Why ***Planck*** (the satellite) Could Have Been ***Zel'dovich***

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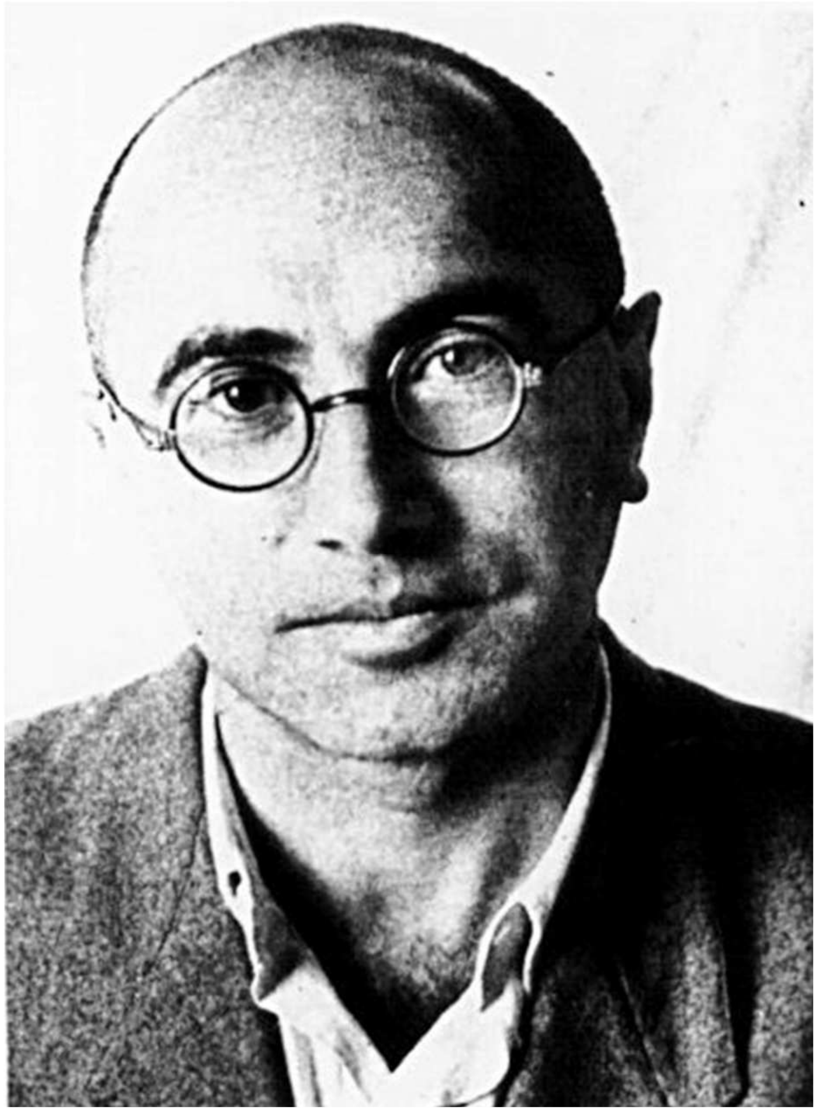
Tallinn For the Planck Team IAU S308

Outline

NOT a review or summary of *Planck* results

Rather, a ***sample*** of mostly
non-cosmological results
I think would have interested
Yakov Borisovich



Selecting topics was hard,
given his wide interests

Topics

1. Planck's picture of the cosmic web at z = 1100

2. The Sunyaev-Zel'dovich (SZ) effect in clusters of galaxies

3. Other loci for the SZ effect

4. The cosmic infrared background (CIB) – light of the cosmic web

5. Gravitational lensing maps of the mass distribution in cosmic space

6. Constraints on Inflation (if time)

And two topics to amuse him:

7. Using *Planck* to calibrate ground-based radio telescopes

8. Using *Planck* and related measurements to measure the mass of neutrinos

Two Quotes

Zel’dovich on his “conversion” to Hot Big Bang cosmology:

“I did not persist in my delusions.”

(Indeed not; he soon made monumental contributions to our understanding of the early Universe)

From Andrei Sakharov, cited by Tsukerman and Azarch:

“Yakov Borisovich was a person of perfect honesty, open to criticism, and ready to admit others’ rectitude or authorship. He took child-like joy in succeeding in something truly difficult.”

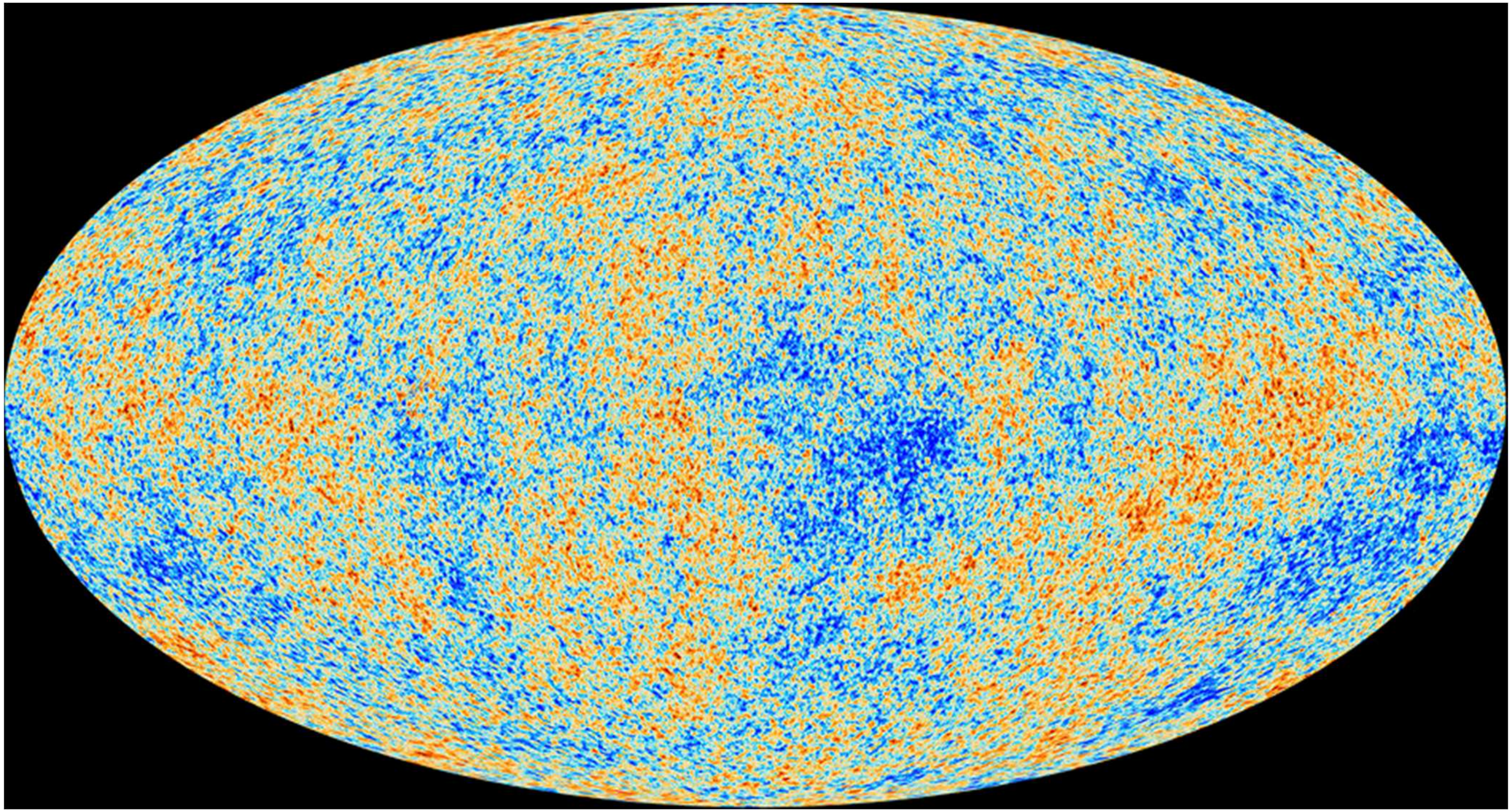
Why ***Planck*** Could Have Been ***Zel'dovich***

The cosmic microwave background (CMB) has an almost perfect blackbody spectrum: hence the name *Planck* for the mission

But *Planck* is designed to measure *anisotropies* in the CMB – the seeds of cosmic structure and a subject of deep interest to Zel'dovich

Given his wide contributions to so much of the science *Planck* was designed to probe, the mission could well have been "*Zel'dovich*"

1. *Planck*'s Map of the Cosmic Web at z = 1100



I will not discuss further (several speakers have already used CMB initial conditions))

I do wish Zel'dovich could have seen this map, or the earlier COBE image

2. *Planck*'s Surveys of Clusters of Galaxies

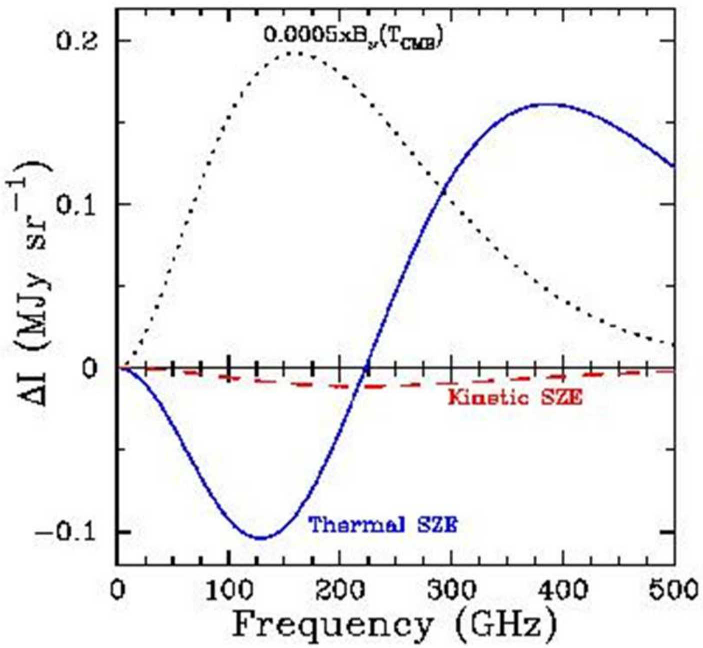
Uses the Sunyaev-Zel'dovich (SZ)* Effect
-- independent of redshift
-- but proportional to pressure of hot electrons in cluster gas

Planck's broad beams limit sensitivity
Consequently, *Planck* is best at detecting massive, hot clusters at all redshifts:
Planck catalog (2013)
1227 clusters

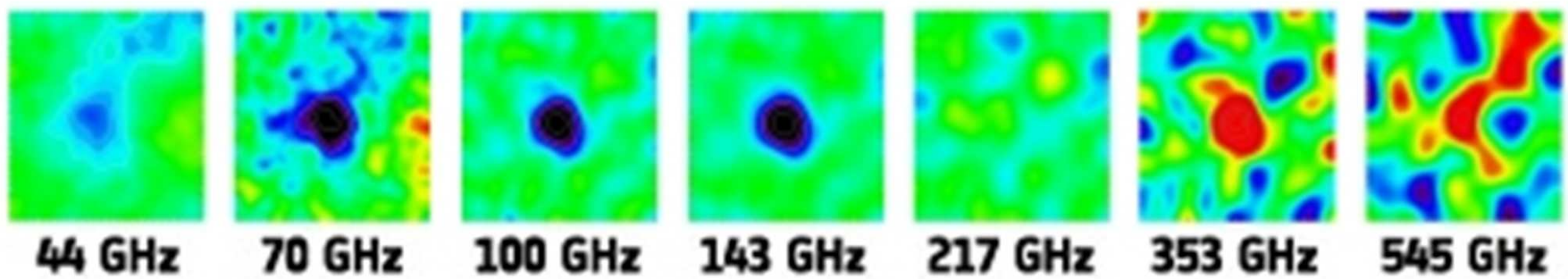
*inverse Compton scattering of CMB photons off electrons in hot IGM

Frequency Dependence of SZ Effect

Characteristic frequency dependence (a decrement at ν < 217 GHz; a “hot spot” at at ν > 217 GHz) makes detection easy and secure

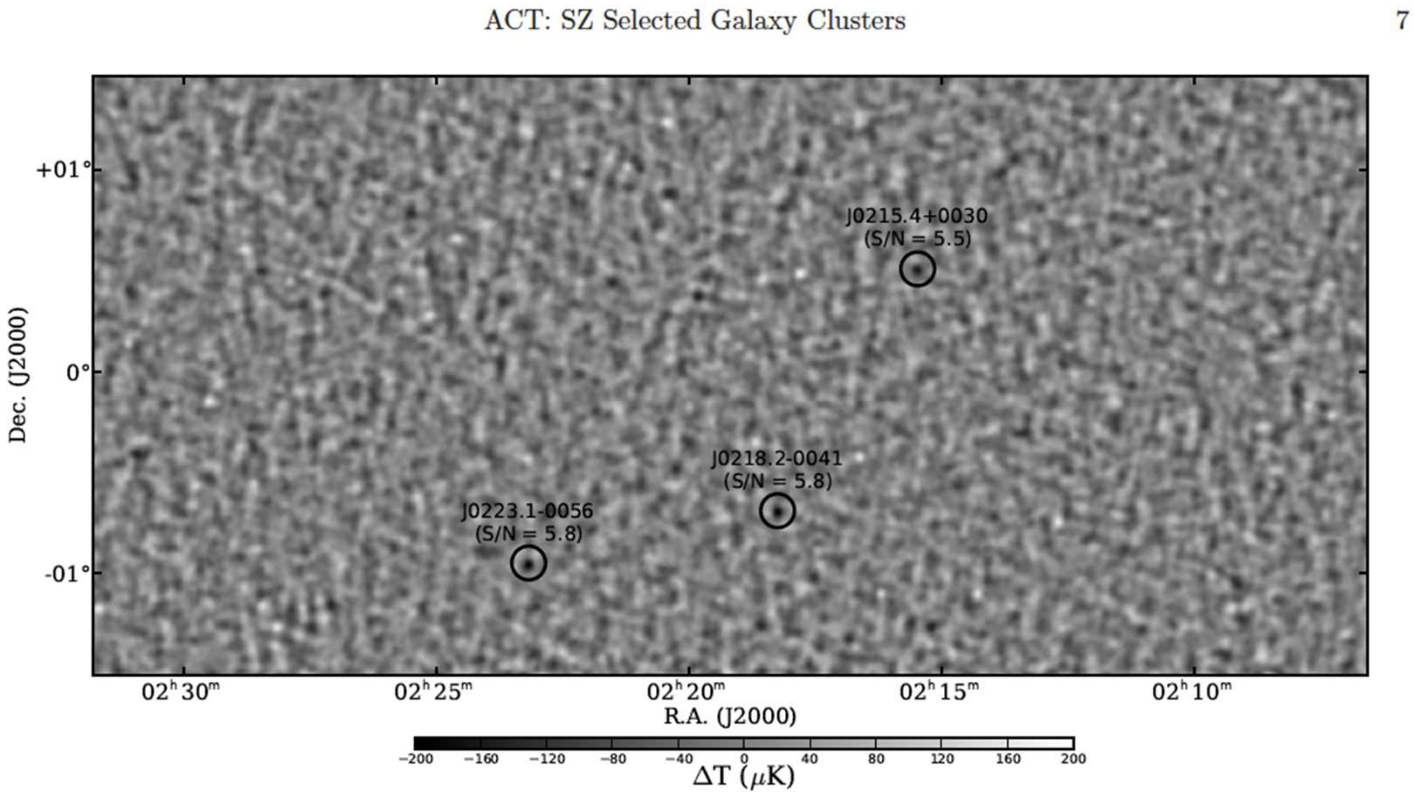


Example – a cluster at 7 *Planck* frequencies:



CMB Surveys using the SZ Effect

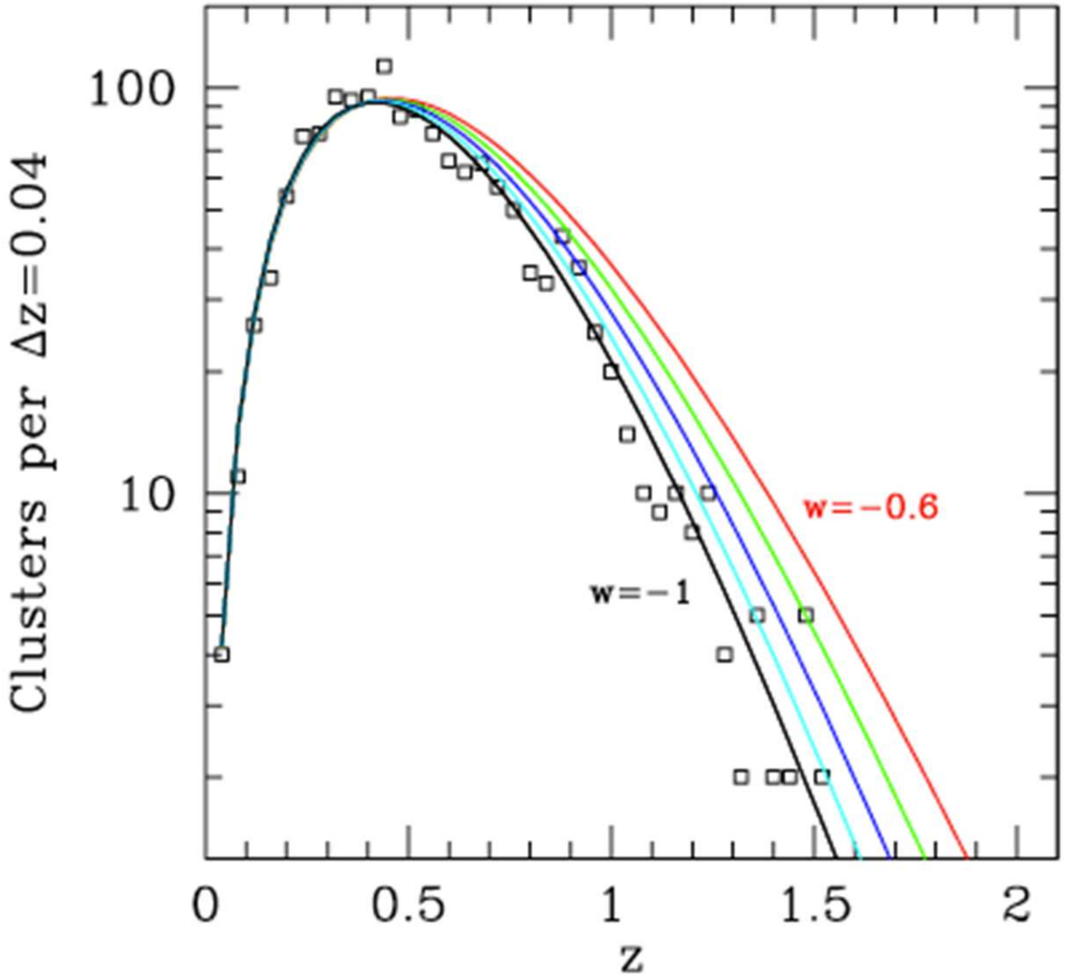
Currently, the best way to conduct *mass-limited* surveys for clusters
-- an example from the Atacama Cosmology Telescope



Planck detects > 1200; SPT cluster catalogs of ~100 well observed clusters
AdvACT should detect ~27,000 clusters in ½ the sky: all clusters with $M > 2x10^{14}$ M_o

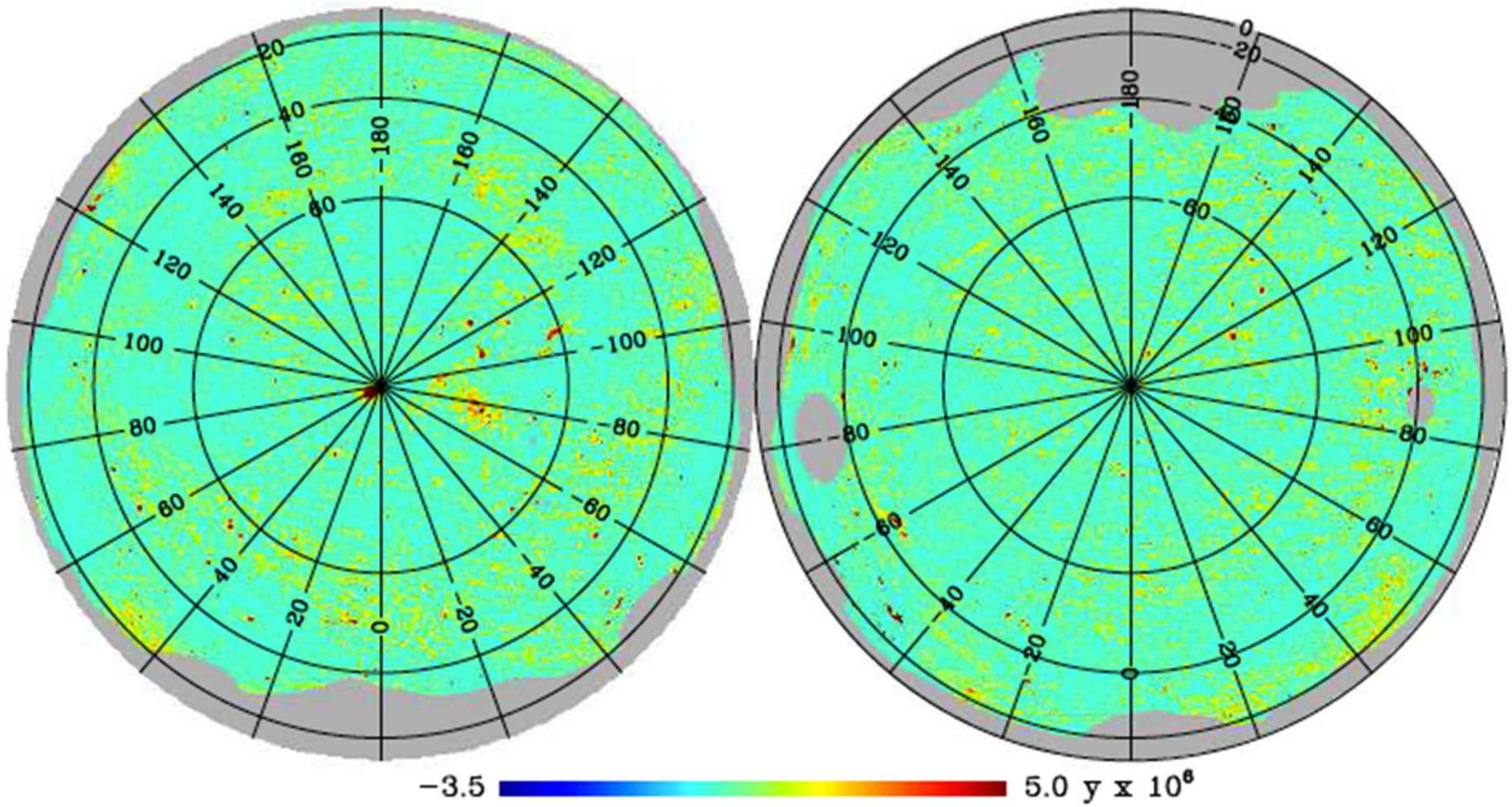
The Power of Cluster Counts

From SPT proposal:
an example of
constraints on
The Dark Energy
equation of state



3. Other Sites for the SZ Effect

Hot gas in the cosmic web – ***all sky*** maps of the SZ signal (proportional to gas pressure) on scales 0.17^o to 3^o (Planck 2013)



Power Spectrum of tSZ

From ***all sky*** maps of the SZ signal on scales 0.17° to 3° (Planck 2013)

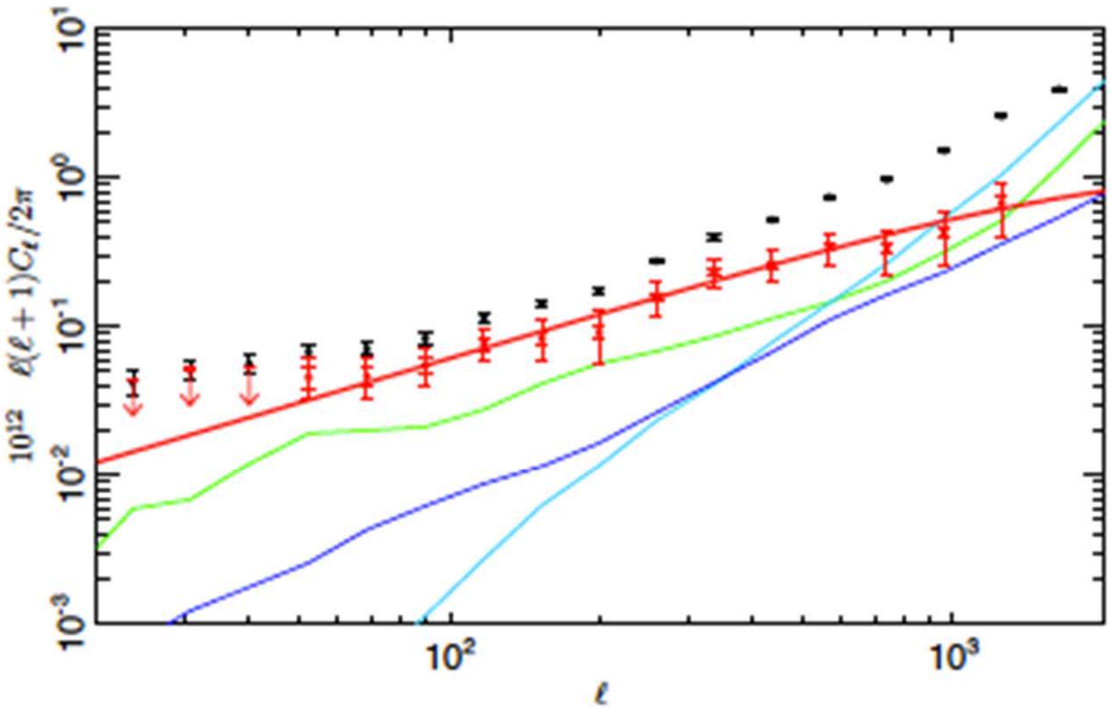


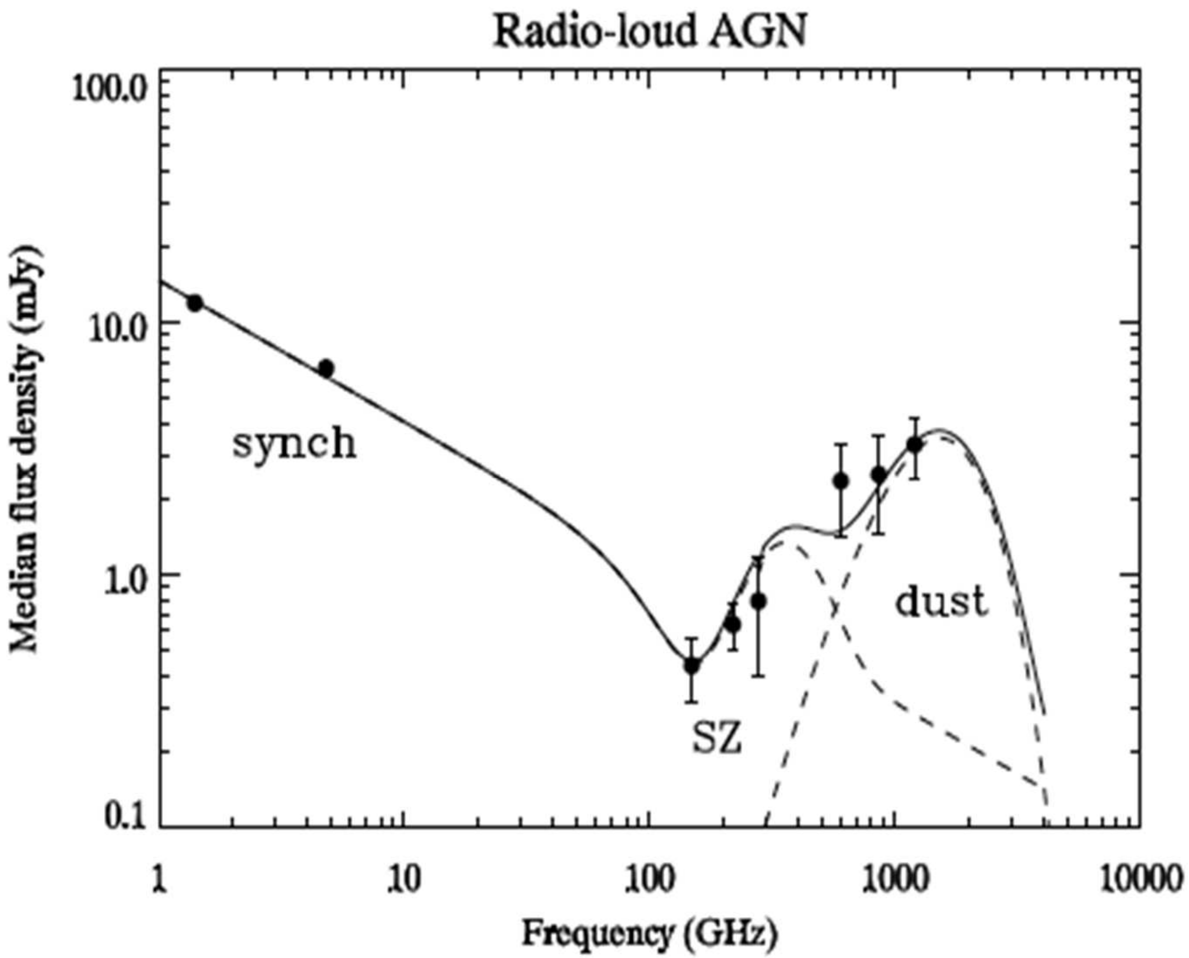
Fig. 7. NILC F/L cross power spectrum before (black points) and after (red points) foreground correction, compared to the power spectra of the physically motivated foreground models. Specifically we show: clustered CIB (green line); infrared sources (cyan line); and radio sources (blue line). The statistical

Red line is tSZ corrected for foregrounds

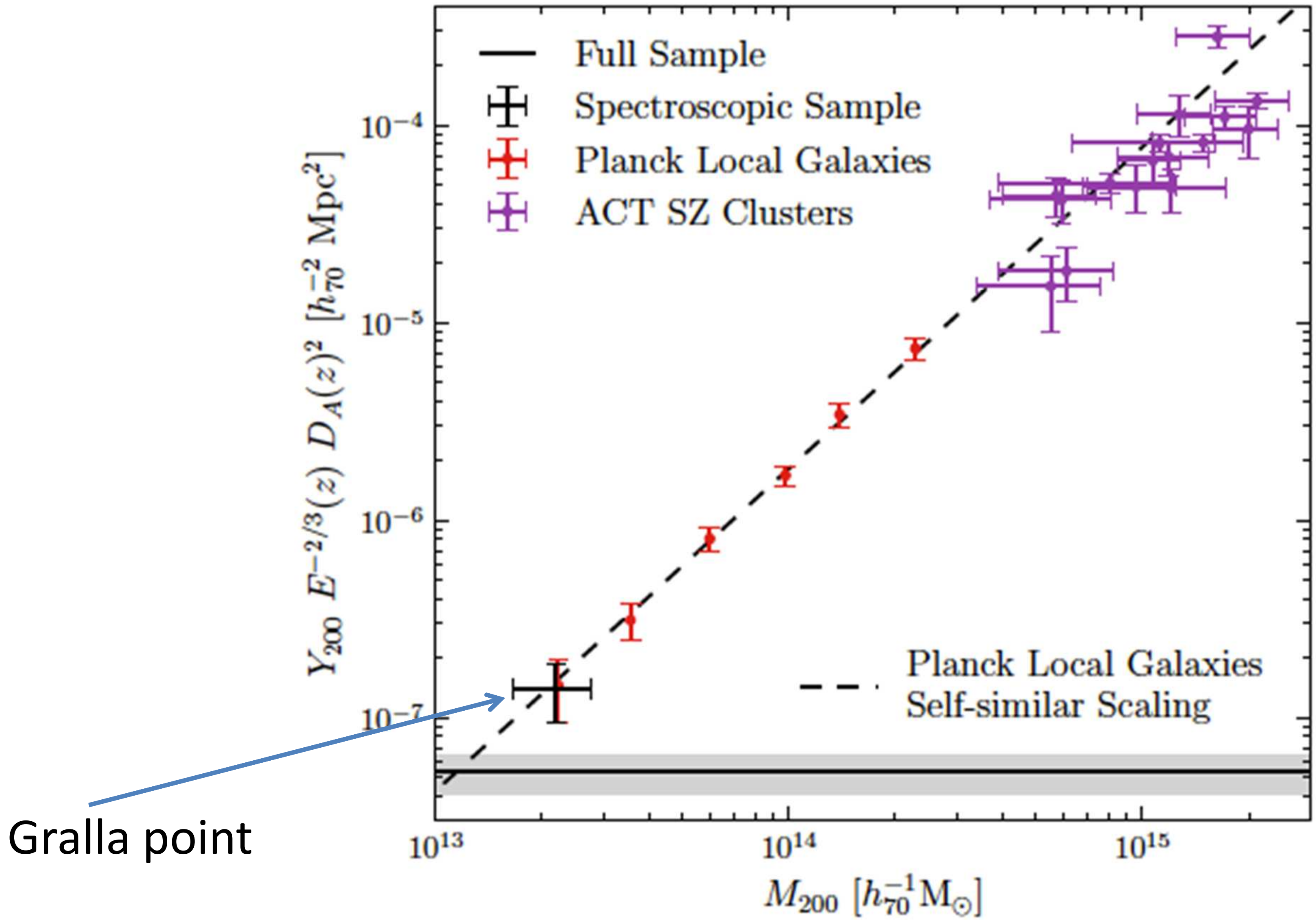
Note strong scale-dependence of foregrounds

3. Other Sites for the SZ Effect

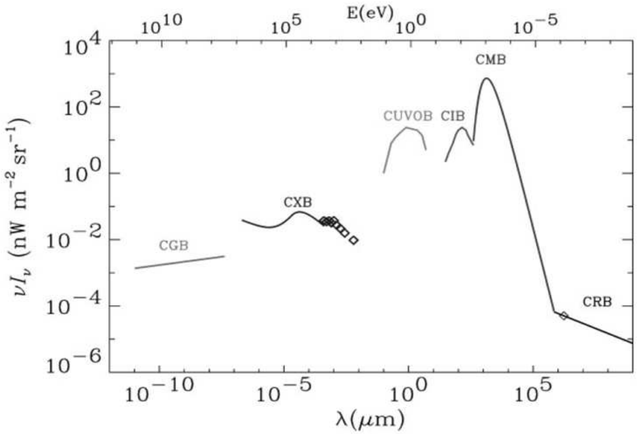
Gaseous halos of AGN (Gralla et al. 2014; stacked spectra)



Her work allows an extension of the scaling relation between cluster mass and the SZ signal (proportional to gas pressure)

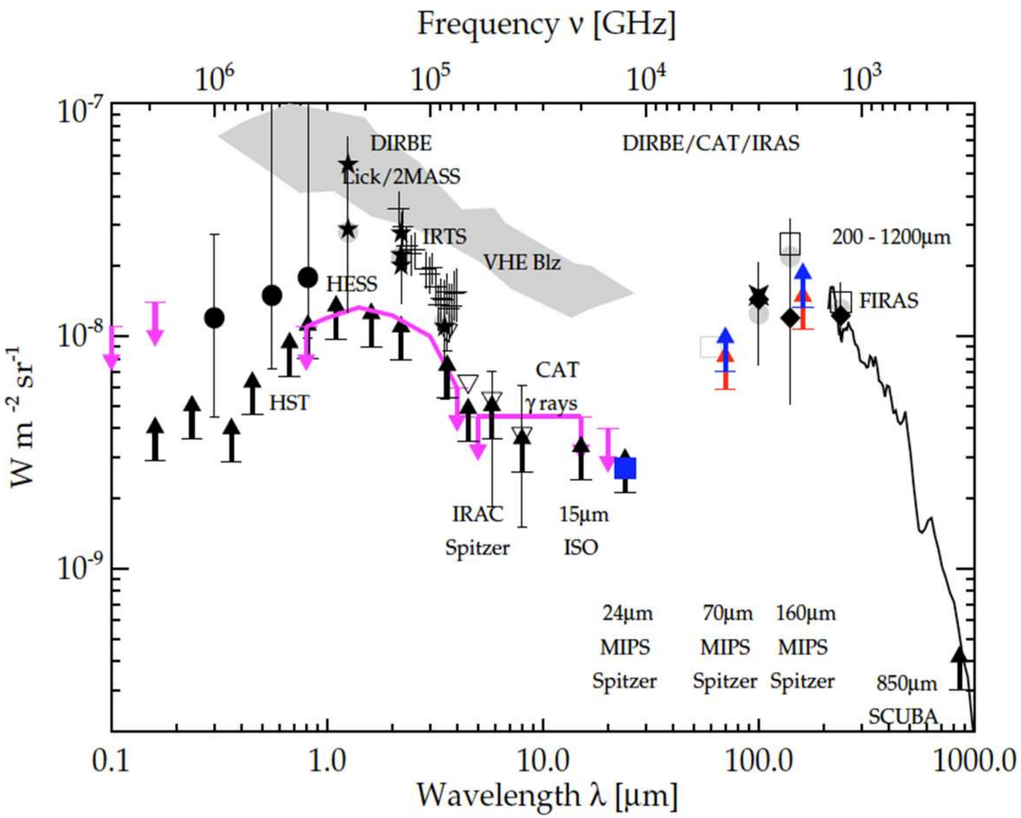


4. The Cosmic Infrared Background (CIB): the Light of the Web



Galaxies trace cosmic web & CIB traces galaxies, esp. star forming ones

Integrated CIB
~ energy density
in optical (Hauser, Dwek et al, 1998; Dole *et al*, 2006)

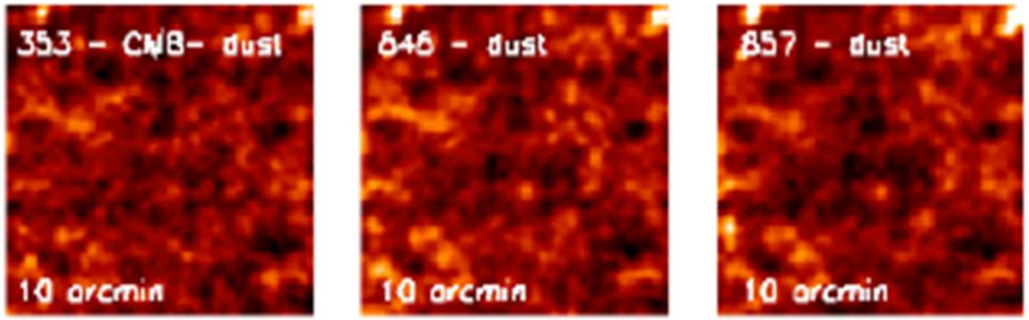


Recent measurements of CIB (Dole *et al*, 2006)

4. The Cosmic Infrared Background: the Light of the Web

The *structure* of the CIB -- *Planck* images of CIB (Planck 2013)

-- with CMB and Galactic dust emission subtracted



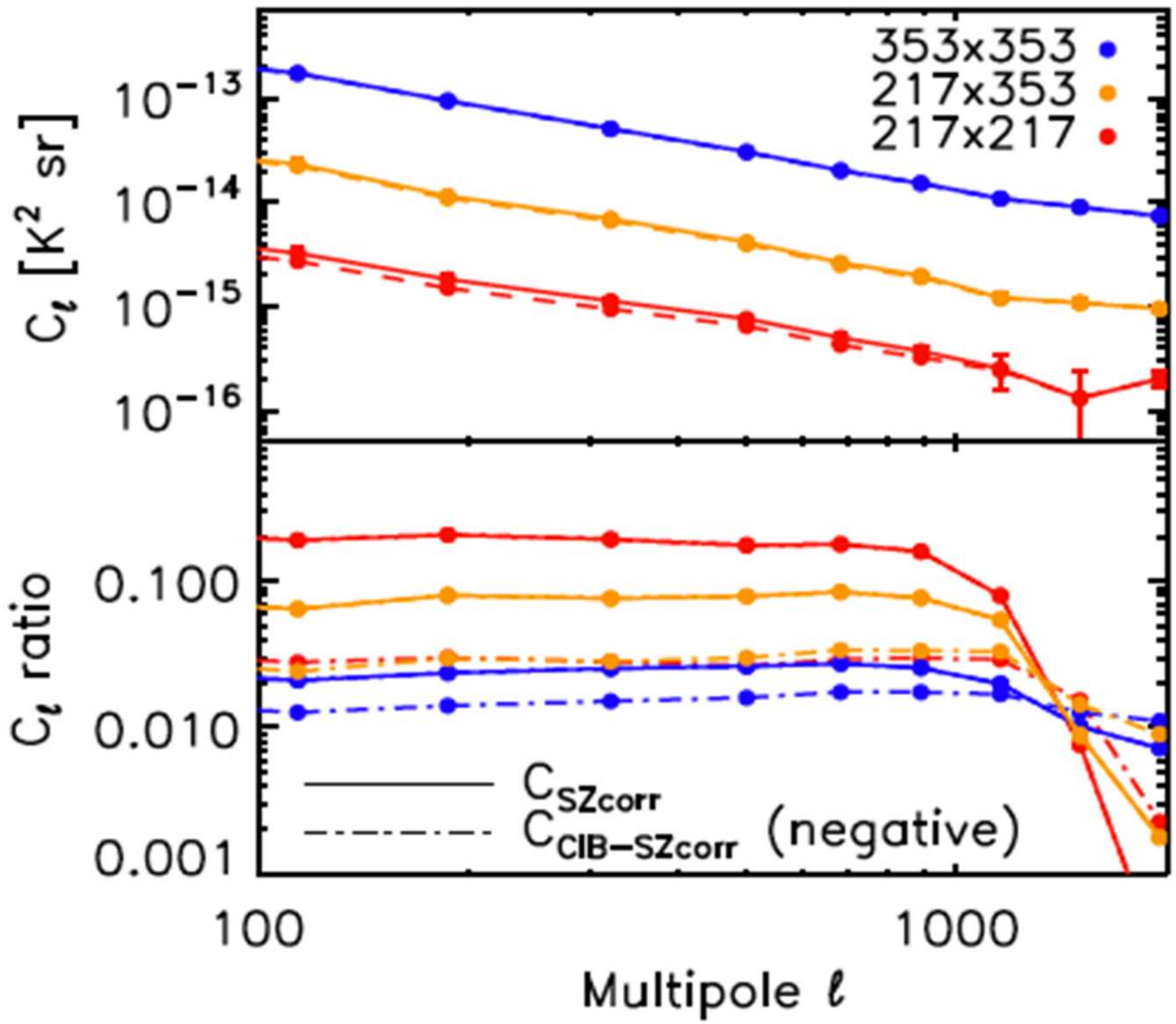
And measurements of the CIB intensity:

Band	νI_ν [nW m^{-2} sr^{-1}]
3000 GHz	13.1 ± 1.0
857 GHz	7.7 ± 0.2
545 GHz	2.3 ± 0.1
353 GHz	0.53 ± 0.02
217 GHz	0.077 ± 0.003

Some Power Spectra of CIB at 217 and 353 GHZ

From one of Planck 2013 papers.

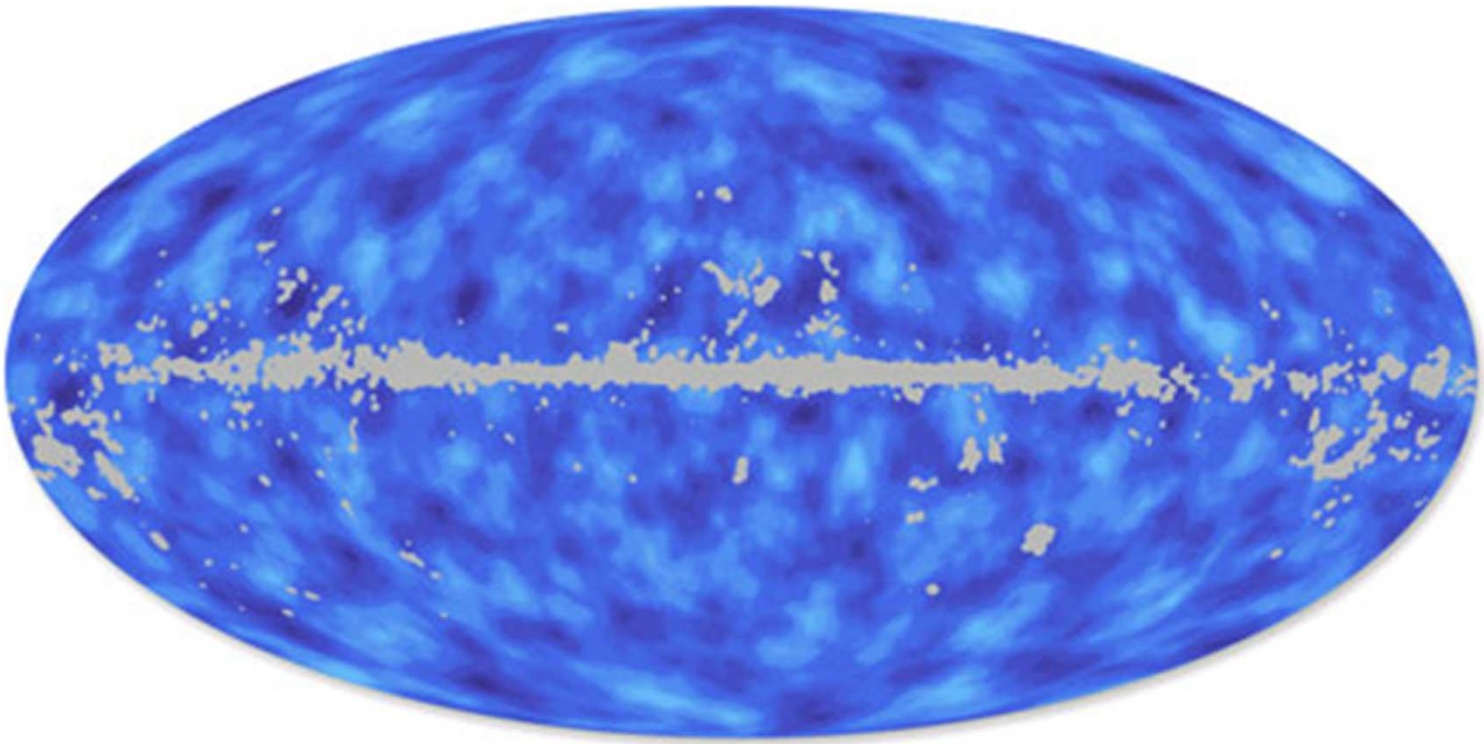
Since CIB spectrum is sharply peaked, different frequencies probe different redshifts: will permit cosmic tomography



5. Gravitational lensing by intervening matter

As CMB photons move through cosmic web, they are are gravitationally lensed

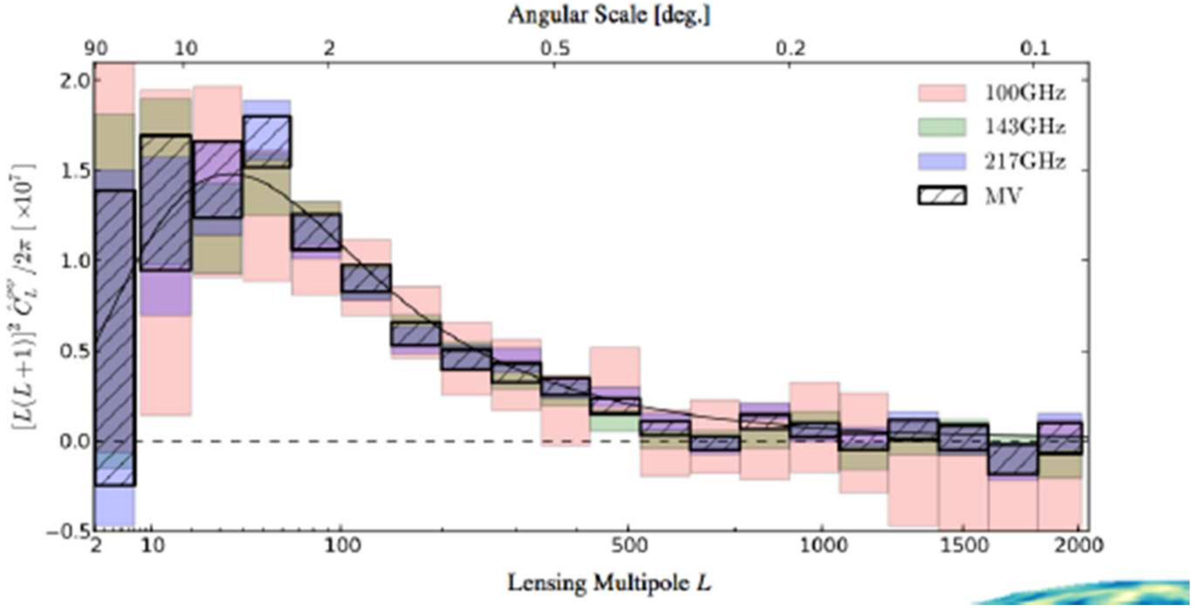
Measuring this lensing permits reconstruction of line-of-sight mass integral across sky (as done in Planck XVII, 2013):



Shown in Galactic coordinates

5. Gravitational lensing by intervening matter

Measuring this lensing also permits reconstruction of the lensing power spectrum (Planck XVII, 2013)

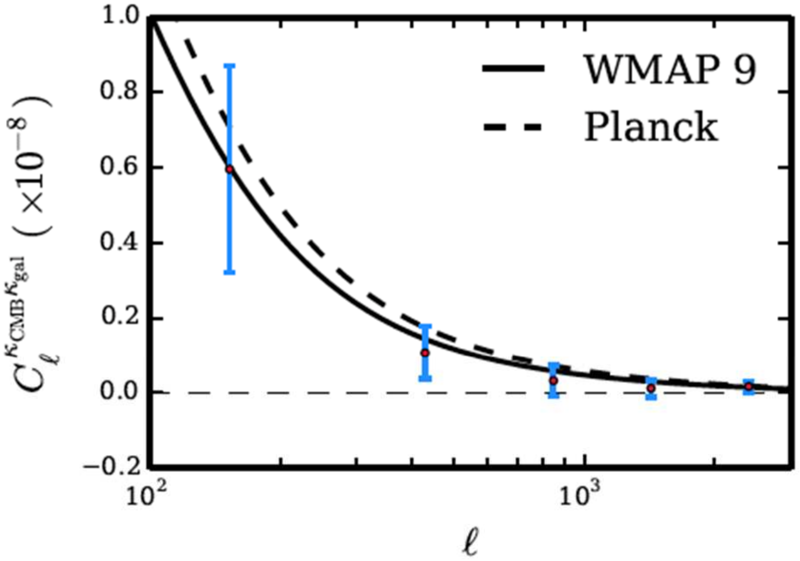


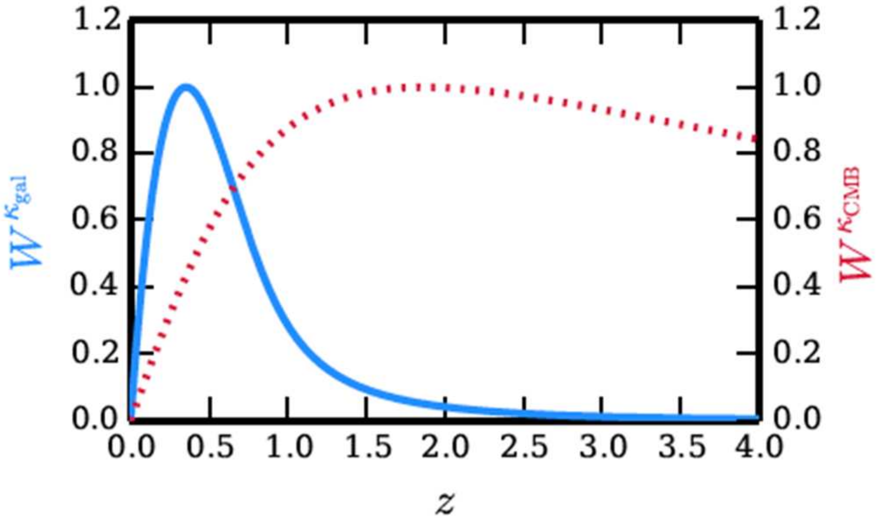
There is good agreement between measured lensing and the value predicted from ΛCDM cosmology (so we know how the cosmic web evolves)

-- if anything, measured lensing a bit larger than expected

Correlation between CMB lensing and optical lensing

First established at ~3.2σ level by N. Hand et al (2014)





Redshift kernels for optical galaxies (blue) and CMB (dashed red) are very different; different epochs of cosmic web are probed

6. Early Inflation

Inflation (per Linde and Guth) amplifies fluctuations in space-time (gravitational waves) as well as density perturbations

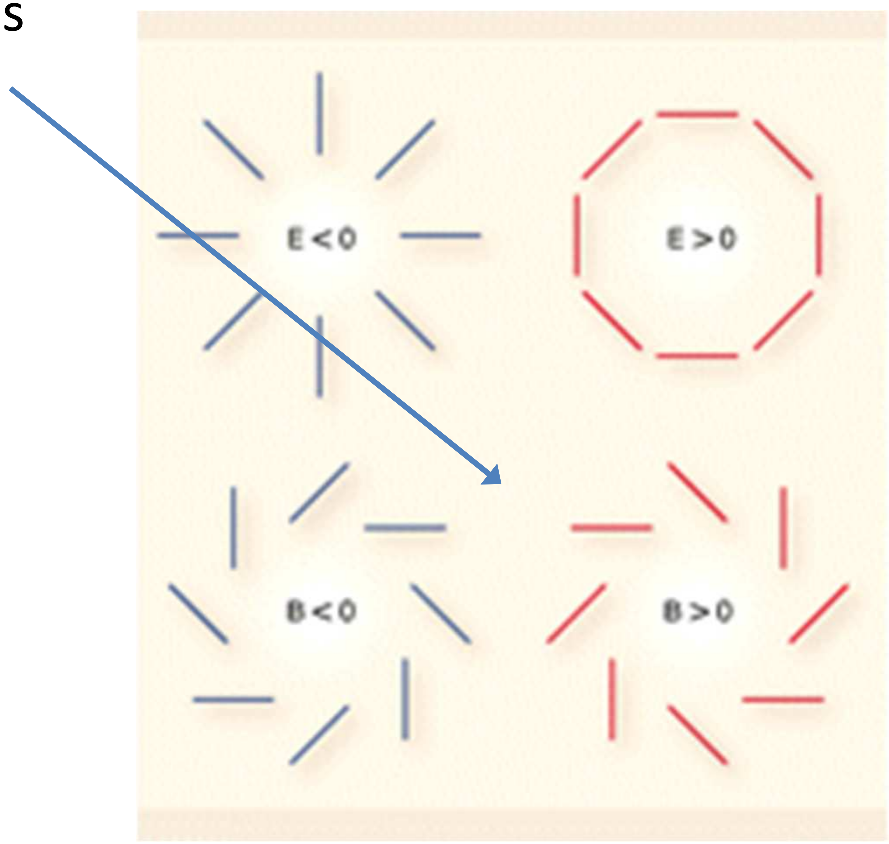
Both influence power spectrum of anisotropies in CMB

And most notably, gravitational waves

impart a unique

pattern of polarization:

the B modes

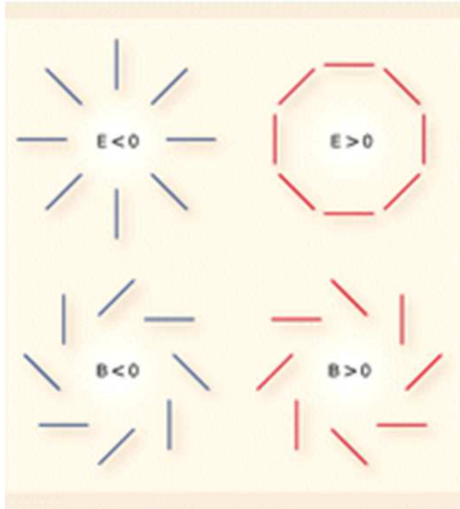


Reported Evidence for Early Inflation

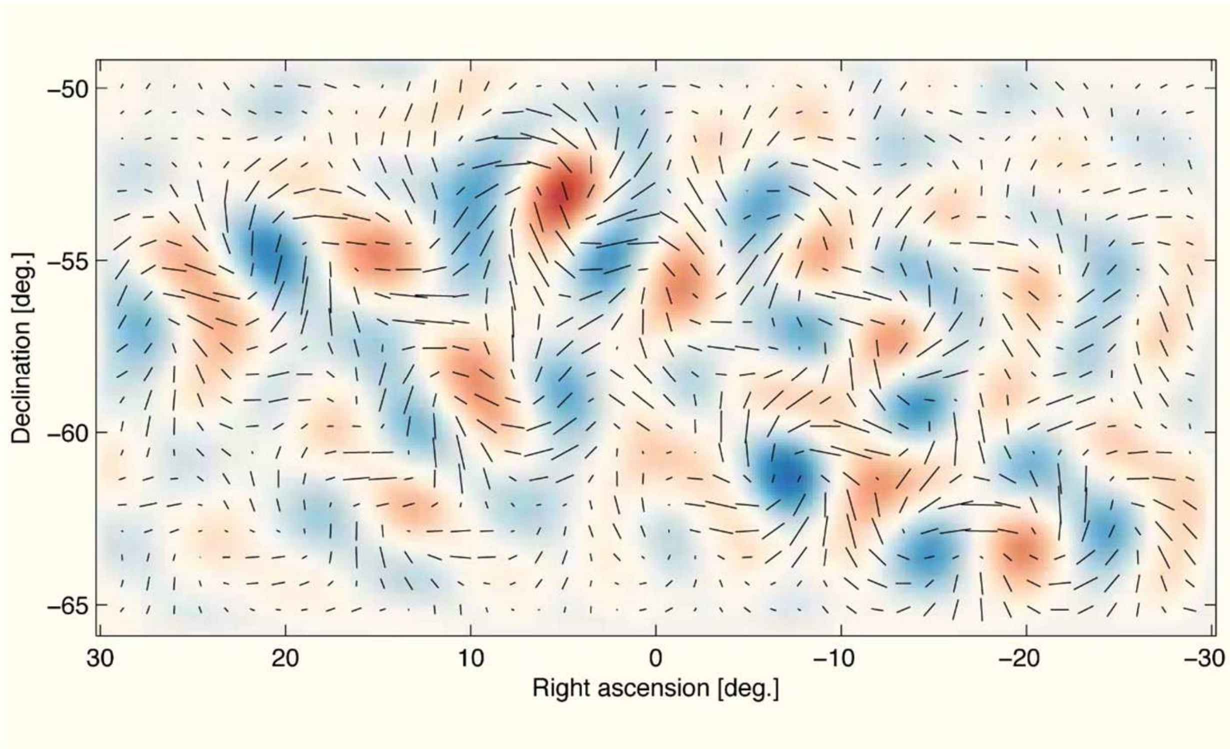
Inflation (per Linde and Guth) amplifies fluctuations in space-time (gravitational waves) as well as density perturbations

And most notably, gravitational waves

Produce B modes



Reported in March by the BICEP2 Team:



Models of Inflation

*Man*y models of early Inflation:

-- can be characterized by

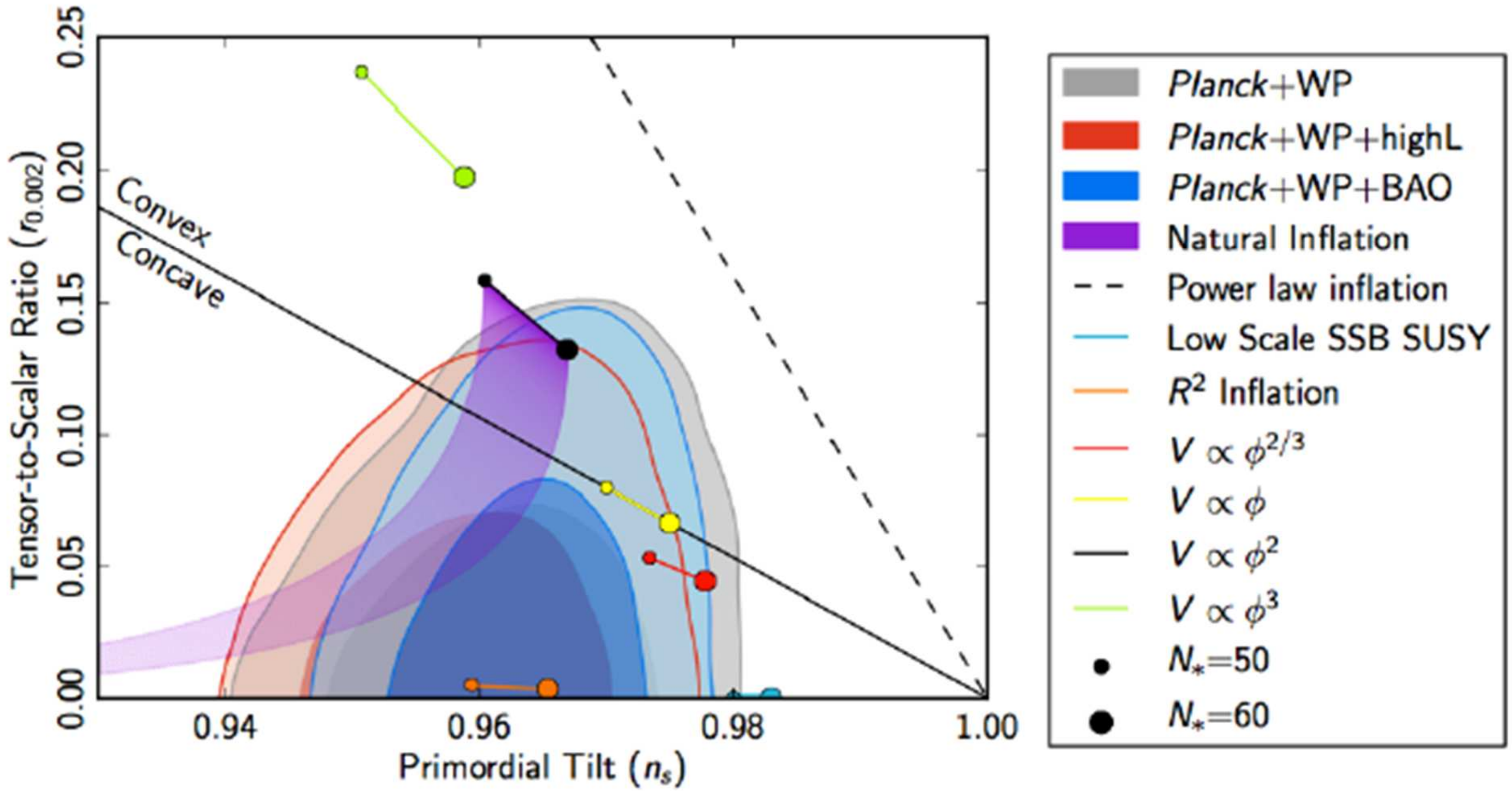
r = ratio of tensor (grav. wave) to scalar (density) perturbations

n_s – the slope of the power spectrum (scale-independent Harrison-Zel'dovich spectrum has $n_s = 1.00$)

These parameters can be bounded by CMB *temperature* measurements (as well as B mode polarization)

Planck limits so far based on *temperature* measurements

Current *Planck* Limits on Inflation Models



Some tension with recent BICEP2 results which favor larger r (~0.02)

Now Two Topics that Might Have Amused Zel'dovich

7. Using *Planck* to Calibrate Ground-Based Radio Telescopes

Calibration of *Planck* is *absolute* – based on satellite motion in solar system

Planck is sensitive enough to observe hundreds of bright radio sources

Comparing *Planck* and ground-based measurements allow us to transfer Planck calibration to VLA, Australia Telescope, etc.

7. Using *Planck* to Calibrate Ground-Based Radio Telescopes

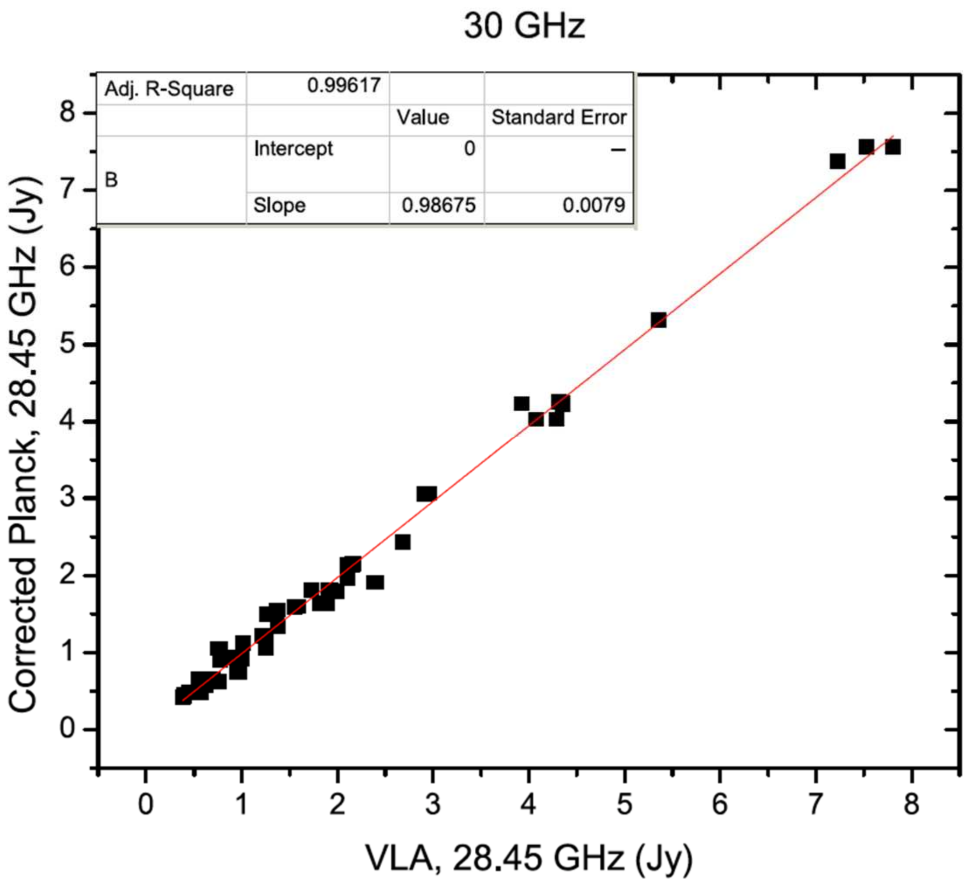
Problem:

Radio sources are *variable*,

Resulting in scatter shown

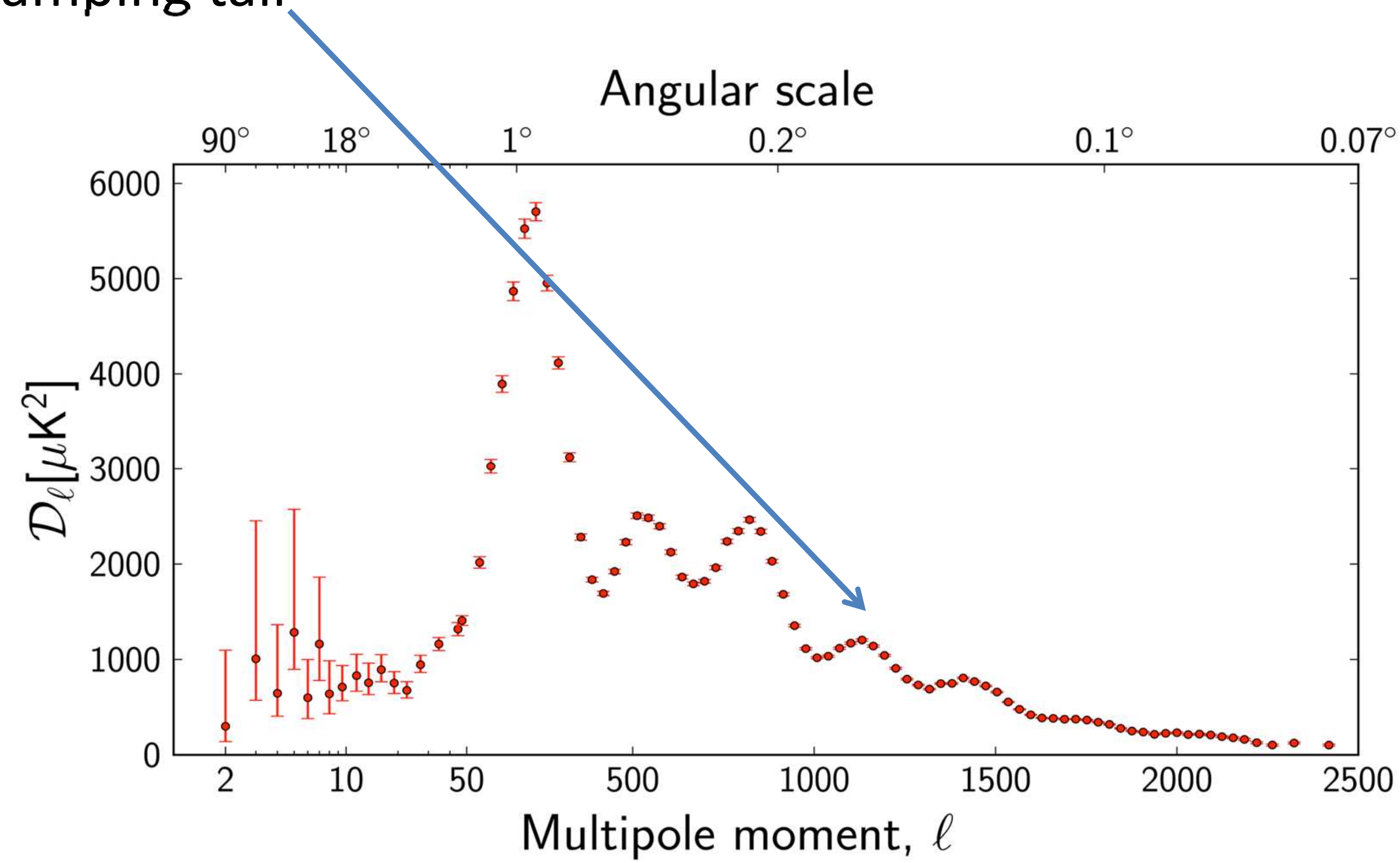
Solution: observe many
and at closely the same time
(Perley, Butler, Partridge, Caniego and Stevens, in prep. 2014)

Result: ~1-2% ***absolute*** accuracy in flux density scales

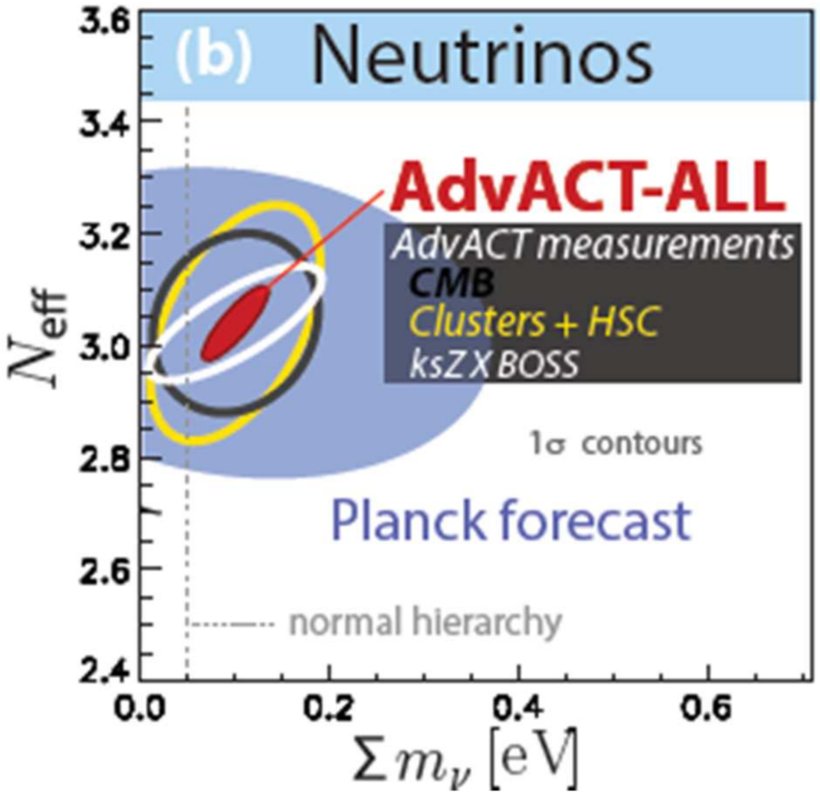


8. Using CMB Observations to Measure Mass of Neutrinos

Mass of neutrinos affects various properties of the power spectrum of anisotropies in the CMB – including small-angle damping tail



An Example: Constraints of Neutrino Mass from Proposed AdvACT Experiment



Compare to 95% limits from *Planck:* < 0.66 eV (or at best < 0.23 eV)

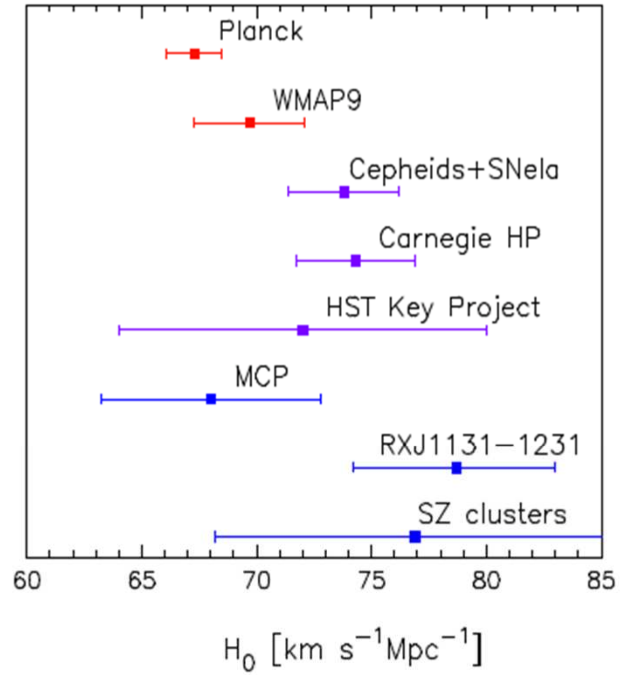
I hope I have convinced you of the value of CMB studies whether or not they relate to the cosmic web.

I know I don’t have to convince you of the wide range of Yakov Borisovich Zel’dovich’s contributions to cosmology.

Since You Asked…

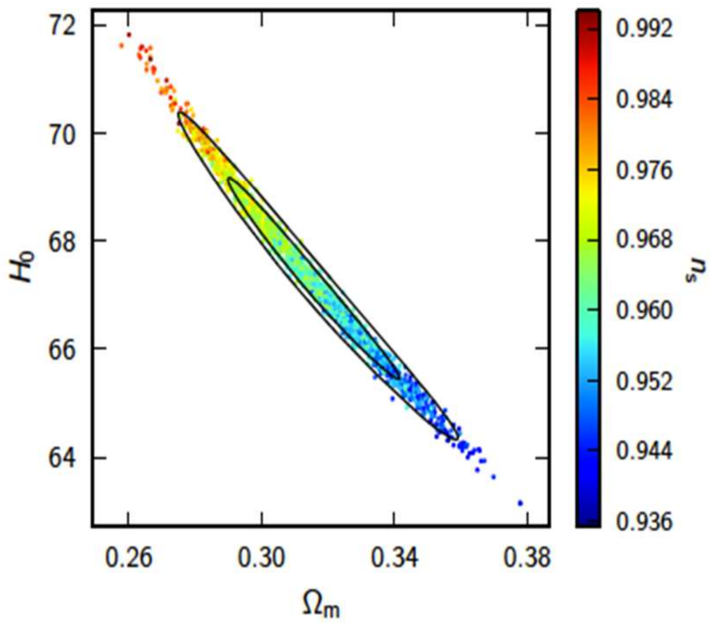
Planck vs. SNe, Tully-Fisher, etc. values of H_o

Planck = 67.8 ± 1.2 Km/sec
per Mpc -- well below SNe values



However, Planck measures acoustic scale, not H_o directly.

H_o values degenerate with matter density:



Finally, *Planck* values agree with BAO

All results from Planck XVI, 2013

BAO Results (Cited in Planck XVI, 2013)

Sample	Ω_m	H_0
6dF	$0.305^{+0.032}_{-0.026}$	$68.3^{+3.2}_{-3.2}$
SDSS	$0.295^{+0.019}_{-0.017}$	$69.5^{+2.2}_{-2.1}$
SDSS(R)	$0.293^{+0.015}_{-0.013}$	$69.6^{+1.7}_{-1.5}$
WiggleZ	$0.309^{+0.041}_{-0.035}$	$67.8^{+4.1}_{-2.8}$
BOSS	$0.315^{+0.015}_{-0.015}$	$67.2^{+1.6}_{-1.5}$
6dF+SDSS+BOSS+WiggleZ	$0.307^{+0.010}_{-0.011}$	$68.1^{+1.1}_{-1.1}$
6dF+SDSS(R)+BOSS	$0.305^{+0.009}_{-0.010}$	$68.4^{+1.0}_{-1.0}$
6dF+SDSS(R)+BOSS+WiggleZ	$0.305^{+0.009}_{-0.008}$	$68.4^{+1.0}_{-1.0}$

Again, Since You Asked…

Preliminary, roughly calibrated, *Planck* polarization results fit to *Planck* cosmology