Cosmological Studies with SZE-determined Peculiar Velocities

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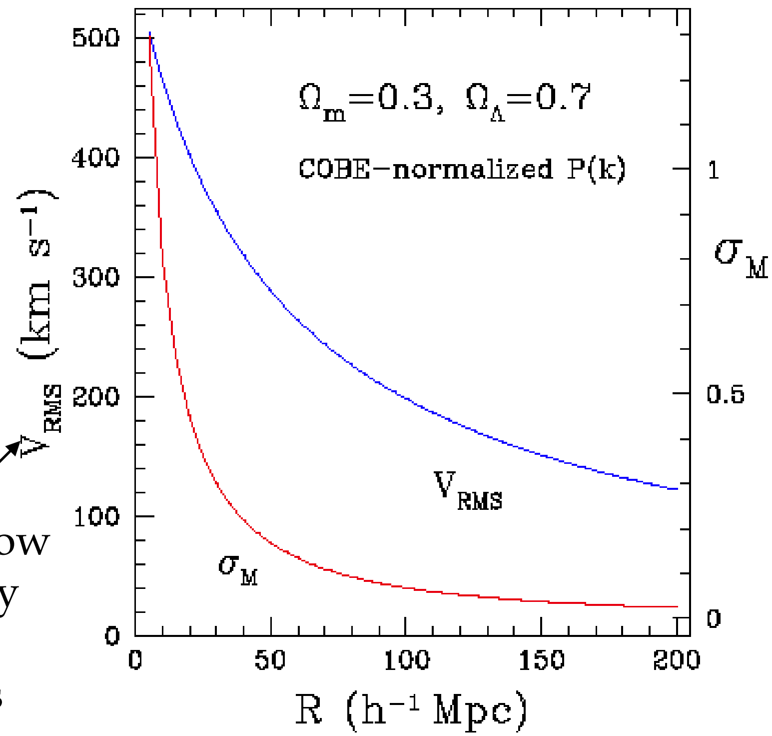
Outline

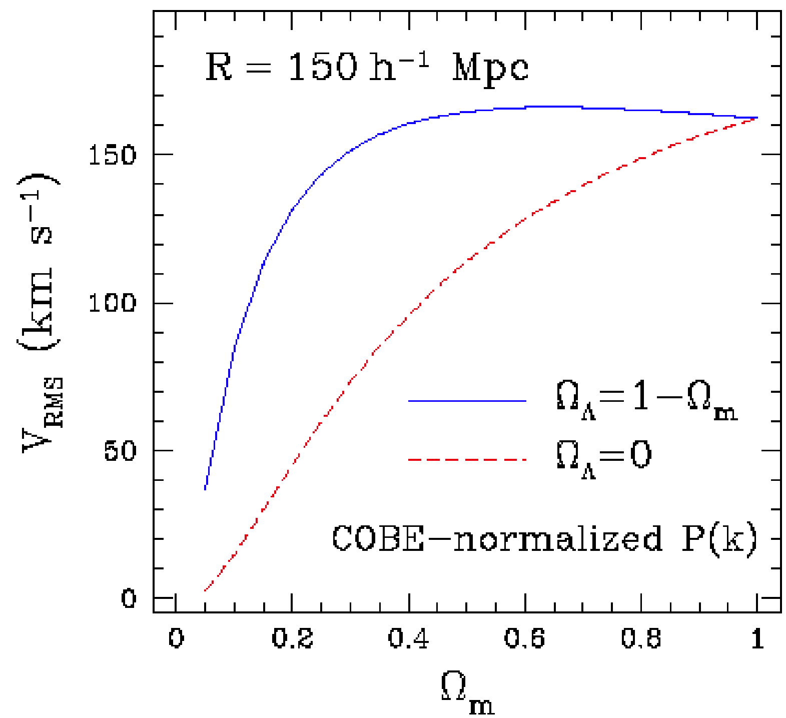
- Why Measure Peculiar Velocities?
  - Cosmological information complements other techniques
- Experimental Status
  - SuZIE – the Sunyaev-Zel'dovich Infrared Experiment
- Other information from SZ spectral measurements
- Future Directions
  - Experiments
  - Theoretical/experimental issues

Peculiar velocities are more sensitive to large scales than density fluctuations

Dependence of present day bulk velocities on volume and matter density, from Willick (2000)



RMS flow of many such regions

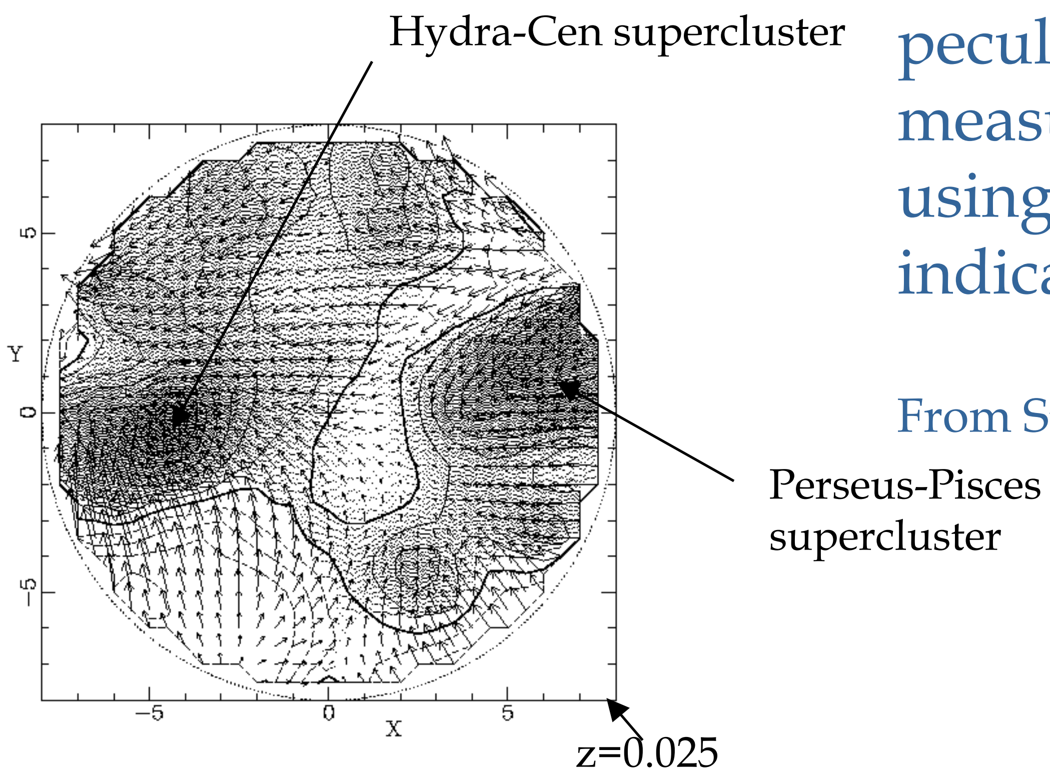


$$\left\langle v^2(R)\right\rangle = \frac{\Omega_m^{1.2}}{2\pi^2}\int_0^\infty dk\, P(k)\widetilde{W}^2(kR)$$

Implies that a measurement of velocity rms can be used to probe Ω_m

$$\left\langle \sigma_M^2(R)\right\rangle = \frac{1}{(2\pi)^3}\int_0^\infty d^3\mathbf{k}\, P(k)\widetilde{W}^2(kR)$$

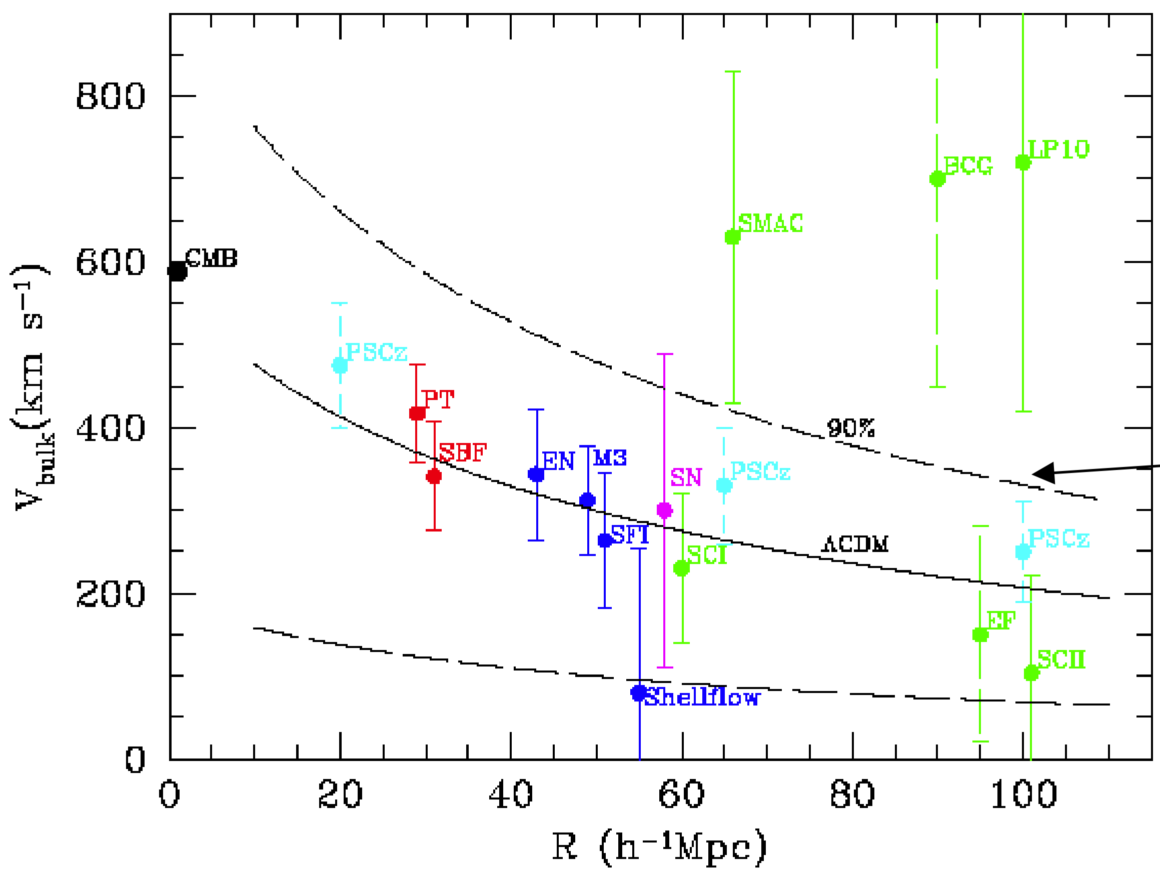
Optically-determined peculiar velocities have been used to trace mass….



Reconstruction of the local mass density from peculiar velocity measurements made using empirical distance indicators.

From Strauss and Willick (1995)

and to measure bulk flows in the local universe



Dekel, astroph/9911501

Cosmic variance limit

The SZ effect can measure peculiar velocities out to high redshifts

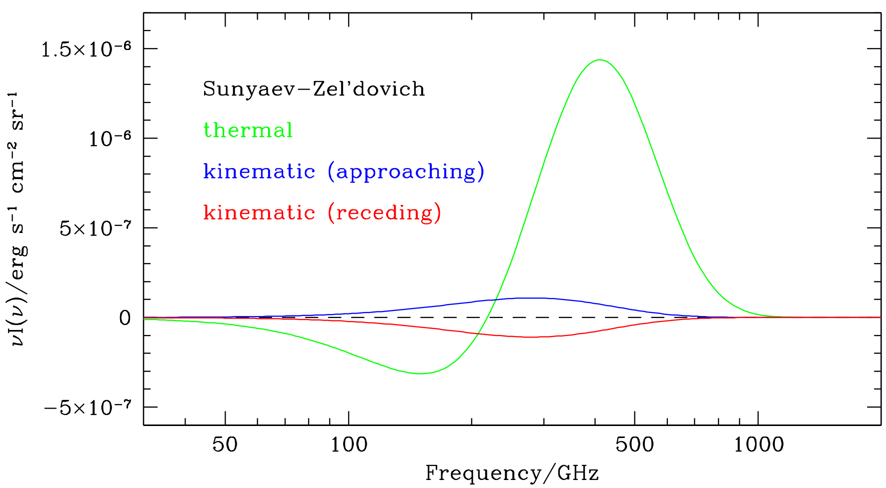
- Thermal effect: $$y_{th} = \tau \times \frac{kT_e}{mc^2}$$

- Kinematic effect: $$y_{kin} = \tau \times \frac{v_{pec}}{c}$$

- If the two effects are separately measured, then:

$$\frac{v_{pec}}{c} = \frac{y_{kin}}{y_{th}} \times \frac{kT_e}{mc^2}$$

- The precision is redshift-independent



Why are SZ-derived peculiar velocities interesting?

- From the continuity equation for mass:

$$ikv = \dot{\delta} \propto \dot{D}(z, \Omega, \Lambda)$$

Where D is the growth function

$\Rightarrow$ cosmological probe

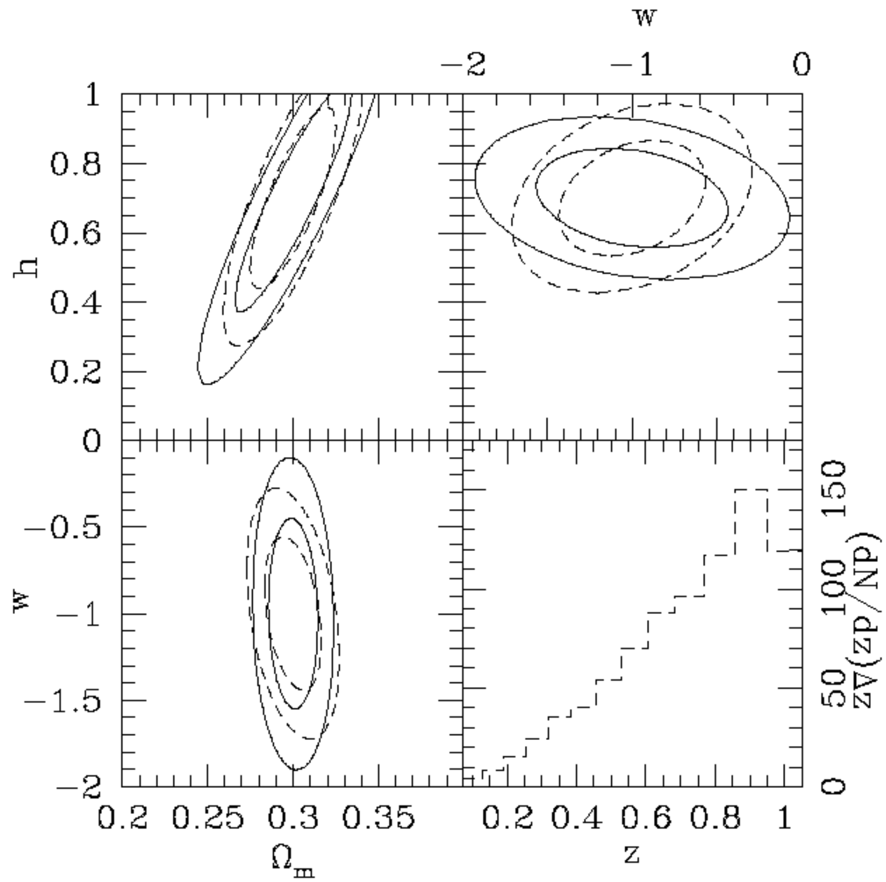
- Derivative of the growth function is less sensitive to w than the growth function itself

  $\Rightarrow$ can determine Ω_m independently of w

  (Peel and Knox, astroph/0205438)

- Reconstruct the Gravitational Potential (Dore, Peel & Knox, 2003, ApJ, 585, L81.)
  - Complements weak lensing

Getting Ω_m from peculiar velocities



A large sample of SZ-derived peculiar velocities can *in principle* be used to constrain Ω_m independently of the dark matter equation of state

Peel & Knox astroph/0205438

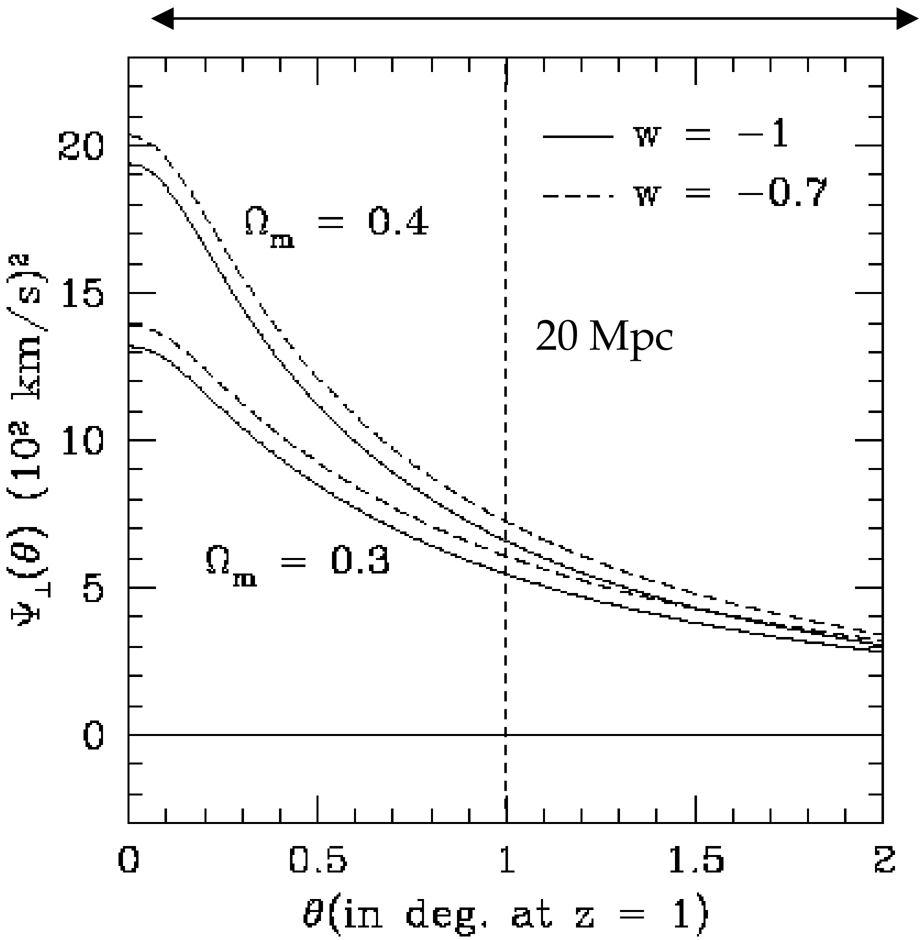
Predictions based on 800 radial velocities to a precision of 100 km/s per cluster

Dashed line – survey of bright clusters over large sky area

Solid line – smaller area deep survey

The technique involves measuring the rms velocity of a cluster sample, and comparing it to theory

Only contains about $1 \geq 10^{14}\ M_\odot$ cluster



Peel and Knox, astroph/0205438

$\Psi_\perp$ – perpendicular correlation function of radial component to the peculiar velocity of clusters at the same redshift

Limits on Ω_m just from the rms velocities (Ψ_0)

$$(\Delta\Omega_m)^2 = \left(\sum_i \left(\frac{\partial\Psi_0(z_i)}{\partial\Omega_m}\right)^2 \frac{1}{2(\Psi_0(z_i)+\sigma_v^2)^2}\right)^{-1}$$

$$\simeq \frac{800}{N}(.01)^2 \qquad (8)$$

If $\sigma^2_v << \Psi_0$

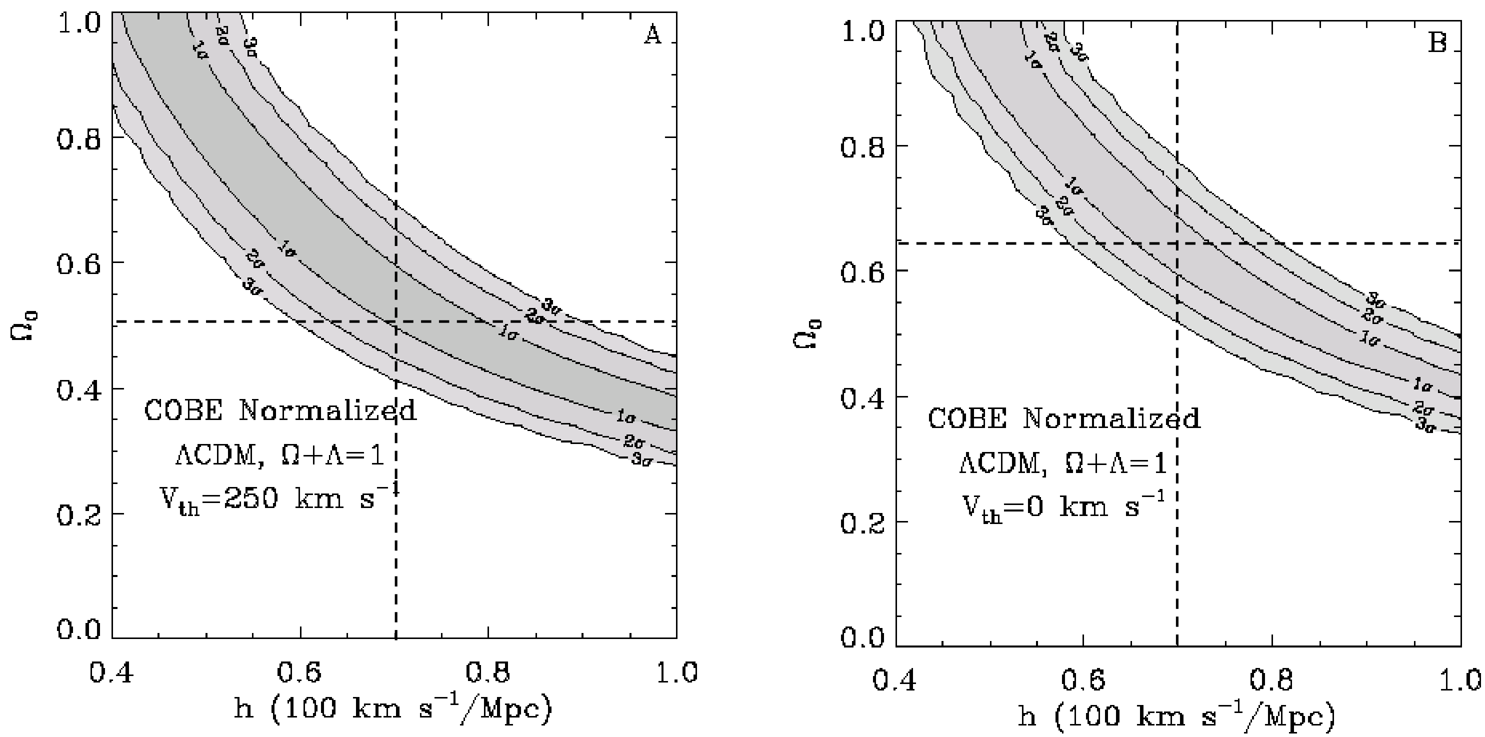
Number of clusters

Measurement variance

Non-linear effects on small scales tend to give high values of Ω_m

Zaroubi et al., 2001, MNRAS, 326, 375

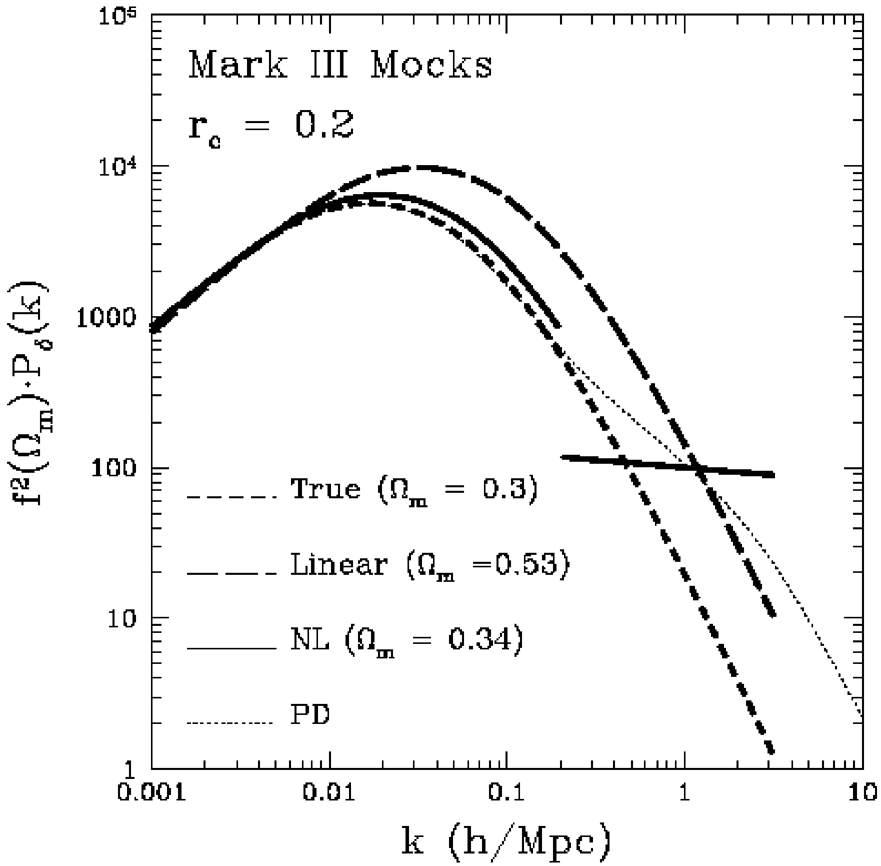
1600 galaxies at < 70 h^{-1} Mpc



V_{th} is an extra assumed component to the rms to take account of non-linearities on small scales.

Clusters are averages over large regions, but biases are still an issue

Effect shows up clearly in simulations



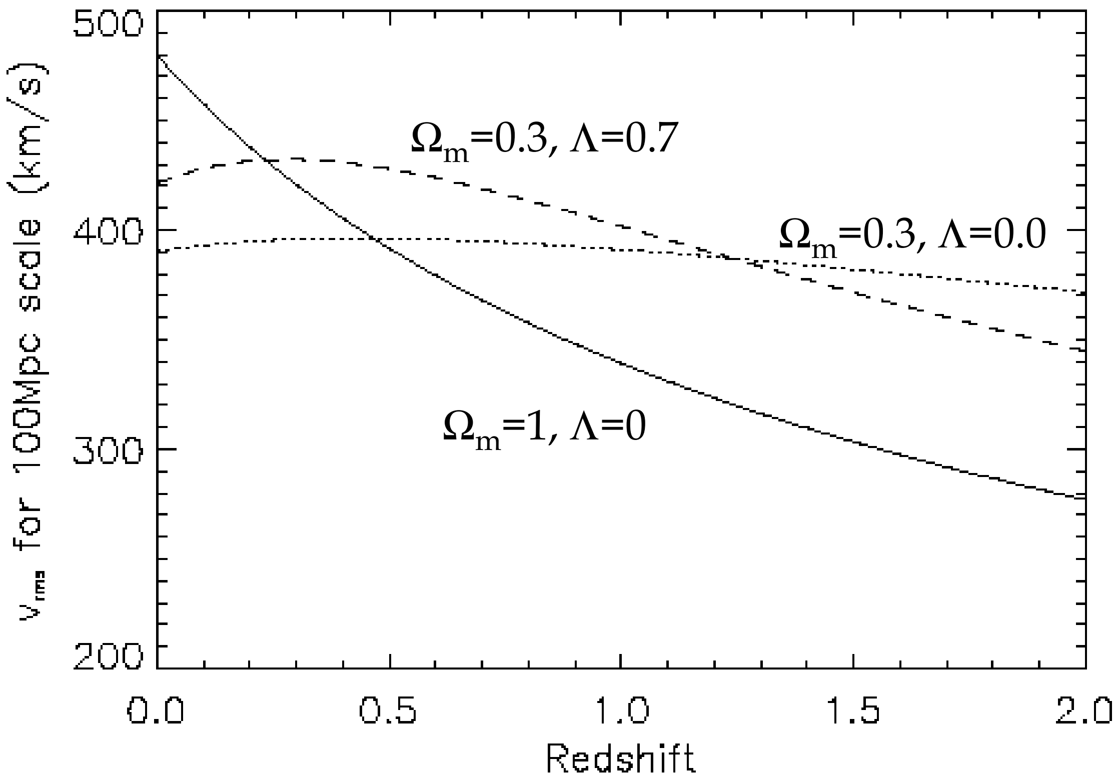
Silberman et al. (2001)

Mock catalogues:

– MK III (Willick et al., 1995) 3000 galaxies within 70 h^{-1} Mpc

PD, NL – variation corrections with non-linear effects

Bulk flows of galaxies, or clusters can also be used…

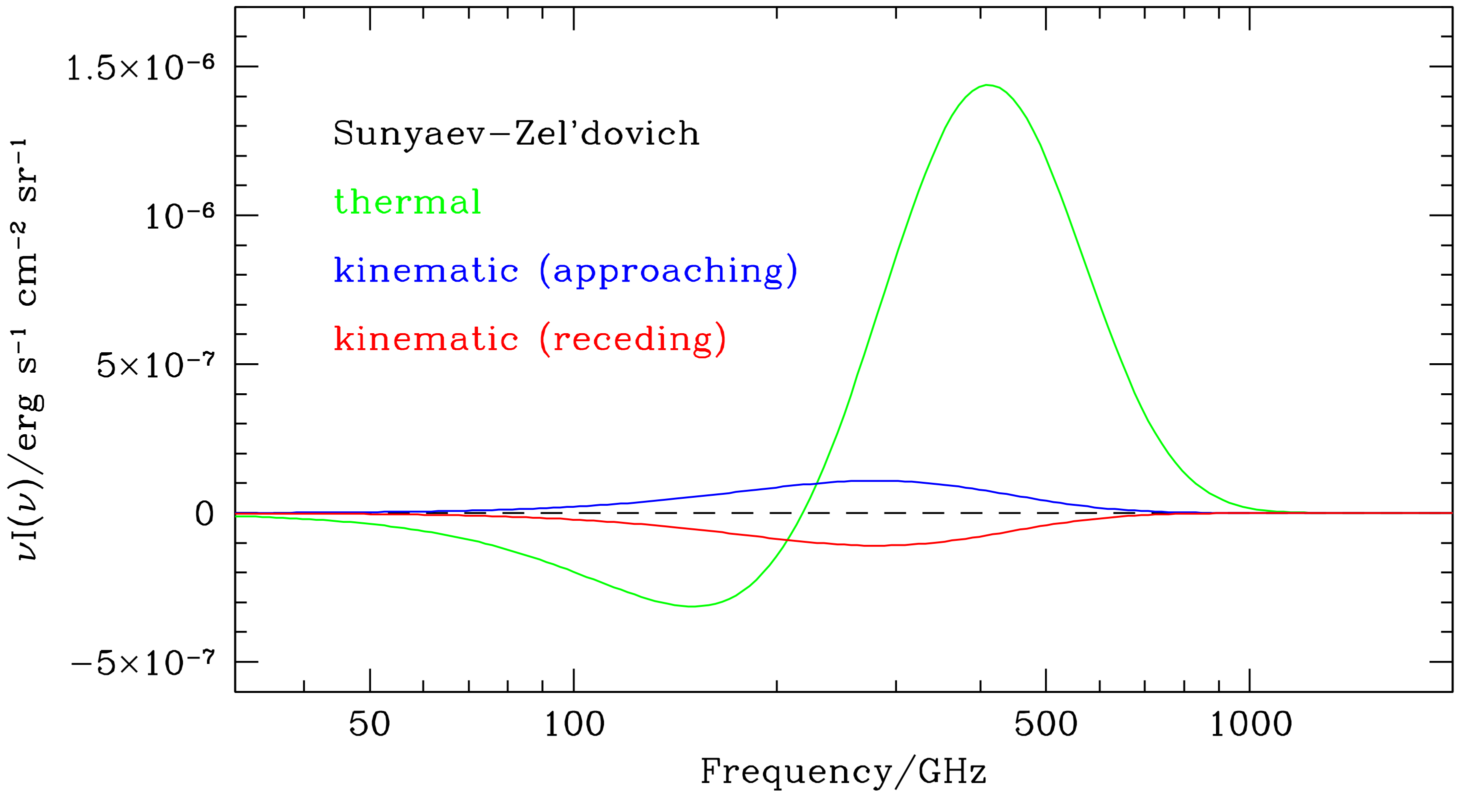


Aghanim Górski & Puget, 2001, A&A, 374, 1

- Average over large region – avoid non-linear effects
- Technique will suffer from cosmic variance at low *z*
- How sensitive are flows to cosmology?

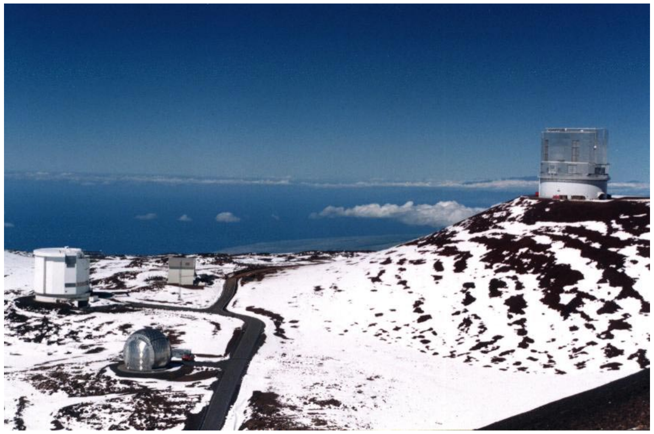
Measuring Peculiar Velocities with the S-Z effect

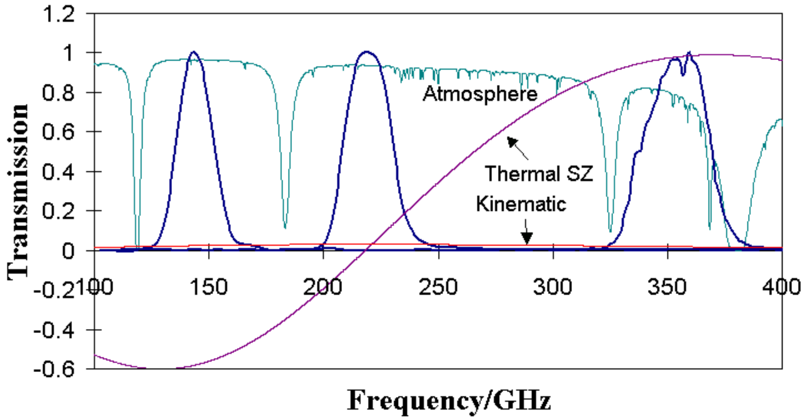
- *Requires* measurements of the SZ spectrum at more than one frequency



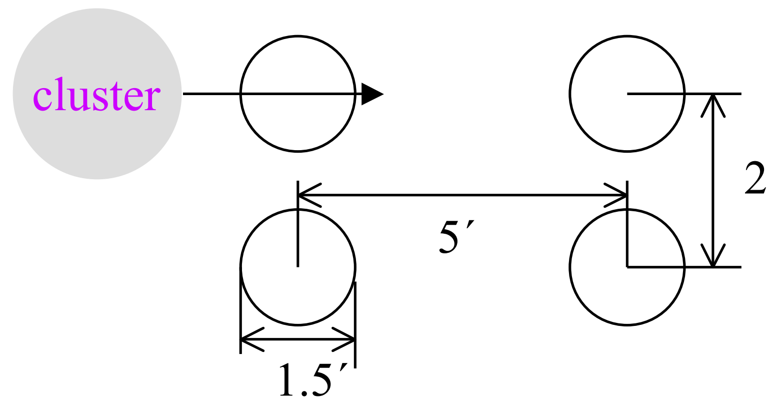
The Sunyaev-Zeldovich Infrared Experiment (SuZIE II)

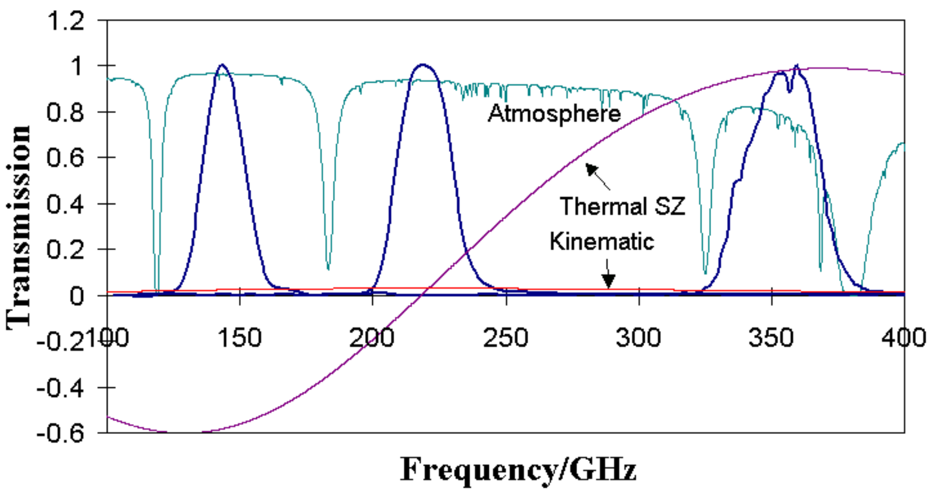
- Only sample of SZ-determined peculiar velocity limits (Benson et al., August 1st 2003 ApJ + new data)
- 4-pixel 3-color bolometer array
- Simultaneous Measurements at 150, 220 and 350 (270) GHz
- Observes at the Caltech Submillimeter Observatory

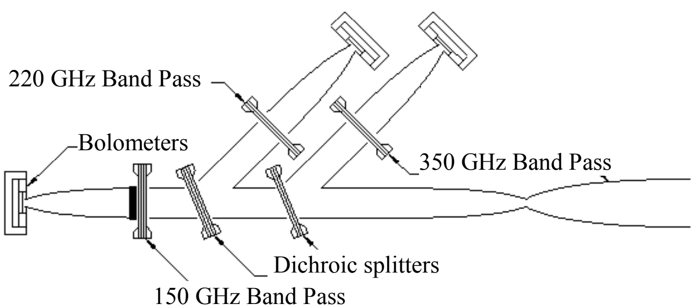


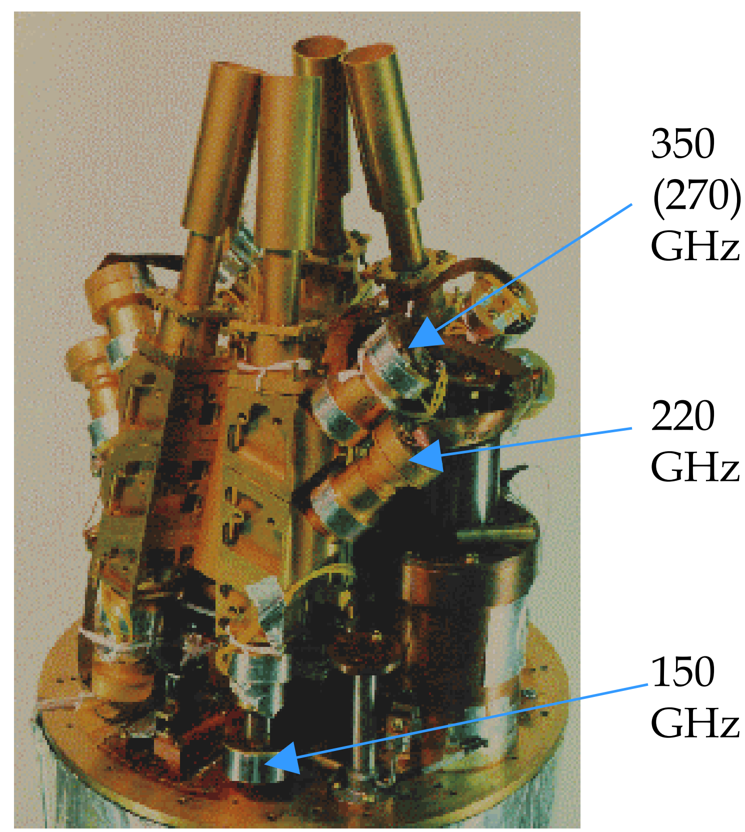


SuZIE bands are optimized to measure the thermal decrement, increment, and the null

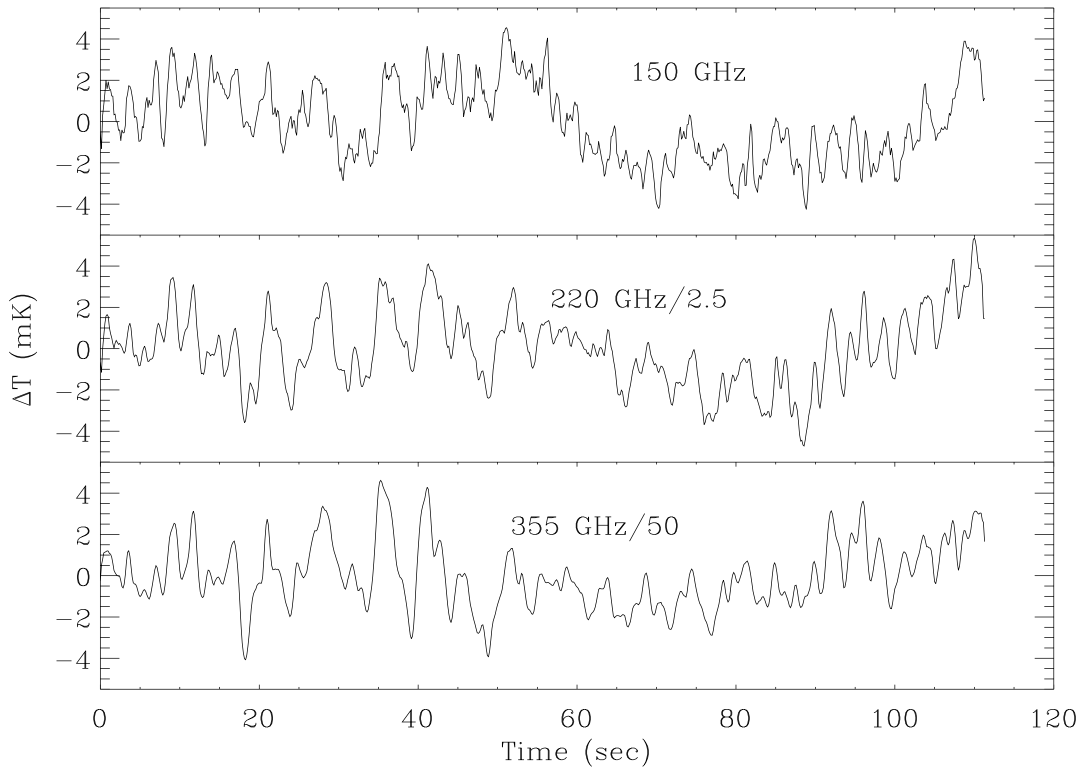








Simultaneous multi-frequency observations reveal strongly correlated atmospheric noise with a steep spectral index



- Data was taken during the Feb 1998 "El Nino" conditions (ppwv only 0.5mm)
- Atmospheric 1/*f* noise at 350 GHz is approx. ***50 times*** that at 150 GHz (in μK).

Simultaneous Multi-frequency Observations Allow Subtraction of Atmospheric Noise

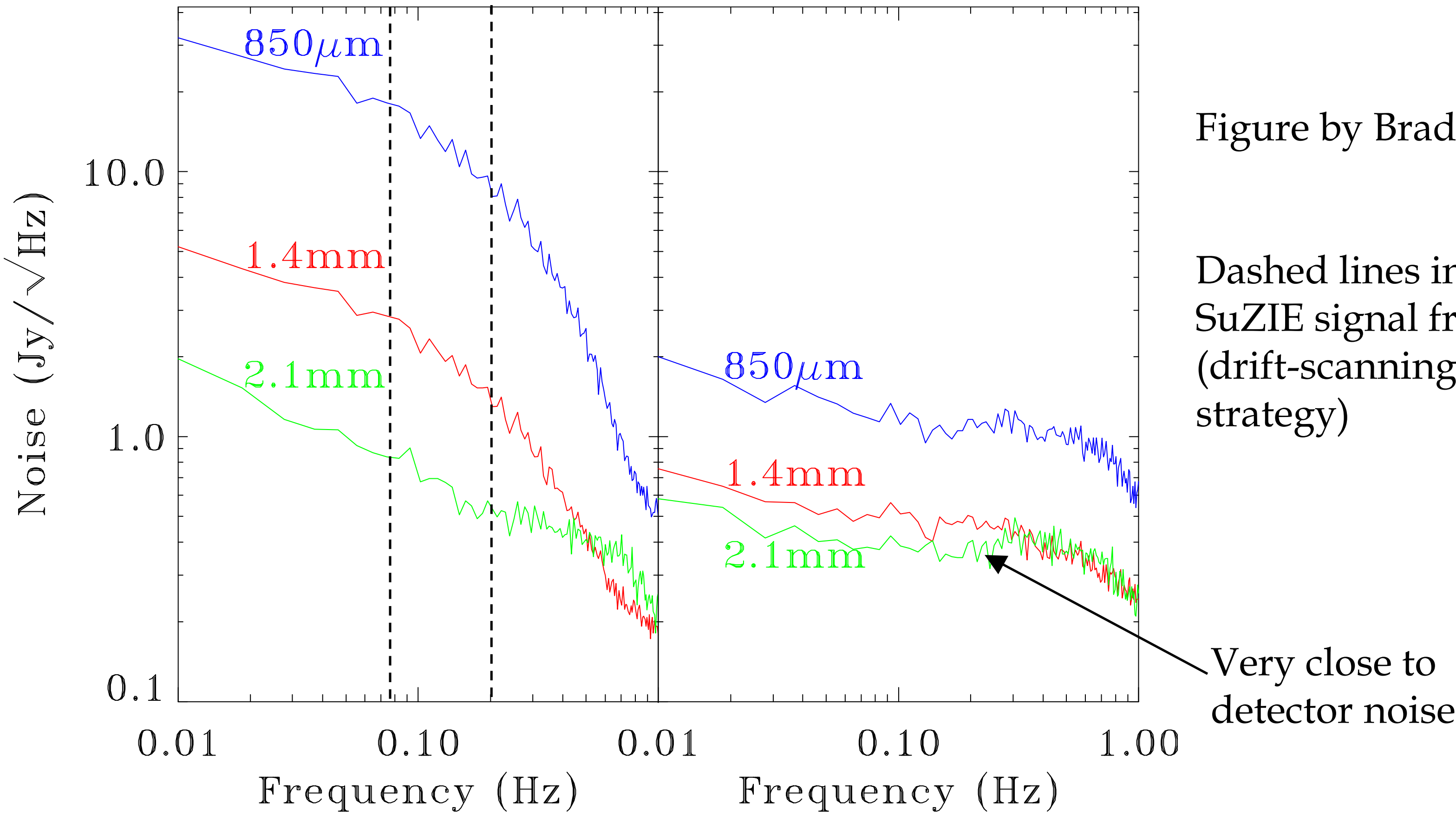


Figure by Brad Benson

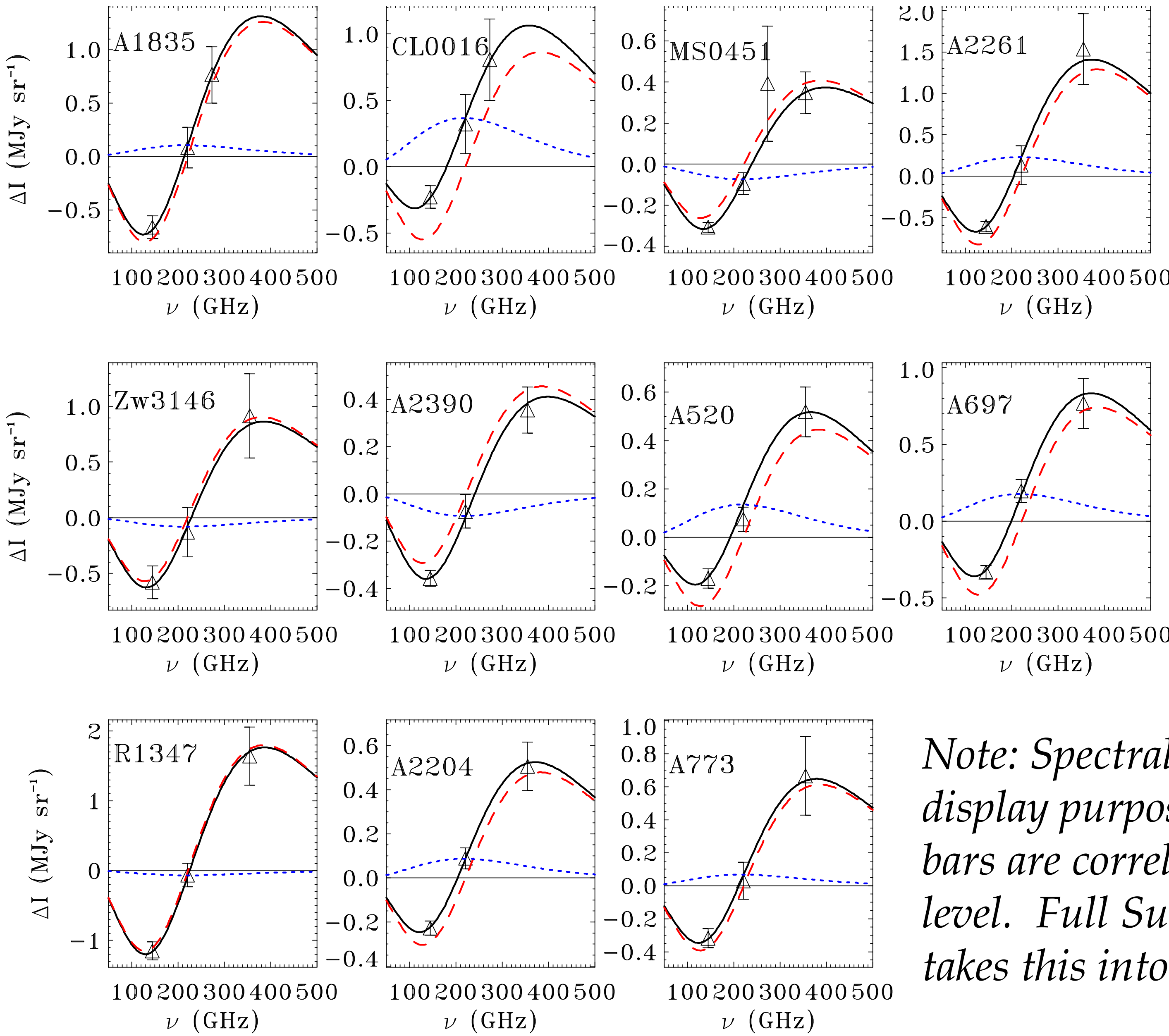
Dashed lines indicate SuZIE signal frequencies (drift-scanning scan strategy)

Atmospheric Subtraction:

(i) introduces correlations between frequencies

(ii) reduces correlations between pixels

SuZIE Spectral Measurements



Between 4 and 20 hours per cluster

Note: Spectral points are for display purposes only, as error bars are correlated at 5-20% level. Full SuZIE data analysis takes this into account

Peculiar velocity is determined from a simultaneous likelihood analysis of all frequencies

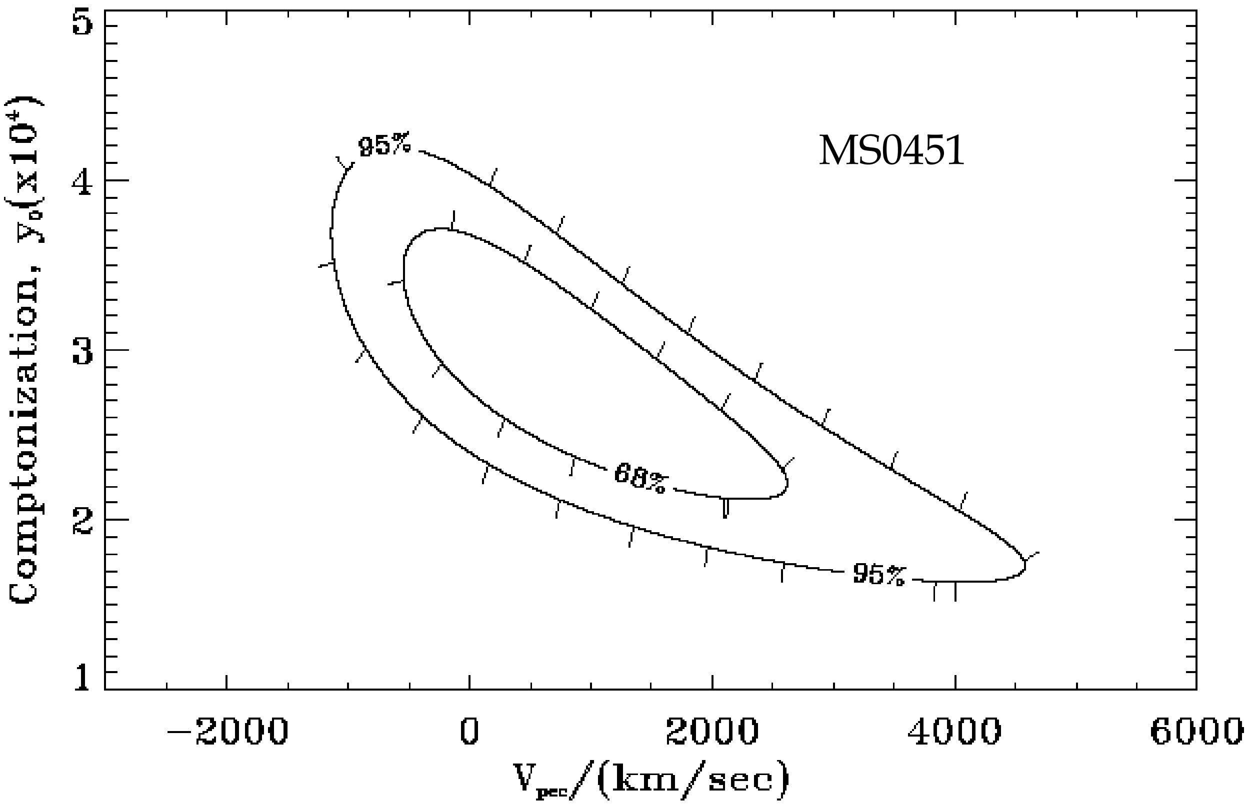
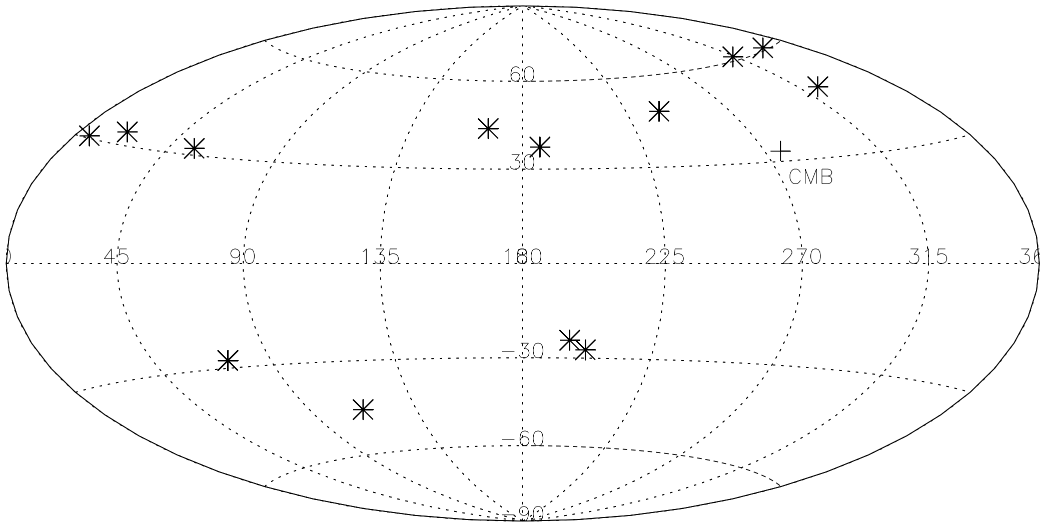
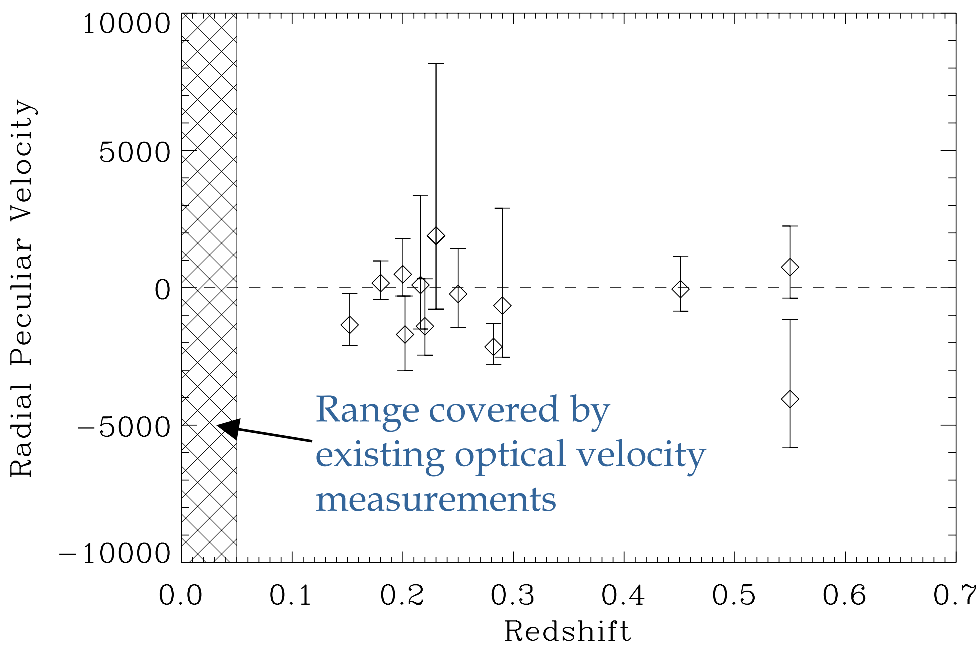


Fig. 3.— Results of the 2-d likelihood fit of the combined measurements of MS0451 in November 1996, 1997, and 2000. The 68.3% and 95.4% confidence regions are shown for peak Comptonization and peculiar velocity.

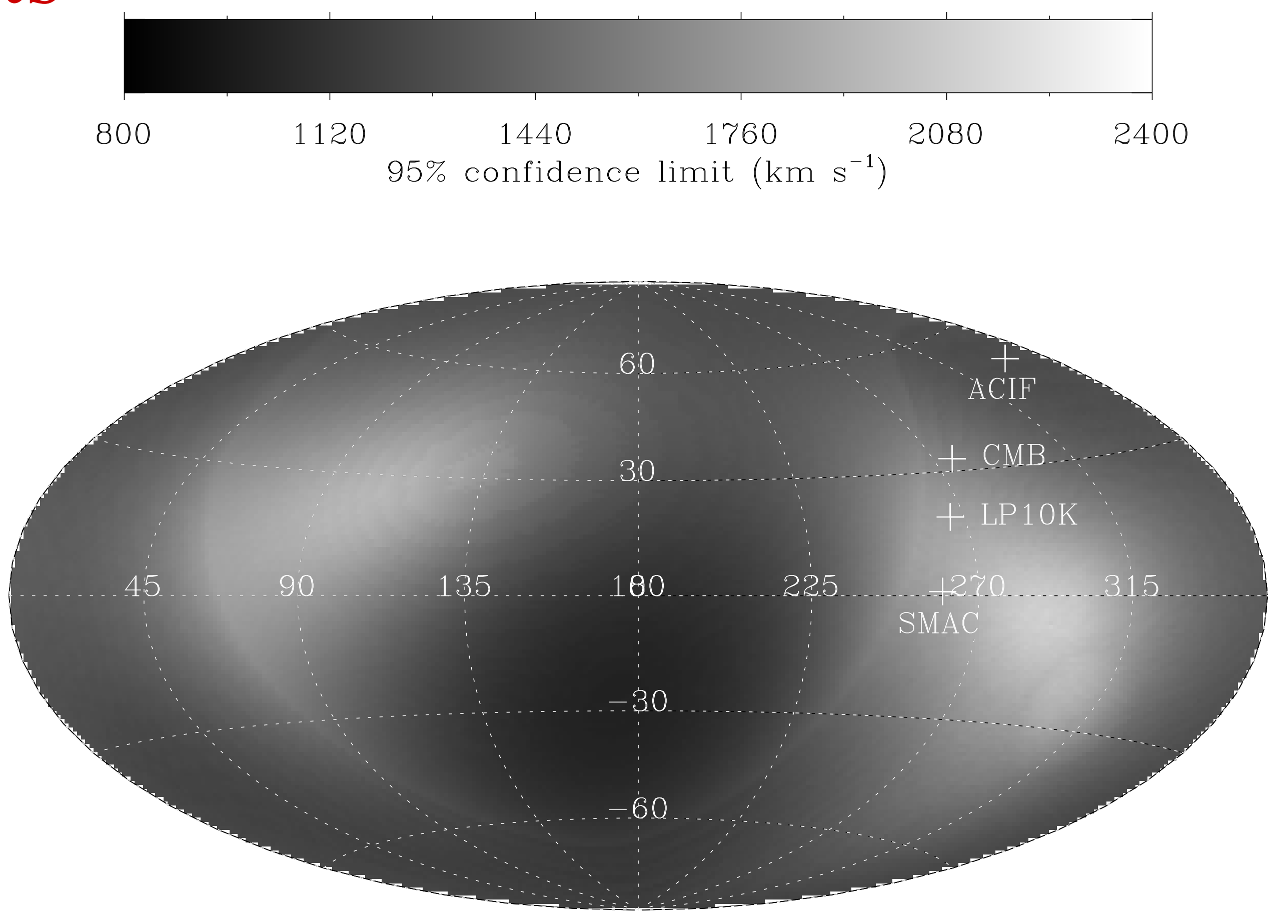
The SuZIE Peculiar Velocity Sample





Apparent bias towards negative (approaching) velocities – foregrounds?

Bulk flow limits at z ~ 0.2



Primarily a test for systematics

- 95% conf. limit < 1550 km s^{-1} towards CMB dipole
- < 2500 km s^{-1} in any direction
- Few percent of the Hubble flow!

Ultimate precision to velocity measurements is limited by systematics

- CMB fluctuations spectrally degenerate with kinematic effect
  - Depends on angular resolution, scan strategy
- Internal cluster velocities (50-100 km/s)
  - Interesting subject in itself….
- Point Sources
- Calibration
  - SuZIE calibration uncertainty is 10%
  - Uncertainties in frequency response of the instrument

Table 3. Break down of the calibration uncertainties

Source	Uncertainty (%)
Detector non-linearities	5
Planetary temperature	6
Atmospheric τ	2
Spectral response	1
Beam uncertainties	5
Total	10

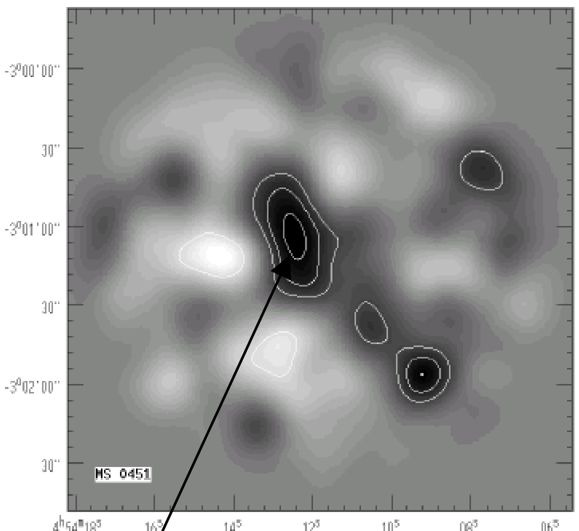
SuZIE error budget for 1 cluster (Benson et al. (2003)

Table 11. Comptonization and Peculiar Velocity Uncertainties for MS0451 (Nov 2000)

Uncertainty	$y_0 \times 10^4$	v_p (km s^{-1})
Statistical:		
SZ measurements	$3.06^{+0.83}_{-0.83}$	-300^{+1950}_{-1250}
Calibration	$^{+0.01}_{-0.04}$	$^{+25}_{-25}$
IC Density Model	$^{+0.01}_{-0.01}$	$^{+25}_{-25}$
IC Gas Temperature	$^{+0.01}_{-0.01}$	$^{+25}_{-25}$
Systematic:		
Common-Mode Atmospheric Removal	$^{+0.06}_{-0.06}$	$^{+10}_{-10}$
Differential-Mode Atmospheric Removal	$^{+0.01}_{-0.04}$	$^{+50}_{-25}$
Primary Anisotropies	$^{+0.05}_{-0.05}$	$^{+380}_{-380}$
Sub-millimeter Galaxies	$^{+0.20}_{-0.20}$	$^{+650}_{-650}$
Total:[a]	$3.06^{+0.83+0.21}_{-0.83-0.21}$	$-300^{+1950+755}_{-1250-755}$

Note. — [a] The first number is the statistical uncertainty, the second is the systematic uncertainty

Point sources are an issue for velocity measurements



17 mJy

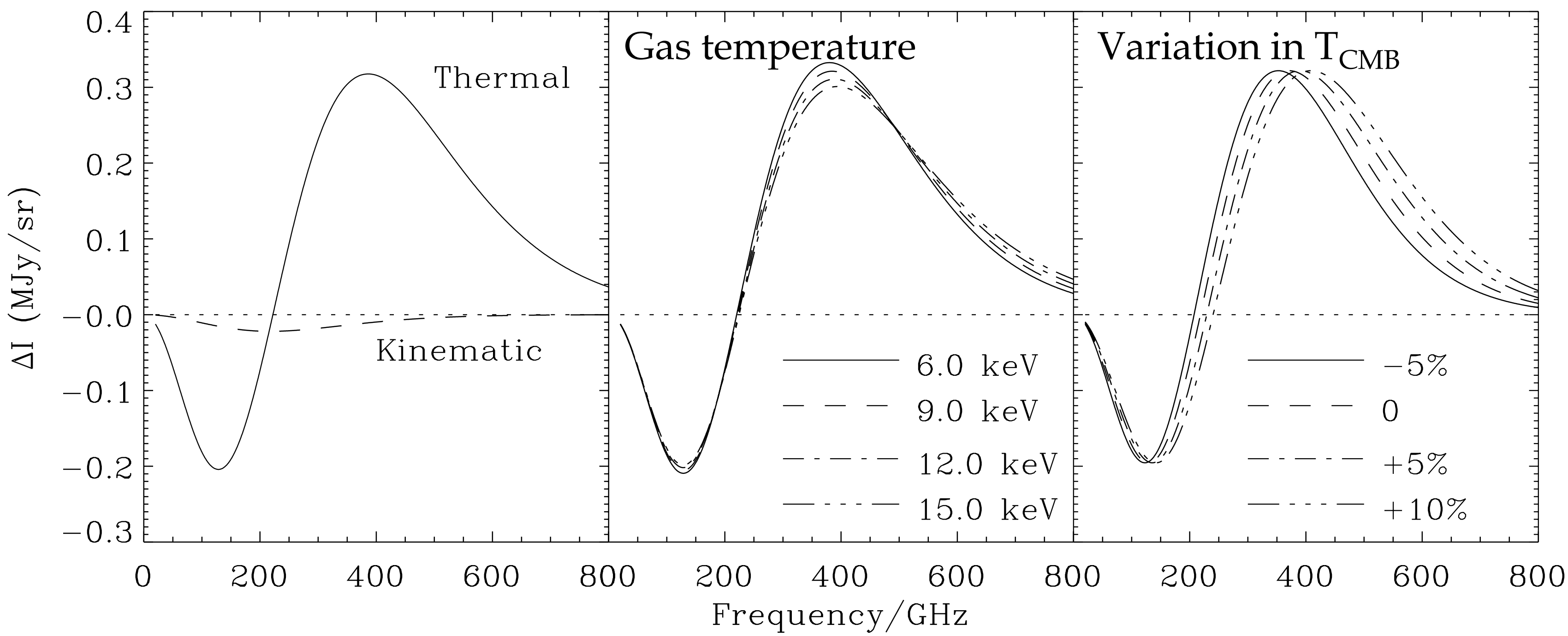
- SCUBA measurements of point sources in cluster MS0451 (Chapman et al. 2001)
- Large effect on peculiar velocity
- Lesser, but non-negligible, effect on optical depth determination
- Efficient strategy needed for removal from large data sets

Effects on Suzie data -
- Benson et al. (2003)

MS0451 SUB-MM GALAXY CONFUSION

Cluster	Spectral Model	Flux/mJys 145GHz	221GHz	355GHz	$y_0 \times 10^4$	v_{pec} km s^-1
MS0451	None	$-23.7^{+3.8}_{-4.1}$	$-3.5^{+5.9}_{-6.1}$	$+51.1^{+13.7}_{-13.7}$	$3.05^{+0.73}_{-0.73}$	-450^{+1600}_{-1100}
	$\alpha = -3$	$-24.3^{+4.1}_{-3.8}$	$-5.3^{+5.9}_{-6.1}$	$+50.9^{+13.8}_{-13.8}$	$2.93^{+0.73}_{-0.73}$	-150^{+1750}_{-1200}
	$\alpha = -2$	$-25.6^{+3.8}_{-4.1}$	$-7.5^{+5.9}_{-6.1}$	$+48.4^{+13.7}_{-13.7}$	$2.85^{+0.73}_{-0.73}$	$+200^{+1950}_{-1250}$

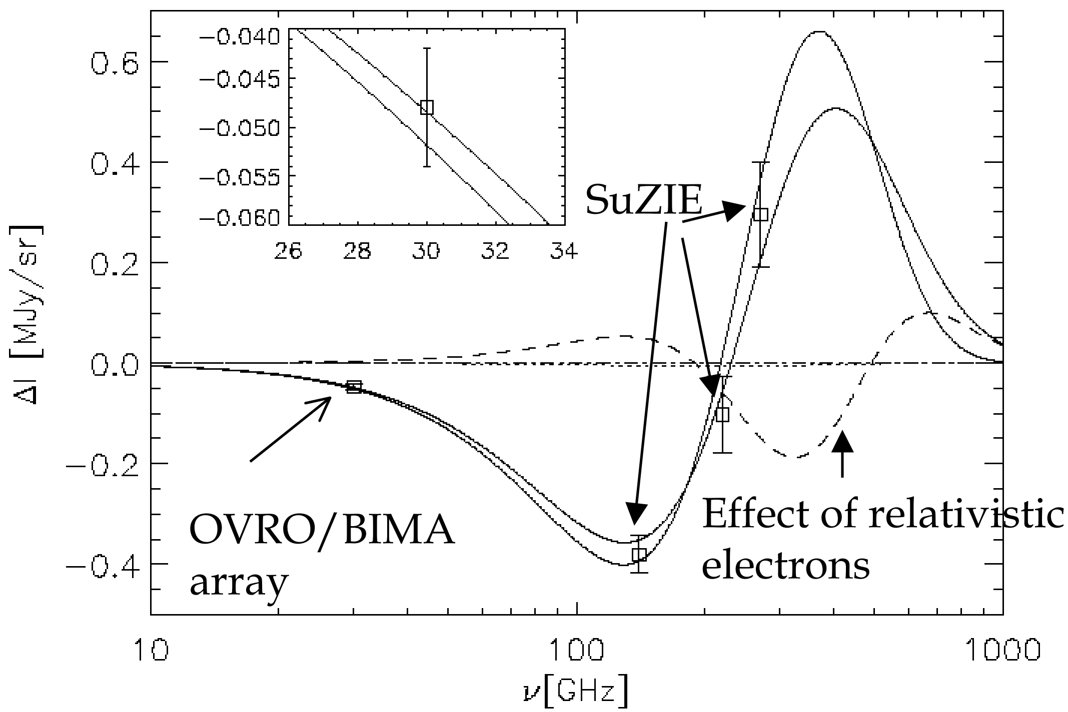
Other science from SZ spectral measurements



- The SZE spectrum is also sensitive to:
  - Gas temperature
  - Departures from $T_{CMB}=T_0(1+z)$

Measuring Cluster Gas Temperatures

Measurements of A2163



Best fit SZ temperature:

26^{+34}_{-19} KeV

Best fit X-ray temperature:

$12.4^{+2.8}_{-1.9}$ KeV

Hansen, Pastor & Semikoz, astroph/0205295

Measuring the Redshift Dependence of T_{CMB} (Rephaeli 1980)

- For non-relativistic gas the thermal effect is given by:

$$I(x) = \frac{2k}{T_{\rm CMB}} \left(\frac{kT_{\rm CMB}}{hc} \right)^2 \frac{x^4 e^x}{(e^x - 1)^2} \left[x \coth \frac{x}{2} - 4 \right] \tau \frac{kT_e}{m_e c^2}$$

where $x = h\nu/kT_{CMB}$

- Consequently a comparison of $I(\nu)$ at several different frequencies probes T_{CMB} as a function of redshift
- More frequencies allow better accounting for non-relativistic effects, peculiar velocities etc.

Cluster	z	$T_{\rm CMB}$
Coma (MITO)	0.0231	$2.789^{+0.080}_{-0.065}$
A2163 (SuZIE)	0.203	$3.377^{+0.101}_{-0.102}$

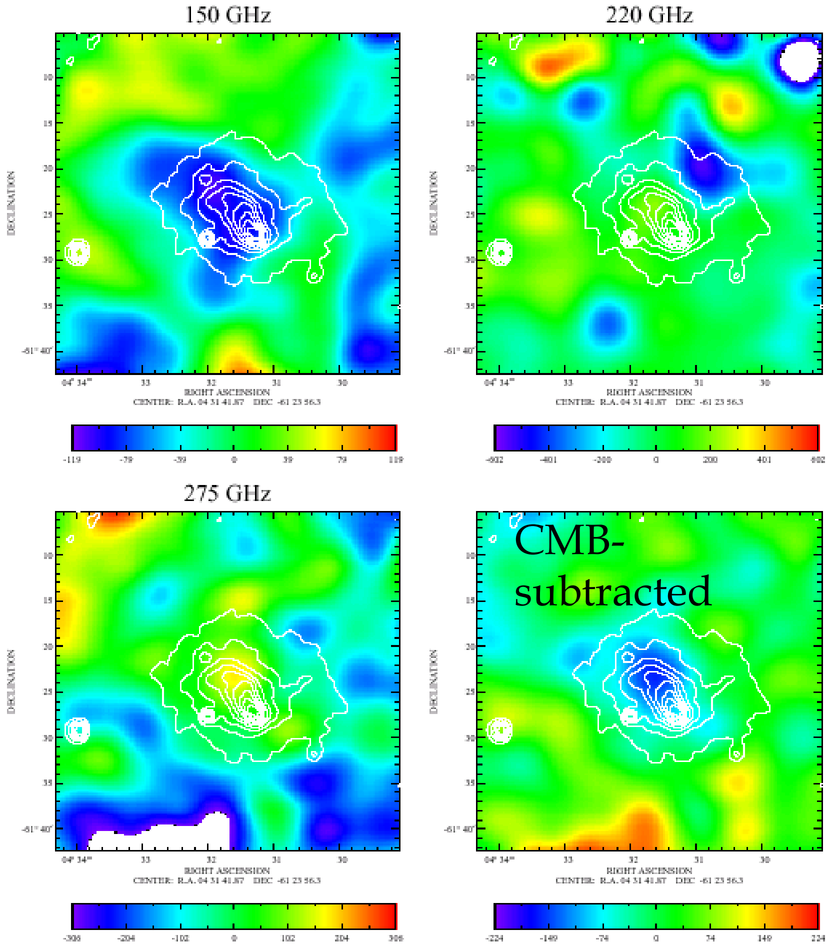
Battistelli et al. astroph/0208027

See Brad Benson's poster

Future multi-frequency measurements

- New improved SuZIE
  - 150, 220, 270 and 350 GHz
  - $\leq 1'$ resolution
- New improved MITO
  - 150, 220, 270 and 350 GHz
- Planck
  - 30-850 GHz
  - $> 5'$ resolution
- ACT
  - 150, 220, 270 GHz proposed
  - $\leq 1.5'$ resolution
- APEX, SPT
  - 150, 220 GHz
  - $\leq 1'$ resolution

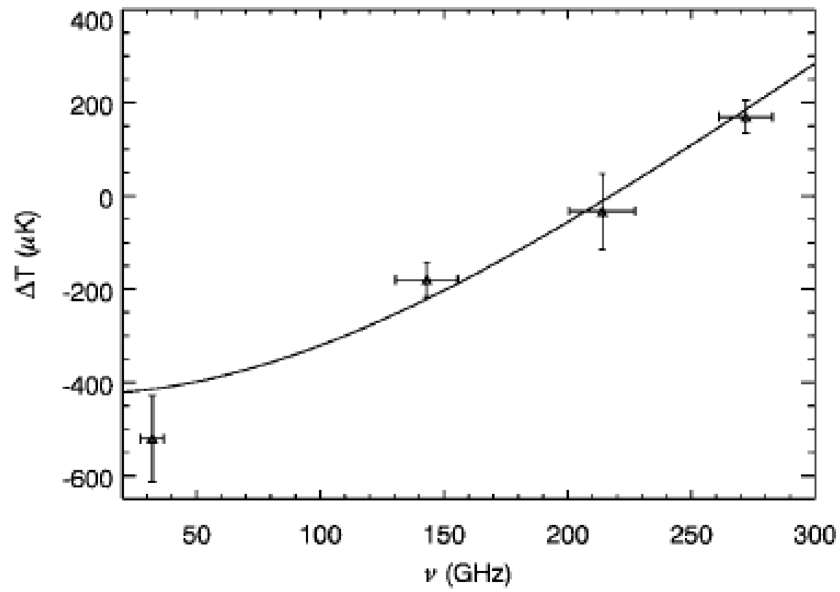
ACBAR maps of A3266 4′ resolution



Gomez et al., astroph/0301024

More from Kathy Romer, this conference!

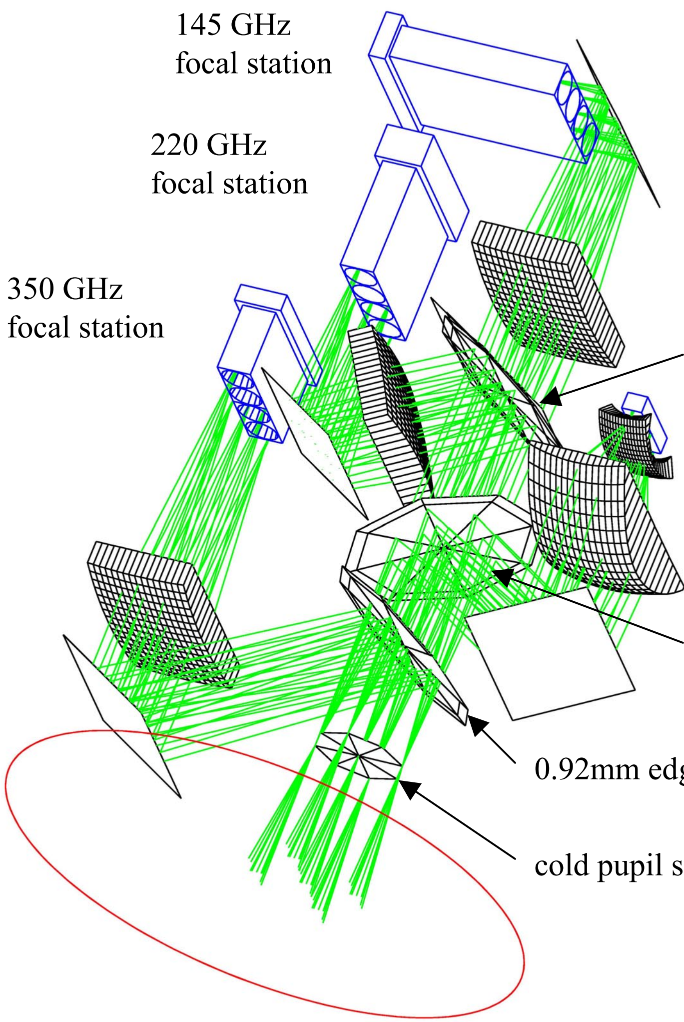
MITO spectrum of COMA 17′ resolution



De Petris et al., 2001, ApJ, 574, L119

More from Luca Lamagna, this conference

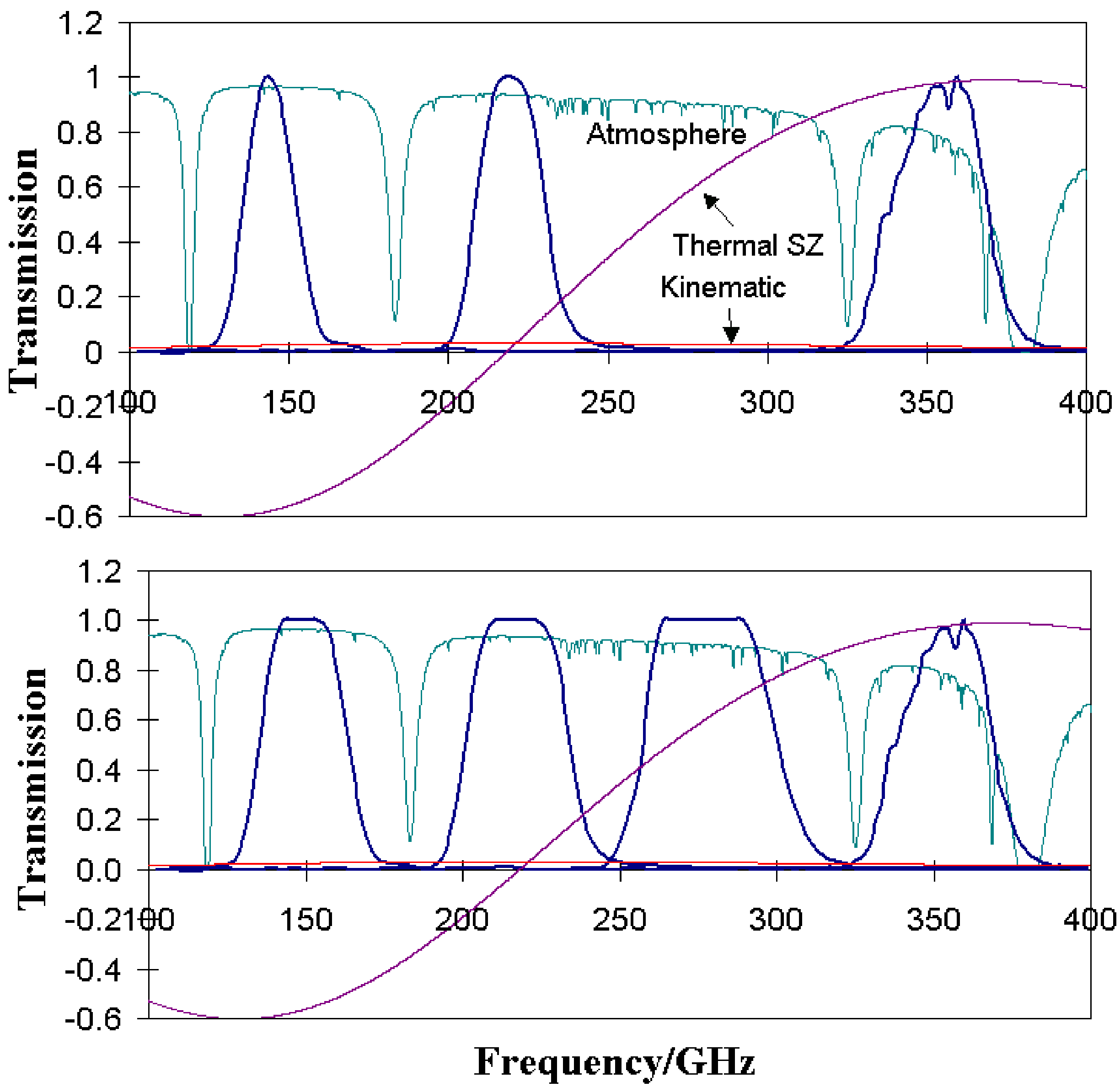
Future plans for SuZIE



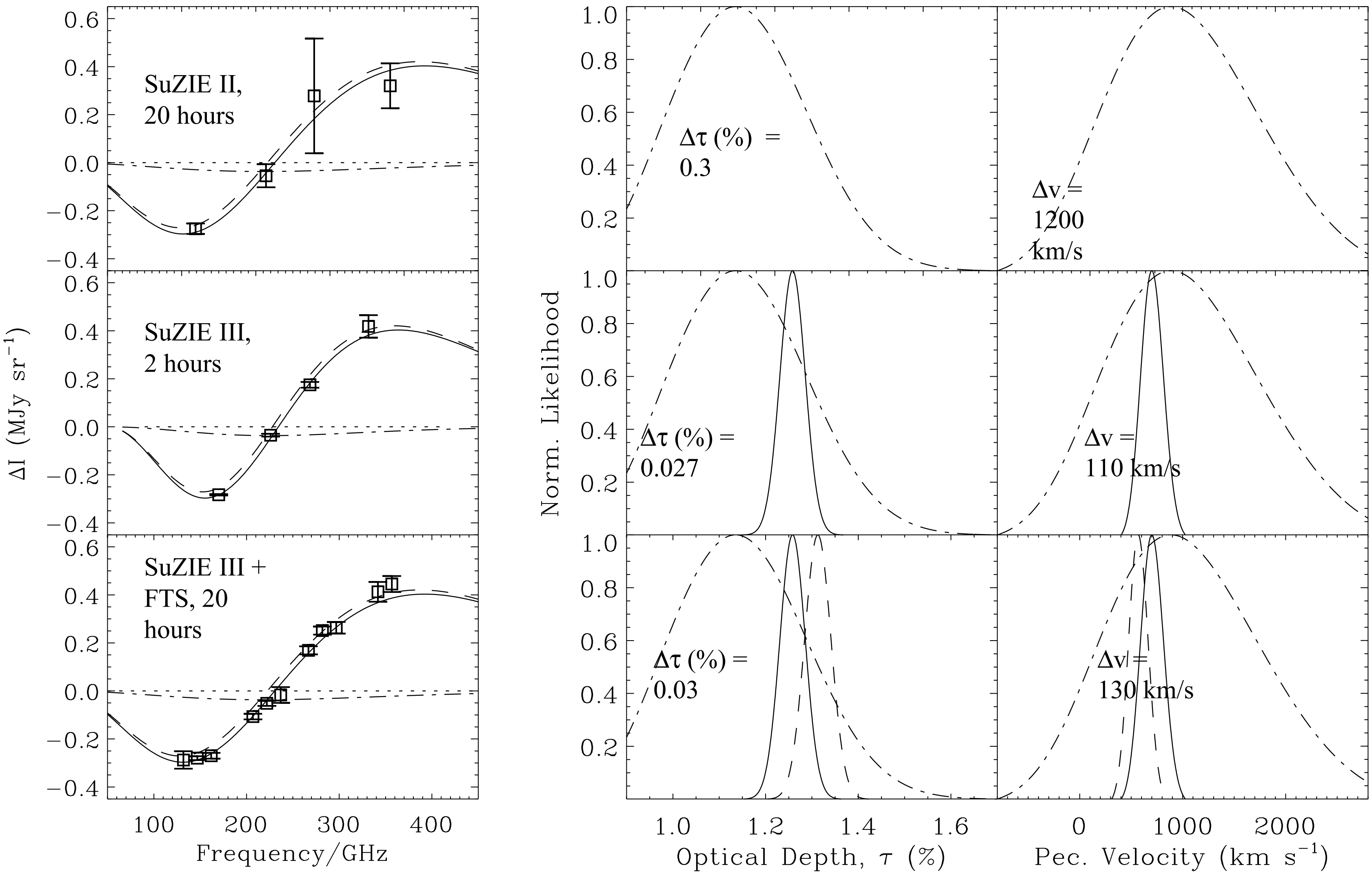
- By summer 2004
  - Add 300 GHz channel
  - Increase bandwidth (x sqrt2)
  - Increase optical efficiency (x4)
  - Optimum detector arrangement (x sqrt2)
  - ×5 increase in sensitivity
  - 100 km/s in 8 hours, projected
- Add diffraction-limited arrays
  - 80 km/s in 4 hours, projected

Existing
SuZIE bands

Proposed
Suzie III
bands

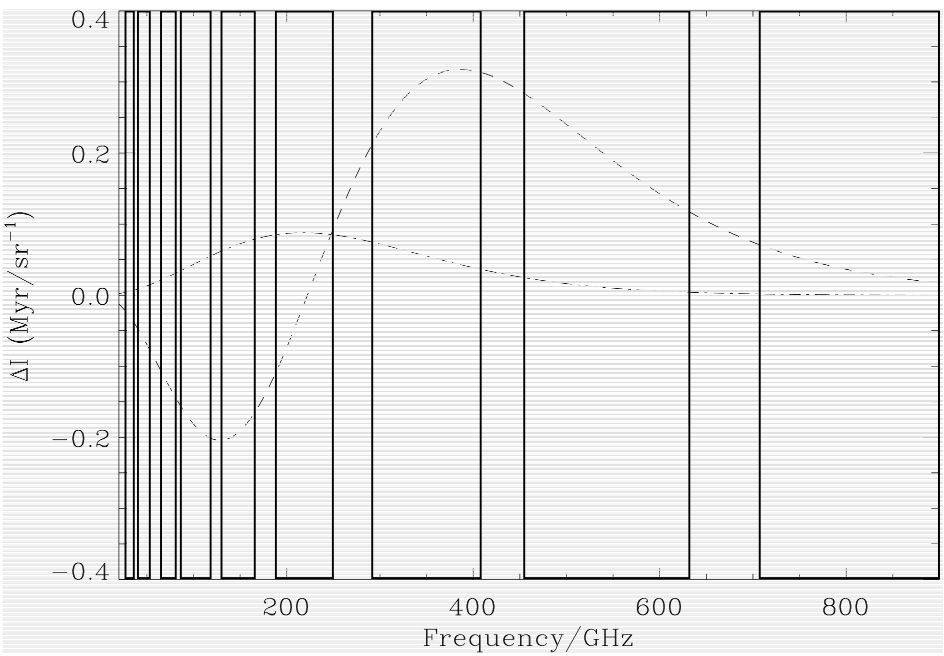


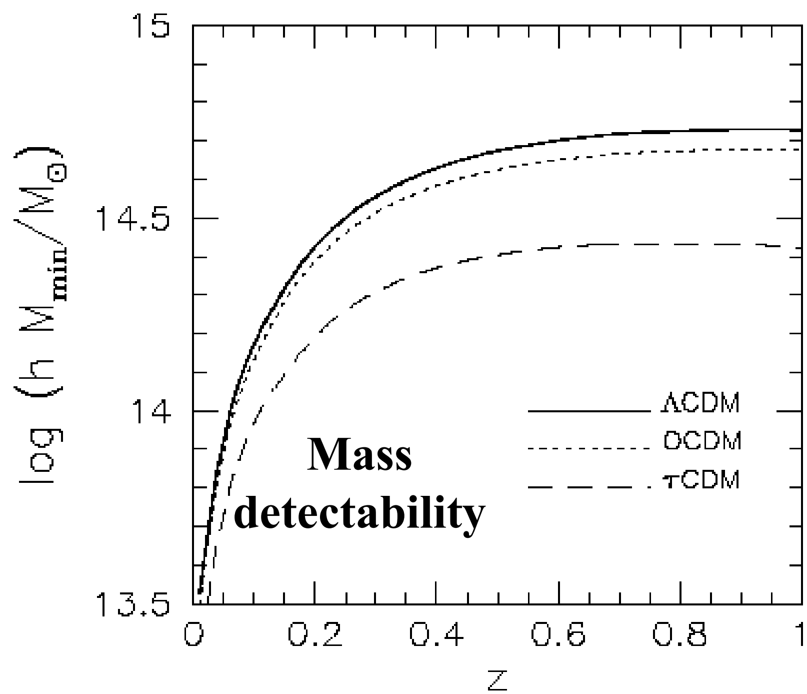
What we can look forward to from SuZIE..



The Planck Satellite may have sufficient frequency coverage to permit direct determination of T_e, as well as peculiar velocities

- Total sample of 10000 clusters expected.
- Locally even small mass concentrations, of the size of galaxy groups, will be detectable
- **Complete spectral coverage of every cluster from 30-850 GHz (low angular resolution below 150 GHz)**





Planck is strongly confusion-limited mostly from CMB fluctuations and other clusters

Because of low angular resolution, therefore ground is potentially more attractive

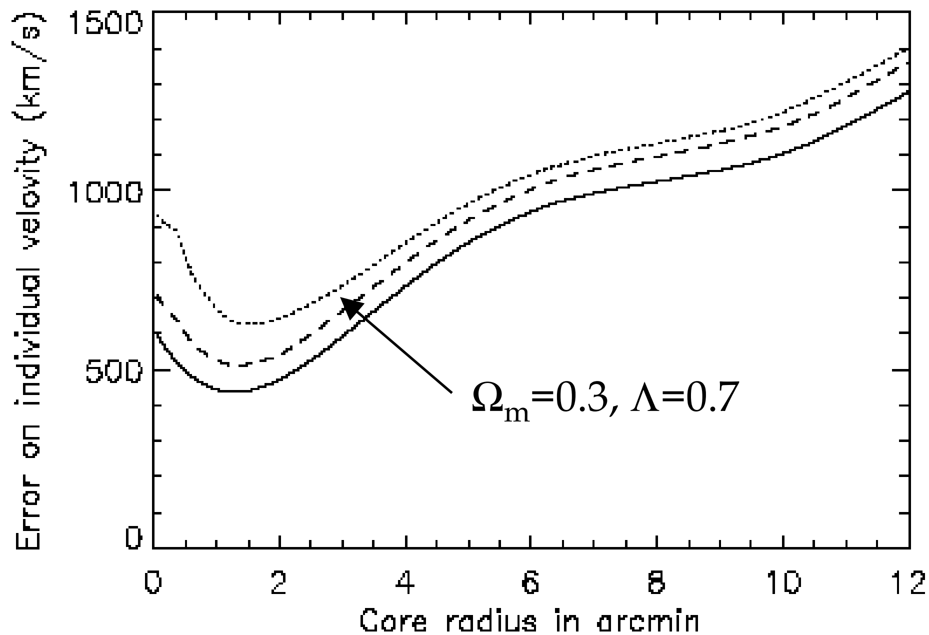
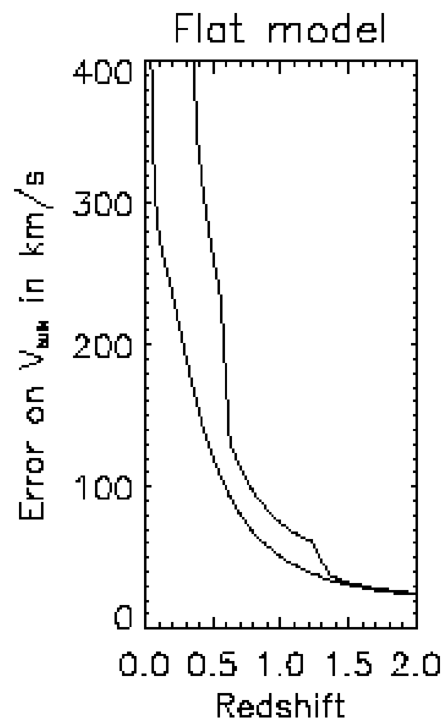


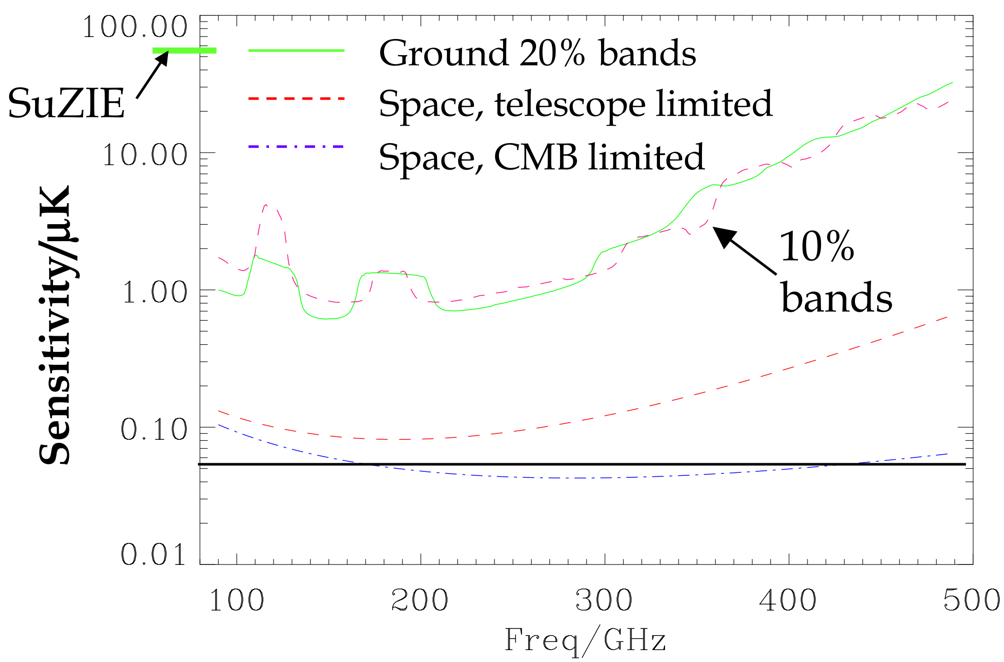
Fig. 4. The total rms error in the individual velocity due to all sources of confusion (CMB, background kinetic SZ, galactic residuals, residuals of component separation, Planck-like instrumental noise). The line-styles stand for the same cosmological results as in Fig. 1.

Aghanim, Górski & Puget, 2001, A&A, 374, 1



Errors on bulk flows large for z < 1.0

How well can we ultimately do from the ground?

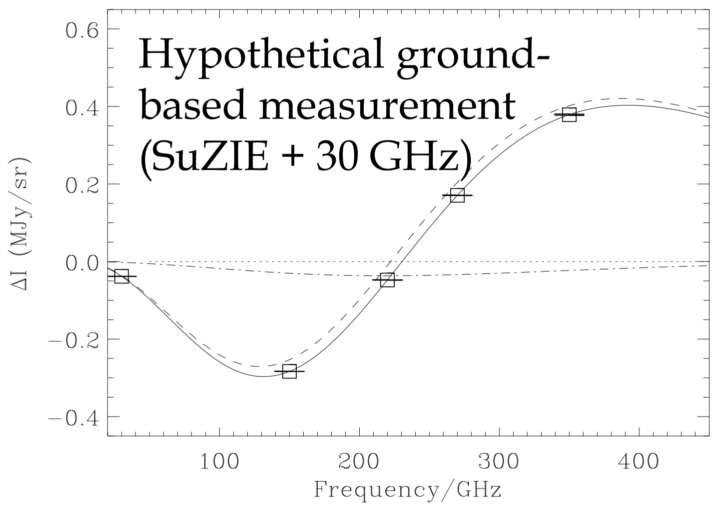


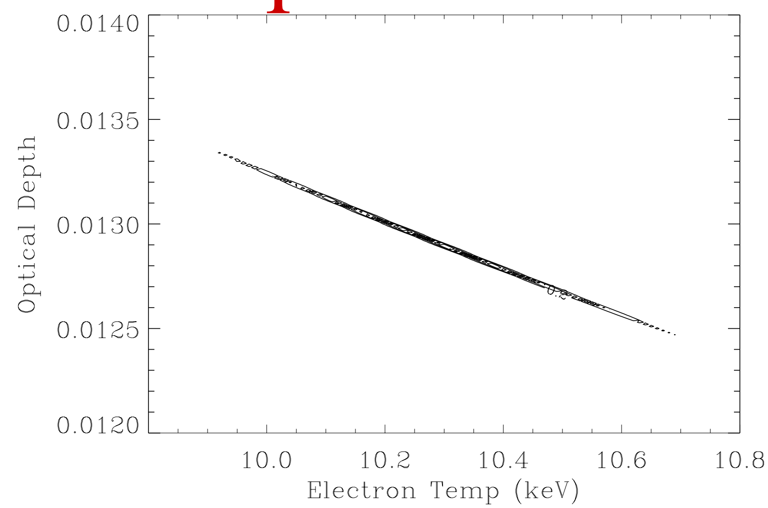
Assumptions:

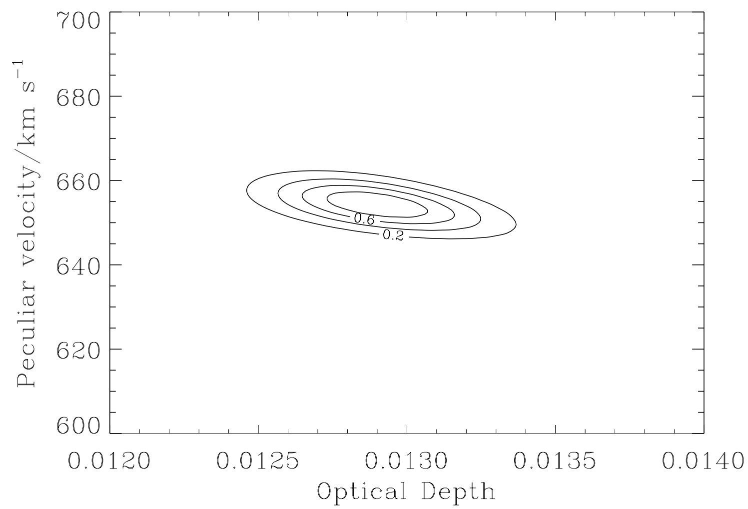
- Ground:
  - 0.25 mm ppwv
  - 15K loading from telescope
- Space
  - passively cooled telescope
- Photon noise limit only
- 4 hours integration

- Equal focal plane area on the sky at each frequency ($N_{det} \propto \nu^2$)
- **Atmospheric noise depends much more steeply on frequency, *and* is strongly correlated between pixels**

Frequency optimization is important







- See, for example, Holder astro-ph/0207600, Aghanim et al. astroph/0212392
- Degeneracy in τ and T_e but velocity is well-determined
- $\Delta T_e = 0.25$ keV

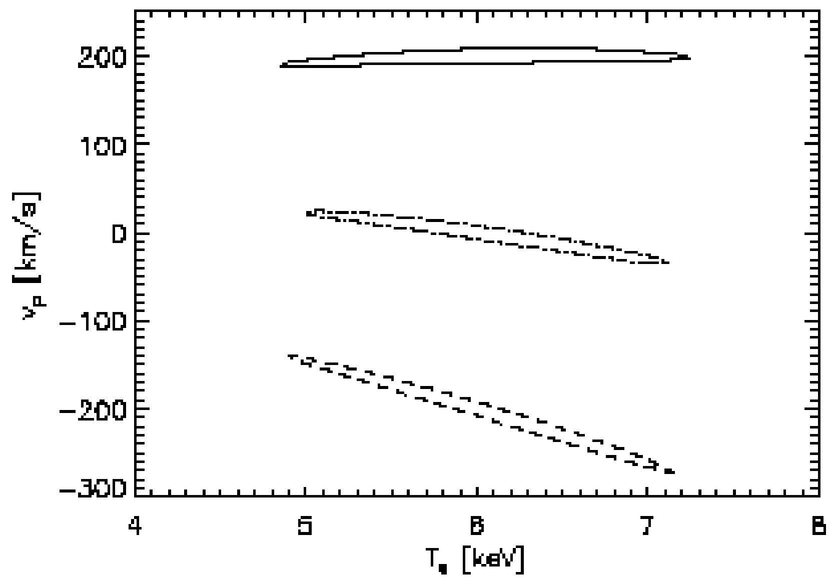
This is based on raw sensitivity only

Point sources, atmosphere, will be an issue, atmosphere especially should be accounted for in any optimization

Systematic velocity limit is much higher

What extra information is needed to use peculiar velocities?

- The good news is that the Te-τ degeneracy has little effect on measurements of *v*.



Assumes 90, 180, 220, 330 GHz bands

Aghanim et al., astroph/0212392

- Still need redshift information…

Conclusions and Future Directions

- Science from SZ spectrum, including peculiar velocities, is only beginning to be exploited
- Experimental Issues:
  - *Don't forget the atmosphere and foregrounds when optimizing frequencies*
  - Point sources removal strategy
    - Higher spatial or spectral resolution?
  - Do we need more than 3-4 spectral bands? Depends on number of free parameters
    - τ, v, T_e, atmosphere, point sources, non-relativistic electrons….
  - Redshifts needed for optimum use of peculiar velocity sample
    - Impacts survey design.
    - Shallow survey of known clusters?
- Theory Issues:
  - Non-linear effects, and potential biases from using high density peaks
  - Relationship to experiments – do we really need 100 km/s per cluster? Or are more clusters better?
  - Effect of systematics on results?

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The Stanford SZ program is funded by:
NSF Extragalactic Astronomy and Cosmology
NASA Long Term Space Astrophysics Program
Stanford University

See Brad's poster for more SuZIE results!