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

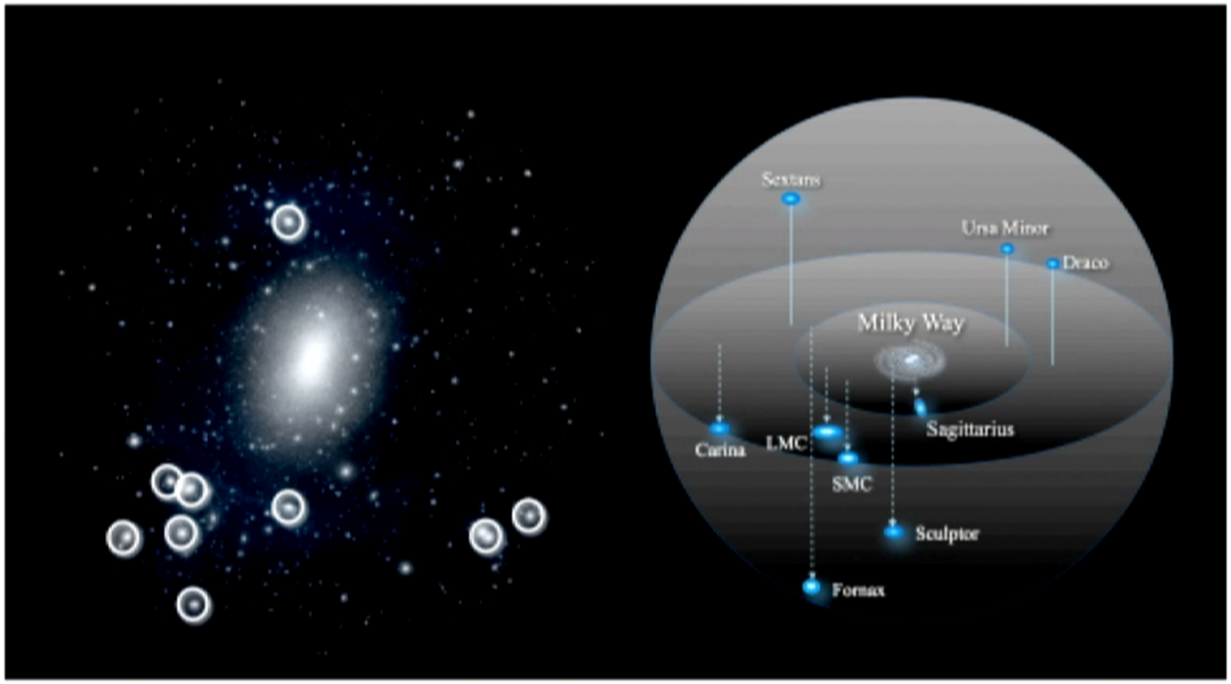
Date: Jul 16, 2015 11:00 AM

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

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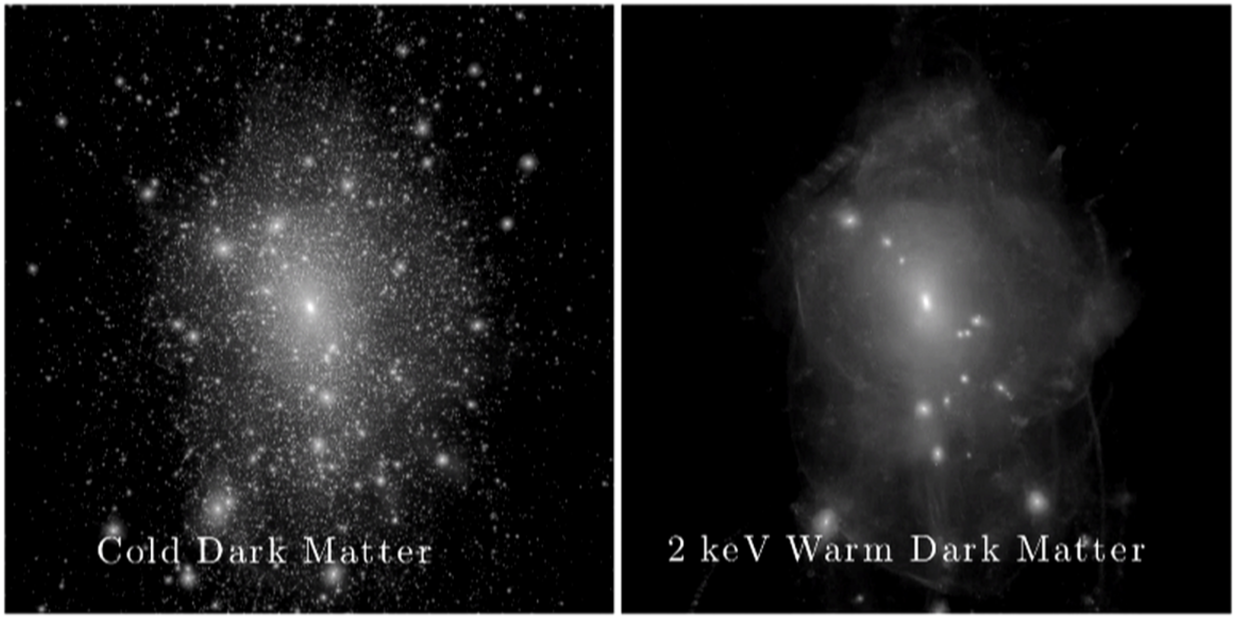
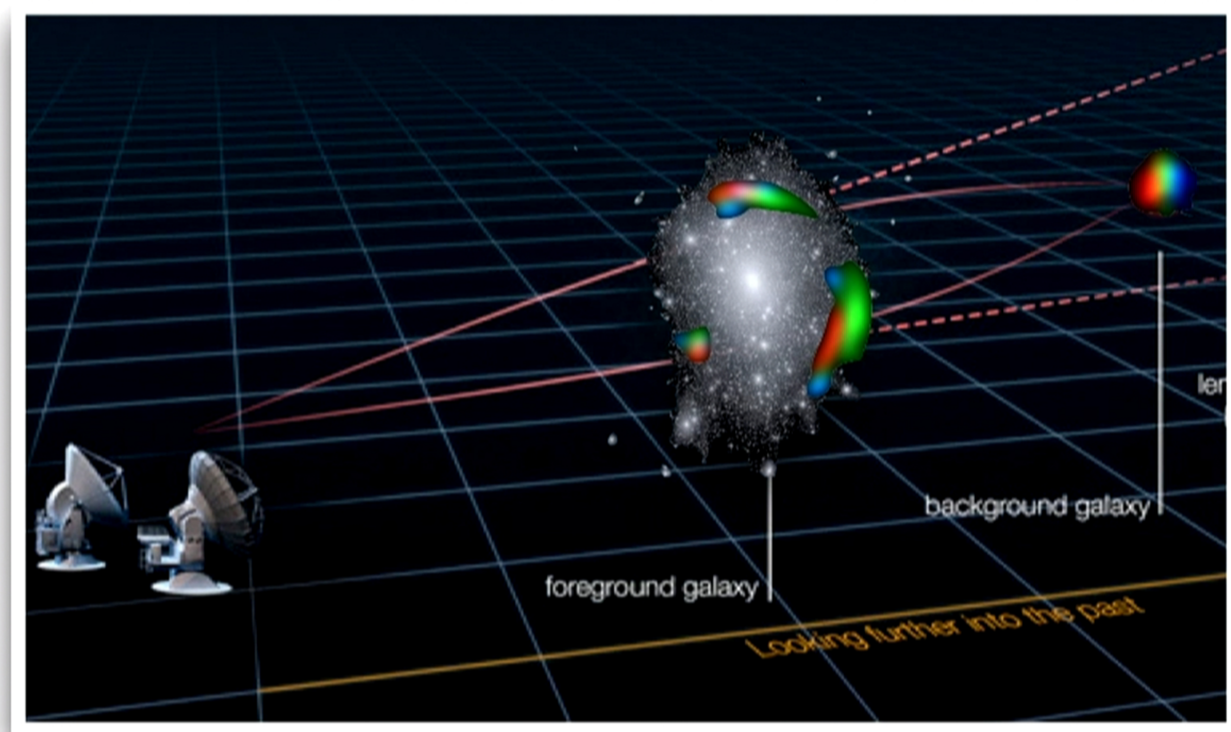
Possible Solutions

BARYONIC GASTROPHYSICS   DARK MATTER PHYSICS

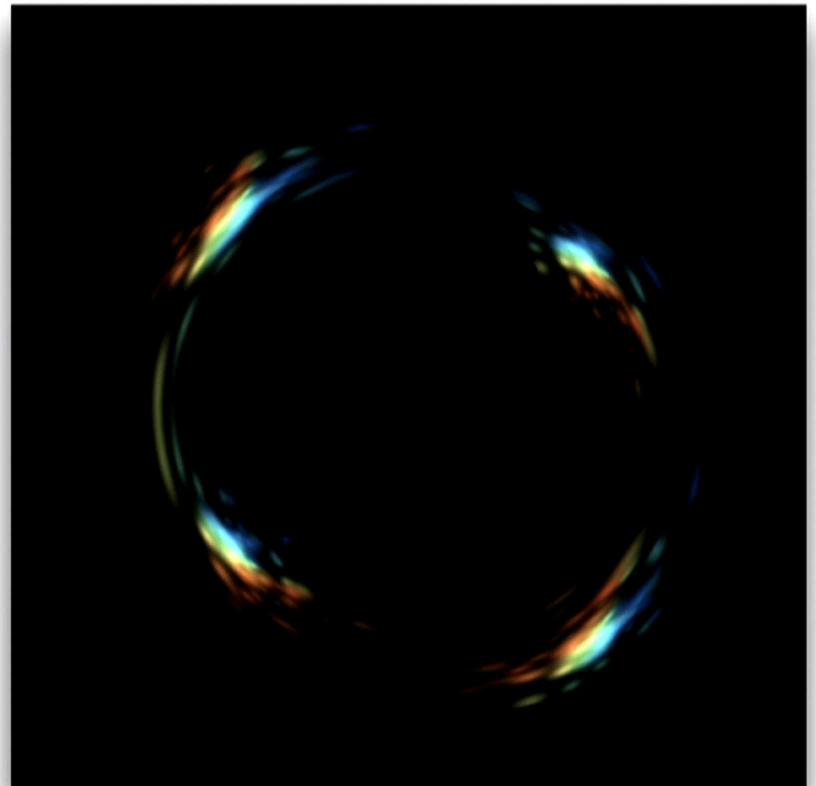


LOVELL ET AL 2012, MNRAS 420, 3

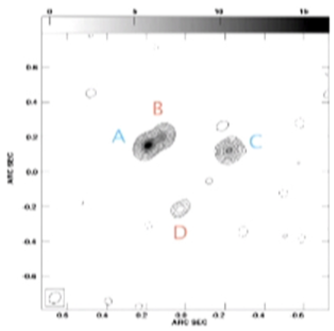
Strong Gravitational Lensing



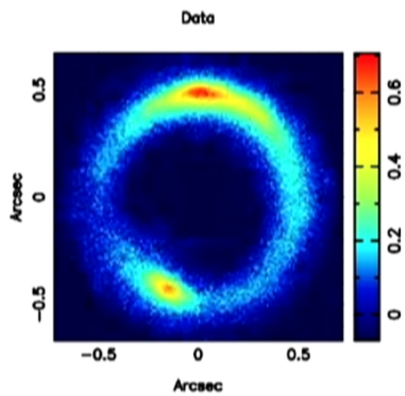
Substructure Lensing



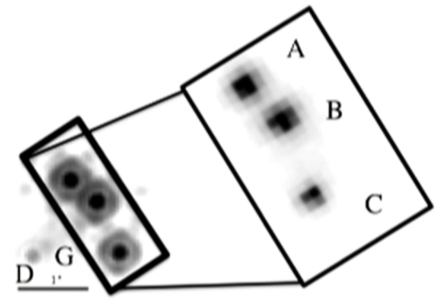
Substructure Lensing



Dalal & Kochenak 2002

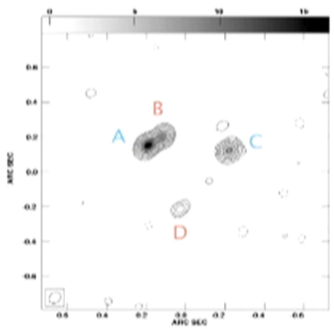


Vegetti et al. 2012

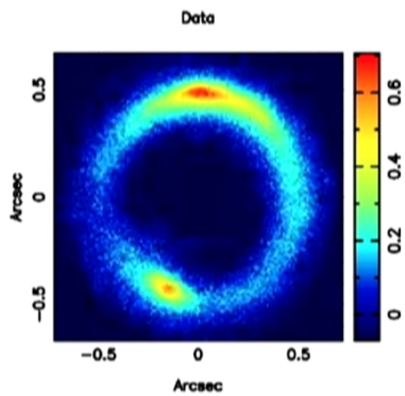


Nierenberg et al. 2014

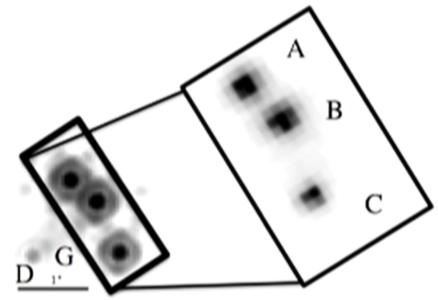
Substructure Lensing



Dalal & Kochenak 2002



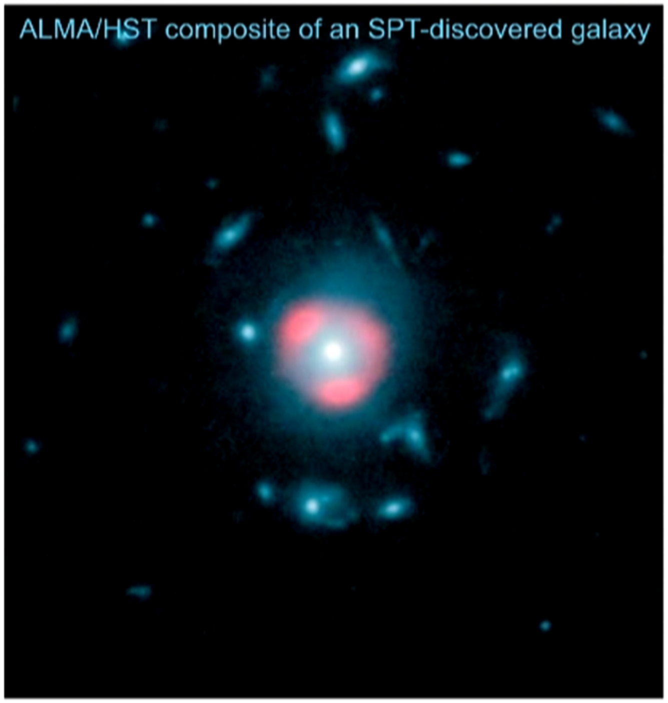
Vegetti et al. 2012



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

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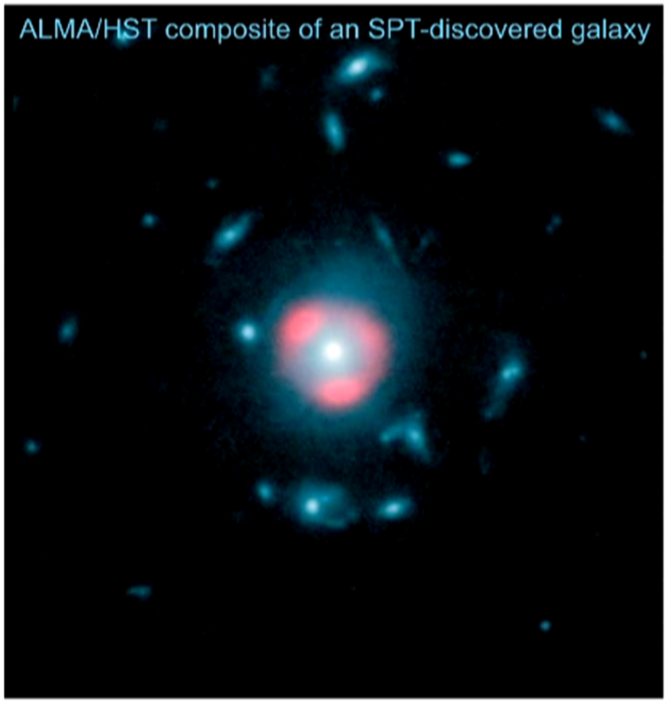

Vieira et al 2013

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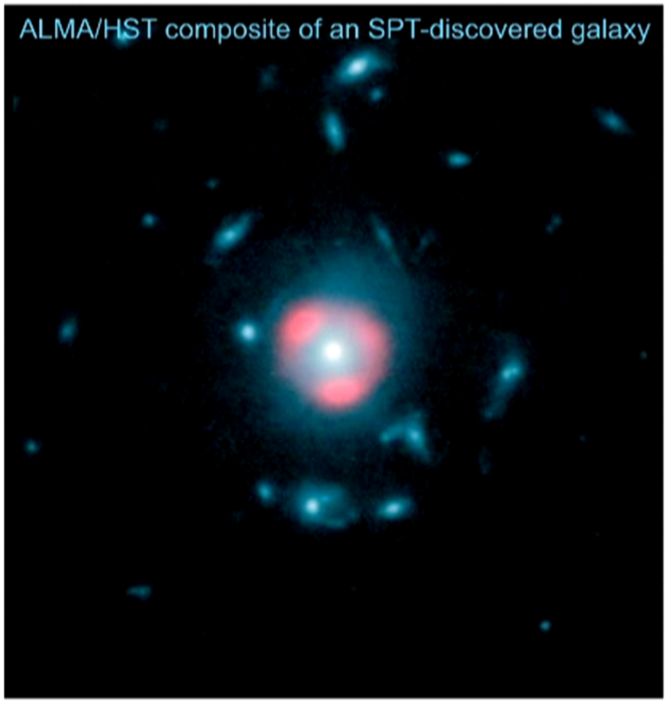
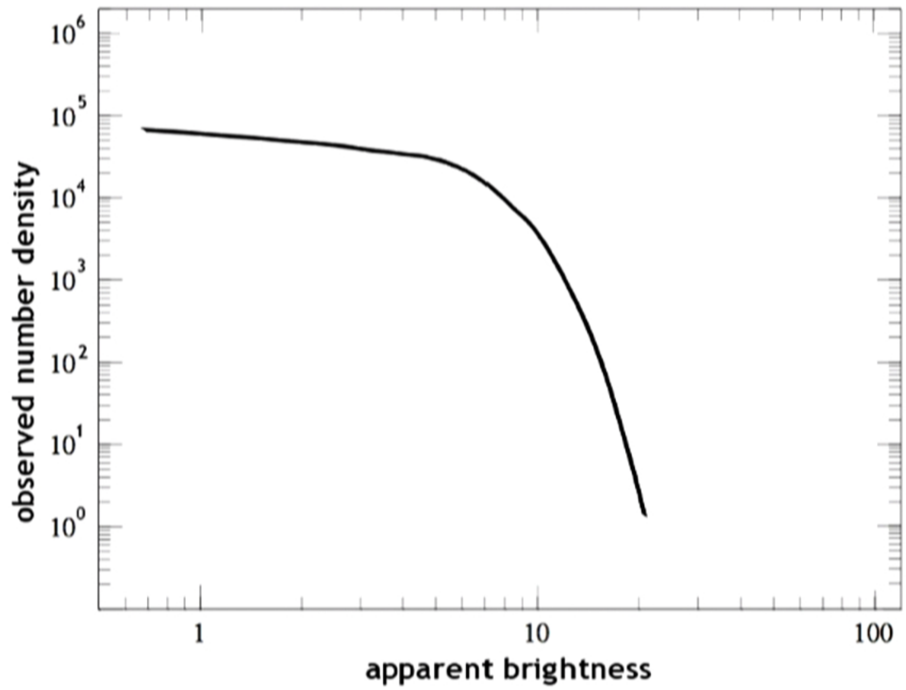
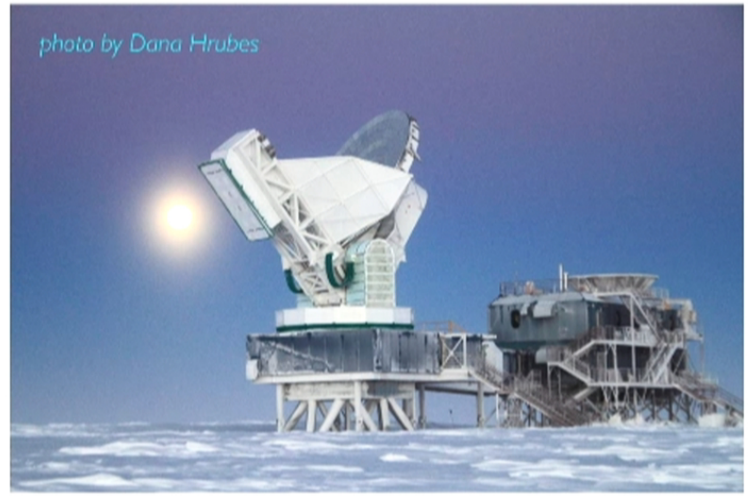


Vieira et al 2013

Number Counts of high-z Galaxies



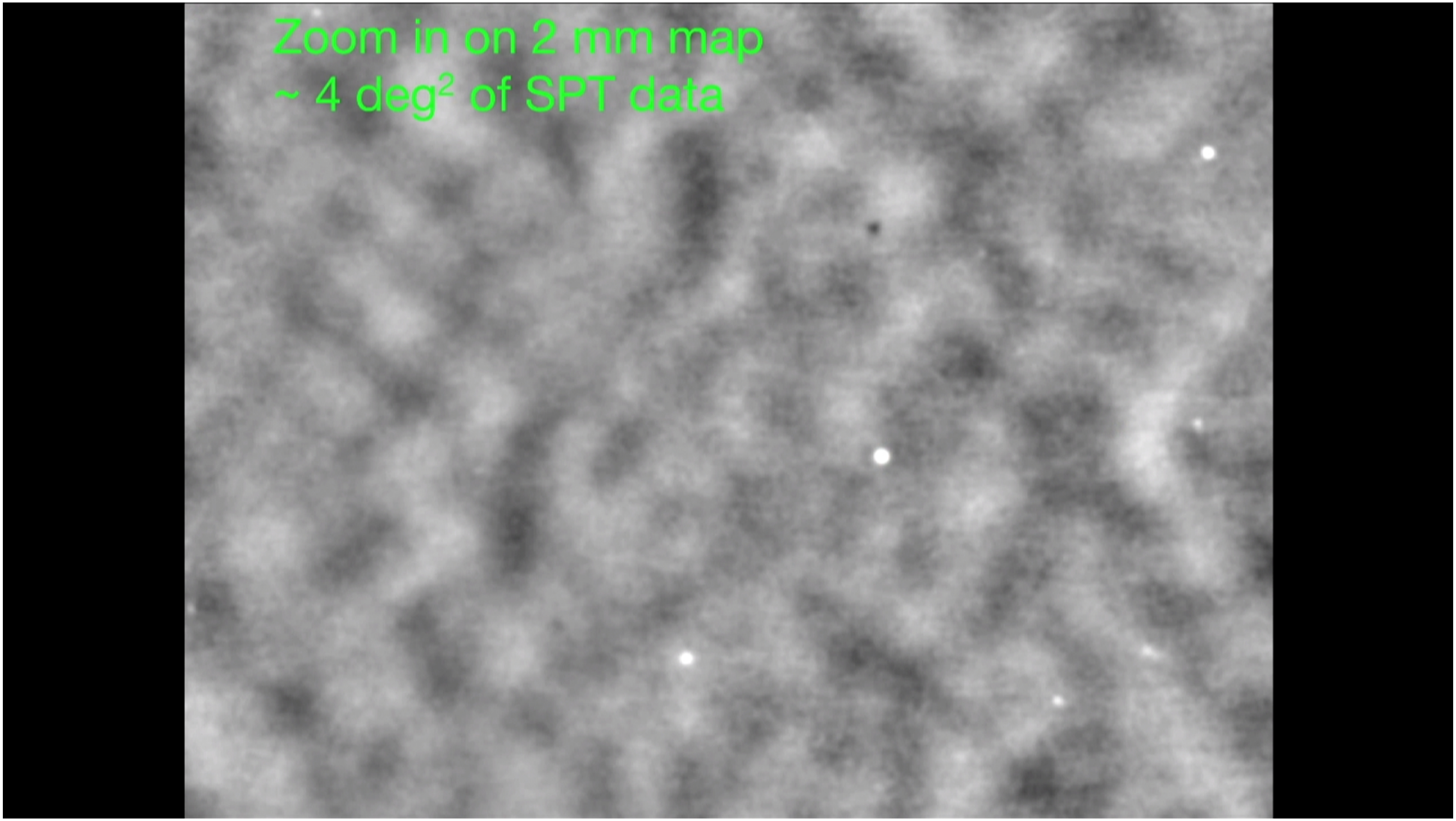
South Pole Telescope

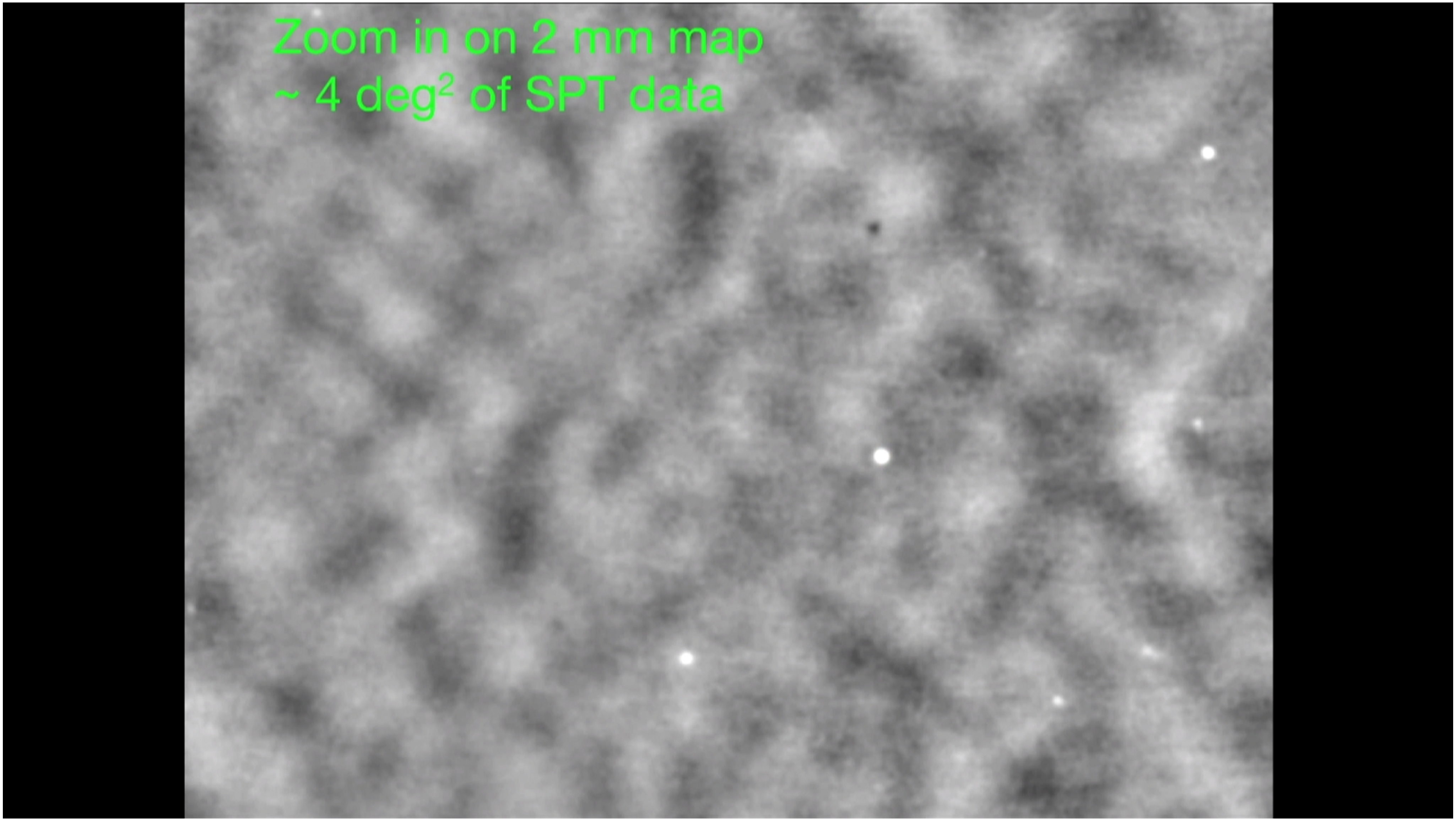


10 m mm-wave (3 different wavelengths) telescope at the south pole

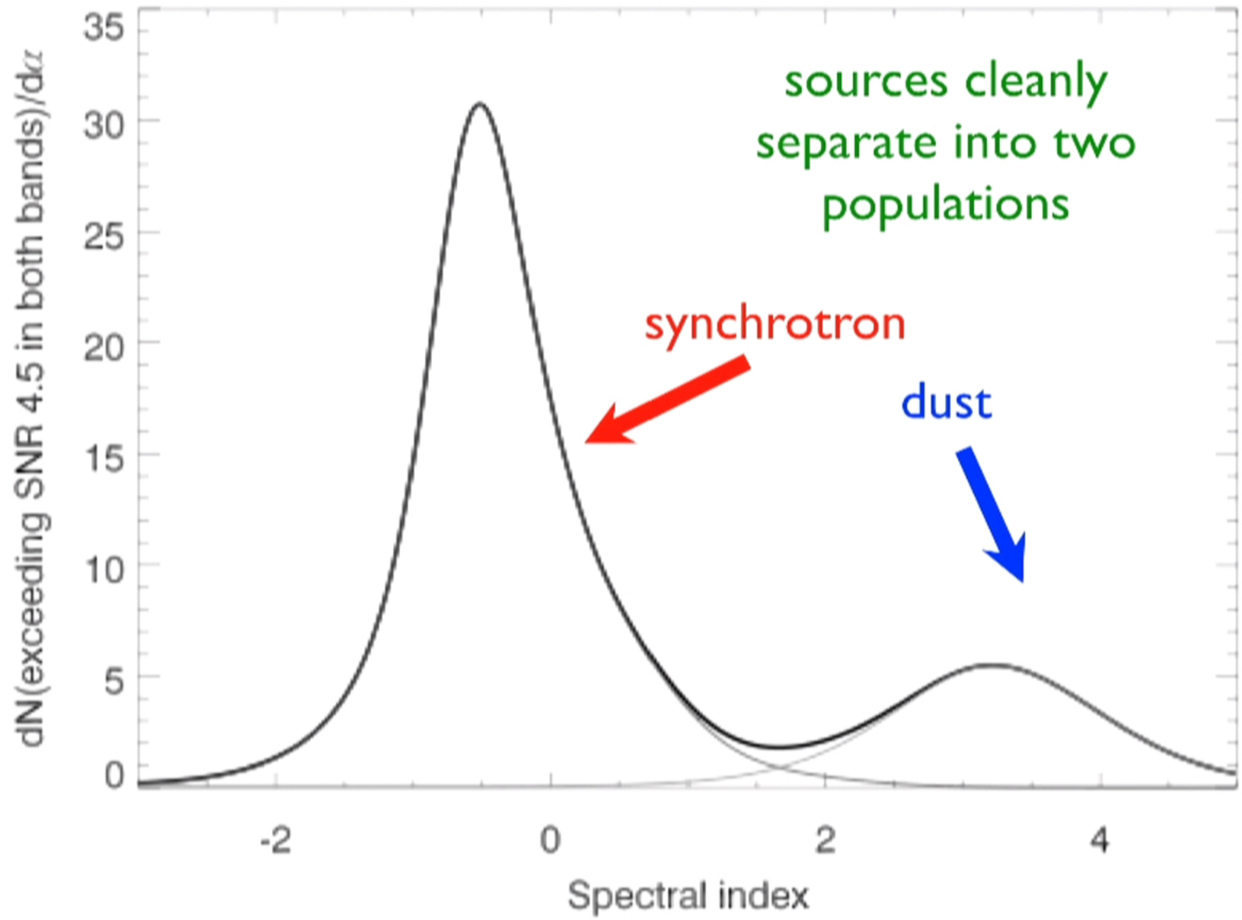
- extremely dry
- very stable
- good support

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

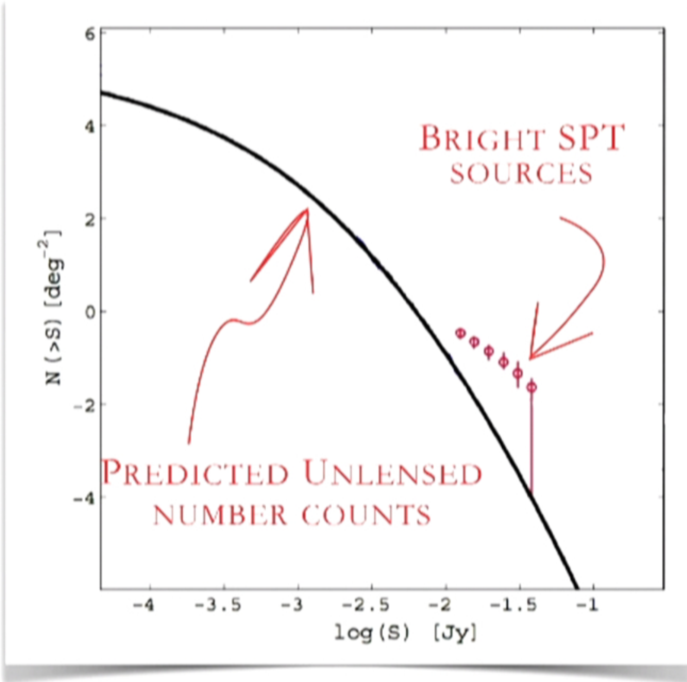

Zoom in on 2 mm map
~ 4 deg^2 of SPT data

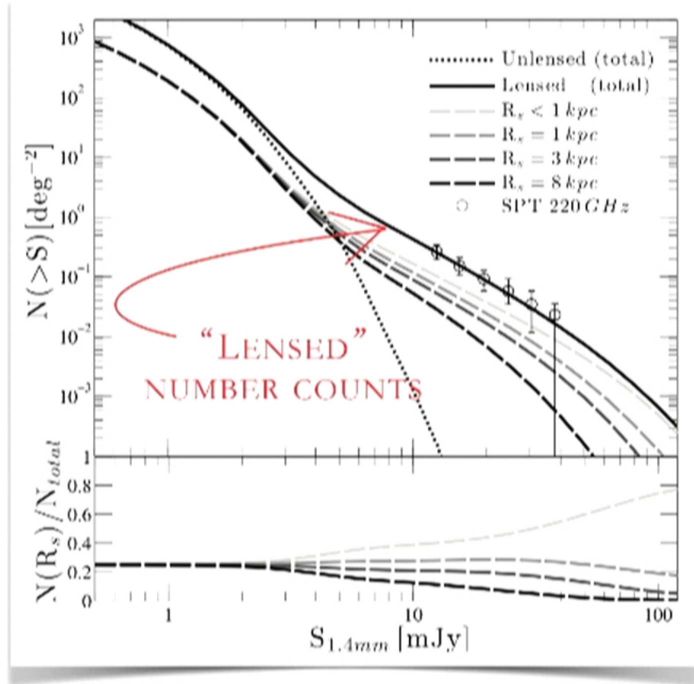

Zoom in on 2 mm map
~ 4 deg^2 of SPT data

Distribution of Spectral Indices



Number Counts of Lensed Galaxies

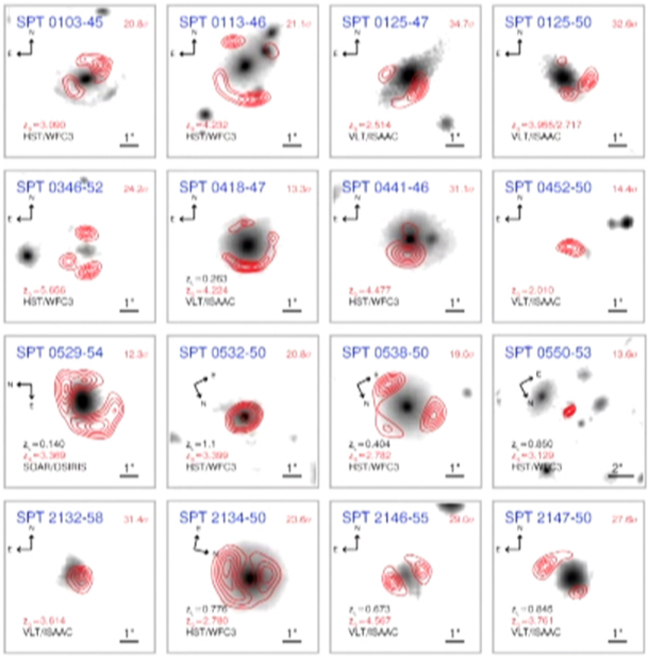




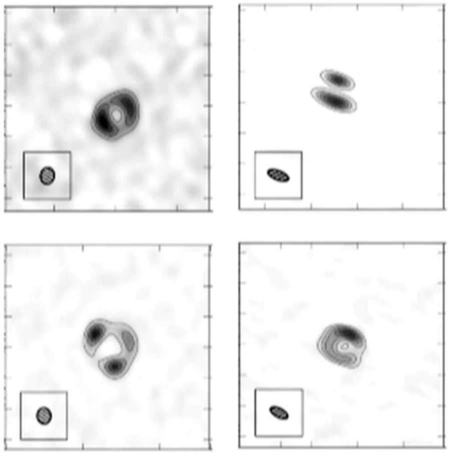
HEZAVEH & HOLDER 2011 APJ

HEZAVEH, MARRONE, & HOLDER 2012 APJ

SPT Strong Lenses

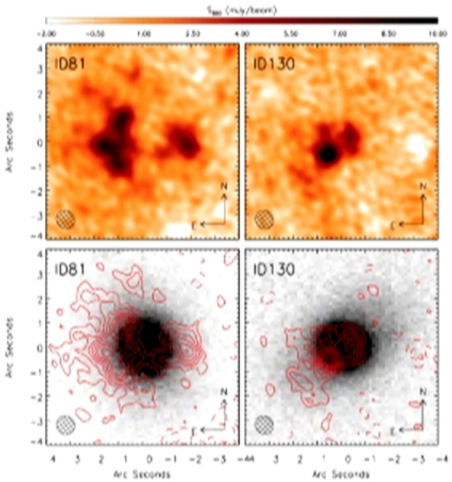


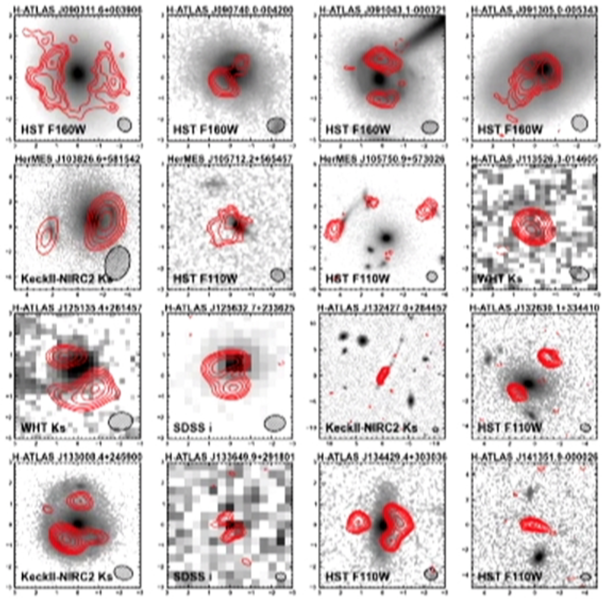
VIEIRA ET AL. NATURE 2013



HEZAVEH ET AL. APJ. 2013

Herschel Strong Lenses



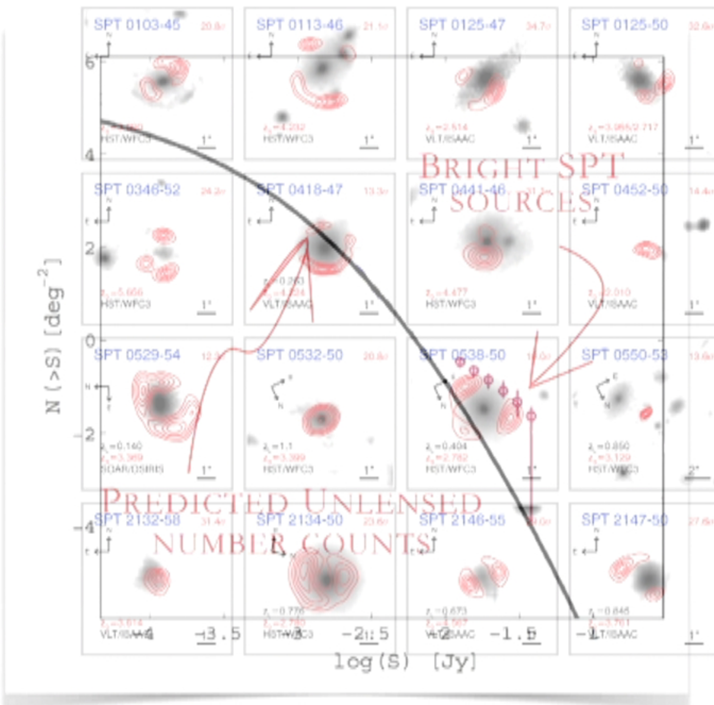


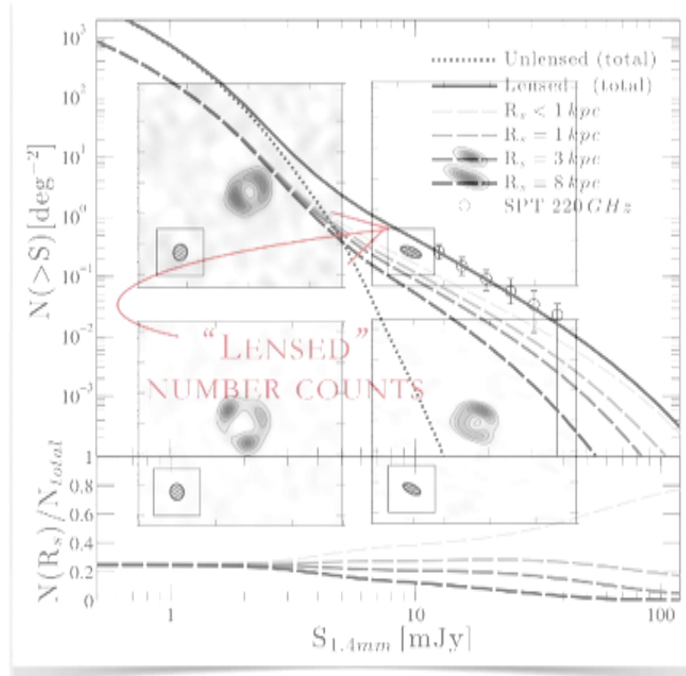
NEGRELLO ET AL. SCIENCE 2010

BUSSMANN ET AL. APJ 2013

Number Counts of Lensed Galaxies

SPT Strong Lenses





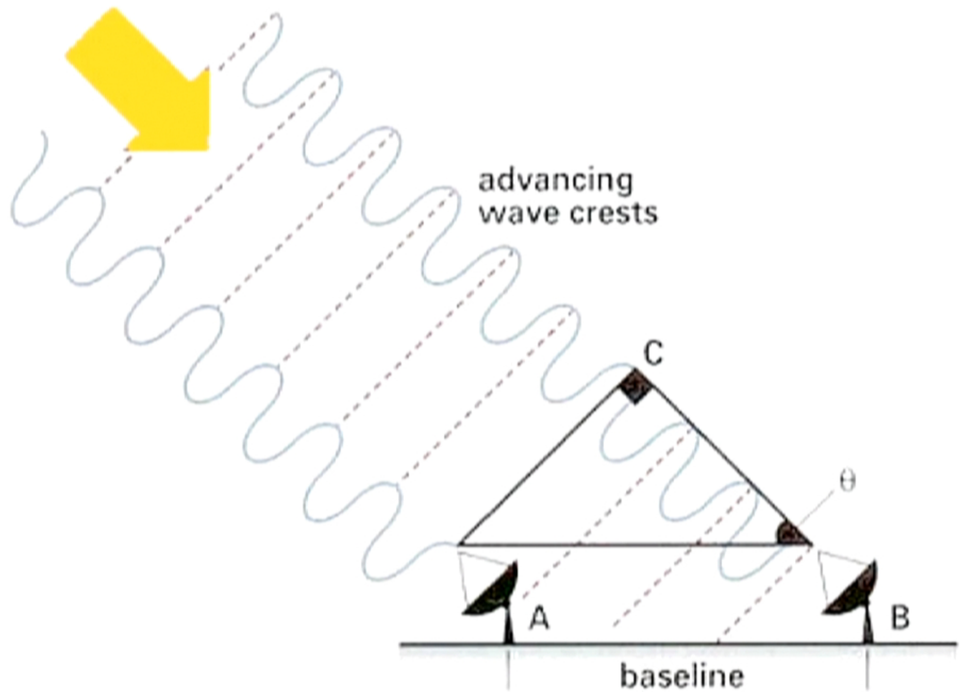
Hezaveh & Holder 2011 ApJ

Vieira et al. Nature 2013

Hezaveh, Marrone, & Holder 2012 ApJ

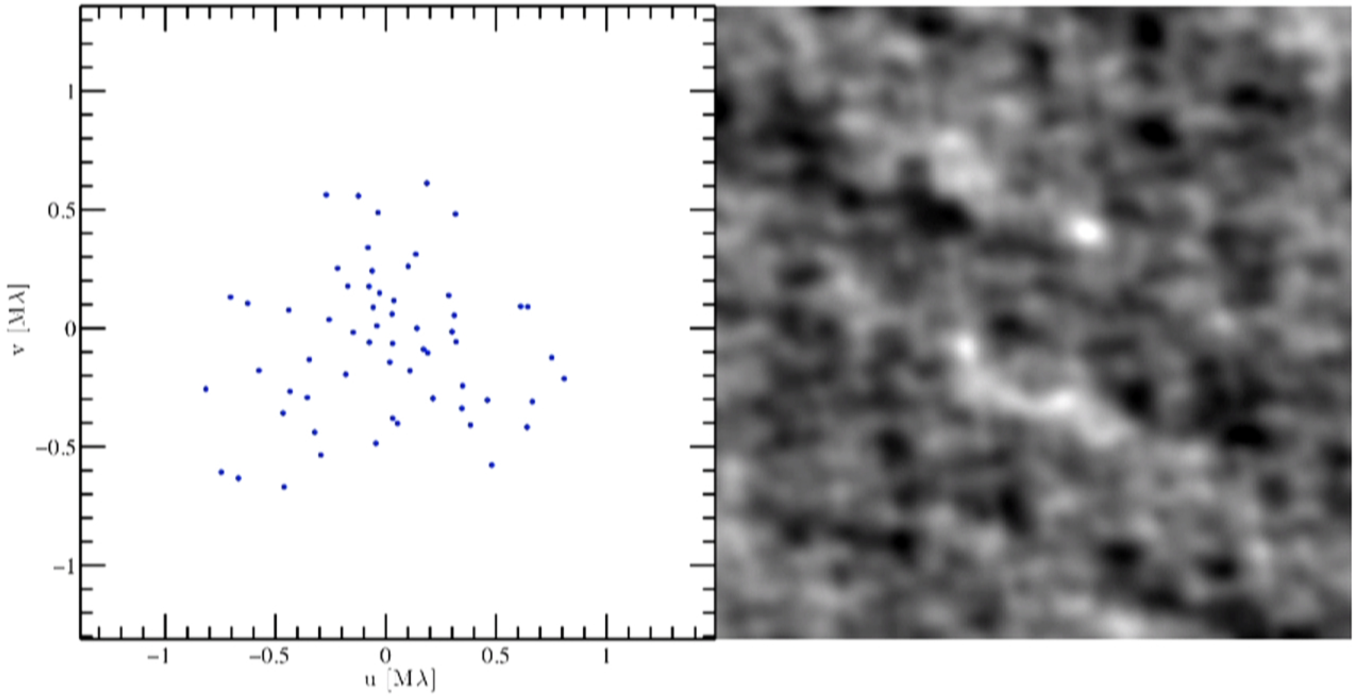
Hezaveh et al. ApJ. 2013

INTERFEROMETRY



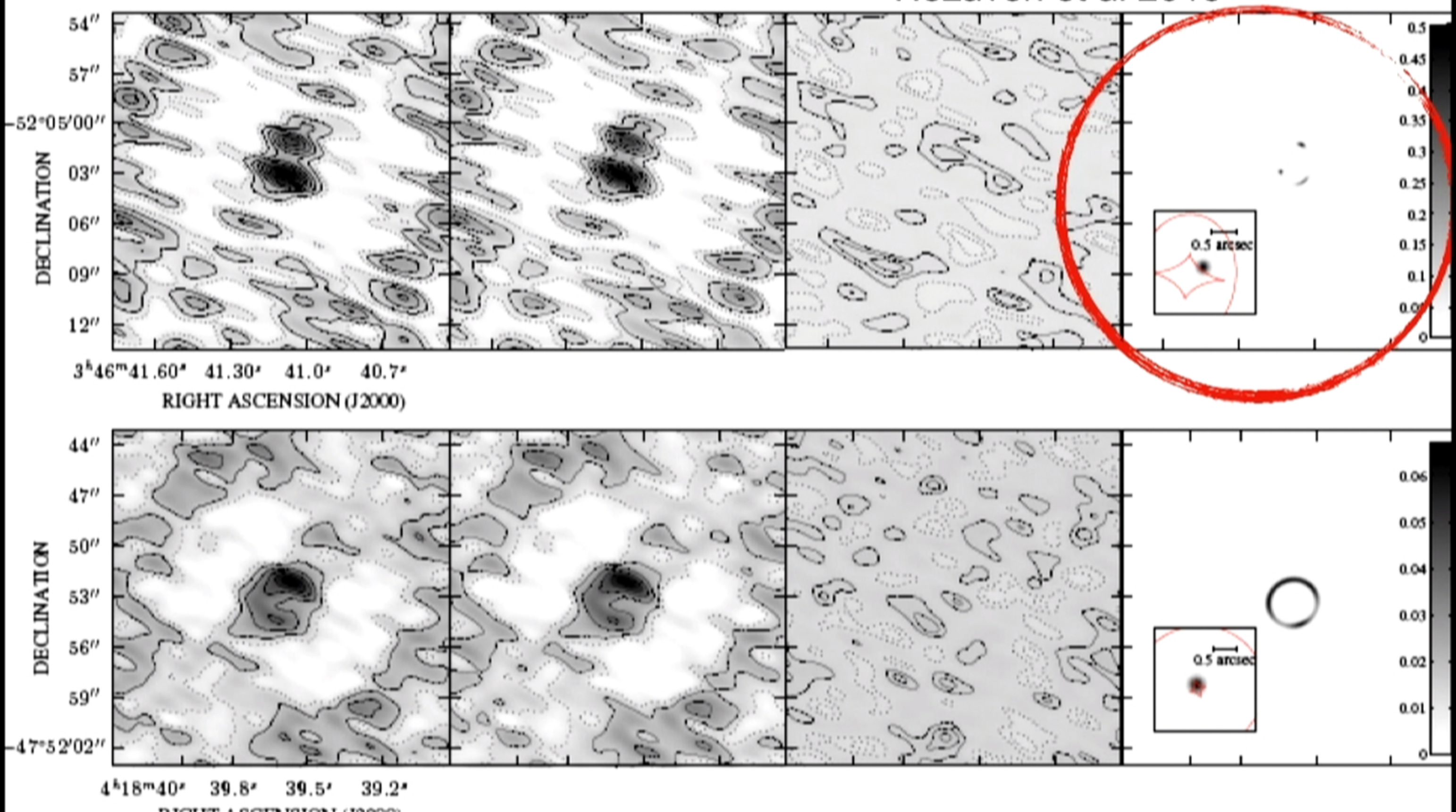
Interferometry

INTERFEROMETRY



Strong Lens Models

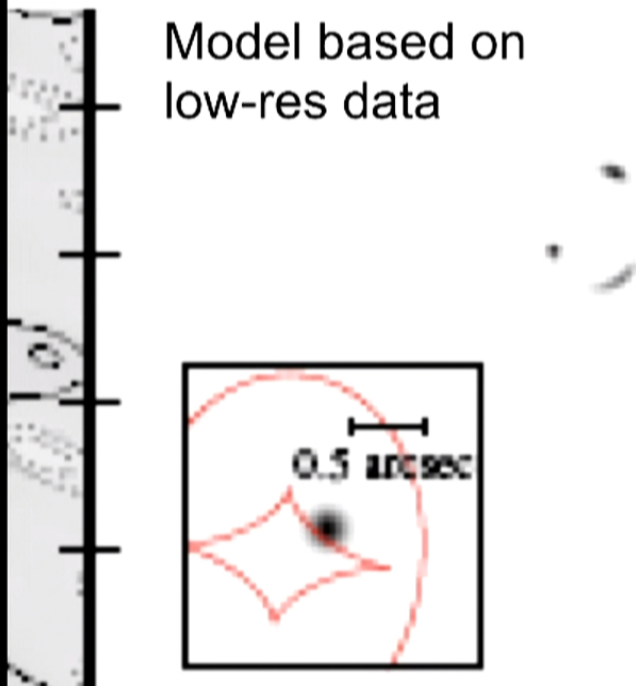
Hezaveh et al 2013

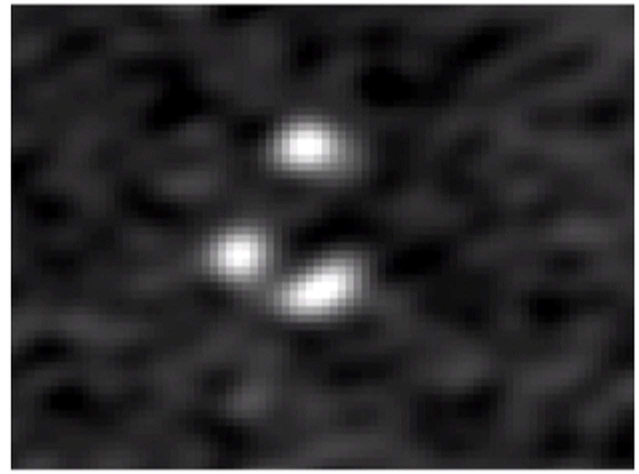


Strong Lens Models

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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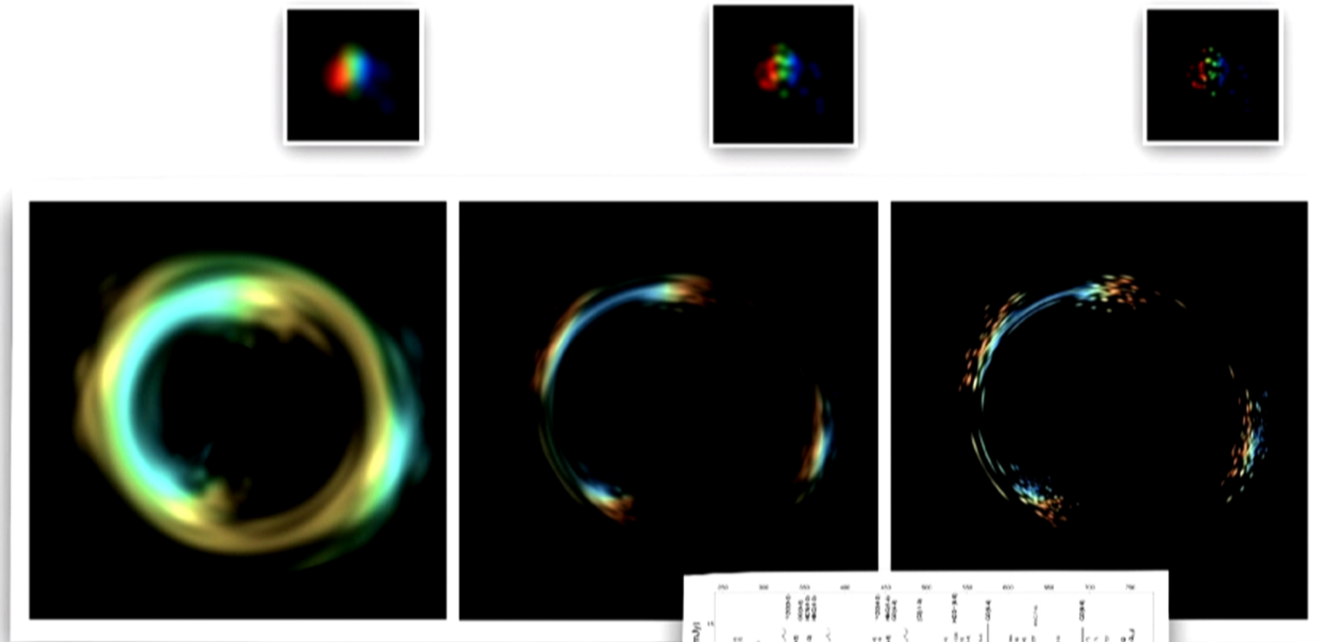
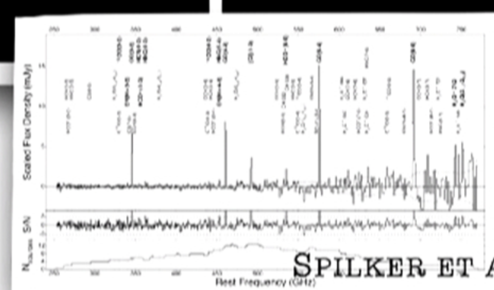
A Wealth of Molecular Lines

LOW EXCITATION GAS HIGH EXCITATION GAS



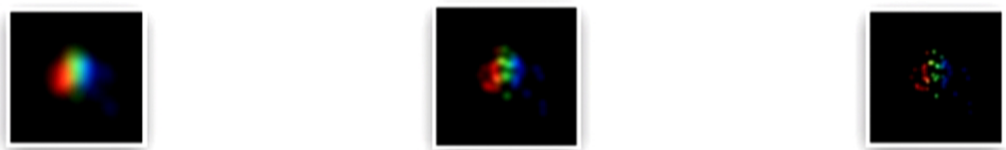


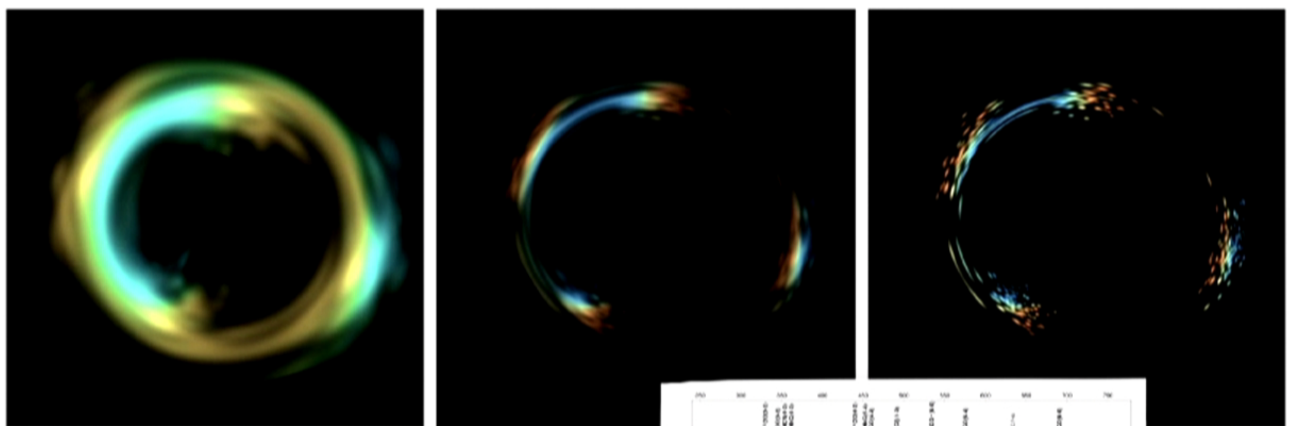
Spilker et al 2014, ApJ

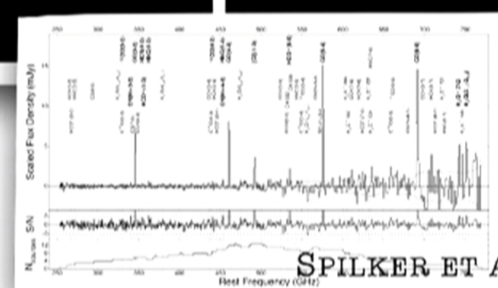
A Wealth of Molecular Lines

Low excitation gas

High excitation gas



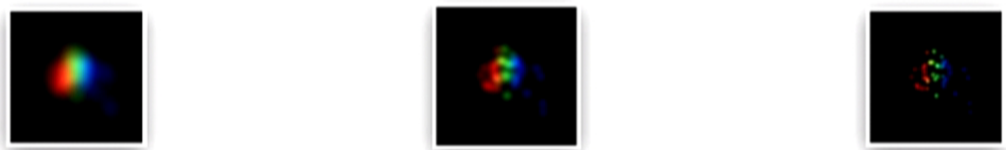


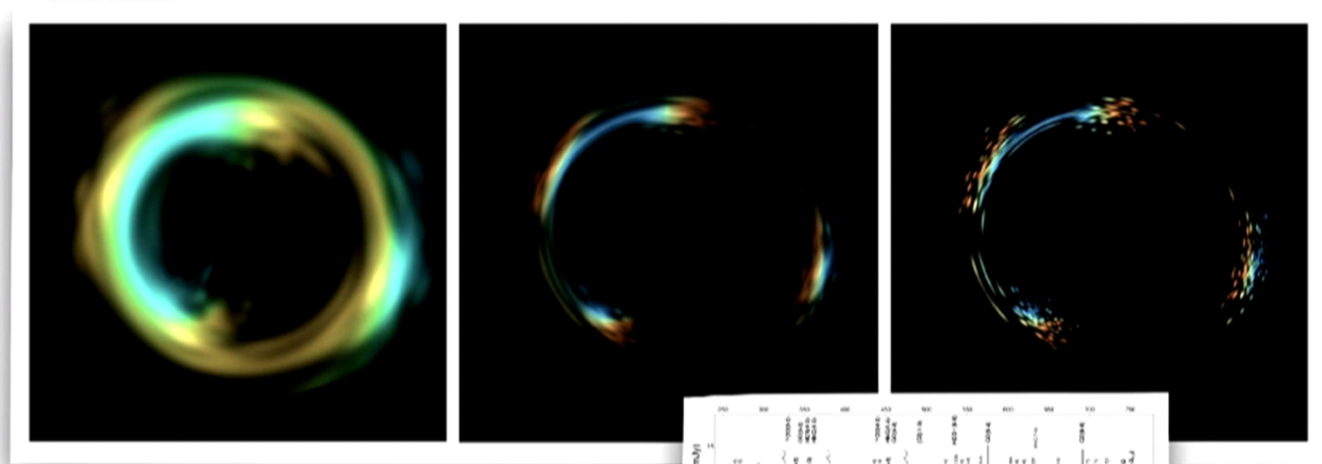


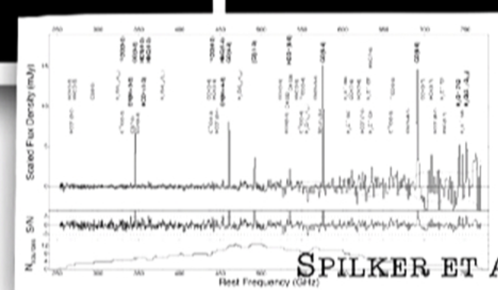
Spilker et al 2014, ApJ

A Wealth of Molecular Lines

LOW EXCITATION GAS — HIGH EXCITATION GAS

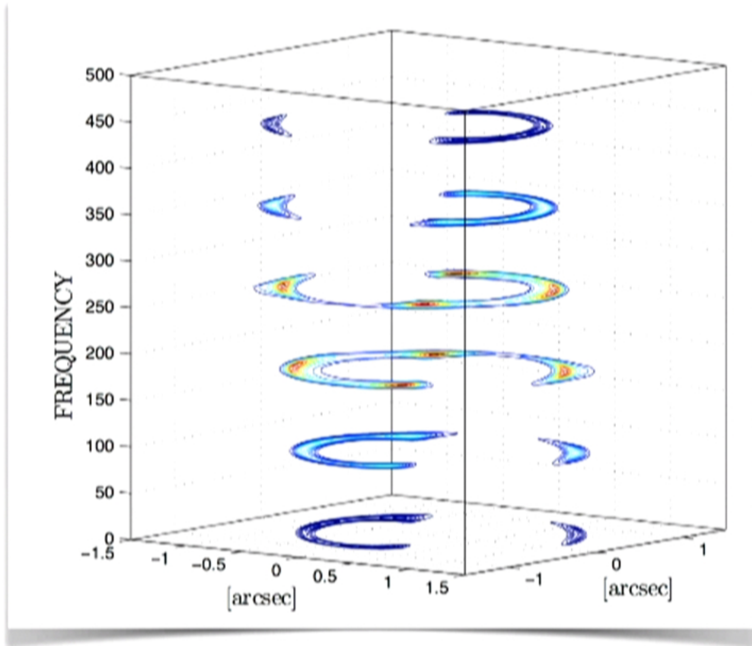




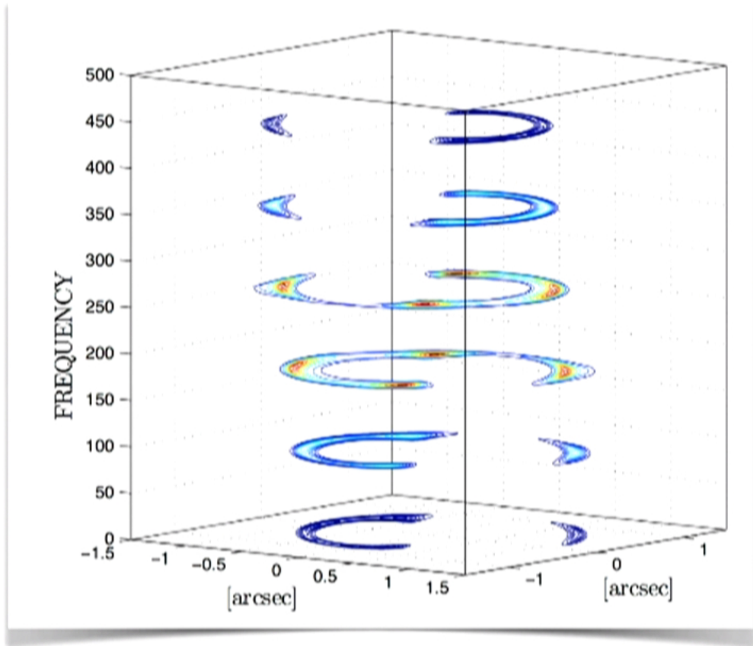


Spilker et al 2014, ApJ

Multiwavelength Lensing



Multiwavelength Lensing

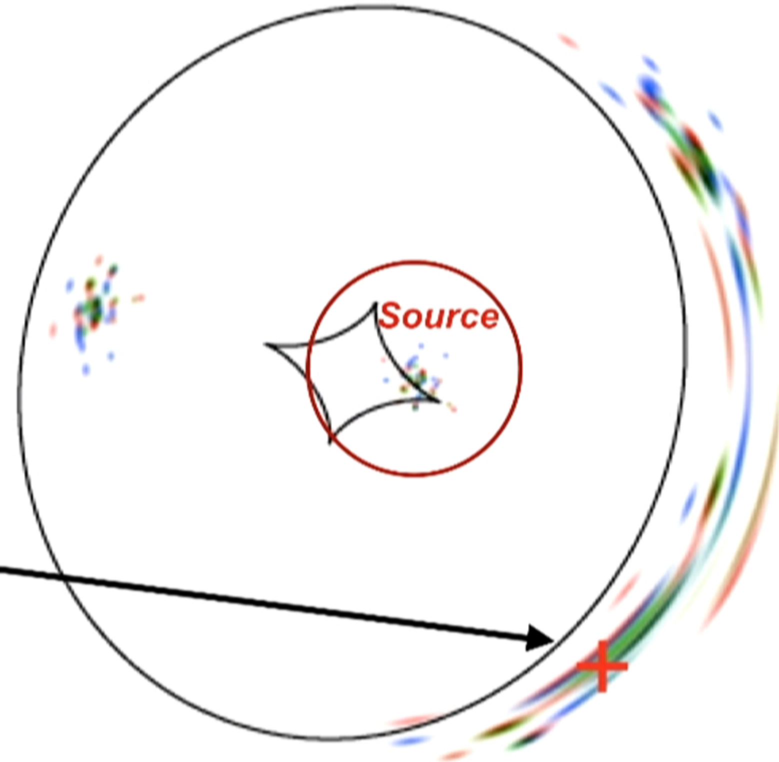


Probing Dark Matter Lumps with Strong Lensing (Simulated Observations)

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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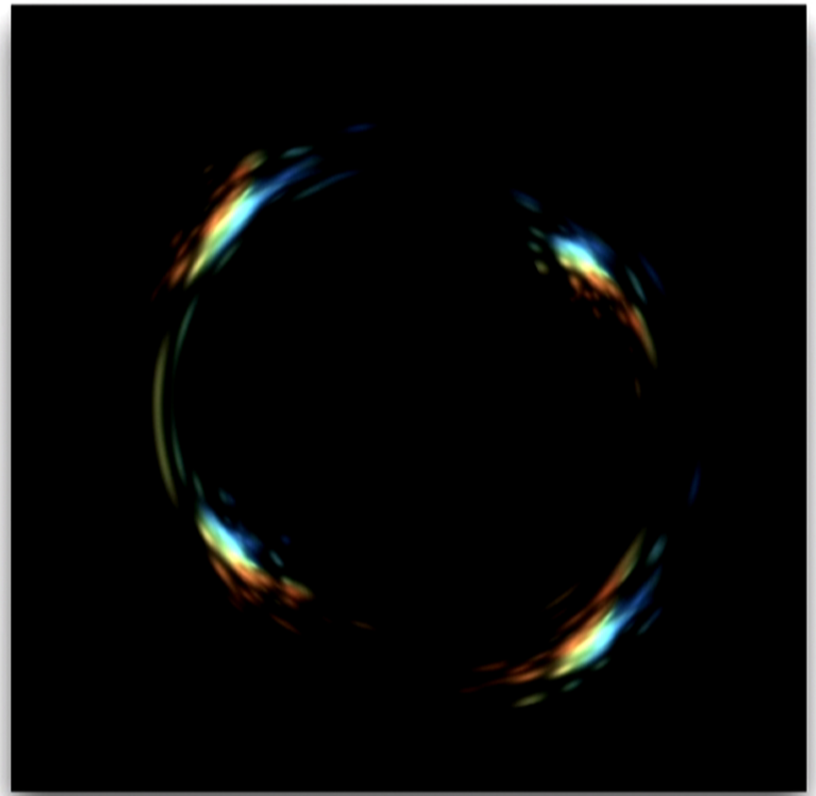
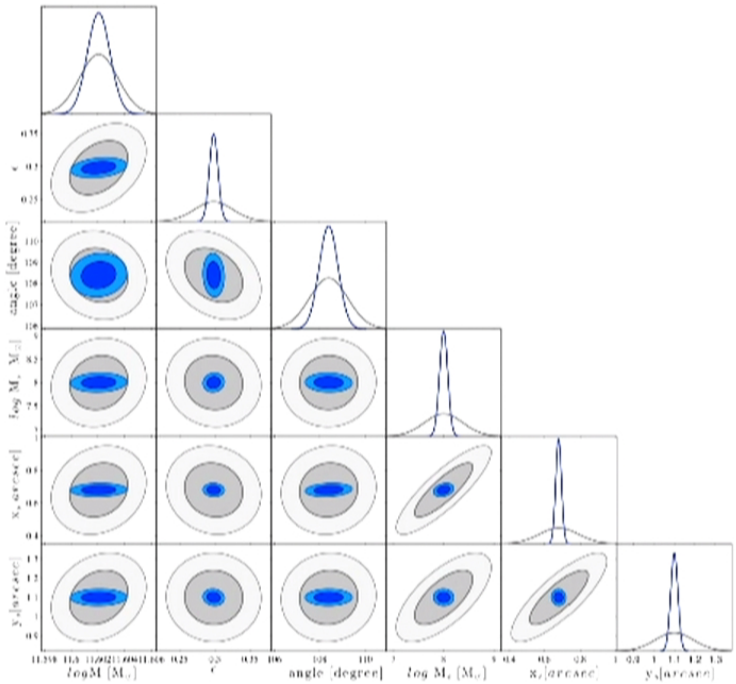
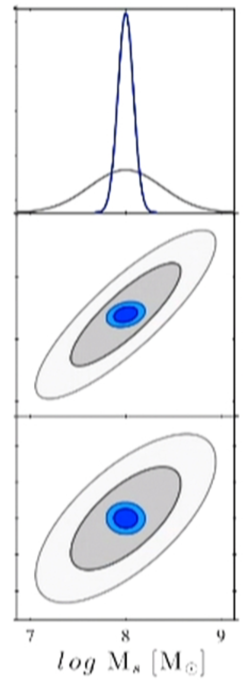
SUBSTRUCTURE LENSING



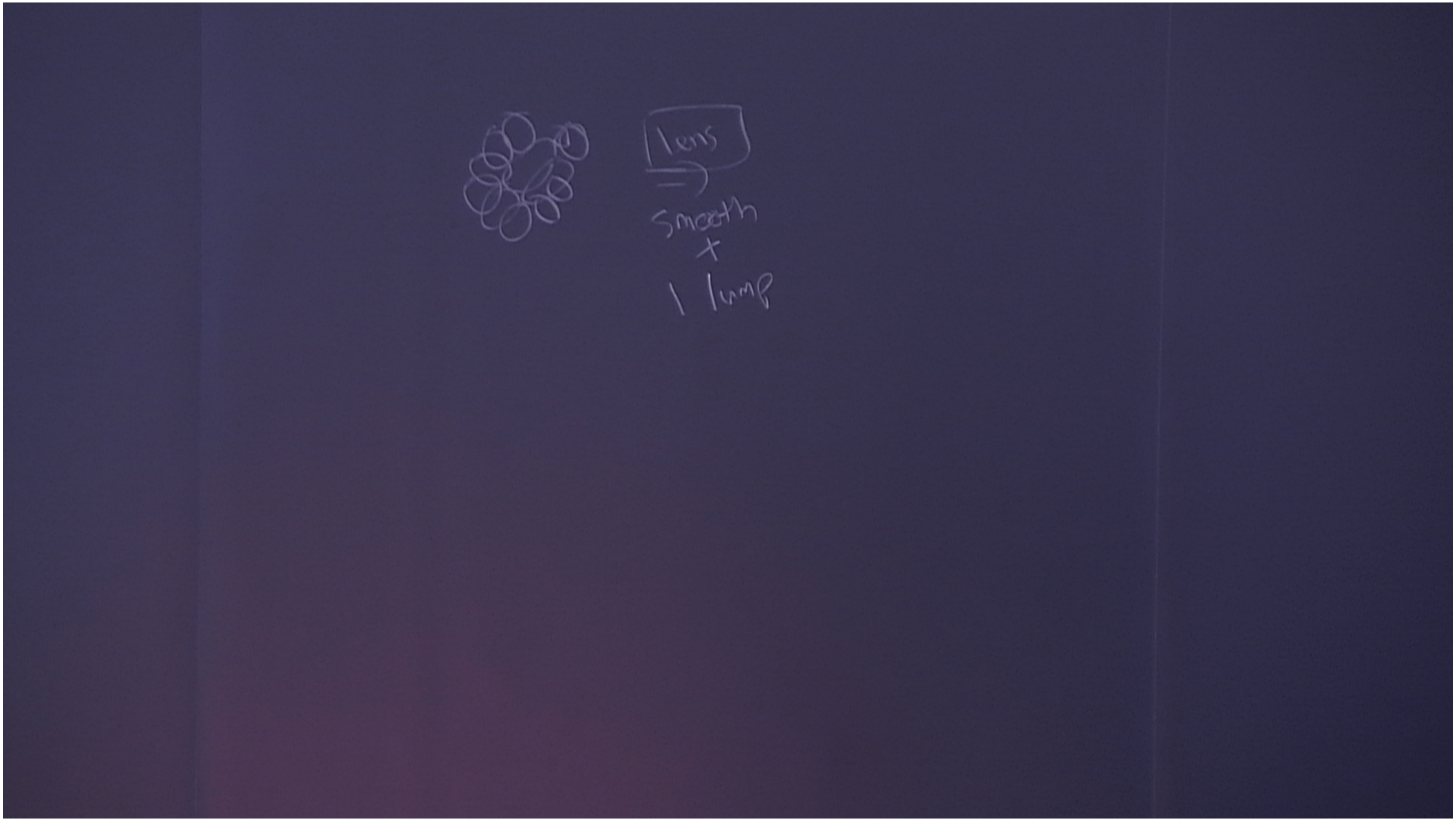
Sensitivity Analysis of Detecting DM Subhalos



After marginalizing over ~60 source parameters

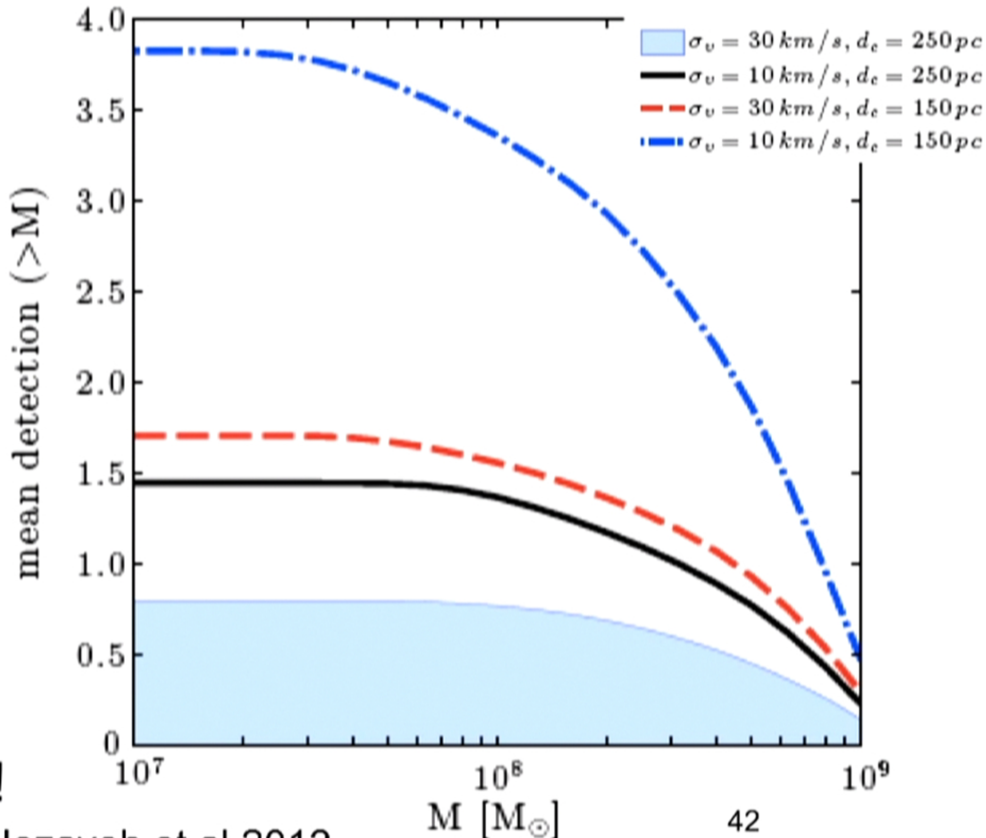


Hezaveh et al 2013, ApJ. 767, 9


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!



Hezaveh et al 2012

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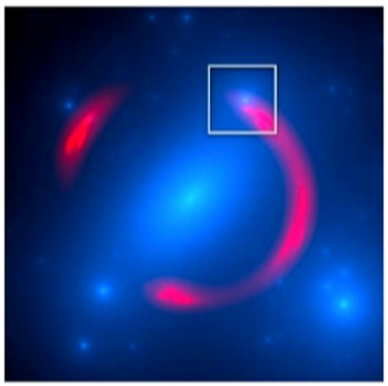
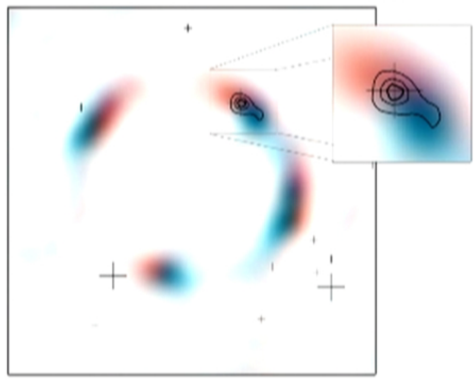
Simulations indicate that with ALMA, we can Detect DM subhalos in these systems

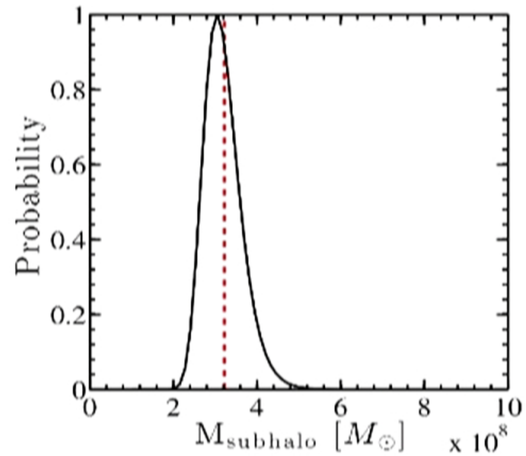


Nbody + ray tracing simulation

Detected subhalo

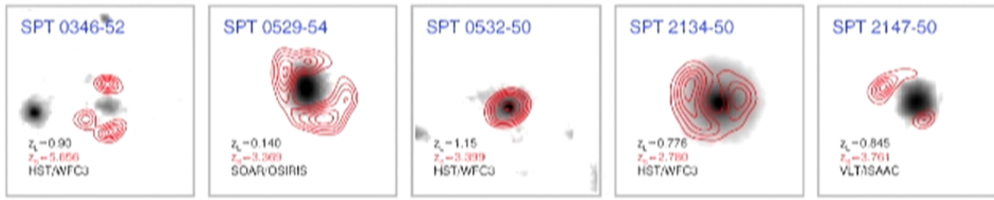


Mock ALMA observation



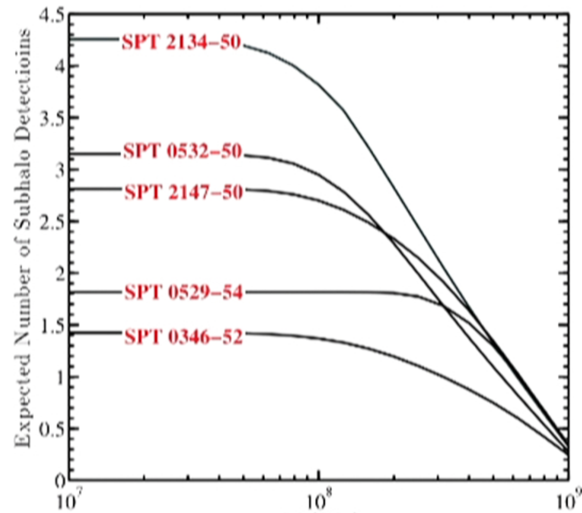
Recovered subhalo mass

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 ~ 1.5 km



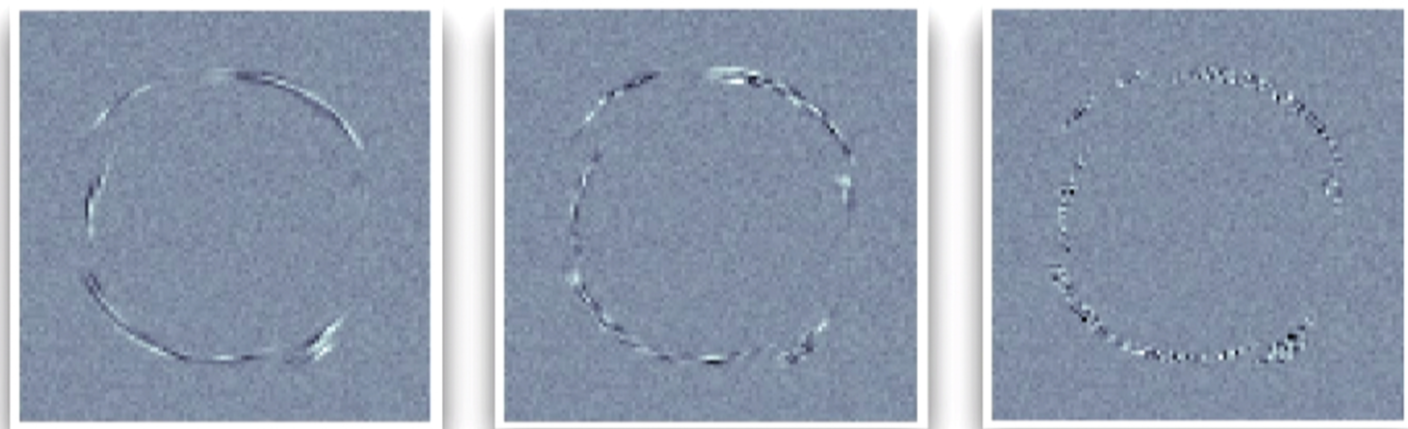
Full ALMA: 64 antennas (4 times more sensitivity)
max baselines = 16 km (10 times higher resolution)

COVARIANCE OF DEFLECTIONS

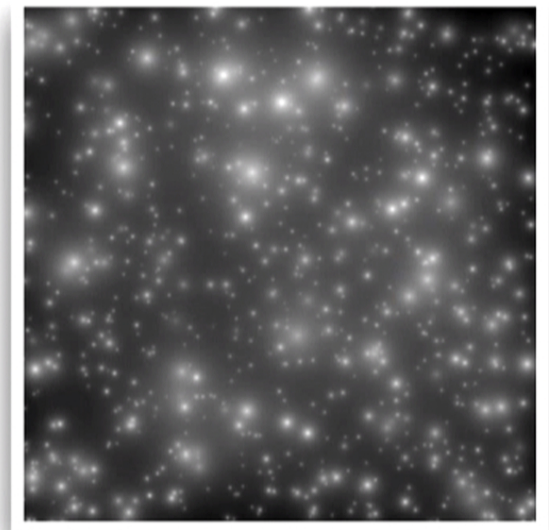
DENSITY POWER SPECTRUM

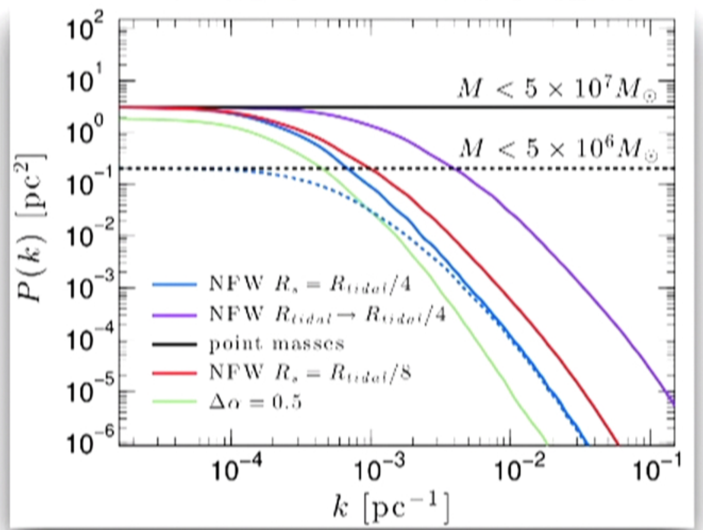
$$\mathbf{C}_\alpha = \langle \alpha_i(\vec{x})\, \alpha_j(\vec{x}+\vec{r}) \rangle = 4 \int P(k) \left(\frac{\delta_{ij}}{k^2 r} J_1(kr) - \frac{r_i r_j}{k r^2} J_2(kr) \right) dk$$

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



Power Spectrum of subhalo density field

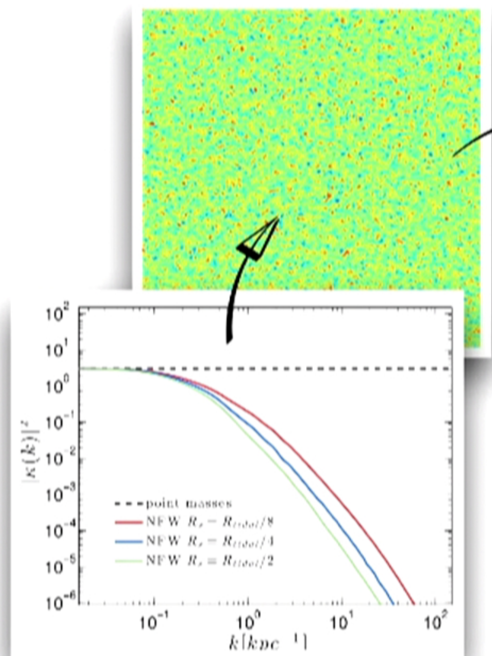




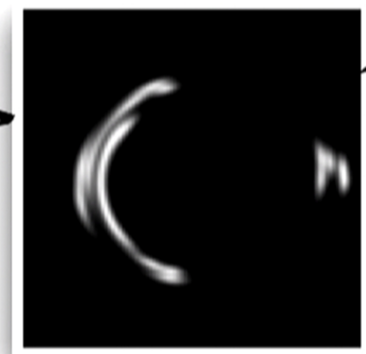
Hezaveh et al 2014

Analysis of mock observations

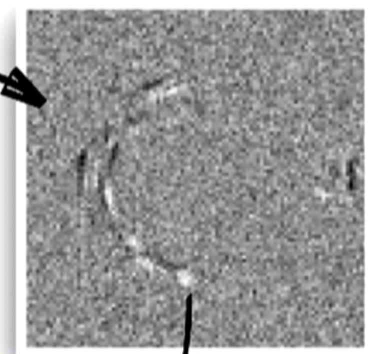
Generate a random subhalo density field with a flat power spectrum



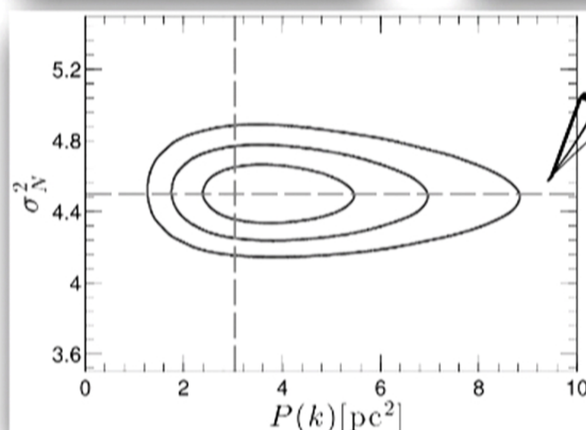
Generate mock observations using a macro halo and the subhalo density field



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

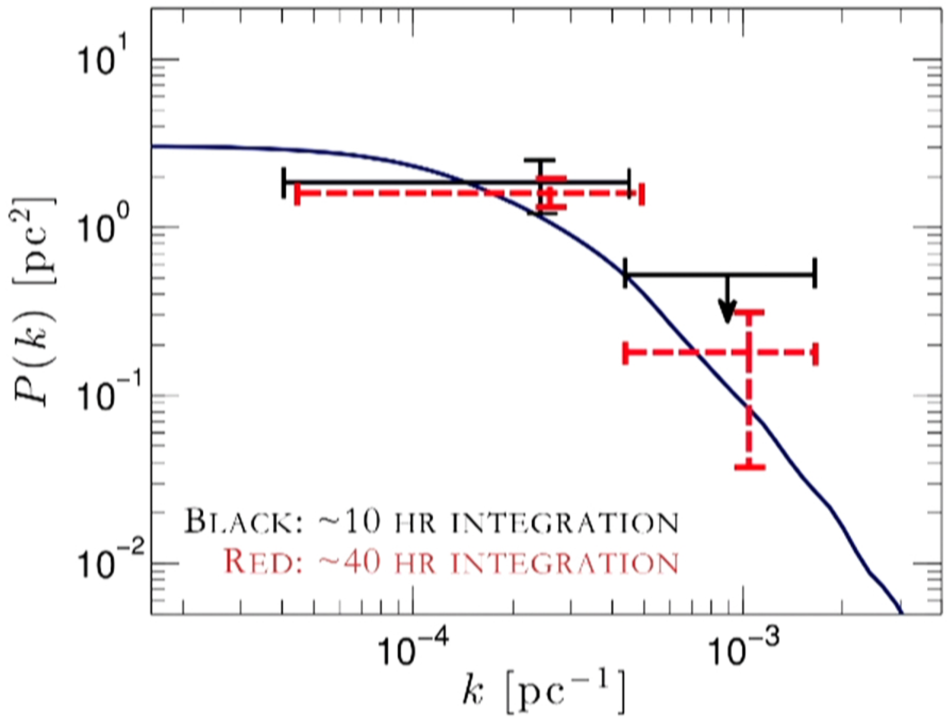


Estimate the likelihood of different covariance matrices using the residuals



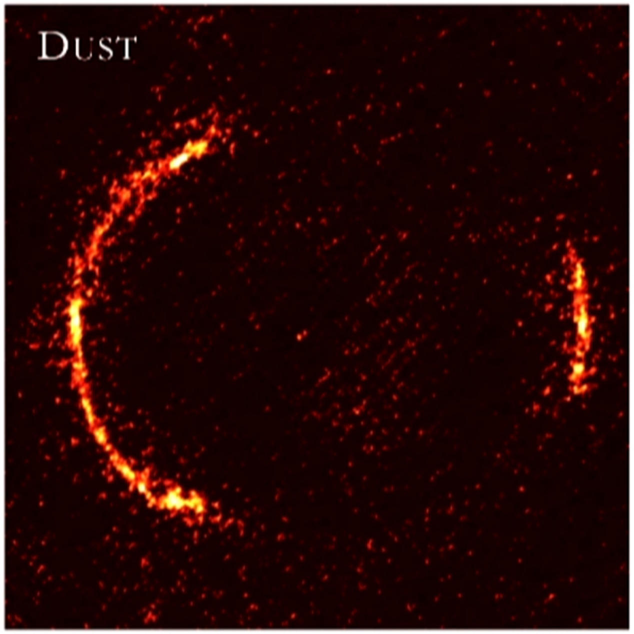
Hezaveh, et al 2014

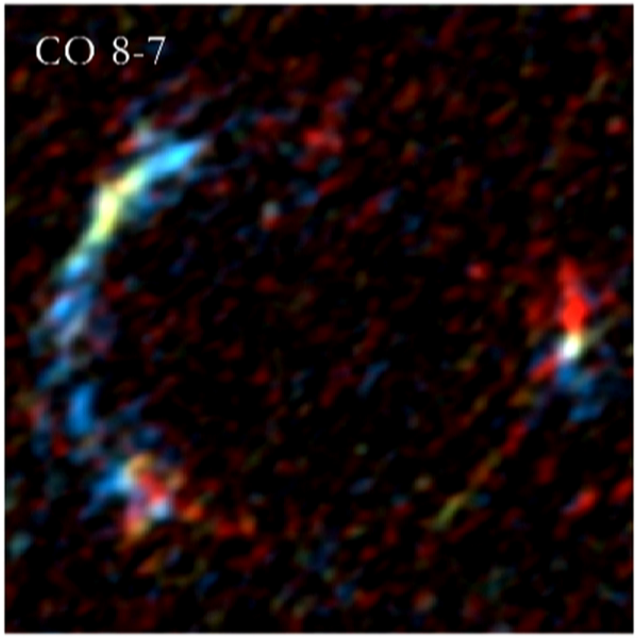
FORECAST FOR MEASURING THE DM SUBHALO POWER SPECTRUM



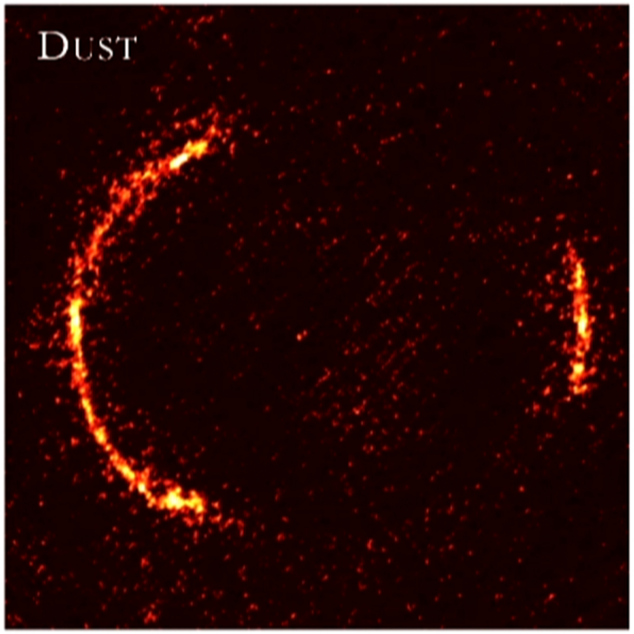
HEZAVEH, DALAL ET AL 2014

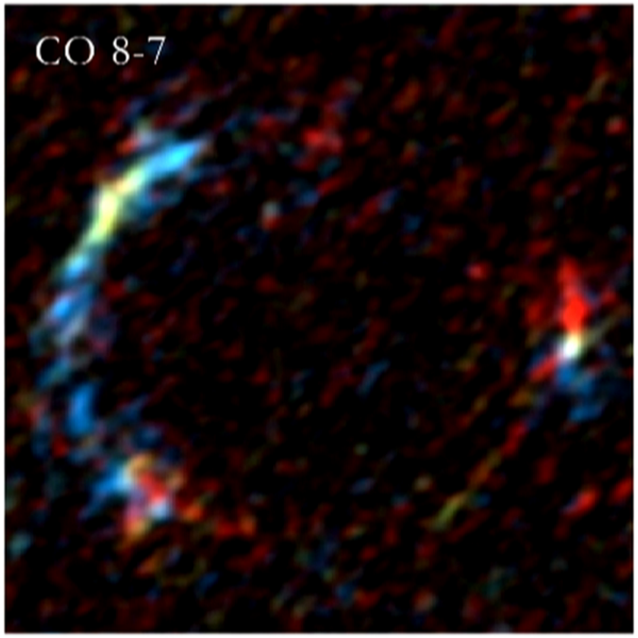
SDP 81
(ALMA science verification data)



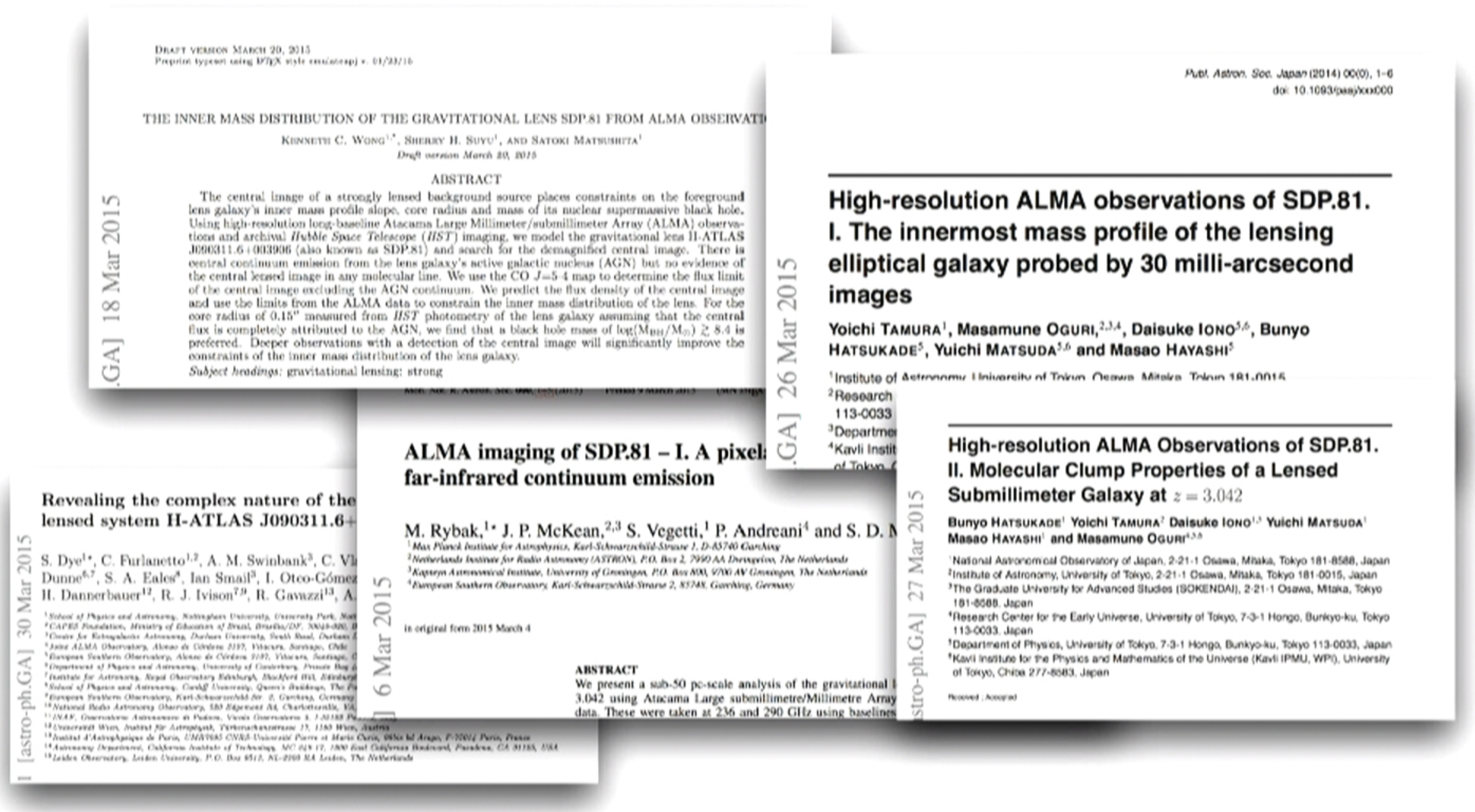


SDP 81
(ALMA science verification data)





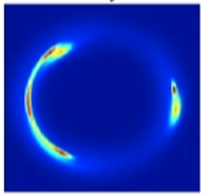
SDP81 papers

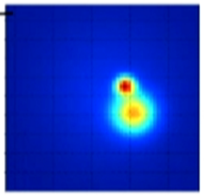


Pixelated Source Lens Modeling

$$v = \mathbf{V}\underbrace{\mathbf{LS}} + \mathbf{N}$$

$$\begin{bmatrix} e^{-i\vec{k}\vec{r}} & \dots \\ \vdots & \end{bmatrix}$$



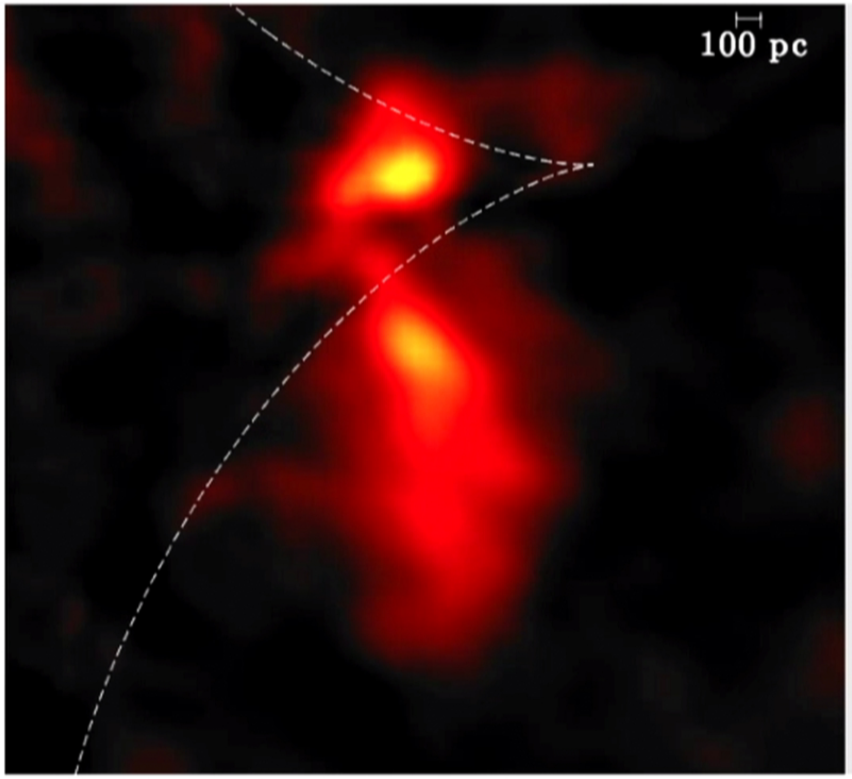


$$\chi^2 = (v_d - v)\mathbf{C}_n^{-1}(v_d - v) + \mathbf{S}\mathbf{C}_s^{-1}\mathbf{S}$$

$$\partial\chi^2/\partial\mathbf{S} = 0$$ 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