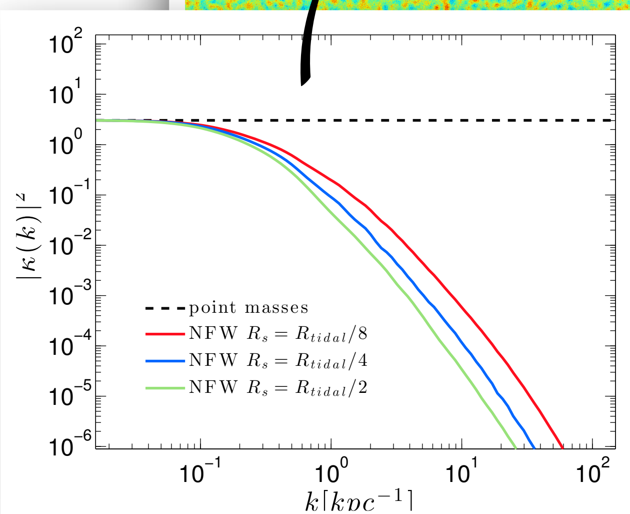


Hezaveh

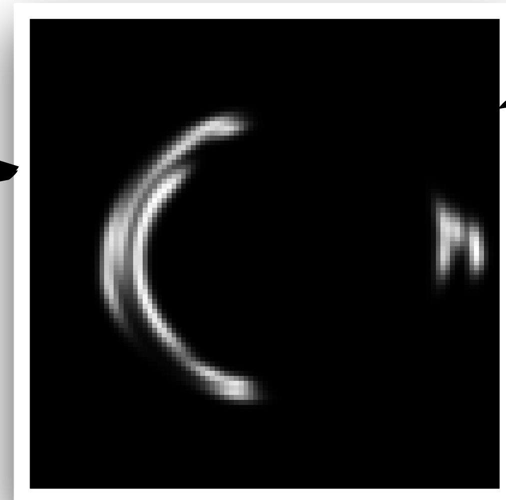
Analysis of mock observations

Generate a random subhalo density field with a flat power spectrum

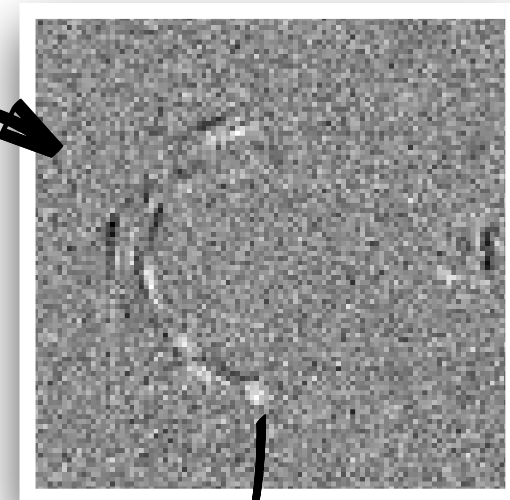




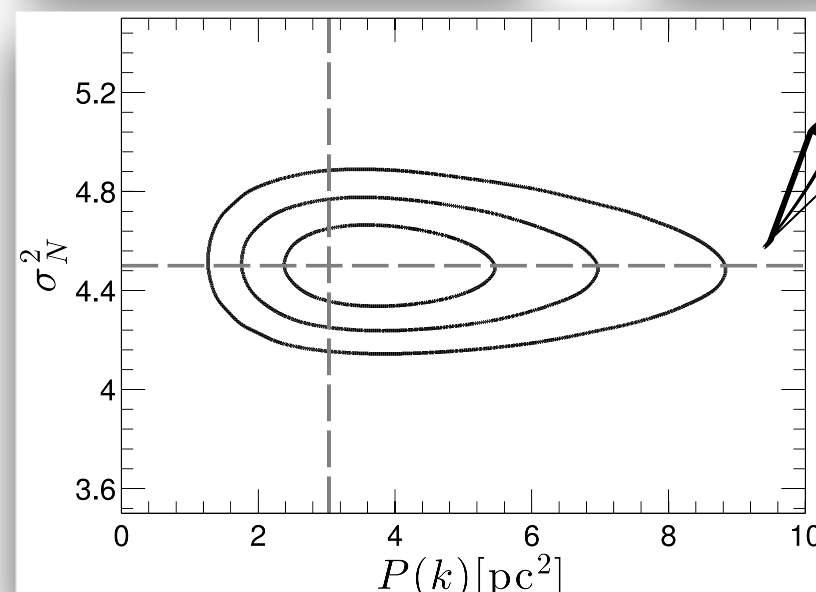
Generate mock observations using a macro halo and the subhalo density field



Fit the mock data with a lens model which only has smooth parameters

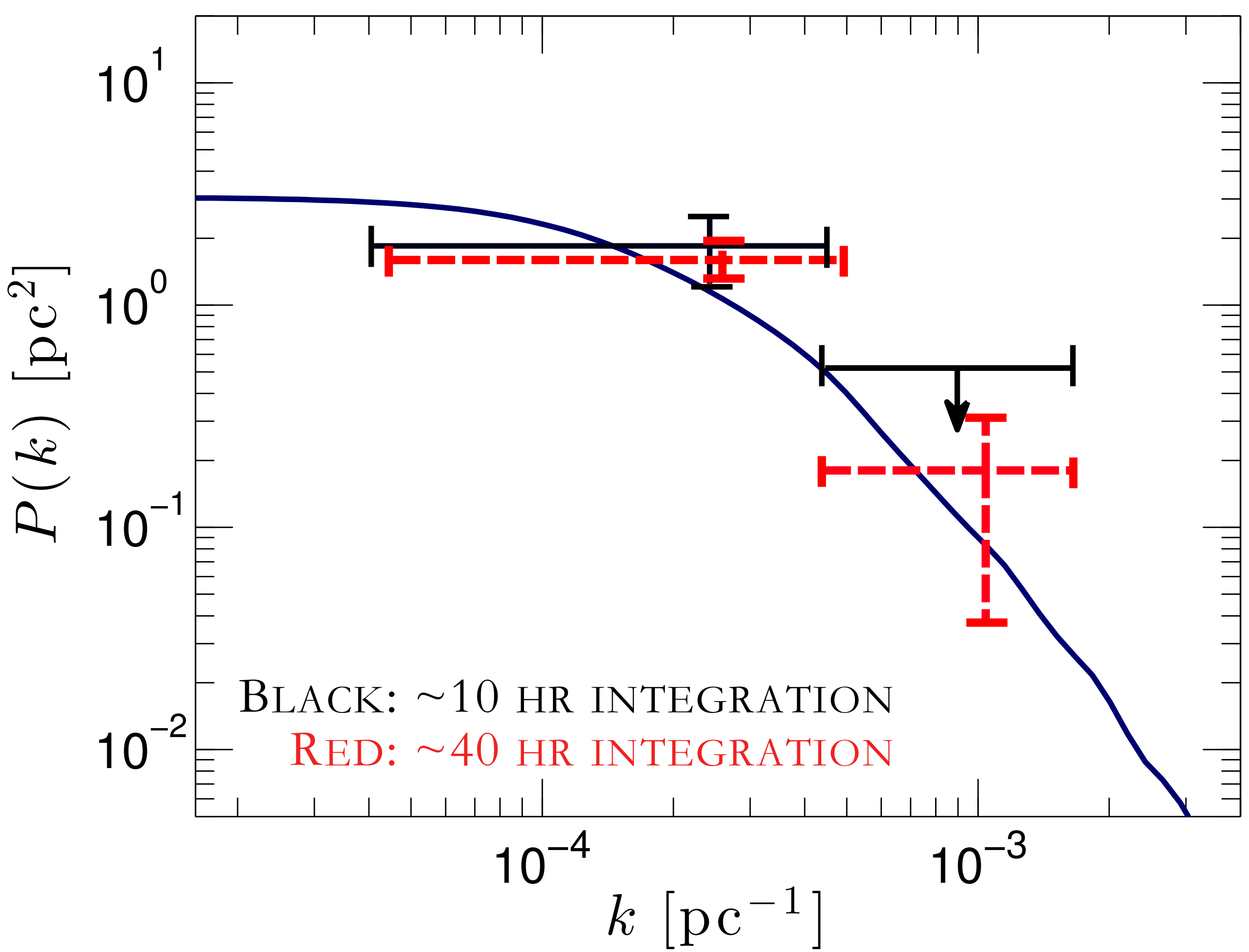


Estimate the likelihood of different covariance matrices using the residuals



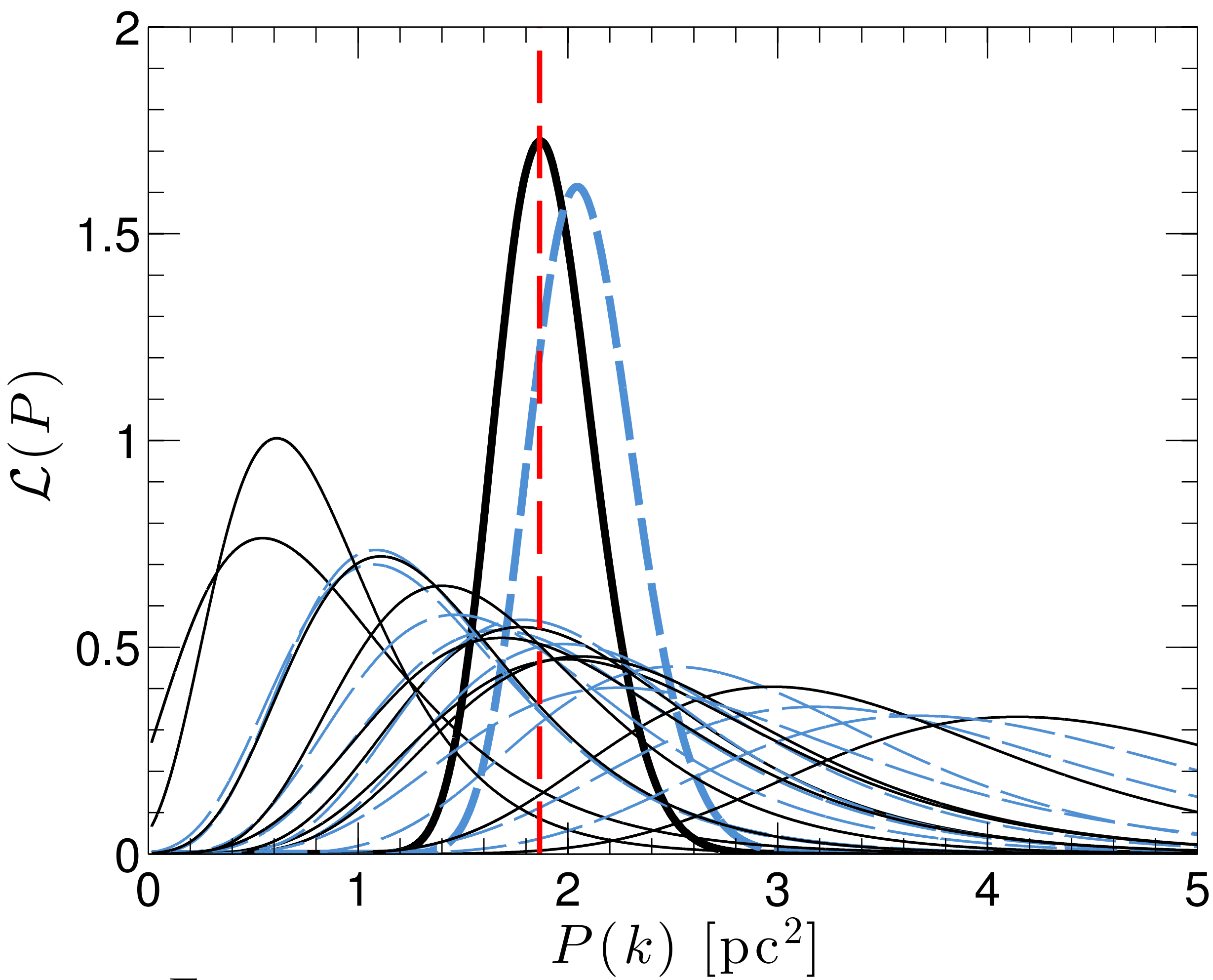
Hezaveh

Forecast for measuring the DM subhalo Power Spectrum



Hezaveh

How much does Non-Gaussianity bias us?



Black: Gaussian Fields
Blue: non-Gaussian Fields

Hezaveh

TAKE-AWAY MESSAGE

- Characterizing the small-scale structure of halos is crucial and can reveal important clues about the nature of dark matter

- ALMA and mm-wave lenses give us a unique opportunity for advancement

- New techniques, including power spectrum analysis, allow us to probe a wide range of subhalo masses and properties