
# Status Report on the South Pole Telescope Survey

Dark Energy Survey


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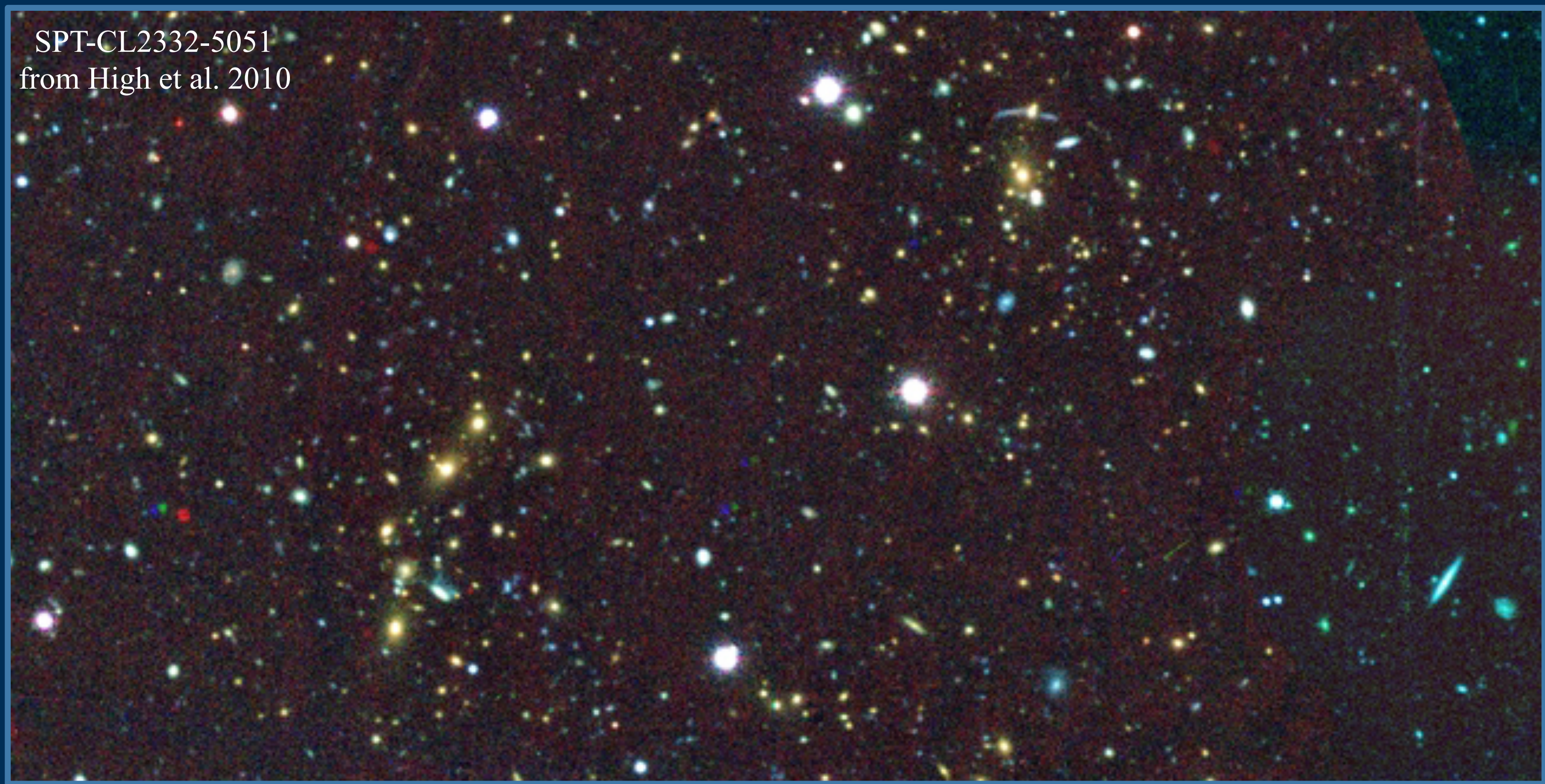


# Galaxy Cluster Redshift Distribution is Sensitive to the Dark Energy Equation of State

- Cluster surveys provide
  - Redshift distribution
  - Luminosity (mass) function
  - Cluster power spectrum
  - Direct mass calibration

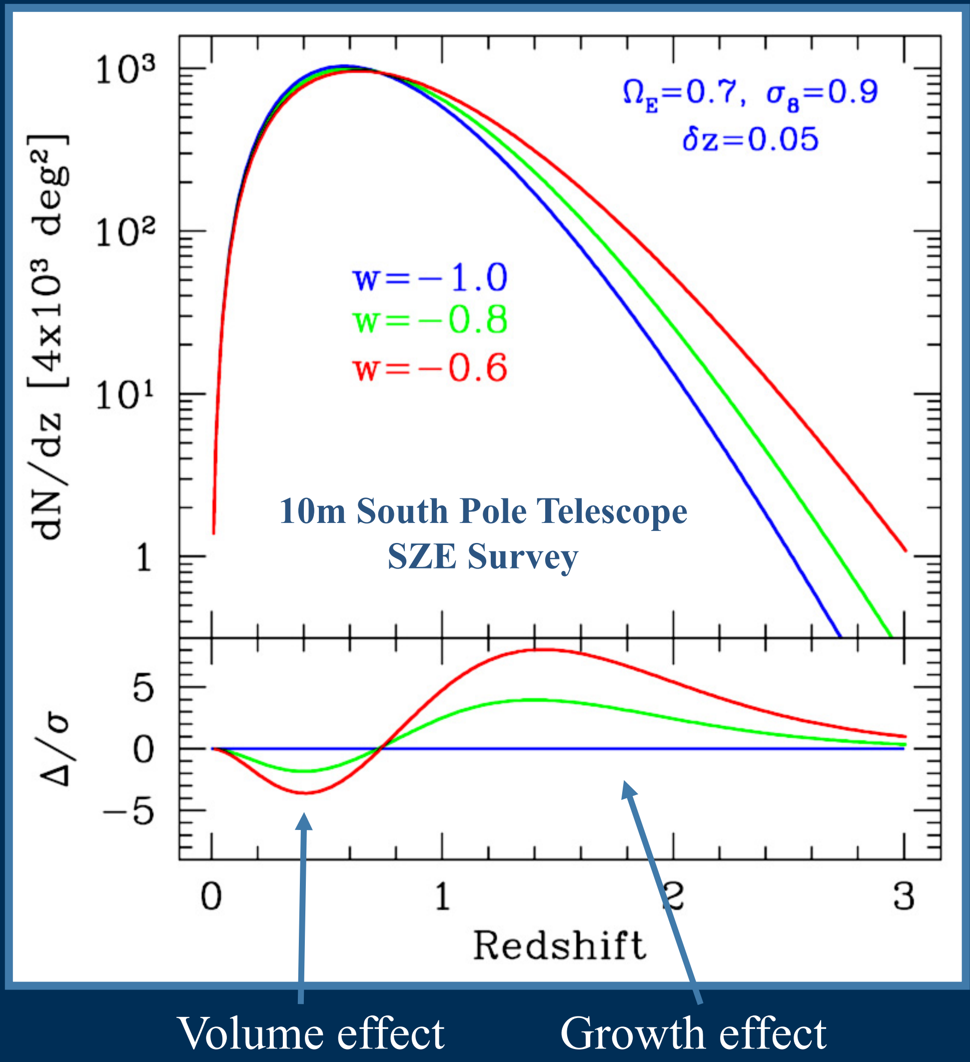
- Each has different cosmological dependence-- very rich dataset

$$\frac{dN(z)}{dz\,d\Omega} = \frac{dV}{dz\,d\Omega}\,n(z)$$

**w** dependency:

Raising **w** at fixed $\Omega_E$:

- Decreases volume surveyed
- Decreases growth rate of density perturbations



# Surveys Measure Cosmic Expansion History *H(z)*

Expansion history reflects changing energy density of universe

$$H(z) = \sqrt{\frac{8\pi G}{3}\rho(z)}$$

## Through the *distance- redshift relation*

Redshift distribution depends on volume {dN/dz=dV/dz*n(z)}
Cluster power spectrum provides standard rods for distances
Direct mass measurements depend on distances

$$d_A(z) \propto \int_0^z \frac{dz'}{H(z')}$$

## Through *growth rate of cosmic structures*

Linear growth of density perturbations is sensitive to H(z) and to the dark matter density
Number density (abundance) of clusters is exponentially sensitive to this growth rate

$$\ddot{\delta} + 2H(t)\dot{\delta} = 4\pi G\rho_o\delta$$

$$\text{where } \delta \equiv \frac{\delta\rho}{\rho_o}$$

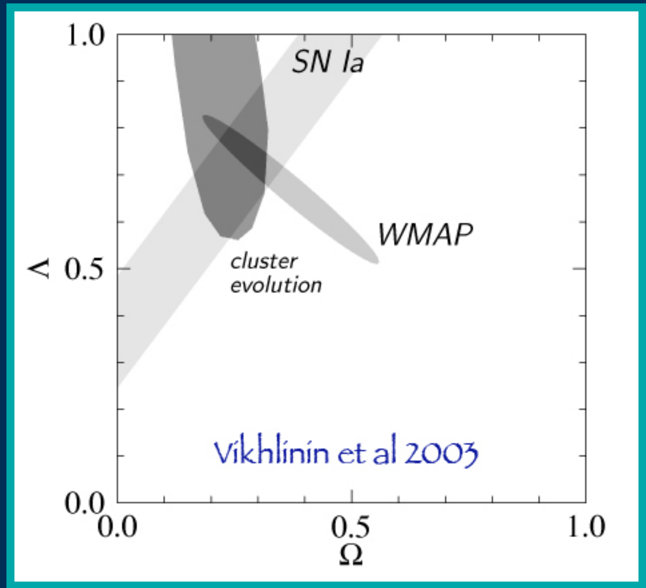
# Challenges Facing Cluster Survey Cosmology

- Primary dependencies:
  - Structure formation theory
  - Cluster selection
  - Cluster masses

- Variety of tools:
  - Simulations with ever more physics
  - Model selection – compare across different wavelengths
  - Direct mass calibration with weak lensing, velocity dispersions and X-ray observations
  - Self-calibration of masses with large enough samples

# Cluster Surveys Directed at Studies of Dark Energy are Underway

- Archival ROSAT Survey Work
  - 18 clusters: Dark energy detected!
  - 37 clusters: EOS param measured
- Optical surveys return
  - RCS (Gladders et al)
  - SDSS (Rozo et al)
- Toward Precision Cosmology… ?




ROSAT 160d survey yields 2σ detection of Λ

Uses: 50 local clusters (shape of mass function) and + 18 z~0.55 clusters (evolution of mass function)

# Recent Results from X-ray Surveys

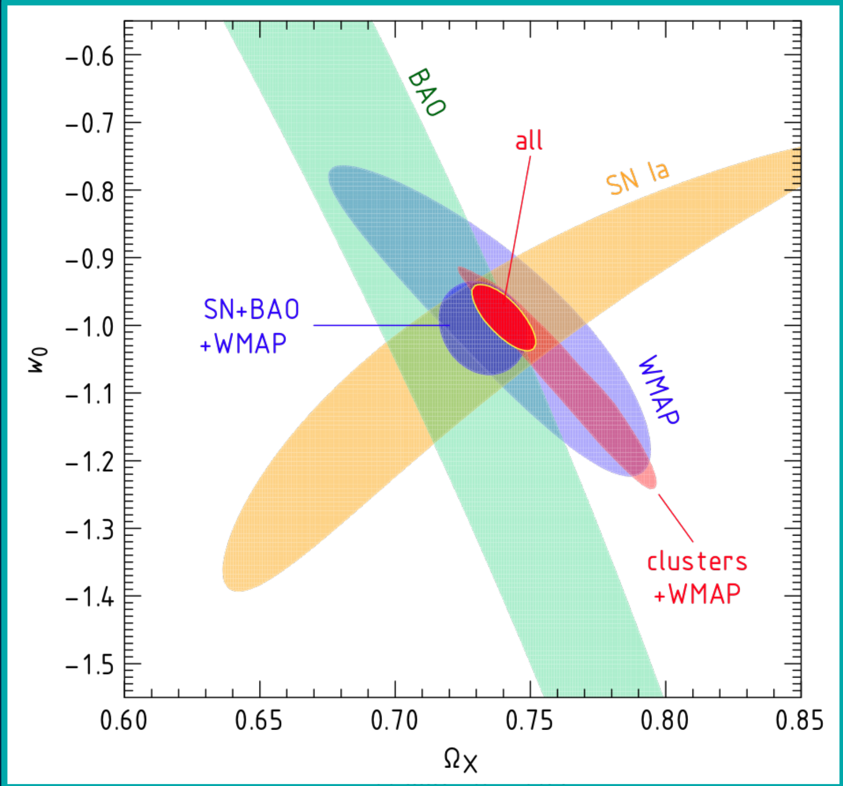
- Vikhlinin et al 2009:
  - Sample:
    - 49 “local” clusters discovered pre-ROSAT- “Edge sample”
    - 37 clusters from 400d ROSAT pointed survey at z>0.35
  - Mass estimates come from Chandra observations: $Y_x$

- Mantz et al 2010:
  - Sample:
    - 238 clusters from the ROSAT All Sky Survey at z<0.5 for mass function
    - Use $M_{ICM}$ as proxy for mass (assume constant $f_{ICM}$)
    - 42 “relaxed” clusters with direct $f_{ICM}$ measurements used

# 400d ROSAT Sample Overview

Vikhlinin et al 2009

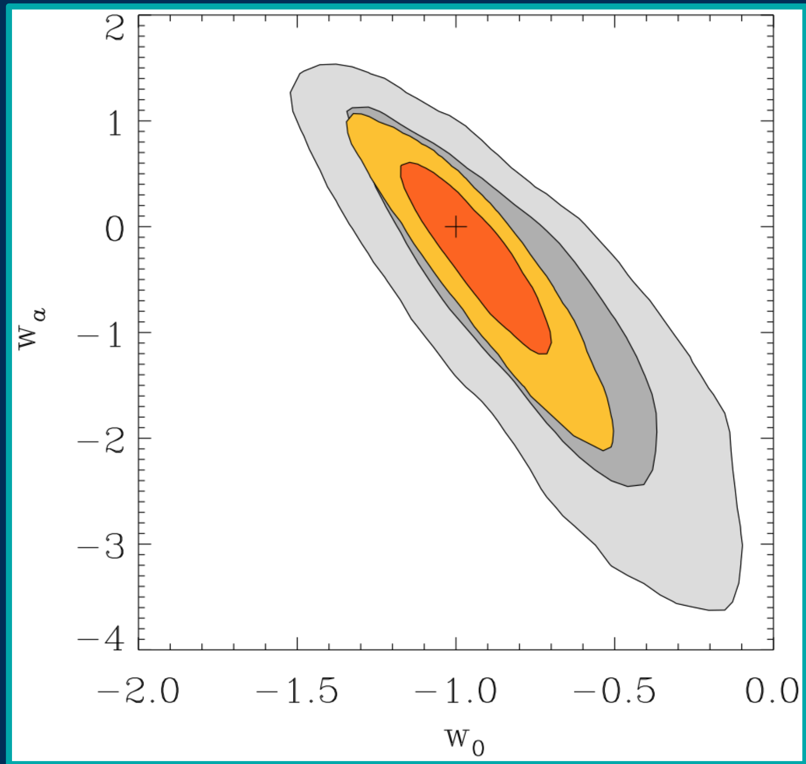
- Analysis:
  - 49 “local” + 37 z>0.35 clusters
  - Mass functions
  - 12 clusters at z>0.55 require Lambda
  - Independent constraints in good agreement with WMAP+ cosmology
  - w constrained to 0.2(clus)/0.05(all)



# ROSAT All Sky Survey Sample

## Mantz et al 2009

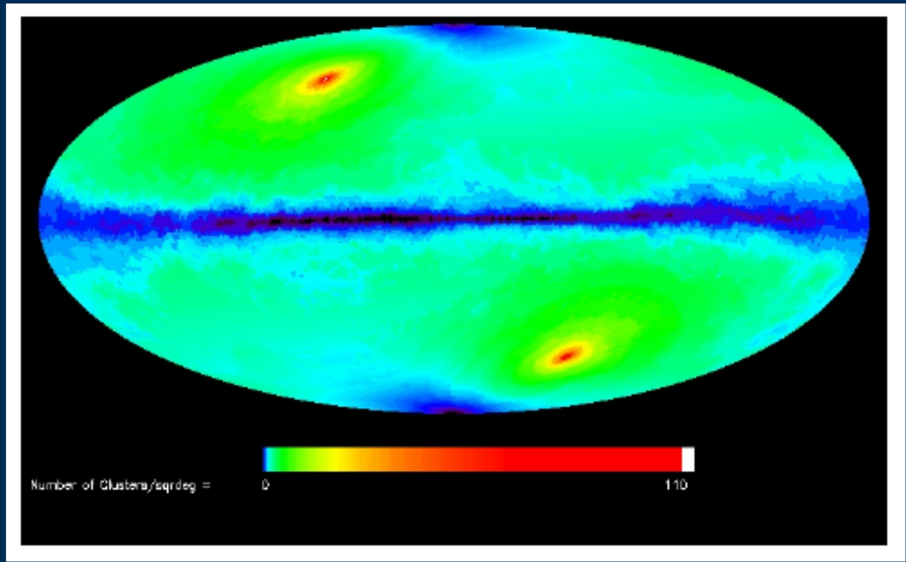
- Analysis:
  - Mass function of full sample
  - Constant $f_{ICM}$ from 42 "relaxed" systems
  - Mass-obs relation normalization freedom allowed and constrained using 6 low z clusters



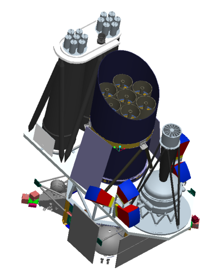

- Independent constraints
  - $\sigma_8$ = 0.82 (0.05)
  - w=-1.01 (0.20)
- Combined constraints
  - WMAP+Sne+BAO+Clusters+$f_{ICM}$:
    - $\sigma_8$ = 0.79 (0.03)
    - w=-0.96 (0.06)
  - DETF FOM =15.5 (~2x improvement)
    - $w_o$=-0.93 (0.16), $w_a$=-0.16 (+0.47,-0.73)

# What's on the Horizon?

- Cosmology with the first SZE surveys
- Studies of XMM serendipitous samples extending beyond z=1
  - XDCP (Faßbender et al)
- $10^3$–$10^4$ $deg^2$ deep optical surveys
  - RCS2, Pan-STARRs, DES, HSC
- $10^5$ X-ray selected clusters
  - e-ROSITA all sky survey = 2013+




Deep X-ray, SZE, multiband optical/NIR Imaging over much of the extragalactic sky



# eROSITA, All Sky X-ray Survey

***extended ROentgen Survey with an Imaging Telescope Array***
***Main Instrument on Spektr-RG (2012-2015)***

## PI: Peter Predehl

**Co-Is:** Hans Böhringer, Ulrich Briel, Hermann Brunner, Evgeniy Churazov, Michael Freyberg, Peter Friedrich, **Günther Hasinger**, Eckhard Kendziorra, Dieter Lutz, Norbert Meidinger, Joe Mohr, Mikhail Pavlinsky, Andrea Santangelo, Jürgen Schmitt, Axel Schwope, Matthias Steinmetz, Lothar Strüder, Rashid Sunyaev, Jörn Wilms

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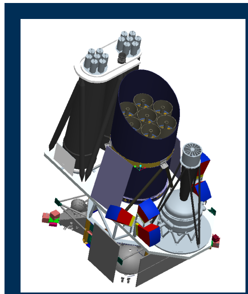
**Product Assurance:** H. Bräuninger, M. Hengmith
**Electronics Engineering:** W. Bornemann, O. Hälker, S. Hermann, W. Kink, S. Müller, Th. Schanz, O. Hans
**Mechanical Engineering:** H. Huber, Chr. Rohé, L. Tiedemann, R. Schreib, B. Mican, K. Lehmann, H. Eibl, F. Huber, R. Sandmair
**Mirror System, PANTER:** P. Friedrich, W. Burkert, M. Freyberg, B. Budau, V. Burwitz
**Cooling, Thermal Engineering:** M. Fürmetz
**CCD-Camera:** N. Meidinger, Robert Hartmann, E. Pfeffermann, G. Schächner, J. Elbs, S. Ebermayer
**Attitude:** A. Schwope
**Calibration, Analysis:** G. Hartner, K. Misaki, U. Briel, K. Dennerl, R. Andritschke, Chr. Tenzer
**Laboratory, Tests:** M. Vongehr, L. Hirschinger, K. Dittrich, F. Schrey
**Ground Software, Simulation**: H. Brunner, N. Cappelluti, G. Lamer, M. Mühlegger, J. Wilms, I. Kreykenbohm, Chr. Schmid
**Mission Planning:** J. Schmitt, J. Robrade

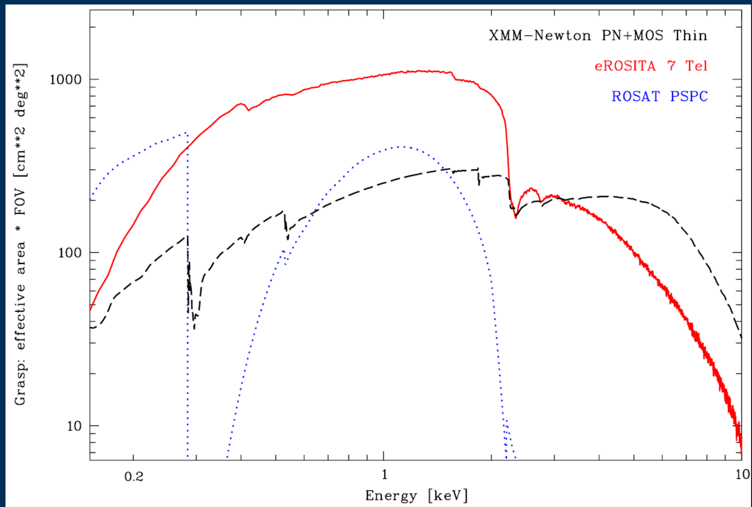
**Institutes:**
Max-Planck-Institut für extraterrestrische Physik, Garching/D
Space Research Institute IKI, Moscow/Ru
Univ. Tübingen/D
Univ. Hamburg/D
Univ. Erlangen-Nürnberg/D
Astrophysikalisches Institut Potsdam/D
Max-Planck-Institut für Astrophysik/D

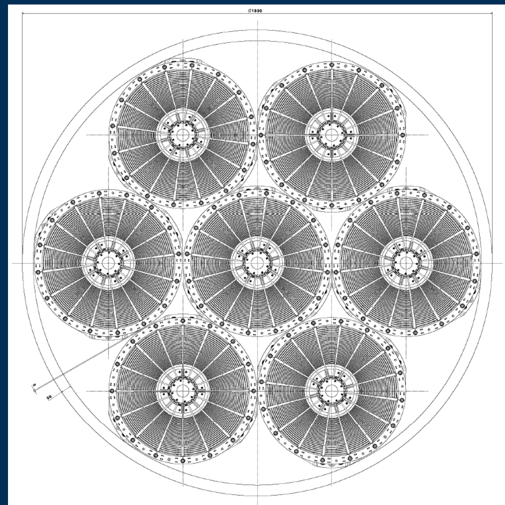
**Industry:**

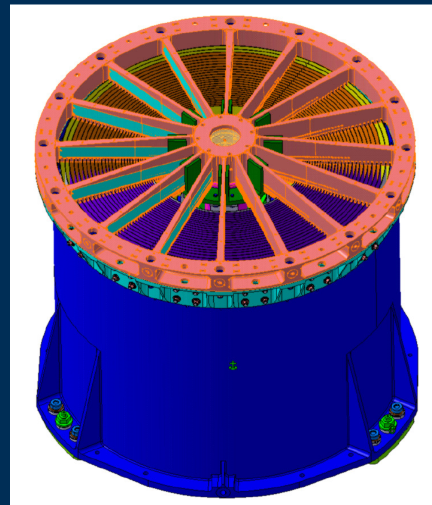
| | |
|---|---|
| Kayser-Threde/D | Mirror System |
| Media Lario/I | Mirror Modules |
| Carl Zeiss/D | Mirror Mandrels |
| Invent/D | Telescope Structure |
| pnSensor/D | CCDs |
| … | |



# *e-ROSITA Mirror System*



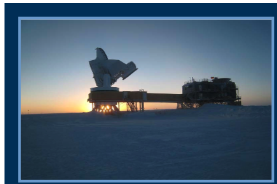





- 7 Mirror Modules, 54 shells each
- 350 cm$^2$ each (totals 2 x XMM-Newton)
- 1 degree diameter FOV
- Good angular resolution – 16 arcsec HPD
- Four year nominal mission
- Characteristic flux limit is ~$10^{-14}$ erg/s/cm$^2$
  (~60X deeper than ROSAT w/ CCD spectroscopy)

# Important Context for eROSITA

- Unlike ROSAT survey, where optical followup was done painstaking night after night, eROSITA takes place in the era of deep, multiband optical sky surveys
  - Shallow multiband OIR surveys
    - 2MASS (available, all sky)
    - SDSS (available, north)
    - Pan-STARRS1 (underway, north)
  - Deep multiband OIR surveys
    - VISTA (underway, south)
    - DES (5000 $deg^2$, 2012+, south)
    - HSC (2000 $deg^2$, 2012+, north)
  - Next generation surveys
    - LSST, Euclid, and WFIRST



# SPT Operating at the Pole

- Feb 16, 2007 SPT first light
- Science survey began May 2007 and will continue to Nov 2011
- Deep, arcminute resolution maps now "routinely" produced
- 1st SZE selected clusters: July 2008

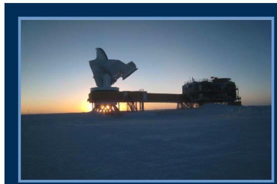
March 24, 2007

South Pole Telescope

Picture by Steve Padin on June 10, 2007

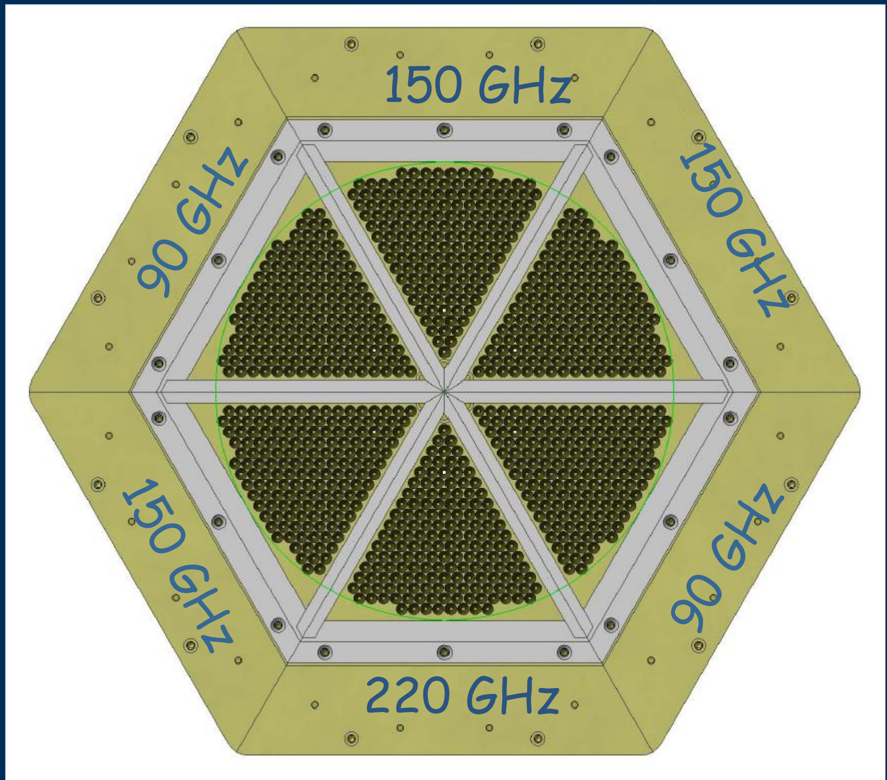
http://spt.uchicago.edu

# South Pole Telescope

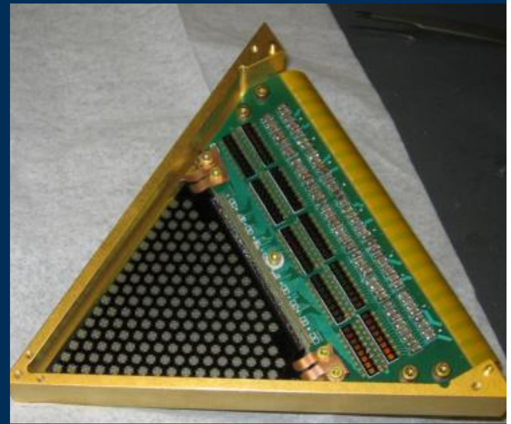


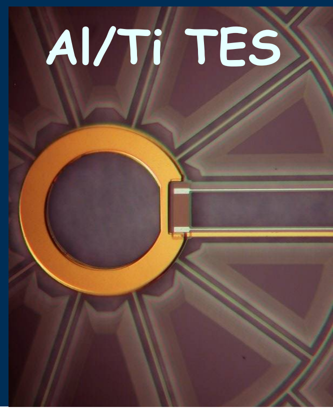
# The SPT Detector Array

180 mm; ~1 degree on sky



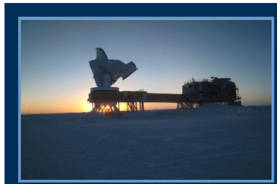

Built at UC Berkeley







- 160 possible channels on each wedge, 8x multiplex
- Transition Edge Sensor bolometers with Tc ~500mK



# 10m South Pole Telescope
# + 960 Element Bolometer Array

**Low noise, precision telescope**

- 20 um rms surface over 10m
- 1 arcsecond pointing
- 1 arcmin resolution at 2 mm
- scan entire telescope
- 3 levels of shielding
  - 1 m radius on primary
  - inner moving shields
  - outer fixed shields

**SZE and CMB Anisotropy**

- up to 5 bands (start w/3)
  **90,150, 220**, 270, 350 GHz
- **2000 sq deg SZE survey**
- deep CMB anisotropy fields
- deep CMB Polarization fields

# SPT Team at Pole

# SPT Collaboration

## John Carlstrom, PI

**Berkeley** (University of California)

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

**Berkeley Lab**

Helmuth Spieler

**Case Western Reserve University**

John Ruhl
Tom Montroy
Zak Staniszewski

**LMU / USM; Illinois**

Joe Mohr
Bob Armstrong
Gurvan Bazin
Shantanu Desai
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Jiayi Liu
Jeeseon Song
Alfredo Zenteno

**The University of Chicago**

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Clem Pryke
Wayne Hu
Andrey Kravtsov
Brad Benson
Tom Crawford
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Kathryn Miknaitis

**Colorado** (University of Colorado at Boulder)

Nils Halverson

**McGill**

Matt Dobbs
Gil Holder
Jonathan Dudley
Keith Vanderline

**Cardiff University / Prifysgol Caerdydd**

Peter Ade

**KICP** (Kavli Institute for Cosmological Physics at the University of Chicago)

Joaquin Vieira
Abbie Crites
Ryan Keisler
Lindsey Bleem
Jonathan Stricker

**JPL**

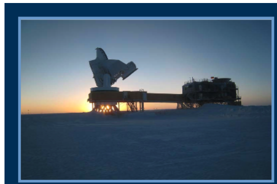
Erik Leitch

**UC Davis** (University of California)

Lloyd Knox
Jason Dick

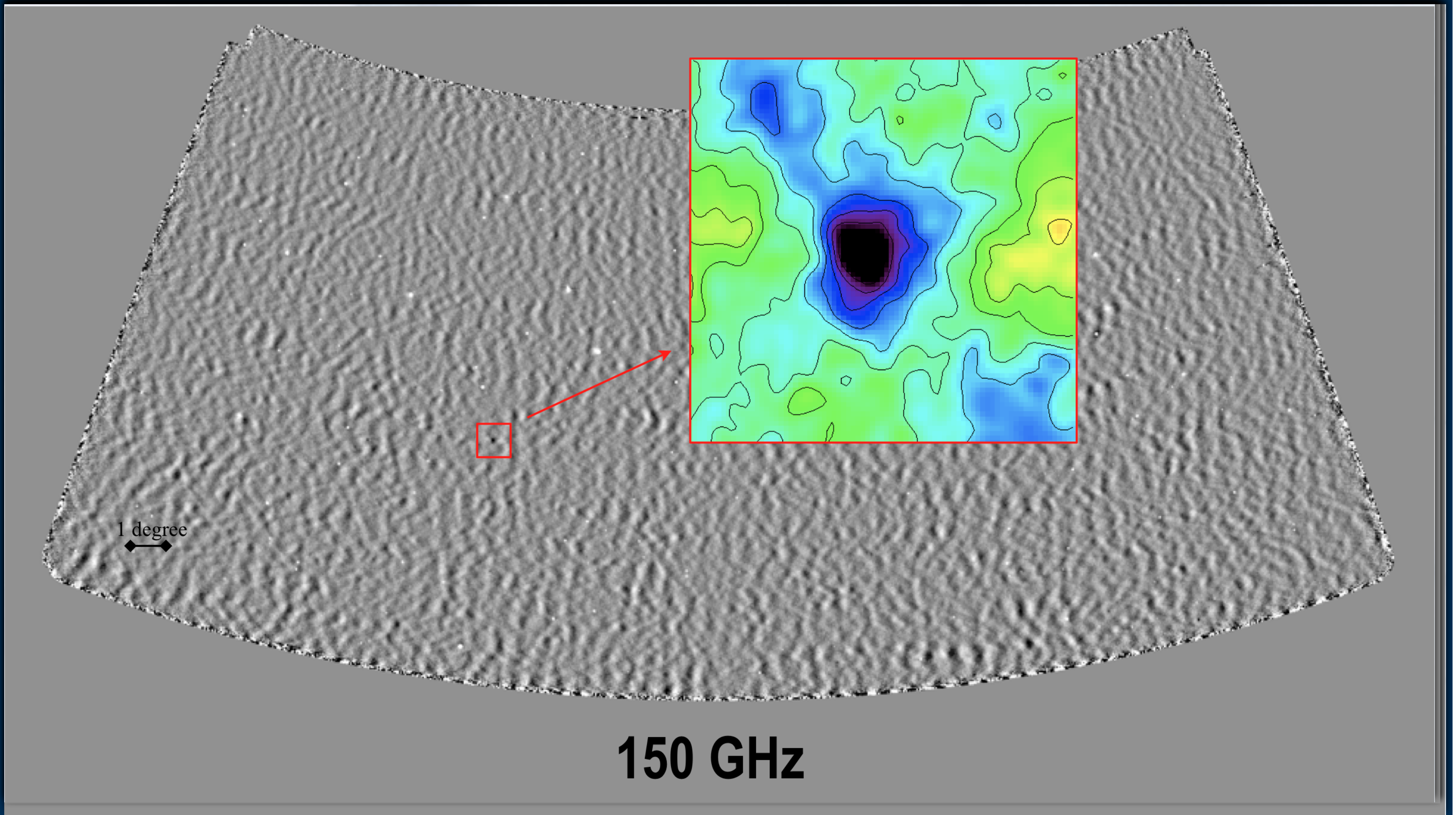
**Harvard-Smithsonian Center for Astrophysics**

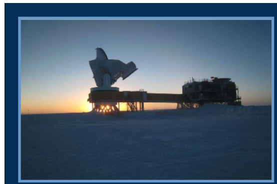
Antony Stark
Chris Stubbs
Will High
Brian Stalder
Jonathan Ruell



# SPT Multi-frequency Survey

Figures from Tom Crawford

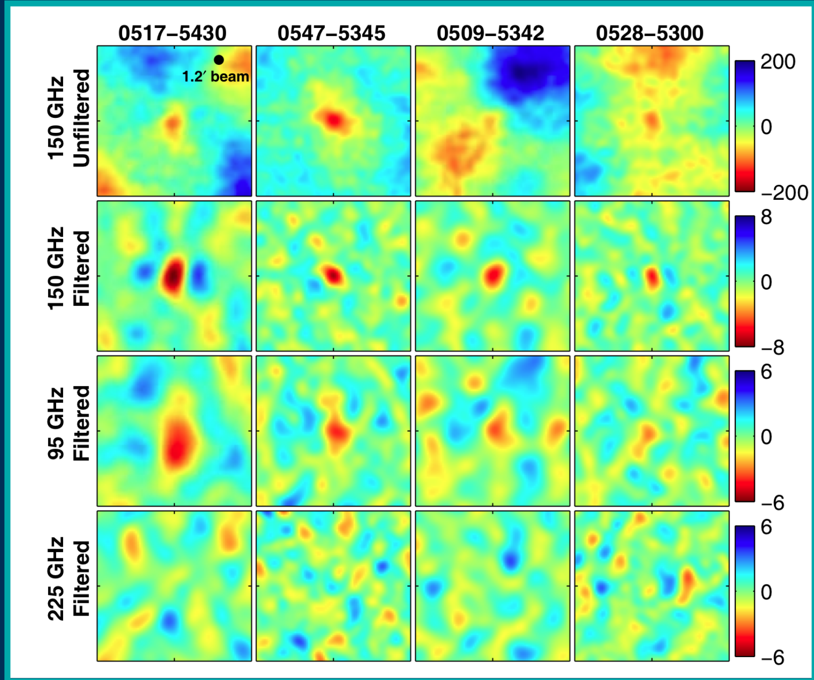




# SZE Cluster Selection Demonstrated

- Feasibility demonstrated 2008
  - First SPT cluster candidate list compared against BCS data at MPE on July 14, 2008
- SZE cluster survey
  - SZE flux closely coupled to cluster mass, independent of redshift
  - Unique spectral signature- low contamination in multifrequency surveys like those from SPT/ACT/ Planck
  - Completeness is modeled using mock observations

SPT Selected Clusters




Stanizewski et al 2009

# Coordinated Optical Observing

- 60 night survey of two 50 $deg^2$ BCS fields to allow early confirmation
  - Target depths
    - $L_*$ to z=1 for cluster galaxies
    - *g,r,i,z*=24,23.9,23.6,22.3 (10σ in 2.3 arcsec aperture)
- Now doing cluster by cluster confirmation and photo-z estimation with Blanco 4m, Magellan 6.5m and DSS+SWOPE 0.9m
- In first season Dark Energy Survey will obtain grizY observations of the entire SPT survey region

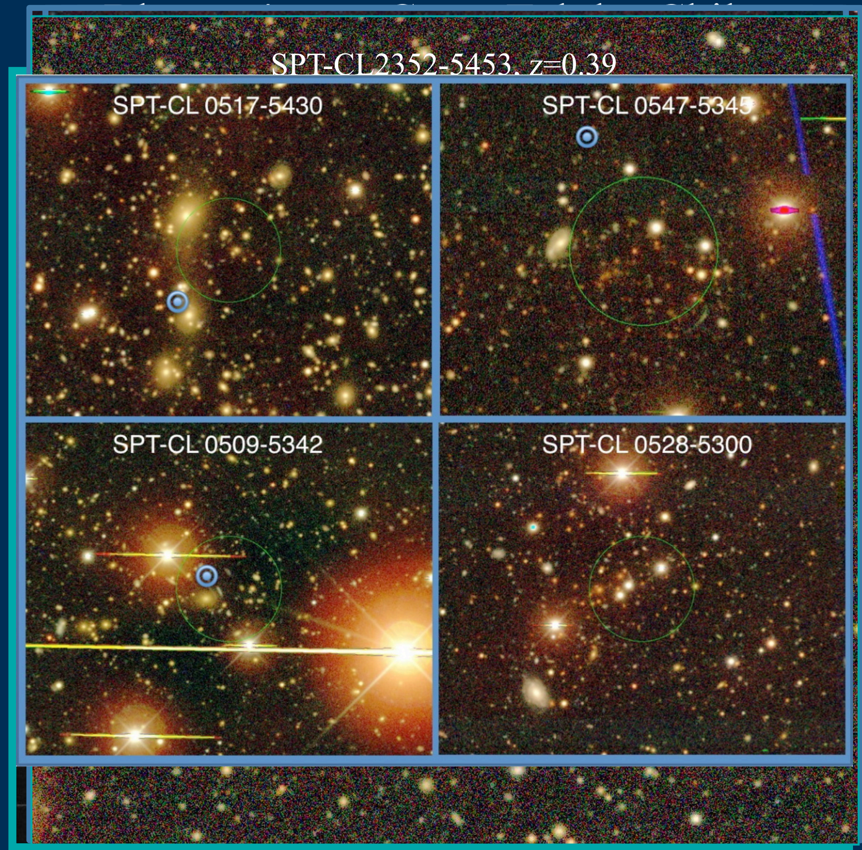
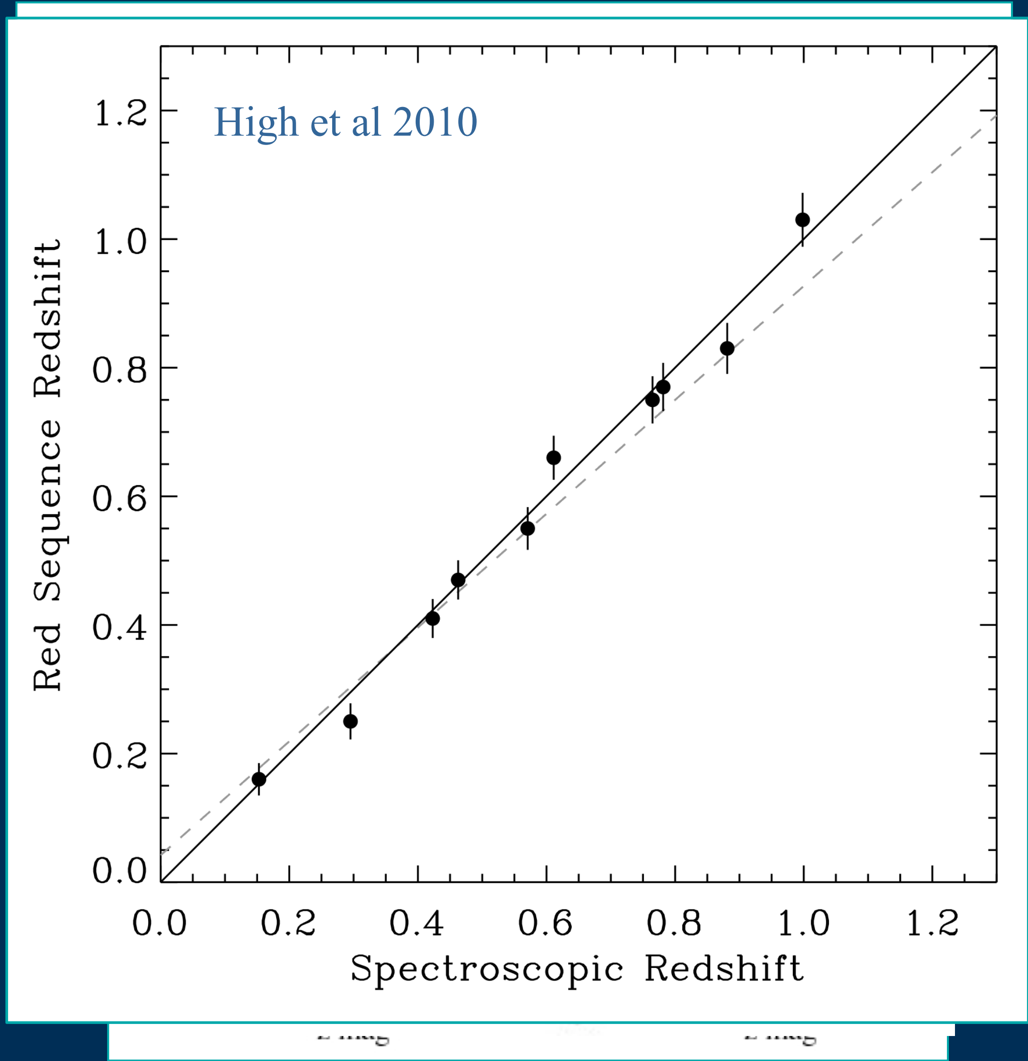
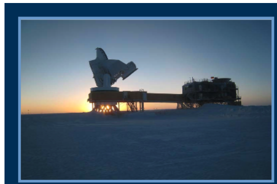



Image credit: Roger Smith/NOAO/AURA/NSF

# Confirmation and Redshifts

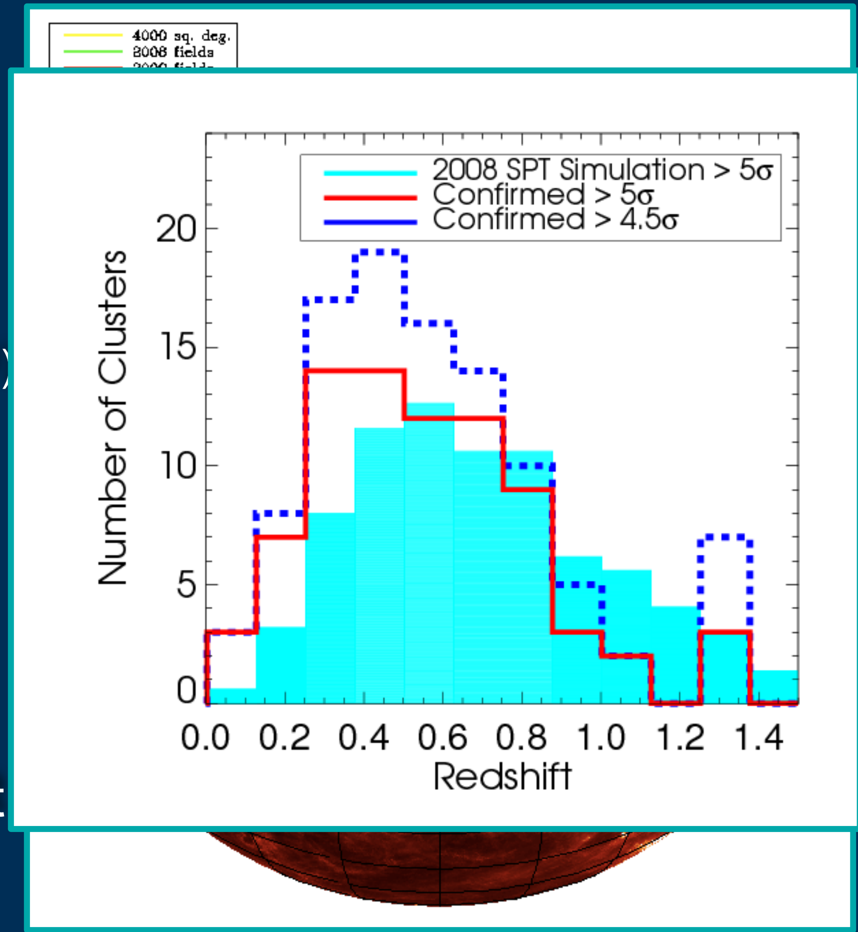
- Use red sequence overdensity to quantify *significance* of optical counterpart and to estimate redshift
- Use spectroscopy to test the redshifts
  - Comparison to SDSS sample shows small bias to z~0.65
  - 10 spec-z's in SPT sample provide direct test of BCS and Magellan photometry

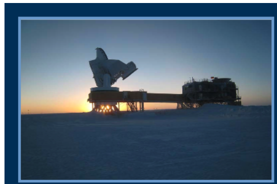




# SPT Survey Status

- Goal:  2500 deg$^2$ survey through 2011
  - 90GHz, 150GHz, 220GHz
  - ~1500 deg$^2$ completed to survey depth
  - >5σ is 0.1/deg$^2$, >4.5σ is 0.25/deg$^2$
- Cluster numbers: ~200 confirmed
  - Blanco 4m: 14 (BCS), 39 (Nov09), 36 (Jul10)
  - Magellan: 53 (2009)
  - DSS+SWOPE 0.9m: ~50 low z systems
  - Spitzer IRAC: 84 in hand, +95 targeted
- Mean redshift for sample is ~0.6
- Contamination: few% at S/N>5, 20% at S/N>4.5
- Expect to detect and measure SZE fluxes for *~500 clusters* at S/N>4.5 by end of 2011





# SPT Publications

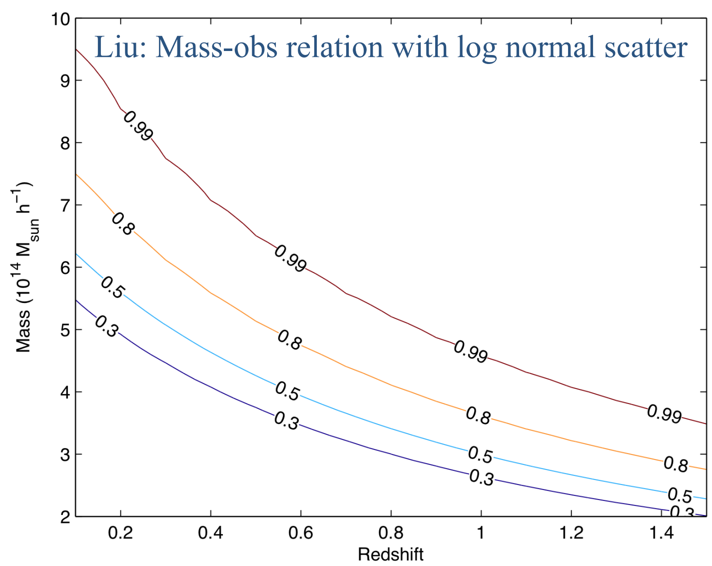
- Instrumentation:
  - Carlstrom et al 2009, Padin et al 2008, Ruhl et al 2005
- 1st SZE selected clusters:
  - Staniszewski et al 2009, ApJ 701, 32
- Point Sources:
  - Vieira et al 2010 ApJ, 719, 763, Hall et al 2010 ApJ, 718, 632
- High l power spectrum:
  - Lueker et al 2010 ApJ 719, 1045
- SZE Properties of 15 known clusters:
  - Plagge et al 2010, ApJ, 716, 1118
- 2008 SPT Cluster Catalog Paper of 21 >5$\sigma$ systems
  - Vanderlinde et al 2010, ApJ in press, High et al 2010, ApJ submitted
- Chandra and XMM X-ray Analysis of 15 systems
  - Andersson et al 2010, ApJ, submitted
- Velocity Dispersion of Massive z>1 Cluster
  - Brodwin et al 2010, ApJ in press

# SPT: What have we learned to date?

- SPT survey provides simple and clean selection by mass at $z>0.2$
- SPT depth is appropriate to cleanly select massive systems ($M_{500}>3x10^{14}$) at any redshift
- SPT mass sensitivity and large solid angle survey is opening a new window on massive clusters at $z>1$

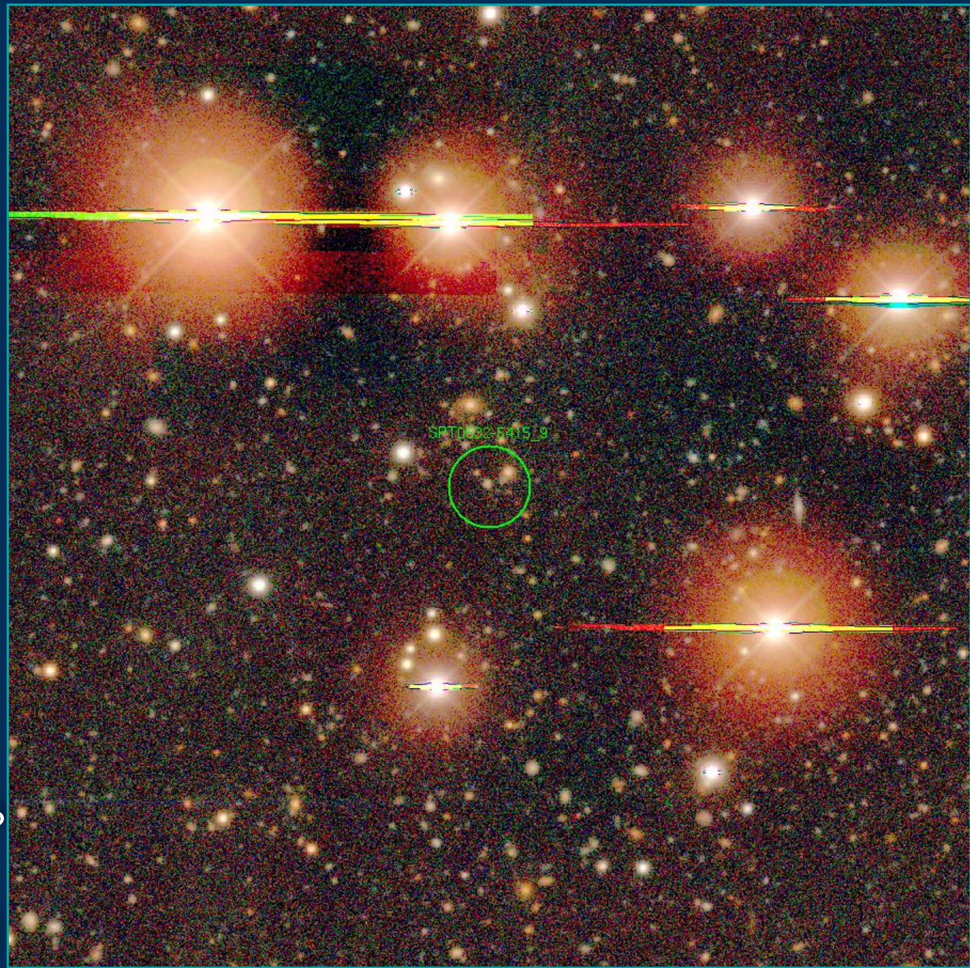
# Modeling selection

- Model cluster selection using mock observations
  - Vanderline et al 2010:  Characterize clusters using “toy model” (Bode et al) calibrated using local cluster X-ray scaling relations
  - Modeling using state of the art hydro simulations (Dolag et al) underway
- Results:  selection well approximated by simple mass-S/N relation with 30% scatter (20% intrinsic, 20% statistical)

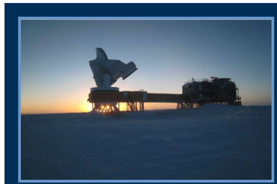


# Impact of AGN

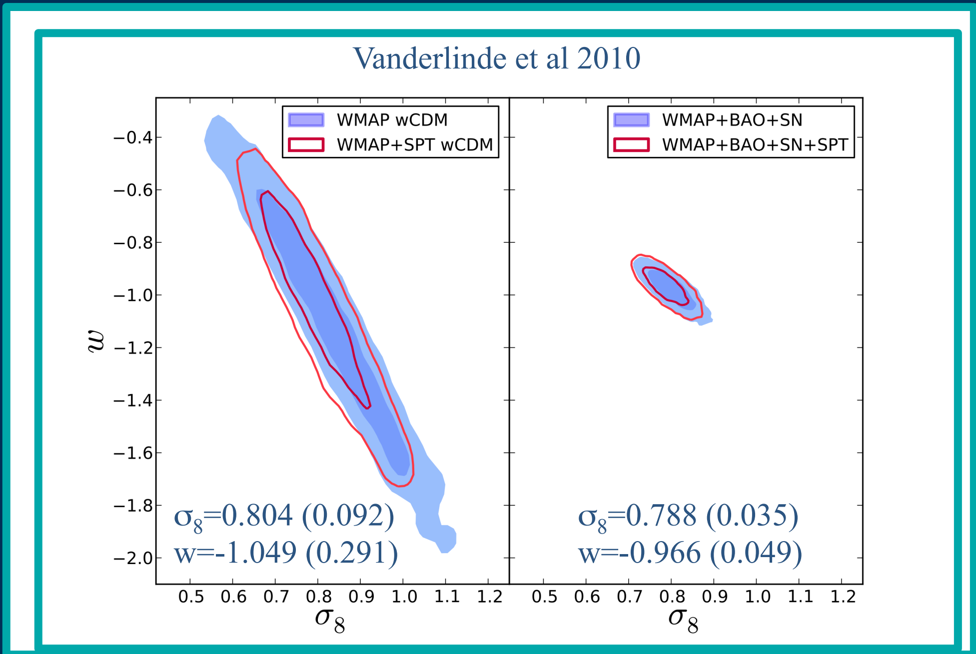
- Source counts:
  - AGN 1/$deg^2$
  - Clusters 0.1 to 0.25/$deg^2$
  - Random superposition probability low (easy to model)
- Cluster AGN expected to impact few % of systems
- Test using SPT AGN sample over BCS survey region
  - Is cluster present?
  - Would cluster have been massive enough for us to have seen it?
  - Evidence of cluster component in SZE?
- Sample of 39 AGN examined- and no problem cluster found
  - Good statistics requires SPT+DES



# Initial Cosmological Analysis: 21 SPT S/N>5 systems from 2008 fields



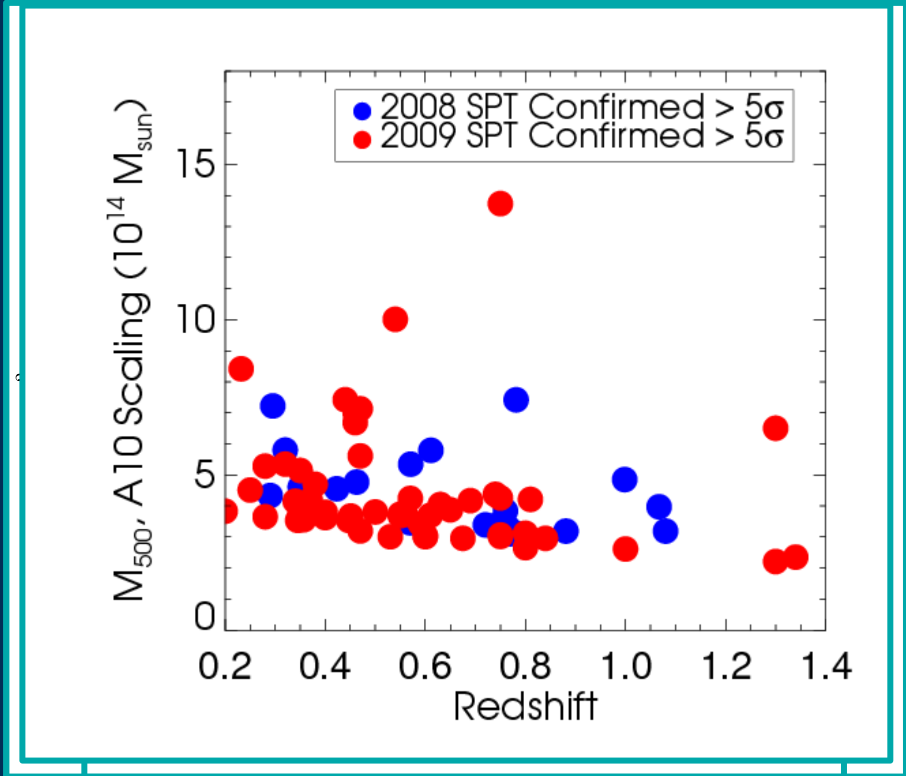
- 21 SPT S/N>5 systems from 2008
  - Taken from 170 $deg^2$ – the first two fields in 23hr and 5hr
  - Highest S/N subset – low contamination in SZE-only selection
- Cosmological implications: (using 30% mass priors)
  - Provides some additional leverage on $\sigma_8$ (in combo with WMAP+)
  - No evidence of tension with WMAP+ in SPT only analysis

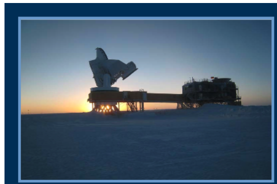


# Initial X-ray Mass Characterization

Andersson et al 2010

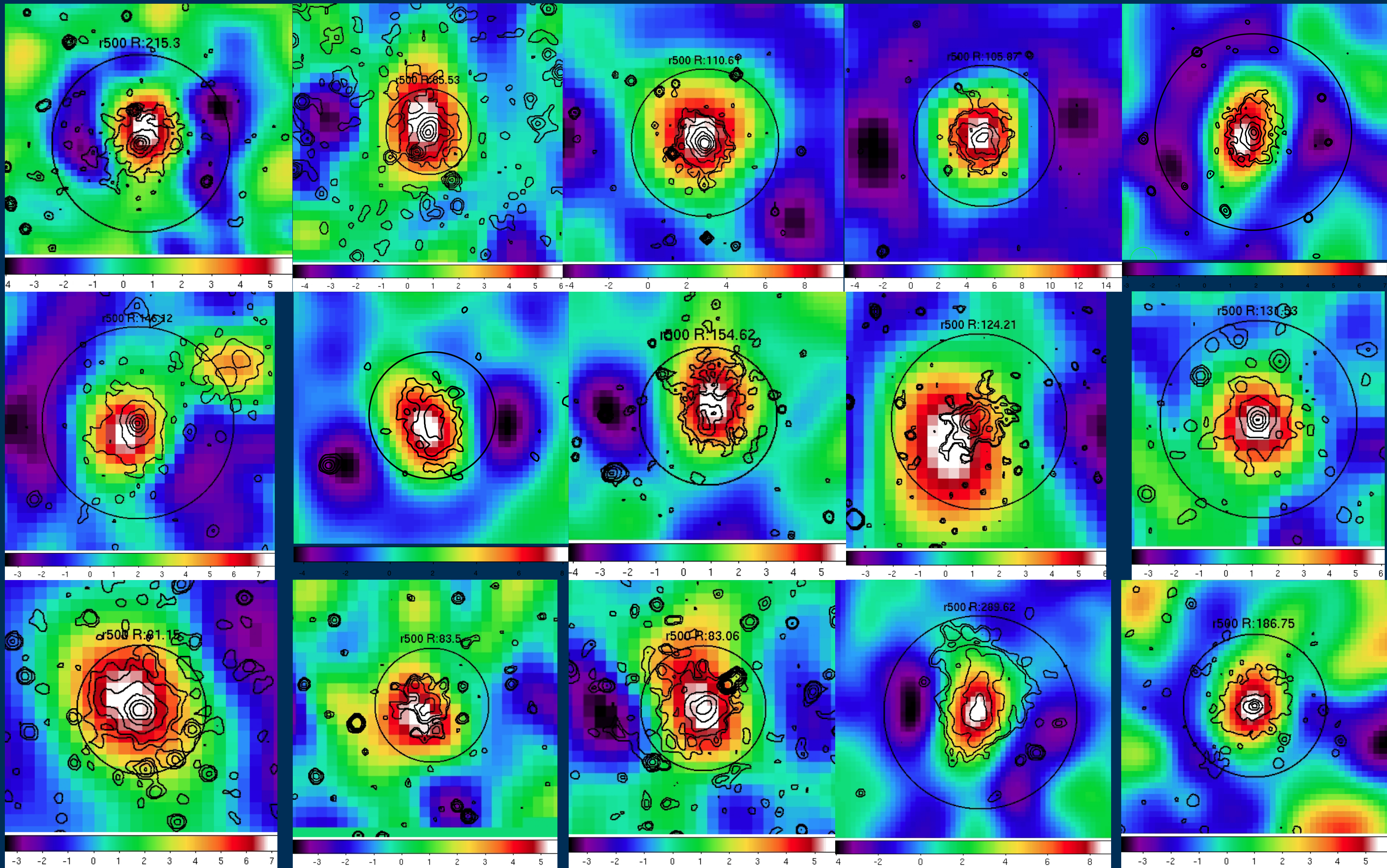
- Chandra+XMM data on 15 clusters provide mass constraints to calibrate SPT mass-obs relation
- Goal: target highest mass (highest $L_x$) systems for 1500 photons to measure $M_{icm}$, $T_x$ and $Y_x$
- Currently this is the best information available on the masses of our systems

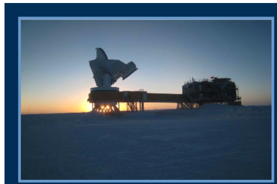




# X-ray-SZE Rogues Gallery

## Andersson et al 2010

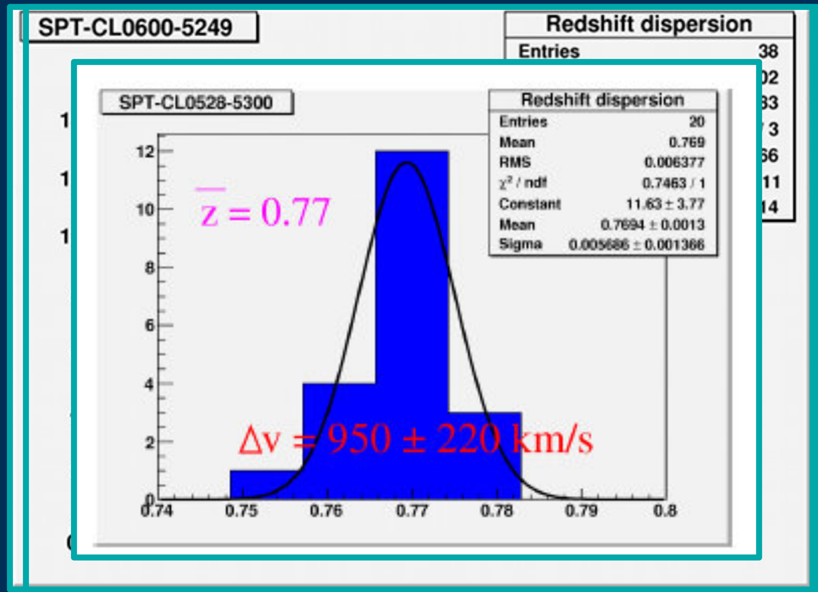




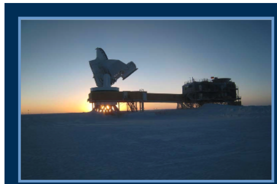
# Velocity Dispersion Mass Constraints

Bazin et al, Brodwin, Ruel et al

- Velocity dispersions provide complementary mass constraints that aren't subject to ICM physics or to sensitivites of weak lensing
  - See Evrard et al 2008, White et al 2010
- Goal: Calibrate SPT mass-obs relation to ~15% in several redshift bins using a sample of dispersions in about 10 clusters per bin
- Require:
  - VLT+FORS2 for high z where fringing becomes problem on Gemini
  - Gemini+GMOS ideal for intermediate z
  - Magellan+IMACS wide field ideal at lower z

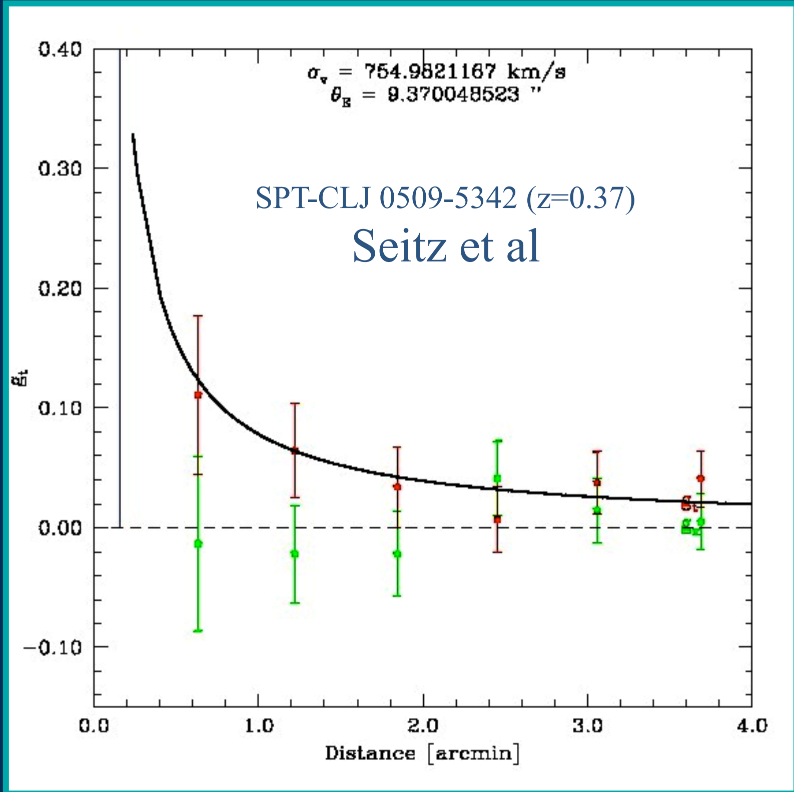



Gemini GMOS Dispersions
Bazin et al



# Weak Lensing Mass Constraints

- We have begun a program to measure weak lensing masses for the SPT clusters
- Program:
  - Pilot study by Seitz et al (MPG 2.2m)
  - HST program to study 7 z>0.55 systems
  - Magellan MEGACAM time coming up
  - Will attempt to use VLT for z~0.5 systems
  - DES constraints on all SPT clusters through stacking



# Overview

Cluster surveys sensitive to distance-redshift, growth of structure.

- Recent analyses of small ROSAT X-ray samples (~37 at z>0.35) provide competitive constraints on dark energy parameters.

SPT cluster survey underway

- SPT sample: *simple selection*, *high mass extending to high z*
- Survey now complete over 1500 deg$^2$, ~192 confirmed clusters in hand
- Sample of ~500 from full survey offers interesting next step in cluster dark energy studies

Other cluster surveys

- XMM archival work underway (similar number of systems)
- Planck all sky SZE survey underway, as is ACT

Future steps

- DES+SPT will improve mass constraints, enable larger sample
- DES, HSC: first really big optically selected samples extending to high z
- eROSITA provides first really big sample with well established single cluster mass estimates