Combined analysis of the integrated Sachs-Wolfe effect

Tommaso Giannantonio

tommaso.giannantonio@astro.uni-bonn.de

Argelander-Institut für Astronomie
Institut für Astronomie, Bonn

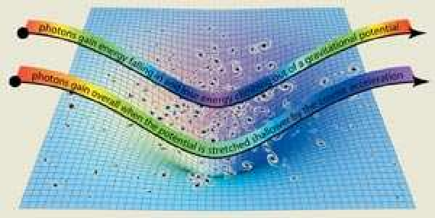
In collaboration with:
R. Crittenden, R. Nichol, R. Scranton, Y.-S. Song, K. Koyama, H. Lampeitl

München, 9 October 2008

outline

1. the integrated Sachs-Wolfe effect
2. combined analysis of the ISW measurements
3. cosmological constraints and combination with other data
4. applications on modified gravity theories

the integrated Sachs-Wolfe effect



- integrated SW: $\frac{\delta T}{T} = 2\int_\gamma \dot{\Phi}[r(t), t]dt$ (Sachs & Wolfe '68)

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

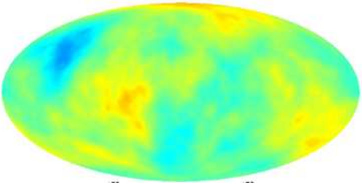
- no effect in matter dominated epoch: $\delta_m \propto a \Rightarrow \dot{\Phi} = 0$
- early ISW in transition from radiation epoch
- late ISW in transition to curvature or DE epoch

in absence of curvature, a measure of the late ISW is a measure of dark energy

measuring the ISW

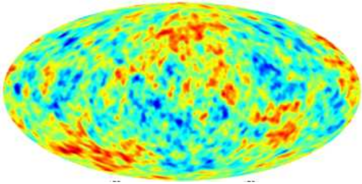
- the observed microwave sky is a superimposition of:

signal



ISW map, $z < 4$

noise

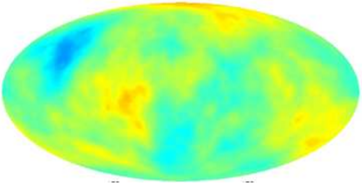


primary CMB map, $z = 1100$

measuring the ISW

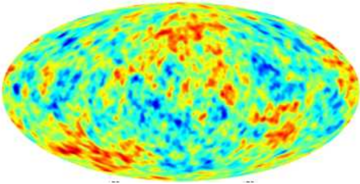
- the observed microwave sky is a superimposition of:

signal

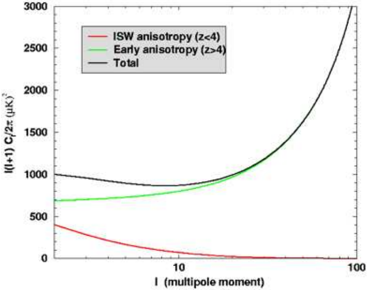


ISW map, $z < 4$

noise



primary CMB map, $z = 1100$



- we would like to measure the C_l^{TT} for the ISW, but...
  - ISW is small (10% of the total)
  - is affected by cosmic variance

a noise dominated, difficult measure

the cross-correlation technique

the ISW is small, but we can measure it:

- the ISW map is correlated with matter density through the gravitational potential
- the primary CMB is not because has been generated long before

cross-correlation CMB-matter can extract the late ISW (Crittenden & Turok '95)

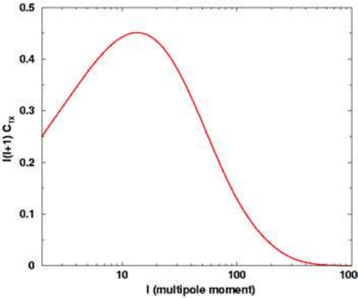
the cross-correlation technique

the ISW is small, but we can measure it:

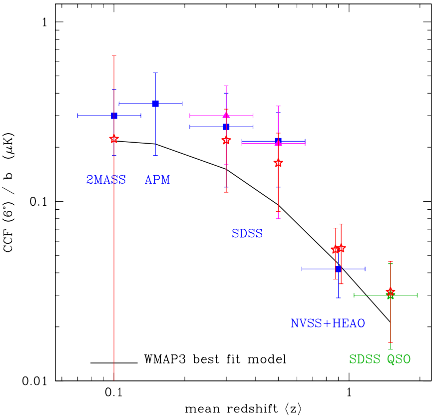
- the ISW map is correlated with matter density through the gravitational potential
- the primary CMB is not because has been generated long before

cross-correlation CMB-matter can extract the late ISW (Crittenden & Turok '95)

- we can measure the $C_l^{T\delta}$ of the cross-correlation
  - they are $\neq 0$ only with dark energy
  - depend on DE parameters $(w, c_s, \ldots)$
  - and on the survey dN/dz
- a linear, large scale effect
- we need wide and deep density maps
  - we assume linear bias b_g relating dark matter and galaxy densities



different procedures generally converge...



- real space: 2-pt function $c^{T\delta}(\vartheta)$
  Boughn & Crittenden '04 , Fosalba & Gaztañaga '04 , Scranton et al. '04 , Fosalba et al. '04 , Nolta et al. '04 , Cabré et al. '06 , TG et al. '06 , **TG et al. '08**
- harmonic space: $C_\ell^{T\delta}$
  Padmanabham et al. '04 , Afshordi et al. '04 , Rassat et al. '06 , **Ho et al. '08**
- wavelets – needlets approach
  Vielva et al. '04 , Pietrobon et al. '06
- localised stacking method
  Granett et al. '08

we now know the covariance!

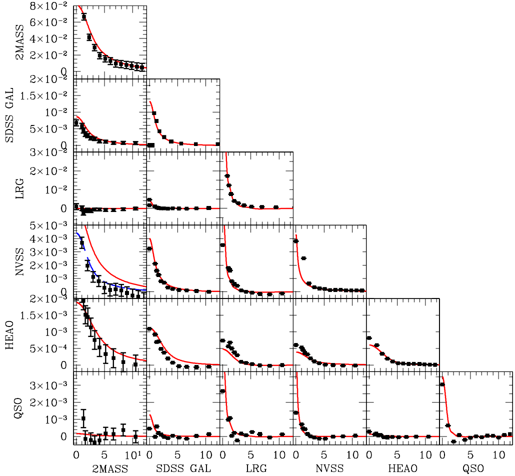
combined analysis of the ISW

(TG, R. Scranton, R. Crittenden, B. Nichol, S. Boughn & G. Richards '08)

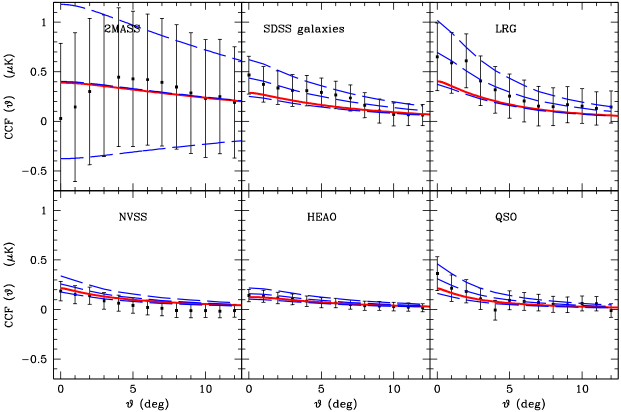
- the catalogues
  - density: six galaxy catalogues at redshift $0 < z < 2$ to measure the evolution of the ISW: 2MASS, SDSS dr6 main + LRGs + QSOs, NVSS, HEAO
  - temperature: the WMAP3/5 *internal linear combination* map, we checked frequency independence
  - data are pixelised on the sphere using the HEALPix scheme (Gorski) with resolution $N_{\rm side} = 64$, pixel side of 0.9 deg
- the masks
  - surveys are not full sky: a geometry mask is needed
  - foregrounds masking the most contaminated areas
    - dust extinction, seeing, and negligible sky brightness and point sources for the data from the SDSS
    - the original masks for the others: excluding the galactic plane and areas around bright sources

the auto (AxA) and AxB correlations

- in agreement with theory with the bias from literature
- errors with 1000 Monte Carlo realisations of all catalogues
- 2MASS-NVSS agrees if we cut the low z tail of NVSS dN/dz

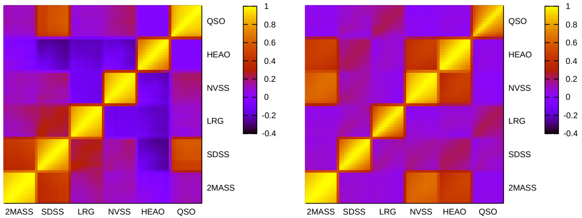


the cross-correlations



- errors generated with 5000 random T and δ maps including the correlations
- fit obtained keeping fixed the shape of the theory
- 2MASS has SZ and very low significance

the total covariance



- we estimate the errors in three ways:
  - MC1: Monte Carlo correlations with random CMB maps, fixed galaxy maps
  - MC2: Monte Carlos with random CMB & random galaxies + Poisson noise
  - JK: Jack Knife errors, obtained excluding patches of the data.
    - it depends on the number and size of patches
- in the rest we choose the MC2 error since they are our best estimation
- the total significance is of 4.3σ fitting a single amplitude

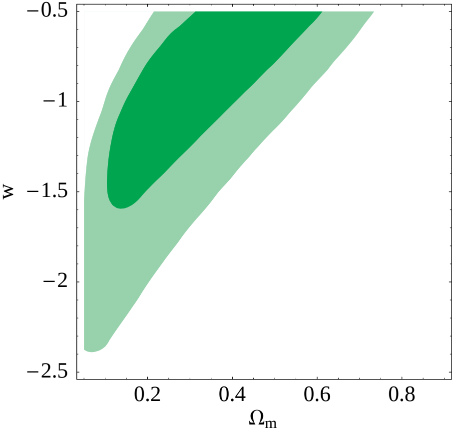
we generally agree with previous results, and now we know their covariance

cosmological constraints: flat case

- a model with no dark energy is ruled out at 4σ

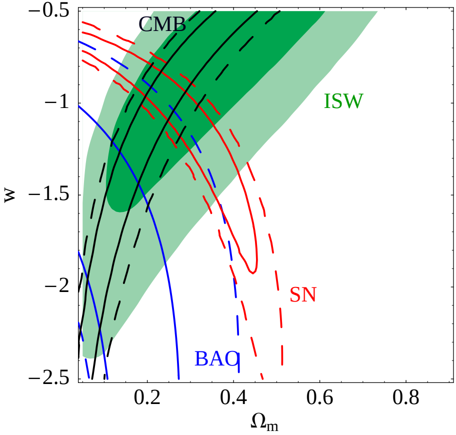
cosmological constraints: flat case

- a model with no dark energy is ruled out at 4σ
- then we study wCDM models with the other parameters fixed to WMAP, and $\Omega_m h^2 = 0.128$ (this has a small effect)
- LCDM is a good fit



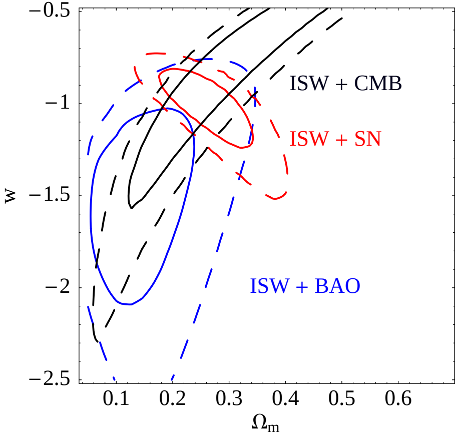
cosmological constraints: flat case

- a model with no dark energy is ruled out at 4σ
- then we study wCDM models with the other parameters fixed to WMAP, and $\Omega_m h^2 = 0.128$ (this has a small effect)
- LCDM is a good fit
- we can intersect with other probes:
  - SNLS SNae
  - CMB shift parameter $R = 1.70 \pm 0.03$ by Wang et al.
  - BAO favours phantom $d_V(0.35)/d_V(0.2) = 1.812 \pm 0.060$ by Percival et al.



cosmological constraints: flat case

- a model with no dark energy is ruled out at 4σ
- then we study wCDM models with the other parameters fixed to WMAP, and $\Omega_m h^2 = 0.128$ (this has a small effect)
- LCDM is a good fit
- we can intersect with other probes:
    - SNLS SNae
    - CMB shift parameter $R = 1.70 \pm 0.03$ by Wang et al.
    - BAO favours phantom $d_V(0.35)/d_V(0.2) = 1.812 \pm 0.060$ by Percival et al.
- the result of the intersections

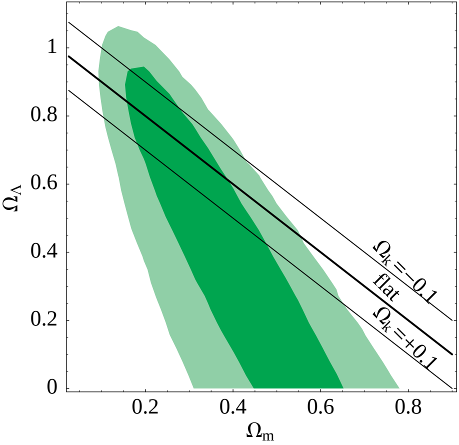


cosmological constraints: curved case

- we can proceed in a similar way for curved LCDM models

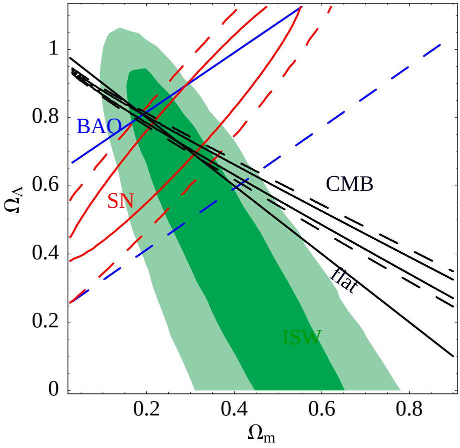
cosmological constraints: curved case

- we can proceed in a similar way for curved LCDM models
- we keep the other parameters fixed to WMAP, and $\Omega_m h^2 = 0.128$ (small effect)
- flat is a good fit



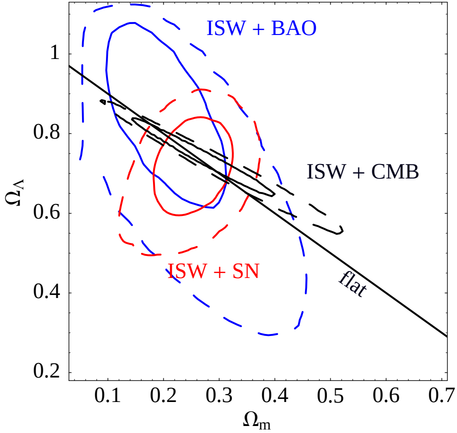
cosmological constraints: curved case

- we can proceed in a similar way for curved LCDM models
- we keep the other parameters fixed to WMAP, and $\Omega_m h^2 = 0.128$ (small effect)
- flat is a good fit
- we can intersect with other probes:
  - SNLS SNae
  - CMB shift parameter $R = 1.70 \pm 0.03$ by Wang et al.
  - BAO favours closed $d_V(0.35)/d_V(0.2) = 1.812 \pm 0.060$ by Percival et al.



cosmological constraints: curved case

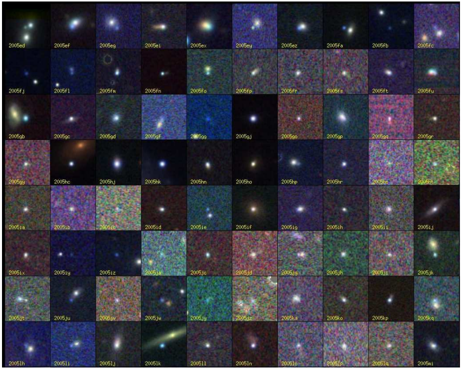
- we can proceed in a similar way for curved LCDM models
- we keep the other parameters fixed to WMAP, and $\Omega_m h^2 = 0.128$ (small effect)
- flat is a good fit
- we can intersect with other probes:
  - SNLS SNae
  - CMB shift parameter $R = 1.70 \pm 0.03$ by Wang et al.
  - BAO favours closed $d_V(0.35)/d_V(0.2) = 1.812 \pm 0.060$ by Percival et al.
- the result of the intersections



combination with SDSS SNae (Lampeitl, TG, Nichol et al. in prep.)

[see Bob Nichol's talk on Friday for more details]

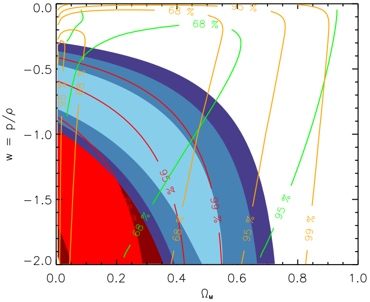
- 102 SNae from the SDSS dr1 at $0.05 < z < 0.4$ (Frieman et al. '08, Kessler et al. in prep.)



combination with SDSS SNae (Lampeitl, TG, Nichol et al. in prep.)

[see Bob Nichol's talk on Friday for more details]

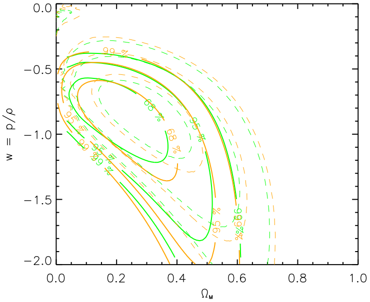
- 102 SNae from the SDSS dr1 at $0.05 < z < 0.4$ (Frieman et al. '08, Kessler et al. in prep.)
- combination of the SNae (blue) with:
  - growth of structure from 2dF (orange) Hawkins '03 ,
  - BAO (red) Percival '07 ,
  - the ISW (green) TG '08 only at low z



combination with SDSS SNae (Lampeitl, TG, Nichol et al. in prep.)

[see Bob Nichol's talk on Friday for more details]

- 102 SNae from the SDSS dr1 at $0.05 < z < 0.4$ (Frieman et al. '08, Kessler et al. in prep.)
- combination of the SNae (blue) with:
  - growth of structure from 2dF (orange) Hawkins '03 ,
  - BAO (red) Percival '07 ,
  - the ISW (green) TG '08 only at low z
- SNae in tension with BAO; the intersection with ISW and GS gives tighter constraints: $w = -0.83 \pm 0.14$ (preliminary).

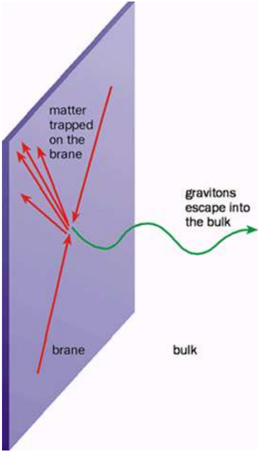


the DGP model of gravity (Dvali, Gabadadze, Porrati '00)

- dark energy can be seen as a modification of the Einstein equation or braneworlds
- DGP model: 4d brane in Minkowski 5d bulk
- background expansion: new Friedmann equation

$$H^2 \mp \frac{1}{r_c}\sqrt{H^2 + \frac{K}{a^2}} = \frac{\kappa^2}{3}\rho + \frac{\Lambda}{3} - \frac{K}{a^2}$$

  - minus sign → self accelerating branch (accelerates today if $r_c \sim H_0^{-1}$) ruled out at 4σ by Fan et al. '08
  - plus sign → normal branch, nDGP has a tension of the brane Λ to achieve acceleration



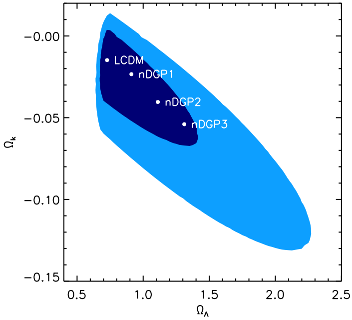
the DGP model of gravity (Dvali, Gabadadze, Porrati '00)

- dark energy can be seen as a modification of the Einstein equation or braneworlds
- DGP model: 4d brane in Minkowski 5d bulk
- background expansion: new Friedmann equation

$$H^2 \mp \frac{1}{r_c}\sqrt{H^2 + \frac{K}{a^2}} = \frac{\kappa^2}{3}\rho + \frac{\Lambda}{3} - \frac{K}{a^2}$$

  - minus sign $\rightarrow$ self accelerating branch (accelerates today if $r_c \sim H_0^{-1}$) ruled out at 4σ by Fan et al. '08
  - plus sign $\rightarrow$ normal branch, nDGP has a tension of the brane Λ to achieve acceleration

nDGP Ω_Λ, Ω_m

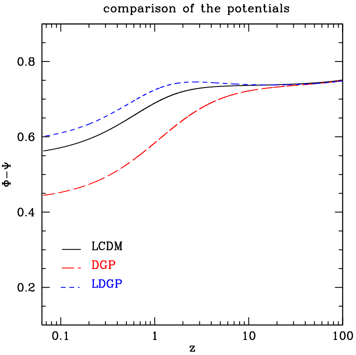


background tests (SN, H_0, CMB shift)

nDGP still allowed with curvature

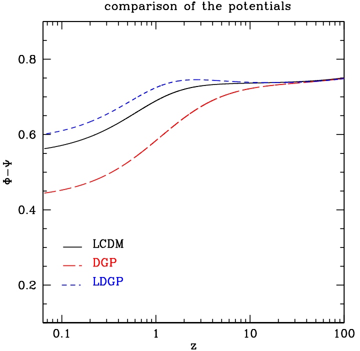
the DGP ISW (TG, Y.-S. Song & K. Koyama '08)

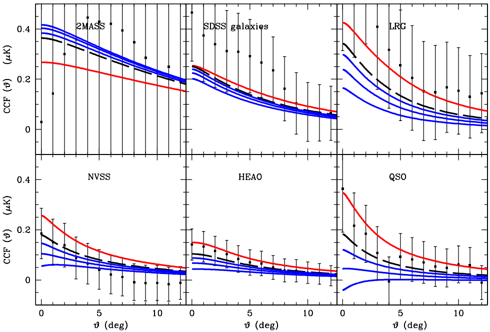
- different models of gravity → different potentials → different ISW (Lue et al. '03)
- in the DGP the potentials decay earlier than in GR; in the nDGP later



the DGP ISW (TG, Y.-S. Song & K. Koyama '08)

- different models of gravity → different potentials → different ISW (Lue et al. '03)
- in the DGP the potentials decay earlier than in GR; in the nDGP later





- at high z we can distinguish between models still allowed by background tests including curvature

ISW linear structure formation tests

(DGP favoured by this test); nDGP can be ruled out at high z

conclusions

- the ISW is a useful tool to study dark energy
- has now been measured a number of times using the cross-correlation of WMAP with different density tracers up to $\bar{z} = 1.5$ with the QSO
- we have performed a full covariance analysis, obtaining consistent results for six datasets and the total significance is $\sim 4.5\sigma$
- the result is consistent with LCDM and is complementary to other data sets (the CMB, SNae, BAO, ...)
- these data can constrain different dark energy and modified gravity models