Finding and Weighing Clusters

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Overview

- Finding clusters
- Weighing clusters
- Some results from cluster cosmology
- The role of Astro-H

Bibliography

- Allen, Evrard & Mantz, 2011 Ann. Rev. Astron. Astrophys. 49, 409
- Benson et al., 2013 ApJ 763, 147
- Hoekstra et al., 2013 arXiv:1303:3274
- Vikhlinin et al., 2009 ApJ 692, 1060

Requirements for Cluster Finding

- Both methods (growth-of-structure and f_b) require cluster samples with:
  * known redshift, over a large range of z
  * known mass and (generally) high mass
- Growth of structure measurement also requires a statistically well-defined sample
  * For dN/dV, must count them all or at least know how many were missed (completeness)

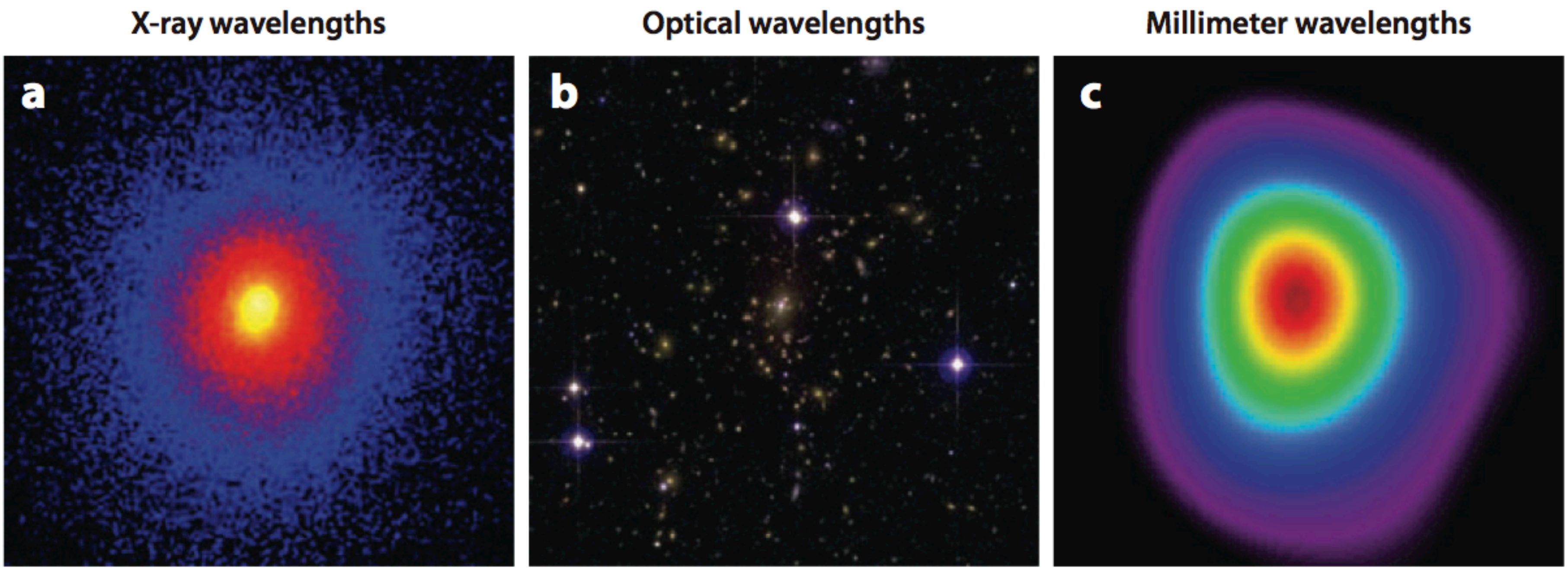
Requirements for Cluster Finding

- Massive clusters are especially important
  - * for growth: massive clusters form most recently, & thus more sensitive to cosmology
  - * for $f_{b:}$ 'fair-sample' hypothesis is most plausible
  - * for both: physics is simpler → mass more accurate
- Massive clusters are rare→ large volumes must be searched

Cluster survey methods

Abell 1835

Allen+ 2011



Chandra/Mantz CFHT/vonderLinden SZA/Marrone

X-ray Surveys

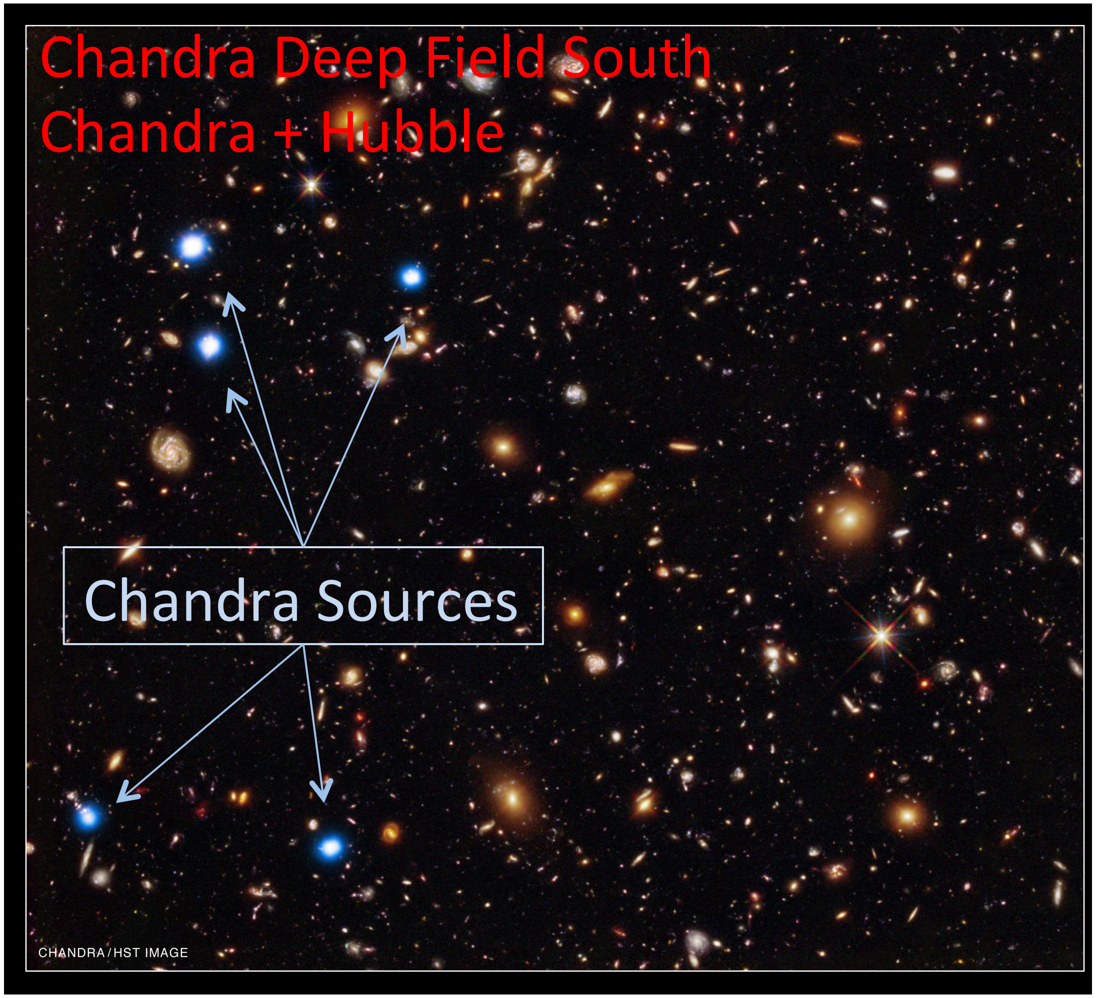
Method

- Scan the sky with an X-ray telescope
  * Or search archive of pointed observations
- Detect sources & identify extended ones
  * Measure flux, size, and, if counts permit, kT
- Measure redshift from the ground

X-ray Surveys

- Virtues
  - * The X-ray sky is dark, with few sources; massive clusters are bright, extended and ‘easy’ to recognize
  - * Imaging spectroscopy gives mass estimate (kT_x, M_{gas})
- Limitations
  - * Requires an expensive space observatory
  - * Requires large time investment to cover large Ω

X-ray vs. Optical Sky



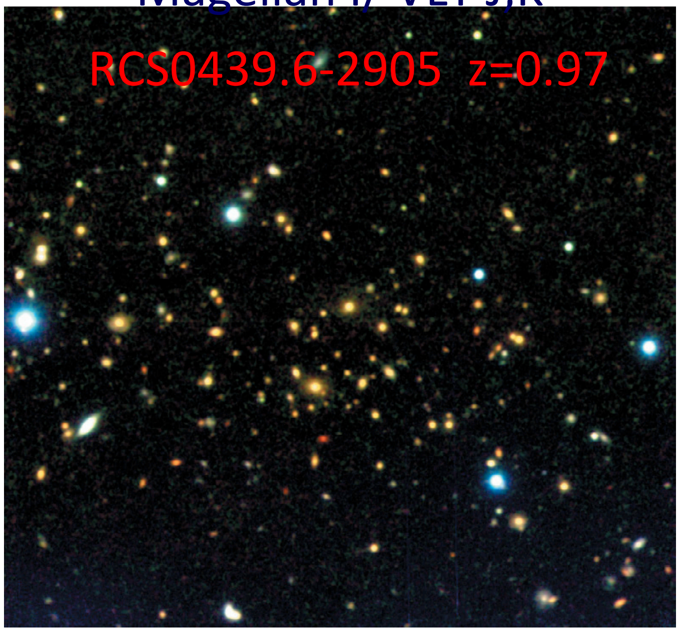
- X-ray source density is MUCH lower than optical source density. In CDFS:
  - 5 X-ray
  - ~5000 optical
- Key challenge for X-ray surveys: collect enough photons
- (Key challenge for optical surveys: assign galaxies to clusters)

(Some) X-ray Cluster Surveys

- Pre-ROSAT (Edge, Fabian, Gioia, Henry+)
  - * Ariel V (1974-80)+HEAO-1 (1977-79)+EXOSAT(1983-86): "All-sky", z < 0.2 (Edge, Fabian+,1990)
  - * Einstein (1978-81) 800 deg^2 z < 0.6 (Gioia et al. 1990)
- ROSAT (1990-98; Böhringer, Fabian,Ebeling, Reiprich, Rosati,Buerinin+)
  - * RASS (all-sky) BCS, REFLEX, HIFLUGCS,MACS, z < 0.5
  - * Pointed: RDCS ~30 deg^2, z < 0.8; 400d 400 deg^2, z < 0.8
- XMM (2006+, Pierre+)
  - * LSS 11 deg^2, XXL 25 deg^2, z < ~1.5-2
- Future: eRosita (see Andy's short talk yesterday)
- *Most X-ray-selected cluster samples come from ROSAT data obtained 15+ years ago*

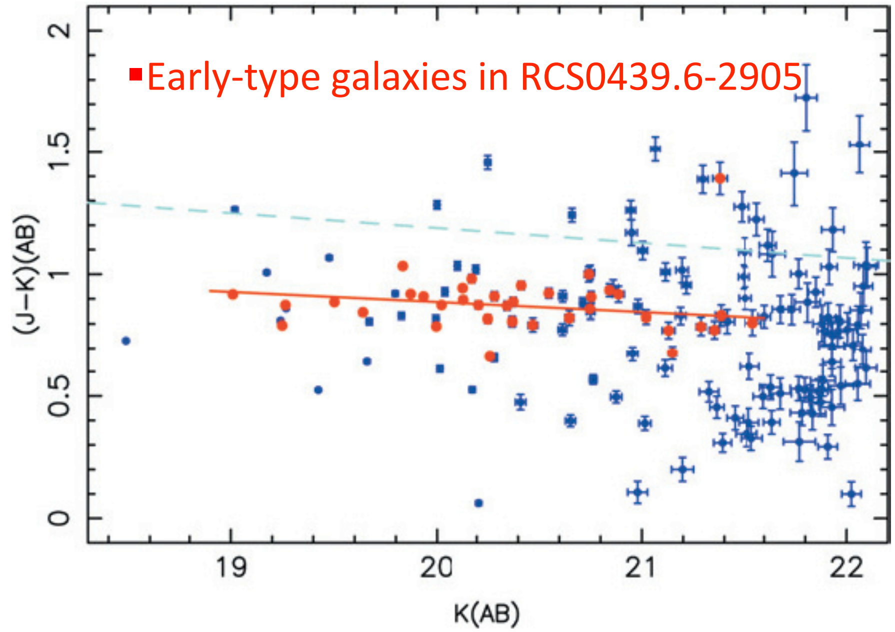
Optical Surveys

Magellan I/ VLT J,K



Barrientos et al., 2003

Color-Magnitude Sequence at z=0.97



Method: Use the cluster red sequence

- Early-type cluster galaxies are redder than foreground objects
- Survey sky in 2+ bands; make images in several color 'bins'
- Search for galaxy over-densities within each color bin
- Color of red-sequence also provides estimate of z

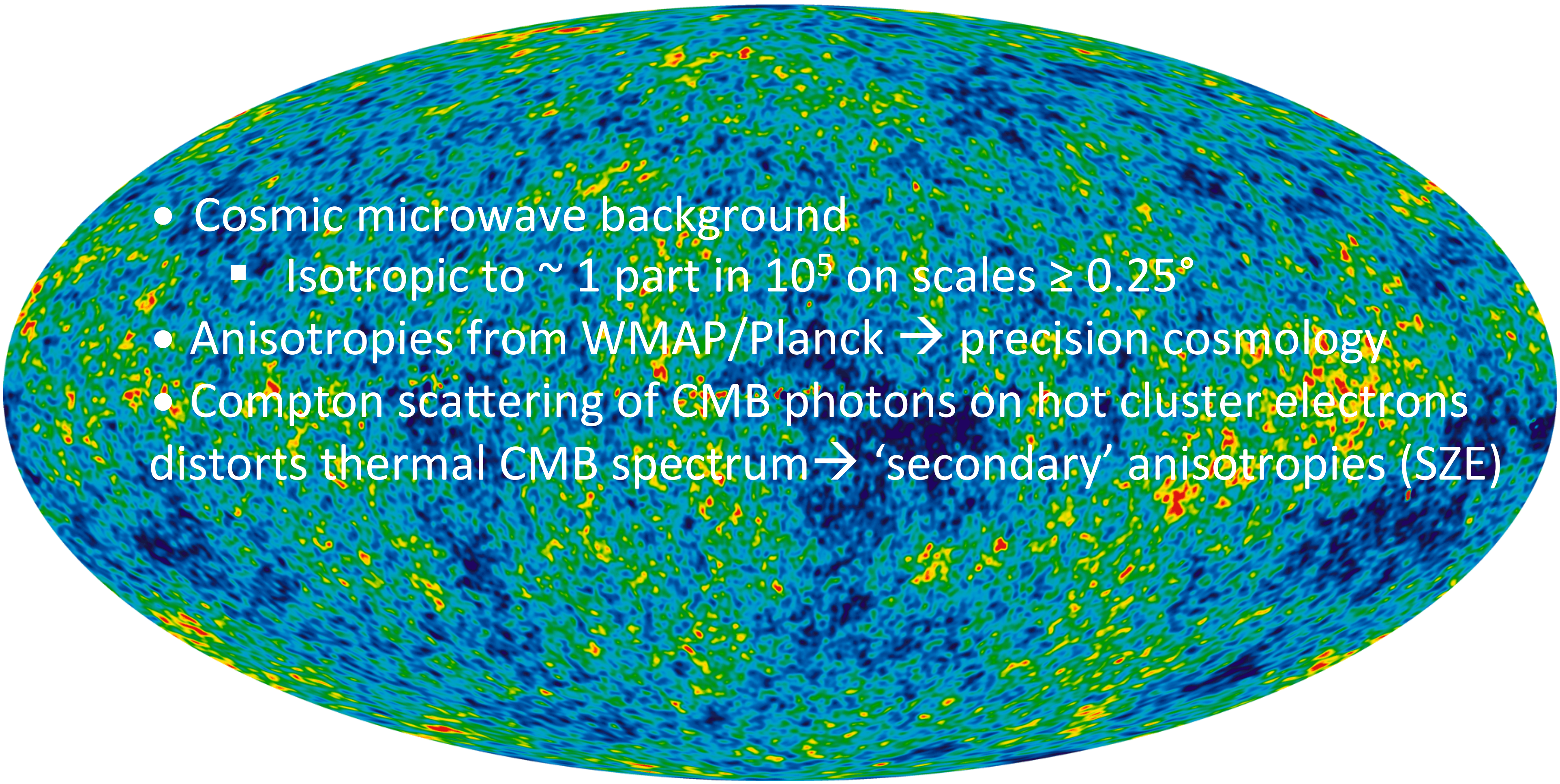
Optical Surveys

- Virtues
  - * Ground-based observation time is (relatively) cheap
  - * New instruments (DES, HSC) are efficient
  - * Only practical way to obtain redshift
  - * In principle provide mass (σ_v, weak lensing)
- Drawbacks
  - * The sky is very crowded; projection is a problem
  - * Mass vs. 'richness' relation is has significant scatter
  - * Requires large time investment to cover large Ω

Optical Cluster Surveys

- Abell (1958)
  * All-sky, 4073 clusters z < ~0.25 (*part* of his PhD thesis!), POSS
  * Zwicky (1961-68)
- Red-sequence Cluster Survey (RCS; Gladders & Yee 2005)
  * 72 deg^2, 956 clusters, z < 1 (CFHT, CTIO)
- SDSS surveys(2007+)
  * Max BCG: 7400 deg^2 ~10,000 clusters, z < 0.3
  * Others (using photo-z): z < 0.6
- Future
  * Dark Energy Survey (DES) 5000 deg^2 10^5 clusters
  * スミレ (SuMIRe) (Subaru+HyperSuprimeCam)

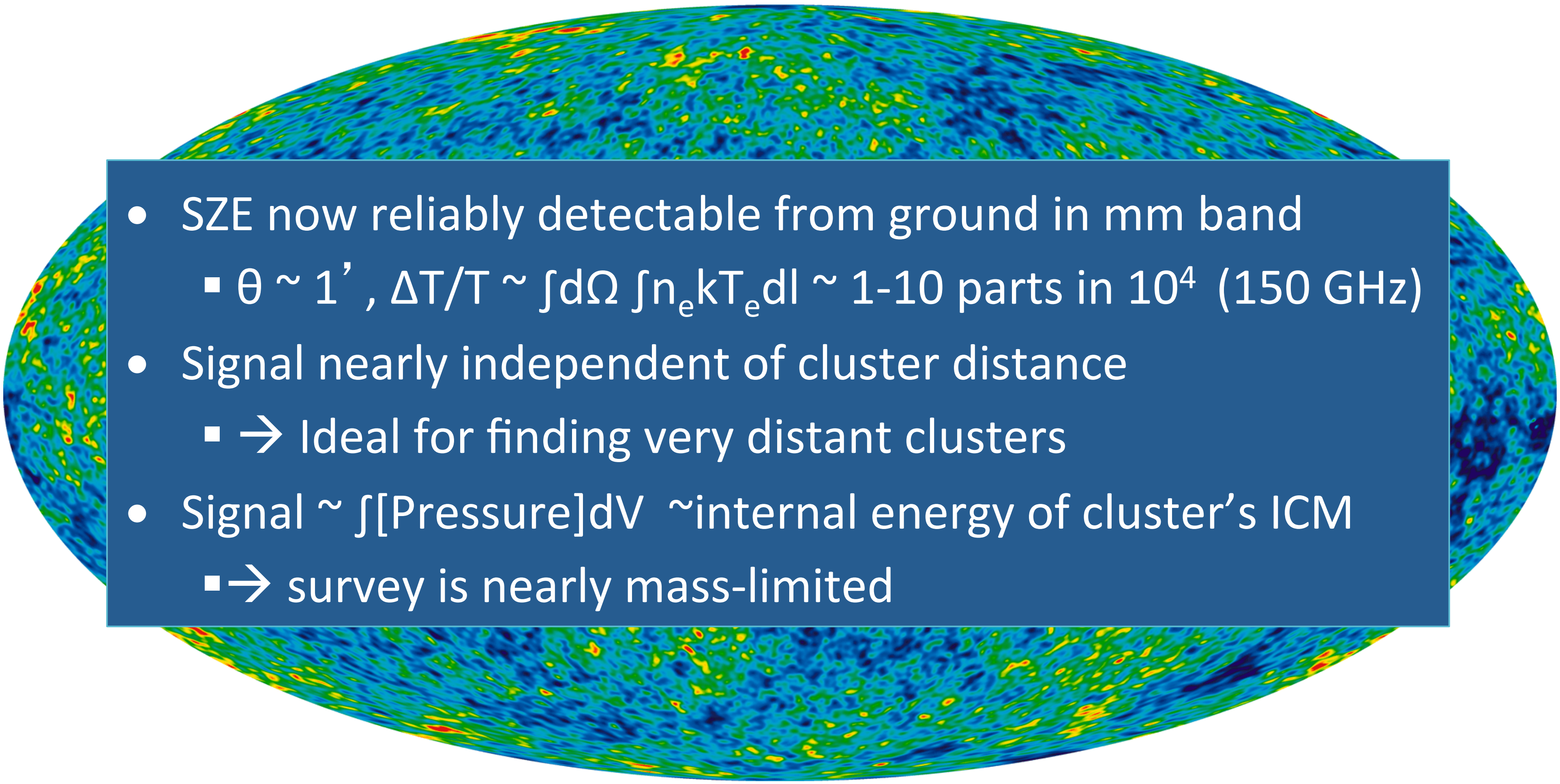
SZ Cluster Surveys: Method



- Cosmic microwave background
  - Isotropic to ~ 1 part in 10^5 on scales ≥ 0.25°
- Anisotropies from WMAP/Planck → precision cosmology
- Compton scattering of CMB photons on hot cluster electrons distorts thermal CMB spectrum→ ‘secondary’ anisotropies (SZE)

WMAP Science Team

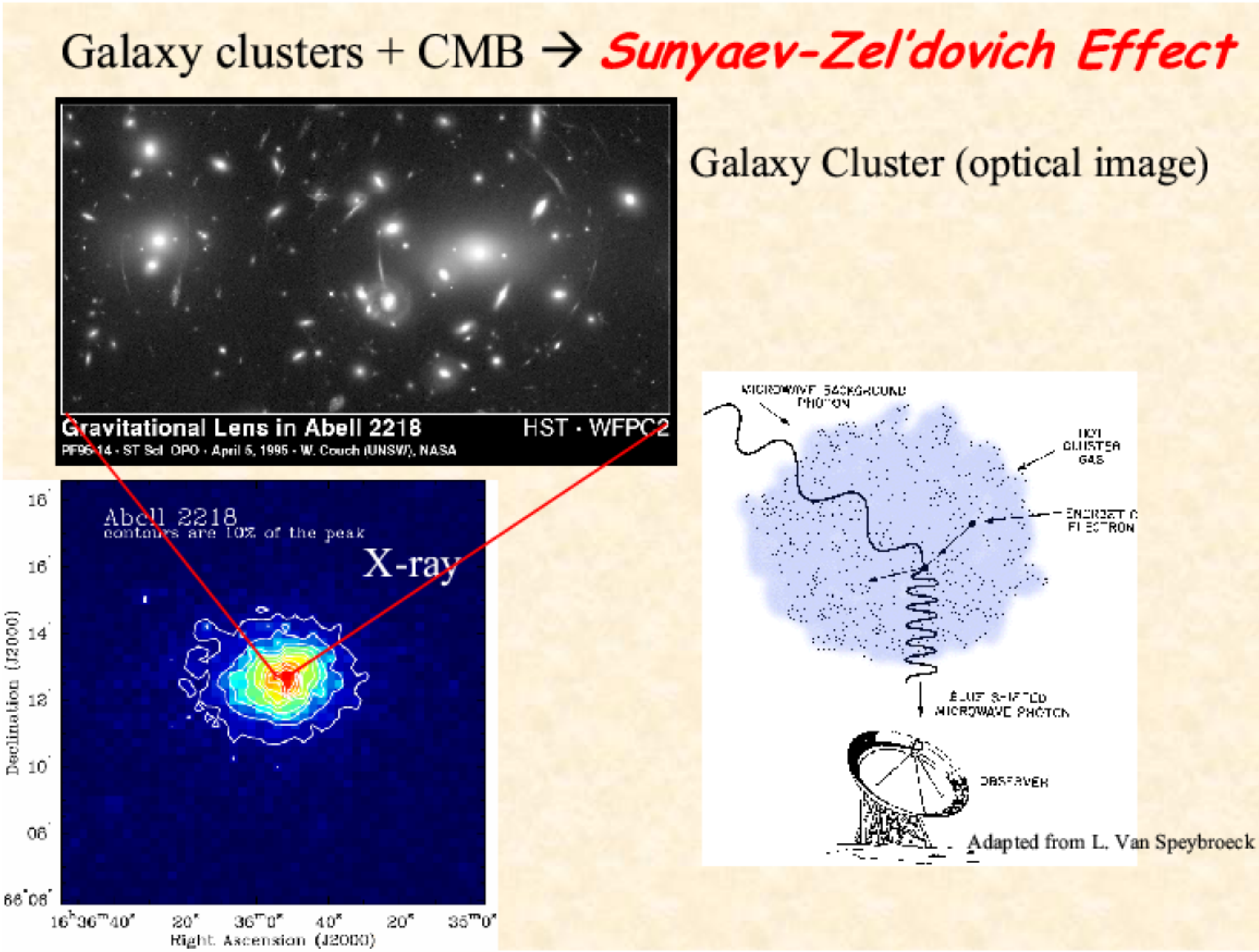
SZ Cluster Surveys: Method



- SZE now reliably detectable from ground in mm band
  - $\theta \sim 1'$, $\Delta T/T \sim \int d\Omega \int n_e k T_e dl \sim$ 1-10 parts in 10^4 (150 GHz)
- Signal nearly independent of cluster distance
  - → Ideal for finding very distant clusters
- Signal ~ ∫[Pressure]dV ~internal energy of cluster's ICM
  - → survey is nearly mass-limited

WMAP Science Team

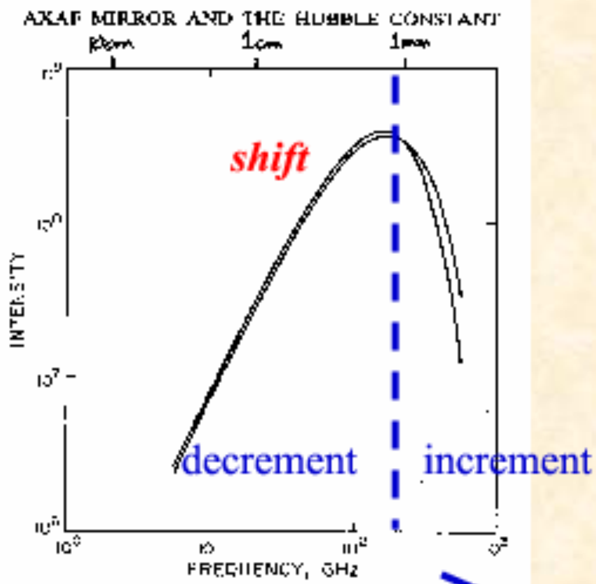
Sunyaev-Zeldovich effect (from John Carlstrom's website)

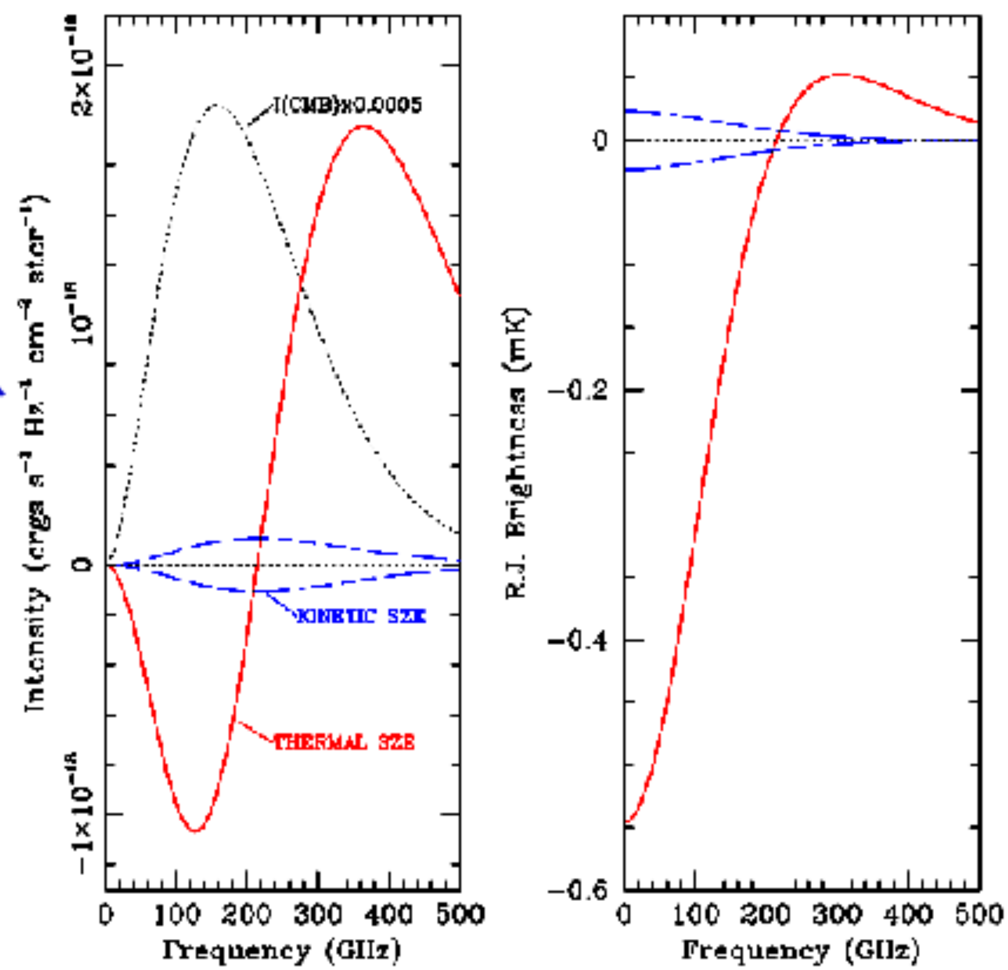


from John Carlstrom's web site:

Sunyaev-Zel'dovich Effect

Spectral Distortion of CMB





Massive cluster:

y = 1.0×10^{-4}

Te = 10 keV

$V_{peculiar}$ = +/-500 km s^{-1}

from John Carlstrom's web site:

SZE for Astrophysics

complement to x-ray and lensing obs

$$\frac{\Delta T_{SZE}}{T_{CMB}} \propto \int n_e T_e dl$$

Cluster physics

- *measure integrated pressure*

Peculiar velocities at high z

Cluster gas mass fraction, Ω_M

- *clean measure of baryon gas mass*

Hubble constant, H(z)

- *combined with x-ray* $\rightarrow D_A(z)$

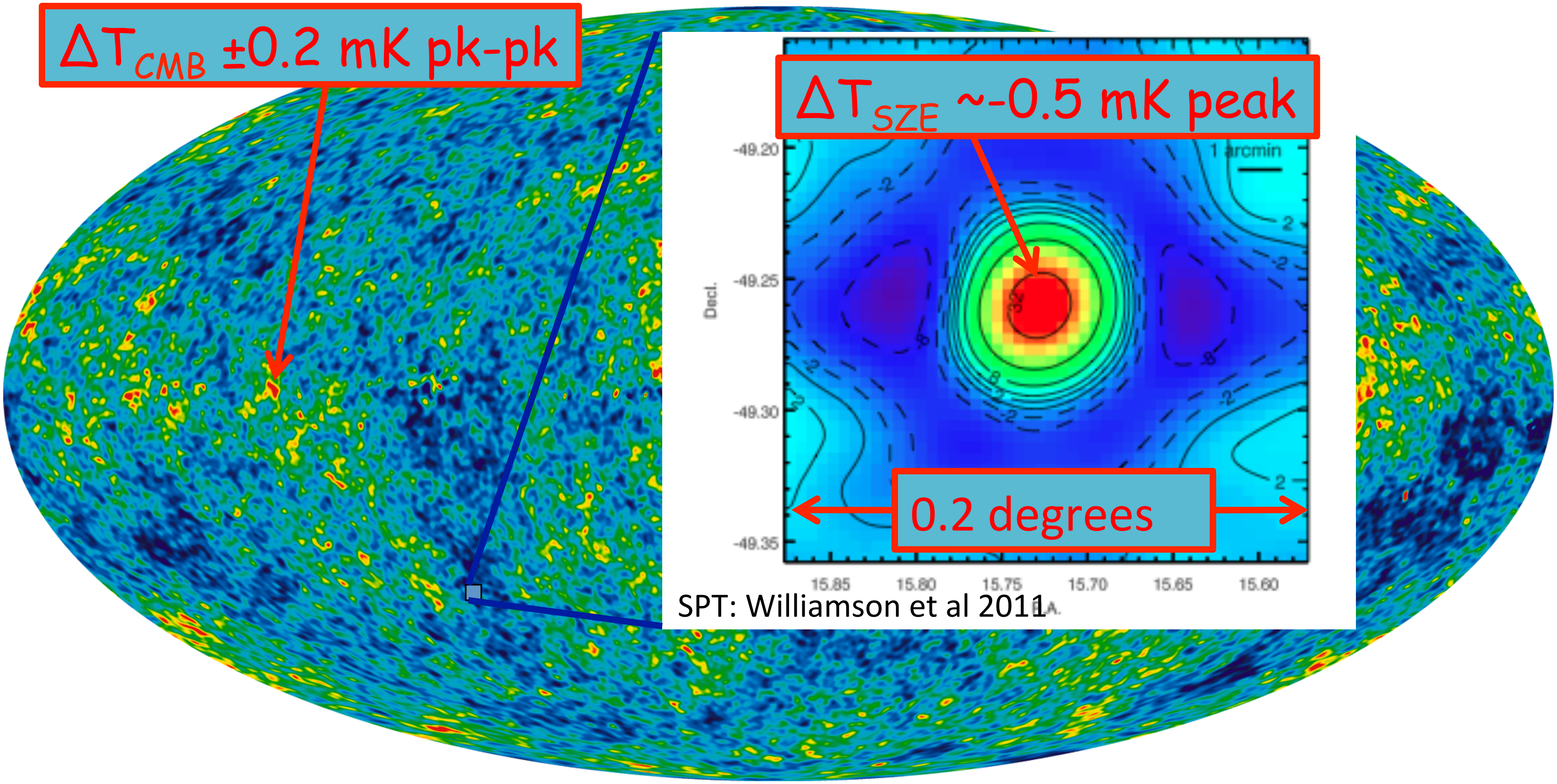
Cluster surveys:

- *exploit redshift independence*
- *constrain* Ω_M , Ω_Λ σ_8, w, w(t)…

$$S \propto \int \Delta T_{SZE} d\Omega$$

$$\propto \frac{1}{D_A(z)^2} \int n_e T_e dV$$

"Primary" CMB vs SZE Anisotropies



WMAP Science Team

South Pole Telescope: Distant Clusters from SZE

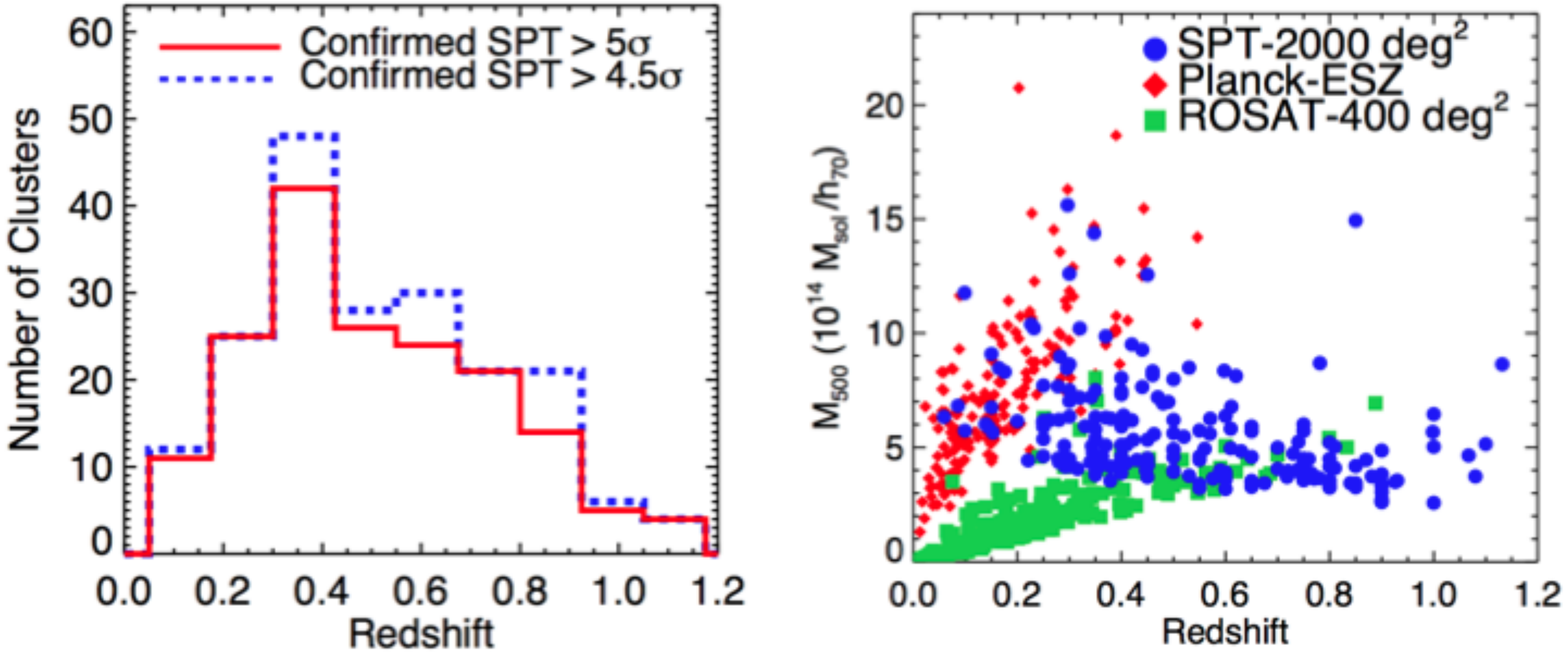


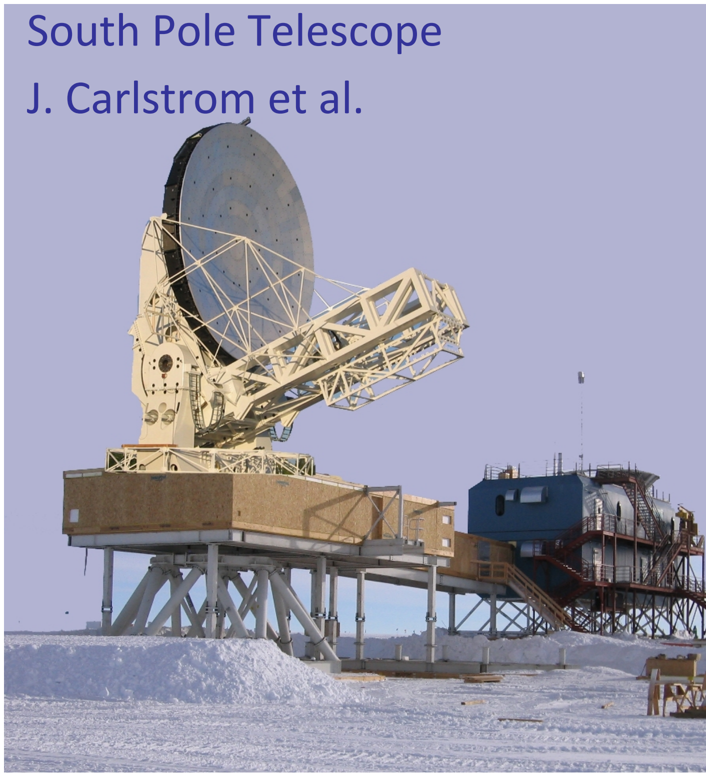
Figure 1: *(Left)* A histogram of SPT cluster number counts versus measured redshift. *(Right)* The mass vs redshift distribution for the SPT 2000d, Planck-ESZ, and ROSAT 400d samples. The SZ selection combined with the excellent match of the SPT beam ($\sim 1'$) to high-redshift clusters makes SPT's selection function nearly redshift independent in contrast to the other surveys. The mass thresholds for the SPT 2000d and ROSAT 400d surveys cross-over at $z \sim 0.6$. Not surprisingly, above this redshift, the proposed SPT-80 sample has 5 times as many clusters as the ROSAT 400d sample used in Vikhlinin et al. (2009a), matching the ratio of areas.

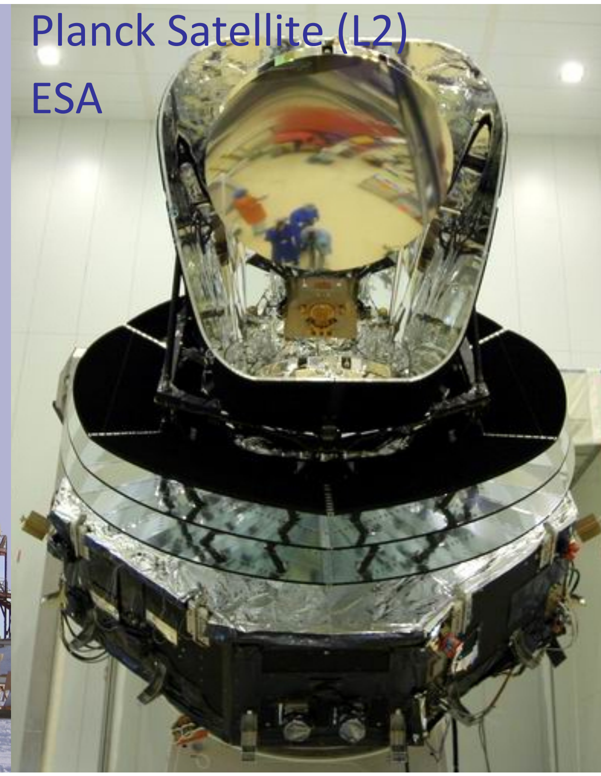
Benson et al. 2011

SZ Surveys

- Virtues
  - * 'Selection function' for a given mass is nearly independent of distance → provides high-z samples
  - * Can be done from the ground → relatively cheap
- Drawbacks
  - * Mass-observable relation must be calibrated with data from another waveband
  - * Primary CMB fluctuations limit sensitivity at low z
  - * Space-based observatory has limited resolution @ λ ~ 2 mm where SZE is best observed

SZ Surveys





D=10m $\delta\theta$ ~ 1 arcmin 2500 deg^2, ~500 clusters M_{med} ~ 2 x10^{14} $M_\odot$, z_{med}~0.5	D=1.5m, $\delta\theta$ ~ 6 arcmin All-sky, 189 clusters (early) M_{med}~ 5 x10^{14} $M_\odot$, z_{med}~0.15	D=6m, $\delta\theta$ ~ 2 arcmin 500 deg^2, 91 clusters M_{min} ~ 4 x10^{14} $M_\odot$, z_{med}~0.5

Why is mass important?

Newton

- Cosmology is gravity: $G_{\mu\nu} = 8\pi G T_{\mu\nu}$
  * Theory predicts evolution of *mass* function
  * To test theory, we need to measure mass
- Astrophysics: Clusters are mostly dark matter
  * So far, mass (or $\rho(r)$) is sole prediction on DM
  * To test structure formation must measure this
  * Gravity (mass) dominates 'baryonic' physics

Ways to measure cluster mass

- There's no such thing as THE mass of a cluster
  * Mass is always measured within a specified radius
- Can measure directly for each cluster in a sample:
  * From dP/dr measured in X-rays (n_e & kT)
  * From lensing (shear) or $\sigma_{v,galaxies}$ in optical
  * From ∫pdV measured at mm wavelengths
- Or indirectly via a (more easily) observable 'proxy' for mass: $T_{X,}$ $L_{X,}$ $Y_{X,}$ galaxy count (richness)
- Proxies require mass-observable scaling relations

Hydrostatic Equilibrium

- Conservation of fluid mass & momentum:

$$\frac{\partial \rho}{\partial t} + \vec{\nabla} \bullet (\rho \vec{\mathrm{v}}) = 0 \; ; \; \frac{\partial \vec{\mathrm{v}}}{\partial t} + (\vec{\mathrm{v}} \bullet \vec{\nabla})\vec{\mathrm{v}} = - \vec{\nabla}\phi - \frac{\vec{\nabla}P}{\rho}$$

- IF:
  * Grav. potential Φ is constant on sound crossing time

    $t_s \approx 6.6 \times 10^8$ yr $(T_{ICM}/10^8 K)^{-1/2}$ (D/Mpc)
  * And all forces are from thermal pressure or gravity
- THEN ICM should be in hydrostatic equilibrium:
  * $v_{ICM} = 0 \rightarrow \rho_{ICM}$= static & $\nabla P_{ICM} = -\rho_{ICM} \nabla \Phi$
- Spherical symmetry & P = nkT lead to:

$$M(r) = -\frac{kT(r)}{G\mu m_p} r \left\{ \frac{d\ln(n_e)}{d\ln(r)} + \frac{d\ln(T)}{d\ln(r)} \right\}$$

Notes on “Hydrostatic Masses”

$$M(r) = -\frac{kT(r)}{G\mu m_p} r \left\{ \frac{d\ln(n_e)}{d\ln(r)} + \frac{d\ln(T)}{d\ln(r)} \right\}$$

- The term in {} depends only on the shapes (not the amplitudes) of $n_e(r)$ and $T(r)$
- Measured quantities must be ‘de-projected’ to estimate $n_e(r)$ and $T(r)$
  - * Often need to ‘regularize’ T(r) (e.g., so $dP/dr < 0$)
- The biggest observational error arises in measuring T(r): typically $\sigma_T/T \approx 10\% \, (1500/N_{ph})^{1/2}$

Abell 1689 Visible (Yellow) + X-ray (Purple)

Mass from Gravitational Lensing

- Cluster potential distorts shapes of background galaxies
  * 'Tangential shear' $\gamma_T(r)$ is added to intrinsic galaxy ellipticity ε_i
  * $\varepsilon_{obs} = \varepsilon_i + \gamma(r)$
- Cluster mass can be inferred from $\gamma(r)$
  * Example: SIS: $\rho=\sigma^2/2\pi G r^2 \rightarrow \gamma(r) = r_E/2r$, with
  * $r_E = 29'' \beta(\sigma/1000 \text{ km s}^{-1})^2$, $\beta=D_{LS}/D_s$
- Intrinsic ellipticities are random but very noisy: $\sigma_{\varepsilon i} \approx 0.25$
- Averaging ellipticities of N_{gal} galaxies gives
  * $<\varepsilon_{obs}> \rightarrow \gamma_T(r)$ + error with RMS shear error $\approx 0.25/N_{gal}^{1/2}$
  * Typical value of shear: $M=10^{15}\ M_\odot$ $z=0.2$, $r_{200}=10'$, $\gamma(r_{200}) \approx 0.015$
  * Need many background galaxies to measure shear → deep exposures

NASA/STSci *NASA/CXC/MIT/E.-H. Peng*

Notes on Weak Lensing Masses

Major systematic errors:

- Background galaxy z affects D_{LS}/D_S
  - * → need photo-z
- Cluster extent along line-of sight is not known
  - * Lensing deflection measures projected mass
  - * Much larger problem for WL than for X-rays
- Shear from unrelated substructures along line of sight adds noise
  - * This adds no bias, but large scatter (few x 10%)
- Weak lensing provides good ensemble average, but a noisy mass measurement for any individual cluster

Properties of Scaling Relations

- Generally assume observable S and mass M related by a power law $S(M) = BM^{\alpha}$
  * In principle B and α depend on redshift
- Also allow for astrophysical *scatter*
  * At fixed mass M, $s = \ln(S)$ is a Gaussian random variable (mean $\langle s \rangle$, variance σ^2_s)
- Ideally
  * $\langle s \rangle = \alpha(\ln(M)) + \ln B$ (S is unbiased)
  * σ^2_s is small (S has low scatter)
- NB: Bias can often be measured, but scatter must usually be estimated from simulations.

Self-Similar Scaling Relations
(Gravity Only)

From $M \sim 200\,\rho_c R^3{}_{200}$ and $\rho_c = 3H^2/8\pi G$, find:

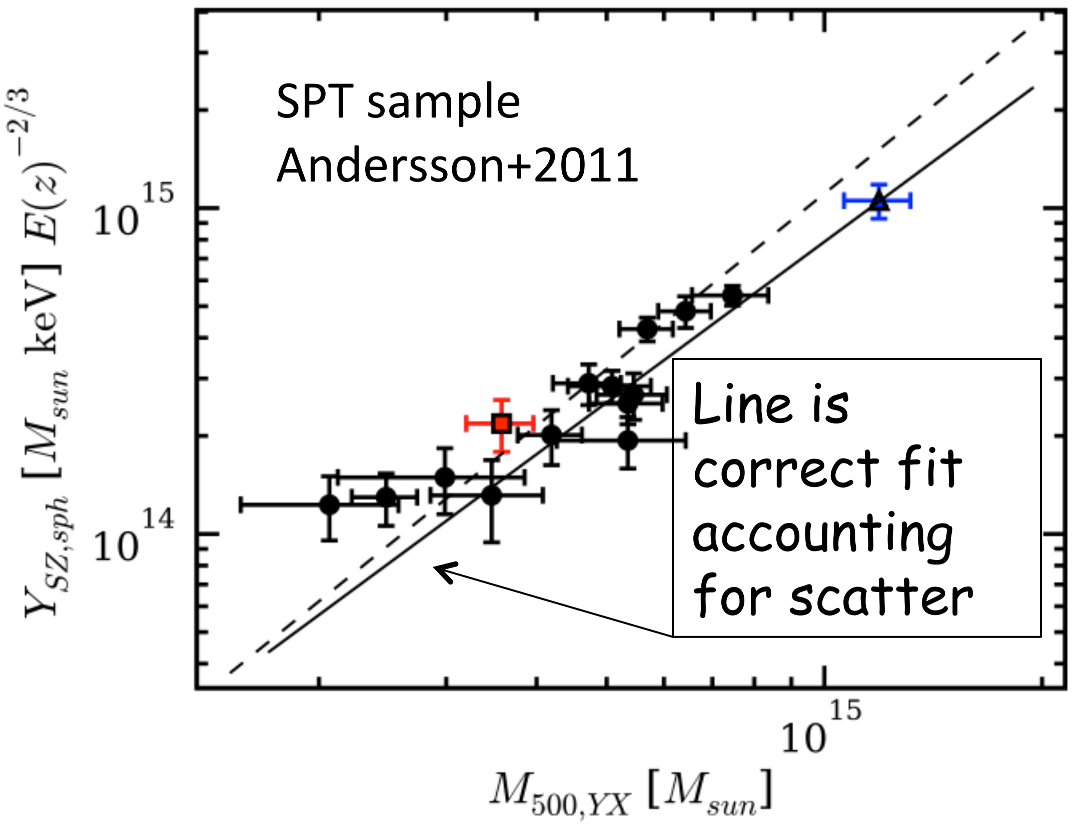
- $R \sim M^{1/3} H^{-2/3}$
- $T_X \sim GM/R \sim M^{2/3} H^{2/3}$
- $L_x \sim j_X V \sim T^{1/2} \rho^2{}_{ICM} R^3 \sim f^2{}_b \rho^2{}_c M^{4/3} H^{-5/3} \sim f^2{}_b M^{4/3} H^{7/3}$
- $Y_X \equiv M_{ICM} T_X \sim M^{5/3} H^{2/3}$
- $L_X \sim T_x^2 H$

NB: 'Baryonic physics' (cooling, feedback) alters these

Properties of Mass Estimators

Estimator/Proxy	Bias	Scatter at fixed M	Remarks
Direct Estimators			
Hydrostatic mass (X-ray)	-10 to -20%		Mahdavi+ 12; Lau+ 09; Depends on dyn. state and r
Weak lensing (Visible)	Small?	~30%	Hoekstra+ 13
Compton Y_{SZ} (mm wave)	20%	33%	Andersson+11;Marrone+ 12
Proxies			
L_X (total)		48%	Vikhlinin+09
Lx (core-excised)		10%	exclude $r<0.15r_{500}$
T_x (core-excised)		20%	exclude $r<0.15r_{500}$
M_{ICM}	<10%	11%	Zhang+10; Vikhlinin+09
$Y_X = M_{ICM} * T_X$	9%	12%	Vikh+09; Benson+ 13
N_{200} (Optical Richness)		40%	Rozo+10

Scatter affects Scaling Relations



- A flux- (or mass-) limited survey will contain the brighter (or more massive) objects.
- Need to know underlying distribution & scatter to get scaling right

What is cluster cosmology best at?

- Parameters affecting a(t) and thus d(z) and g(z):
  - * $\Omega_{m,}$ Ω_{DE},w
  - * These affect dV/dz/dΩ, M_{obs}, $f_{b\ obs}$
  - * Measures these at z < ~1 when clusters are forming
- Parameters affecting amplitude of density fluctuations at fixed z:
  - * σ_8, others [n,m_ν,...]
  - * Cluster dN/dm is exponentially sensitive to σ_8

Early Cluster Cosmology from ASCA

Before SNIa & WMAP results

THE ASTROPHYSICAL JOURNAL, 489:L1–L5, 1997 November 1

A MEASUREMENT OF THE DENSITY PARAMETER DERIVED FROM THE EVOLUTION OF CLUSTER X-RAY TEMPERATURES

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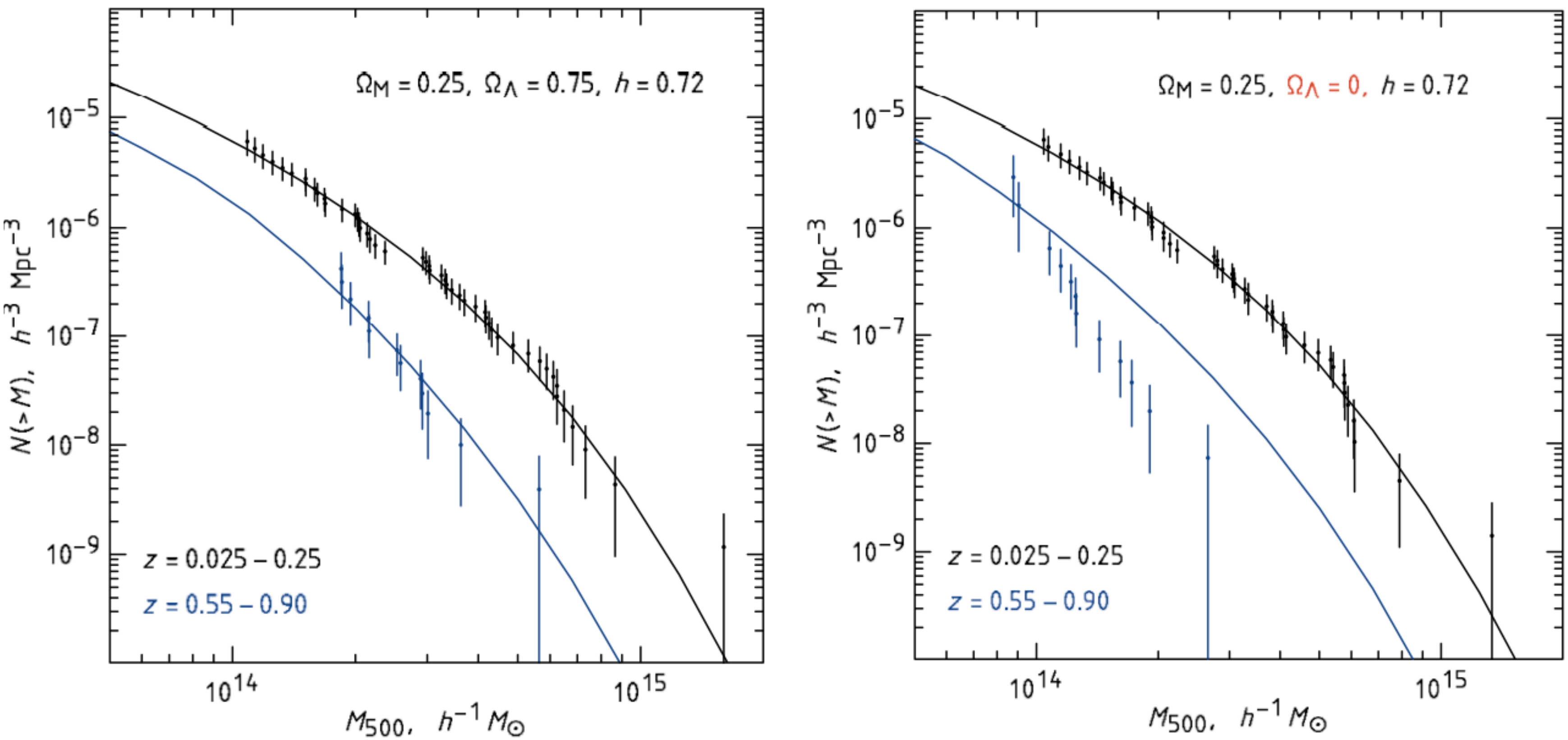
ABSTRACT

We have, for the first time, determined the cluster X-ray temperature function at a redshift other than zero. The observed evolution of the temperatures is mild to a redshift of one-third. The normalization of the luminosity-temperature relation is 0.92 ± 0.07 of the low-redshift relation (1 σ error), assuming that its shape is the same. Such behavior occurs when clusters form with constant central entropy. The evolution of the temperature function implies that Ω_0 is 0.50 ± 0.14 assuming an open universe, or 0.55 ± 0.17 assuming that a cosmological constant produces a flat universe (1 σ symmetrized errors). A closed universe, $\Omega_0 \geq 1$, is excluded at greater than 99% confidence. The amplitude of the mass density fluctuations averaged over 8 h^{-1} Mpc spheres, σ_8, is $0.66^{+0.22}_{-0.08}$ and $0.66^{+0.34}_{-0.17}$ (1 σ errors) for the open and flat models, respectively.

Subject headings: cosmology: observations — galaxies: clusters: general — large-scale structure of universe — X-rays: galaxies

Results: Growth of Structure

VIKHLININ ET AL. 2009



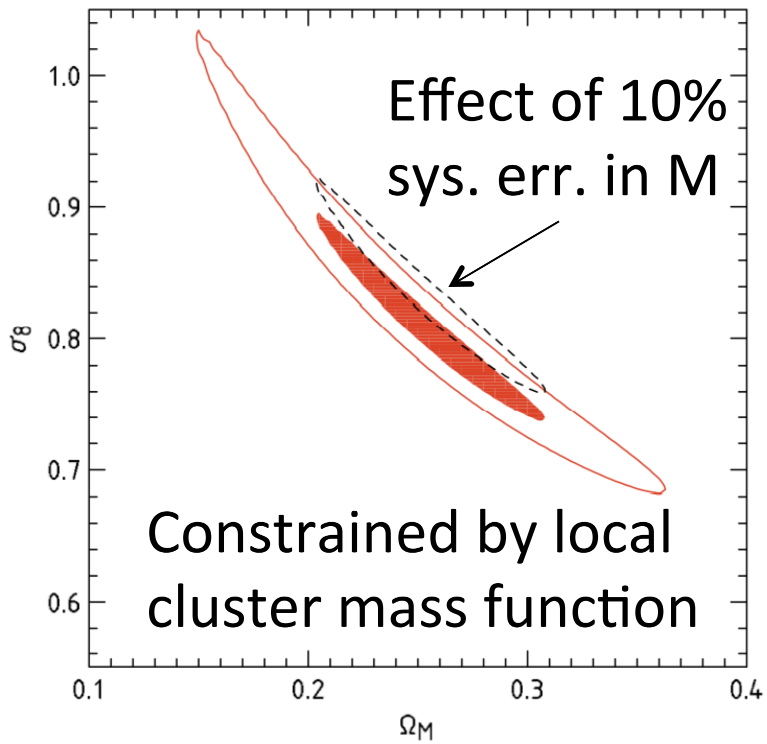
September 2013

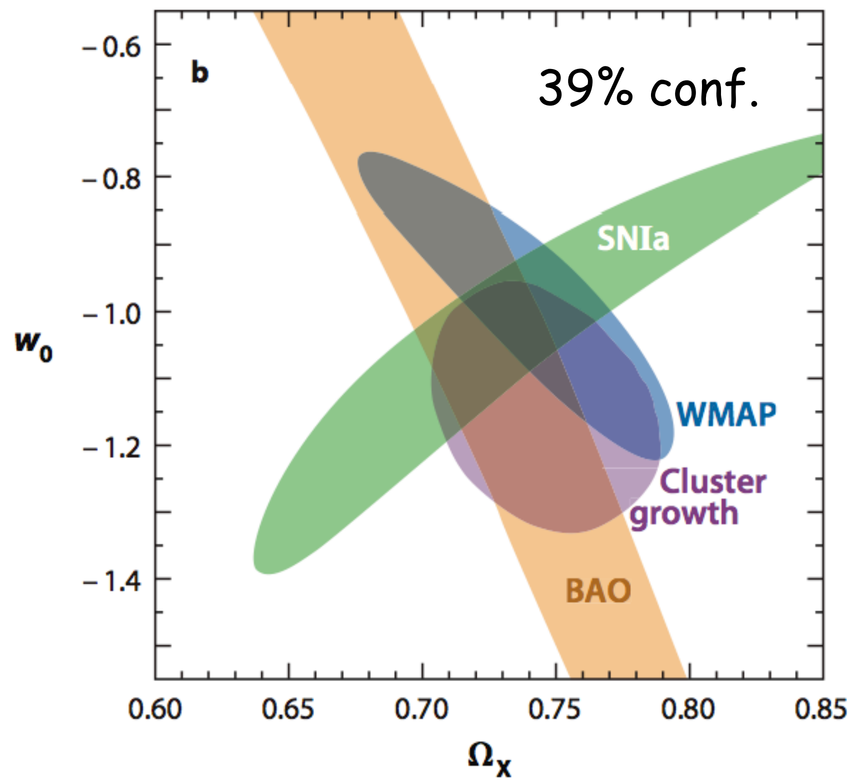
Astro-H Summer School
Shuzenji

Results: Growth of Structure

Vikhlinin et al. 2009

Figure from Allen+ 2011

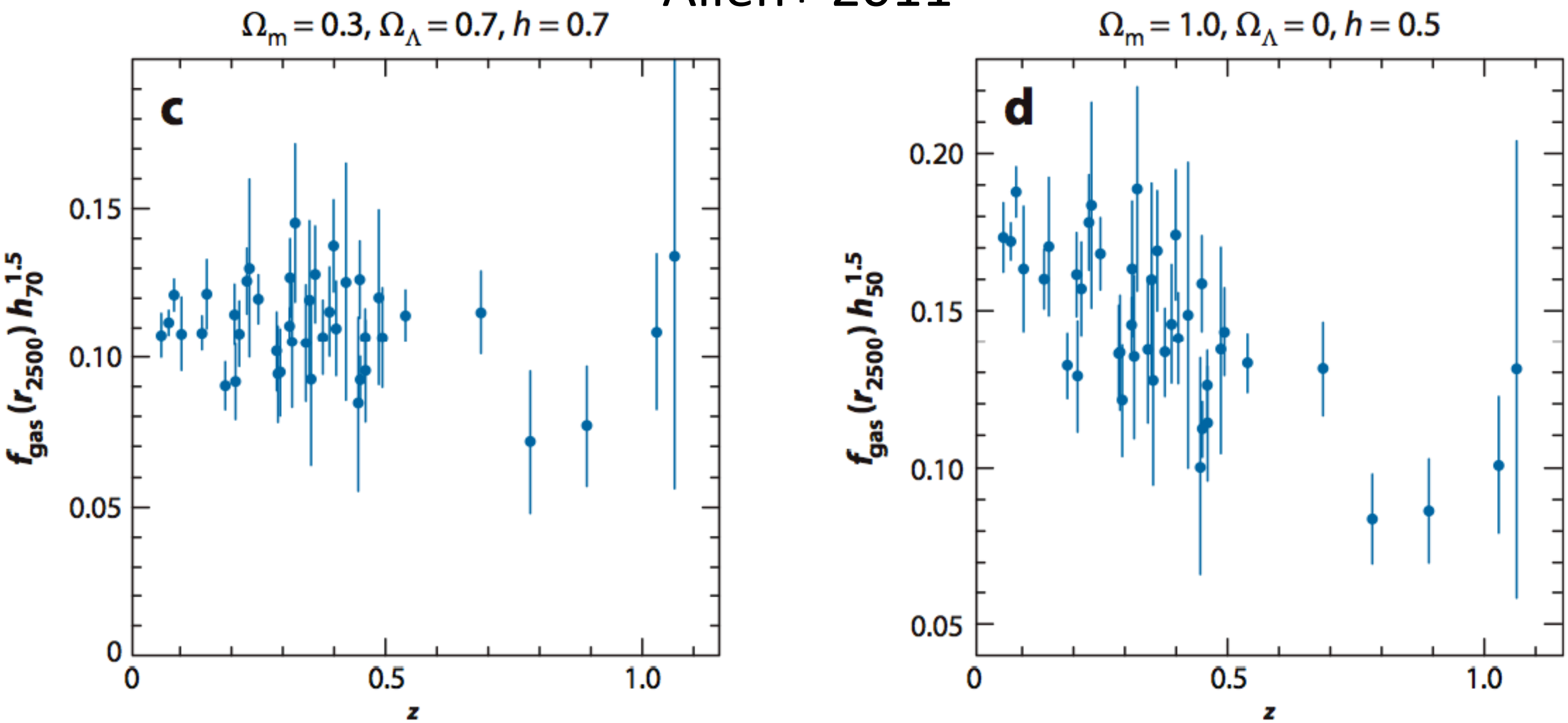




Flat Universe assumed

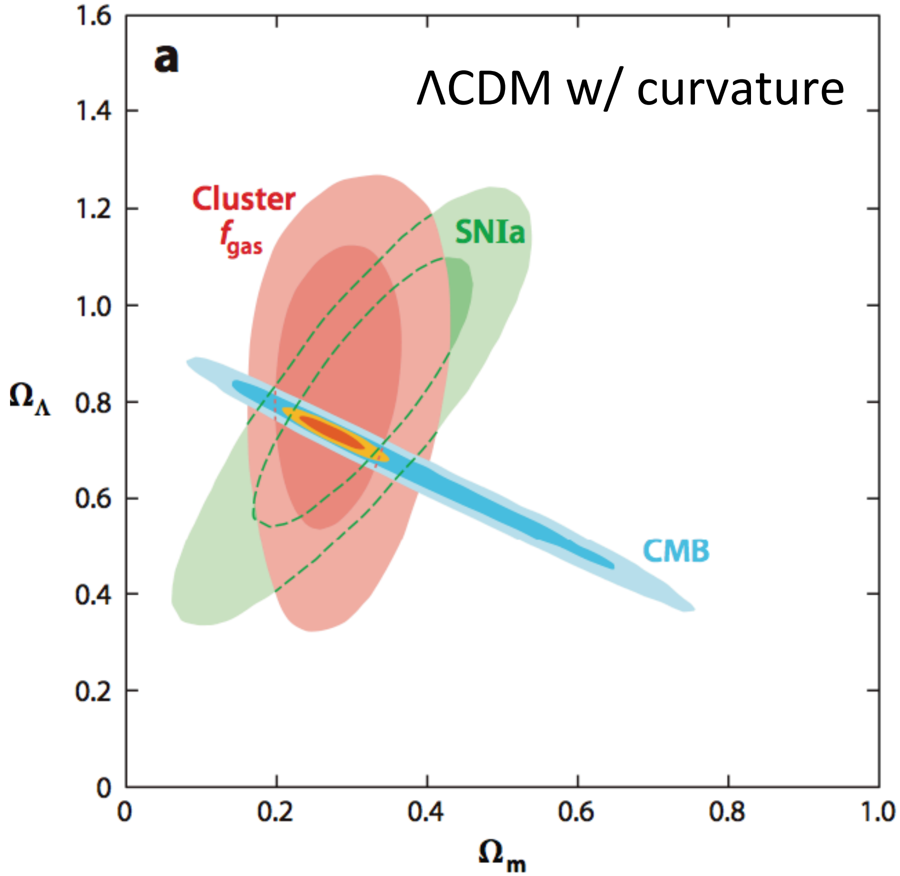
Results: f_b

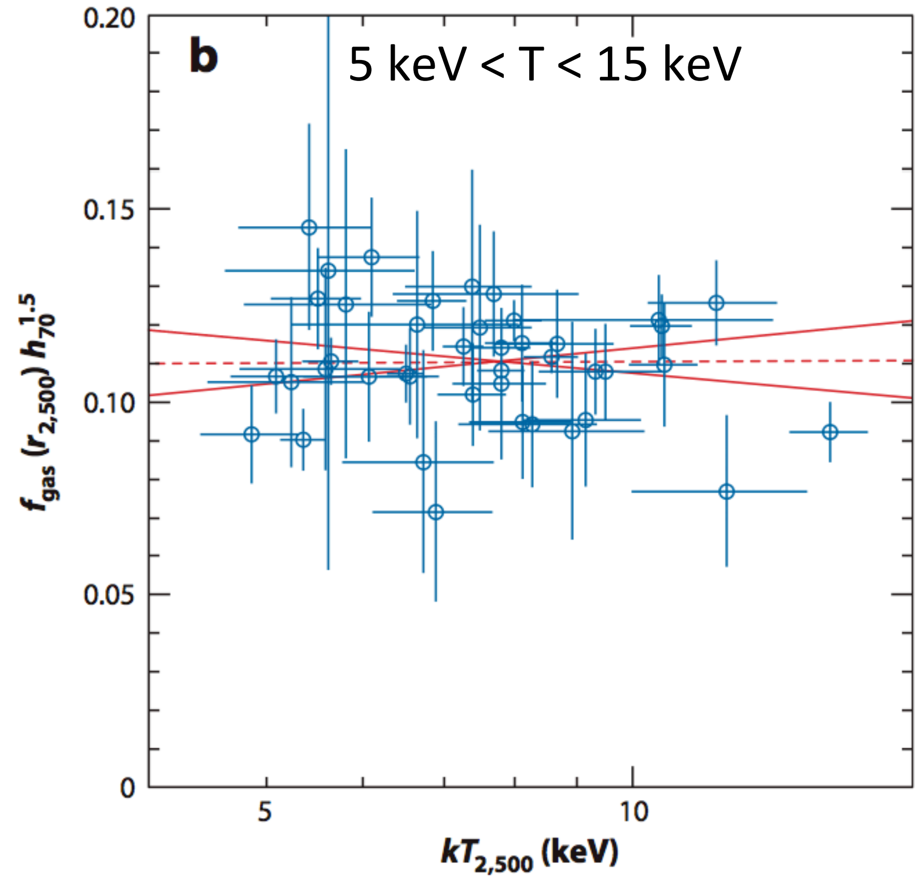
Allen+ 2011



Results: f_b

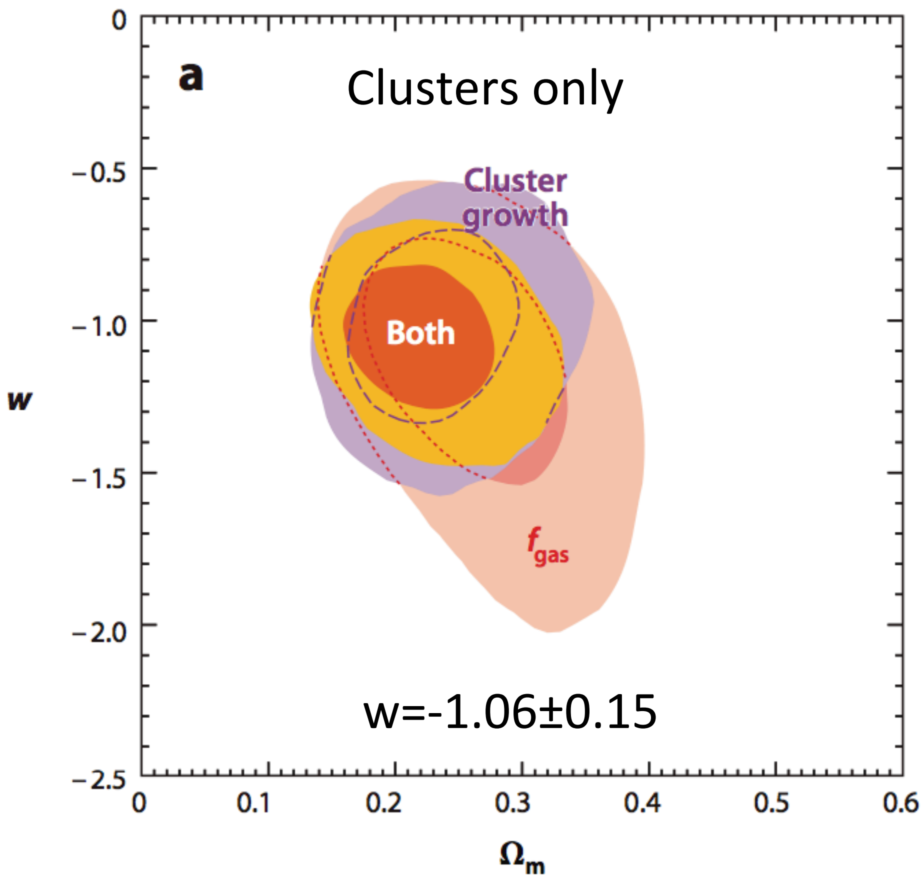
Allen+ 2011





Results: Growth + f_b

Allen+ 2008; Mantz+ 2010



Figures: Allen+ 2011

Role of Astro-H

- In principle, Astro-H could make very precise mass measurements for a few clusters
- Biggest contribution may be to test our understanding of cluster astrophysics
  - E.G., Do simulations predict the correct scatter in X-ray mass proxies?
- Tomorrow: cluster astrophysics relevant to cosmology

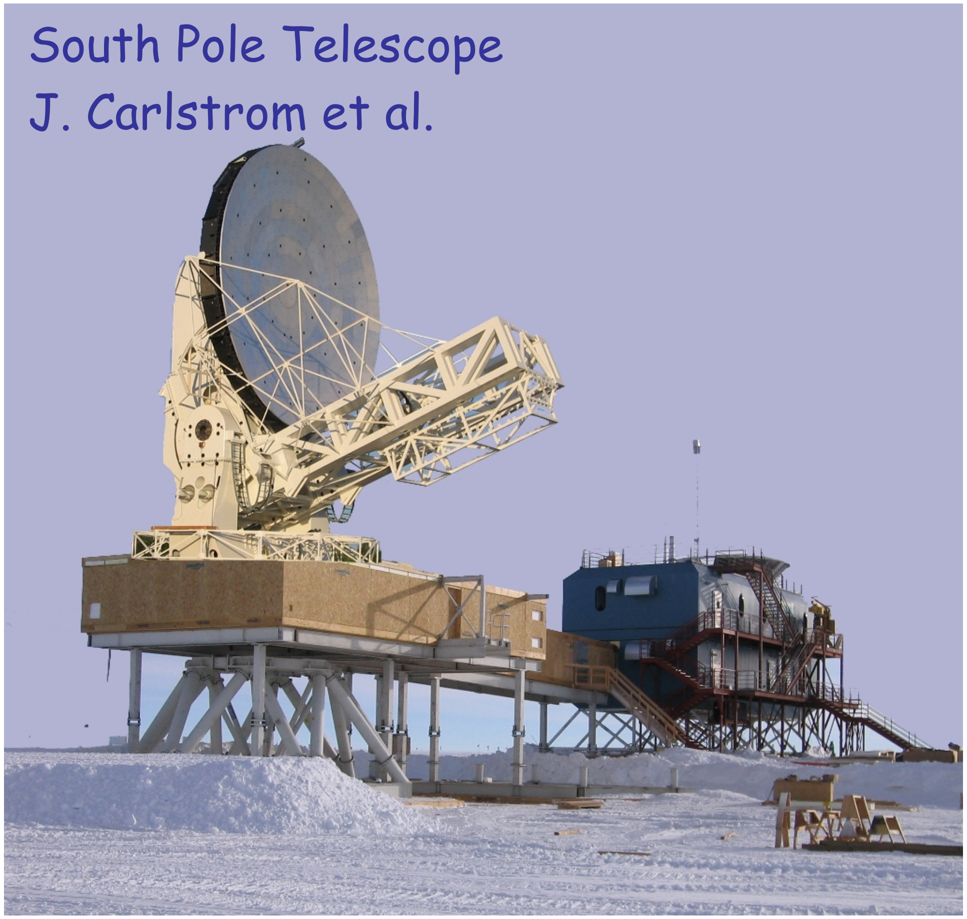
Bonus

Optical Surveys

Method (modern approach)

- Relies on cluster Red sequence
  * Survey the sky in two or more passbands
  * Make images in several color 'bins'
  * Search for galaxy over-densities within each color bin
    - Finds 'red-sequence' with that color
  * Estimate redshift (via photometry or spectroscopy)

Surveying the cluster population at earlier times



Find them at λ = 3mm

Weigh them at λ = 1nm

X-ray/mm-wave connection

- SPT & Chandra measure the same plasma:
  * mm (SZE) signal: $\Delta T/T = Y \sim \int n_e T_e dV \sim P \times V$
  * X-ray: $S_X \sim \int n_e^2 dl$; $dN_X(E)/dE \rightarrow T_e$; (n, T, V)
- Chandra provides spatial resolution…
  * $\delta\theta_{X\text{-}ray} \sim 1''$ cf $\delta\theta_{mm} \sim 1' \sim \theta_{cluster}$
  * X-ray density profile improves mm Y est.
- …And more accurate (if model-dependent) mass estimates (better SNR)

Optical Cluster Surveys

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- Future
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  - スミレ (SuMIRe) (Subaru

Mass Estimates

- X-ray:
  * ICM pressure gradient (Hydrostatic equilibrium)
  * Y_X
- Optical
  * Richness
  * Galaxy velocities (virial theorem)
  * Lensing
- SZ
  * Y_{SZ}