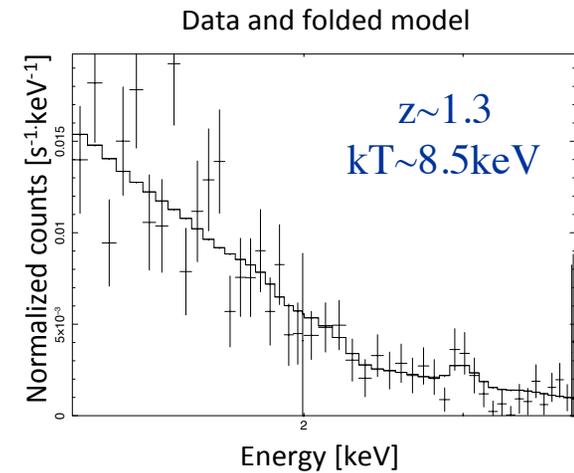
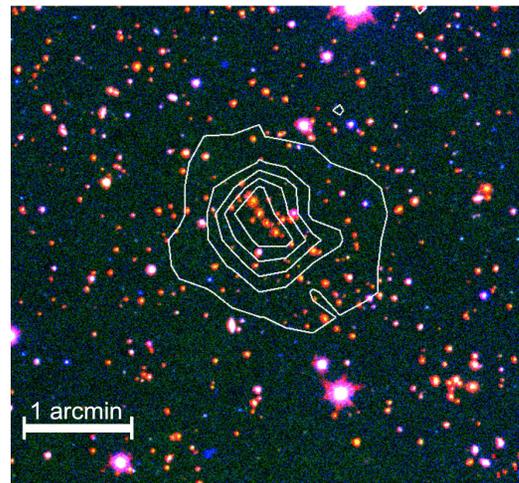
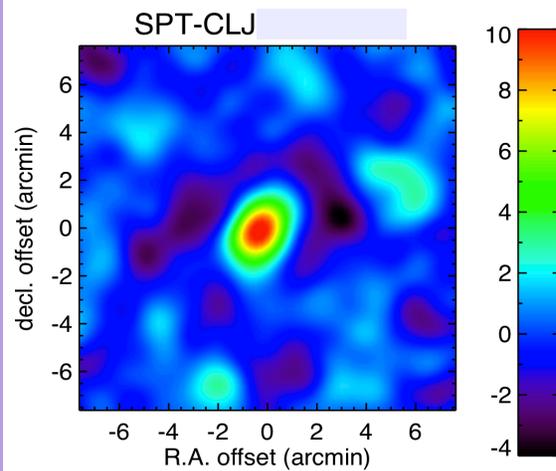
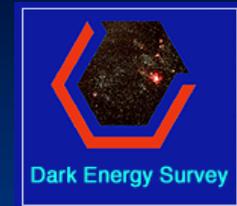




# The South Pole Telescope Galaxy Cluster Survey

Joe Mohr  
LMU and MPE, Munich





# South Pole Telescope in Operation

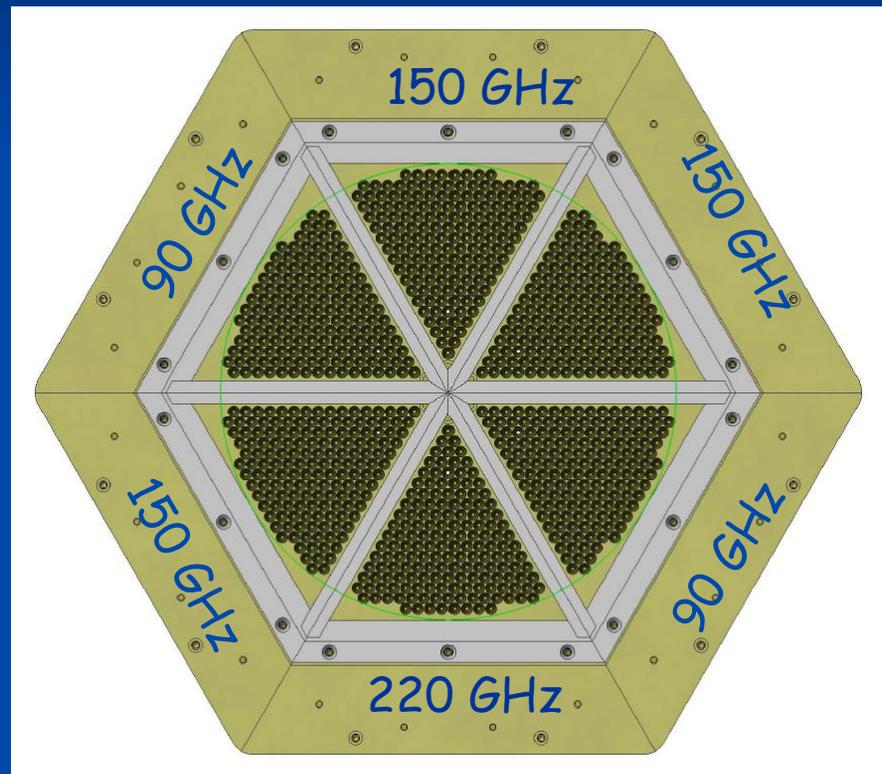
PI: John Carlstrom (U Chicago)

- Funded by NSF in 2002
- Feb 16, 2007 SPT first light
- Science survey began May 2007 and continues today
- Deep, arcminute resolution maps now “routinely” produced

March 24, 2007



180 mm; ~1 degree on sky



<http://spt.uchicago.edu>





# South Pole Telescope



# SPT Collaboration

John Carlstrom, PI



William Holzapfel  
Adrian Lee  
Martin White  
Sherry Cho  
Huan Tran  
Martin Lueker  
Jared Mehl  
Christian Reichart  
Dan Schwan  
Erik Shirokoff  
Oliver Zahn



Helmuth Spieler



Jeff McMahon  
Jeeseon Song



Case  
CASE WESTERN  
RESERVE UNIVERSITY

John Ruhl  
Tom Montroy



Joe Mohr  
Gurvan Bazin  
Shantanu Desai  
Alex Saro  
Robert Suhada  
Sebastian Bocquet  
Jiayi Liu  
Alfredo Zenteno



THE UNIVERSITY OF  
CHICAGO

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Steve Padin  
Stephan Meyer  
Clem Pryke  
Wayne Hu  
Andrey Kravtsov  
Brad Benson  
Clarence Chang  
Tom Crawford  
Will High  
Tom Plagge

Colorado

University of Colorado at Boulder

Nils Halverson



McGill

Matt Dobbs  
Gil Holder  
Jonathan Dudley  
Keith Vanderline



Peter Ade



Kavli Institute  
for Cosmological Physics  
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Joaquin Vieira  
Abbie Crites  
Ryan Keisler  
Lindsey Bleem  
Jonathan Stricker



Erik Leitch  
UC DAVIS  
UNIVERSITY OF CALIFORNIA

Lloyd Knox  
Jason Dick



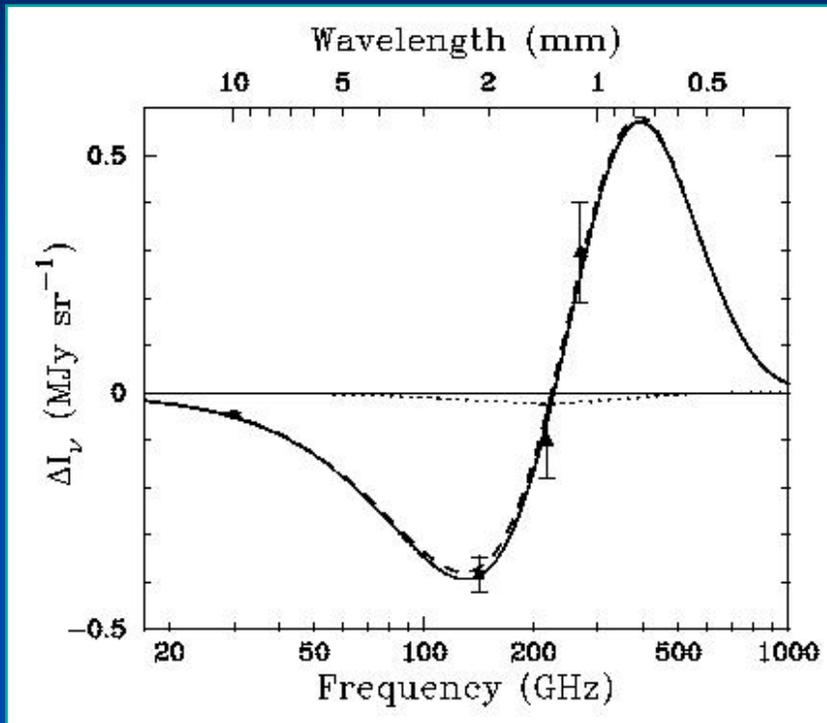
Harvard-Smithsonian  
Center for Astrophysics

Antony Stark  
Chris Stubbs  
Brian Stalder  
Jonathan Ruell

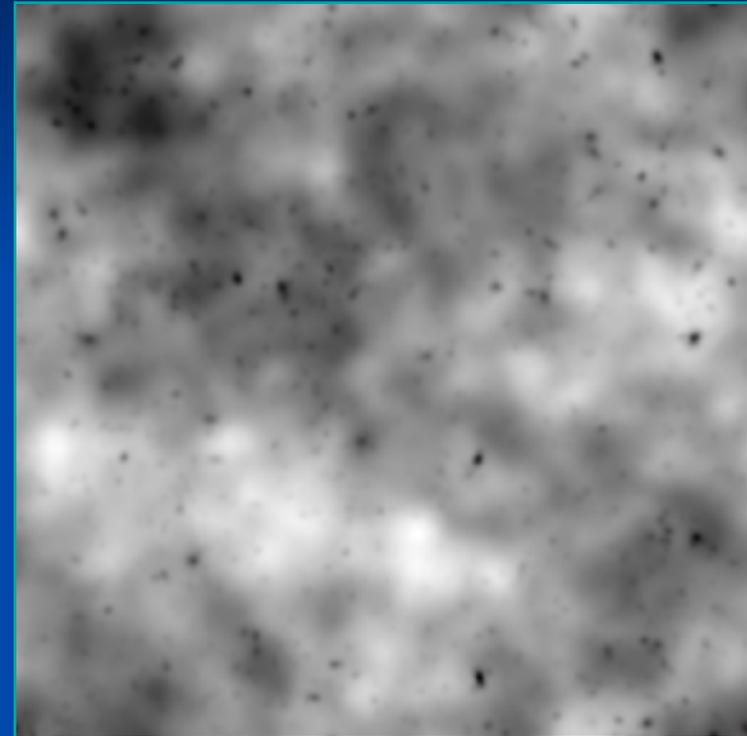


# SZE Signature of Galaxy Clusters

Unique spectrum



Unique angular scale



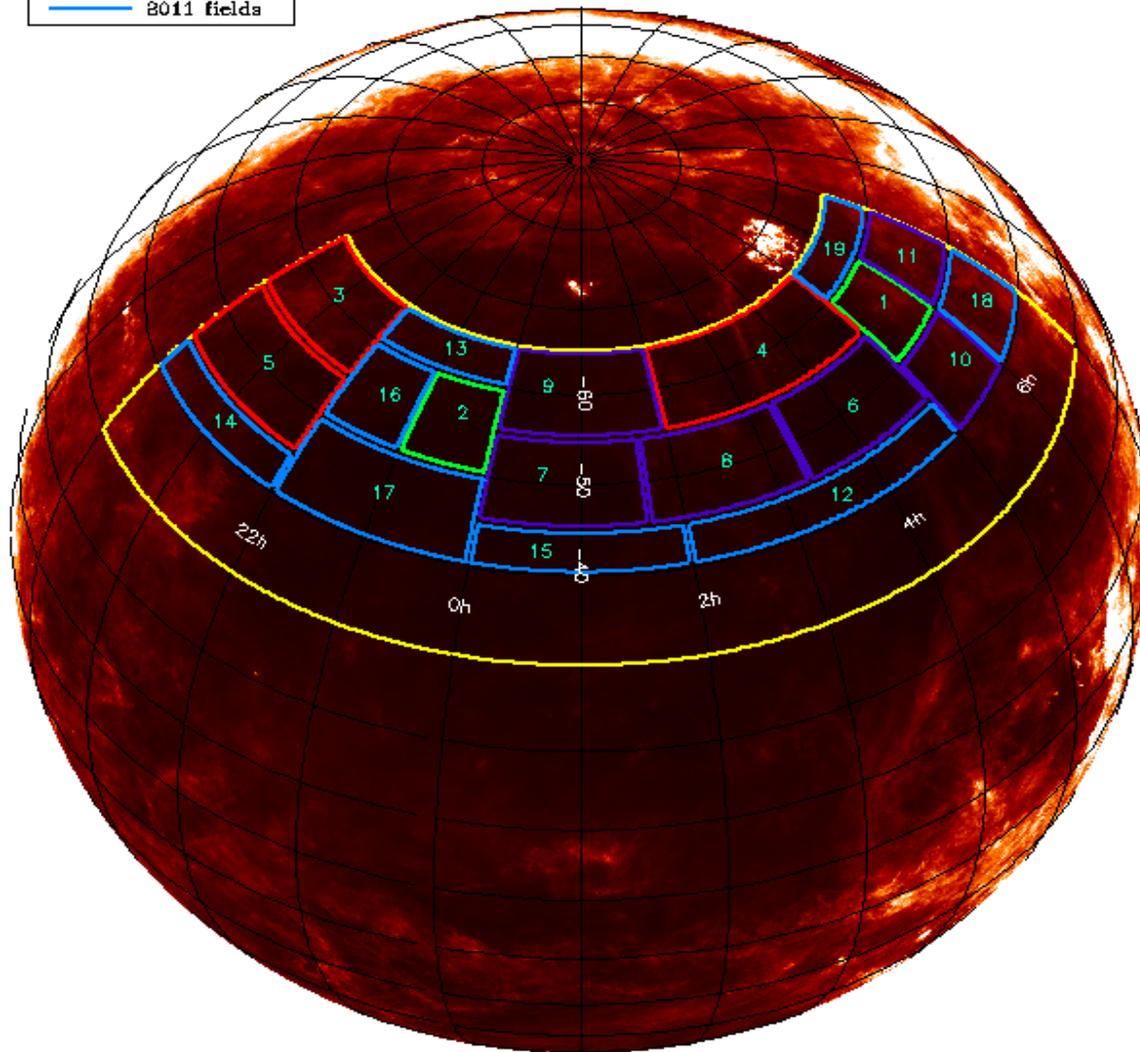
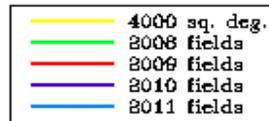
Simulations provided by M. White

Cluster SZE flux proportional to total thermal energy in the electron population.

**Promise: clean, low scatter, redshift independent cluster selection technique!**



From: Keisler & Crawford



## Full Depth Solid Angle

- 2008  
171deg<sup>2</sup>
- 2009  
567deg<sup>2</sup>
- 2010  
737deg<sup>2</sup>
- 2011  
1015deg<sup>2</sup>
- **Total**  
**2491deg<sup>2</sup>**

## Candidates

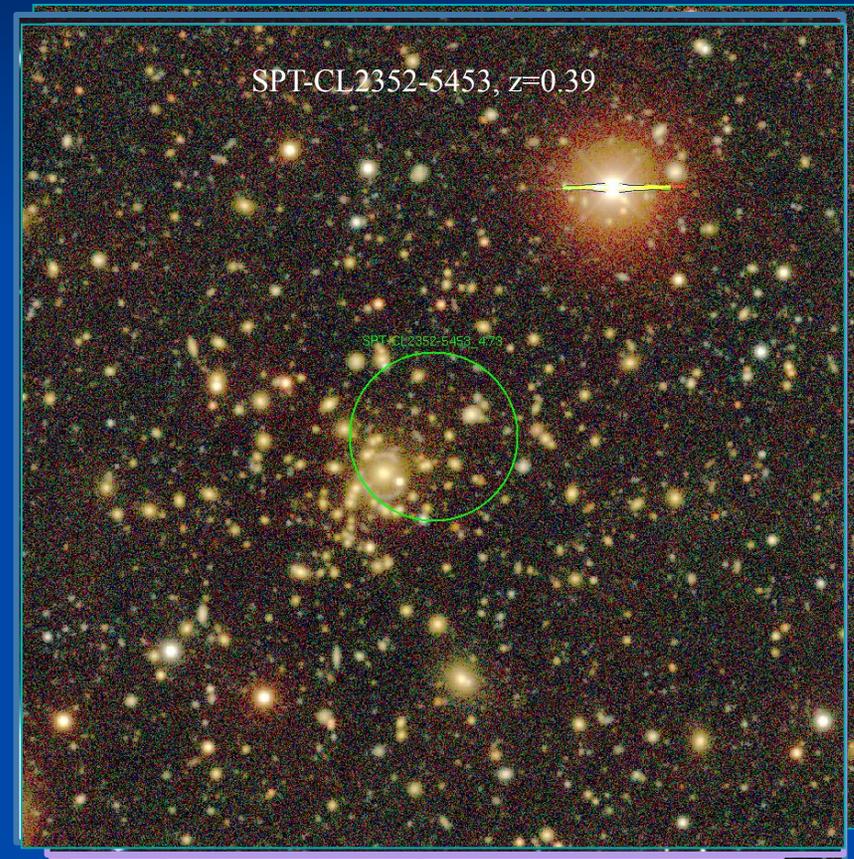
- 2008  
39 (21)
- 2009  
183 (98)
- 2010  
232 (146)
- 2011  
323 (190)
- **Total**  
**777 (455)**



# SPT Optical Followup



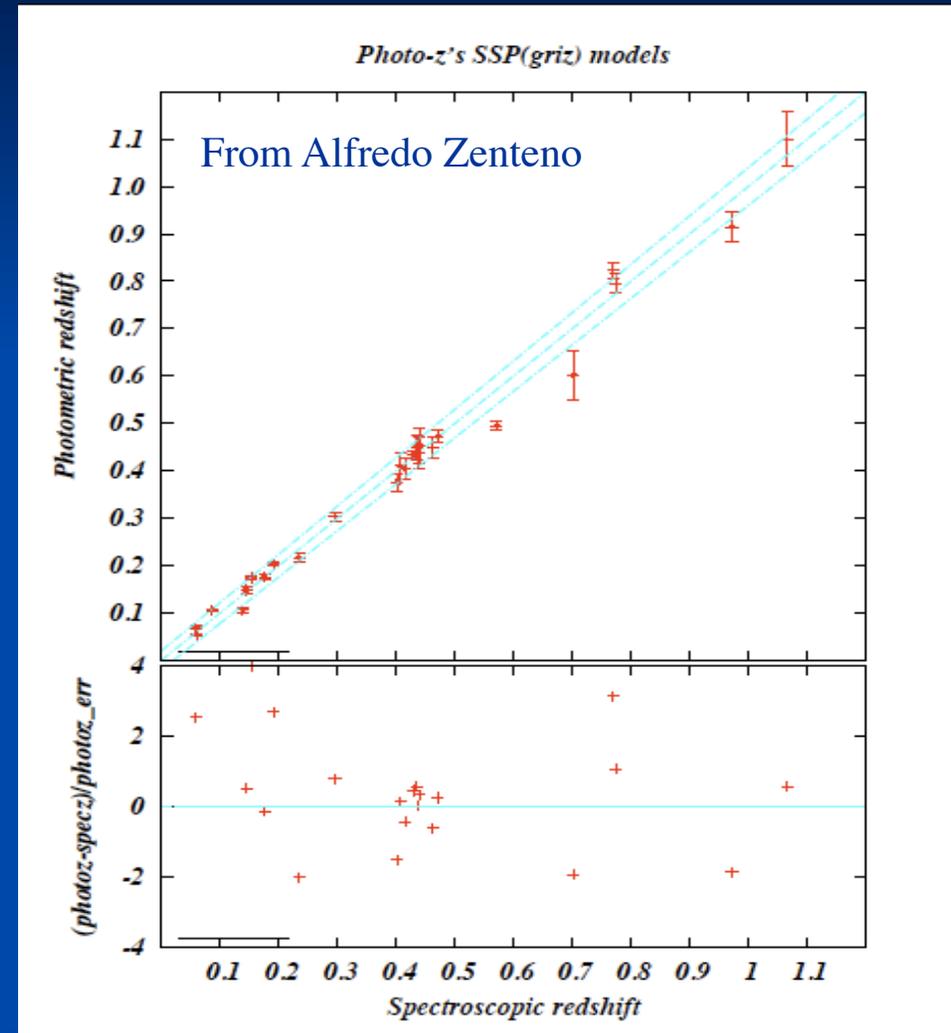
- We examine DSS around each candidate
  - Image w/Medium aperture for  $z > 0.5$   
Blanco 4m, Magellan 6.5m, (SOAR, NTT)
  - Image w/Small aperture for  $z < 0.5$   
Swope 0.9m, ESO/MPG 2.2m
- We use multiband photometry to get red sequence cluster redshifts
- We obtain Spitzer IRAC imaging for all candidates at  $S/N > 4.8$ 
  - NIR Imaging for any non-confirmation or  $z > 0.9$





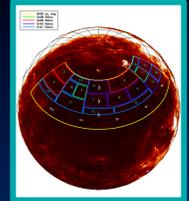
# Photometric Redshifts

- Two sub-teams work pseudo independently to provide a crosscheck
- We calibrate photometry using the distribution of stars in color-color space (stellar locus)
  - See High et al 2009 for overview
- Spectroscopic followup program has allowed good cross-checks, and photo-z performance is good
  - Characteristic accuracy is  $\sim 0.03(1+z)$





# SPT Cluster Sample – Followup Status



- At present we are followup limited

<5% Contamination

~20% Contamination

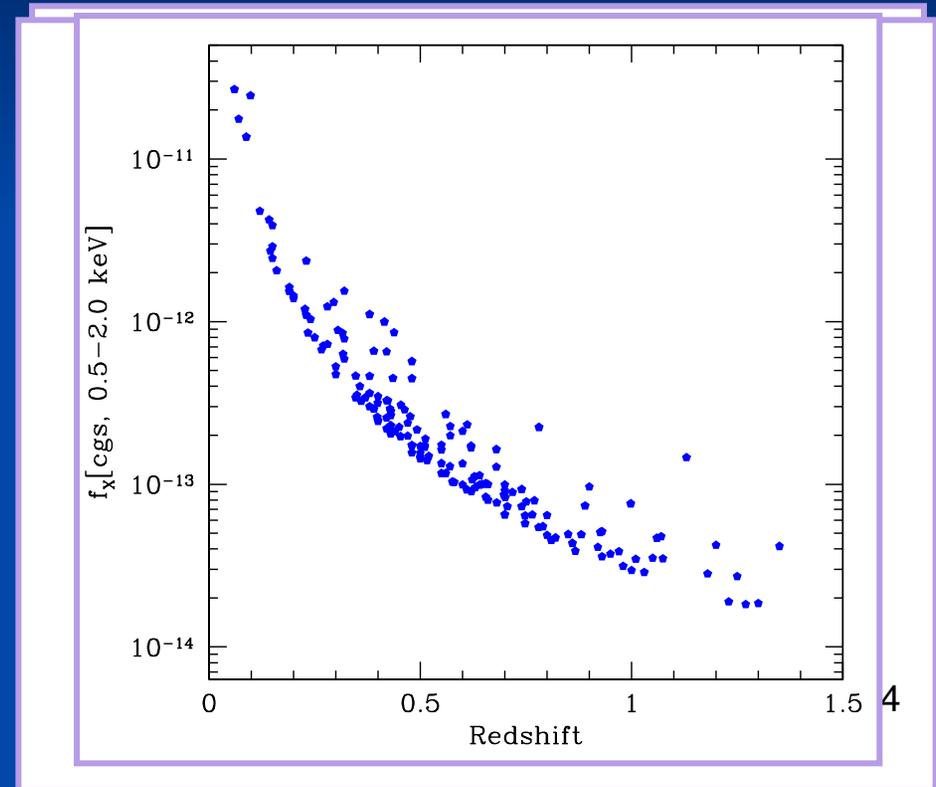
Year	Candidates >5 $\sigma$	Followed Up >5 $\sigma$	Candidates >4.5 $\sigma$	Followed Up >4.5 $\sigma$
2008	22	22	40	40
2009	98	98	184	184
2010	172	122	259	>153
2011	--	--	--	~100
Total:	455	242	777	>490

- 2011 has been similar to 2010, so in full sample we expect:
  - ~450 clusters at >5 $\sigma$  and ~600 clusters at >4.5 $\sigma$  over 2500 deg<sup>2</sup>



# Characteristics of SPT Cluster Sample from 750deg<sup>2</sup> Followup-Complete Region

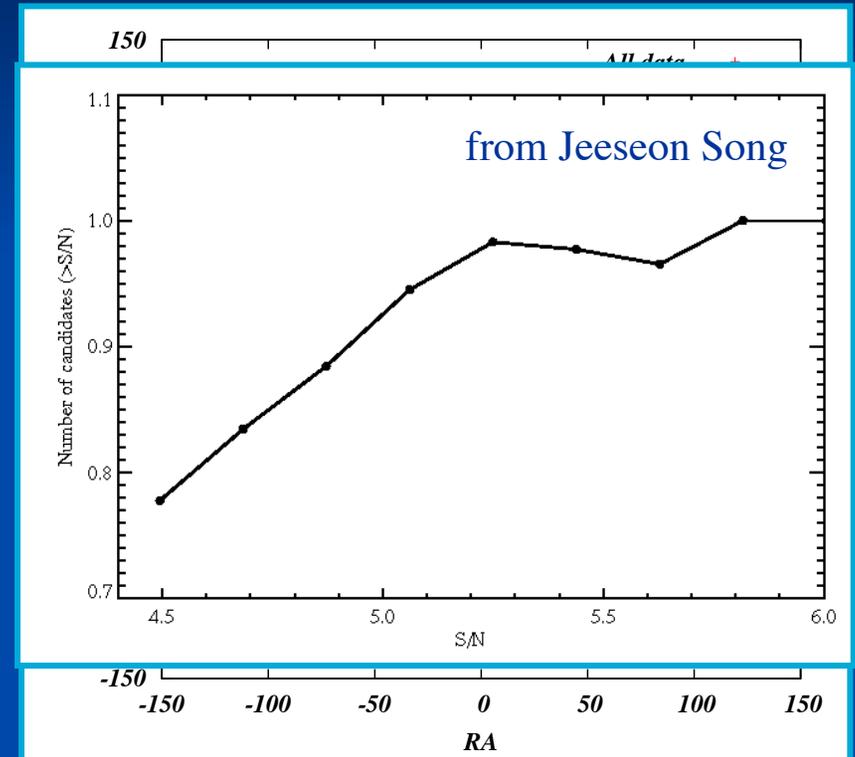
- 171 clusters S/N>4.5
- Mean redshift is  $\sim 0.55$
- $\sim 20\%$  of sample is at  $z > 0.8$
- Mass selection is approx  $M_{500} > 3 \times 10^{14}$  (Andersson et al 2011)
- With 2500 deg<sup>2</sup> solid angle the SPT survey provides unique window on rare, high mass clusters at any redshift!





# Characteristics of SPT Cluster Sample from 750deg<sup>2</sup> Followup-Complete Region

- Offsets between SPT candidate position and Brightest Red Cluster Galaxy
- Contamination
  - Filtered CMB maps exhibit Gaussian noise. Easy to calculate sky density of noise peaks at  $>4.5\sigma$ ,  $>5\sigma$
  - Together with cluster S/N distribution one can estimate contamination fraction
  - Sims:  $<5\%$  ( $S/N>5$ ),  $\sim 20\%$  ( $S/N>4.5$ )
  - Measurements  $\rightarrow$  agree

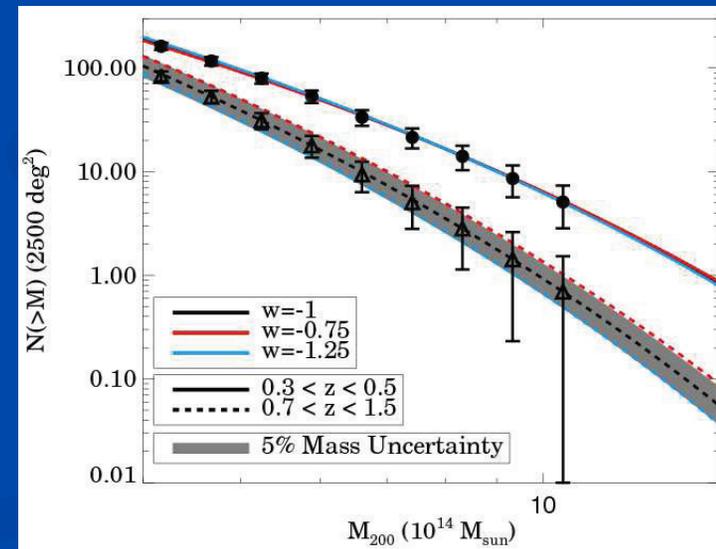
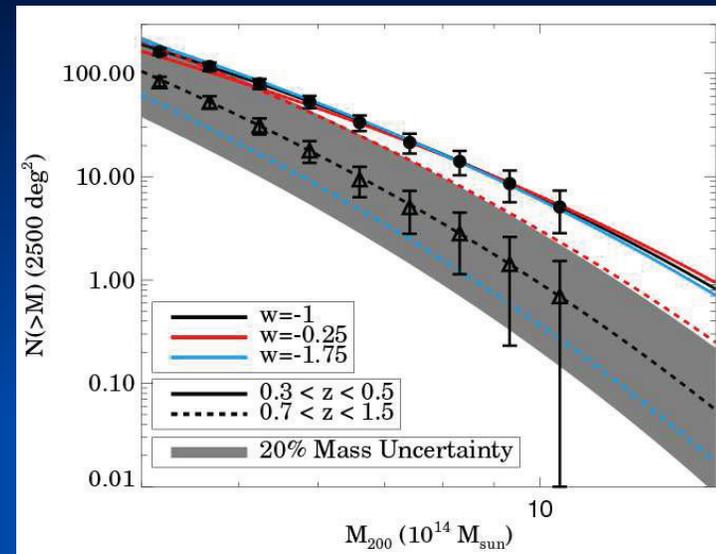


*SPT-only* selection produces  $>95\%$  pure sample at  $S/N>5$   
*SPT+optical* followup produces  $\sim 100\%$  pure sample at  $S/N>4.5$



# Implications for Cosmology

- The final cluster sample can now be reliably estimated
- To take advantage of the  $\sim 600$  cluster sample, we need to push the mass calibration below the 5% level
  - Redshift evolution
  - Full S/N range
- Multi-wavelength approach
  - X-ray: leverage existing calibrations (secondary cal)
  - Weak lensing: direct cal
  - Velocity dispersions: direct cal





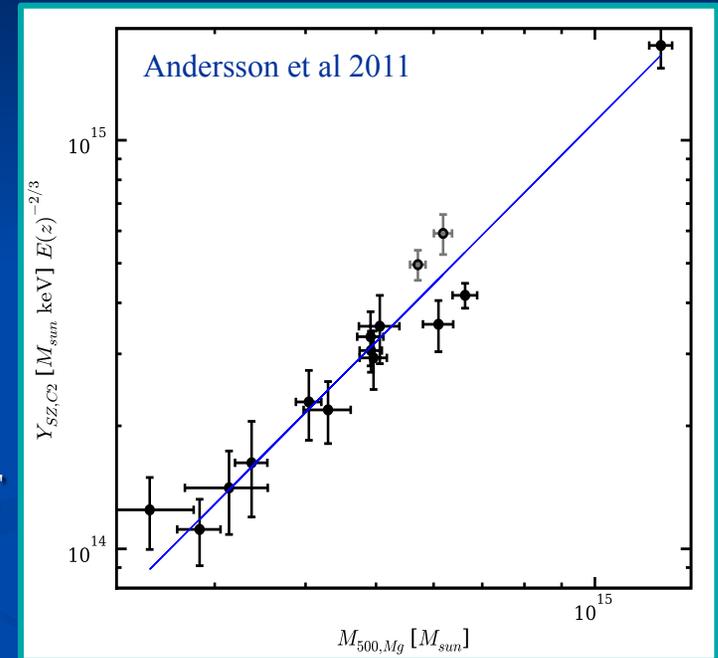
# Initial Cluster Mass Calibration

- Gravitational collapse leads to  $T_x/Y_x/M_{\text{icm}}$ -mass relations

- X-ray mass-obs relation well studied nearby
- Low scatter ( $\sim 10\%$ ), complex systematics
- Strategy:
  - Obtain  $\sim 2000$  source photons to enable  $Y_x$ ,  $T_x$  and  $M_{\text{icm}}$  mass estimates
  - Use published calibration of mass-obs relations
  - Note: extrapolate from nearby calibration

- Status

- Chandra/XMM obs of complete sample of 15 SPT selected clusters indicate cluster masses should be  $\sim 25\%$  higher (Andersson et al 2011)



## Future Data:

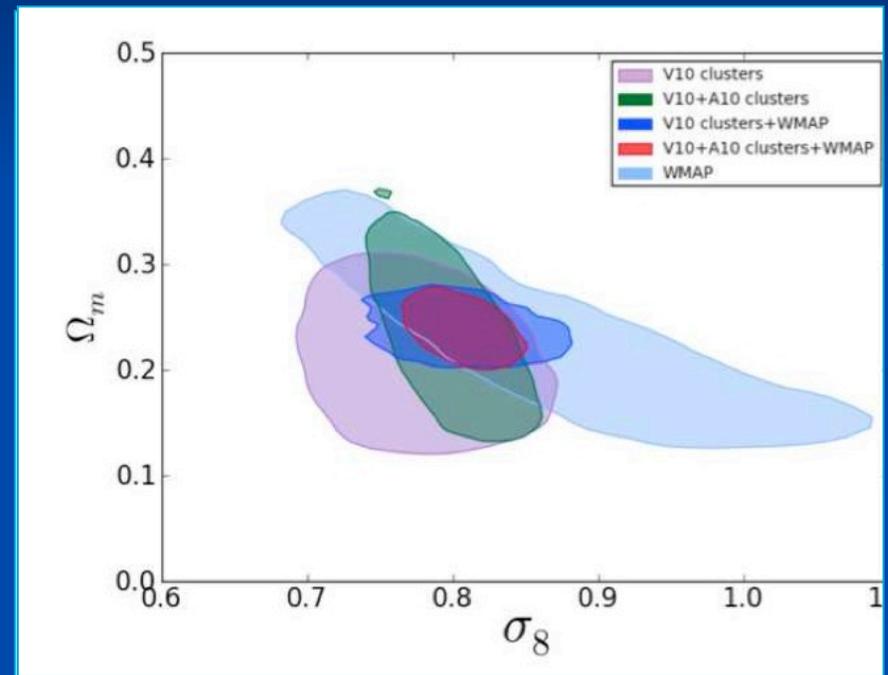
- XMM observations of 9 high- $z$  systems ( $z > 0.8$ ) *accepted*
- Chandra X-ray Visionary Program *accepted* to complete observations of 80 most massive systems ( $S/N > 6.9$ ) over full  $2500 \text{deg}^2$  survey.



# Preliminary Cosmology Results (including X-ray Mass Calibration)

- Using A11 mass calibration, Benson et al reanalyze sample of 21 clusters within initial 178deg<sup>2</sup> survey
- Initial X-ray mass cal tightens constraints
- Results in good agreement with previous cluster constraints (Mantz et al, Vikhlinin et al)

Benson et al 2011

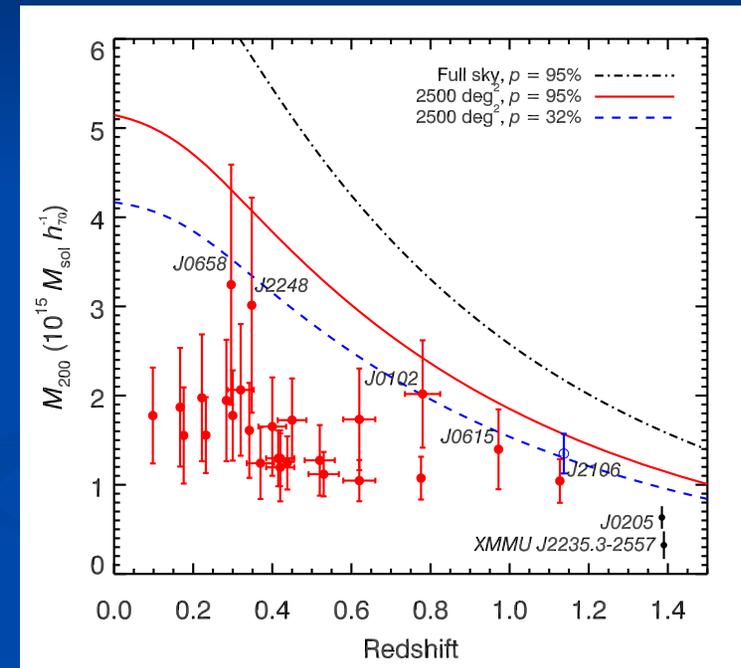




# Rarest, Most Massive Clusters

- About a year ago SPT finished shallow “preview” scans of the full  $2500\text{deg}^2$ 
  - Adequate to select the 26 most massive clusters, independent of redshift
- Mortonson analysis suggests no single cluster in tension with  $\Lambda\text{CMD}$
- Constraints on non-Gaussianity parameter  $f_{\text{NL}}=20+/-450$  from Likelihood analysis over full sample

Williamson et al 2011



# Summary

- SPT cluster survey to  $18 \mu\text{K-arcmin}$  over  $2500 \text{ deg}^2$  drawing to a close
- Optical/NIR followup effort to measure redshifts and remove contamination will wind down over the next year
  - Final sample will be  $\sim 400$  clusters at  $S/N > 5$ ,  $\sim 600$  clusters at  $S/N > 4.5$
  - SPT-only selection has low contamination ( $\sim 5\%$  at  $S/N > 5$ ,  $\sim 20\%$  at  $S/N > 4.5$ )
  - SPT+optical followup sample has extremely high purity ( $\sim 100\%$ )
- Cosmology
  - Uniform selection with mass ( $\sim$ independent of redshift) over large solid angle – opens new window on rare, massive clusters at high  $z$
  - Initial cosmology tests with small sample promising
  - Next test is with sample of 171 (2008+2009 sample)
- Mass calibration effort using X-ray, dispersions and weak lensing underway

