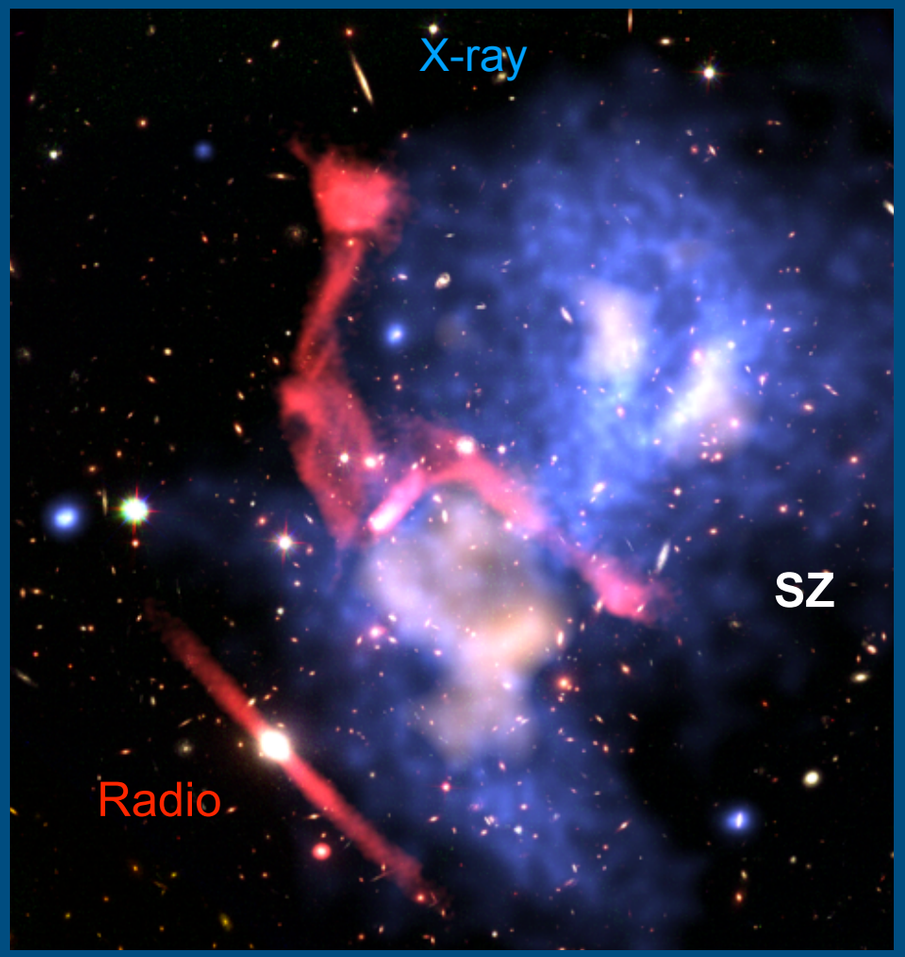
Galaxy Cluster Science: 5-10 year view of the GBT's Role



Brian Mason (NRAO)

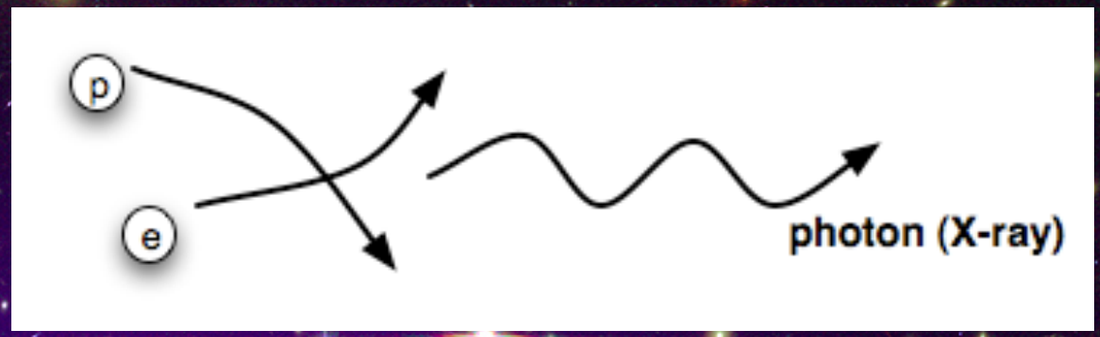
Green Bank Observatory Transformational Science Workshop

October 16, 2017

Galaxy Clusters

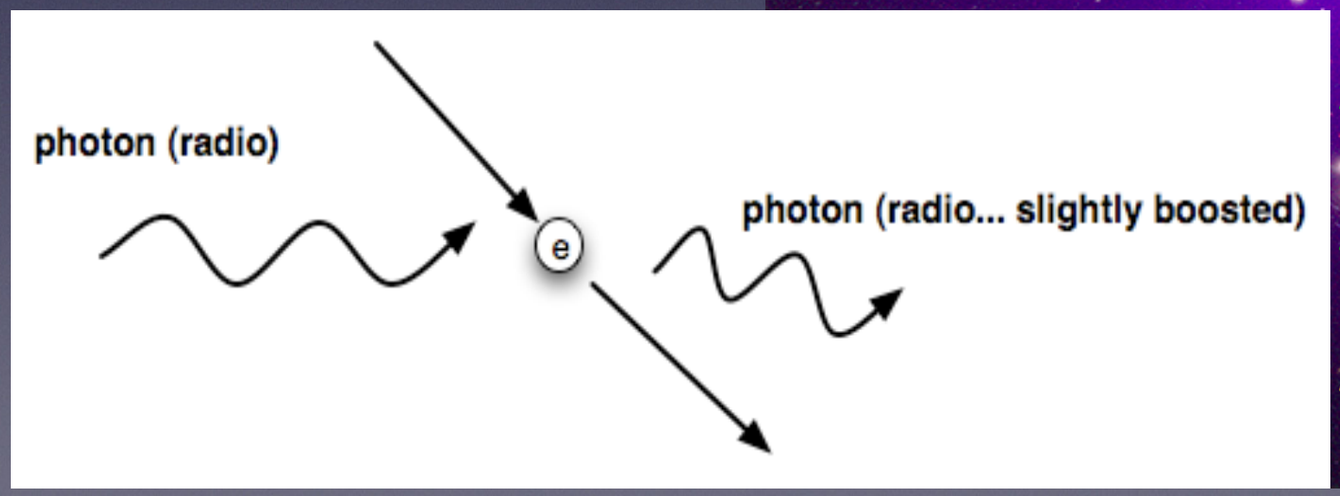
Galaxies
+
Hot Intra-Cluster Plasma
+
Dark Matter

x-ray bremmstrahlung



*** Excellent view of density variations**
*** Some Spectral Information — but not useful in low-density regions (outside cluster core) or hi-z**

Sunyaev-Zel'Dovich Effect (SZE)



*** Outstanding sensitivity to hot gas**
*** Redshift-independent: effective tool at high-z**
*** requires sensitive detectors**

Abell 1689: HST + Chandra

500 Mpc/h

Galaxy cluster

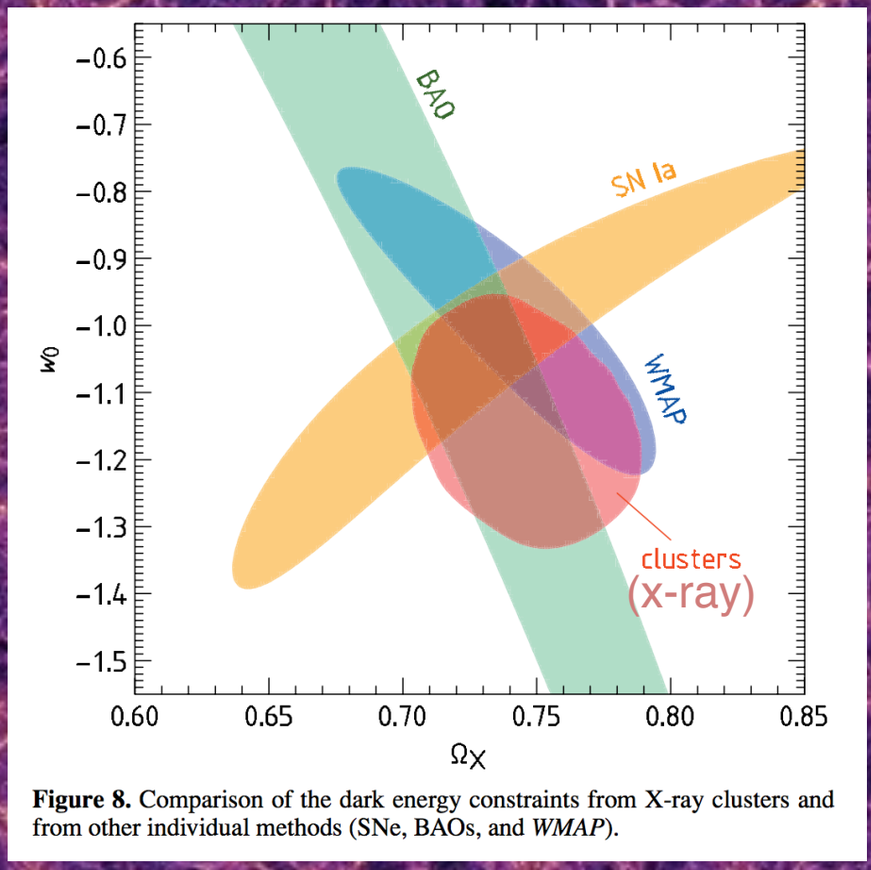


Figure 8. Comparison of the dark energy constraints from X-ray clusters and from other individual methods (SNe, BAOs, and *WMAP*).

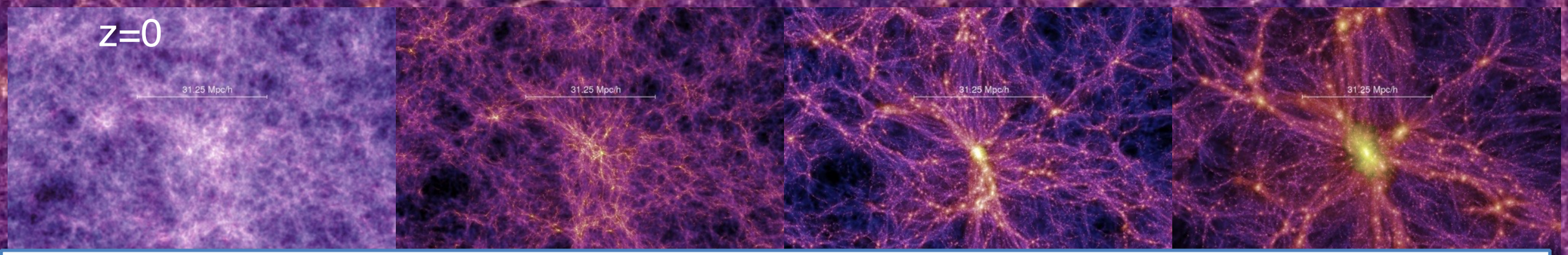
Vikhlinin et al. 2009

z=18.3

z=5.7

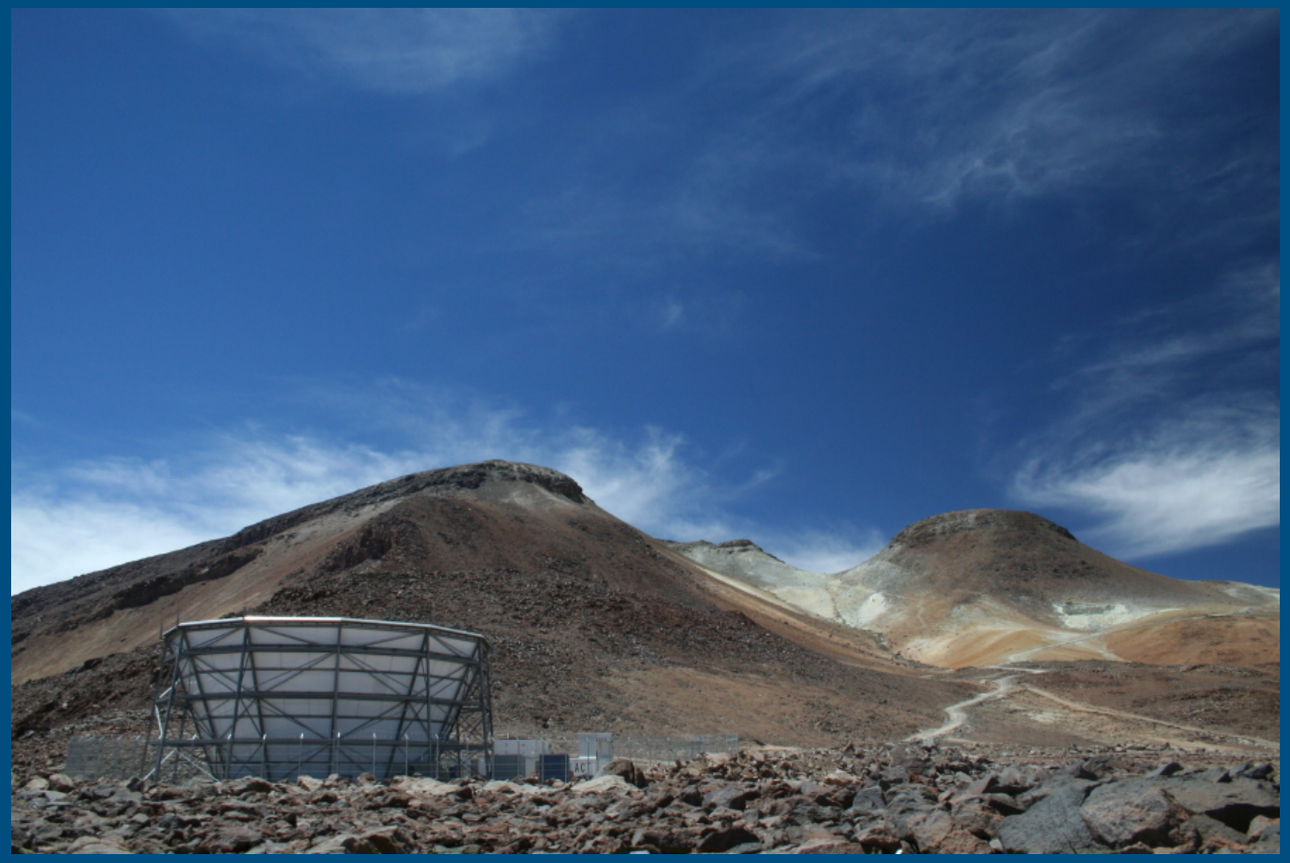
z=1.4

z=0



We can learn about our cosmology by studying the abundance and properties of these extreme halos as functions of Mass and z.

Max Planck inst. Springel et al 2005; Dark Matter Only



Atacama Cosmology Telescope (Cerro Toco)

South Pole Telescope (SPT)

SZ Selected Clusters

2008: zero

2011: ACT (23) + SPT (26) + PLANCK (169+20)= 238

1/2 to 3/4 of the clusters found by ACT & SPT were previously unknown (missed by Abell, RASS, etc.).

Atacama Cosmology Telescope (Cerro T… …pe (SPT)

Like nearly all SZ instruments these have low resolution (~1') and cannot usefully resolve the ICM.

The GBT @ 3mm (9") can

SZ Selected Clusters

2008: zero

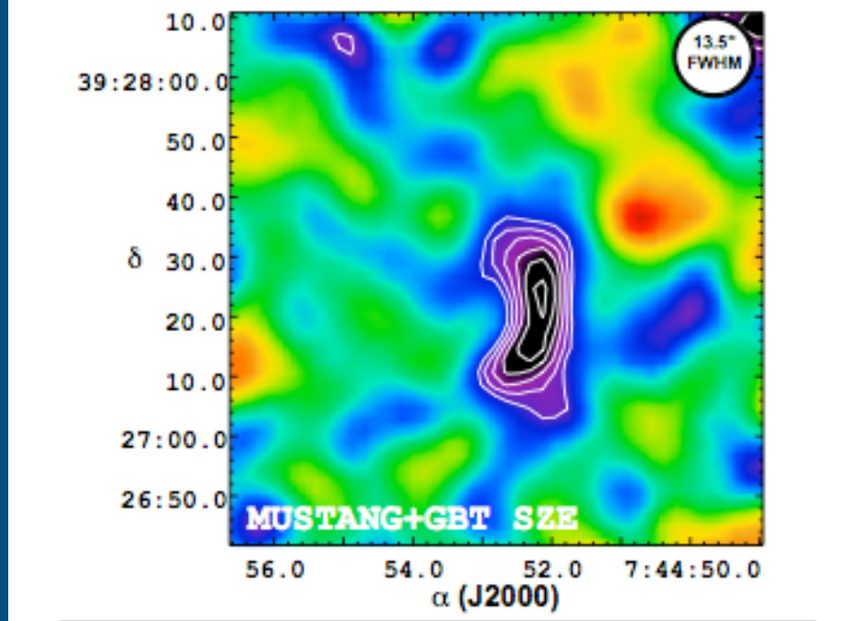
2011: ACT (23) + SPT (26) + PLA… …20)= 238

1/2 to 3/4 of the clusters found by ACT & SPT were previously unknown (missed by Abell, RASS, etc.).

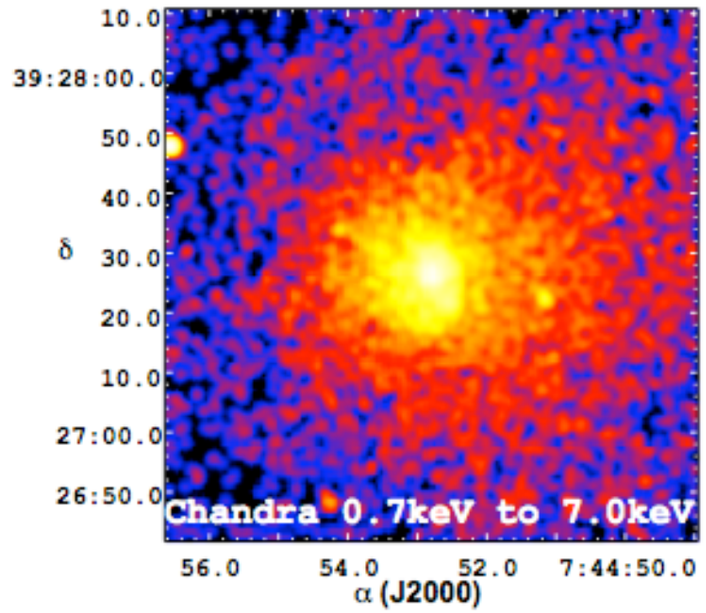
MACS 0744+3927

[z=0.69, M-Y outlier]

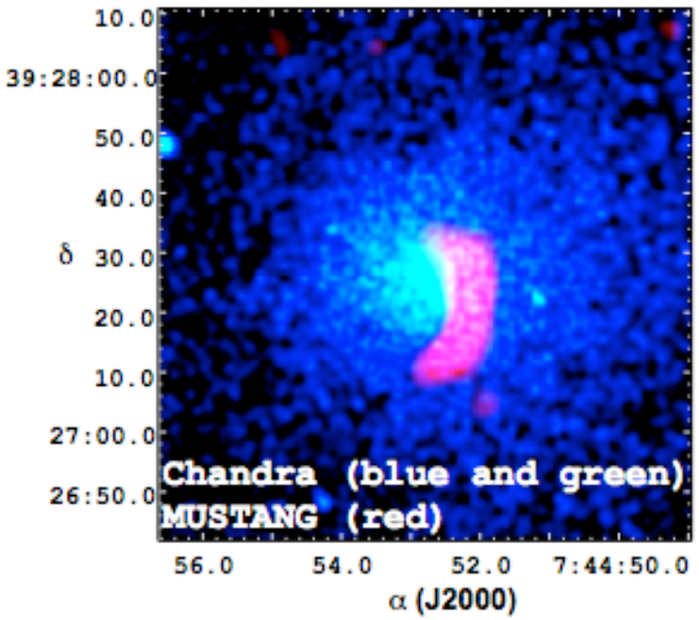
MUSTANG SZE (14")



Chandra



SZ+X



Korngut et al. 2011

14" SZE Imaging reveals an M ~1.5 shock

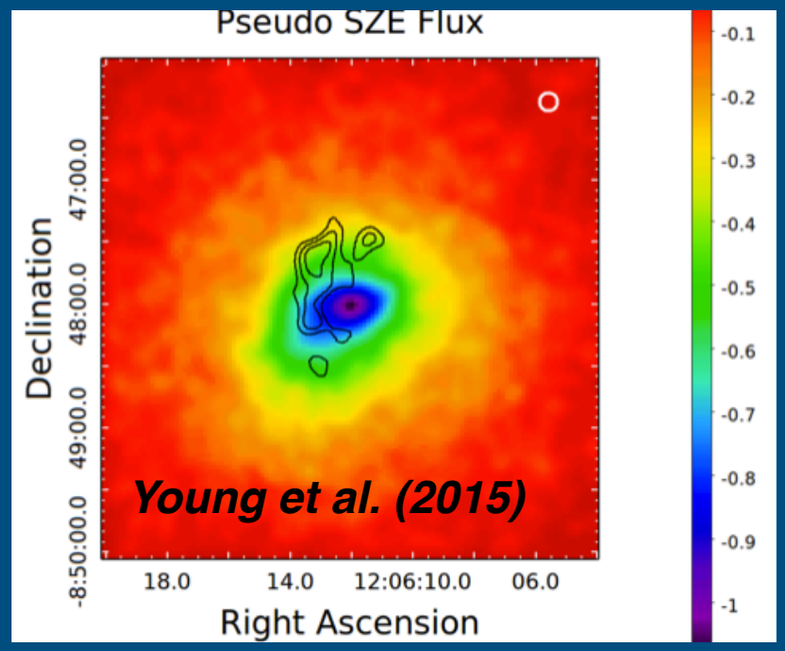
*evident in x-ray data *a posteriori*

Other MUSTANG SZ results

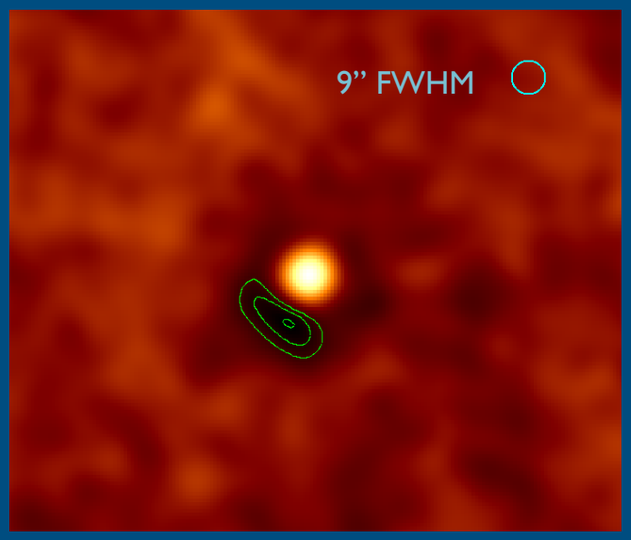
SZE reveals high-pressure structure not seen in previous x-ray data.

100 ksec XMM follow-up observation + 3hr ALMA Cycle4 observations obtained

MACS 1206-0847



RXJ1347-1145

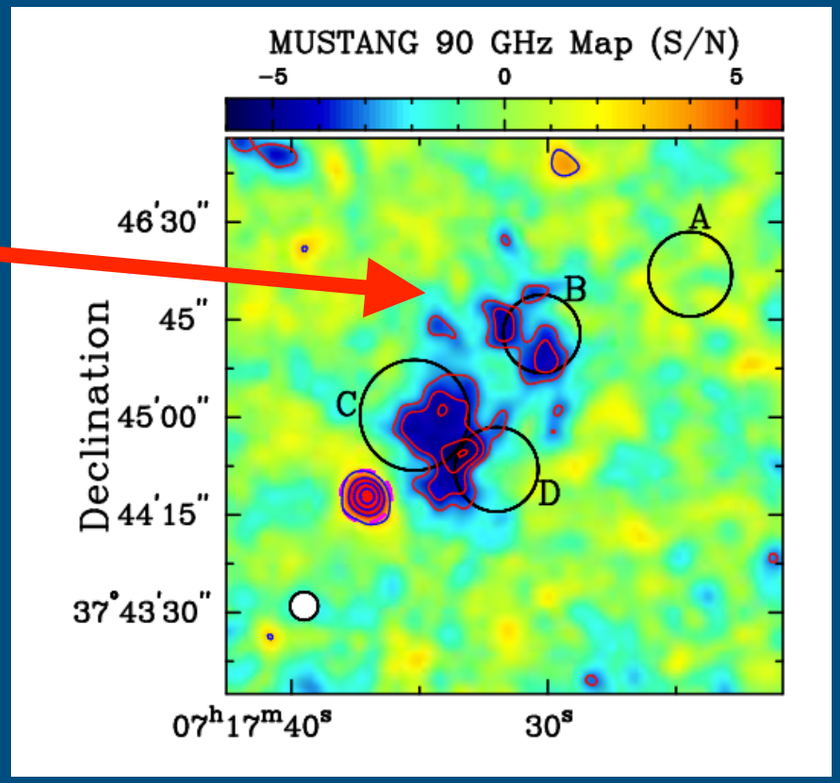


Mason et al 2010
Romero et al. 2017

MACS 0717+3745

CSO+BOLOCAM SZE observations @140 & 268 GHz (Sayers et al. 2013) show cluster B to be a "line of sight Bullet cluster" [+3200 km/s]

First detection of the kinematic SZE in an individual object



Mroczkowski et al. 2012
VanWeeren et al. 2015

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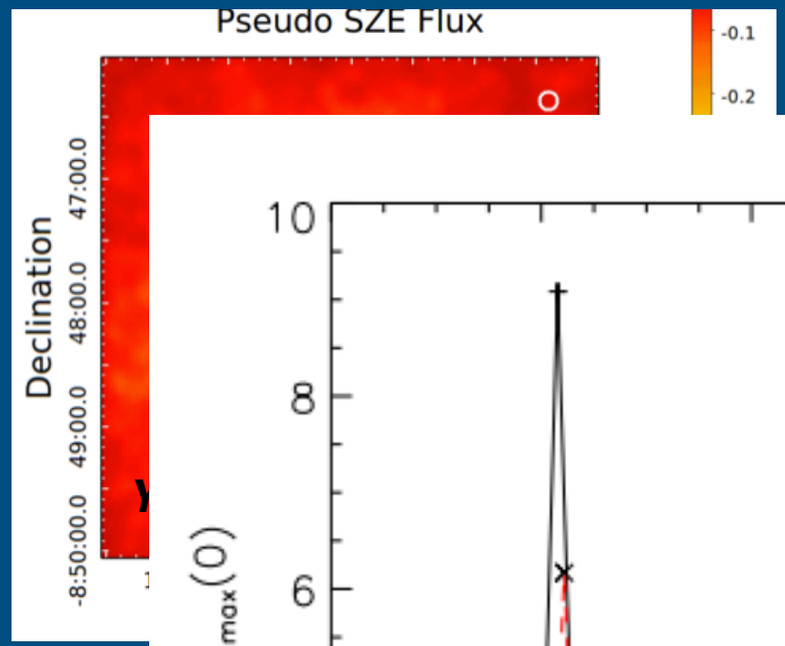
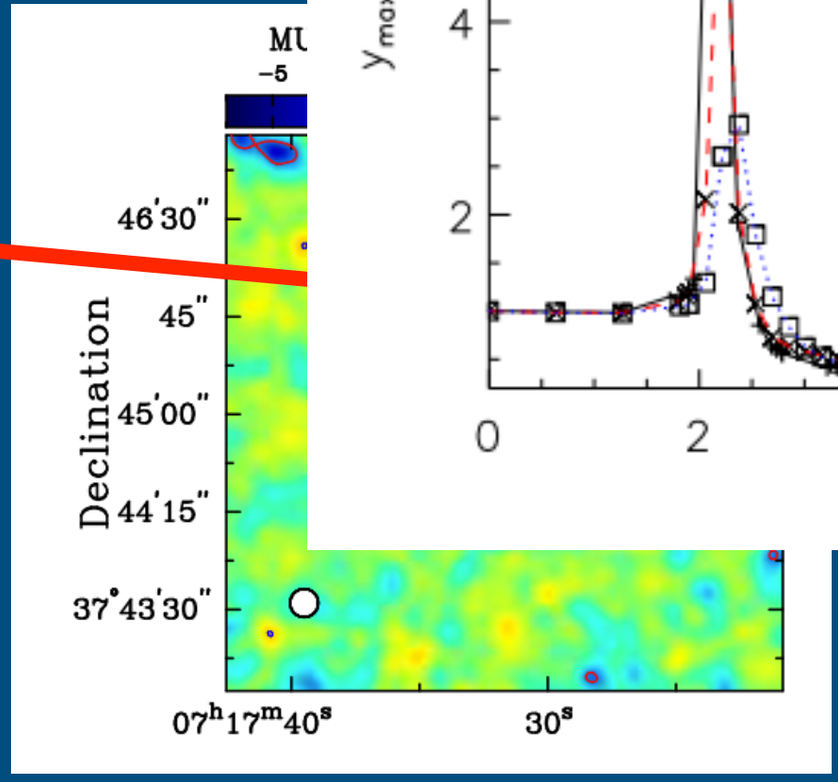
MACS 1206-0847





RXJ1347-1145

Mroczkowski et al. 2012
VanWeeren et al. 2015

2017
2018
2019
2020
2021
2022
2023
2024
2025
2026
2027
2028
2029
⋮

Dark Energy Survey

5,000 sq.deg. optical survey

Chandra (degrading)

?

XARM

ASTRO-H/ Hitomi replacement

LSST

Athena?

Advanced ACTpol & SPT3G

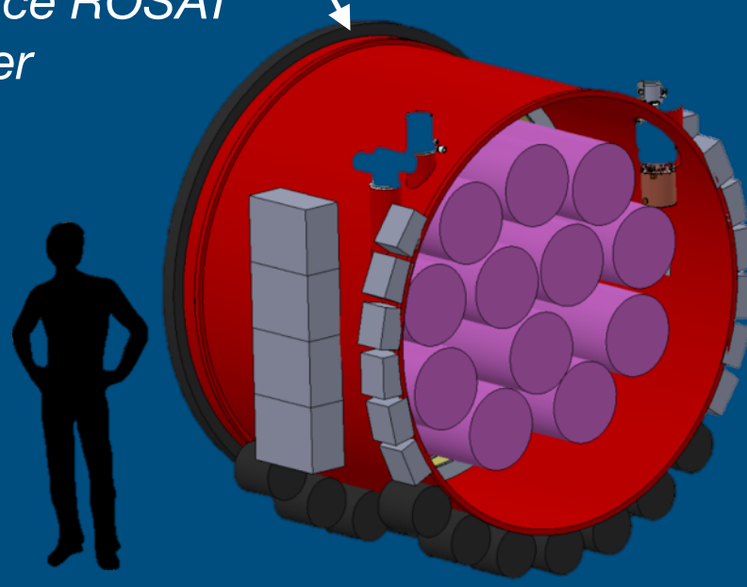
10k-pixel class millimeter survey cameras

Simons Observatory

100k-pixel class millimeter survey cameras

eROSITA

1st X-ray all-sky survey since ROSAT 30x deeper



KEY: X-ray Optical SZE

2017
2018
2019
2020
2021
2022
2023
2024
2025
2026
2027
2028
2029
⋮

Dark Energy Survey

5,000 sq.deg. optical survey

Chandra (degrading) 0.5”

?

XARM 1’-2’

ASTRO-H/ Hitomi replacement

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Advanced ACTpol & SPT3G 1’

10k-pixel class millimeter survey cameras

Simons Observatory 1’

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eROSITA 30”

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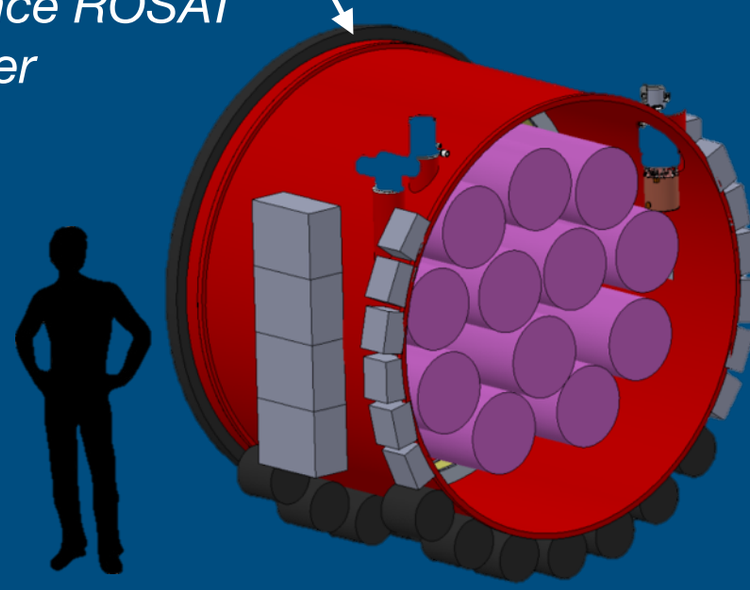
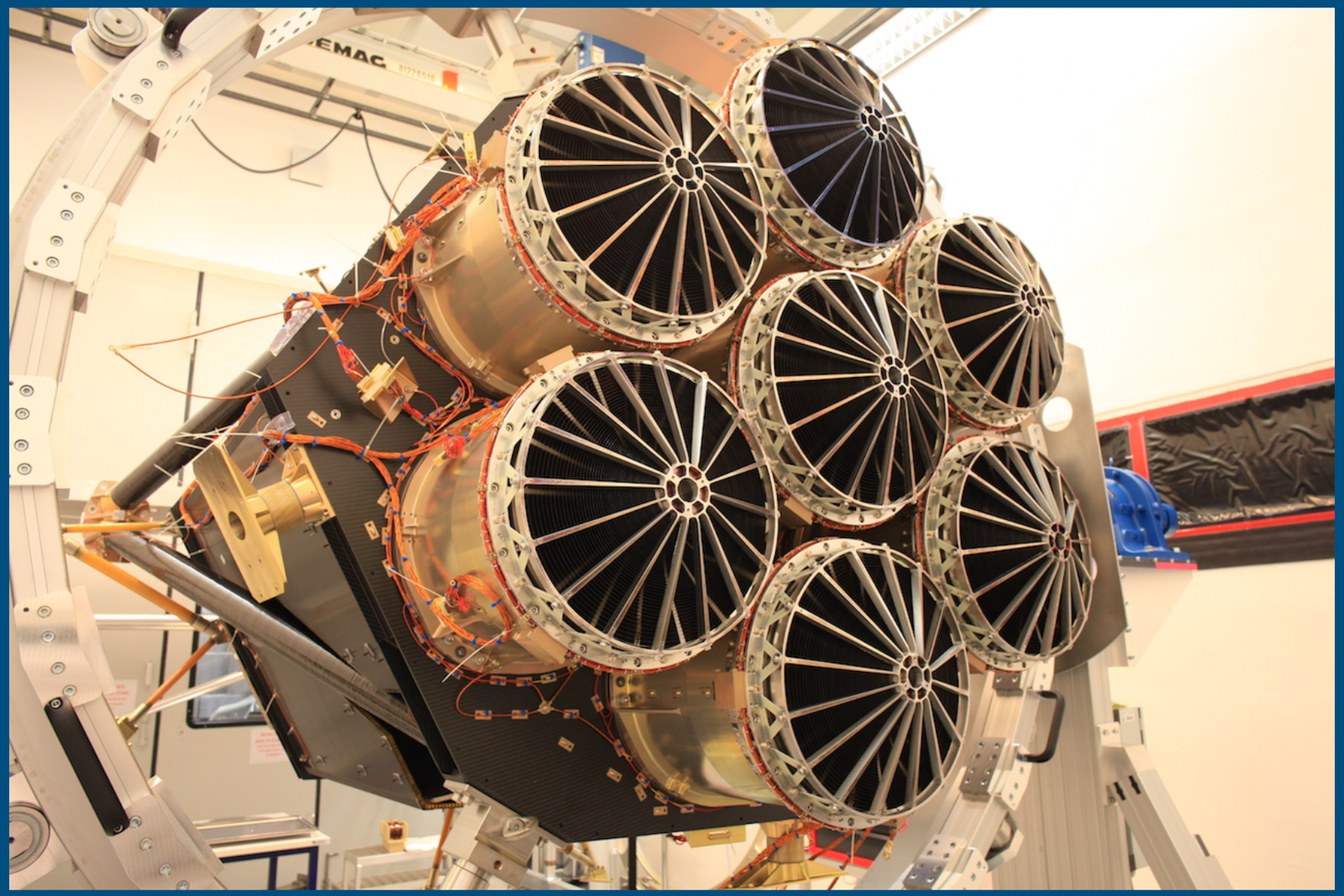


KEY: X-ray | Optical | SZE | Angular Resolution

eROSITA

currently in Moscow being integrated with SRG spacecraft

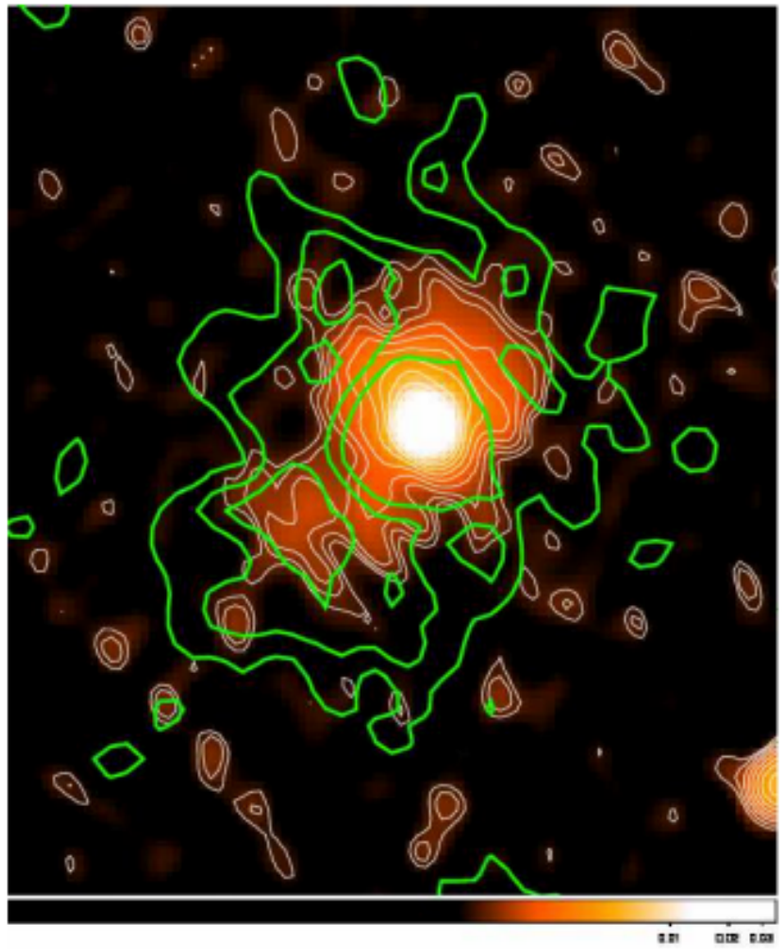


- GOAL: characterize dark energy by mapping massive halo density to z~1.5
  - detect > 2k massive galaxy clusters @ z > 0.8
- 25” FWHM, ~100 photons/cluster @ z=1

High-z clusters are very hard to study with x-ray or optical data — resolved SZE provides dynamical state, pressure profiles, masses

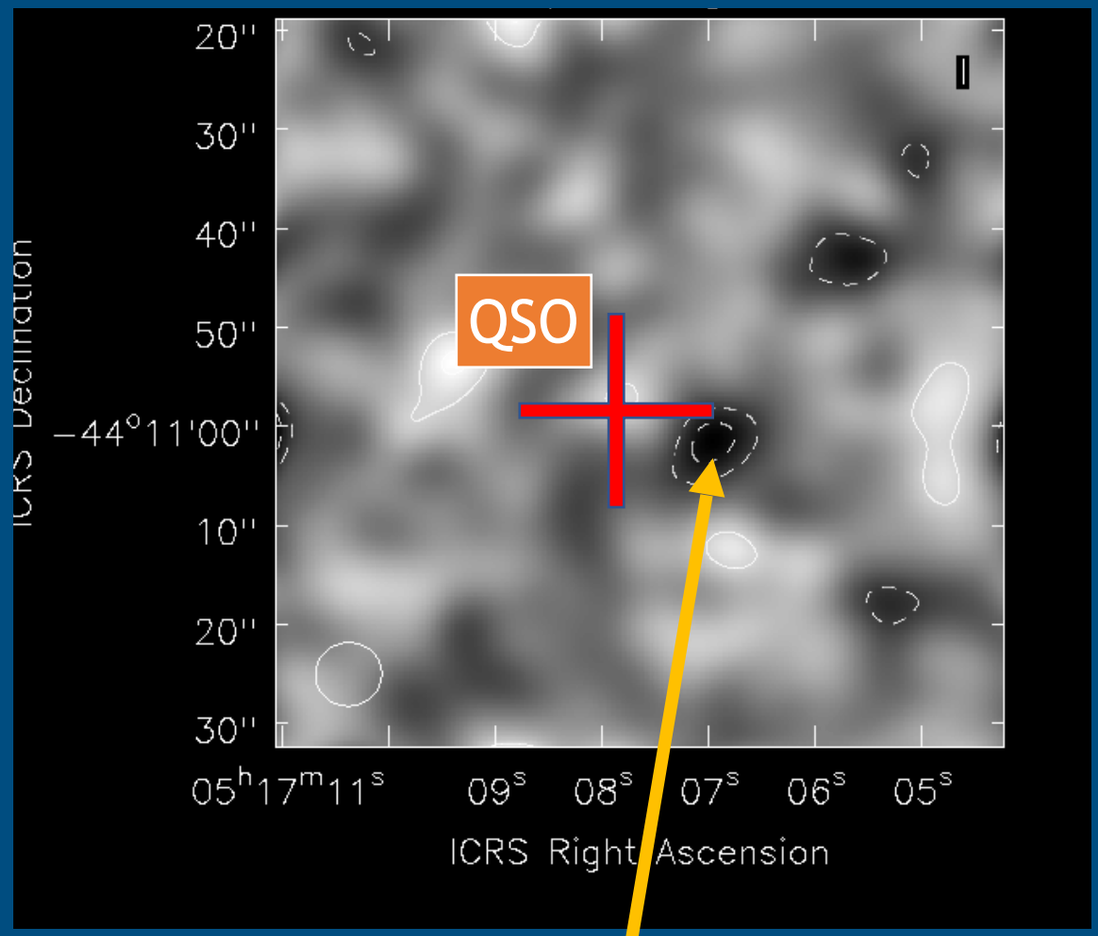
Astrophysics with the SZE

Ferrari et al. (2011)



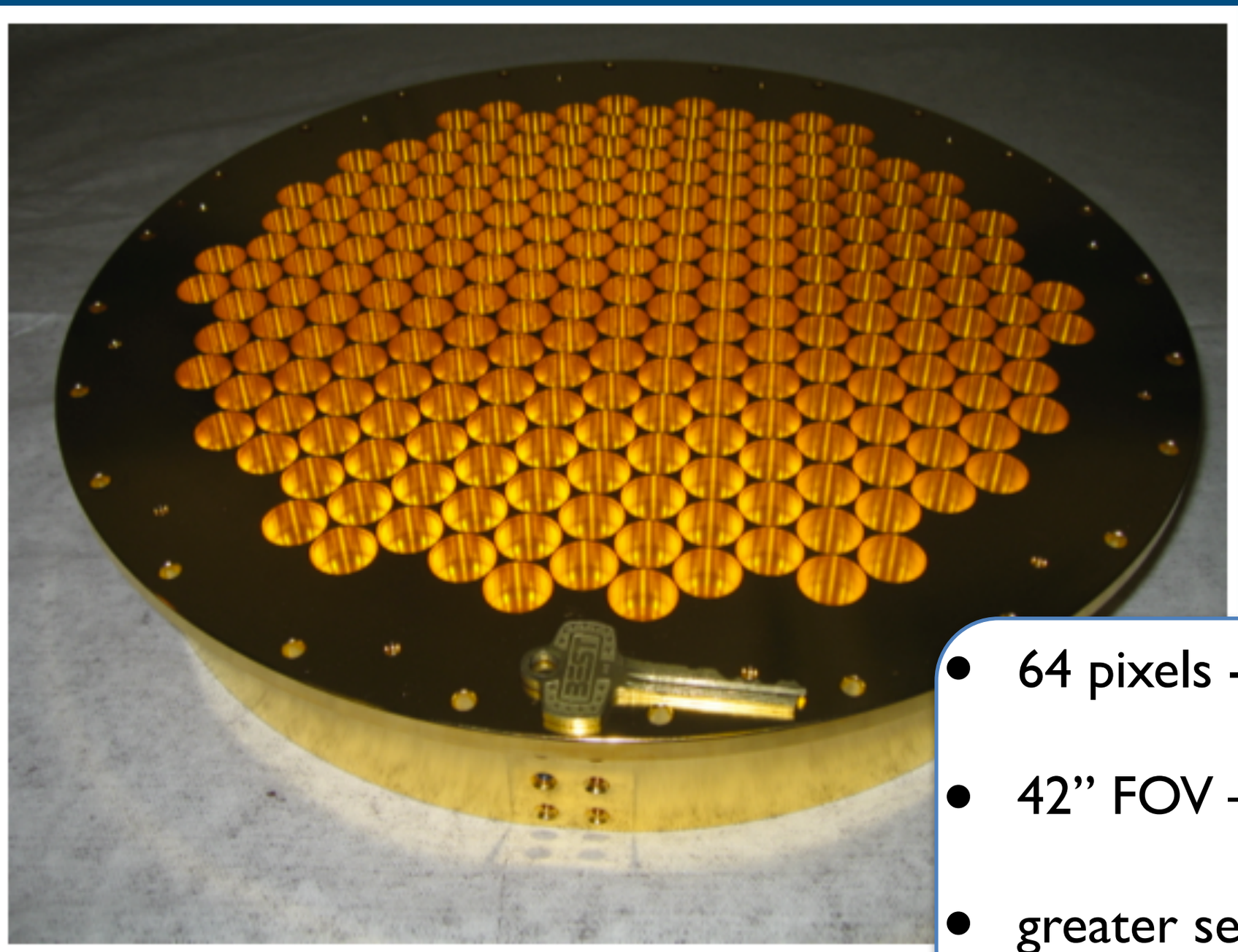
MUSTANG SZE + GMRT 600 MHz show a strong connection between shock-heated thermal & non-thermal ICM phases

ALMA Cycle 4
Lacy et al.



Possible outflow SZE

MUSTANG-2



U.Penn (Devin, Dicker, Stanchfield+)

NRAO (DAQ & control software; analysis software; receiver rotator, dewar)

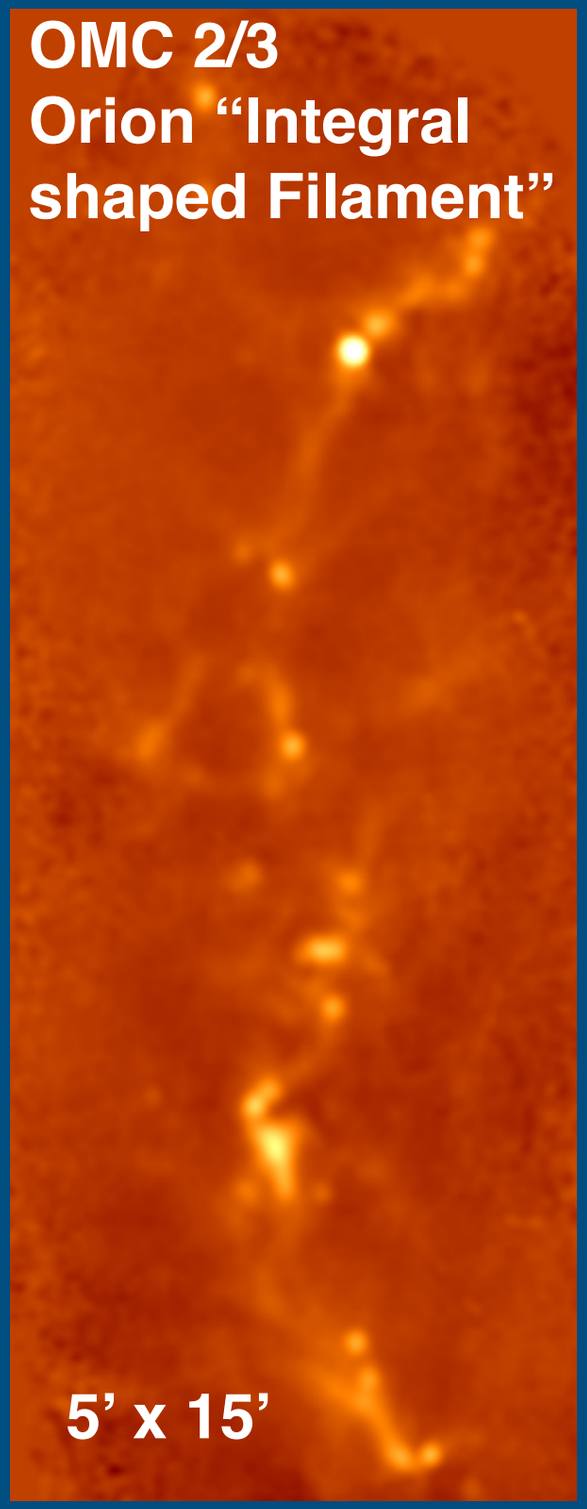
NIST (detectors & MUX)

Detectors funded by NSF-ATI in 2015

- 64 pixels -> 215 pixels
- 42” FOV —> > 4’ FOV
- greater sensitivity per beam

Available in Feb 1 GBO call for proposals (shared-risk in collab. w/PI)

MUSTANG-2

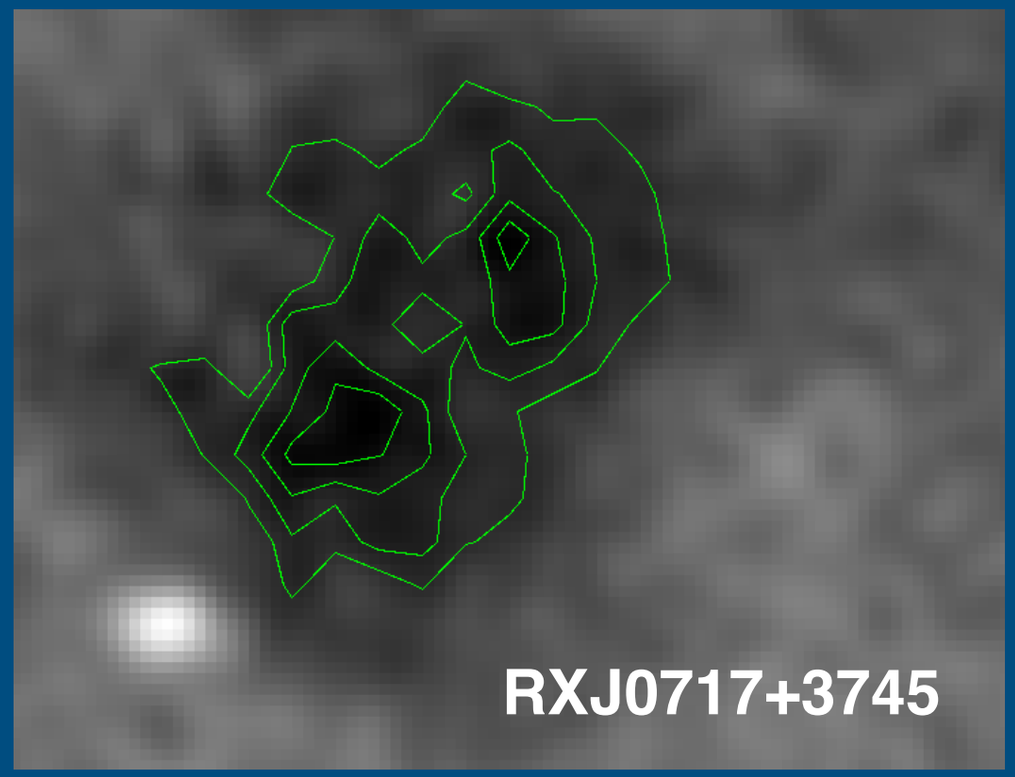


40 minutes on-source (commissioning winter 16/17)

MUSTANG-2 Commissioning observation of SZE in

(winter 16/17)

2h integration time on source



Available in Feb 1 GBO call for proposals (shared-risk in collab. w/PI)

MUSTANG-2 SZ Science

From accepted proposals currently in the GBT observing Queue:

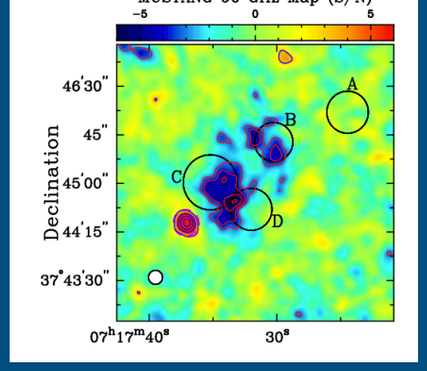
*more accurately determine the **masses and ICM pressure profiles in high redshift (z>1) clusters** which are very difficult and expensive to study with x-rays (17A-358, 17B-218)

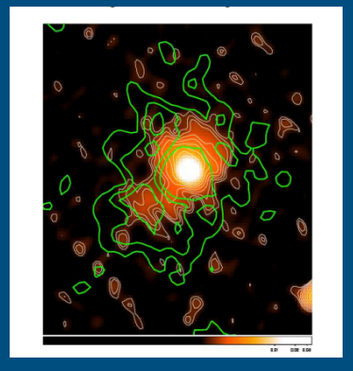
*provide 10" resolution imaging of SZ-selected clusters discovered in ACT equatorial survey, **observationally quantifying scatter and bias in M-Y relationship**. (17B-334)

* cluster astrophysics: **detect unknown shocks in the intra-cluster medium; probe shock mechanics** (17B-266)**; probe AGN bubble composition** (17A-340); study **thermal/non-thermal ICM phase connections** (17B-314)

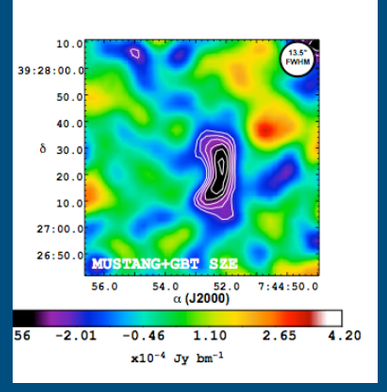
* measure **ICM pressure profiles in Weak-Lensing selected cluster sample** (17B-101

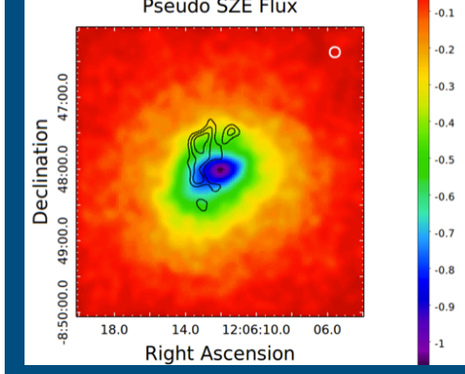
* measure **ICM turbulence** from SZE pressure fluctuations (17B-082)





Summary

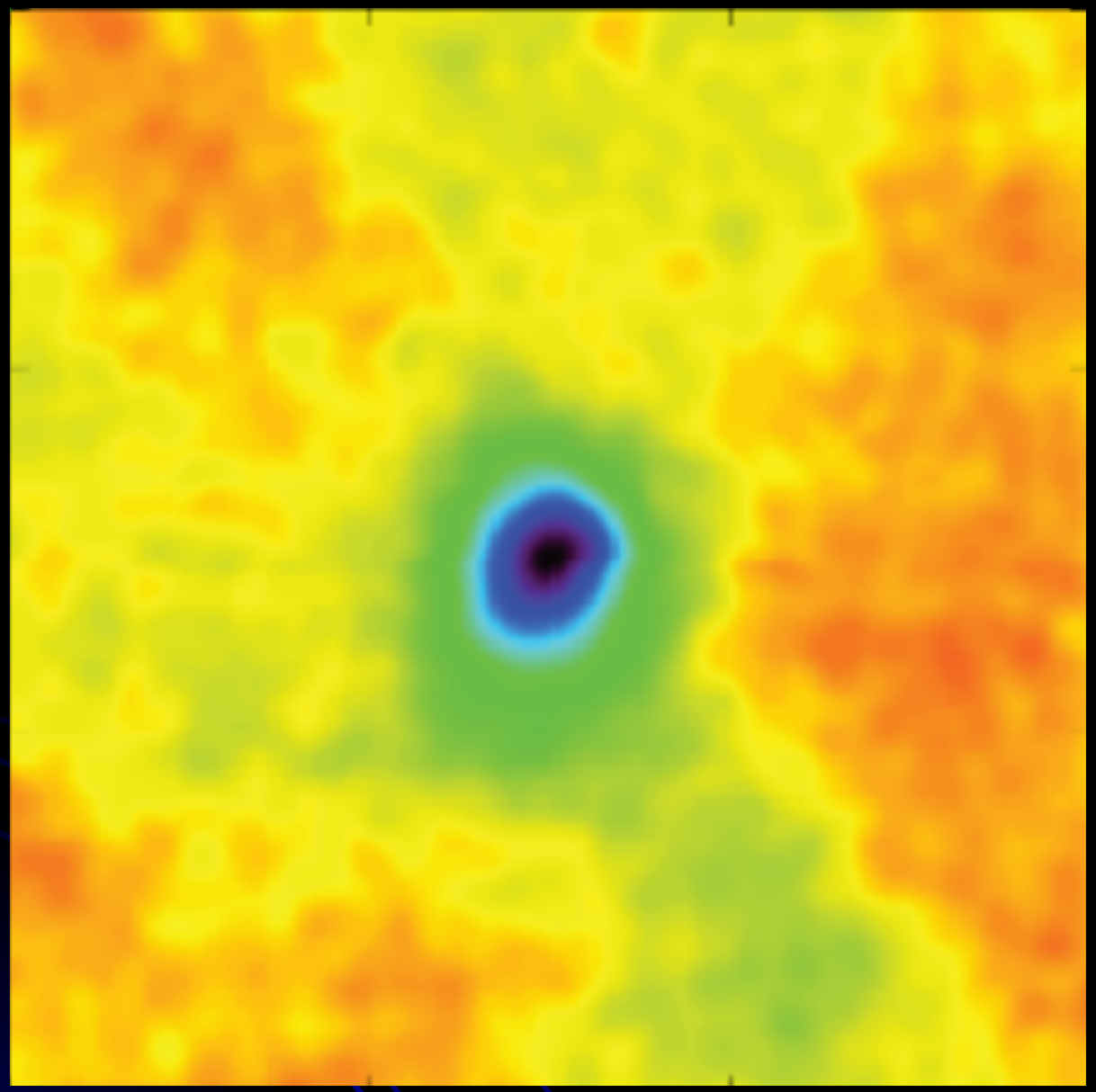




- SZE imaging has moved beyond single #s or detailed study of only the most extreme single cluster. We can *trust our images and start learning from them!*
- X-rays alone provide an incomplete view of the Intra-cluster medium and clusters' dynamical state
  - high resolution SZ data will provide essential information for maximizing the cosmological returns from existing & ongoing cluster surveys
- Looking to the future: there is abundant SZ science at 10" resolution
  - ALMA Band 1 in the south
  - ***Large cameras on Large mm single dishes: GBT@3mm***
  - having a robust, sensitive, high-resolution SZ imaging capability routinely available will transform the field.

end

SPT SZ Decrement Map (resolution = 1’.2)



Plagge et al. 2010

Chandra (resolution = 1”)
Weak Lensing mass map

Markevitch / Clowe+

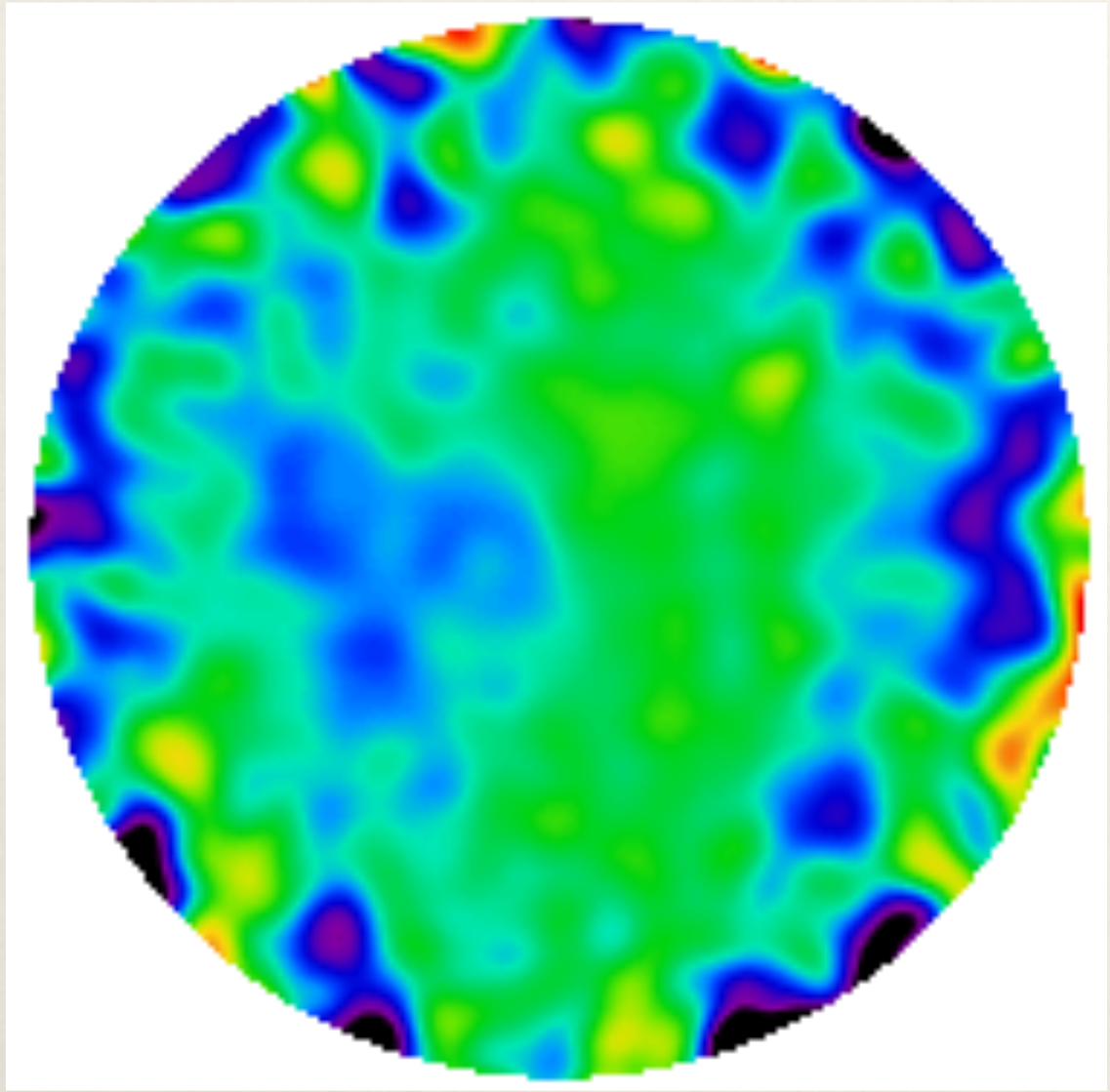
Real (cycle 2) ALMA observation

* Note: the region here is 56″ in radius (twice the diameter of the 12-meter array's primary beam).

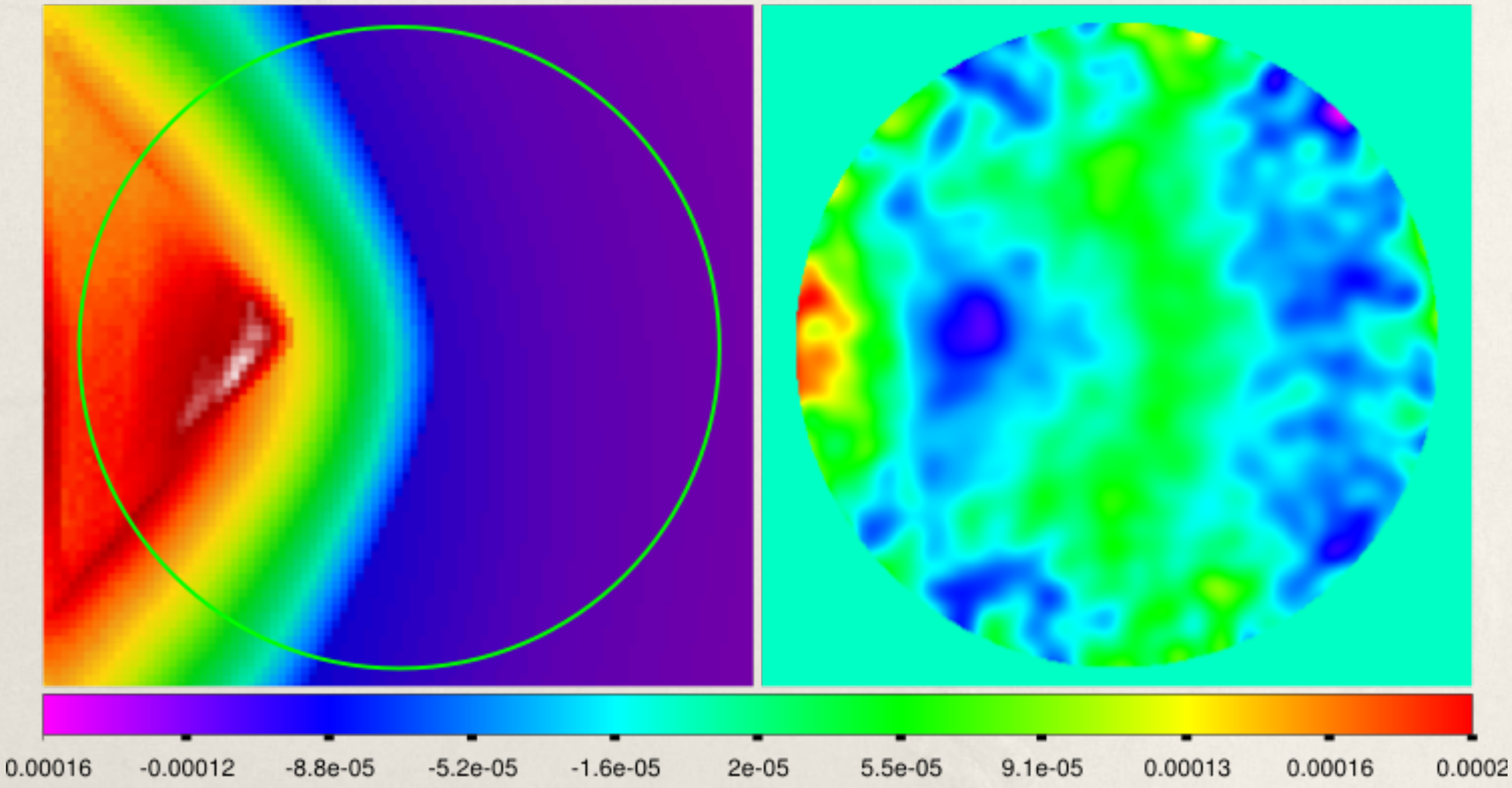
* Compton-*y* model seems to give a reasonable reduced χ^2.

* Now working to model the signal more fully.

* Upgrades to ALMA including Band 1 & Band 2+3 receivers will allow for larger scales to be recovered.



Mock ALMA observation



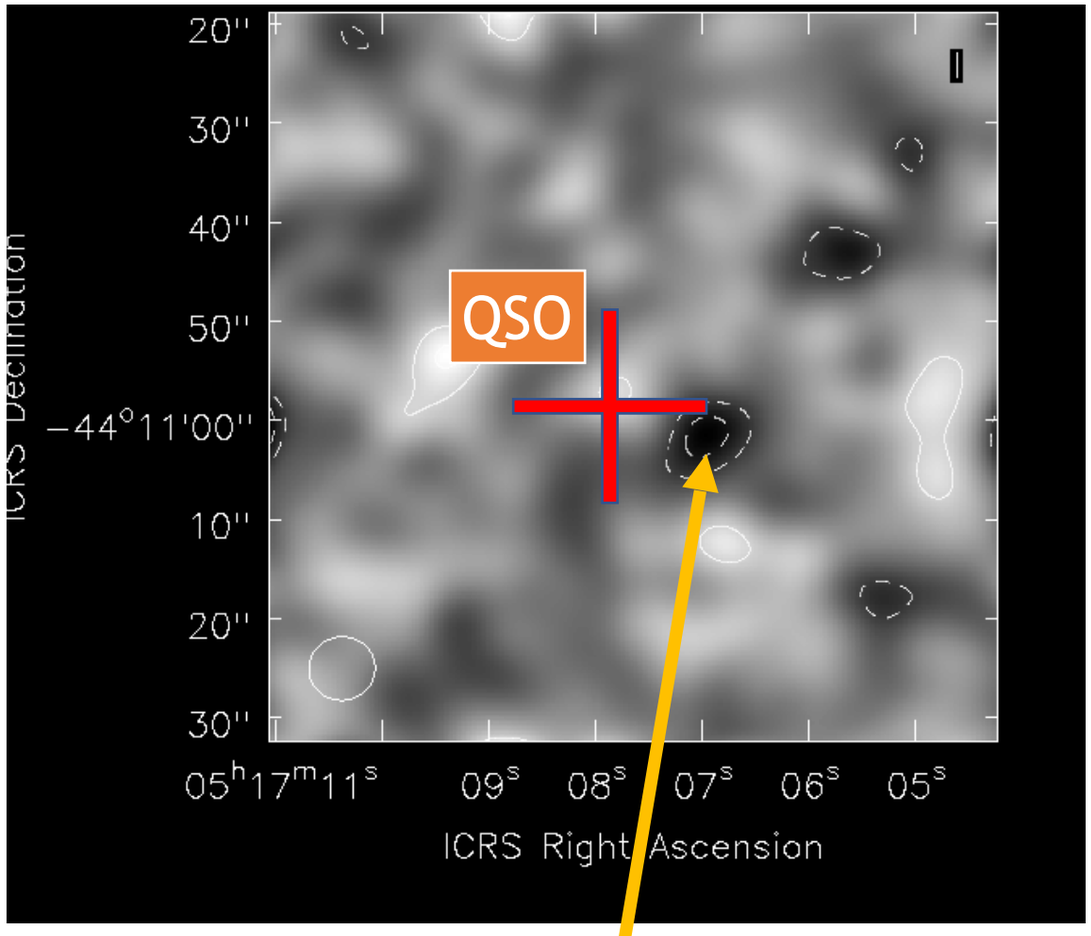
* Left: Compton-*y* model, zoomed in. Circle is 2.7′ in diameter.
* Right: Mock ALMA Band 3 observation, down to ~7 μJy RMS.

Most of the energy in AGN and starburst winds is in hot (~$10^{7\text{-}8}$K) gas.

Too diffuse to detect in X-rays, but feasible via the SZ effect.

Claims of detections of QSO winds from stacking: Planck, ACT or SPT data, but contamination is a problem in large beams.

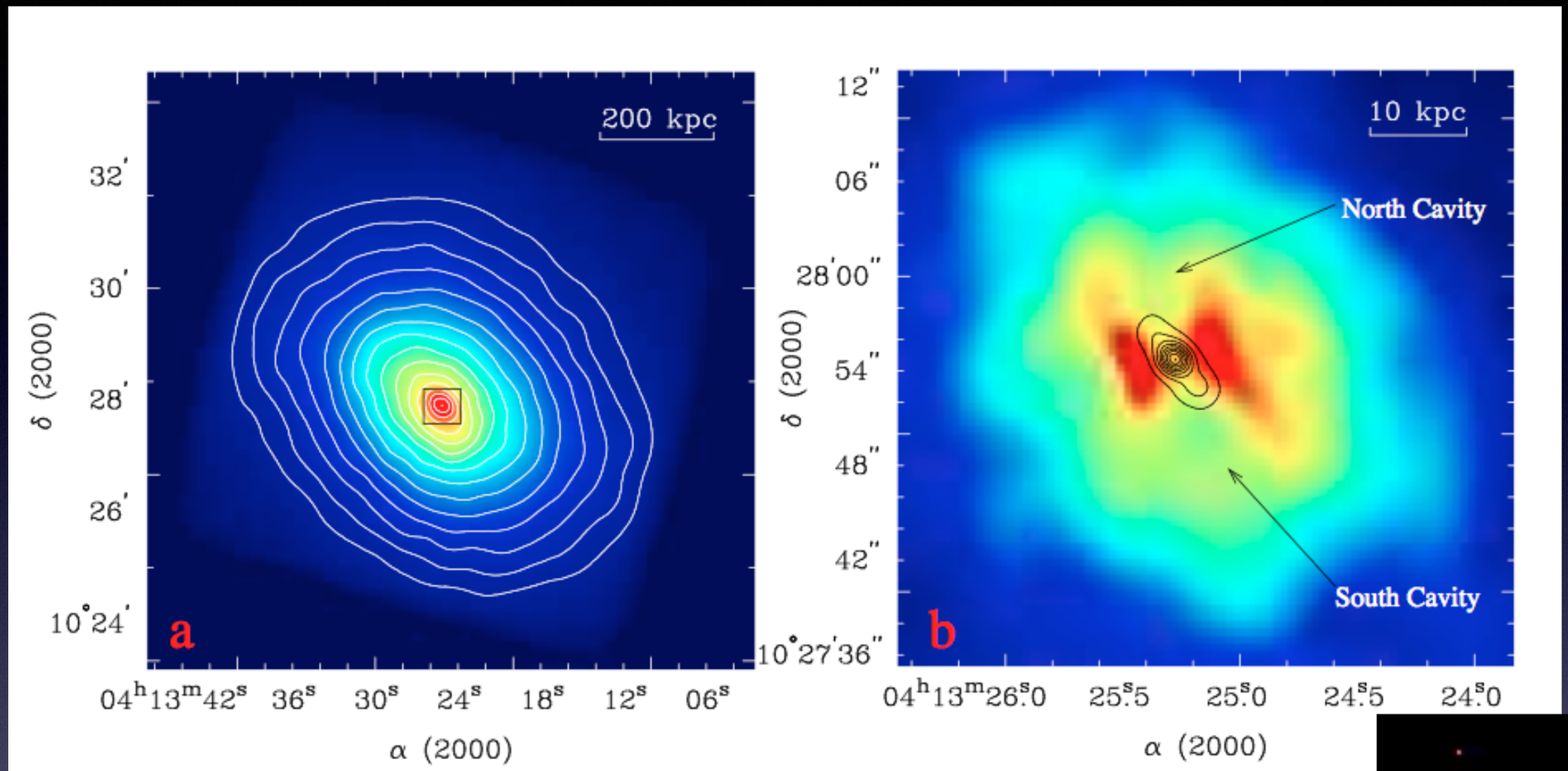
Hyperluminous quasars and starburst winds may just be detectable with 10-100 hour observations using current telescopes e.g. ALMA (shown), VLA or GBT with tens of micro-K sensitivity on scales of a few arcsec in the 2-10mm bands.



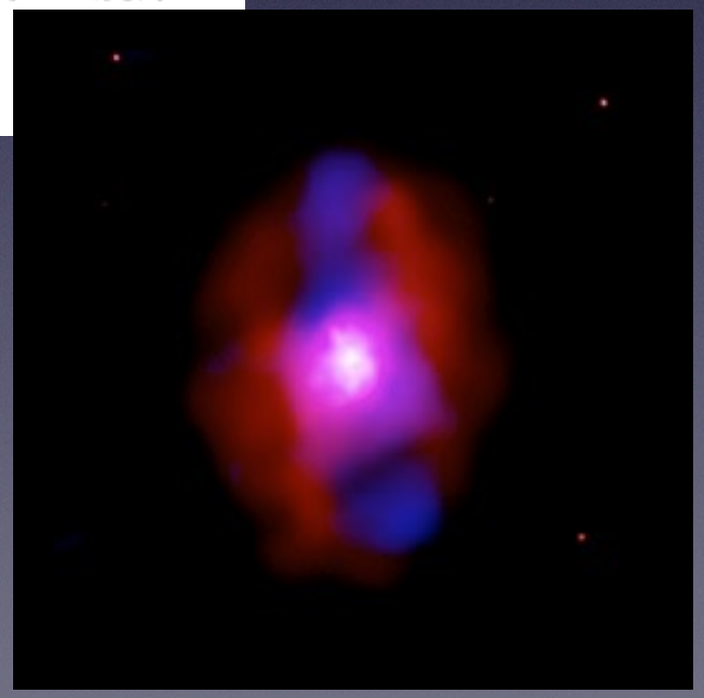
Possible SZ hole (or at least good l

X-Ray Cavities/Bubbles

Abell 478 *(Sun et al. 2003)*

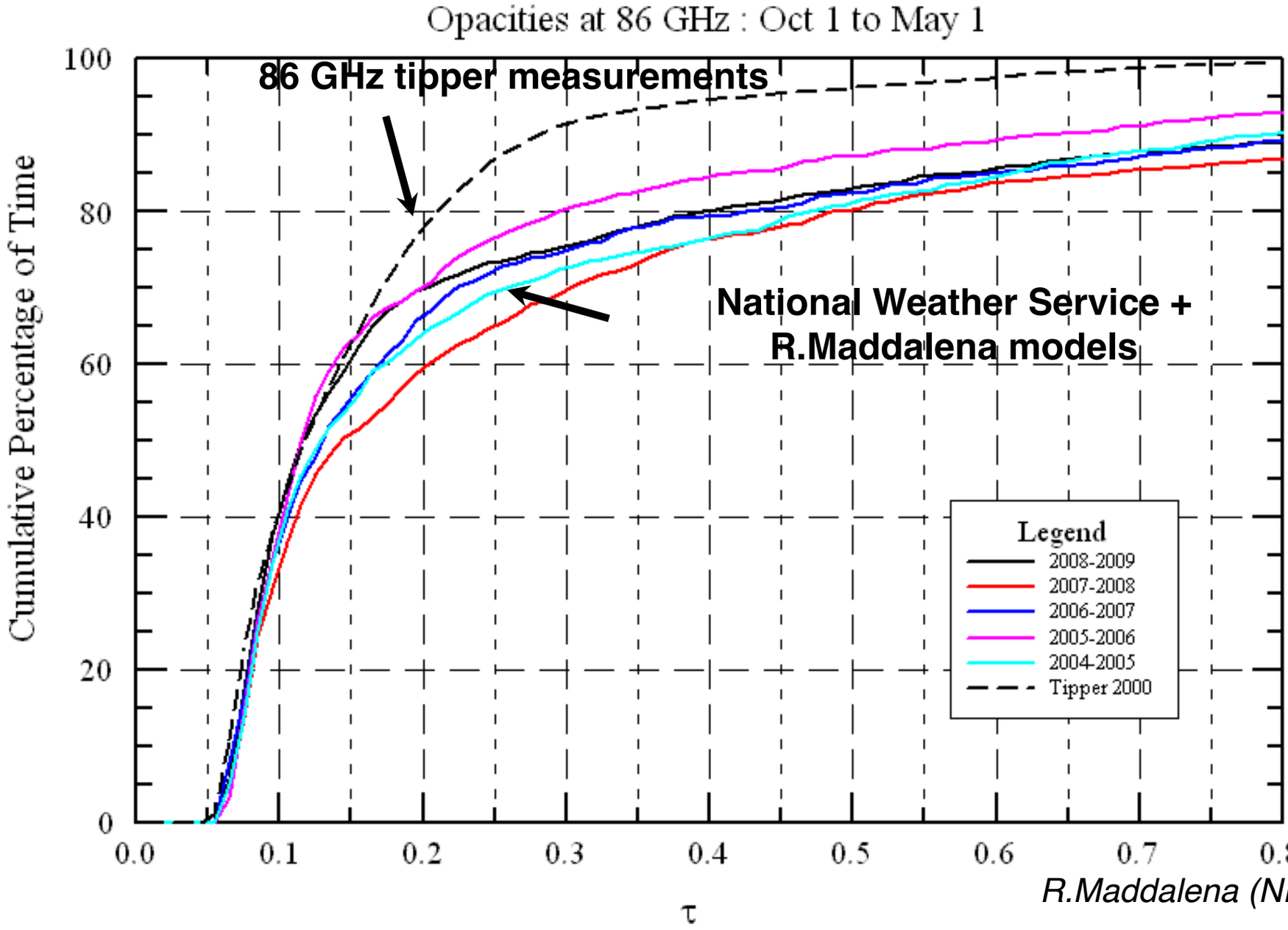


MS0735.6+7421
McNamara et al. 2005
Chandra/VLA composite



AGN outflows carve out holes in the cluster plasma.
Resolved SZ can probe the composition of the medium inside x-ray cavities.

Green B
Weath



R.Maddalena (N

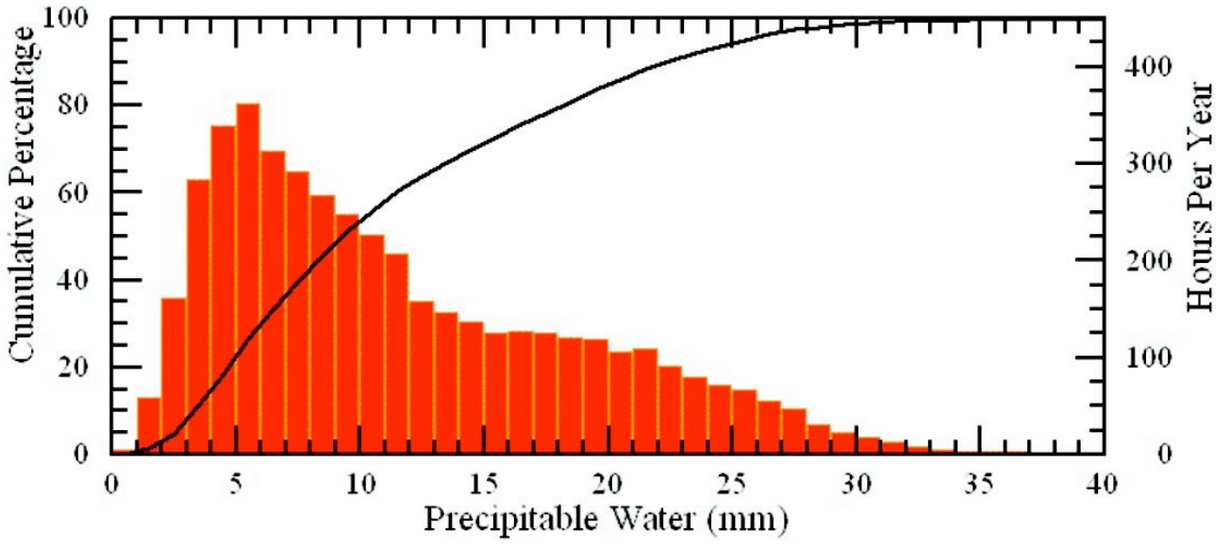
including other, current constraints on GBT mm observing:
**3h post-sunset to sunrise*
**winds < 10mph*

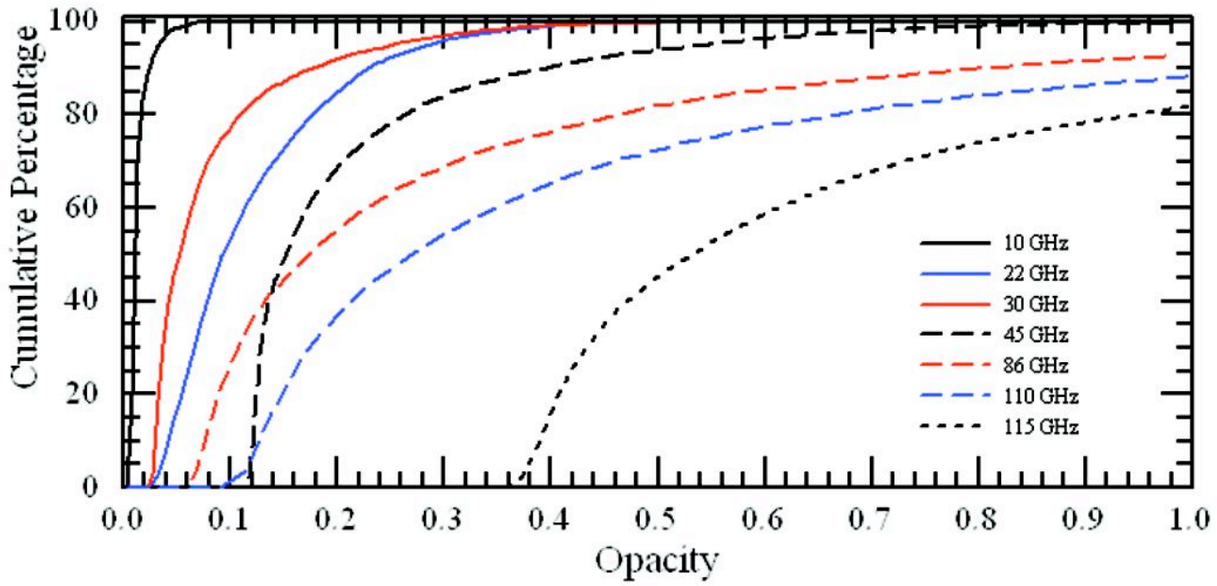
~540h useful 3mm/4mm observing time per year

In 2010, 1776h of science at > 18 GHz were scheduled on the GBT

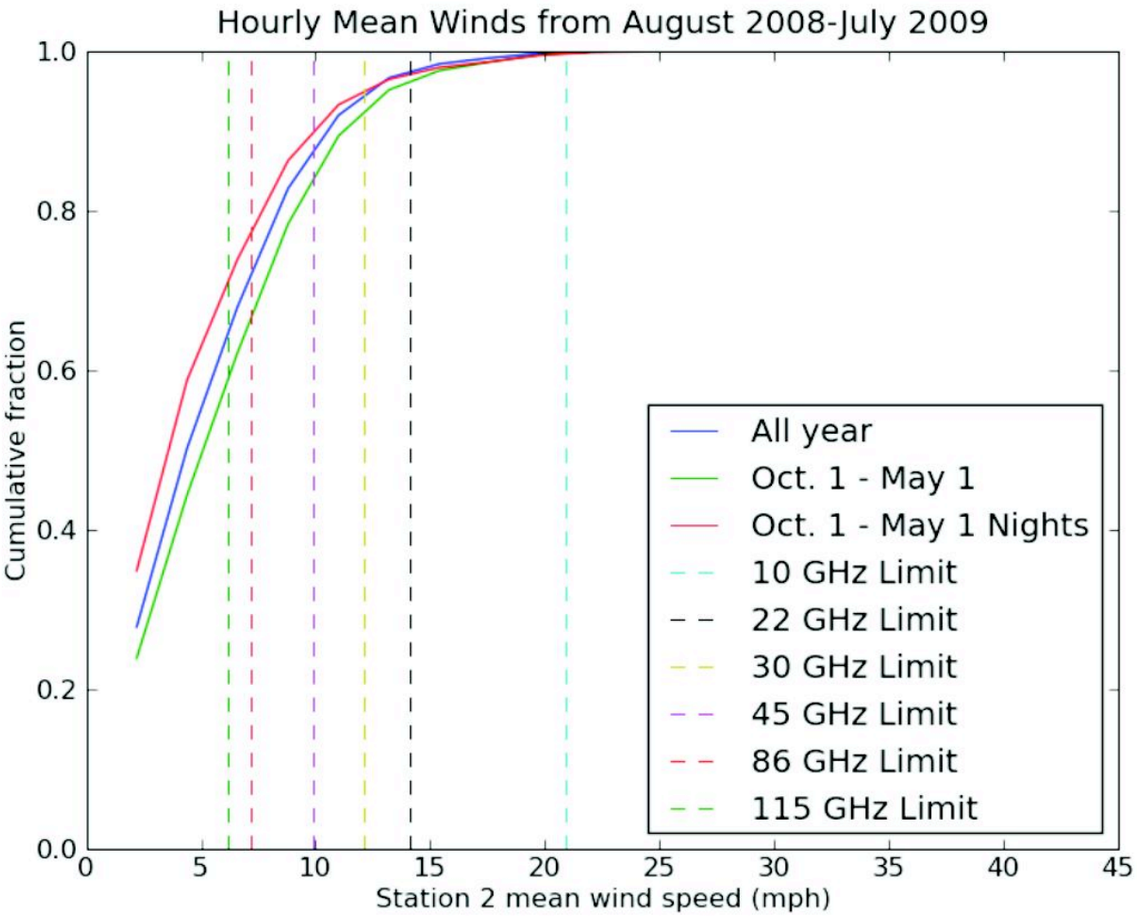
see GBT memos 267, 269; and other DSS & PTCS memos

Weather at Green Bank good for 3mm observations for 1000-2000hrs per year





(from Ron Maddalena's weather studies)

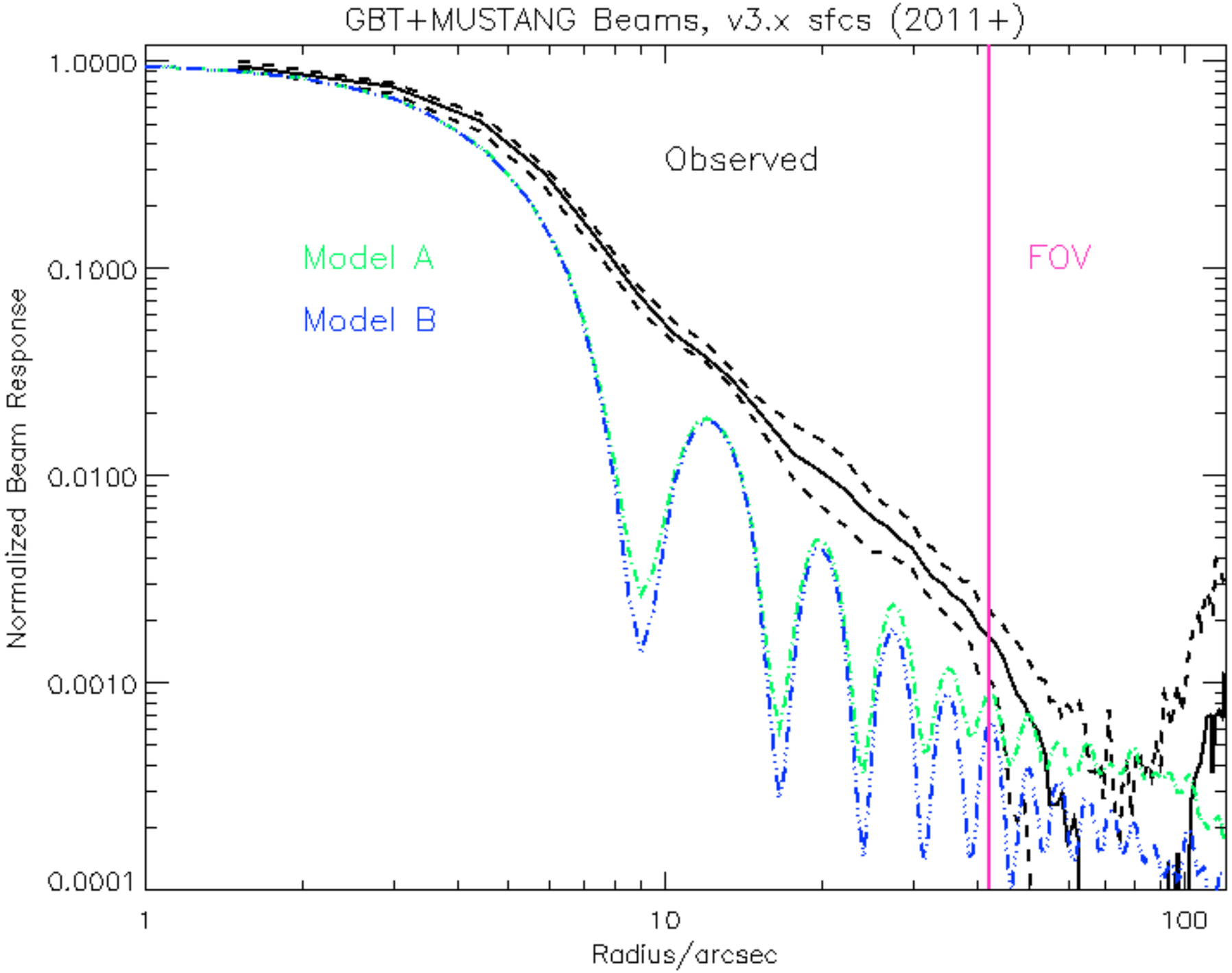


Hours available per year with acceptable winds and tau:

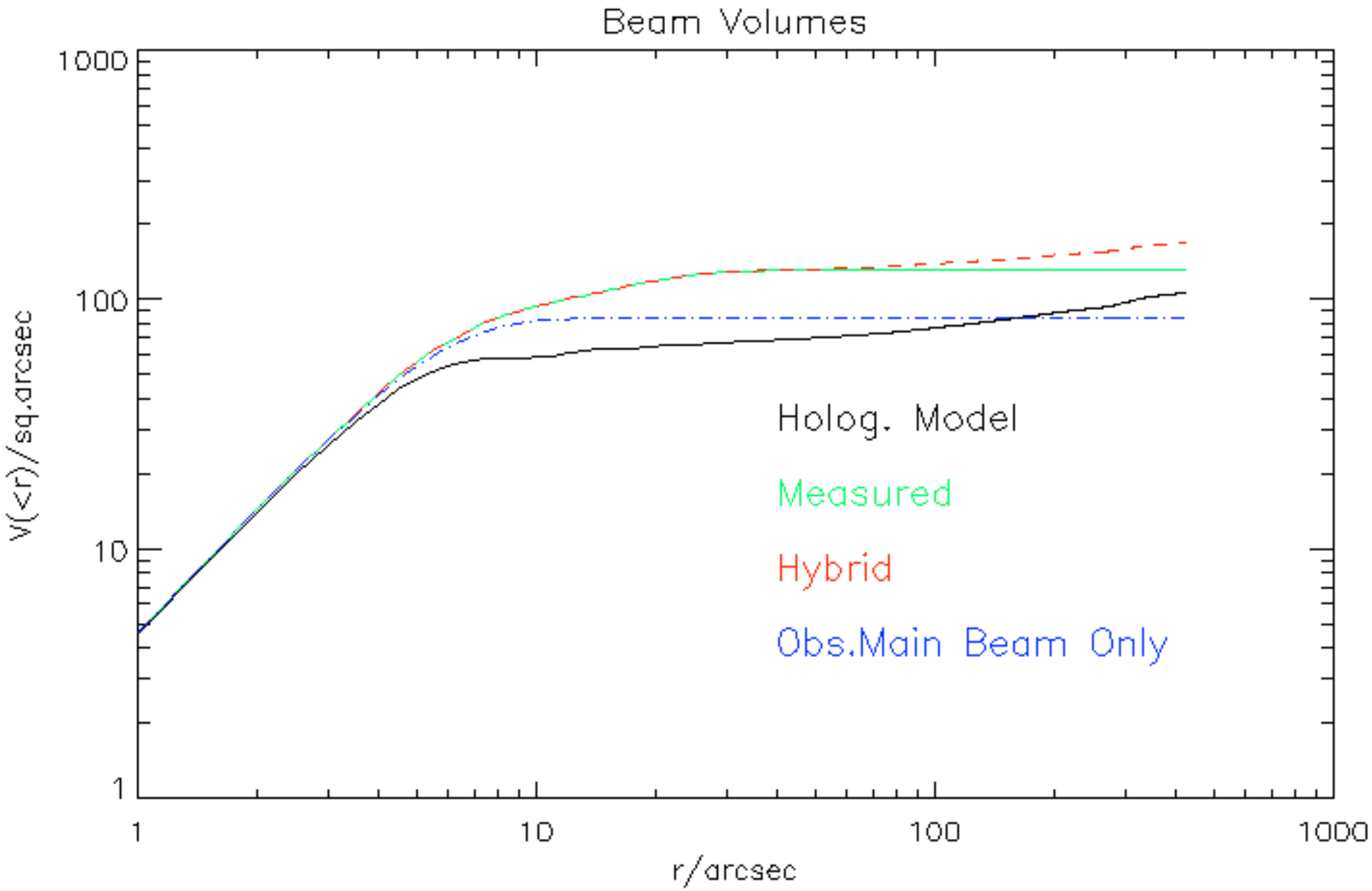
Frequency	tau < 0.1	tau < 0.2
22 GHz	2600 h	4000 h
45 GHz	---	2800 h
86 GHz	975 h	2100 h

Frayer ()

GBT Beam

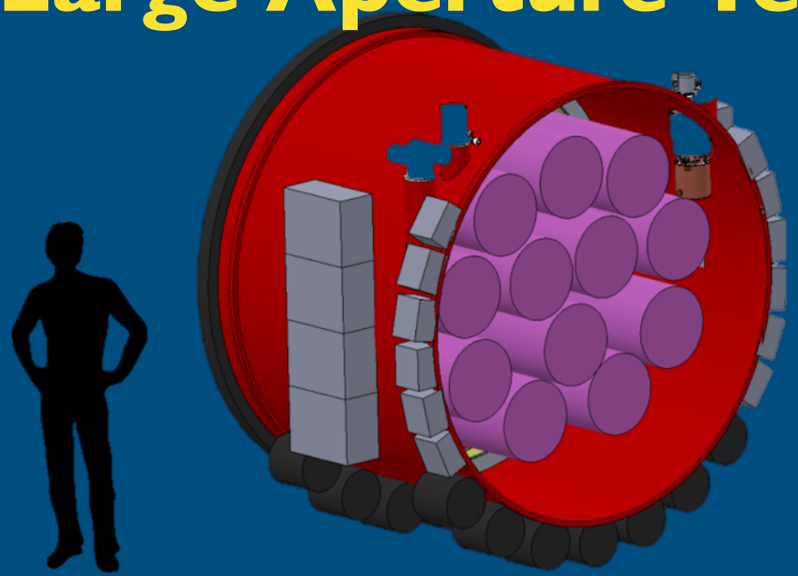

GBT+MUSTANG Beams, v3.x sfcs (2011+)
Observed
Model A
Model B
FOV
1.0000
0.1000
0.0100
0.0010
0.0001
Normalized Beam Response
1
10
100
Radius/arcsec

GBT Beam


Beam Volumes
1000
100
10
1
V(<r)/sq.arcsec
1
10
100
1000
r/arcsec
Holog. Model
Measured
Hybrid
Obs.Main Beam Only

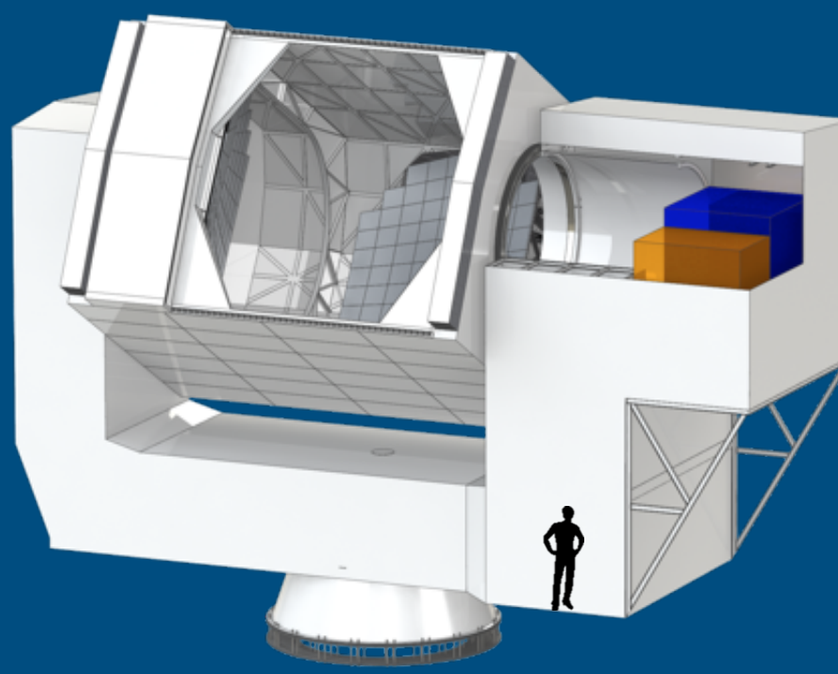
Simons Observatory

Large Aperture Telescope Camera



$40M grant from the Simons Foundation and the Heising-Simons Foundation.

10 m



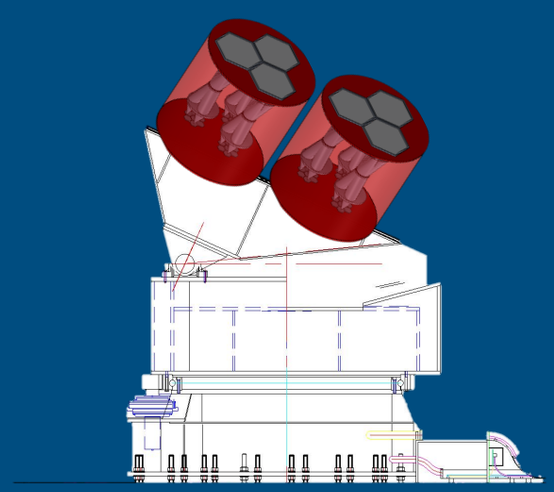
6 meter diameter Cross-Dragone Telescope

~1.7 arcminute resolution at 150 GHz

Up to 80,0000 Detectors

Small Aperture Cameras

- 30-50 cm apertures
- ~ 1 degree resolution.
- CMB polarization

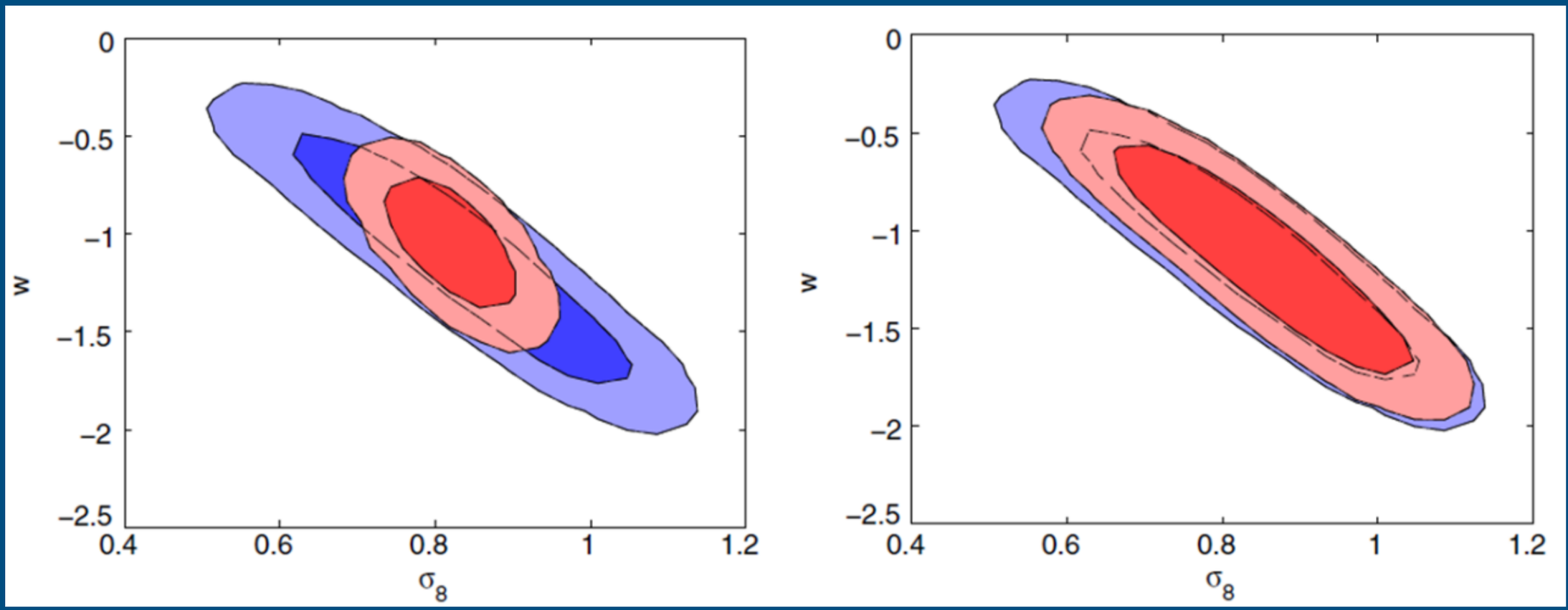


Early 2021 Commissioning

Aye, there's a rub: systematics matter

Without astrophysical uncertainties

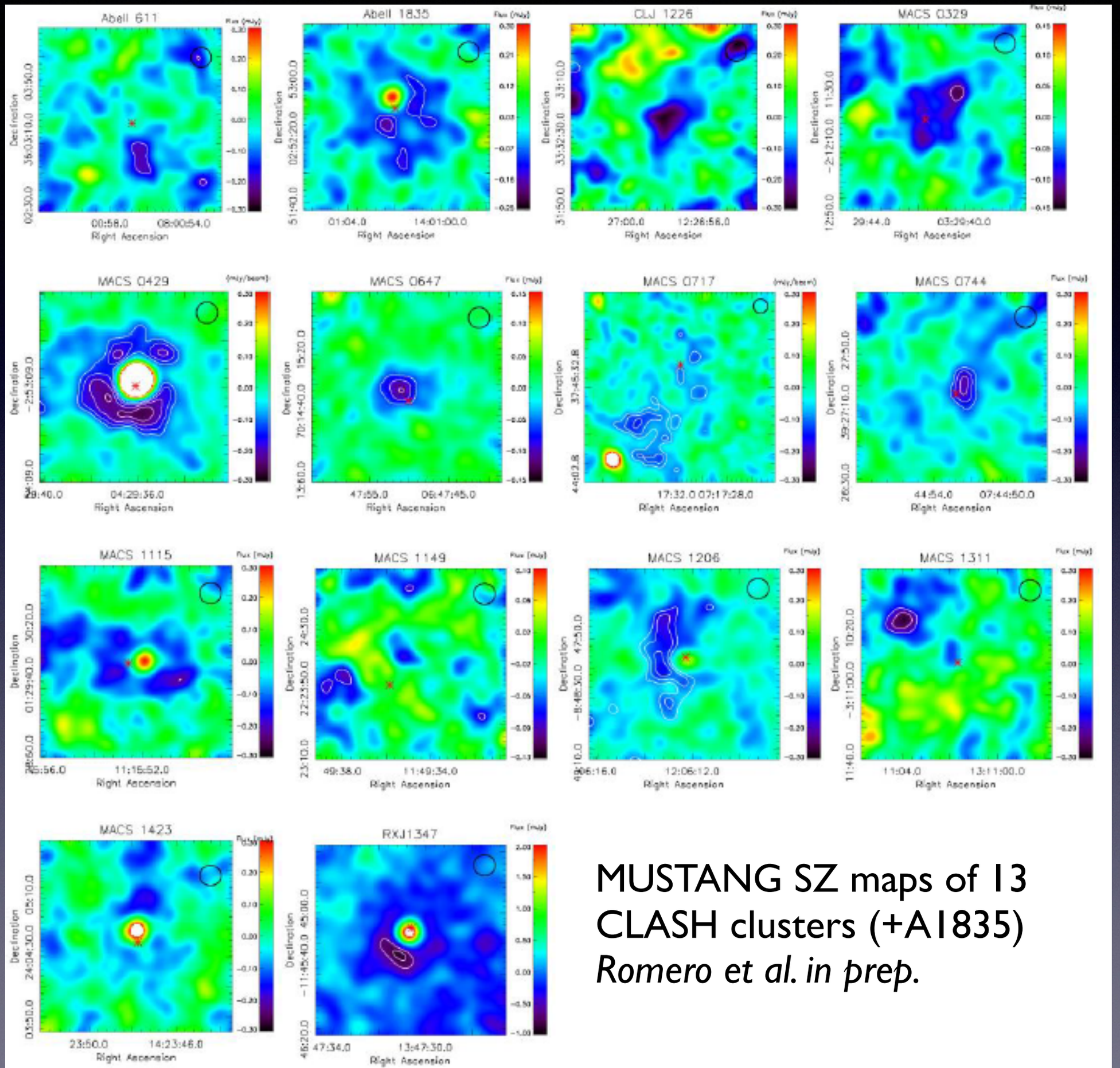
with astrophysical uncertainties:



First cosmological constraints from ACT SZE survey

Sehgal et al. 2011 — used only **9** rich, optically confirmed clusters

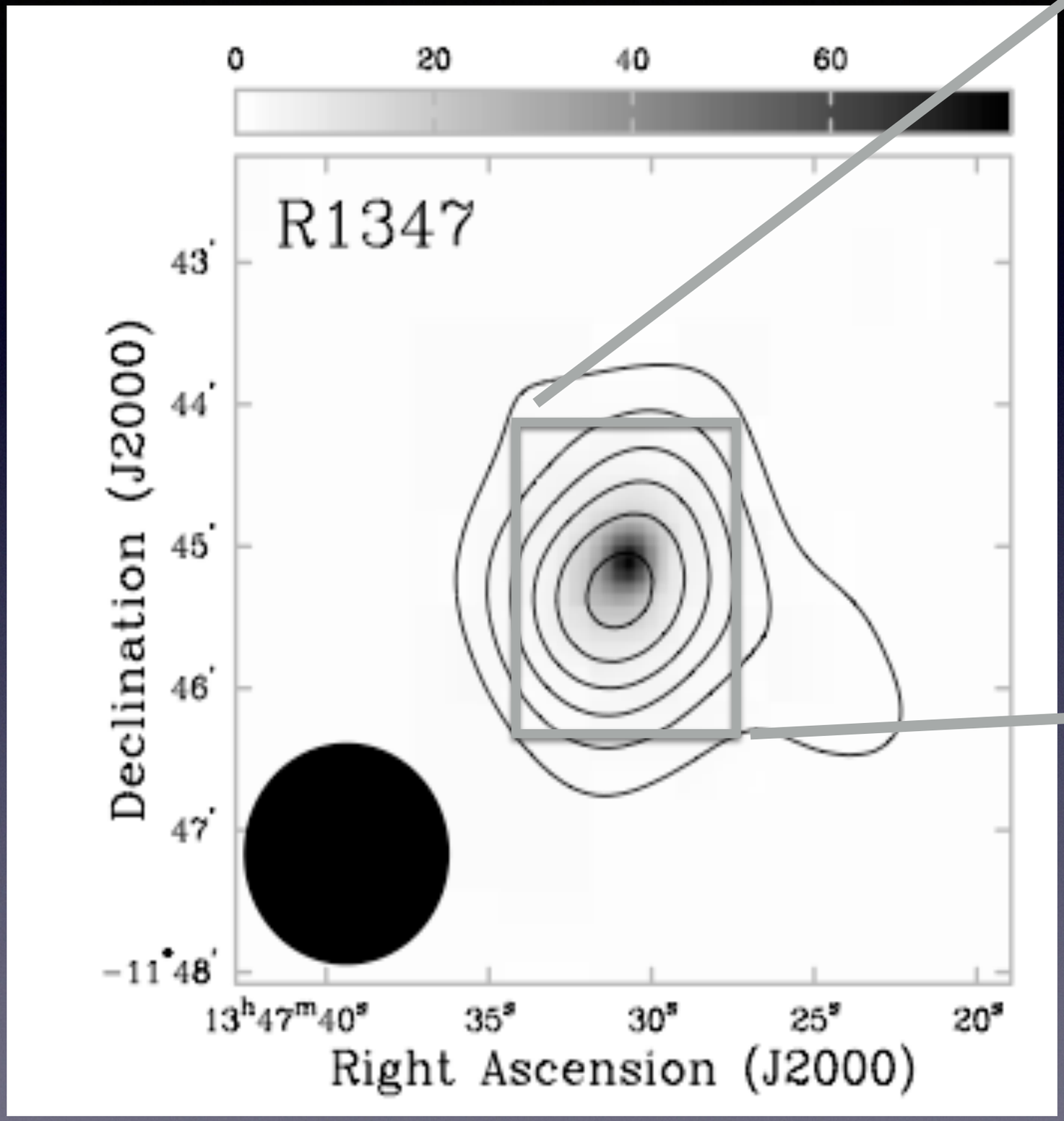
These will continue to limit what we learn from larger, future samples. (see e.g. Dark Energy Task Force report, 2006)

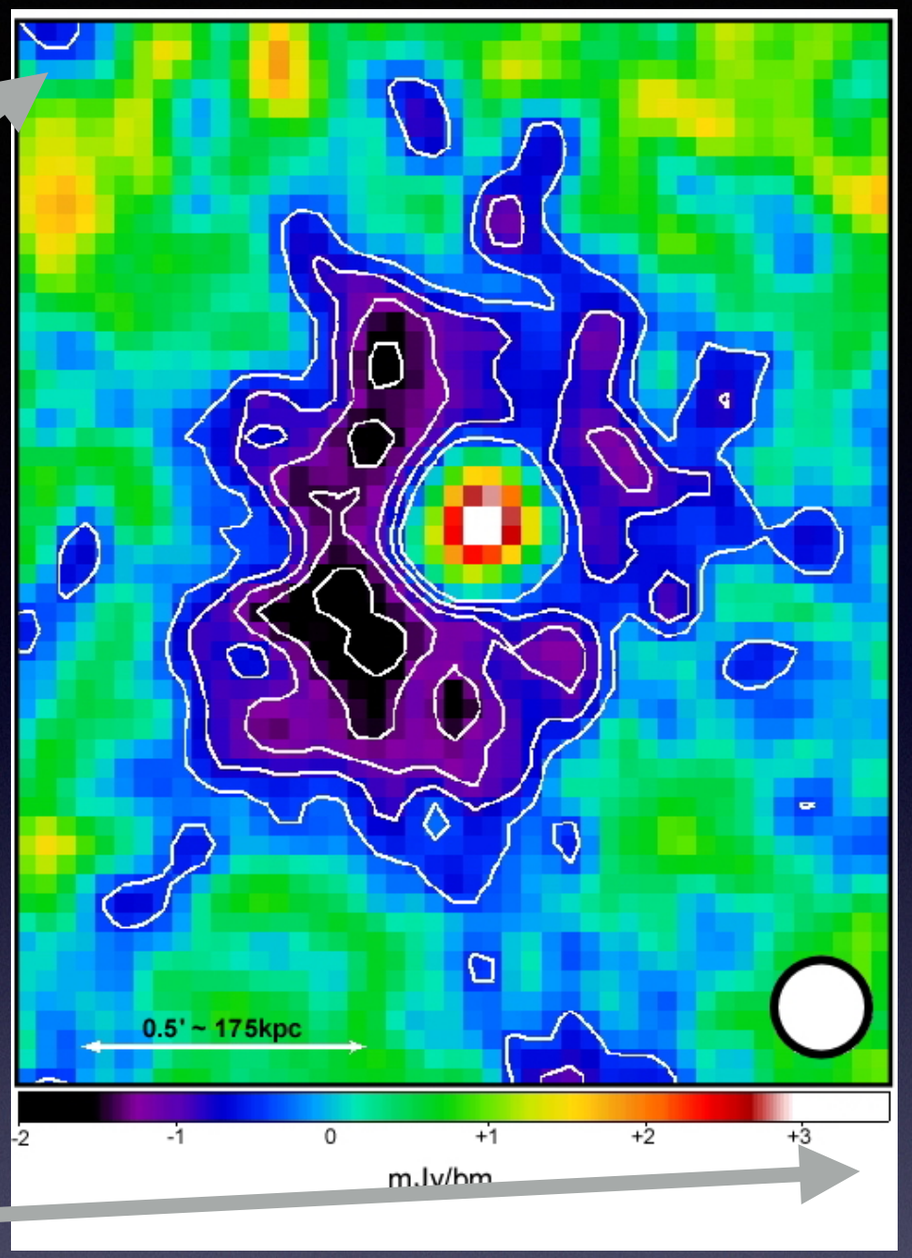


MUSTANG SZ maps of 13 CLASH clusters (+A1835)

Romero et al. in prep.

RXJ1347-1145





3.3h on-source with
GBT+MUSTANG
Mason+2010 / Korngut+2011

> 25 keV gas

moderate mass-ratio cluster merger in progress and near closest approach

Reese et al. 2002; BIMA (30 GHz, 20 hours)