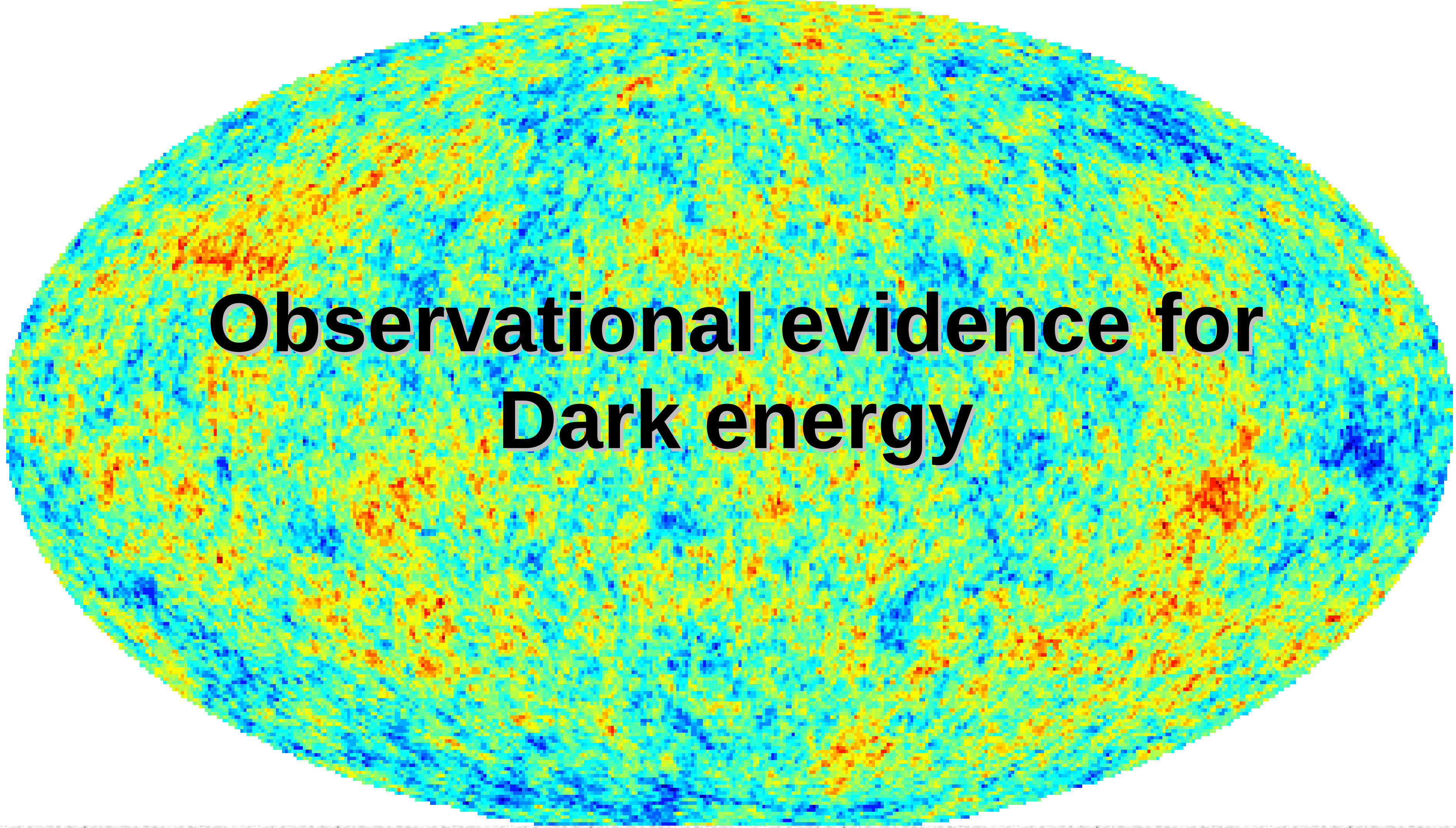
Observational evidence for Dark energy



ICSW-07 (Jun 2-9, 2007)

Tarun Souradeep

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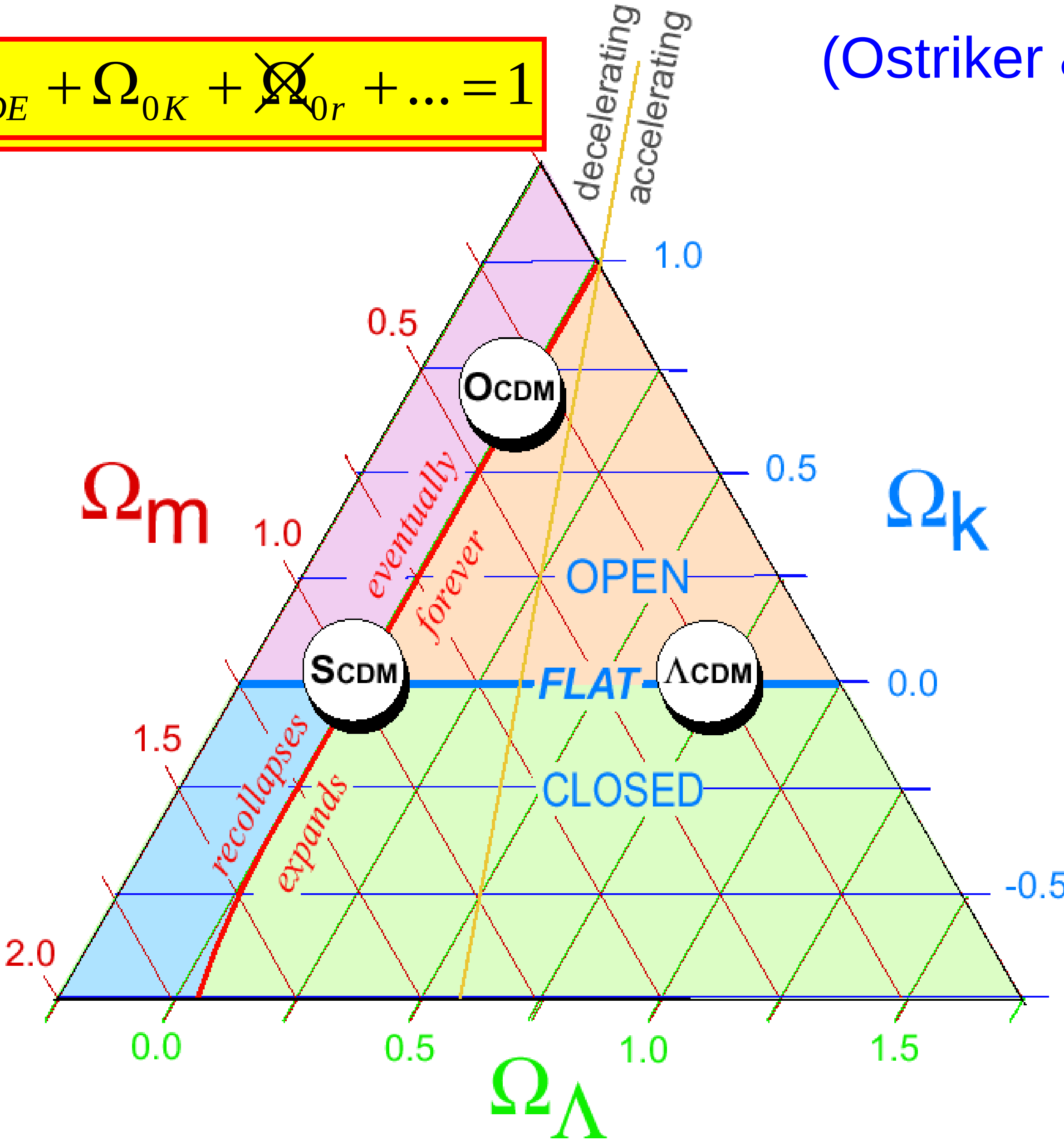
Observational evidence for DE poses a major challenge for theoretical cosmology.

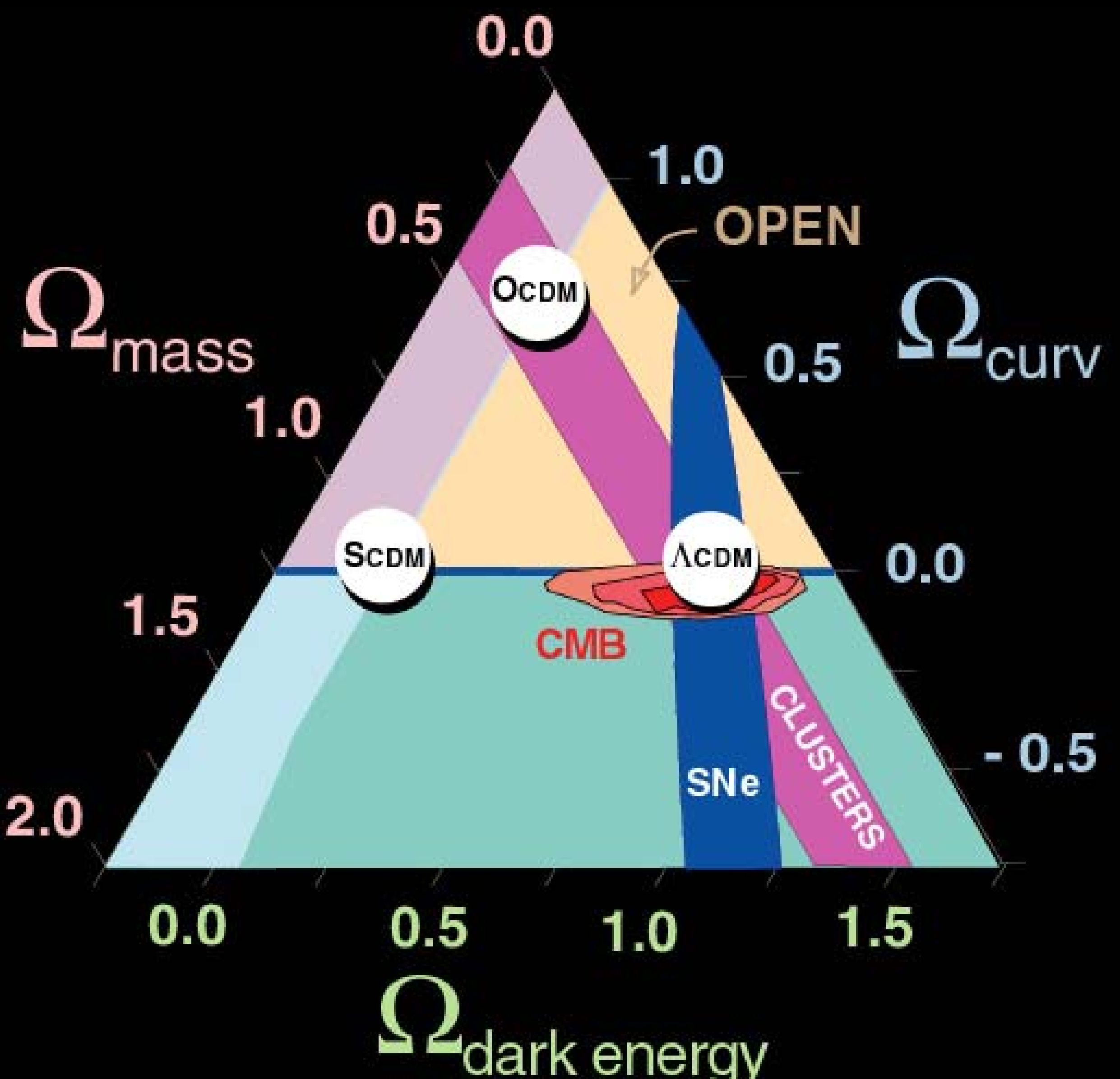
The Cosmic Triangle

$$\Omega_{0m} + \Omega_{0DE} + \Omega_{0K} + \cancel{\Omega_{0r}} + \ldots = 1$$

(Ostriker & Steinhardt)



The Cosmic Triangle



CMB Angular power spectrum

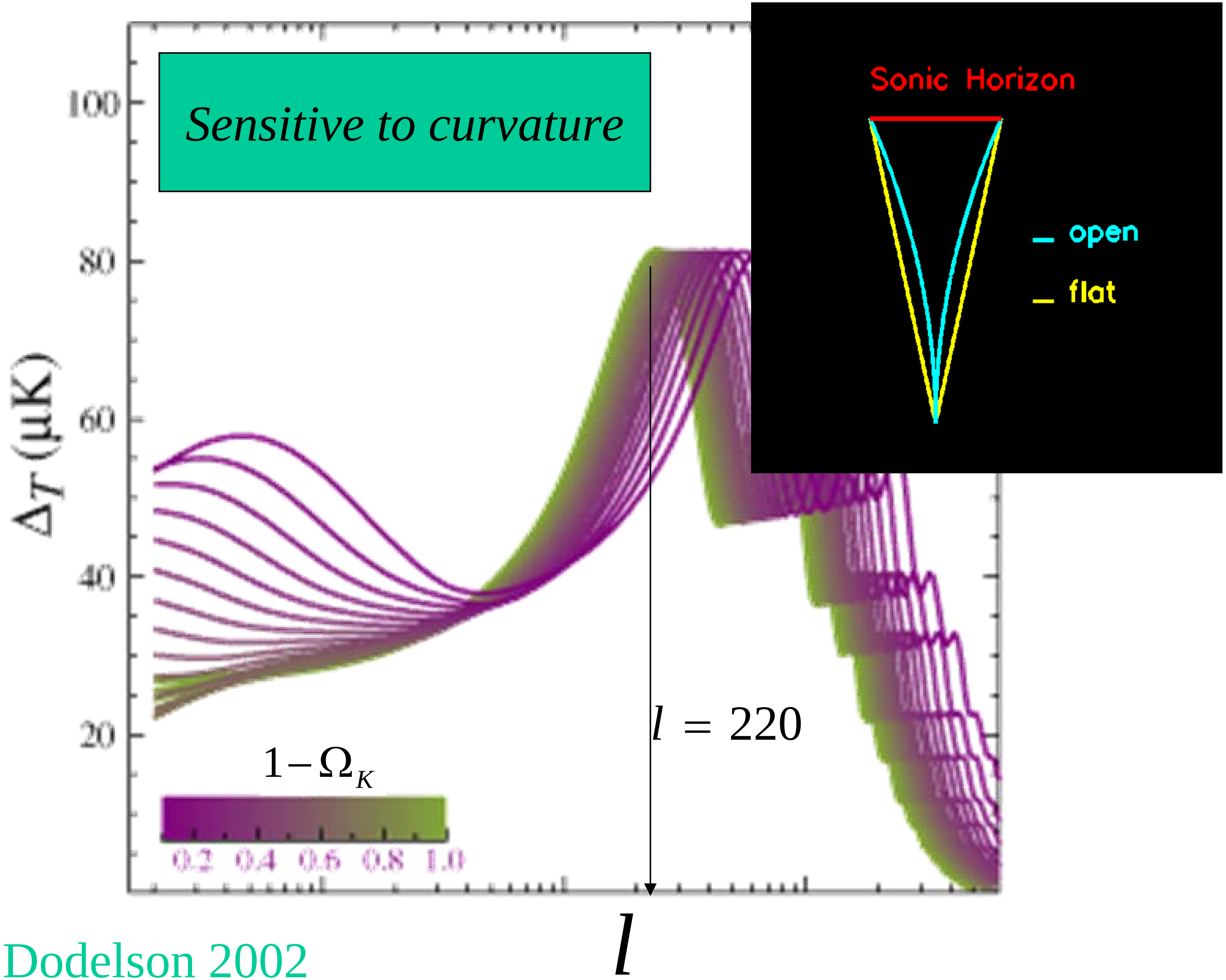
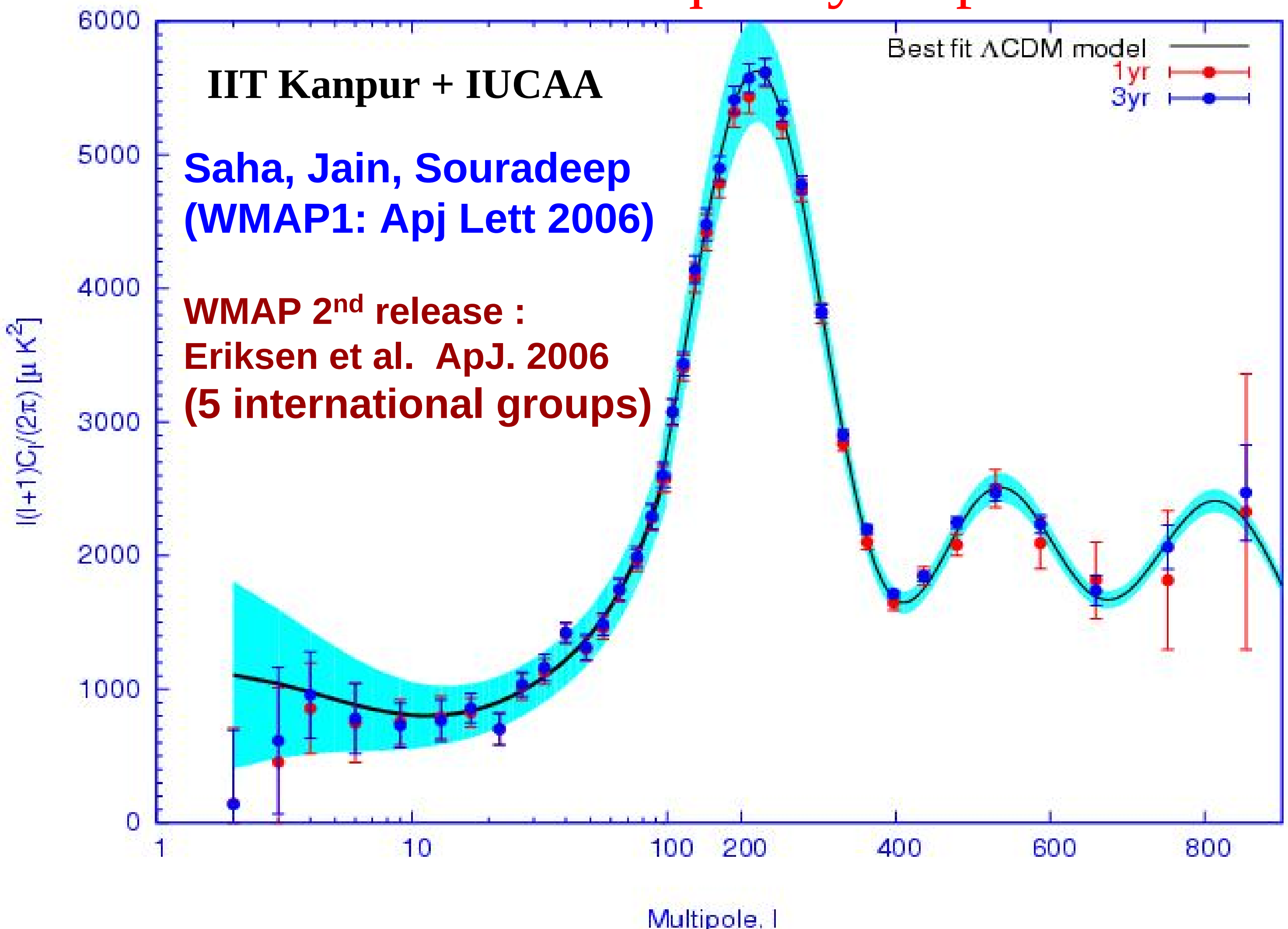


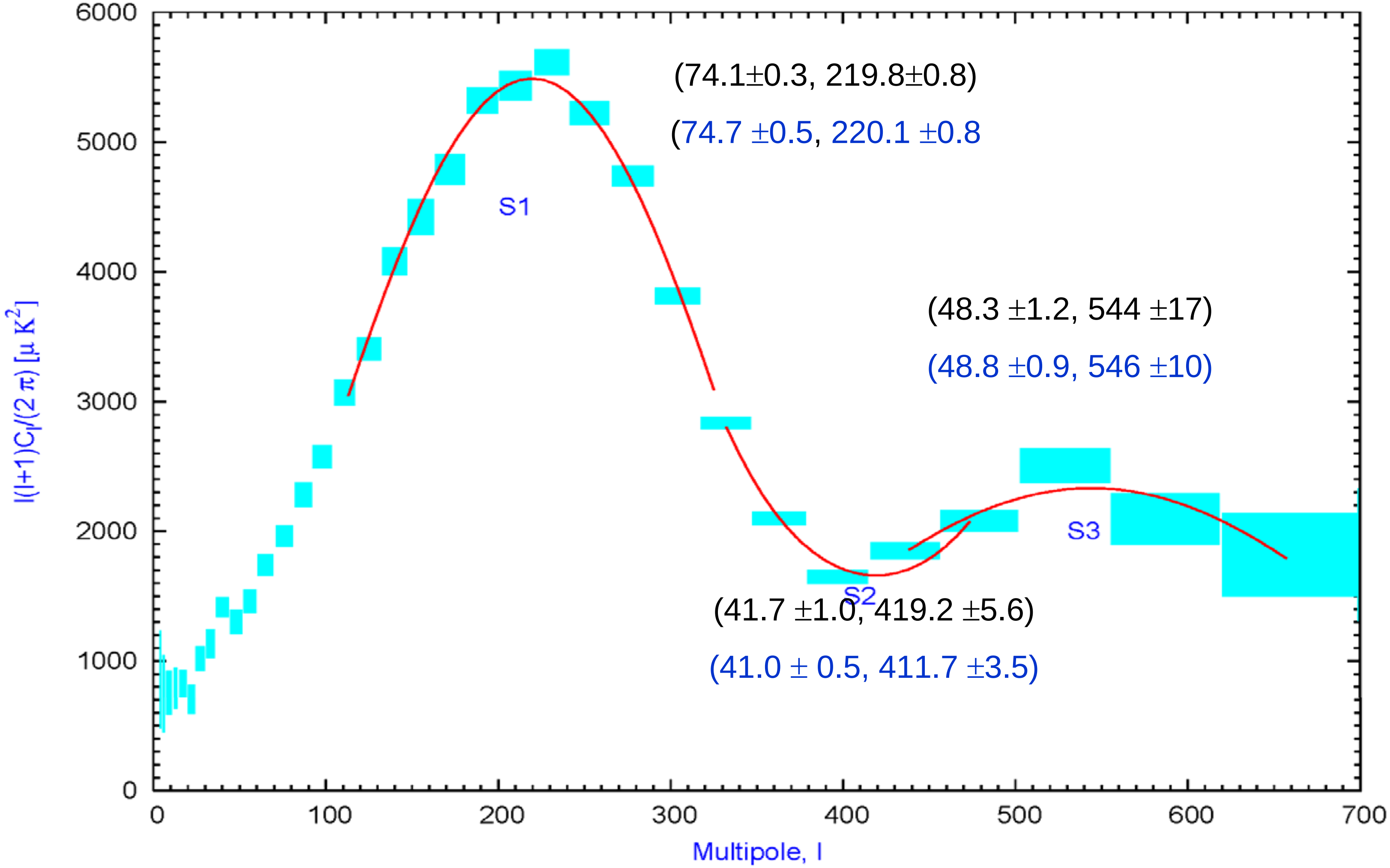
Fig:Hu & Dodelson 2002

WMAP: Angular power spectrum

Independent, **self contained** analysis of WMAP multi-frequency maps



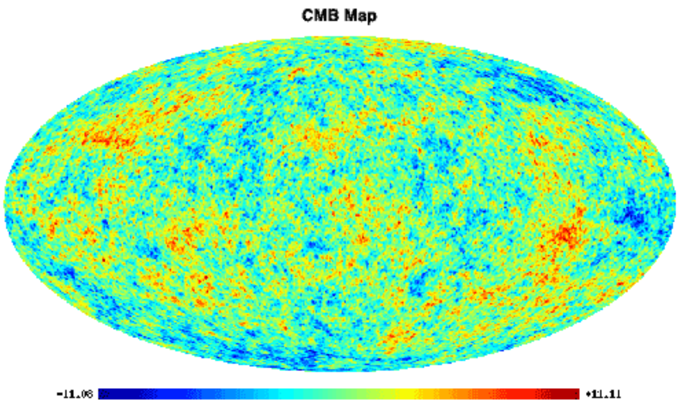
Peaks of the angular power spectrum



(Saha, Jain, Souradeep Apj Lett 2006)

Gravitational Instability

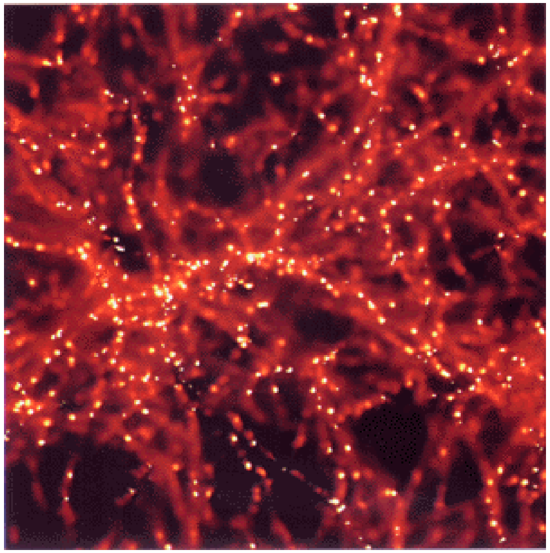
Mildly Perturbed universe at z=1100



Cosmic matter content

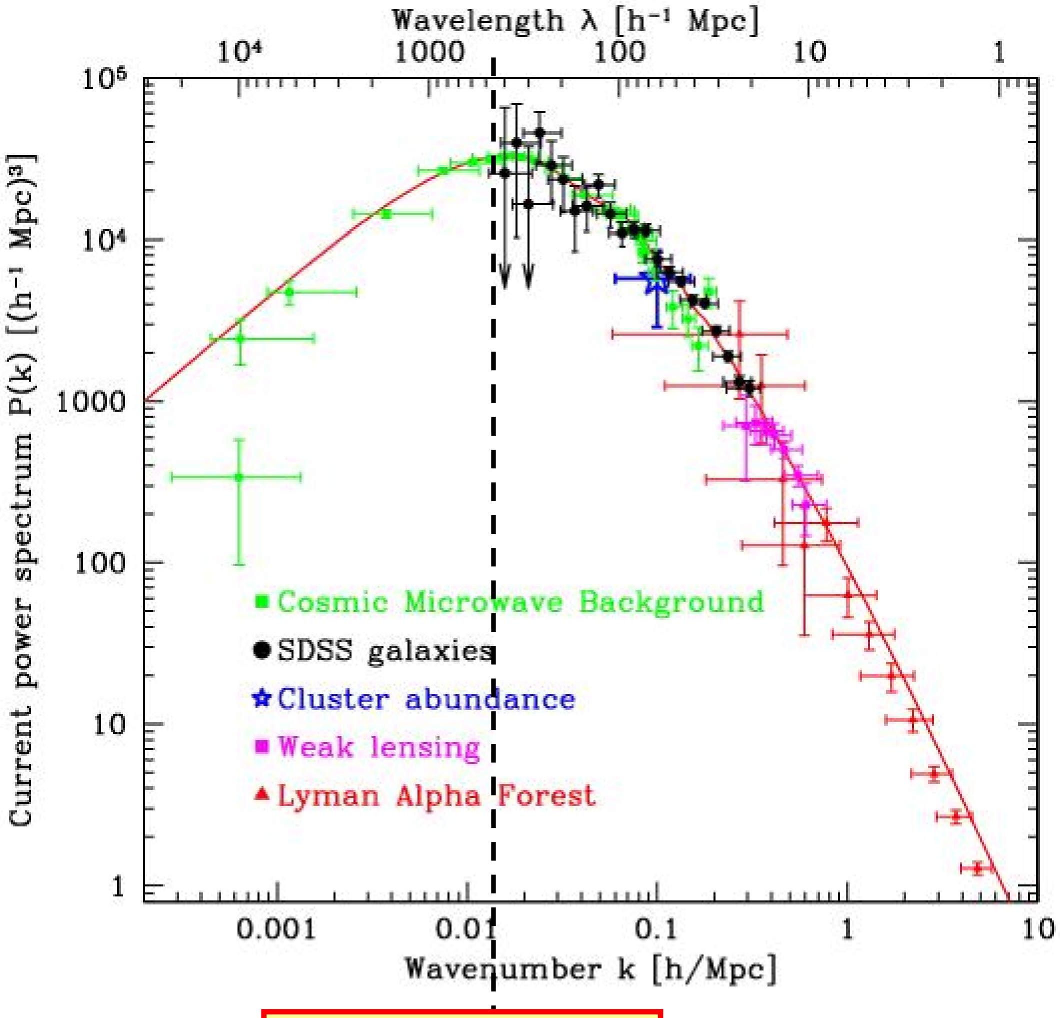
Ω_{tot}
Ω_b
Ω_{DM}
Ω_Λ
H_0

Present universe at z=0



(credit: Virgo simulations)

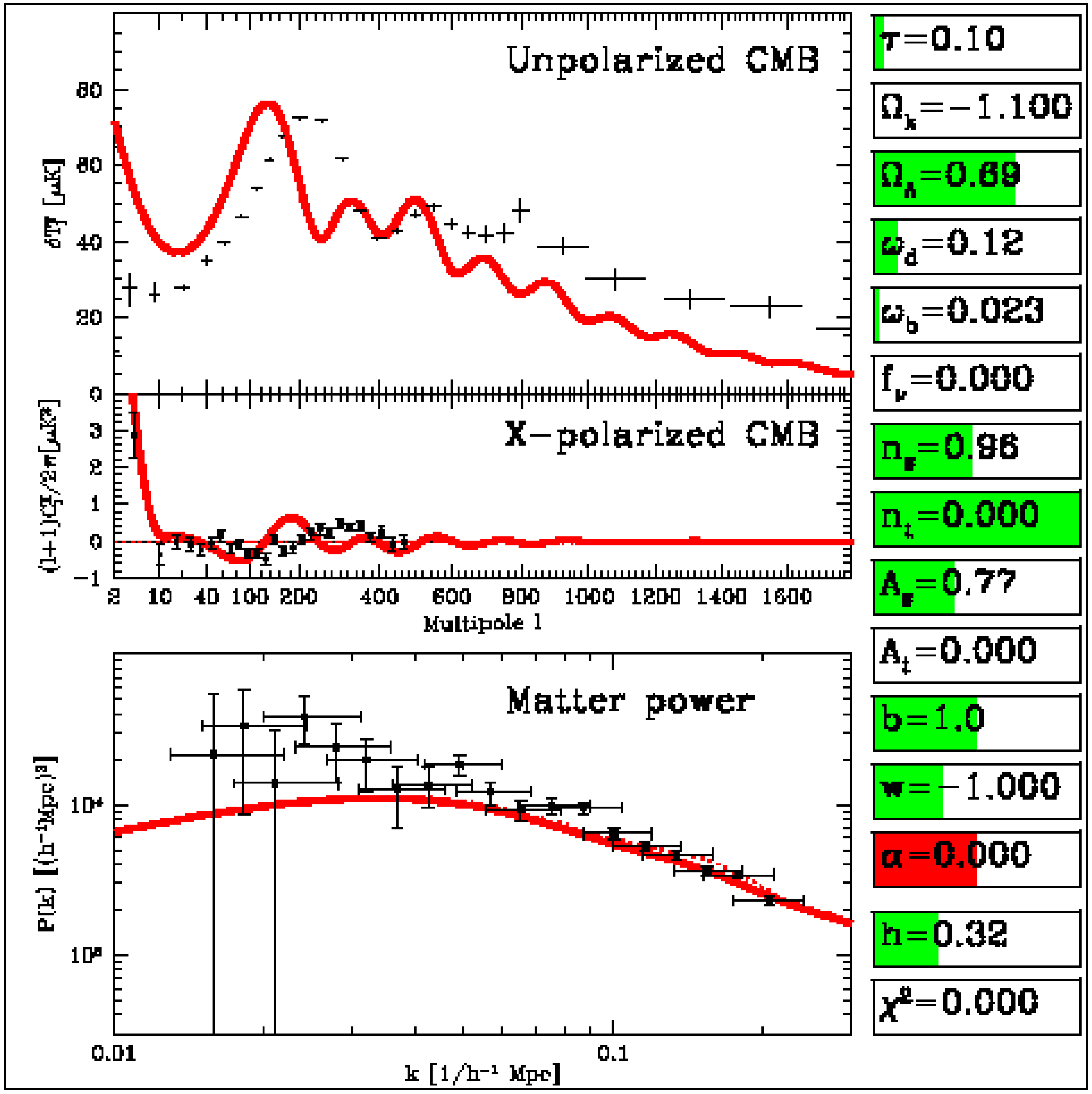
Power spectrum of mass distribution



k_{eq}: $k_{eq}\,\tau_{eq}=1$

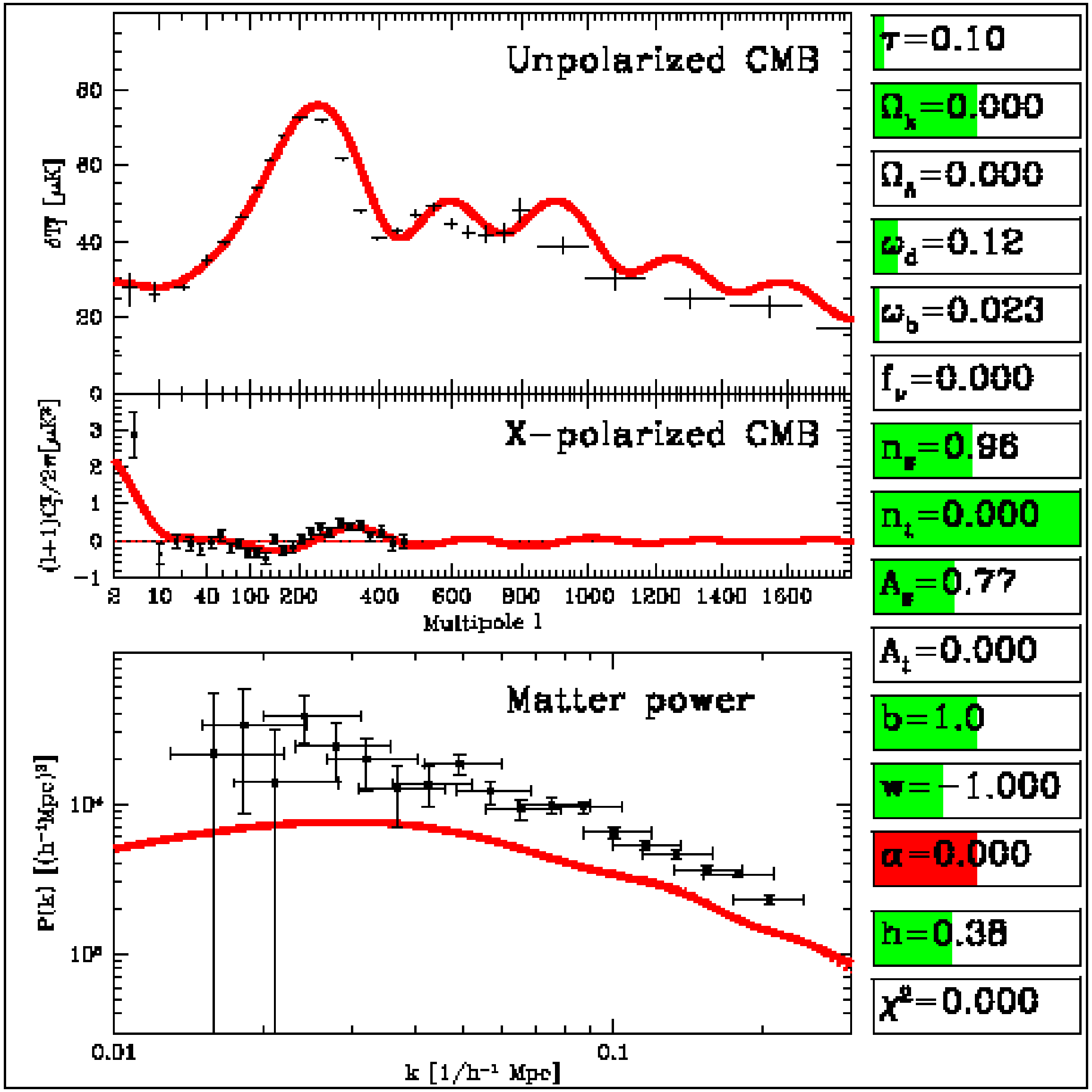
(Tegmark et al. 2004)

Sensitivity to curvature

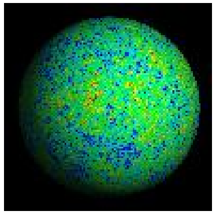


(credit: Tegmark)

Sensitivity to Dark Energy fraction

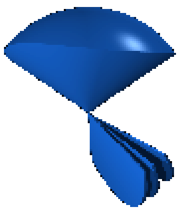


(credit: Tegmark)

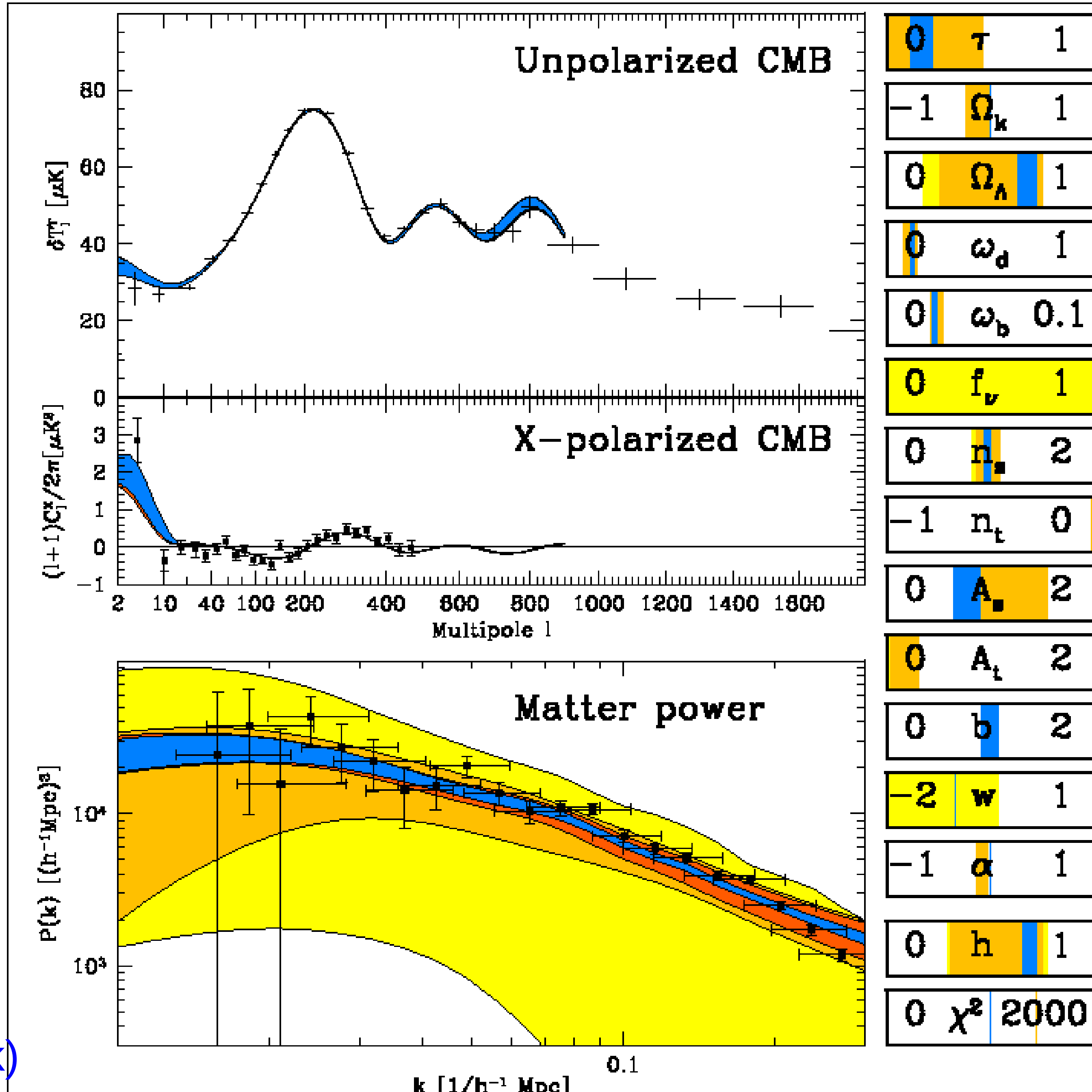


CMB

+



LSS



(credit: Tegmark)

Theoretical possibilities

Possibility 1: Universe permeated by energy density, constant in time and uniform in space (Einstein's Λ).

Possibility 2: DE some kind of '*unknown*' dynamical fluid. Its eqn of state varies with time (or redshift z or $a = (1+z)^{-1}$).

Impact of DE (or different theories) can be expressed in terms of different "evolution of equation of state"

$w(a) = p(a) / \rho(a)$ with $w(a) = -1$ for Λ.

Possibility 3: GR incorrect, modified Lagrangian, Braneworld scenario (higher derivative/dimensional gravity)

Possibility 4: `Inhomogeneous' cosmos – backreaction of gravitational. instablity

And the probes are:

Supernovae

Background universe

measure flux and redshift of Type Ia SNe.

Weak Lensing

measure distortion of background images due to gravitational lensing.

Baryon Acoustic Oscillations (BAO)

measure features in distribution of galaxies.

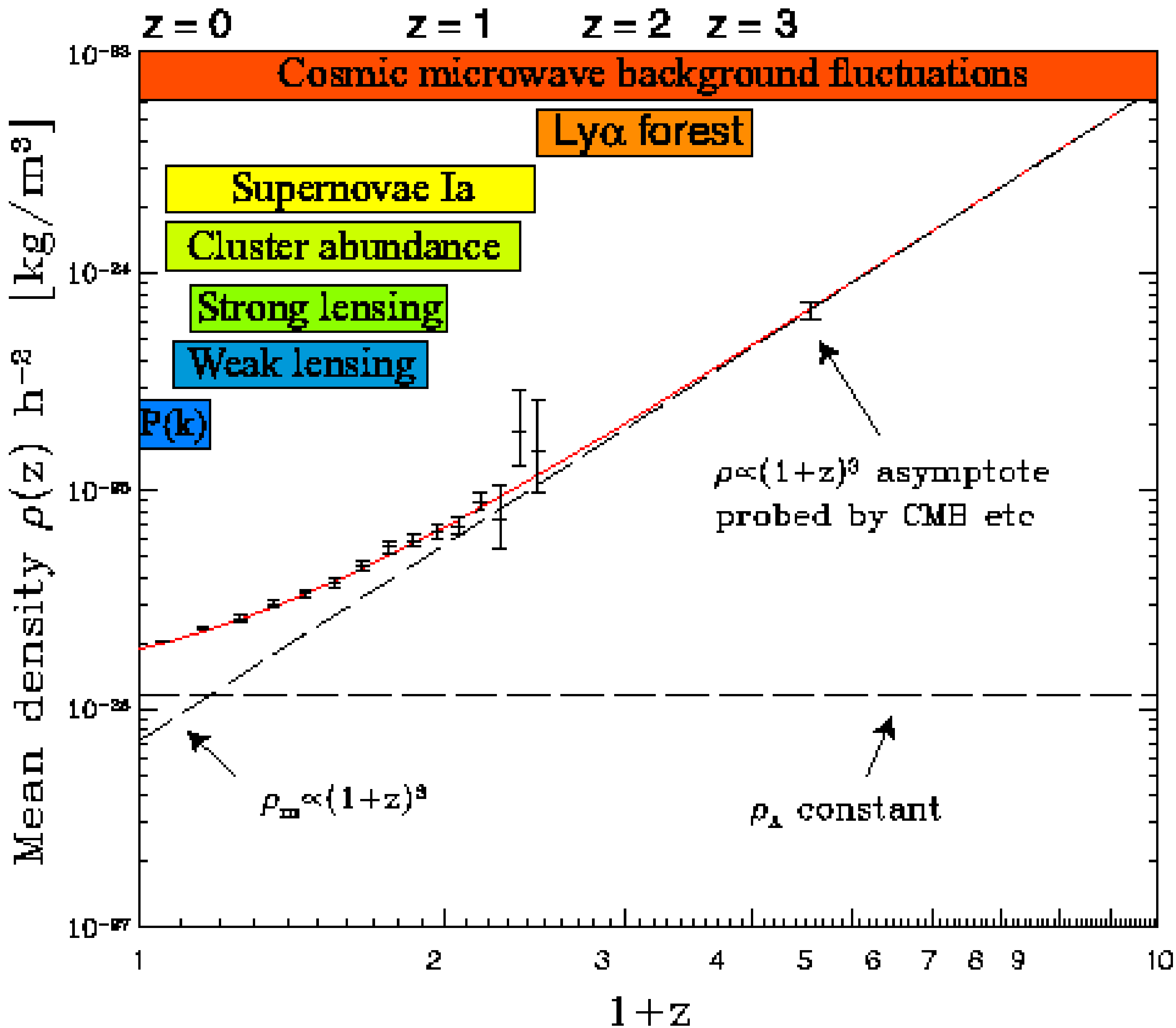
Clusters

measure spatial distribution of galaxy clusters.

CMB related :

CMB peaks and LSS
ISW - LSS cross correlation
SZ based cluster surveys
BAO

perturbed universe



z = 0
z = 1
z = 2
z = 3
Cosmic microwave background fluctuations
Lyα forest
Supernovae Ia
Cluster abundance
Strong lensing
Weak lensing
P(k)
Mean density ρ(z) h⁻² [kg/m³]
10⁻²⁴
ρ∝(1+z)³ asymptote
probed by CMB etc
ρ_m∝(1+z)³
ρ_Λ constant
1
2
3
4
5
6
7
8
9
10
1+z

DE and Growth of structures

- DE alters the evolution of the Hubble Expansion H(z) through the Friedman eqn.

  -This then modifies the distance to an object (SNe, galaxy correlations)

- It alters the evolution of g(z), the growth function of structures, through the perturbation eqn.

  -large scale structures are sensitive to both g(z) and H(z)

Number of collapsed objects vs redshift

Number count of clusters vs. redshift ($dN/dz - z$)

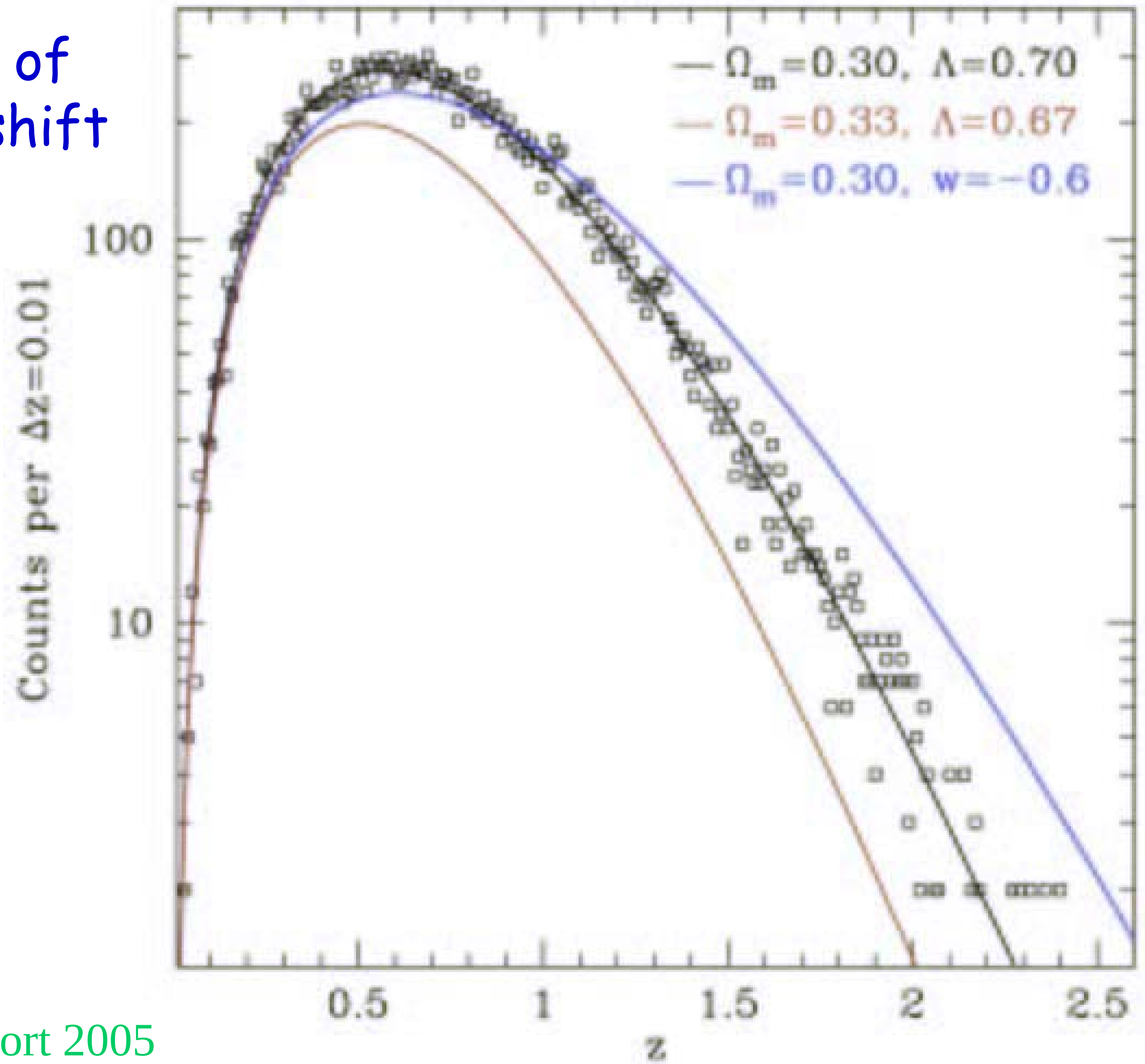
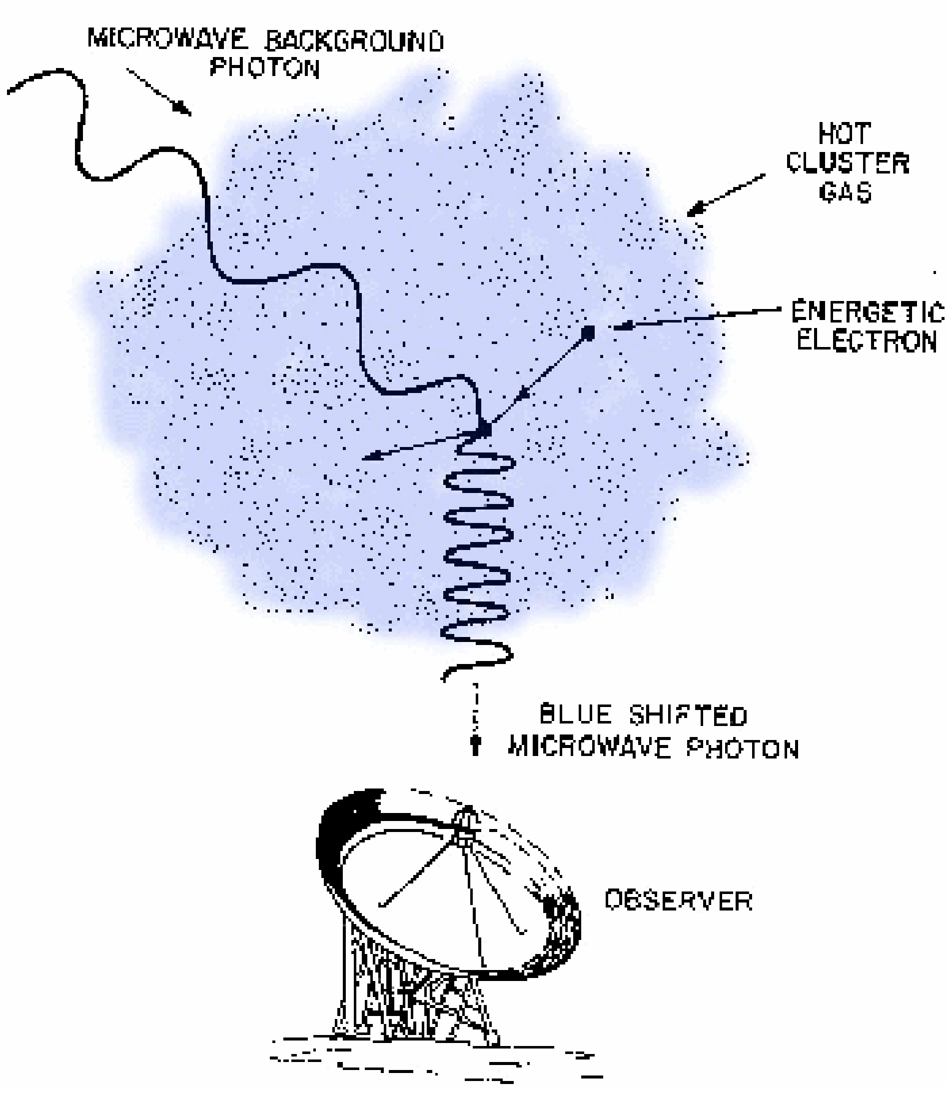
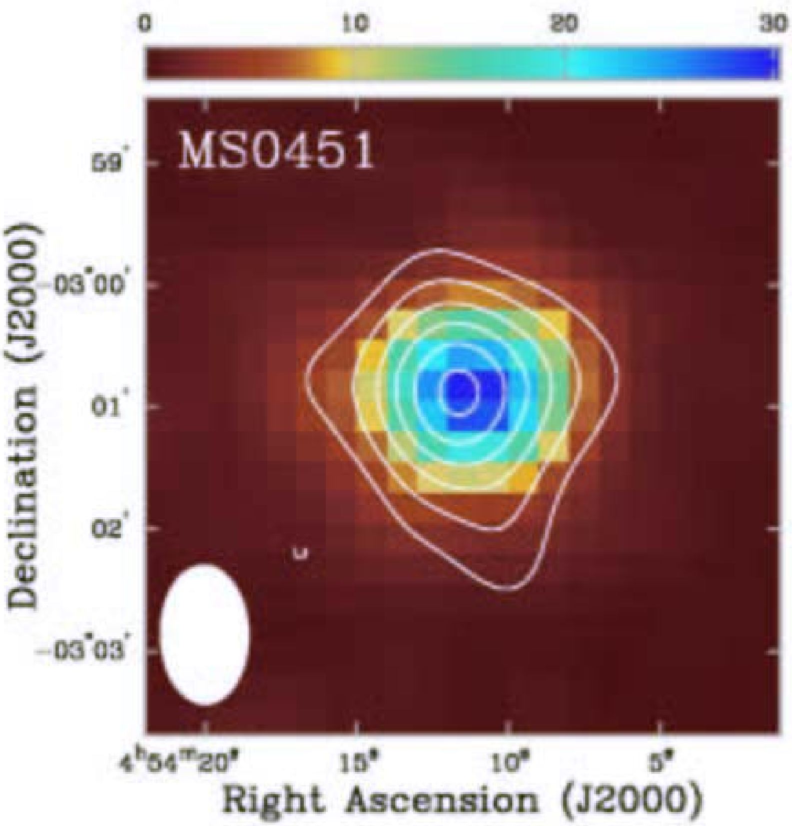


Fig: CMB Task force report 2005

CMB: Sunyaev-Zeldovich Effect



CMB: Sunyaev-Zeldovich Effect



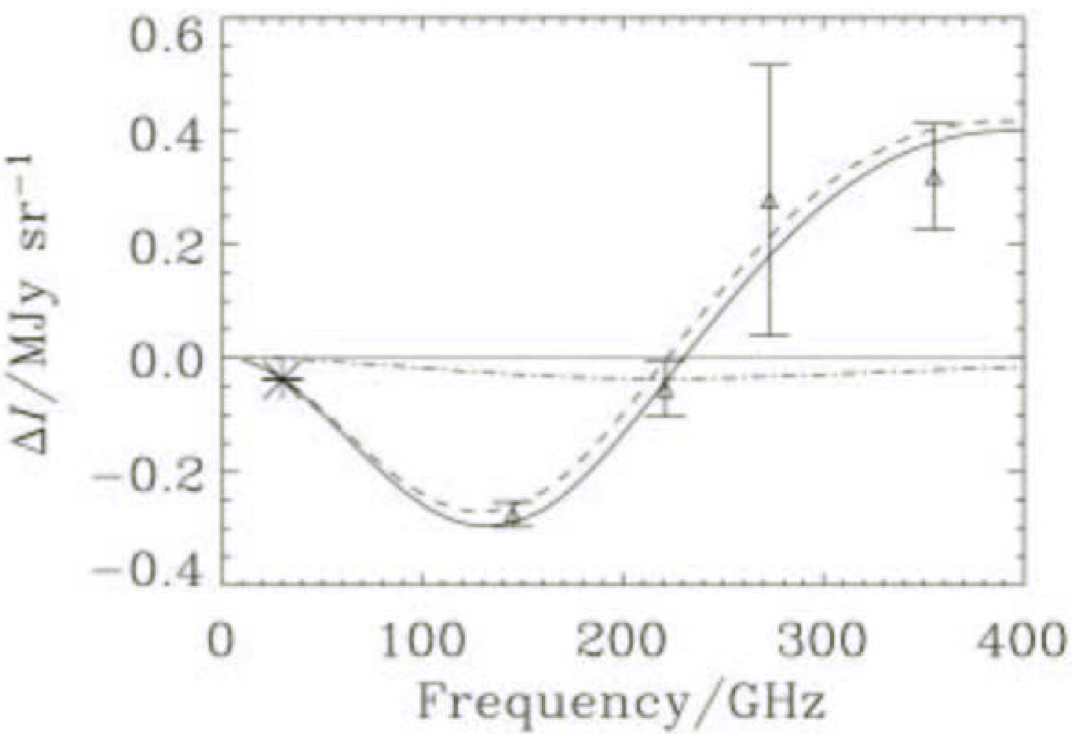
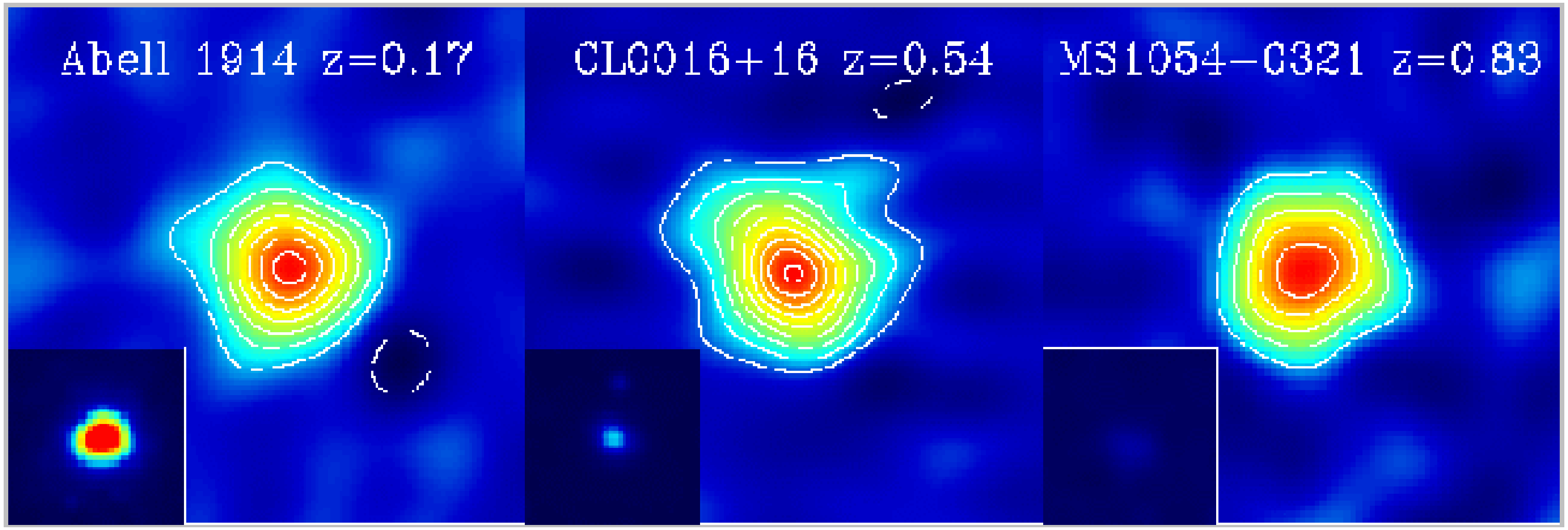


Fig: CMB Task force report 2005

Advantages of SZ Cluster survey

1) Of course, the distinct spectral signature

2) More or less redshift independent



Courtesy : S. Majumdar

Upcoming SZ Surveys

Planck : >**12 μK, 10' for LFI; >5μk , 5' for HFI , whole sky**

SPT : **1' resolution, 150, 220, (>220 ?) GHz, 4000 sq-deg**

1000 bolometer array in a 8 m dish

ACT **: 0.9'-1.7', 145, 225, 267 GHz, 100 sq-deg**

Cerro-Toco, Chile

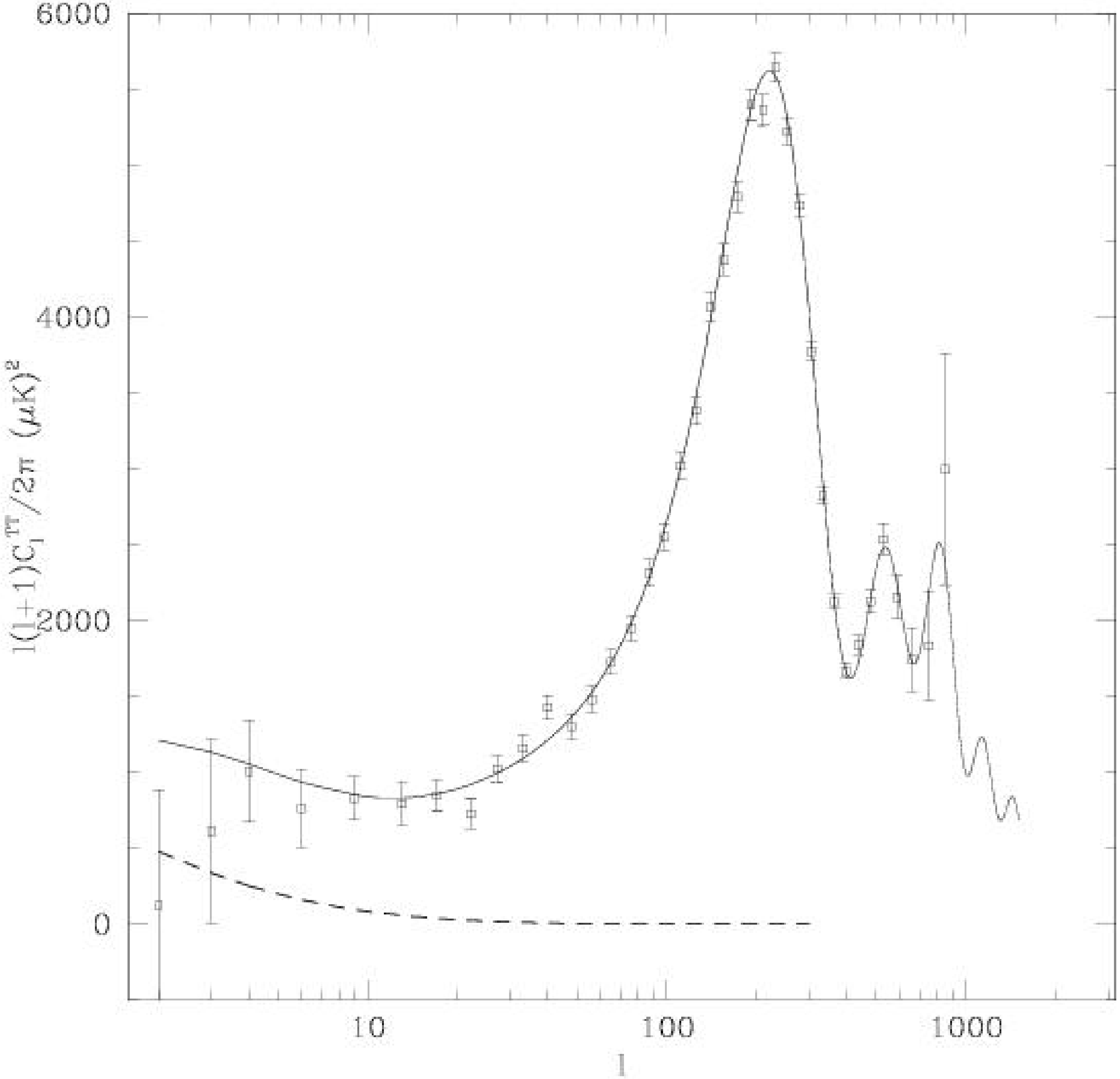
APEX**: 0.6'-0.75', 150, 220, 270(?) GHz, 150-200 sq-deg**

330 bolometers, Atacama

SZA : **interferometer, array of 8, 3.5 m telescopes, 12 sq-deg**

Courtesy : S. Majumdar

CMB: Integrated Sachs-Wolfe effect



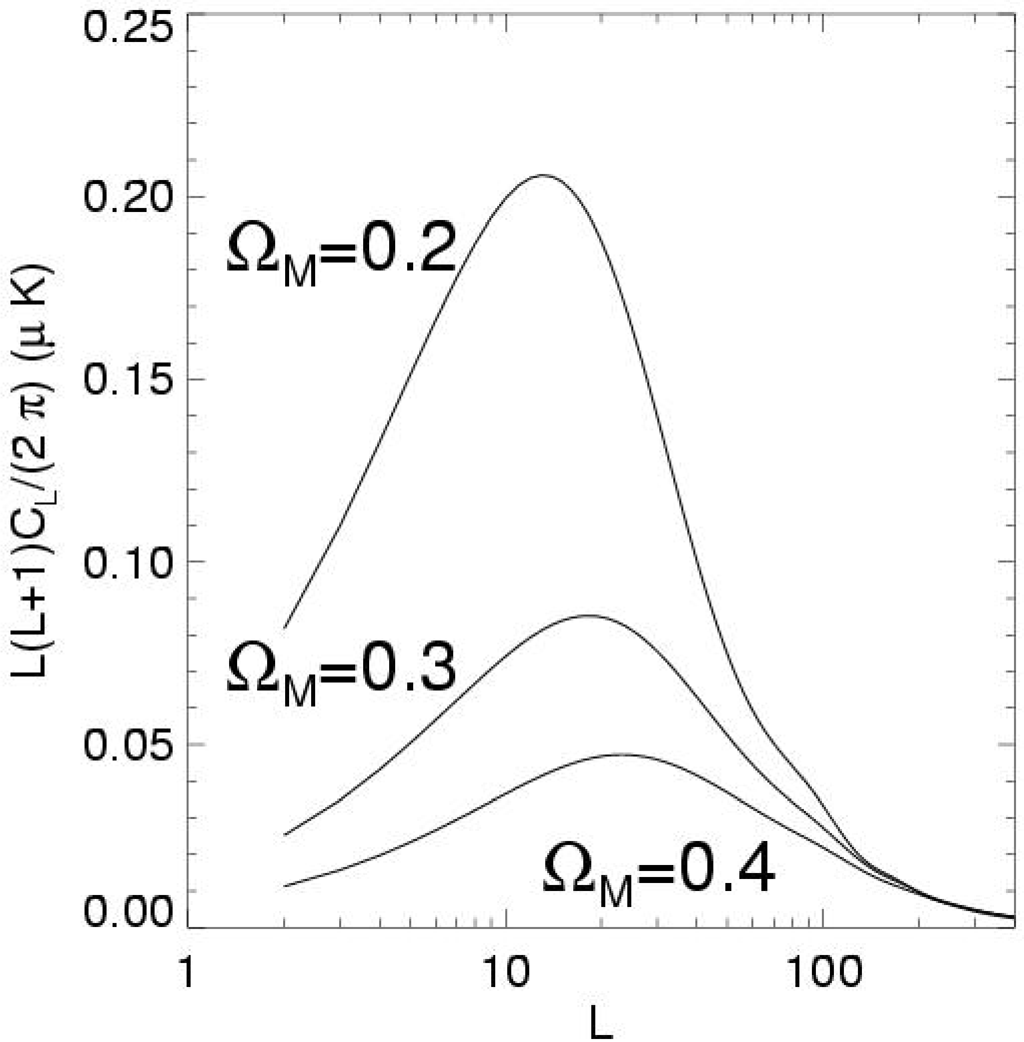
CMB ISW-LSS Correlation

CMB-ISW is correlated with the large scale structure !

Angular power spectrum of

h Δ T δρ/ρi

cross-correlation



CMB ISW-LSS Correlation

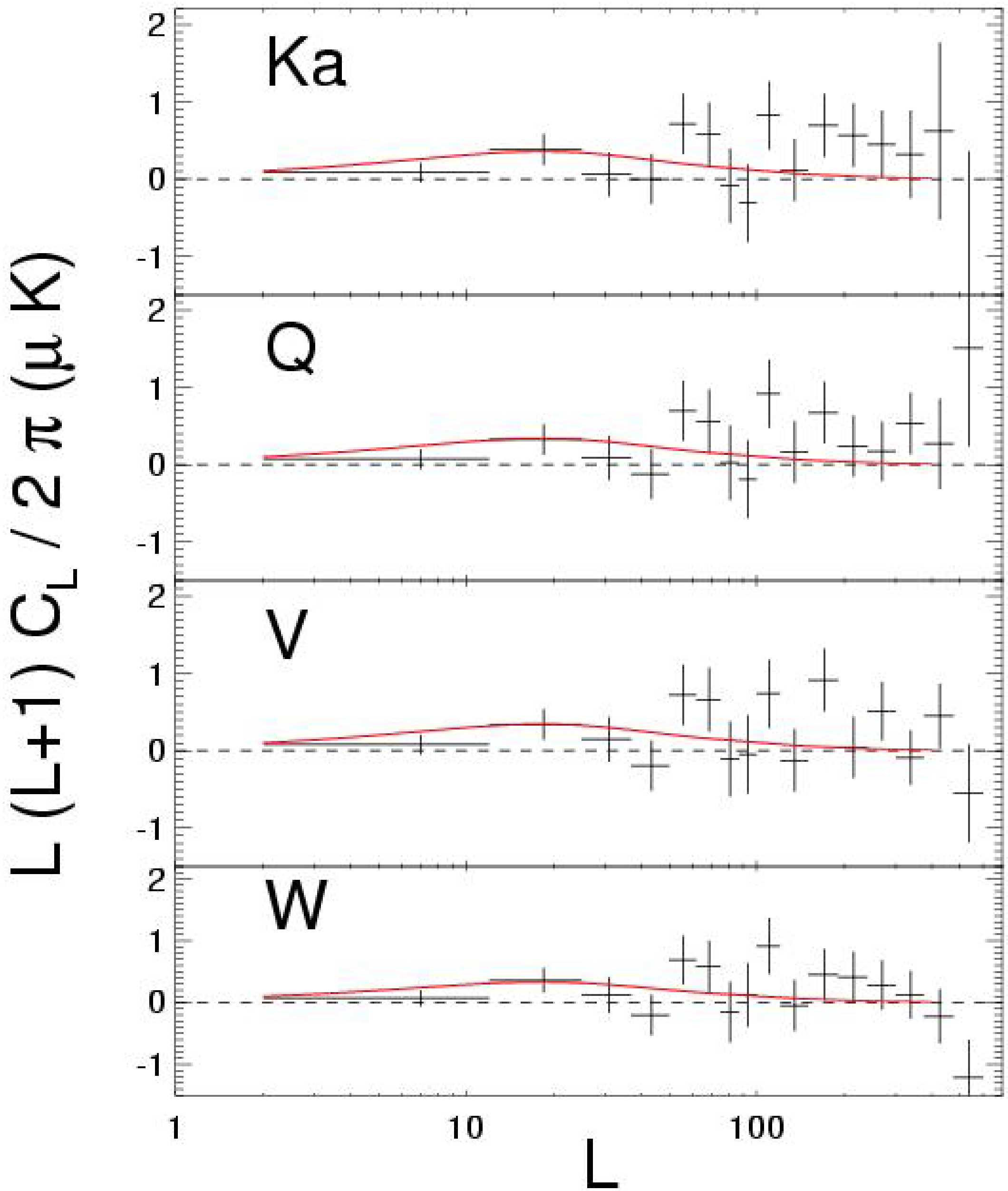
Measured Angular power spectrum of the

h ΔT δρ/ρi

cross-correlation

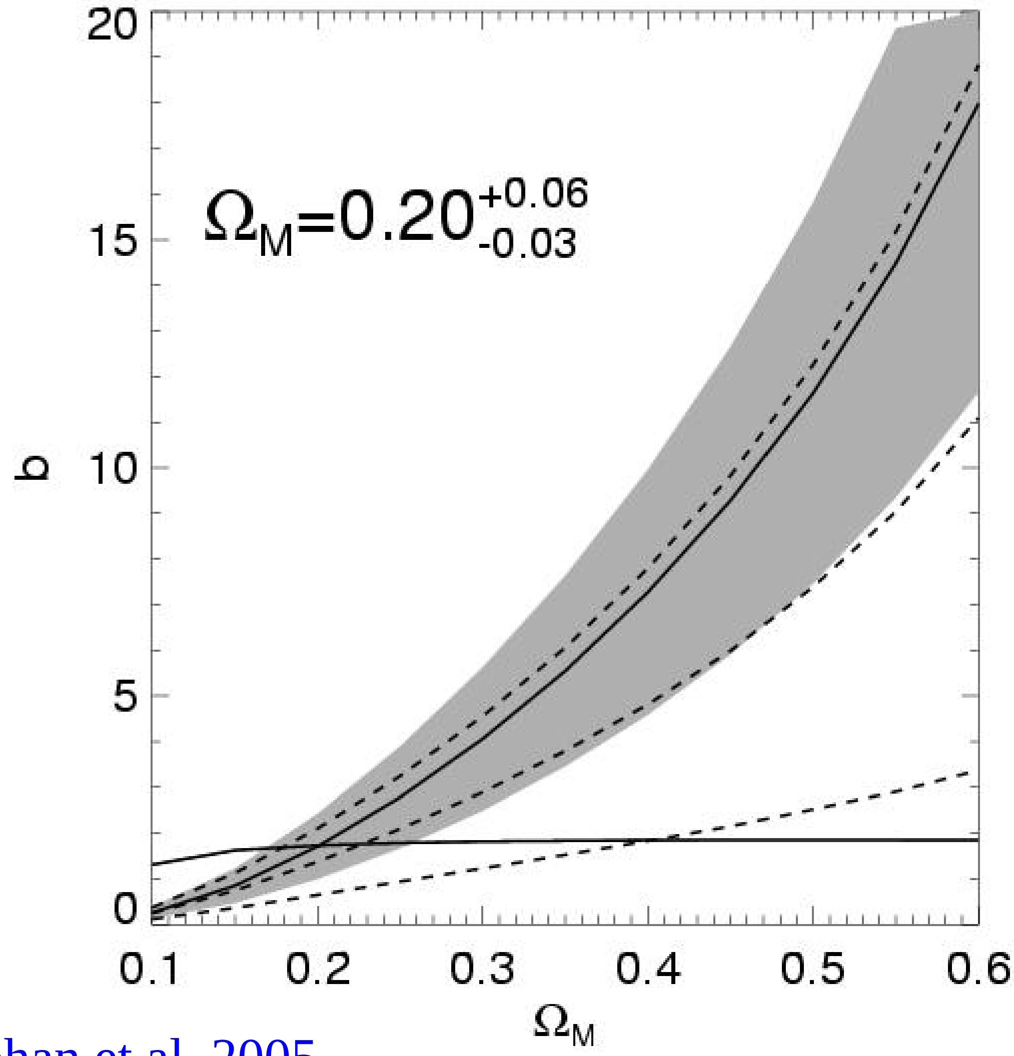
WMAP-SDSS(LRG)

in WMAP bands



Nikhil Padmanabhan et al. 2005

CMB ISW-LSS Correlation



Nikhil Padmanabhan et al. 2005

CMB ISW-LSS Correlation

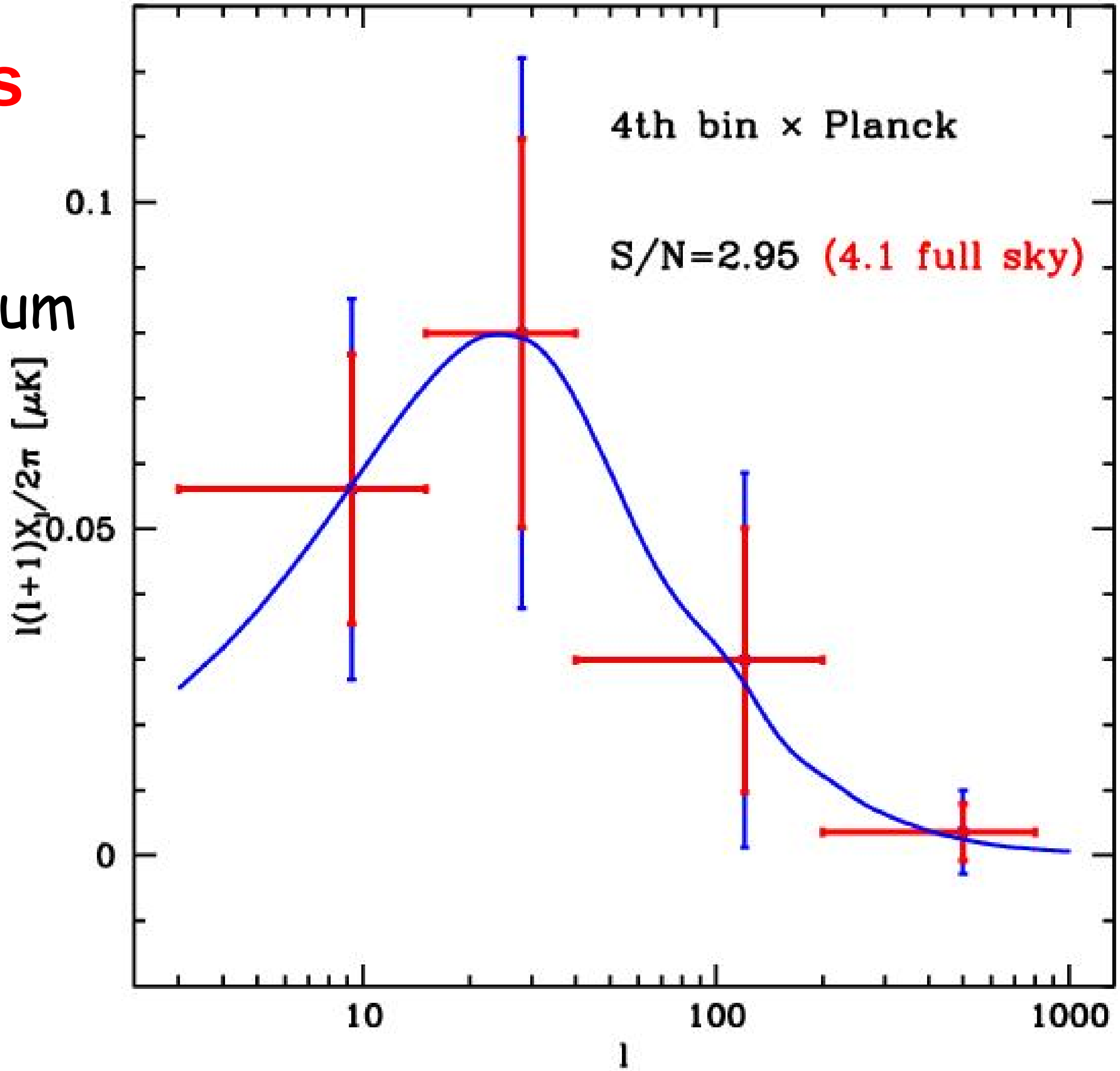
Future prospects

Planck -LSST

Angular power spectrum of the

h ΔT δρ/ρi

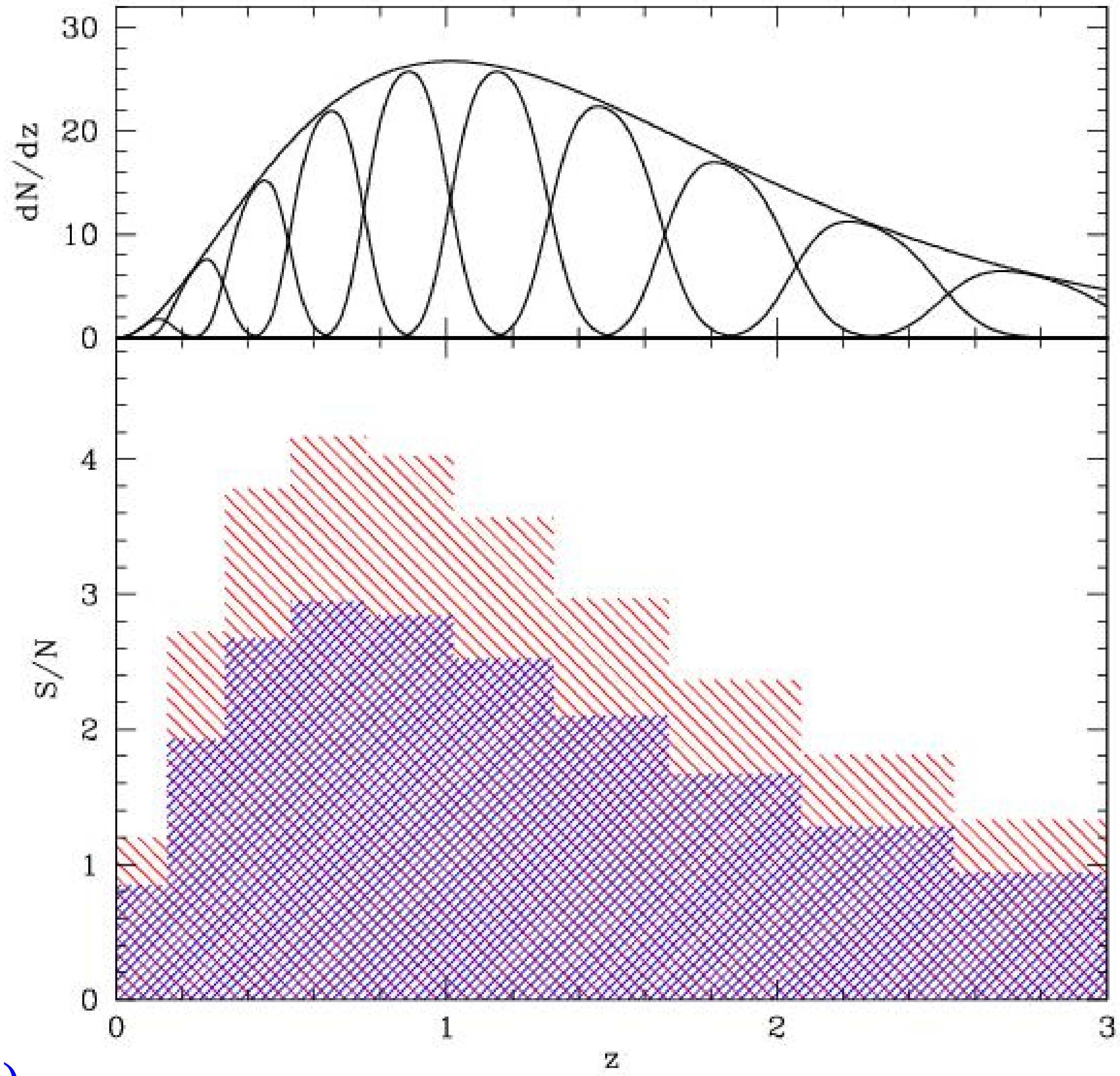
cross-correlation



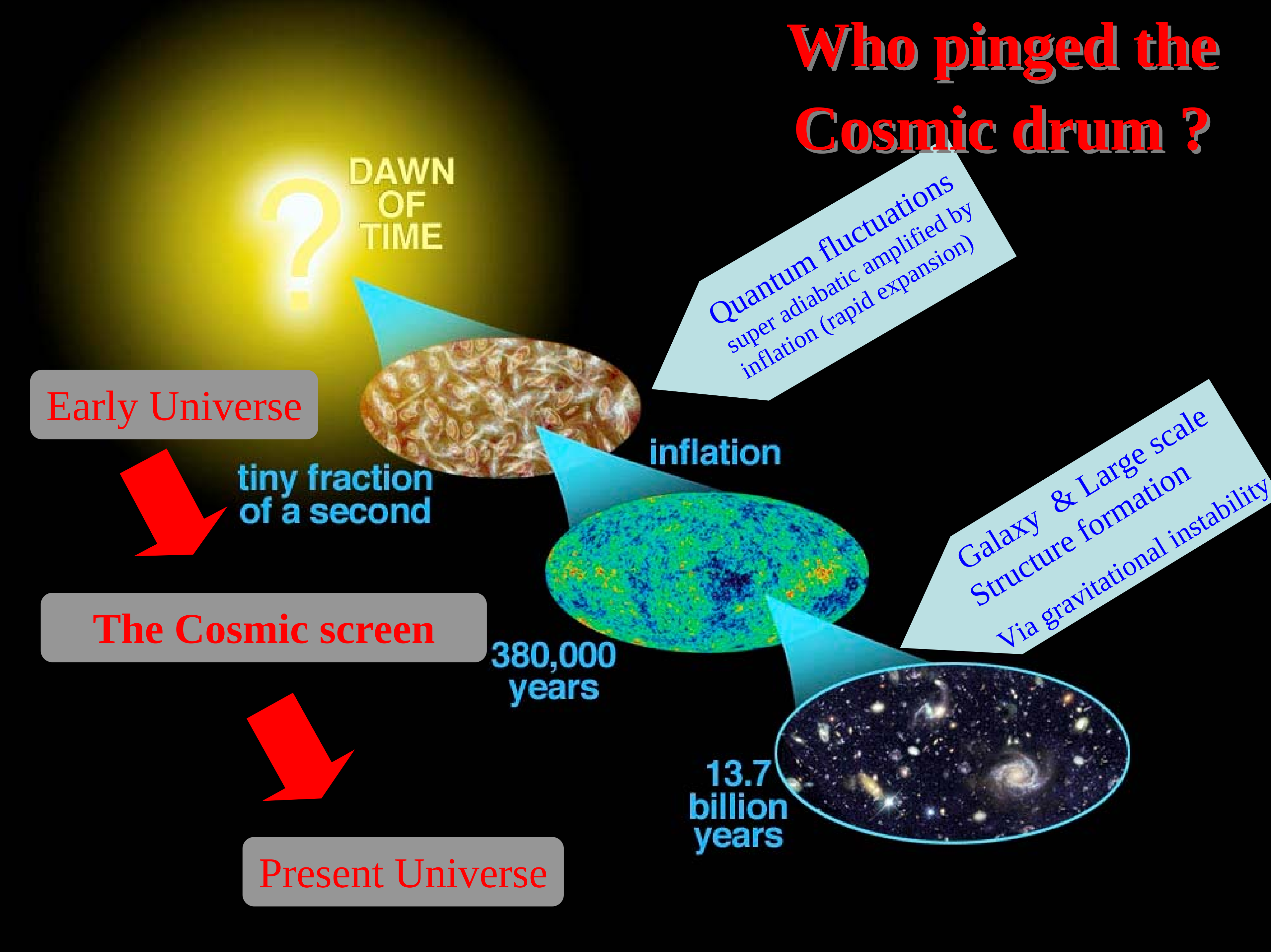
(Levon Posian 2006)

CMB ISW-LSS Correlation

Future prospects from Planck -LSST



(Levon Posian 2006)



Who pinged the Cosmic drum ?
DAWN OF TIME
Quantum fluctuations
super adiabatic amplified by inflation (rapid expansion)
Early Universe
inflation
tiny fraction of a second
The Cosmic screen
380,000 years
Galaxy & Large scale Structure formation
Via gravitational instability
13.7 billion years
Present Universe

Early Universe in CMB

The Background universe

- Homogeneous & isotropic space: ***Cosmological principle***
- Flat (Euclidean) Geometry

The nature of initial/primordial perturbations

- **Power spectrum :** ***'Nearly' Scale invariant /scale free form***
- **Spin characteristics: (*Scalar) Density perturbations***

  … cosmic (Tensor) Gravity waves ?
- **Type of scalar perturbation:** ***Adiabatic -- no entropy fluctuations***
- **Underlying statistics:** ***Gaussian***

Generic Inflation model

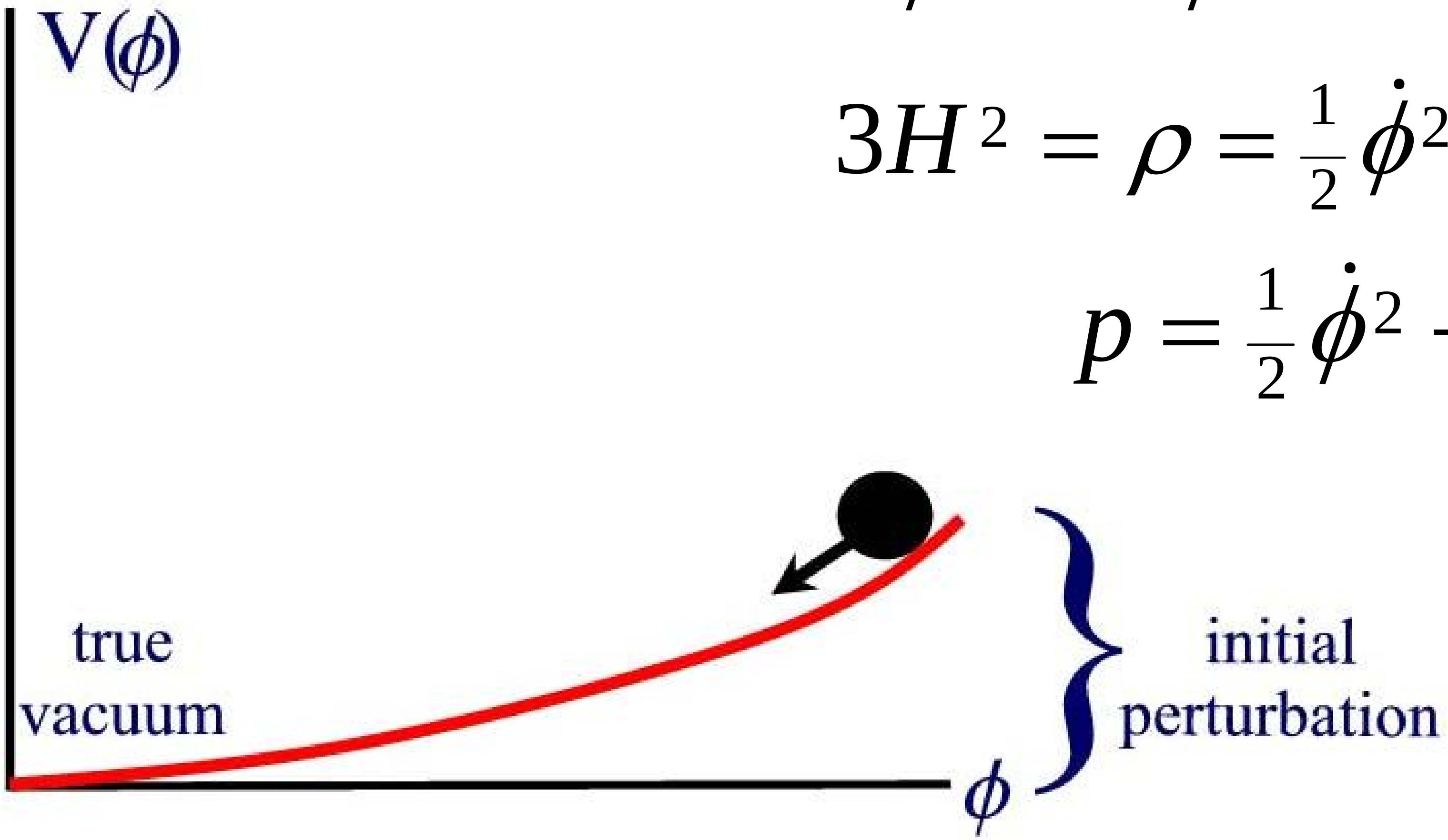
A scalar field displaced from the minima of its potential

Linde's chaotic inflation

$$\ddot{\phi} + 3H\dot{\phi} + V' = 0$$

$$3H^2 = \rho = \frac{1}{2}\dot{\phi}^2 + V$$

$$p = \frac{1}{2}\dot{\phi}^2 - V$$

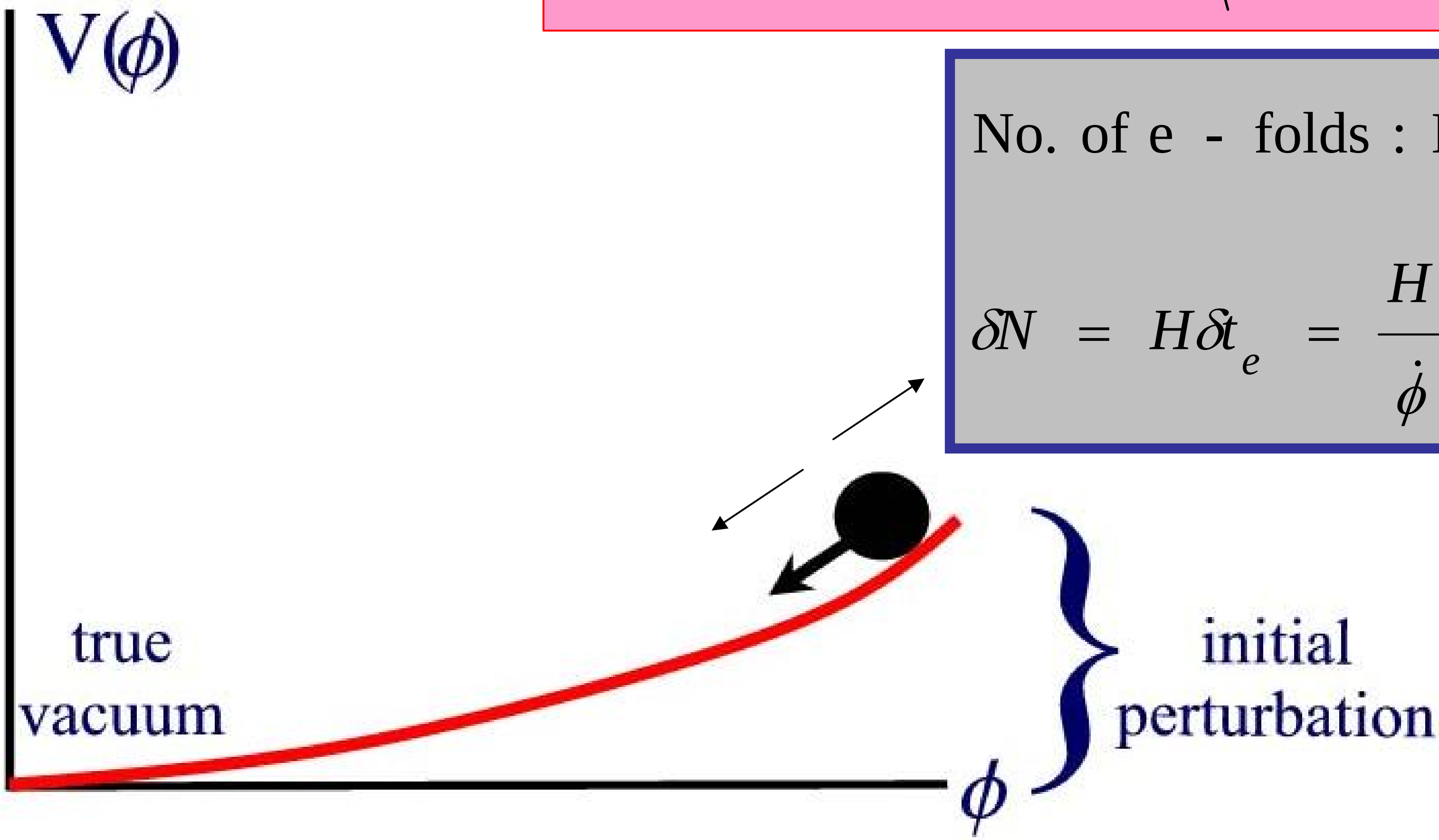


Generation of fluctuations

$$\text{"DeSitter" q. fluc.:} \ \delta\phi \equiv \left\langle (\delta\phi)^2 \right\rangle^{\frac{1}{2}} \approx H$$

$$\text{No. of e-folds: } N = \int H\,dt$$

$$\delta N = H\delta t_e = \frac{H}{\dot{\phi}}\,\delta\phi$$



Detecting the relic GW background :

Energy scale & mechanism of inflation

Early Universe in CMB

- **Tensor to scalar ratio is crucial discriminant of EU scenarios**

Scalar --- Density perturbations

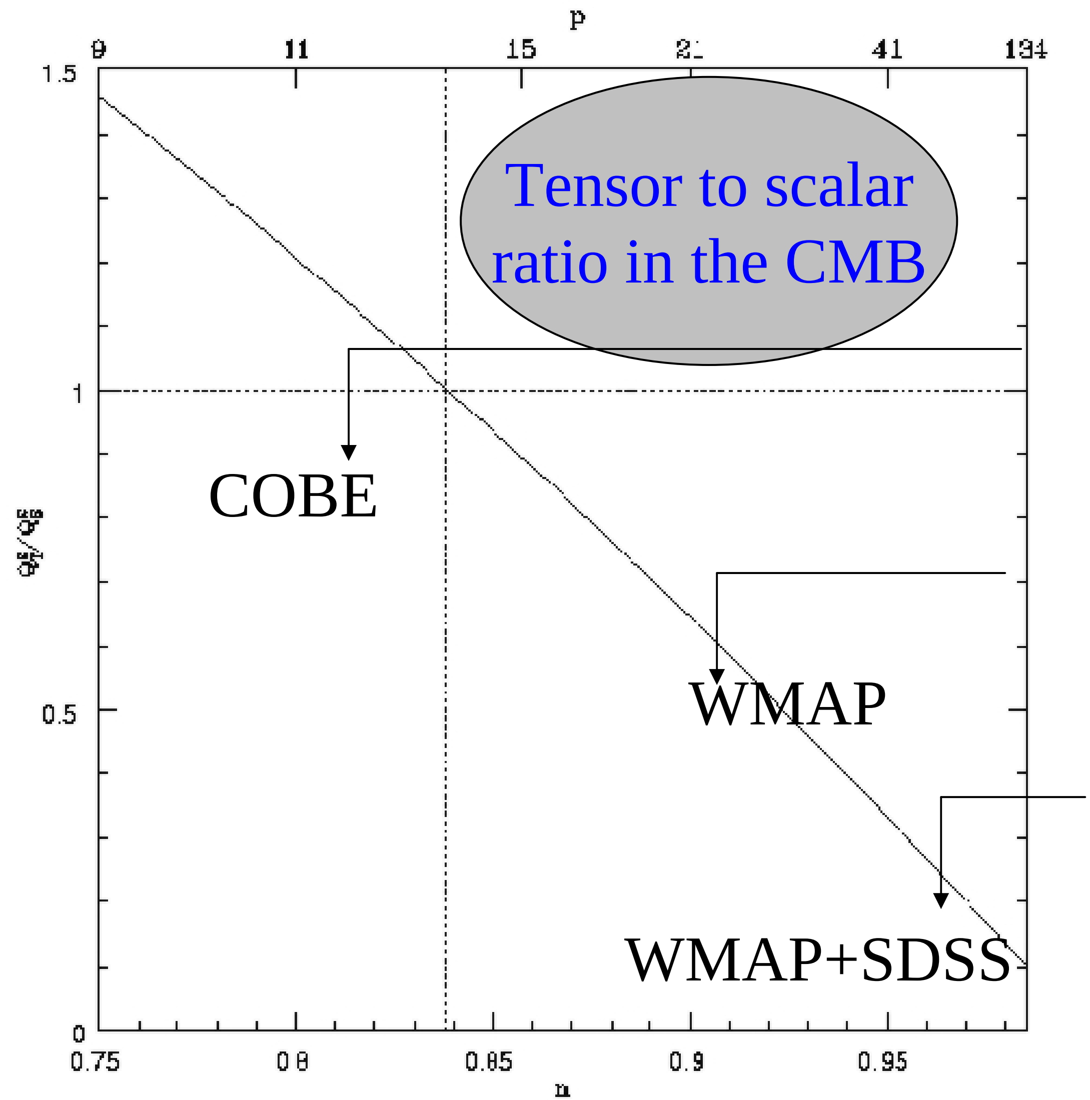
→ **Large scale structure in galaxy clustering**

Tensor --- Gravitational waves

→ **Relic stochastic GW background**

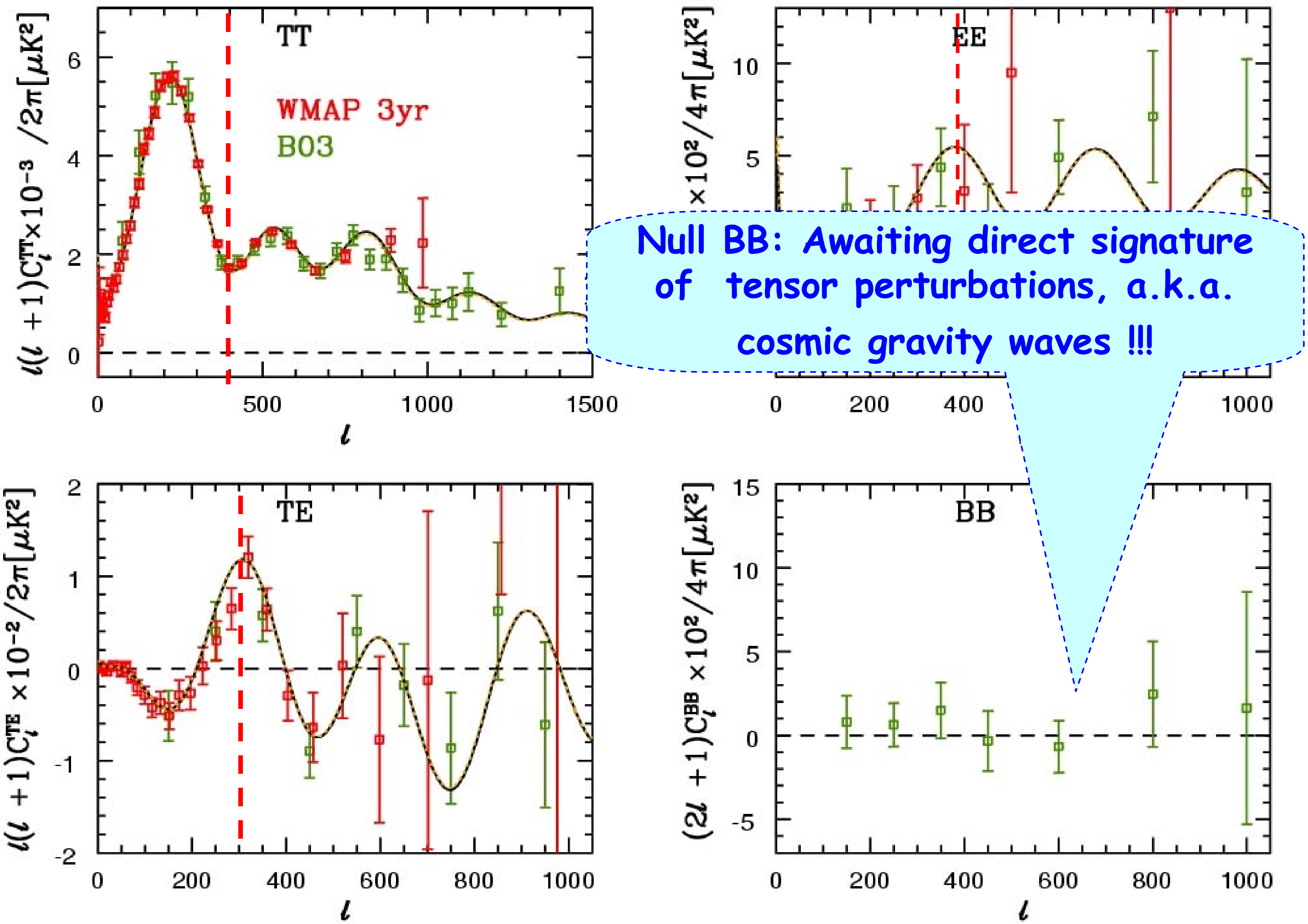
Vector --- rotational modes

→ **Perhaps unimportant, but primordial magnetic field**

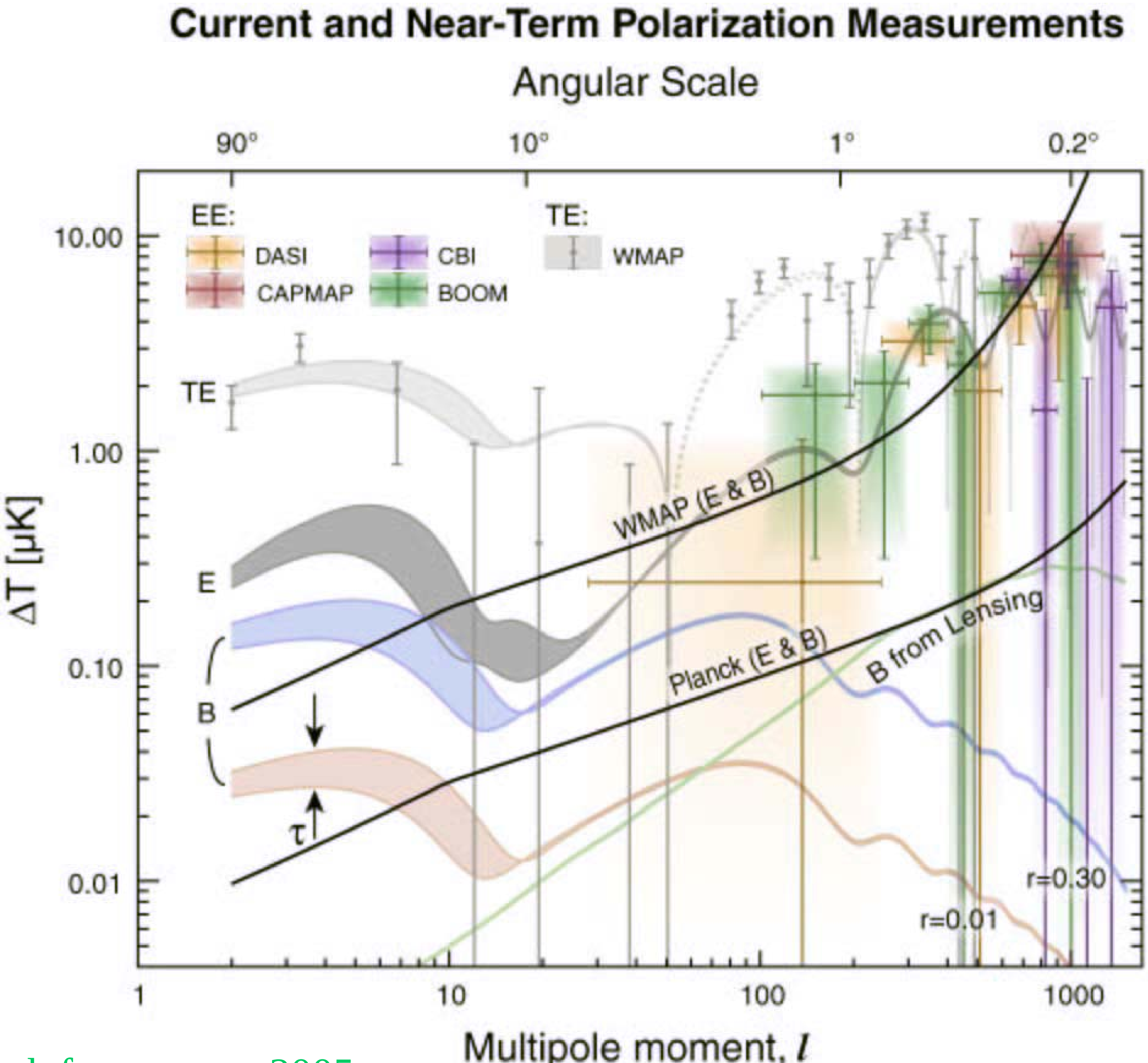


(Souradeep & Sahni, 1992, Souradeep, Ph.D.thesis, 1995)

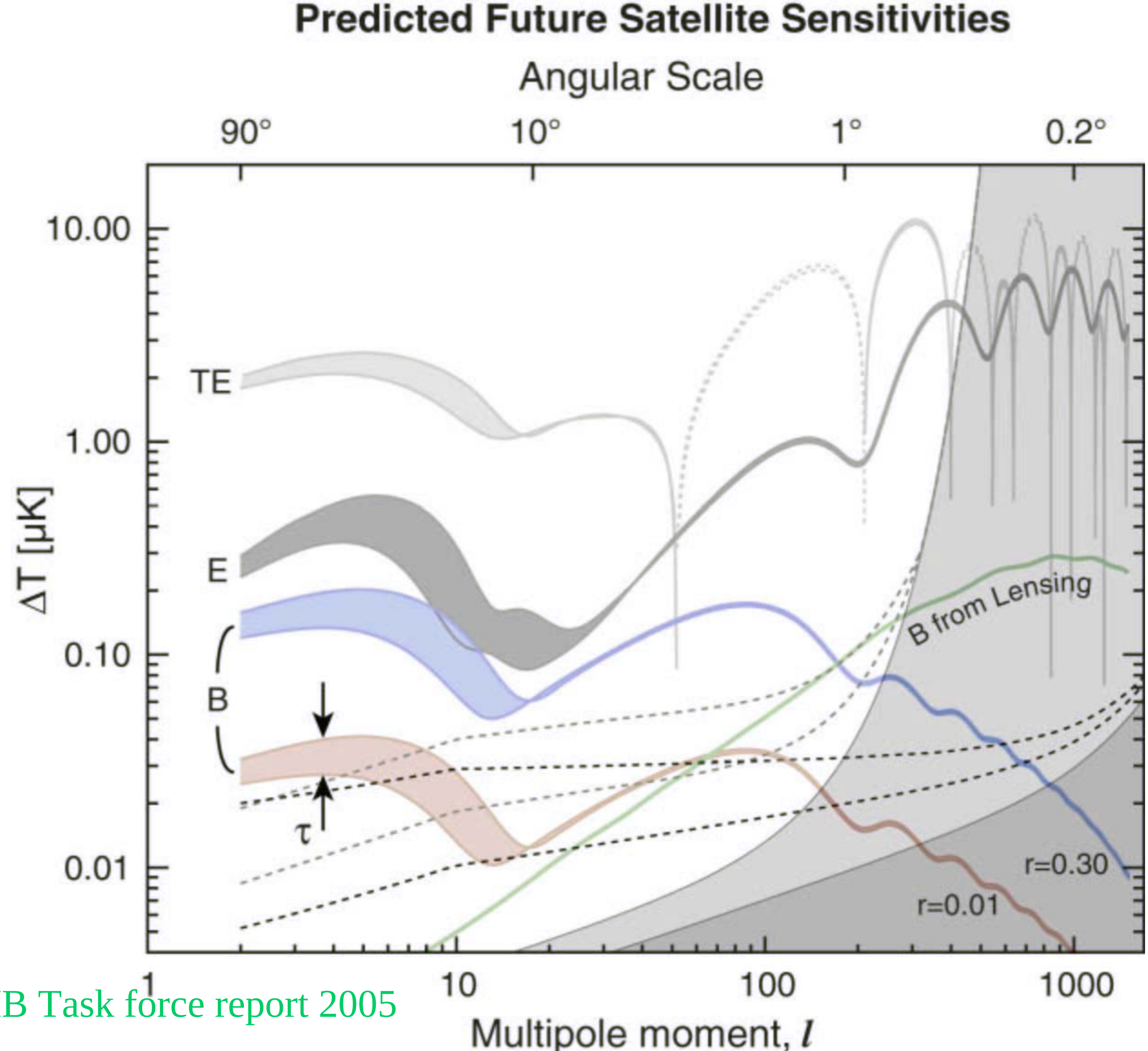
Current status of CMB Spectra



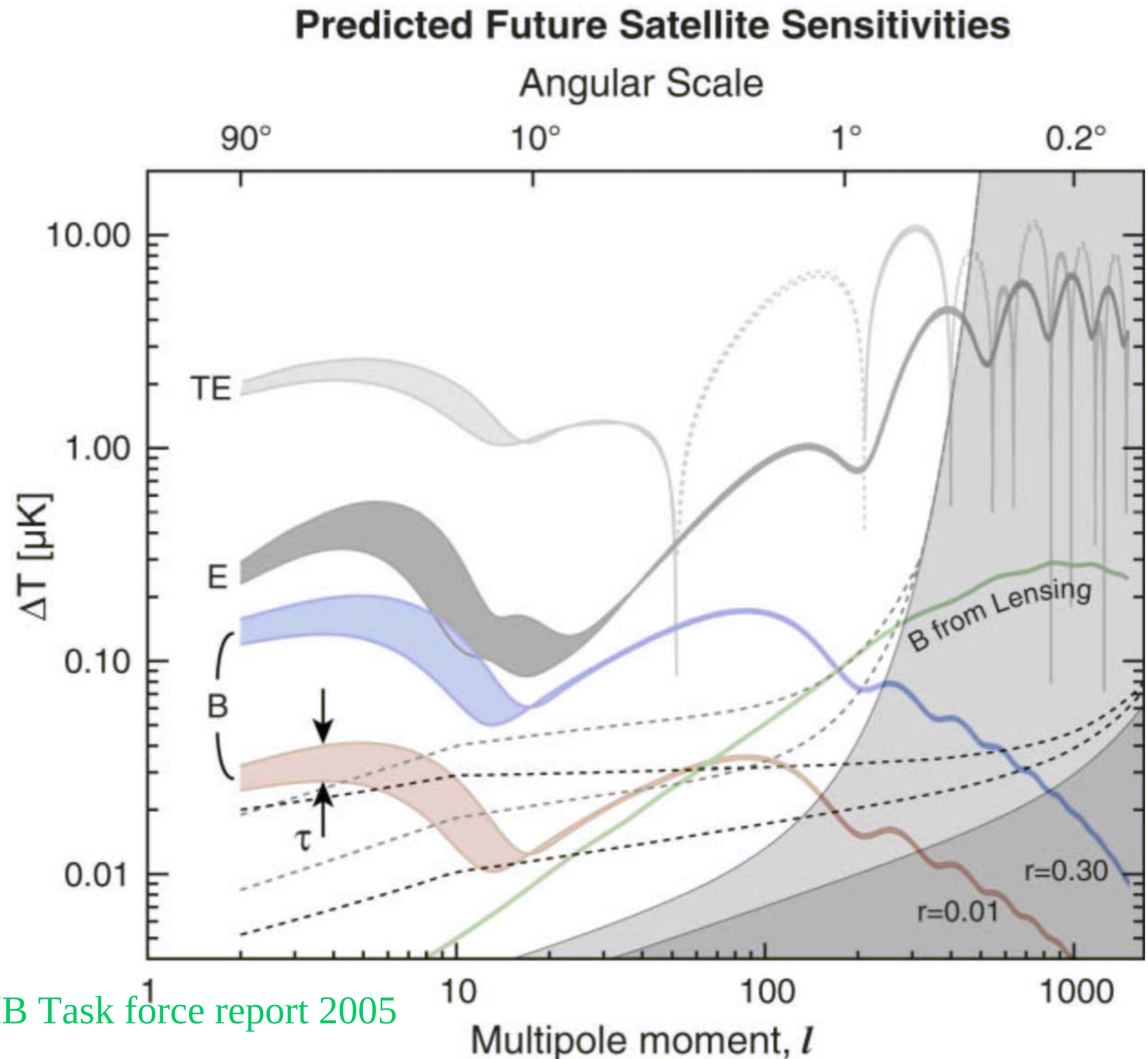
(Boomerang 2003, WMAP-3)



CMB Task force report 2005



CMB Task force report 2005



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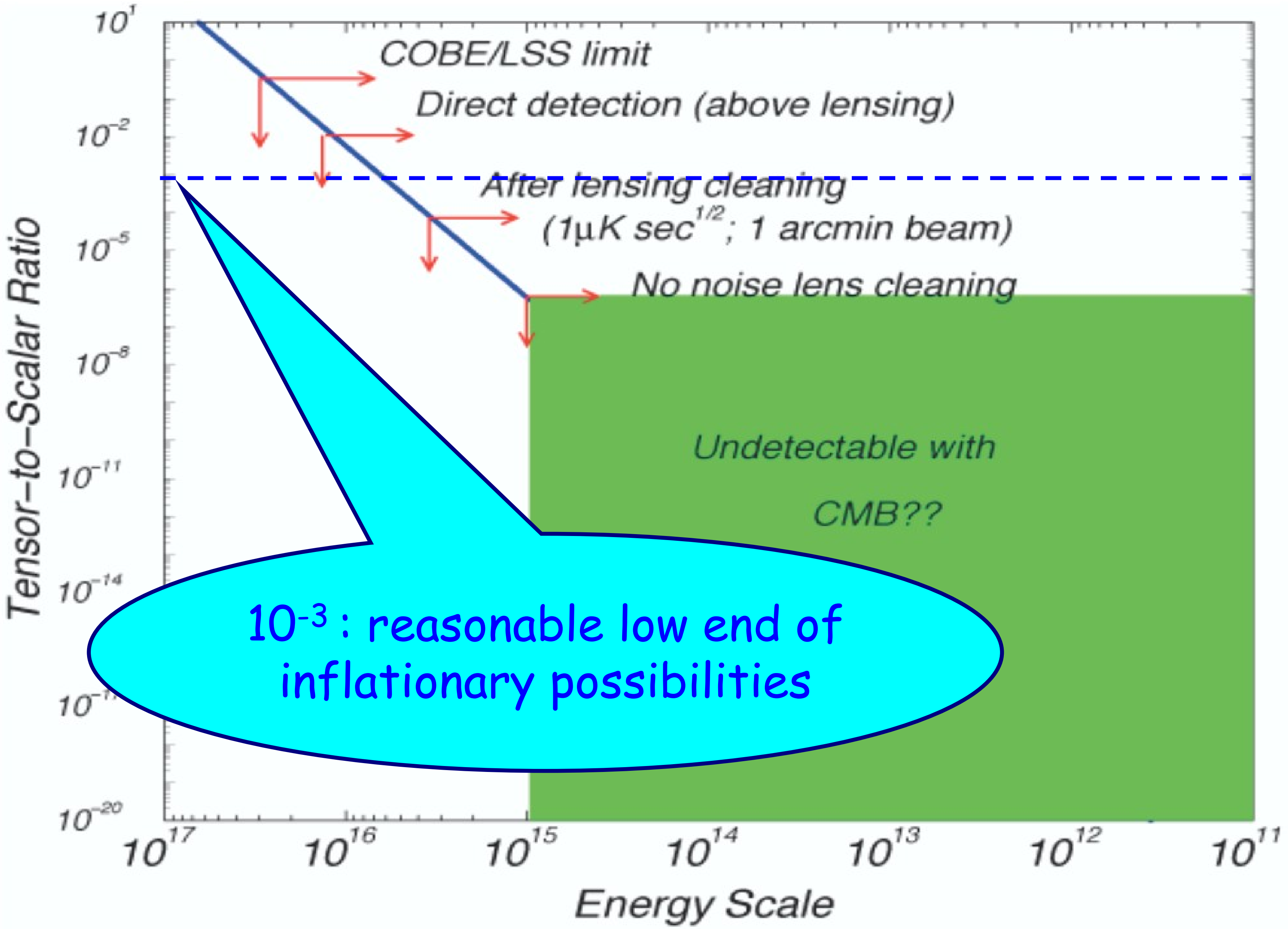
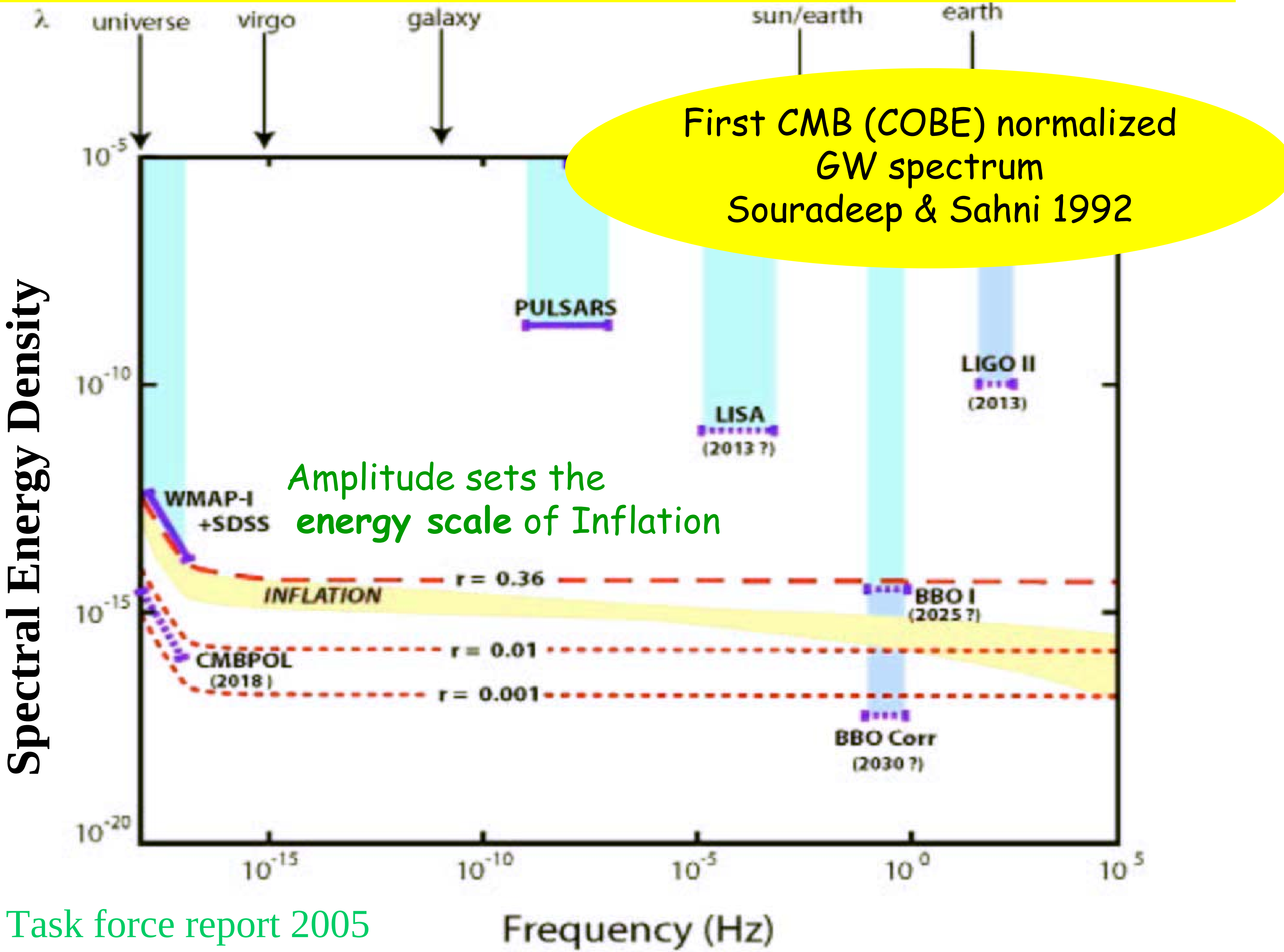


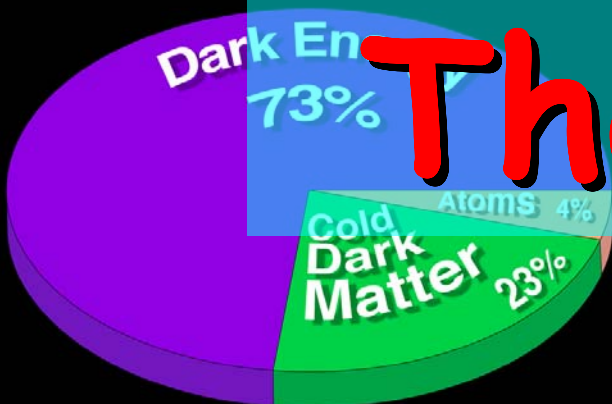
Courtesy: A. Coorey (EPIC)

Cosmic Gravity wave background



CMB Task force report 2005

Dark Energy?



Thank you !!!

Is it the Cosmological constant?

Interestingly enough, current cosmological observations are consistent with it being the Λ term 'blunder' in GR!!!