The CCAT-prime Project

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CCAT Board Members
• Terry Herter (Chair)
• Juergen Stutzki
• Frank Bertoldi
The CCAT-prime Project

What happened to CCAT?

High science priority remains:
- Need for a large wide-field submillimeter telescope at a high site

Funding opportunities evaporated:
- Poor funding scenario
  - Large vs mid vs small; facilities vs grants
  - Aversion to risk/new commitments
  - Mid-scale program ≠ Mid-scale facilities

Prediction: A large, wide-field submillimeter telescope will be built by the ALMA partnership in ~10 years.
The CCAT-prime Project

**Early 2016**: We have a working partnership, access to a unique site and some funding: is there a Plan B?

**Principles:**
- Enable forefront science that is a significant step forward
- Exploit CCAT partnership framework
- Build on experience gained from CCAT project

**Constraints:**
- Significant partner funding needs to be committed by April 1

**Result**: We have gone through a very quick study phase: we are not as ready as we’d like to be but we believe we understand the project, its uncertainties and risks.
The CCAT-prime Project

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 throughput, mapping speed, dedicated time, undertaken by partners (not PI-science)
The CCAT-prime Project

Principles:

• **Enable forefront science**
  – Compelling, unique-capability science of interest to partner faculty/staff who will play leading roles in science planning, execution and analysis and in technology development

• Exploit CCAT partnership framework

• Build on experience gained from CCAT project
The CCAT-prime Project

Principles:

• Enable forefront science

• **Exploit CCAT partnership framework**
  – Established international collaboration
  – Established legal entity
  – Access to same/other funding sources for smaller project
  – Possibility to expand, especially Chilean partners

• Build on experience gained from CCAT project
The CCAT-prime Project

Principles:

• Enable forefront science
• Exploit CCAT partnership framework
• **Build on experience gained from CCAT project**
  – Understanding and analysis of infrastructure requirements, solutions, costs and risks
  – Body of CCAT documents: established capability
  – Confidence from review outcomes: demonstrated capability
  – Carry-over of “shovel ready” aspects
The CCAT-prime Project

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

**IM/EOR**: Intensity mapping of [CII] at z = 6-8

**GEvo**: “Galaxy evolution” studies of dusty SF galaxies

**GEco**: “Galactic ecology” studies of the dynamic ISM

Plus potential for:

**CMB-S4**: Stage IV ground-based CMB observatory
The CCAT-prime Project

**Status:**

- Telescope design studies design review mid February
- Telescope design vendor bids soon after that.
- (Continue with) Science studies: survey predictions and strategies
  - Need to know telescope design to make further progress
- Infrastructure:
  - Efforts to establish real costs in various stages of certainty
- Land concession being transferred from AUI to U Cologne
- Funding:
  - Significant funding available and identified but not there yet

**Goal:**

- Get telescope to the site by end of 2021
CCAT P Science Case
The CCAT-P Concept

5.5-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 yielding ⇒ wide, flat field-of-view for Galactic, Cluster, and EoR science
- Optimized throughput ⇒ platform for as Stage IV CMB observatory
- Plan targeted “campaign-mode” science: aperture size, throughput, mapping speed, superb site
Cerro Chajnantor at 5600 m
5000 meter is good, but 5600 meters is better

- Submillimeter sensitivity is all about telluric transmission
- Simon Radford has been running tipping radiometers at primary sites for more than a decade –
- Simultaneous period for CCAT vs. ALMA site: median is 0.6 vs. 1 mm H$_2$O $\Rightarrow$ factor of 1.7 in sensitivity
Median **Zenith** Transmission

ATM 2002 Model (Pardo et al.)

Median CCAT transmission even better than South Pole due to warmer, less dense atmosphere

Tropics: $\Omega = 3\, \pi\, \text{sr}$, $A_{\text{med}} = 1.1\, (z < 60^\circ)$

Pole: $\Omega = 1\, \pi\, \text{sr}$, $A_{\text{med}} = 1.4\, (z < 60^\circ)$
Chajnantor Site opens up the THz Windows

ATM 2002 Model (Pardo et al.)

273 K PWV

- CCAT 10%: 5600 m (520 mb) 200 μm
- CCAT 25%: 5600 m (520 mb) 400 μm
- CCAT 50%: 5600 m (520 mb) 600 μm
- ALMA 50%: 5000 m (560 mb) 1000 μm
- CSO 50%: 4100 m (625 mb) 2000 μm

Zenith Transmission [%]

Frequency [GHz]

18 February 2017
CCAT-Prime Science

• **GEco:** Investigating the physical processes associated with star formation in the Milky Way, the Magellanic clouds and other nearby galaxies through submm spectroscopy and photometry

• **kSZ:** Probing of the nature of dark energy, gravity on large scales and neutrino mass sum through kinetic SZ effect
  – GEvo commensal survey: evolution of dust obscured star formation

• **IM-EoR:** Probing the process of reionization in the early Universe through intensity mapping of the [CII] 158 μm line emission associated with star formation in the epoch of reionization at redshifts from 6 to 8 (goal 5 to 9).

• **Stage IV CMB:** The CCAT design also well suited to a “Stage IV” CMBR observatory with ~ 10 times the mapping speed of current facilities enabling probes of inflationary gravity waves and the sum of the neutrino masses.
GECO: Galactic Ecology Science

- 15” imaging over 200 ($^\circ$)$^2$ scales of the Milky Way, LMC, SMC in:
  - [CI] tracing gas temperature and mass
  - Mid and high-J CO & $^{13}$CO tracing gas excitation, shocks, density and mass
  - Also: [NII] tracing embedded SF regions and numbers of ionizing photons
- Tracing accumulation and flows of gas into cores and young stars
- Requires high site for short submm (200 $\mu$m, or 1.5 THz) studies
“CO dark” Gas

[Graph showing integrated intensity vs. mass fraction with various labels for different transitions like [CI] $^3P_1-^3P_0$ and $^3P_2-^3P_1$]
GEco Needs High Altitude
Heterodyne, dual frequency array

500 GHz (600 μm) and 850 GHz (350 μm): CO(4-3), CO(7-6) [CI] × 2

64 (baseline), 128 (goal) pixels in each band
## GEco Science Program

- GEco: total time: 1900 hours, or ~ 250 days

<table>
<thead>
<tr>
<th>Source</th>
<th>Line</th>
<th>$^{(\circ)^2}$</th>
<th>Noise/$\Delta v$</th>
<th>Time</th>
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<td>Gal Plane and CMZ</td>
<td>[Cl] (1-0): CO(4-3)</td>
<td>200</td>
<td>0.25 K/0.5 km/s, 0.25 K/0.5 km/s</td>
<td>250 hours</td>
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<td></td>
<td></td>
<td>200</td>
<td></td>
<td>100 hours</td>
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<td>LMC</td>
<td>[Cl] (1-0): CO(4-3)</td>
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<td>0.1 K/1 km/s, 0.1 K/1 km/s</td>
<td>250</td>
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<tr>
<td></td>
<td></td>
<td>64</td>
<td></td>
<td>100 hours</td>
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<tr>
<td>SMC</td>
<td>[Cl] (1-0): CO(4-3)</td>
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<td>0.1 K/1 km/s, 0.1 K/1 km/s</td>
<td>80 hours</td>
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<td>30 hours</td>
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<tr>
<td>Gould Belt</td>
<td>CO (6-5)</td>
<td>30</td>
<td>0.25 K/0.25 km/s, 0.25 K/0.25 km/s</td>
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<tr>
<td></td>
<td>$^{13}$CO(6-5)</td>
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<td>135 hours</td>
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<td></td>
<td>$^{13}$CO(8-7)</td>
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<td>120 hours</td>
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<tr>
<td>Zoom-ins</td>
<td>[Cl] (2-1): CO(11-10)</td>
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<td>0.25 K/0.5 km/s, 0.25 K/0.25 km/s</td>
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<td>CO(13-12)</td>
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<td>0.25 K/0.25 km/s, 0.25 K/0.25 km/s</td>
<td>96 hours</td>
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<tr>
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<td></td>
<td>1</td>
<td></td>
<td>63 hours</td>
</tr>
<tr>
<td>Continuum</td>
<td>All bands</td>
<td>200</td>
<td>6 mJy → 0.6 mJy</td>
<td>300 hours</td>
</tr>
</tbody>
</table>
kSZ: Cluster Science through the Sunyaev-Zel’dovich Effects

*Direct observations of the most massive bound entities in the Universe through Sunyaev-Zel’dovich effects*

- **7 colors:** 0.35 to 3 mm spectral coverage separates out the tSZ, rSZ, radio galaxies and submm galaxies from kSZ
- **Constraints:** optical depth, velocity, and electron temperature

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Simultaneous bands 350 μm – 3 mm

Mike Zemcov

18 February 2017
Fundamental Physics Probes

Directly measure velocities of 1000’s of clusters

- Constrains and/or eliminate models about dark energy and modified gravity.
- Improve constraints on the measurements of the sum of the neutrino masses.
- Cluster characterization to inform cosmology.
- Example Survey 1000 $(^\circ)^2$ measuring 3000 clusters with $M > 2.7 \times 10^{14} \, M_\odot$ in 3000 hrs

CCAT-prime velocities appear much better than Advanced ACTPol

F. de Bernardis and A. Mittal
kSZ Science Program

• Separate cluster components to make best velocity measurements and constrain cosmology
• Studying range of survey options; total time: 3,000 – 10,000 hrs
• Additional science:
  – Polarized foreground measurement niche
  – GEvo survey of DSFGs over wide z range
  – CMB lensing

<table>
<thead>
<tr>
<th>CCAT-p area ($^\circ)^2$</th>
<th>Average mass ($M_\odot$)</th>
<th>Number of Clusters</th>
<th>Integration time (hrs)</th>
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<tbody>
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<td>1,000</td>
<td>$2.71 \times 10^{14}$</td>
<td>3,000</td>
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<td>10,000</td>
<td>$3.32 \times 10^{14}$</td>
<td>16,000</td>
<td>3,000</td>
</tr>
<tr>
<td>10,000</td>
<td>$3.06 \times 10^{14}$</td>
<td>21,000</td>
<td>10,000</td>
</tr>
</tbody>
</table>
P-Cam

- Seven subcamera “tubes” populated with ~1.5 fλ pixels with dichroic polarization sensitive TES bolometers
- FoV ~ 0.9 degree ⇒ 20,000 pixels at 350 μm; 6000 at 1.1 mm
- Cameras are modular (size, optics, filtration), easily exchanged
- Start with very modest numbers of pixels and growth to fill out camera, then entire CCAT-Prime FoV if so desired
Additional Science with kSZ Instrument: 
Polarized CMB, GEvo, & Lensing

- **Polarized CMB foregrounds**
  - Currently limit constraints on \( r \)
  - kSZ instrument should provide best dust foreground measurements

- **GEvo: Galaxy Evolution**
  - Dusty Star Forming Galaxies
  - Excellent \( z \) range and photo-z estimates
  - Niche between Planck, Herschel, SCUBA-2, and CMB surveys

- **CMB lensing**
  - Exciting new area for cosmology
  - Foregrounds not yet understood

**kSZ instrument sketch with 7 bands**
(more details in instrument slides)
Obscured SF over Cosmic Time

- CCAT-p aperture lowers Herschel confusion limits
- Herschel surveys limited to ~25 mJy confusion limit \(\Rightarrow\) resolve the CIRB at 10% level
- Statistically inferred at 50% level to 2 mJy/beam
- 5.5 m CCAT-p goes a factor of ~4 deeper into the confusion
  - 6 mJy level in 1 hr at 350 μm
- \(\rightarrow\) large \((100^{(\circ)}^2; 350 \, \mu \text{m})\) per year surveys pushing into the most active epoch of assembly of galaxies and large scale structures in the Universe

\[\nu I_\nu \, [\, \text{pW/m}^2\cdot\text{sr}^{-1}]\]

\[
\begin{array}{c|c|c}
\text{Flux Density [Jy]} & 0.001 & 0.010 \quad 0.100 \\
\hline
250\mu m & 60\% & 60\% \quad \text{45\%} \\
350\mu m & & \\
500\mu m & \\
\end{array}
\]

See Patanchon et al. (2010), Glenn et al. (2011)
EoR-IM: Intensity Mapping of [CII] in the Epoch of Reionization

- Aggregate [CII] signal from star forming galaxies at $z \sim 5$ to 9 $\Rightarrow$ 3-D information:
  - Reveals the **process of reionization** and the underlying dark matter distribution over the cosmic time when the first galaxies formed
- Combine with SKA 21 cm HI line tracing neutral ISM concentrations

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.
A Familiar Example of Intensity Mapping

- **Spectral line intensity mapping:** Not just fluctuation spectrum at an instant in time, but how the spectrum changes over EOR redshift interval

- **Cosmological Probes:** fluctuations will correlate with the underlying dark matter density fluctuations over EoR epoch
Intensity Mapping of \([\text{CII}]\) from the EOR

- Measure large scale spatial fluctuations of collective aggregate of faint galaxies via redshifted \([\text{CII}]\) 158 \(\mu\text{m}\) line (+possibly other lines at other z’s)
  - Resolution into individual galaxies not required
    - Clustering scale 0.5 to 1 Mpc or \(~1-2’\) at \(z = 5-9\), - good match for 6-m aperture (40”@ 1mm)
    - 16°² surveys: spectral/spatial mapping speed critical
    - FoV \(~ > 1°\) matches 40 Mpc void size-scale: systematics
    - Need moderate spectral resolution \(R \sim 300-500\)
  - Bandwidth of \(z \sim 5-9\) signal is 0.95-1.6 mm (190-315 GHz)
    - Identify interloper lower \(z\) CO by line multiplicity – complete at \(z > 0.8\)
    - Sensitivity is at a premium: high site, very low emissivity telescope is essential!
Large BW × FoV Spectrometer

• Trans-mm wave from ~ 0.95 to 1.6 mm (315-188 GHz)
• Direct detection for optical sensitivity
• Resolving power requirement is modest, ~ 500 or 600 km/sec
• Need a spectral × spatial product > 20,000 to complete a 16°² survey in 4000 hours.
Spectrometer on a Chip

- Essentially filter bank tapping off of a superconducting transmission line.
- Each channel is a half-wave resonator that dumps power to the detector.
- Can cover very large instantaneous bandwidths, so that source redshifts (and science) are obtained.
- 312 spectral $\times$ 64 spatial pixels.
- Early in development, but promising.

Several groups working in this field including:

**Delft**: DESHIMA 320-950 GHz, 6-9 pixels, R $\sim$ 1000 (A. Endo)

**GSFC**: MicroSpect: S.H. Moseley

**JPL**: SuperSpec 95-520 GHz, R $\sim$ 400 to 700 (C.M. Bradford)
Or...

“Traditional” grating spectrometer with full BW and “long slit”

Might well be an “evolution” from first light spectrometer to more sophisticated technologies

Imaging FPI spectrometer that spatially multiplexes with large FoV cameras
EoR IM Science Program

- EoR IM: total time: 4100 hours, or ~ 410 days
- IF, we can use 2 - 1.1 mm camera tubes for spectroscopy

<table>
<thead>
<tr>
<th>CCAT-p Survey area ($^\circ$)$^2$</th>
<th>Noise Limit on sky (W/m$^2$/sr)</th>
<th>Number of FPI Cameras</th>
<th>Integration time (hours)</th>
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</thead>
<tbody>
<tr>
<td>8</td>
<td>$8 \times 10^{-14}$</td>
<td>2</td>
<td>4100</td>
</tr>
<tr>
<td>16</td>
<td>$8 \times 10^{-14}$</td>
<td>4</td>
<td>4100</td>
</tr>
</tbody>
</table>

- IFU spectrometer: 64 spatial positions and 300 spectral samples $\Rightarrow$ 20,000 total
CMB-S4

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 on 6 m telescope would enable mapping CMB 10 times 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.
- Synergistic with Simons Observatory
  - Adds the high frequency component that may be critical for removing submm galaxy foregrounds
CMB-S4 Survey Timeline and Targets

<table>
<thead>
<tr>
<th>Year</th>
<th>Stage</th>
<th>Detectors</th>
<th>Sensitivity ($\mu K^2$)</th>
<th>$\sigma(r)$</th>
<th>$\sigma(N_{eff})$</th>
<th>$\sigma(\Sigma m_\nu)$</th>
<th>Dark Energy F.O.M</th>
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<tbody>
<tr>
<td>2015</td>
<td>Stage 2</td>
<td>1000</td>
<td>$\gtrsim 10^{-5}$</td>
<td>0.035</td>
<td>0.14</td>
<td>0.15eV</td>
<td>Boss BAO prior</td>
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<tr>
<td></td>
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<td>2016</td>
<td>Stage 3</td>
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<td>0.006</td>
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<td>0.06eV</td>
<td>DES + DESI</td>
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<tr>
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<td>SZ Clusters</td>
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<tr>
<td>2017</td>
<td>Stage 3</td>
<td>10,000</td>
<td>$10^{-6}$</td>
<td>0.006</td>
<td>0.06</td>
<td>0.06eV</td>
<td>~300-600</td>
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<td>2018</td>
<td>Stage 3</td>
<td>10,000</td>
<td>$10^{-6}$</td>
<td>0.006</td>
<td>0.06</td>
<td>0.06eV</td>
<td>~300-600</td>
</tr>
<tr>
<td>2019</td>
<td>Stage 3</td>
<td>10,000</td>
<td>$10^{-6}$</td>
<td>0.006</td>
<td>0.06</td>
<td>0.06eV</td>
<td>~300-600</td>
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<tr>
<td>2020</td>
<td>Stage 4</td>
<td>~500,000</td>
<td>$10^{-8}$</td>
<td>0.0005</td>
<td>0.027</td>
<td>0.015eV</td>
<td>DESI BOA + T_e</td>
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<tr>
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<td>2021</td>
<td>Stage 4</td>
<td>~500,000</td>
<td>$10^{-8}$</td>
<td>0.0005</td>
<td>0.027</td>
<td>0.015eV</td>
<td>DESI + LSST</td>
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<td>2022</td>
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<td>$10^{-8}$</td>
<td>0.0005</td>
<td>0.027</td>
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<td>2023</td>
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<td>0.0005</td>
<td>0.027</td>
<td>0.015eV</td>
<td>DESI + LSST</td>
</tr>
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</table>

Target: $10^{-8}$, $0.0005$, $0.027$, $0.015$eV, 1250

CMB-S4 Motivation for arcminute-scale resolution

$N_{\text{eff}}$ from CMB-S4 Science Book (arXiv:1610.02743)

Forecasts for $\sigma(N_{\text{eff}})$

5.5m aperture CCAT-prime resolution is well-matched to CMB-S4 science (1.5’ at 150 GHz, 2.3’ at 90 GHz)
CCAT-prime: Large Aperture Telescope to map the CMB 10x faster

6m aperture crossed-Dragone design delivers a large, flat focal ~8 degree plane

Can illuminate 10x more detectors than Stage III telescopes (Advanced ACTPol, SPT-3G, Polarbear2)

(Niemack, Applied Optics 2016)

**CCAT-prime consortium:**
Cornell, Cologne, Bonn, AUI Association of Canadian Universities
CCAT-prime: Large Aperture Telescope to map the CMB 10x faster

Close-packed reimaging optics with 30 cm diameter optics tubes are well matched to 15 cm superconducting detector fabrication capabilities.
CCAT-prime: Large Aperture Telescope to map the CMB 10x faster

Smaller scale instruments are natural for first light

Prototype receiver based on a 50 optics tube design

This instrument could illuminate > $10^5$ CMB detectors, and map the CMB 10x faster than Advanced ACTPol and SPT-3G

(Niemack, Applied Optics 2016)
Comparisons to other Coeval Facilities

- **EoR IM**: win with surface brightness sensitivity due to Ruze factor, emissivity, site, and mapping speed with FoV:
  - 2 and 4 times more sensitive than APEX and Llama per beam plus FoV is $250 \times$ larger $\Rightarrow 1000$'s times faster

- **GEcos**: win with surface brightness due to Ruze factor, site, and mapping speed with FoV:
  - CHAI/CCAT-p is $2 \times 1.8$ more sensitive @ 810 (690) GHz than APEX
  - CHAI/CCAT-p maps large scales structures $8 \times$ faster than ALMA
Comparisons to other Coeval Facilities

- **kSZ and GEvo**: win with surface brightness sensitivity due to Ruze factor, emissivity, site, and mapping speed with FoV:
  - APEX
  - Current CMB projects

- **CMB-S4**: win with surface brightness sensitivity due to Ruze factor, emissivity, site, and mapping speed with FoV