MAPPING THE SMALL-SCALE STRUCTURE OF DARK MATTER HALOS WITH ALMA OBSERVATIONS OF STRONG LENSES

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SDP 81
(ALMA SCIENCE VERIFICATION DATA)

Blue: HST
Red: ALMA
SDP 81
(ALMA SCIENCE VERIFICATION DATA)

Blue: HST
Red: ALMA
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 the abundance of Milky Way satellites to dark matter subhalos in simulations

Theory: $N >> 1000$  
Observation $N \sim 10$
THE MISSING SATELLITE PROBLEM

LONG STANDING PROBLEM FOR CDM

STRIGARI
SOLUTIONS

INEFFICIENT GALAXY FORMATION

Cold Dark Matter

2 keV Warm Dark Matter

DARK MATTER PHYSICS

Lovell
STRONG GRAVITATIONAL LENSING

MULTIPLY IMAGED FISH
STRONG GRAVITATIONAL LENSING
Substructure Lensing
Substructure Lensing
SUBSTRUCTURE LENSING

LENSED RADIO QUASARS

DALAL & KOCHANEK 2002

LENSED GALAXIES (OPTICAL)

VEGETTI ET AL. 2012

LENSED OPTICAL QUASARS

NIERENBERG ET AL. 2014
ALMA OBSERVATIONS OF SPT-DISCOVERED SOURCES

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

Vieira et al. Nature 2013
LENS MODELING

**Postulate a Source Morphology (with parameters Ps)**

**Postulate a Mass Distribution in the Lens (with parameters Pm)**

**Maximize the likelihood of the model parameters given the data**

**Ray-Tracing Simulation**

**Generate the lensed image of the source**

**Model**

**Data**
LENS MODELING FOR INTERFEROMETRIC DATA

1 - Postulate Sky Model Parameterized by Source and Lens Properties

2 - Predict the Visibilities on the measured uv coverage

3 - Add additional parameters for antenna phases

4 - Form a $\chi^2$ likelihood and Sample the posterior using a parameter exploration method (MCMC, etc.)
MARGINALIZING OVER TIME-VARIABLE ANTENNA PHASE ERRORS

MORNINGSTAR ET AL. IN-PREP
**PROBABILITY OF THE PRESENCE OF A SUBHALO**

mock without subhalo

mock with subhalo

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

**Hezaveh et al. 2016**
SIMULATIONS WITH AND WITHOUT A SUBHALO
SIMULATIONS WITH AND WITHOUT A SUBHALO
SDP 81
(ALMA SCIENCE VERIFICATION DATA)

Blue: HST
Red: ALMA
SDP 81
RECONSTRUCTED BACKGROUND SOURCE

Also see poster by M. Rybak

Hezaveh et al. 2016
FIRST DETECTION OF A DM SUBHALO WITH ALMA

Hezaveh et al. 2016
FIRST DETECTION OF A DM SUBHALO WITH ALMA

HEZAVEH ET AL. 2016
Probability of a second subhalo

SDP.81
\[ \log \frac{M_{\text{sub}}}{M_\odot} = 7.4 \]

SDP.81
\[ \log \frac{M_{\text{sub}}}{M_\odot} = 7.6 \]

SDP.81
\[ \log \frac{M_{\text{sub}}}{M_\odot} = 8.0 \]

SDP.81
\[ \log \frac{M_{\text{sub}}}{M_\odot} = 8.2 \]

SDP.81
\[ \log \frac{M_{\text{sub}}}{M_\odot} = 8.6 \]

SDP.81
\[ \log \frac{M_{\text{sub}}}{M_\odot} = 9.0 \]
CONSTRAINTS ON THE MASS FUNCTION OF SUBHALOS IN THE HOST HALO

\begin{center}
\includegraphics[width=\textwidth]{constraint_mass_subhalos}
\end{center}

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
ALMA Cycle 2 Data

SPT 0532-50

Dirty Map | Predicted Map | Residuals | Skymodel | Reconstructed Source

Flux (Jy/Beam) | Flux (Jy/Beam) | Flux (Jy/Beam) | Flux (Jy/str) | Flux (Jy/str)

Dirty Map | Predicted Map | Residuals | Skymodel | Reconstructed Source

Flux (Jy/Beam) | Flux (Jy/Beam) | Flux (Jy/Beam) | Flux (Jy/str) | Flux (Jy/str)

Morningstar et al. In-Prep
ALMA Cycle 2 Data

Morningstar et al. IN-PREP
ALMA Cycle 2 Data

Morningstar et al. in-prep
ALMA Cycle 4 data

Three sources (30 hours) - 6 km baselines
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
What about the thousands of lower mass ones? Can we detect them as a whole?
**Residuals from Modeling with a Smooth Lens:**

- Smooth density field
- Lensed by a field with low-k power
- Lensed by a field with high-k power
\[ C_\alpha = \langle \alpha_i(\vec{x}) \alpha_j(\vec{x} + \vec{r}) \rangle = 4 \int P(k) \left( \frac{\delta_{ij}}{k^2 r} J_1(kr) - \frac{r_i r_j}{kr^2} J_2(kr) \right) dk \]

\[ L(C_\alpha) = (|C_N||C_\alpha||C_p||M|)^{-1/2} e^{\frac{1}{2} B^T M B} e^{-\frac{1}{2} (\Delta O^T C_N^{-1} \Delta O + p_0 C_p^{-1} p_0)} \]
DM subhalo density Power Spectrum

![Graph showing the power spectrum of DM subhalos against wavenumber (k) in units of pc$^{-1}$ and power (P(k)) in units of [pc$^2$]. The graph displays a horizontal line at a constant power level.](image-url)
DM subhalo density Power Spectrum

\[ P(k) \text{ [pc}^2] \]

\[ k \text{ [pc}^{-1}] \]
DM subhalo density Power Spectrum

\[ P(k) \quad [\text{pc}^2] \]

\[ k \quad [\text{pc}^{-1}] \]
DM subhalo density Power Spectrum
DM subhalo density Power Spectrum

\[ P(k) \text{ [pc}^2]\] vs. \( k \text{ [pc}^{-1}]\)
DM subhalo density Power Spectrum

\[ P(k) \propto k^{-4} \]
DM subhalo density Power Spectrum

\[ P(k) \propto \frac{1}{k^3} \]

where \( k \) is the wave number in \( \text{pc}^{-1} \).
DM subhalo density Power Spectrum
DM subhalo density Power Spectrum
DM subhalo density Power Spectrum
DM subhalo density Power Spectrum
\textbf{Power Spectrum of subhalo density field}

\begin{center}
\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{power_spectrum}
\caption{Power spectrum of subhalo density field.}
\end{figure}
\end{center}
FORECAST FOR MEASURING THE
DM SUBHALO POWER SPECTRUM WITH ALMA

Black: ~10 hr integration
Red: ~40 hr integration
**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.

\[ M_{\text{subhalo}} \sim \]