An Inhomogeneous World View

Modern Cosmology – Benasque August 2010

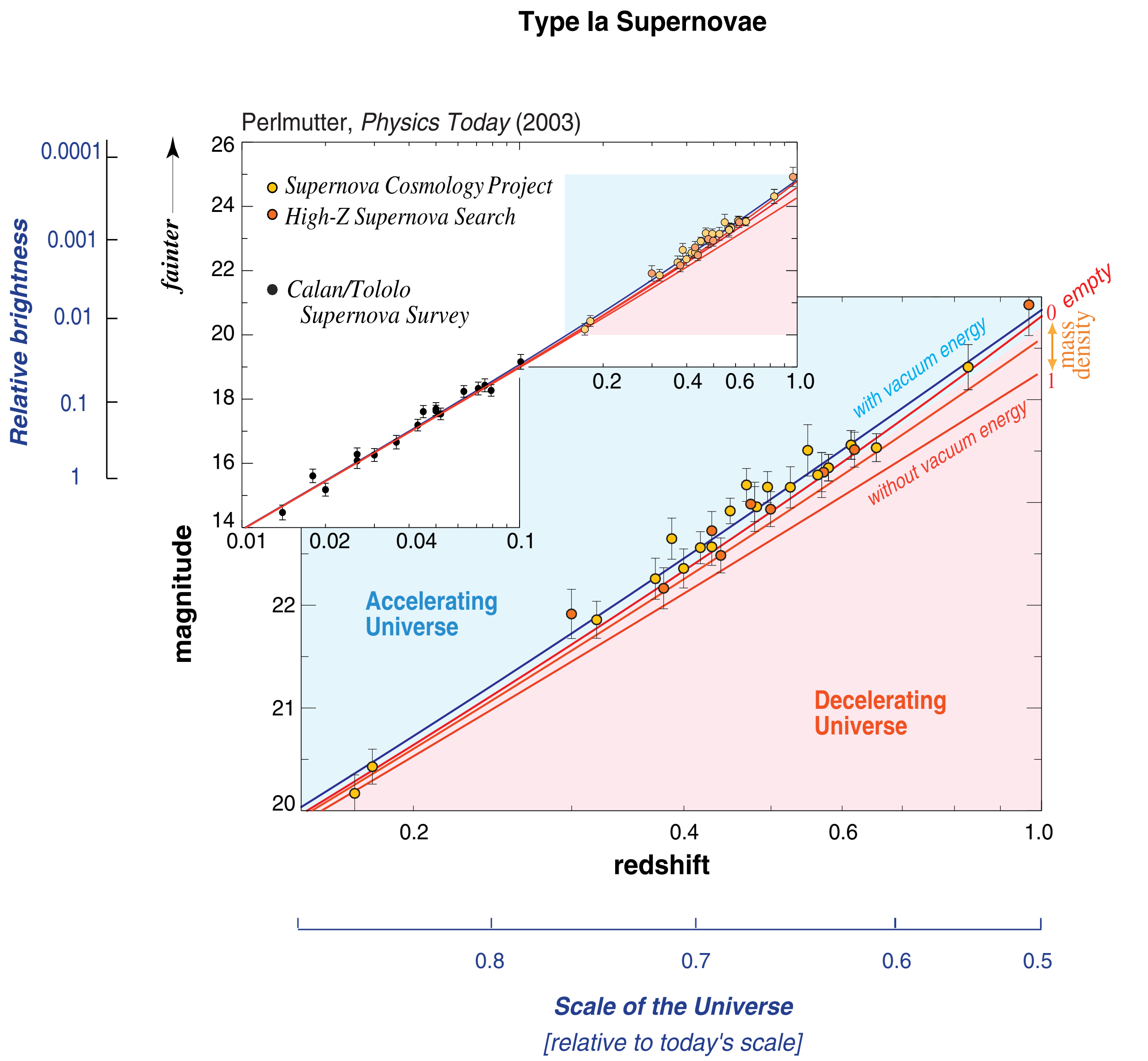
Troels Haugbølle

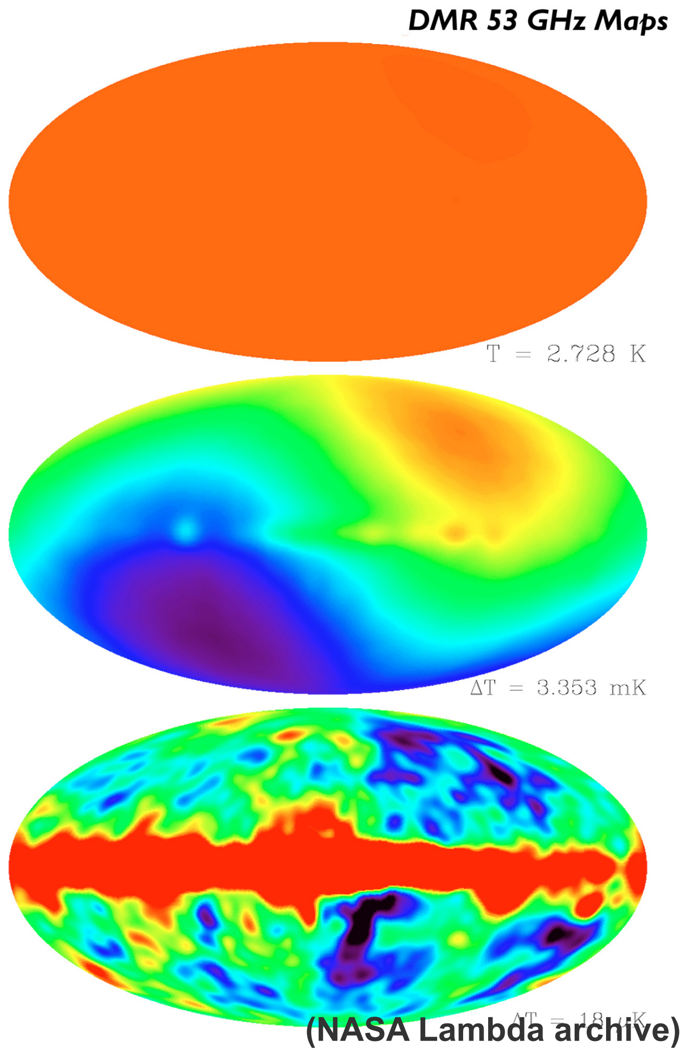
haugboel@nbi.dk

Niels Bohr Institute, University of Copenhagen

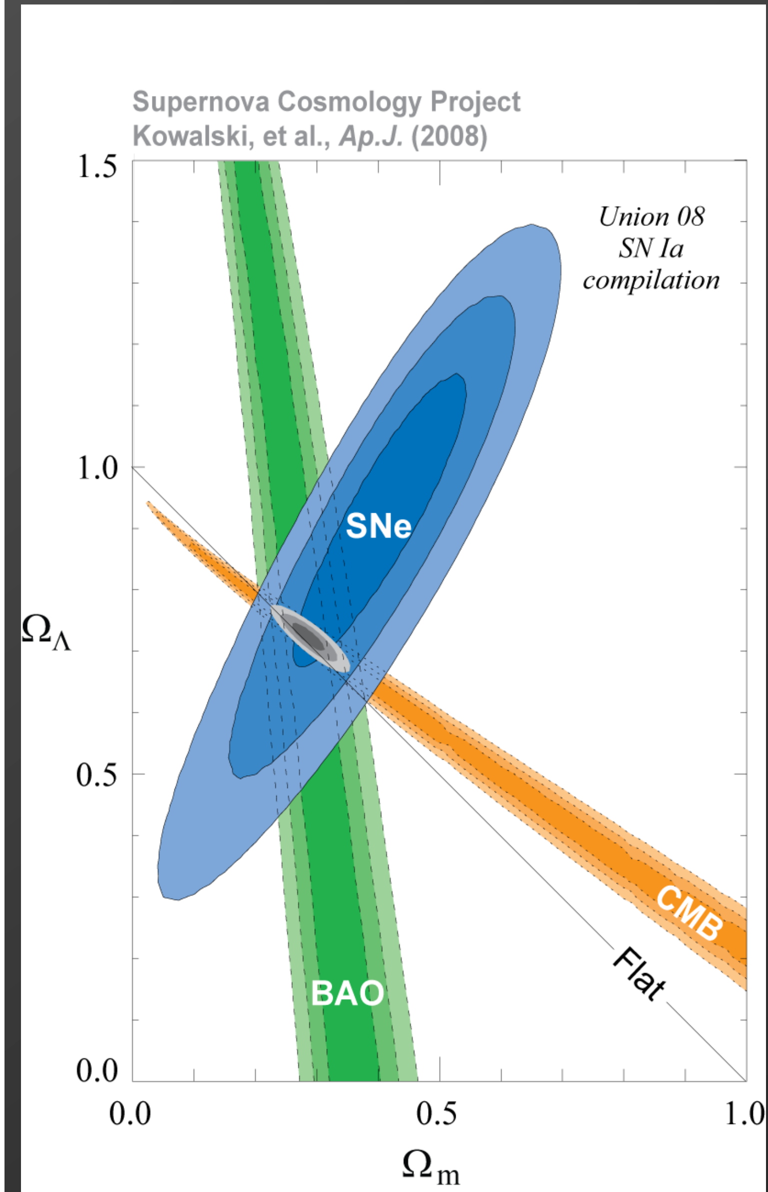
Collaborators:
David Alonso
Tamara Davis
Juan Garcia-Bellido
Benjamin Sinclair
Julian Vicente

We live in an Accelerating & Isotropic Universe





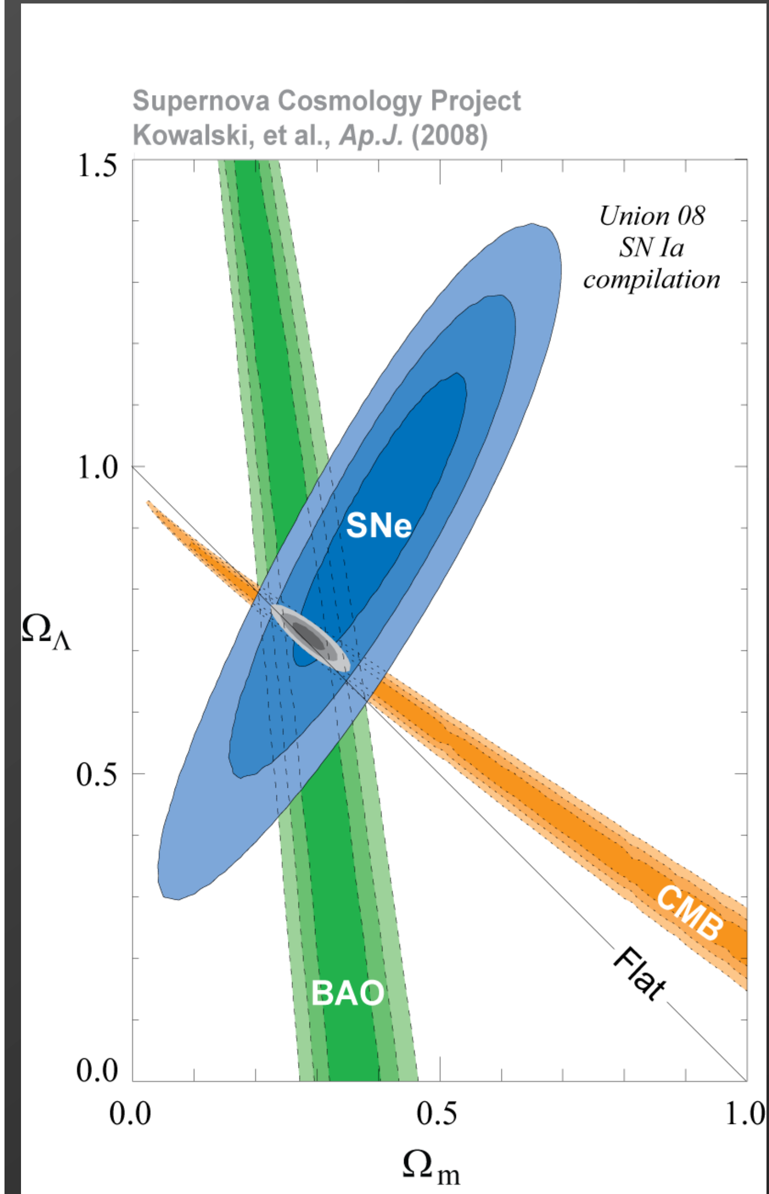
The Standard ΛCDM model



t_0 = 13.73 ± 0.12 Gyr	Age of Universe
H_0 = 70.1 ± 1.3 km s^{-1} Mpc^{-1}	Expansion rate
Ω_b = 0.0462 ± 0.0015	Baryon density
Ω_c = 0.233 ± 0.013	Dark Matter density
Ω_Λ = 0.721 ± 0.015	Dark energy density
n_s = 0.960 ± 0.014	Scalar spectral index
Δ_R^2 = 2.46 ± 0.09 10^{-9}	Fluctuation amplitude

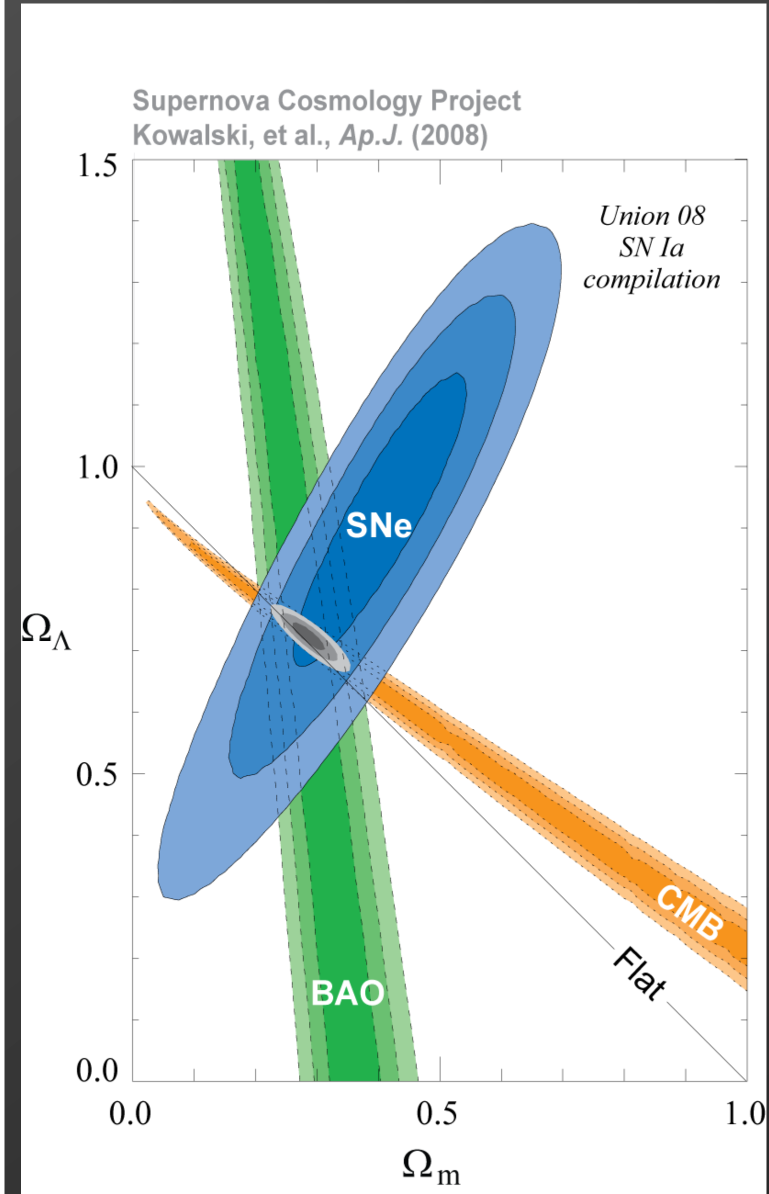
The numbers
are impressive,
but can we trust
the model ???

The Pillars of the ΛCDM model



- General Relativity
- The FRW model of a homogeneous universe
- Dark Matter & fields with strange equations of state

The Pillars of the ΛCDM model

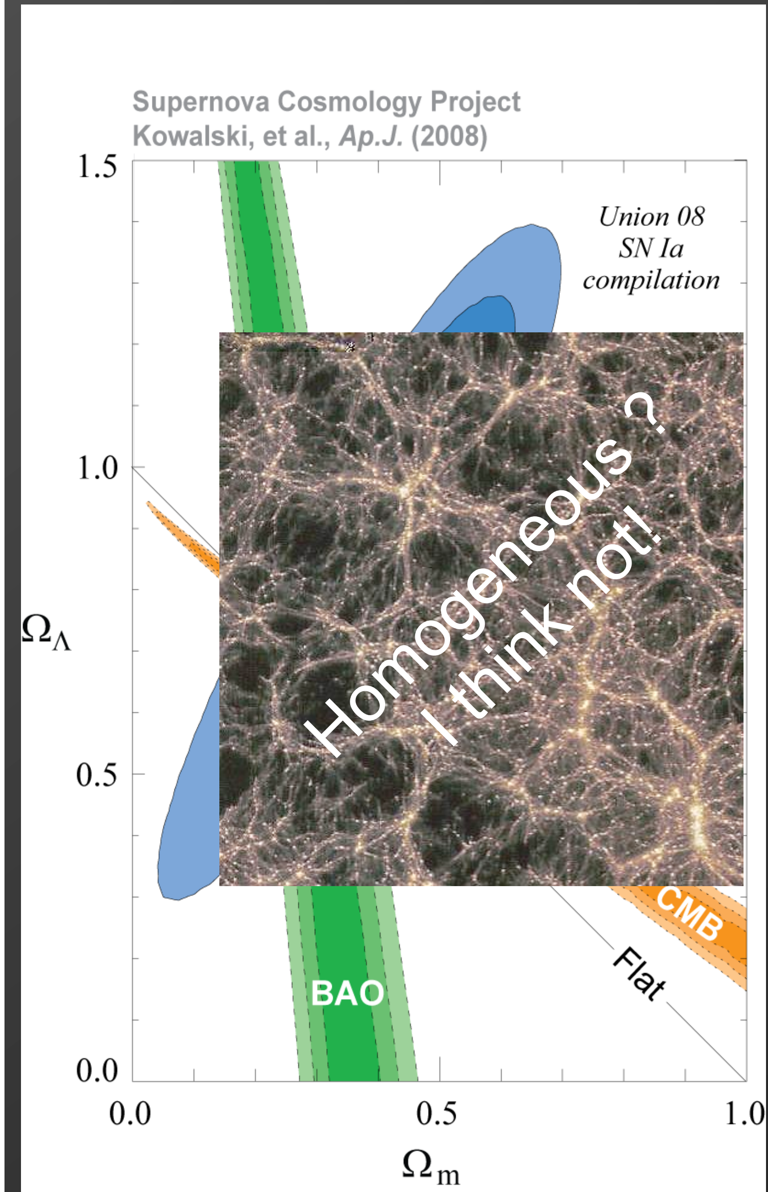


Modify Gravity

- ~~General Relativity~~
- The FRW model of a homogeneous universe
- Dark Matter ~~& fields with strange equations of state~~

Alternative Scenario

The Pillars of the ΛCDM model



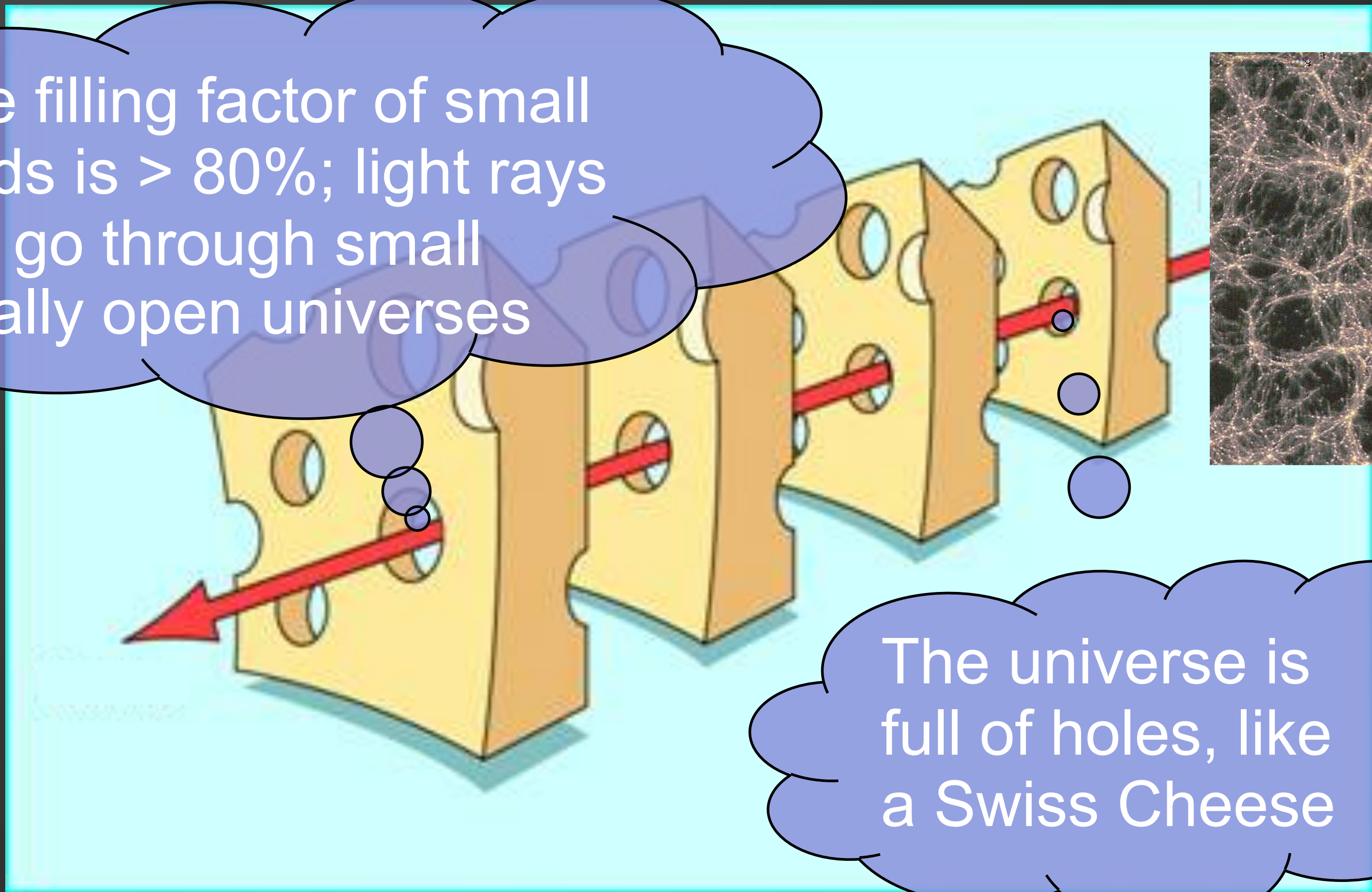
- General Relativity

Modify the Geometry

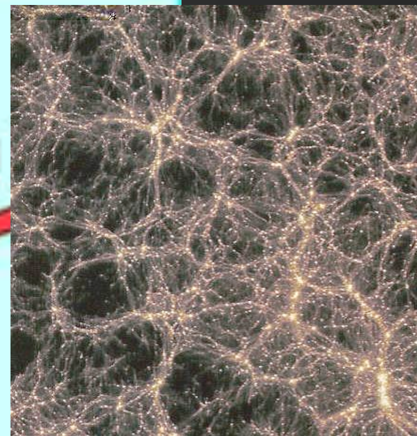
- The FRW model of a homogeneous universe

- Dark Matter & fields with strange equations of state

Alternative scenario I
Its Swiss Cheese



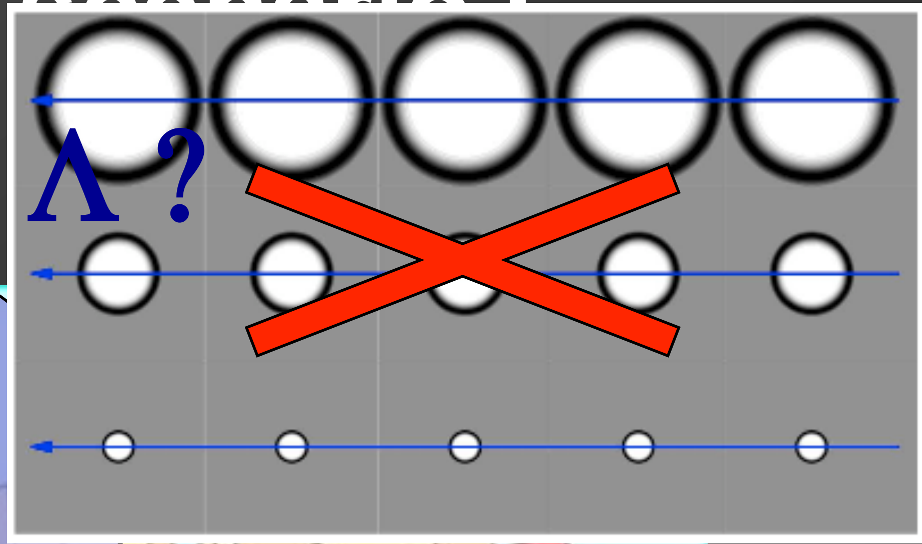
The filling factor of small voids is > 80%; light rays will go through small locally open universes



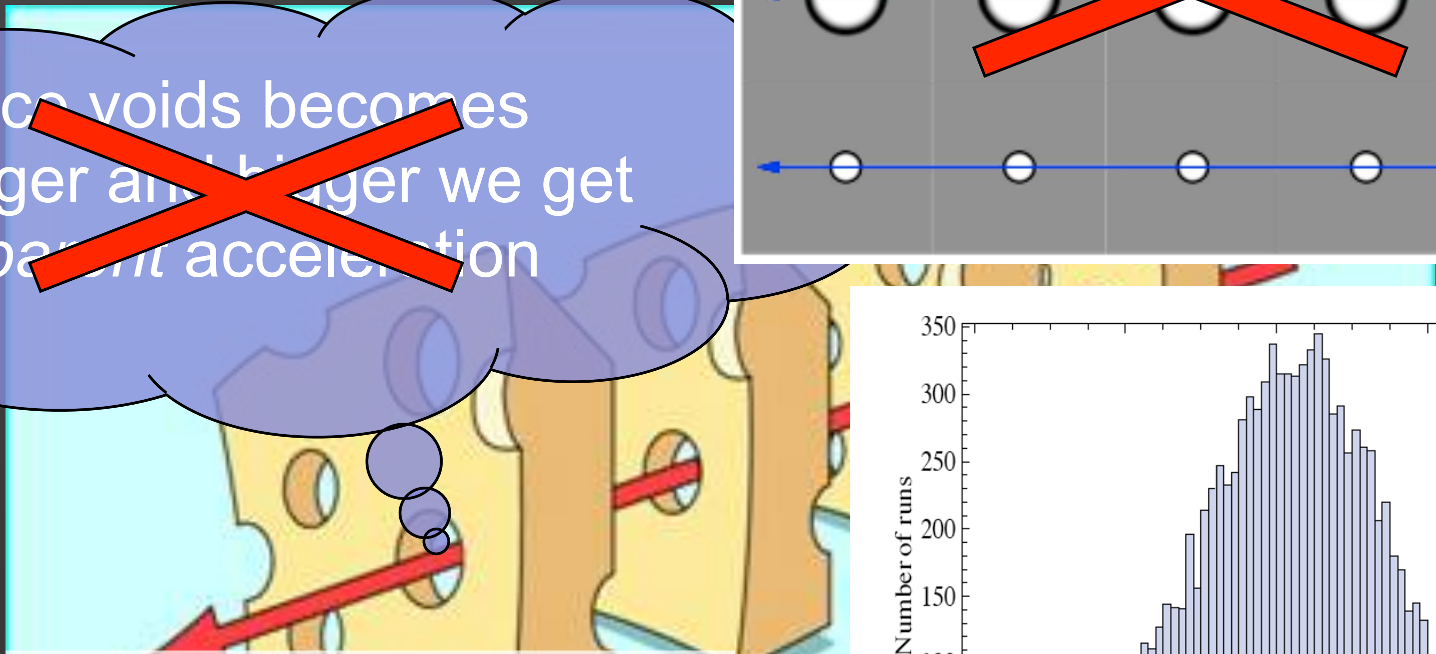
The universe is full of holes, like a Swiss Cheese

Alternative scenario I

Its Swiss



Since voids becomes bigger and bigger we get *apparent* acceleration



But randomising the positions of the voids removes the effect.

Swiss Cheese Stinks!

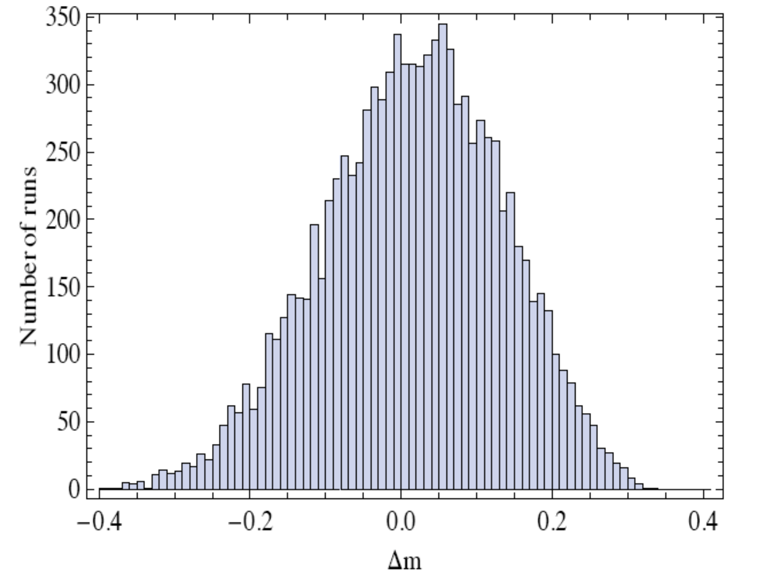
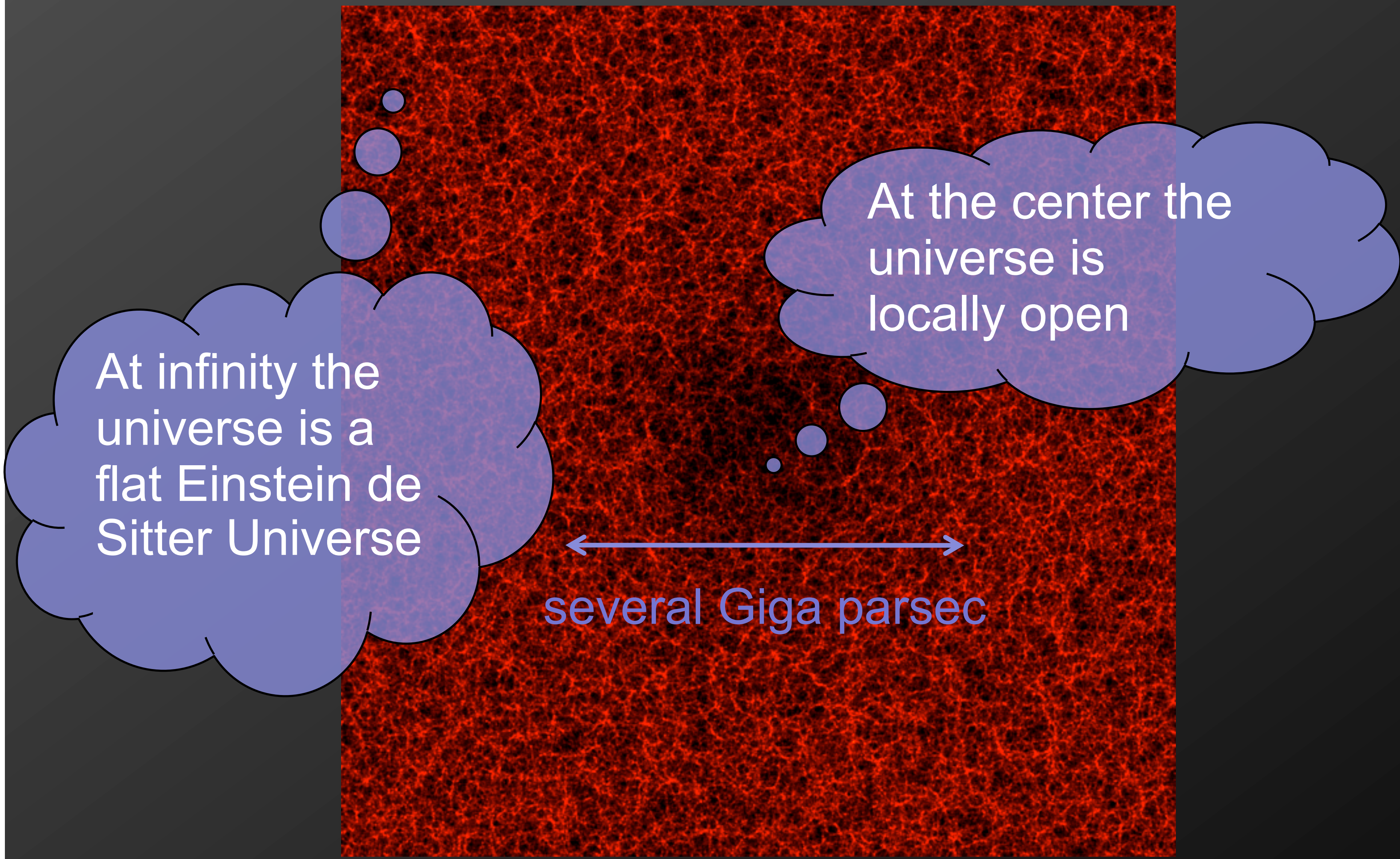


FIG. 2: A histogram of the distance modulus shifts Δm found for 10, 000 realizations of our randomized void scenario

Vanderveld et al 2008

Alternative scenario II
We are living inside a giant void



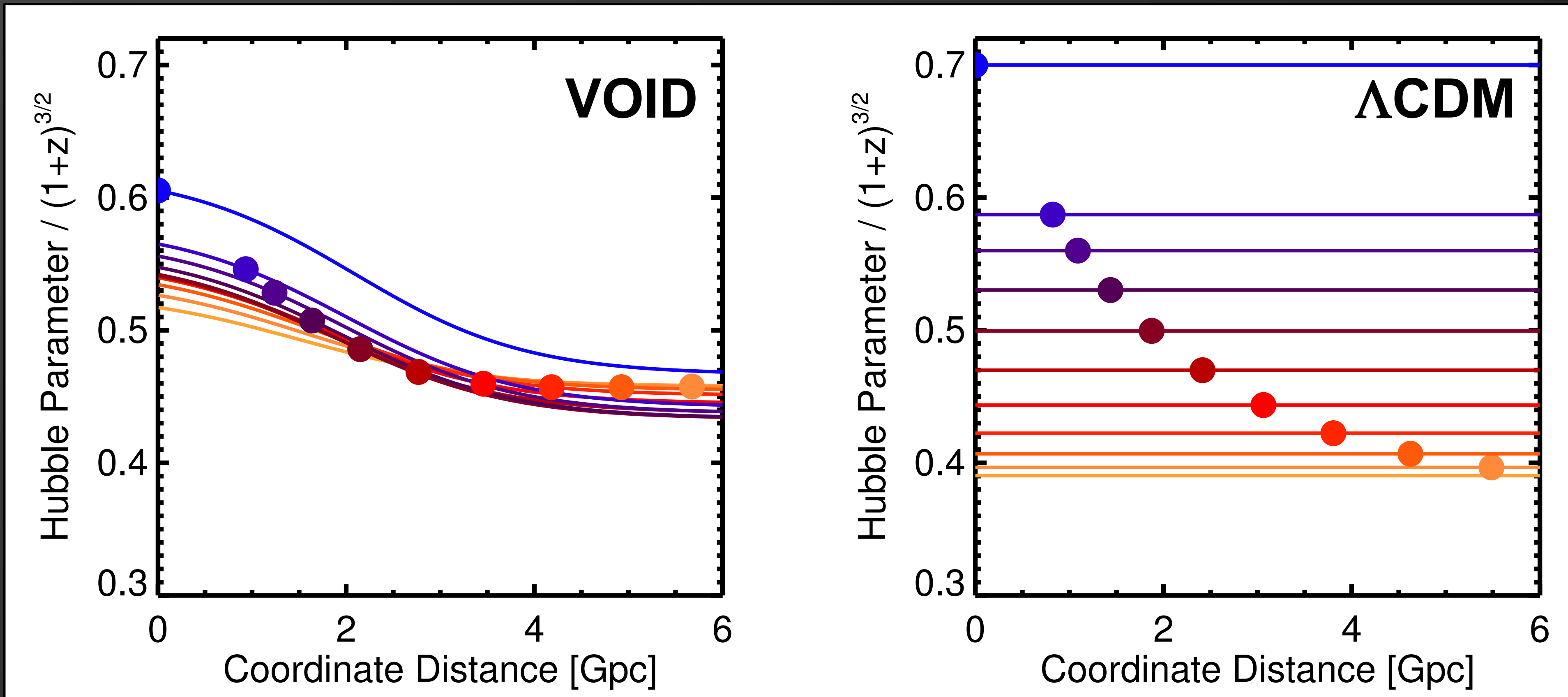
How does a Central Void Help Explain Dark Energy?

- We observe in the redshift cone: Acceleration can be due to both spatial and temporal changes in the expansion rate. Maybe the Universe is tricking us?

$$\frac{D}{Dt} \simeq \frac{\partial}{\partial t} - c\frac{\partial}{\partial r}$$

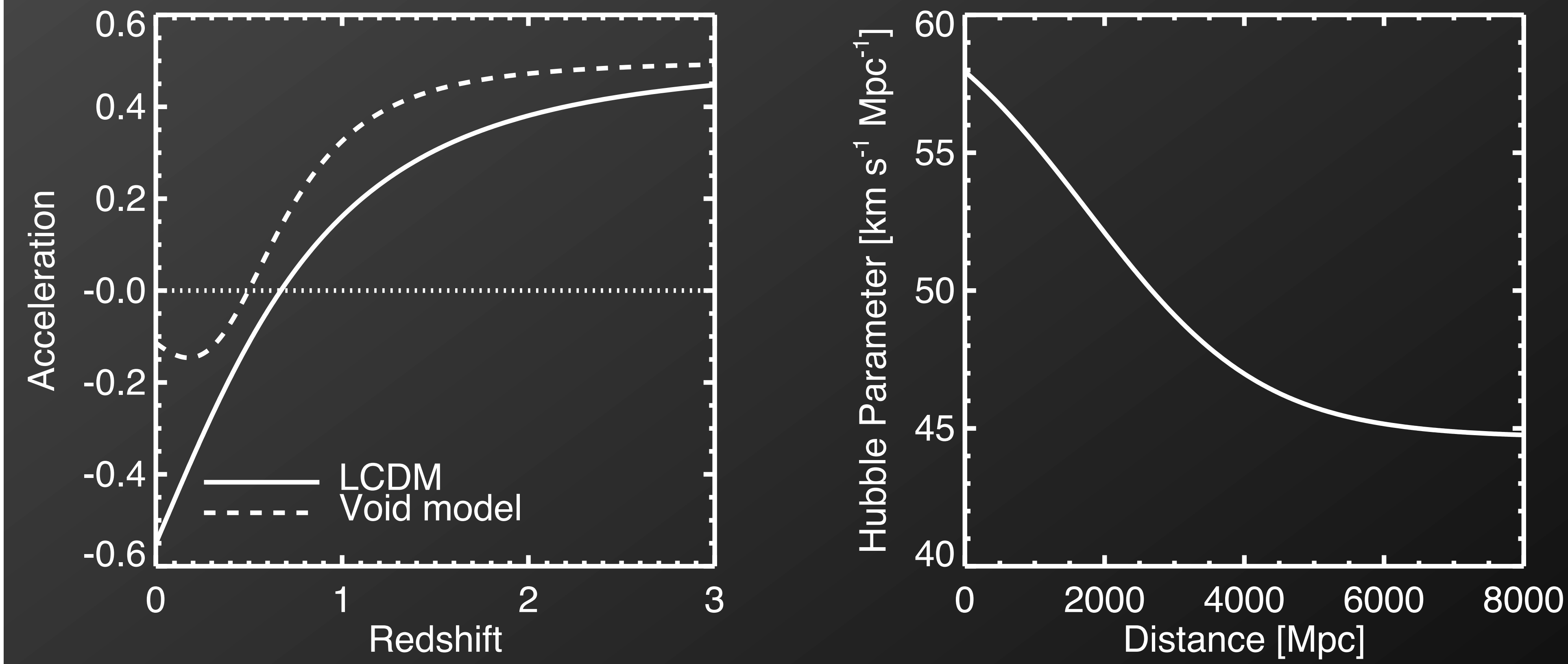
How does a Central Void Help Explain Dark Energy?

- We observe in the redshift cone: Acceleration can be due to both spatial and temporal changes in the expansion rate. Maybe the Universe is tricking us?



How does a Central Void Help Explain Dark Energy?

- We observe in the redshift cone: Acceleration can be due to both spatial and temporal changes in the expansion rate. Maybe the Universe is tricking us?



Void Construction 101
The Lemaître-Tolman-Bondi Model

- Describes a space-time, which has spherical symmetry in the spatial dimensions, but with time and radial dependence

$$ds^2 = -dt^2 + X^2(r,t)\,dr^2 + A^2(r,t)\,d\Omega^2$$

- Defining an effective matter density and the Hubble rate as

$$H(r,t) = \frac{\dot{A}(r,t)}{A(r,t)}\,,$$

$$F(r) = H_0^2(r)\,\Omega_M(r)\,A_0^3(r)\,,$$

$$k(r) = H_0^2(r)\Big(\Omega_M(r) - 1\Big)\,A_0^2(r)\,,$$

Void Construction 101
The Lemaître-Tolman-Bondi Model

- Describes a space-time, which has spherical symmetry in the spatial dimensions, but with time and radial dependence

$$ds^2 = -dt^2 + X^2(r,t)\,dr^2 + A^2(r,t)\,d\Omega^2$$

- A “local analogy” to the Friedman equation can be derived

$$H^2(r,t) = H_0^2(r)\left[\Omega_M(r)\left(\frac{A_0(r)}{A(r,t)}\right)^3 + (1-\Omega_M(r))\left(\frac{A_0(r)}{A(r,t)}\right)^2\right]$$

Void Construction 101
The Lemaître-Tolman-Bondi Model

- Describes a space-time, which has spherical symmetry in the spatial dimensions, but with time and radial dependence

$$ds^2 = -dt^2 + X^2(r,t)\,dr^2 + A^2(r,t)\,d\Omega^2$$

- A "local analogy" to the Friedman equation can be derived

$$H^2(r,t) = H_0^2(r)\left[\Omega_M(r)\left(\frac{A_0(r)}{A(r,t)}\right)^3 + (1-\Omega_M(r))\left(\frac{A_0(r)}{A(r,t)}\right)^2\right]$$

where $H_0(r)$, the expansion rate at t_0, and $\Omega_M(r)$, the total matter density inside r at t_0, uniquely describes our model.

Functional form fixed due to gauge choice

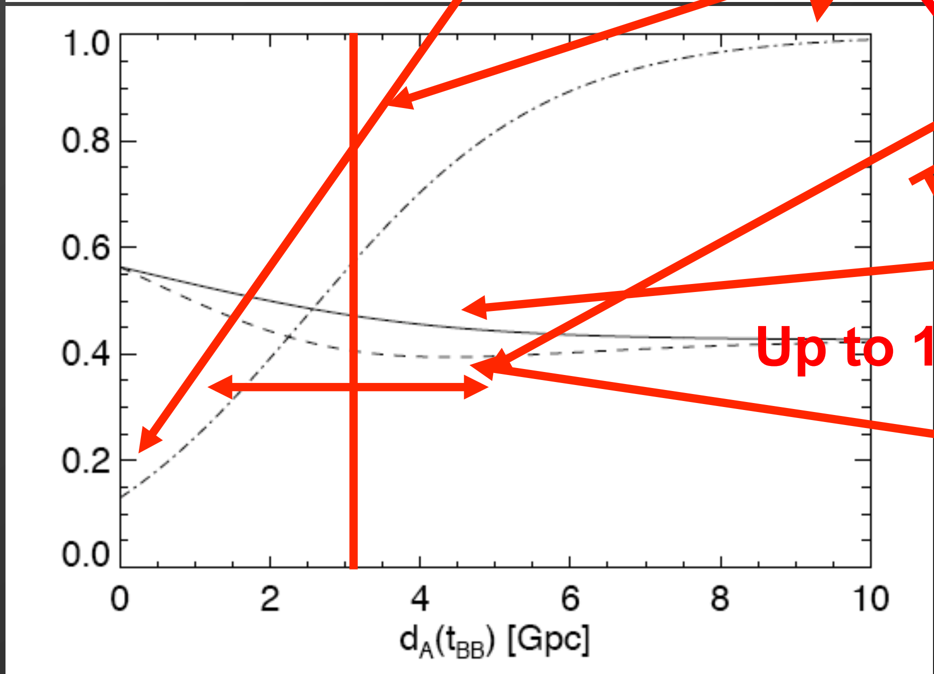
A simple model for the void

$$\Omega_M(r) = \Omega_{\rm out} + \left(\boxed{\Omega_{\rm in}} - \boxed{\Omega_{\rm out}}\right)\left(\frac{1-\tanh[(r-r_0)/2\Delta r]}{1+\tanh[\boxed{r0}/2\boxed{\Delta r}]}\right)$$

$$H_0(r) = H_0\left[\frac{1}{\Omega_K(r)} - \frac{\Omega_M(r)}{\sqrt{\Omega_K^3(r)}}\sinh^{-1}\sqrt{\frac{\Omega_K(r)}{\Omega_M(r)}}\right]$$

Void Size

Transition Width

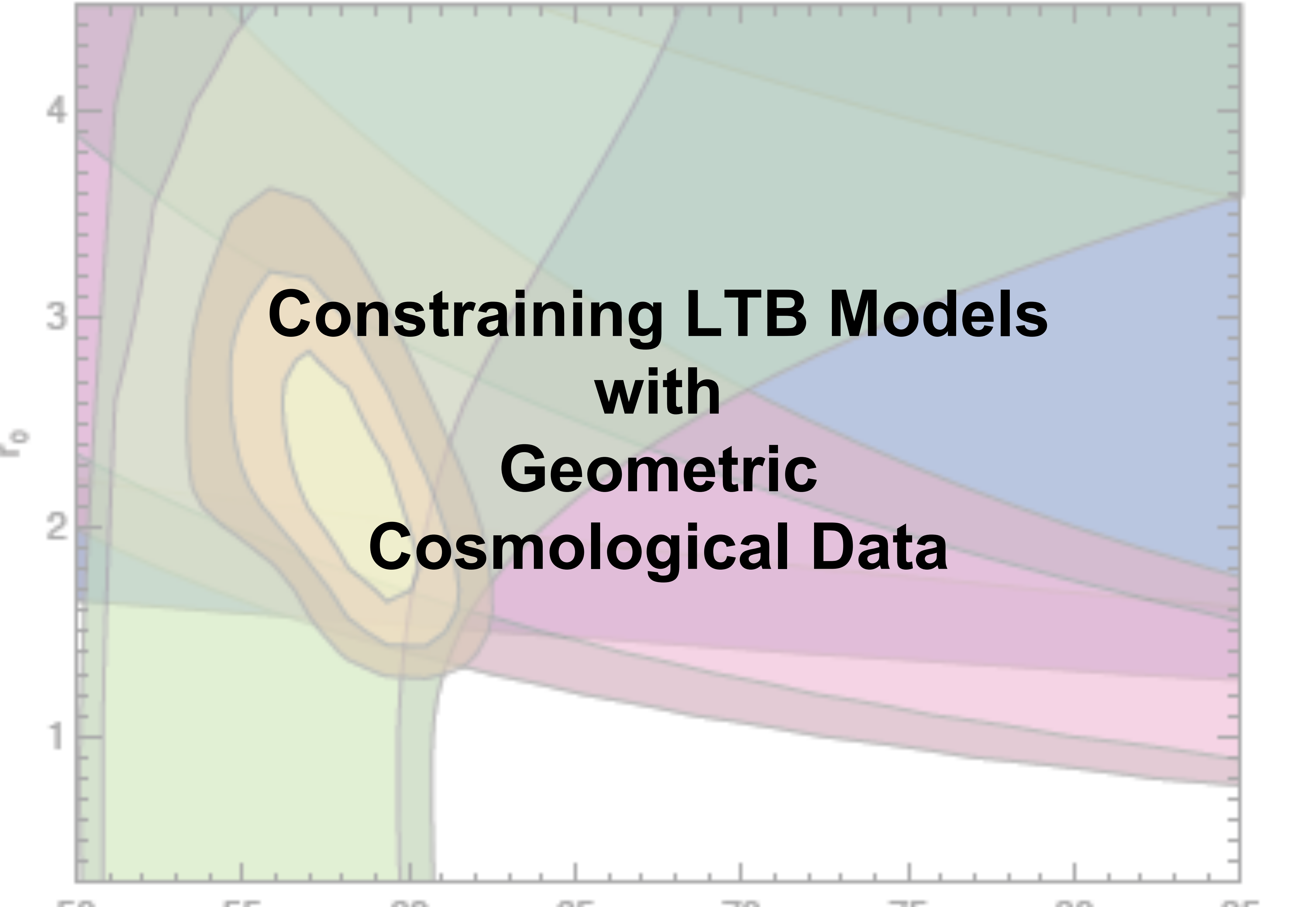


Up to 10 % difference!

$$H_T(r,t) \equiv \frac{\dot{A}(r,t)}{A(r,t)},$$

$$H_L(r,t) \equiv \frac{\dot{A}'(r,t)}{A'(r,t)}.$$

Constraining LTB Models with Geometric Cosmological Data



Constraining Cosmological Data

- **Type Ia Supernovae**: 307 SNe compiled by many different sources, and published as the UNION data set.
  - Simple to do since we just fit against $d_L(z)$

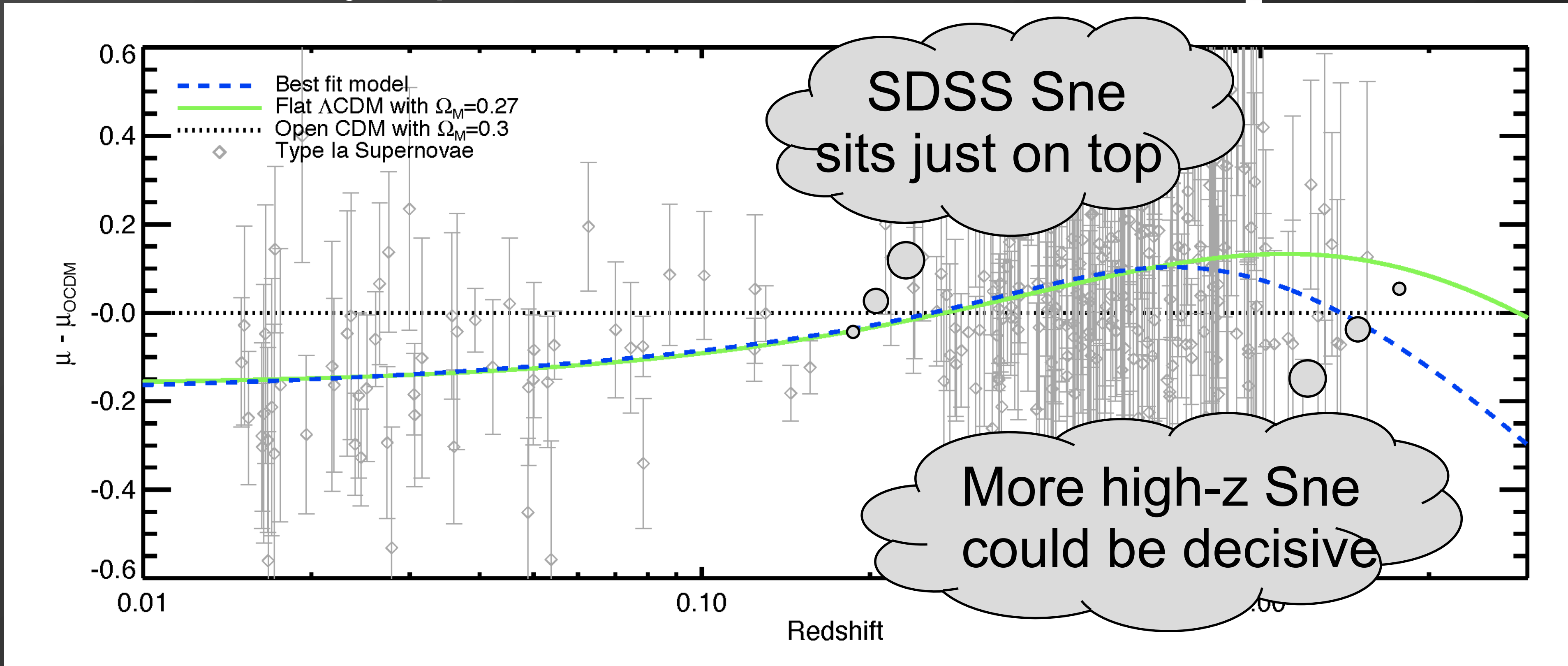
- **1^{st} acoustic peak in the CMB**: $d_C(z_{rec})$, sound horizon

- **Radial Baryon Acoustic Oscilations**:
  - Sound horizon, and the longitudinal Hubble rate H_L

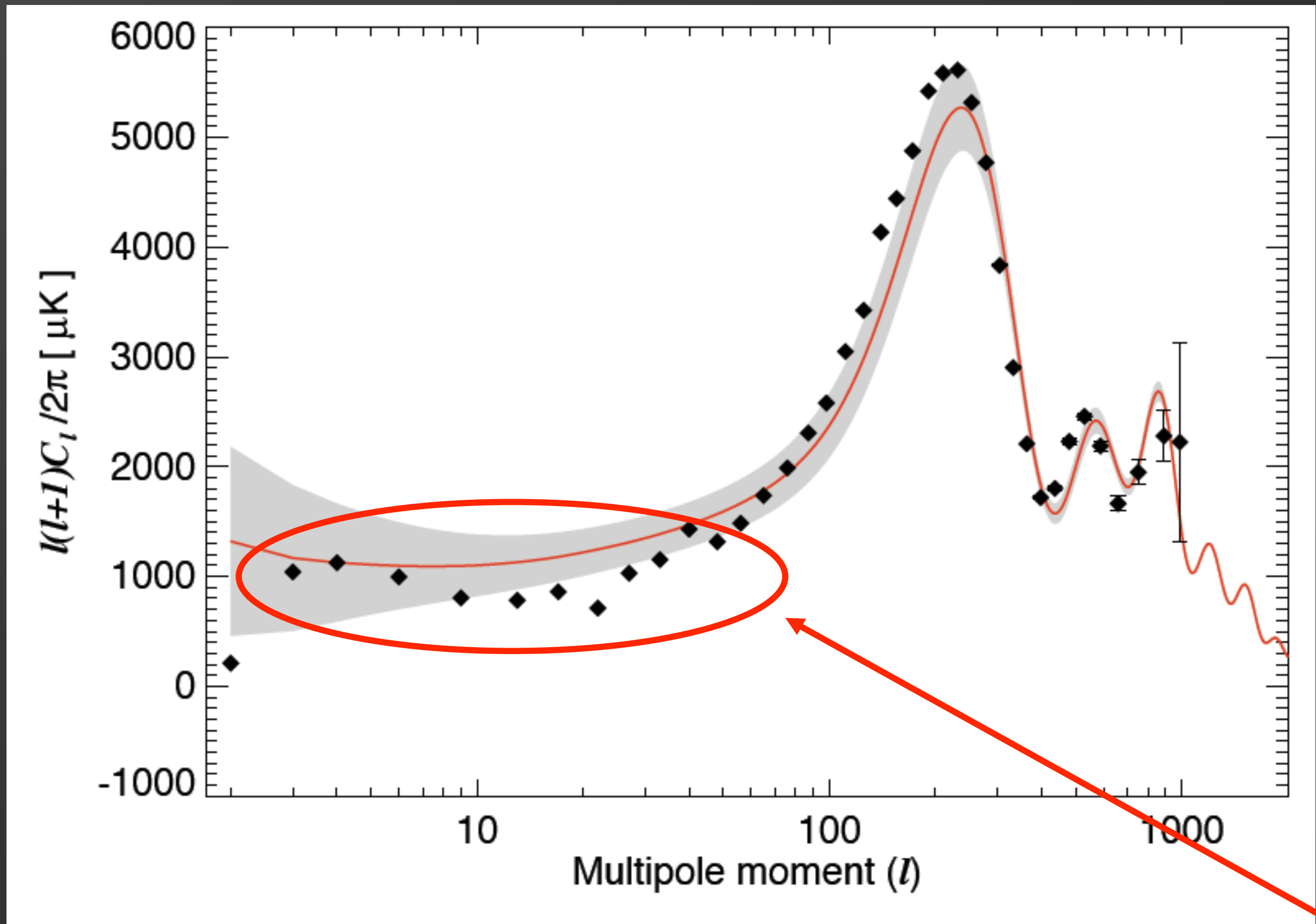
Fitting the Type Ia Supernovae

The best fit model has no problems with Type Ia Sne,

It basically reproduces the standard ΛCDM z-d_L relation.

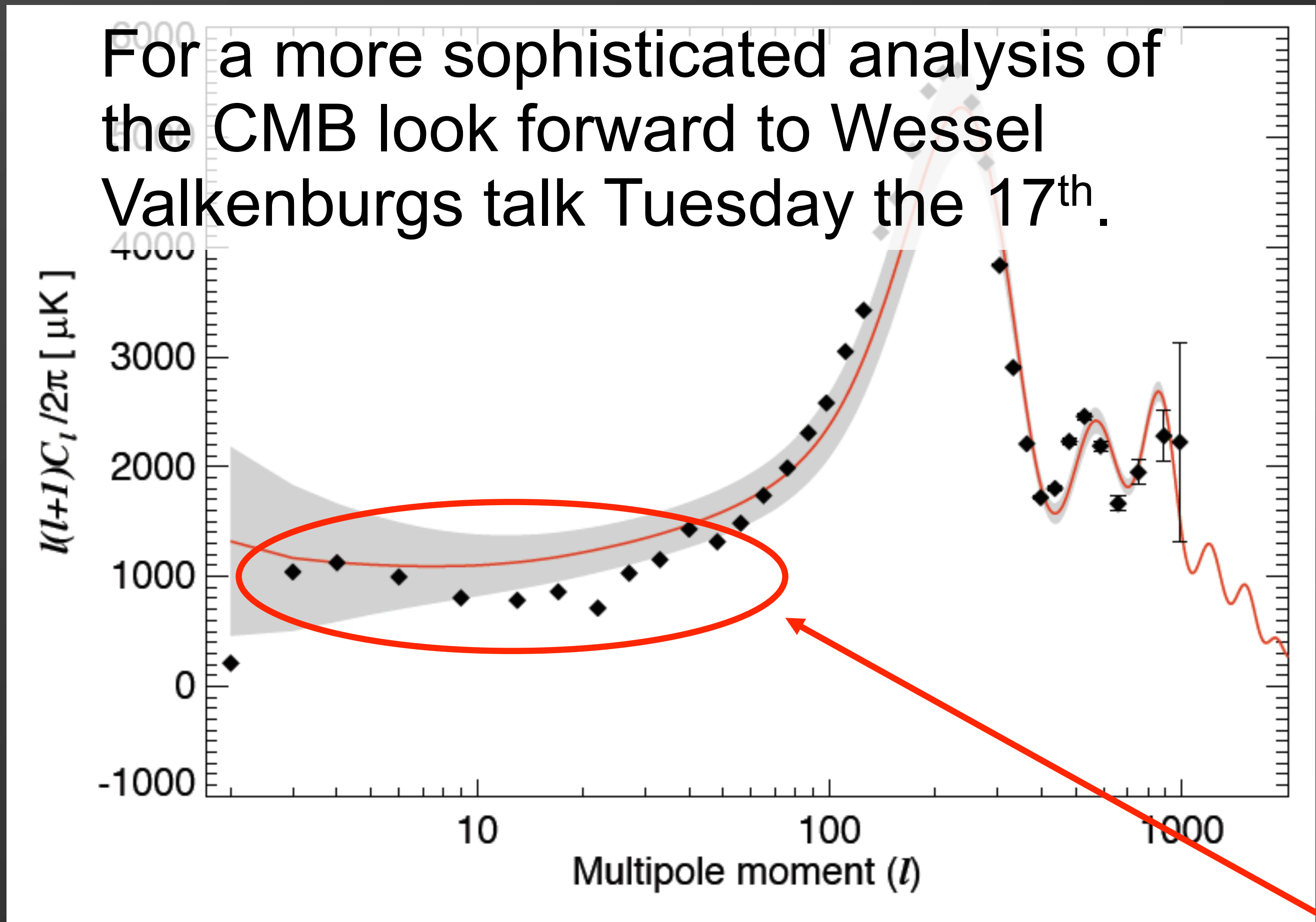


Fitting the 1st Peak in the CMB



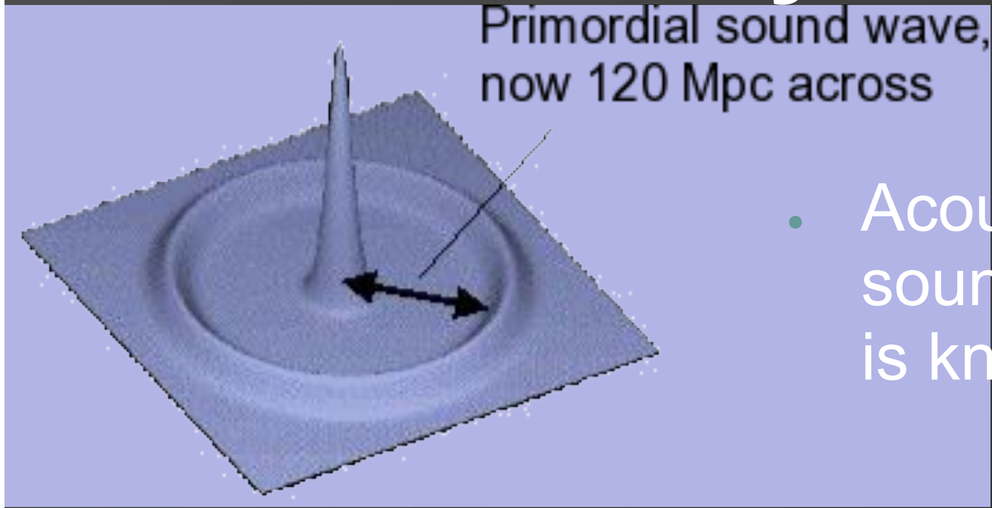
- The fit to the *first* peak is ok - we did not try to fit all data
- LTB perturbation theory is needed to explain low l (ISW)

Fitting the 1st Peak in the CMB

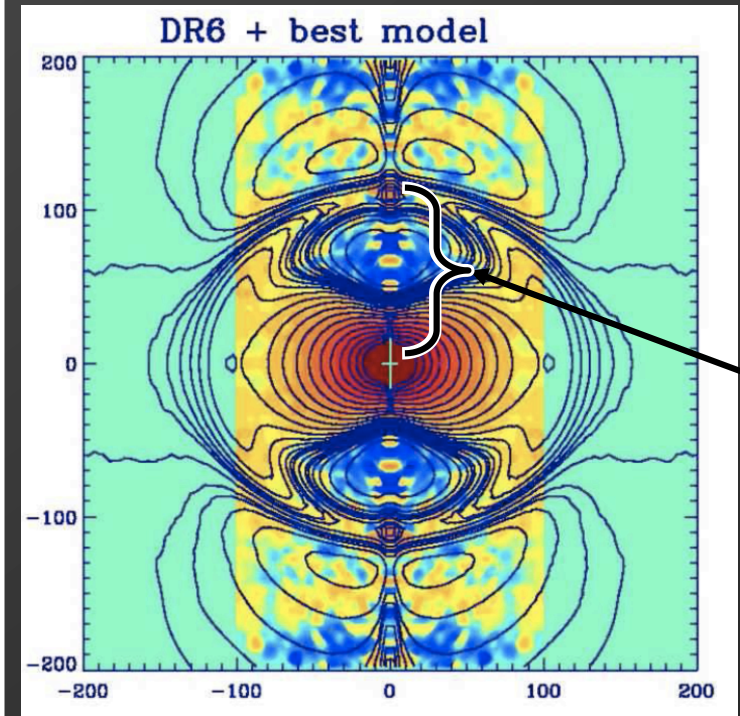


- The fit to the *first* peak is ok - we did not try to fit all data
- LTB perturbation theory is needed to explain low *l* (ISW)

Radial Baryon Acoustic Scale



- Acoustic oscillations are frozen sound waves and the physical size is known from early universe physics

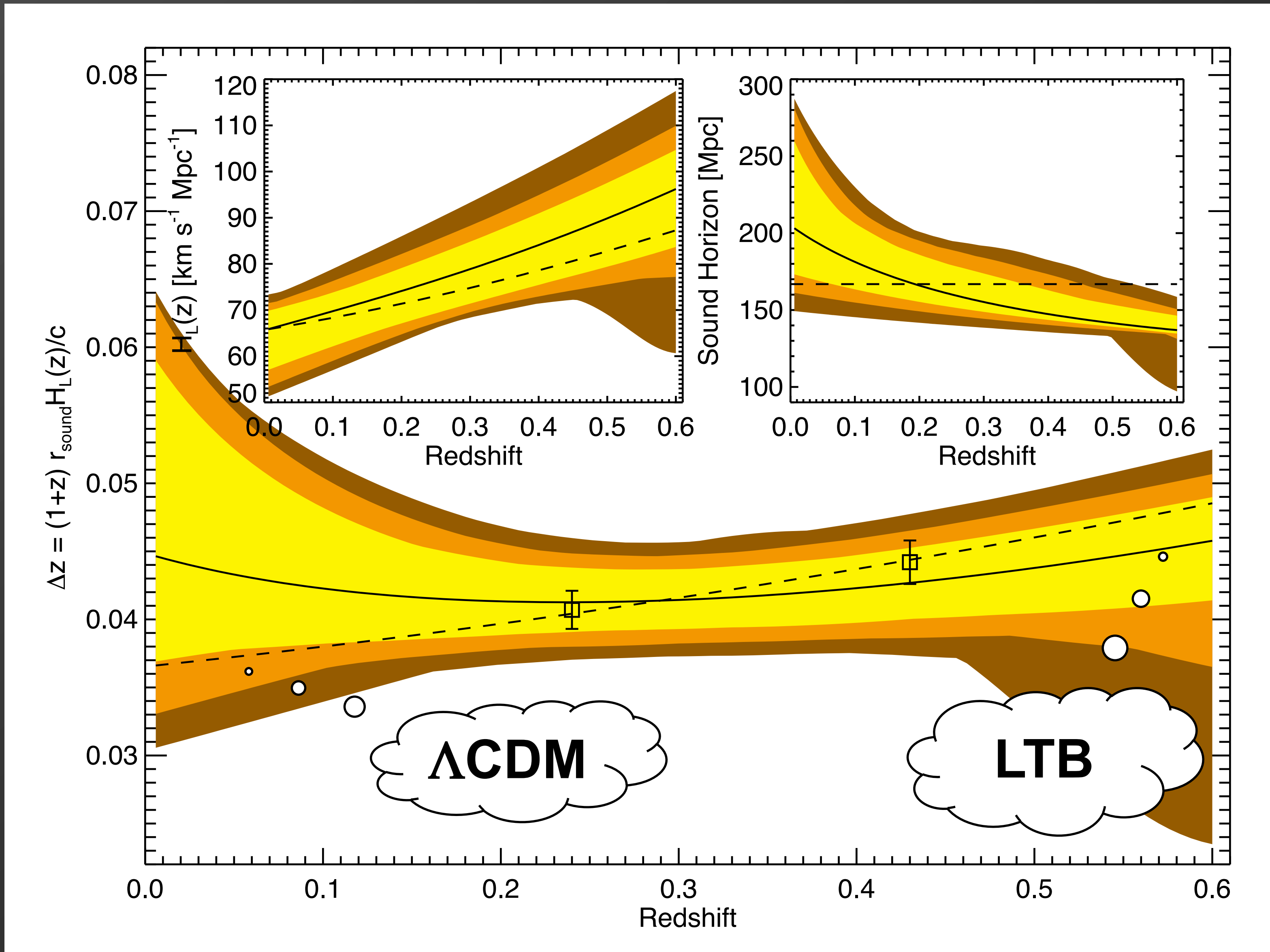


arXiv: 0807.3551 Gaztañaga et al

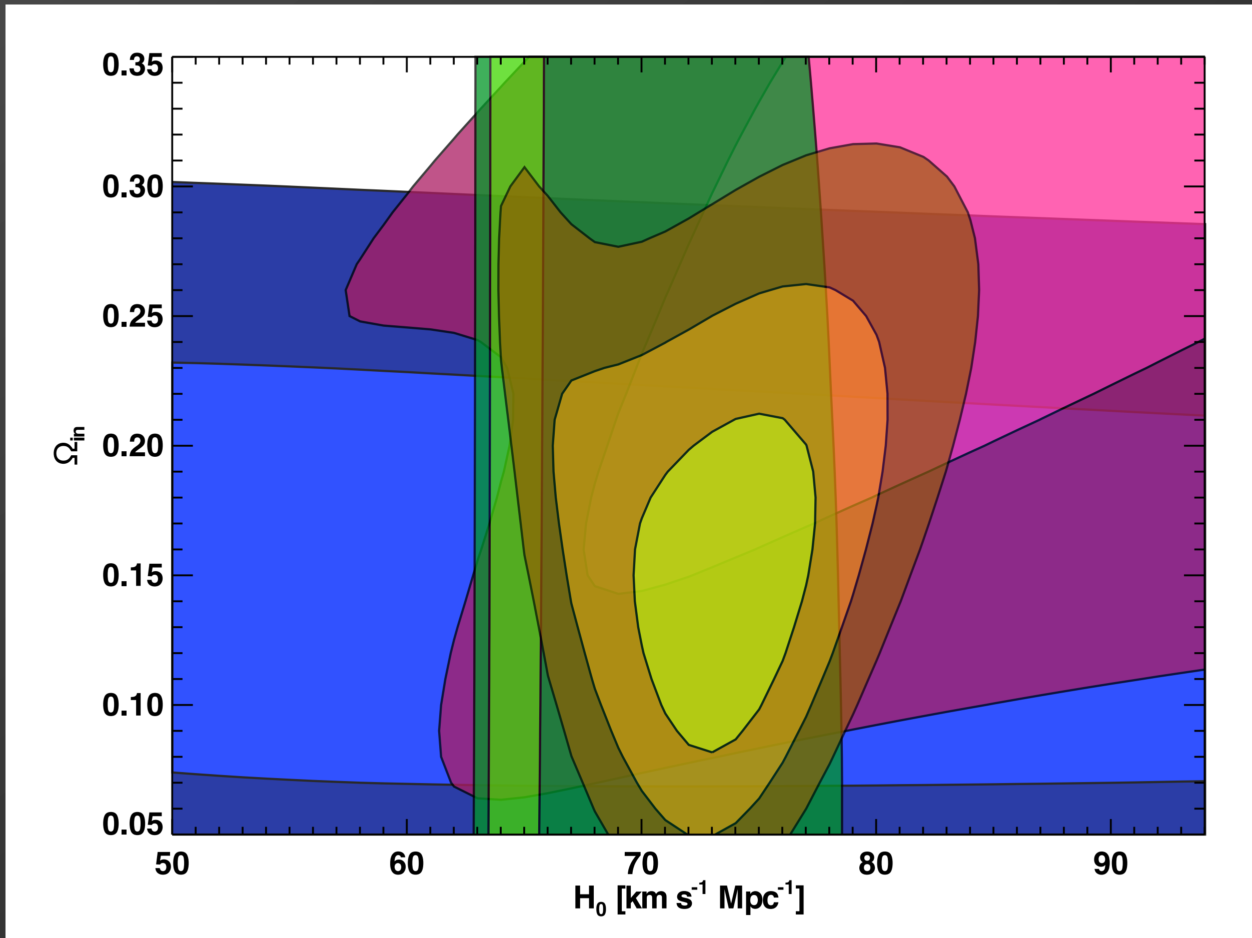
- Measuring the correlation function along the line of sight gives a clean measure of $H_L(z)$

$$\Delta z_{LTB} = \frac{H_L(z) r_s(z)}{c}$$

Radial Baryon Acoustic Scale

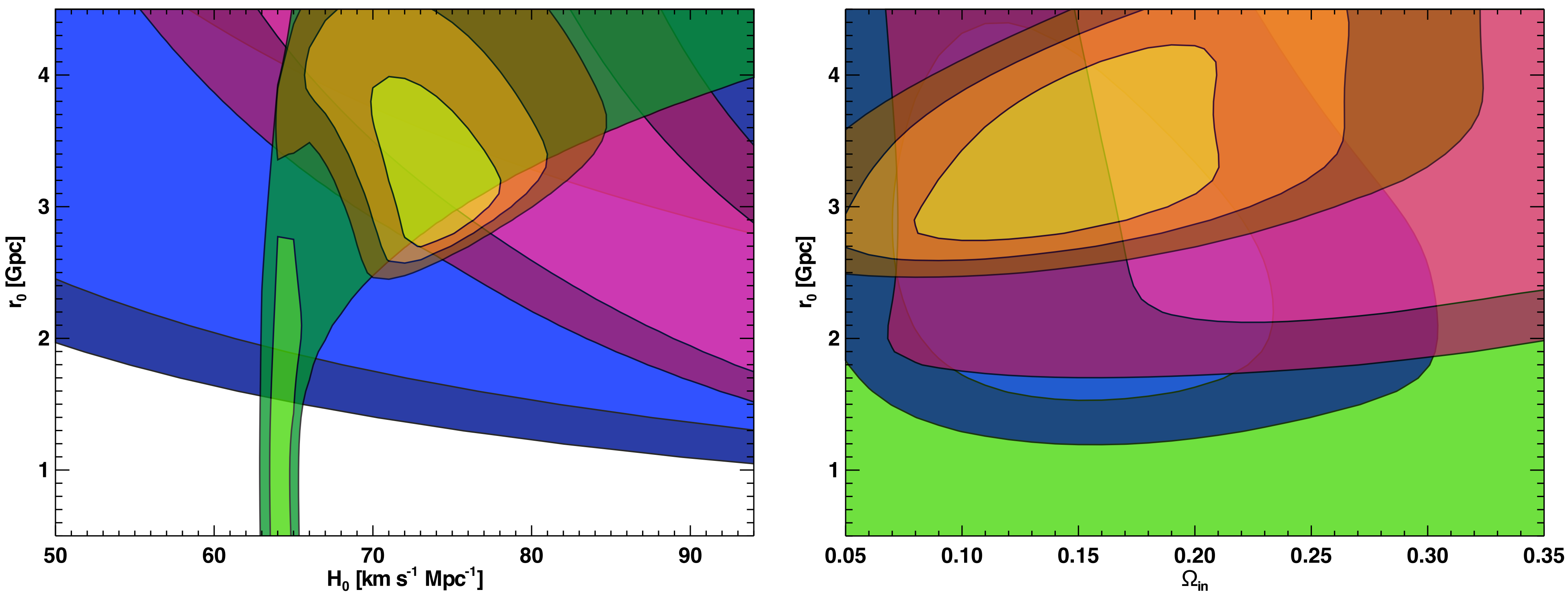


Scanning the Model Space



- Yellow: Everything, Blue: SNe Ia. Green: CMB. Purple: BAO
- The Type Ia Supernovae constrain Ω_{matter}
- CMB constrains the Hubble param, because Ω_{out}=1 & ω_b=const

Scanning the Model Space



- Yellow: Everything, Blue: SNe Ia. Green: CMB. Purple: BAO
- The SNe and BAO pushes the void size to > 2 Gpc
- Some tension between BAO and SNe (high-z SNe are useful)

Best Fit and Marginalised Errors

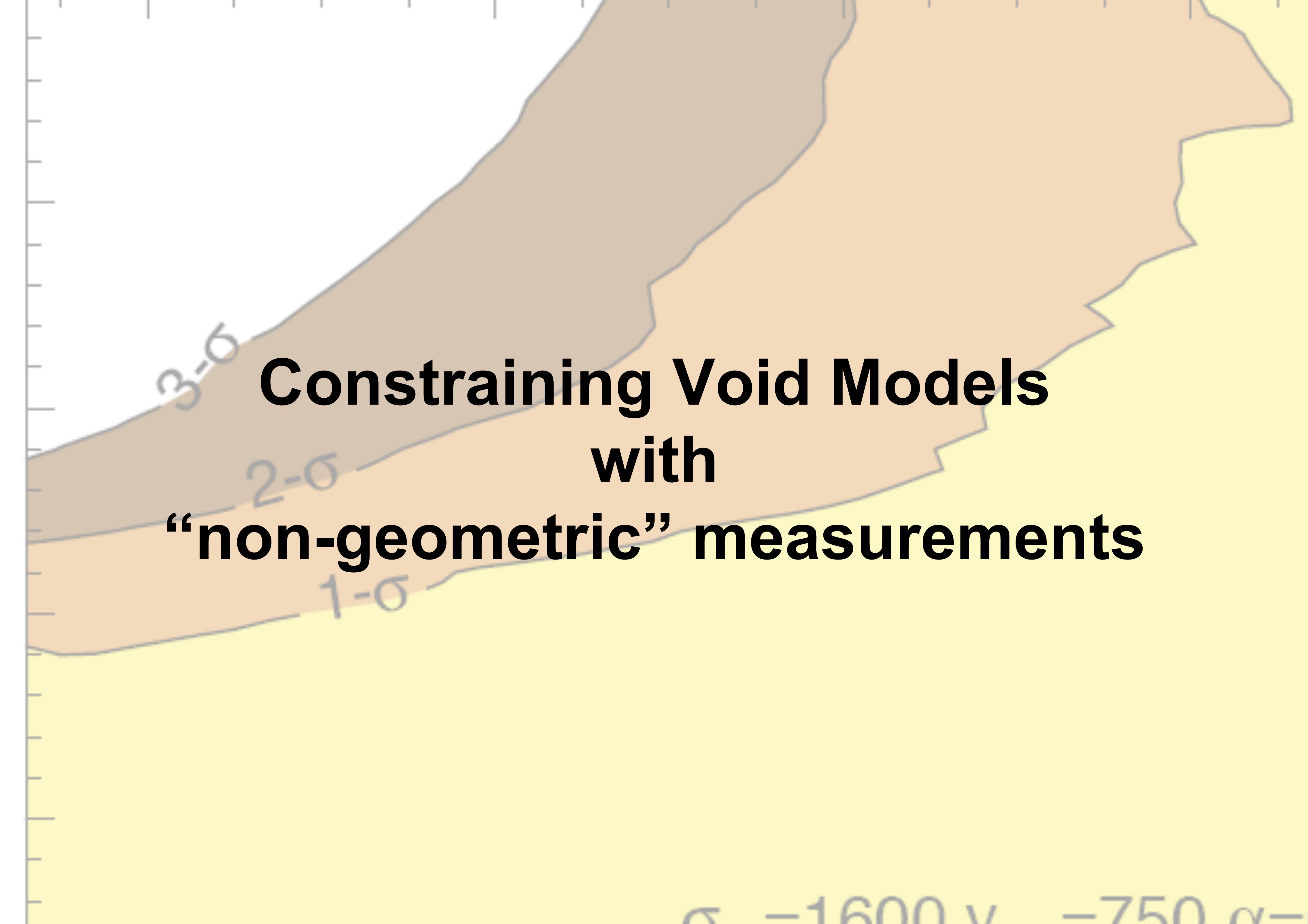
	H_0	$H_{r=0}$	$H_{r=\infty}$
units	100 km s^{-1} Mpc^{-1}		
Priors	$0.50-0.95$	$0.4-0.89$	$0.33-0.63$
Best Fit $\pm$ 2-σ	0.67 ± 0.03	0.58	0.45

	$\Omega_{\rm in}$	r_0	Δr
units		Gpc	r_0
Priors	$0.05-0.35$	$0.5-4.5$	$0.1-0.9$
Best Fit $\pm$ 2-σ	0.16 ± 0.09	2.7 ± 0.8	$0.44(>0.12)$

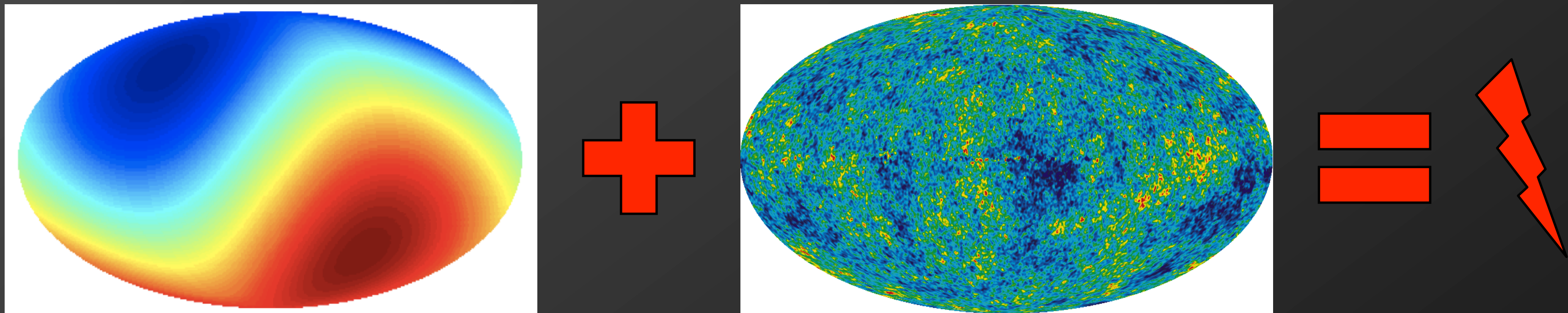
Conclusions From First Part

- An LTB model of a giant void can convincingly fit a large set of current cosmological observations and do it as well as the ΛCDM model.
- The void model only contains 4 parameters: It is a simple model.
- The best fit void size is ~2.7±1 Gpc, approximately the size of the cold spot in the CMB, if it was near the surface of last scattering.
- Combining many small voids in a “swiss-cheese universe” does not seem to work

Constraining Void Models with "non-geometric" measurements



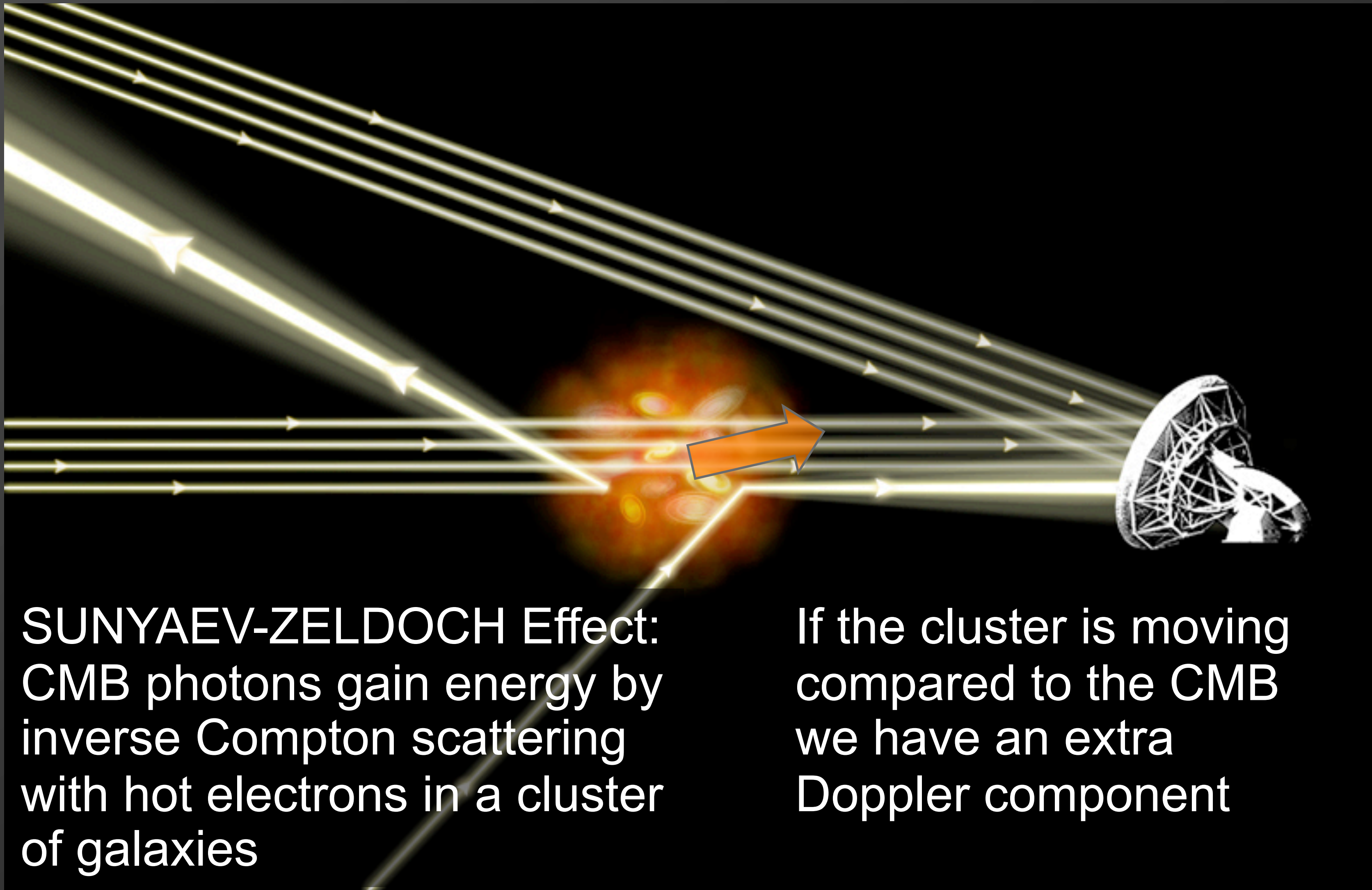
Using the CMB dipole to constrain our position in the void



- An off-center observer will see an extra dipole in the CMB because of different *integrated* expansion rates – i.e. redshifts – in different directions.
- Same effect for Supernovae, can be combined
- For a large void the constraint is pretty tight ~ 40 Mpc h^{-1}

(Blomqvist & Mörtsell 2010)

Using the Kinetic Sunyaev-Zeldovich Effect



Using the Kinetic Sunyaev-Zeldovich Effect

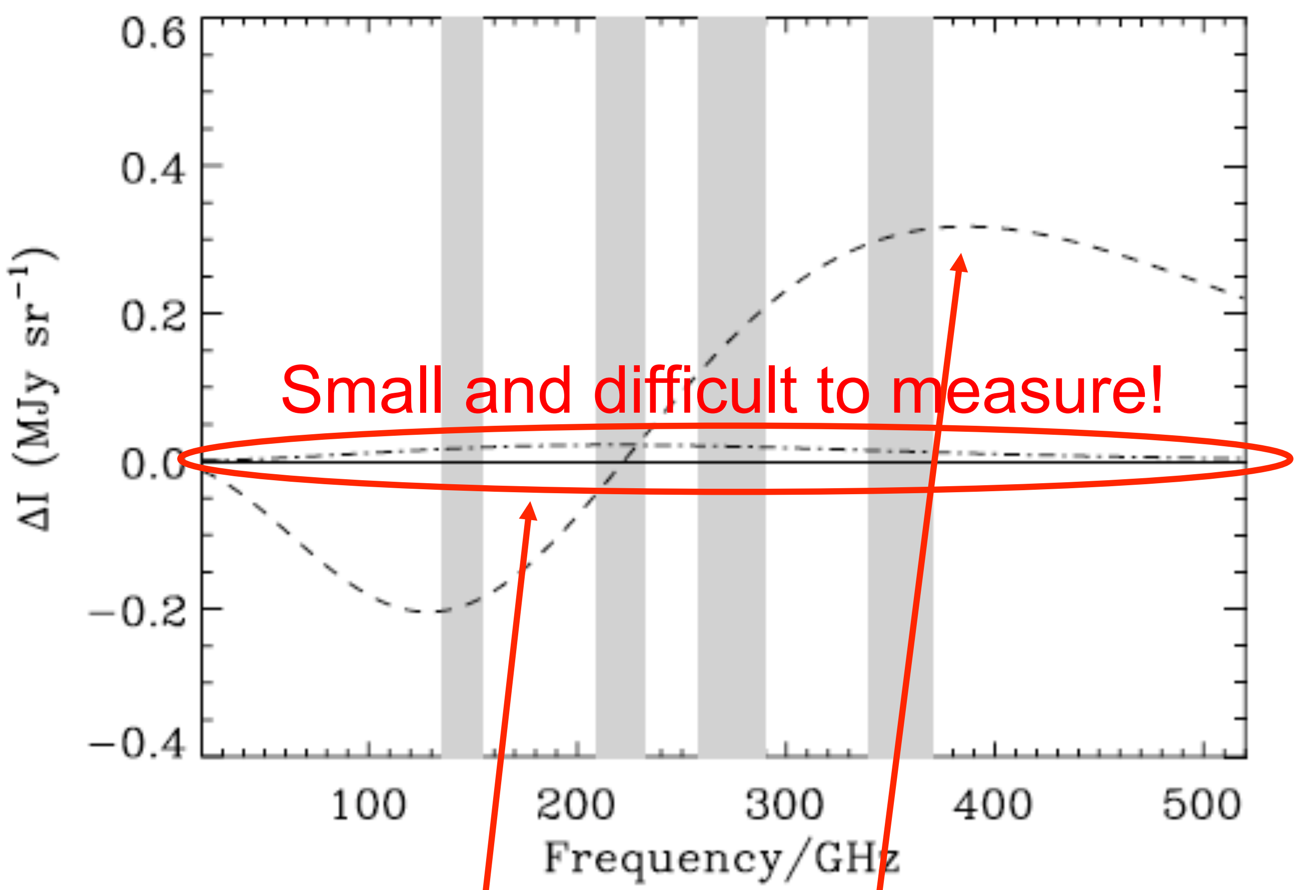
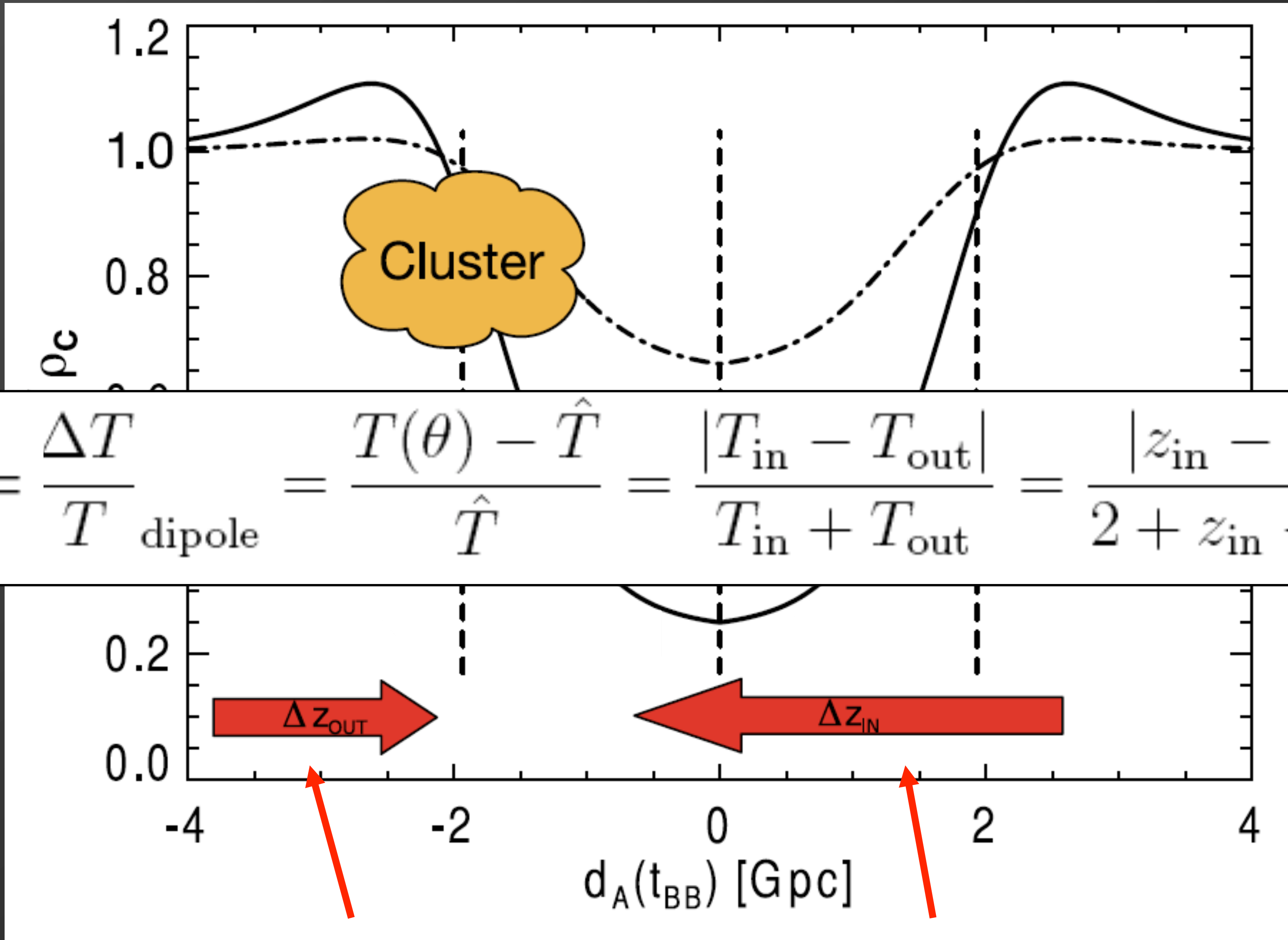


FIG. 1.—Frequency dependence of the SZ effect for a cluster with optical depth $\tau = 0.01$, gas temperature 10 keV, and a peculiar velocity of -500 km s^{-1} (toward the observer). The thermal SZ spectrum is indicated by the dashed line, the kinematic effect by the dot-dashed line. The shaded regions indicate the bands in which SuZIE II observes.

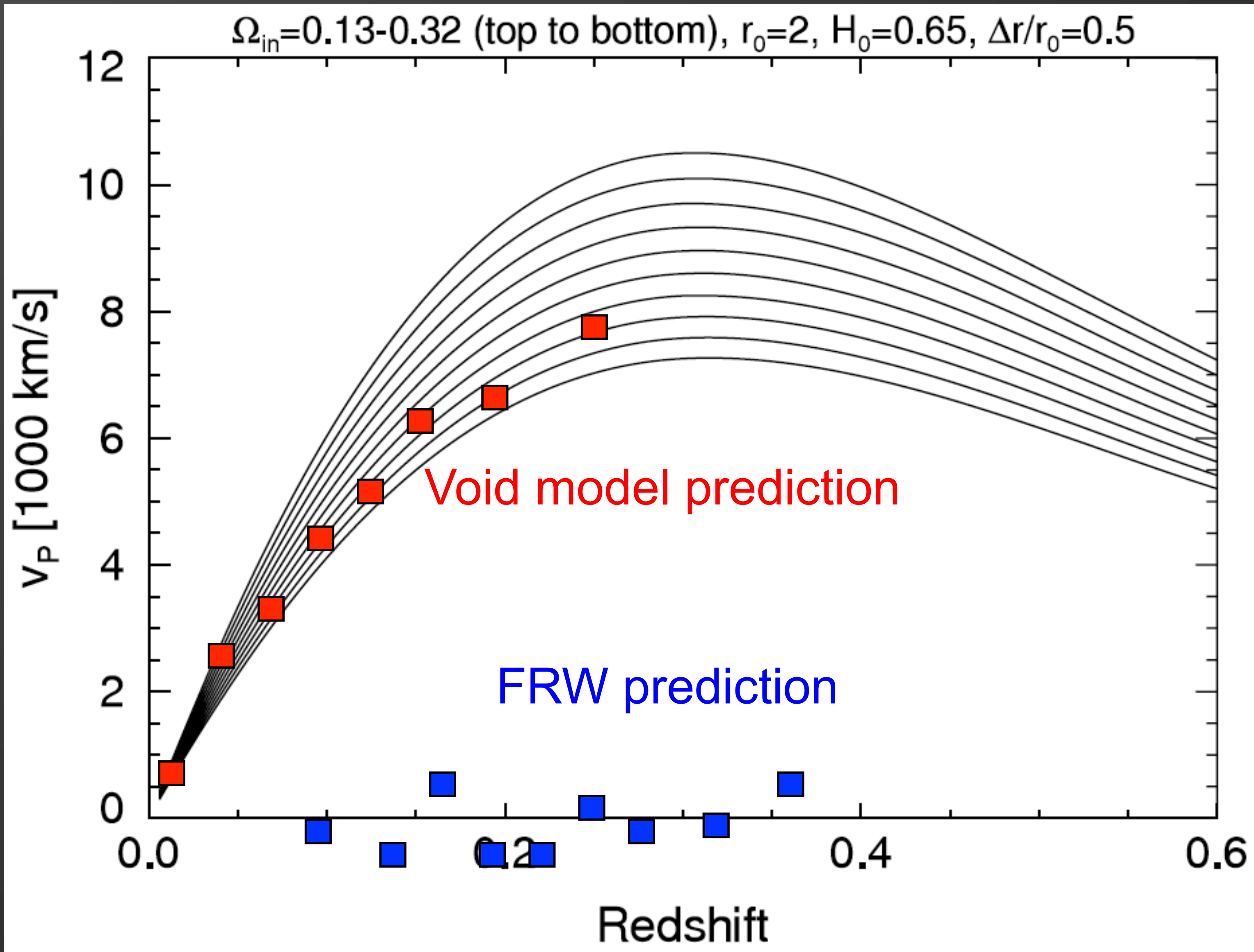
The Induced Dipole for an Off-centered Cluster



$$\frac{v_p}{c} = \frac{\Delta T}{T}_{\text{dipole}} = \frac{T(\theta) - \hat{T}}{\hat{T}} = \frac{|T_{\text{in}} - T_{\text{out}}|}{T_{\text{in}} + T_{\text{out}}} = \frac{|z_{\text{in}} - z_{\text{out}}|}{2 + z_{\text{in}} + z_{\text{out}}}$$

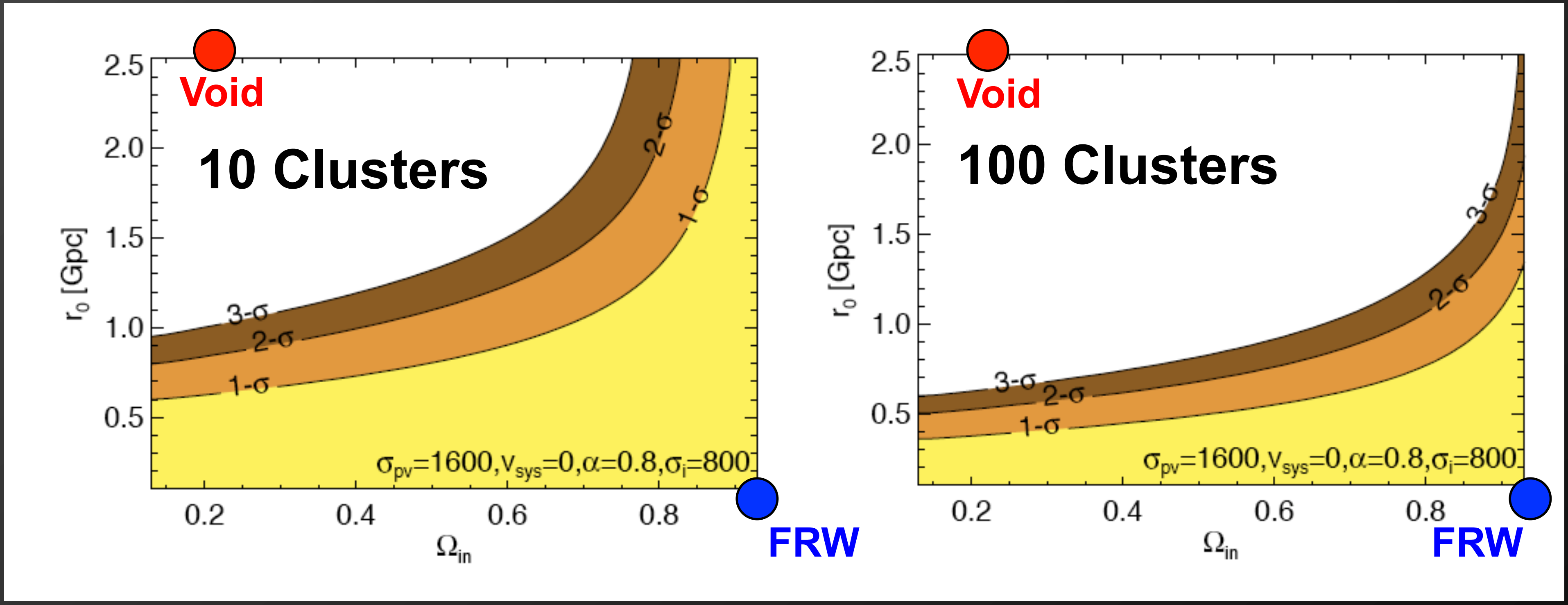
Different expansion histories => different redshifts!

Forecasted kSZ for void models

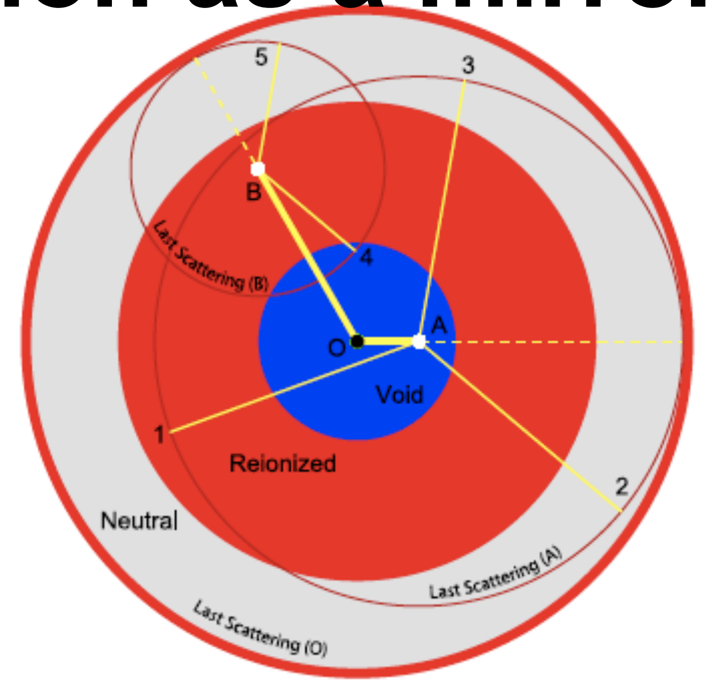


Future Bounds from ACT or SPT

- While the ACT and the SPT telescopes will make thousands of thermal SZ cluster observations we need follow up in X-rays, radio and/or optical for kSZ
- In the very first kSZ data release the LTB model could be definitively ruled out



Using Cosmic reionization as a mirror



u-distortion

A blackbody spectrum at temperature T mixed with a blackbody at temperature T+ΔT produces a *u*-distorted blackbody.

Stebbins, astro-ph/0703541

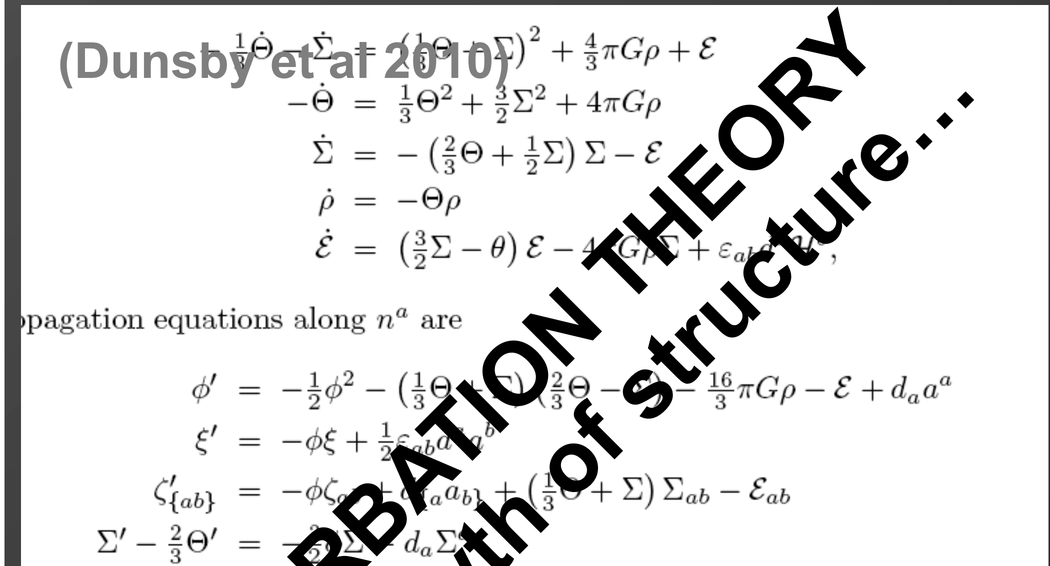
$$u[\hat{n}] = \frac{3}{16\pi}\int_0^\infty dz' \, \frac{d\tau}{dz'} \int d\hat{n}'(1+(\hat{n}\cdot\hat{n}')^2) \times \left(\frac{\Delta T}{T}[\hat{n},\hat{n},z] - \frac{\Delta T}{T}[\hat{n}',\hat{n},z]\right)^2$$

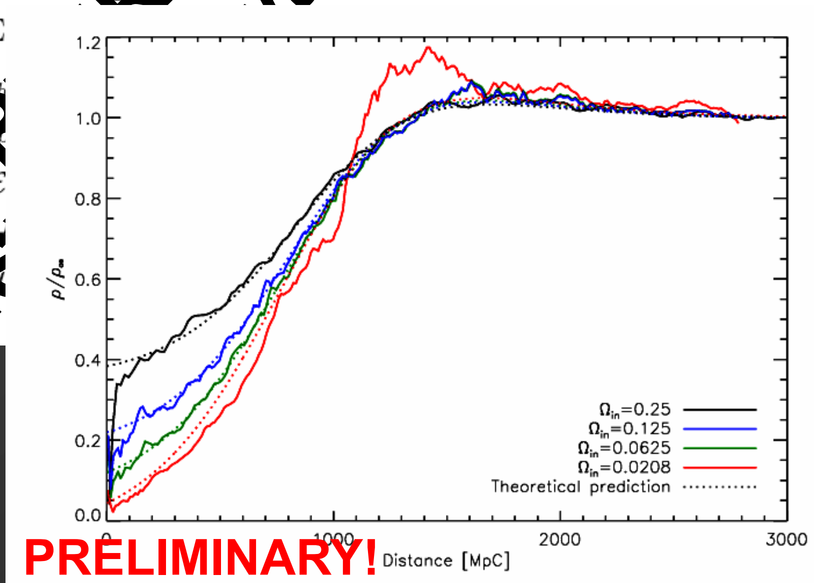
Degenerate with Compton y-distortion parameter: u = 2y

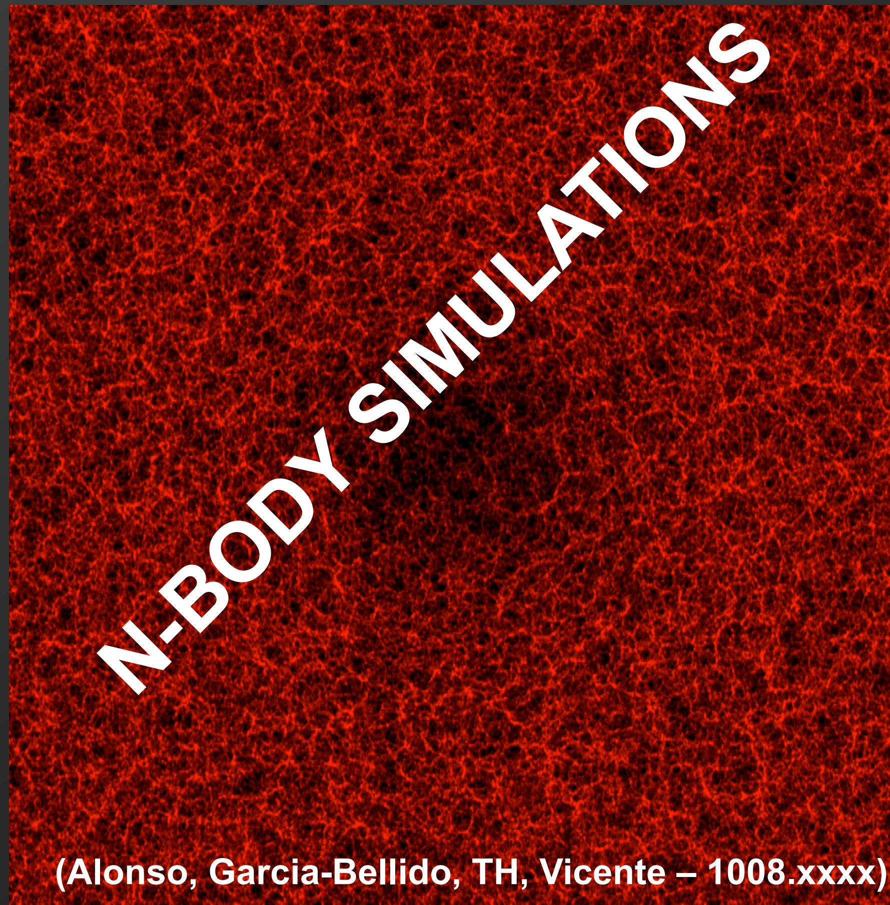
FIRAS: $y < 15 \times 10^{-6}$ (95%): Fixen et al, ApJ 473, 576 (1996)

Slide from Robert Caldwell's presentation at Cosmo 2008

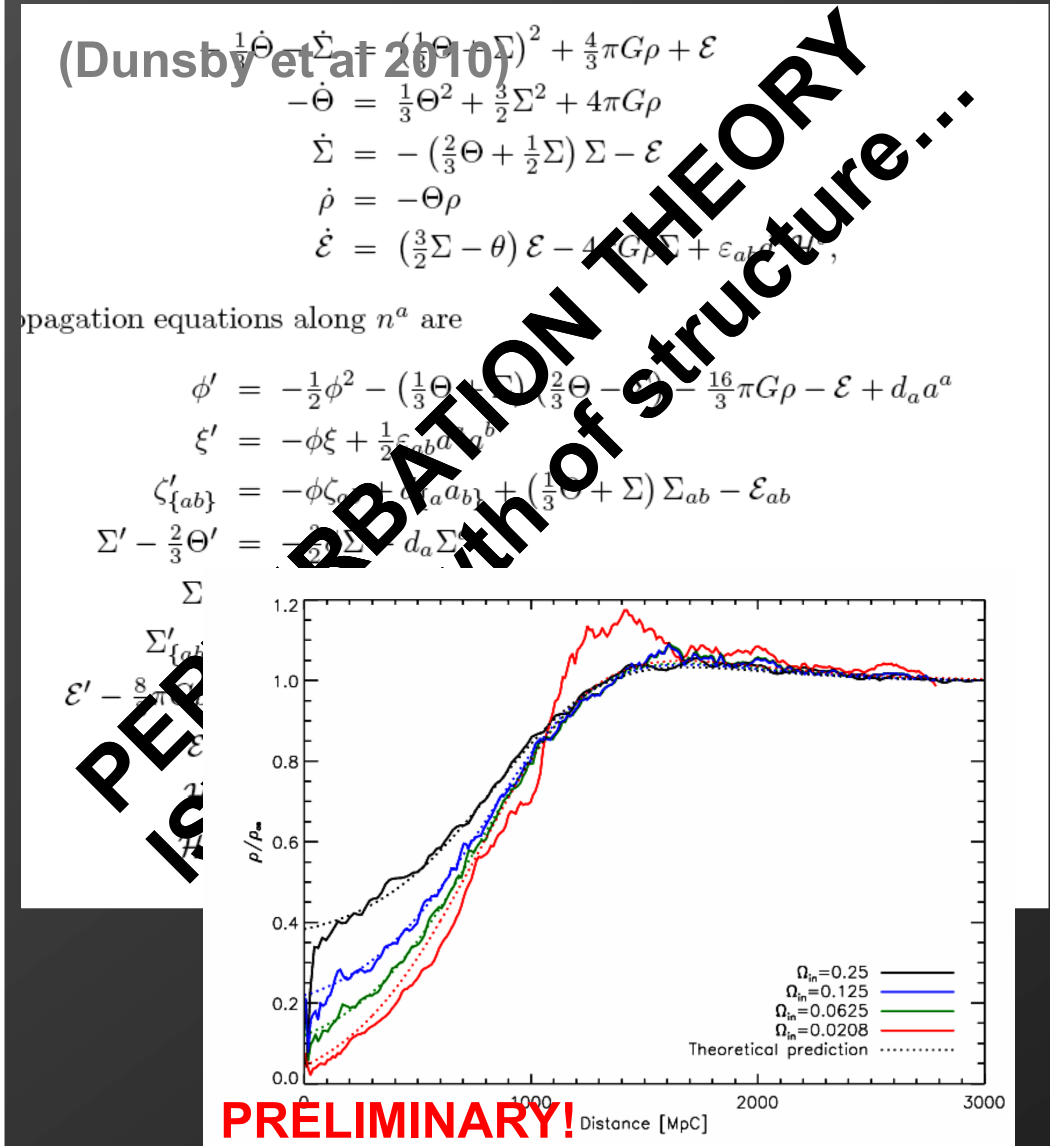
The next frontier:
Structure Formation & Perturbations

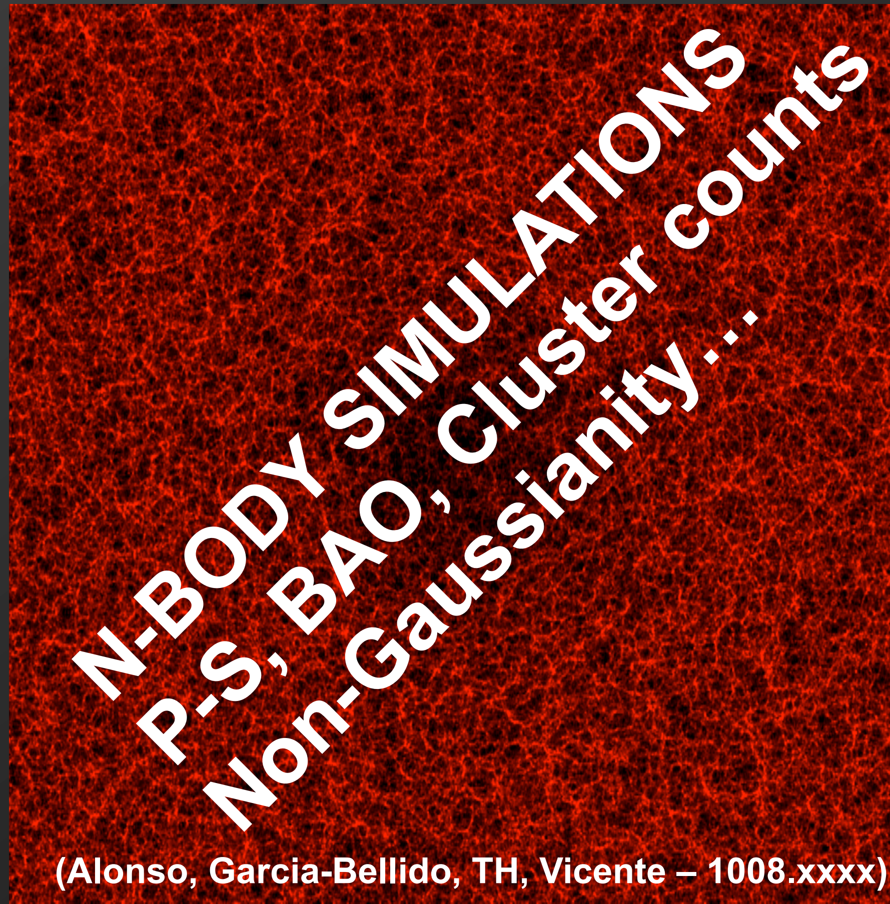






The next frontier:
Structure Formation & Perturbations





Summary

- Void models, observationally, seem a real alternative to the standard model. While they break with the Copernican principle, they do not need dark energy.

- A void model with a size of ~2.7 Gpc yields a very good fit to observations constraining the *geometry* of the universe.

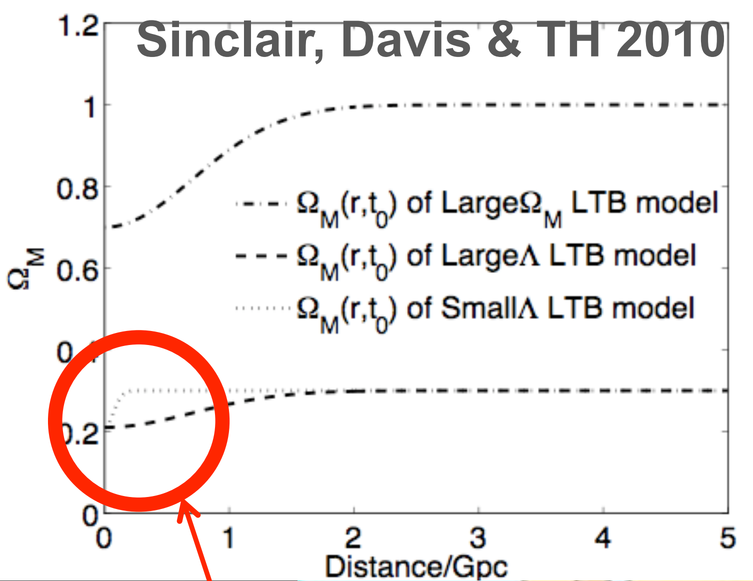
- There are many new observations and ways to tests the model related to structure, and to distortions of the CMB:

  - CMB and large scale structure (More theory+simulations)
  - Remote measurements of the CMB: The Kinetic Sunyaev Zeldovich effect (Apex, ACT, SPT, Planck)
  - Spectral distortions in the CMB (FIRAS is almost good enough)

Outlook

- The void model may be ruled out in the near future, just like the Swiss Cheese model was
- But given the quality of the observations today, people will keep testing inhomogeneous models – it is the next natural step after FRW
- The void model may be wrong, but it helps in getting a better understanding of the perturbed ΛCDM model
- Example:
  - How are Ω_{matter} and Ω_{Λ} biased by a local void? How do we cope with the bias ?

Using LTB to model the impact of a small void on Supernova Cosmology



The last hole in the cheese matters

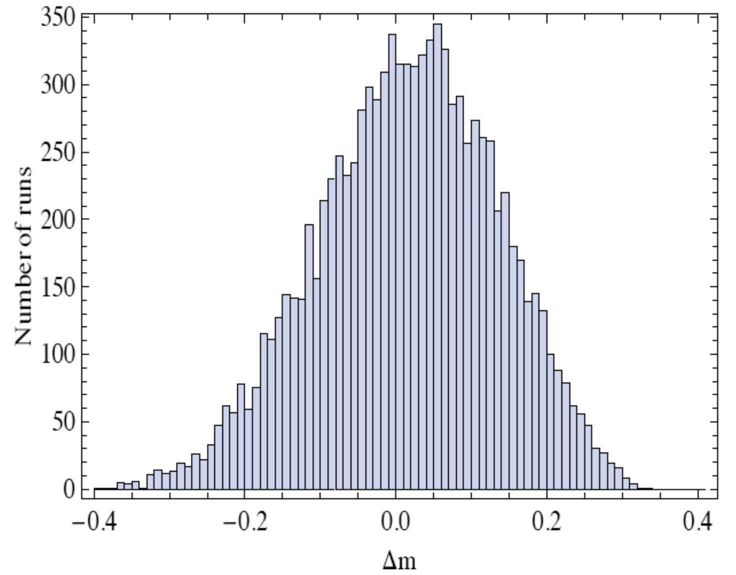
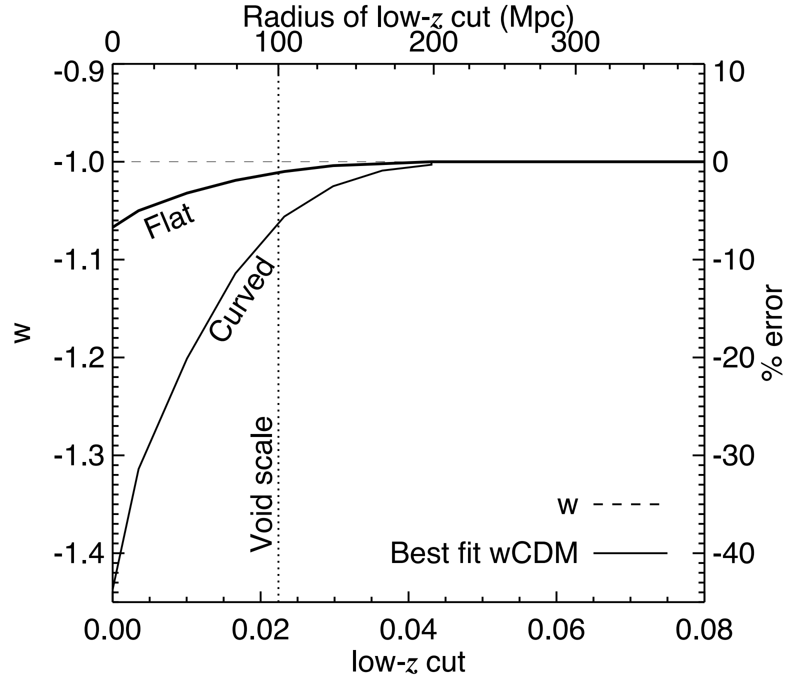


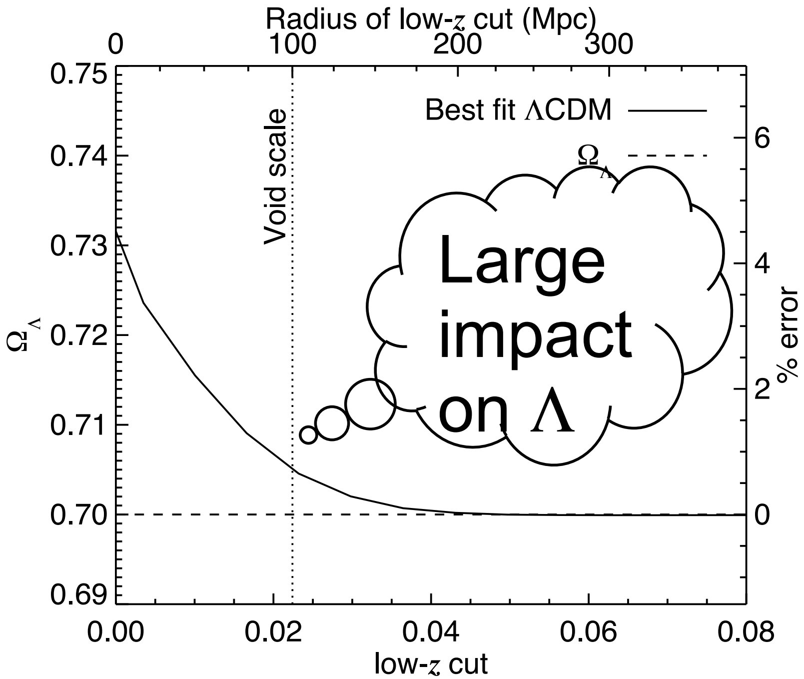
FIG. 2: A histogram of the distance modulus shifts Δm found for 10, 000 realizations of our randomized void scenario.

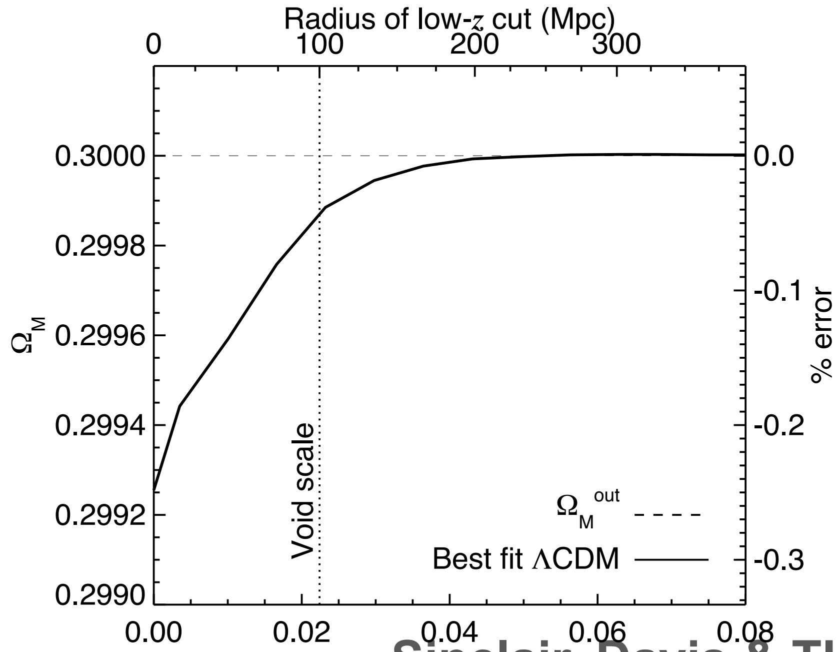
Vanderveld et al 2008

Impact of a small void on Supernova Cosmology



- The LTB model is extended with Λ
- We can then embed a small void – we use 70 Mpc h^{-1} – in a LCDM universe
- We construct a sample of 301 supernovae with z<1.7
- When fitting a LCDM model to the mock data, the impact can be appreciable for upcoming surveys
- It is essential to discard low redshift supernovae with z<0.02 for a <1% error





Sinclair, Davis & TH 2010

Can we measure geometry ??

- The shear to expansion ratio gives a normalised measure of inhomogeneity, with a straight forward theoretical interpretation

$$\varepsilon = \sqrt{\frac{3}{2}}\frac{\sigma}{\Theta} = \frac{H_T - H_L}{H_L + 2H_T}$$

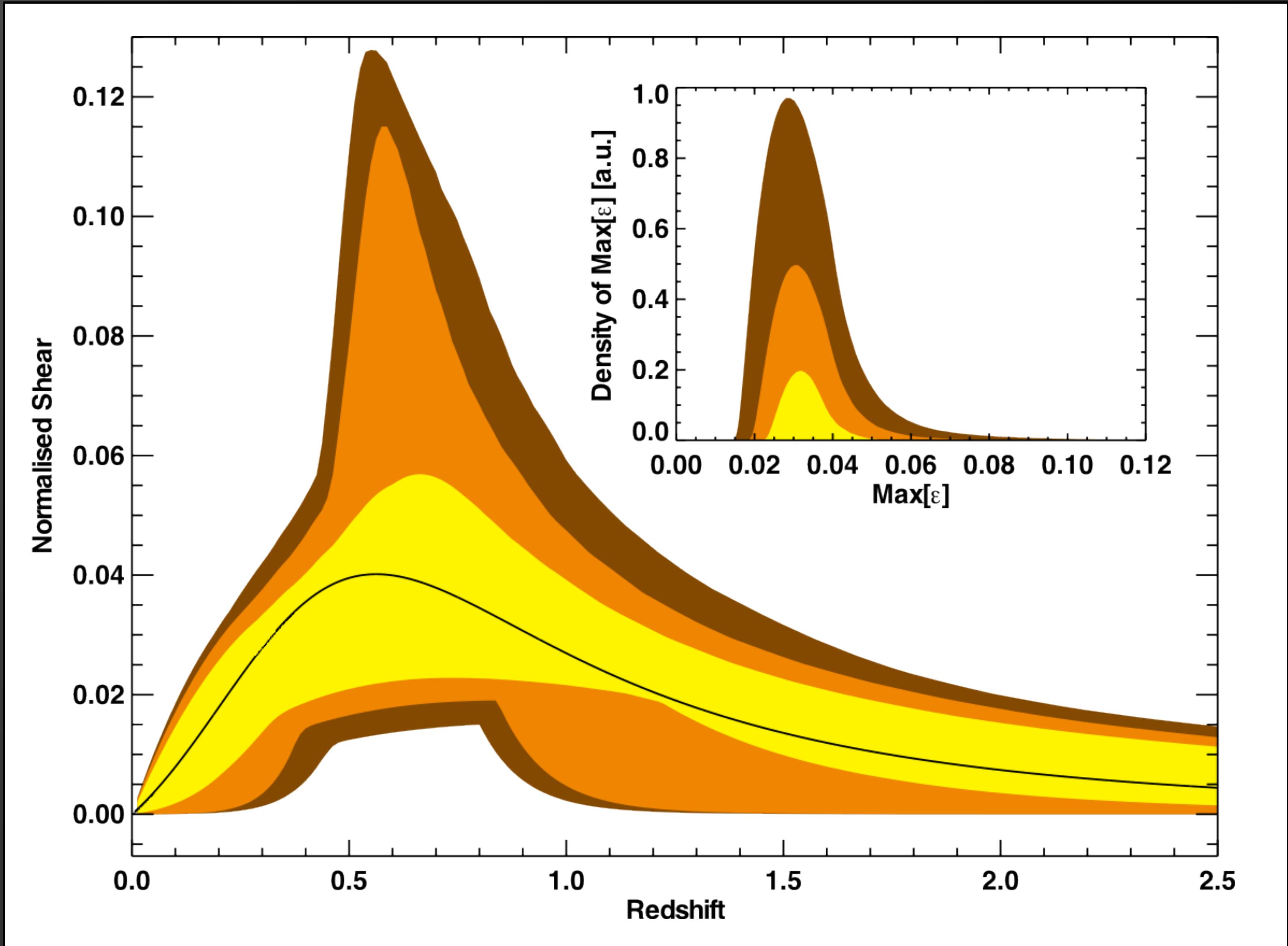
- Notice that $H_L = H_T + \partial_{\ln A} H_T$

Radial inhomogeneity $\Leftrightarrow$ $\varepsilon \neq 0$

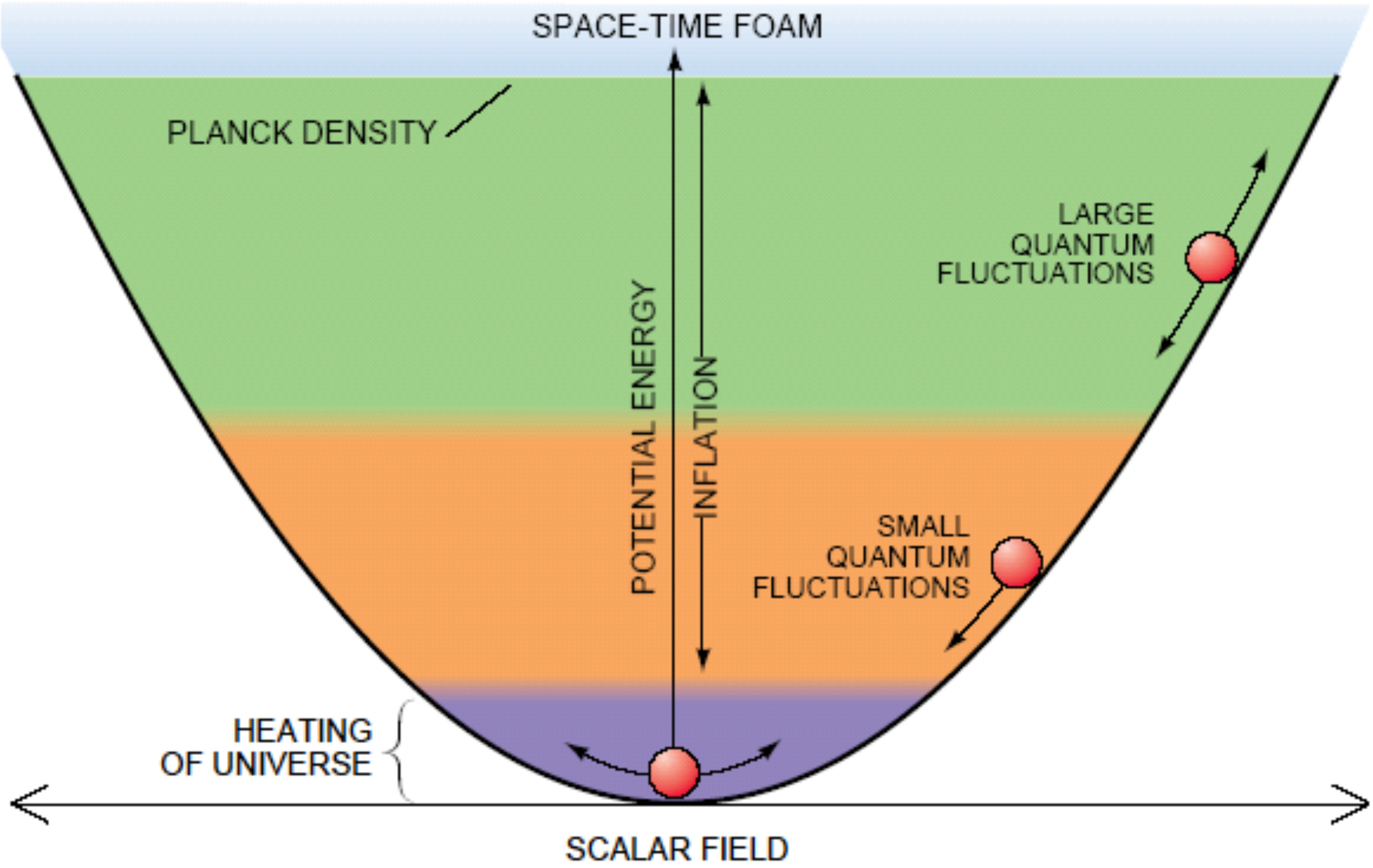
- The strength of ε is that it can be measured in the future by combining radial BAO measurements (giving H_L) and measurements of the distance (giving d_A)

$$\varepsilon = \frac{\sqrt{1-k(r)} - H_L(d_A + (1+z)\,d'_A(z))}{2\sqrt{1-k(r)} + H_L(d_A - 2(1+z)\,d'_A(z))}$$

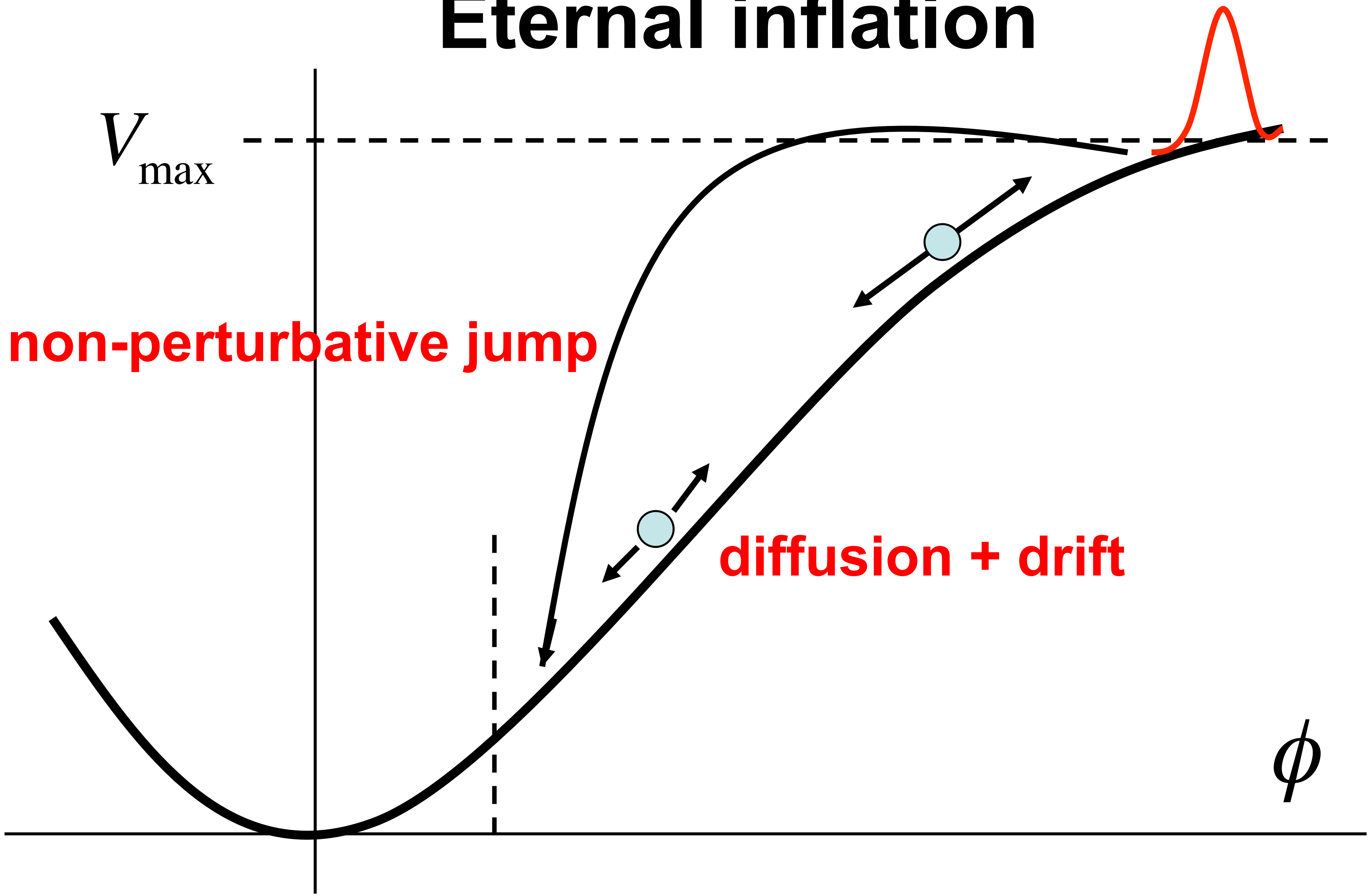
Can we measure geometry ??



A void model from Chaotic Inflation

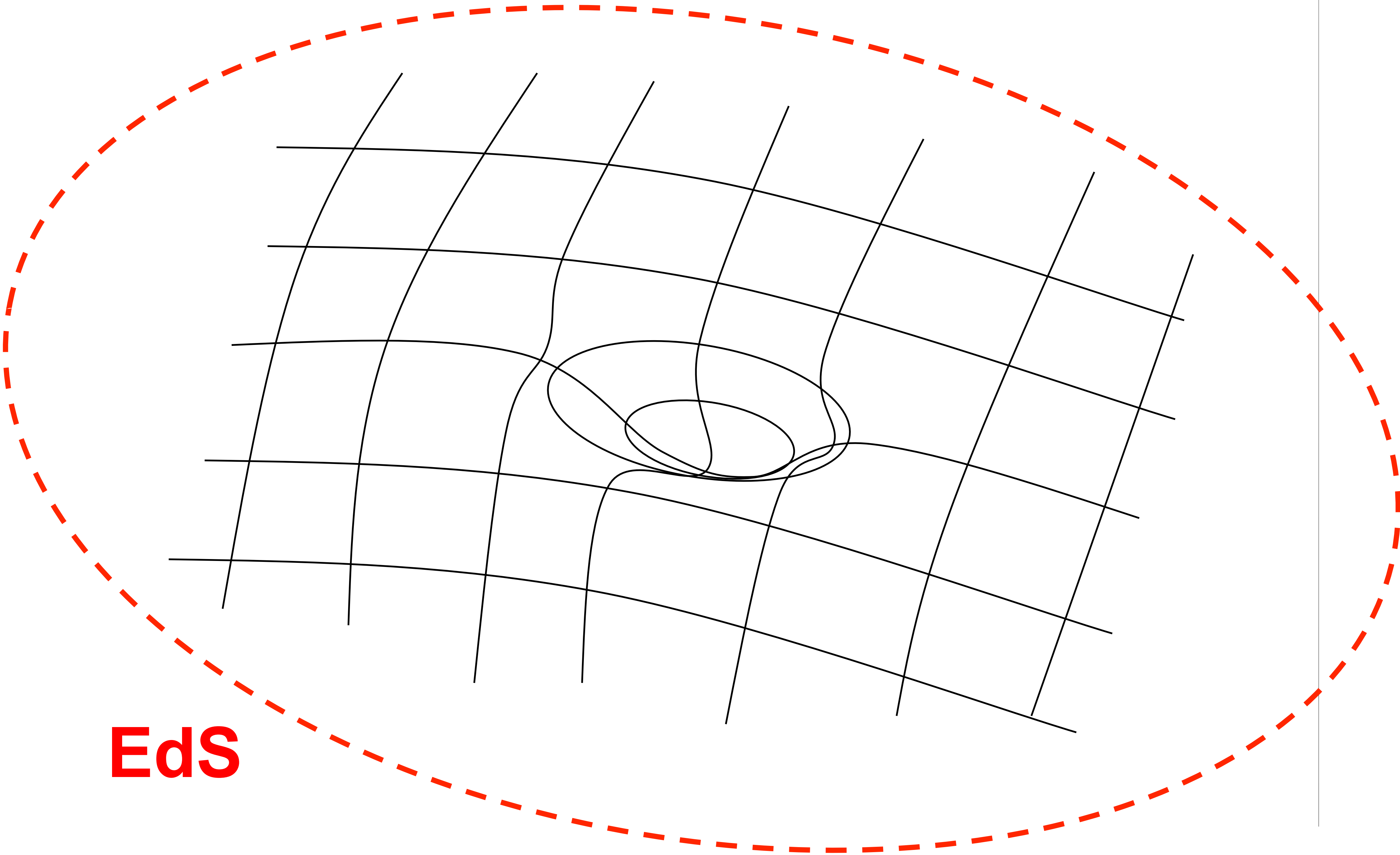


Eternal inflation

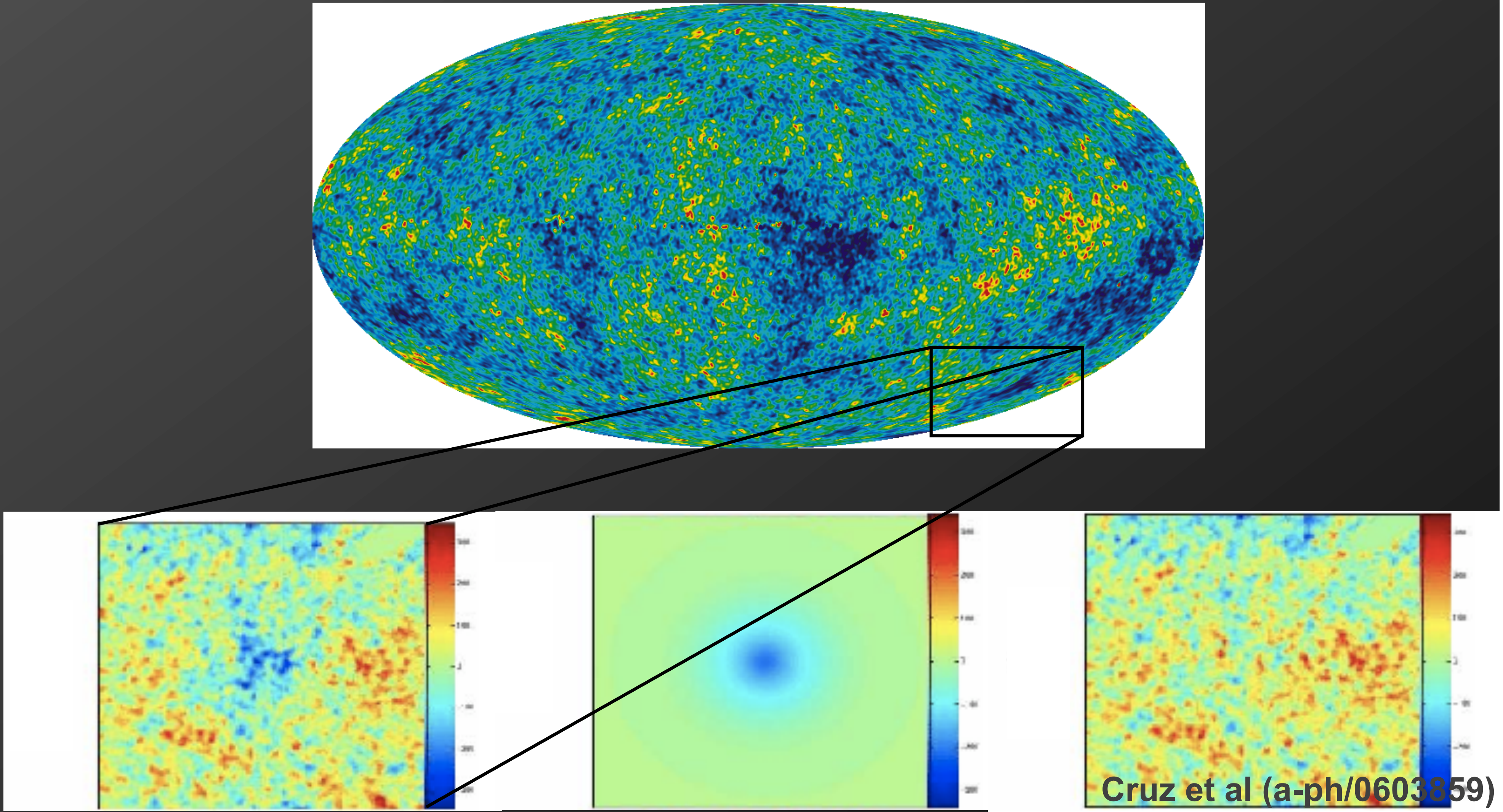


(Linde, Linde, Mezhlumian, PLB 345, 203, 1995)

The Infloid = LTB Model



Could the *Cold Spot* in the cosmic microwave background be an infloid ?



Approximately 2 Gpc comoving size