Title: Mapping dark matter on the largest and smallest scales

Date: Jun 16, 2016 03:50 PM

URL: http://pirsa.org/16060023

Abstract: Using lensing of the CMB we can make maps of the dark matter distribution on the largest cosmological scales, perhaps allowing new insights into gravity, particle physics, and cosmology. With high-resolution maps of distant star-forming galaxies we can map dark matter on small scales within individual galaxies, measuring the small-scale clumping properties of dark matter.

Mapping dark matter on the largest and smallest scales

Gil Holder

McGill

CIFAR
CANADIAN INSTITUTE for ADVANCED RESEARCH

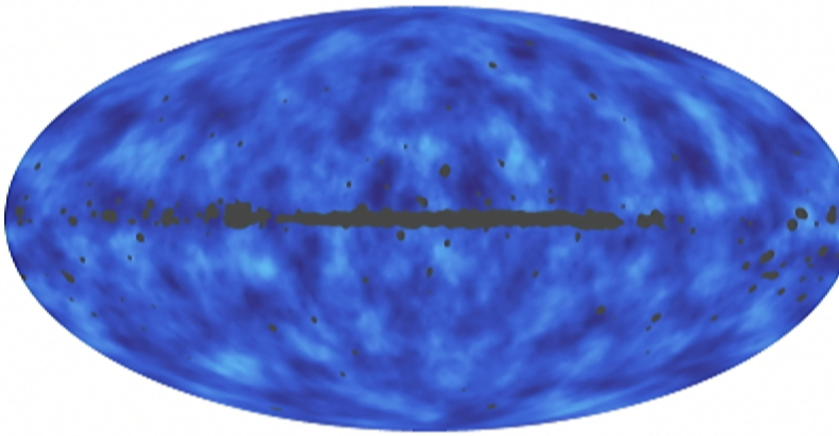
Yuuki Omori
Eric Baxter
Donnacha Kirk

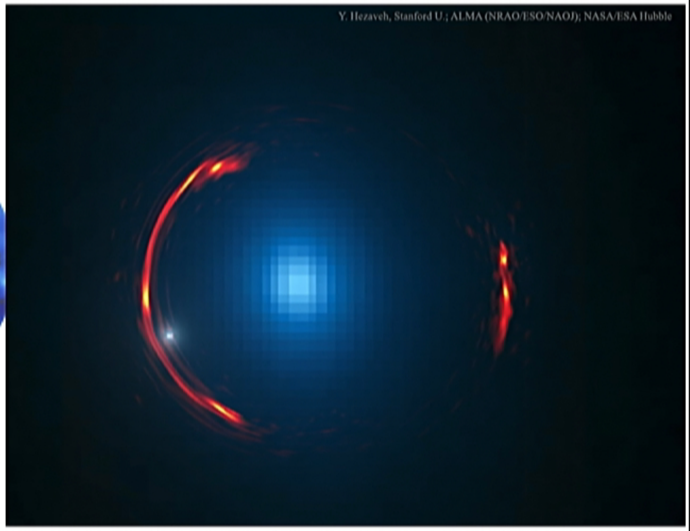
+SPT
+SPTPol
+DES

Yashar Hezavehe
Neal Dalal
Dan Marrone
++

"Next Generation Cosmological Probes"

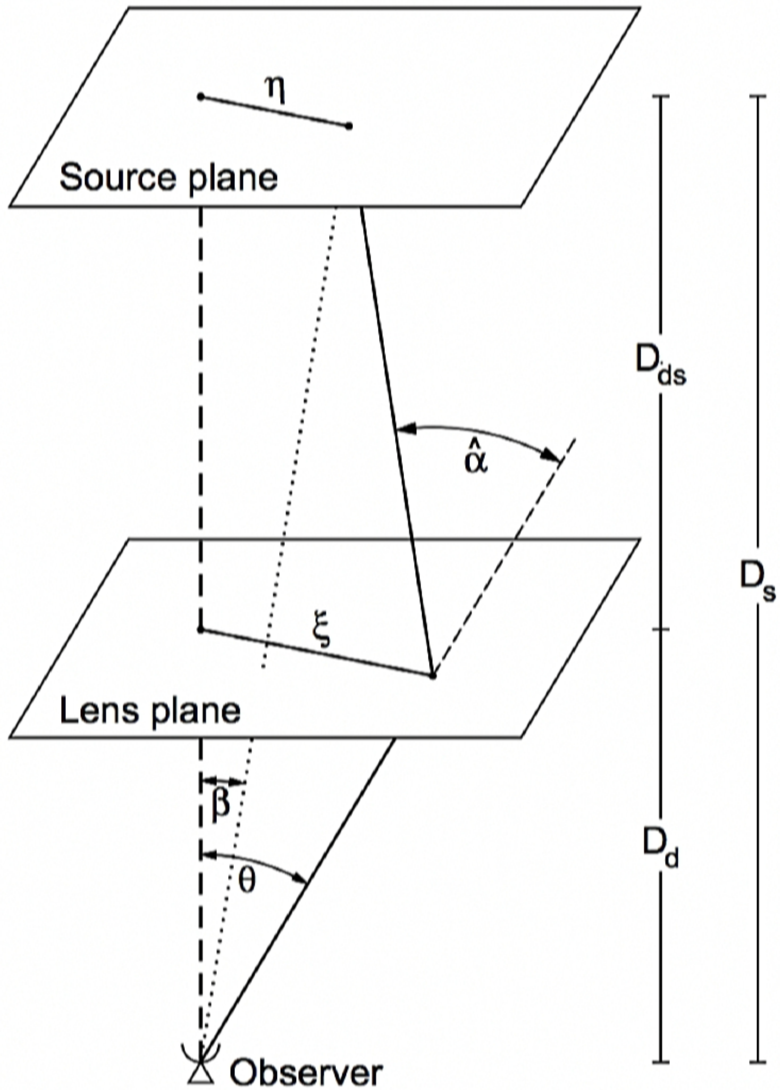
- CMB lensing
  - measures large scale structure at z~3
  - probes gravity on large scales
  - nicely complementary to galaxy lensing & galaxy clustering
- strong lensing of high-z star-forming galaxies
  - allows high-resolution search for dark matter substructures in lens galaxies




Y. Hezaveh, Stanford U.; ALMA (NRAO/ESO/NAOJ); NASA/ESA Hubble

Gravitational lensing

$$\hat{\alpha} = \frac{4GM}{c^2 \xi}$$

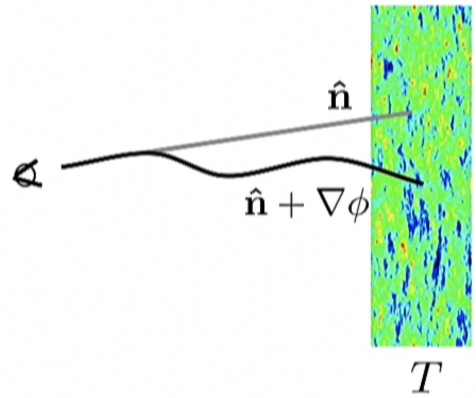


Bartelmann & Schneider
http://arxiv.org/abs/astro-ph/9912508

CMB Lensing

Photons get shifted

$$T^L(\hat{\mathbf{n}}) = T^U(\hat{\mathbf{n}} + \nabla\phi(\hat{\mathbf{n}}))$$



In WL limit, add many deflections along line of sight

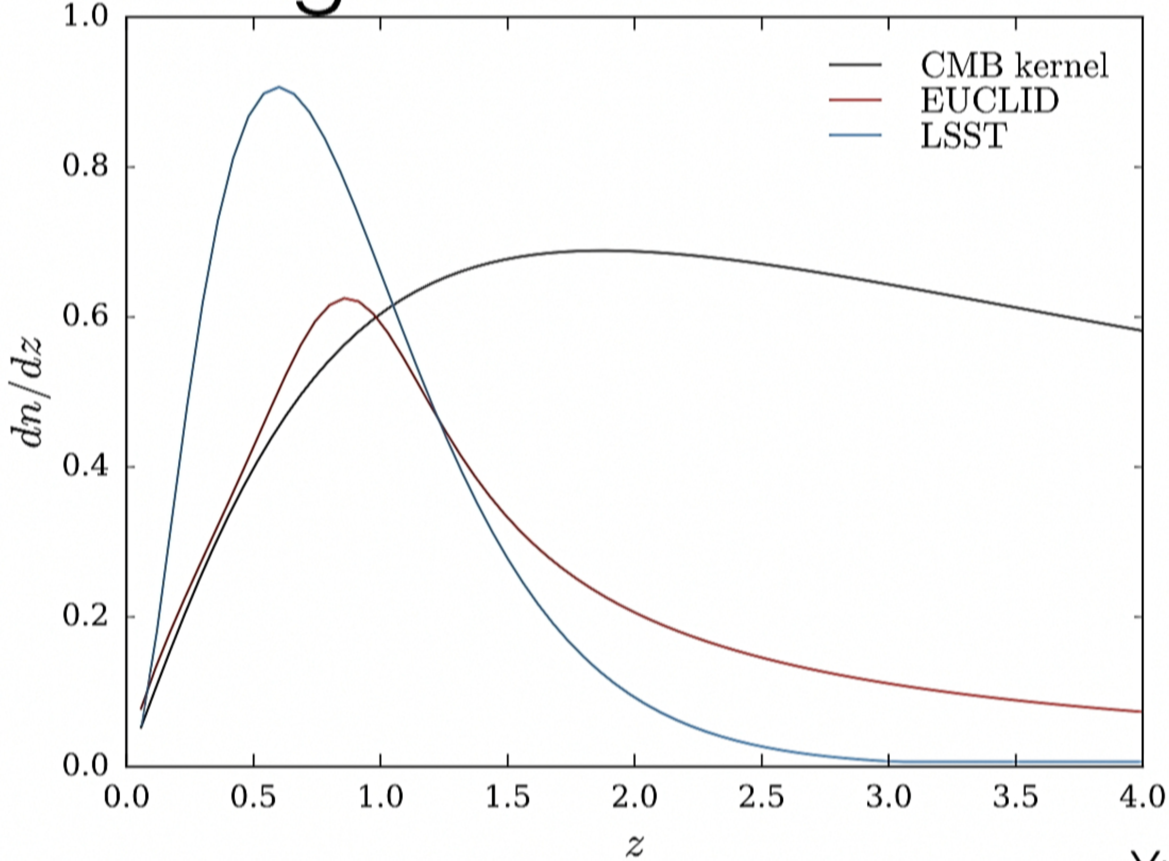
$$\nabla\phi(\hat{\mathbf{n}}) = -2\int_0^{\chi_\star} d\chi\, \frac{\chi_\star - \chi}{\chi_\star \chi} \nabla_\perp \Phi(\chi\hat{\mathbf{n}}, \chi)$$

Broad kernel, peaks at z ~ 2

- CMB is a unique source for lensing
  - Gaussian, with well-understood power spectrum (contains all info)
  - At redshift which is (a) unique, (b) known, and (c) highest

some slides from Alex van Engelen

CMB lensing sensitive to higher z sources



Yuuki Omori

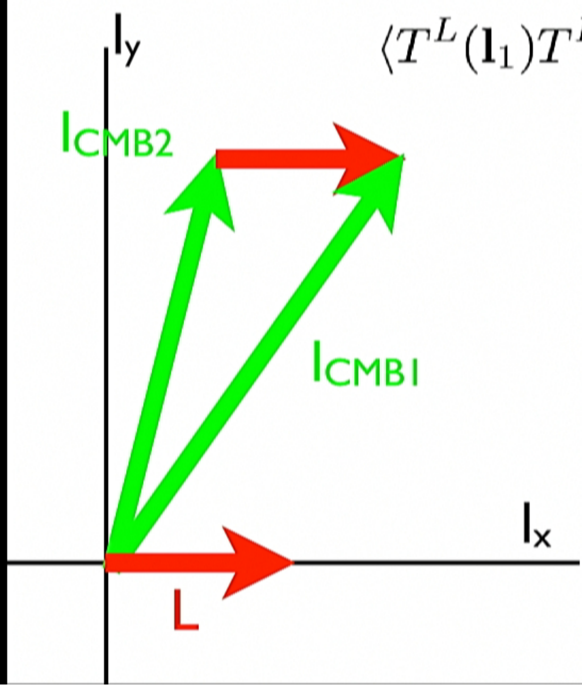
Mode Coupling from Lensing

$$T^L(\hat{\mathbf{n}}) = T^U(\hat{\mathbf{n}} + \nabla\phi(\hat{\mathbf{n}})) = T^U(\hat{\mathbf{n}}) + \nabla T^U(\hat{\mathbf{n}}) \cdot \nabla\phi(\hat{\mathbf{n}}) + O(\phi^2),$$

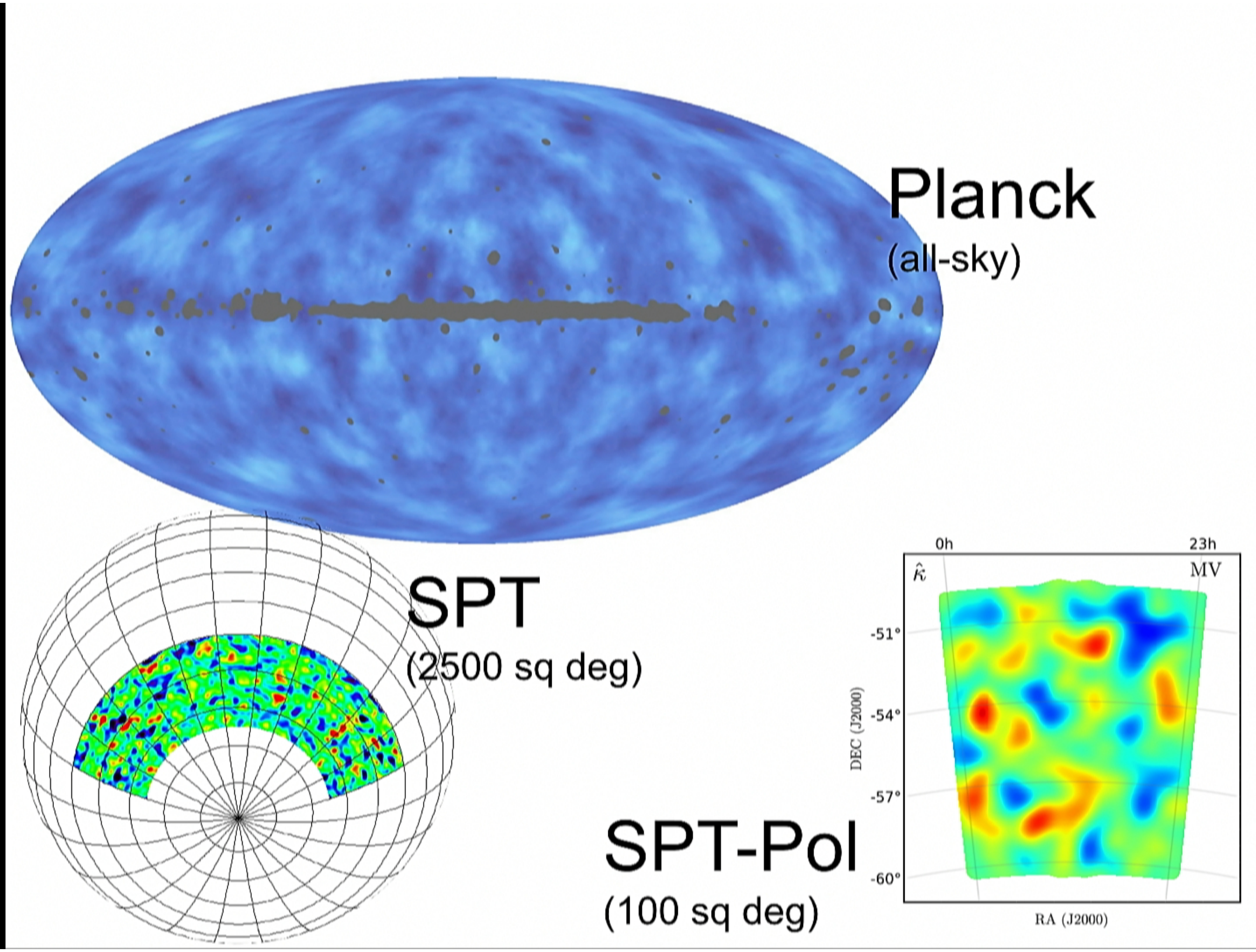
- Non-gaussian mode coupling for $\mathbf{l_1} \neq -\mathbf{l_2}$:

$$\langle T^L(\mathbf{l}_1) T^L(\mathbf{l}_2)\rangle = \mathbf{L}\cdot(\mathbf{l}_1 C^T_{l_1} + \mathbf{l}_2 C^T_{l_2})\phi(\mathbf{L}) + O(\phi^2)$$

$$\mathbf{L} = \mathbf{l}_1 + \mathbf{l}_2$$



- We extract ϕ by taking a suitable average over CMB multipoles separated by a distance L
- We use the standard Hu quadratic estimator.


Planck
(all-sky)
SPT
(2500 sq deg)
SPT-Pol
(100 sq deg)
0h
23h
$\hat{\kappa}$
MV
-51°
-54°
-57°
-60°
DEC (J2000)
RA (J2000)

The South Pole Telescope (SPT)

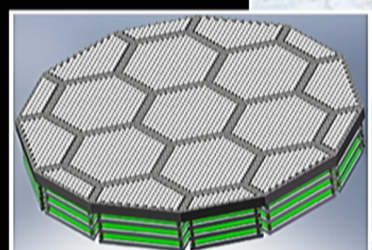
10-meter sub-mm quality wavelength telescope

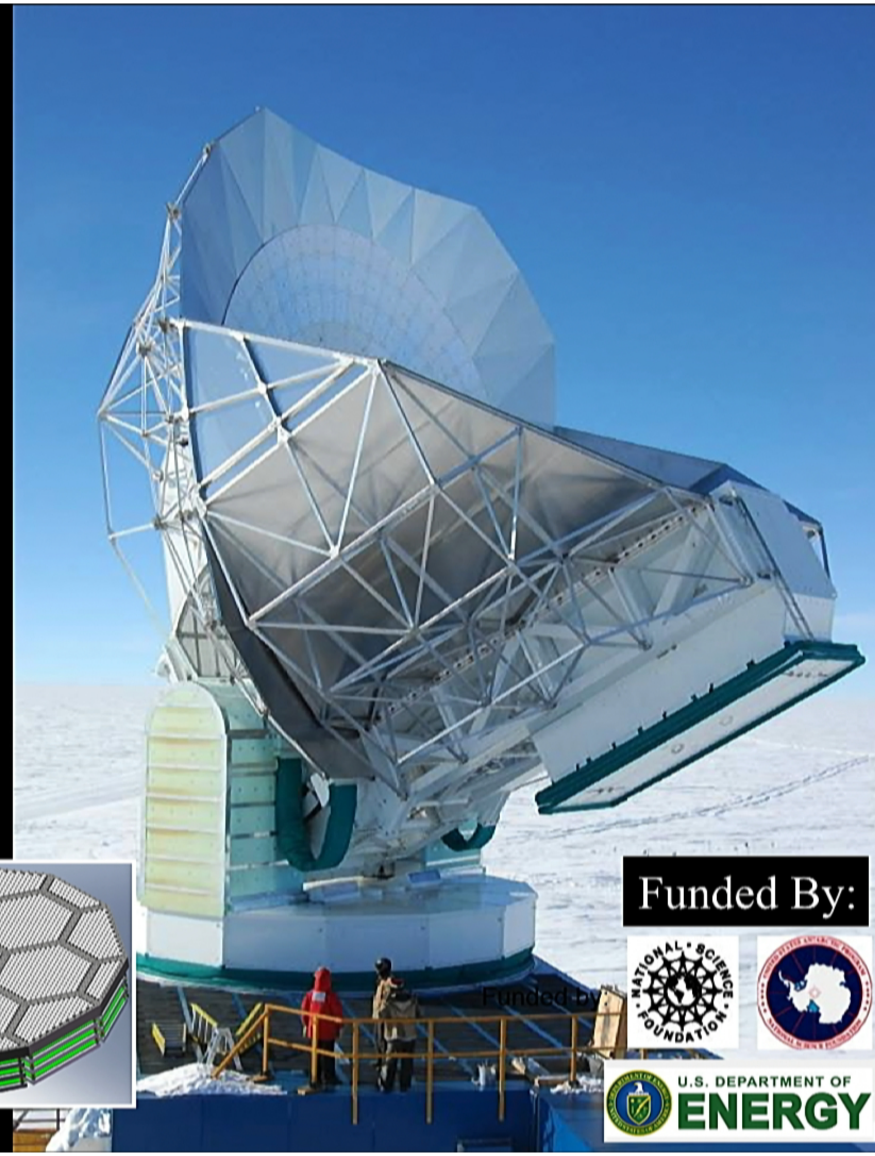
100, 150, 220 GHz and
1.6, 1.2, 1.0 arcmin resolution

2007: SPT-SZ
960 detectors
100,150,220 GHz

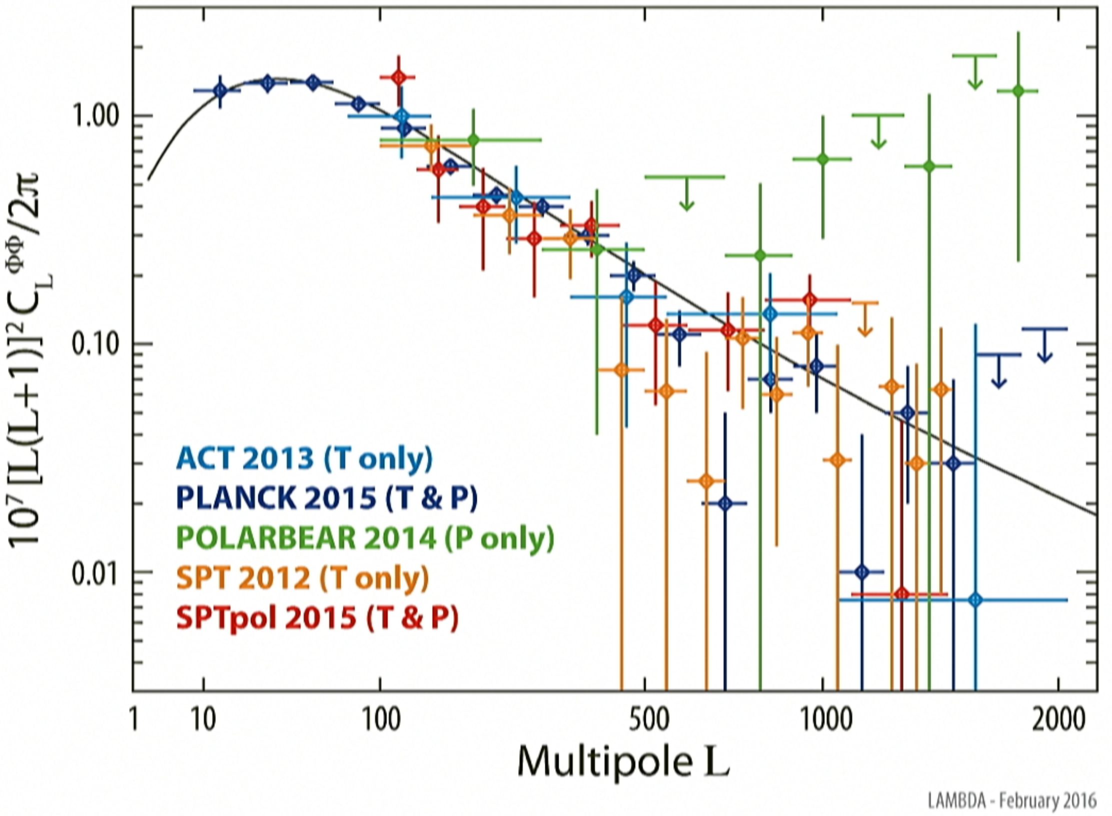
2012: SPTpol
1600 detectors
100,150 GHz
+Polarization

2016: SPT-3G
~15,200 detectors
100,150,220 GHz
+Polarization



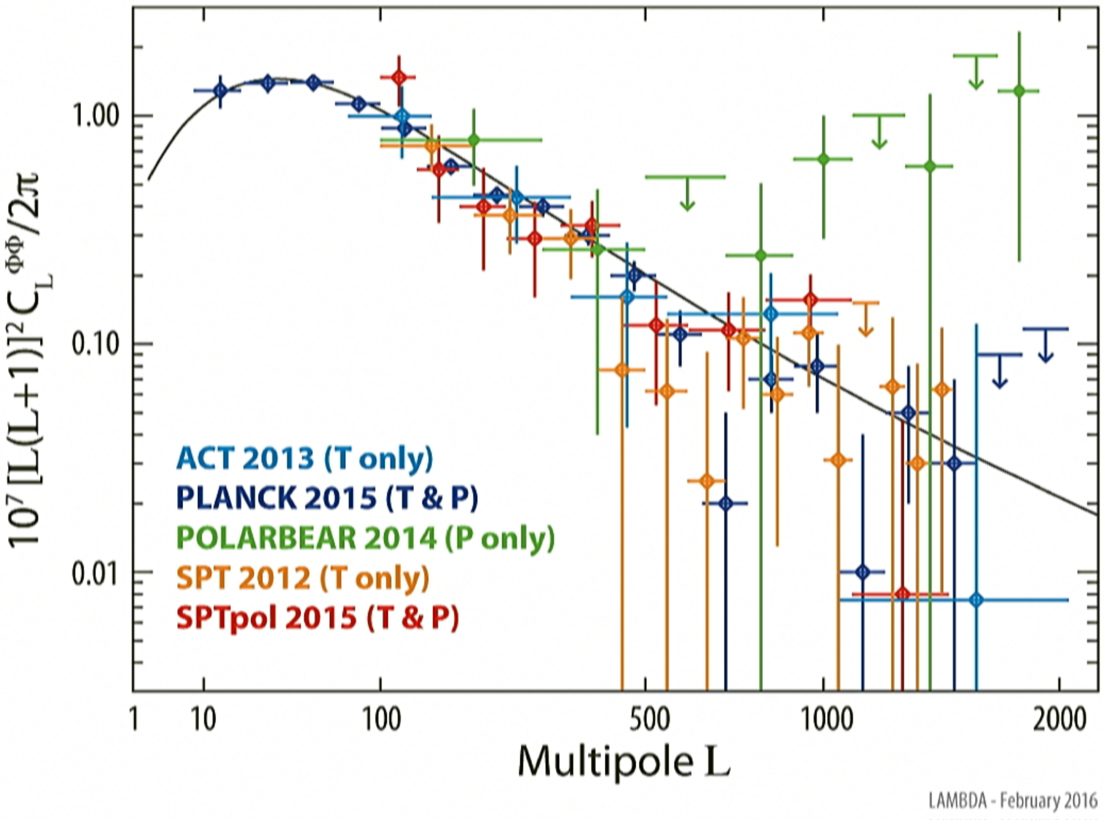


CMB Lensing Power Spectrum



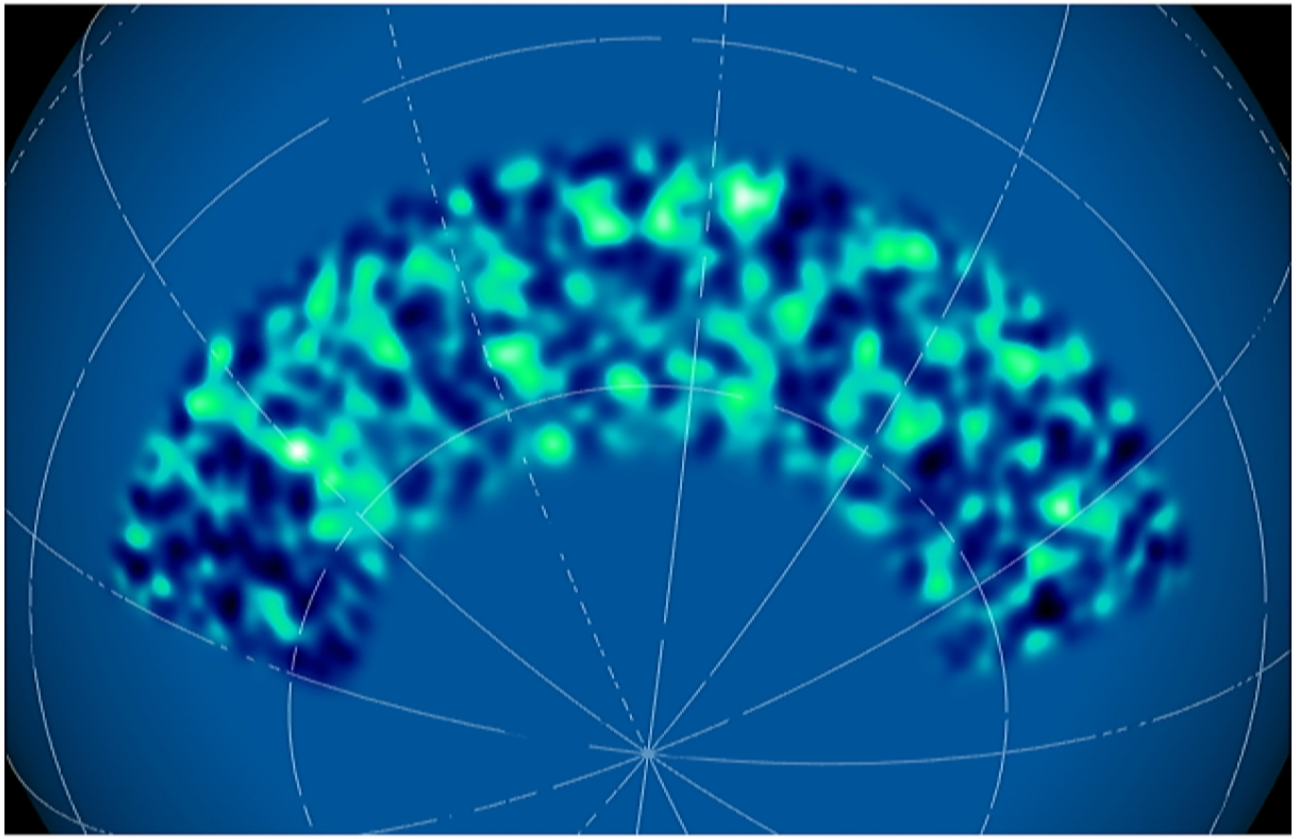
- direct measurement of the mass fluctuations in the Hubble volume

CMB Lensing Power Spectrum



- direct measurement of the mass fluctuations in the Hubble volume

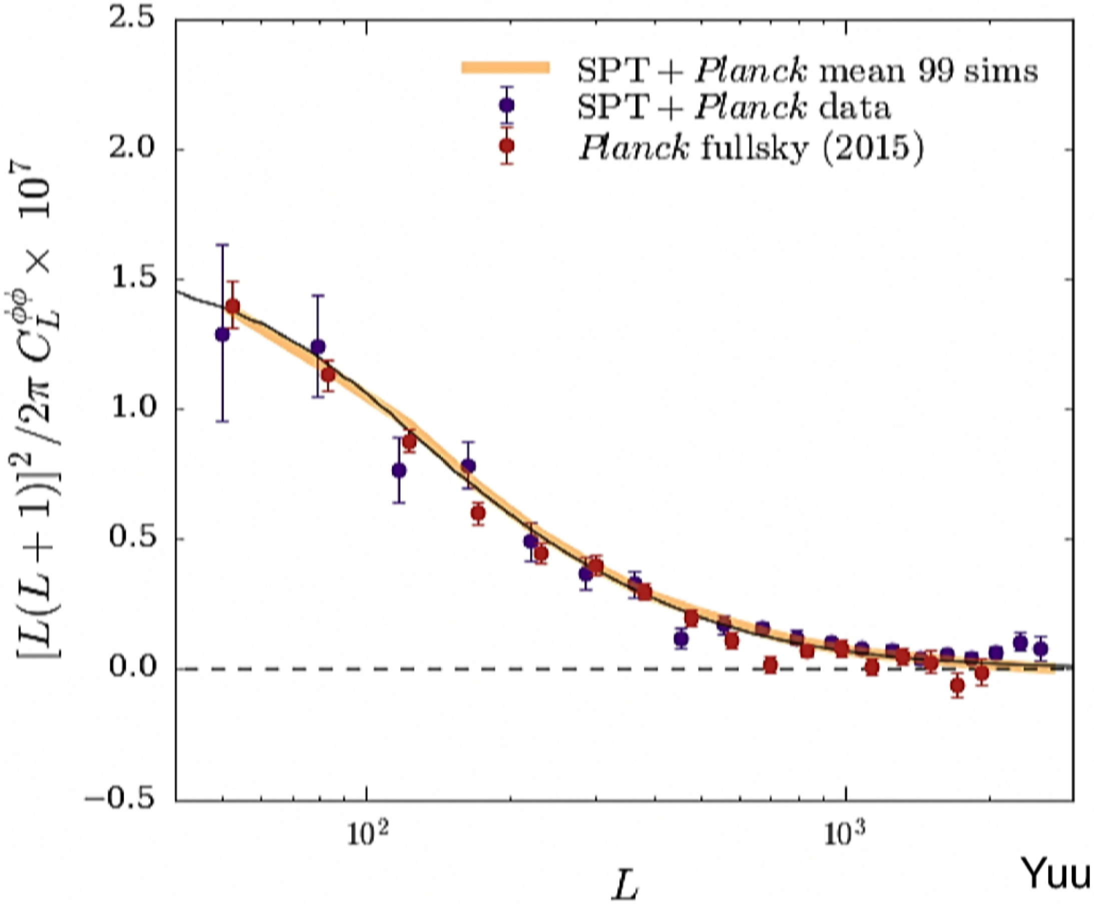
SPT+Planck lensing (in prep)



lensing map constructed from 2500 sq deg SPT+Planck combined map

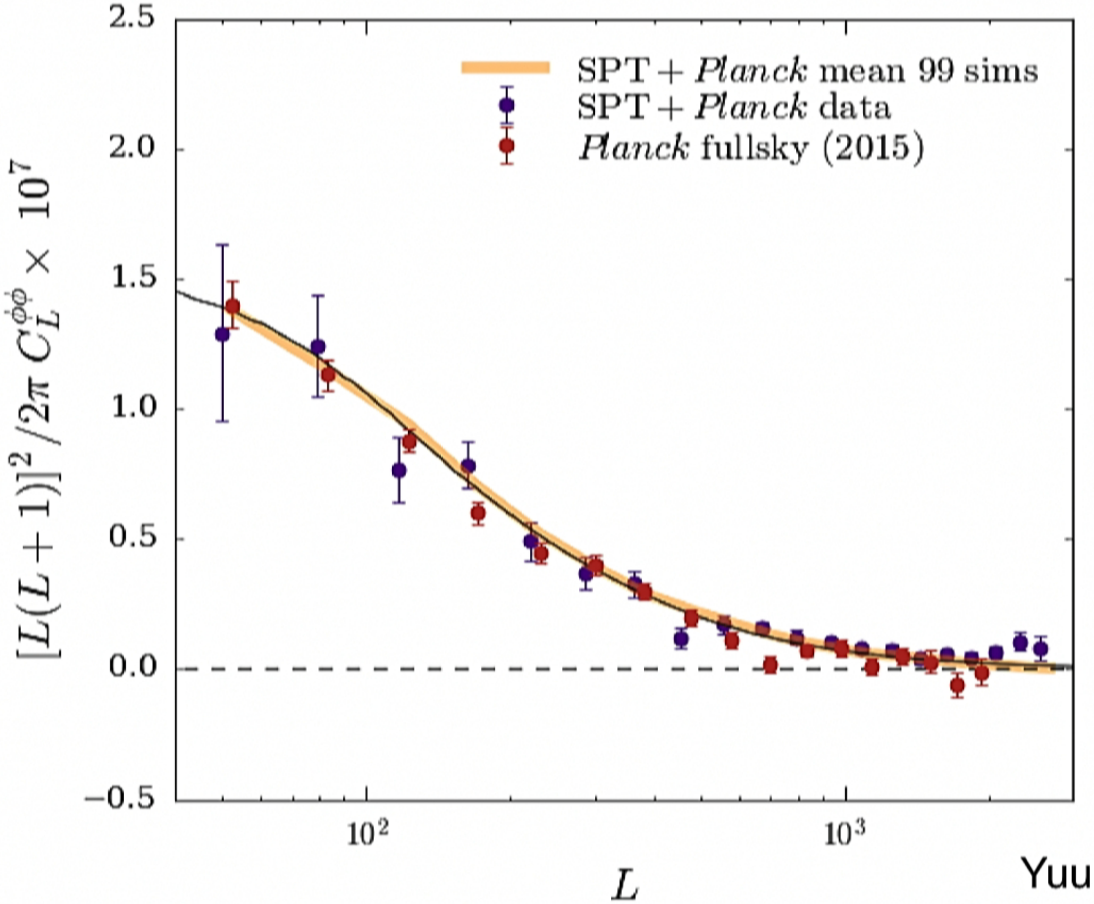
Yuuki Omori

SPT+Planck lensing (in prep)



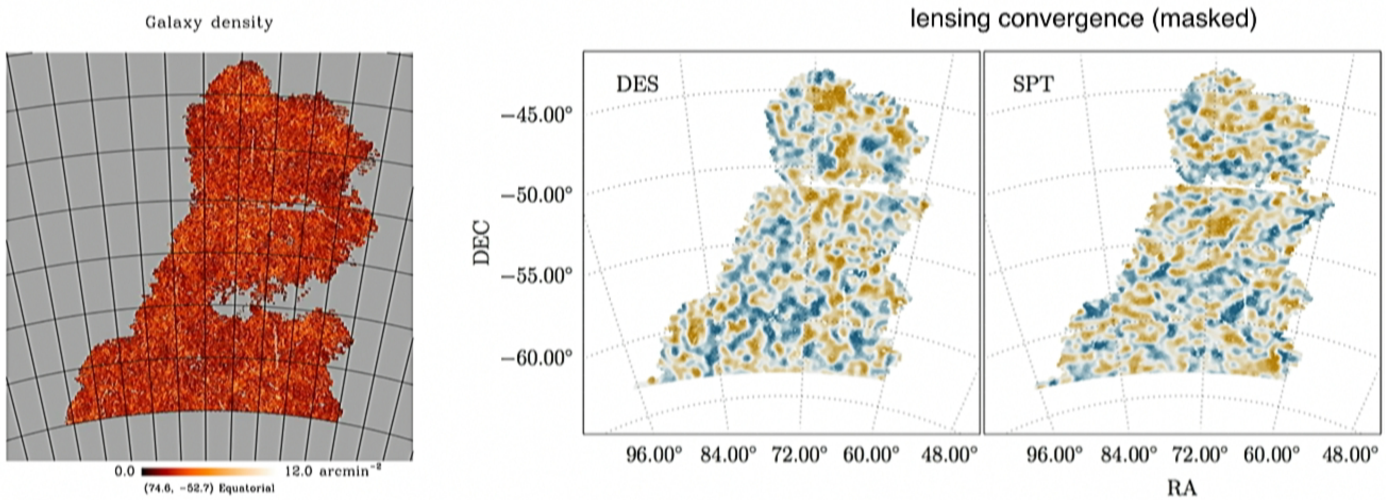
Yuuki Omori

SPT+Planck lensing (in prep)



Yuuki Omori

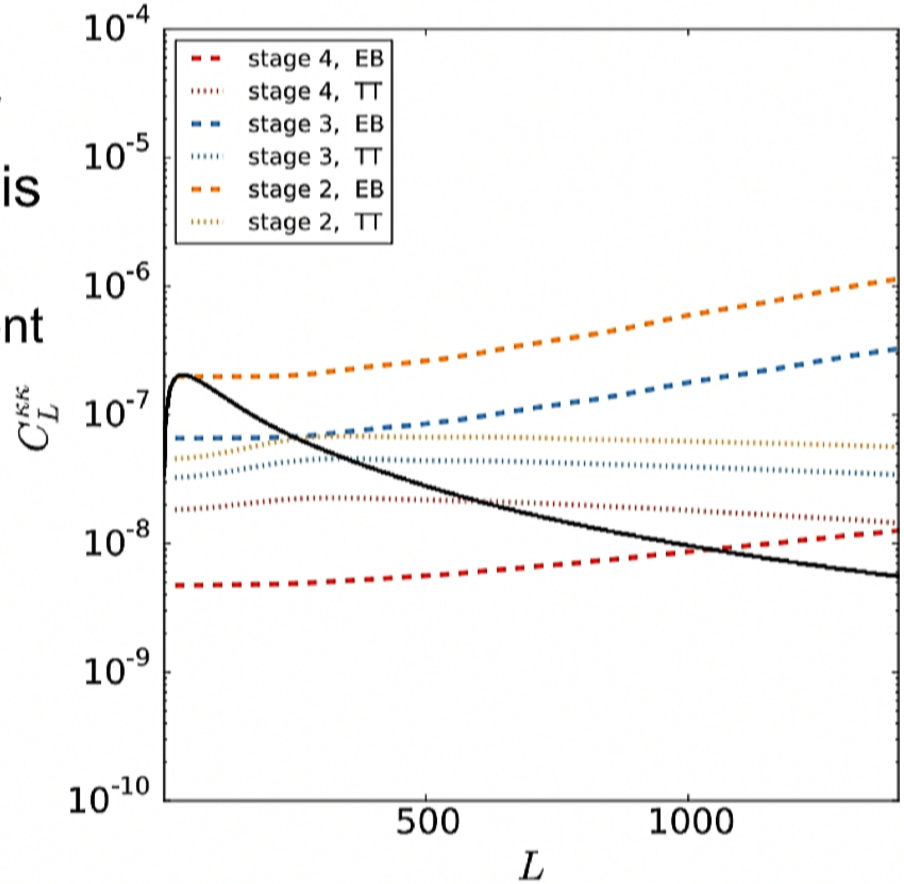
Cross-Correlation: SPT/DES



- overlapping sky coverage of SPT and DES allows tests for large scale structure
  – how do galaxies trace dark matter?
  – how does galaxy shear relate to CMB lensing?
  – first round of DES/SPT papers on Science Verification data
- [also lensing x-corr using WMAP, Planck, ACT]

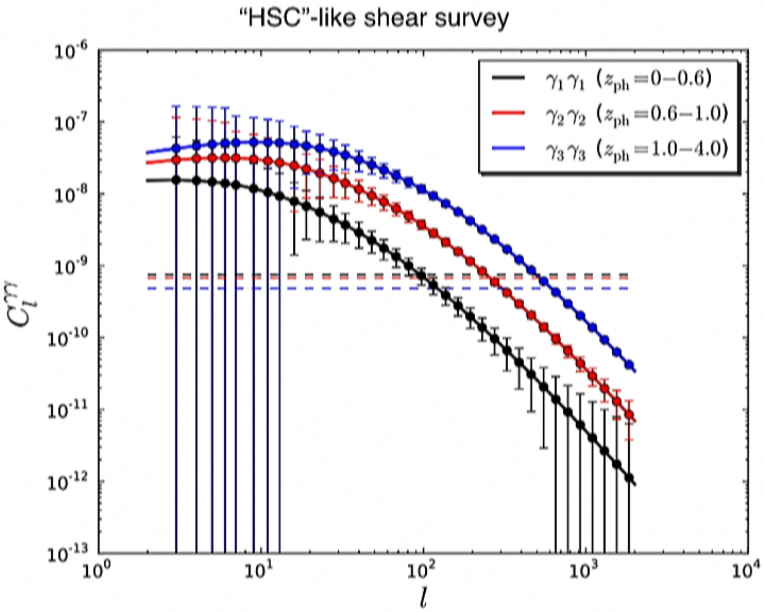
Next in CMB lensing

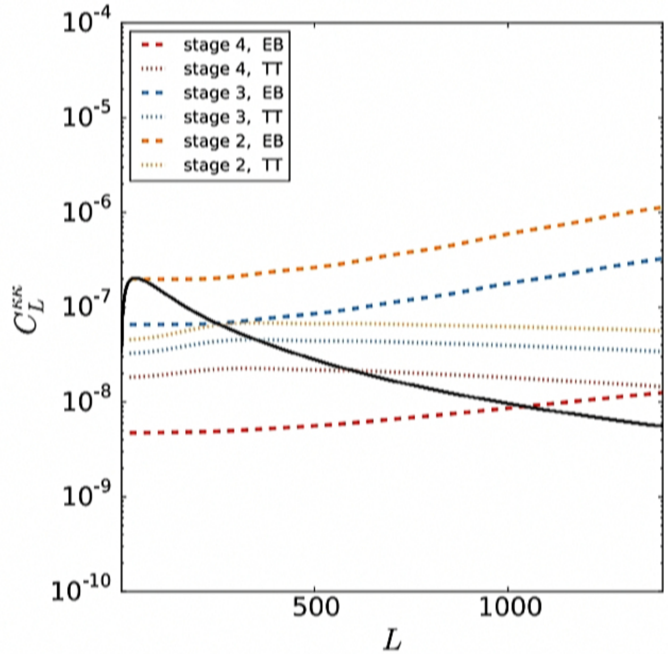
- data is getting better
- current lensing data is dominated by TT
  - even if the experiment is labeled "…Pol"
- once sensitivity gets well below 5 uK-arcmin, pol-based lensing becomes important
  - "imaging" lensing B-modes



https://cosmo.uchicago.edu/CMB-S4workshops/images/Cmbs4_scibook_160517.pdf

CMB Lensing vs "Cosmic Shear"





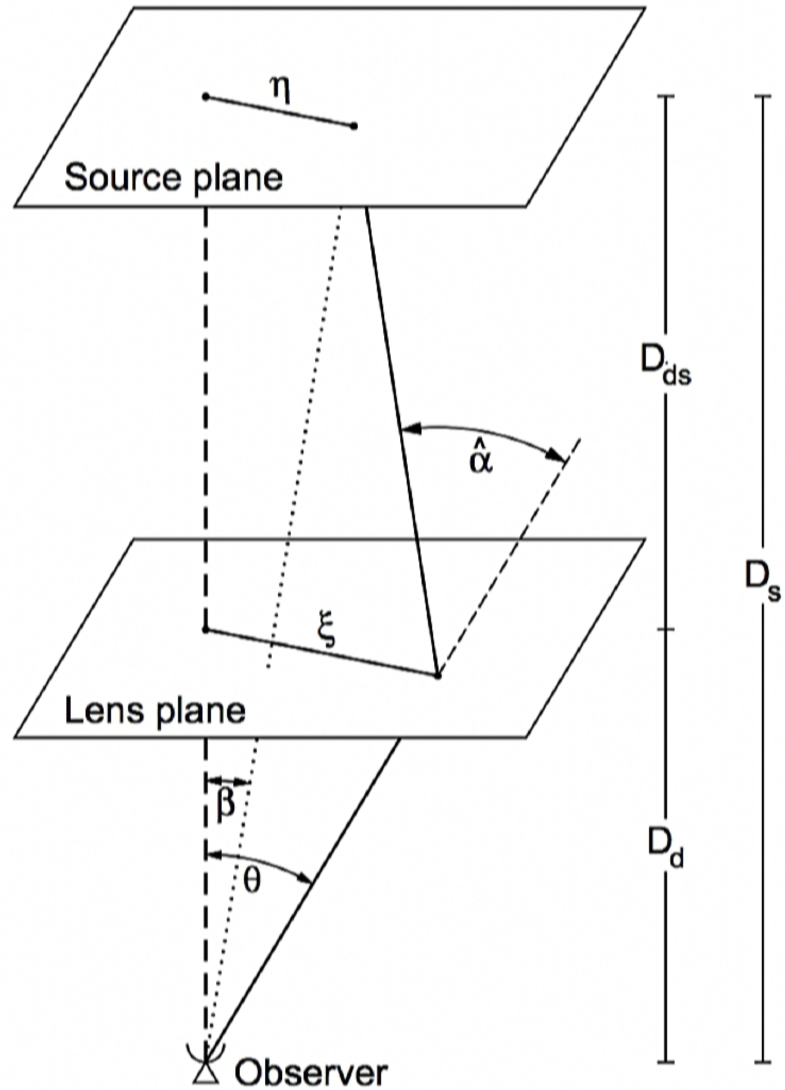
de Putter, Dore, & Das
1306.0534

https://cosmo.uchicago.edu/CMB-S4workshops/images/Cmbs4_scibook_160517.pdf

Gravitational lensing

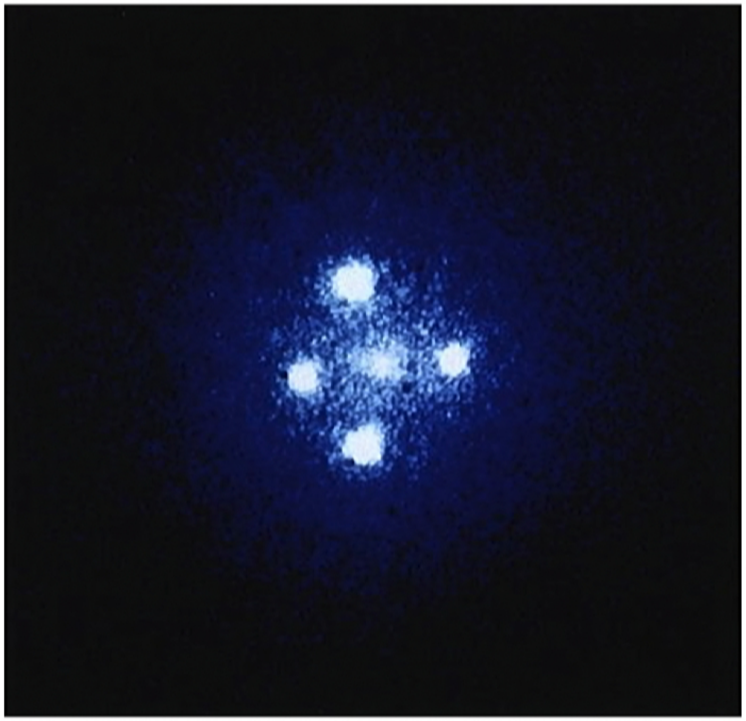
$$\hat{\alpha} = \frac{4GM}{c^2 \xi}$$

Bartelmann & Schneider
http://arxiv.org/abs/astro-ph/9912508



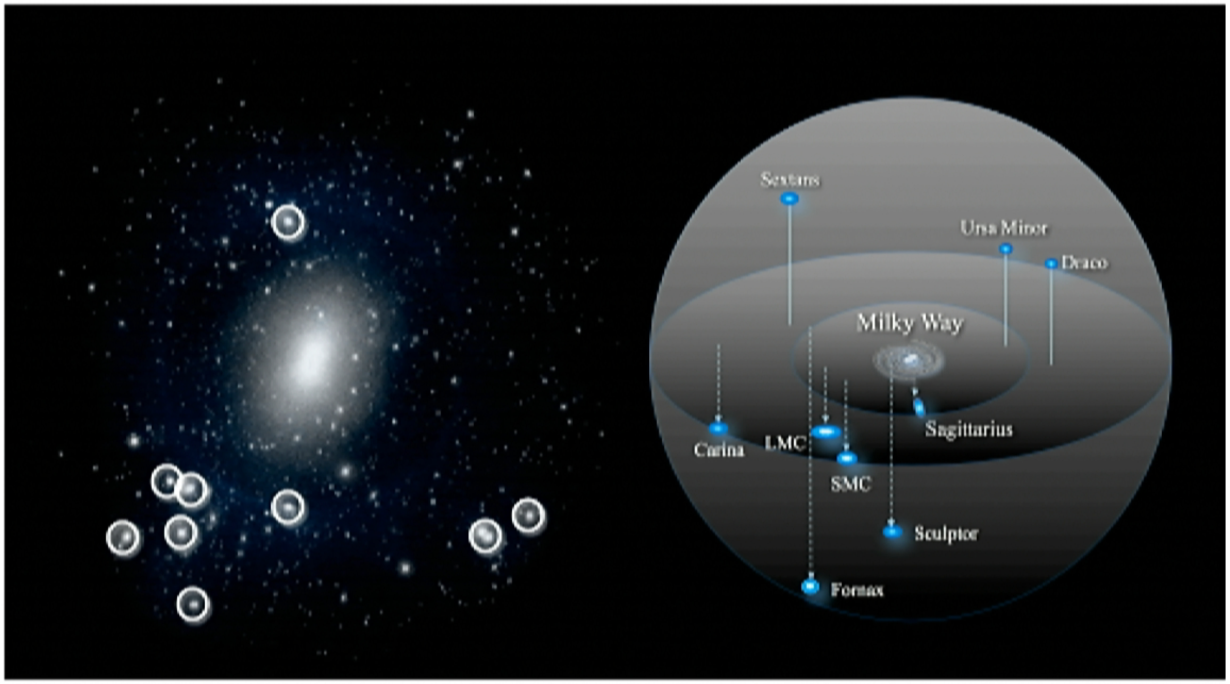
Strong lensing

- multiple paths from source to observer due to gravitational lens along line of sight
- lenses have been discovered in many wavelengths: radio, mm, submm, optical
- excellent way to map out the mass distribution in the **lens**



Missing satellite galaxies?

comparison of simulated and observed satellites for MW-like galaxy



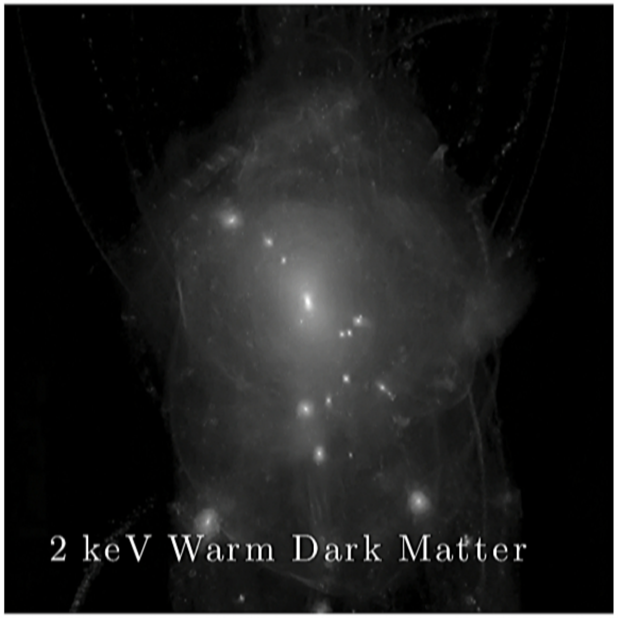
Weinberg et al arXiv:1306.0913

21

Possible Solutions

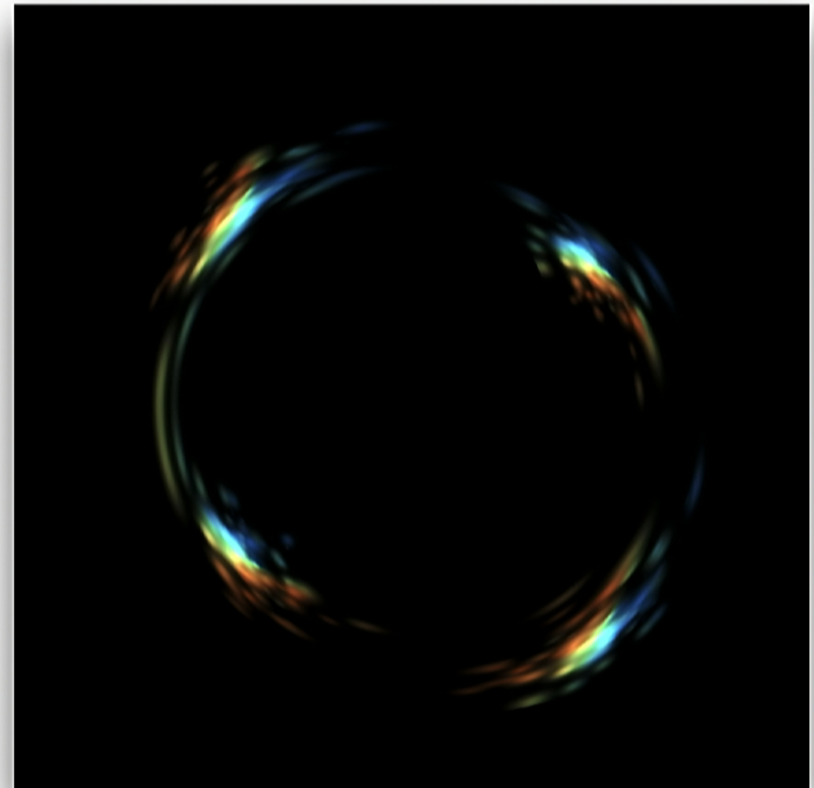
Baryonic Gastrophysics

Dark Matter Physics

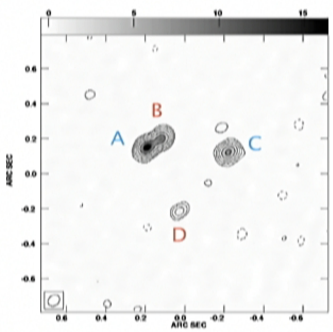


Lovell et al 2012, MNRAS 420, 3

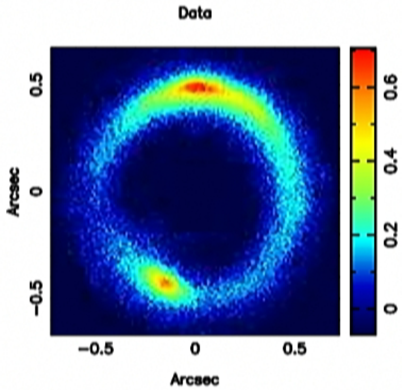
Substructure Lensing



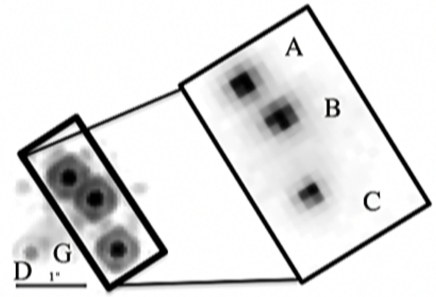
Substructure Lensing



DALAL & KOCHENAK 2002



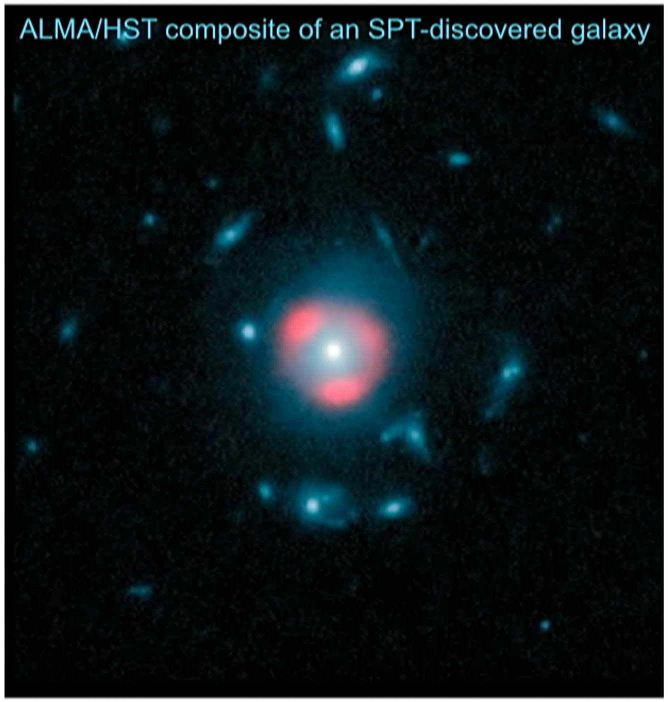
VEGETTI ET AL. 2012



NIERENBERG ET AL. 2014

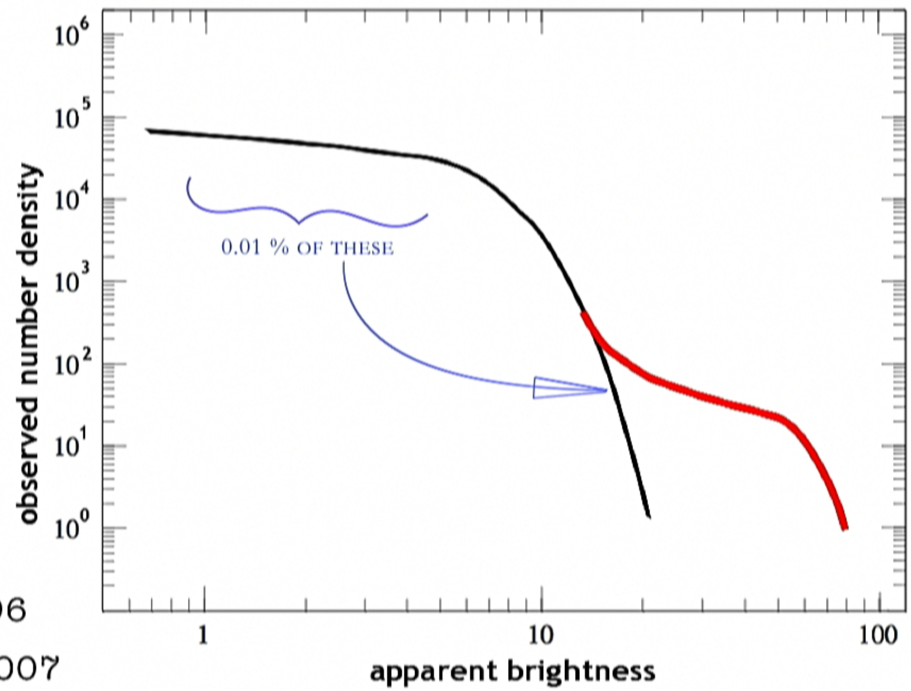
Strong lensing of mm-wave selected galaxies

- selecting bright sources at mm/submm wavelengths turns out to be a remarkably efficient way to discover strong lensing
  - more than 100 new systems discovered recently



Vieira et al 2013

Number Counts of high-z star-forming Galaxies



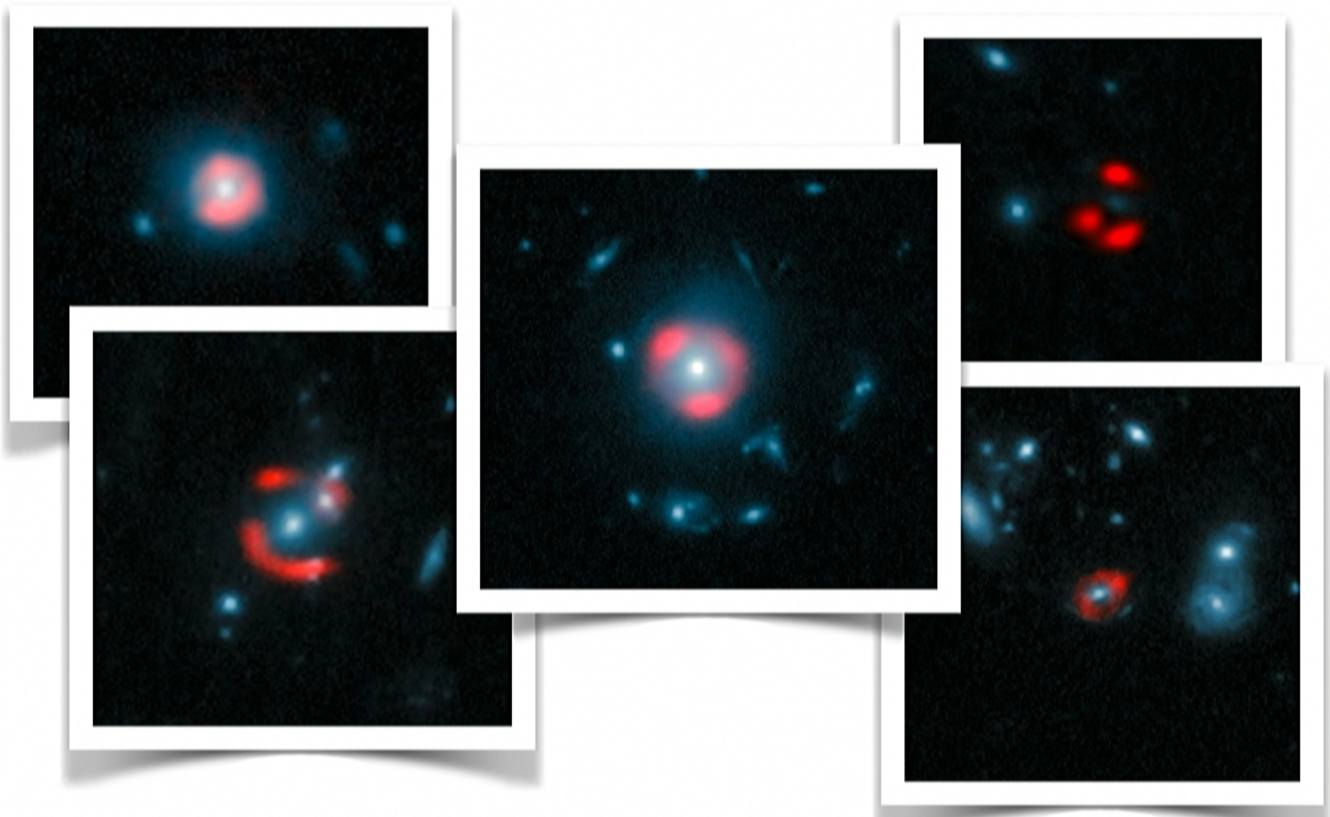
BLAIN 1996

NEGRELLO 2007

LIMA ET AL. 2010

ALMA observations of SPT-discovered sources

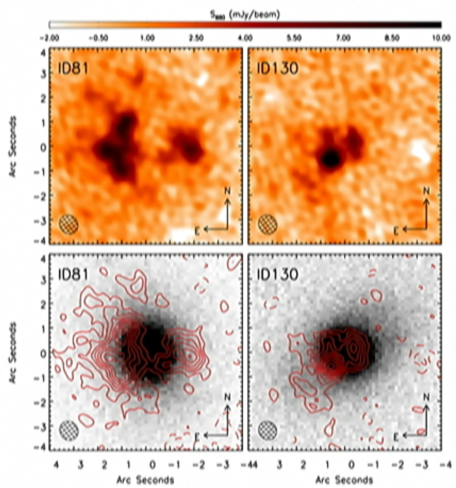
BLUE: HST (OPTICAL), RED: ALMA

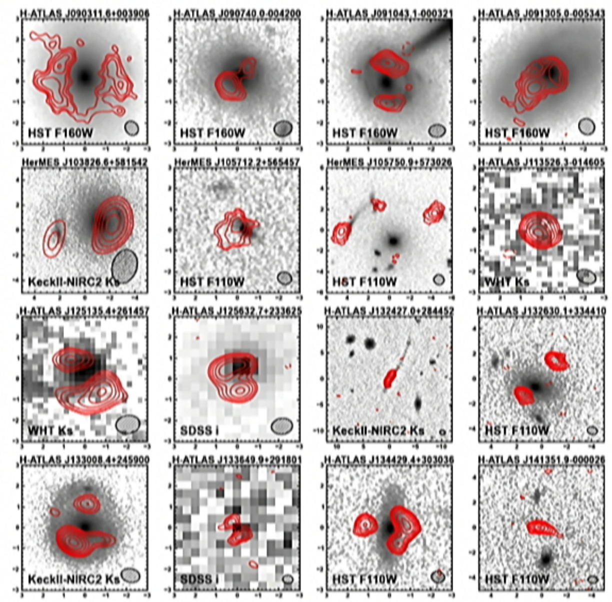


VIEIRA ET AL. NATURE 2013

HEZAVEH ET AL. APJ. 2013

Herschel Strong Lenses

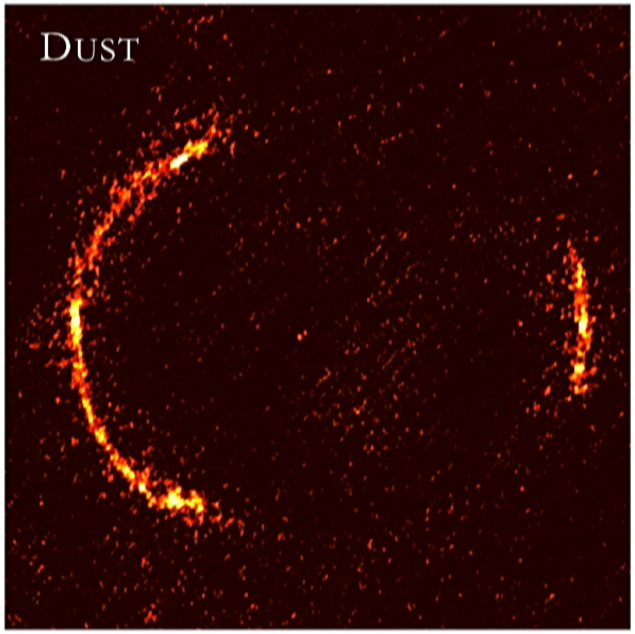


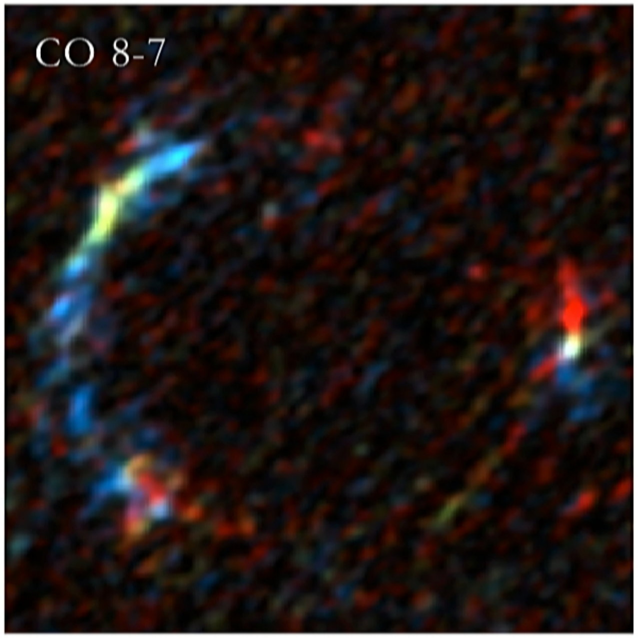


Negrello et al. Science 2010

Bussmann et al. ApJ 2013

SDP 81
(ALMA science verification data)





SDP81 papers

Draft version March 20, 2015
Preprint typeset using LaTeX style emulateapj v. 01/23/15

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

Kenneth C. Wong[1,*], Sherry H. Suyu[1], and Satoki Matsushita[1]
Draft version March 20, 2015

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 $\log(M_{BH}/M_\odot) \gtrsim 8.4$ 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

.GA] 18 Mar 2015

Publ. Astron. Soc. Japan (2014) 00(0), 1–6
doi: 10.1093/pasj/xxx000

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

Yoichi Tamura[1], Masamune Oguri,[2,3,4], Daisuke Iono[5,6], Bunyo Hatsukade[5], Yuichi Matsuda[5,6] and Masao Hayashi[5]

[1]Institute of Astronomy, University of Tokyo, Osawa, Mitaka, Tokyo 181-0015
[2]Research
113-0033
[3]Departme
[4]Kavli Instit

.GA] 26 Mar 2015

ALMA imaging of SDP.81 – I. A pixel far-infrared continuum emission

M. Rybak,[1*] J. P. McKean,[2,3] S. Vegetti,[1] P. Andreani[4] and S. D. M
[1]Max Planck Institute for Astrophysics, Karl-Schwarzschild-Strasse 1, D-85740 Garching
[2]Netherlands Institute for Radio Astronomy (ASTRON), P.O. Box 2, 7990 AA Dwingeloo, The Netherlands
[3]Kapteyn Astronomical Institute, University of Groningen, P.O. Box 800, 9700 AV Groningen, The Netherlands
[4]European Southern Observatory, Karl-Schwarzschild-Strasse 2, 85748, Garching, Germany

in original form 2015 March 4

ABSTRACT
We present a sub-50 pc-scale analysis of the gravitational
3.042 using Atacama Large submillimetre/Millimetre Array
data. These were taken at 236 and 290 GHz using baselines

] 6 Mar 2015

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

S. Dye[1*], C. Furlanetto[1,2], A. M. Swinbank[3], C. Vl
Dunne[6,7], S. A. Eales[8], Ian Smail[3], I. Oteo-Gómez
H. Dannerbauer[12], R. J. Ivison[7,9], R. Gavazzi[13], A.

1 [astro-ph.GA] 30 Mar 2015

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

Bunyo Hatsukade[1] Yoichi Tamura[2] Daisuke Iono[1,3] Yuichi Matsuda[1] Masao Hayashi[1] and Masamune Oguri[4,5,6]

[1]National Astronomical Observatory of Japan, 2-21-1 Osawa, Mitaka, Tokyo 181-8588, Japan
[2]Institute of Astronomy, University of Tokyo, 2-21-1 Osawa, Mitaka, Tokyo 181-0015, Japan
[3]The Graduate University for Advanced Studies (SOKENDAI), 2-21-1 Osawa, Mitaka, Tokyo 181-8588, Japan
[4]Research Center for the Early Universe, University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033, Japan
[5]Department of Physics, University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033, Japan
[6]Kavli Institute for the Physics and Mathematics of the Universe (Kavli IPMU, WPI), University of Tokyo, Chiba 277-8583, Japan

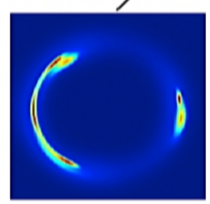
Received ; Accepted

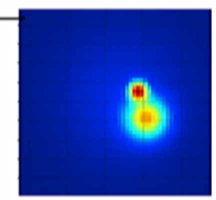
astro-ph.GA] 27 Mar 2015

Pixelated Source Lens Modeling

$$v = \mathbf{V}\underbrace{\mathbf{L}\mathbf{S}} + \mathbf{N}$$

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



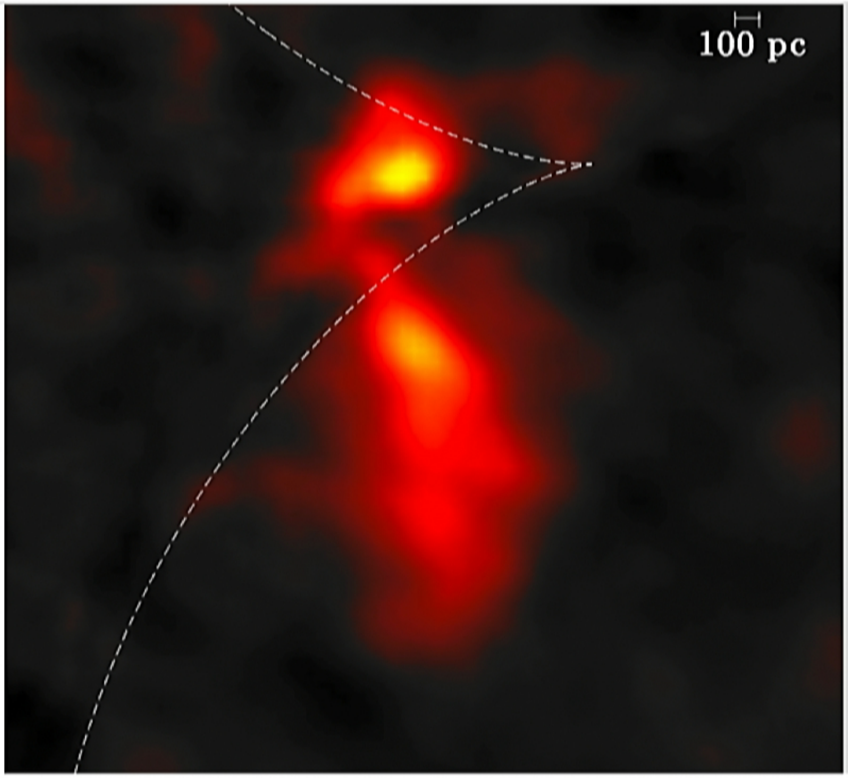


$$\chi^2 = (v_d - v)\mathbf{C}_n^{-1}(v_d - v) + \mathbf{S}\mathbf{C}_s^{-1}\mathbf{S}$$

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

SDP.81 Source Reconstruction

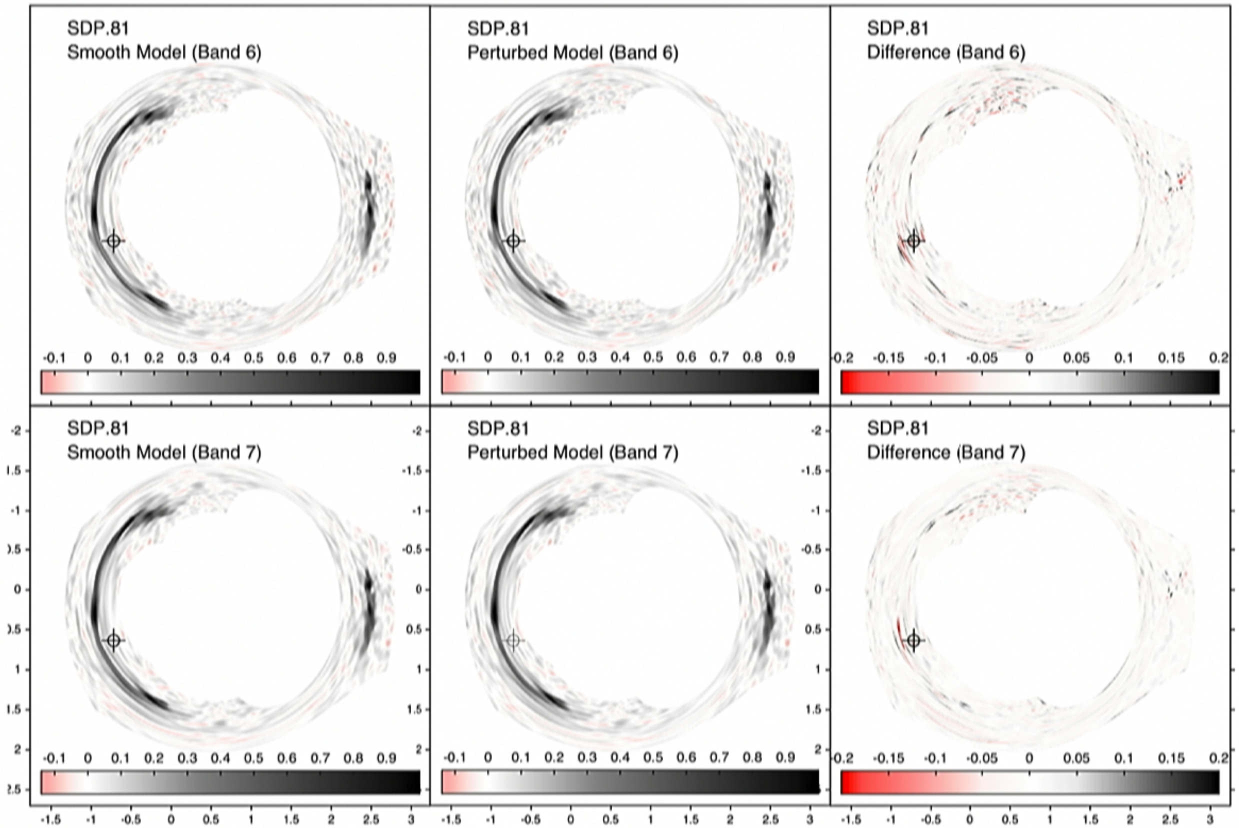
- here showing the source for the best-fit smooth lens model
- joint estimate of lensing potential and source morphology
  - prior on power spectrum of source



Substructure in the lens model

Hezaveh et al 2016 in press arXiv 1601.01388

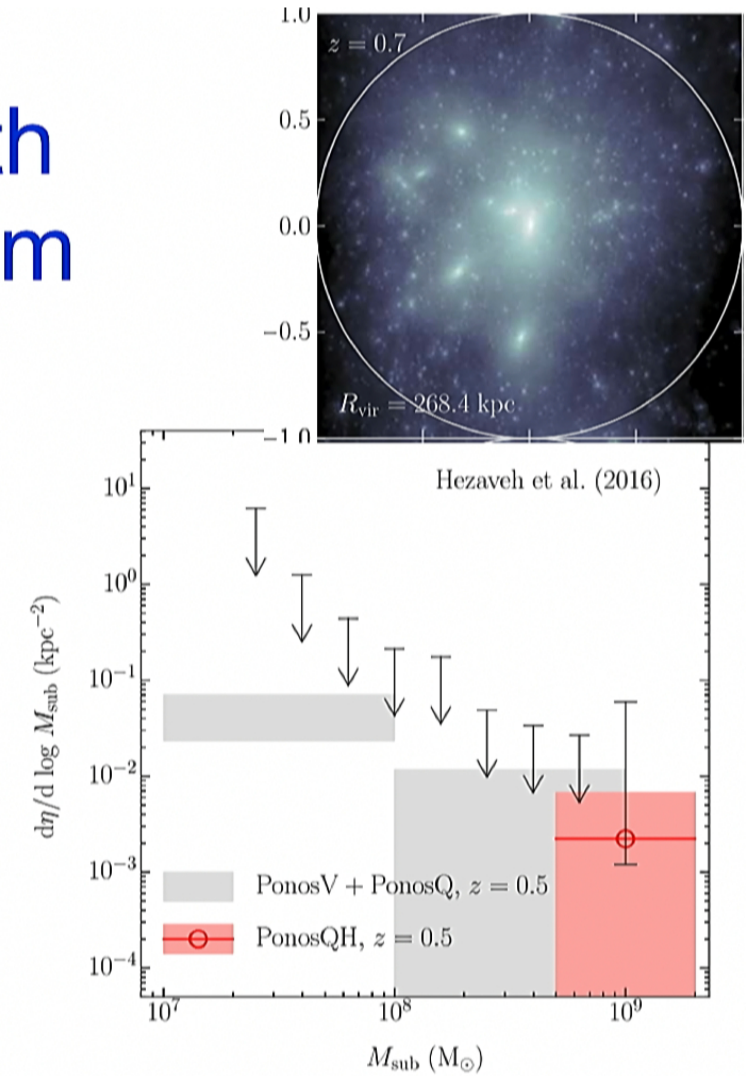
- to fit the ALMA data down to expected level of residuals, require a small extra lump of matter



– requires $\log_{10}(\text{mass})=9.0\pm0.1$

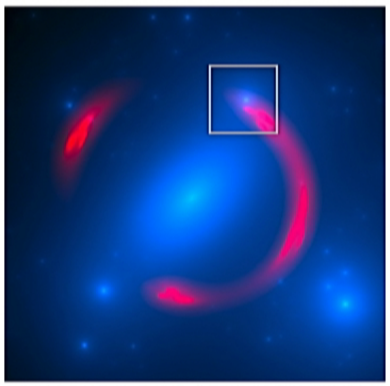
Comparison with expectations from CDM models

- 1 subhalo detected in this 1 system consistent with N-body simulations
  - no lower-mass sub halos detected also consistent with sensitivity
- need more systems,, different lensing configurations
  - there now exist large catalogs (>100) of possible targets!



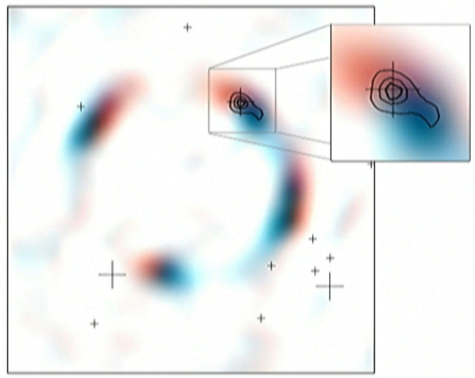
Fiacconi et al 2016

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

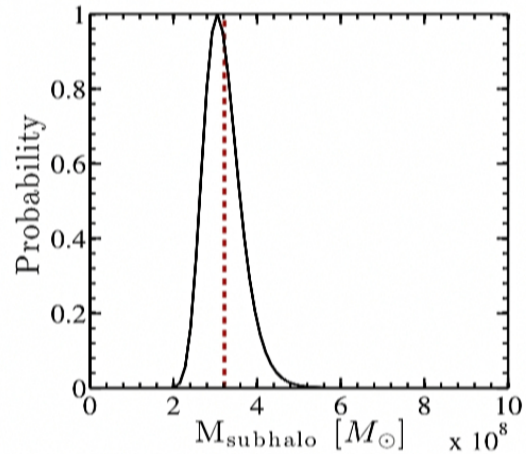


Nbody + ray tracing simulation

Detected subhalo

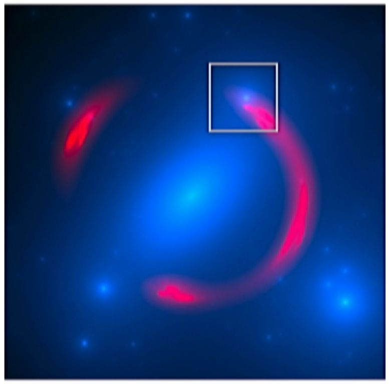


Mock ALMA observation

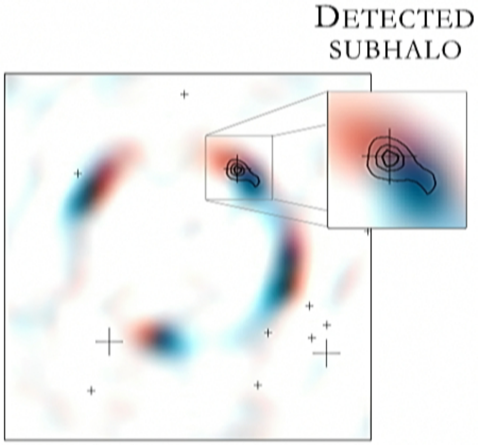


Recovered subhalo mass

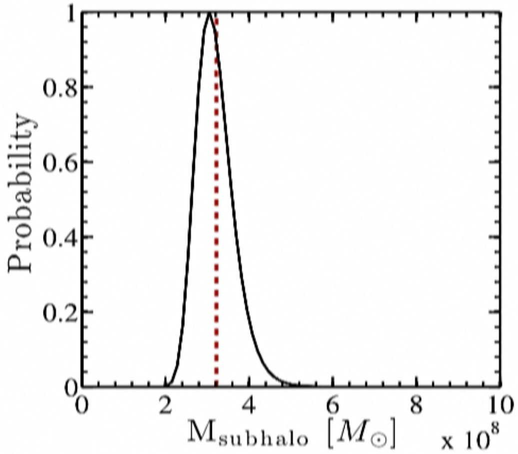
Simulations indicate that with ALMA, we can Detect Much Smaller DM subhalos in these systems



Nbody + ray tracing simulation



Mock ALMA observation



Recovered subhalo mass

“Next Generation Cosmological Probes”

- CMB lensing
  - measures large scale structure at z~3
  - probes gravity on large scales
  - nicely complementary to galaxy lensing & galaxy clustering
- strong lensing of high-z star-forming galaxies
  - allows high-resolution search for dark matter substructures in lens galaxies