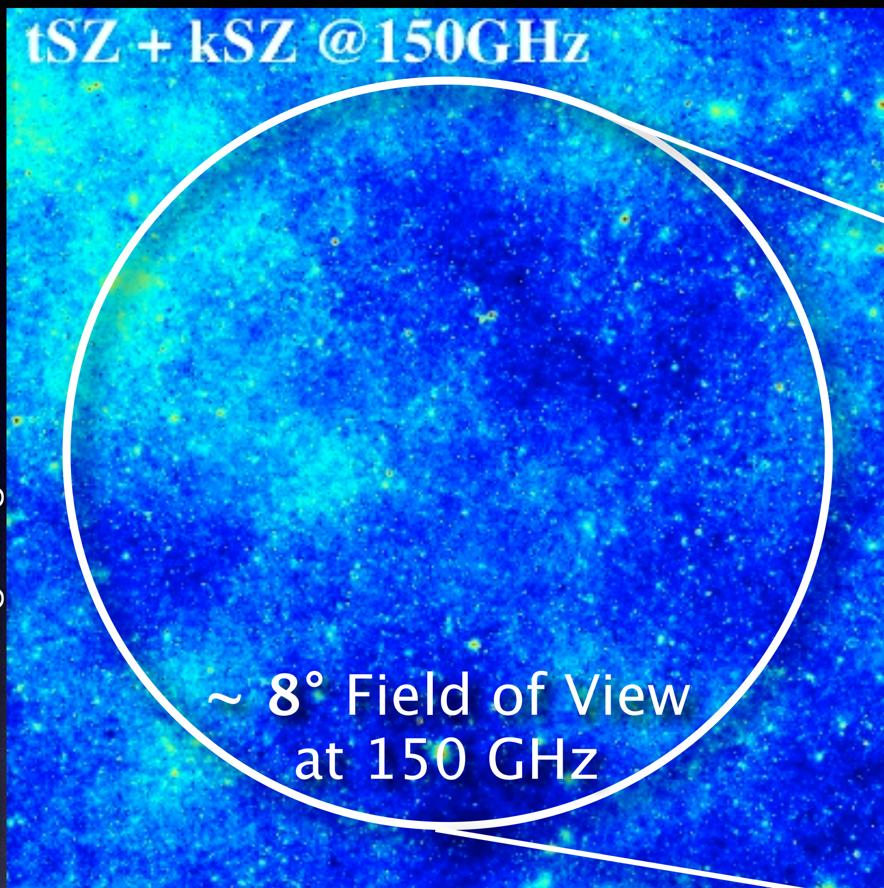
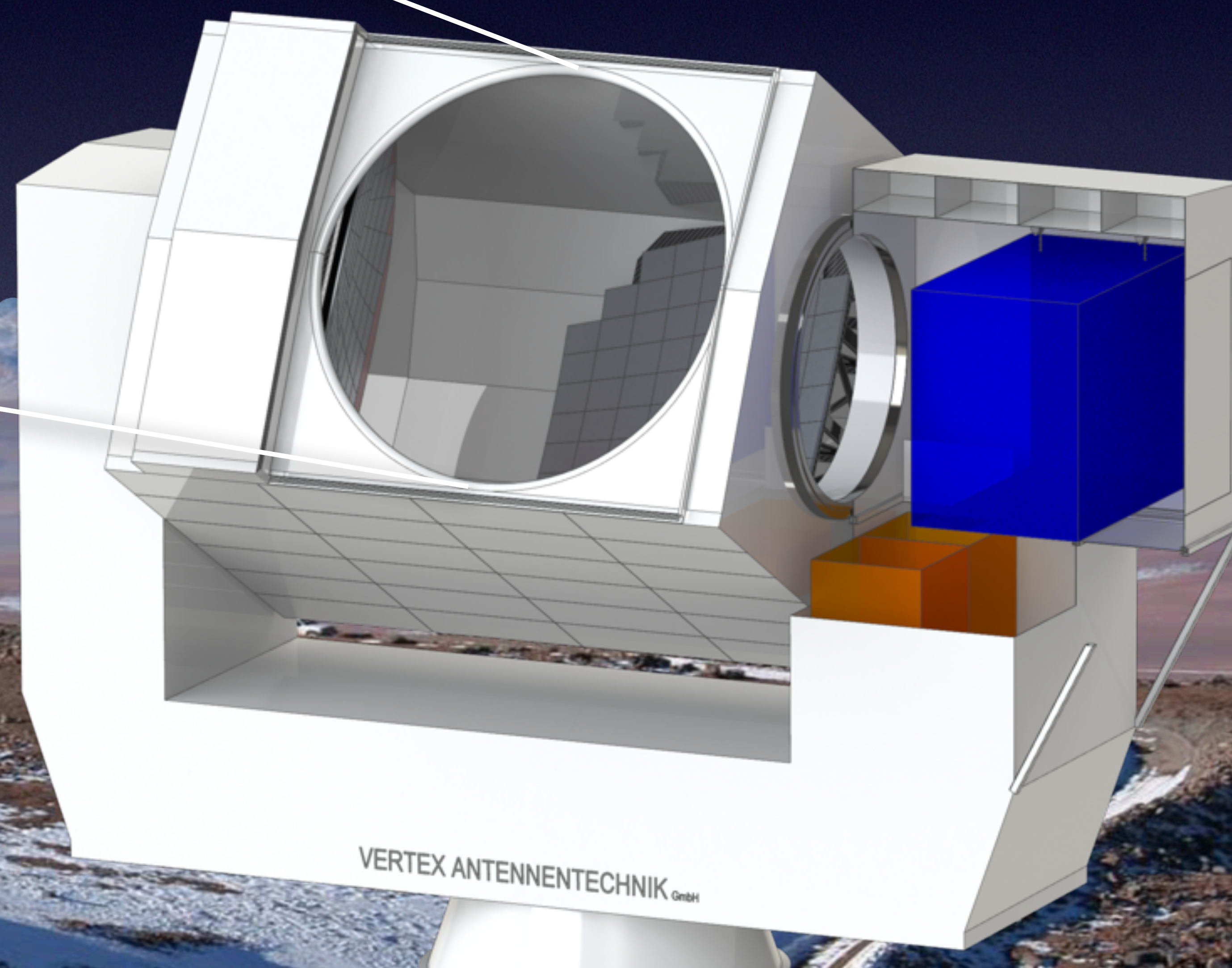
An update on

CCAT-prime

- ***Telescope & site***
- ***Instruments***
- ***Project status***
- ***Science***



Credit: K.Dolag/Magneticum sim. 8.8°×8.8°



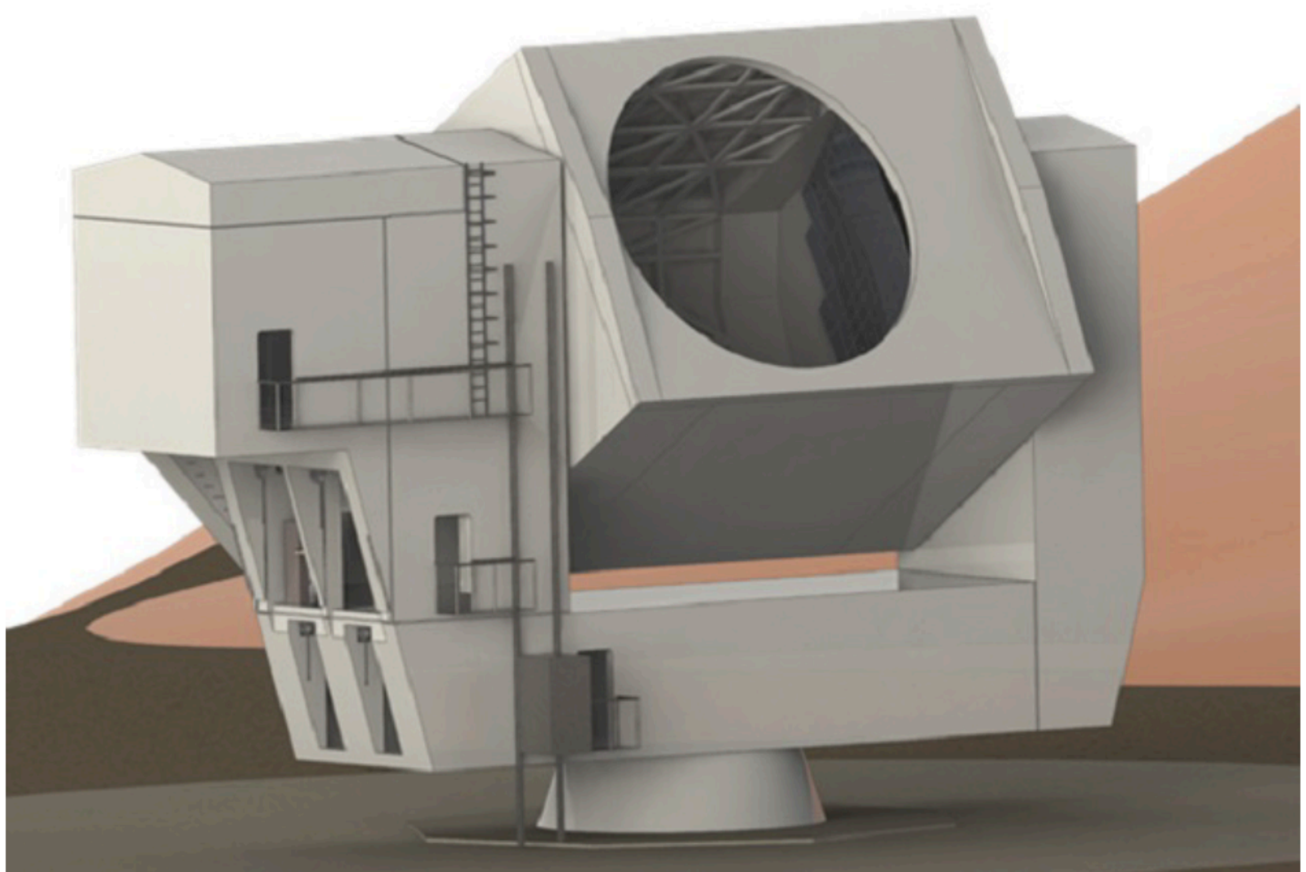
Kaustuv Basu (Universität Bonn)

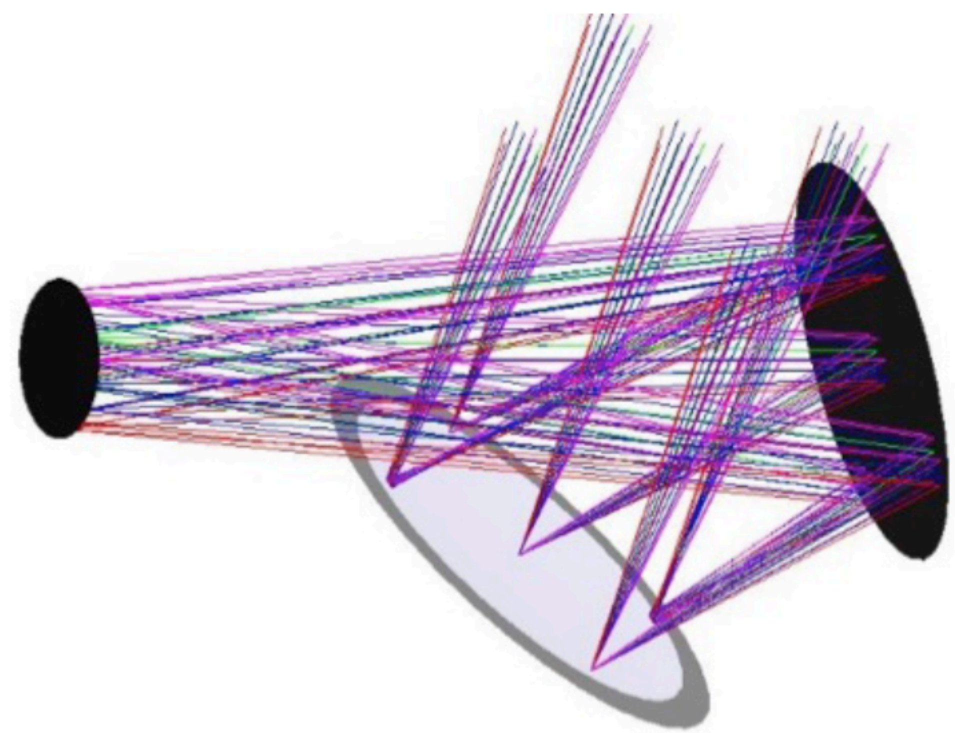
On behalf of the *CCAT-prime* collaboration
(Special thanks to F. Bertoldi & J. Erler)

What is CCAT-prime?

CCAT-p

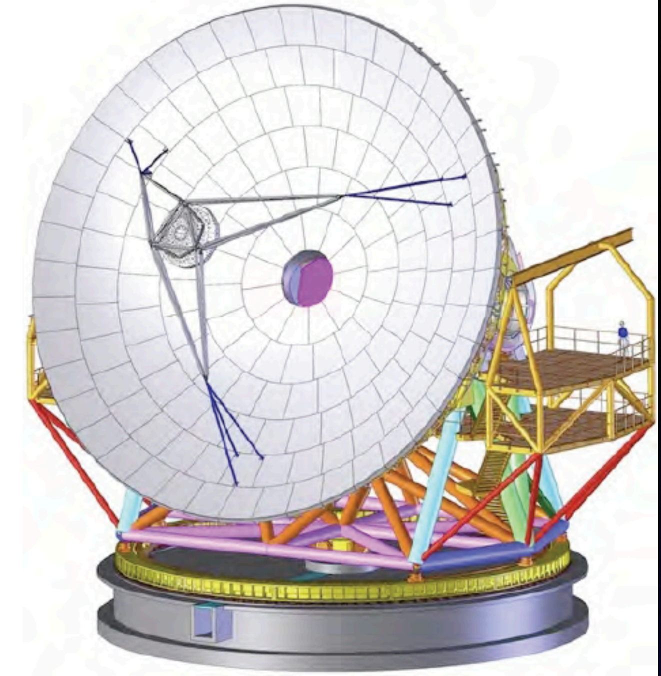
A high surface accuracy, high throughput
6 m aperture, submm (0.2-3mm) telescope
for dedicated surveys





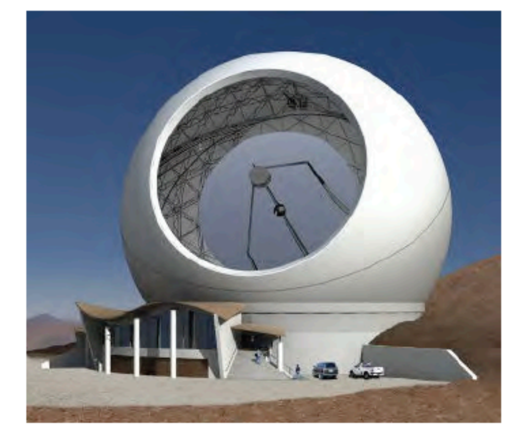
Backstory:

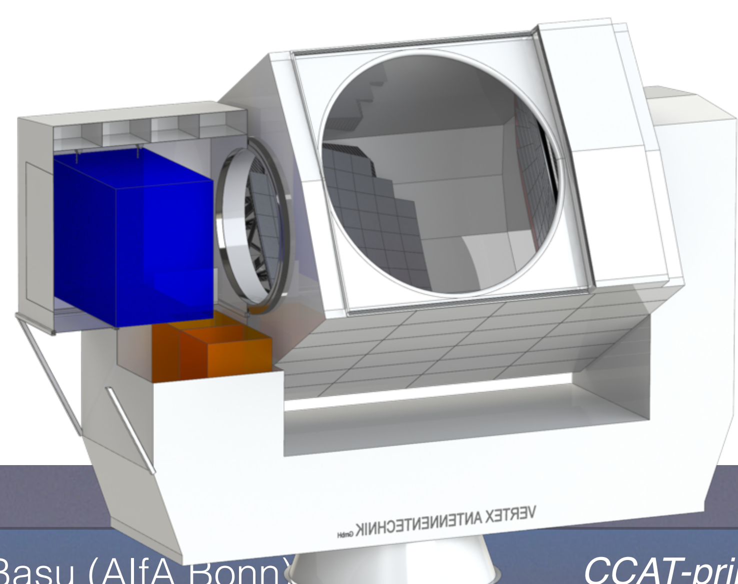
Cerro Chajnantor Atacama Telescope

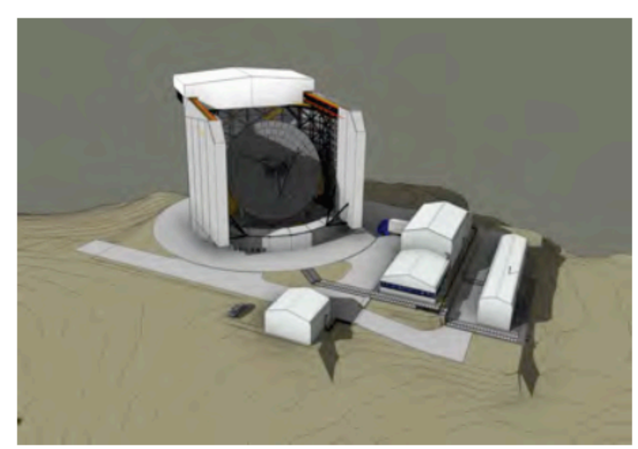


25 m
FoV 30'
<15 μm surface

2003	Partnership workshop Pasadena
2004	MoU Caltech, JPL, Cornell
2005	project office
2006	feasibility study review
2007-9	site selection, joining Colorado, Cologne/Bonn, AUI, Canada
2010	astro2010 recommendation
2011-14	Engineering Design Phase (NSF-supported): reference design
2013	EDP external review
2013-15	NSF MSIP proposals fail; Caltech, Colorado leave
2015	MTM, Vertex provided turn-key design studies & pricing
2016	CCAT terminated, CCAT-prime born







Who is CCAT-prime ?

University consortium with strong emphasis on training & development

- **Cornell University, Director 70%**
- **Univ. Cologne & Univ. Bonn 25%**
  - joining: LMU (Mohr), MPA (Komatsu)
- **Canadian University consortium 5%**
  - Waterloo, Toronto/CITA, British Columbia, Calgary, Dalhousie, McGill, McMaster, Western Ontario
- **Chilean University collaborators**
  - U. Chile, PUC, UCSC, UDP, and others
- **Prime-Cam collaborators**
  - U. Michigan, NIST, Stanford/SLAC, Cardiff U., SO, and others

Funded by: private donor and Cornell university

DFG Großgeräte, Univ. Köln & Bonn, SFB956 (CHAI)

Where is CCAT-p?

Cerro Chajnantor at 5600 m w/ TAO

Where is CCAT-p?

Cerro Chajnantor at 5600 m w/ TAO

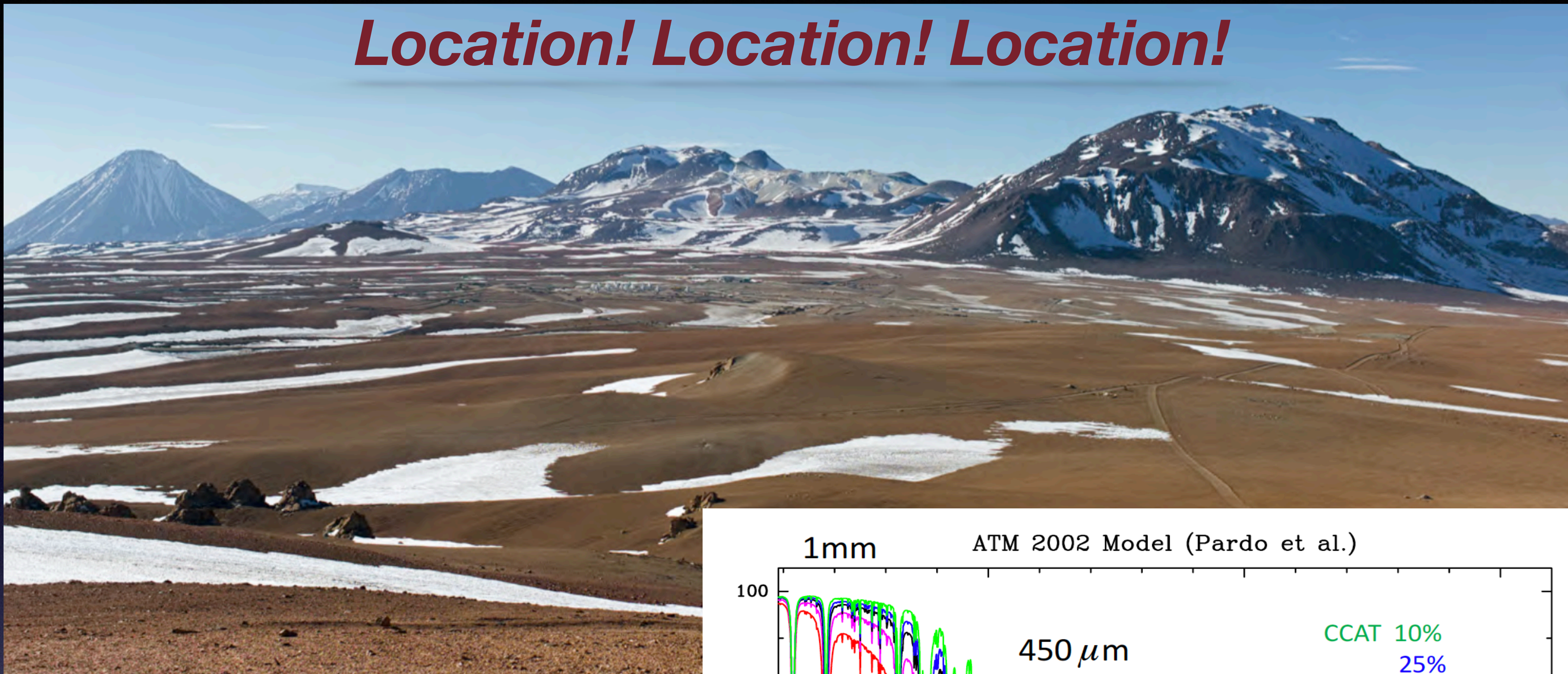
Cerro Chajnantor peak at 5640 m

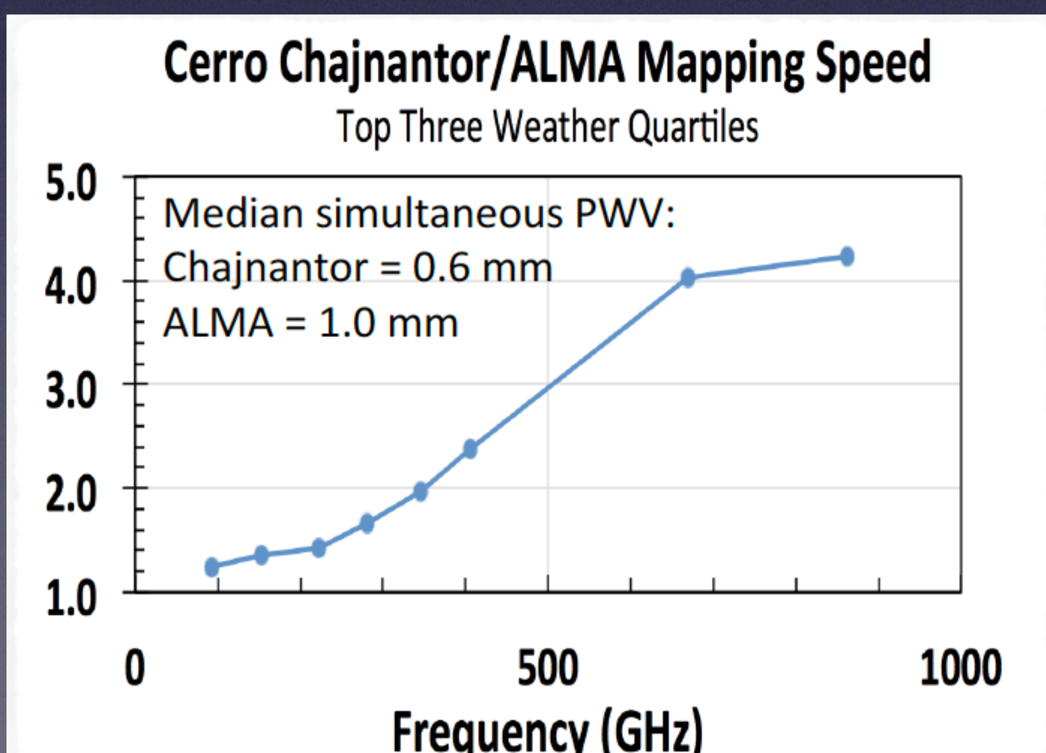
Tokyo Atacama Telescope : 6.5m infrared-optimized telescope on the summit, Institute of Astronomy (IoA), the University of Tokyo & other Japanese facilities incl. the National Astronomical Observatory, ISAS/JAXA, and the University of Chile.

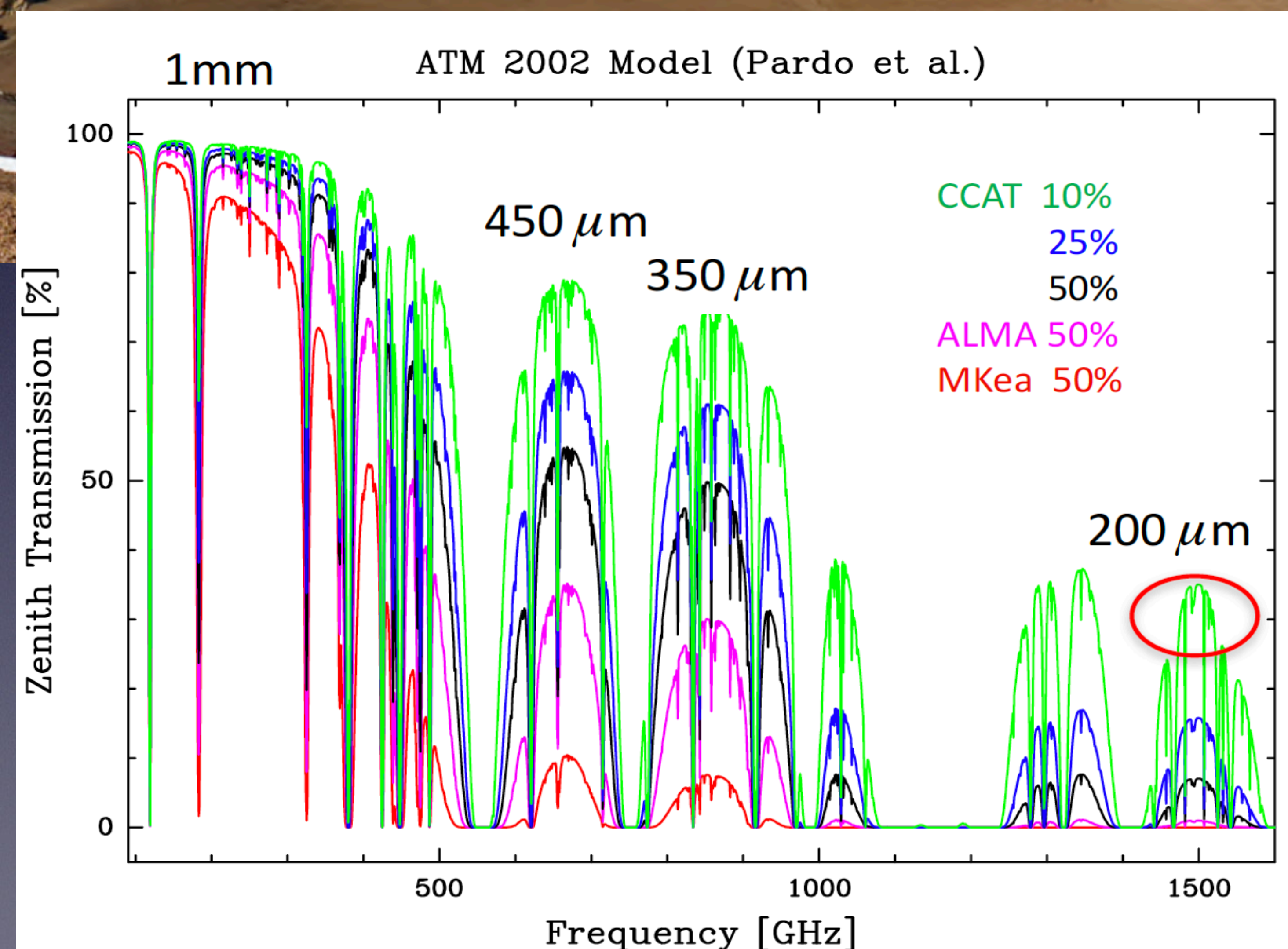
- Share mountain top – constructing road
- Draft agreement to share common costs: road maintenance, power, etc

12 June 2017

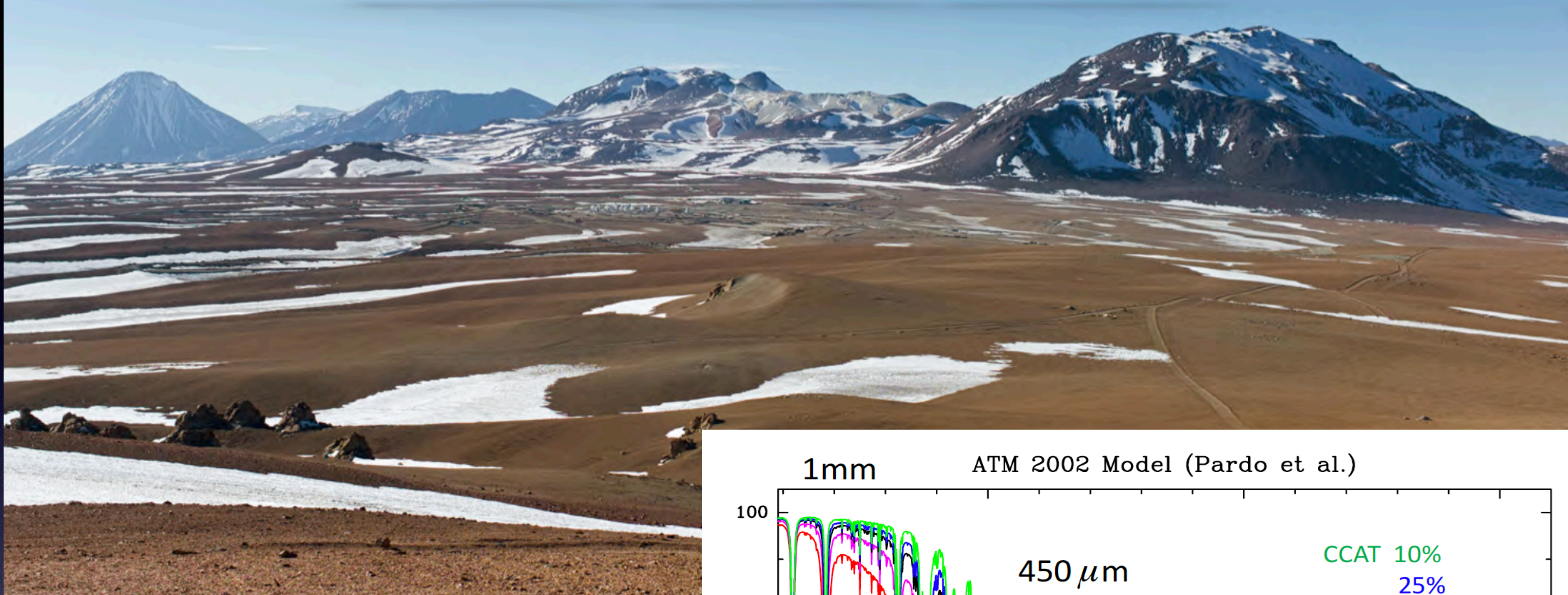
Location! Location! Location!

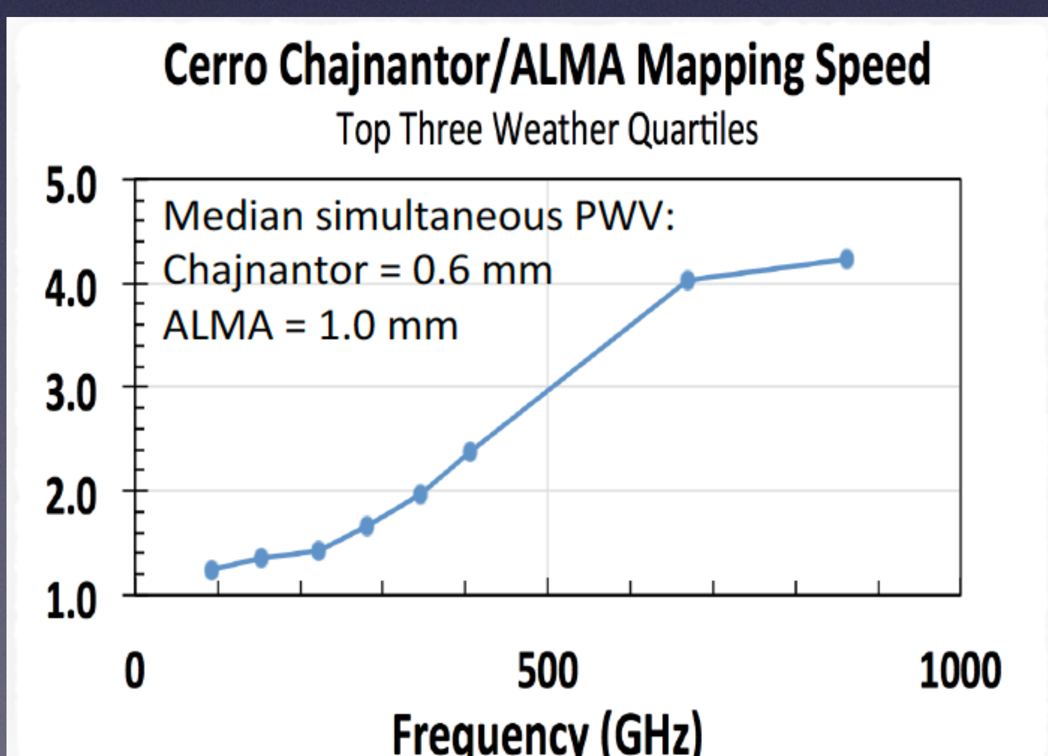


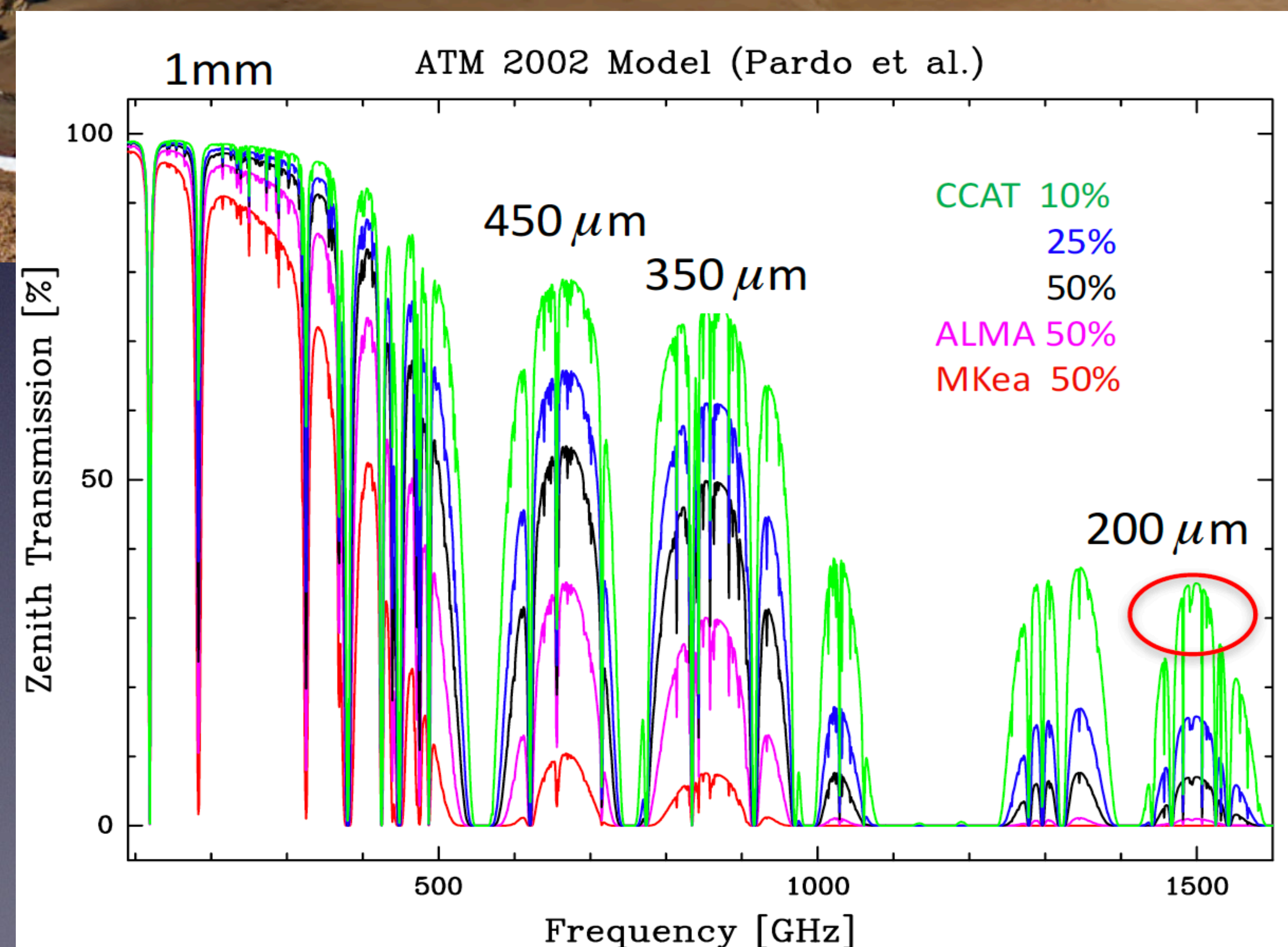




Location! Location! Location!







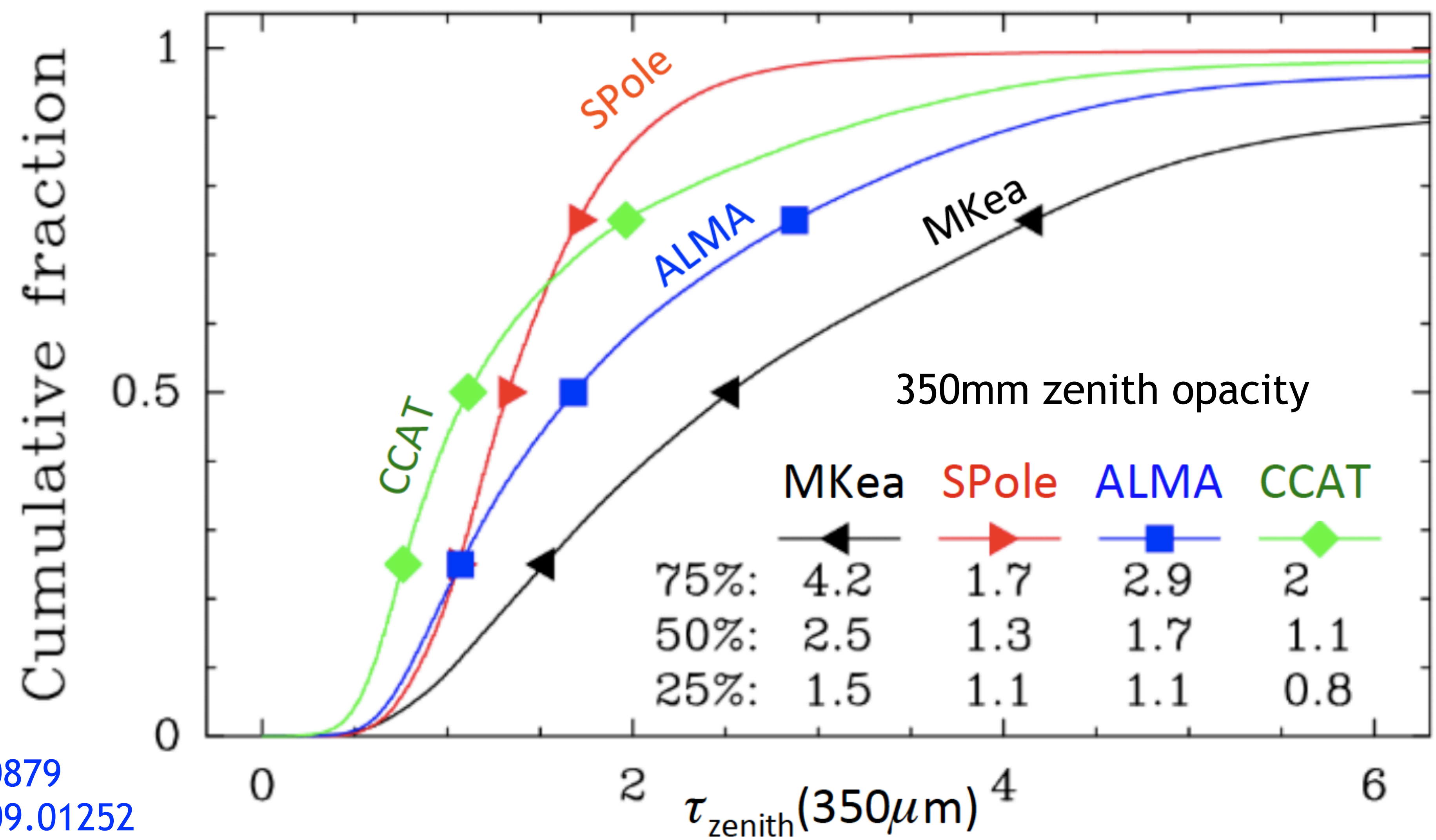
Why bother moving to the peak?

Submillimeter sensitivity is all about atmospheric transmission.

5100 m is good, 5600 m is better !

CCAT vs. ALMA sites: median H_2O 0.6 vs. 1 mm, $\tau(350\,\mu m)$= 1.1 vs. 1.7

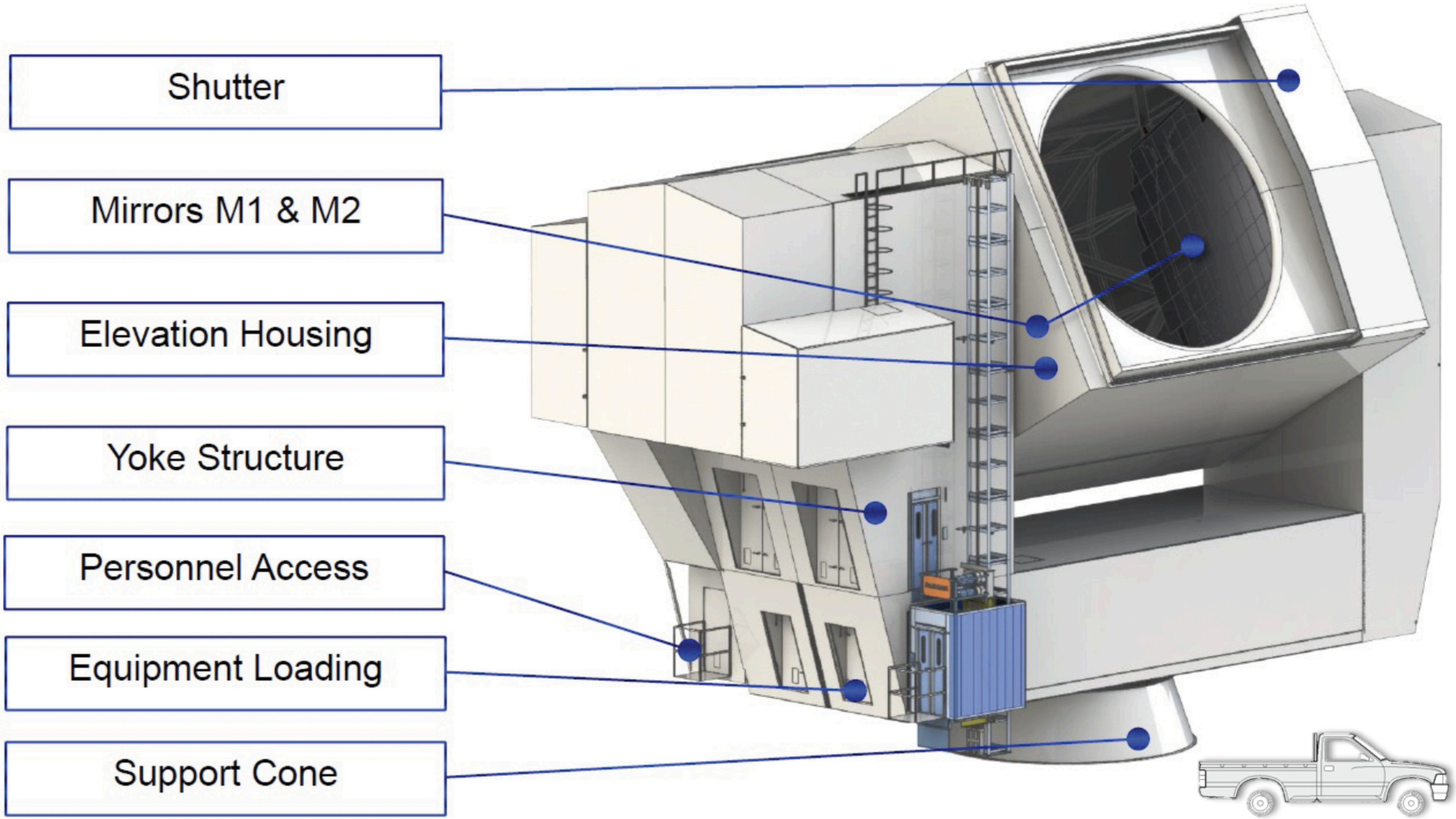
$\Rightarrow$ *factor of 2 in sensitivity*



Radford & Peterson, arXiv:1602.0879
Cortes, Reeves, Bustos, arXiv:1609.01252

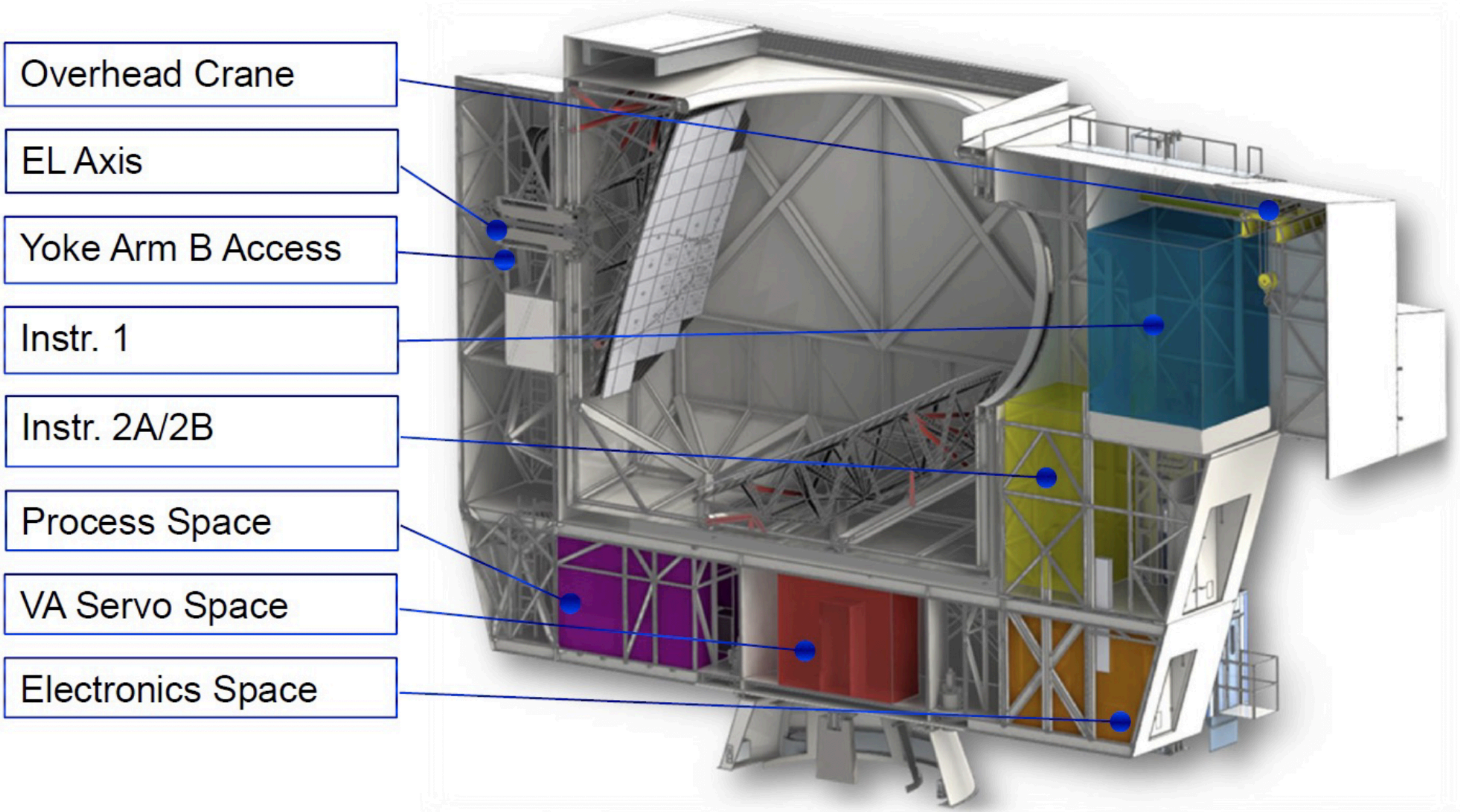
Telescope

designed and built by Vertex Antennentechnik GmbH, Duisburg



CCAT-p

Telescope

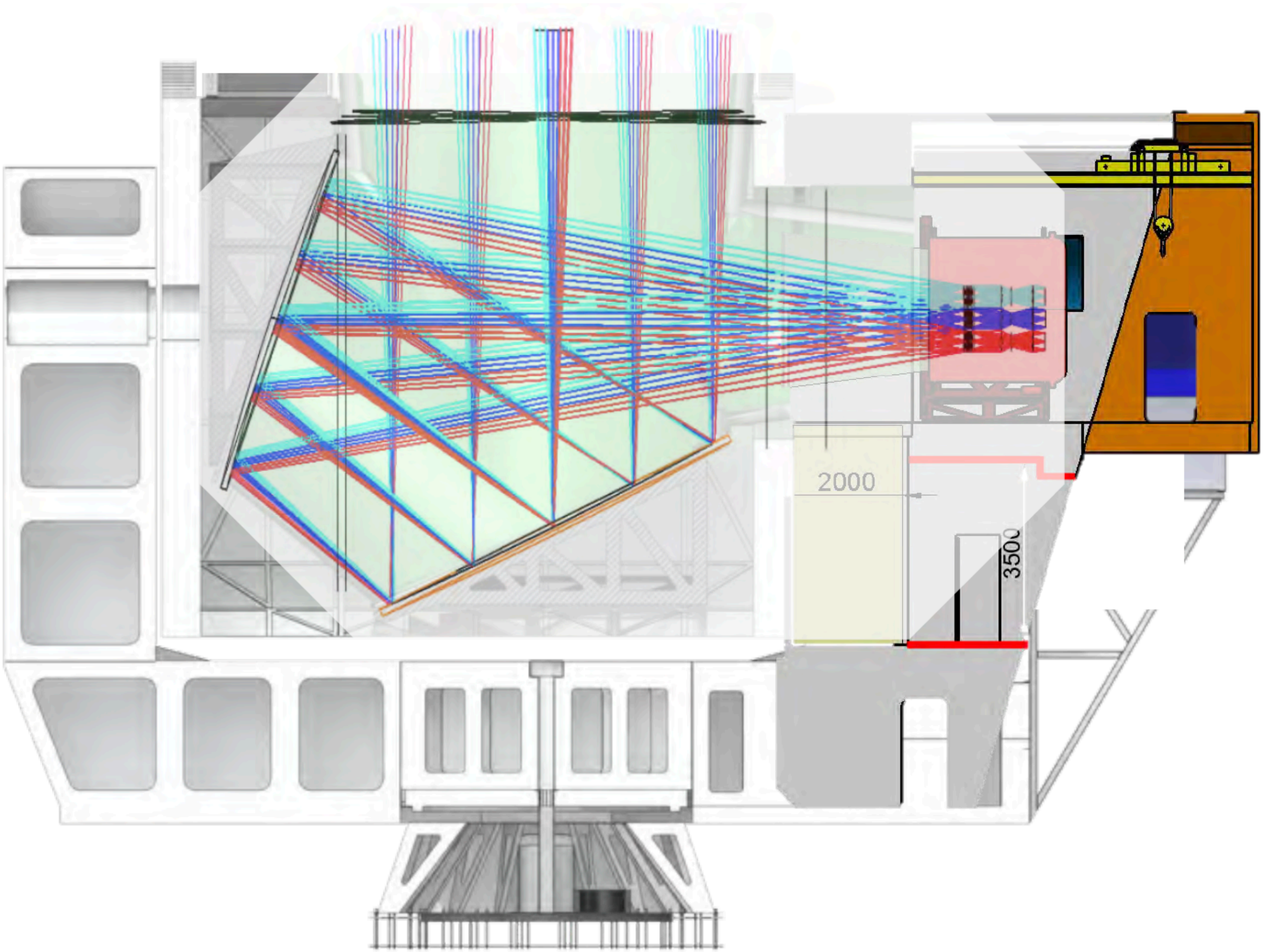


Crossed-Dragone Optics Design

coma-corrected f/2.6 with 5.5m free aperture

high throughput, 8 deg field-of-view, flat focal plane, zero geometric blockage

telescope emissivity < 2%, total system emissivity < 7%



Crossed-Dragone Optics Design

high throughput, 8 deg field-of-view, flat focal plane, zero geometric blockage

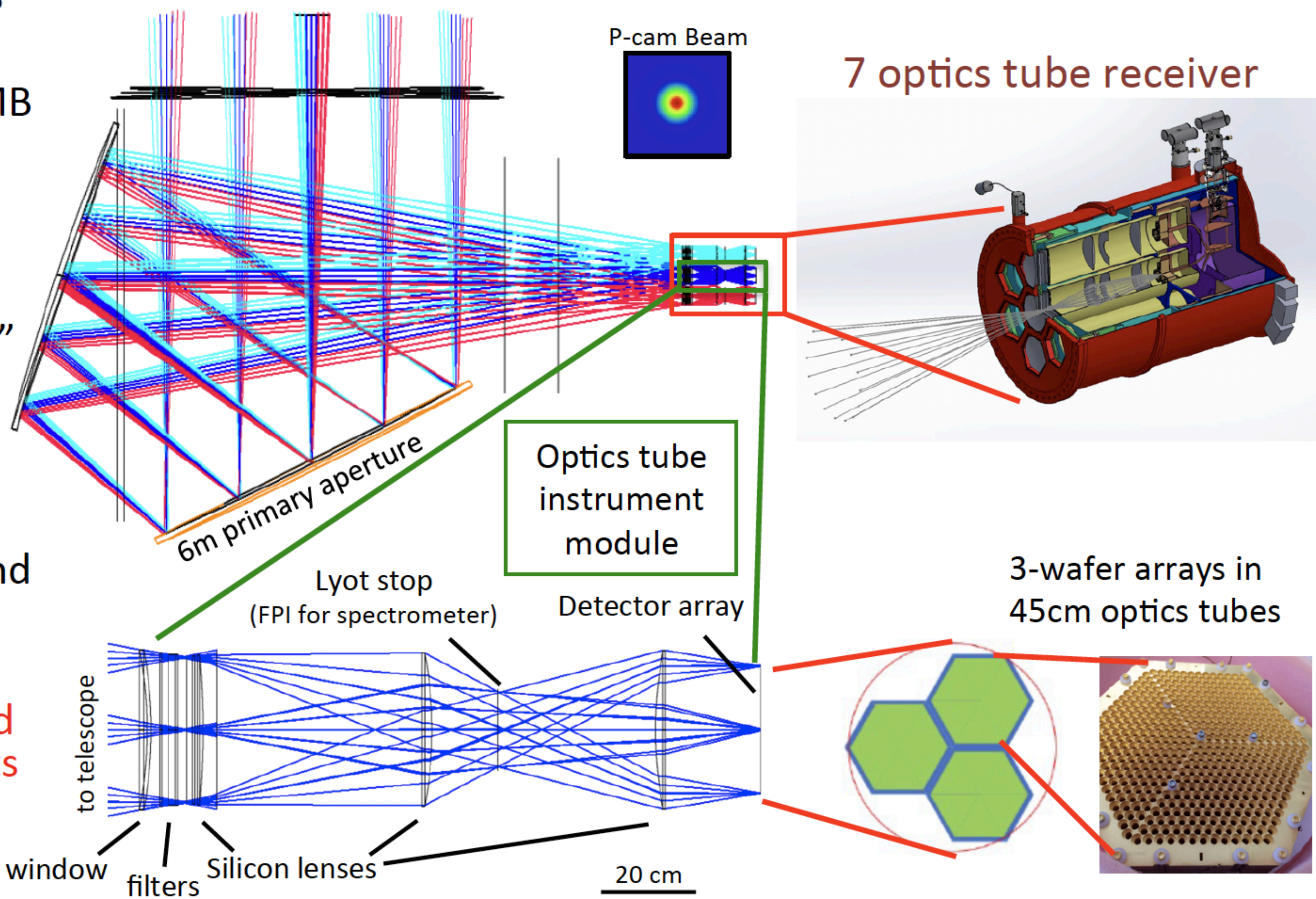
Concept by C. Dragone 1978

Used in “small aperture” CMB experiments
(QUIET, Atacama B-Mode Search, QUIJOTE)

Designs for “large apertures”
to map the CMB ~10x faster
(Niemack 2016, Applied Optics)

Working with *Simons Observatory* on telescope and receiver optics designs

6m aperture coma-corrected f/2.6 design for both projects
(Parshley, Hills, Mauskopf, Dicker, Gallardo and others)



Status CCAT-p/SO Telescope

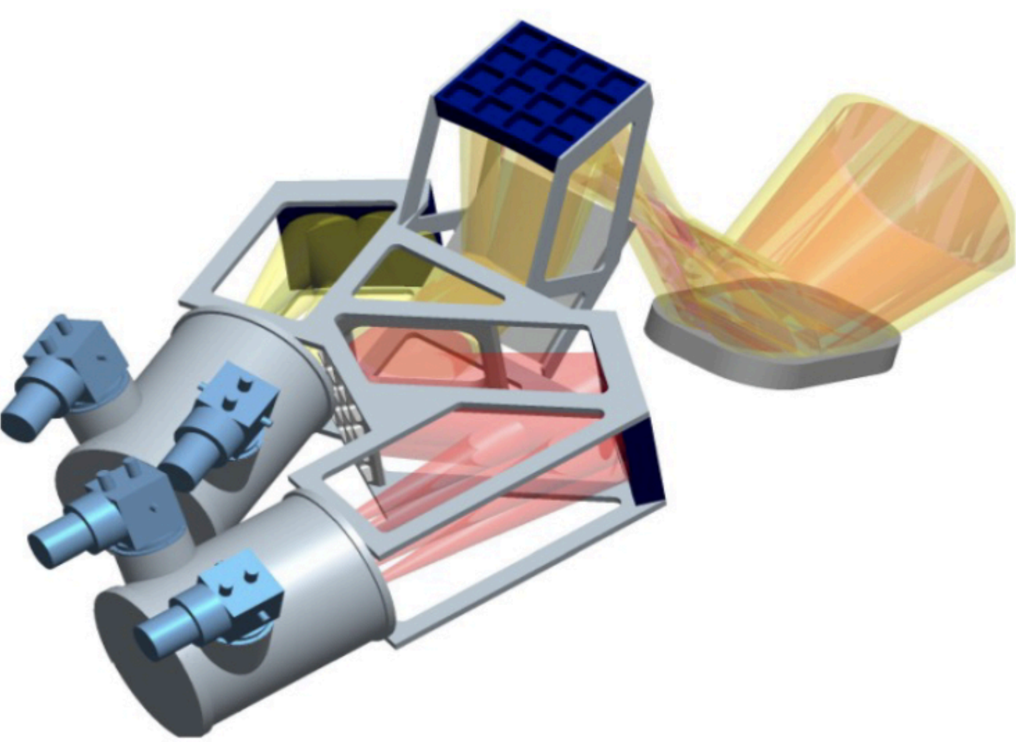
CCAT-p

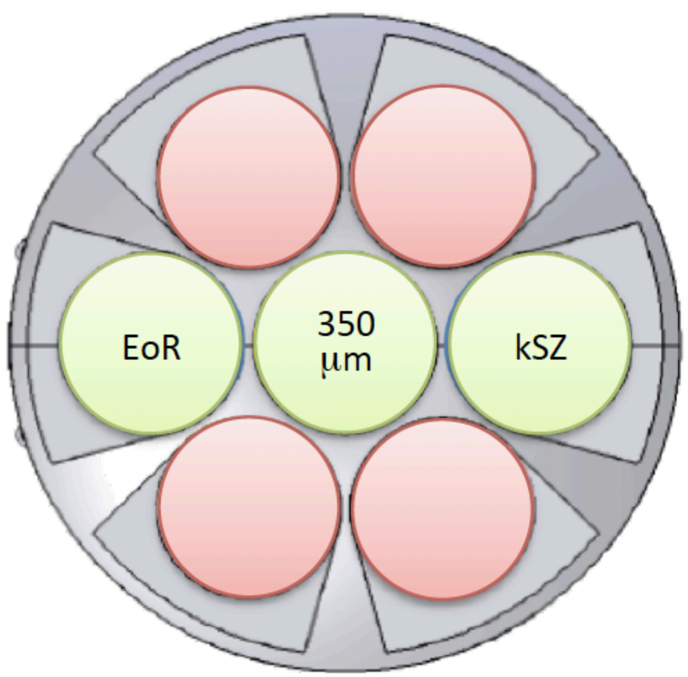
VERTEX ANTENNENTECHNIK GmbH
A GENERAL DYNAMICS COMPANY

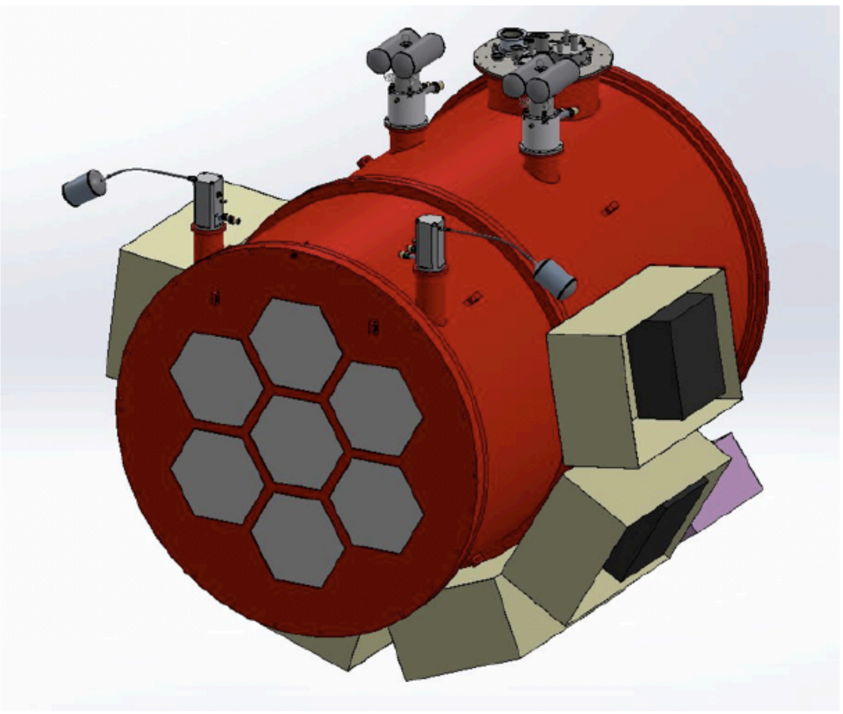
- Vertex contract start: July 1, 2017
- Kick-off meeting: July 14
- Advanced Progress Meeting: December 5-6
  - Required because post CCAT conceptual design changes required engineering work
  - first joint CCAT & SO design review
- Preliminary Design Review: March 20-22
  - SO stray light concerns > investigate change in top of elevation structure.
- Critical Design Review: October 2018
- Final Design Review: Spring 2019

Instrumentation

Name	Primary Science	λ range	FoV	No. Pixels	1st Light?
CHAI	GEco	200 – 700 um	17’ x 8.5’	64 (256 goal)	yes
P-Cam	kSZ, GEvo	350 – 1300 um	3^o diameter	$5.9x10^4$	yes
P-Cam	IM/EOR	740 – 1300 um	--	$2.0x10^4$	yes



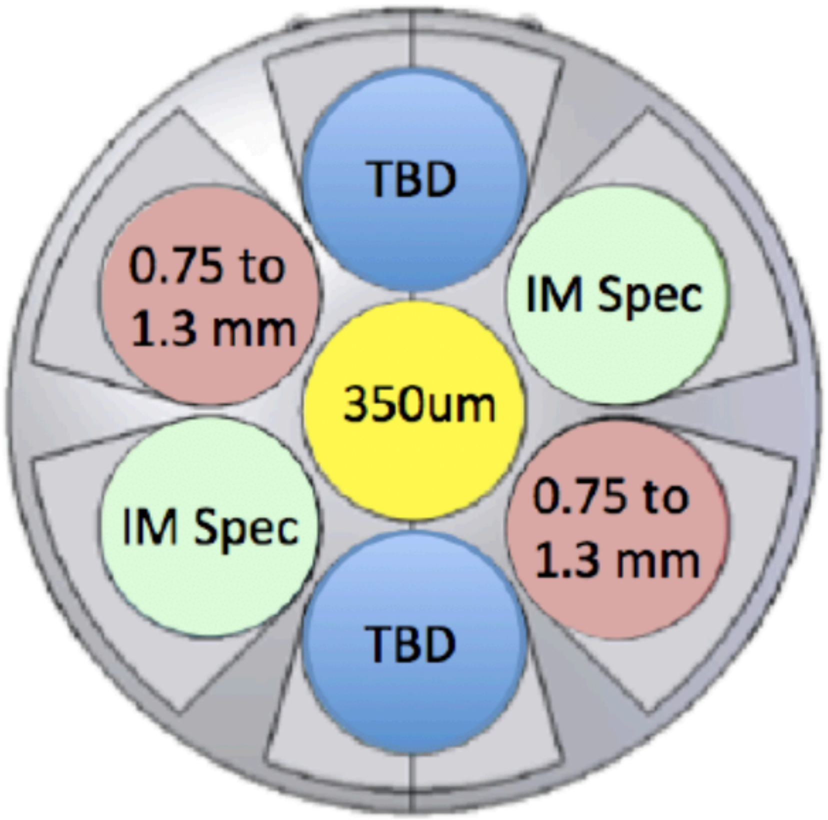


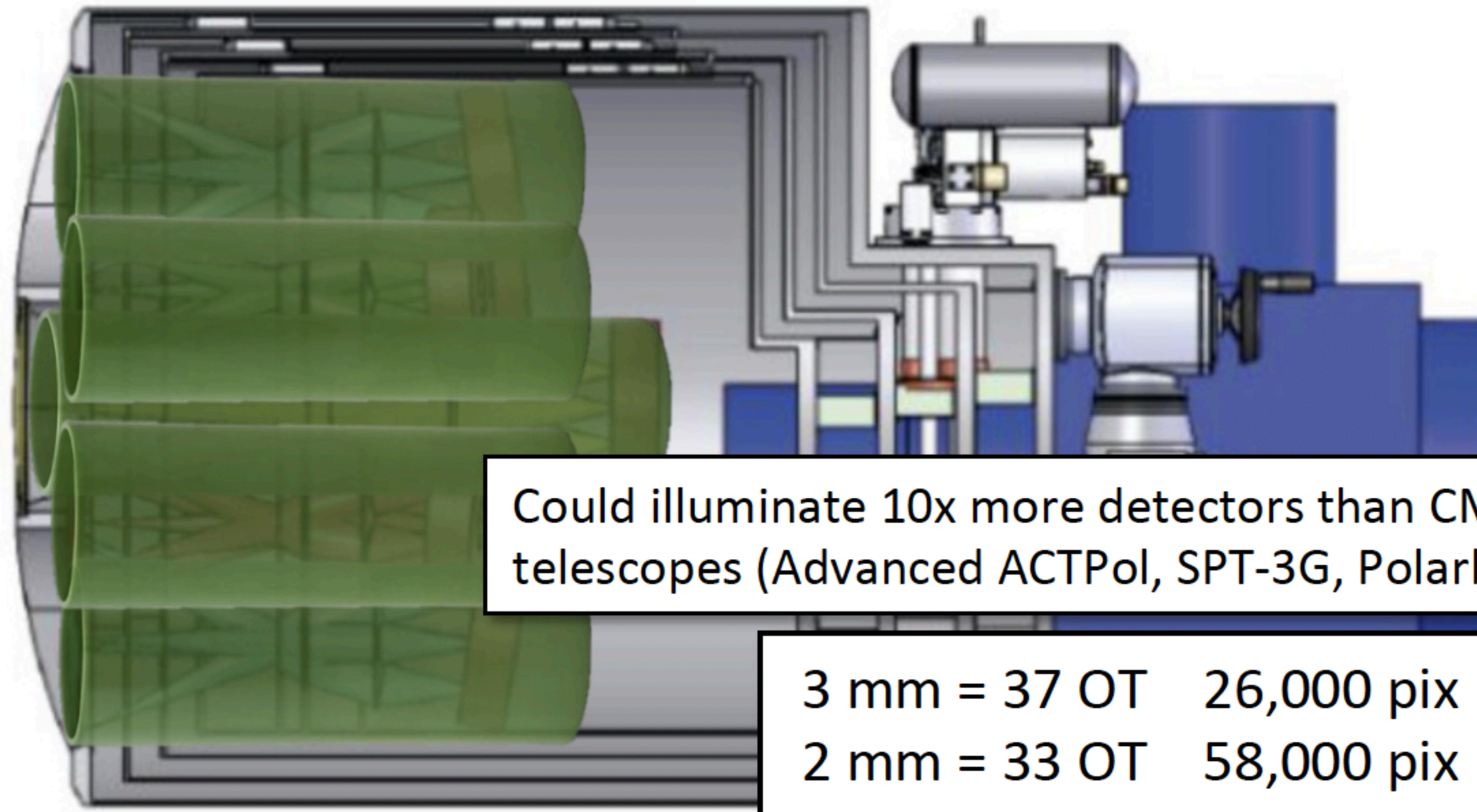


CHAI

Prime-Cam

Continuum Camera: initial design





Could illuminate 10x more detectors than CMB S3 telescopes (Advanced ACTPol, SPT-3G, Polarbear2)

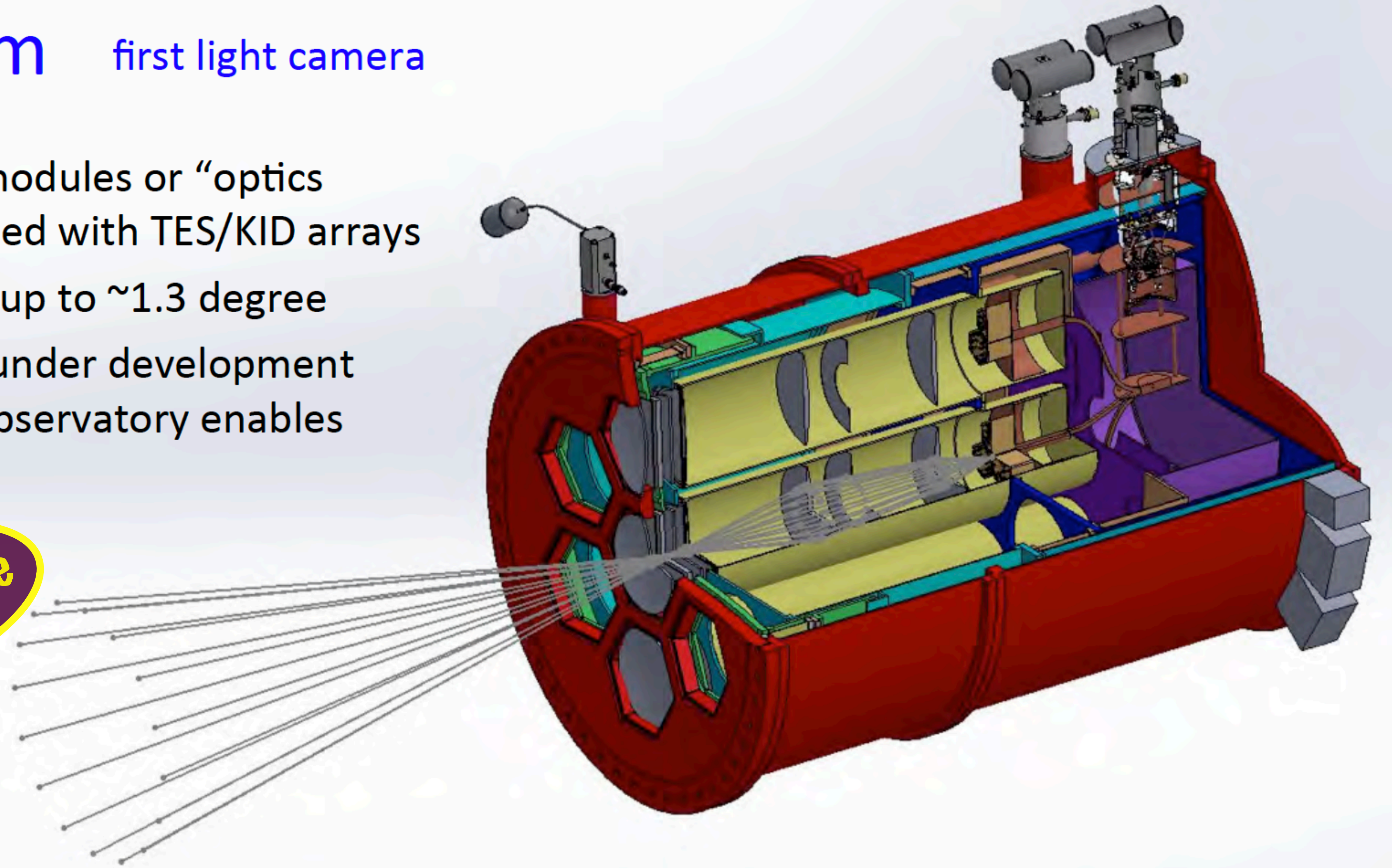
3 mm = 37 OT	26,000 pix
2 mm = 33 OT	58,000 pix
1 mm = 19 OT	110,000 pix
0.35 mm = 7 OT	400,000 pix

- 7 subcamera 45cm “optics tubes” populated with TES/KID bolometers
- each have FoV ~ 1.3 degree
- Fabry-Perot Interferometers on two tubes for intensity mapping.
- Cameras are modular (size, optics, filtration), easily exchanged
- Start with modest numbers of pixels and grow to fill out camera, then entire FoV if desired/affordable

Prime-Cam first light camera

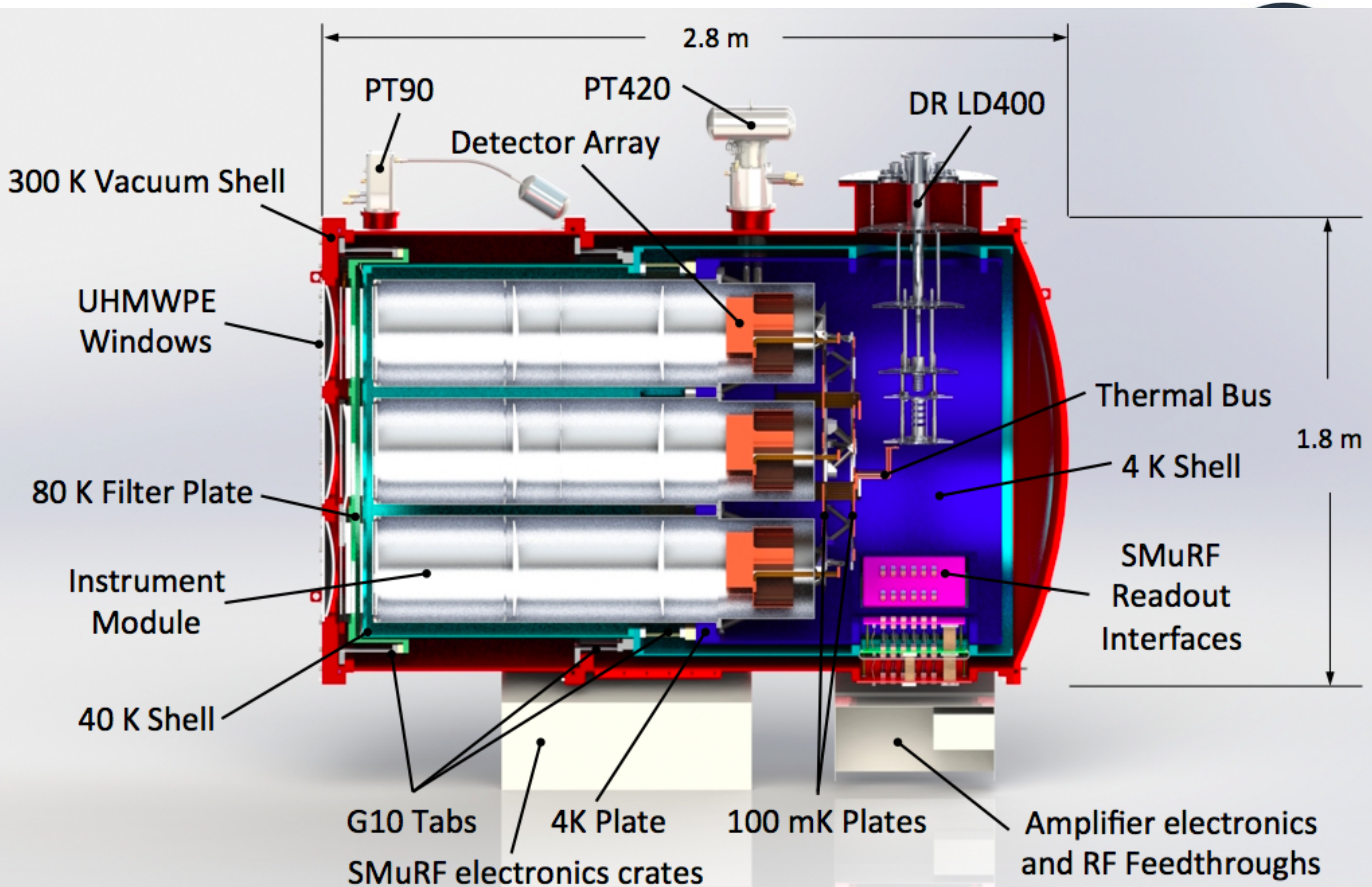
- 7 instrument modules or "optics tubes" populated with TES/KID arrays
- Each tube FoV up to ~1.3 degree
- Modul design under development with Simons Observatory enables upgrades

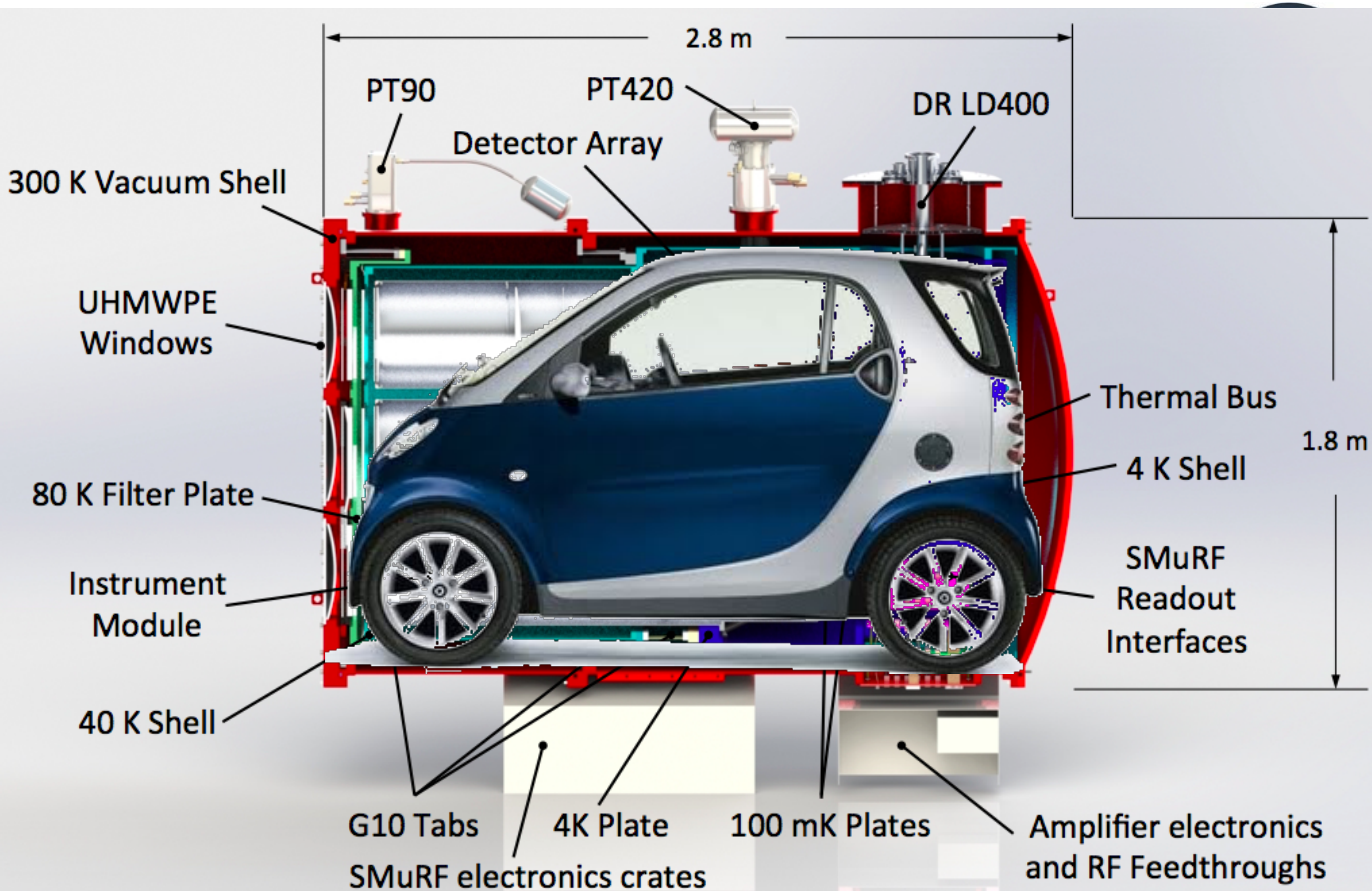
for SZ science



Plan for first 3 optics tubes: 2 broadband (bb) one spectrometer (sp)

Science cases[a]	Type[b]	Frequencies[c] (GHz)	Resolution (arcsec)	Detectors type	Detectors #	Survey Areas[d] (deg^2) pilot	Survey Areas[d] (deg^2) full
SZ, CMB, SF	bb, pol	230, 270, 350, 410	60, 50, 40, 35	TES	9000	100	12,000[e]
EoR, SZ	sp	230, 270, 350, 410	60, 50, 40, 35	TES	6000	4	16
SZ, SF	bb	860	15	KID	18,000	both	both


2.8 m
PT90
PT420
DR LD400
Detector Array
300 K Vacuum Shell
UHMWPE
Windows
Thermal Bus
1.8 m
4 K Shell
80 K Filter Plate
SMuRF
Readout
Interfaces
Instrument
Module
40 K Shell
G10 Tabs
4K Plate
100 mK Plates
Amplifier electronics
and RF Feedthroughs
SMuRF electronics crates


2.8 m
PT90
PT420
DR LD400
Detector Array
300 K Vacuum Shell
UHMWPE Windows
Thermal Bus
1.8 m
4 K Shell
80 K Filter Plate
SMuRF Readout Interfaces
Instrument Module
40 K Shell
G10 Tabs
4K Plate
100 mK Plates
Amplifier electronics and RF Feedthroughs
SMuRF electronics crates

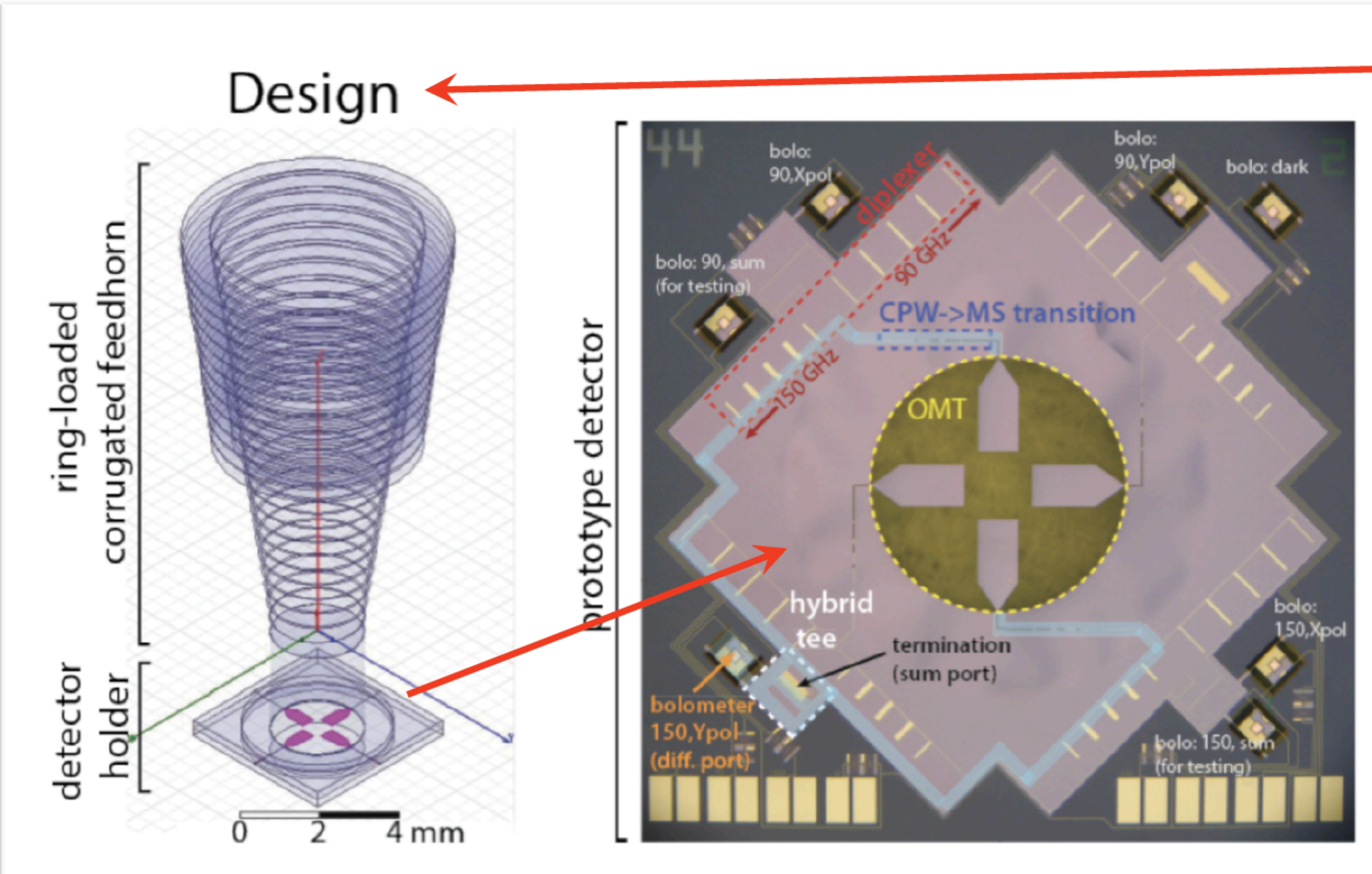
Detector concept for Prime-Cam

(with NIST, Michigan, Stanford/SLAC, and others)

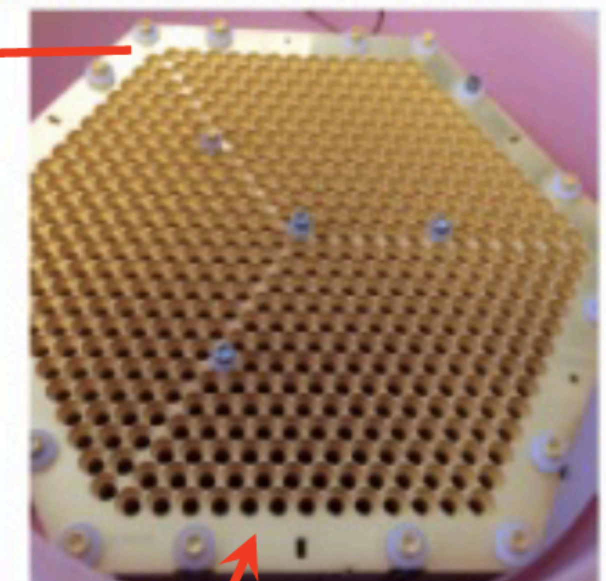
CCAT-p

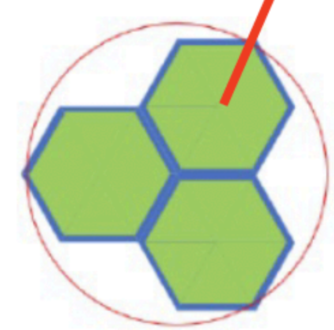
- Feedhorn-coupled multichroic TES arrays with 4 bands per feedhorn: 740, 860, 1100, 1400 μm
- Feedhorn coupled MKID array at 350 μm (NIST)
- 3x 15cm feed detector arrays tiled in each optics tube

Heritage:
Advanced ACTPol
BLAST-TNG



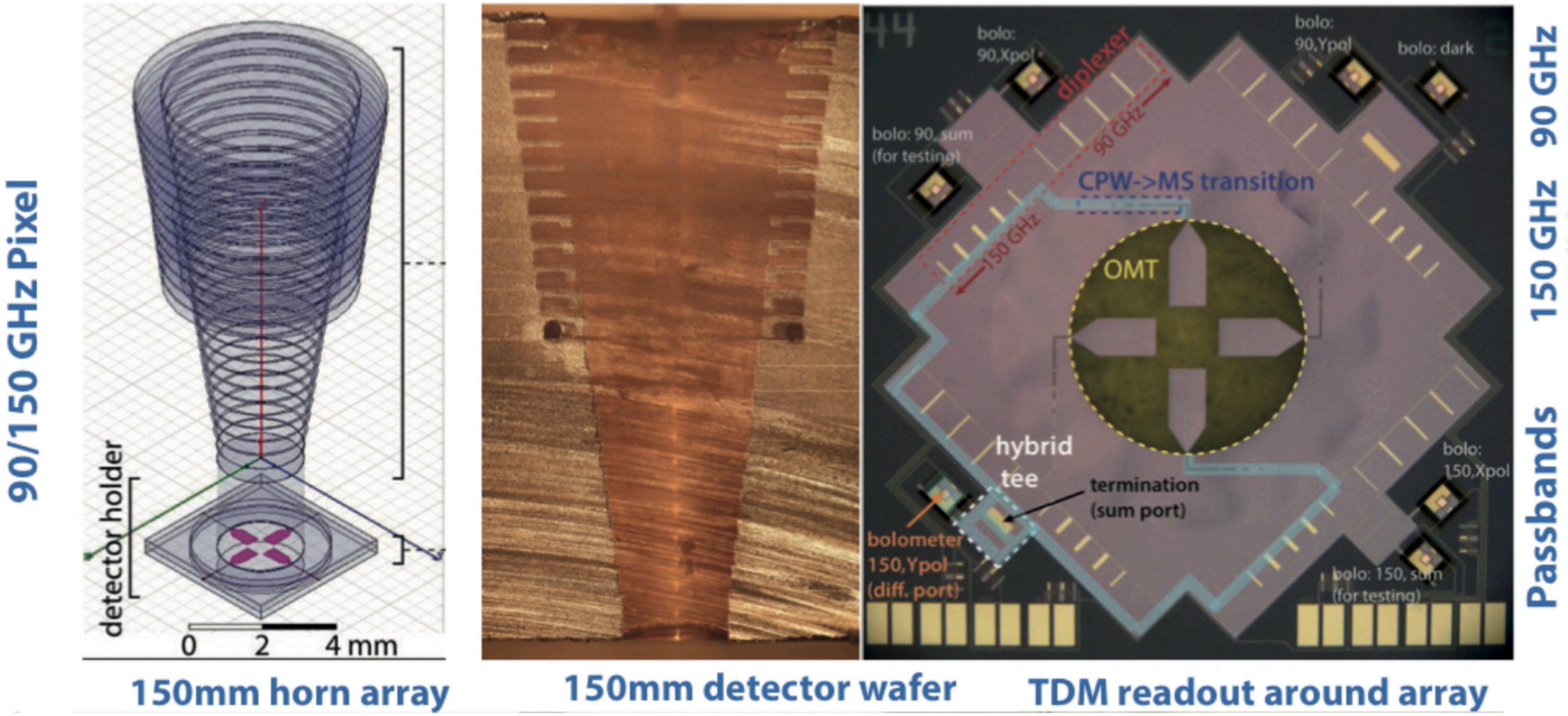
Multichroic feedhorn array





3-wafer detector array

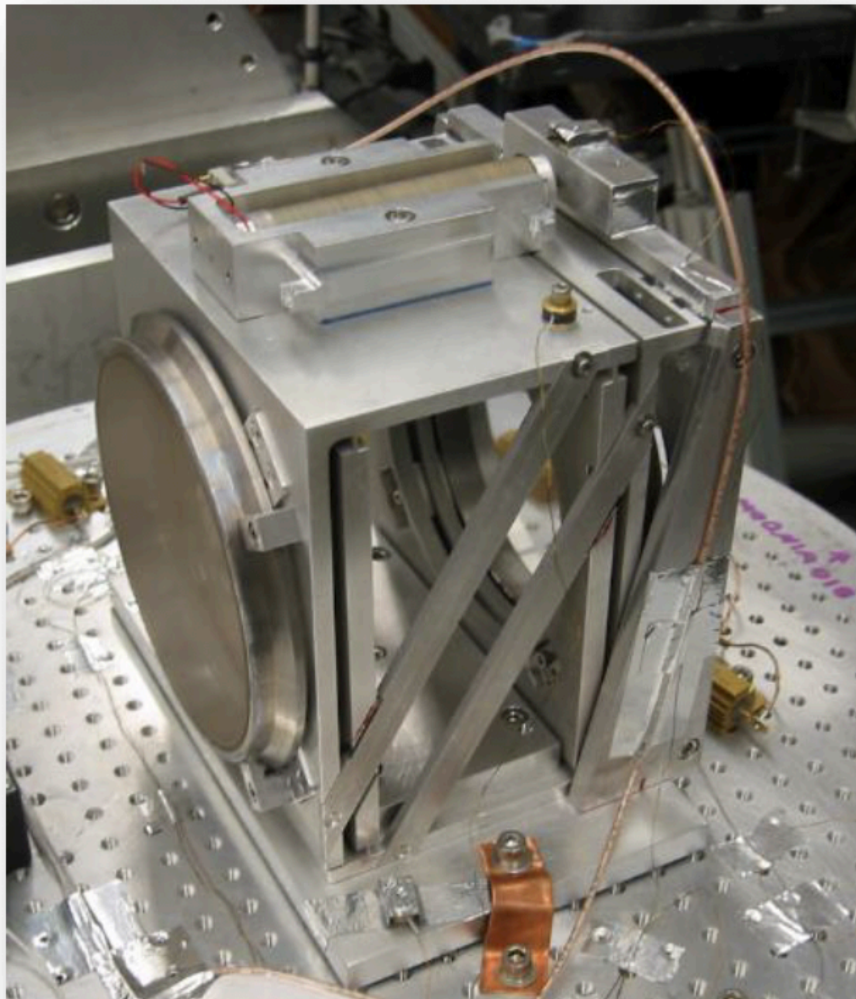
Multichroic Detectors



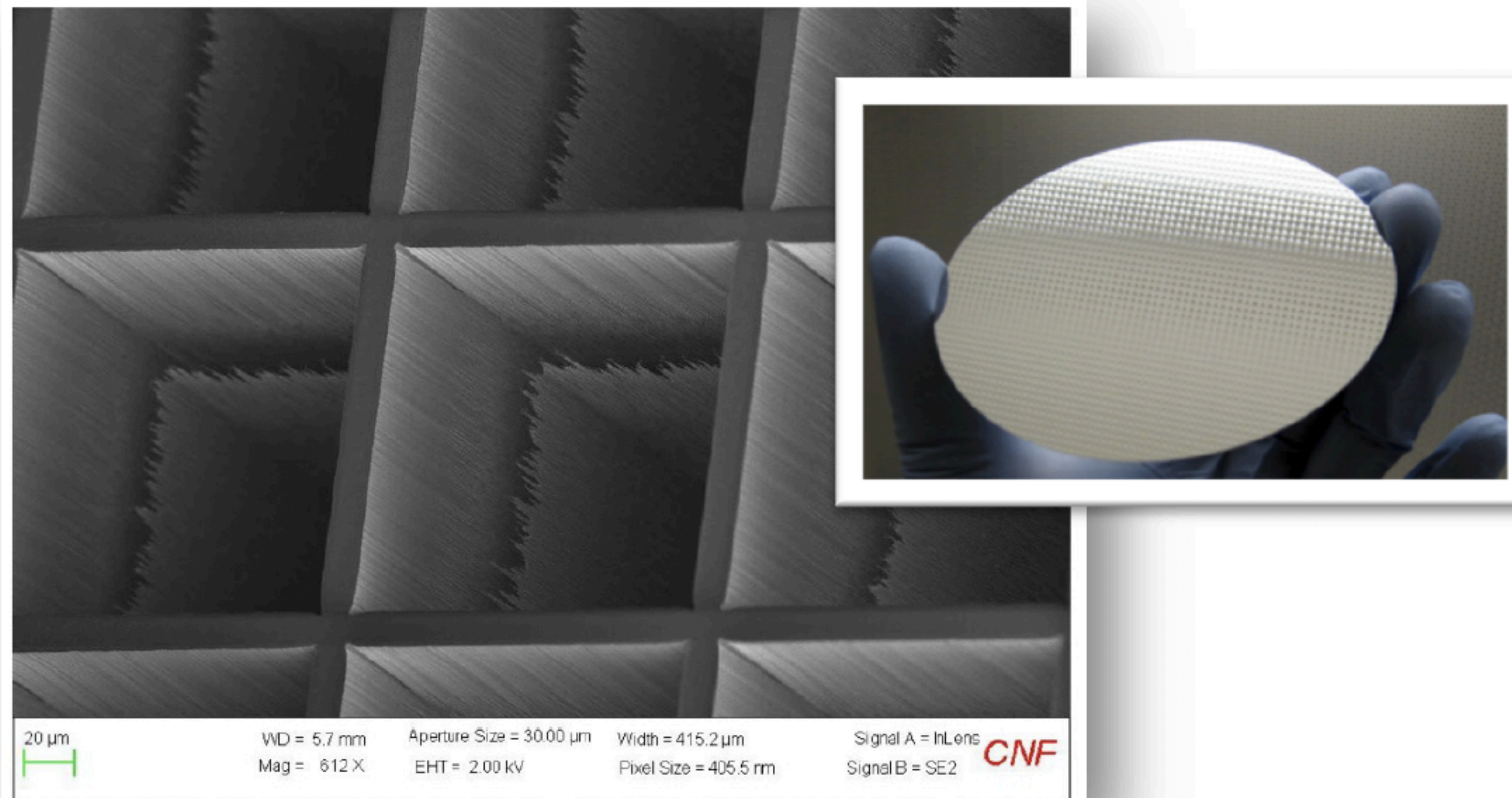
- Horns launch 740 um, 857 um, 1.1 mm and 1.4 mm beams
- Being developed by McMahon at U. Michigan
- Polarization sensitive with 4 bands per feedhorn: requires 8 detectors/horn
- Working with 2λ/D @ 1.4 mm (220 GHz) feedhorns
- 350 um band requires different technology, e.g. MKIDs

Fabry-Perot Interferometer for Intensity-Mapping

CCAT-p



Anti-reflective coating on 12′ Si wafer

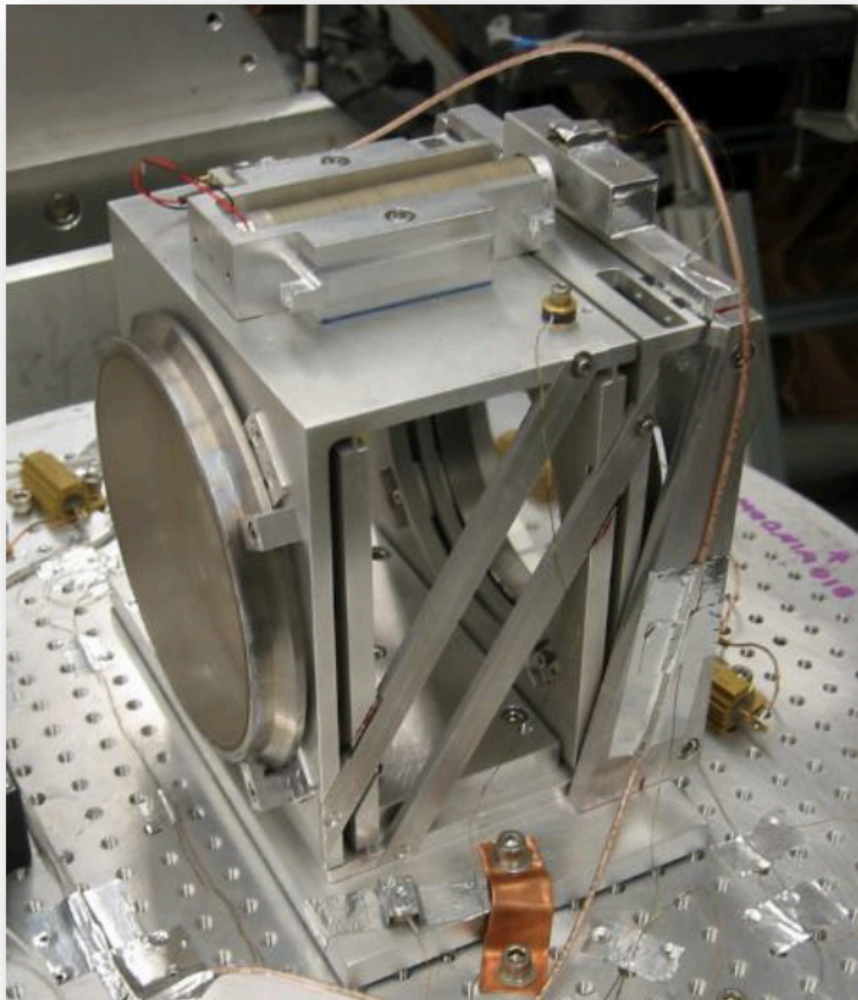


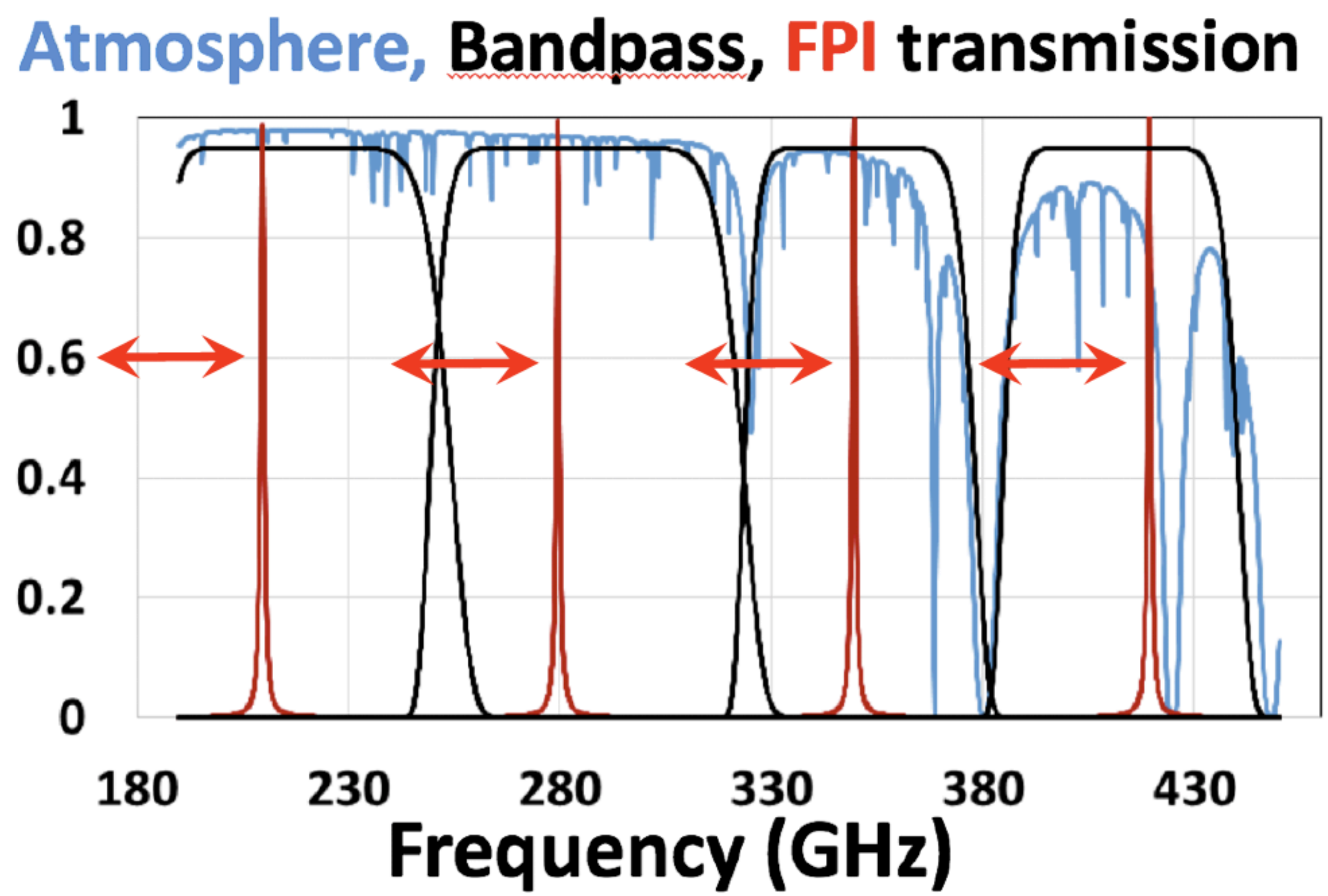
<u>Heritage</u>:
R = 10^6 FPI at 112 μm for HIRMES on SOFIA based on (fragile) free-standing metal mesh.

<u>Now</u> developing superconducting metalized **silicon** substrate FPI w/ R=300-500, scanning multiple orders.

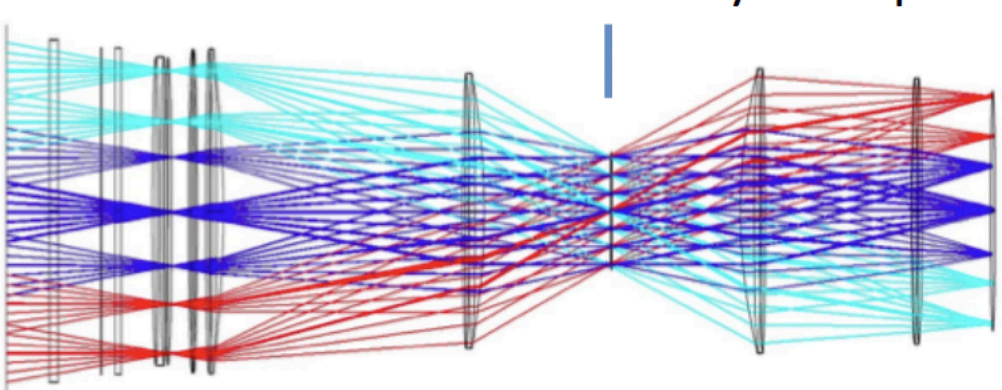
T. Nicola, Henderson et al., Cornell U.

Fabry-Perot Interferometer for Intensity-Mapping





FPI for spectrometer
at Prime-Cam module Lyot stop



Scan 185-440 GHz range in 4 bands across ~1 deg^2 per optics tube simultaneously (3^{rd} to 6^{th} order)

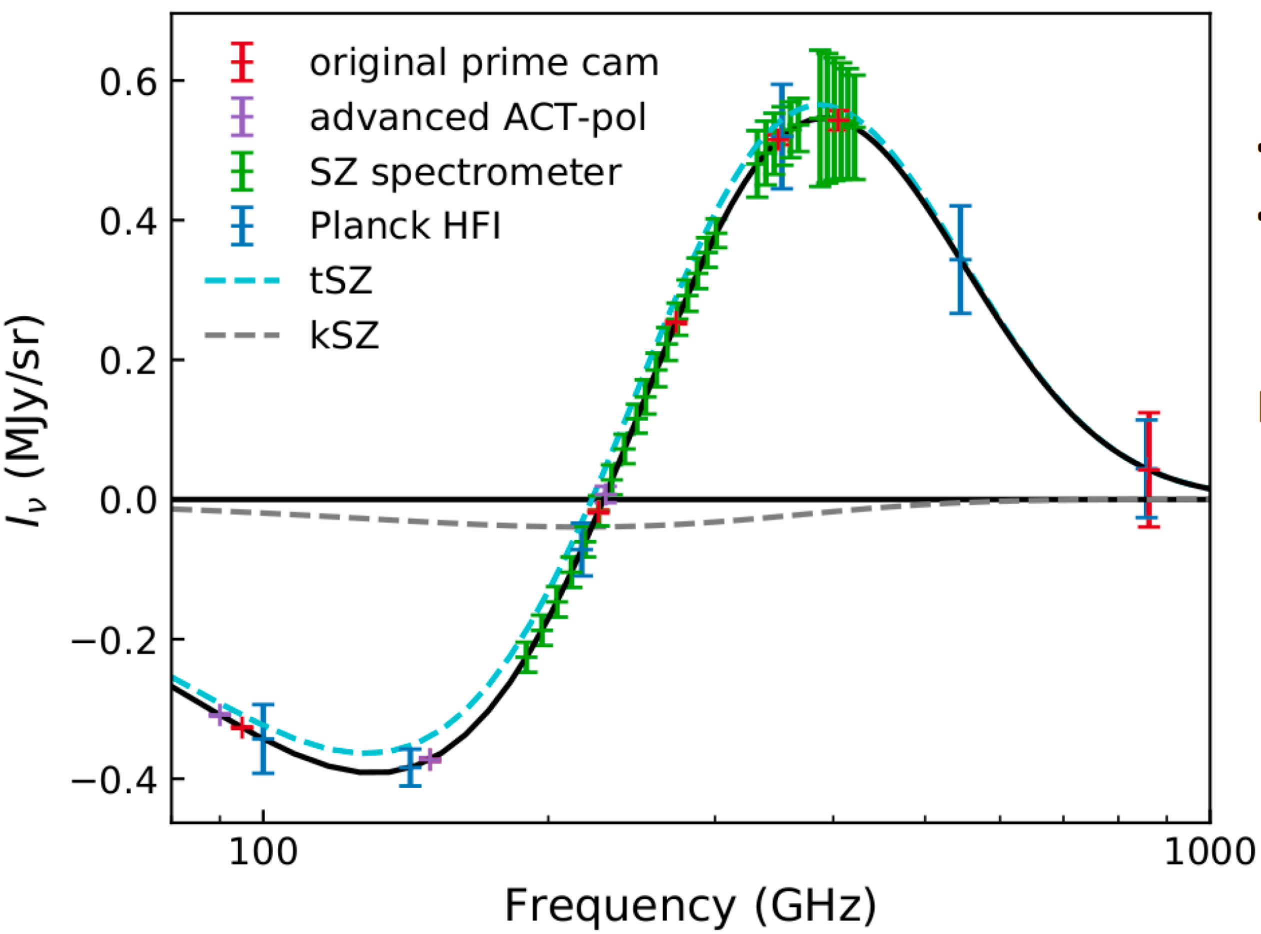
→ [CII] 158 µm at z=3.3-9.3

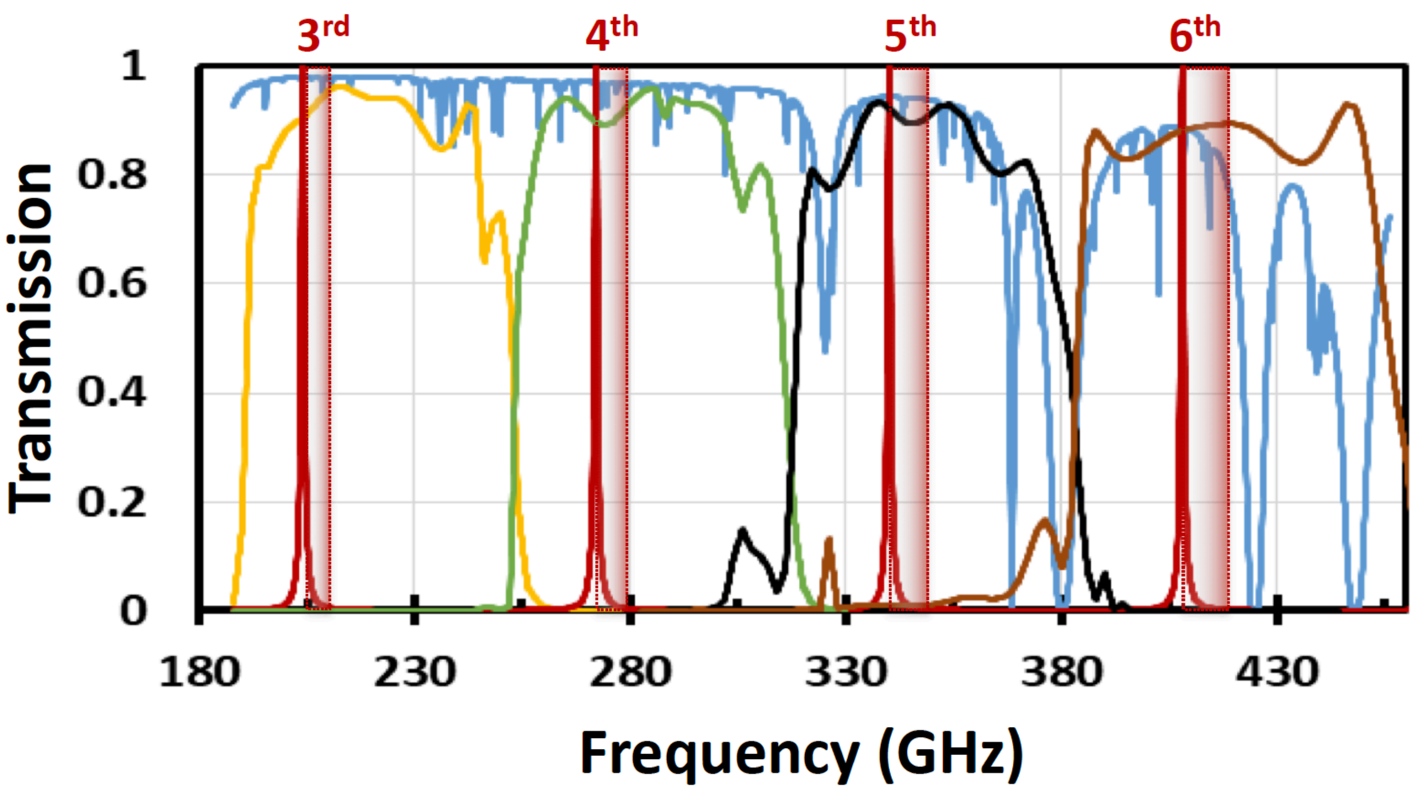
→ [OIII] 88 µm at z>6.7

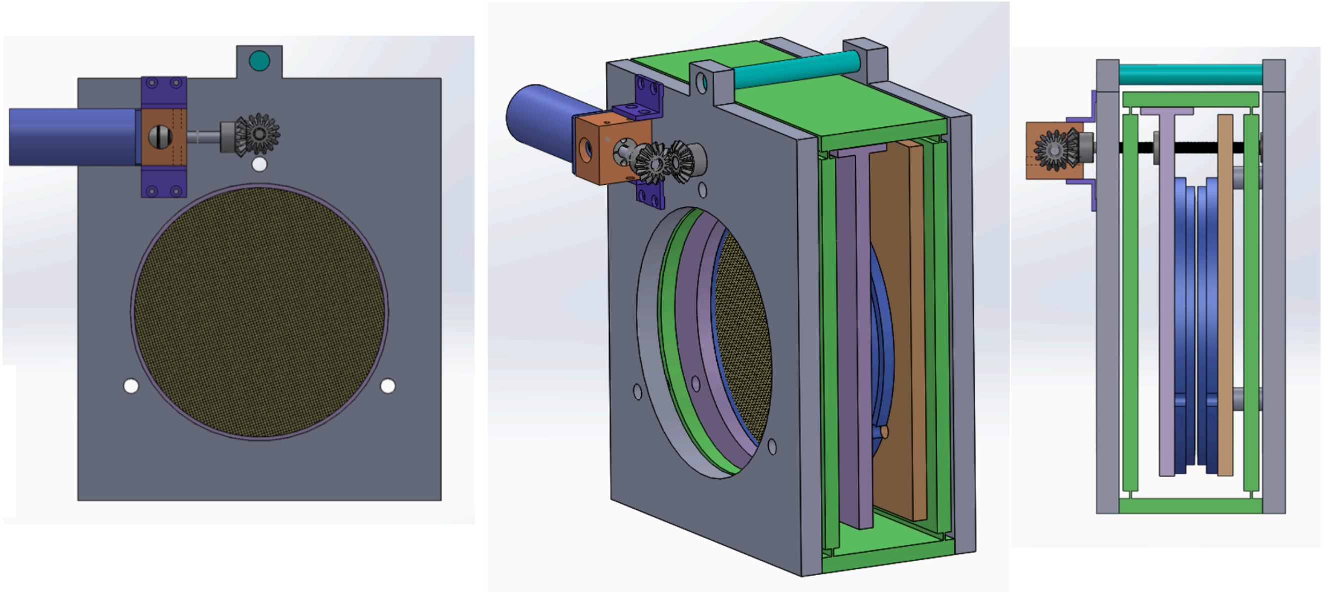
→ CO 2-1 and higher at virtually any z

Initial concepts for an SZ spectrometer

Credit: Gordon Stacey





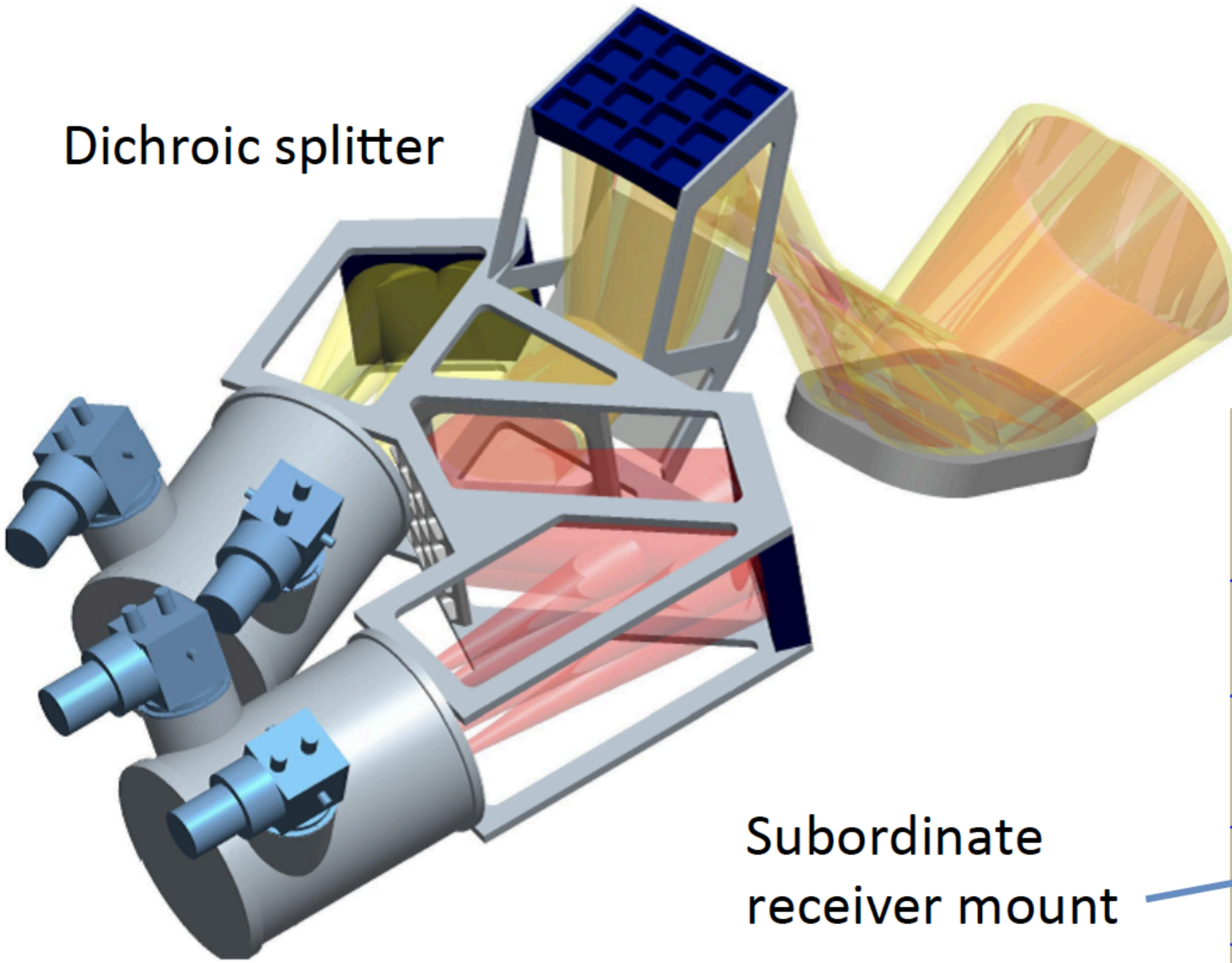


It is quite easy to scan the FPI with a stepper motor to access all the frequencies of interest

Galactic Ecology instrument:
CCAT Heterodyne Array Instrument "CHAI"

CCAT-p

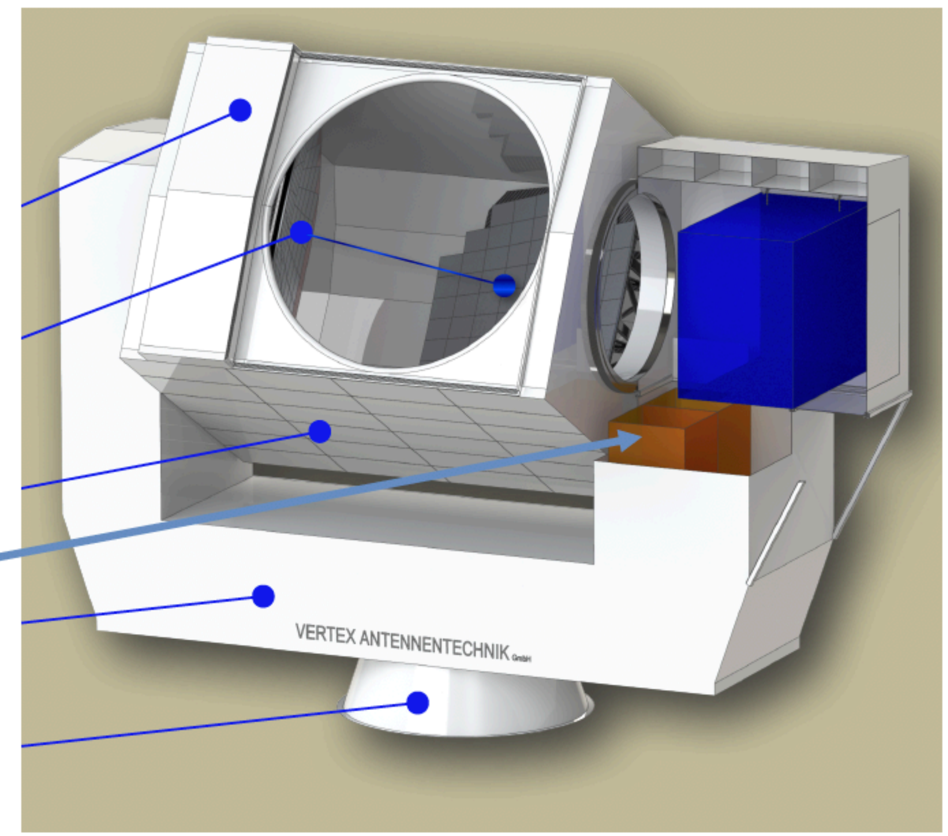
Dichroic splitter



SFB 956

Universität zu Köln

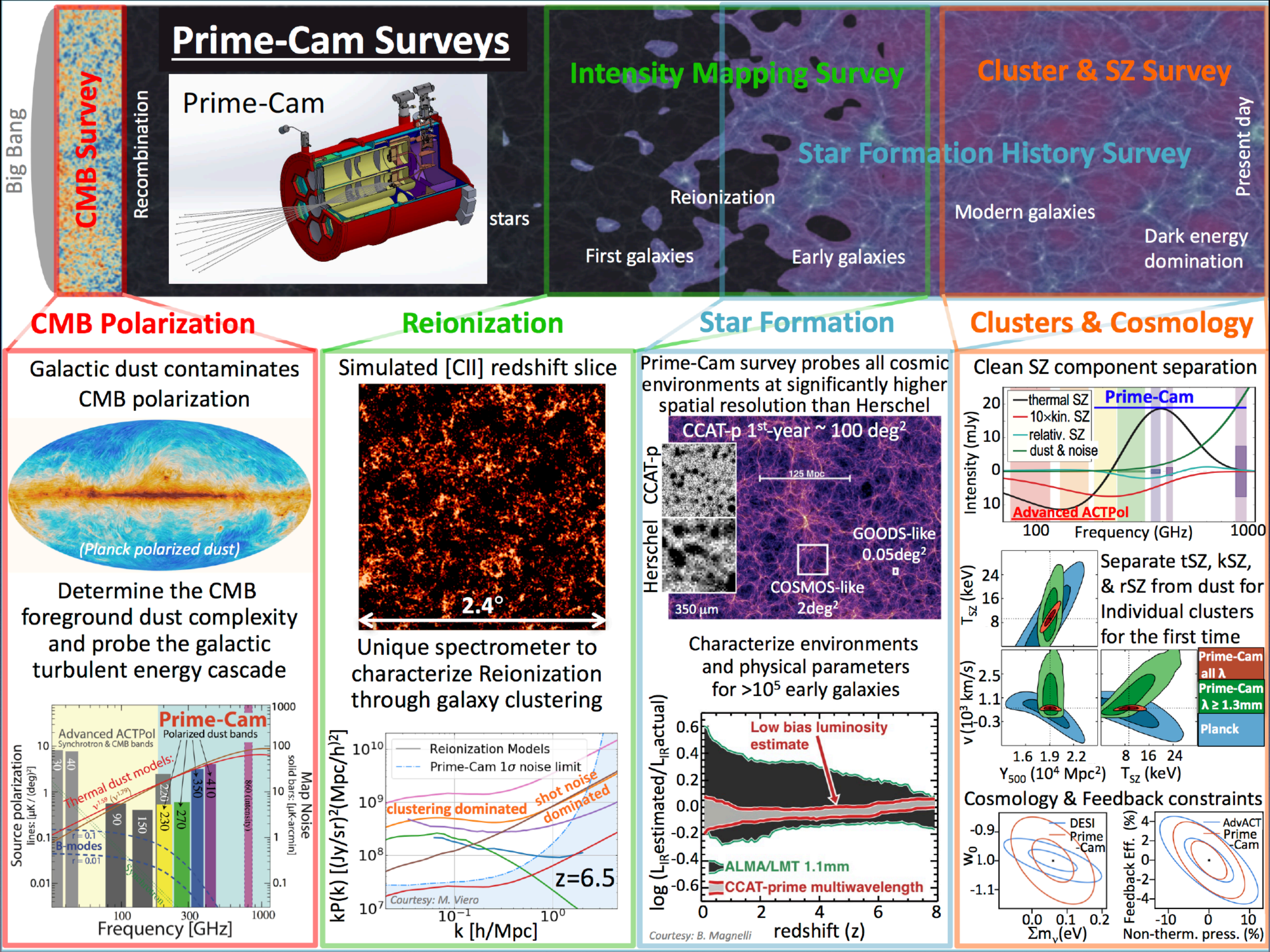
Graf, Stutzki et al.



Max-Planck-Institut für Radioastronomie

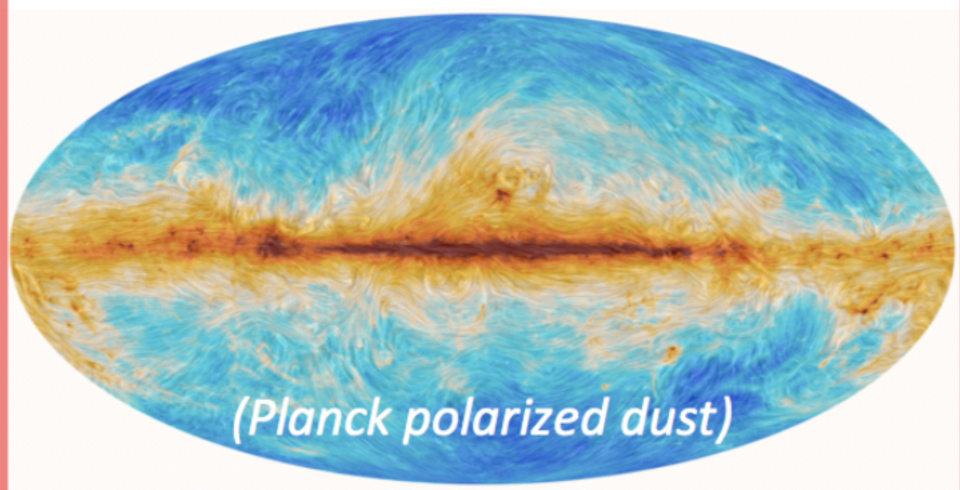
Subordinate receiver mount

- Heterodyne, dual frequency array
- 500 GHz (600 μm) and 850 GHz (350 μm): CO 4-3,7-6 [CI]2-1,1-0
- 64 pixels (baseline), 128 pixels (goal) in each band

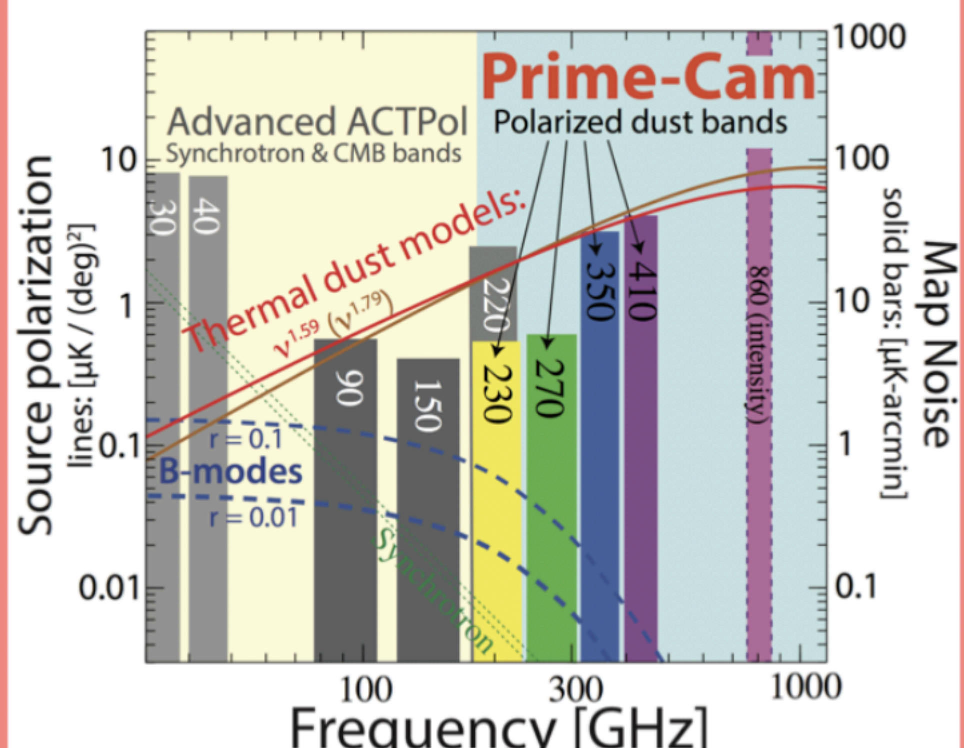

Prime-Cam Surveys
Prime-Cam
Big Bang
CMB Survey
Recombination
stars
Intensity Mapping Survey
Reionization
First galaxies
Early galaxies
Star Formation History Survey
Cluster & SZ Survey
Modern galaxies
Dark energy domination
Present day
CMB Polarization
Reionization
Star Formation
Clusters & Cosmology
Galactic dust contaminates CMB polarization
(Planck polarized dust)
Determine the CMB foreground dust complexity and probe the galactic turbulent energy cascade
Prime-Cam
Polarized dust bands
Advanced ACTPol
Synchrotron & CMB bands
Thermal dust models
B-modes
Source polarization
Map Noise
Frequency [GHz]
Simulated [CII] redshift slice
2.4°
Unique spectrometer to characterize Reionization through galaxy clustering
Reionization Models
Prime-Cam 1σ noise limit
clustering dominated
shot noise dominated
z=6.5
Courtesy: M. Viero
kP(k) [(Jy/sr)^2(Mpc/h)^2]
k [h/Mpc]
Prime-Cam survey probes all cosmic environments at significantly higher spatial resolution than Herschel
CCAT-p 1st-year ~ 100 deg^2
CCAT-p
Herschel
125 Mpc
GOODS-like 0.05deg^2
COSMOS-like 2deg^2
350 μm
Characterize environments and physical parameters for >10^5 early galaxies
Low bias luminosity estimate
ALMA/LMT 1.1mm
CCAT-prime multiwavelength
log (L_IR estimated/L_IR actual)
redshift (z)
Courtesy: B. Magnelli
Clean SZ component separation
thermal SZ
10×kin. SZ
relativ. SZ
dust & noise
Prime-Cam
Advanced ACTPol
Intensity (mJy)
Frequency (GHz)
Separate tSZ, kSZ, & rSZ from dust for Individual clusters for the first time
Prime-Cam all λ
Prime-Cam λ ≥ 1.3mm
Planck
T_SZ (keV)
v (10^3 km/s)
Y_500 (10^4 Mpc^2)
T_SZ (keV)
Cosmology & Feedback constraints
DESI
Prime-Cam
AdvACT
Prime-Cam
w_0
Σm_ν(eV)
Feedback Eff. (%)
Non-therm. press. (%)

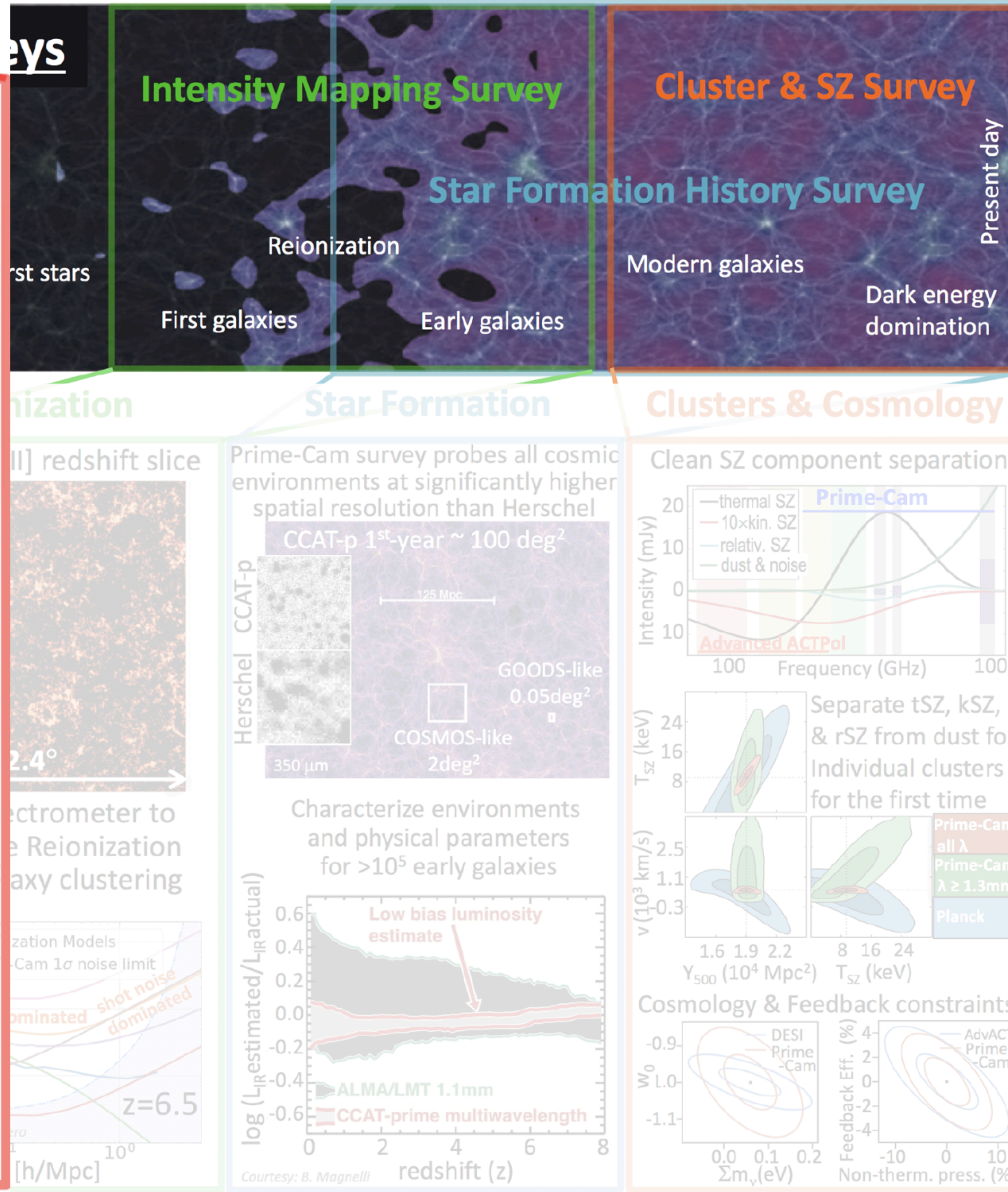
CMB Polarization

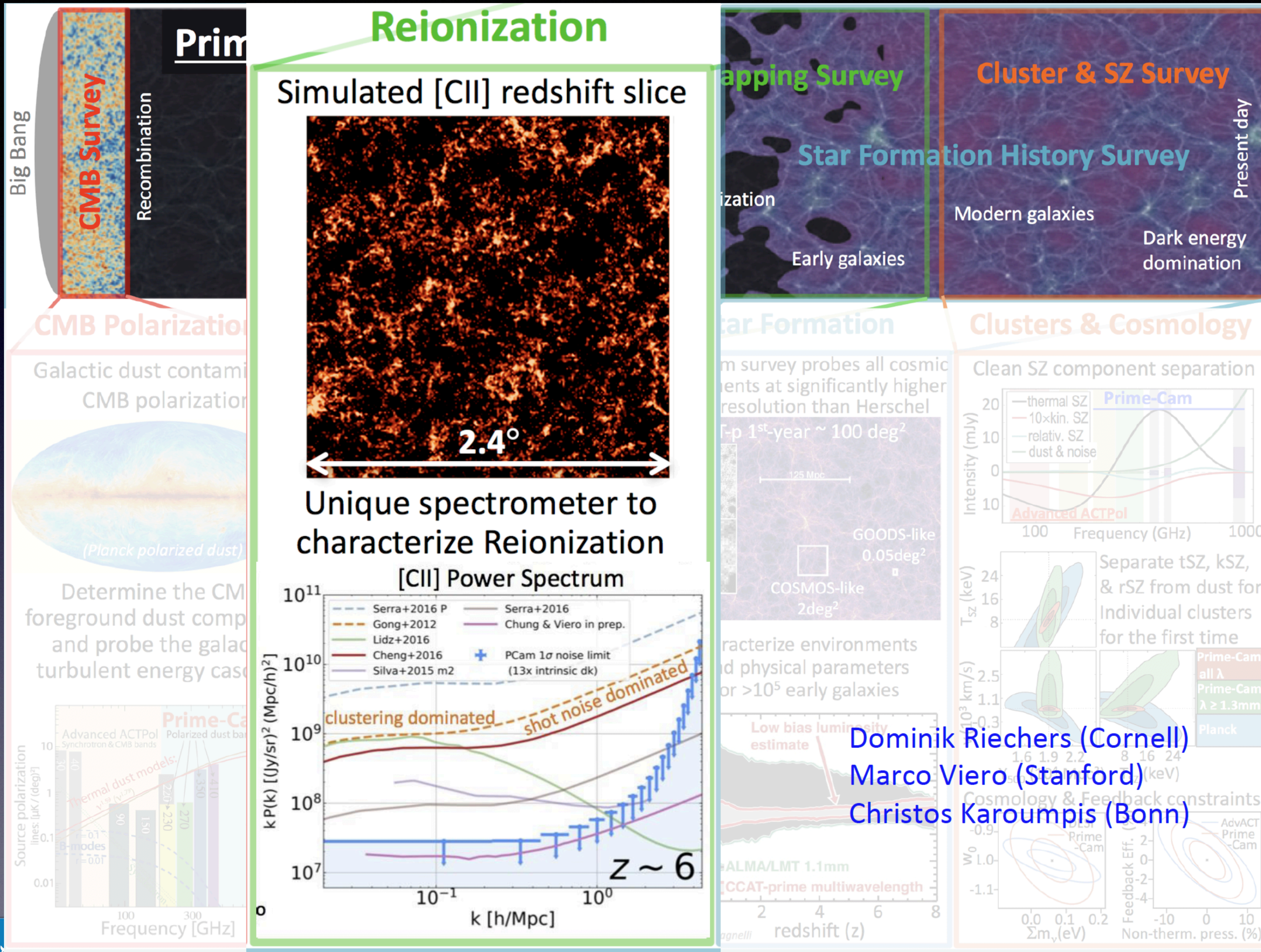
Galactic dust contaminates CMB polarization



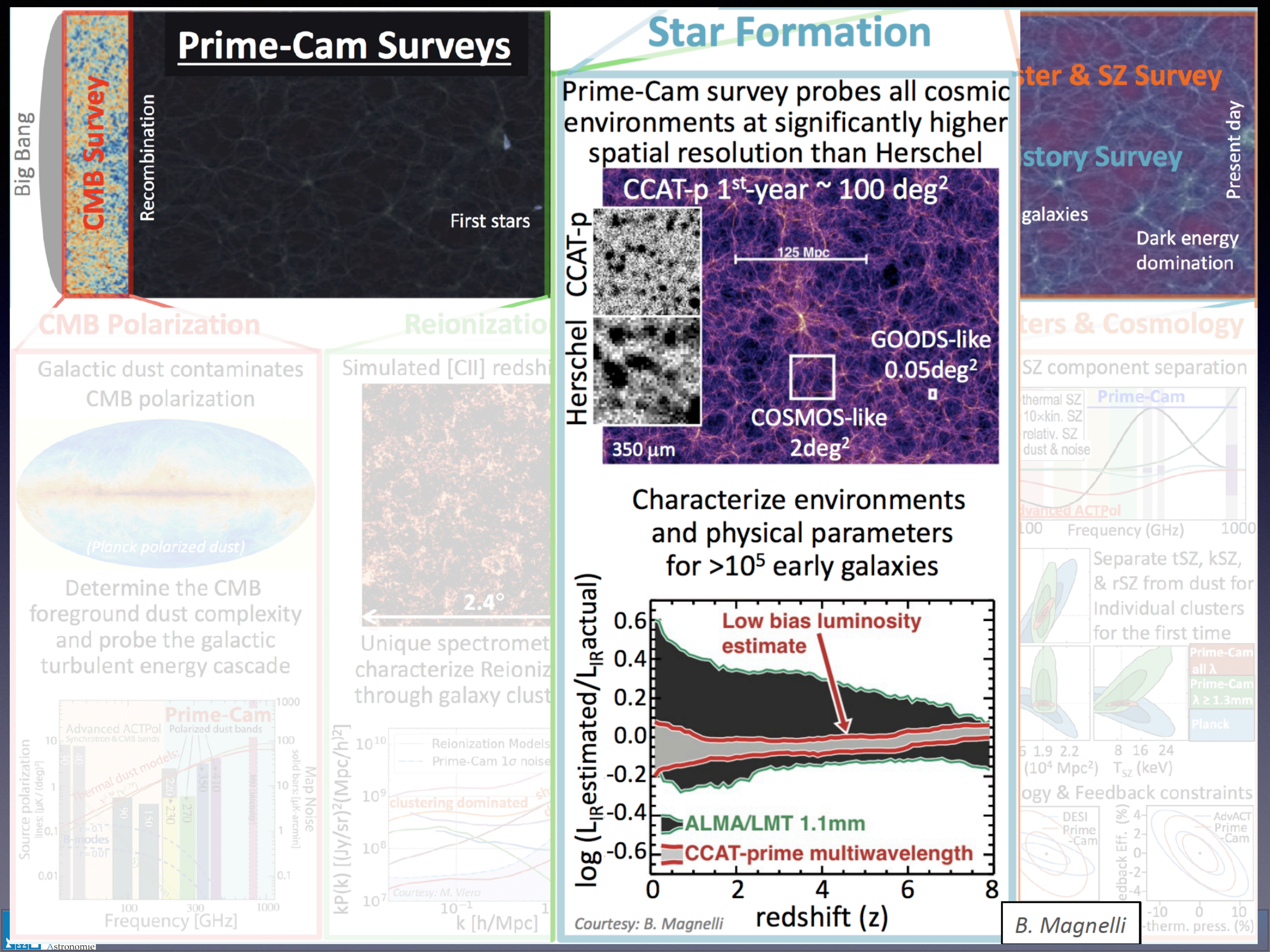
Determine the CMB foreground dust complexity and probe the galactic turbulent energy cascade



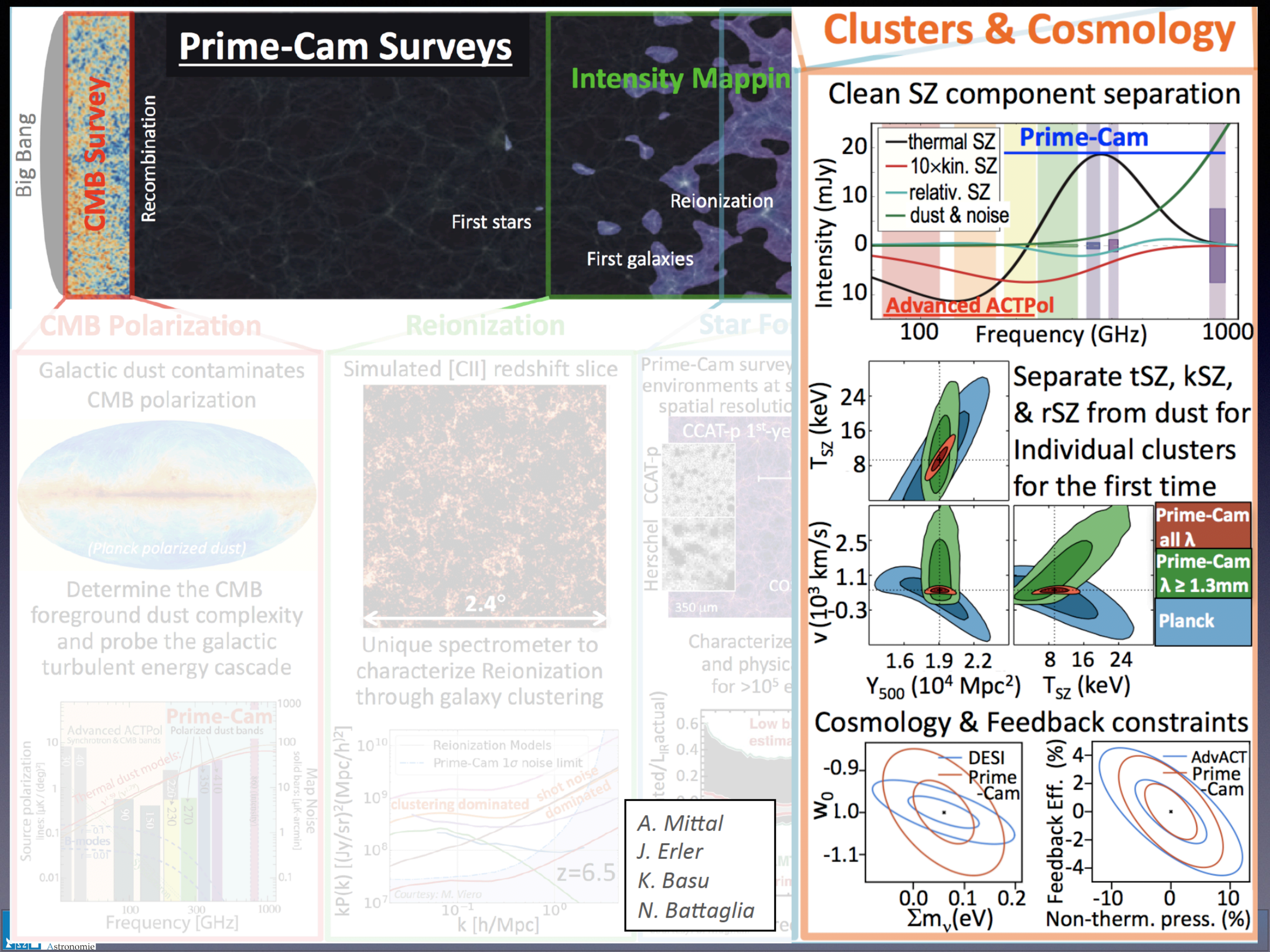




Reionization
Big Bang
CMB Survey
Recombination
Prim
Simulated [CII] redshift slice
2.4°
Unique spectrometer to
characterize Reionization
[CII] Power Spectrum
Serra+2016 P
Gong+2012
Lidz+2016
Cheng+2016
Silva+2015 m2
Serra+2016
Chung & Viero in prep.
PCam 1σ noise limit
(13x intrinsic dk)
clustering dominated
shot noise dominated
z ~ 6
k P(k) [(Jy/sr)^2 (Mpc/h)^2]
k [h/Mpc]
apping Survey
Cluster & SZ Survey
Star Formation History Survey
Present day
ization
Modern galaxies
Early galaxies
Dark energy
domination
CMB Polarizatio
tar Formation
Clusters & Cosmology
Galactic dust contami
CMB polarization
(Planck polarized dust)
Determine the CM
foreground dust comp
and probe the galac
turbulent energy casc
m survey probes all cosmic
ents at significantly higher
resolution than Herschel
Clean SZ component separation
Separate tSZ, kSZ,
& rSZ from dust for
Individual clusters
for the first time
racterize environments
d physical parameters
or >10^5 early galaxies
GOODS-like
0.05deg²
COSMOS-like
2deg²
Cosmology & Feedback constraints
Frequency (GHz)
Frequency [GHz]
redshift (z)
Non-therm. press. (%)
Dominik Riechers (Cornell)
Marco Viero (Stanford)
Christos Karoumpis (Bonn)



Prime-Cam Surveys
Big Bang
CMB Survey
Recombination
First stars
Star Formation
Prime-Cam survey probes all cosmic environments at significantly higher spatial resolution than Herschel
CCAT-p 1st-year ~ 100 deg²
CCAT-p
Herschel
125 Mpc
GOODS-like 0.05deg²
COSMOS-like 2deg²
350 µm
Characterize environments and physical parameters for >10⁵ early galaxies
Low bias luminosity estimate
ALMA/LMT 1.1mm
CCAT-prime multiwavelength
log (L_IR estimated/L_IR actual)
redshift (z)
Courtesy: B. Magnelli
B. Magnelli
ter & SZ Survey
story Survey
galaxies
Present day
Dark energy domination
CMB Polarization
Galactic dust contaminates CMB polarization
(Planck polarized dust)
Determine the CMB foreground dust complexity and probe the galactic turbulent energy cascade
Frequency [GHz]
Reionizatio
Simulated [CII] redshi
2.4°
Unique spectromet characterize Reioniz through galaxy clust
Reionization Models
Prime-Cam 1σ noise
clustering dominated
Courtesy: M. Viero
k [h/Mpc]
ters & Cosmology
SZ component separation
Prime-Cam
Frequency (GHz)
Separate tSZ, kSZ, & rSZ from dust for Individual clusters for the first time
ogy & Feedback constraints



Prime-Cam Surveys
Big Bang
CMB Survey
Recombination
First stars
Intensity Mappin
Reionization
First galaxies
Clusters & Cosmology
Clean SZ component separation
thermal SZ
10×kin. SZ
relativ. SZ
dust & noise
Prime-Cam
Advanced ACTPol
Intensity (mJy)
Frequency (GHz)
Separate tSZ, kSZ, & rSZ from dust for Individual clusters for the first time
Prime-Cam all λ
Prime-Cam λ ≥ 1.3mm
Planck
T_{SZ} (keV)
v (10^3 km/s)
Y_{500} (10^4 Mpc^2)
T_{SZ} (keV)
Cosmology & Feedback constraints
DESI
Prime -Cam
AdvACT
Prime -Cam
w_0
Σm_ν(eV)
Feedback Eff. (%)
Non-therm. press. (%)
CMB Polarization
Galactic dust contaminates CMB polarization
(Planck polarized dust)
Determine the CMB foreground dust complexity and probe the galactic turbulent energy cascade
Advanced ACTPol
Prime-Cam
Polarized dust bands
Frequency [GHz]
Reionization
Simulated [CII] redshift slice
2.4°
Unique spectrometer to characterize Reionization through galaxy clustering
Reionization Models
Prime-Cam 1σ noise limit
clustering dominated
shot noise dominated
z=6.5
k [h/Mpc]
Star Fo
Prime-Cam survey
Herschel
CCAT-p
350 μm
A. Mittal
J. Erler
K. Basu
N. Battaglia

SPIE Proceedings 2018

arXiv:1807.04354
arXiv:1807.06675
arXiv:1807.06678
arXiv:1807.00058

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CCAT-Prime: science with an ultra-widefield submillimeter observatory on Cerro Chajnantor

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M. Nolta; S. C. Parsh
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Michele Limon; Fr
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Author(s): E. M. Vavagiakis; Z. Ahmed; A. Ali; K. Basu; N. Battaglia; F. Bertoldi; R. Bond; R. Bustos; S. C. Chapman; D. Chung; G. Coppi; N. F. Cothard; S. Dicker; C. J. Duell; S. M. Duff; J. Erler; M. Fich; N. Galitzki; P. A. Gallardo; S. W. Henderson; T. L. Herter; G. Hilton; J. Hubmayr; K. D. Irwin; B. J. Koopman; J. McMahon; N. Murray; M. D. Niemack; T. Nikola; M. Nolta; J. Orlowski-Scherer; S. C. Parshley; D. A. Riechers; K. Rossi; D. Scott; C. Sierra; M. Silva-Feaver; S. M. Simon; G. J. Stacey; J. R. Stevens; J. N. Ullom; M. R. Vissers; S. Walker; E. J. Wollack; Z. Xu; N. Zhu

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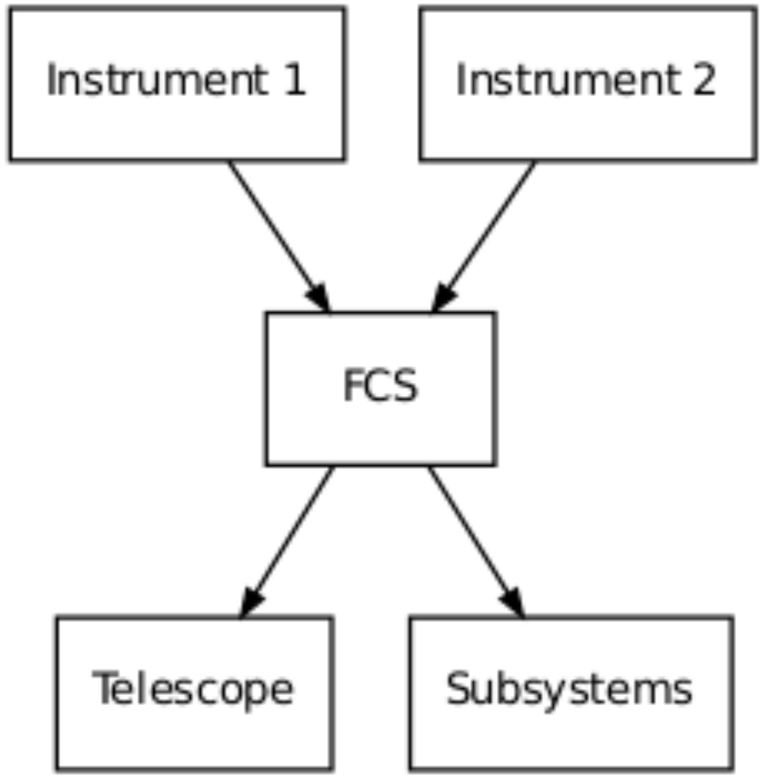
Status update

- Project
  - **on schedule**, in cost frame ($/€ a concern), basic infrastructure costs still uncertain
- Telescope
  - Vertex: **passed PDR**, no technical risk items
  - Work proceeding on mirror metrology
- Chile
  - TAO: everything approved for road, construction begins
  - San Pedro base camp: Radiosky not selected yet
  - CCAT concession not yet reissued but assurances from CONICYT
  - talking to ALMA about power
- **Prime-Cam proposals** (first round were not successful)
  - MSIP: 3-tube instrument ~ $7.5M
  - NASA AST submitted by Niemack – CMB/SZ science single tube, smaller arrays
  - NASA APRA submitted by Stacey – EoR science, single tube, smaller array
- Four **SPIE papers** are now online
- Synergies with SO still a work in progress
  - Telescope, Radiosky and Prime-Cam already proceeding
  - Software and infrastructure
- Consortium Agreements
  - CCAT Corp. signed
  - German Agreement being iterated
- Weekly science (Wed. 17h) and technical/software telecon

CCAT-prime Software

Software Group:
Mike Nolta (lead; Uni Toronto), Higgins, Buchbender, Simon (Uni Köln), Schaaf (Uni Bonn), Nikola (Cornell), Fich (Waterloo); Uni Toronto will hire additional software developer

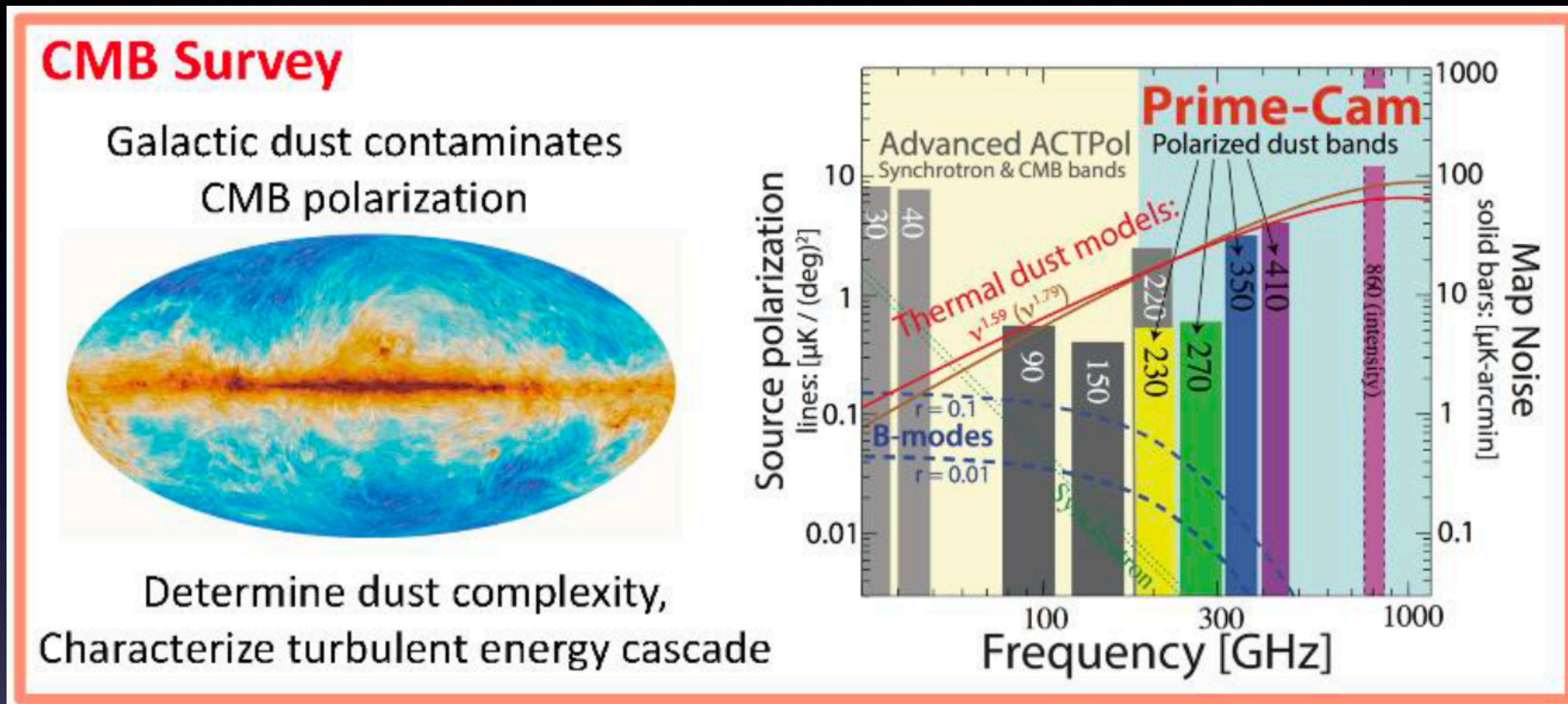
CCAT-prime will have small number of instruments, operated by instrument teams who want to be in control of operations with their existing tools. Approach: Give instrument software access to telescope and subsystems through Facility Control System (FCS).



Software Timeline:

- July 2018: Instruments-FCS-ICD ready
- End 2018: Design FCS ready
- Mid 2019: Telescope Control System (TCS) and File Transport System (FTS) ready
- Mid 2020: All subsystems ready

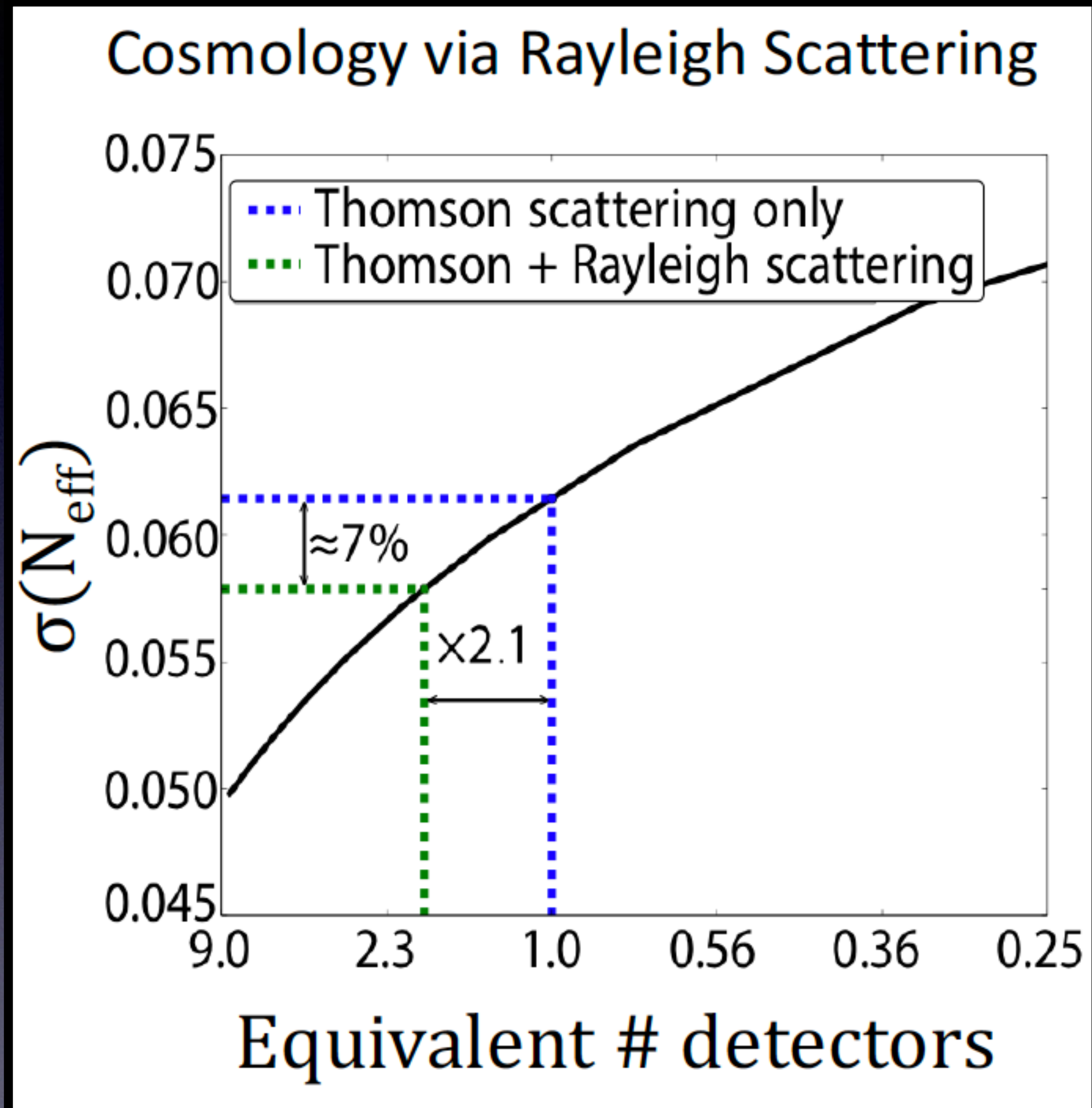
CMB science: Dust & Rayleigh scattering



Change of the dust SED and polarization properties within the large beams for B-mode experiments (e.g. LiteBIRD) will be a big problem for accurate subtraction of the foreground and reach the necessary sensitivity for *r* ≲*0.01.*

CCAT-prime will provide accurate averages of dust spectrum and polarization by making high-sensitivity sub arcminute-scale measurements above 250 GHz.

CMB science: Dust & Rayleigh scattering



Credit: Mike Niemack, CCAT-p MSIP proposal

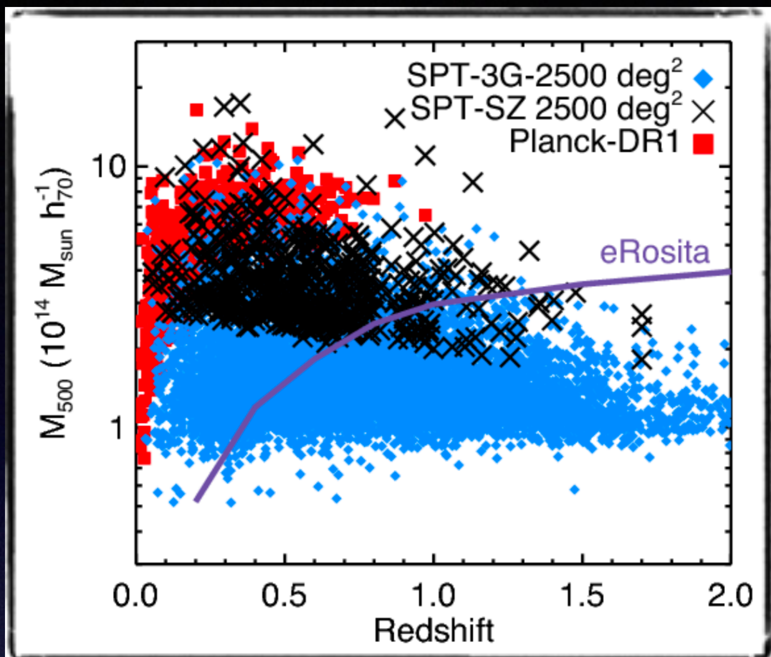
Rayleigh scattering of CMB photons by neutral H and He atoms is a standard prediction of cosmology, introducing a frequency-dependent change to the visibility function.

Due to the frequency^4 dependence high frequency measurements are critical.

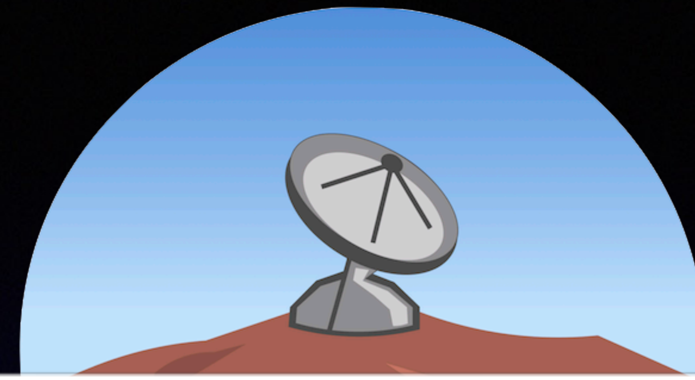
Measuring the Rayleigh scattering will offer on average ~10% improvement on cosmological parameter errors.

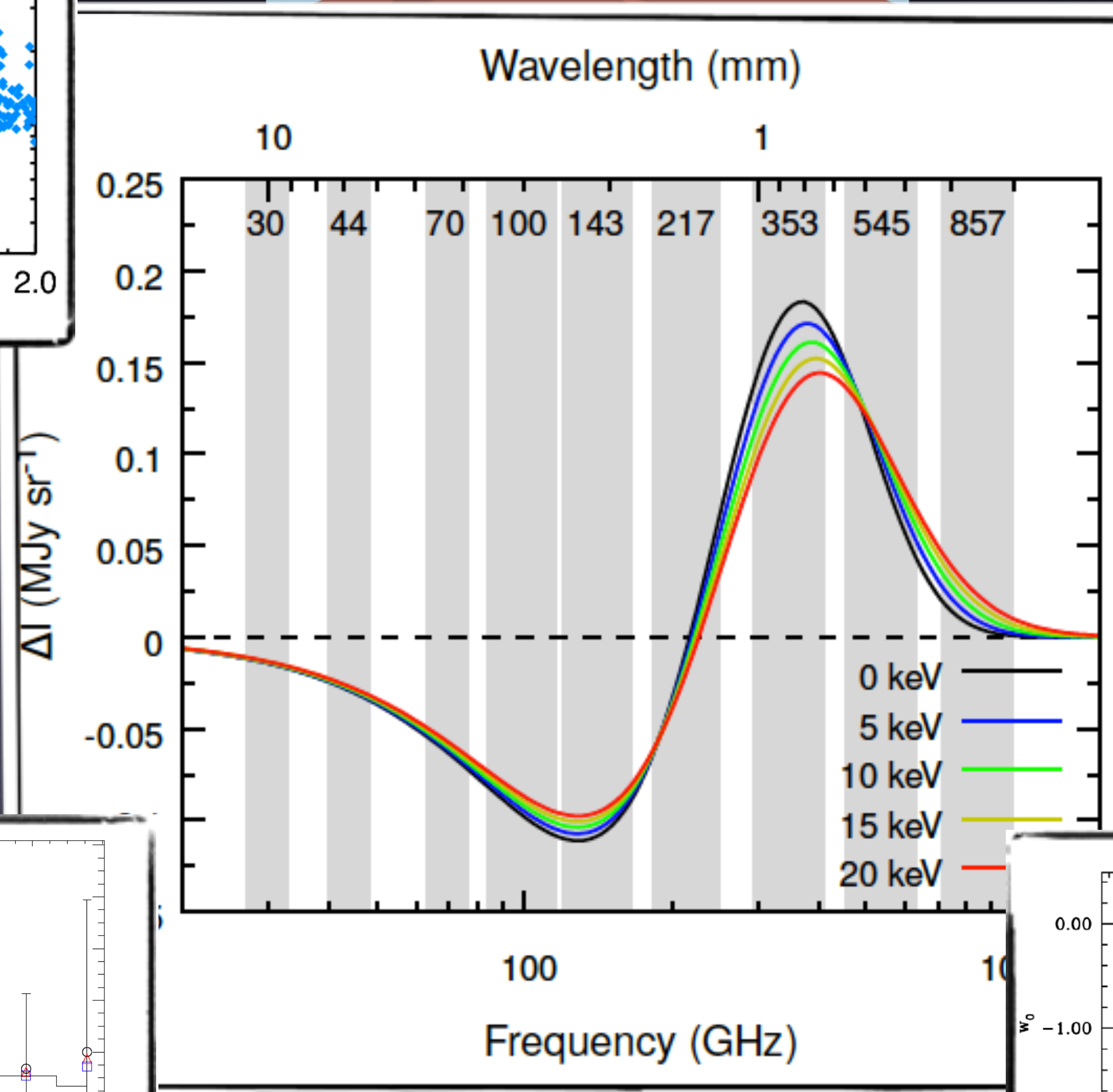
This modest improvement can be translated into a significant improvement in the number of detectors needed to make similar progress.

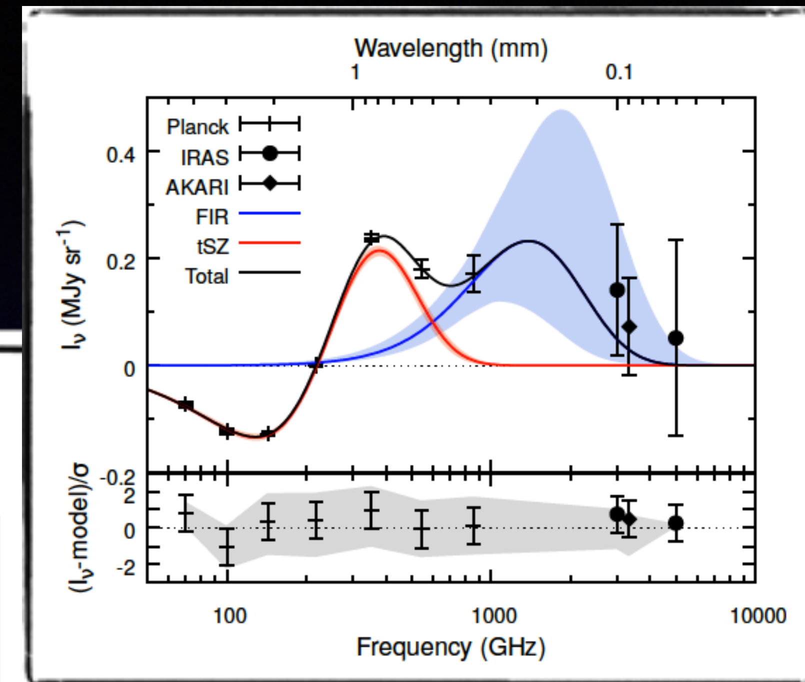
SZ Spectroscopy with CCAT-p and beyond



SZ cluster number count



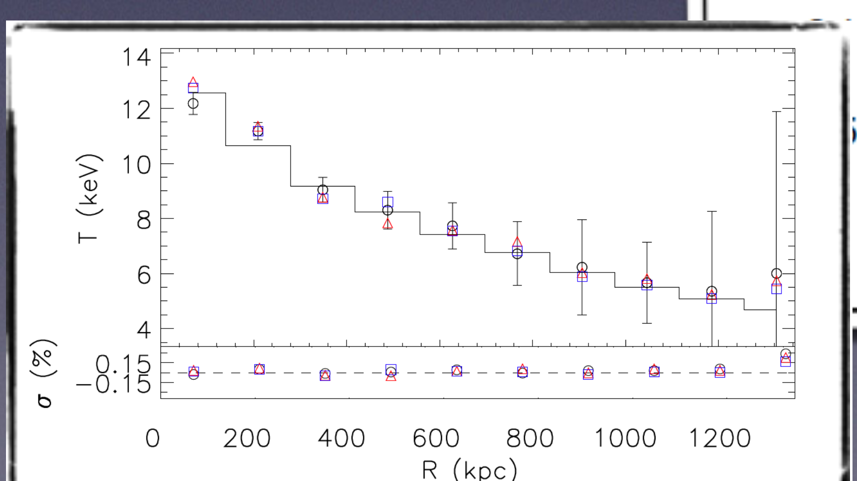


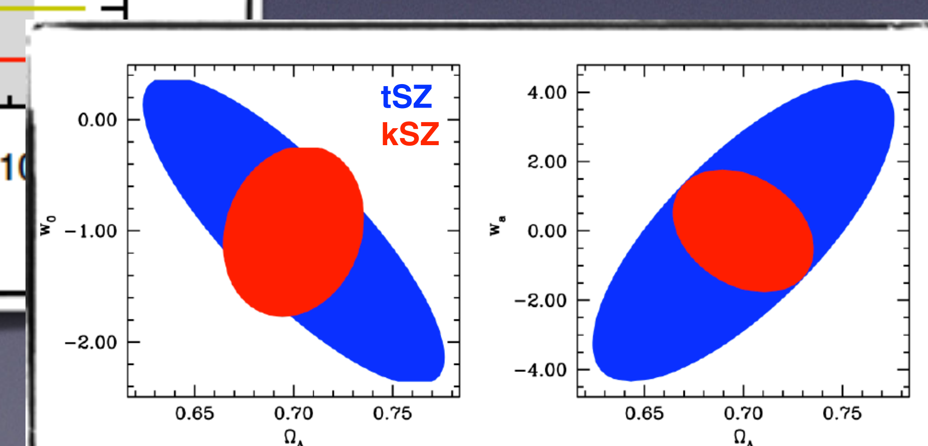


Custer FIR contamination

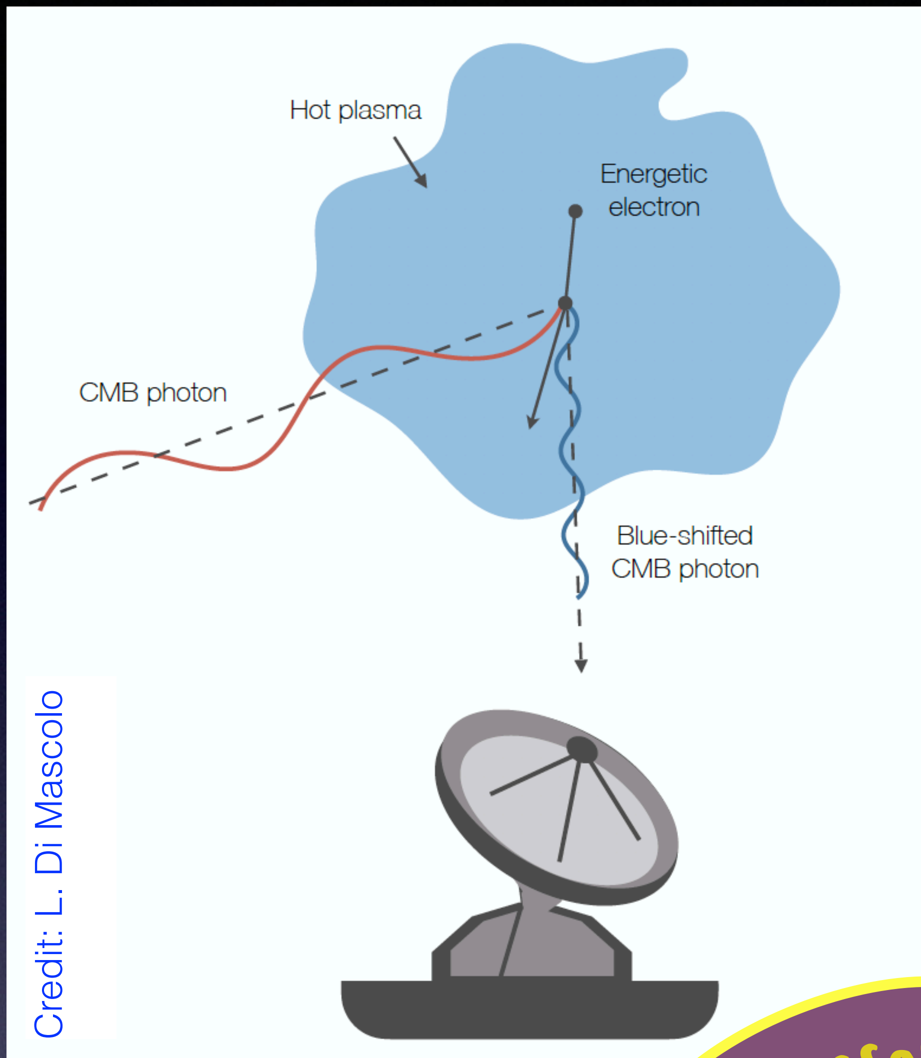
rSZ temperature profile

kSZ cosmology





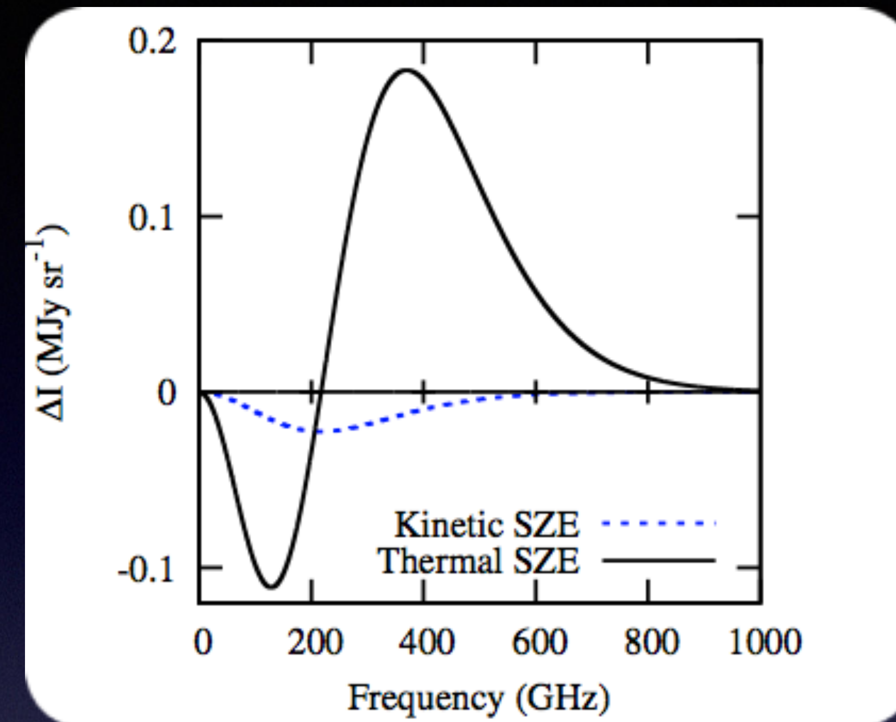
The Sunyaev-Zel'dovich effect

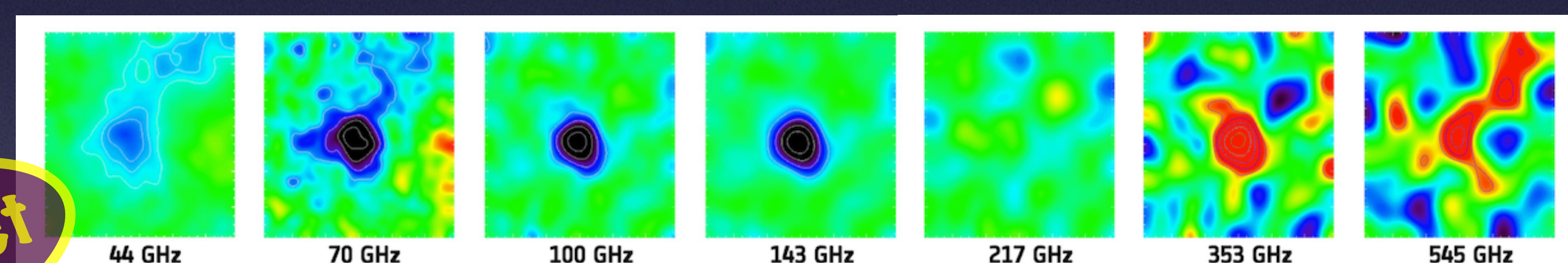


Inverse Compton scattering producing unique spectral distortion on the background CMB.

An ideal tool for finding and characterizing galaxy clusters.

Resolved source flux is redshift independent and scales linearly with the gas density!

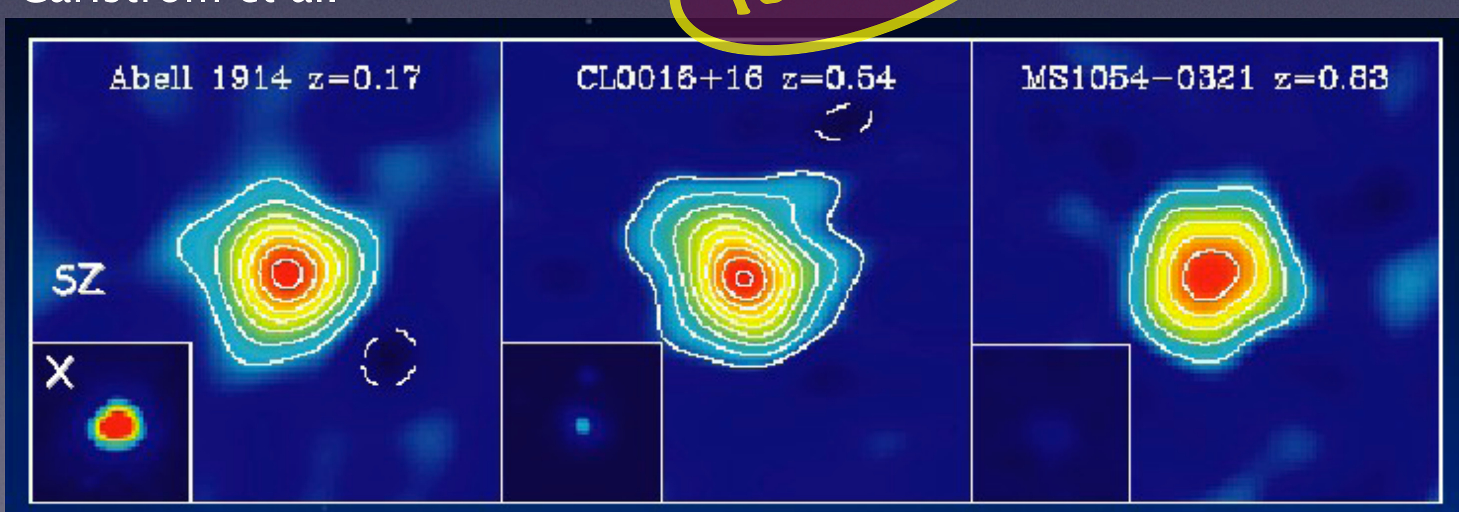




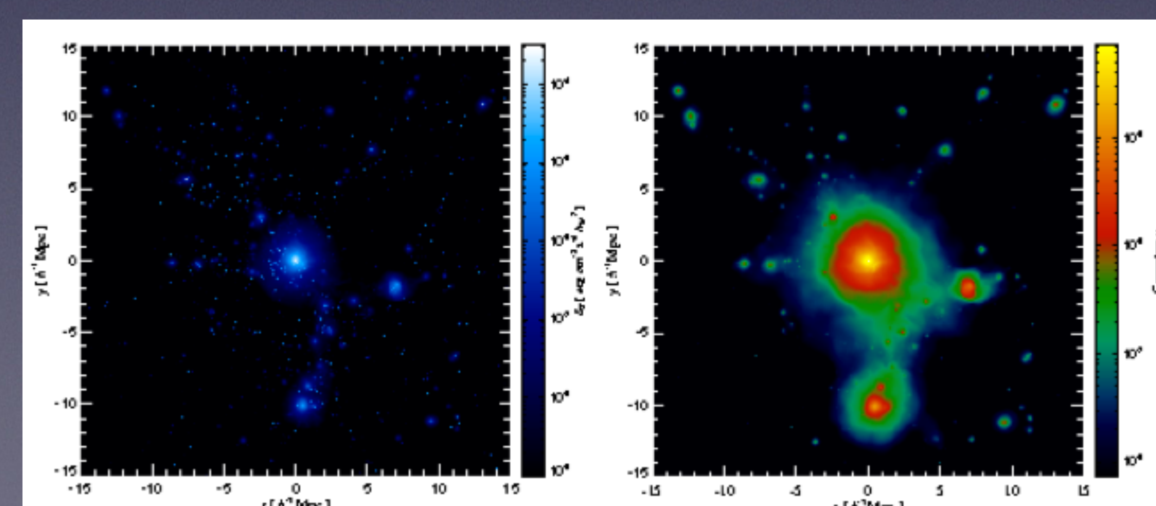
Credit: Planck collaboration

tSZ Effect

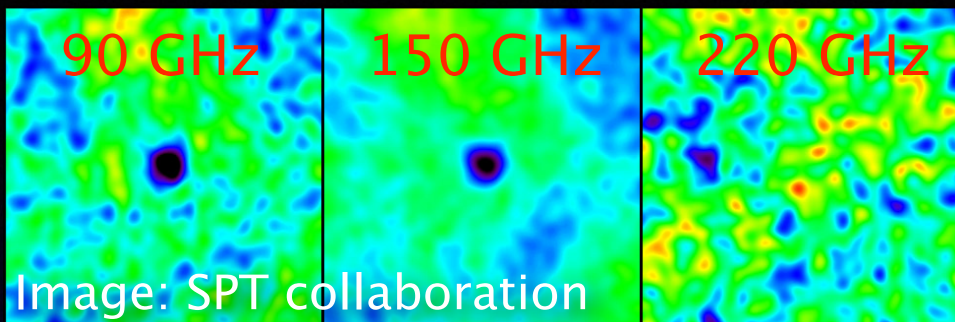
Carlstrom et al.



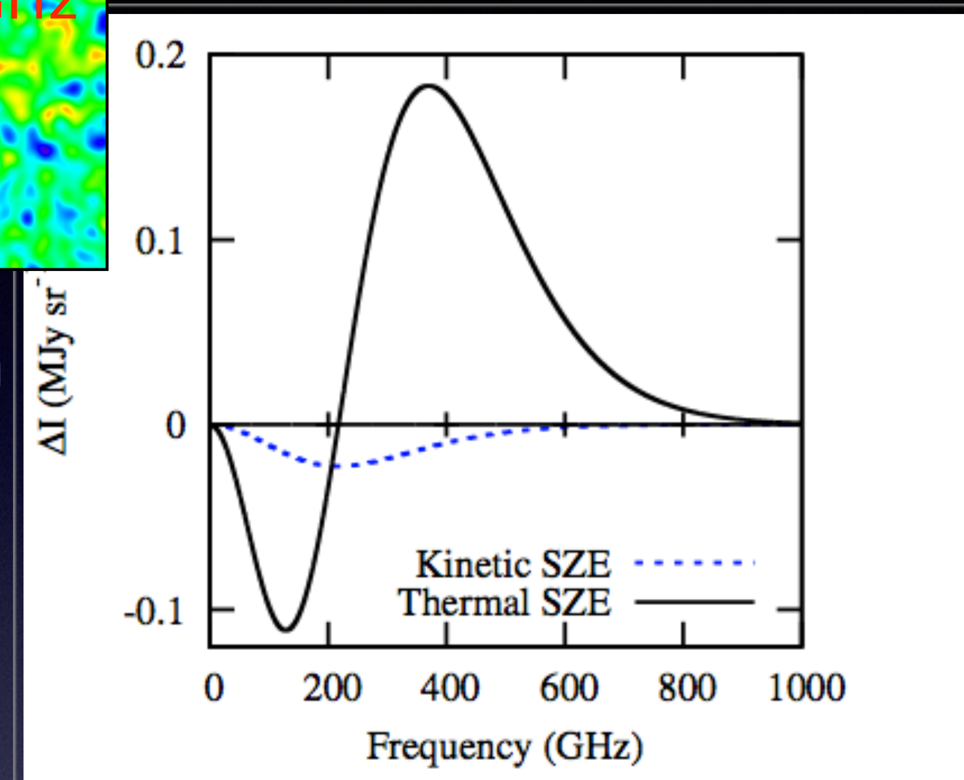
Sims: Pfrommer et al.



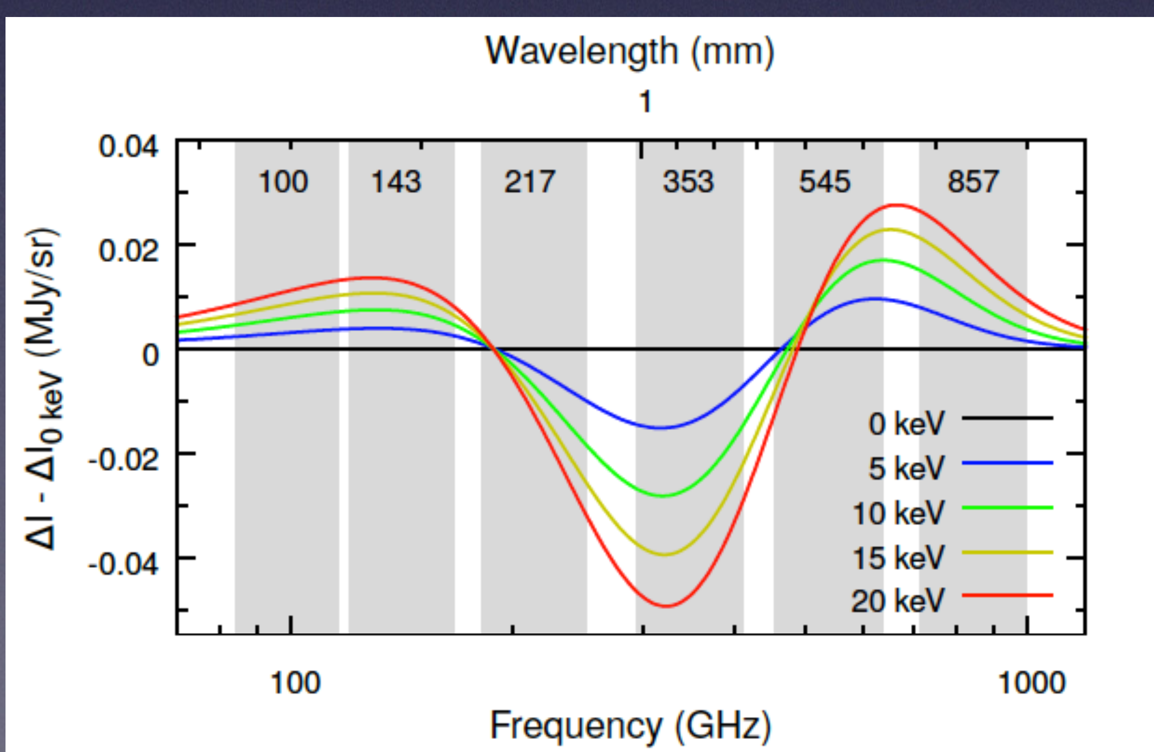
Different favours of the SZ effect



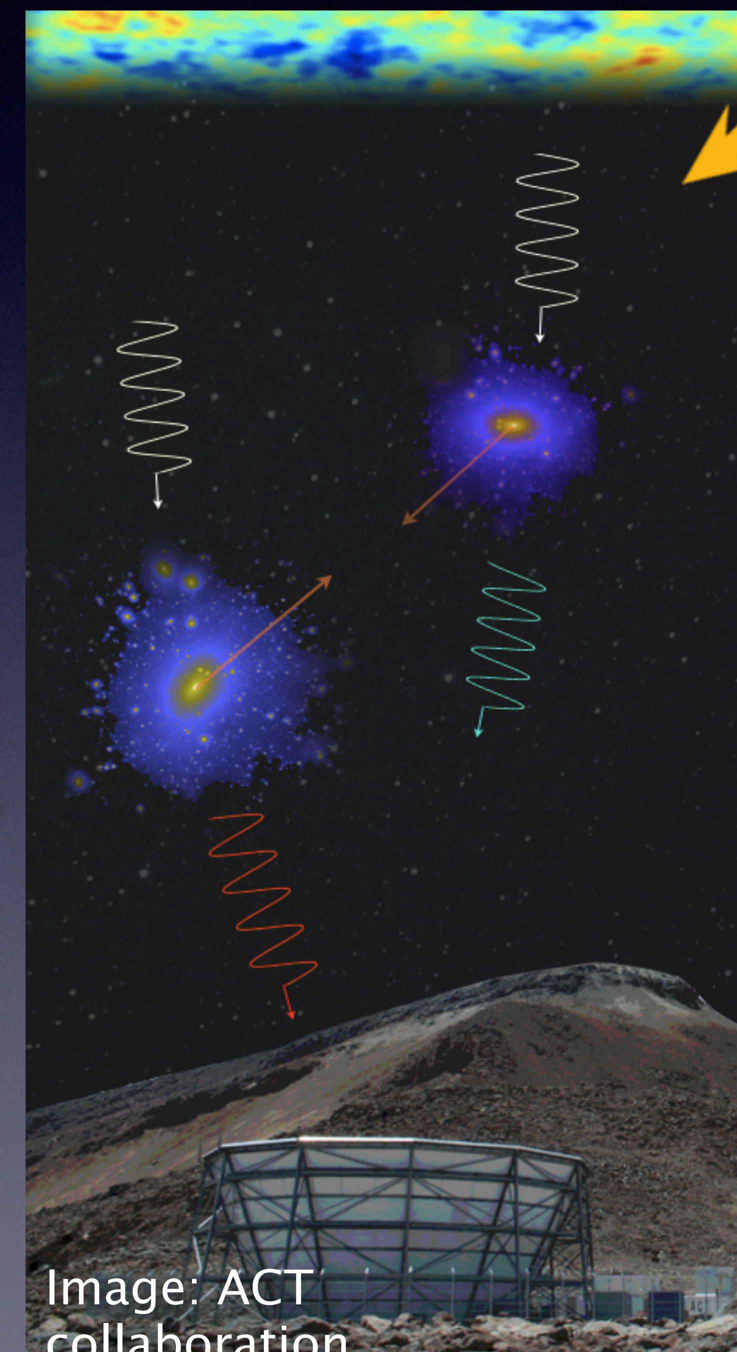
tSZ effect for cluster selection and basic characterization



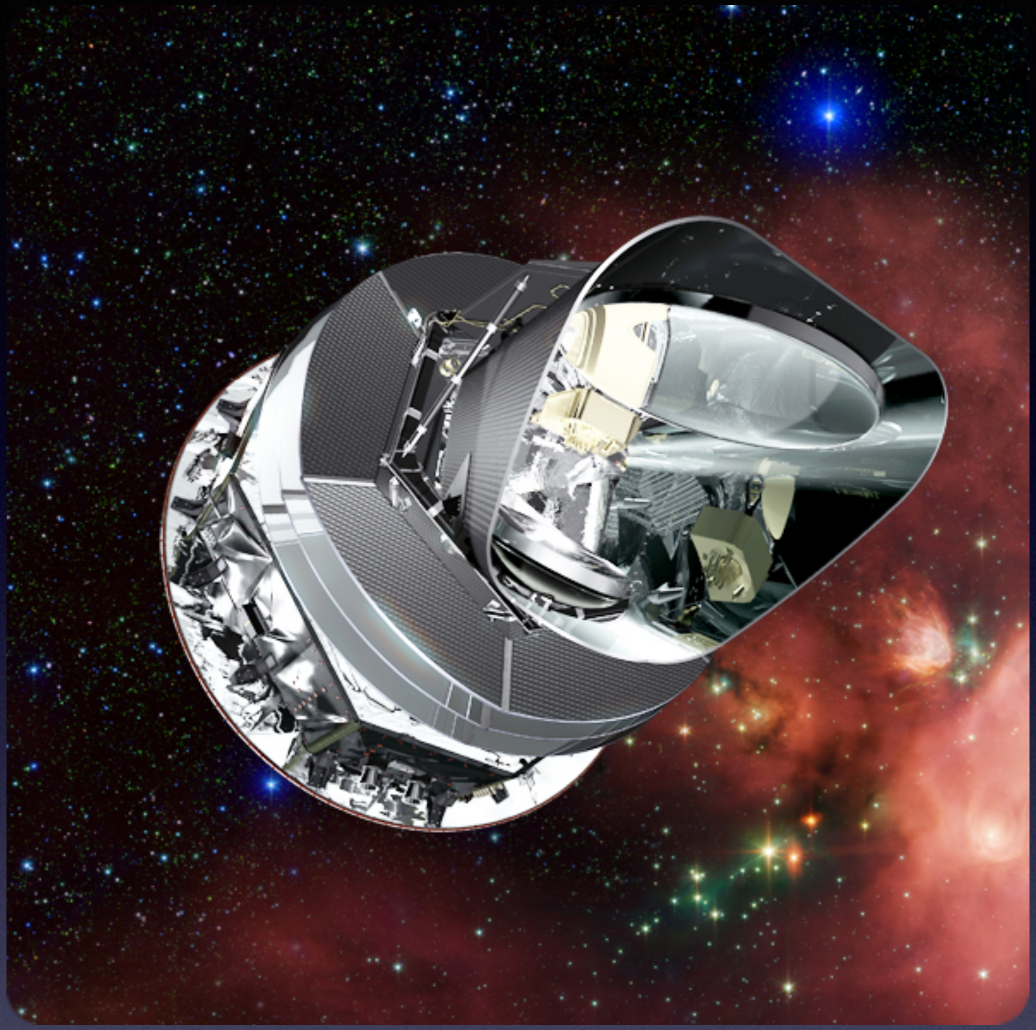
kSZ effect to measure cluster l.o.s. momentum (both pairwise and individual)

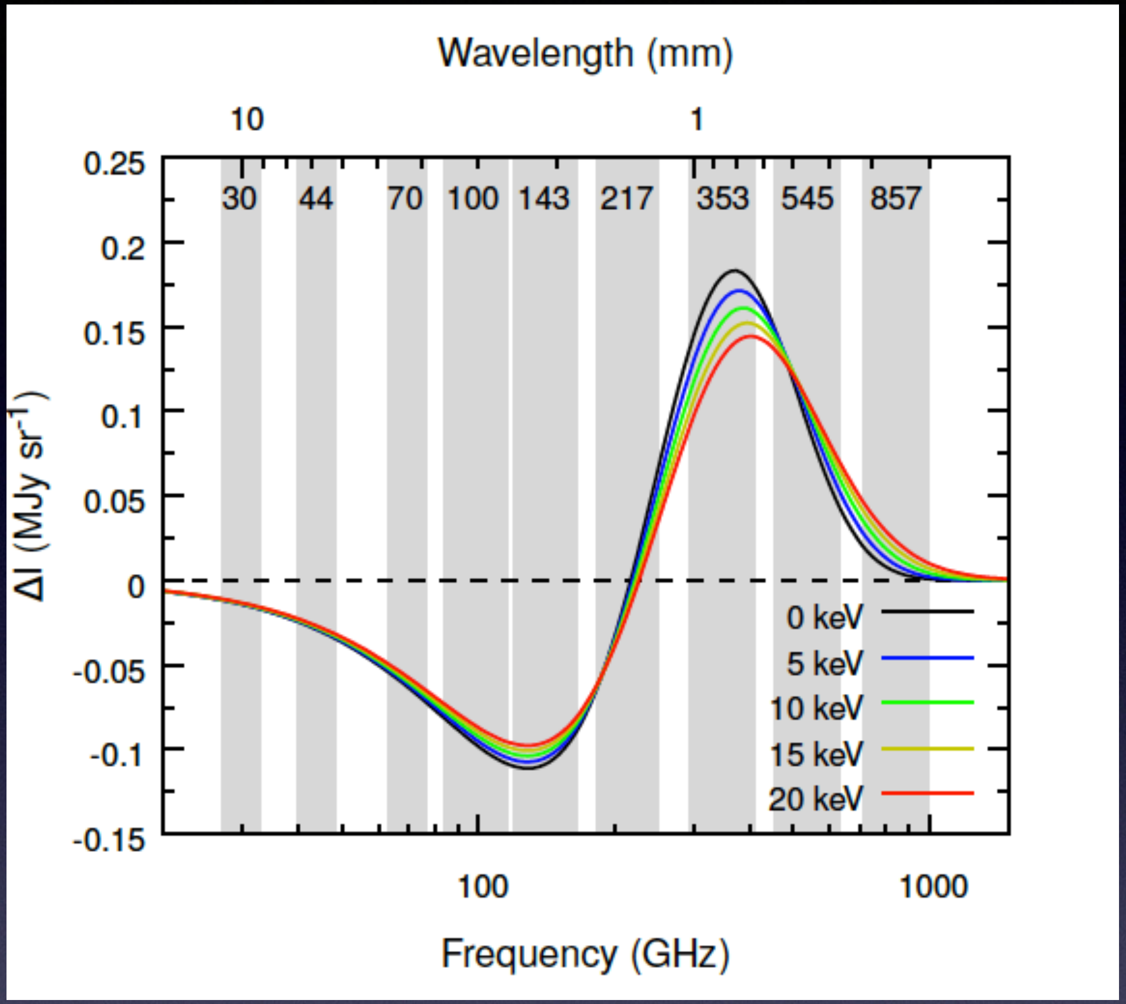


rSZ effect (or the relativistic tSZ effect) for cluster temperatures



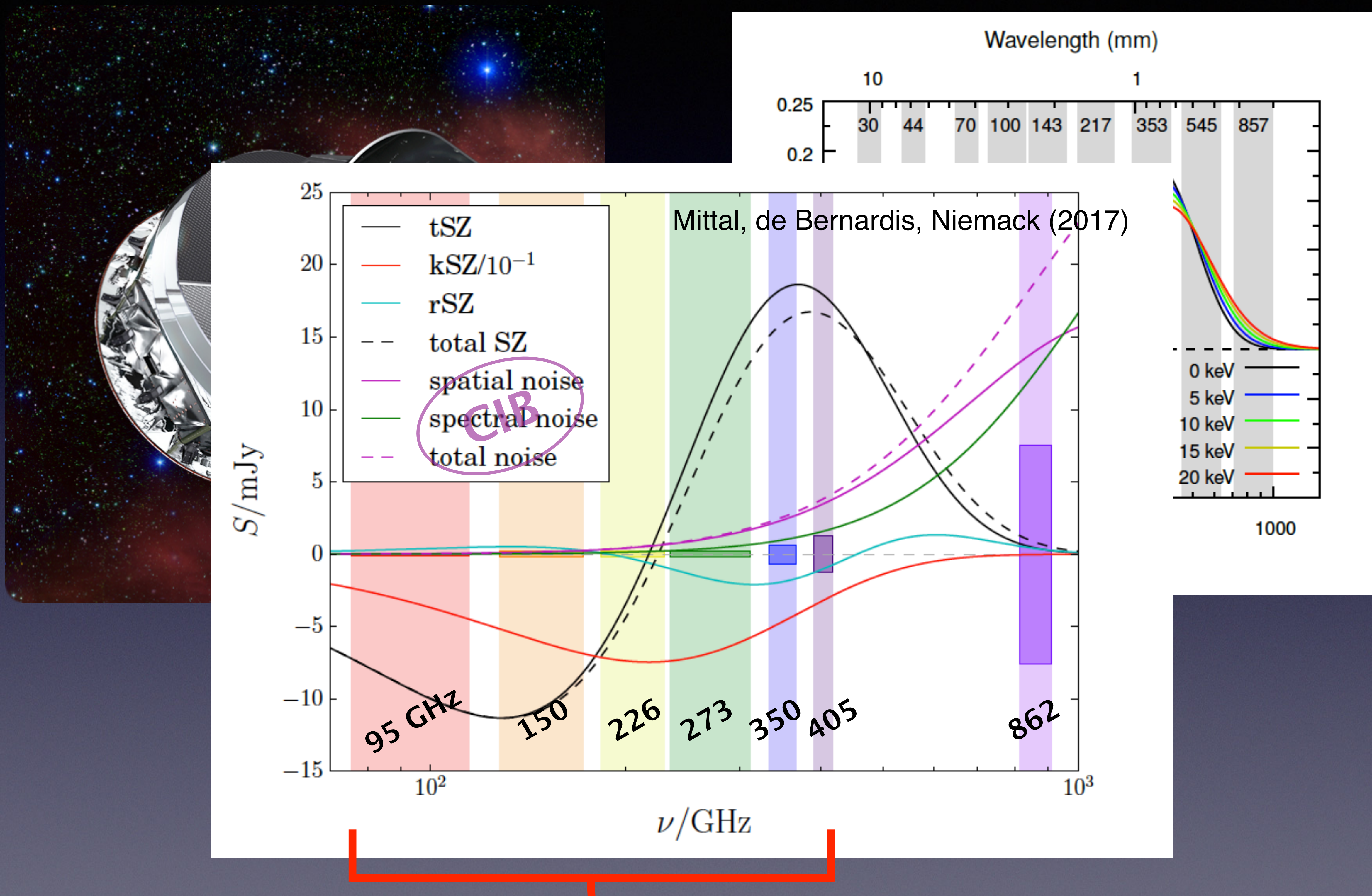
Requirement for SZ spectroscopy





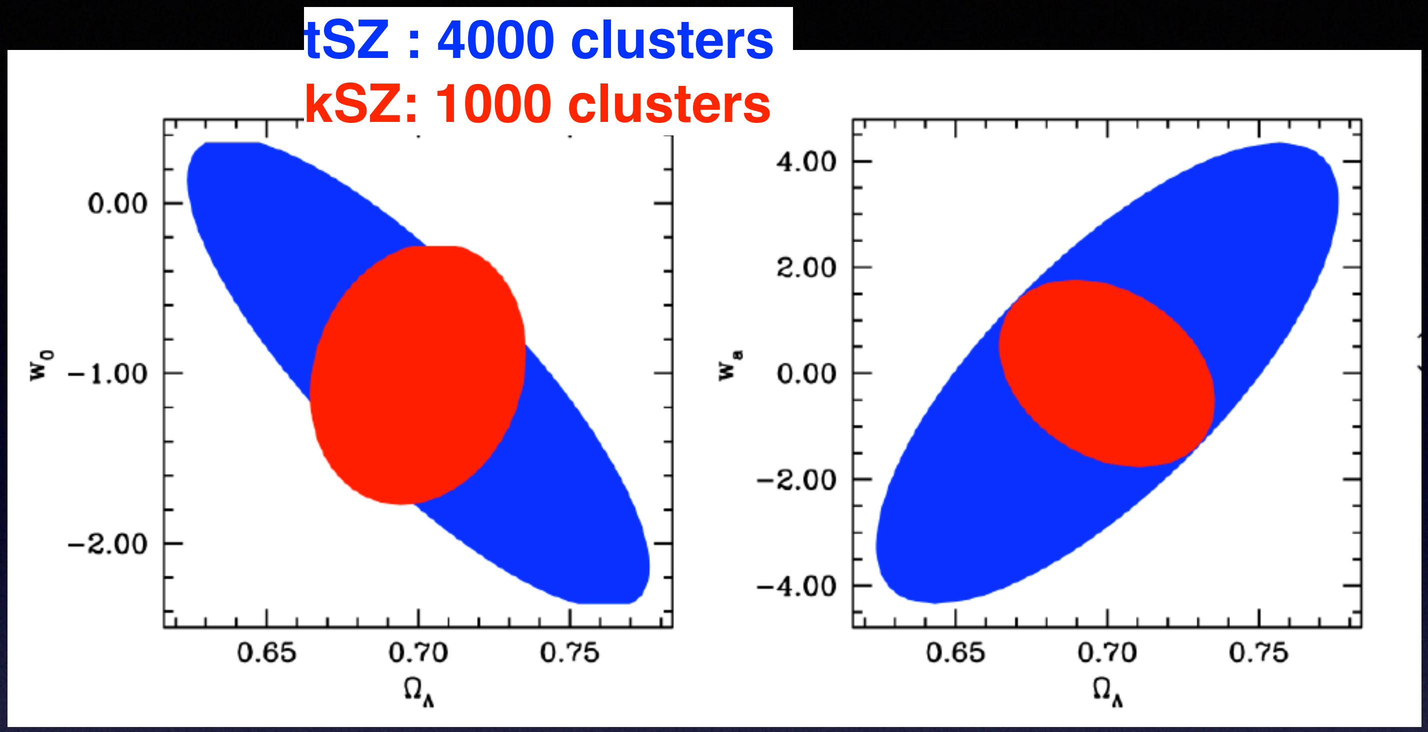
Currently *Planck* is the only instrument to provide a complete coverage of the SZ spectrum: for efficient **separation of multiple SZ signals** and **removal of foregrounds**.

Requirement for SZ spectroscopy



CCAT-p sensitivity is on average 5 to 15 times better than Planck (angular resolution ~6 times better)

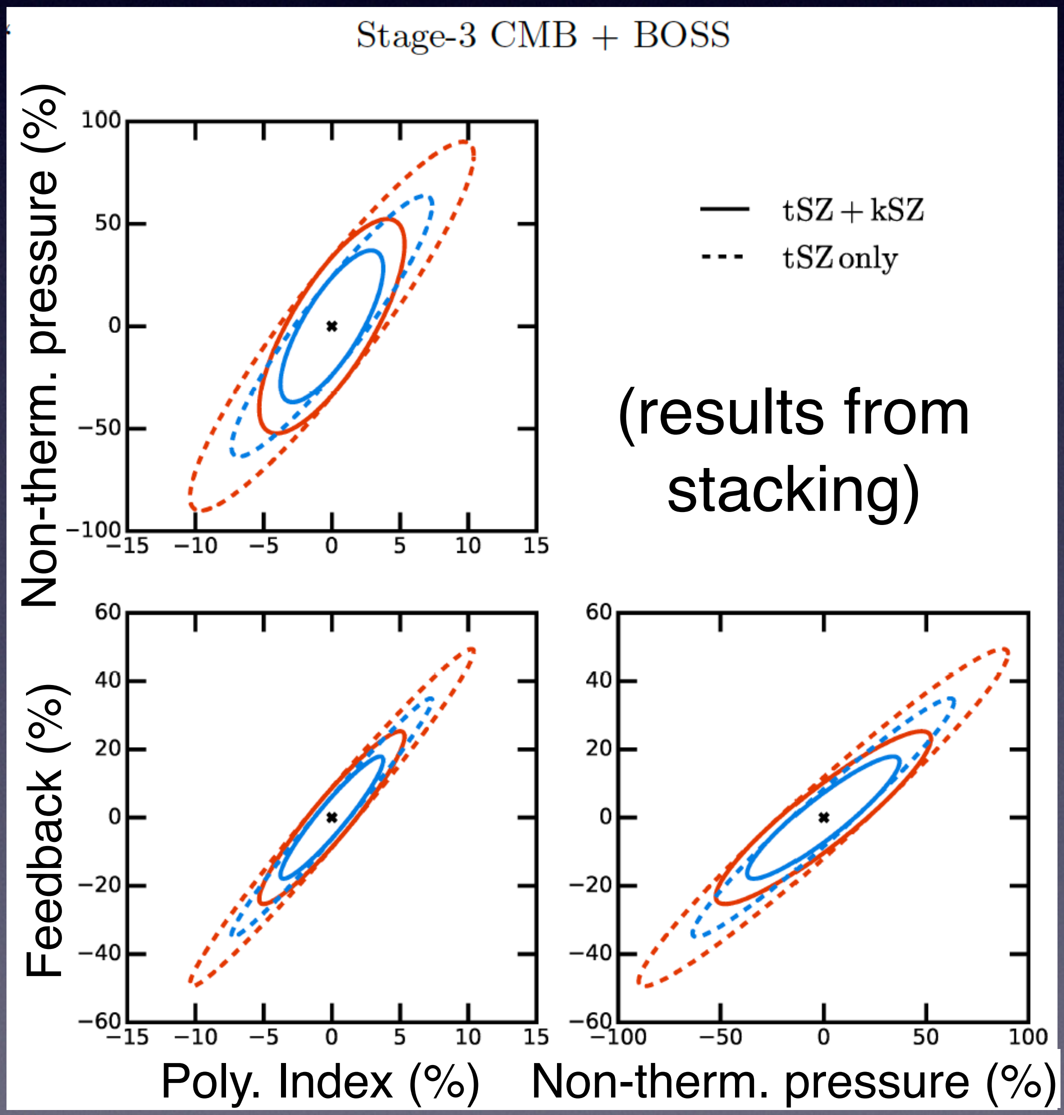
kSZ science: cosmology and astrophysics



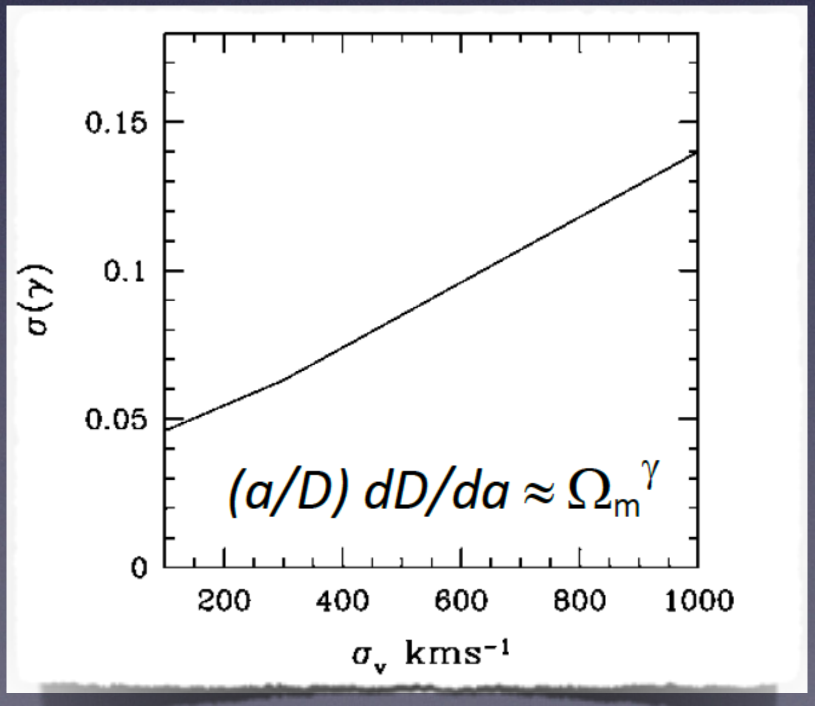
Dark energy parameter constraints from a CCAT-like kSZ survey (fig. from **Bhattacharya & Kosowsky 2008**)

Combined **tSZ + kSZ + optical** data can put tight constraints on baryonic physics of DM halos: *not only clusters but galaxies, QSOs,..*

(Battaglia et al. 2017)



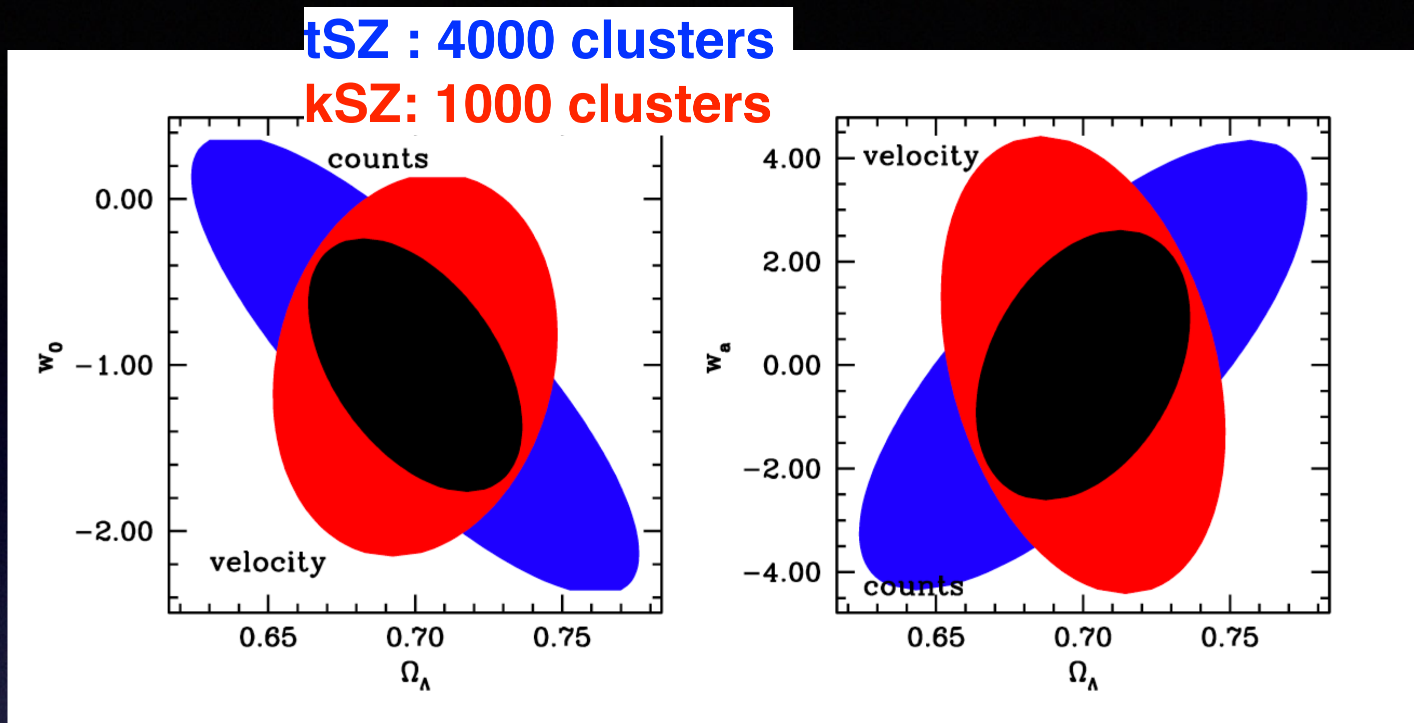
(results from stacking)



kSZ is a very sensitive prove for the cosmological growth index. For example, a CCAT-like kSZ survey can constrain several modified gravity theories from ΛCDM (which has γ=0.55) at good significance.

Kosowsky & Bhattacharya (2009)

kSZ science: cosmology and astrophysics



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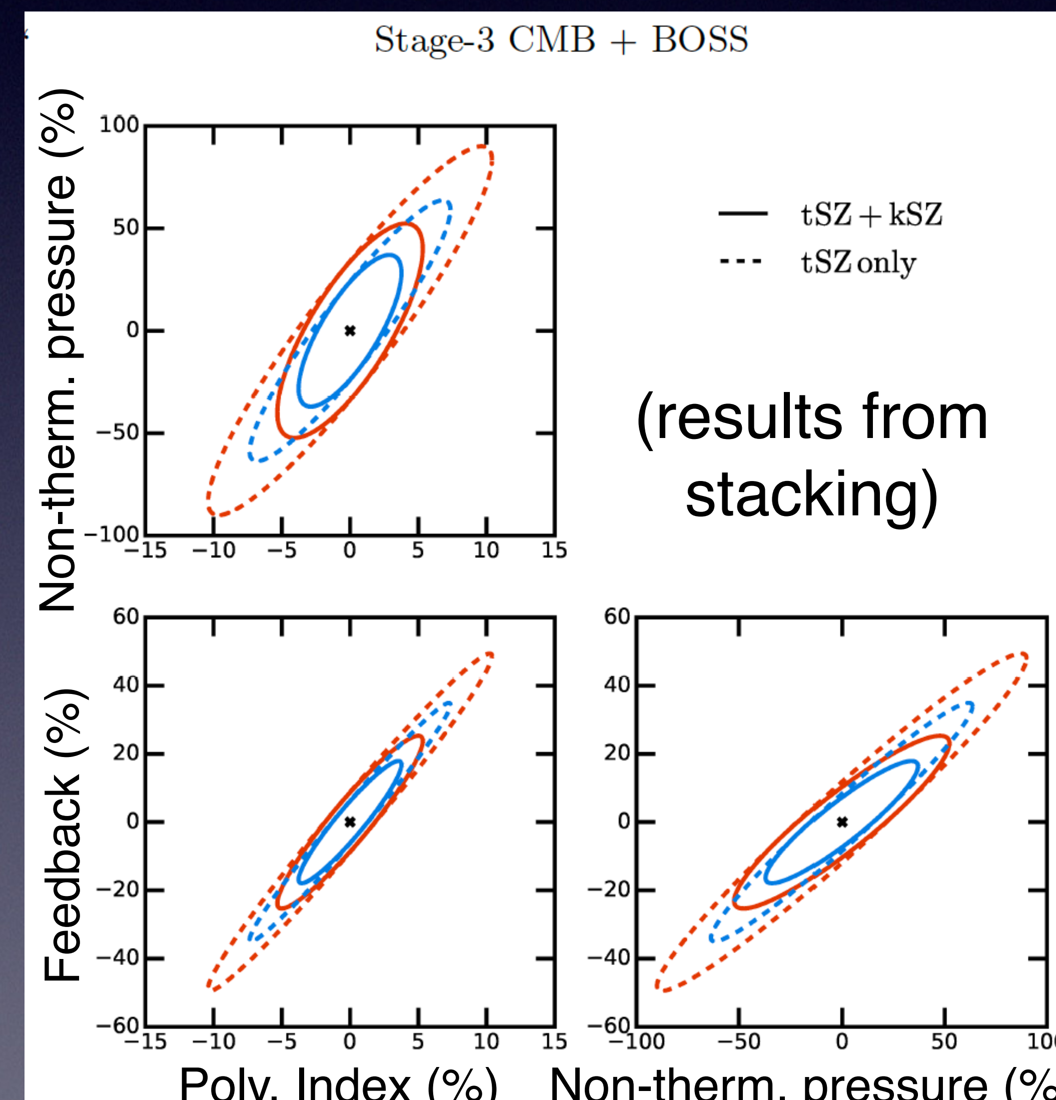
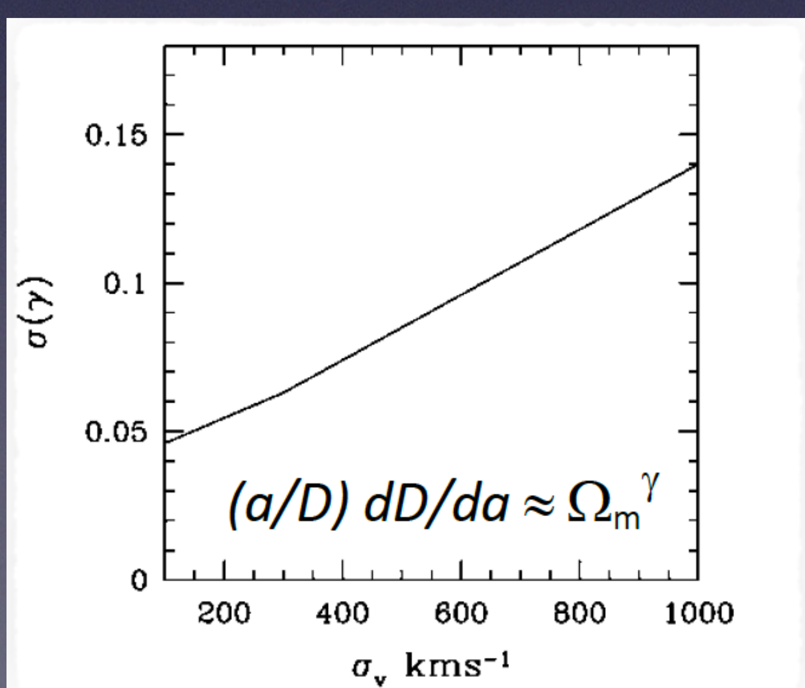


(results from stacking)



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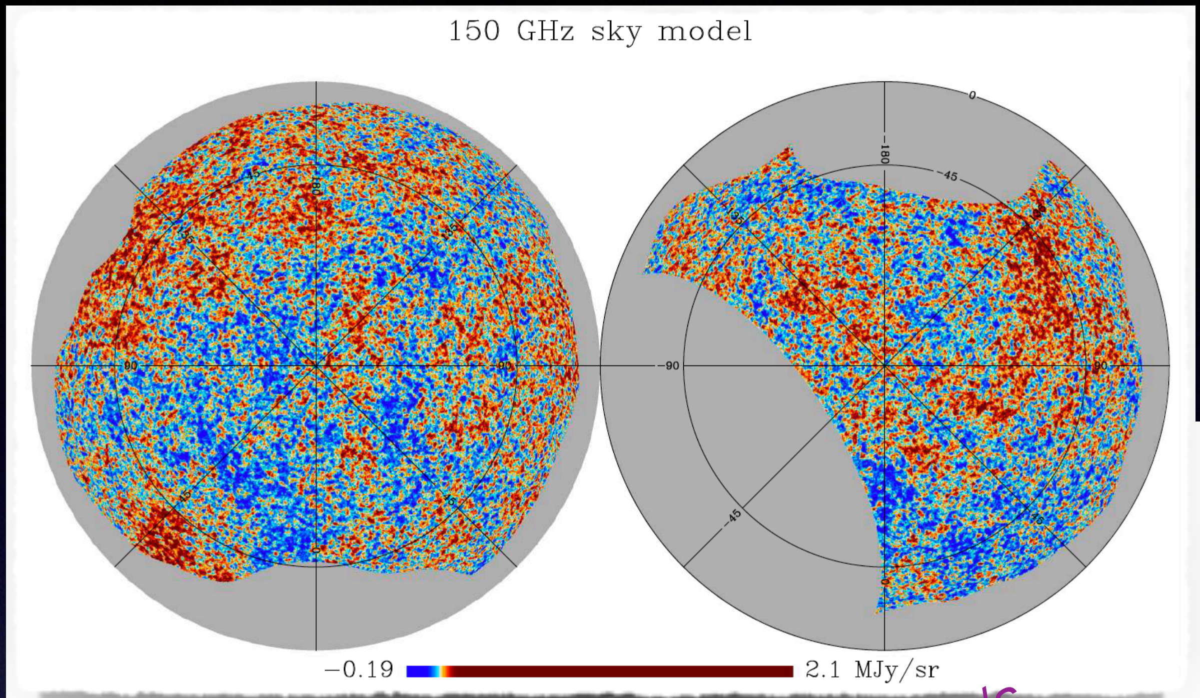
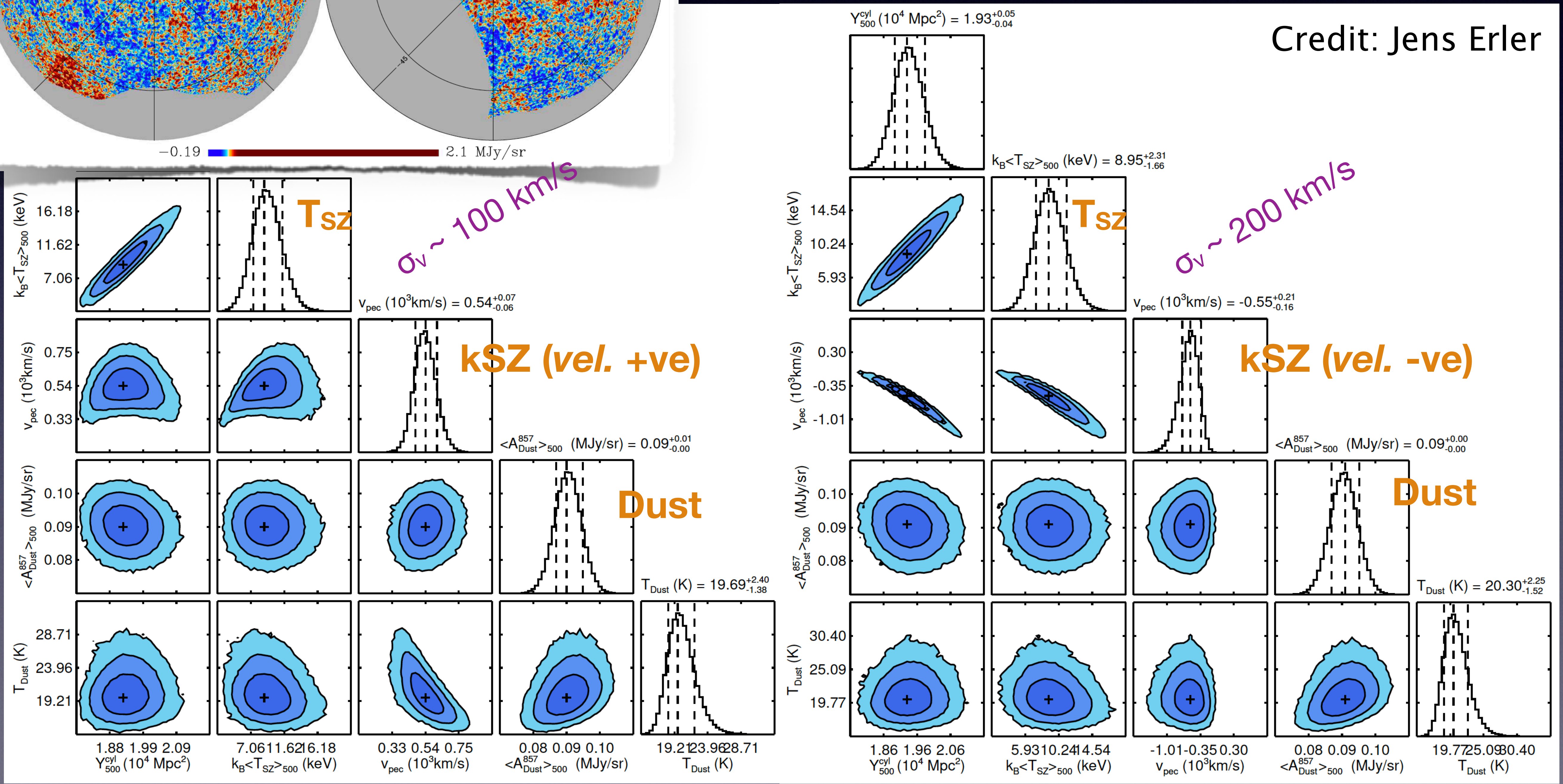
Kosowsky & Bhattacharya (2009)

kSZ: expected accuracy

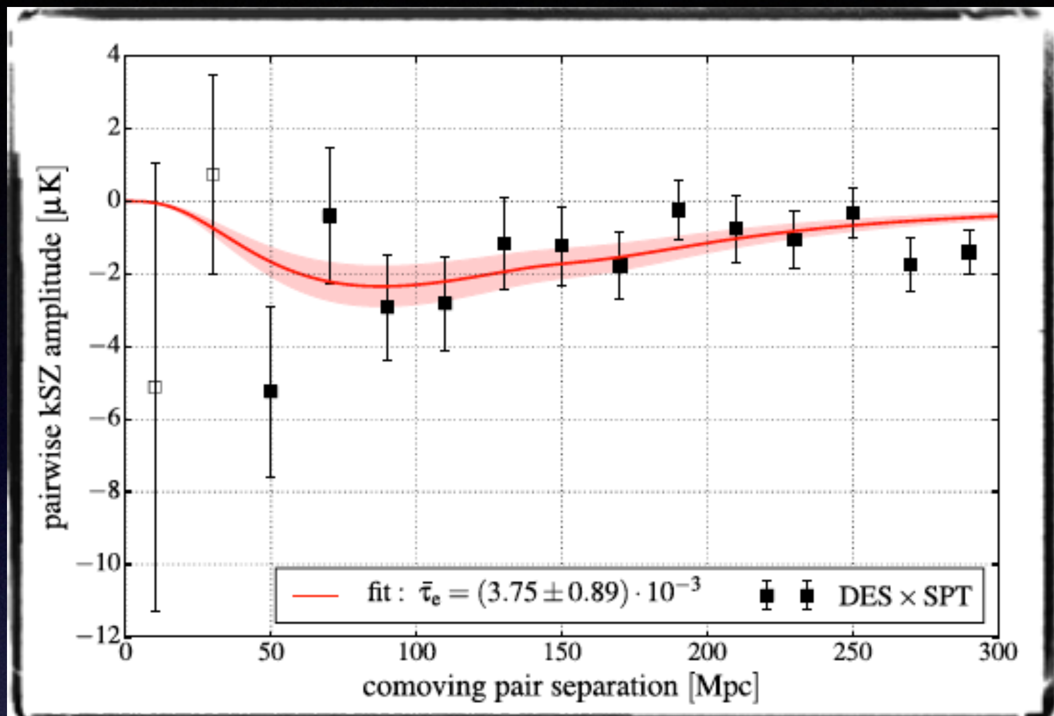
By simulating clusters in realistic CCAT-p foreground we predict velocity errors of the order σ_v ~ 100–200 km/s will be achievable for ~1000 clusters, using matched filtering with ~arcminute resolution.





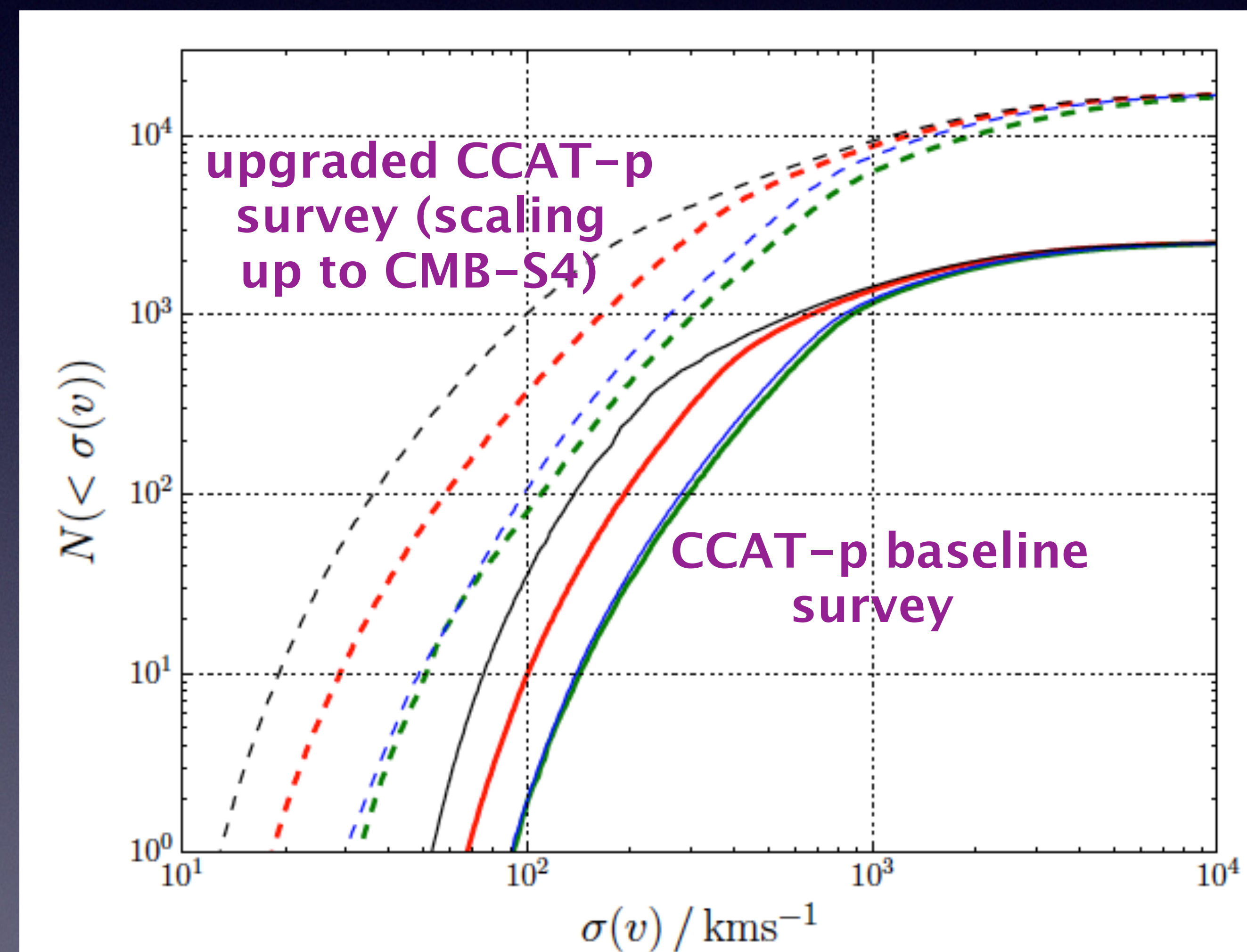
kSZ science: cosmology and astrophysics

Pairwise kSZ detection
(e.g., Soergel et al. 2016)

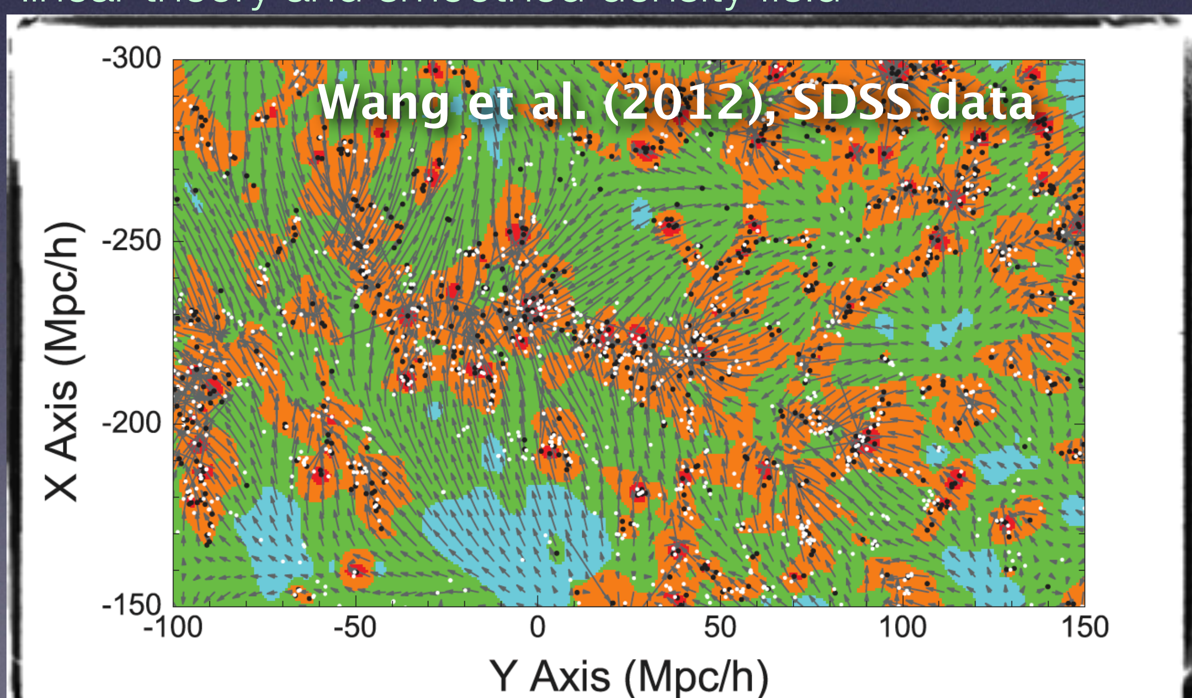


No individual cluster kSZ detection yet

CCAT-p kSZ prediction (Mittal et al. 2018)

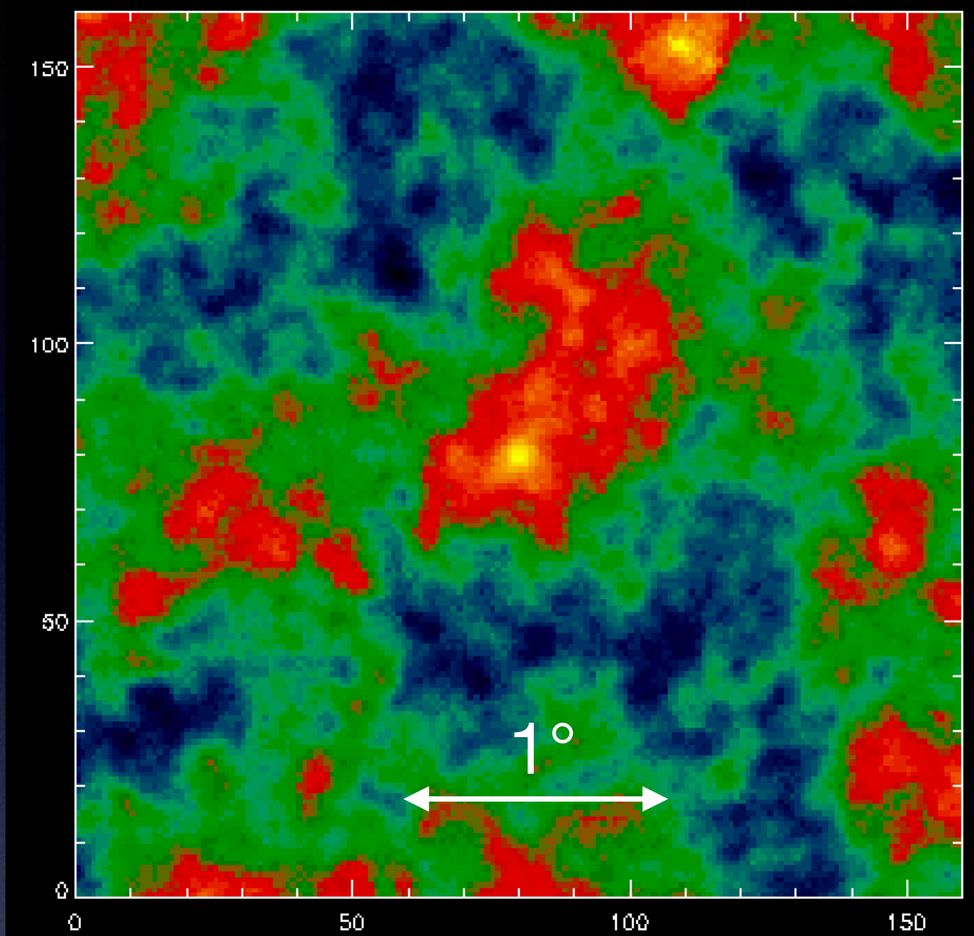


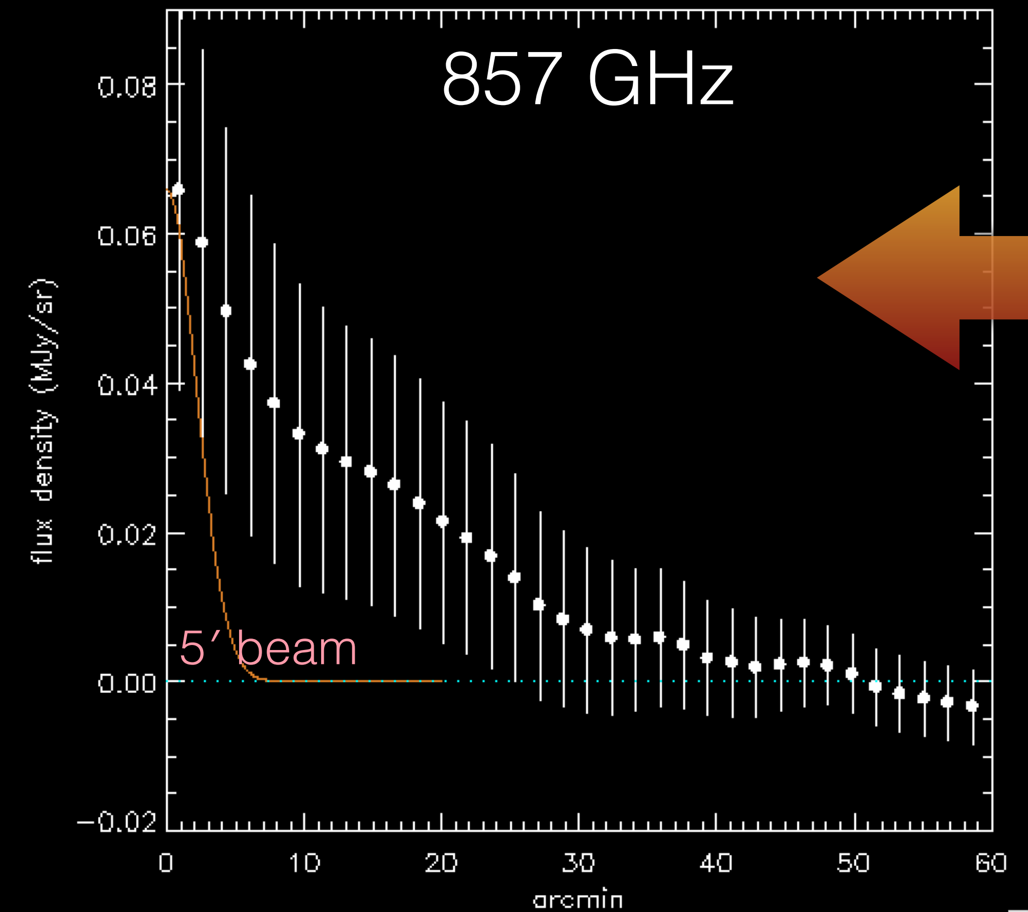
Optical velocity field reconstruction from linear theory and smoothed density field



Synergy with optical & X-ray surveys

But beware! Dust in galaxy clusters

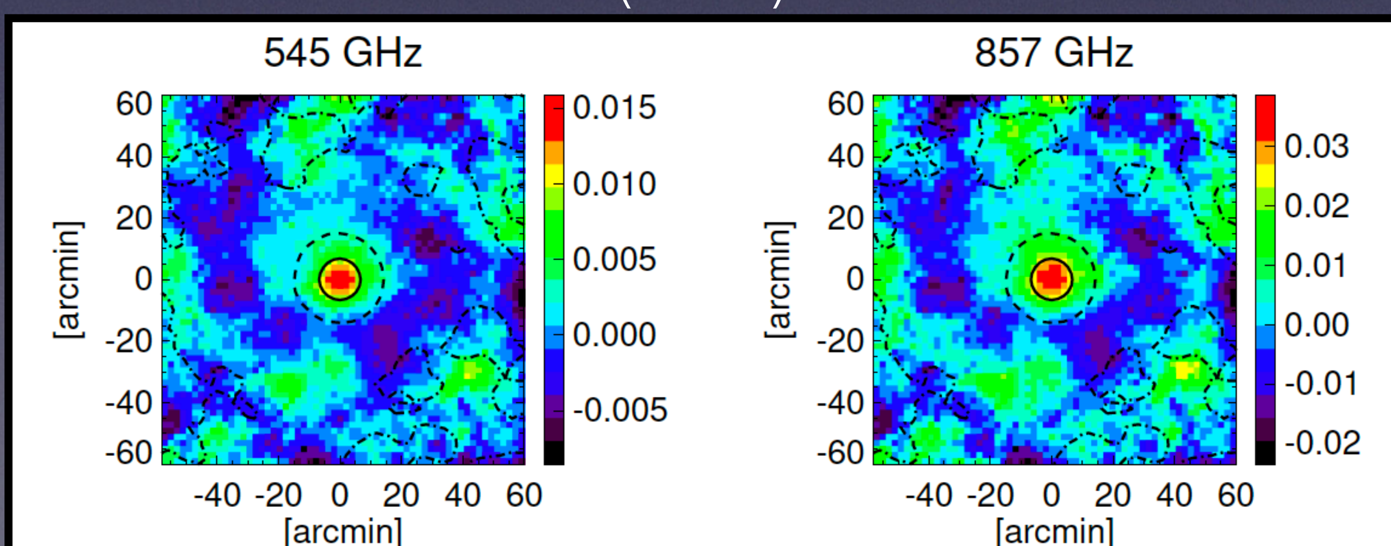


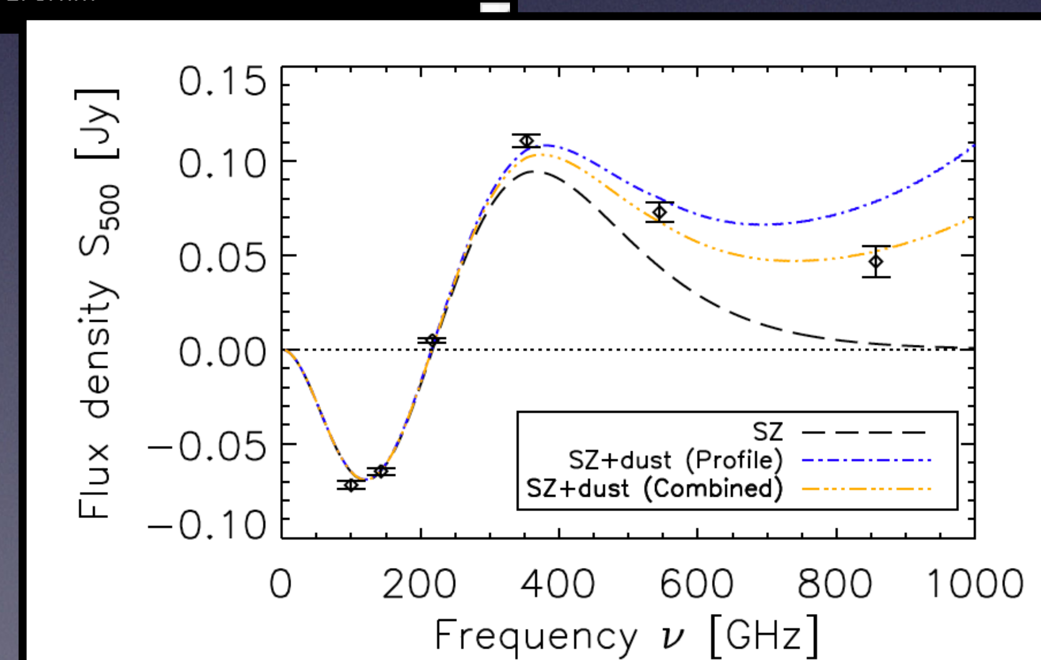


FIR excess observed at cluster positions from stacking ~800 *Planck* clusters

Melin et al. (2018)

Planck collaboration (2016)

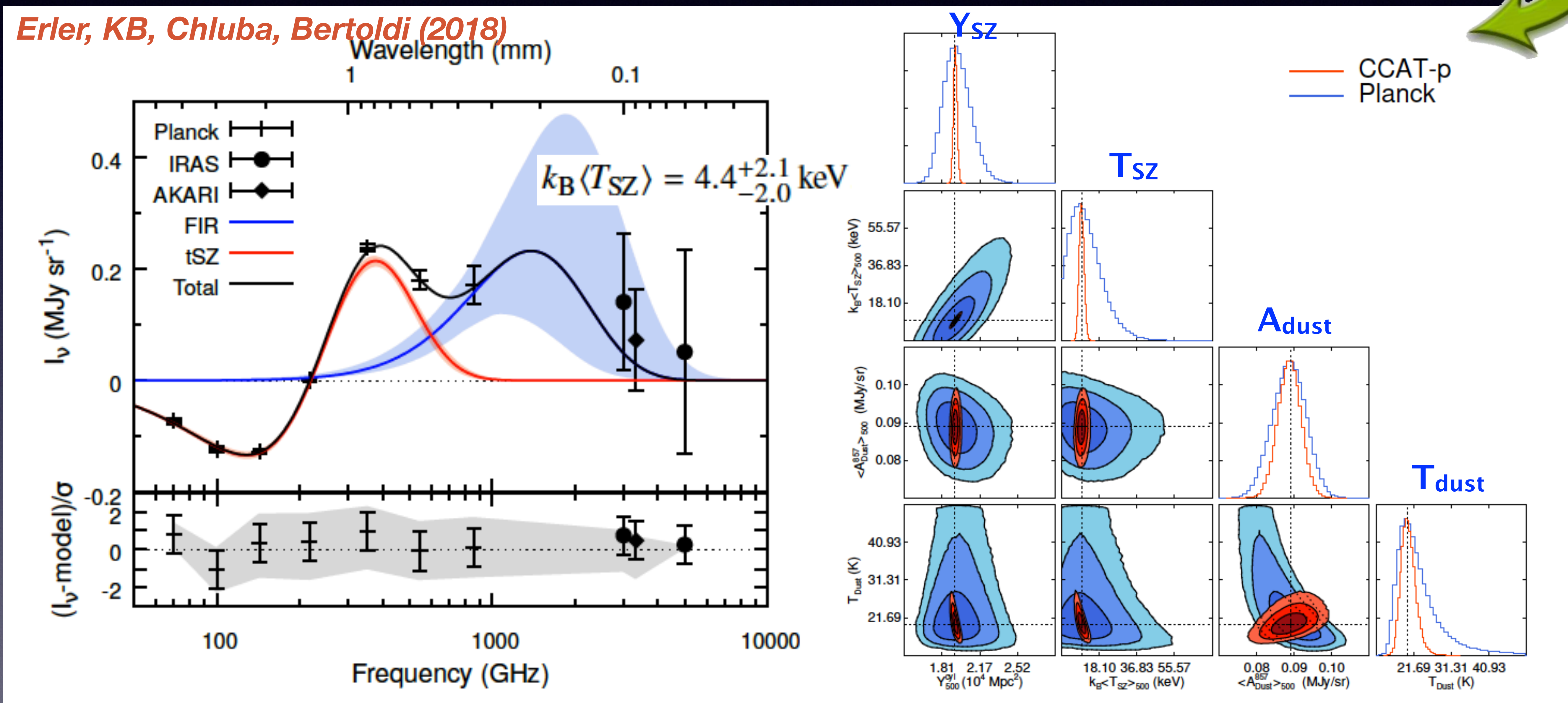




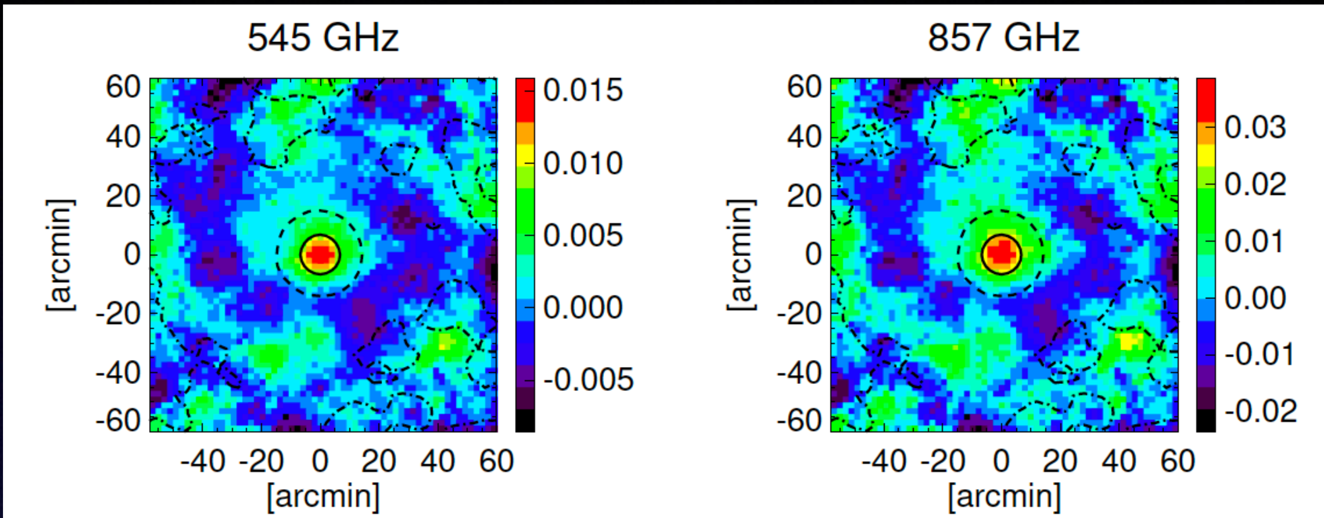
rSZ now with *Planck* and with CCAT-prime

With current *Planck* data, roughly 2.3σ significance detection of cluster temperature is obtained after stacking 772 clusters.

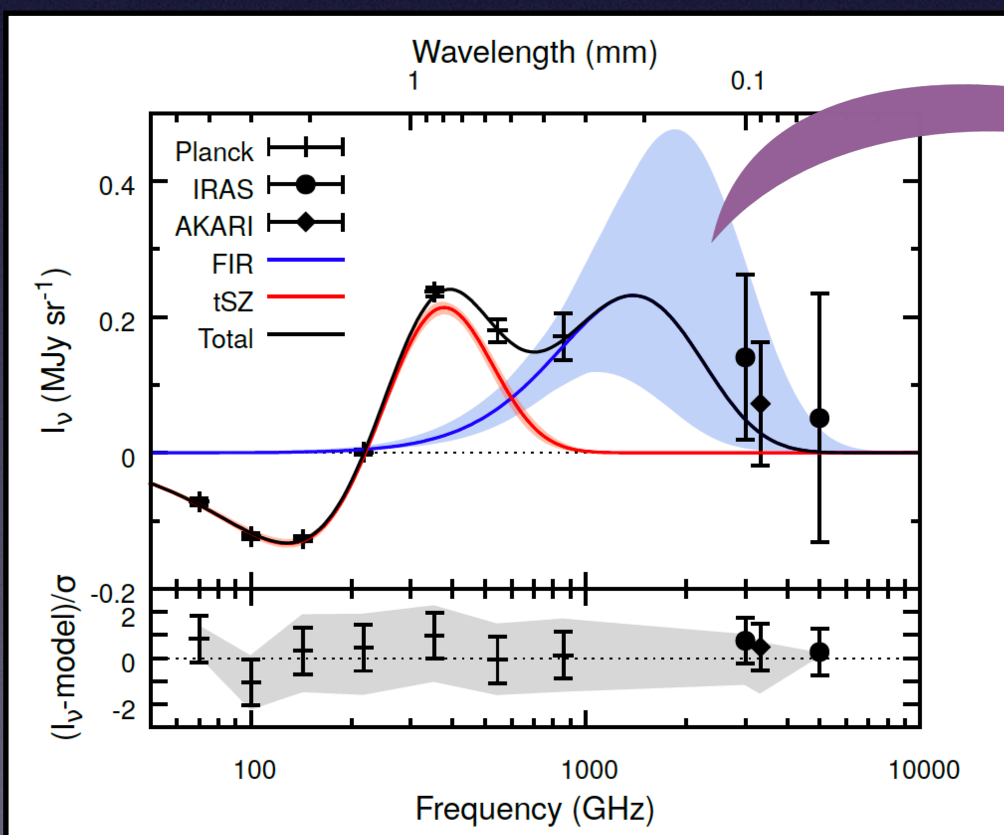
*With CCAT-p the temperature of a **single massive cluster** can be measured at 5–10 σ.*



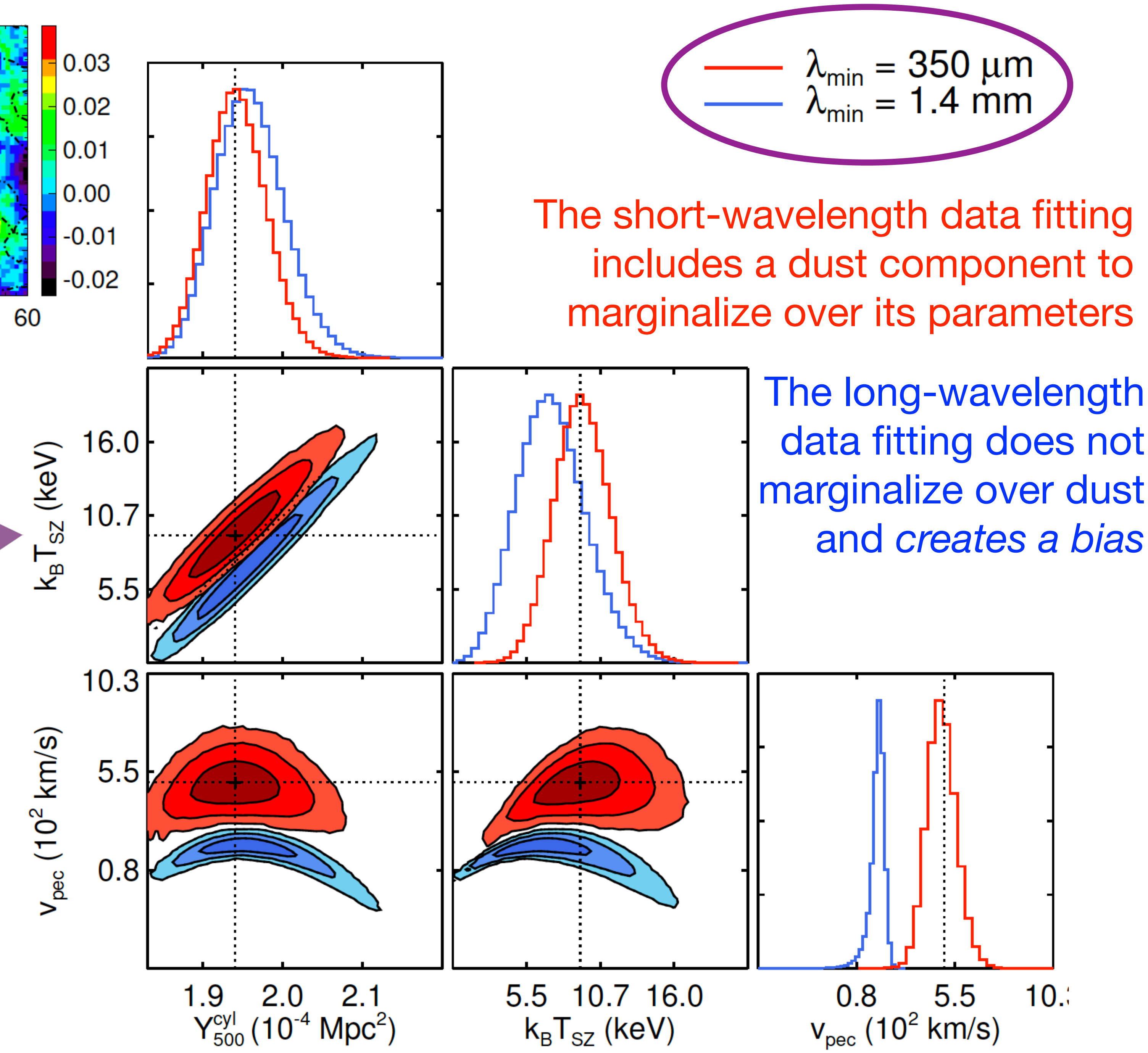
The case for sub-mm: dust in clusters



Planck collaboration (2016)



Erler et al. (2018)

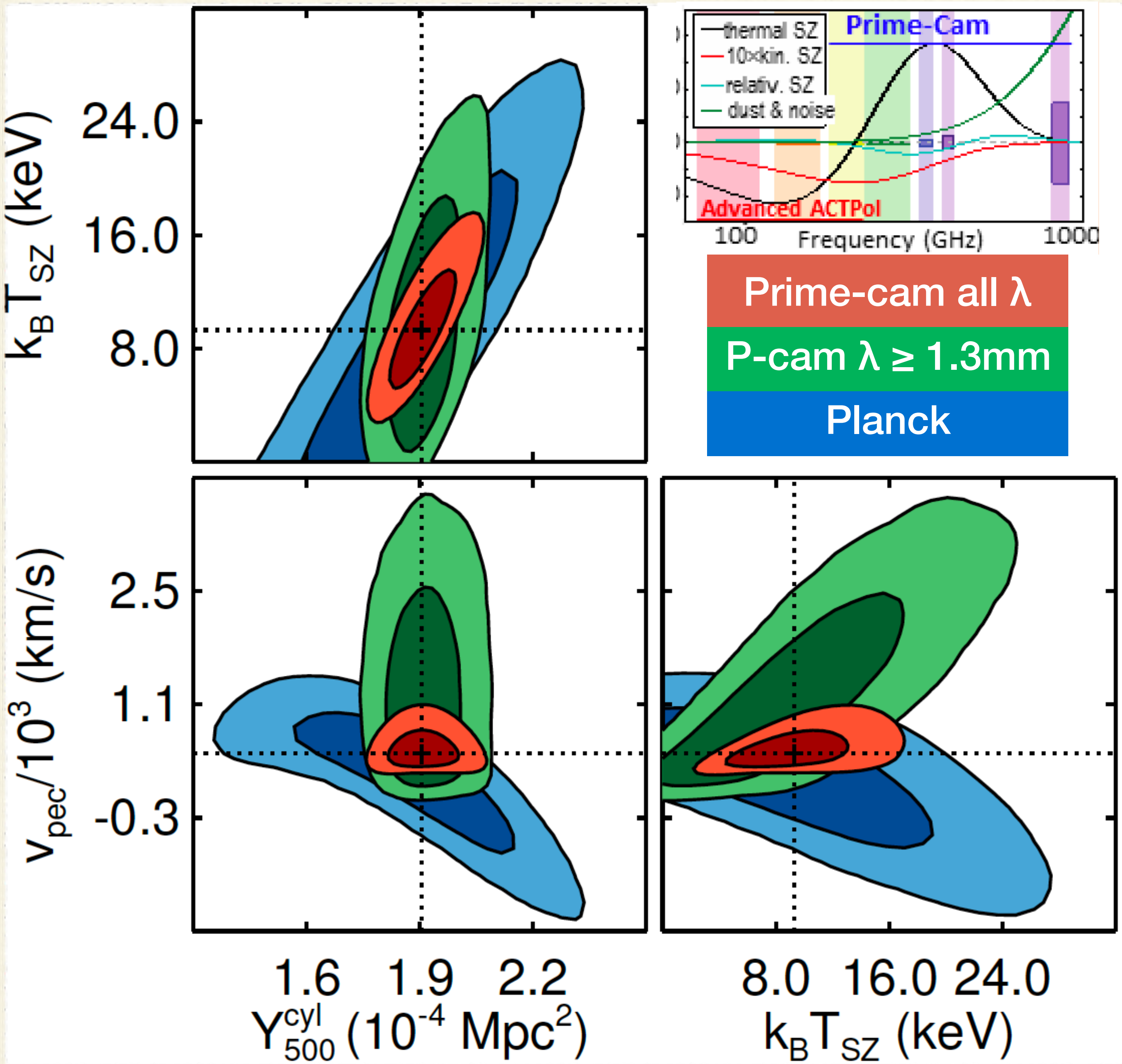


The short-wavelength data fitting includes a dust component to marginalize over its parameters

The long-wavelength data fitting does not marginalize over dust and *creates a bias*

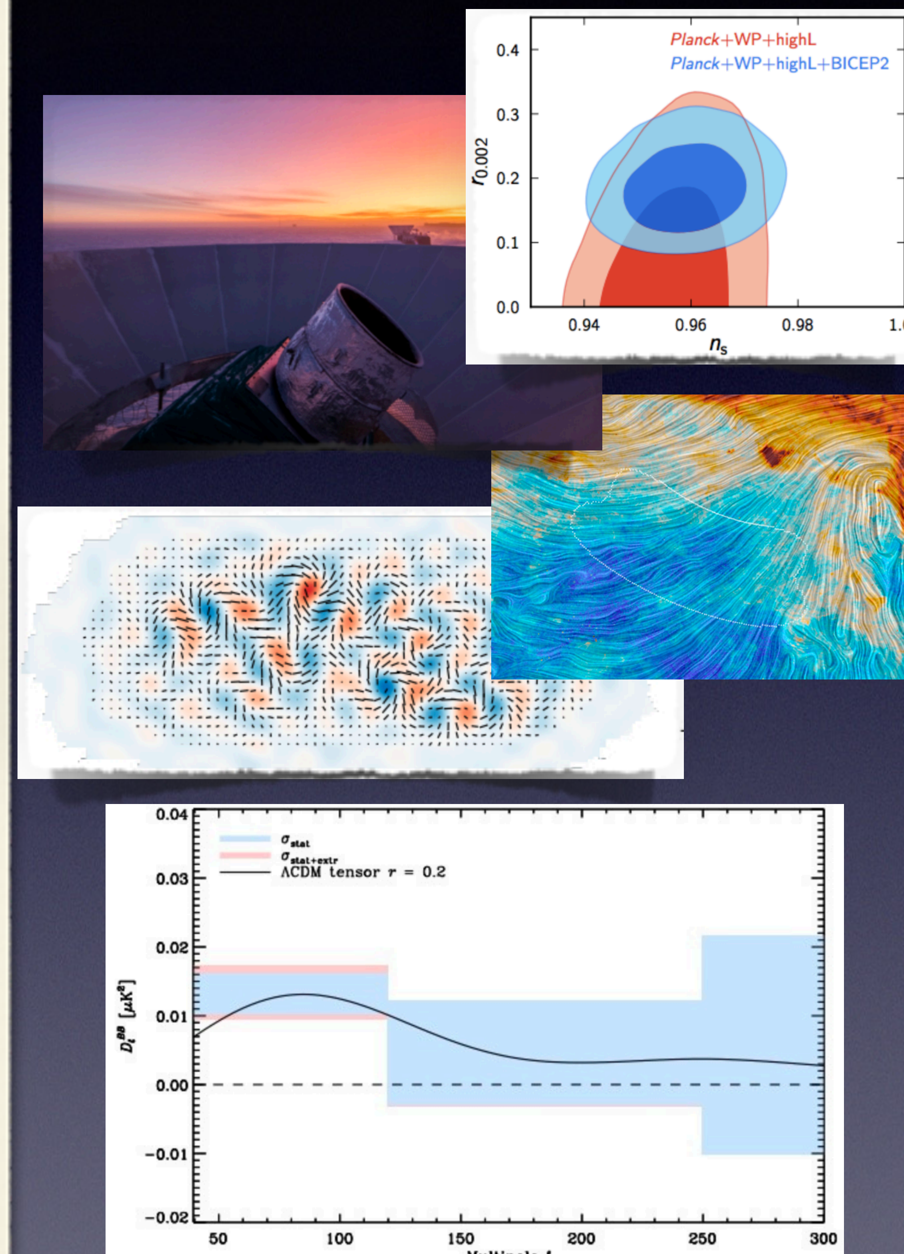
CCAT-p/CMB-S4 prediction, KB et al. *in prep*

The impact of dust

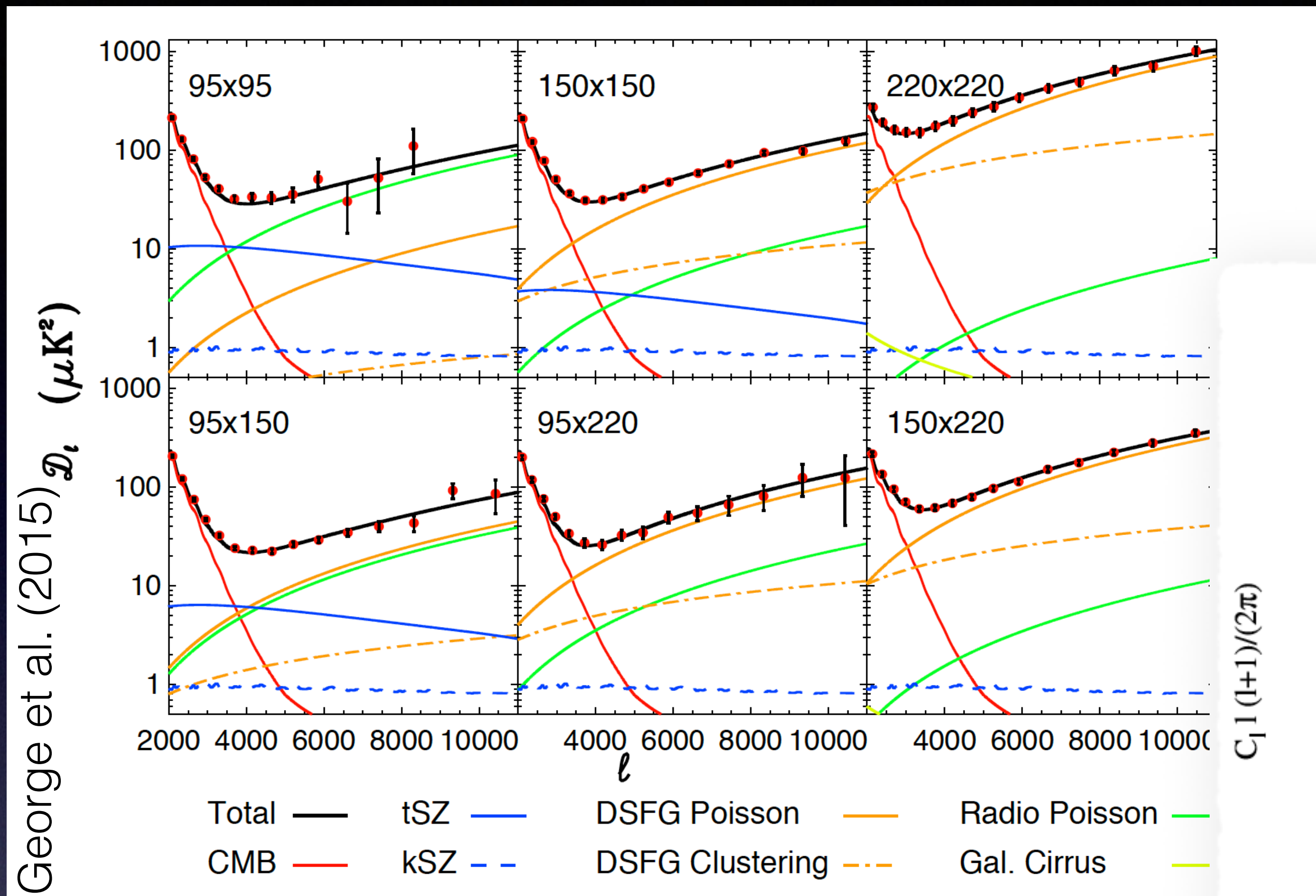


KB, Erler et al., in prep.

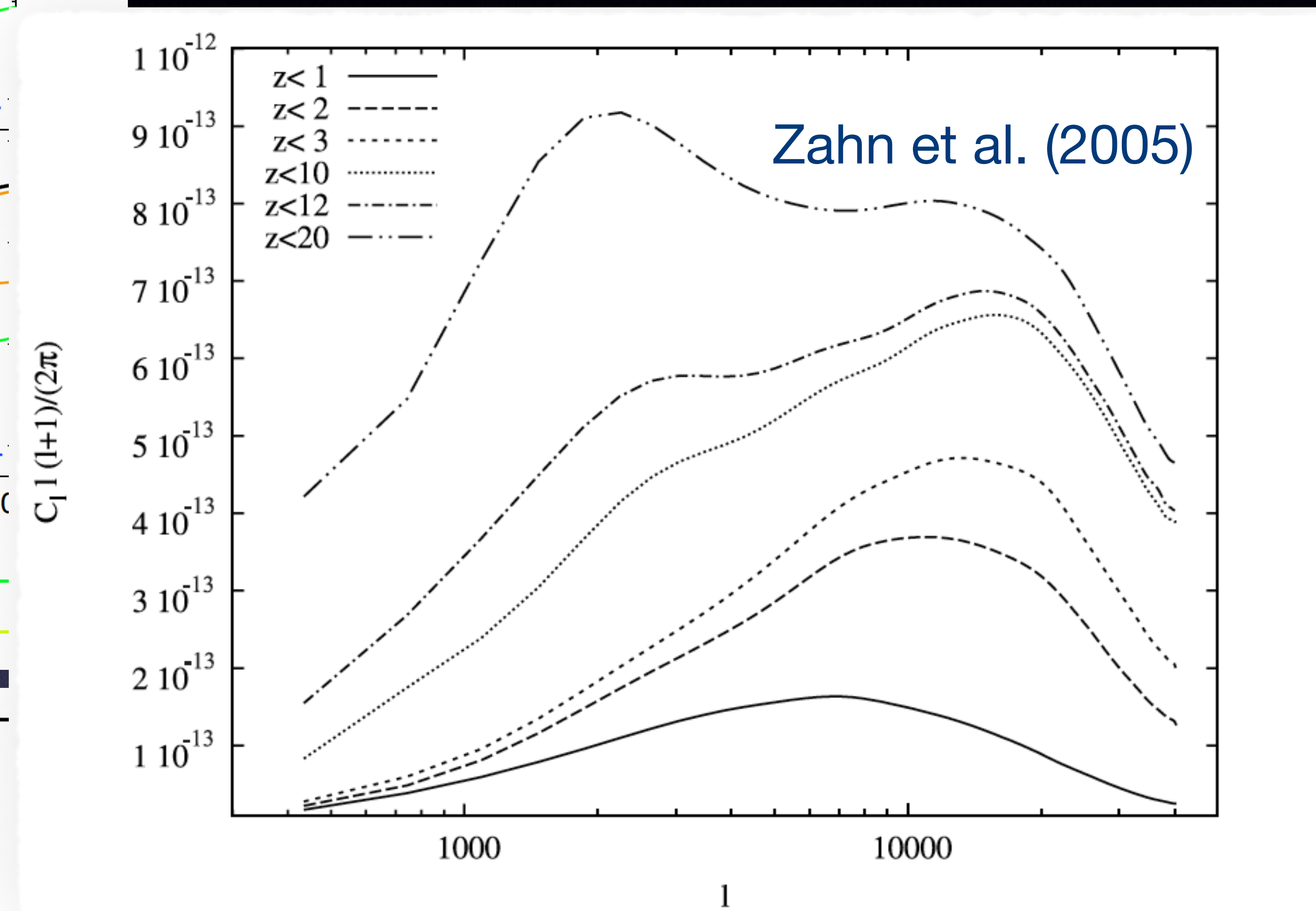
Dust: A cautionary tale



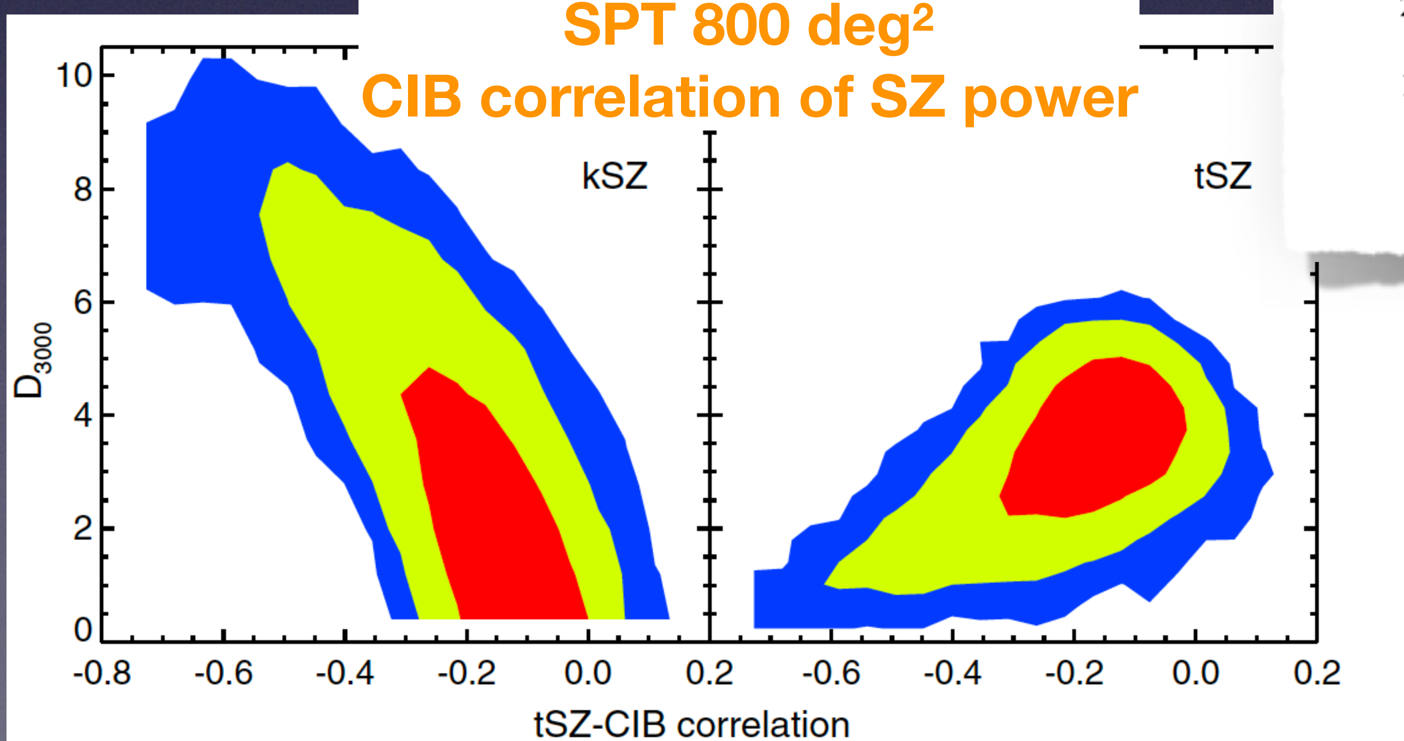
SZ power spectra and the CIB



Extended reionization models with both extended and patchy kSZ contributions



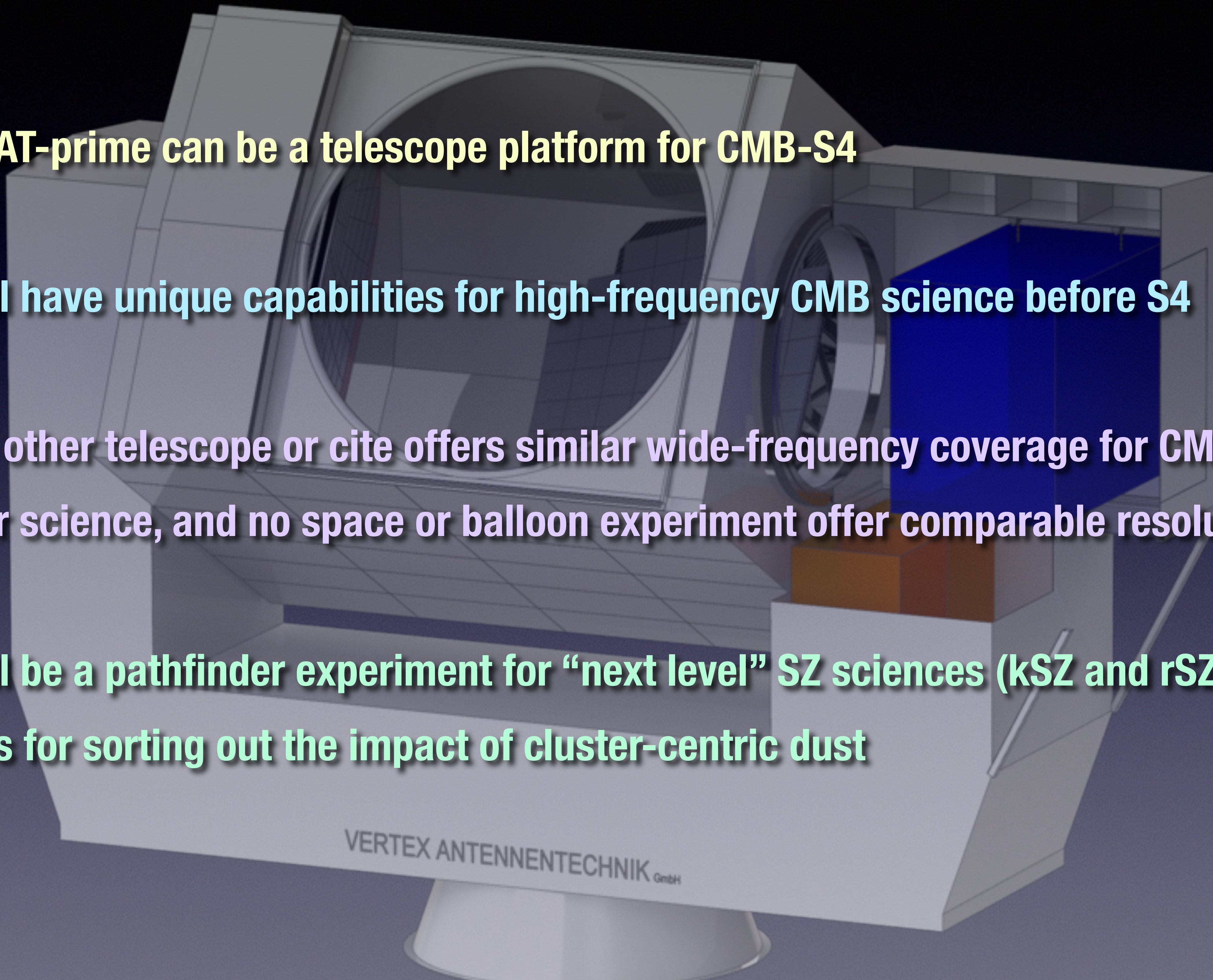
SPT 800 deg²
CIB correlation of SZ power



kSZ power can probe the history of cosmic reionizarion, but dust power limits its sensitivity

Results from SPT-SZ 800 deg² survey (Reichardt et al. 2012)

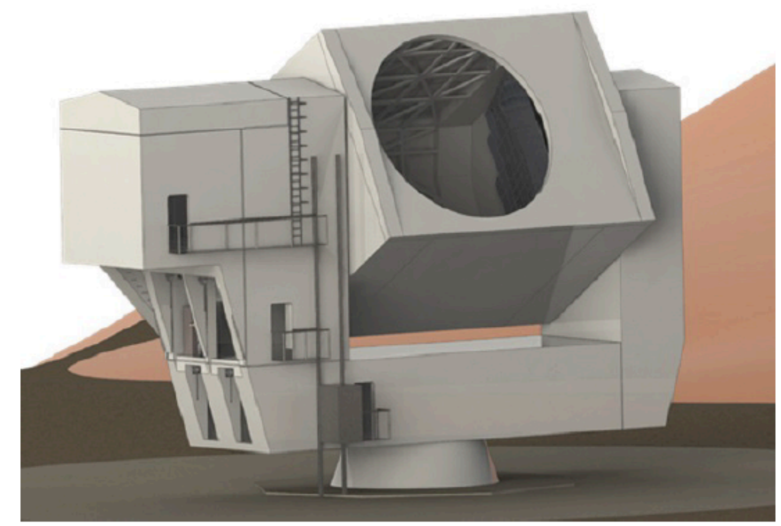
A few take-home points



- **CCAT-prime can be a telescope platform for CMB-S4**
- **Will have unique capabilities for high-frequency CMB science before S4**
- **No other telescope or cite offers similar wide-frequency coverage for CMB and cluster science, and no space or balloon experiment offer comparable resolution**
- **Will be a pathfinder experiment for “next level” SZ sciences (kSZ and rSZ) as well as for sorting out the impact of cluster-centric dust**

CCAT-prime Schedule

Telescope: 4 year construction (6/2017 to 6/2021)
- 20 months detailed design
- 13 months fabrication incl. trial assembly in Duisburg
- 3 months shipping & receiving
- 12 months assembly/checkout



Cameras under design & construction, $€ still being raised (NSF: MSIP, DFG: SFB, ...)

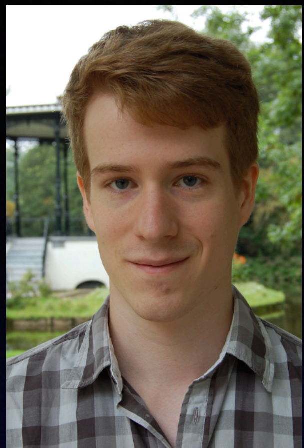
Possible platform for CMB "Stage IV" survey in future

Project has started, but still welcomes new partners.

www.ccatobservatory.org

Appendices

An improved matched filtering technique



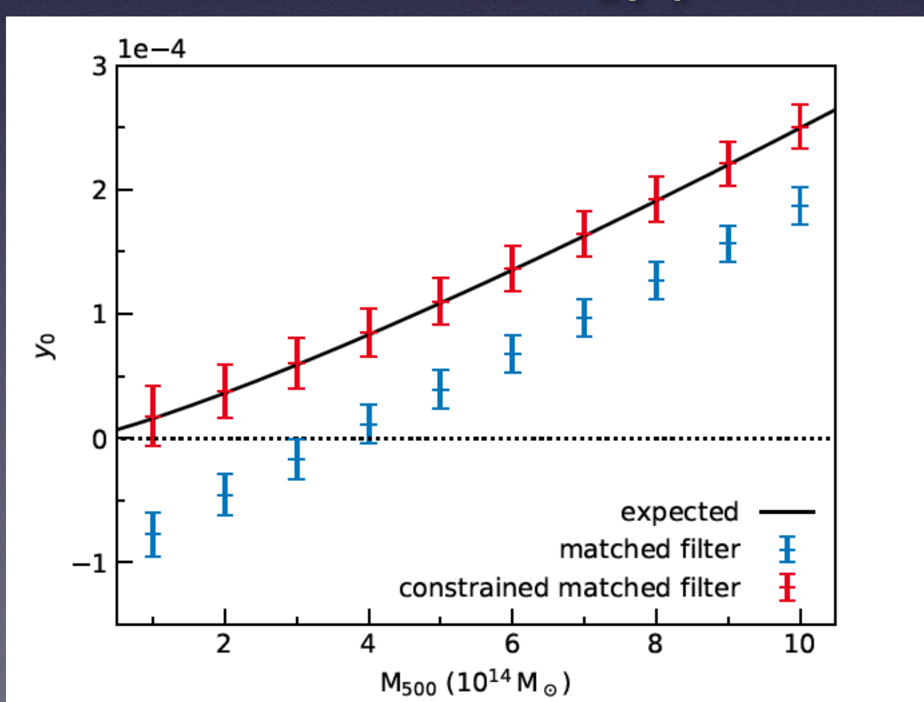
Constrained Matched Filtering
Erler et al., submitted

arXiv:1809.06446
https://github.com/j-erler/pymf

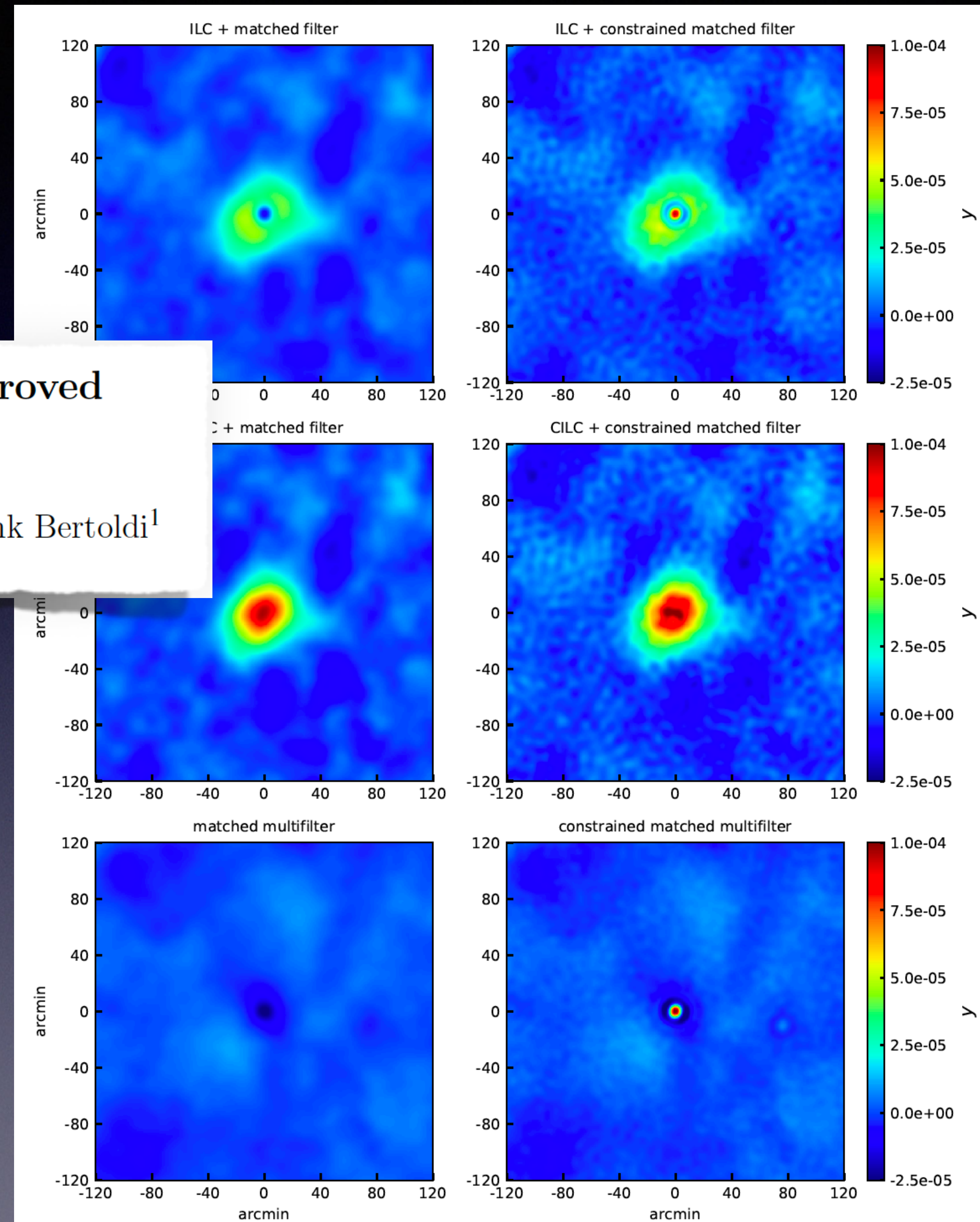
Introducing constrained matched filters for improved separation of point sources from galaxy clusters

Jens Erler[1★ †], Miriam E. Ramos–Ceja[1], Kaustuv Basu[1] and Frank Bertoldi[1]
[1] *Argelander-Institut für Astronomie, Universität Bonn, Auf dem Hügel 71, 53121 Bonn, Germany*

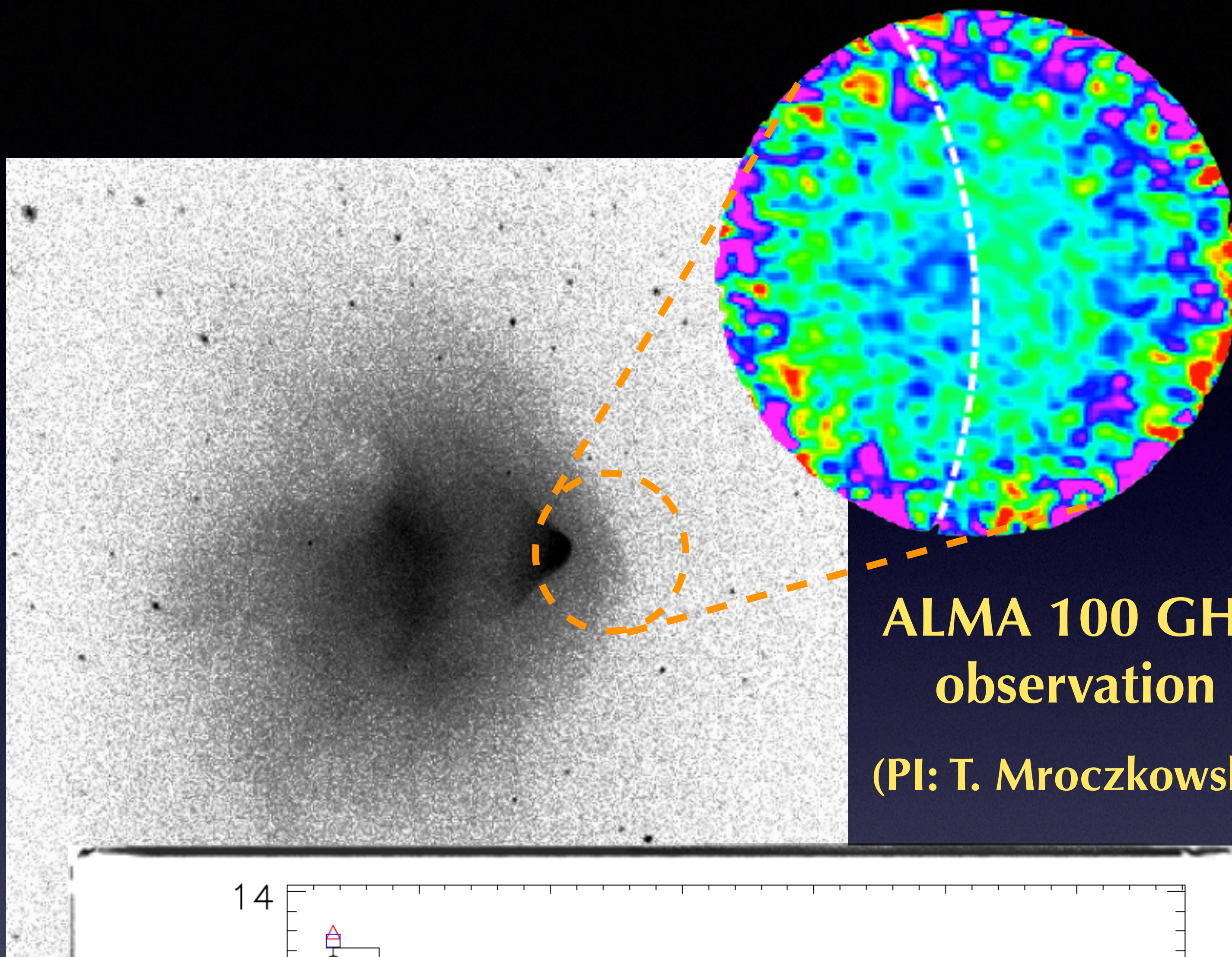
Simulation with 10 mJy point source



Real Planck data of Perseus cluster



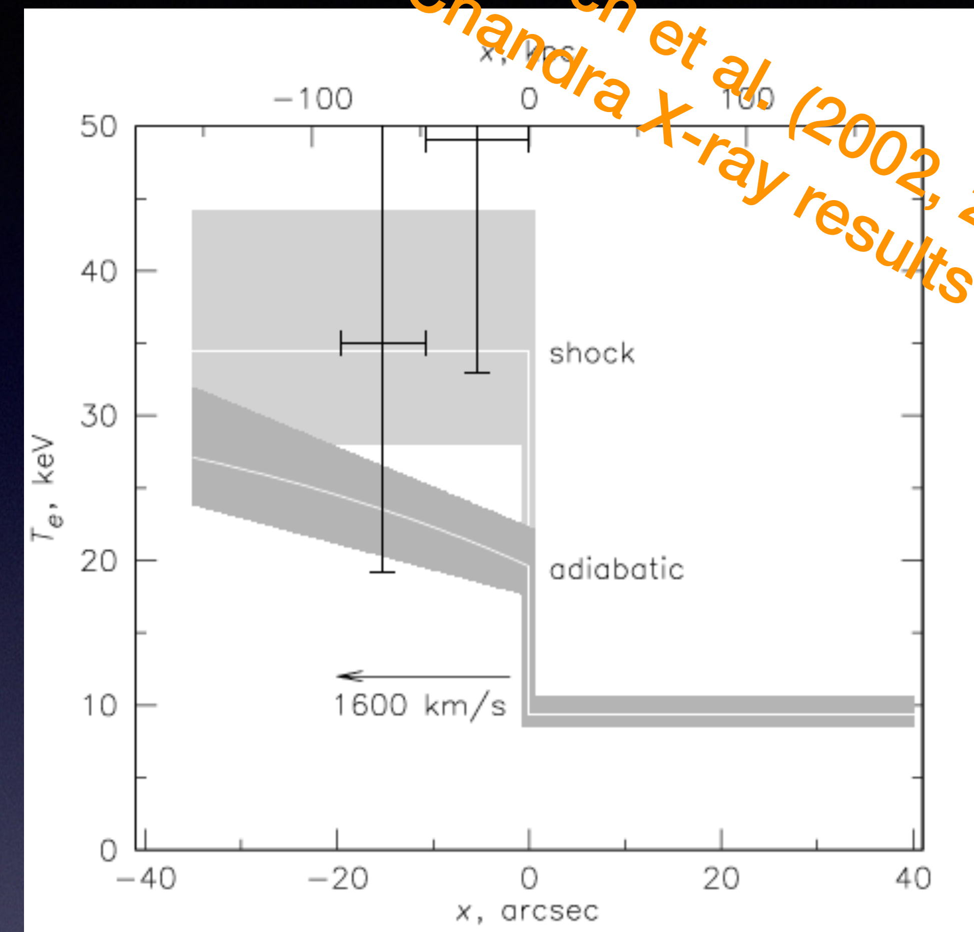
rSZ science: shocks and temperature profiles

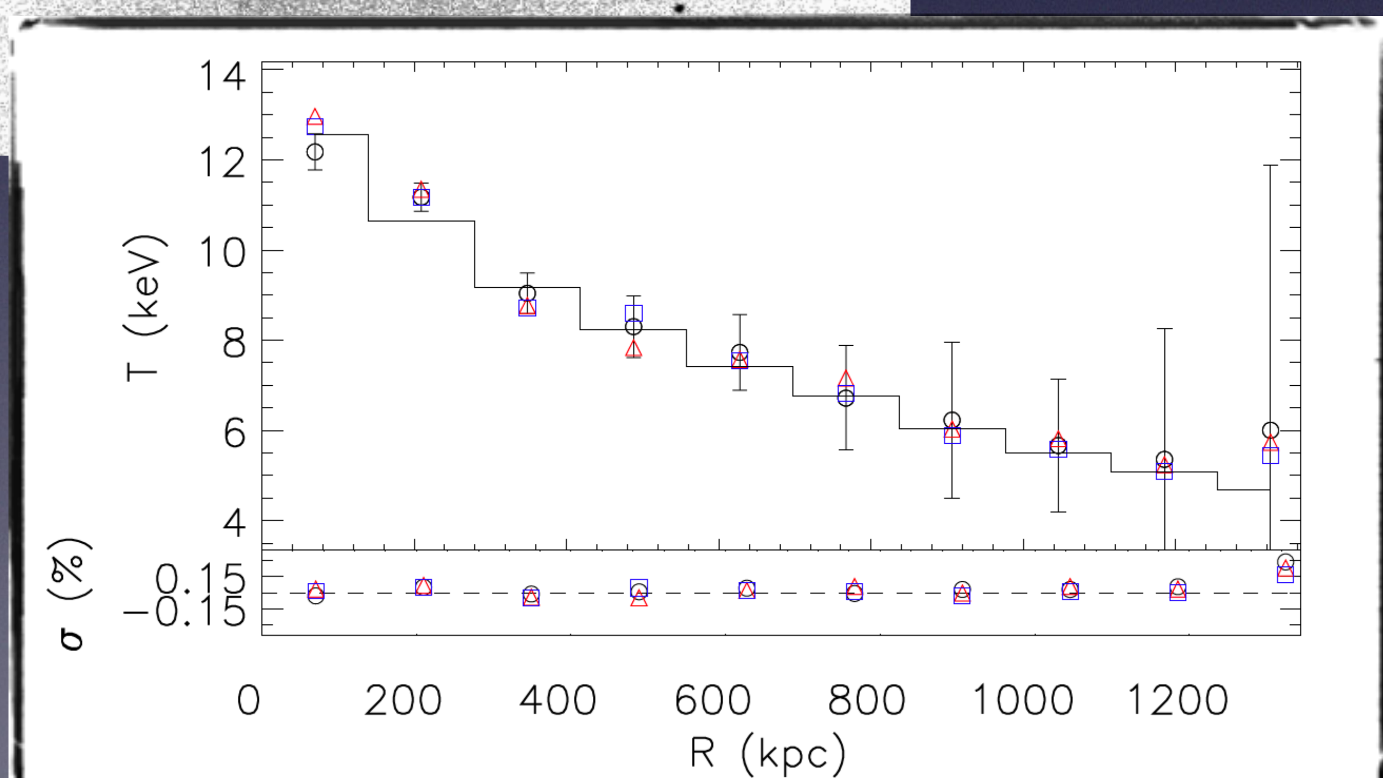


ALMA 100 GHz observation

(PI: T. Mroczkowski)

Markevitch et al. (2002, 2006)
Chandra X-ray results

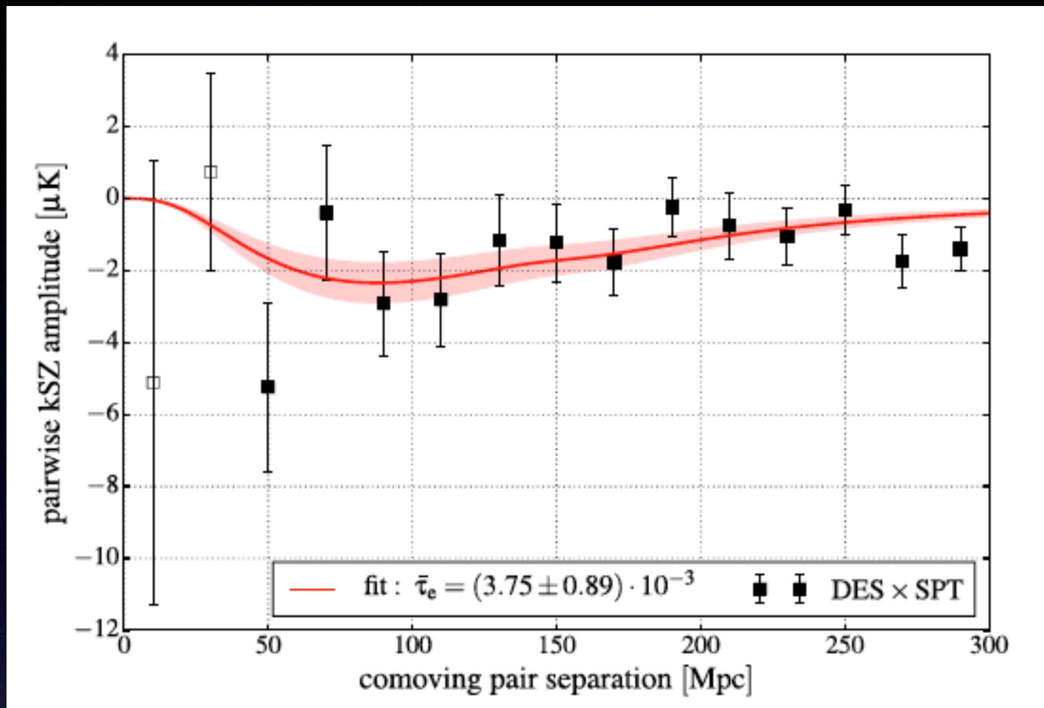




Comparison of T_{SZ} and T_X can lead to knowledge on cluster triaxiality and gas clumping

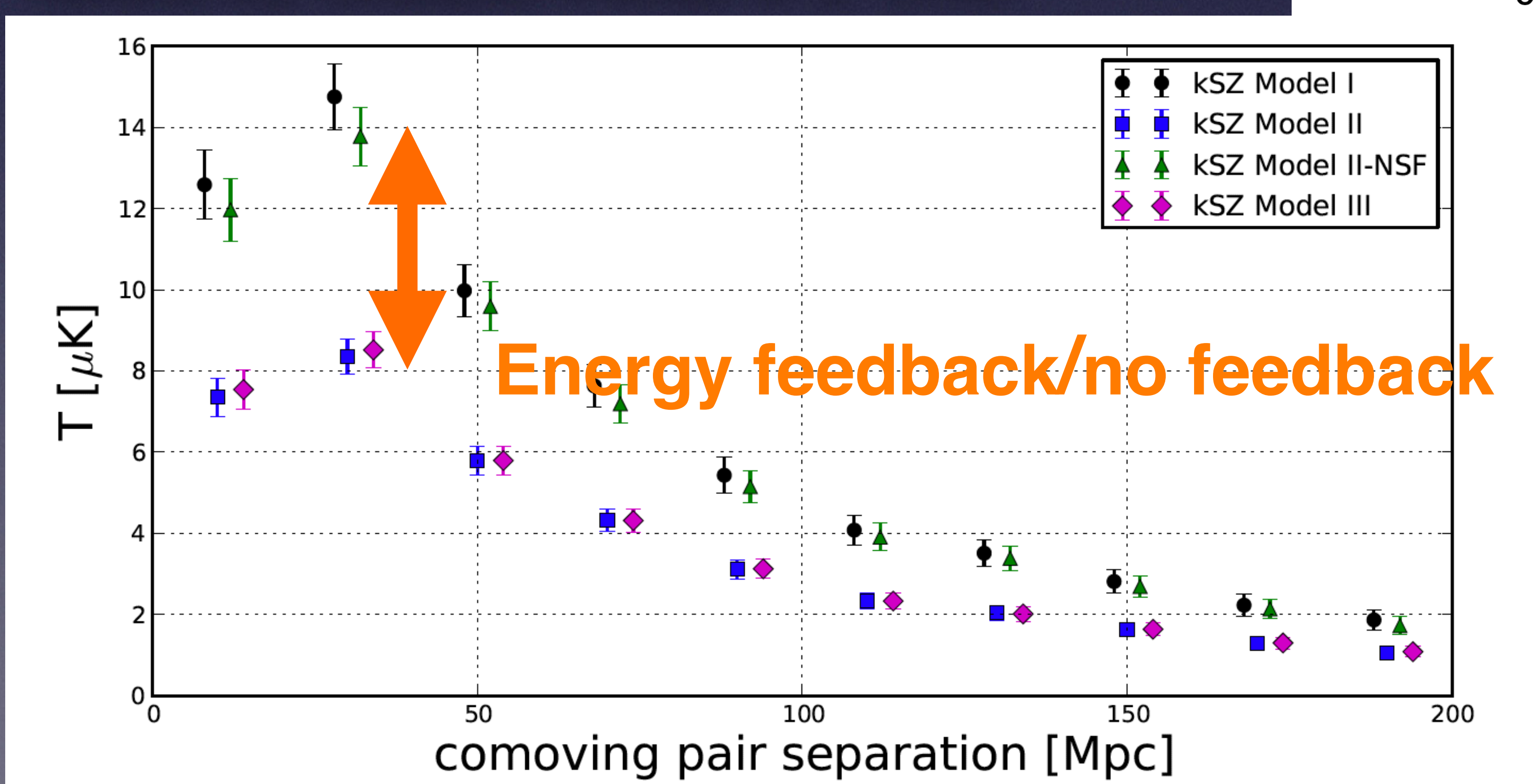
CCAT 25m (LWCam) predictions by Morandi, Cui, Nagai, and Sayers

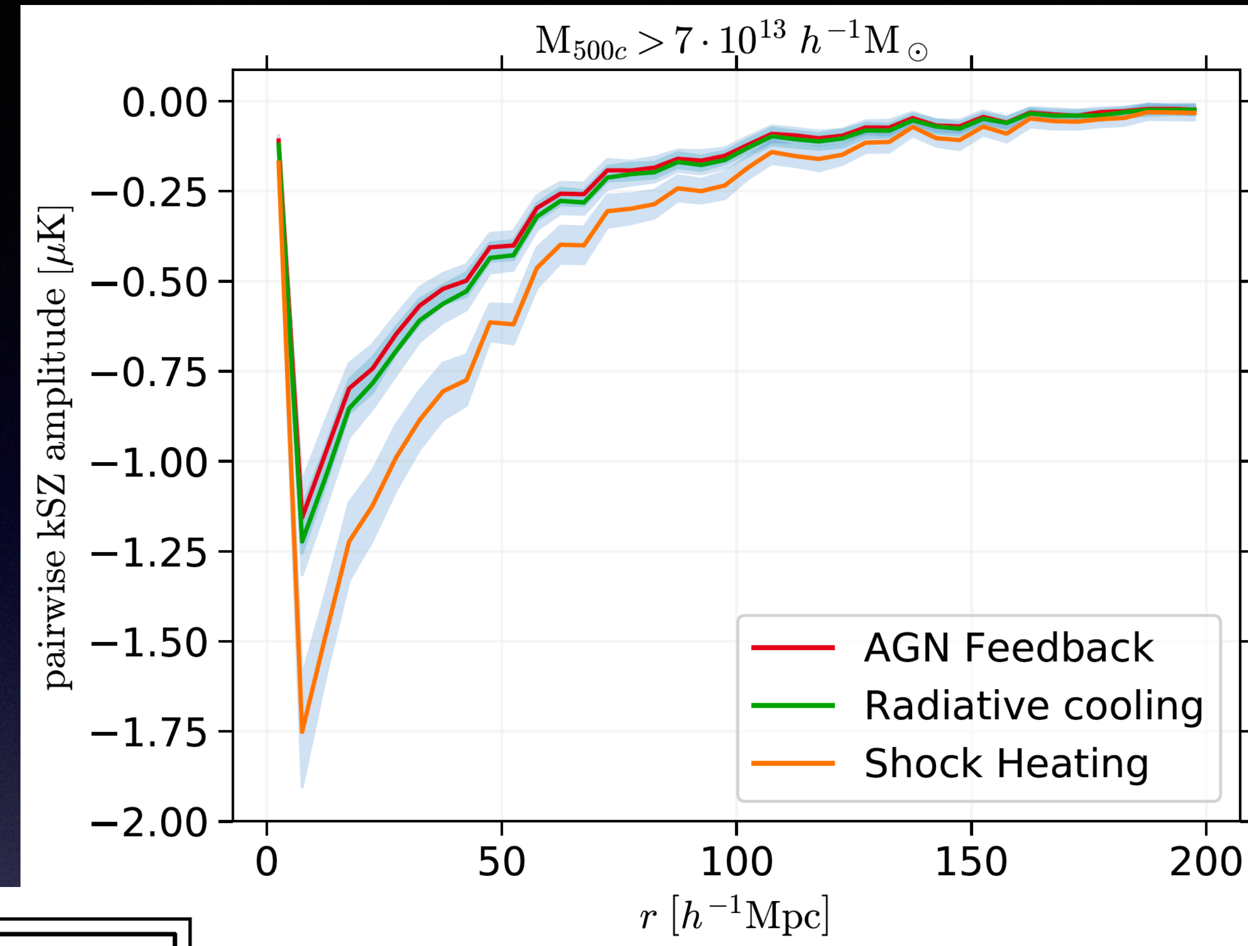
kSZ: cluster τ and pairwise momentum



Pairwise kSZ measurement (Soergel et al. 2016)

Pairwise kSZ simulation (Flender et al. 2016)





J. Kuruvilla et al. (preliminary)

τ-M scaling relation parameters from Battaglia et al. (2017) hydro sims

Combined tSZ + kSZ + optical data can put tight constraints on baryonic physics of DM halos: not only clusters but galaxies & QSOs