What can you do with the CMB as a backlight?

Princeton University

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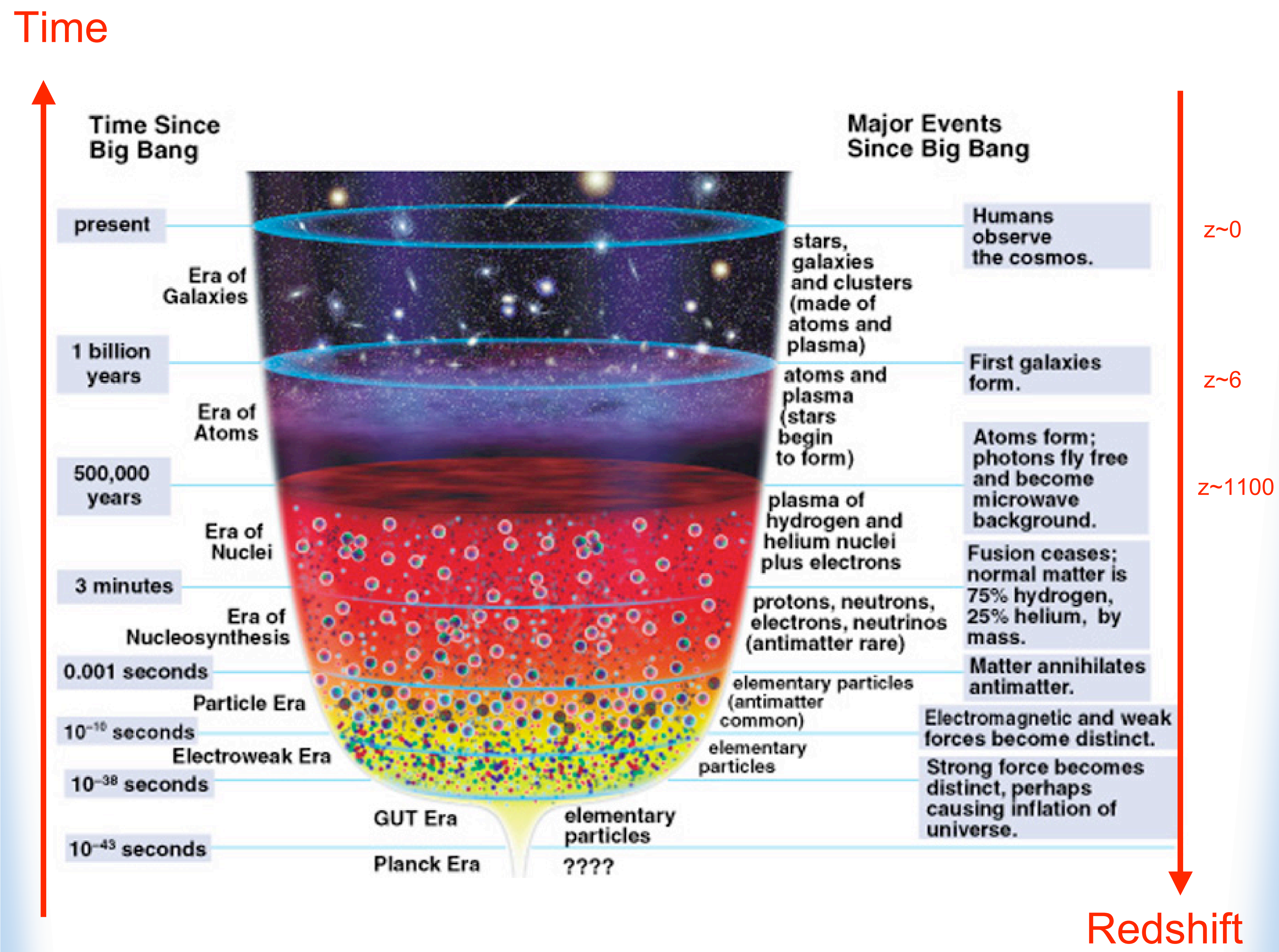
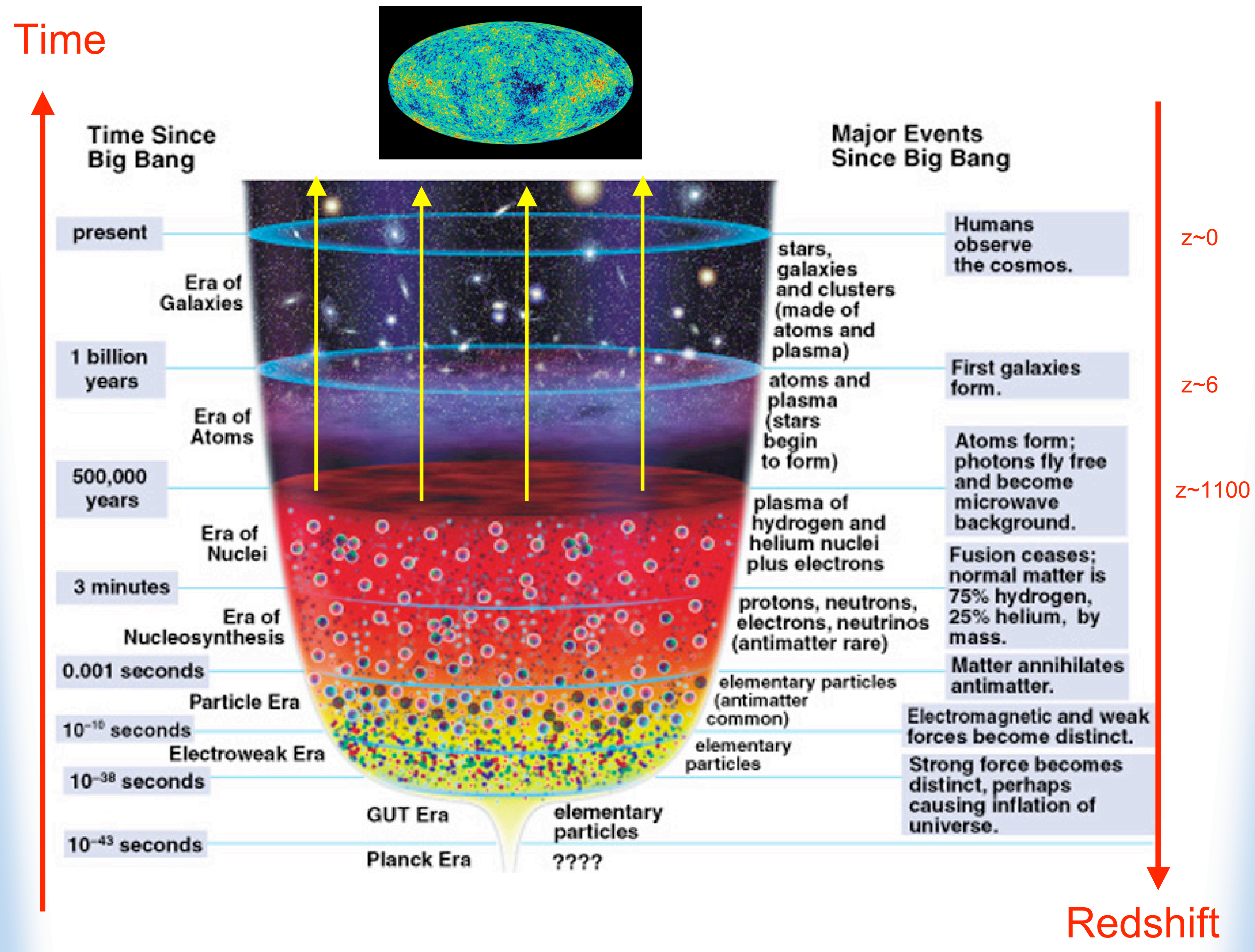
With wonderful collaborators:

Chris Hirata
Nikhil Padmanabhan
Uros Seljak
Simon DeDeo
Edwin Sirko
David Spergel

LBNL Research Progress Meeting
12/19/07


Time
Redshift
Time Since Big Bang
Major Events Since Big Bang
present
Era of Galaxies
1 billion years
Era of Atoms
500,000 years
Era of Nuclei
3 minutes
Era of Nucleosynthesis
0.001 seconds
Particle Era
10^-10 seconds
Electroweak Era
10^-38 seconds
GUT Era
10^-43 seconds
Planck Era
stars, galaxies and clusters (made of atoms and plasma)
atoms and plasma (stars begin to form)
plasma of hydrogen and helium nuclei plus electrons
protons, neutrons, electrons, neutrinos (antimatter rare)
elementary particles (antimatter common)
elementary particles
elementary particles
????
Humans observe the cosmos.
First galaxies form.
Atoms form; photons fly free and become microwave background.
Fusion ceases; normal matter is 75% hydrogen, 25% helium, by mass.
Matter annihilates antimatter.
Electromagnetic and weak forces become distinct.
Strong force becomes distinct, perhaps causing inflation of universe.
z~0
z~6
z~1100



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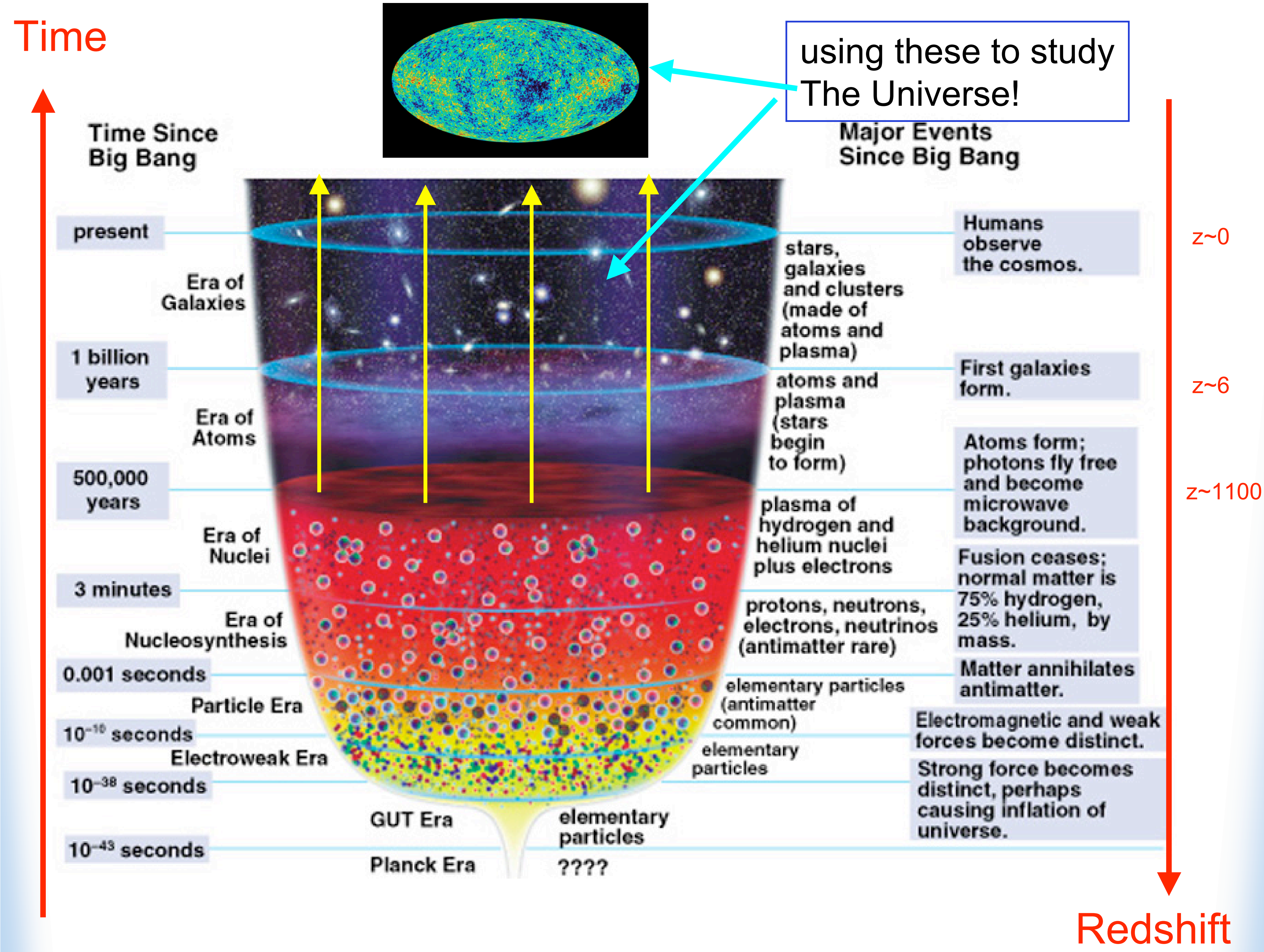

Time
using these to study The Universe!
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Outline

- Motivations -- Why am I doing this?

- Integrated Sachs Wolfe (ISW) Effect

  -> study the geometry of the Universe

- Weak Lensing (WL) of CMB (mini-version)

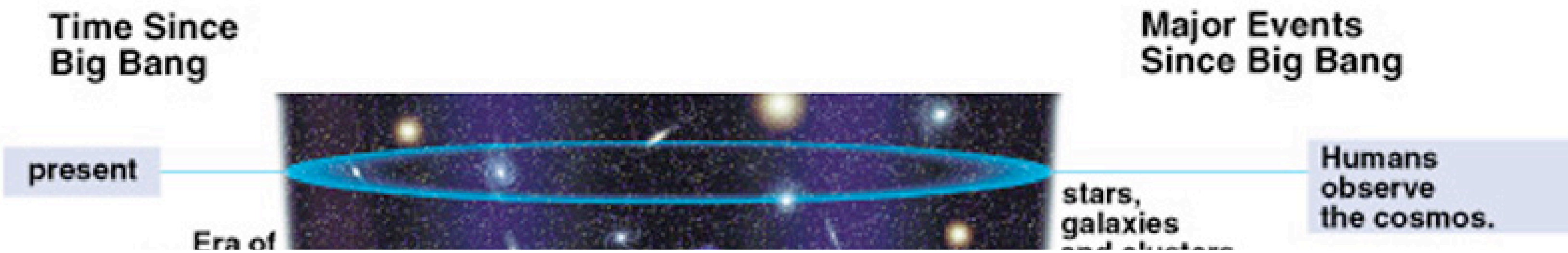
  -> study the matter between us and the last scattering surface

  Cosmological constraints from ISW and WL of CMB

- Kinetic Sunyaev Zeldovich (kSZ) Effect

  -> finding Missing Baryons!

Time



Gravity + observing movement of local galaxies -> "Dark Matter"

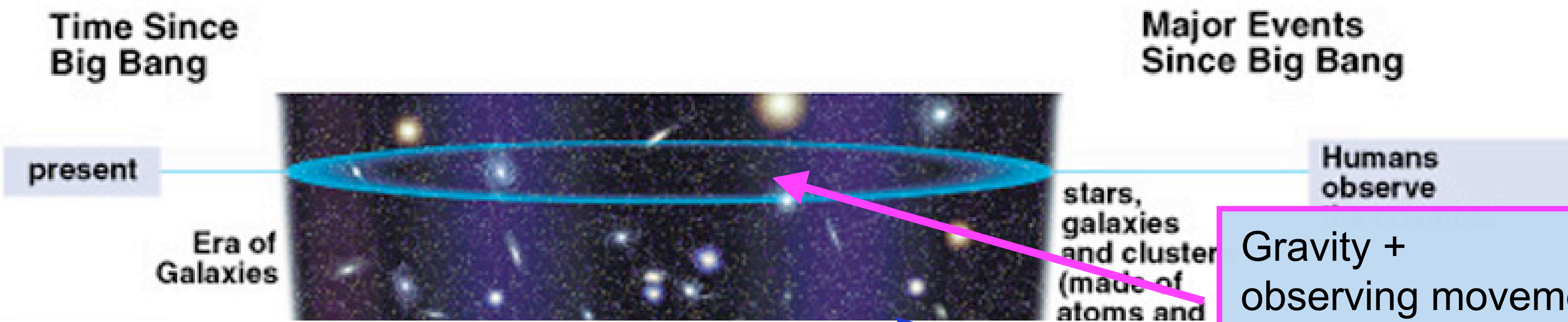
z~0

z~6

z~1100

Redshift

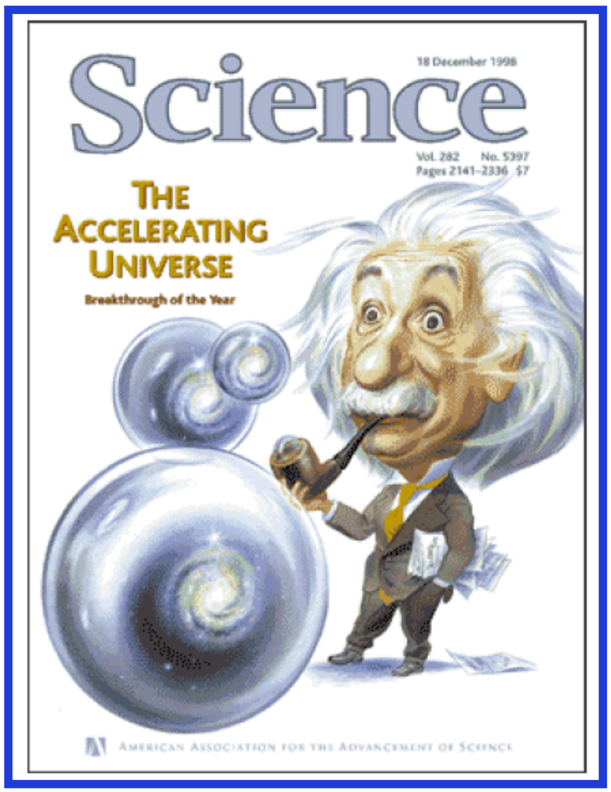
Time



z~0

Gravity +
observing movement
of local galaxies

z~6

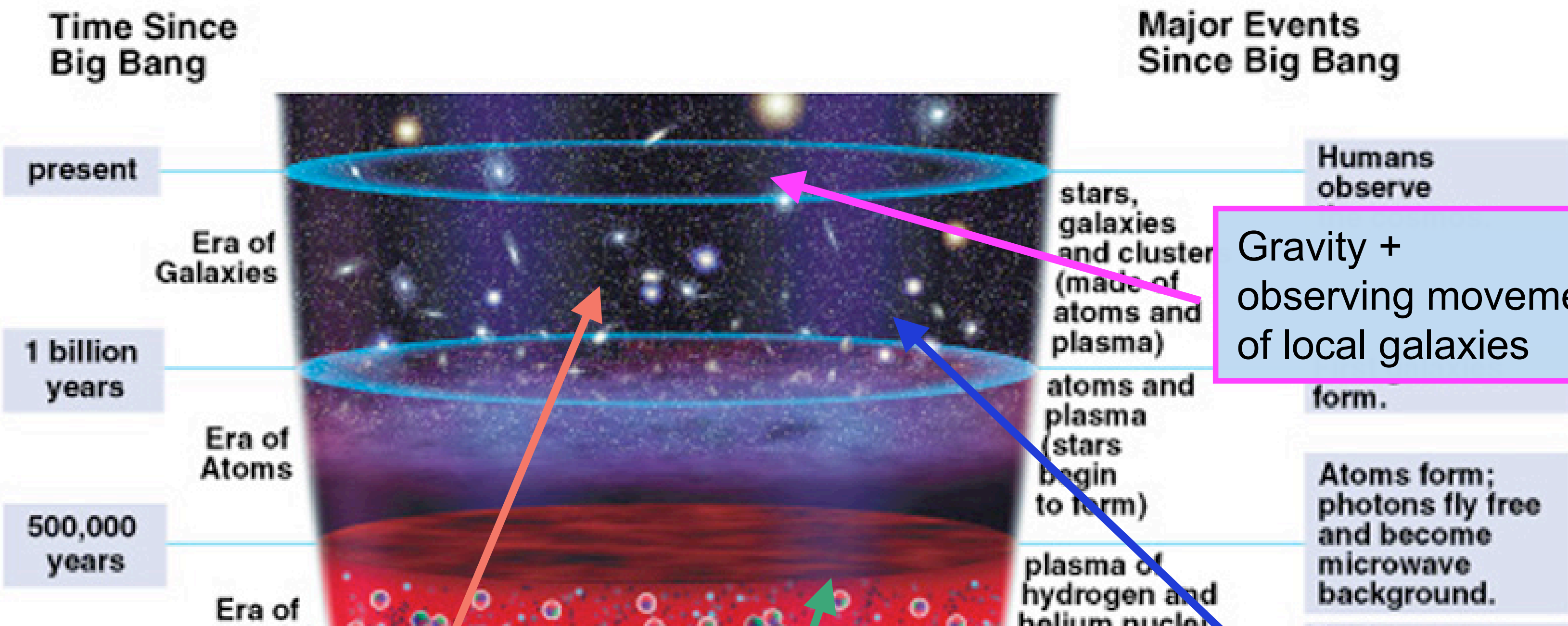


Distant supernovas appear
fainter than expected (1998)->
Universe is accelerating ->
Cosmological Constant?
Dark Energy?

z~1100

Redshift

Time



z~0

Gravity + observing movement of local galaxies

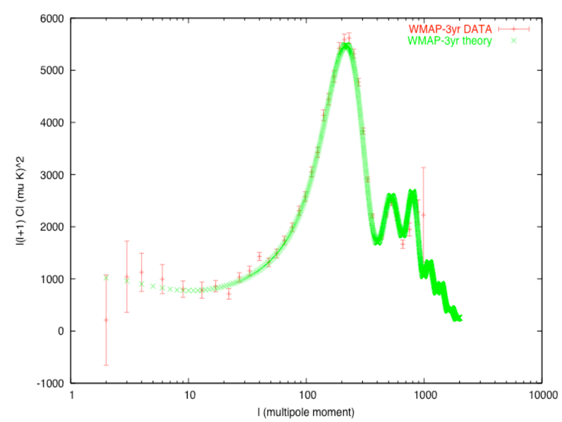
z~6

z~1100

Distant supernovas appear fainter than expected

Observations of how galaxies cluster

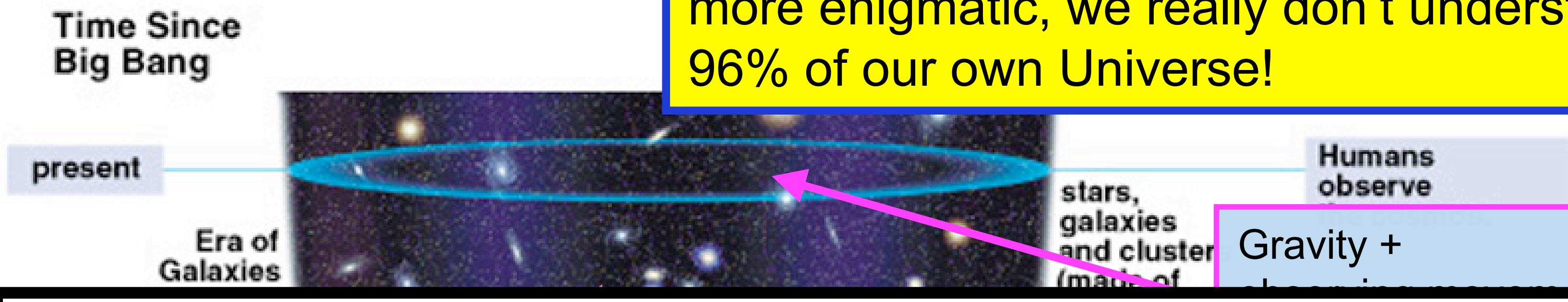
Observations of Cosmic Microwave Background -> angular powerspectrum of temperature anisotropies



Redshift

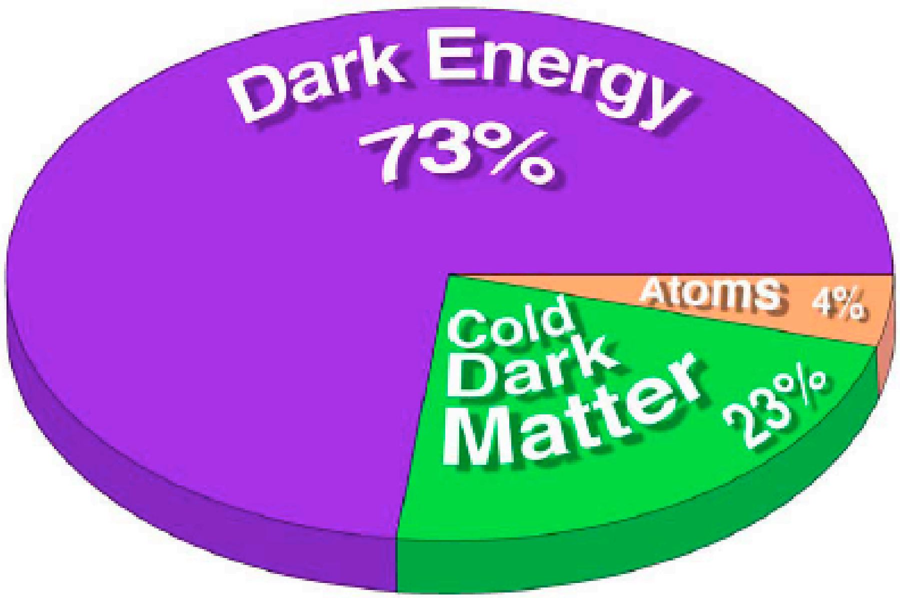
Time

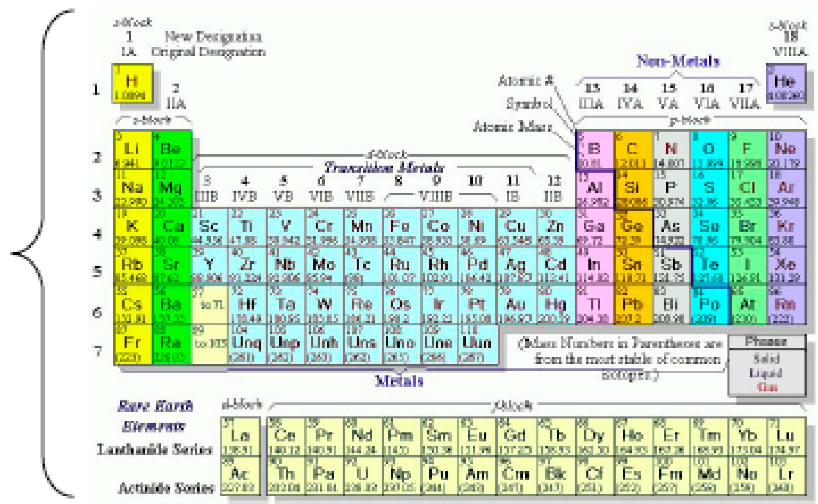
As we look further and further away from home, the Universe becomes more and more enigmatic, we really don't understand 96% of our own Universe!



z~0

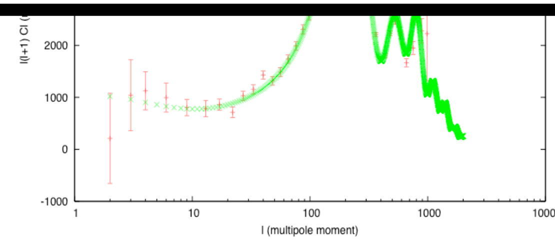
Gravity +





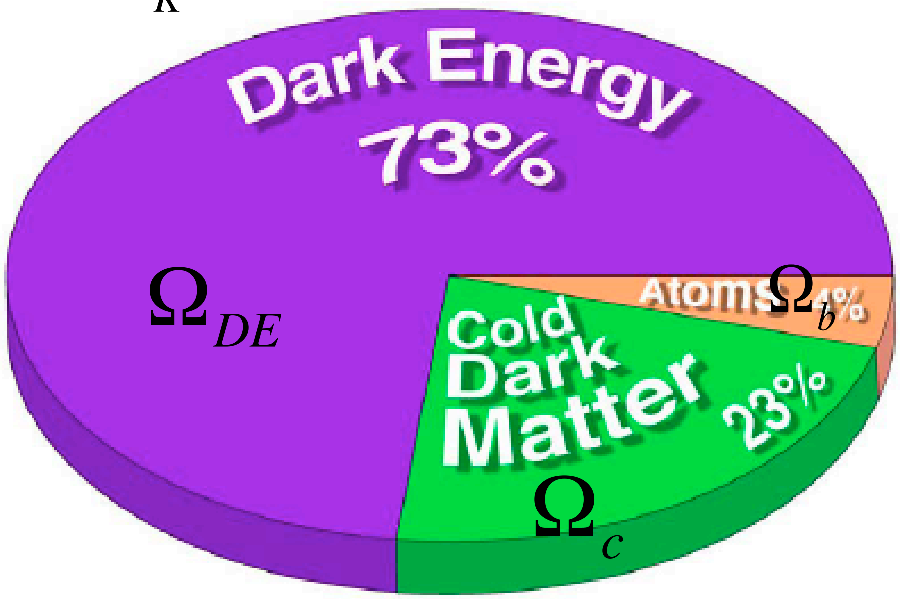
100

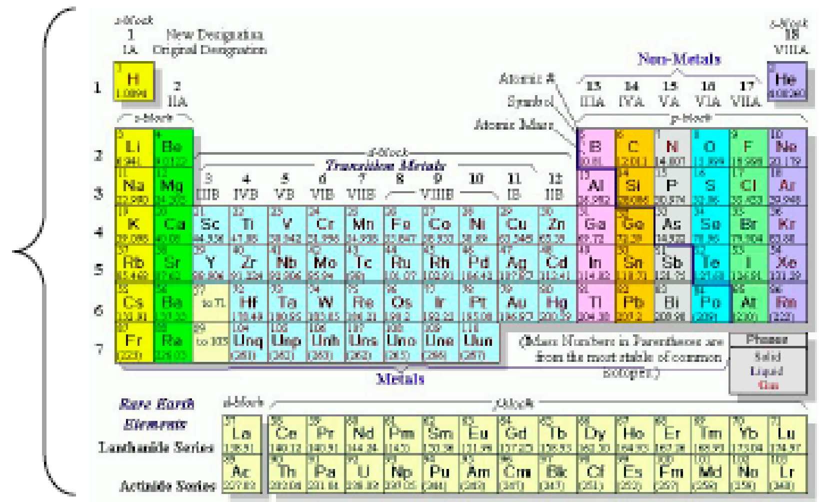
Observations of
Cosmic Microwave Background
-> angular powerspectrum of temperature anisotropies



Redshift

$$\Omega_K = 0$$





Ω_b is the **baryon density** expressed in terms of critical density

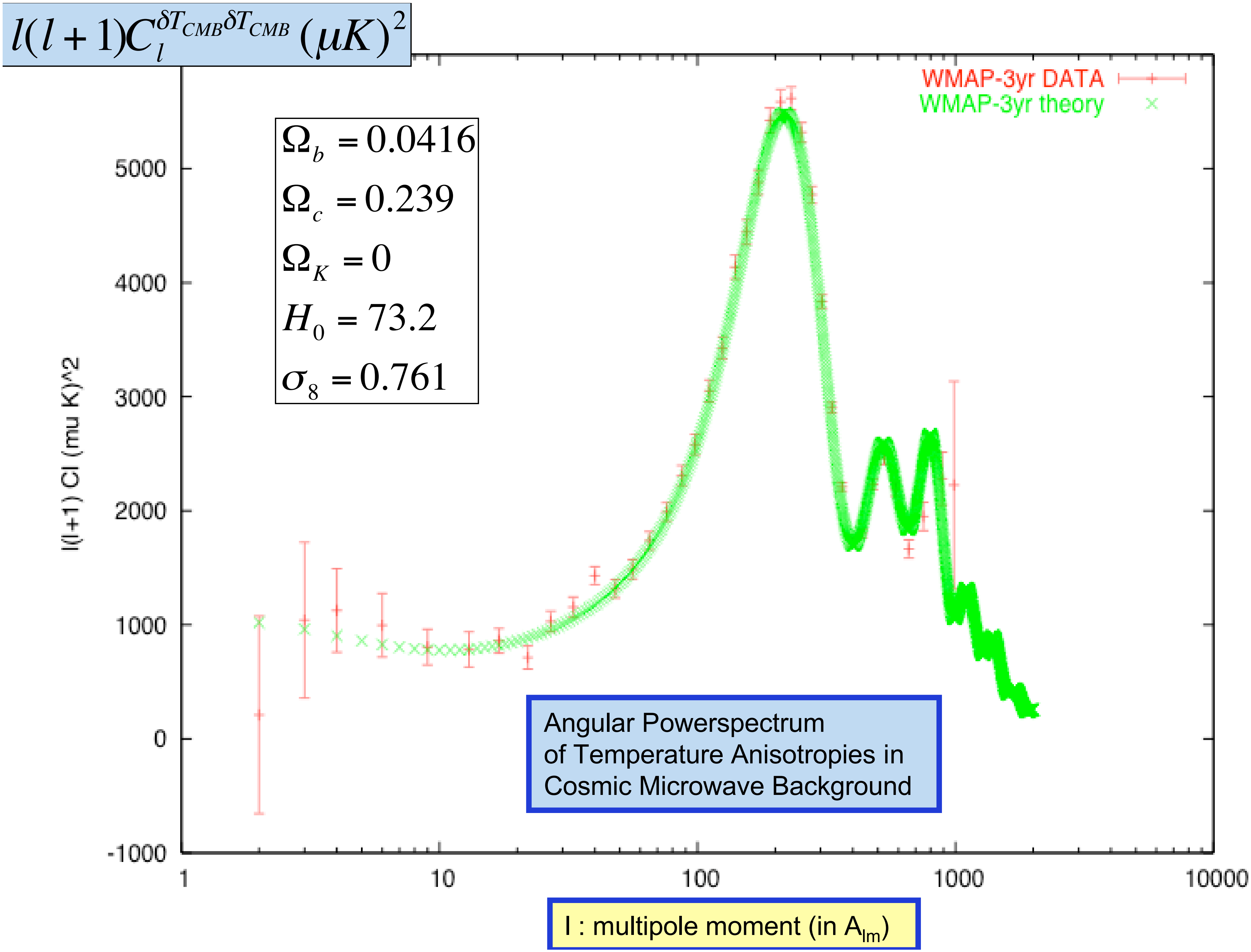
Ω_c is the **cold dark matter density** expressed in terms of critical density

$\Omega_K = -K/H_0^2$ is the **curvature** expressed in terms of critical density

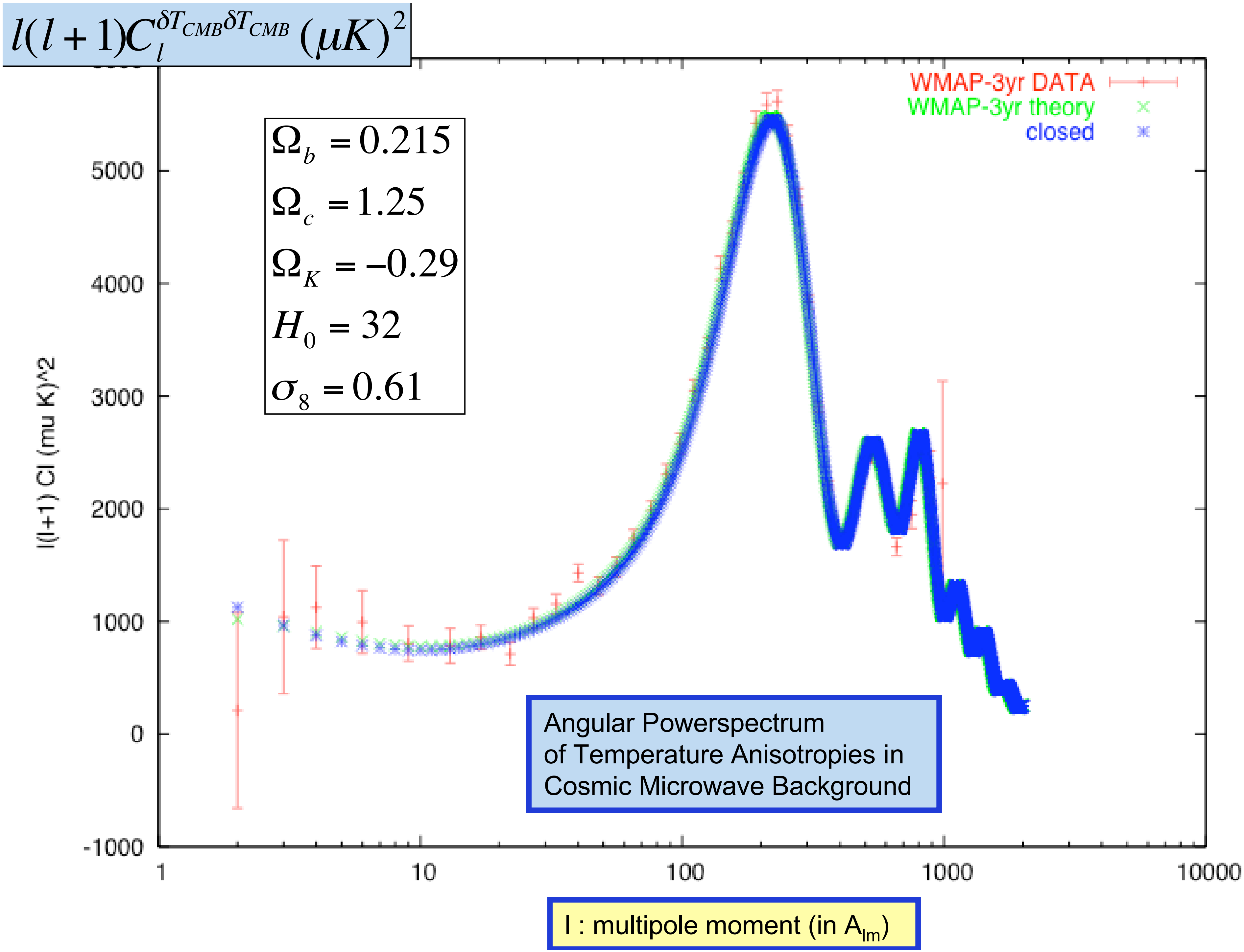
Ω_{DE} is the **dark energy density** expressed in terms of critical density

H_0 is the **Hubble constant** which dictates how fast the Universe is expanding

σ_8 measures how strong the **fluctuation of matter density** is



$l(l+1)C_l^{\delta T_{CMB}\delta T_{CMB}}\ (\mu K)^2$
WMAP-3yr DATA
WMAP-3yr theory
$\Omega_b = 0.0416$
$\Omega_c = 0.239$
$\Omega_K = 0$
$H_0 = 73.2$
$\sigma_8 = 0.761$
l(l+1) Cl (mu K)^2
5000
4000
3000
2000
1000
0
-1000
1
10
100
1000
10000
Angular Powerspectrum
of Temperature Anisotropies in
Cosmic Microwave Background
l : multipole moment (in A_{lm})



$l(l+1)C_l^{\delta T_{CMB}\delta T_{CMB}}\ (\mu K)^2$
WMAP-3yr DATA
WMAP-3yr theory
closed
$\Omega_b = 0.215$
$\Omega_c = 1.25$
$\Omega_K = -0.29$
$H_0 = 32$
$\sigma_8 = 0.61$
l(l+1) Cl (mu K)^2
5000
4000
3000
2000
1000
0
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1
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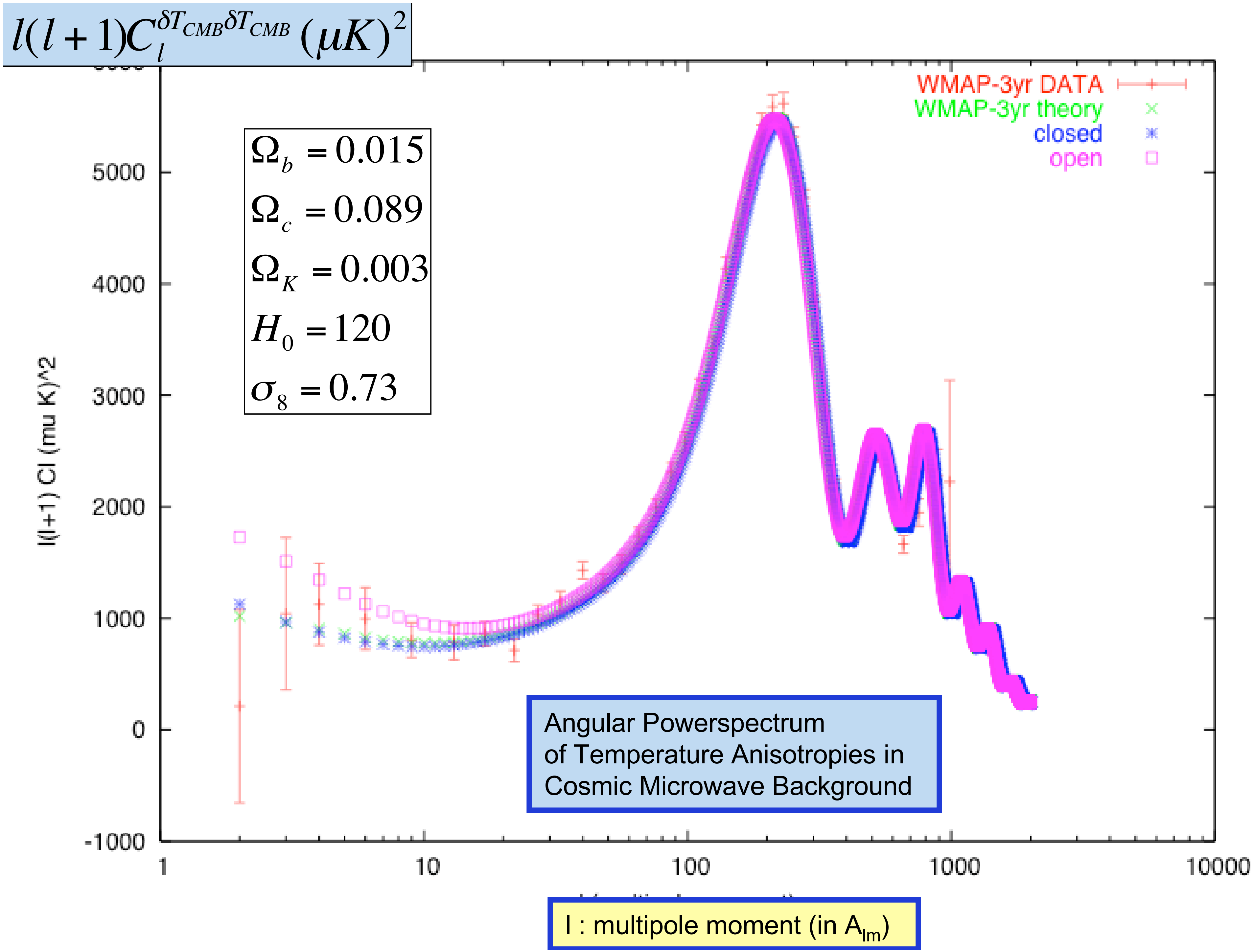
$l(l+1)C_l^{\delta T_{CMB}\delta T_{CMB}}\ (\mu K)^2$
$\Omega_b = 0.015$
$\Omega_c = 0.089$
$\Omega_K = 0.003$
$H_0 = 120$
$\sigma_8 = 0.73$
WMAP-3yr DATA
WMAP-3yr theory
closed
open
l(l+1) Cl (mu K)^2
5000
4000
3000
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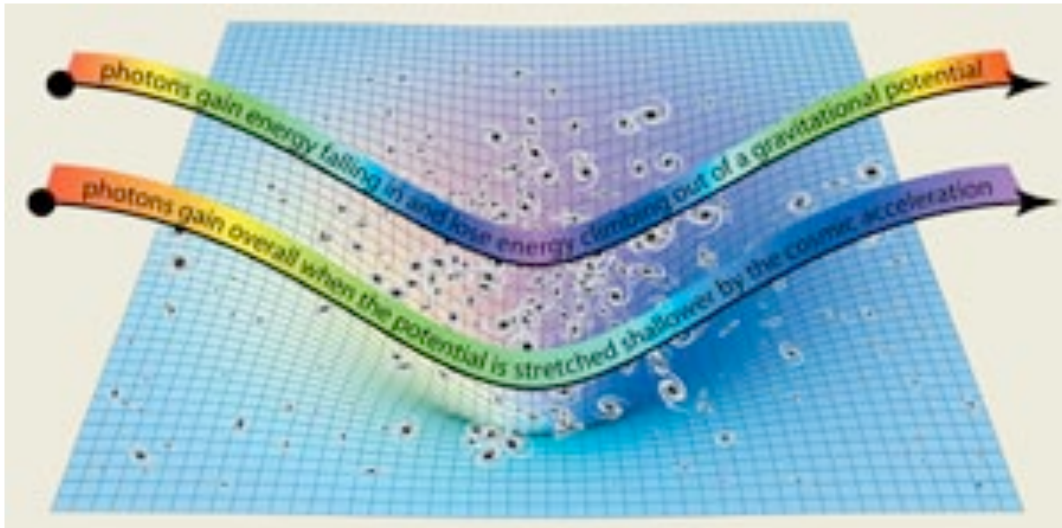
Physics of ISW:

CMB photons



$$\frac{\delta T_{ISW}}{T_{CMB}}(\hat{\theta}) = 2\int_{\eta_r}^{\eta_0} d\eta \frac{\partial \phi}{\partial \eta}$$

ϕ → Gravitational Potential of The Universe

- Photons gain energy going down potential well, lose energy climbing out.
- As $\Phi \to 0$ and a blue-shift is observed in overdense ($\Phi<0$) regions.

Thus we see a positive correlation between CMB temperature and density.

-> Unique Probe into the change of gravitational potential of the Universe

Physics of ISW:

•Since the change in temperature due to ISW is very small compared to the primary fluctuations of CMB, we can only detect the ISW by looking at where ISW effect happens.

$b = \frac{\delta g}{\delta \rho}$ describe how galaxies are related to cold dark matter

$\frac{dN}{dz}$ describe how many galaxies are there at each dz bin

$D(z)$ describe how matter grows

$P(\frac{l+\frac{1}{2}}{\chi})$ describe how matter cluster (matter powerspectrum)

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$$\phi(k,z) = -\frac{3}{2}\frac{H_0^2}{c^2}\Omega_m(1+z)\frac{\delta(k,z=0)}{k^2}D(z)$$

Poisson equation. in fourier space

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$$[g]_l(k) = \int b * \frac{dN}{dz} D(z)\delta_\rho(k,z=0) j_l(k\chi(z))dz$$

Galaxy overdensity in fourier space

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Change in CMB temperature due to ISW

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Change in CMB temperature due to ISW

Galaxy-ISW 2D correlation

$$C_l^{g\delta T_{ISW}} = \frac{3\Omega_m H_0^2 T_{CMB}}{c^2(l+\frac{1}{2})^2}\int b * \frac{dN}{dz}\frac{H(z)}{c}D(z)\frac{d}{dz}[D(z)(1+z)]P(\frac{l+\frac{1}{2}}{\chi})dz$$

What can ISW do?

- Unique Probe to the change of gravitational potential of the Universe.
- Puts independent constraints on parameters of Universe such as curvature, dark energy equation of state.
- ISW is expected to be a strong discriminator of modified gravity models, which have very distinctive ISW predictions (Song et al. 2007).

What can ISW do?

- Unique Probe to the Gravitational Potential of the Universe
- Puts independent constrai
  as
- ISV
  alt   et al.
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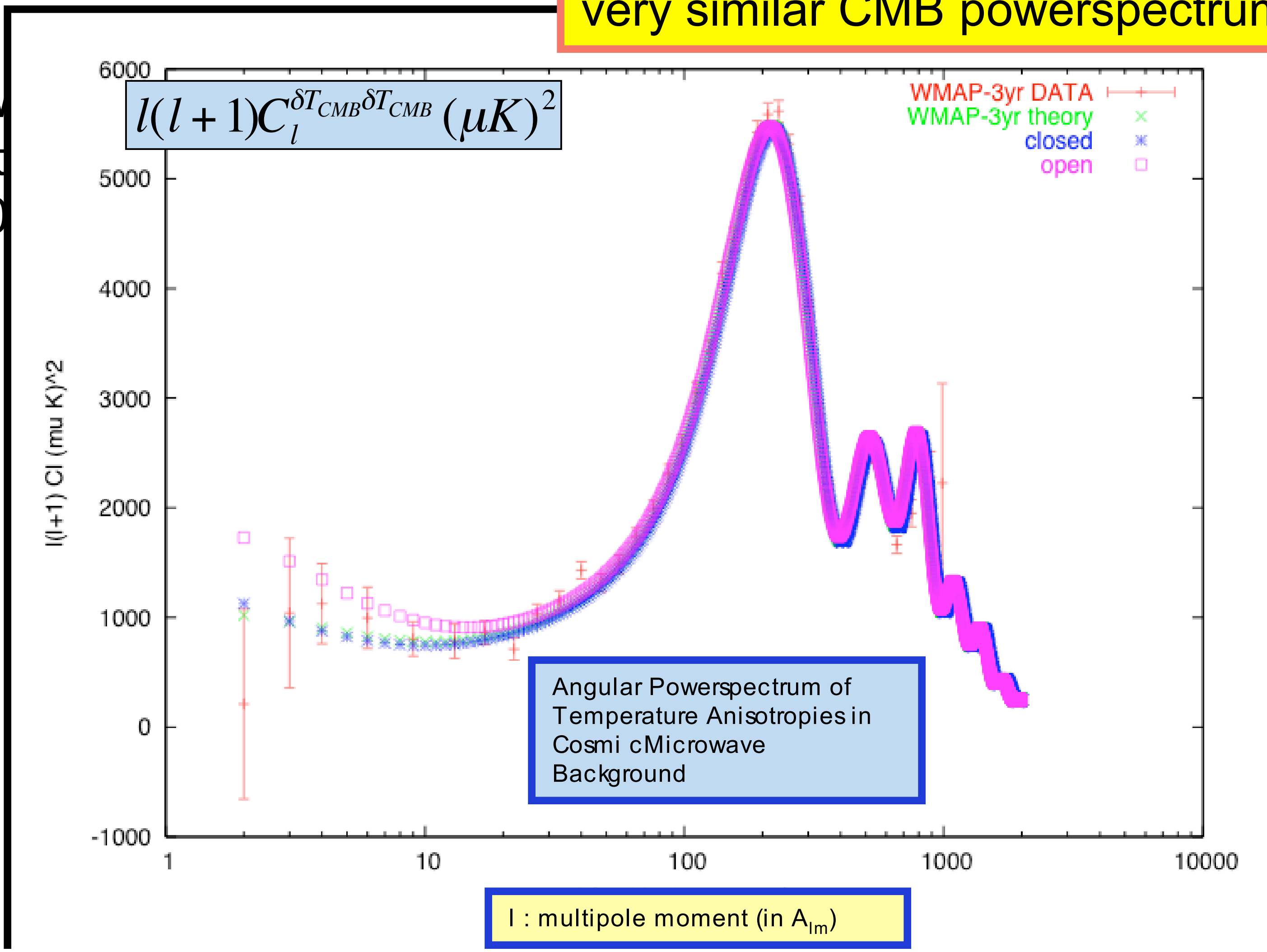
Recall the three universes that produce very similar CMB powerspectrum



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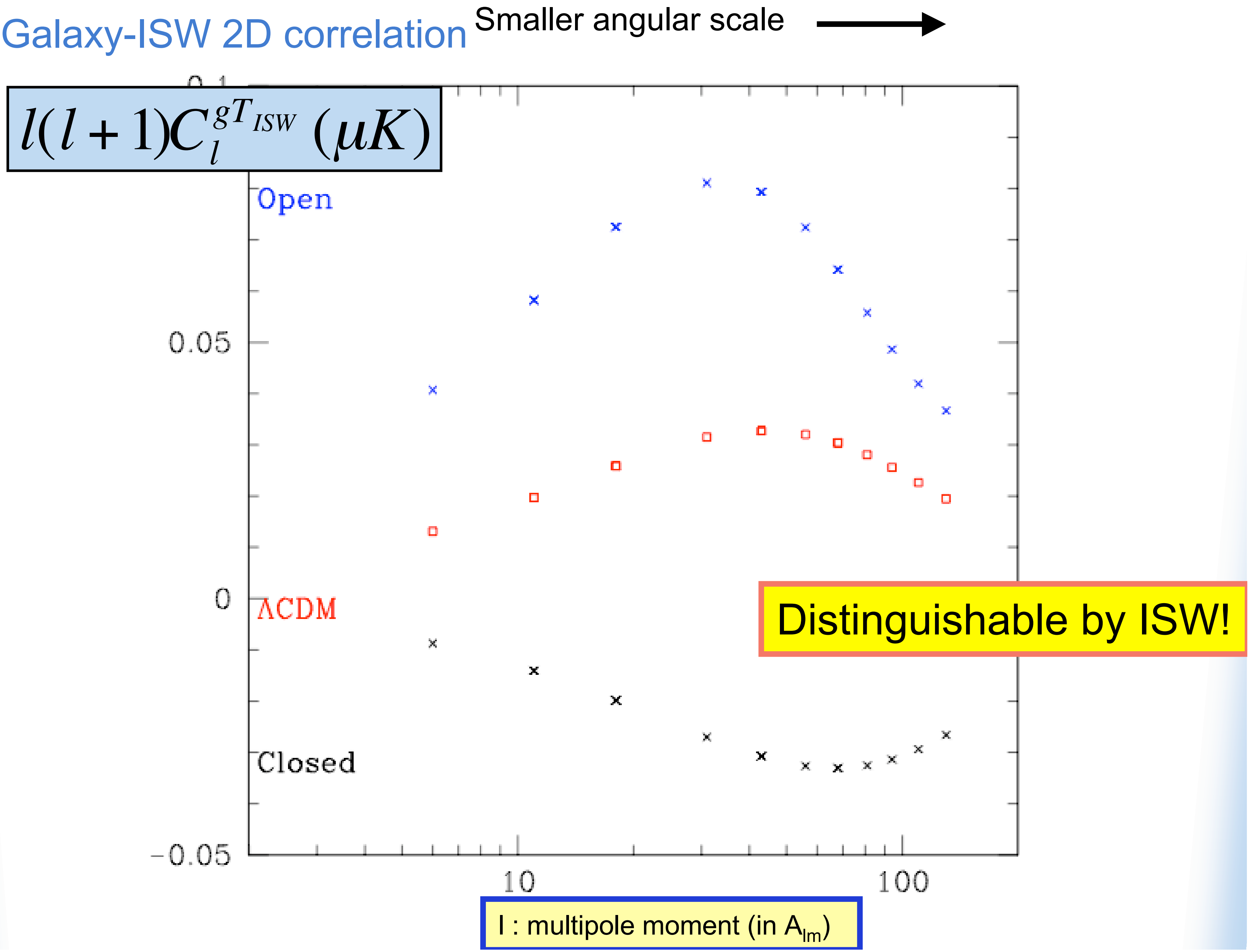
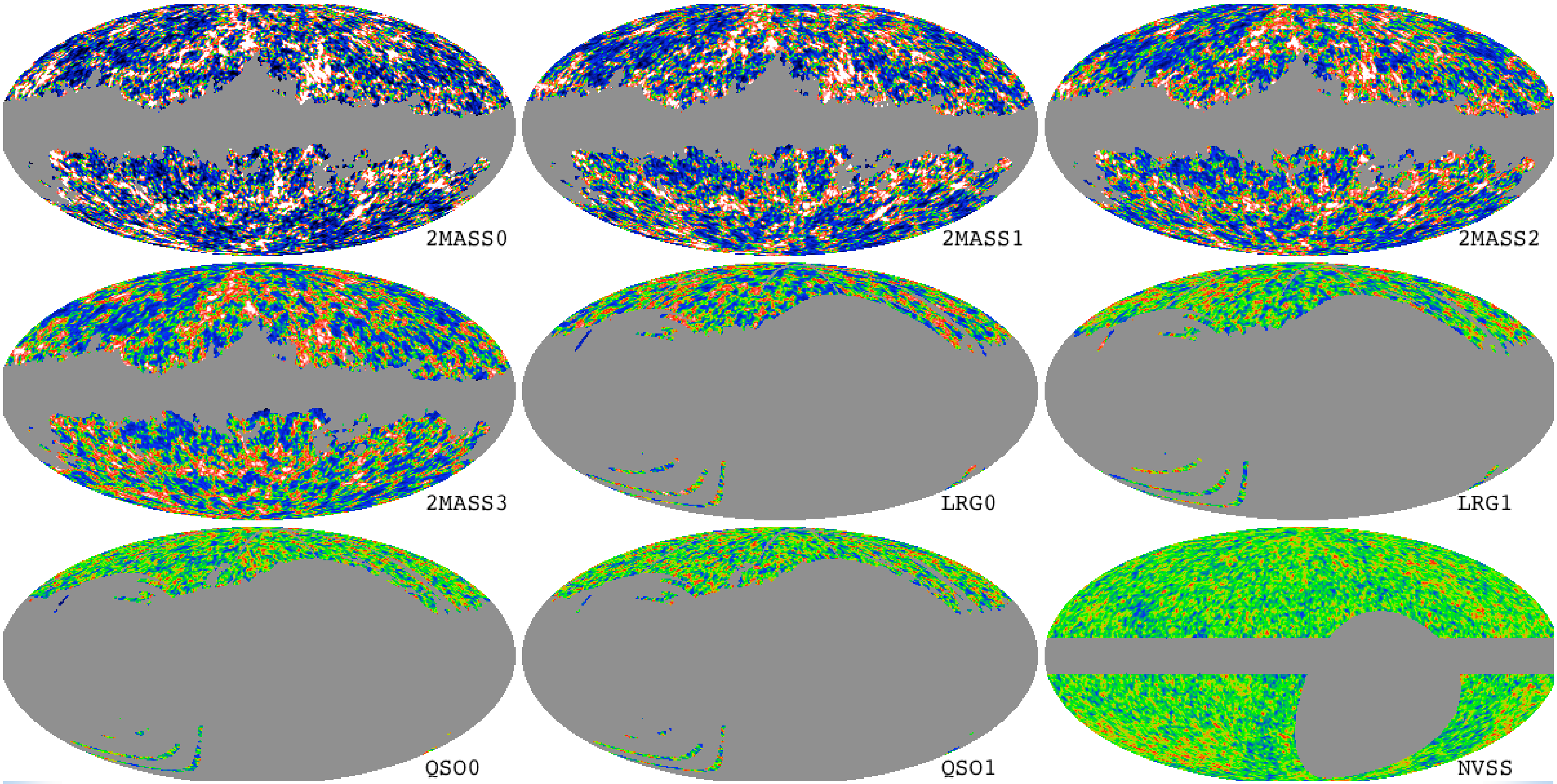


Large scale structure samples:
2MASS(2-Micron All Sky Survey)
LRG(SDSS Luminous Red Galaxies)
QSO(SDSS Quasars/Quasi-Stellar Objects)
NVSS(NRAO VLA Sky Survey)



Ho, Hirata, Padmanabhan & Seljak (2007, being reviewed)

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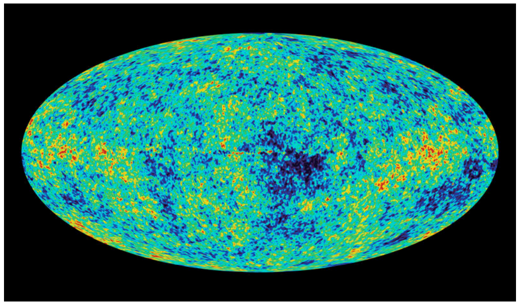
- We cross correlate the CMB sky (from WMAP) with the large scale structure which traces the mass, thus potential wells of the Universe:



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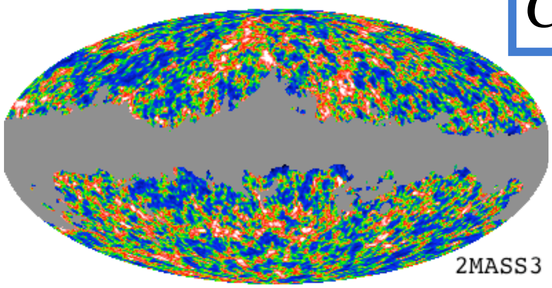
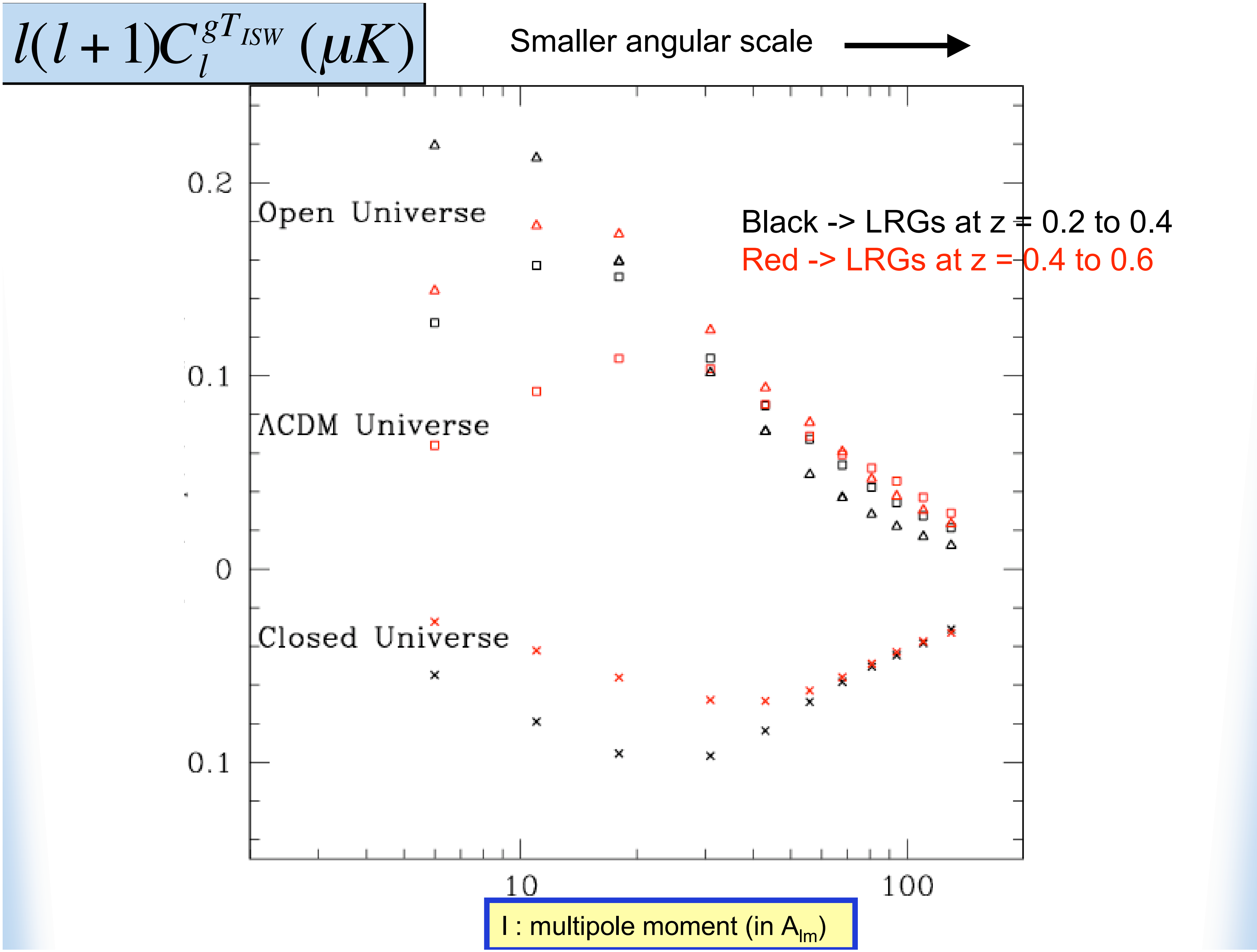


C_l^{gT} (Data)

- But in order to determine cosmological constraints from $C_l^{gT}(Data)$, we need to be able to **predict** the correlation amplitude.
- To do that, what do we need? $C_l^{gT_{ISW}}(Theory)$

$$C_l^{g\delta T_{ISW}} = \frac{3\Omega_m H_0^2 T_{CMB}}{c^2(l+\frac{1}{2})^2}\int b*\frac{dN}{dz}\frac{H(z)}{c}D(z)\frac{d}{dz}[D(z)(1+z)]P(\frac{l+\frac{1}{2}}{\chi})dz$$



$l(l+1)C_l^{gT_{ISW}}\ (\mu K)$
Smaller angular scale
Open Universe
ΛCDM Universe
Closed Universe
Black -> LRGs at z = 0.2 to 0.4
Red -> LRGs at z = 0.4 to 0.6
0.2
0.1
0
0.1
10
100
l : multipole moment (in A_{lm})

Bias and Redshift distributions:

- What we know:

2MASS	positions, colors of galaxies
LRGs	positions, colors of galaxies, has good photo-z
QSOs	positions, colors of quasar, has photo-z.
NVSS	positions, measure of "light" at 1 frequency.

- What we don't know: their bias and redshift distribution.
- What do we do?

(a) Get spectroscopic redshifts (when you can) to estimate a preliminary dn/dz

(b) Use clustering data to estimate the b*dn/dz

(c) Then this will only give you b*dn/dz for 2MASS, LRGs and QSOs, how about NVSS?

-> **Cross correlate with datasets that we know their distributions**!!

Bias and Redshift distributions:

- What we know:

4000 Angstrom break

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LRGs	positions, colors of galaxies, has good photo-z
QSOs	
NVSS	

- What we do
- What do

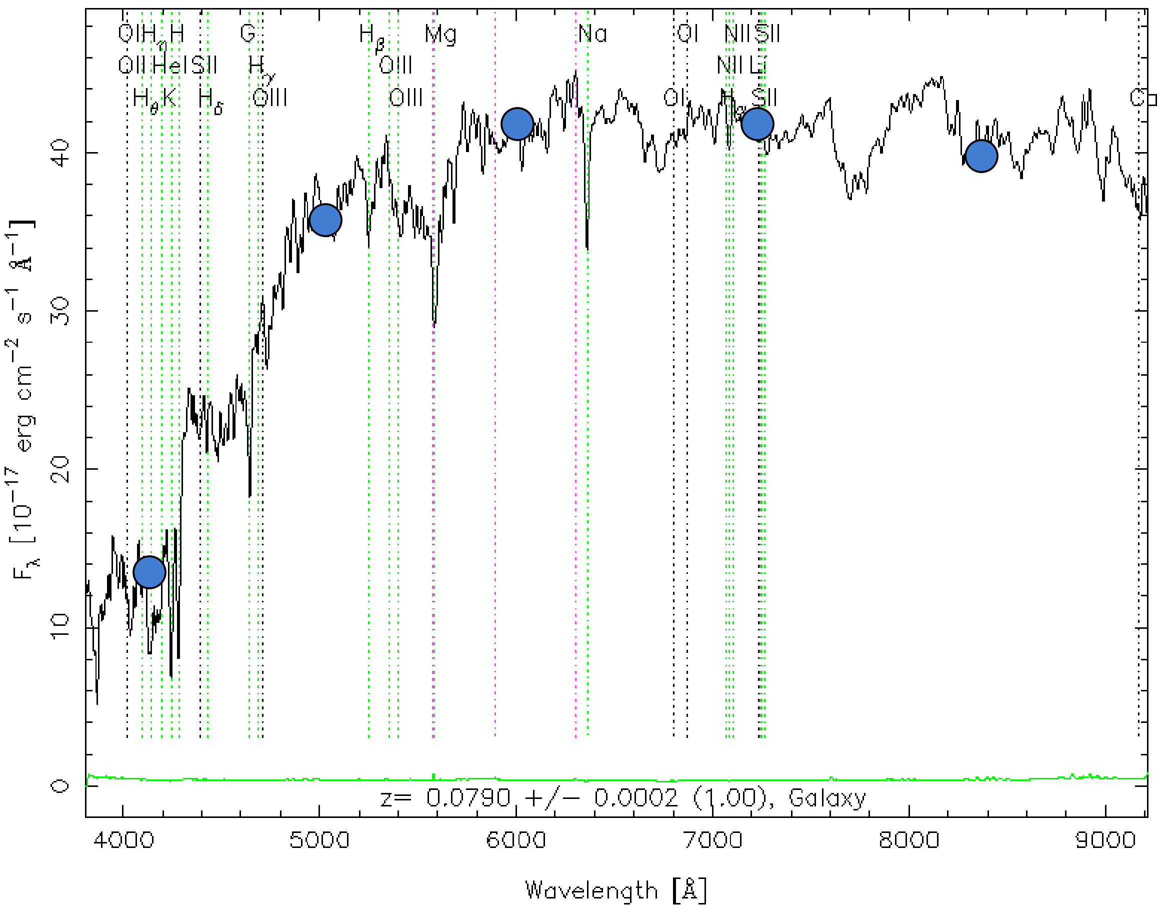
(a) Get spectr ... dn/dz

(b) Use cluste

(c) Then this v

how about N

-> **Cross** ... **ributions!!**



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Bias and Redshift distributions:

$$C_l^{gg} \sim \int (b * \frac{dN}{dz})^2 P(k,z) dz$$

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LRGs	
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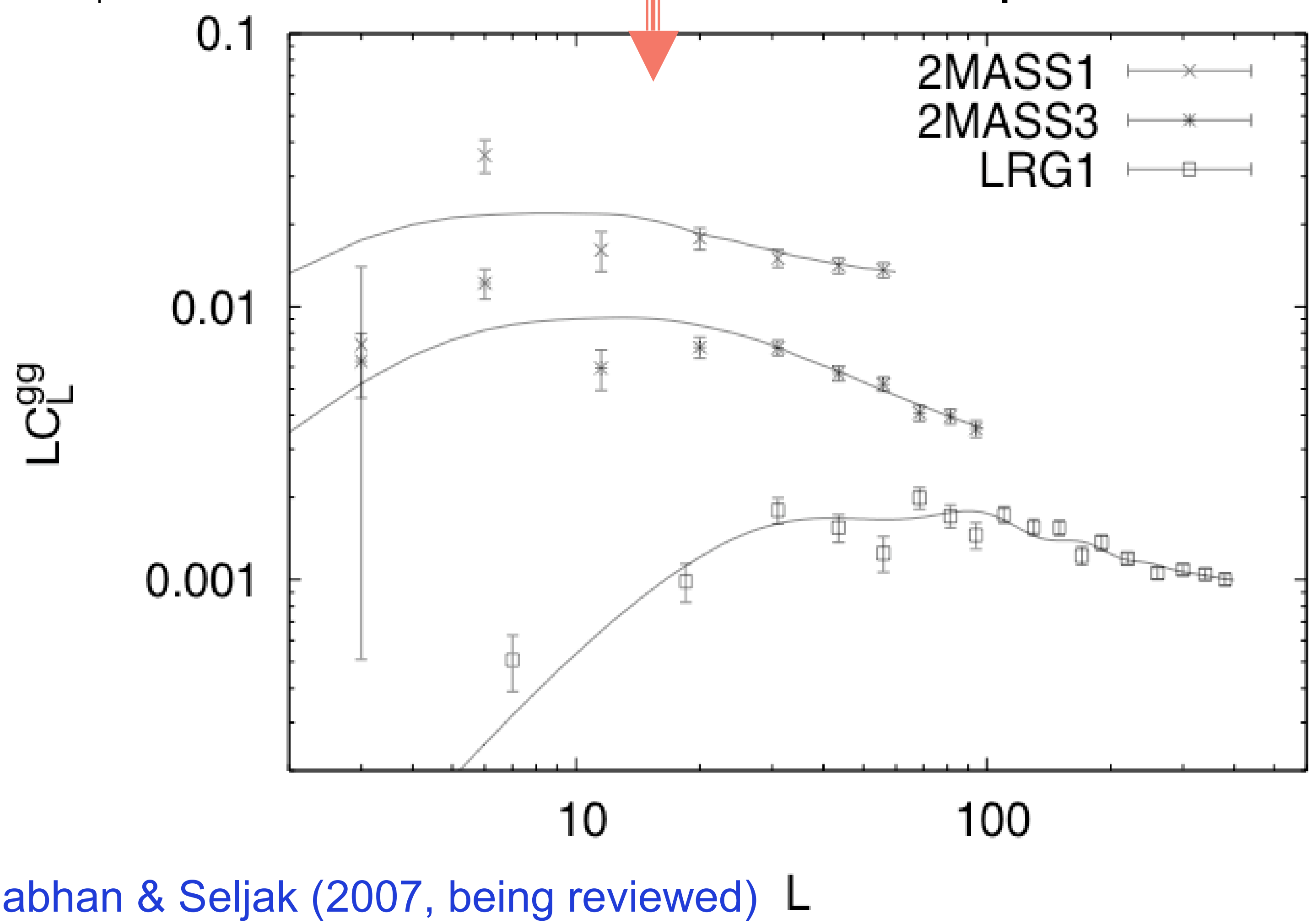

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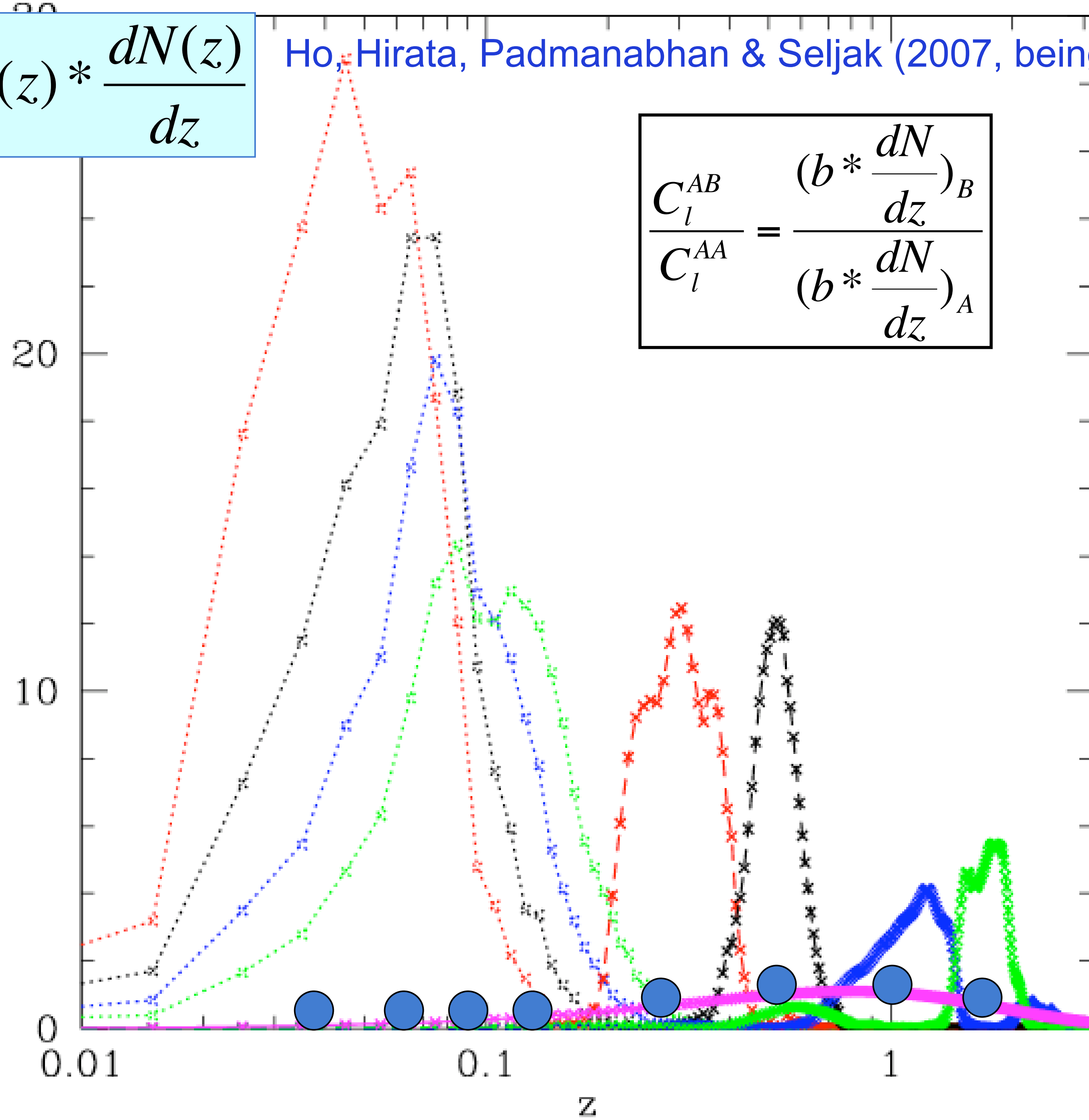
$$b(z) * \frac{dN(z)}{dz}$$

Ho, Hirata, Padmanabhan & Seljak (2007, being reviewed)

$$\frac{C_l^{AB}}{C_l^{AA}} = \frac{(b * \frac{dN}{dz})_B}{(b * \frac{dN}{dz})_A}$$



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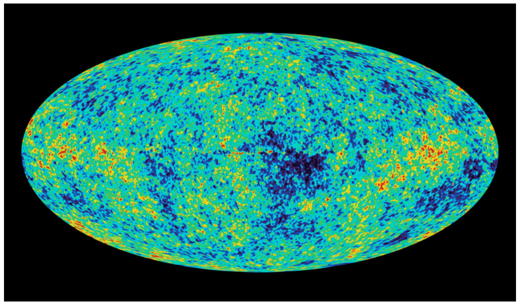

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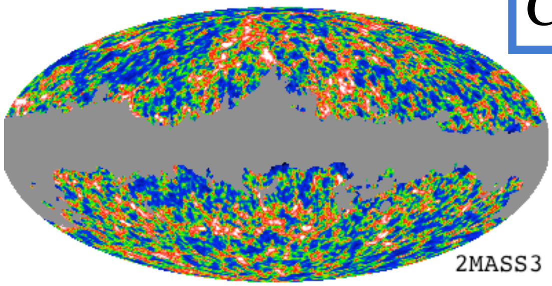

C_l^{gT} $(Data)$ ✔

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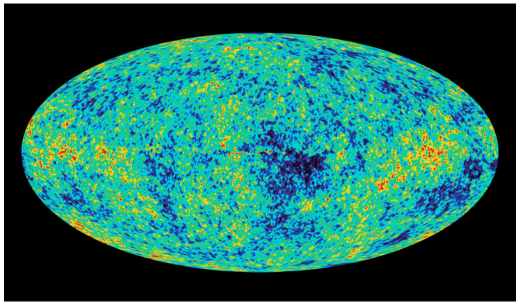
- To do that, what do we need? $C_l^{gT_{ISW}}$ $(Theory)$

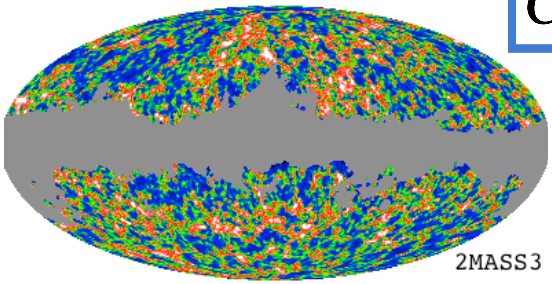
$$C_l^{g\delta T_{ISW}} = \frac{3\Omega_m H_0^2 T_{CMB}}{c^2(l+\frac{1}{2})^2} \int b * \frac{dN}{dz} \frac{H(z)}{c} D(z) \frac{d}{dz}[D(z)(1+z)] P(\frac{l+\frac{1}{2}}{\chi}) dz$$

Looks easy:

- We cross correlate the CMB sky (from WMAP) with the large scale structure which traces the mass, thus potential wells of the Universe:



X



$C_l^{gT}\ (Data)$ ✔

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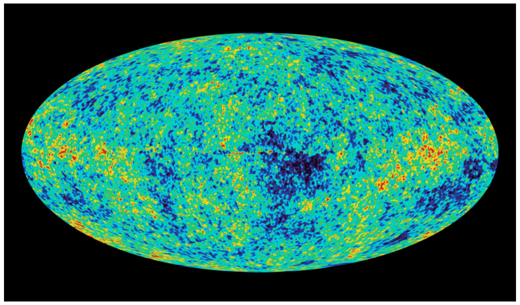

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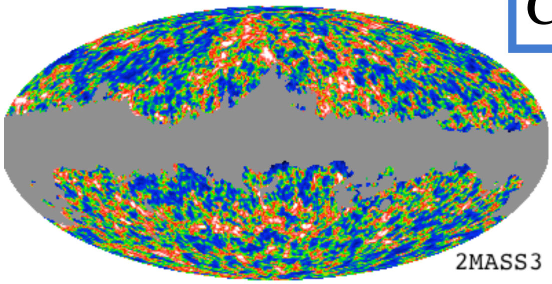

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✔ ✔ ✔

There is more to it… systematics!

$$C_l^{gT_{CMB}} \neq C_l^{gT_{ISW}}$$

$$C_l^{gT_{CMB}} = C_l^{gT_{ISW}} + C_l^{g_{dust}T_{CMB}} + C_l^{g_{stars}T_{CMB}} + C_l^{gT_{FG}} + C_l^{gT_{PS}} + C_l^{gT_{TSZ}}$$

Dust extinction:
Cross correlate the Dust extinction map with CMB map.

Stellar contamination:
a) Check for any dependence of galaxy density on stellar density,
b)cross-correlate the stellar density map with CMB map.

Galactic Foregrounds:
Cross-correlations between galaxy overdensity and foreground templates.

Point Source (Extragalactic sources emitting in microwave): Estimate the strength of point sources by looking at correlations of galaxies with different frequency CMB maps.

Thermal SZ (Hot electrons in cluster Compton scatter CMB photons): Using Halo models (Komatsu & Seljak 2002) to find the upper limit of contribution from tSZ (and other systematics)

Summary for ISW systematics

$$\frac{\Delta_{contam} A}{\sigma(A)}$$

- We select a specific multipole range such that these multipoles are not affected by i) non-linearities, ii) systematic effects.
- We discard the first multipole bin, and also discard any multipole bins that correspond to scale smaller than k=0.05 Mpc/h.
- We then check for the total effects of systematics on these chosen bins by checking the **upper limit** on the total number of sigmas of contaminations that can be introduced by the specific systematics:

$$C_l^{gT_{CMB}} = C_l^{gT_{ISW}} + C_l^{g_{dust}T_{CMB}} + C_l^{g_{stars}T_{CMB}} + C_l^{gT_{FG}} + C_l^{gT_{PS}} + C_l^{gT_{TSZ}}$$

Dust extinction: 0.23

Stellar contamination: 0.15

Galactic Foregrounds: 0.66

Point Source: 0.49 (could double count with foregrounds)

Thermal SZ: 0.11

Ho, Hirata, Padmanabhan & Seljak (2007, being reviewed)

Summary for ISW systematics

$$\frac{\Delta_{contam} A}{\sigma(A)}$$

- We select a specific multipole range such that these multipoles are not affected by i) non-linearities, ii) systematic effects.
- We
  mu
- We
  by
  con

Sample	Amplitude A			
	Ka	Q	V	W
2MASS0	-9.04 ± 8.21	-3.54 ± 8.19	-2.01 ± 8.11	-3.38 ± 7.79
2MASS1	1.80 ± 3.97	2.73 ± 3.94	2.17 ± 3.93	1.64 ± 3.86
2MASS2	2.16 ± 2.66	2.95 ± 2.65	2.42 ± 2.63	2.04 ± 2.61
2MASS3	1.74 ± 1.72	2.56 ± 1.72	2.58 ± 1.72	2.39 ± 1.69
LRG0	2.00 ± 1.44	2.05 ± 1.44	1.86 ± 1.45	1.92 ± 1.46
LRG1	2.67 ± 1.04	2.59 ± 1.04	2.85 ± 1.05	2.92 ± 1.06
QSO0	0.62 ± 1.90	0.39 ± 1.92	0.61 ± 1.89	0.63 ± 1.94
QSO1	2.41 ± 1.90	2.17 ± 1.92	2.36 ± 1.90	1.93 ± 1.90
NVSS	2.56 ± 1.01	2.80 ± 1.01	3.04 ± 1.02	2.88 ± 1.02

n.
n bins
:

C_l^{gT} ... tSZ

Dust
0.23

Foregrounds:
0.66

Point source:
0.49 (could double count with foregrounds)

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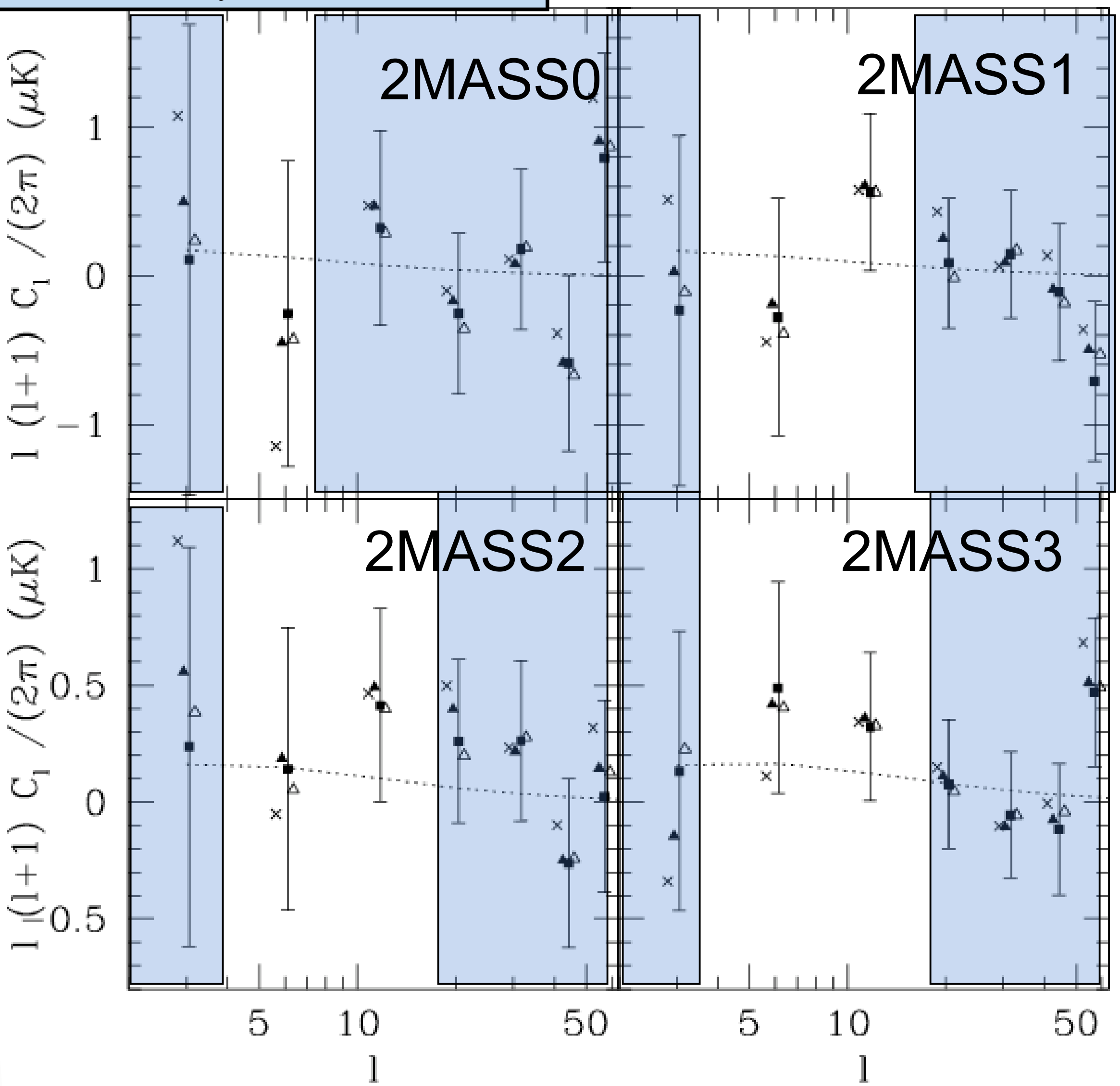
Ho, Hirata, Padmanabhan & Seljak (2007, being reviewed)

ISW Cross-correlations

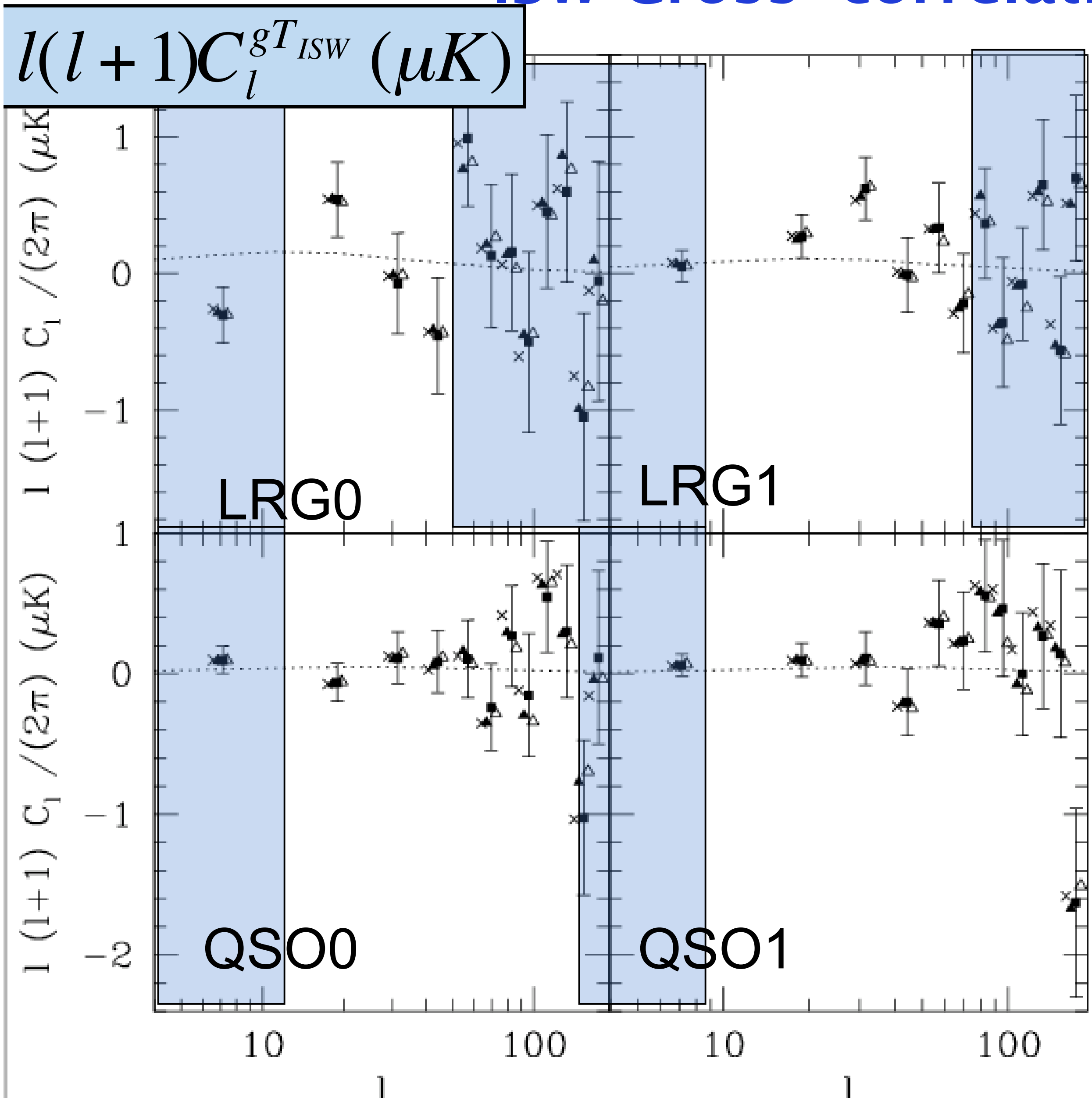
$l(l+1)C_l^{gT_{ISW}}\ (\mu K)$



Sample	Amplitude +/- error
2MASS0	-2.01 +/-11.41
2MASS1	+3.44 +/- 4.47
2MASS2	+2.86 +/- 2.87
2MASS3	+2.44 +/-1.73

Ho, Hirata, Padmanabhan & Seljak (2007, being reviewed)

ISW Cross-correlations

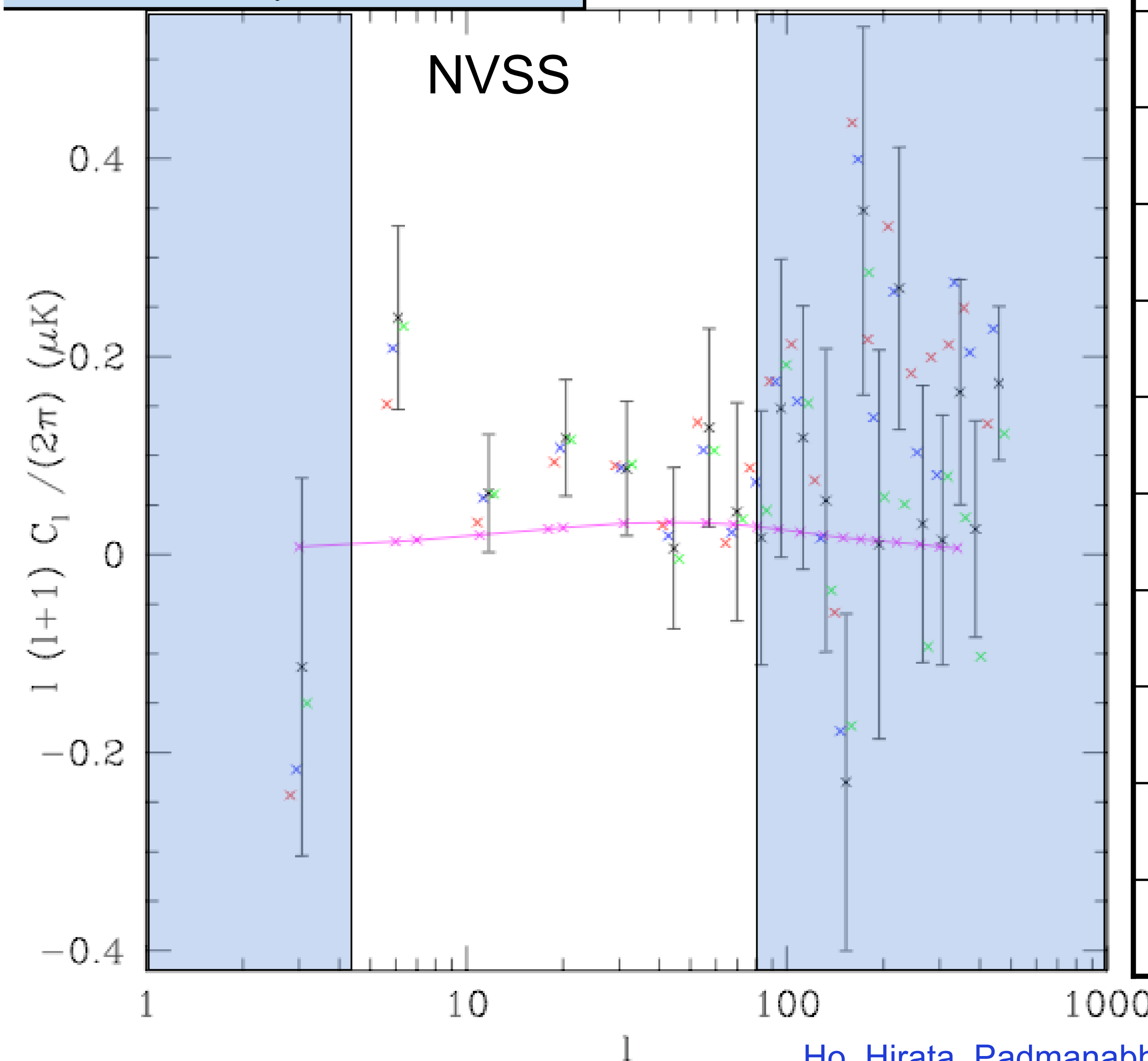


Sample	Amplitude +/- error	
2MASS0	-2.01	+/-11.41
2MASS1	+3.44	+/- 4.47
2MASS2	+2.86	+/- 2.87
2MASS3	+2.44	+/- 1.73
LRG0	+1.82	+/- 1.46
LRG1	+2.79	+/- 1.14
QSO0	+0.26	+/- 1.69
QSO1	+2.59	+/- 1.87

Ho, Hirata, Padmanabhan & Seljak (2007, being reviewed)

ISW Cross-correlations

$$l(l+1)C_l^{gT_{ISW}}\ (\mu K)$$



Sample	Amplitude +/− error	
2MASS0	−2.01	+/−11.41
2MASS1	+3.44	+/− 4.47
2MASS2	+2.86	+/− 2.87
2MASS3	+2.44	+/− 1.73
LRG0	+1.82	+/− 1.46
LRG1	+2.79	+/− 1.14
QSO0	+0.26	+/− 1.69
QSO1	+2.59	+/− 1.87
NVSS	+2.92	+/− 1.02
ALL	+2.23	+/− 0.60

Ho, Hirata, Padmanabhan & Seljak (2007, being reviewed)

Outline

- Motivations -- Why am I doing this?

- Integrated Sachs Wolfe (ISW) Effect

  -> study the geometry of the Universe

- Weak Lensing (WL) of CMB (mini-version)

  -> study the matter between us and the last scattering surface

  Cosmological constraints from ISW and WL of CMB

- Kinetic Sunyaev Zeldovich (kSZ) Effect

  -> finding Missing Baryons!

Weak Lensing of CMB (mini-version)

- Probe matter in between us and the last scattering surface!
- We find **evidence for a positive cross-correlation at the 2.5 σ level**
- The cross correlation amplitude is 1.06 +/- 0.42 times that expected for the WMAP cosmological parameters. (amplitude =1 implies that this is exactly as expected by WMAP cosmological parameters)
- Our analysis extends other recent analyses in that we carefully determine bias weighted redshift distribution of the sources, which is needed for a meaningful cosmological interpretation of the detected signal.
- We investigate contamination of the signal by Galactic emission, extragalactic radio and infrared sources, thermal and kinetic Sunyaev-Zel'dovich effects, and the Rees-Sciama effect, and find **all of them to be negligible**.

Hirata, Ho, Padmanabhan & Seljak (2007, being reviewed)

Outline

- Motivations -- Why am I doing this?

- Integrated Sachs Wolfe (ISW) Effect

  -> study the geometry of the Universe

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Cosmological parameters

- **First likelihood analysis using both ISW and WL of CMB that allows all cosmological parameters to vary.**
- Using markov chain monte carlo to search through all the parameter space in these models:

a) LCDM

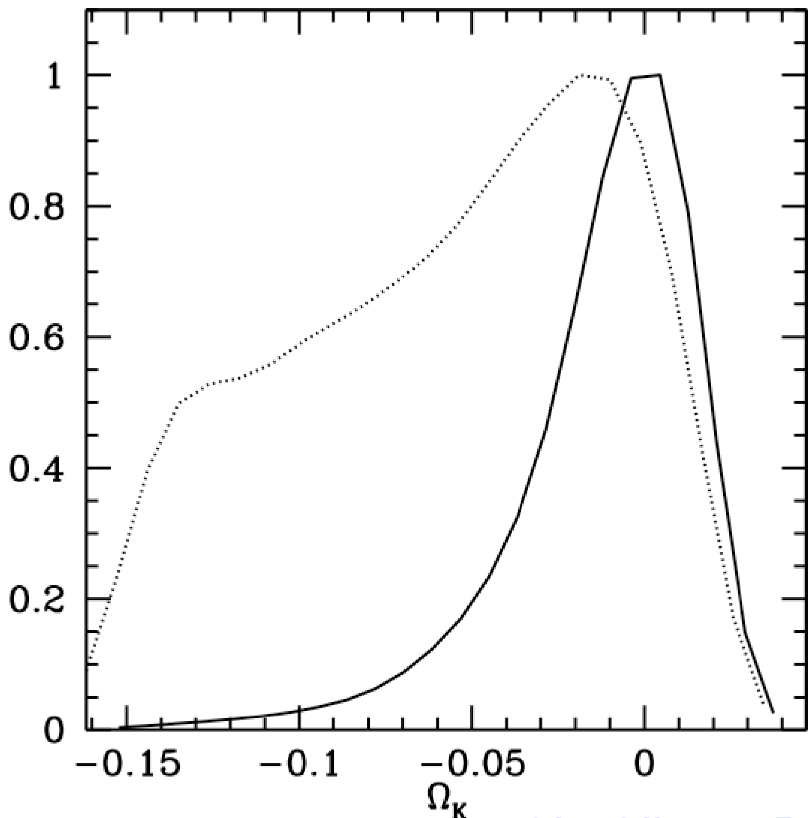
b) CDM + Ω_K (allowing curvature)

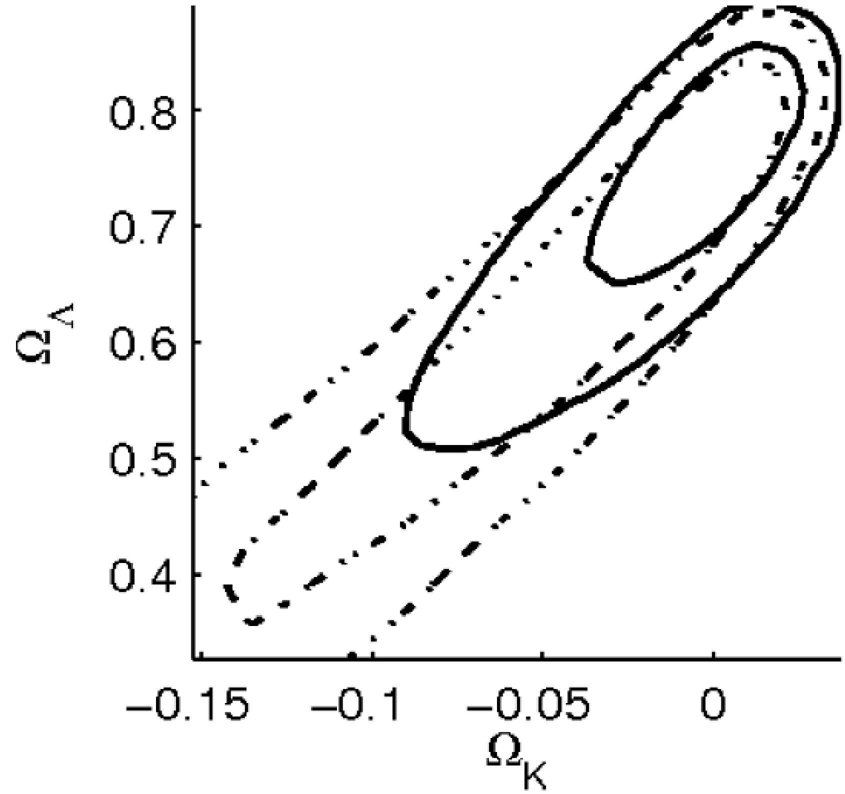
c) CDM + w (allowing dark energy equation of state)

- Further Constraints on modified gravity models.

CDM+Ω_K

- Testing the flatness of universe!





Solid: CMB+ISW+WL
Dotted: CMB only

Ho, Hirata, Padmanabhan & Seljak (2007, being reviewed)

CDM+Ω_K

Independent probe to Geometry and Vacuum Energy

$$WMAP + ISW + WL \ldots\ldots\ldots \Omega_K = -0.006^{+0.017}_{-0.028} \ldots\ldots \Omega_\Lambda = 0.744^{+0.059}_{-0.089}$$

TABLE 12

JOINT DATA SET CONSTRAINTS ON GEOMETRY AND VACUUM ENERGY

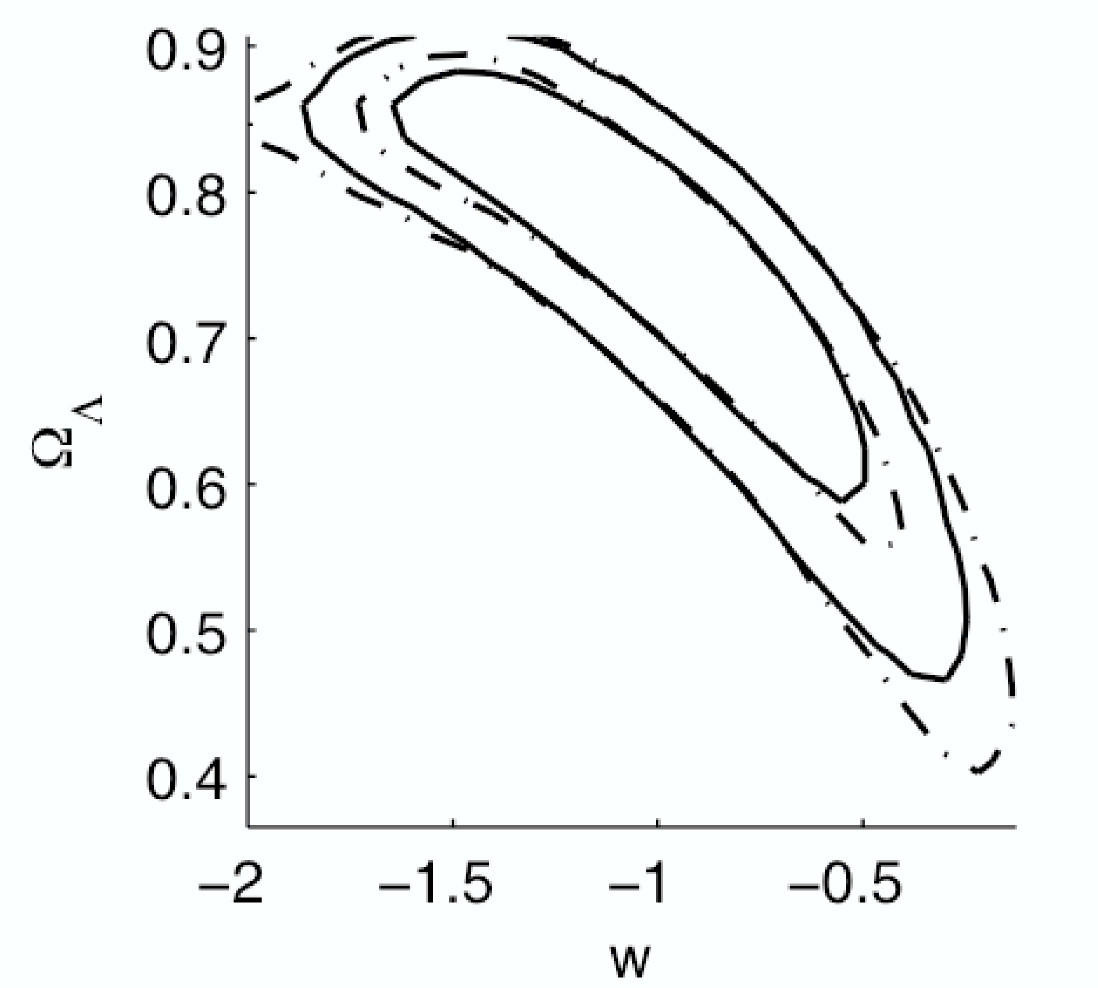
Data Set	Ω_K	Ω_Λ
WMAP + $h = 0.72 \pm 0.08$	-0.014 ± 0.017	0.716 ± 0.055
WMAP + SDSS.........................	$-0.0053^{+0.0068}_{-0.0060}$	0.707 ± 0.041
WMAP + 2dFGRS	$-0.0093^{+0.0098}_{-0.0092}$	$0.745^{+0.025}_{-0.024}$
WMAP + SDSS LRG	-0.012 ± 0.010	0.728 ± 0.021
WMAP + SNLS	-0.011 ± 0.012	0.738 ± 0.030
WMAP + SNGold	-0.023 ± 0.014	0.700 ± 0.031

Spergel et al. 2007

CDM+w

- Constraining w to 15% better than CMB alone

Solid: CMB+ISW+WL
Dotted: CMB only



Ho, Hirata, Padmanabhan & Seljak (2007, being reviewed)

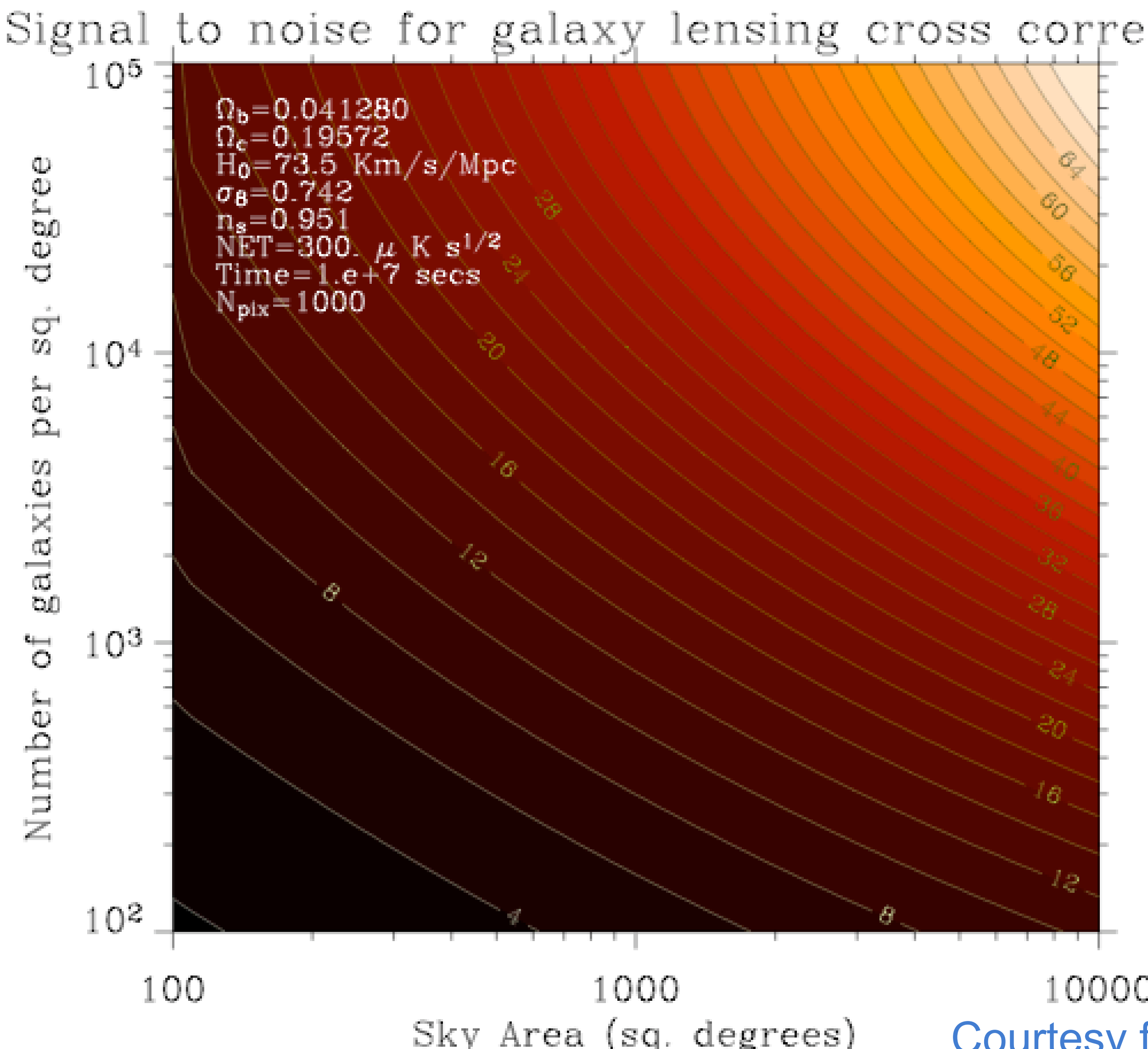
Future of ISW and WL of CMB

- Constraints on modified gravity models will be coming soon.
- CMB+ISW+WL of CMB will improve further on the following:

a) Deeper galaxy surveys with better redshift determination, such as SDSSIII

b) Upcoming/future CMB data such as PLANCK, ACT, APEX, SPT will significantly improve the weak lensing by lower-noise reconstruction.

Future of ISW and WL of CMB



- Con
- CMB ... g:

a) De ... , such as SDS...

b) Up ... SPT will sign... reco...

Courtesy from Sudeep Das

Mini-conclusion

- ISW (Integrated Sachs Wolfe) effect:

  (1) We go beyond reporting detections towards developing a reliable likelihood analysis that allows one to determine cosmological constraints from ISW observations.

  (2) Independent and complementary probe into characteristics of the Universe

  -> We learn about the Geometry of the Universe.
- Weak Lensing of CMB:

  (1) We find **evidence for a positive cross-correlation at the 2.5 σ level**.

  (2) This is the first analysis to use it for cosmological constraints).

  -> We learn about the Matter density of the Universe.
- Cosmological Constraints from first likelihood analysis of ISW and WL of CMB that allows all the cosmological parameters to vary:

- Now, looking into the future, there is another important cosmological piece that we can deal with using the same technique

  ➔ finding the Missing Baryons using Kinetic Sunyaev Zel'dovich Effect!

Outline

- Motivations -- Why am I doing this?

- Integrated Sachs Wolfe (ISW) Effect

  -> study the geometry of the Universe

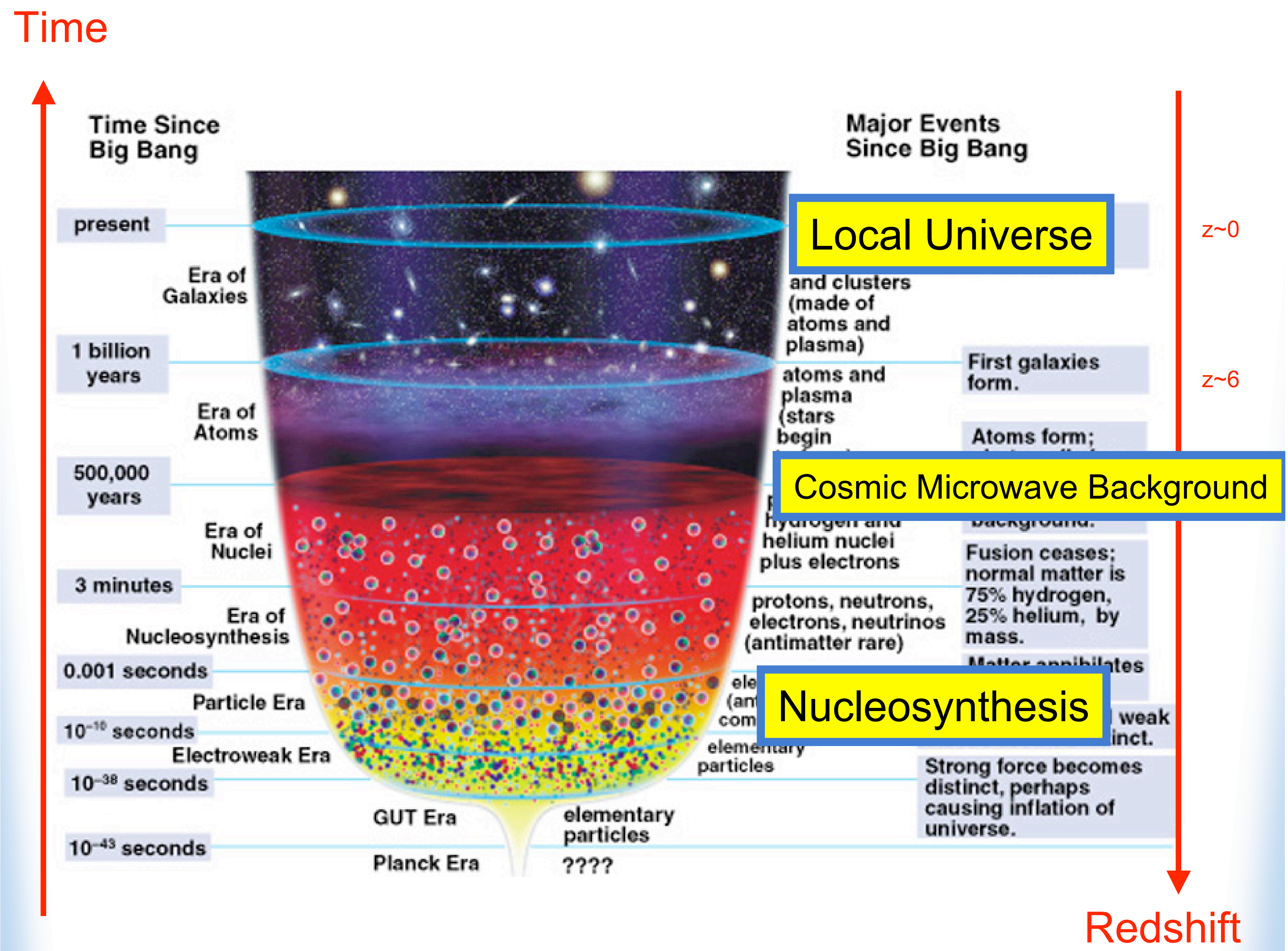
- Weak Lensing (WL) of CMB (mini-version)

  -> study the matter between us and the last scattering surface

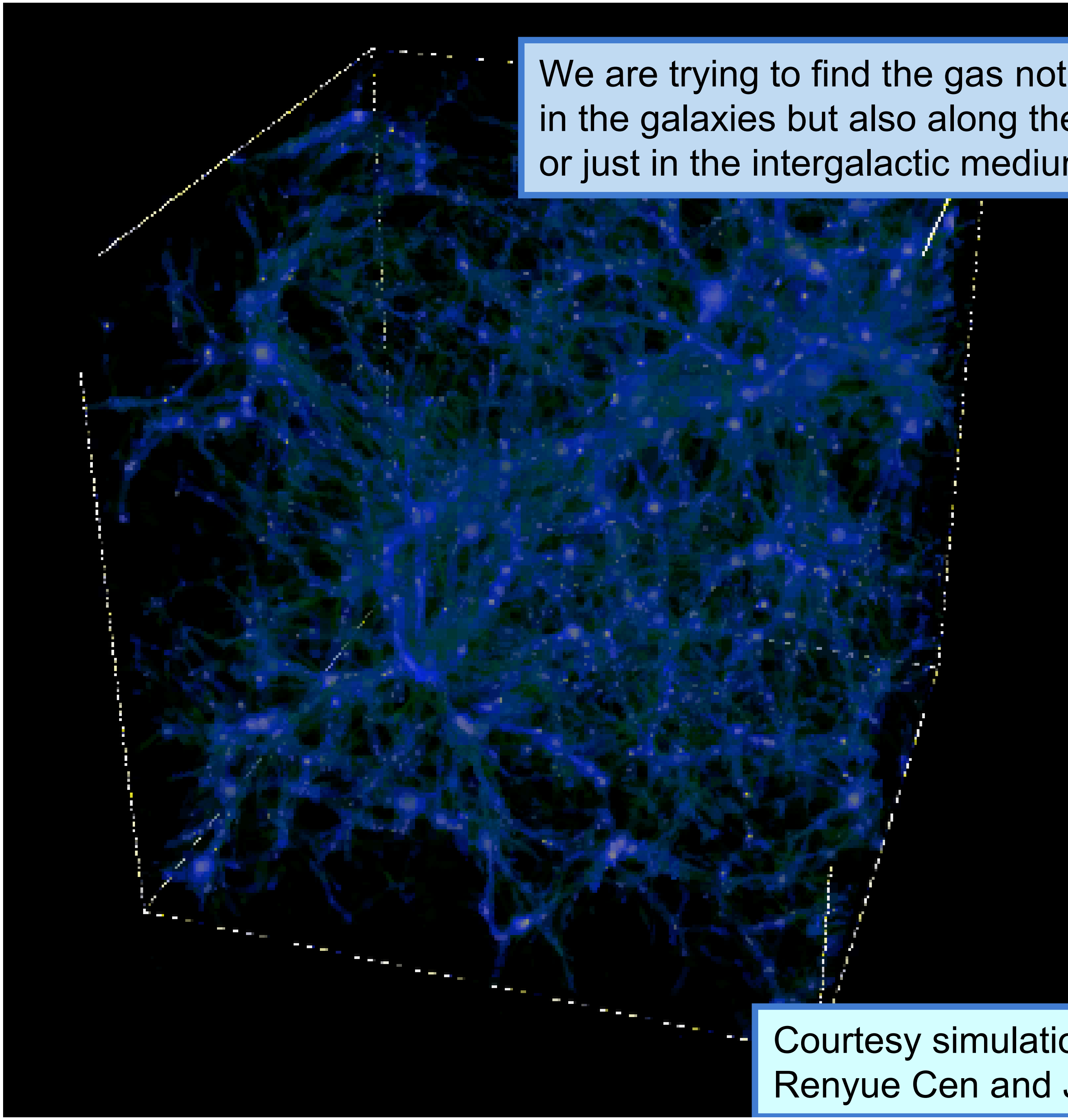
Cosmological constraints from ISW and WL of CMB

- Kinetic Sunyaev Zeldovich (kSZ) Effect

  -> finding Missing Baryons!



Time
Time Since Big Bang
Major Events Since Big Bang
present
Local Universe
z~0
Era of Galaxies
and clusters (made of atoms and plasma)
1 billion years
First galaxies form.
z~6
Era of Atoms
atoms and plasma (stars begin
Atoms form;
500,000 years
Cosmic Microwave Background
Era of Nuclei
helium nuclei plus electrons
Fusion ceases; normal matter is 75% hydrogen, 25% helium, by mass.
3 minutes
Era of Nucleosynthesis
protons, neutrons, electrons, neutrinos (antimatter rare)
0.001 seconds
Nucleosynthesis
Particle Era
10^-10 seconds
weak
inct.
Electroweak Era
elementary particles
10^-38 seconds
Strong force becomes distinct, perhaps causing inflation of universe.
GUT Era
elementary particles
10^-43 seconds
Planck Era
????
Redshift


We are trying to find the gas not only
in the galaxies but also along these filaments
or just in the intergalactic medium!
Courtesy simulation of gas from
Renyue Cen and Jerry Ostriker

Physics of KSZ:

–Kinetic Sunyaev Zeldovich:

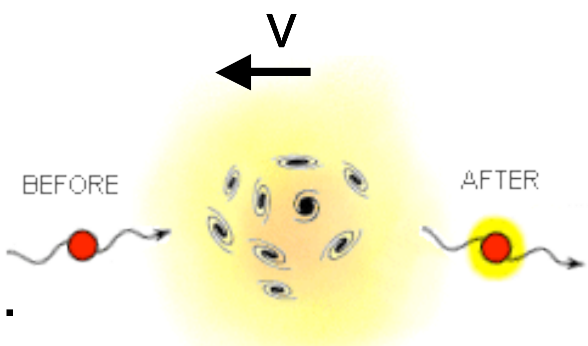
$$\frac{\delta T_{ksz}}{T_{cmb}} = -\int n_e \sigma_T (\frac{\vec{v}}{c} \cdot \hat{n}) dl$$

1)electrons interact with photons!

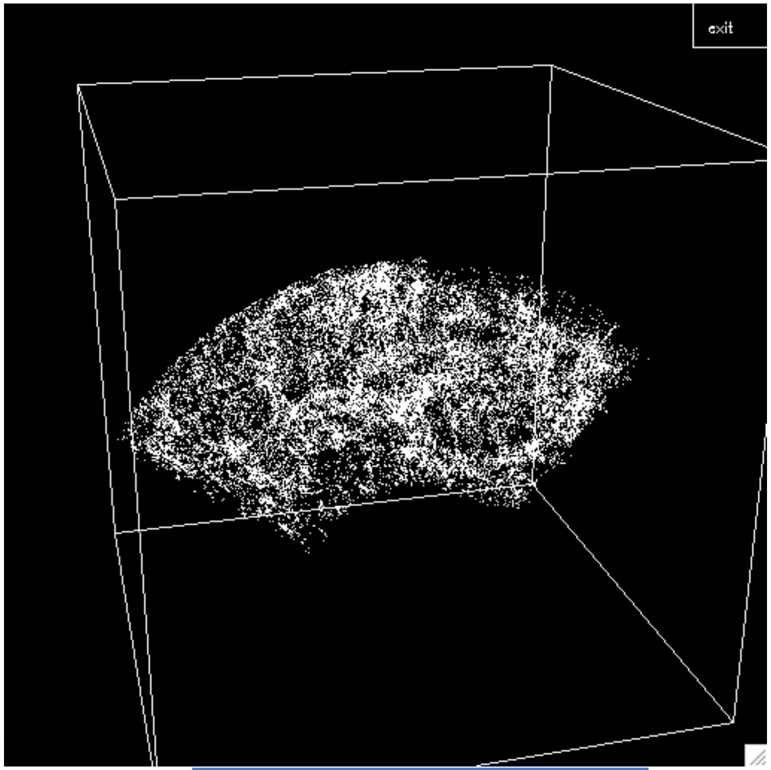
-> a incre/decrement of the photon energy depending on the direction of the **velocities**.

-> amount of ionized electrons

-> baryon fraction in the universe.



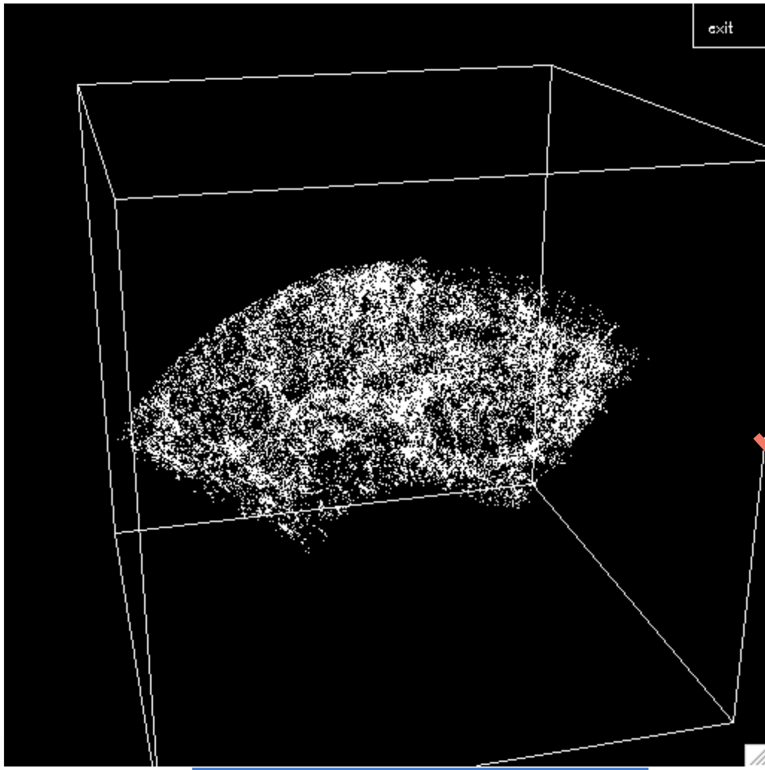
How to find Missing Baryons?



Galaxy field

$$\mathbf{v}(\mathbf{k}, a) \propto H(a) \frac{d \ln D}{d \ln a} \delta(k) \frac{\mathbf{k}}{k^2}$$

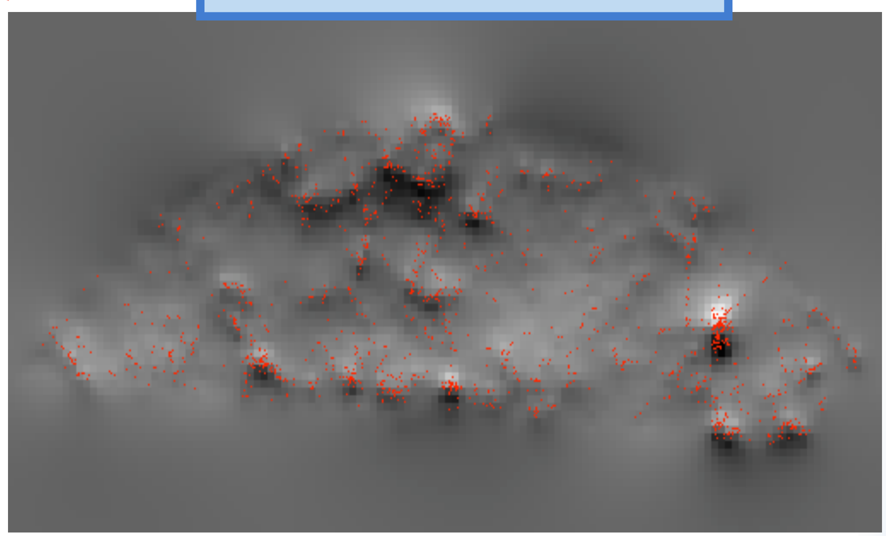
How to find Missing Baryons?



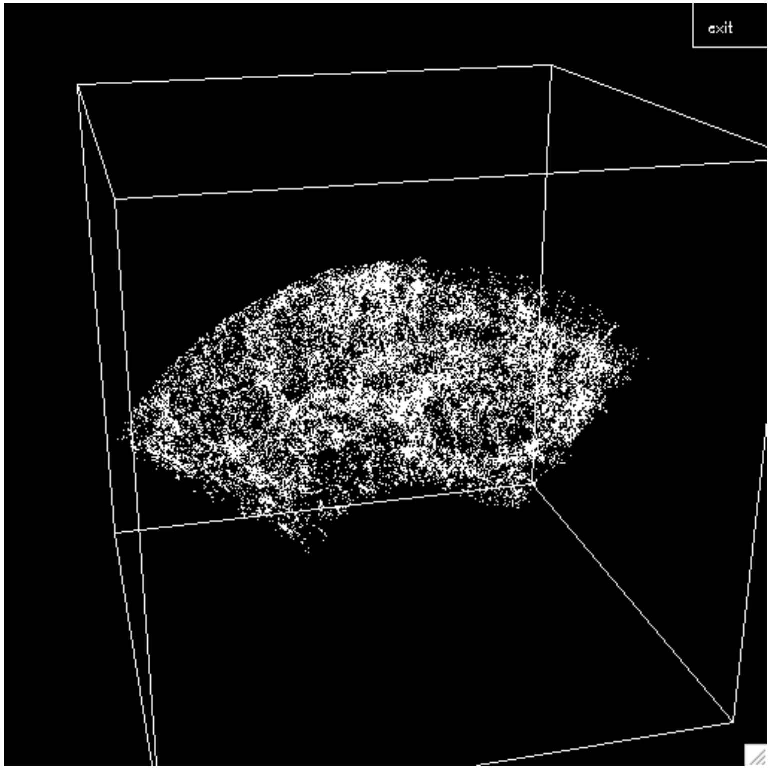
Galaxy field

$$\mathbf{v}(\mathbf{k}, a) \propto H(a) \frac{d \ln D}{d \ln a} \delta(k) \frac{\mathbf{k}}{k^2}$$

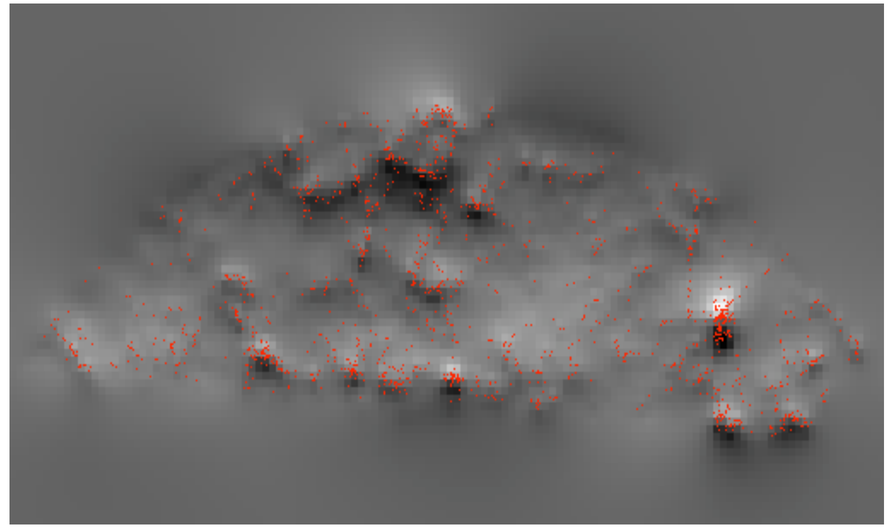
Velocity field



How to find Missing Baryons?



✖



Parameterize gas profile around each galaxy/region of interest:

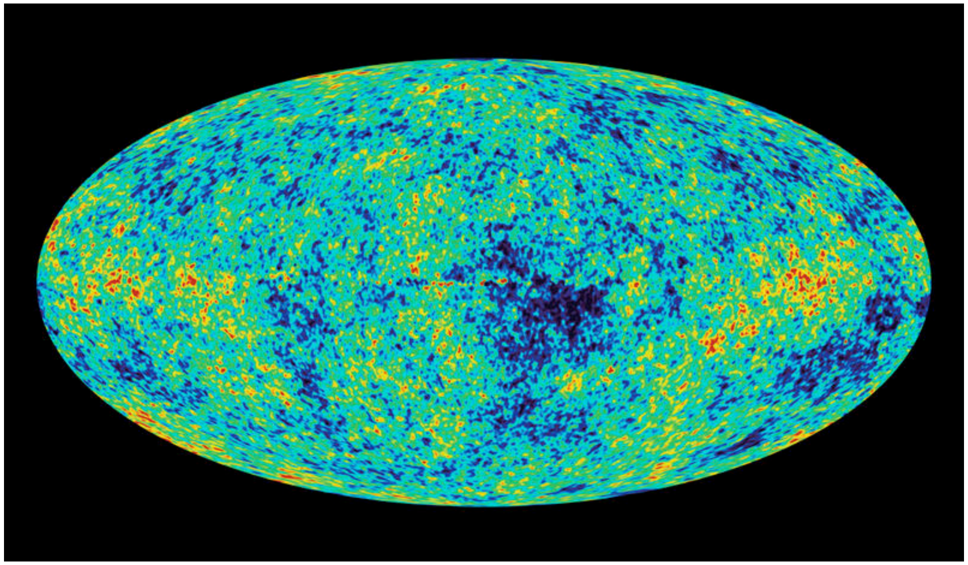
$$\rho_{gas} = \rho_{gas}(r)$$

KSZ template to cross-correlate with observed CMB.

How to find Missing Baryons?

KSZ template to cross-correlate with observed CMB.

✖



See what gas profile gives the best correlation.

$$\rho_{gas} = \rho_{gas}(r)$$

Average gas profile around any types of galaxies!
or regions! [such as filaments or just intergalactic space]

KSZ Applications!

- Applicable to any high resolution cosmic microwave background maps with any spectroscopic large scale survey, such as:

  1) ACT (Atacama Cosmology Telescope)
     with SDSS (Sloan Digital Sky Survey) or
        BOSS (Baryon Oscillation Spectroscopic Survey)

  2) SPT (South Pole Telescope)
     with SALT (South African Large Telescope) or
        ADEPT (Advanced Dark Energy Physics Telescope) or LSST (Large Synoptic Survey Telescope)

  3) PLANCK
      with SDSS or BOSS or ADEPT or LSST

KSZ estimated S/N

	ACT 2000 deg^2	APEX 200 deg^2	SPT 100 deg^2	PLANCK 10,000 deg^2
SDSS	~10 (only equatorial overlap)	~10 (only equatorial overlap)		~100
SDSSIII/ BOSS	~15	~15		~100
SALT	~10	~10	~5	
ADEPT/ LSST	~100	~15	~8	~400

Ho, Dedeo & Spergel 2007, in prep

Conclusion

- More to learn about the Universe
- Lots to gain by cross correlating Cosmic Microwave Background with Large Scale Structures with current and upcoming experiments!
  - ➔ Geometry of the Universe
  - ➔ Dark Energy, Dark Matter…
  - ➔ Missing Baryons

THANK YOU for listening!