The impact of superstructures in the Cosmic Microwave Background

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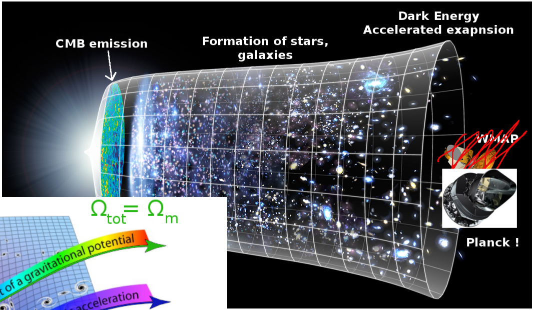
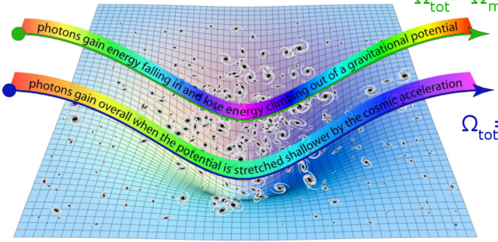
Tallinn IAU Symposium 308
28th June 2014

The iSW effect in one equation (and two images)

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



$\Omega_{tot} = \Omega_m$



$\Omega_{tot} \neq \Omega_m$

Caldwell

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]	SDSS Quasars	Optical	[illegible]	2σ
Giannantonio et al. (2008)	[illegible]			[illegible]	2.5σ
Xia et al. (2009)	[illegible]			[illegible]	2.7σ
Scranton et al. (2003)	[illegible]			[illegible]	$> 2\sigma$
Padmanabhan et al. (2005)	[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 σ
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)	CO[illegible]			D2	No
Nolta et al. (2004)	W[illegible]			D2	2.2σ
Pietrobon et al. (2006)	W[illegible]		[illegible]Radio	D3	$> 4\sigma$
Vielva et al. (2006)	W[illegible]			D3	3.3σ
McEwen et al. (2007)	W[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	[illegible]
Giannantonio et al. (2008)	W3			D2	4.5σ

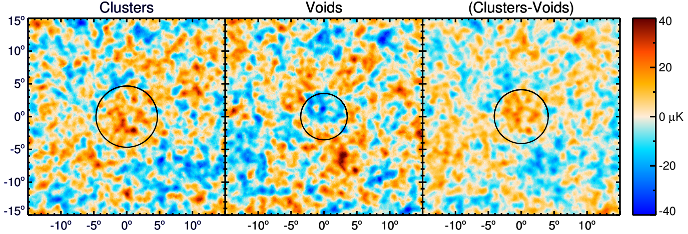
'No detection'

4.5σ

Dupé et al., A&A, 2011

Idea : CMB stacking at superstructures locations

Granett et al. (2008) catalogue (SDSS DR4 LRG)
50 superclusters / 50 supervoids (~ 100 Mpc.h^{-1}, $0.4 < z < 0.7$)



Focus on voids :

- Aperture photometry (at 4°) : $\sim -10.8\,\mu$K
- Significance (w.r.t. null hypothesis) : $\sim 3.3\,\sigma$

ΛCDM in danger ?

- **Significant** signal...
- ...but **amplitude claimed to be too high** for ΛCDM :
  N-body simulations, analytical calculations,...
- Lower significance with other catalogues : Ilić et al. (2013), Cai et al. (2014), Hotchkiss et al. (2014),...

However :

- Predictions not always representative
- Limited sample
- Fortuitous signal ?
- Selection effects ?
- Wrong identification ?

Before any conclusion : need for full, exact computation of expected signal from such structures

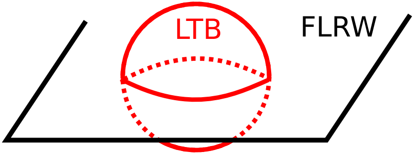
Roadmap

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**

Inputs to LTB metric

- Two free functions : $M(r)$ and $K(r)$
- Translatable into $\rho(r)$ and $v(r)$ at given time

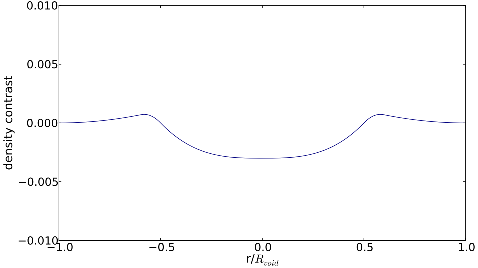
Granett et al. voids

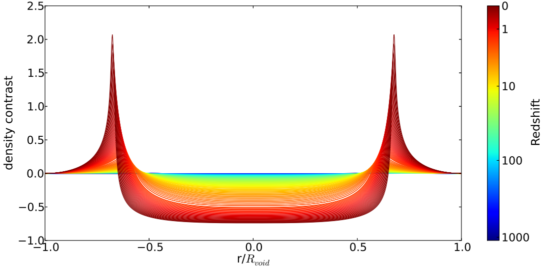
- (Relatively) Limited information
- Redshift z
- Density contrasts : δ_{min}, $\langle\delta\rangle_{\delta<0}$
- Effective radiii

We can reproduce these properties with arbitrary precision

Evolution of a LTB void

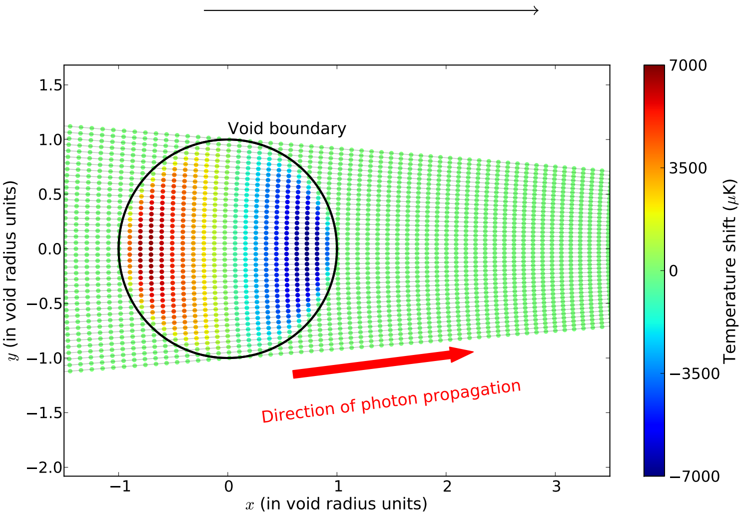
Solving Einstein equations





Photons crossing a LTB void

Solving geodesic equations



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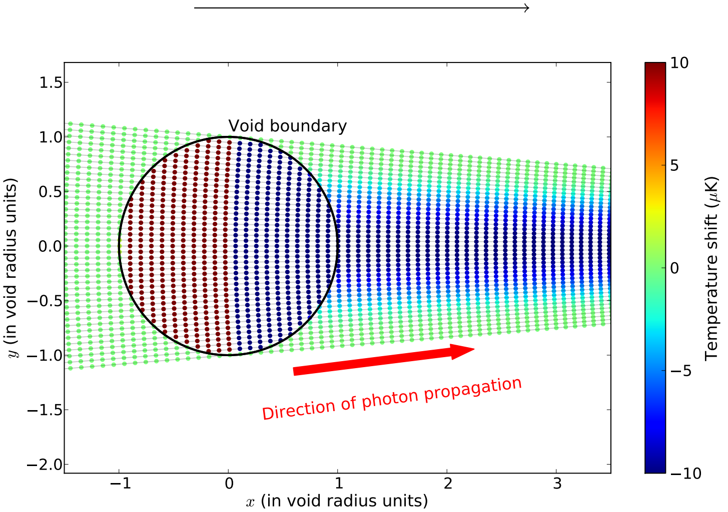
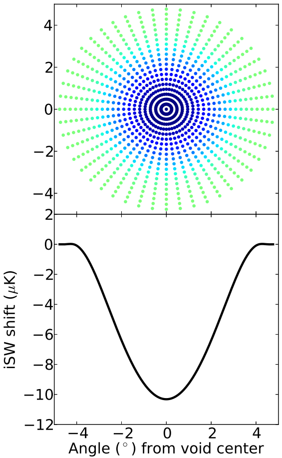


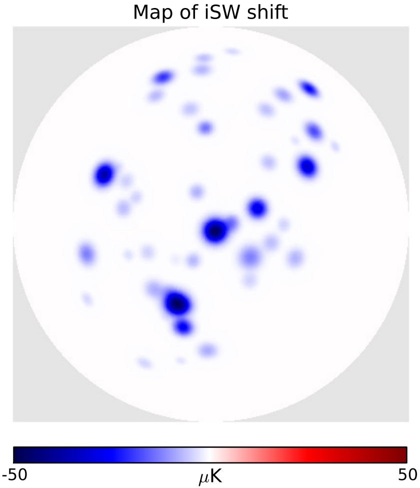
Photons crossing a LTB void

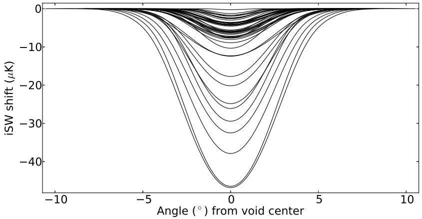
Solving geodesic equations

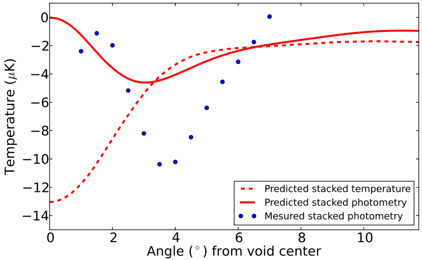
$\longrightarrow$



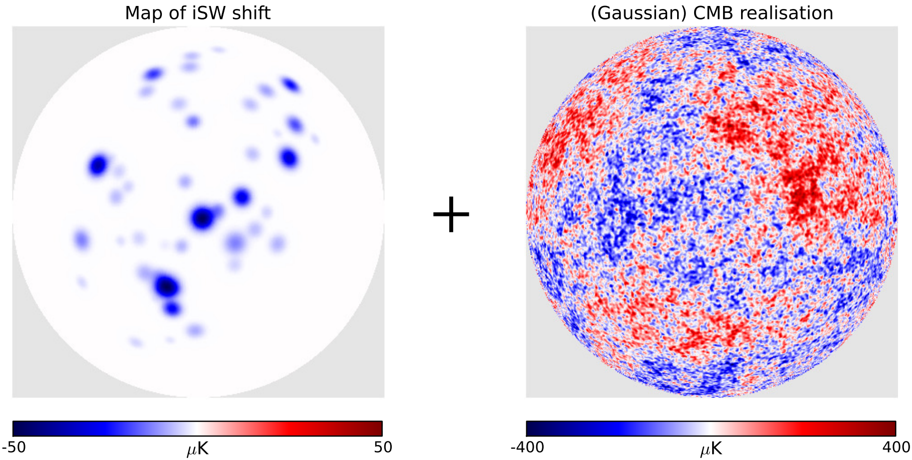
Simulating the "iSW sky"





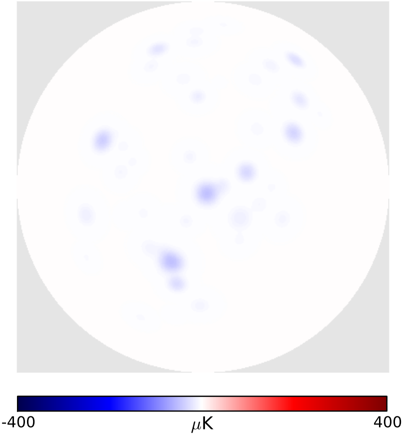


Assessing the CMB contamination



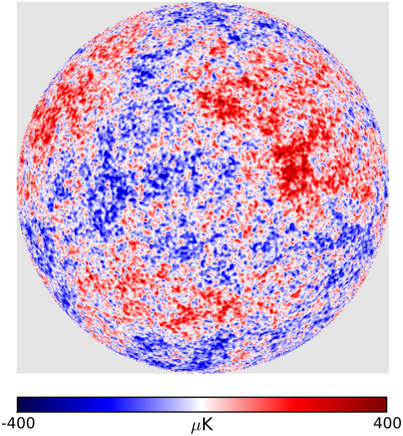
Assessing the CMB contamination

Map of iSW shift



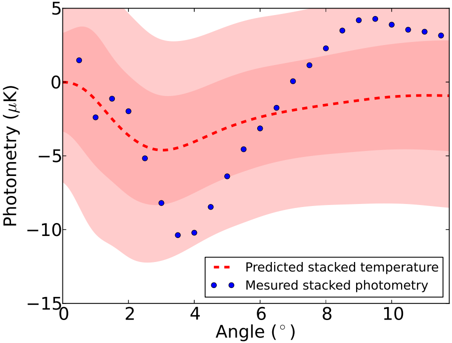
+

(Gaussian) CMB realisation



Assessing the CMB contamination

- 10,000 CMB realisations
- 10,000 simulated photometry
- Where does the data stand ?
  - $\sim 1.7\sigma$ from expected photometry at 4°
  - $\chi^2_{\rm red}$ of whole photometry ~ 1



Conclusions

Granett et al. voids

- Signal compatible with ΛCDM
- Mixture of iSW and primordial CMB
- Detection of iSW is tricky !

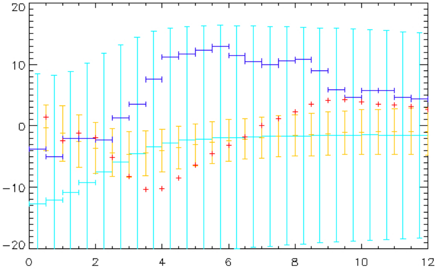
LTB framework

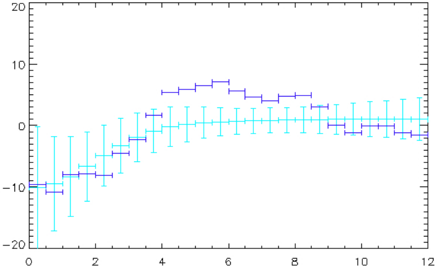
- Powerful and versatile tool for predictions
- Optimisation of detection (future surveys)
- Can help answer : is stacking a viable probe of iSW ?

Going futher :

- Benefits from increasing knowledge of voids
- Non-compensated voids
- Non-spherical voids
- Other cosmologies

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

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

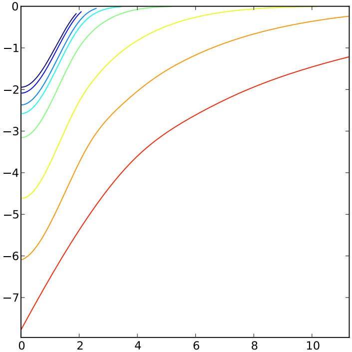
- $\Phi \sim 4\pi G \bar{\rho}_m L^2 \delta$
- $\dot{\Phi} \sim \Phi/\tau$, Λ-dom $\Rightarrow \tau \sim H^{-1}$
- $\int \mathrm{d}t \sim L/c$

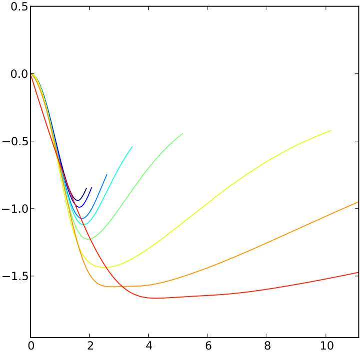
$$(\frac{\delta T}{T})_{\text{iSW}} \sim 8\pi G L^3 c^{-3} H \bar{\rho}_m \delta$$

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

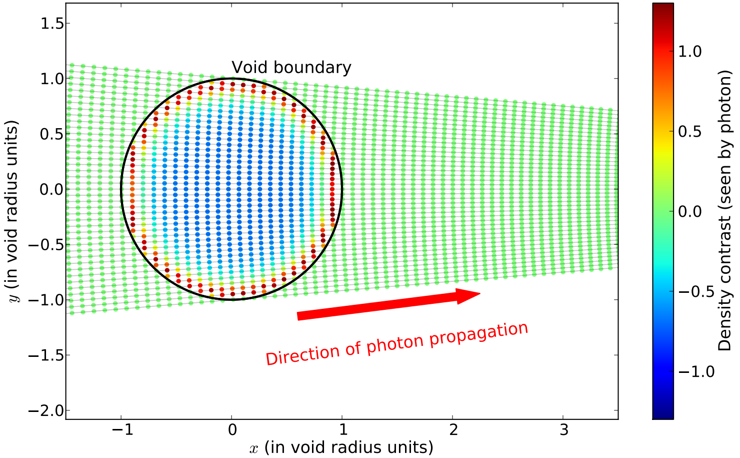
$$(\frac{\delta T}{T})_{\text{iSW}} \sim 3\left(\frac{L}{R_H}\right)^3 \Omega_m \sqrt{\Omega_{\text{Tot}}}\delta \sim 10^{-6} h^3 \left(\frac{L}{10\text{Mpc}}\right)^3 \frac{\delta}{10} \Omega_m \sqrt{\Omega_{\text{Tot}}}$$

Compensation test





Photons crossing a void



Large scale structures

Linear perturbation theory :

- Describes time-evolution of $\delta = \rho/\langle\rho\rangle - 1$ (for $\delta \ll 1$)
- $\delta(t) \propto D(t) \to$ 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

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

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

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

Photon in LTB theory

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

$$\frac{d\epsilon}{dt} = -\frac{R_{,rt}}{R_{,r}}\epsilon \quad (5)$$

$$\frac{dr}{dt} = \frac{k^r}{k^t} \quad (6)$$

$$\frac{d\theta}{dt} = \frac{k^\theta}{k^t} \quad (7)$$

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

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

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

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