Title: TBA

Date: Jun 17, 2016 11:40 AM

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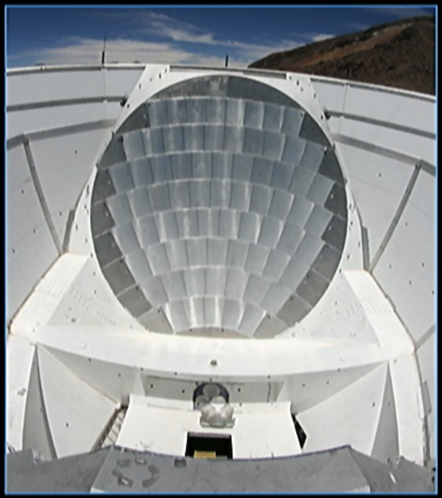
Abstract:

(non-SKA) Cosmology at UKZN

Jonathan Sievers for HIRAX, SCI-HI, ACT collaborations
(with apologies to HERA, MUSTANG2, SPIDER, C-BASS…)



(non-SKA) Cosmology at UKZN

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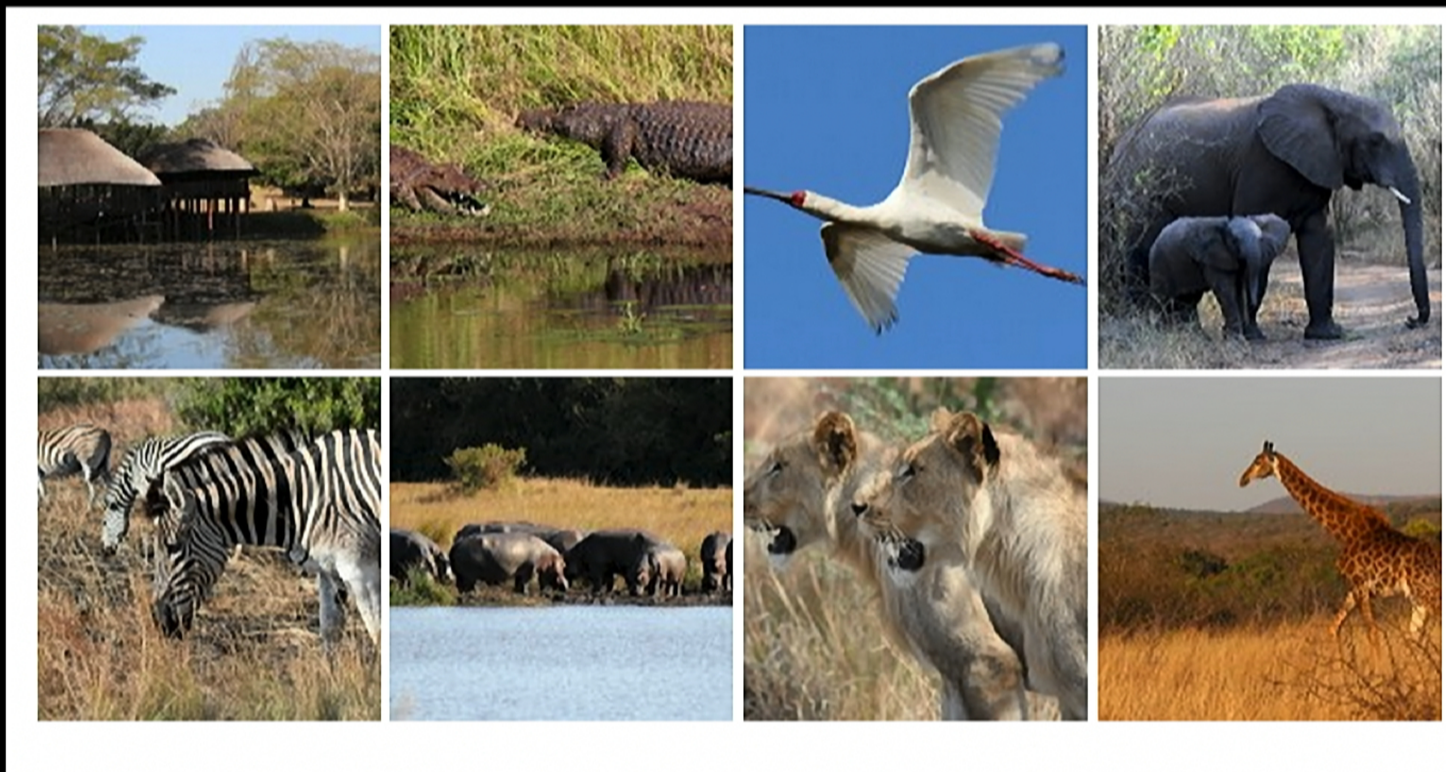
Come be Warm! (Late Jan/Early Feb 2017)

http://www.acru.ukzn.ac.za/~cosmosafari/



All pictures by Cynthia Chiang over 1 weekend

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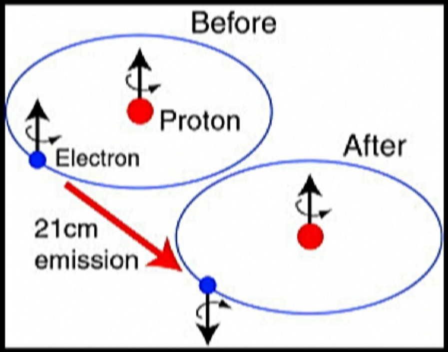
The Hydrogen Intensity and
Real-time Analysis eXperiment
Jonathan Sievers for HIRAX Collaborations

http://www.acru.ukzn.ac.za/~hirax/

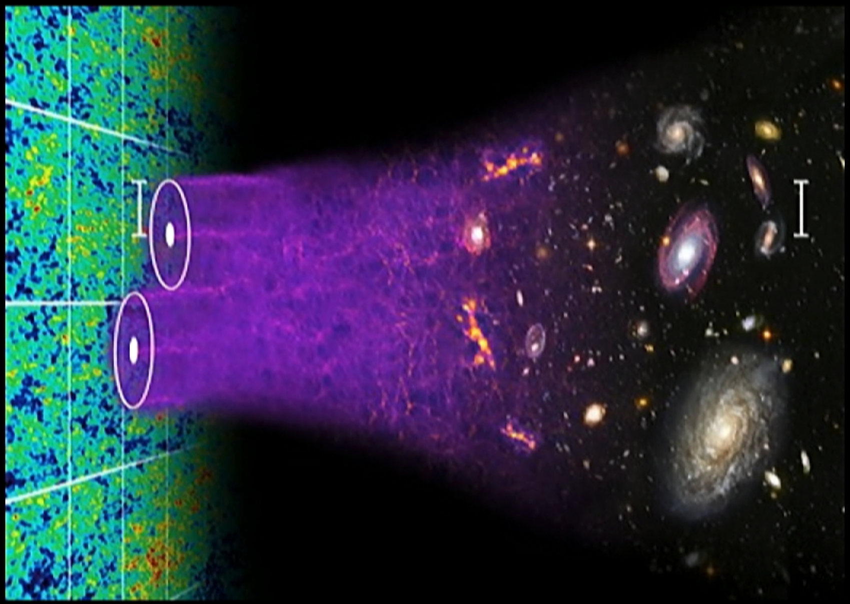
21 CM Transition



- Neutral (atomic) hydrogen (HI to astronomers) has a spin-flip transition. Electron spin aligned with proton, then flips to opposite spin.
- Energy very small - rest wavelength is 21 cm (1.4 GHz)
- Transition is forbidden, lifetime of excited state is about 10 million years.
- Long lifetime means kinetic temperature T_k (atomic motions) can decouple from spin temperature T_s, set by fraction of HI.
- No 21 cm from molecular hydrogen H_2, or ionized hydrogen.

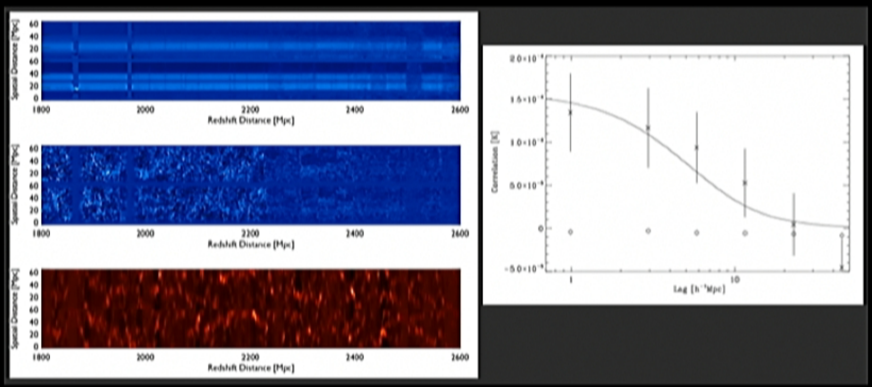
Baryon Acoustic Oscillations

- Comoving BAO size the sound horizon at recombination. Know how to calculate apparent size given cosmology, redshift.
- BAO scale large - >100 Mpc. c.f. entire volume of universe within z=0.1 only order 10^2 BAO volumes.
- To do precision cosmology, need lots of volume: large sky area, big redshift range.



Intensity Mapping

- Would like to have large spectroscopic survey.
- Have ~10^5 L_* galaxies/BAO volume - individual galaxies not that important.
- Hydrogen 21 cm line can be used. Very faint per galaxy.
- Instead, stack up signal from many galaxies with low resolution survey.
- First detection made comparing HI maps to galaxy maps, Chang et al.



First intensity mapping detection, Chang et al.

Canada at Forefront of Intensity Mapping

CHIME is Canadian cylinder telescope looking for BAOs in neutral hydrogen. 4 20x100m cylinders, 1024 feeds.

HIRAX

- We would like to measure dark energy via intensity mapping.
- Natural non-cylinder design: smallish dishes (6m) at z~1 (~700 MHz). Too high, no DE effects. Too low, no volume.
- BAO signal faint, need lots of elements to reach sensitivity.
- Significant development for CHIME (Canadian cylinder BAO experiment), digital electronics basically identical.
- HIRAX supported by UKZN as part of NRF Institutional Engagement and Partnership Development.

HIRAX

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- HIRAX supp ement and Partnership I

Current Design Plan

- Order 10^3 close-packed 6m dishes.
- Operate between 400-800 MHz
- Channelizing on FPGA ICE boards (McGill/Matt Dobbs)
- Correlation on GPUs (Toronto/Keith Vanderlinde).
- Dishes tilt N/S: when "deep enough" on a strip, tilt over to increase f_{sky}.
- Will beamform in correlator, for FRBs, kick out small subset of beams (~20) to external processing for pulsar search/monitoring, HI absorbers…

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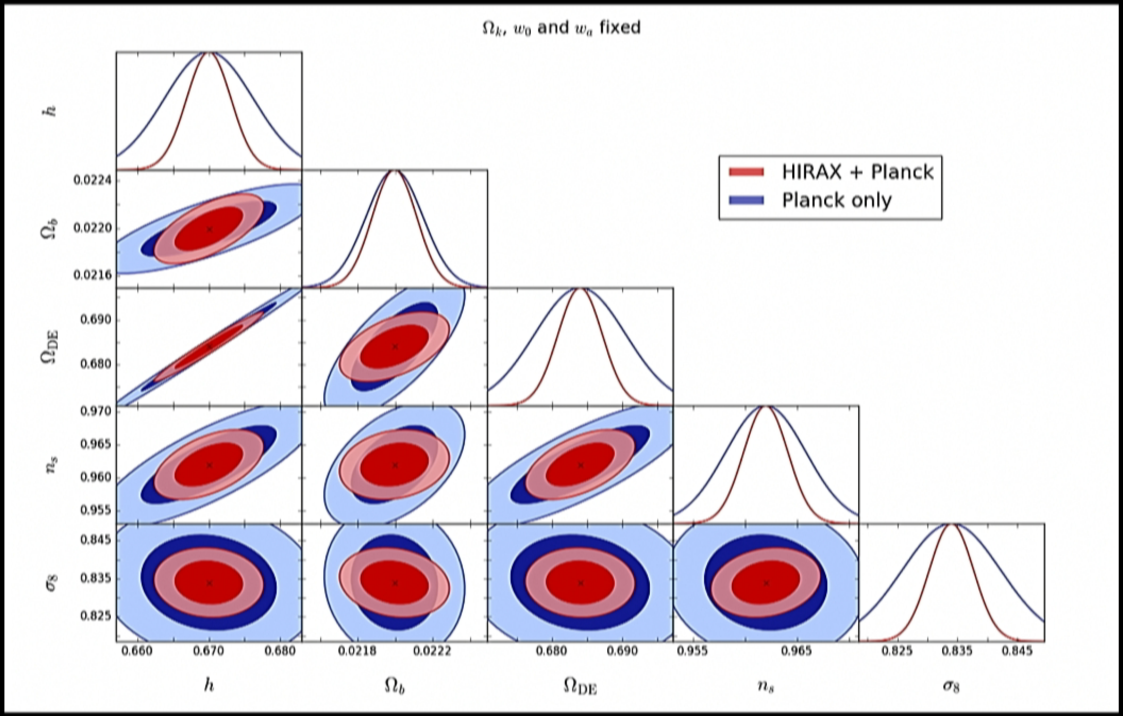
Preliminary Forecast (Amadeus Witzemann and Mario Santos)



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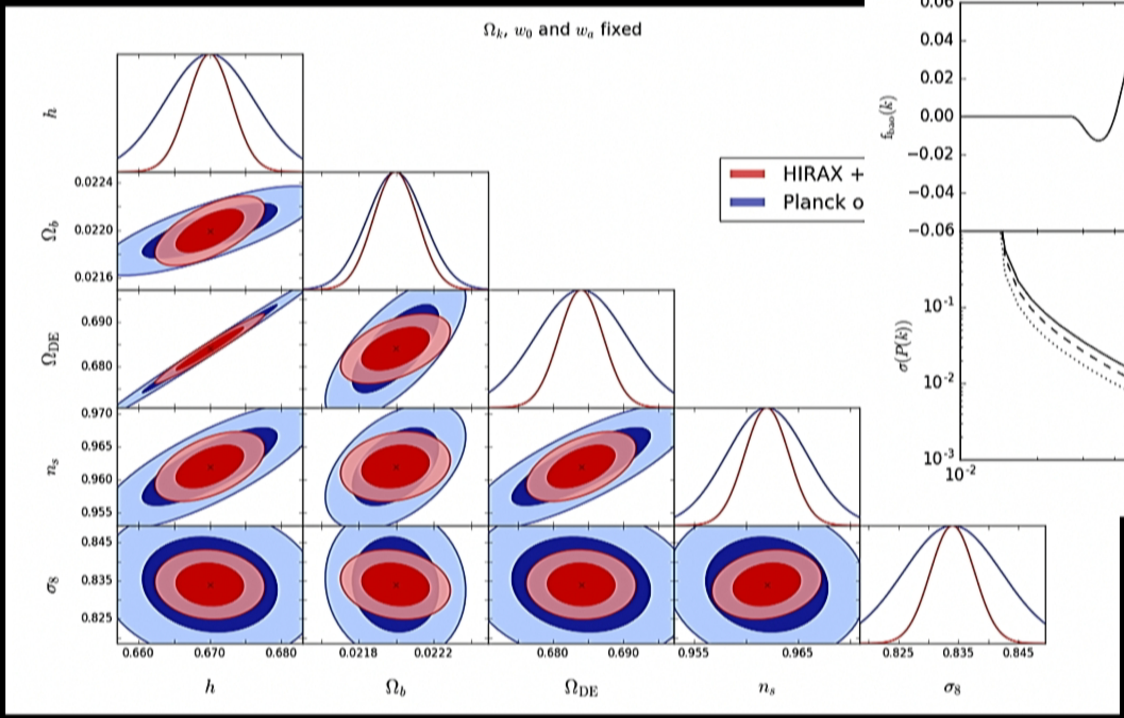
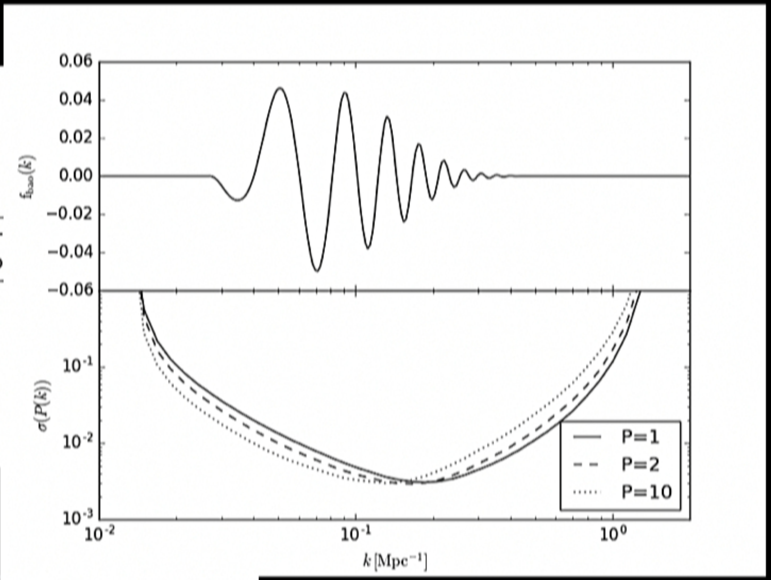
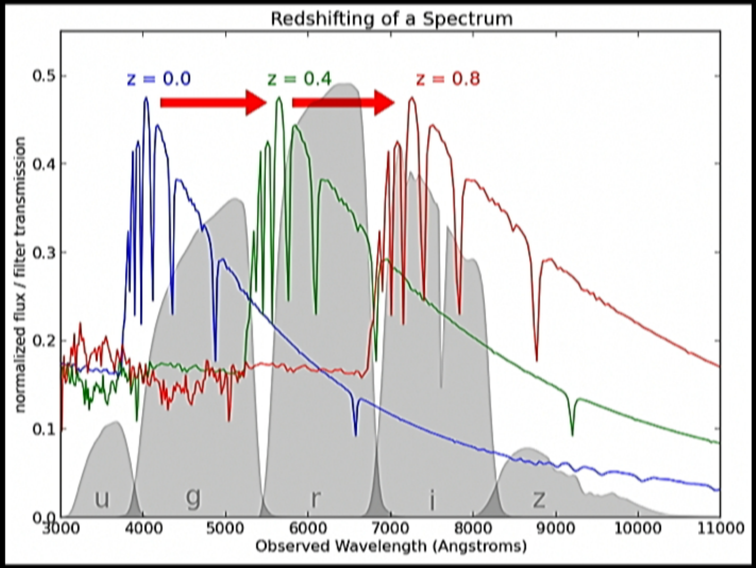
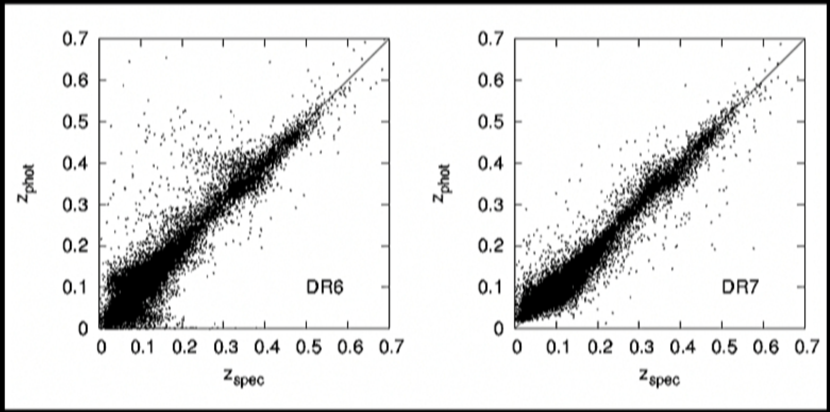




Redshift Catalog

- New photometric surveys (e.g. DES, LSST…) will have many new populations of sources/need spectroscopic calibration.
- Essential to get redshift distributions to understand physics/calibrate photo-z's etc.
- HIRAX spectroscopically traces matter field. Unknown population can get biased redshift distribution by cross-correlating w/ HIRAX.



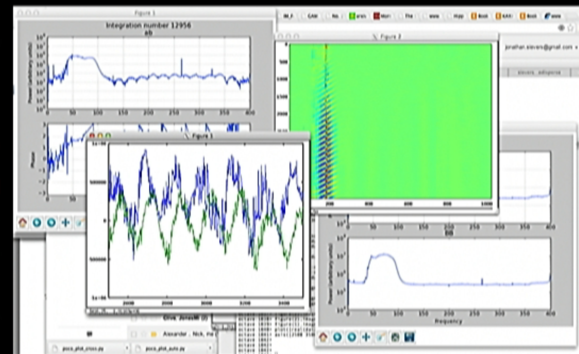


Proto-proto-prototype

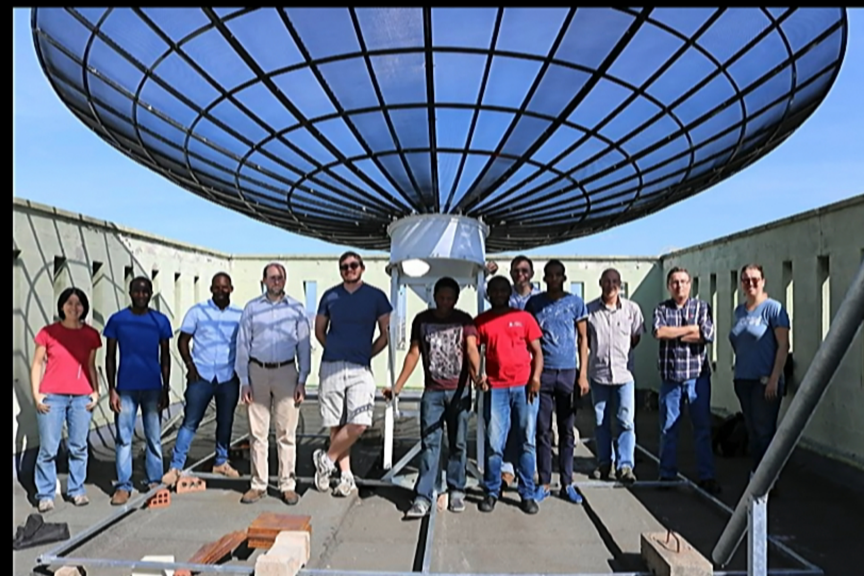
Borrowed travelling ROACH board, went to DUT to build 2-element interferometer with Chiang, Peterson, Van Vuuren, Macpherson.

With Installed dishes on roof, cabled everything up through RF chain. Got fringes on sun within 24 hours - first in KZN!

Clockwise, bottom left:
Dish w/ team, including SKA MSc stdents Allotey, Sengate
Inside DUT control rom
First fringes!
Prototype HIRAX feed

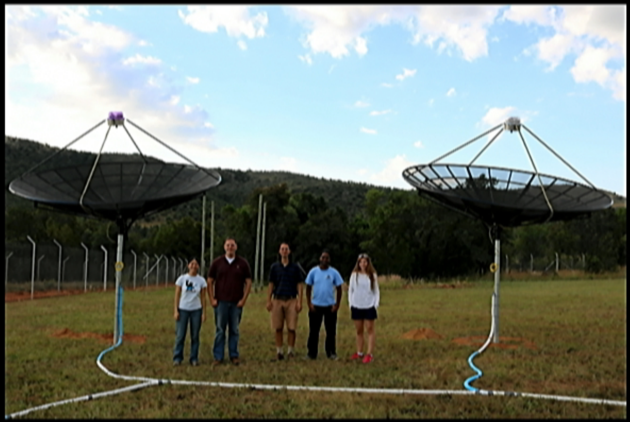


Prototype 6m Dish



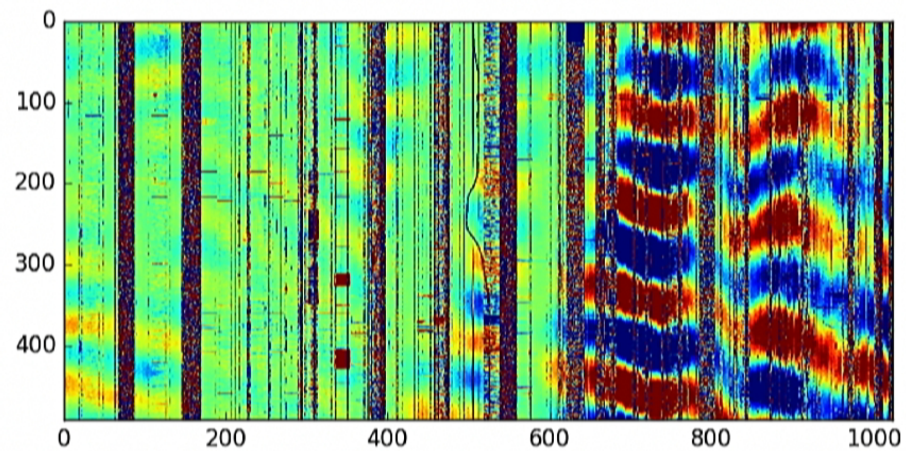
Jeff Peterson, Zhi-Ping Chen with prototype mount (L),
Cynthia Chiang as flower (C), DUT/UKZN crew (R)

4-Dish Installation



Fringe!

- Low frequency on right side of plot. Time increasing down. Ripples on right side are from an astronomical source.
- Vertical columns of stuff is RFI - we would lose these frequencies from HartRAO.

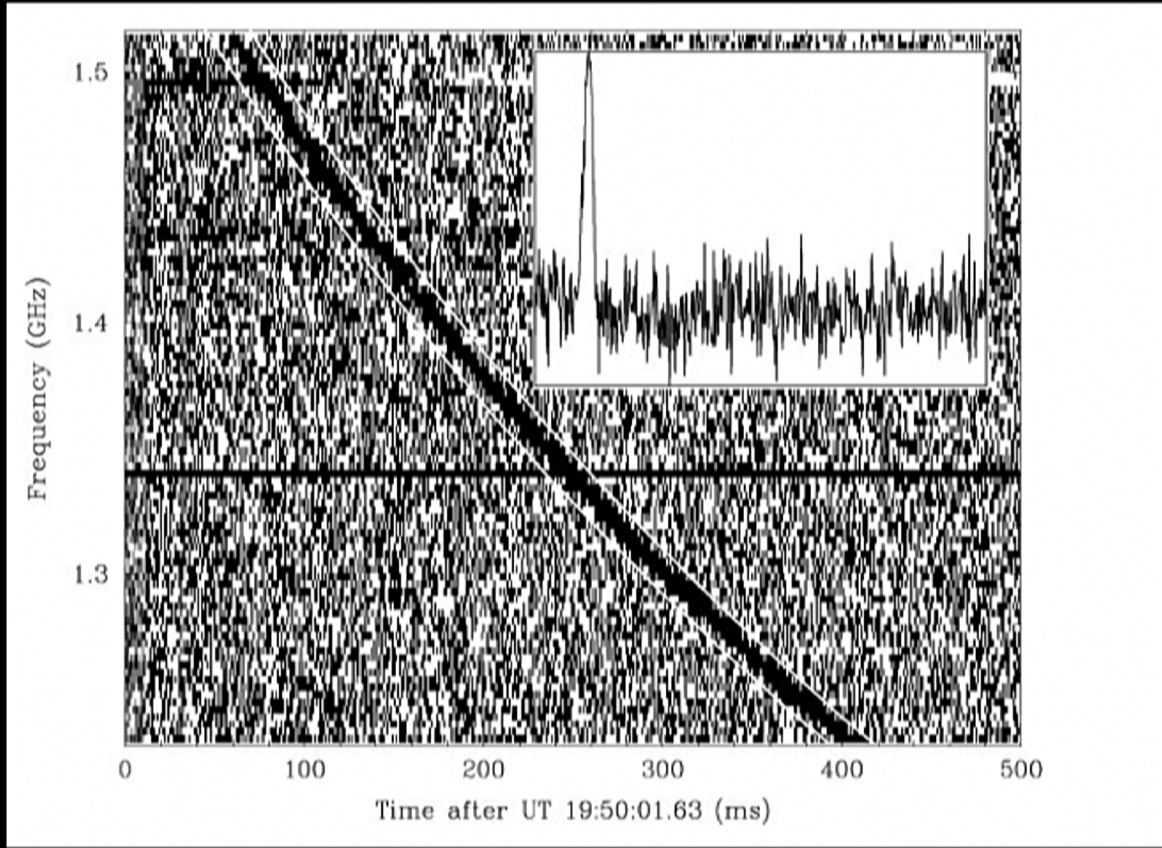


HIRAX & Pulsars/FRB

- At nominal sensitivity, get to ~12 μJy/beam/day (RMS).
- Need to search ~couple dozen beams simultaneously to cover full survey (approx 15,000 square degrees) once. Correlator will upgrade frequency resolution on beams.
- Full survey ~1 μJy/beam. What needs to be saved to maximize science? Will have ~1000 channels, search for stacked slow pulsars?
- Fantastic FRB machine. For Euclidean counts, event rate proportional to effective dish diameter times # of beams, so should have ~500x Parkes rate.

Fast Radio Bursts

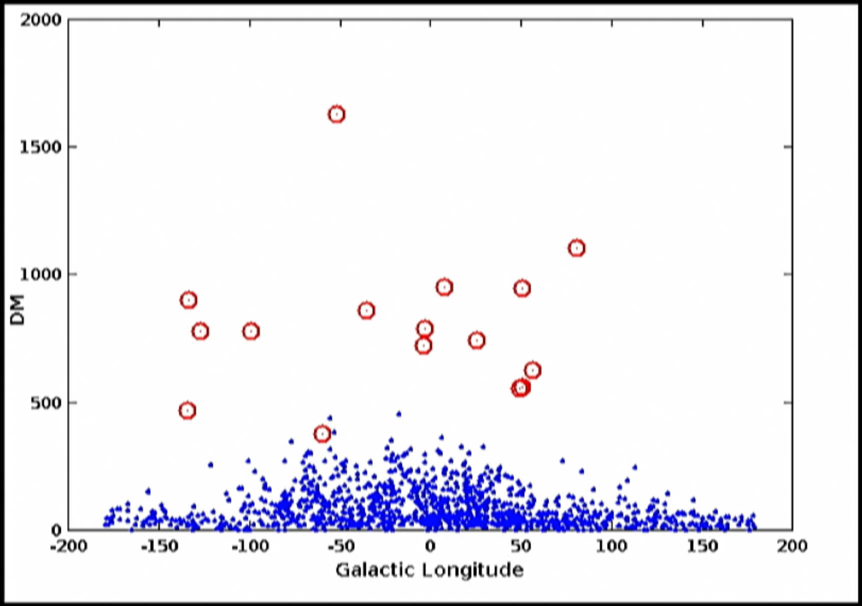
- Found in a pulsar search of archived data from Parkes
- Delay caused by e- along line of sight.
- Pulsar folks quote DM for column density. DM~500,000τ

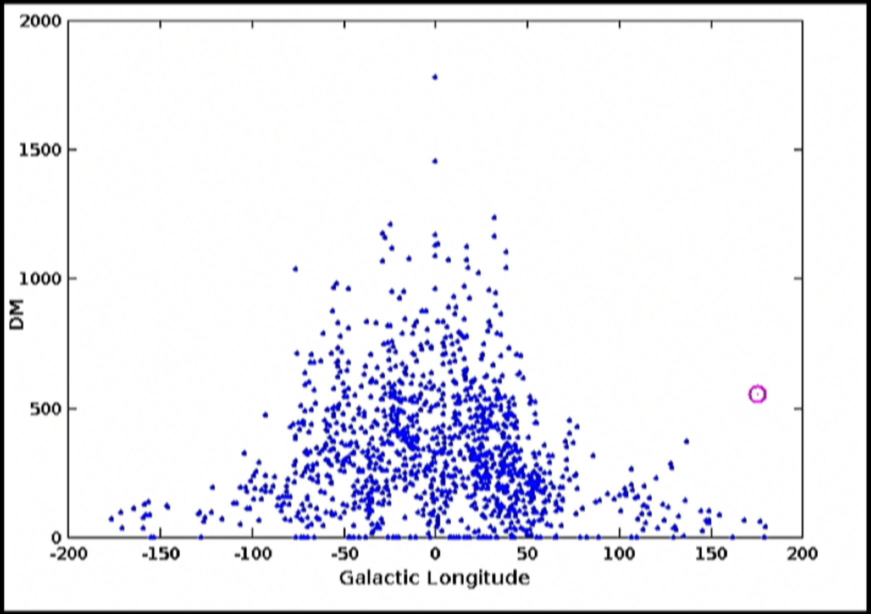


Still only ~20 FRBs Known

Event	Telescope	gl [deg]	gb [deg]	FWHM [deg]	DM [cm^{-3} pc]	S/N	W_{obs} [ms]	$S_{peak,obs}$ [Jy]	F_{obs} [Jy ms]	Ref
FRB010125	parkes	356.641	-20.020	0.25	790(3)	17	$9.40^{+0.20}_{-0.20}$	0.30	2.82	1
FRB010621	parkes	25.433	-4.003	0.25	745(10)		7.00	0.41	2.87	2
FRB010724	parkes	300.653	-41.805	0.25	375	23	5.00	$>30.00^{+10.00}_{-10.00}$	>150.00	3
FRB090625	parkes	226.443	-60.030	0.25	899.55(1)	30	$1.92^{+0.83}_{-0.77}$	$1.14^{+0.42}_{-0.21}$	$2.19^{+2.10}_{-1.12}$	4
FRB110220	parkes	50.828	-54.766	0.25	944.38(5)	49	$5.60^{+0.10}_{-0.10}$	$1.30^{+0.00}_{-0.00}$	$7.28^{+0.13}_{-0.13}$	5
FRB110523	GBT	56.119	-37.819	0.26	623.30(6)	42	$1.73^{+0.17}_{-0.17}$	0.60	1.04	6
FRB110626	parkes	355.861	-41.752	0.25	723.0(3)	11	1.40	0.40	0.56	5
FRB110703	parkes	80.997	-59.019	0.25	1103.6(7)	16	4.30	0.50	2.15	5
FRB120127	parkes	49.287	-66.203	0.25	553.3(3)	11	1.10	0.50	0.55	5
FRB121002	parkes	308.219	-26.264	0.25	1629.18(2)	16	$5.44^{+3.50}_{-1.20}$	$0.43^{+0.33}_{-0.06}$	$2.34^{+4.46}_{-0.77}$	4
FRB121102	arecibo	174.950	-0.225	0.05	557(2)	14	$3.00^{+0.50}_{-0.50}$	$0.40^{+0.40}_{-0.10}$	$1.20^{+1.60}_{-0.45}$	7
FRB130626	parkes	7.450	27.420	0.25	952.4(1)	21	$1.98^{+1.20}_{-0.44}$	$0.74^{+0.49}_{-0.11}$	$1.47^{+2.45}_{-0.50}$	4
FRB130628	parkes	225.955	30.655	0.25	469.88(1)	29	$0.64^{+0.13}_{-0.13}$	$1.91^{+0.29}_{-0.23}$	$1.22^{+0.47}_{-0.37}$	4
FRB130729	parkes	324.787	54.744	0.25	861(2)	14	$15.61^{+9.98}_{-6.27}$	$0.22^{+0.17}_{-0.05}$	$3.43^{+6.55}_{-1.81}$	4
FRB131104	parkes	260.549	-21.925	0.25	779(1)	30	2.08	1.12	2.33	8
FRB140514	parkes	50.841	-54.611	0.25	562.7(6)	16	$2.80^{+3.50}_{-0.70}$	$0.47^{+0.11}_{-0.08}$	$1.32^{+2.34}_{-0.50}$	9
FRB150418	parkes	232.665	-3.234	0.25	776.2(5)	39	$0.80^{+0.30}_{-0.30}$	$2.20^{+0.60}_{-0.30}$	$1.76^{+1.32}_{-0.81}$	10

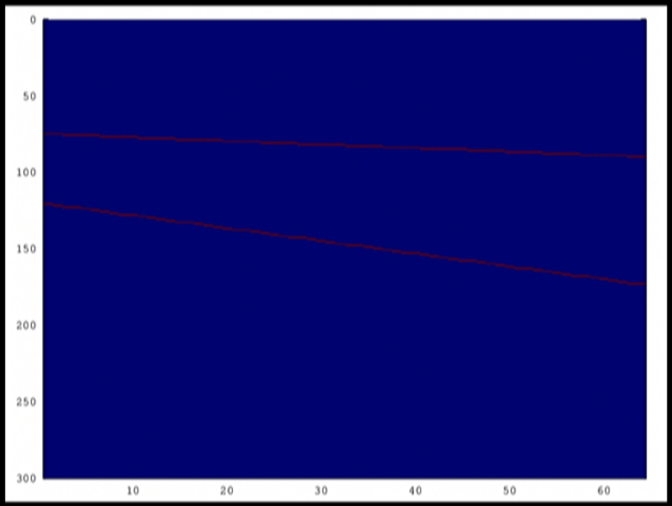
FRBs Differ from MW Pulsars



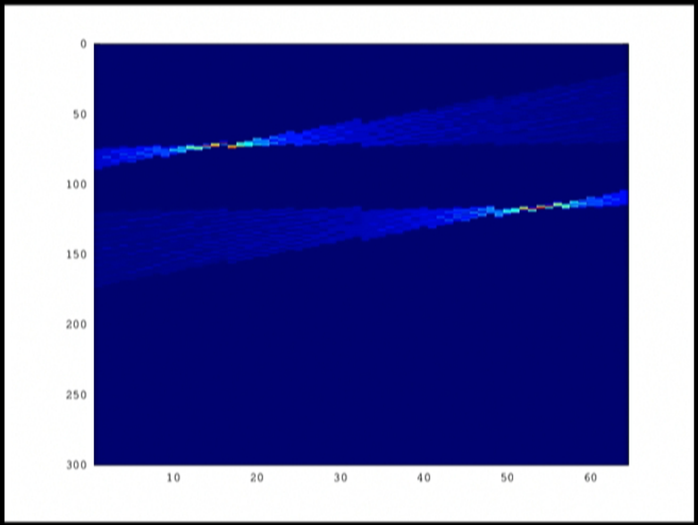


Left: high-latitude FRBs/pulsars (|b|>3)
Right: low-latitude FRBs/pulsars
Magenta - repeating FRB (b=-0.25)

Fast DM Transform



t_{burst} ↓



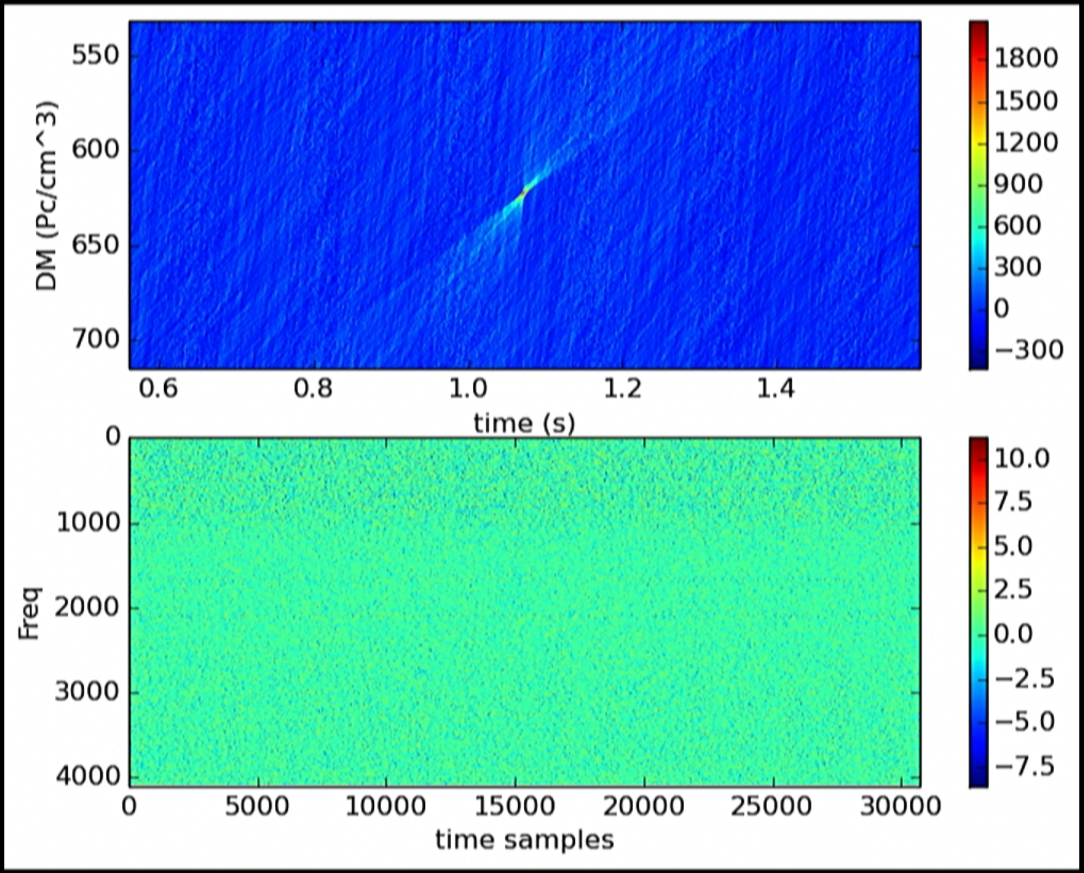
DM →

Developed fast FRB search algorithms for use with HIRAX. K. Smith expanding for CHIME

Test w/ GBT Archival Data

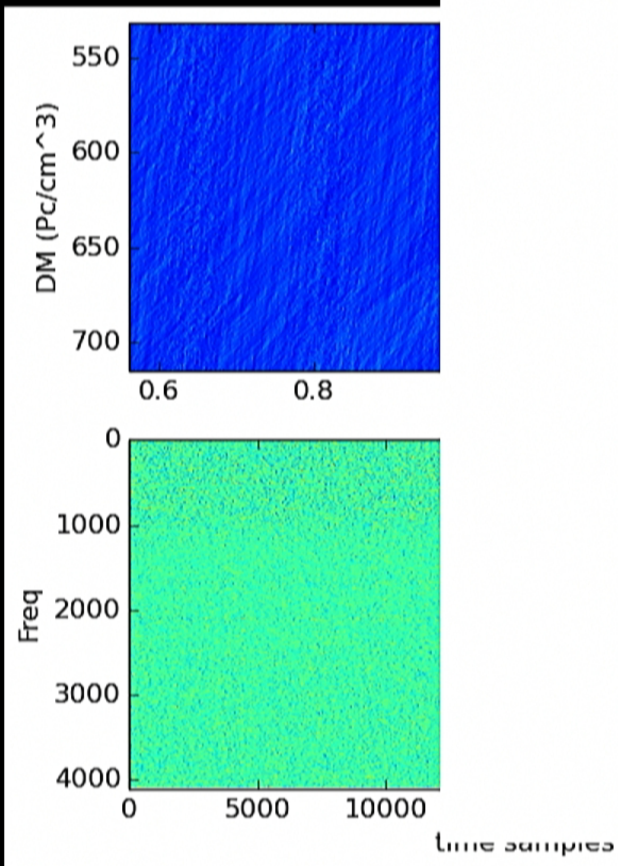
- 650 Hours of data w/ polarization
- Frequency 700 to 900 MHz
- Spectra recorded every 1.024 ms
- 15 arcminute angular resolution
- NB - telescope scanning during data collection

FRB w/ GBT

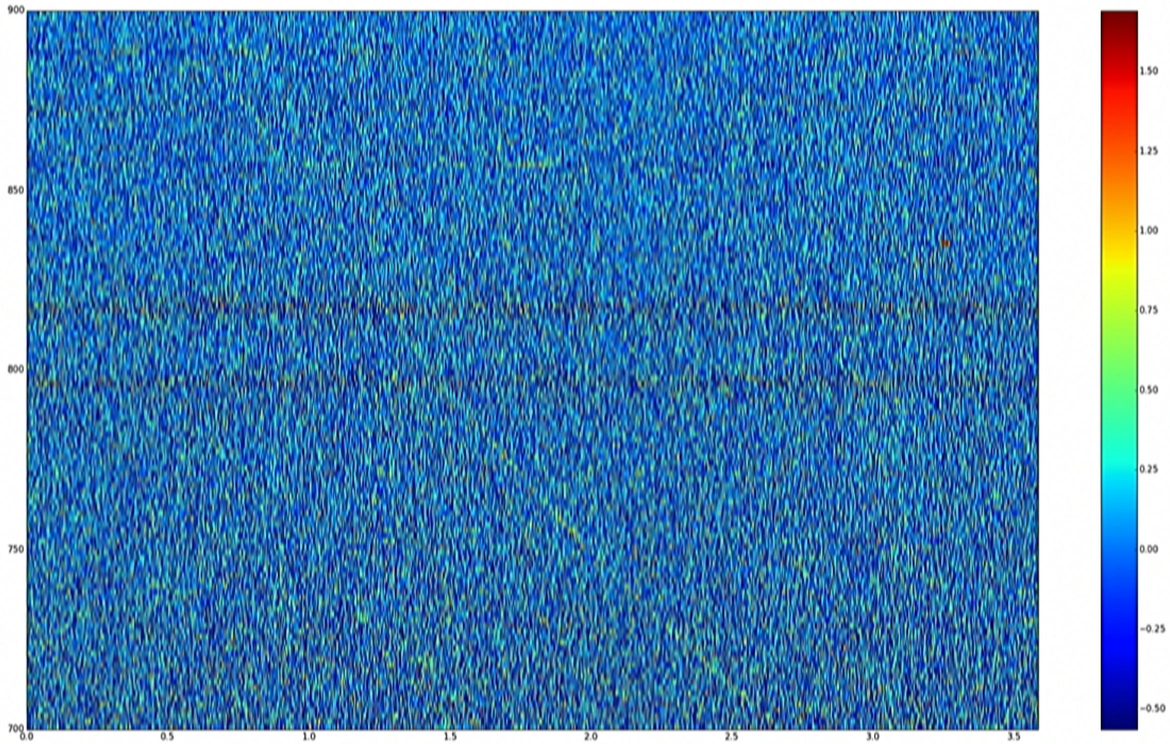


DM (Pc/cm^3)
550
600
650
700
0.6
0.8
1.0
1.2
1.4
time (s)
1800
1500
1200
900
600
300
0
−300
Freq
0
1000
2000
3000
4000
0
5000
10000
15000
20000
25000
30000
time samples
10.0
7.5
5.0
2.5
0.0
−2.5
−5.0
−7.5

FRB w/ GBT



DM (Pc/cm^3)
550
600
650
700
0.6
0.8
Freq
0
1000
2000
3000
4000
0
5000
10000
time samples

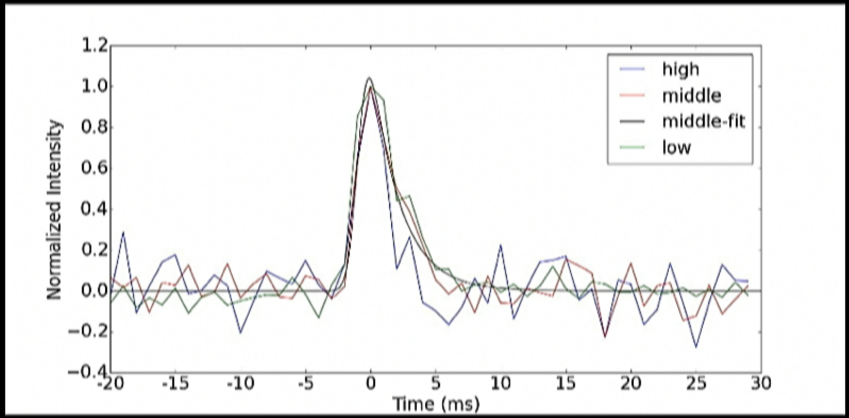


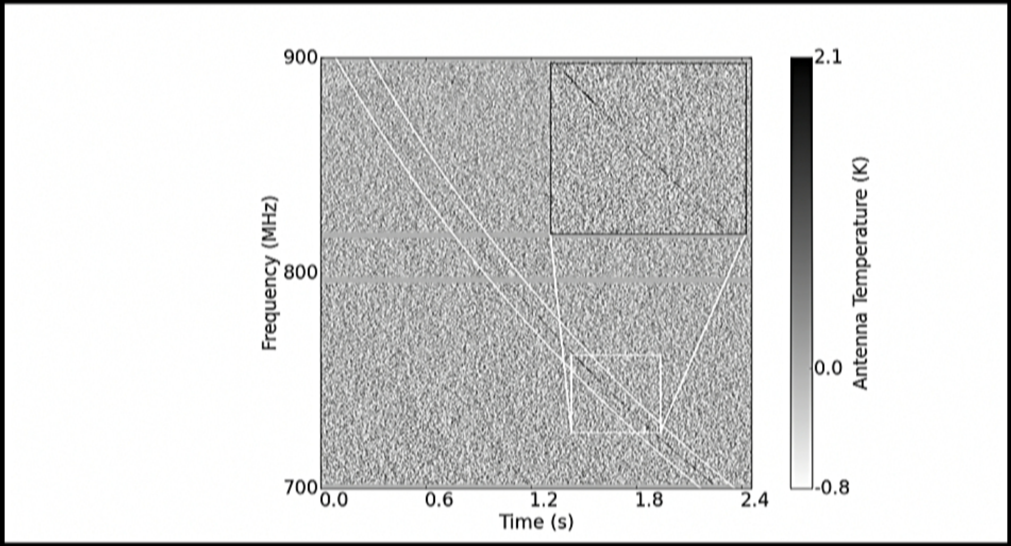
Burst Fit Parameters

Barycentric $\nu = \infty$ arrival (MJD)	55704.62939511
GBT boresight at 900 MHz arrival	RA = $21^h45^m31^s$ Dec = $-00^d15^m23^s$ l = 56.0795° b = −37.9435°
GBT boresight at 700 MHz arrival	RA = $21^h45^m12^s$ Dec = $-00^d09^m37^s$ l = 56.1215° b = −37.8234°
Dispersion measure (pc cm^{-3})	623.30(6)
Fluence at 800 MHz (K ms)	3.79(15)
Spectral index	−7.8(4)
Unscattered pulse FWHM (ms)	1.73(17)
Scattering time at 800 MHz (ms)	1.66(14)
Linear polarization fraction (%)	44(3)
Rotation measure (rad m^{-2})	−186.1(1.4)
Polarization rotation rate (rad ms^{-1})	−0.25(5)
Dispersion measure index	−1.998(3)
Scattering index	−3.6(1.4)
Rotation measure index	−1.7(2)

- First seen by GBT
- First seen in CHIME/HIRAX band
- First seen with linear polarization - Faraday rotation seen.
- Burst behaves just like astrophysical signal would.

Scattering and Scintillation Detected





Burst both seen to be multi-path scattered (top) and scintillate (bottom). Scintillation consistent with galactic expectation.

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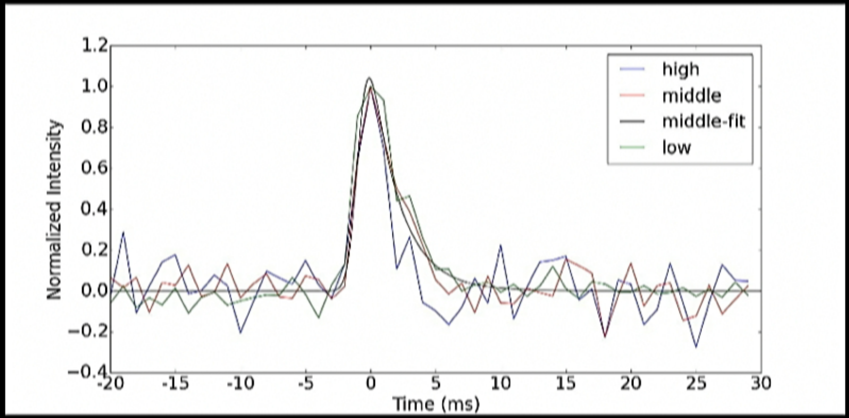

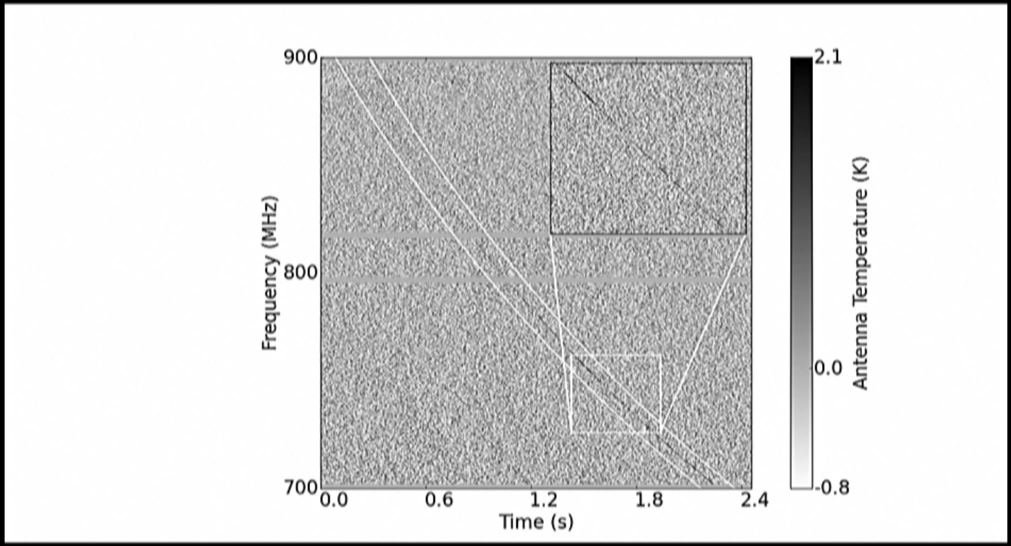

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Dispersion Index

- True dispersion relation is k2= ω2+ ωp2
- At frequencies "near" plasma frequency, dispersion relation deviates from λ2.
- Precise measurement of spectral index (-1.998±0.003) lets us plasma frequency
- Implies ne<1.3e7cm-3 (95%), minimum size of DM region 10 AU.
- Combined w/ scattering & scintillation - burst extragalactic.

What We Know

- FRBs do not look like MW pulsars. Could be giant pulses from extragalactic pulsars.
- Only repeating FRB in galactic plane (expect 0.1/20 at that latitude or lower).
- GBT burst extragalactic, but seems to have nearby electrons.
- Many FRBs seen by Parkes have no evidence of scattering, some show no Faraday rotation above expected MW component.
- Multiple populations entirely possible.
- Still no redshifts.

FRBs for Fun & Profit

- CHIME/HIRAX (+Tienlai+MeerKAT+ASKAP+…) will soon mean thousands of FRBs. Column density incredibly precisely measured.
- FRBs may be able to break kSZ, tSZ degeneracies.
- FRBs can test equivalence principle. Maybe dark energy.
- Soon have ~1% of sky monitored. If NS mergers source (some) FRBs, may be able to pin down location.

HIRAX outriggers could get sub-arcsecond (mili?) positions for all HIRAX FRBs.

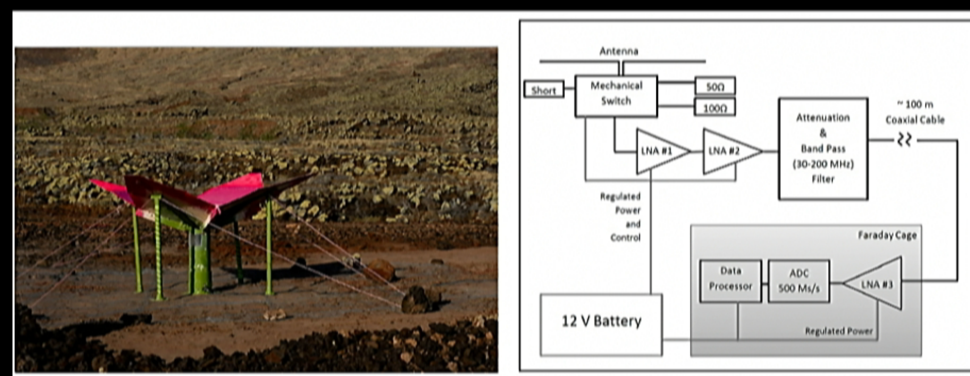
Current Status

- Approval from NRF, final pending site agreement with SKA. UKZN research office has committed funding over 5 years. Have seed money for prototype/128-element pathfinder.
- Next step finish 8-element prototype, at HartRAO. Full buildout over ~2-3 years.
- AMD GPU released last year sufficient for CHIME. Moore's Law no longer required (but nice!) for HIRAX. 16 nm nodes showing up now (single card NVidia @21 TFLOPS, half-precision). AMDs coming out imminently.
- If you have other science you'd like to do, please talk to us!

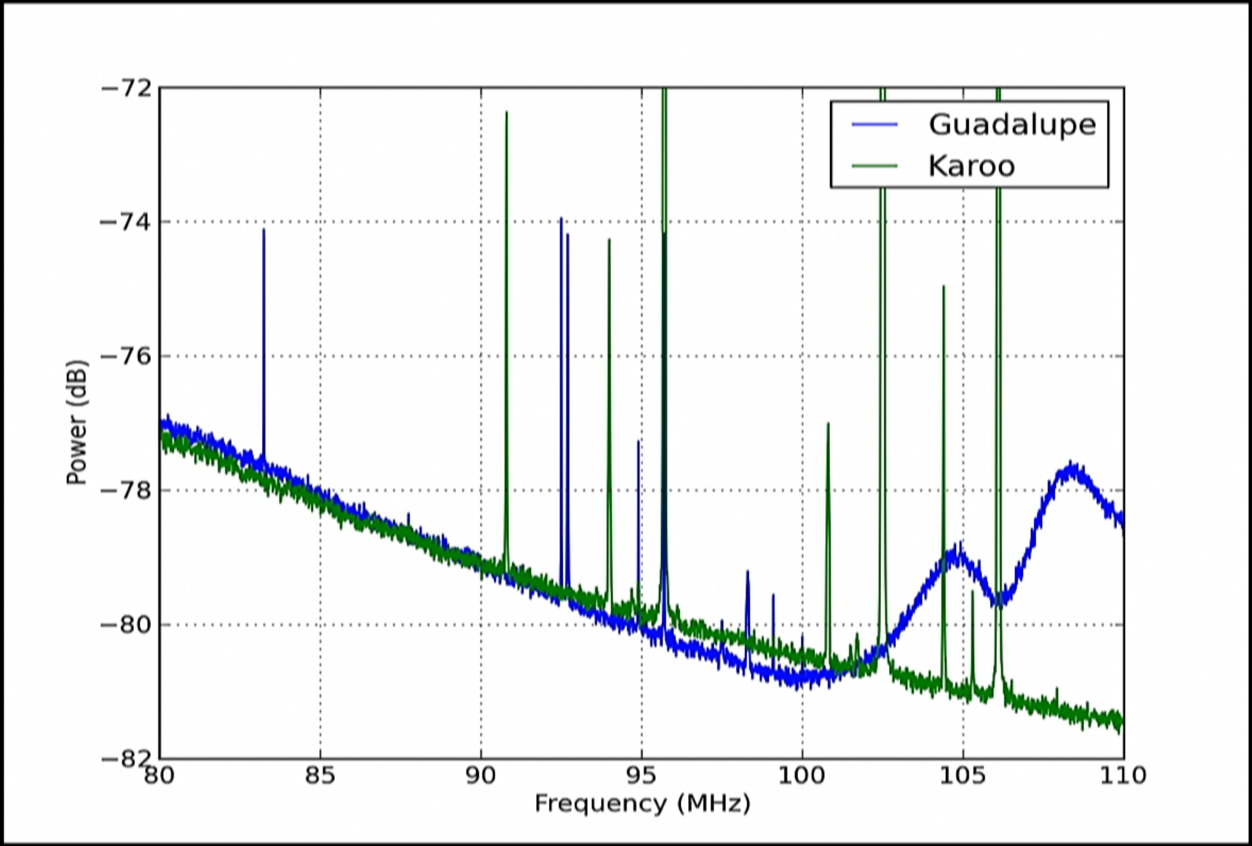
21 CM from EoR

- Early in the universe, hydrogen coupled to CMB
- As universe expands, $T_{CMB} \sim a^{-4/3}$. $T_{gas} \sim a^{-5/3}$. So, gas cools faster than CMB. Shows up as absorption.
- Eventually Lyman-α photons excite hydrogen, which decays back to ground state, raising spin temperature.
- Mean brightness of universe vs. CMB in 21cm line will drop with increasing time, then go up. After universe is ionized, temperature goes back to T_{CMB}.

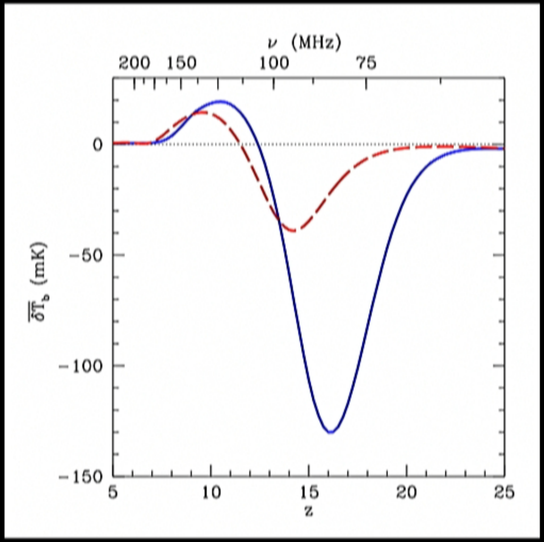
Above: EDGES. Also, LEDA, proposed DARE (far side of moon)
Below: SCI-HI



SCI-HI At Guadalupe & Karoo
RFI Problematic



SCI-HI In the SubAntarctic (SHISA)



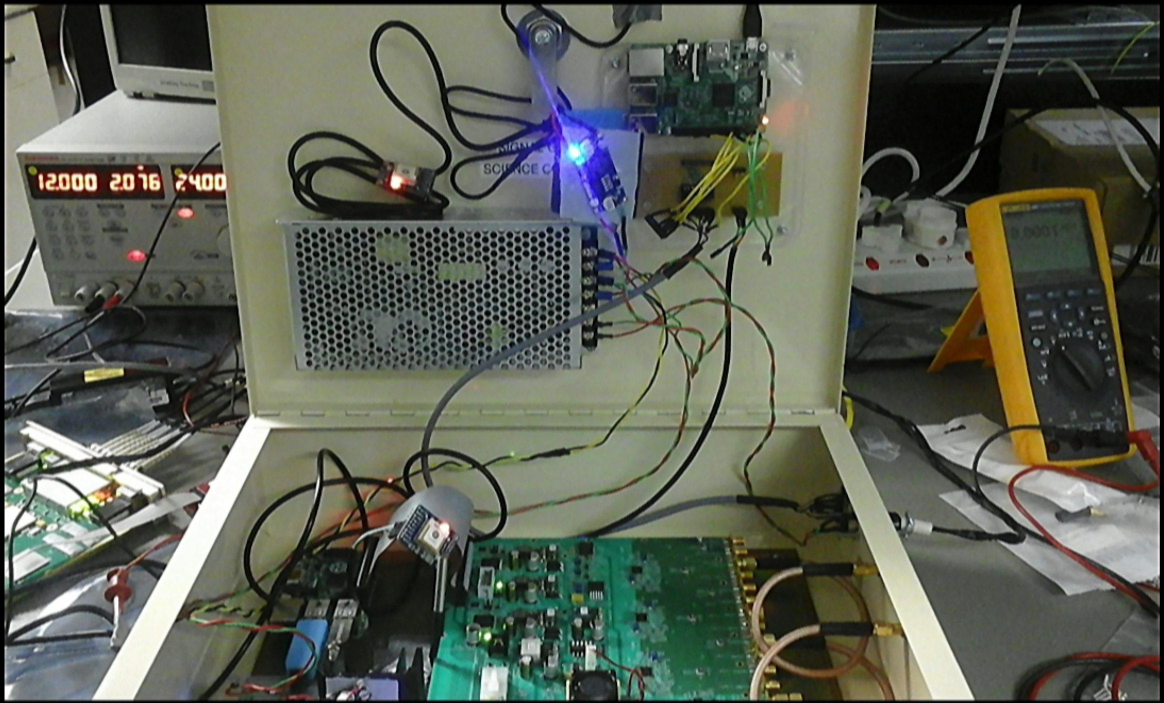
Sub-Antarctic location very good for ionosphere, particularly during winter.

Reionization leaves a signal in the mean brightness of the sky. Different sorts of objects that reionize the universe leave vastly different imprints (above - blue=pop II stars, red=pop III).

Global signals require exquisite control of RFI; getting away from people good. We have taken SCI-HI (above) experiment to sub-Antarctic islands (Marion), 2000 km from nearest people.

SNAP Board

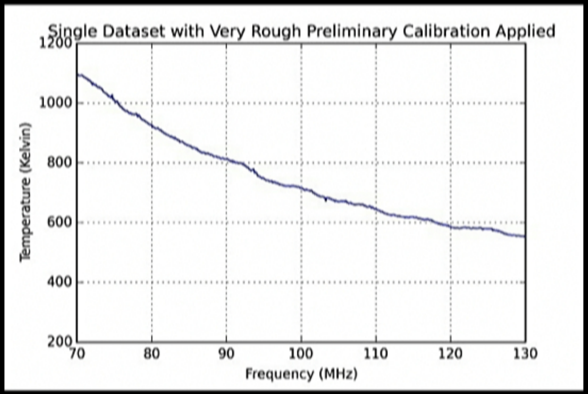
- Using SNAP board from Berkeley for SCI-HI back end. Designed for HERA, but SCI-HI is first field deployment.
- Whole system uses <30W, can run for at least a day on 2 car batteries. While Fourier transforming 4-8 billion numbers/second.



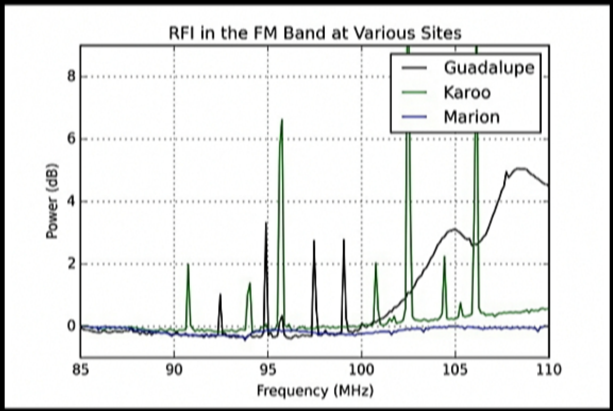
SCI-HI at Marion!

- Deployed SCI-HI in field at Marion (Voytek, Spann, Philip)
- Curious seals meant uphill location.
- Logistical challenges limited to a few days of data.
- Plan to leave over winter next year.

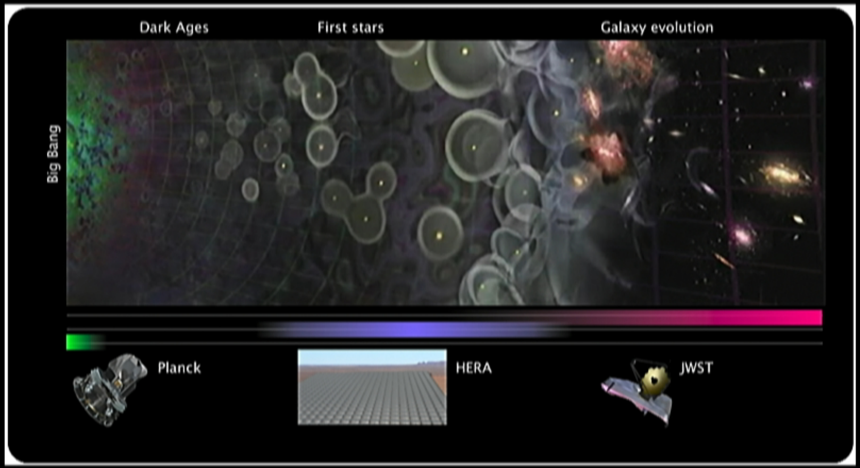
Some of Cleanest Data Ever



- Quick look at data show no detectable RFI, even in FM band.
- Plenty of sensitivity for detection even with limited data.
- Analysis just starting. Stay tuned…

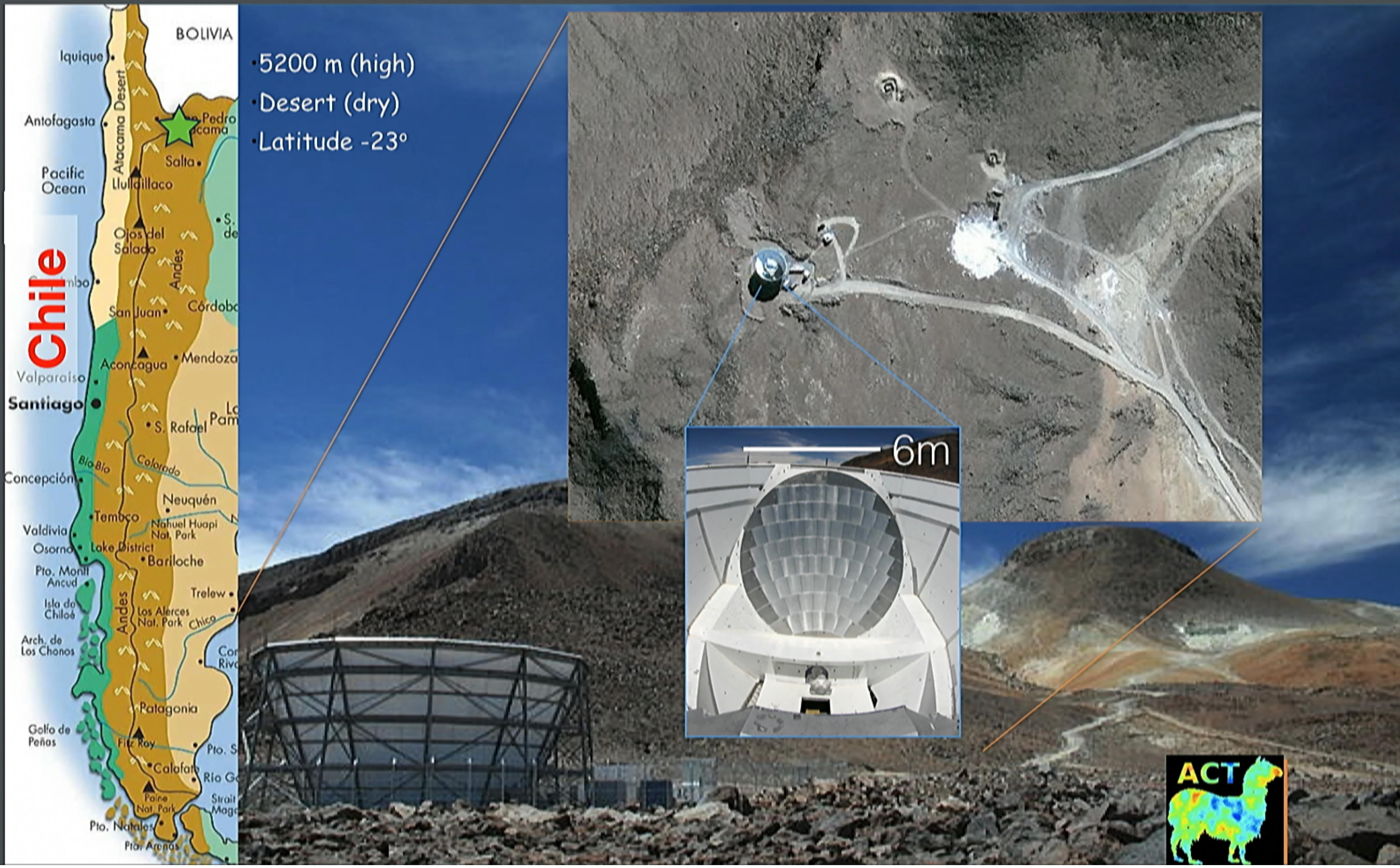


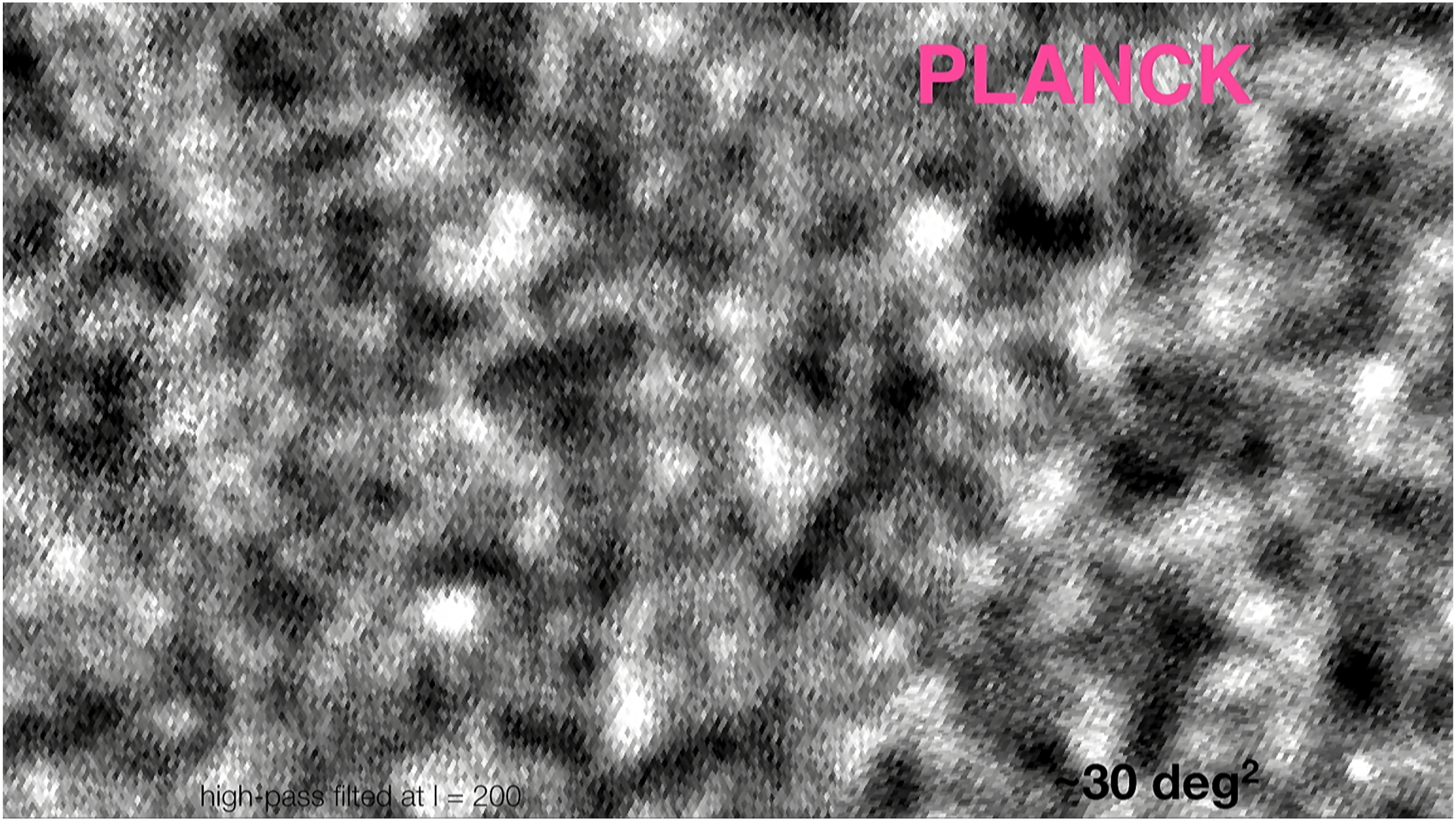
Fluctuations Should Also be Visible

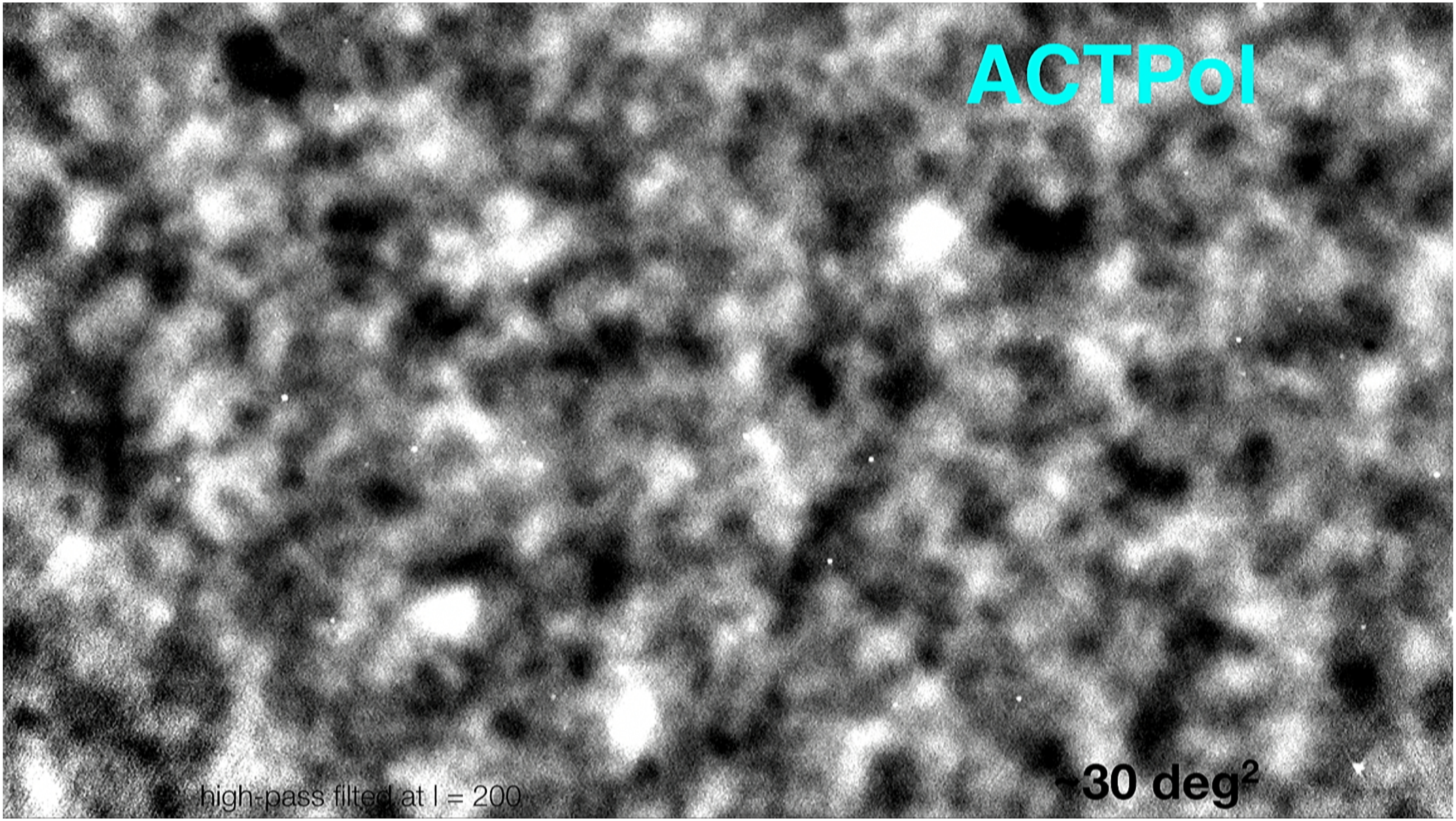


Hydrogen Epoch of Reionization Array (HERA). SA-based instrument to measure power spectrum of fluctuations. 19 dishes installed already!

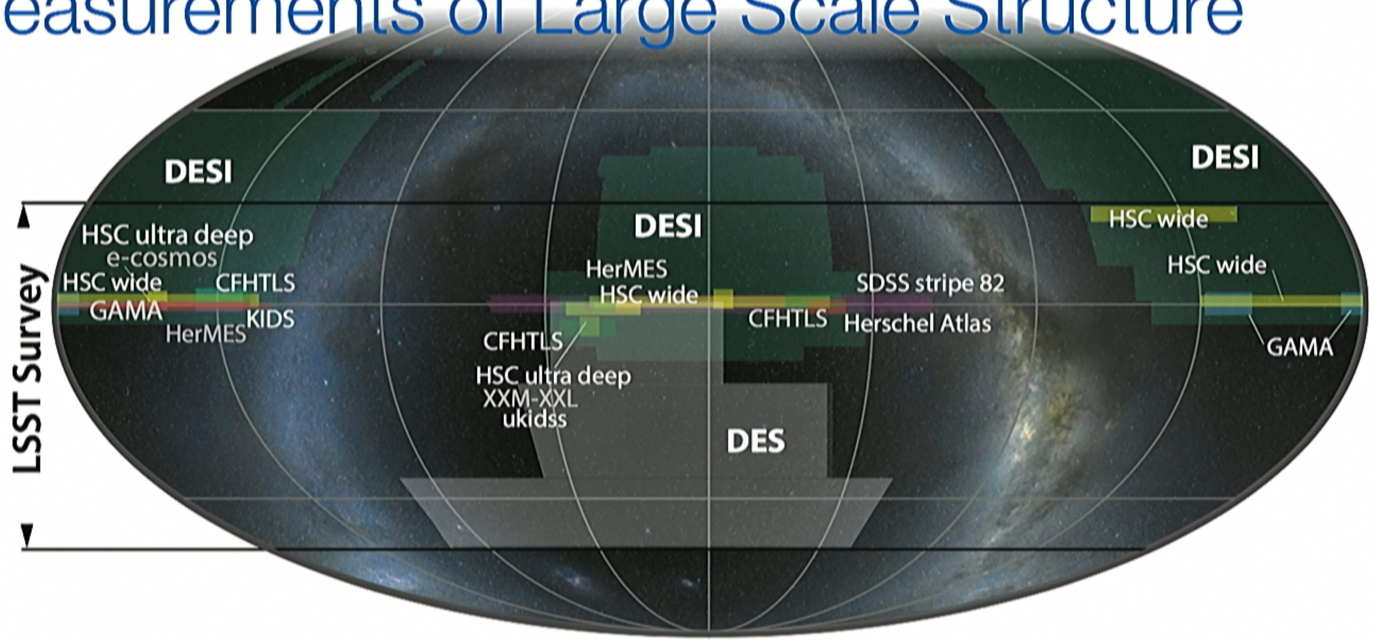
The Atacama Cosmology Telescope




PLANCK
high-pass filted at l = 200
~30 deg^2

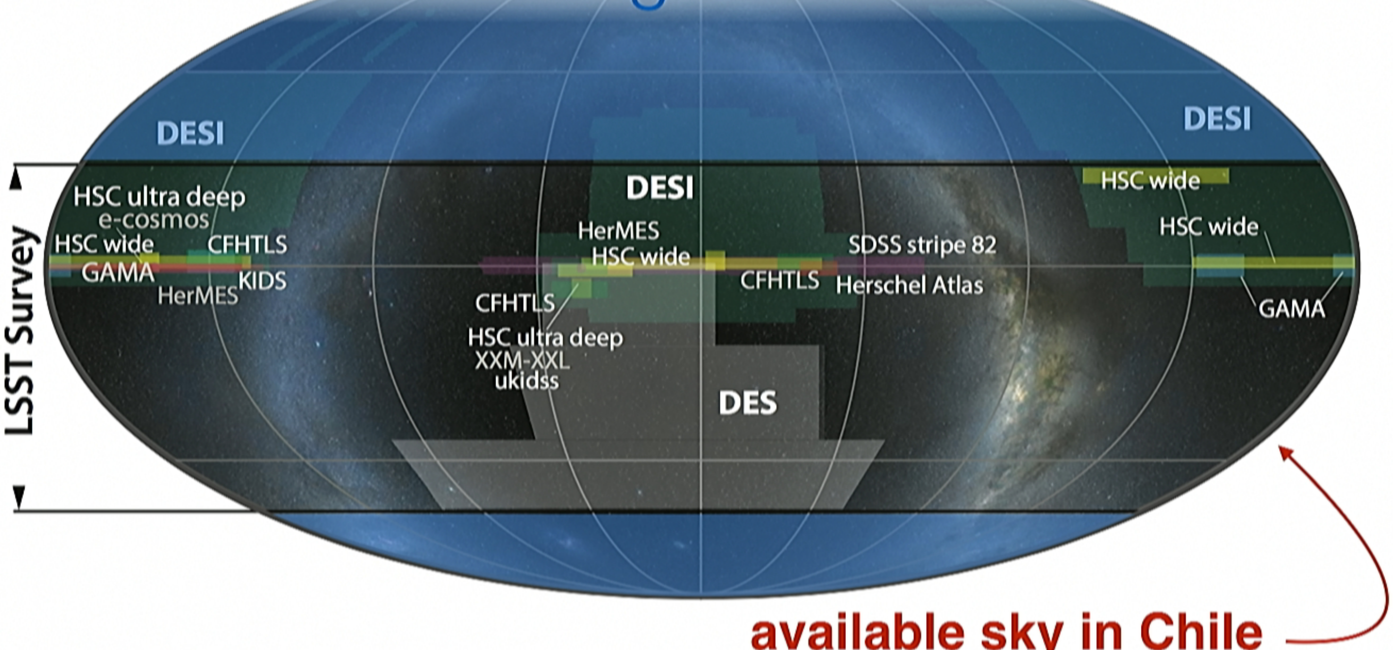

ACTPol
high-pass filted at l = 200
~30 deg²

Cross-correlations with optical measurements of Large Scale Structure



survey type	measurements	complementarity
photometric surveys	clusters	clusters tSZ, scaling relations, mass calibraiton (CMB lensing)
spectroscopic surveys	matter power spectrum / BAO	velocity field (kSZ), calibration
galaxy shear lensing	matter power spectrum	calibration of multiplicative bias

Cross-correlations with optical measurements of Large Scale Structure



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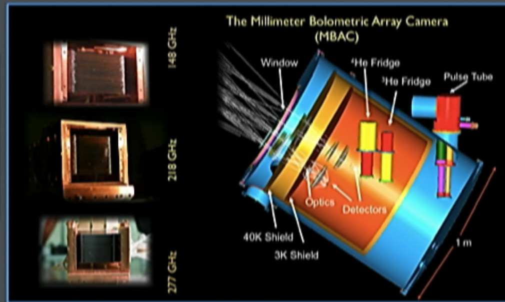
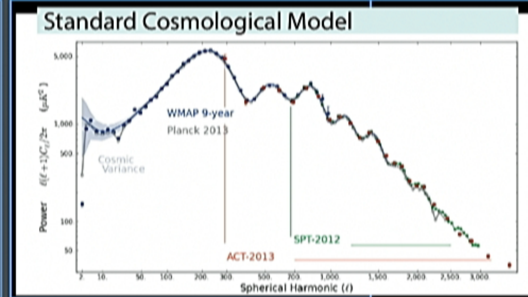
galaxy shear lensing	matter power spectrum	calibration of multiplicative bias

ACT Cameras and future instruments

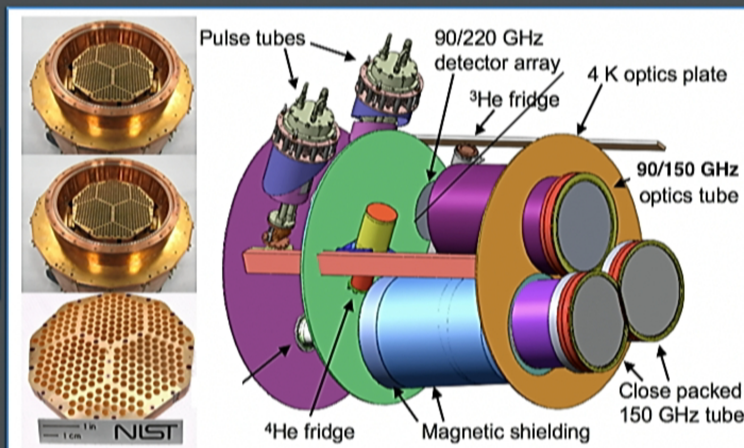
The Past:
2007-2010
MBAC



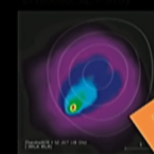


ACT discovery highlights

The Present:
2012-2015
ACTPol

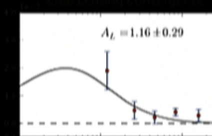


Sunyaev-Zel'dovich Effect



Most massive at t/2!

Gravitational Lensing



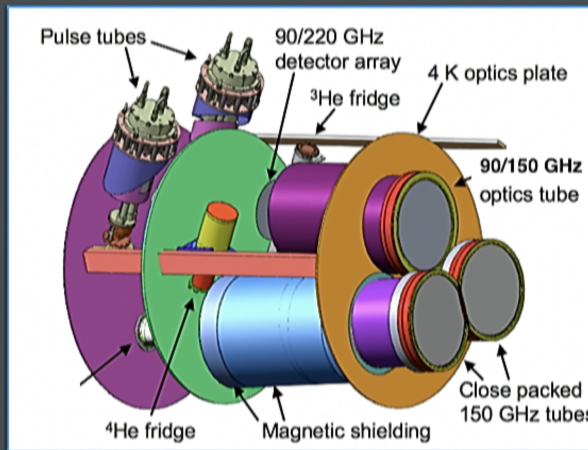
FIRST!

barely

The Future:
2016-2019
Advanced ACTPol (AdvACT)

2020 and beyond
Simons Observatory
CMB-S4

the **ACTPol** Receiver

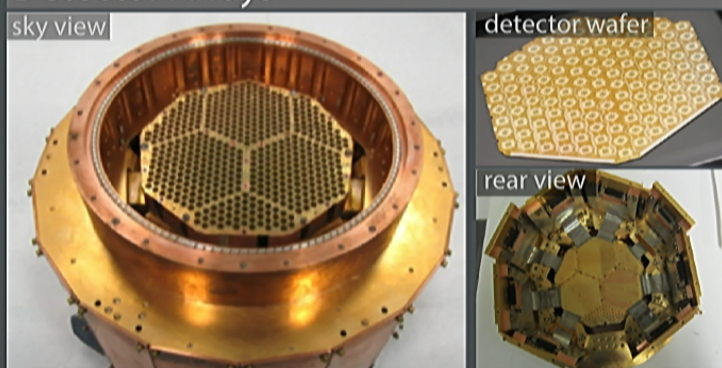


3 optics tubes
- 2 @ 150 GHz arrays
- 1 @ 90/150 multichroic

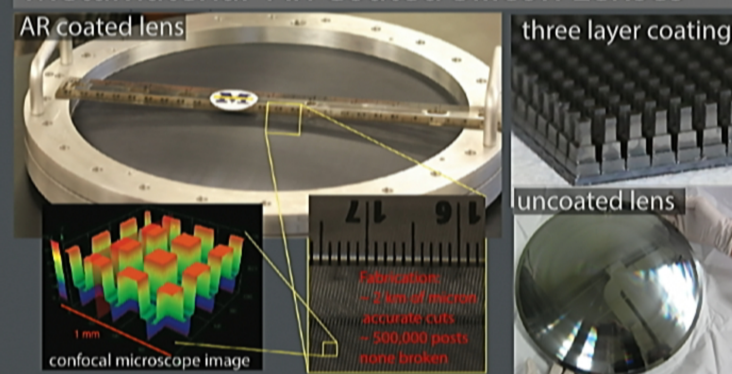
Metamaterial AR silicon lenses
-low reflectance
-low dielectric loss

Dilution refrigerator
- 90 mK base
- continous operation

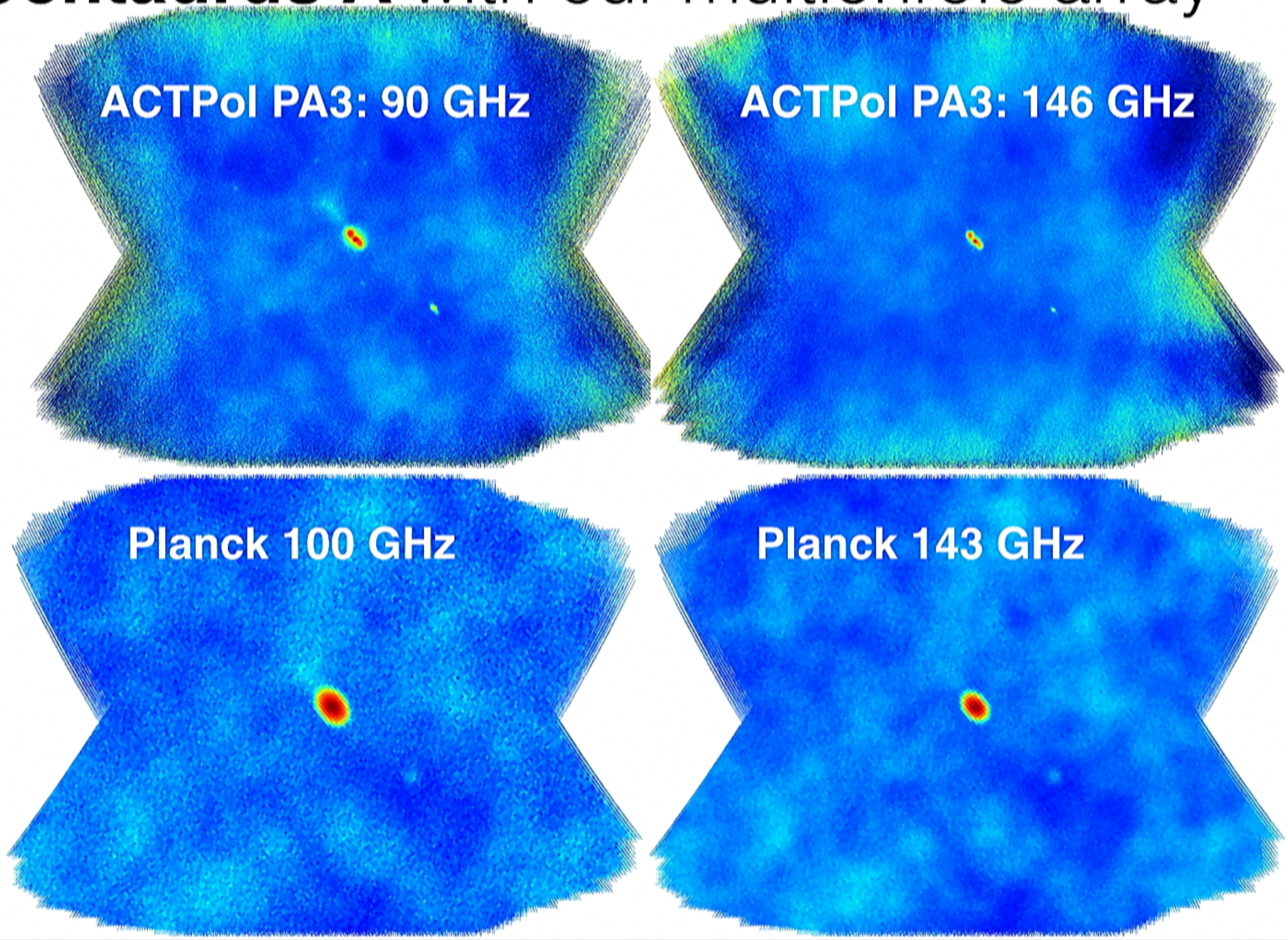
Detector Arrays

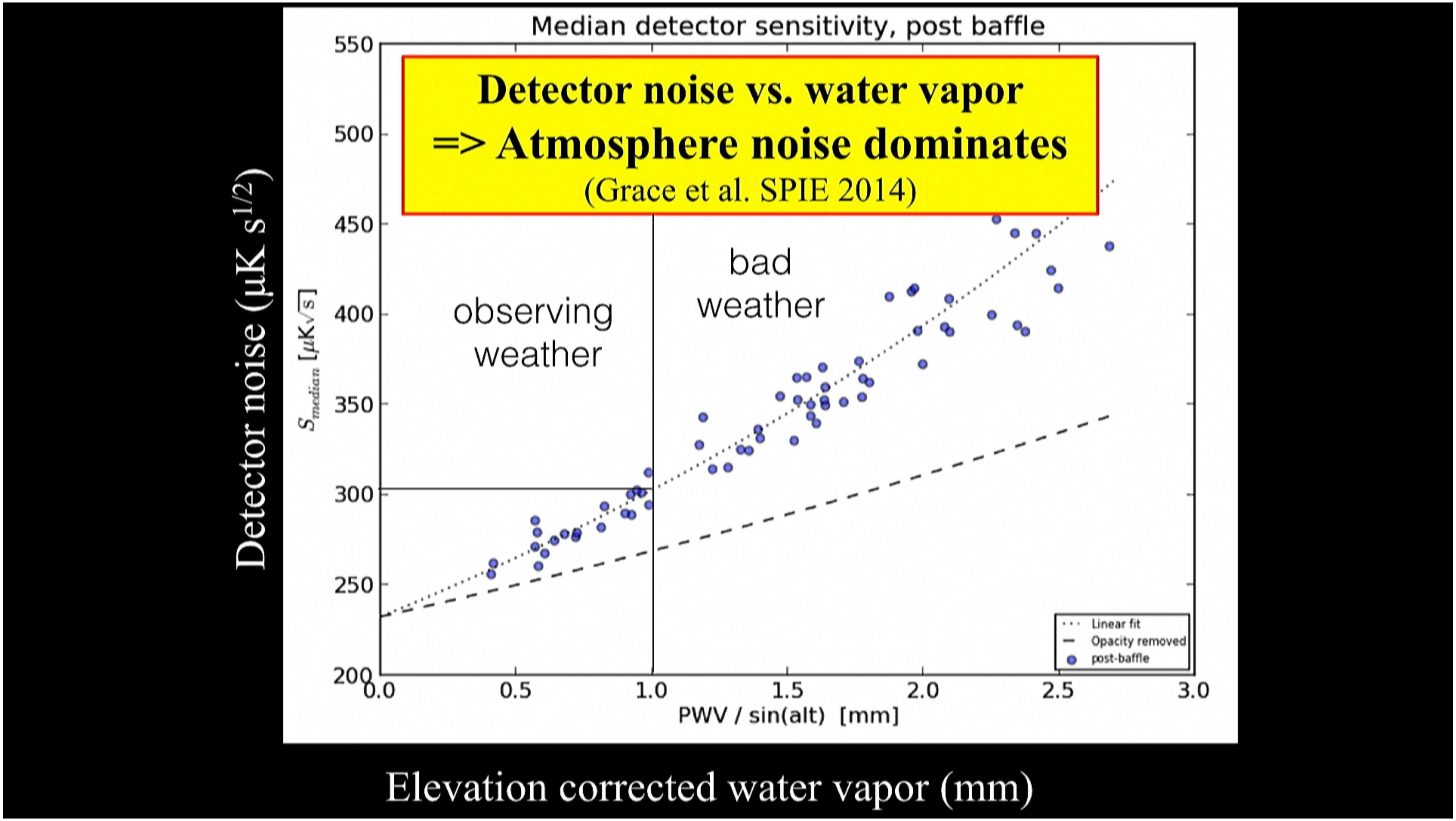


Metamaterial AR Coated Silicon Lenses

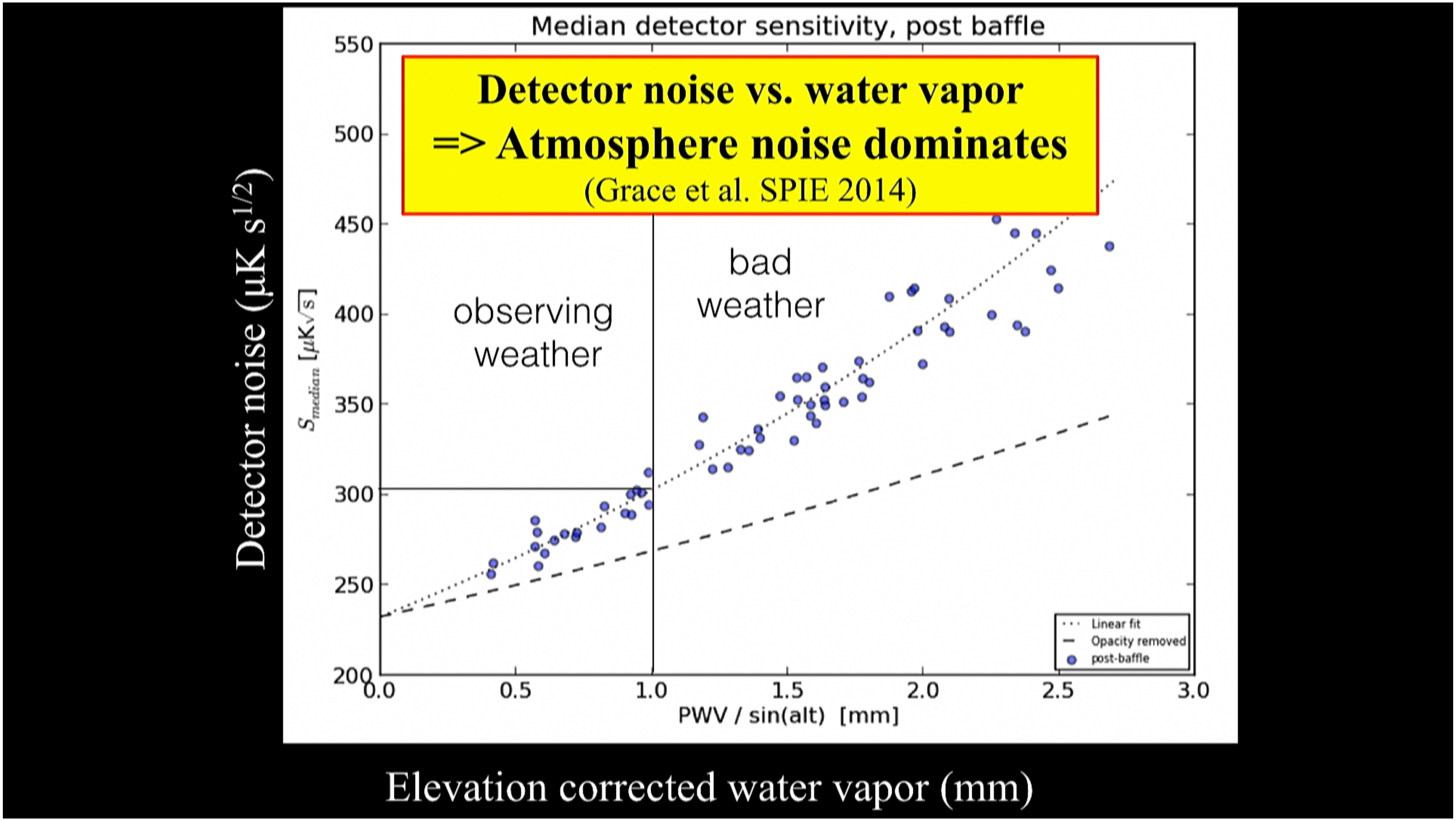


Centaurus A with our multichroic array





Median detector sensitivity, post baffle
Detector noise vs. water vapor
=> Atmosphere noise dominates
(Grace et al. SPIE 2014)
observing
weather
bad
weather
Linear fit
Opacity removed
post-baffle
550
500
450
400
350
300
250
200
0.0
0.5
1.0
1.5
2.0
2.5
3.0
PWV / sin(alt) [mm]
Detector noise (μK s^1/2)
Elevation corrected water vapor (mm)


Median detector sensitivity, post baffle
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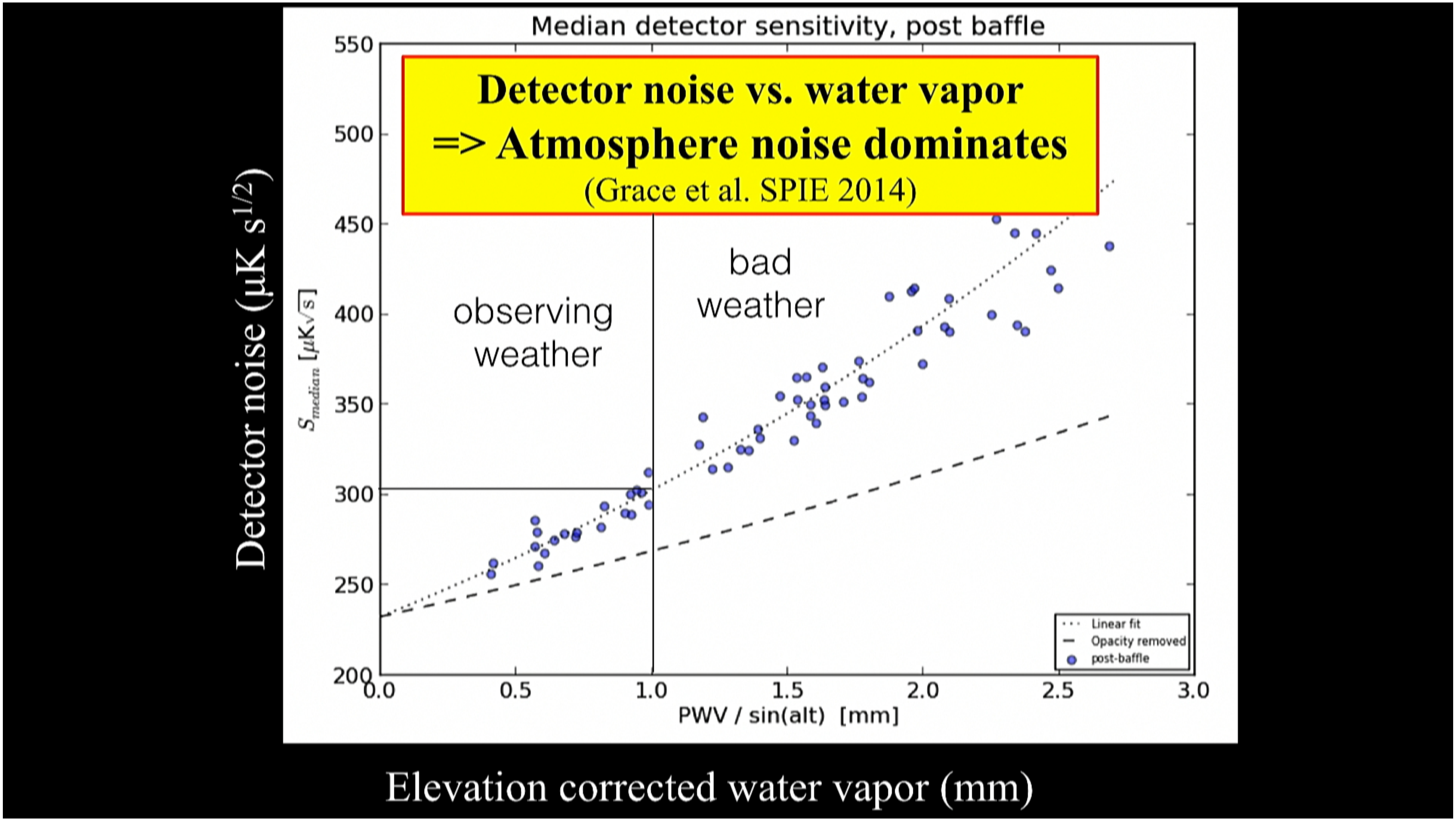
S_median [μK√s]
550
500
450
400
350
300
250
200
0.0
0.5
1.0
1.5
2.0
2.5
3.0
PWV / sin(alt) [mm]
Linear fit
Opacity removed
post-baffle
Elevation corrected water vapor (mm)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550
500
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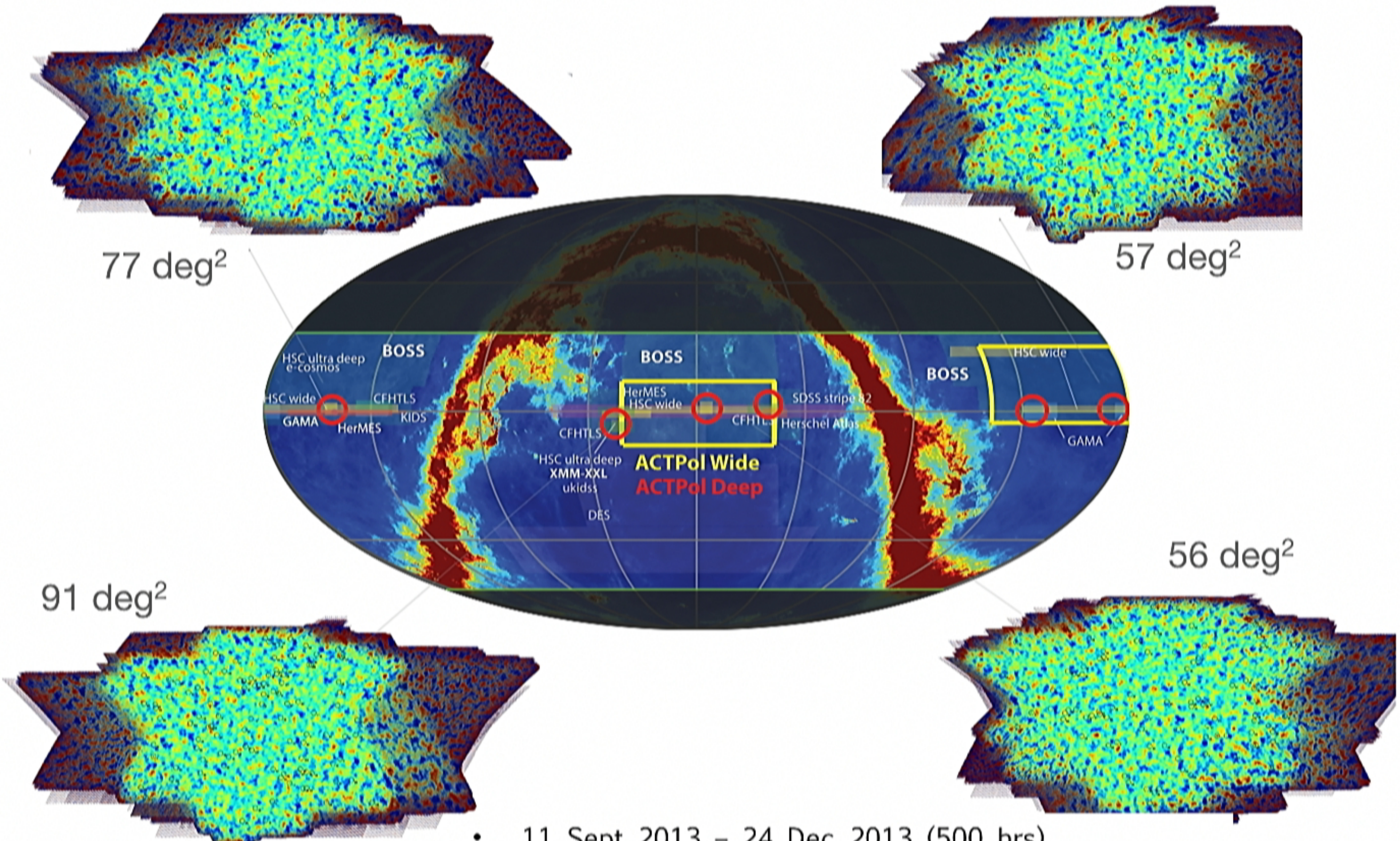
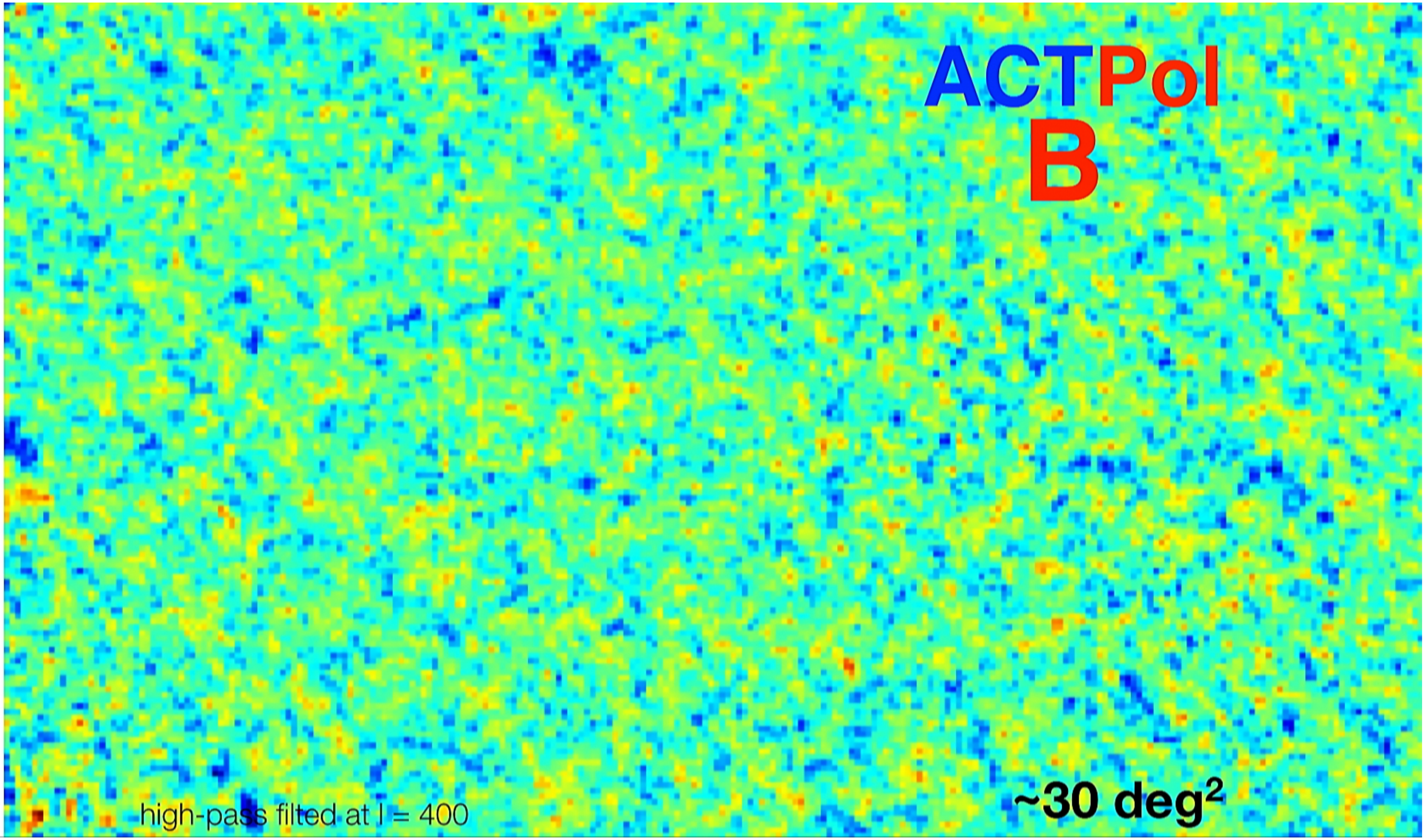
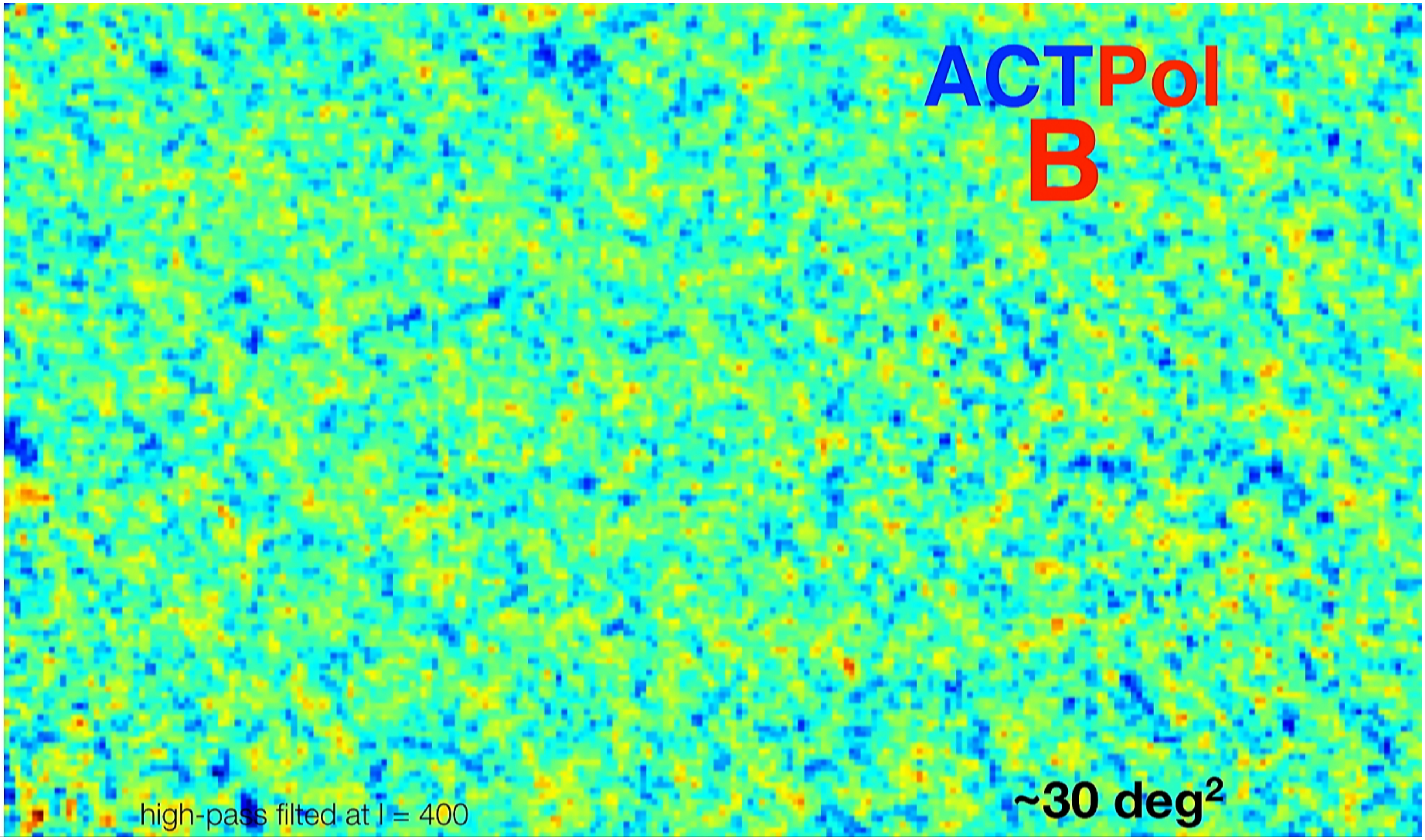
0.0
0.5
1.0
1.5
2.0
2.5
3.0
PWV / sin(alt) [mm]
Linear fit
Opacity removed
post-baffle
Elevation corrected water vapor (mm)

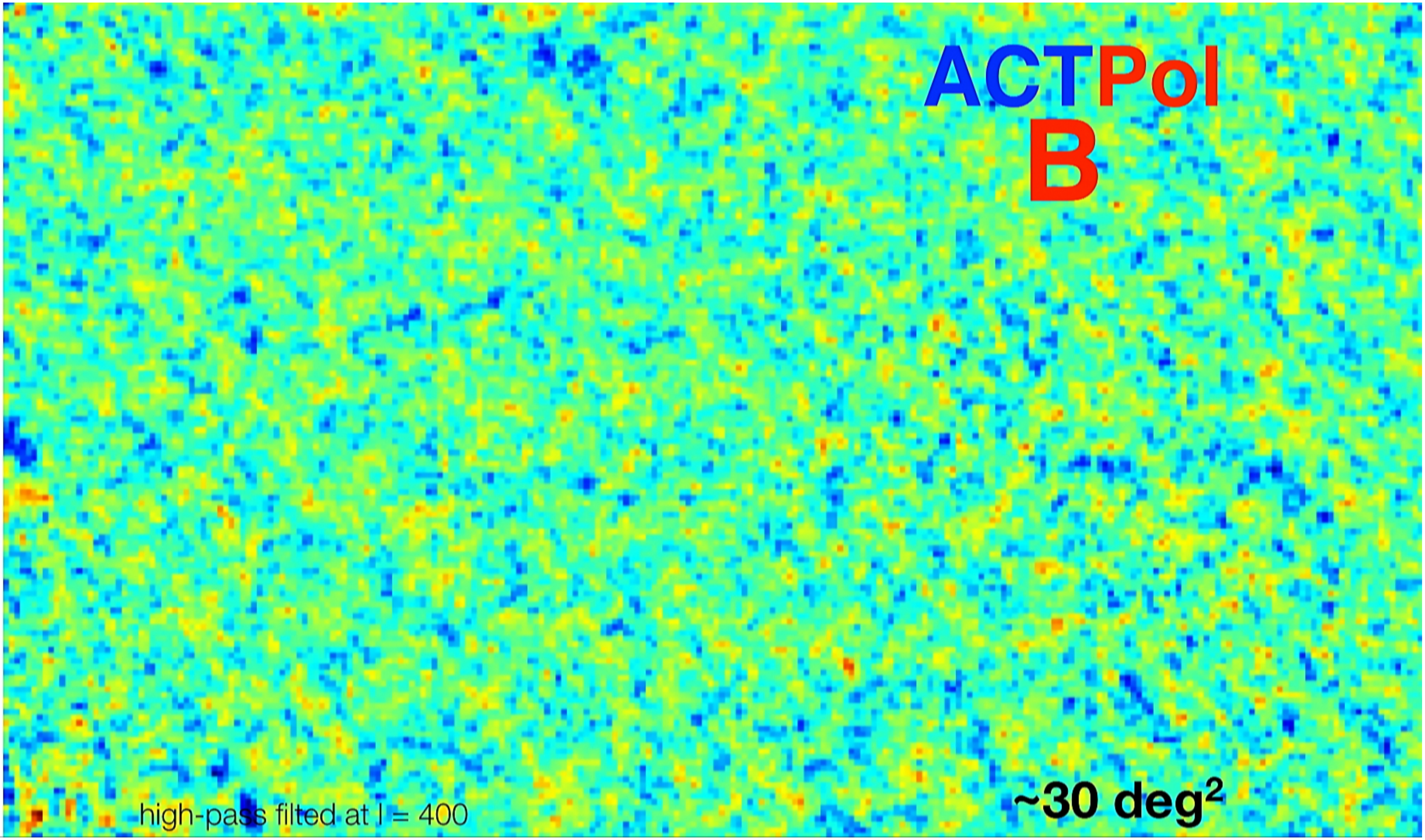
ACTPol Survey 2013

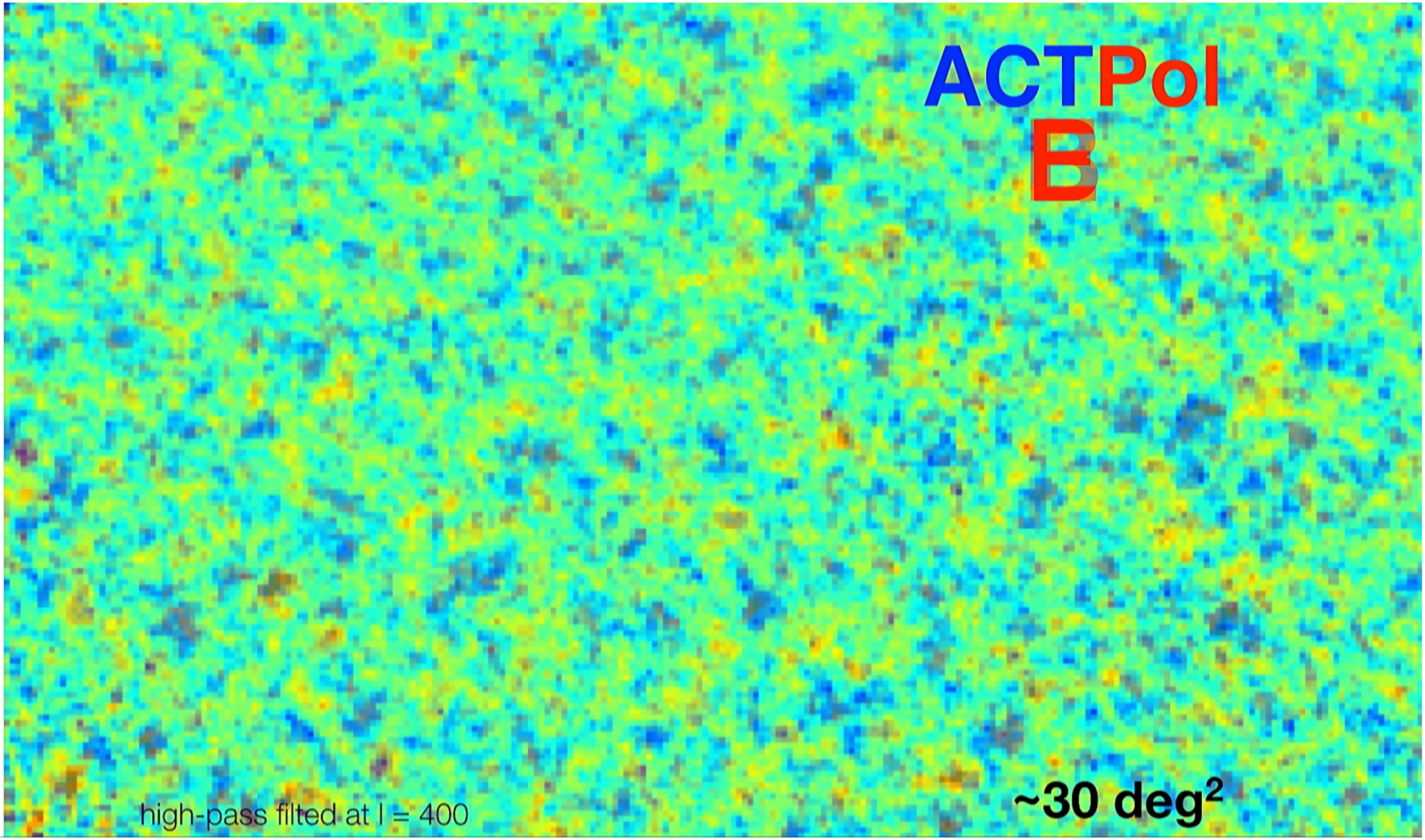


- 11 Sept 2013 – 24 Dec 2013 (500 hrs)
- Only one 150 GHz array installed then
- Four ~ 70 deg^2 patches


ACTPol
B
~30 deg^2
high-pass filted at l = 400

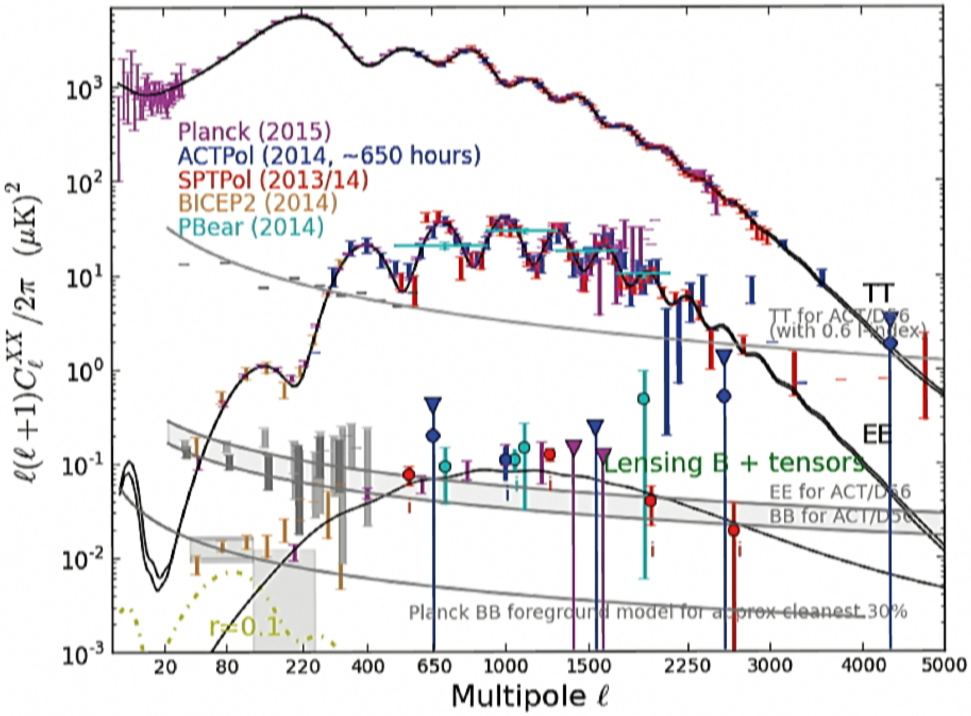

ACTPol
B
~30 deg^2
high-pass filted at l = 400


ACTPol
B
~30 deg²
high-pass filted at l = 400


ACTPol
B
~30 deg²
high-pass filted at l = 400

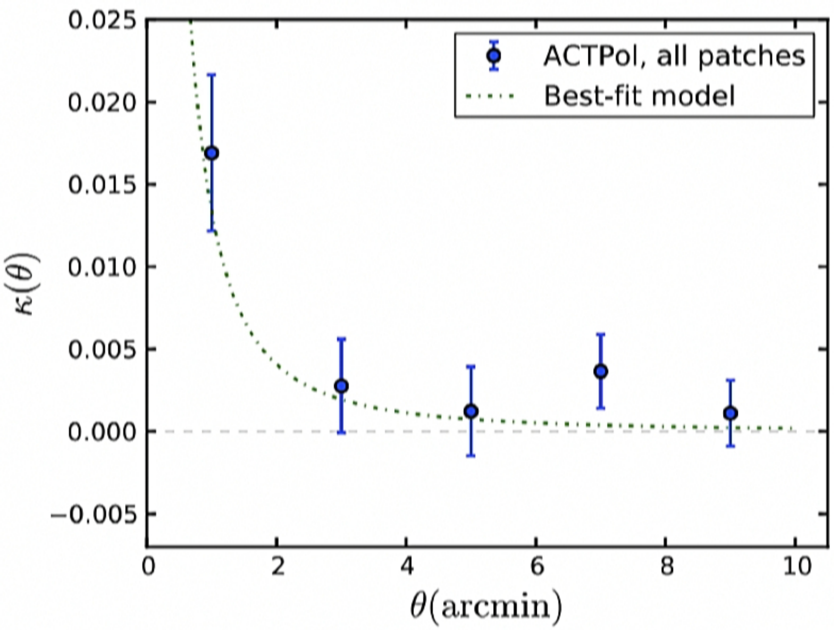
CMB Status

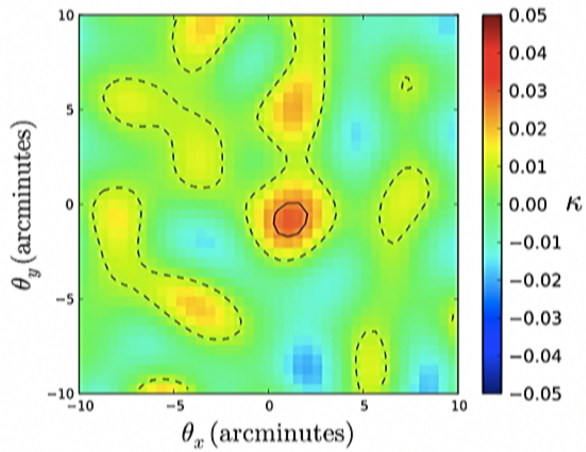
(data as of March 2015)



CLUSTERS LENSING the CMB

3.2σ; stack of 12,000 CMASS galaxies (SDSS/BOSS)



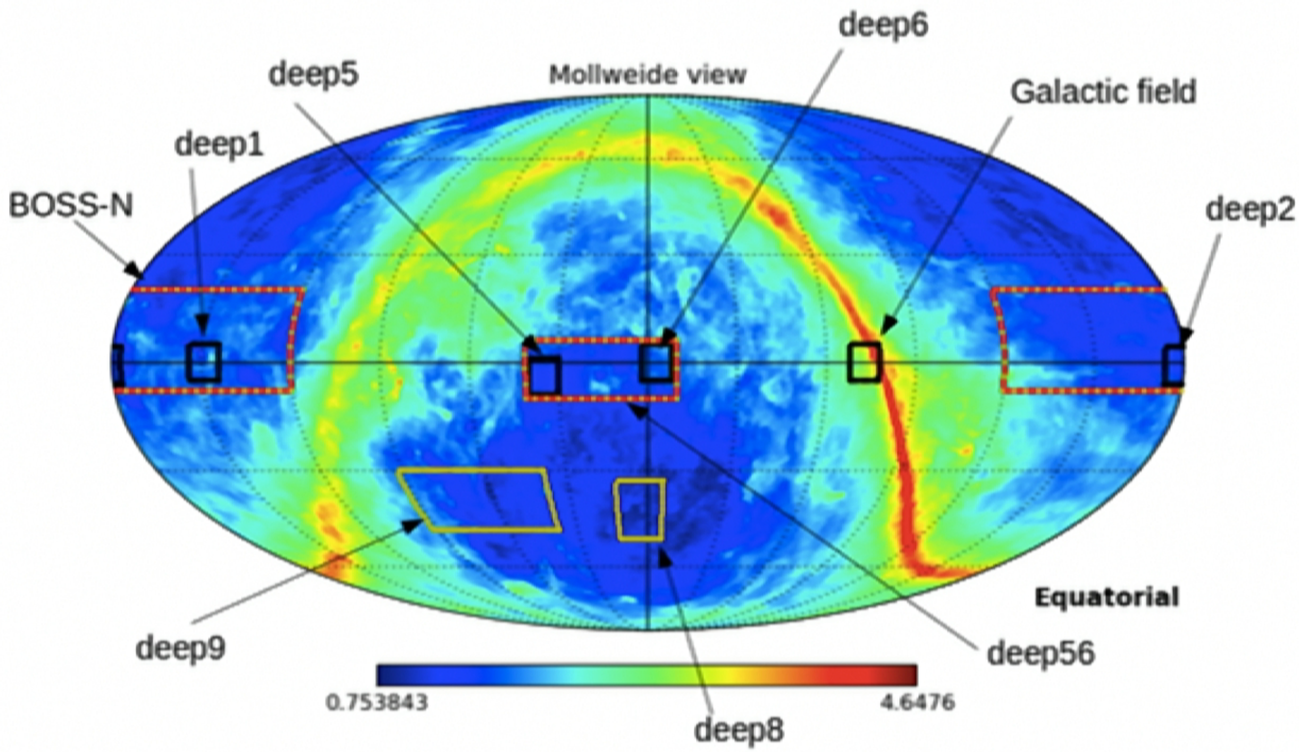


Madhavacheril et al – PRL 114, 151302, 2015. (ACTPol 2014 D1, D5, D6 fields.)

Full ACTPol survey

2014 & 2015

- Data already complete
- ~2000 square-degrees (BOSS N)
- ~600 square-degrees (deep 5-6)



The Near Future: ACTPol Data Analysis

preliminary results

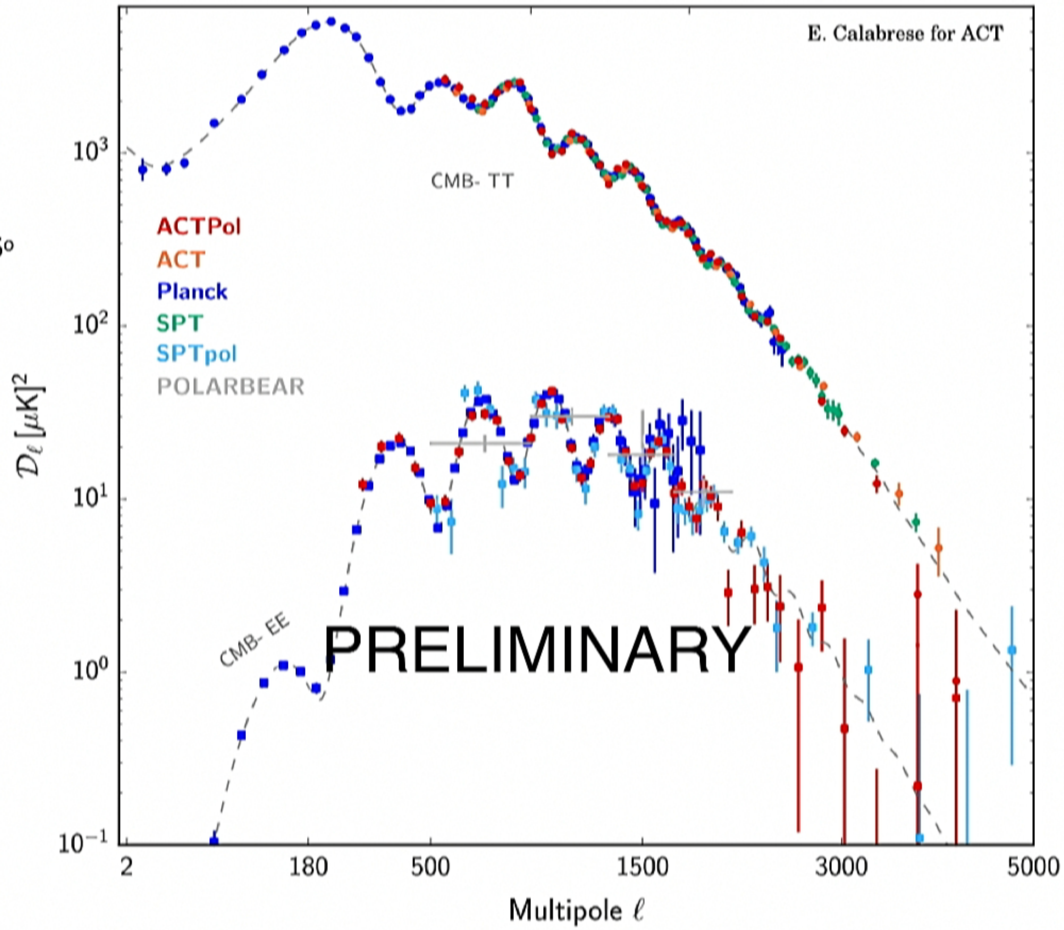
D56 Field
(12% of the ACTPol data)

~ 650 deg², @ δ ~ -3°, RA ~ 15°

up next:

(1) lensing, SZ, and cross correlations with this map

(2) analyze the rest of 2014 and all of 2015

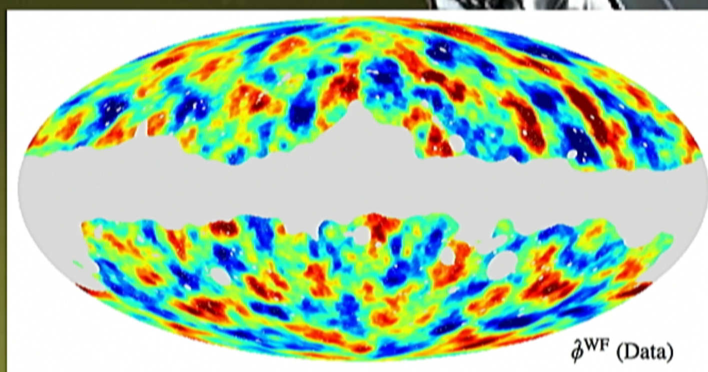


CMB Lensing

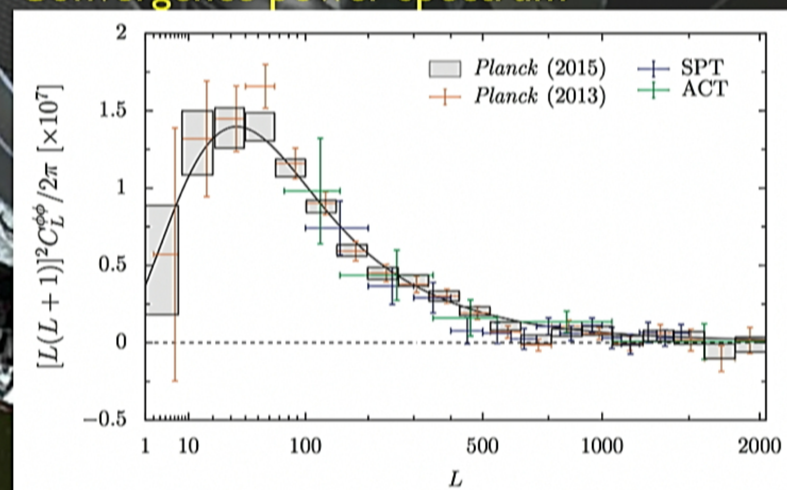
see Planck 2015 Results Paper XV and XIII

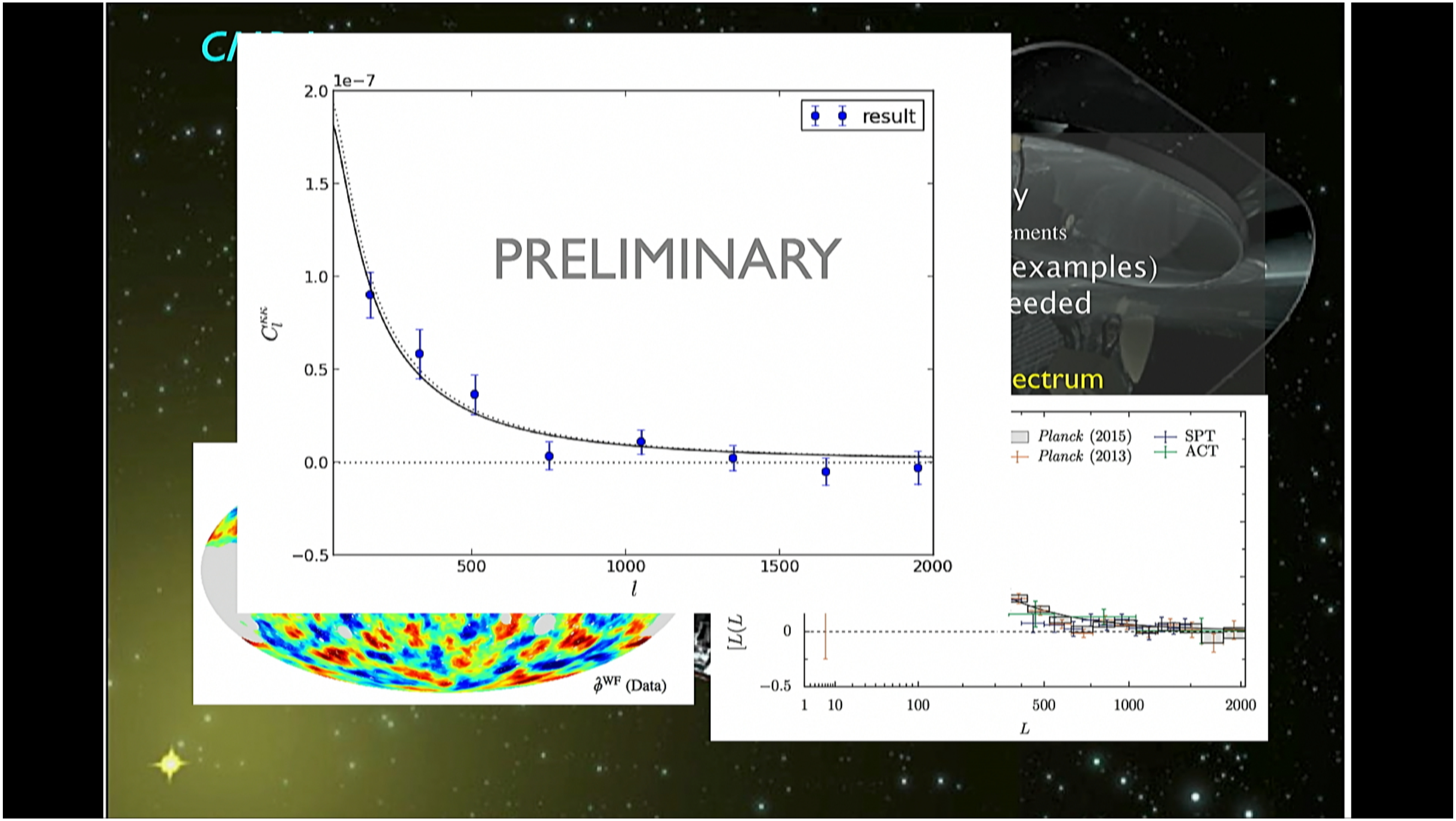
- 40 σ detection
- percent level constraints on curvature and dark energy
- limits $\sum m_\nu < 0.68$ eV from lensing alone, < 0.2 from a combination of measurements
- demonstrated power of cross correlations (CIB, other examples)
- CMB lensing is rapidly maturing -- more sensitivity needed

Lensing Reconstruction



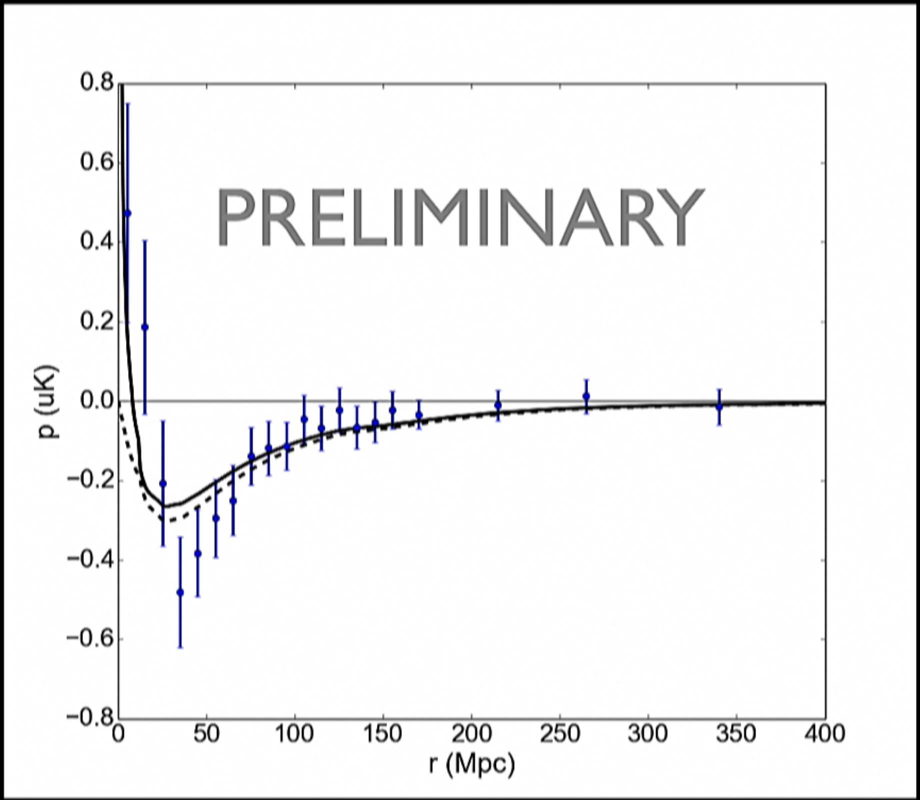
Convergence power spectrum





CM
1e−7
2.0
1.5
1.0
0.5
0.0
−0.5
result
PRELIMINARY
$C_l^{\kappa\kappa}$
500
1000
1500
2000
l
y
ments
examples)
eeded
ectrum
Planck (2015)
Planck (2013)
SPT
ACT
$[L(L$
0
−0.5
1
10
100
500
1000
2000
L
$\hat{\phi}^{\mathrm{WF}}$ (Data)

Pairwise kSZ

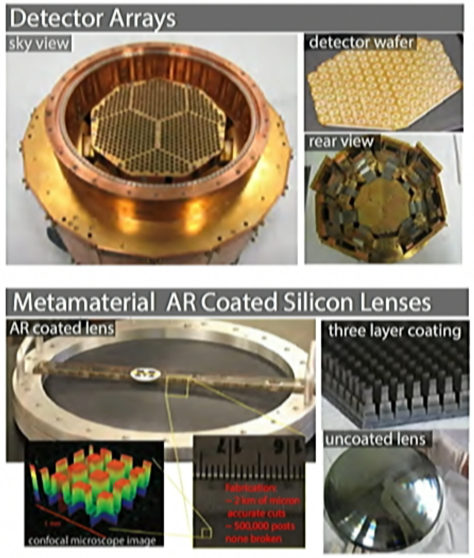


- kSZ normally hard to predict due to l.o.s. velocity uncertainty.
- velocities from nearby pairs of haloes can be estimated, provides template for kSZ.
- 22000 DS11 galaxies with L > 7.7e10 $L_\odot$.
- ~50% correlation.

Look for de Bernardis et al.

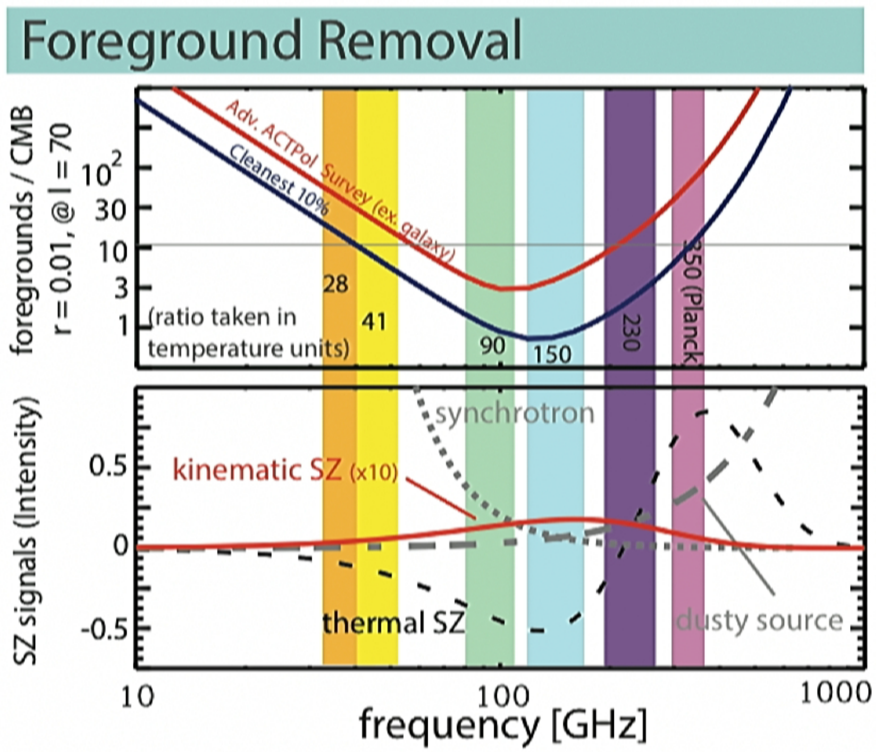
Advanced ACTPol

based on ACT technology



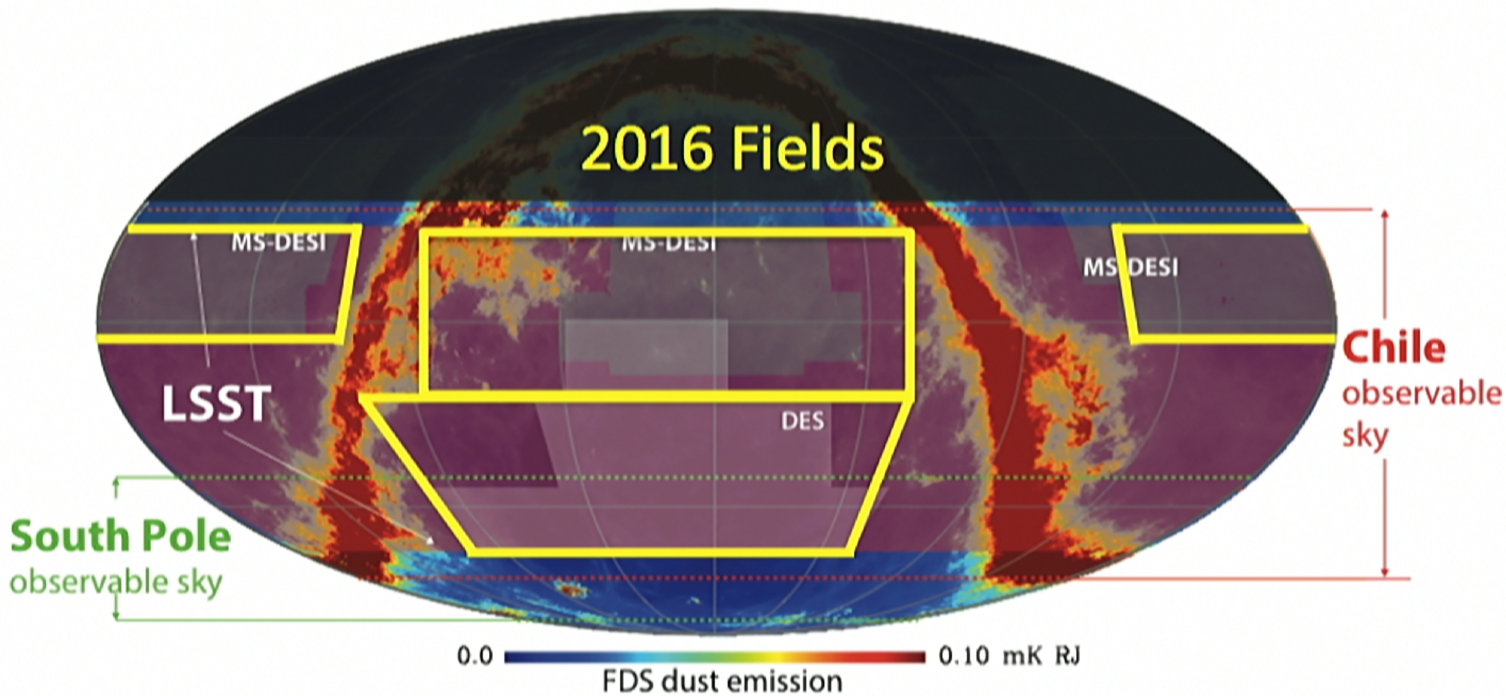
+ metamaterial Half Wave Plate

5 frequency bands



The Future Starts ~Now:

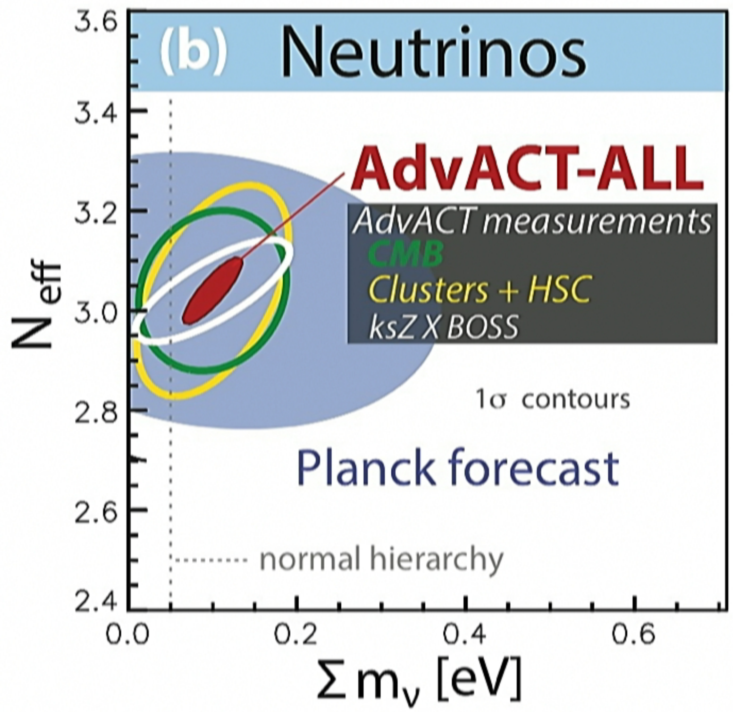
Advanced ACTPol Survey: 2016-2018

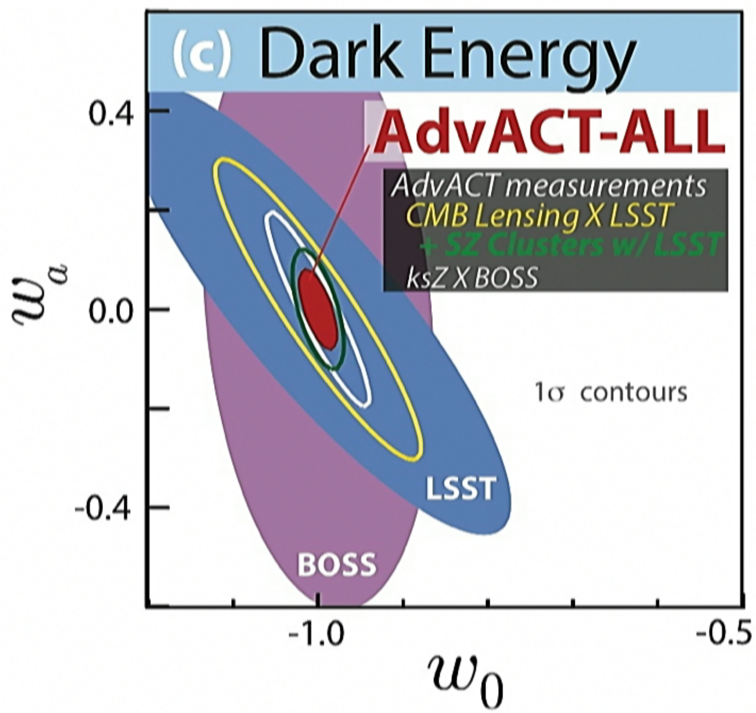


Cross Correlation Projections

Projected to improve Planck limit on Σm_ν by 10x!

Projected to improve LSST's DE FOM by 20x!





The Simons Observatory

http://simonsobservatory.org

ALMA

- A five year, $45M+ program to pursue key Cosmic Microwave Background science targets, and advance technology and infrastructure in preparation for CMB-S4.
- Merger of the ACT and POLARBEAR/Simons Array teams.
- Tentative plans include:
  - Major site infrastructure
  - Technology development (detectors, optics, cameras)
  - Demonstration of new high throughput telescopes.
  - CMB-S4 class receivers with partially filled focal planes.
  - Data analysis

ACT

POLARBEAR/Simons Array

Thanks!

- 21 cm line a powerful tool for cosmology
- HIRAX will use it to measure Dark Energy
- SCI-HI will use it to measure average signal from first generation of stars
- Near-term ground-based CMB developing quickly.
- As FRB would say. “Modes - gotta catch ‘em all!”