SDSS quasars & WMAP3

a high–z detection of the Integrated Sachs–Wolfe effect

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in collaboration with
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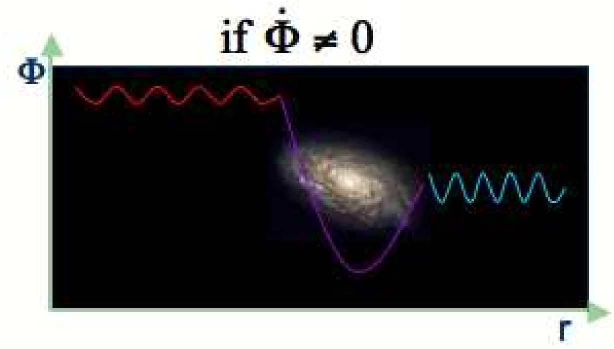
the SDSS collaboration

overview

- introduction to the Integrated Sachs–Wolfe effect
  - how dark energy can leave its mark on the CMB image
  - the ISW effect(s)
  - extracting the signal
- the measure of the ISW for a high redshift sample of quasars
  - the SDSS quasar catalog
  - looking for systematics
  - the auto–correlation function
  - the *WMAP3* CMB maps
  - the cross–correlation function
- results and cosmological constraints
  - universe seems still ΛCDM at $z = 1.5$
  - constraints on dark energy parameters
  - comparison with previous measures

Sachs–Wolfe effects

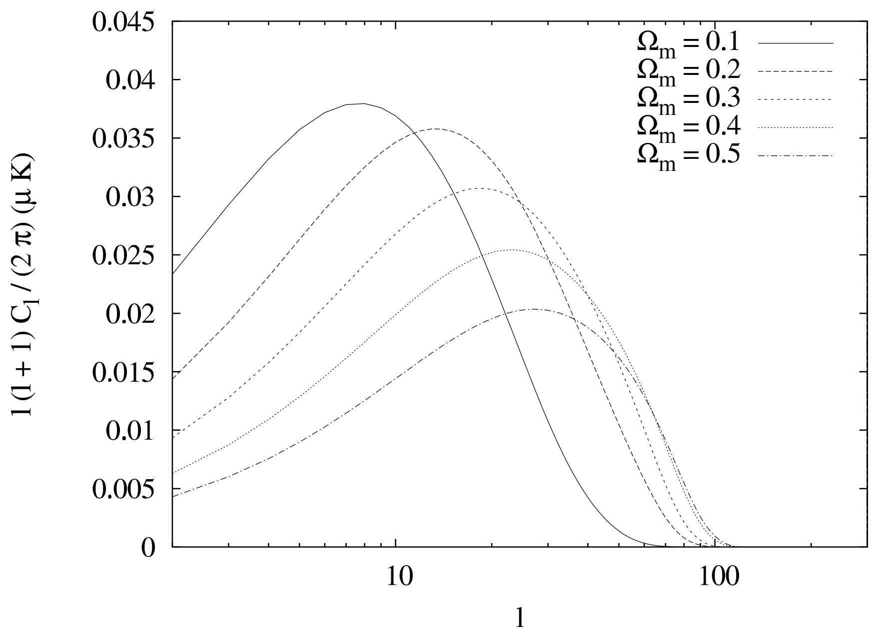


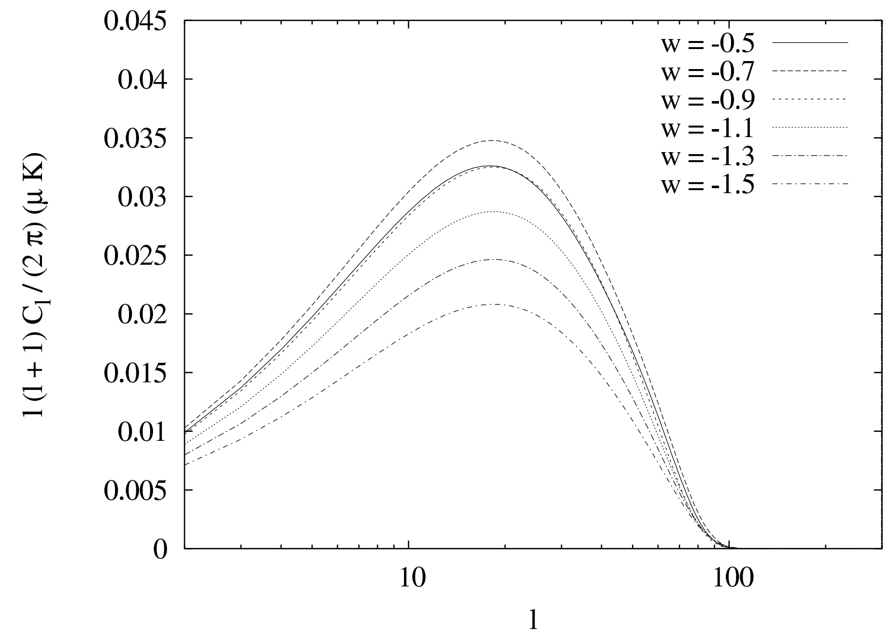
- ★ unintegrated SW: $\Theta_{SW} \propto \Delta\Phi$
- ★ integrated SW: $\Theta_{ISW} = 2 \int_\gamma \dot{\Phi}[r(t), t]dt$ *[Sachs and Wolfe '68]*

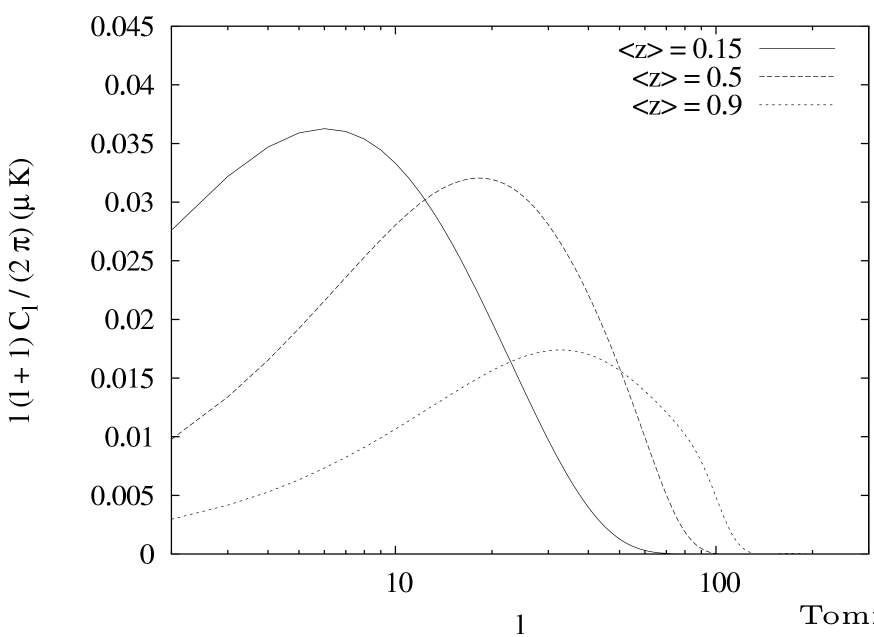
$$\nabla^2 \Phi = 4\pi G a^2 \rho \delta \quad \rightarrow \quad \Phi \propto \frac{\delta}{a} \tag{1}$$

  - ▶ no effect in matter dominated epoch: $\delta_m \propto a \quad \Rightarrow \quad \dot{\Phi} = 0$
  - ▶ early ISW in transition from radiation epoch
  - ▶ late ISW in transition to curvature or DE epoch
- ★ Cross–correlation CMB–matter can extract the late ISW *[Crittenden, Turok '95]*

dependence on the parameters







- Ω_m: max for low values,big Ω_Λ
- w: for $w \to 0$ no DE and for $w < -1$ became important later
- $\bar{z}$: max for low values: more DE in recent times

state of art

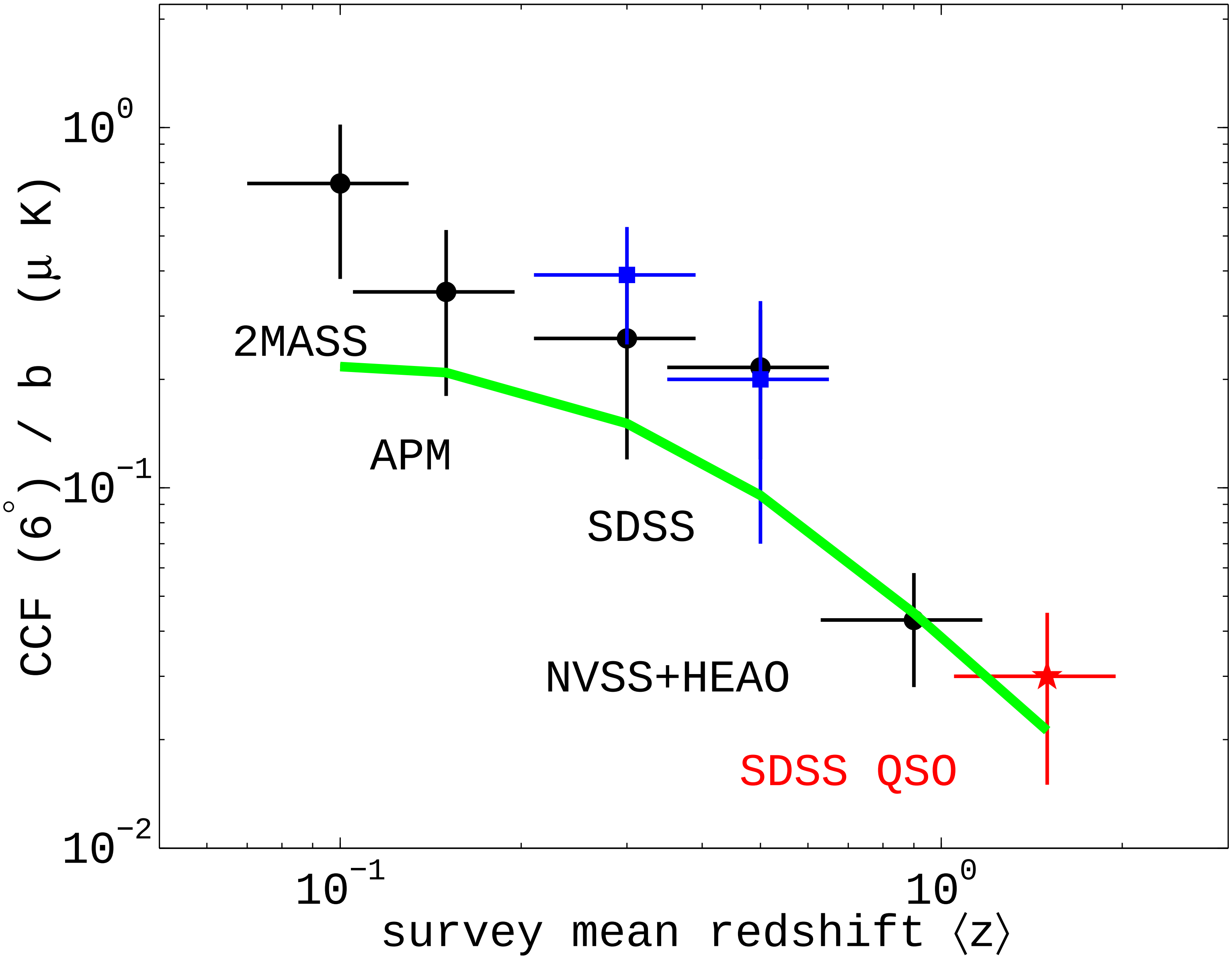
★ real space: $c^{Tg}(\vartheta)$, all have a significance $> 2\sigma$

survey	CMB map	band	z̄	reference
2MASS	WMAP1	IR	0.10	*Afshordi et al. '04*
APM	WMAP1	optical	0.15	*Fosalba, Gaztañaga '04*
SDSS	WMAP1	optical	$0.3, 0.5$	*Scranton et al. '04*
				Fosalba et al. '04
SDSS	WMAP3	optical	$0.3, 0.5$	*Cabré et al. '06*
NVSS, HEAO	WMAP1	radio, X	0.9	*Boughn, Crittenden '04*
NVSS	WMAP1	radio	0.9	*Nolta et al. '04*
SDSS QSO	WMAP3	optical	1.5	*TG et al. in preparation*

★ harmonic space: C_l^{Tg}

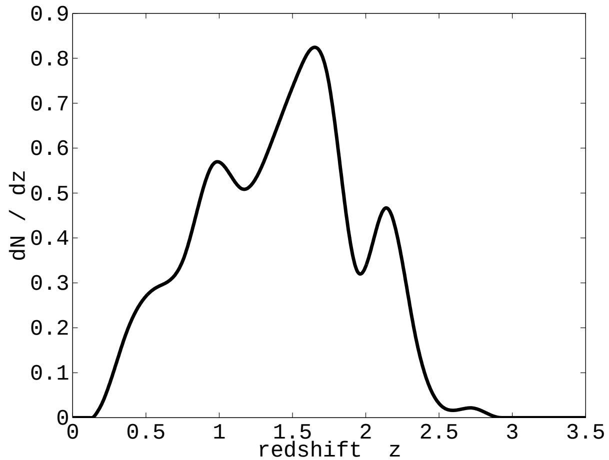
SDSS LRG	WMAP1	optical	0.5	*Padmanabham et al. '04*

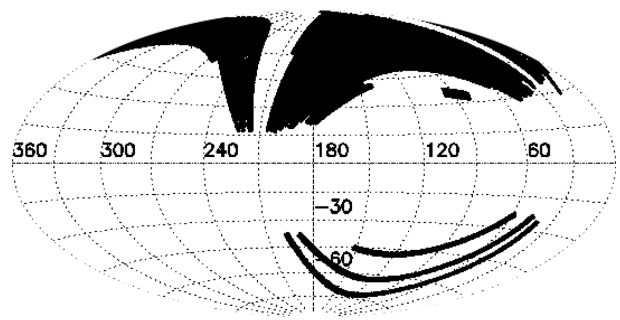
★ wavelet space

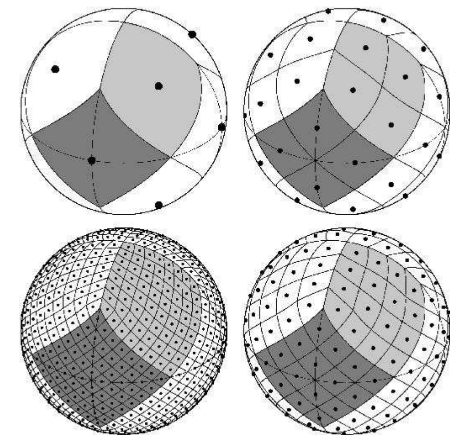


10^0
10^{-1}
10^{-2}
CCF (6°) / b (μ K)
2MASS
APM
SDSS
NVSS+HEAO
SDSS QSO
10^{-1}
10^0
survey mean redshift ⟨z⟩

the SDSS dr4 quasar catalog







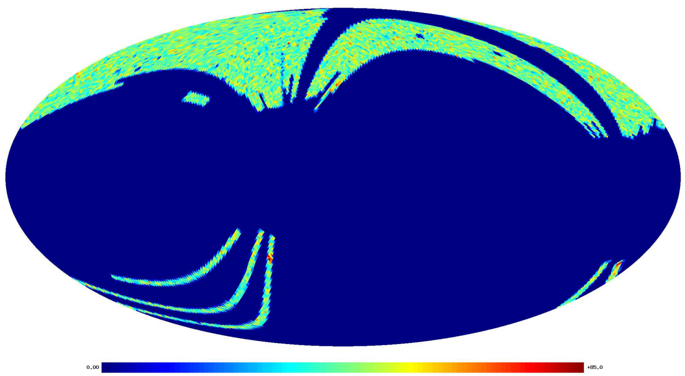
★ NBC–KDE algorithm *[Richards et al. '04]*

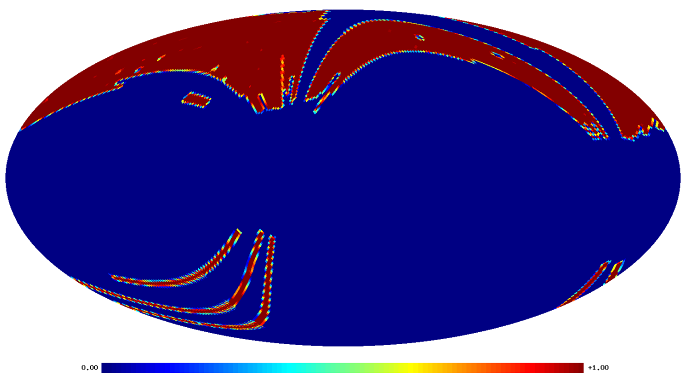
- based on previous multicolor data of quasars and stars
- $> 95\%$ complete, contains $3 \cdot 10^5$ objects up to redshift $z = 2.7$
- has a fraction $k \sim 5\%$ of stellar contamination to magnitude $i = 21$

★ *HEALPix* pixelisation *[Gorski et al. '05]*

- $N\mathrm{side} = 64$: the celestial sphere is divided in $N\mathrm{pix} = 5 \cdot 10^5$ pixels of side 0.9°, enough to measure the ISW
- 16% of the pixels are in the SDSS covered area: for them $\bar{n} = 43$

systematics I: pixelization

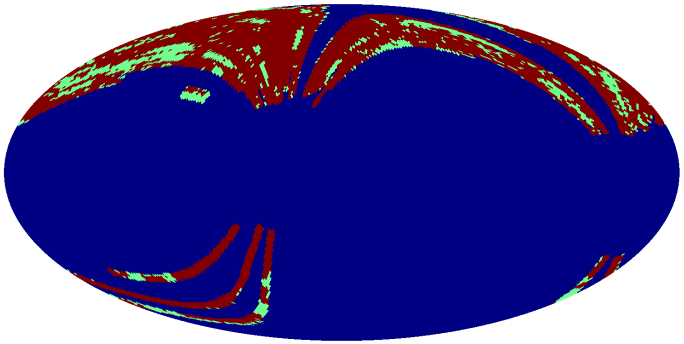




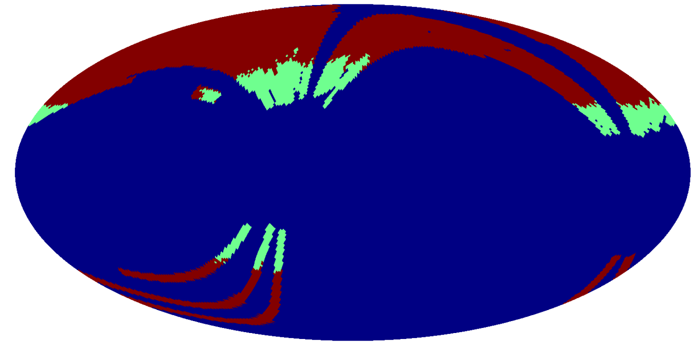
- 20% of the pixels are on the edge of the survey
  - their occupation number is lower
  - the expectation value must be calculated individually for each pixel
- an edge mask is built
  - with a random catalog of $5 \cdot 10^6$ galaxies from SDSS
  - higher resolution pixelization $N\mathrm{side}_{\mathrm{up}} = 512$ so $\bar{n}_{\mathrm{up}} = 10$
  - for each *big* pixel, how many *small* subpixels are covered by the survey?
- the number of sources should be rescaled with the coverage fraction f_i:

$$f_i = N\mathrm{fill}_{\mathrm{up},i} \frac{N\mathrm{pix}}{N\mathrm{pix}_{\mathrm{up}}} \tag{2}$$

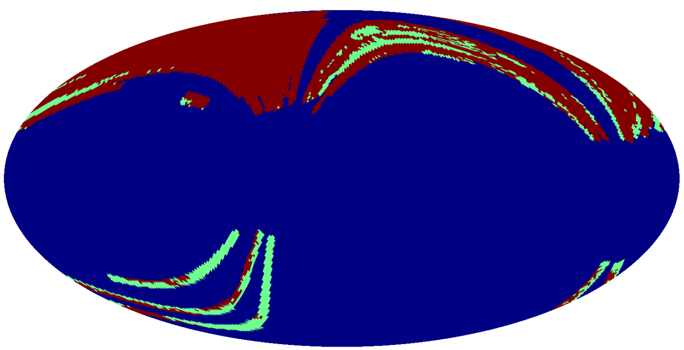
systematics II: foregrounds



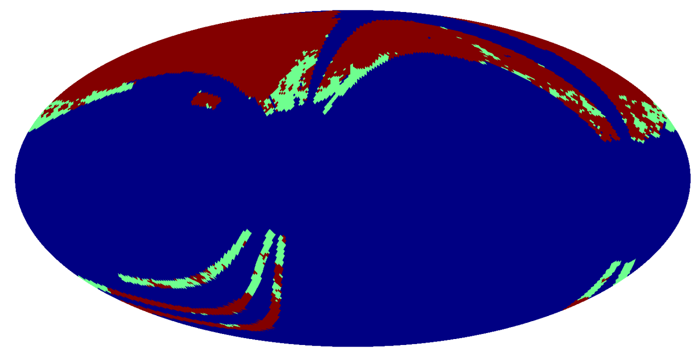
★ seeing



★ point sources



★ sky brightness



★ reddening

- make sample less complete
- hinder precise redshift measure
- introduce stellar contamination

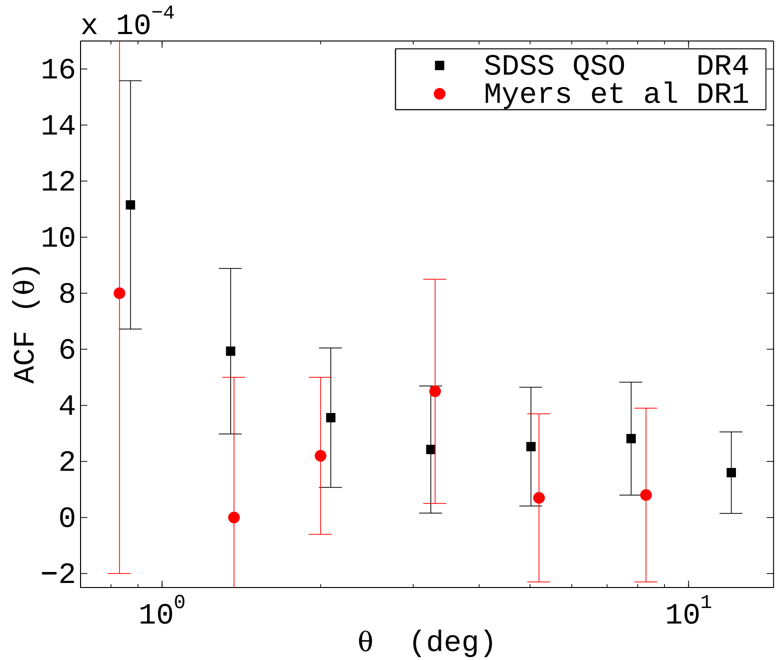
the auto–correlation I

★ we measure the total ACF in real space for $0.8^\circ < \vartheta < 15^\circ$

- it is composed by stars and quasars in the proportion $k^2 : (1-k)^2$
- the estimator for the total is

$$\hat{c}^{tt}(\vartheta) = \frac{1}{N_\vartheta} \sum_{i,j} f_i f_j \left(\frac{n_i}{f_i} - \bar{n} \right) \left(\frac{n_j}{f_j} - \bar{n} \right) \quad (3)$$

- N_ϑ is the number of pixels separated by ϑ weighted with f_i



★ in agreement with Myers et al '05

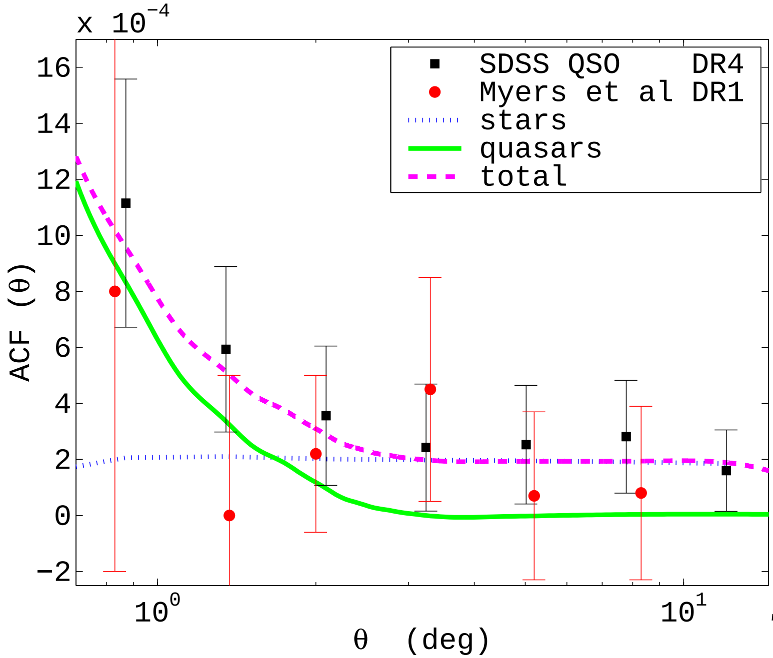
- error bars calculated with 1000 Monte Carlo
- smaller error bars because bigger sample
- we see still power at $\vartheta \sim 10^\circ$

the auto–correlation II

★ we model the total theoretical ACF $c^{tt}(\vartheta)$ with its components

$$c^{tt}(\vartheta) = (1-k)^2 c^{qq}(\vartheta) + k^2 c^{ss}(\vartheta) \quad (4)$$

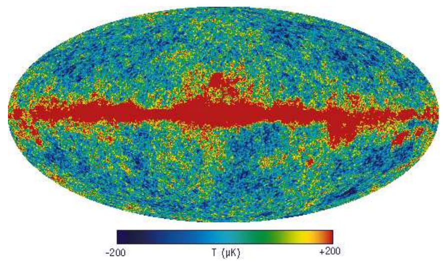
- ▶ the stellar part is estimated with a random subsample of kN_q stars from a big sample of $2 \cdot 10^6$ stars from SDSS
- ▶ quasar part from the theoretical matter $c^{qq}(\vartheta) = b^2 c^{mm}(\vartheta)$ with *CMBFAST* with WMAP3 best fit parameters
- ▶ smoothing on small scales due to pixel window function



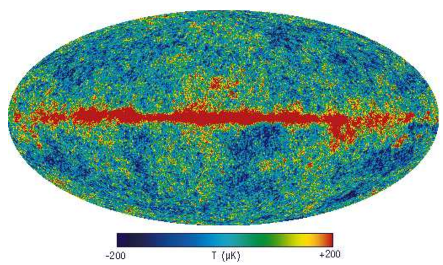
★ good agreement with measure

- ▶ best value for contamination $k = 0.05 \pm 0.01$, as expected
- ▶ for bias $b = 2.4 \pm 0.2$, as measured by Myers et al. '05, Croom et al. '05

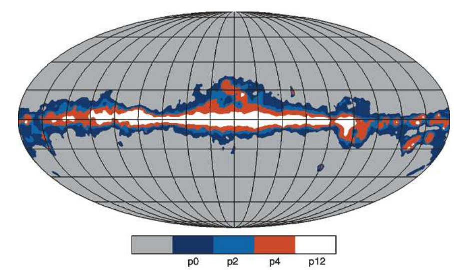
the CMB map from WMAP

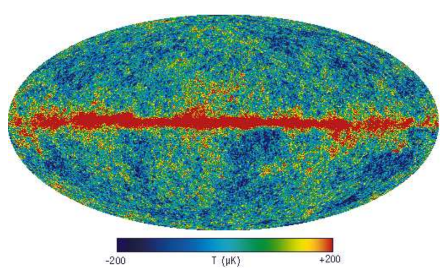


★ Q band (41 GHz)
- ▶ synchrotron radiation



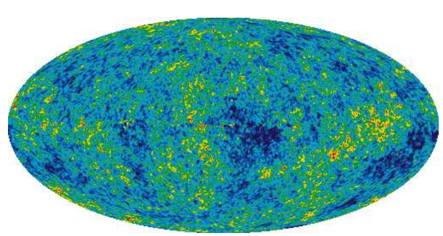
★ V band (61 GHz)
- ▶ free–free





★ W band (94 GHz)
- ▶ thermal dust

★ *kp0* mask for all



★ *Internal Linear Combination* (ILC) map

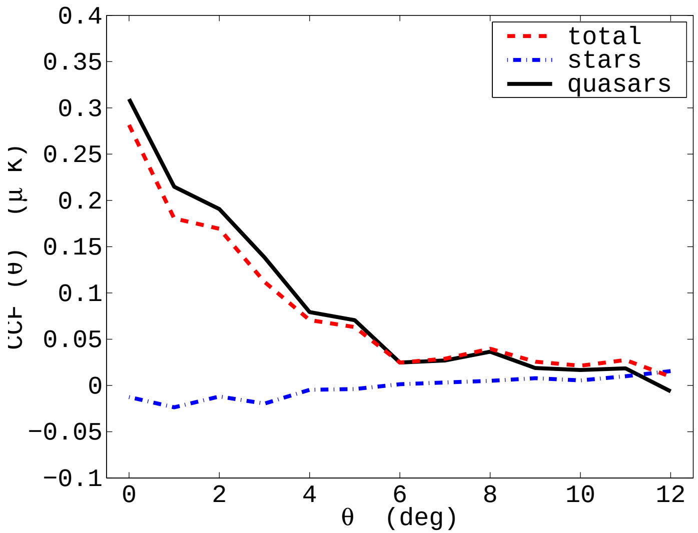
the CCF I: the observation

- the estimator for the correlation total catalog–CMB $\hat{c}^{Tt}(\vartheta)$ is

$$\hat{c}^{Tt}(\vartheta) = \frac{1}{N_\vartheta} \sum_{i,j} f_i \left(\frac{n_i}{f_i} - \bar{n} \right) (T_j - \bar{T}), \quad (5)$$

- similar estimator for the stellar correlation with the CMB $\hat{c}^{Ts}(\vartheta)$ (should be zero if the CMB map were clean)
- $\Rightarrow$ the quasar only $\hat{c}^{Tq}(\vartheta)$ is derived from these:

$$\hat{c}^{Tq}(\vartheta) = \frac{\hat{c}^{Tt}(\vartheta) - k\hat{c}^{Ts}(\vartheta)}{1-k} \quad (6)$$



- the star sample is almost uncorrelated with *WMAP*
  - CMB maps are clean

the CCF II: the significance

- two sources of statistical errors:
  - cosmic variance (we observe only one CMB map and one matter distribution)
  - Poisson error (oscillations in the pixel counts)
- Monte Carlo method to find the errors
  - given a power spectrum and a phase we can generate random gaussian maps with the same statistical properties of the observed maps
    - random CMB maps T_i^r: from the best fit *WMAP*3 model C_l^{TT}
    - random quasar density δ_i^r maps: from the observed ACF and following C_l^{qq}
    - a random quasar number map is given by $n_i^r = (1 + \delta_i^r)\bar{n}$
  - correlation between thousands of these maps yields the covariance matrix, but something is missing...

the CCF III: the significance

- ...Monte Carlo method (cont'd)
  - we include the known correlation between the two maps
    - we split the temperature spectrum into correlated $C_l^{TT\parallel}$ and uncorrelated $C_l^{TT\perp}$ parts

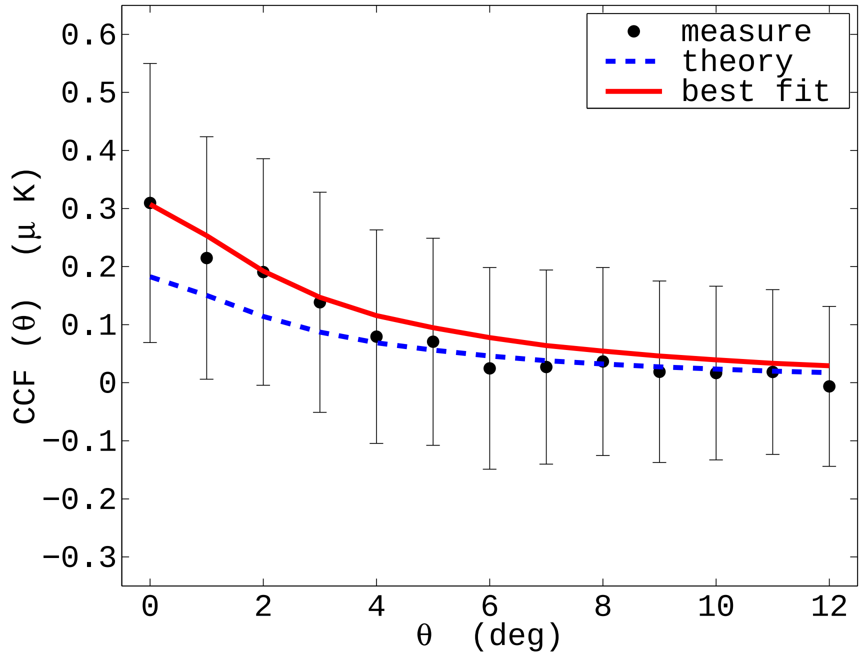
$$(7) \quad C_l^{TT\parallel} \equiv \frac{(C_l^{Tq})^2}{C_l^{qq}}; \qquad C_l^{TT\perp} \equiv C_l^{TT} - \frac{(C_l^{Tq})^2}{C_l^{qq}}$$

    - two random temperature maps $T_i^{r\parallel}, T_i^{r\perp}$
    - the first is the correlated part if produced in phase with the quasar map and $T_i^r \equiv T_i^{r\parallel} + T_i^{r\perp}$ is a random map with the same statistics of the CMB
  - random Poisson noise is added to the quasar map
- with 2000 runs we find the covariance matrix

$$(8) \qquad R_{ij}^{Tq} = \alpha R_{ij}^{Tt} + \beta R_{ij}^{Ts} + \gamma_{ij}\sigma_k^2$$

  - σ_k is the error on the stellar contamination

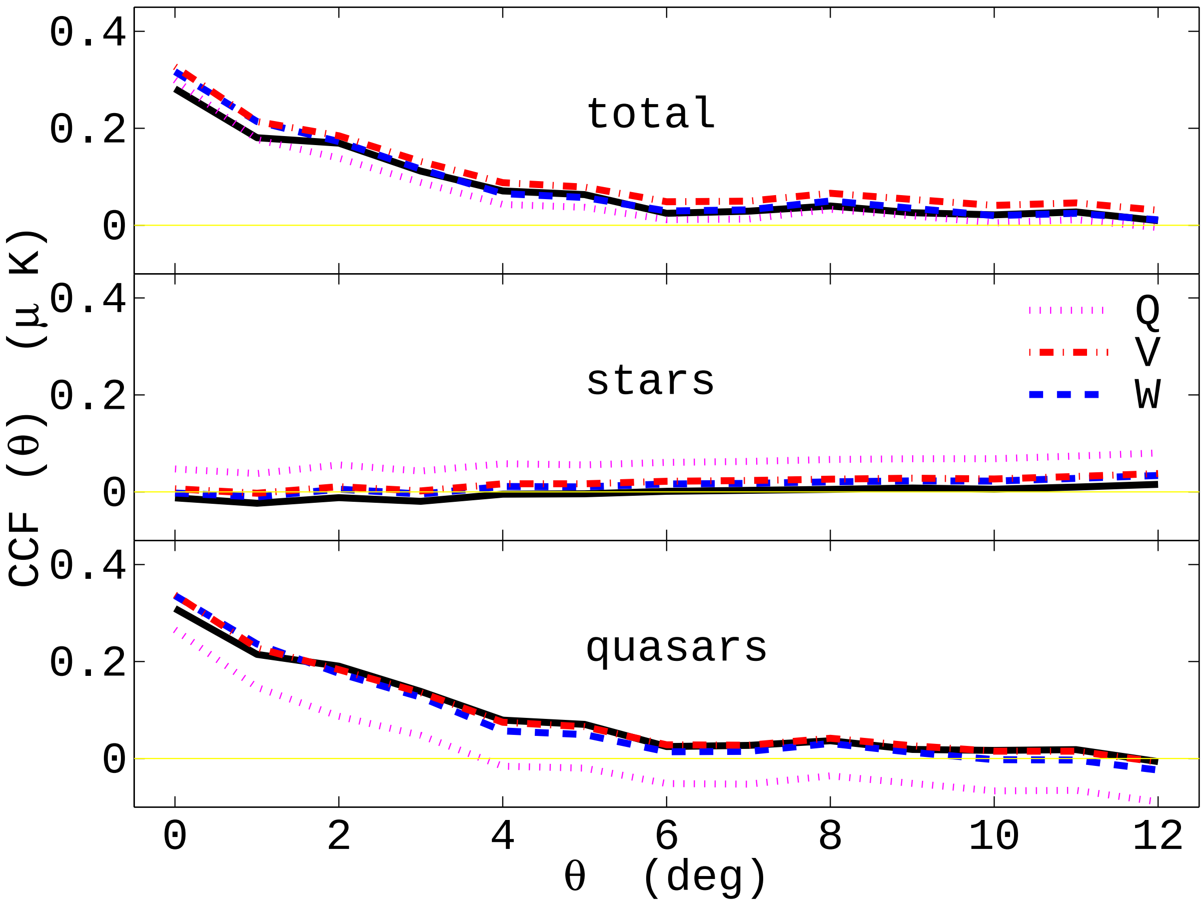
the CCF IV: the result



- the fit is done keeping constant the shape of the theoretical curve
- for the amplitude is found

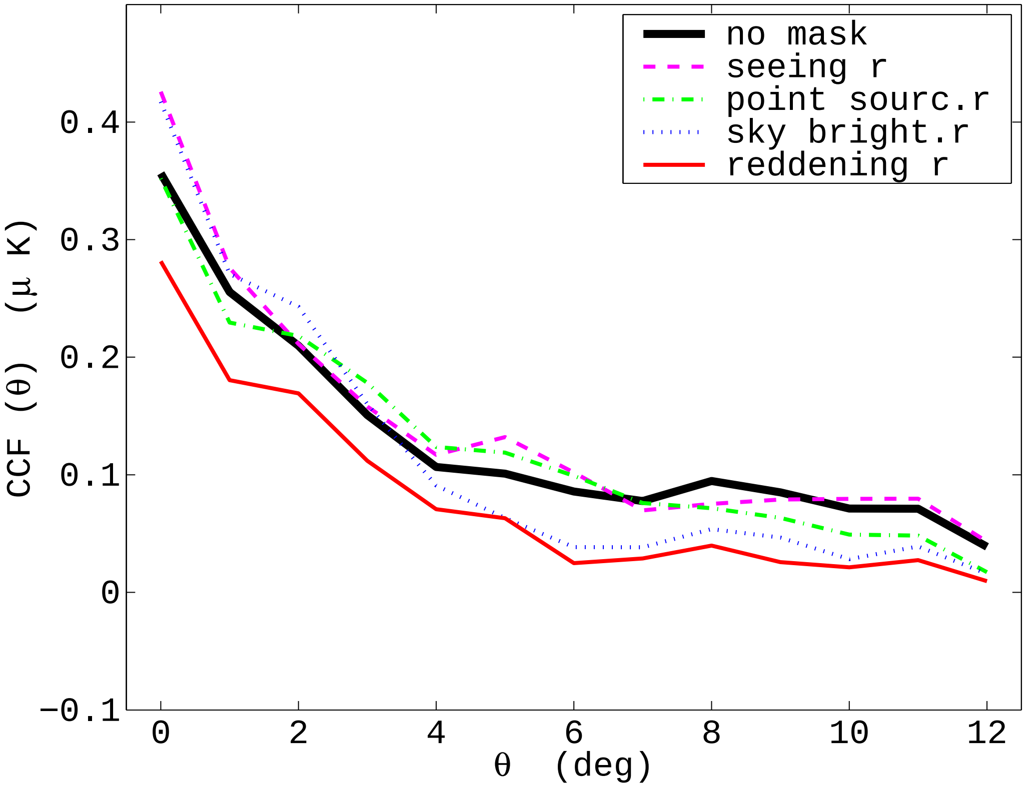
$$A = 0.30 \pm 0.15 \tag{9}$$

frequency dependence



- it's achromatic for all bands except Q
- in Q band (41 GHz) stars begin to be correlated with *WMAP*: synchrotron radiation

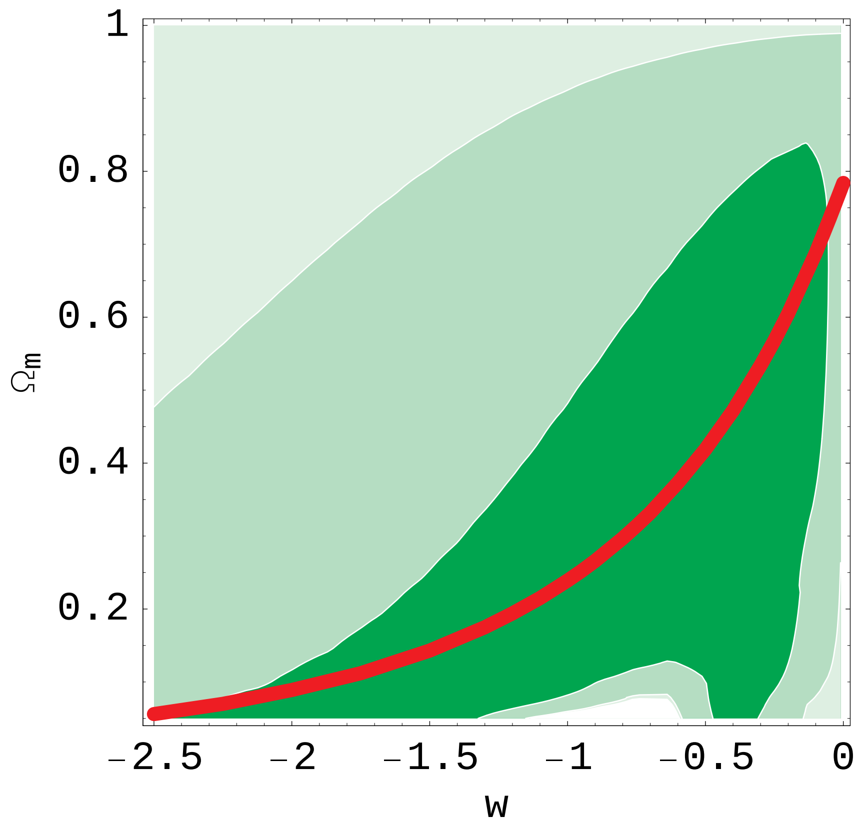
foregrounds dependence



- ★ the reddening mask is the most conservative choice
- ★ the rest of the masks seem less influent

cosmological constraints I

- ★ from this detection only
  - ▶ SCDM can't produce any ISW: is ruled out at 2σ
  - ▶ flat wCDM models

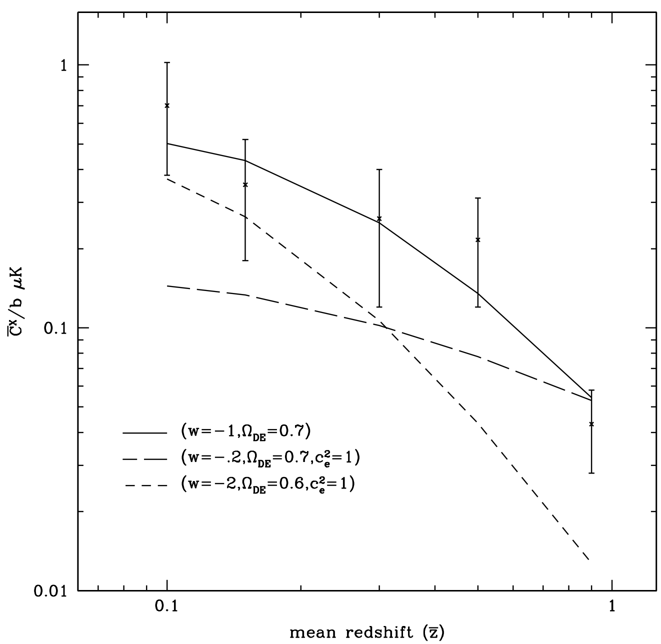


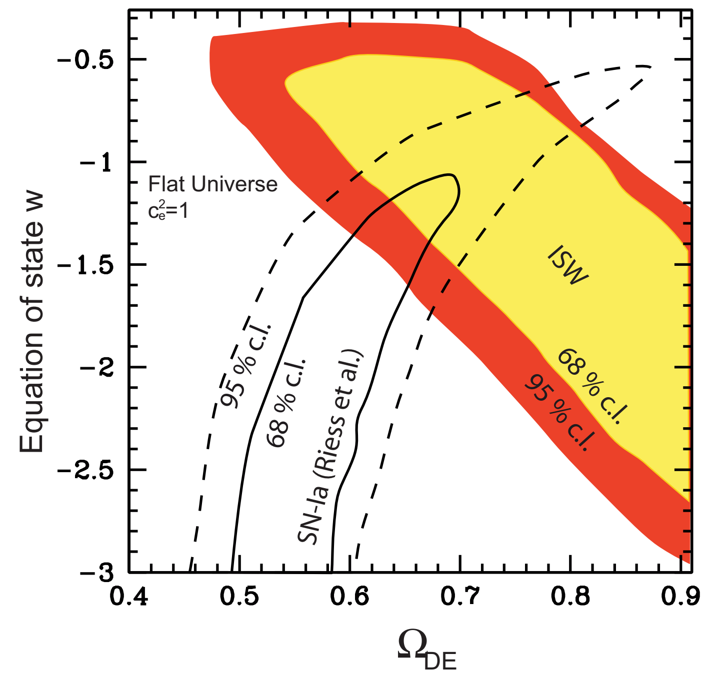
- ★ fixing the others parameters to *WMAP3*
  - ▶ $\omega_m \equiv \Omega_m h^2$, $\omega_b \equiv \Omega_b h^2$ fixed, but tiny effect
  - ▶ red line: models with same TT spectrum as *WMAP*, same D_*^A

- ★ steep transition: a particular class of models ruled out

cosmological constraints II

- ★ from all current detections: which models should we test?
- ★ unbound models: wCDM with any value for the DE parameters and the others fixed by *WMAP*





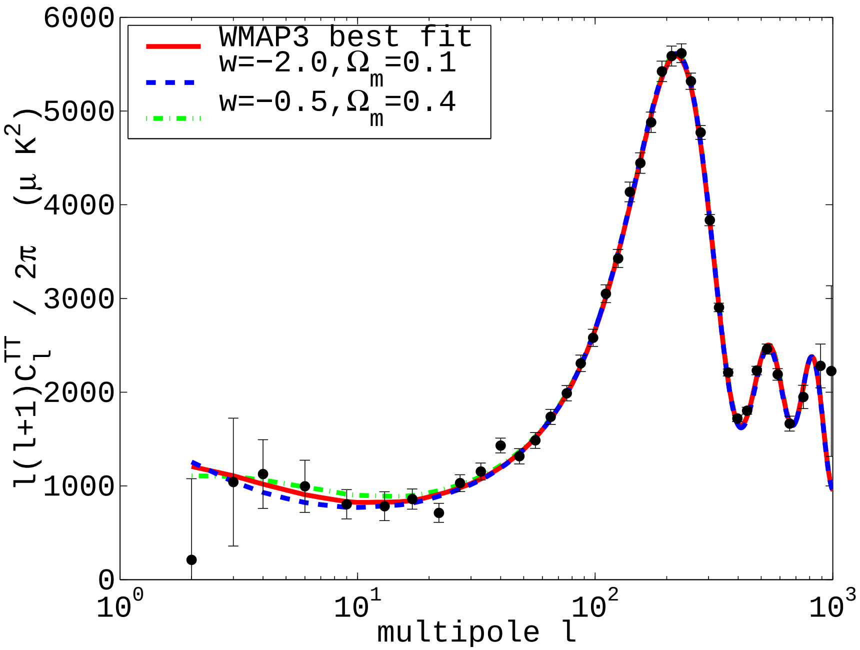
[Corasaniti, TG, Melchiorri '05], not including QSO

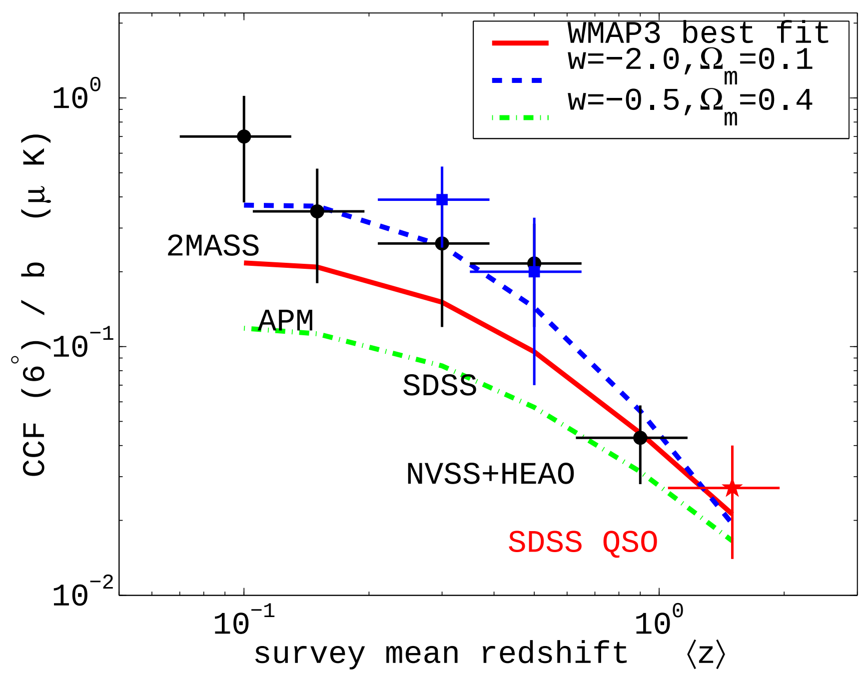
- agreement with ΛCDM
- constraints against different models
- but these are models ruled out by the TT spectrum...

cosmological constraints III

★ from all current detections: constrained models

- ▶ models with TT spectrum fixed by *WMAP*





★ agreement with ΛCDM and phantom

★ ISW can brake the DE parameters degeneracy only weakly

★ better accuracy, use of angular information, account for correlation between the points needed to select models

conclusion

- ★ we measured the ISW at 2σ for the SDSS quasars
  - the universe is still consistent with ΛCDM model at $z = 1.5$
  - a model without dark energy is ruled out
- ★ stronger constraints can be found combining all detections
  - correlations between the points must be considered carefully
  - dark energy parameters: the degeneracy of TT spectrum can be broken only weakly (with a constant w parametrization)