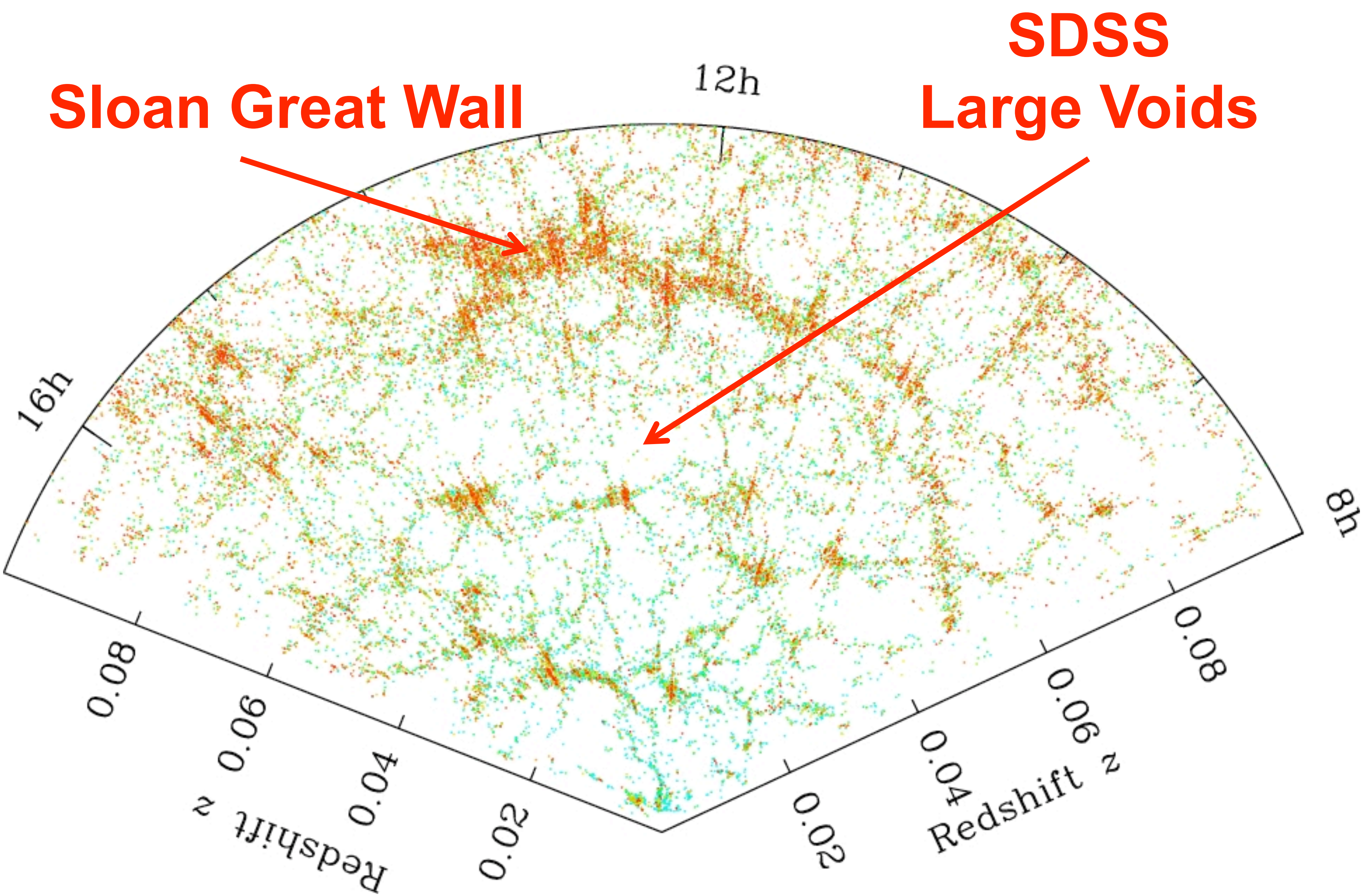
DO WE LIVE INSIDE A BIG VOID?

COSMO 2009
CERN
7th September 2009

Juan García-Bellido
IFT-UAM/CSIC
CERN

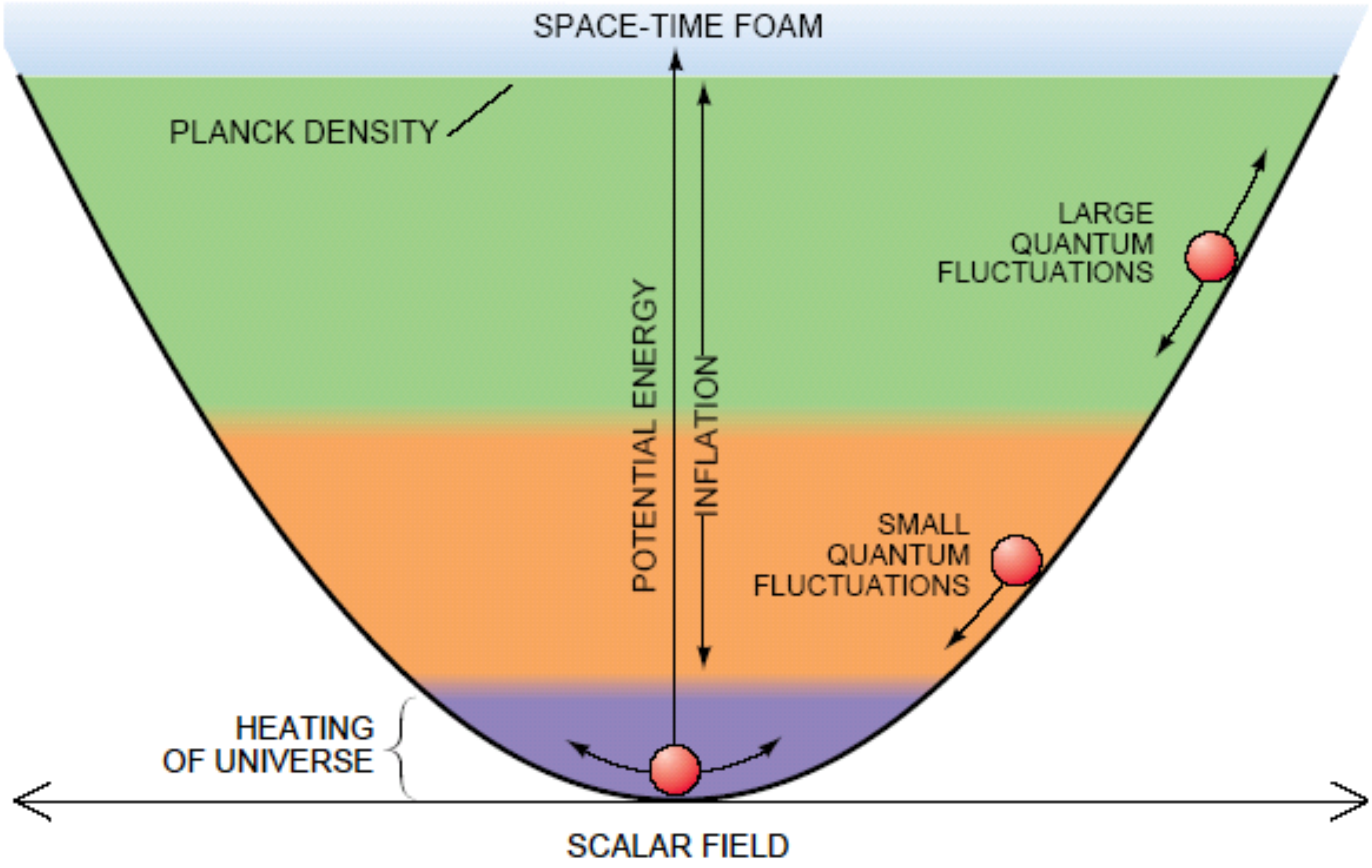


SDSS
Large Voids
Sloan Great Wall
12h
16h
8h
0.08
0.06
0.04
0.02
Redshift z
0.08
0.06
0.04
0.02
Redshift z

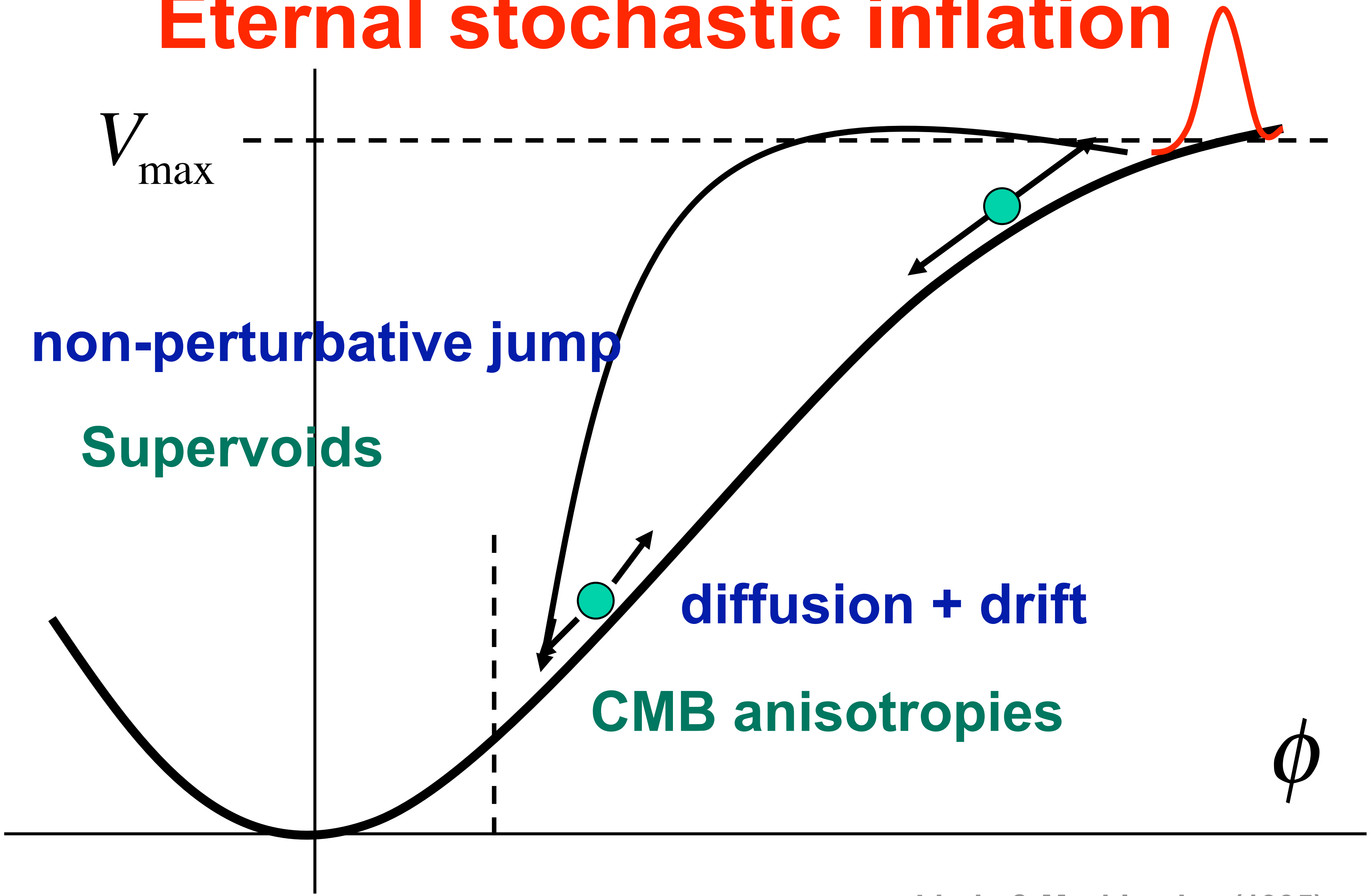
If we live in a highly inhomogeneous Universe…

what is
the origin of
dens. perturbations?

Chaotic Inflation



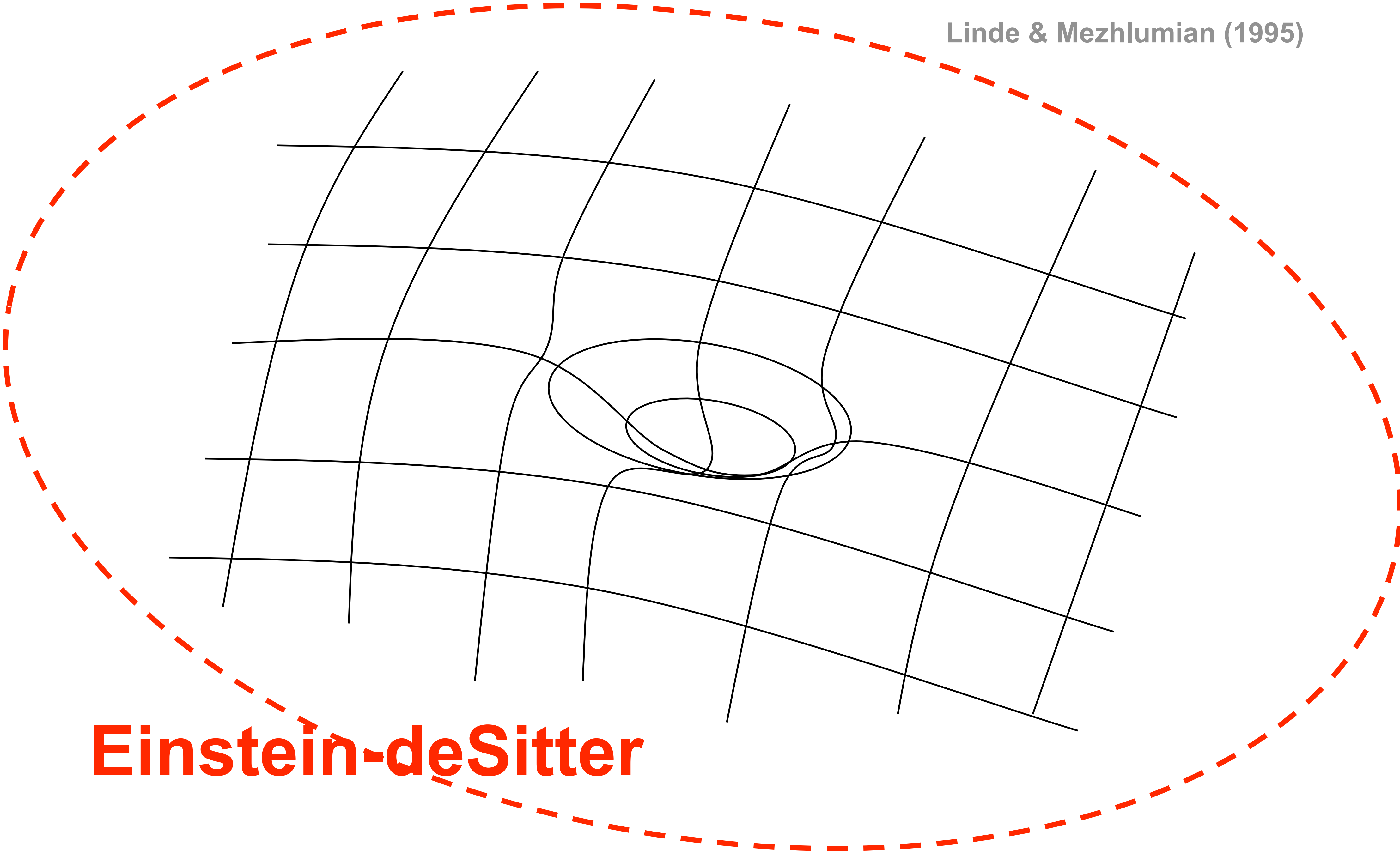
Eternal stochastic inflation



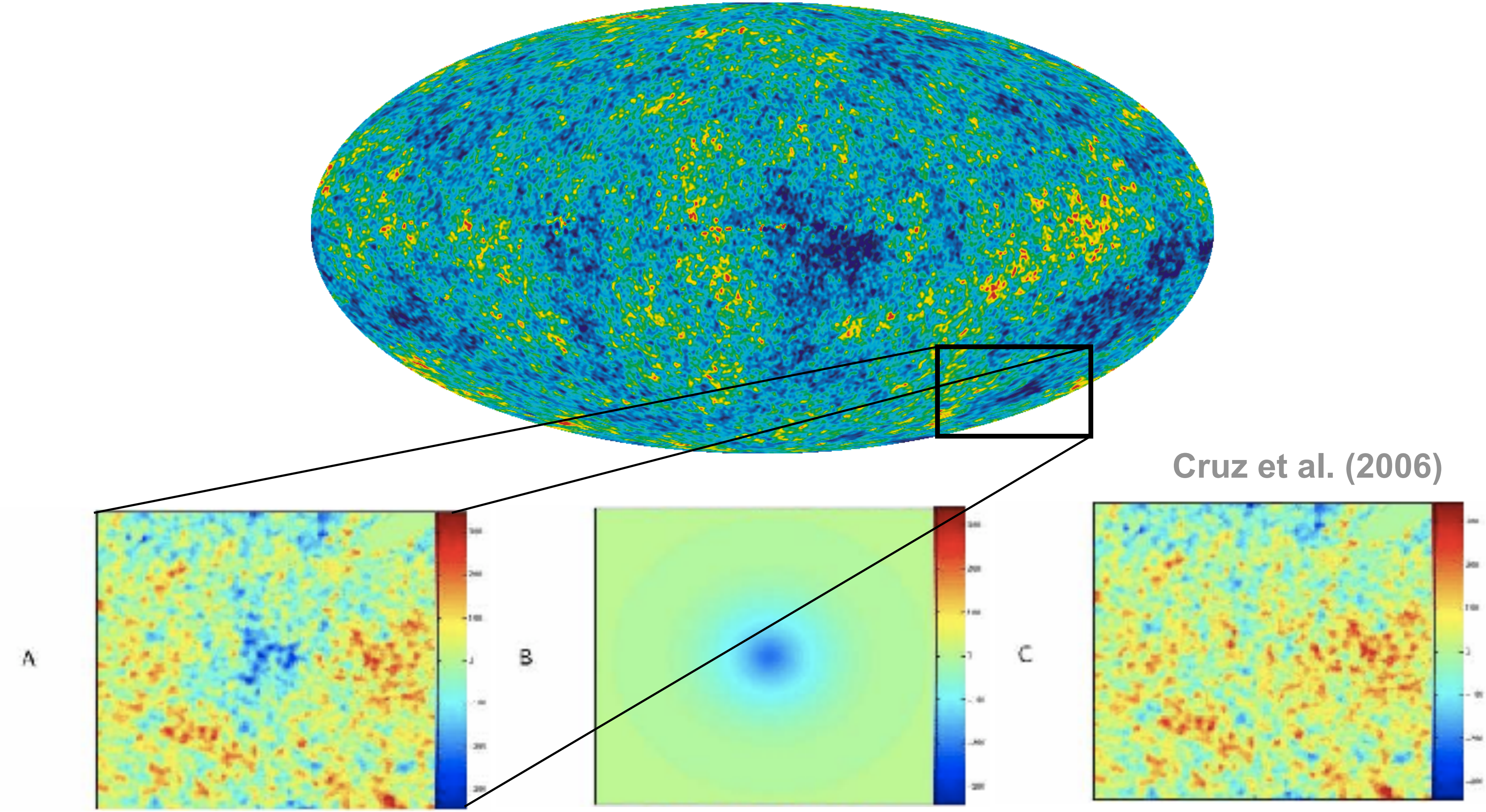
Linde & Mezhlumian (1995)

Infloid = Lemaitre-Tolman-Bondi Model

Linde & Mezhlumian (1995)



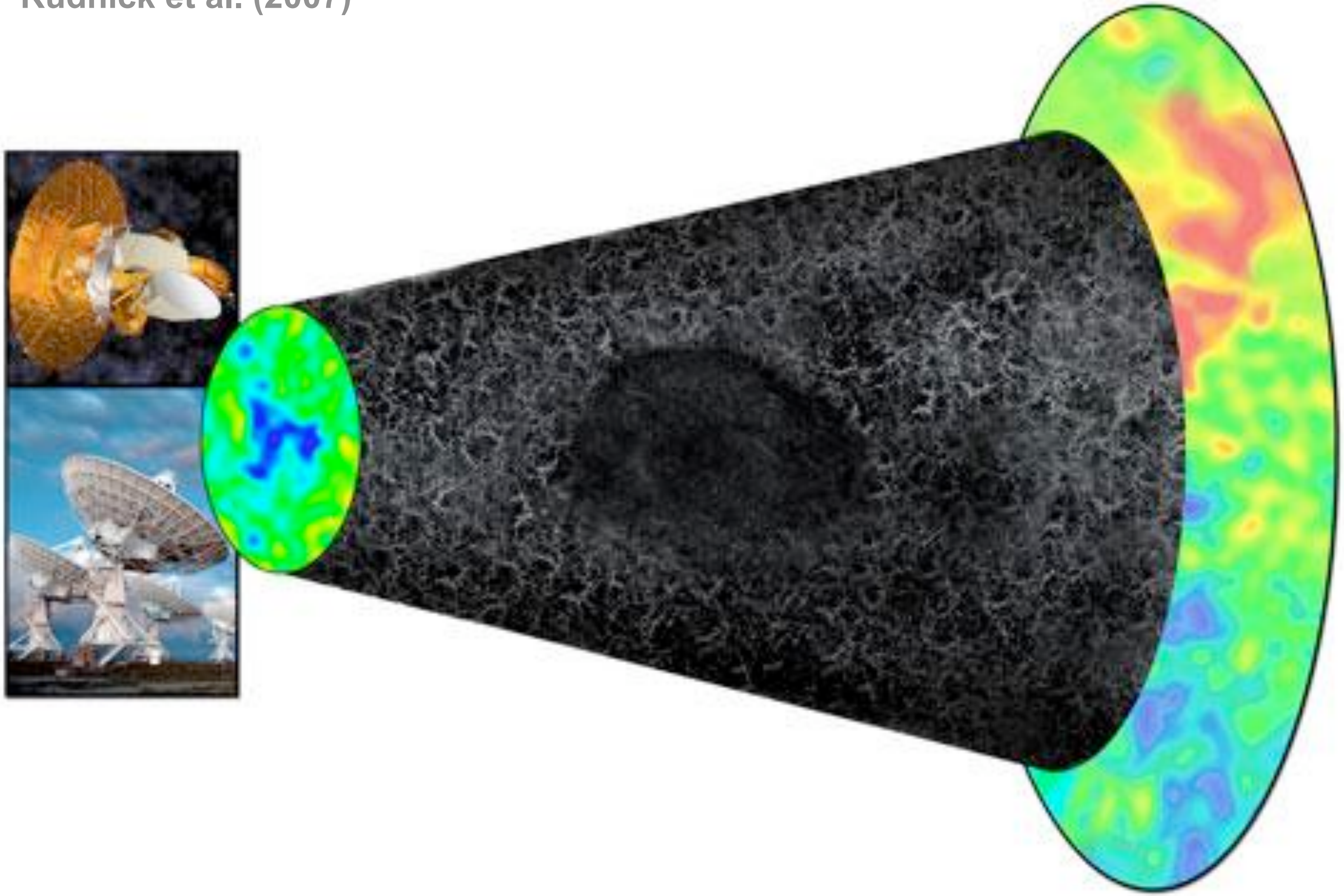
Could the Cold Spot in CMB be an "infloid" ?



A large void, approximately 2 Gpc in size

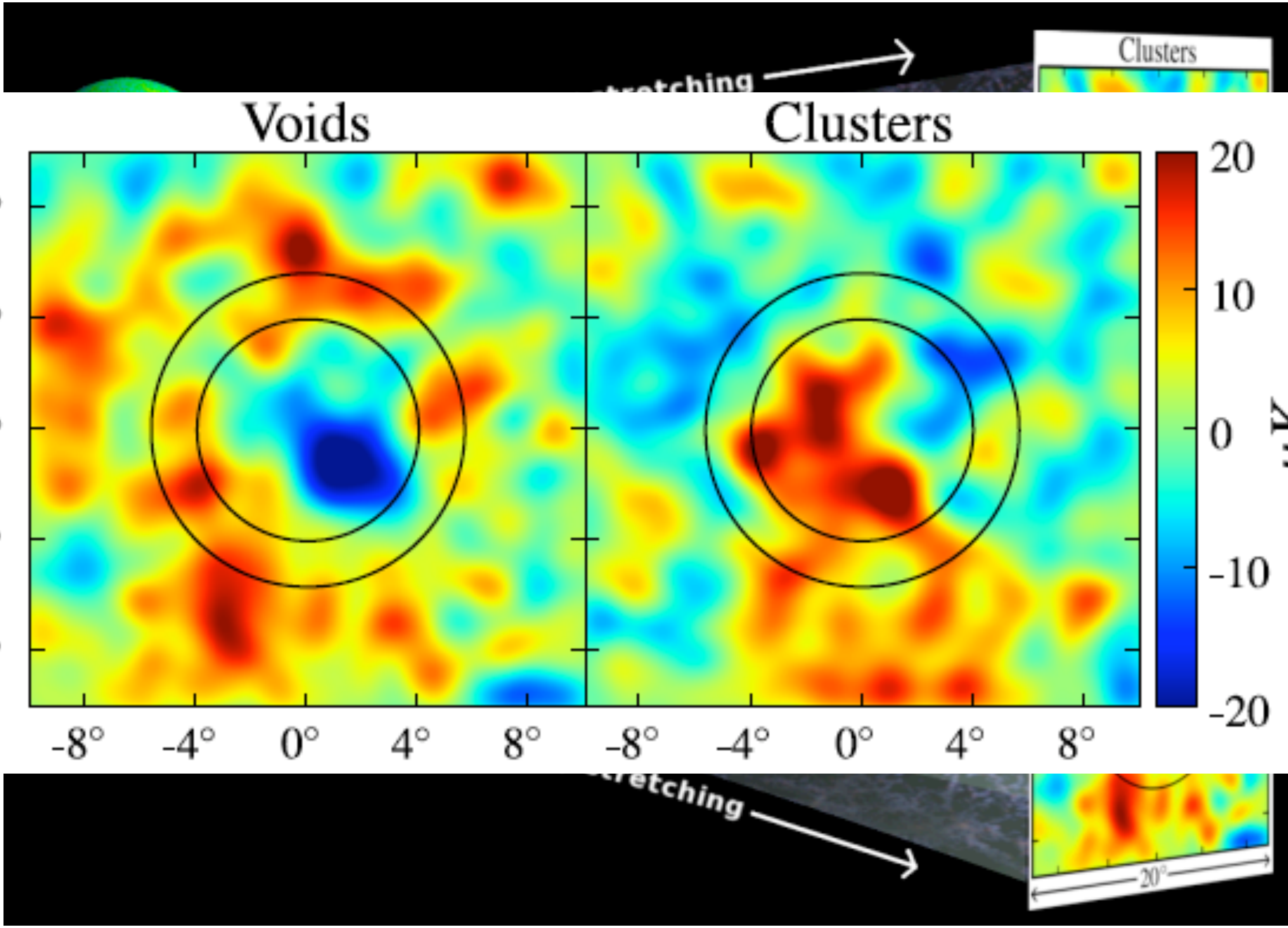
Could the Cold Spot in CMB be an “infloid” ?

Rudnick et al. (2007)



Voids and Superclusters in SDSS

Granett et al. (2008)



The Lemaître-Tolman-Bondi Model

Celerier (1999), Tomita(2000), Moffat (2005), Alnes et al. (2005)

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

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

- From the 0-r part of the Einstein-Equations we get:

$$X(r,t) \quad = \quad A'(r,t)/\sqrt{1-k(r)}$$

- One can recover the FRW model setting:

$$A(r,t) = a(t)\,r \qquad k(r) = k\,r^2$$

The Lemaitre-Tolman-Bondi Model

- Matter content:

$$T^{\mu}_{\nu} = -\rho_M(r,t)\,\delta^{\mu}_{0}\,\delta^{0}_{\nu}$$

- The other Einstein equations give:

$$\frac{\dot{A}^2 + k}{A^2} + 2\frac{\dot{A}\dot{A}'}{AA'} + \frac{k'(r)}{AA'} = 8\pi G\,\rho_M$$

$$\dot{A}^2 + 2A\ddot{A} + k(r) = 0$$

- Integrating the last equation:

Enqvist & Mattsson(2006)

$$\frac{\dot{A}^2}{A^2} = \frac{F(r)}{A^3} - \frac{k(r)}{A^2}$$

The Lemaitre-Tolman-Bondi Model

García-Bellido & Haugbølle (2008)

- All we need to specify:

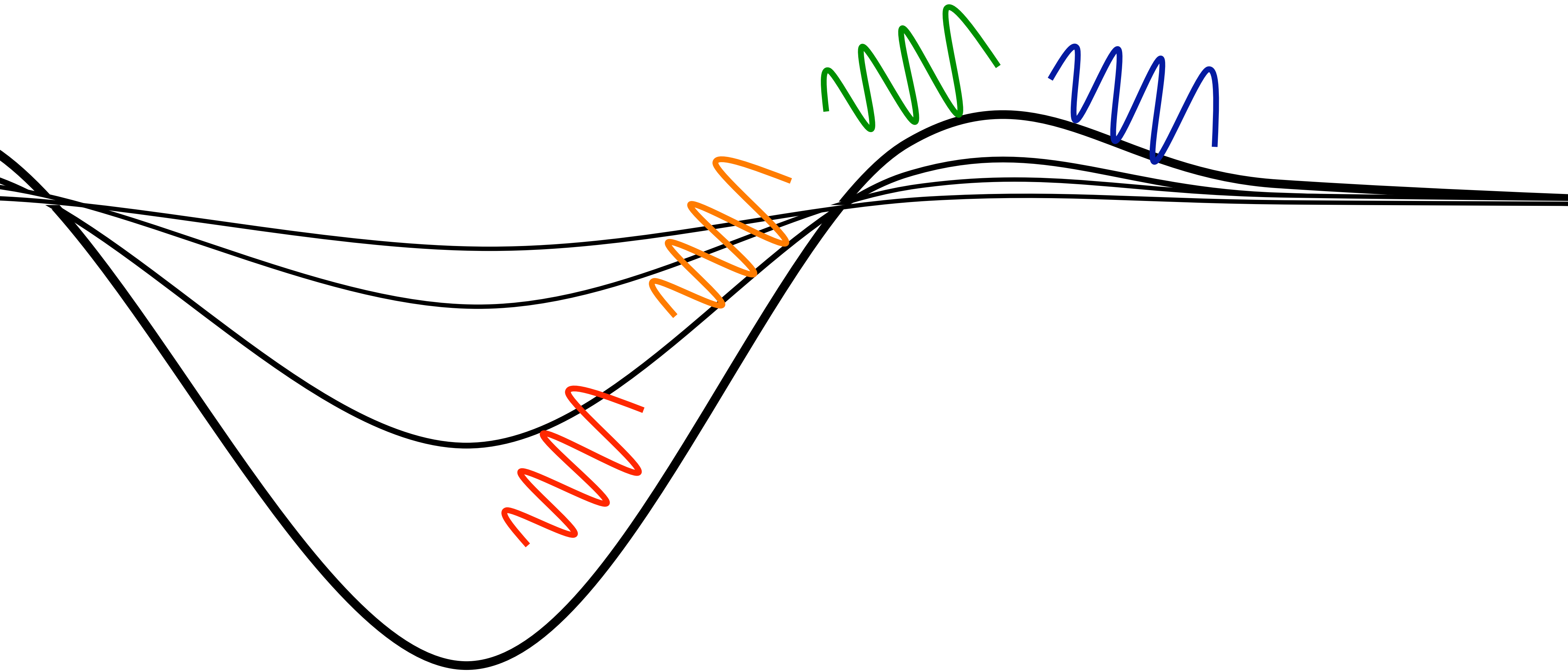
$$F(r) = H_0^2(r)\,\Omega_M(r)\,A_0^3(r)$$

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

- Then the Hubble rate can be integrated to give A(r,t):

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

Density profile



Light Ray Propagation

- By looking at the geodesic equation, we can find the equation of motion for light rays:

$$\frac{dt}{dN} = -\frac{A'(r,t)}{\dot{A}'(r,t)} \qquad \frac{dr}{dN} = \frac{\sqrt{1-k(r)}}{\dot{A}'(r,t)}$$

where N = ln(1+z) are the # e-folds before present time.

- The various distances as a function of redshift are:

$$d_L(z) = (1+z)^2 A[r(z), t(z)]$$

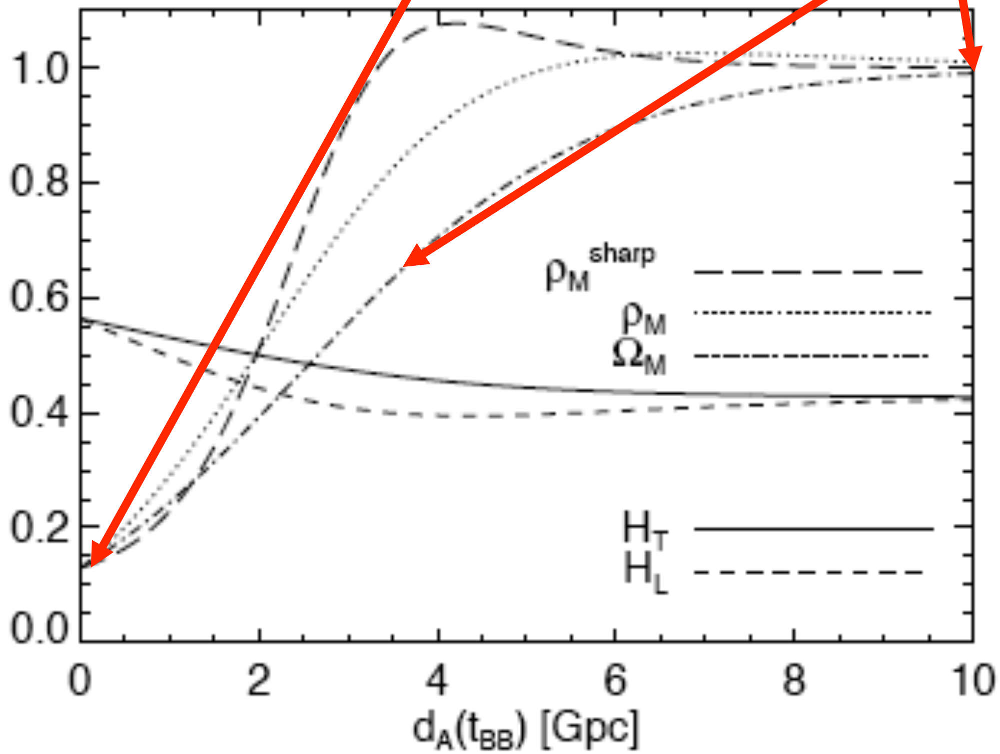
$$d_C(z) = (1+z)\, A[r(z), t(z)]$$

$$d_A(z) = A[r(z), t(z)]$$

The LTB-GBH model

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

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



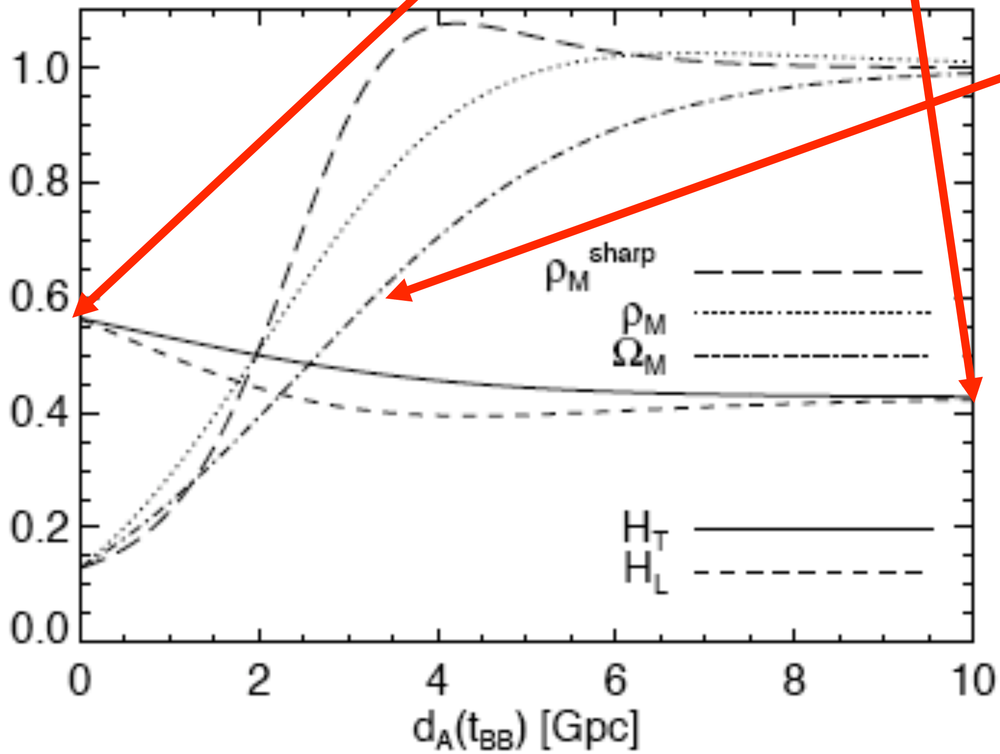
- If we assume asymptotic flatness, then the model has **5** parameters
- If we require a homogeneous Big Bang then the model has **4** parameters

García-Bellido & Haugbølle (2008)

The LTB-GBH model

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

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



- If we assume asymptotic flatness, then the model has **5** parameters
- If we require a homogeneous Big Bang then the model has **4** parameters

García-Bellido & Haugbølle (2008)

Constraining Cosmological Data

- Type Ia Supernovae: 307 SNIa Union Supernovae

  Simple to do since we just fit against $d_L(z)$

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

3 distances

- Baryon Acoustic Oscillations:

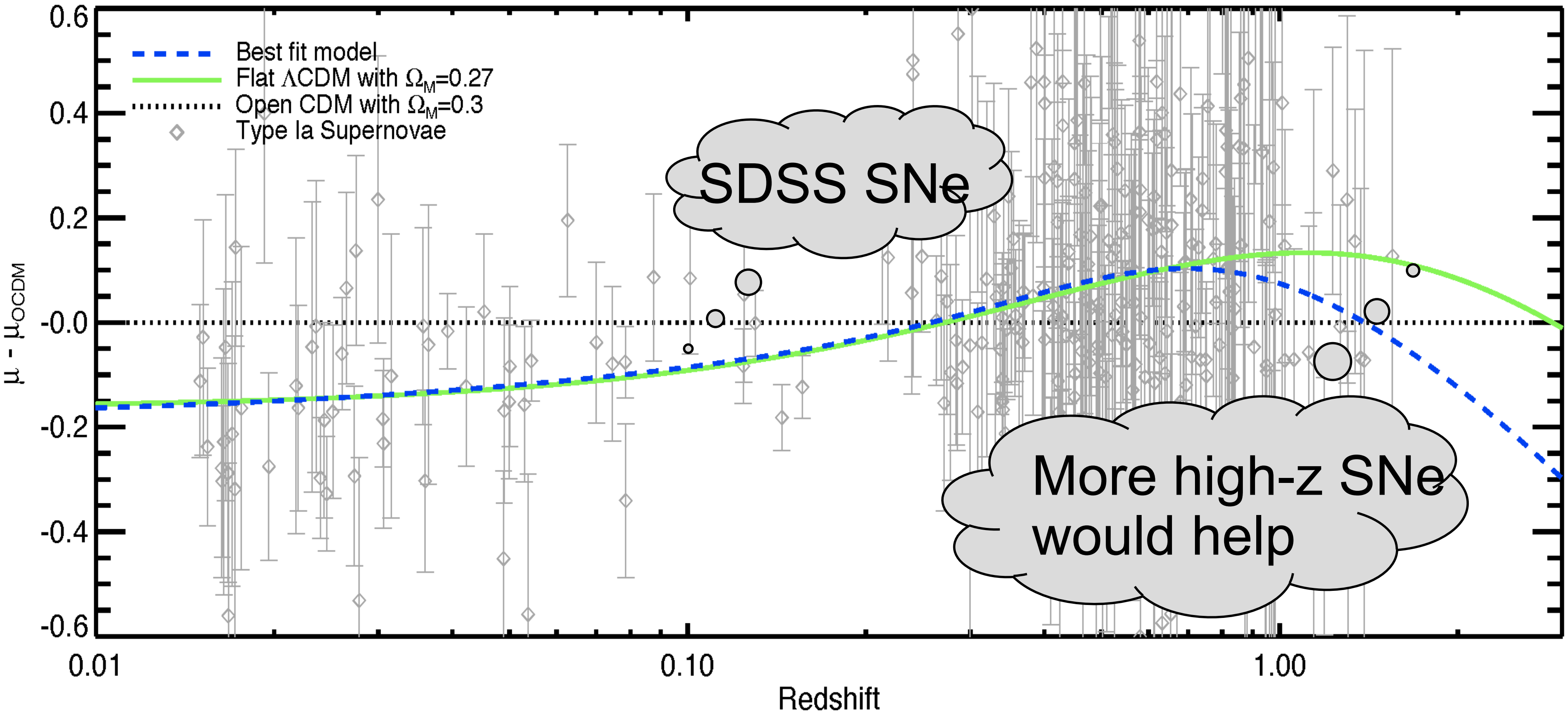
  Sound horizon $$D_V(z) = \left[d_A^2(z)(1+z)^2 \frac{cz}{H_L(z)} \right]^{1/3}$$

- Other constraints:
  - $f_{gas} = \rho_b / \rho_m = \omega_b / (\Omega_m h^2)$
  - Hubble key project: $H_0 = 72 \pm 8$ km/s/Mpc (1σ)
  - Globular cluster lifetimes ($t_{BB} > 11.2$ Gyr)

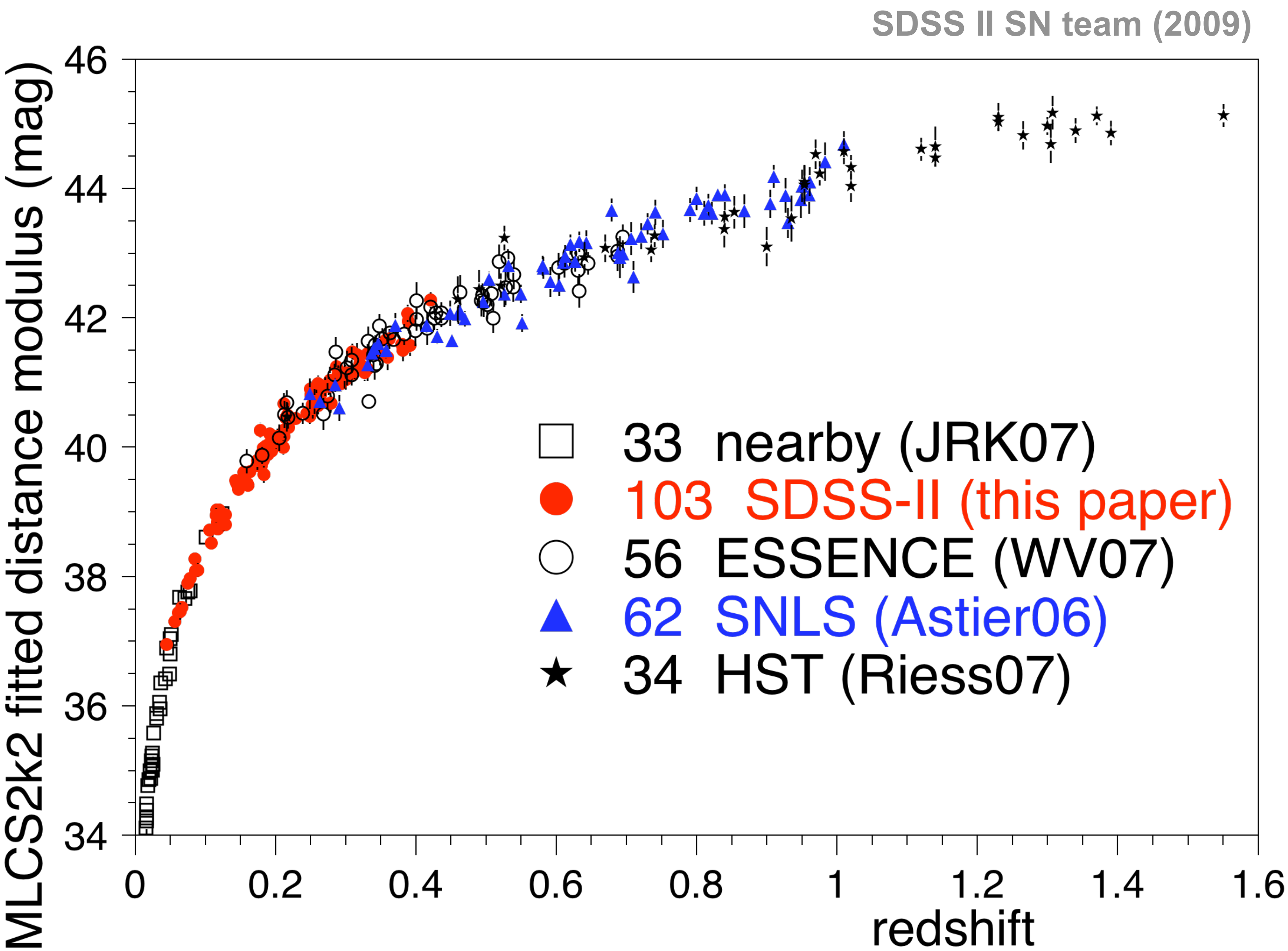
Fitting the Union Supernovae

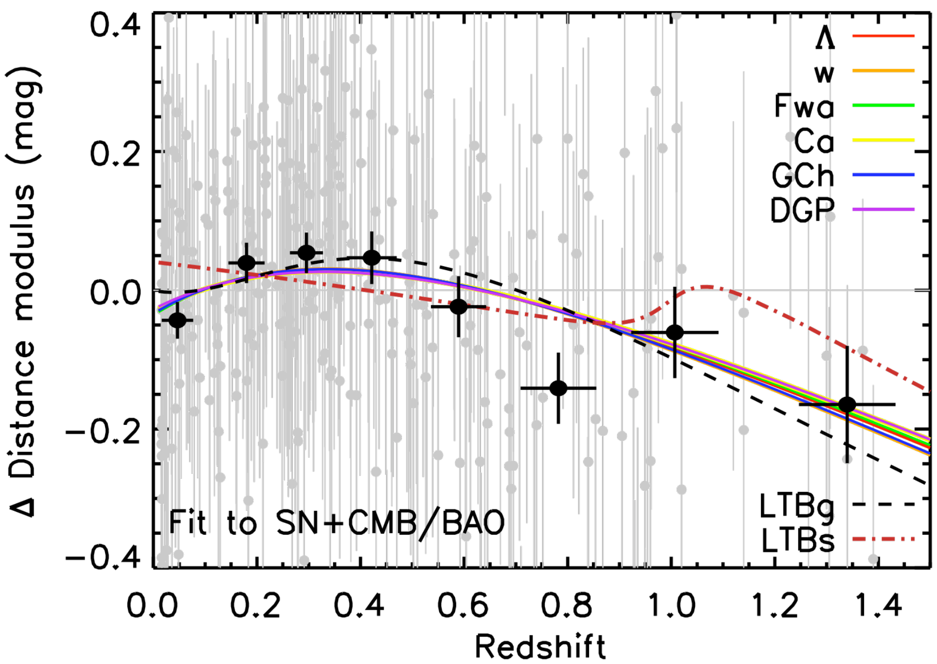
- The best fit GBH-model has no problem with SNe Ia
- One can always find a void model that fits SNe as ΛCDM

García-Bellido & Haugbølle (2009)



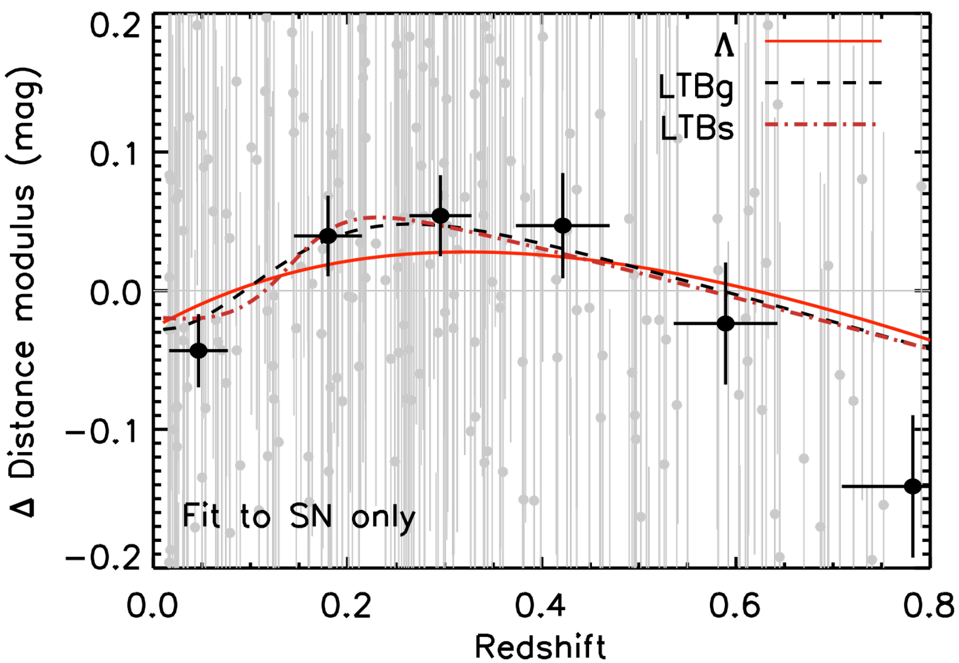
Fitting the SDSS II Supernovae



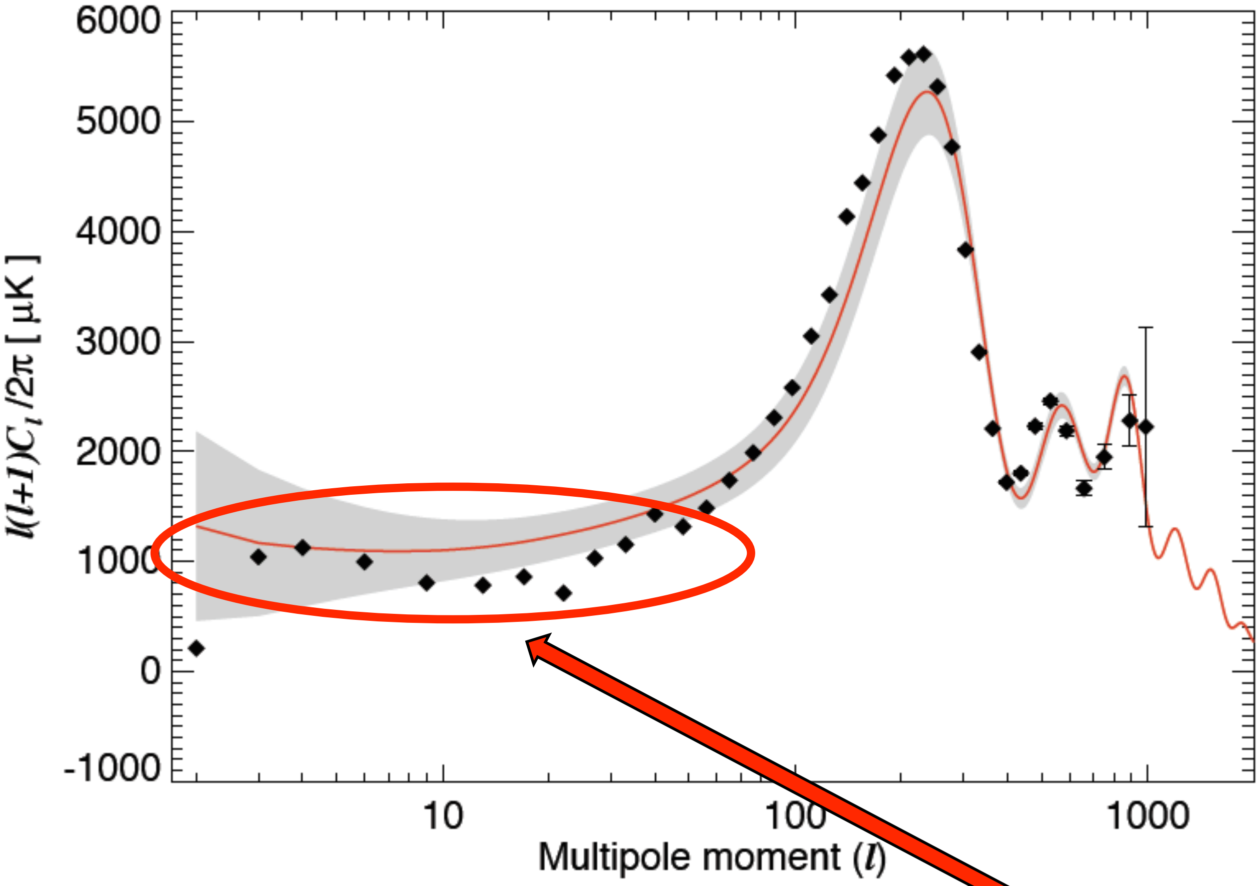


Fitting the SDSS II Supernovae

SDSS II SN team (2009)

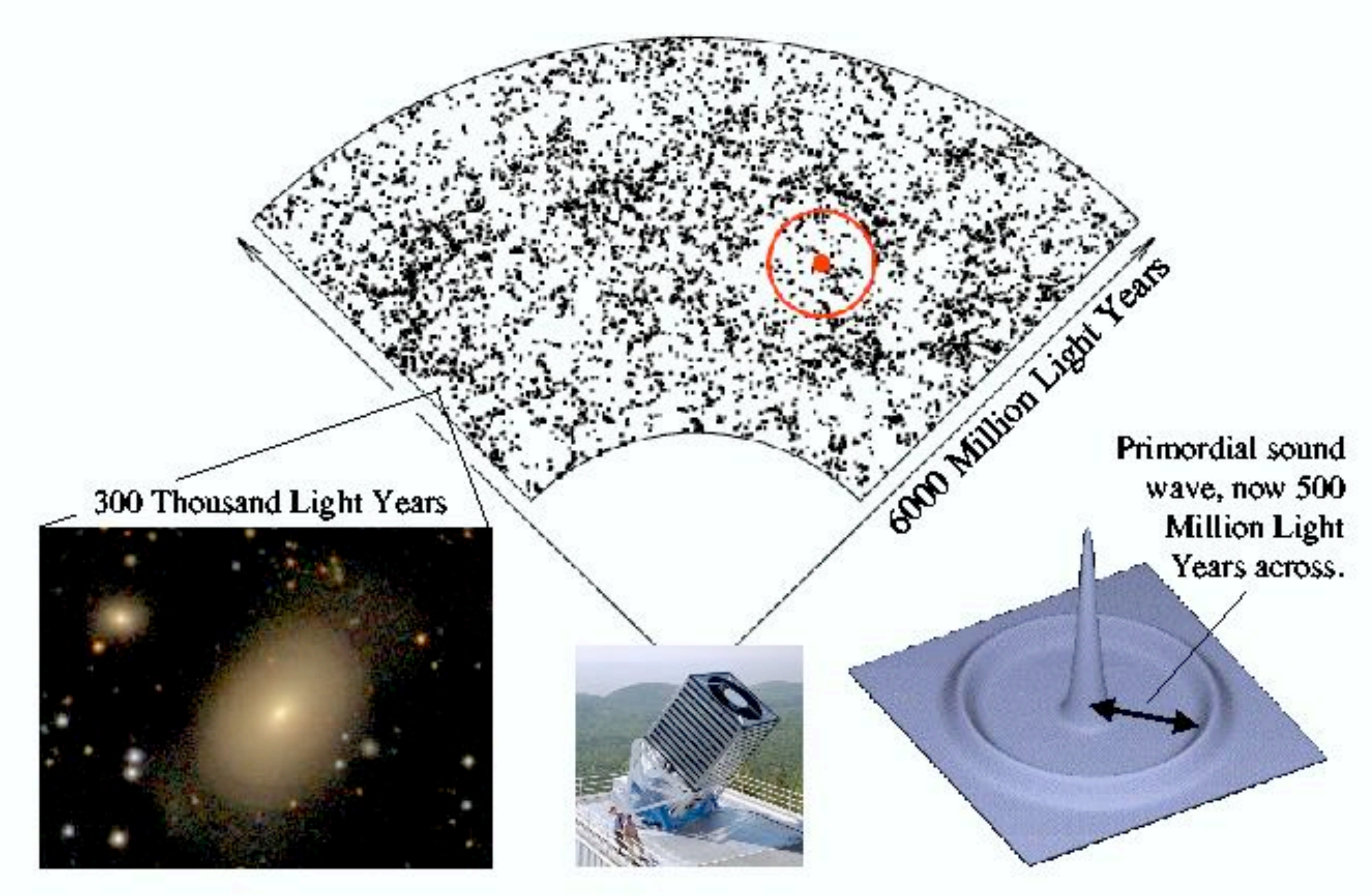


Fitting the acoustic peaks in the CMB



- 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)

Baryon Acoustic Oscillations



Radial BAO & LTB

$$\Delta z_{BAO}(z_i) = \frac{H(z_i) r_s}{c}$$

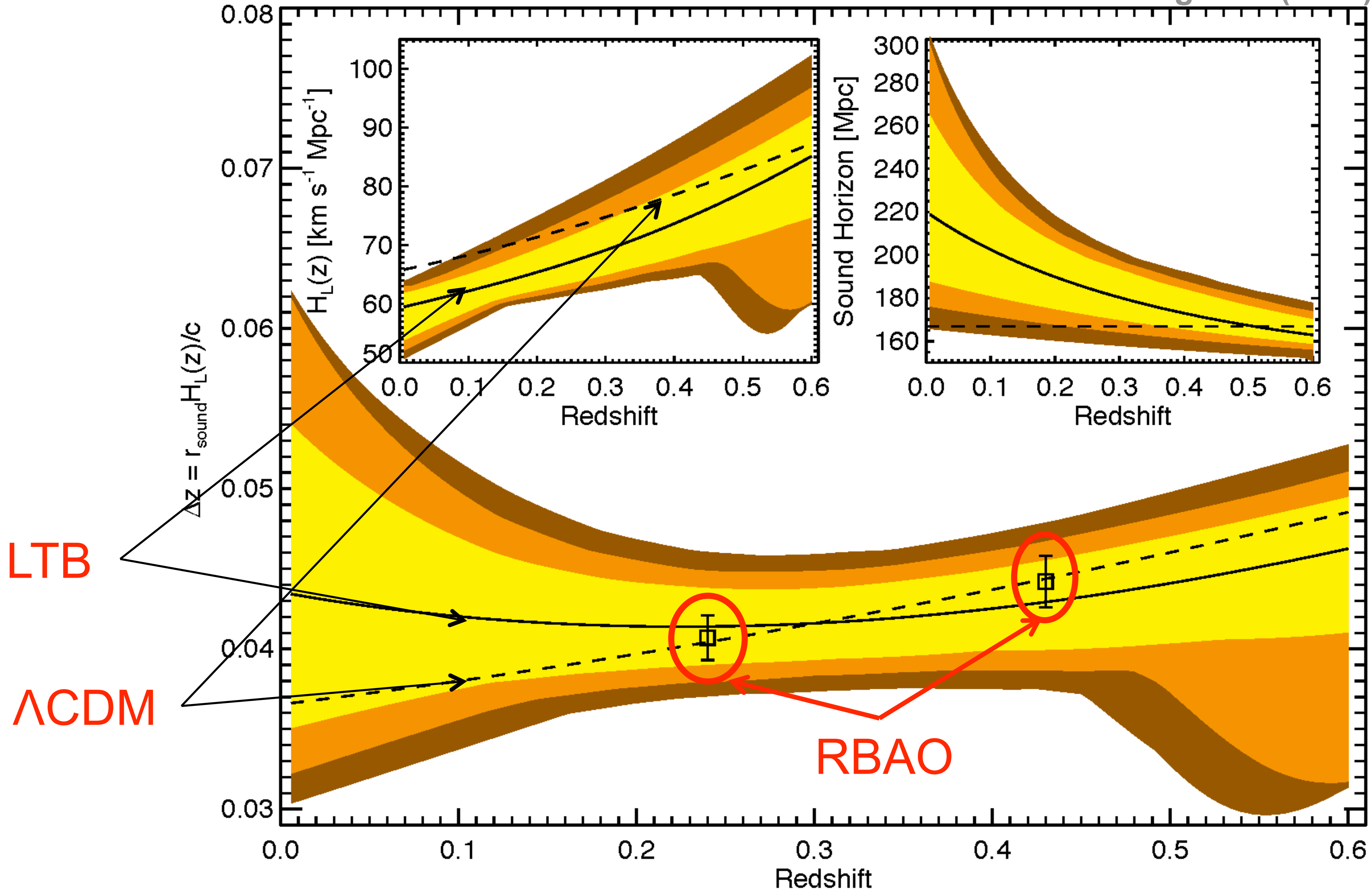
scaled distances: $$\Delta z_{LTB} = \frac{H_L(z) r_s(z)}{c}$$

r_s = sound horizon at recombination

Sample z range	z_m	r_{BAO} Mpc/h	σ_{st}	σ_{sys}	Δz_{BAO}	σ_{st}	σ_{sys}
0.15-0.30	0.24	110.3	2.5	1.35	0.0407	0.0009	0.0005
0.40-0.47	0.43	108.9	2.8	1.22	0.0442	0.0011	0.0005

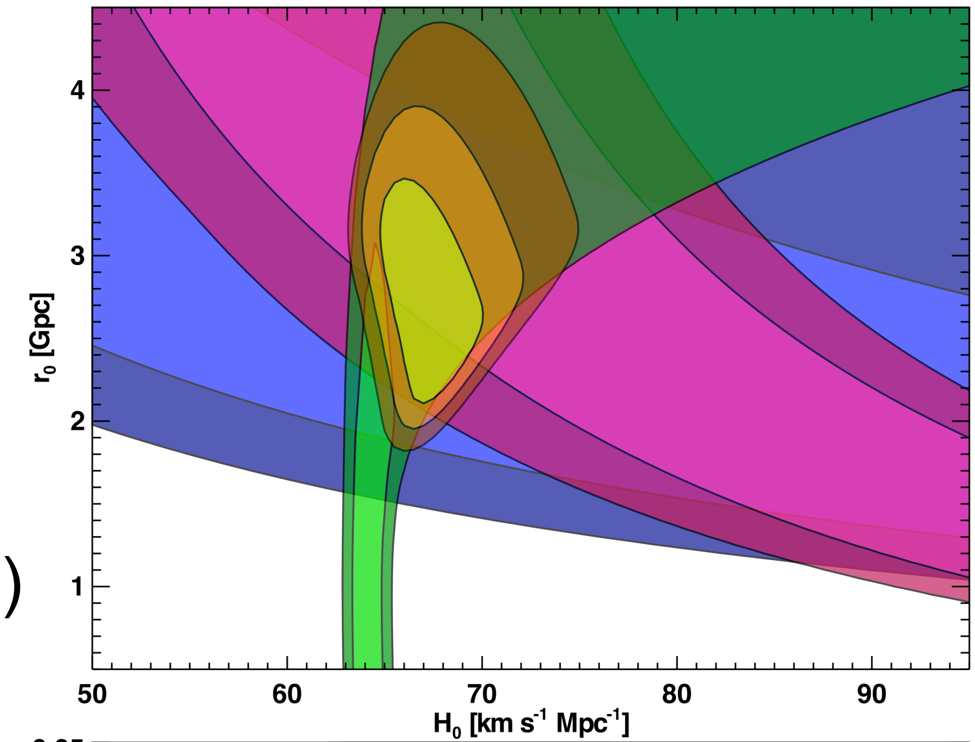
Sound horizon and line of sight rate of expansion

García-Bellido & Haugbølle (2009)

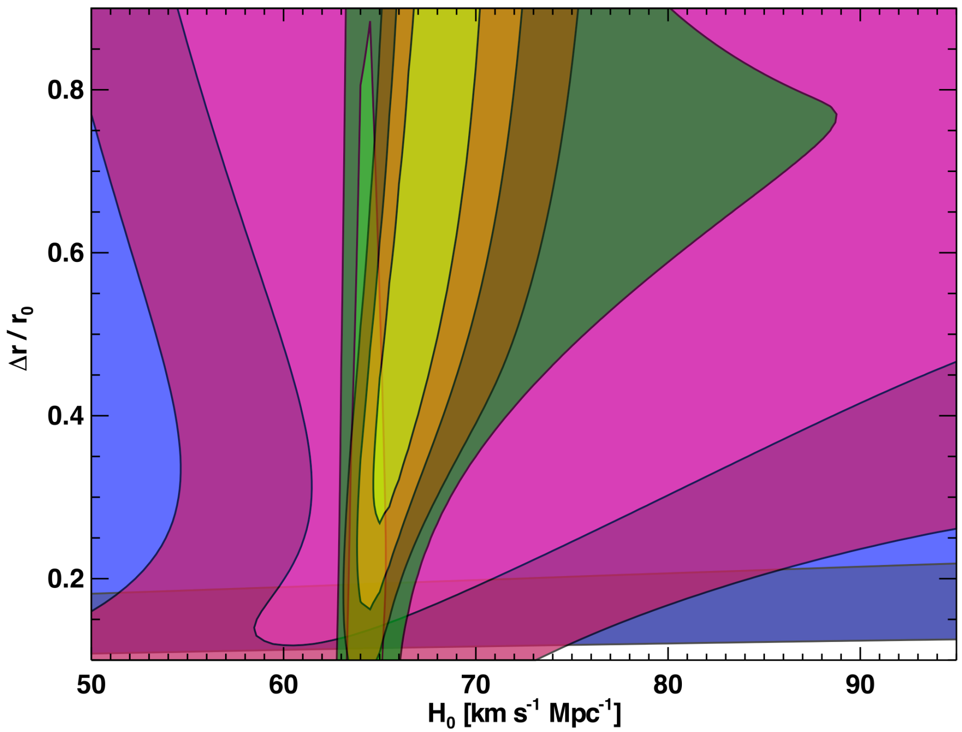


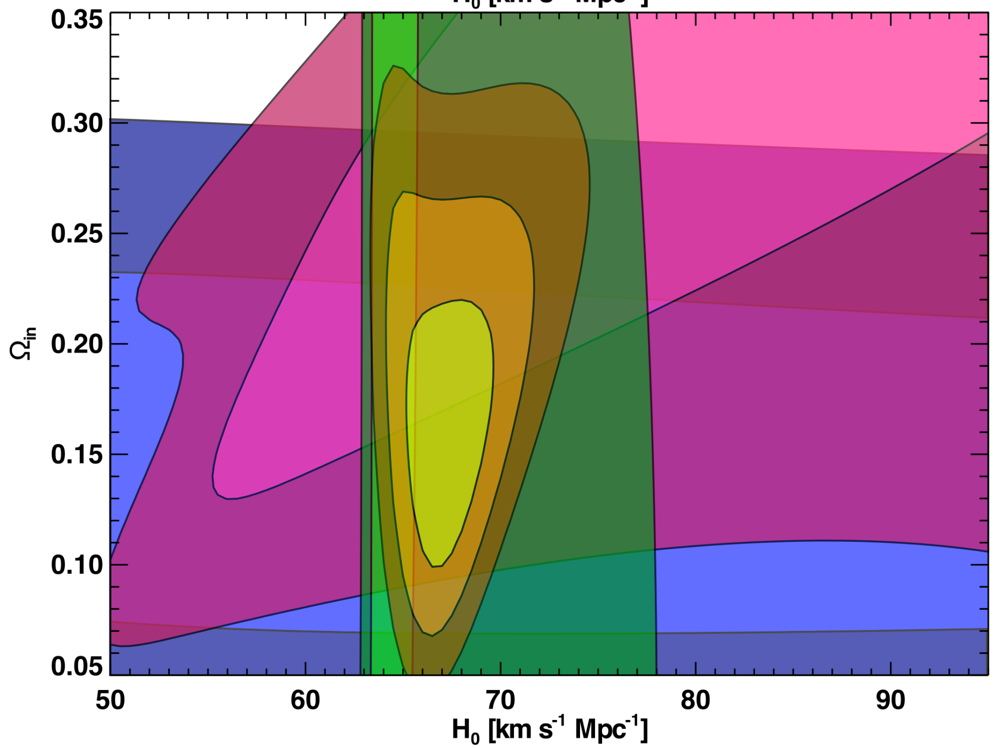
Scanning the model

- Yellow: Everything, Blue: SNe .
- Green: CMB. Purple: BAO
- Supernovae constrain Ω_{matter}
- CMB constrains the H_0, (Ω_{out}=1)

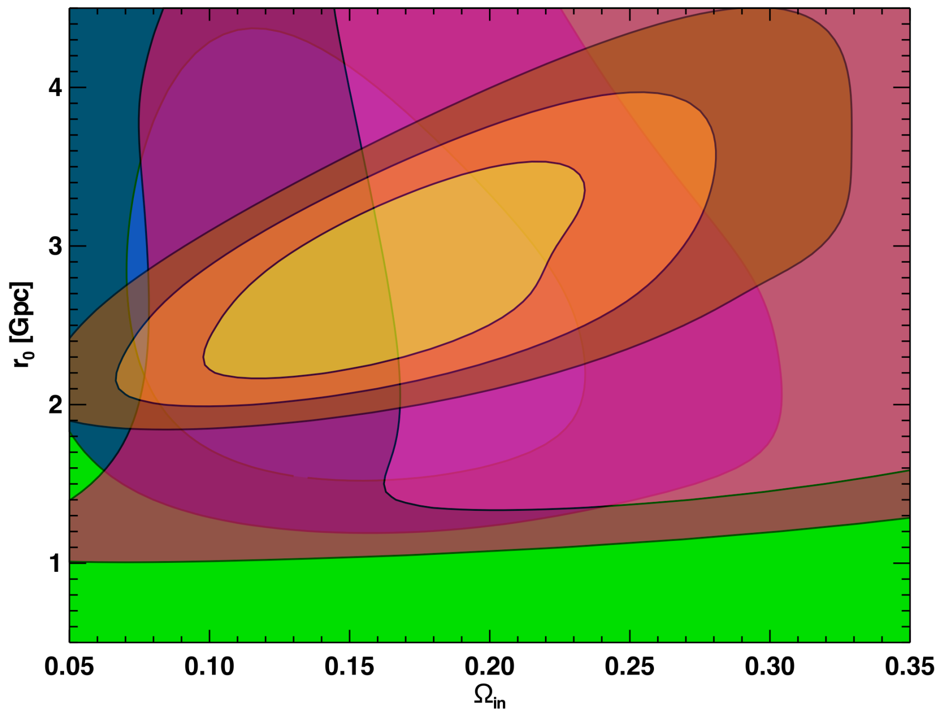


García-Bellido & Haugbølle (2009)

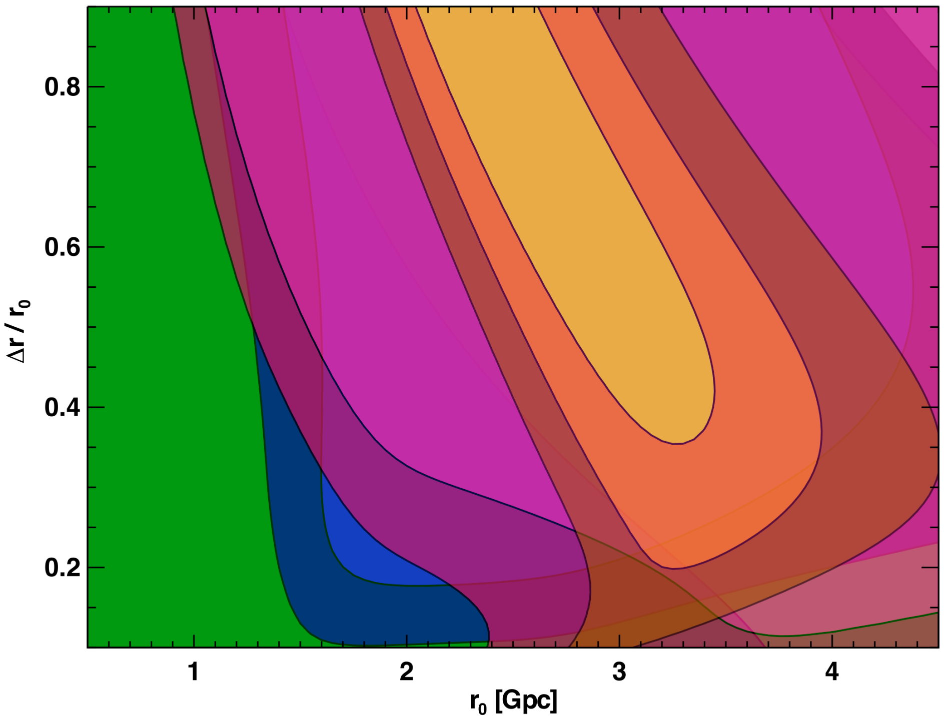


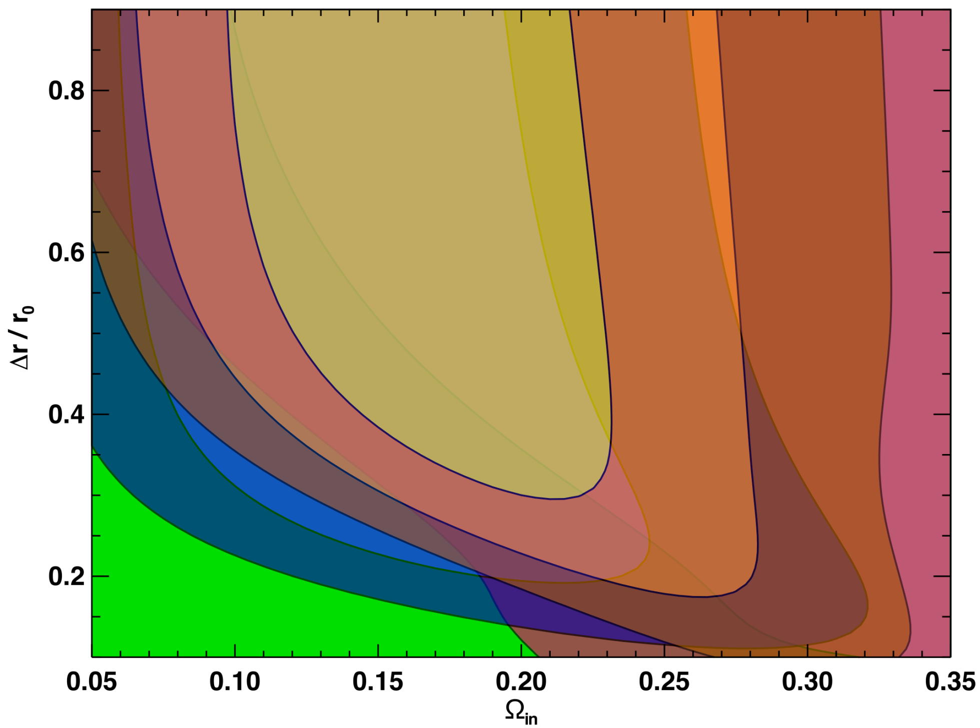


- The SNe and BAO pushes the void size to r_0 > 1.8 Gpc
- Some tension between RBAO and SNe (waiting for high-z SNe)
- Large degeneracy between r_0 and $\Delta r/r_0$



García-Bellido & Haugbølle (2009)





Marginalized errors

García-Bellido & Haugbølle (2009)

Model	H_0	$H_{\rm in}$	$H_{\rm out}$	$H_{\rm eff}$
units	$100\ {\rm km\ s^{-1}\ Mpc^{-1}}$			
GBH	–	0.58±0.03	0.49±0.2	0.43
Constrained	0.64±0.03	0.56	0.43	0.42

Model	$\Omega_{\rm in}$	r_0	Δr	t_{BB}
units		Gpc	r_0	Gyr
GBH	0.13±0.06	2.3±0.9	0.62(>0.20)	14.8
Constrained	0.13±0.06	2.5±0.7	0.64(>0.21)	15.3

!!

$$\chi^2_{\Lambda CDM}/d.o.f. = 1.021 \qquad \chi^2_{LTB-GBH}/d.o.f. = 1.036$$

A new observable: cosmic shear

García-Bellido & Haugbølle (2009)

$$\frac{d\Theta}{d\tau} = -\frac{1}{3}\Theta^2 - \sigma_{\mu\nu}\sigma^{\mu\nu} + \omega_{\mu\nu}\omega^{\mu\nu} - R_{\mu\nu}n^\mu n^\nu$$

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

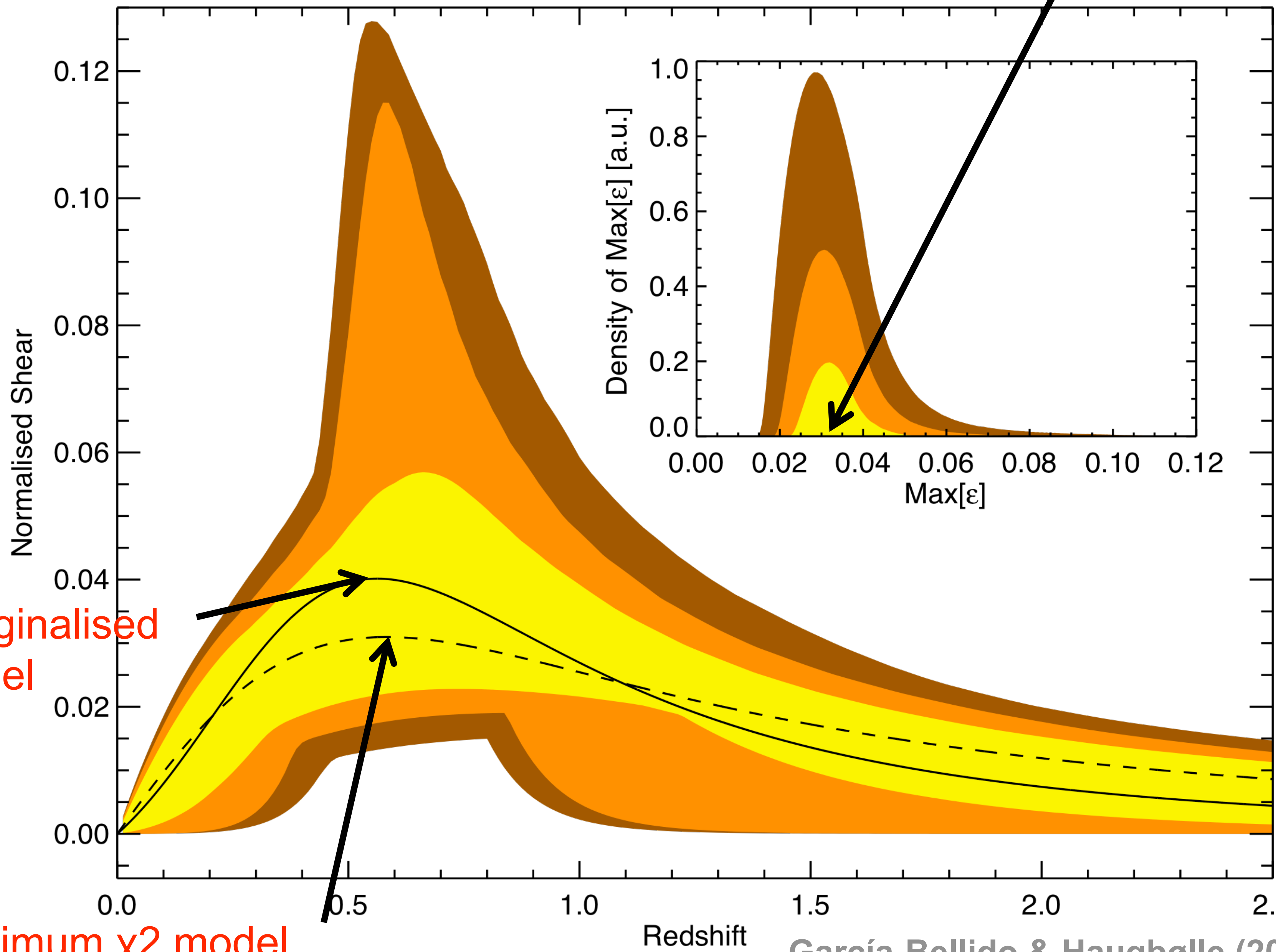
$$\boxed{\varepsilon(z) = \frac{1 - H_L(z)[(1+z)\,d_A(z)]'}{3H_L(z)d_A(z) + 2 - 2H_L(z)[(1+z)\,d_A(z)]'}}$$

FRW: $H_L = H_T = H$ shearless

$$(1+z)d_A = \int dz/H(z) \qquad \varepsilon(z) = 0$$

Normalized shear

$\varepsilon \approx 2 - 5\%$ at maximum

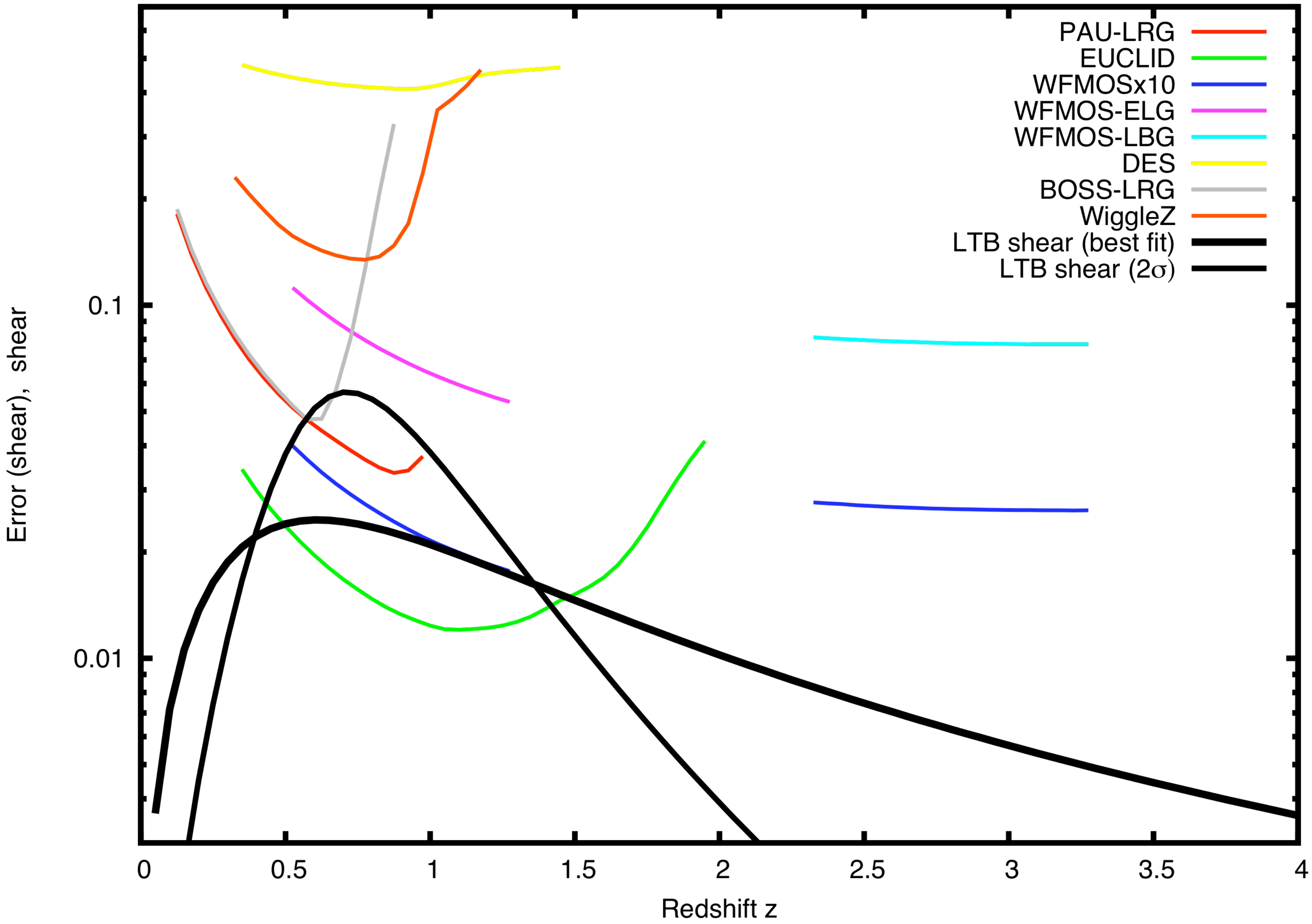


marginalised model

minimum χ2 model

García-Bellido & Haugbølle (2009)

Sensitivity to shear of future surveys



Discussion

- Void models, observationally, seem a real alternative to the standard model. While they break away from the Copernican Principle, they do not need dark energy.
- There is no coincidence problem either: It was there always.

  The question “Why Now?” becomes “Why Here?”
- A void model with a size of ~ 2 Gpc yields a perfect fit to observations constraining the geometry of the universe.
- The final test will be comparing the model to observations:
  - Cosmic shear + bulk flows near z~0.5 (DES, PAU)
  - CMB, and matter power spectra (More theory: ISW)
  - Remote measurements of the CMB: The kinematic Sunyaev Zeldovich effect (ACT, SPT, Planck)