Dark Matter with ALMA

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Conclusions:

The Dark Matter (DM) distribution in this galaxy is inferred from CO(3–2) emission observations with the Atacama Large Millimeter/submillimeter Array (ALMA). The DM traces the virialized potential well of the galaxy, and the CO(3–2)/CO(1–0) flux ratio of $5.9 \pm 0.5$ suggests subthermally excited gas. The cold gas mass is derived from the rotation curve of the CO(1–0) emission, with a value of $5 \times 10^{11} M_{\odot}$.

The DM is found to be concentrated in the central regions of the galaxy, with a projected separation of 1.5 kpc between the emission regions A and B, which are separated by bright star-forming regions in the source plane (A, B, C, and D). The Sub-Millimeter Array map contains the bulk of the 870-mJy flux, suggesting that the structures in the LABOCA map are resolved. The CO(3–2) emissions show eight individual components, separated by up to 400 pc. The redshift and the multiple velocity components seen in CO(1–0) indicate that the DM is associated with the galaxy's morphology.

Figure 1 shows the mid-infrared counterparts of the galaxy, which are clearly visible as an extended red galaxy. The mid-infrared counterpart is centred at the sub-millimetre position. The LABOCA and SABOCA full-resolution maps are shown, with white contours denoting the 870-mJy flux. The CO(3–2) emission is confirmed both with LABOCA on the APEX telescope and with Submillimetre APEX Telescope (SABOCA) observations, with root-mean-square noise of 23 mJy.

Figure 2 displays the CO(3–2) emission contours, with a factor of 20 lower than the most extreme 'hyper'-starbursts at redshift 0.0001. The components A, B, C, and D are separated by 1.5 kpc in projection. These components represent two mirror images of the source, each comprising four emission regions, reflected about the lensing critical curve. The inset shows the 0.33-mJy, 4.5-mJy, and 8.0-mJy images, with the 0.002, 0.004, and 0.006 contour levels.

The red line is the same as the 3.6-mJy image of the cluster core with contours denoting the 350-mJy flux, and is associated with a faint optical counterpart with magnitude $I_J = 12.9 ± 0.9$. The red line is the same as the 3.6-mJy image of the lensed galaxy. The map shows the mid-infrared counterparts of the galaxy, with contours denoting the 870-mJy flux. The CO(3–2) emission is confirmed both with LABOCA on the APEX telescope and with Submillimetre APEX Telescope (SABOCA) observations, with root-mean-square noise of 23 mJy.
People

- Illinois
  - G. Holder
  - J. Vieira
- CITA
  - N. Murray
- Arizona
  - D. Marrone
- Stanford
  - R. Blandford
  - Y. Hezaveh
  - P. Marshall
  - W. Morningstar
  - R. Wechsler
SMALL SCALE STRUCTURE

IT'S ABOUT THIS BIG
small-scale structure

small-scale $P(k)$ is interesting!

- shape of primordial power spectrum related to shape of inflaton potential (e.g. running $\Rightarrow V''''$)
- small-scale $P(k)$ sensitive to physics of DM particles

Current best probe is Ly $\alpha$ forest (e.g. Seljak et al. 2006), but already approaching gas Jeans scale!

In future, CMB spectral distortions can probe $k \sim 10^4$ (PIXIE)
NO MORE FOREST

WHAT ELSE IS THERE?
abundances

- abundance of objects (e.g. cluster dn/dM) is sensitive to power spectrum
abundances

- abundance of objects (e.g. cluster \( \frac{dn}{dM} \)) is sensitive to power spectrum
- low mass halos & sub-halos sensitive to small-scale \( P(k) \)
Dark matter substructure

$z=11.9$

800 x 600 physical kpc

“Via Lactea”
Diemand et al. 2006

Diemand, Kuhlen, Madau 2006
substructure is sensitive to DM physics

Figure 1: **Left:** Density projection in the Via Lactea-II simulation [18]. **Middle:** Similar, but excluding particles belonging to subhalos whose masses never exceeded $10^8 M_\odot$ any time throughout the simulation. **Right:** Like the middle panel, but excluding subhalos with $M_{\text{max}} < 10^{10} M_\odot$. This sequence should qualitatively illustrate the effect of truncating the power spectrum on substructure content in DM halos.
How to measure?

- count small galaxies / satellites

⇒ missing satellite problem (see Kravtsov 2012, Bullock & Boylan-Kolchin 2017 for reviews)
How to measure?

- count small galaxies / satellites
  ➡ missing satellite problem (see Kravtsov 2012, Bullock & Boylan-Kolchin 2017 for reviews)
  ➡ but low-mass halos could be dark...
- need gravitational probe to see dark halos/subhalos
  - tidal streams from GAIA (e.g. Carlberg, Bovy, Erkal et al.)
  - gravitational lensing!

![Figure 11. Estimated gap rate vs. stream width relation for M31 NW, Pal 5, the EBS, and the CDM halo prediction. All data are normalized to 100 kpc. The width of the theoretical relation is evaluated from the dispersion in the length-height relation of Figure 8. Predictions for an arbitrary alternative mass functions, $N(M) \propto M^{-1.8}$, normalized to have 33 halos above $10^9 M_\odot$ are shown with a dotted line.](image-url)
Gravitational lensing

- the deflection of light rays caused by inhomogeneities
- also distorts the apparent shapes & sizes of observed sources
- amount of lensing characterized by convergence $\kappa \sim \int \delta \rho \ dl$

Two regimes:

- **weak lensing** ($|\kappa| \ll 1$): small distortion
- **strong lensing** ($\kappa \gtrsim 1$): large distortion & multiple imaging
subhalo lensing

small ($M<10^8 \ M_\odot$) halos and subhalos are wimpy lenses!

- lensing amplitude is weak (central $\kappa,\gamma \approx 0.1$)
- small size, so each one affects a small fraction of the sky
- can’t stack if they’re dark (where to stack?)
- need a way to boost their effect to detect them...
strong lensing

- if a small halo/subhalo projects near a **strong lens**, then the big lens can magnify the lensing effect of the small

\[ \Delta \theta \approx M \cdot \Delta \alpha \]

if high magnification, then perturbation can have big effect! (Mao & Schneider 1998)
universality relations

- when 2 images are close together, they should have nearly equal brightness

\[
\frac{\Delta f}{f} \propto \frac{\Delta r}{r_s}
\]

- similar relation when 3 images occur close together:

\[
\frac{f_A - f_B + f_C}{f_A + f_B + f_C} \propto \frac{\Delta r}{r_s}
\]
universality relations

\[ \frac{\Delta f}{f} \propto \frac{\Delta r}{r_s} \]

\[ \frac{f_A - f_B + f_C}{f_A + f_B + f_C} \propto \frac{\Delta r}{r_s} \]
flux anomalies

• implication: local scale length $r_s$ is much smaller than size of the system $\Rightarrow$ substructure in the potential

• in radio quasars, flux ratio anomalies can only be caused by mass substructure (not true for optical lenses)

• flux anomalies occur in almost all of the observed quasar lenses $\Rightarrow$ lots of substructure!
how do we know it’s substructure?

- radio flux ratios independent of $\lambda$, as expected for lensing but unlike propagation effects (like scintillation or dust extinction)

- observed parity dependence: 
  + parity magnified,  – parity demagnified

- radio quasars too big to be affected by stellar microlensing, unlike stellar QSO’s.

- see Kochanek & Dalal (2003) for more...
Dalal & Kochanek (2002) analyzed sample of 7 radio lenses

- found that ~ 1% of projected mass at 5kpc is in substructure

- but uncertainty was about factor of 10!

\[ \sim 10^{10} M_\odot \]

\[ \sim 10^6 M_\odot \]
how to improve?

• we need a new class of lensed sources!
ALMA

- Interferometric array of 66 telescopes
- Wavelength: mm/submm
- Resolution: ~10 milli-arcsec (16 km baseline)
- Started Operating in 2012
ALMA

• ALMA is a new observatory, often used for studying newly formed solar systems

  • ex: HL tau planet formation in action

• we realized that ALMA’s high sensitivity, resolution, & spectroscopy would also be great for studying dark matter substructure (Hezaveh et al. 2013)
ALMA Cycle 0 Band 7 350 GHz
2 minute snapshots

Note that sources are bright in submm and invisible in visible/IR,
while lenses are invisible in submm and bright in visible/IR.
okay.... so what?

- lensed SMG's are *perfect* for detecting DM substructure!
- theoretically, we expect these galaxies to contain many **compact** star-forming clumps (~100pc) inside much bigger GMC's (~kpc). see also local analogues like Arp 220
- clumps are extremely bright in lines like CO 7-6
- example: high resolution SMA imaging of lensed SMG reveals compact source clumps (Swinbank et al. 2010)

![Image of galaxy cluster with contours and labels](Image)
The Strength of Substructure Lensing Signal Depends on the Source Size

Compact Sources Are Perturbed More Strongly
Spatially resolved spectroscopy

**Figure 1.** SMM J131201: this system displays a complex, irregular morphology, it most likely is an advanced pre-encounter merger. The RGR image (magenta, red, green, and blue parts of the spectrum) shows no indication of rotation. Spectra are, left: northeast (top) and southeast (bottom) arm, right: entire system (top) and central part (bottom). The beam size (0.259 x 0.47, P.A. = 30.3°) is displayed in the lower left corner of the flux map. North is up and east is to the left. Scale bar denotes 1''.

(A color version of this figure is available in the online journal.)

Velocity decomposition can separate small features of the source so each SMG is equivalent to having many sources behind each lens!
Preliminary results

Our first observations are slowly coming in; here are some early results...
data slowly coming in...

SPT 0418
0.4 ARCSEC RESOLUTION (2013)

SPT 0418
0.1 ARCSEC RESOLUTION (2017)

SPT 0418
0.025 ARCSEC RESOLUTION (2018)
examples
(preliminary, still missing long baselines)

short-baseline observations in Cycle 2
also 4 new systems coming in this month from Cycle 4
**Lens modeling**

- ALMA is an interferometer, so the observables are (millions of) visibilities in the $uv$ plane
- We fit the visibilities, not CLEAN images
- Our model has 10’s of thousands of free parameters, including things like time-varying antenna phase errors. We marginalize over all of them.
- This is crucial! Improper treatment of phase errors will lead to spurious detection of subhalos
Subhalo detection

- a $M=10^9 \, M_\odot$ subhalo is detected at $\sim 7$-sigma confidence in the first system we analyzed
detected in multiple bands
covariance
Other subhalos?

- this map shows how the fit improves ($\Delta \chi^2$) as we add a subhalo at various other locations...

- seems to be $\sim 4.5\sigma$ hint for an additional subhalo with $M=10^8 M_\odot$
bounds on the subhalo mass function
comparison with theory
Conclusion:

- SMG lensing is great for DM substructure
- stay tuned!