

Title: Searching for dark matter subhalos using strong lensing of dusty star forming galaxies

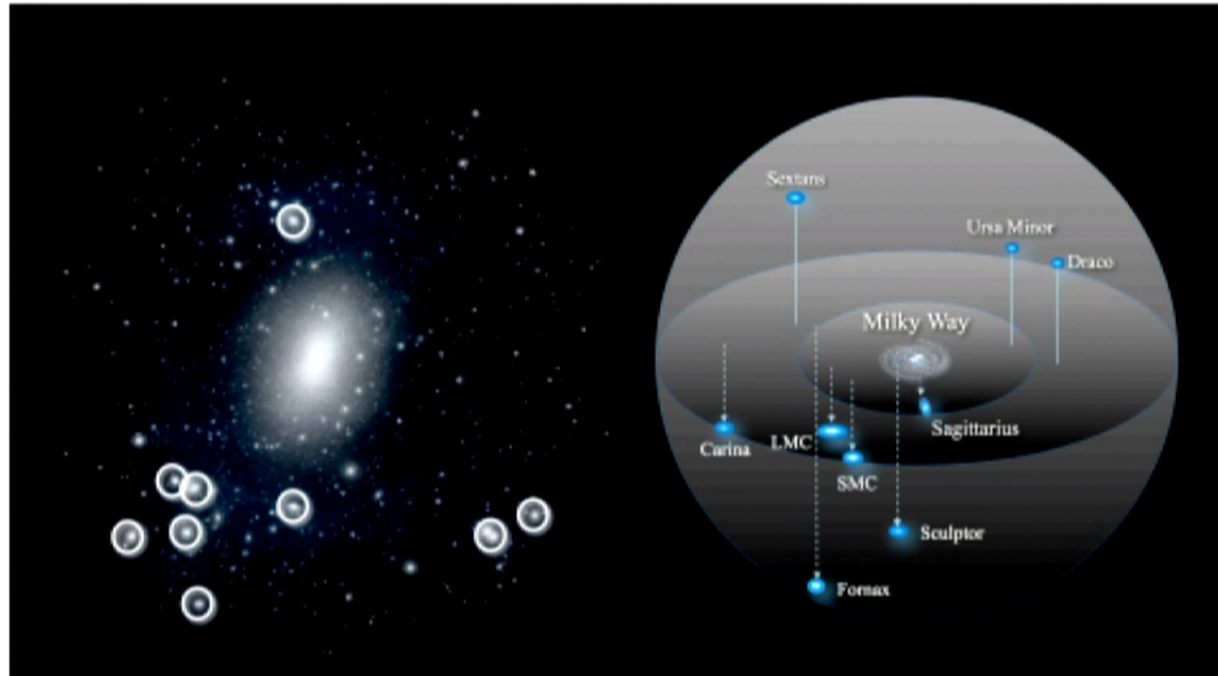
Date: Jul 16, 2015 11:00 AM

URL: <http://pirsa.org/15070087>

Abstract: <p>On small scales, our understanding of dark matter in galaxies is incomplete. One example is that high resolution simulations predict a large number of subhalos in dark matter halos, which should be seen in our Milky Way galaxy as a host of satellite galaxies. Many plausible astrophysical mechanisms have been proposed to explain why we don't clearly see large numbers of such satellite galaxies, but this remains a test of the cold dark matter scenario that has yet to be passed. Gravitational lensing provides a direct probe of subhalos in distant galaxies, but requires high sensitivity and angular resolution. I will talk about a search that is now started using strong lensing of the mm and submm-wave emission from dust grains in high-redshift star-forming galaxies. The properties of the dust emission are well-matched to the typical expected scales of the dark matter subhalos, and ALMA (the Atacama Large Millimeter Array) now has the sensitivity and angular resolution to start to see the lensing signature of these subhalos. We haven't found any yet in early data, but we should see some soon if the cold dark matter paradigm is correct.</p>

# Missing satellite galaxies?

comparison of simulated and observed satellites for MW-like galaxy



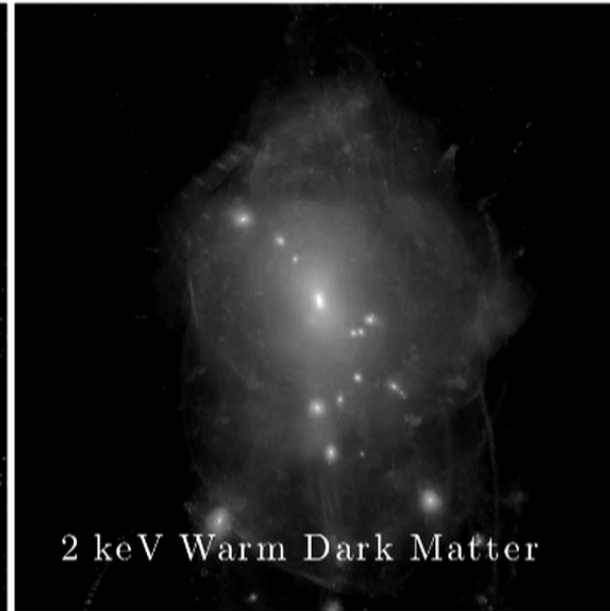
Weinberg et al [arXiv:1306.0913](https://arxiv.org/abs/1306.0913)

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# Possible Solutions

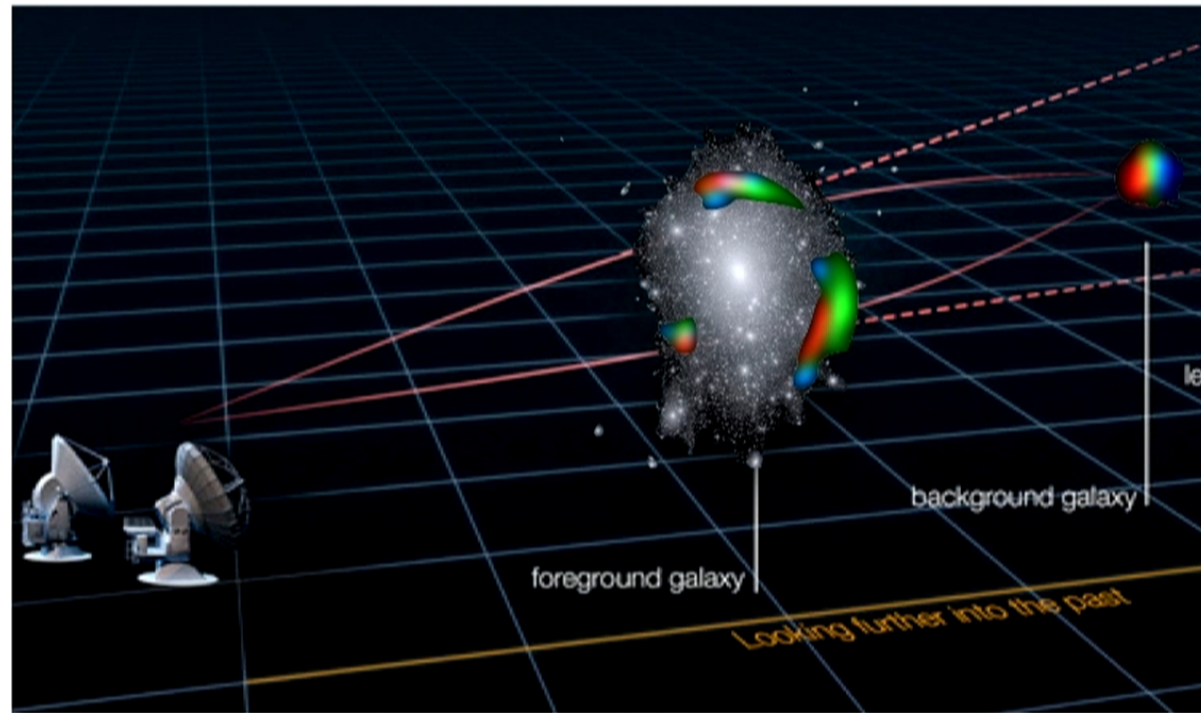
BARYONIC GASTROPHYSICS

DARK MATTER PHYSICS

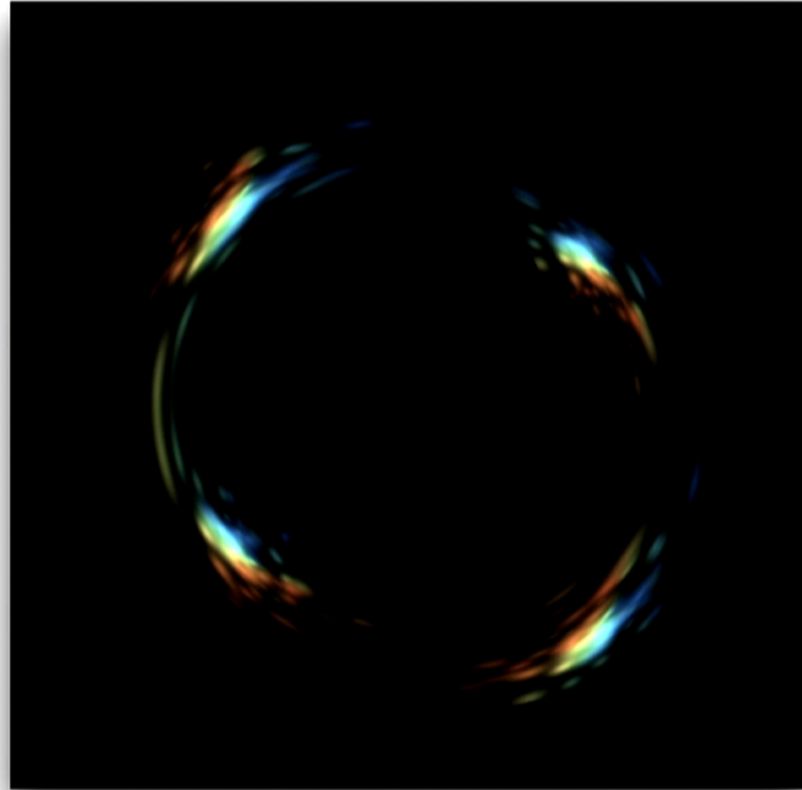


LOVELL ET AL 2012, MNRAS 420, 3

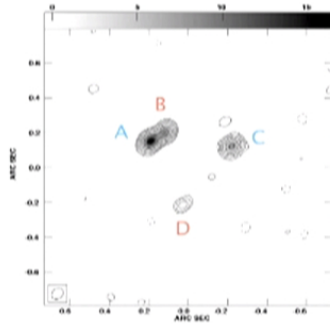
# Strong Gravitational Lensing



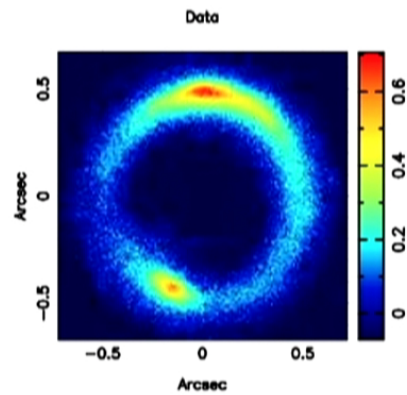
# Substructure Lensing



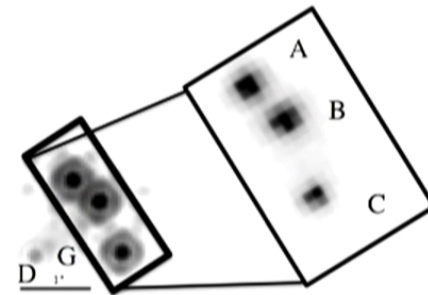
# Substructure Lensing



DALAL & KOCHENAK 2002

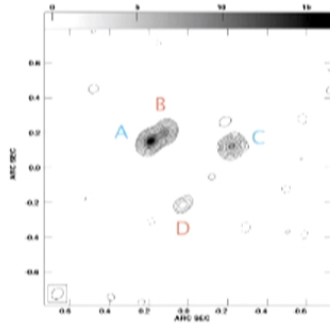


VEGETTI ET AL. 2012

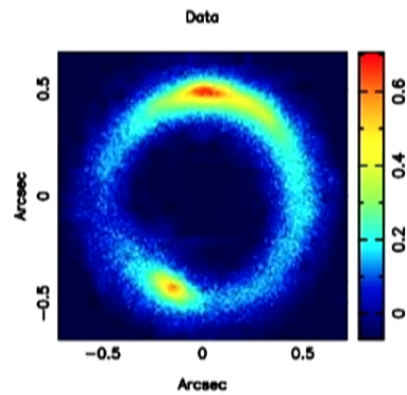


NIERENBERG ET AL. 2014

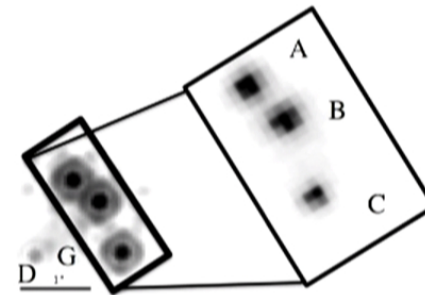
# Substructure Lensing



DALAL & KOCHENAK 2002



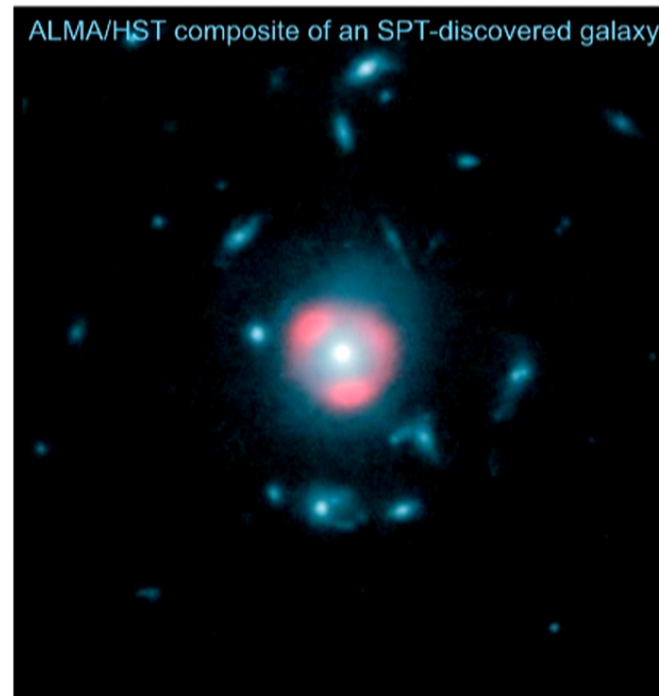
VEGETTI ET AL. 2012



NIERENBERG ET AL. 2014

# Strong lensing of mm-wave selected galaxies

- selecting bright sources at mm-wave turns out to be a remarkably efficient way to discover strong lensing
  - dozens of new systems discovered

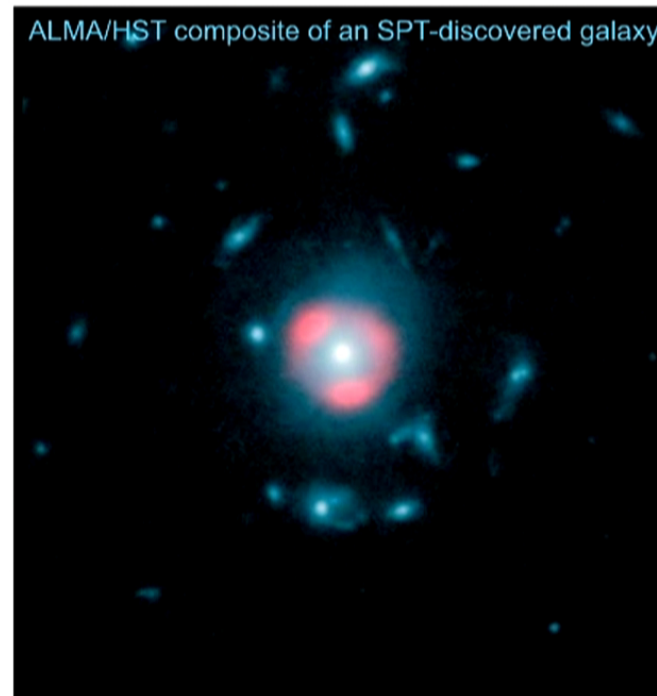


Vieira et al 2013



# Strong lensing of mm-wave selected galaxies

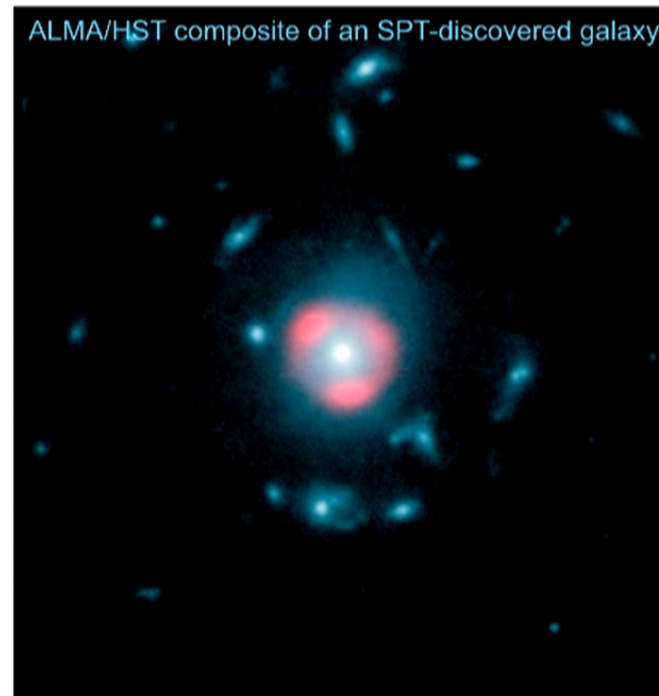
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Vieira et al 2013

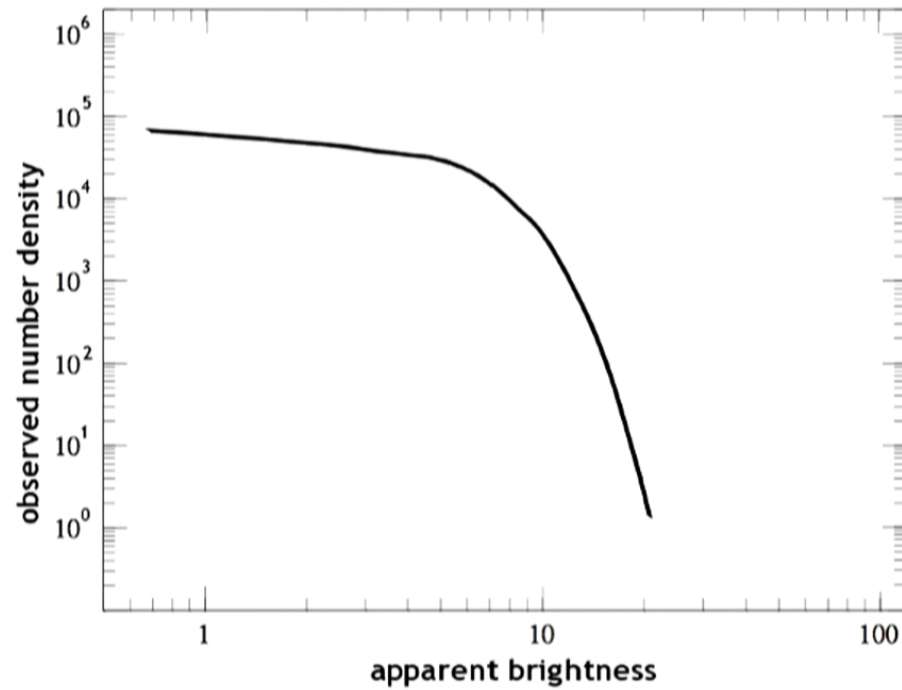
# Strong lensing of mm-wave selected galaxies

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  - dozens of new systems discovered



Vieira et al 2013

# Number Counts of high-z Galaxies



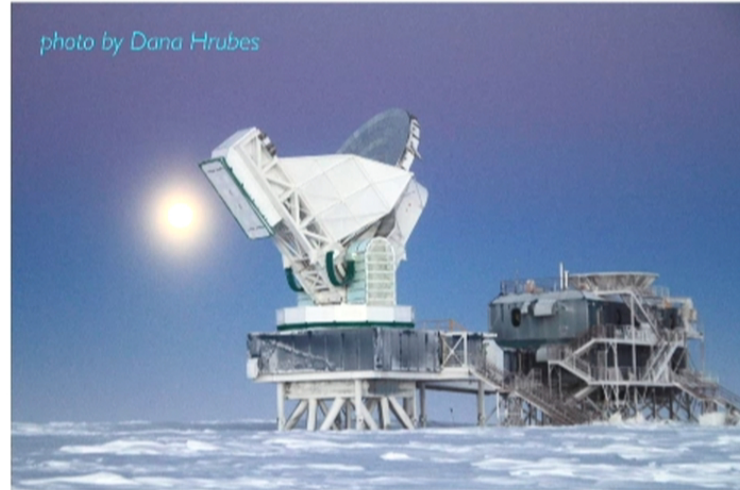
# South Pole Telescope

10m mm-wave (3 different wavelengths) telescope at the south pole

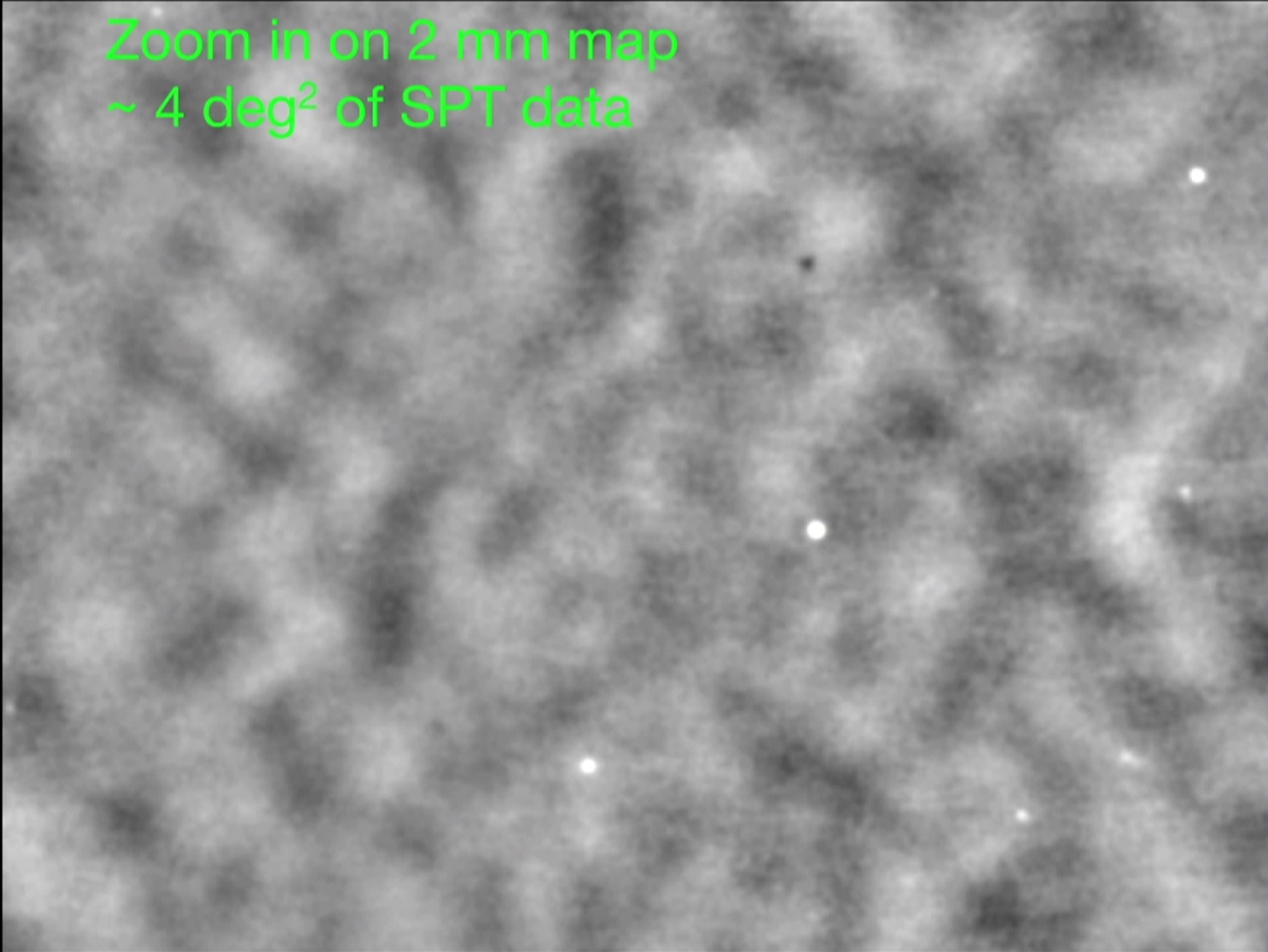
- extremely dry
- very stable
- good support



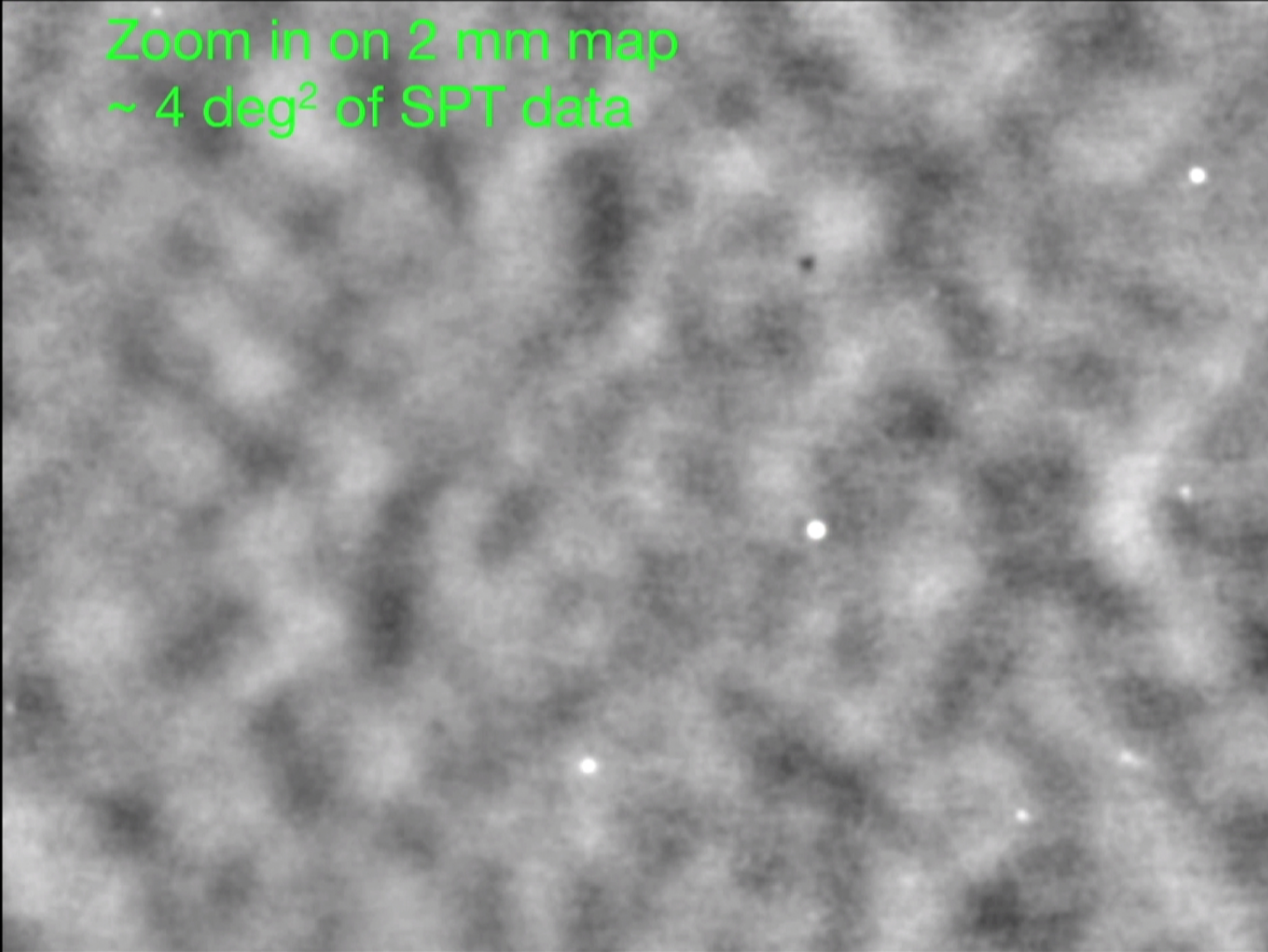
Chicago Colorado  
UC Berkeley Case Western  
McGill Harvard  
UC Davis Munich +++



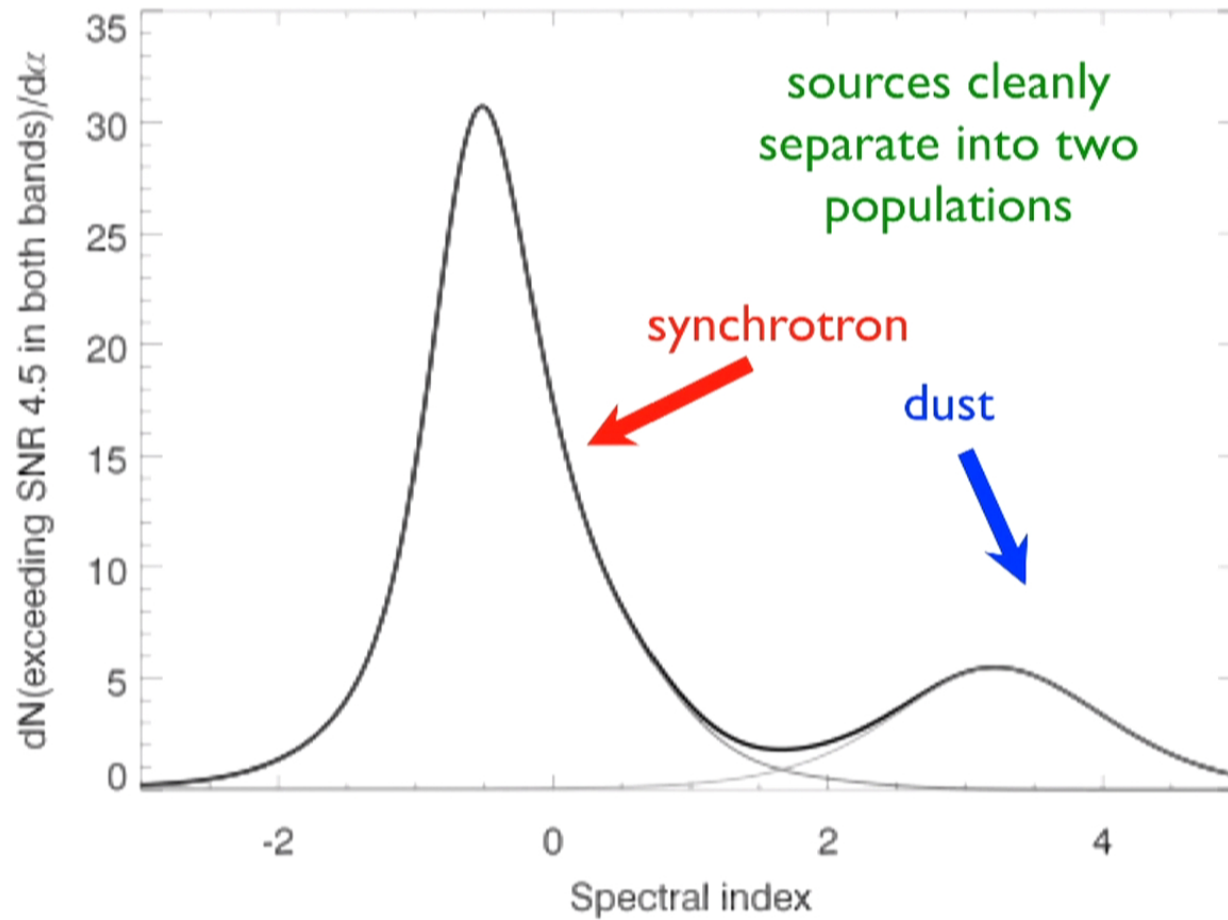
Zoom in on 2 mm map  
~ 4 deg<sup>2</sup> of SPT data



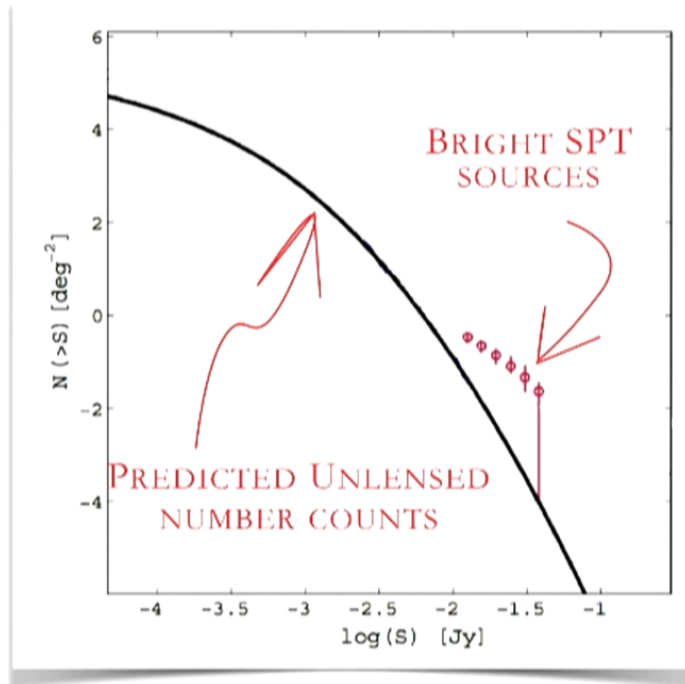
Zoom in on 2 mm map  
~ 4 deg<sup>2</sup> of SPT data



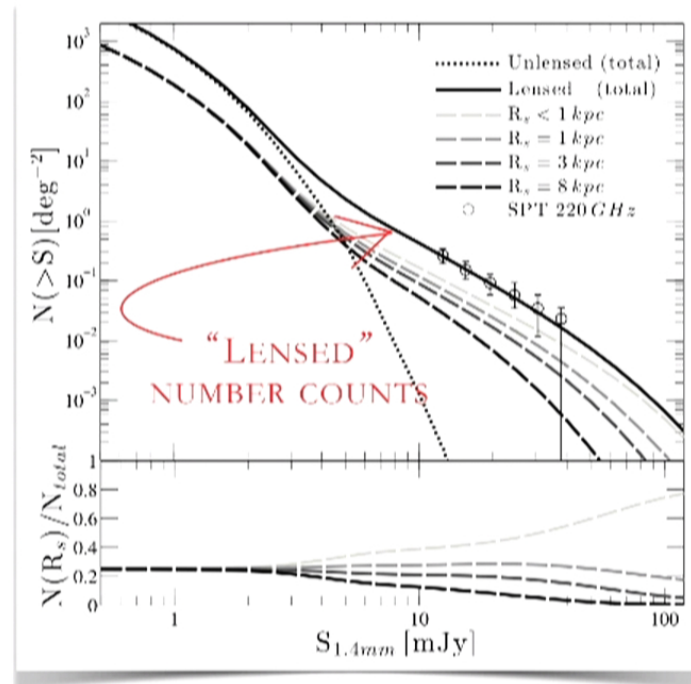
## Distribution of Spectral Indices



# Number Counts of Lensed Galaxies



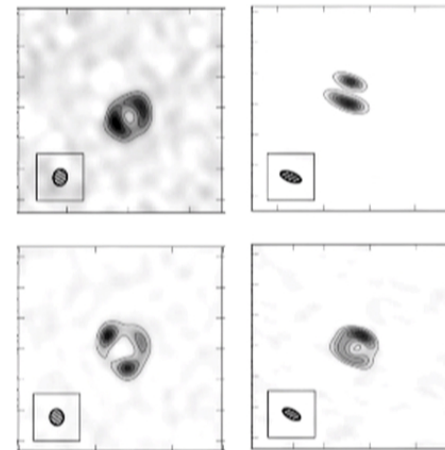
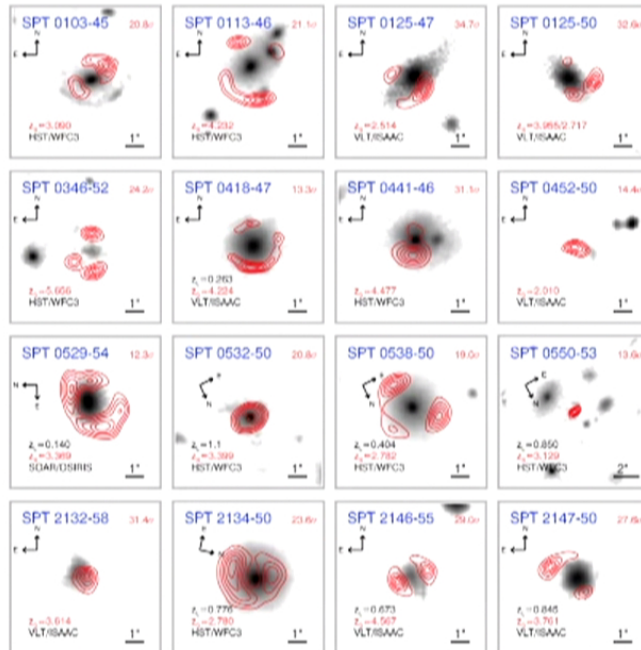
HEZAVEH & HOLDER 2011 APJ



HEZAVEH, MARRONE, & HOLDER 2012 APJ



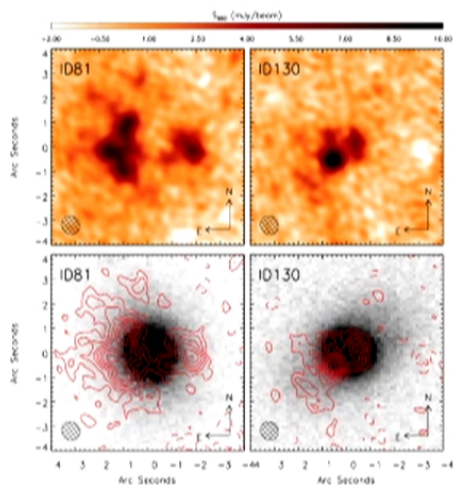
# SPT Strong Lenses



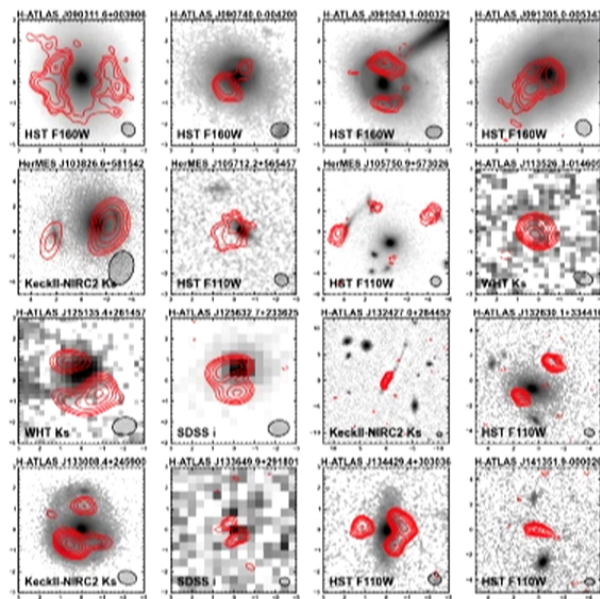
VIEIRA ET AL. NATURE 2013

HEZAVEH ET AL. APJ. 2013

# Herschel Strong Lenses

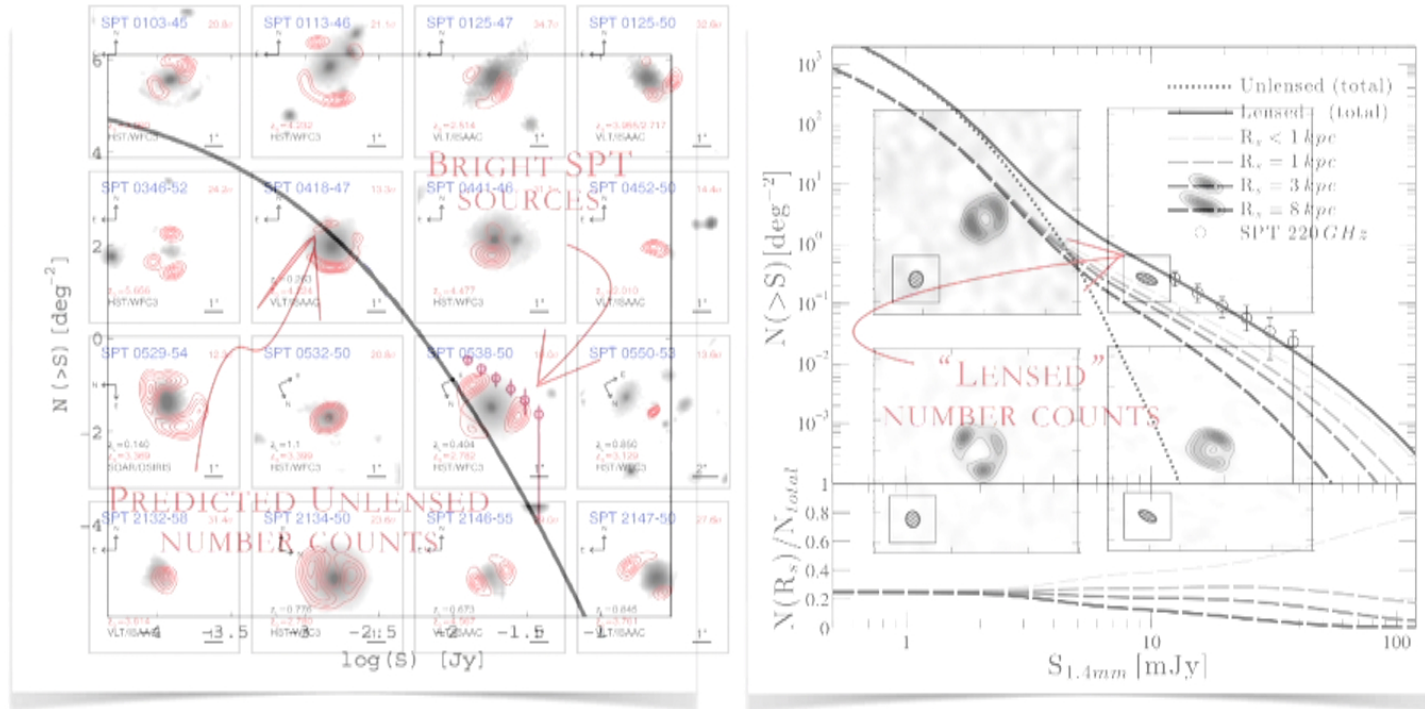


NEGRELLO ET AL. SCIENCE 2010



BUSSMANN ET AL. APJ 2013

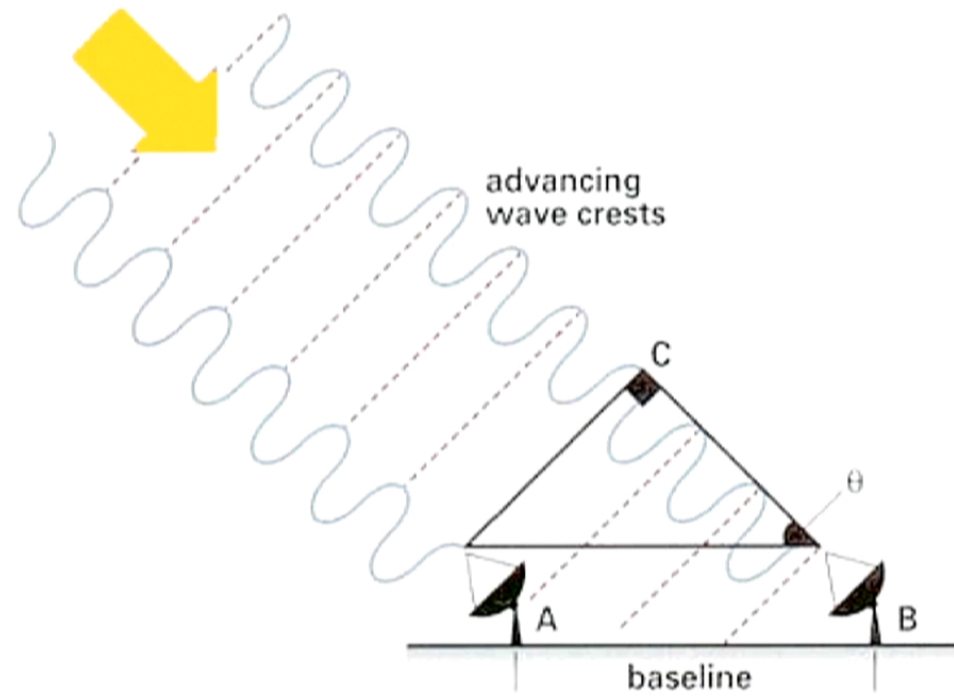
# NSPT Counts of Lensed Galaxies



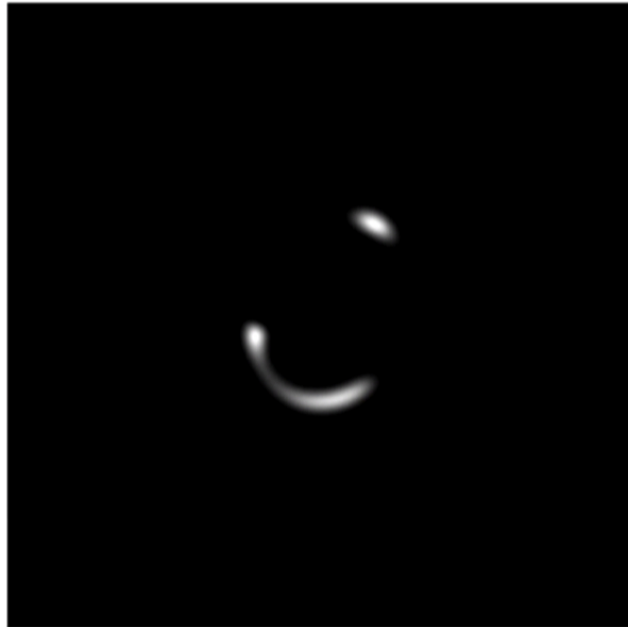
HEZAVEH & HOLDER 2011 APJ  
 VIEIRA ET AL. NATURE 2013

HEZAVEH, MARRONE, & HOLDER 2012 APJ  
 HEZAVEH ET AL. APJ 2013

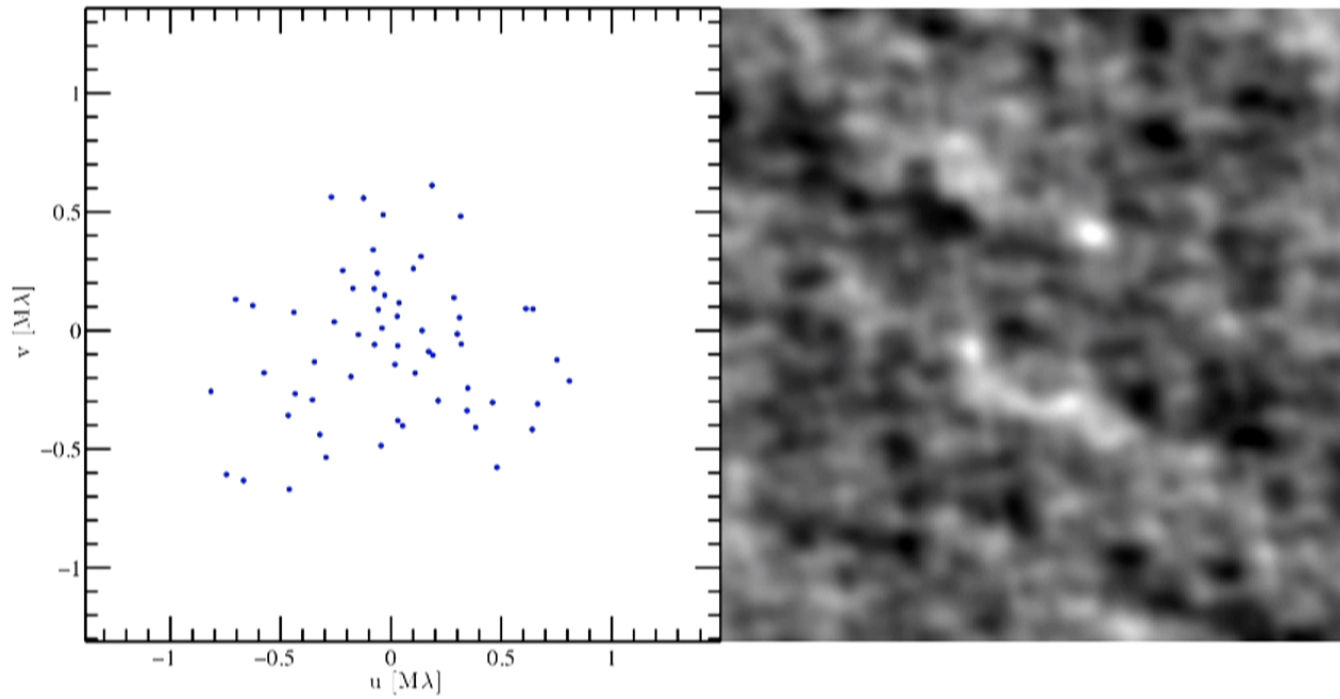
# INTERFEROMETRY



# INTERFEROMETRY

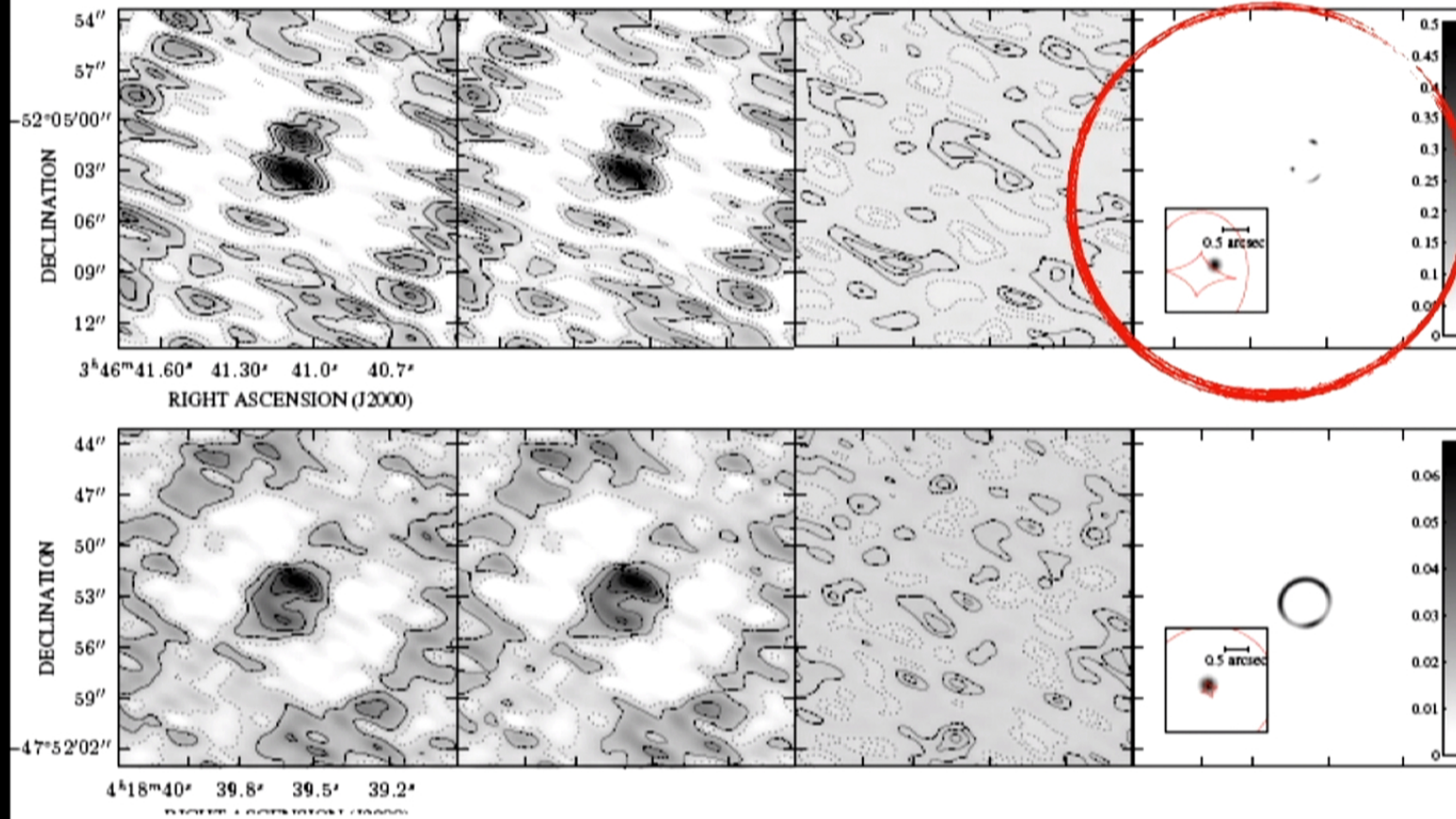


# INTERFEROMETRY



# Strong Lens Models

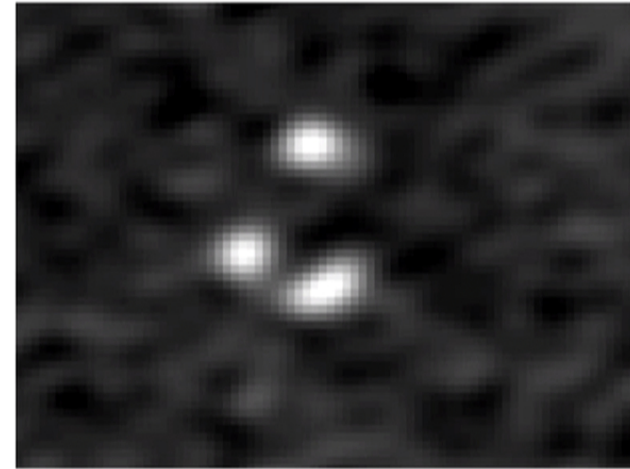
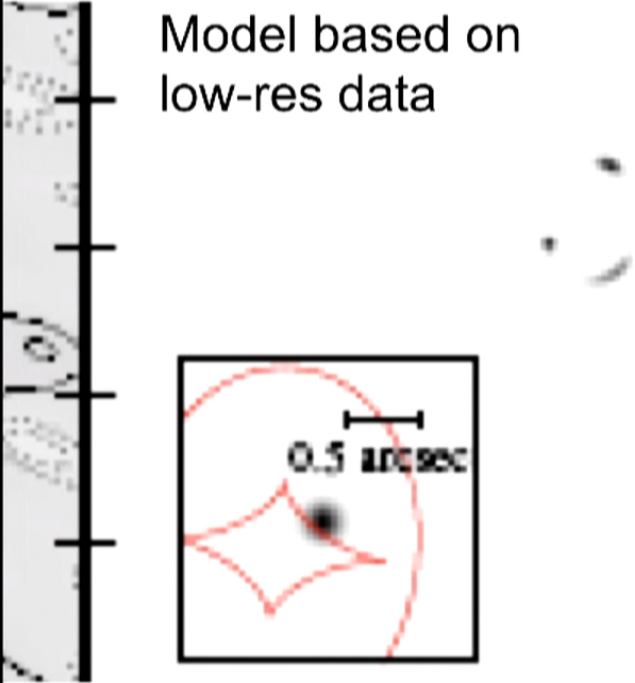
Hezaveh et al 2013



# Strong Lens Models

Hezaveh et al 2013

Model based on  
low-res data



High-res ALMA  
observations

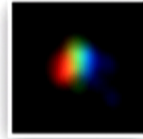
*should be possible for ~100 SPT sources*

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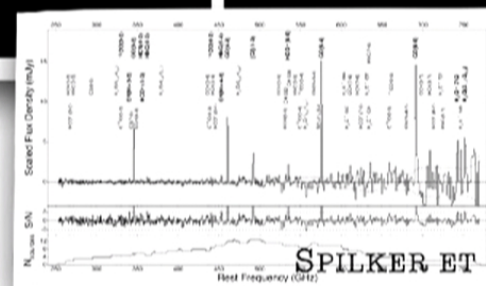
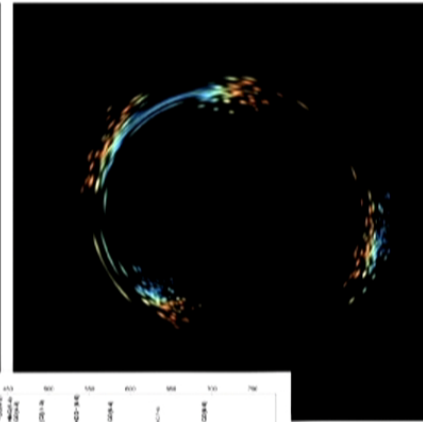
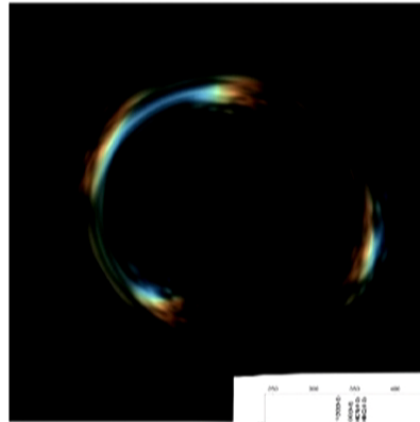
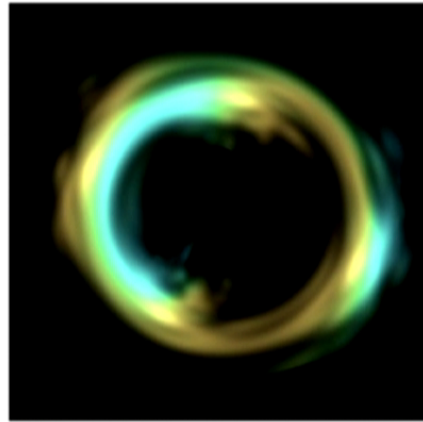
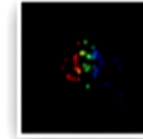
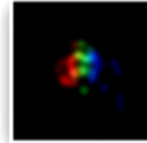


# A WEALTH OF MOLECULAR LINES

LOW EXCITATION GAS



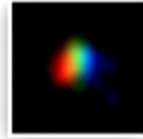
HIGH EXCITATION GAS



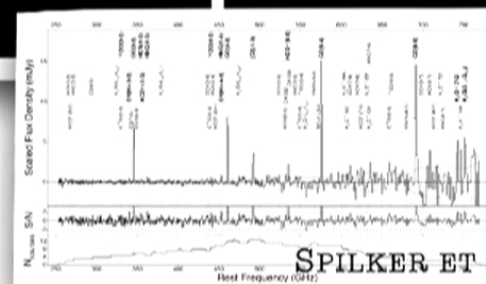
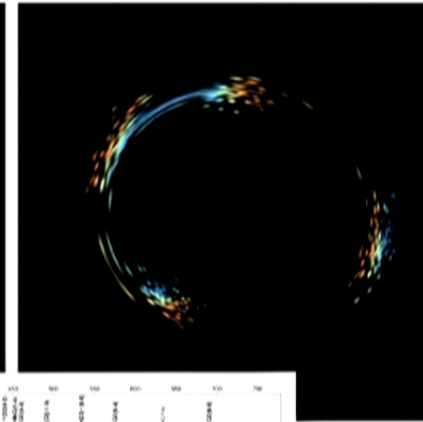
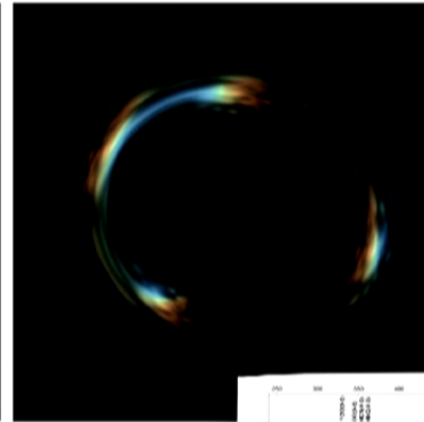
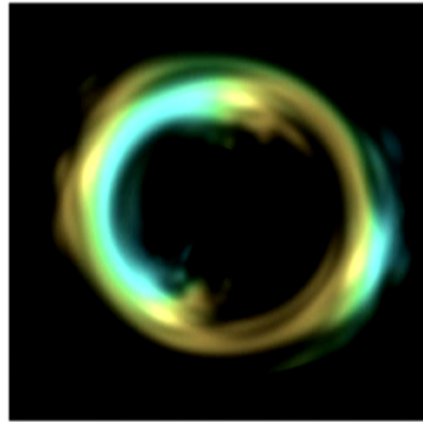
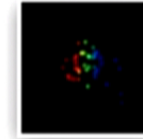
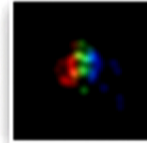
SPIPKER ET AL 2014, APJ

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LOW EXCITATION GAS

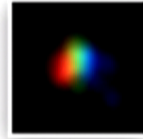


HIGH EXCITATION GAS

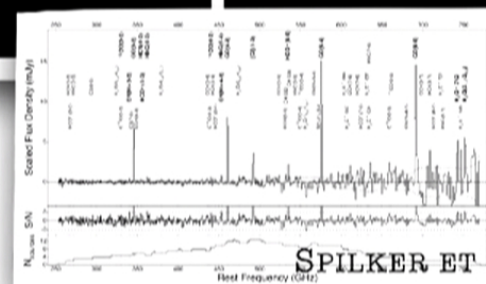
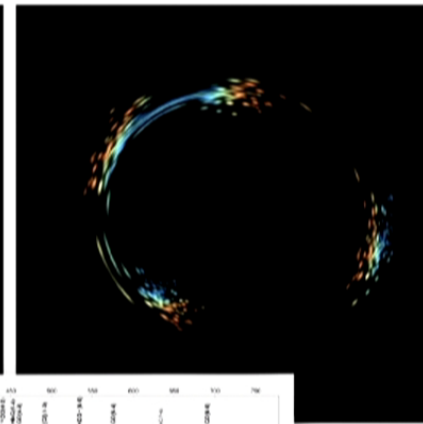
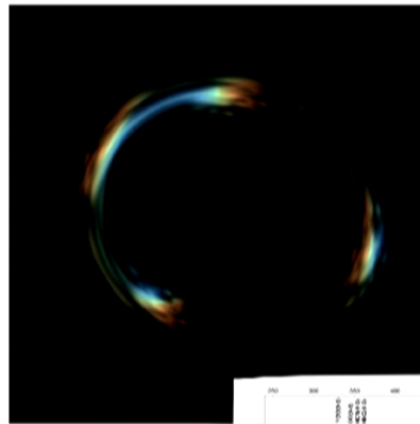
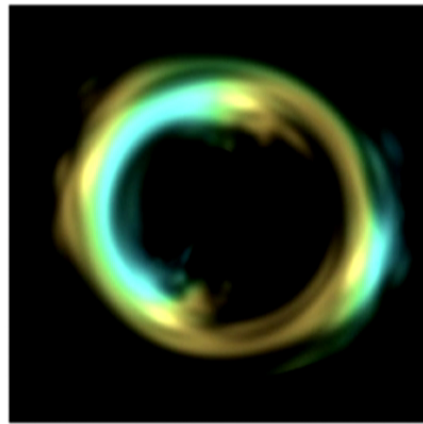
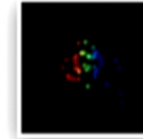
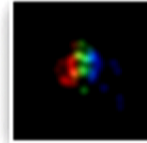


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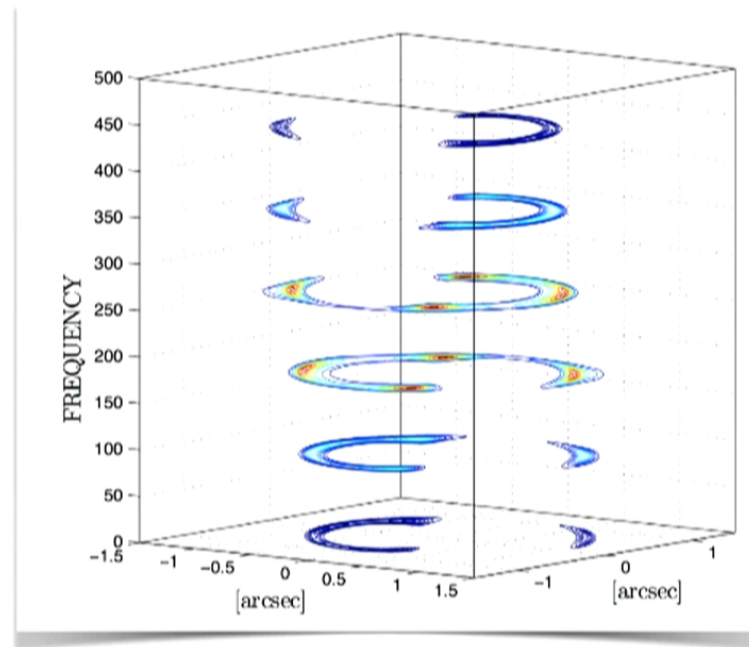
LOW EXCITATION GAS



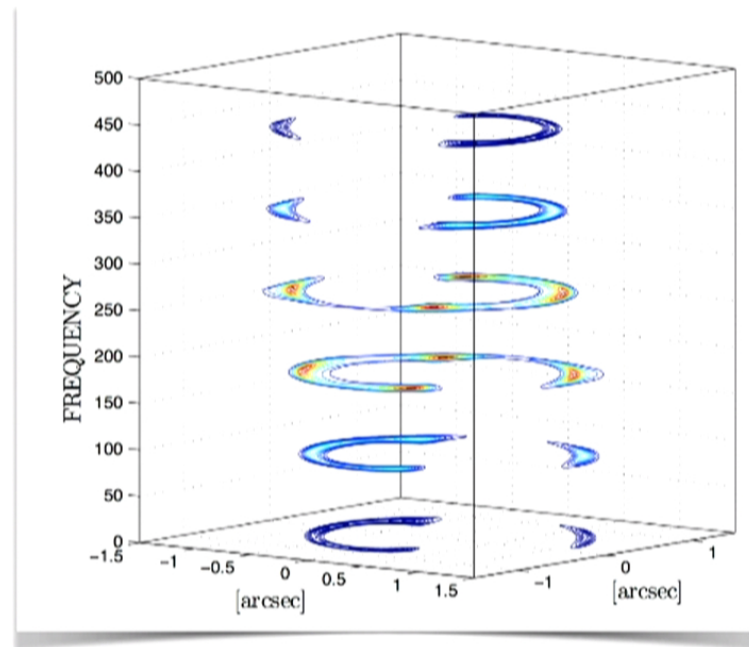
HIGH EXCITATION GAS



# Multiwavelength Lensing



# Multiwavelength Lensing

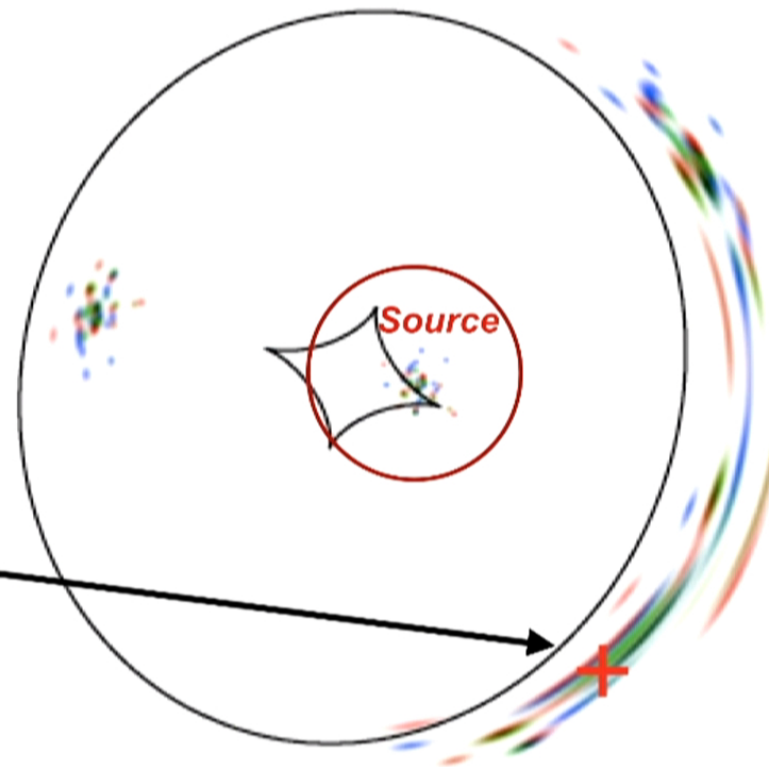


# Probing Dark Matter Lumps with Strong Lensing (Simulated Observations)

Hezaveh et al 2012

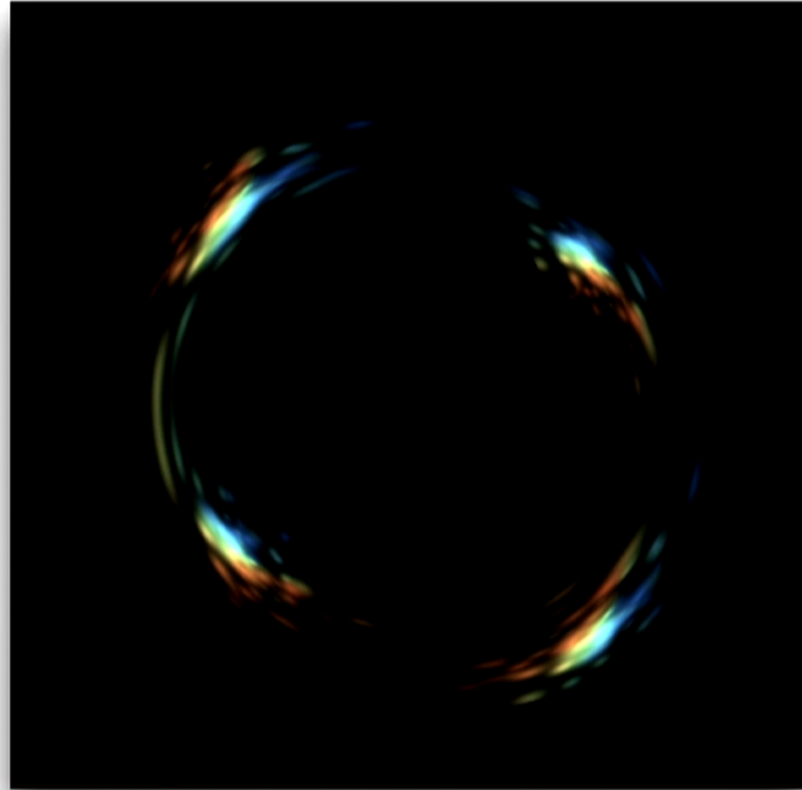
Different lumps of star formation should be offset in frequency from each other

Images form at different locations, possibly near lumps of dark matter

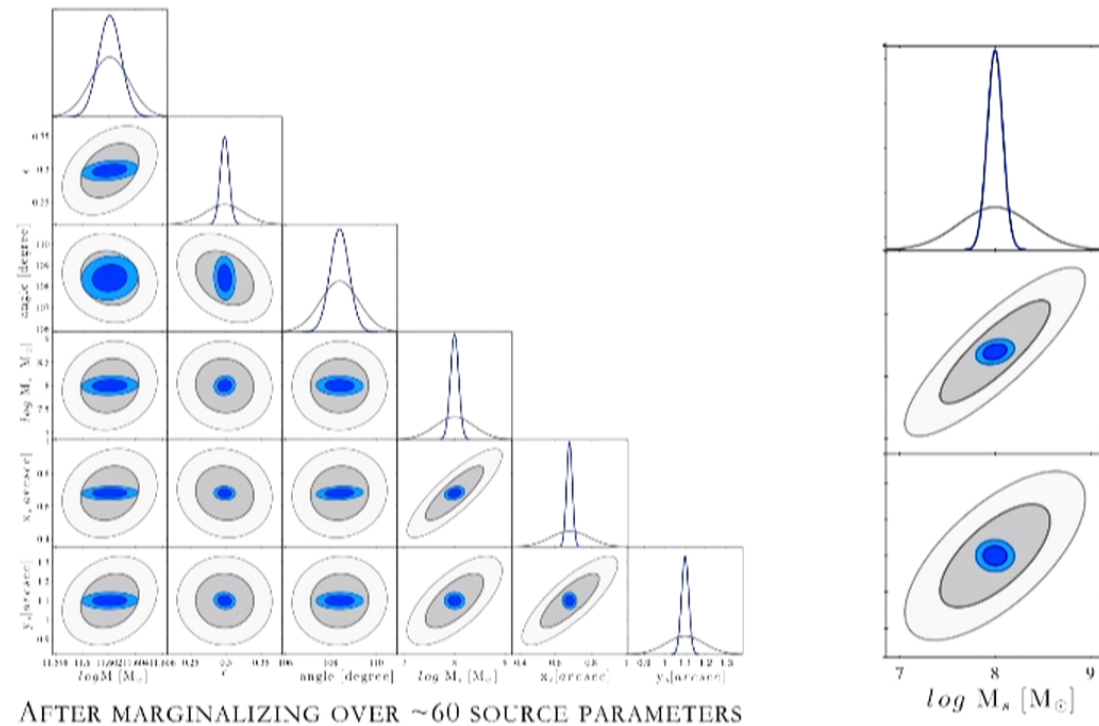


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## SUBSTRUCTURE LENSING



# SENSITIVITY ANALYSIS OF DETECTING DM SUBHALOS



HEZAVEH ET AL 2013, APJ. 767, 9

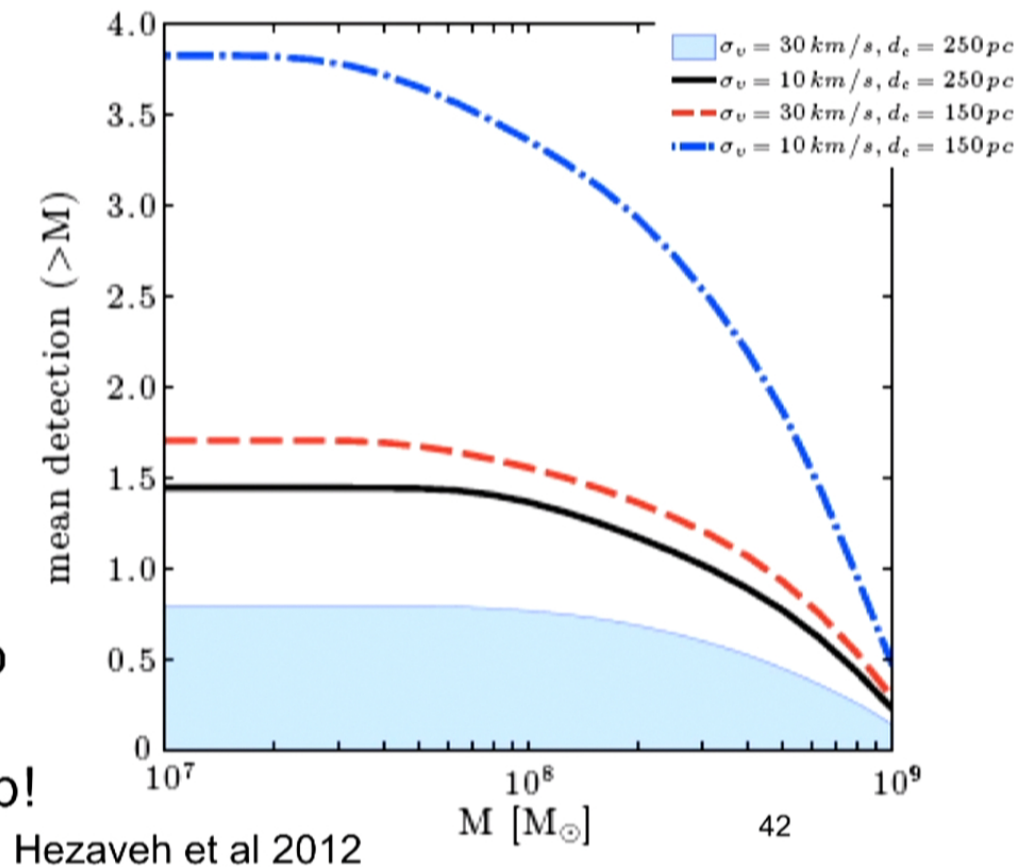




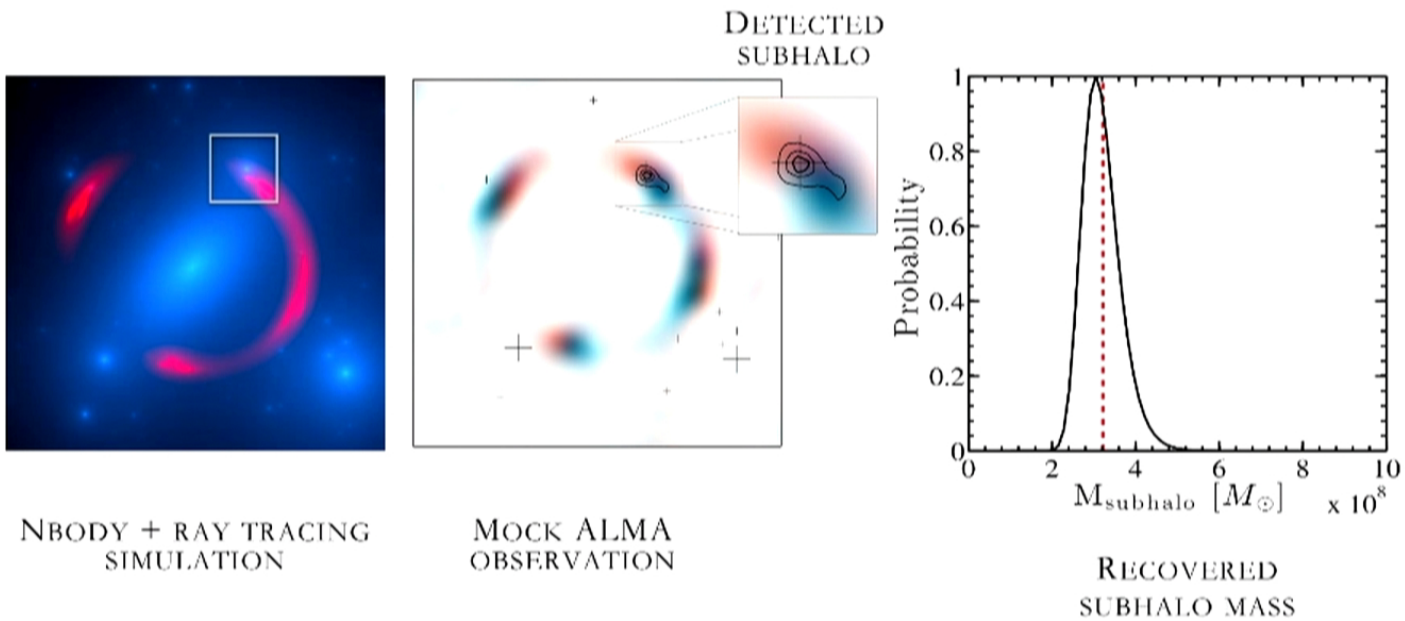
lens  
→  
Smooth  
+  
1 lump

# Prospects for Subhalo Detection with current ALMA

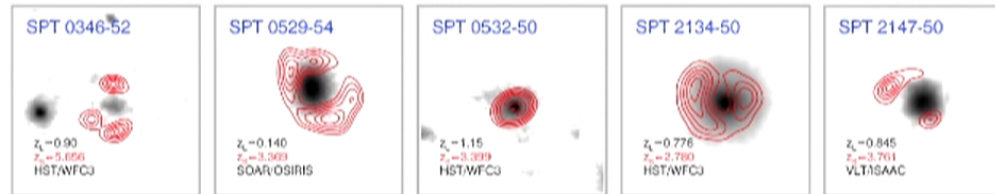
- expected detection rates depend on (currently not well-known) source properties
- expect almost every source to have a detectable lump!



SIMULATIONS INDICATE THAT WITH ALMA,  
WE CAN DETECT DM SUBHALOS IN THESE SYSTEMS



# SPT-DMS ALMA CYCLE 2 PROGRAM



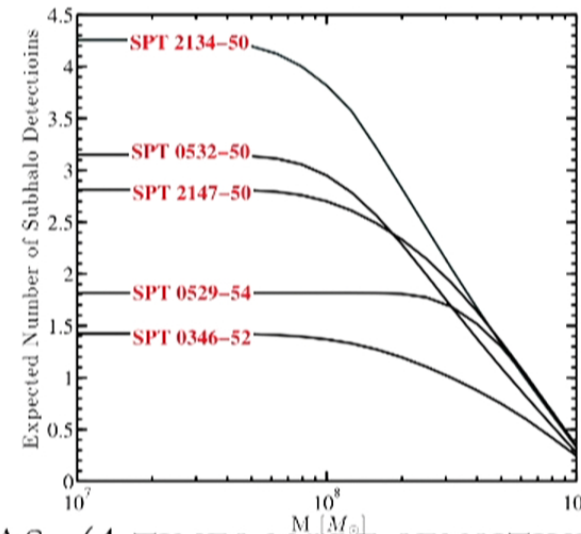
## ALMA CYCLE II PLAN

CO 7-6 MOLECULAR LINES  
5 TARGETS

PREDICTIONS FOR:  
ONE HOUR OBSERVATION  
CYCLE 2:

32 ANTENNAS  
MAX BASELINES  $\sim$  1.5 KM

FULL ALMA: 64 ANTENNAS (4 TIMES MORE SENSITIVITY)  
MAX BASELINES = 16 KM (10 TIMES HIGHER  
RESOLUTION)

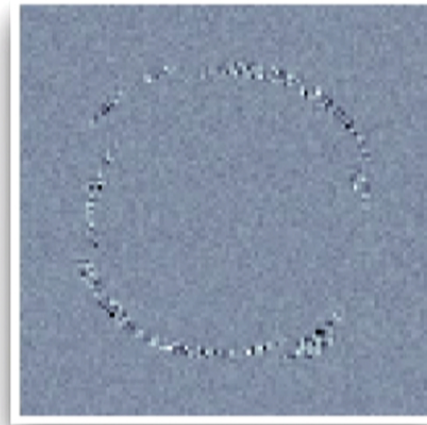
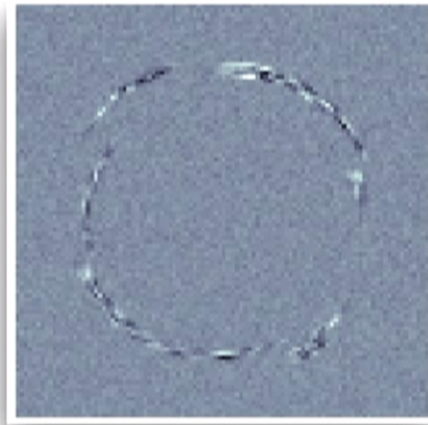
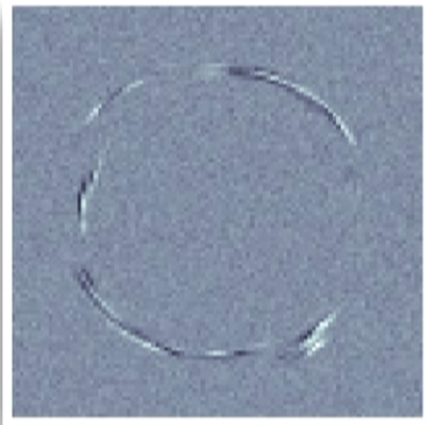


## COVARIANCE OF DEFLECTIONS

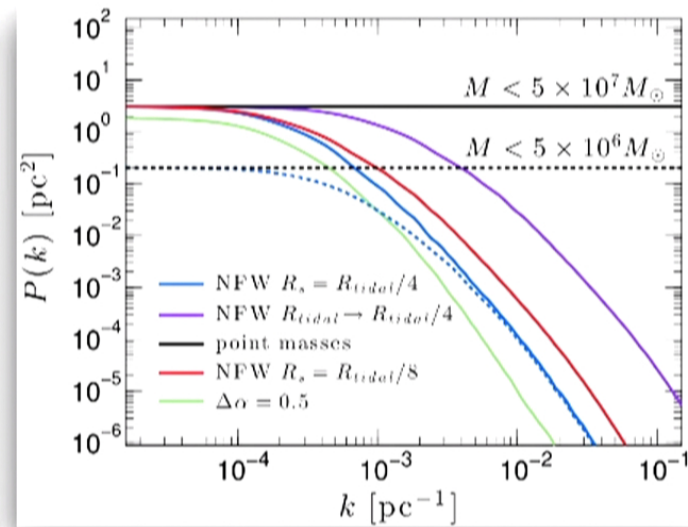
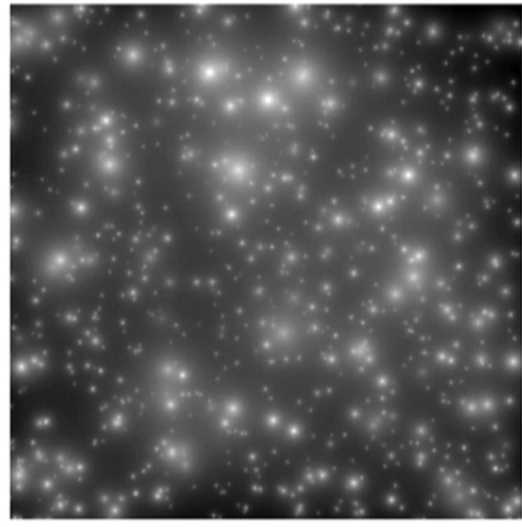
## DENSITY POWER SPECTRUM

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

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



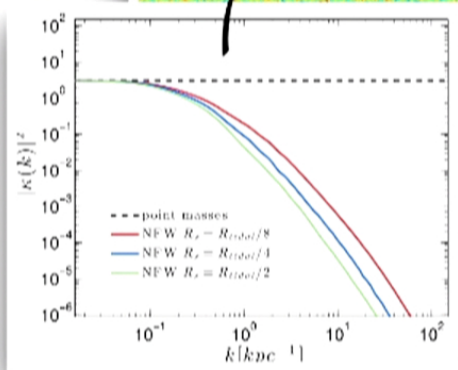
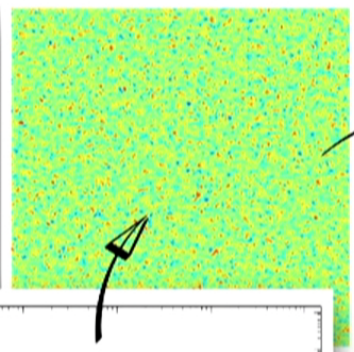
# POWER SPECTRUM OF SUBHALO DENSITY FIELD



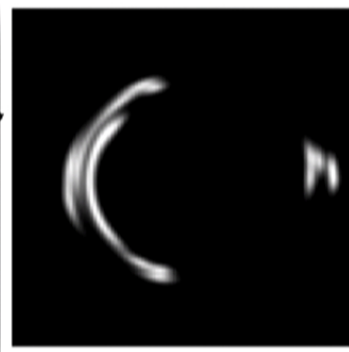
HEZAVEH ET AL 2014

# ANALYSIS OF MOCK OBSERVATIONS

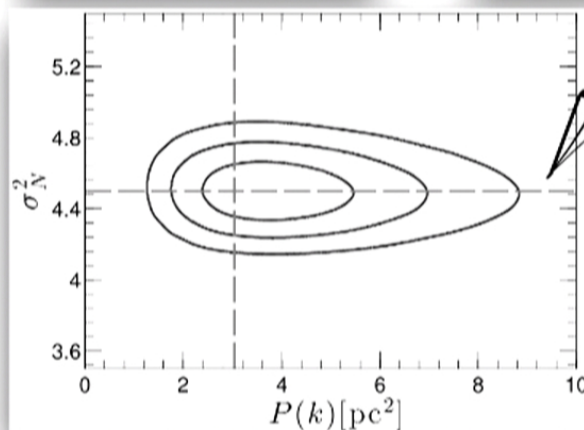
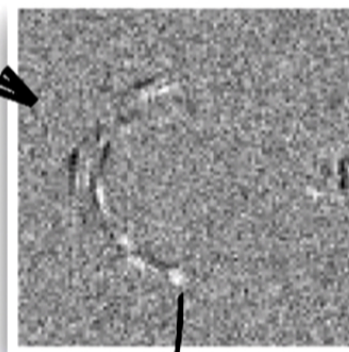
GENERATE A RANDOM SUBHALO DENSITY FIELD WITH A FLAT POWER SPECTRUM



GENERATE MOCK OBSERVATIONS USING A MACRO HALO AND THE SUBHALO DENSITY FIELD



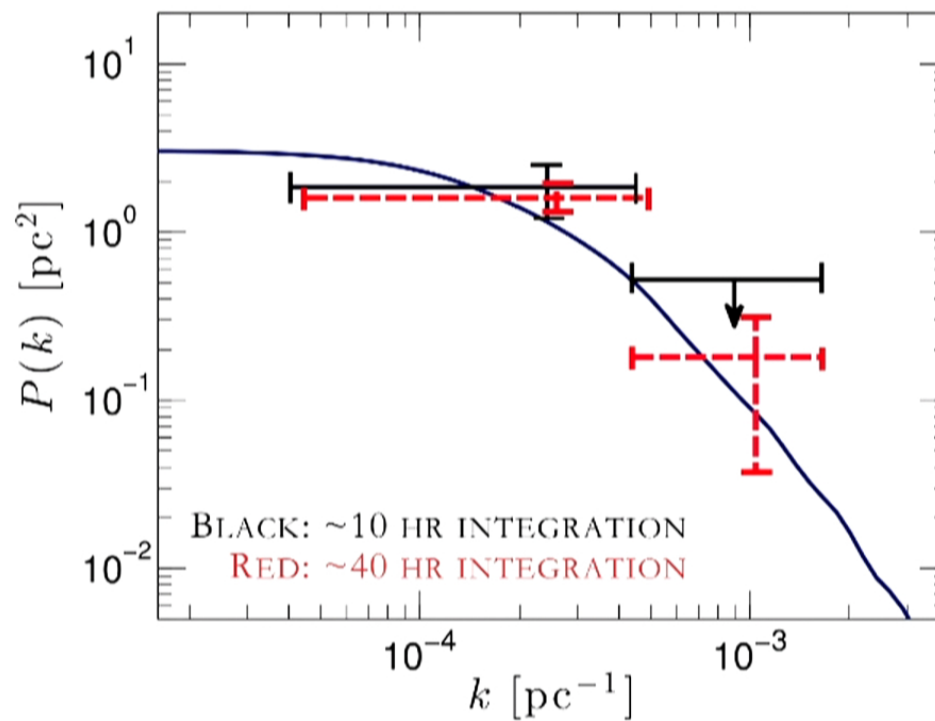
FIT THE MOCK DATA WITH A LENS MODEL WHICH ONLY HAS SMOOTH PARAMETERS



ESTIMATE THE LIKELIHOOD OF DIFFERENT COVARIANCE MATRICES USING THE RESIDUALS

HEZAVEH, ET AL 2014

## FORECAST FOR MEASURING THE DM SUBHALO POWER SPECTRUM

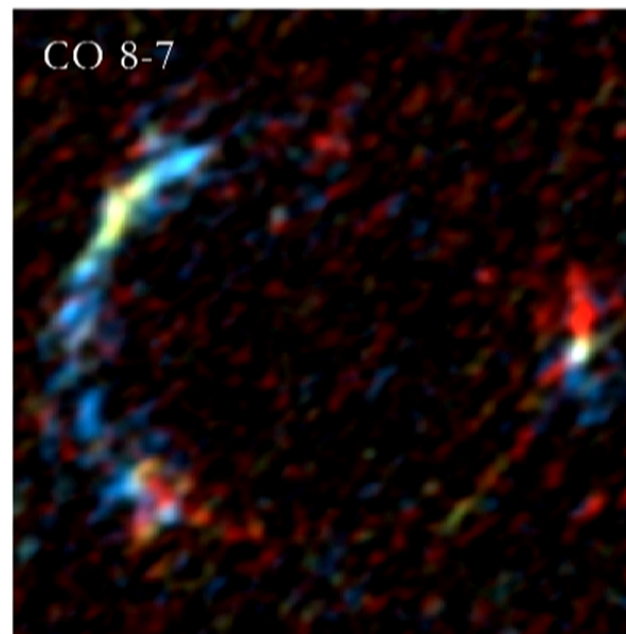
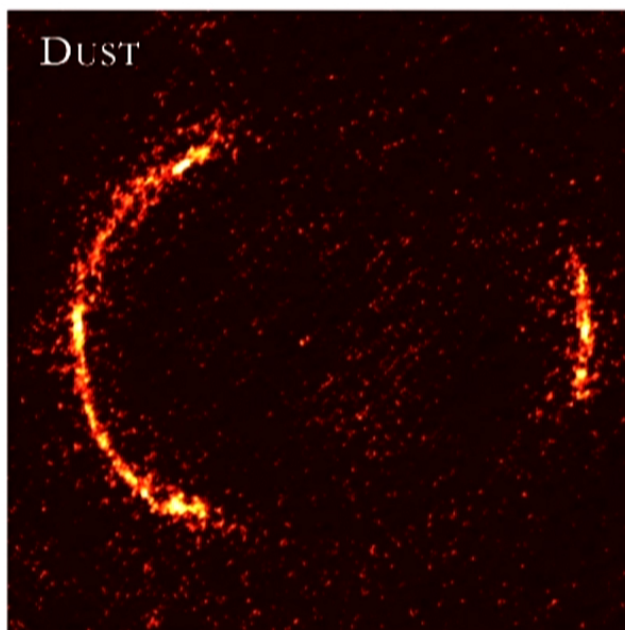


HEZAVEH, DALAL ET AL 2014



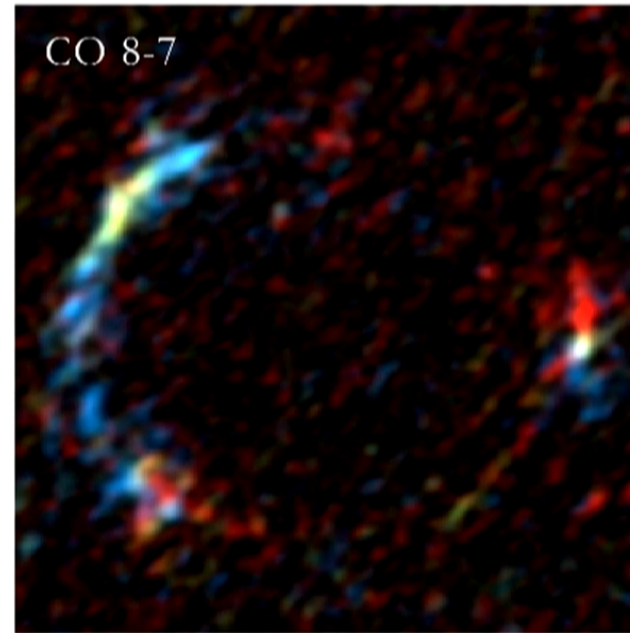
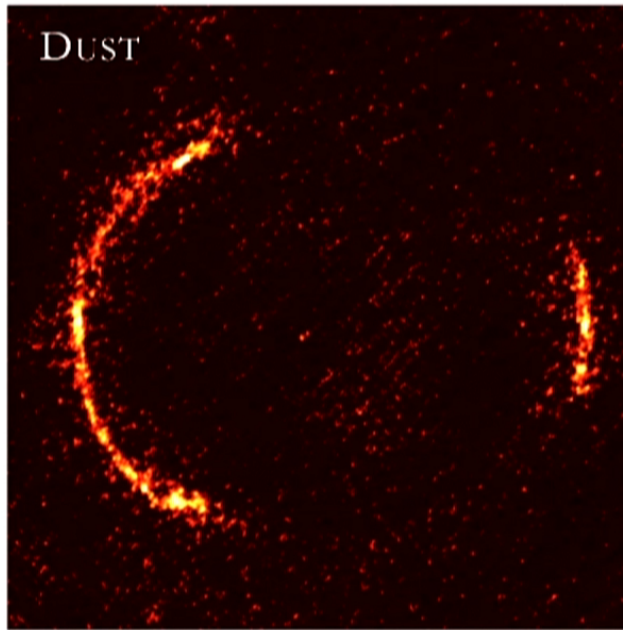
# SDP 81

(ALMA science verification data)



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(ALMA science verification data)



# SDP81 papers

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## THE INNER MASS DISTRIBUTION OF THE GRAVITATIONAL LENS SDP.81 FROM ALMA OBSERVATIONS

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### ABSTRACT

The central image of a strongly lensed background source places constraints on the foreground lens galaxy's inner mass profile slope, core radius and mass of its nuclear supermassive black hole. Using high-resolution long-baseline Atacama Large Millimeter/submillimeter Array (ALMA) observations and archival Hubble Space Telescope (HST) imaging, we model the gravitational lens H-ATLAS J090311.6+003906 (also known as SDP.81) and search for the demagnified central image. There is central continuum emission from the lens galaxy's active galactic nucleus (AGN) but no evidence of the central lensed image in any molecular line. We use the CO  $J=5-4$  map to determine the flux limit of the central image excluding the AGN continuum. We predict the flux density of the central image and use the limits from the ALMA data to constrain the inner mass distribution of the lens. For the core radius of  $0.15''$  measured from HST photometry of the lens galaxy assuming that the central flux is completely attributed to the AGN, we find that a black hole mass of  $\log(M_{\text{BH}}/M_{\odot}) \geq 8.4$  is preferred. Deeper observations with a detection of the central image will significantly improve the constraints of the inner mass distribution of the lens galaxy.

Subject headings: gravitational lensing: strong

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## High-resolution ALMA observations of SDP.81. I. The innermost mass profile of the lensing elliptical galaxy probed by 30 milli-arcsecond images

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## High-resolution ALMA Observations of SDP.81. II. Molecular Clump Properties of a Lensed Submillimeter Galaxy at $z = 3.042$

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## ALMA imaging of SDP.81 – I. A pixel-by-pixel analysis of the far-infrared continuum emission

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In original form 2015 March 4

### ABSTRACT

We present a sub-50 pc-scale analysis of the gravitational lens SDP.81 using Atacama Large submillimeter/millimeter Array data. These were taken at 236 and 290 GHz using baselines

## Revealing the complex nature of the lensed system H-ATLAS J090311.6+003906

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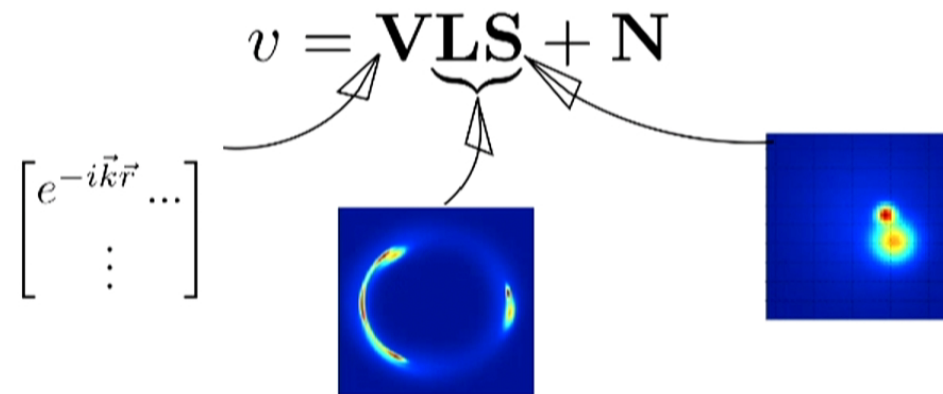
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# Pixelated Source Lens Modeling

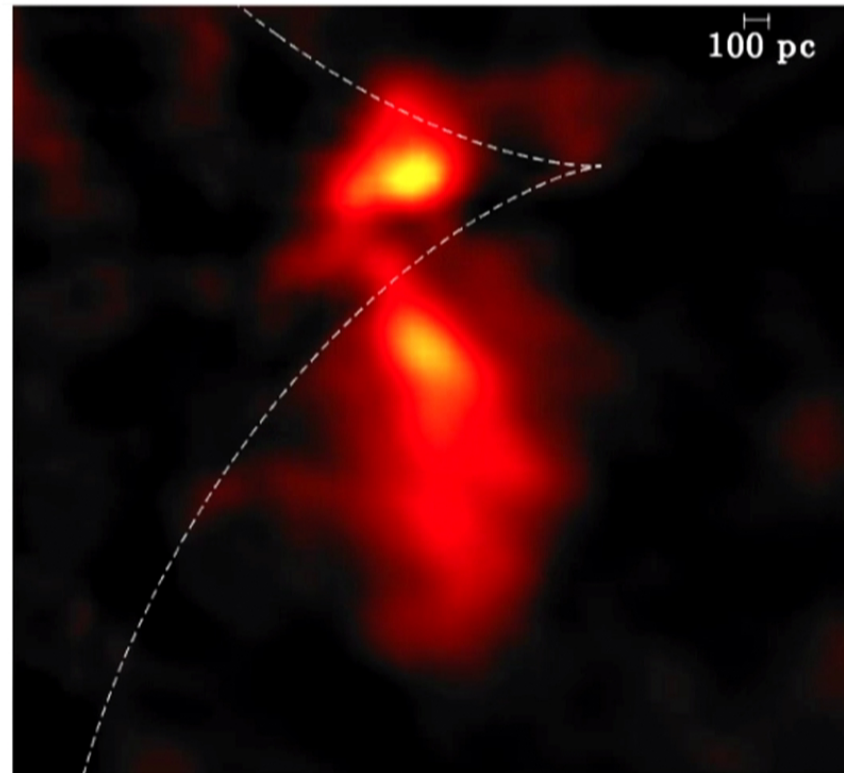


$$\chi^2 = (v_d - v)\mathbf{C}_n^{-1}(v_d - v) + \mathbf{S}\mathbf{C}_s^{-1}\mathbf{S}$$

$$\partial\chi^2/\partial\mathbf{S} = 0 \quad \text{AND SOLVE FOR S}$$

# SDP.81 Source Reconstruction

- here showing the source for the best-fit smooth lens model
- joint estimate of lensing potential and source morphology
  - prior on power spectrum of source



# Summary

- large samples of strongly lensed galaxies found at mm and submm wavelengths
- ALMA observations well-matched for high resolution reconstruction of source and lens properties
- dark matter substructure should be detectable with current ALMA capabilities, stay tuned for results soon