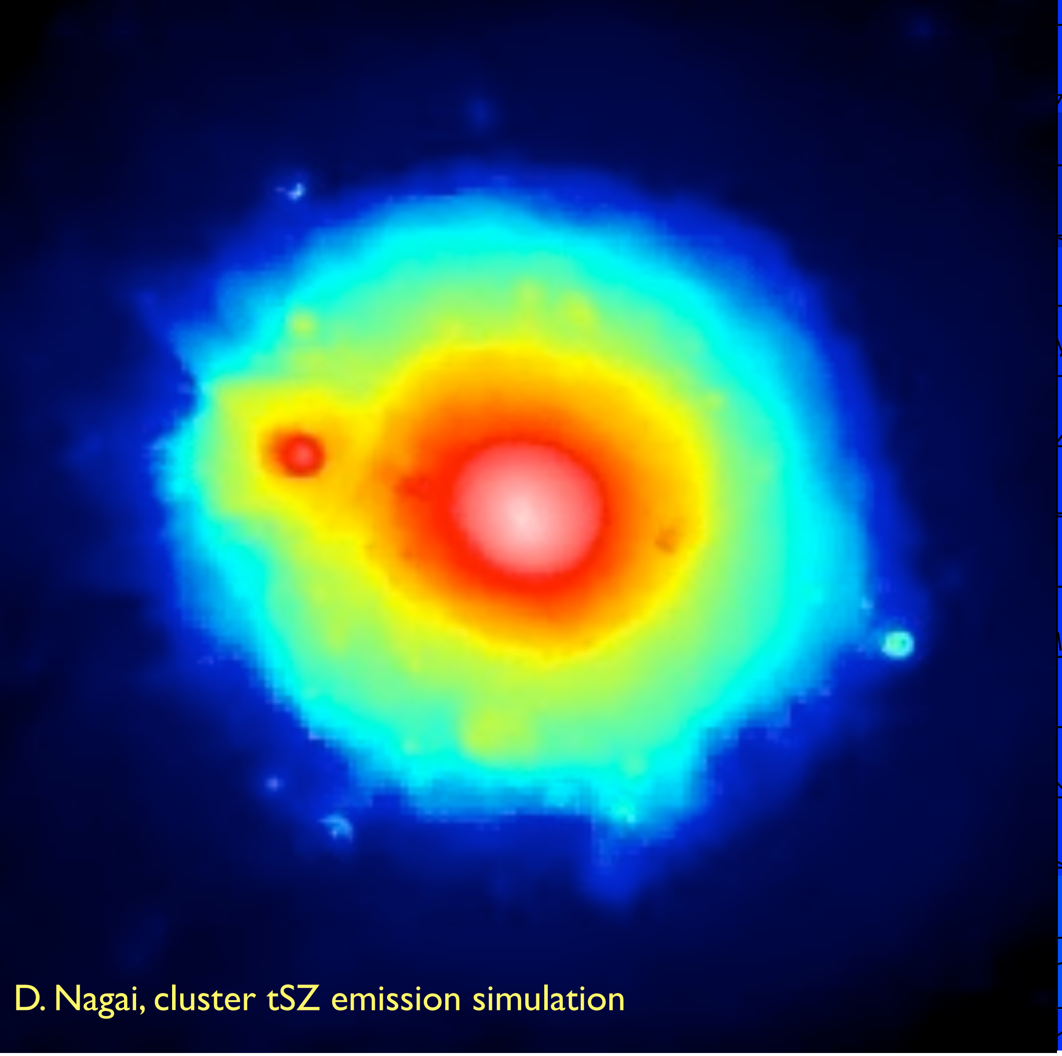
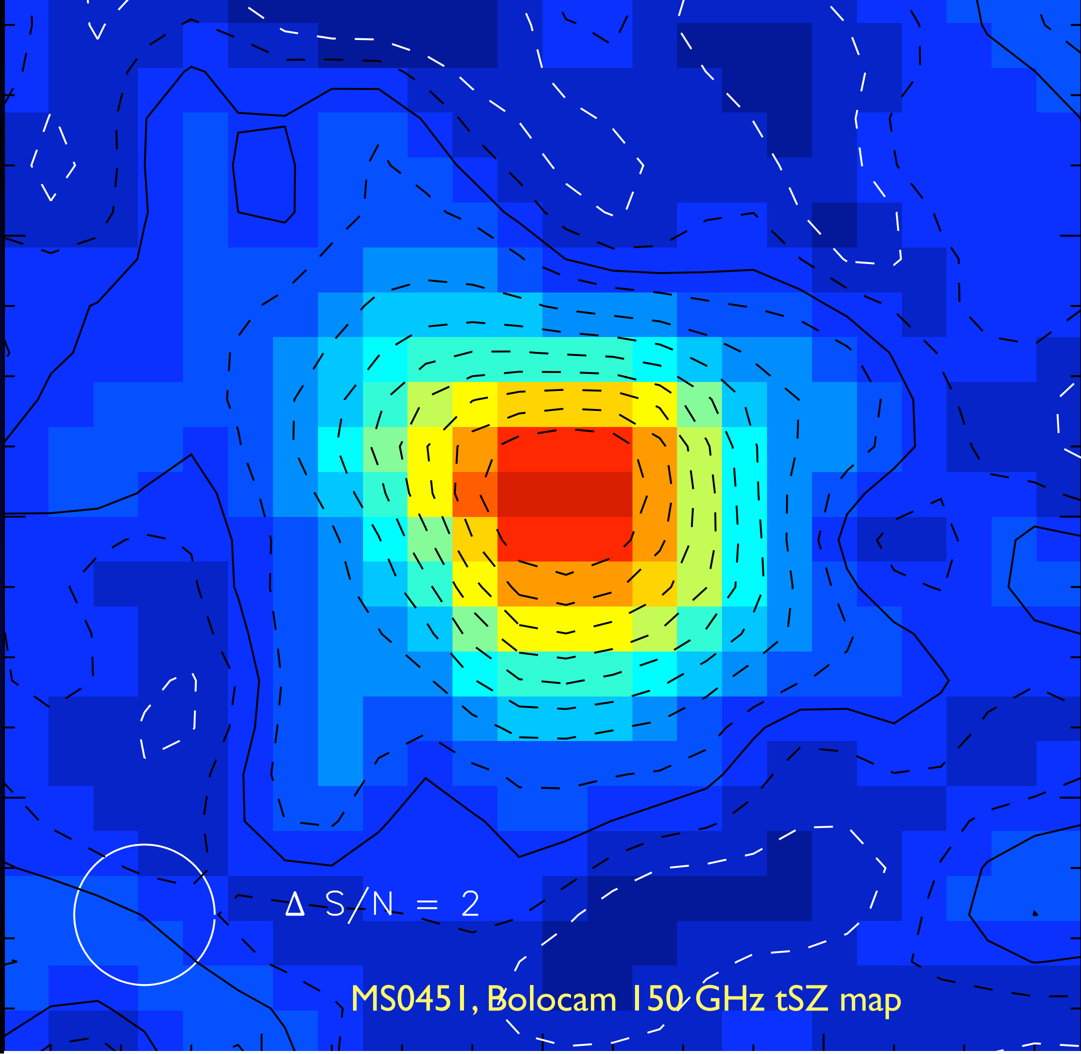
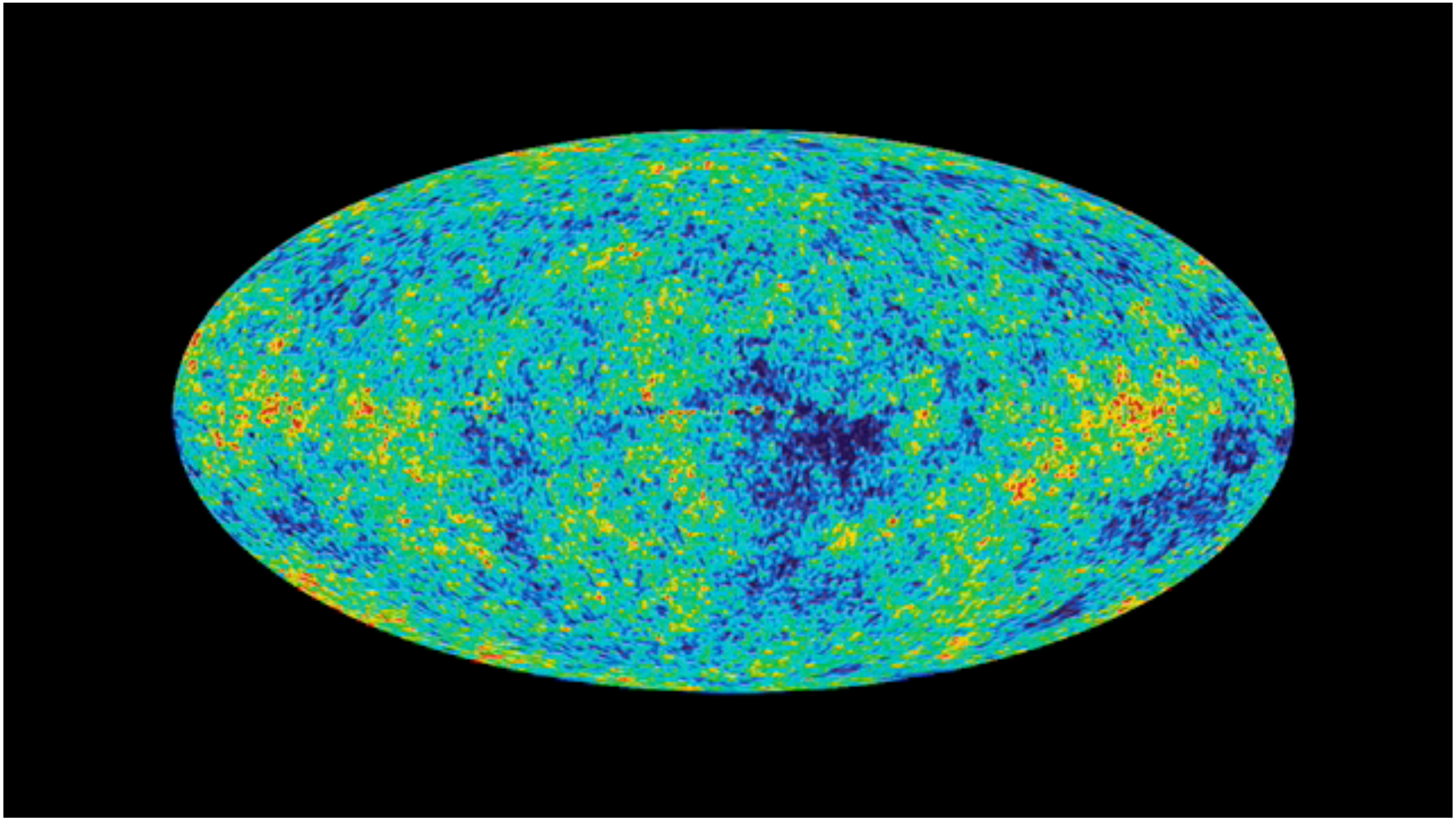




Galaxy Clusters: Astrophysical Challenges and Cosmological Uses

Sunil Golwala JPL/Caltech Seminar May 5, 2011 http://map.gsfc.nasa.gov/media/030651/index.html



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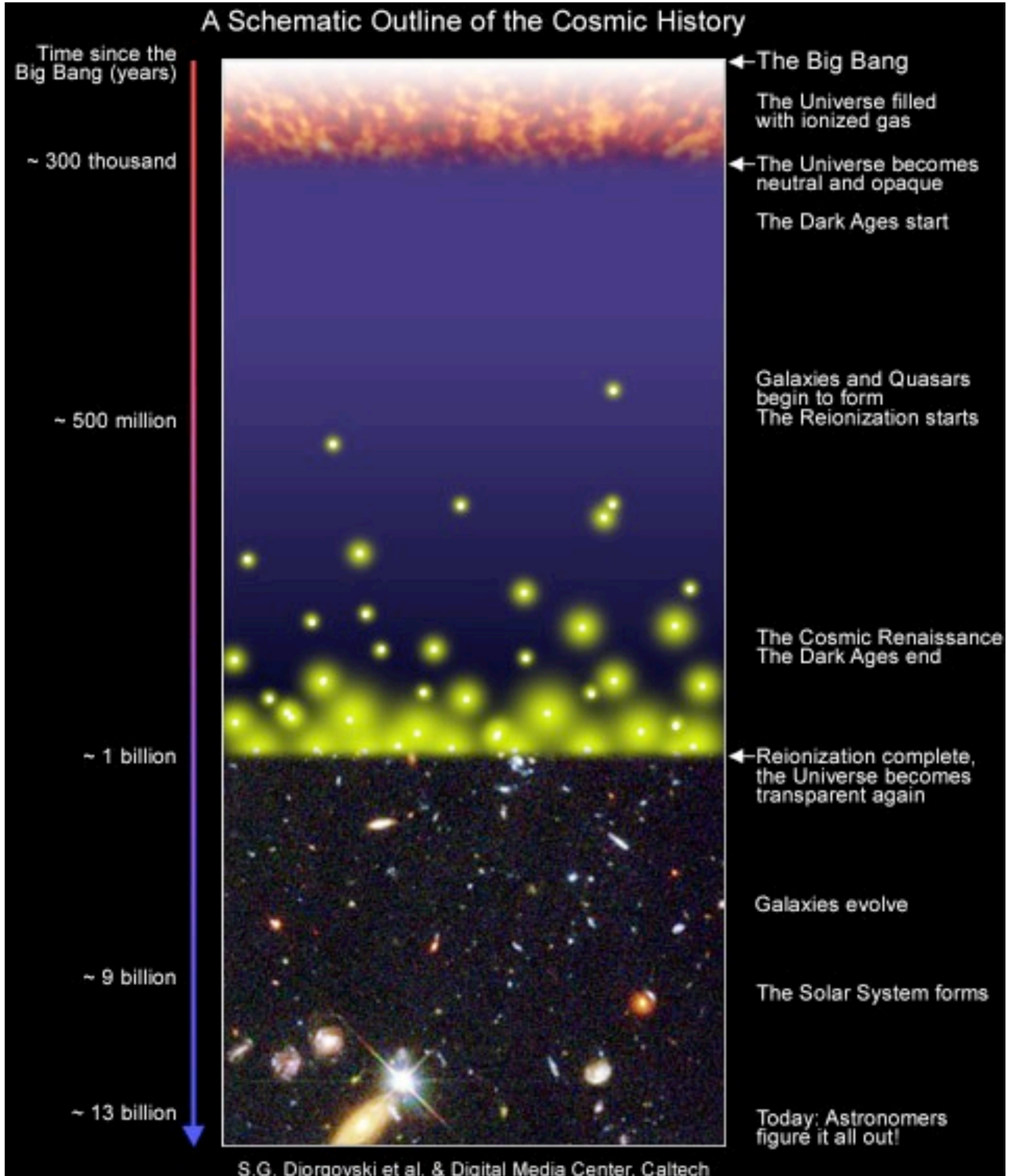
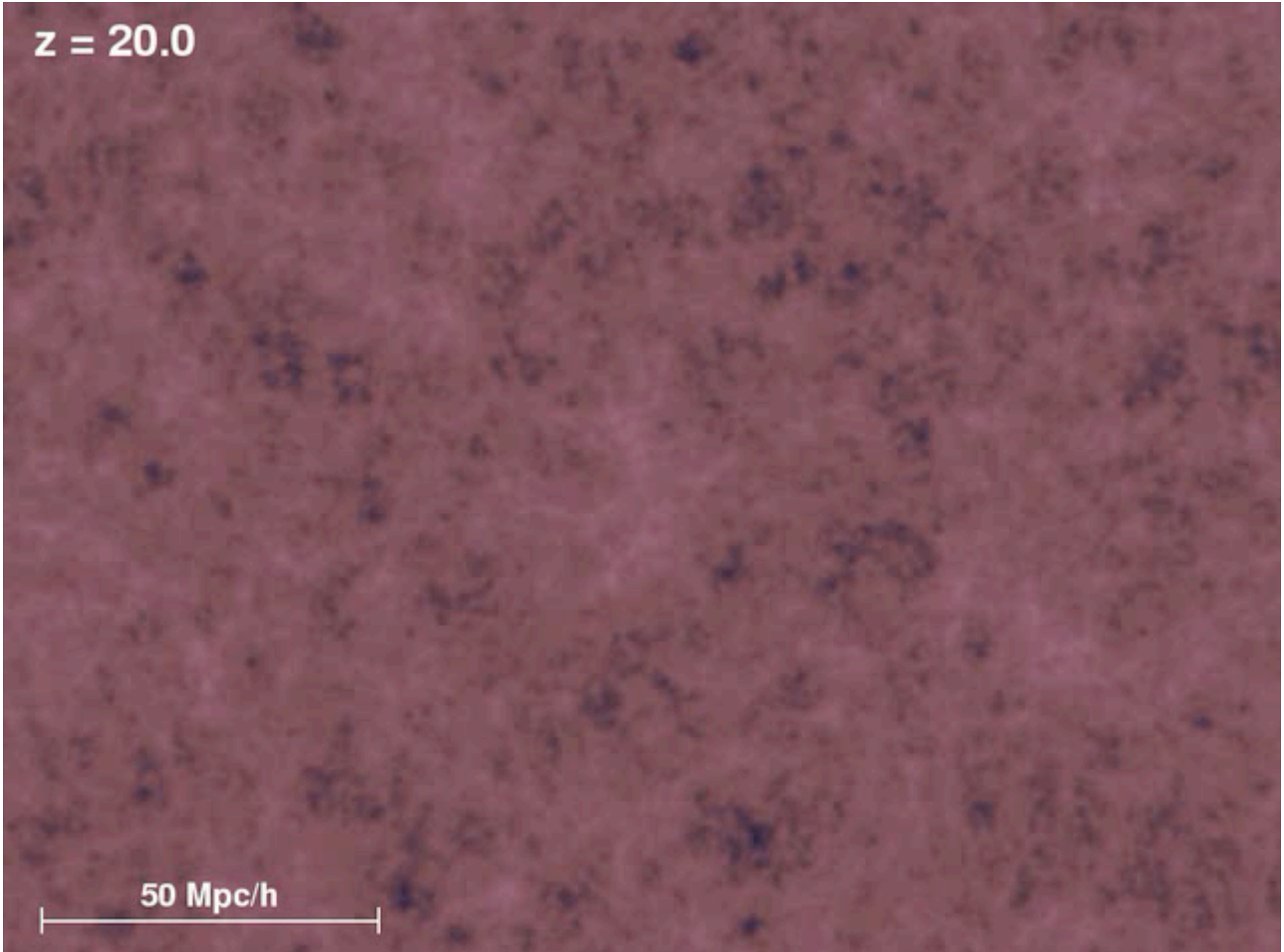

A Schematic Outline of the Cosmic History
Time since the Big Bang (years)
~ 300 thousand
~ 500 million
~ 1 billion
~ 9 billion
~ 13 billion
The Big Bang
The Universe filled with ionized gas
The Universe becomes neutral and opaque
The Dark Ages start
Galaxies and Quasars begin to form
The Reionization starts
The Cosmic Renaissance
The Dark Ages end
Reionization complete, the Universe becomes transparent again
Galaxies evolve
The Solar System forms
Today: Astronomers figure it all out!
S.G. Djorgovski et al. & Digital Media Center, Caltech

http://www.mpa-garching.mpg.de/galform/data_vis/index.shtml



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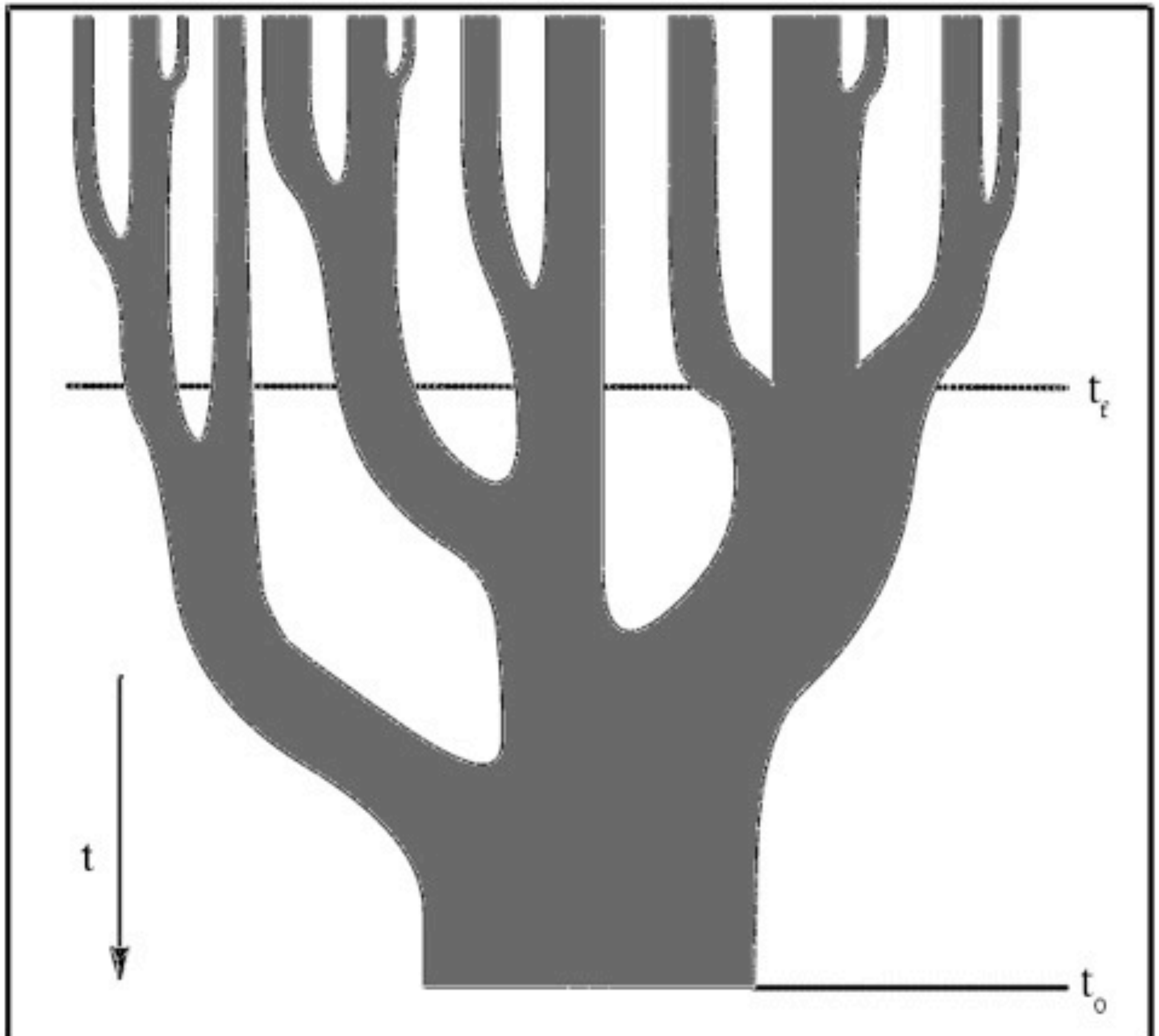
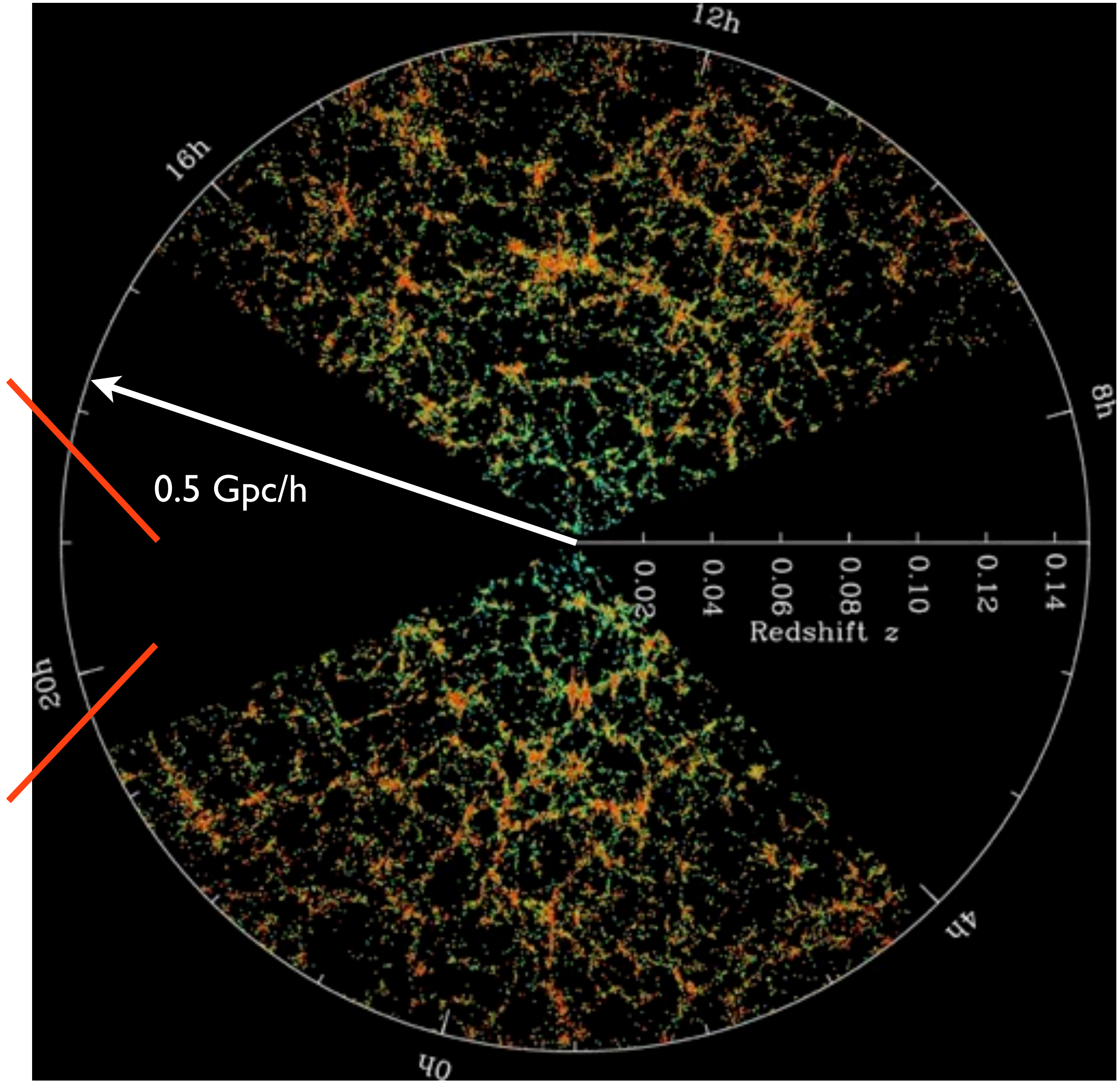
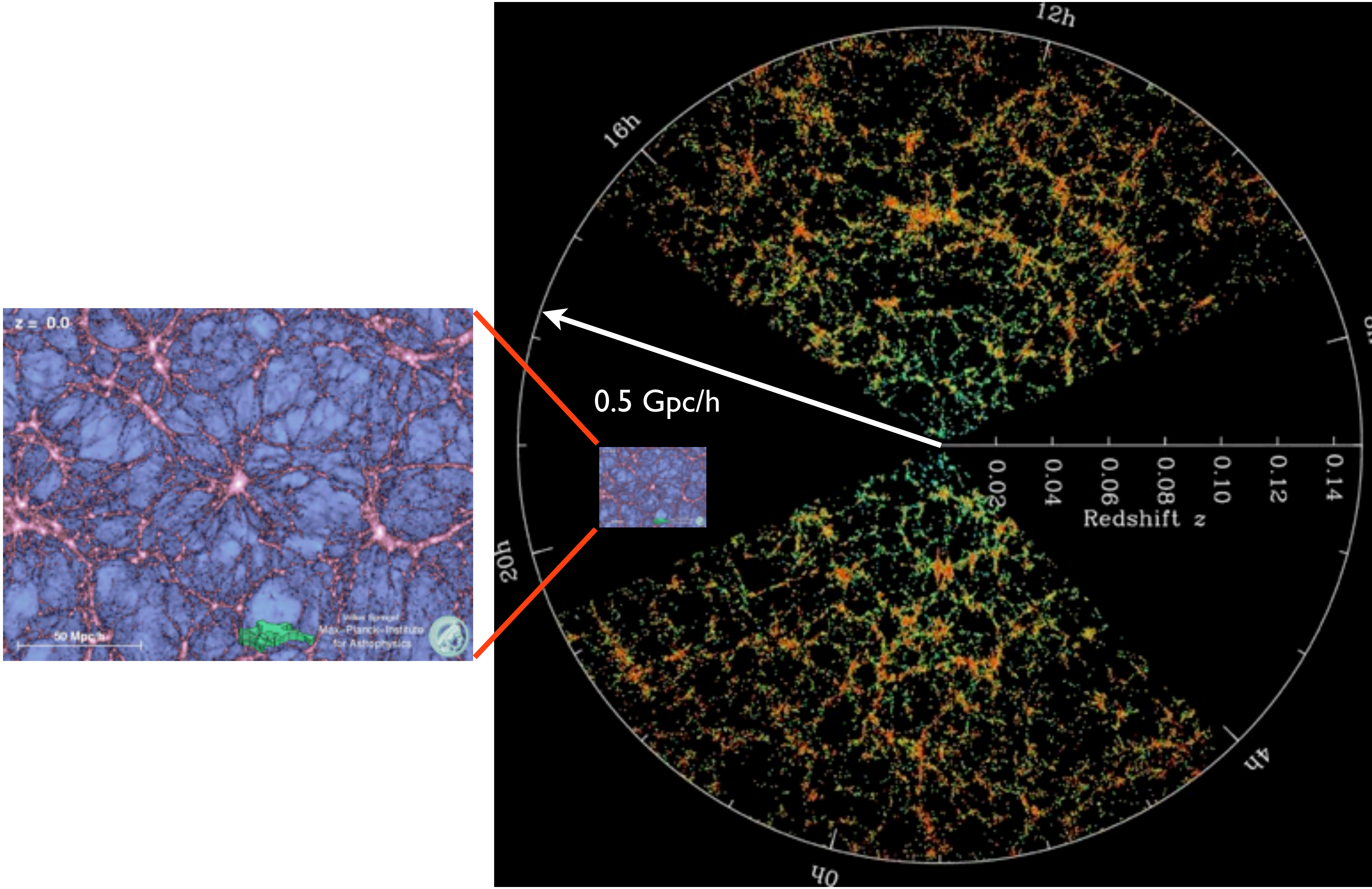


Figure 6. A schematic representation of a "merger tree" depicting the growth of a halo as the result of a series of mergers. Time increases from top to bottom in this figure and the widths of the branches of the tree represent the masses of the individual parent halos. Slicing through the tree horizontally gives the distribution of masses in the parent halos at a given time. The present time t_0 and the formation time t_f are marked by horizontal lines, where the formation time is defined as the time at which a parent halo containing in excess of half of the mass of the final halo was first created.

Lacey and Cole MNRAS 262 627 (1993)



http://www.sdss.org/includes/sideimages/sdss_pie2.html



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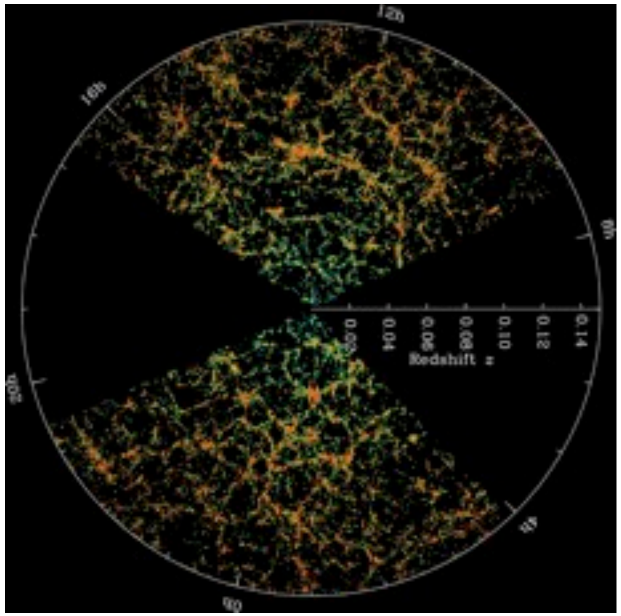
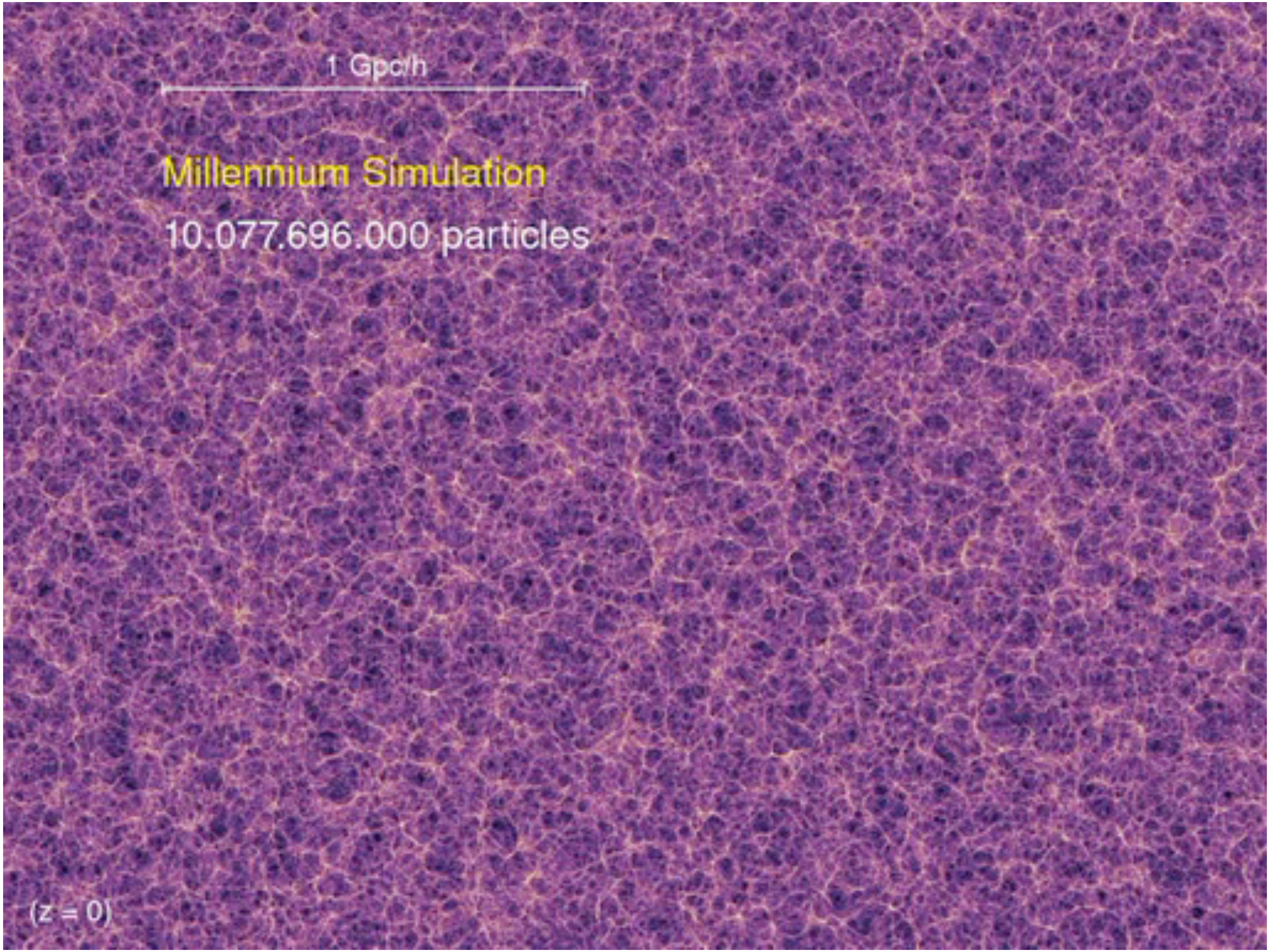
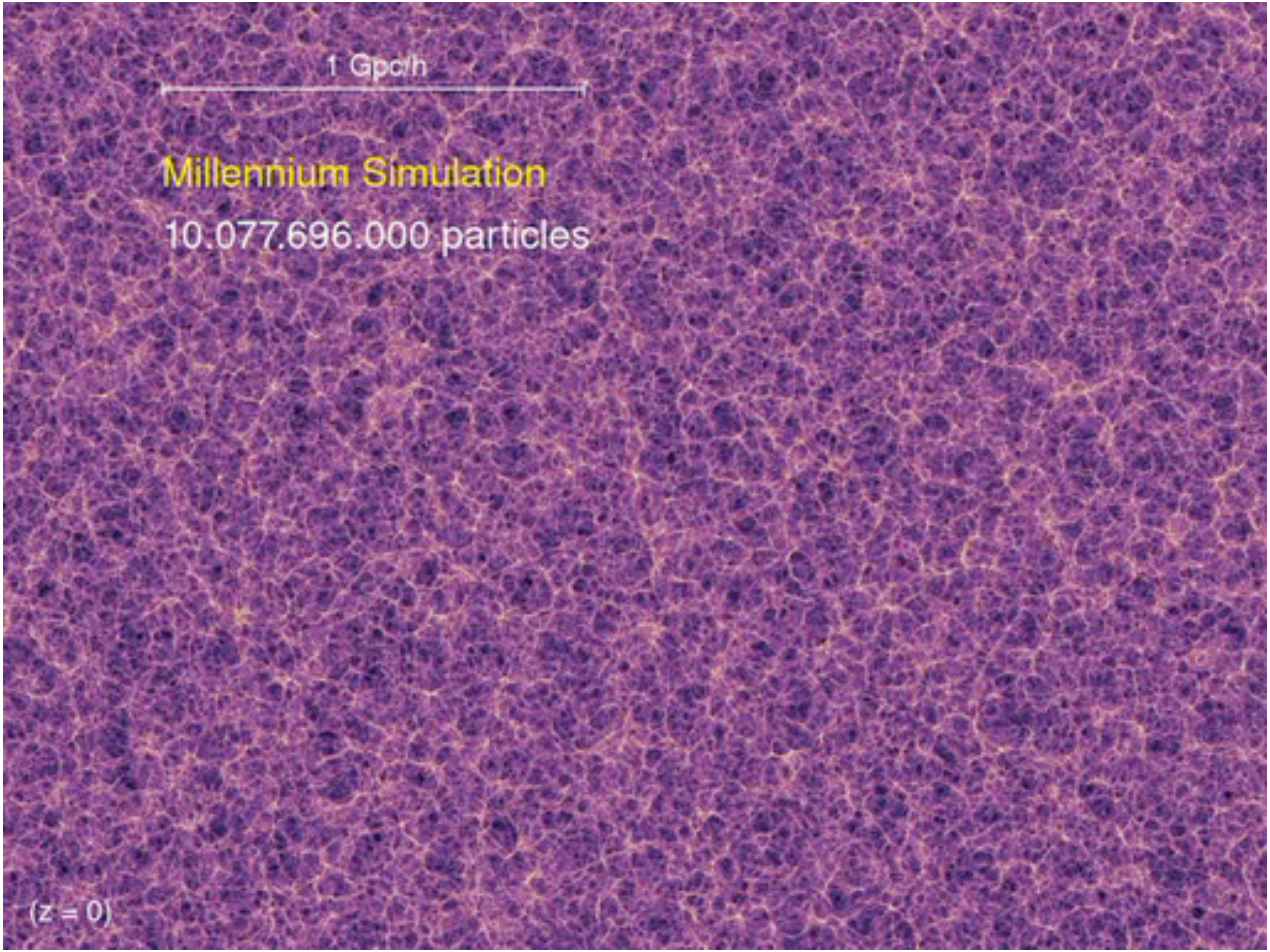
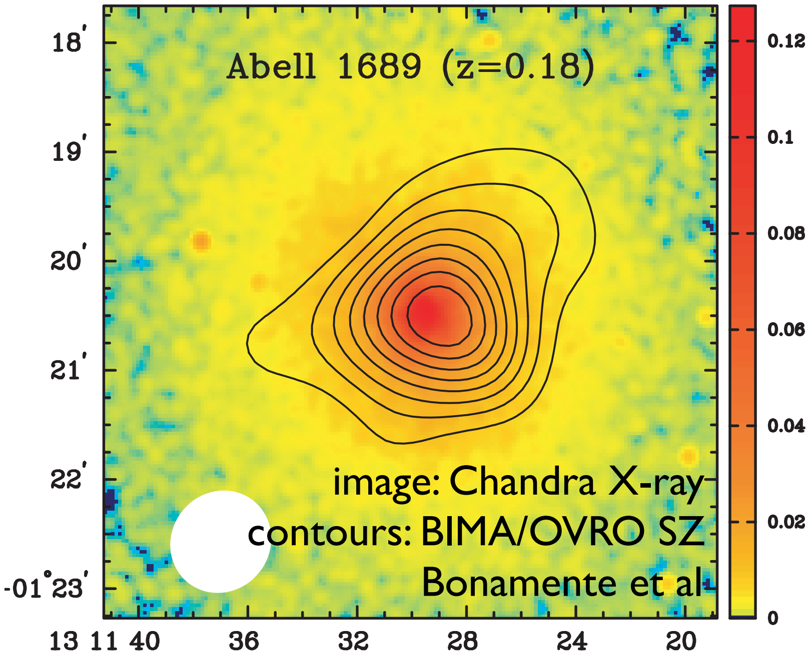

12h
16h
0h
20h
4h
8h
0.02
0.04
0.06
0.08
0.10
0.12
0.14
Redshift z


1 Gpc/h
Millennium Simulation
10.077.696.000 particles
(z = 0)


1 Gpc/h
Millennium Simulation
10.077.696.000 particles
(z = 0)

Galaxy Cluster Primer

- Most massive collapsed objects in universe
- Characteristics:
  - R ~ 1-3 Mpc (10^{25} cm), few arcmin, collapsed from ~10 Mpc region
  - M ~ 10^{14} $M_\odot$ to few x 10^{15} $M_\odot$, mostly dark matter
  - Hot baryonic plasma ~ 15-20% of mass
    - T ~ 10^8 K = few keV
    - $L_X = 10^{43}$-10^{45} erg/sec
    - density = 0.001- 0.1/cm^3
    - sound crossing time ~ 0.5 Gyr << age → close to hydrostatic equilibrium
    - gas somewhere between isothermal ($P \propto \rho$) and adiabatic ($P \propto \rho^{5/3}$)
    - thermal conduction substantial but not perfect
    - metallicity ~ 1/3-1/2 solar
  - 10s to 100s of galaxies, ~2-3% of mass
  - magnetic field ~ 1 μG
  - Most formed between z = 1 and today
- Observable in O/IR via detection of member galaxies
- Lensing of background galaxies in O/IR maps dark matter

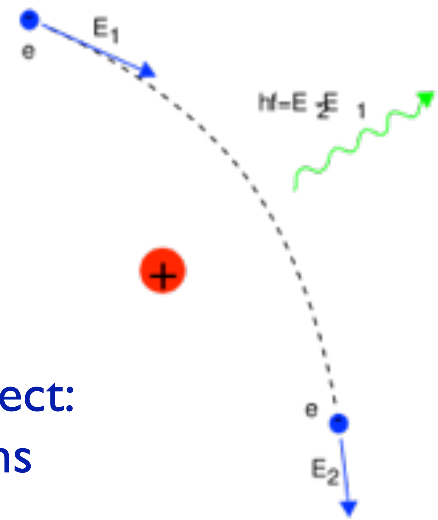


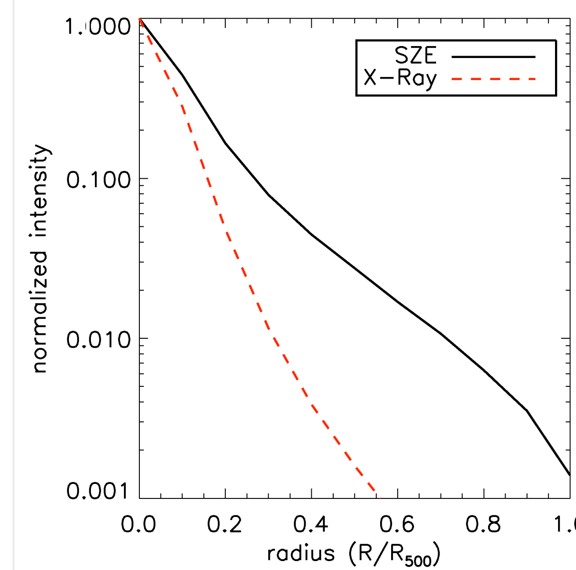
Galaxy Cluster Primer

- Intracluster medium "emission" mechanisms:
  - X-ray emission from thermal bremsstrahlung

$$S_X = \frac{1}{4\pi(1+z)^4}\int n_e^2 \Lambda_{ee}\, dl$$

Λ_{ee} = cooling function $\propto T_e^{1/2}$

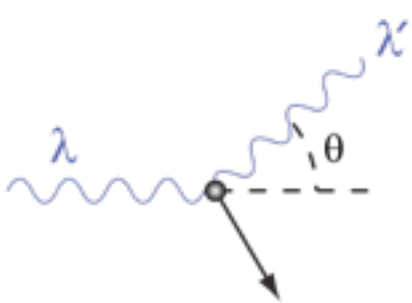


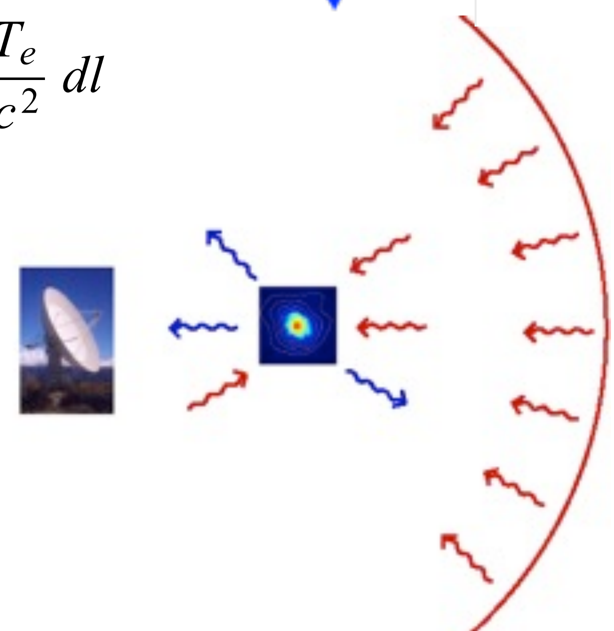


  - Thermal Sunyaev-Zeldovich (SZ) effect: Compton scattering of CMB photons

$$\Delta T_{\rm CMB} = f_{(x,T_e)} T_{\rm CMB} \int \sigma_{\rm T} n_e \frac{k_B T_e}{m_e c^2}\, dl$$

$\sigma_{\rm T}$ = Thomson cross-section





Note the different dependences on n_e and T_e!

Self-Similar, Universal Cluster Model

- Assume gravity dominates, not baryonic physics
  - A spherical overdensity breaks away from expansion, collapses, and virializes; density at virialization is cosmology-dependent $\Delta_v \approx 180$. Defines virial radius ("edge of cluster"), total mass M_{tot}

$$\frac{4}{3}\pi\rho_c(z)\Delta_v(z)r_{\rm vir}^3 = M_{\rm tot}$$

$\rho_c(z)$ = critical density at redshift z

$\propto \; E^2(z) = \Omega_{M0}(1+z)^3 + \Omega_\Lambda + \Omega_{k0}(1+z)^2$

  - Assume isothermality of gas (virialization to logical extreme) in non-singular isothermal sphere with gas temperature related to galaxy velocities

$$n_e(\boldsymbol{r}) = n_{e_0}\left(1+\frac{r^2}{r_c^2}\right)^{-3\beta/2} \qquad \beta = \frac{\mu m_p \sigma^2}{k T_e}$$

σ = 1D galaxy velocity dispersion

T_e = gas (electron) temperature

β = 1 for ideal gas in equipartition, no gravity

  - Require hydrostatic equilibrium (gas pressure provides support against gravity): relates total mass sourcing gravity to gas temperature and density profile

$$M(r) = \frac{3\beta k T_e}{G\mu m_p}\frac{r^3}{r_c^2+r^2}$$

Scaling Relations

- Self-similar model implies scaling relations between quantities
  - With $M_{tot} = M(r_{vir})$, one has

$$T_e \propto M_{\rm tot}^{2/3} E(z)^{2/3} \qquad E^2(z) = \Omega_{M0}(1+z)^3 + \Omega_\Lambda + \Omega_{k0}(1+z)^2$$

(cosmological factor due to dependence of ρ_c on z)

  - Assuming a universal gas fraction ($f_{\rm gas} = M_{\rm gas}/M_{\rm tot}$), one also has

$$T_e f_{\rm gas}^{2/3} \propto M_{\rm gas}^{2/3} E(z)^{2/3}$$

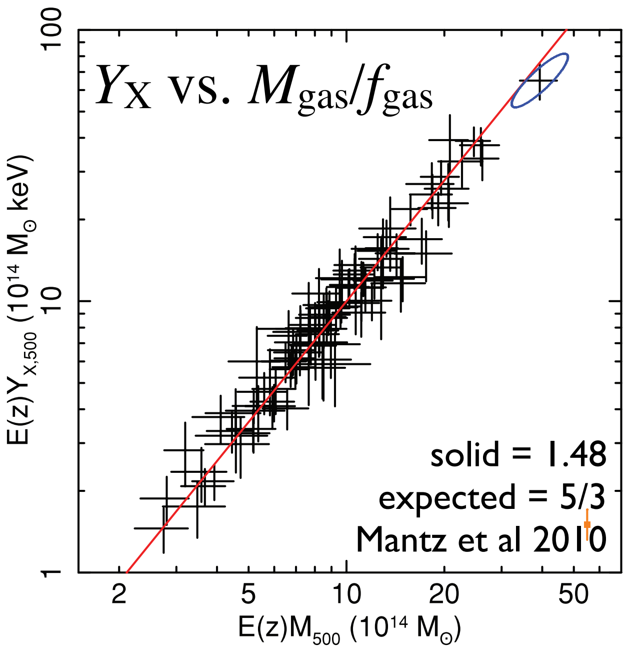
  - One can compute observables:
    - X-ray temperature $T_{\rm X}$: same as electron temperature T_e. If isothermality valid, then "emission-weighted" vs "mass-weighted" (ρ or ρ^2 weighting) does not matter.
    - X-ray luminosity $L_{\rm X}$

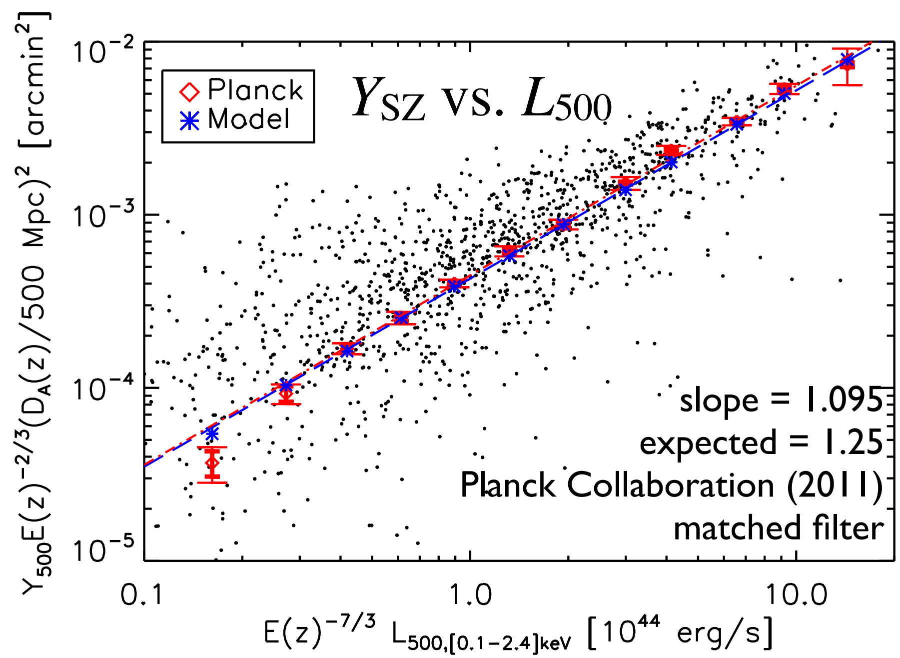
$$L_X \propto M_{\rm gas}\rho_{\rm gas}T_e^{1/2} \propto f_{\rm gas}^2 M_{\rm tot} E(z)^2 T_e^{1/2} \propto f_{\rm gas}^2 M_{\rm tot}^{4/3} E(z)^{7/3}$$

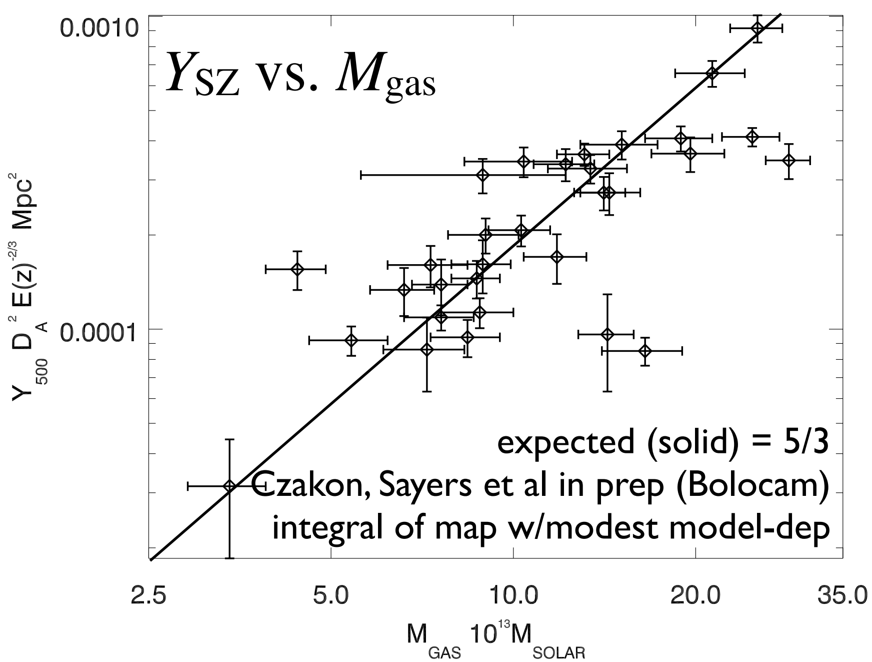
    - Integrated thermal energy $Y = M_{\rm gas} T_e$, accessible by X-ray estimated $M_{\rm gas}$ and $T_{\rm X}$ or by integrated thermal Sunyaev-Zeldovich effect flux

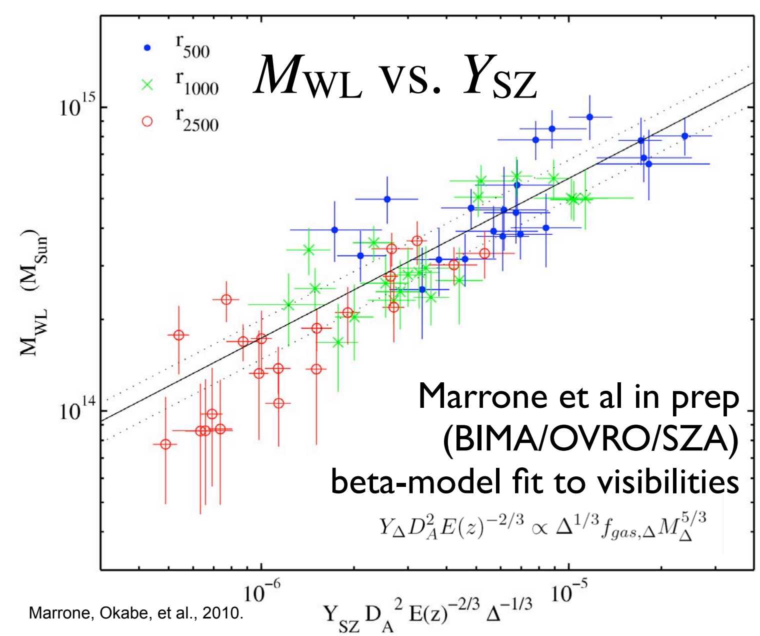
$$Y \propto f_{\rm gas} M_{\rm tot} T_e \propto f_{\rm gas} M_{\rm tot}^{5/3} E(z)^{2/3}$$

Scaling Relations: Data

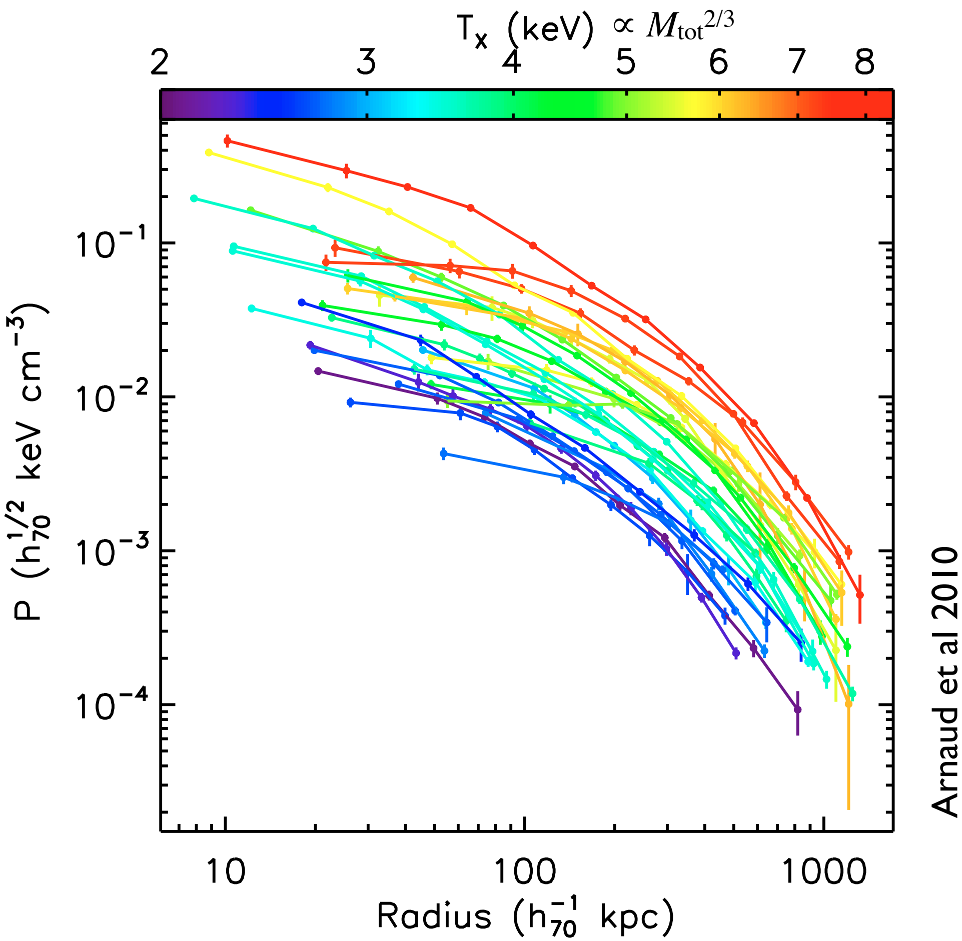


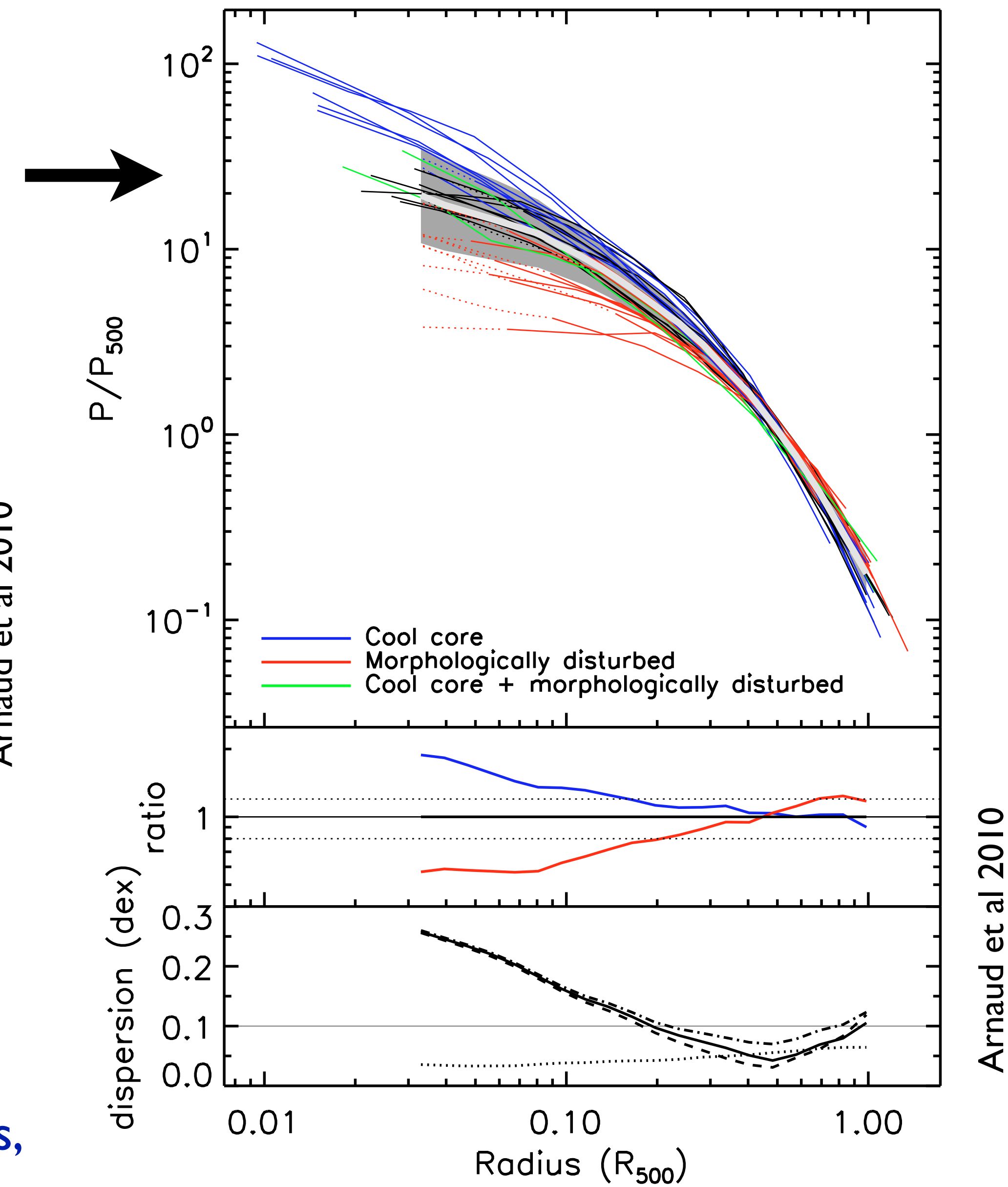






Self-Similar, Universal Model: Pressure





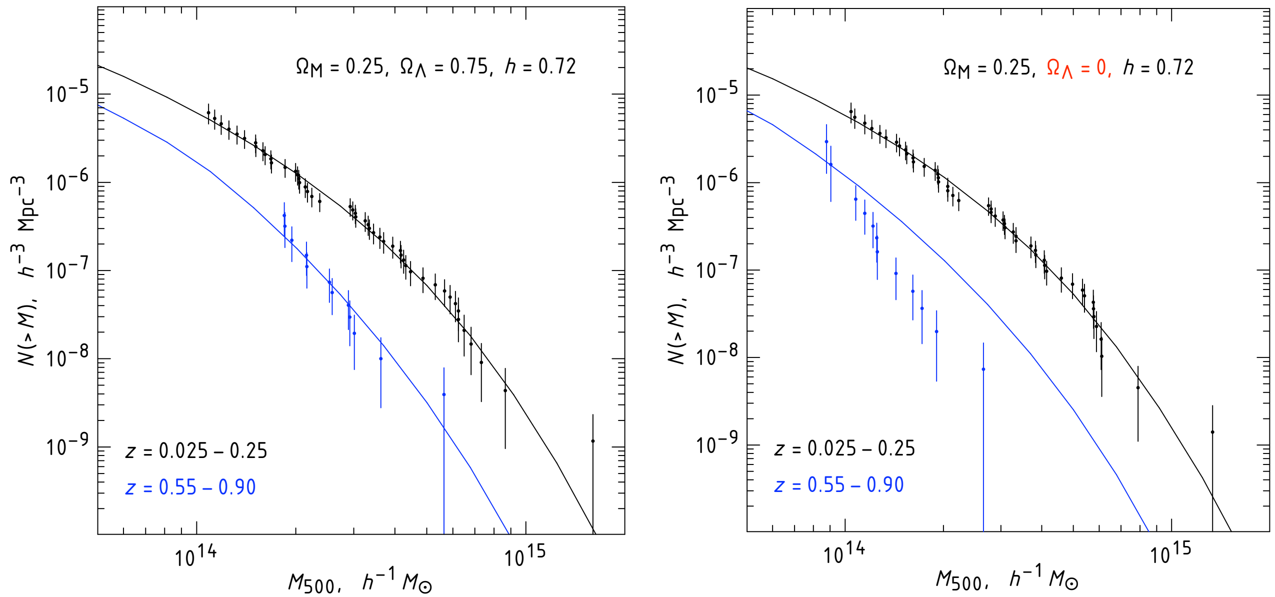
- Universal pressure profile
  - outside the core, there appears to be a universal pressure profile
  - But study uses only $z < 0.2$ clusters, what about redshift evolution?

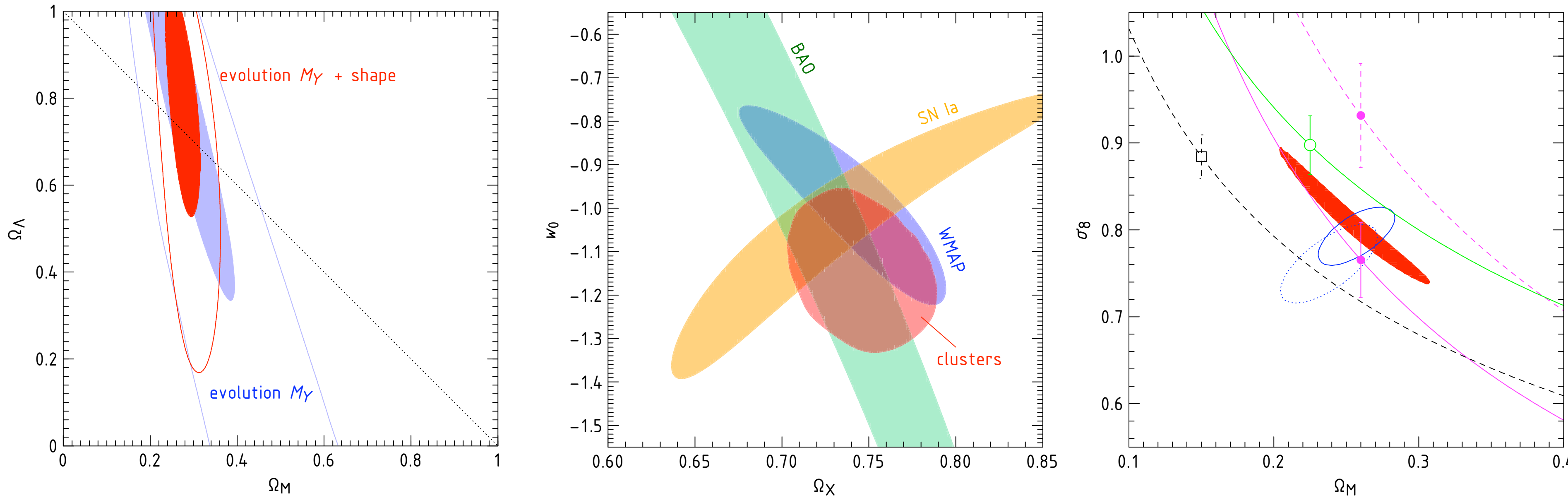
Clusters as Cosmological Tools

- Scaling relations and universal pressure profile suggest clusters are "well-behaved" and close to self-similar expectations
- What can we do with them?
  - Geometrical tests
    - Angular diameter distance as function of z:
      - assume X-ray and SZ derived from same spherical plasma; different dependences on D_A enable reconstruction of D_A (e.g., Bonamente et al 2006)
      - assume f_{gas} is independent of z and use differing dependences of estimates for M_{gas} and M_{tot} on D_A to estimate D_A (e.g., Allen et al 2008)
  - Growth function + volume element tests: indirect measurements of cosmo params Ω_m, Ω_Λ, equation of state parameter w
    - $dN(>M)/dz$ as function of z: abundance of clusters above a mass threshold as function of z measures combination of growth function and volume element, present day value measures normalization of density fluct. PS, σ_8
    - dN/dM as function of z: variation in mass function with z measures growth function, present day value measures normalization of density fluct. PS, σ_8
    - SZ secondary anisotropy spectrum: ensemble of clusters over cosmic time
    - All need connection between M and an observable: scaling relations v. important

Cosmological Tests

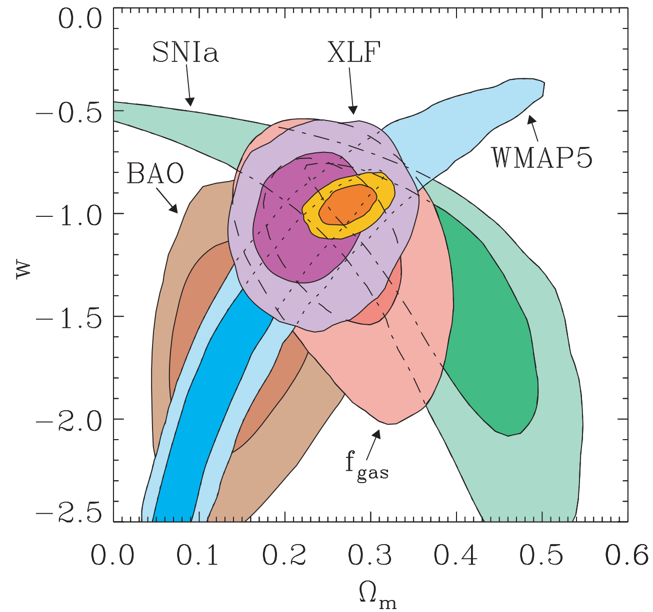
- Vikhlinin et al 2009
  - 49 z < 0.35 and 37 0.55 < z < 0.90 clusters, quasi-mass-limited sample selected using ROSAT, followed up with Chandra
  - dN/dM vs. z, no evolution of scaling relations

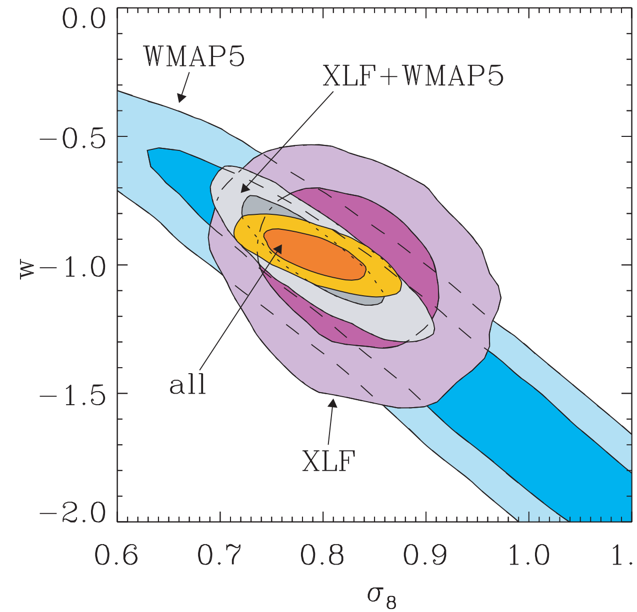


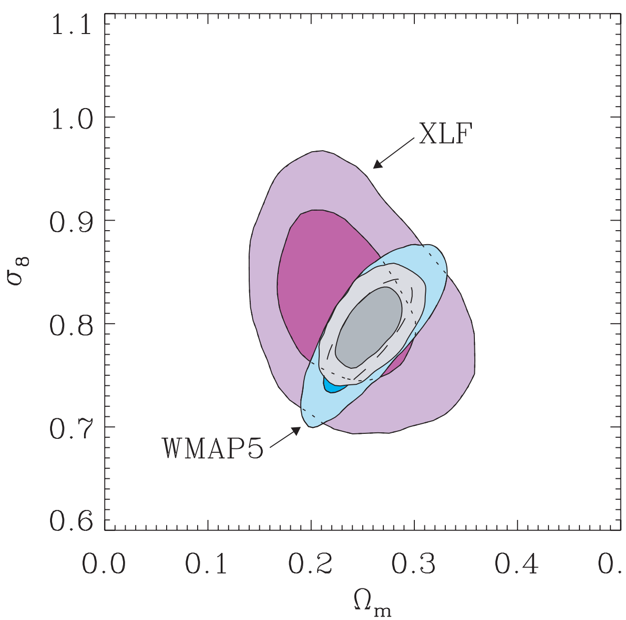


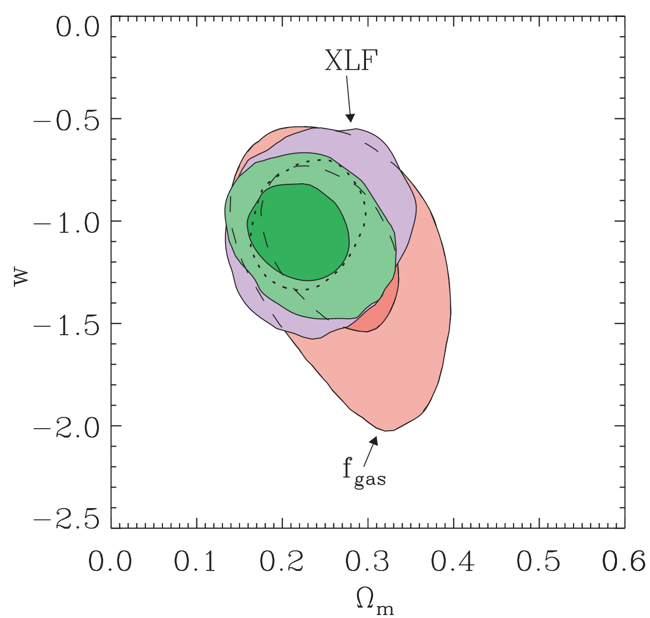
Cosmological Tests

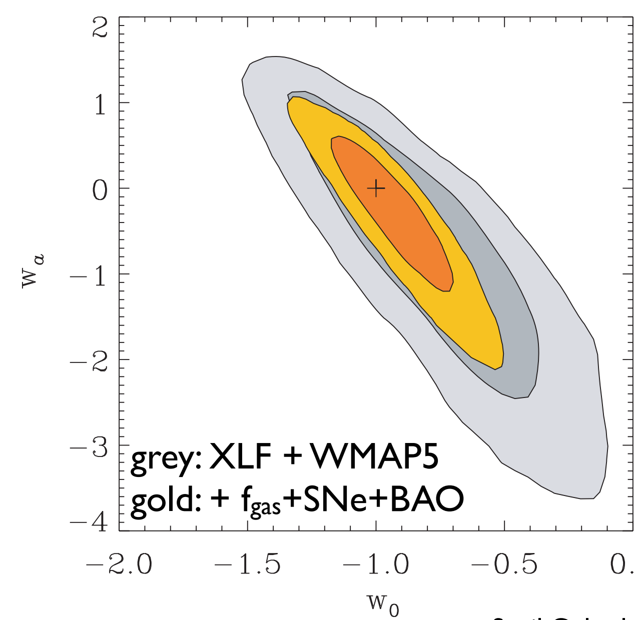
- Mantz et al 2010
  - Statistically complete set of 238 ROSAT -selected clusters, 94 w/Chandra data, z < 0.5
  - XLF, f_{gas} analyses
  - Self-consistently find scaling relations, allow $(1+z)^{\gamma}$ evolution







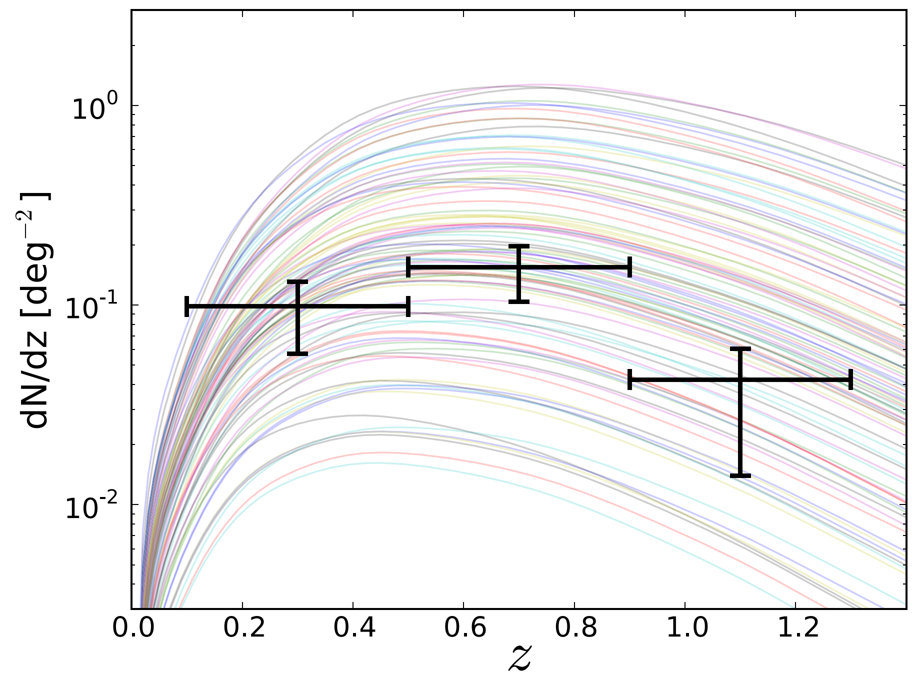




Cosmological Tests

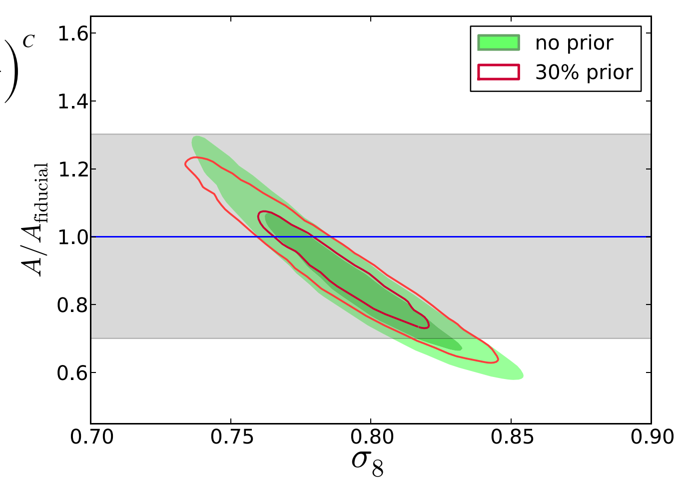
Vanderlinde et al 2010

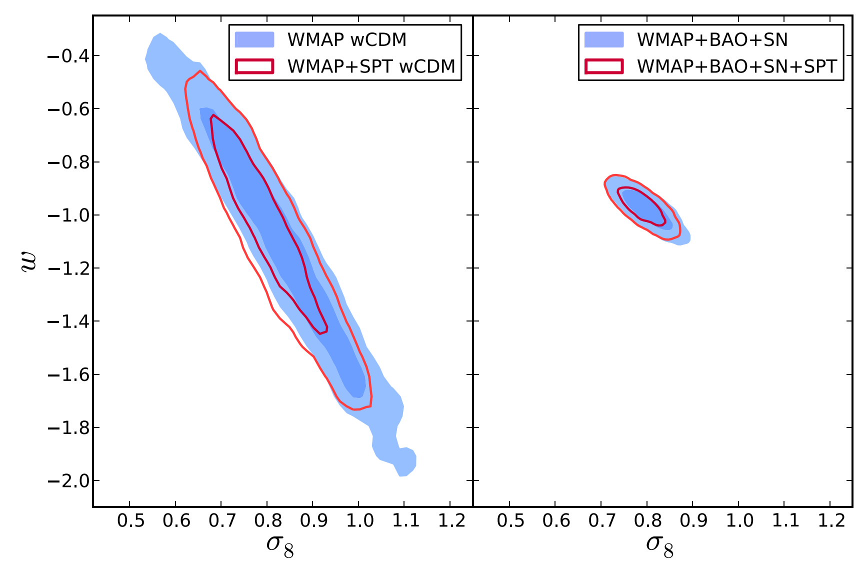
- dN/dZ from SZ-selected surveys
  - SPT: 21 clusters detected (2008 data only)
  - ACT: 23 clusters selected (2008 data only), no dN/dz plot
  - Cosmological constraints limited by uncertainty in scaling relation between signal and mass; 10% error in mass limit, same size as statistical uncertainty for current data set



$$\zeta = A\left(\frac{M}{5\times 10^{14}\,M_\odot\,h^{-1}}\right)^B\left(\frac{1+z}{1.6}\right)^C$$

ζ = detection significance
B = 1.31
C = 1.6
$A/A_{fiducial}$ = ratio of normalization to nominal from sims

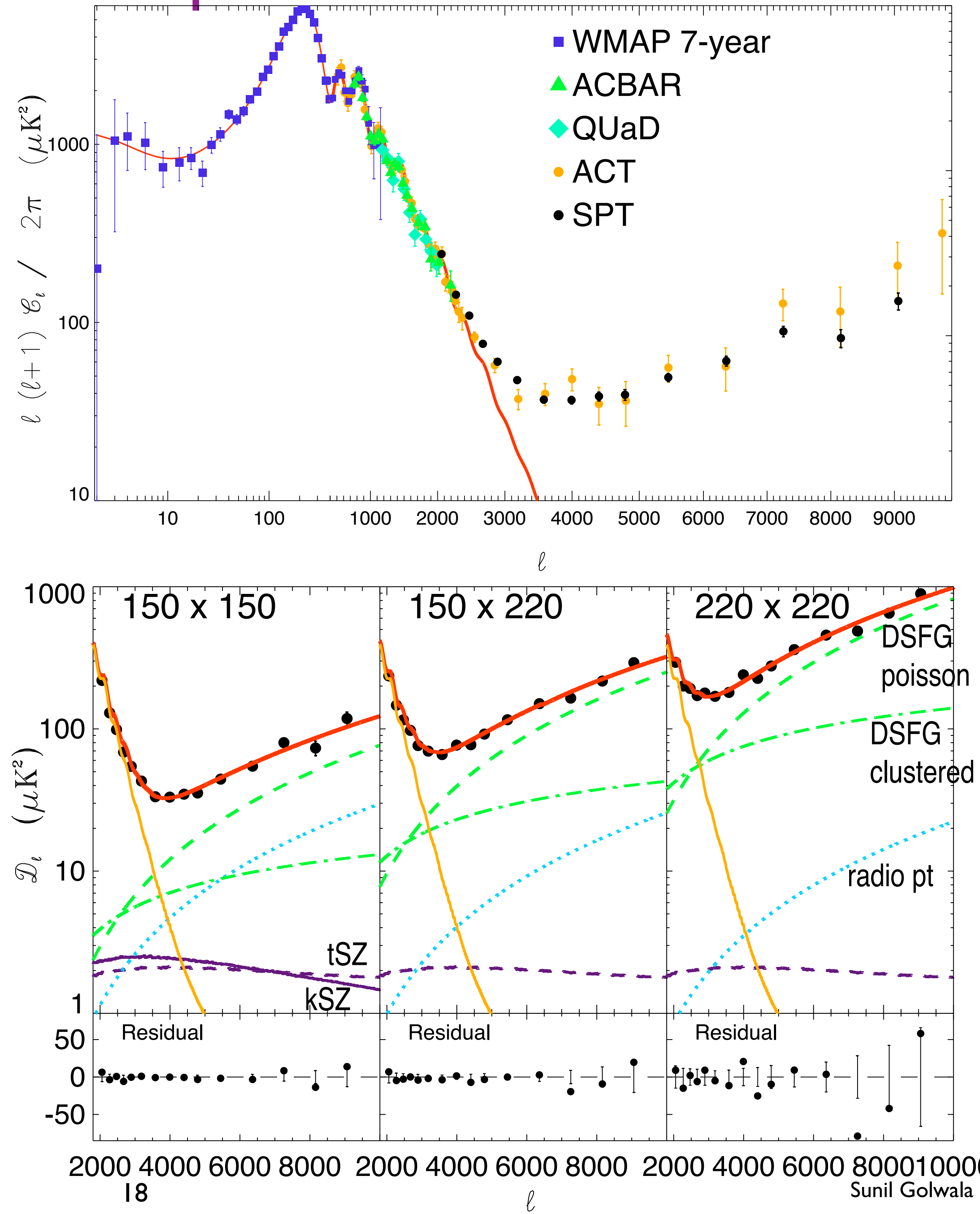




SZ power spectrum

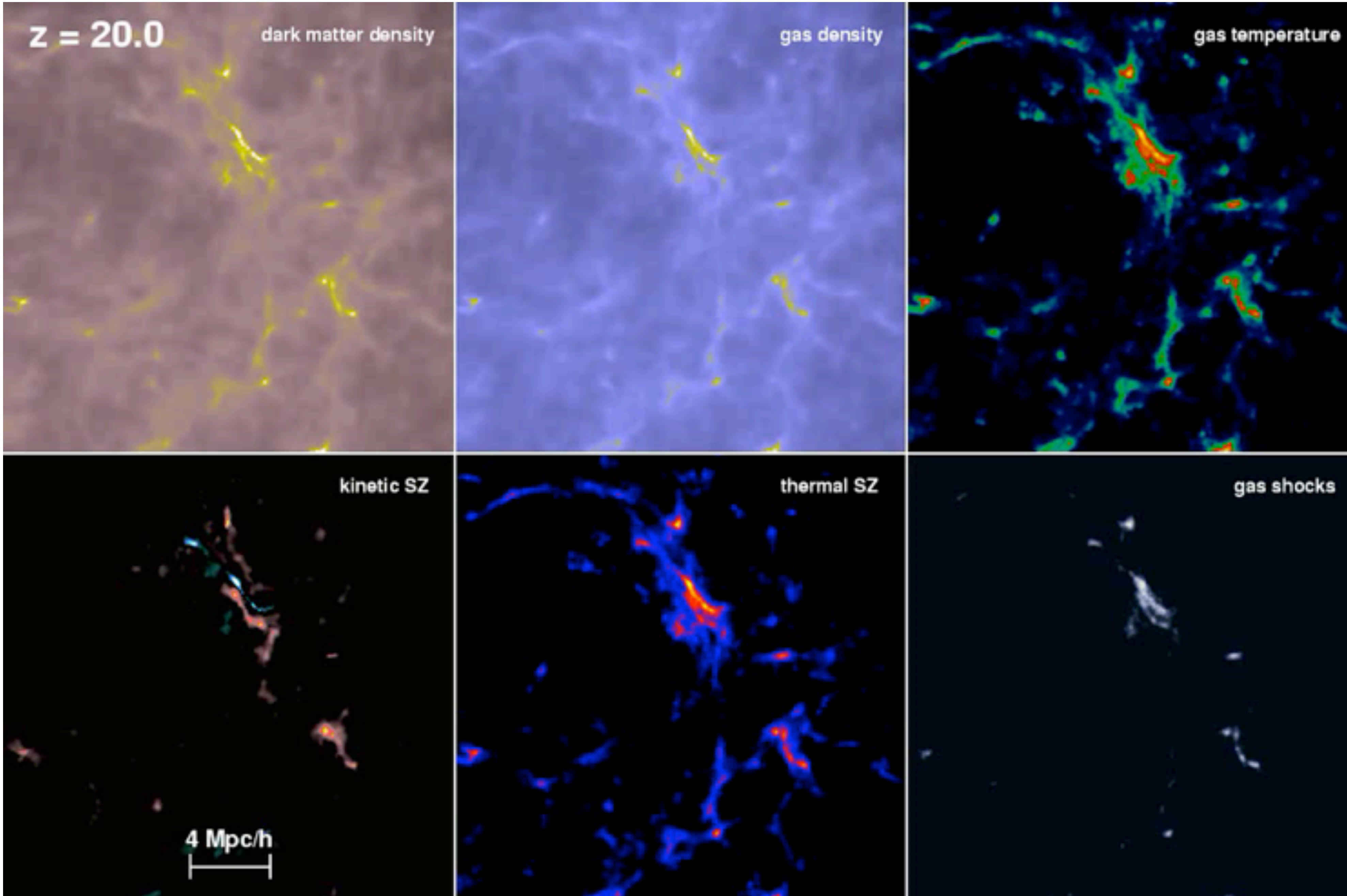
Shirokoff et al 2011

- Ensemble of clusters over all z produces secondary anisotropy in CMB
- Measurement does not need redshifts
- Low value of σ_8 and dominance of dusty star-forming galaxies (DSFGs) makes it very difficult!
- Relies on templates for power spectra of all components
- Current low S/N detections by SPT in tension with other σ_8 measurements; ACT not precise enough yet. Probably due to insufficient understanding of ICM in cluster outskirts



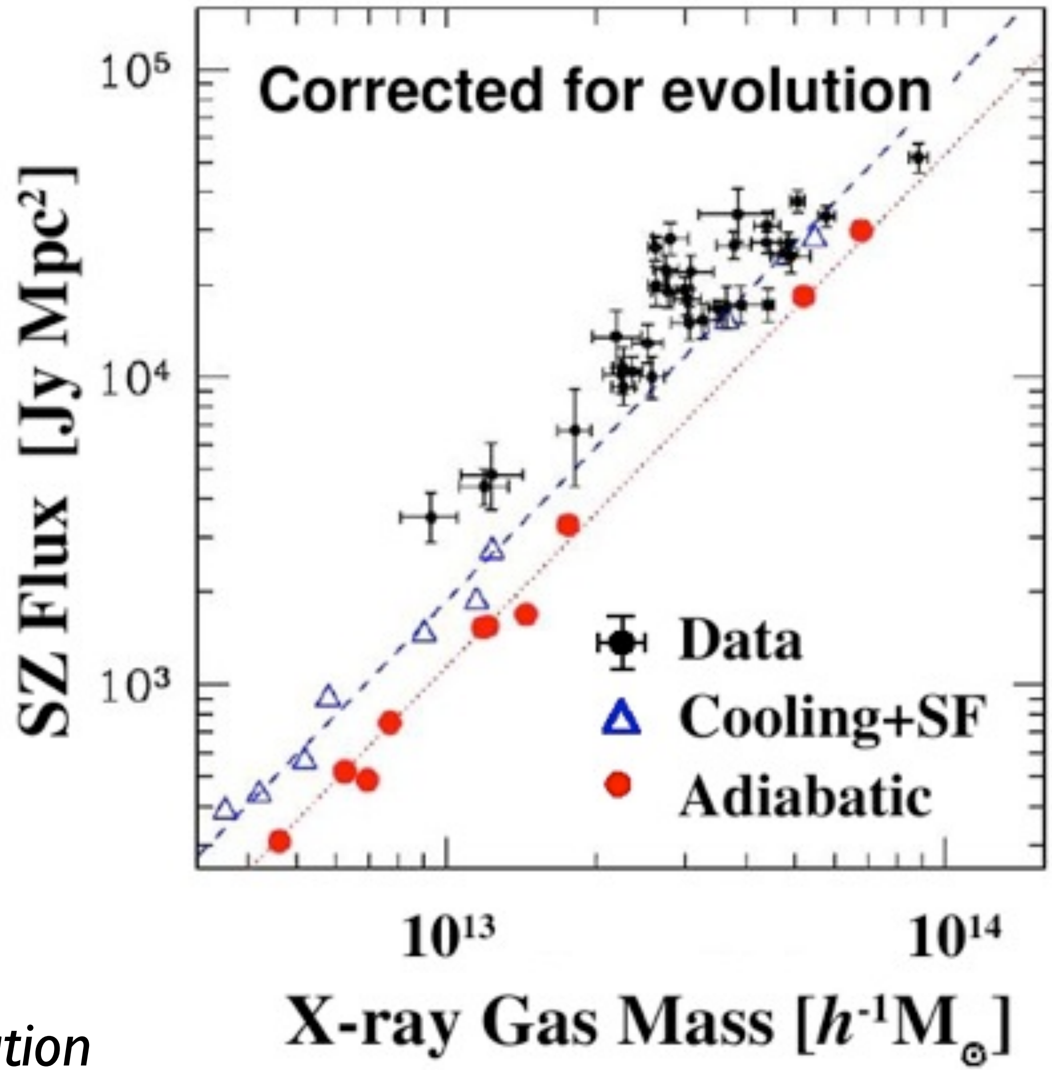
Why everything I have said to now is a lie...

Why everything I have said to now is a lie...



Scaling Relations, Revisited

- Power-law slopes usually a good match to self-similarity
- But normalization often reflects deviations
  - e.g. Y_{SZ} vs. M_{gas} data prefer inclusion of radiative cooling and galaxy formation; but data still deviate, and the way they were included is subject to debate
- Observations only now beginning to reach virial radius
  - Perhaps this will reduce such deviations?
- Exhaustive studies of *normalization* of scaling relations as a function of enclosing radius are needed

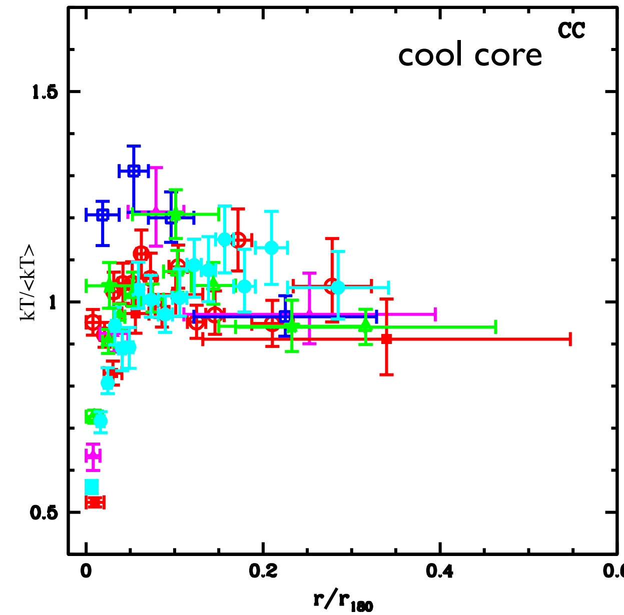


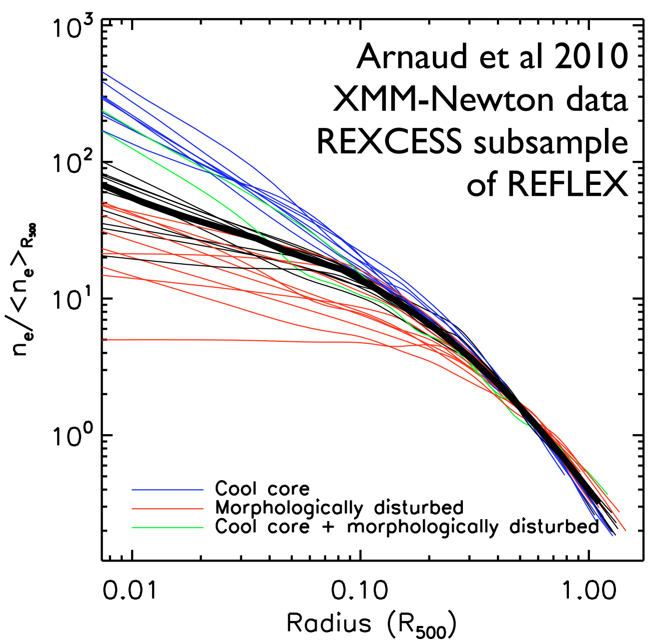
data from Bonamente *et al* 2008, simulations by Nagai and Kravtsov 2006

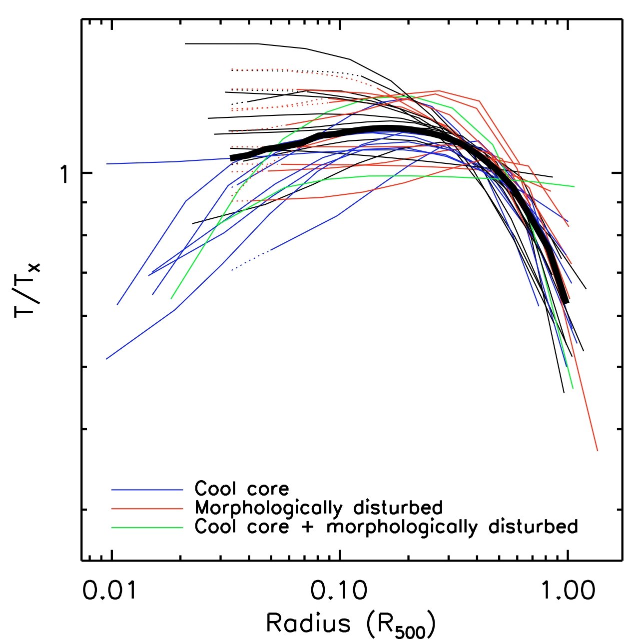
Cool Cores, T(r)

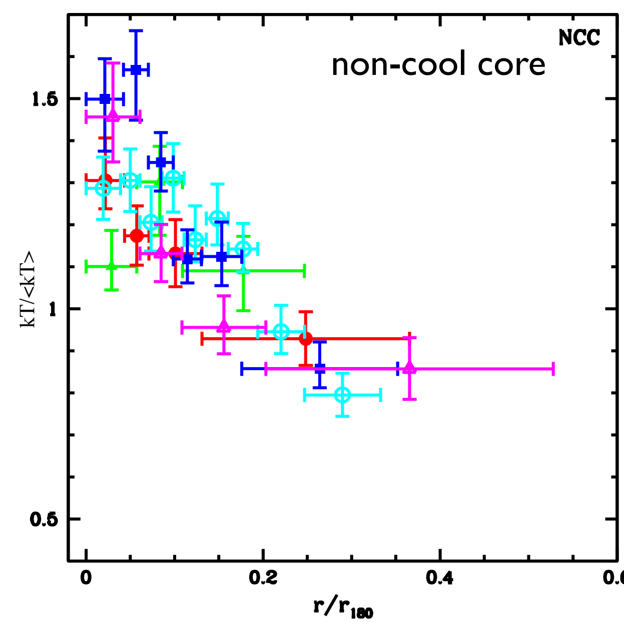
- Generic downward temperature gradient to outskirts
- Cool-core clusters have sharp drop in T at < $0.1 r_{\rm vir}$

→ Thermal conductivity is not infinite, virialization is not fully valid.





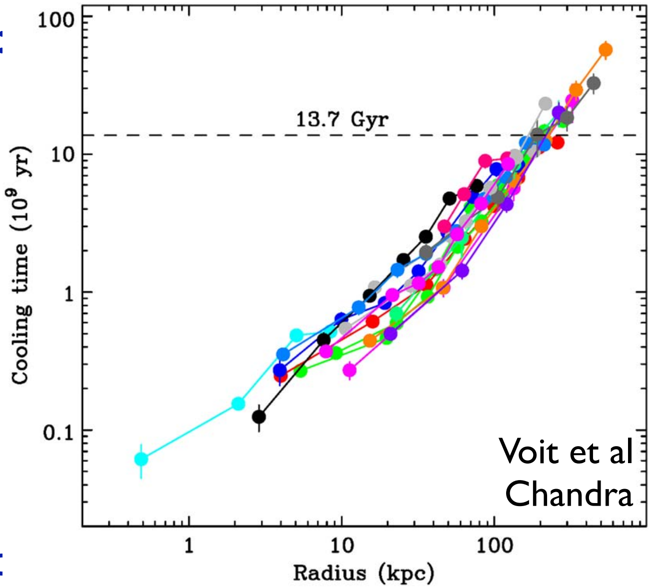




Baldi et al 2008, Chandra archival data

The Cooling-Flow Problem

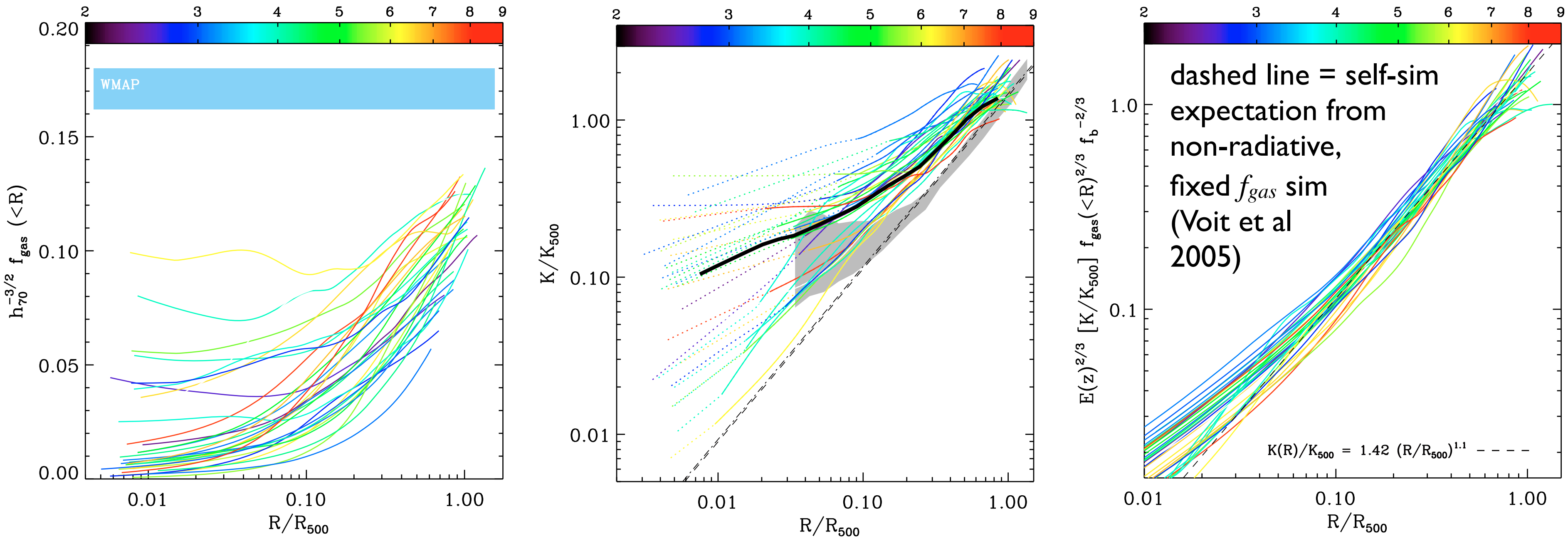
- Shouldn't the cool cores cool further?
  - Bremsstrahlung radiative cooling time obeys:
    $$t_{cool} = 85\ \mathrm{Gyr}\ (10^{-3}\ \mathrm{cm}^{-3}/n_e)\ (T_e/10^8\ \mathrm{K})^{1/2}$$
  - t_{cool} > age of universe at large radius, but t_{cool} is shorter in cool cluster cores bec. n_e larger by x10-100 and T_e reduced: Gas should condense out of ICM.
    → $dM_{gas}/dt = -(100\text{-}500)\ M_\odot/\mathrm{yr}$
    → expect low-energy line emission from "cooled" gas, "cooling flow" inward to replenish lost material



- But they don't: cold gas emission not seen by XMM (Peterson et al 2001, 2003), Chandra.
- Classical cooling flow discarded. Current belief:
  - entropy injection from galaxies likely to prevent condensation
  - Detailed mechanism not yet solid: hard to get high enough efficiency. Many good ideas, though, will be interesting to see these tested.
  - Some reduced version of cooling flows may be present (e.g., Voit, Donahue et al):
    - Signs of enhanced star formation in central galaxies when t_{cool} is short
    - Self-regulation? Enhanced star formation ↗ entropy injection into ICM, heating up remaining gas.
    - Similar feedback mechanism for AGN (cold ICM gas feeds AGN, which then heats ICM)

Gas Mass Fraction and Entropy

color bar is T_X [keV] $\propto M_{tot}^{2/3}$



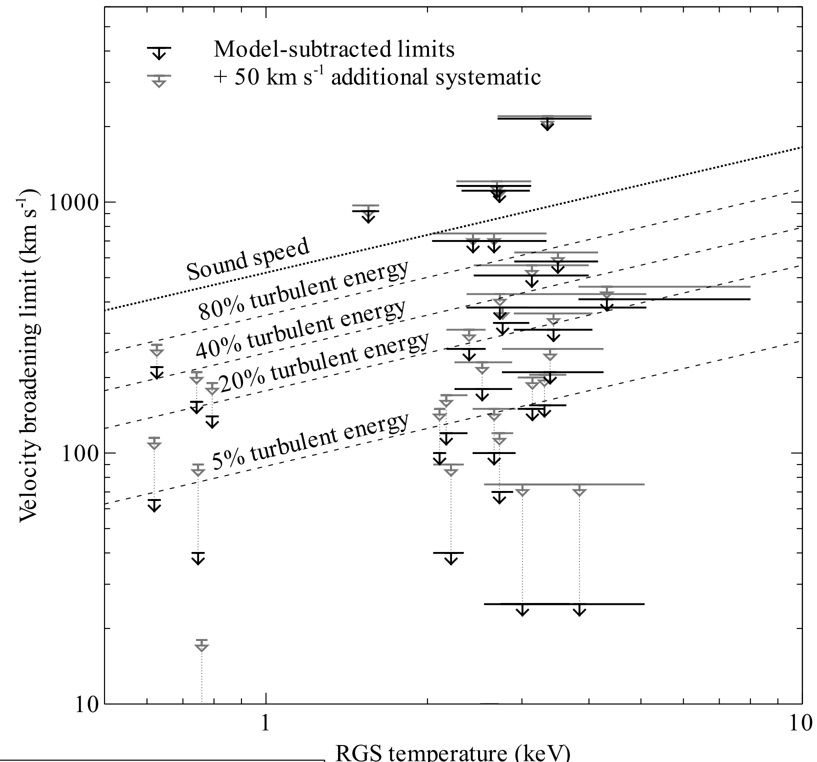
Pratt et al 2009

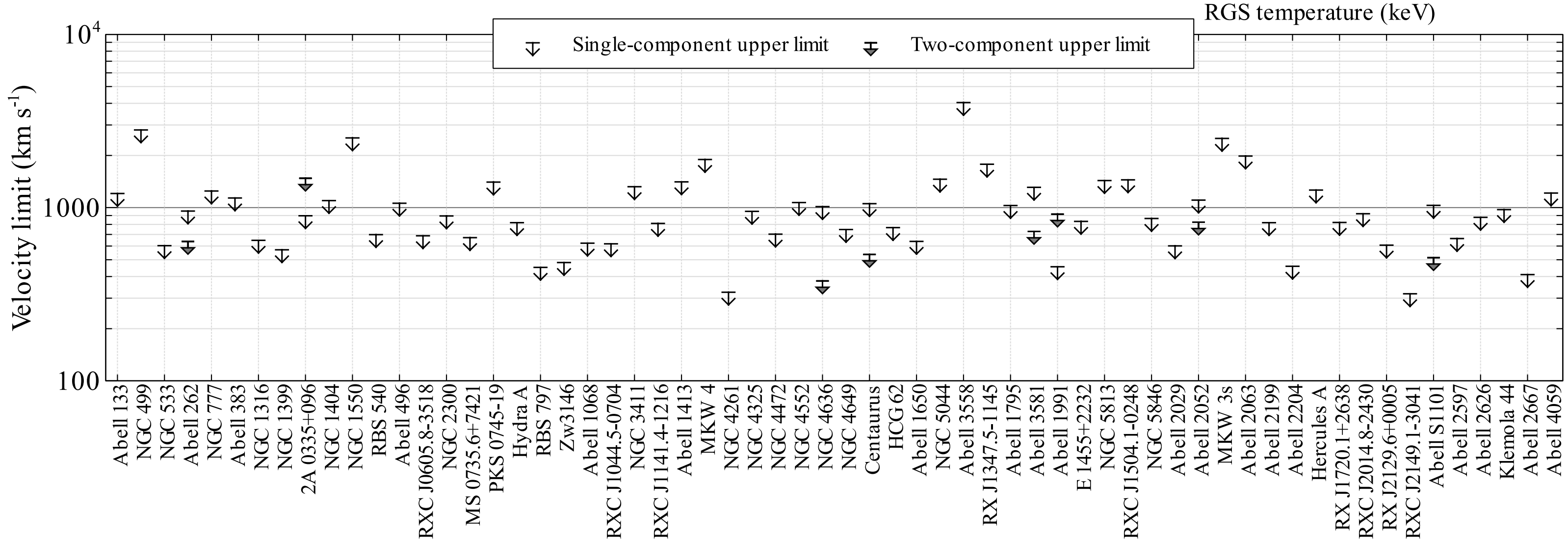
- Gas mass fraction increases with r and M, *always < universal value.*
- Entropy profiles
  - Entropy ($kT/n_e^{2/3}$) reflects non-adiabatic effects, so reflects non-self-similar history
  - Entropy is elevated in non-cool-core clusters.
  - See large variations in entropy profile,with convergence to self-similar behavior occurring at smaller r/r_{500} for larger M; entropy floor effects more important at lower M
- Product of gas fraction and entropy much better matches self-similarity
  - → Elevated entropy due to reduced gas density due to loss of gas. May explain $L_X \propto T_X^3$ deviation from $L_X \propto T_X^2$ self-similar expectation.
  - Cool-core clusters may have not suffered disturbing events that eject gas, enabling cooling.

Turbulence

Sanders et al 2011

- Turbulence and convection generally expected because thermal conductance is not infinite and it may be anisotropic due to B fields.
- Can be probed by searching for excess spectral line widths; upper limits very constraining in some cases.





Questions, Questions, Questions

Does the dark matter profile evolve with time?
Is it reflective of the redshift of formation?

What is the baryon fraction as a function of radius and redshift?

How much dark matter substructure is preserved?

Does the ICM have bulk motions? What do they tell us about the cluster assembly history?

How are the baryons divided among stars, cold gas, and hot gas?

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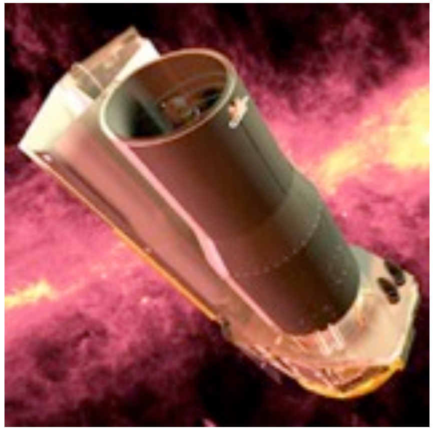
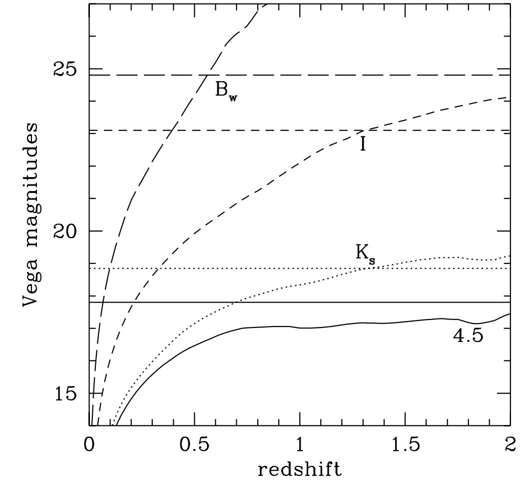
What are the systematic limits on our ability to constrain cosmology with clusters?

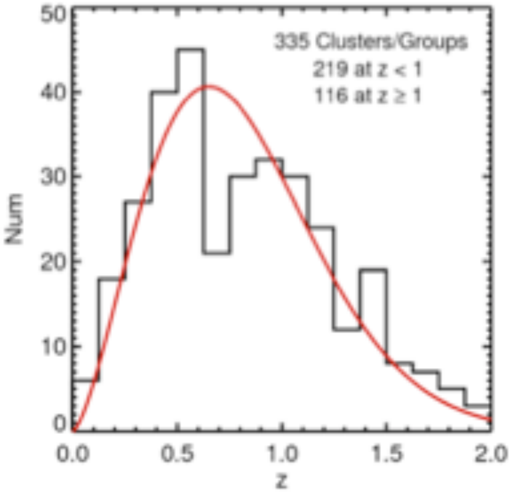
Spitzer and WISE

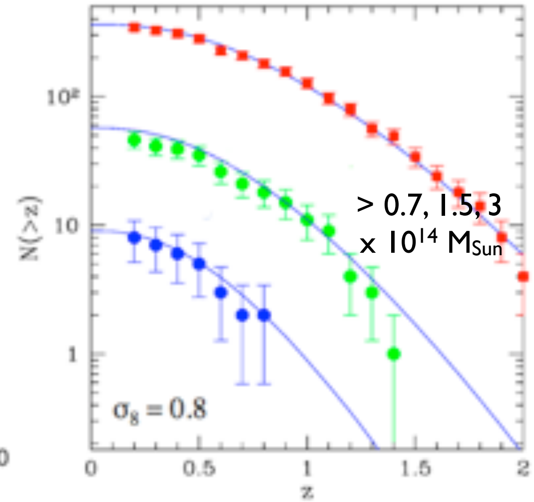
- Spitzer
  - IRAC Shallow Cluster Survey (Eisenardt et al.)
    - Galaxy overdensities selected using wavelet filter applied to 4.5-μm IRAC images + photometric z data in 7.25 deg2
    - dN/dz matches predictions
  - SpARCS: Spitzer Adaptation of the Red-Sequence Cluster Survey
    - Uses "red sequence" in R/3.6 μm color vs. 3.6 μm flux to identify
    - 99 clusters in Spitzer FLS already; ~13x area, √2 deeper in process
- WISE
  - Similar searches on full sky beginning
  - Shallower → larger M; better for SZ, X-ray



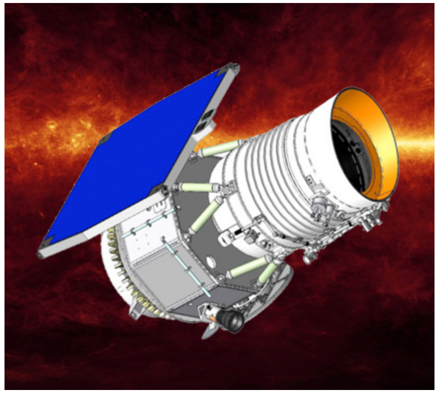


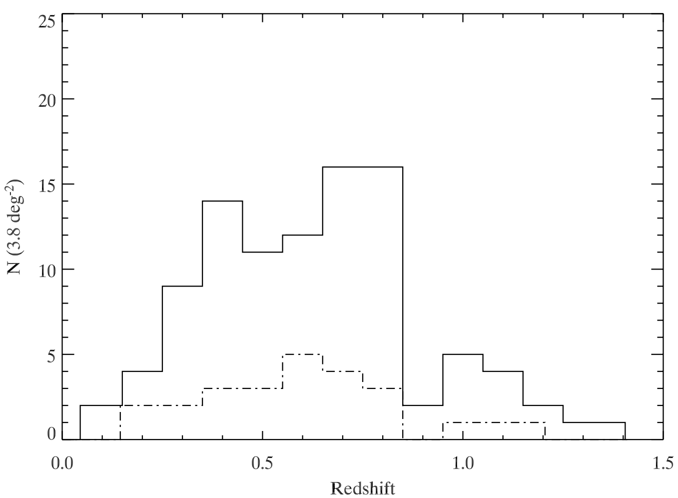
ISCS: Eisenhardt et al 2008





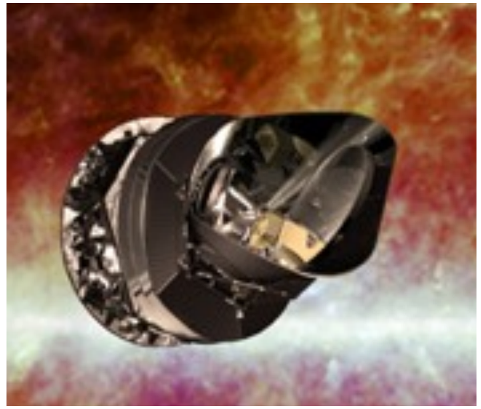
ISCS: Brodwin et al





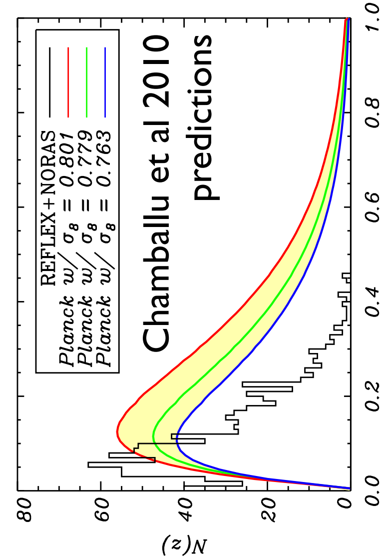
SpARCS FLS: Muzzin et al (2008)

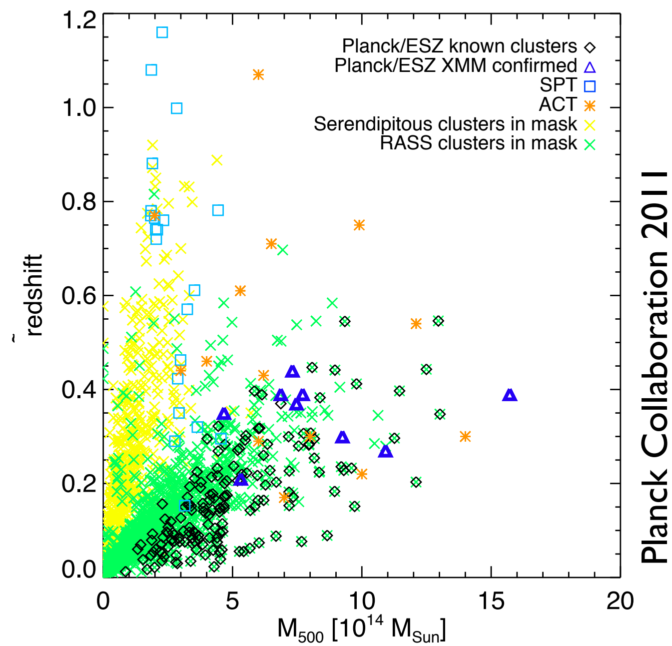
Planck

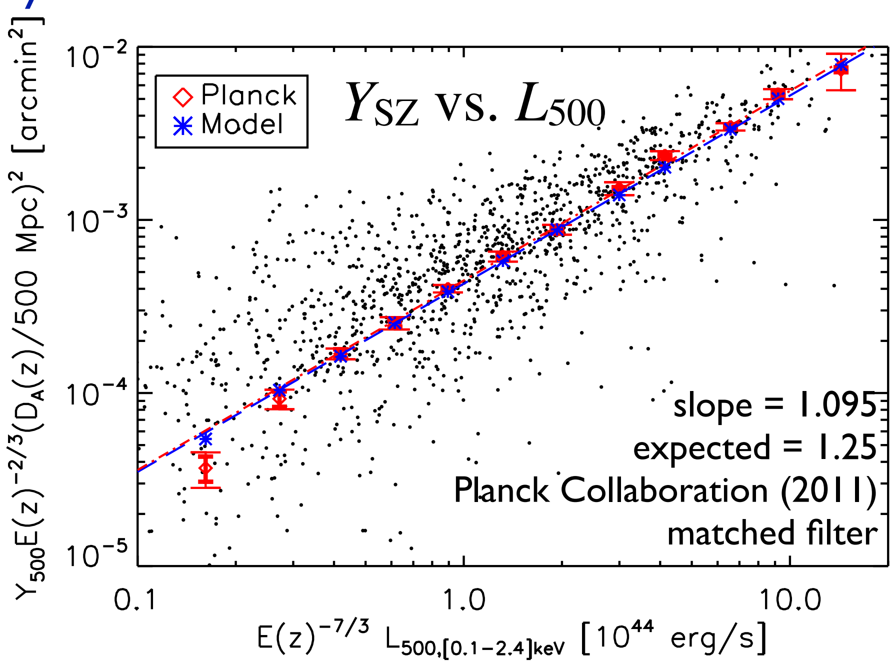


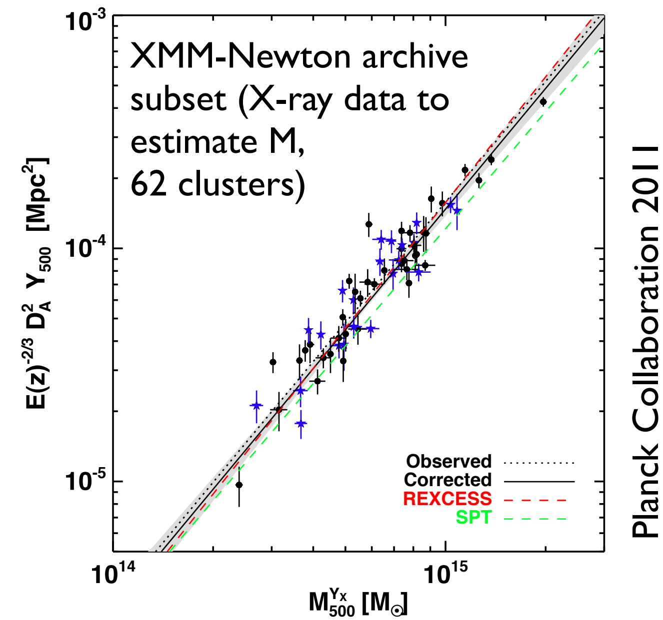
*Large JPL group deeply involved in Planck, produced Early Release Compact Source Catalog

- Search using multifrequency matched filter
  - Separates SZ from CMB, point sources
- Early SZ cluster sample
  - 169 known clusters, 20 new, $0 < z < 0.55$, 1-15 x 10^{14} M_{Sun}
  - Clusters not resolved (7' FHWM at 150 GHz), so parameter estimation depends on X-ray info
- Optical, X-ray, SZ followup will enhance utility
- Future releases will increase stats, go to higher z



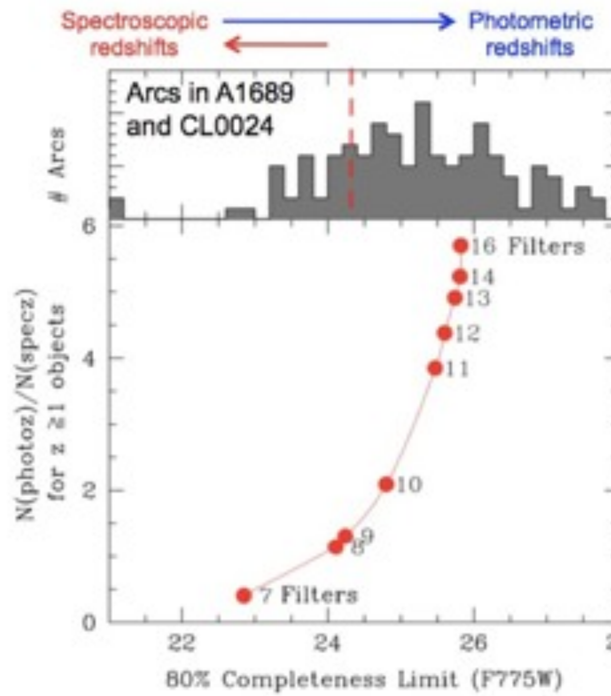


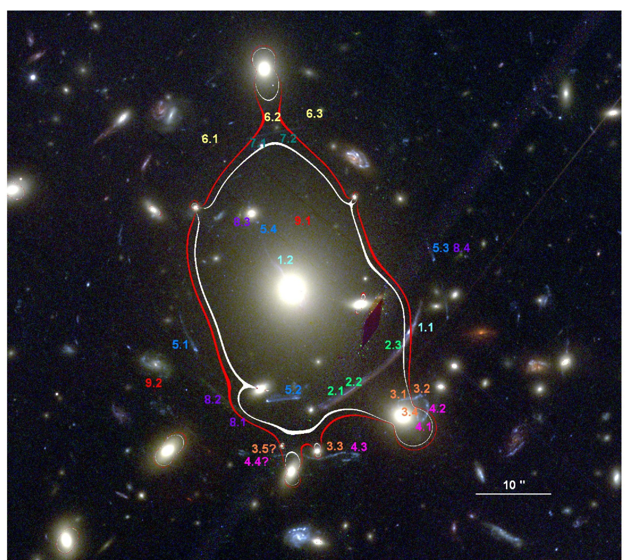


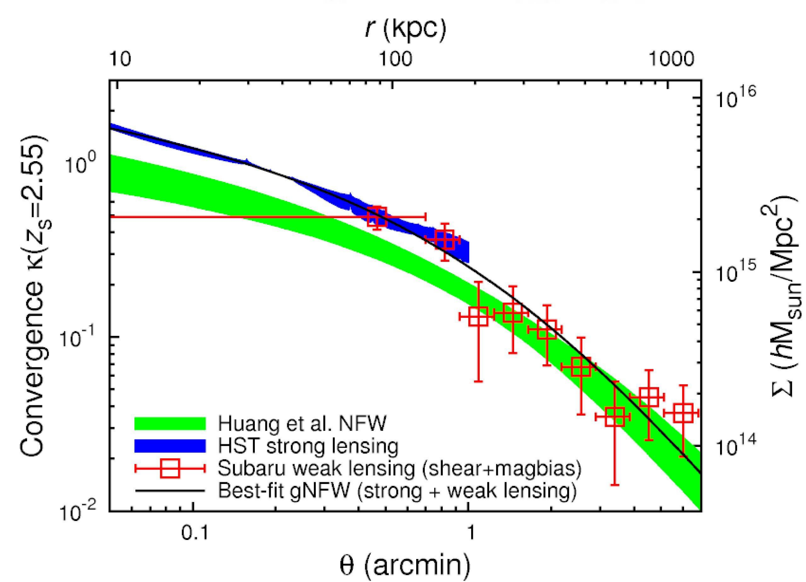


CLASH

- Cluster Lensing and Supernova survey with Hubble
  - 25-cluster Hubble Treasury program;
    PI: Marc Postman; JPL lead: Lexi Moustakas
  - HST strong lensing, 16 filters to maximize photo-z determination of bgnd sources (2' FoV), Subaru weak lensing (30' FoV)
  - Ancillary data includes
    - Chandra and XMM X-ray (8'-30' FoV)
    - SZ: SZA 2' resolution/30 GHz/12' FoV,
      MUSTANG 9" resolution/90 GHz/1' FoV
      Bolocam 1' resolution/150 GHz/8' FoV
  - First results on Abell 383 out (Zitrin et al.)
    - very precise HST lensing constraints!

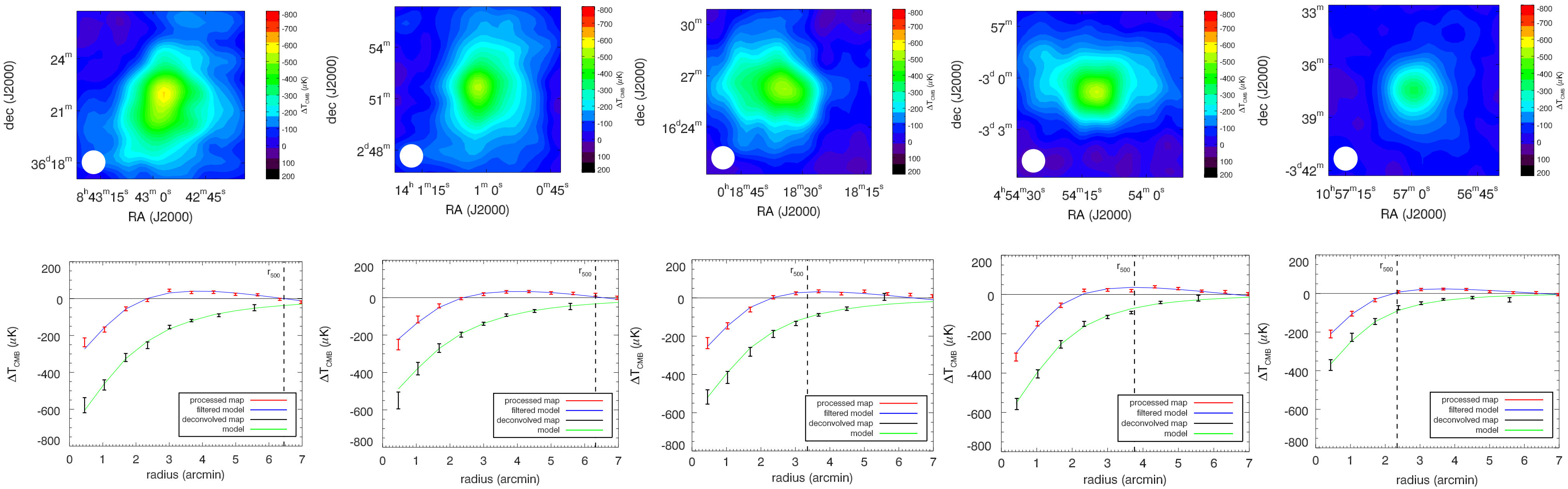






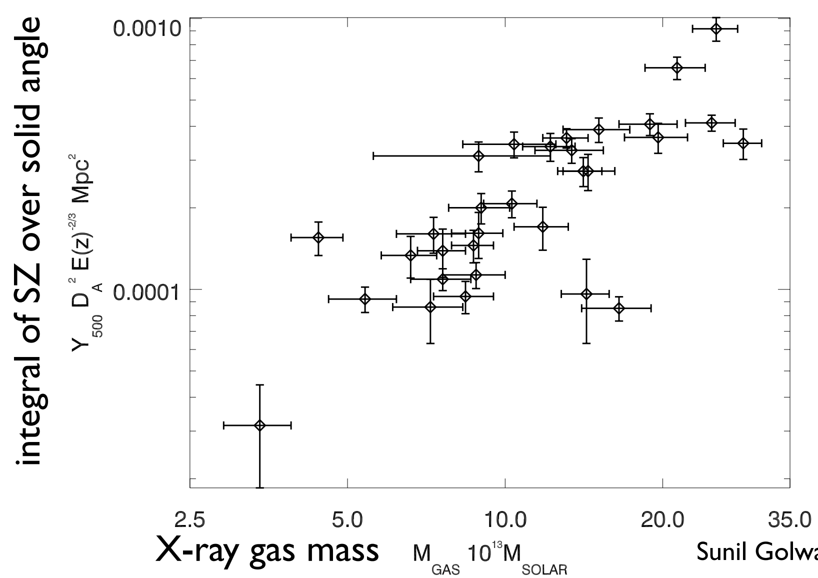
Bolocam SZ Followup

A697	A1835	CL0016	MS0451	MS1054
z=0.28	z = 0.25	z = 0.54	z = 0.55	z = 0.83



Sayers et al 2011

- 150 GHz/1' FWHM/8' FoV camera on Caltech Submm Observatory
  - Built with Bock, Nguyen at JPL, Glenn (CU), Lange, Golwala (CIT)
  - Sayers on NPP at JPL during this work; developed Spitzer and CLASH collaborations
  - Czakon on GSRP at JPL



Czakon et al in prep

Bolocam SZ Followup

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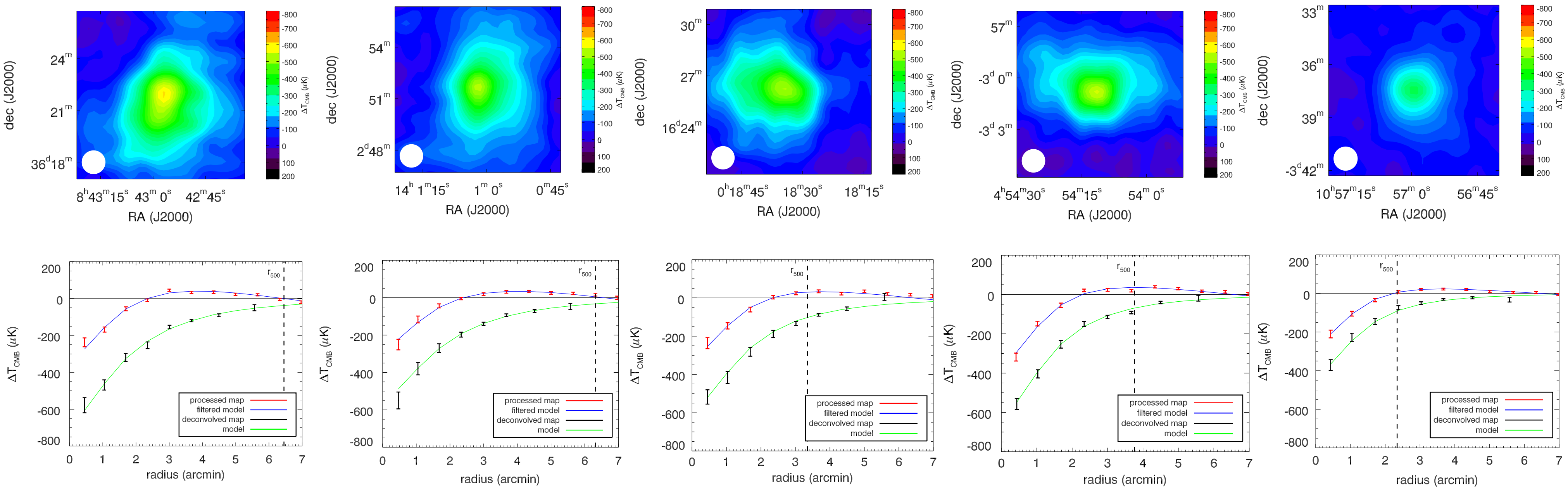
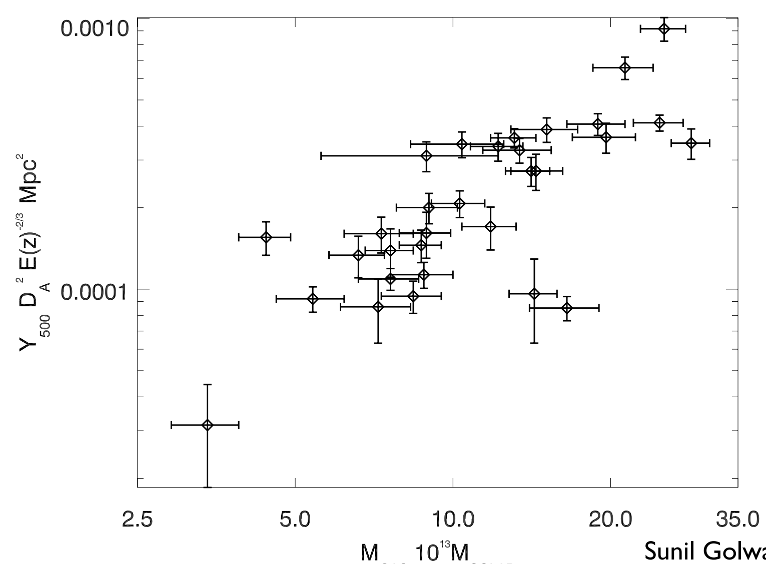


Sayers et al 2011

- Initial 5-cluster sample (Sayers et al 2011)
  - All show evidence of ellipticity in plane of sky;mean ellipticity = 0.27±0.03
  - All fit generalized NFW well except A697, which shows NE/SW asymmetry
  - Sensitivity out to r_{vir} at high z
- 40 clusters reduced, scaling relation in hand



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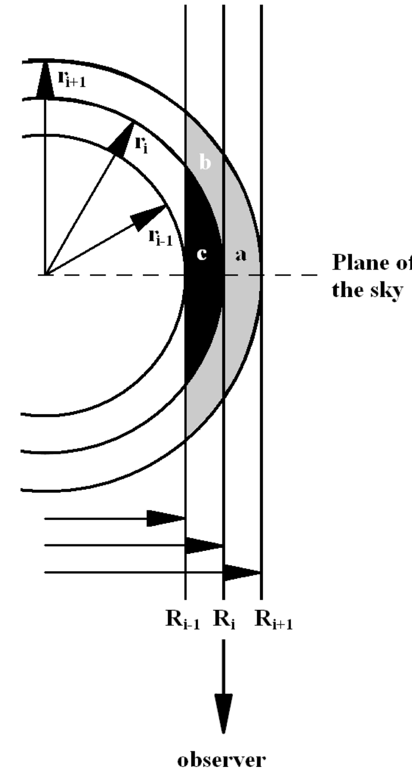
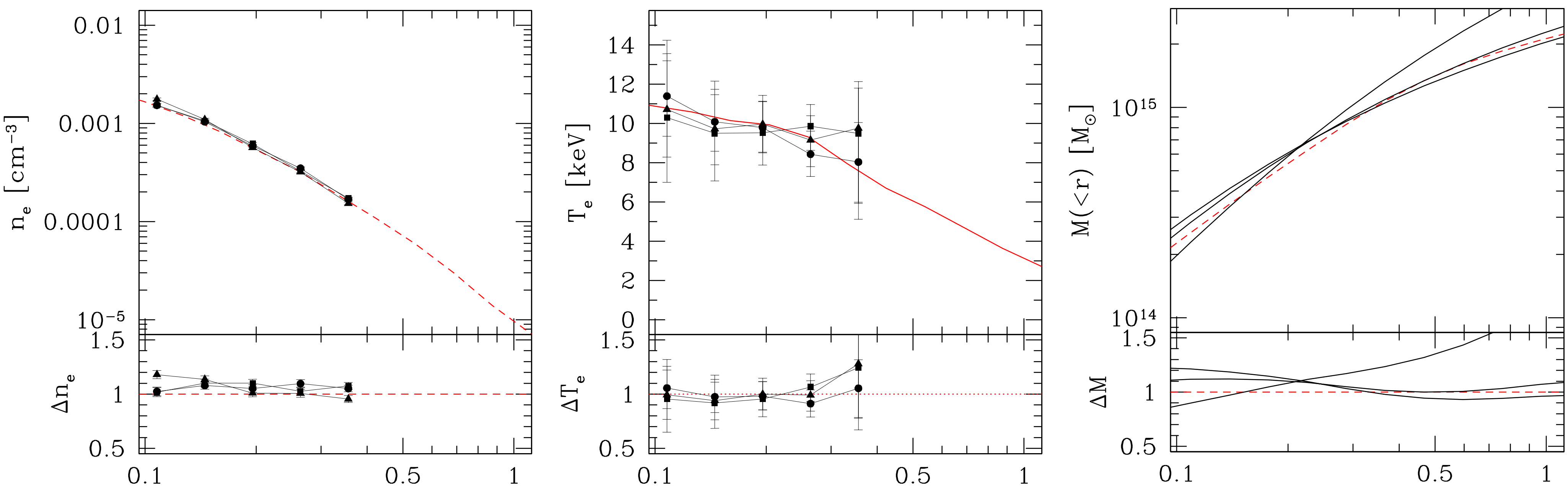


- Joint deprojection with X-ray data
  - Ameglio et al 2007, 2009, work w/Pierpaoli and Ameglio at USC
  - Assume onion-skin structure for cluster and fit density and temperature model to observed data
  - Apply regularization to likelihood to minimize 2nd derivative
  - Gives T_X profile without X-ray spectroscopy; mass-weighted and unbiased; n_e also recovered very precisely and accurately
  - Gives $M(r)$ using hydrostatic equilibrium; small biases
  - Other deprojection methods also possible (e.g., Abel integral)



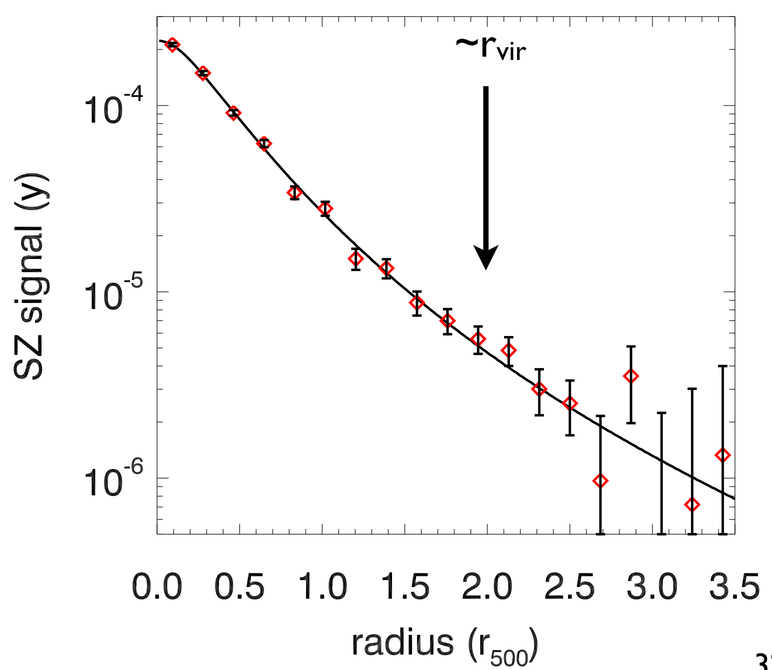
Cluster SZ with MUSIC

- MUlticolor Sub/millimeter Inductance Camera: deploying late 2011
- New technologies enable ~background-limited, multi-color camera (850 μm - 2 mm) with wide FOV (14', 600 spatial pixels)
  - Large-format planar photolithographic phased-array antennas: ~2:1 bandwidth
  - Planar photolithographic bandpass filters: many colors from a single antenna
  - Microwave Kinetic Inductance Detectors (MKIDs): a new, highly multiplexable detector (Day, LeDuc, Zmuidzinas)
- Deeper integrations on CLASH, ~200 clusters based on Planck, WISE, ACT

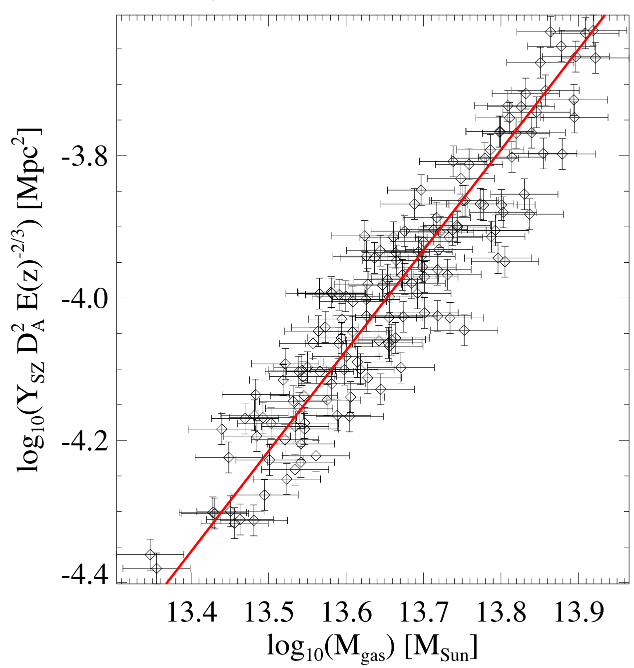
Technologies dev'd w/support from Caltech trustee Alex Lidow, JPL RTD, NASA, Moore Foundation.

Camera dev'd w/ NSF, Moore Foundation support

azimuthally averaged radial profile expected for deep integration on MS0451-like cluster

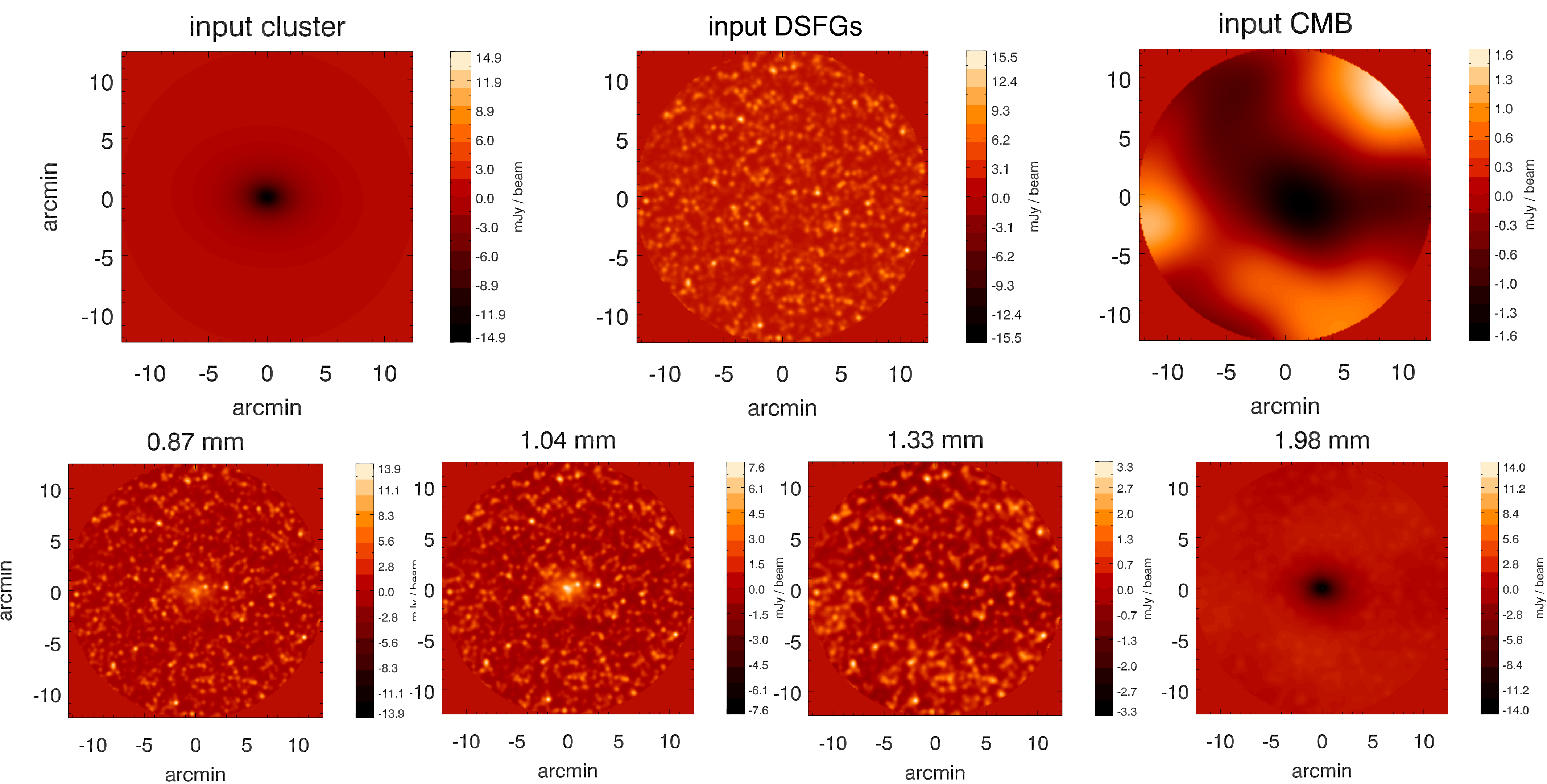


scaling relation determination



MUSIC Galaxy Cluster Studies

- Study galaxy clusters across wavelength regime where SZ gives way to DSFGs; separate SZ, CMB, and DSFGs using multicolor information.

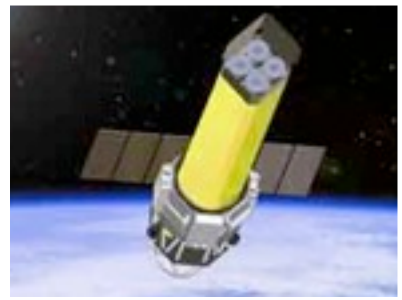


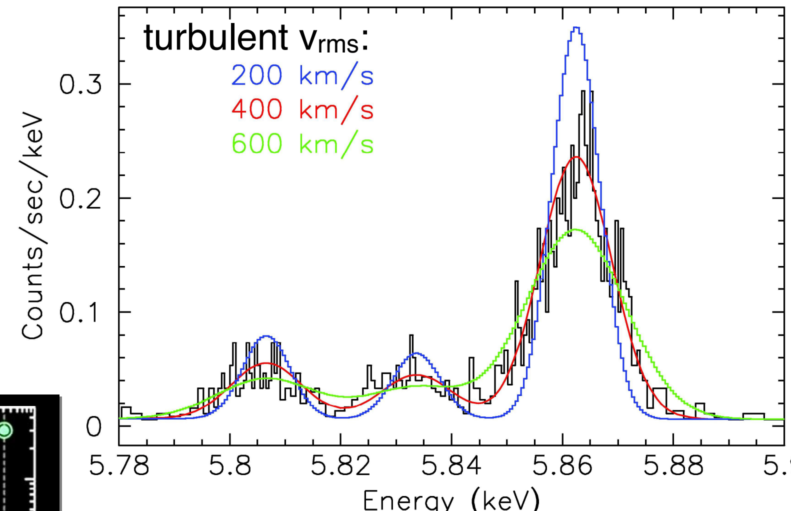
The MUSIC Team

- Instrument Team
  - CU: Jason Glenn, Phil Maloney, James Schlaerth (past GSRP)
  - JPL: Peter Day, Rick LeDuc, Hien Nguyen
  - Caltech: Nicole Czakon (GSRP), Tom Downes, Ran Duan, Sunil Golwala, Matt Hollister (NPP), Dave Miller, Omid Noroozian, Jack Sayers (past NPP), Seth Siegel, Tasos Vayonakis, Jonas Zmuidzinas
  - UCSB: Ben Mazin, Sean McHugh
- Survey Team
  - Arizona: Dan Marrone
  - JPL/Caltech: Ranga-Ram Chary
  - CU: Alex Conley
  - Rutgers: Andrew Baker
- Science Team
  - Caltech: Andrew Benson
  - CU: Nils Halverson
  - JPL/IPAC/Caltech: Colin Borys, Darren Dowell, Olivier Dore
  - USC: Elena Pierpaoli

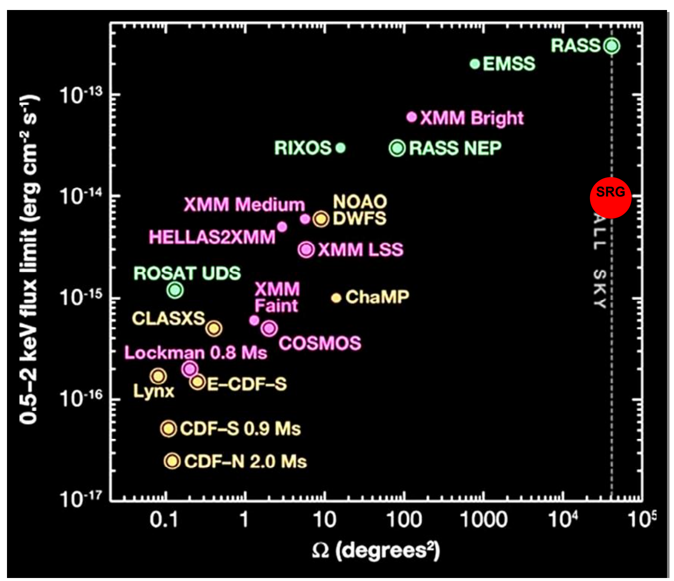
Next-Generation X-Ray Observatories

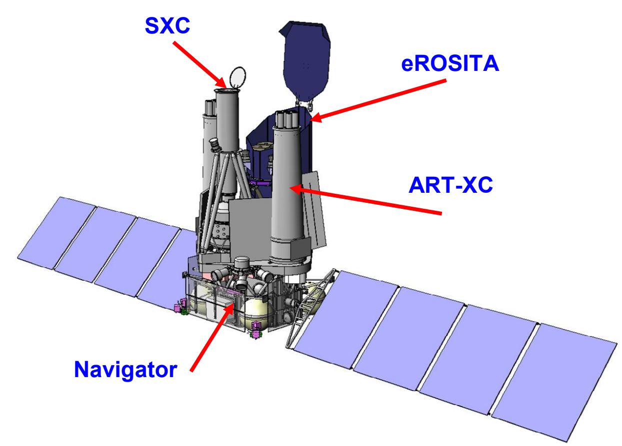
- Cluster studies at higher z will soon become limited by X-ray followup
  - e.g. z = 1.45 XMMXCS J2215.9-1738:
    T_X = 7.4 keV +/- 20% with ~200 ksec XMM-Newton time, 1100 photons detected!
  - Need: higher throughput, better energy resolution for spectral lines, lower bgnd
- Astro-H
  - Increased A_{eff} at high E: more sensitive to high T_X
  - ΔE/E ~ 0.1% (1-2% for Chandra/XMM): new sensitivity to turbulence





- eROSITA
  - First all-sky survey since ROSAT (early 1990s), 30x better sensitivity
  - Clusters to z > 1!
- IXO...

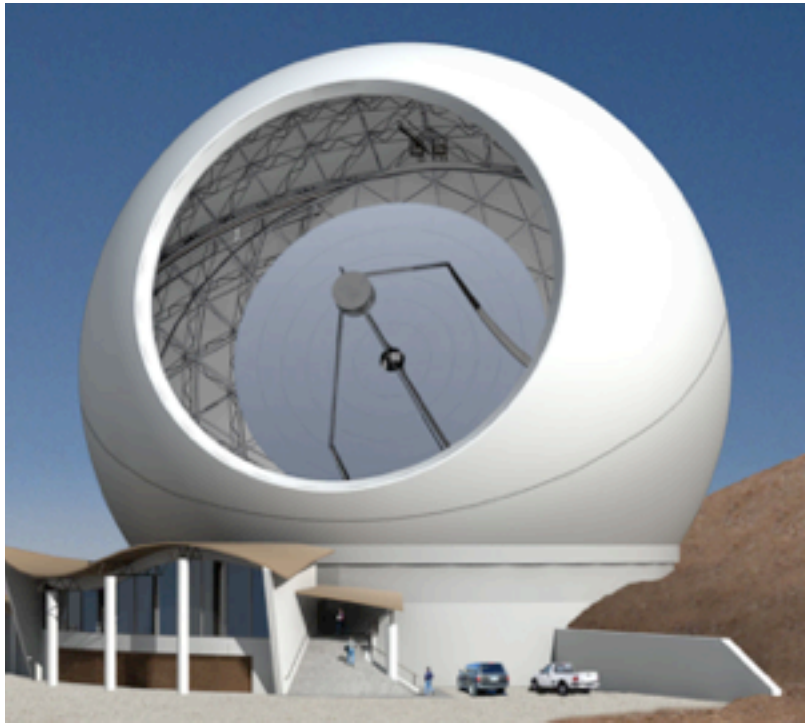




Next-Generation SZ with CCAT

- Cerro Chajnantor, Atacama, Chile, 5600m
- Cornell, Caltech/JPL, + partners (incl. Canada, Colorado, Germany)
- Wavelengths 2-0.2 mm, Frequencies 150-1500 GHz
- Surface accuracy 10 µm
- 25-m; angular resolution 2-20”
- Facility instruments:
  - Large FoV submm/mm cameras
  - Multi-object spectroscopy
- Coincident with ALMA
- www.submm.org
- Substantial JPL technical and scientific involvement on primary deformation control and science from star formation to cosmology

Next Generation SZ with CCAT



- Vital characteristics
  - Site much better than Mauna Kea
  - Larger dish (25 m vs. 10 m CSO)
    → 0.4’ at 150 GHz, 0.2’ at 275 GHz
  - Large $A_{tel}\ \Omega_{FoV}$ product; FoV = 1°
- SZ: Higher angular resolution followup of clusters from wide-area surveys
  - good angular resolution out to R_{vir}
  - better sensitivity to point sources
  - cluster substructure and calibration
- Instrumentation: MUSIC follow-on
  - Cover 5-6 colors in each pixel, 750 μm to 2 or 3 mm
  - Multiscale pixels to match pixel size to Airy function (wider bandwidth)
  - New channelizer concept? Enormous spectral information.

Band GHz (μm)	Δν (GHz)	Pixel Size f·λ	Number of Spatial Pixels
150 (2000)	30	2.3	16 tiles × 64 = 1024
220 (1400)	40	3.2	16 tiles × 64 = 1024
275 (1100)	50	2.1	16 tiles × 256 = 4096
350 (870)	40	0.7 2.8	4 tiles×4096 = 16384 12 tiles × 256 = 3072
405 (740)	30	0.8 3.2	4 tiles×4096 = 16384 12 tiles × 256 = 3072
Total			45,056 detectors

Questions, Questions, Questions

Does the dark matter profile evolve with time?
Is it reflective of the redshift of formation?

What is the baryon fraction as a function of radius and redshift?

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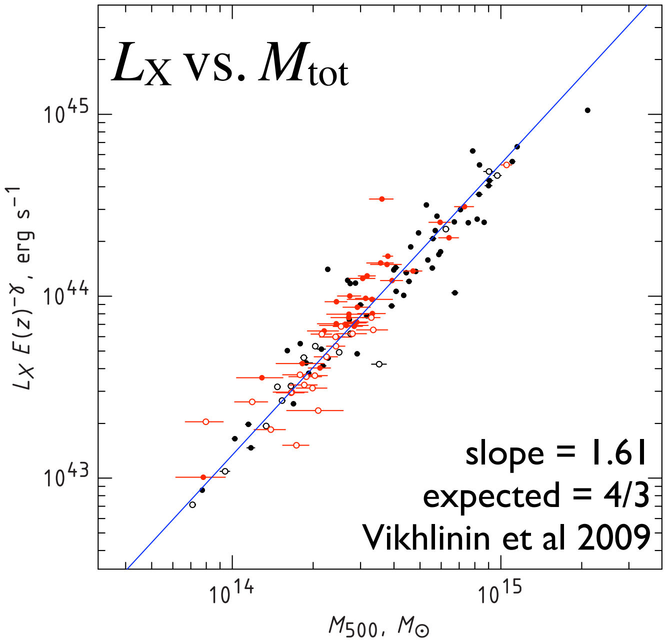
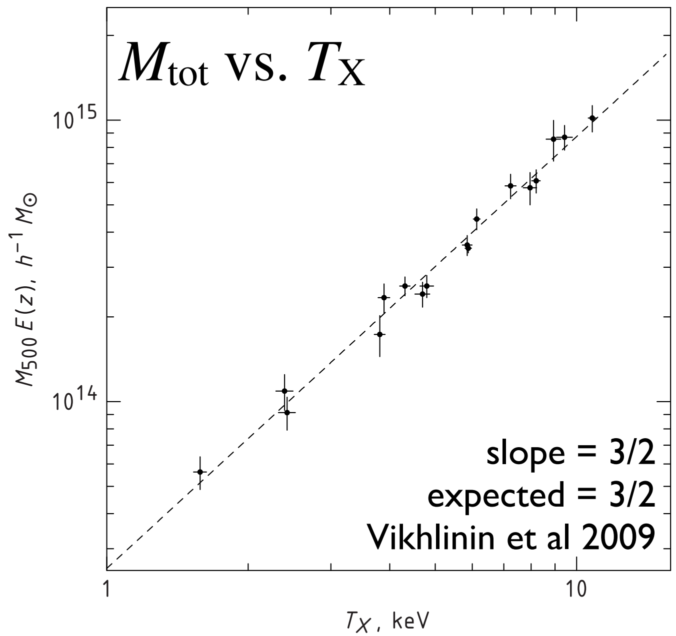
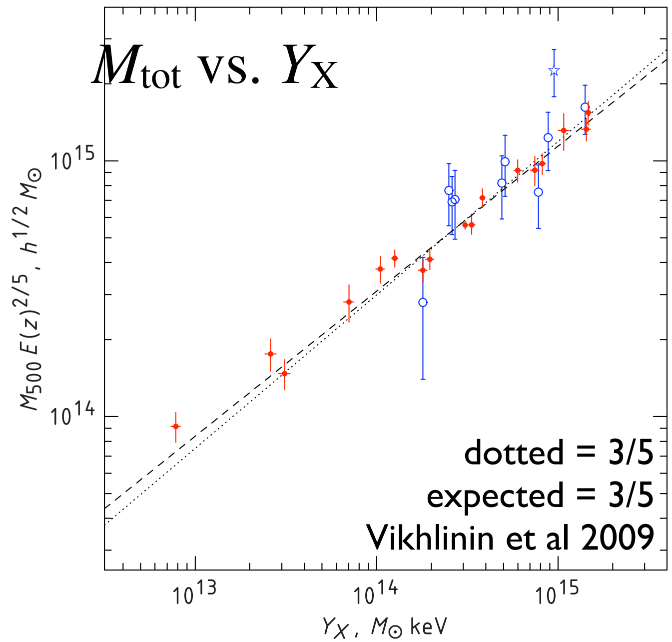
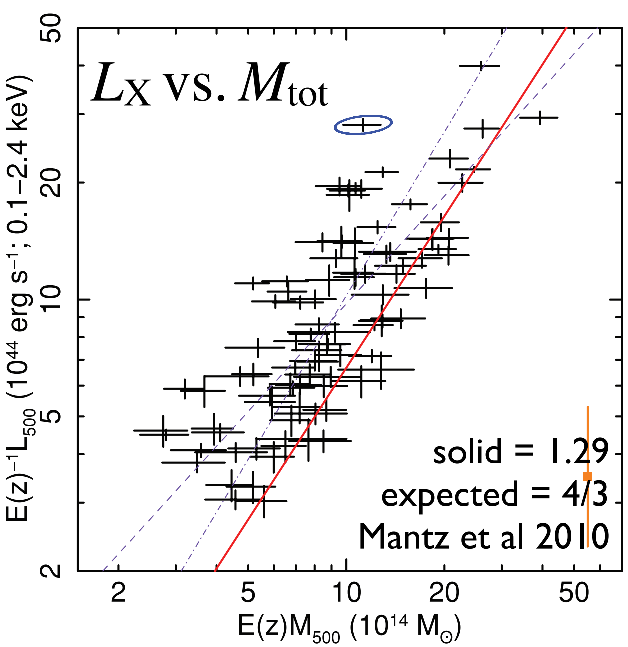
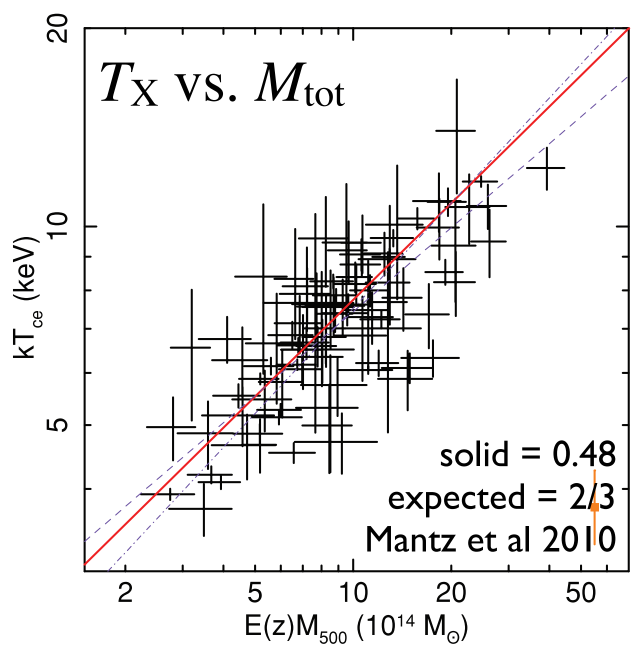
Scaling Relations: X-ray Only

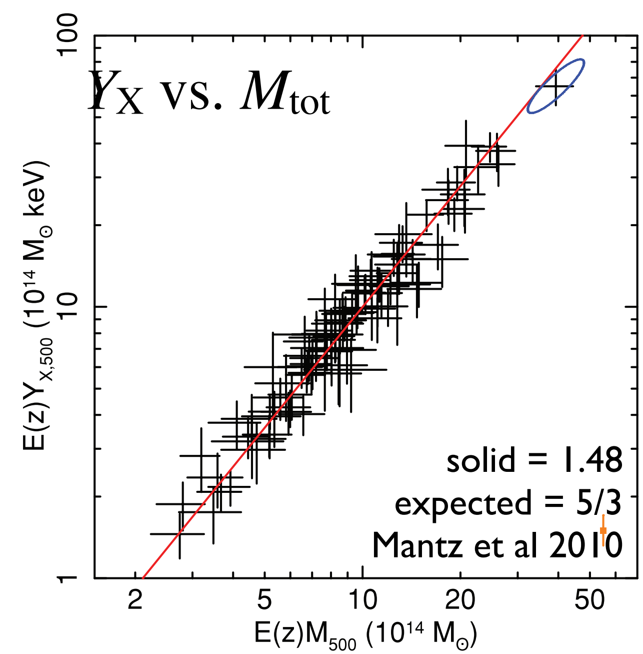




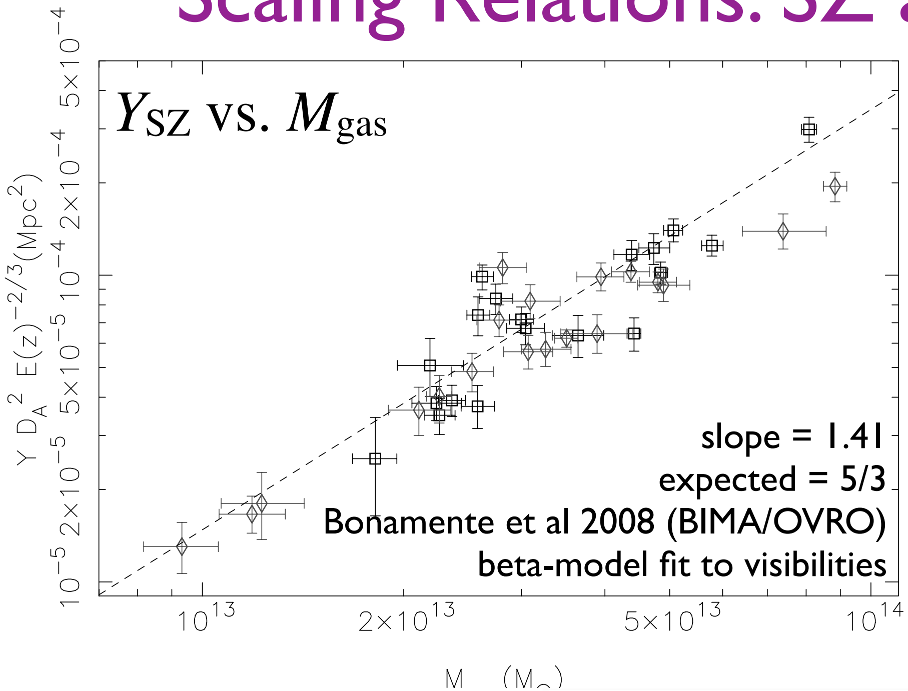


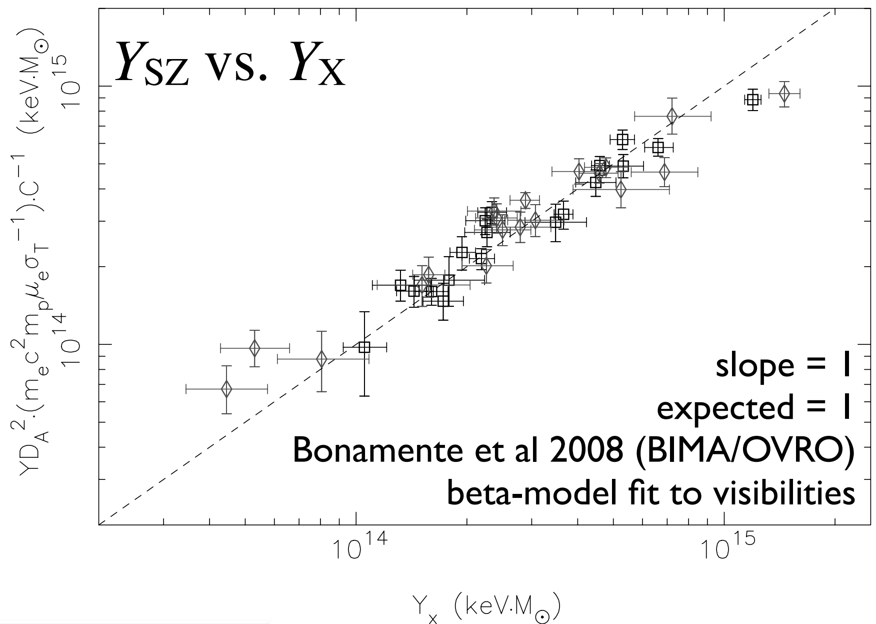


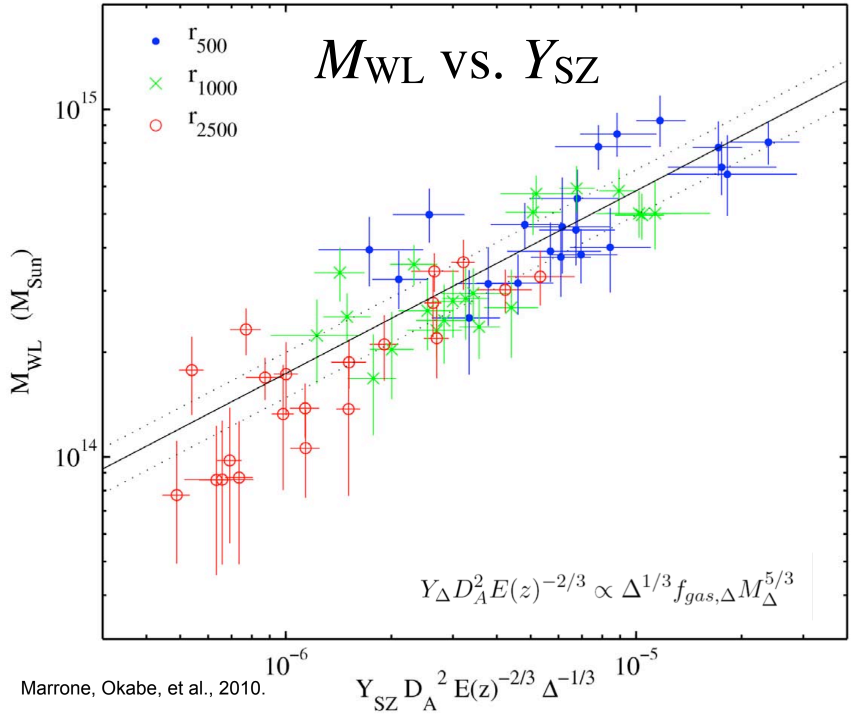




Scaling Relations: SZ and X-ray, Weak Lensing

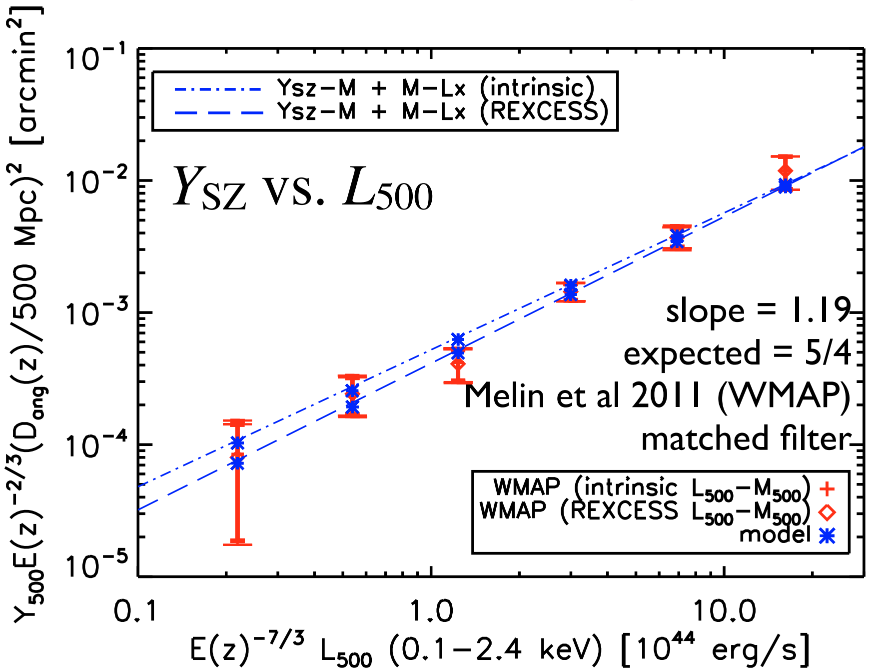


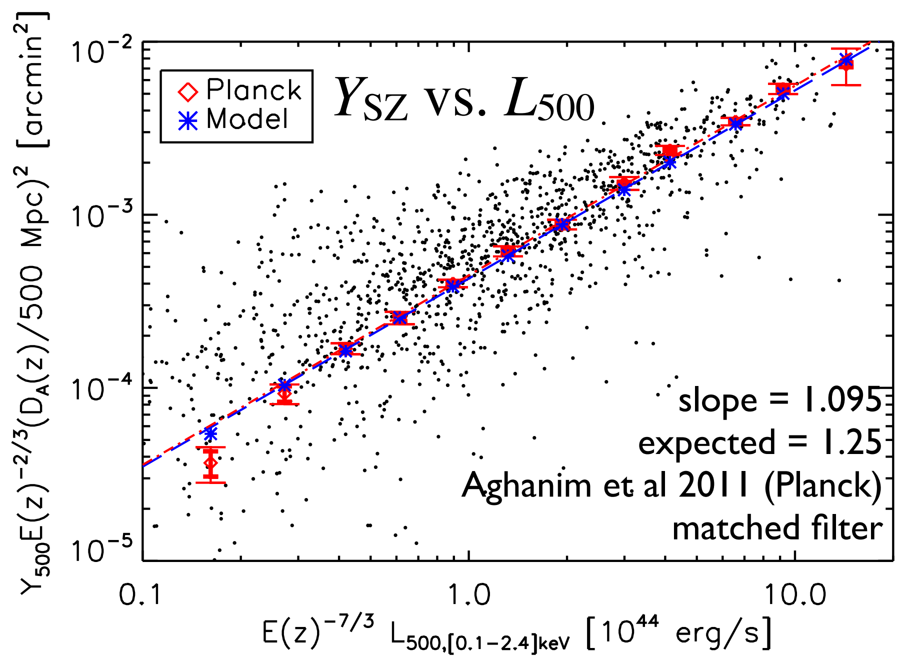


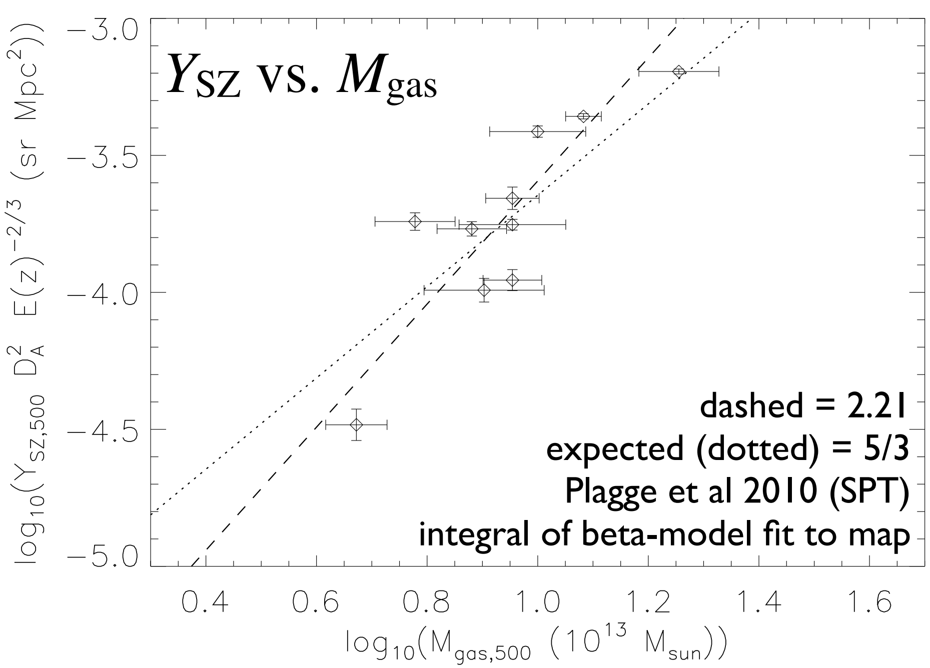


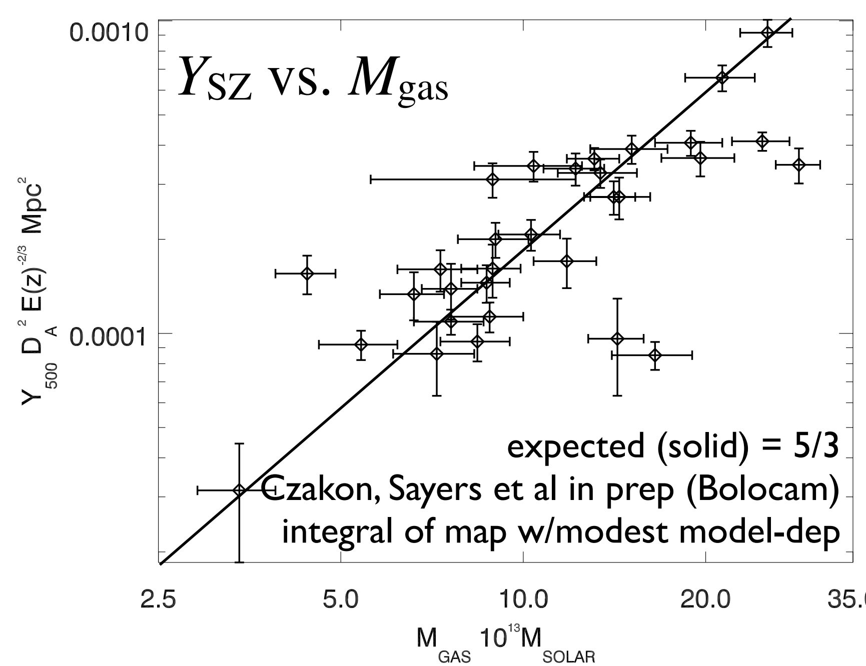
Marrone et al in prep (BIMA/OVRO/SZA)
beta-model fit to visibilities

Scaling Relations: SZ and X-ray



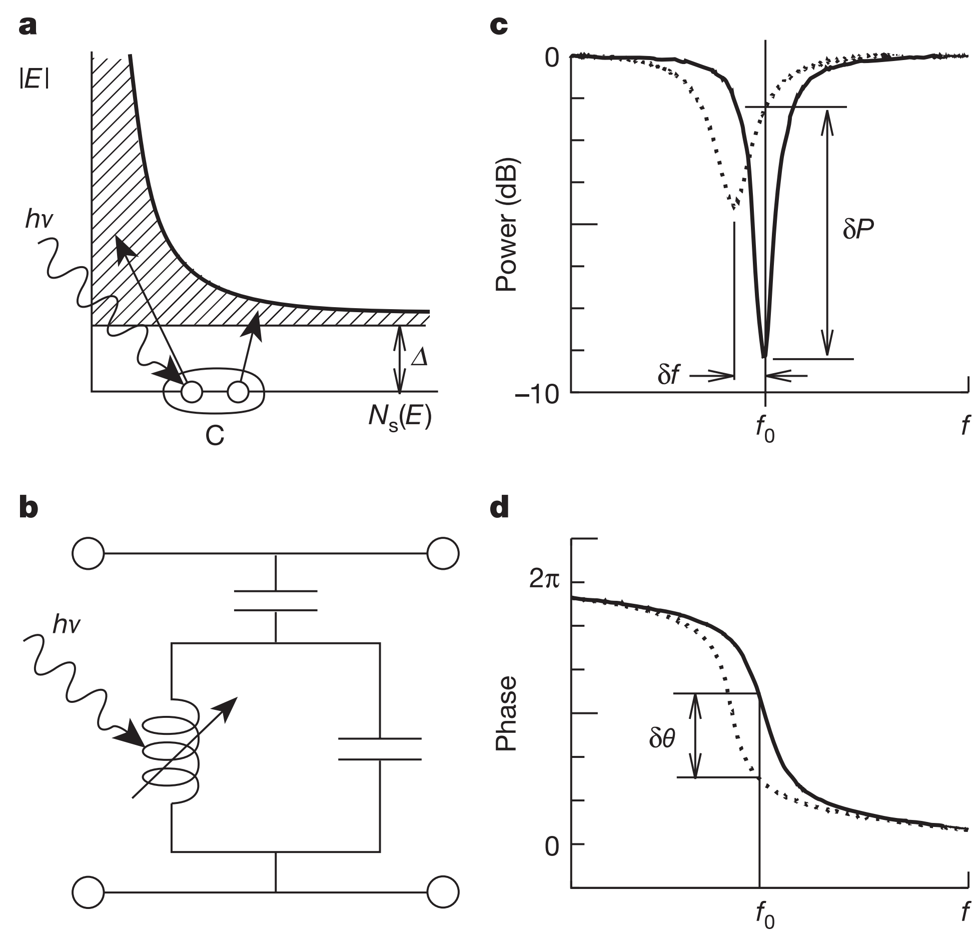




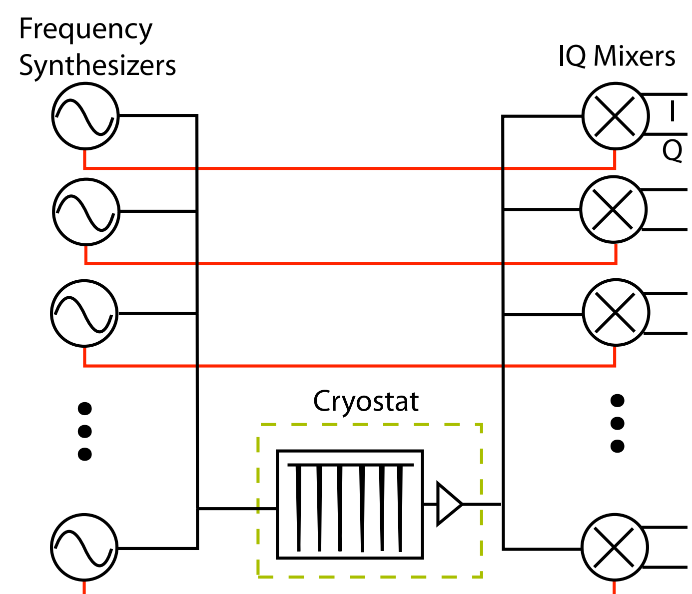


MKIDs

- Microwave Kinetic Inductance Detectors (Zmuidzinas et al, Day et al, Mazin PhD thesis) sense energy deposition via change in superconductor's *kinetic inductance* (Cooper pair inertia) as measured by frequency shift of resonator
- Can be as sensitive as bolometric detectors, w/many prospective advantages:
  - easier to fabricate
  - completely athermal detection mechanism
  - highly multiplexable w/large individual sensor bandwidth due to unique RF readout



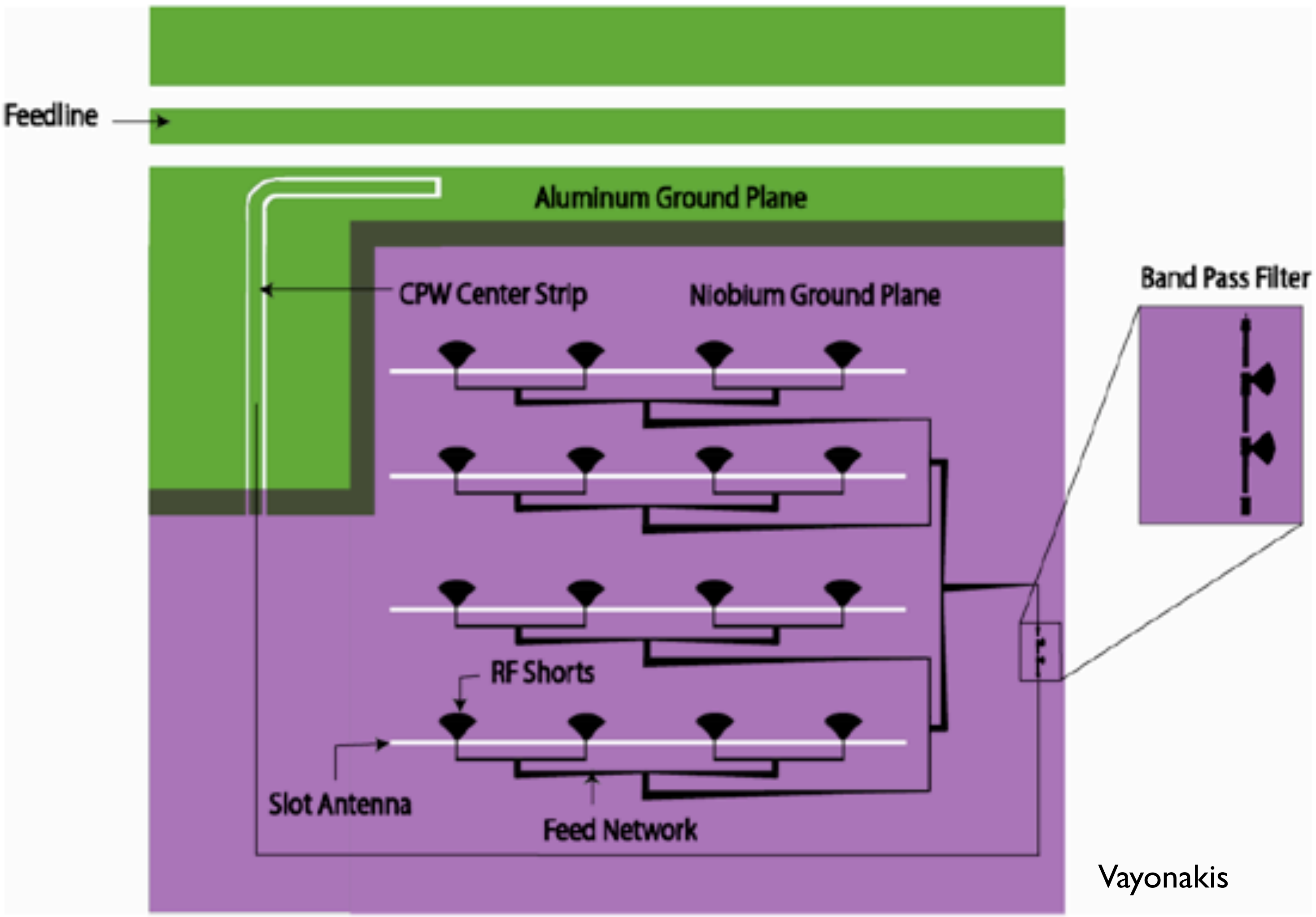
Day et al, Nature (2003)



Mazin

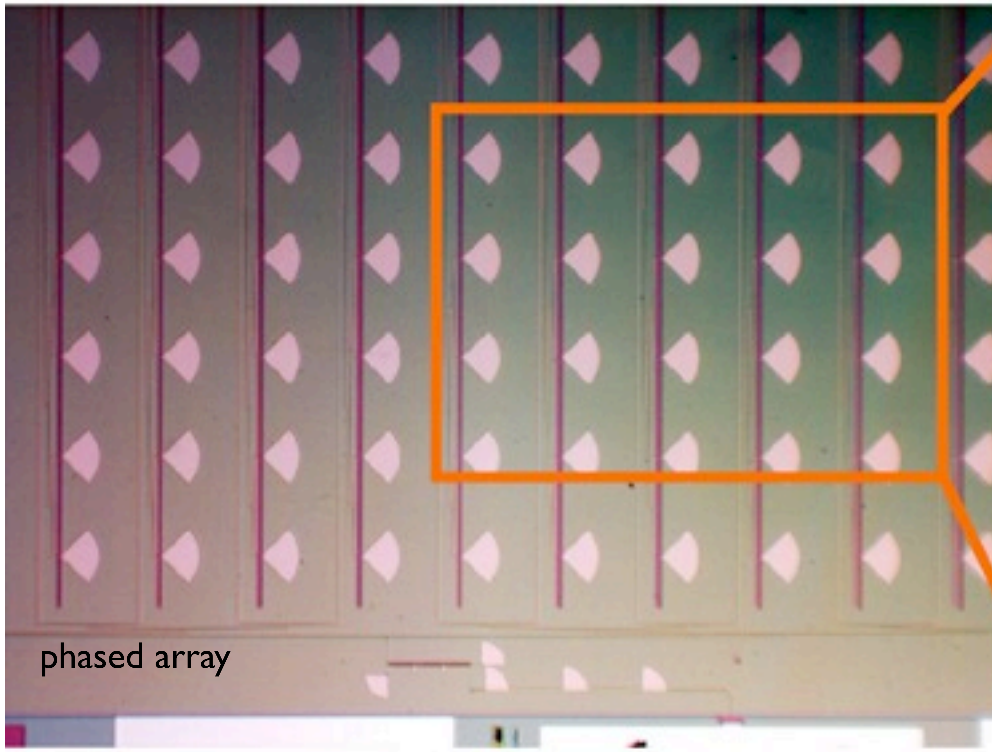
Antenna Coupling and Inline Bandpass Filters

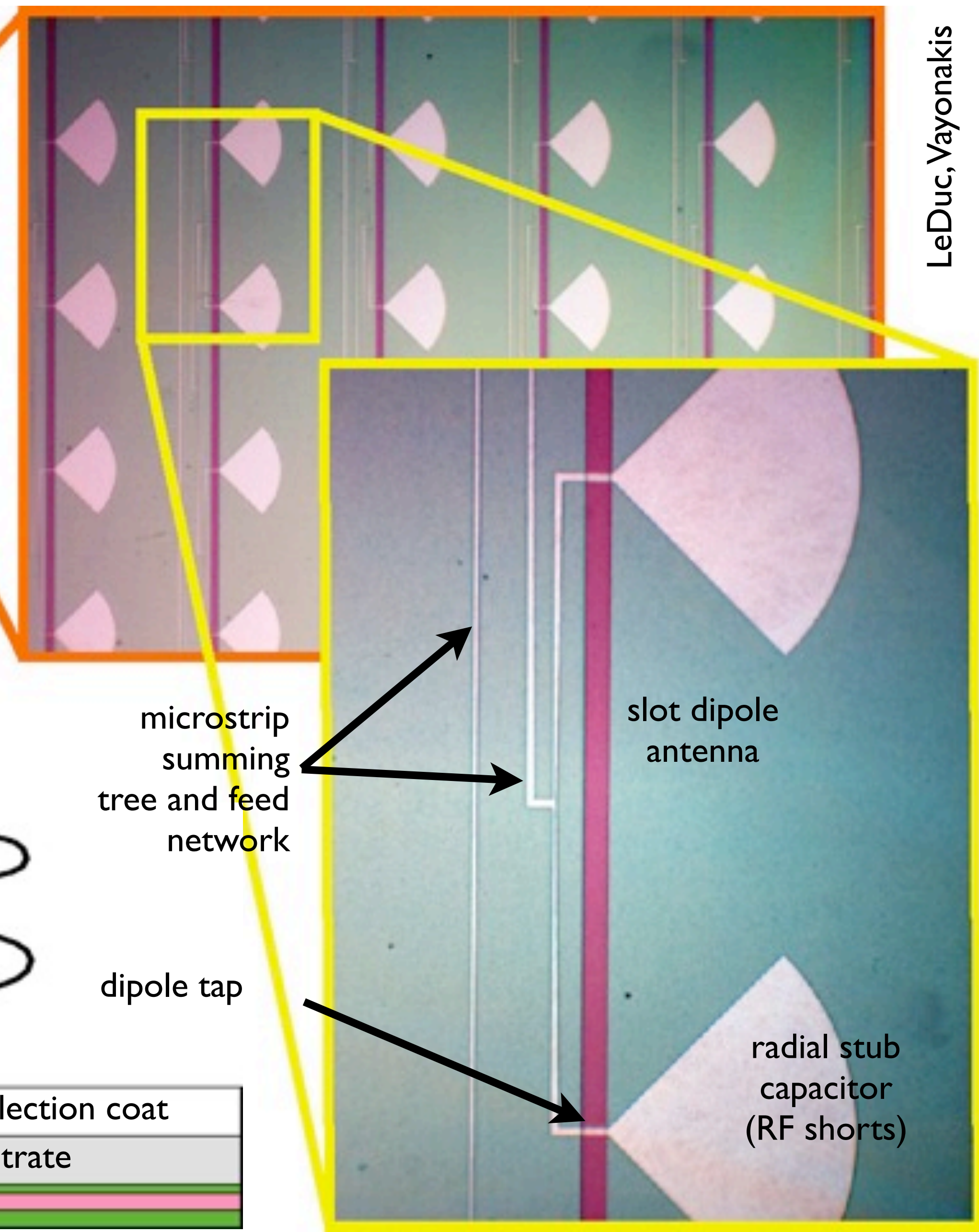
- Feedhorns are bulky, low fill-factor, and monochromatic
- Perform the beam definition with a phased-array antenna (Bock, Day, Zmuidzinas)
  - planar geometry, photolithographic fabrication
  - ~octave bandwidth
  - power exits on microstrip transmission line
  - bandpass filters may be inserted
  - separates optical absorption from power detection (decouples detector size)
  - power absorbed in MKID resonator



Vayonakis

Antenna Coupling

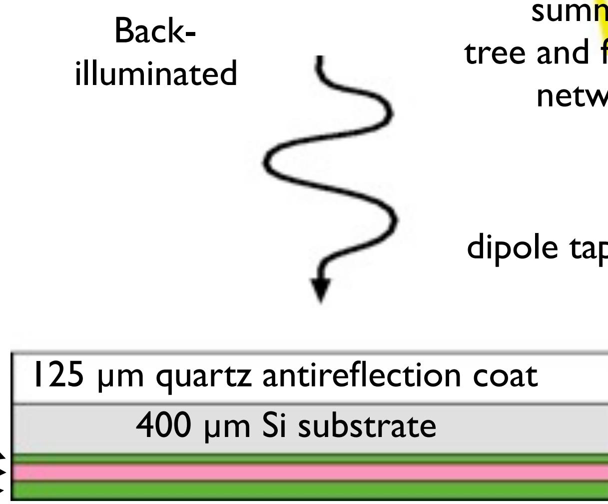




3 mm slot length, 3 mm array width
16 slots, 16 feeds per slot
188 μm feed and slot spacing
20 micron slot width

40 nm Al MKID

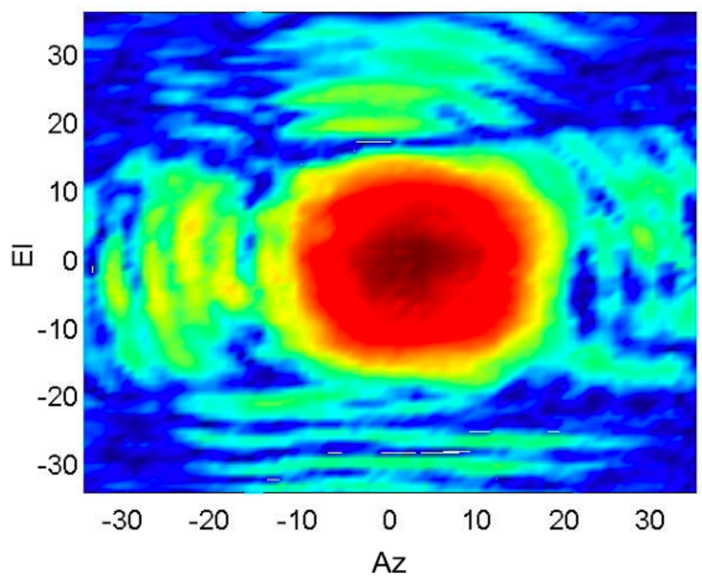
200 nm Nb ground plane
400 nm SiO_2 microstrip dielectric
400 nm Nb wiring layer



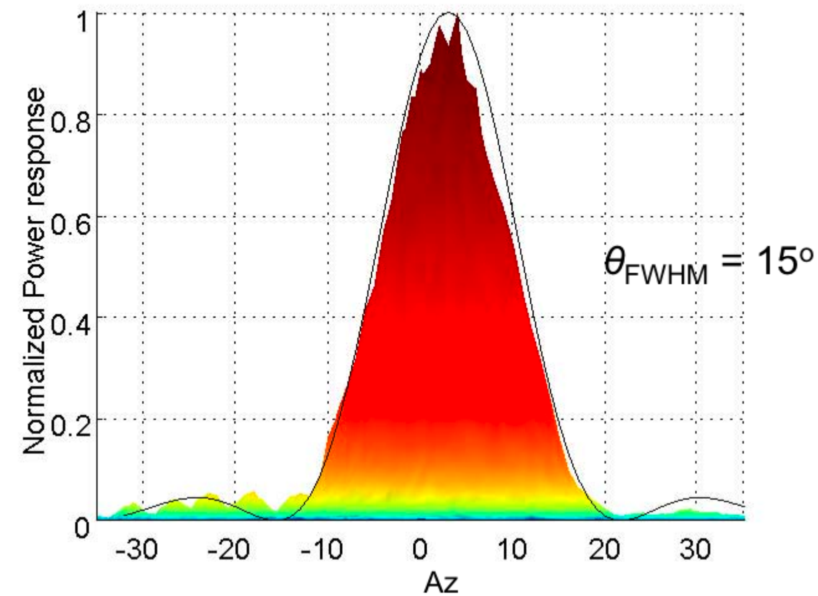
Antenna Coupling

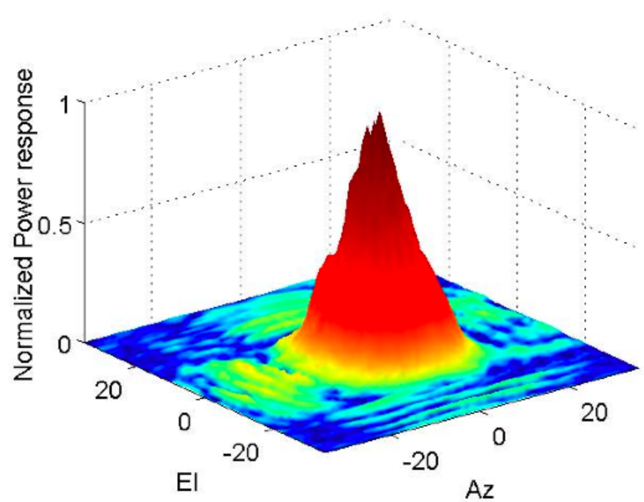
- 100 GHz scale model measurements (narrowband source)

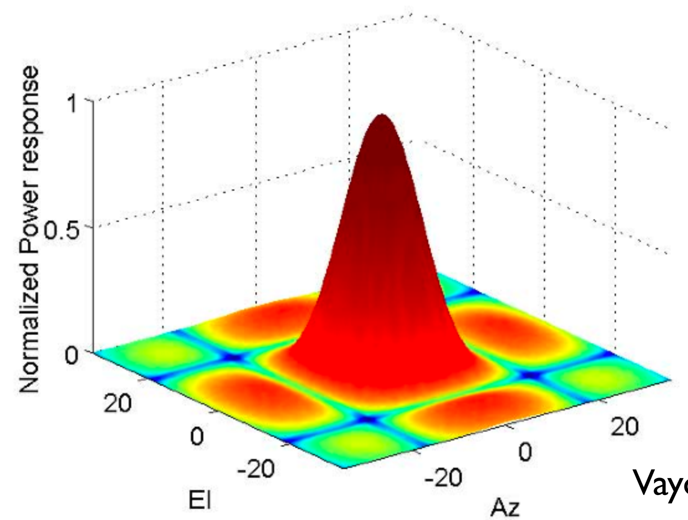
Measured:



Calculated:

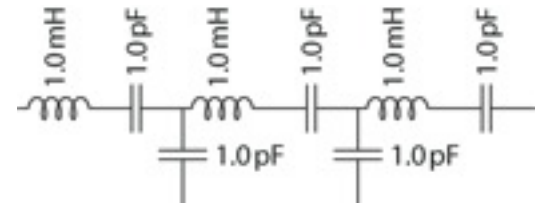




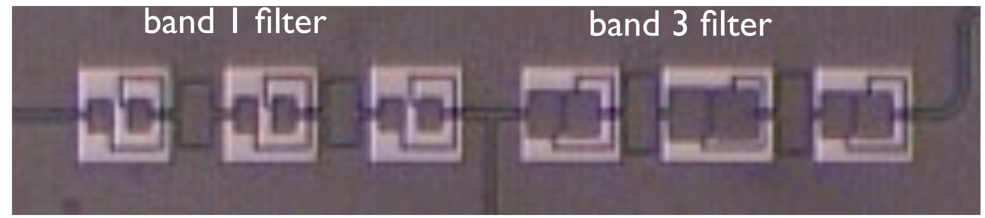


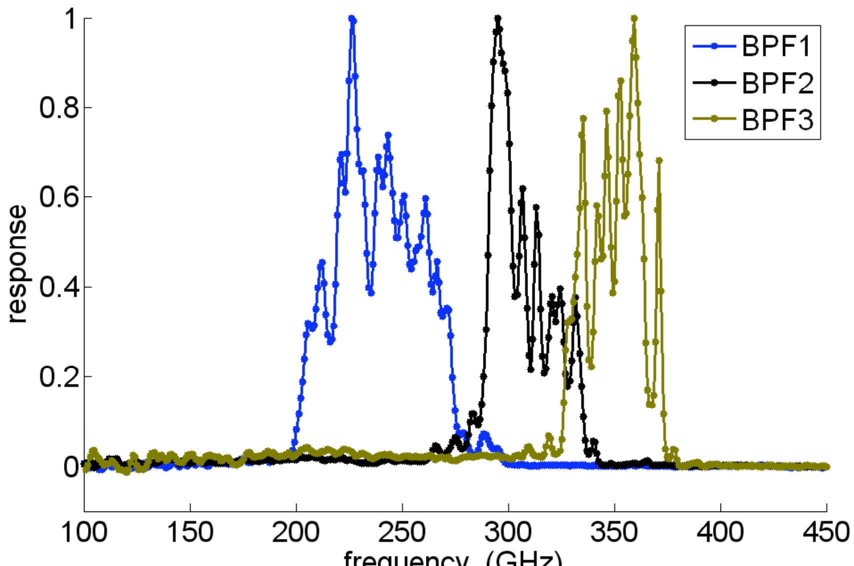
Vayonakis

Antenna Coupling

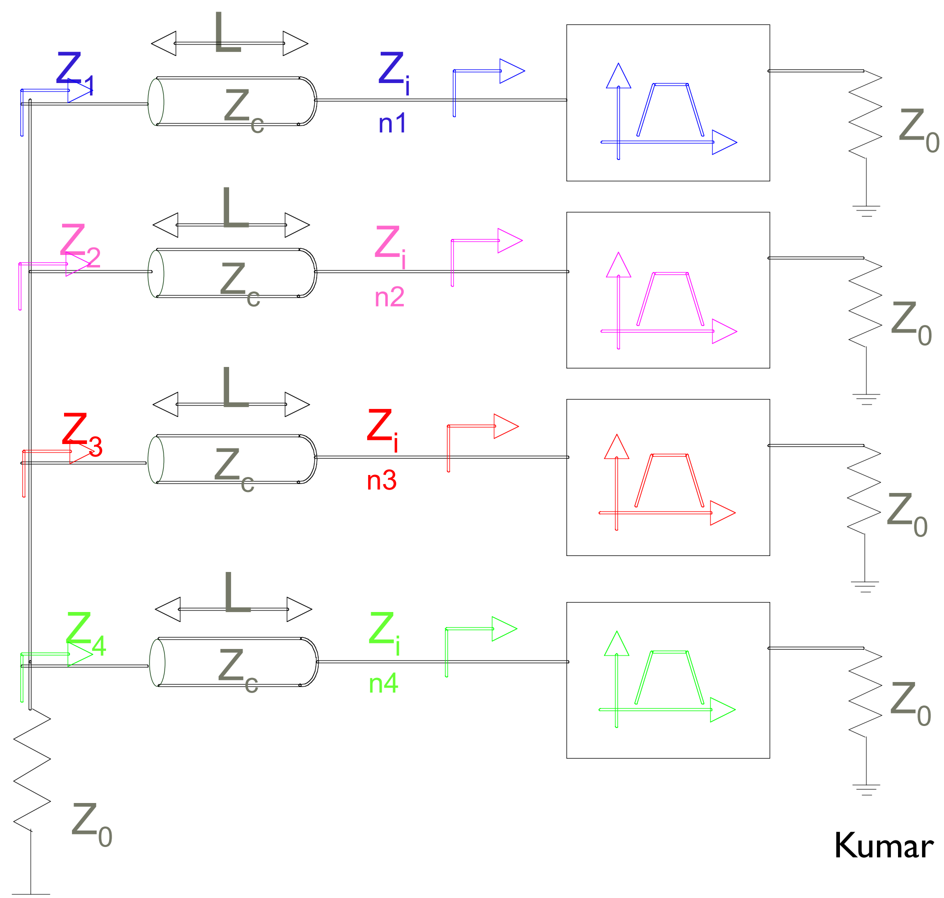


- Colors defined by in-line bandpass filters
  - lumped-element LC filters
  - High out-of-band impedance allows many filters in parallel
  - Maximally efficient use of all photons received
  - Good match to SZ and thermal emission from dusty submm galaxies



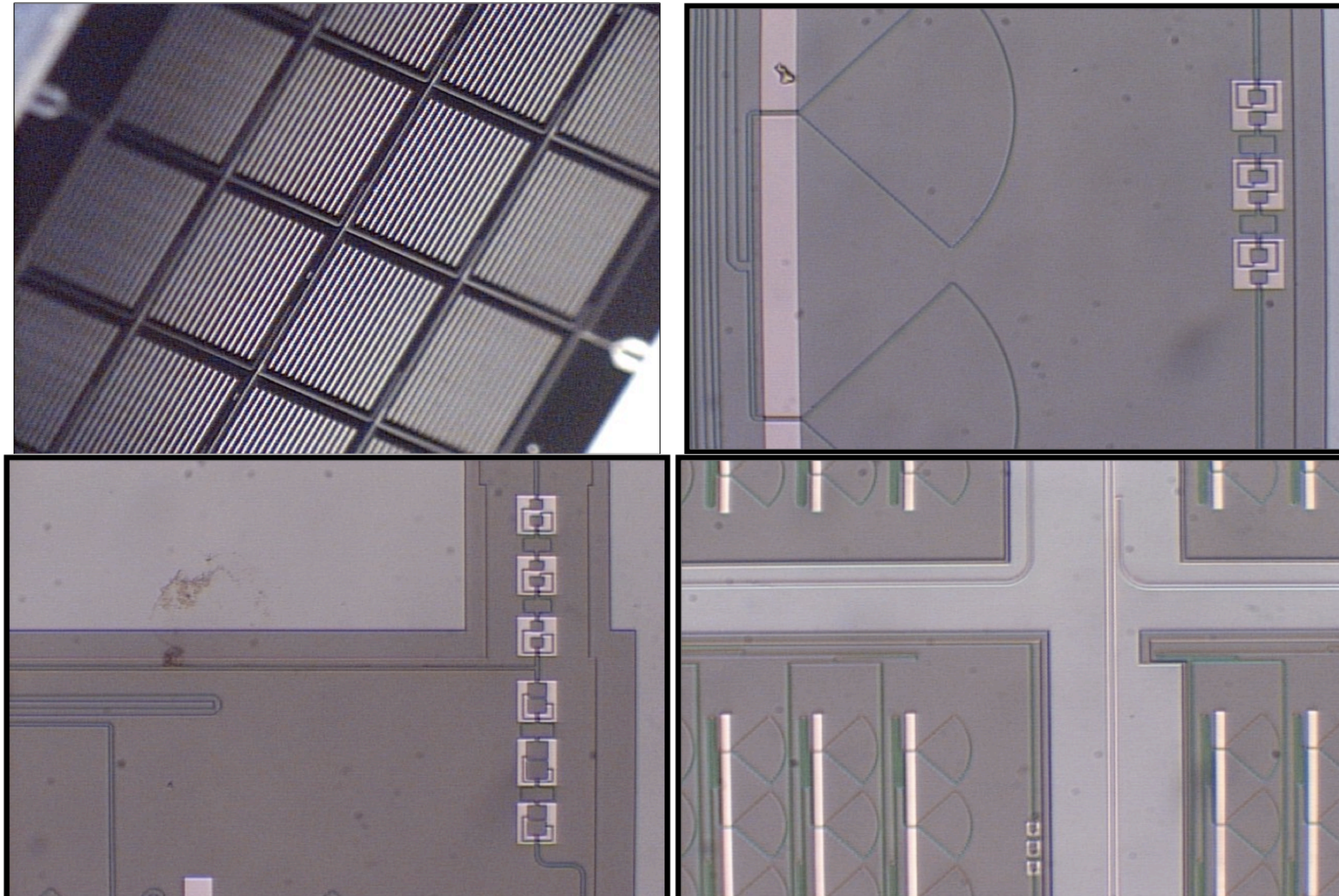


Vayonakis



Kumar

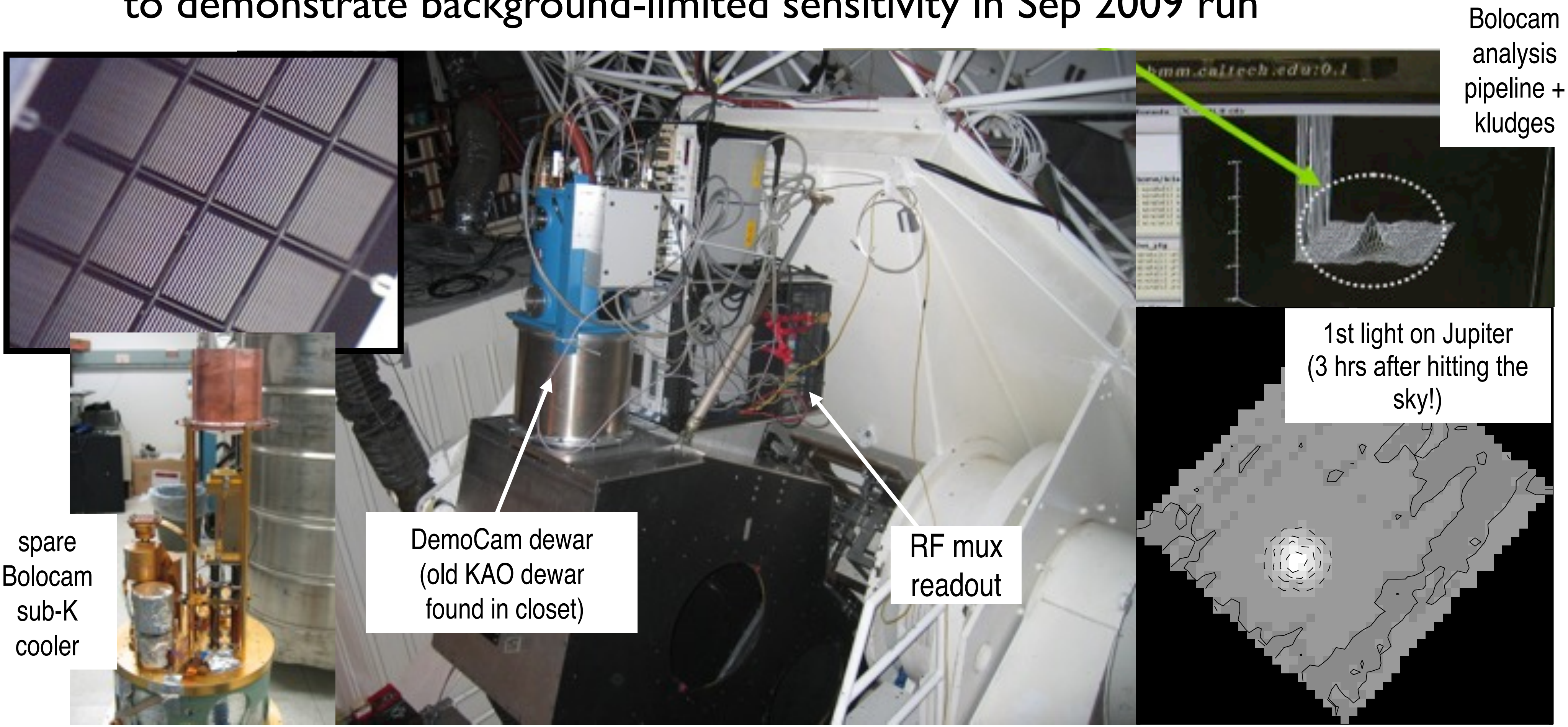
Multicolor Antenna-Coupled MKIDs



Detector development funded by JPL RTD, NASA APRA, Moore Foundation

Submm/mm MKID Demonstration Camera

- 16-pixel/2-color DemoCam fielded at CSO in 2007 and 2010
- *First astronomical photons for antennae, bandpass filters, and MKIDs (2007)*
- All components functional, observed planets and bright sources
- Sensitivity ~20x off goal, largely understood at this point; expect to demonstrate background-limited sensitivity in Sep 2009 run



MUSIC Status

- System-level pieces coming together well
  - Dewar/cryogenics working well
  - New relay optics done
  - Final version of RF readout electronics in hand
  - Beams and bandpasses look good
- Challenges: sensitivity being limited by:
  - Low optical efficiency: 6-12% for device, expect ~50-60%.
    - Working on improving this by fully optimizing AR coatings, etc.
  - Direct optical absorption by MKIDs
    - Testing modified MKID designs less susceptible to direct absorption
  - 1/f in electronics
    - New iteration with more careful thermal design
    - Studying RF amplifier 1/f; promising results obtained
  - Expect to solve these soon and go into production on science arrays!
- Instrument integration summer 2011
- Commissioning in fall, 2011