On the origin of the Cold Spot

Kaiki Taro Inoue (KINDAI)

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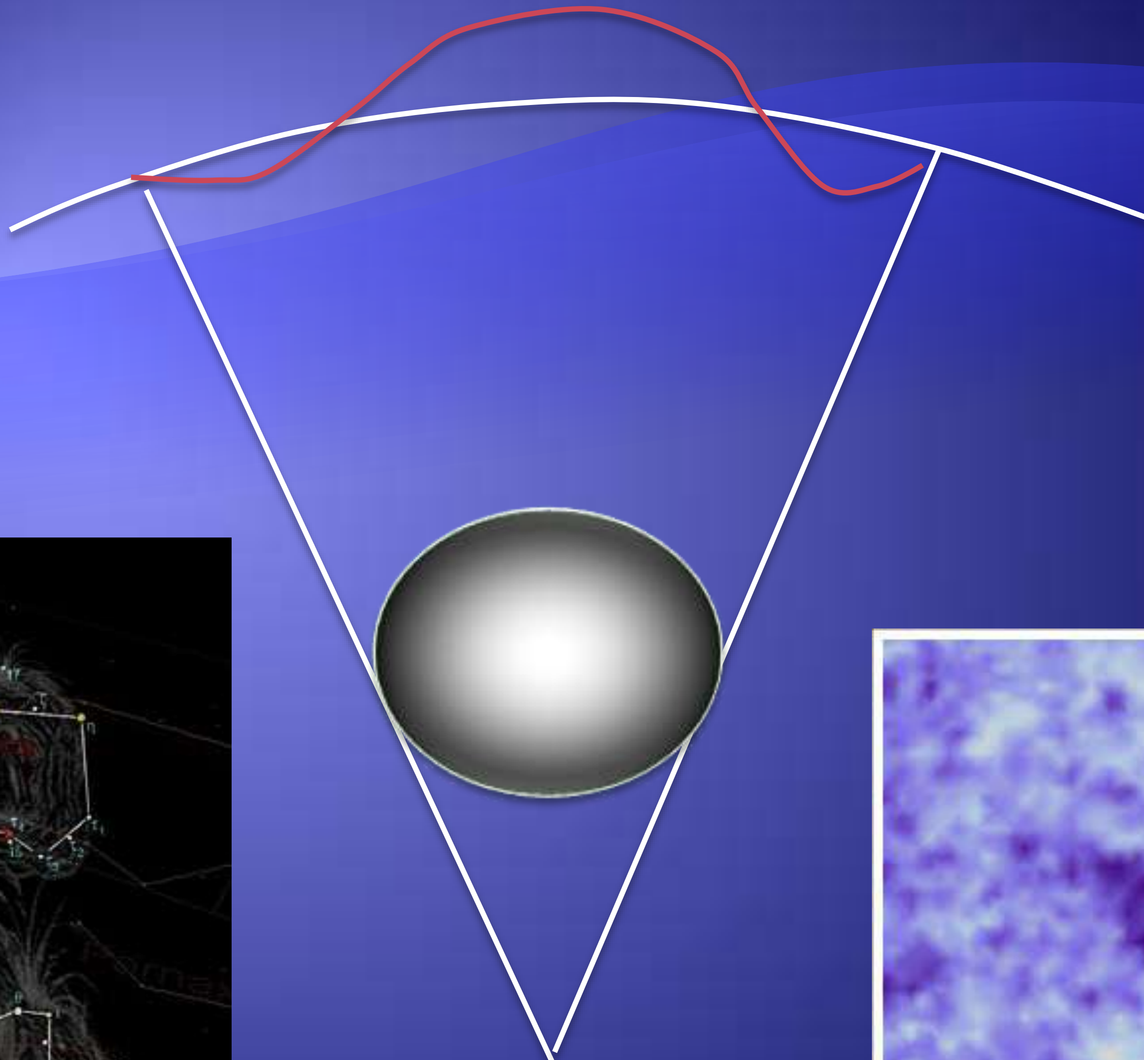
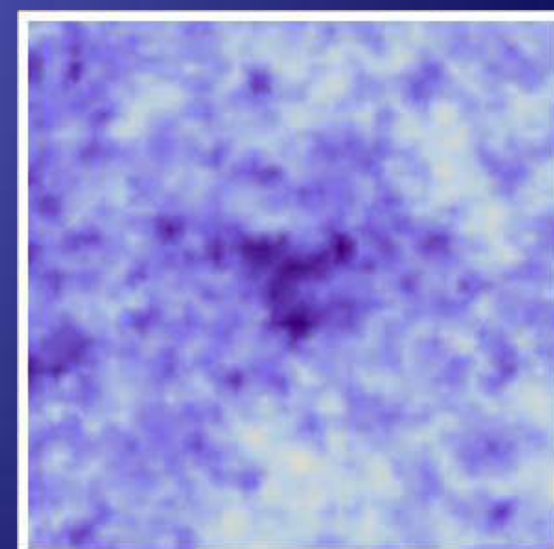
Astrophysics Seminar

Outline

- Introduction
- ISW effect due to spherical voids/clusters
- Late ISW effect & other CMB effects
- Statistical analysis
- Summary
- Future prospects

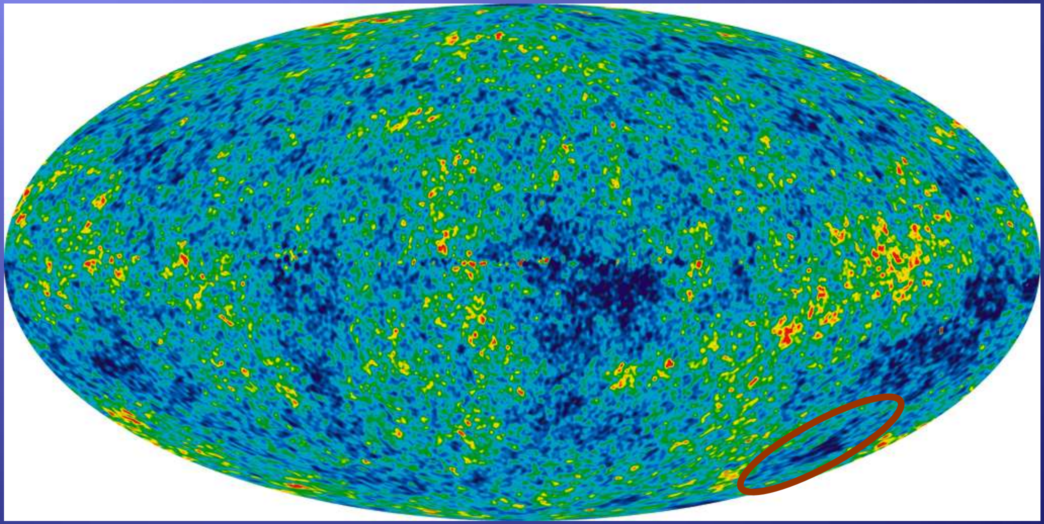




Introduction

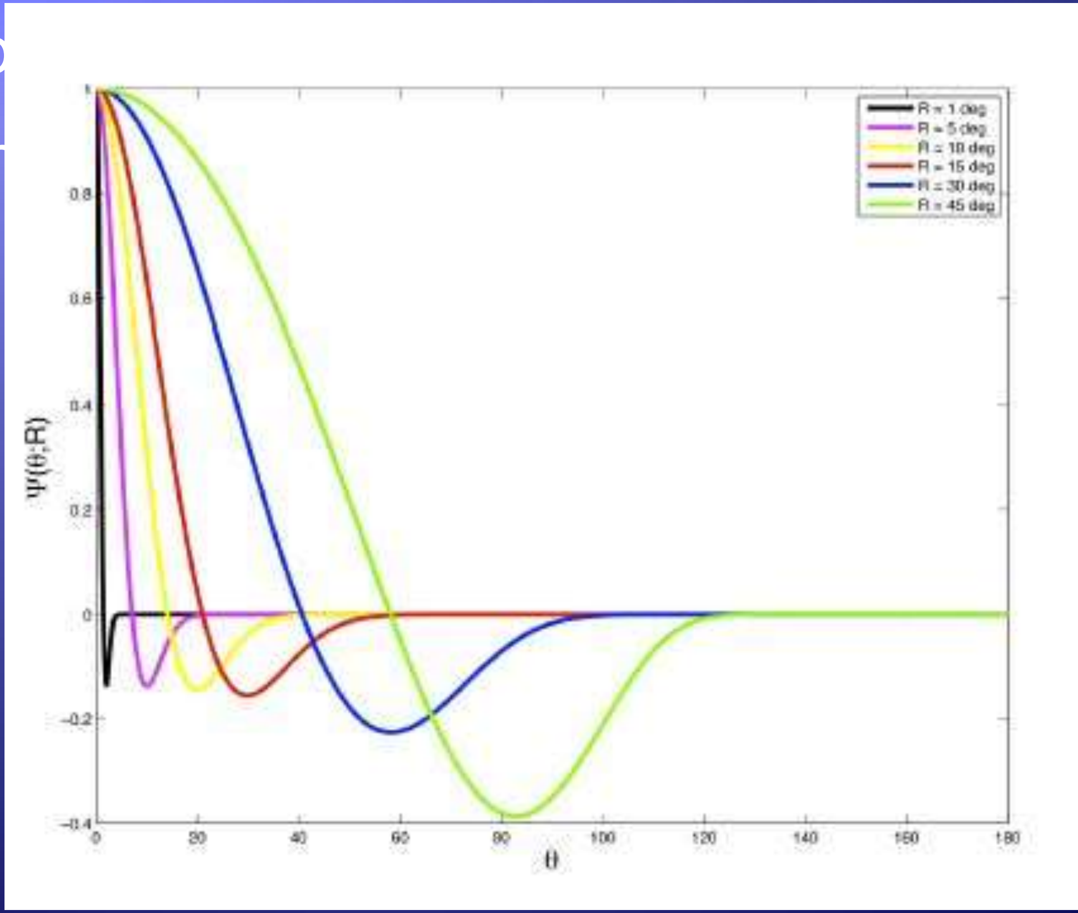
The CMB Cold Spot

- ~3σ deviation in kurtosis using spherical mexican-hat wavelets (Cruz et al. 2003)



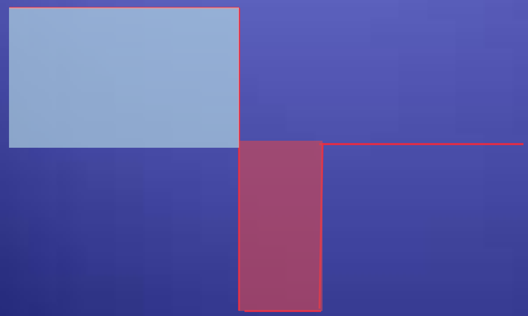
The CMB Cold Spot

- ~3σ deviation in kurtosis using spherical mexican-hat wavelets (Cruz et al. 2003)
- but no … filters (Smith …



The CMB Cold Spot

- ~3σ deviation in kurtosis using spherical mexican-hat wavelets (Cruz et al. 2003)
- but not significant for non-compensated filters (Smith &Huterer 2010)
- ~3σ deviation for signals smoothed by a top-hat compensating filter (Inoue, Sakai & Tomita 2010)



Temperature profile of the Cold Spot

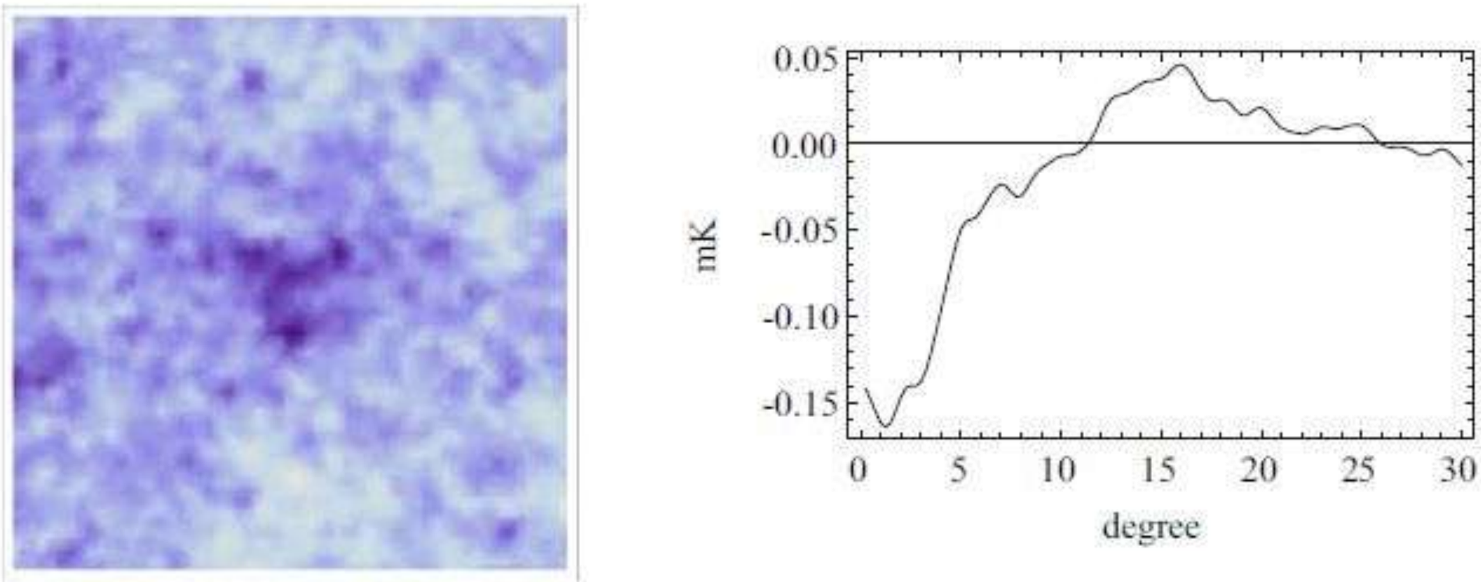
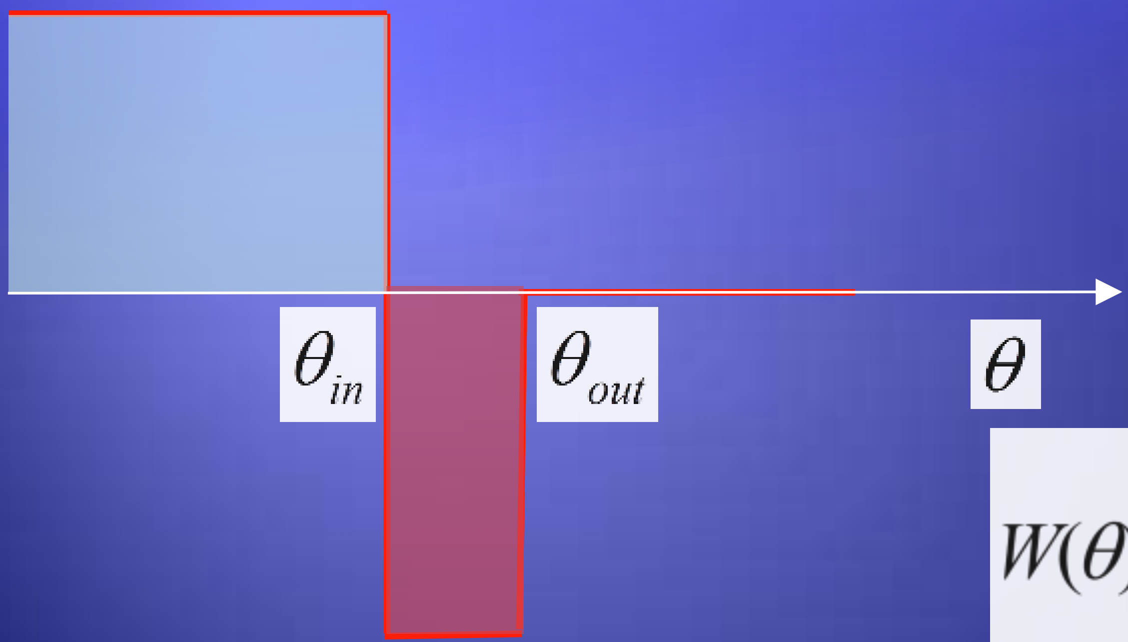


Fig. 10.— Left: the WMAP7 ILC temperature map ($40^\circ \times 40^\circ$) smoothed at 1° scale. Right: the averaged radial profile of the ILC map as a function of inclination angle θ from the center of the cold spot $(l, b) = (207.8^\circ, -56.3^\circ)$. A peak at $\theta \sim 15^\circ$ corresponds to a hot ring.

Compensated top-hat filter



$$W(\theta)=\begin{cases}1 & , \ \theta<\theta_{in} \\ -1 & , \ \theta_{in}\le\theta<\theta_{out}\end{cases}$$

$$\int_0^{\theta_{out}} 2\pi\theta W(\theta)\sin\theta \, d\theta=0$$

- Areas are the same.

For those who like math …

where $A = 2\pi(1 - \cos\theta_{in})$. Plugging ΔT expanded in spherical harmonics Y_{lm},

$$\Delta T = \sum_{lm} a_{lm} Y_{lm} \tag{C2}$$

into equation (A1), we have

$$\Delta T_f = A^{-1} \sum_{l} a_{l0} G_l, \tag{C3}$$

where

$$\begin{aligned} G_l &= \frac{\sqrt{\pi(2l+1)}}{l+1}\left[2\Big(-x_{in}P_l(x_{in}) + P_{l-1}(x_{in})\Big) + x_{out}P_l(x_{out}) - P_{l-1}(x_{out})\right], \\ x_{in} &= \cos\theta_{in}, \quad x_{out} = 2x_{in} - 1. \end{aligned} \tag{C4}$$

Note that we have used a formula for the Legendre function P_l,

$$\frac{dP_l(x)}{dx} = \frac{l(l+1)}{1-x^2}\int_x^1 P_l(x)dx \tag{C5}$$

in deriving equation A4. Because ΔT is assumed to be isotropic on S^2, the variance of ΔT_f can be written as a function of the angular power spectrum C_l as

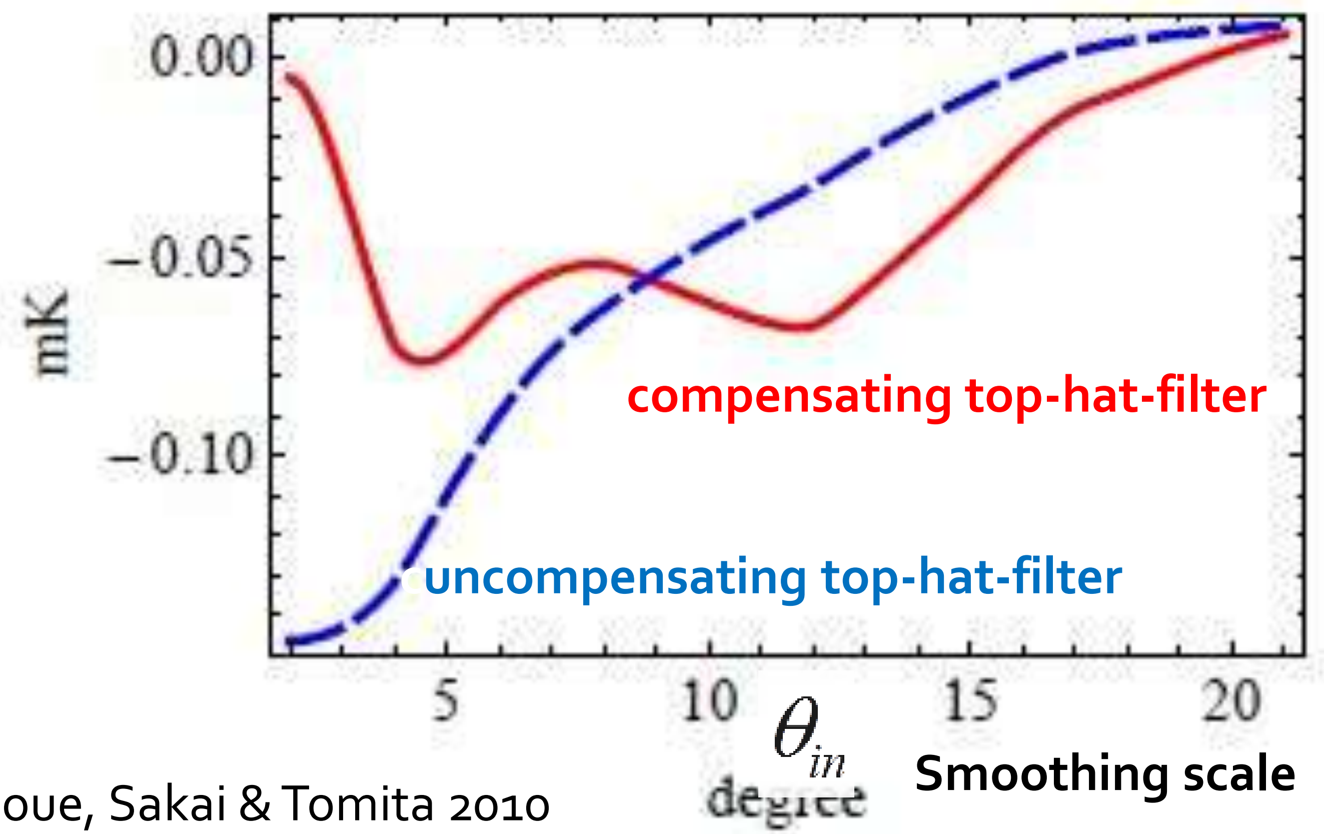
$$\sigma_f^2 = A^{-2} \sum_l C_l G_l^2. \tag{C6}$$

If the CMB sky is smoothed by a Gaussian beam with the FWHM θ_s, then the variance is

$$\sigma_f^2 = A^{-2} \sum_l C_l B_l G_l^2, \tag{C7}$$

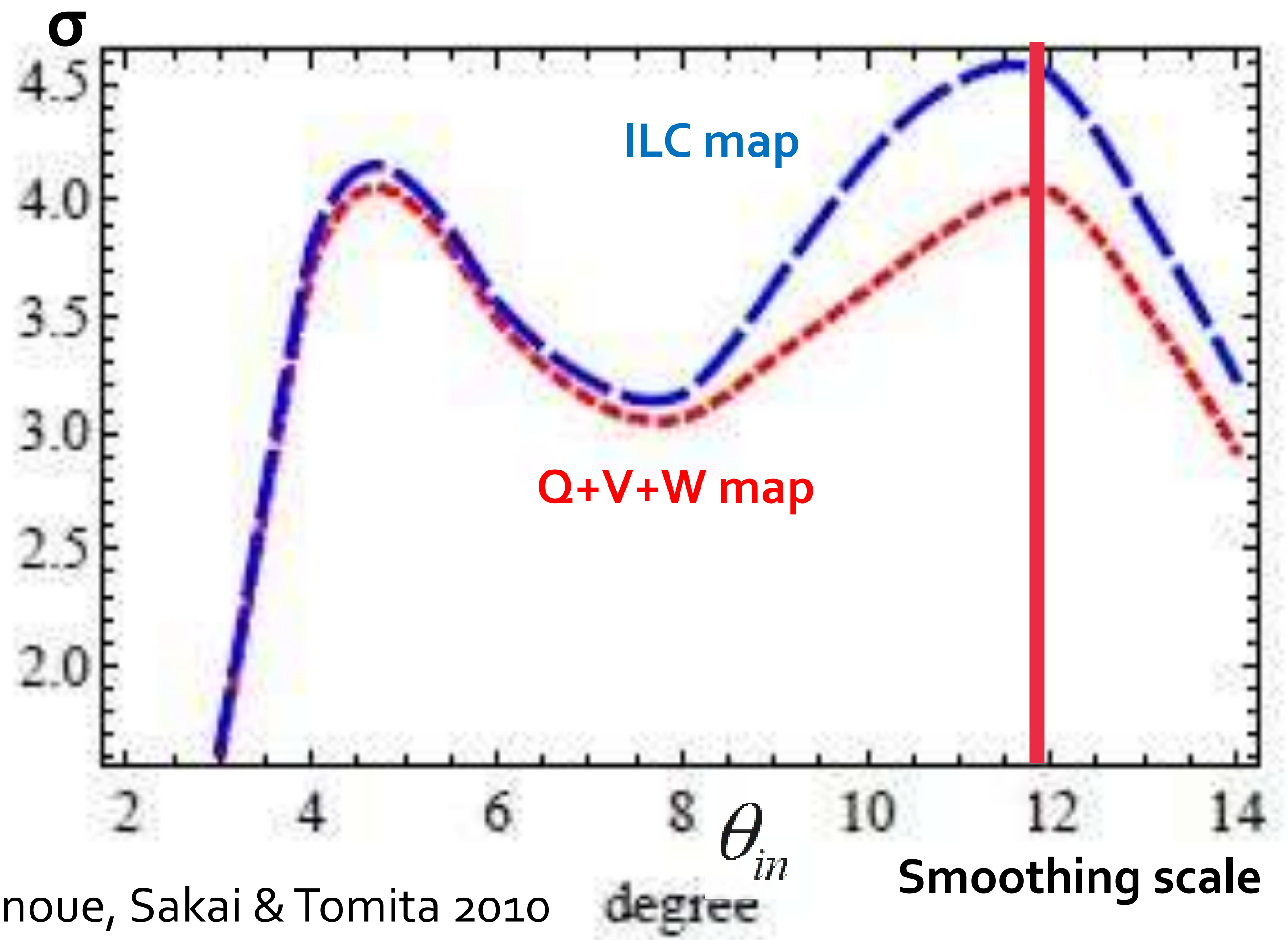
where $B_l = \exp[-\sigma_s^2 l(l+1)/2]$, and $\sigma_s = (8\ln 2)^{-1/2}\theta_s$.

Temperature profile of CS



Inoue, Sakai & Tomita 2010

Statistical significance



Inoue, Sakai & Tomita 2010

Statistical significance for the full sky

- Sample number~observed area/size of filtering
- At =5 degree , significance is 0.7-1 %(~2σ)
  at =12 degree, significance is 0.01-0.2%(~3σ)

Optimal filter for a cold spot surrounded by a hot ring?

Origin of the CS

- A supervoid with r~200Mpc/h, δ~-0.3 at z~1 (Inoue & Silk 2006)
- A hot ring cannot be produced by a compensating void (Tomita & Inoue 2007 Inoue & Sakai 2008)
- A texture at z~5 (Cruz et al. 2007)
- Statistical fluke?

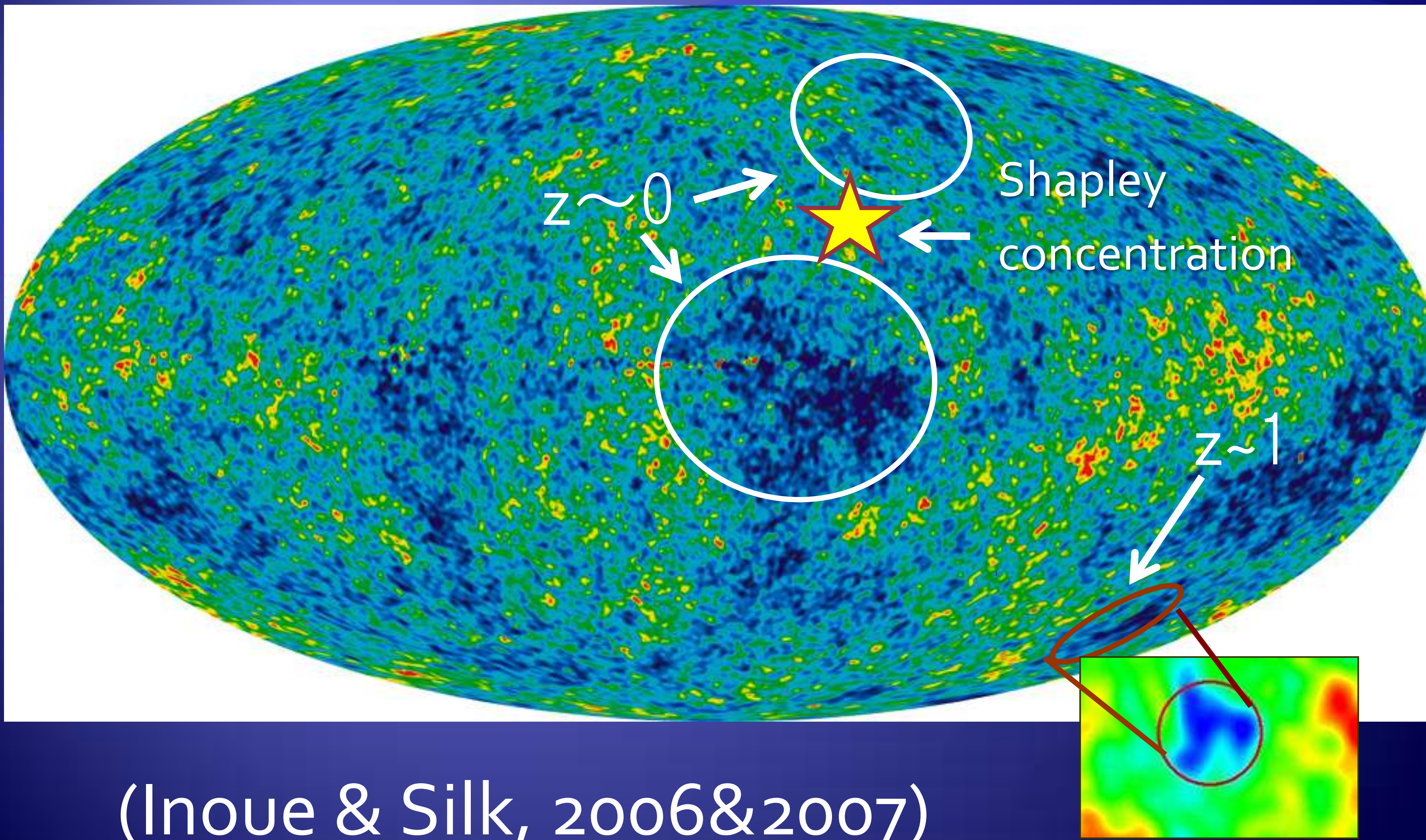
Supervoid ?

- A dip of 20-45% in the surface brightness in radio bands (Rudnick, Brown, & Williams 2007)

- No significant dip in galaxy counts at $0.3<z<1$ in the l.o.s to the center of the CS (Bremer et al. 2010, Granett et al. 2010)

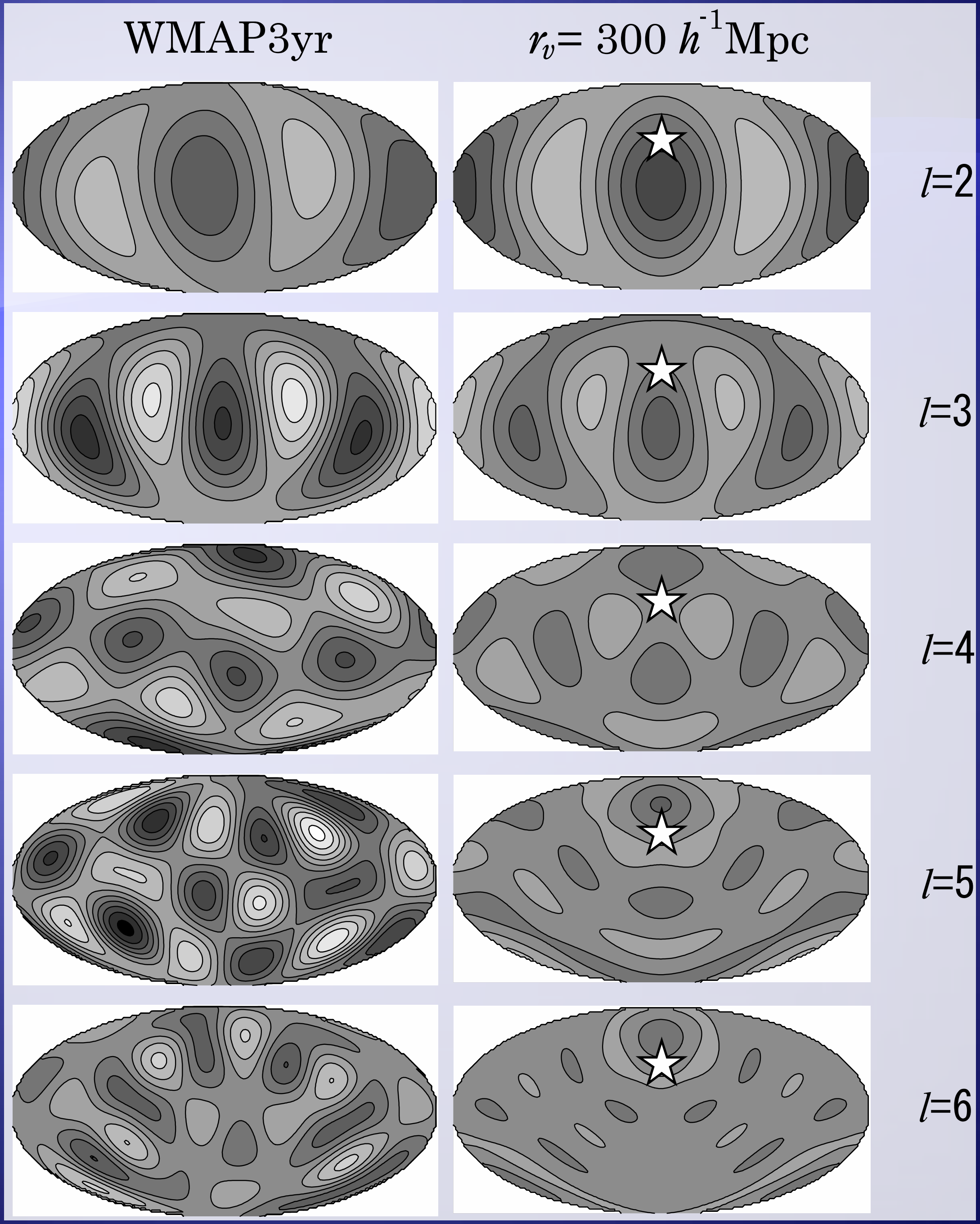
- A low-density region at $z\sim0.2$ in 2MASS galaxy catalog may contribute 8μK to the CS (Francis & Peacock 2010)

Supervoids ?



"the Cold Spot"

(Inoue & Silk, 2006&2007)



(Inoue & Silk 2007)

2MASS | Local ISW

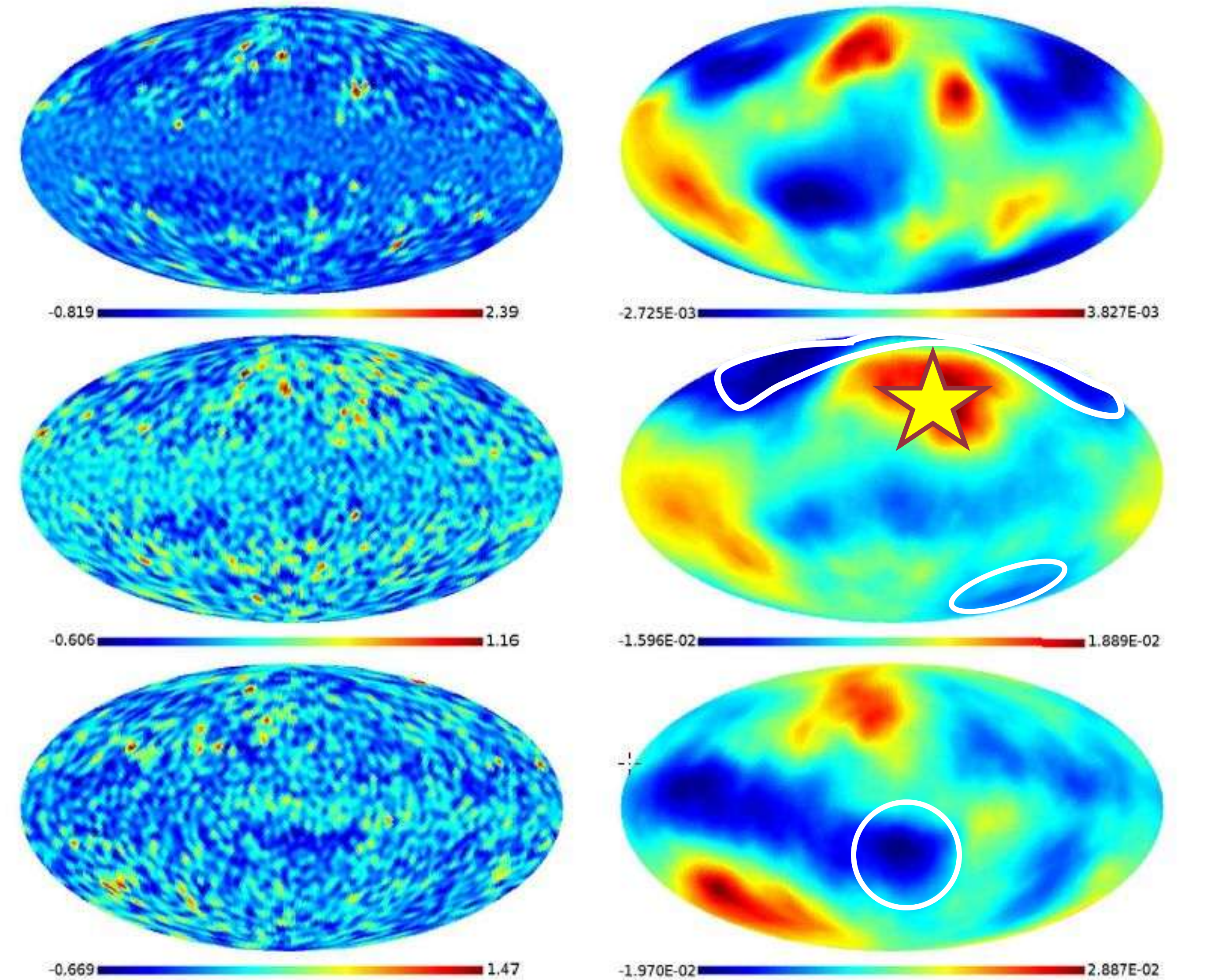


Figure 1. (Left) The 2D reconstruction of the local density field described in Section 2.1 in three photometric redshift shells: $0.0 < z < 0.1$ (top), $0.1 < z < 0.2$ (middle) and $0.2 < z < 0.3$ (bottom). The plots show overdensity δ on a scale $-0.6 \leqslant \delta \leqslant 0.6$. (Right) The corresponding ISW signal in mK computed from the reconstructed density field using equation (4).

0.0<z<0.1

0.1<z<0.2

0.2<z<0.3

(Francis & Peacock, 2010)

Questions

Q1. If a void is non-compensated, can a hot ring be produced and statistically more probable?

→ A1. Yes it can. But not probable.

Q2. Even if it is a fluke, what is the expected ISW contribution from a possible low-density region to the CS?

→ A2. It is about 10 %.

For those who want to know the reason…

Press continue

ISW effect due to spherical voids/clusters

ISW (RS) effects from SSS

Theory

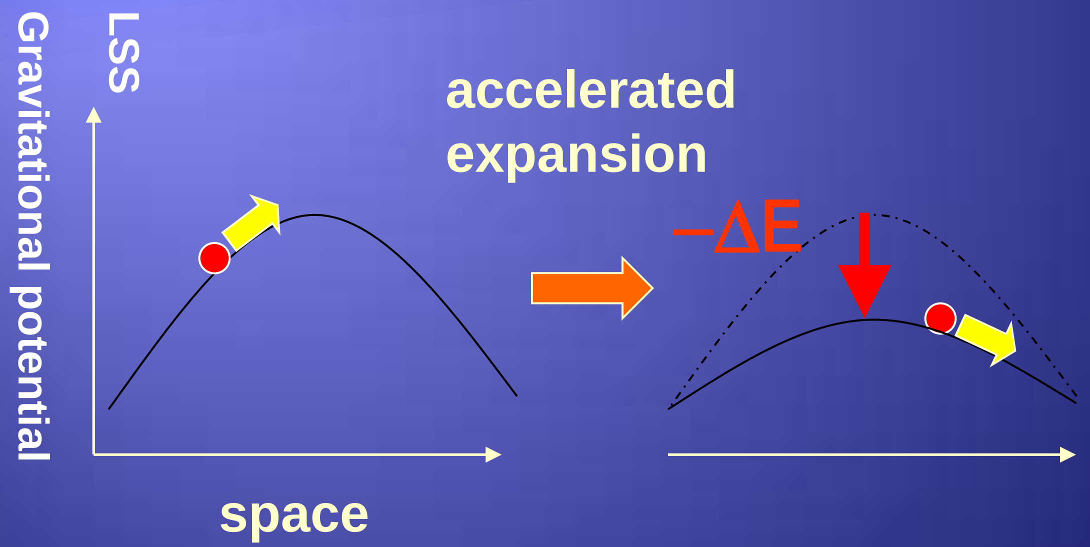
- Thin-shell approx. (Inoue & Silk 2006&2007)
- 2nd order perturbations (Tomita & Inoue 2008)
- LTB solutions (Sakai & Inoue 2008)

Observation

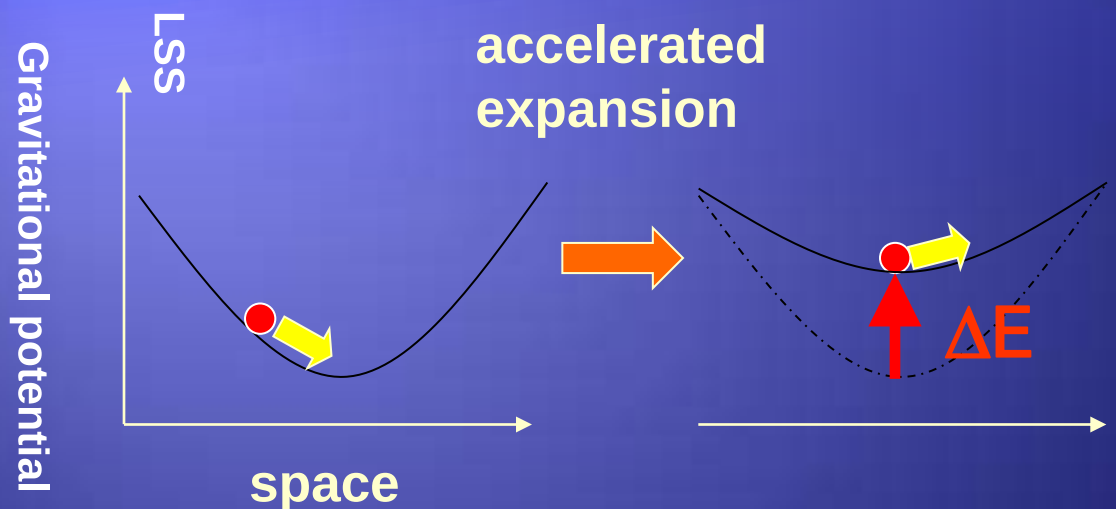
- SDSS LRGs (Granett et al. 2008)
- 2MASS photo-z (Francis & Peacock 2009)

Integrated Sachs-Wolfe (ISW) Effect

temperature fluctuation due to time-evolving gravitational potential

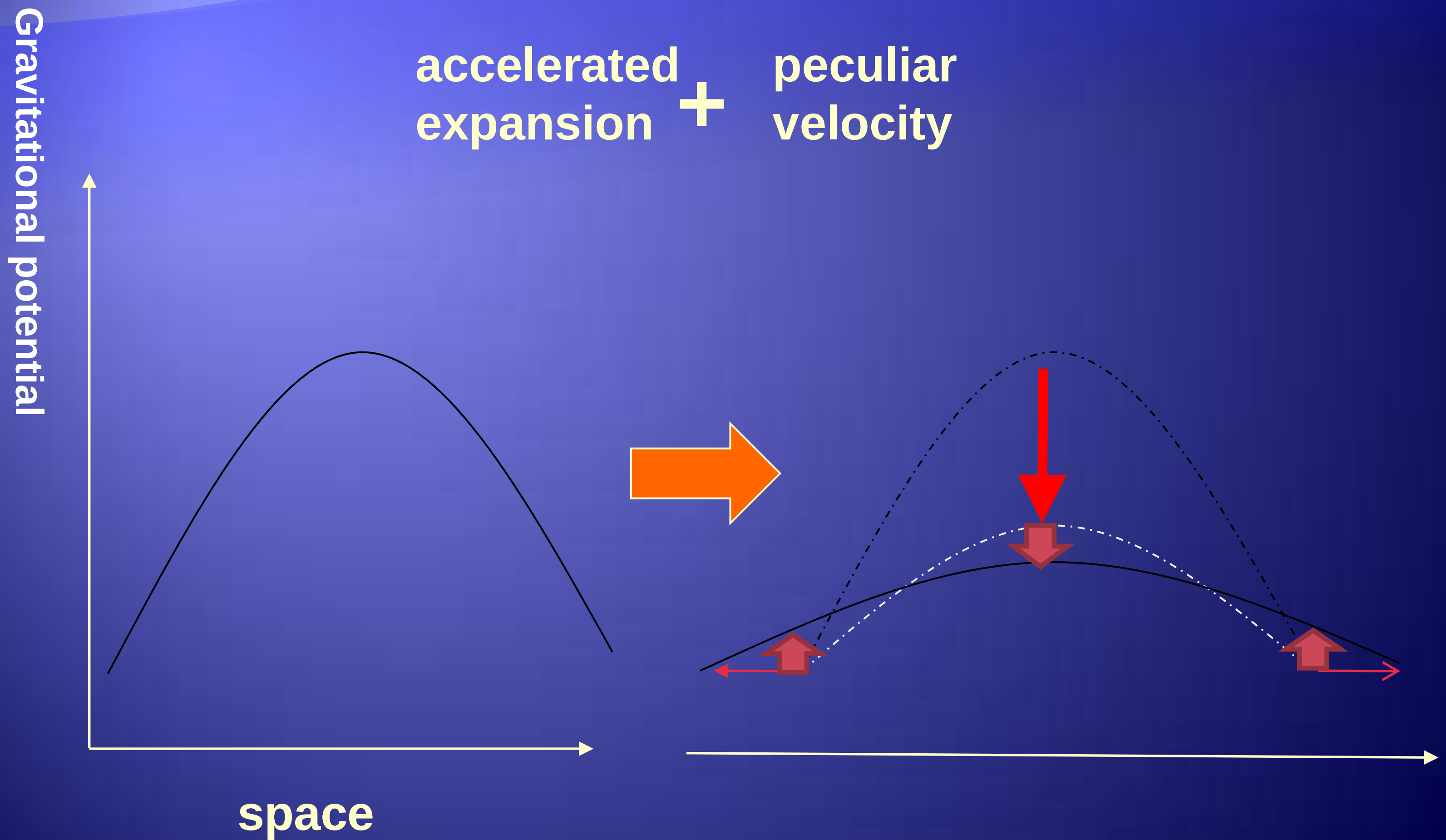


→low temperature for CMB photons that pass through a void temperature fluctuation due to time-evolving gravitational potential

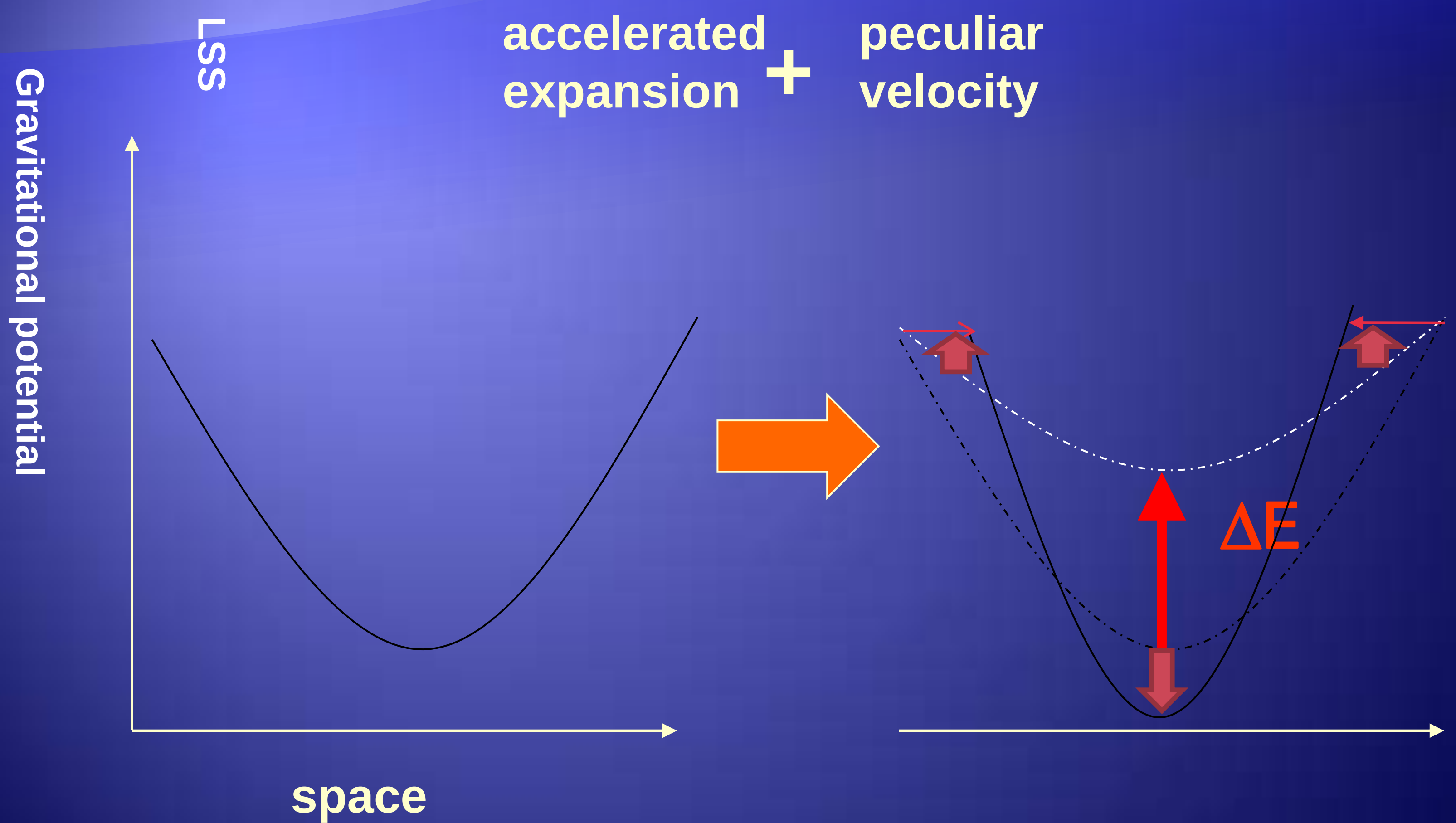


→high temperature for CMB photons that pass through a cluster

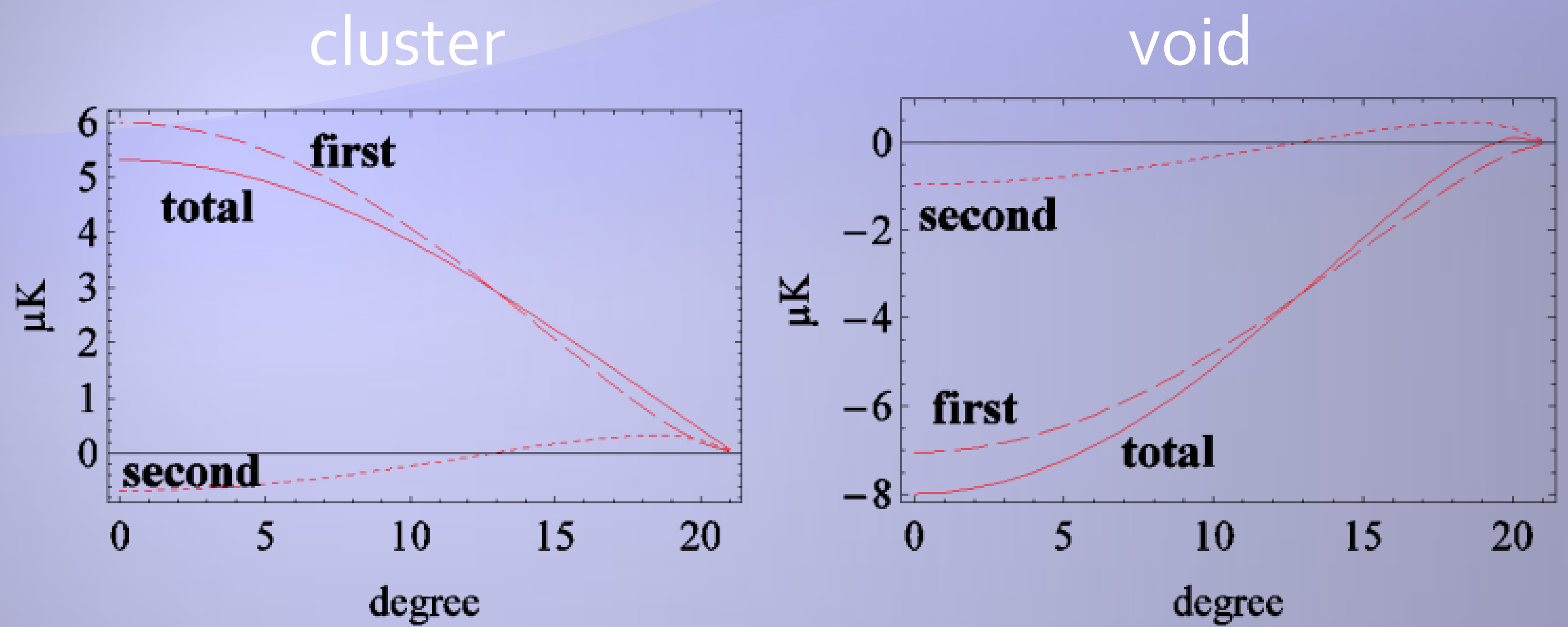
Second order ISW (RS) Effect



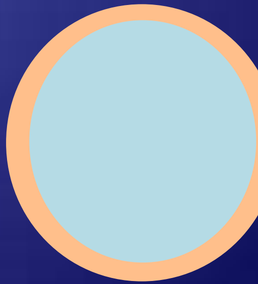
Second order ISW (RS) Effect



1st & 2nd order ISW effects



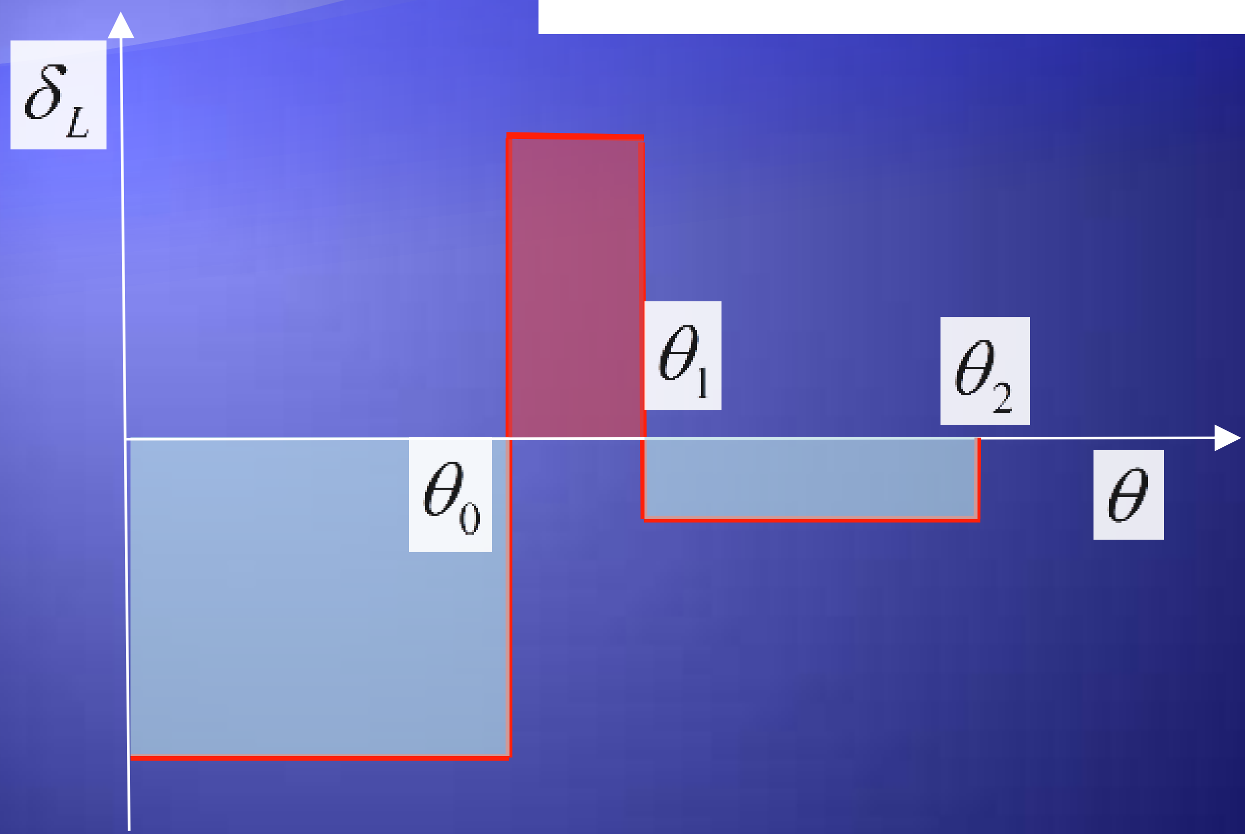
(Tomita & Inoue 2008)



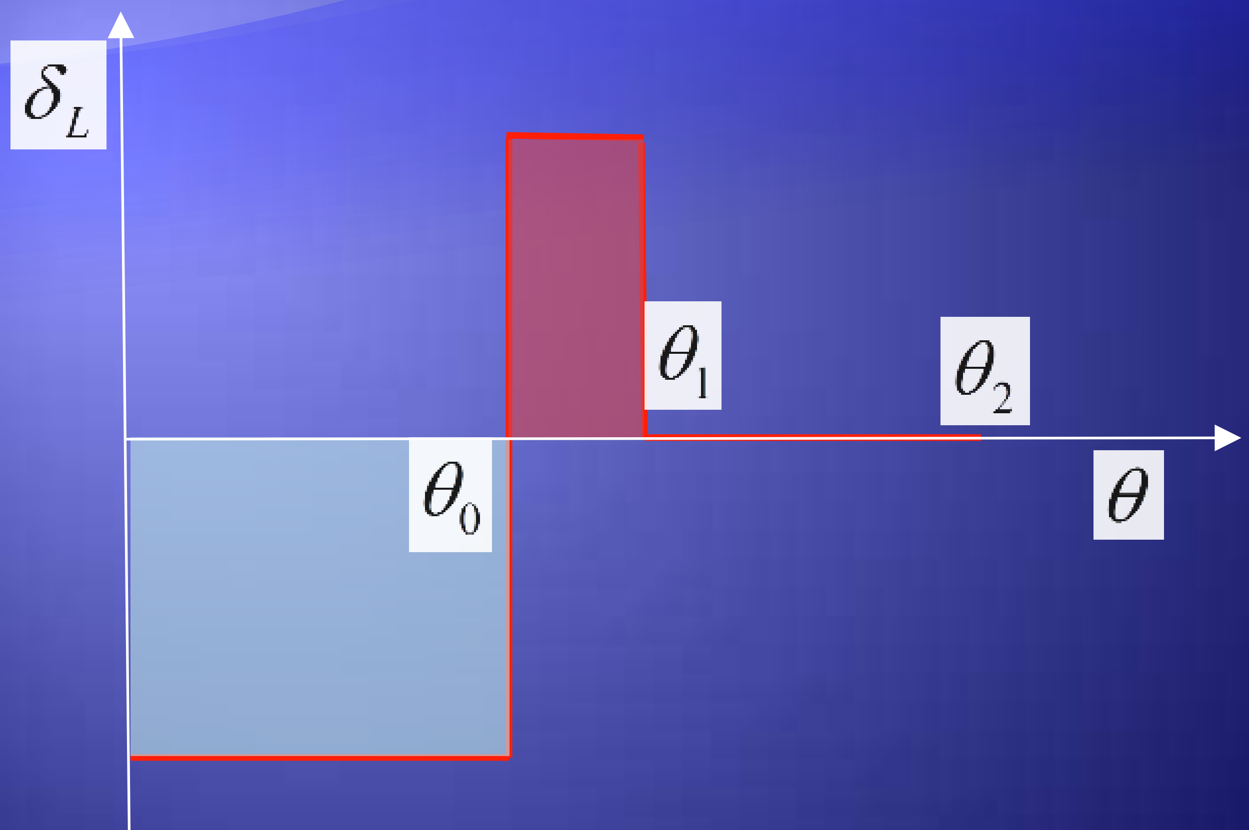
Non-compensation effect

- Massive wall around a void could increase the CMB temperature.
- Less massive “void wall” around a cluster could decrease the CMB temperature.
- Quasi-linear perturbation can be estimated using 2nd order perturbation (Tomita & Inoue 2008)

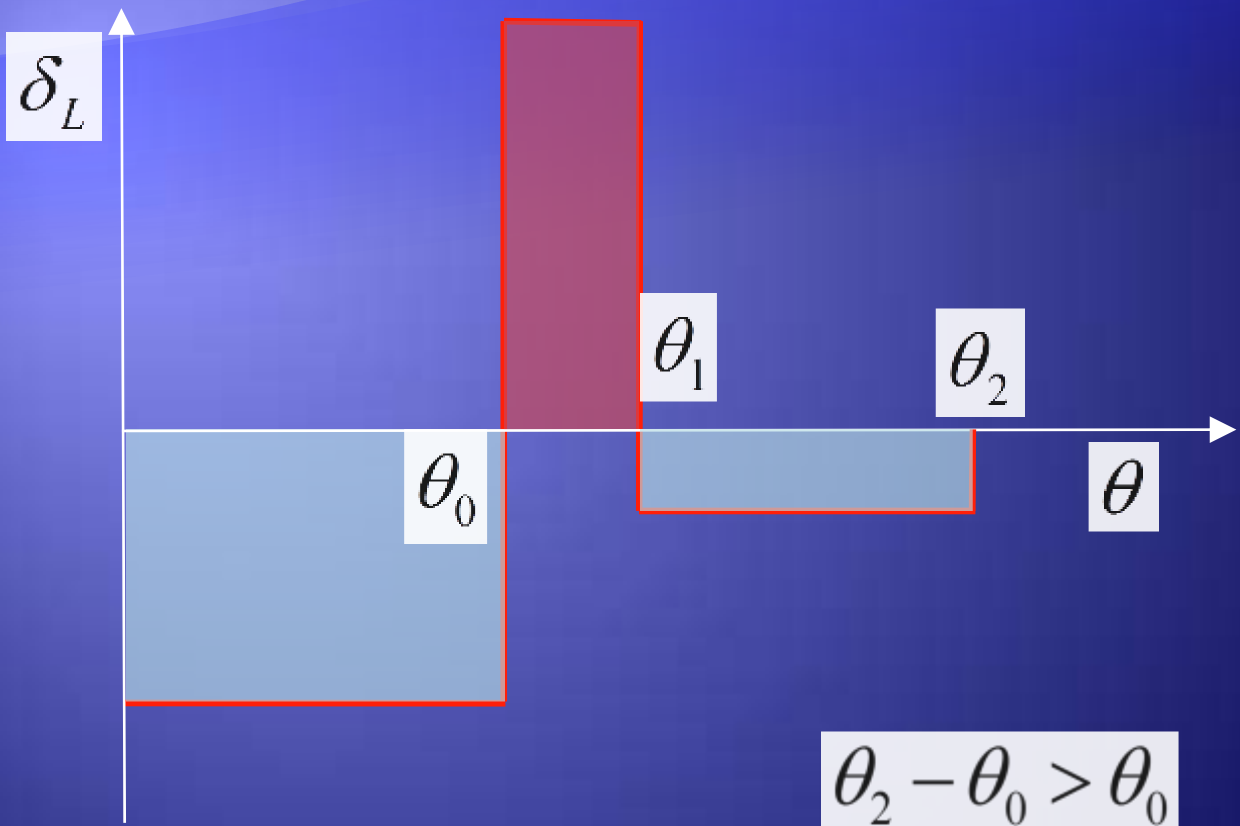
$$\varepsilon \equiv \frac{\delta_0^L r_0^3 + \delta_1^L (r_1^3 - r_0^3)}{|\delta_0^L r_0^3|}.$$



Compensating model $\varepsilon = 0$

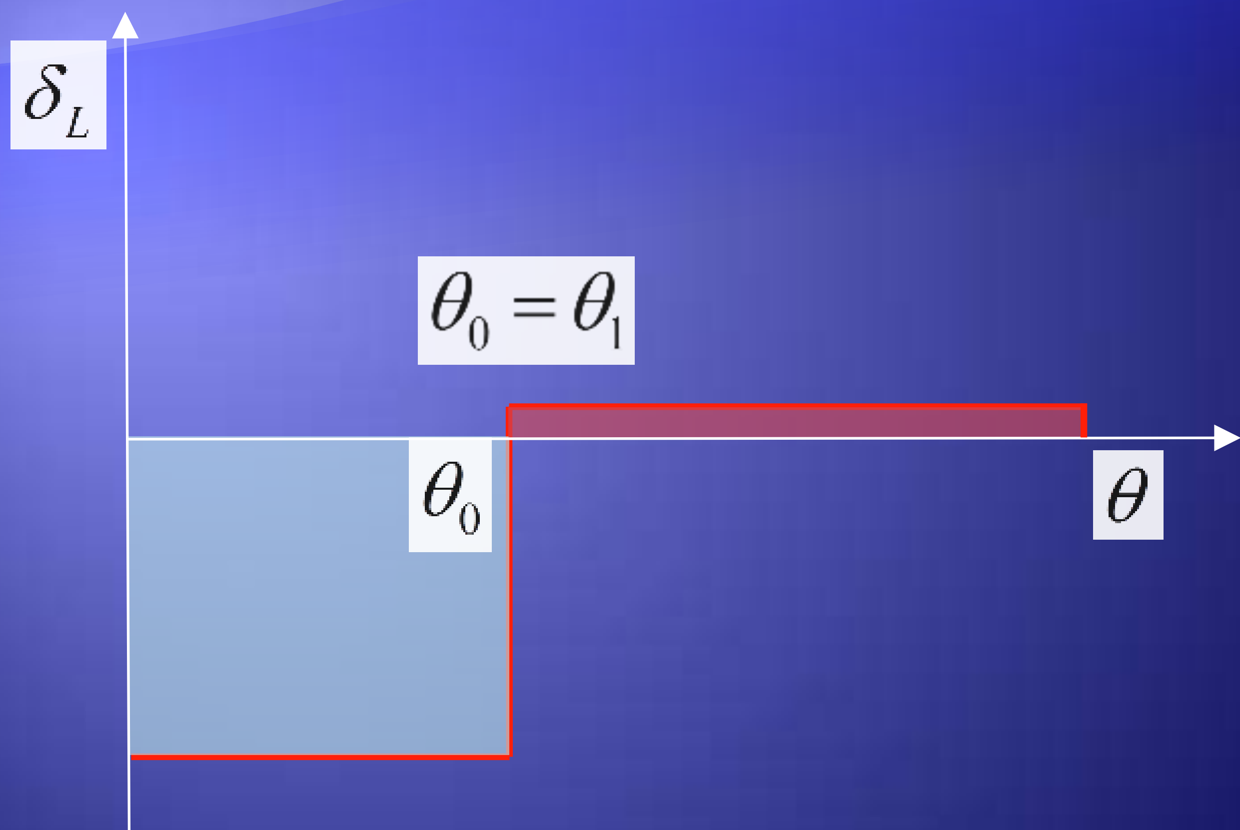


Over-compensating model $\varepsilon > 0$



$$\theta_2 - \theta_0 > \theta_0$$

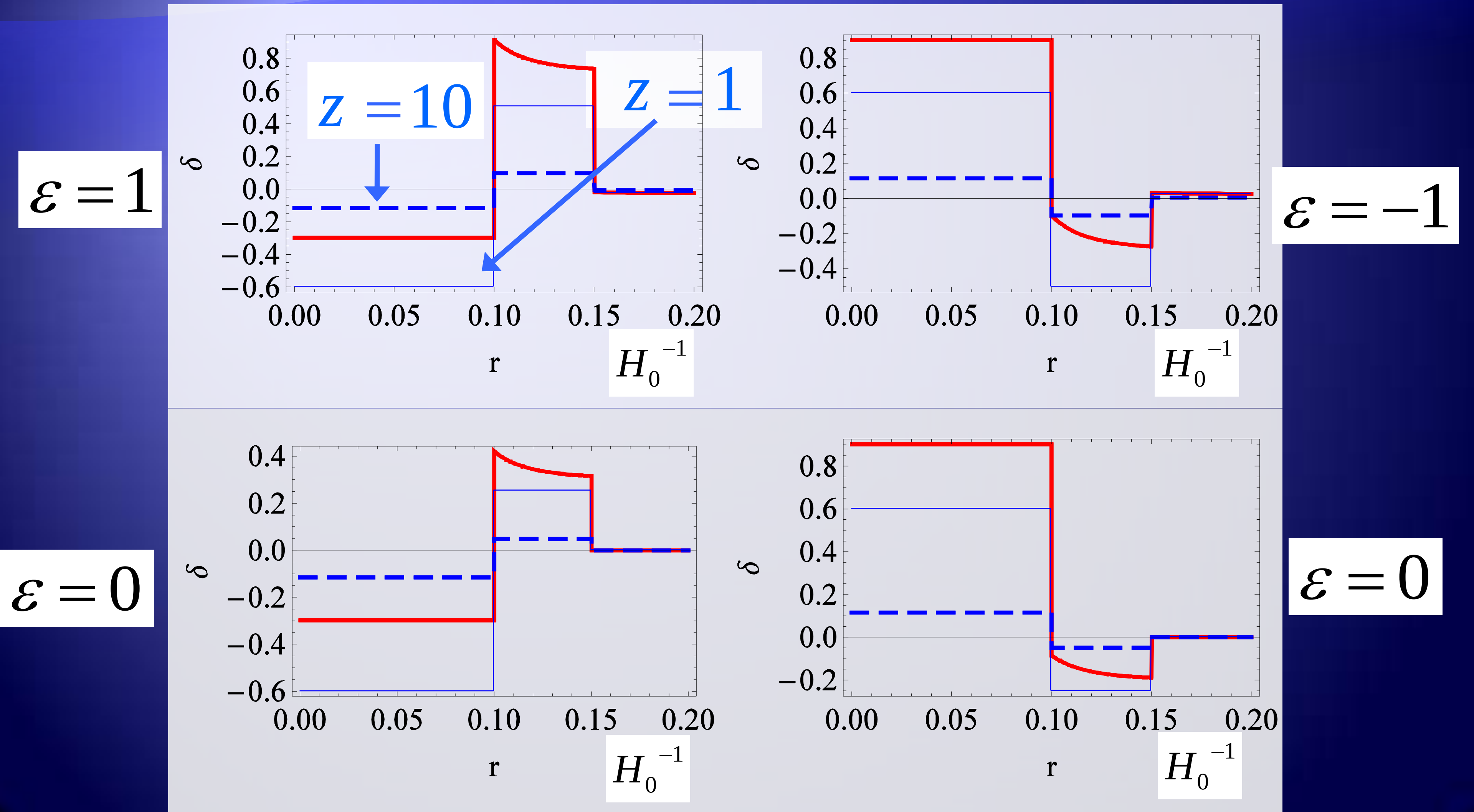
Under-compensating model $\varepsilon < 0$



$$\theta_2 - \theta_0 > \theta_0$$

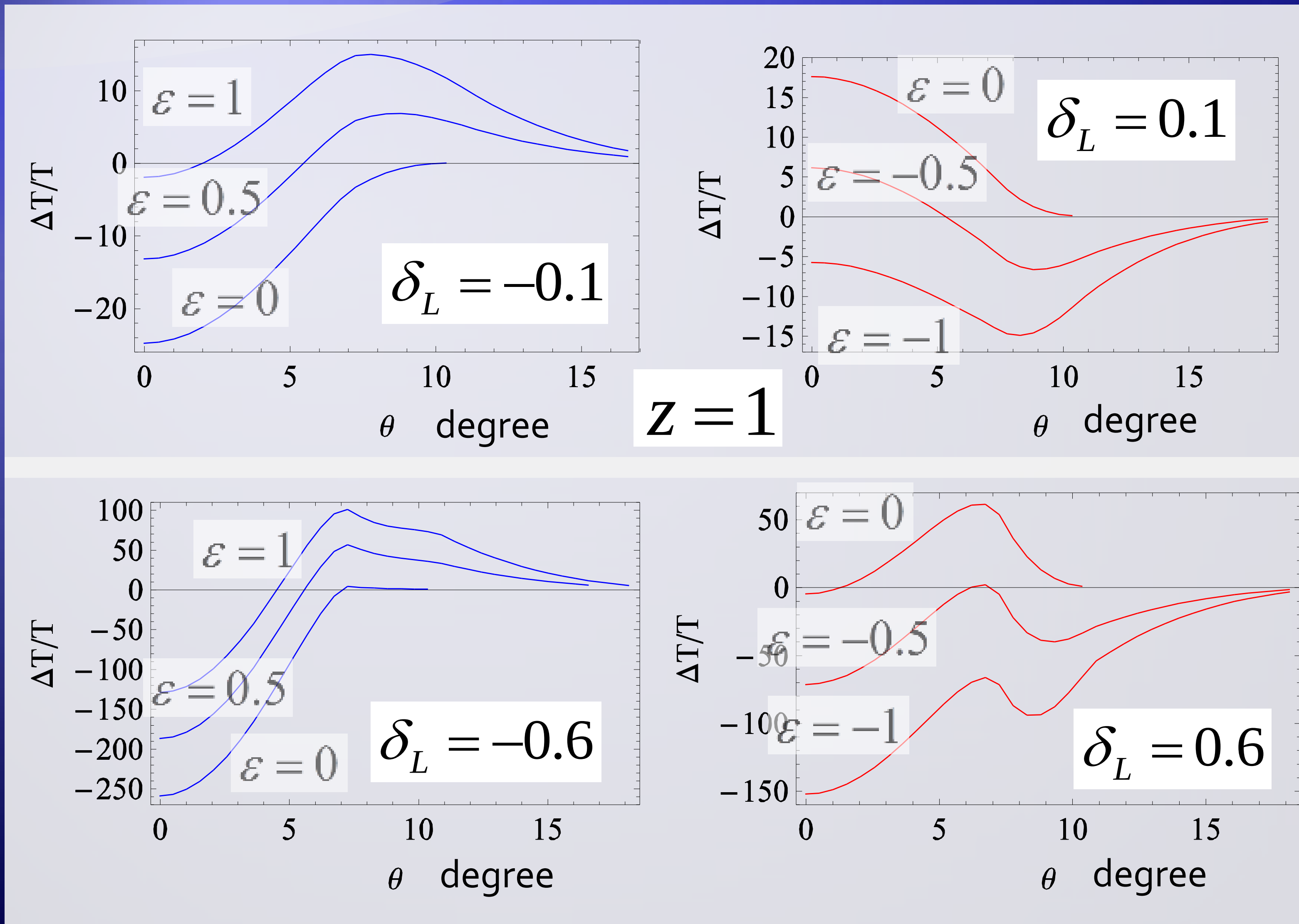
Non-compensation effect

void density contrast cluster



Non-compensation effect

void temperature variation cluster



Non-compensation effect

- A hot ring surrounding a cold spot can be produced by an over-compensated void even in an accelerating epoch.
- A cold ring surrounding a hot spot can be produced by an under-compensated cluster even in an accelerating epoch.
- A cold ring surrounding a cold spot can be produced by an under-compensated non-linear cluster.

Non-compensation effect

- A hot ring surrounding a cold spot can be produced by an over-compensated void even in an accelerating epoch.
- A cold ring surrounding a hot spot can be produced by an under-uncompensated cluster even in an accelerating epoch.
- A cold ring surrounding a cold spot can be produced by an under-uncompensated non-linear cluster.

Late ISW effect & other CMB effects

Temperature anisotropy

- Ordinary Sachs-Wolfe (OSW) effect

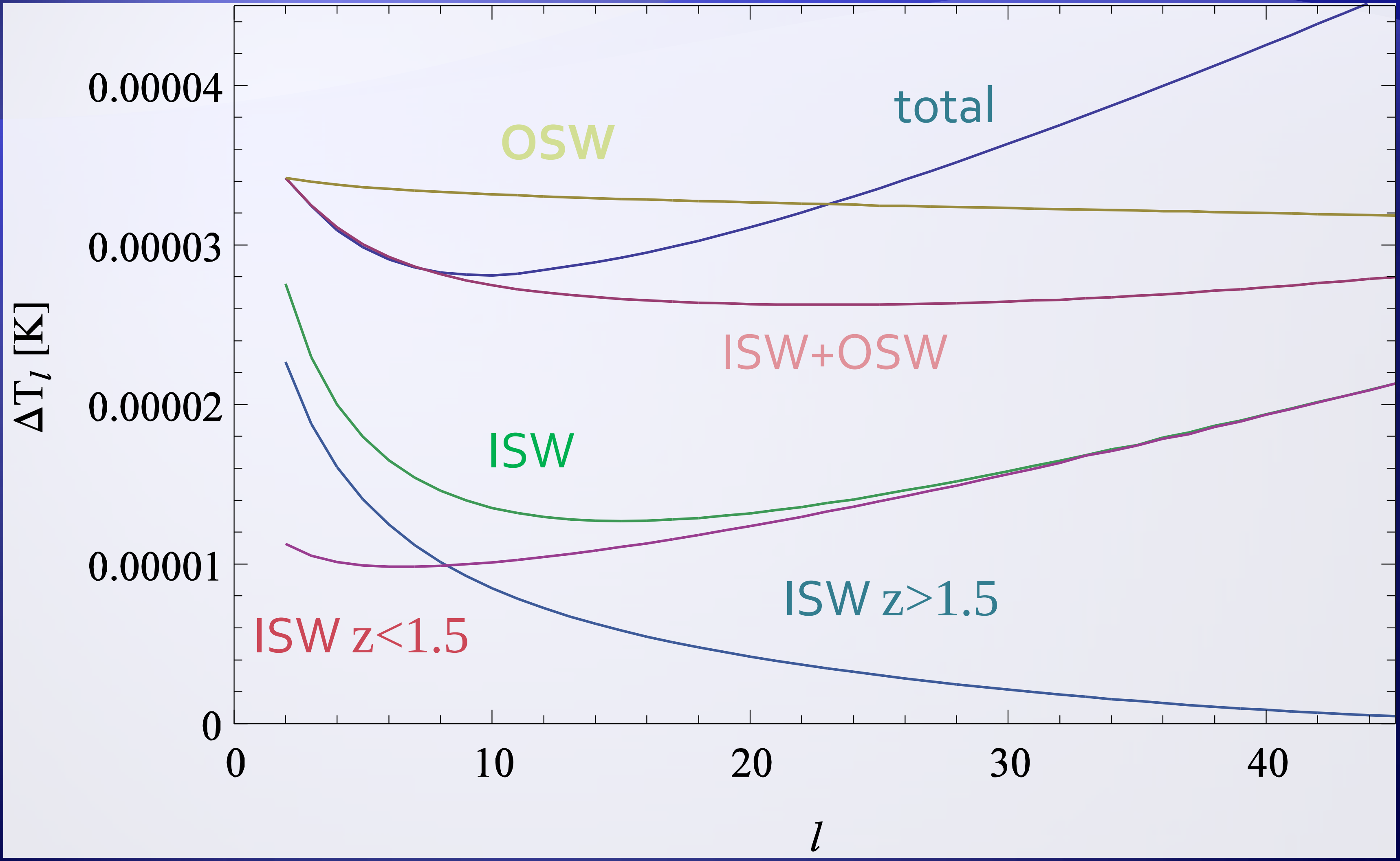
  : spatial fluctuation on the last scattering surface.
- Doppler effect

  :spatial fluctuation of the fluid velocity on LSS.
- Early integrated Sachs-Wolfe (ISW) effect

  : time evolving potential at radiation->matter epoch.
- Late integrated Sachs-Wolfe (ISW) effect

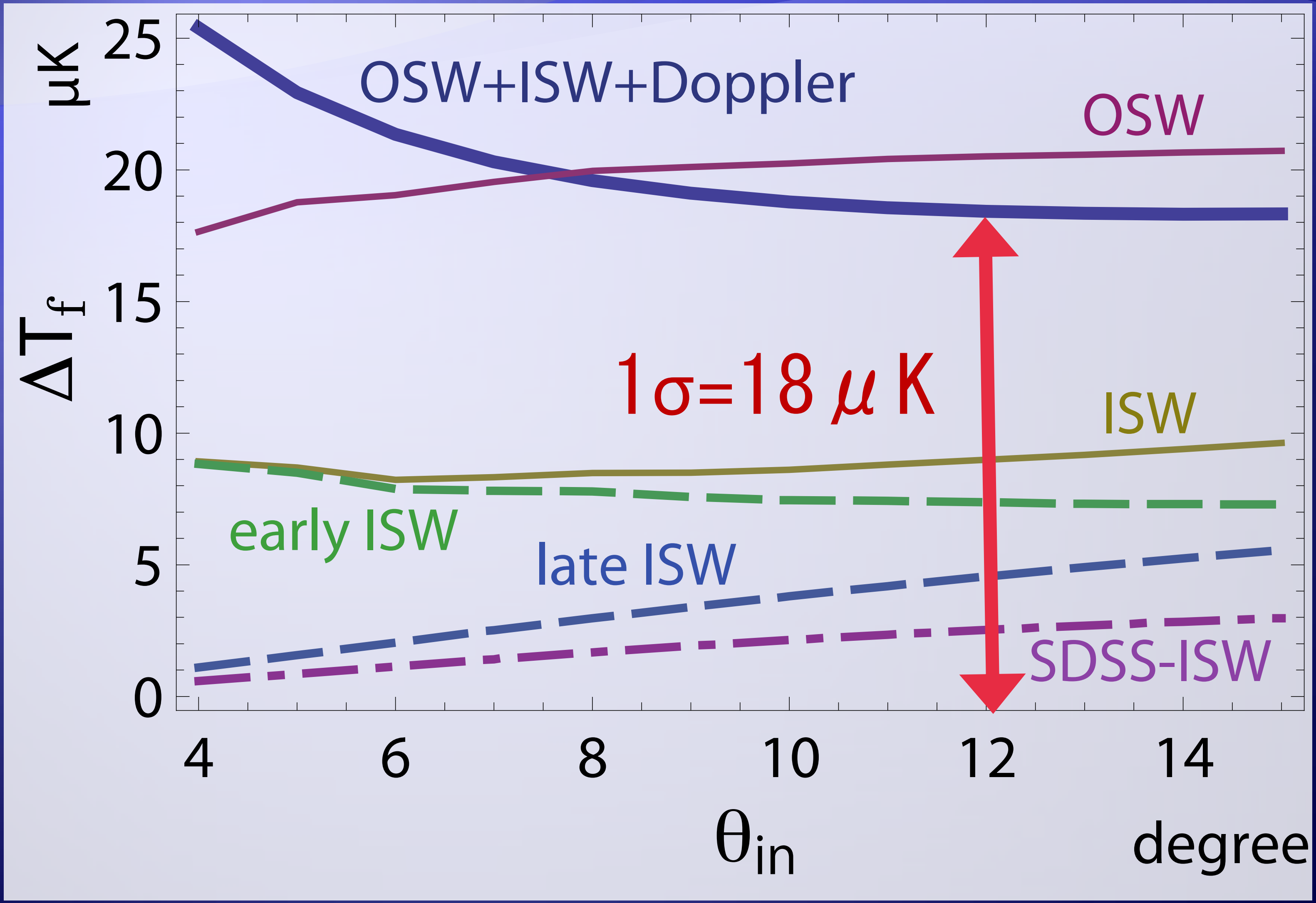
  : time evolving potential at matter->Λ epoch.

Temperature anisotropy



2.73K × sqrt of angular power

Temperature anisotropy smoothed by a compensated top-hat filter



Statistical analysis

A single void model

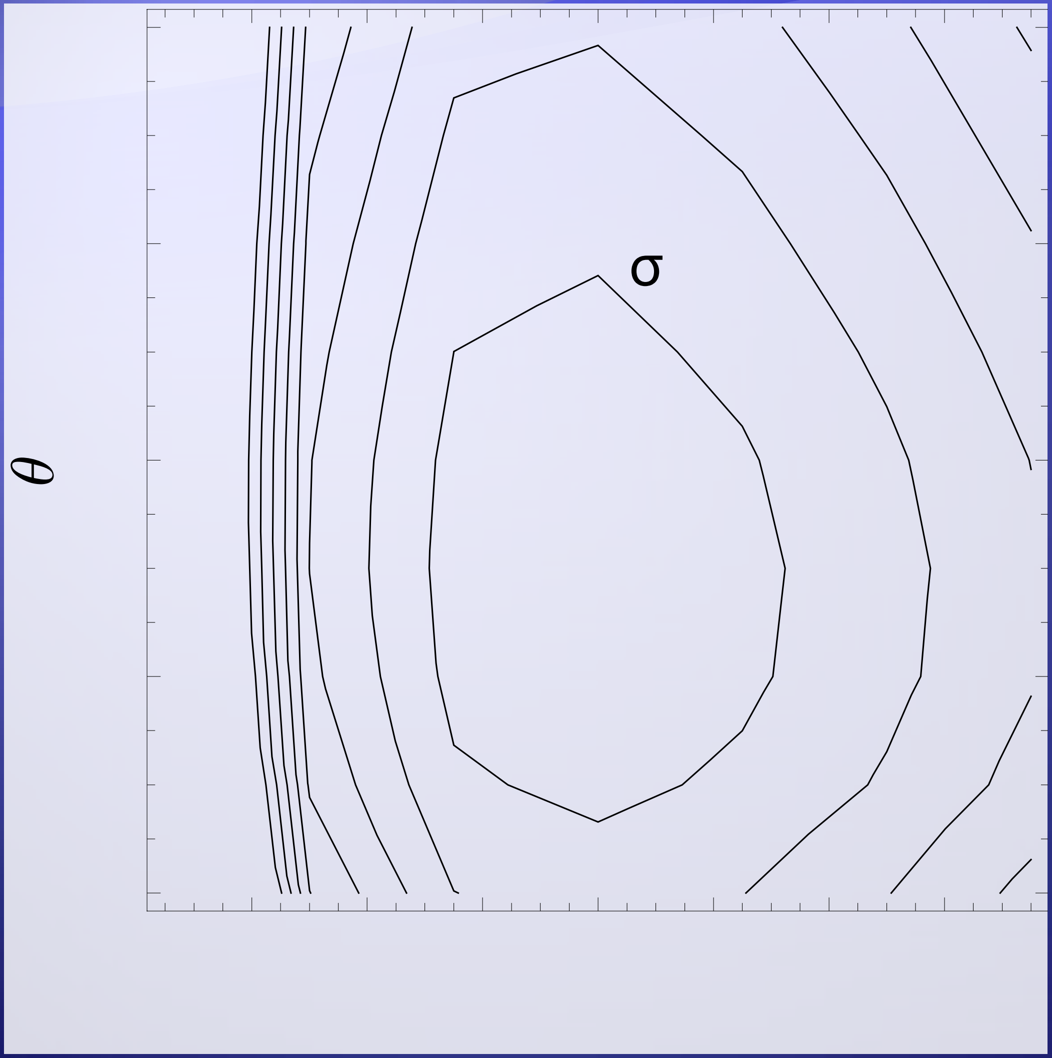
- We assume there is a spherical top-hat type void (low density region) in the l.o.s. to the CS at $z<1.5$.

- We assume a concordant cosmology with

$$(\Omega_\Lambda = 0.74, \Omega_m = 0.26, \Omega_b = 0.044, \sigma_8 = 0.80, h = 0.72, n = 0.96)$$

- We assume that the CS is produced by a late ISW due to a void at $z<1.5$ (low density region) plus the OSW, earlyISW, and Doppler effects. No correlation with the fluctuations at the LSS is assumed.

Over-compensated void



$$\theta_1 = \frac{\theta_0 + \theta_2}{2}$$

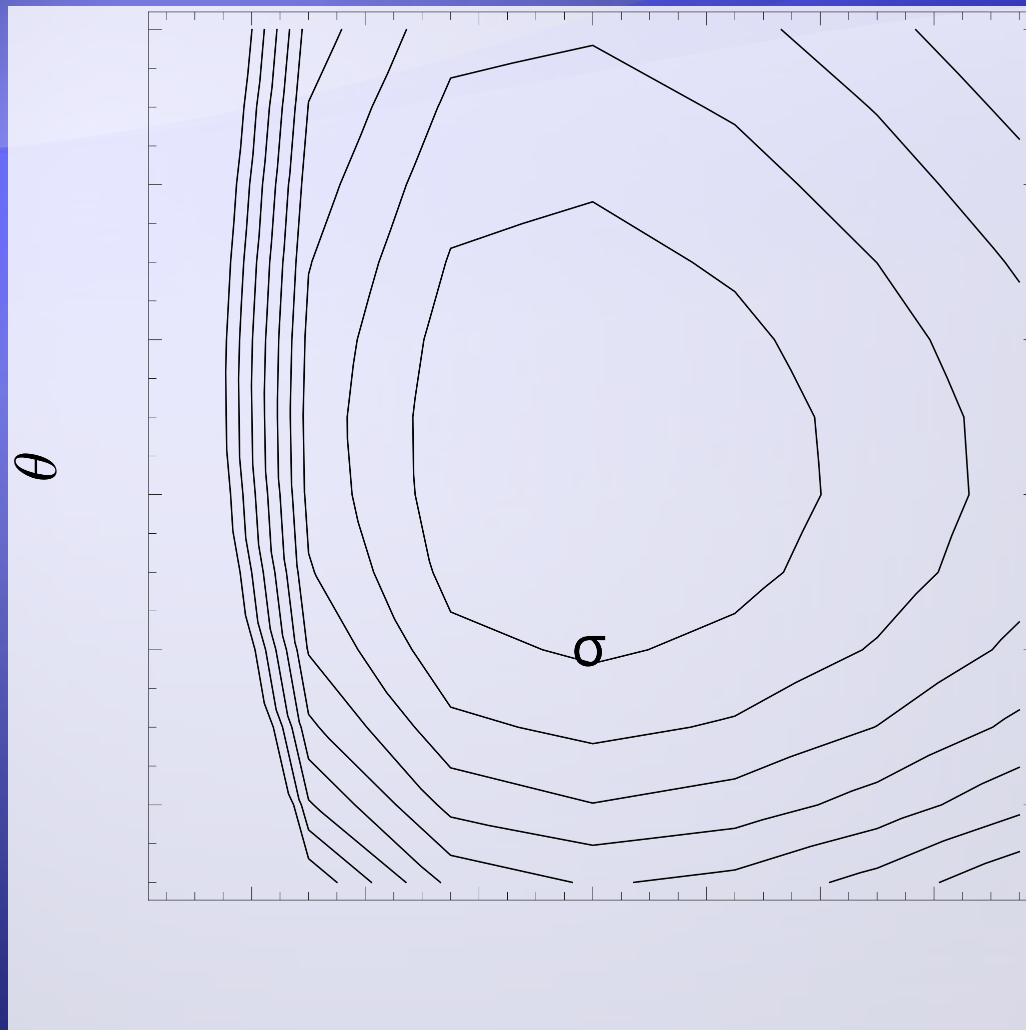
$\Delta T_f(1\sigma)$ $=18\,\mu K$

$\varepsilon=1$

$\theta_{in}=12^o$

$$\theta_2 = 30^o$$

Compensated void



$\Delta T_f(1\sigma) = 18\,\mu K$

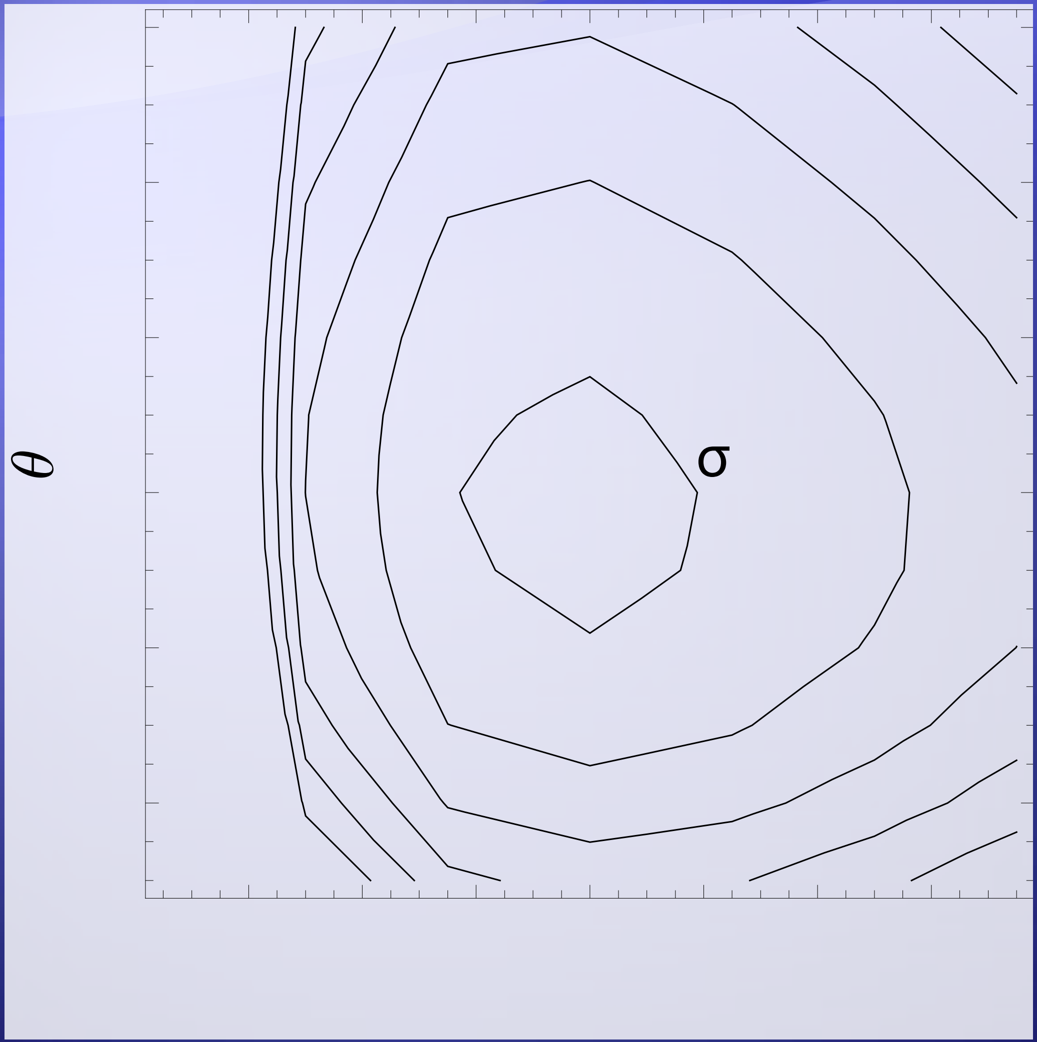
$\varepsilon = 0$

$\theta_{in} = 12^o$

$$\theta_1 = \frac{\theta_0 + \theta_2}{2}$$

$$\theta_2 = 30^o$$

Under-compensated void



$\Delta T_f(1\sigma)$
$=18\,\mu K$
$\varepsilon=-1$

$\theta_{in}=12^o$

$$\theta_0=\theta_1, \theta_2=30^o$$

Why peak at z~1?

$$\frac{\Delta T}{T} \propto \delta_0 r^3 \frac{d\Phi}{d\eta}$$

$$\propto r \frac{d\Phi}{d\eta}$$

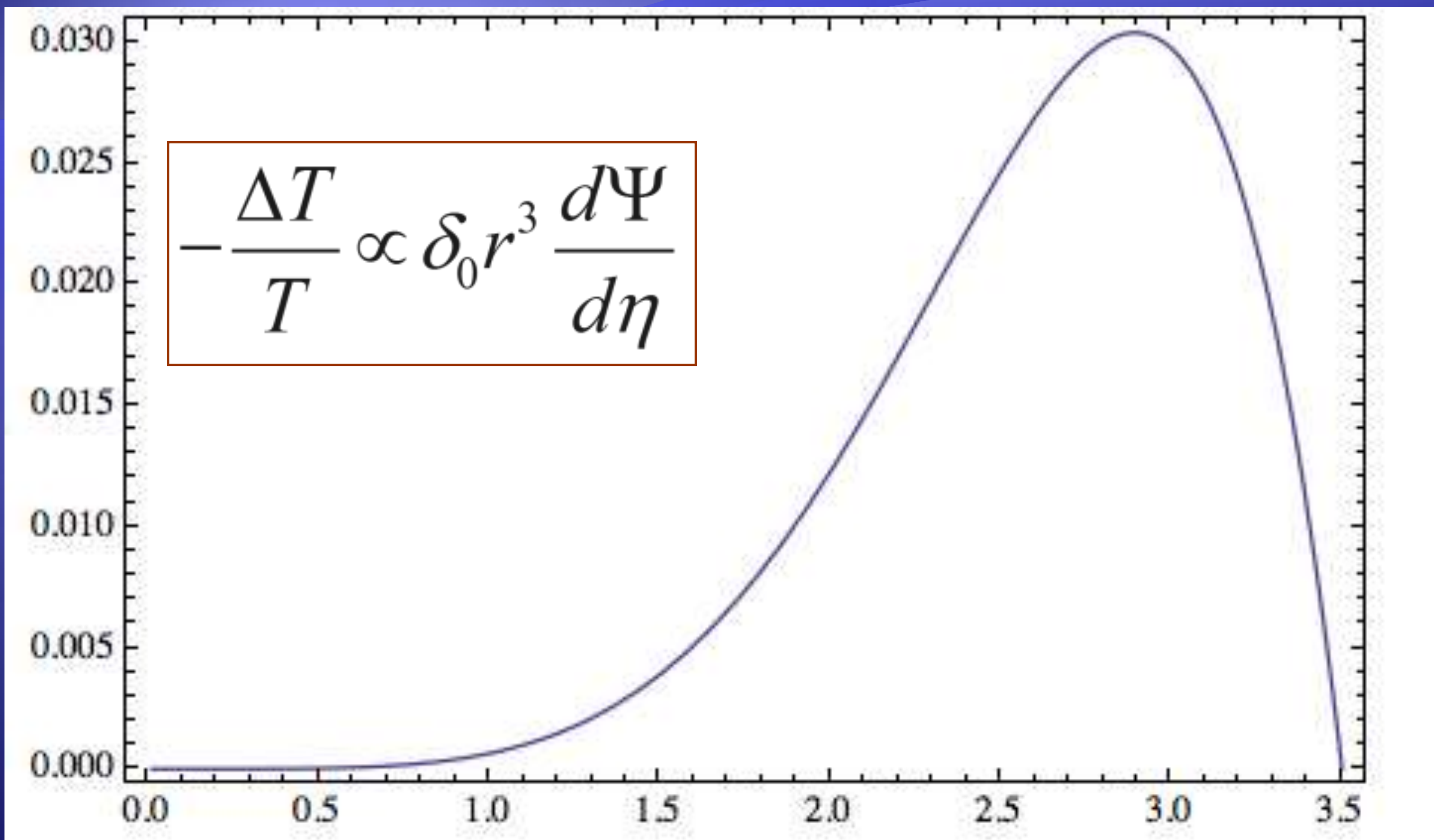
Why peak at z~1?

$$M \propto \delta r^3, F \propto -\delta r$$

$$\Psi \propto -\delta r^2 + const.$$

$$\frac{\Delta T}{T} \propto -\frac{\partial \Psi}{\partial \eta} \Delta \eta \propto -\delta r^3 \frac{d\Psi_t}{d\eta}$$

Why peak at z~1?



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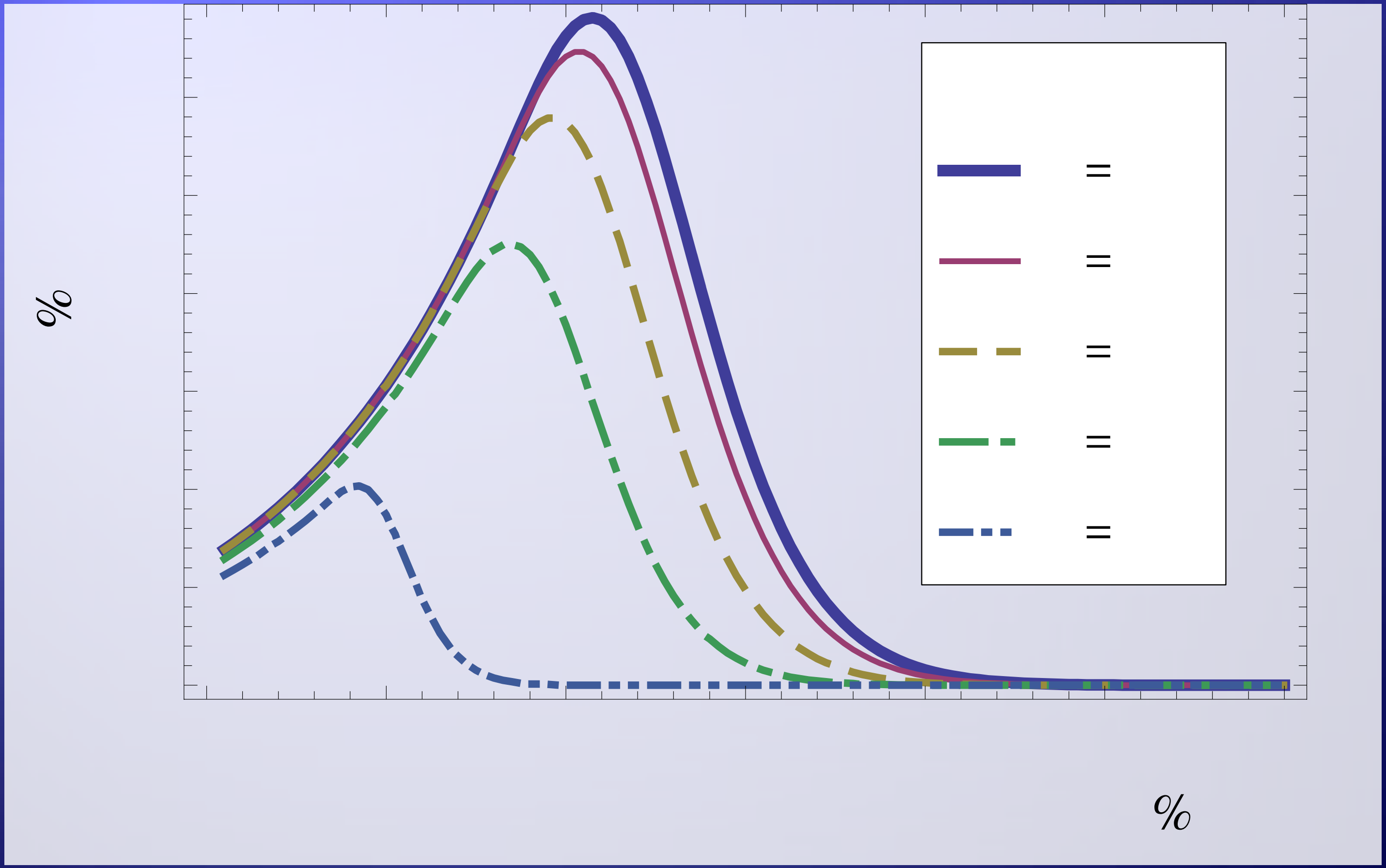
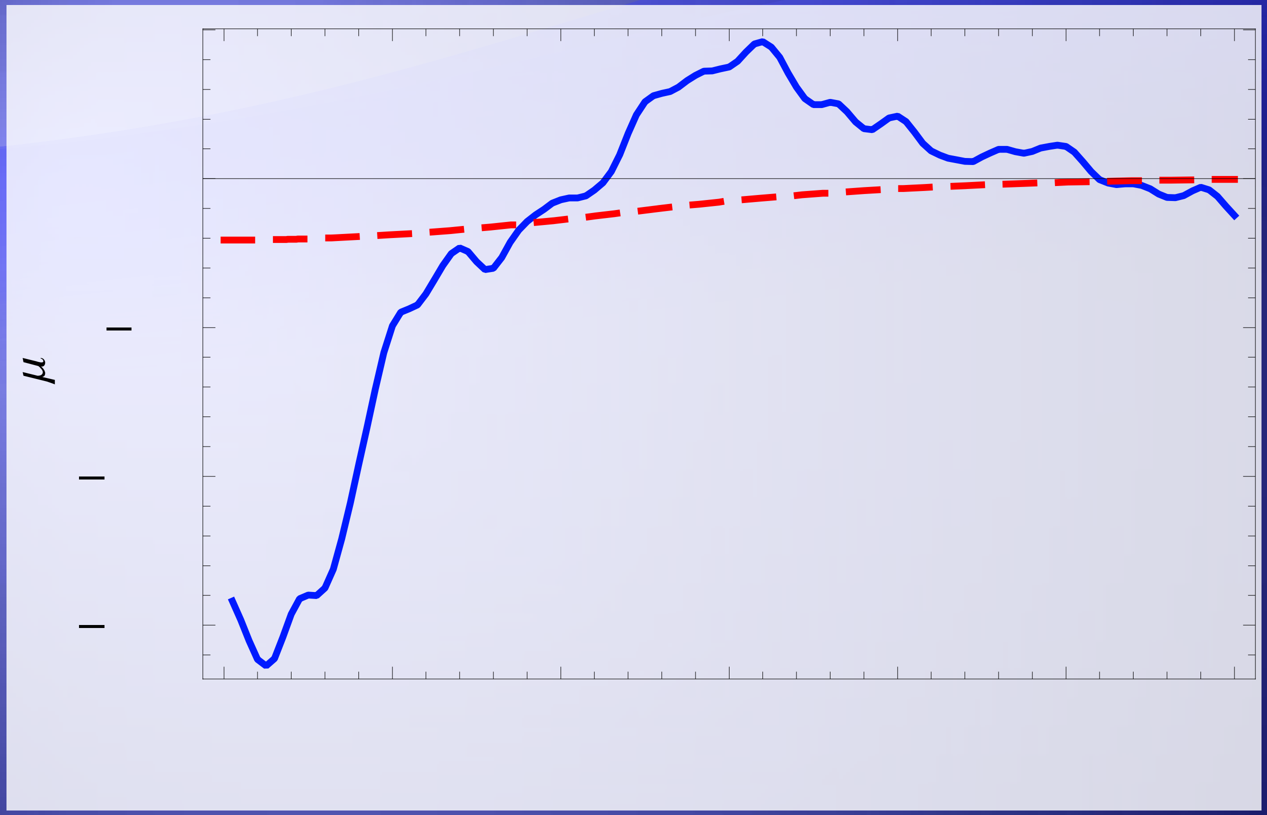
Significance of ISW contribution

$$P_{all} = P_{LSS} P_{ISW} b$$



ISW effect vs LSS effect



z	δ_0^L	θ_0	θ_1	r_0	$\Delta T_f\,(\text{void})$	$P_{\text{all}}(\%)$
1.0	-0.0085	14°	30°	$570h^{-1}\text{Mpc}$	$7.7\mu\text{K}$	0.68

Why 12 % ISW contribution?

$$P = P_{LSS} P_{ISW} b$$

$$\Delta T = \Delta T_{LSS} + \Delta T_{ISW}$$

$$P_{\max} \sim P_{LSS}(\Delta T / 2) P_{ISW}(\Delta T / 2) b$$

$$LSS : 20\,\mu\mathrm{K} \times 3 = 60\,\mu\mathrm{K}$$

$$void : 3\,\mu\mathrm{K} \times 3 = 9\,\mu\mathrm{K}$$

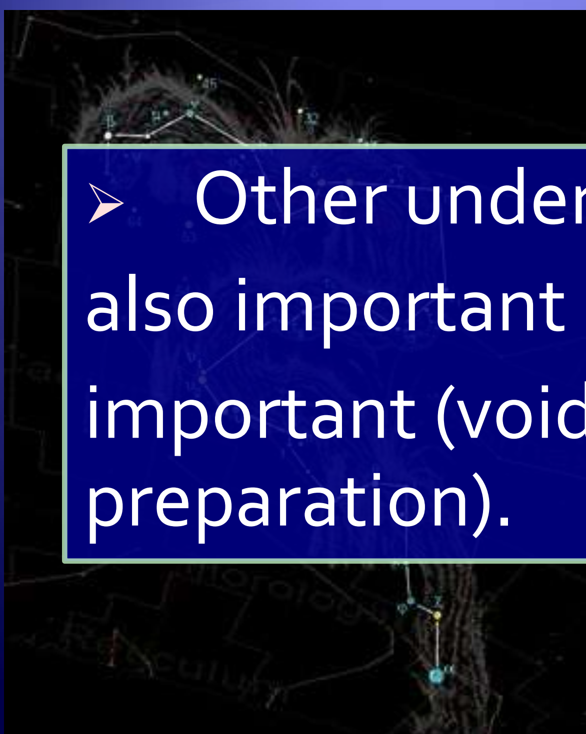
Summary

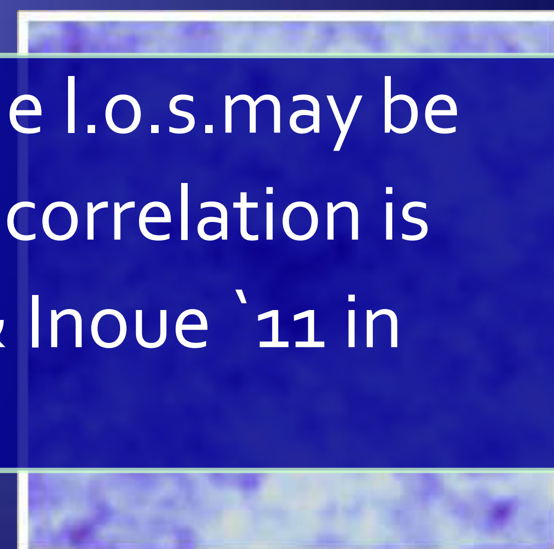
- Even in an accelerated epoch, a hot ring surrounding a cold spot can be produced if a void is locally over-compensated but it is less probable.

- Assuming that a single moderately undercompensated low density region in the direction to the CS at z<1.5, the expected contribution to the CMB is about 10 % and the radius is about 600 h^{-1} Mpc and $\delta \sim -0.009$ at z~1. The probability of chance alignment is 0.7%. 100% LSS is 7 times less probable.

Caveat

- Deviation from perfect spherical symmetry may be important as the assumed underdense region is in linear regime.





- Other underdense regions in the l.o.s.may be also important especially if spatial correlation is important (void-in-void) (Tomita & Inoue `11 in preparation).

Future prospects

- If a low density region at z~1 does not exist, we need to consider more anomalous fluctuations at z<1 or z>1.

- Photo-z or spectroscopic survey aiming at z<1.5 with a wide-range field (>100 degree^2) to the CS is important.

- About 10 % decrease in TE correlation in the l.o.s to the CS is expected (observable by Planck?)