Is living in a void compatible with observational cosmology?

Cosmo, Madison, August 2008

Troels Haugbølle

haugboel@phys.au.dk

(arXiv: 0802.1523, 0807.1326 [astro-ph])

In Collaboration with Juan García-Bellido (UAM, Madrid)

Universidad Autonoma, Madrid & Institute for Physics & Astronomy, Århus University

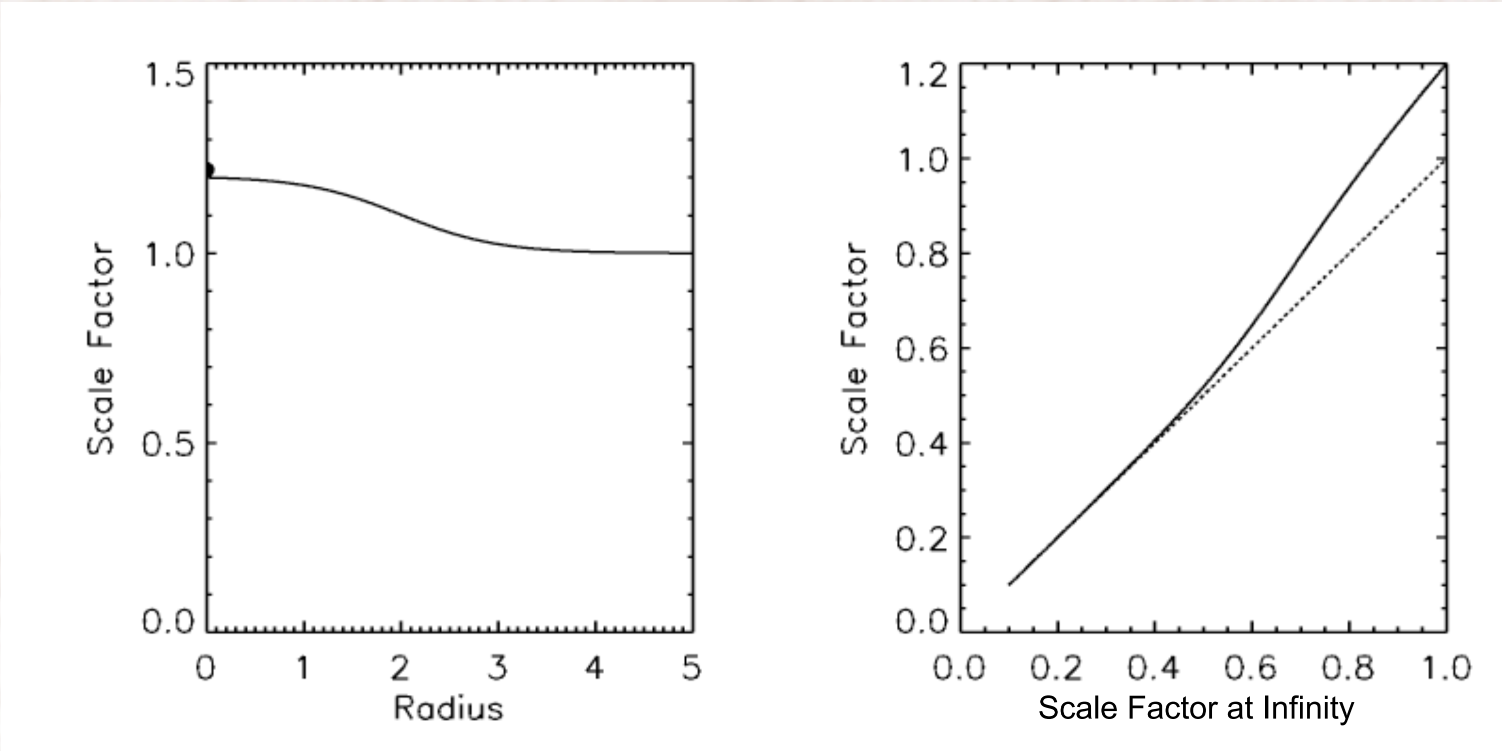
How does a Central Void Help Explain Dark Energy?

- 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?

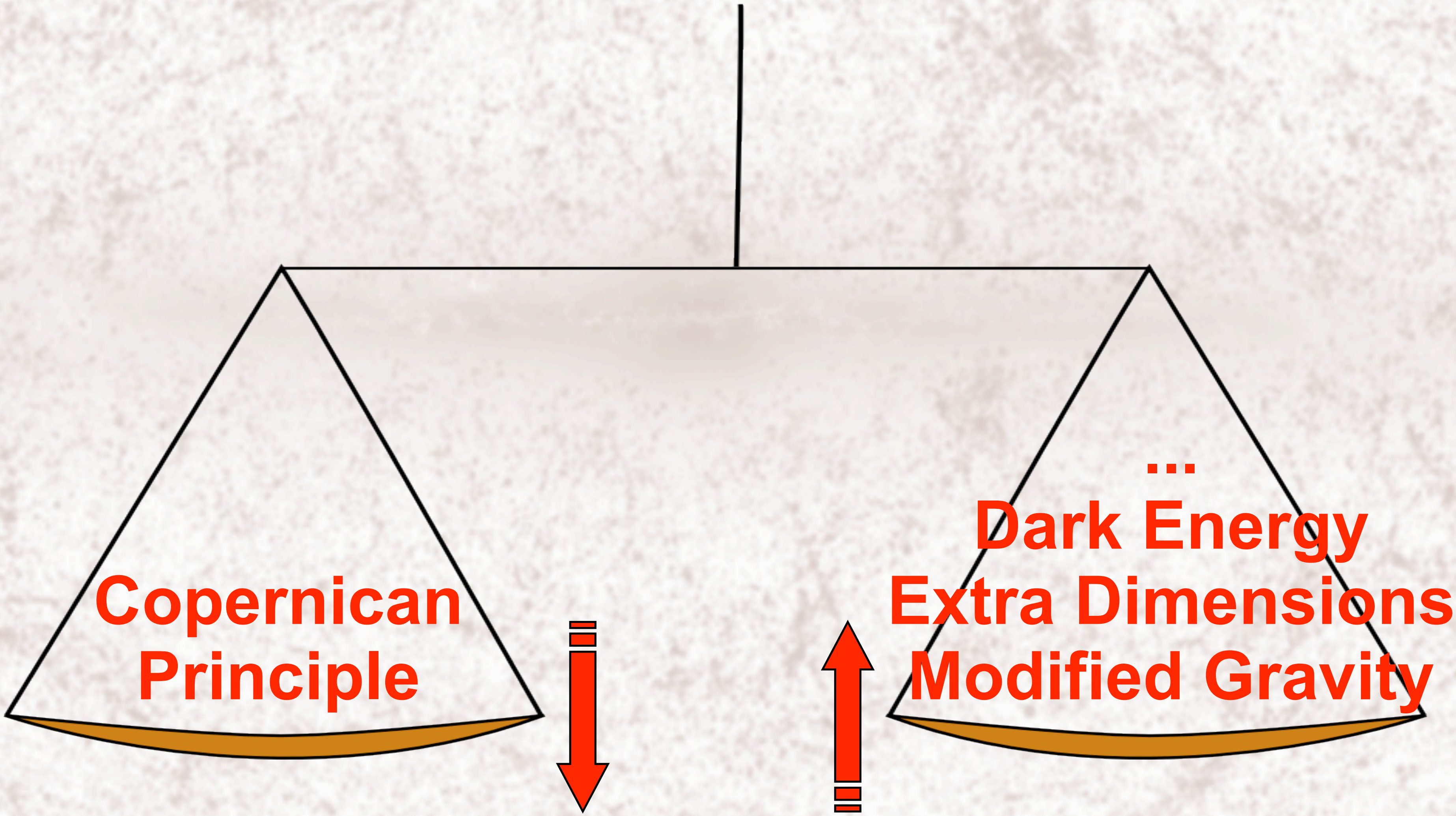
$$\frac{D}{Dt} \simeq \frac{\partial}{\partial t} - c\frac{\partial}{\partial r}$$

Trading Dark Energy for a Void

- 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?

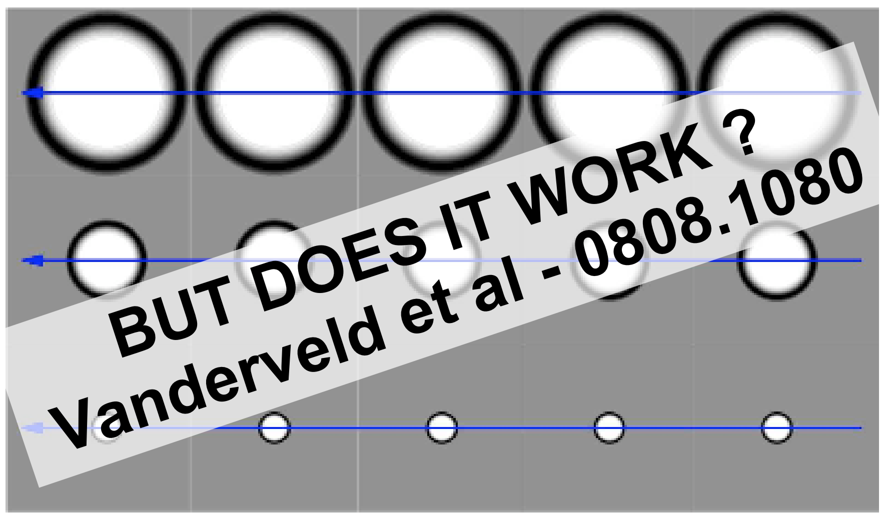


Trading Dark Energy for a Void



... or Trading Dark Energy for Voids

Swiss cheese - 250 Mpc holes, please! **(arXiv:0710.5505)**



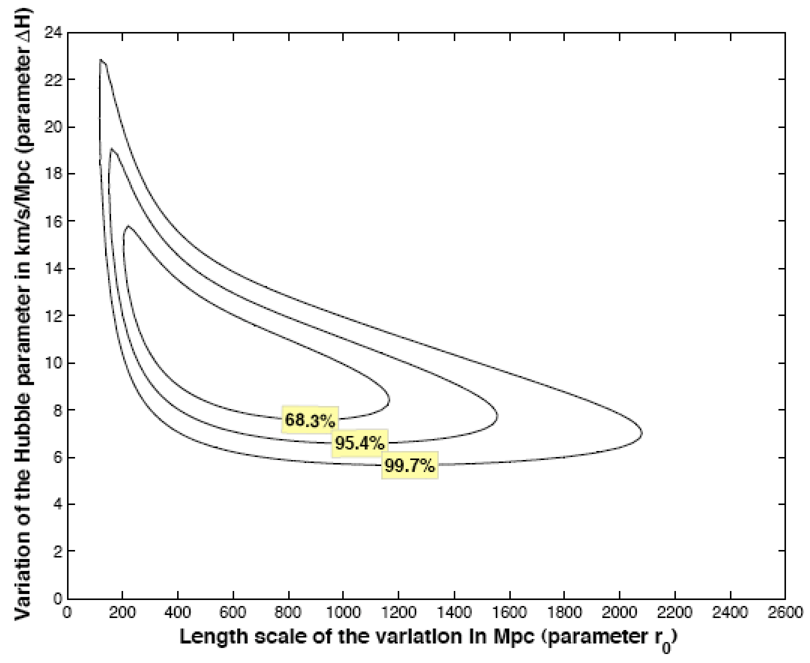


Figure 1: Confidence level contours in the LTB model with $\Omega_M(r) = \text{constant} = 0.45$ and $H_0(r) = 56.3\,\text{km/s/Mpc} + \Delta H e^{-r/r_0}$. From [31].

...and many many more. In fact **56 articles** on ADS with the words "Tolman" and "Bondi" in their abstract **since 2006**

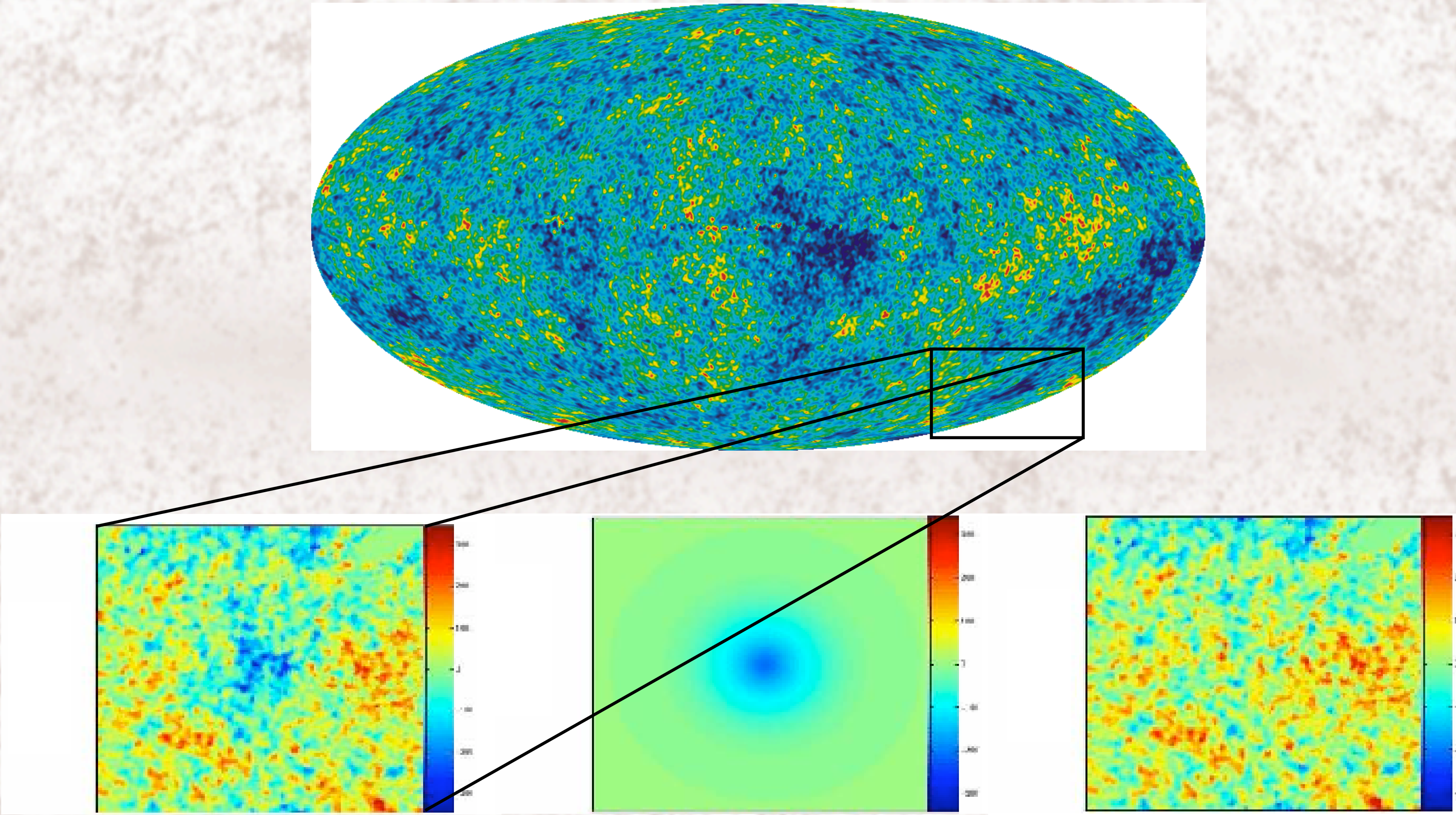
almost two per month!

- Observational bounds from CMB and SNe

Only in 2006 the first paper with a χ^2

(arXiv:0712.0370, 0711.4264, 0709.2044, a-ph/0610331, a-ph/0609120, a-ph/0607334, a-ph/0512006)

Is the Cold Spot Due to a Void ?



Approximately 2 Gpc comoving size near the horizon

Cruz et al (a-ph/0603859)

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

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

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

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

The Lemaître-Tolman-Bondi Model

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

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

- We find the “local analogy” to the Friedman Equation

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

The Lemaître-Tolman-Bondi Model

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

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

- We find the “local analogy” to the Friedman Equation

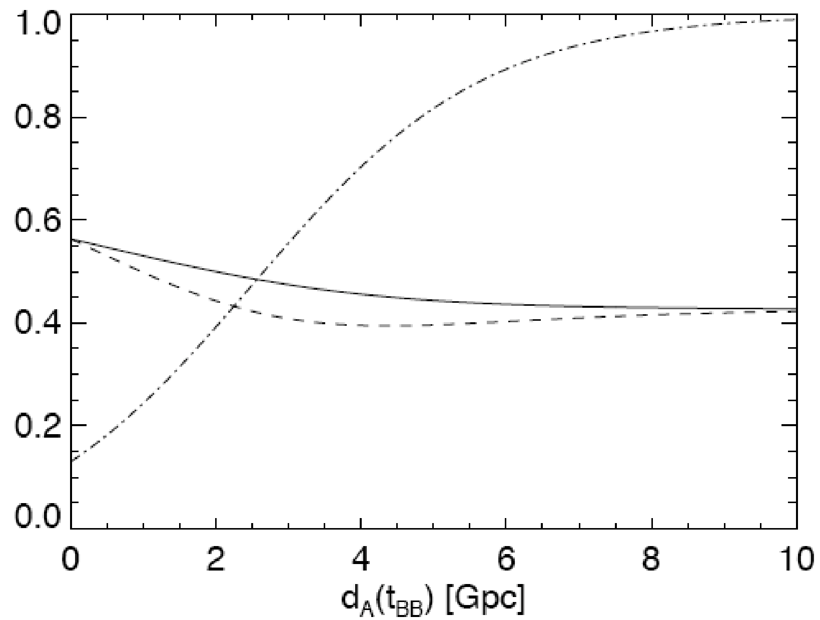
$$H^2(r,t) = H_0^2(r)\left[\Omega_M(r)\left(\frac{A_0(r)}{A(r,t)}\right)^3 + (1-\Omega_M(r))\left(\frac{A_0(r)}{A(r,t)}\right)^2\right]$$

where $H_0(r)$ and $\Omega_M(r)$ uniquely describes our model

Our Model (aka the GBH model)

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

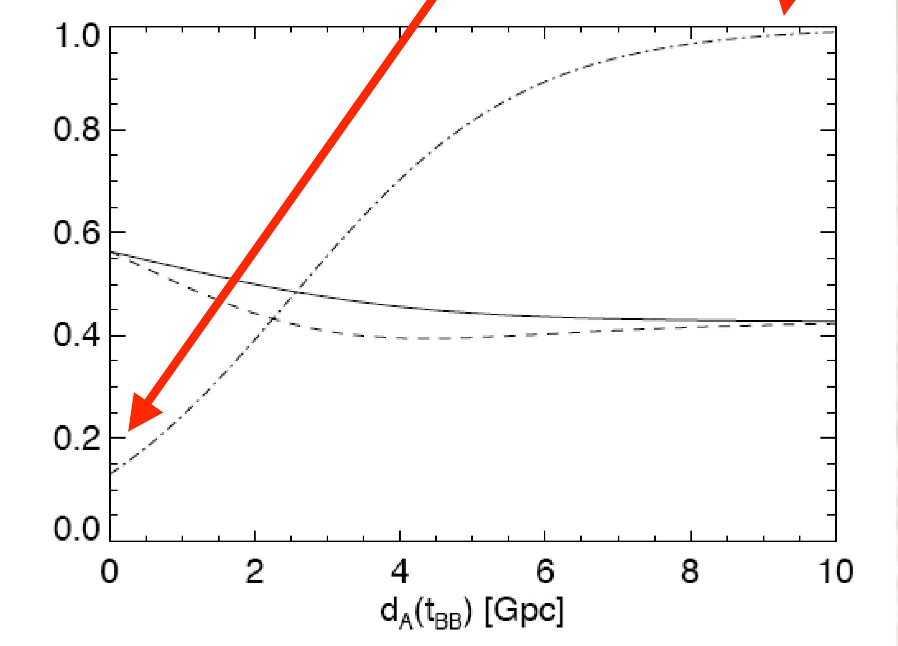
$$H_0(r) = H_{\rm out} + \left(H_{\rm in} - H_{\rm out}\right)\left(\frac{1-\tanh[(r-r_0)/2\Delta r]}{1+\tanh[r0/2\Delta r]}\right)$$



Our Model (aka the GBH model)

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

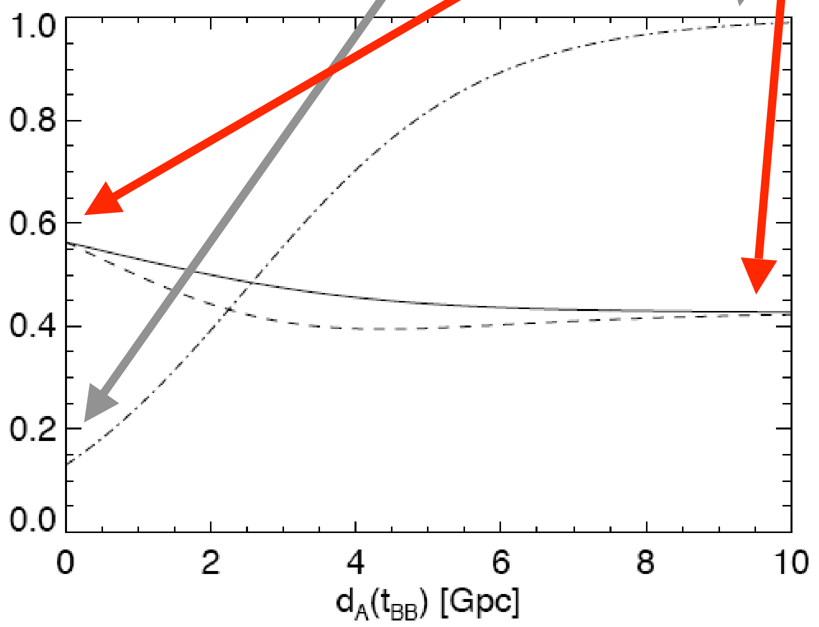
$$H_0(r) = H_{\text{out}} + \left(H_{\text{in}} - H_{\text{out}}\right)\left(\frac{1 - \tanh[(r - r_0)/2\Delta r]}{1 + \tanh[r0/2\Delta r]}\right)$$



Our Model (aka the GBH model)

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

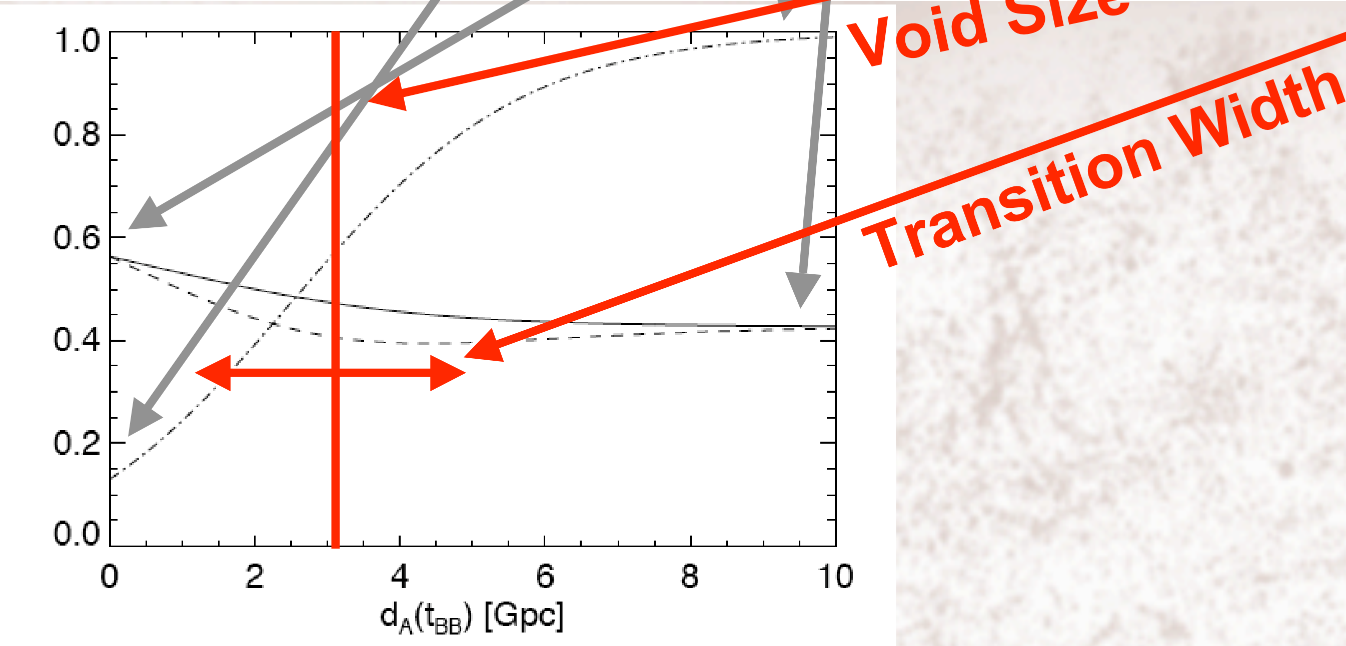
$$H_0(r) = H_{\rm out} + \left(\boxed{H_{\rm in}} - \boxed{H_{\rm out}}\right)\left(\frac{1-\tanh[(r-r_0)/2\Delta r]}{1+\tanh[r0/2\Delta r]}\right)$$



Our Model (aka the GBH model)

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

$$H_0(r) = H_{\rm out} + \left(\boxed{H_{\rm in}} - \boxed{H_{\rm out}}\right)\left(\frac{1-\tanh[(r-\boxed{r_0})/2\Delta r]}{1+\tanh[r0/2\boxed{\Delta r}]}\right)$$



Constraining LTB Models with Standard Cosmological Data

Constraining Cosmological Data

- **Type Ia Supernovae**: 192 SNe compiled by Davis et al
  - Simple to do since we just fit against $d_L(z)$

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

- **Baryon Acoustic Oscillations**:
  - Sound horizon, and $D_V(z) = \left[d_A^2(z)(1+z)^2 \frac{cz}{H_L(z)} \right]^{1/3}$

- **Other constraints**:
  - $f_{gas} = \rho_b / \rho_m = \omega_b / (\Omega_m h^2) = 0.1104 \pm 0.0016 \pm 0.1$
  - Hubble key project: $H = 72 \pm 8$ km/s/Mpc (1-σ)
  - Globular cluster ages ($t_{Big\ Bang} > 11.2$ Gyr)

Fitting the Type Ia Supernovae

The best fit GBH-model has no problem with Type Ia SNe

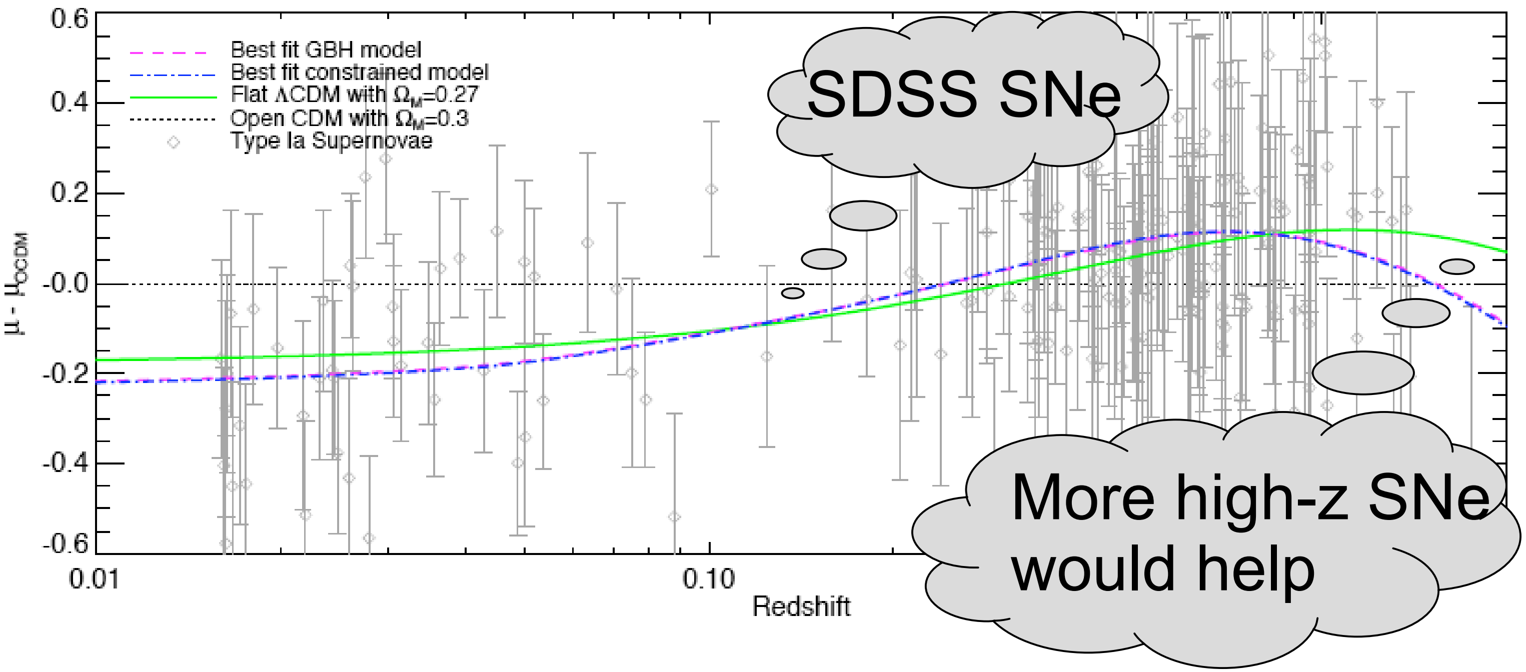
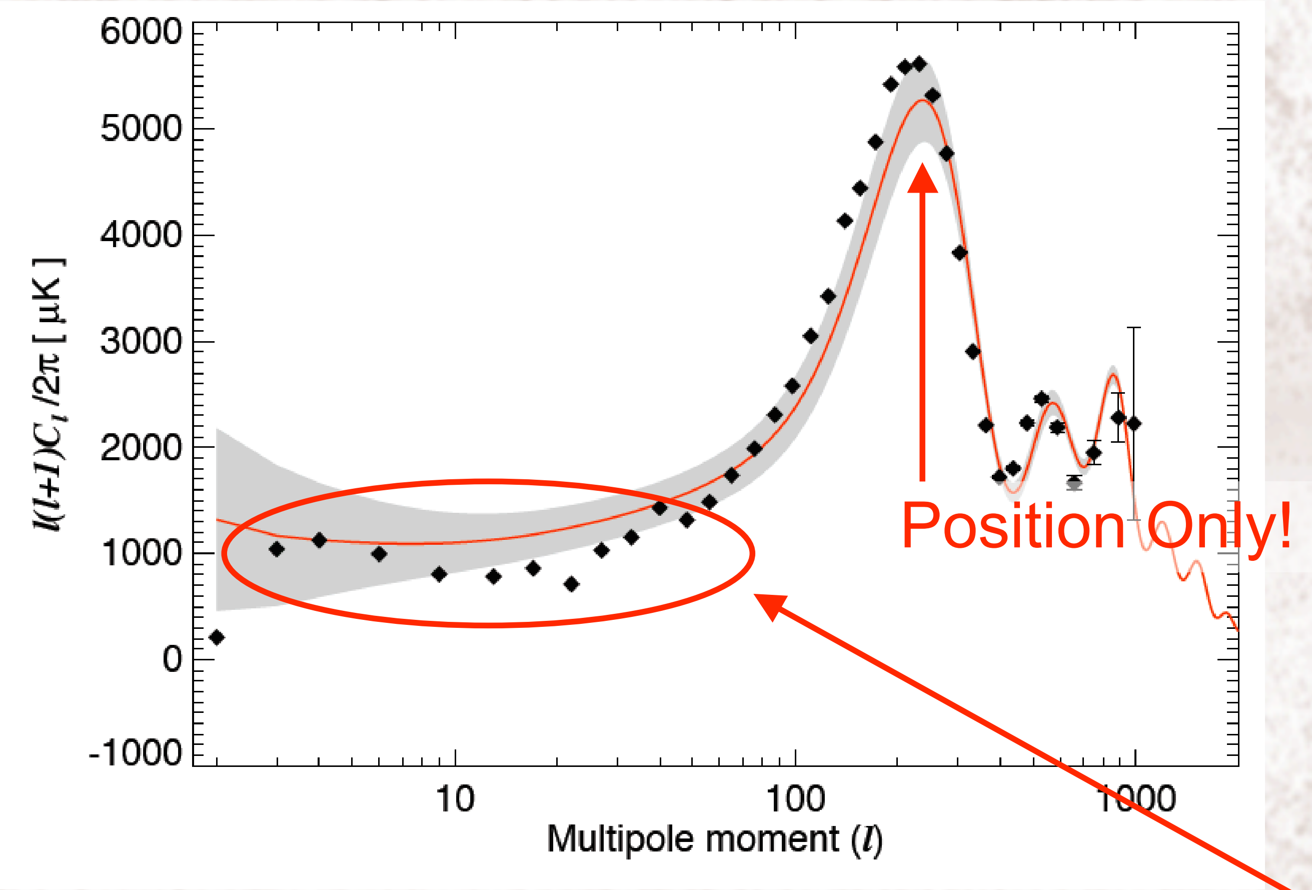


Figure 4. Apparent magnitude residuals for the two best fit LTB models, standard open CDM, and the best fit ΛCDM FRW models compared to Type Ia Supernovae data.

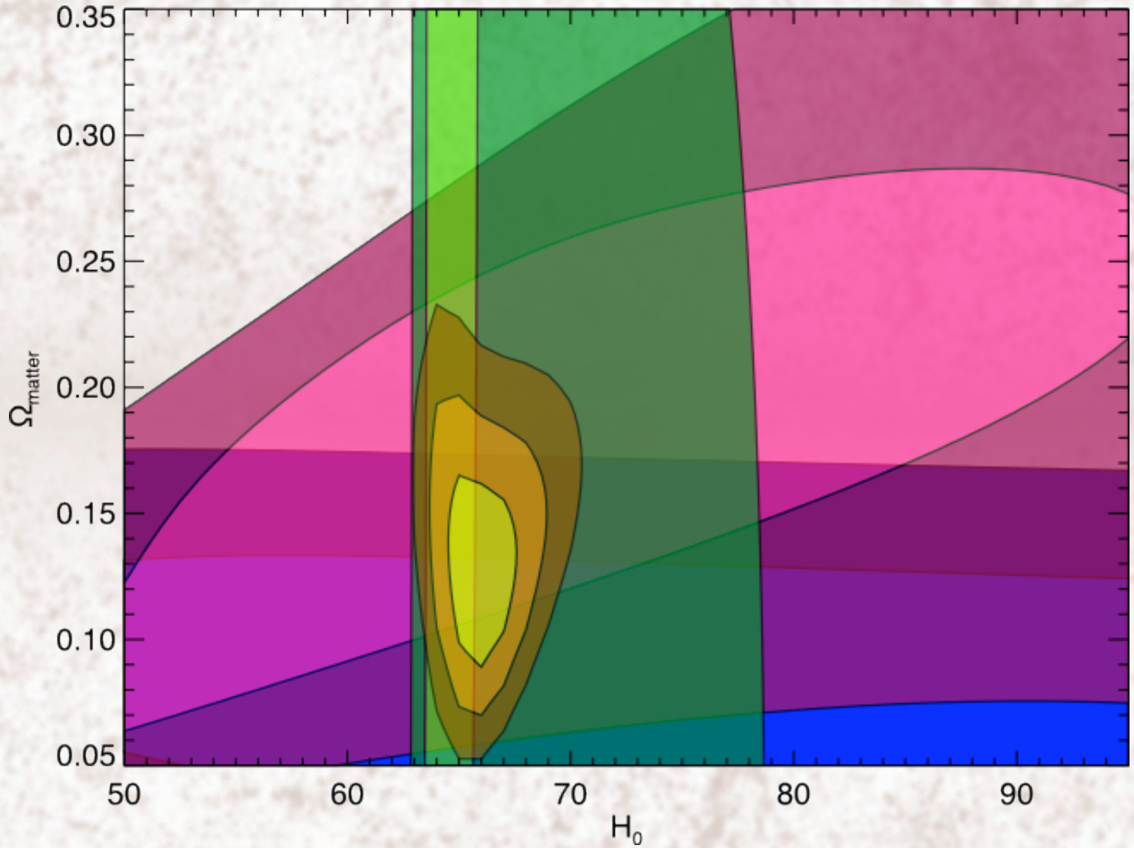
Fitting the 1st Peak in the CMB



The fit to the *first* peak is ok - we did not try to fit all data

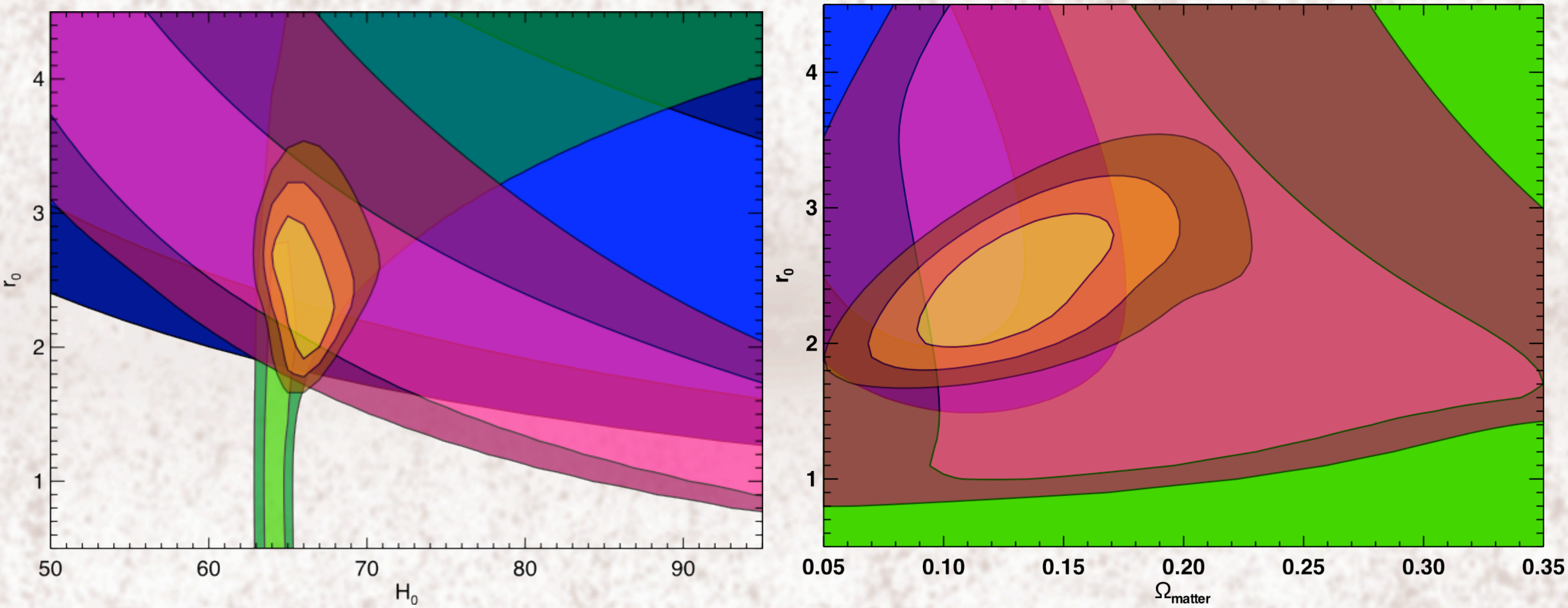
LTB perturbation theory (work in progress) to explain low *l* (ISW)

Scanning the Model Space



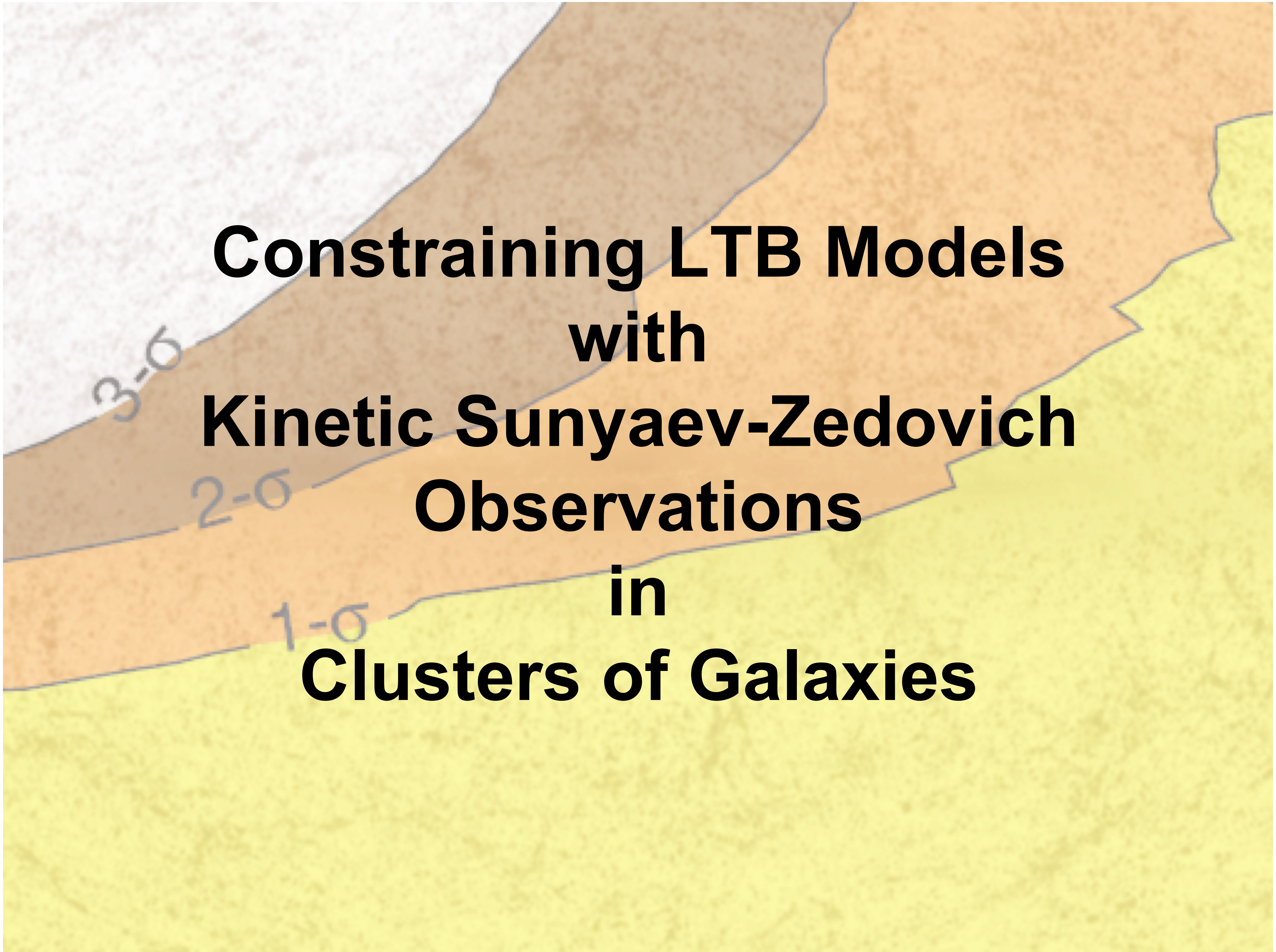
- Yellow: Everything, Blue: SNe Ia. Green: CMB. Purple: BAO
- The Type Ia Supernovae constrain Ω_{matter}
- CMB constrains the Hubble param, because Ω_{out}=1 & ω_b=const

Scanning the Model Space



- **Yellow: Everything, Blue: SNe Ia. Green: CMB. Purple: BAO**
- The SNe and BAO pushes the void size to > 1.5 Gpc
- Some tension between BAO and SNe (waiting for high-z SNe)

Constraining LTB Models with Kinetic Sunyaev-Zedovich Observations in Clusters of Galaxies



The Kinetic Sunyaev-Zeldovich Effect

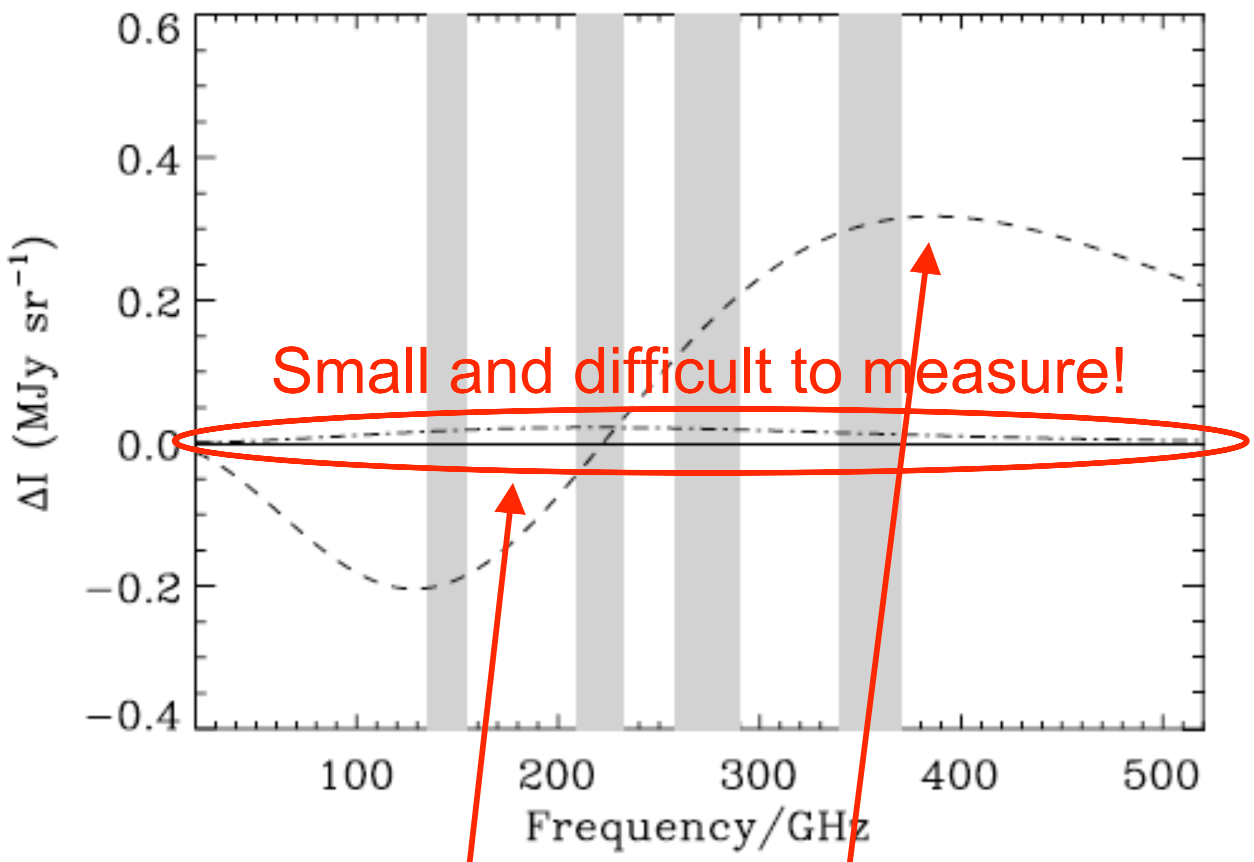
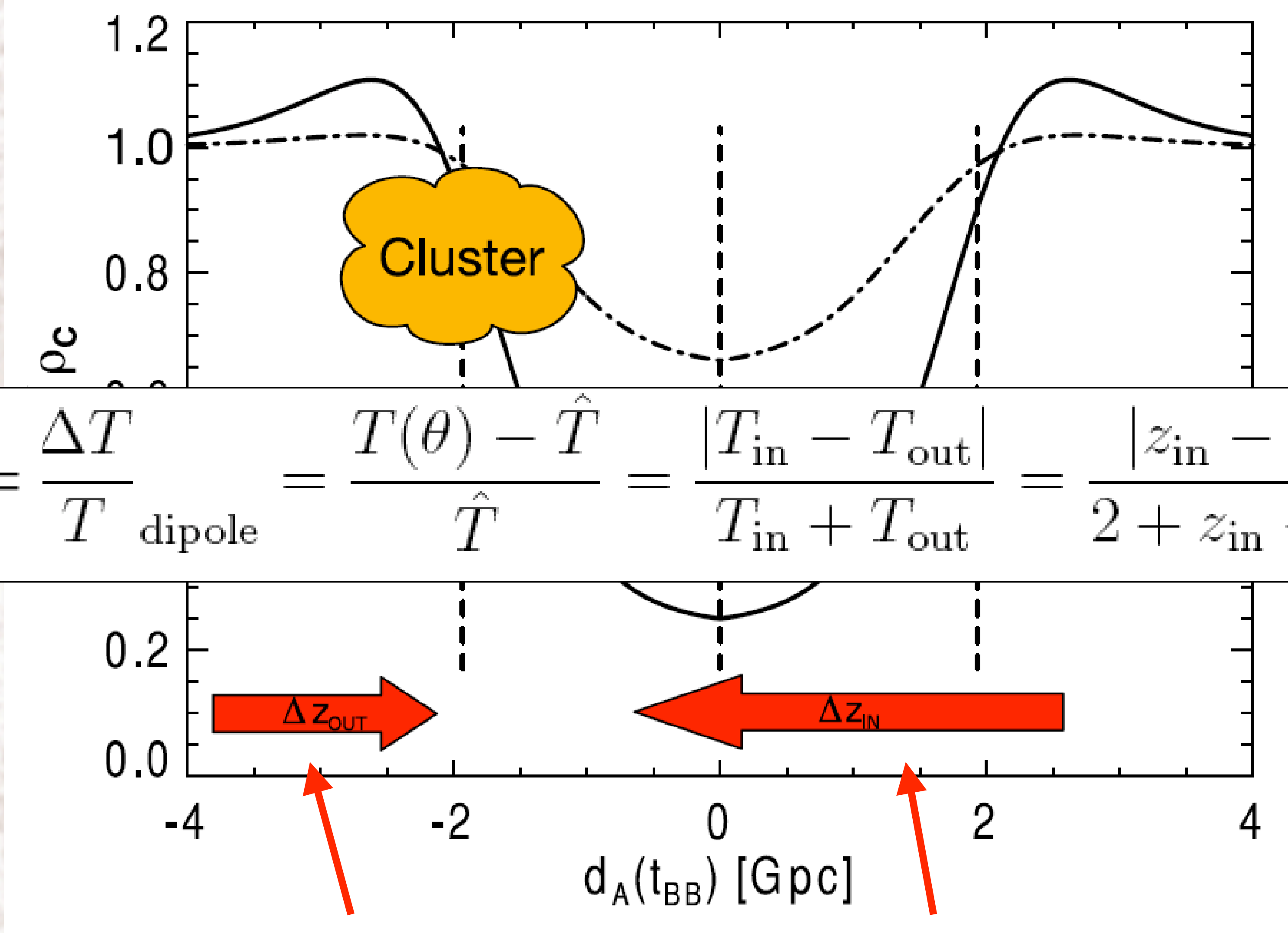


FIG. 1.—Frequency dependence of the SZ effect for a cluster with optical depth $\tau = 0.01$, gas temperature 10 keV, and a peculiar velocity of -500 km s^{-1} (toward the observer). The thermal SZ spectrum is indicated by the dashed line, the kinematic effect by the dot-dashed line. The shaded regions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

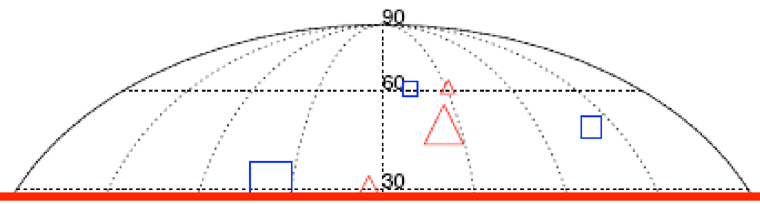
The Induced Dipole for an Off-centered Cluster

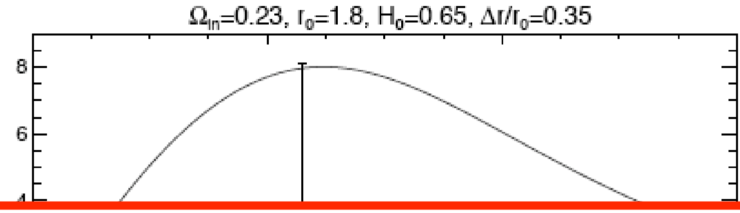


$$\frac{v_p}{c} = \frac{\Delta T}{T}_{\text{dipole}} = \frac{T(\theta) - \hat{T}}{\hat{T}} = \frac{|T_{\text{in}} - T_{\text{out}}|}{T_{\text{in}} + T_{\text{out}}} = \frac{|z_{\text{in}} - z_{\text{out}}|}{2 + z_{\text{in}} + z_{\text{out}}}$$

Different expansion histories => different redshifts!

Current Bounds from Observations

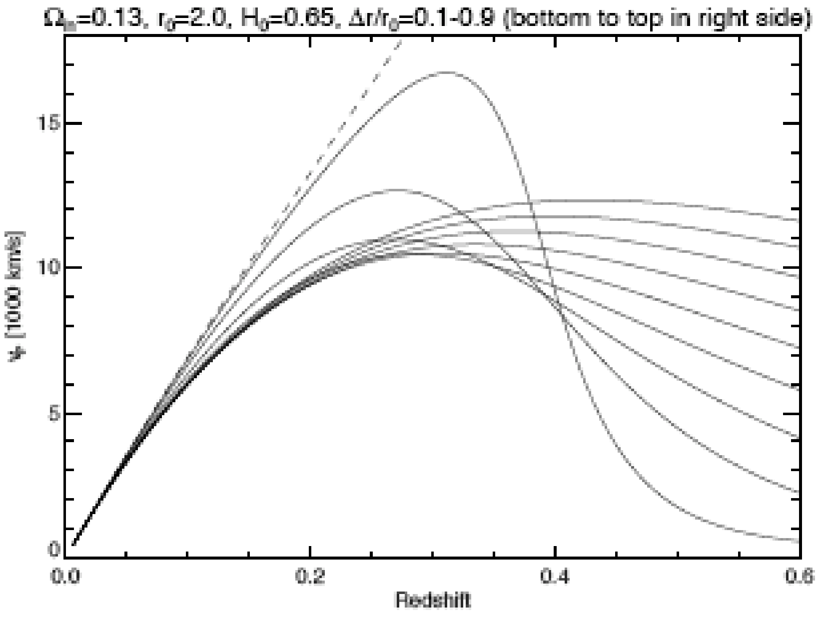


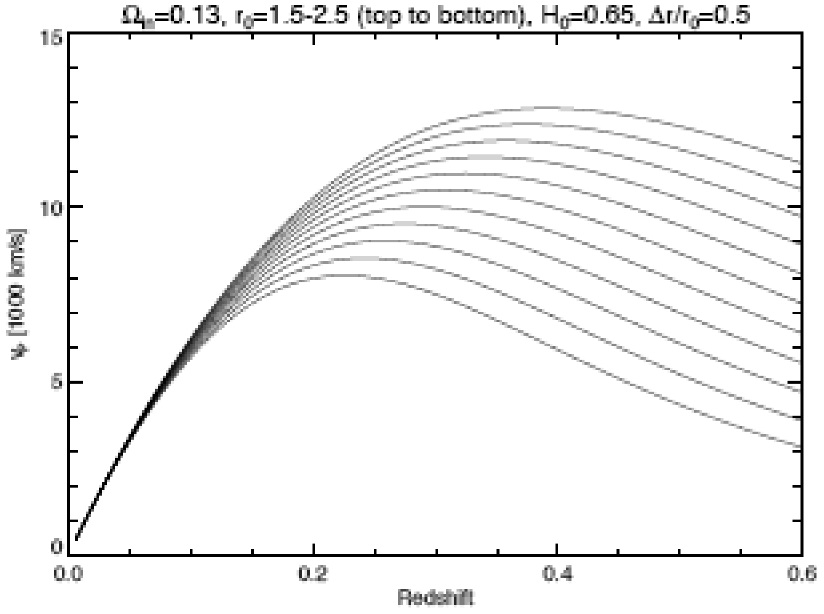


Something fishy with the internal velocity scatter ?

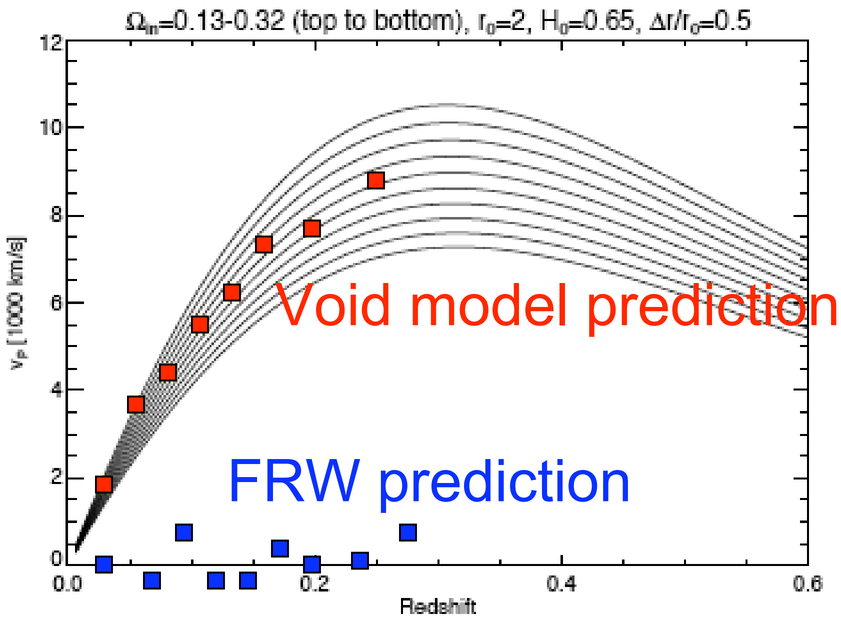
Sample	$\bar{v}$ [km s^{-1}]	σ_v [km s^{-1}]	#clusters
All clusters	320^{+440}_{-400}	1630^{+400}_{-350}	9
Cluster in [41, 42]	190^{+480}_{-430}	1630^{+440}_{-370}	8
Clusters in [42]	-250^{+750}_{-660}	2210^{+710}_{-580}	6

Forecasted kSZ for LTB models





$$\frac{v_p}{c} = \frac{h_{in} - h_{out}}{3000\,\mathrm{Mpc}} d_{obs}$$



Bounds from Current Observations
- and the role of uncertainties -

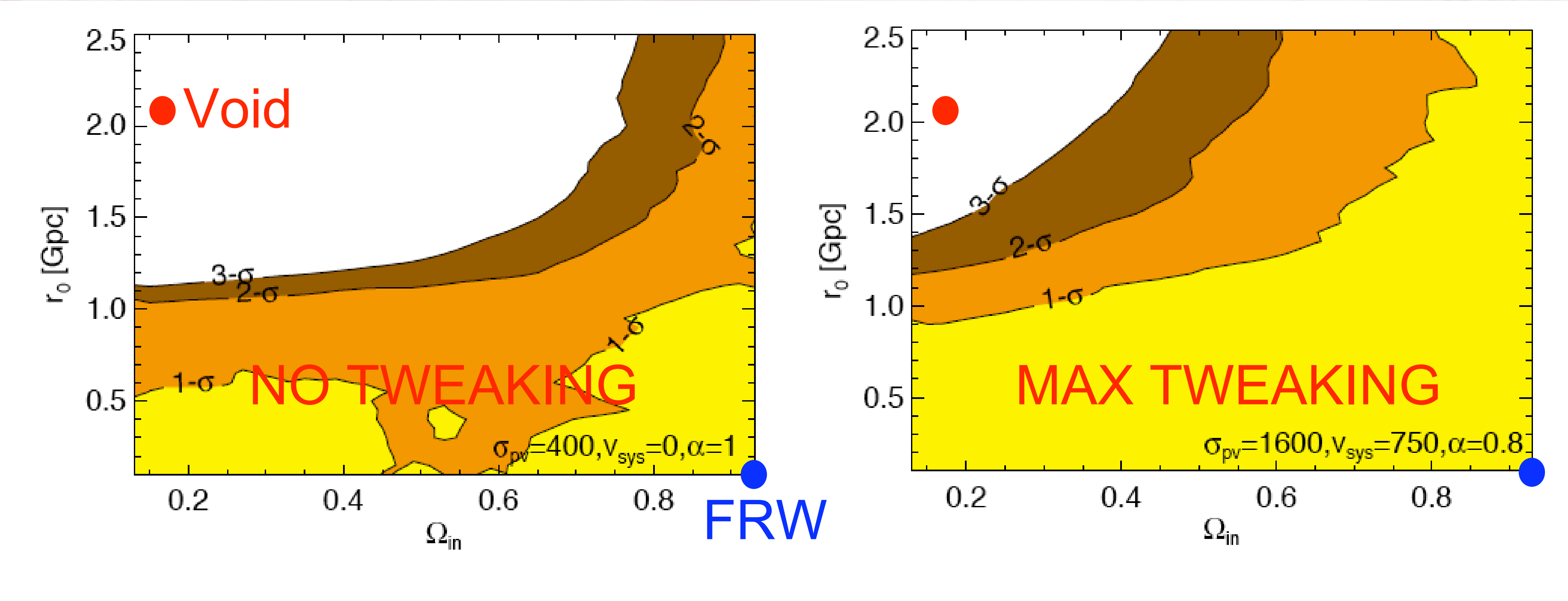
Theoretical error

Observed velocity

$$-2\ln\mathcal{L} = \sum_i \left[\frac{\boxed{v_i} - \boxed{\alpha}\, v(\vec{p}, z_i) + \boxed{v_{\rm sys}}}{\left[\sigma_i^{\pm 2} + \boxed{\sigma_{\rm pv}^2}\right]^{1/2}}\right]^2$$

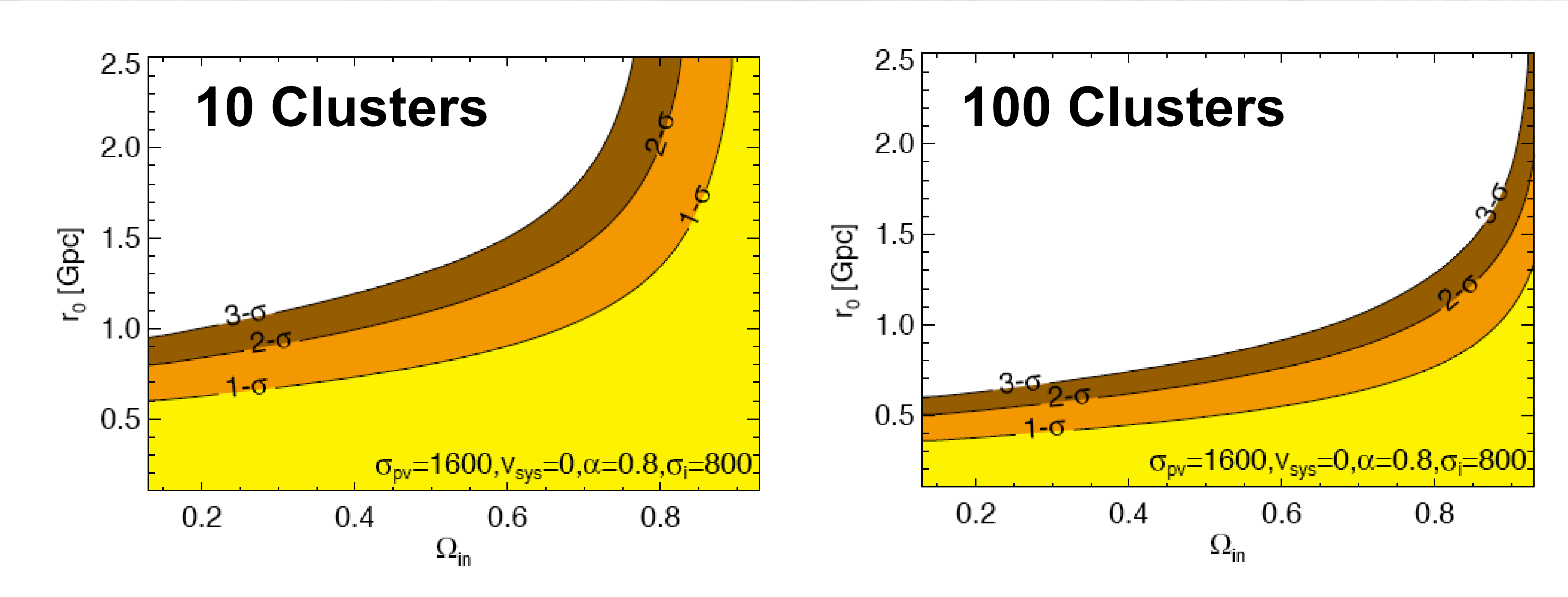
Systematic shift

Peculiar velocity scatter



Future Bounds from ACT or SPT

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



Conclusions

- Our model can convincingly fit a large set of current cosmological observations and do it as well as the ΛCDM model.
- The best fit void size is ~2.3±1 Gpc, approximately the size of the cold spot.
- LTB models are in mild contradiction with current kinetic Sunyaev-Zeldovich observations, if we believe them.
- In a years time or so the ACT will report their first results, and either large scale voids are ruled out or confirmed.
- It seems clear that kSZ measurements will put by far the strongest observational constraints on LTB models compared to other cosmological data.