Shedding light on Dark Energy : the integrated Sachs-Wolfe effect

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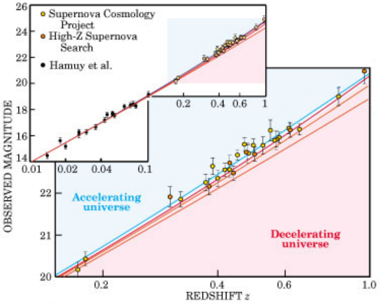
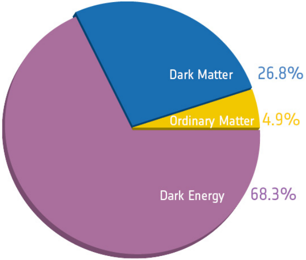
The Dark Energy mystery

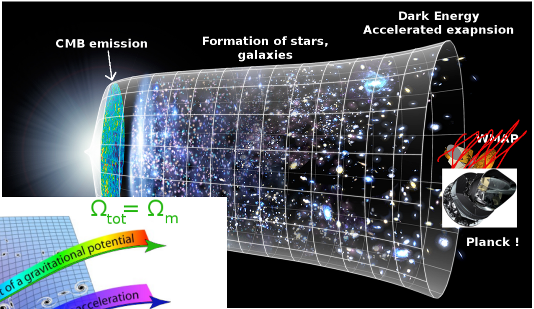


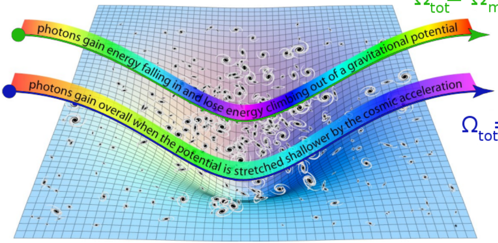


- Standard model : $\Lambda \rightarrow$ most "economical"
- Alternatives :
  - scalar fields
  - modified gravities
  - inhomogeneous models...

The iSW effect in one equation (and two images)

$$\delta T_{\text{iSW}} = \frac{2}{c^2} \int_{t_{\text{far}}}^{t_{\text{now}}} dt \frac{\partial \Phi}{\partial t}$$





$\Omega_{tot} = \Omega_m$

$\Omega_{tot} \neq \Omega_m$

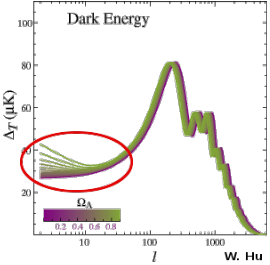
Caldwell

Characteristics of the iSW effect

$$\delta T_{\text{iSW}} = \frac{2}{c^2} \int_{t_{\text{far}}}^{t_{\text{now}}} dt \frac{\partial \Phi}{\partial t}$$

Features

- Cumulated effect
- Achromatic
- Impact on CMB anisotropies power spectrum



How to detect it ?

- Need for external data
- Tracers of the **gravitational potentials**

Which tracers ?
How do we proceed ?

Classical approach : CMB-galaxy χ-correlation

Author	CMB	LSS Tracer	Wavelength	Method	Claimed Detection
Boughn & Crittenden (2002)	COBE	XRB	Xray	D2	No
Giannantonio et al. (2008)	W3			D2	2.7σ
Boughn & Crittenden (2004, 2005)	W1	XRB/NVSS	Xray/Radio	D2	'tentative' (2-3 σ)
Fosalba et al. (2003)	W1	SDSS DR1		D2	2σ (low z) 3.6σ (high z)
Cabré et al. (2006)	W3	SDSS DR4	Optical	D2	$> 2\sigma$
Giannantonio et al. (2008)	W3	SDSS DR6		D2	2.2σ
Sawangwit et al. (2010)	W5	SDSS DR5		D2	'marginal'
López-Corredoira et al. (2010)	W5	SDSS DR7		D2	'No detection'
Giannantonio et al. (2006)	[illegible]	[illegible]	[illegible]	[illegible]	2σ
Giannantonio et al. (2008)	[illegible]	[illegible]	[illegible]	[illegible]	2.5σ
Xia et al. (2009)	[illegible]	[illegible]	[illegible]	[illegible]	2.7σ
Scranton et al. (2003)	[illegible]	[illegible]	[illegible]	[illegible]	$> 2\sigma$
Padmanabhan et al. (2005)	[illegible]	[illegible]	[illegible]	[illegible]	2.5σ
Granett et al. (2009)	W3	SDSS LRG	Optical	D1	2σ
Giannantonio et al. (2008)	W3			D2	2.2σ
Sawangwit et al. (2010)	W5	SDSS LRG, 2SLAQ		D2	'marginal'
Sawangwit et al. (2010)	W5	AAOmega LRG		D2	Null
Fosalba & Gaztañaga (2004)	W1	APM	Optical	D2	2.5σ
Afshordi et al. (2004)	W1			D1	$2.5\ \sigma$
Rassat et al. (2007)	W3	2MASS	NIR	D1	2σ
Giannantonio et al. (2008)	W3			D2	0.5σ
Francis & Peacock (2010b)	W3			D1	'weak'
Boughn & Crittenden (2002)	[illegible]	[illegible]	[illegible]	D2	No
Nolta et al. (2004)	[illegible]	[illegible]	[illegible]	D2	2.2σ
Pietrobon et al. (2006)	[illegible]	[illegible]	[illegible]	D3	$> 4\sigma$
Vielva et al. (2006)	[illegible]	[illegible]	[illegible]	D3	3.3σ
McEwen et al. (2007)	[illegible]	[illegible]	[illegible]	D3	$> 2.5\sigma$
Raccanelli et al. (2008)	W3			D2	2.7σ
McEwen et al. (2008)	W3			D3	$\sim 4\sigma$
Giannantonio et al. (2008)	W3			D2	3.3σ
Hernández-Monteagudo (2009)	W3			D1	2σ
Sawangwit et al. (2010)	W5			D2	'marginal' ($\sim 2\sigma$)
Corasaniti et al. (2005)	W1			D2	$> 2\sigma$
Gaztanaga et al. (2006)	W1			D2	2σ
Ho et al. (2008)	W3	Combination	Combination	D1	2.7σ
Giannantonio et al. (2008)	W3			D2	4.5σ

'No detection'

4.5σ

Dupé et al., A&A, 2011

Contradictory results

Shortcomings

- Small sky coverage ($f_{\rm sky}$)
- Low redshift depth ($\bar{z}$)

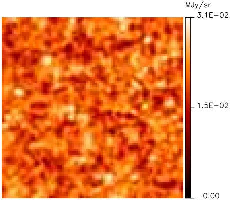
Ideal survey

- $f_{\rm sky} > 0.35$ & $\bar{z} > 0.8$ for $\geq 4\,\sigma$ detection
- Next generation surveys : LSST, Euclid $\rightarrow \sim 5\,\sigma$

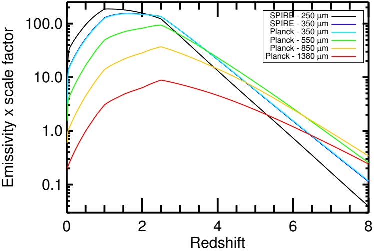
(Douspis et al., 2008)

A new tracer : the Cosmic Infrared Background (CIB)

$f_{\text{sky}} > 0.35$ & $\bar{z} > 0.8$: already at hand !



CIB at 217 GHz,
Planck Collaboration et al., 2011



- Unresolved, dusty, star-forming galaxies
- **Available** : IRAS, Planck, ...
- Anisotropies
  → structures
  → gravitational potentials
  ⇒ **iSW**

Realistic modelisation and scenarii

Sources of noise and S/N degradation

- Partial sky coverage
- CIB → CIB + CMB resid. + foregrounds resid. + instr. noise
- Two scenarii : optimistic & pessimistic

Realistic S/N (for Planck)

Frequency (GHz)	**857**	**545**	**353**	**217**
Wavelength (μm)	**350**	**550**	**850**	**1380**
Ideal case S/N	6.26	6.83	6.98	6.95
Joint S/N	7.12			
Real case 1 (optimistic) ($f_{\rm sky} = 0.75$)	5.36	5.73	5.39	3.56
Joint S/N	5.88			
Real case 2 (pessimistic) ($f_{\rm sky} = 0.15$)	2.40	2.56	2.41	1.59
Joint S/N	2.63			

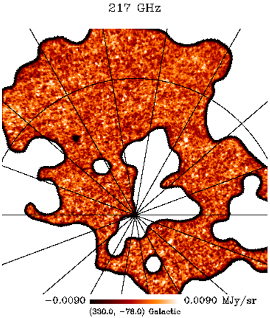
Full results in **Ilić et al., 2011, MNRAS**

Challenges of the CIB-CMB cross-correlation

CIB extraction requires :

- Cleaning of dust and cirrus
- Accurate tracers of dust (HI,...)
- Efficient component separation (CMB removal)

Current status



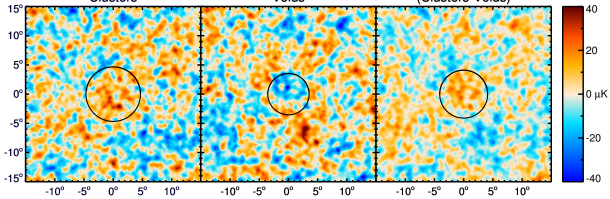
$\sim 10\%$ recovered to this date
(cf. Planck 2013 results. XXX)

1. Introduction
2. Cross-correlation with large scale structures
3. Impact of individual strucutres on the CMB
   - CMB stacking
   - Predicting the iSW impact of a structure
4. Working with the latest Planck CMB data

CMB stacking at superstructure locations

Granett et al. (2008, Gr08) :

- 50 superclusters & 50 supervoids identified in SDSS
- "Stacking" of CMB patches at their positions



CF. PLANCK COLLABORATION (INCL. ILIĆ), 2013, A&A

$4\,\sigma$ signal, claimed to be **at odds with** ΛCDM

Interrogations

- Such a **high** signal for such a **few** number of objects ?
- Is it **robust** ? **Unique** to their data ?
- Enough to "bring ΛCDM down" ?

Going further with CMB stacking

In-depth analysis of Granett et al. objects (Ilić et al., 2013, A&A)

- **Full** temperature and photometric profiles
  ⇒ Peculiar features
- **Large** frequency coverage of Planck
  ⇒ Achromatic nature confirmed
- Rescaling analysis
  ⇒ Some discrepancies in the signal scales

But still a strongly significant signal

Going further with CMB stacking

Two new catalogues of 1000+ voids (Ilić et al., 2013, A&A)

- Pan et al. (2012), $z < 0.1$
  $\Rightarrow$ No signal, expected from its shallowness
- Sutter et al. (2012)
  $\Rightarrow$ Hints of signal
  $\Rightarrow$ Compatible with expectations
  $\Rightarrow$ Lower significance ($\sim 2.5\,\sigma$)

Despite more stat, signal not as significant

Is ΛCDM in danger ? $\rightarrow$ We can't say

No conclusions possible without an exact prediction of the iSW effect from these structures

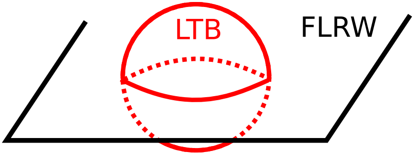
Roadmap

Objectives ?

- Model a single structure and its evolution
- Compute its iSW impact on CMB

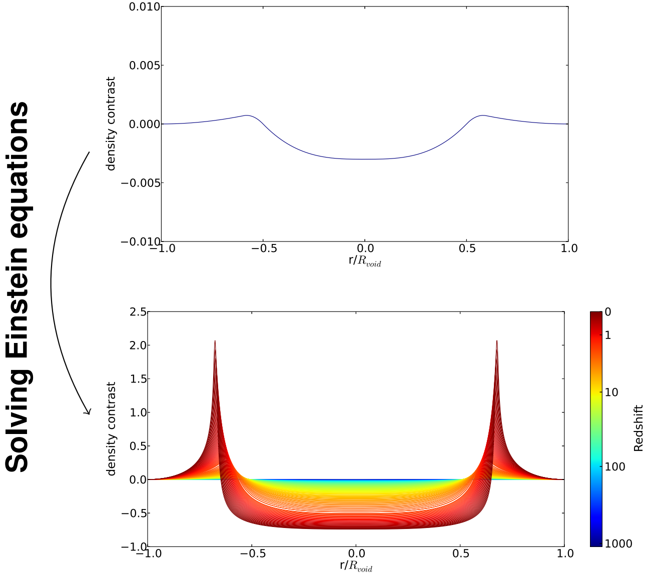
Tools ?

- Gravity & photons → **General Relativity**
- Spherical structure → **Lemaître-Tolman-Bondi (LTB) metric**



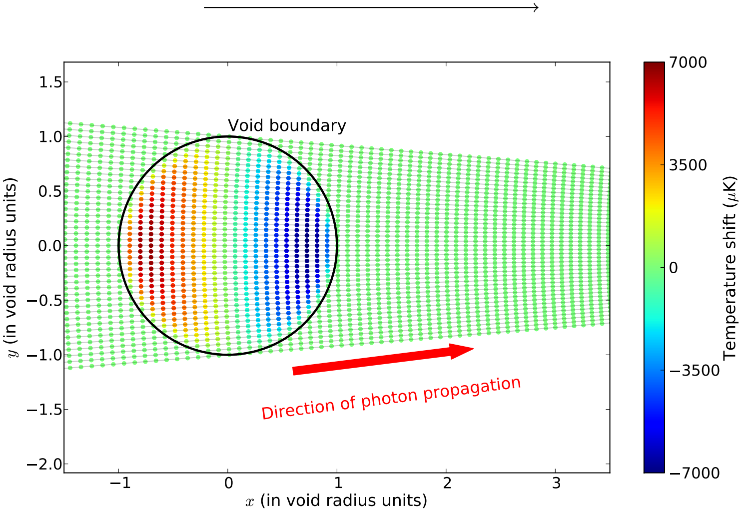
Working hypothesis : **compensated structures**

Evolution of a LTB void (Ilić et al., TBS)



Photons crossing a LTB void (Ilić et al., TBS)

Solving geodesic equations



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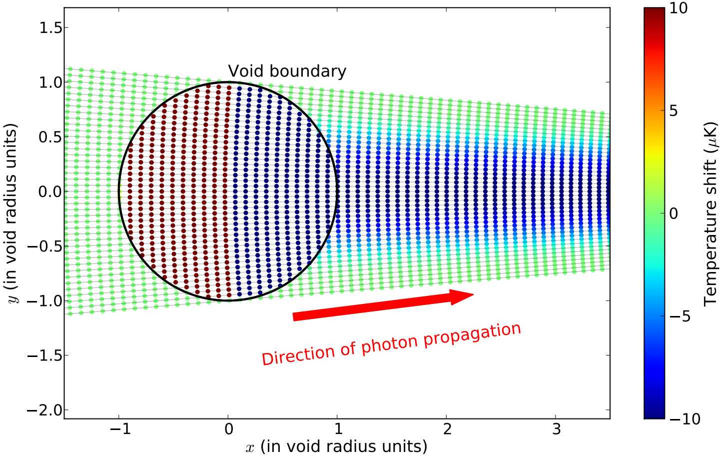
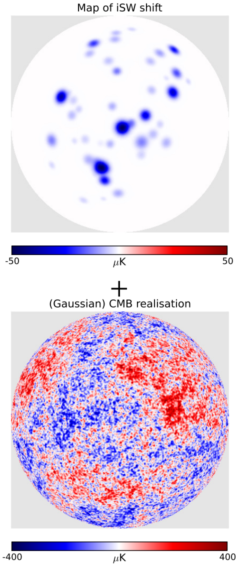
Solving geodesic equations



Assessing the CMB contamination (Ilić et al., TBS)



- Map of the simulated iSW signal
- 10,000 primordial CMB realisations as noise
- Comparison with the data :
  - $\sim 1.7\sigma$ from predicted photometry at 4°
  - $\chi^2_{\rm red}$ of whole signal ~ 1

$\Rightarrow$ **Compatible with ΛCDM**

Planck iSW Working Group

In Planck Collaboration (incl. Ilić) 2013 results XIX.

- Combined cross-correlations of galaxy surveys
- Lensing potential map (+ bispectrum)
- CMB stacking

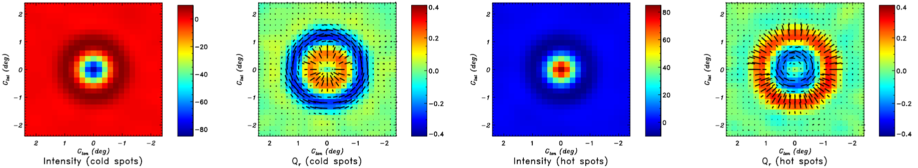
In the 2014/2015 release

- Implementing the latest datasets
- Cosmological constraints
- **Use of the CMB polarisation data**

CMB polarisation in iSW studies

Why use polarisation ? → as a **discriminant**

- Primordial CMB T → contaminant
- Primordial CMB T correlated to CMB polarisation ($C_\ell^{TE} \neq 0$)
- ISW T signal **not** correlated to CMB polarisation

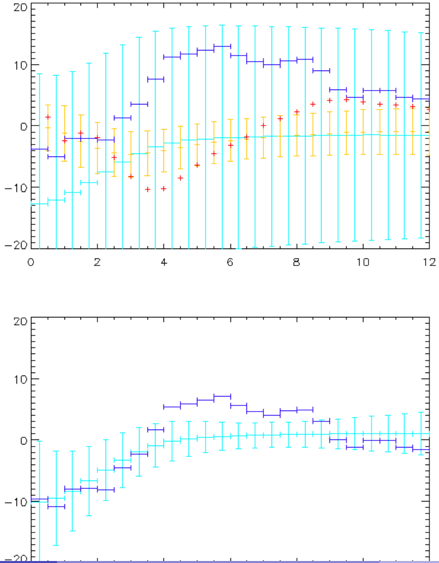


Where to use it ?

- Noise reduction in galaxy cross-correlation
- Stacking : help identifying “false iSW signals”

Thank you for your attention !

More on profiles



Specifying LTB models

- a density profile $\rho_i(r)$ is given at time t_i
- a velocity profile $(R_{,t})_i(r)$ is given at time t_i ,
- the bang time is simultaneous,
- the crunch time is simultaneous,
- the time of maximum expansion is simultaneous,
- the model becomes homogeneous at late times,
- only growing modes are present,
- only decaying modes are present,
- a velocity profile $(R_{,t})(r)$ is given at late times,
- a time-scaled density profile $t^3\rho(M)$ is given at late times.

iSW approximation

$$(\frac{\delta T}{T})_{\text{iSW}} = 2\int \mathrm{d}t \frac{\dot{\Phi}}{c^2}$$

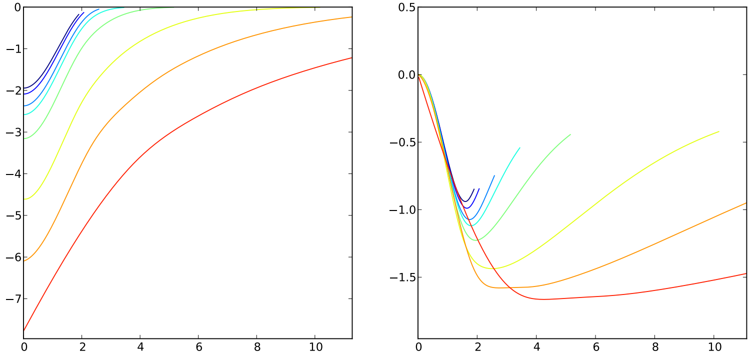
- $\Phi \sim 4\pi G\bar{\rho}_m L^2 \delta$
- $\dot{\Phi} \sim \Phi/\tau$, Λ-dom $\Rightarrow \tau \sim H^{-1}$
- $\int \mathrm{d}t \sim L/c$

$$(\frac{\delta T}{T})_{\text{iSW}} \sim 8\pi G L^3 c^{-3} H \bar{\rho}_m \delta$$

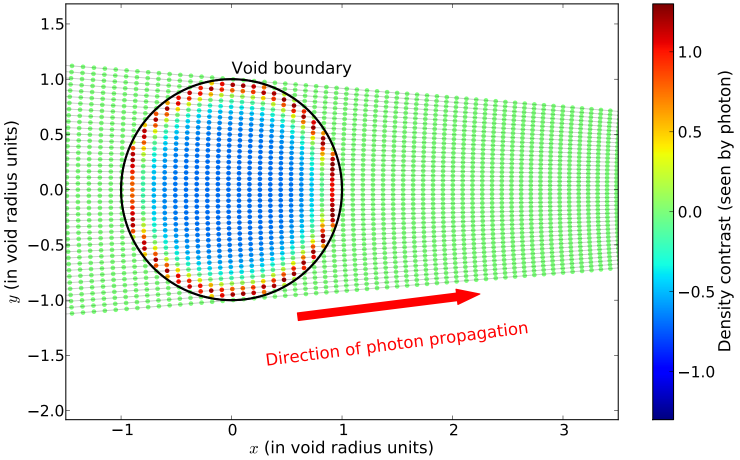
- $\bar{\rho}_m = \Omega_m \rho_c = \Omega_m (3H_0^2/8\pi G)$
- $H = H_0 \sqrt{\Omega_{\text{Tot}}}$
- $R_H = c/H_0$

$$(\frac{\delta T}{T})_{\text{iSW}} \sim 3\left(\frac{L}{R_H}\right)^3 \Omega_m \sqrt{\Omega_{\text{Tot}}}\delta \sim 10^{-6} h^3 \left(\frac{L}{10\text{Mpc}}\right)^3 \frac{\delta}{10} \Omega_m \sqrt{\Omega_{\text{Tot}}}$$

Compensation test



Photons crossing a void



Large scale structures

Linear perturbation theory :

- Describes time-evolution of $\delta = \rho/\langle\rho\rangle - 1$ (for $\delta \ll 1$)
- $\delta(t) \propto D(t) \rightarrow$ growth function
- Poisson : $\Delta\Phi = 4\pi\langle\rho\rangle G a^2 \delta \Longrightarrow \Phi \propto D(t)/a(t)$

Consequences

- In flat matter-dominated Universe : $D(t) \propto a(t) \Rightarrow \Phi$ is **constant**
- In any other case : $d\Phi/dt \neq 0$
- In ΛCDM : Φ **decays with time**

LTB theory

$$ds^2 = -dt^2 + \frac{{R_{,r}}^2}{1 + 2E(r)} dr^2 + R^2(r,t) d\Omega^2. \qquad (1)$$

$$R_{,t}{}^2 = 2E(r) + \frac{2GM(r)}{R} - \frac{1}{3}\Lambda R^2 \qquad (2)$$

$$4\pi\rho(r) = \frac{M_{,r}(r)}{R^2 R_{,r}}. \qquad (3)$$

Photon in LTB theory

$$\frac{dr}{dt} = \pm \frac{\sqrt{1+2E}}{R_{,r}}. \tag{4}$$

$$\frac{d\epsilon}{dt} = -\frac{R_{,rt}}{R_{,r}}\epsilon \tag{5}$$

$$\frac{dr}{dt} = \frac{k^r}{k^t} \tag{6}$$

$$\frac{d\theta}{dt} = \frac{k^\theta}{k^t} \tag{7}$$

$$\frac{dk^t}{dt} = -\frac{1}{k^t}\left(\frac{R_{,rt}\,R_{,r}}{1+2E}(k^r)^2 + R_{,t}\,R(k^\theta)^2\right) \tag{8}$$

$$\frac{dk^r}{dt} = \frac{1}{k^t}\left[\left(\frac{E_{,r}}{1+2E} - \frac{R_{,rr}}{R_{,r}}\right)(k^r)^2 + \frac{(1+2E)R}{R_{,r}}(k^\theta)^2\right] - \frac{2R_{,rt}}{R_{,r}}k^r \tag{9}$$

$$\frac{dk^\theta}{dt} = -\frac{2k^\theta}{R}\left(R_{,t} + \frac{R_{,r}\,k^r}{k^t}\right) \tag{10}$$

with $k^\chi = d\chi/d\lambda$ ($\chi = t, r, \theta$)