Fall 2008: first 4 clusters discovered by the SZ effect, 3 previously unknown

THE ASTROPHYSICAL JOURNAL, 701:32–41, 2009 August 10
doi:10.1088/0004-637X/701/1/32

GALAXY CLUSTERS DISCOVERED WITH A SUNYAEV–ZEL'DOVICH EFFECT SURVEY

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March 2010: total list expanded to 21, with 18 previously unknown

SUBMITTED TO APJ
Preprint typeset using LaTeX style emulateapj v. 08/29/06

arXiv:1003.0003

GALAXY CLUSTERS SELECTED WITH THE SUNYAEV-ZEL'DOVICH EFFECT FROM 2008 SOUTH POLE TELESCOPE OBSERVATIONS

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March 2010: because redshifts don't come free! <u>Median redshift of sample = 0.74</u>

SUBMITTED TO APJ
Preprint typeset using LaTeX style emulateapj v. 11/10/09

arXiv:1003.0005

OPTICAL REDSHIFT AND RICHNESS ESTIMATES FOR GALAXY CLUSTERS SELECTED WITH THE SUNYAEV-ZEL'DOVICH EFFECT FROM 2008 SOUTH POLE TELESCOPE OBSERVATIONS

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Outline

1. Galaxy clusters, the SZE, and cosmology
2. Proof of concept: SPT 2008 cluster survey
3. The problem of following up ~10^3 clusters
   A. A software solution: Stellar Locus Regression
   B. A hardware solution: Parallel Imager for Southern Cosmological Observations (PISCO)
4. Wrap-up

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What a galaxy cluster is

X-ray: NASA/CXC/CfA/M.Markevitch et al.; Optical: NASA/STScI; Magellan/U.Arizona/D.Clowe et al.; Lensing Map: NASA/STScI; ESO WFI; Magellan/U.Arizona/D.Clowe et al.

The cluster mass budget

Matter component	% total mass	% baryonic mass	% stellar mass
Dark matter	***85-90***	***(na)***	***(na)***
Baryons	***10-15***	***100***	***(na)***
Hot gas	7-14	70-95	(na)
Stars	0.5-5	5-30	100
Galaxies	0.5-4	4-27	70-90
Intracluster stars	0.05-1	0.5-9	10-30
Non-luminous baryons	?	?	?

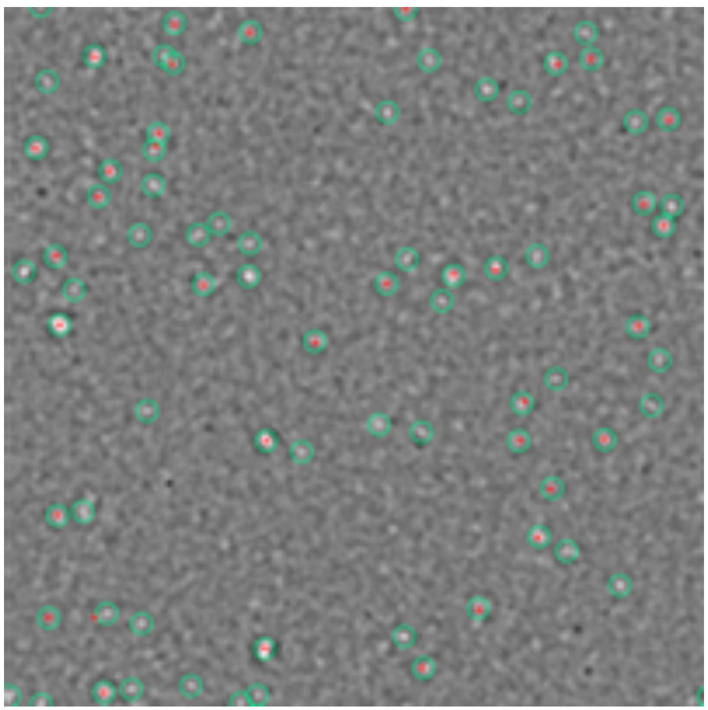
The galaxies make up ~1% of total cluster mass.

Why we care about clusters

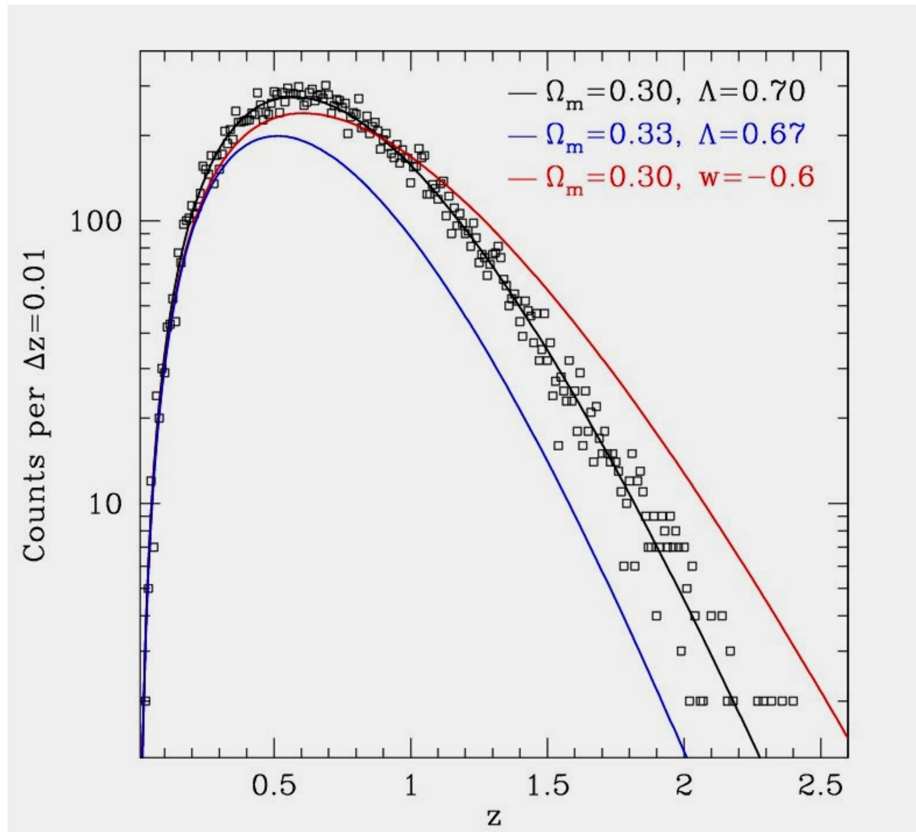
- 1933: How dark matter was originally discovered (galaxy velocity dispersions in Coma, Fritz Zwicky)
- Today: Unique sensitivity to dark energy, via *growth*, not just geometry (cf. Dark Energy Task Force, Albrecht et al. 2006)
- Galaxy formation and evolution, "gastro-physics", supernovae, fundamental test of gravity

Galaxy Cluster Number Count Cosmology

1. Find Clusters

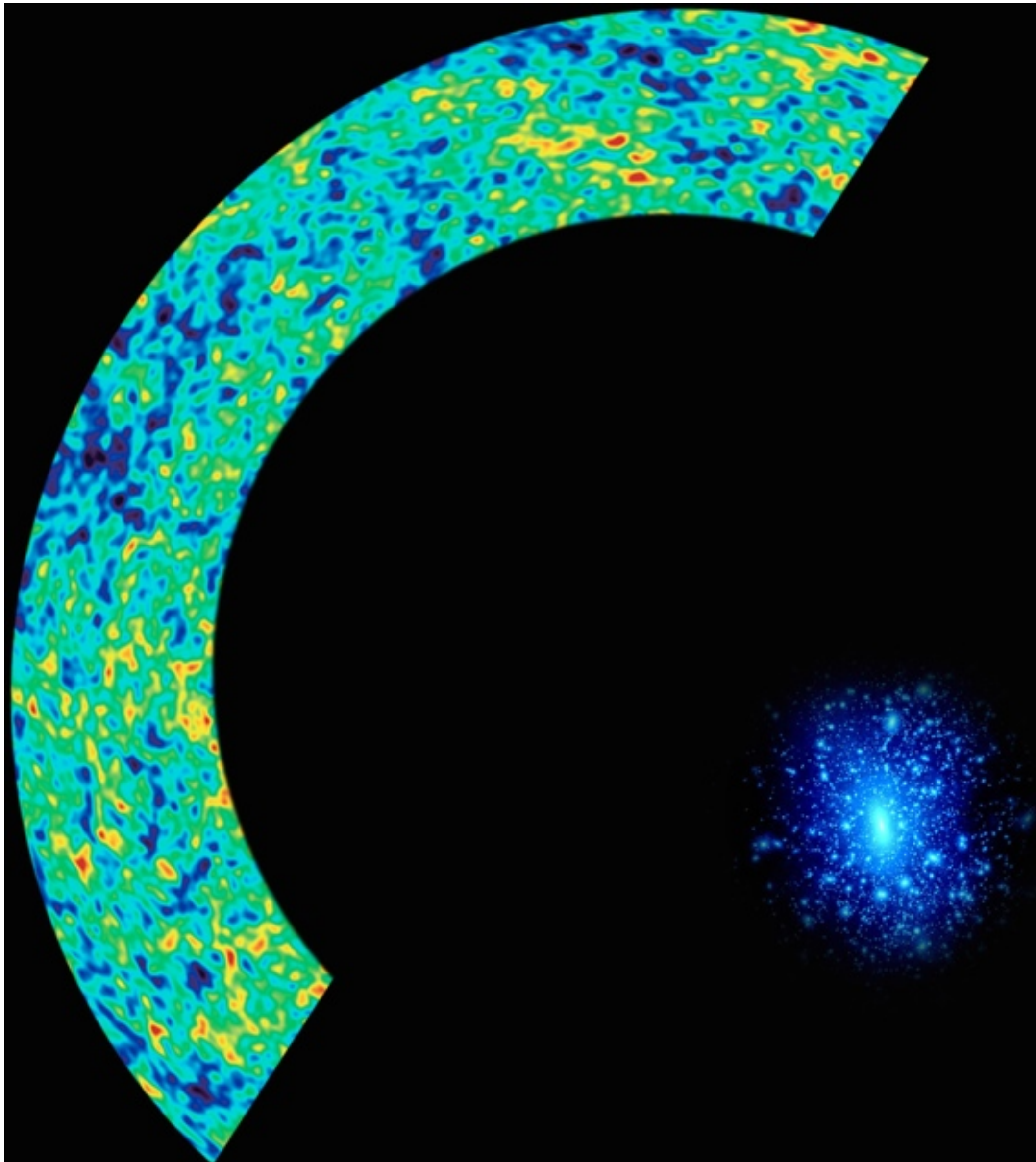


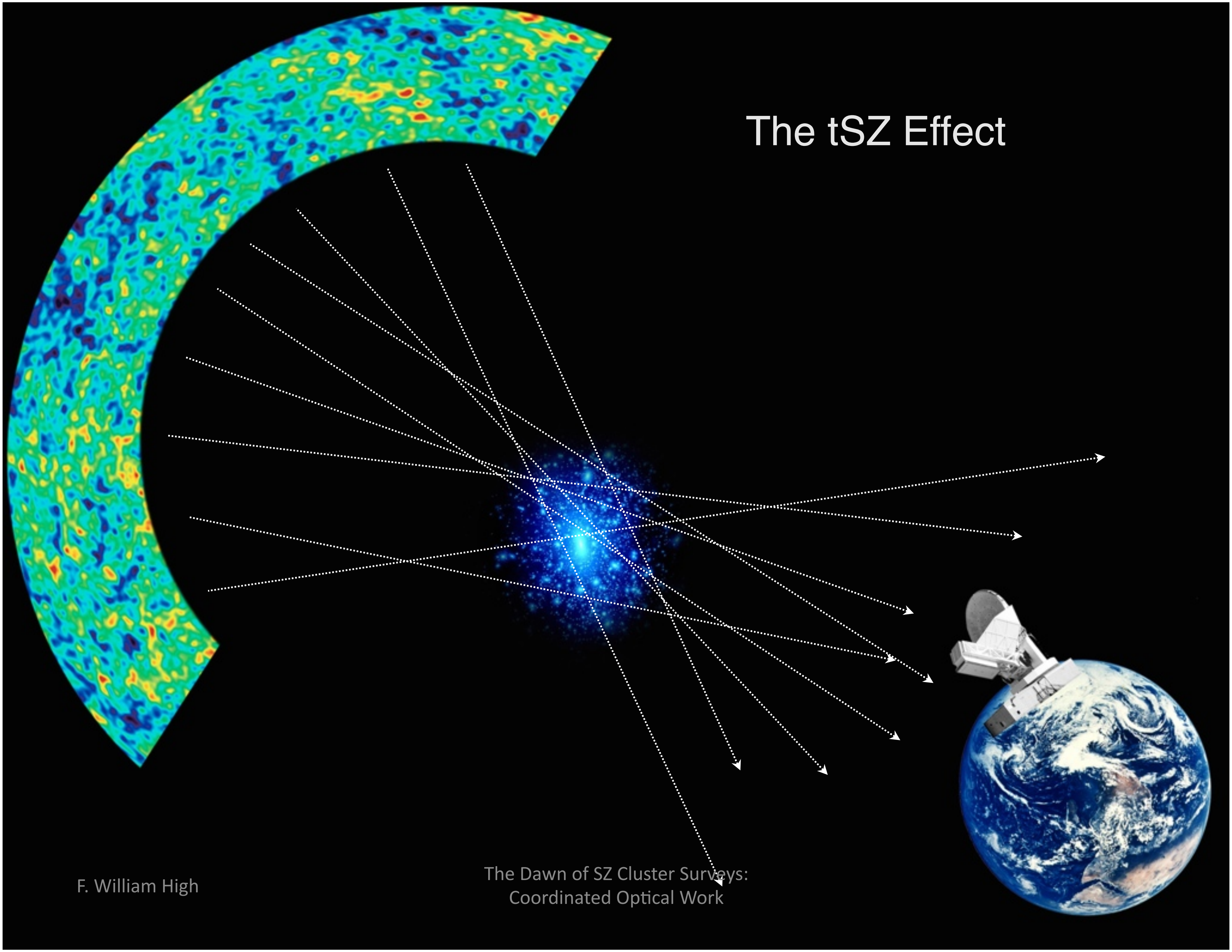
2. Constrain DE



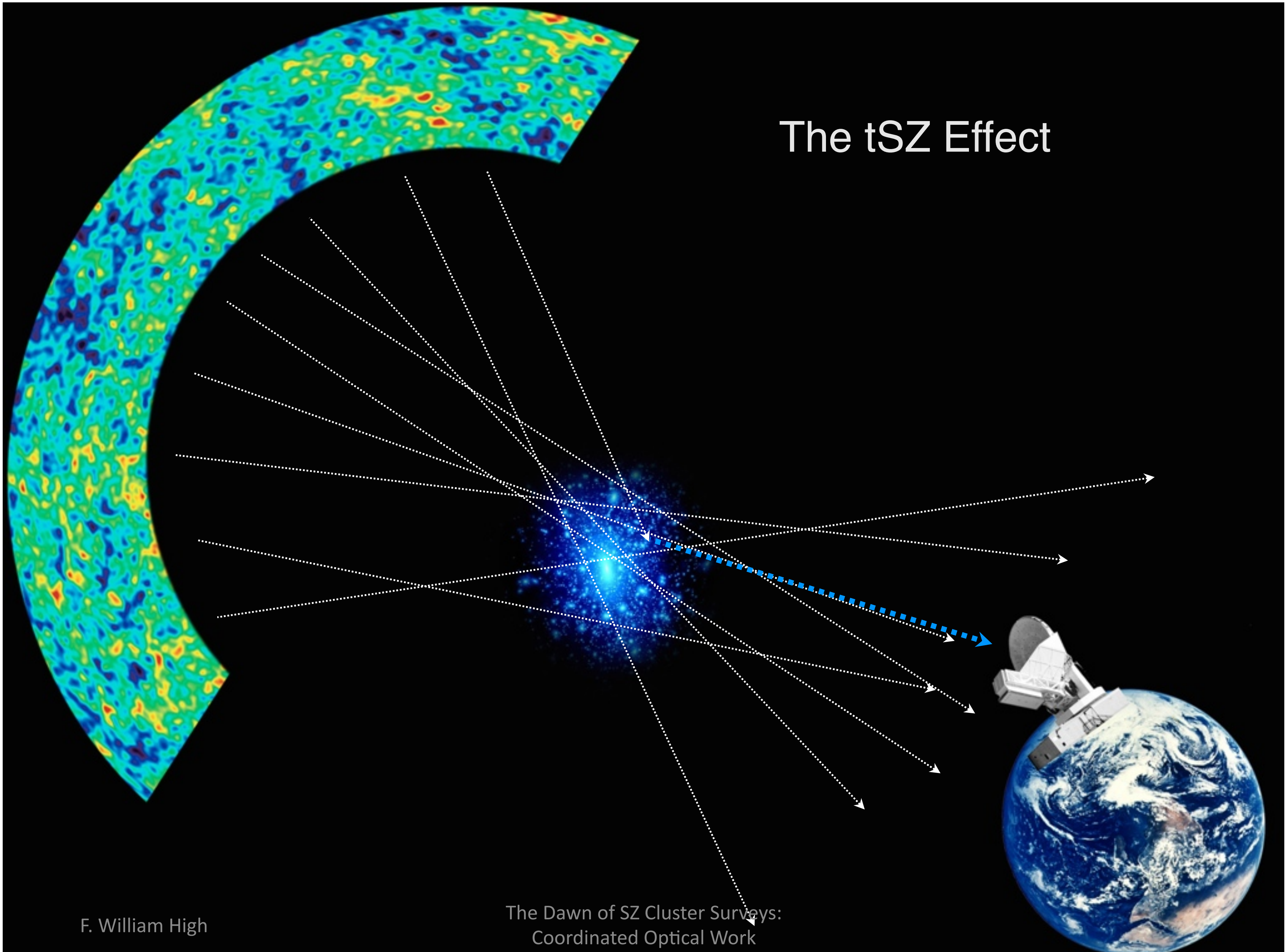
(3. Fame & Glory)

The tSZ Effect



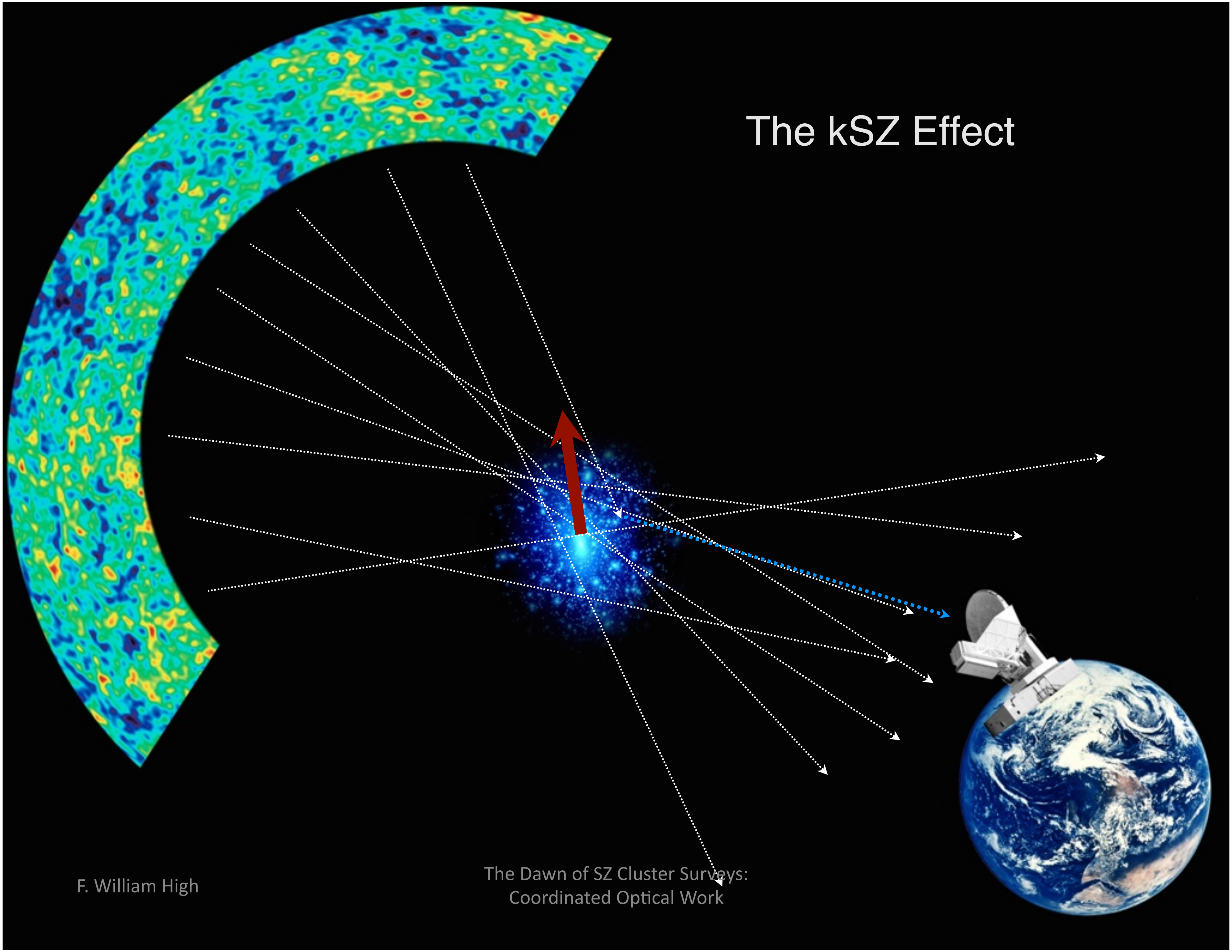

The tSZ Effect
F. William High
The Dawn of SZ Cluster Surveys:
Coordinated Optical Work

The tSZ Effect

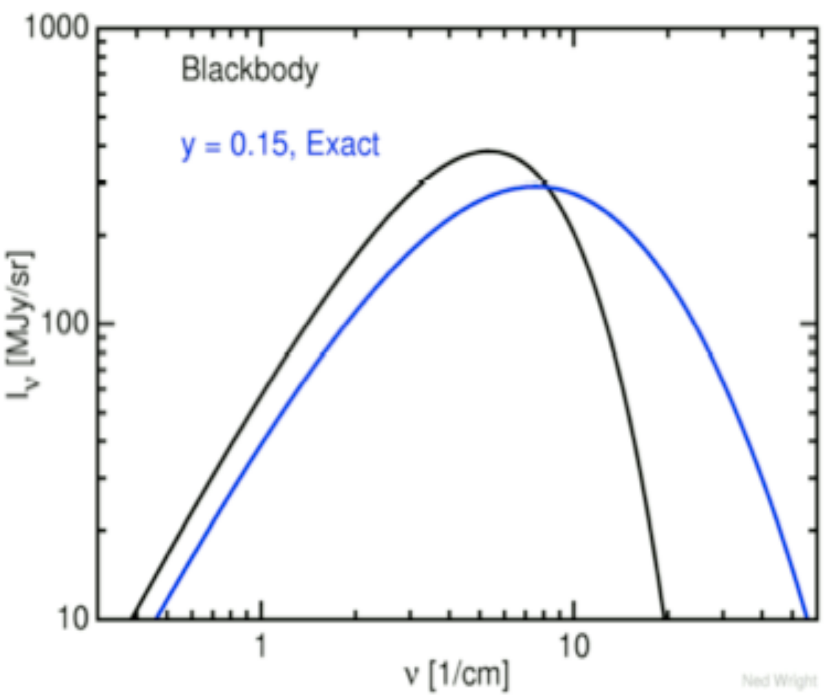


F. William High

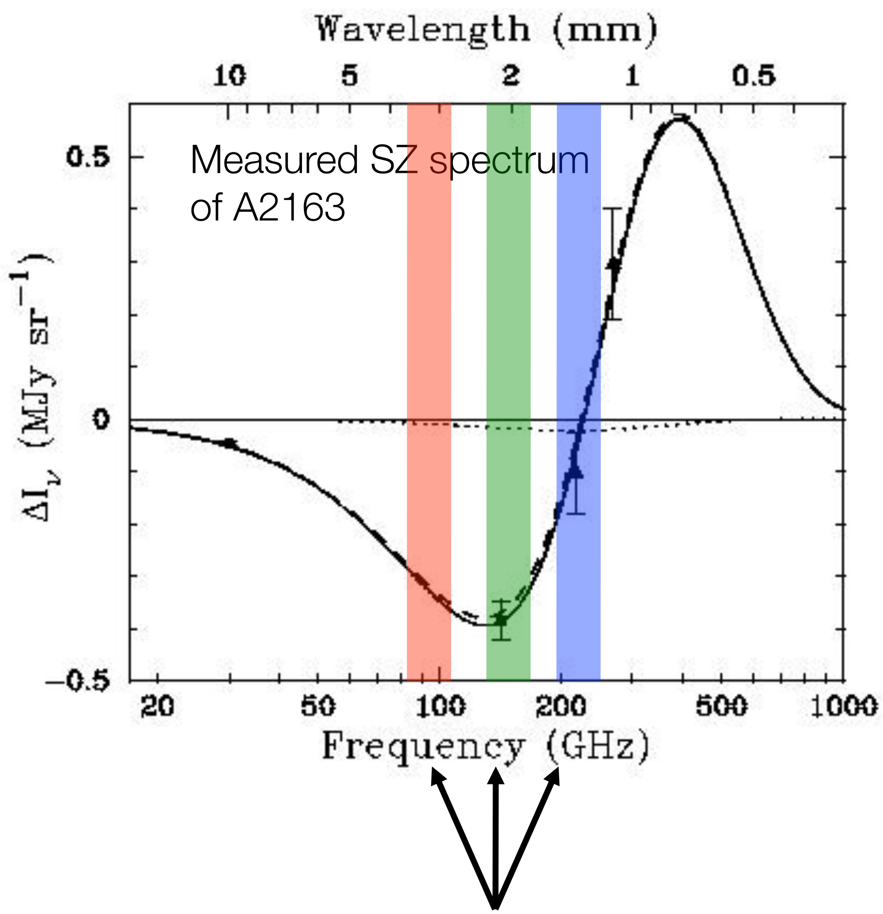
The Dawn of SZ Cluster Surveys:
Coordinated Optical Work


The kSZ Effect
F. William High
The Dawn of SZ Cluster Surveys:
Coordinated Optical Work

Sunyaev-Zel'dovich Effect



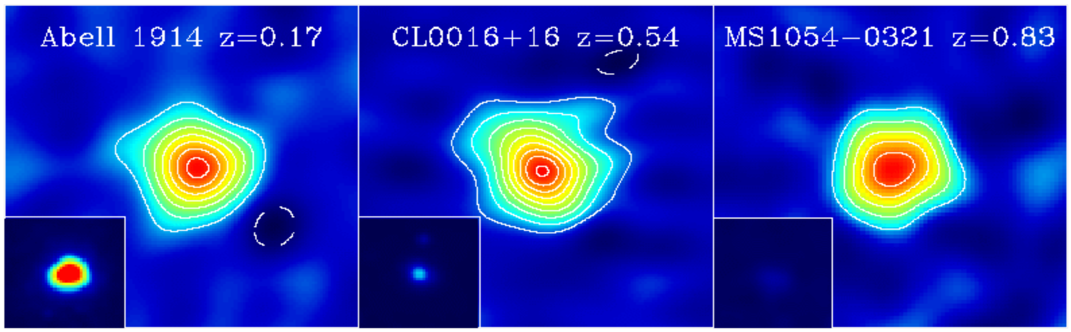
from Ned Wright



SPT Bands

SZE take home message

$$\frac{\Delta T_{cmb}}{T_{cmb}} \equiv f_\nu(x)y = \left(\frac{k_B\sigma_T}{m_c c^2}\right)\int n_e(l)T_c(l)dl$$



Credit: Mohr & Carlstrom

- Galaxy clusters are the ***largest gravitationally collapsed structures*** in the universe and trace the mass density peaks in the universe.
- SZ flux is proportional to total thermal energy of the cluster and therefore should be ***good proxy for cluster mass***.
- Because the SZE is a spectral distortion of the CMB, it is ***redshift independent***

= A good way to make a mass-limited cluster catalog all the way out to the epoch of cluster formation

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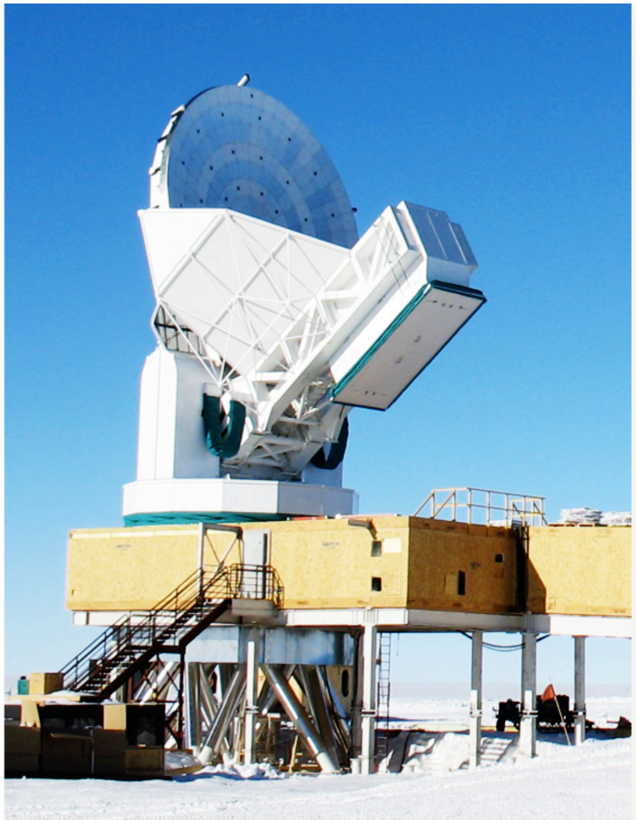
4. Additional uses for these clusters
5. Wrap-up

The South Pole Telescope (SPT)



An experiment optimized for fine-scale anisotropy measurements of the CMB

- **Dedicated 10-m telescope at the South Pole**
- **Background-limited 960-element mm camera**

Science Goals:

- **Mass-limited SZ survey of galaxy clusters**
  - **study growth of structure, dark energy equation of state**
- **Fine-scale CMB temperature anisotropies**
  - **tSZ power spectrum to measure σ_8**
  - **kSZ power spectrum to constrain reionization**
- **mm sources**
  - **dusty star forming galaxies**
  - **AGN**
  - **Other rare objects**

- **NEXT: Polarization**

Funded by NSF

SPT Team February 2007

KICP
Kavli Institute for Cosmological Physics
AT THE UNIVERSITY OF CHICAGO

THE UNIVERSITY OF CHICAGO

Berkeley
University of California

McGill

Harvard-Smithsonian Center for Astrophysics

Berkeley Lab

ASTRONOMY
UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

UCDAVIS
UNIVERSITY OF CALIFORNIA

Case
CASE WESTERN RESERVE UNIVERSITY

Colorado
University of Colorado at Boulder

CARDIFF UNIVERSITY
PRIFYSGOL CAERDYDD

KICP Kavli Institute for Cosmological Physics at the University of Chicago

Berkeley University of California

Astronomy University of Illinois at Urbana-Champaign

Case Case Western Reserve University

McGill

The University of Chicago

Harvard-Smithsonian Center for Astrophysics

Berkeley Lab

Cardiff University Prifysgol Caerdydd

UC Davis University of California

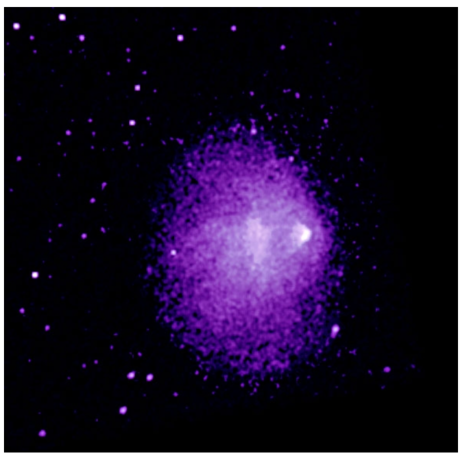
Colorado University of Colorado at Boulder

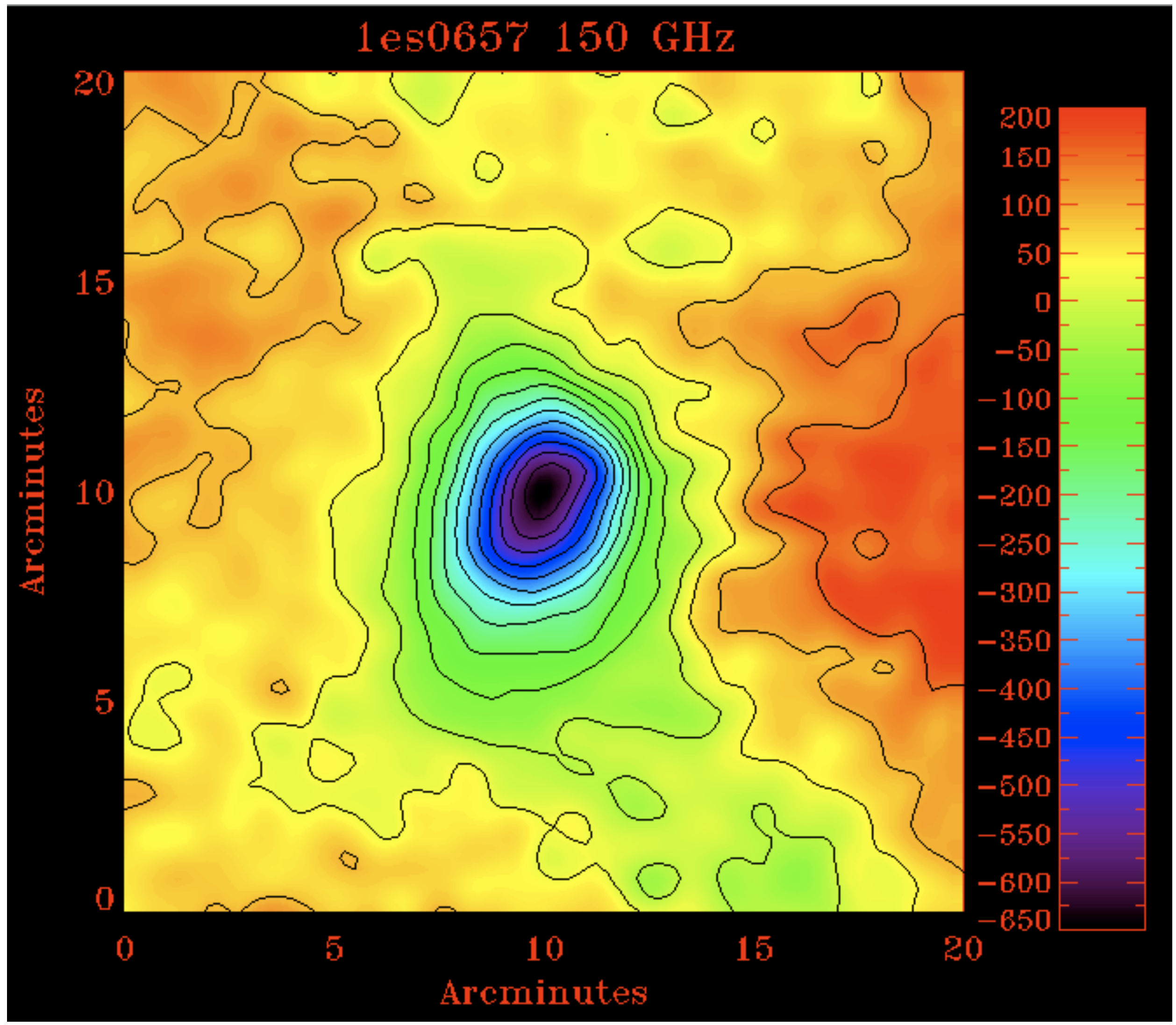
Targeted Clusters

SZ Image of Bullet Cluster

- z = 0.297
- 7 hours of observation
- ~ 20 μK RMS per 1' pixel

Chandra X-ray Image
- 140 hour observation (0.5 Ms)



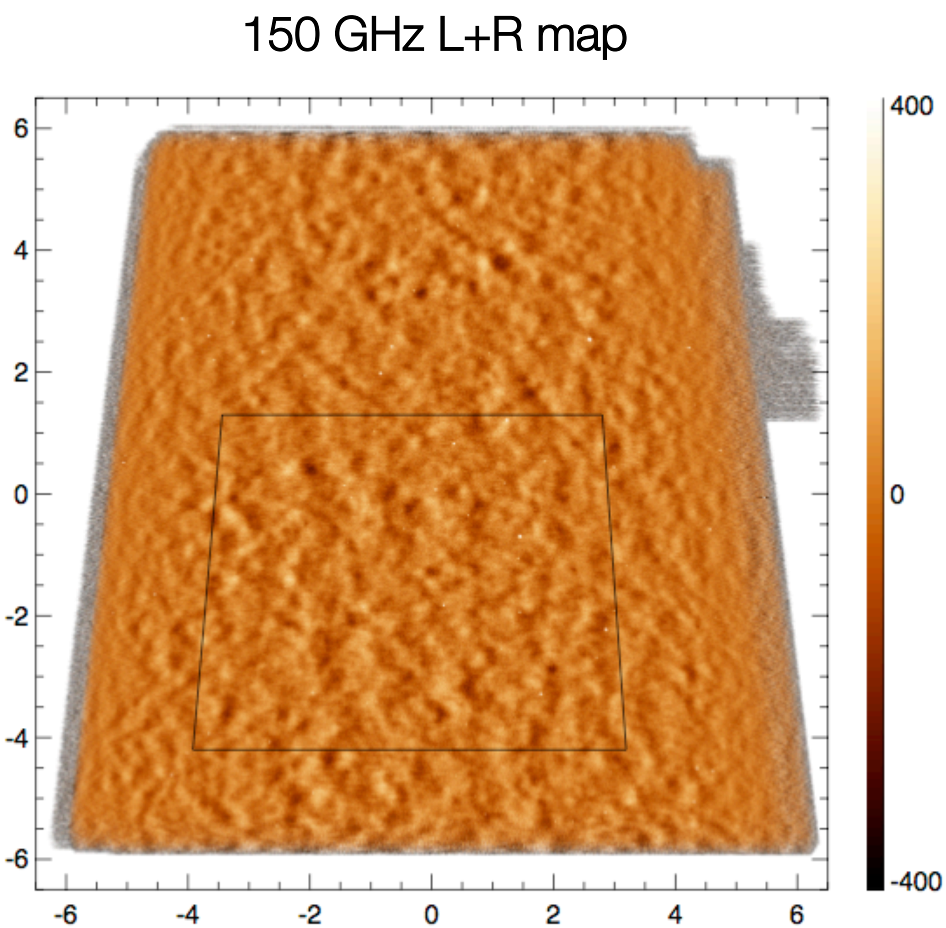


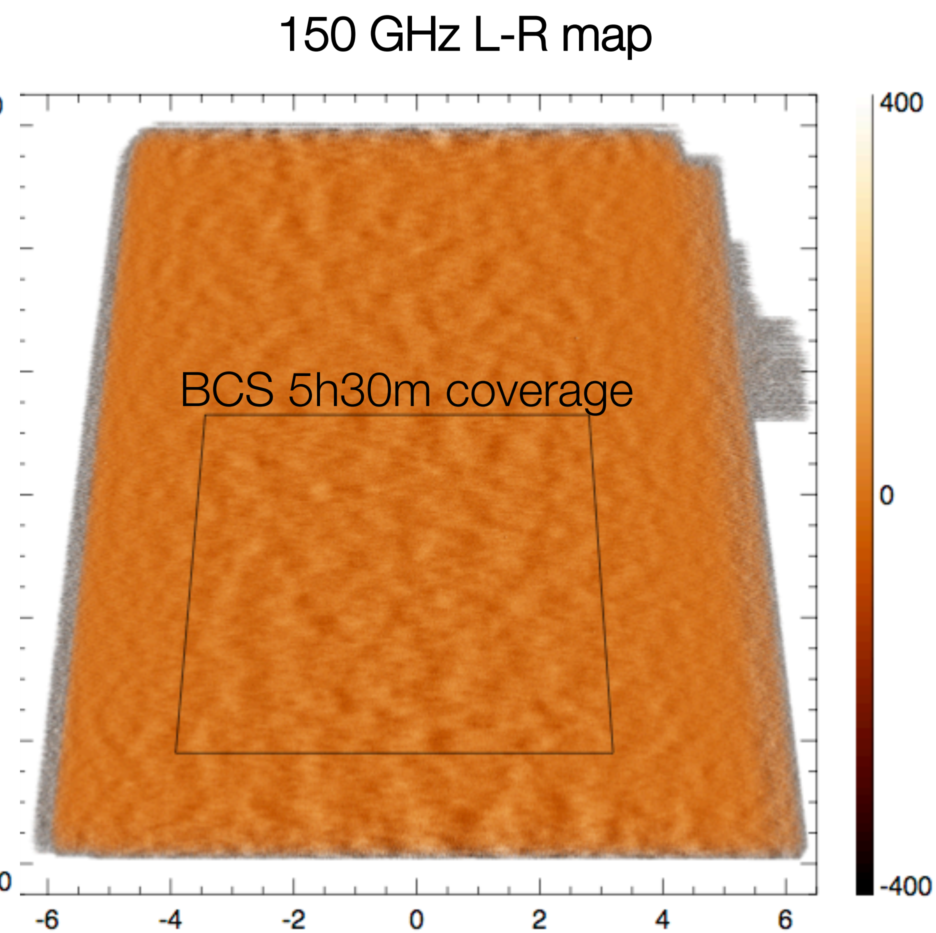
T. Plagge, B. Benson

F. William High

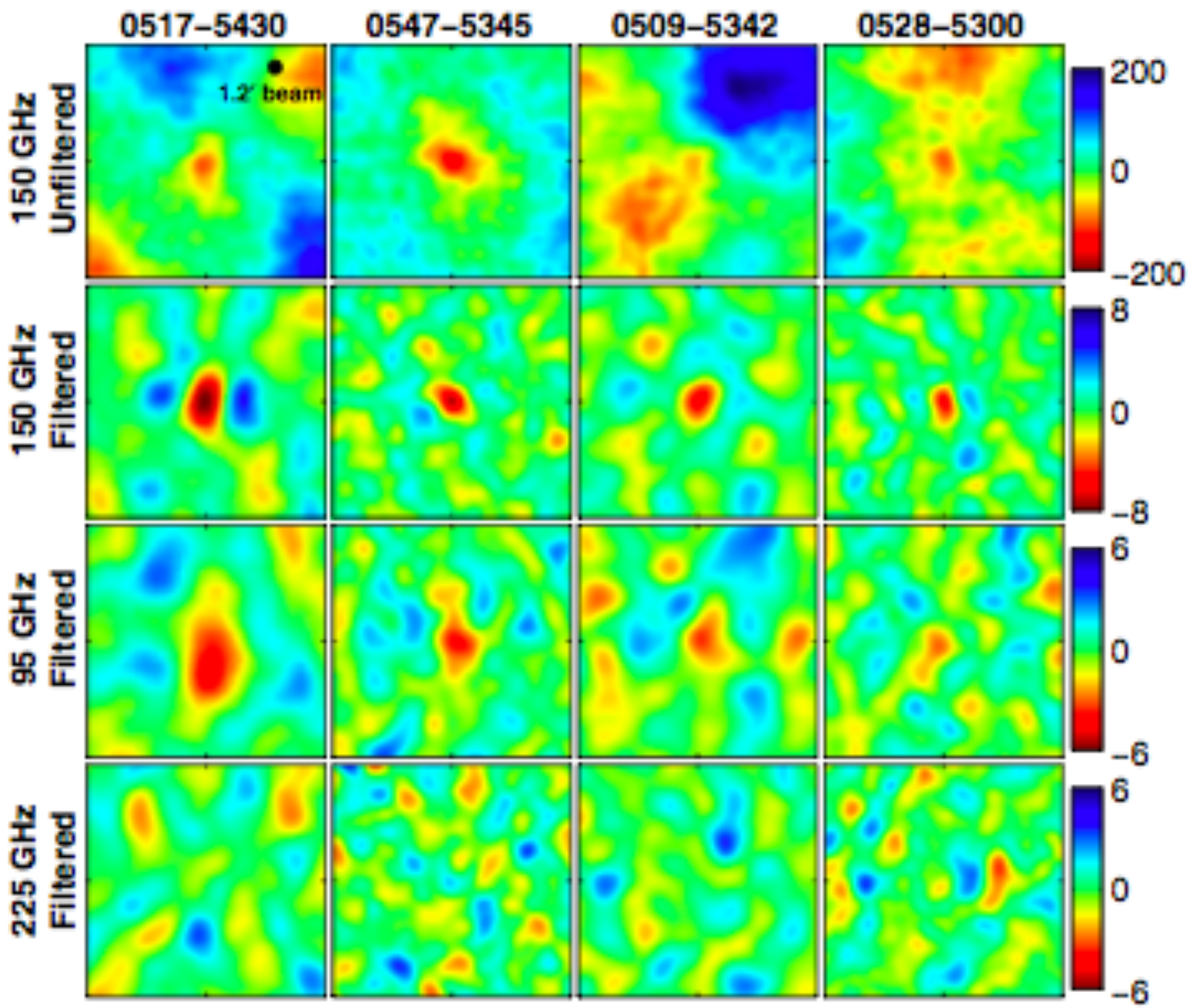
1st SPT Survey field at RA 5 hrs

- Mapped with interleaved azimuth raster scans
- ~800 hours of observation
- 90 deg^2 ~17 uK/arcmin pixel
- 40 deg^2 overlap with optical BCS *griz* 5h30m field



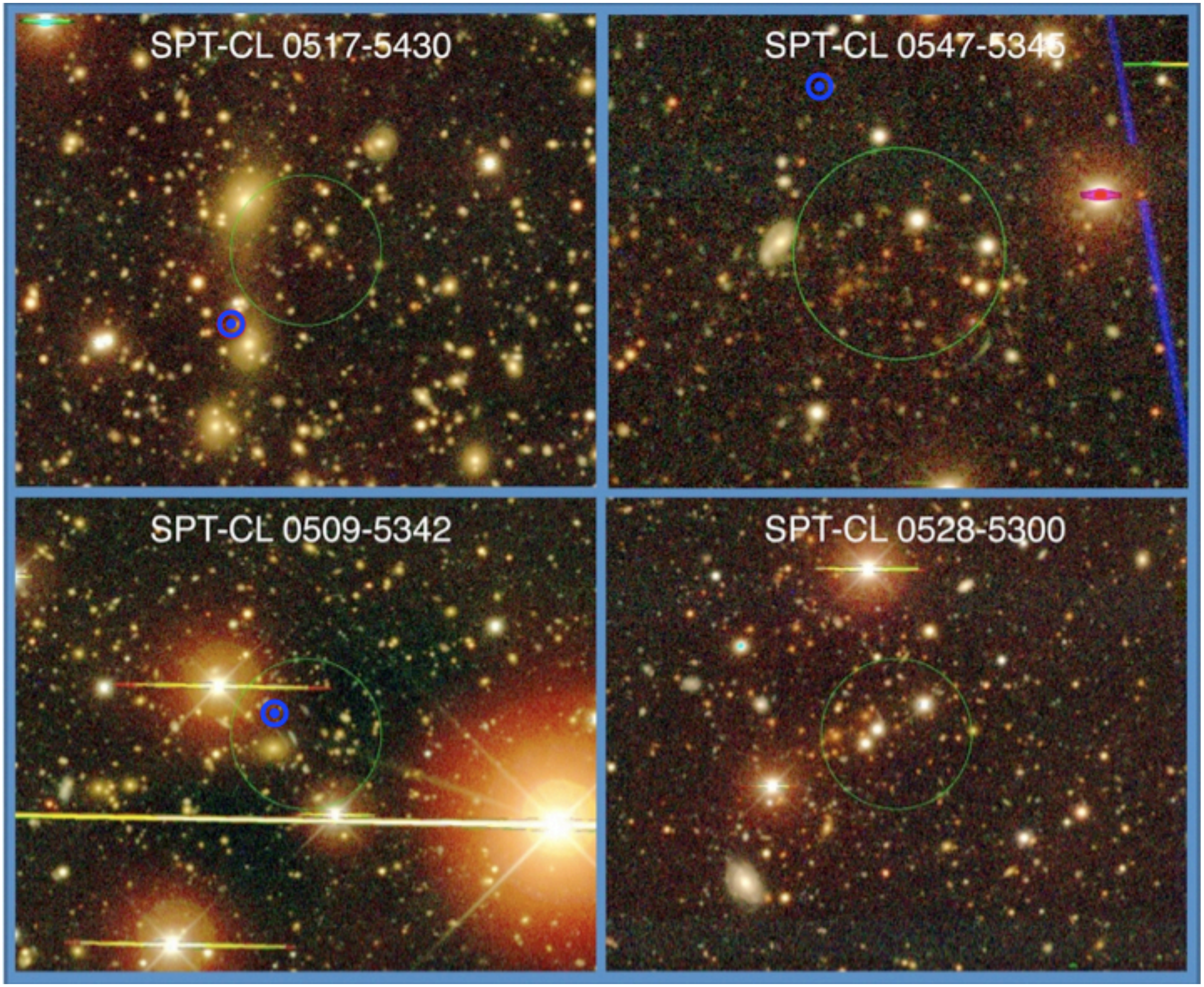


The four most significant SPT 150 GHz detections in region overlapping 40 deg^2 BCS5h30m field



Staniszewski et al., ApJ & astro-ph/0810.1578

BCS *gri* pseudo color images of the SPT detection fields



Green circles mark 1' diameter centered on SPT location

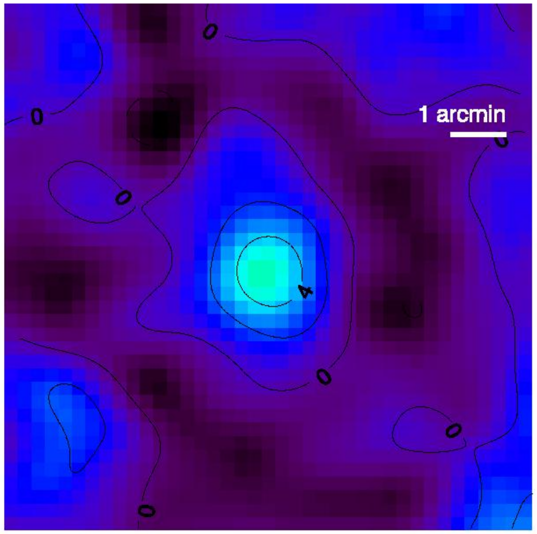
Optical imaging follow-up

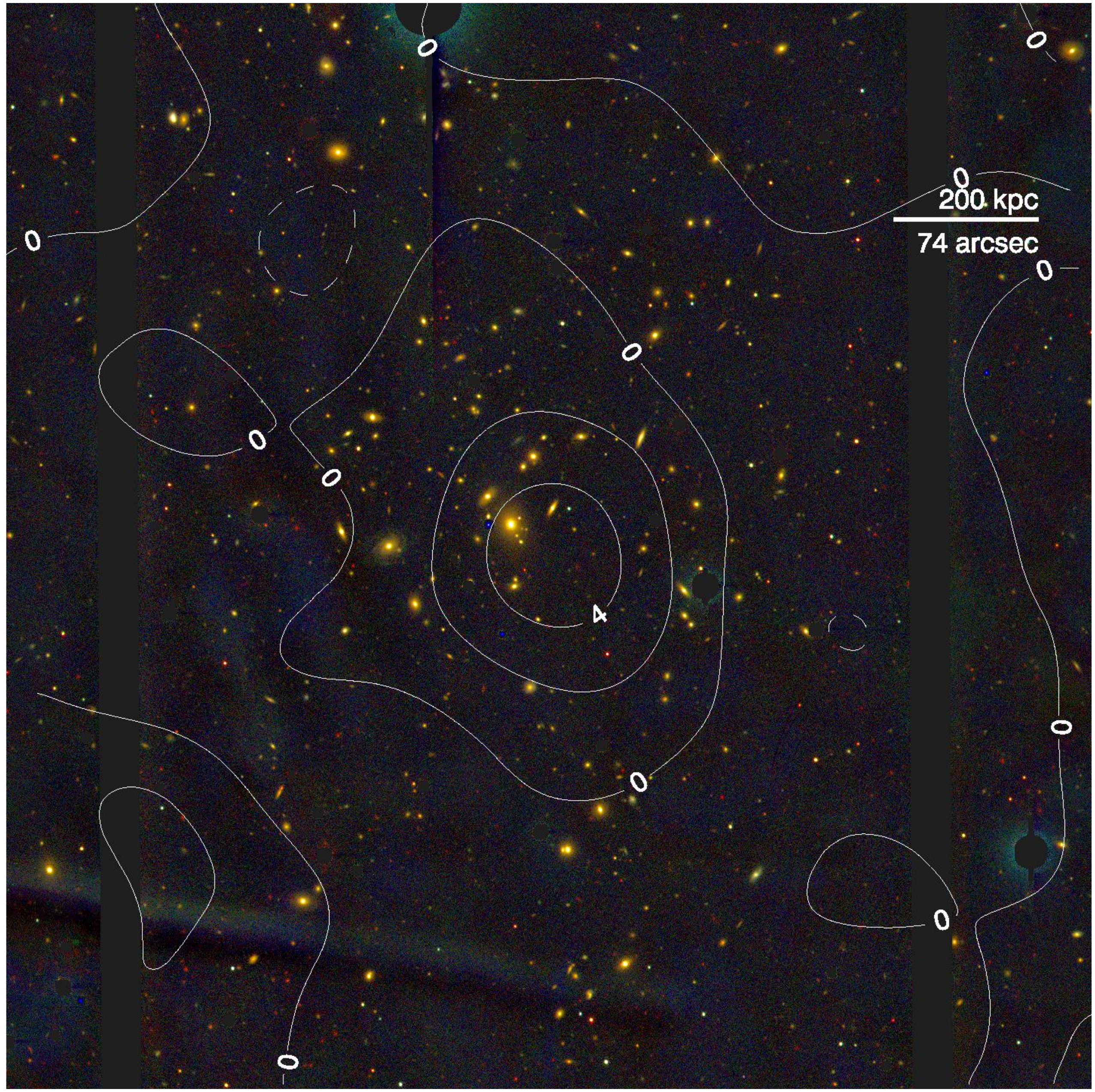
- Blanco Cosmology Survey (existing)
  - 2x50deg^2 at R.A. 5hr and 23 hr, Decl. -55deg
  - Approx. 1 mag deeper than SDSS
- Magellan (ongoing)
  - Pointed observations (not a survey)
  - Variable (adaptive) depth
  - Existing cameras, PISCO camera in the future
- Dark Energy Survey (fall 2011)
  - New camera for CTIO/Blanco 4m
  - 5000deg^2 overlapping entirely with SPT's survey

Role of optical

1. Search for galaxy overdensities @ SZ locations
2. Cluster redshifts
3. (Cluster richness)

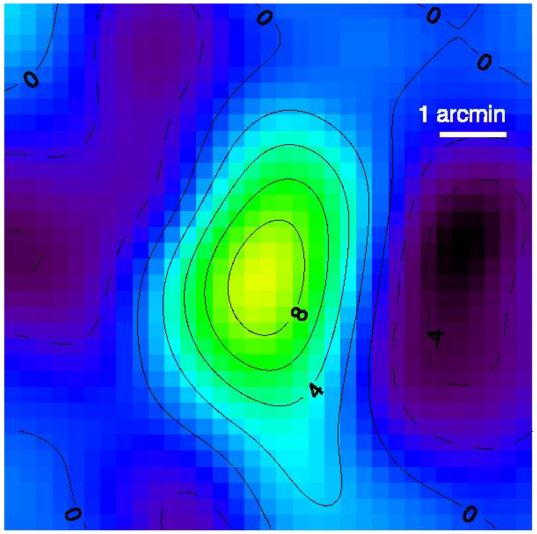
SPT-CL J2259-5617, Abell 3950 (no previous z) Redshift: 0.1528, age of universe: 11.8 Gyr

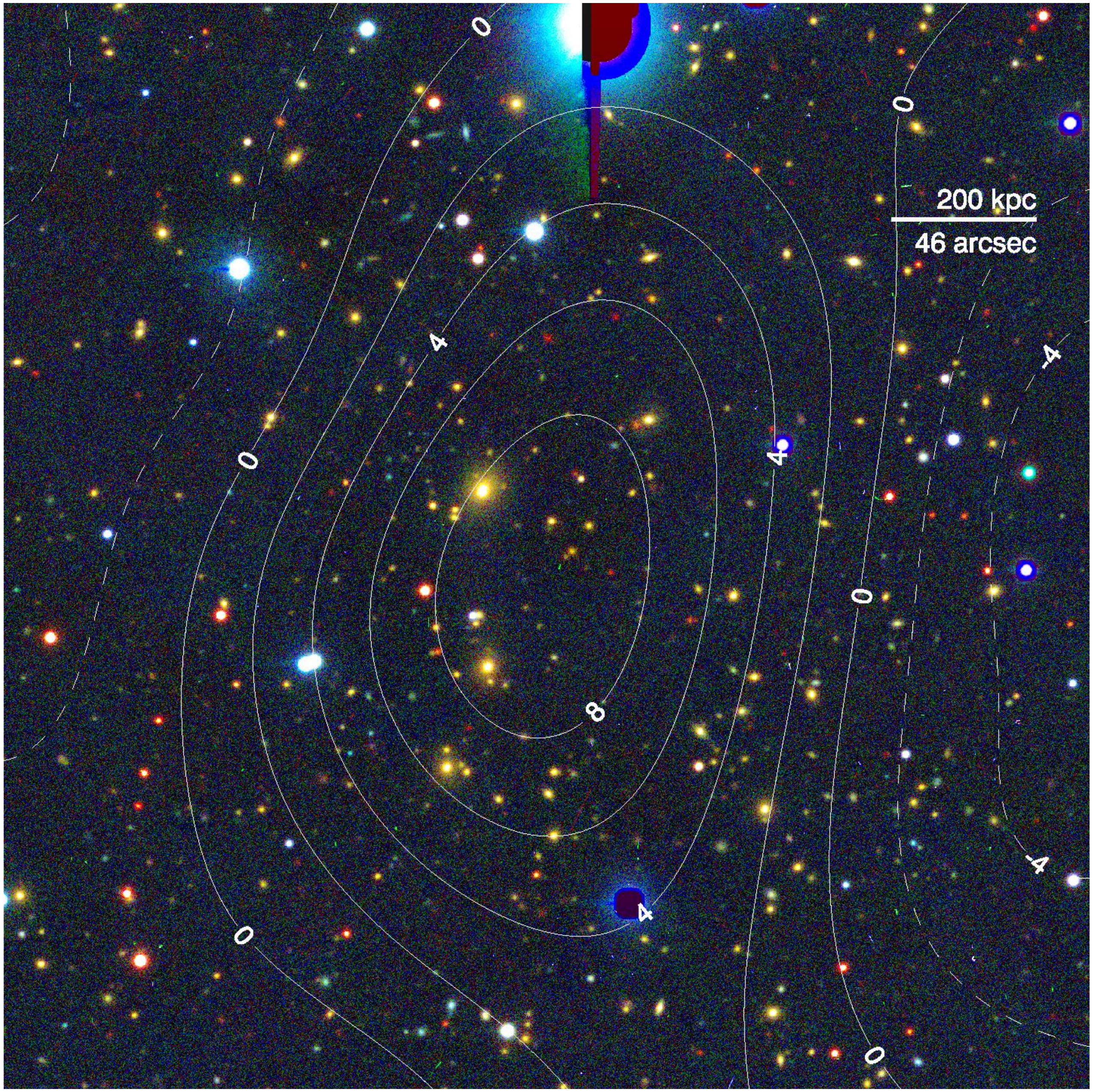




SPT-CL J0516-5430, Abell S0520

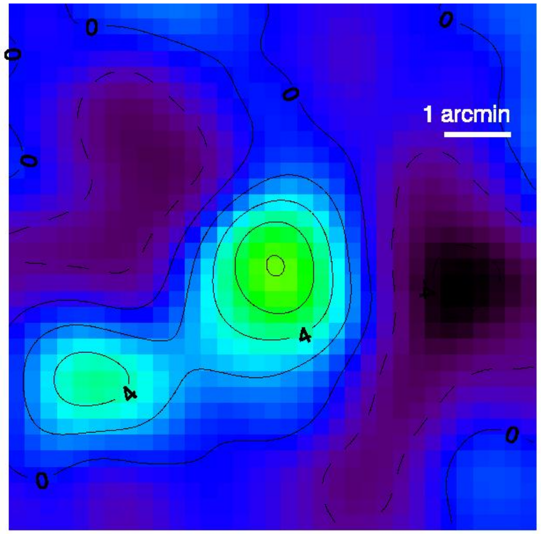
Redshift: 0.2925, age of universe: 10.4 Gyr

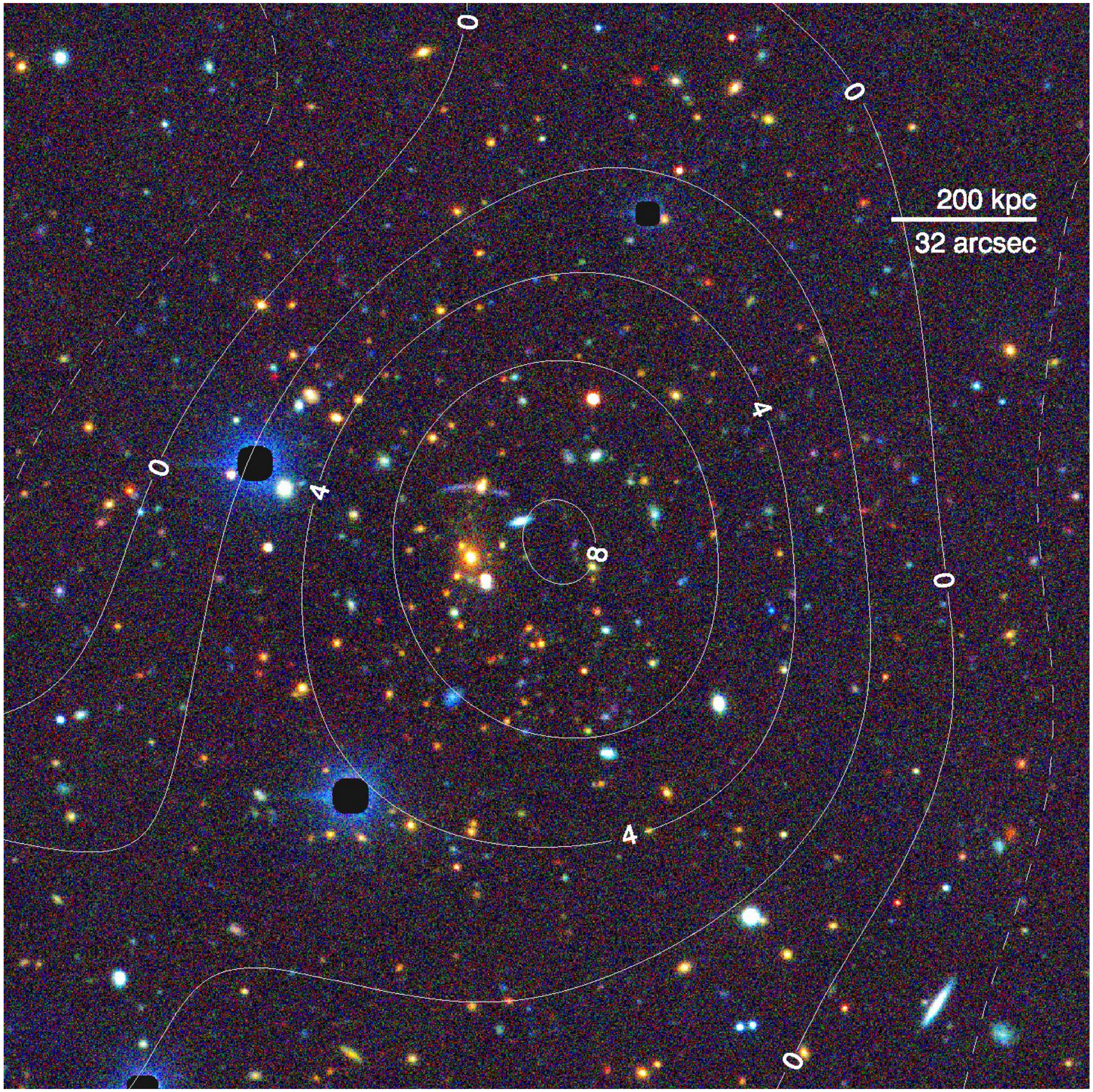




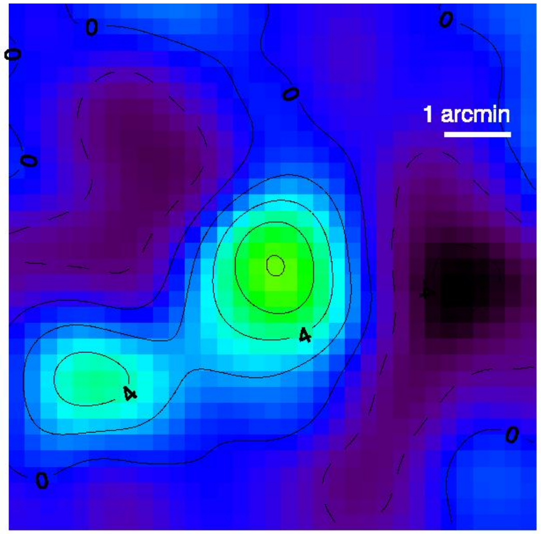
SPT-CL J2332-5031, Brightest giant arc

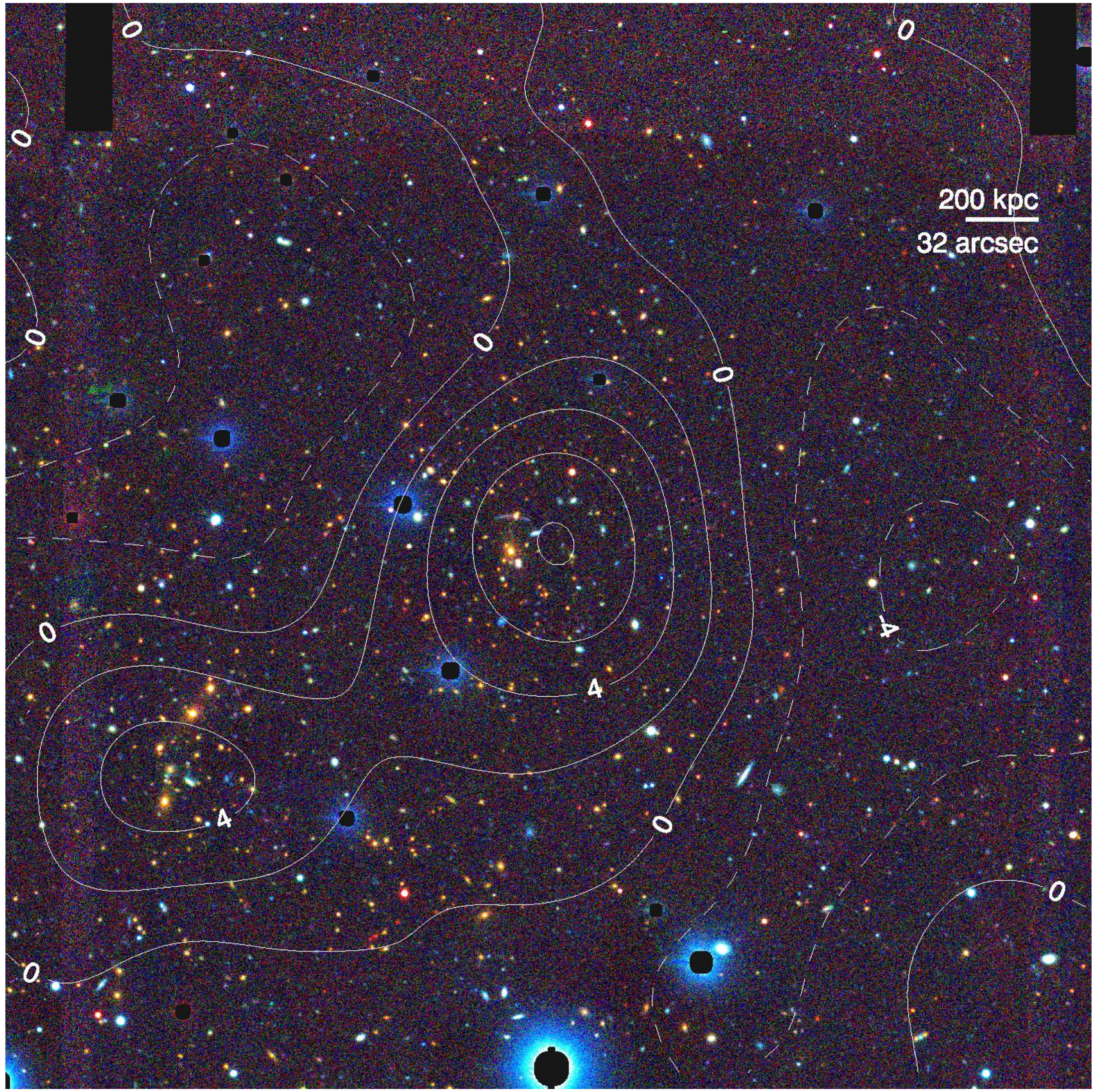
Redshift: 0.5707, age of universe: 8.2 Gyr





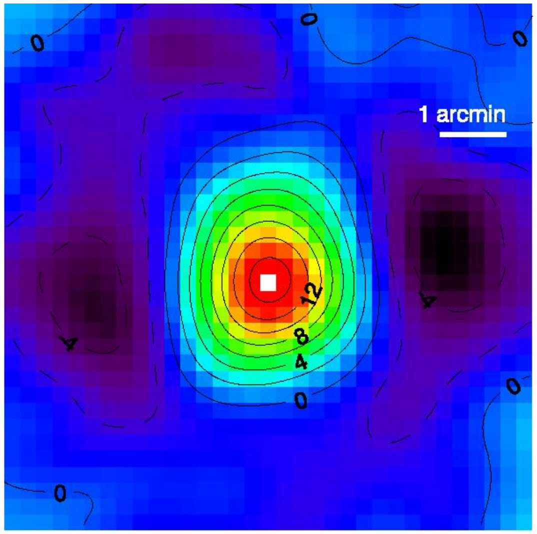
SPT-CL J2332-5031, Brightest giant arc, supercluster Redshift: 0.5707, age of universe: 8.2 Gyr

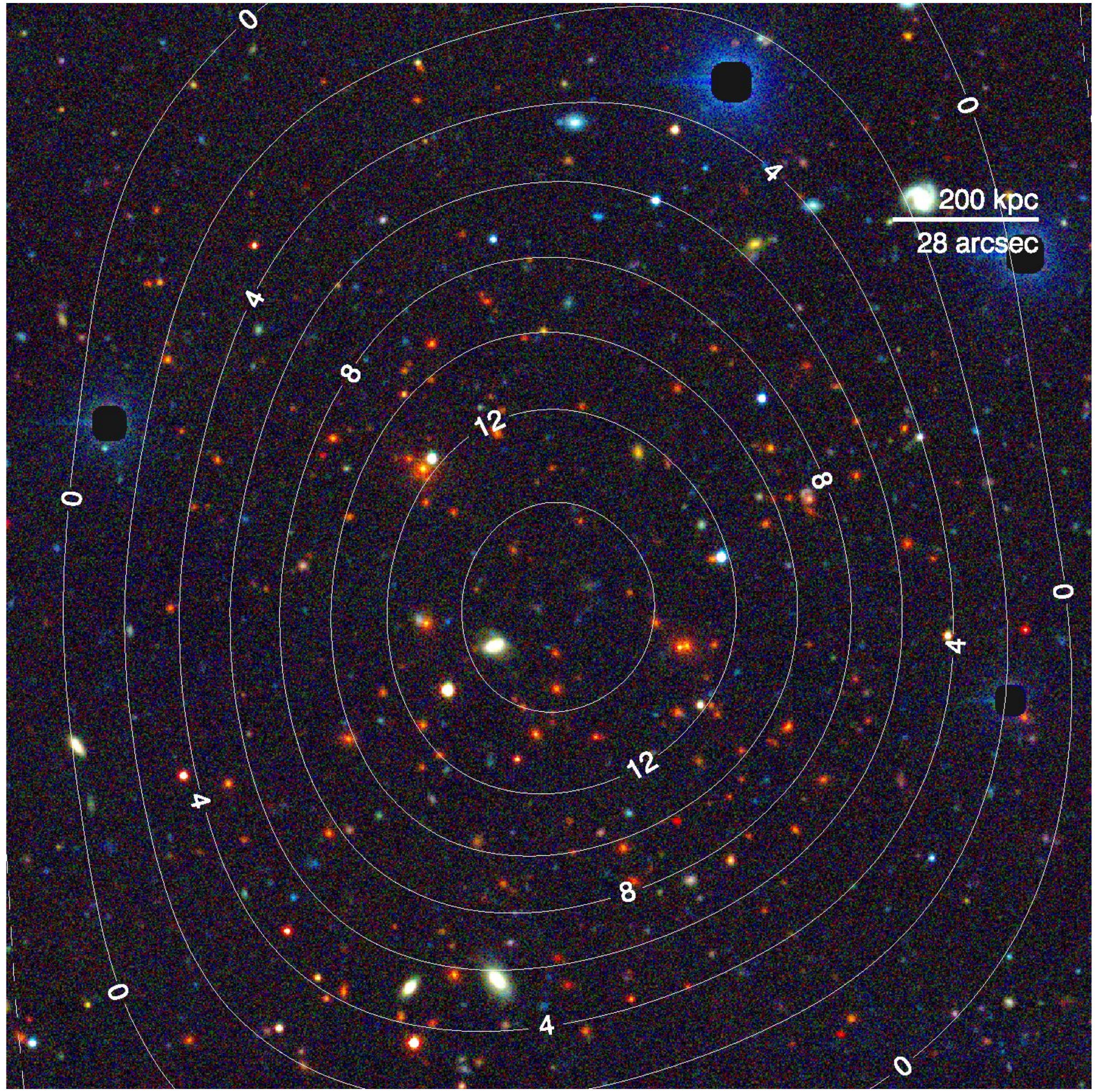




SPT-CL J2337-5942, Highest SZ S/N (14.9)

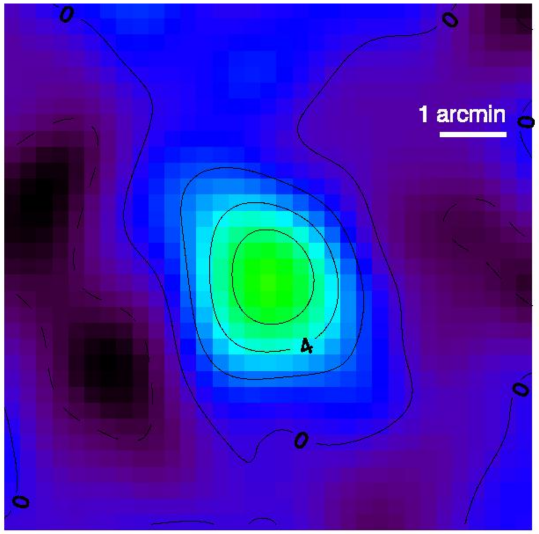
Redshift: 0.7814, age of universe: 6.9 Gyr

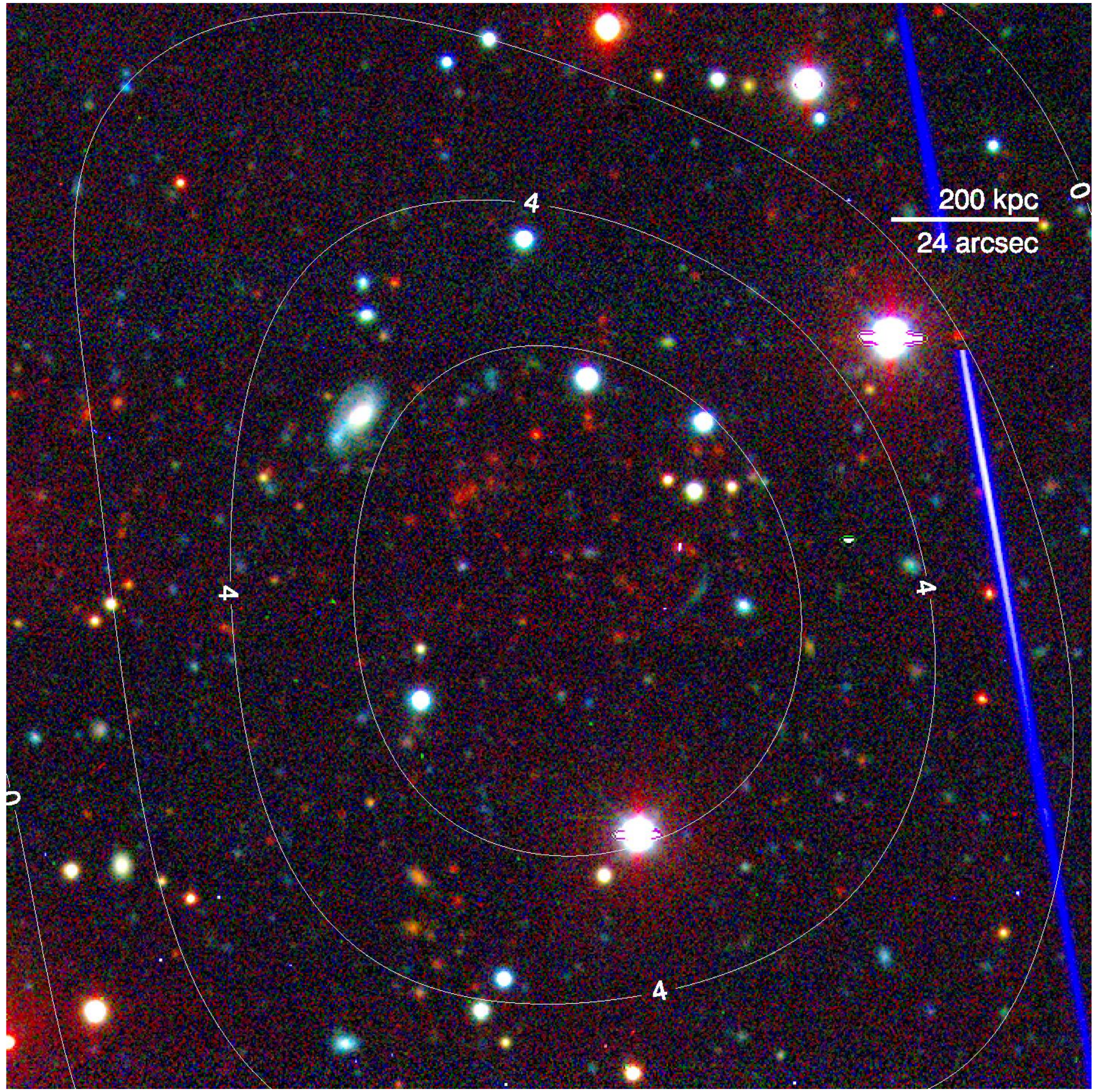




SPT-CL J0546-5345, highest z w/ spec confirmation

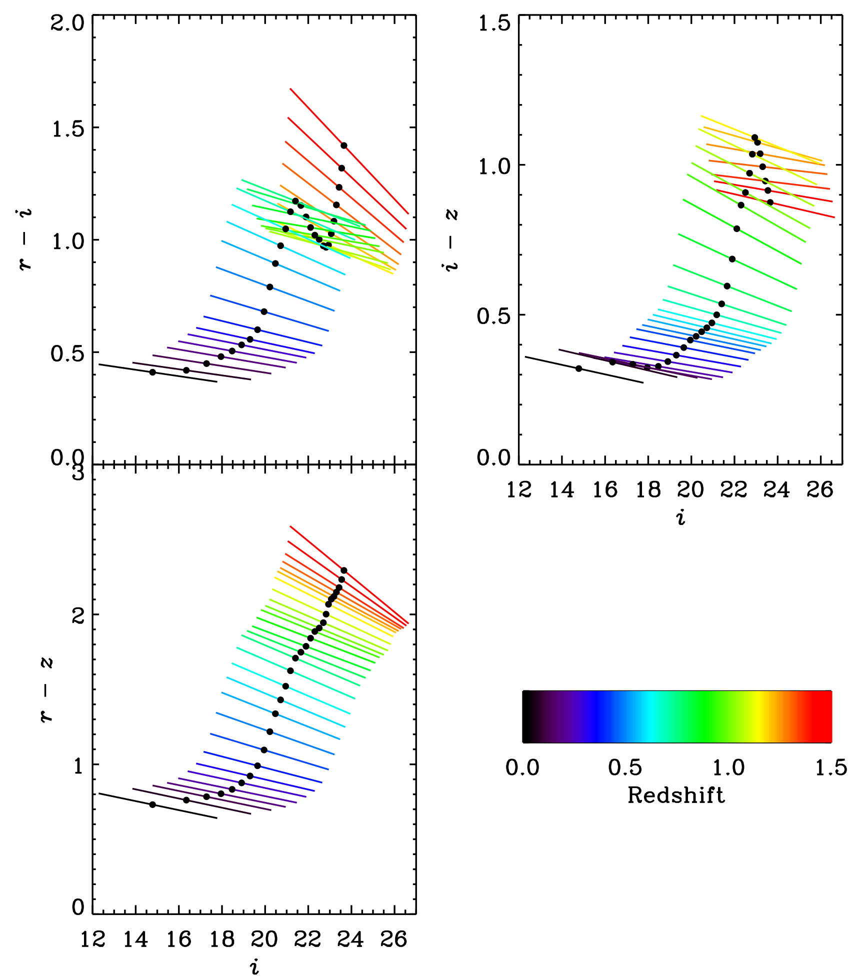
Redshift: 1.07, age of universe: 5.7 Gyr



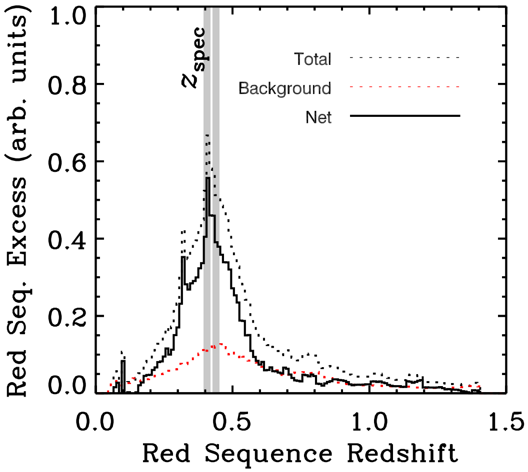


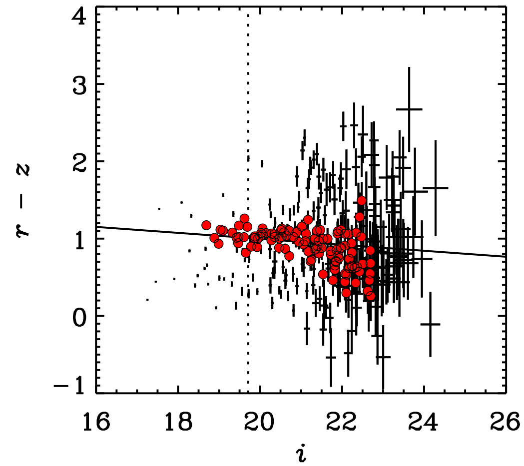
Redshifts

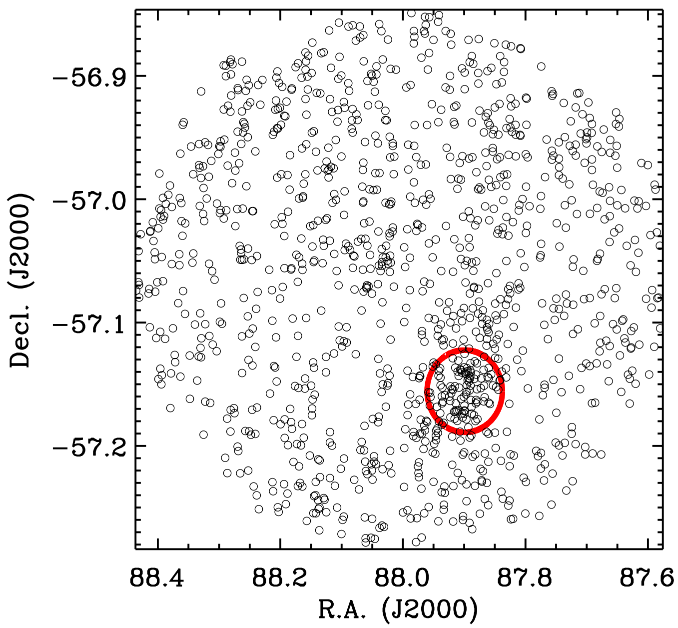
- Red sequence method (eg, Gladders & Yee 2000)
- Passively evolved Bruzual & Charlot (2003) stellar synthesis
- $z_{formation} = 3$
- Step through catalog CMDs inside spatial apertures and count RS galaxies



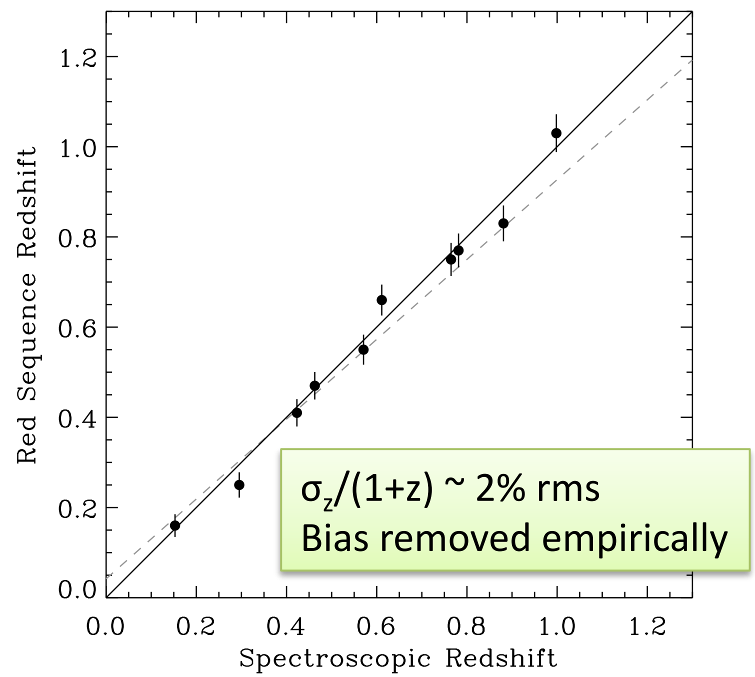
Looking for red-sequence overdensities







Red-sequence redshift performance wrt spectroscopic subsample



Cosmological results

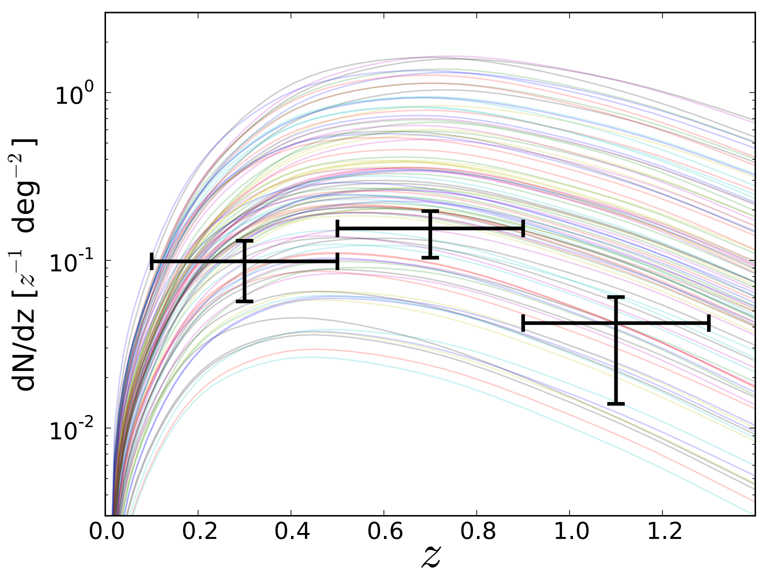


TABLE 2
COSMOLOGICAL PARAMETER CONSTRAINTS

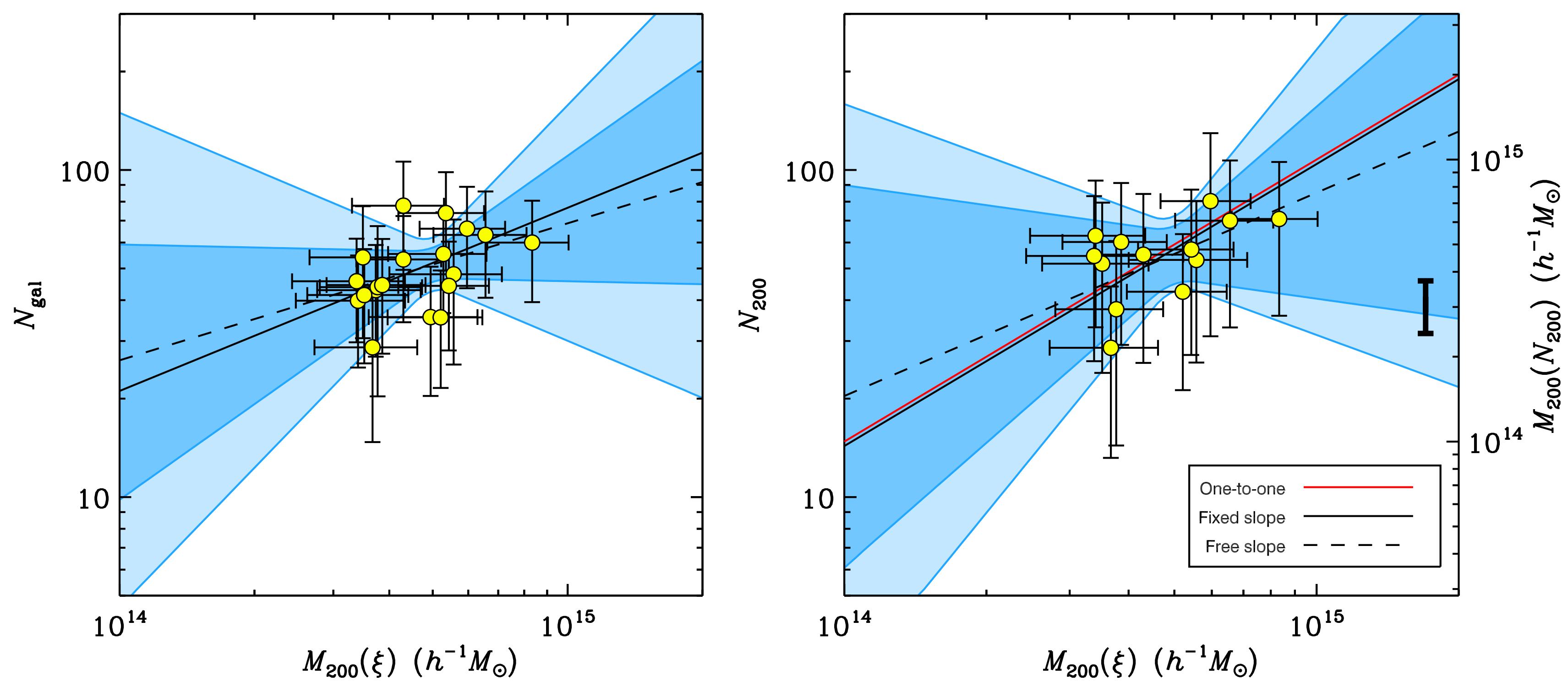
Chain	σ_8	w
ΛCDM WMAP7	0.801 ± 0.030	-1
ΛCDM WMAP7+SPT	0.790 ± 0.028	-1
ΛCDM CMBall	0.794 ± 0.029	-1
ΛCDM CMBall+SPT	0.787 ± 0.026	-1
wCDM WMAP7	0.832 ± 0.134	-1.118 ± 0.394
wCDM WMAP7+SPT	0.804 ± 0.092	-1.049 ± 0.291
wCDM WMAP7+BAO+SNe	0.802 ± 0.038	-0.980 ± 0.053
wCDM WMAP7+BAO+SNe+SPT	0.788 ± 0.035	-0.966 ± 0.049

Limited by mass uncertainties @ 30%

Optical and SZ(-ish) masses

- MaxBCG prescription, w/ Schechter LF
- N200 – mass relation from stacked weak lensing (Johnston et al. 2007 and Reyes et al. 2008)

- Millimeter masses derived from S/N of SZ detection, scaled with simulations
- 30% uncertainty in overall normalization



Studies of the universe's most extreme environments

- Mass-observable scaling for cosmology
  - Lensing vs X-ray vs SZ vs optical
  - Dark matter sub-structure
- Galaxy populations
  - Cluster galaxy luminosity function
  - Fractions of red and blue galaxies
- Supernovae in and behind clusters
  - Take advantage of dust-free ellipticals and extremely high-mass environment
- Dark energy evolution and fundamental tests of GR
  - Non-Gaussianity (gasp!)
- Next generation in lineage of statistical cluster samples of cosmological significance
  - Largest product of mass * redshift of any previous experiment
  - Most uniform selection wrt distance

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Optical follow-up is necessary

- 21 clusters at SZ S/N > 5 in 178 deg^2 (a >3e14M_{sol} cluster every 8 deg^2)
- Push down in SZ S/N to, say, a >~1e14 M_{sol} cluster every ~ deg^2
- 500 deg^2 surveyed per year
- Need redshifts on all of these

Two viable approaches

	Examples	Advantages	Disadvantages
Contiguous Survey	• Blanco Cosmology Survey • Dark Energy Survey	• Auxiliary science, eg, optical cluster finding • Can acquire before or after SZ survey • Uniform depth: reasonable optical selection functions	• Uniform depth: what if cluster is higher redshift? • Inefficient wrt principle science goal of cluster abundance measurement • Inefficient way to follow up rarest clusters
Point-and-shoot	• Our Magellan and Blanco programs • PISCO	• Highly efficient • Optimum use of available telescope time • Variability in depth • Ideal for an SZ survey	• Not as much auxiliary science • Can only acquire after SZ survey

A conventional optical strategy

Goals and assumptions

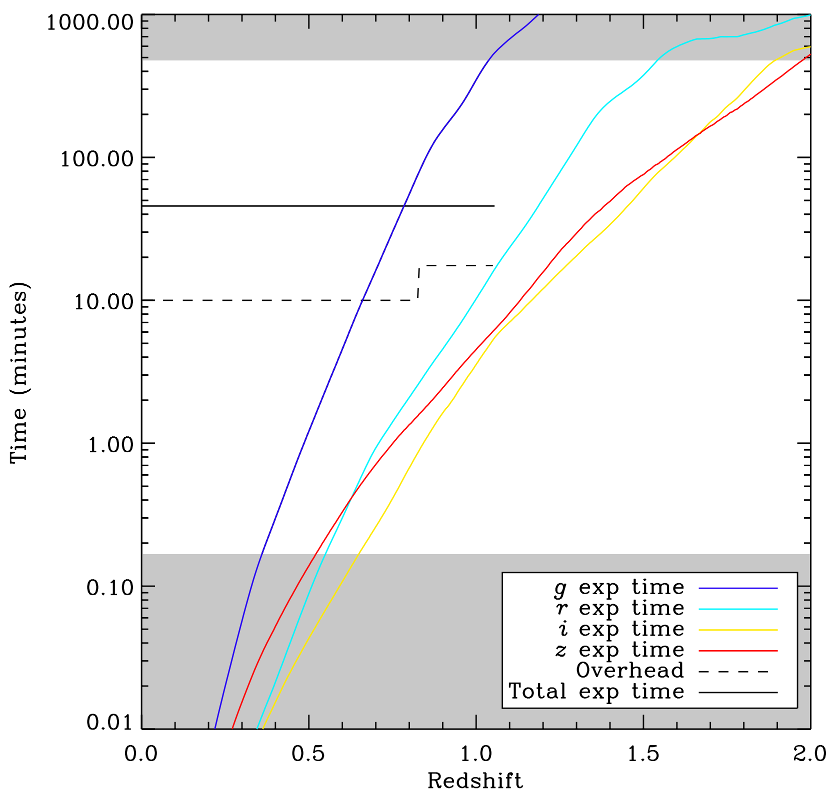
- Cluster discovery
- Detect 0.4L* early-type cluster galaxies to 10 sigma in 4” apertures in three bands: r, i, and z
- Assume SZ survey-type cluster redshift distribution
- No redshift prior
- ***Choose target redshift (~1)***

Procedure

100s griz exposures (~ 20-21 mag)

riz exposures to target redshift

A conventional optical strategy



- CTIO/Blanco 4m
- 2.5min readout
- z response is quite optimistic here

45 minutes per cluster, or
1 ⅓ cluster per hr, or
10 clusters per night

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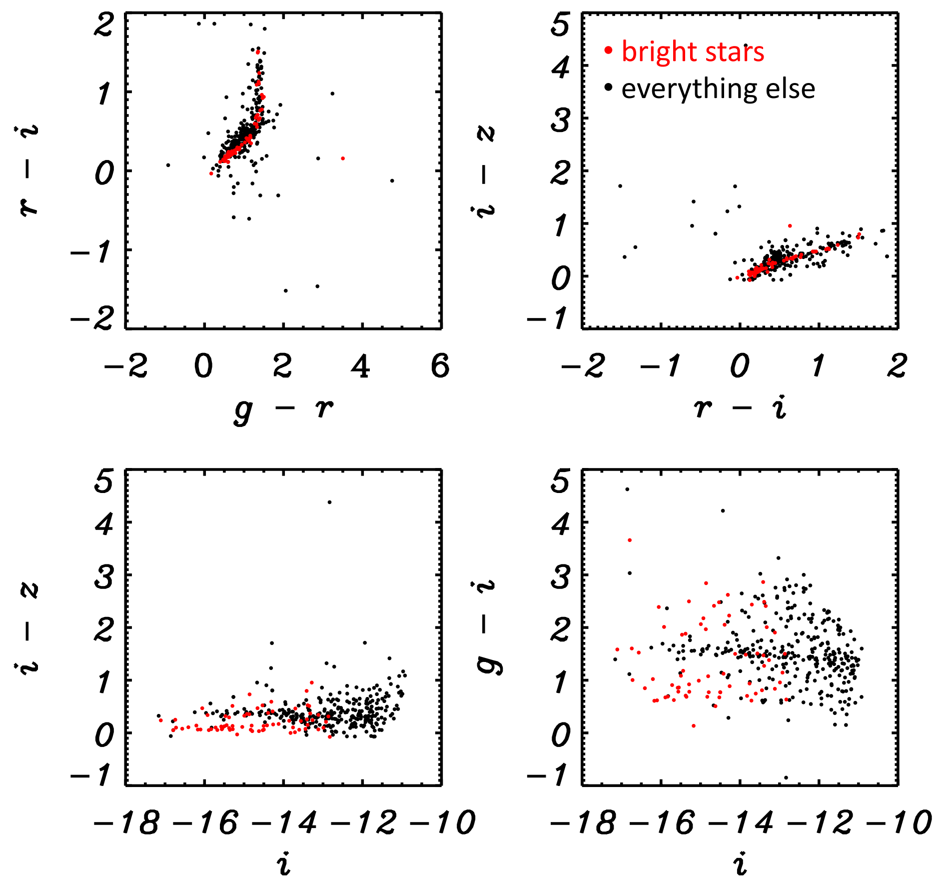
SLR is very simple

1. Calibrate *images* in usual way
2. Run SExtractor on *griz* images individually
3. Cross-match catalogs
4. Select CLASS_STAR > 0.8 and S/N > 10 objects
5. Plot color vs. color and color vs. mag

Instrumental photometry toward Abell 3675
~100s exposures
Magellan 6.5m telescope, LDSS3



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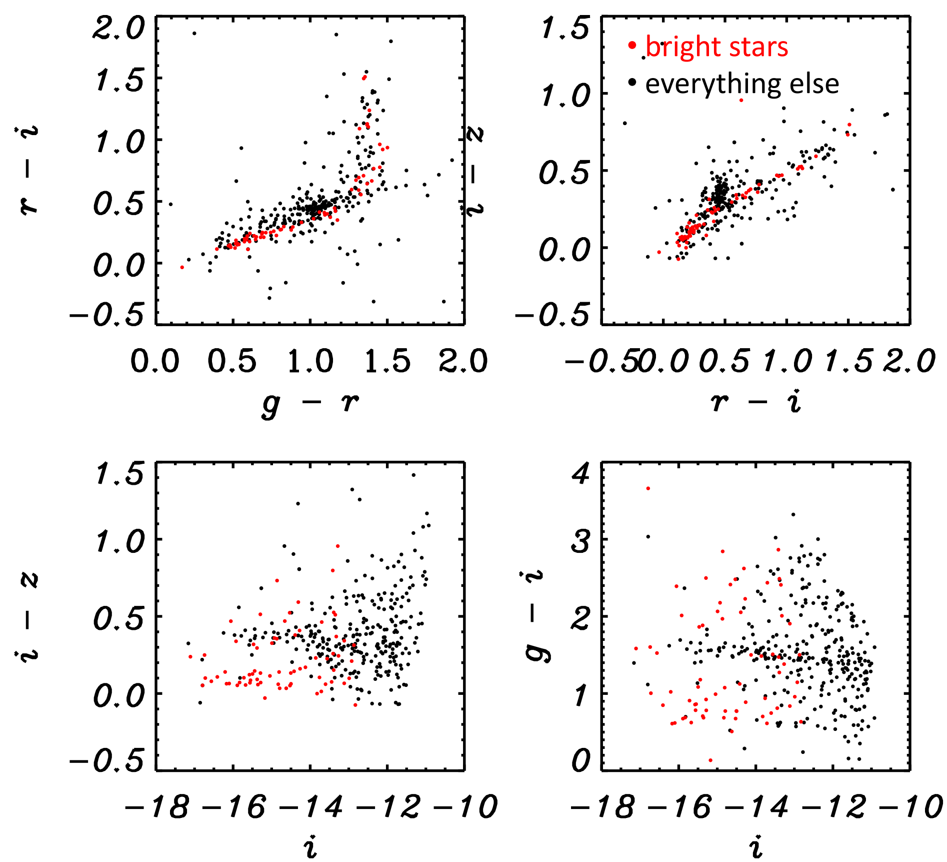
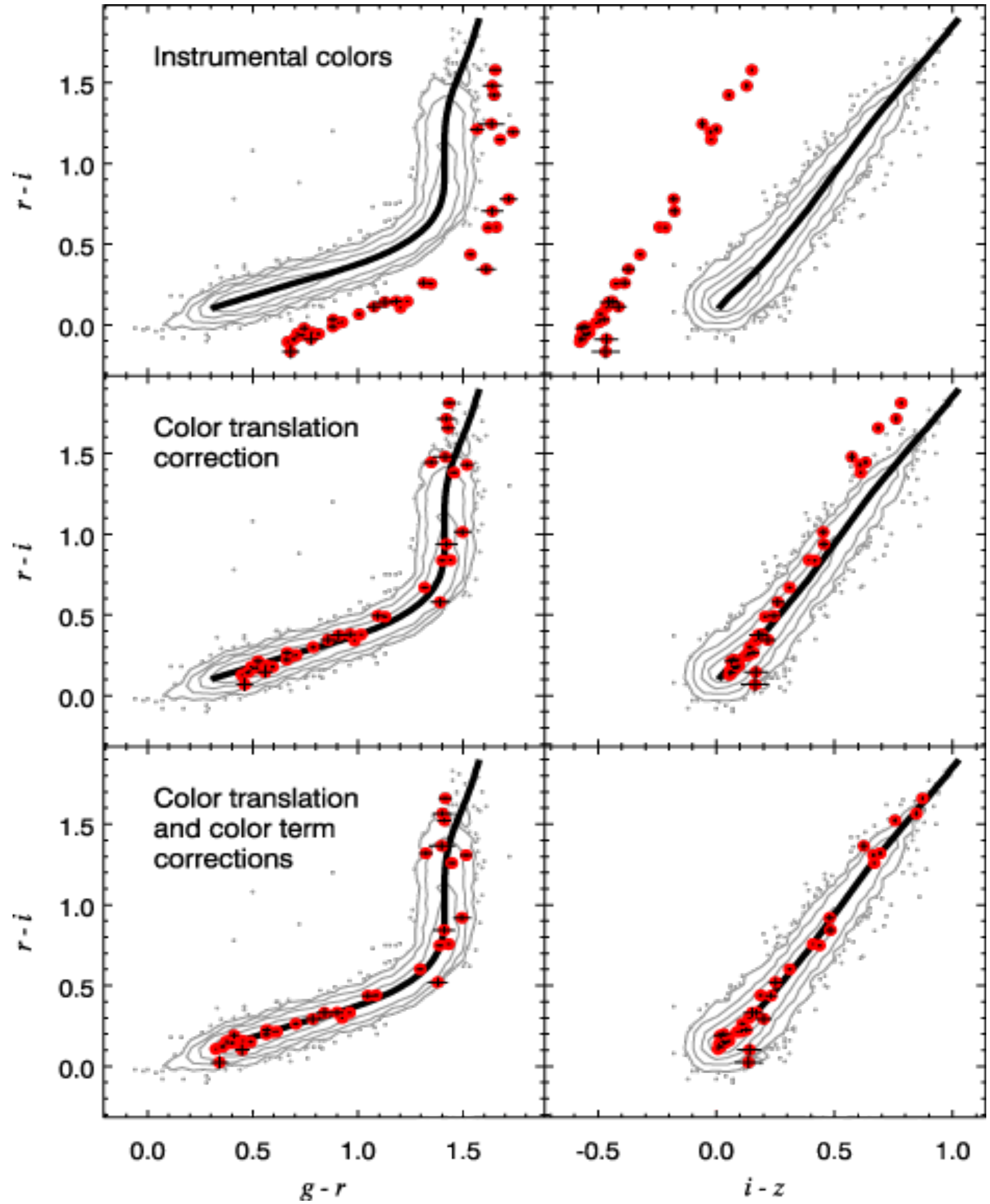




Standard locus:

- Smoothed running median of ~10^5 SDSS+2MASS stars (Covey et al. 2007)
- Could alternatively use Pickles (1998) stellar spectra library, but I argue *empirical is better when you can get it, because you don't have to fool around with transmission curves*

What this does

Typical photometric calibration equations:

$$g = g_0 + a_g + k_g \chi_g + A_g$$

$$r = r_0 + a_r + k_r \chi_r + A_r$$

$$i = i_0 + a_i + k_i \chi_i + A_i$$

$$z = z_0 + a_z + k_z \chi_z + A_z$$

Instrumental mags

truth

zeropoints

Atmospheric extinction

Galactic extinction

What this does

Typical photometric calibration equations:

$$g = g_0 + a_g + k_g \chi_g + A_g + b_g(g_0 - r_0)$$
$$r = r_0 + a_r + k_r \chi_r + A_r + b_r(r_0 - i_0)$$
$$i = i_0 + a_i + k_i \chi_i + A_i + b_i(i_0 - z_0)$$
$$z = z_0 + a_z + k_z \chi_z + A_z + b_z(i_0 - z_0)$$

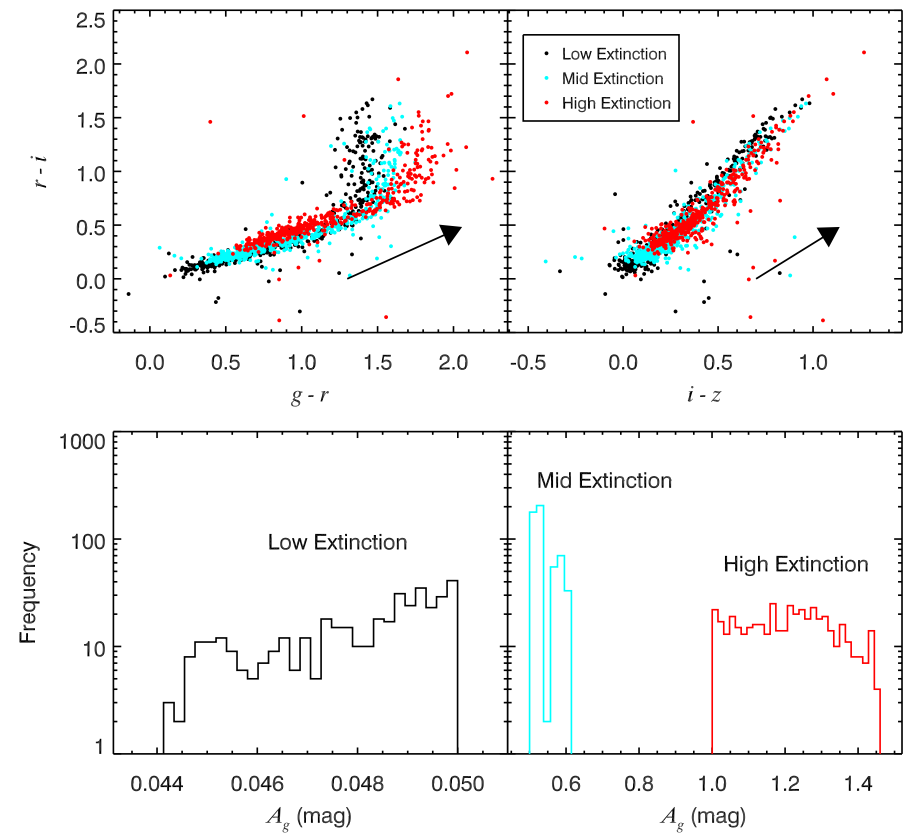
Color terms

Is the stellar locus position really sensitive to Galactic reddening?

Procedure:

- Query SDSS database for stars through narrow ranges of predicted Galactic extinction values
- Run SLR on catalogs (not dereddened)
- Compare best-fit color-translation terms to Schlegel, Finkbeiner & Davis (1998) prediction

Galactic extinction



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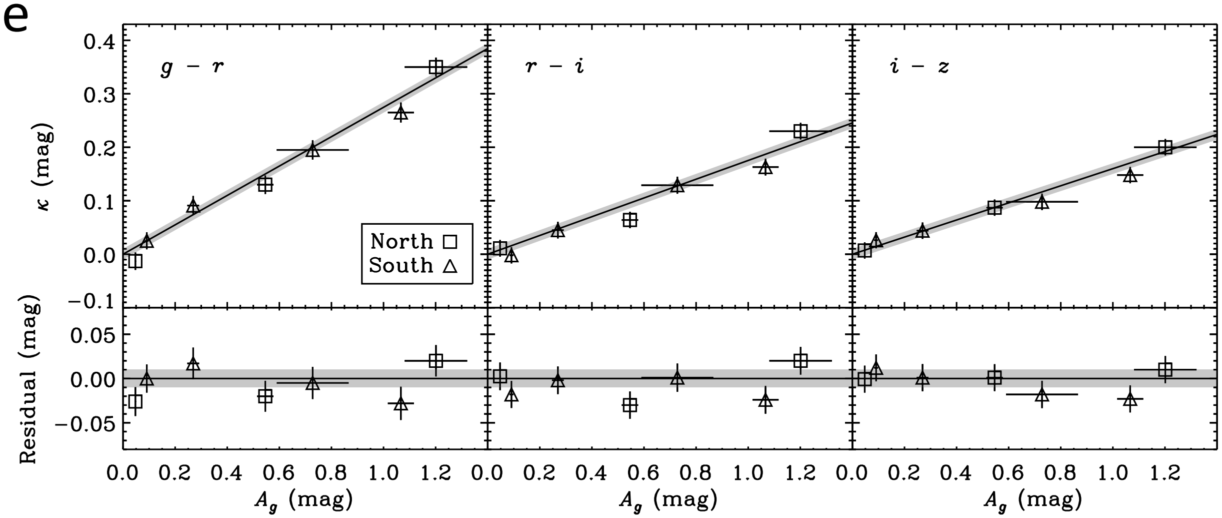
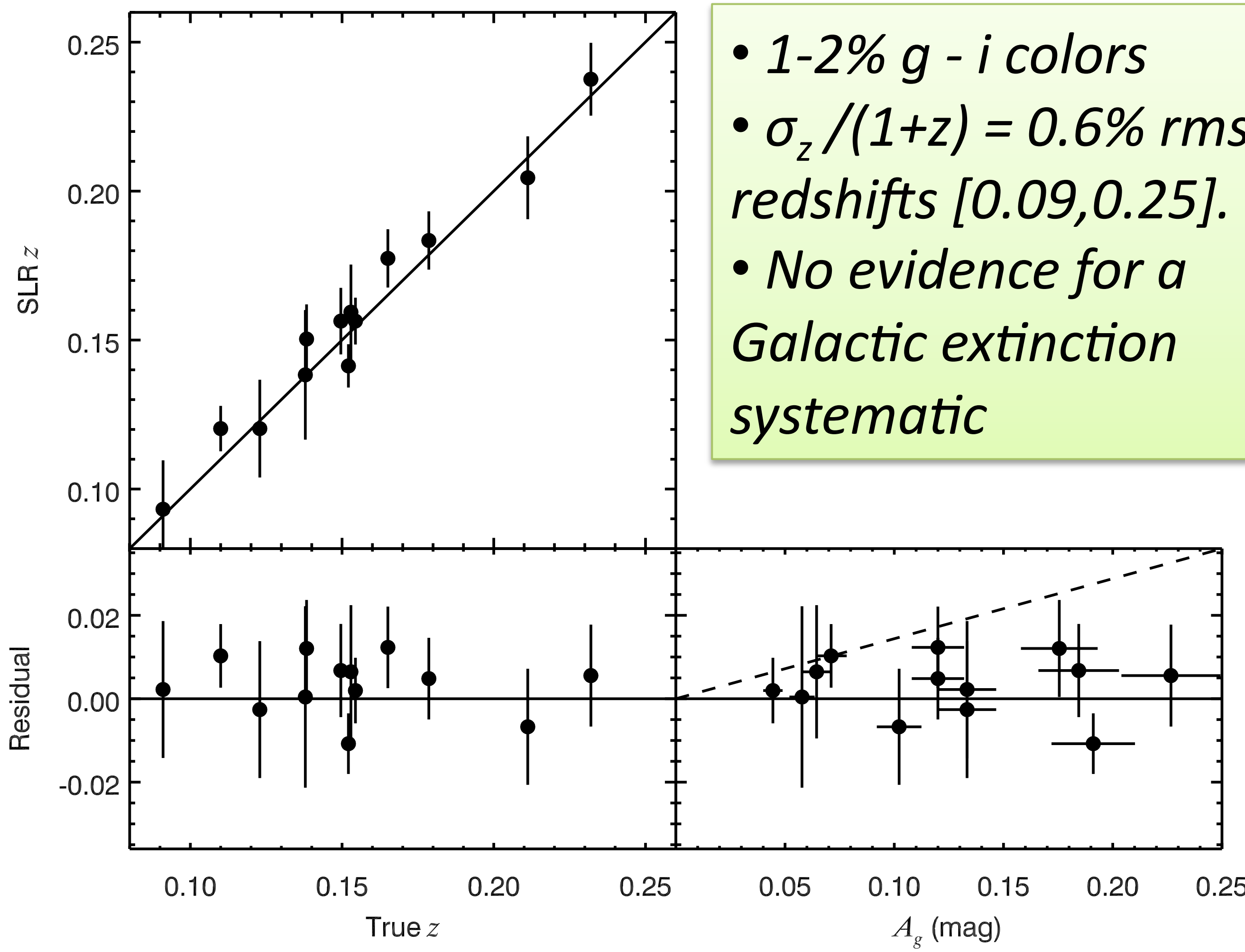
Galactic extinction



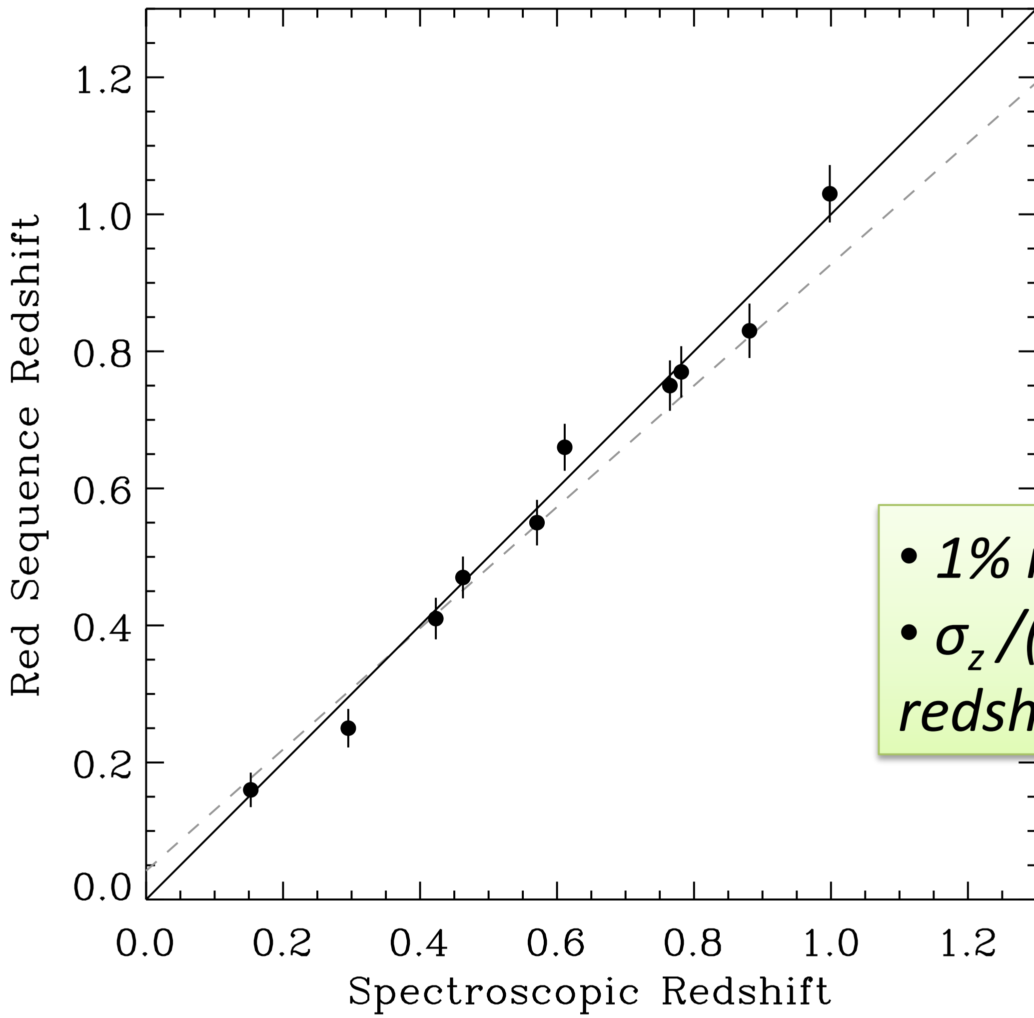
Correction good to (2, 2, 1)% rms in (g – r, r – i, i – z) over [0,1] mag of extinction in both Galactic hemispheres

Measuring cluster redshifts



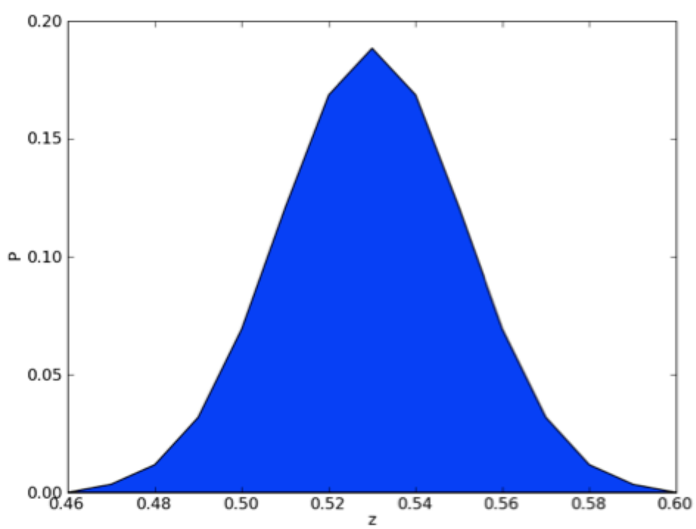
- *1-2% g - i colors*
- *$\sigma_z/(1+z)$ = 0.6% rms at redshifts [0.09,0.25].*
- *No evidence for a Galactic extinction systematic*

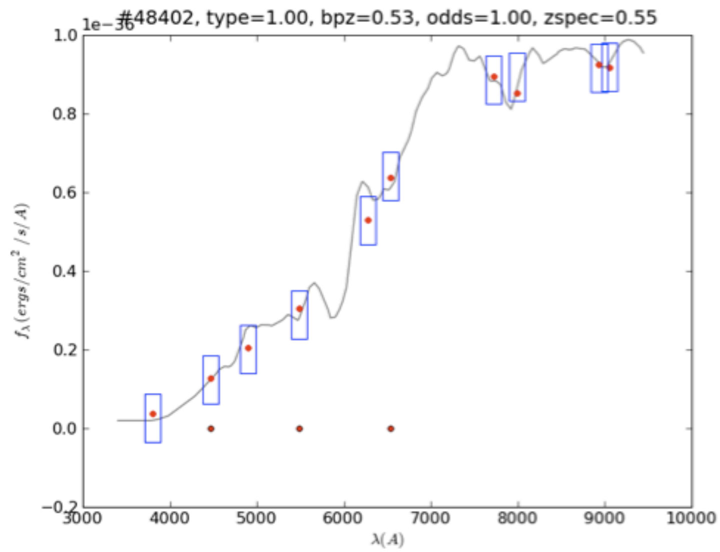
Measuring cluster redshifts

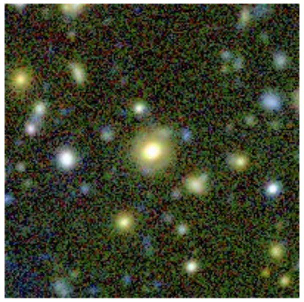


- *1% r – i & i - z colors*
- *σ_z /(1+z) = 2% rms at redshifts [0.15,1.0].*

The general photo-z problem

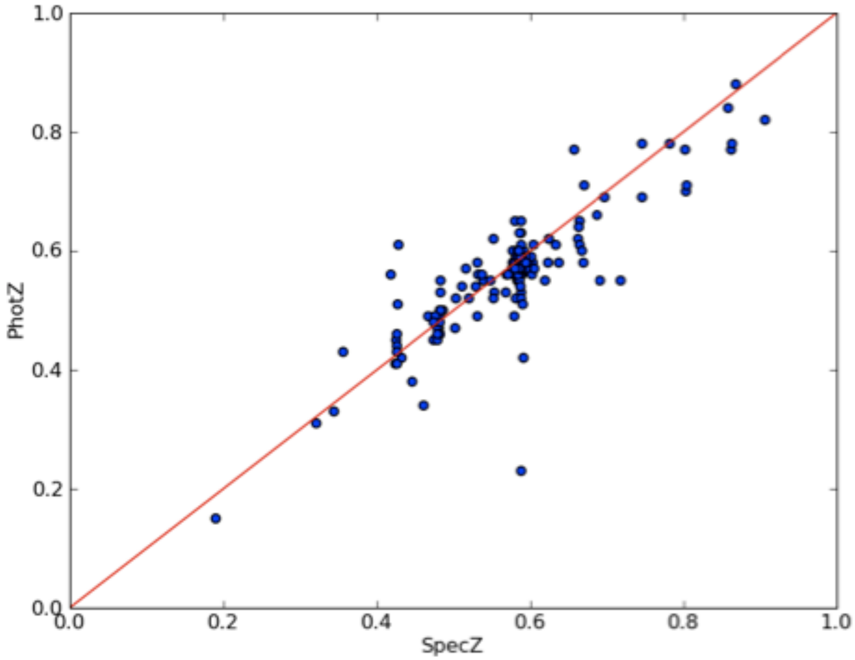


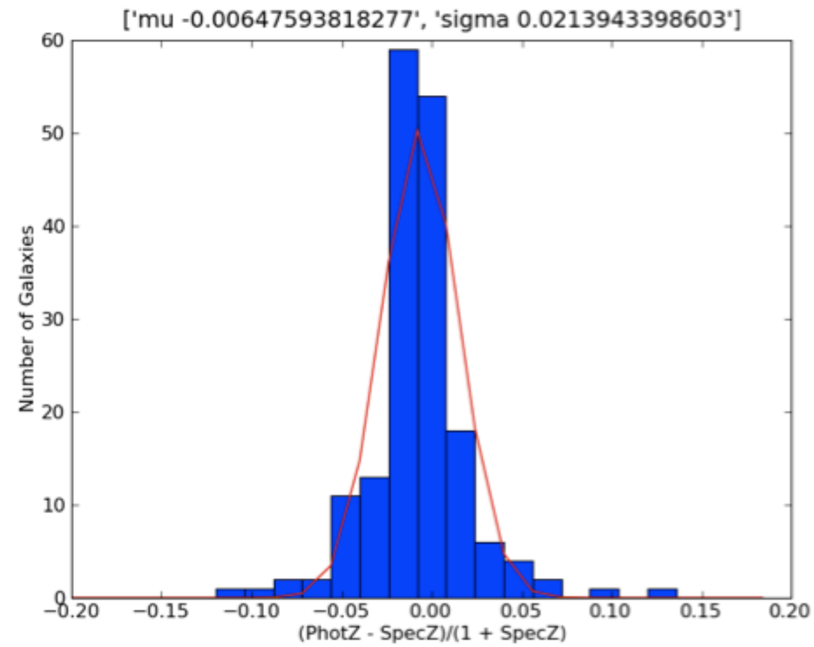




uBgVrRiIz photometry w/ Subaru
Hacked IDL code from stellar-locus-regression.googlecode.com
Pat Kelly, Anja von der Linden, Doug Applegate w/ Steve Allen @ Stanford

The general photo-z problem



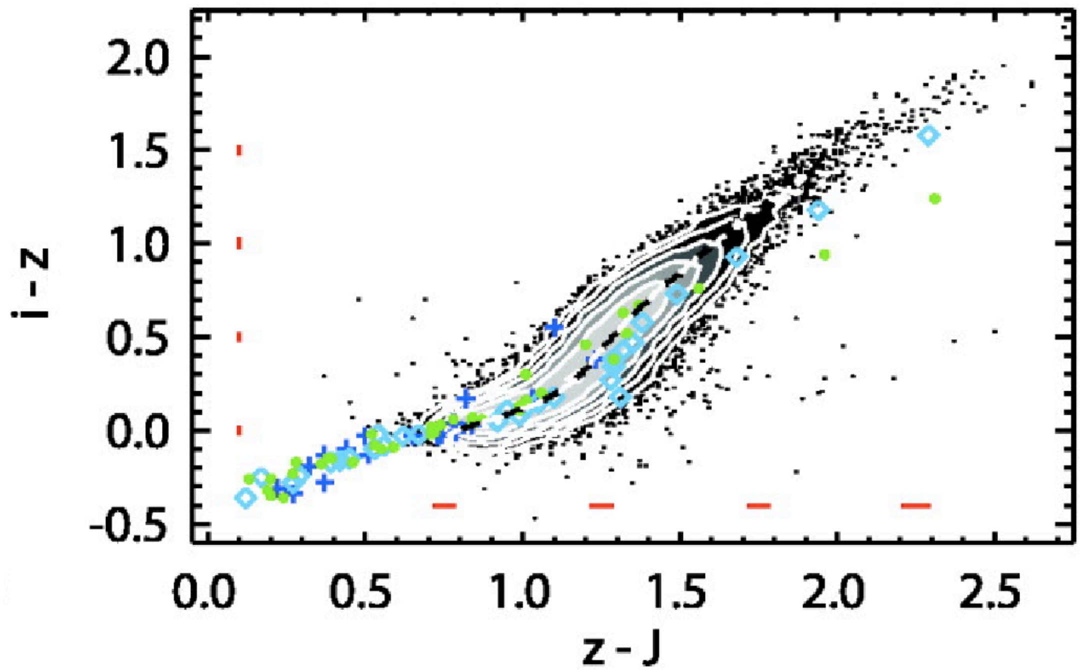


uBgVrRiIz photometry w/ Subaru
Hacked IDL code from stellar-locus-regression.googlecode.com
Pat Kelly, Anja von der Linden, Doug Applegate w/ Steve Allen @ Stanford

Arriving at *magnitudes* using 2MASS

2MASS J mags are already calibrated:

$$J = J_0,$$



Covey et al. (2007)

Only free parameters are z band calibration terms:

$$(z - J) = (z_0 - J_0) + a_z + E_z + A_z + b_z(i_0 - z_0) + c_z X_z(i_0 - z_0).$$

An efficient optical strategy

Goals and assumptions

- Cluster discovery
- Detect 0.4L* early-type cluster galaxies to 10 sigma in 4” apertures in three bands: r, i, and z
- Assume SZ survey-type cluster redshift distribution
- No redshift prior

Procedure

100s griz exposures (~ 20-21 mag)

for clusters not detected:

go 1 mag deeper in r, and correspondingly deeper in i and z

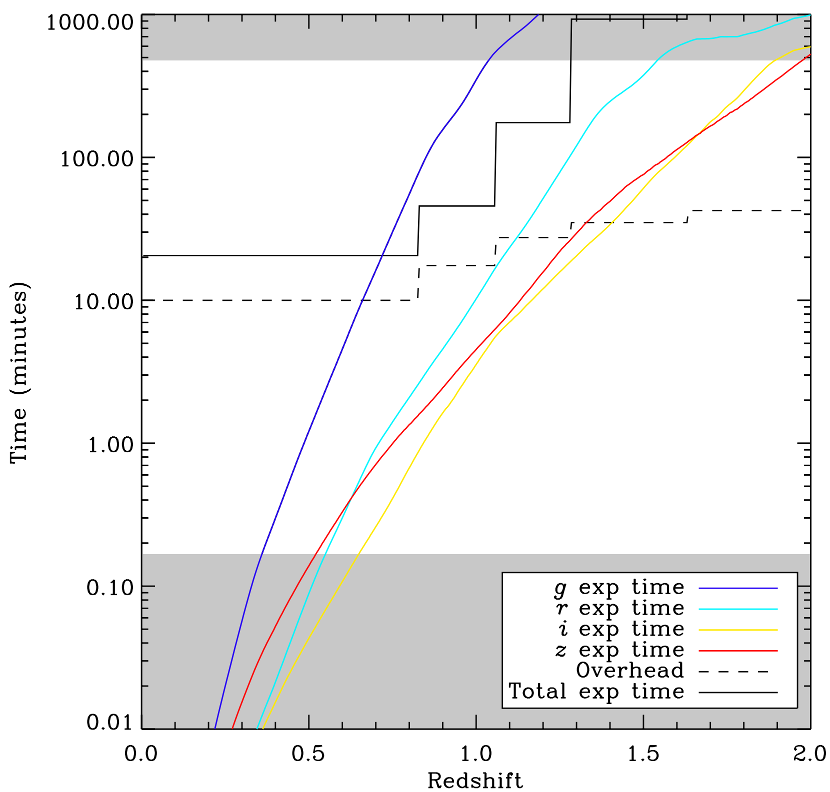
if min(possible redshift) > X:

give up

repeat until list is empty

An efficient optical strategy

Minutes per cluster vs redshift:



- Blanco/MOSAIC-II 4m
- 2.5min readout
- On-site reductions at 2min per image set, but no overhead (SLR)

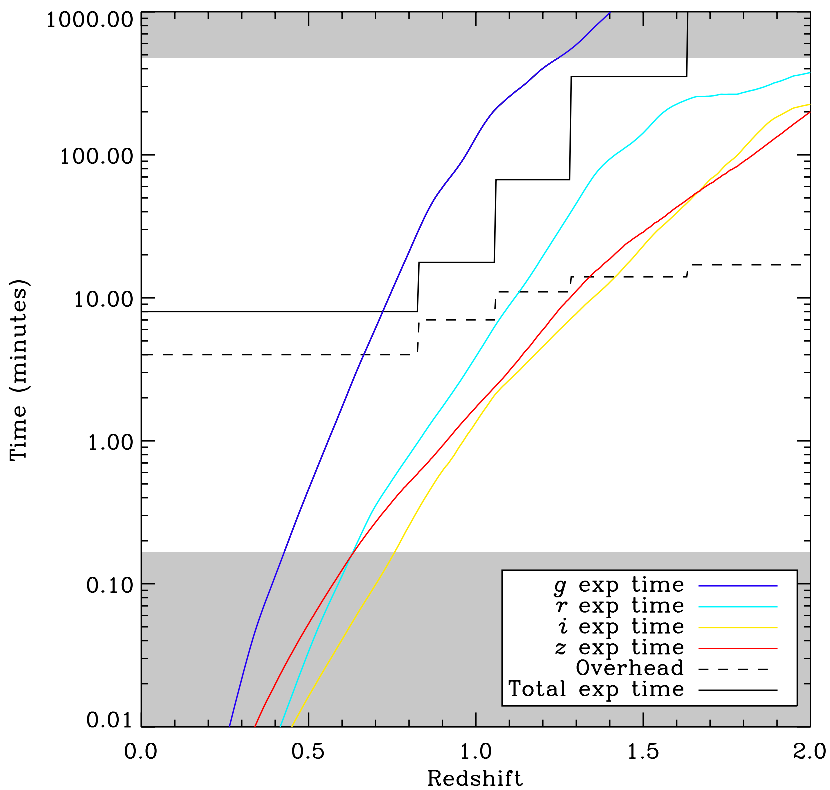
25 minutes per cluster, or
2 ⅖ clusters per hr, or
20 clusters per night
2 times more than conv'l strategy
****Arrive at results ~10³ times faster***


Blanco 4m, Cerro Tololo, Chile


Magellan 6.5m, Las Campanas, Chile

An efficient optical strategy

Minutes per cluster vs redshift:



- Magellan/IMACS 6.5m
- 1min readout
- On-site reductions at 2min per image set, but no overhead (SLR)

10 minutes per cluster, or
6 clusters per hr, or
50 clusters per night
2 ½ times more than Blanco 4m
****Arrive at results ~10³ times faster***

SLR summary

THE ASTRONOMICAL JOURNAL, 138:110–129, 2009 July doi:10.1088/0004-6256/138/1/110

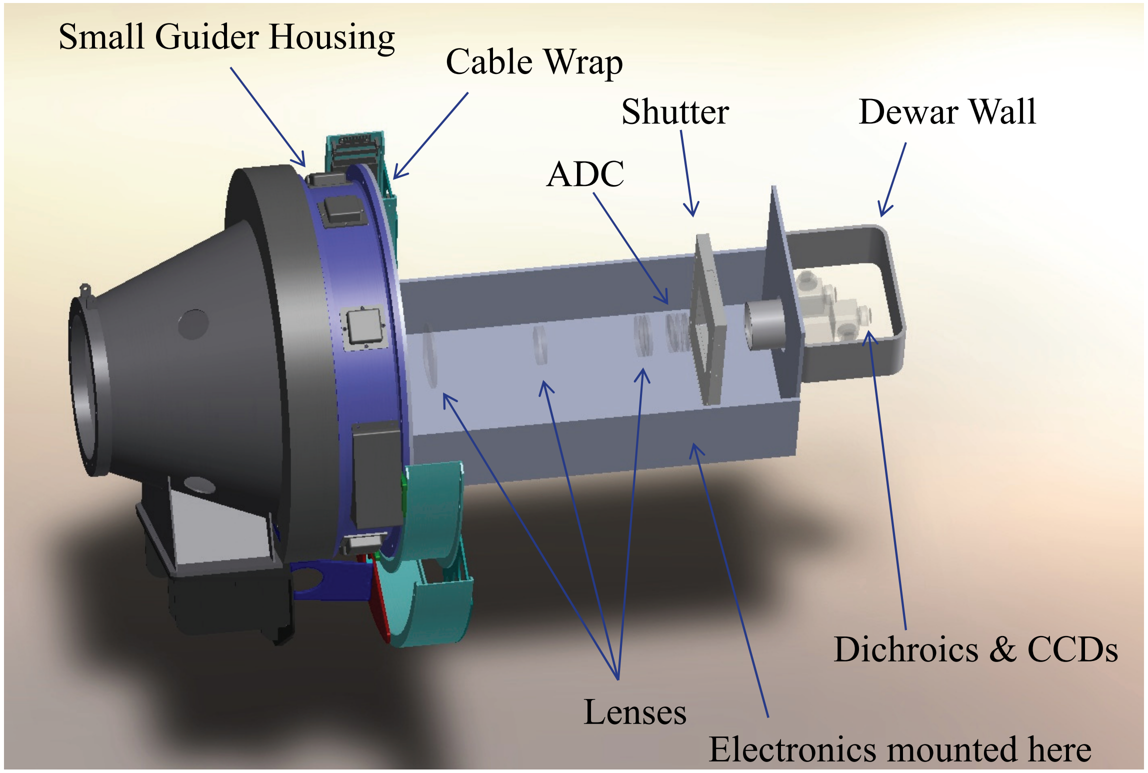
STELLAR LOCUS REGRESSION: ACCURATE COLOR CALIBRATION AND THE REAL-TIME DETERMINATION OF GALAXY CLUSTER PHOTOMETRIC REDSHIFTS

F. WILLIAM HIGH, CHRISTOPHER W. STUBBS, ARMIN REST, BRIAN STALDER, AND PETER CHALLIS
Department of Physics and Harvard-Smithsonian Center for Astrophysics, Harvard University, Cambridge, MA, USA; high@physics.harvard.edu
Received 2009 January 30; accepted 2009 April 24; published 2009 May 27

- Code publicly available at http://stellar-locus-regression.googlecode.com/
- SLR calibrations are easy, fast, accurate, and no standard stars are needed
- Remarkable Galactic dereddening capability… new tool for Galactic extinction corrections, entirely independent of SFD
- Steve Allen and team at Stanford have used it to solve the general photo-z problem in their X-ray cluster weak lensing program, Subaru BVRIz
- Sub-percent calibrations in *i*/*z* bands (notoriously difficult), probably *y* too
- A way for Pan-STARRS & LSST to calibrate images on readout
- Did I mention Galactic extinction?

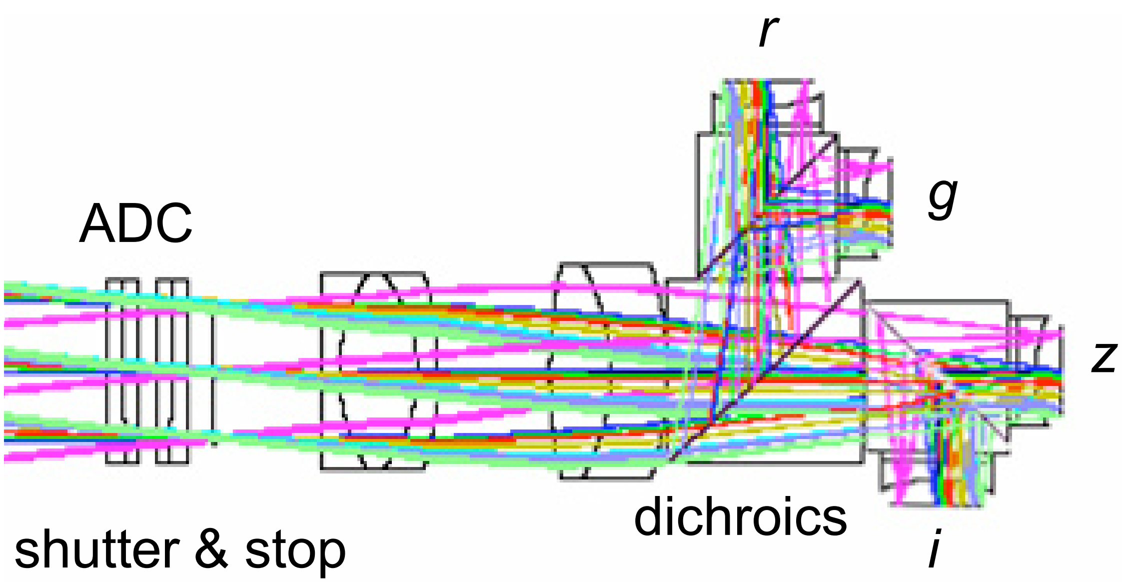
Outline

1. Galaxy clusters, the SZE, and cosmology
2. Proof of concept: SPT 2008 cluster survey
3. The problem of following up ~10^3 clusters
    A. A software solution: Stellar Locus Regression
    B. A hardware solution: Parallel Imager for Southern Cosmological Observations (PISCO)
4. Wrap-up



Parallel Imager for Southern Cosmological Observations

An f/11 reimaging CCD camera for a Magellan 6.5m Nasmyth port. Four focal planes, three dichroic beamsplitters, *one shutter.*



Parallel Imager for Southern Cosmological Observations

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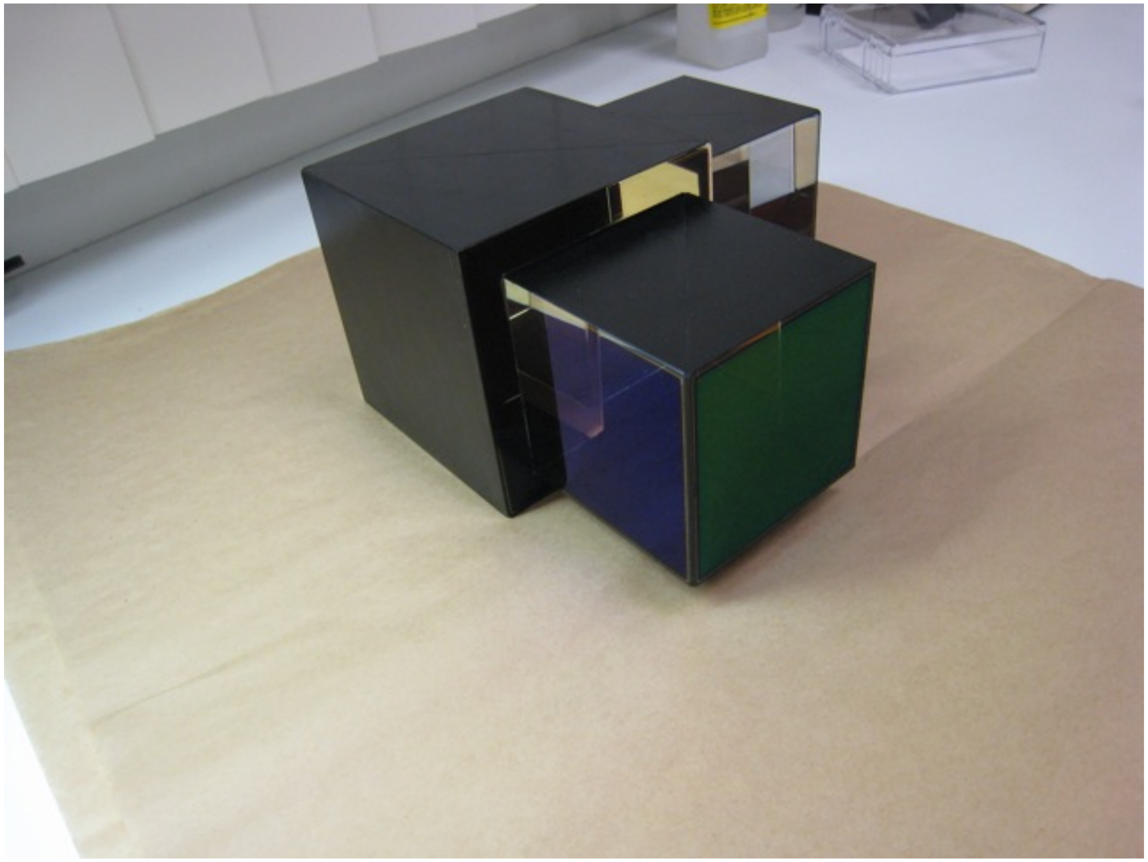

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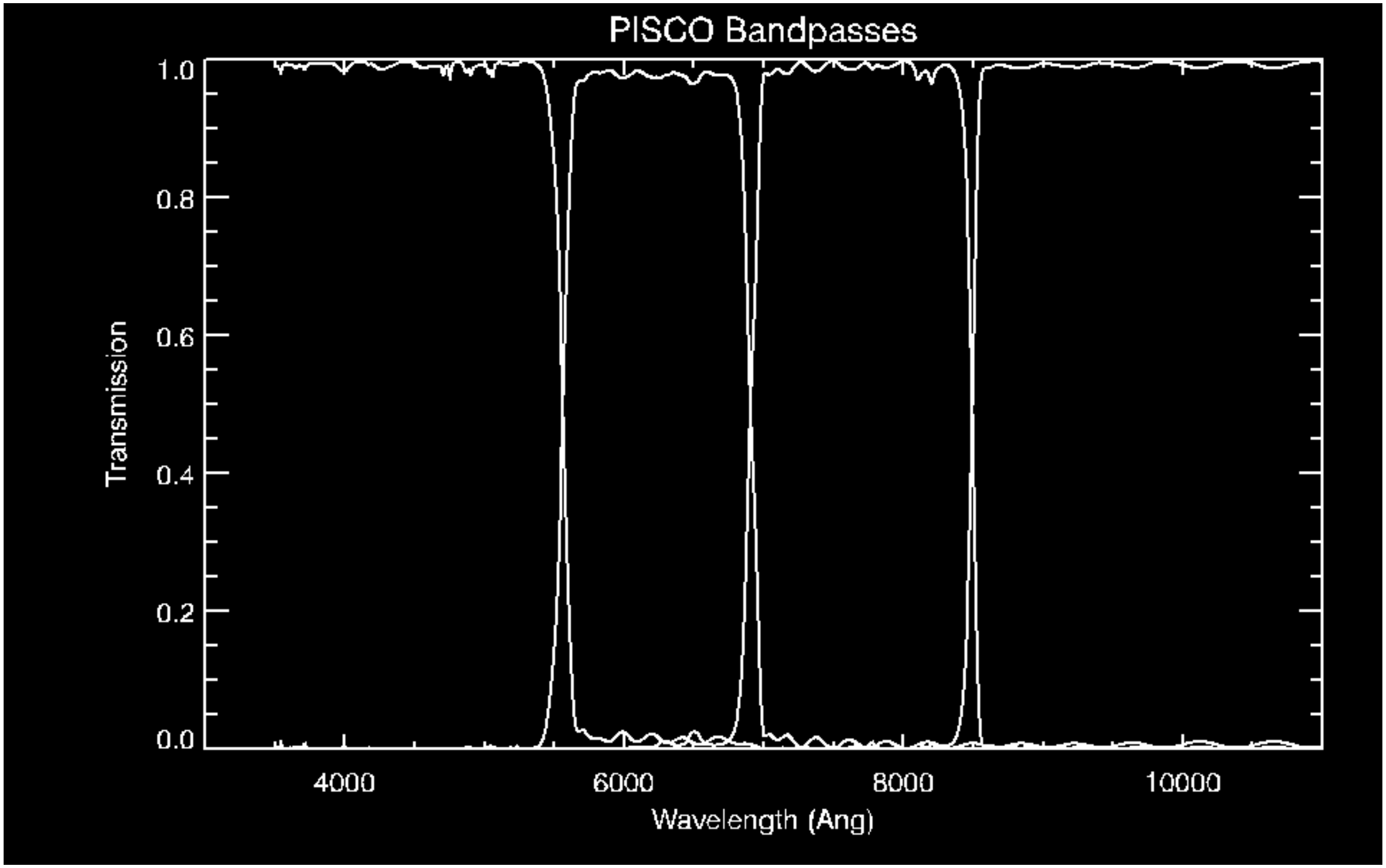

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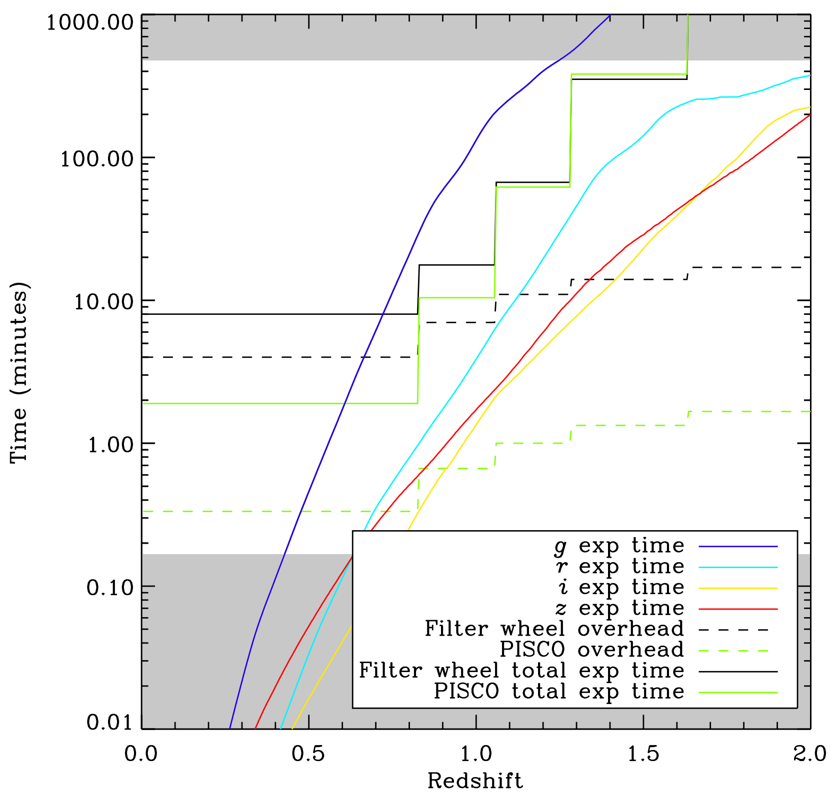
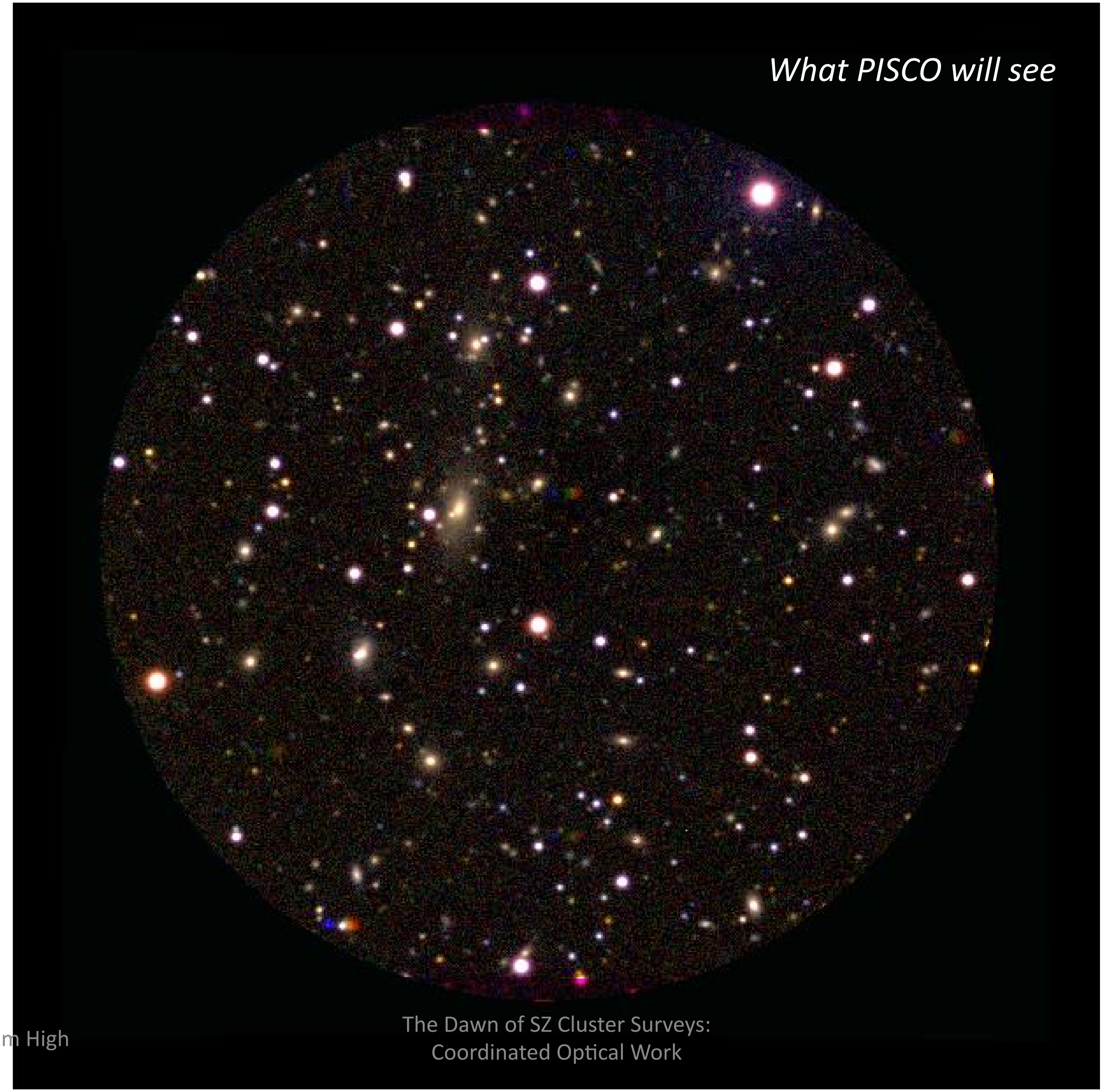
An efficient optical strategy

Minutes per cluster vs redshift:



- Magellan/PISCO 6.5m
- 20sec readout
- 20% reduction in efficiency from glass
- Real-time reductions

4 minutes per cluster, or
17 cluster per hr, or
130 clusters per night
3 times more than IMACS
7 times more than Blanco 4m
13 times more than conv'l strategy
****Arrive at results ~10^3 times faster***


What PISCO will see

PISCO Team

Faculty PI's:

- Chris Stubbs (Harvard/CfA)
- Tony Stark (SAO)

External:

- John Geary (CfA)
- Steve Amato (CfA)
- Steve Shectman (Carnegie)
- Steve Sansone (Harvard)

Post-docs:

- Brian Stalder (Harvard)
- Armin Rest (Harvard)
- Andrea Loehr (SAO→ industry)

Graduate Students

- James Battat (CfA→MIT)
- Will High (Harvard)

Summary

- We have just announced a uniform selection of 21 galaxy clusters from the SZ effect, using the South Pole Telescope and coordinated optical observations
  - arXiv:1003.0003
  - arXiv:1003.0005
- Follow-up ain't easy, and we've made major headway with
  - Stellar Locus Regression (+efficient observing)
  - PISCO
- These clusters should be of broad interest, in cosmology and astrophysics