# What can you do with Cosmic Microwave Background as a backlight?


Lawrence Berkeley National Lab /

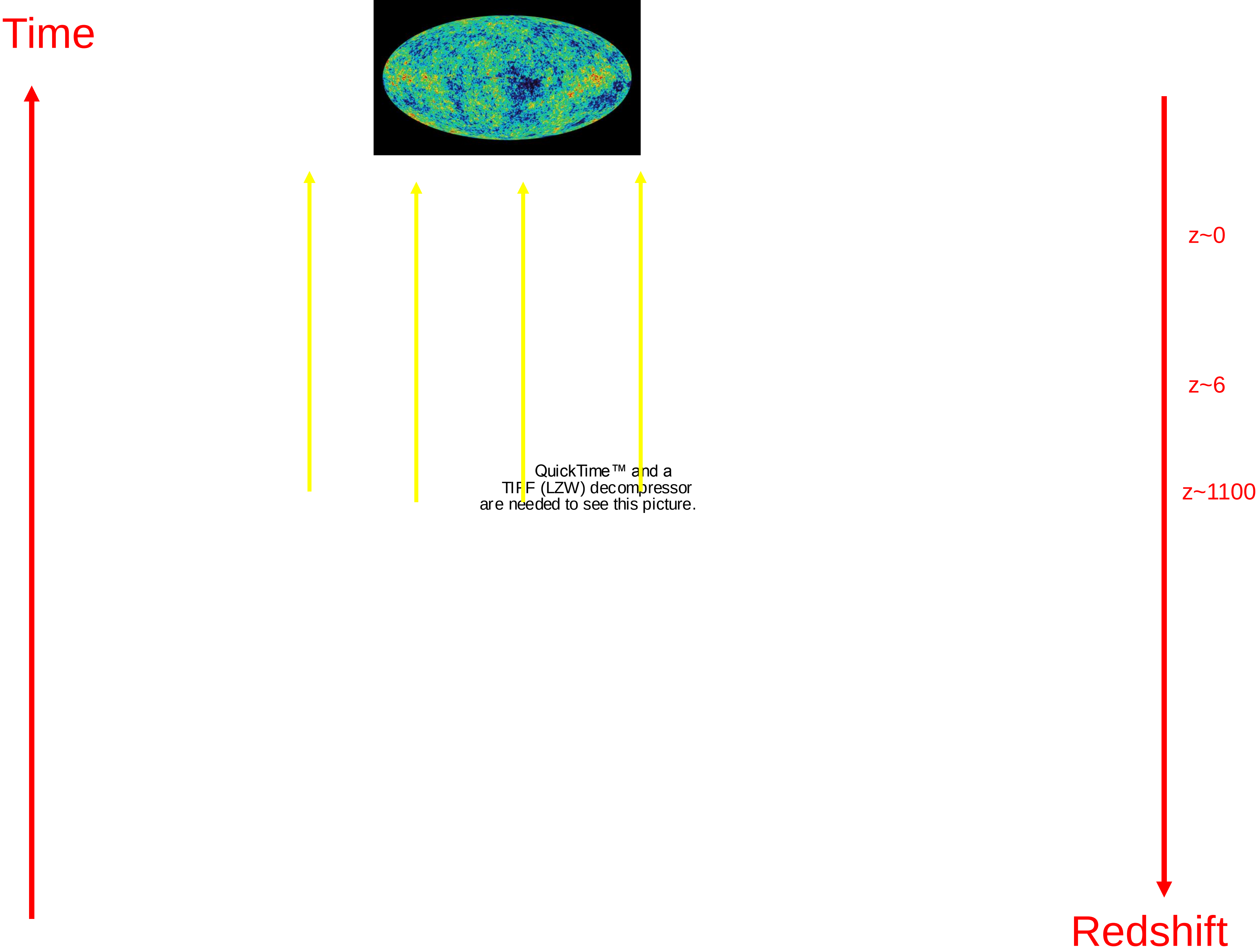
Princeton University

Shirley Ho


11/10/08

Institute of Physics and Mathematics of the Universe


Time
z~0
z~6
QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.
z~1100
Redshift


Time
z~0
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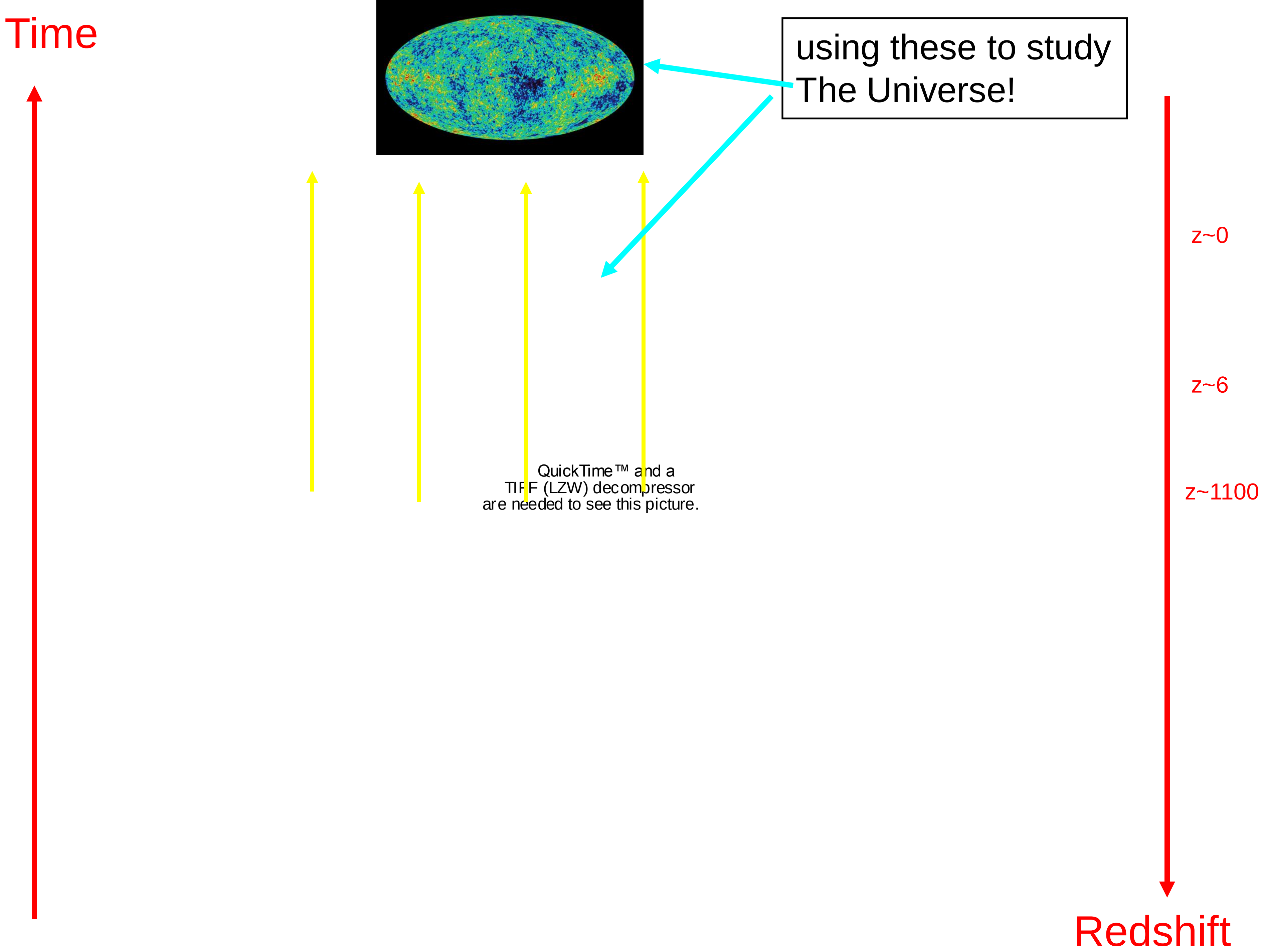
Time
using these to study
The Universe!
z~0
z~6
z~1100
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Redshift

# Outline

- Motivations -- Why am I doing this?
- Integrated Sachs Wolfe (ISW) Effect

➔ study the geometry of the Universe

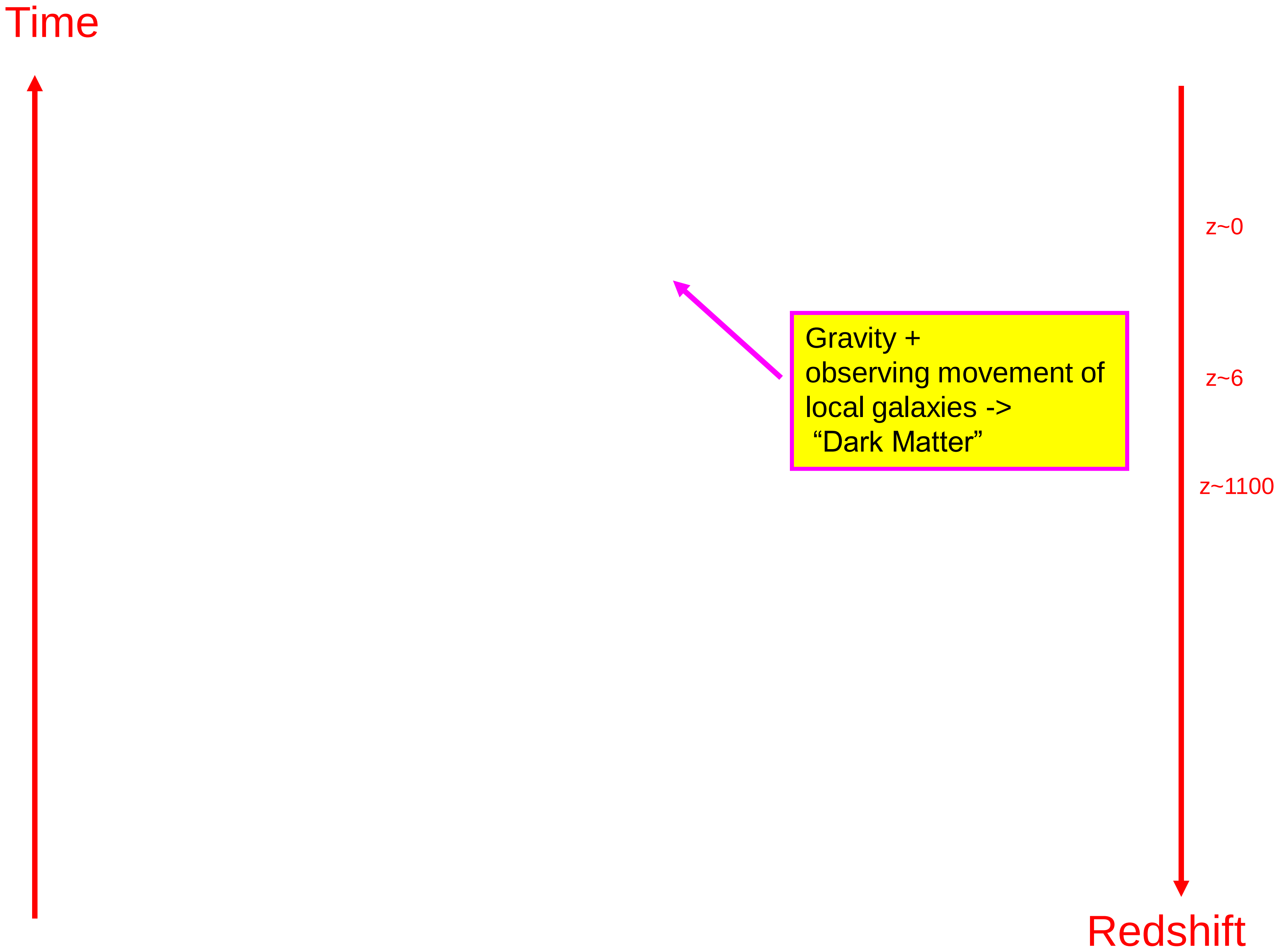
- Weak Lensing (WL) of CMB (mini-version)

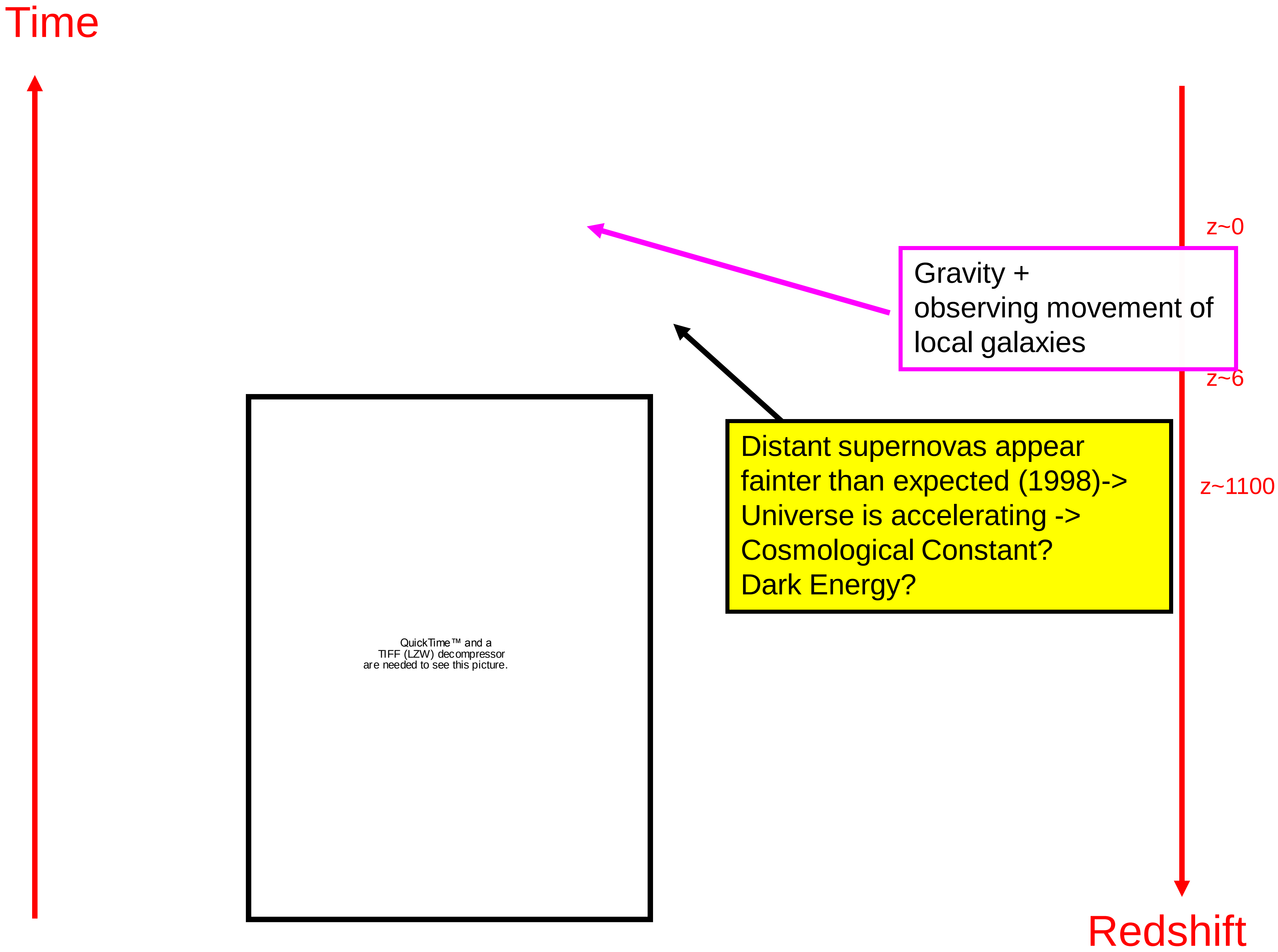
➔ study the matter between us and the last scattering surface

Cosmological constraints from ISW and WL of CMB

- Kinetic Sunyaev Zeldovich (kSZ) Effect

➔ find the Missing Baryons!


Time
z~0
Gravity +
observing movement of
local galaxies ->
"Dark Matter"
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
QuickTime™ and a
TIFF (LZW) decompressor
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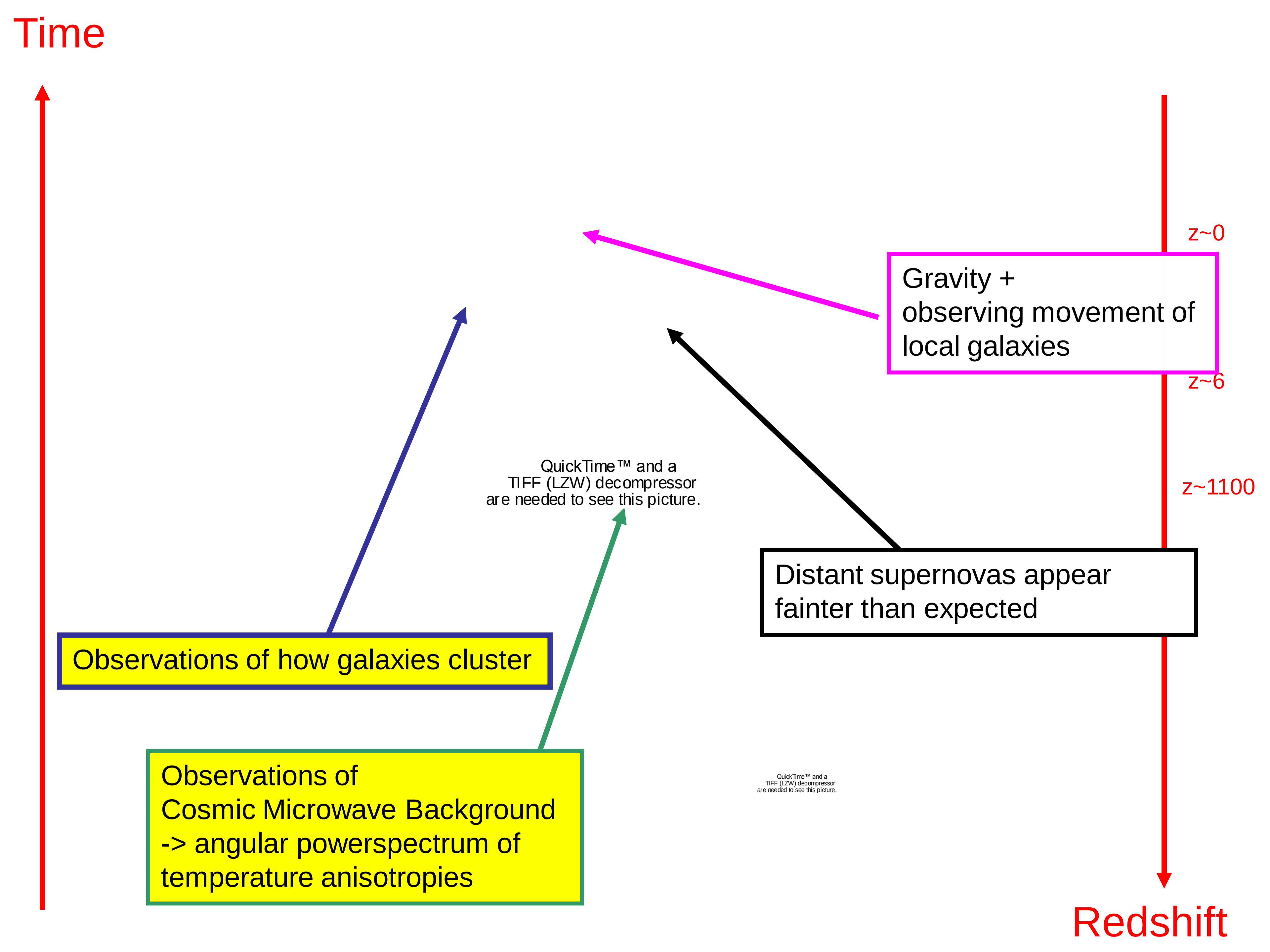
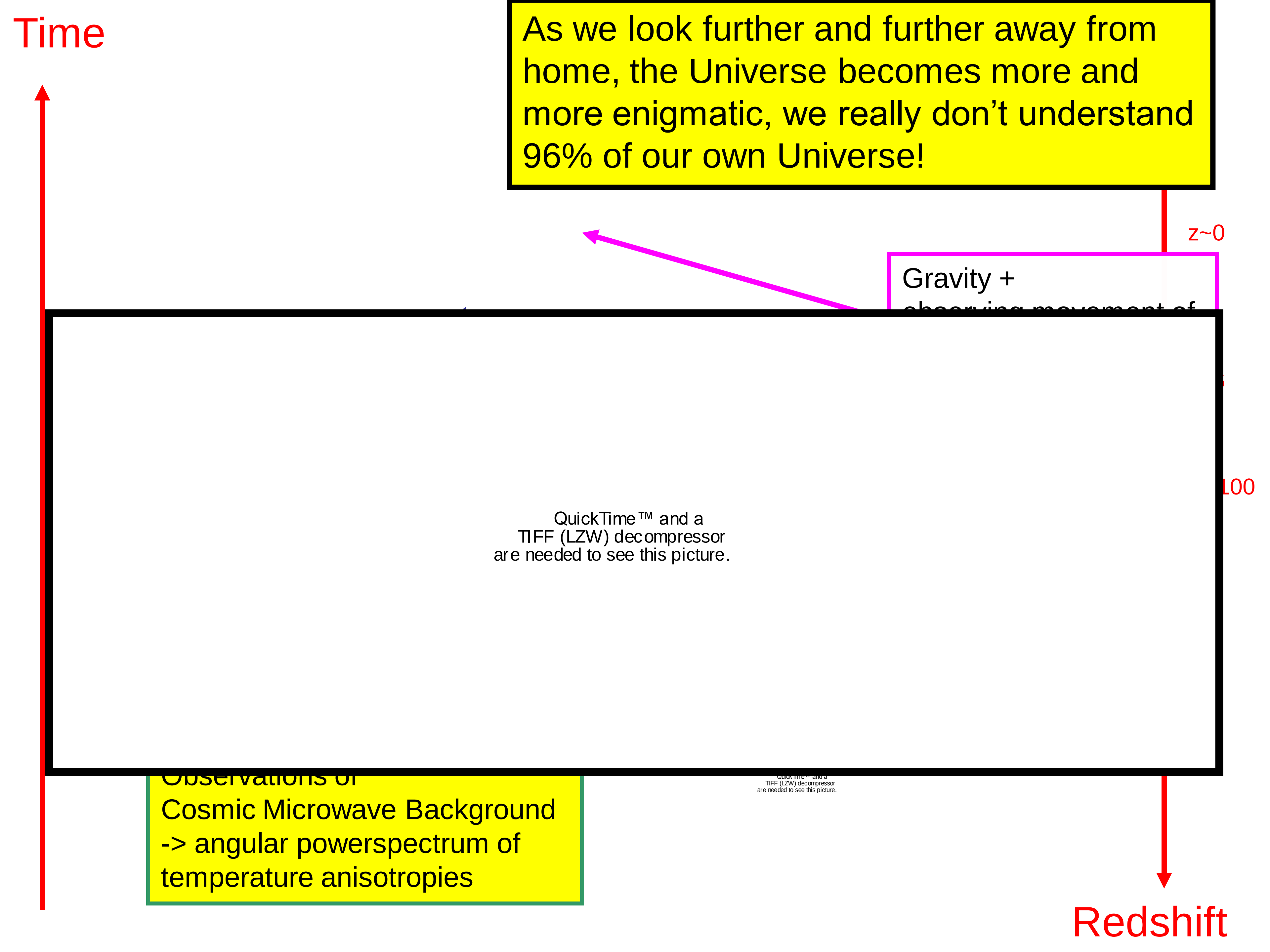
Redshift


Time
z~0
Gravity +
observing movement of
local galaxies
z~6
QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.
z~1100
Distant supernovas appear
fainter than expected
Observations of how galaxies cluster
Observations of
Cosmic Microwave Background
-> angular powerspectrum of
temperature anisotropies
QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.
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 +
QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.
Observations of
Cosmic Microwave Background
-> angular powerspectrum of
temperature anisotropies
Redshift

$$\Omega_K = 0$$

$\Omega_{DE}$

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

$\Omega_b$

$\Omega_c$

$\Omega_b$ is the **baryon density** expressed in terms of critical density

$\Omega_c$ 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

$\Omega_{DE}$ 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

$\sigma_8$ measures how strong the **fluctuation of matter density** is

$$l(l+1)C_l^{\delta T_{CMB}\delta T_{CMB}}\,(\mu K)^2$$

$$\Omega_b = 0.0416$$
$$\Omega_c = 0.239$$
$$\Omega_K = 0$$
$$H_0 = 73.2$$
$$\sigma_8 = 0.761$$

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

Angular Powerspectrum
of Temperature Anisotropies in
Cosmic Microwave Background

l : multipole moment (in $A_{lm}$)

$$l(l+1)C_l^{\delta T_{CMB}\delta T_{CMB}}\ (\mu K)^2$$

$$\Omega_b = 0.215$$
$$\Omega_c = 1.25$$
$$\Omega_K = -0.29$$
$$H_0 = 32$$
$$\sigma_8 = 0.61$$

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

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l : multipole moment (in $A_{lm}$)

$$l(l+1)C_l^{\delta T_{CMB}\delta T_{CMB}}\ (\mu K)^2$$

$$\Omega_b = 0.015$$
$$\Omega_c = 0.089$$
$$\Omega_K = 0.003$$
$$H_0 = 120$$
$$\sigma_8 = 0.73$$

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TIFF (LZW) decompressor
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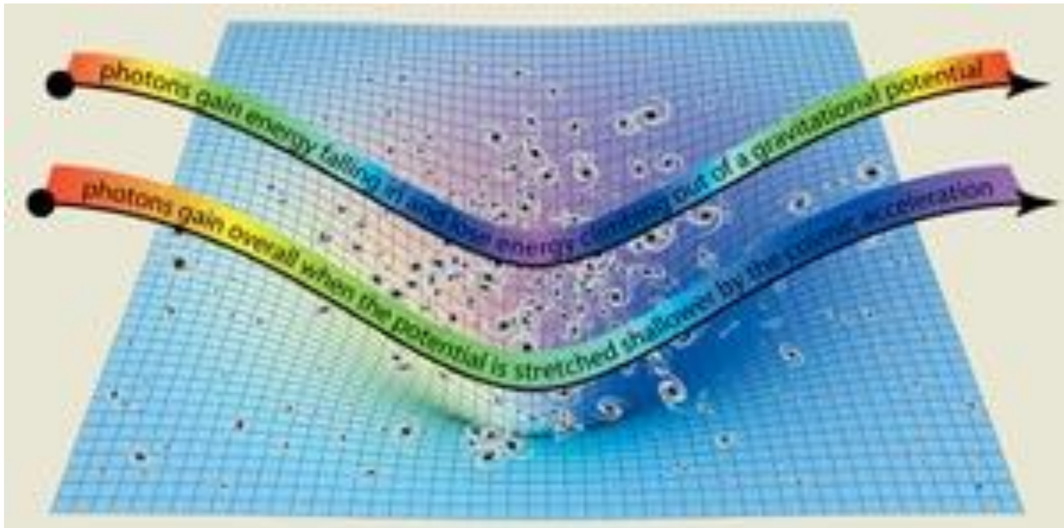
# Physics of Integrated Sachs Wolfe Effect:

CMB photons




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

$\phi$ → Gravitational Potential of The Universe

- Photons gain energy going down potential well, lose energy climbing out.
- As $\Phi \rightarrow 0$ 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?

Universes with vastly different curvature can have very similar CMB powerspectrum

$$l(l+1)C_l^{\delta T_{CMB}\delta T_{CMB}}\ (\mu K)^2$$

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

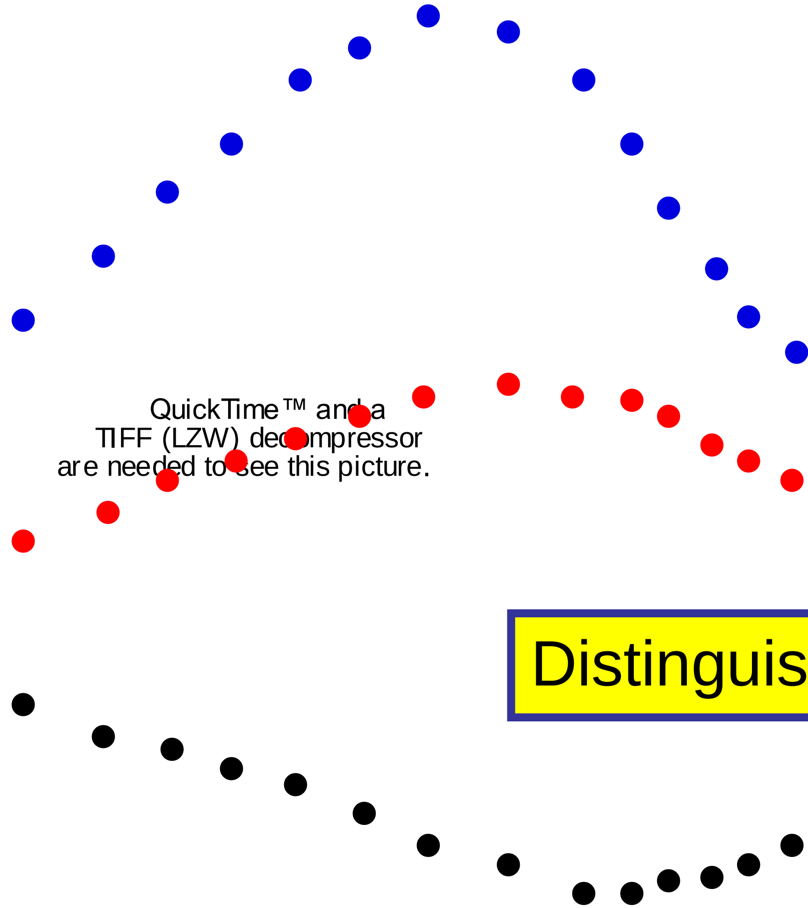
Angular Power spectrum of
Temperature Anisotropies in
Cosmic Microwave Background

l : multipole moment (in $A_{lm}$)

# Galaxy-ISW 2D correlation

**Smaller angular scale →**

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




Distinguishable by ISW!

l : multipole moment (in $A_{lm}$)

# 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)

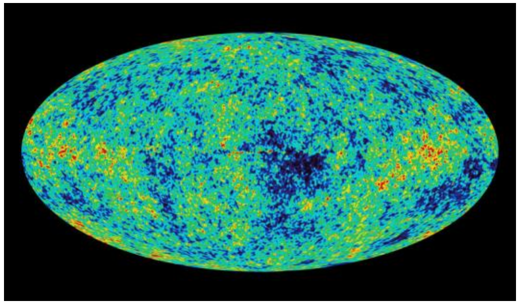
QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

Ho, Hirata, Padmanabhan, Seljak & Bahcall (2008)

# 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:

$$C_l^{gT}\ (Data)$$



X

- But in order to determine cosmological constraint, 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** →

**Black -> LRGs at z = 0.2 to 0.4**

**Red -> LRGs at z = 0.4 to 0.6**

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

l : multipole moment (in $A_{lm}$)

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

**Ho, Hirata, Padmanabhan, Seljak & Bahcall (2008)**

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

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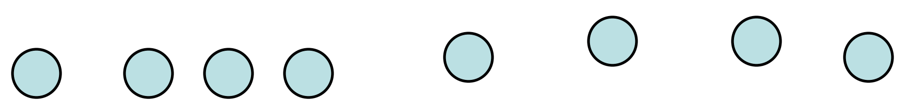

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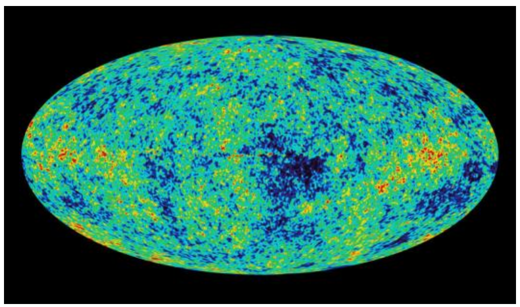

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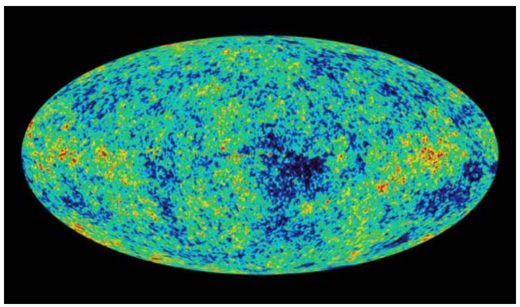

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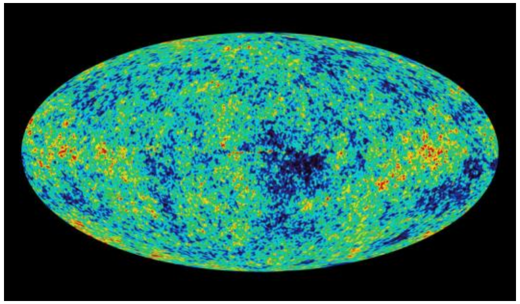

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# There is more to it… systematics!

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

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

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

**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.

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

**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 & Bahcall (2008)

# Summary for ISW systematics

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

• We select a specific multipole range such that these multipoles

Amplitudes of the cross correlations w.r.t WMAP3 predictions

• We

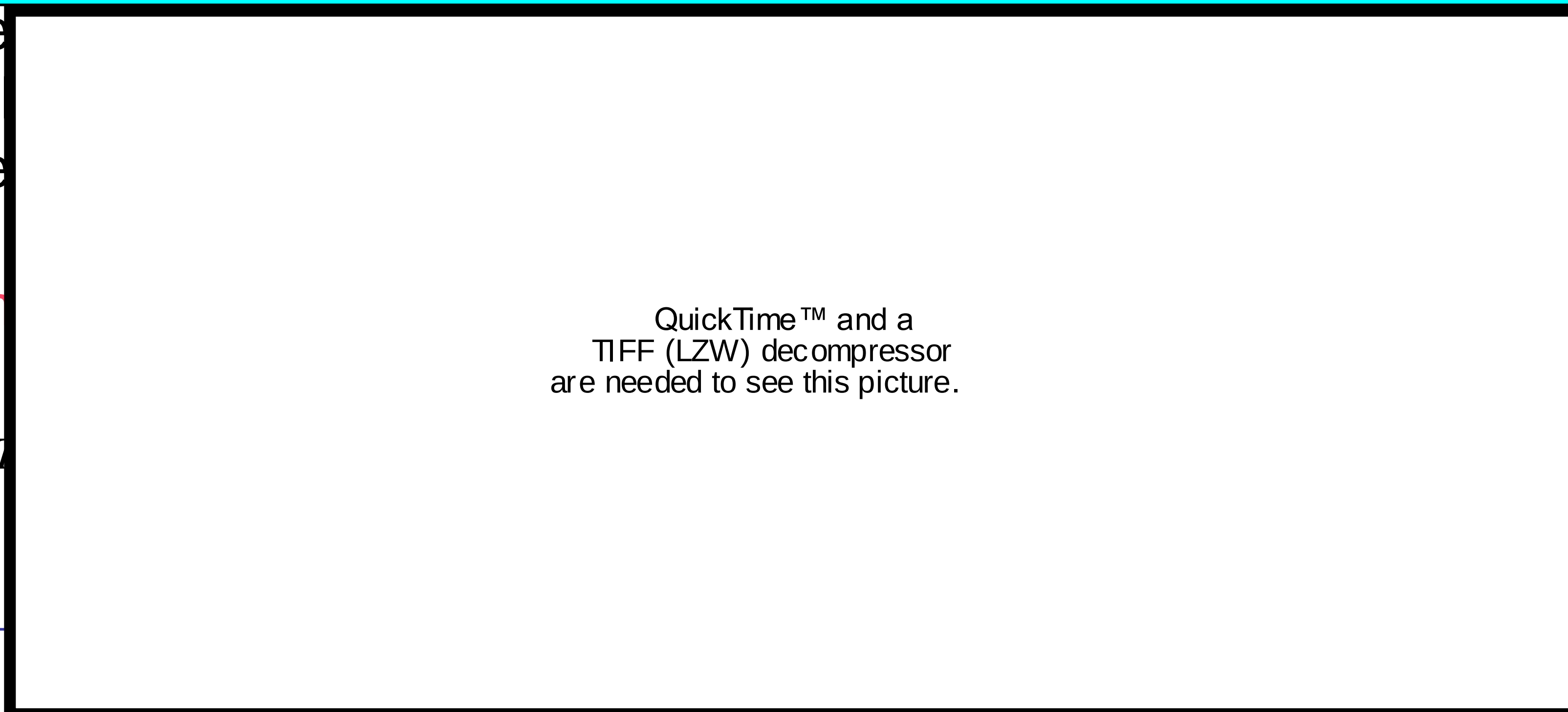
mu c/h.

• We n

bins

con :

$C_l^{gT}$ TSZ

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# Weak Lensing of CMB (mini-version)

- Probes matter in between us and the last scattering surface!
- We find **evidence for a positive cross-correlation at the 2.5 $\sigma$ level**
- The cross correlation amplitude is 1.06 +/- 0.42 times that expected for the WMAP cosmological parameters.
- Our analysis extends other recent analysis 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 & Bahcall (2008)

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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 + $\Omega_K$ (allowing curvature)

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

- Further Constraints on modified gravity models.

# CDM+ $\Omega_K$

Testing the flatness of universe!

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

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Solid: CMB+ISW+WL
Dotted: CMB only

Ho, Hirata, Padmanabhan, Seljak & Bahcall (2008)

CDM+ $\Omega_K$

Independent probe to Geometry and Vacuum Energy

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



TABLE 12

JOINT DATA SET CONSTRAINTS ON GEOMETRY AND VACUUM ENERGY

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

Spergel et al. 2007

# Mini-conclusion

- ISW (Integrated Sachs Wolfe) effect:

  (1) First effort that goes 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

➔ Probes the geometry of the Universe

- Weak Lensing of CMB:

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

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

➔ Probes the matter in the Universe

- Cosmological Constraints from first likelihood analysis of ISW and WL of CMB that allows all the cosmological parameters to vary.

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

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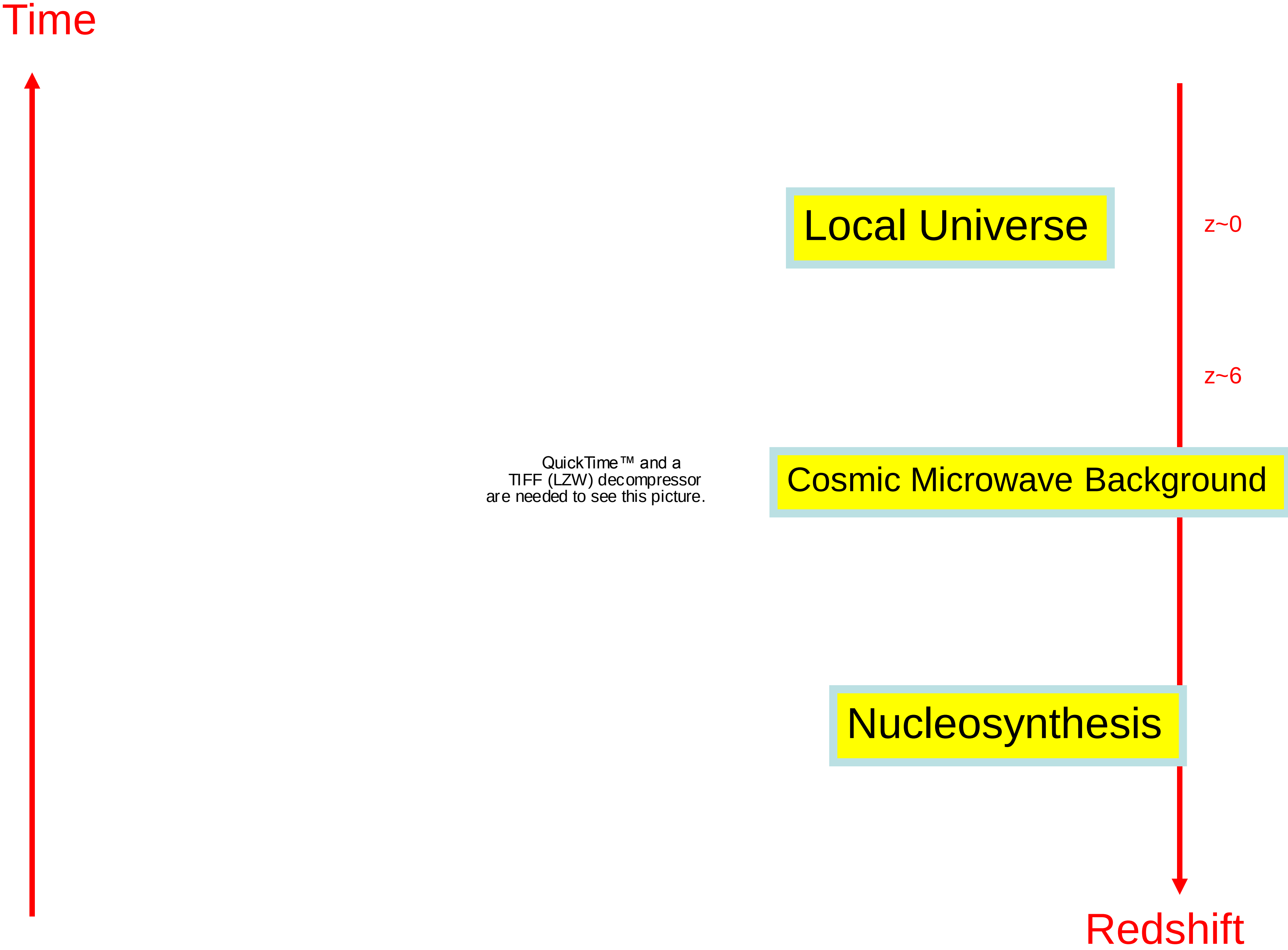
Time
Local Universe
z~0
z~6
QuickTime™ and a
TIFF (LZW) decompressor
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Cosmic Microwave Background
Nucleosynthesis
Redshift

We are trying to find the gas not only in the galaxies but also along these filaments or just in the intergalactic medium!

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

Courtesy simulation of gas from Renyue Cen and Jerry Ostriker

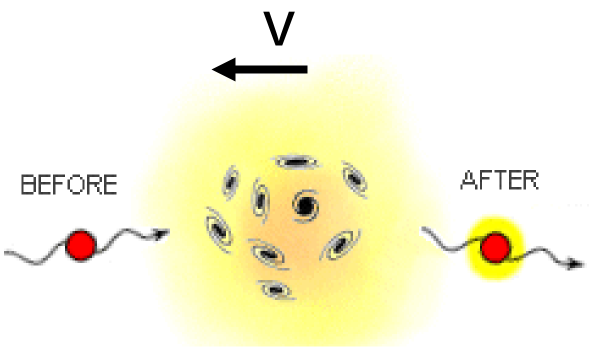
# Physics of KSZ:

-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!

Electrons moving towards us:
➔ HOT spot
electrons moving away from us:
➔ COLD spot

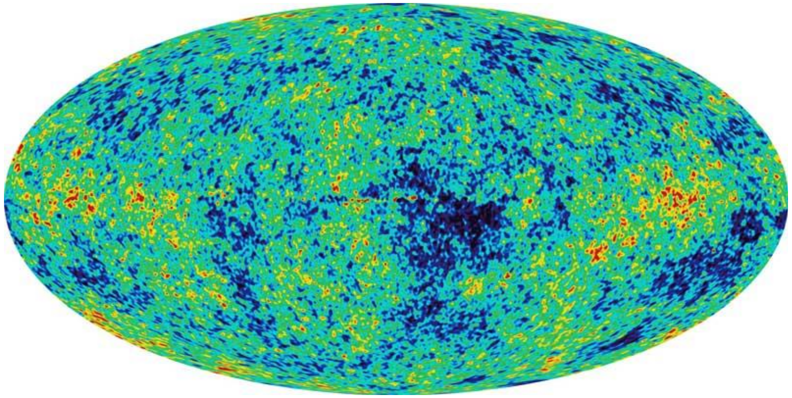



# A New way to find missing baryons

## Step 0: Introduce the components

Momentum field of universe

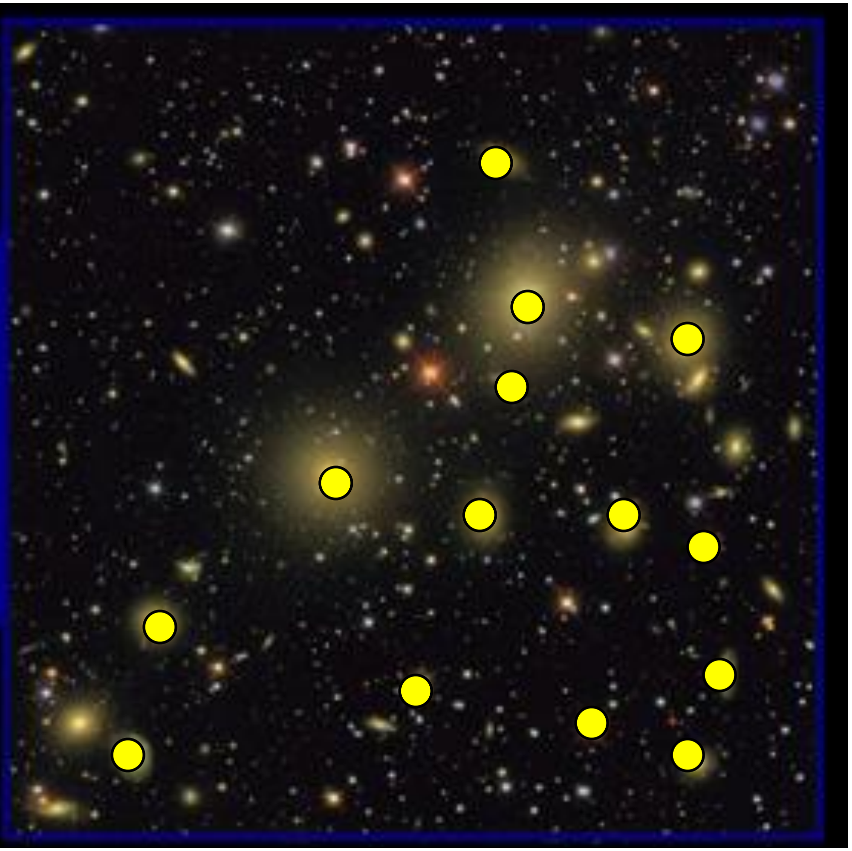
x



Observed CMB

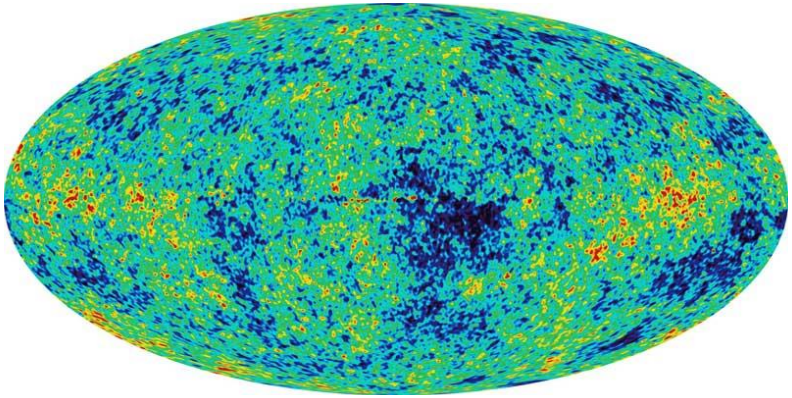
# A New way to find missing baryons

## Step 1: Locate the galaxies



Momentum field of universe

x

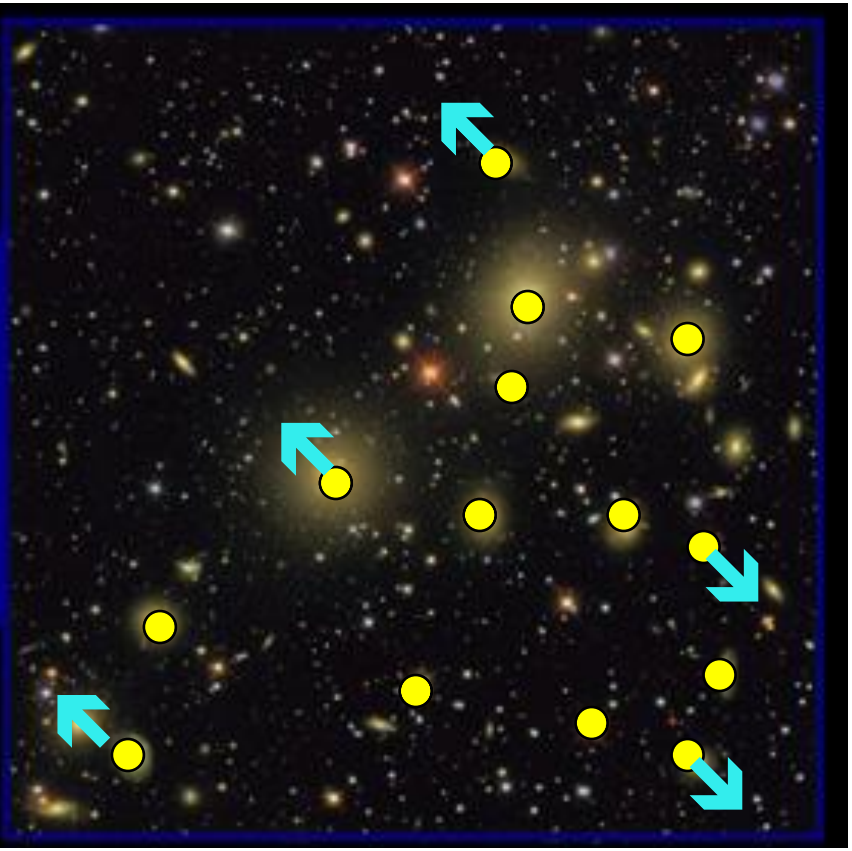


Observed CMB

# A New way to find missing baryons

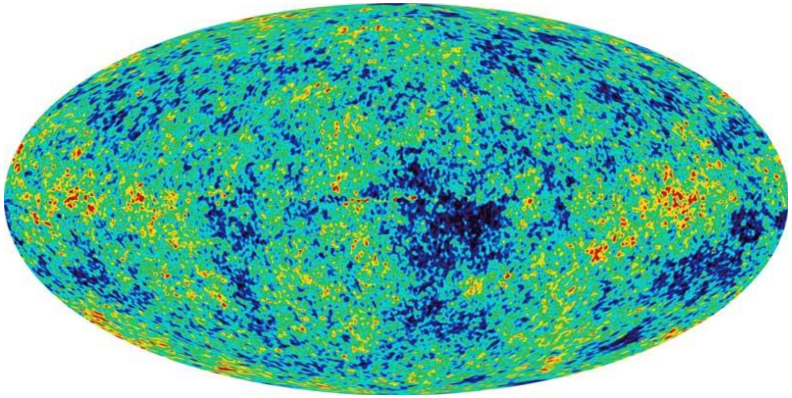
Step 2: reconstruct the velocities from density

$$\vec{v}(k,a) = i\frac{d\ln D}{d\ln a}aH\delta(k)\frac{\vec{k}}{k^2}$$



Momentum field of universe

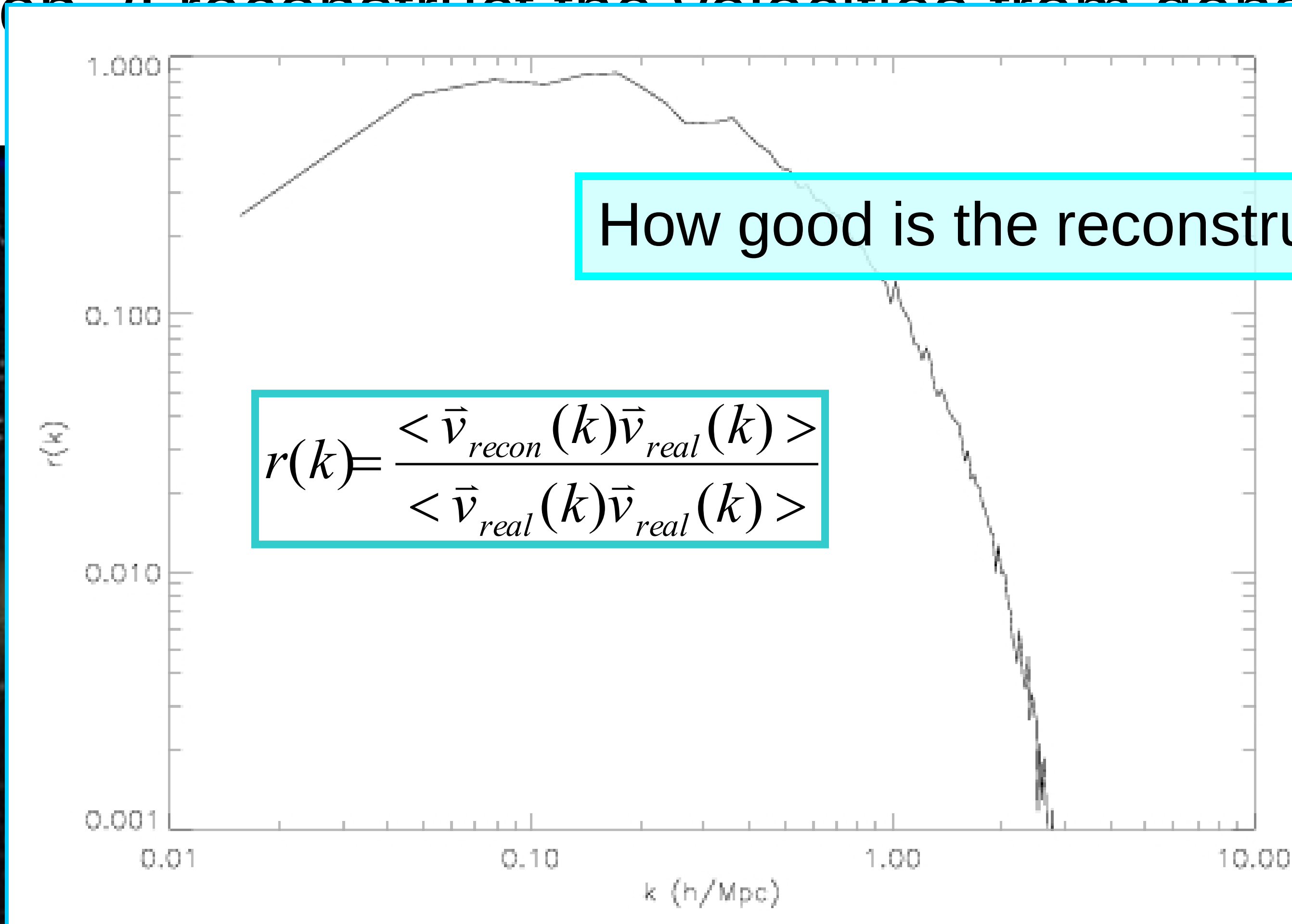
X



Observed CMB

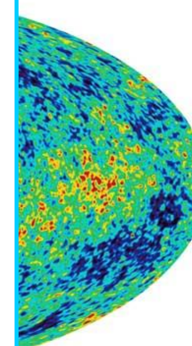
# A New way to find missing baryons

## Step 2: reconstruct the velocities from density




$$r(k) = \frac{< \vec{v}_{recon}(k)\vec{v}_{real}(k) >}{< \vec{v}_{real}(k)\vec{v}_{real}(k) >}$$

How good is the reconstruction?

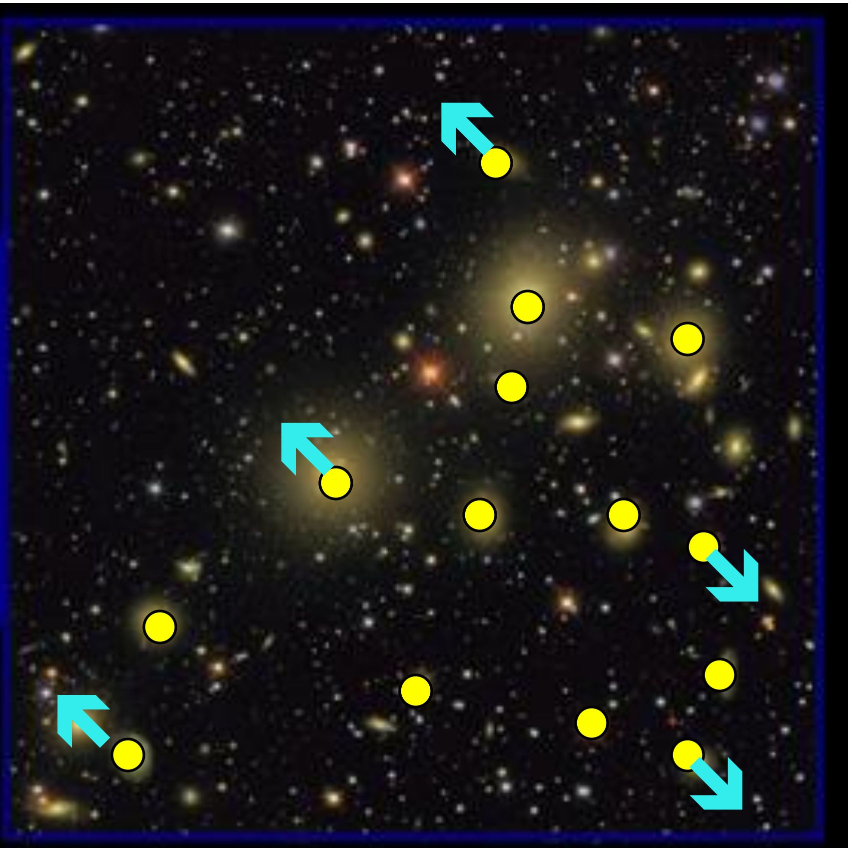


B

Momentum field of universe

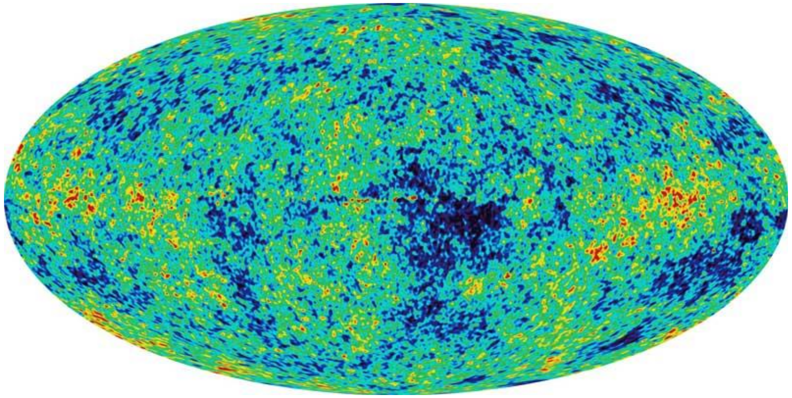
# A New way to find missing baryons

## Step 3: Cross correlate momentum field with CMB



Momentum field of universe

X

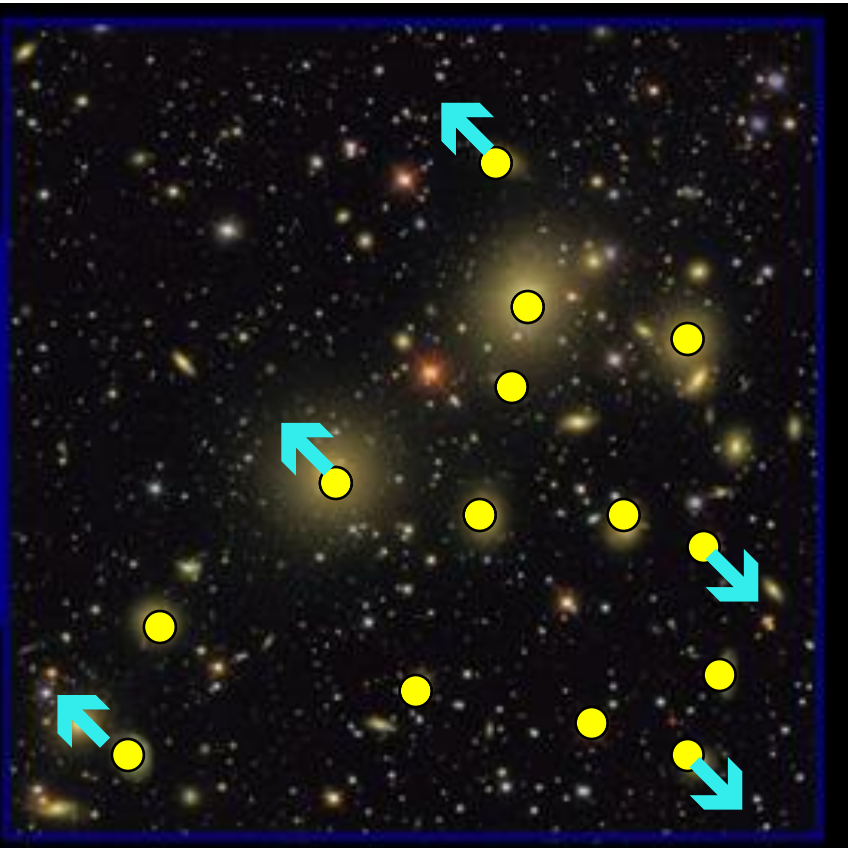


Observed CMB

# A New way to find missing baryons

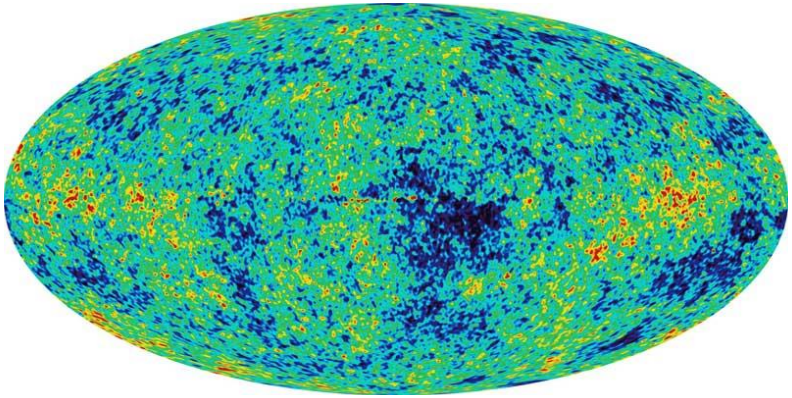
## Step 3: Cross correlate momentum field with CMB

How does this work?



Momentum field of universe

X



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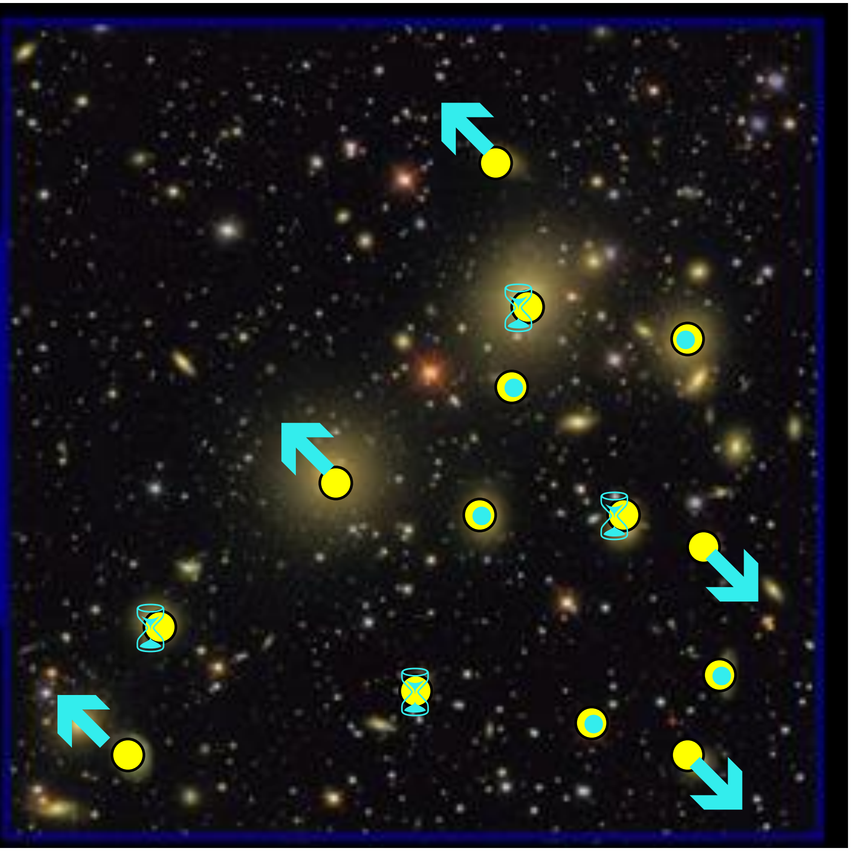
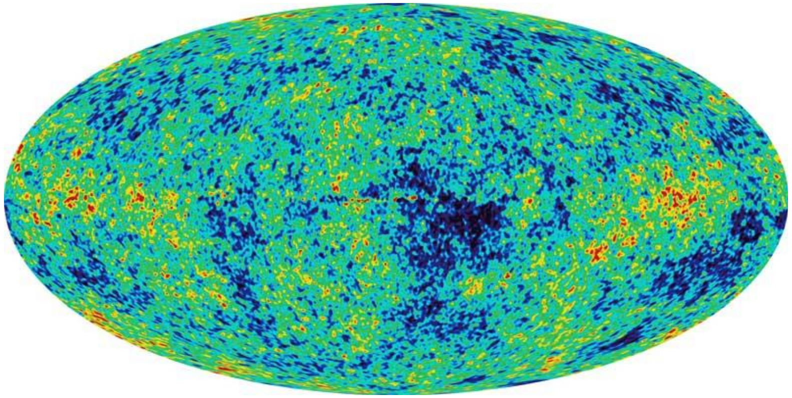


Momentum field of universe

X



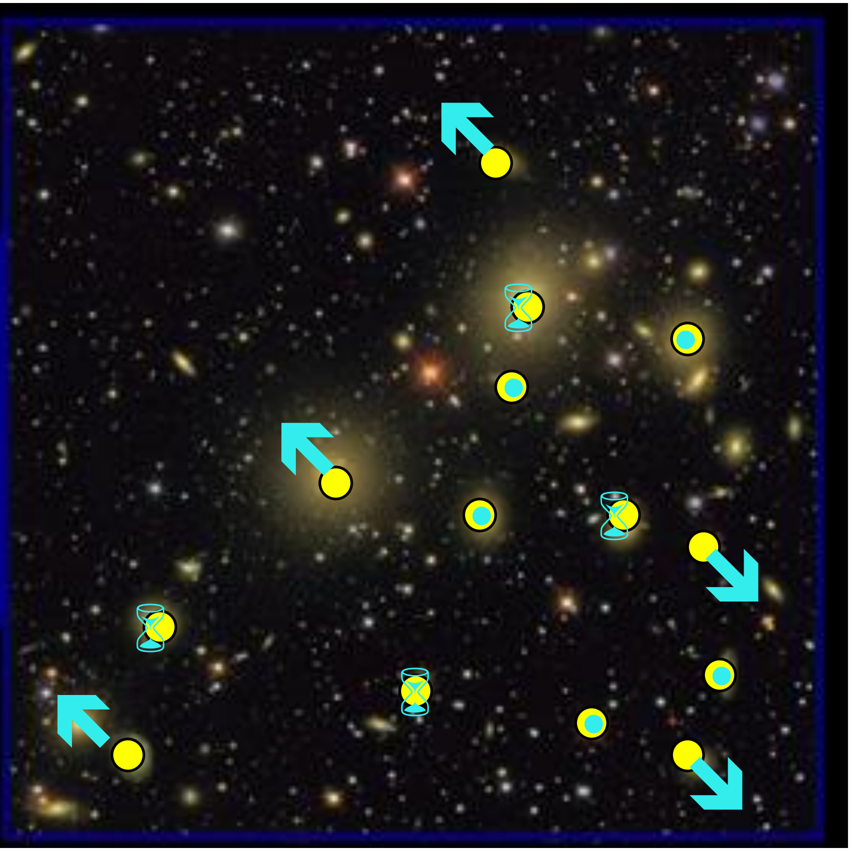
Observed CMB

Moving towards us
Moving away from us

# A New way to find missing baryons

## Step 3: Cross correlate momentum field with CMB

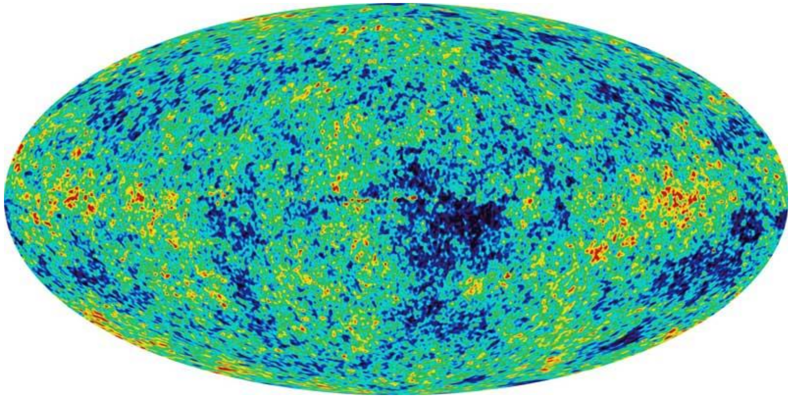
How does this work? kSZ !



Momentum field of universe

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

X



Observed CMB

Moving towards us

⌛ Moving away from us

# A New way to find missing baryons

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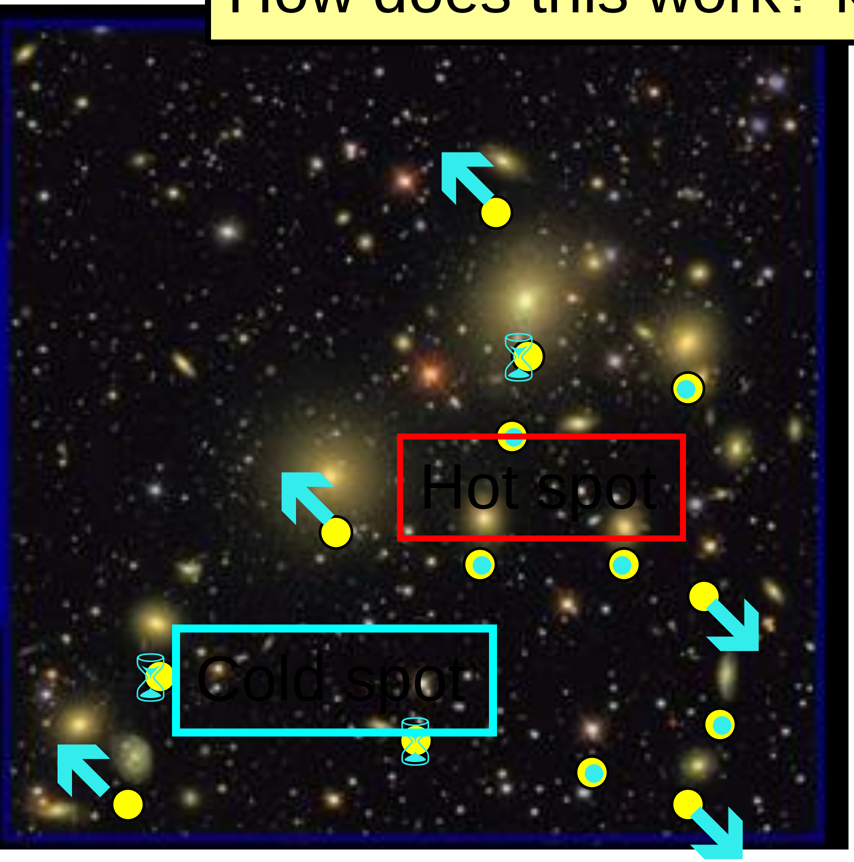


Momentum field of universe

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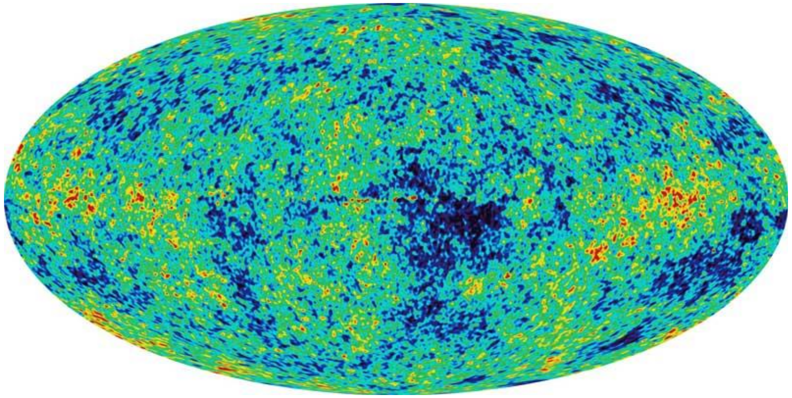


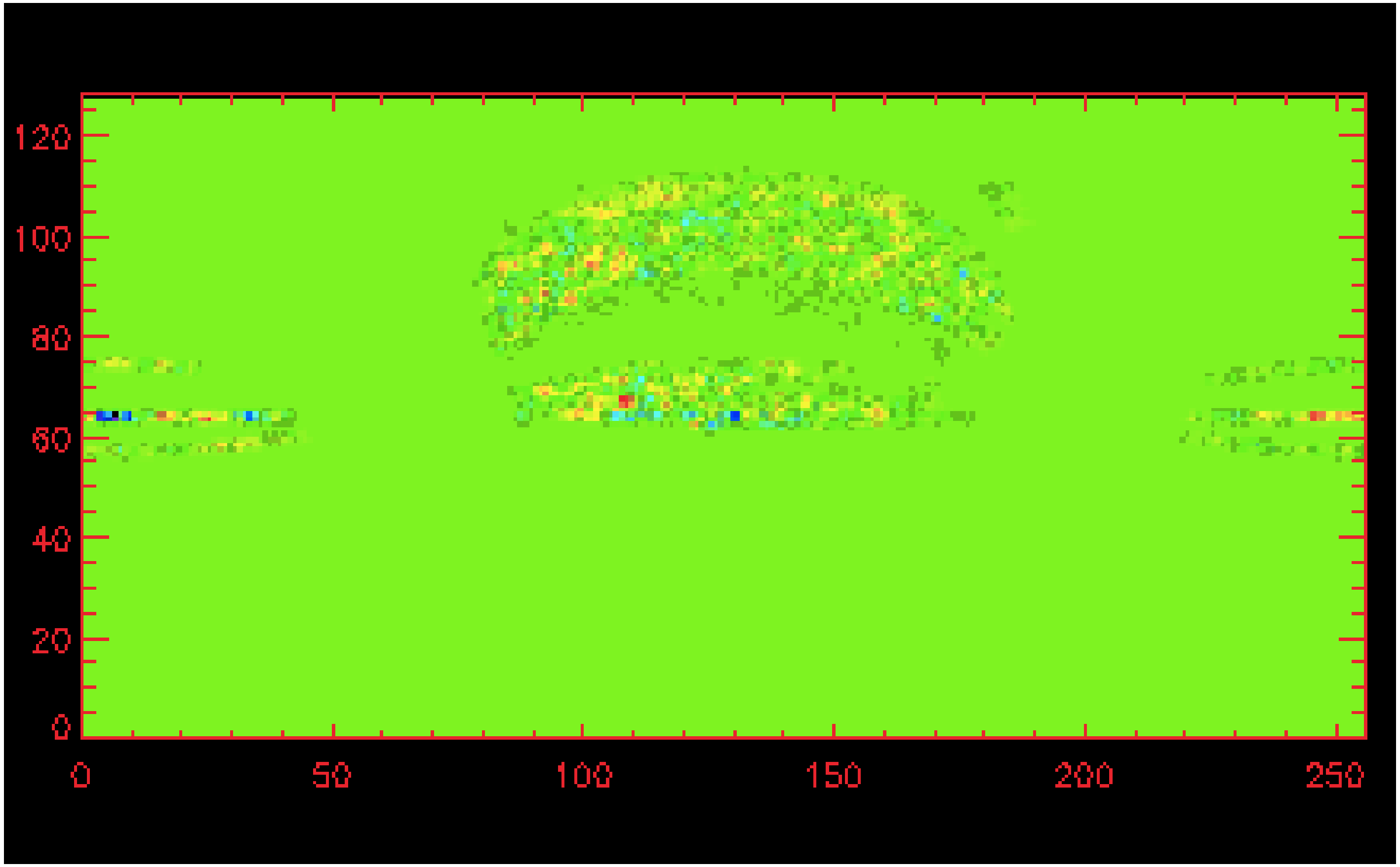
Observed CMB

Moving towards us

Moving away from us

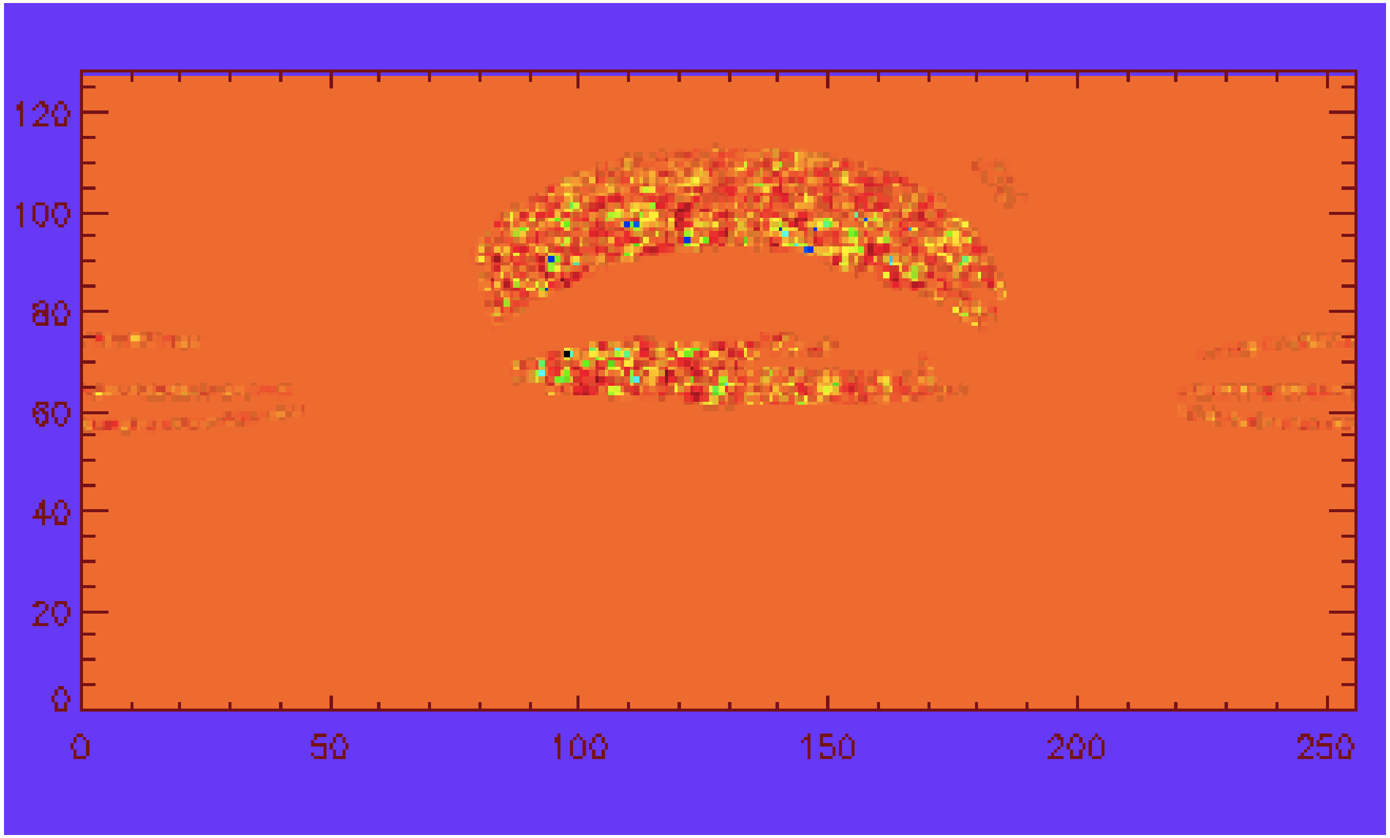
# Momentum fields!

- SDSS DR4 main galaxies



# Momentum fields!

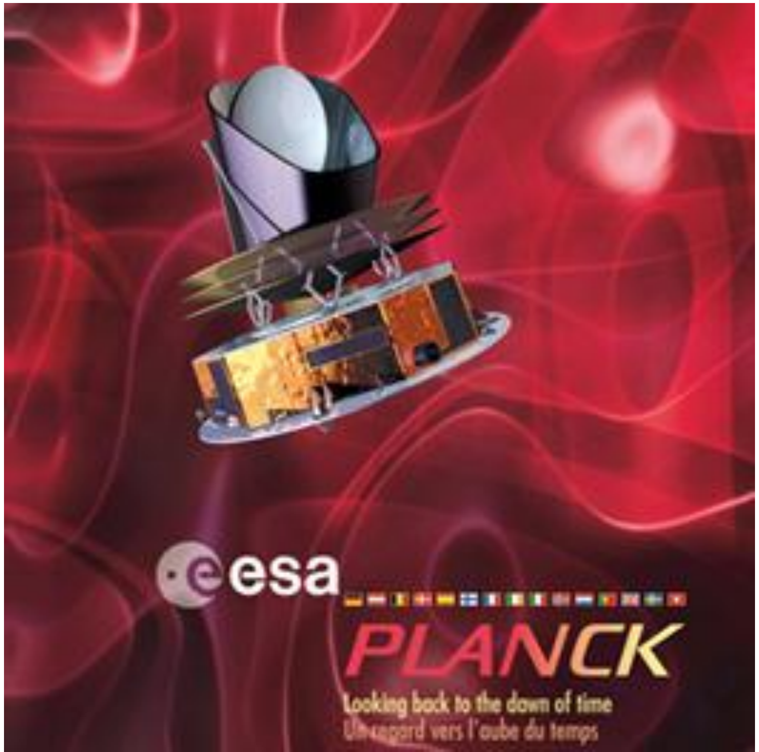
- SDSS DR4 Luminous Red Galaxies



# CMB Observations

Atacama Cosmology Telescope

Planck Satellite



# Missing Baryon ratio

Galaxy Momentum - kSZ temperature change cross-correlation

$$C_l^{P\theta} = \frac{\pi^2}{2l^5}\int b * \frac{dN}{d\eta} g(\eta)\left(\frac{dD(\eta)}{d\eta}\frac{1}{D}\right)^2 I_{P\theta}(l/\eta)\, d\eta$$

A function of $f_{gas}$

$$C_l^{P\theta} = f_{gas}\left[\frac{\pi^2}{2l^5}\int b * \frac{dN}{d\eta} g'(\eta)\left(\frac{dD(\eta)}{d\eta}\frac{1}{D}\right)^2 I_{P\theta}(l/\eta)\, d\eta\right]$$

This will be available alongside with the momentum templates

# Missing Baryon ratio

$$C_l^{P\theta} = f_{gas}\left[\frac{\pi^2}{2l^5}\int b * \frac{dN}{d\eta} g'(\eta)\left(\frac{dD(\eta)}{d\eta}\frac{1}{D}\right)^2 I_{P\theta}(l/\eta)\,d\eta\right]$$

Provided

Cross correlate the Momentum fields with CMB sky

# Missing Baryon ratio

$$C_l^{P\theta} = f_{gas}\left[\frac{\pi^2}{2l^5}\int b * \frac{dN}{d\eta} g^{'}(\eta)\left(\frac{dD(\eta)}{d\eta}\frac{1}{D}\right)^2 I_{P\theta}(l/\eta)\, d\eta\right]$$

Provided

Cross correlate the Momentum fields with CMB sky

What is Left!

# KSZ estimated S/N

| | ACT 260 deg$^2$ | ACT 4000 deg$^2$ | Planck |
|---|---|---|---|
| SDSS DR4 | 1.068 | 4.19 | 11.27 |
| SDSS3 | 3.789 | 14.84 | 41.95 |
| ADEPT | 4.432 | 17.39 | 55.97 |

Ho, Dedeo & Spergel 2008, 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!