Submillimeter Astronomy in the Chajnantor: The Atacama Large Millimeter Array: ALMA and CCAT-prime

Martha Haynes

Discovering Dusty Galaxies

July 7, 2016

CCAT-p

ALMA and the Clouds of Magellan

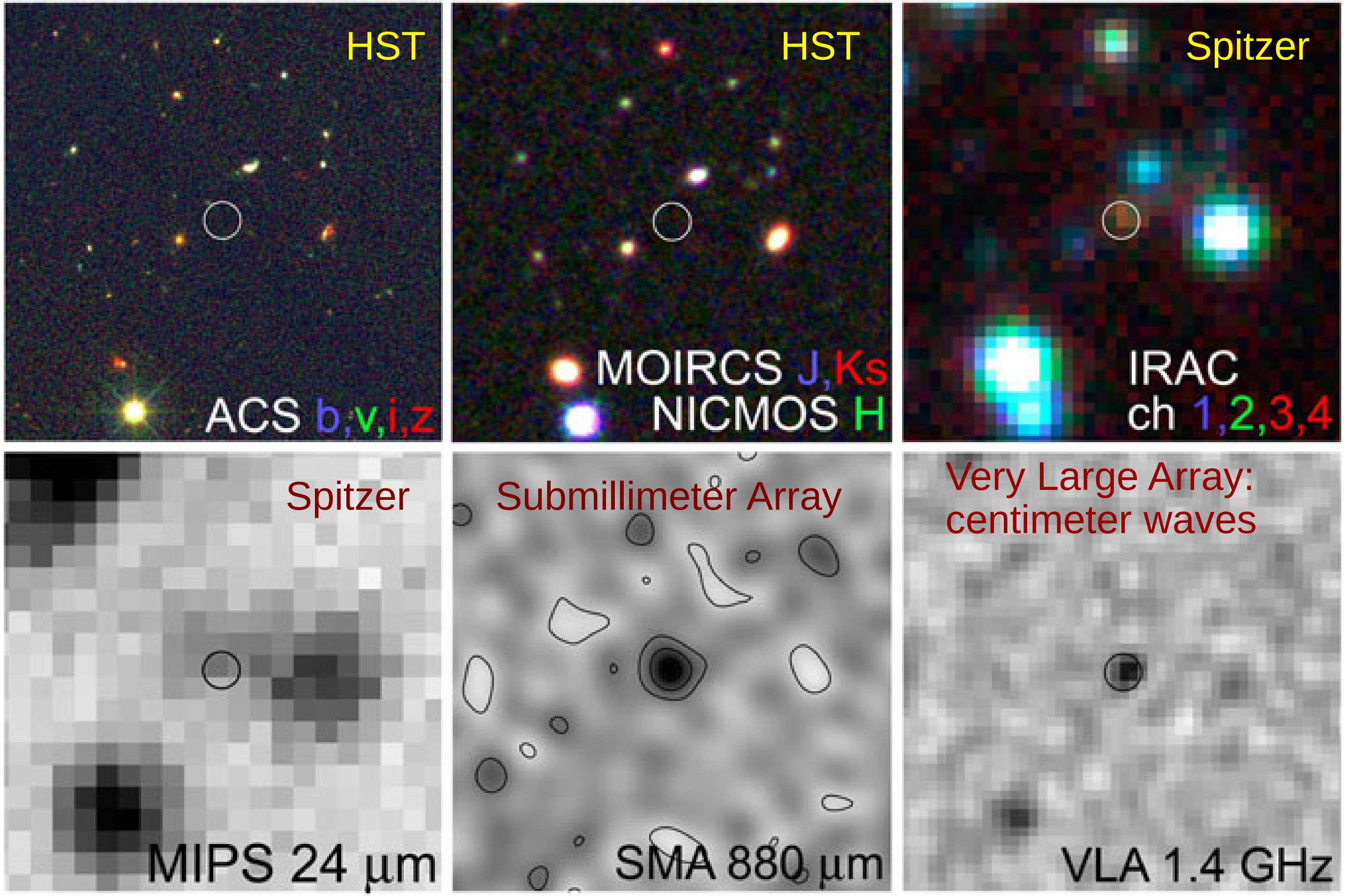
What is ALMA?

- Fifty 12-meter diameter antennas
  - Plus the Compact Array of 4 x 12m and 12 x 7m antennas from Japan
- Baselines from 15 meters to 15 kilometers
- 5000 m (16,500 ft) elevation site in Atacama desert
- Receivers: low-noise, wide-band (8GHz), dual-polarization
- Digital correlator, >= 8192 spectral channels
- Sensitive, precision imaging between 30 (1cm) and 950 GHz (350μm)
  - 350 GHz continuum sensitivity: about 1.4mJy in one second
  - Angular resolution will reach ~40 mas at 100 GHz (~5 mas at 900 GHz)
  - Initial system has 6 bands: 100, 140, 230, 345, 460 and 650 GHz + 900 GHz (Japan)
- Constructed (cost $1.6B) and operated by a global consortium of countries in North America, Europe and East Asia with Chile as the host country See: http://www.almaobservatory.org/

Designed to be 10-100 times more sensitive and have 10-100 times better angular resolution compared to previous mm/submm telescopes

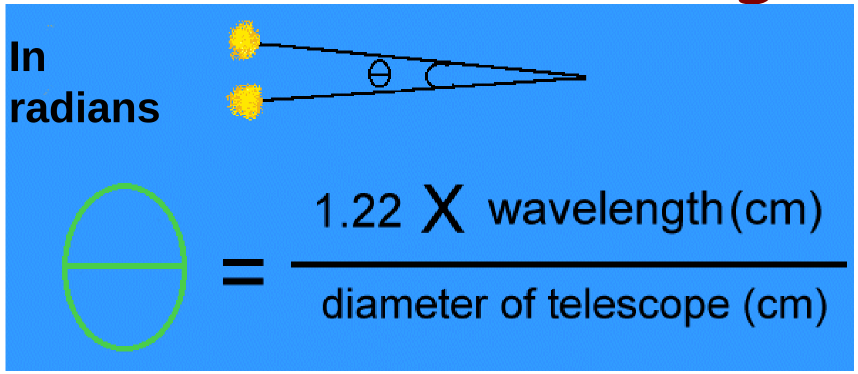
Optically obscured galaxies in the early universe

Wang, Barger & Cowie 2009 ApJ 690, 319



ALMA sees "young" galaxies (that are billions of light years away, so that we are looking back in time!) that contain lots of dust – and therefore are invisible to optical telescopes.

Radio Astronomers need Big Telescopes



How big would a radio telescope have to be to have a diffraction limit of 0.1 arc second at a wavelength of 1 mm?

$$\Theta = \frac{1.22 \times 0.1 \text{ cm}}{\text{Diameter cm}} = 0.1 \text{ arcsec}/206{,}265 \text{ arcsec/radian}$$

$$\text{Diam (cm)} = 1.22 \times 0.1 \times 206{,}265/0.1 = 2.5 \times 10^5 \text{ cm}$$

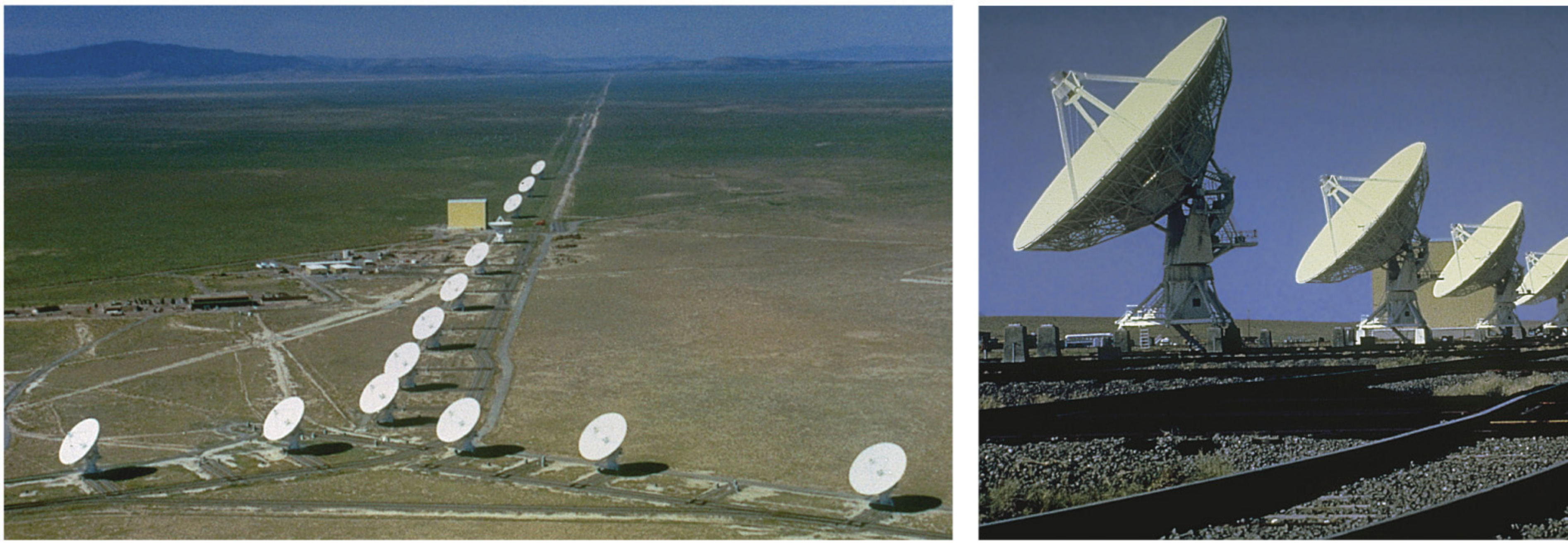
$$= 2.5 \text{ km (!)}$$

How can we possibly build a telescope that big???!

Interferometry

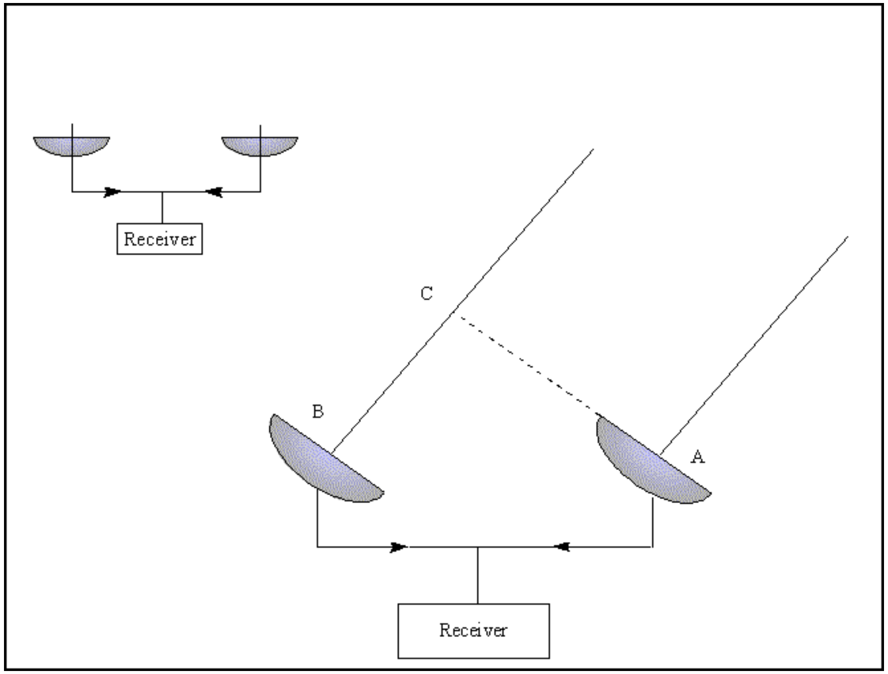
Combine information from several widely-spread radio telescopes as if they came from a single dish

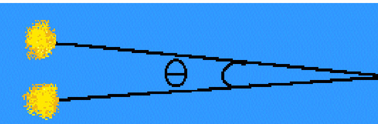
- Resolution will be that of dish whose diameter = largest separation between dishes ("aperture synthesis")



(a) (b)

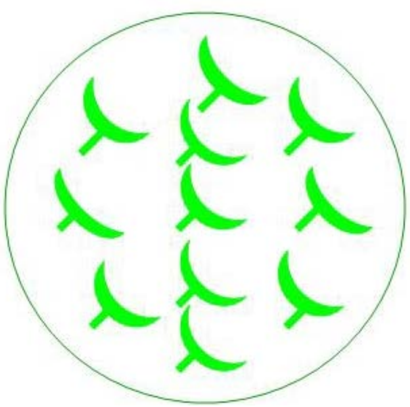
Aperture Synthesis or Interferometry





$$\theta = \frac{1.22 \times \text{wavelength (cm)}}{\text{diameter of telescope (cm)}}$$

Sir Martin Ryle:
1974 Nobel prize in physics



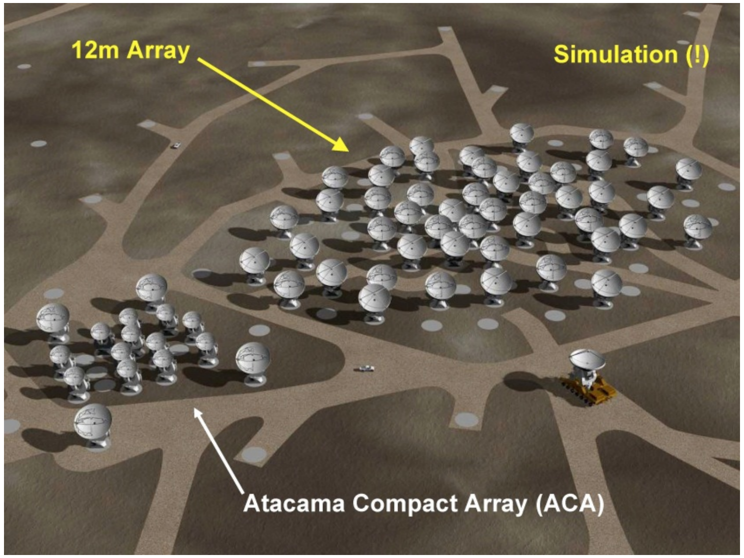
Use an array of smaller telescopes to achieve the image detail of a larger one that covers (sparsely) the area of the array.
Resolution => corresponds to largest "baseline"
Image fidelity => improved by more antennas

The Karl Jansky Very Large Array

- 27 antennas, each one 25 m (85 ft) in diameter
- Array in “Wye” (Y) shape; 4 configurations of “Wye” from compact to very spread out.
- Located 70 miles west of Socorro New Mexico, which is about 70 miles south of Albuquerque.
- Part of the National Radio Astronomy Observatory.

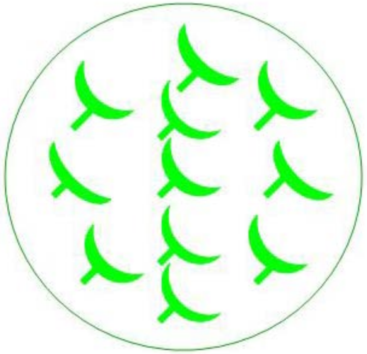
Array design considerations

- Water vapor in the atmosphere absorbs mm and sub-mm wavelength photons => need high, dry site
- Arrays achieve angular resolution comparable to an aperture equal to the maximum antenna separation (baseline)



- Image fidelity achieved by "filling the aperture" with a large number of antennas (same principle as EVLA and VLBA at longer radio wavelengths)

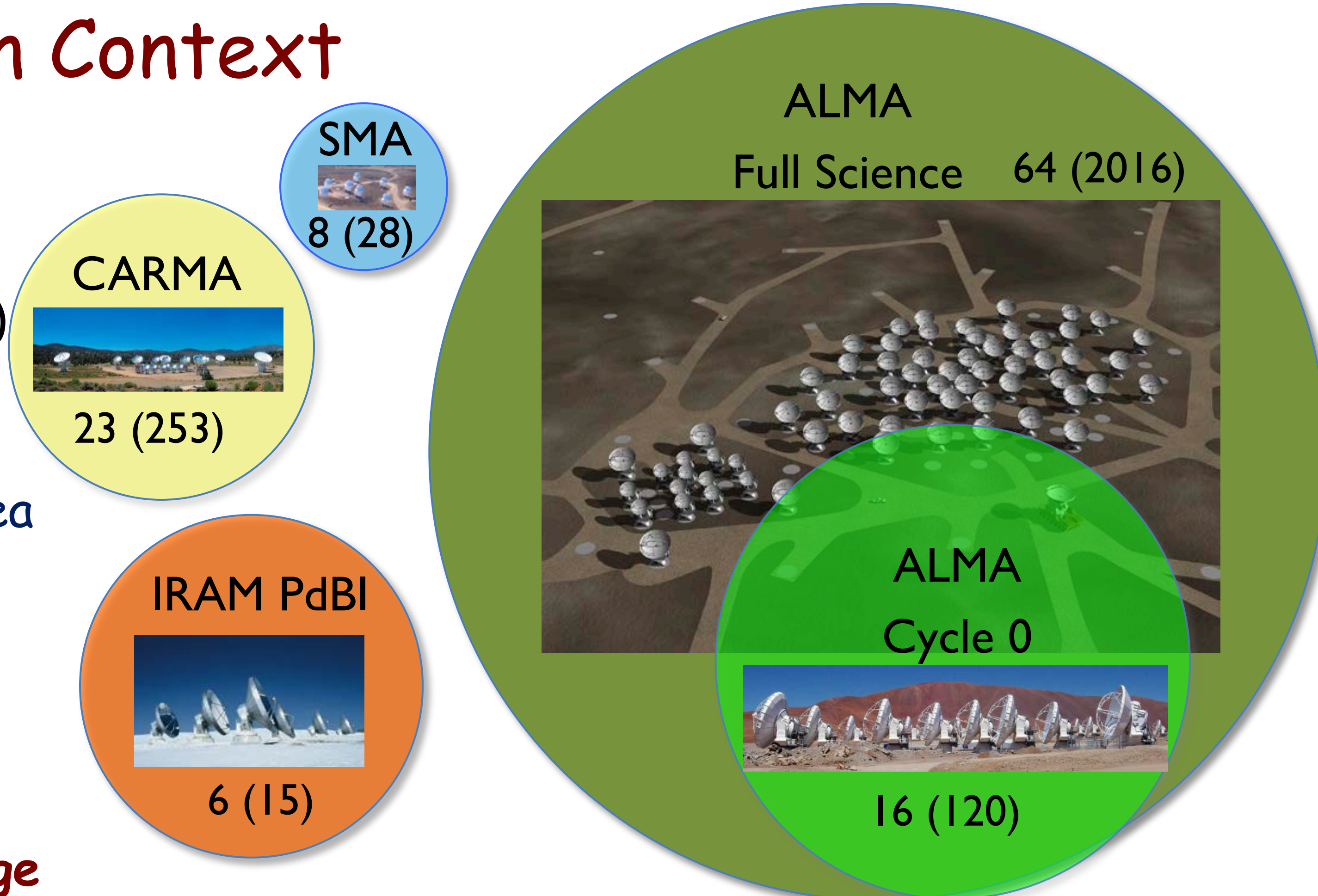
Main Array: 50 x 12m antennas
+ Total Power Array 4 x 12m
+ Atacama Compact Array (ACA): smaller array of 12 x 7m antennas



ALMA in Context

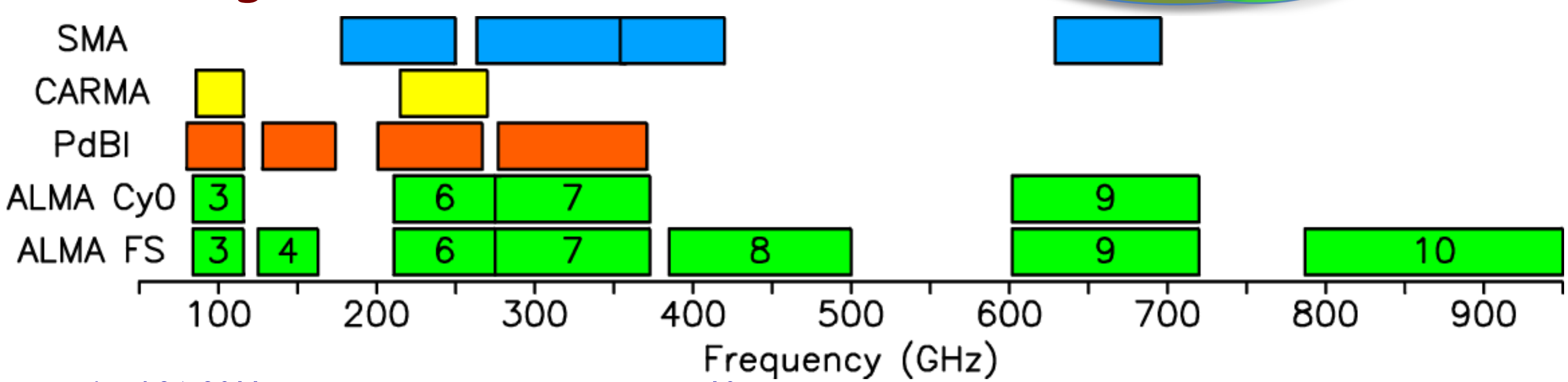
Collecting Area

of Antennas
(# of baselines)

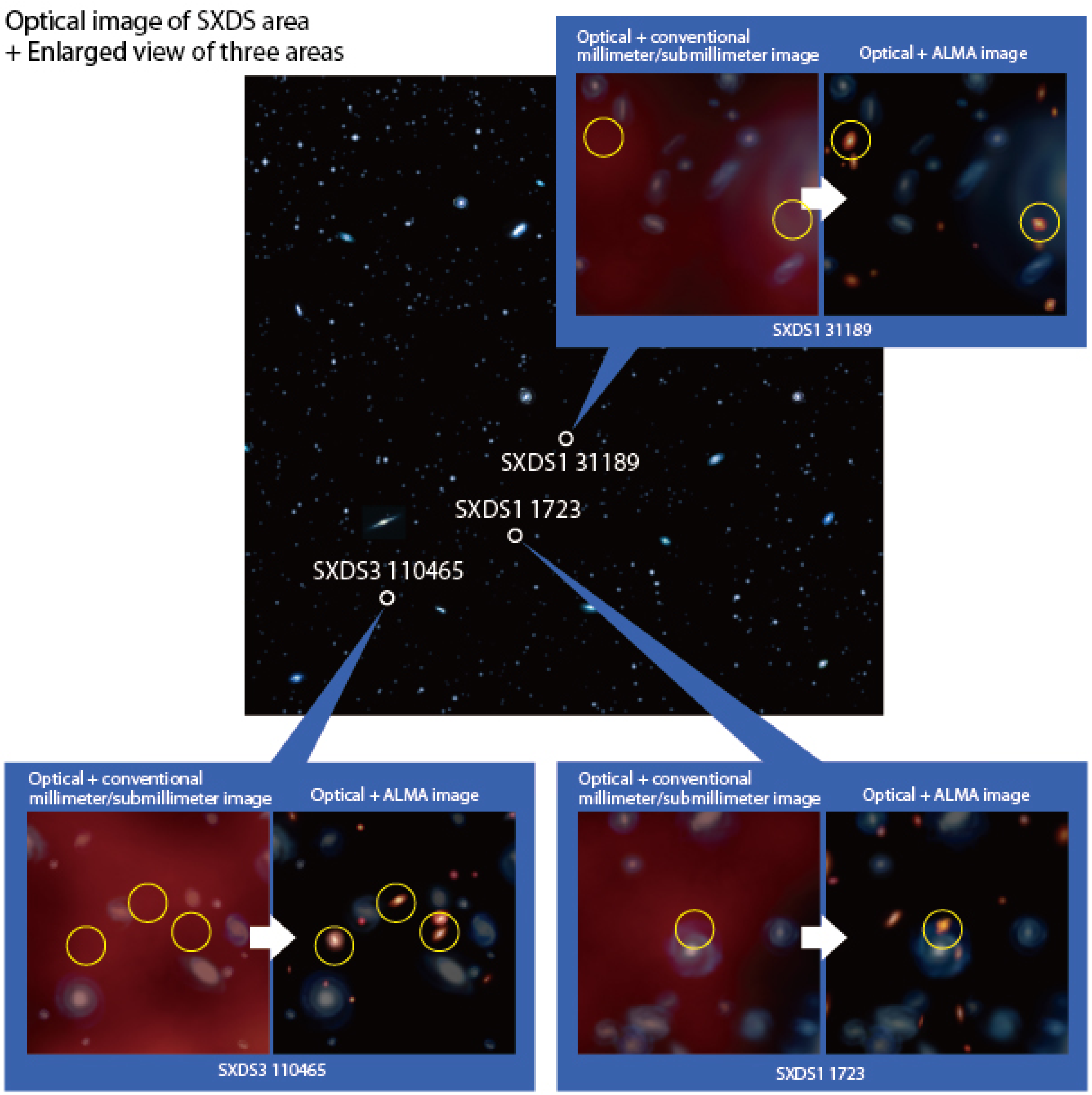


- Sensitivity goes as collecting area
- Image fidelity goes as # of baselines

Spectral Coverage



ALMA sees what Hubble doesn't



From the MMA to ALMA

1978: VLA completed

Early '80s: Community/NRAO discuss future millimeter array

1983: NSF-AST subcommittee report

1990: AUI submits proposal for MMA

1991: NRC Decade Survey endorses MMA

1992: NSF requests 3-year plan for design

1994: NSB approves project development for MMA

1997: Congress approves MMA D&D

1998: MMA Phase I starts

2002: MREFC funding; NSB authorizes

2003: ALMA joint agreement signed

2011: ALMA first science (16 antennas)

2013: ALMA completed (almost)

2015: Construction fully closed-out

Towards an International Collaboration

February 21-23, 1999
Joint Design and Development of the MMA-LSA
View a PDF version
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March 23, 1998
Collaboration with Japanese Project Extended

March 10, 1998
LMSA/LSA/MMA Site Testing Workshop

March 6, 1998
MMA/LSA Technical Workshop

November 15, 1997
MMA Advisory Committee Report (MAC Report)

October 31, 1997
Recommendation to the MMA/LSA Management Board

September 24, 1997
USA MMA/LSA Proposal

September 22, 1997
MMA/LSA Proposal from the European Science Group

August 11, 1997
Second Mailing to American Astronomers

July 22, 1997
First Mailing to American Astronomers

July 11, 1997
Millimeter Array Advisory Committee Meeting

July 1, 1997
Moving Towards an LSA/MMA Resolution

June 26, 1997
LSA/MMA Resolution

March 16, 1997
Japan-US Workshop on Millimeter and Submillimeter Astronomy at 10 milliarcseconds Resolution

Related MMA Memos

Memo Number	Title
254	The 15m (12.8m) Telescopes for the MMA/LSA Project
242	Suggestion on LSA/MMA Front-end Optical Layout
216	Self-Similar Spiral Geometries for the LSA/MMA
193	Report of the LSA/MMA Antenna Study Committee
189	Reference Pointing of LSA/MMA Antennas
188	Another Look at Anomalous Refraction on Chajnantor
186	Calculation of Anomalous Refraction on Chajnantor
182	A 12-m Antenna Design for a Joint US-European Array
181	Notes on Possible Sensors for Improving the Pointing of MMA Antennas
180	Imaging with Heterogeneous Arrays
178	Effects of Point Errors on Mosaic Images with 8m, 12m, and 15m Dishes
177	Sensitivity Comparisons of the Various LSA/MSA Collaboration Options

www.alma.nrao

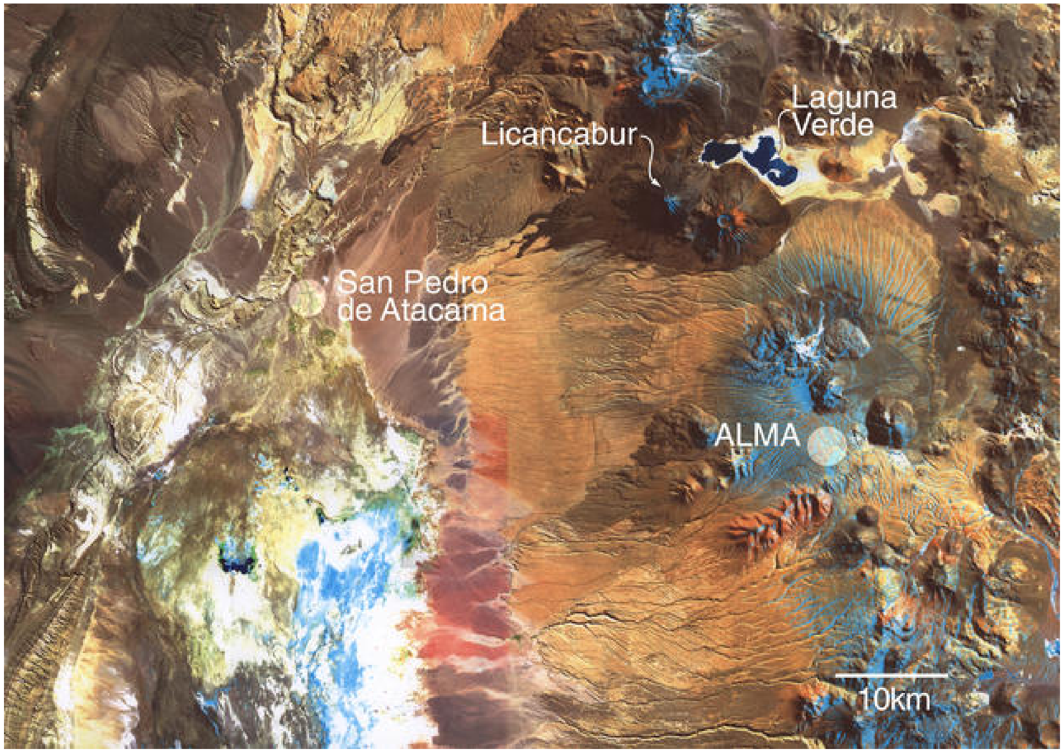
Chilean President Frei signs bill granting land concession to ALMA (1998)

That's me as Interim President of Associated Univ. Inc (1997-8) presenting gift to Pres. Frei at bill-signing ceremony

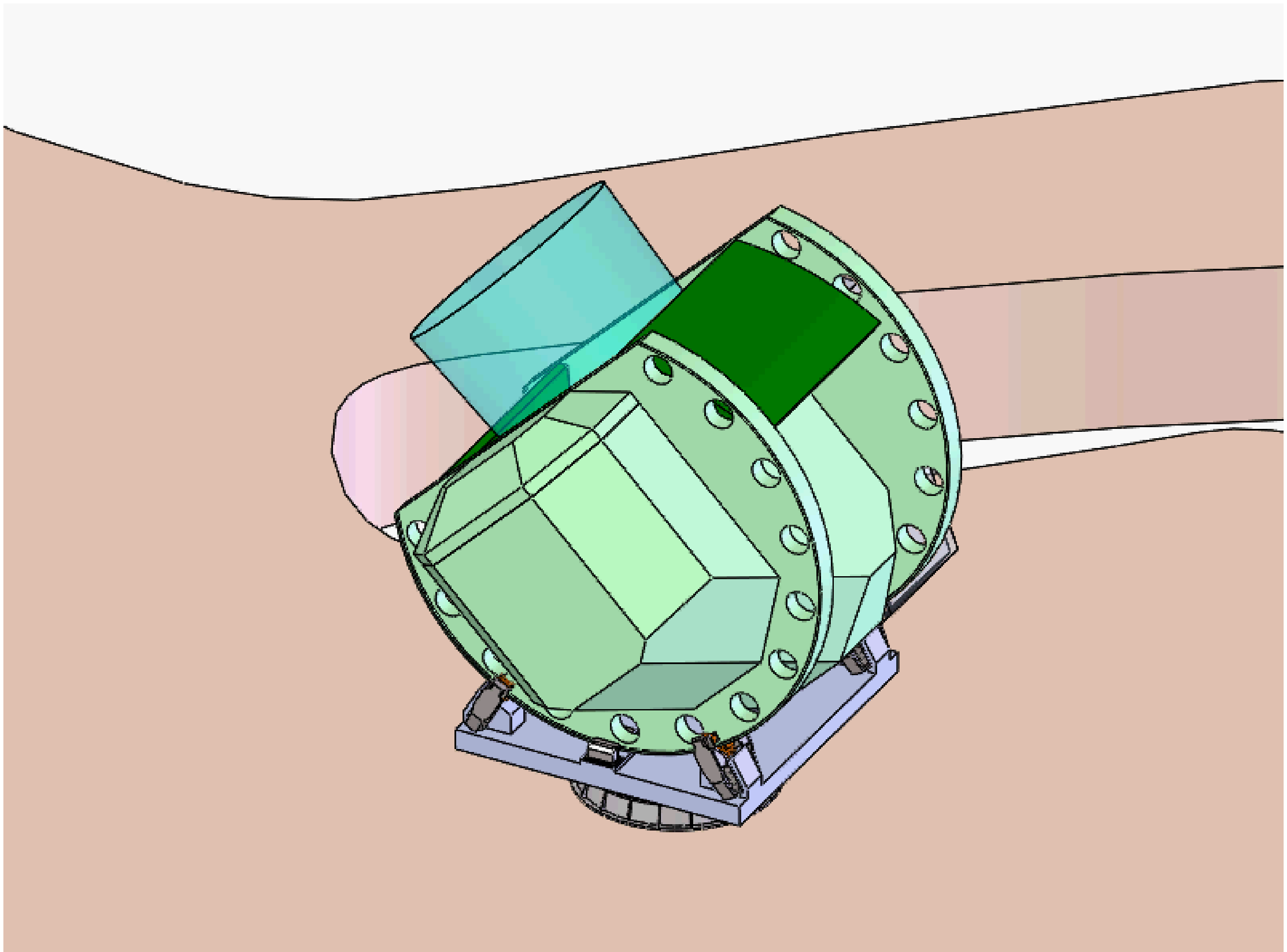
ALMA: The Dream Becomes Reality

Location of the ALMA site

- ALMA is sited at 16,500 feet (5000 meters) in the high Atacama desert; the nearest town is San Pedro de Atacama



CCAT-prime: CCAT-p



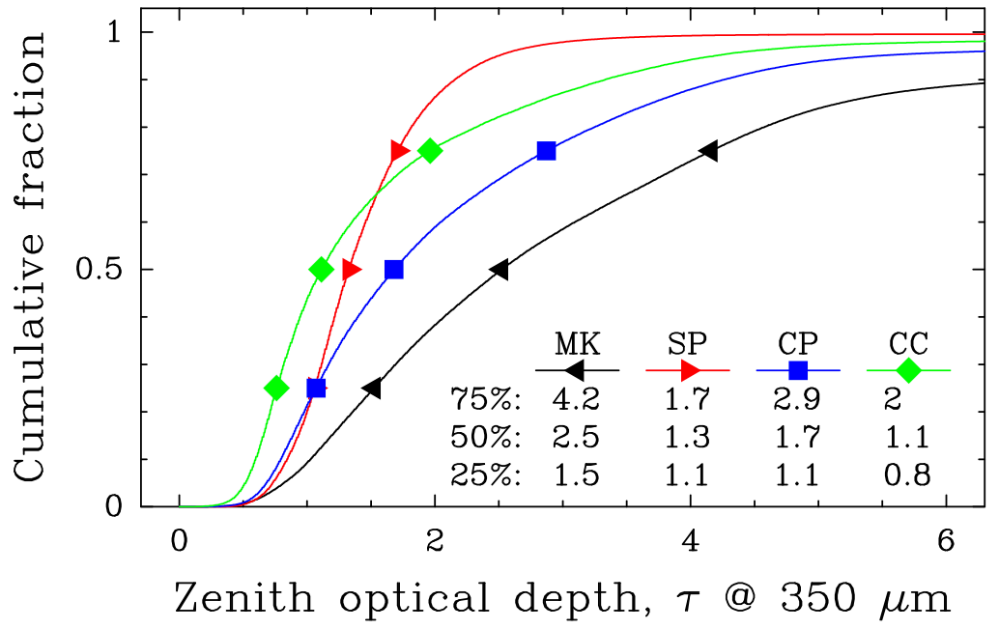
The CCAT-p Concept

- **6-meter off-axis submm telescope located at CCAT site at 5600 meters on Cerro Chajnantor**
  - Surface accuracy of <10 μm (7 μm goal)
  - High site gives routine access to 350 μm, 10% best weather to 200 μm, advantage at longer λs
  - Novel off-axis crossed-Dragone design (Niemack 2016) yielding high throughput, wide field-of-view, flat focal plane immediately plus potential as Stage IV CMB observatory
  - Targeted science programs taking advantage of aperture size, throughput, mapping speed, superb site, dedicated time, undertaken by partners (not PI-science)

The CCAT-p Concept

Cerro Chajnantor (5600 m) has better observing than South Pole, ALMA plateau, & Mauna Kea

(Radford & Peterson, arXiv:1602.08795)



Conversion of 350 μm opacity to PWV robust:

$PWV[mm] = 0.84\ \tau(350\mu m) - 0.31$

- 350μm: routine
- 200μm: best 10%
- Longer λ: increased sensitivity & efficiency

Water Vapor Scale Height

	$\tau(350\ \mu m)$ Chaj. plateau	$\tau(350\ \mu m)$ Cerro Chaj.	PWV [mm] Chaj. plateau	PWV [mm] Cerro Chaj.	WV scl. ht. [m] *
75 %	2.7	1.9	2.0	1.3	1280
50 %	1.5	1.1	1.0	0.6	1080
25 %	1.0	0.7	0.53	0.28	860

* WV scale height = $550\,m/\ln(PWV_{cp}/PWV_{cc})$

The CCAT-p Concept

Designs for a large-aperture telescope to map the CMB $10\times$ faster

astro-ph/1511.04506
Applied Optics 15, 1688

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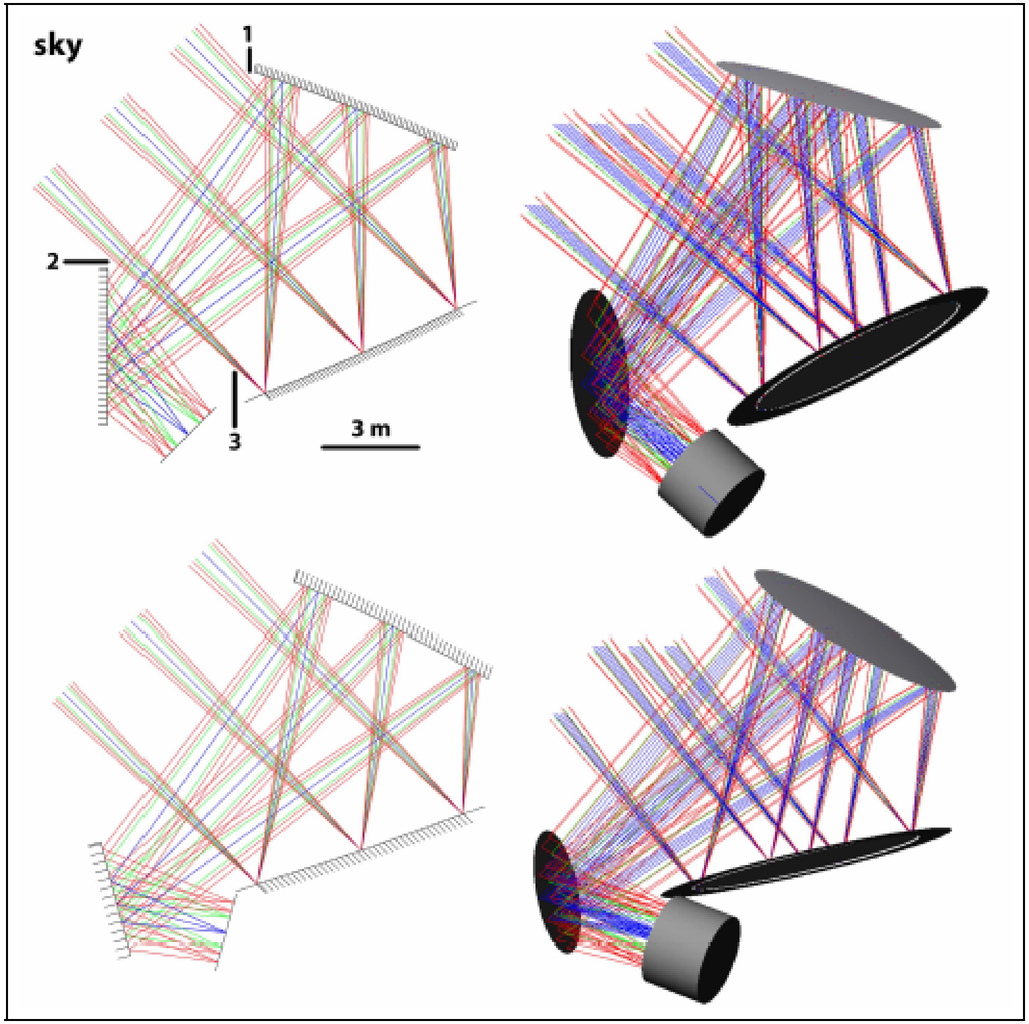
Current large-aperture cosmic microwave background (CMB) telescopes have nearly maximized the number of detectors that can be illuminated while maintaining diffraction-limited image quality. The polarization-sensitive detector arrays being deployed in these telescopes in the next few years will have roughly 10^4 detectors. Increasing the mapping speed of future instruments by at least an order of magnitude is important to enable precise probes of the inflationary paradigm in the first fraction of a second after the big bang and provide strong constraints on cosmological parameters. The CMB community has begun planning a next generation "Stage IV" CMB project that will be comprised of multiple telescopes with between $10^5 - 10^6$ detectors to pursue these goals. This paper introduces new crossed Dragone telescope and receiver optics designs that increase the usable diffraction-limited field-of-view, and therefore the mapping speed, by an order of magnitude compared to the upcoming generation of large-aperture instruments. Polarization systematics and engineering considerations are presented, including a preliminary receiver model to demonstrate that these designs will enable high efficiency illumination of $> 10^5$ detectors in a next generation CMB telescope.

OCIS codes: *(110.6770) Telescopes; (350.1260) Astronomical Optics; (350.4010) Microwaves; (040.1240) Detector Arrays.*

http://dx.doi.org/XXXXXX

The CCAT-p Concept



Niemack, 2016
astro-ph/1511.04506
Applied Optics 15, 1688

- f/3
- High throughput
- Wide FoV
- Flat focal plane
- Accommodate > 10^5 detectors at longer λs; even more at shorter.

The CCAT-p Concept

Principles:

- **Enable forefront science**
  - High throughput, wide-field, precise surface telescope located at a superb high altitude site
  - Modest aperture = 6 meters

kSZ: kinematic Sunyaev-Zel'dovich signature
GEco: "Galactic ecology" studies of the dynamic ISM
IM/EOR: Intensity mapping of [CII] at z = 6-8

Plus potential for:
CMB: Stage IV ground-based CMB observatory

The CCAT-p Concept

GEco: Galactic Ecology of the dynamic ISM

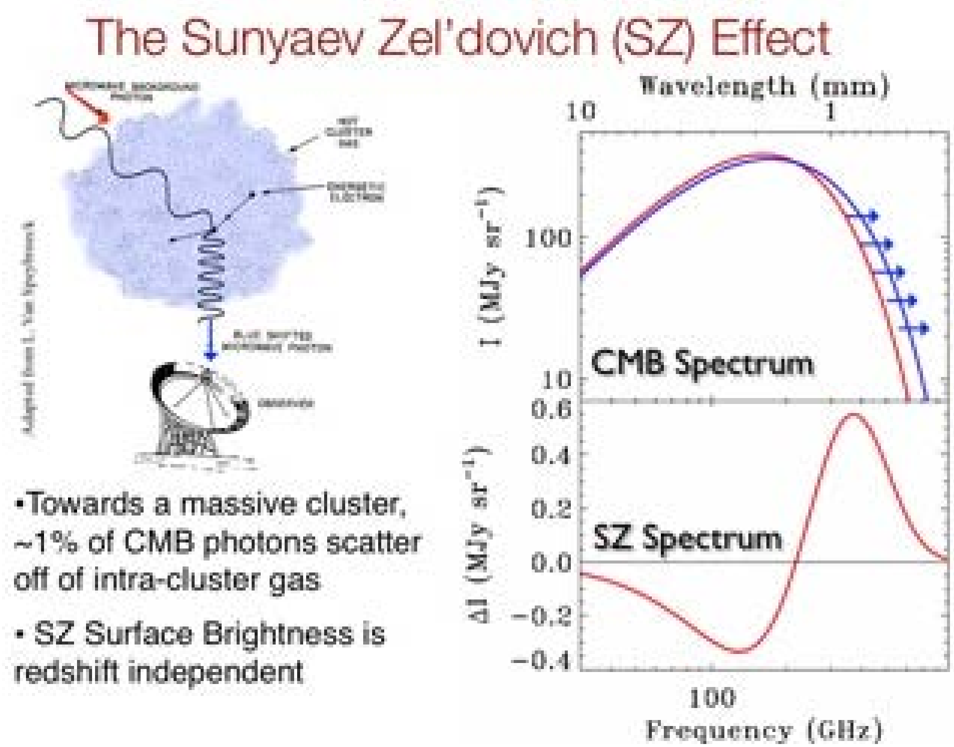
- Spectral (+continuum) mapping of fine structure and mid-/high-excitation CO lines as diagnostics of physical conditions and motions
  - Lines trace coolants in regions of molecular cloud/star formation in range of SF environments
  - High site essential for shortest submm λs/THz
  - Maps at (15”$\times$ λ/350μm) resolution over degree scales of MW including GC plus MCs (low metallicity)
  - Builds on SOFIA (2.5m) with better resolution and much more observing time
  - CHAI under construction (J. Stutzki, UCologne)

The CCAT-p Concept

SZE: Sunyaev-Zel'dovich Effect

Spectral distortions of CMB spectrum:

- **tSZ**: due to random thermal motions of scattering electrons
- **rSZ**: due to populations of relativistic electrons
- **kSZ**: due to bulk velocity of the cluster relative to the CMB rest frame

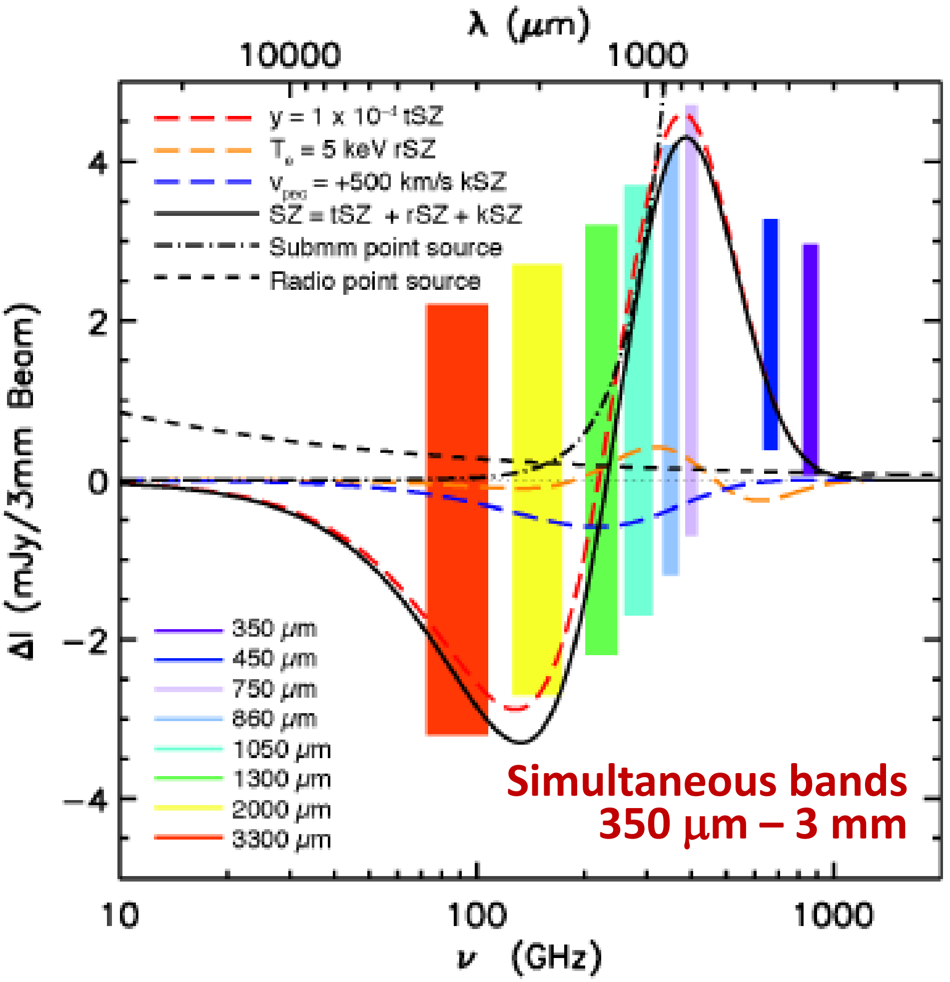


The CCAT-p Concept

kSZ: Kinetic Sunyaev-Zel'dovich Effect

tSZ: dashed **red**
rSZ: dashed **orange**
kSZ: dashed **blue**

- Challenge to characterize and remove CMB, tSZ, bright submm galaxies and radio sources
  - Observations over wider range of λs inc. submm
  - Requires better sensitivity and resolution than Planck

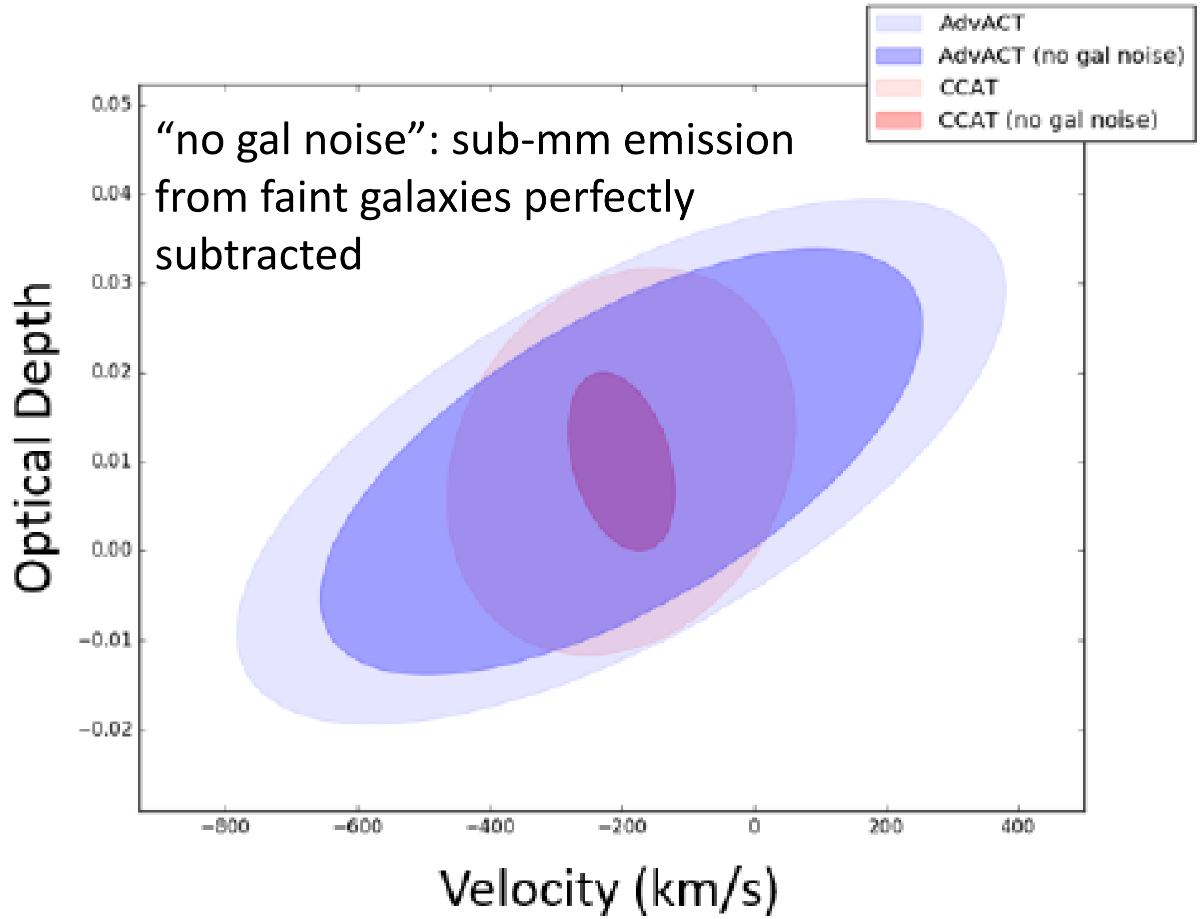


The CCAT-p Concept

kSZ: Kinetic Sunyaev-Zel'dovich Effect

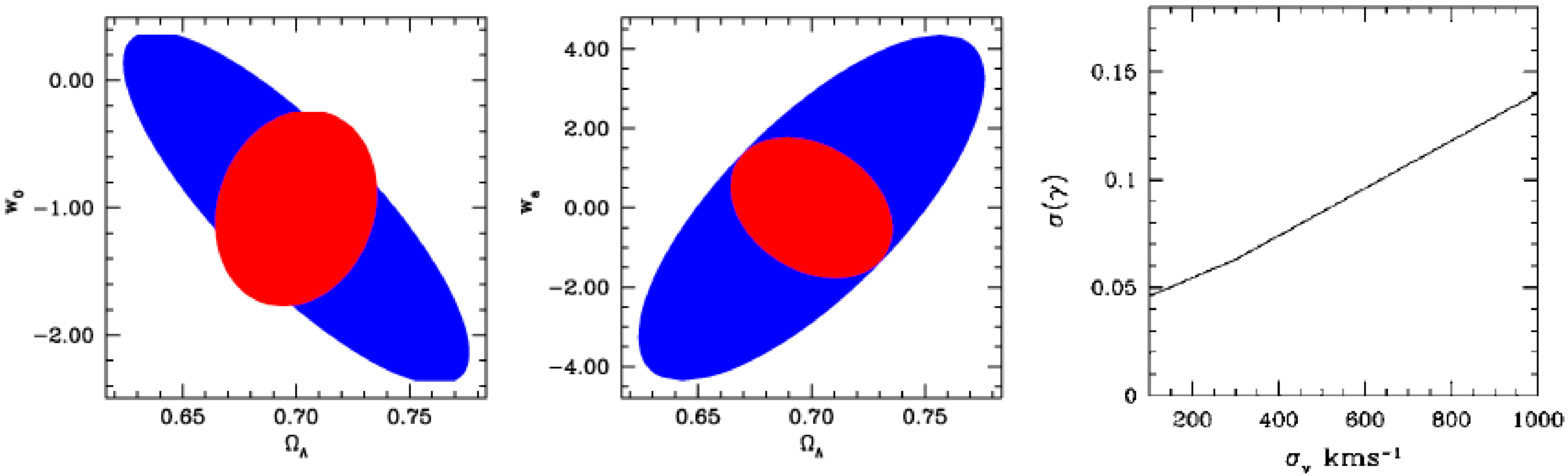
A survey of 3000 hours, over ~1000 sqd with CCAT-p will substantially improve on upcoming CMB surveys.

On-going analysis by M. Niemack and F. deBernardis



The CCAT-p Concept

kSZ: Kinetic Sunyaev-Zel'dovich Effect



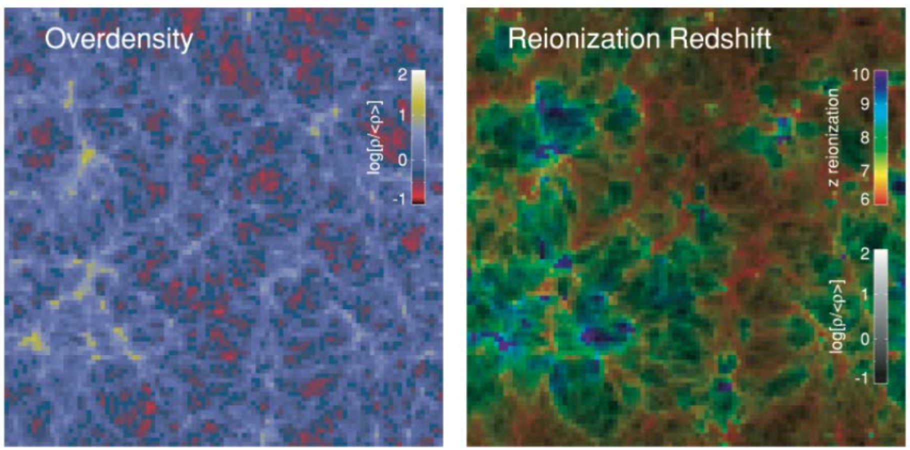
- Forecast dark energy and modified gravity constraints based on measuring 1000 clusters with 100 km/s accuracy (**red**); SPT-3G projections shown in **blue**.
- Such uncertainties will also enable a measurement of the sum of neutrino masses with a 1σ uncertainty of ~0.03 eV.

The CCAT-p Concept

IM/EOR: Intensity Mapping of [CII] from the Epoch of Reionization

- Detect aggregate clustering signal of faint galaxies in the EOR via redshifted [CII] 158 μm line
- Spectral line IM gives 3-D spatial information
  - Process of structure formation
  - Fluctuations trace DM density fluctuations
- SKA 21 cm HI line (HERA)
  - Requires SKA collecting area
  - Foreground contamination/RFI

Simulating Reionization



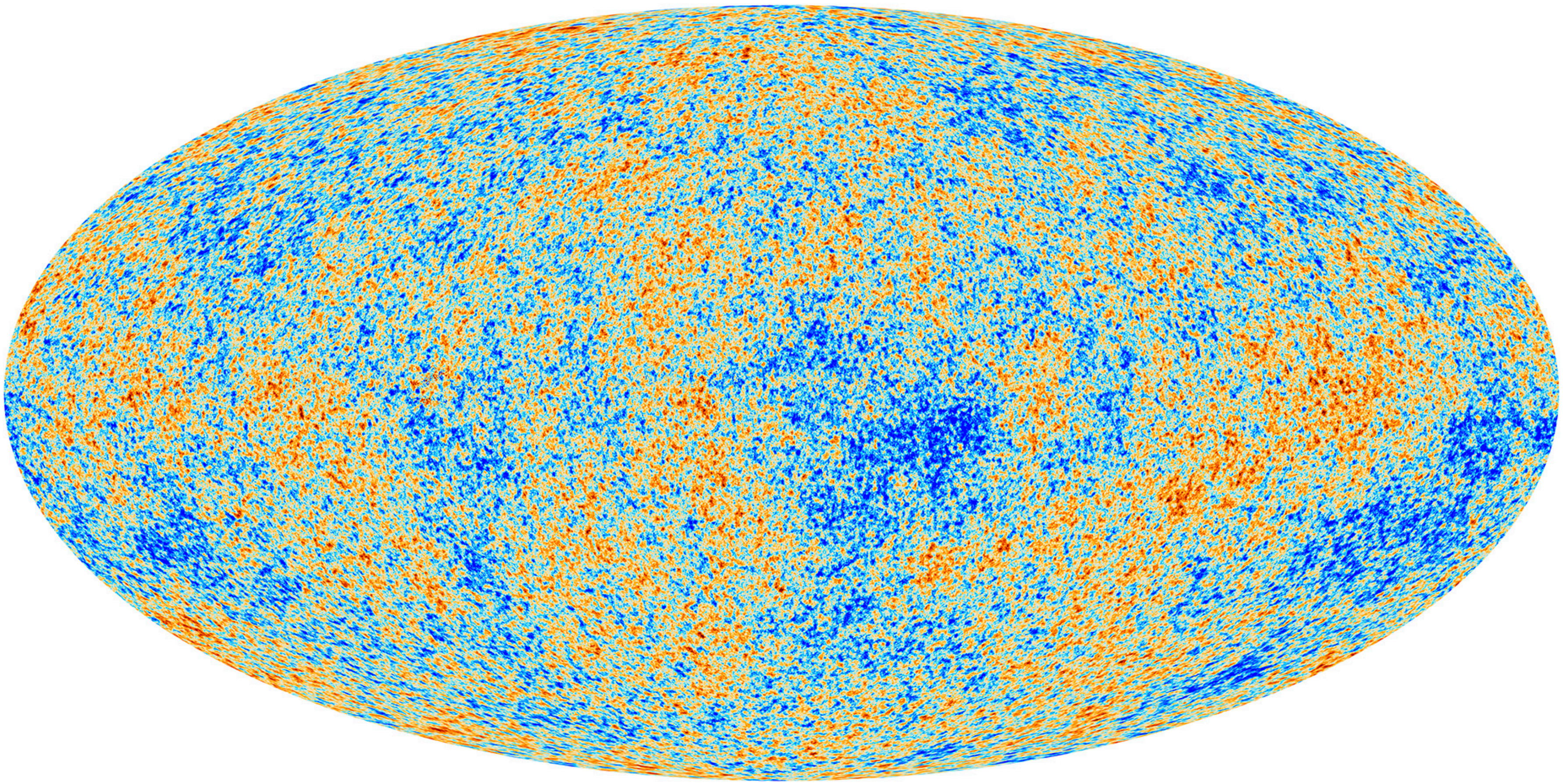
(a) Overdensity $\rho/\bar{\rho}$ at $z = 6.49$.

(b) Redshift of reionization, defined as the redshift at which the hydrogen neutral fraction first dips below 10^{-3}.

Reionization appears not to occur instantaneously, but rather depends on local density (see Finlator et al. 2009). First things to reionize are overdense regions, then voids, then moderate-density structures.

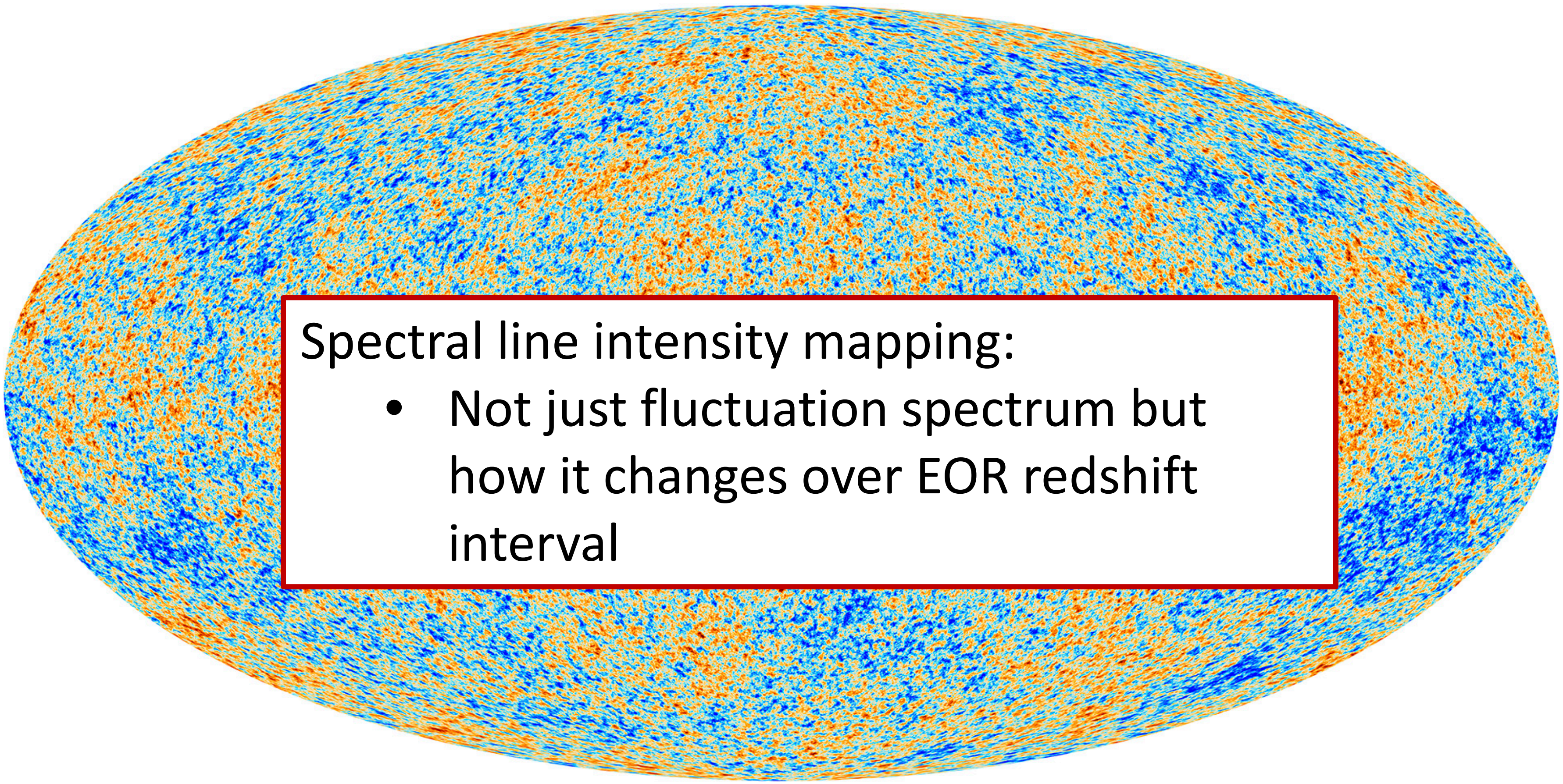
The CCAT-p Concept

Familiar example of Intensity Mapping



The CCAT-p Concept

Familiar example of Intensity Mapping



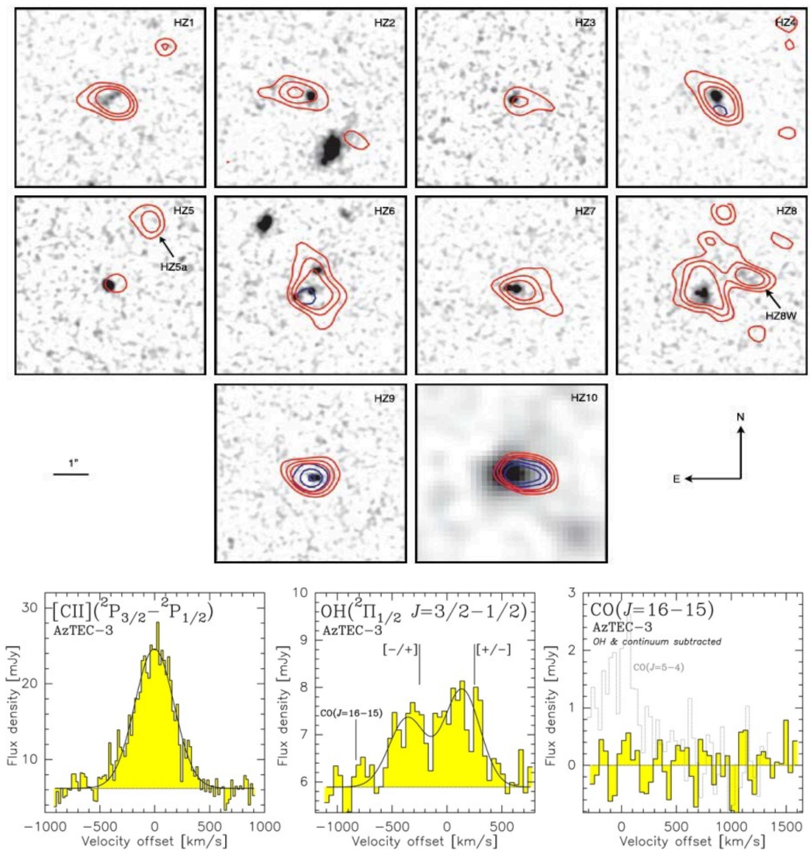
Spectral line intensity mapping:

- Not just fluctuation spectrum but how it changes over EOR redshift interval

The CCAT-p Concept

IM/EOR: Intensity Mapping of [CII] from the EOR

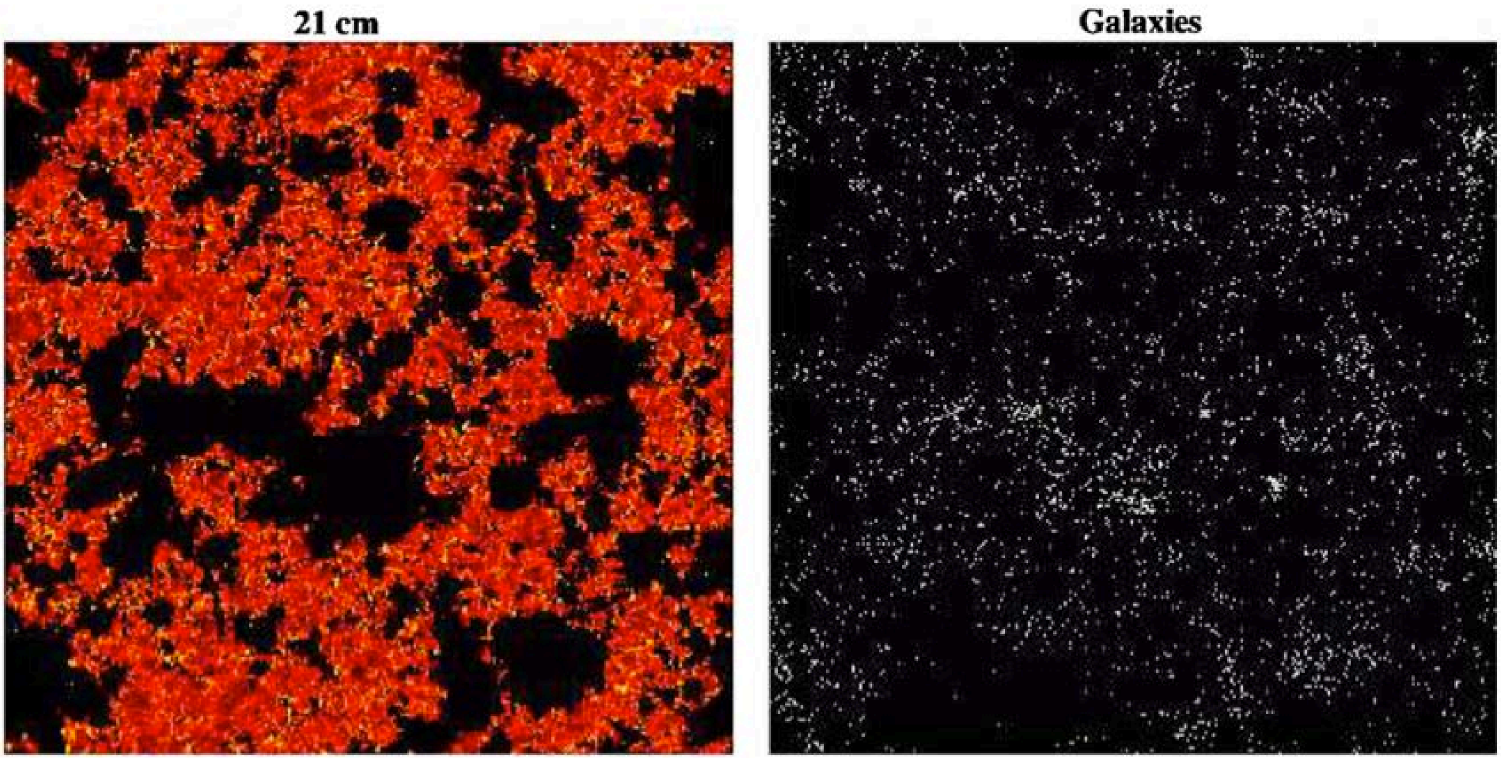
- Detect aggregate clustering signal of faint galaxies in the EOR via redshifted [CII] 158 μm line
- [CII] directly traces sources of reionization (SF galaxies)
  - Recent ALMA detection of [CII] in "normal" galaxies at z = 5-6 (e.g. Riechers+ 2014)
  - Enhanced [CII] to dust continuum compared to lower redshifts → strong signal



The CCAT-p Concept

Full power in combination with HI 21cm experiments

- HI 21cm: traces neutral gas not yet re-ionized
- [CII] 158μm: traces ionization sources (star forming galaxies)



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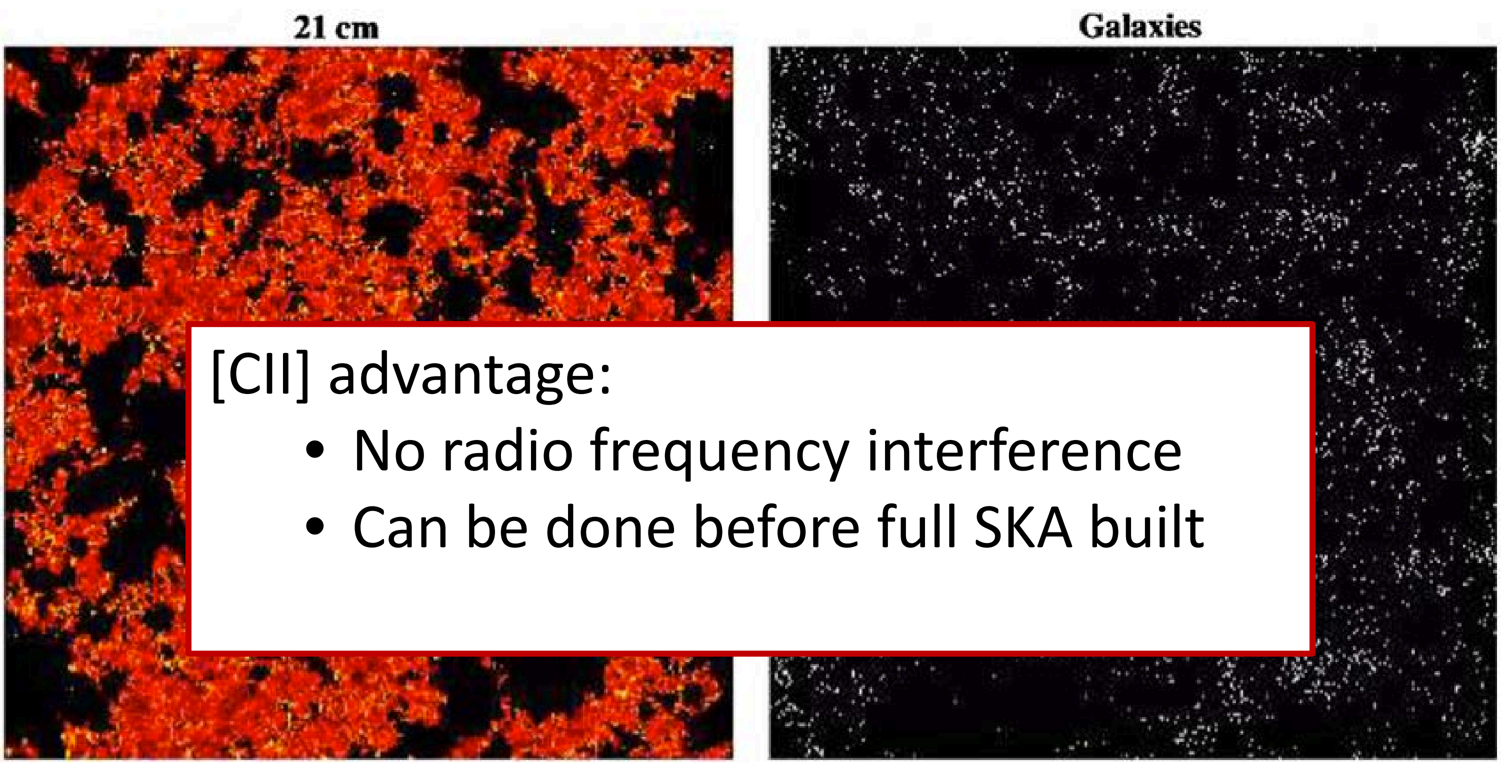

[CII] advantage:

- No radio frequency interference
- Can be done before full SKA built

The CCAT-p Concept

IM/EOR: Intensity Mapping of [CII] from the EOR

- Measure large scale spatial fluctuations of collective aggregate of faint galaxies via redshifted [CII] 158 μm line (+possibly other lines at other z's)
  - Resolution into individual galaxies not required
    - Clustering scale at z = 6-8 of few arcmin good match for 6-m aperture (<1' @ 1mm) plus mapping speed
  - Need moderate spectral resolution R~300-500
    - Spectral imaging technology will improve with time
  - Instantaneous bandwidth over mm band (1.1-1.4 mm requirement; goal of 0.95-1.6 mm to get z = 5 to 9)
    - Identify interloper lower z CO lines
    - Atmospheric stability of high site advantageous

The CCAT-p Concept

CMB: Future Stage IV CMB Observatory

- Next generation CMB mapping
  - Probe inflationary gravity waves at tensor-to-scalar ratios as low as 0.001
  - High-significance measurement of neutrino mass sum
  - High-throughput, wide-field, flat focal plane design at high site even on modest aperture telescope would enable mapping CMB 10X faster than ACTPol or SPT-3G
    - CCAT-p would offer existing platform for deployment of cameras with > 10^5 detectors, likely developed with DOE funding on 5+ year timescale.

The CCAT-p Concept

Instrumentation

- **P-Cam**: Modular, wide-field imaging camera for **kSZ**
  - Based on design of CCAT SWCam; reconfigurable
  - One module at 350 μm for first light ; others TBD
  - Optimized layout for kSZ
- **CHAI**: Heterodyne array spectrometer for **GEco**
  - Under construction at UCologne (J. Stutzski)
- **"P-Spec":** Imaging spectrometer for **IM/EOR**
  - P-Cam(+FP): initial modification of P-Cam as an imaging Fabry-Perot interferometer
  - Future development of grating MOS?
- **"P-CMBcam":** future CMB camera

CCAT-p