Cluster Cosmology with the South Pole Telescope

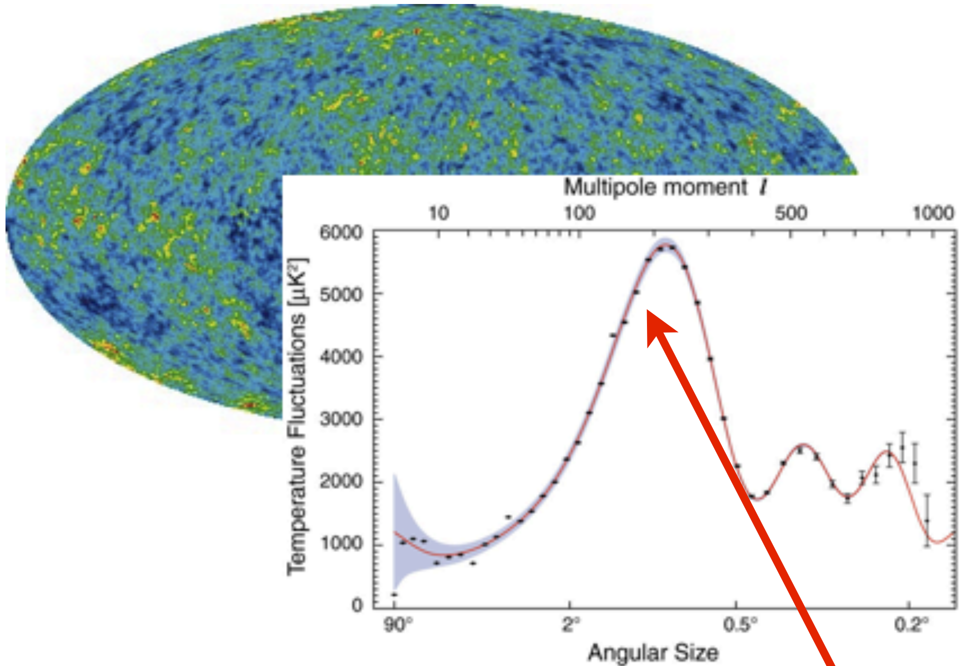
Lindsey Bleem

July 1, 2013

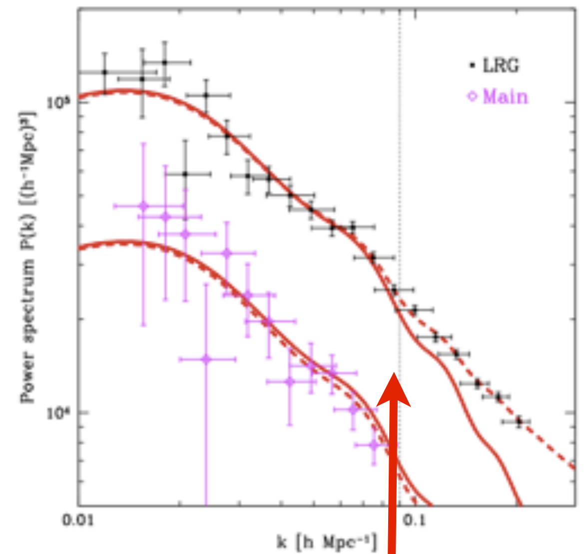
SPT Team July 2010

Outline

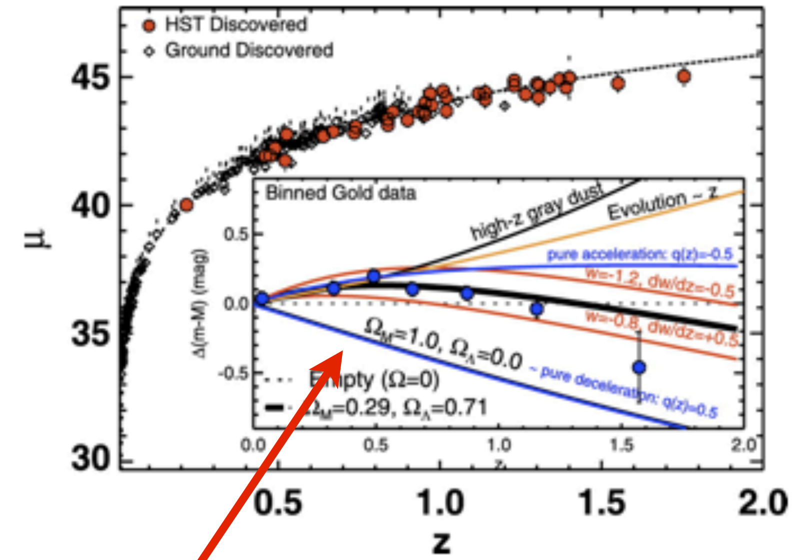
- Brief Introduction
- The SPT Cluster Sample
- Example Joint Optical-SZ Study



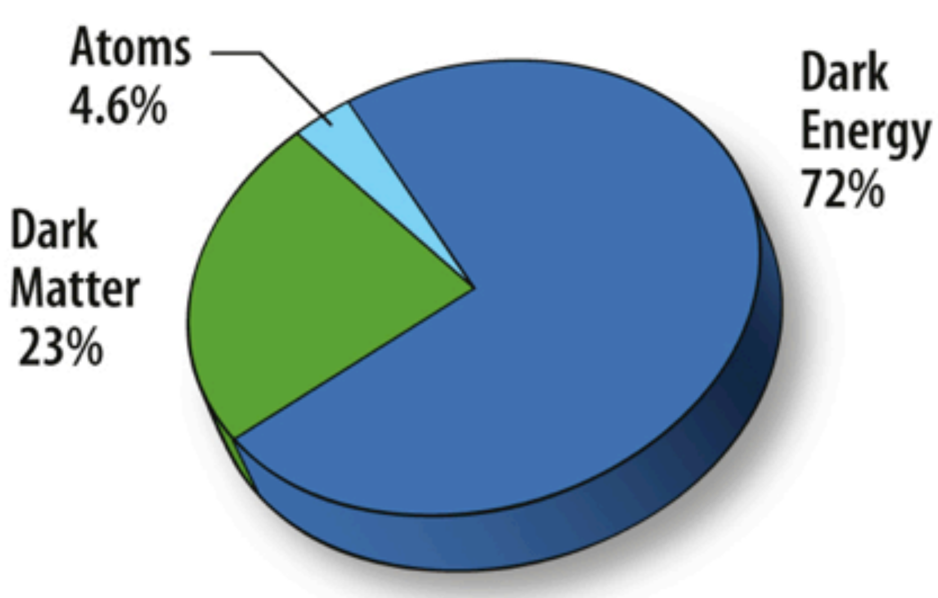
Tegmark et al 2006



Riess et al 2007

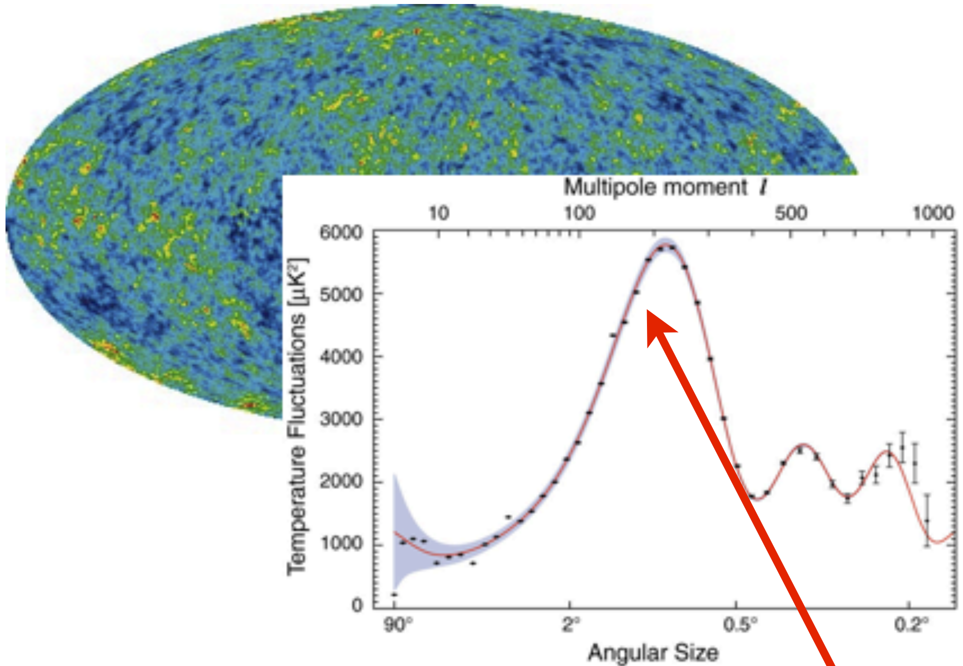


CMB + Large Scale Structure + SNe Ia

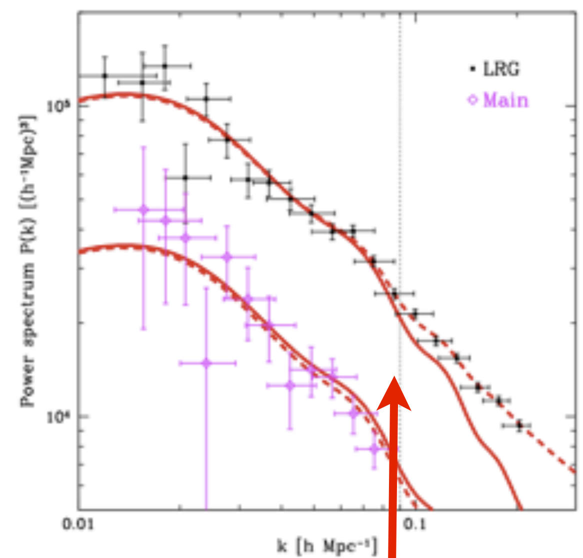


We live in a flat universe whose density is dominated by dark energy

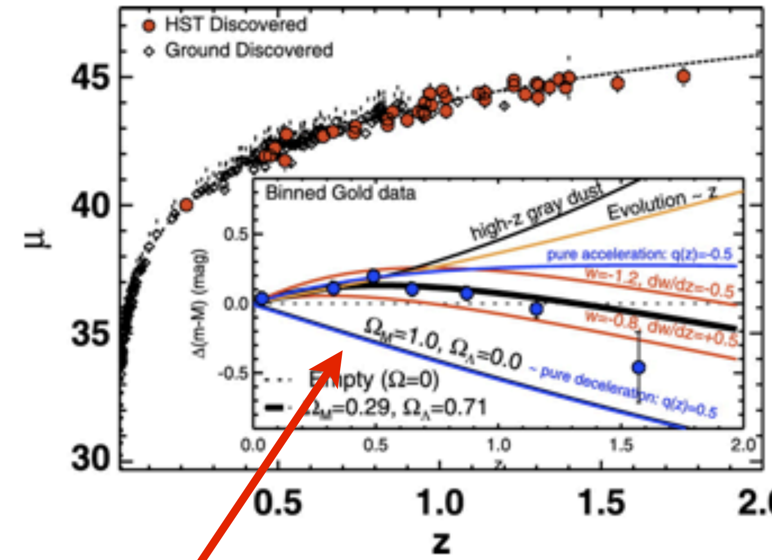
... but what is dark energy?



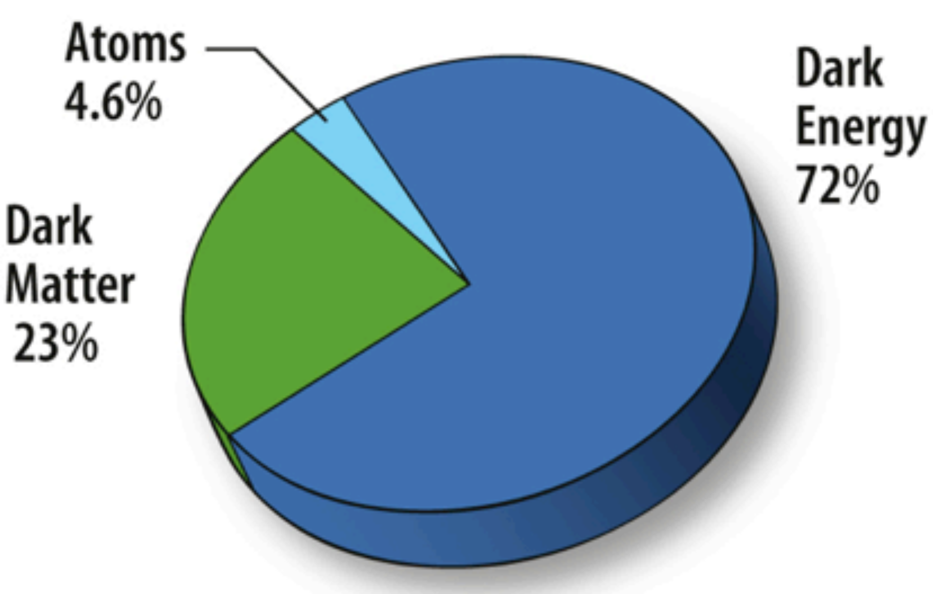
Tegmark et al 2006



Riess et al 2007

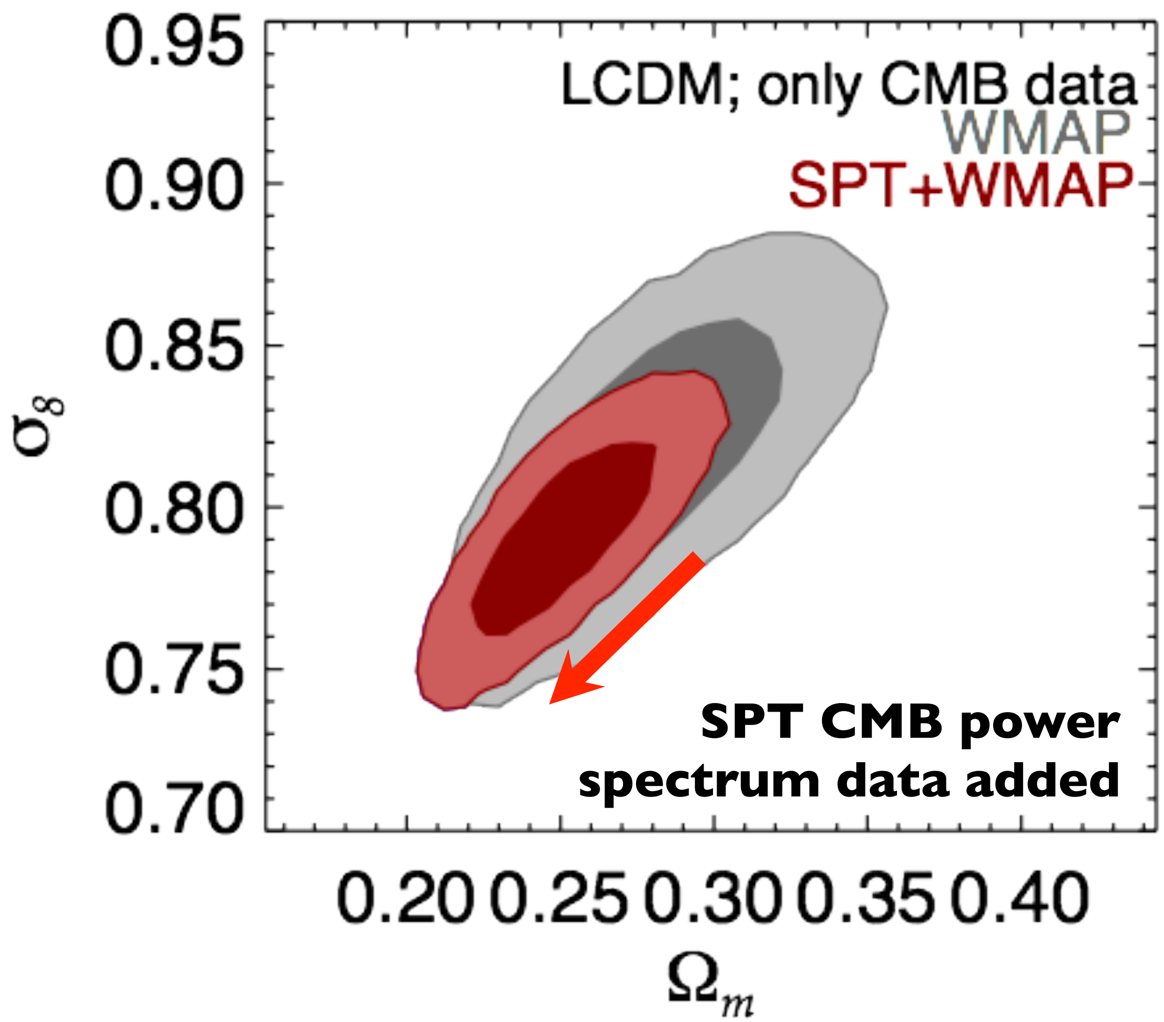


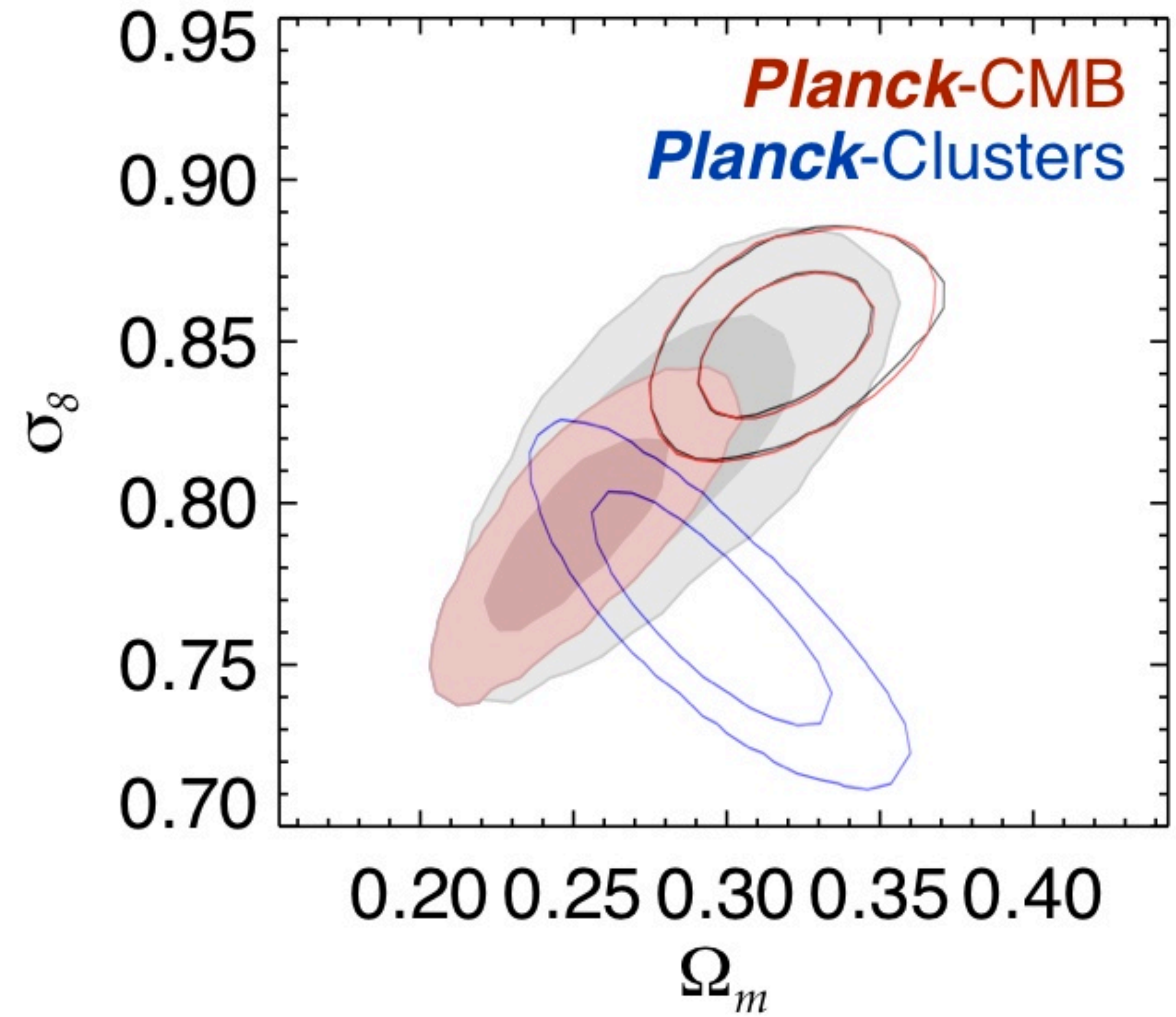
CMB + Large Scale Structure + SNe Ia



Galaxy clusters, as a probes of the growth of structure, can be used to study Dark Energy.

CMB Constraints on σ_8, Ω_m

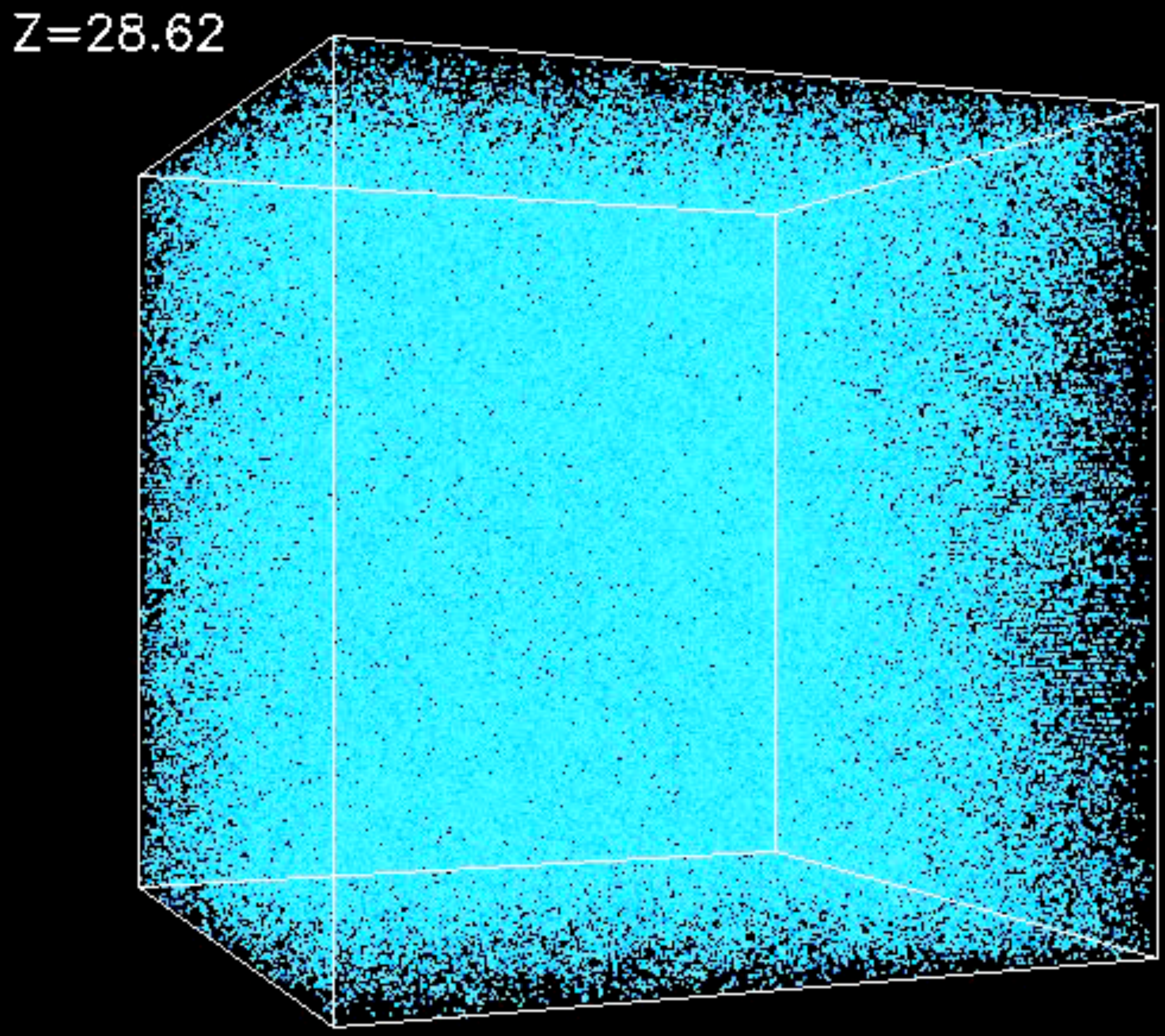




	WMAP7	WMAP7+SPT	Planck-CMB
σ_8	0.819 +/- 0.031	**0.795 +/- 0.022**	**0.829 +/- 0.012**
Ω_m	0.276 +/- 0.029	**0.250 +/- 0.020**	**0.315 +/- 0.016**

(WMAP7) Komatsu +2011
(SPT) Story+2012
Planck XX 2013
Planck XVI 2013

Sim & Image: Andrey Kravtsov



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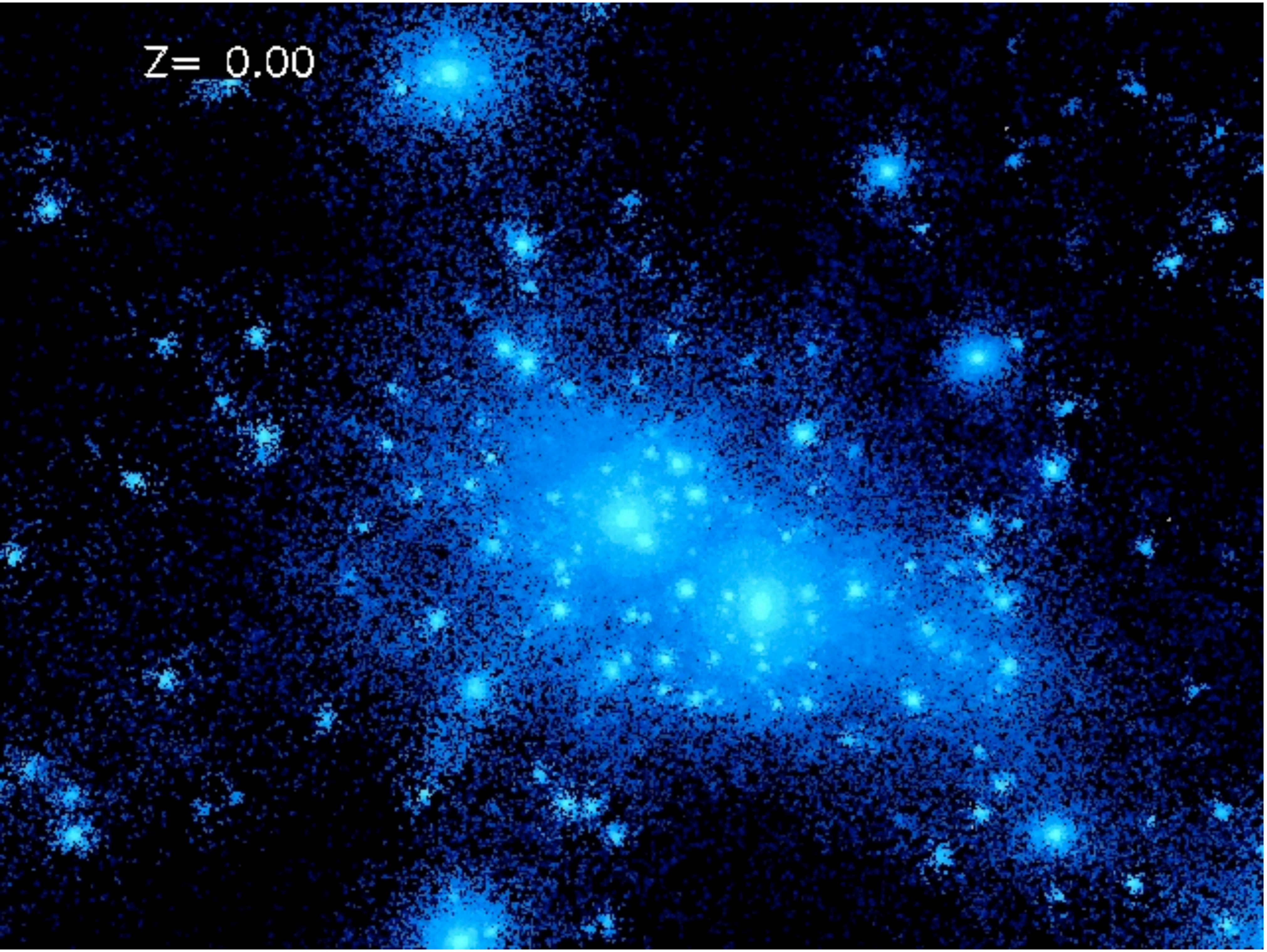
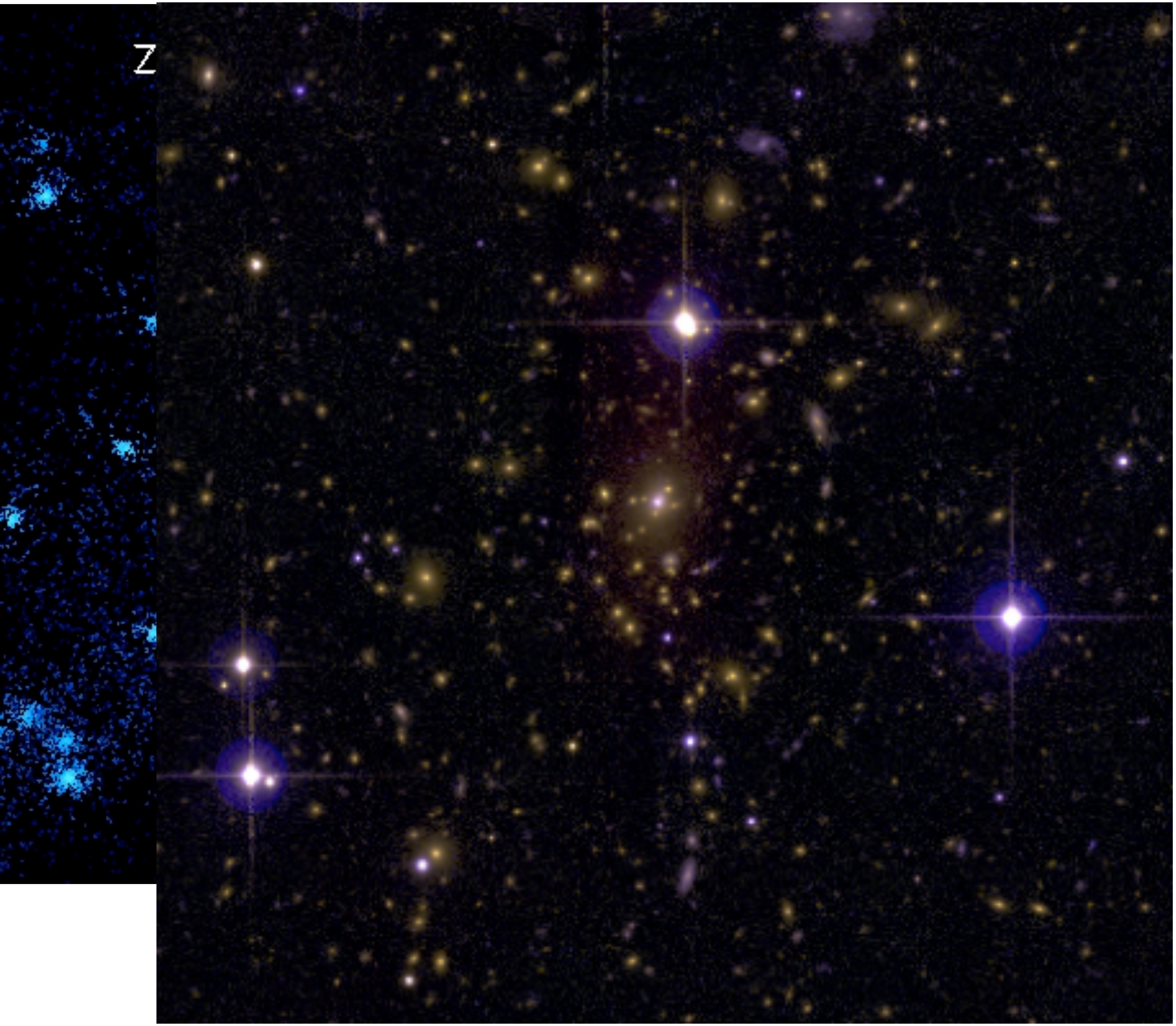


Simulations

Scale: 4Mpc

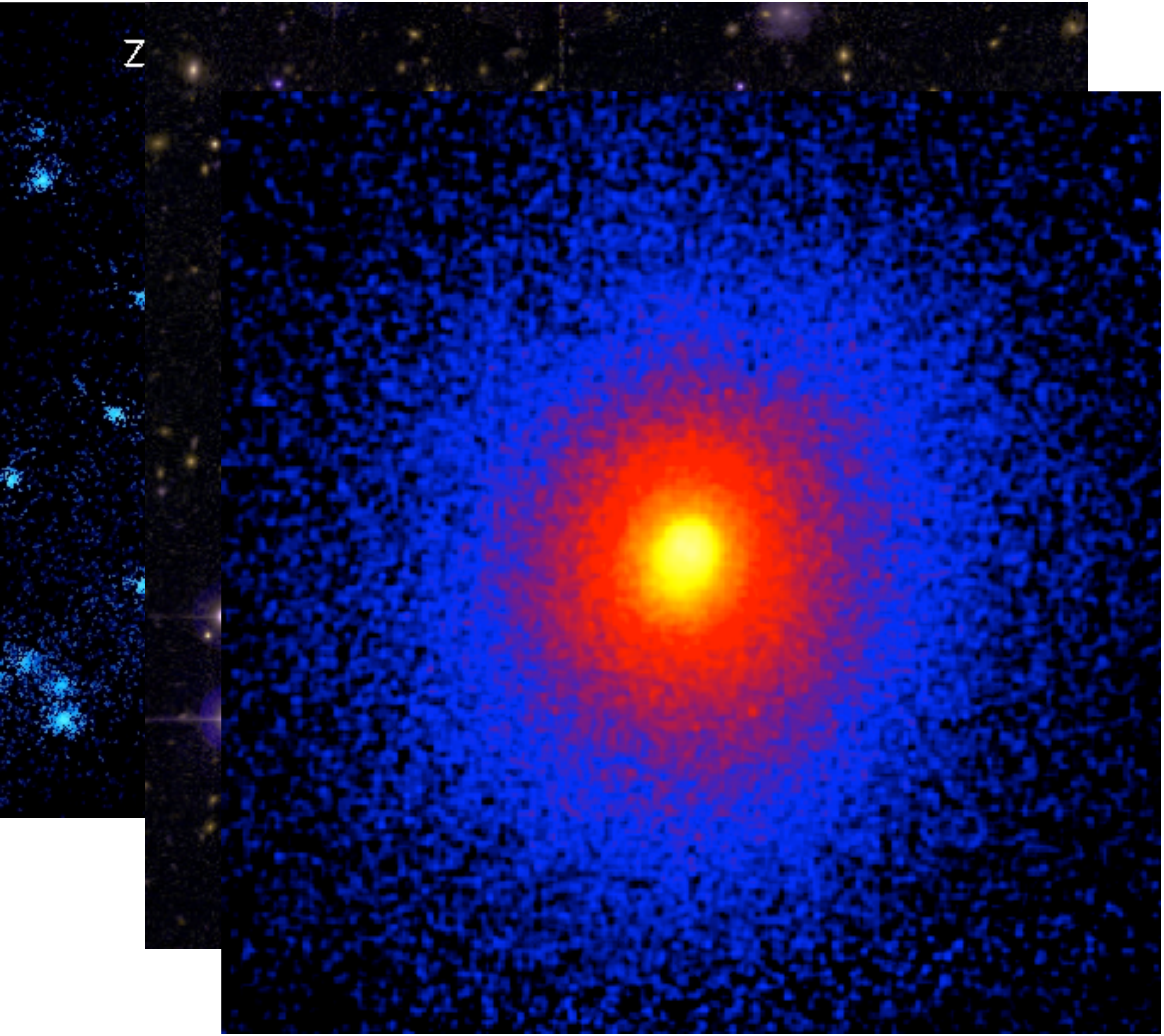
Kravtsov et al.



Optical

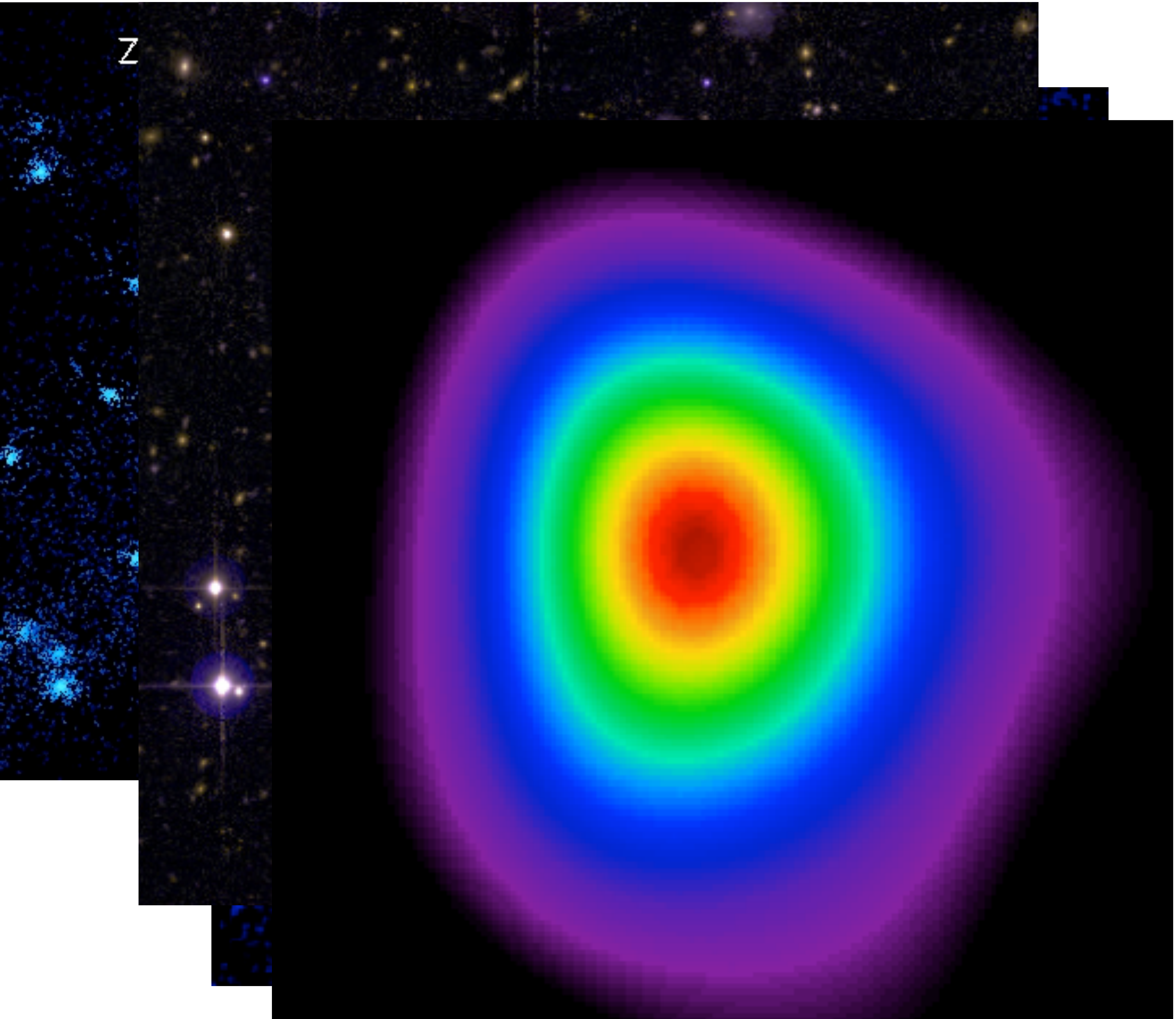
Scale 1.2 Mpc
(5’, z=0.23)

Allen et al.



X-ray

Allen et al.



mm

Allen et al.

We can use the abundance of clusters to probe dark energy.

Cluster Abundance, dN/dz

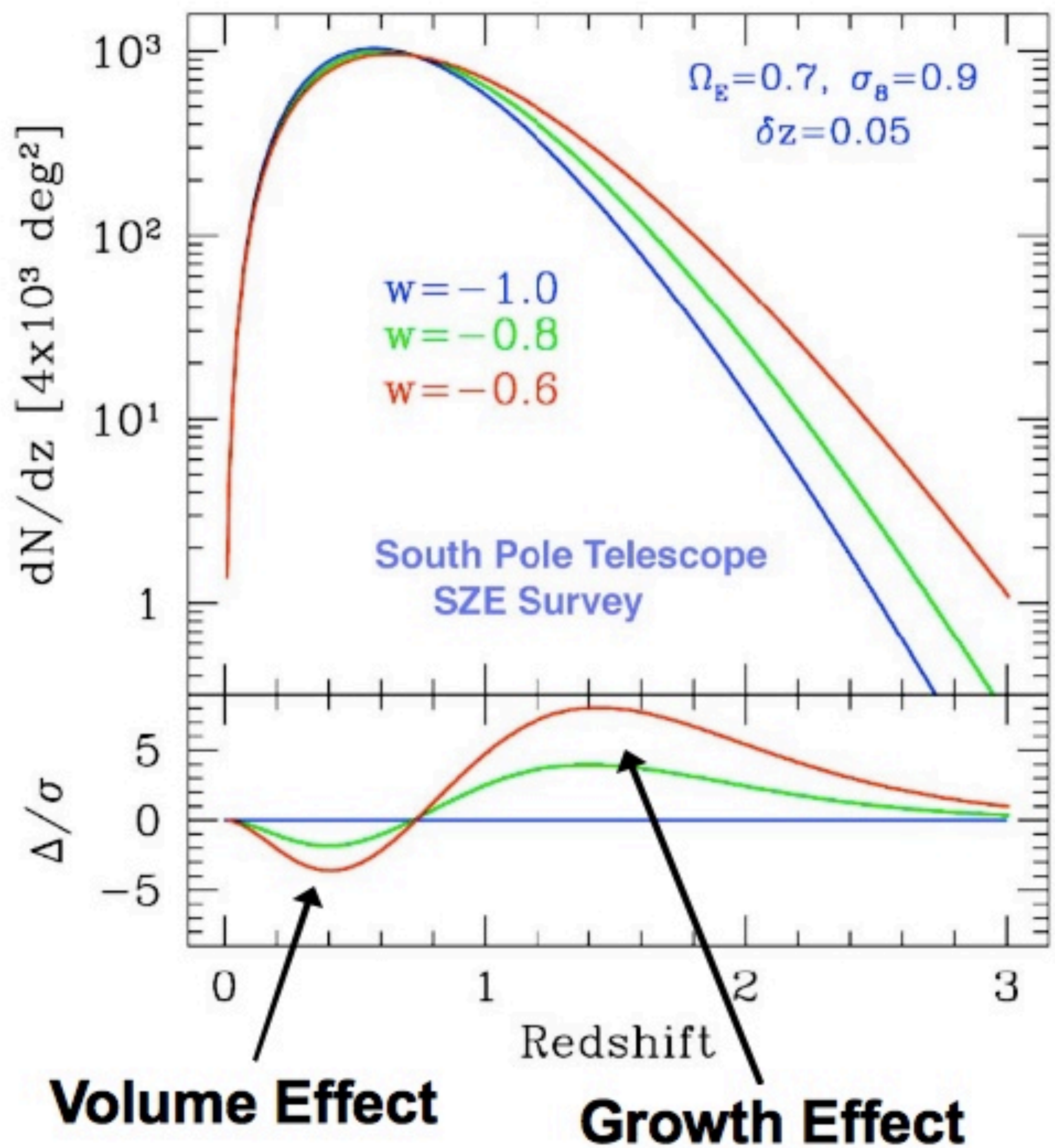
$$\frac{dN}{d\Omega dz} = n(z)\frac{dV}{d\Omega dz}$$

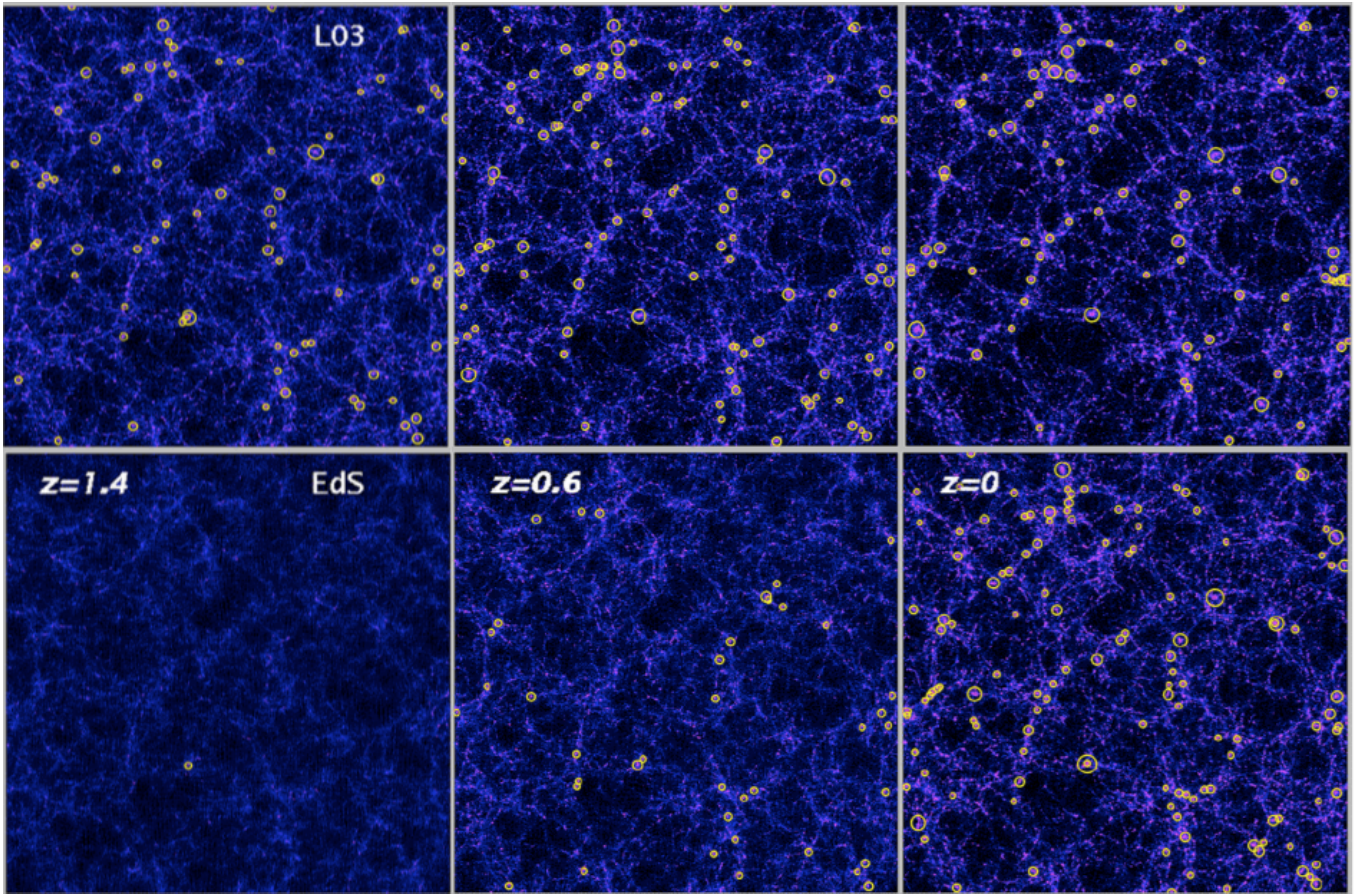
Depends on:
Matter Power Spectrum, *P(k)*
& *exponentially on the*
Growth Rate of Structure, D(z)

Depends on:
Rate of Expansion, *H(z)*

$$\rho \propto a^{-3(1+w)}$$

Credit: Joe Mohr





Source Borgani and Guzzo 2001

The cluster mass budget

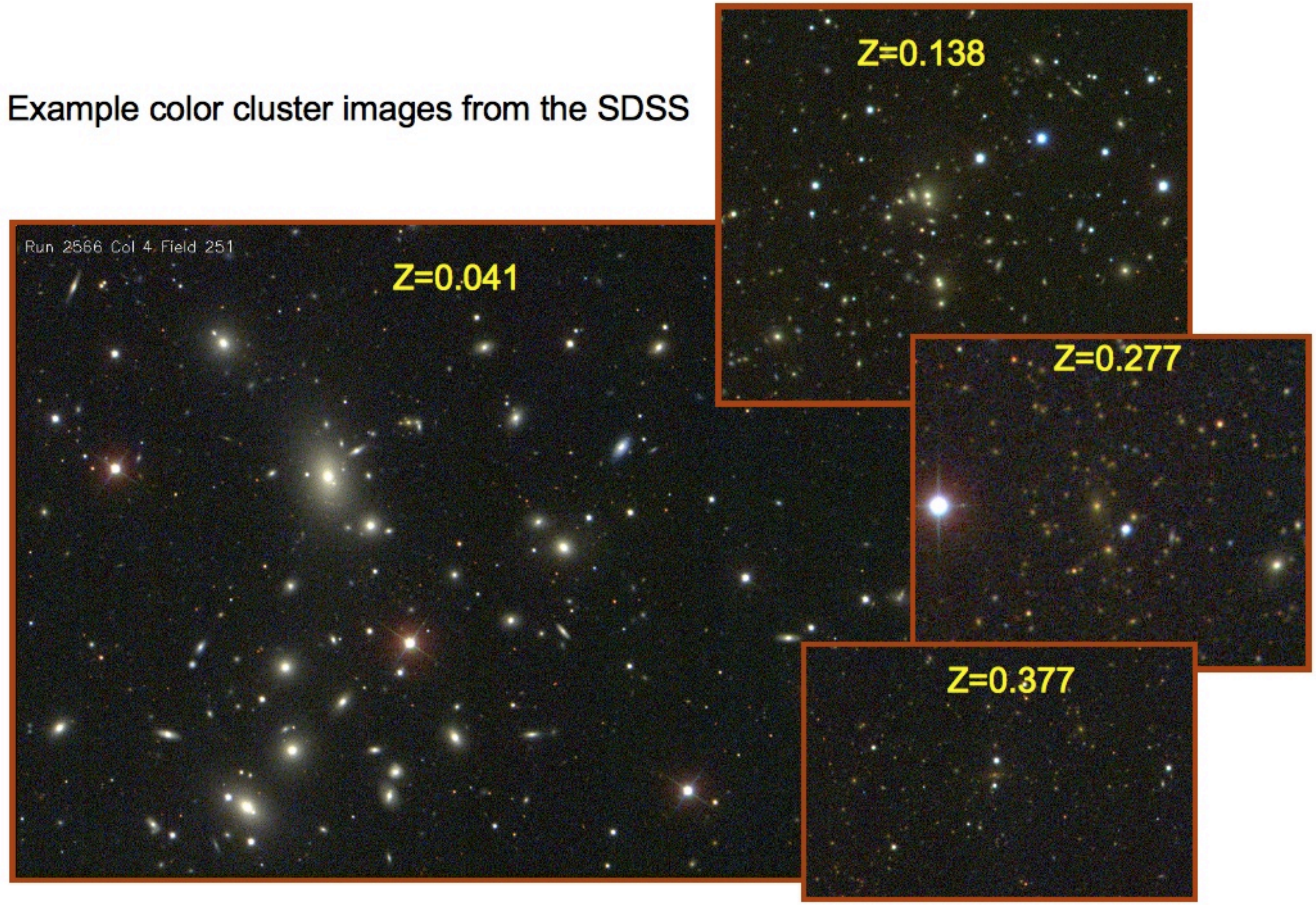
Matter component	% total mass	% baryonic mass
Dark matter	***85-90 %***	***(na)***
Baryons	***10-15 %***	***100 %***
Hot gas	7-14 %	70-95%
Stars	0.5-5 %	5-30 %
Galaxies	0.5-4 %	4-27 %

For Cosmology with Clusters We Need To

Find Them.

“Weigh” Them.

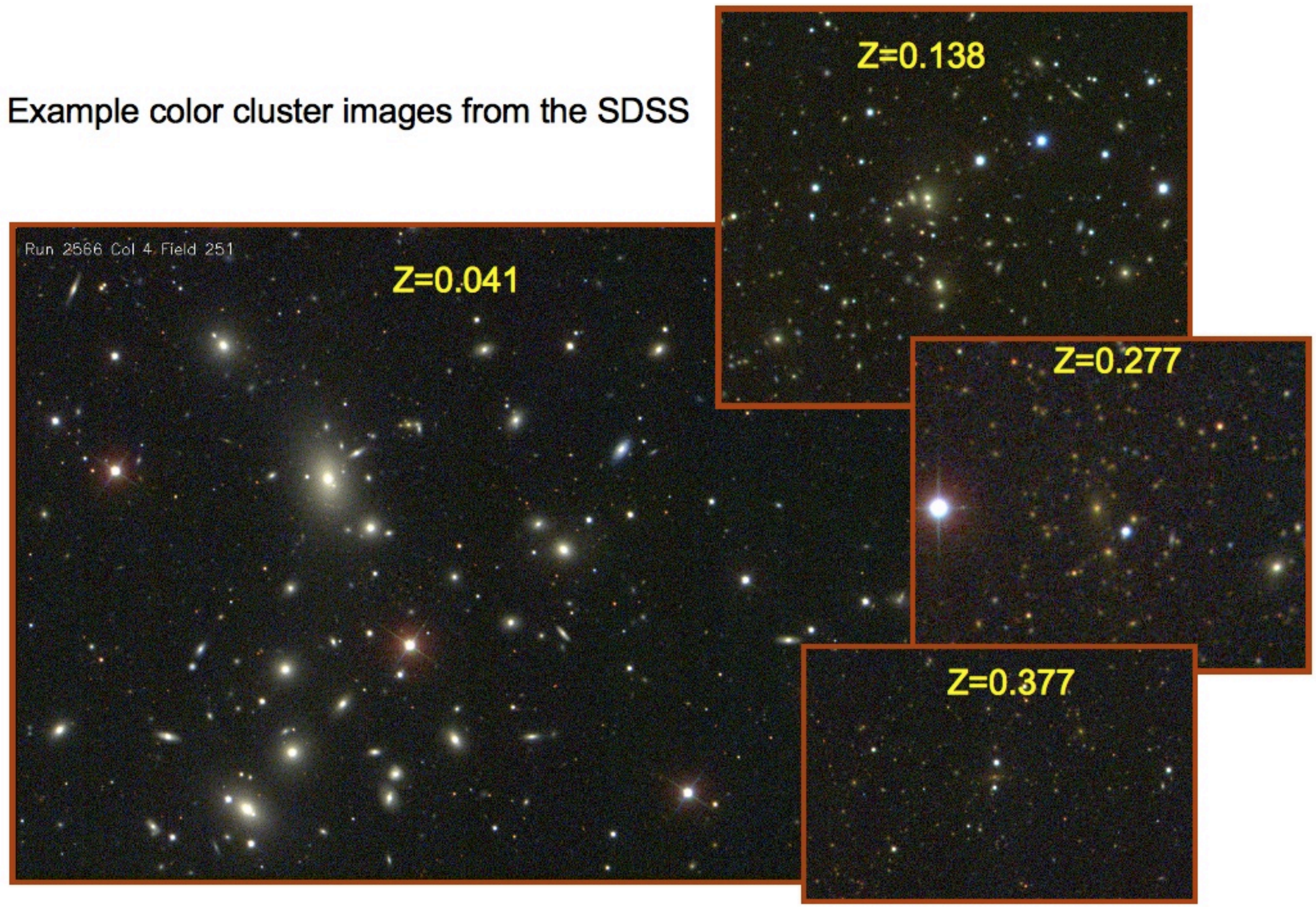
Optical Cluster Surveys: find lots of clusters!



- MaxBCG (SDSS) 13,823 clusters

Image: Tim McKay

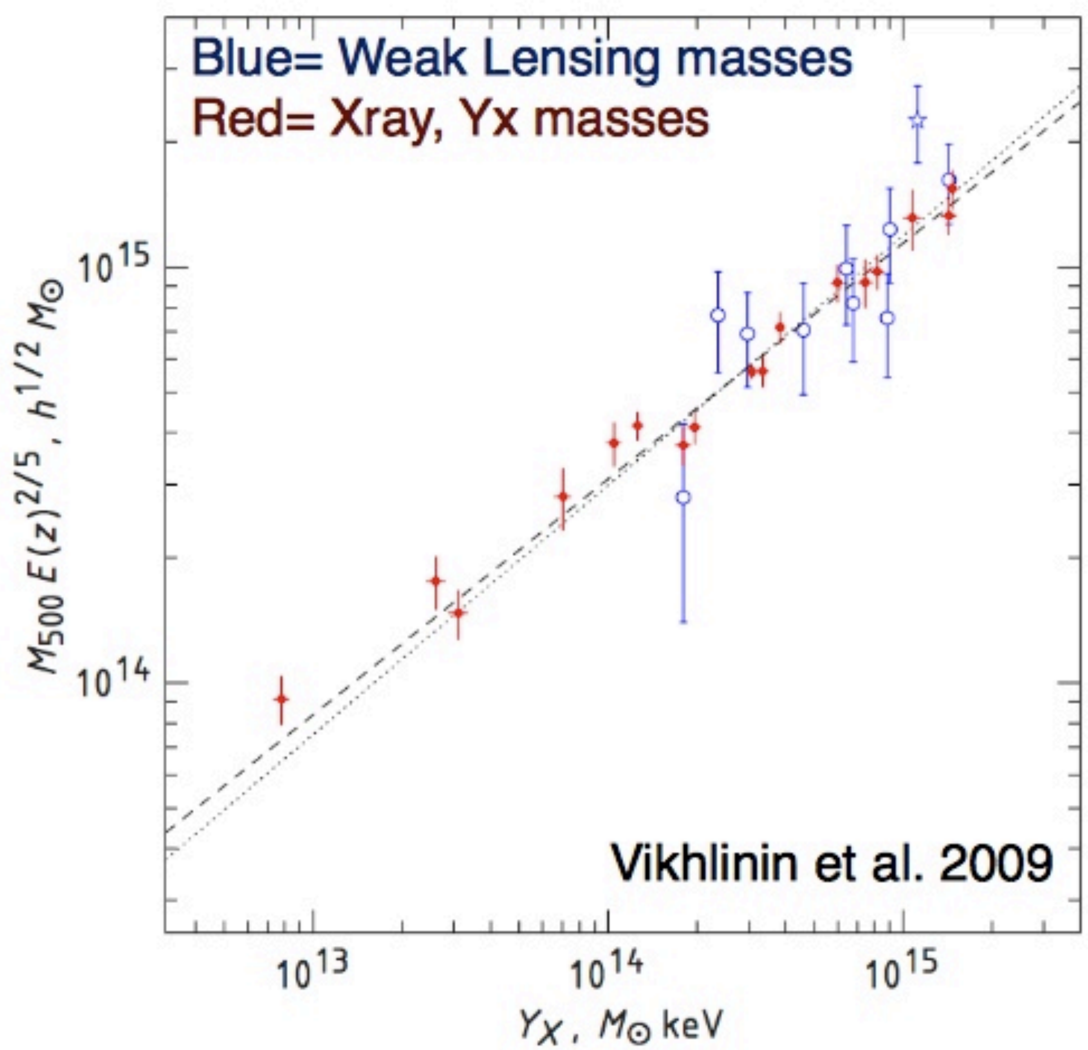
But have large scatter mass proxies.

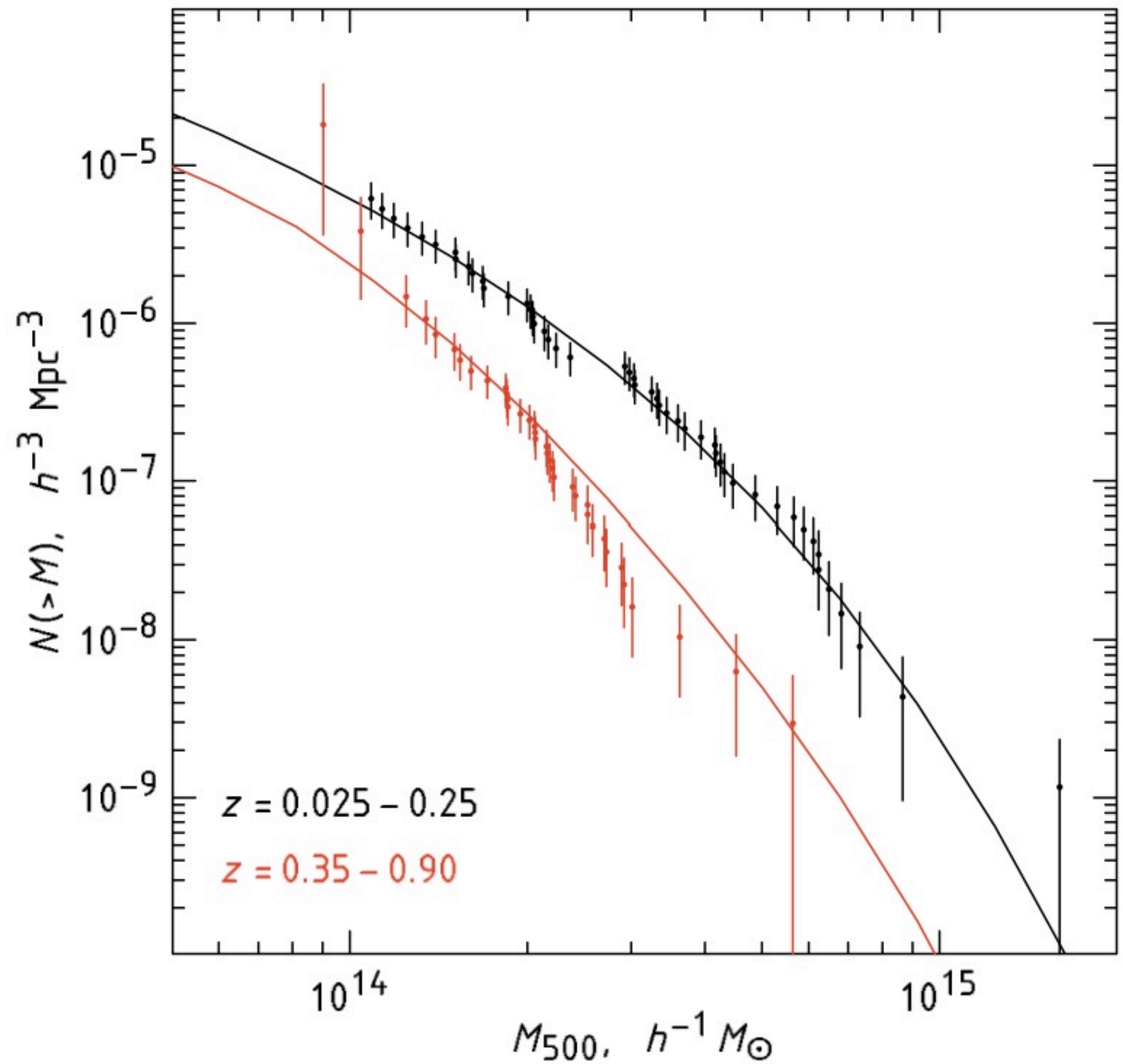


- MaxBCG (SDSS) 13,823 clusters

Image: Tim McKay

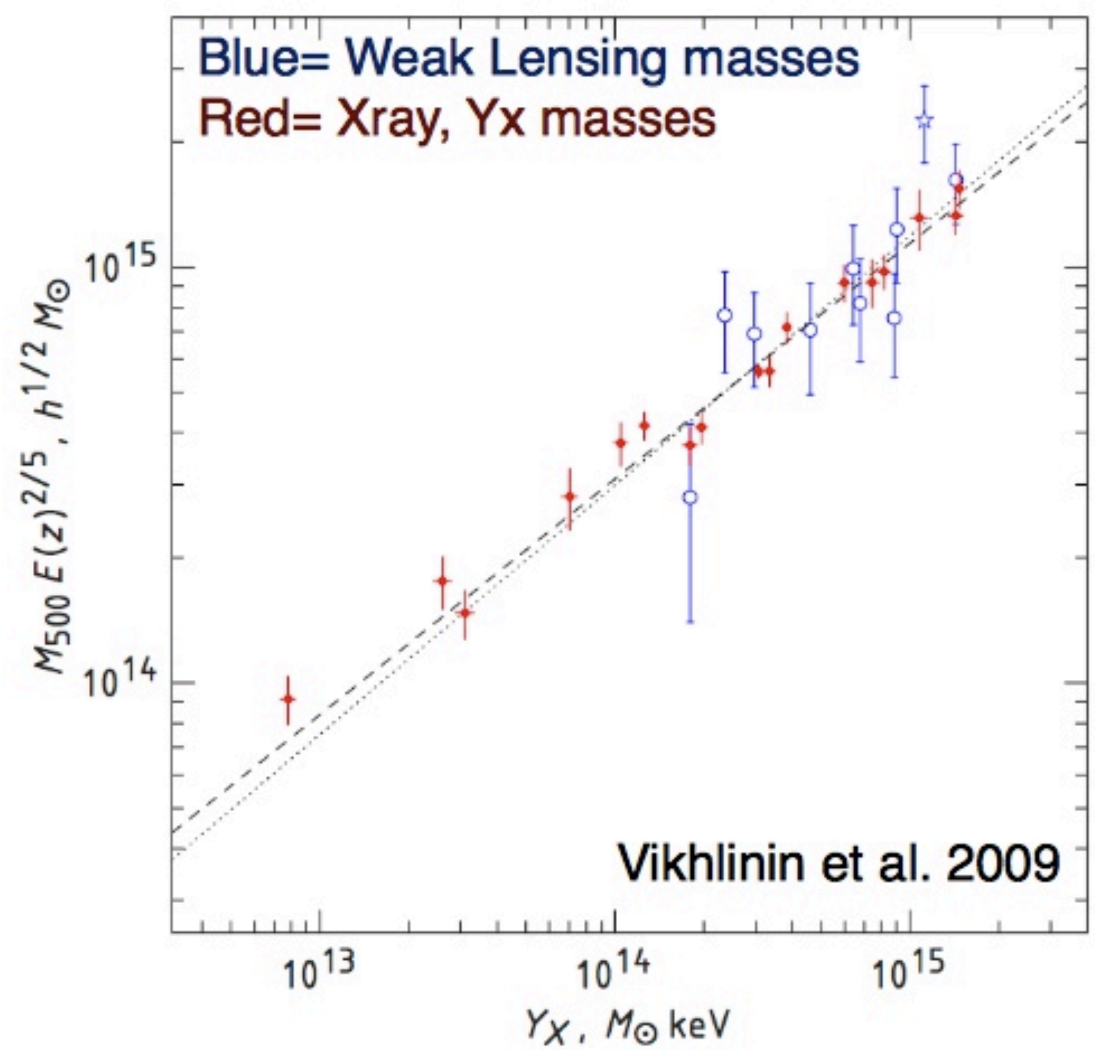
X-Ray Cluster Surveys have clean selection and tight mass proxies ...

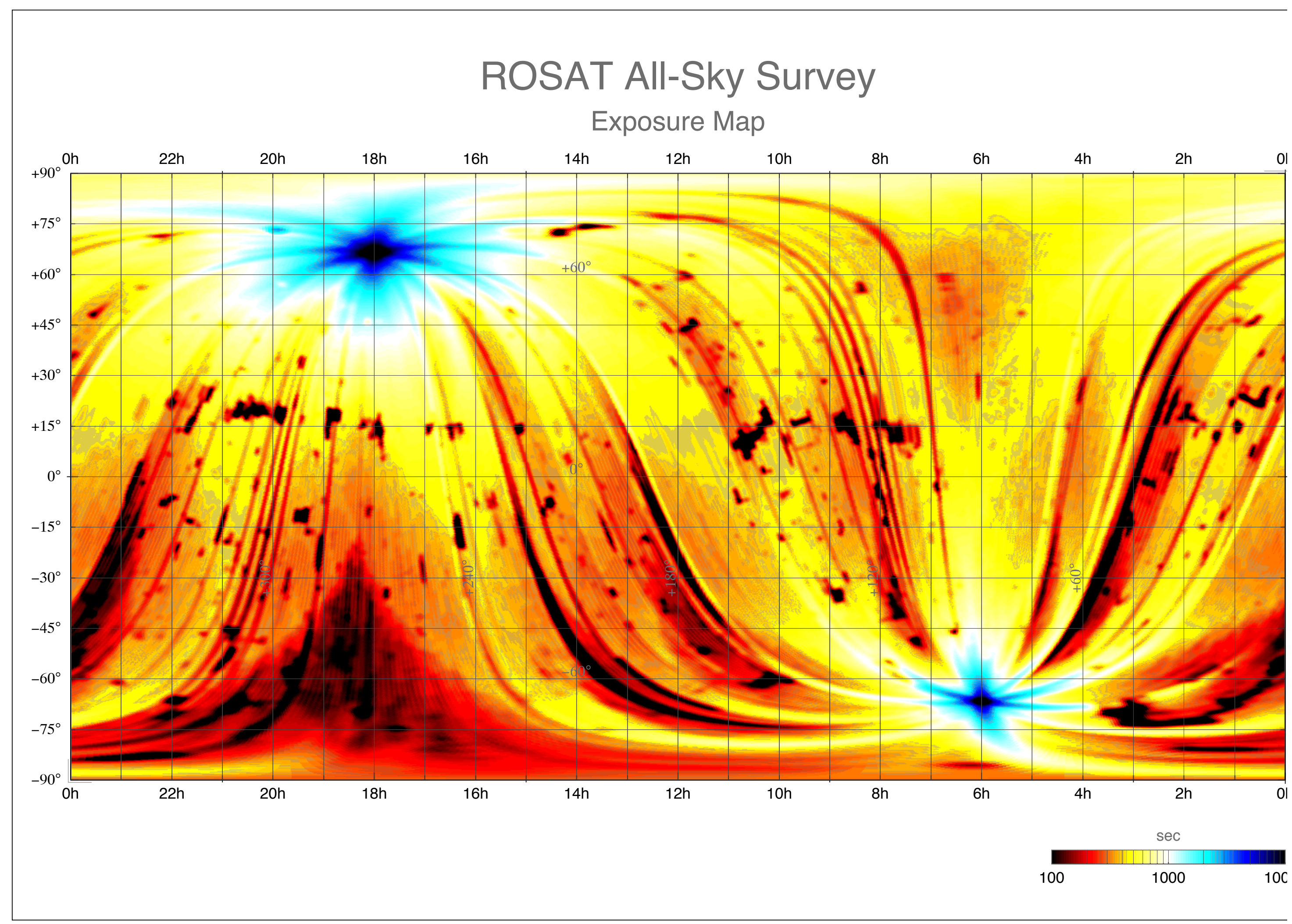




Vikhlinin et al, 2009 0812.2720

.... but are expensive to do on large areas.





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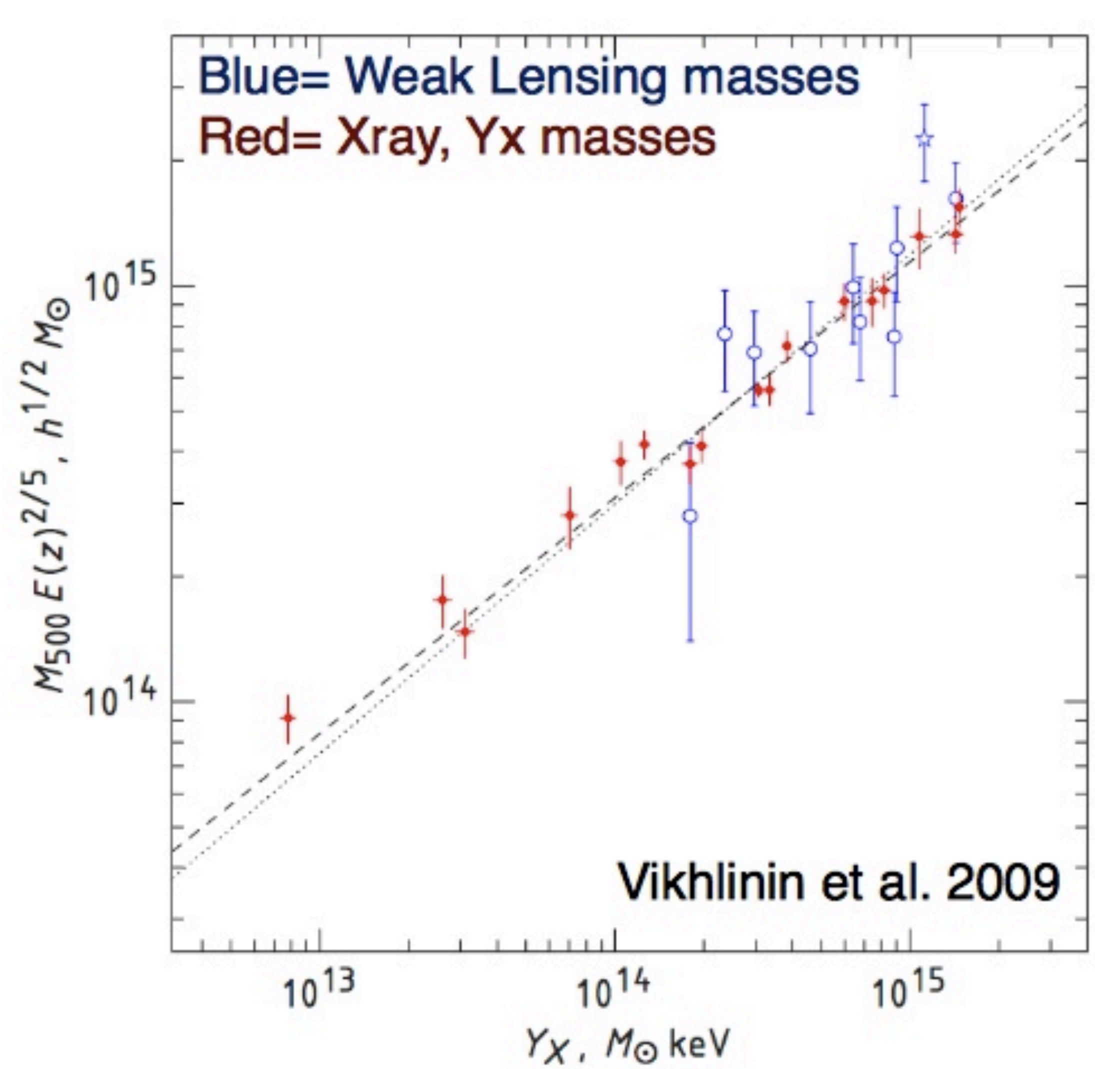
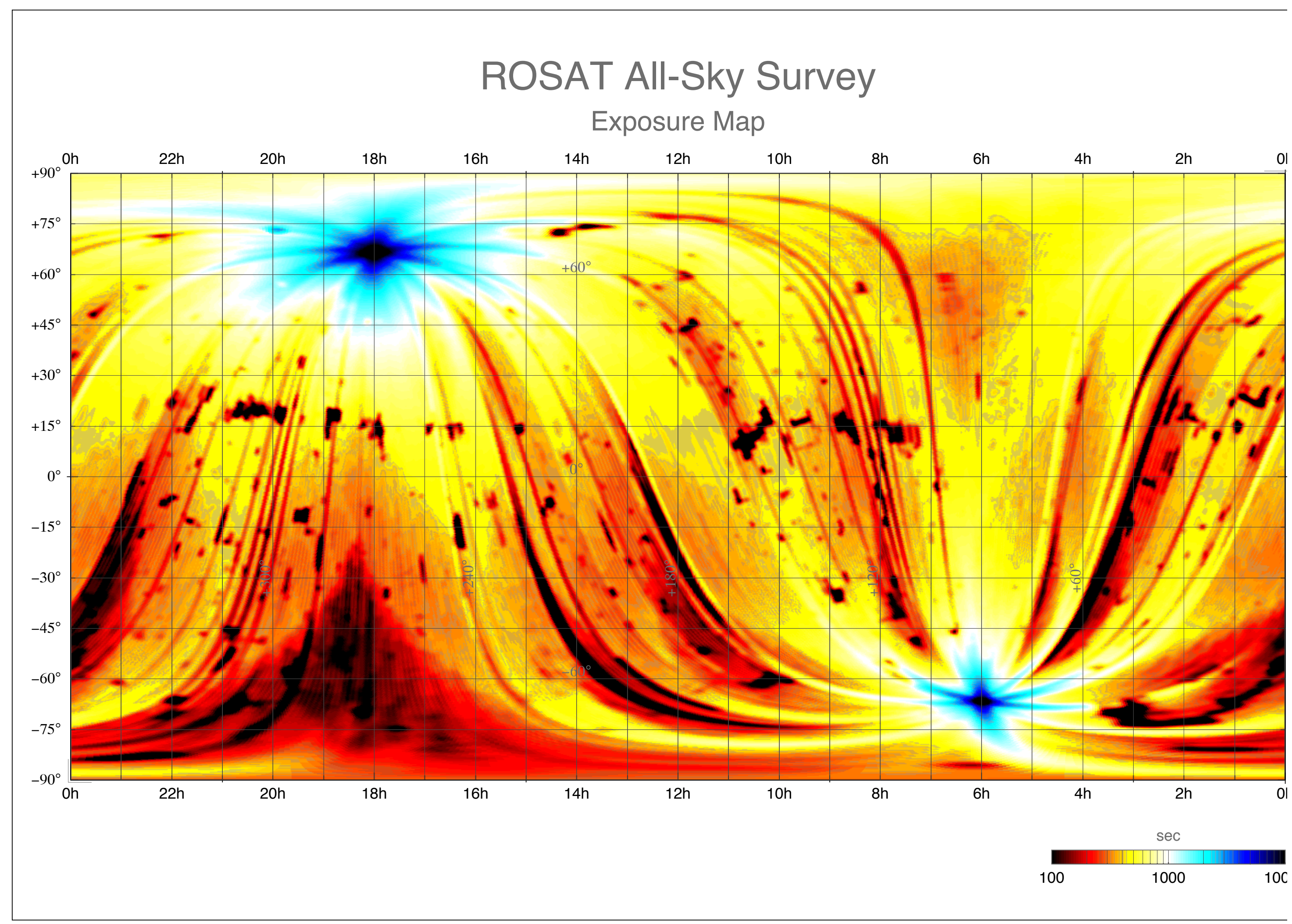
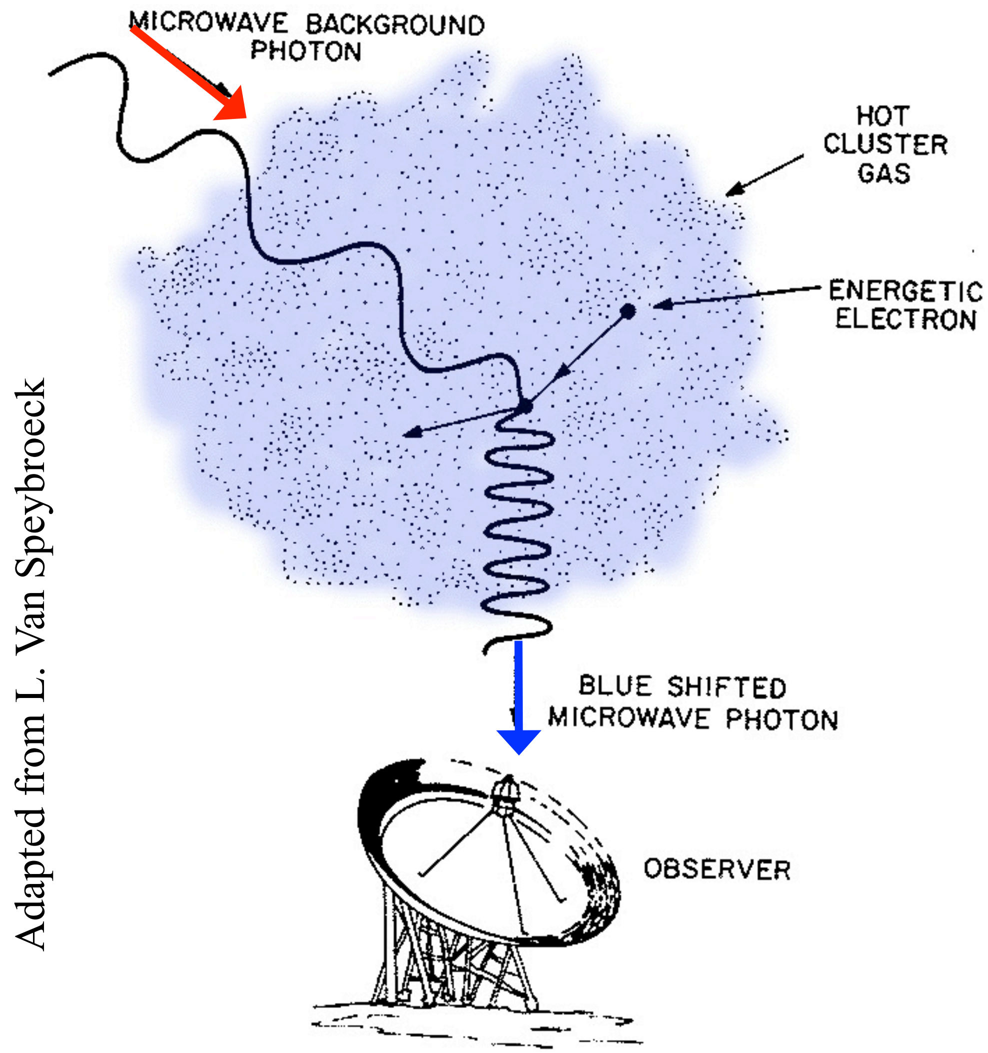
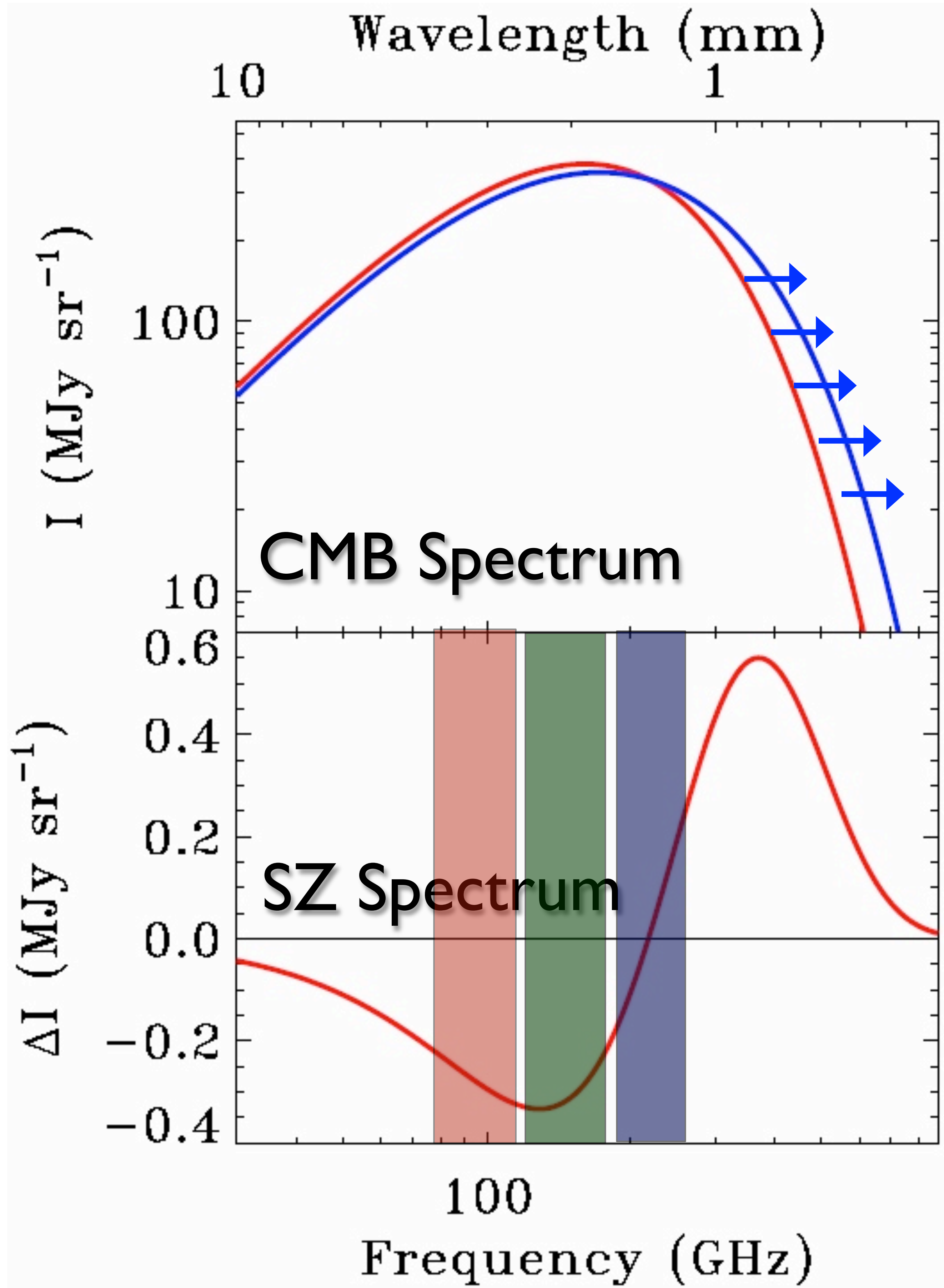




eRosita launch next year!

The Sunyaev Zel'dovich (SZ) Effect



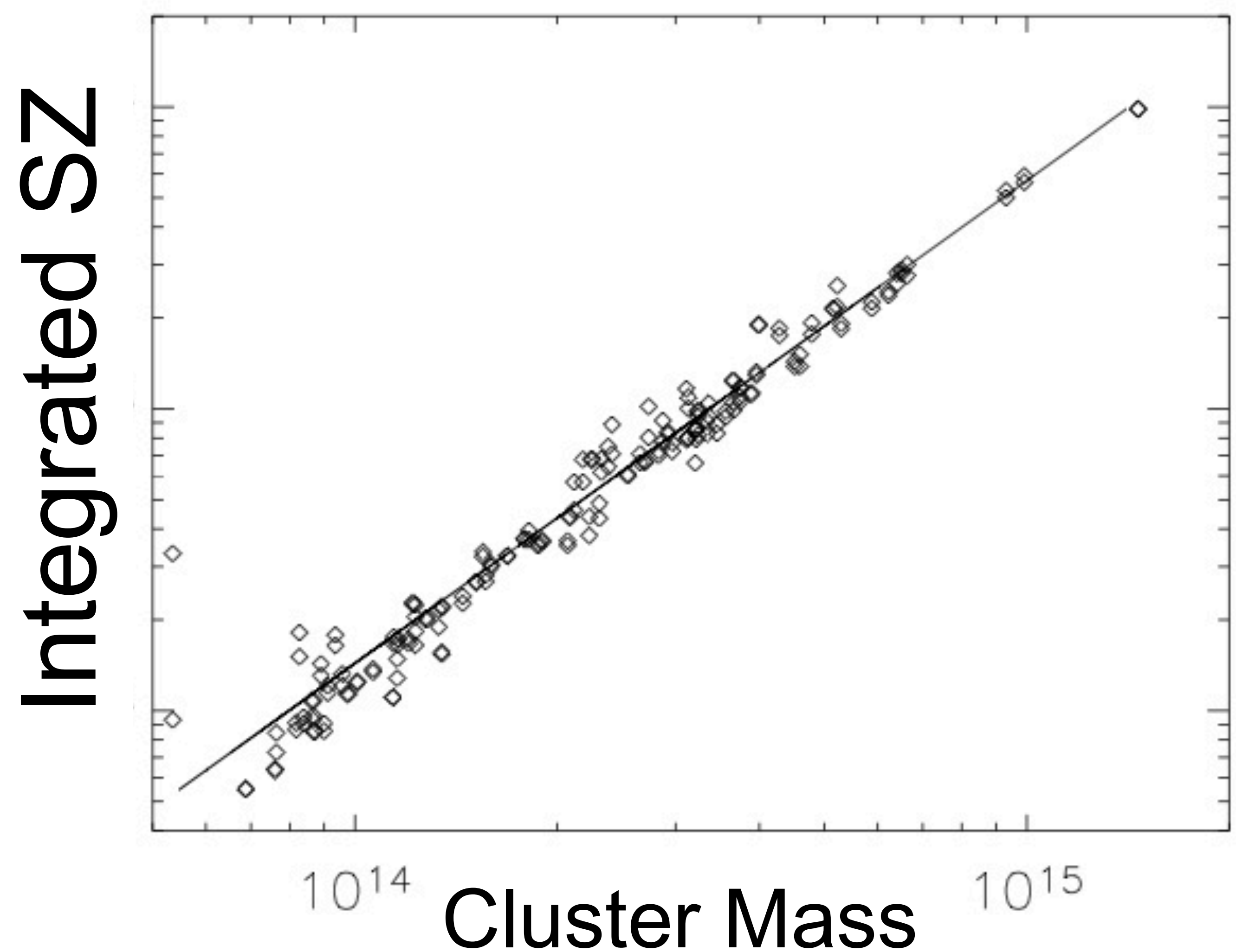


Towards a massive cluster, ~1% of CMB photons scatter off of intra-cluster gas

The SZ-observable is tightly correlated with mass.

$$\int y \, d\Omega \propto \frac{kT_e}{m_e c^2} \sigma_T \frac{N_e}{D_A^2}$$

Integrated Signal proportional to total thermal energy, should faithfully track cluster mass



Motl et al 2005

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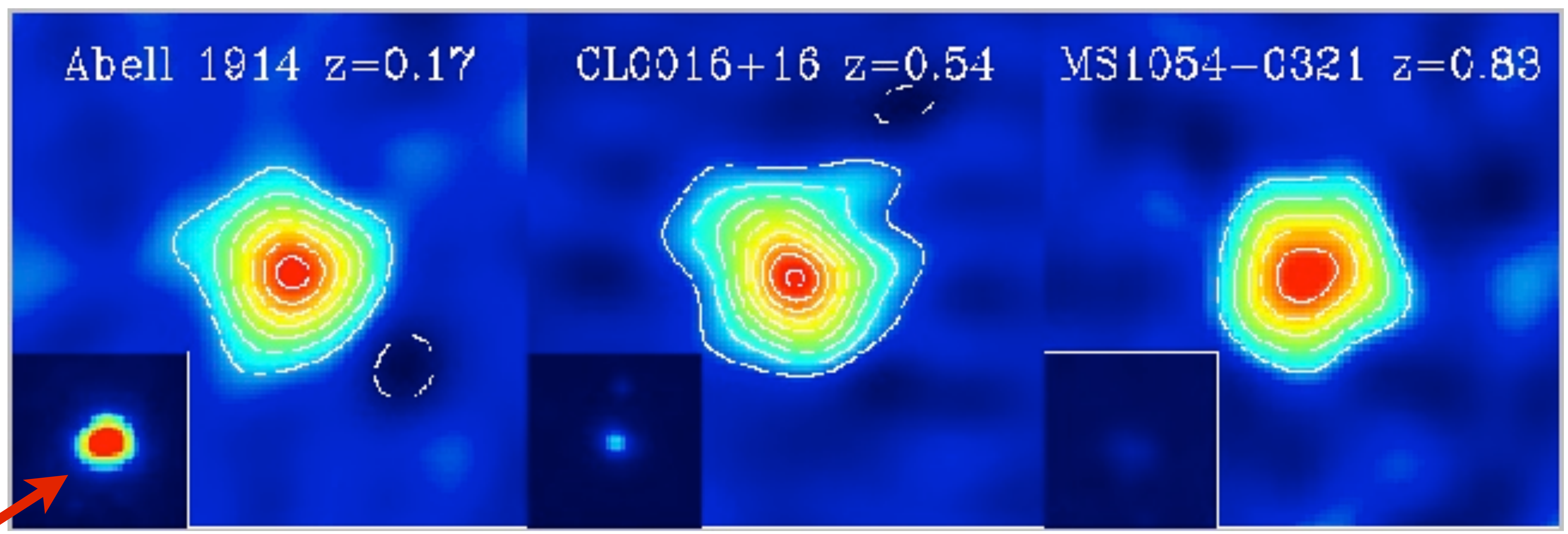
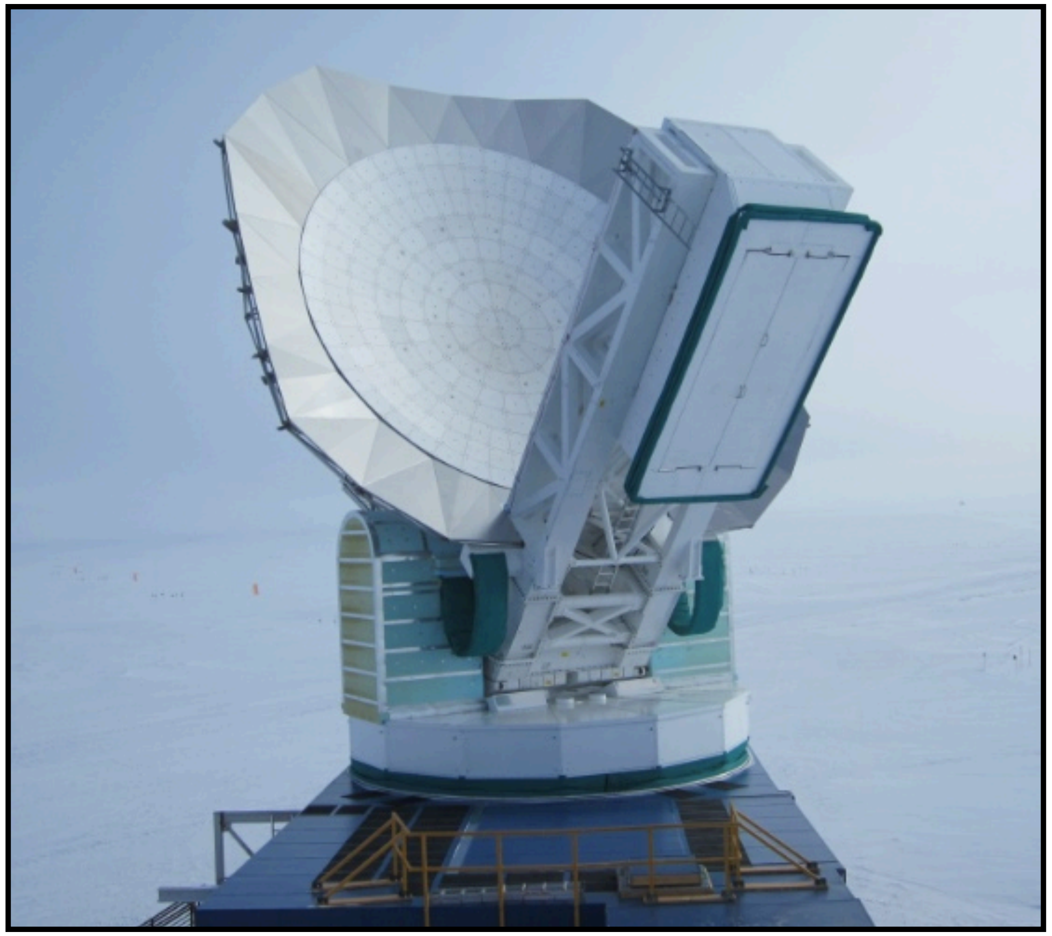


X-Ray

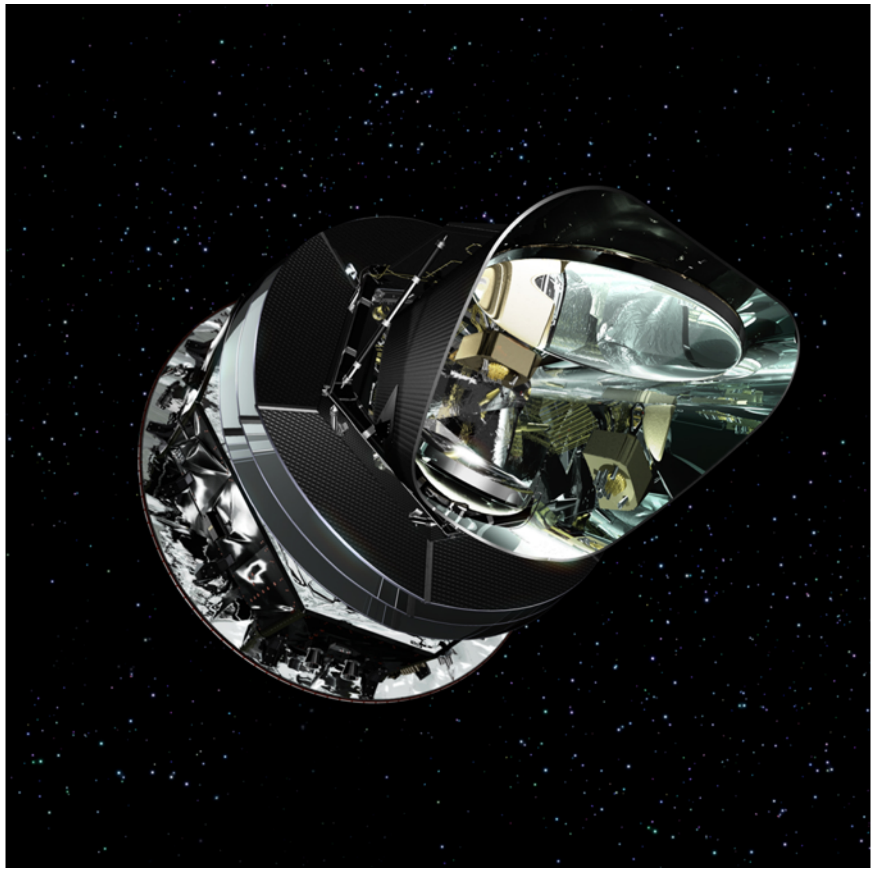
Credit Carlstrom et al.

High resolution, low noise observations are required to detect clusters.

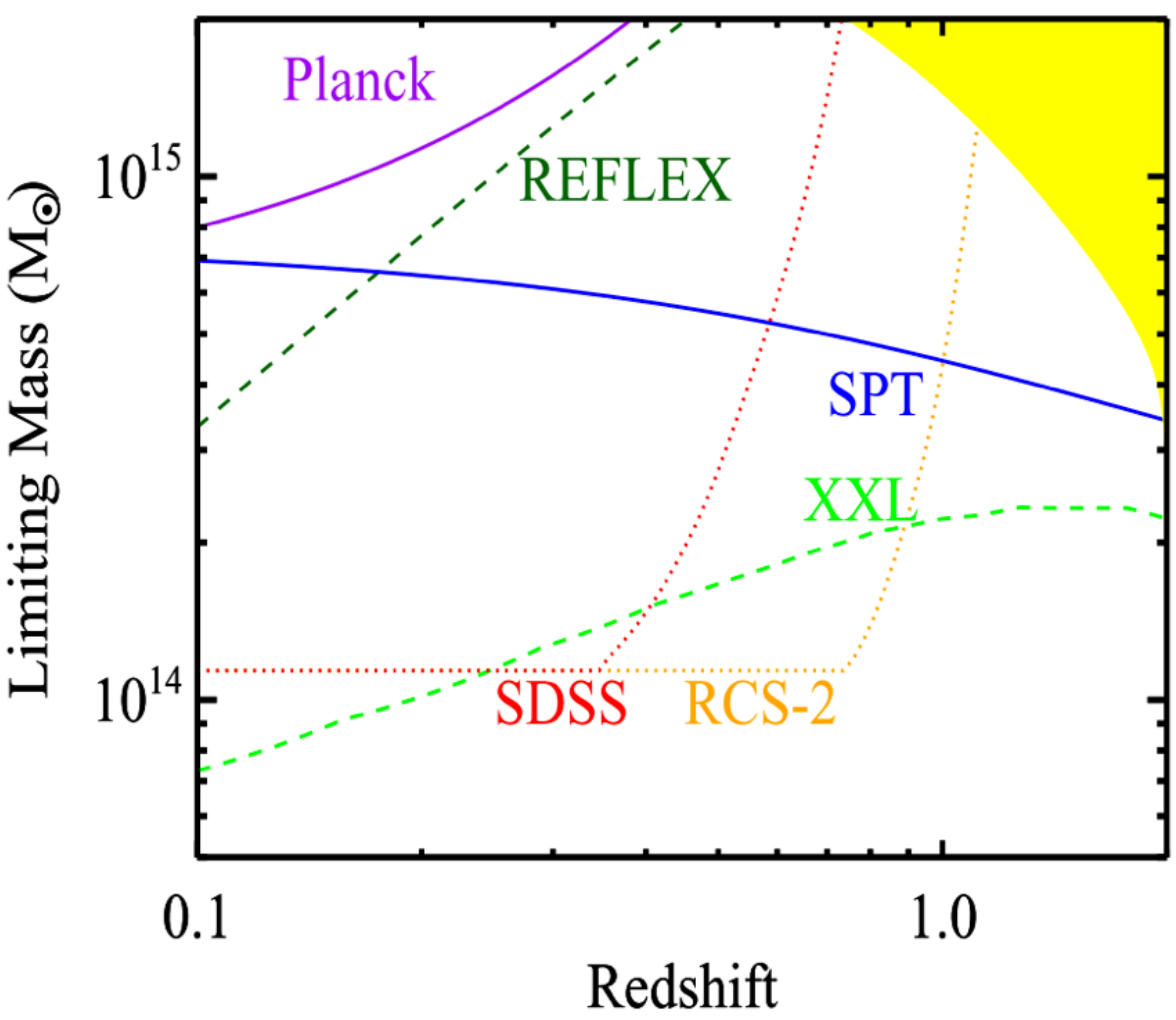


South Pole Telescope

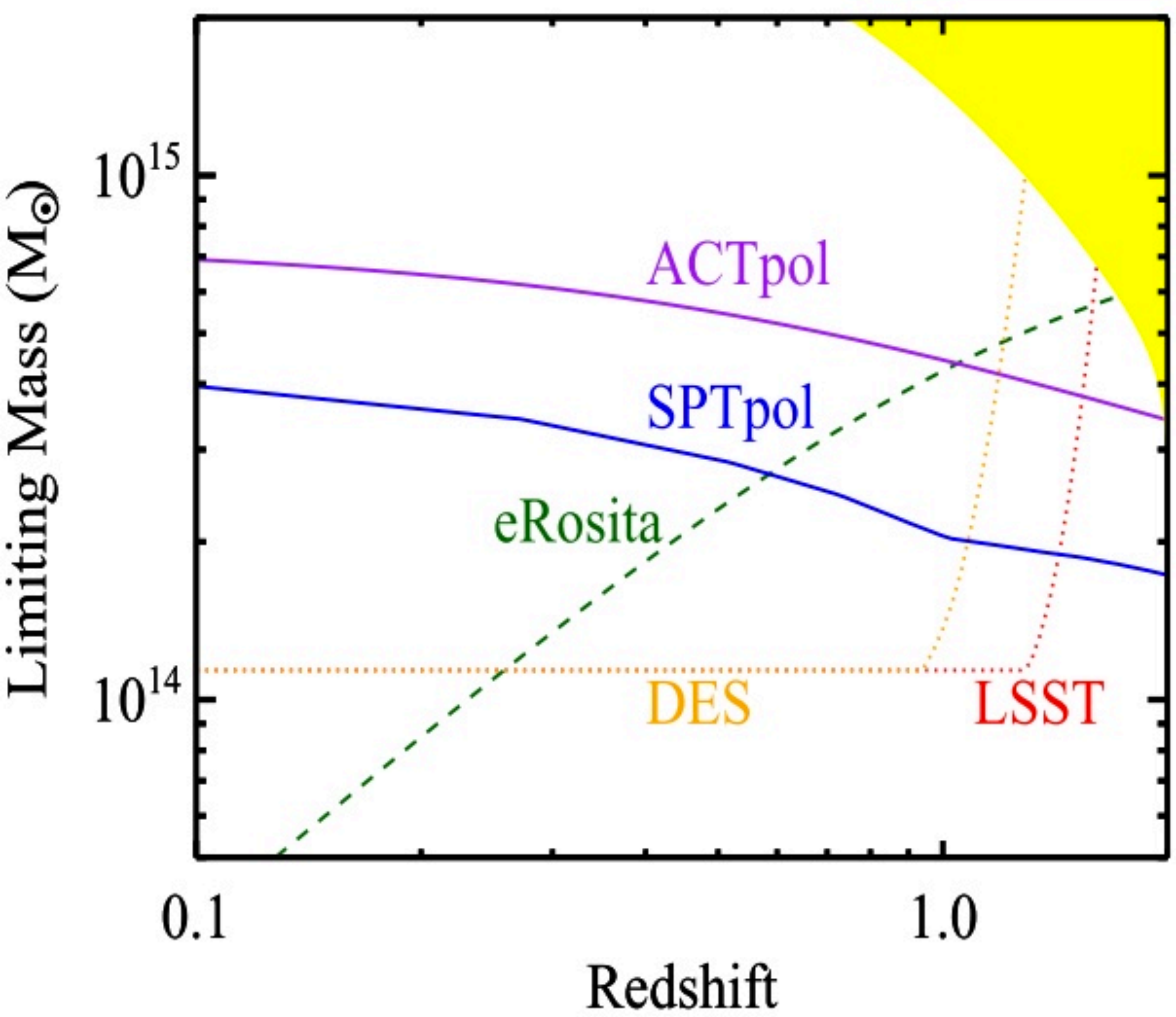
Atacama Cosmology Telescope



Planck

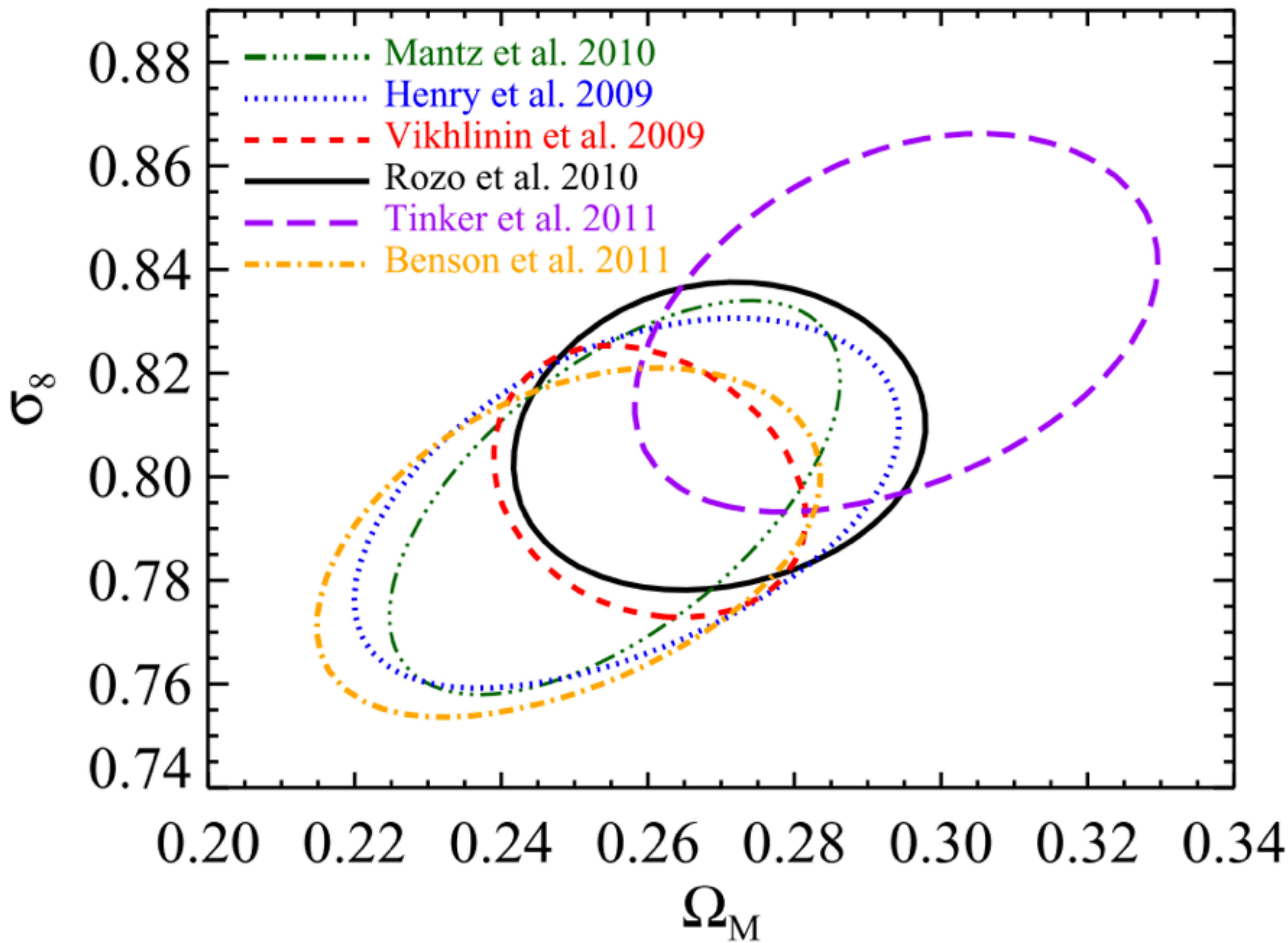


Current



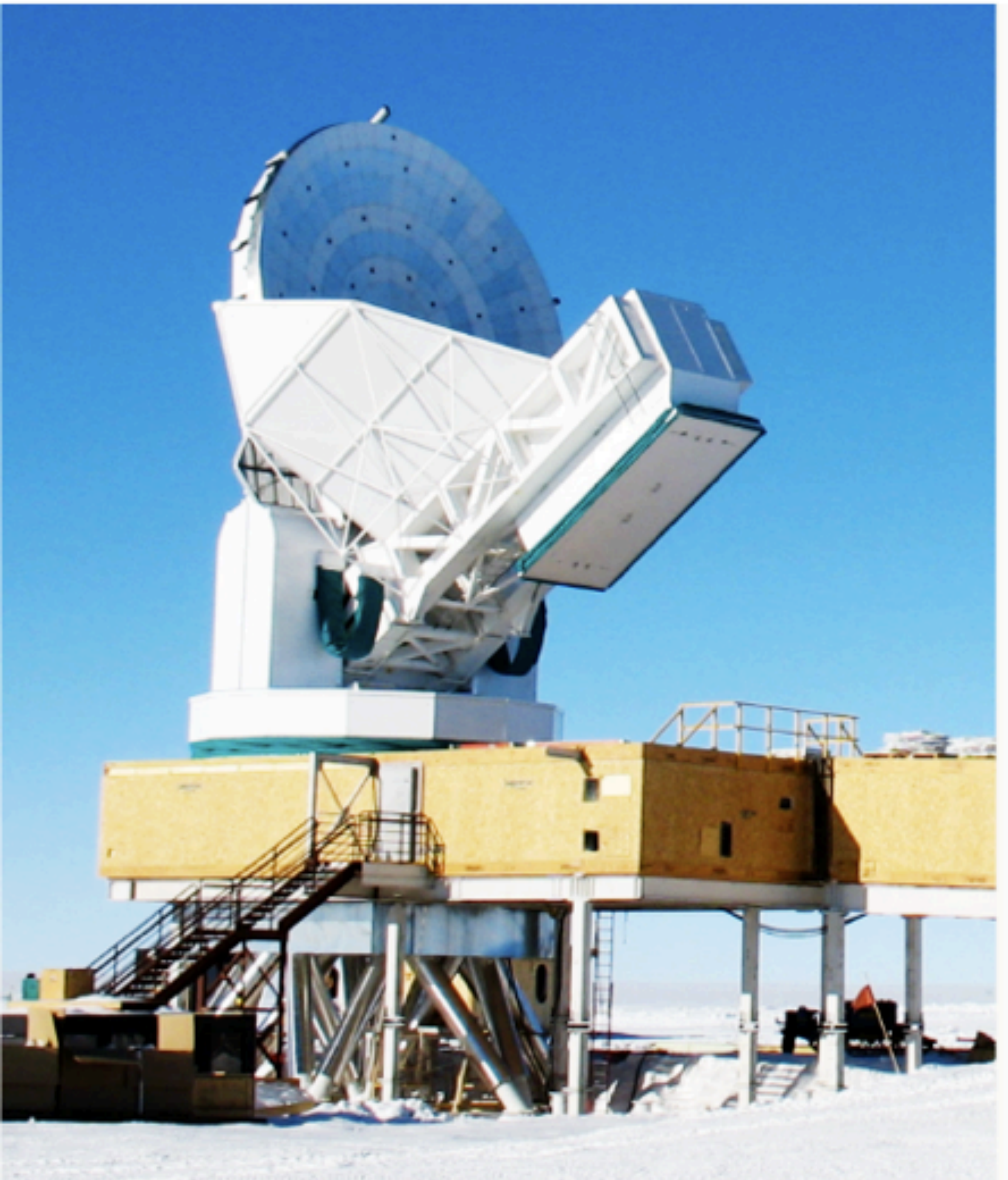
Online/Near Future

Weinberg et al. 1201.2434



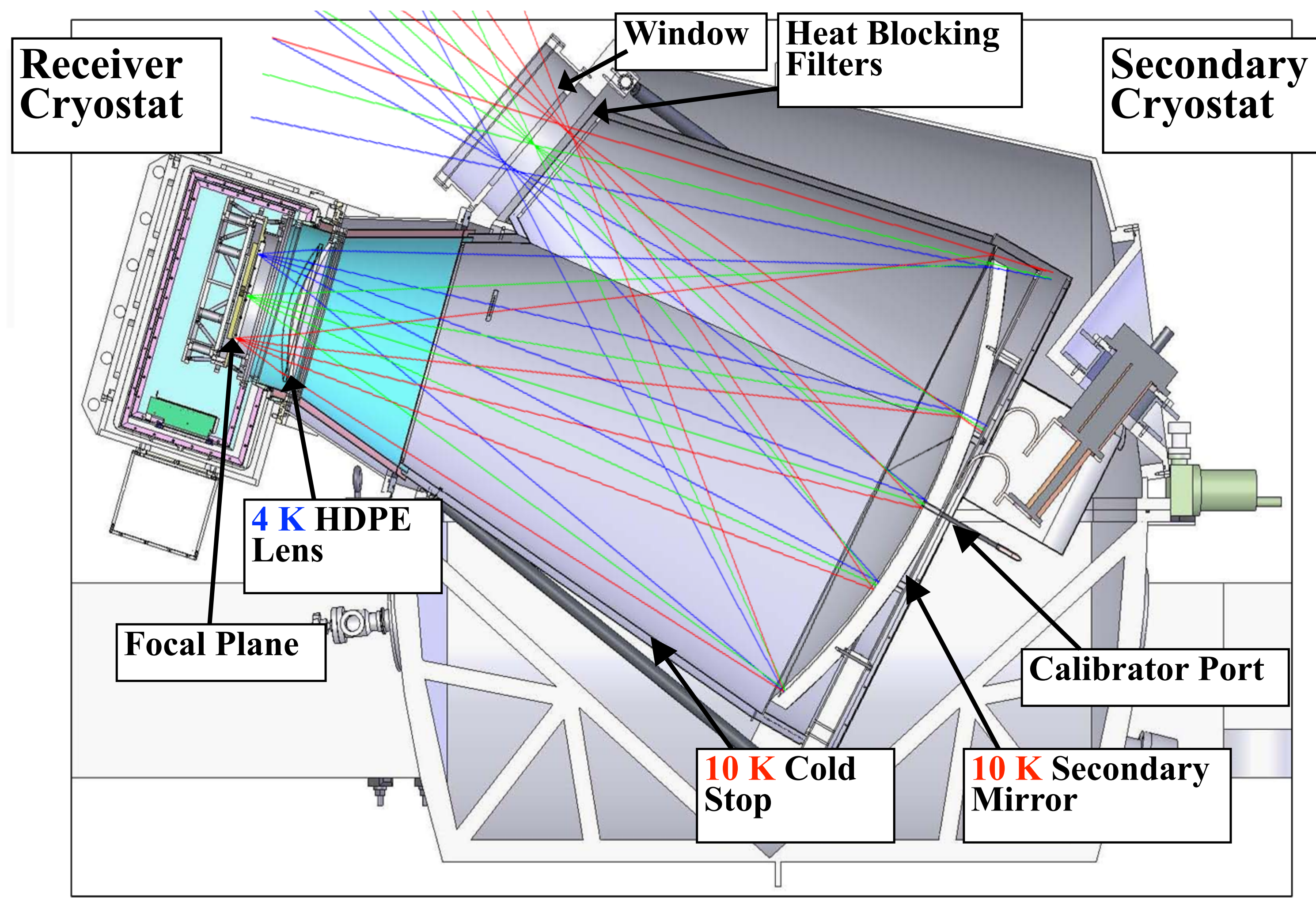
Weinberg et al. 1201.2434

The South Pole Telescope (SPT)



Sub-millimeter Wavelength Telescope:

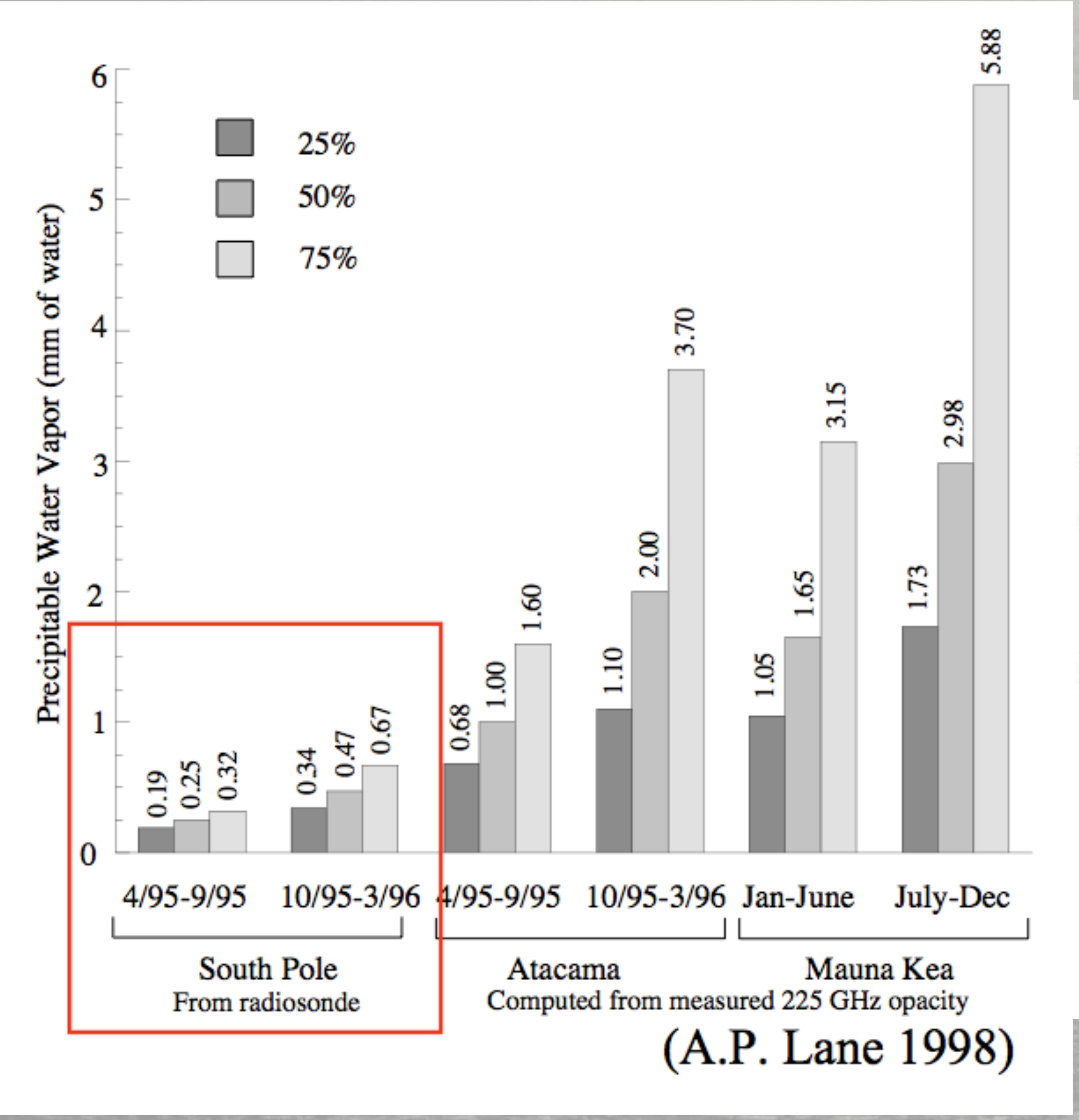
- 10 meter telescope
- Off-axis Gregorian optics design
- 20 microns RMS surface accuracy
- 1 arc-second pointing
- Fast scanning (up to 4 deg/sec in azimuth)

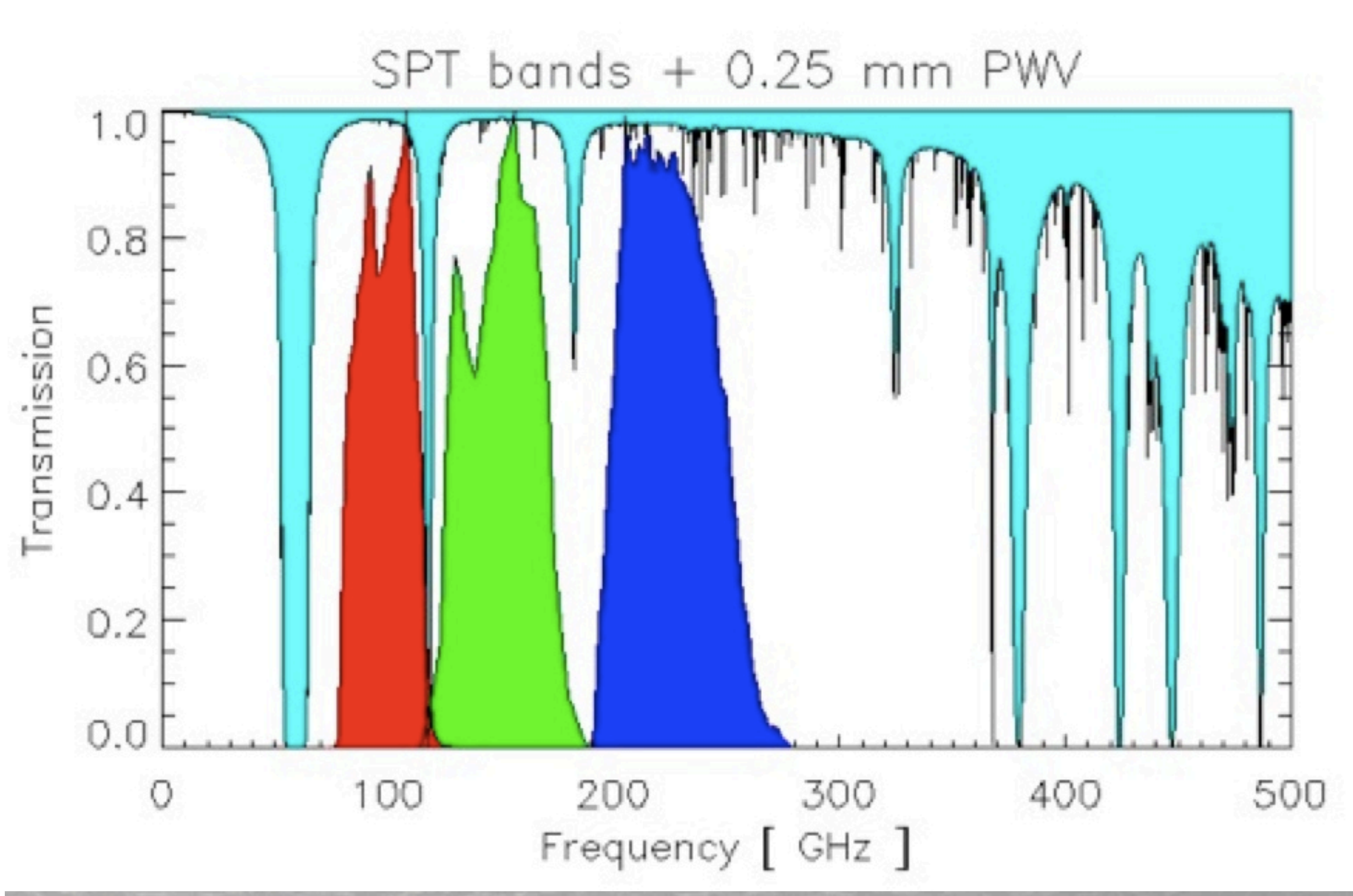


Funded by NSF

We go to the South Pole for the weather.

We go to the South Pole for the weather.

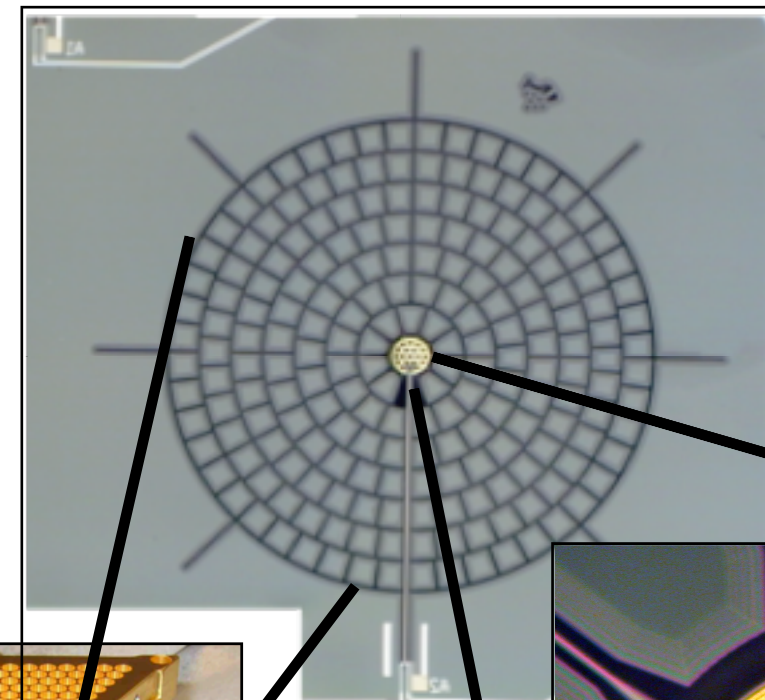


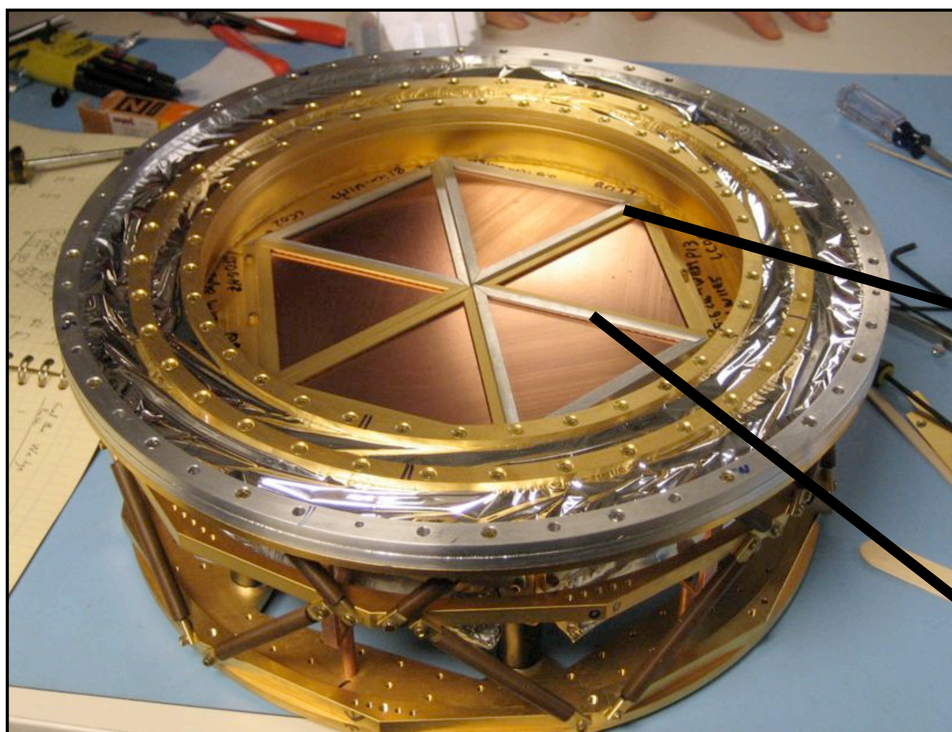


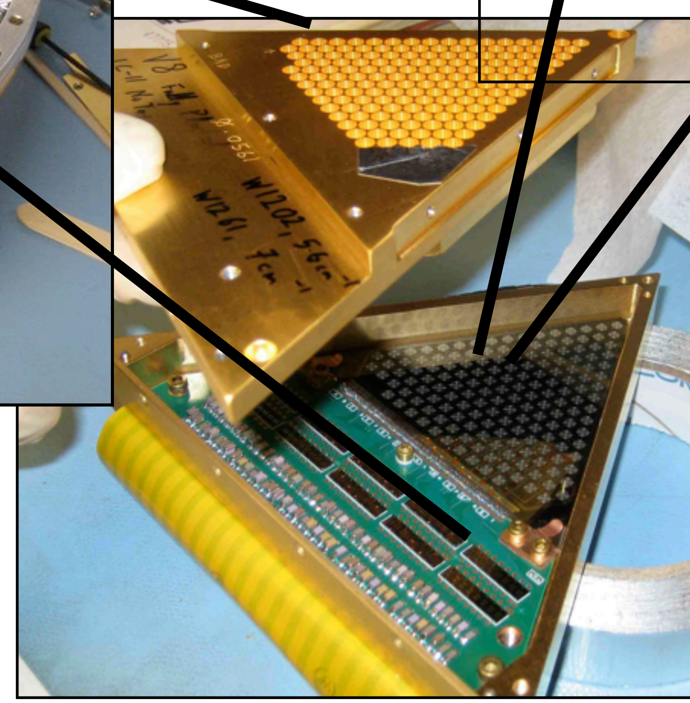
SPT Focal Plane

SPT Focal Plane
- 6 wedges of 160 detectors
- 90, 150, 220 GHz

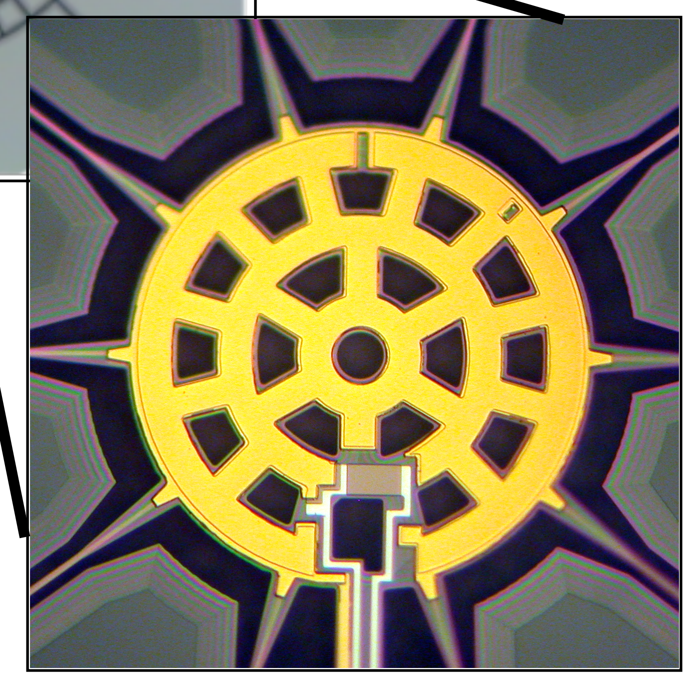
Each detector is a 4mm diameter gold web that absorbs microwaves





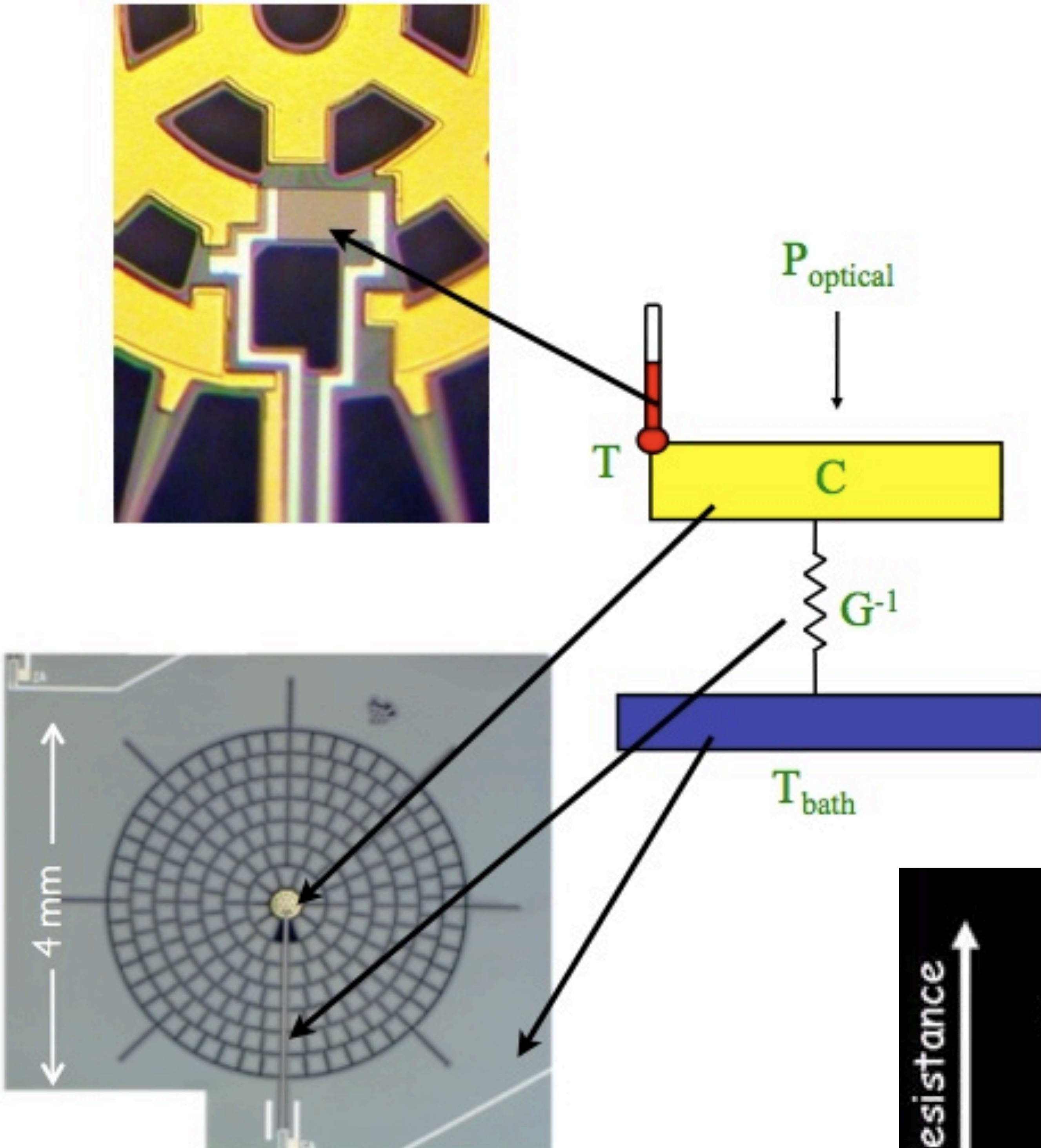


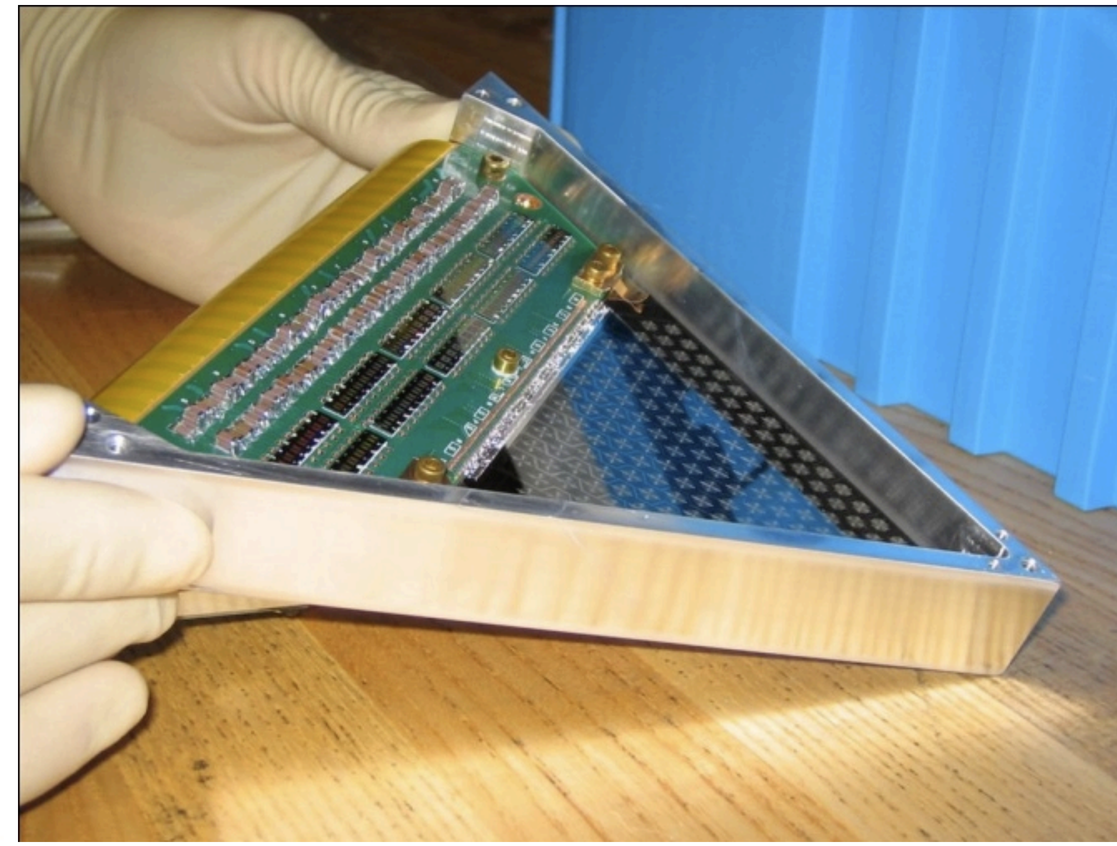
Wedge of
160 detectors

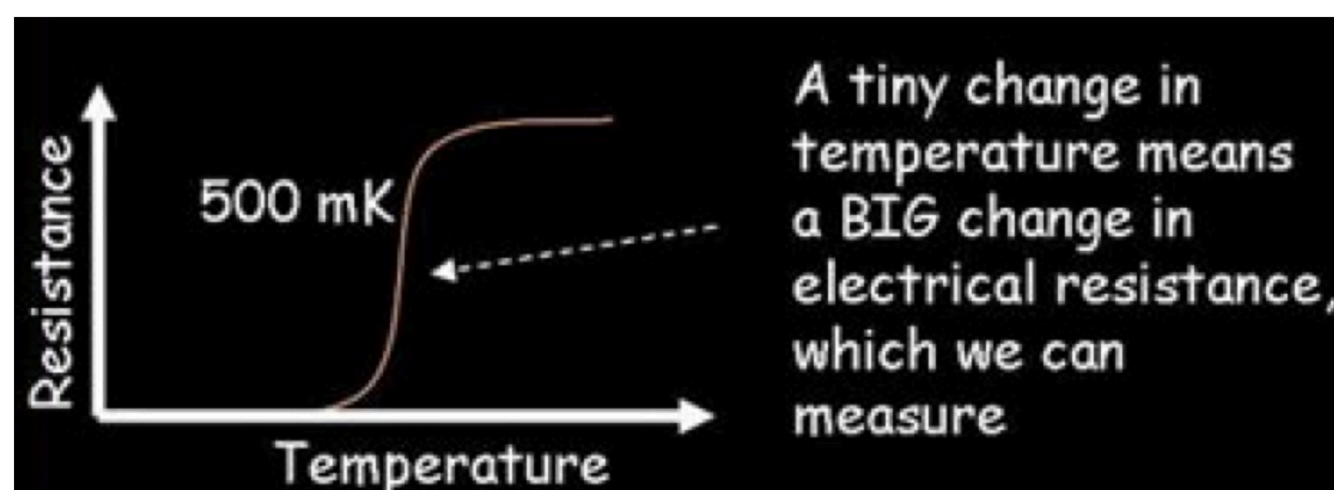


Al-Ti bi-layer Transition Edge Sensor (TES) with T_c = 0.55 K

Our detectors are bolometers.

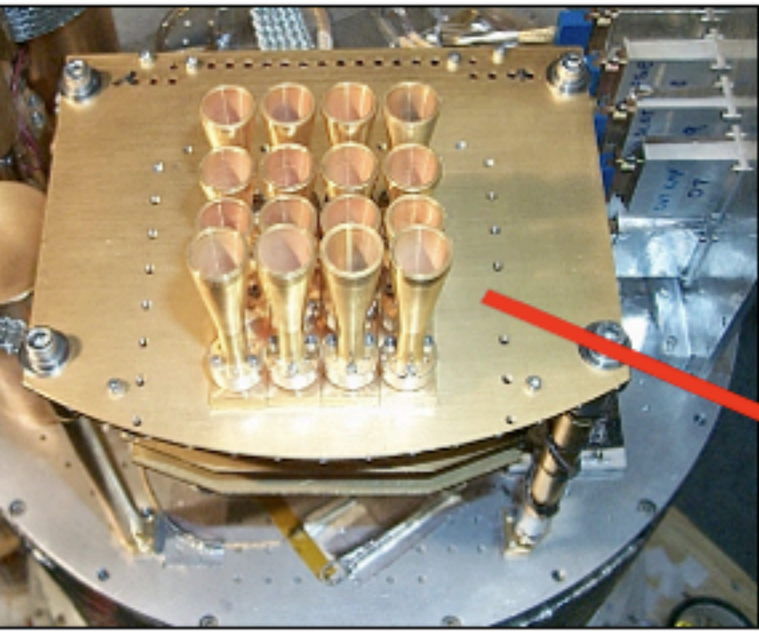




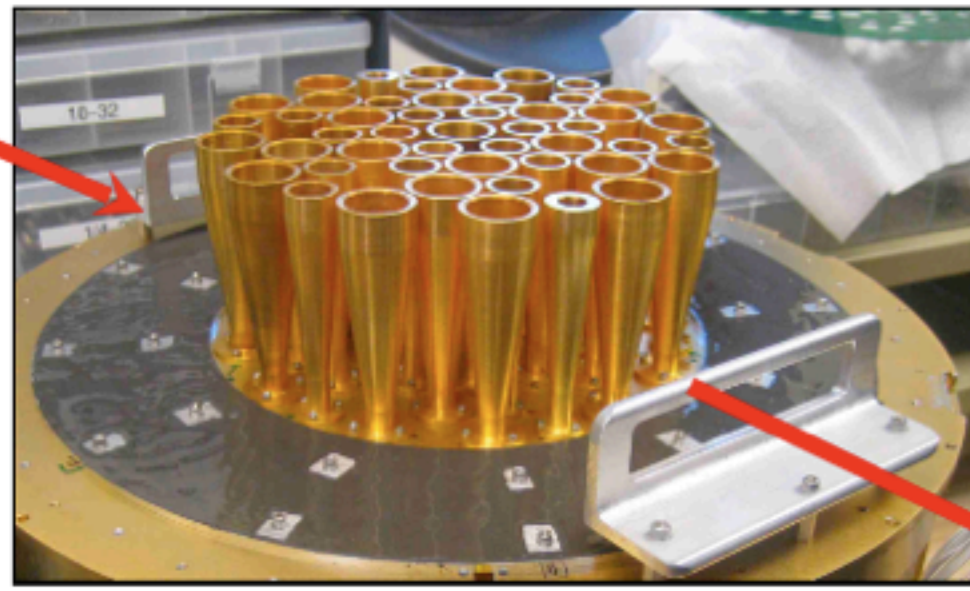


History of Recent CMB Focal Planes

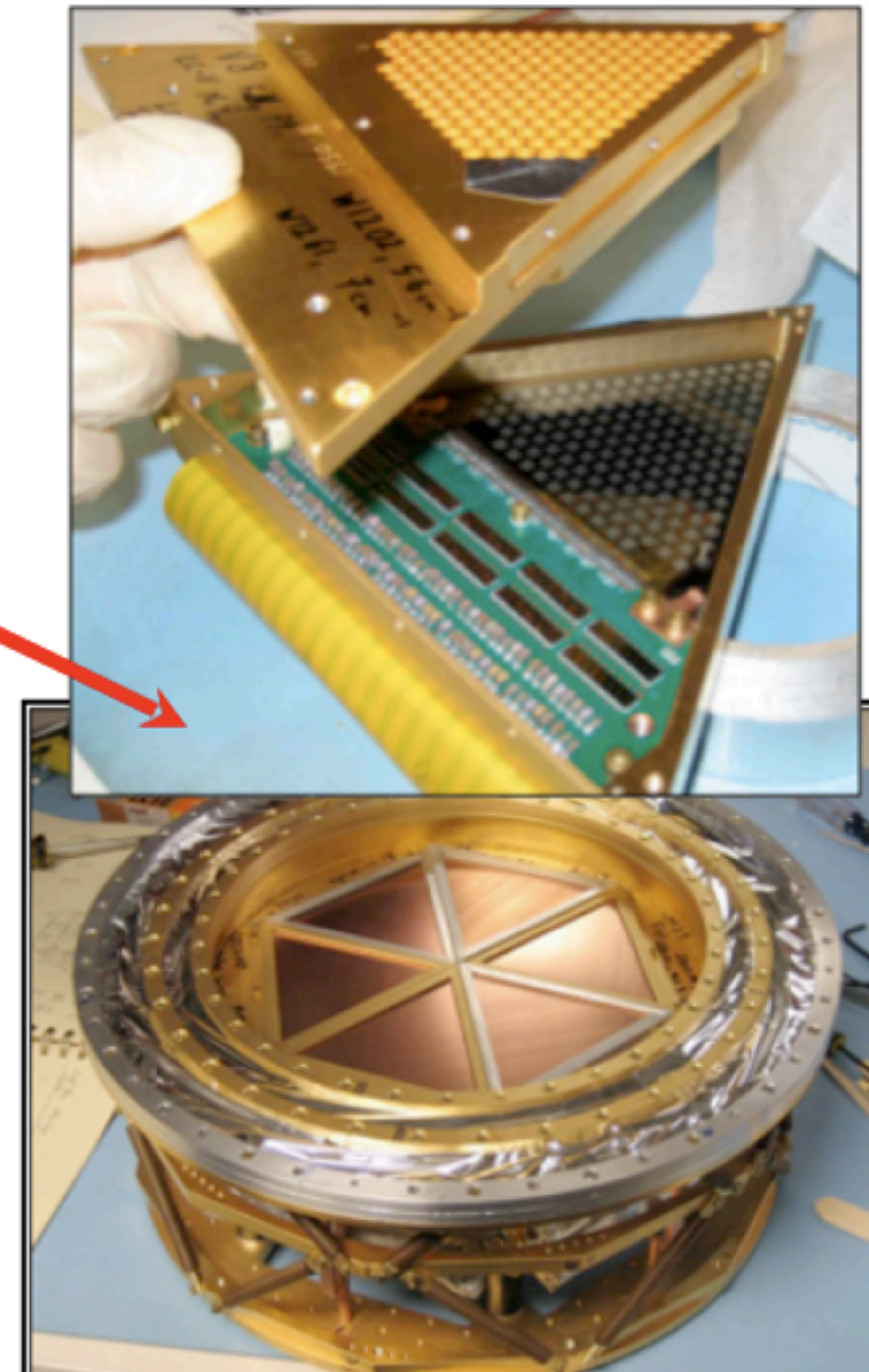
2001: ACBAR
16 detectors



2005: BICEP
~50 detectors



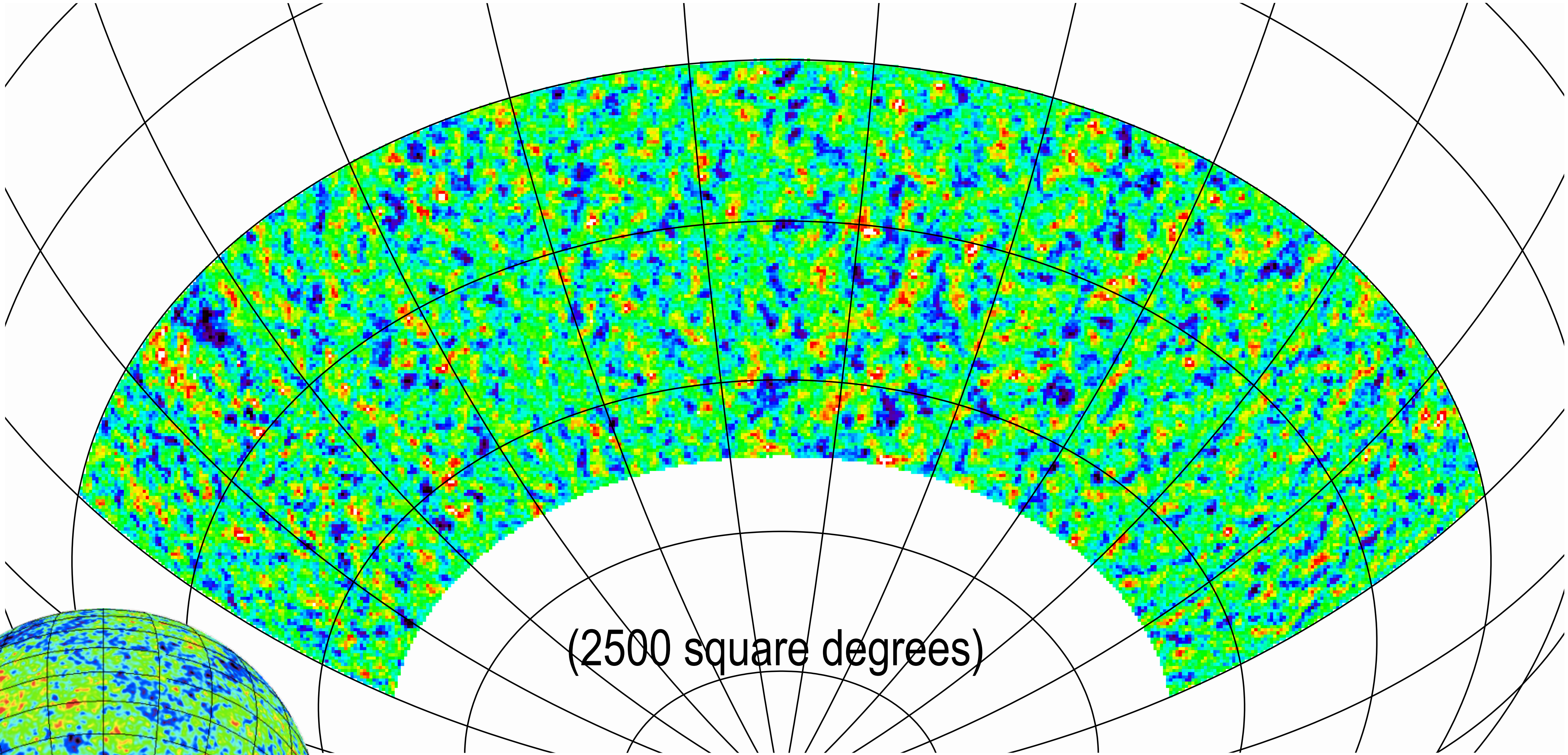
2007: SPT
~1000 detectors

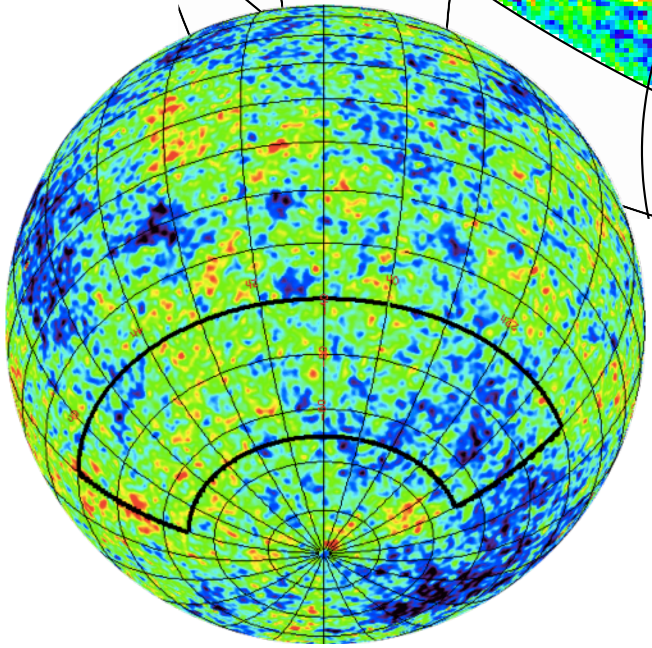


- ACBAR was the first experiment to make a "background limited" detector (limited by random arrival time of photons)
- To make these measurements, we need more detectors

SPT has produced the

highest resolution and sensitivity map of the CMB

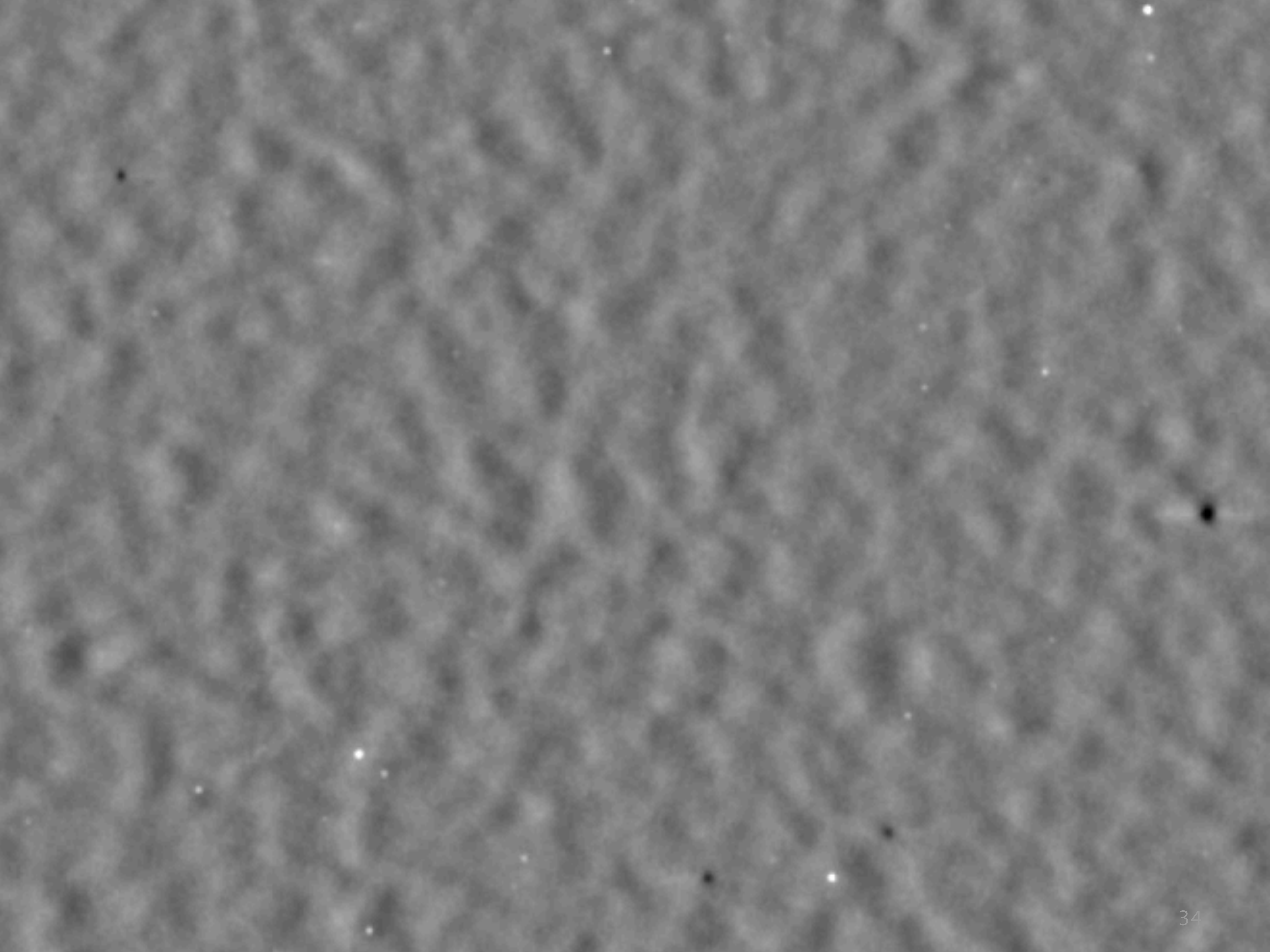




WMAP lower resolution full sky map with SPT area marked

Survey depths:

- 90 GHz: 42 uK_{CMB}-arcmin
- 150 GHz: <18 uK_{CMB}-arcmin
- 220 GHz: 85 uK_{CMB}-arcmin



Zoom in on highpass filtered SPT map

~50 square degrees from
2500 square degree survey

CMB Anisotropy

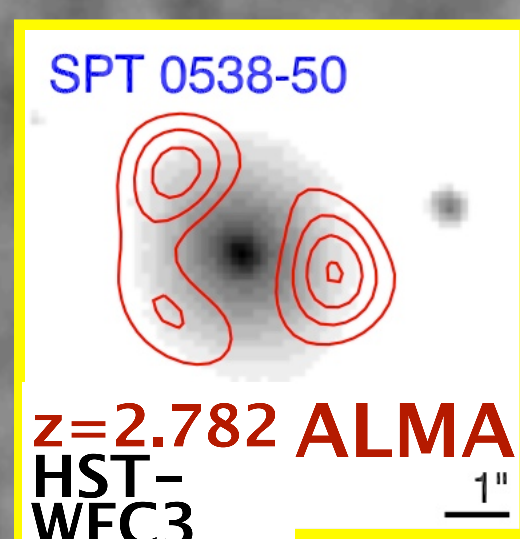
- Primordial and secondary anisotropy in the CMB

Story et al. astro-ph/1210.7231
Hou et al. astro-ph/1212.6267
Reichardt et al. 2012 ApJ, 755, 70
van Engelen et al. 2012 ApJ 756, 142
and more!

Zoom in on highpass filtered SPT map

~50 square degrees from
2500 square degree survey

Point Sources – **Bright radio galaxies, AGN, and discovery of rare lensed, high redshift dusty star forming galaxies**



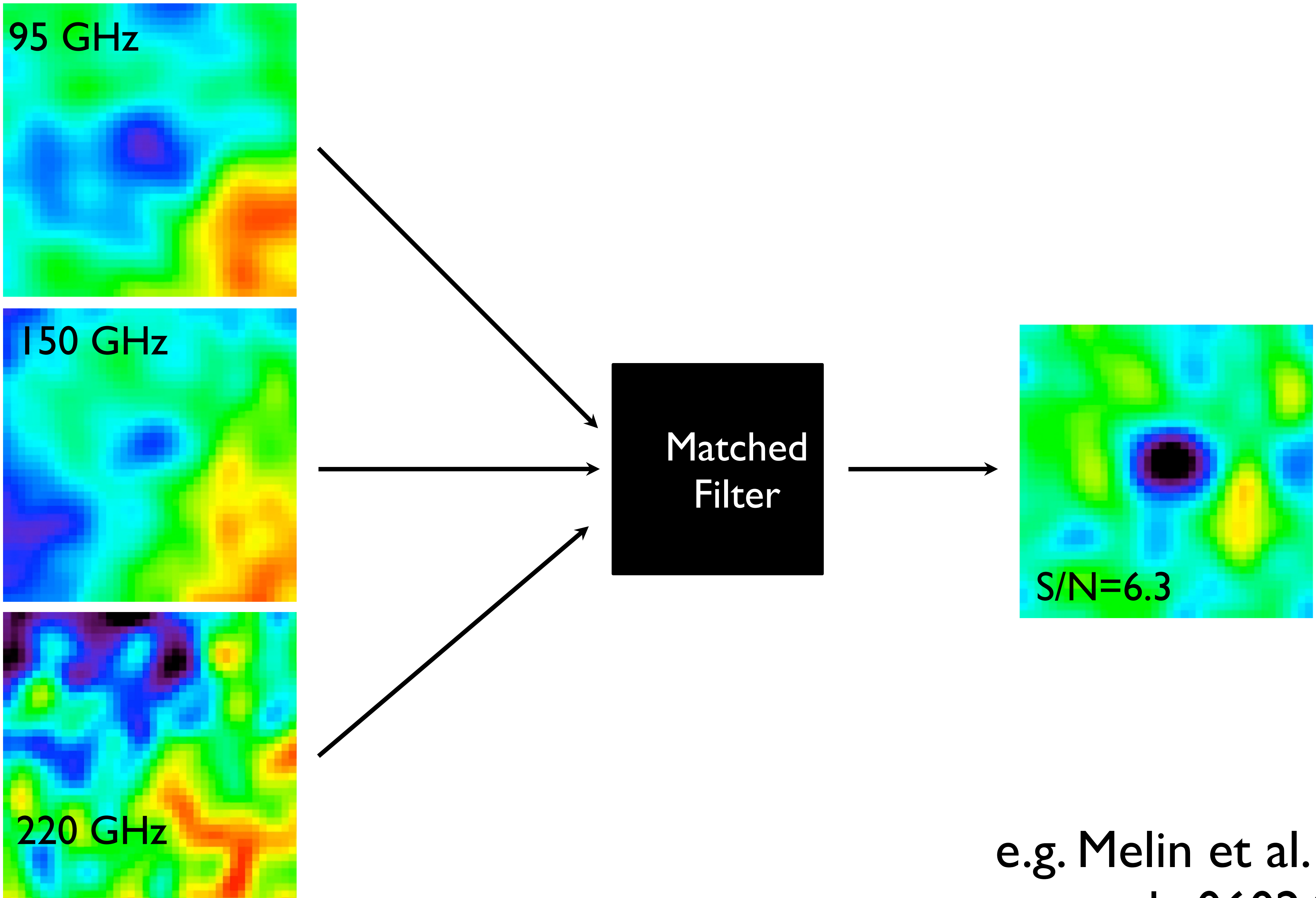
Hezaveh et al. ApJ 767, (2013) ,132
Weiss et al. ApJ, 767, (2013), 88
Vieira et al. Nature, 495 (2013), 344
and more!

Zoom in on highpass filtered SPT map

~50 square degrees from
2500 square degree survey

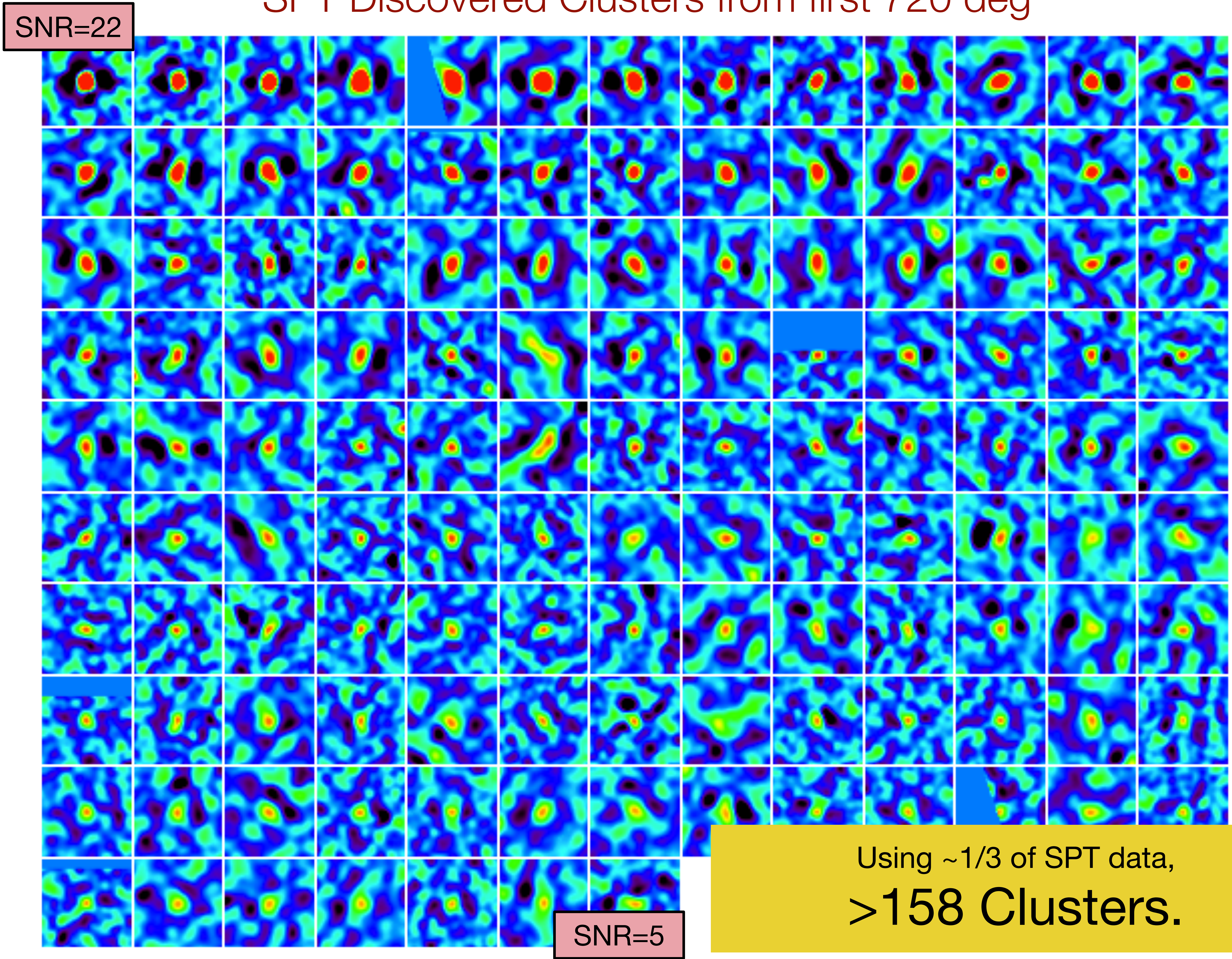
Galaxy Clusters – High signal-to-noise SZ galaxy cluster detections appear as “shadows” against the CMB!

Finding Clusters in the SPT Survey



e.g. Melin et al.
astro-ph: 0602424

SPT Discovered Clusters from first 720 deg^2



Reichardt et al 2013

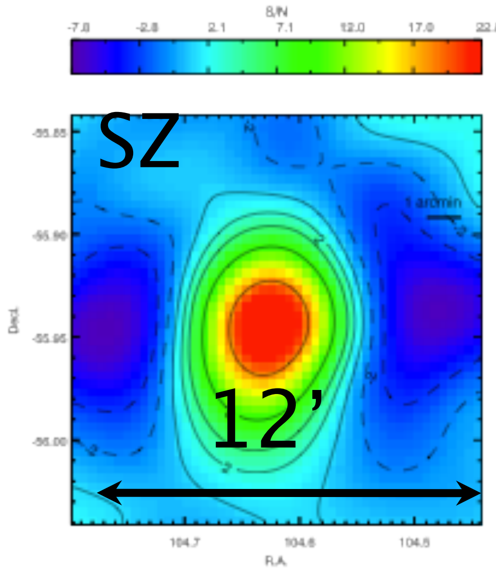
Using ~1/3 of SPT data,

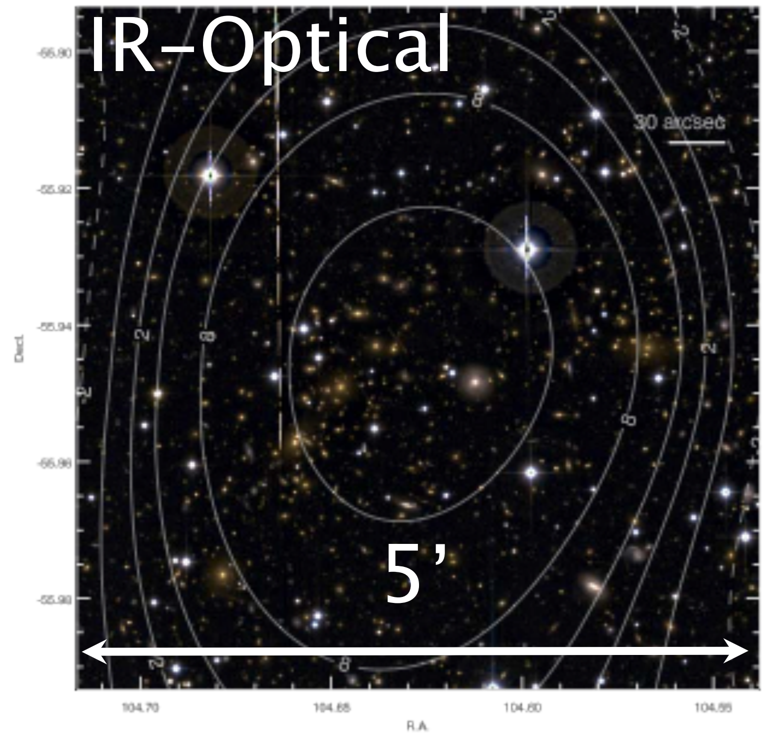
>158 Clusters.

Example Massive SPT Clusters

0658-5358 (z=0.30)

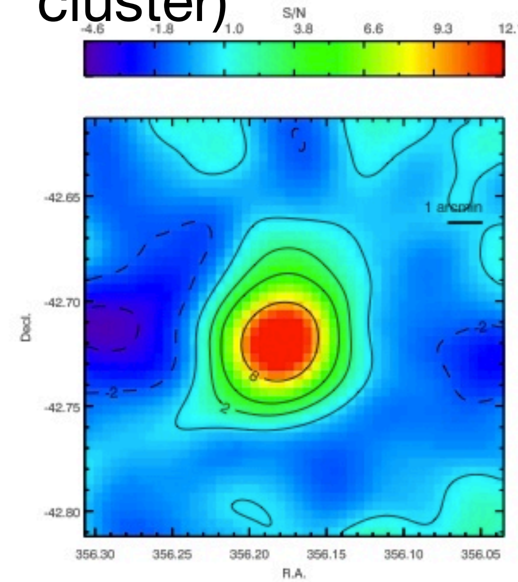
(Bullet)

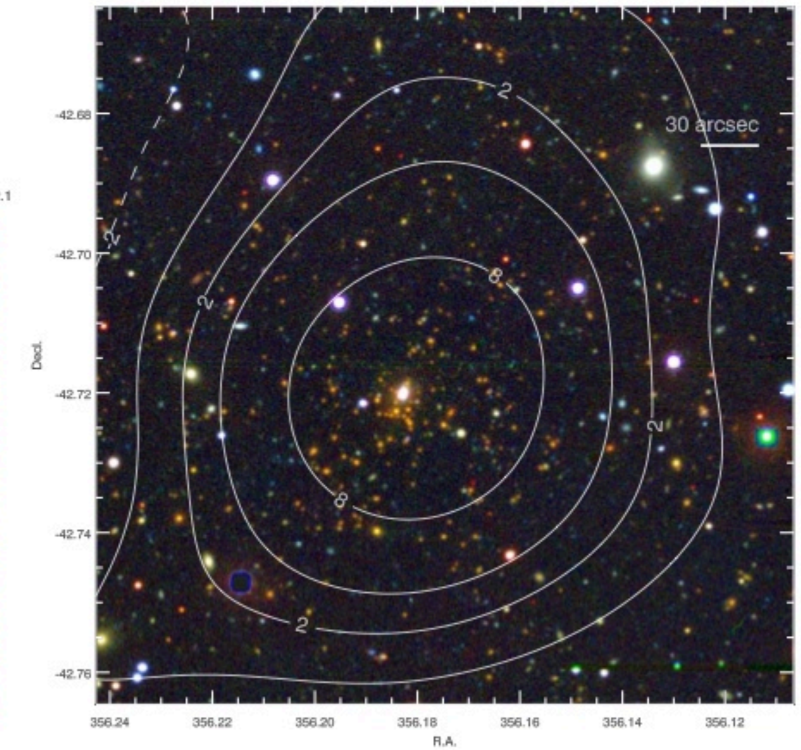




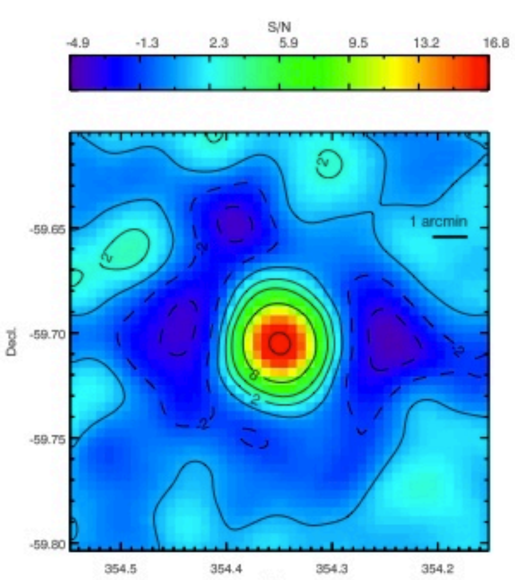
2344-4243 (z=0.62)

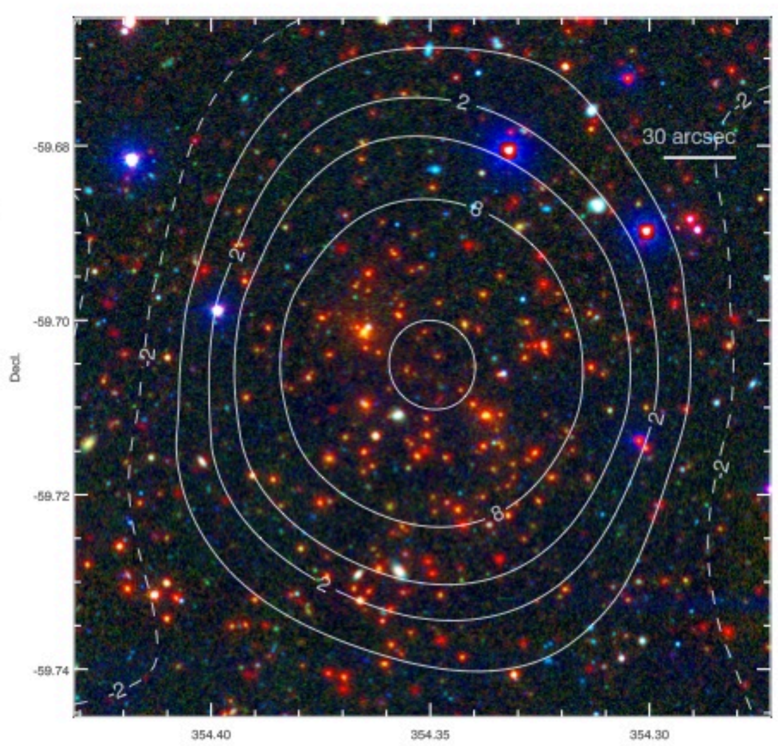
(Most X-ray luminous known cluster)





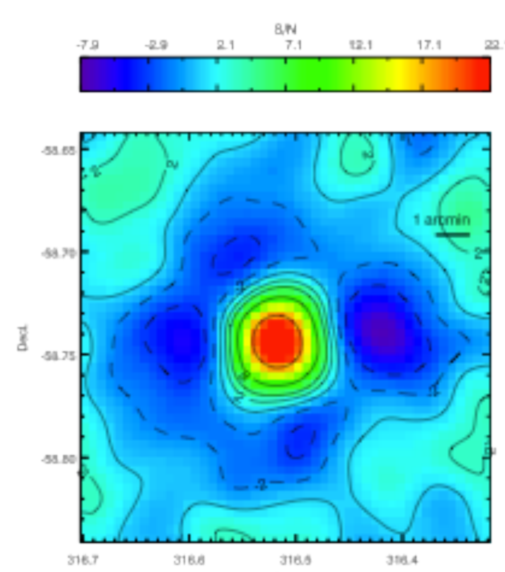
2337-5942 (z=0.78)

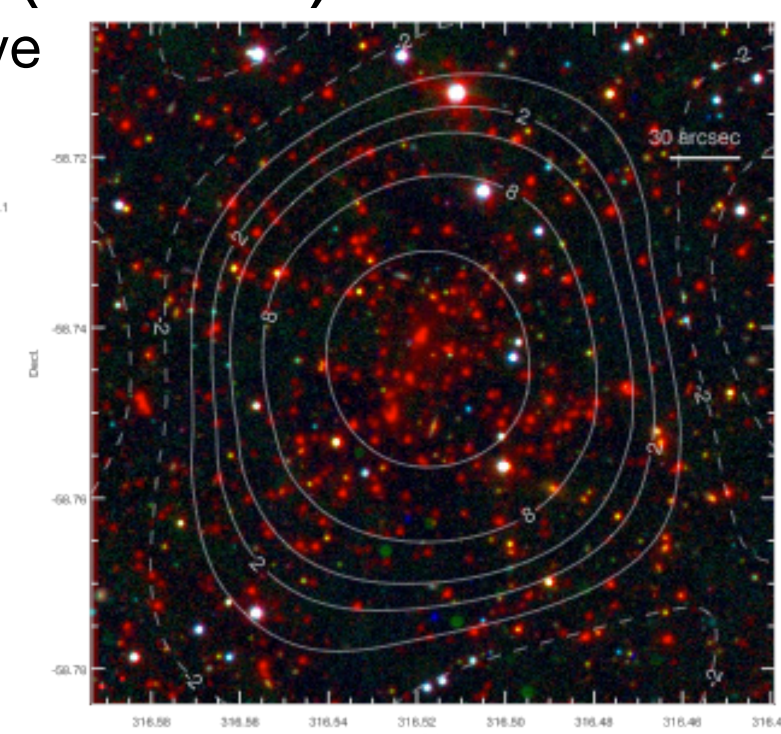




2106-5844 (z=1.13)

(The most massive cluster at z > 1)





Cosmological Analysis:

Combine X-ray Measurements with SZ Cluster Survey

Developed Markov-Chain Monte Carlo (MCMC) method to vary cosmology and cluster observable-mass relation simultaneously, while accounting for SZ selection in a self-consistent way

6 Cosmology Parameters (plus extension parameters)

- ΛCDM Cosmology

- $\Omega_m h^2$, $\Omega_b h^2$, A_s, n_s, τ, θs

- Extension Cosmology

- w, Σm_ν, f_{NL}, N_{eff}

9 Scaling Relation Parameters

- X-ray (Yx-M) and SZ (ζ-M) relations (4 and 5 parameters):

A) normalization,

B) slope,

C) redshift evolution,

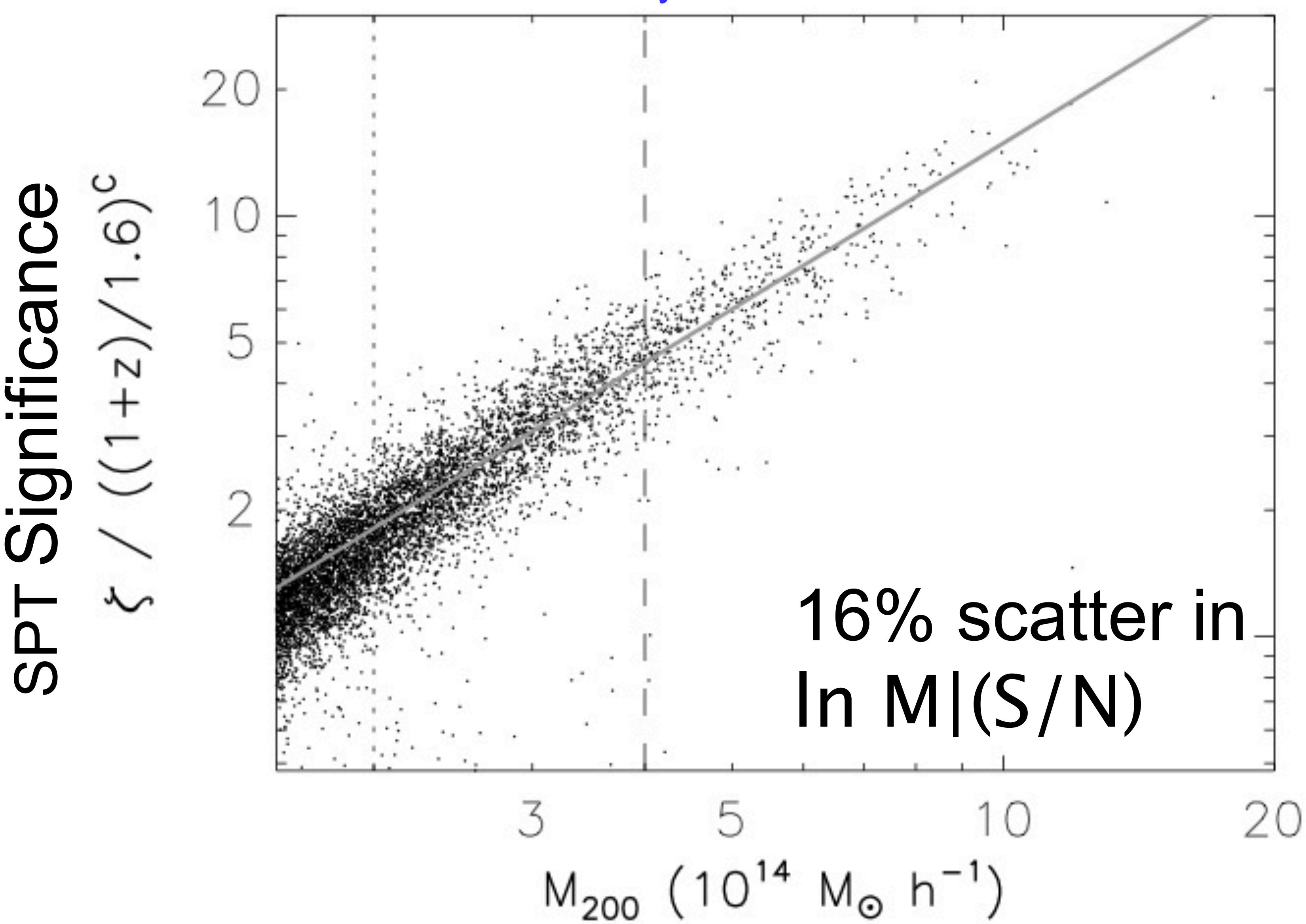
D) scatter,

F) correlated scatter

Benson et al 2013, arXiv: 1112.5435

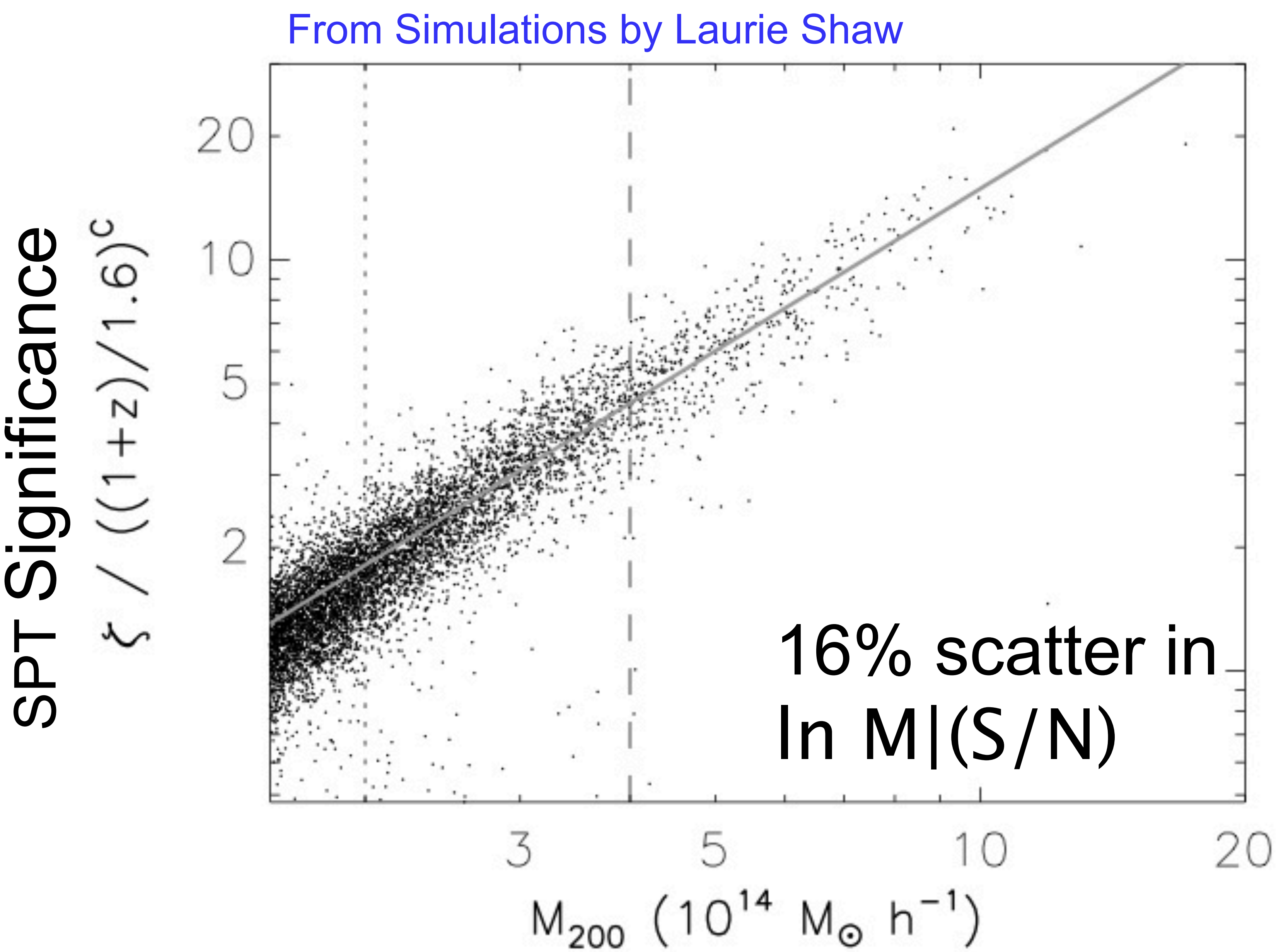
SPT Significance as a Mass Proxy

From Simulations by Laurie Shaw



- For any cluster survey, challenge is to link cluster "observable" to cluster mass
- Y_{SZ} should have low scatter (Kravstov 2006, Battaglia 2012)
- From simulations, signal-to-noise in spatial filtered SPT map is a relatively good mass proxy (Vanderlinde et al 2010)
- **Need to calibrate SZ significance to cluster mass!**

SPT Significance as a Mass Proxy



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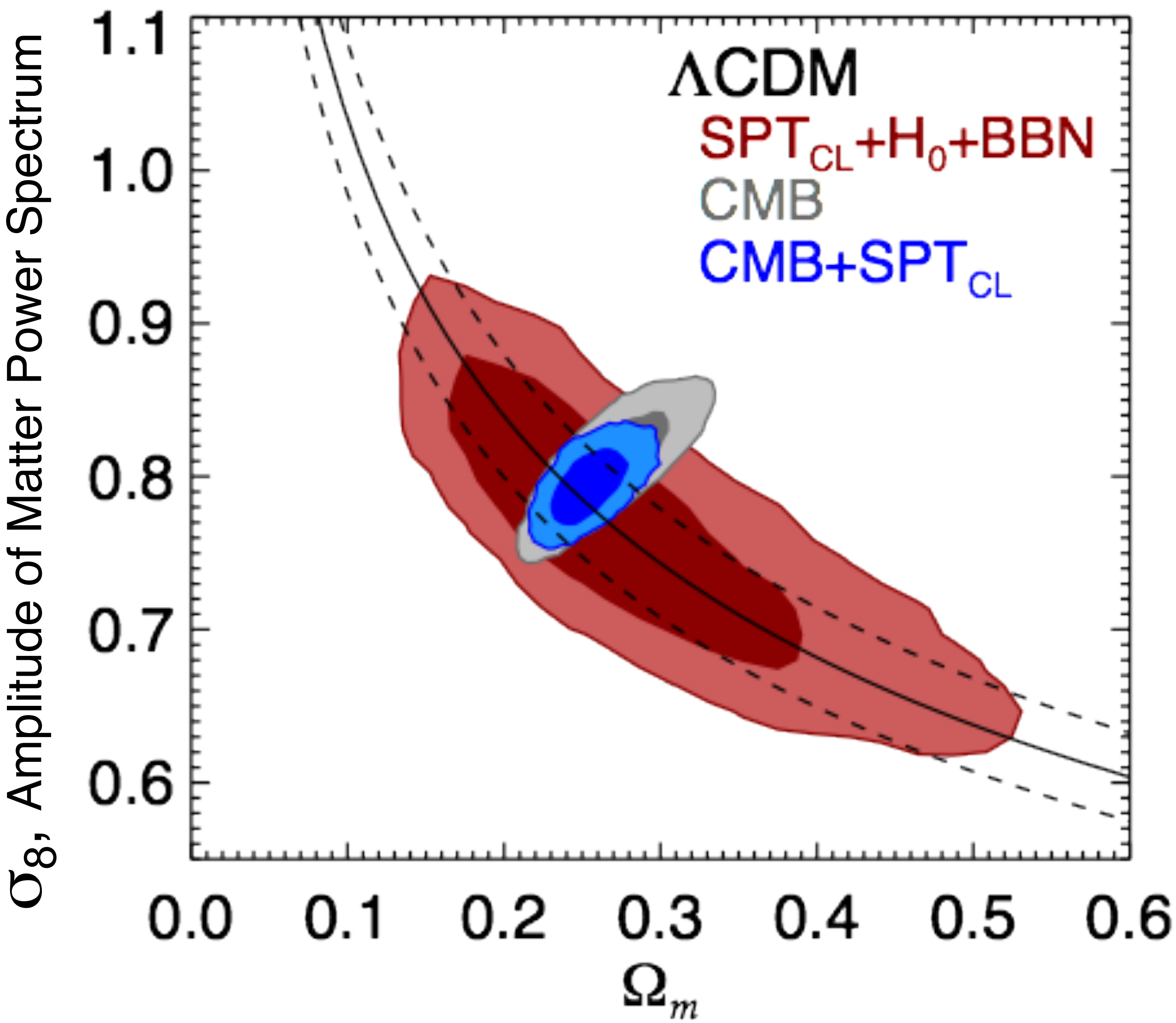
- **Need to calibrate SZ significance to cluster mass!**

ΛCDM Constraints:

Test X-ray Mass Calibration on 18 clusters (Benson et al. 2011)



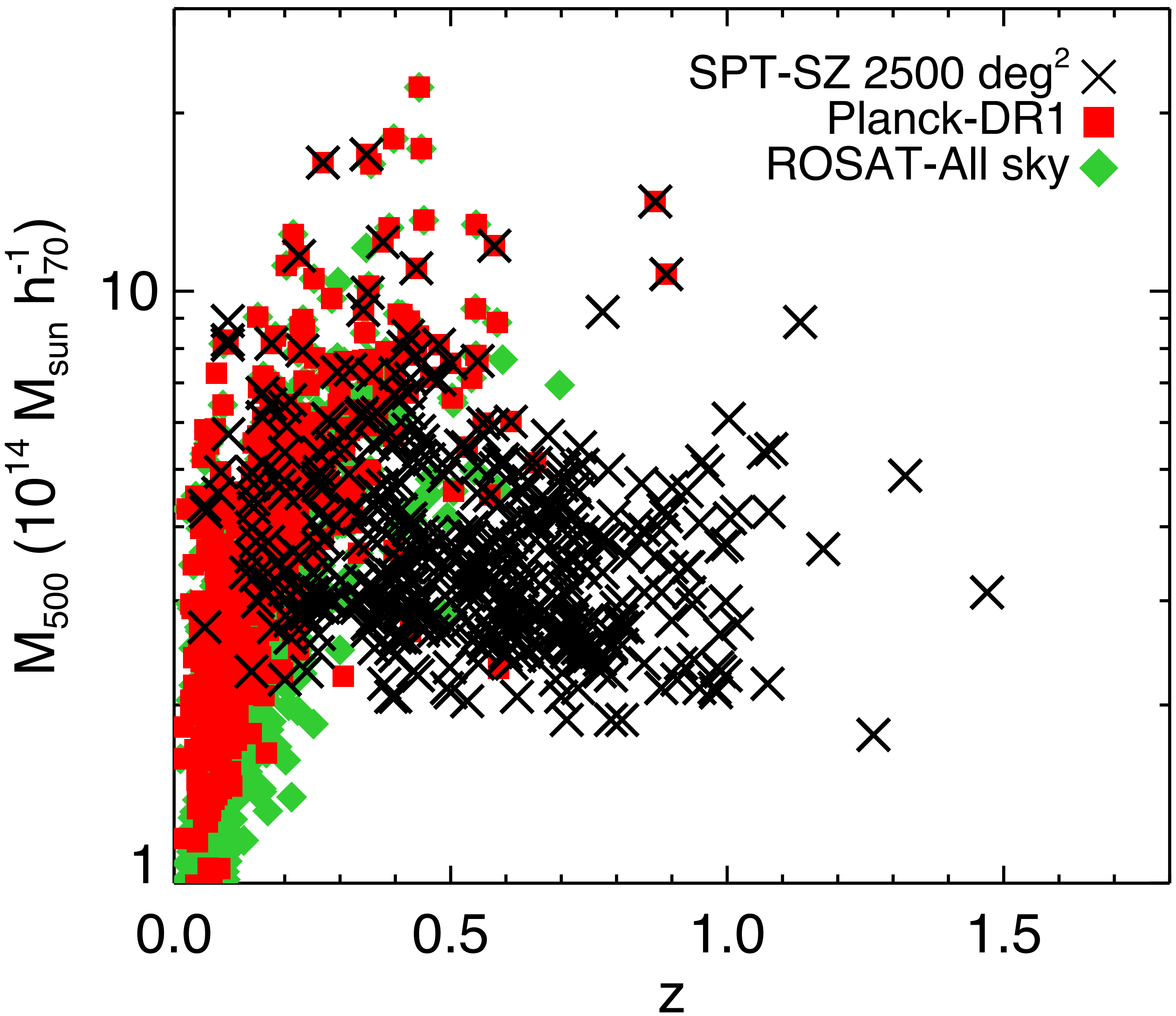
- SPT$_{CL}$+H_0+BBN ΛCDM fit best constrains:
  - $\sigma_8(\Omega_m/0.25)^{0.30}$=0.785 +/- 0.037
  - ***Limited by accuracy of cluster mass calibration!***
- Adding SPT$_{CL}$ to CMB improves σ_8 and Ω_m constraint by factor of 1.5:
  - σ_8 = 0.795 +/- 0.016
  - Ω_m= 0.255 +/- 0.016

σ_8, Ω_m - 68, 95% Confidence Contours

H_0 = 73.8 +/- 2.4 km / s Mpc (Riess et al 2011)
CMB: WMAP7 + SPT (Komatsu et al 2011, Keisler et al. 2011)
BBN: $\Omega_b h^2$ = 0.022 +/- 0.002 (Kirkman et al. 2003)

SPT-2500d Cluster Sample

Cluster Mass vs Redshift

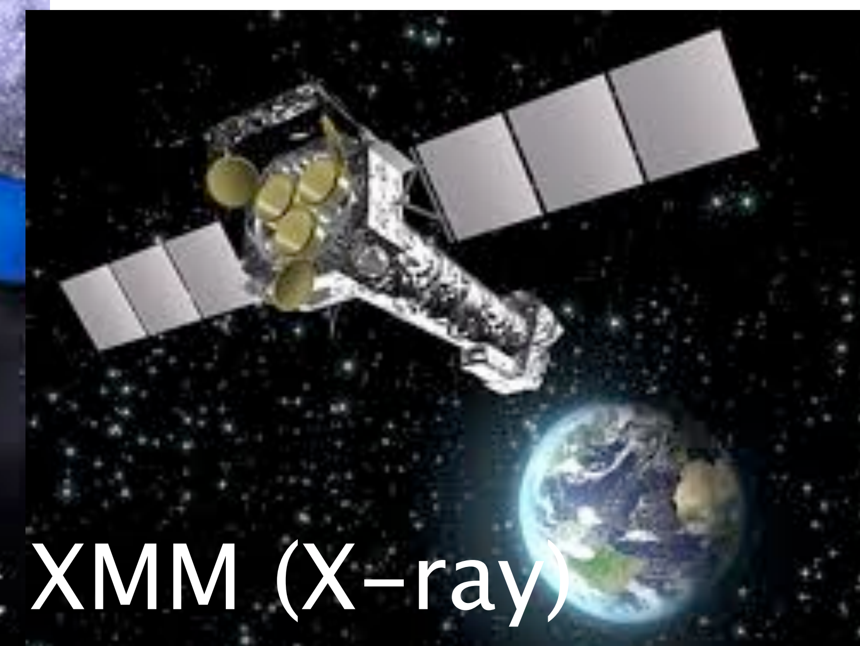


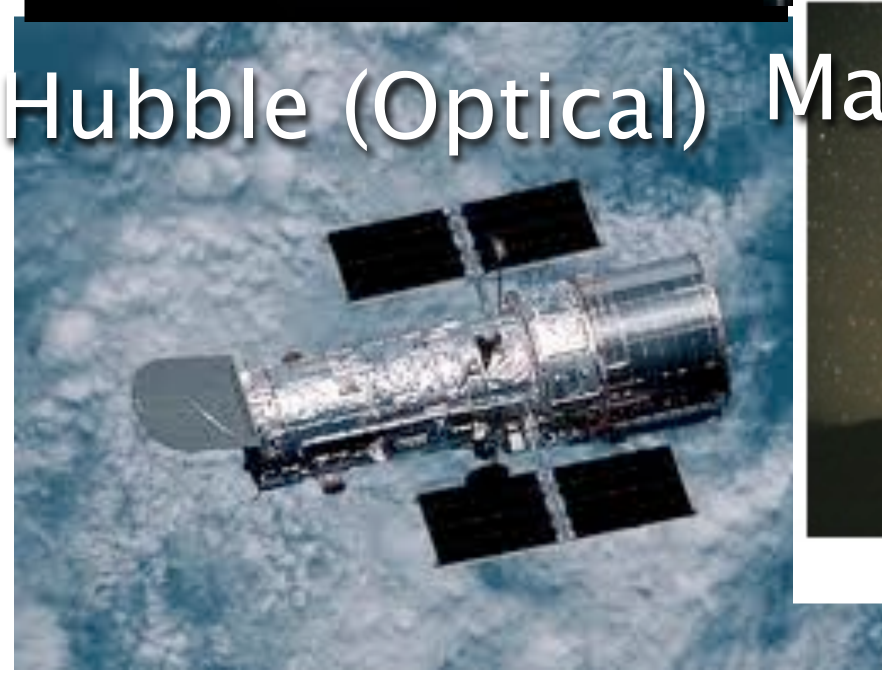
- Reichardt et al. 2013 presented a catalog of 158 clusters from first 1/3 of survey
  - 80% are newly discovered
  - < z > ~ 0.55
  - 20% of sample at z > 0.8
  - Mass threshold falls with redshift, at z = 0.6 - **M_{500} > 3x10^{14} M_{sol}/h_{70}**
- ~500 clusters in 2500 deg^2 catalog; >400 with measured redshifts, analysis on-going

See, Reichardt et al ApJ 763 (2013), 127 for results from first 720d

Multi-wavelength Observations:
Mass Calibration

- **Multi-wavelength mass calibration campaign, including:**
  1. **X-ray** with Chandra and XMM
  2. **Weak lensing** from Magellan ($0.3 < z < 0.6$) and HST ($z > 0.6$)
  3. **Dynamical masses** from NOAO 3-year survey on Gemini ($0.3 < z < 0.8$), also VLT at ($z > 0.8$)





Multi-wavelength Observations:

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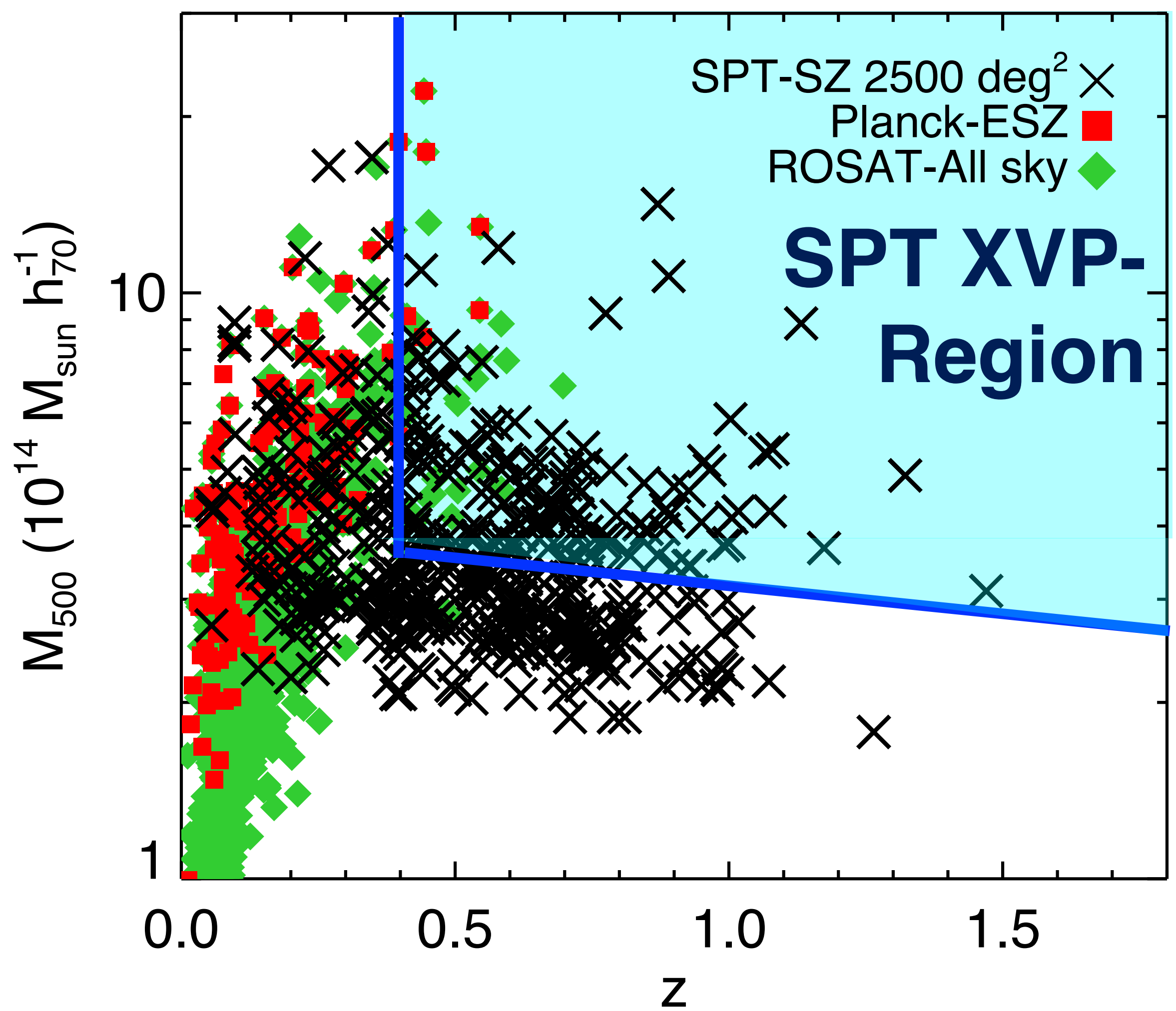

- 90 clusters at 0.3 < *z* < 1.2 with 5.7 < SPT-significance < 43
- Optical Follow-up complete, analysis on-going. Look for results soon!

Multi-wavelength Observations:
Mass Calibration

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  1. **X-ray** with Chandra and XMM **(PI:** Benson, Vikhlinin**)**
  2. **Weak lensing** from Magellan (0.3 < z < 0.6) and HST (z > 0.6) **(PI:** High, Hoekstra, Schrabback)
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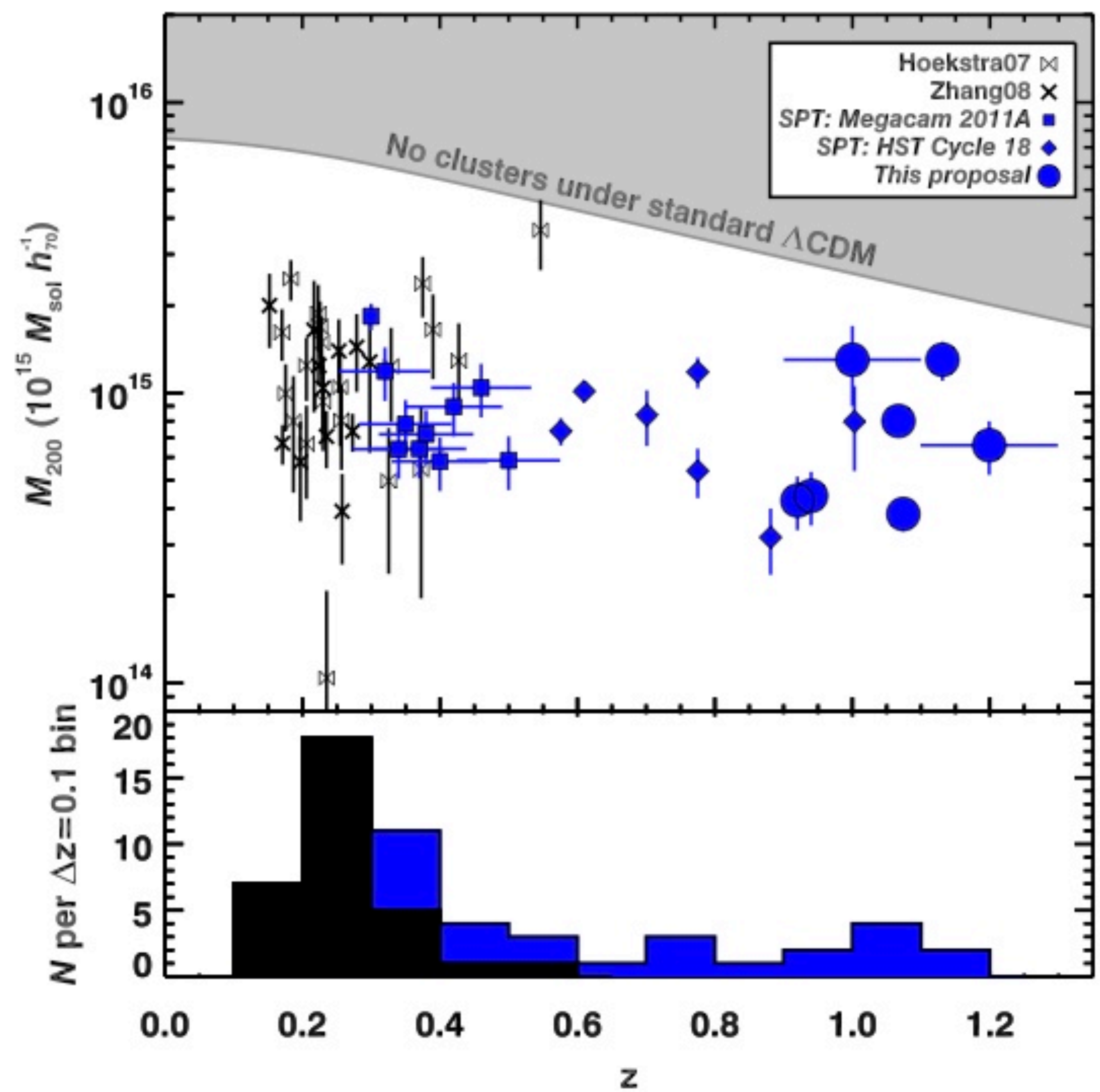
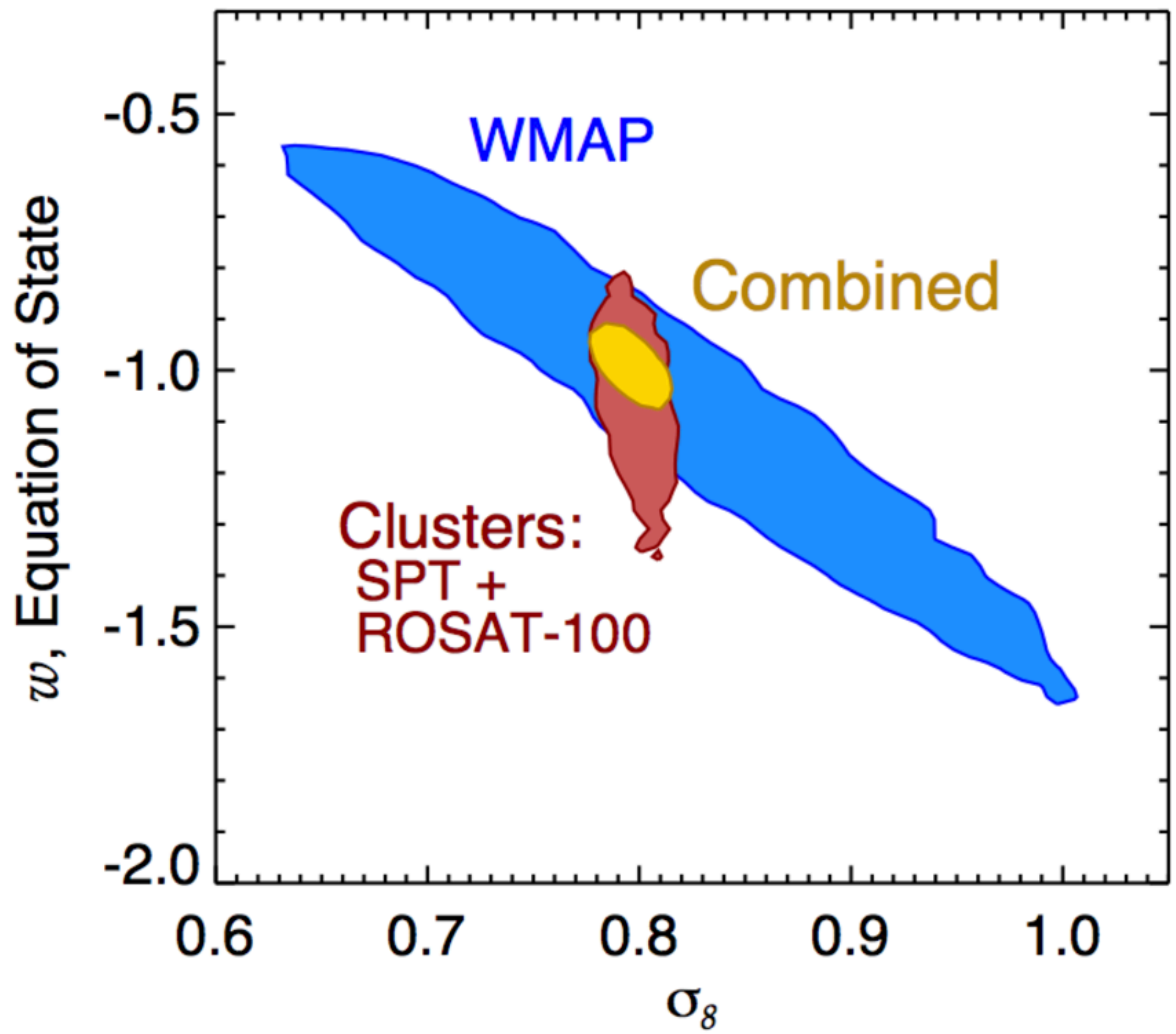
Weak Lensing Sample



See: High et al ApJ 758 (2012), 68

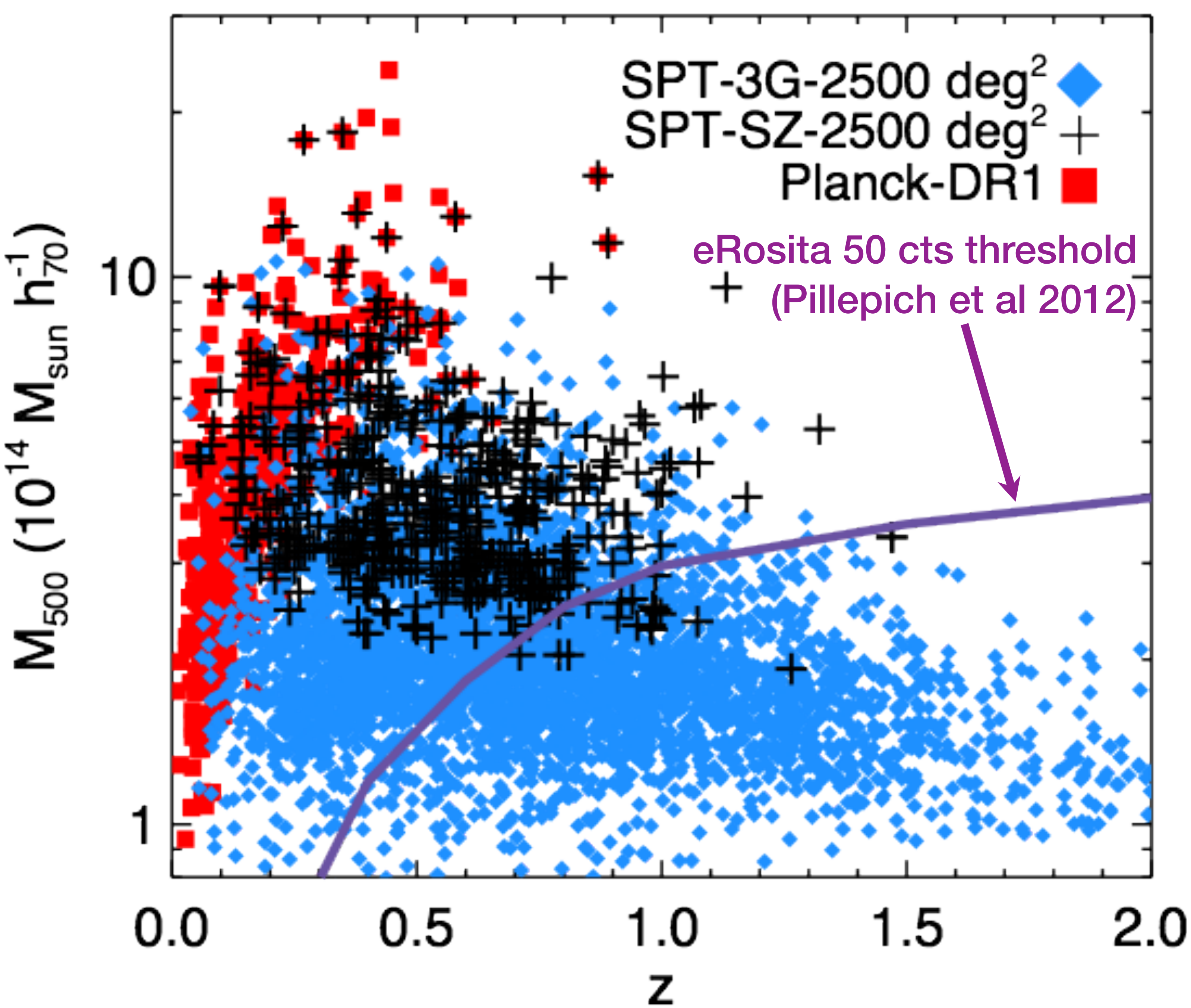
SPT Cosmological Constraints:
2500 deg^2 (projected)



SPT 2500 deg^2 survey has detected ~550 clusters, assuming mass calibration expected with X-ray and Lensing programs then:

- **Combined CMB + SPT cluster survey will constrain dw ~ 7.5%, ****independent***** *of constraints from SNe, BAO***

SPT-3G:
Cluster Survey



- SPT-3G will survey 2500 deg^2 to a level 10x deeper than SPT-SZ survey
- >10x increase in number of clusters over SPT-SZ
  - 4000 clusters at 99% purity threshold
- CMB-cluster lensing would provide a 3% cluster mass calibration
  - competitive with stacked weak-lensing (Rozo et al. 2011)

Credit: B. Benson

Dark Energy Survey (DES) and SPT

Image credit: Roger Smith/NOAO/AURA/NSF

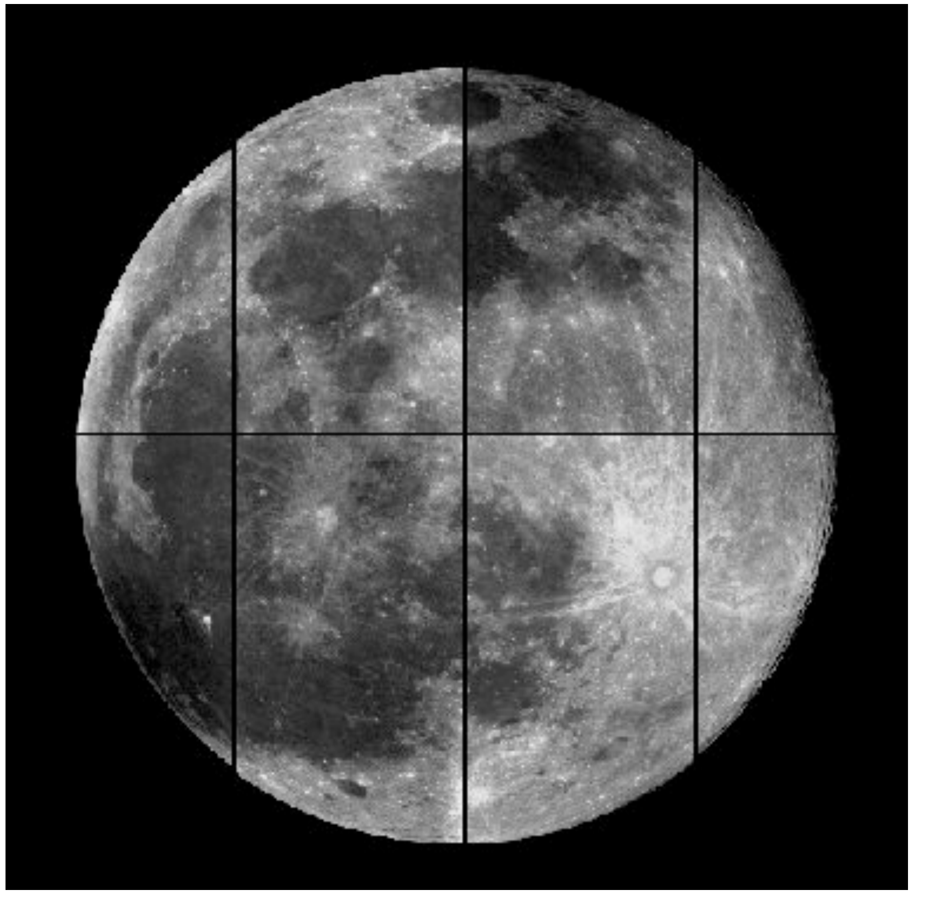
Blanco 4m. Cerro Tololo, Chile

- Wide field (2.2 deg^2) optical camera for 4-meter Blanco telescope (Chile)
- **Optical survey (2012-2016) to cover ~5000 deg^2 which will detect ~100,000 clusters out to *z*~1**
- Multiple probes of dark energy (cluster survey, weak lensing, BAO, SN)
- Coordinated to overlap with SPT

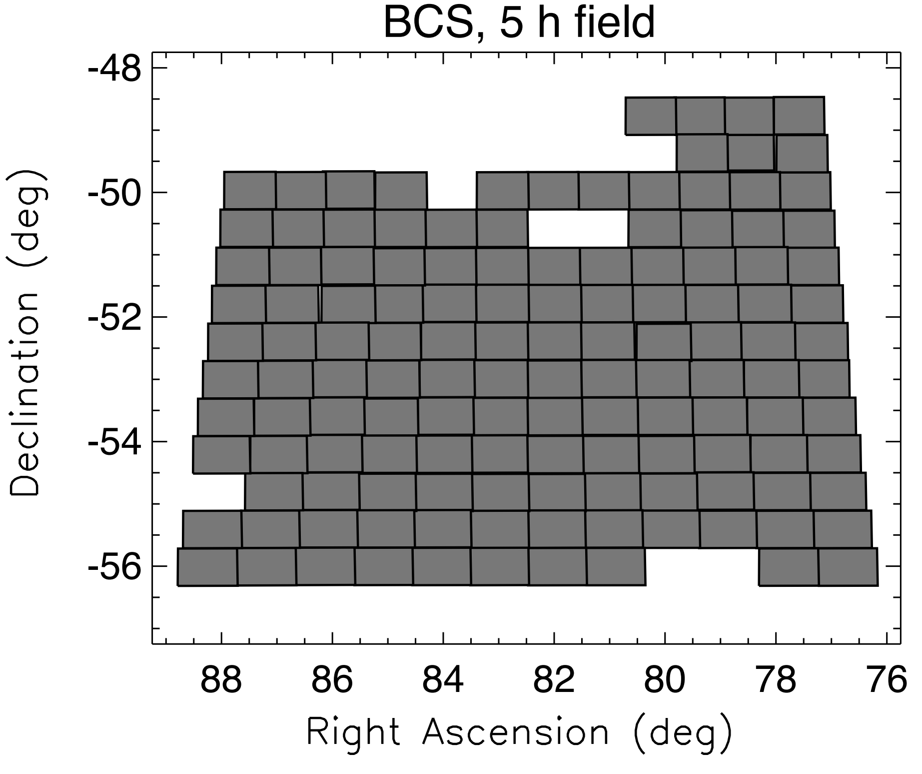
But before there was DES...

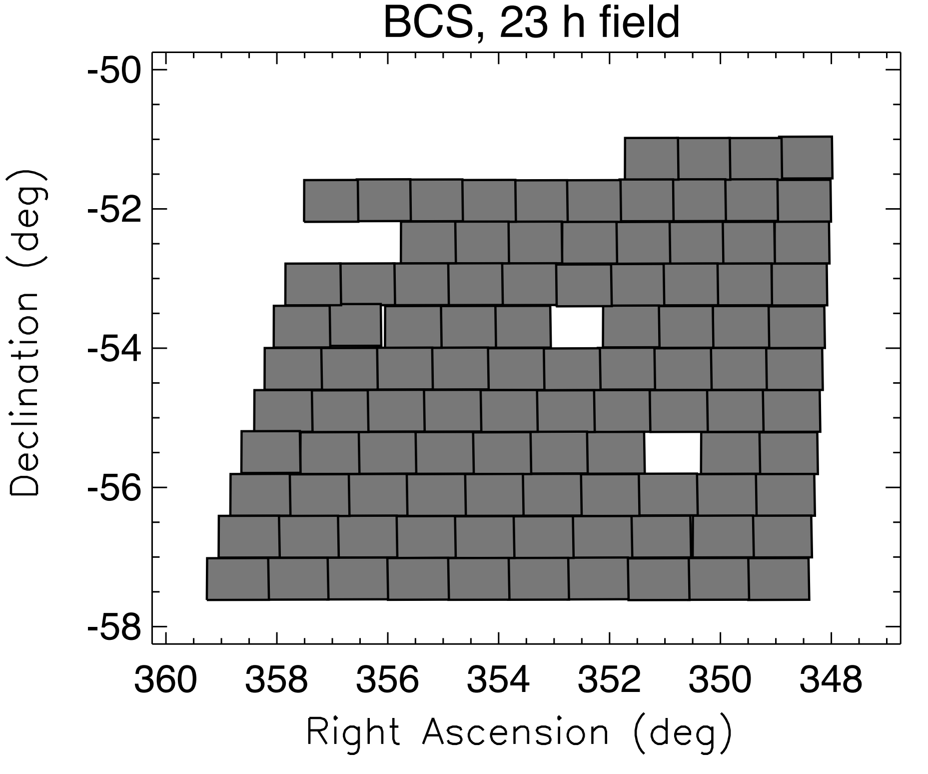
The Blanco Cosmology Survey

- NOAO Large Survey
- ~80 deg^2 over 2 fields
- 57 nights Nov 2005-2008
- Survey coordinated with SPT

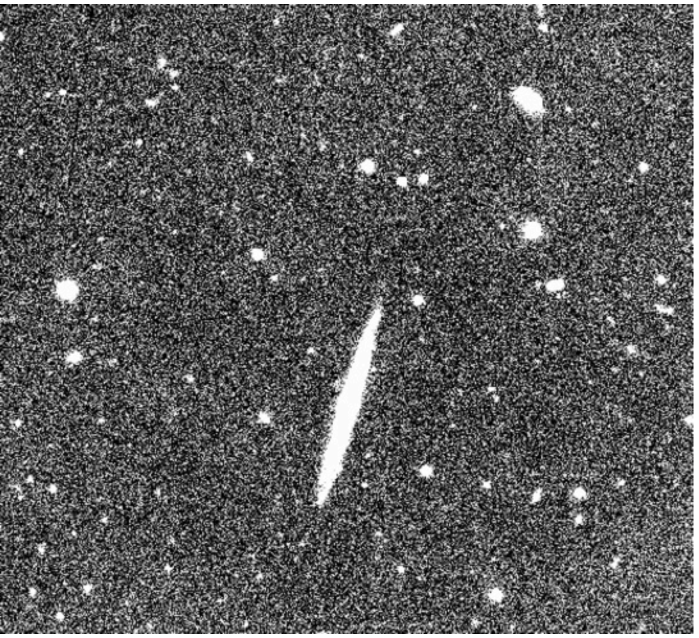


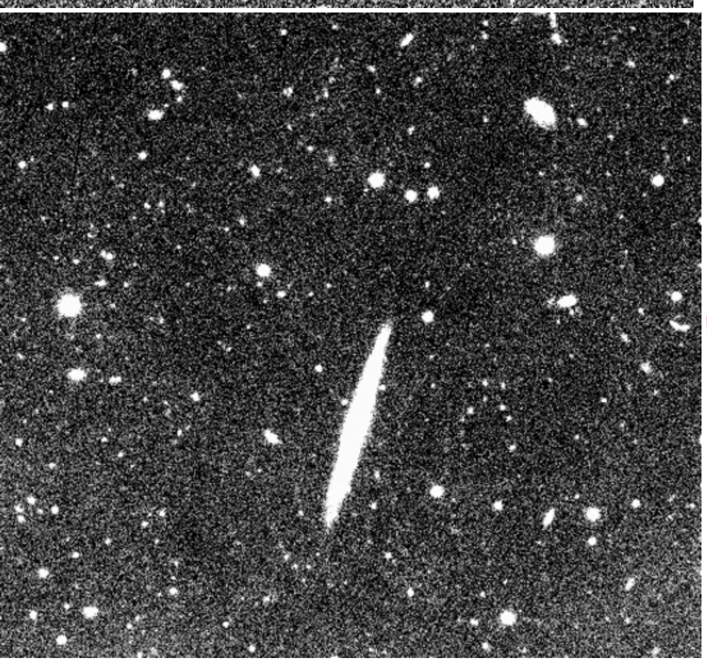
Mosaic-II FOV

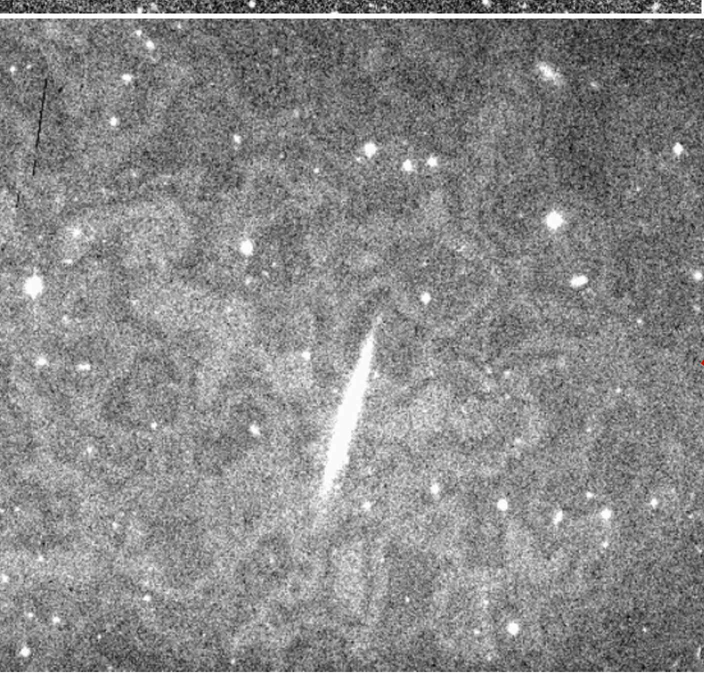


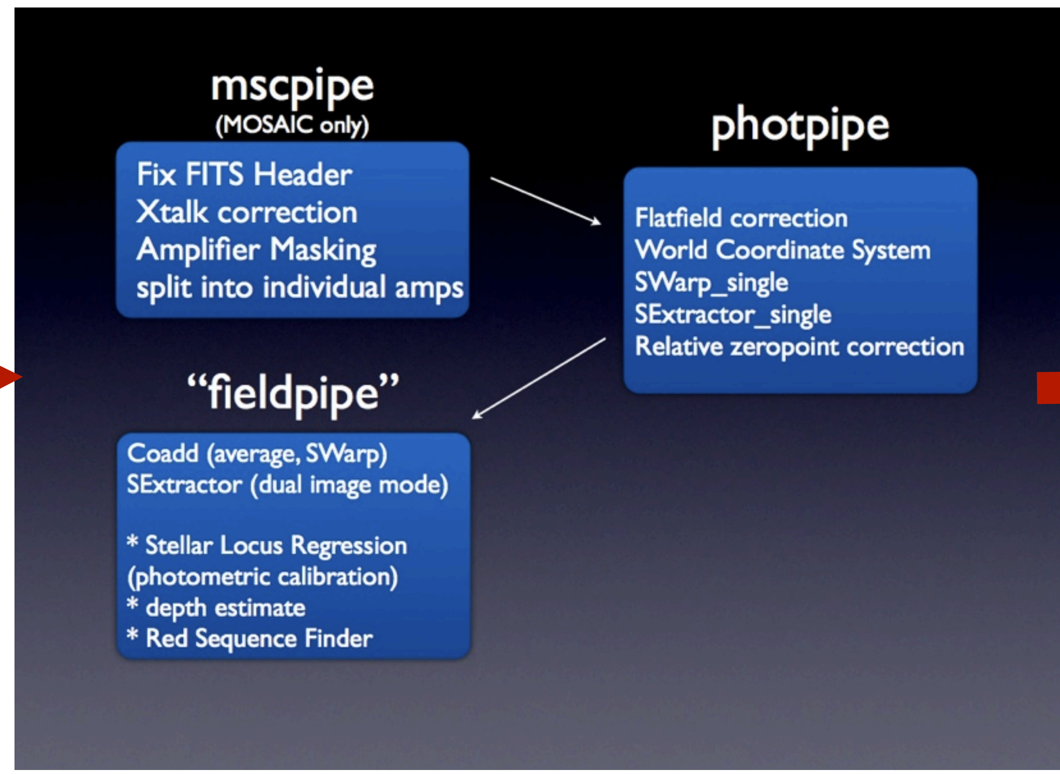


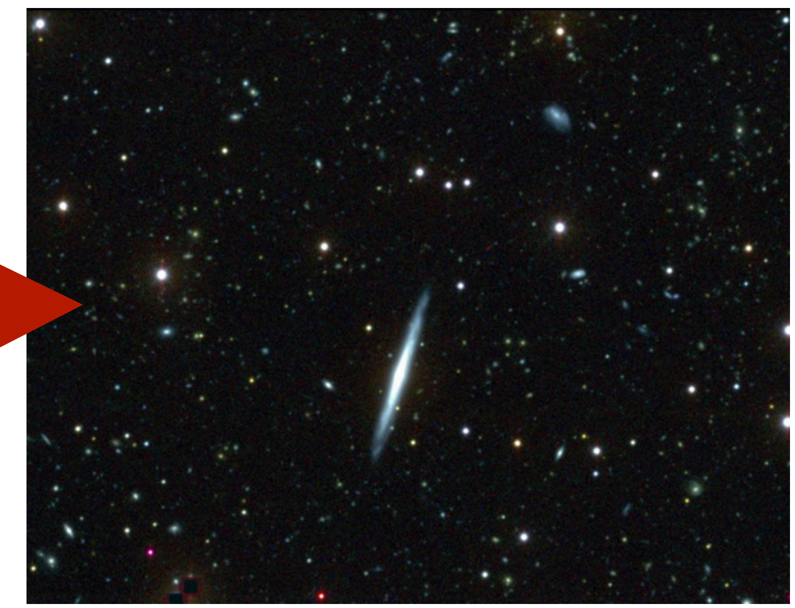
Data was reduced with the photpipe algorithm.











>3000 Individual Exposures
(Including Calibration Files)

A crash course in optical observing

- Observing Considerations
- “Reducing” the images
- Photometry

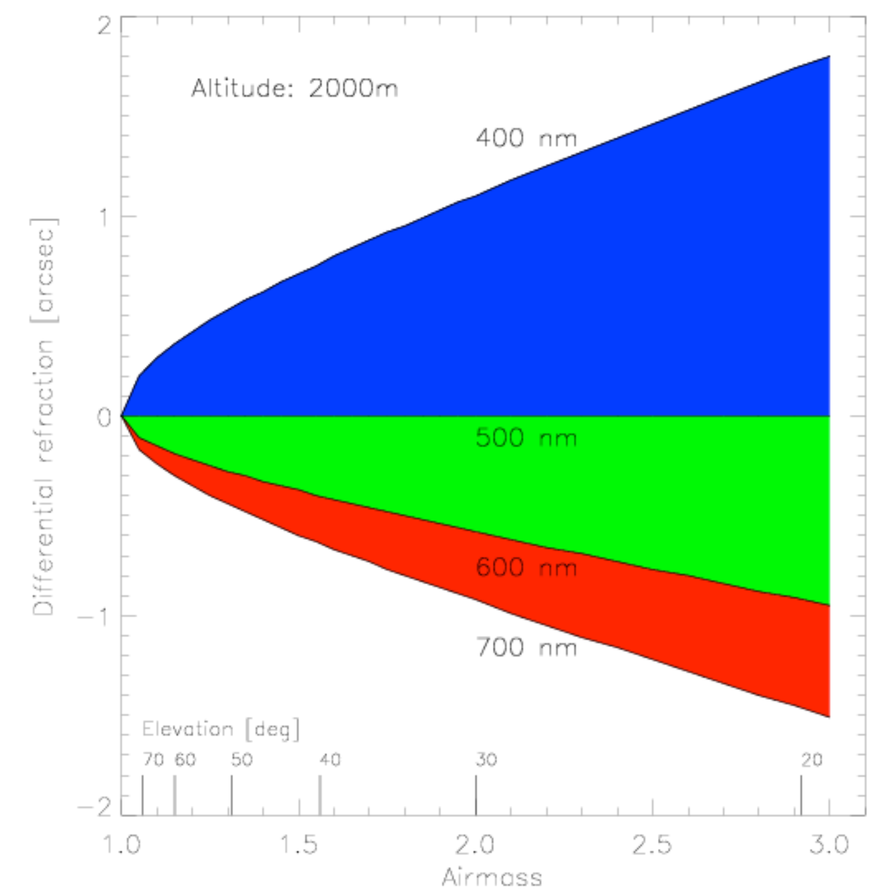
Planning

- Target Visibility
- Scientific Objective
    - filter choices
    - lunar phase
    - observation strategy

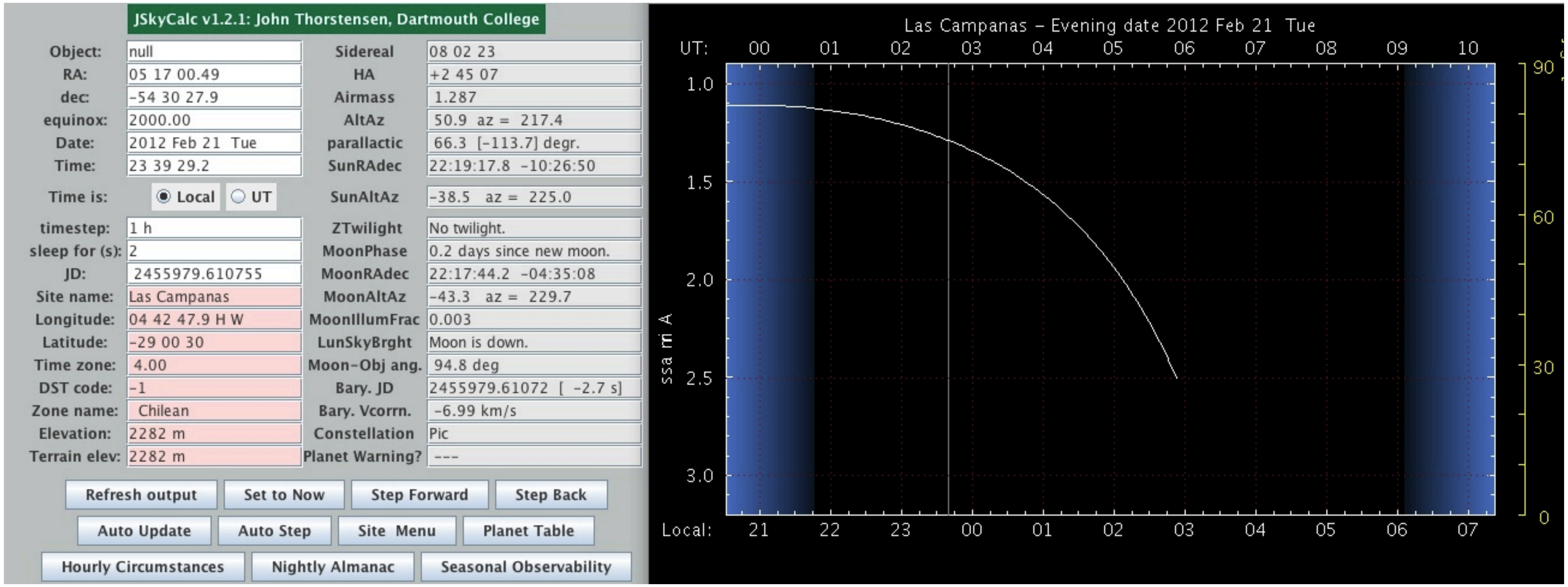
Johannes Vermeer

Target Visibility

- Airmass - path length relative to zenith
- Seeing ~airmass^0.6
- Differential Atmospheric Refraction

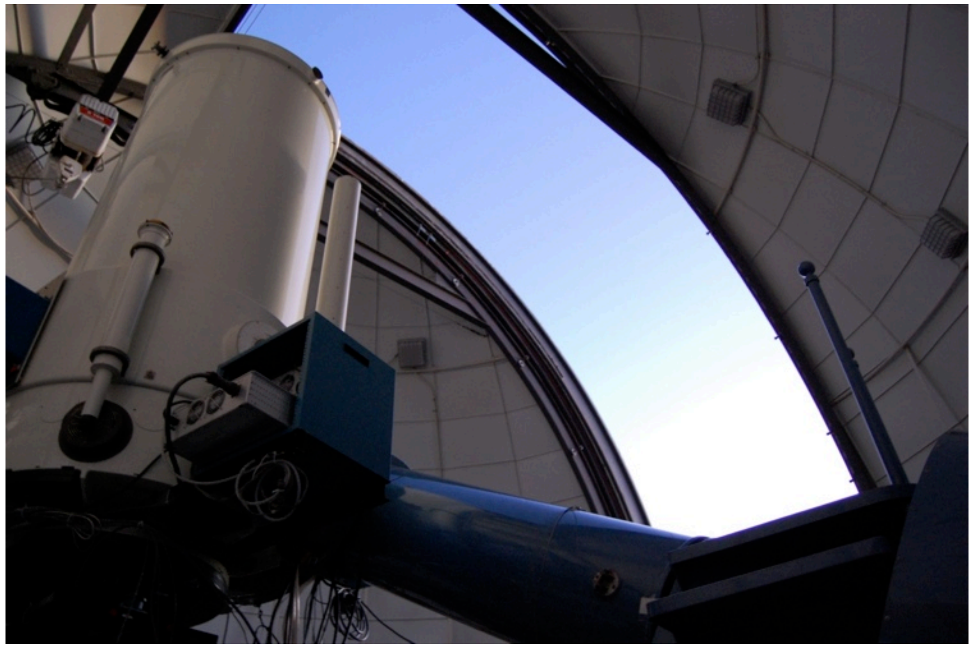


HTTP://WWW.ASTRO.UNI-BONN.DE/~MISCHA/OBSTIPS/AIRMASS.HTML



Observing Plan

- Filter Choice
  - Bright v/s Dark Time
  - Air Glow
  - Dither Strategy



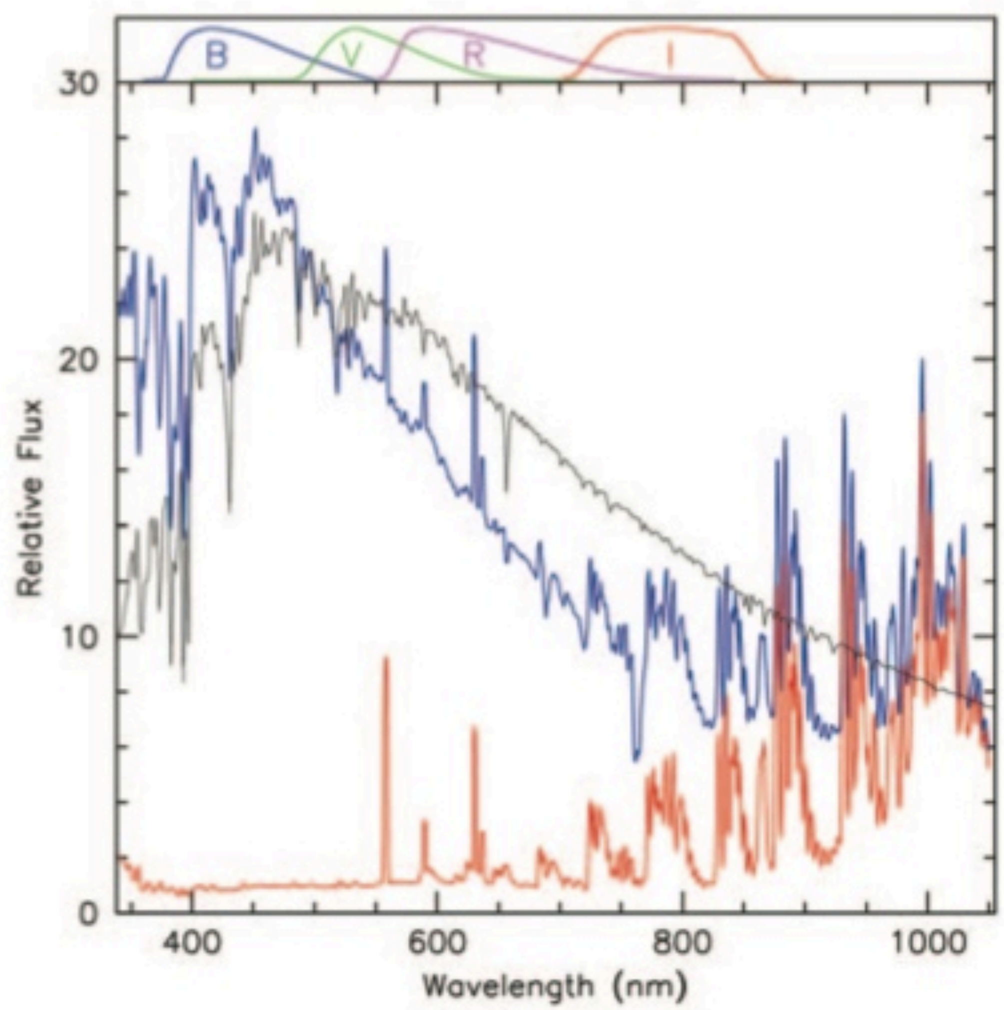
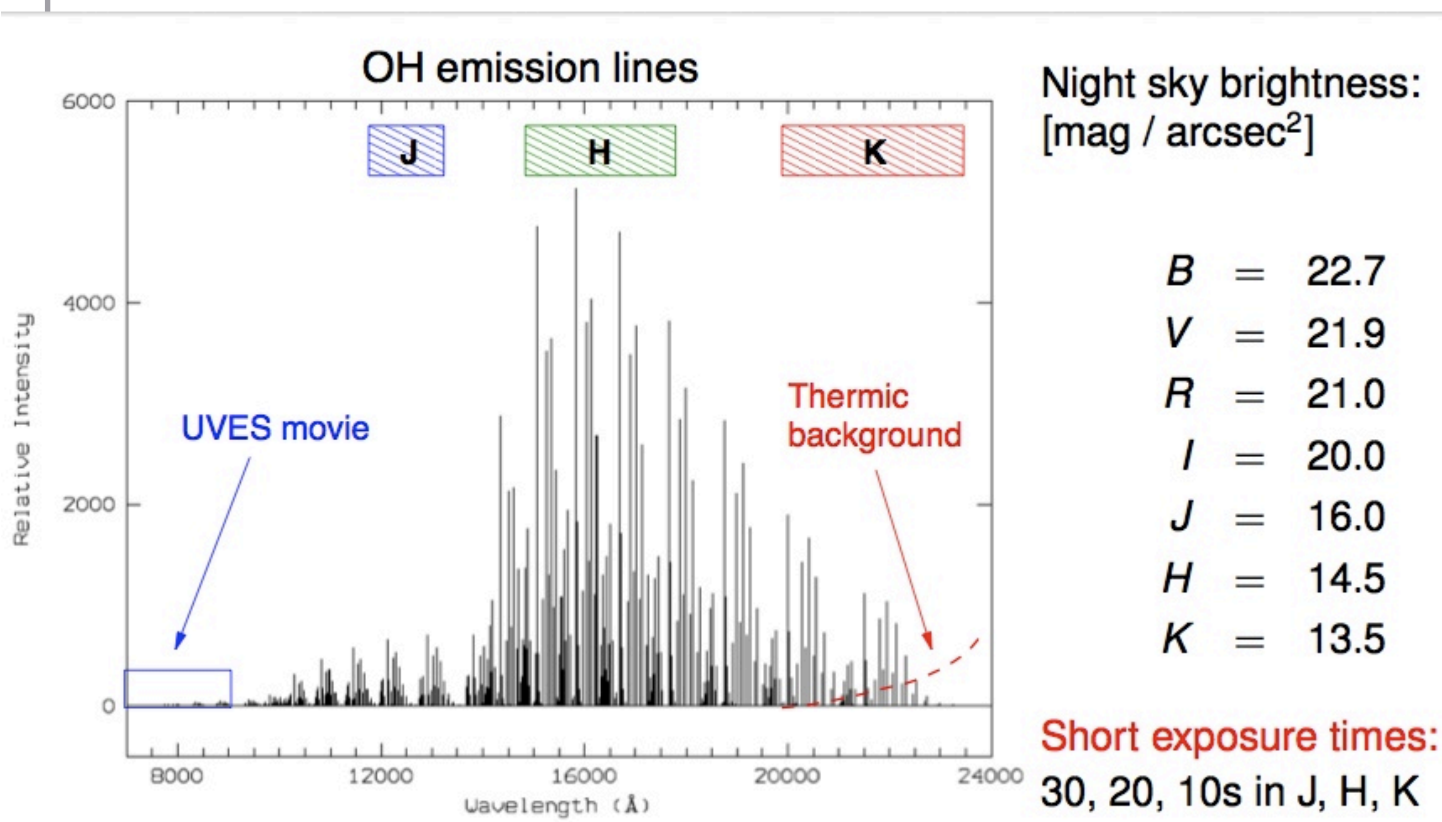


Figure 2: Comparison between the night sky spectrum during dark time (red line, Patat 2003) and bright time (blue line). The latter was obtained with FORS1 on September 1, 2004 using the low dispersion grism 150I and no order sorter filter. Due to the very blue continuum, the spectral region at wavelengths redder than 650 nm is probably contaminated by the grism second order. Both spectra have been normalized to the continuum of the first one at 500 nm. For comparison, the model spectrum of a solar-type star is also plotted (black line). For presentation, this has been normalized to the moonlit night sky spectrum at 500 nm. The upper plot shows the standard *BVRI* Johnson-Cousins passbands.

Patat 2003

Observing Plan

- Air Glow



Mischa Schirmer

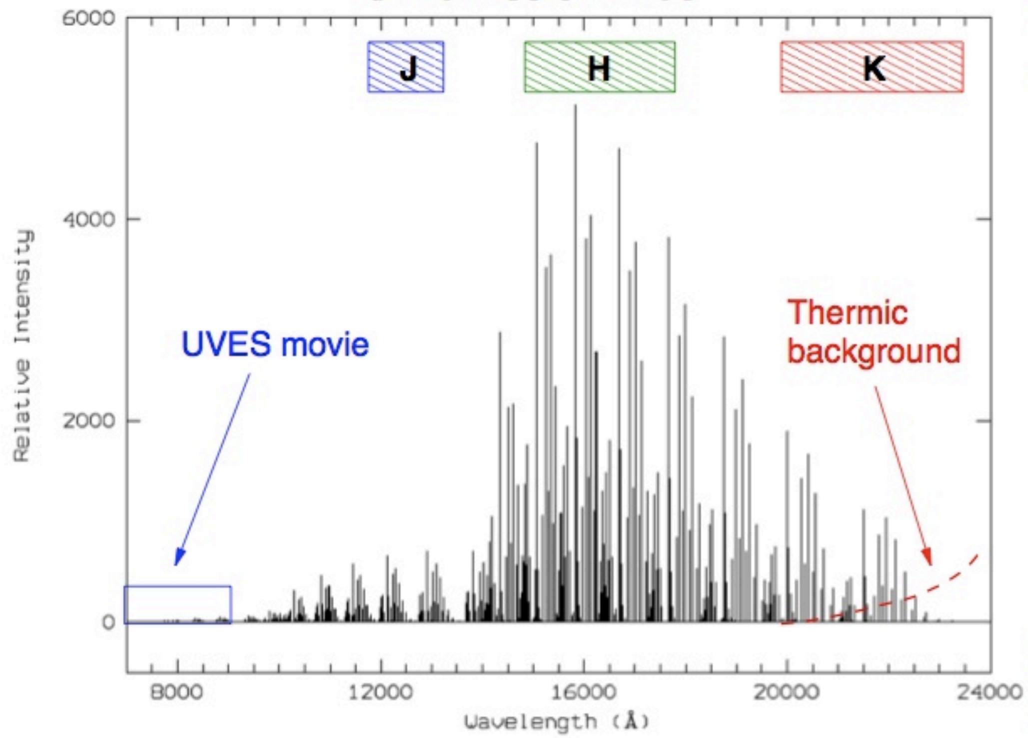
WIDE-FIELD AIRGLOW EXPERIMENT
FOR THE 2-MICRON ALL-SKY SURVEY (2MASS)

1SEC MOVIE = 7.5 MIN

Observing Plan

- Air Glow

OH emission lines

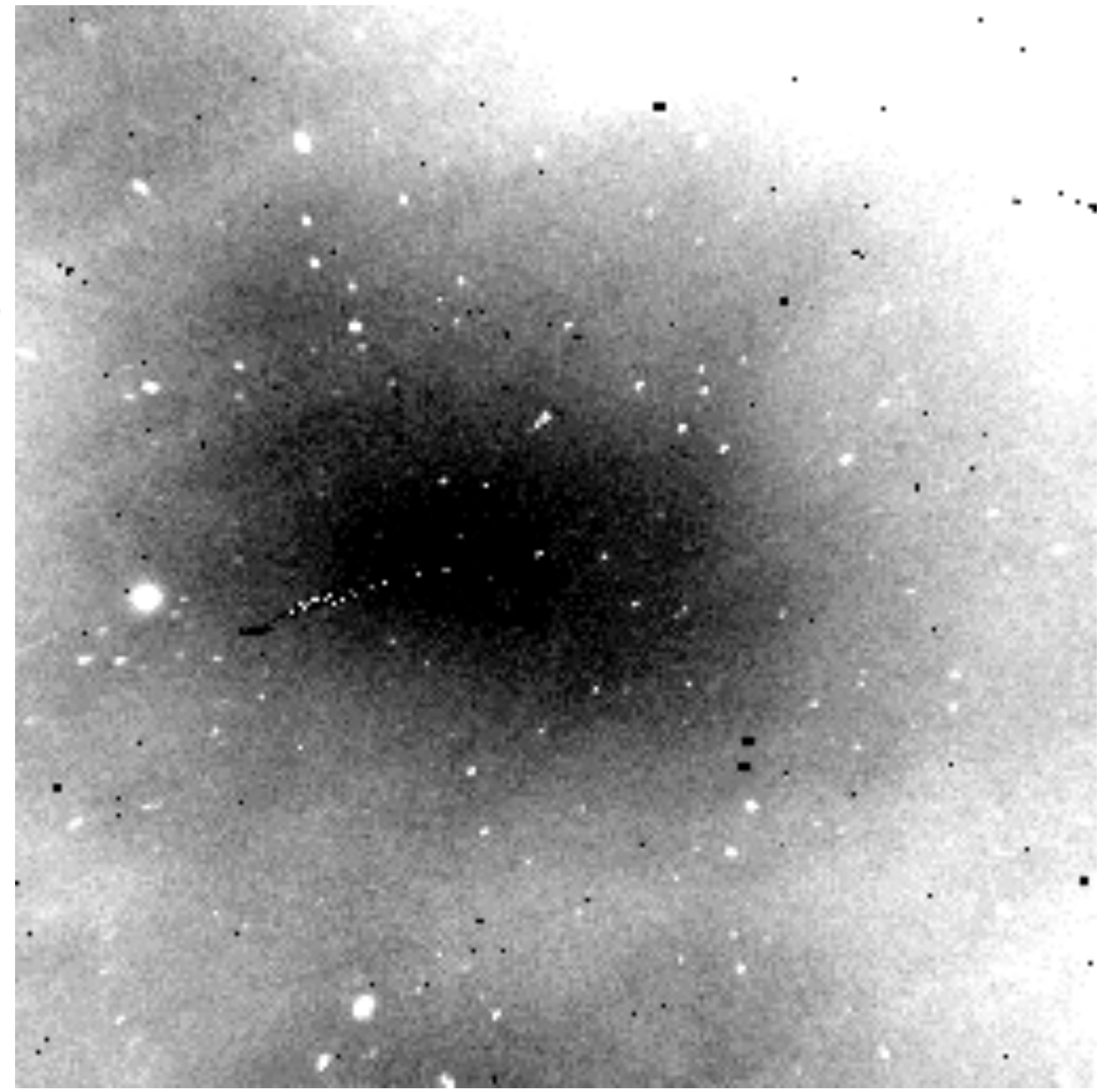


Night sky brightness:
[mag / arcsec^2]

$B = 22.7$
$V = 21.9$
$R = 21.0$
$I = 20.0$
$J = 16.0$
$H = 14.5$
$K = 13.5$

Short exposure times:
30, 20, 10s in J, H, K

Mischa Schirmer



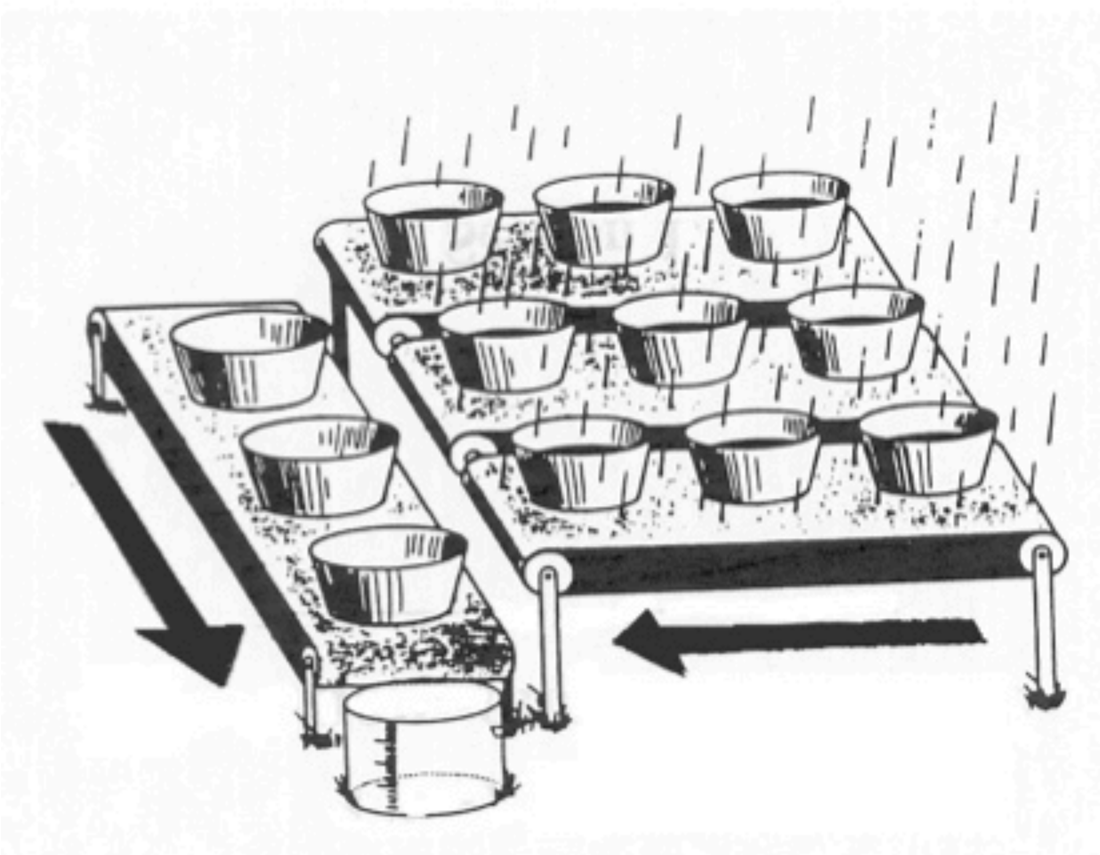
WIDE-FIELD AIRGLOW EXPERIMENT
FOR THE 2-MICRON ALL-SKY SURVEY
(2MASS)

1SEC MOVIE = 7.5 MIN

Raw Images -> Science

- Calibration Files
    - Bias
    - X-talk corrections (mosaic cameras)
    - Flat Fielding
    - Fringe Frames
- Distortions
    - WCS, PSF

CCD Operation in a nutshell



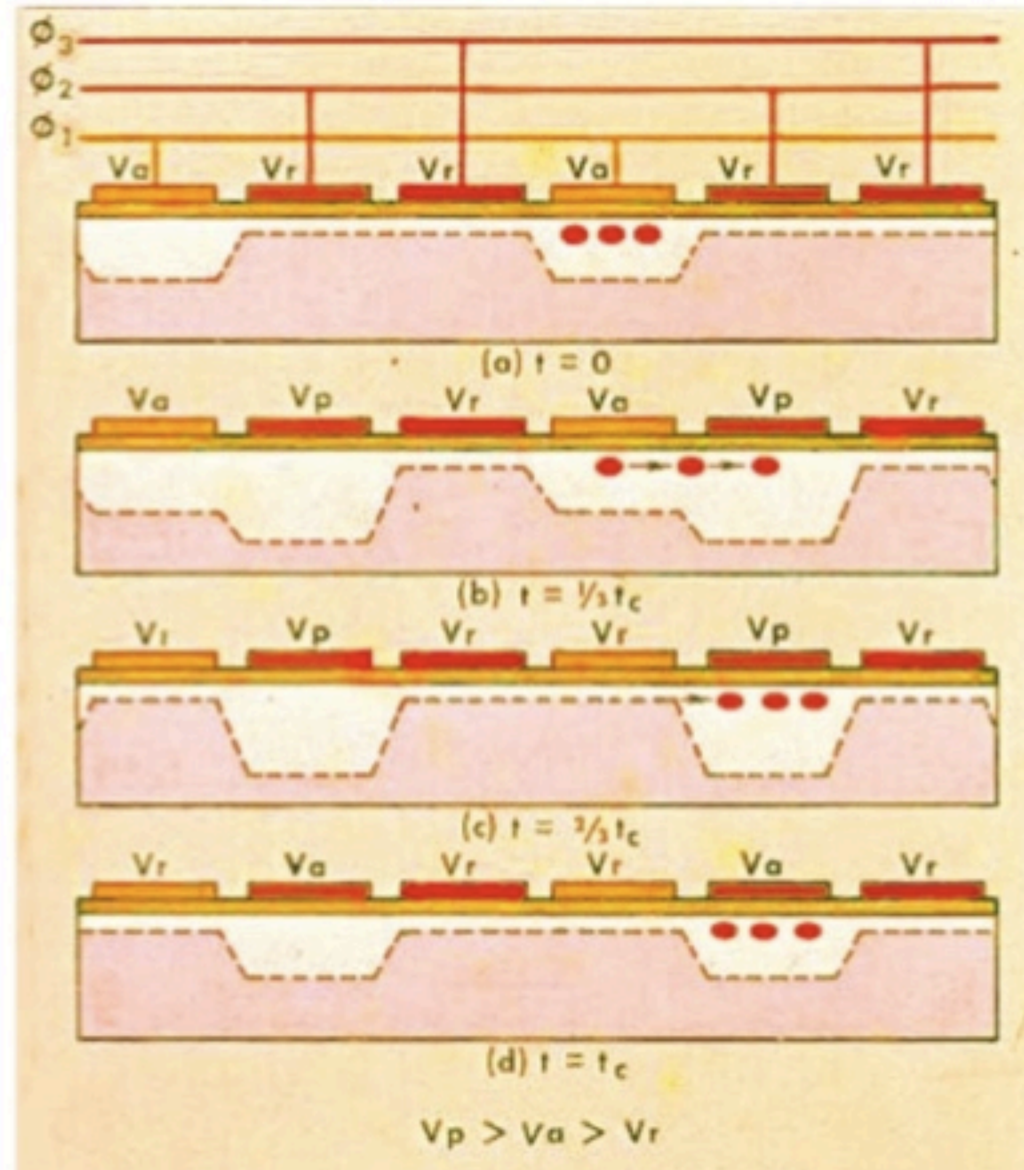
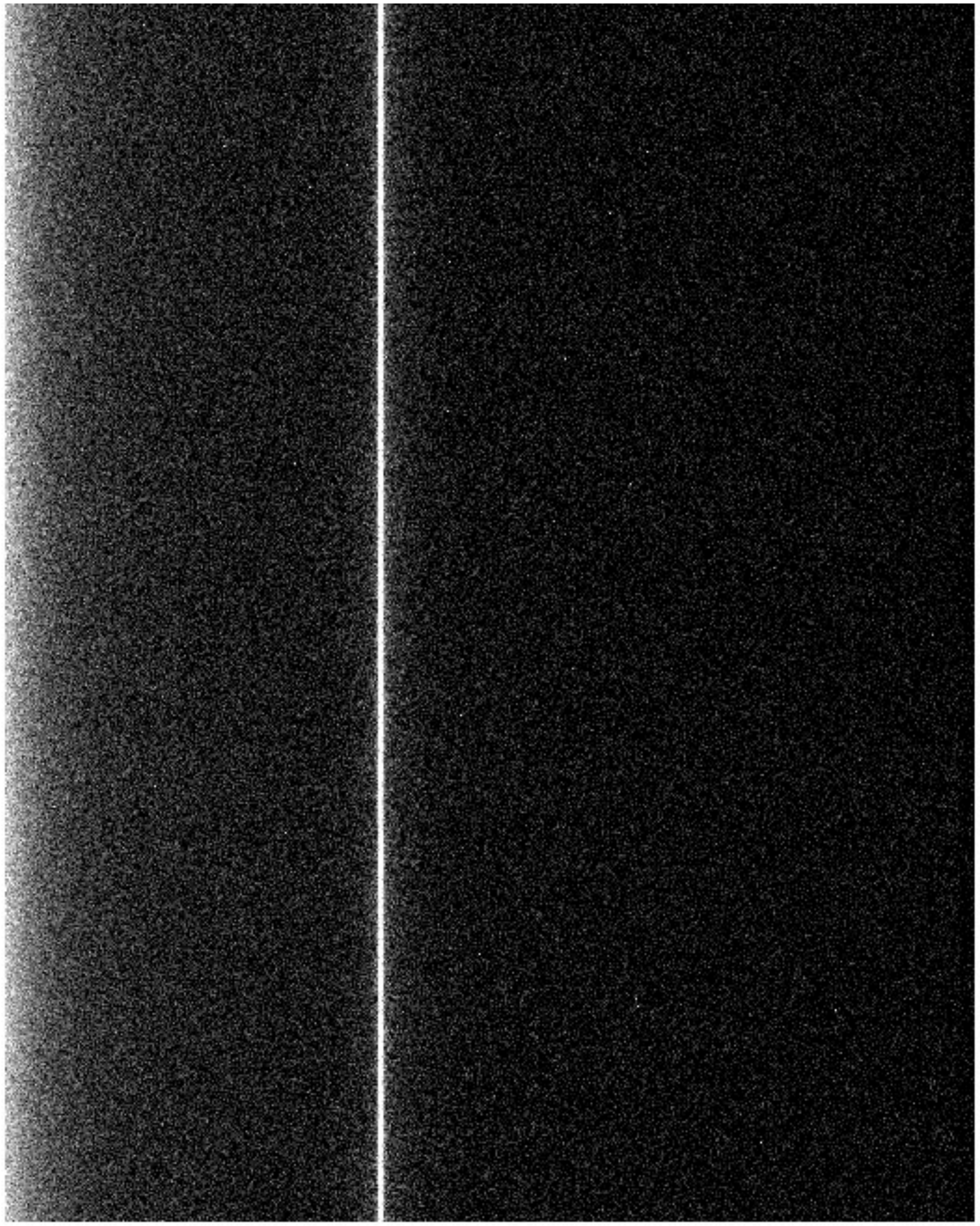


Figure 6. The basic CCD structure.

GEORGE SMITH

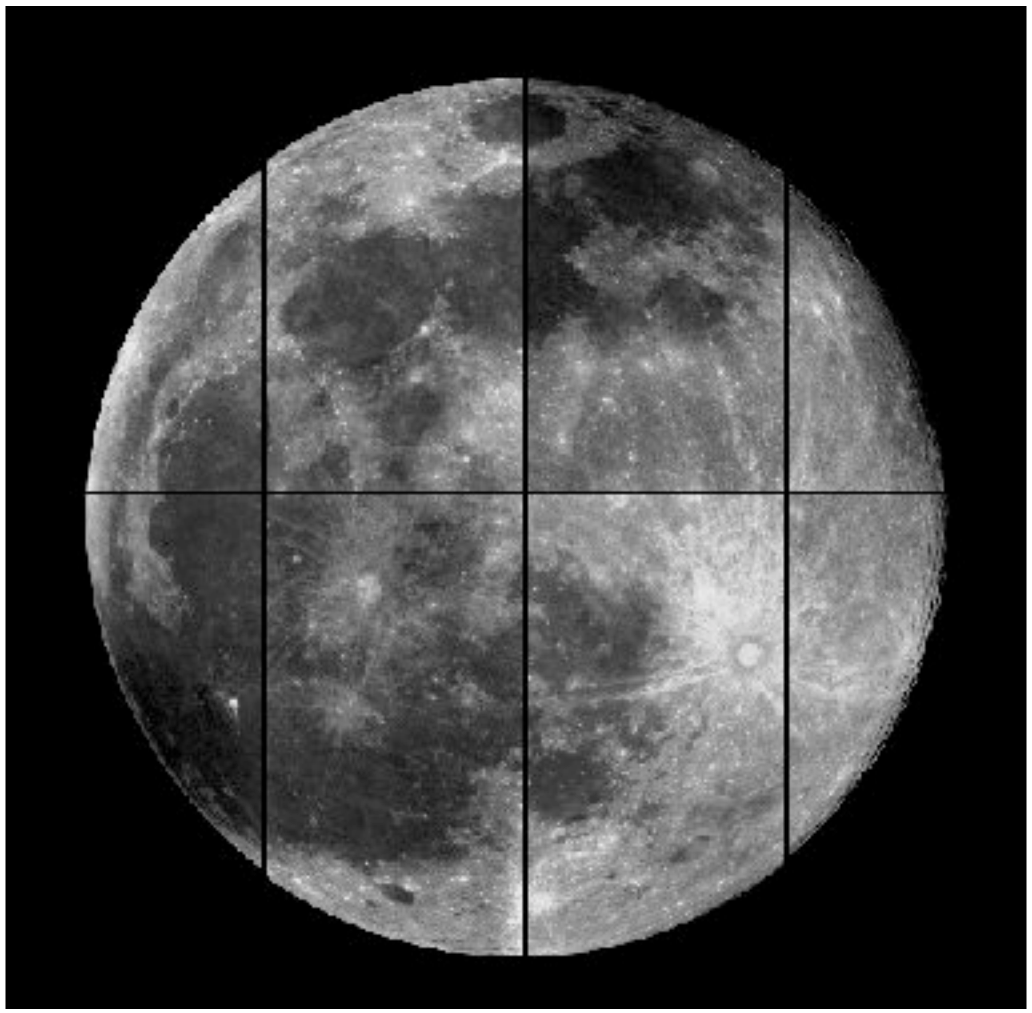
Bias

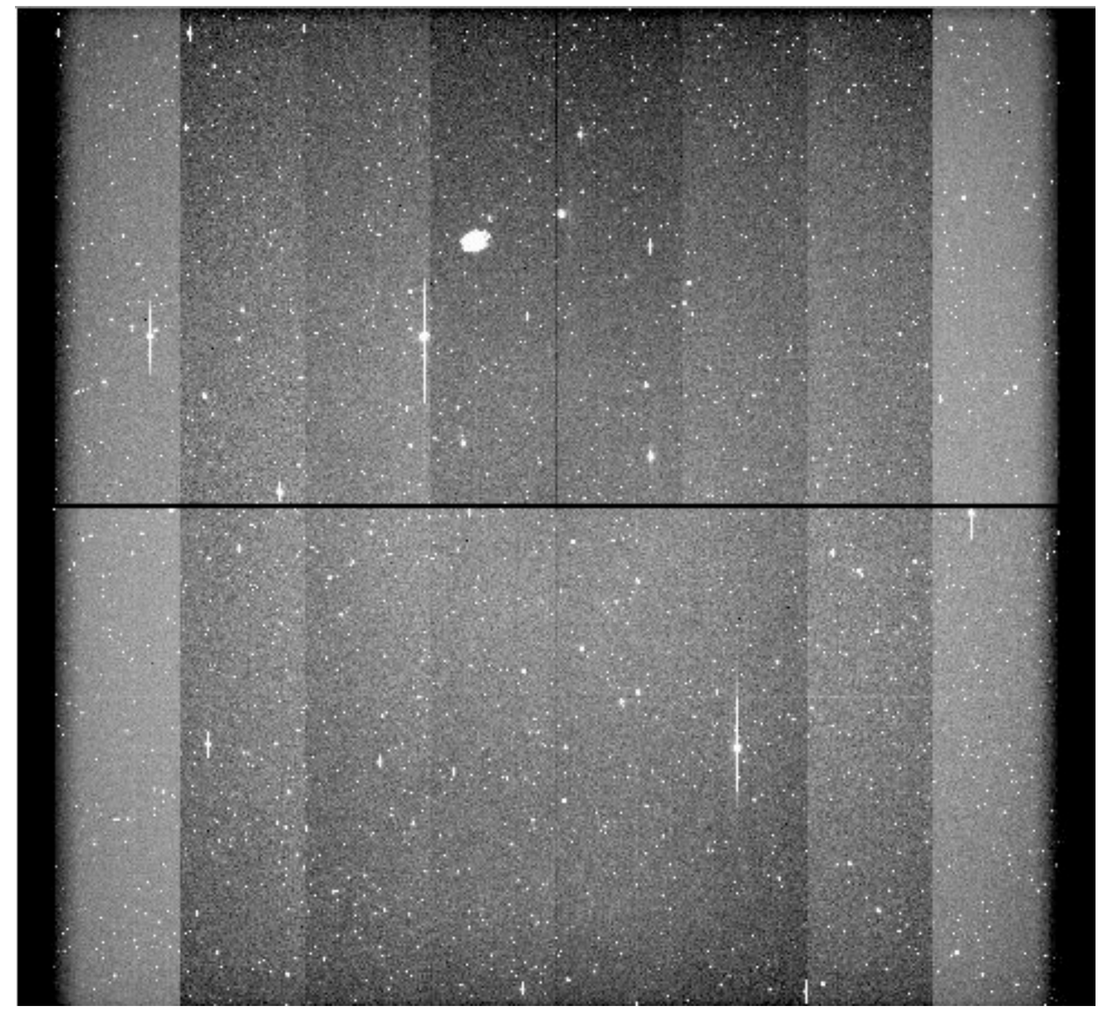
- 0 second (dark) exposures that allow us to correct for pixel to pixel structure in the read noise of an image
- Take a decent number and average to get a master bias that we will then apply to all images for a night.



EXAMPLE BIAS SWOPE 0.9M

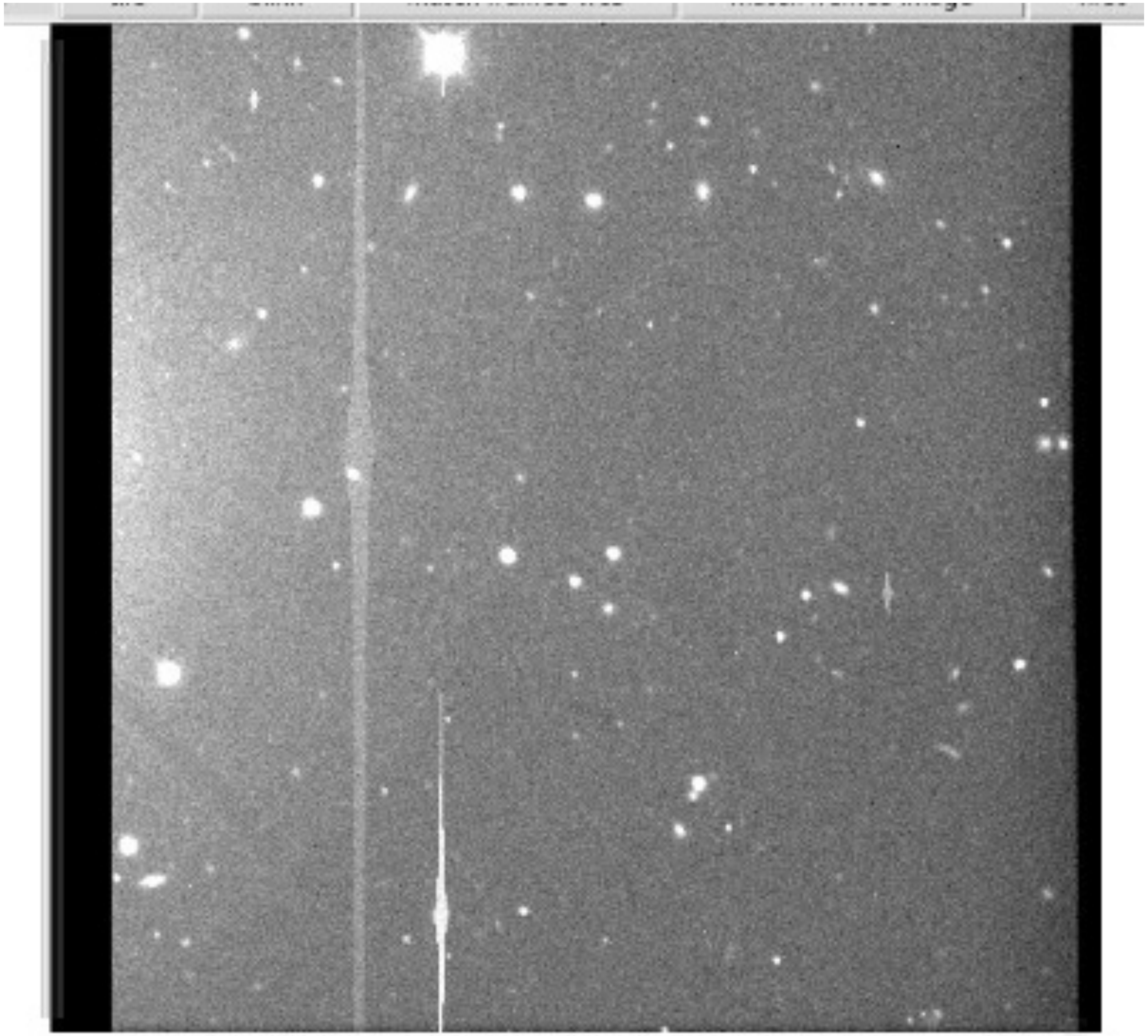
X-Talk Corrections





NOAO MOSAIC I

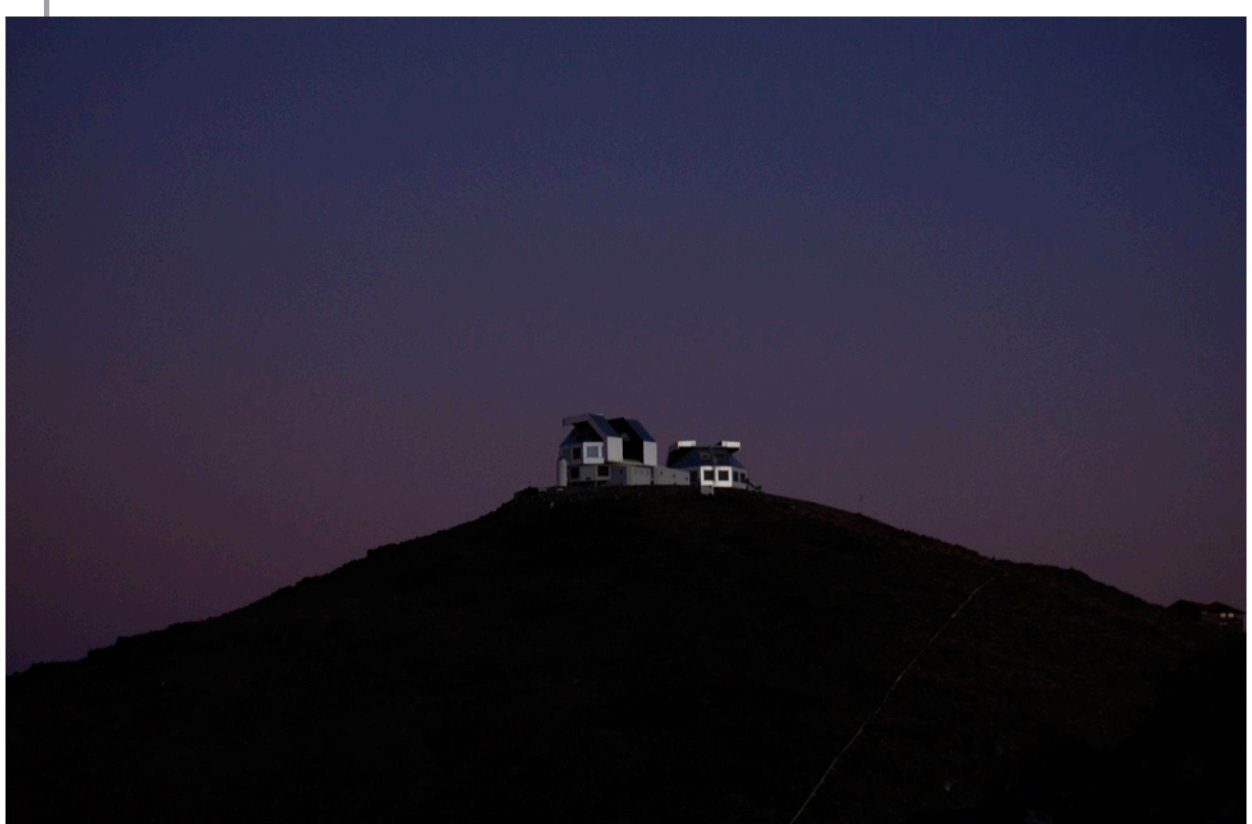
X-Talk Corrections



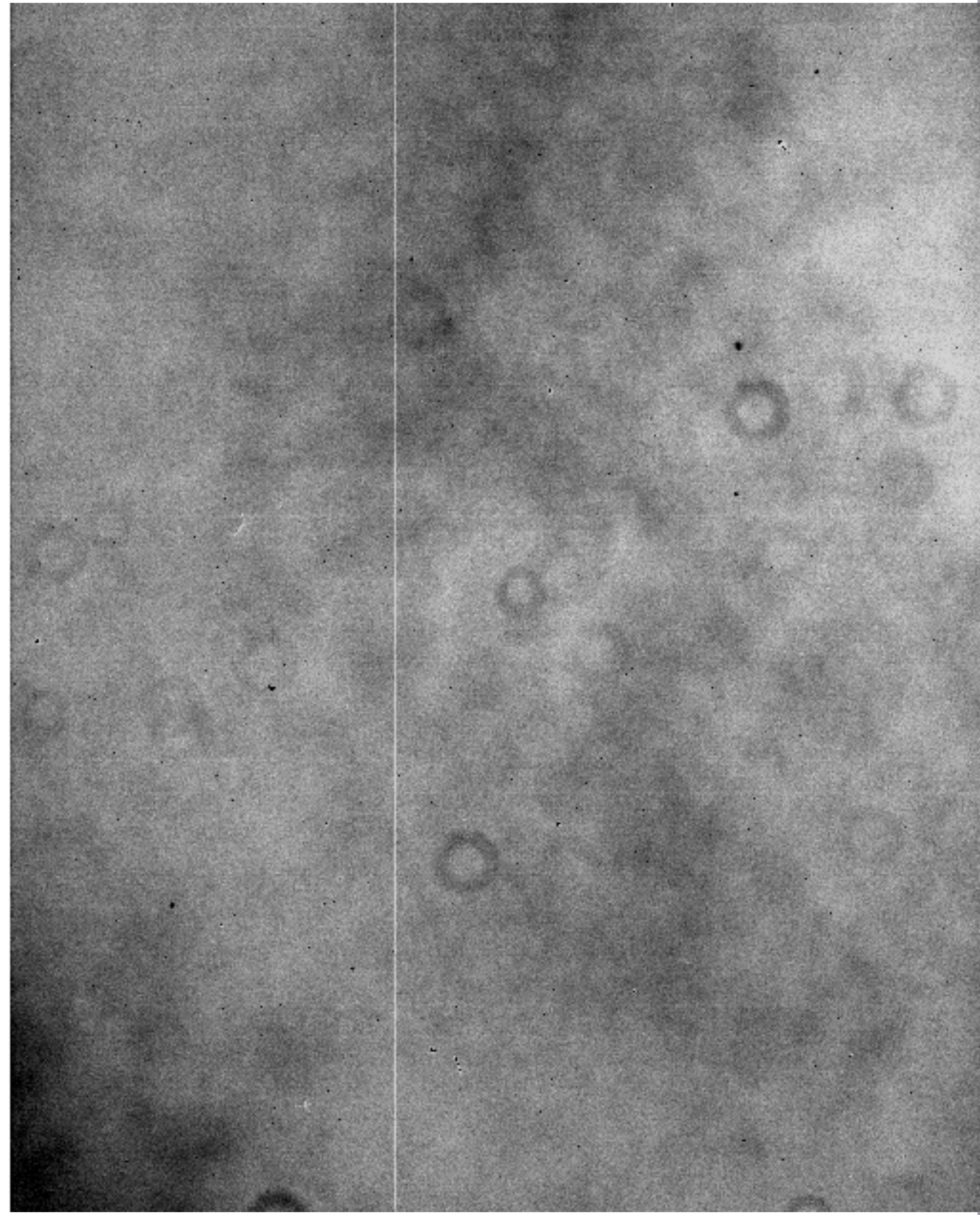
Blanco 4m g-band

Flat Fielding

- Need to measure relative gain of all of the pixels
- Dome Flats
- Twilight/Sky Flats



Magellan at Twilight

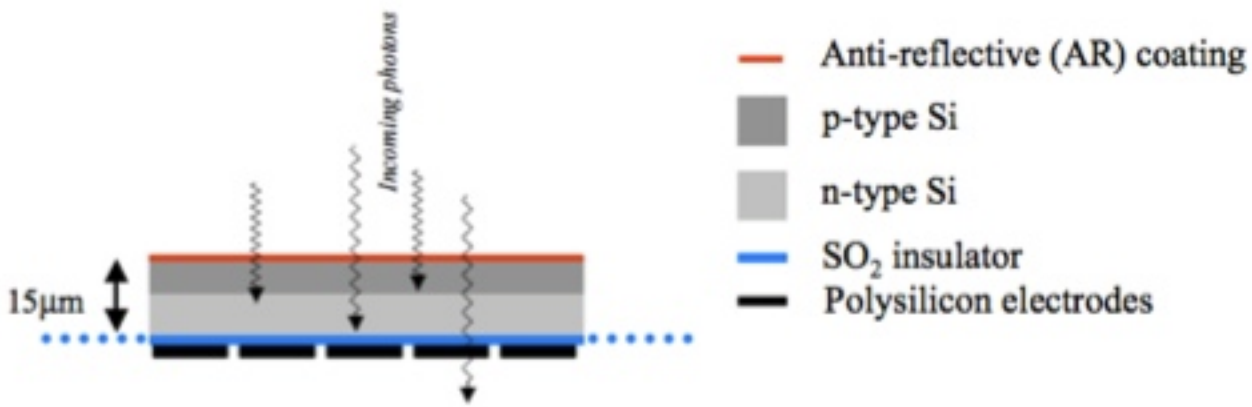


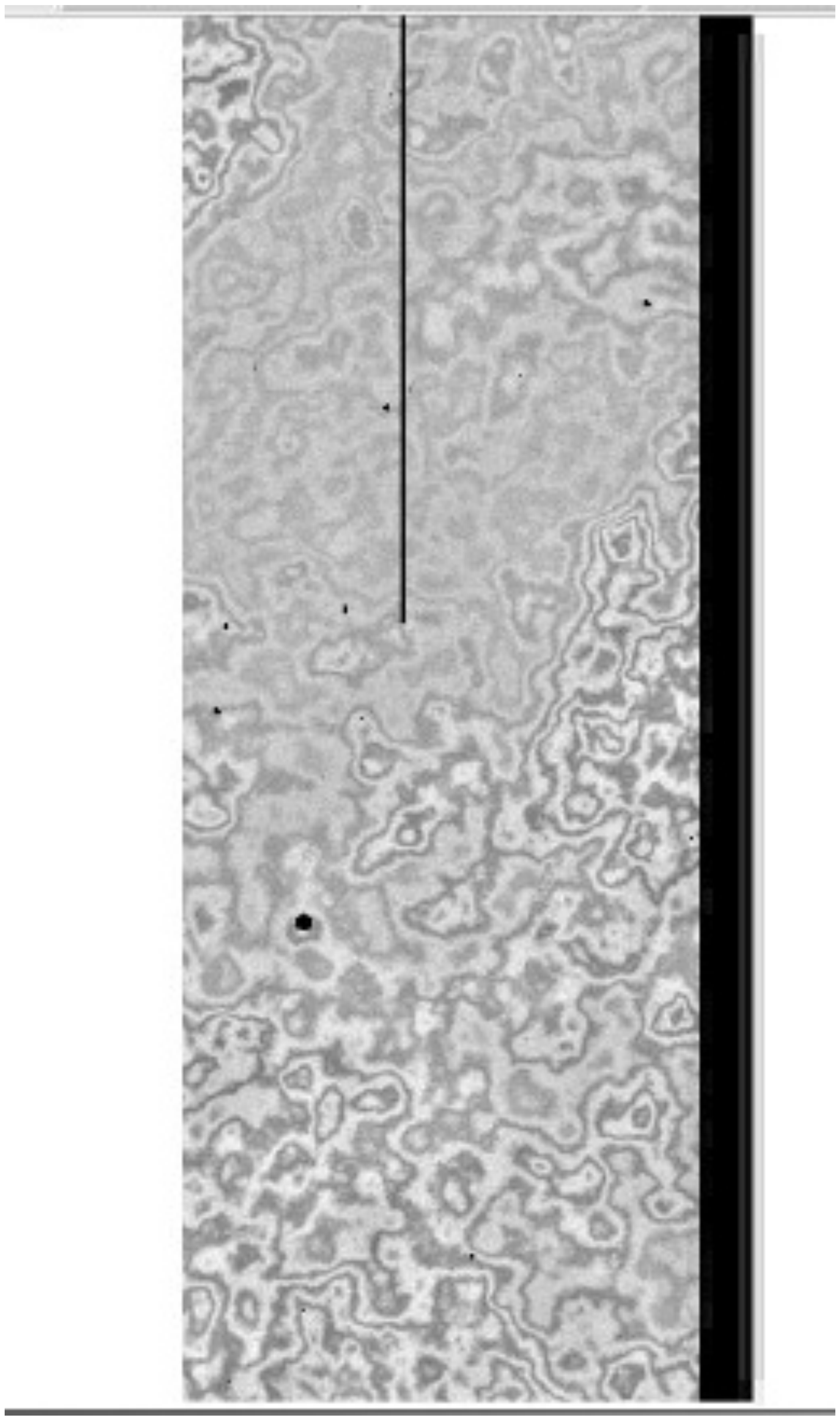
Swope 0.9m Dome flat

Fringe Frames

- Caused by thin-film interference effects in the detector
- Mitigate CCD design

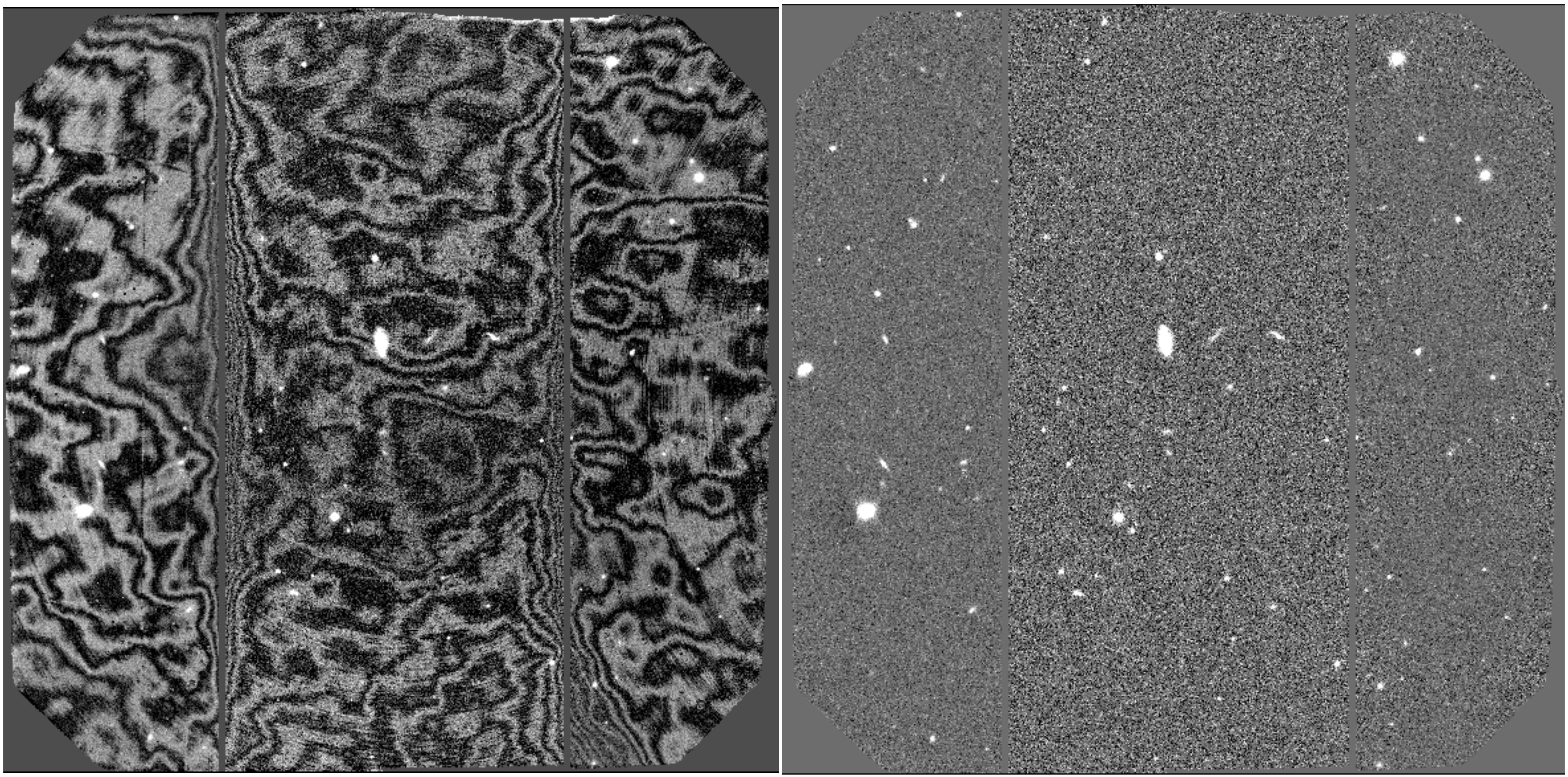
Thinned Back-side Illuminated CCD





BLANCO 4M Z-BAND FRINGE FRAME

Fringing: Subtraction



GMOS-N

Distortions - Examples

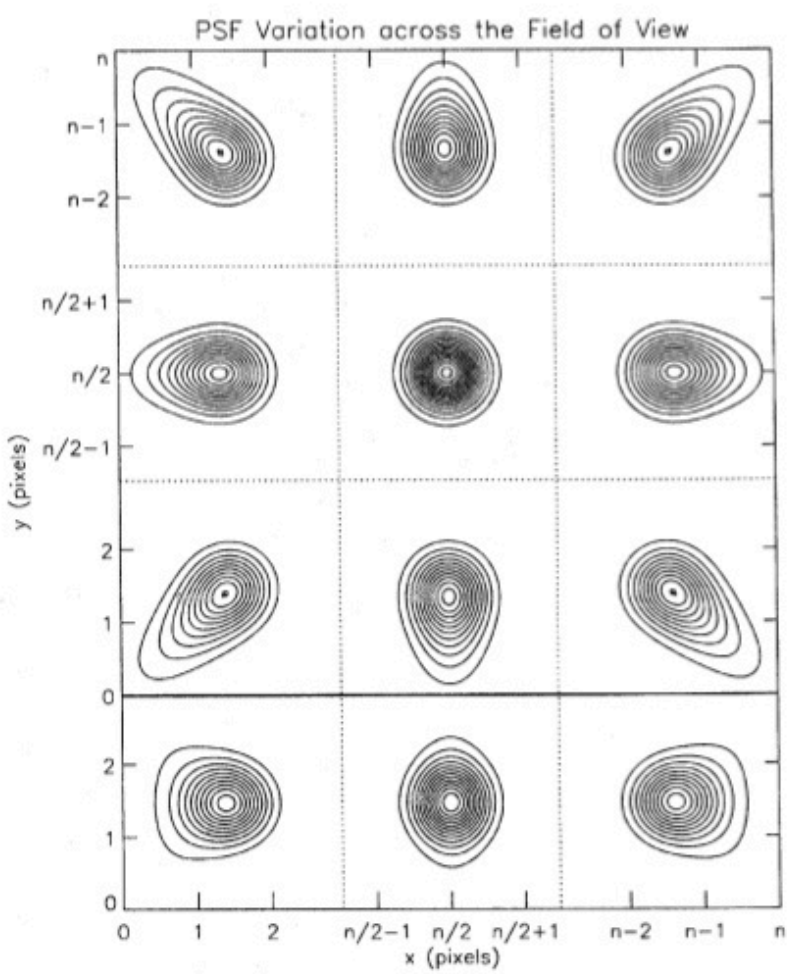
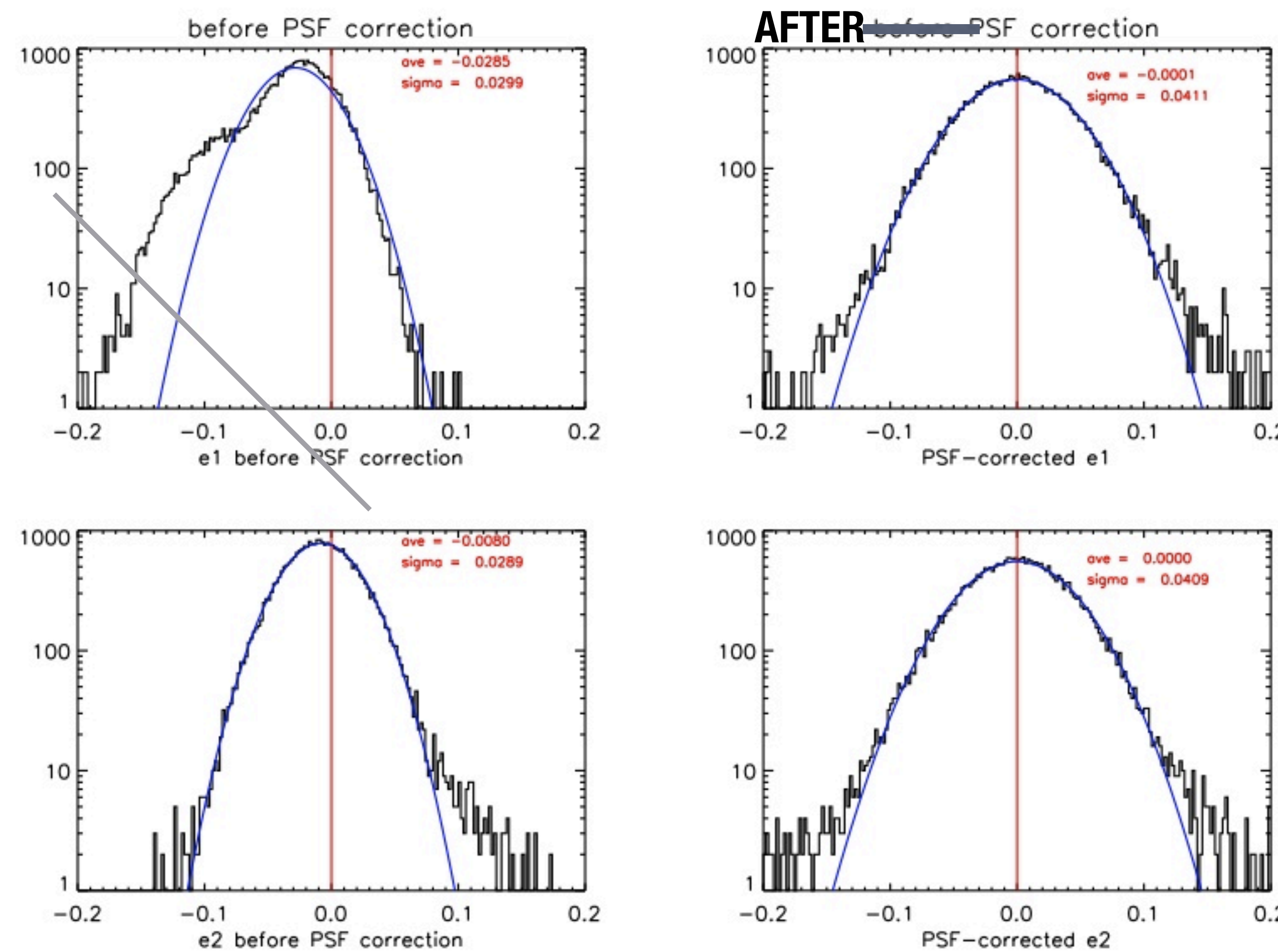
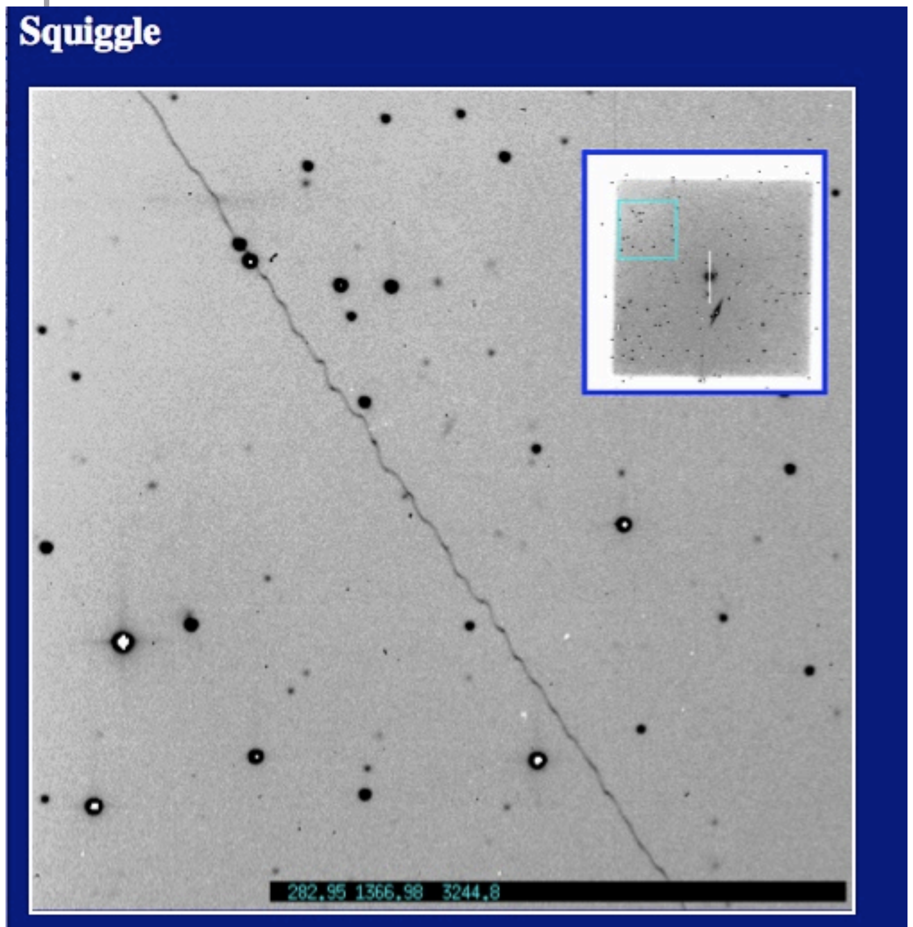


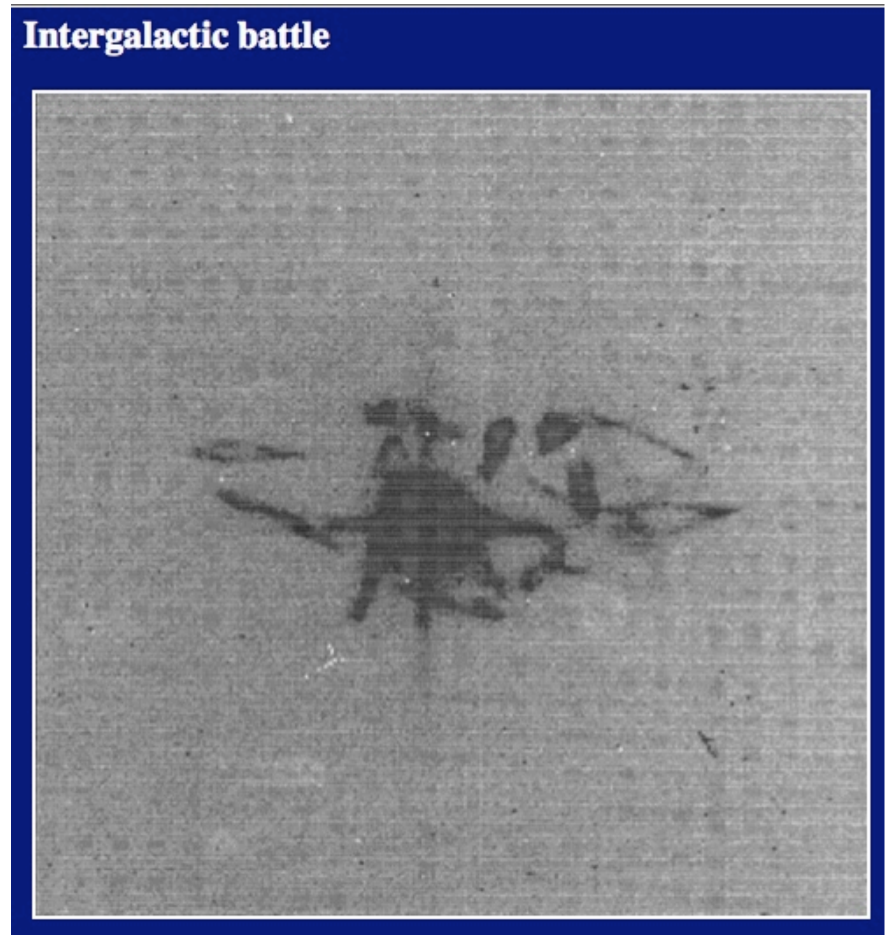
FIG. 3. Contour diagrams indicating schematically how the LONEOS PSF varies over the focal plane of the camera. The 9 PSFs in the top of the diagram indicate the way a star image would appear in a stare-mode frame where n is the total number of pixels in x or y (2048 in this case). As the point-source image approaches the edges of the CCD mosaic, chromatic aberration spreads the PSF. In scan mode, each point source will be transferred across the CCD from top to bottom. The bottom of this figure shows the resulting accumulated PSF as read from the camera. Each is the renormalized sum of the three PSFs above it.

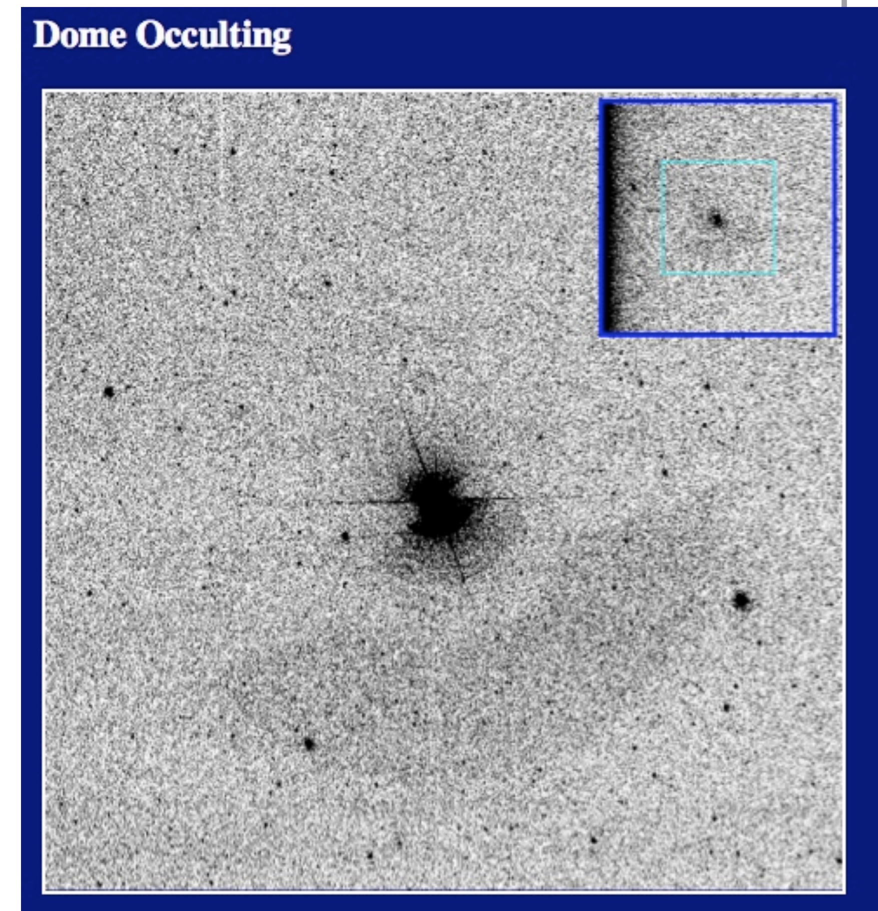


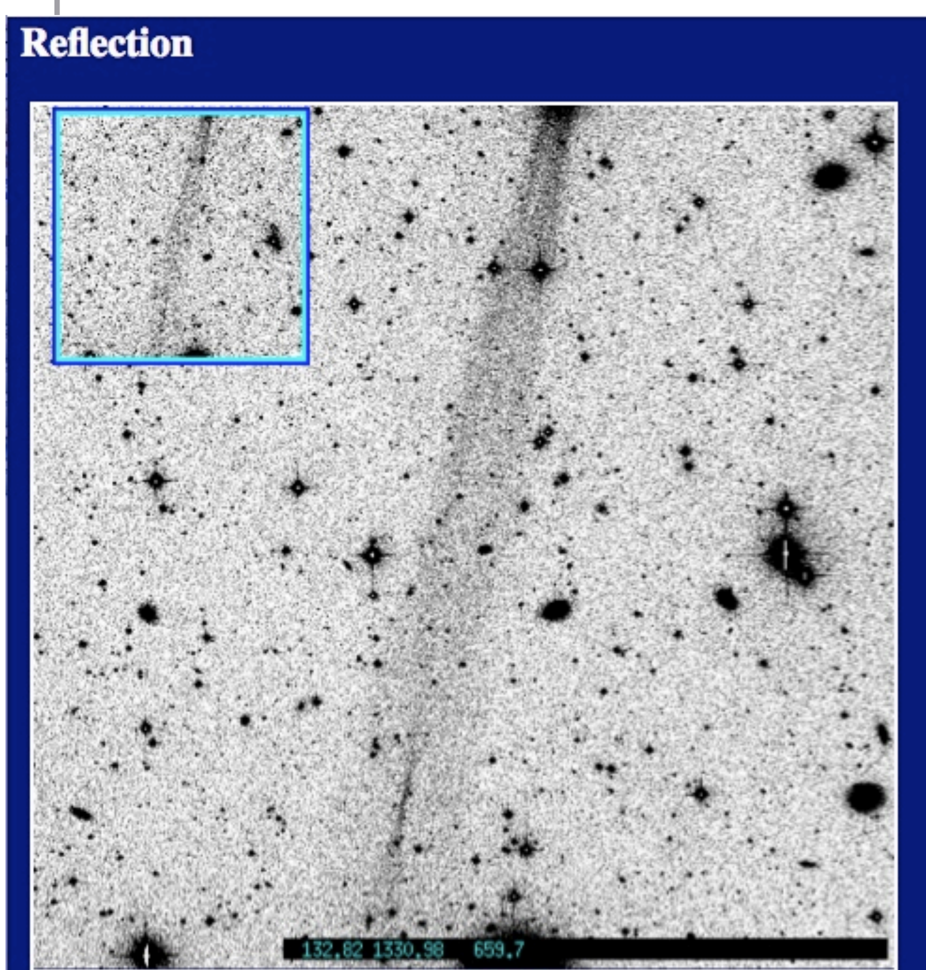
SDSS, LIN ET AL

Problems!

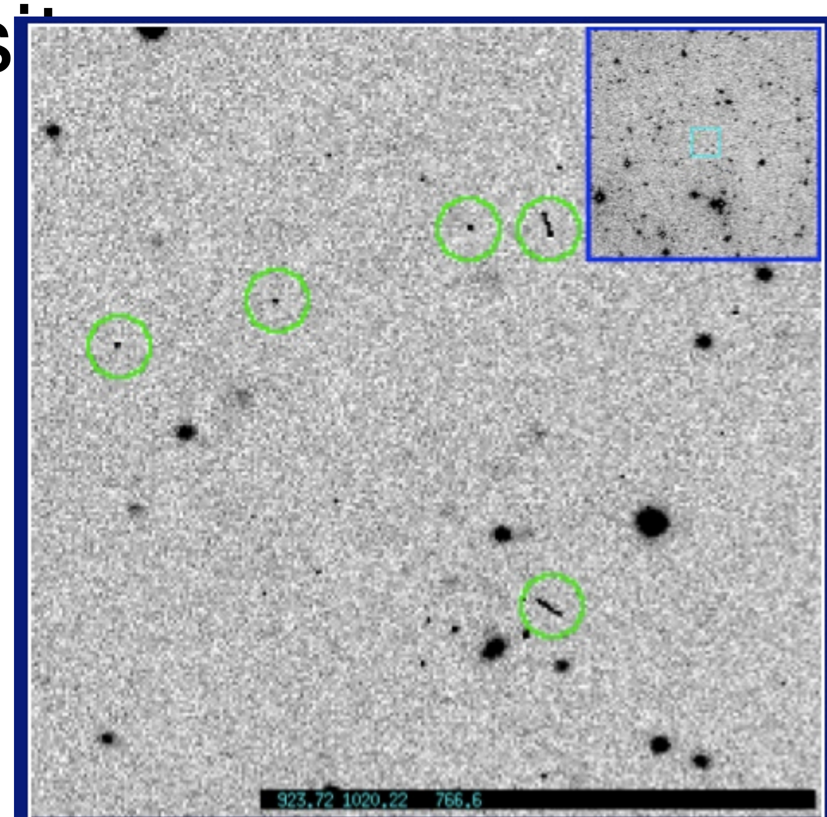


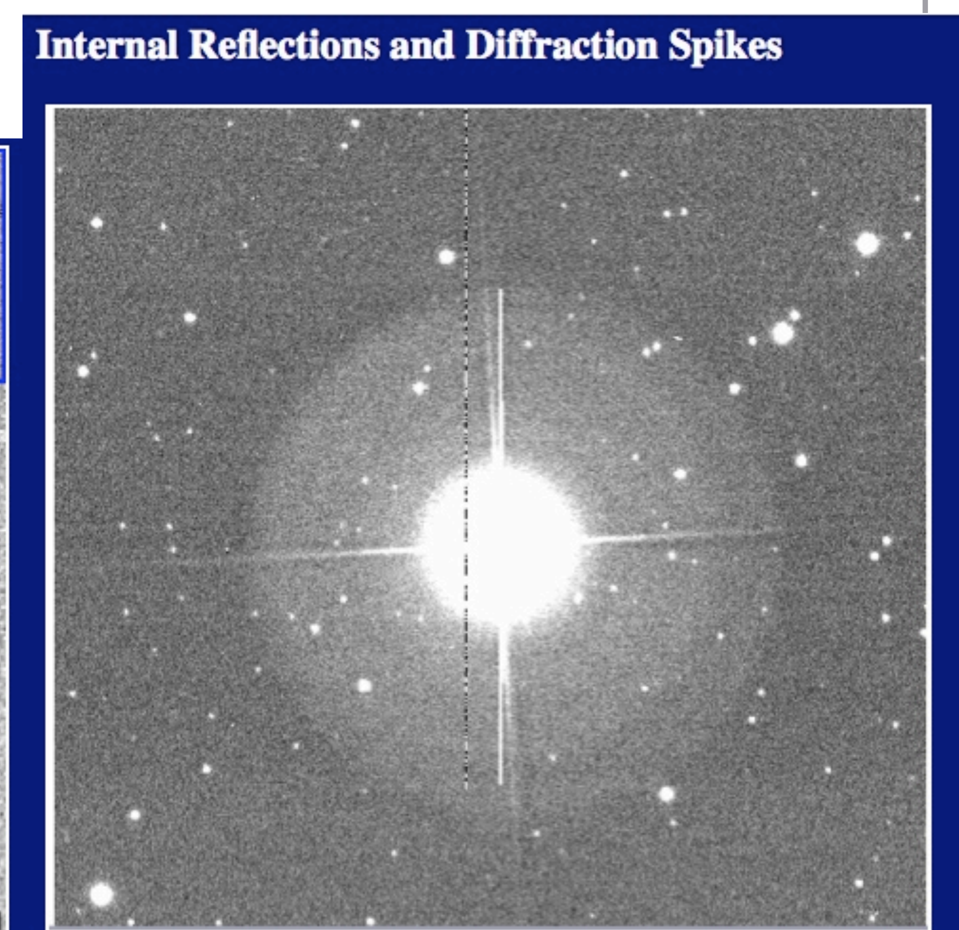






COSMIC RAYS

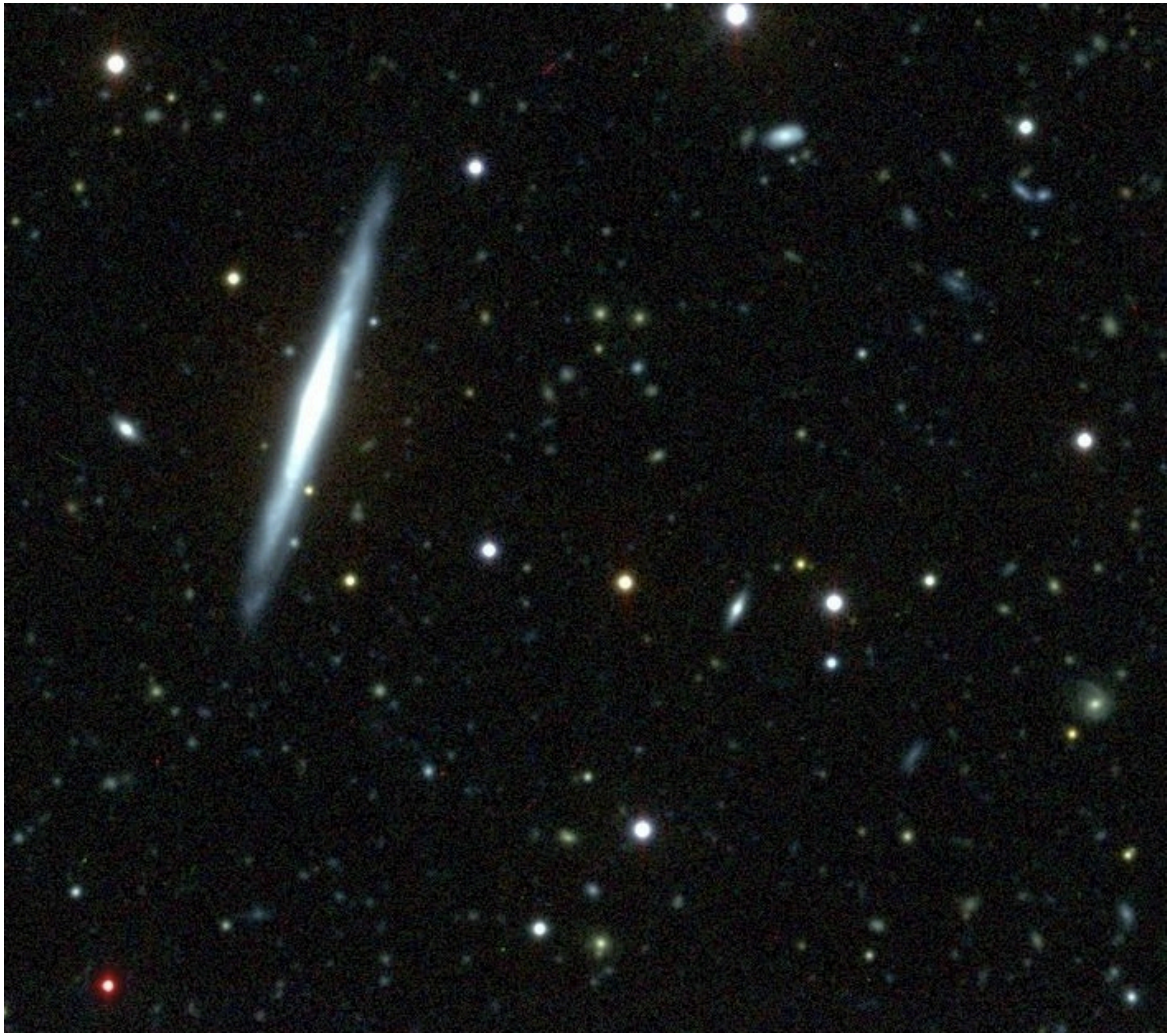




HTTP://SPIDER.IPAC.CALTECH.EDU/STAFF/KASPAR/OBS_MISHAPS/IMAGES/ALL.HTML

Photometry

- Sextractor
- DAOPhot
- Photo (SDSS)
- And many more!



BCS0508-5223

Sextractor

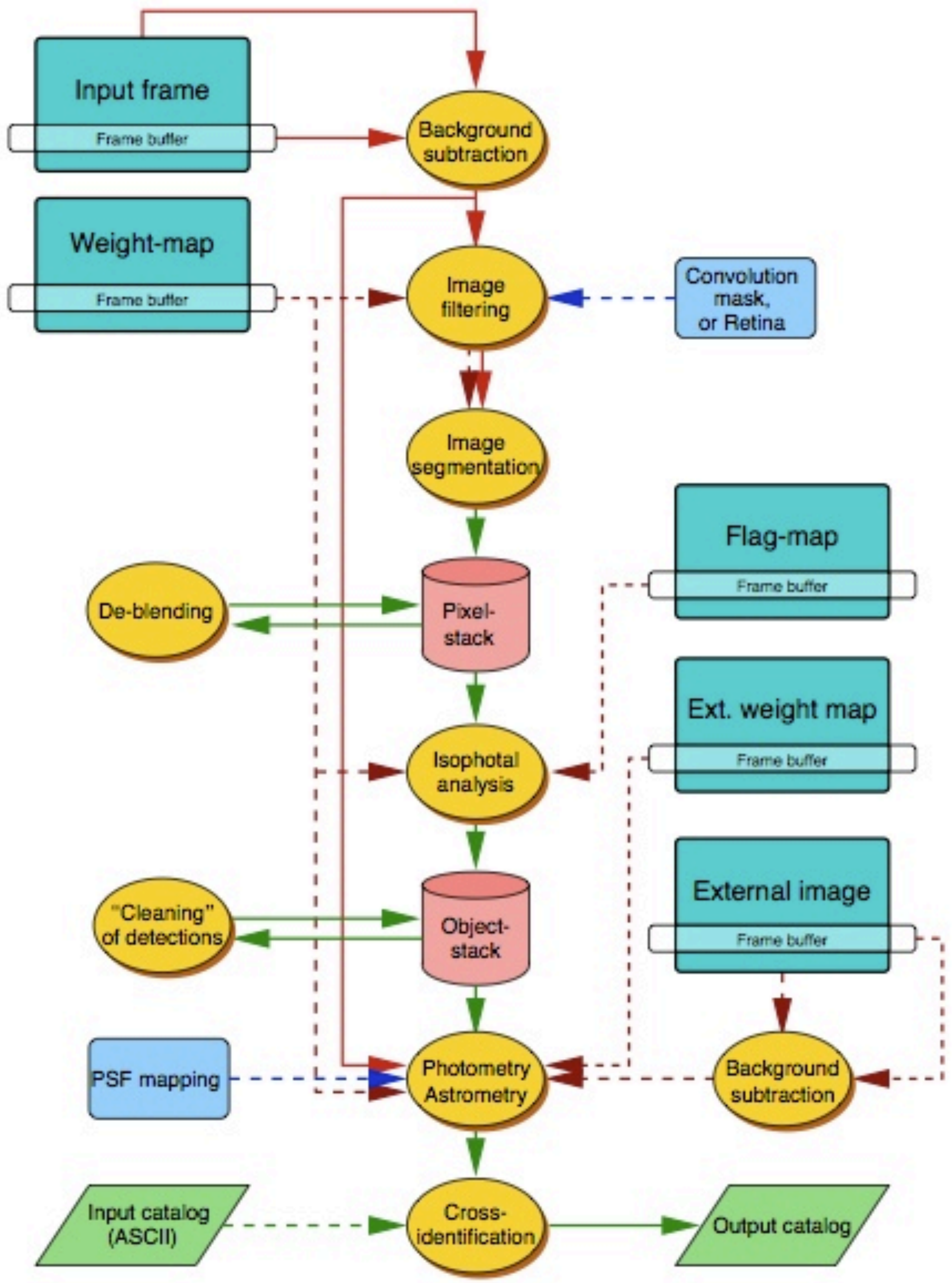
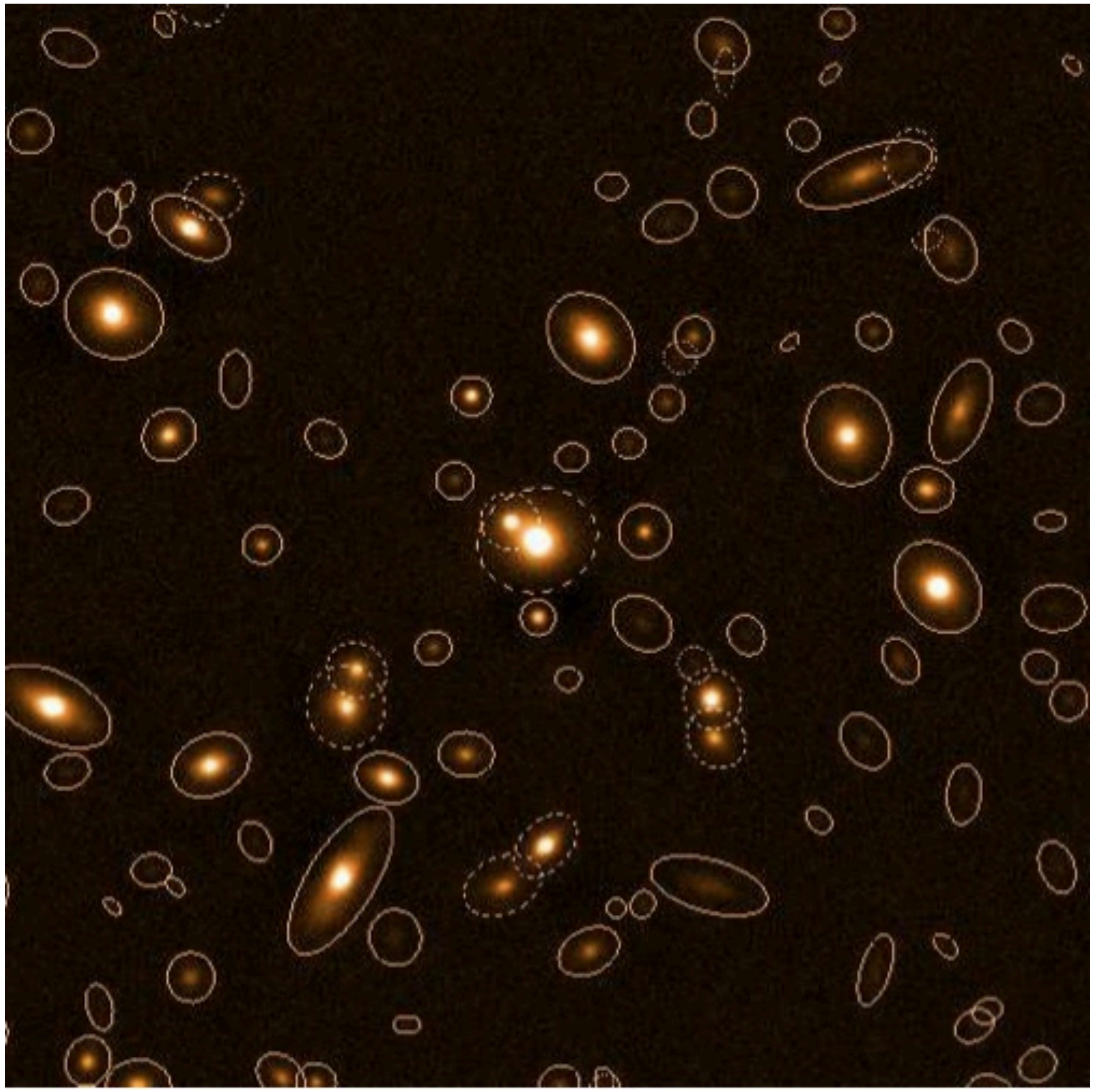
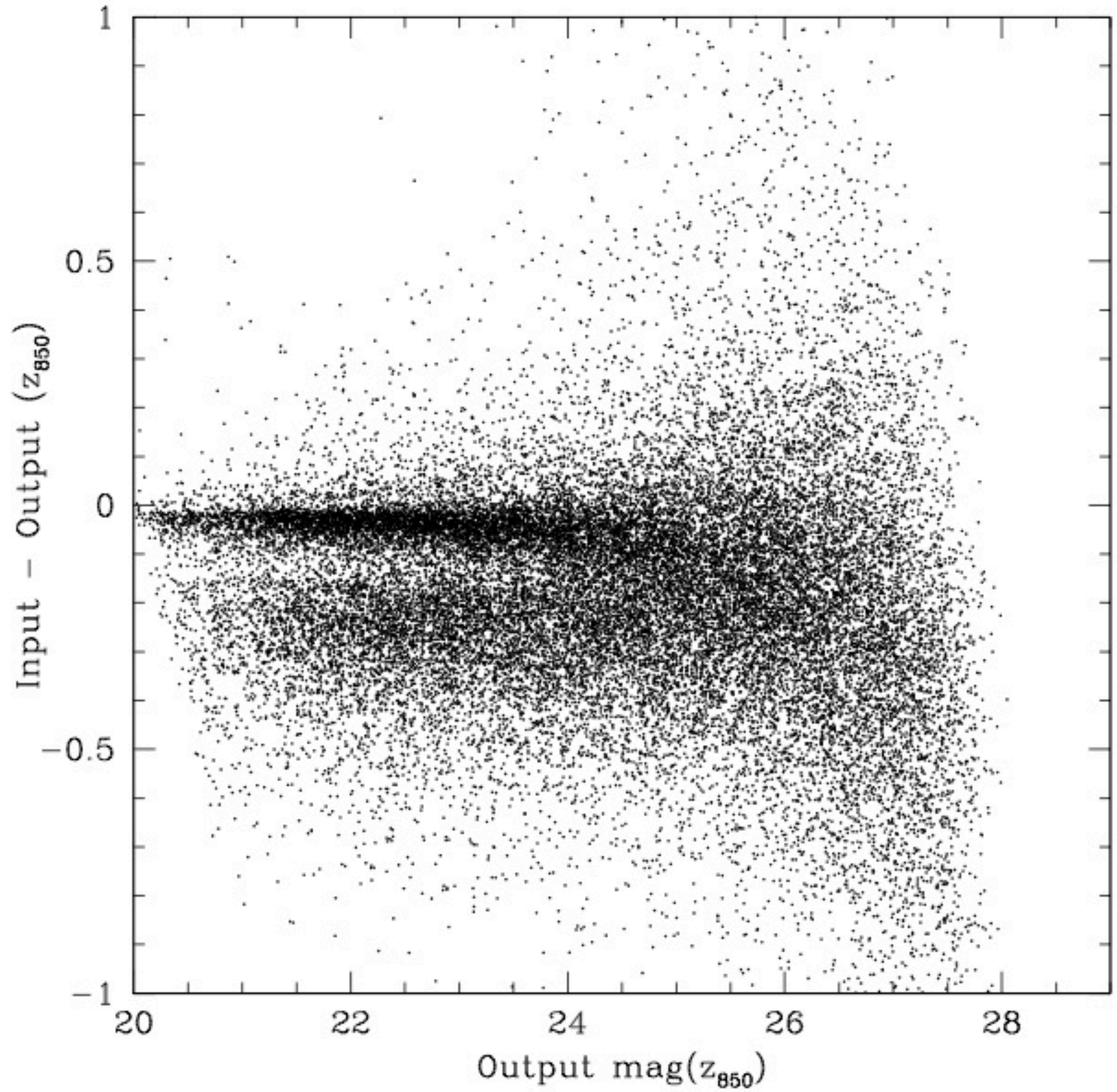


Figure 1: Layout of the main SExtractor procedures. Dashed arrows represent optional inputs.



E. Bertin

Sextractor



GOODS SIMULATIONS --
2 POPULATIONS: DISKS AND SPHEROIDS

HTTP://WWW.STSCI.EDU/SCIENCE/GOODS/CATALOGS/R1.0Z_README/#6.0

Photometric Calibration

- Standard Stars
- Stellar Locus Regression (SLR)

Performing photometric calibrations

- In general, standard stars (usually from the compilations of **Landolt** or **Stetson** should be observed at a variety of zenith distances and colours.
- They should be at approximately the same airmasses at the target field.

$$m_{\mathrm{calib}} = m_{\mathrm{inst}} - A + Z + \kappa X$$

- This is a simple least-squares fit. But in general a system of equations will have to be solved:

$$\begin{aligned}
U &= U_{\mathrm{inst}} - A_u + Z_u + C_u(U-B) + \kappa_u X \\
B &= B_{\mathrm{inst}} - A_b + Z_b + C_b(B-V) + \kappa_b X \\
V &= V_{\mathrm{inst}} - A_v + Z_v + C_v(B-V) + \kappa_v X
\end{aligned}$$

EXTINCTION*AIRMASS

COLORTERM

ESTIMATED GALACTIC EXTINCTION

ZEROPOINT

source: Henry Joy McCracken

SLR

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

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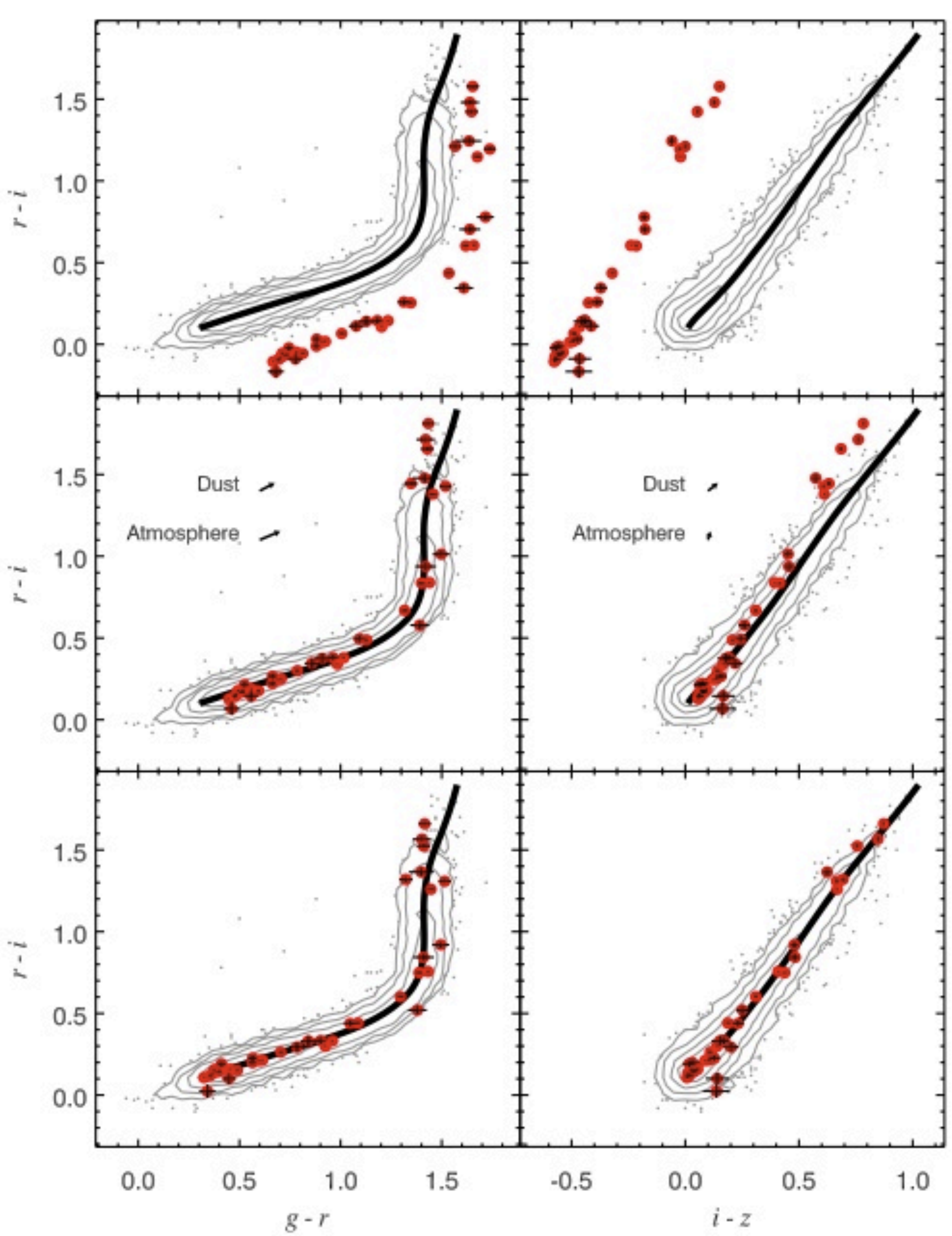
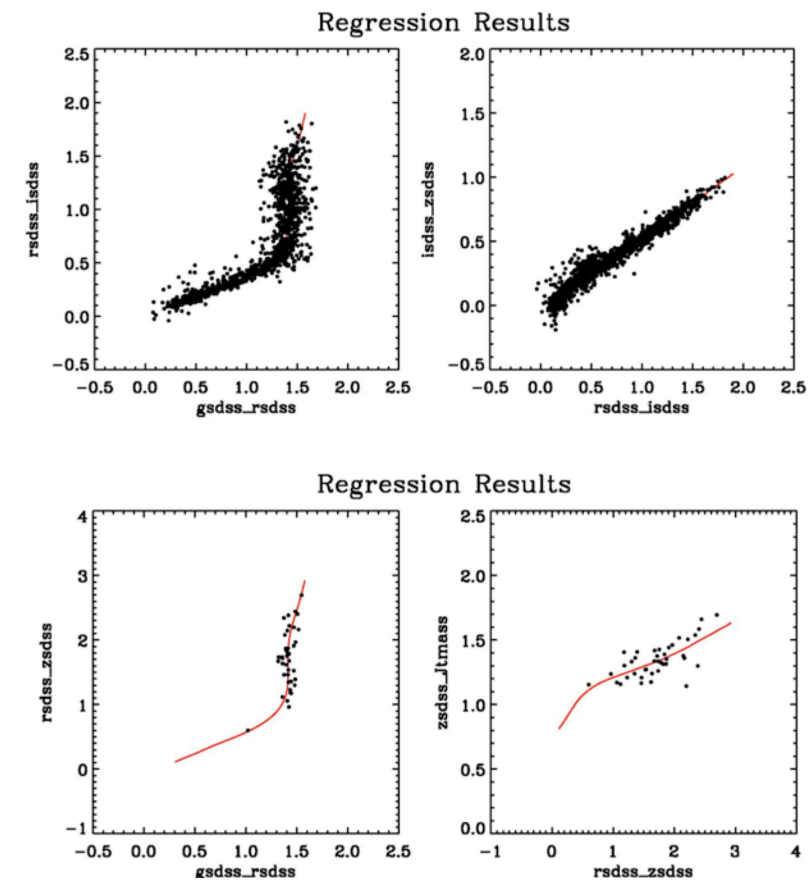
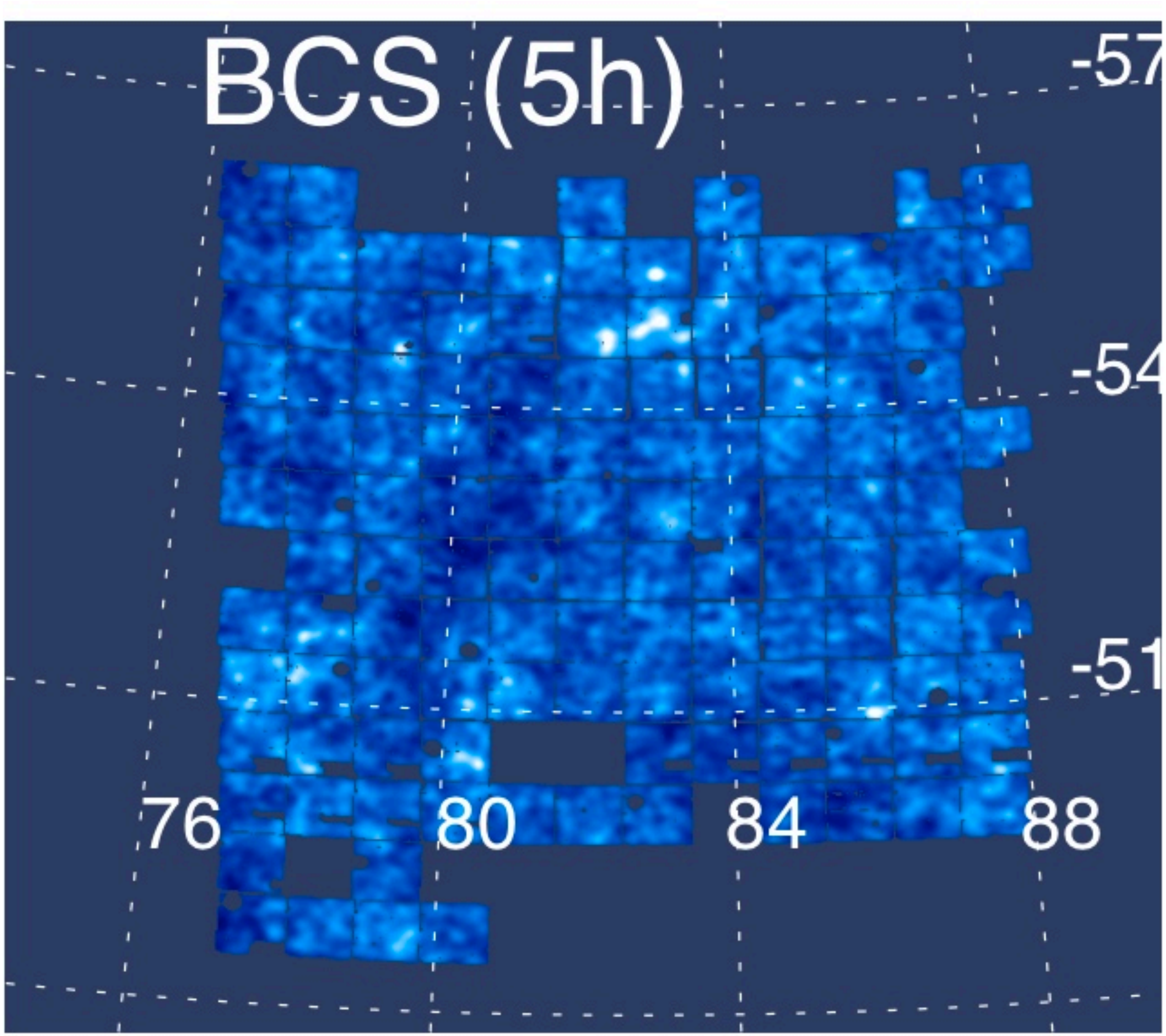
HIGH ET AL.

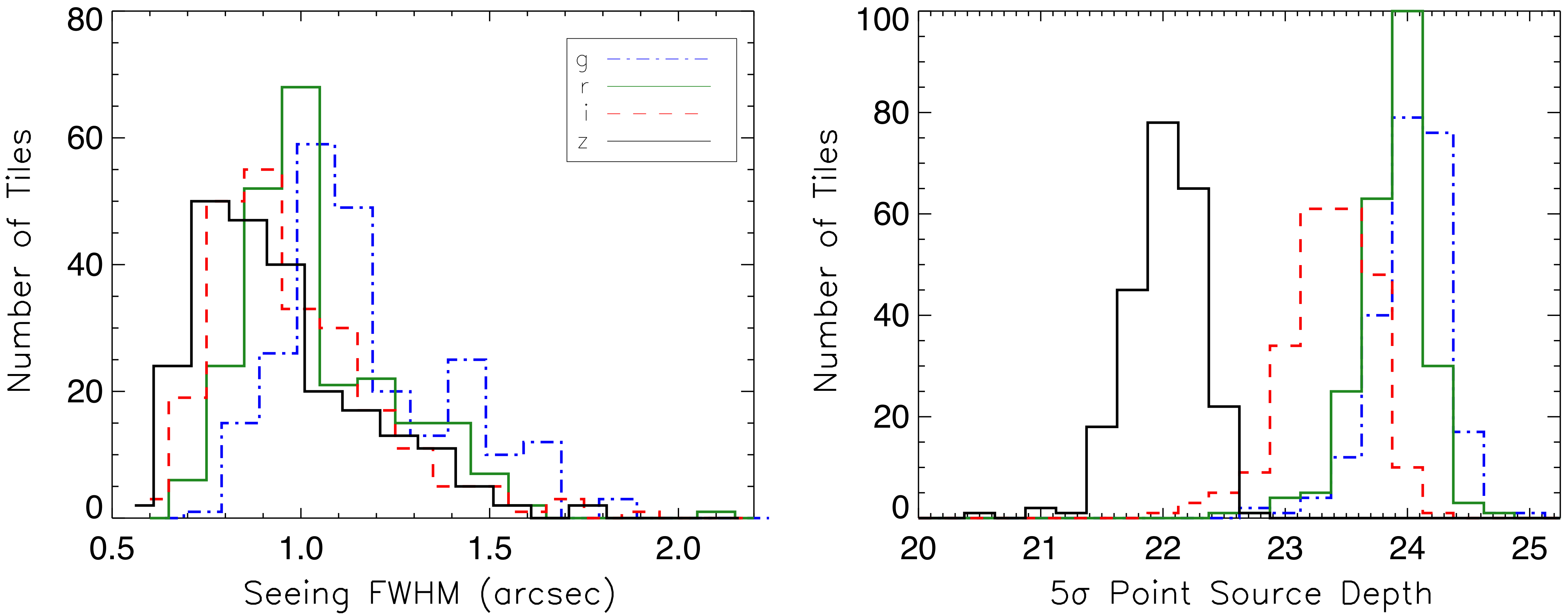




$$(g-r) = (g_0 - r_0) + (a_g - a_r) + (E_g - E_r) + (A_g - A_r) + b_g(g_0 - r_0) - b_r(r_0 - i_0) + c_g X_g(g_0 - r_0) - c_r X_r(r_0 - i_0) \quad \text{(A2a)}$$

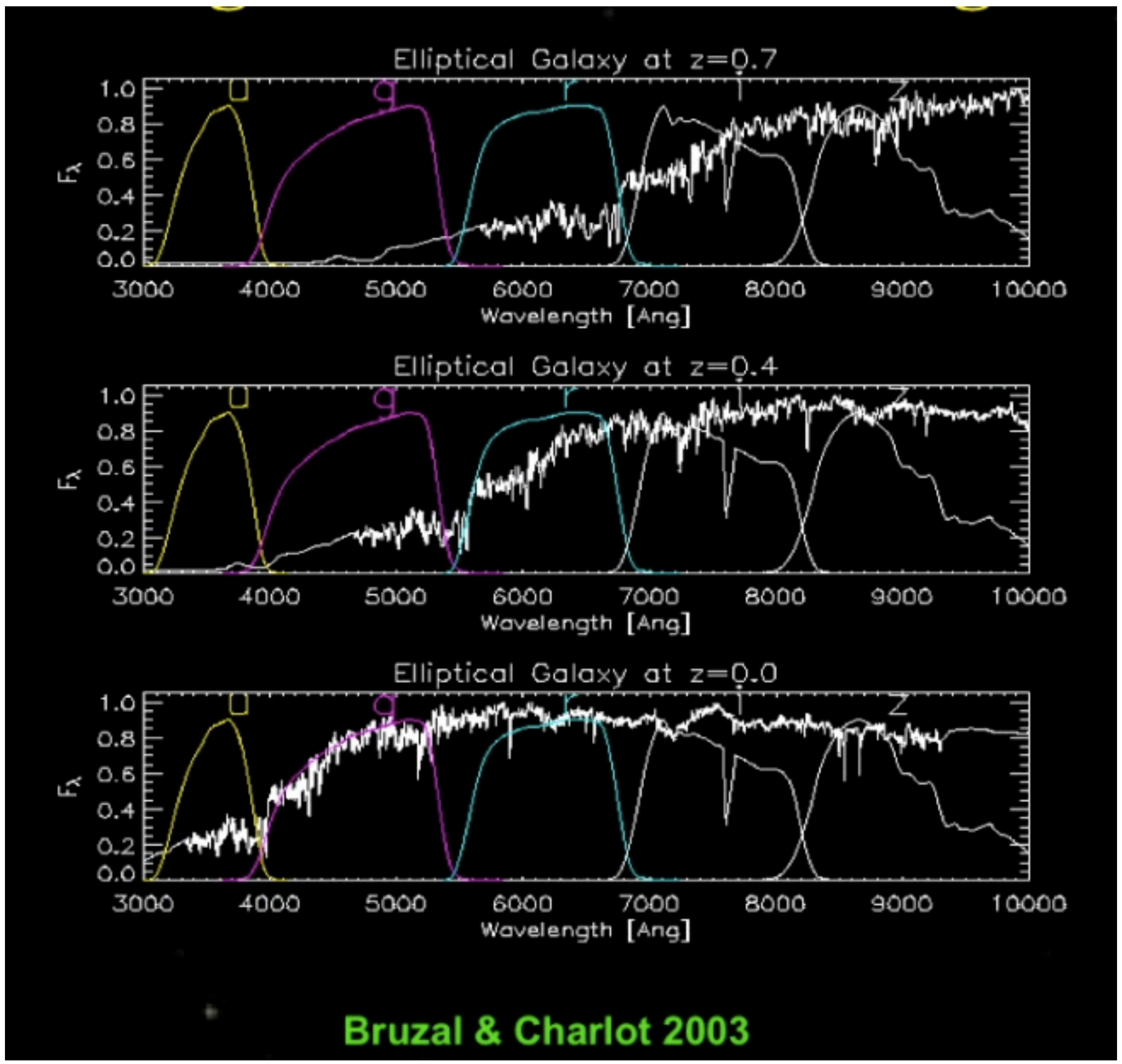


>3000 INDIVIDUAL EXPOSURES (INCLUDING CALIBRATION FILES)

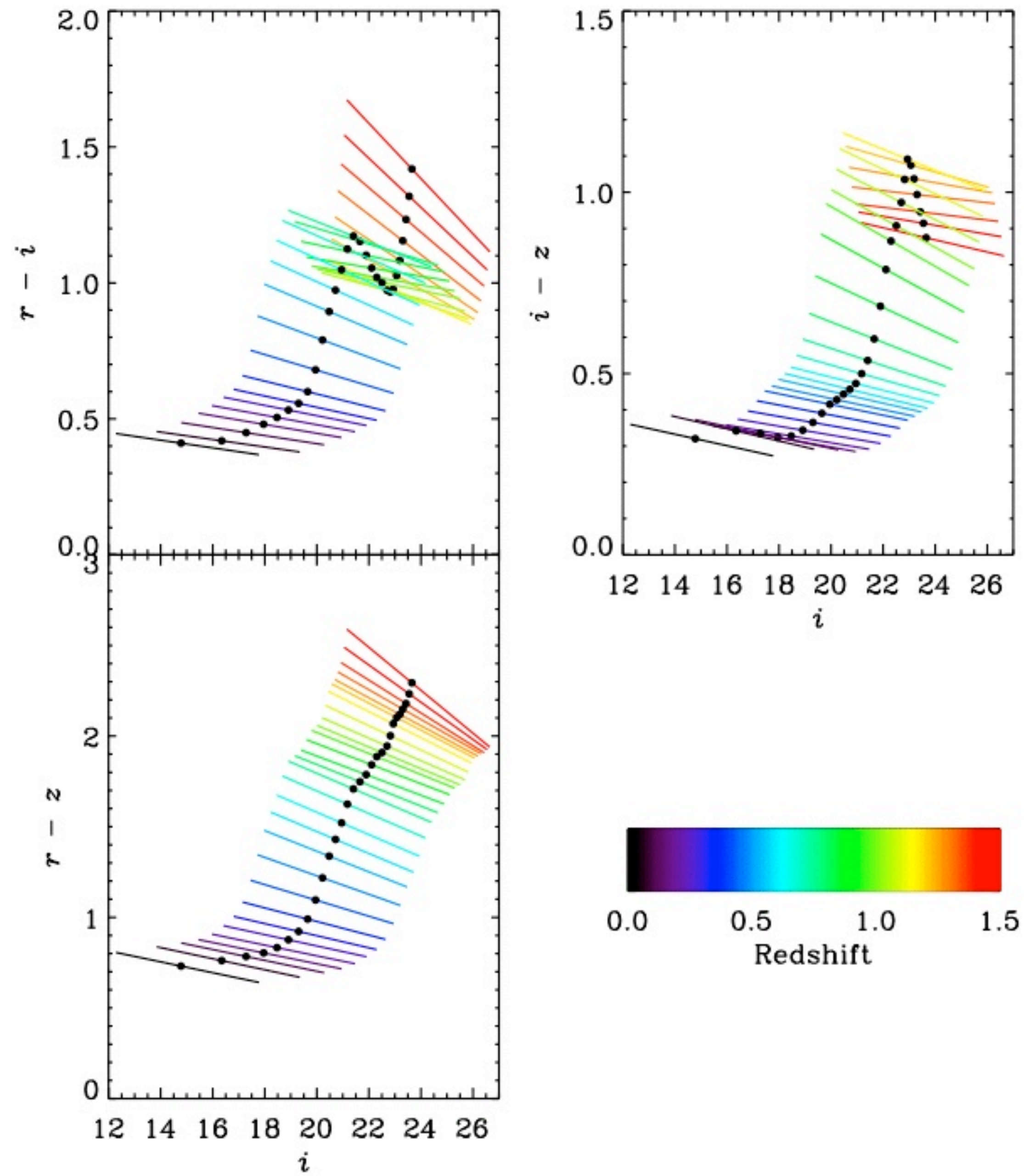


- Data sufficient for detection of L* galaxies to z=1.
  But .... heterogeneous depth across the survey

The Red-Sequence provides a tight relation for cluster galaxies in color-magnitude space.



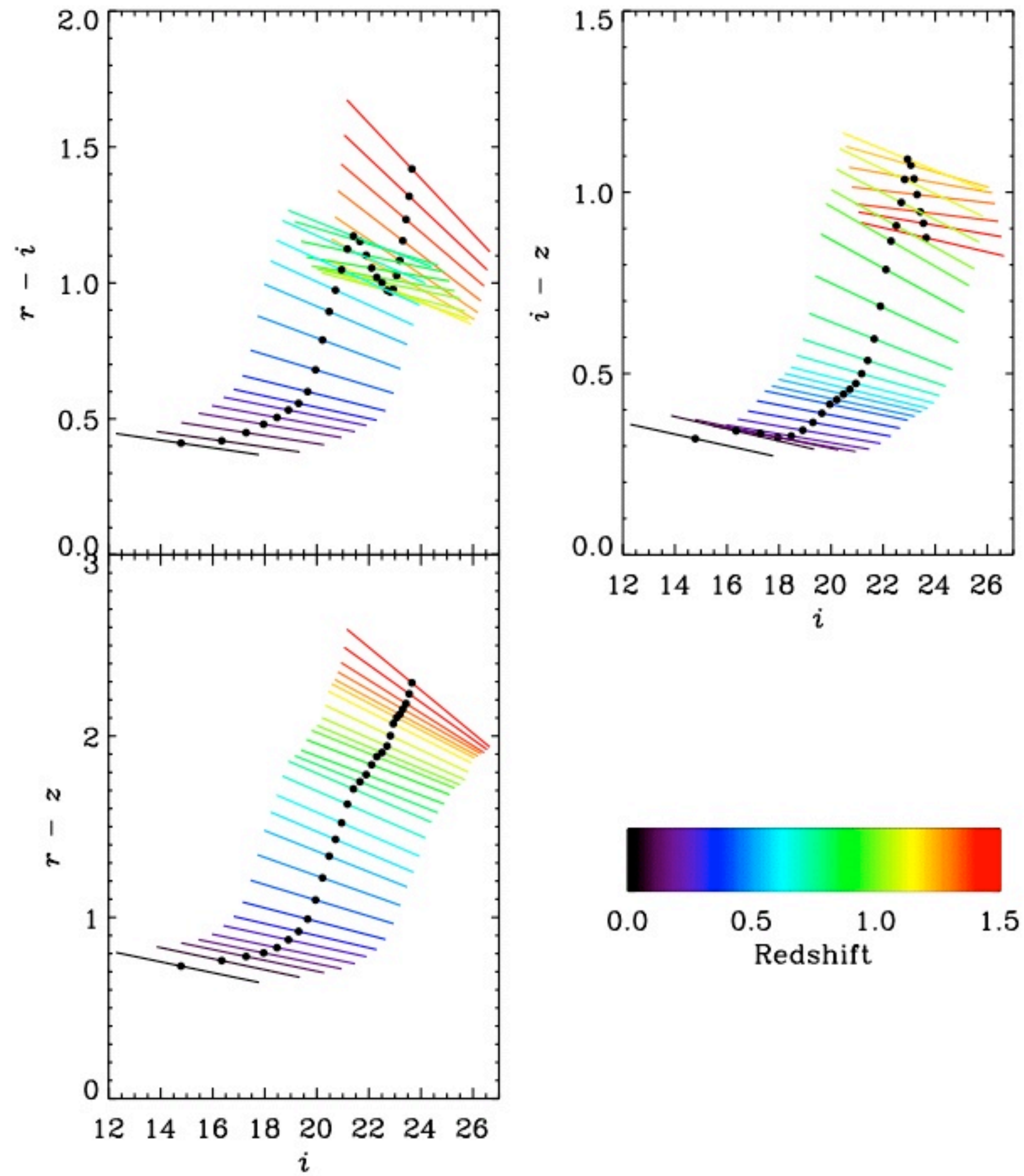
J. Hao



High et al, 2010

The Red-Sequence provides a tight relation for cluster galaxies in color-magnitude space.

Build a filter to pull out clusters based on:
1) Color
2) Magnitude
3) Spatial Profile



High et al, 2010

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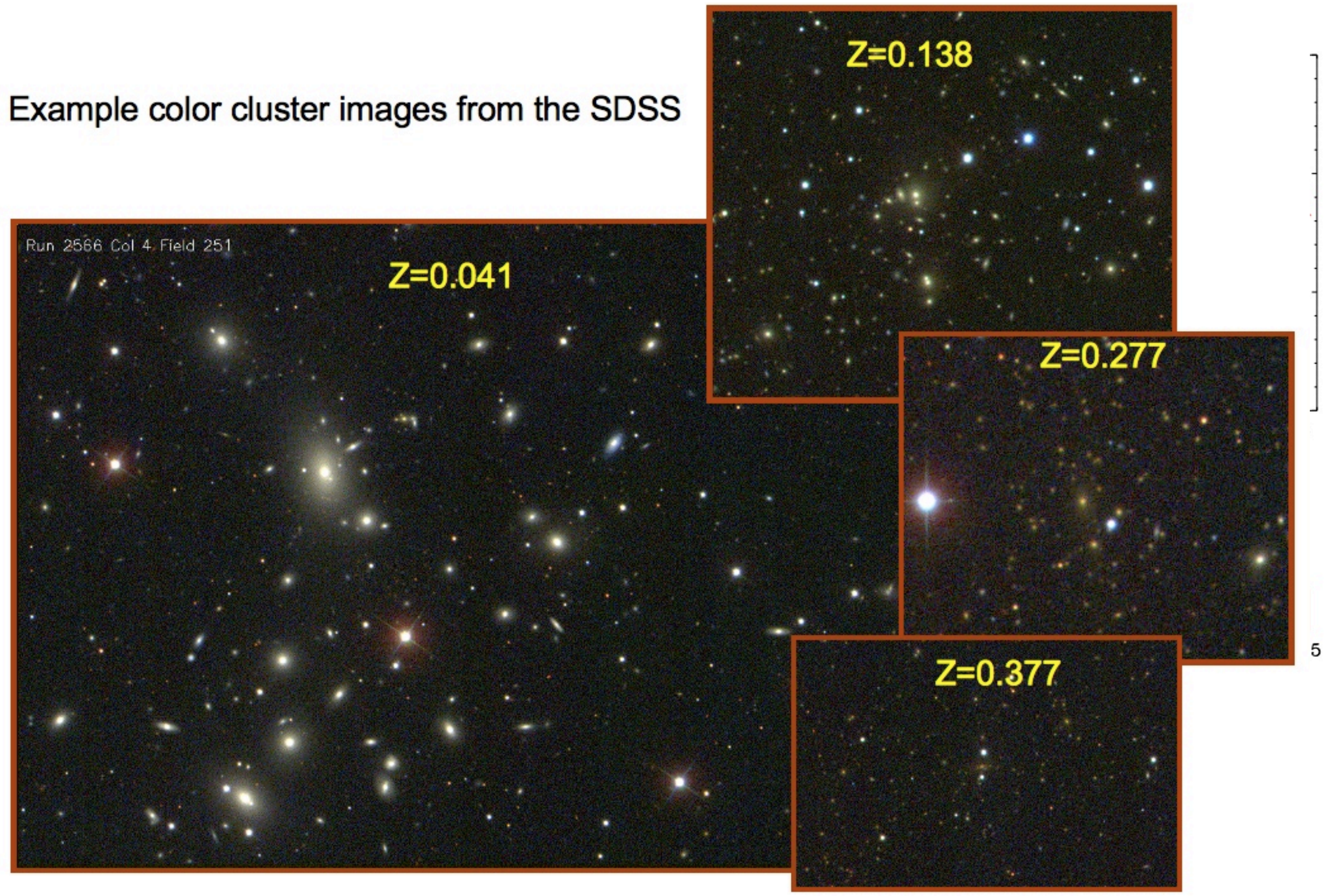
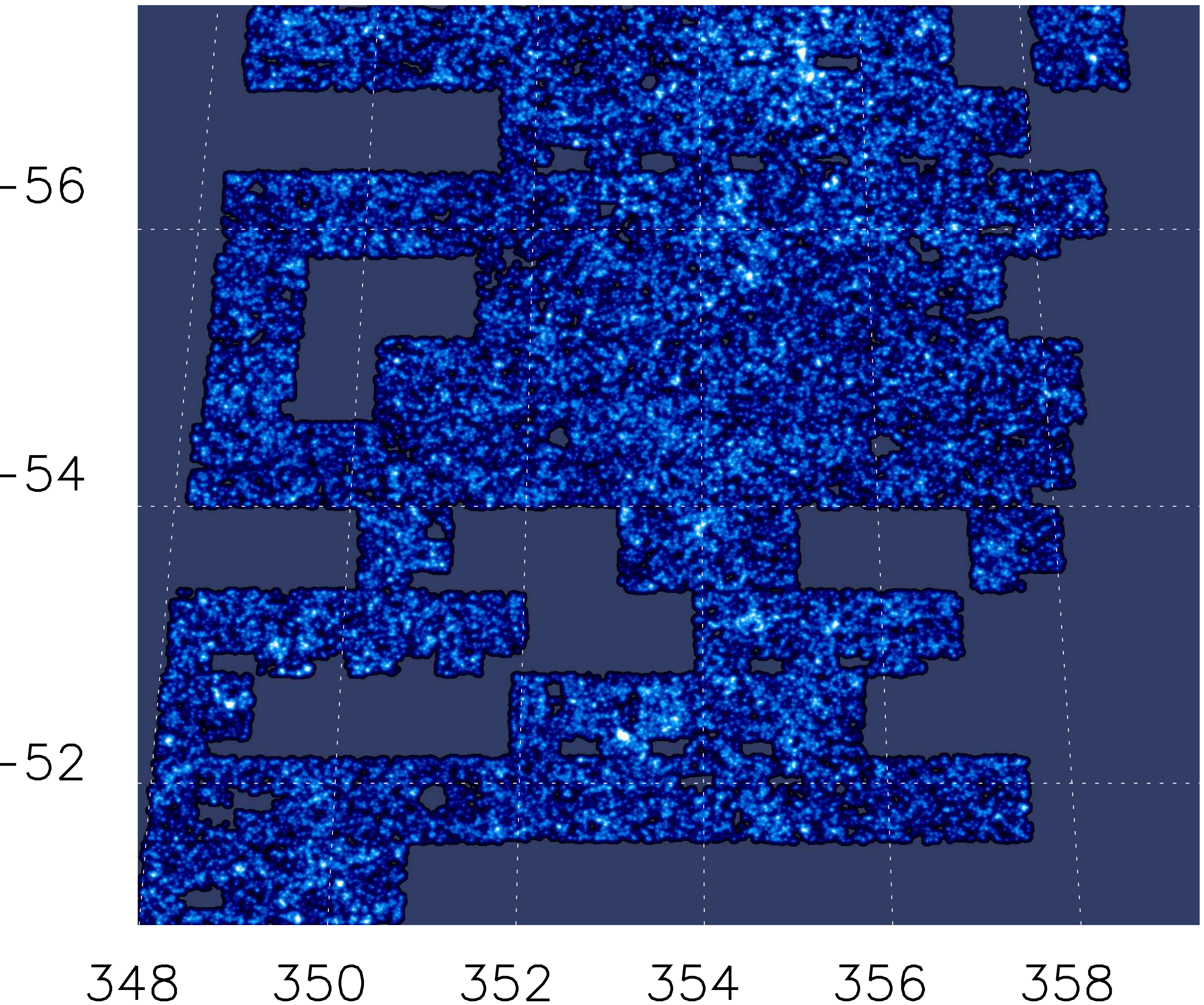


Koester et al. astro-ph/0701265

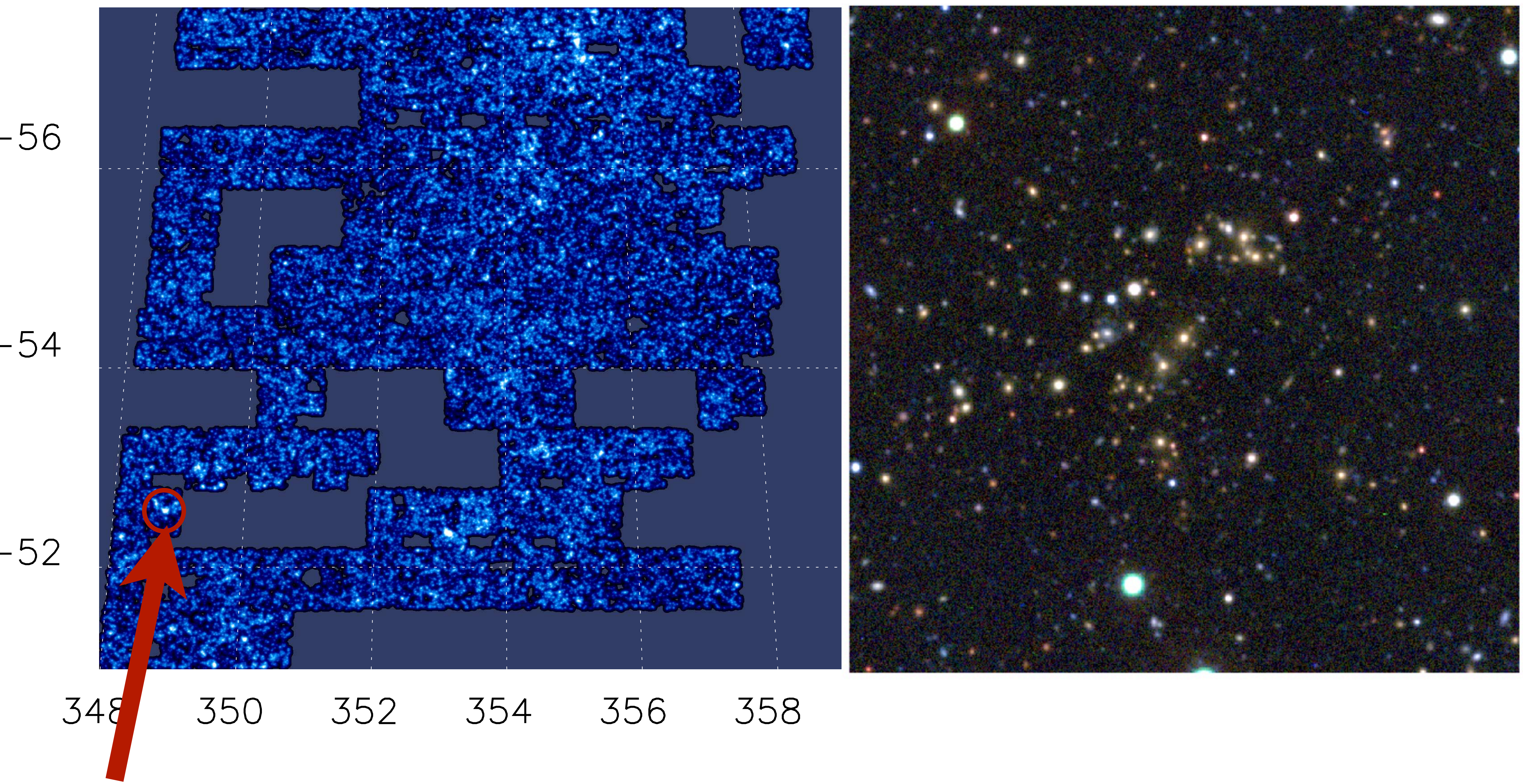
Image: Tim McKay

Example Cluster-finder Slice at z=0.46



Algorithm based on Gladders & Yee, 2000

Example Cluster-finder Slice at z=0.46



The Optical-Richness, λ, is a weighted galaxy count.

$$p(\mathbf{x}) = \frac{\lambda u(\mathbf{x}|\lambda)}{\lambda u(\mathbf{x}|\lambda) + b(\mathbf{x})}.$$

Probability of Cluster membership

Color, magnitude, radial filter

background density

$$\lambda = \sum p(\mathbf{x}|\lambda) = \sum_{R<R_c(\lambda)} \frac{\lambda u(\mathbf{x}|\lambda)}{\lambda u(\mathbf{x}|\lambda) + b(\mathbf{x})}$$

Here lambda is run
after the cluster finder.

Rozo et al, 2009;
Rykoff et al 2012

But new cluster finder algorithm redMaPPer developed for DES by Rykoff et al

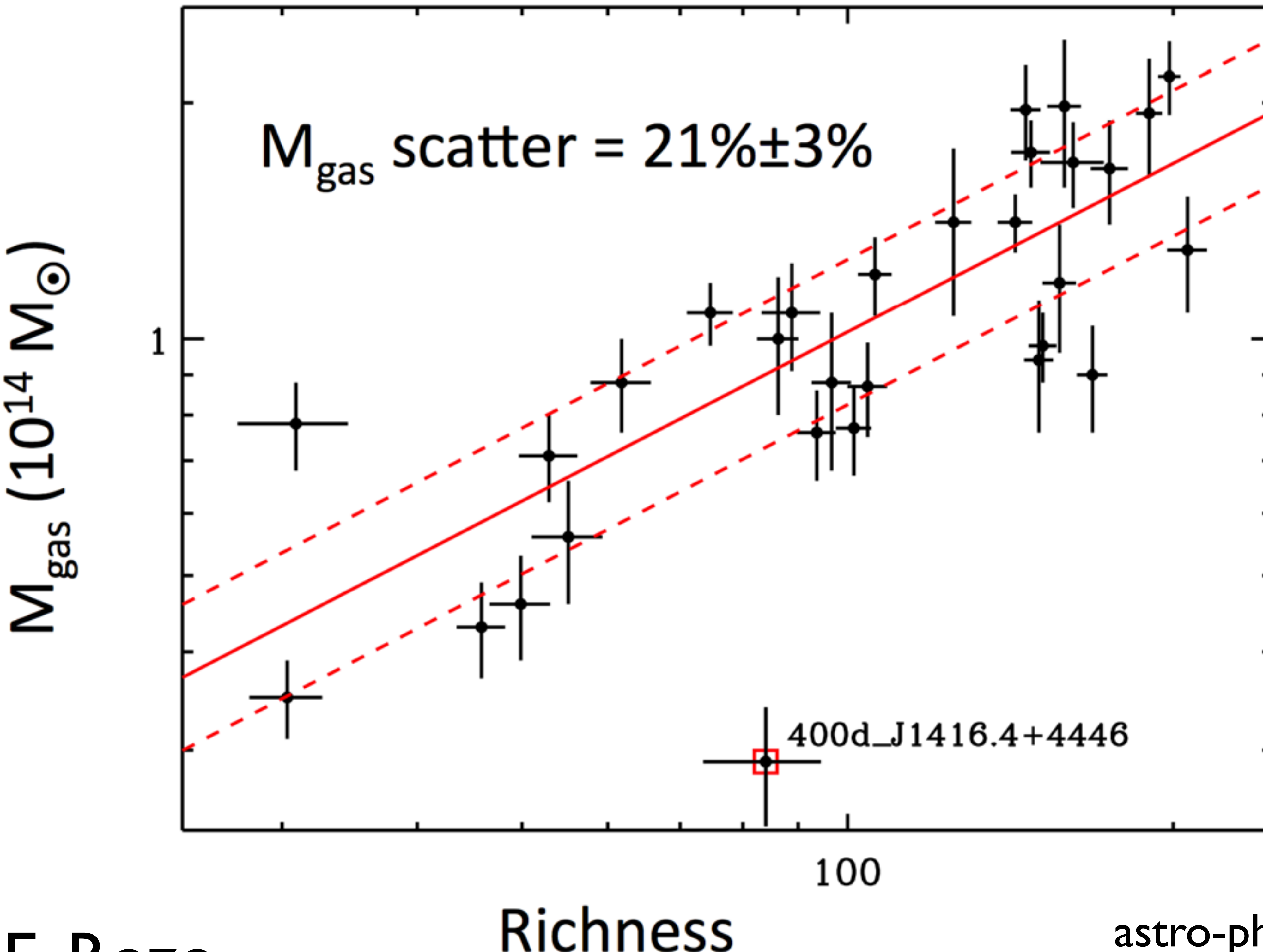


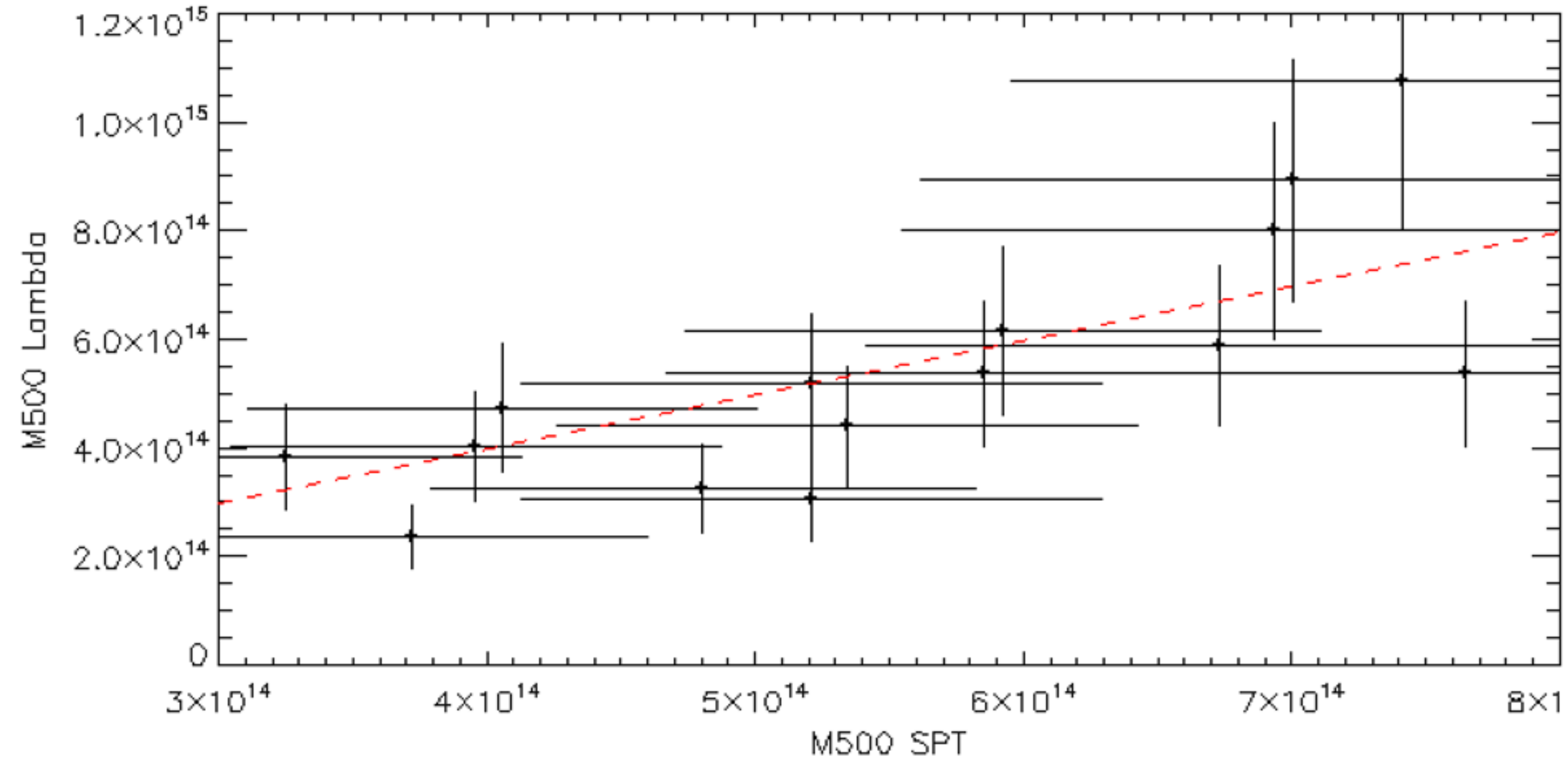
Image: E. Rozo

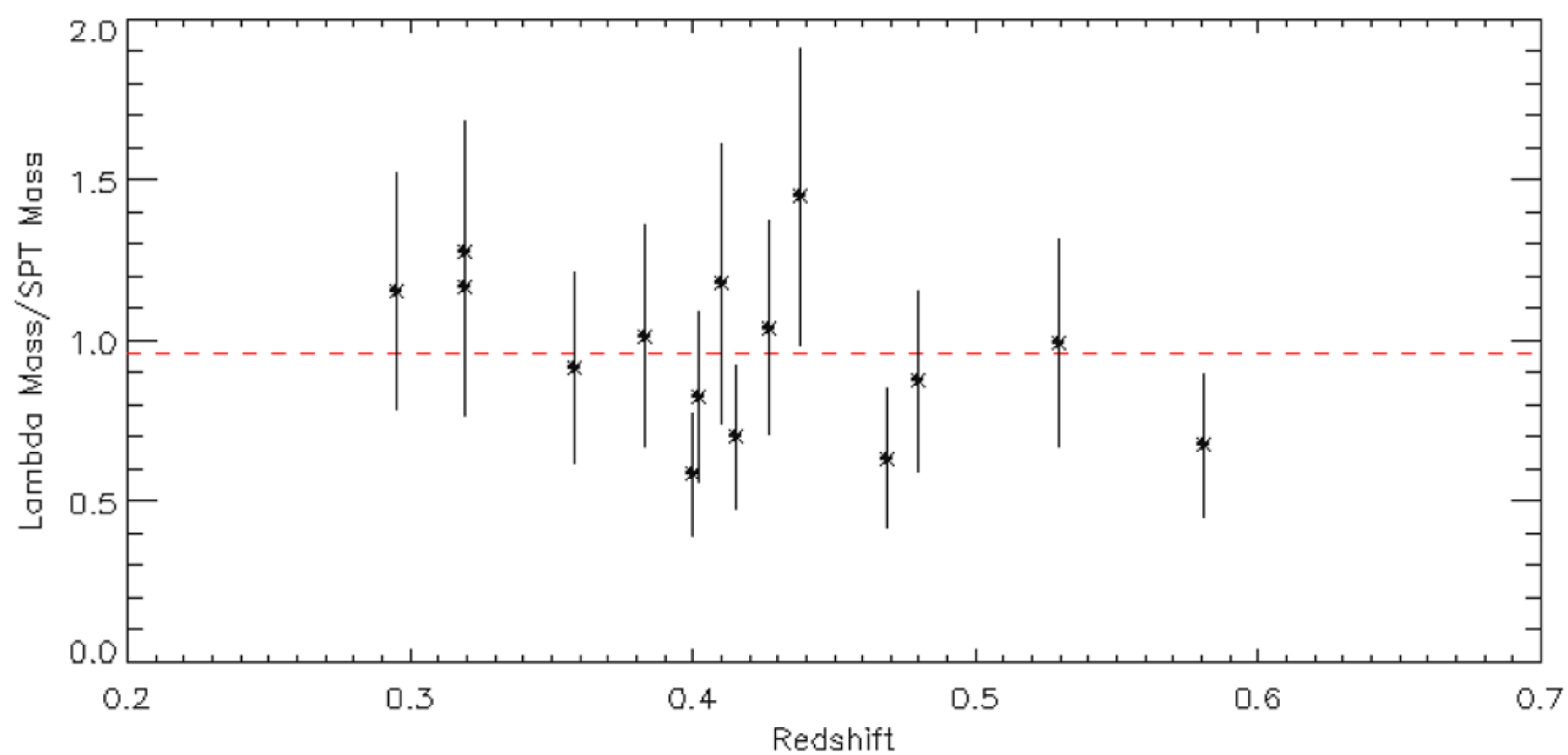
astro-ph/1303.3562
1303.3373

Back to our story ...

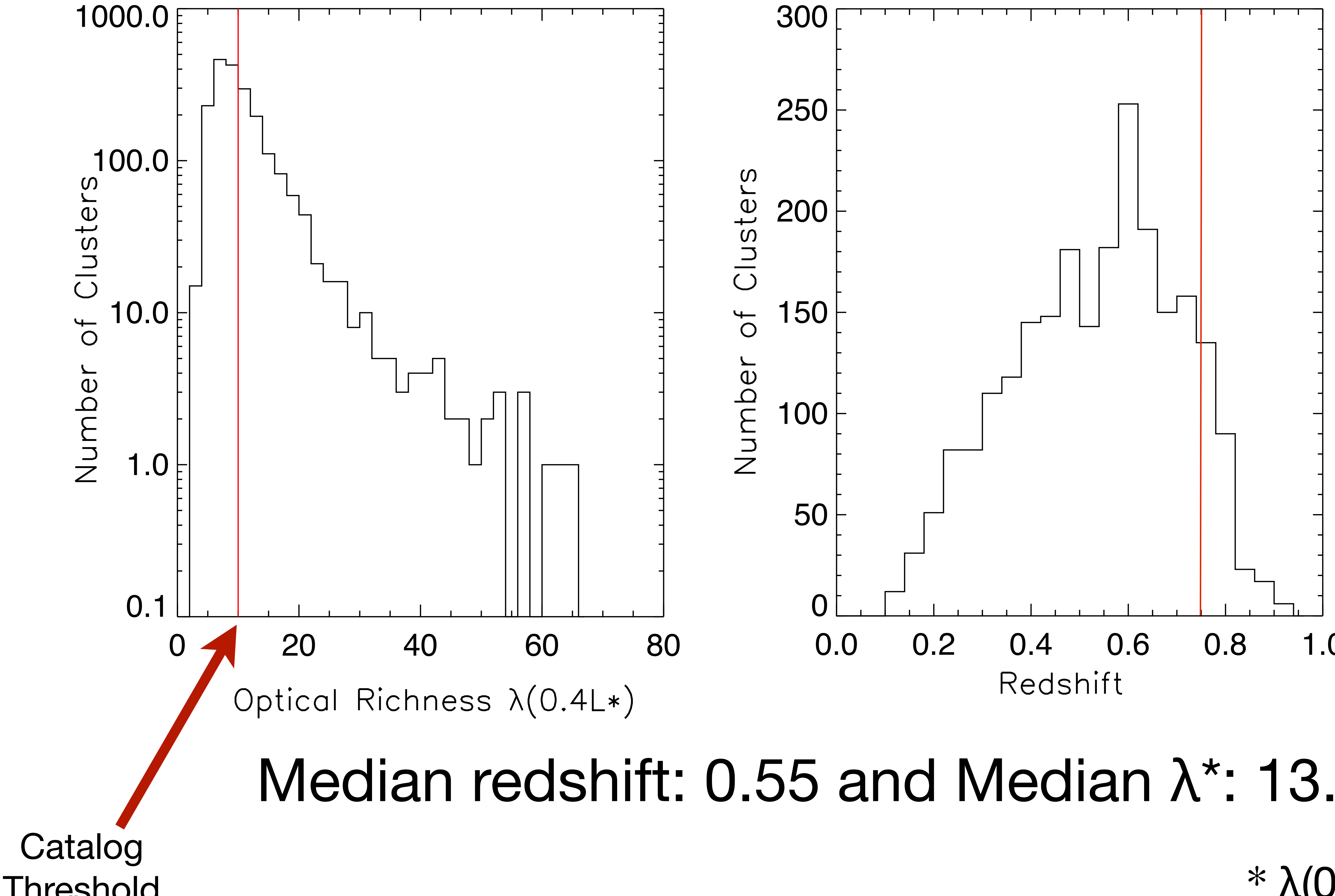
Excellent agreement at the high mass end when using the best fit SPT cosmology.

$\langle M_\lambda / M_{SPT} \rangle = 0.96 \pm 0.06$





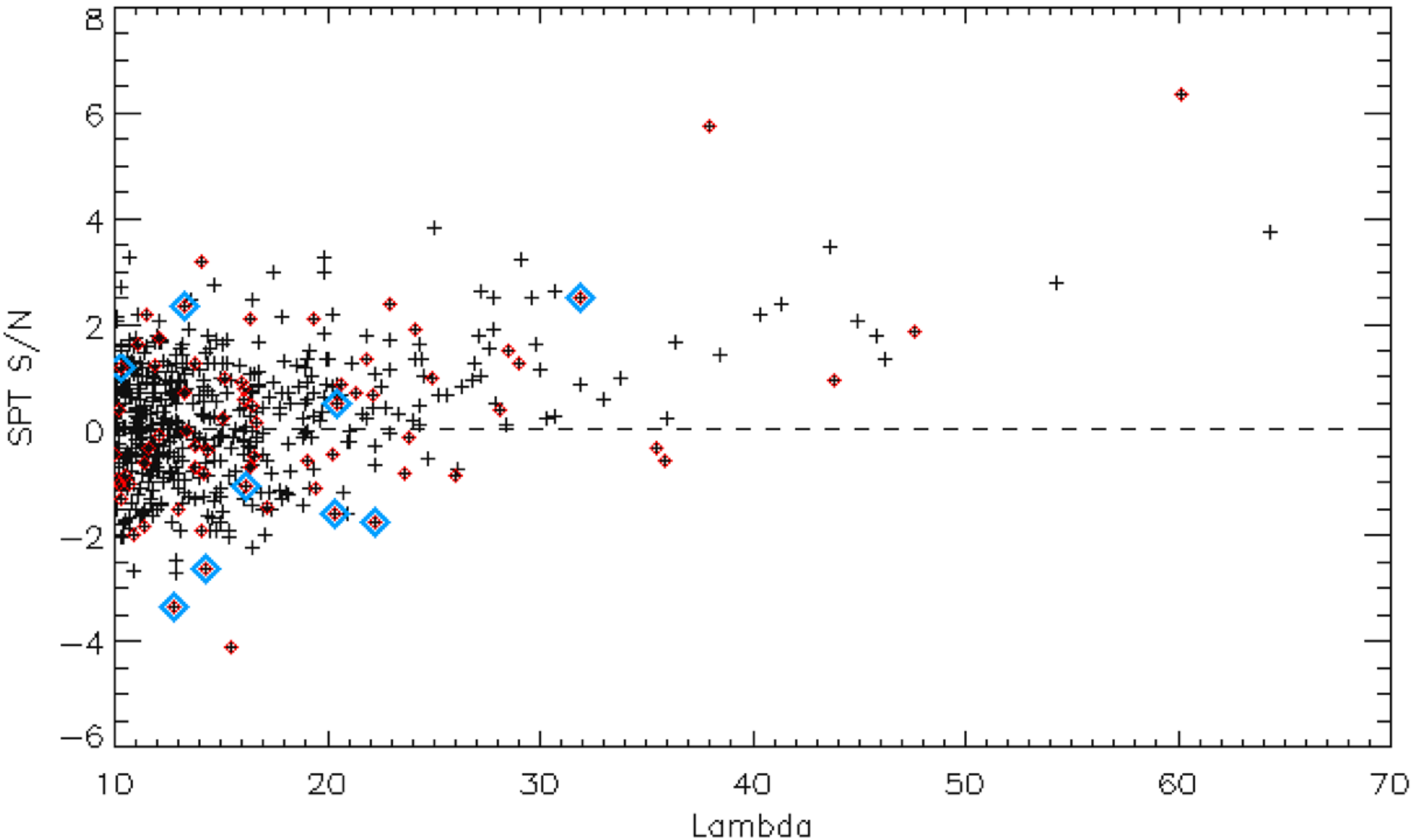
The BCS Cluster Sample



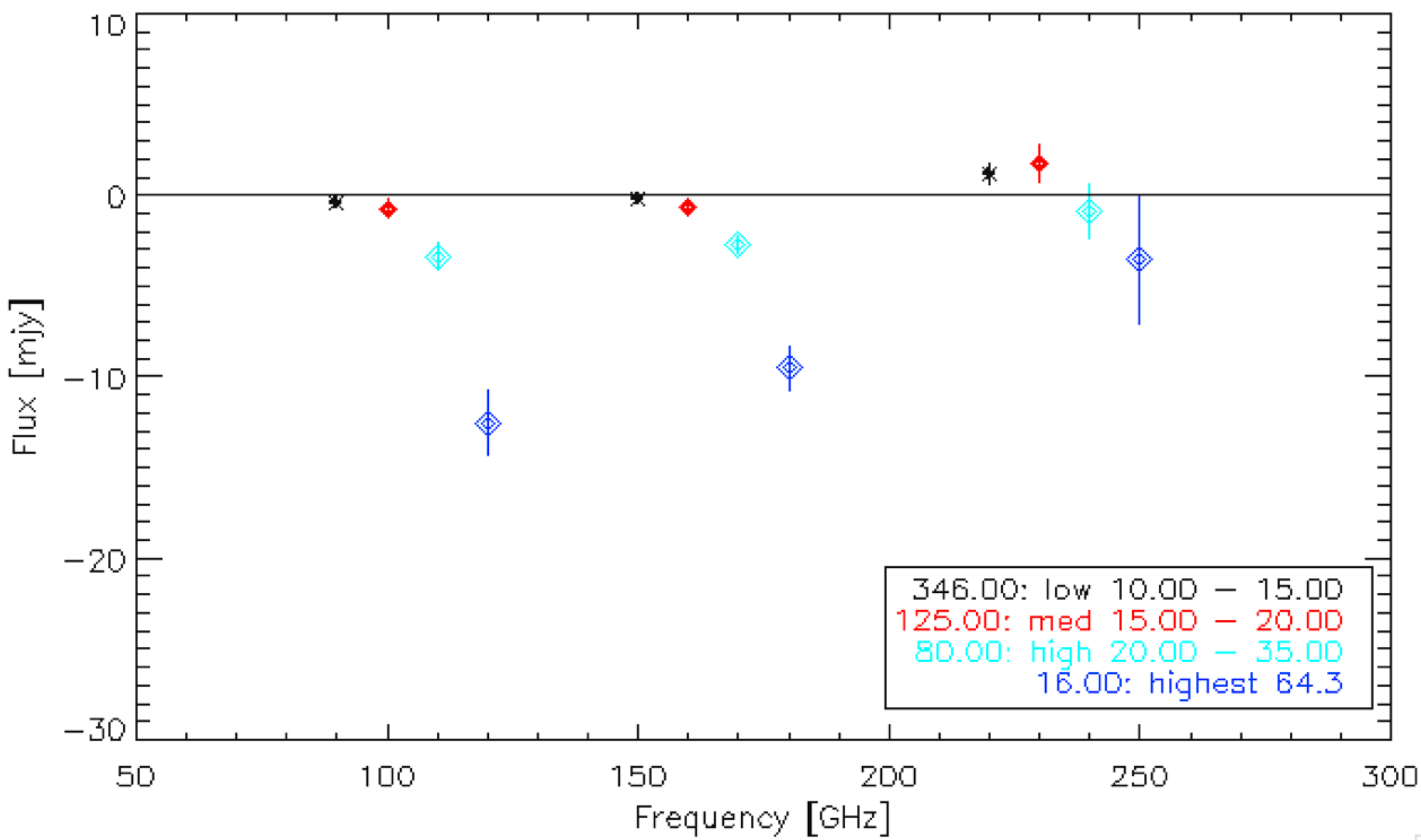
Median redshift: 0.55 and Median λ*: 13.6

* λ(0.4L*)

We filter the SPT-SZ maps at the cluster locations to extract the cluster signal.



Stacking the data to boost the signal-to-noise



λ-mass

↓

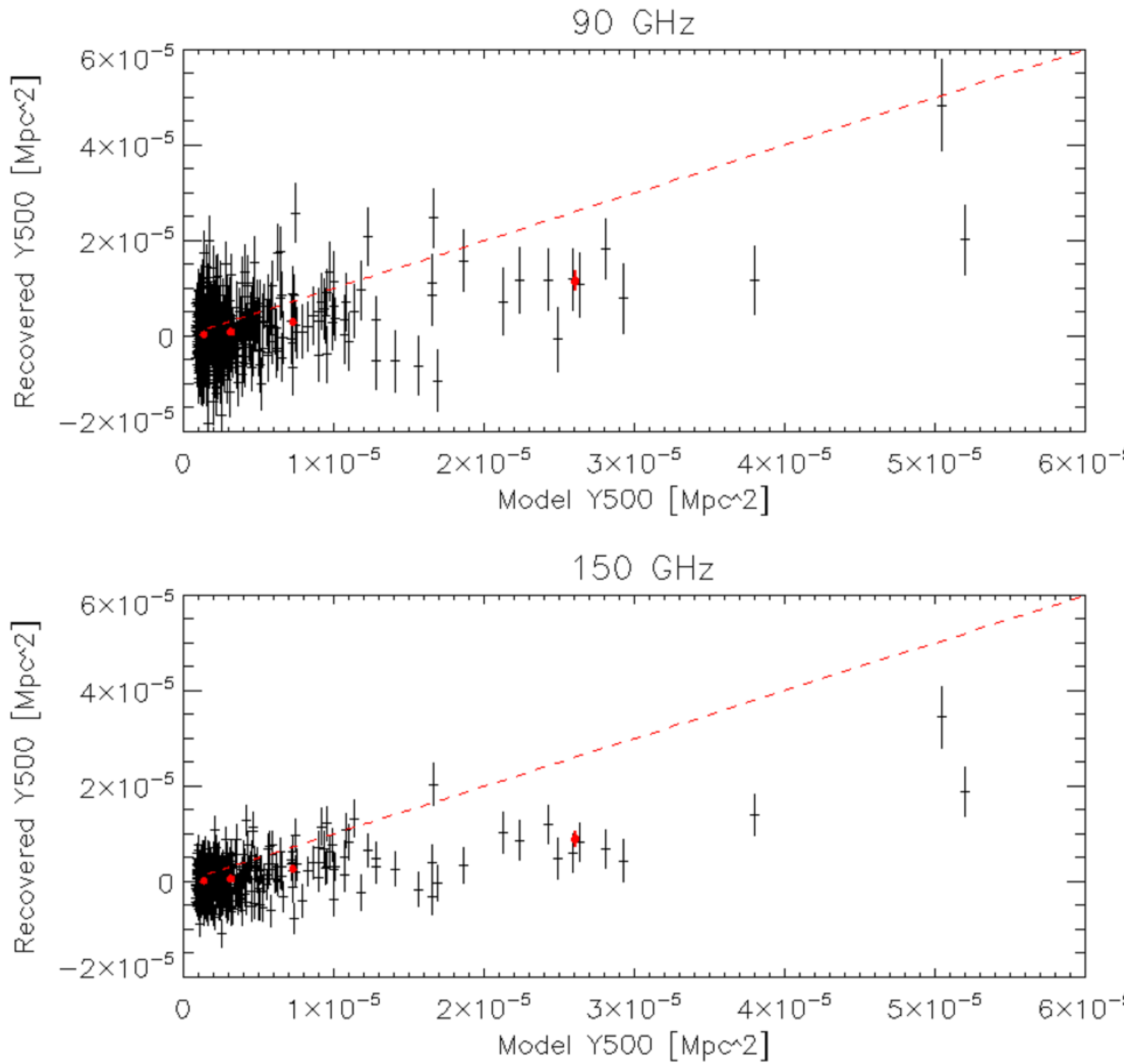
Arnaud Model

$$Y_{500} = h(z)^{2/3} A_x \left(\frac{M_{500}}{3 \times 10^{14} h_{70}^{-1} M_\odot} \right)^{\alpha} h_{70}^{-\frac{5}{2}}$$

↓

Expected Signal

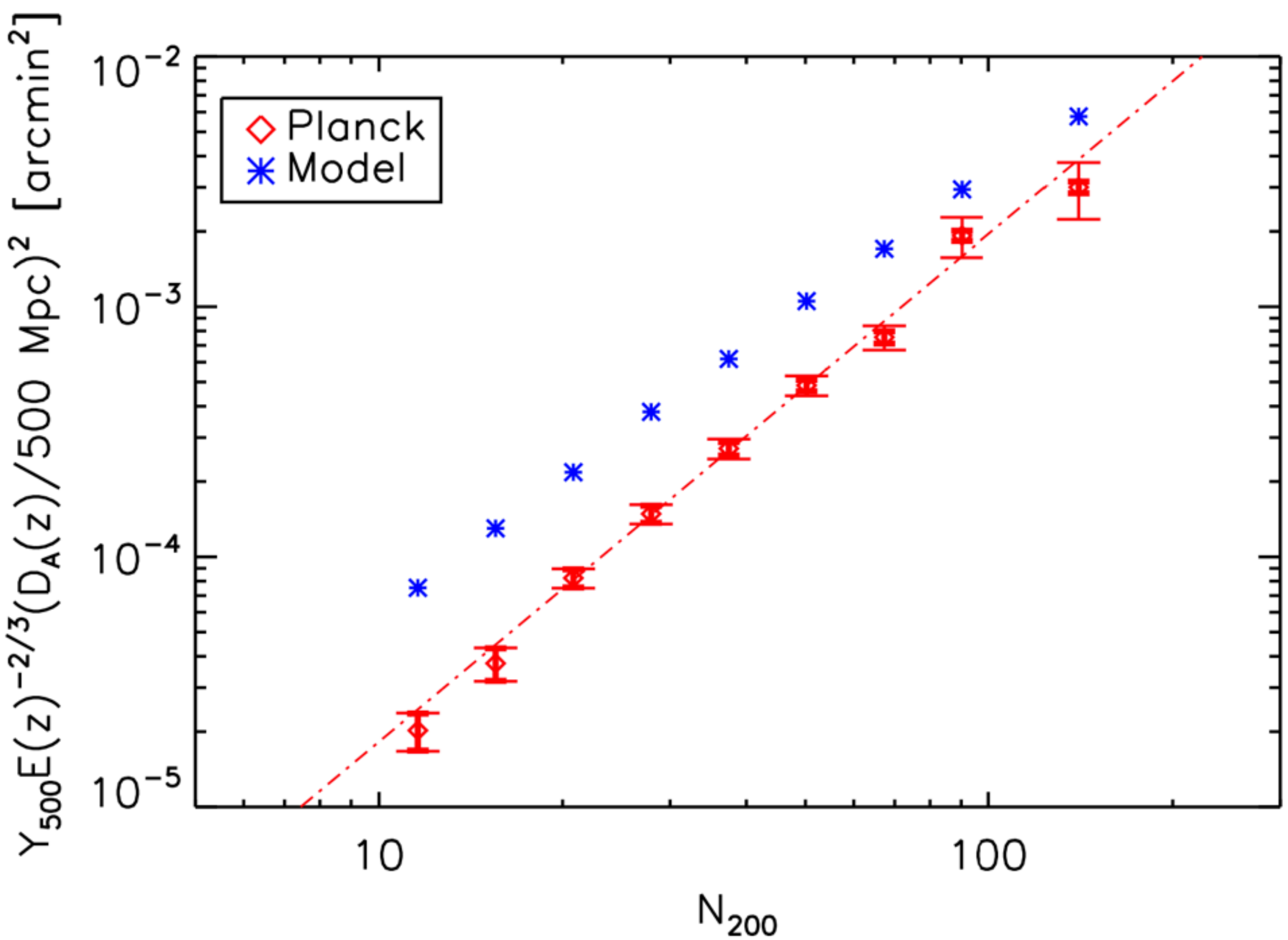
$A_x = 10^{-4.739}$, $\alpha = 1.79$, $h(z) = H_0[\Omega_m(1+z)^3 + \Omega_\Lambda]^{1/2}$, $H_0 = 72.5$ km/s/Mpc



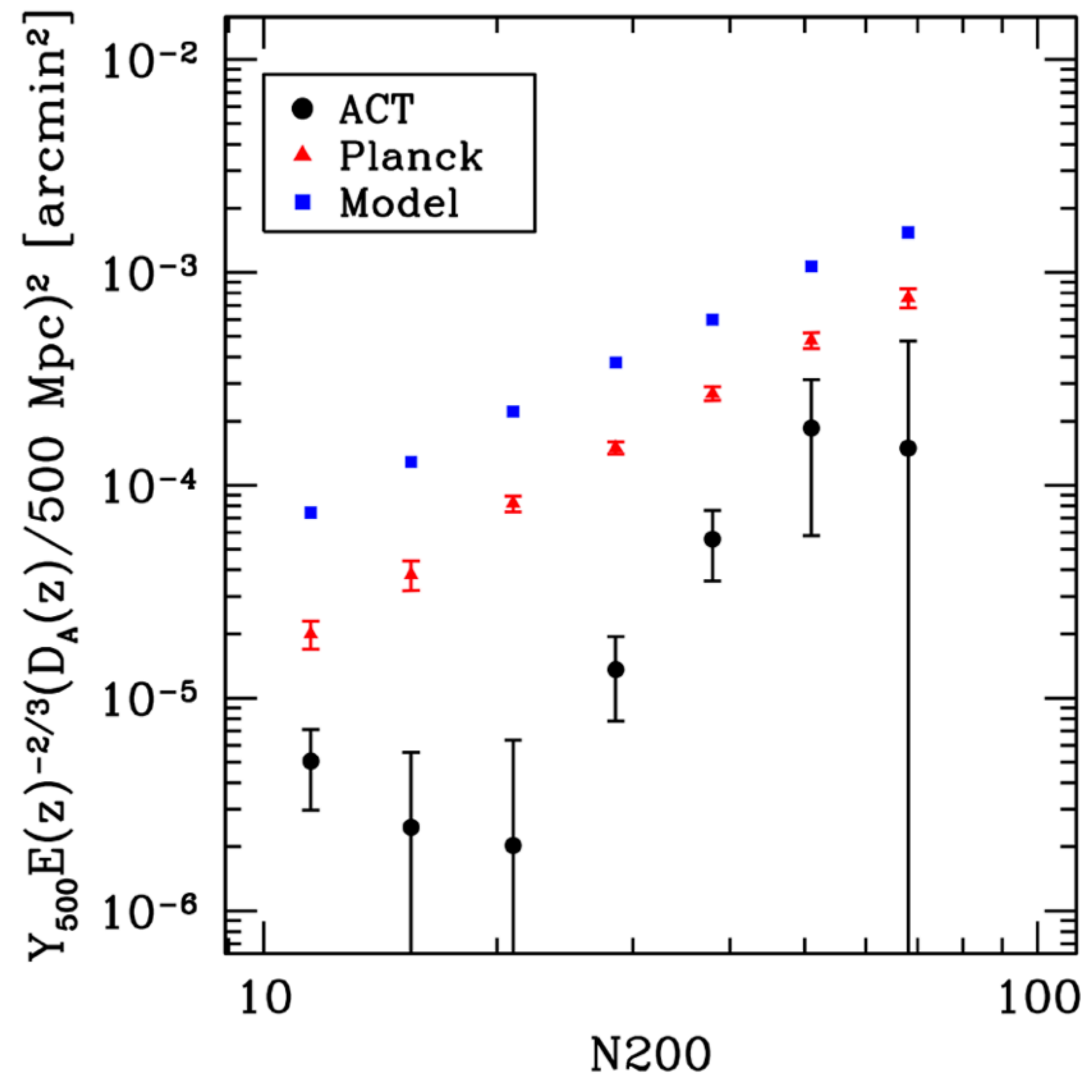
90 GHz
Recovered Y500 [Mpc^2]
Model Y500 [Mpc^2]
150 GHz
Recovered Y500 [Mpc^2]
Model Y500 [Mpc^2]

What happened?

We have seen this before (?)

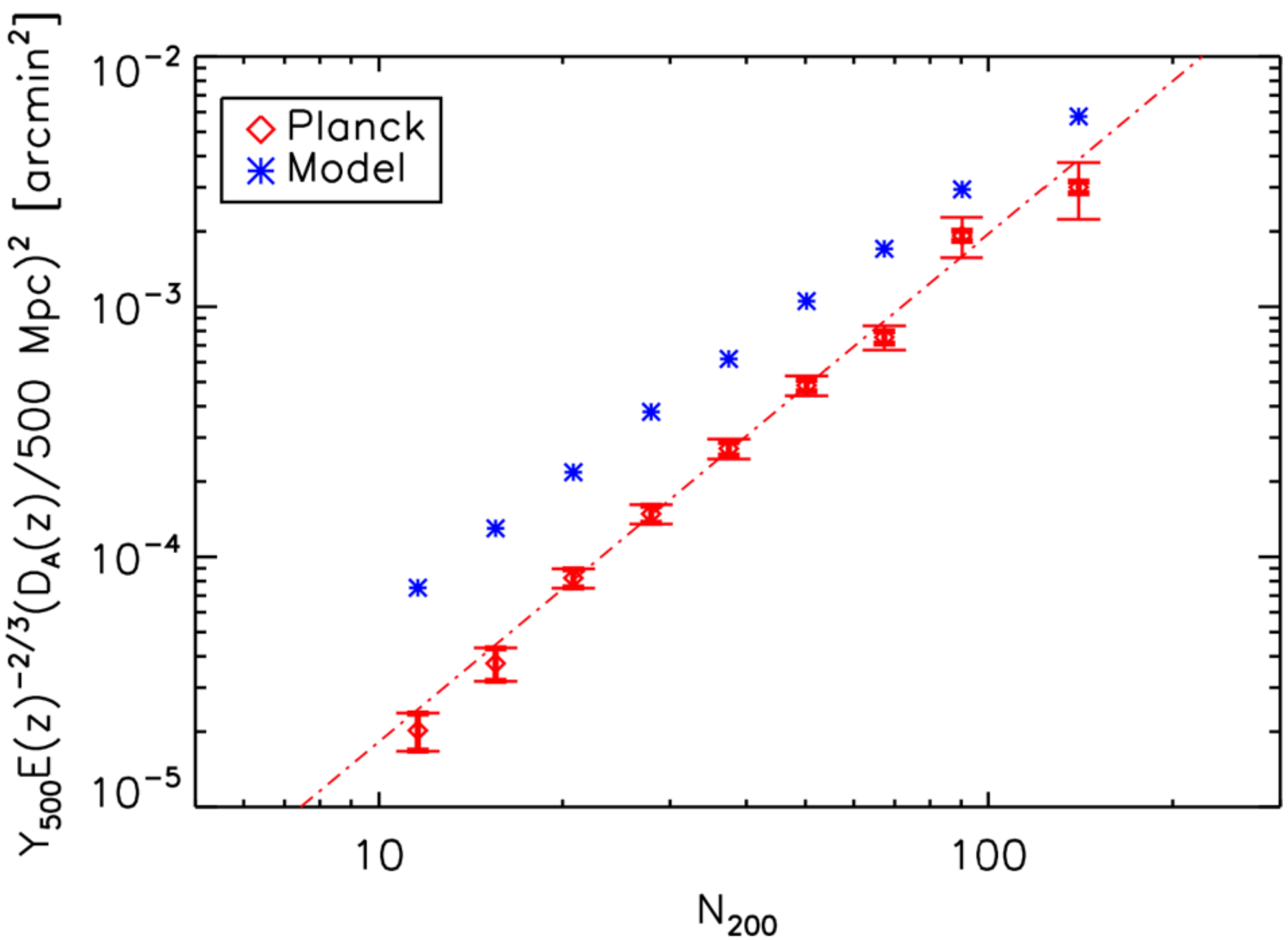


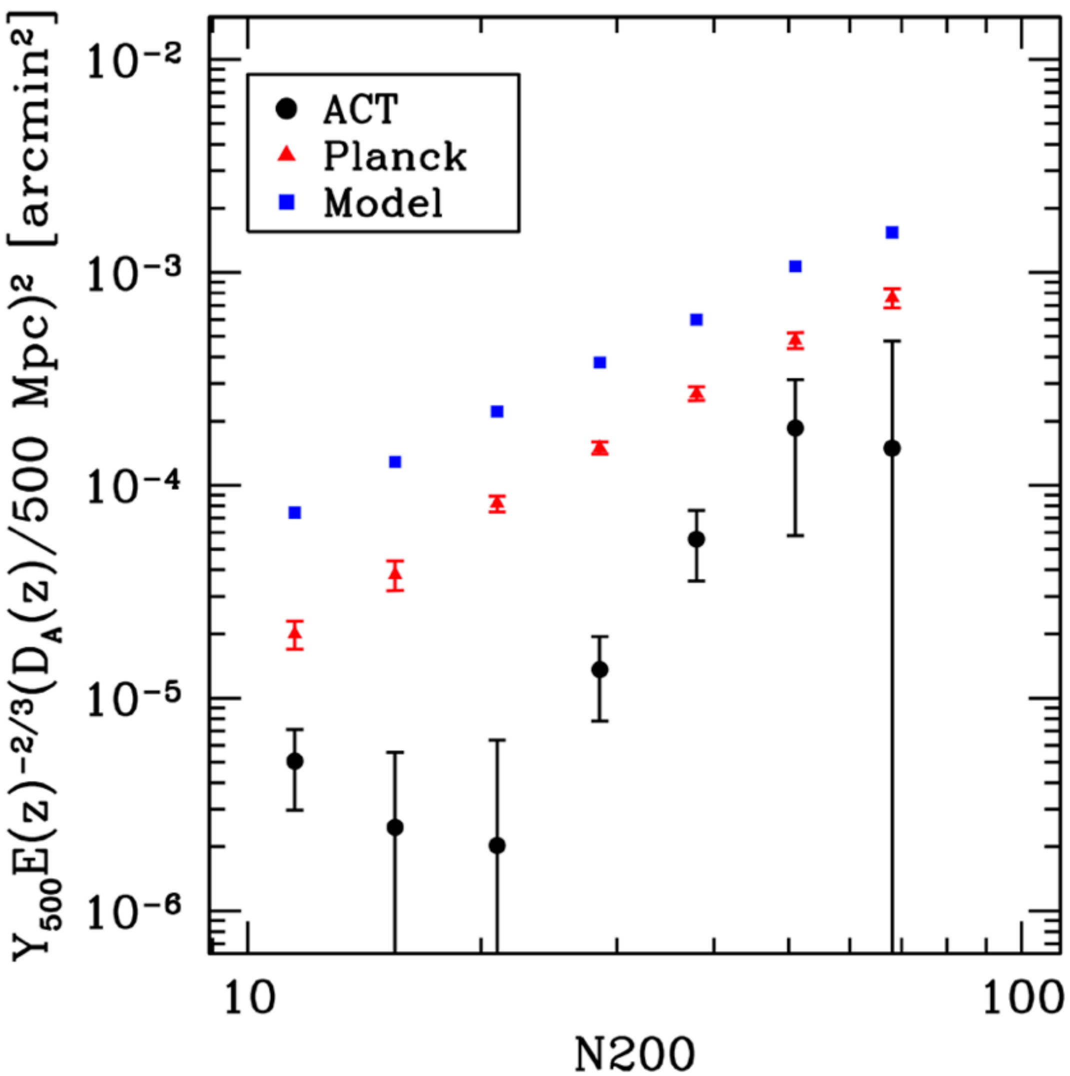
Planck Collaboration,
Planck2011-5.2c



Sehgal et al 2013
(1205.2369)

We have seen this before (?)





See:

Biesiadzinski et al. 1201.1282

Angulo et al. 1203.3216

Rozo et al. 1204.6305

SZ contamination?

Radio Sources? No.

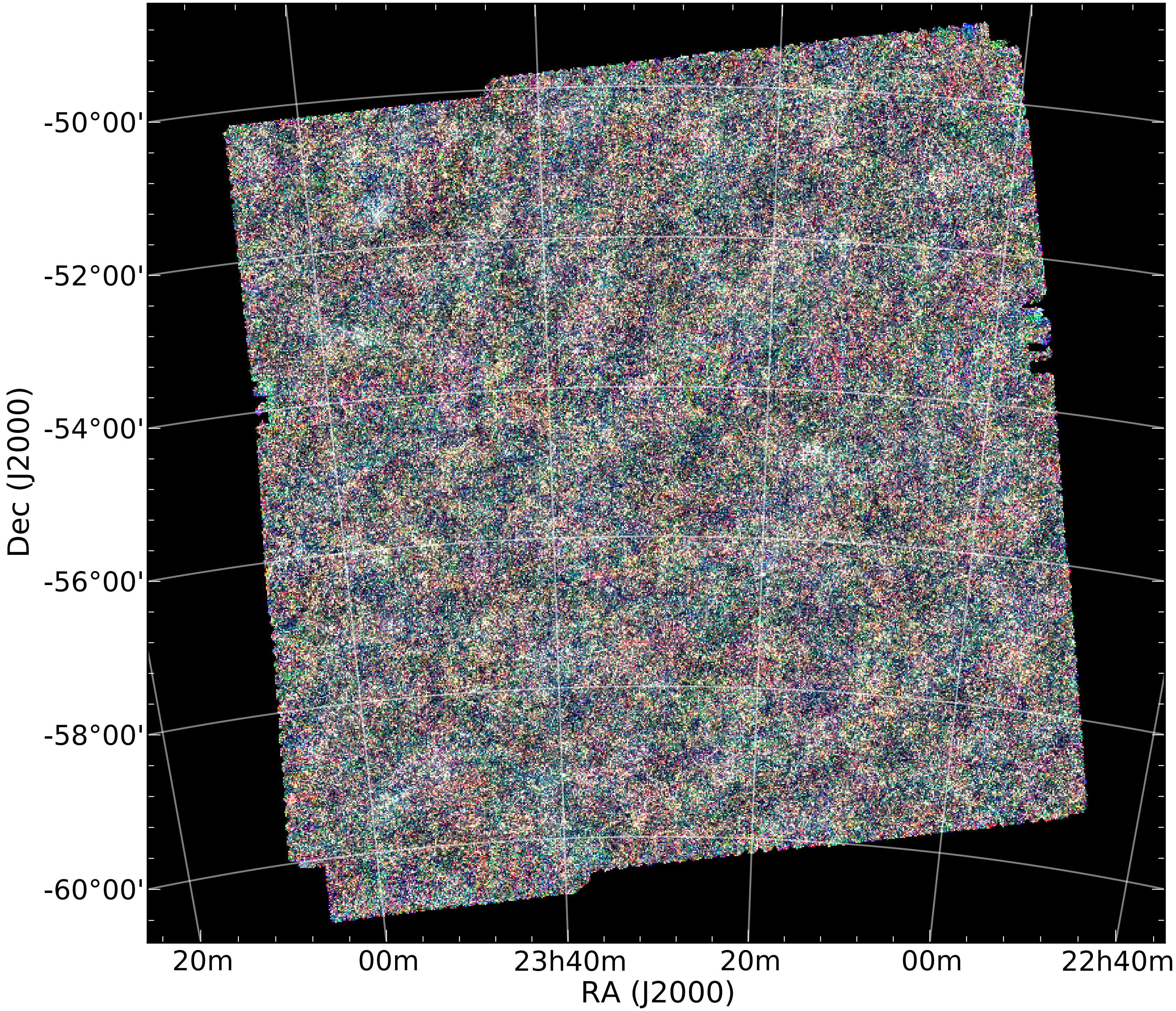
Sydney University Molonglo Sky Survey (SUMSS), (Mauch et al., 2003)

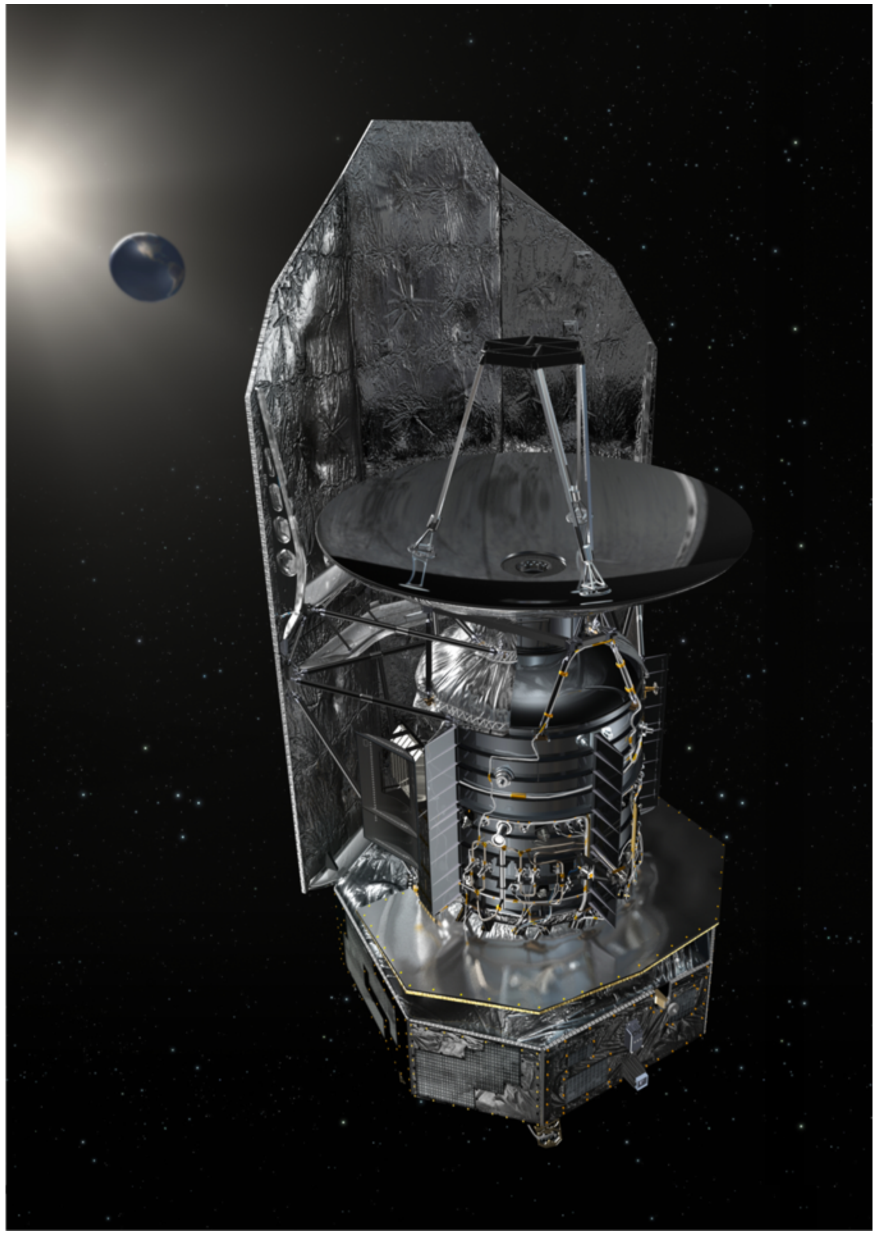
Complete to 8 mJy at 845 MHz

$$S_{96\mathrm{GHz}} = S_{845\mathrm{MHz}} \left(\frac{845\ \mathrm{MHz}}{96\ \mathrm{GHz}} \right)^{\alpha}$$

λ	M_{500}	N_{sys}	N_{Radio}	845 MHz (mJy)	SPT 96 GHz (mJy)	$\alpha = 1$	$\alpha = 1/2$
$10 - 15$	6.5e13	333	30	1596	-114 $\pm$ 95	13%	62%
$15 - 20$	1.0e14	121	16	454	-90 $\pm$ 62	5%	37%
$20 - 35$	1.6e14	77	18	1410	-260 $\pm$ 55	6%	38%
$35 - 65$	3.3e14	17	6	241	-224 $\pm$ 29	1%	11%

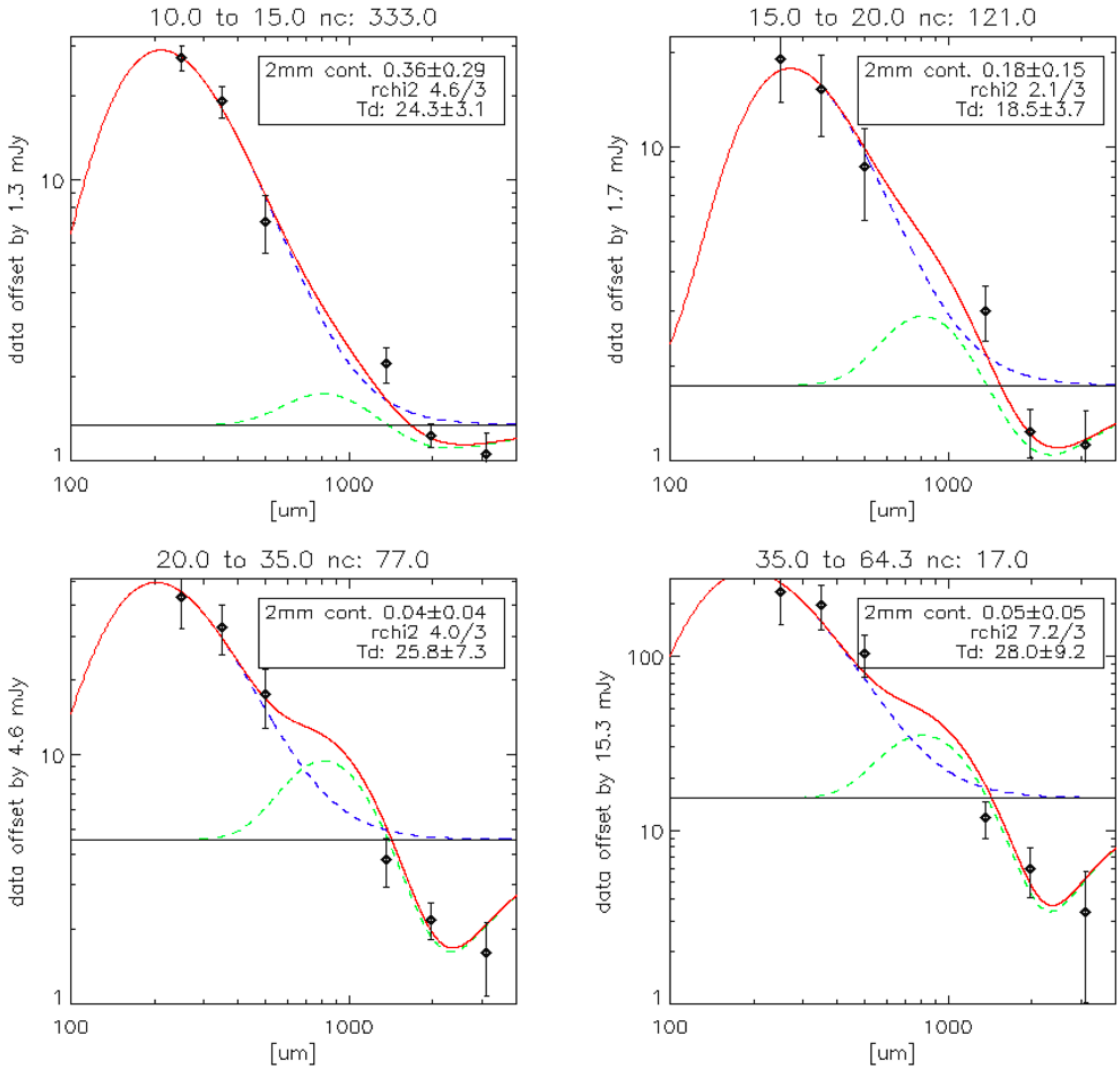
Dust? Check with submm-data from *Herschel*/ SPIRE in the 23 h field





http://herschel.esac.esa.int/

Dust contamination? No.



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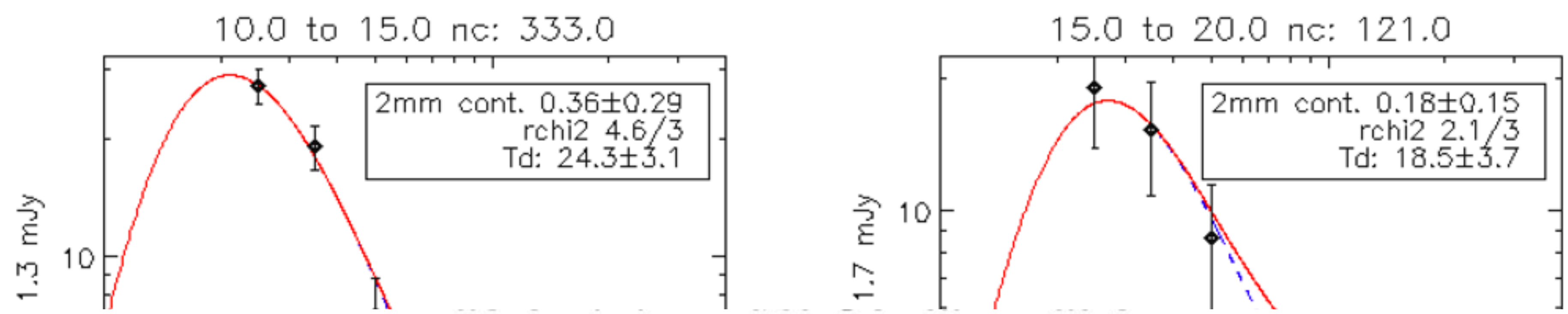
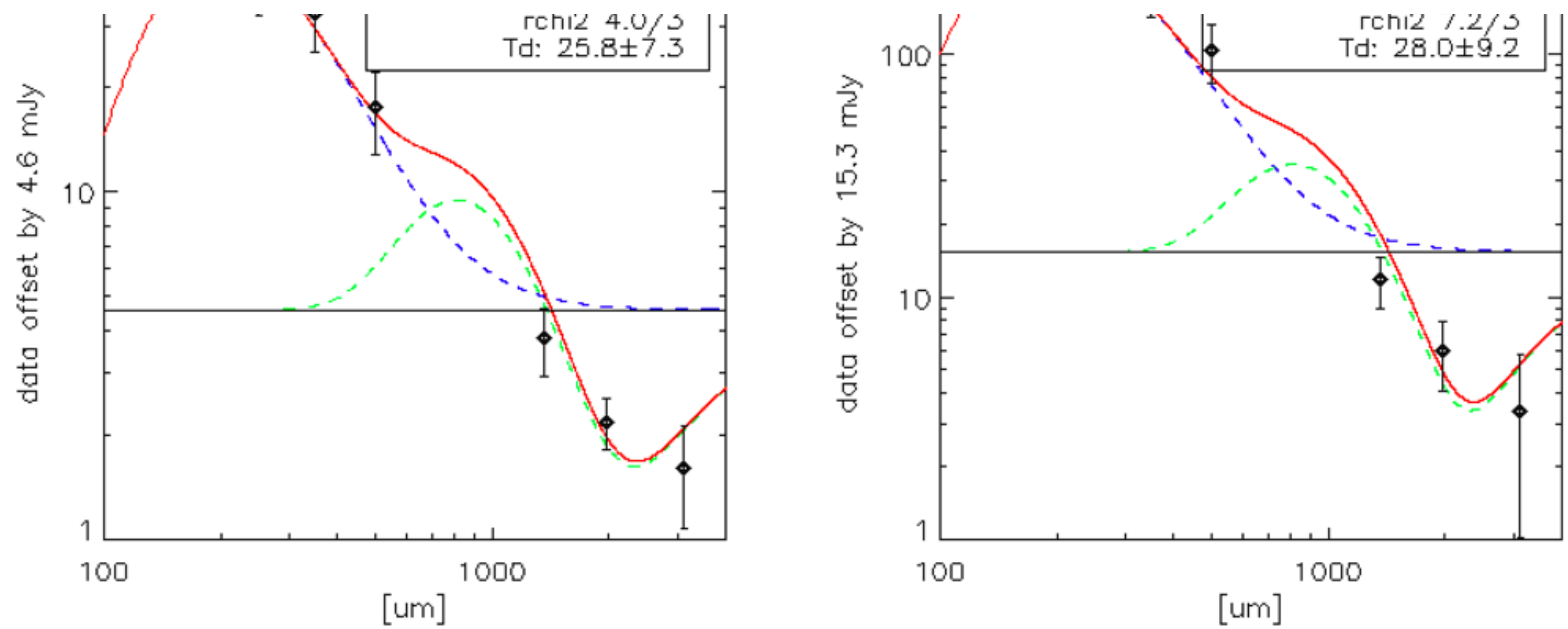


λ	M_{500}	N_{sys}	N_{SPIRE}	T_{dust}	Contamination	$\text{Contamination}_{25K}$
$10 - 15$	6.5e13	333	165	24 ± 3	0.4 ± 0.3	0.34 ± 0.26
$15 - 20$	1.0e14	121	51	19 ± 4	0.2 ± 0.15	0.10 ± 0.06
$20 - 35$	1.6e14	77	35	26 ± 7	0.04 ± 0.04	0.04 ± 0.02
$35 - 65$	3.3e14	17	11	28 ± 9	0.05 ± 0.05	0.06 ± 0.03



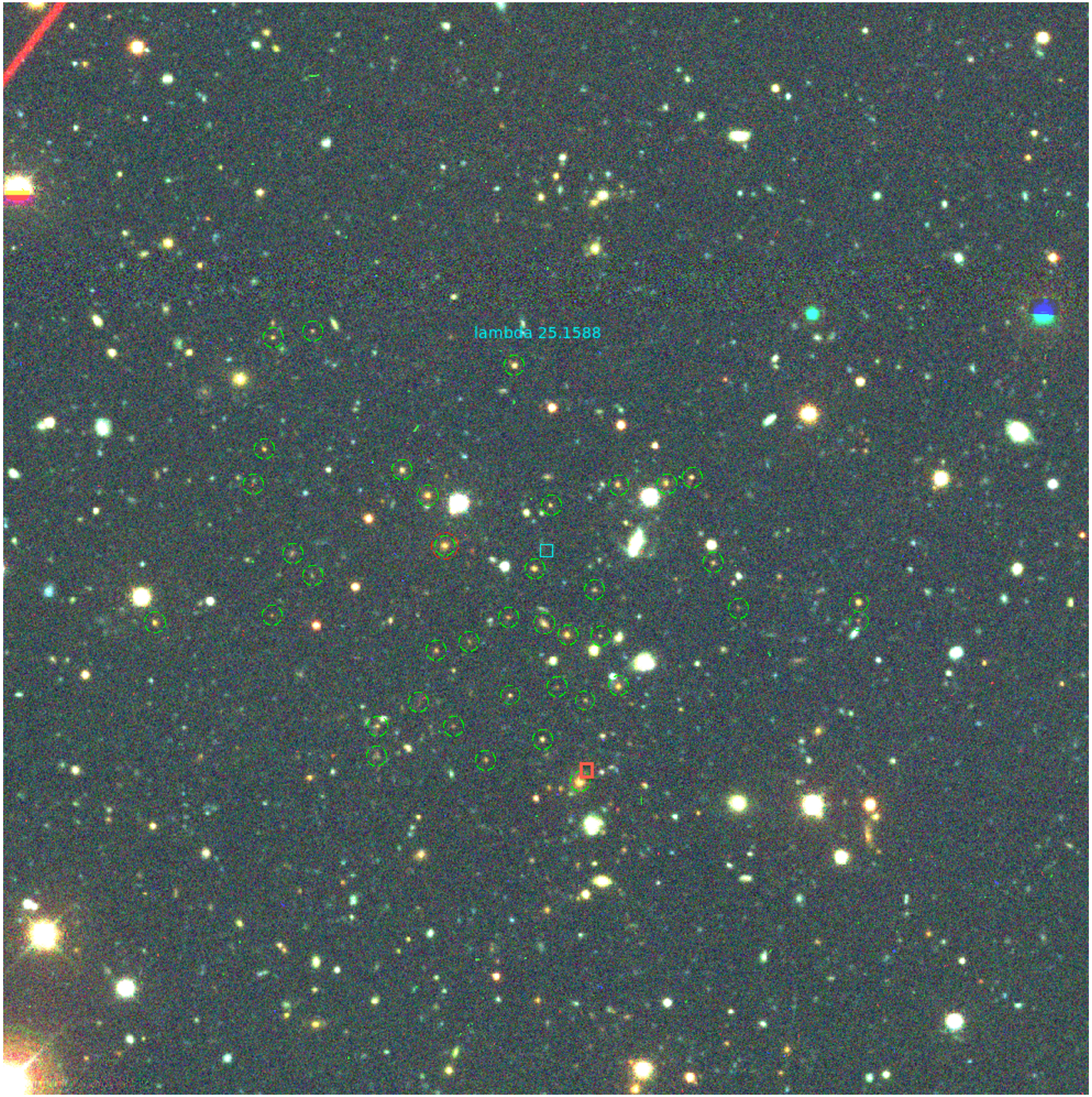
Optical Tracer?

Optical Tracer?

- Mass Calibration?
  - Good agreement at high-mass end and Eddington bias insufficient to explain discrepancy
  - Overall sample is lower mass, higher redshift (and different photometry) than SDSS cluster sample used to calibrate lambda

- What about optical centers?
  - ratio of recovered Y(90GHz)/Y150(GHz) ~4/3 !??!!
  - for X-ray and SZ samples ratio 1.

Miscentering: Maybe?



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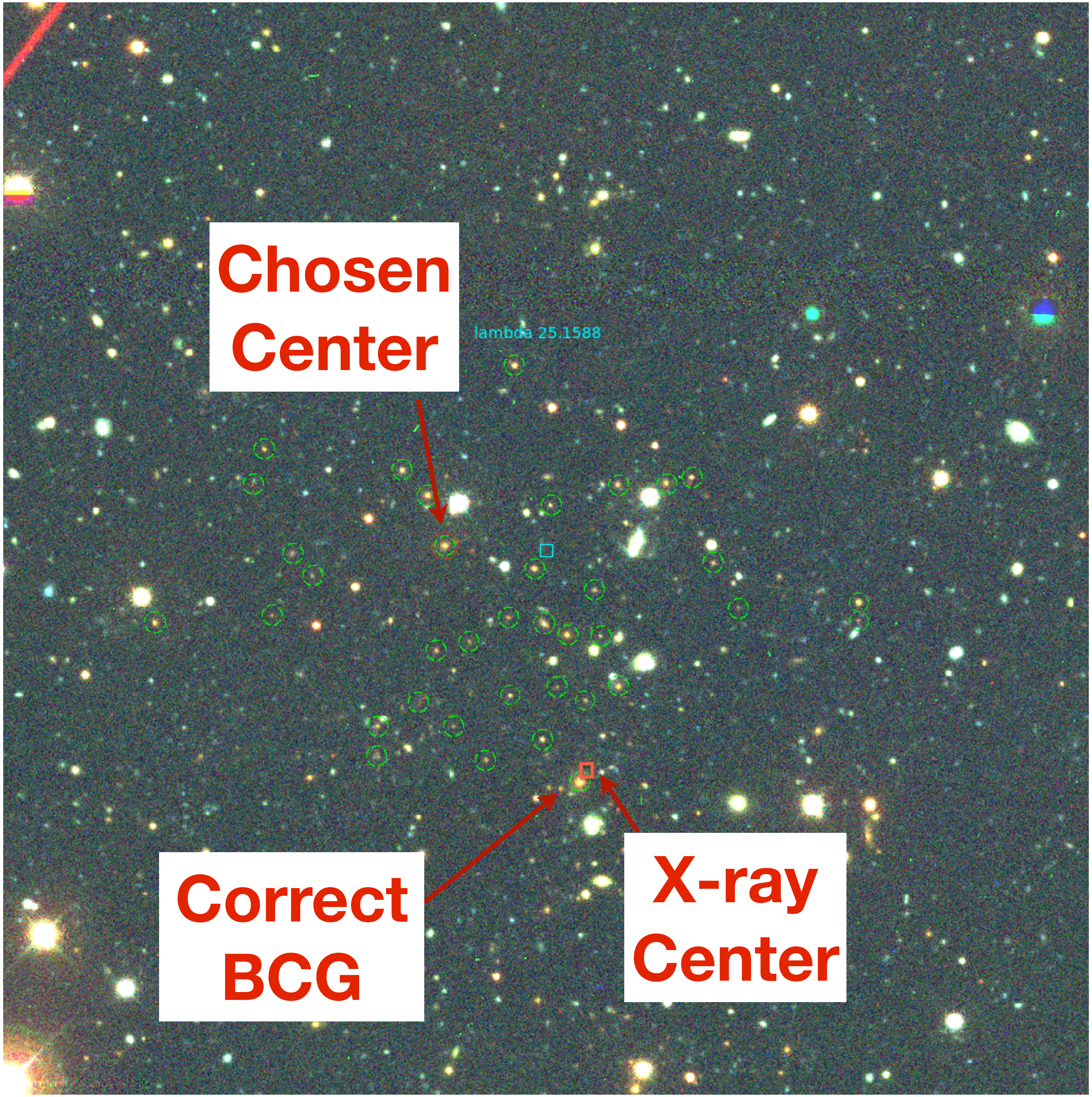
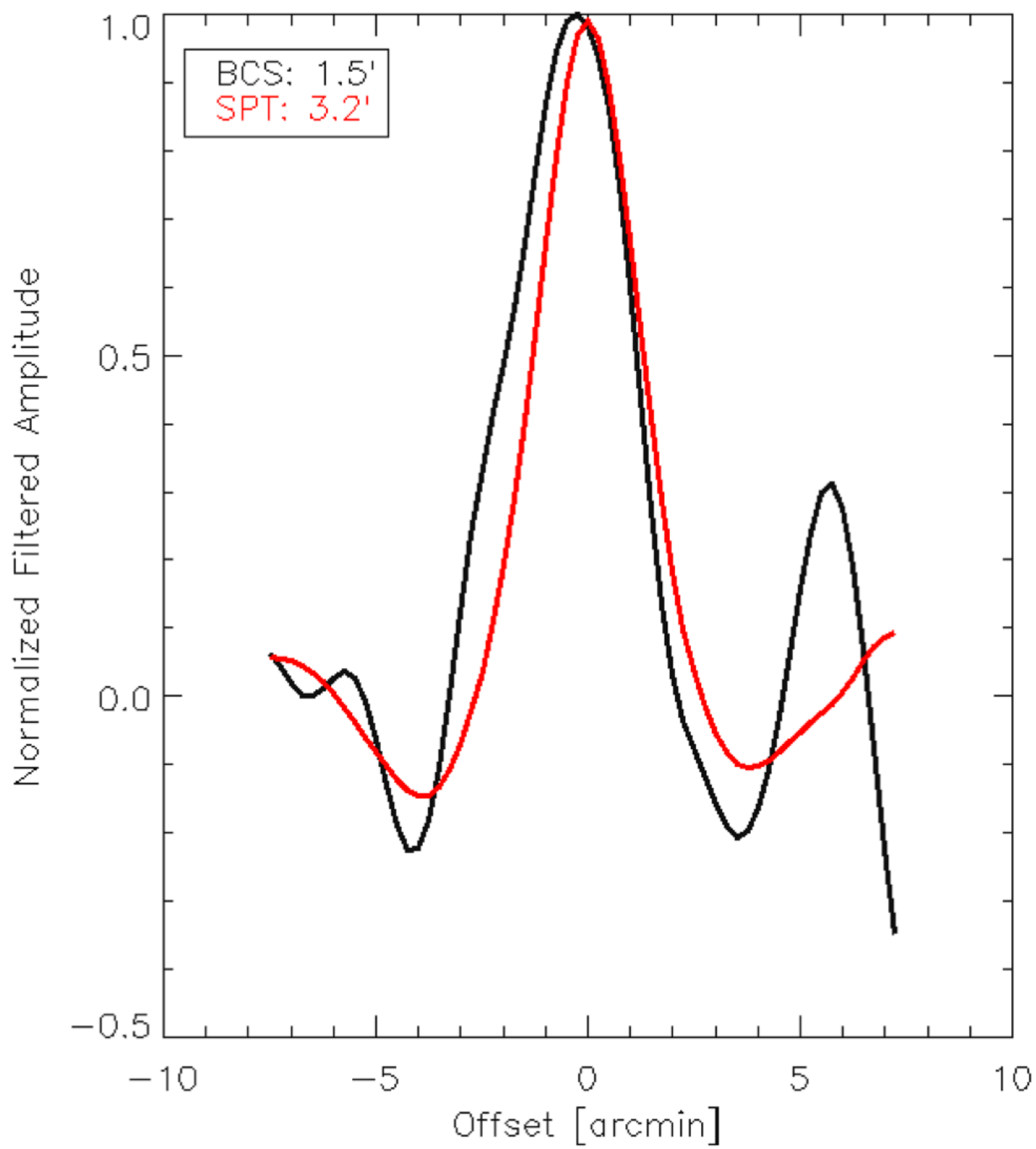
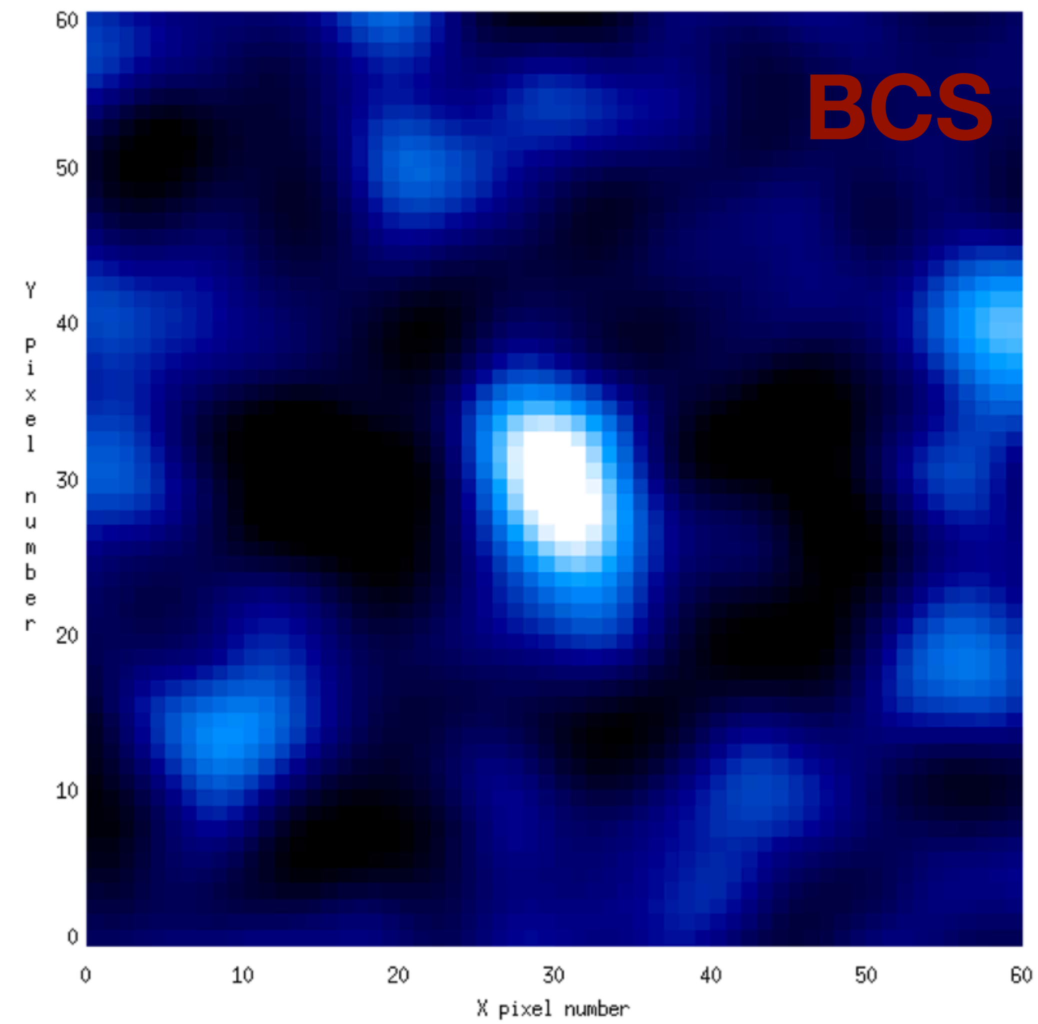
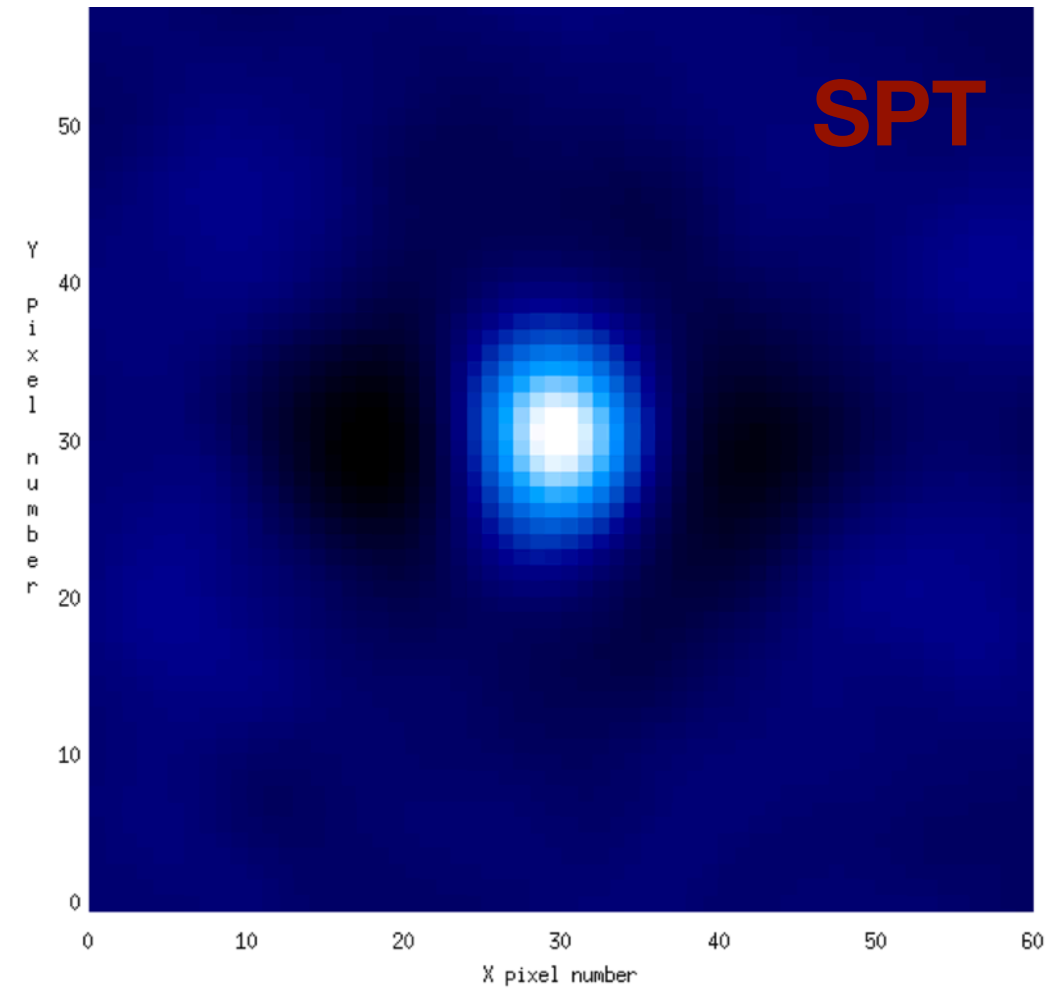


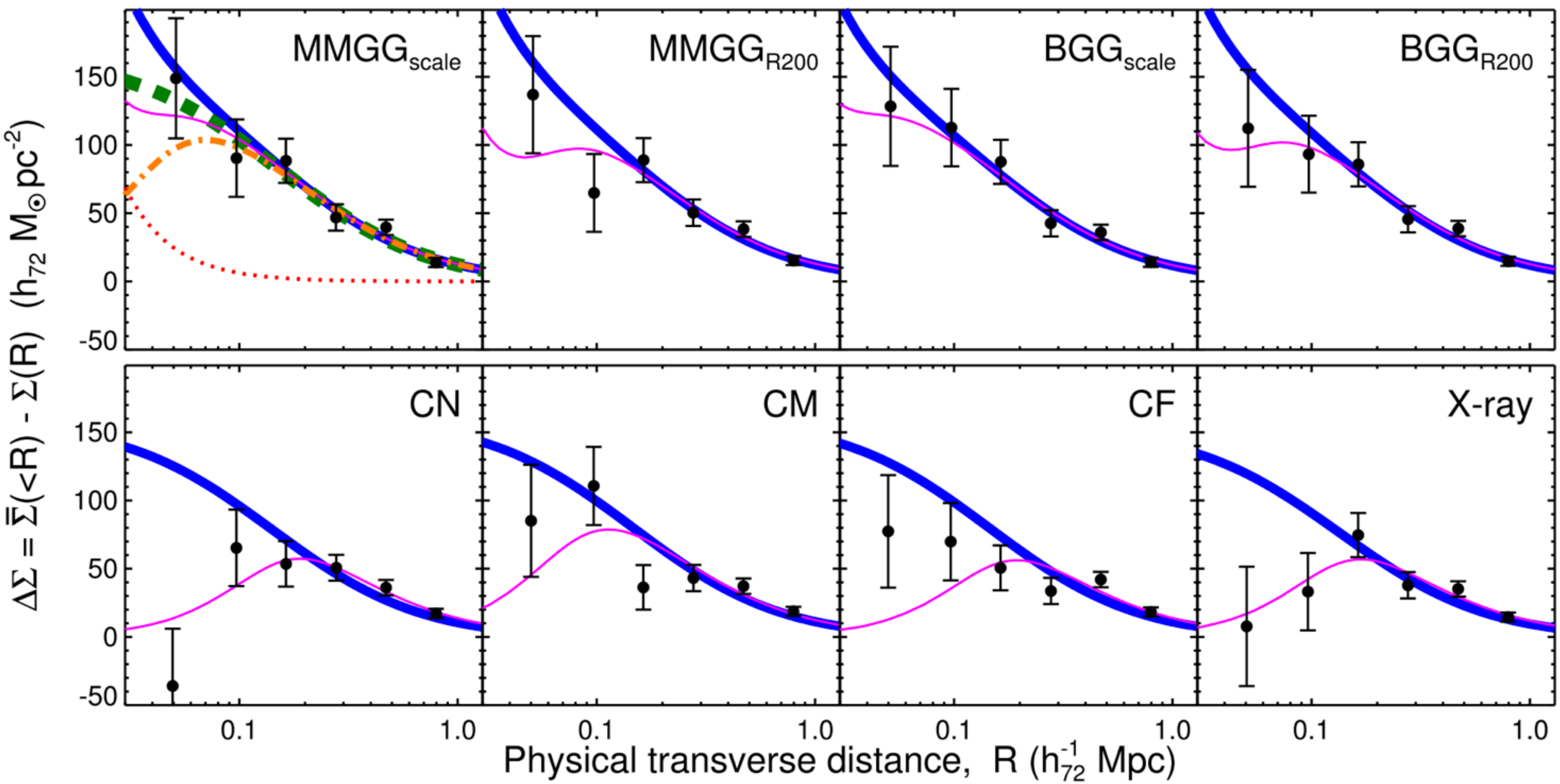
Miscentering: Maybe?







In the future can combine with weak lensing observations.



George et al. 1205.4262

Conclusions

- Clusters are powerful tools to test models of dark energy.

- Full 2500d SPT-SZ Cluster catalog coming soon!

- Large optically-selected cluster catalogs from DES on the horizon.

- Joint analyses provide important tests for systematics and tighter cosmological constraints.


Thanks!
Photo credit: Keith Vanderlinde