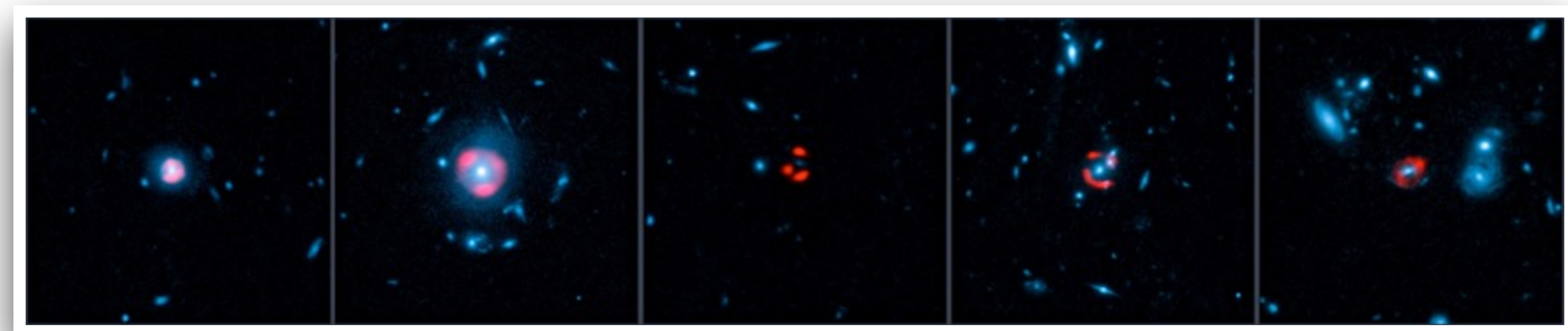
# Mapping the small-scale structure of Dark Matter halos with ALMA Observations of Strong Lenses



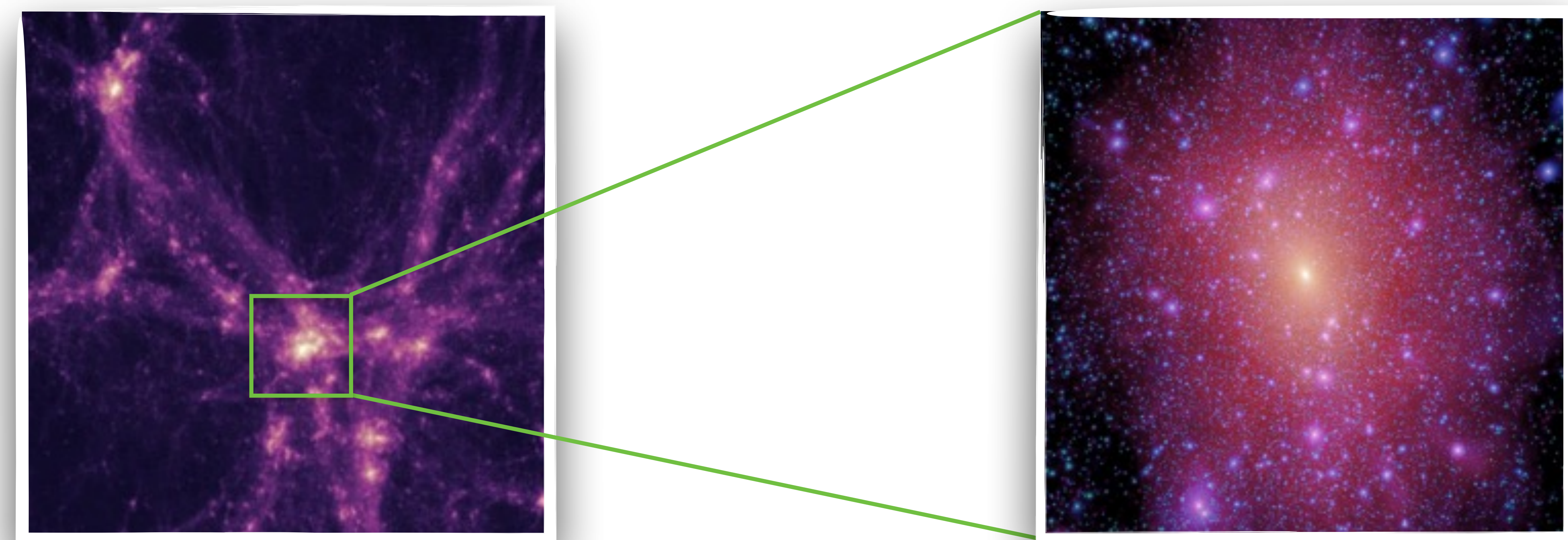

Yashar Hezaveh

Hubble Fellow - KIPAC - Stanford University

Rencontre du Vietnam - Qui Nhon - 2016

N. Dalal, D. Marrone, G. Holder, Y. Mao, W. Morningstar
R. Blandford, J. Carlstrom, C. Fassnacht, P. Marshall, N. Murray
L. Perreault Levasseur, J. Vieira, R. Wechsler
and the South Pole Telescope DMS team

# Small-Scale Structure of Dark Matter

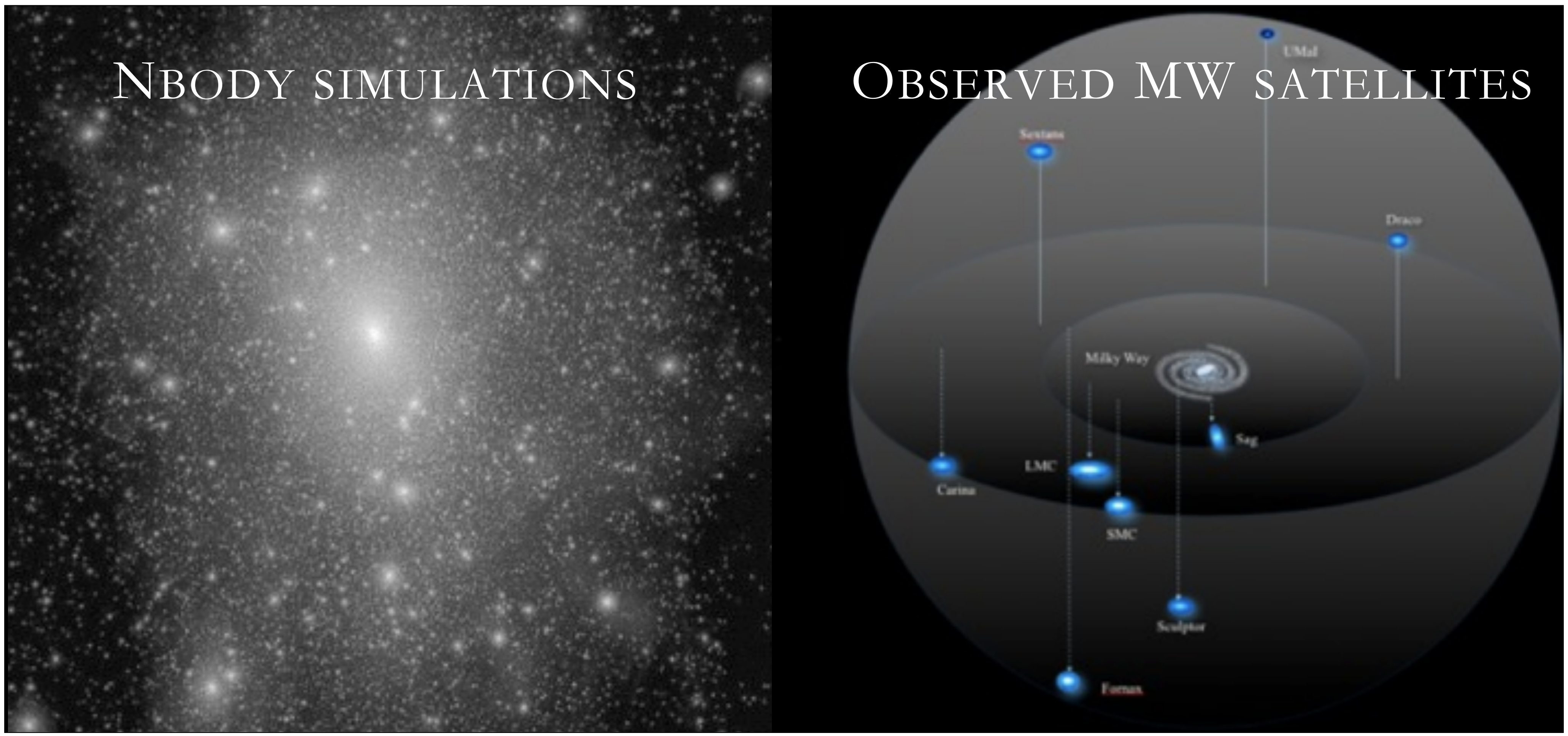


Large scale structure is very well constrained.

Small scale distribution of dark matter is not well understood.

# Motivation

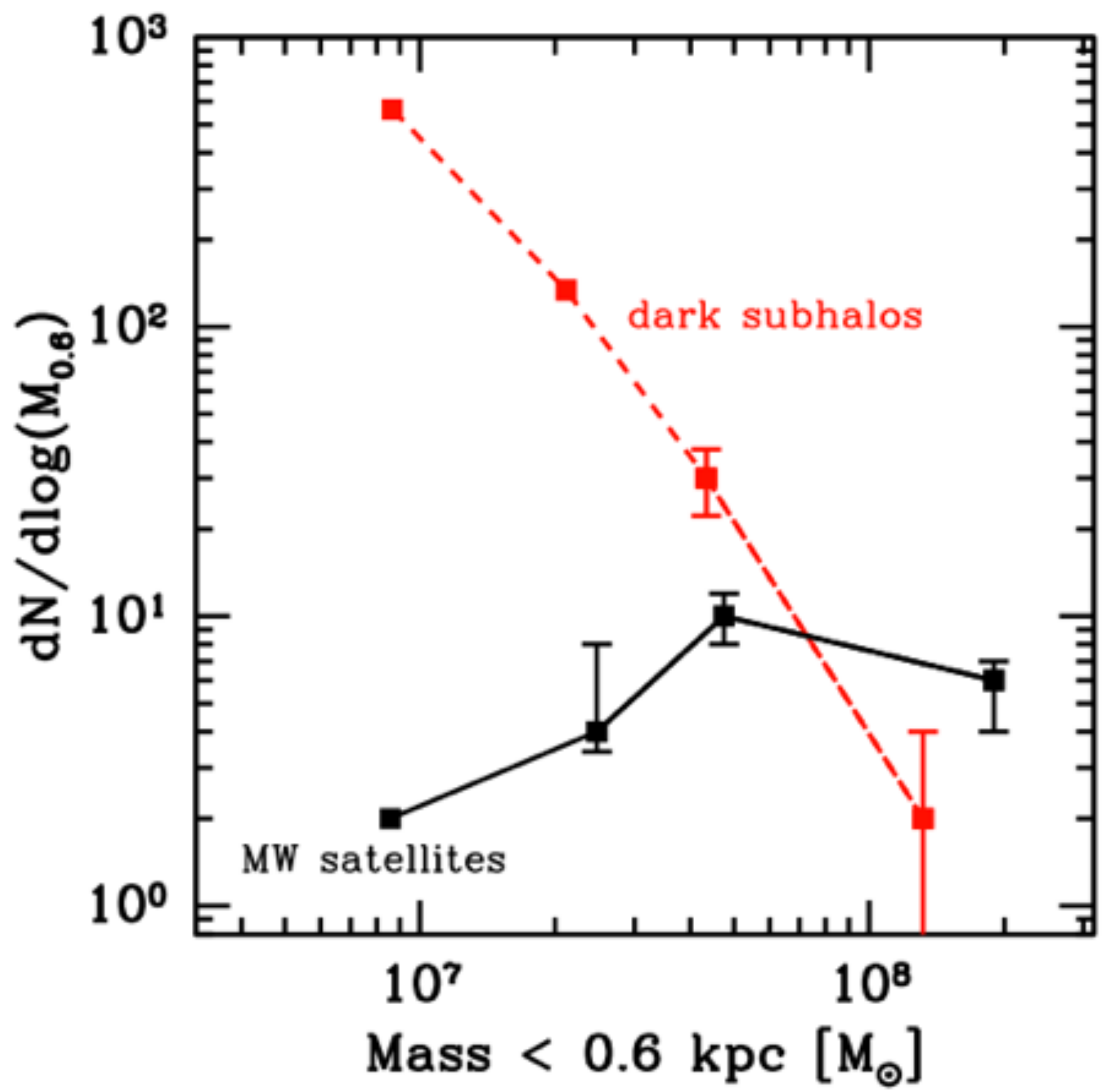
## Comparing MW dwarf galaxies to DM subhalos




Theory: N>> 1000

Observation N~10

# The Missing Satellite Problem



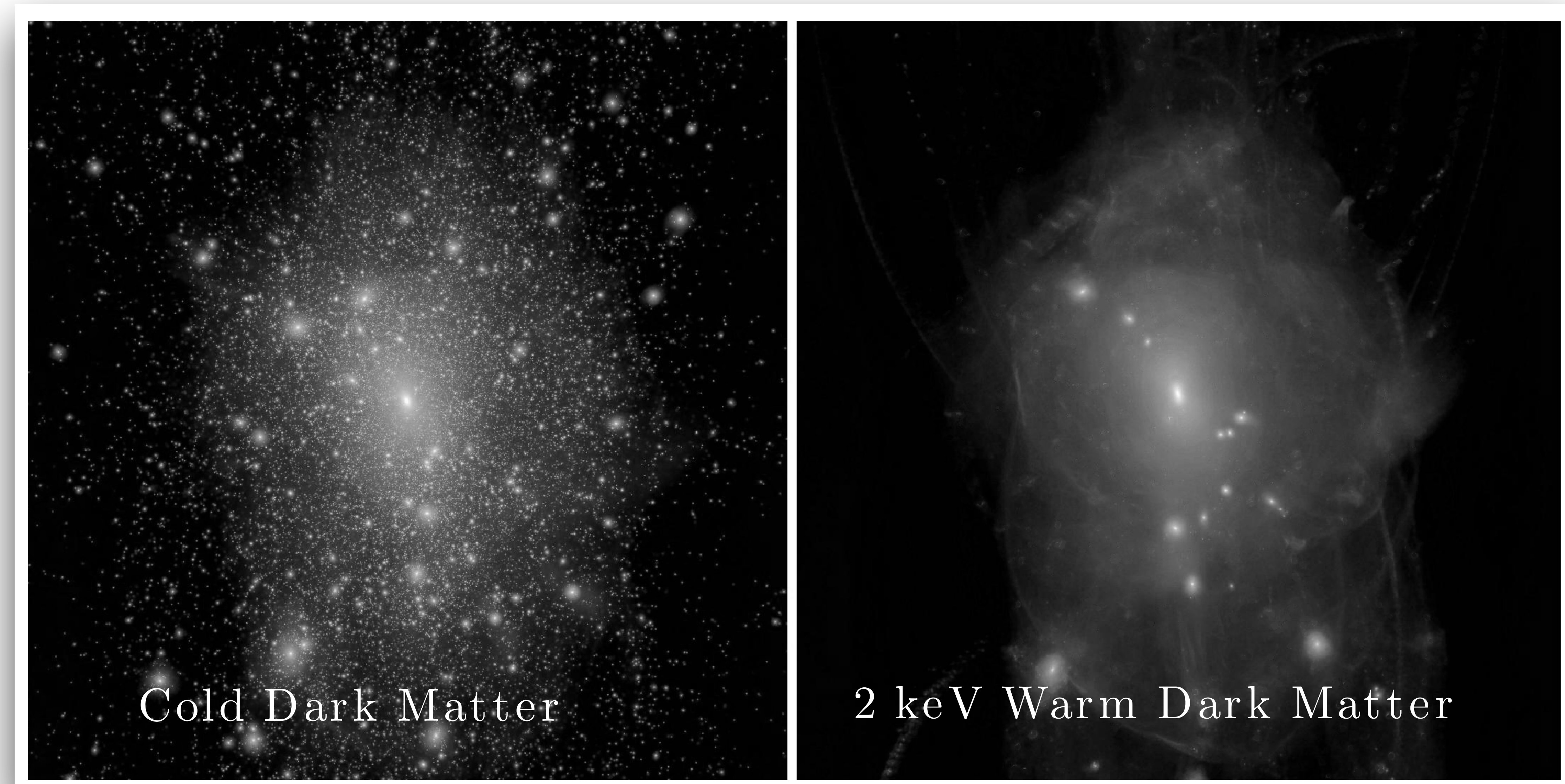

Long standing problem for CDM

Strigari et al. 2007 ApJ. 669, 676

# Solutions

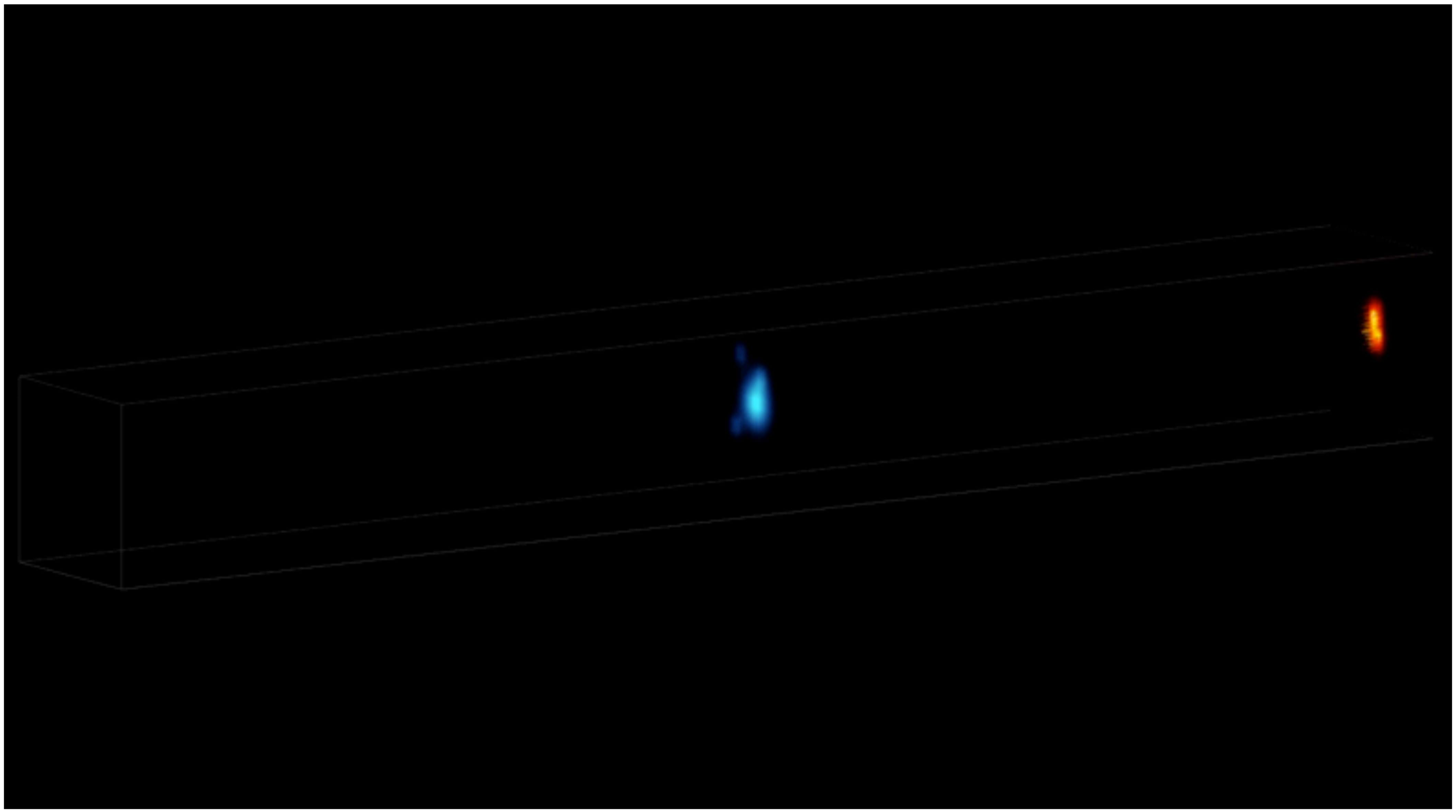
## Baryonic Gastrophysics

## Dark Matter Physics

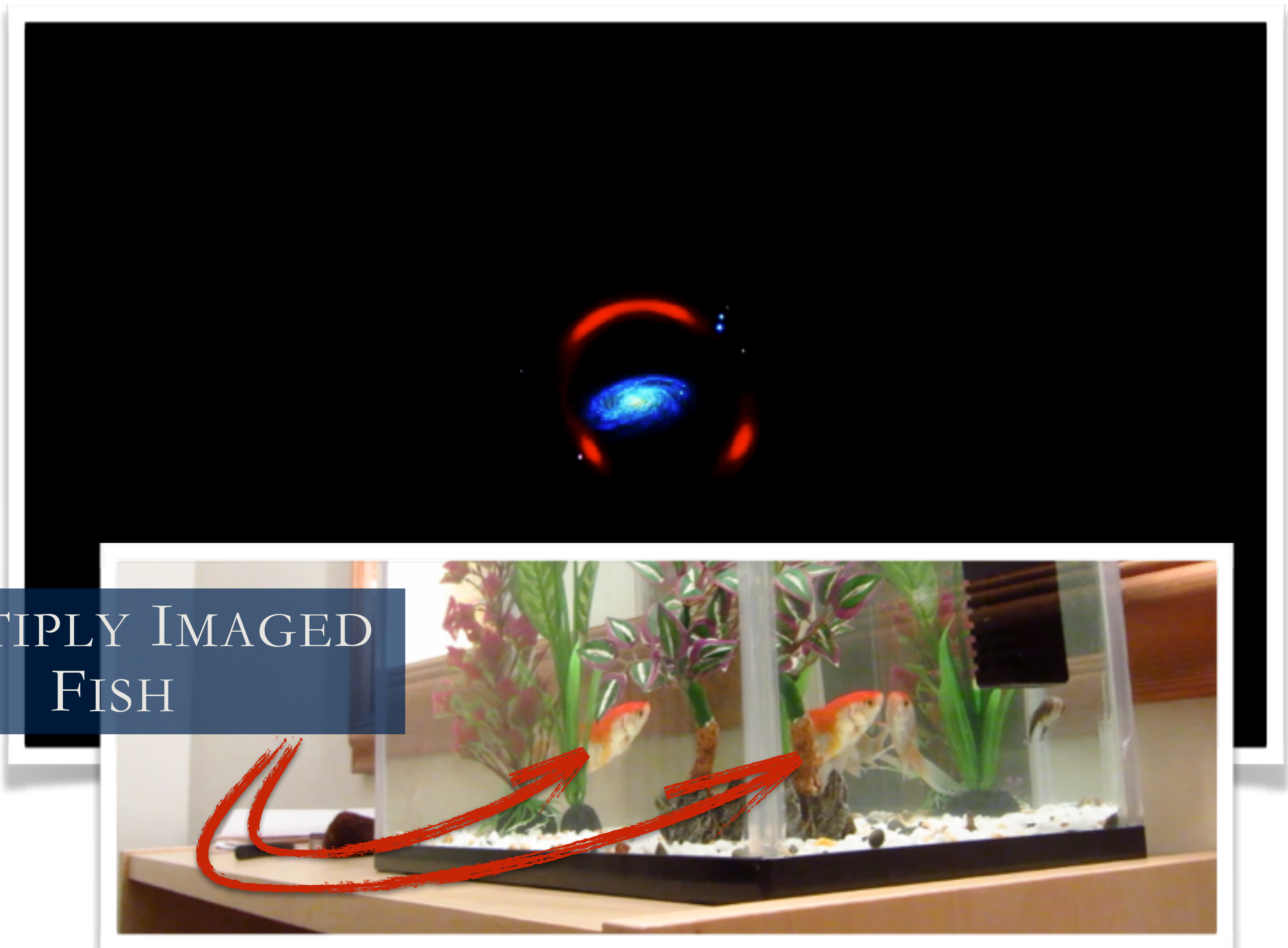



Lovell et al 2012, MNRAS 420, 3

# Strong Gravitational Lensing

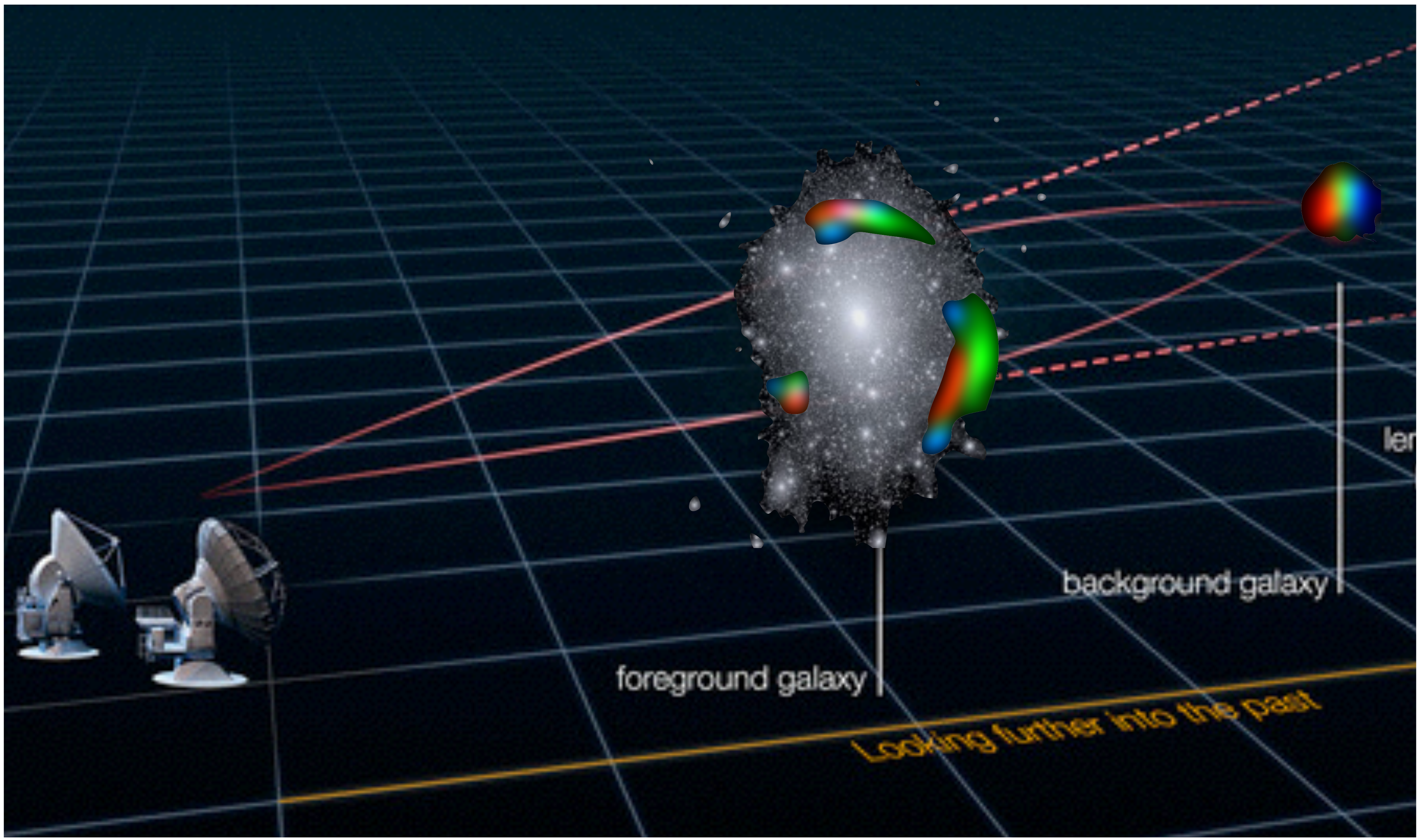


# Strong Gravitational Lensing

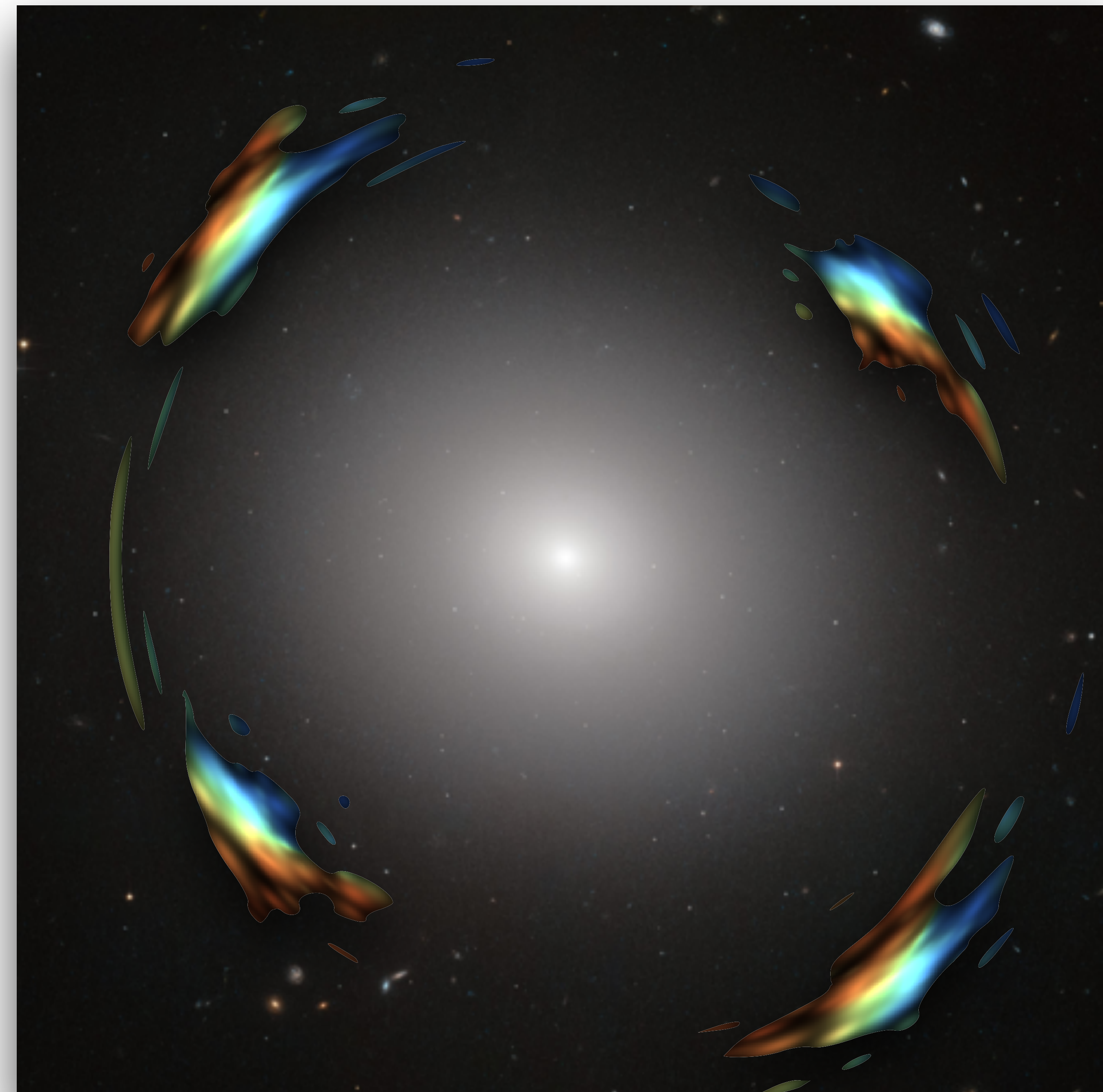


Multiply Imaged Fish

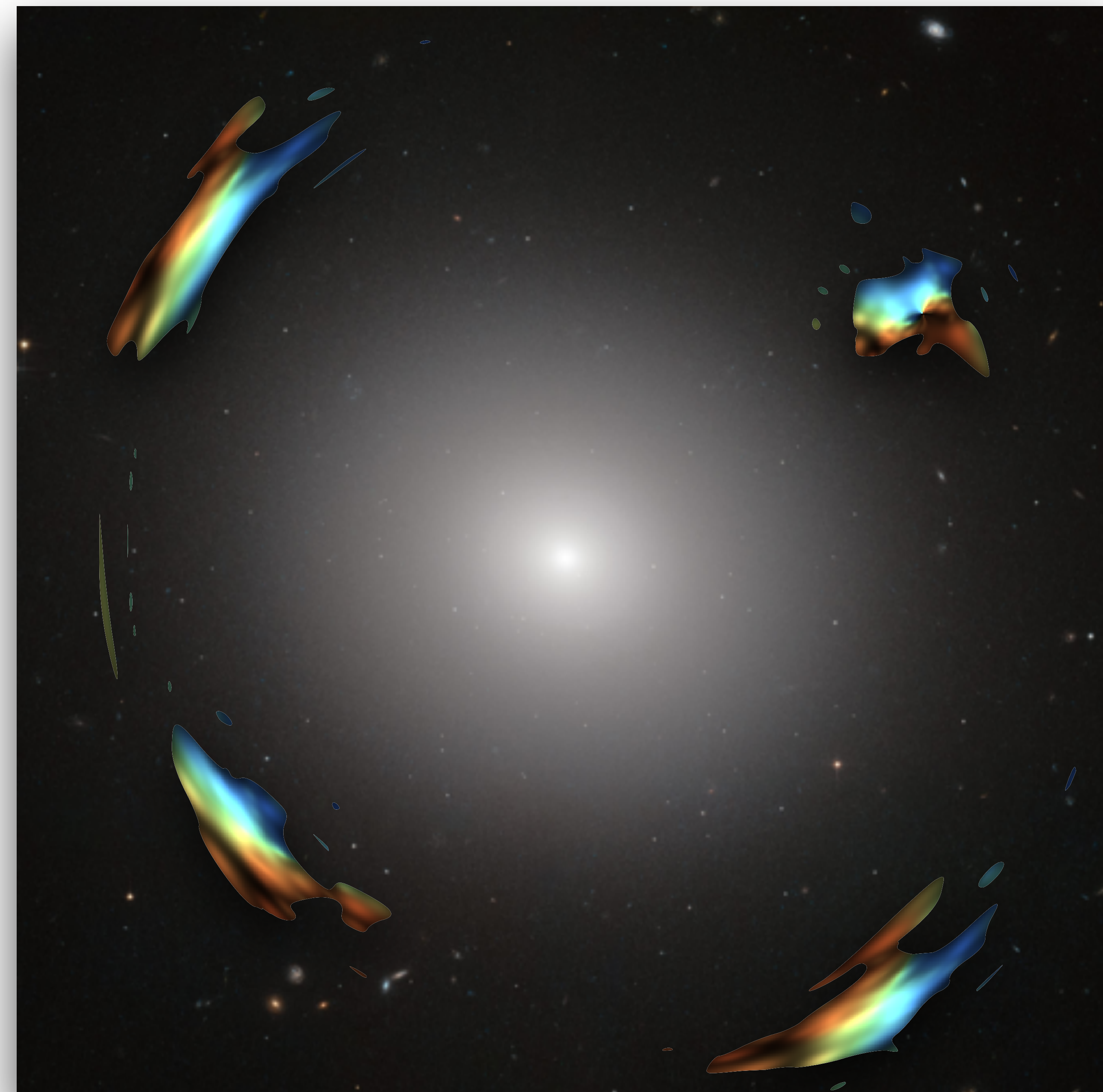
# Strong Gravitational Lensing



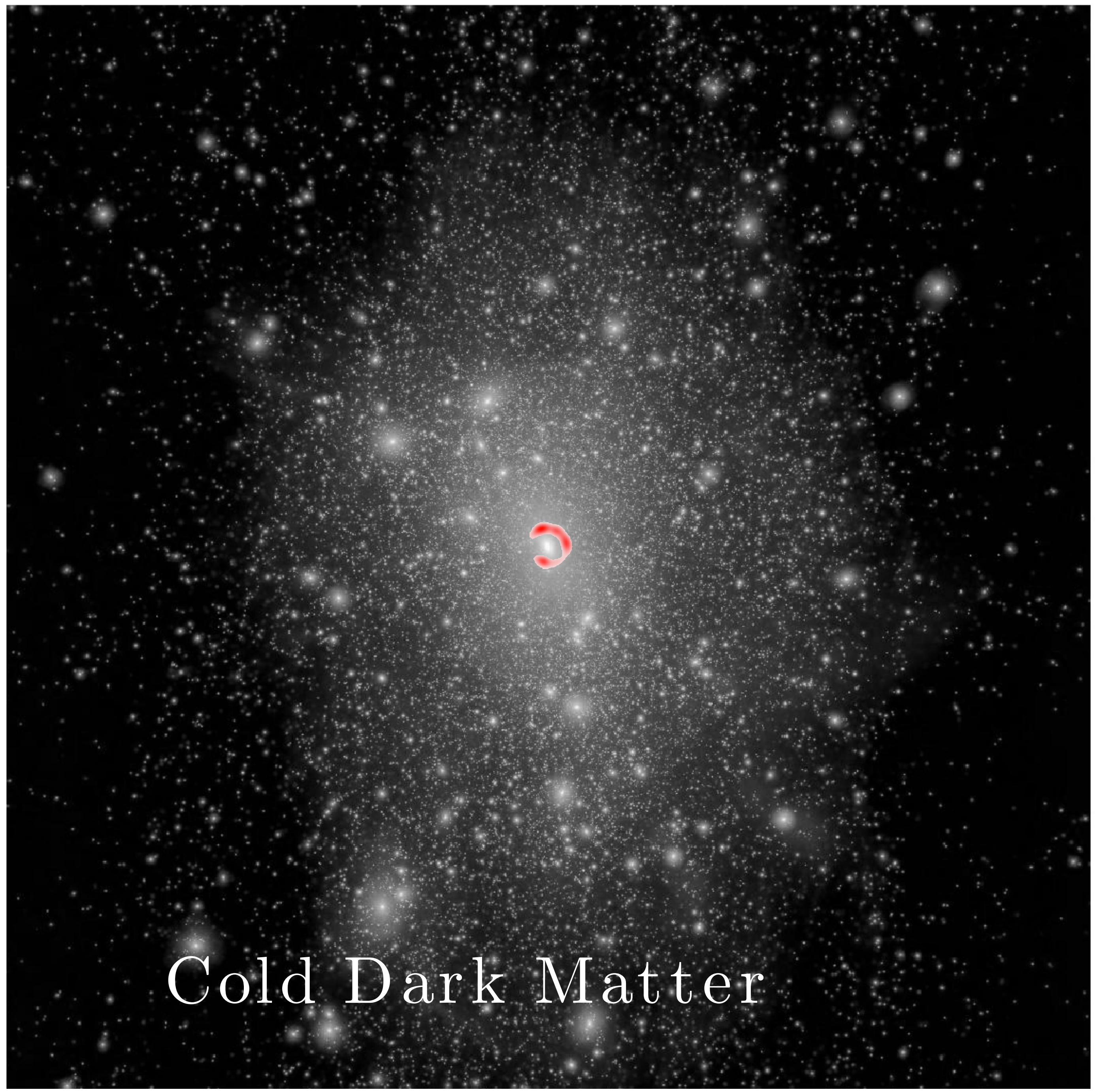
# Substructure Lensing



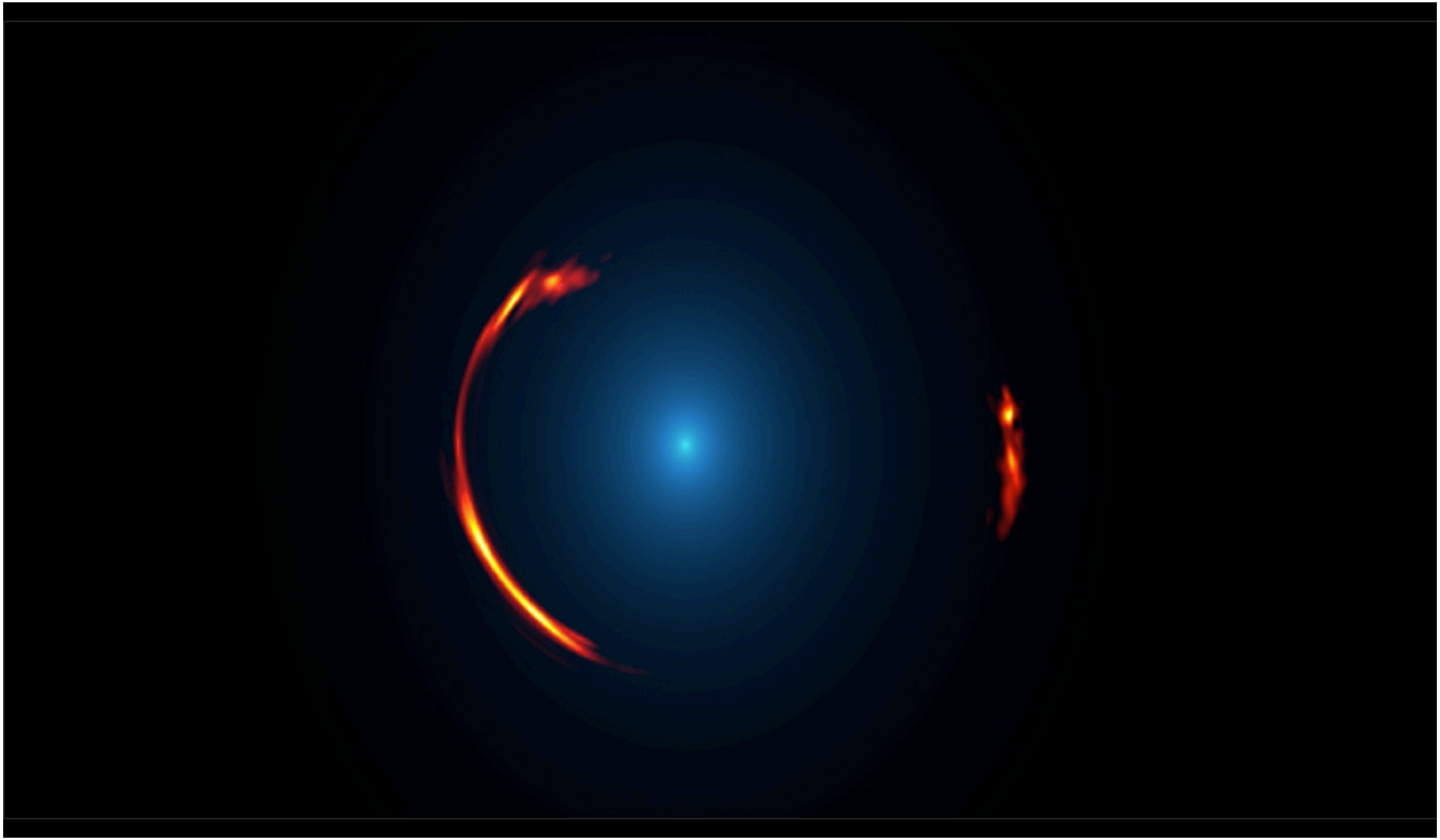
# Substructure Lensing



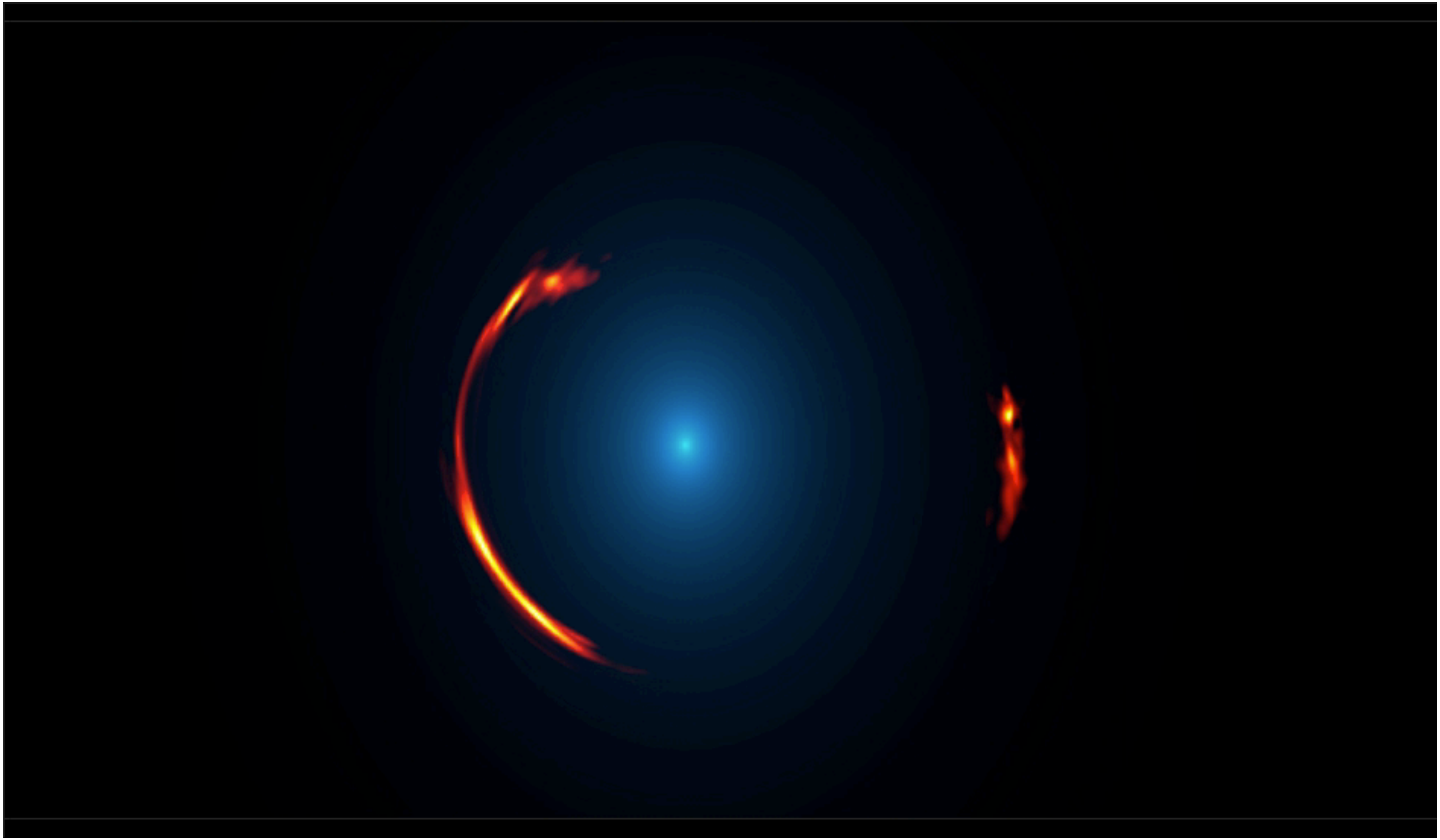
# A sense of scale...



# SDP.81

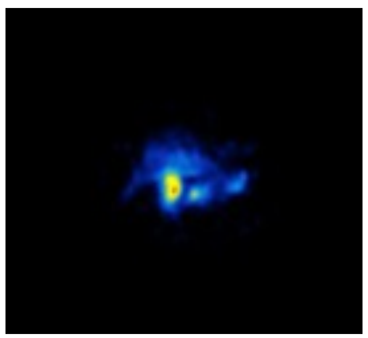


# SDP.81



# Lens Modeling

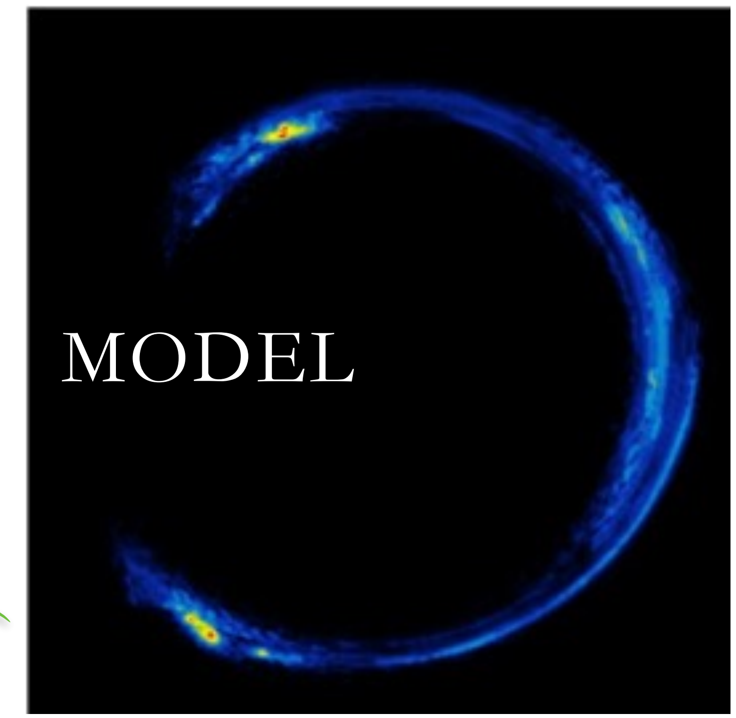
Postulate a Source Morphology (with parameters Ps)

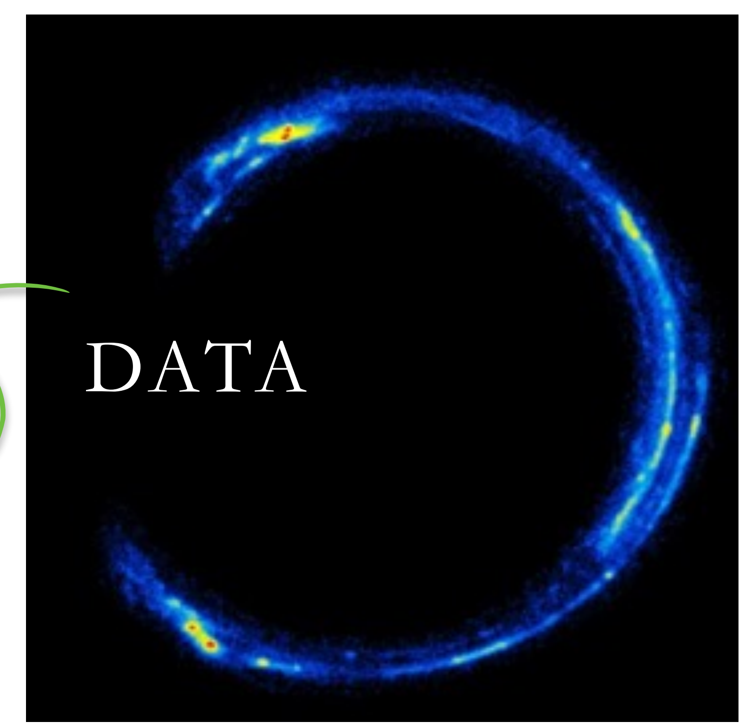


Postulate a Mass distribution in the lens (with parameters Pm)

Ray-tracing simulation

Generate the lensed image of the source

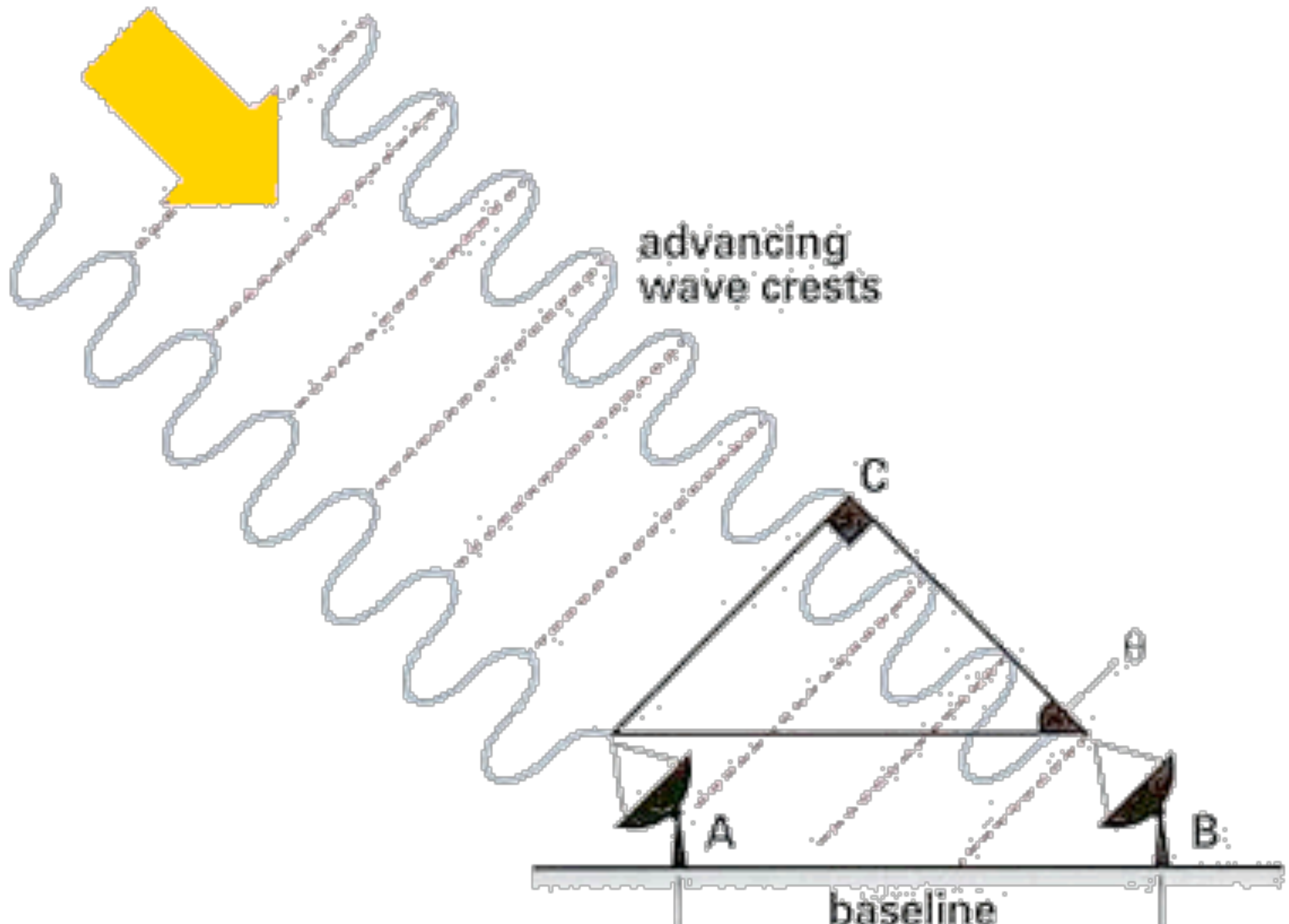



Maximize the likelihood of the model parameters given the data

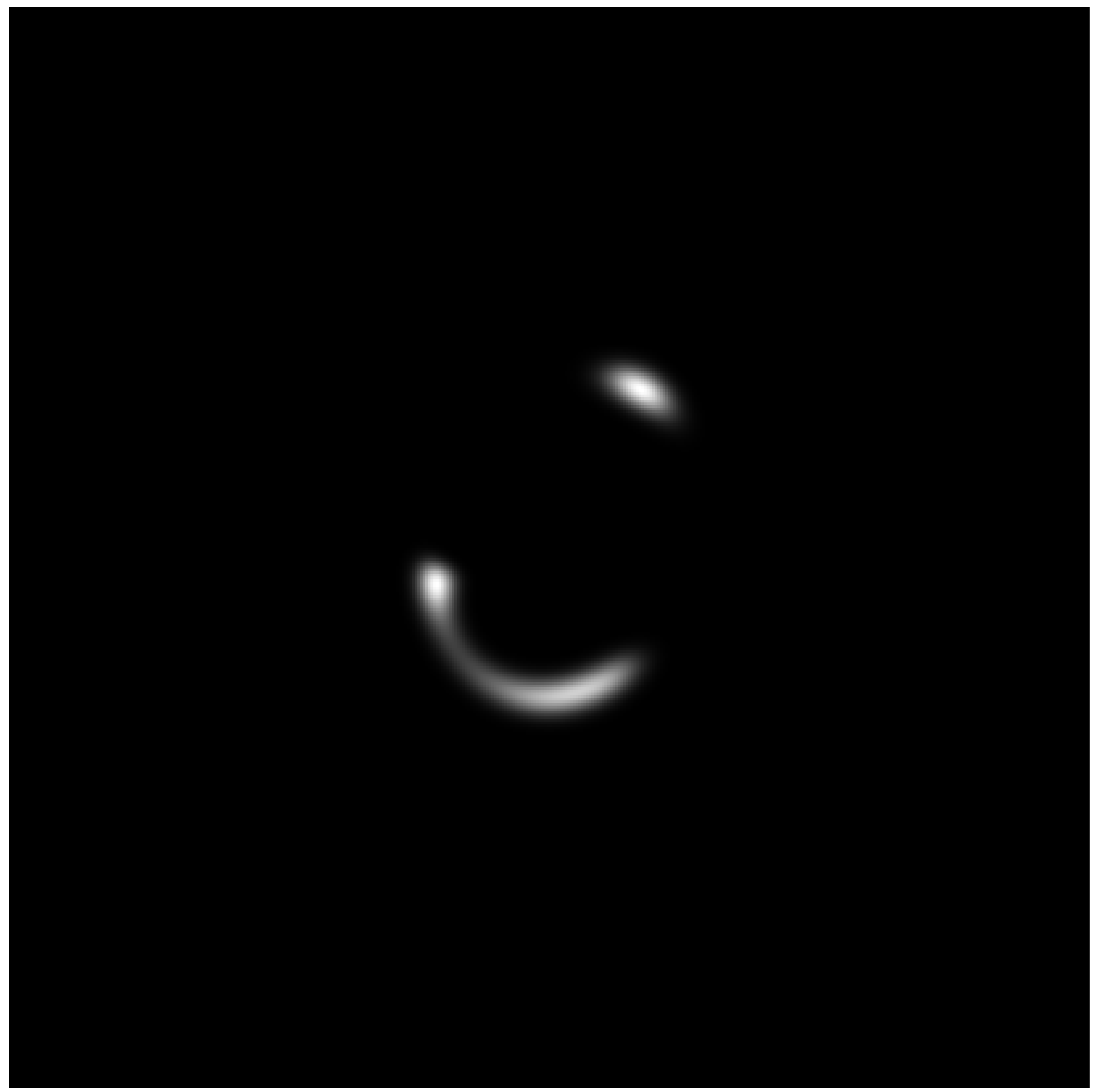
# INTERFEROMETRY:

(WHAT DOES ALMA MEASURE?)



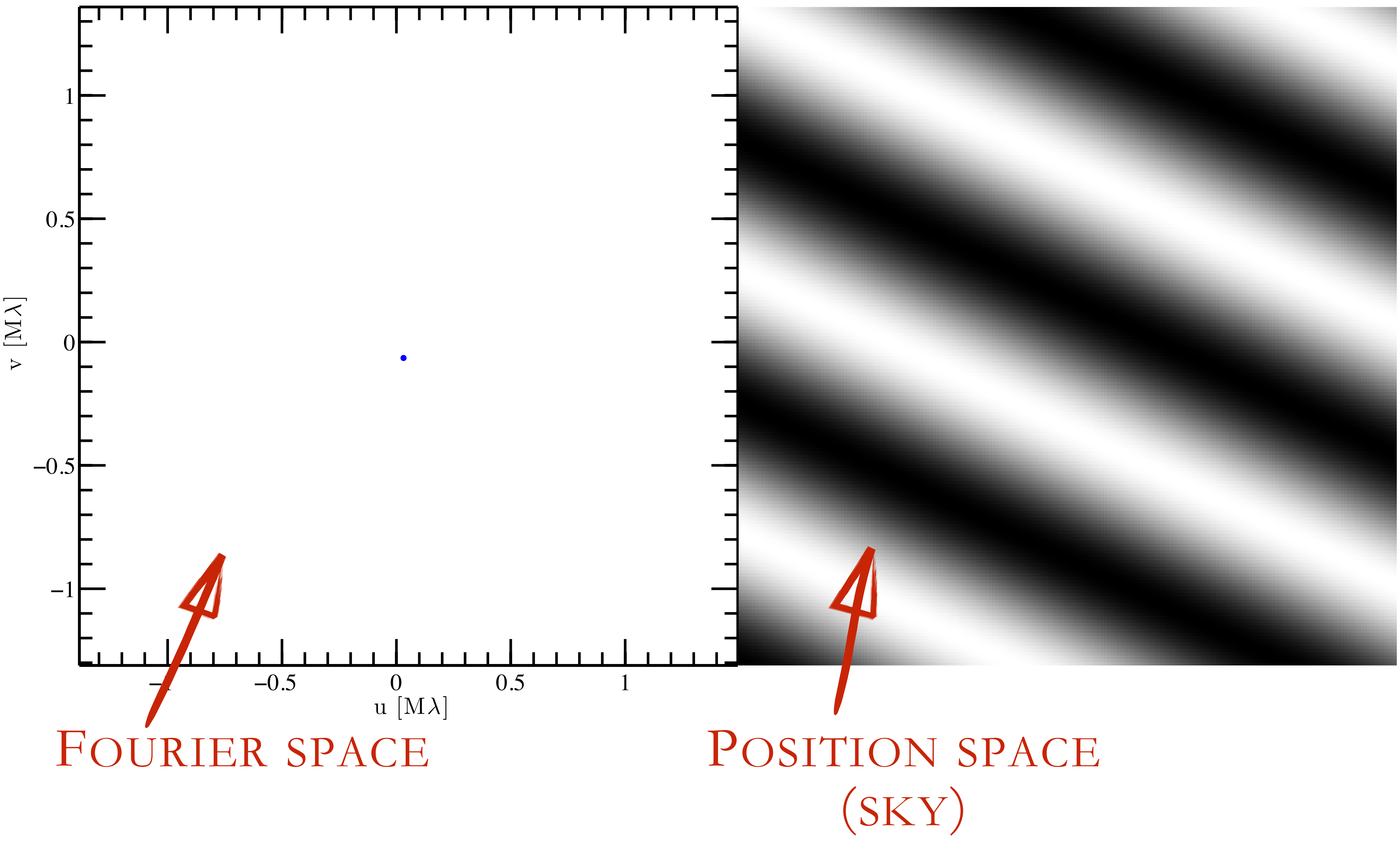
# Interferometry:

(what does ALMA measure?)



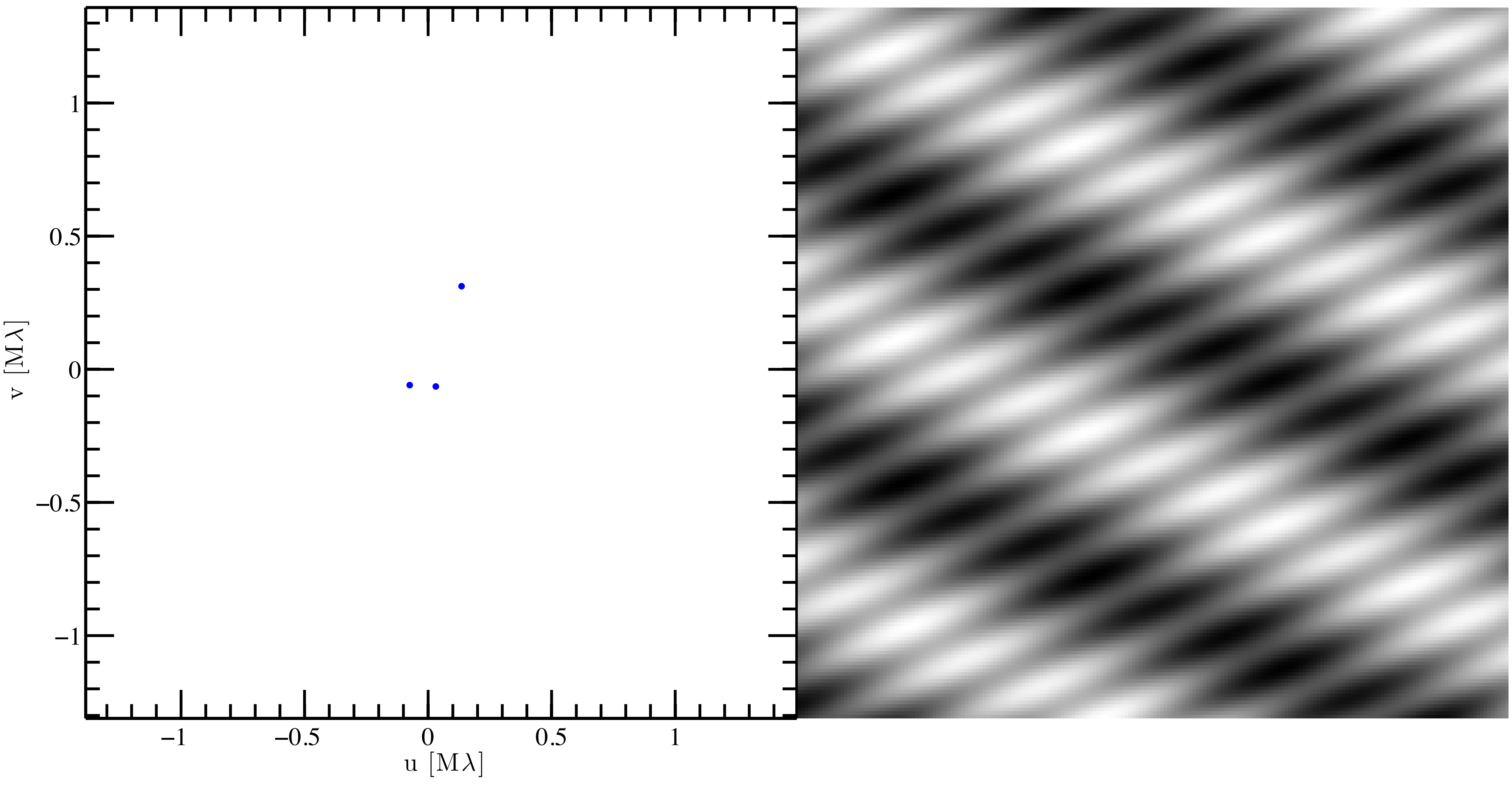
# Interferometry:

(what does ALMA measure?)



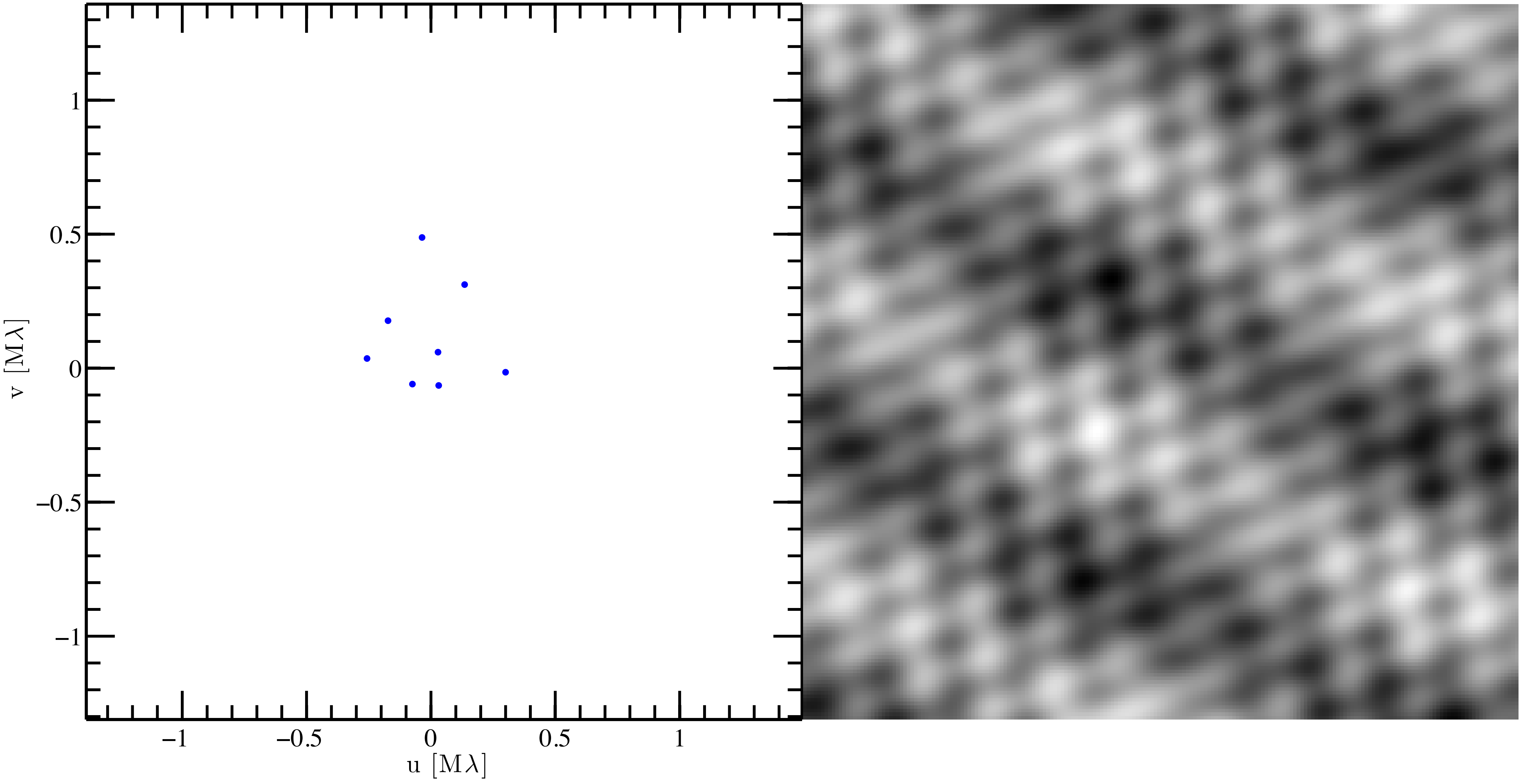
# Interferometry:

## (what does ALMA measure?)



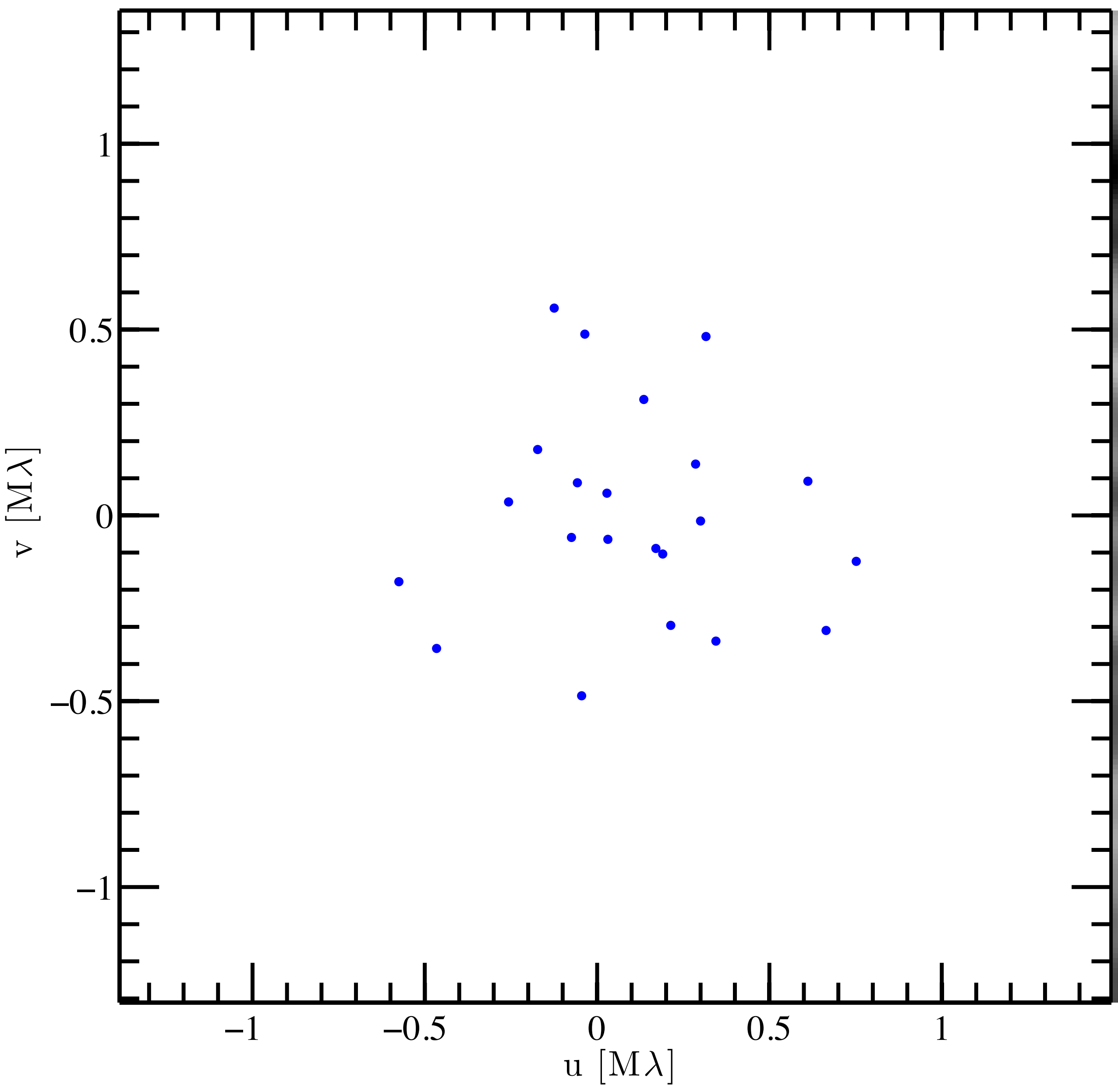
# Interferometry:

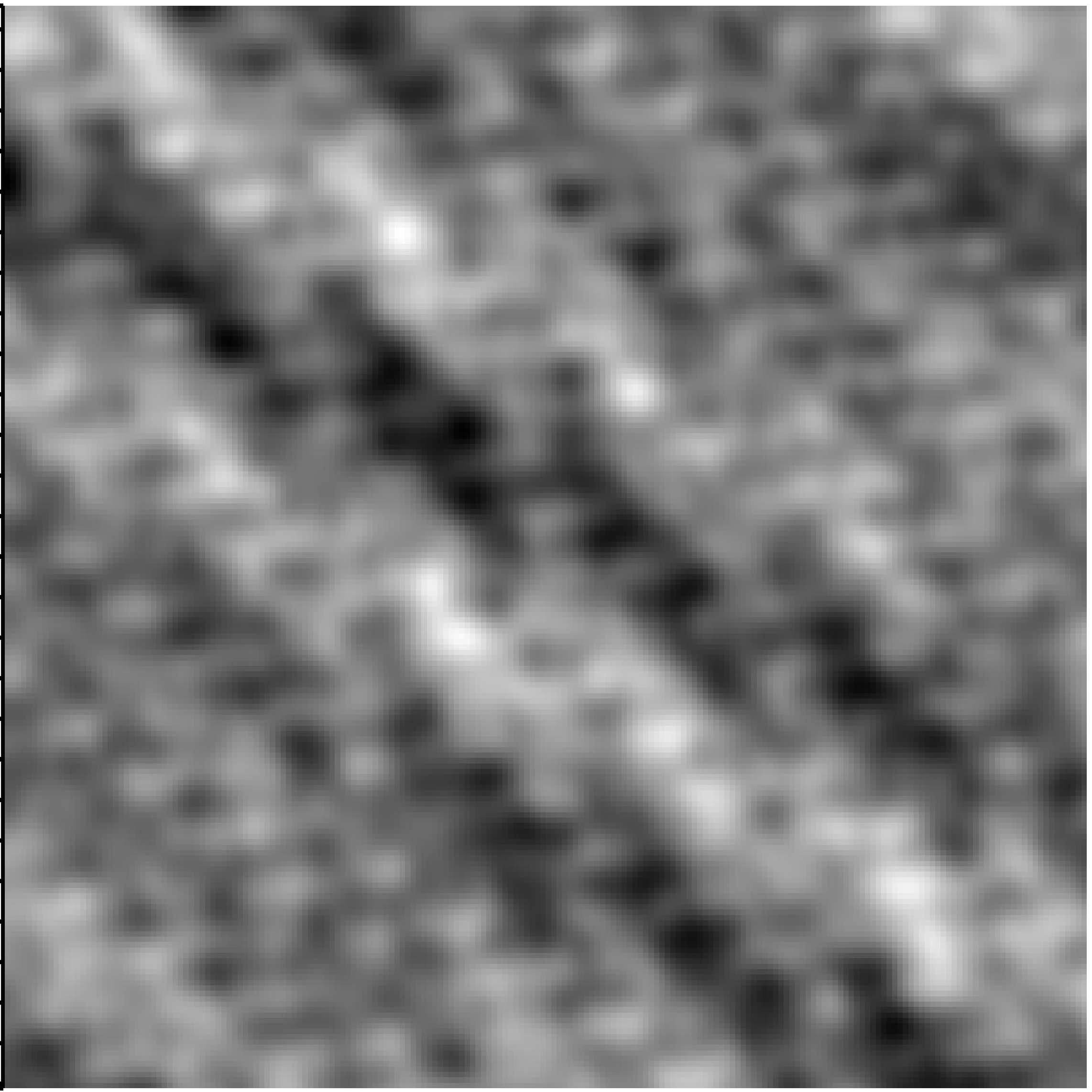
## (what does ALMA measure?)



# Interferometry:

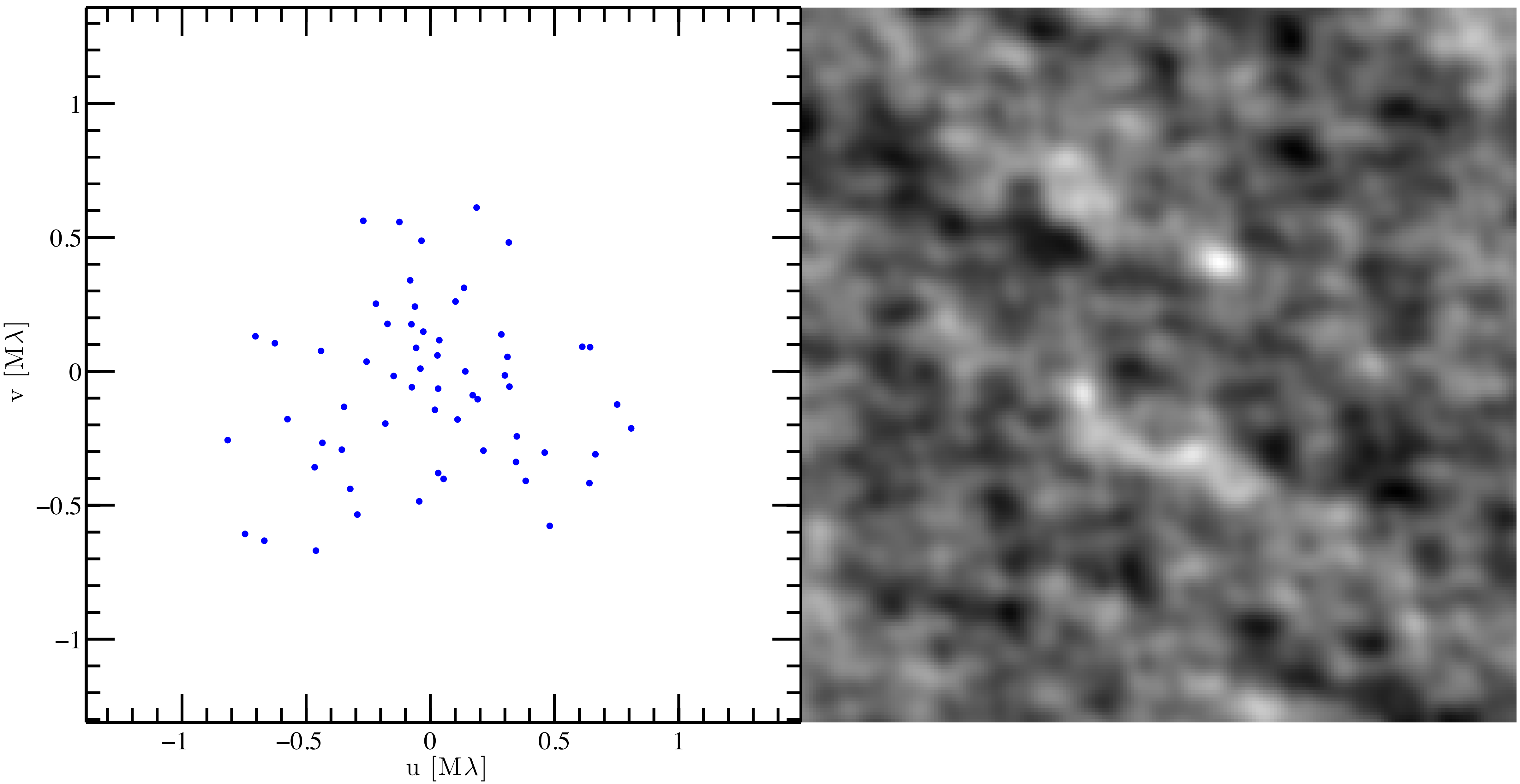
## (what does ALMA measure?)



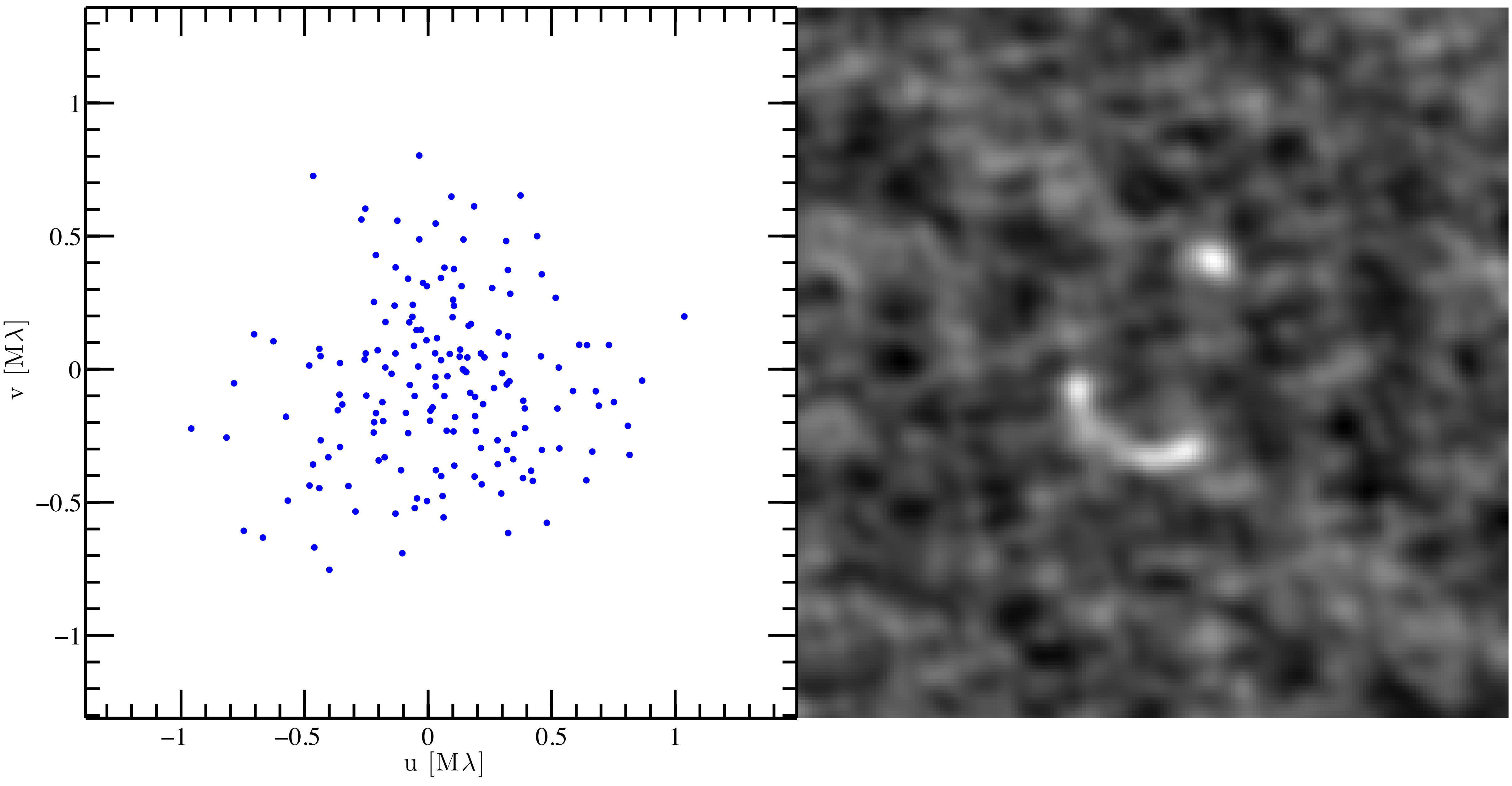
# Interferometry:

(what does ALMA measure?)



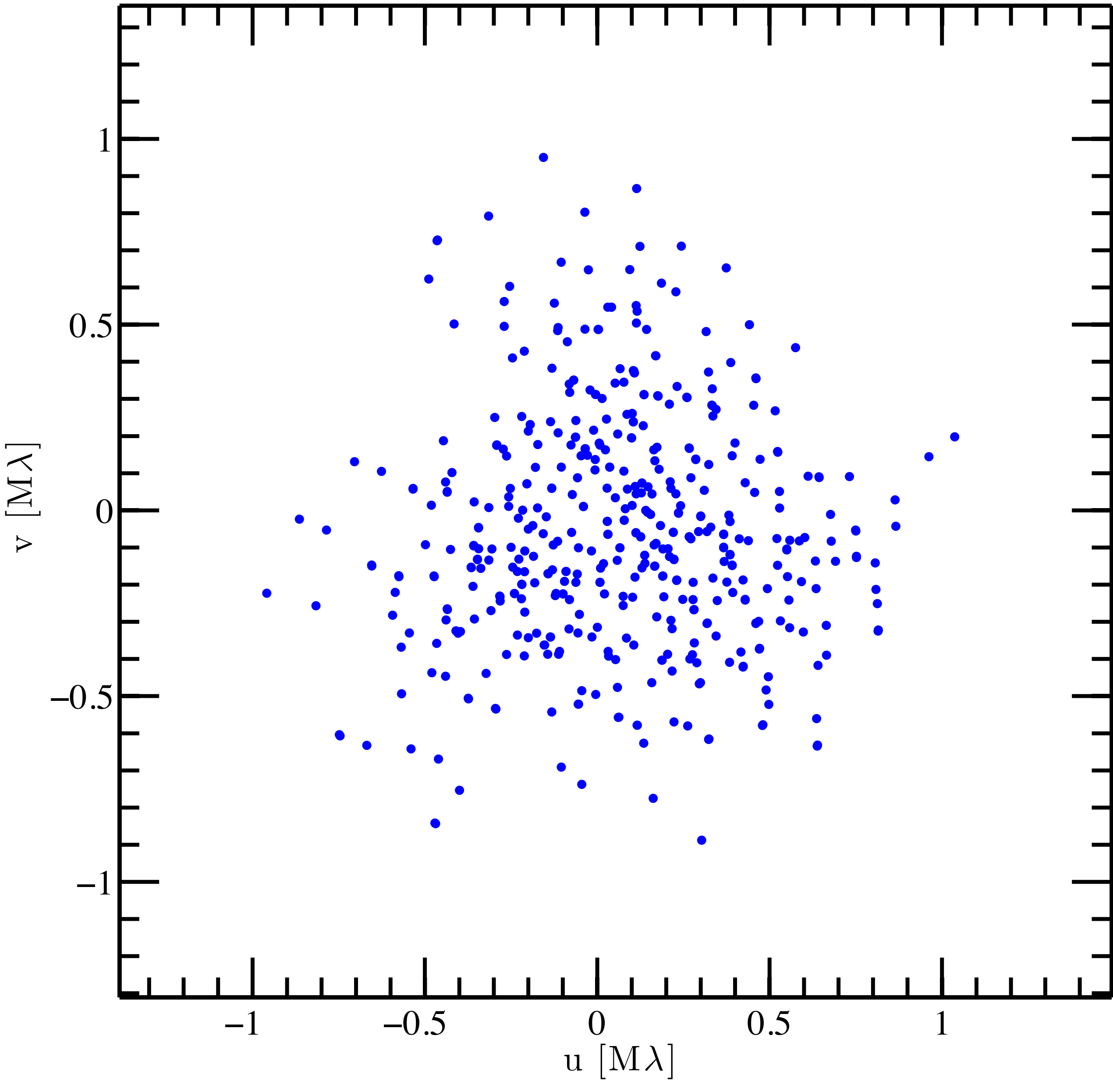
# Interferometry:

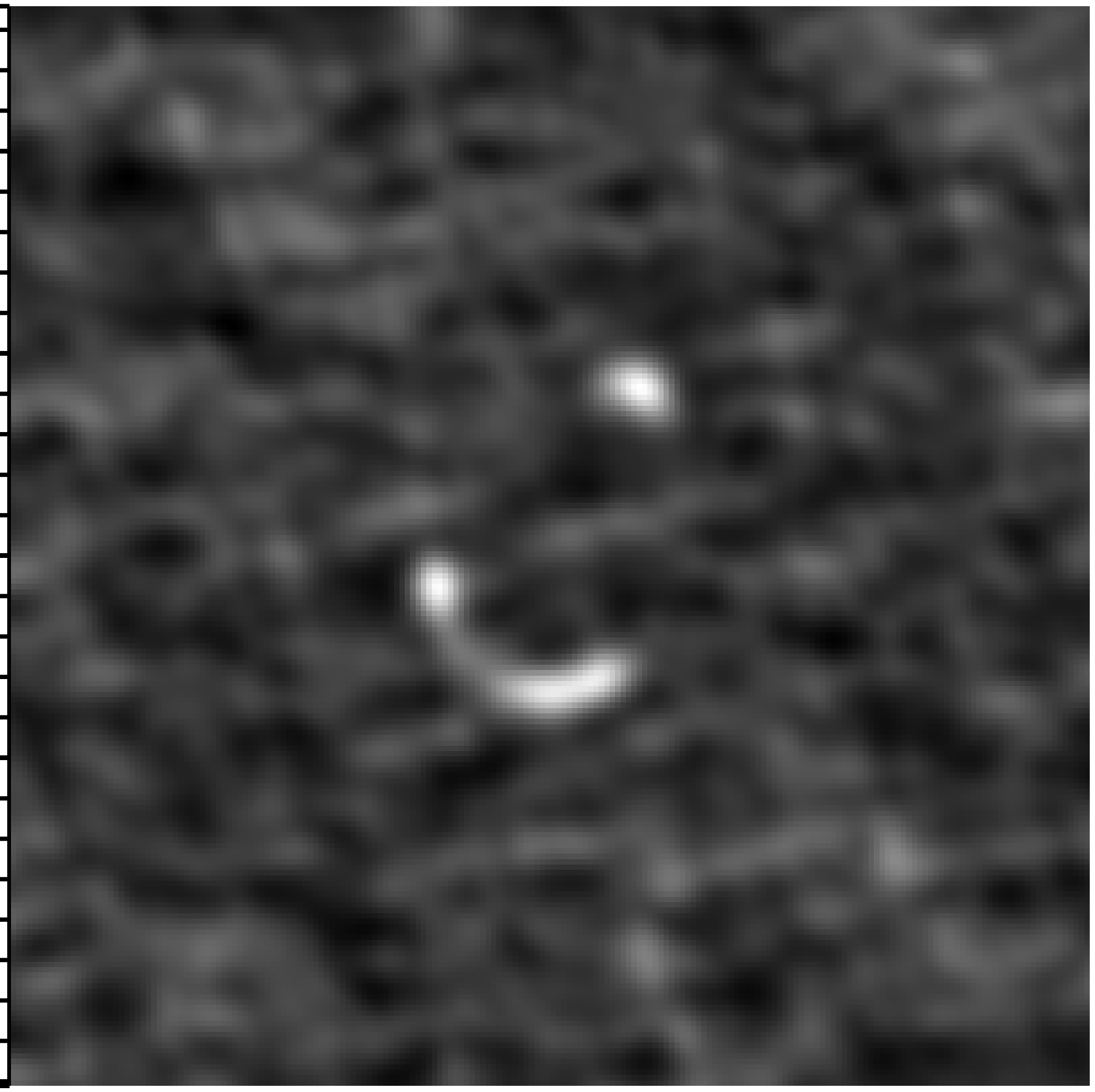
## (what does ALMA measure?)



# Interferometry:

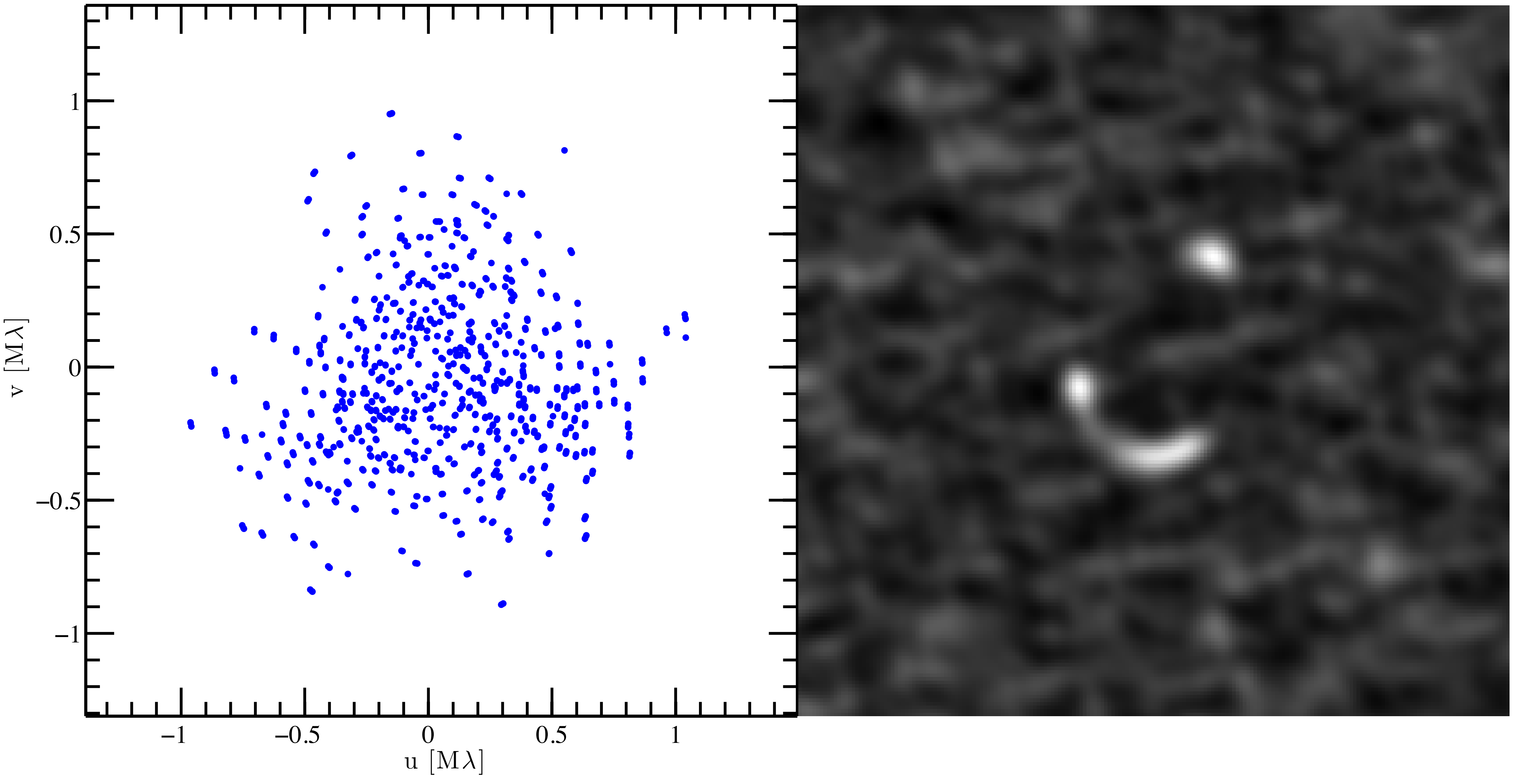
## (what does ALMA measure?)



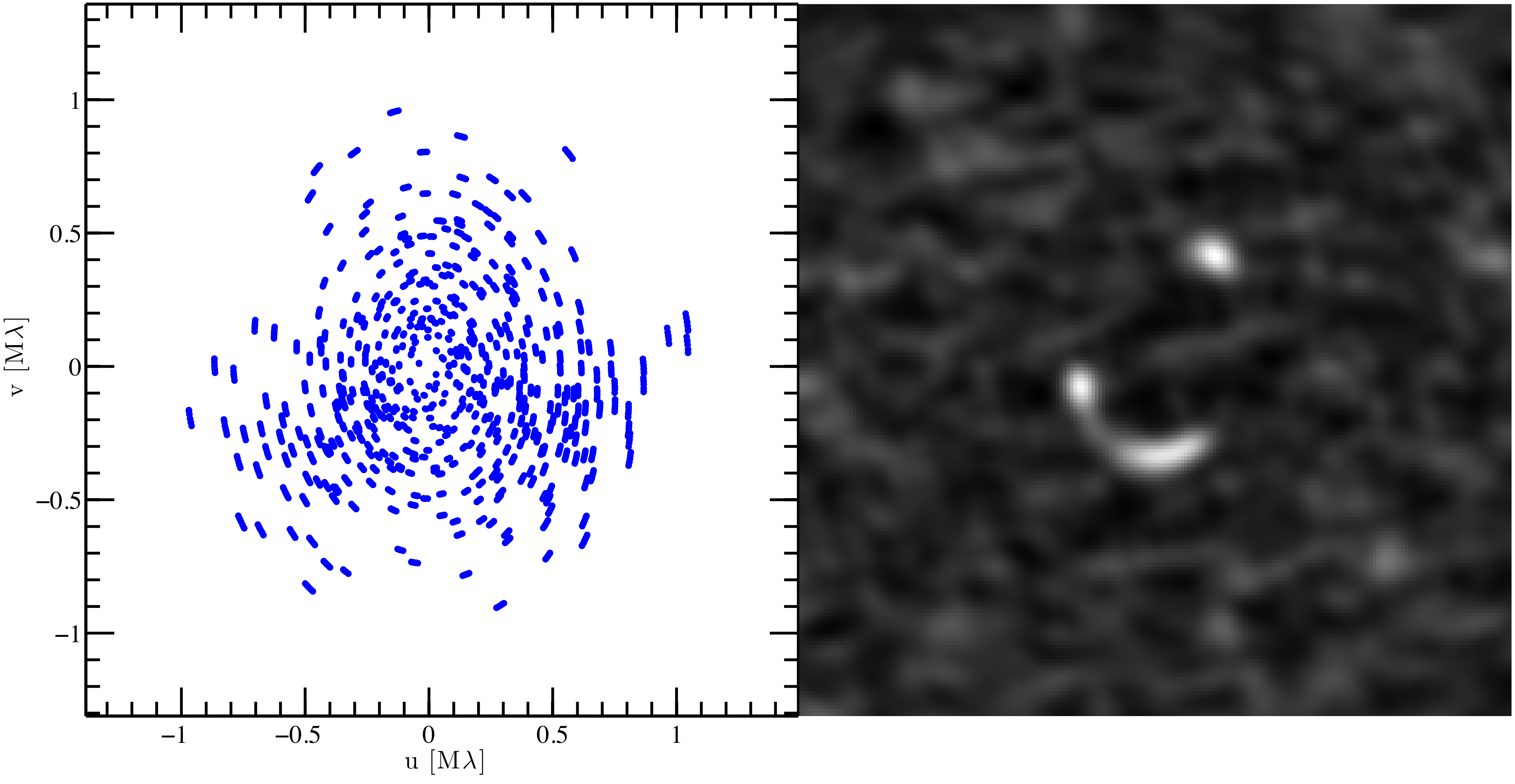
# Interferometry:

## (what does ALMA measure?)



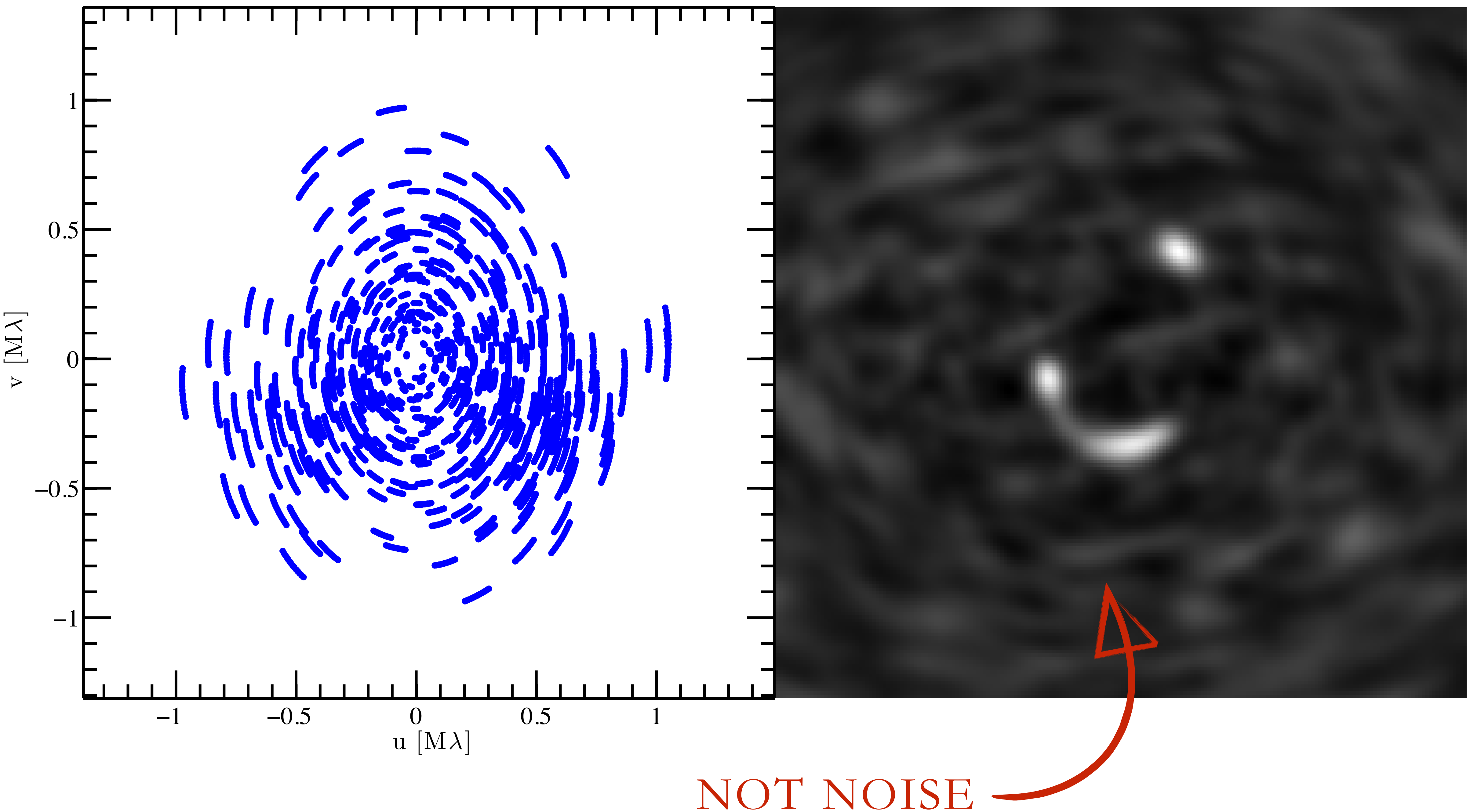
# INTERFEROMETRY:

## (WHAT DOES ALMA MEASURE?)

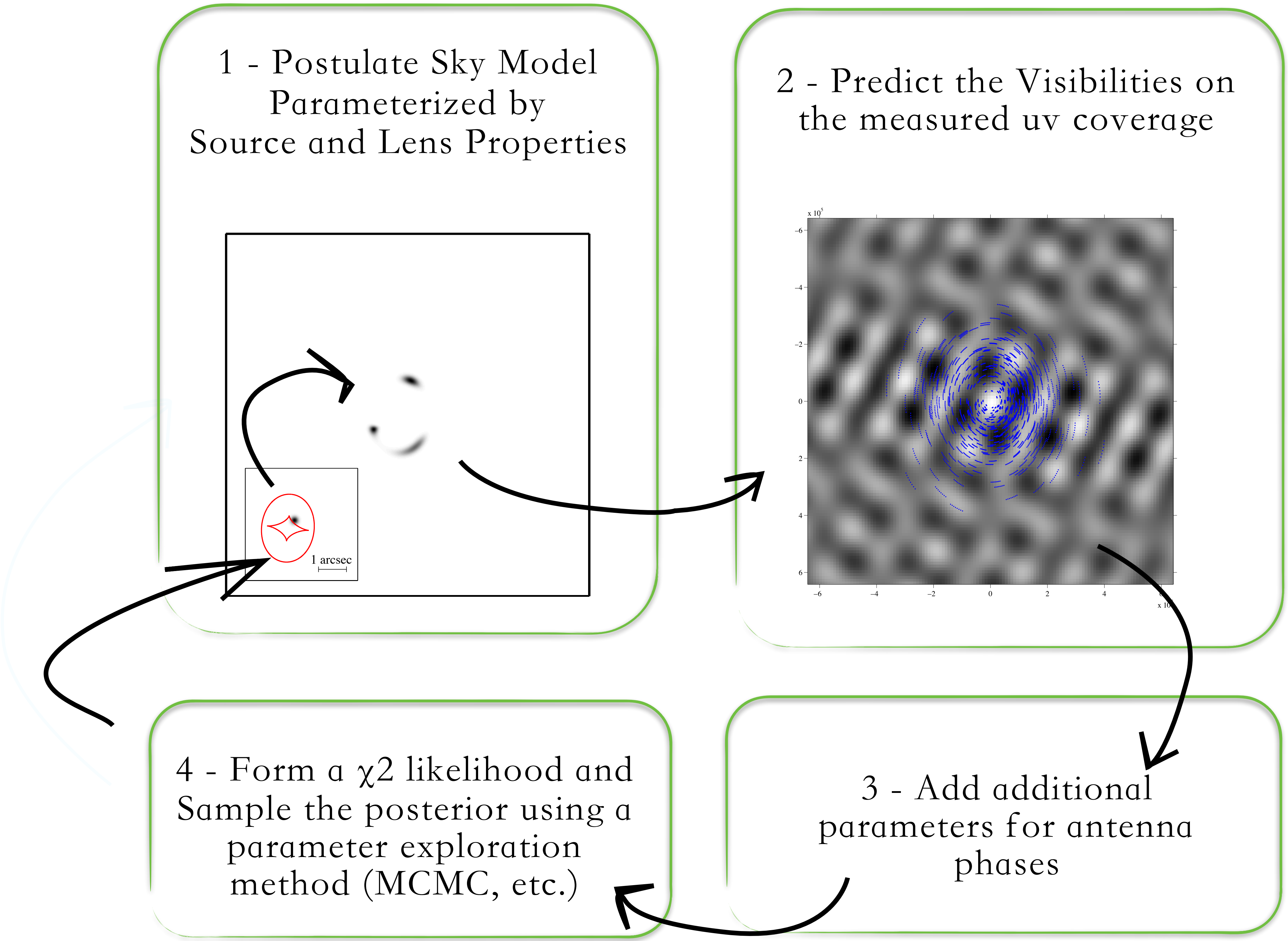


# Interferometry:

## (what does ALMA measure?)



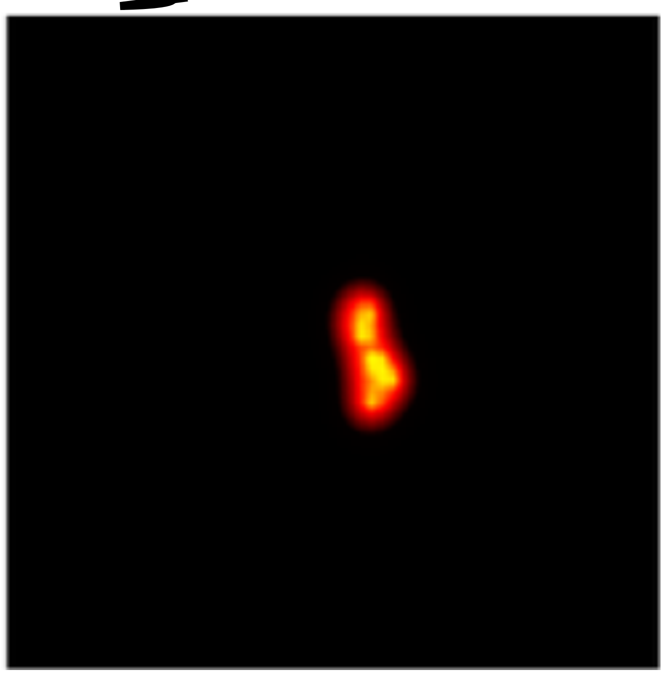
# Lens Modeling for Interferometric Data

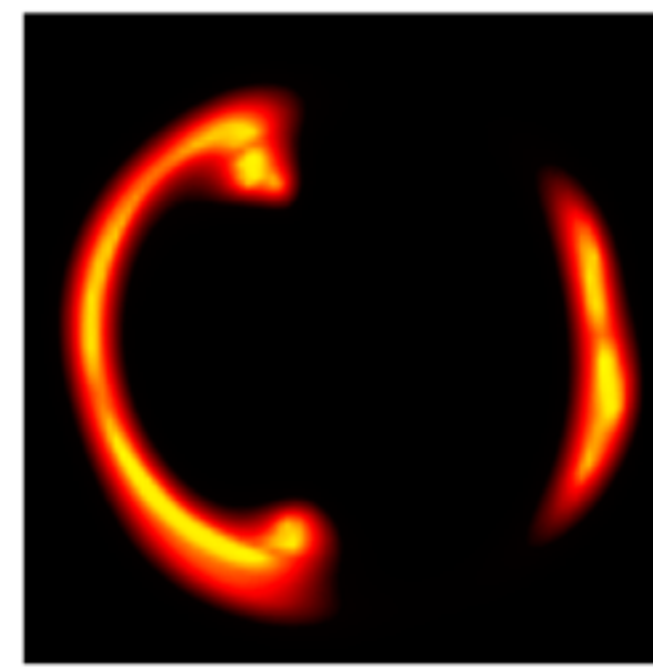


# Model Parameters

parameters describing the light distribution
in the background source ($P_{source}$)

sky emission

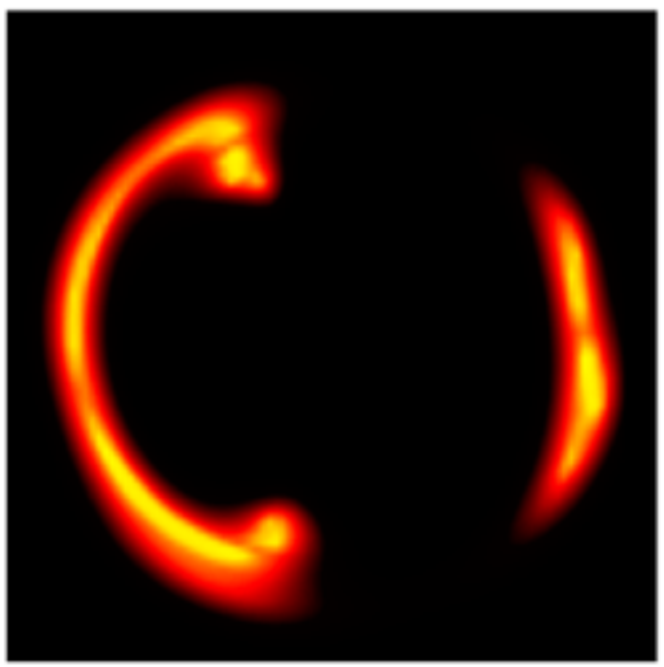




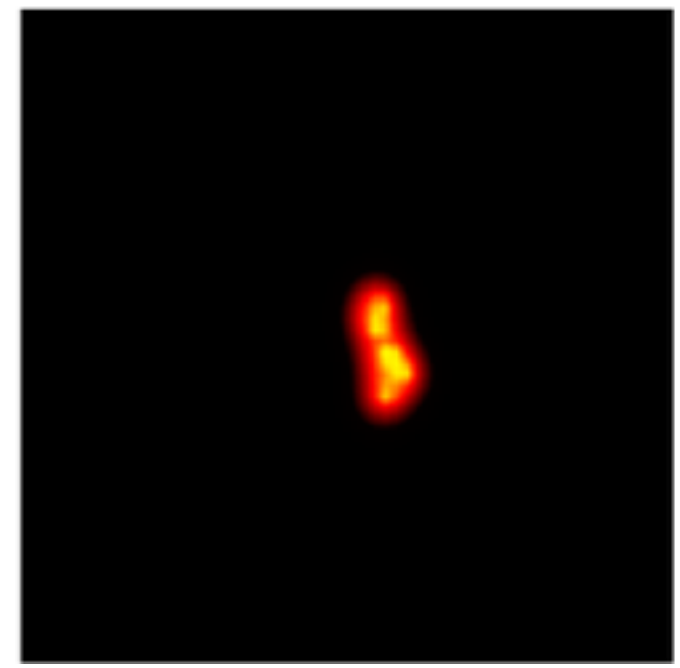
parameters describing the mass distribution
in the foreground lens ($P_{lens}$)

# Lens modeling with pixelated sources

$p_{\text{source}}$

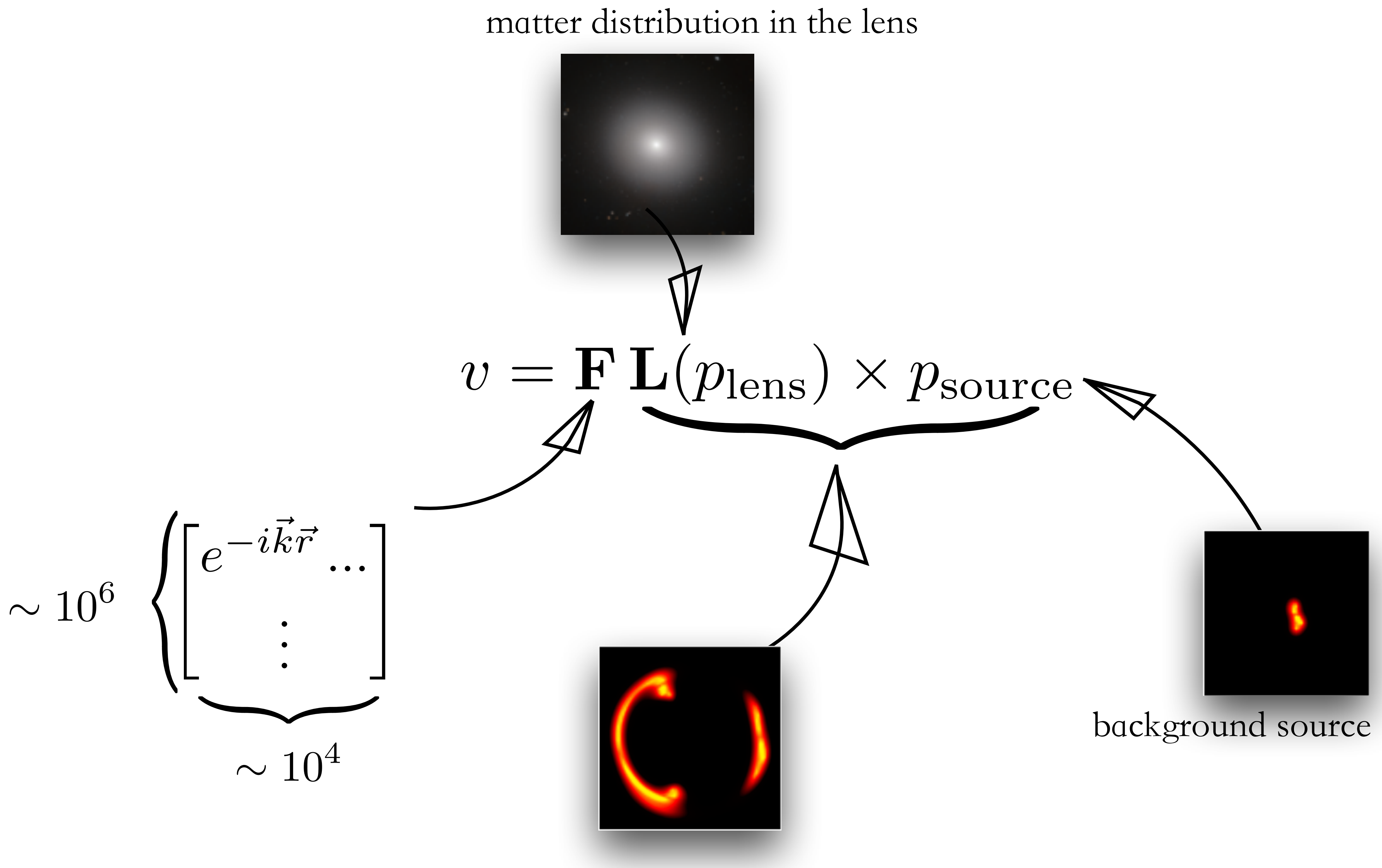


$$= \mathbf{L}(p_{\text{lens}}) \times$$

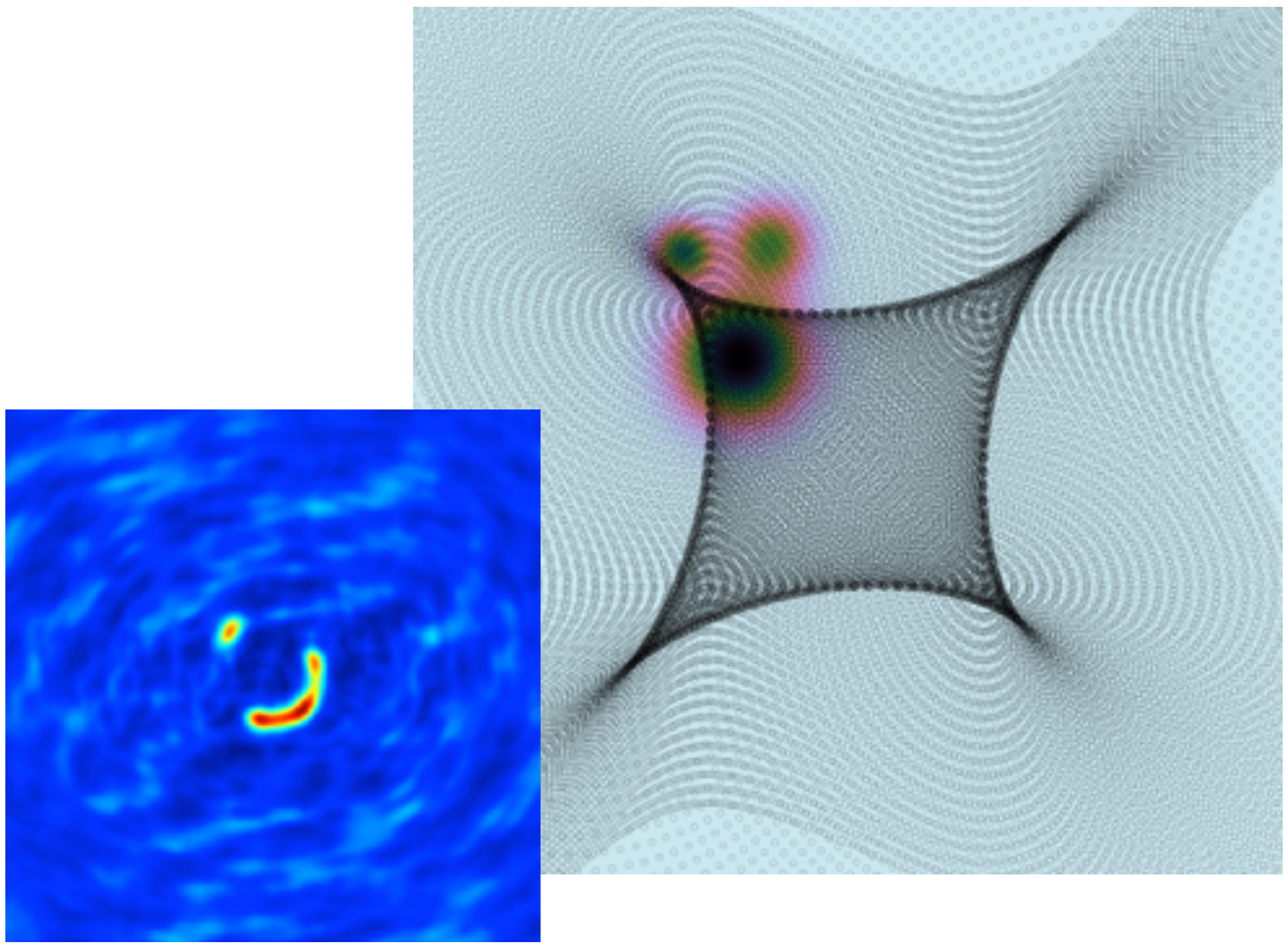


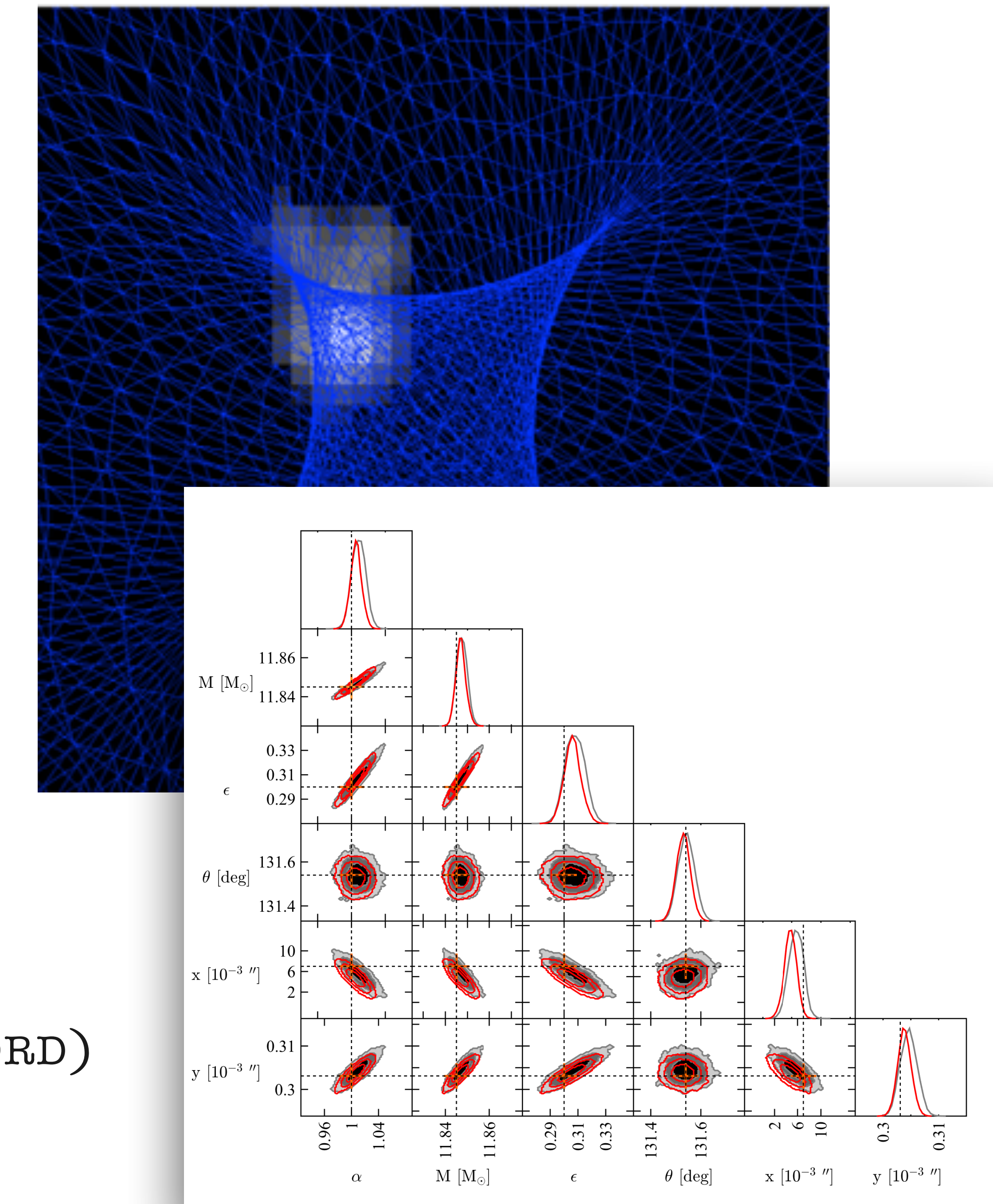
$$\text{sky surface brightness} = \mathbf{L}(p_{\text{lens}}) \times p_{\text{source}}$$

# Lens Modeling with pixelated sources



# SUCCESSFULLY TESTED ON MOCKS GENERATED WITH AN INDEPENDENT CODE

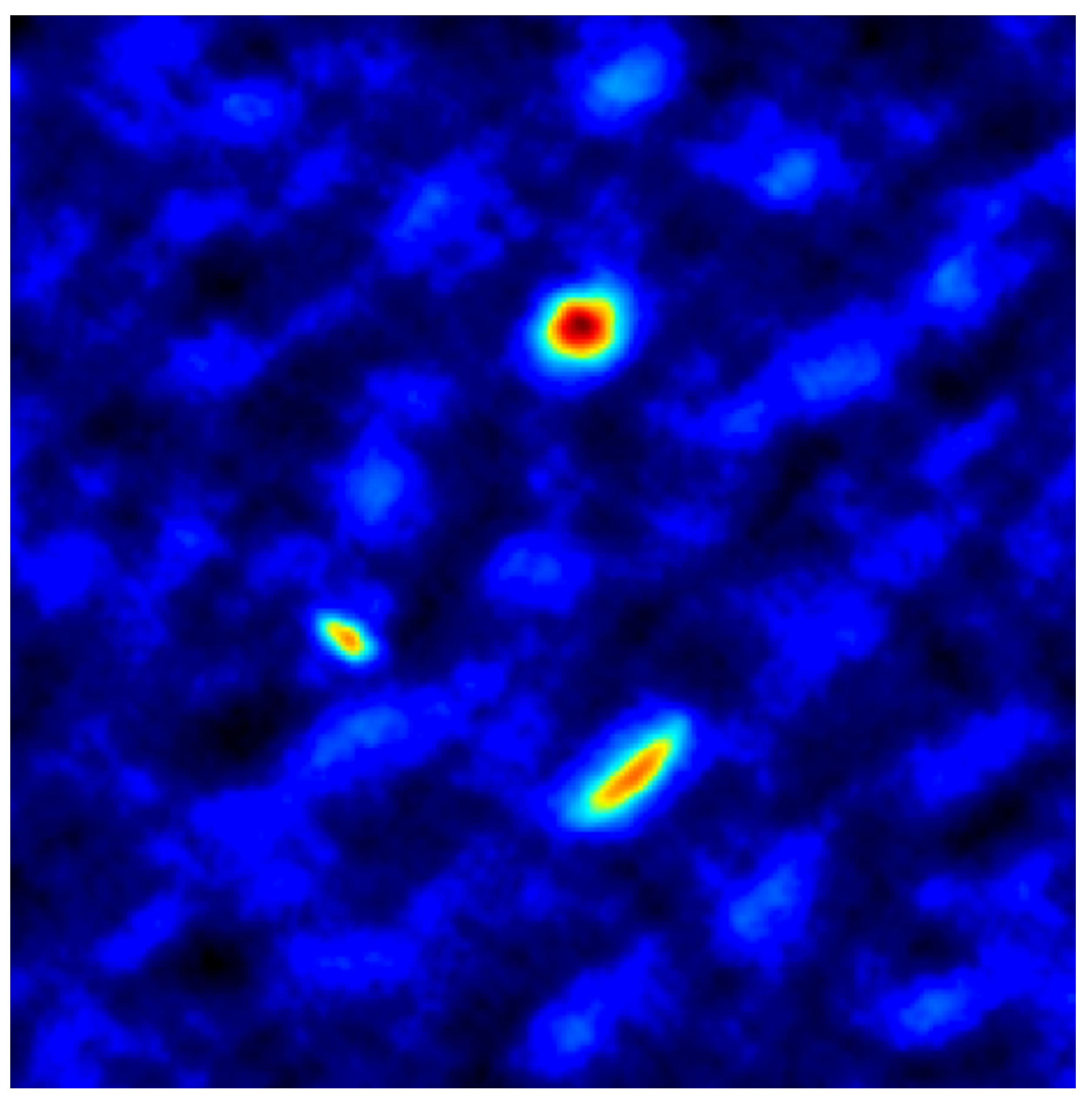





Warren Morningstar (grad @ Stanford)

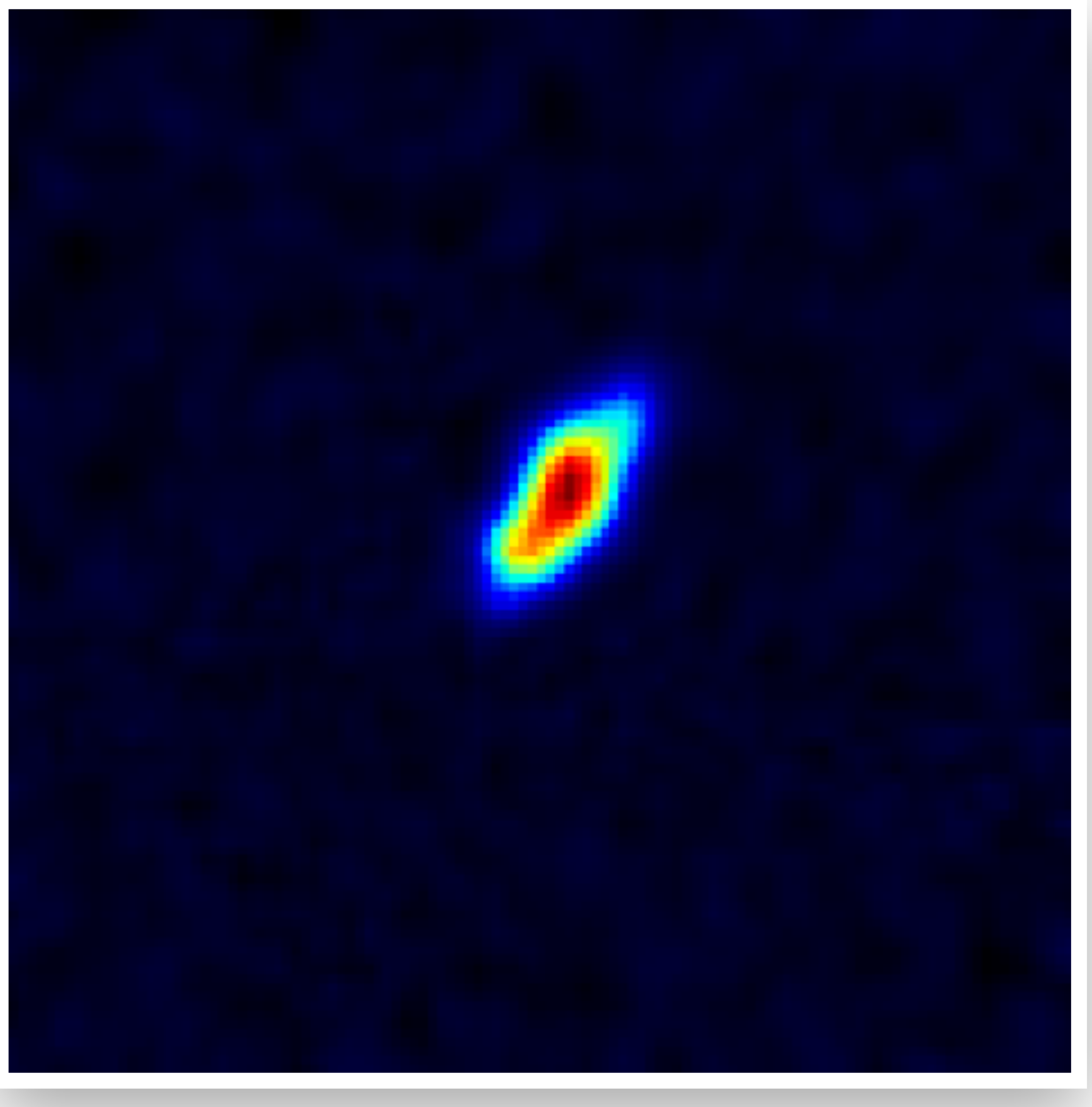
# EXAMPLE: SOURCE RECONSTRUCTION

mock data (dirty image)



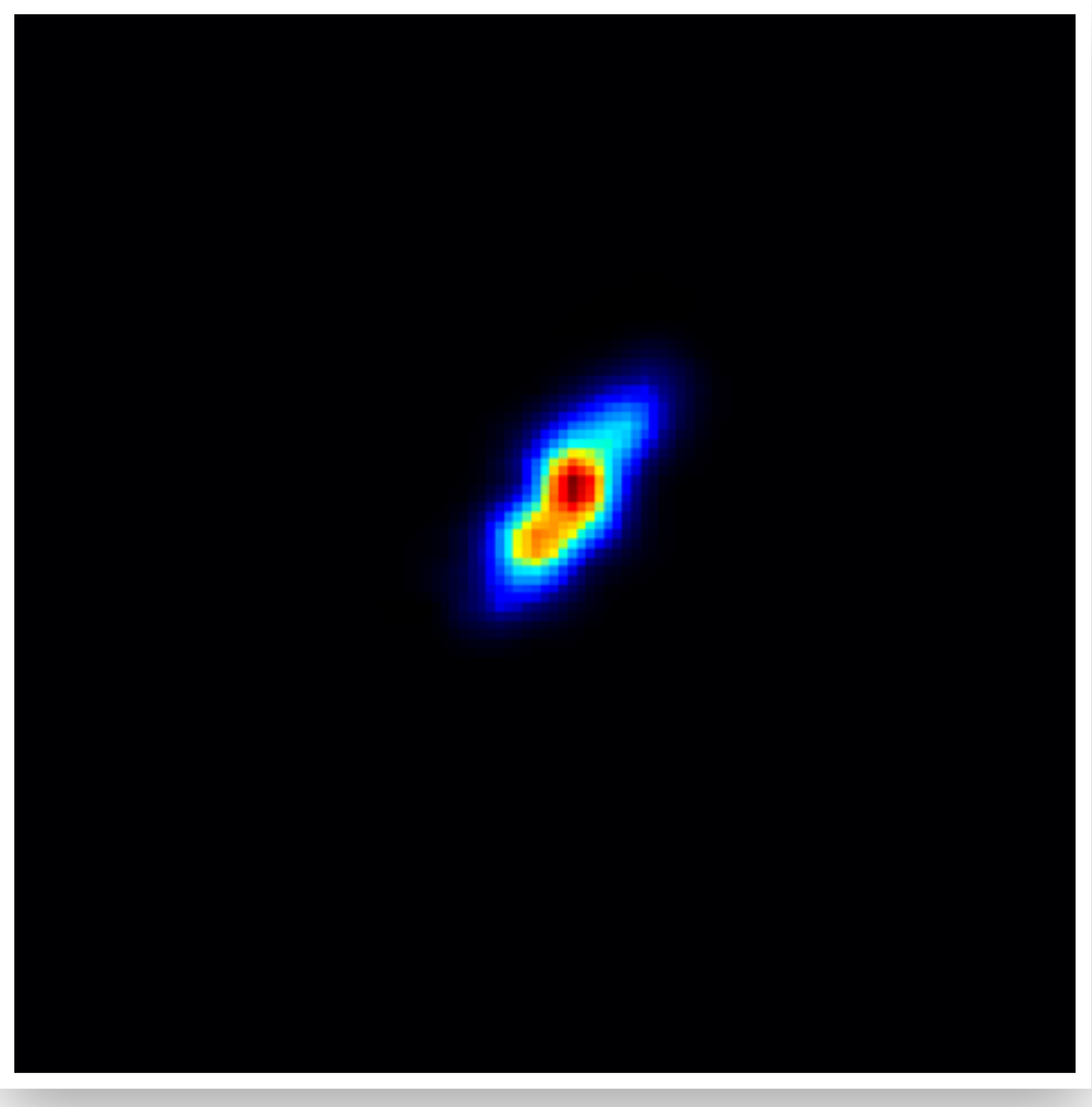
# EXAMPLE: SOURCE RECONSTRUCTION

reconstructed source



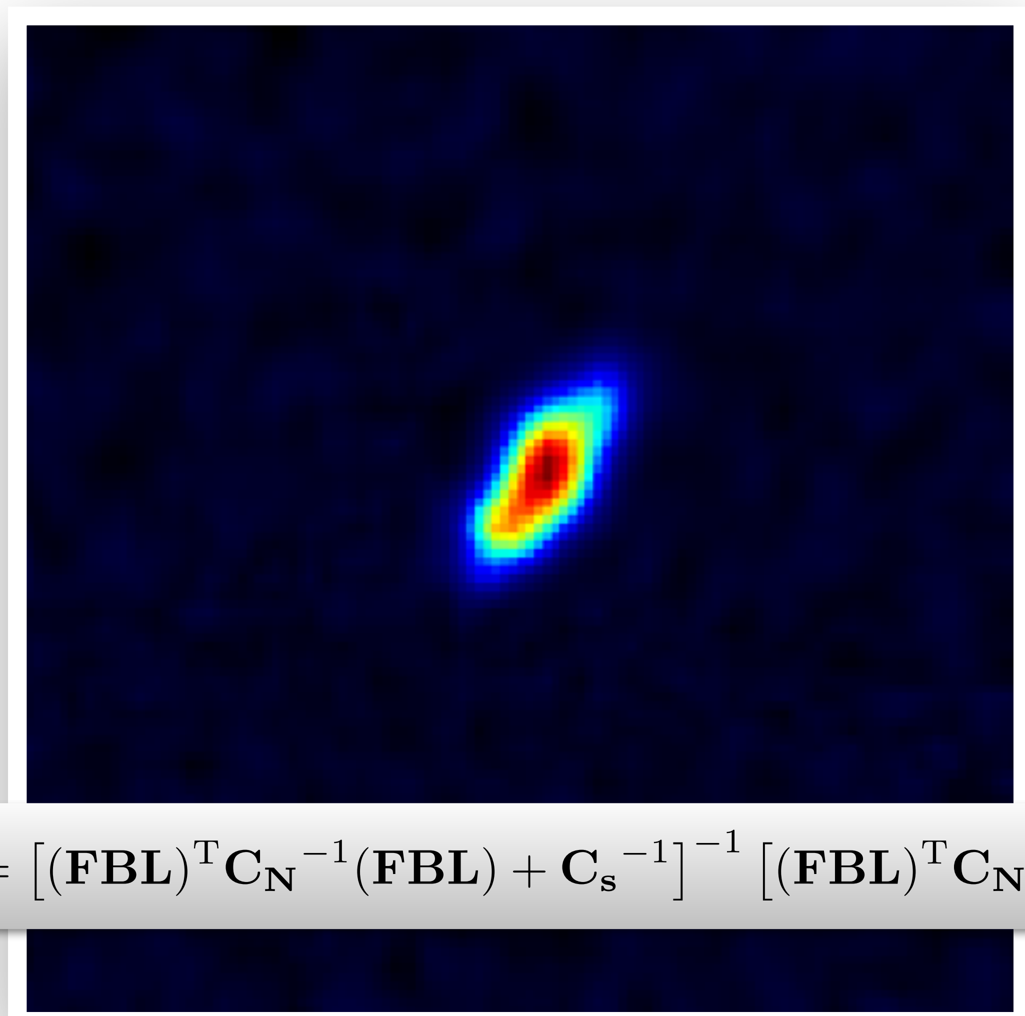
# EXAMPLE: SOURCE RECONSTRUCTION

true source (mock)

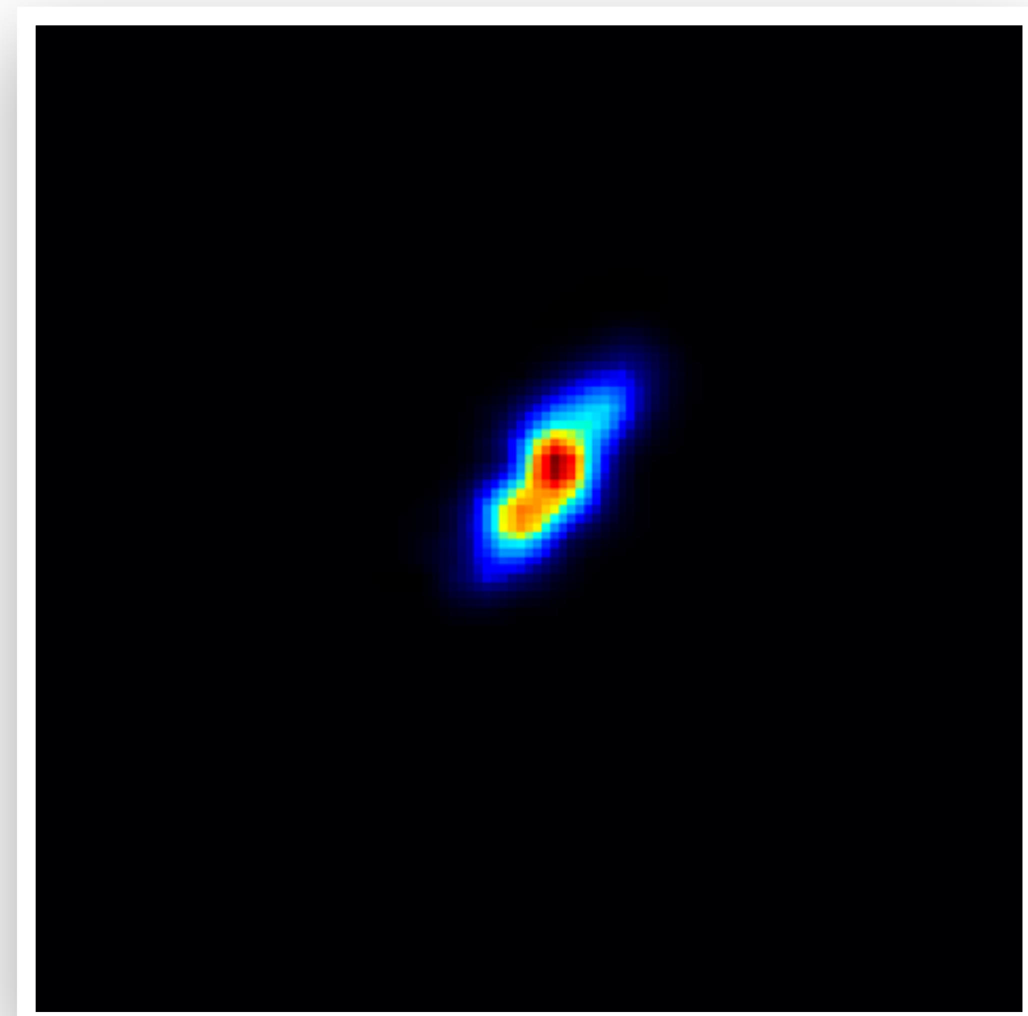


# EXAMPLE: SOURCE RECONSTRUCTION

reconstructed source



true source (mock)



$$S = \left[(\mathbf{FBL})^{\mathrm{T}}\mathbf{C_N}^{-1}(\mathbf{FBL}) + \mathbf{C_s}^{-1}\right]^{-1}\left[(\mathbf{FBL})^{\mathrm{T}}\mathbf{C_N}^{-1}\mathbf{D}\right]$$

For realistic ALMA data, solving this requires thousands of cpu-cores.

# Linearizing the Model (subhalo finder)

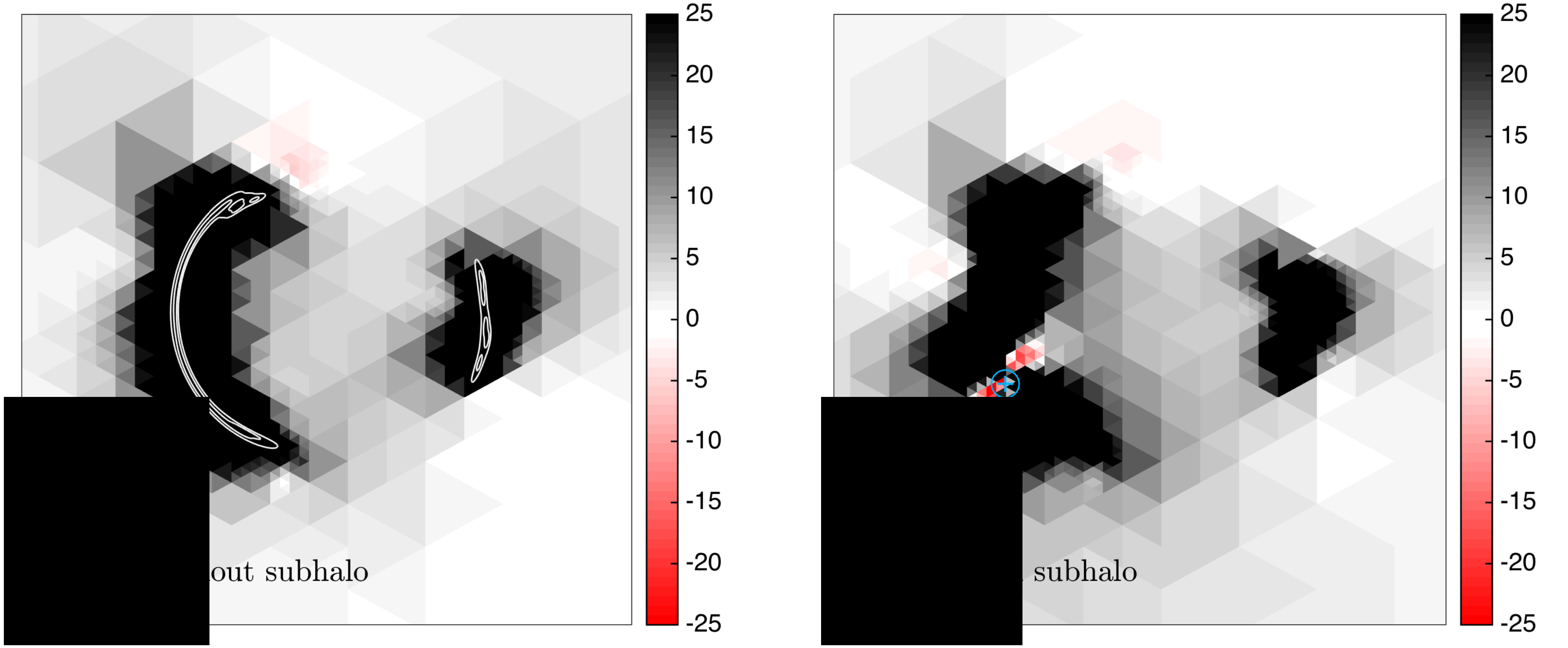
- Generally, likelihood evaluation is computationally very expensive.

- In a small neighborhood of the maximum posterior model, all parameters could be treated linearly for small perturbation to the fiducial model.

$$M(p = p_0 + \Delta p) = M(p_0) + \frac{\partial M}{\partial p} \Delta p$$

- We can use this linearized model to estimate the marginalized posterior for different subhalo models.

# Probability of the presence of a subhalo

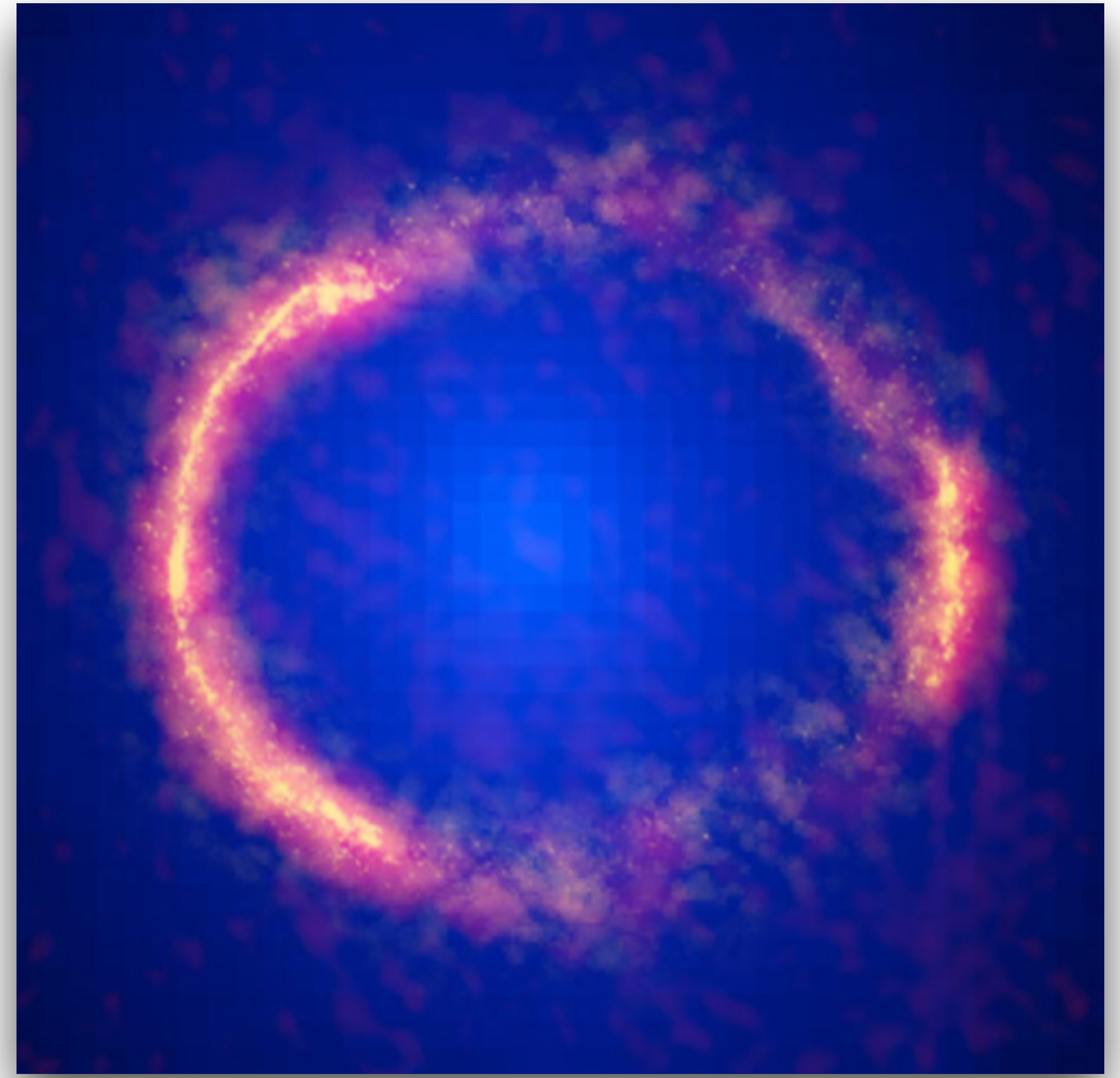



greyscale: difference in log posterior between a model which includes a subhalo and a smooth model (no subhalos)

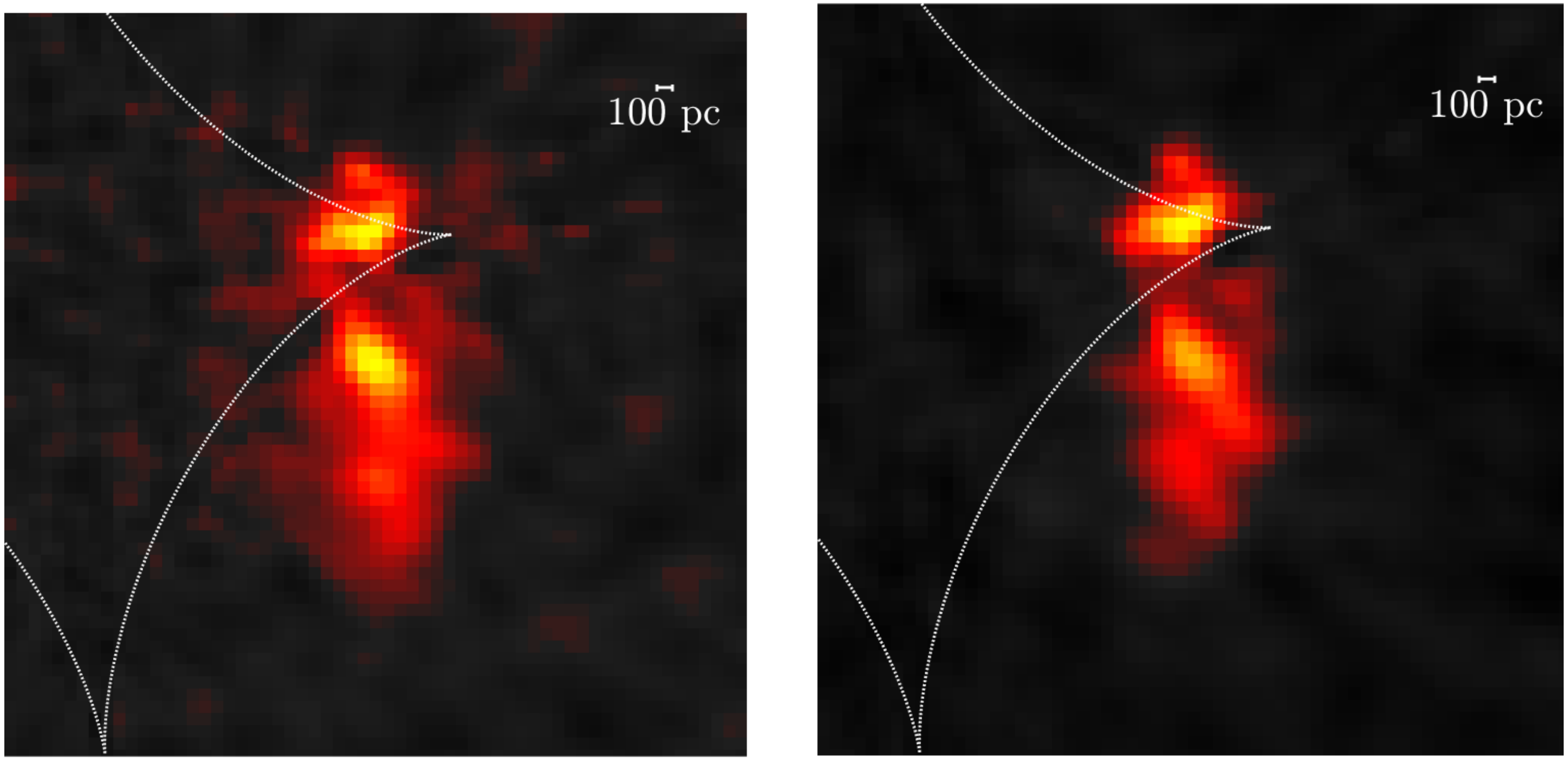
Hezaveh et al. 2016

# SDP 81
## (ALMA science verification data)

Blue: HST
Red: ALMA

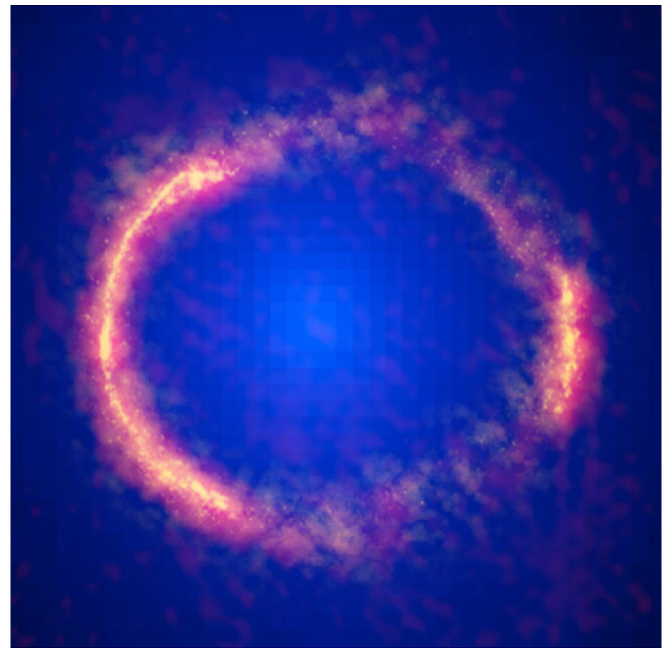


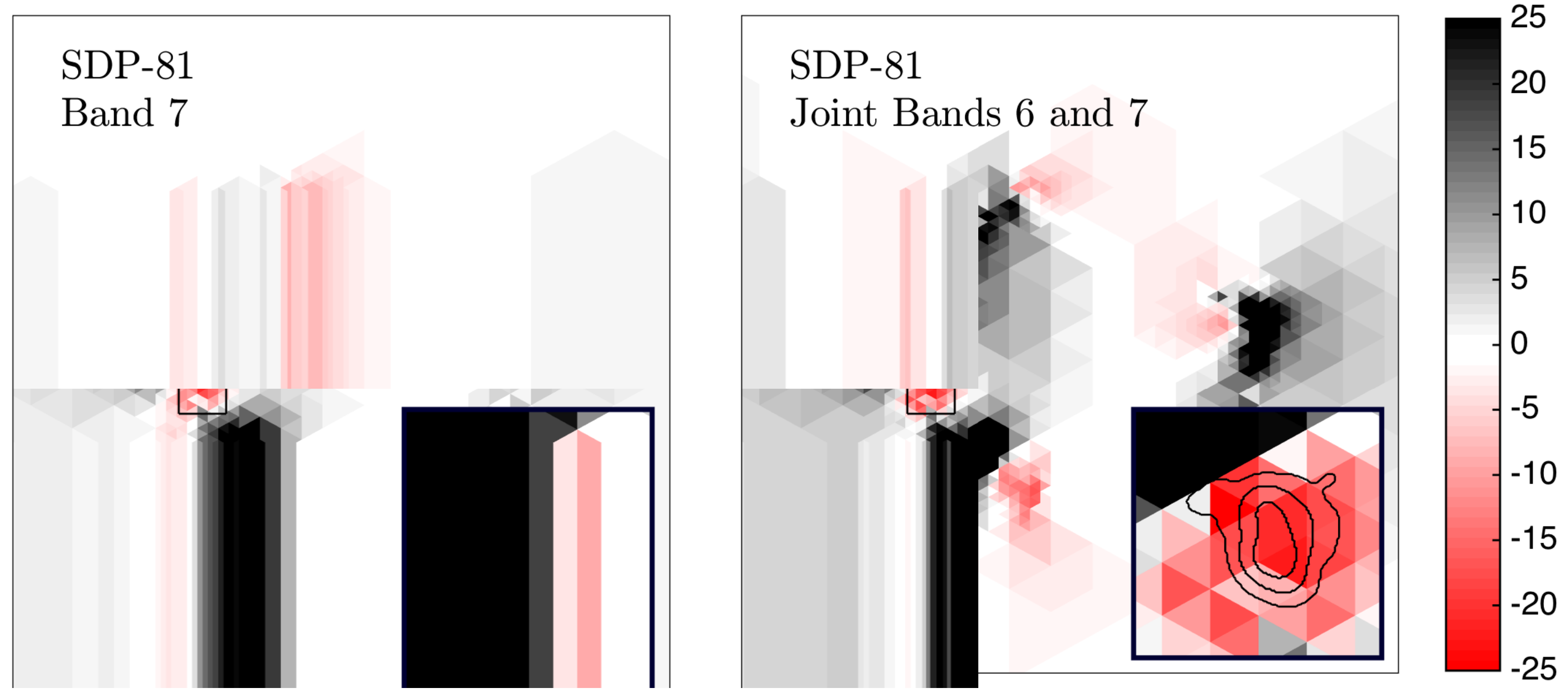
# SDP 81
## Reconstructed Background Source




Hezaveh et al. 2016

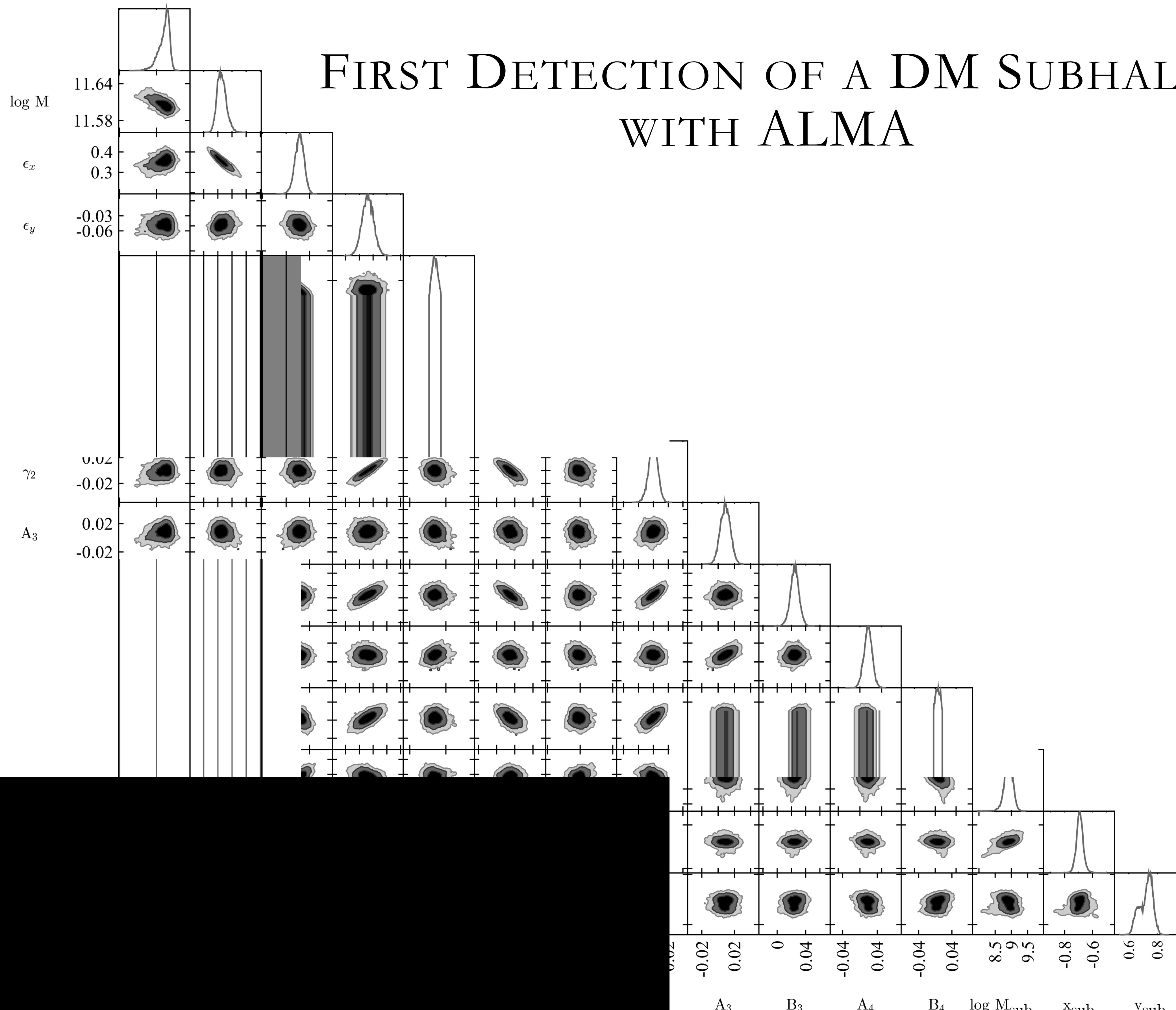
# First Detection of a DM Subhalo with ALMA






Hezaveh et al. 2016

# First Detection of a DM Subhalo with ALMA



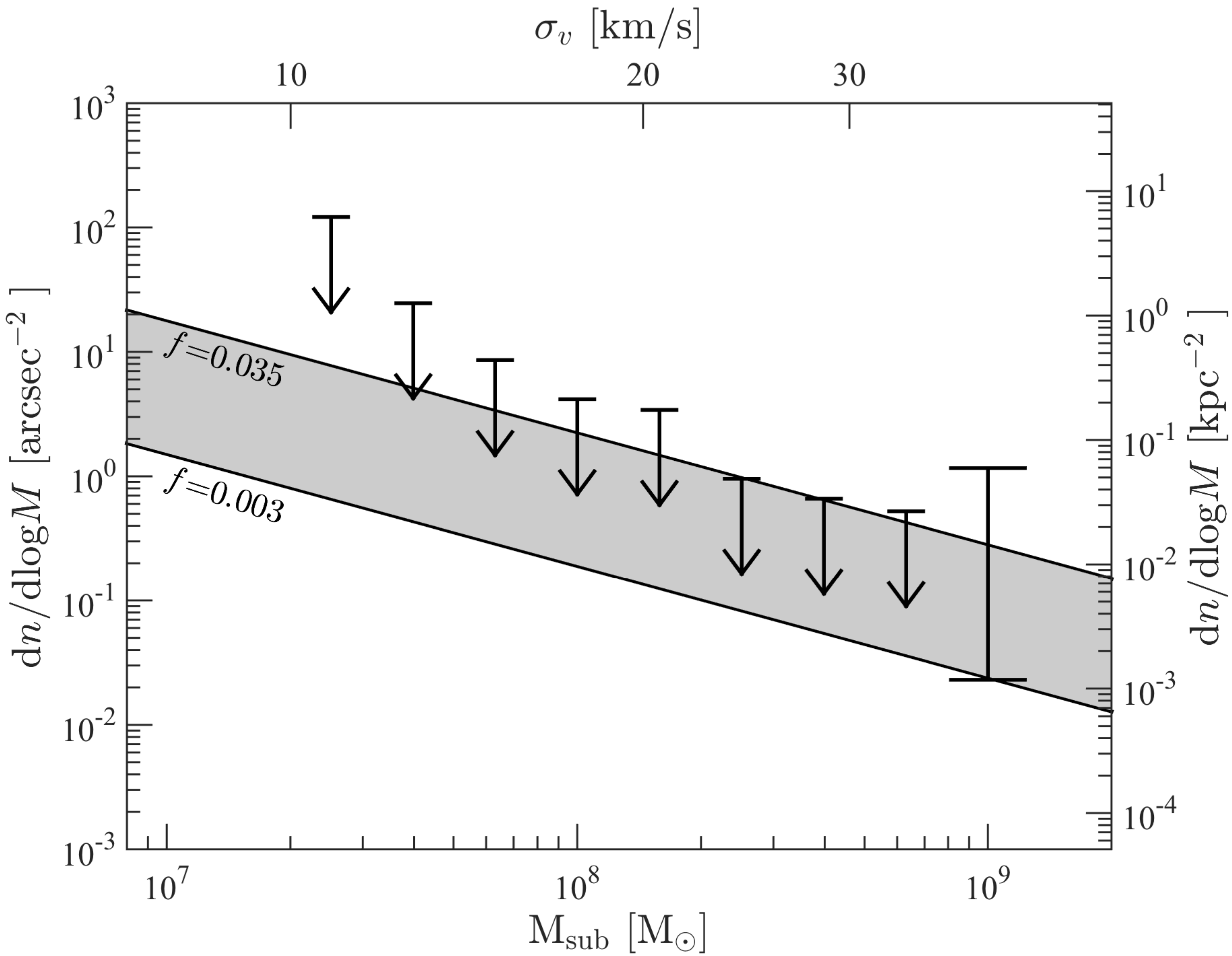

[redacted]

Hezaveh et al. 2016

# Probability of a second Subhalo

Hezaveh et al. 2016

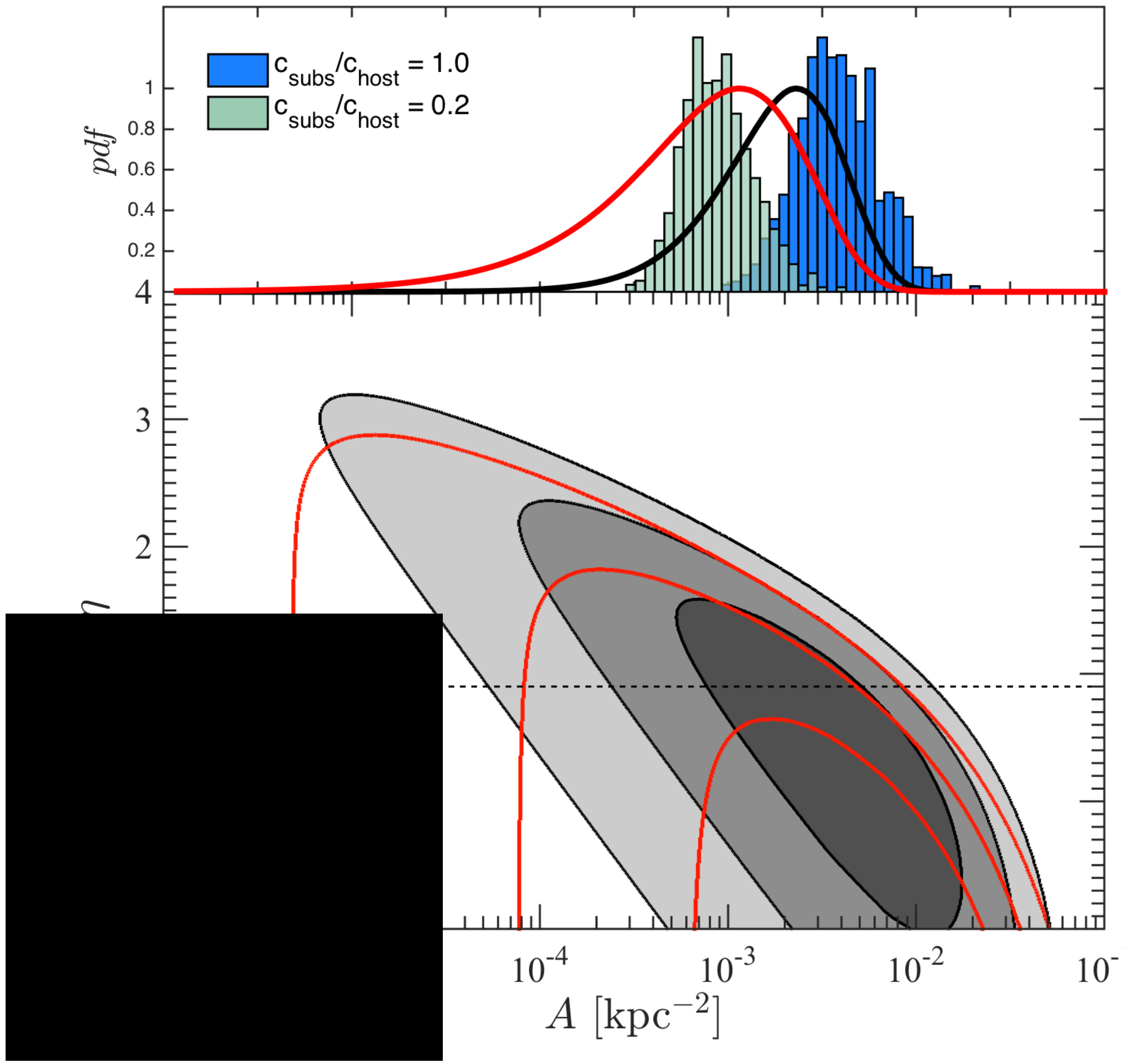
# Constraints on the Mass Function of Subhalos in the Host Halo




Hezaveh et al. 2016

# Constraints on the Mass Function of Subhalos in the Host Halo

Theory: Yao-Yuan Mao



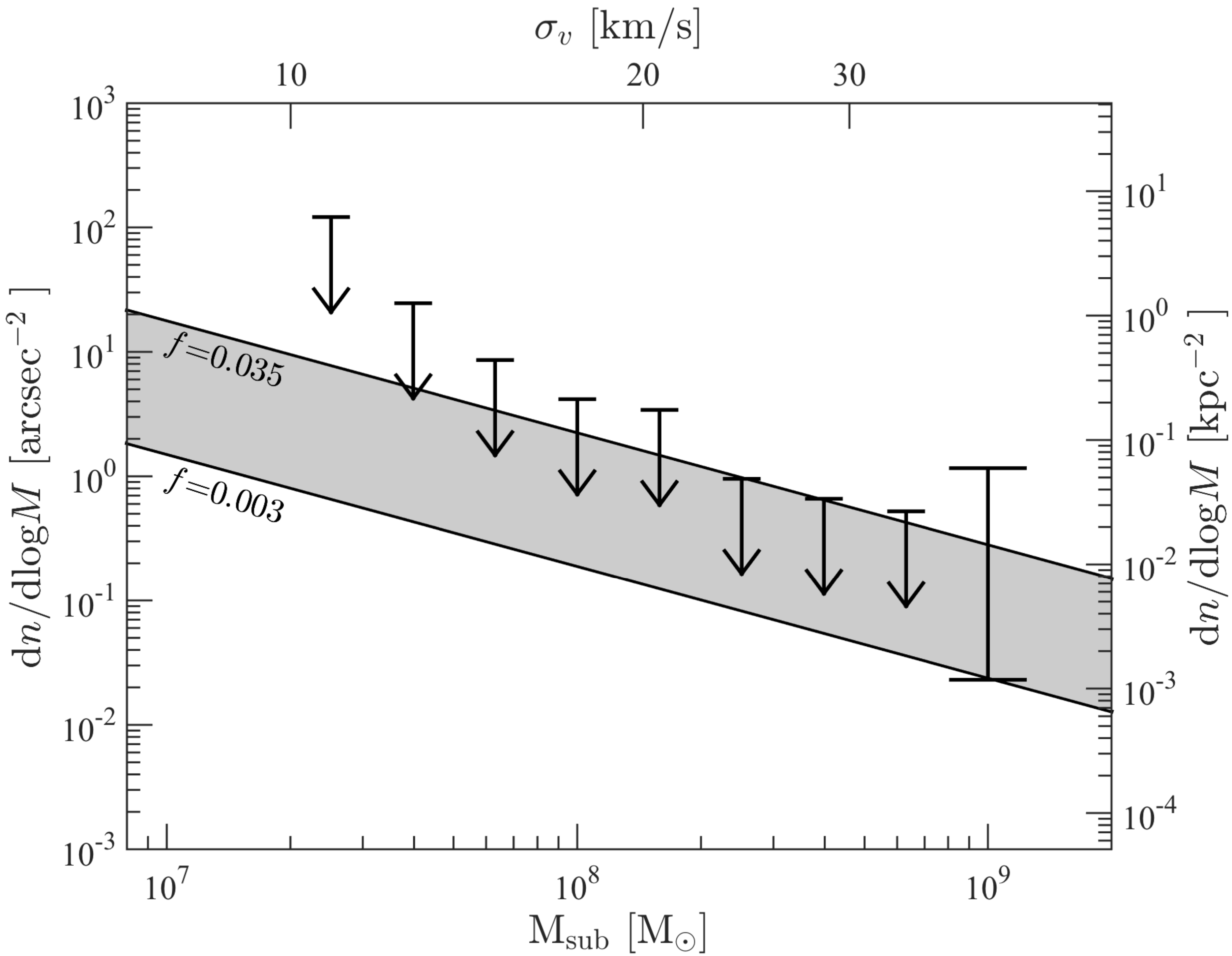

Hezaveh et al. 2016

# Comparison to Theoretical Predictions

Theory: Yao-Yuan Mao

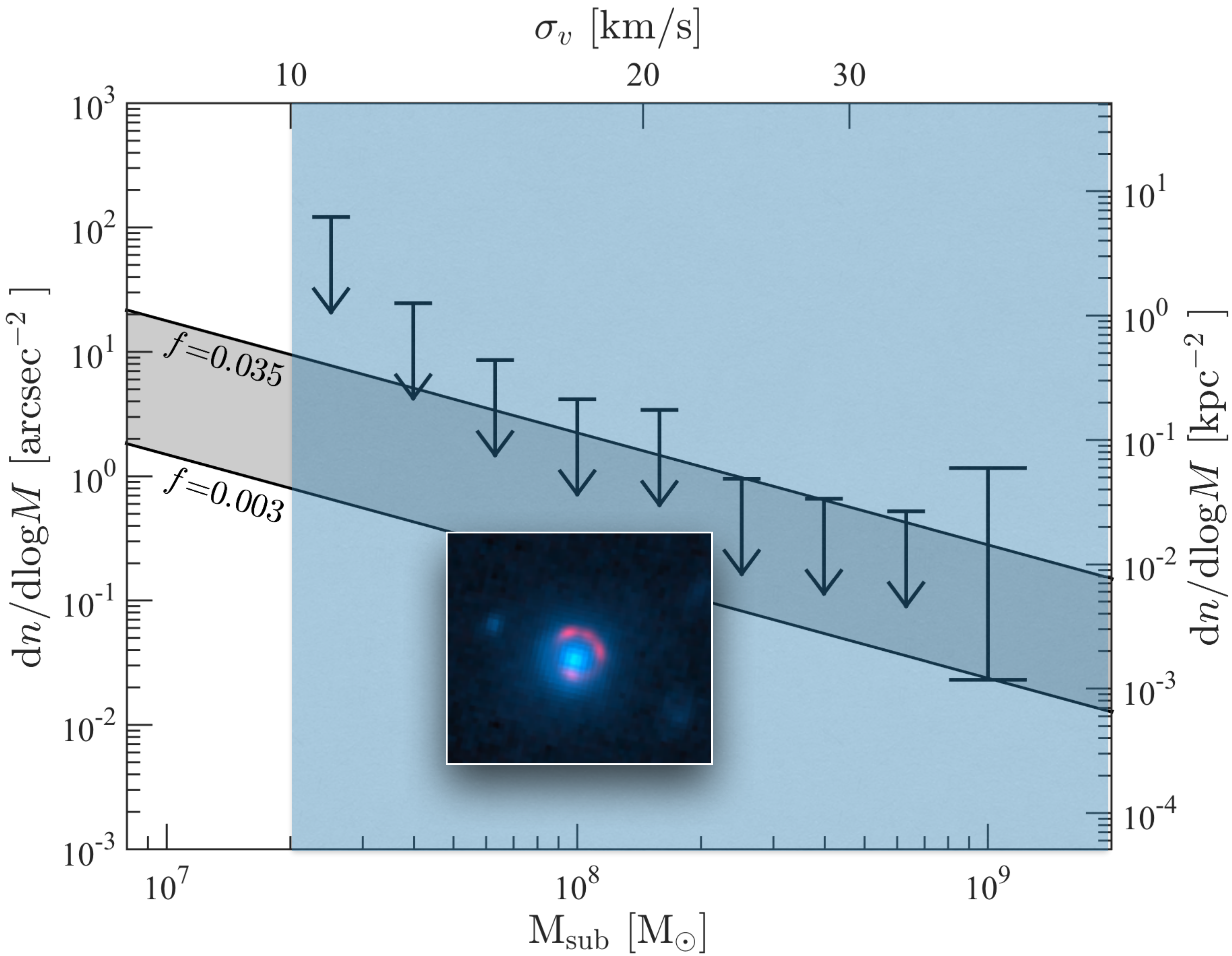
Hezaveh et al. 2016

# Constraints on the Mass Function of Subhalos in the Host Halo




Hezaveh et al. 2016

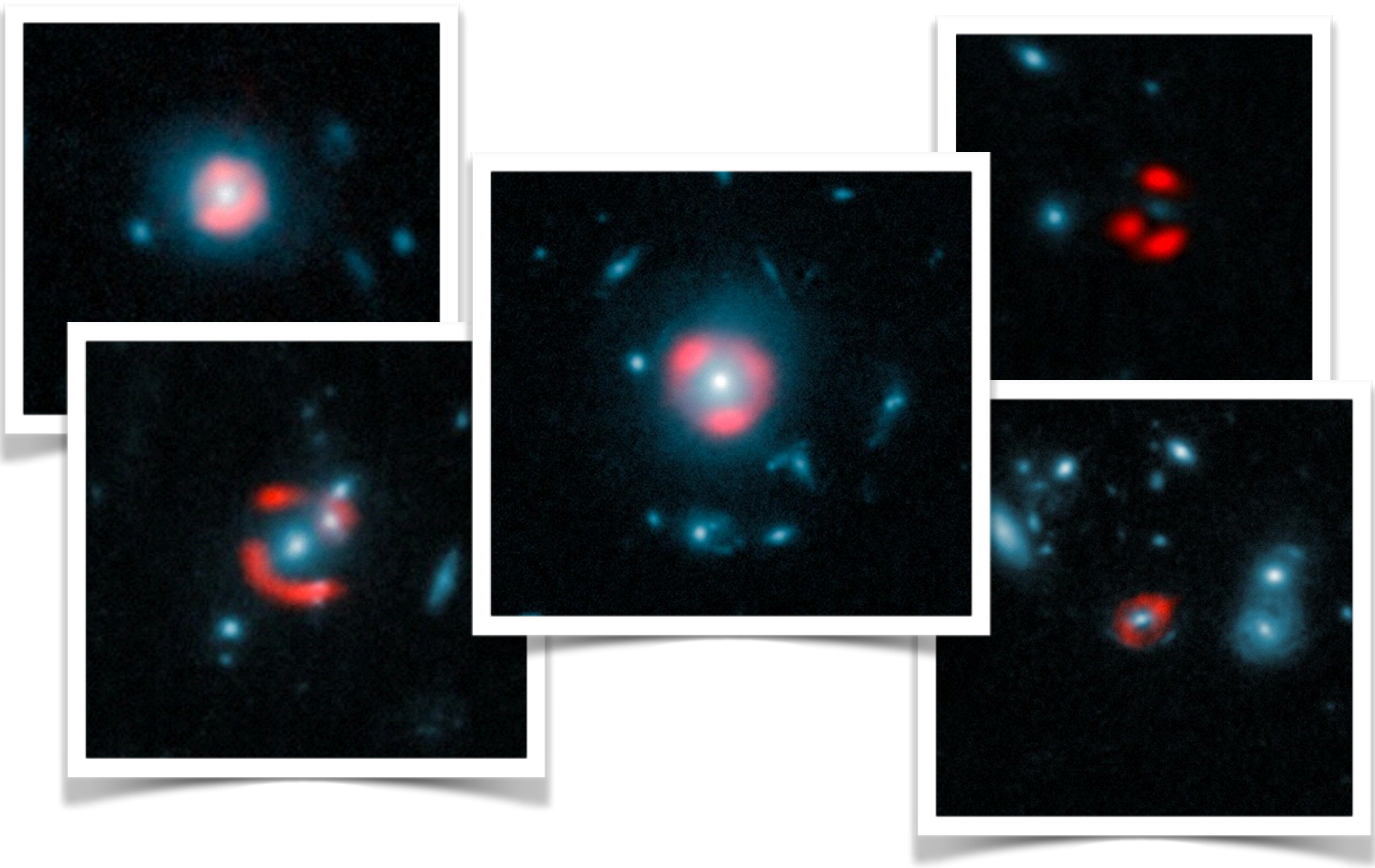
# Constraints on the Mass Function of Subhalos in the Host Halo




Hezaveh et al. 2016

# ALMA observations of SPT-discovered sources

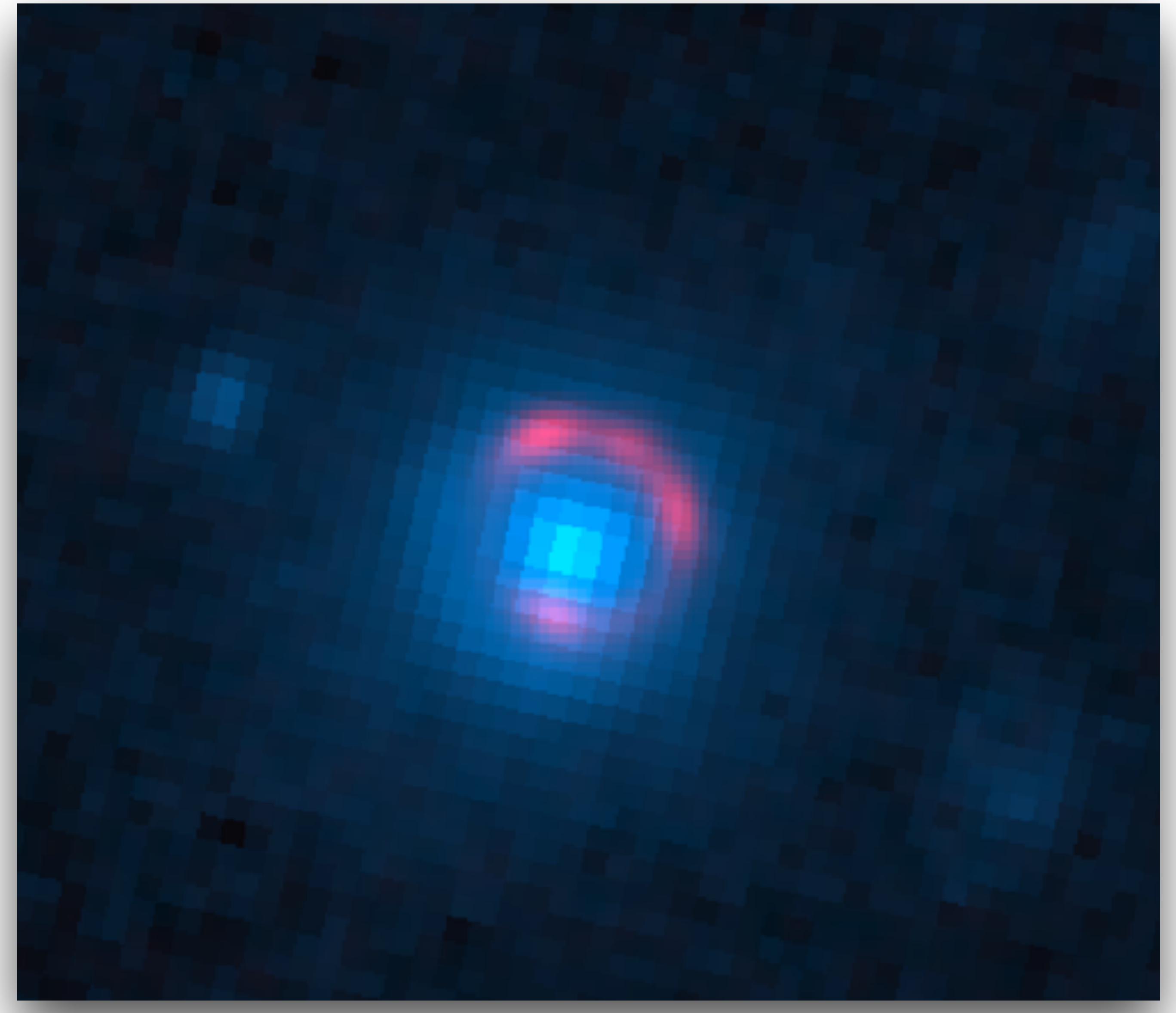
Blue: HST (optical), Red: ALMA (Cycle 0)



Vieira et al. Nature 2013

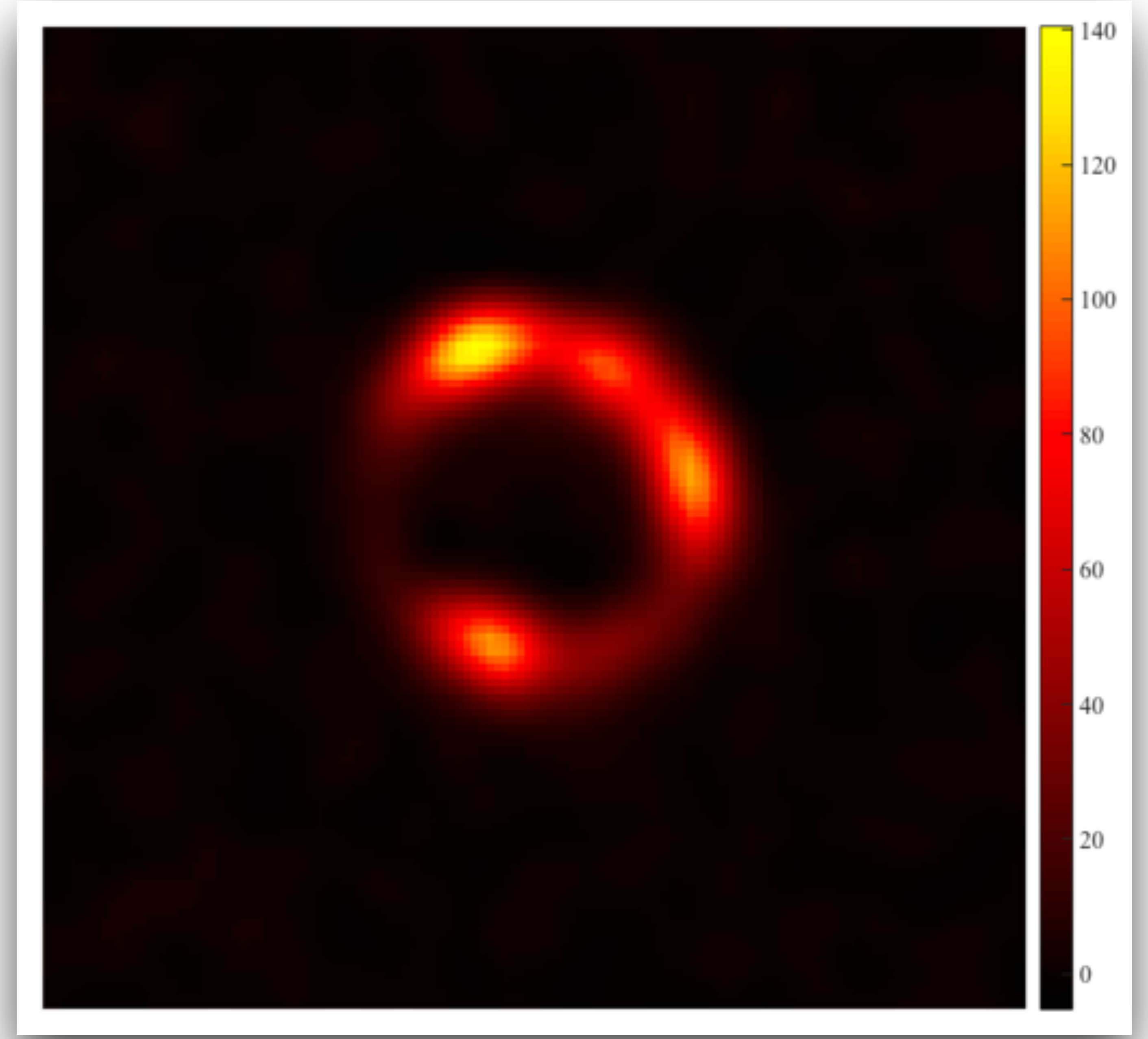
Hezaveh et al. ApJ. 2013

# SPT2134-50 (ALMA Cycle 2)
# Band 6 (red: ALMA continuum, blue: HST)



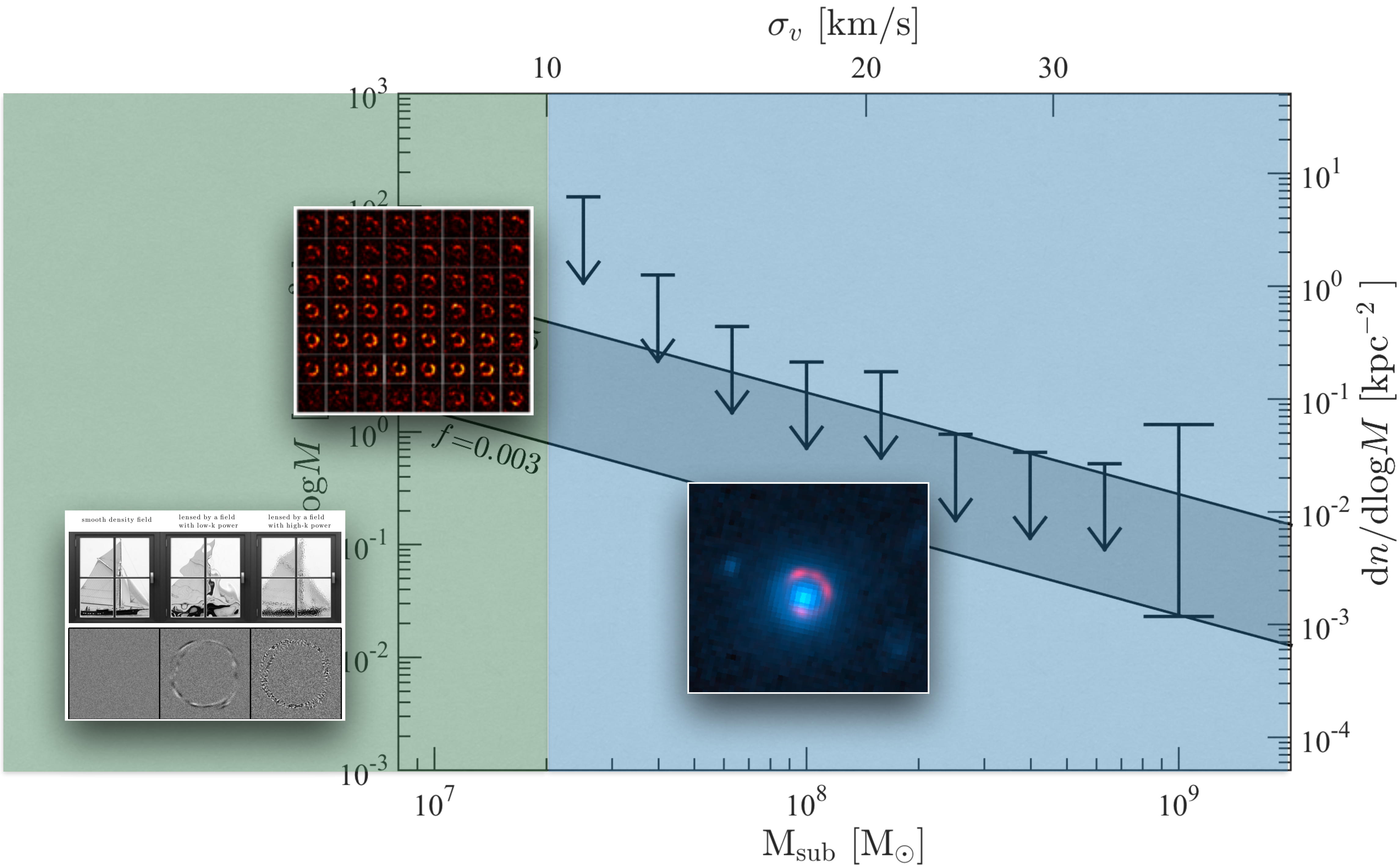
Morningstar leading the analysis

# SPT2134-50 (ALMA Cycle 2)
# Band 6 (continuum)




Morningstar leading the analysis

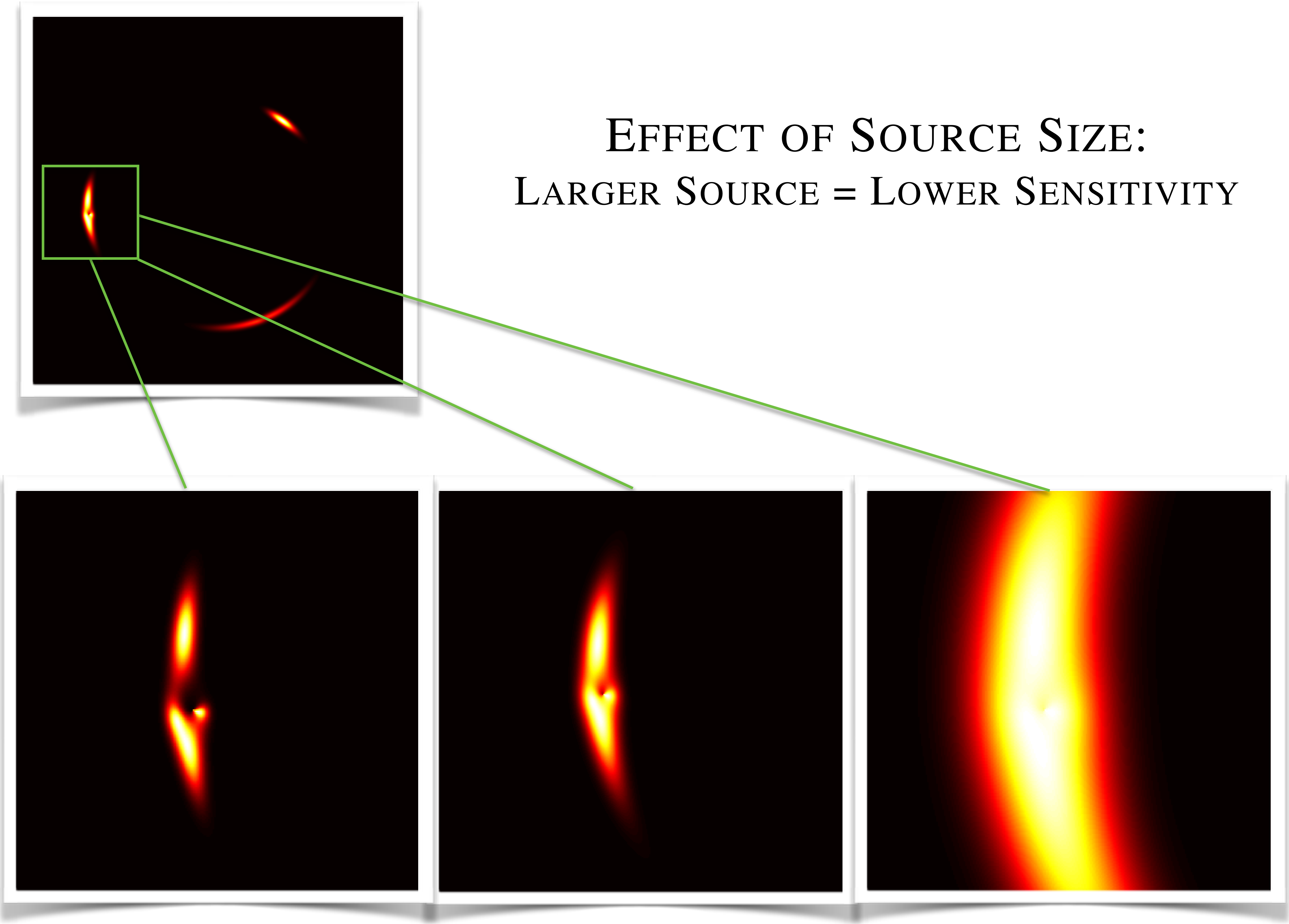
# Constraints on the Mass Function of Subhalos in the Host Halo



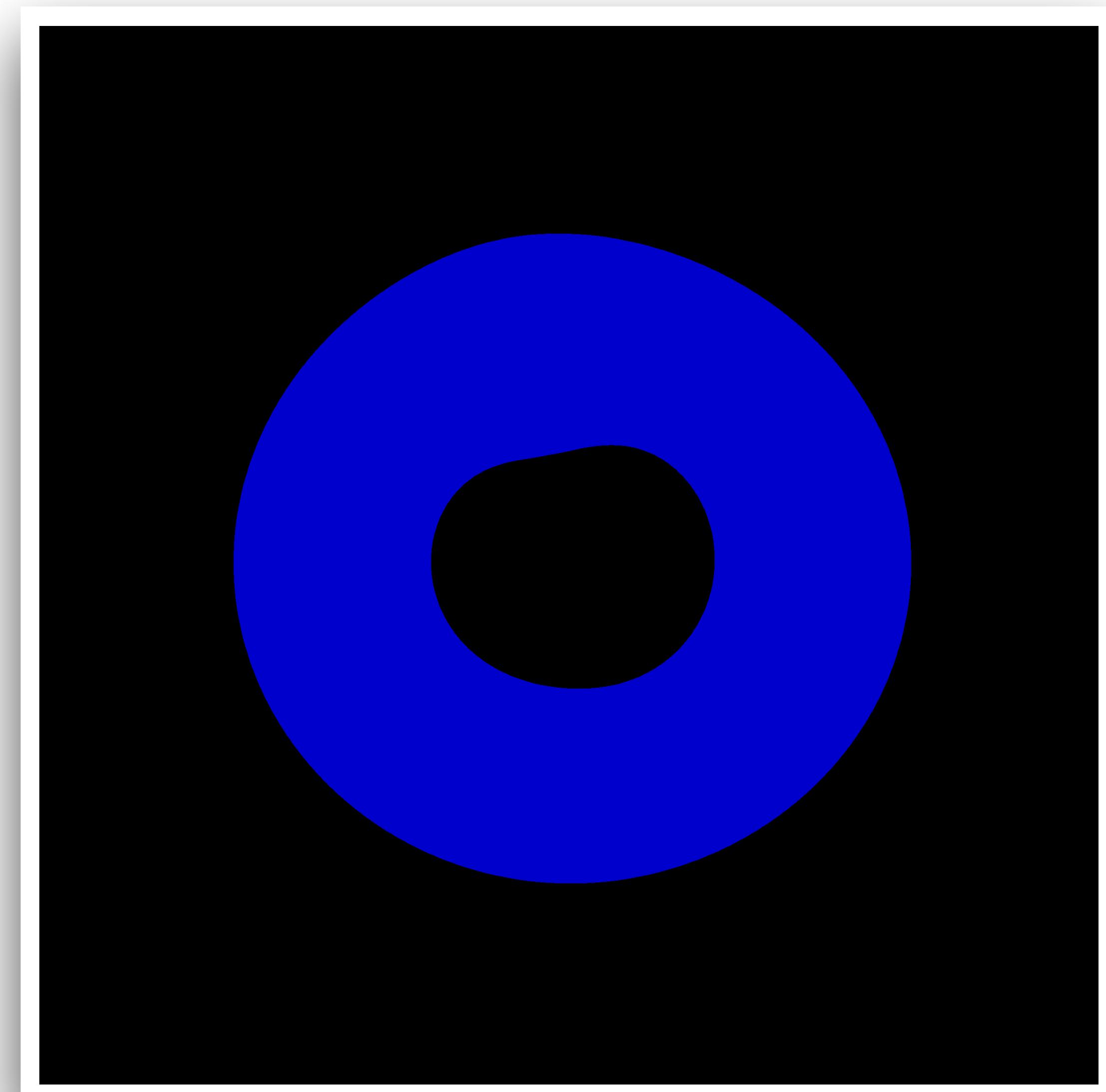

Hezaveh et al. 2016

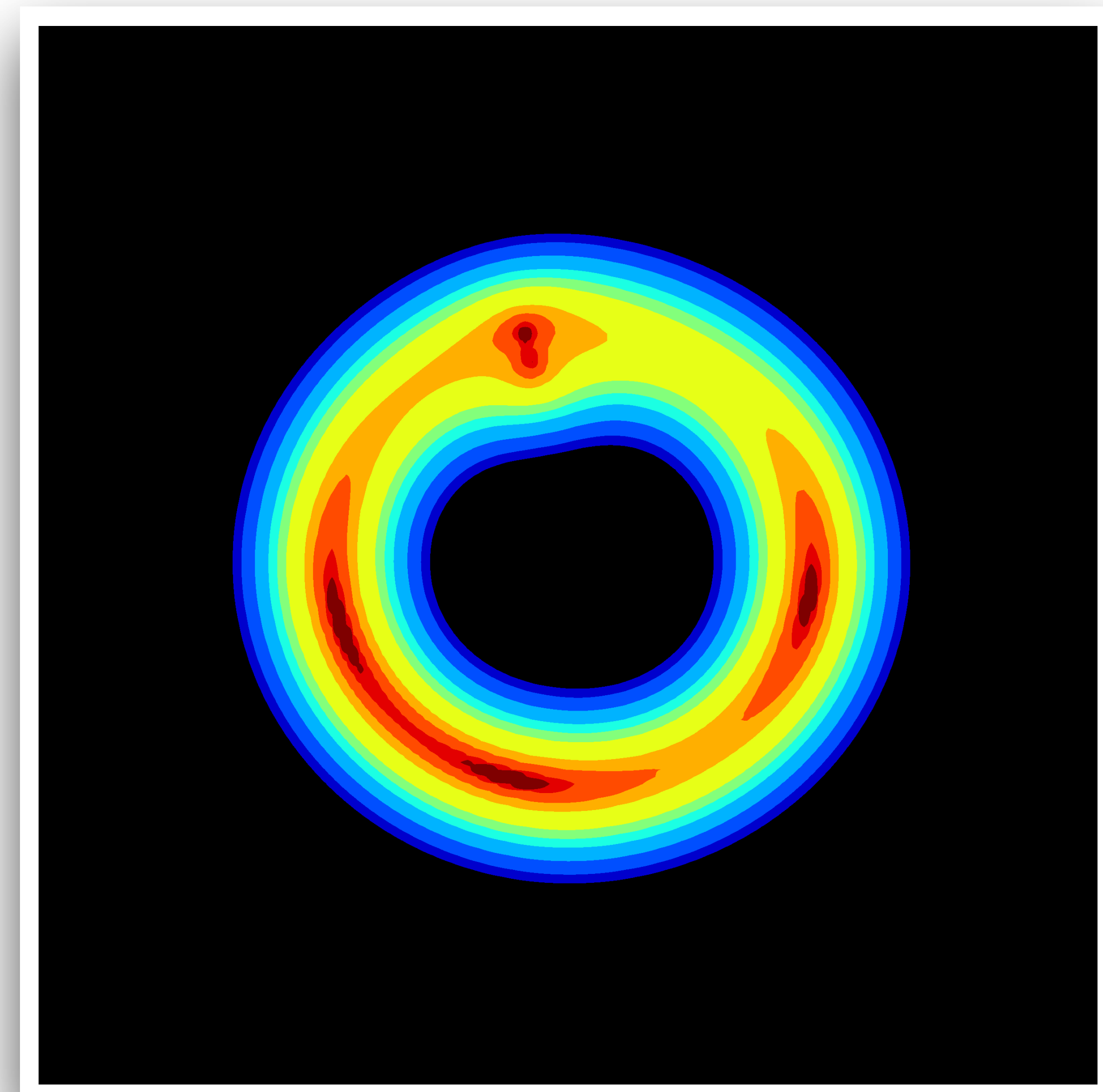
## Effect of Source Size:

### Larger Source = Lower Sensitivity



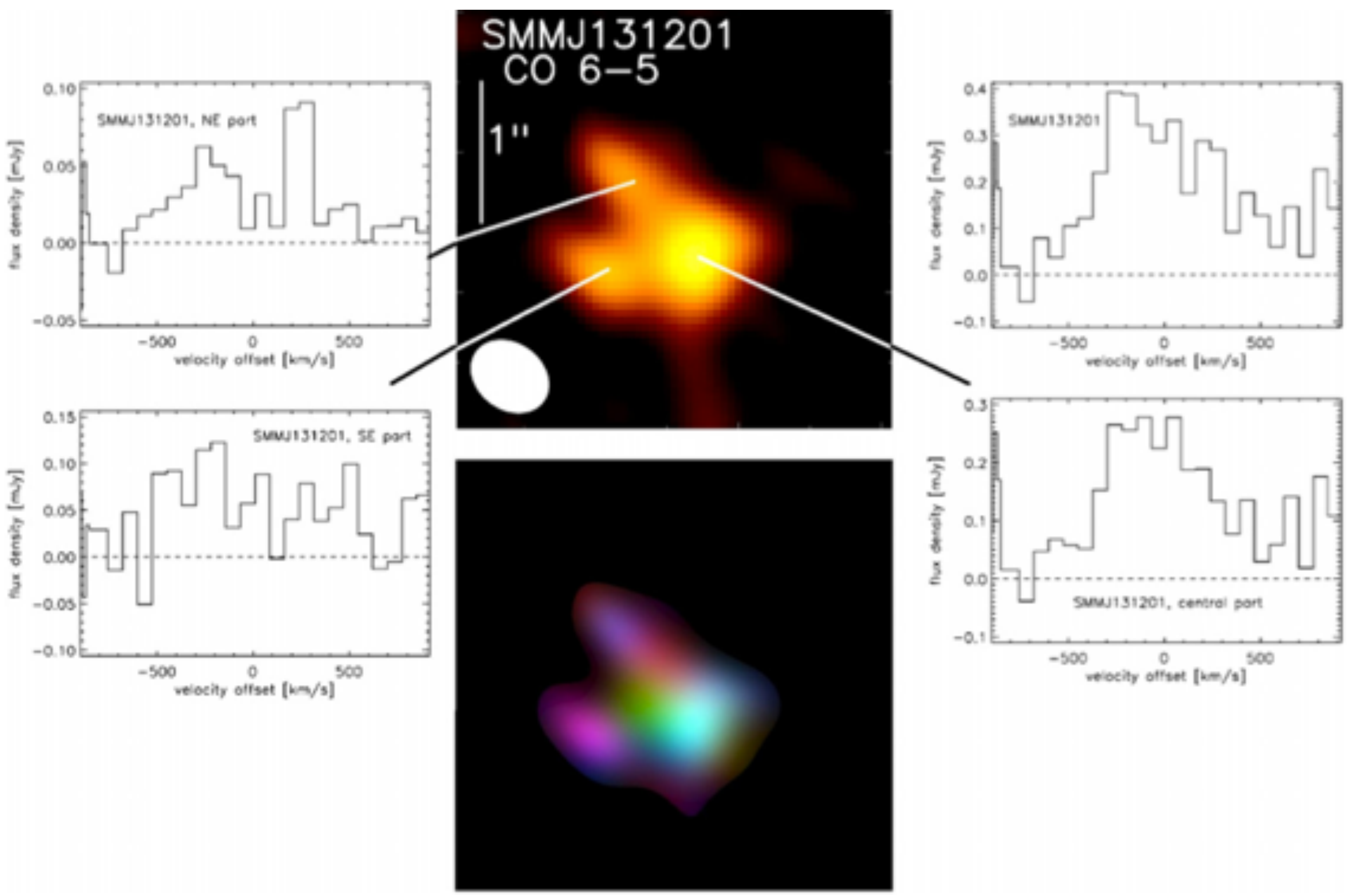
# We need a small source, or a source with small features...





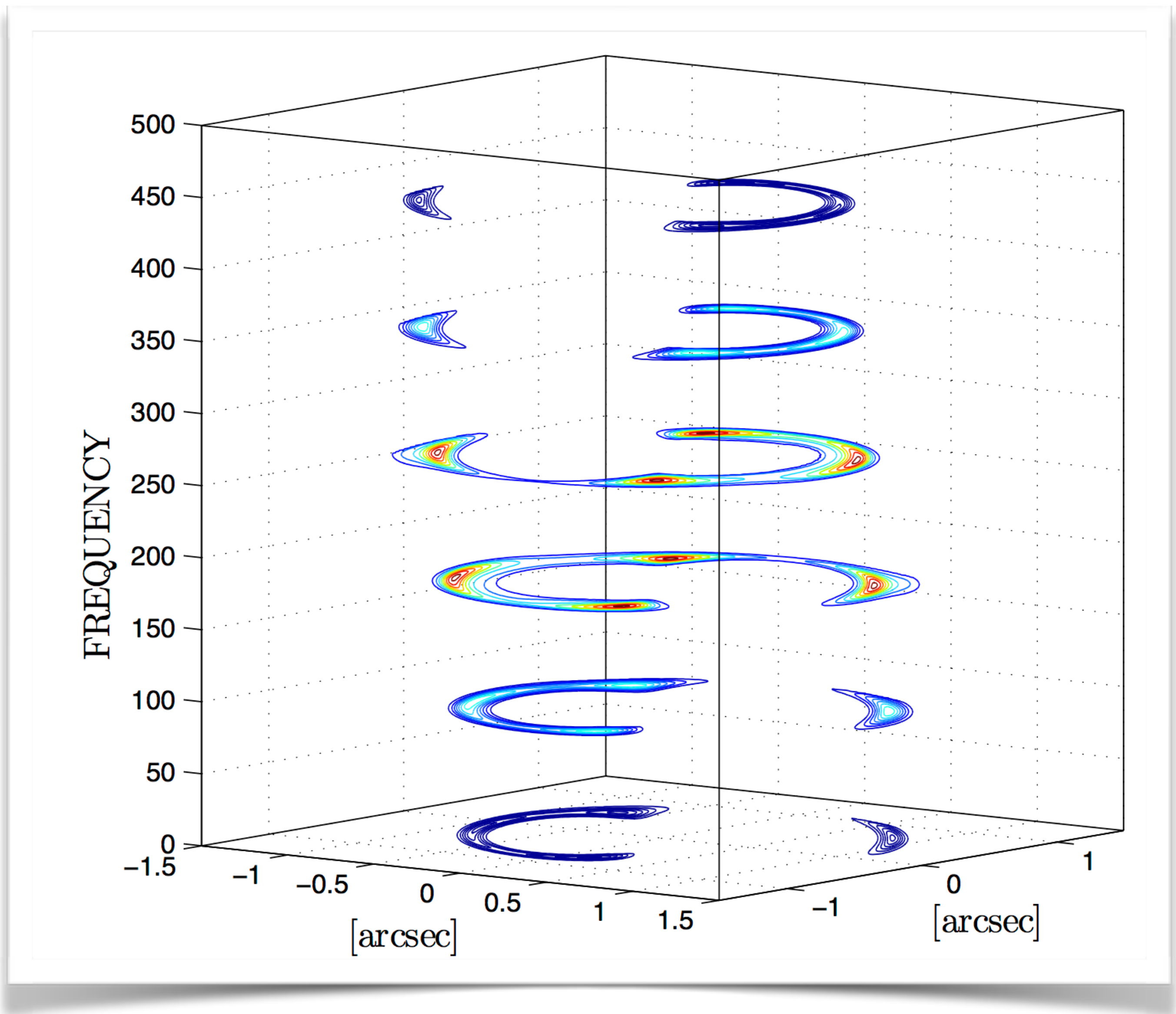
# We need a small source, or a source with small features...

velocity structure

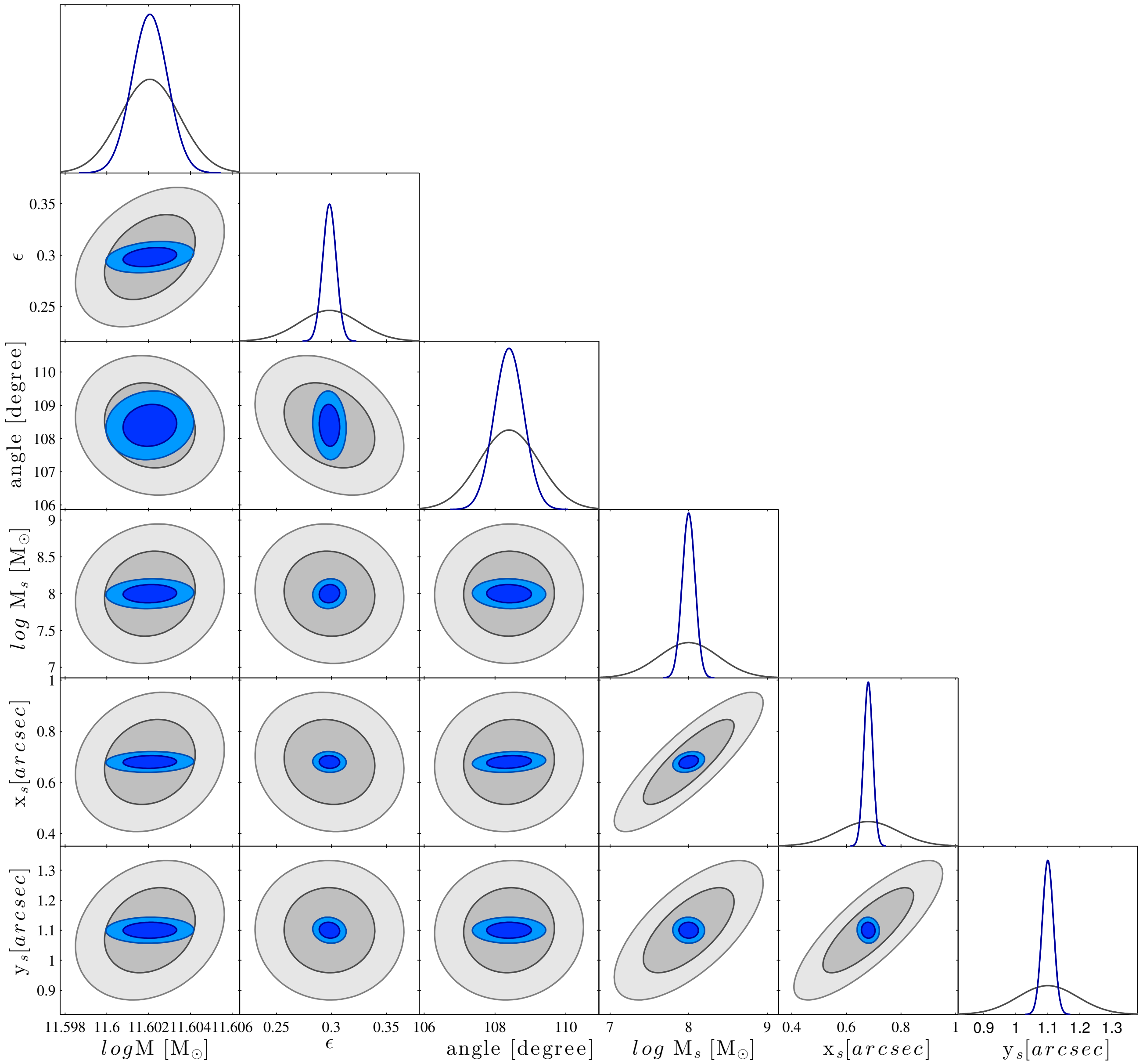



Engel et al 2010, ApJ

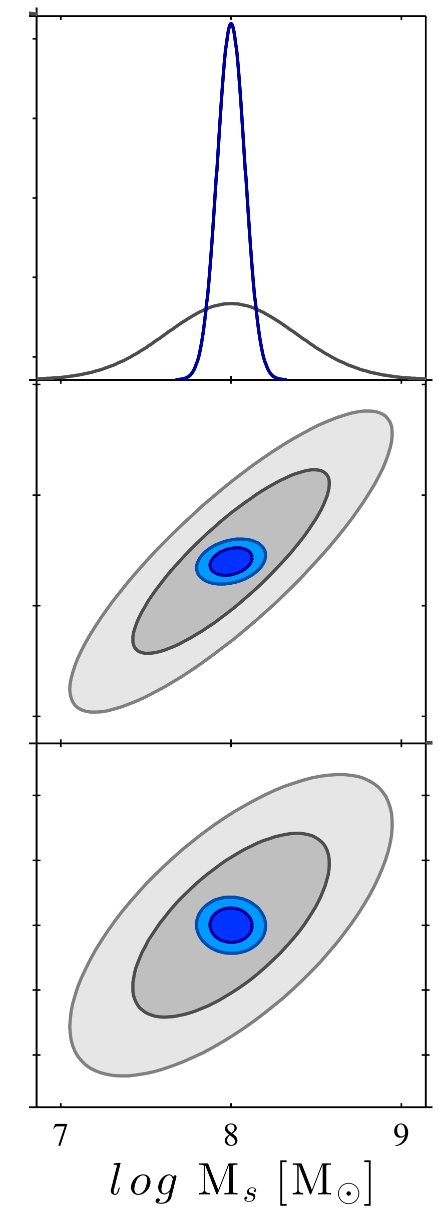
# 3D LENS MODELING
# (3RD DIMENSION=WAVELENGTH)



# Sensitivity Analysis of Detecting DM Subhalos

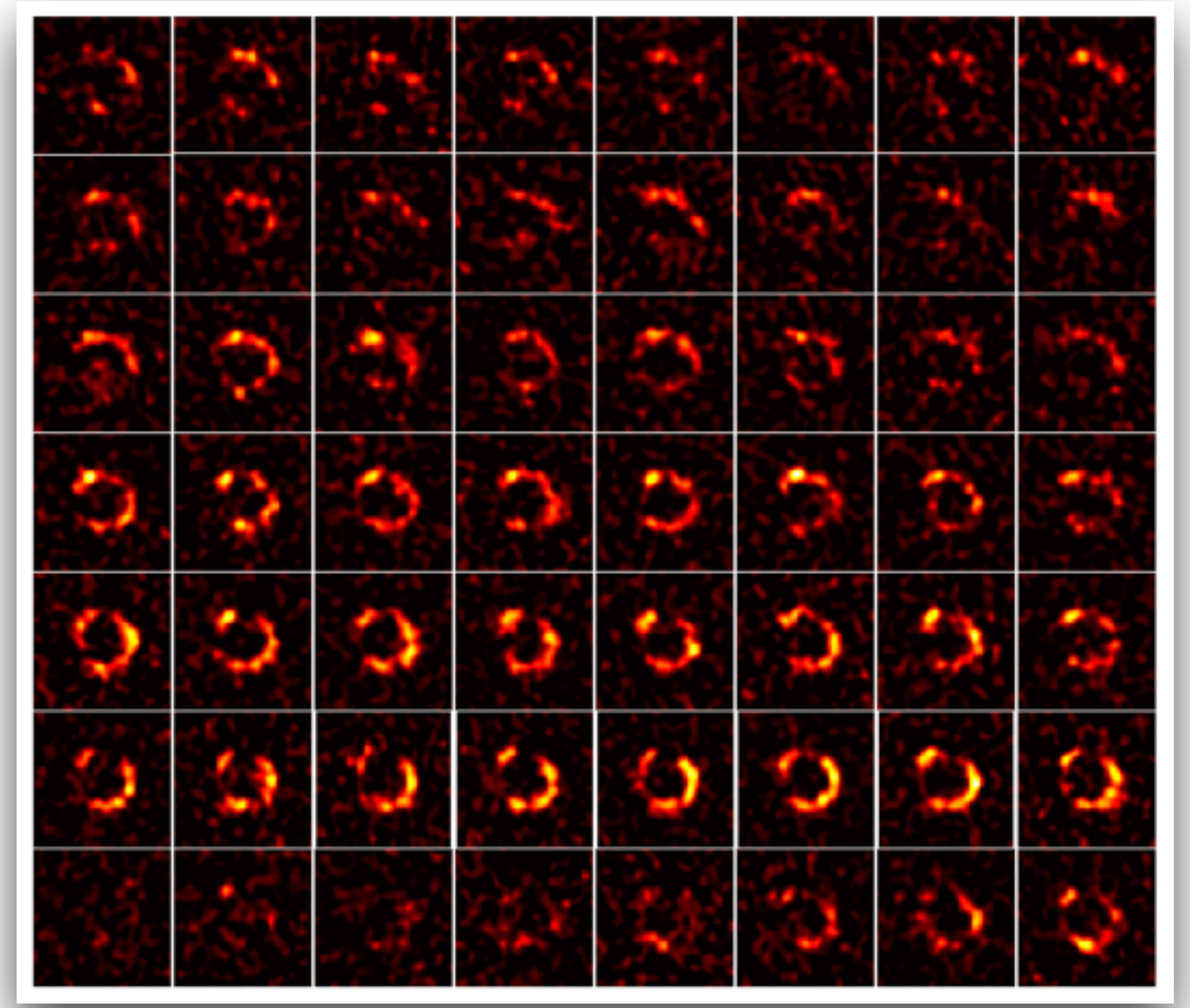



After marginalizing over ~60 source parameters



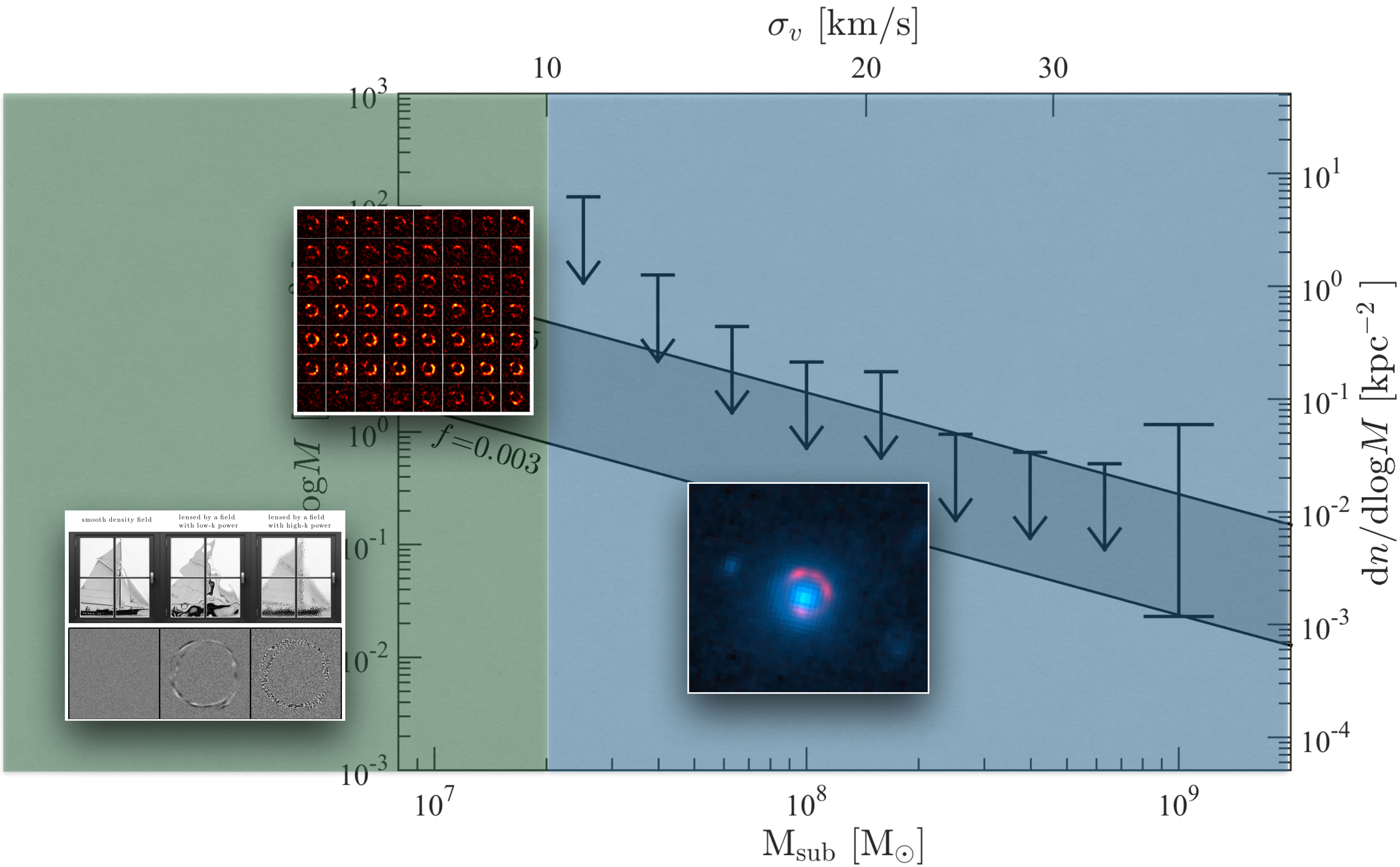

Hezaveh, Dalal et al 2013, ApJ. 767, 9

# SPT2134-50 (ALMA Cycle 2)
# Band 6 (CO 7-6)



Morningstar leading the analysis

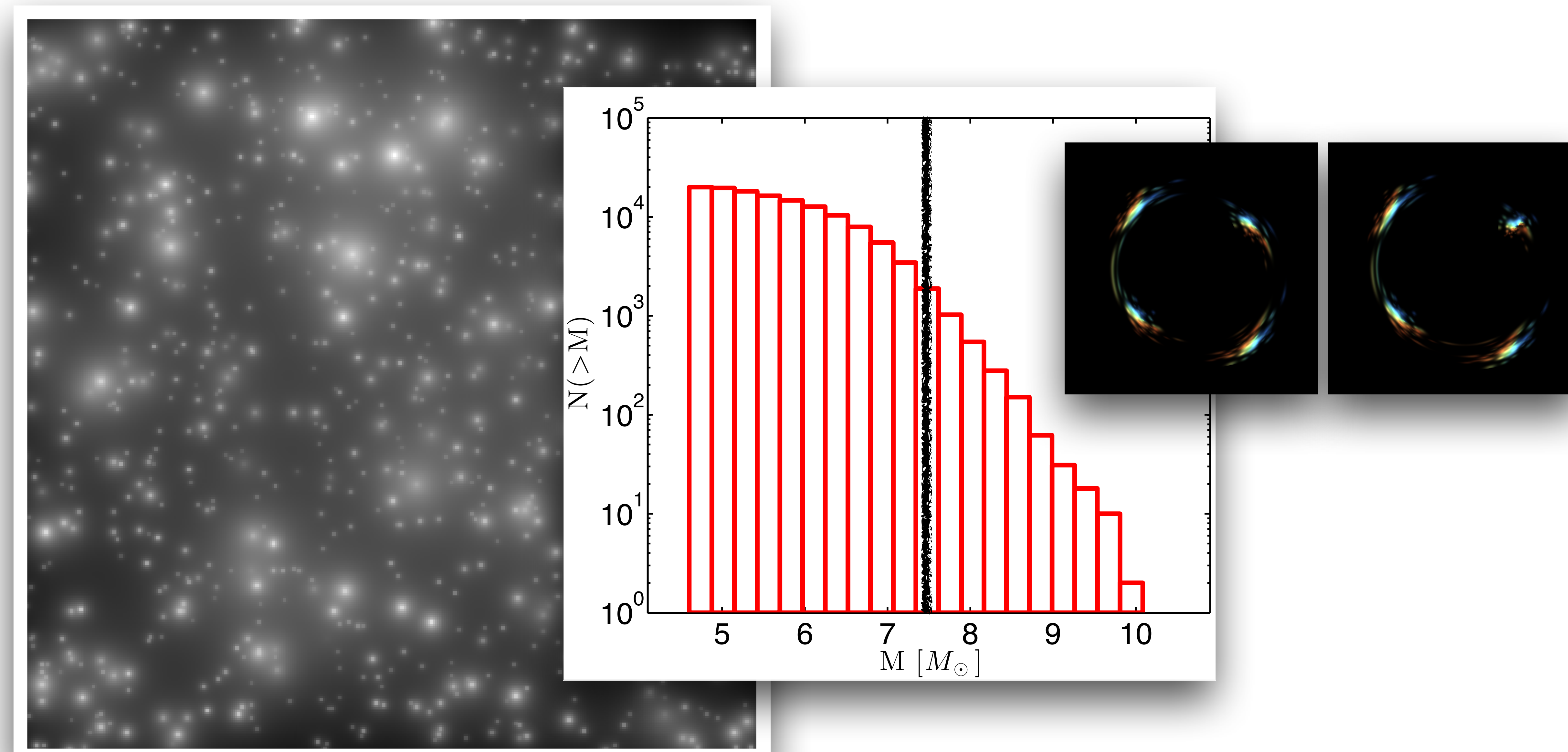
# Constraints on the Mass Function of Subhalos in the Host Halo



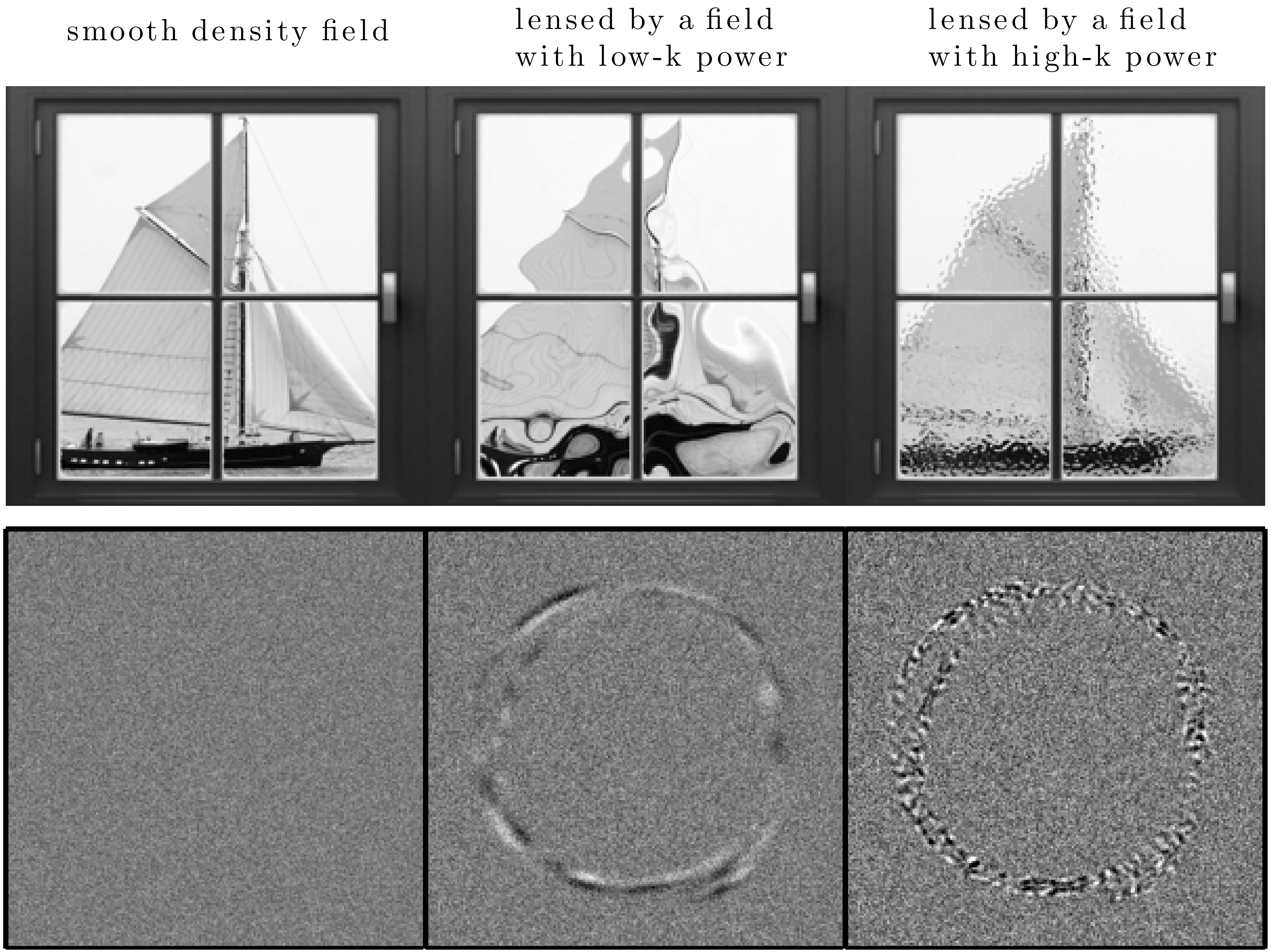

Hezaveh et al. 2016

# We can detect and model massive subhalos

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



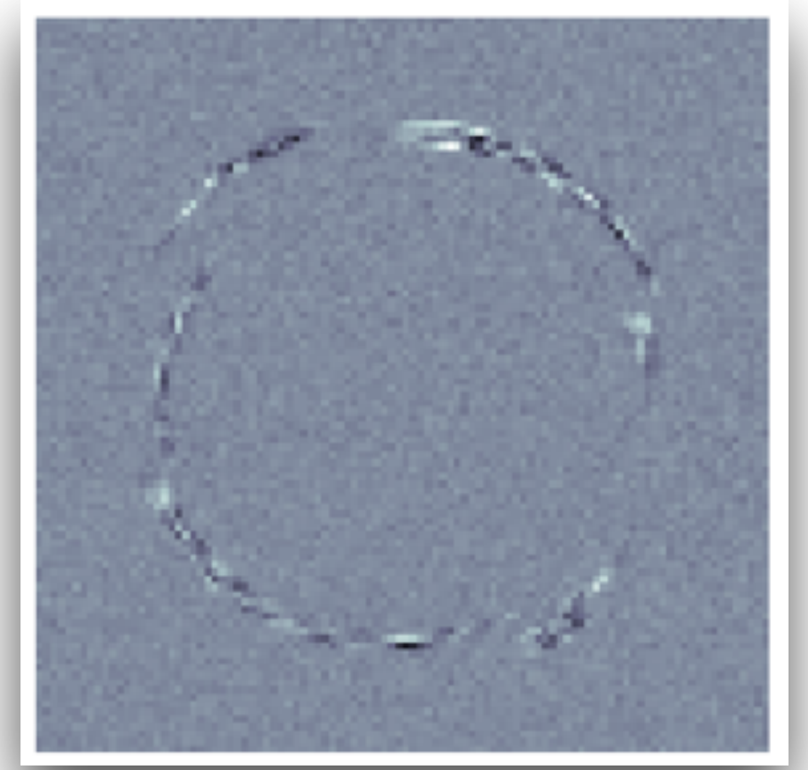
# RESIDUALS FROM MODELING WITH A SMOOTH LENS:

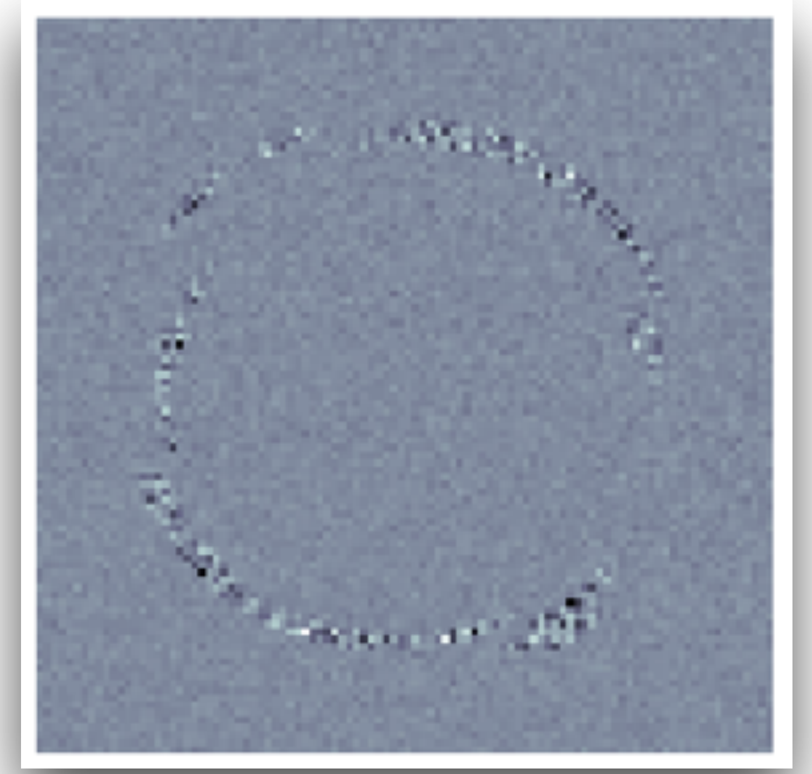


COVARIANCE OF DEFLECTIONS

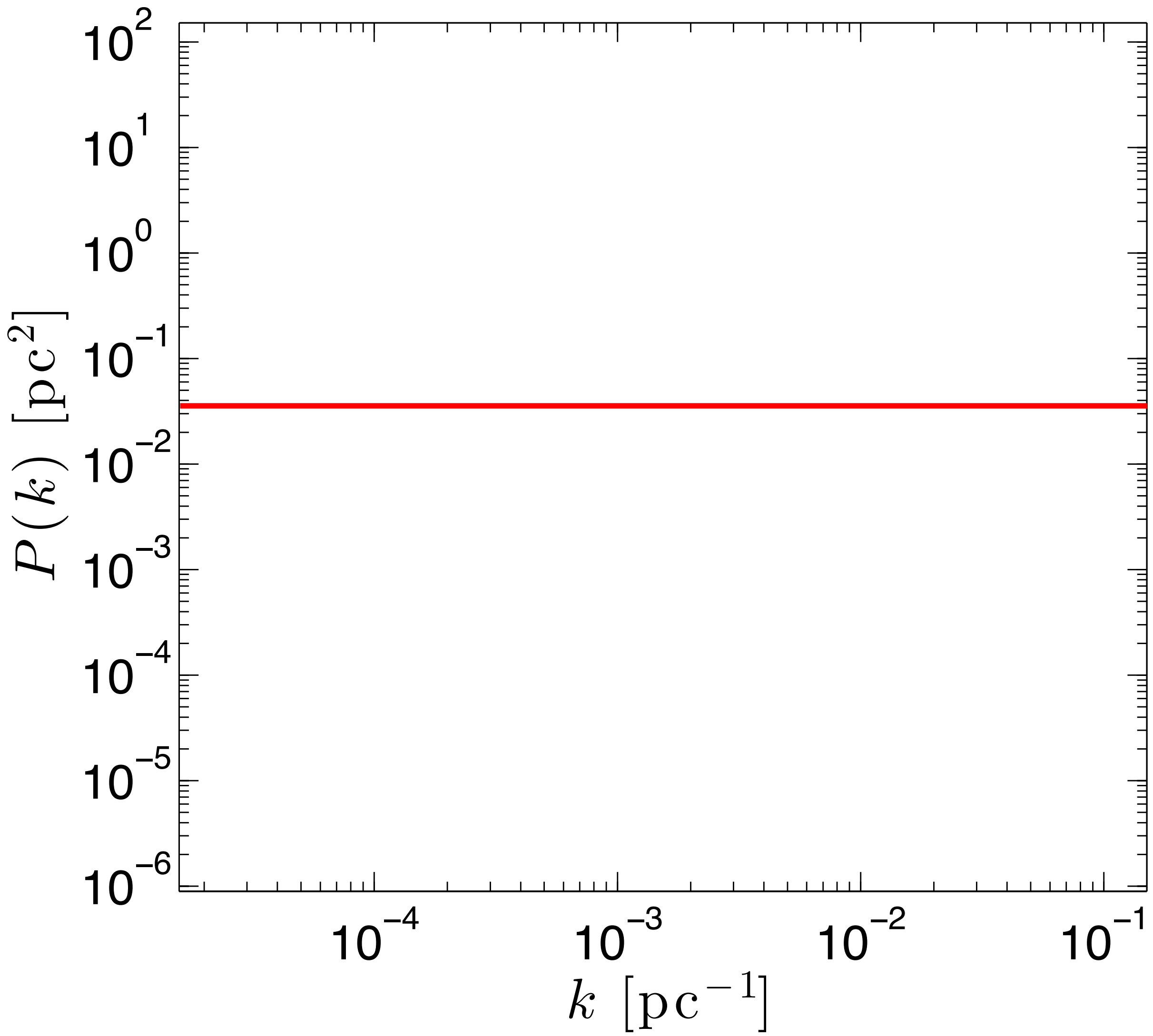
DENSITY POWER SPECTRUM

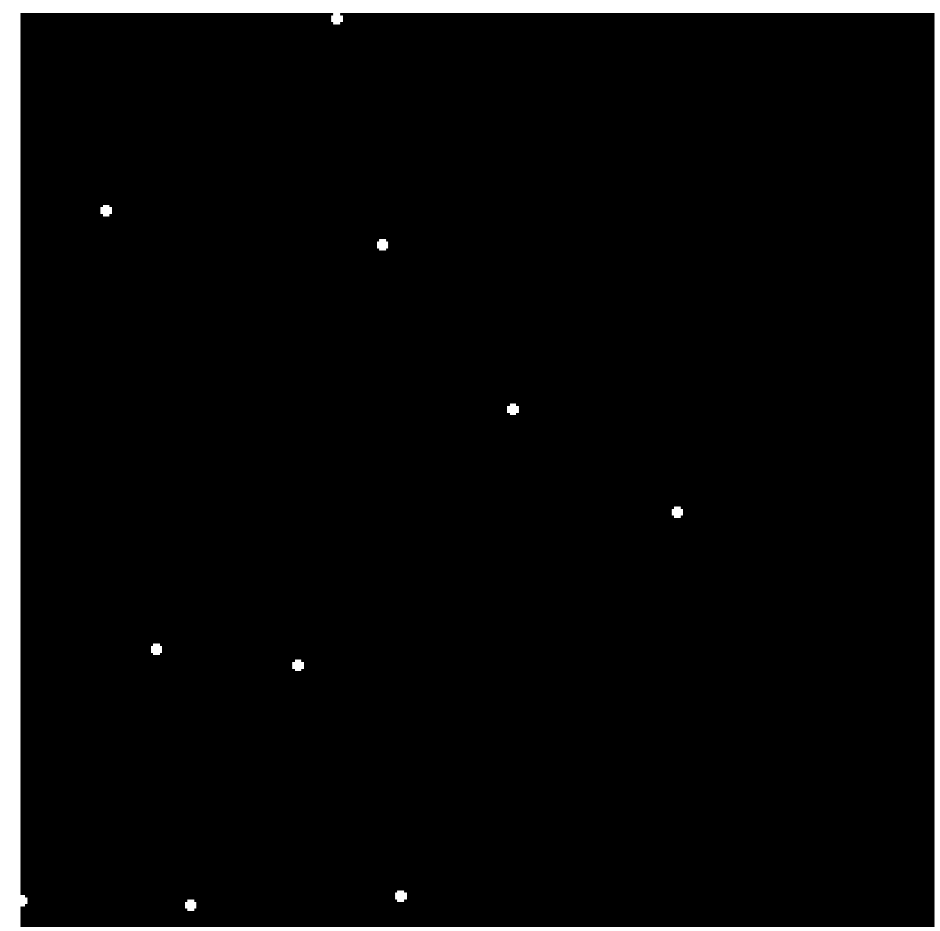
$$\mathcal{L}(C_\alpha) = (|C_N|\,|C_\alpha|\,|C_p||M|)^{-1/2} e^{\frac{1}{2}B^T\,M\,B} \quad e^{-\frac{1}{2}(\boldsymbol{\Delta O}^T C_N^{-1} \boldsymbol{\Delta O} + \boldsymbol{p}_0 C_p^{-1} \boldsymbol{p}_0)}$$





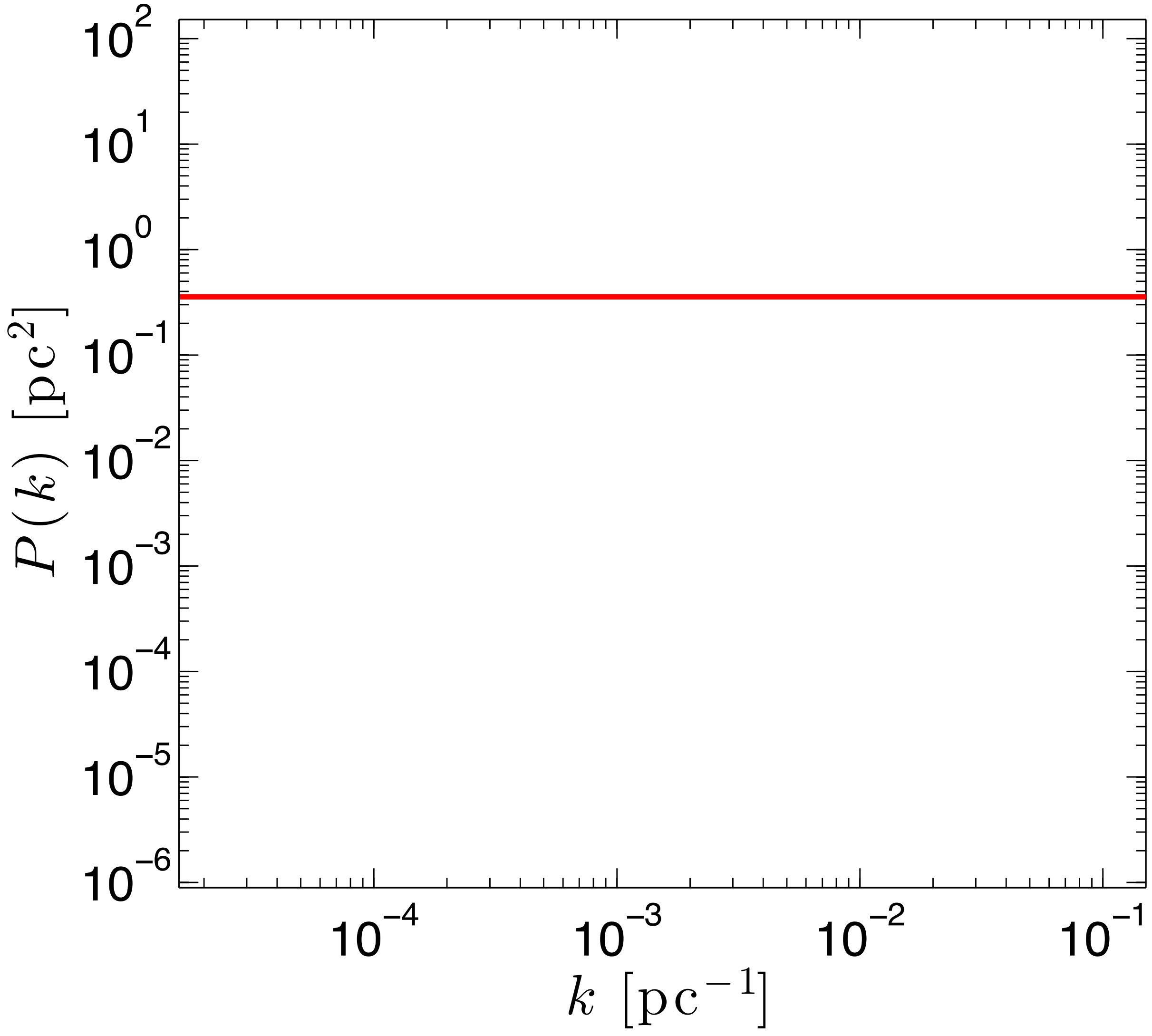
# DM subhalo density Power Spectrum

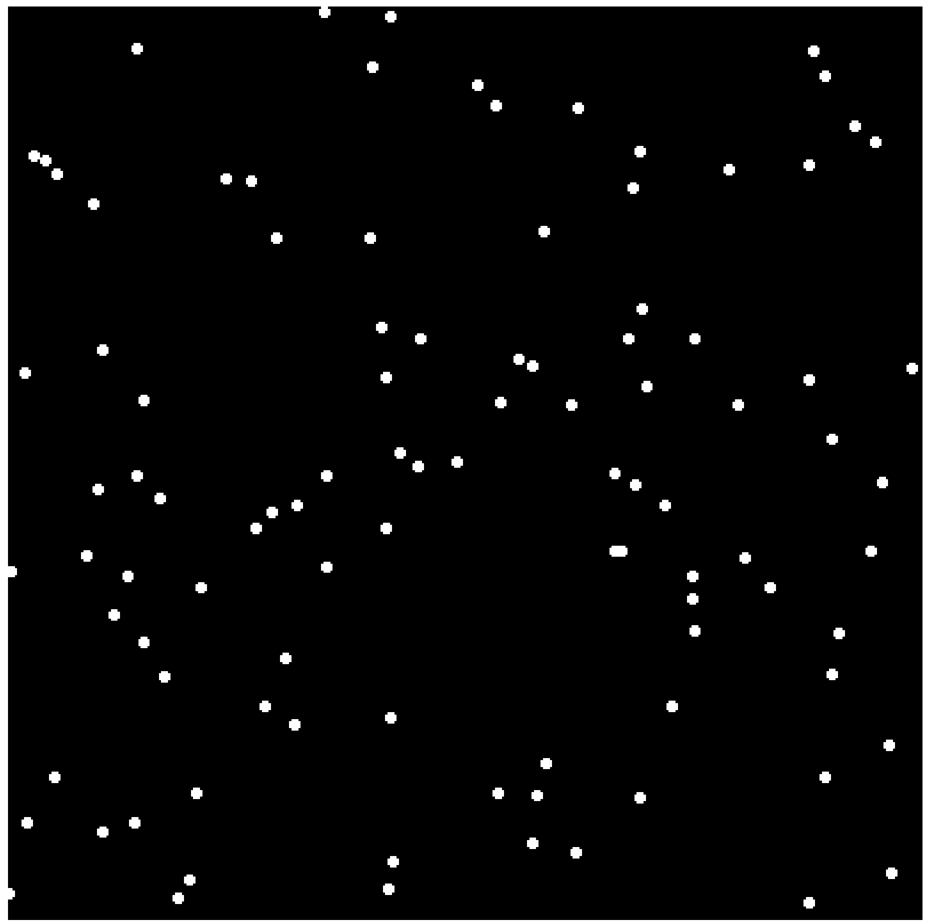


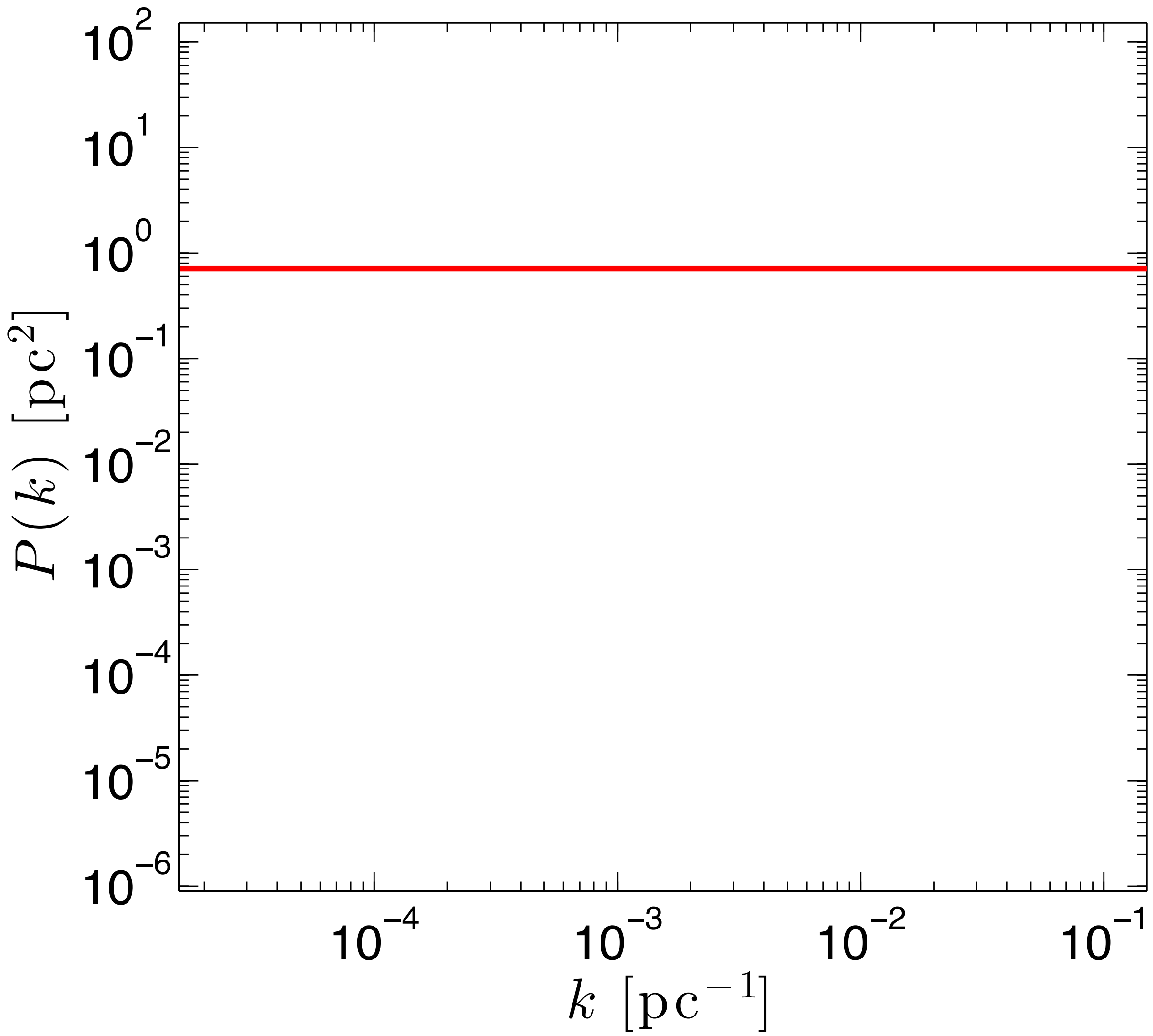
# DM subhalo density Power Spectrum

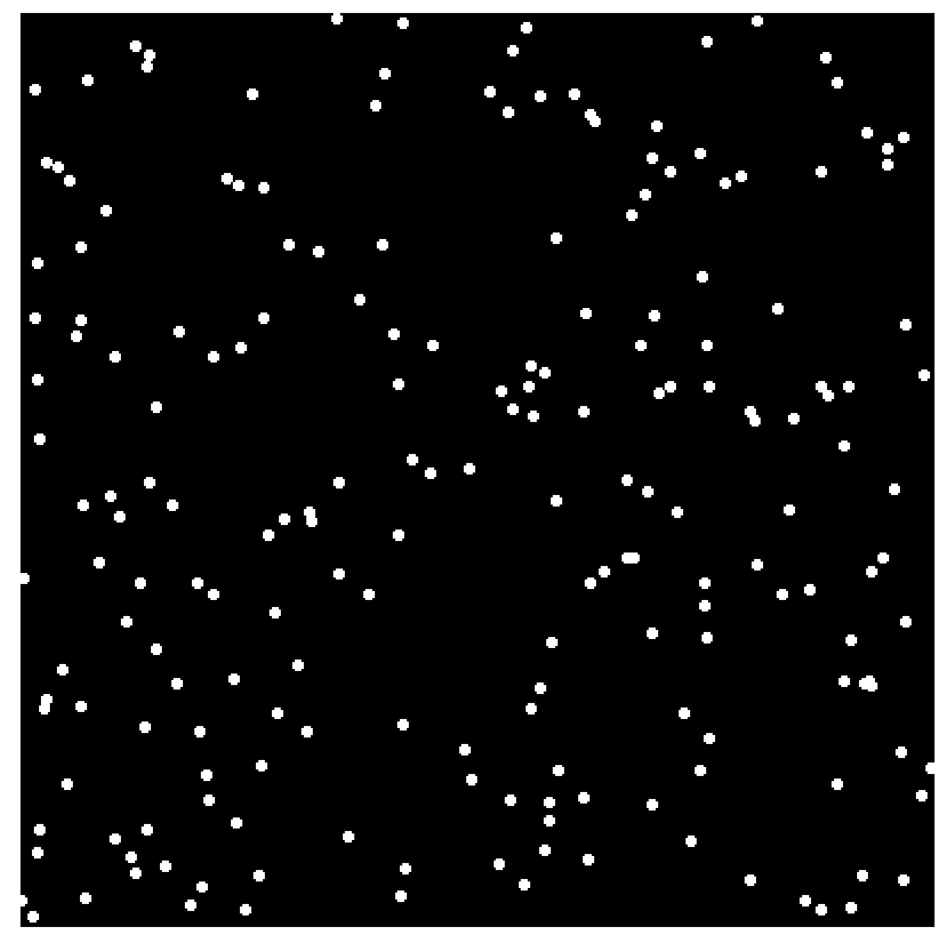
# DM subhalo density Power Spectrum



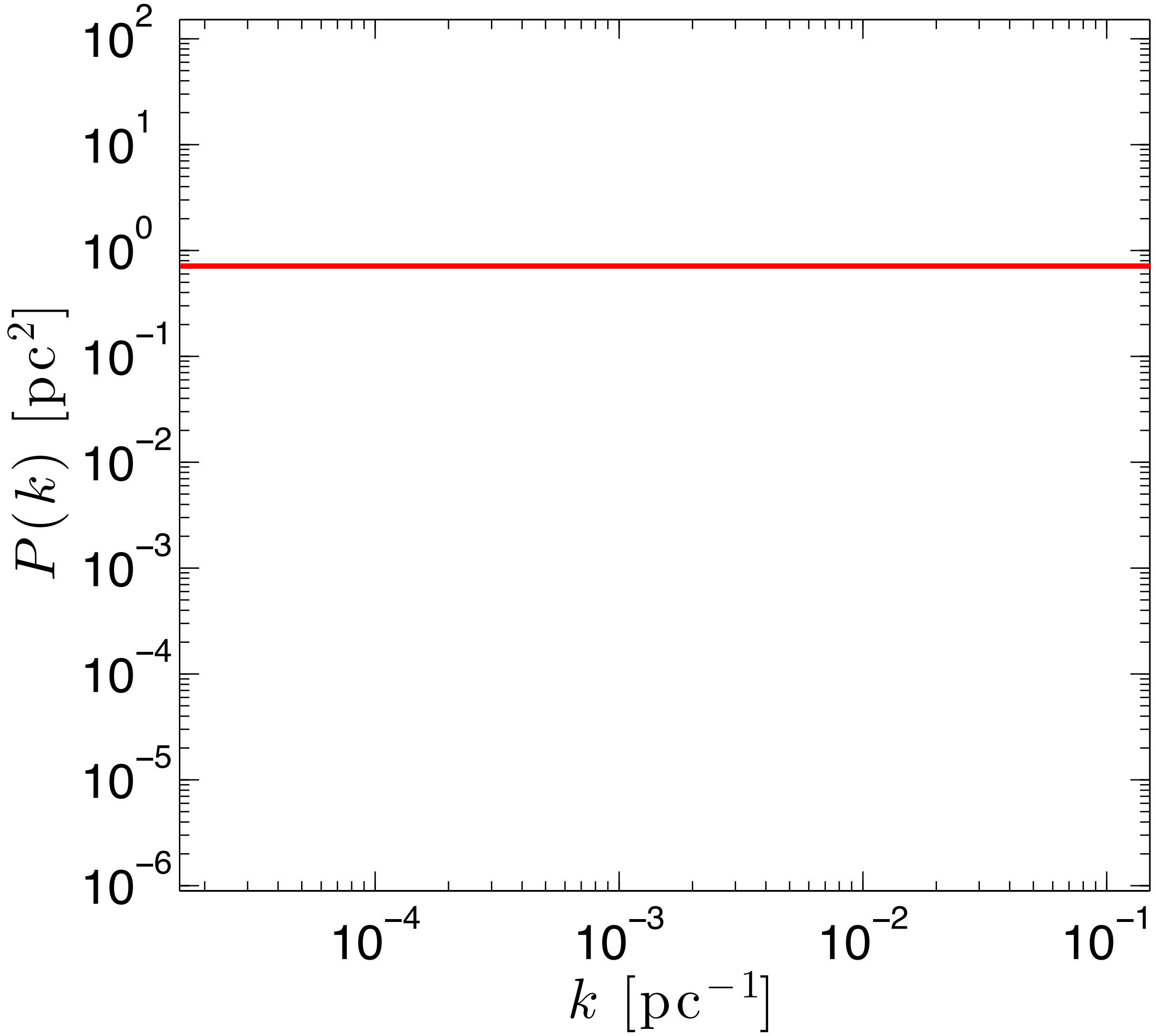



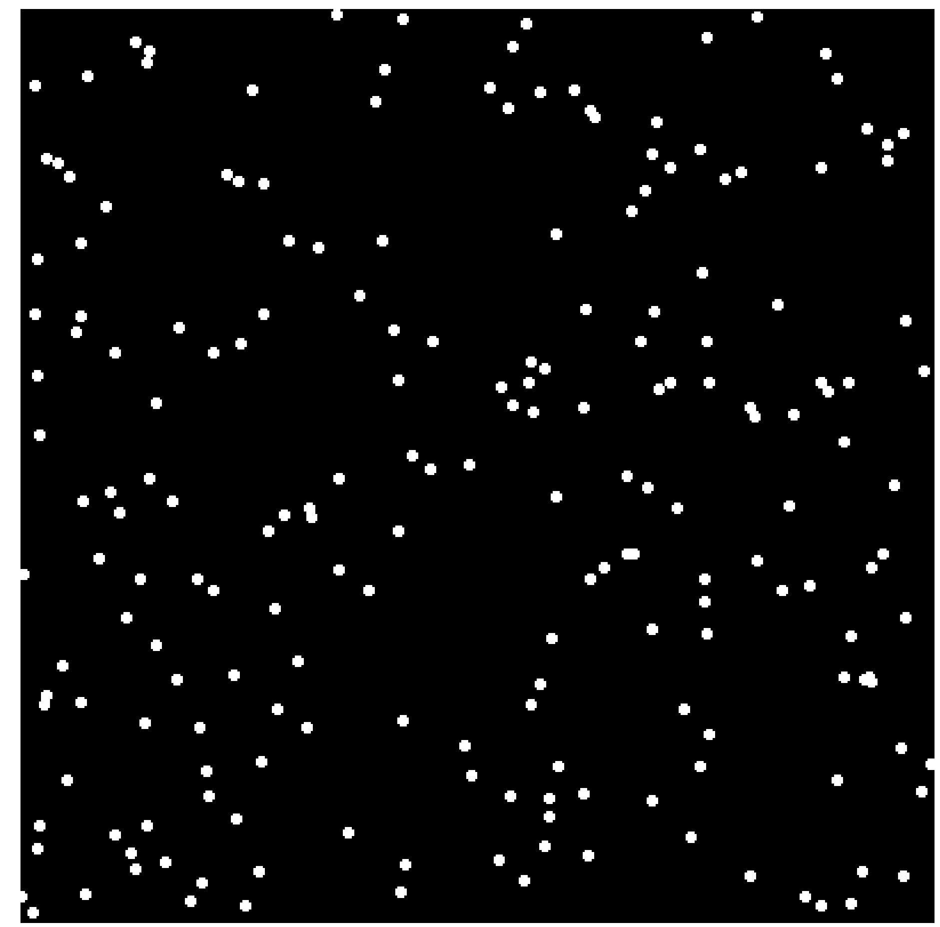
# DM subhalo density Power Spectrum



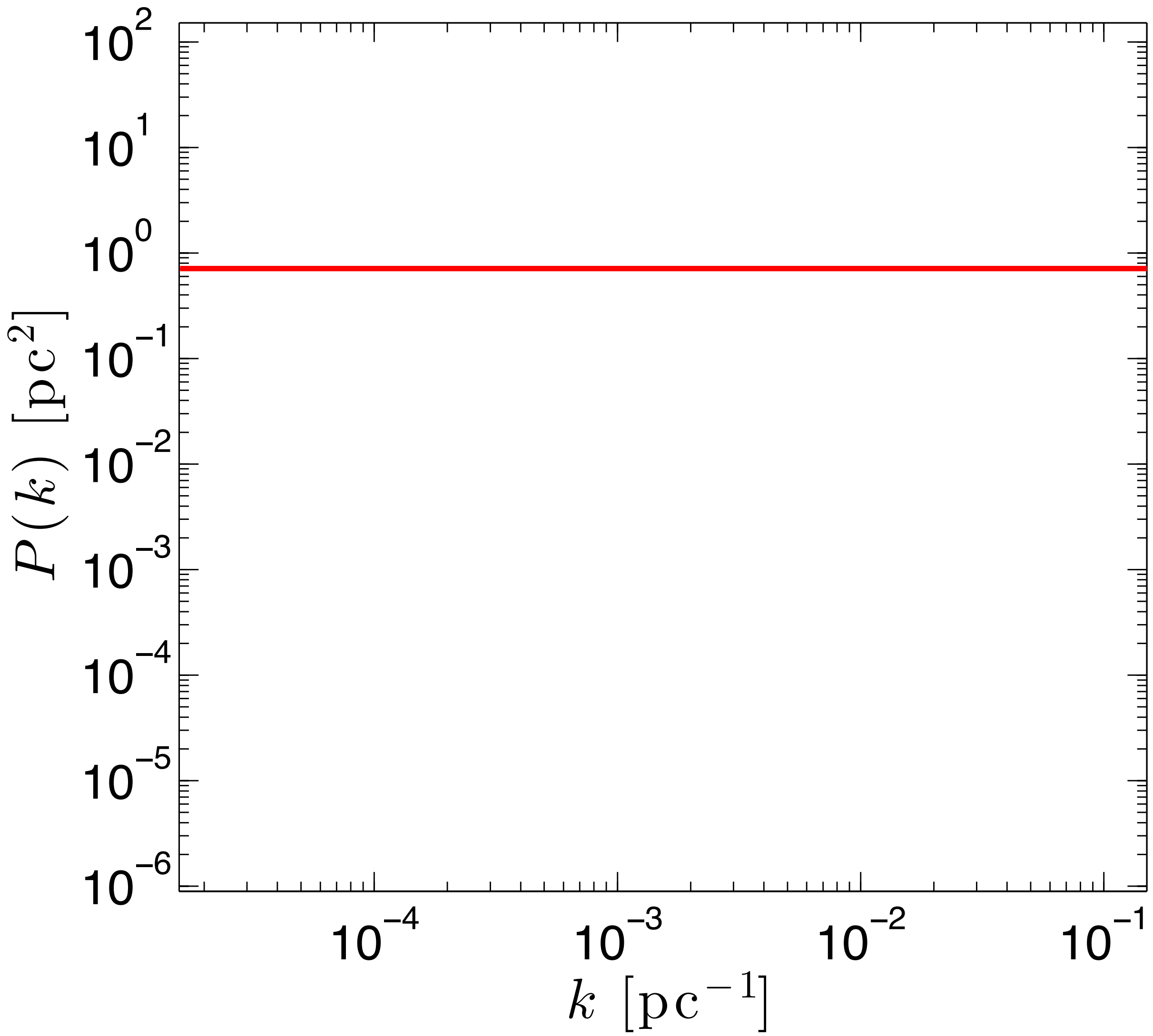



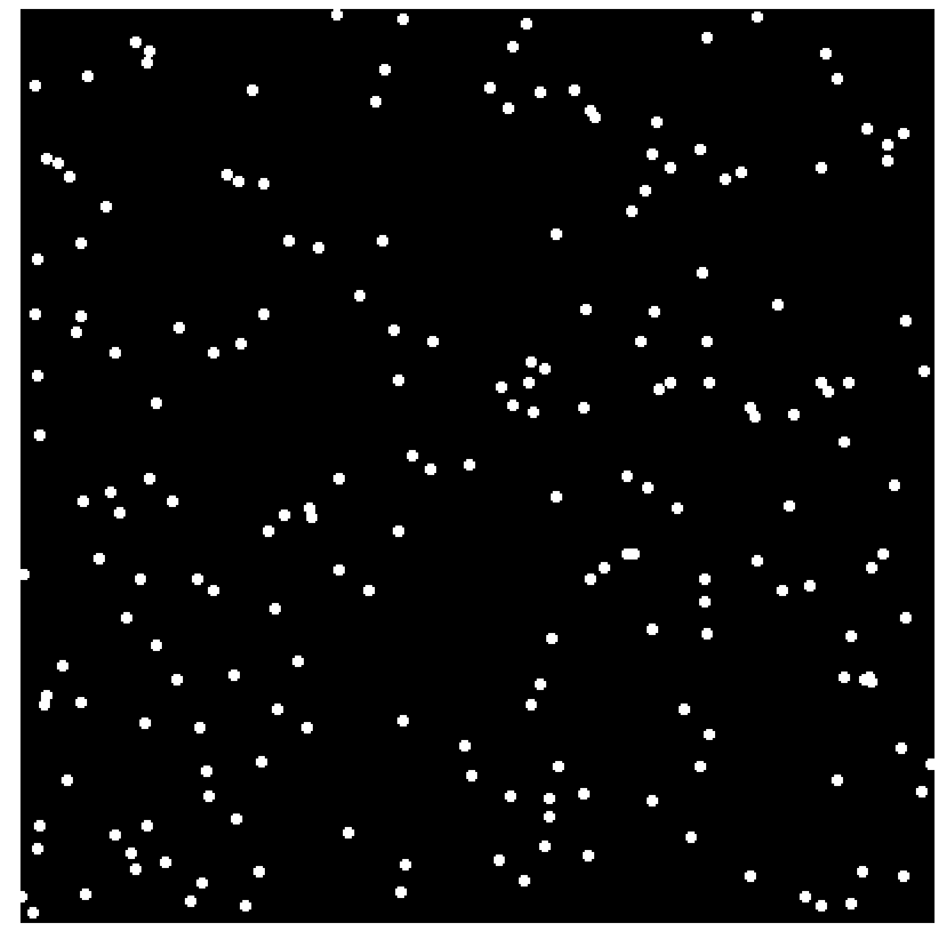
# DM subhalo density Power Spectrum



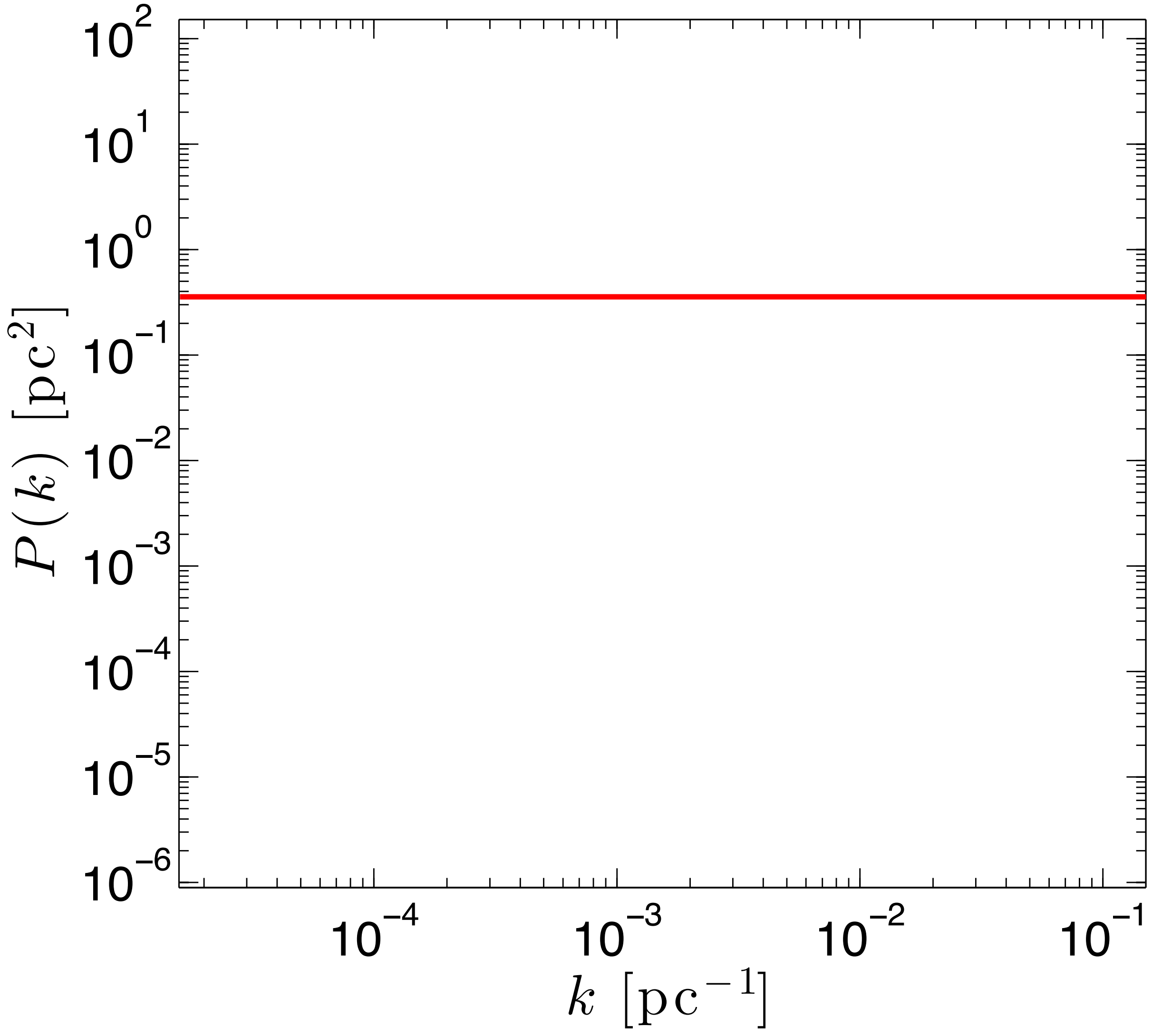



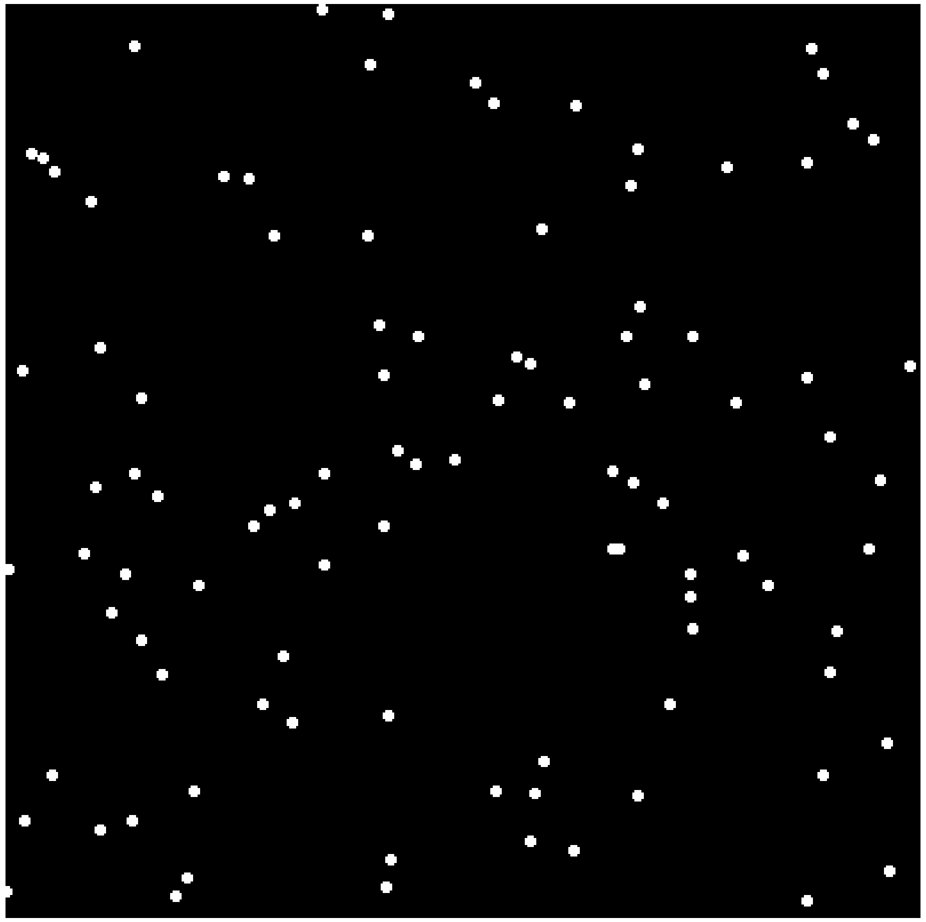
# DM subhalo density Power Spectrum



# DM subhalo density Power Spectrum



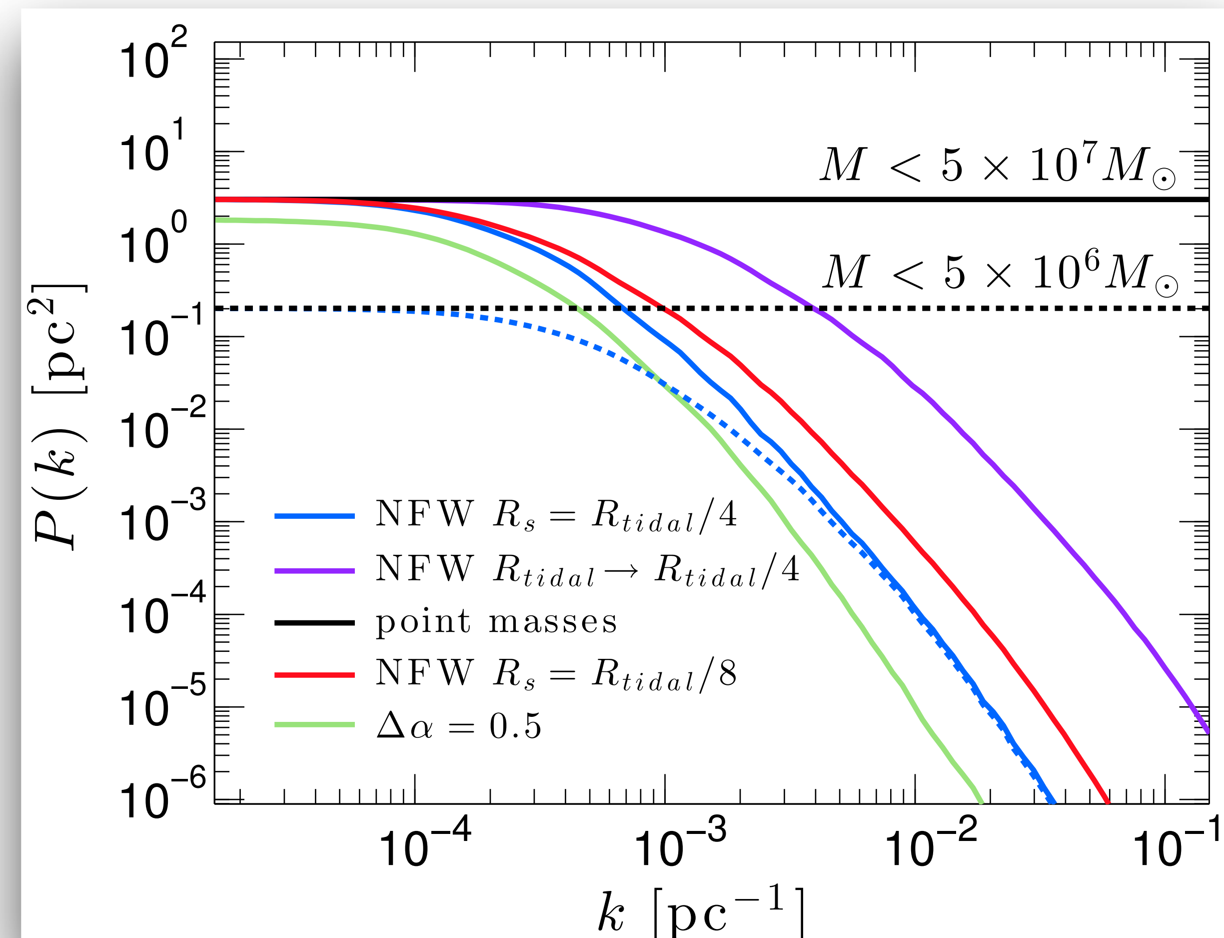
# DM subhalo density Power Spectrum

# DM subhalo density Power Spectrum

# DM subhalo density Power Spectrum

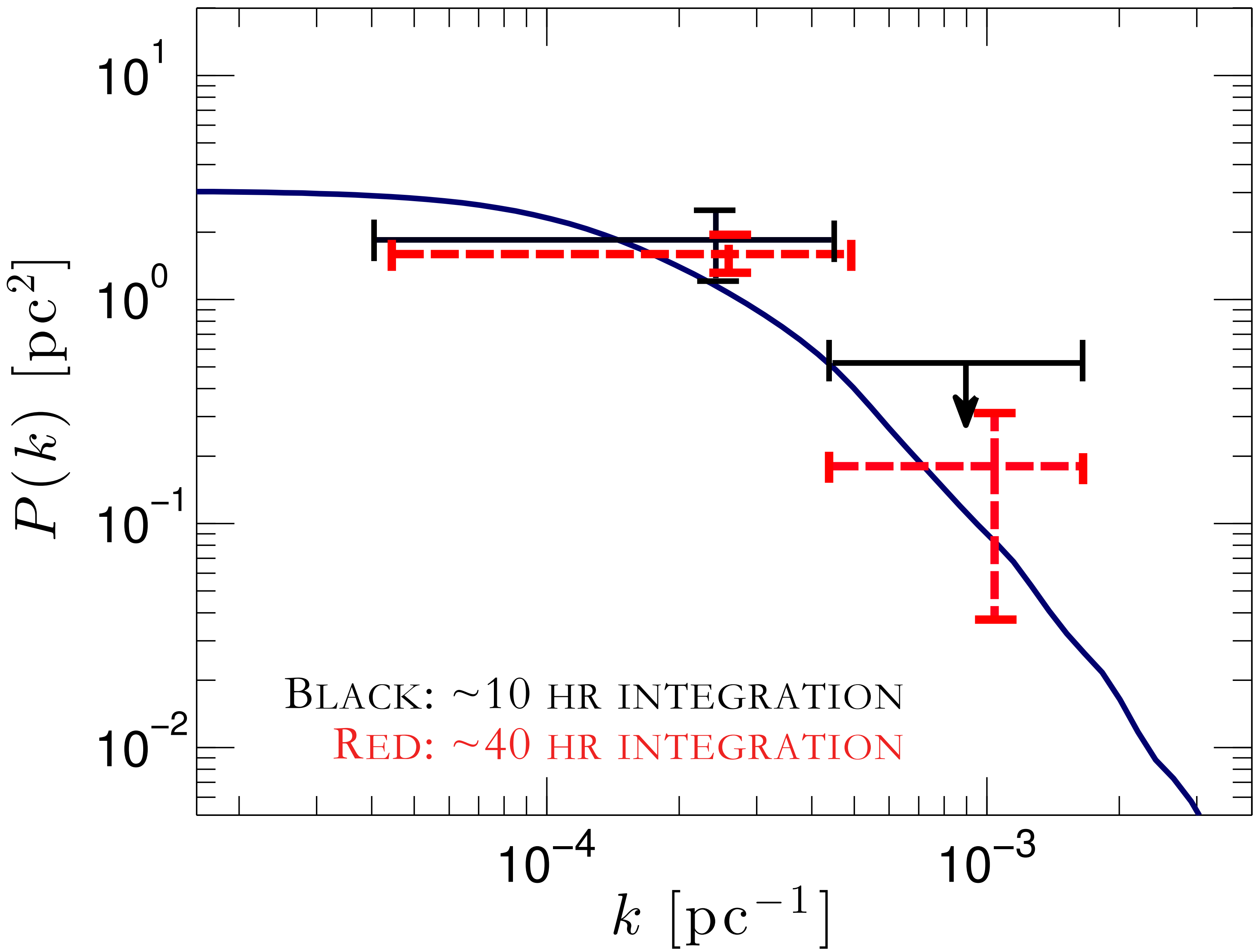
# DM subhalo density Power Spectrum

# Power Spectrum of subhalo density field




Hezaveh, Dalal et al 2014

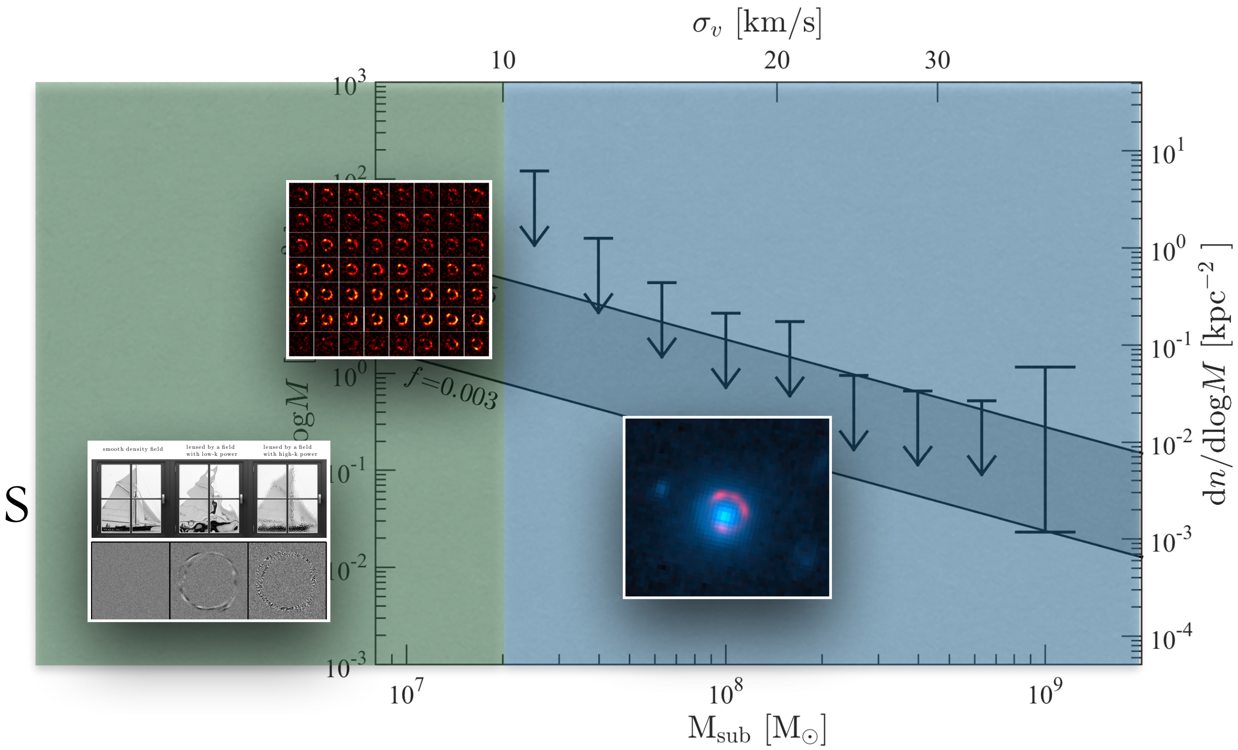
# Forecast for measuring the DM subhalo Power Spectrum with ALMA

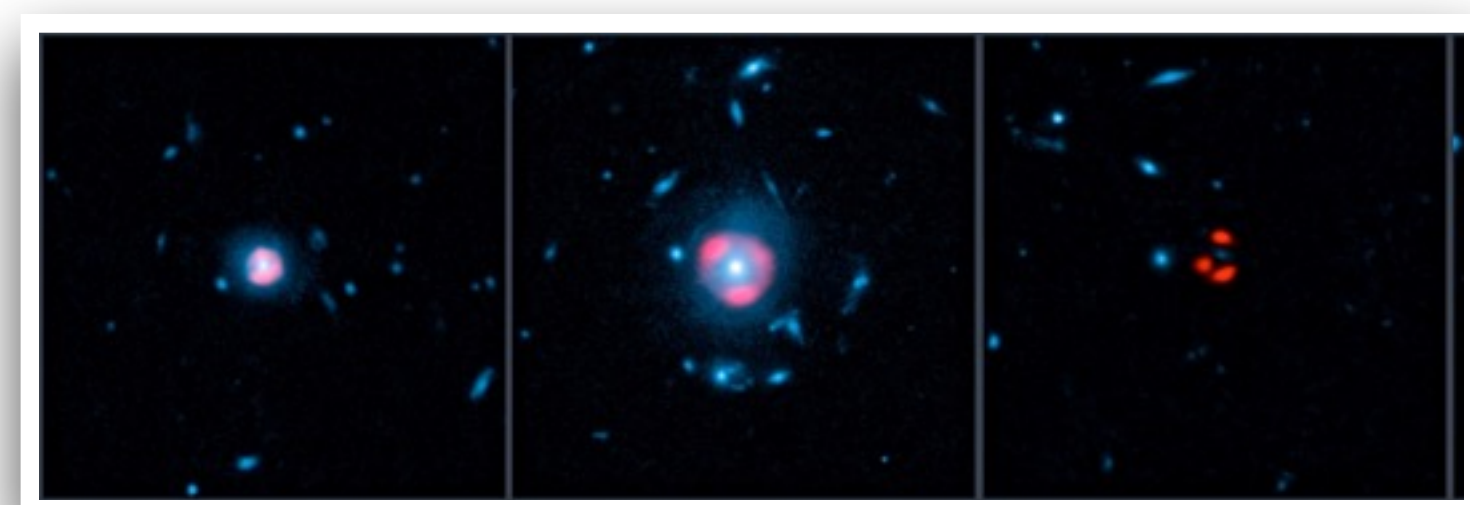


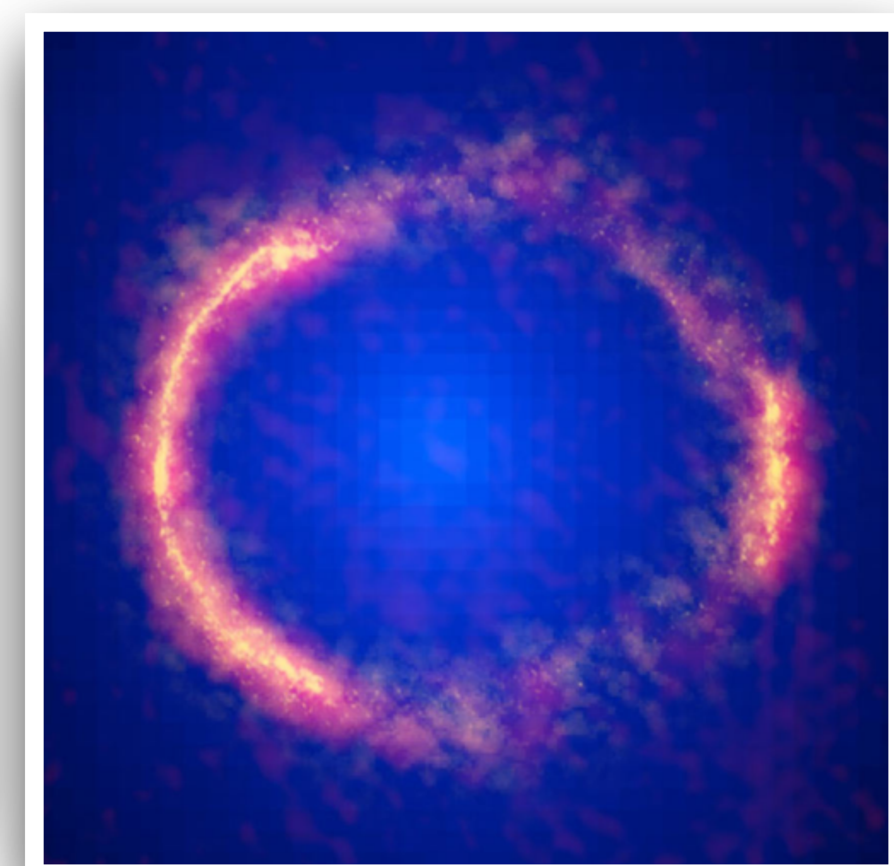

Hezaveh, Dalal et al 2014

# Summary

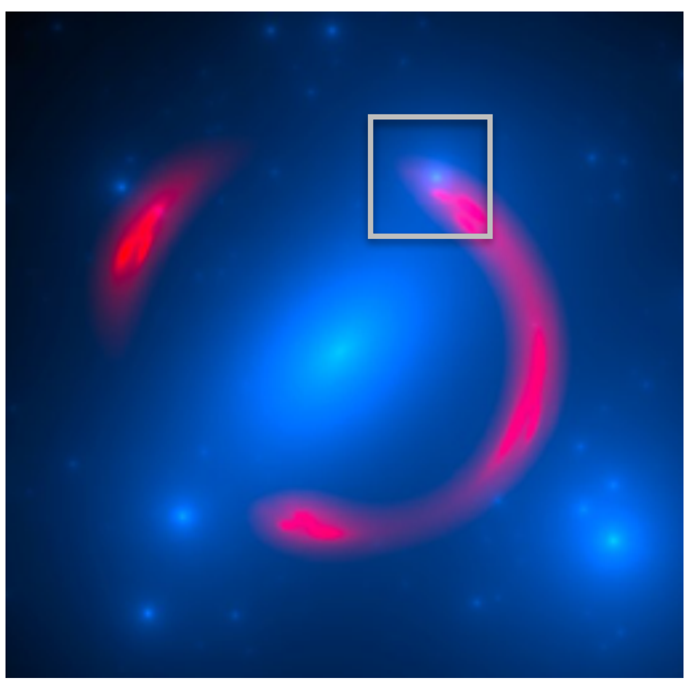
- First Detection of DM subhalo with ALMA (in the first source studied).
- First measurement of the subhalo mass function with ALMA.
- The Power of ALMA and the abundance of targets promises a bright future for DM studies.



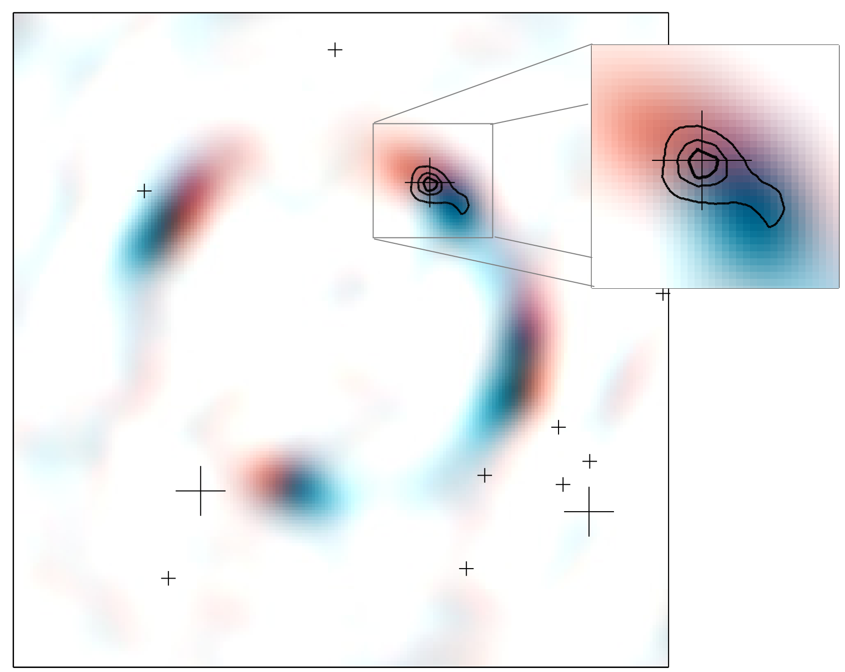


# Simulations indicate that with ALMA, we can Detect DM subhalos in these systems

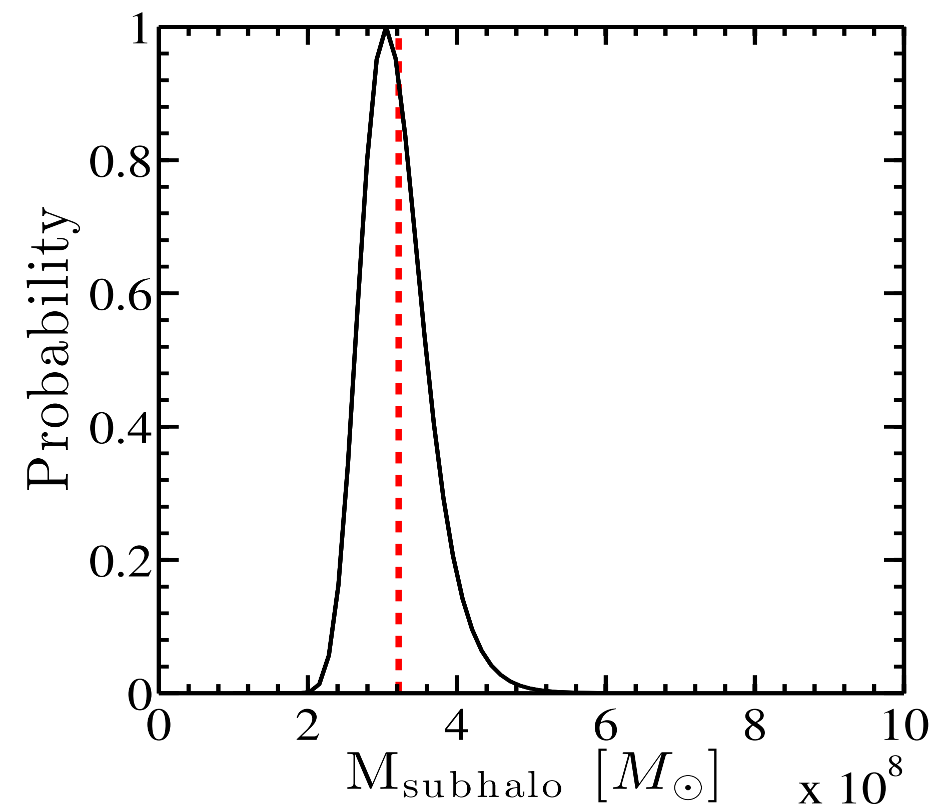


Nbody + ray tracing simulation

Detected subhalo



Mock ALMA observation




Recovered subhalo mass