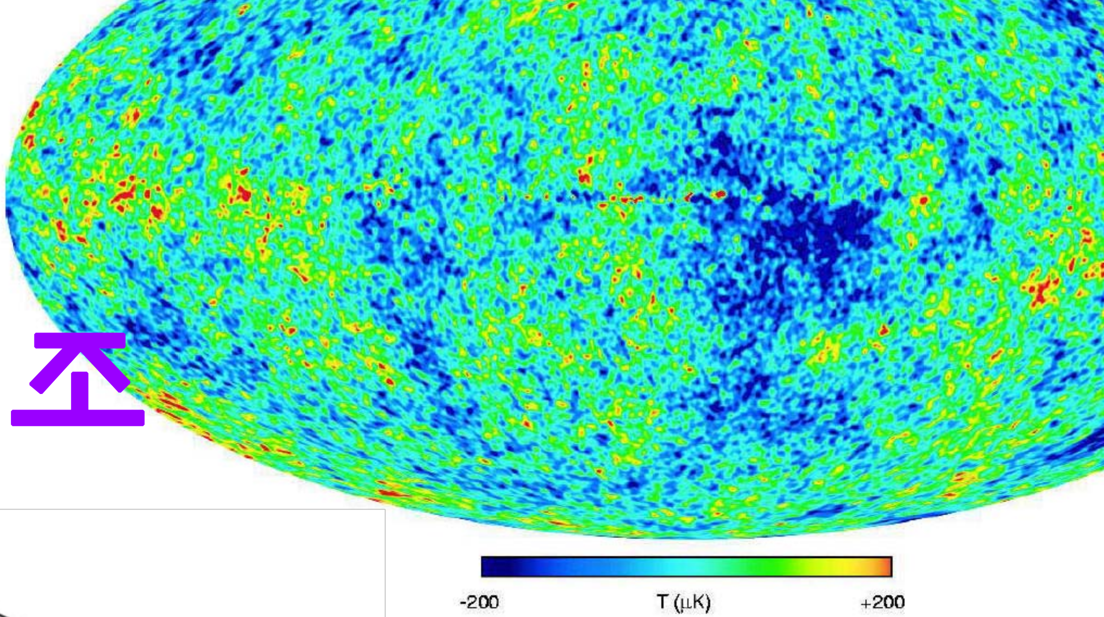
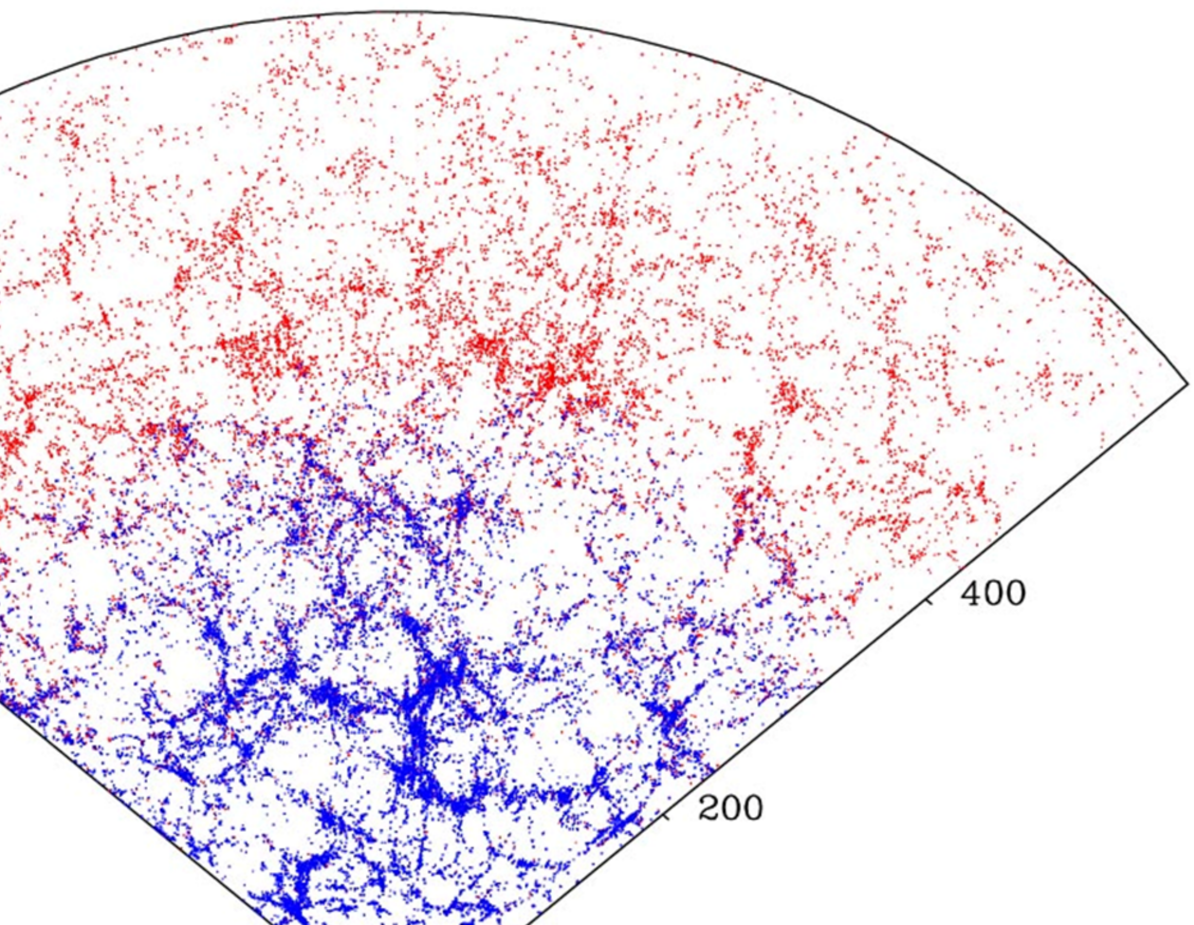
우주거대구조





박 창 범

고등과학원

Jan. 31-Feb. 7, 2010

고등과학원-서울대 겨울학교

요약

지난 20여년 간 별, 외부은하와 우주거대구조, 우주배경복사에 대한 각종 관측은 차차 그 간극이 메워지면서 하나의 **총체적 우주 탐사 작업**으로 통일되기 시작.

향후 20년 이상의 기간 동안 세계 천문학계가 가장 역점을 두어 수행할 대형 우주탐사 사업들은 이제 이러한 **전체적 시야**를 가지고 그 역할을 찾아가야 할 상황.

본 강연은 현재 추진하고 있는, 또는 미래에 추진될 대형 우주탐사들이 우주를 이해하기 위해서 이용하고자 하는 **물리적 현상/원리**들을 정리하고 **상호연관성**을 보이고자 한다.

외부은하천문학에 중점/특정 탐사들을 리뷰X

최근 우주史

BB 빛분리시기

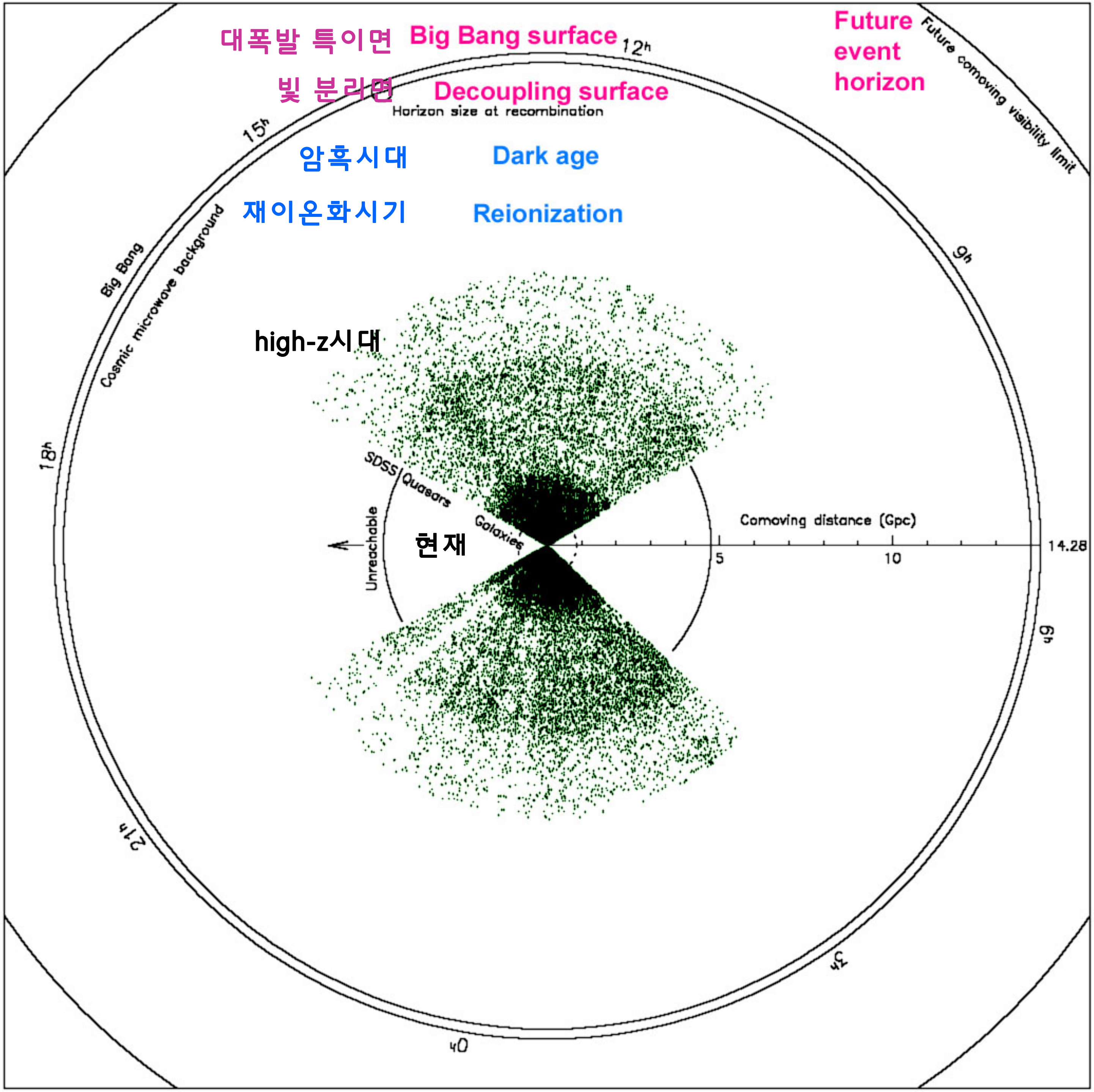
암흑시대	재이온화시기		천체생성 & 진화기	현재	현상
중성수소	최초천체생성	은하진화	은하단/우주거대구조 생성	복잡계우주	물질

Inflation 감속팽창 (빛우세)

감속팽창(물질우세)	가속팽창(DE우세)	공간

우주 조망도

관측 가능한 시공간



최근 우주연구史

LSS

CMBR

1917Einstein's static model

1922External galaxies

22-24Friedmann's models

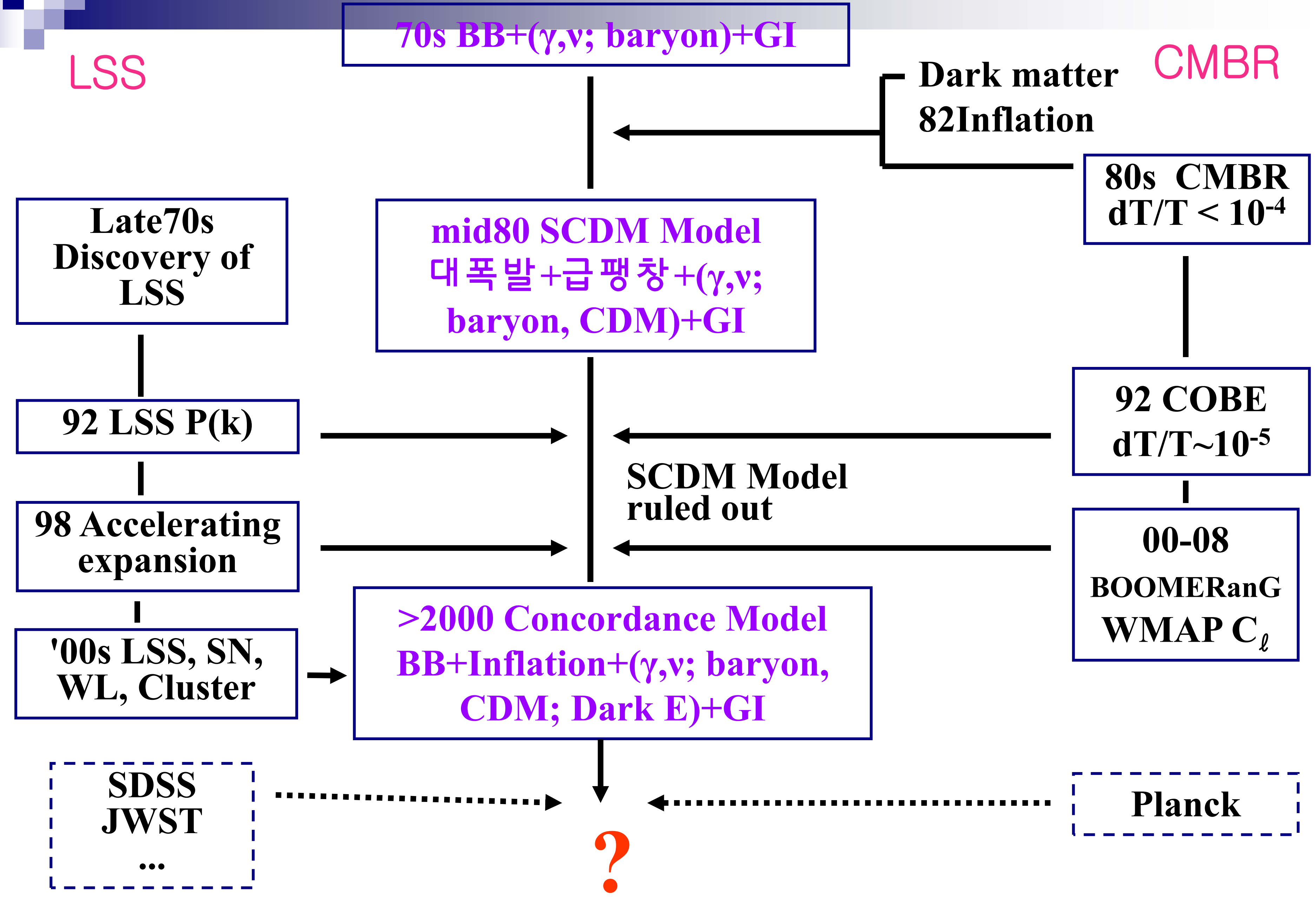
29Expansion of space

29Big Bang model

50s Gravitational Instability(GI) Theory

65 Discovery of CMBR

70s BB+(γ,ν; baryon)+GI


LSS
70s BB+(γ,ν; baryon)+GI
CMBR
Dark matter
82Inflation
80s CMBR
dT/T < 10-4
Late70s
Discovery of
LSS
mid80 SCDM Model
대폭발+급팽창+(γ,ν;
baryon, CDM)+GI
92 LSS P(k)
92 COBE
dT/T~10-5
SCDM Model
ruled out
98 Accelerating
expansion
00-08
BOOMERanG
WMAP Cℓ
'00s LSS, SN,
WL, Cluster
>2000 Concordance Model
BB+Inflation+(γ,ν; baryon,
CDM; Dark E)+GI
SDSS
JWST
...
Planck
?

『외부은하천문학/우주론의 현 이슈』

1. Spacetime

Space : homogeneous & isotropic ?

Geometry & topology of space (flat & infinite? multiply connected?)

Expansion of space (→ matter)

Past and future of the Universe (why now?)

2. Matter

Contents and nature (what & how much)

Primordial fluctuation (initial conditions)

Structure formation & evolution (when & how, environment)

3. Phenomena/Laws

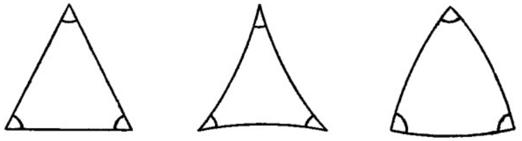
New physics (GR correct?)

관측 대상 - 천문현상 & 천체

1. primordial fluctuations (initial conditions)

CMB (+neutrino, gravitational wave)

=> geometry of space, matter contents, matter P(k), non-Gaussianity



2. Expansion history of the space

standard candle	$D_L(z) = (1+z)\, r(z)$	SN Ia	HST Legacy, Essence, DES, SNAP
standard ruler	$D_A(z) = (1+z)^{-1}\, r(z)$	AP test, BAO, topology	SDSS
standard population	$dV/dz d\Omega = r^2(z)/H(z)$	topology	redshift surveys

=> H(z) or $r(z) = \int_0^z \frac{dz'}{H(z')}$

3. Growth of structures

ISW	l<30 CMB CC btw CMB & LSS	CMB, LSS	WMAP-Planck * SNAP-LSST-SDSS
Population density	comoving V * # density ~> dn/dz	clusters (SZ, Xray), galaxies	SDSS, ACT, APEX, DES, SPT
Weak lensing	shear convergence	imaging, photo-z	CFHTLS, SNAP, DES, LSST

=> depends on both expansion of space H(z) & matter power spectrum P(k)

4. Properties of non-linear structures

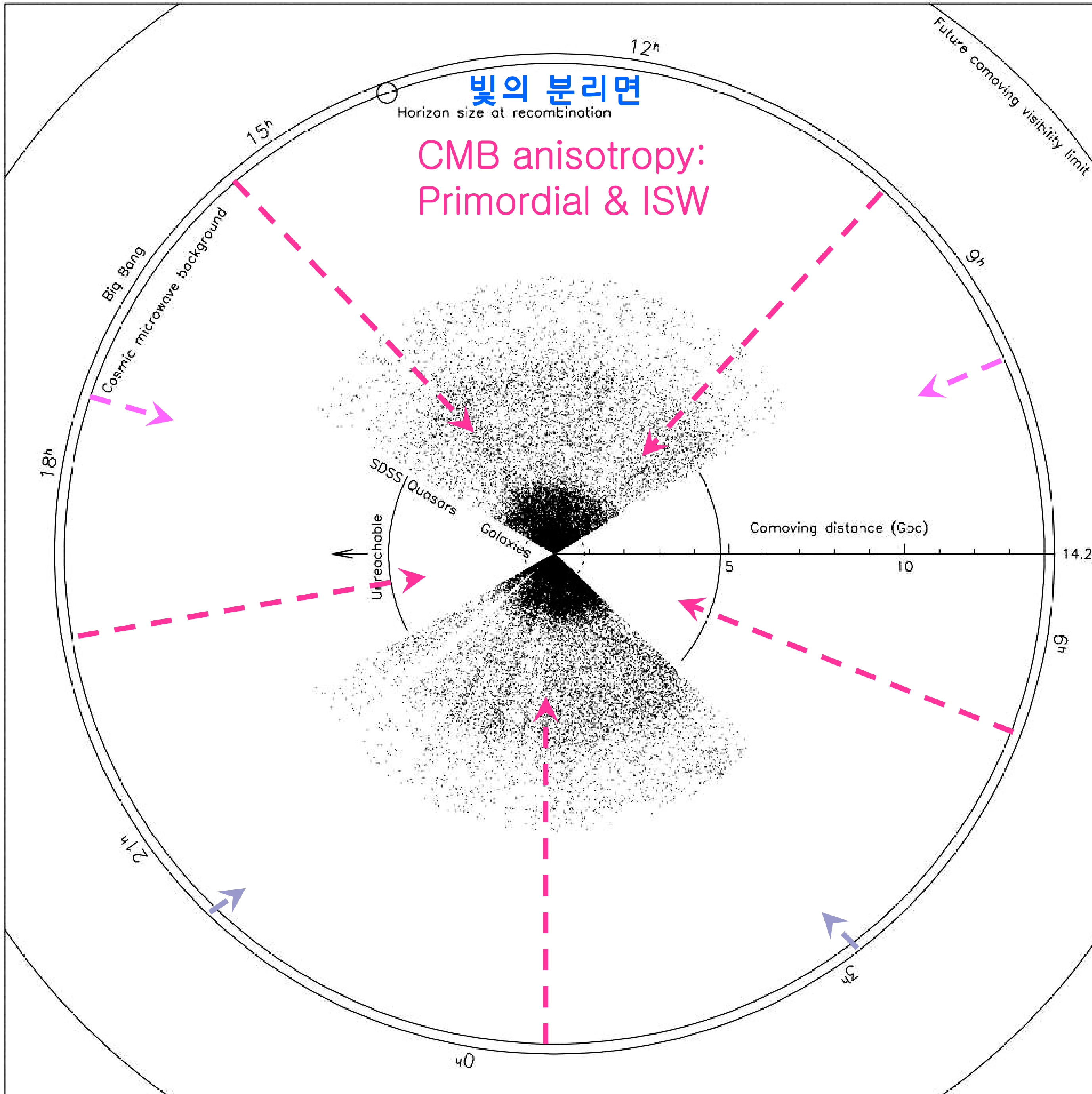
properties of galaxies, AGNs, cluster of galaxies, globular cluster

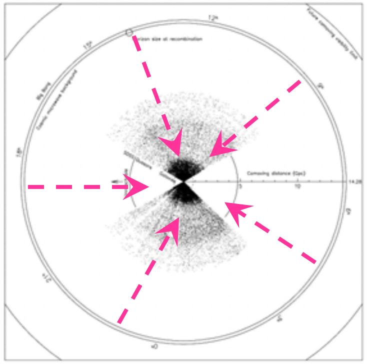
=> depends on H(z), P(k), non-linear physics

Cosmic microwave background anisotropy:

geometry of space,
matter contents,
matter P(k),
non-Gaussianity

only at z~1100,
2d map,
foregrounds

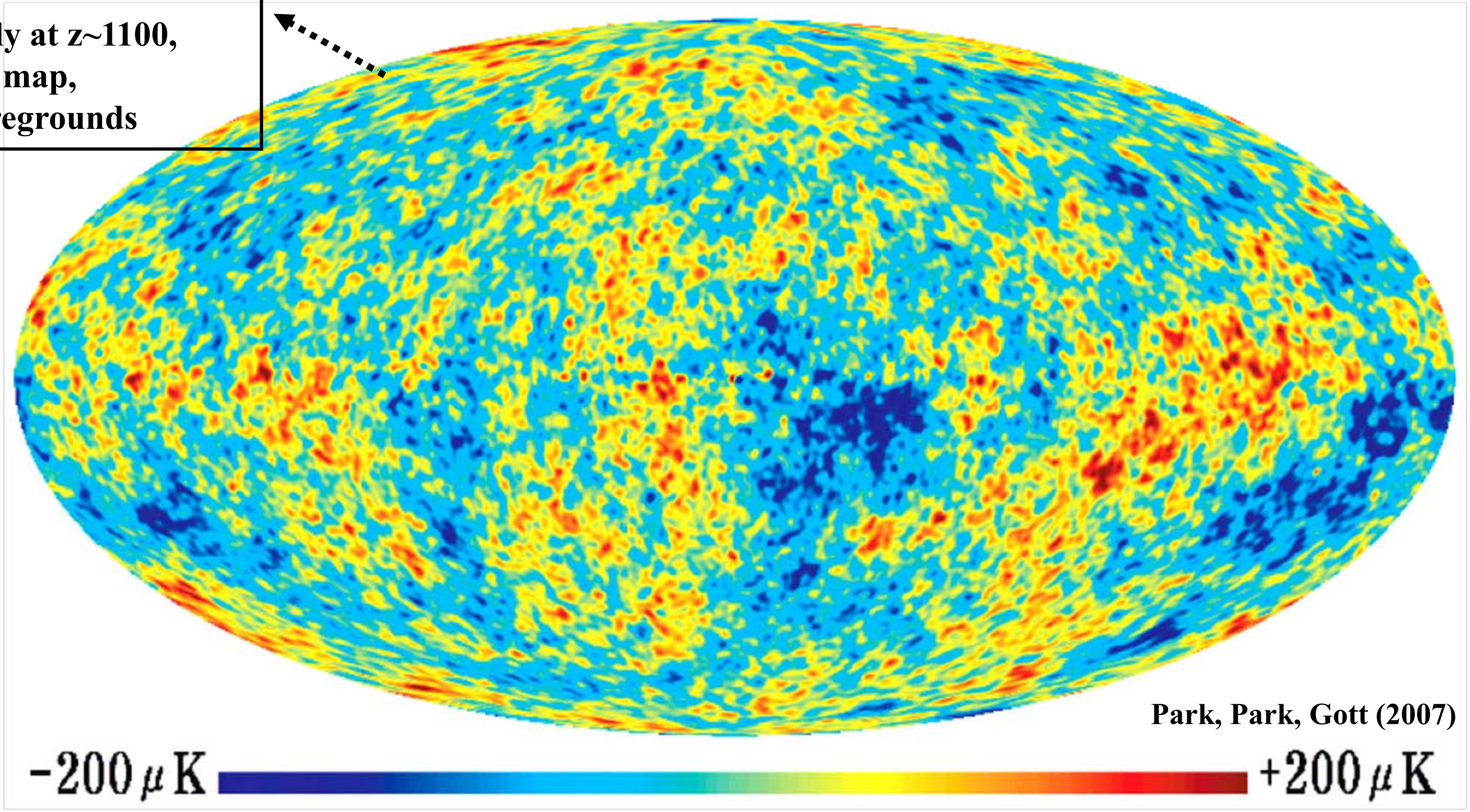




WMAP's 3 year Map

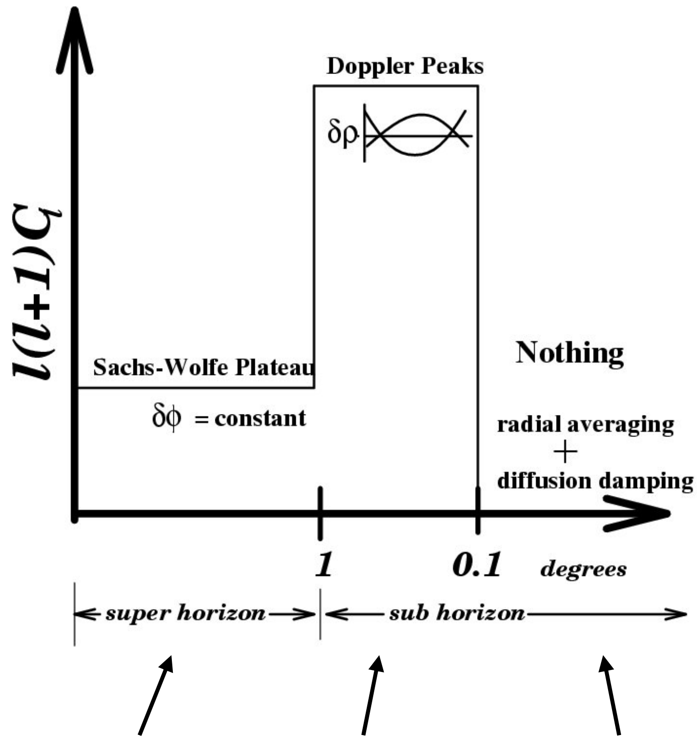
geometry of space,
matter contents,
matter P(k),
non-Gaussianity

only at z~1100,
2d map,
foregrounds

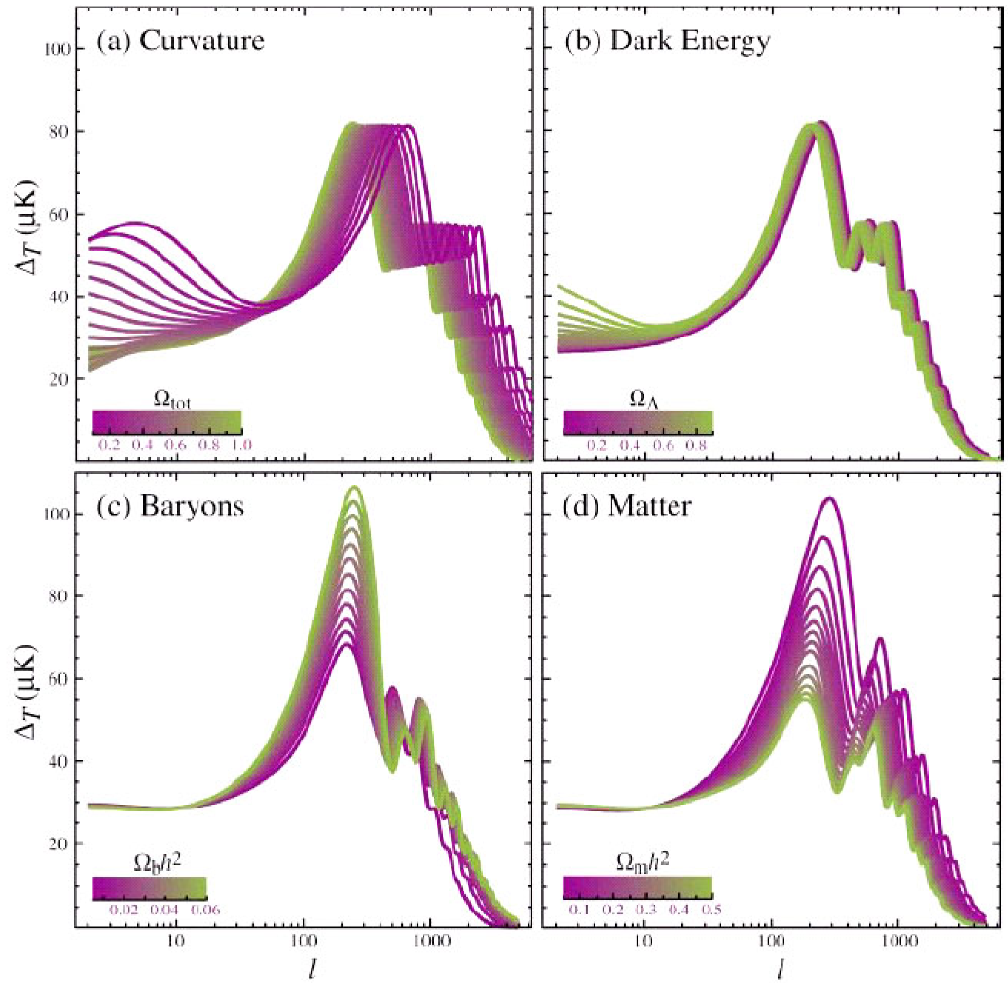


Park, Park, Gott (2007)

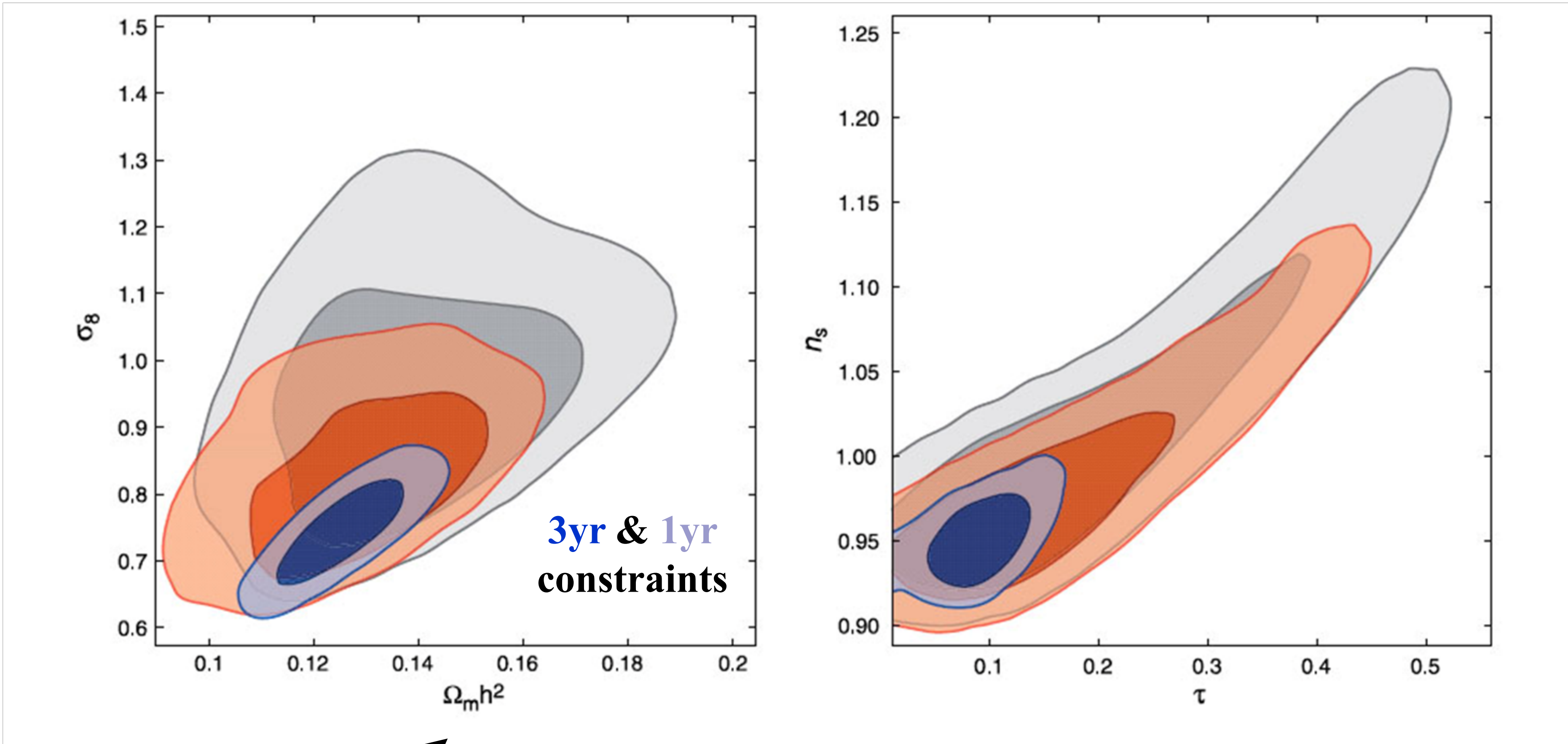
Shape of T Power Spectrum



Super-horizon scale fluc. **SW effect**	**1～0.1r_H fluc. with initially coherent phases** **Oscillation & Doppler effect**	**Radial averaging & radiation diffusion**



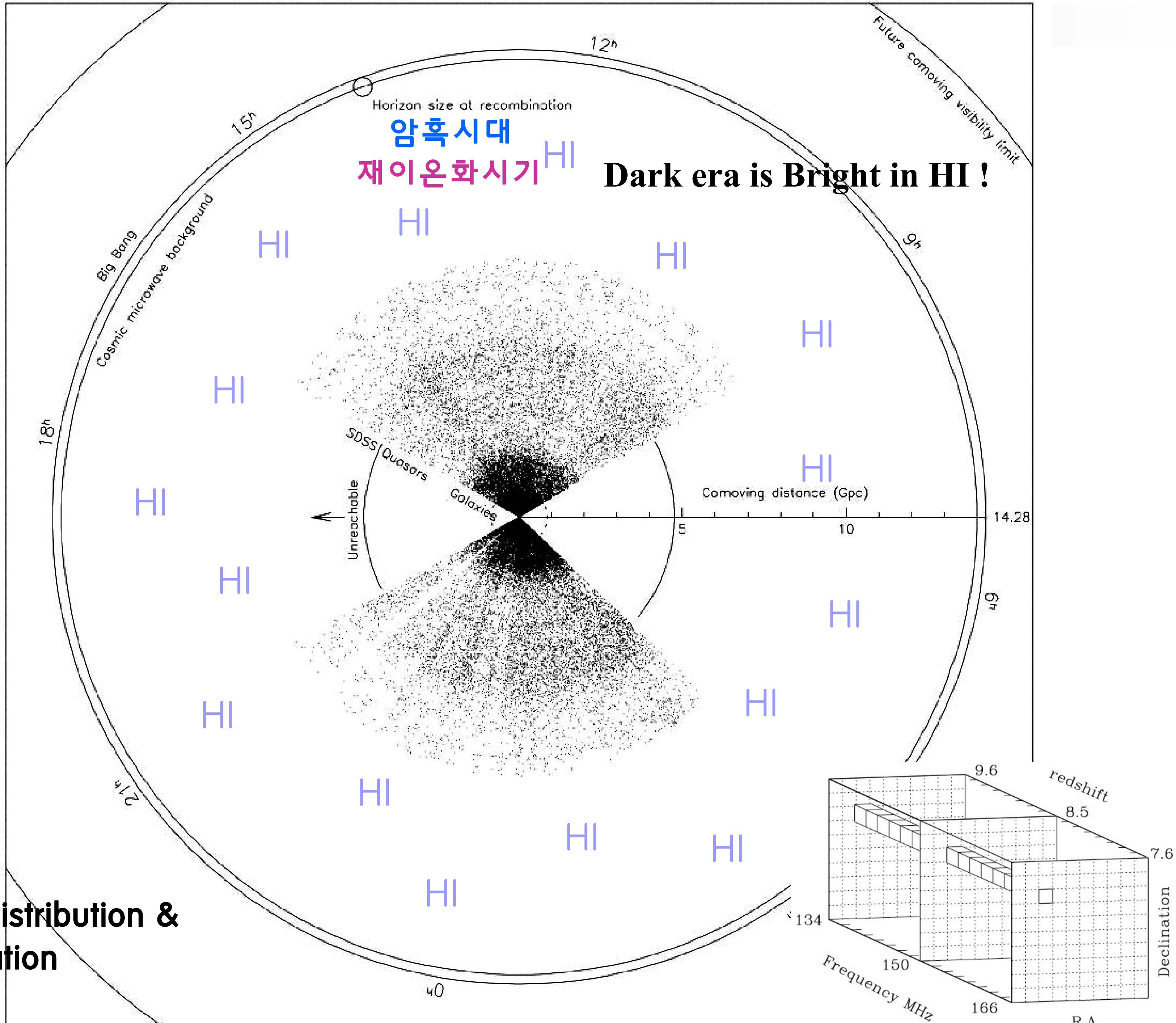
Spergel et al. (2007)



d_A to the last scattering surface

Redshifted 21cm line

History and morphology of reionization. Birth of the 1st objects



3D HI distribution & reionization

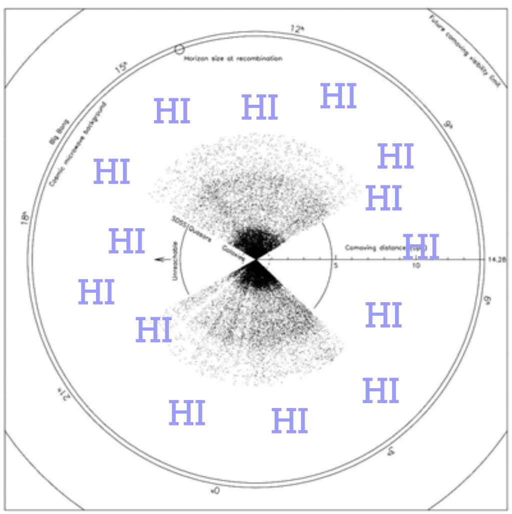
3D HI distribution : 21cm tomography

Spin T: $\delta T \sim (1+\delta)x_H\,(T_S - T_{CMB})/T_S * (1+z)^{0.5}$ mK

Power spectrum of 21cm fluctuations

$$P_{\Delta T}(\mathbf{k}) = \tilde{T}_b^2 \{[\bar{x}_H^2 P_{\delta\delta} - 2\bar{x}_H P_{x\delta} + P_{xx}] + 2\mu^2[\bar{x}_H^2 P_{\delta\delta} - \bar{x}_H P_{x\delta}] + \mu^4 \bar{x}_H^2 P_{\delta\delta}\}$$

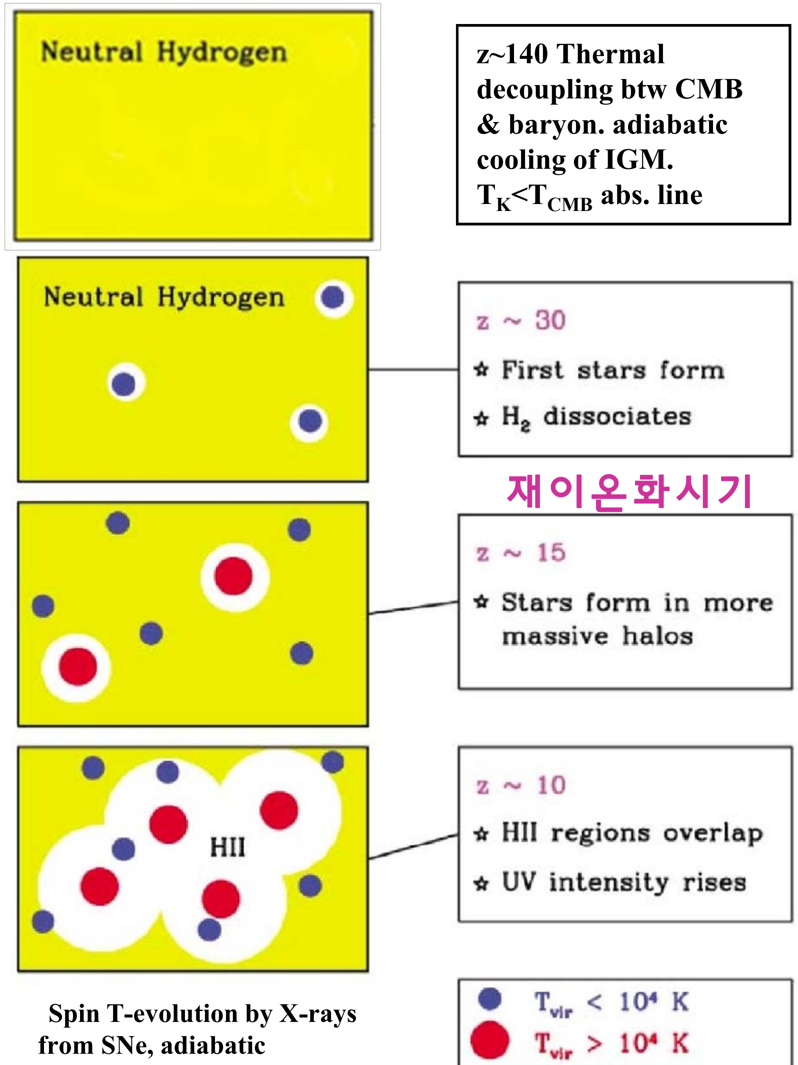
$P_{xx} = \bar{x}_i^2 P_{\delta_x \delta_x}$ and $P_{x\delta} = \bar{x}_i P_{\delta_x \delta}$ are the ionization power spectrum and the density-ionization power spectrum



빛 분리시기
암흑시대

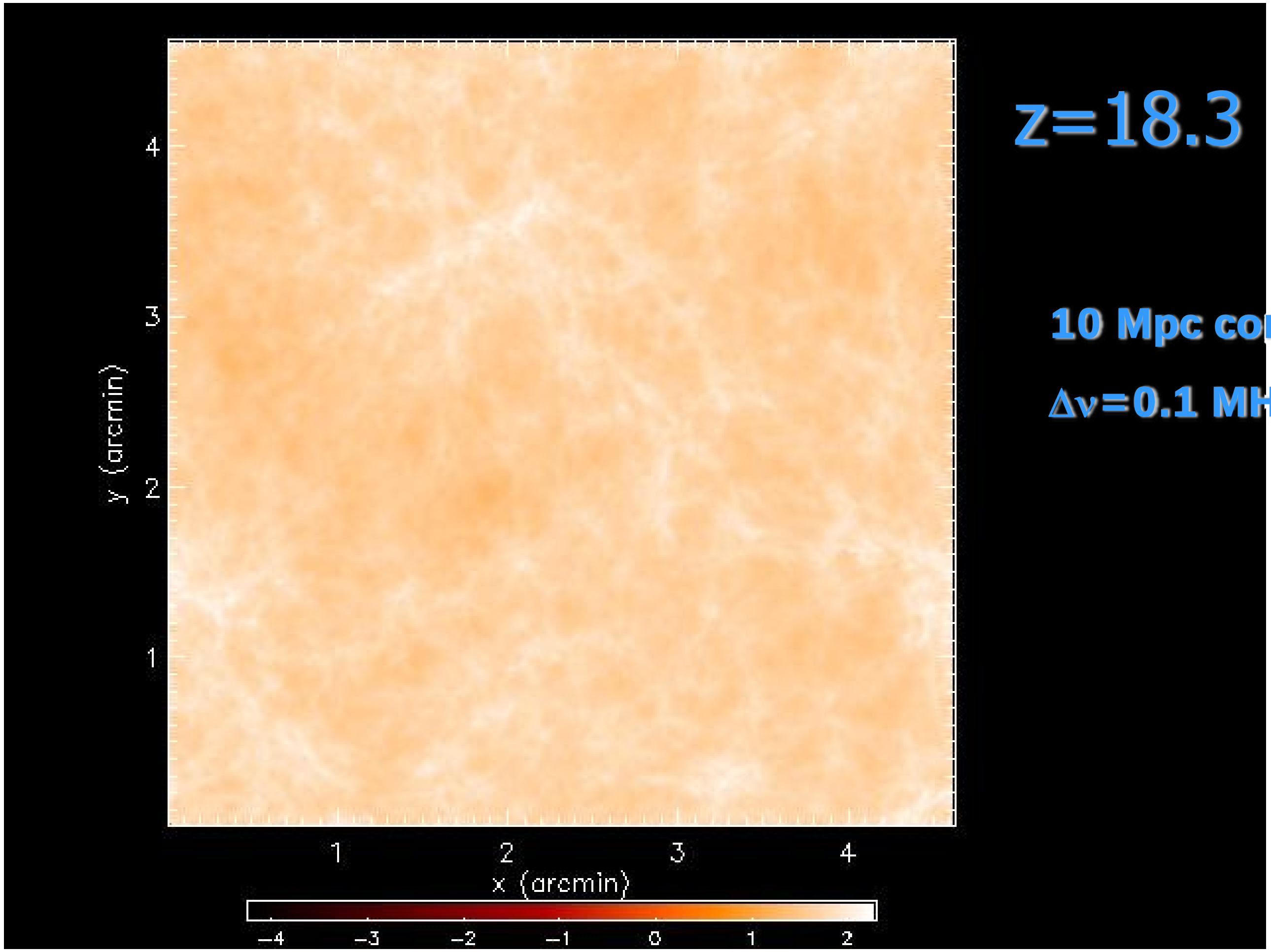
z~140 Thermal decoupling btw CMB & baryon. adiabatic cooling of IGM. $T_K < T_{CMB}$ abs. line

재이온화시기



Spin T-evolution by X-rays from SNe, adiabatic compression, structure formation shocks

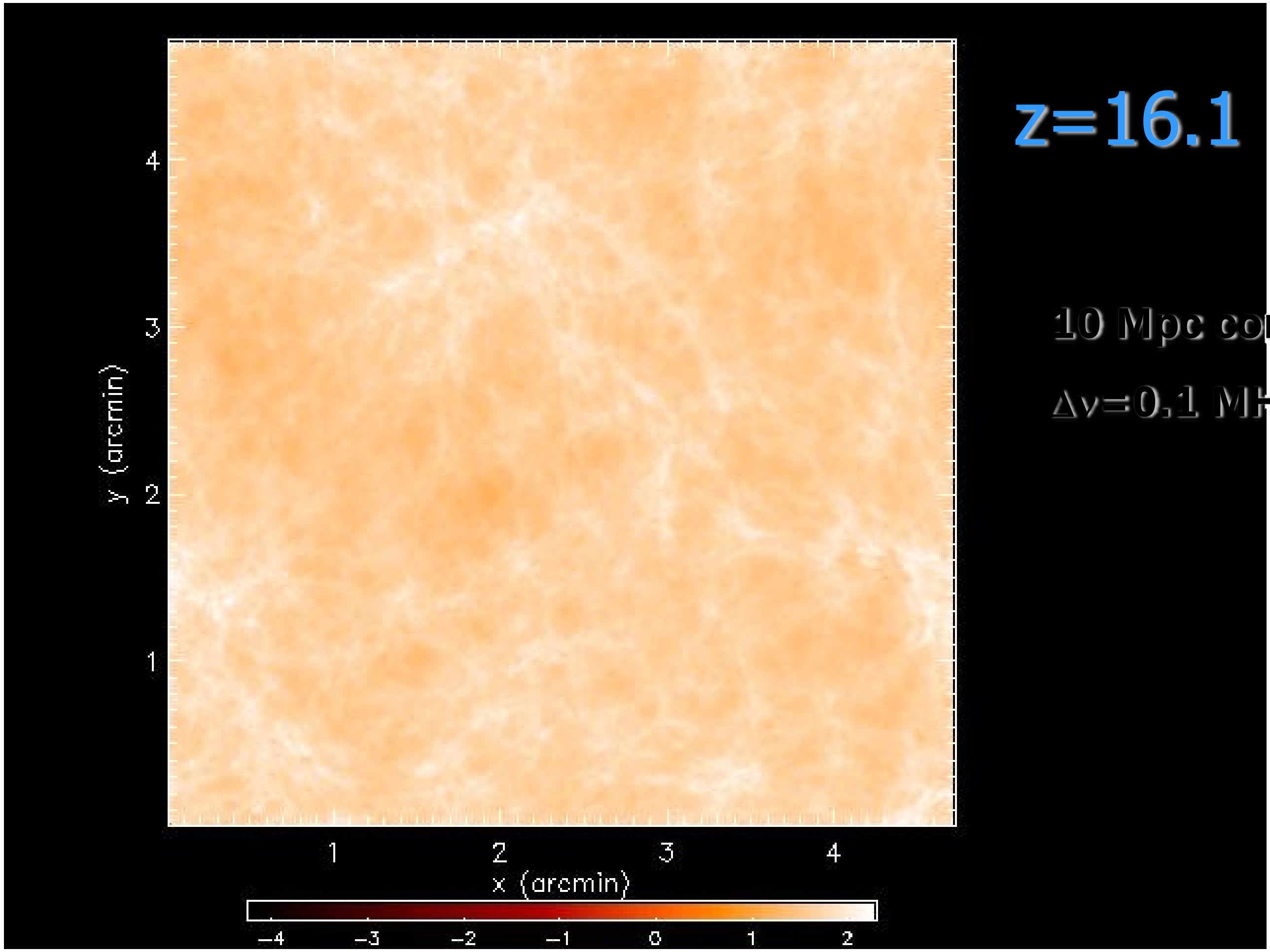
21 cm Observations: Emission



brightness temperature of 21cm

Furlanetto et al. (2003)

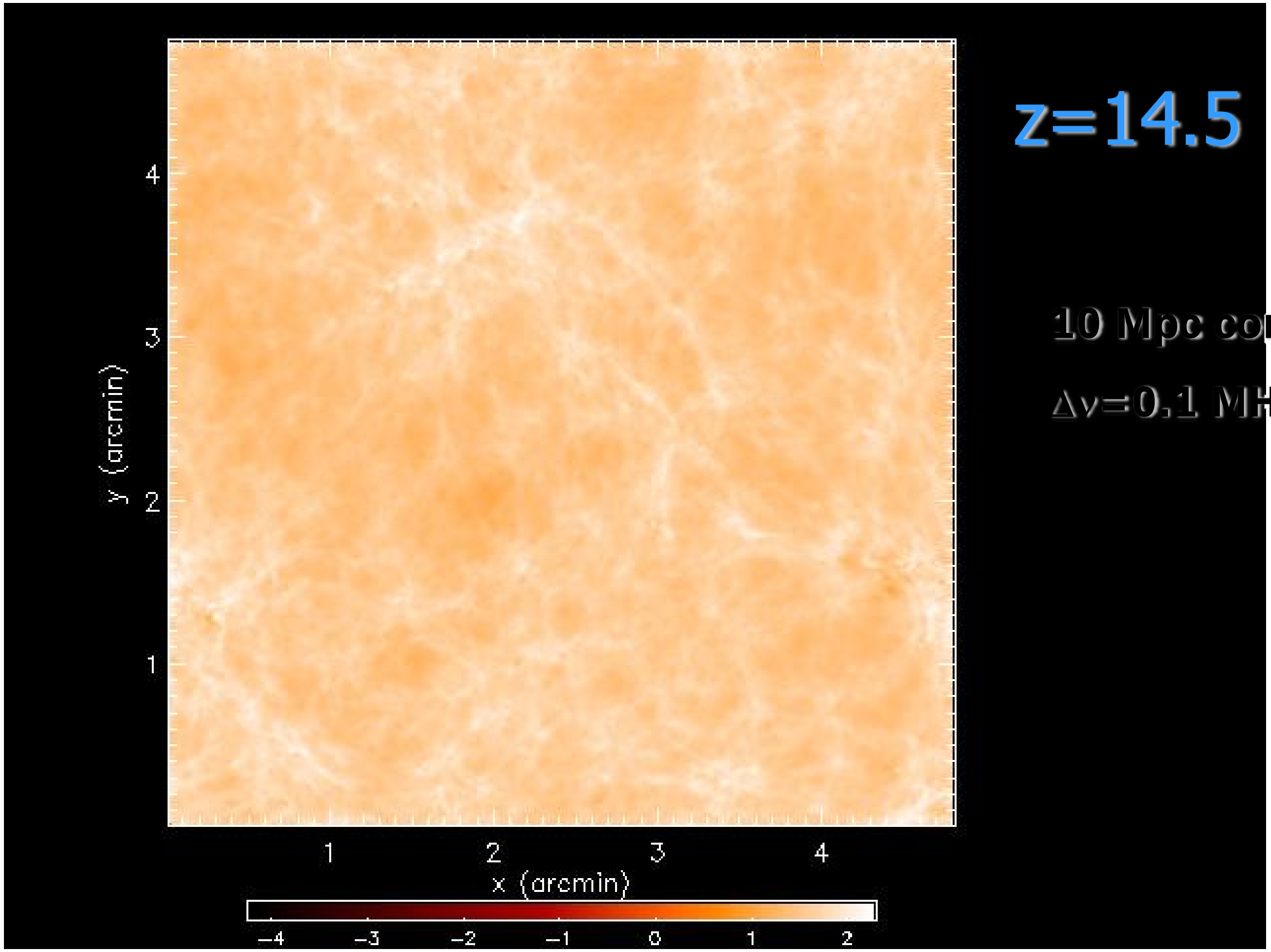
21 cm Observations: Emission



10 Mpc comoving

Δν=0.1 MHz

Furlanetto et al. (2003)

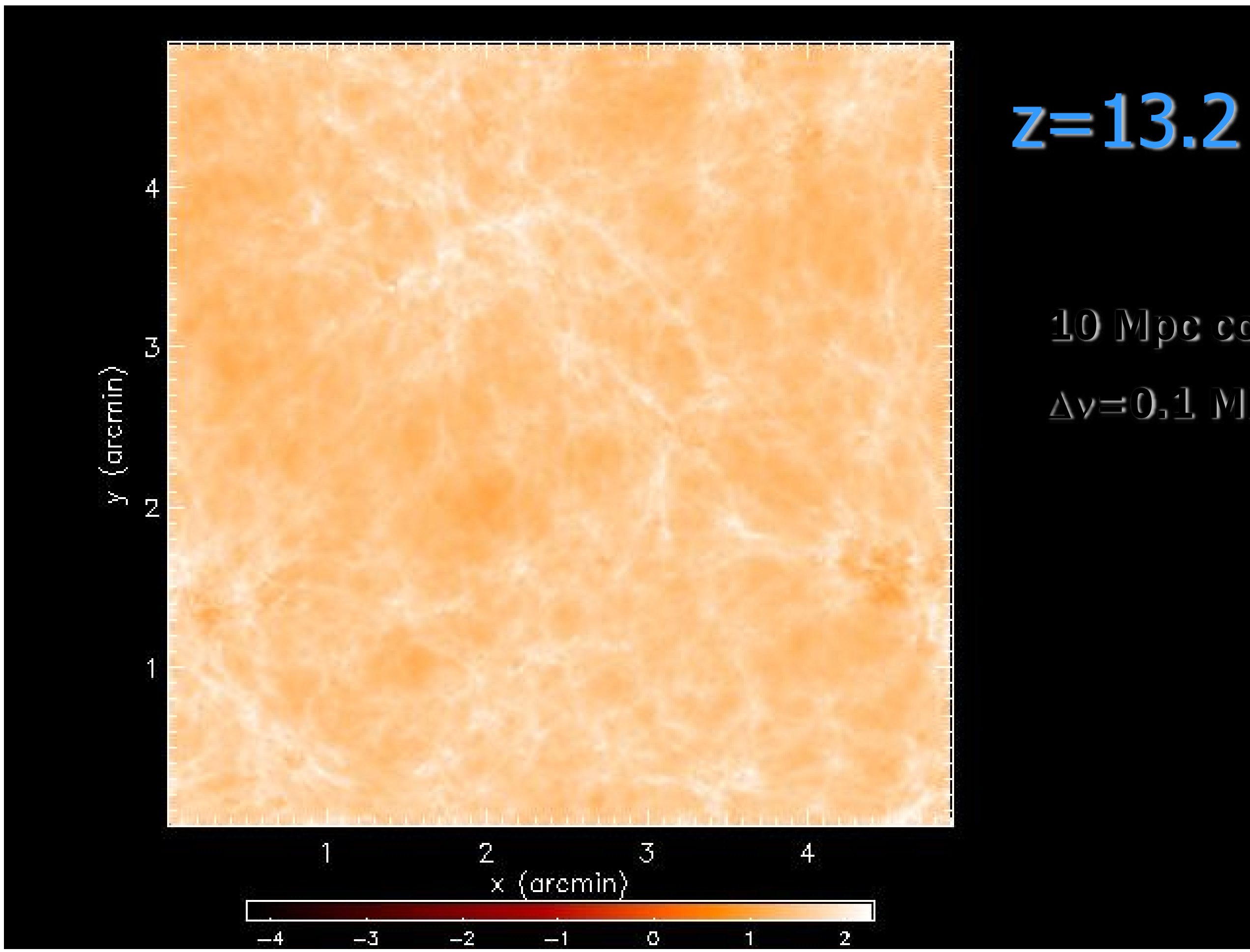


z=14.5

10 Mpc comoving

$\Delta\nu$=0.1 MHz

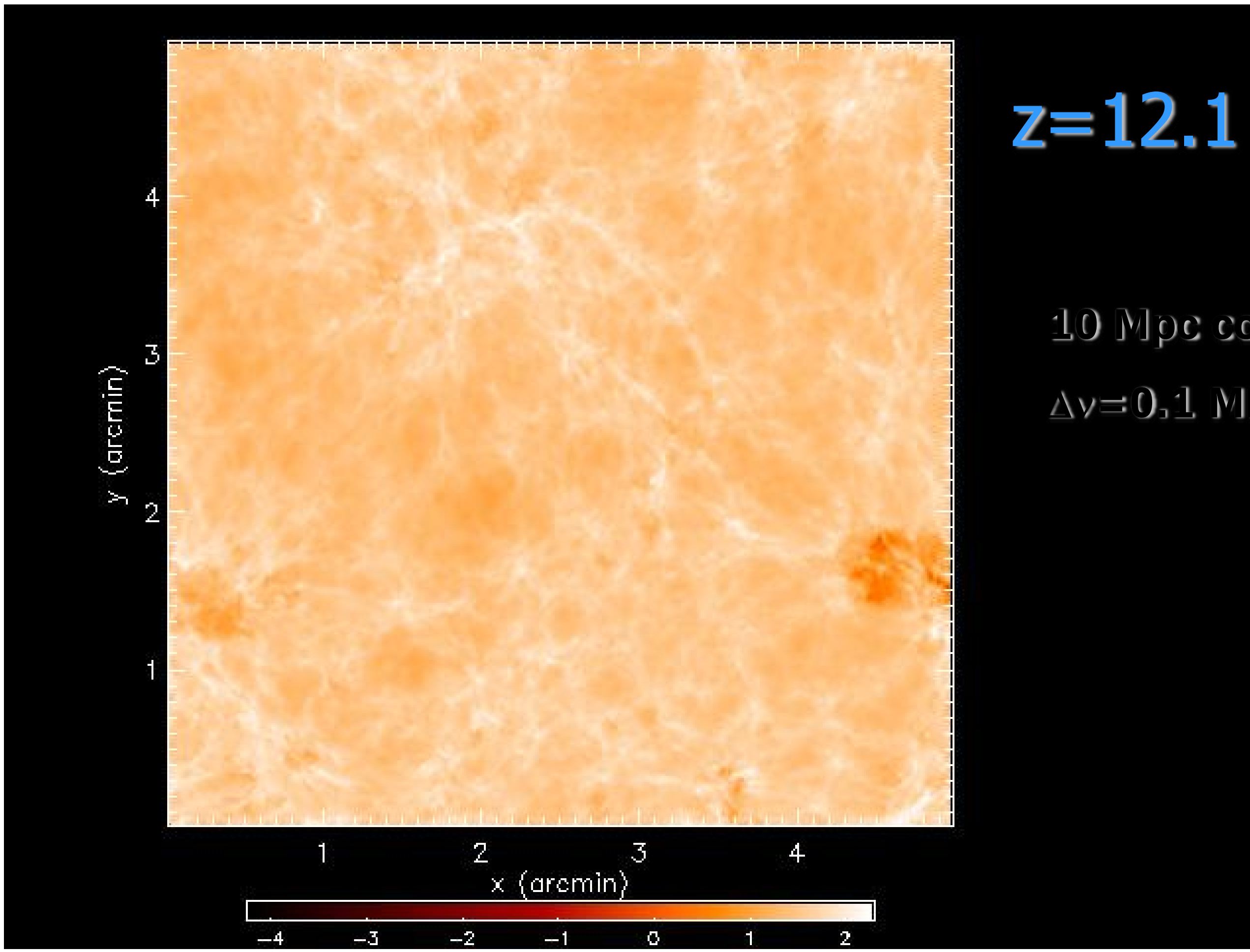
Furlanetto et al. (2003)



10 Mpc comoving

$\Delta\nu$=0.1 MHz

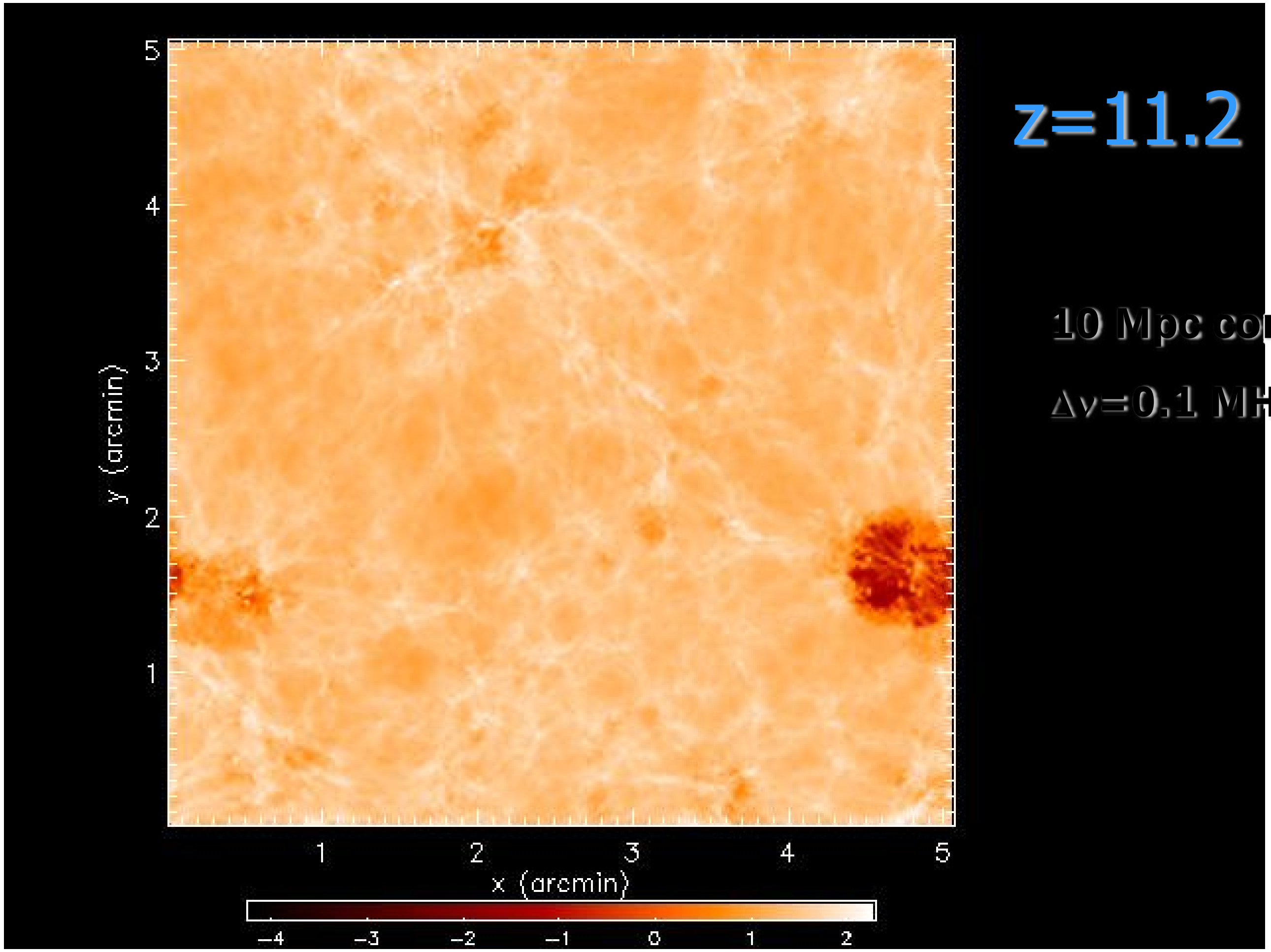
Furlanetto et al. (2003)



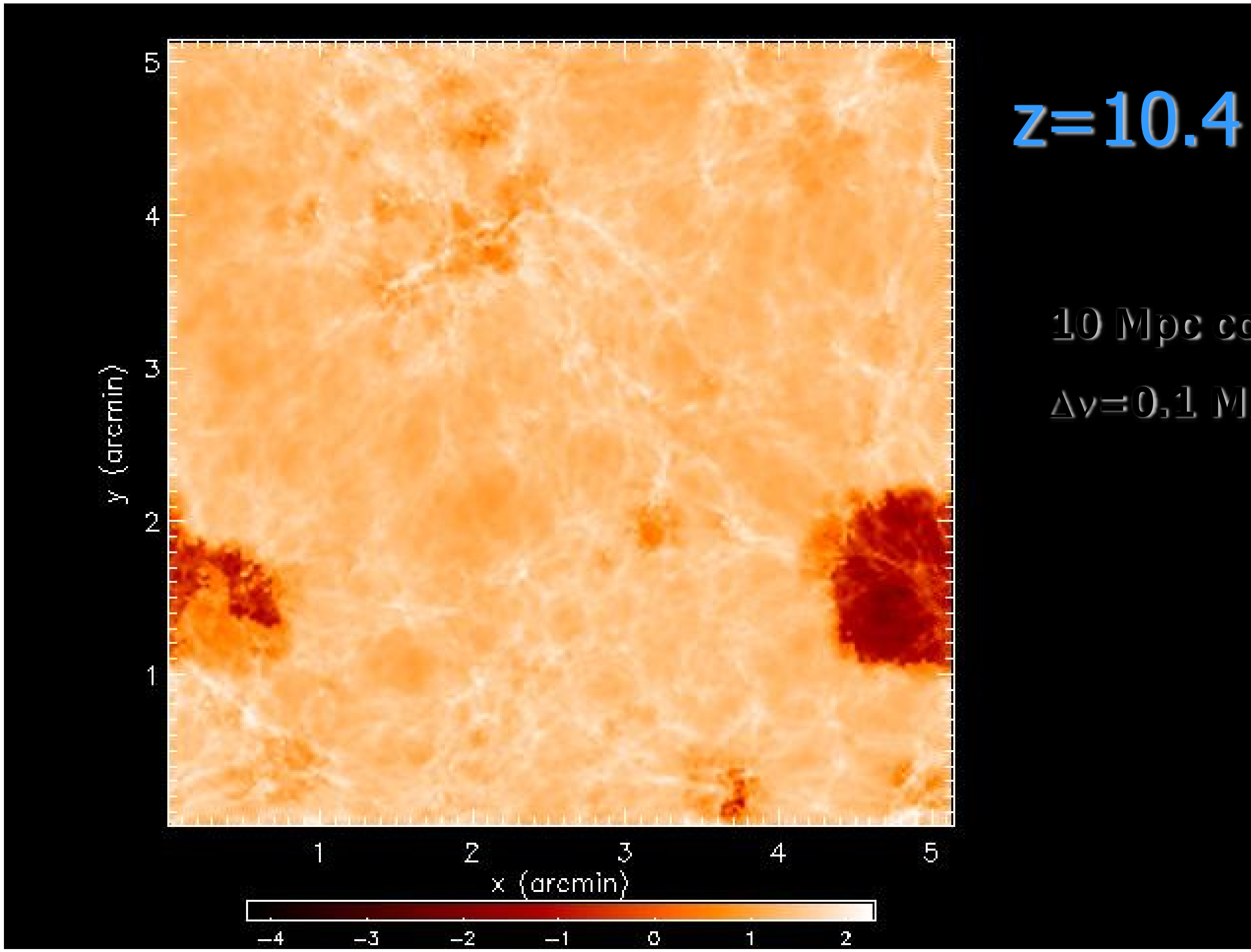
10 Mpc comoving

$\Delta\nu$=0.1 MHz

Furlanetto et al. (2003)



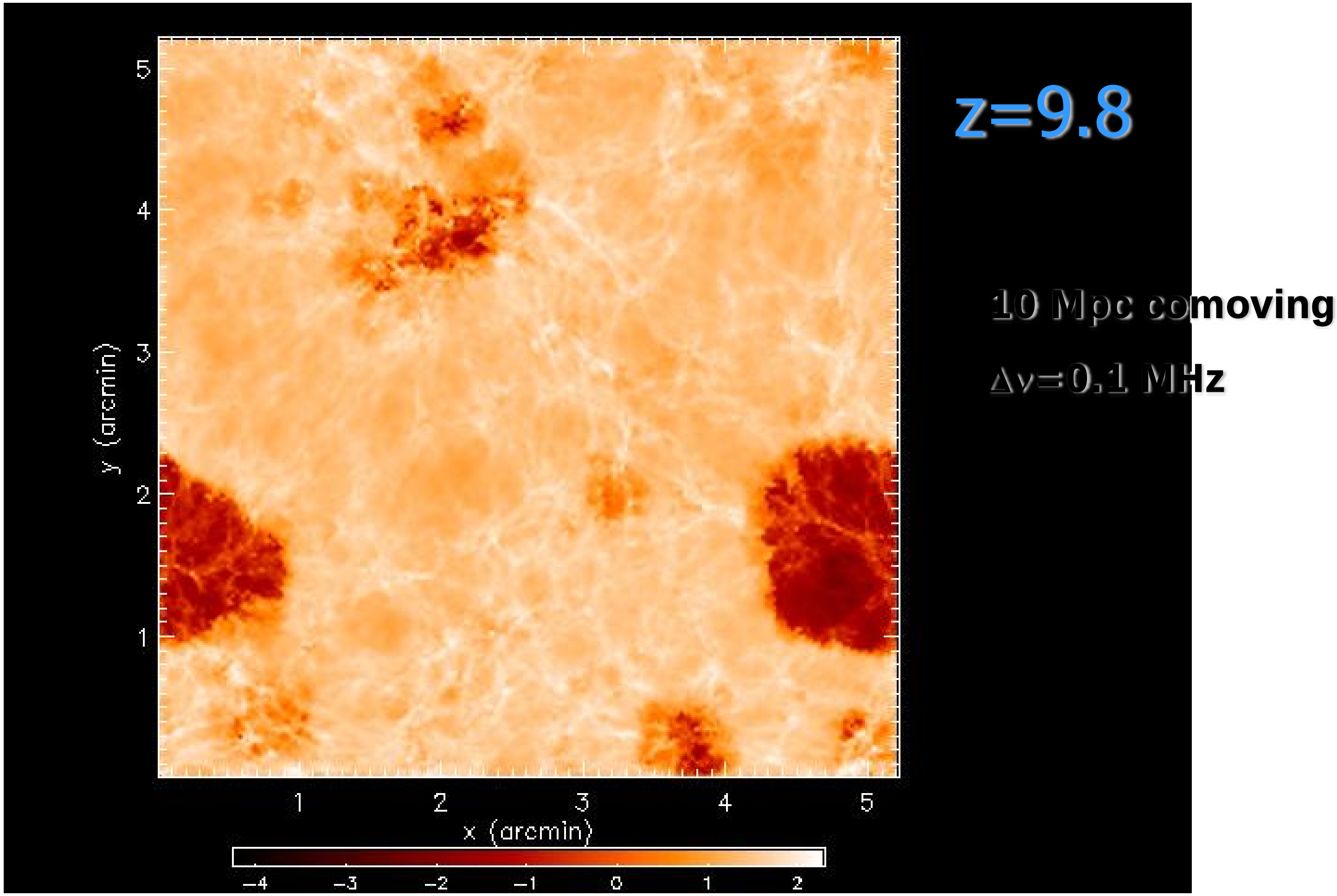
Furlanetto et al. (2003)



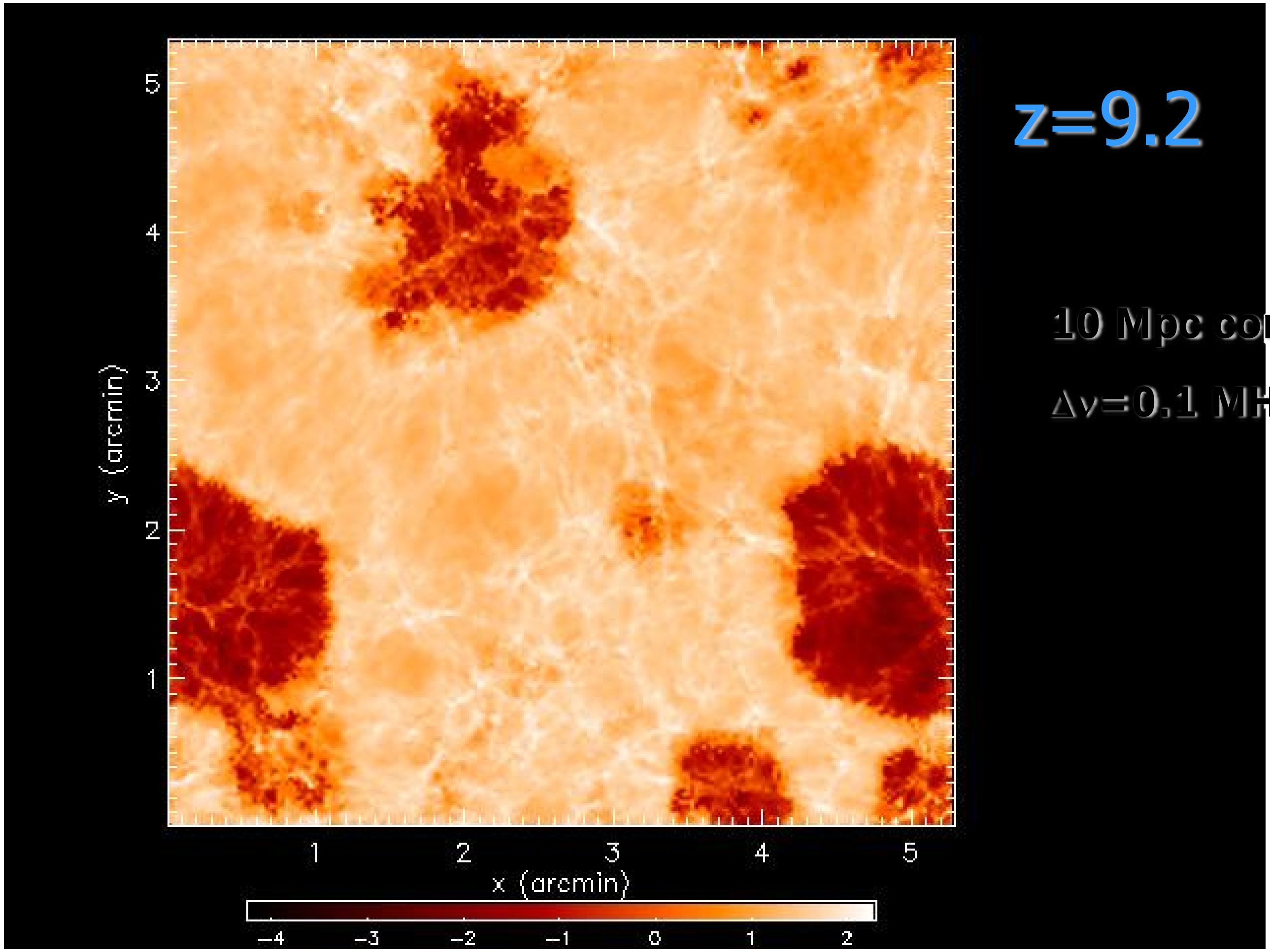
10 Mpc comoving

$\Delta\nu$=0.1 MHz

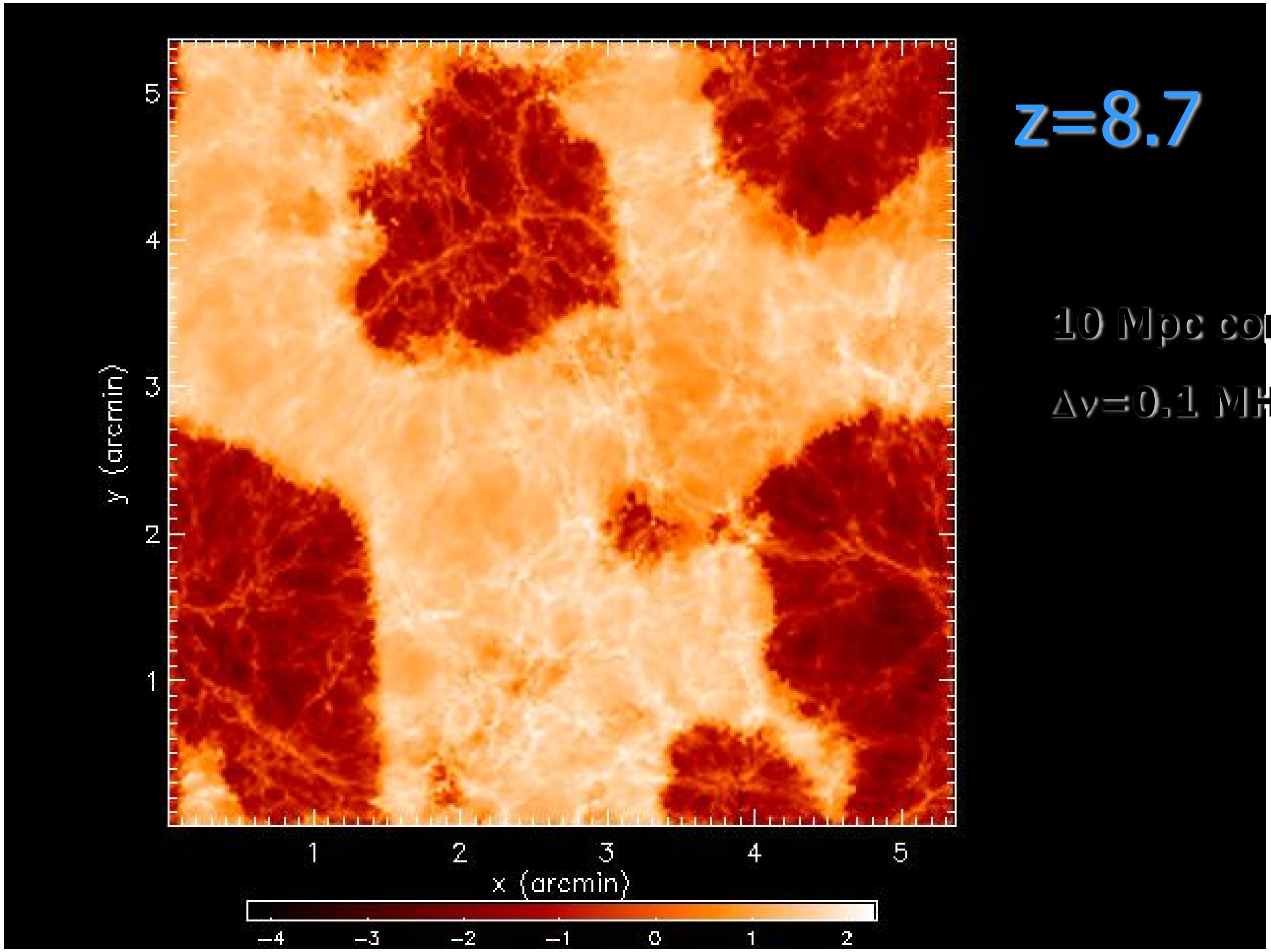
Furlanetto et al. (2003)



Furlanetto et al. (2003)



Furlanetto et al. (2003)

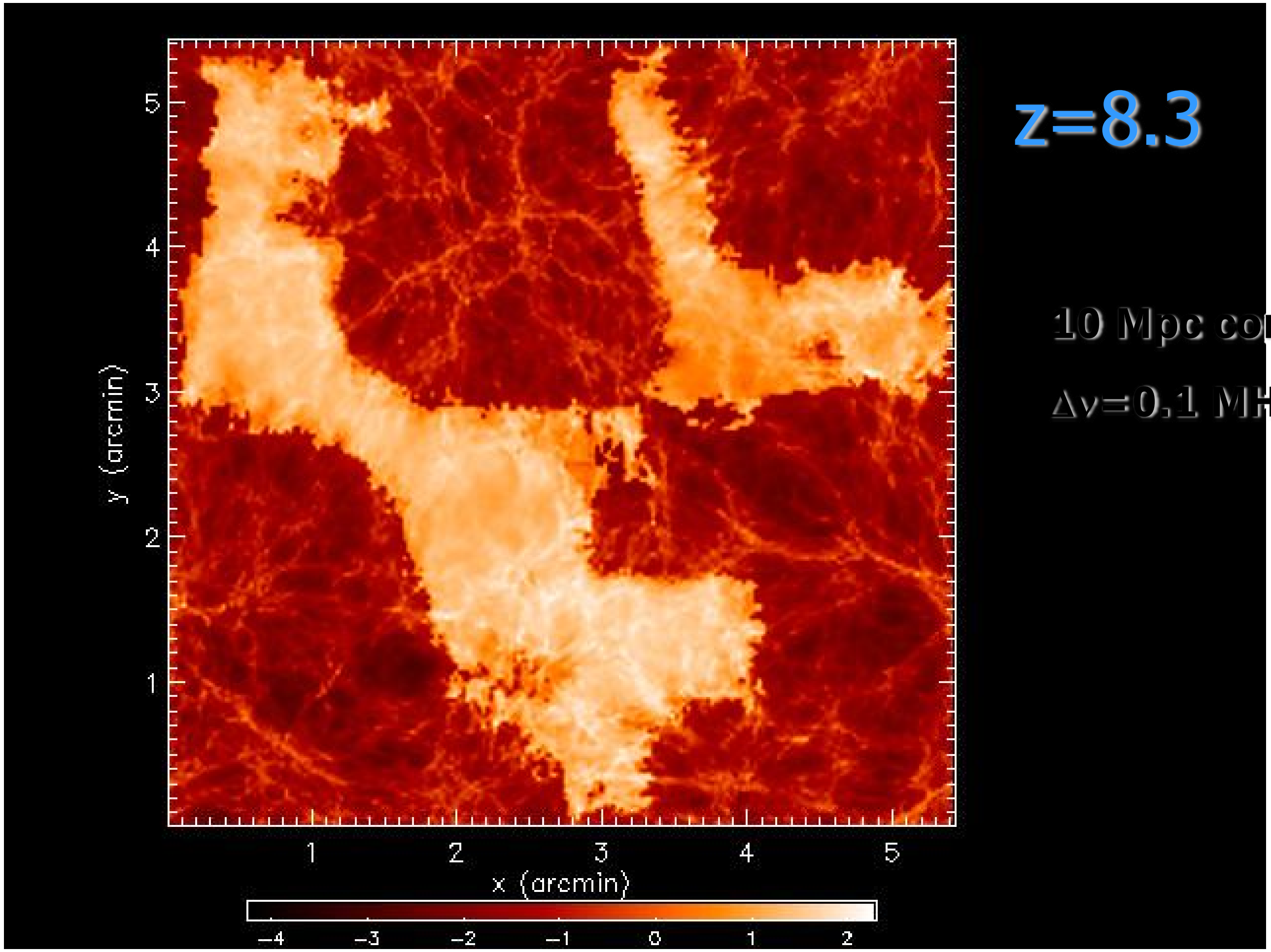


z=8.7

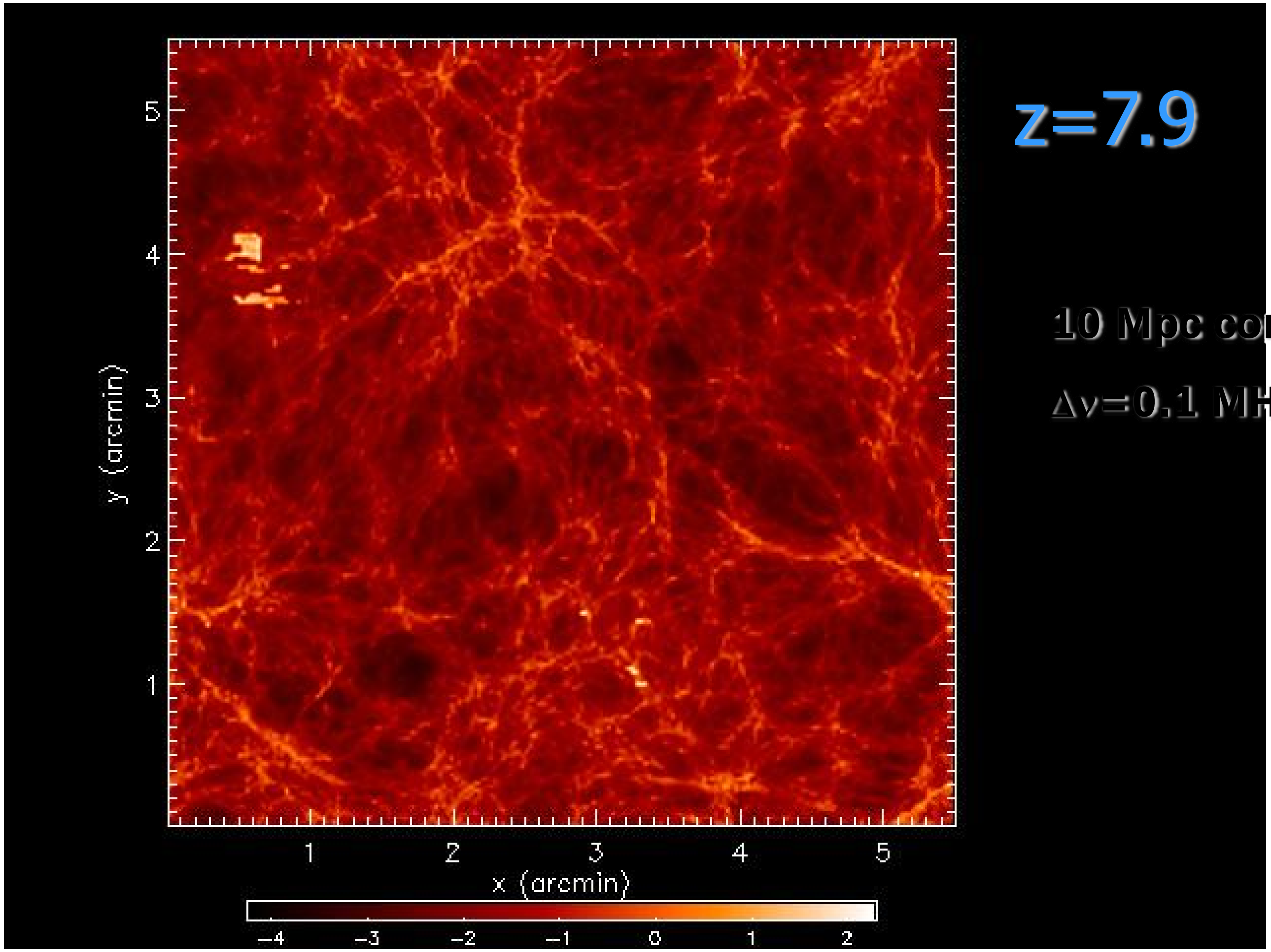
10 Mpc comoving

$\Delta\nu$=0.1 MHz

Furlanetto et al. (2003)



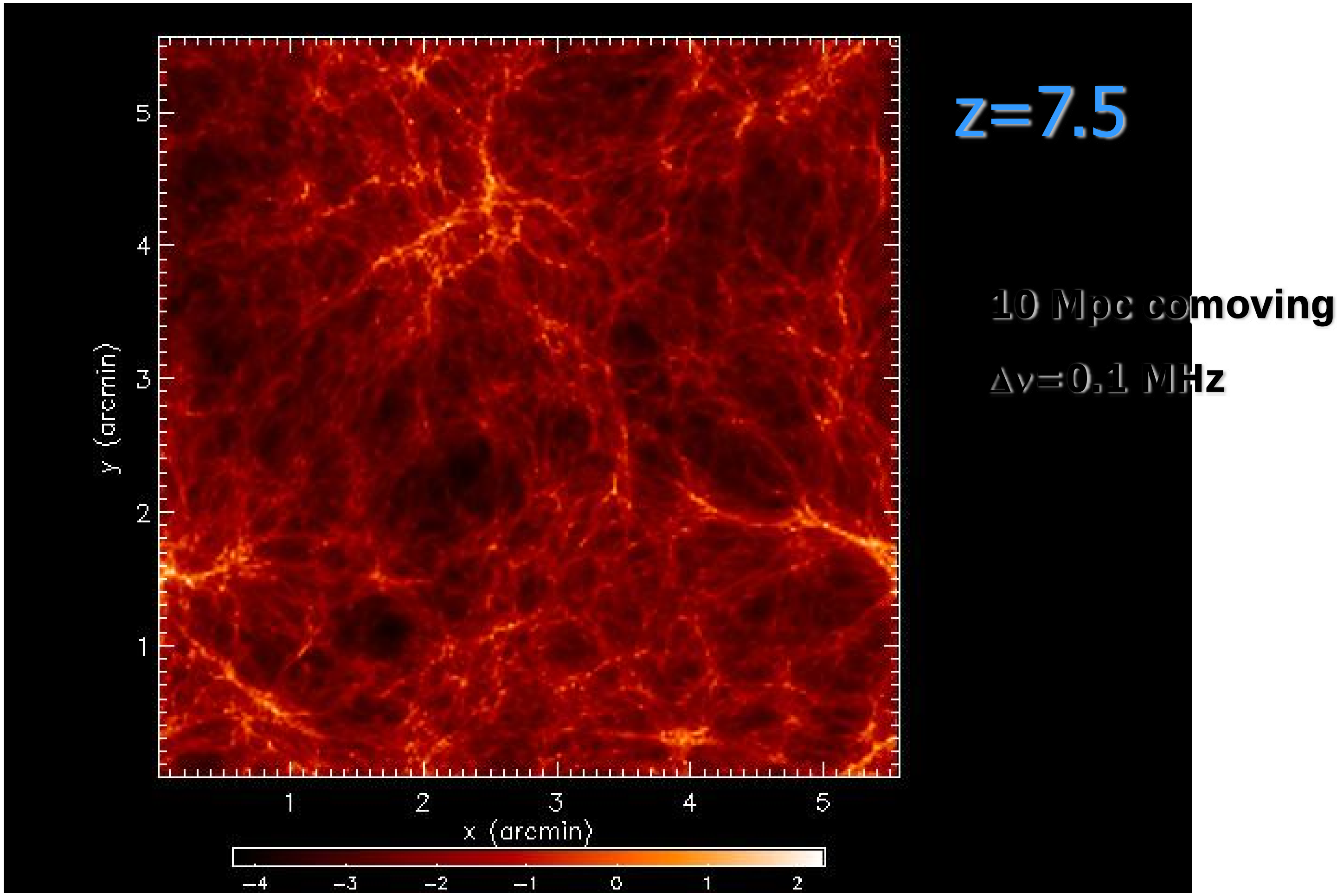
Furlanetto et al. (2003)



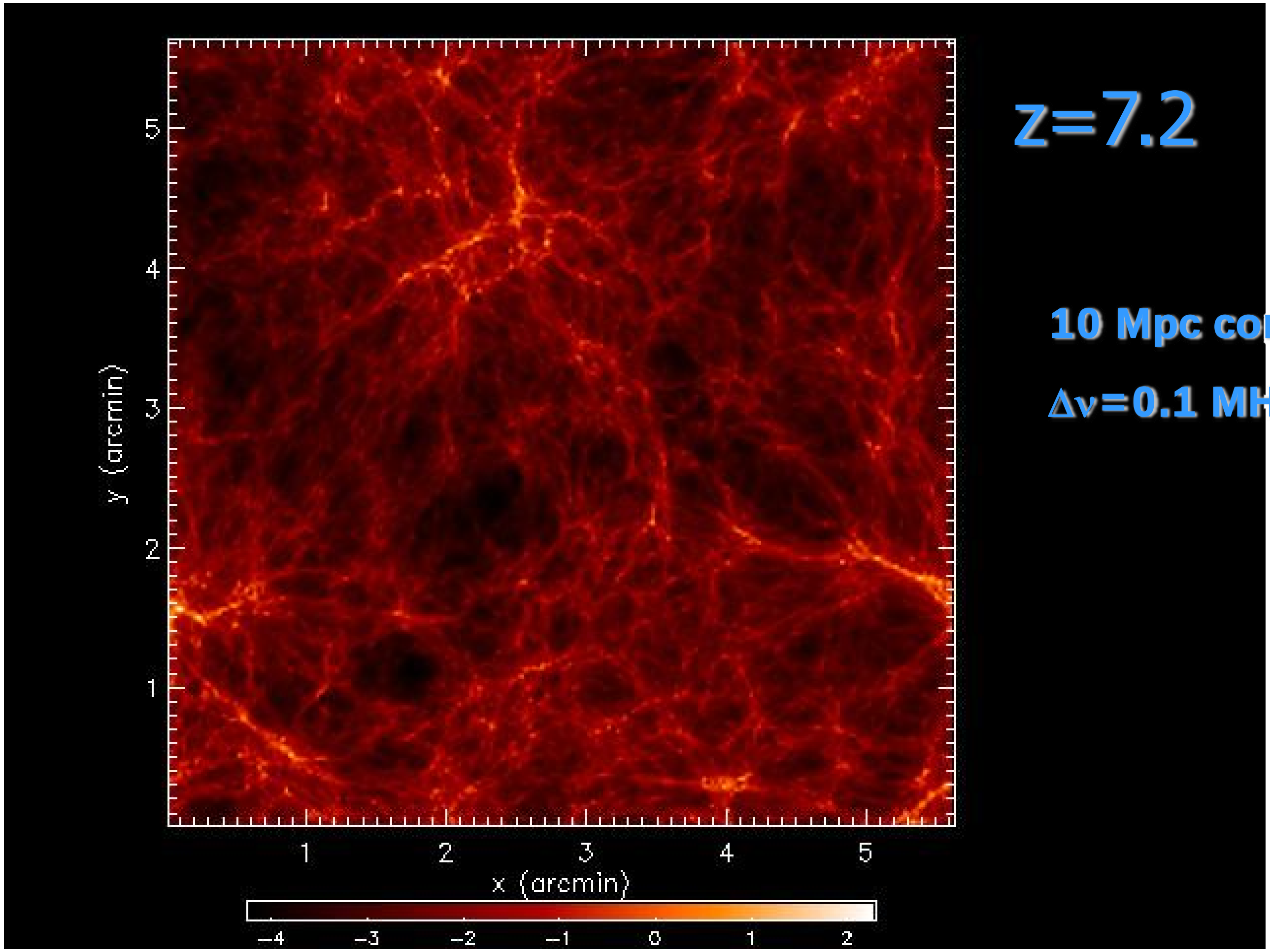
10 Mpc comoving

Δν=0.1 MHz

Furlanetto et al. (2003)



Furlanetto et al. (2003)

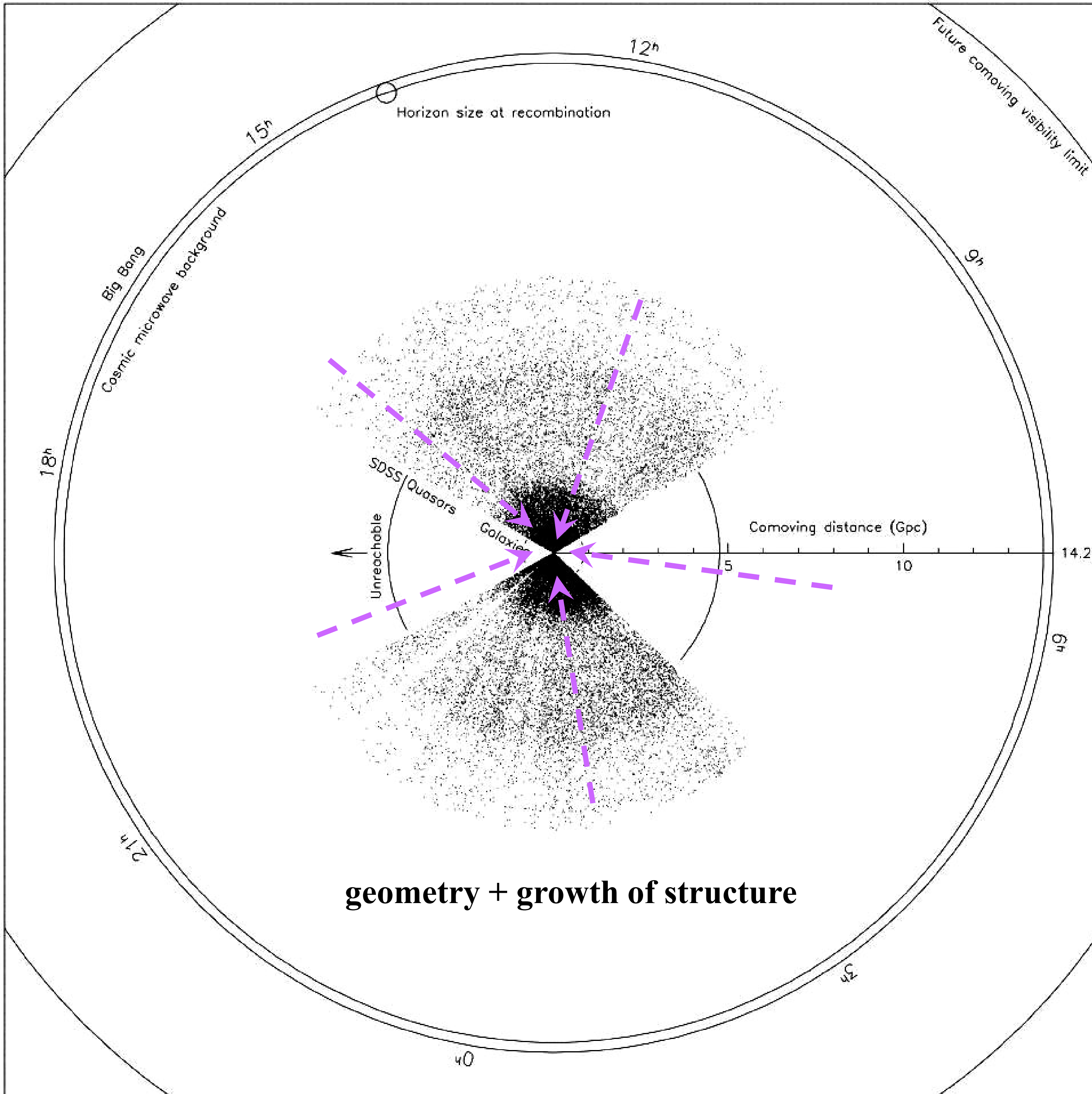


Furlanetto et al. (2003)

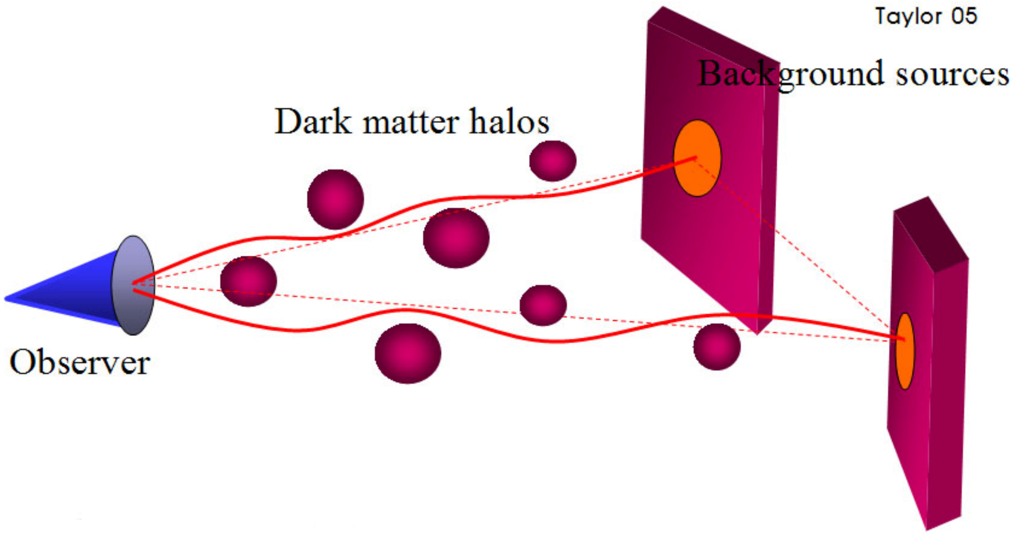
Gravitational Lensing:
Strong & Weak

Only projected mass along the line of sight

But tomography possible

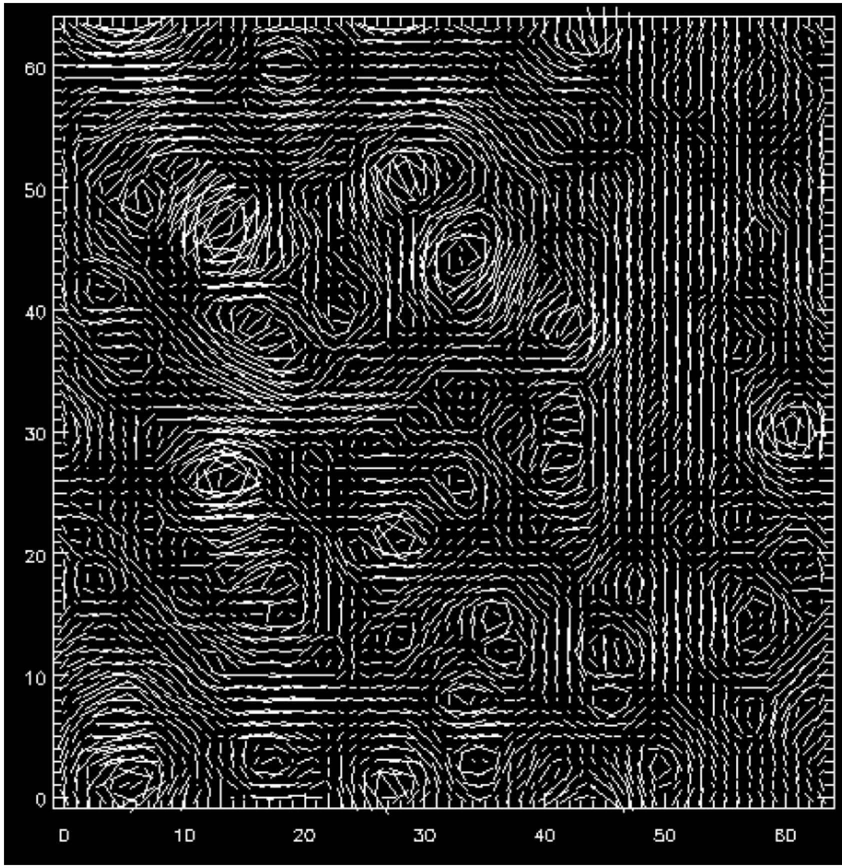


Weak lensing



Mass fluctuations along the line of sight
=> Coherent distortions in the observed shapes of background galaxies

Jain, Seljak & White (2000)



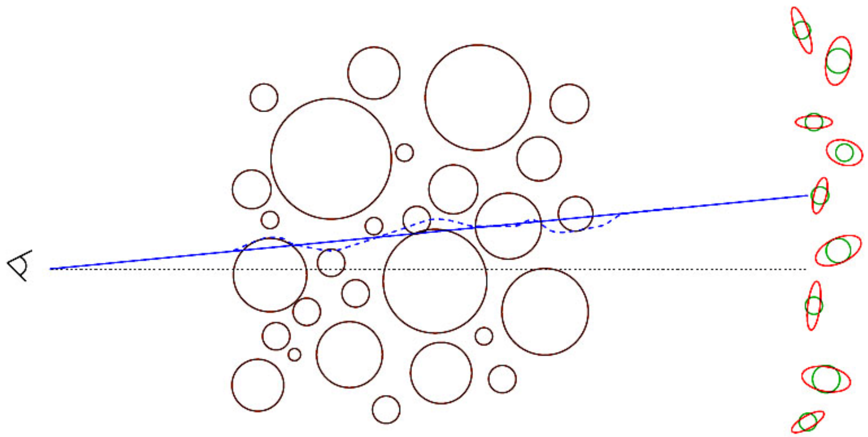
Shear map expected in SCDM

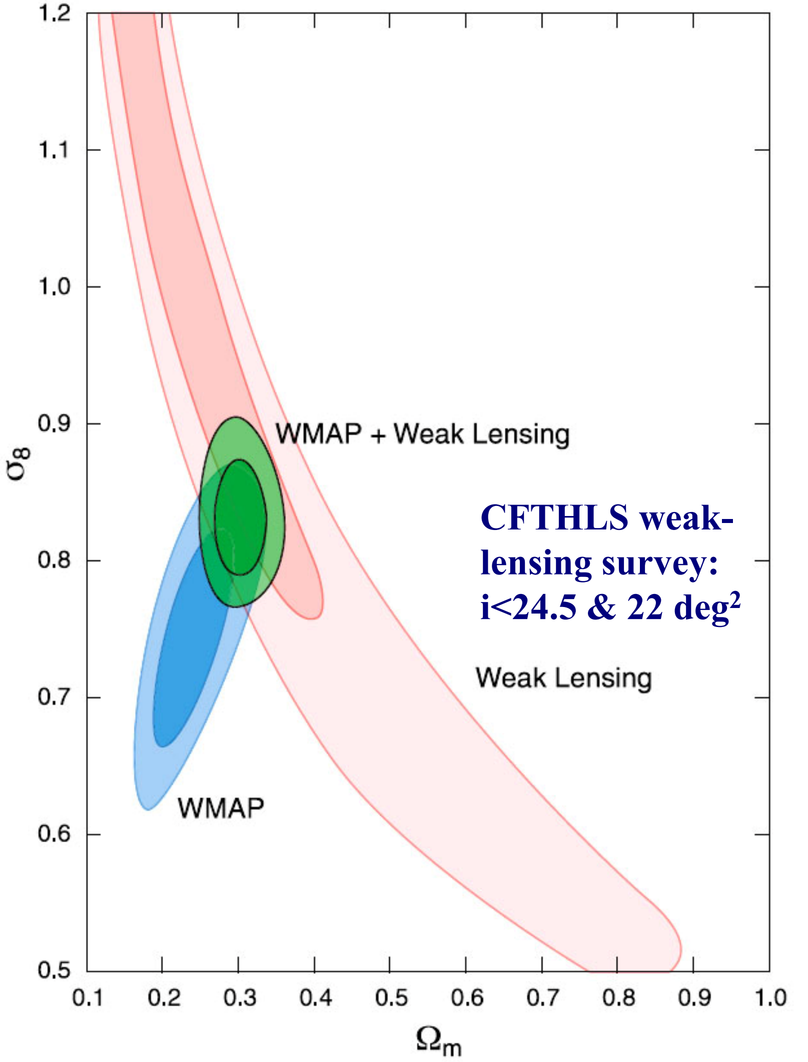
- **Statistical measure of shear pattern, ~1% distortion.**
- **Radial distances, r(z), depends on geometry of Universe.**
- **Dark Matter pattern & growth depends cosmological parameters.**

2D weak lensing : shear-shear correlation, average over redshift

2.5D : 2D in slices & cross-correlations (tomography)

3D : shear field at points in 3D



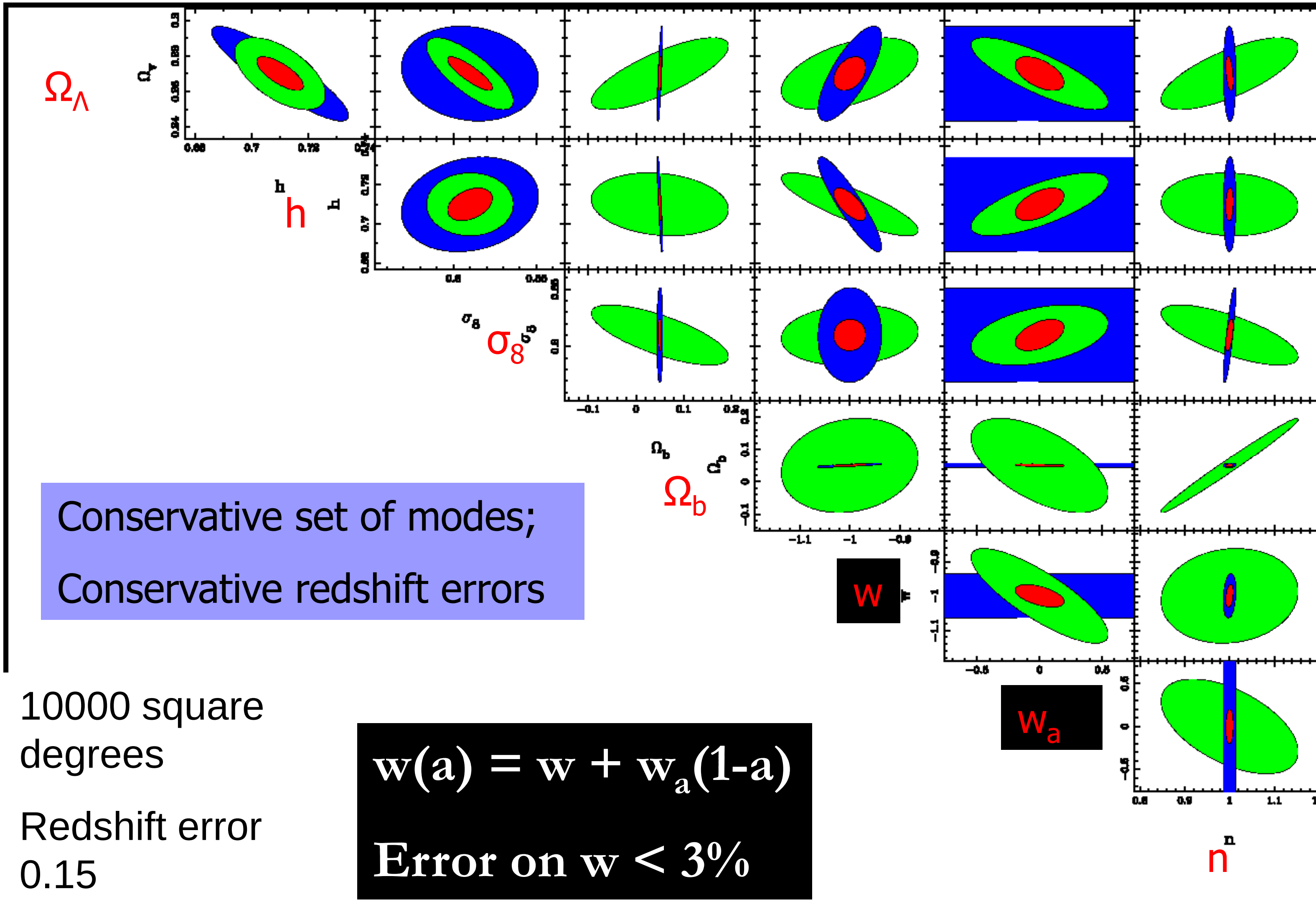


CFTHLS weak-lensing survey: i<24.5 & 22 deg²

FIG. 7.—Prediction for the mass fluctuations measured by the CFTHLS weak-lensing survey from the ΛCDM model fit to the *WMAP* data only. The blue, red, and green contours show the joint 2D marginalized 68% and 95% confidence limits in the (σ_8, Ω_m) plane for *WMAP* only, CFHTLS only and *WMAP* + CFHTLS, respectively, for the power-law ΛCDM models. All constraints come from assuming the same priors on input parameters, with the additional marginalization over z_s in the weak lensing analysis, using a top-hat prior of $0.613 < z_s < 0.721$. While lensing data favors higher values of $\sigma_8 \simeq 0.8$–1.0 (see § 4.1.7), X-ray cluster studies favor lower values of $\sigma_8 \simeq 0.7$–0.8 (see § 4.1.9).

Spergel (2007)

PS with darkCAM on VISTA 4m 2 sq deg FOV



Conservative set of modes;

Conservative redshift errors

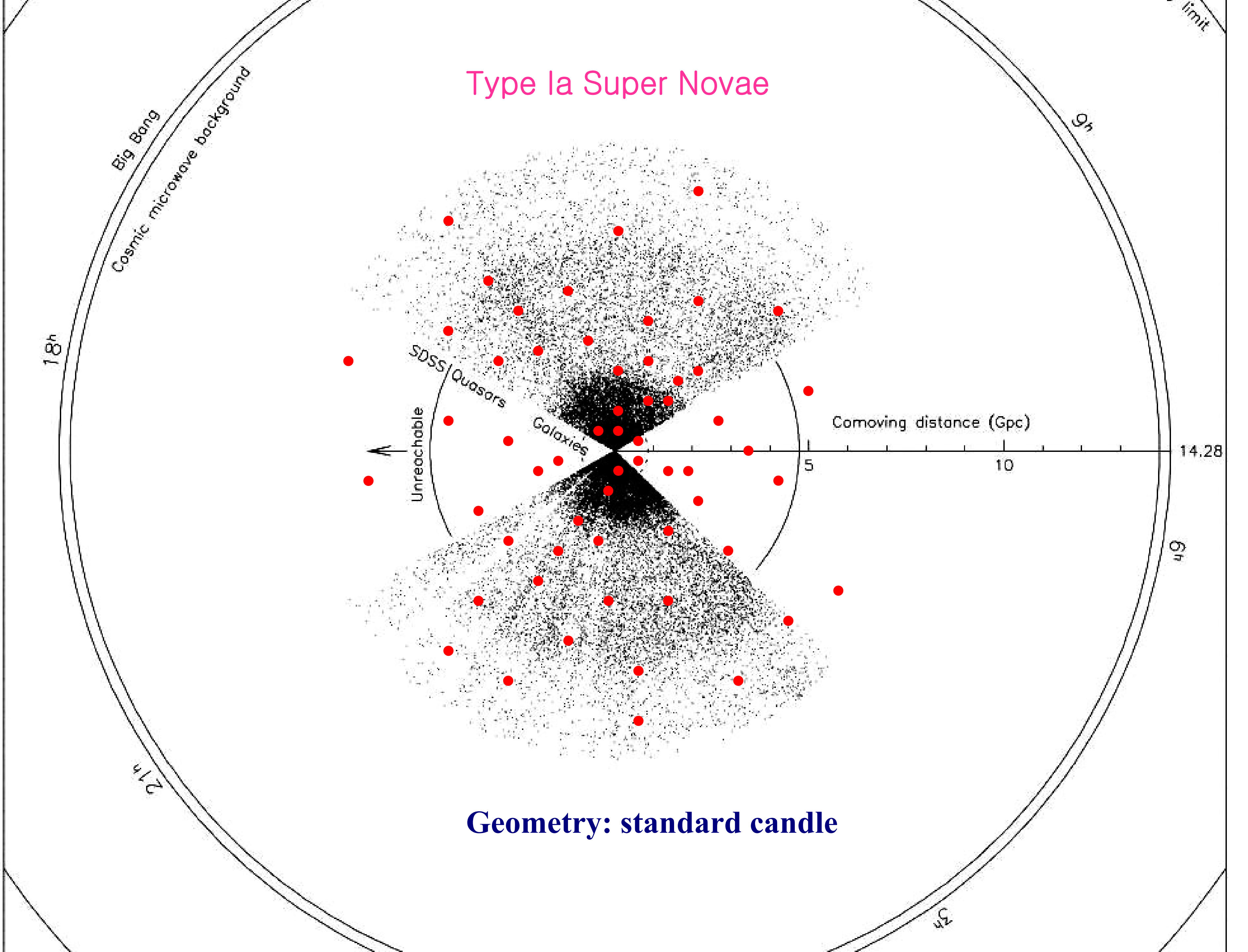
10000 square degrees

Redshift error 0.15

$w(a) = w + w_a(1\text{-}a)$

Error on w < 3%

Type Ia Super Novae

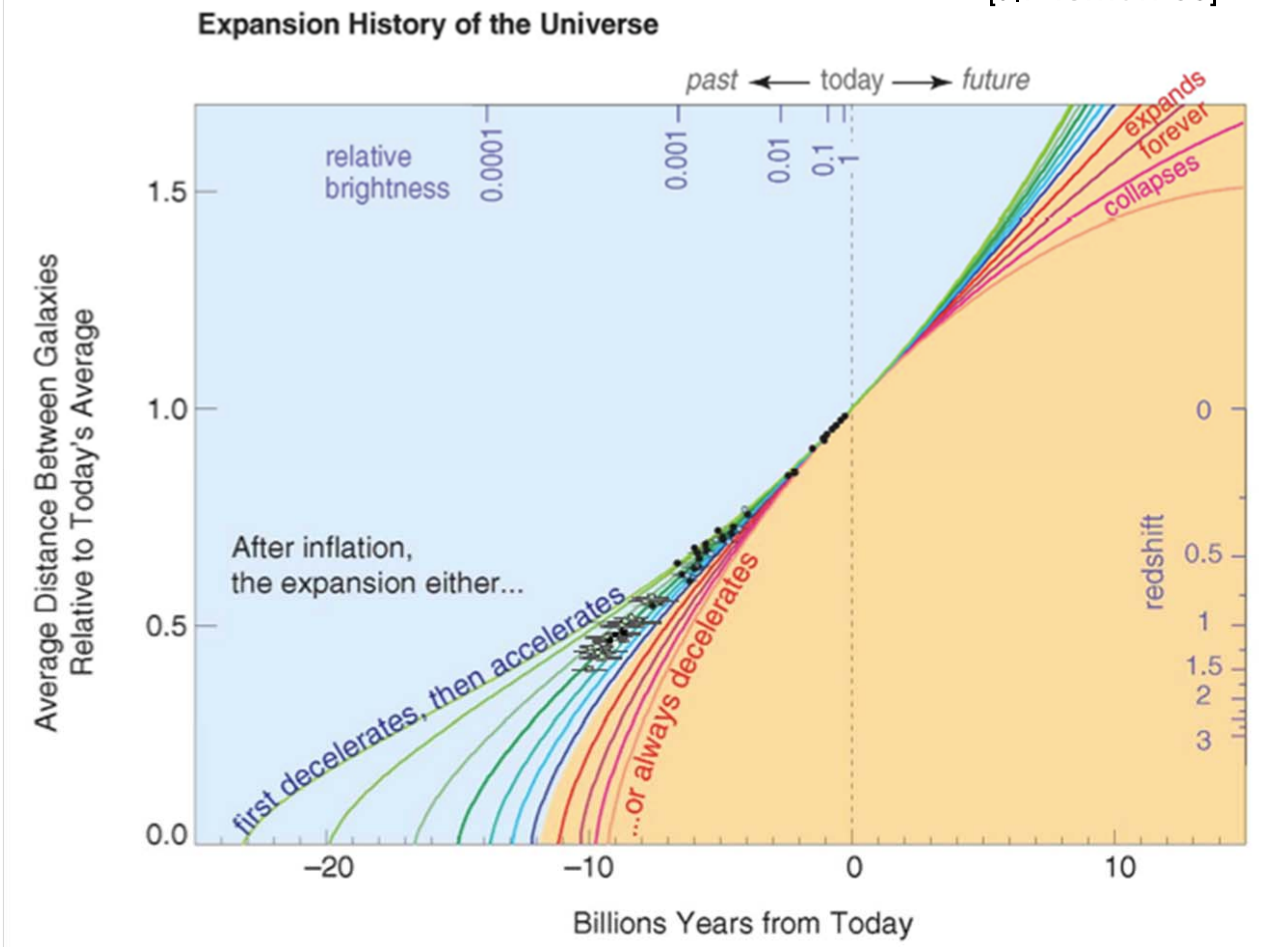


Geometry: standard candle

Nearby SN 1994D (Ia)

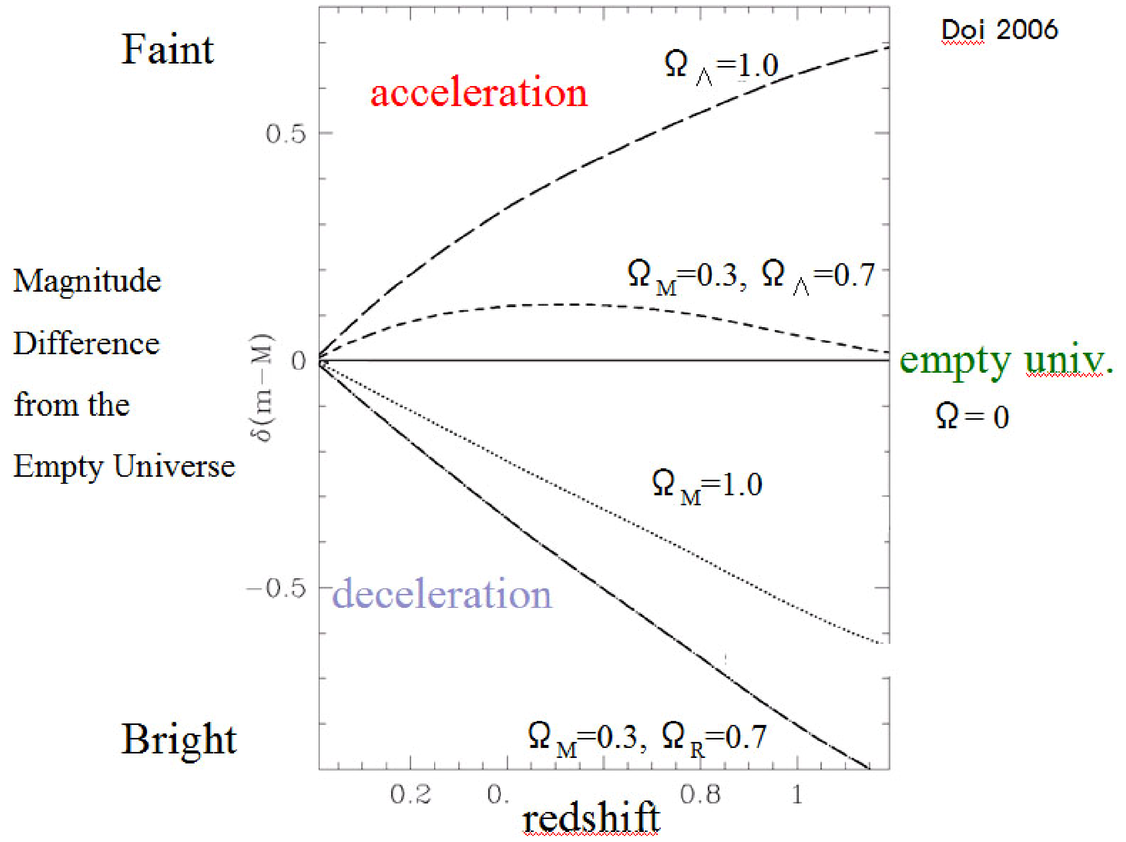
SNe Ia are thermonuclear explosions of C+O WD

[J.Frieman 05]



Expansion History of the Universe
past ← today → future
relative brightness
0.0001
0.001
0.01
0.1
1
expands forever
collapses
1.5
1.0
0.5
0.0
Average Distance Between Galaxies Relative to Today's Average
After inflation, the expansion either...
first decelerates, then accelerates
...or always decelerates
0
0.5
1
1.5
2
3
redshift
−20
−10
0
10
Billions Years from Today

Ω, z dependence of apparent magnitude of a standard candle



$$m(z) - M_B = -5\log(H_0) + 25 + 5\log[H_0 D_L(z,\Omega_m,\Omega_{DE},w)] + K_{Bx} + A$$

$$d_L = cH_0^{-1}(1+z)\int_0^z dz[(1+z)^3(\Omega_M) + (1-\Omega_M)(1+z)^{3(1+w)}]^{-1/2}$$

Three steps of SN Ia finding

Wide-Field imaging

imaging with ~1months interval or "rolling"

→ find candidates

Spectroscopy

confirmation of SN spectrum（⇔AGN, variable stars）

SN type and redshift determination

follow-up photometry, color

light curve → luminosity

K correction

evaluation of dust extinction of host galaxy

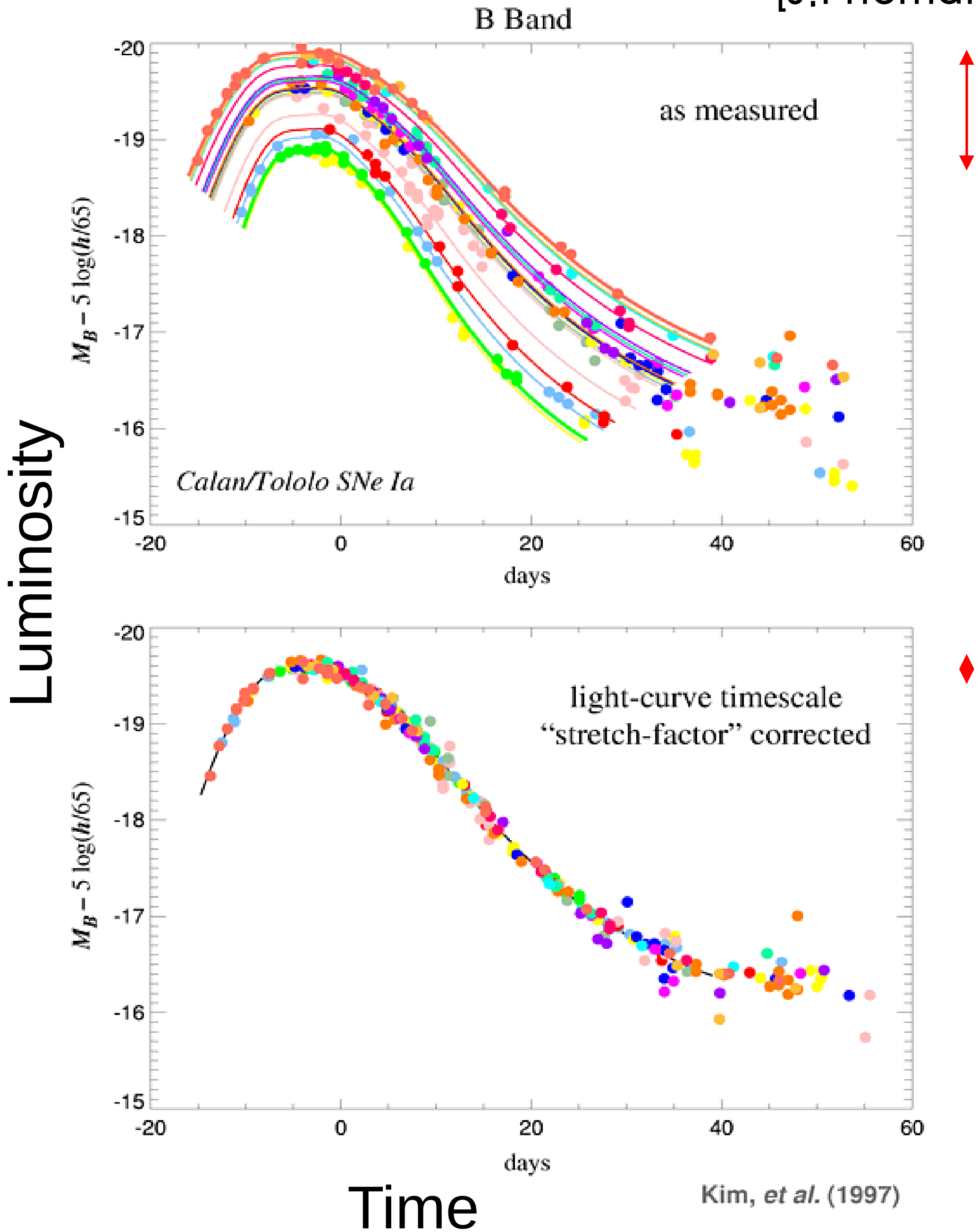
[J.Frieman 05]

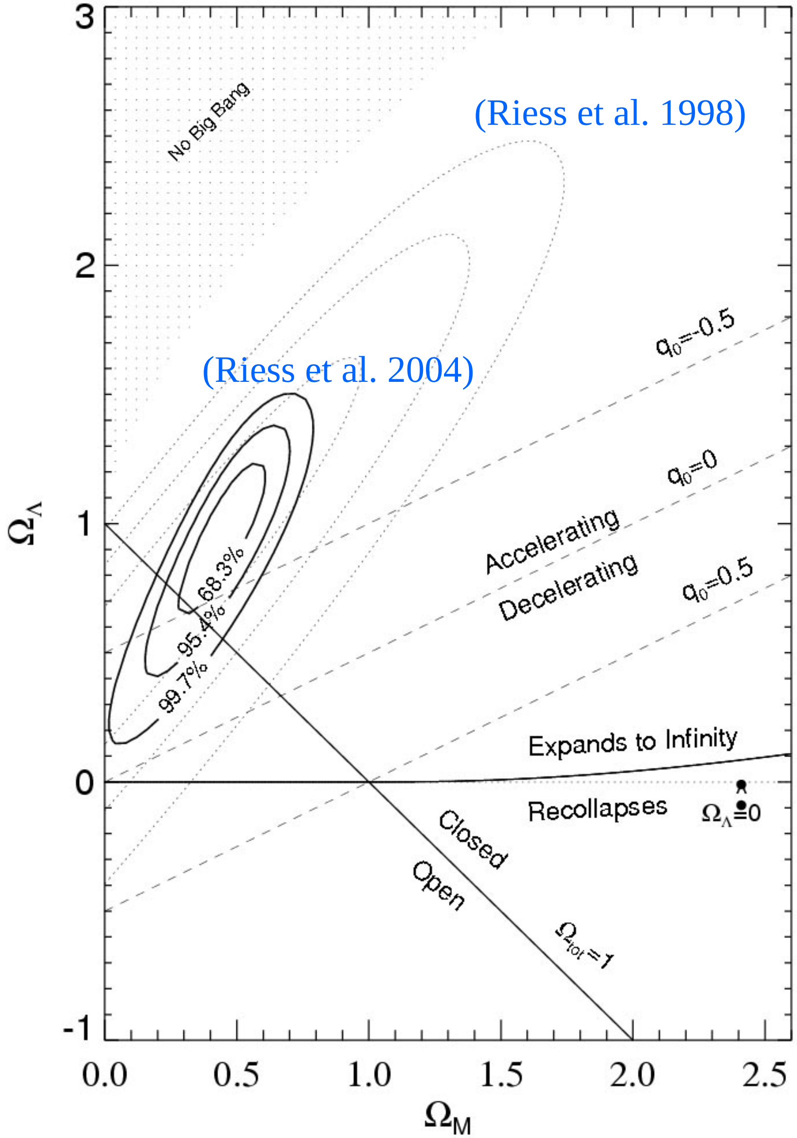
Type Ia SN
Peak Brightness
as calibrated
Standard Candle

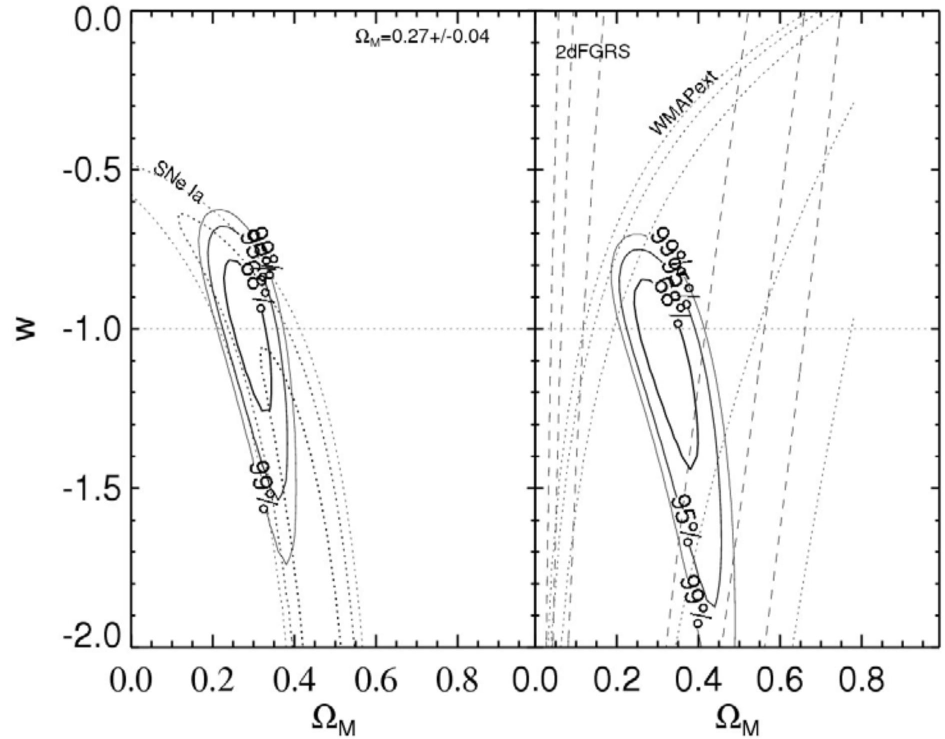
Peak brightness
correlates with
decline rate

After correction,
σ~ 0.15 mag

(~7% distance error)







Matter contents

$\Omega_m = 0.29 \pm^{0.05}_{0.03}$, $\Omega_\Lambda = 0.71$ (if flat U)

Dark energy

$w = -1.02 \pm^{0.13}_{0.19}$, $w < -0.76$ at 95% (if $P = w\rho c^2$)

Complementarity with CMB:

SN Ia survey

Advantages:

small dispersion in peak brightness (standardized candles)
single objects (simpler than galaxies)
can be observed over wide redshift range (bright)

Challenges/Systematic concerns:

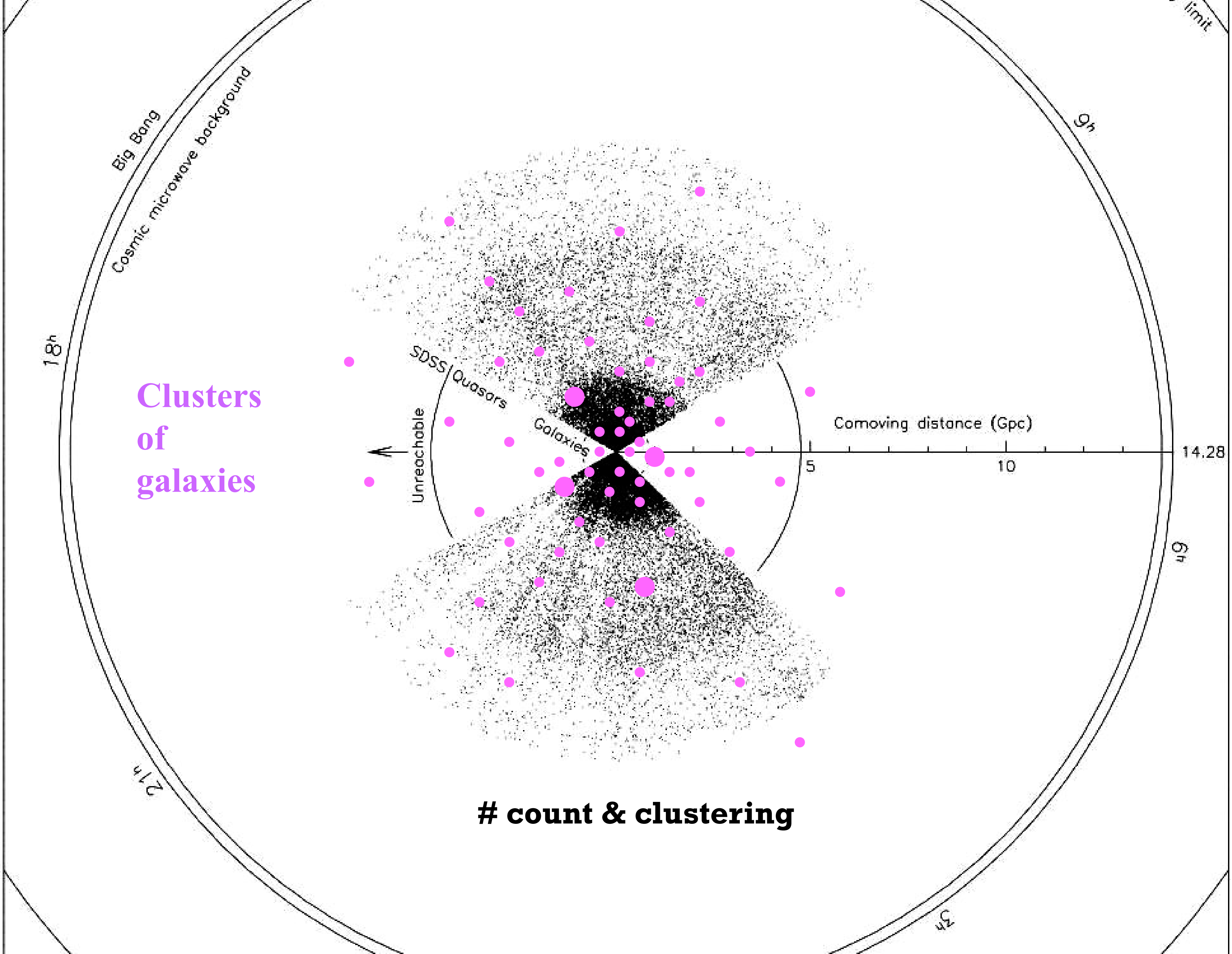
dust extinction (in or beyond host galaxy)
- chemical composition variations/evolution
- evolution of progenitor population
- photometric calibration, stability & host galaxy subtraction
- Malmquist bias
- environmental differences
- K correction uncertainties

SNIa rate is larger for late-type or star-forming hosts?

SNIa fainter for early type Host (e.g. Reindl et al. 2005) , but roughly canceled by host extinction?

Future:

w_0 to ~5% & dw/dz to ~20%
1~2% relative distance measurements in Δz~0.1 bins
>3000 SN Ia over z=0.3~1.7 + low-z sample

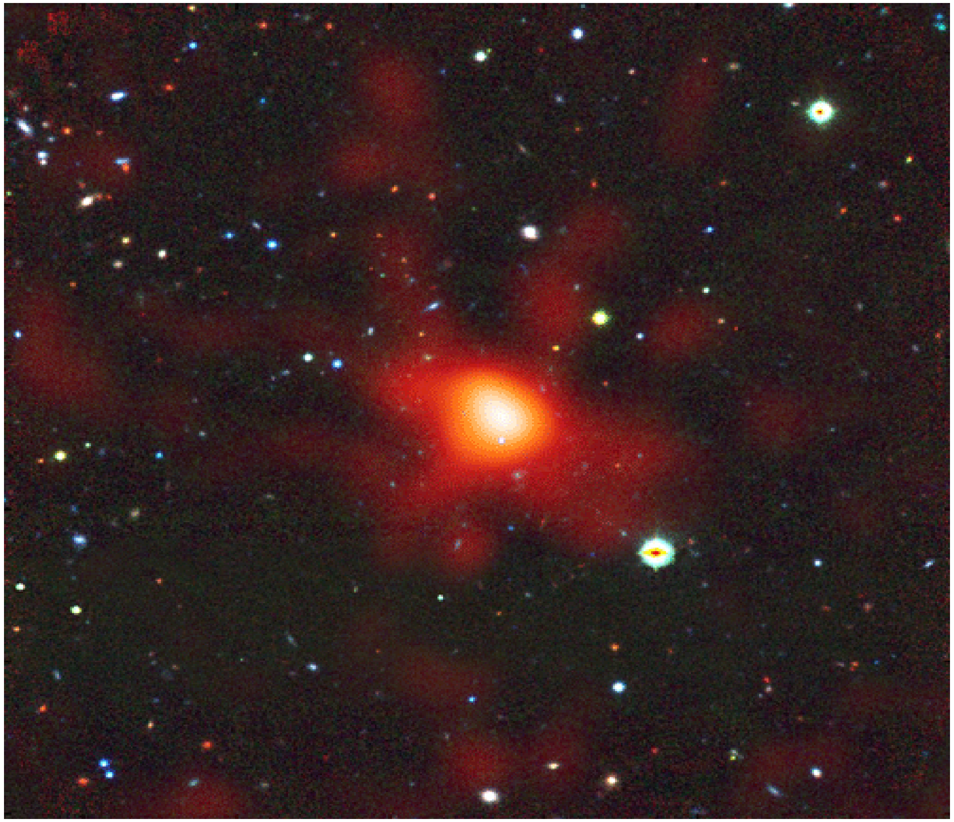


Clusters of galaxies

 # count & clustering

The highest-z X-ray cluster found to date

(z=1.4; Mullis et al 2005)



Clusters of galaxies

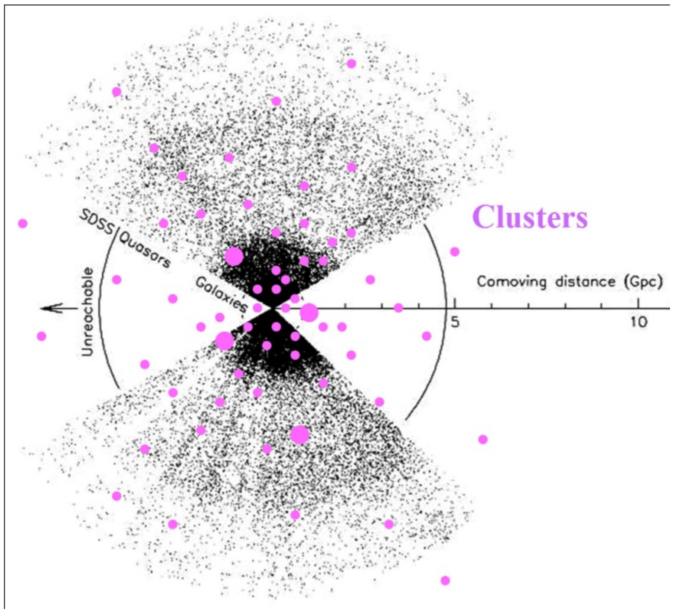
Cluster # count

A census of clusters by X-ray or SZ effect as a function of redshift and mass

Compared with model predictions to derive cosmological parameters

abundance $d^2N/dMdz$

$$\frac{d^2N}{dz\,d\Omega} = \frac{c}{H(z)} d_A^2(z)\,(1+z)^2 \int_0^\infty dM\, \frac{dn}{dM}(M,z)\, f(M,z)$$



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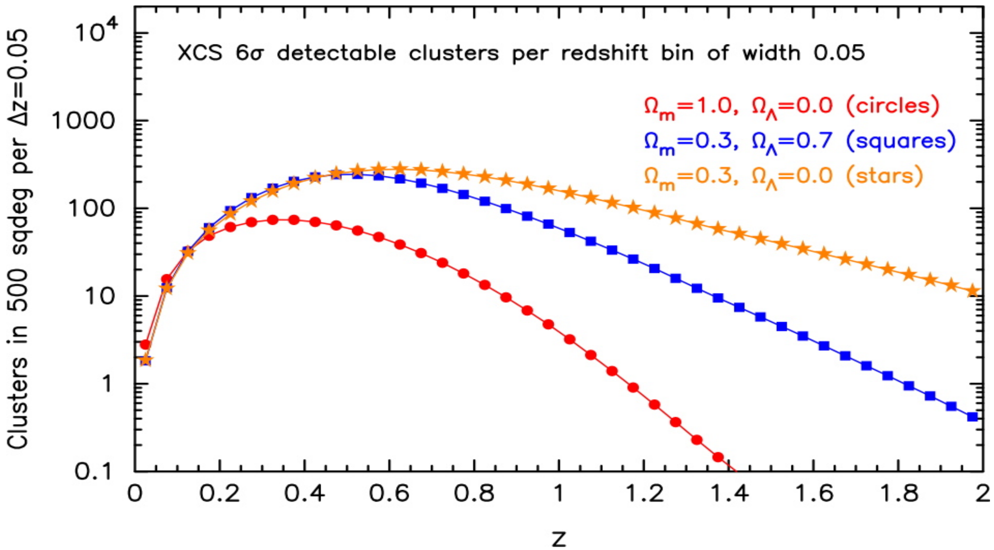
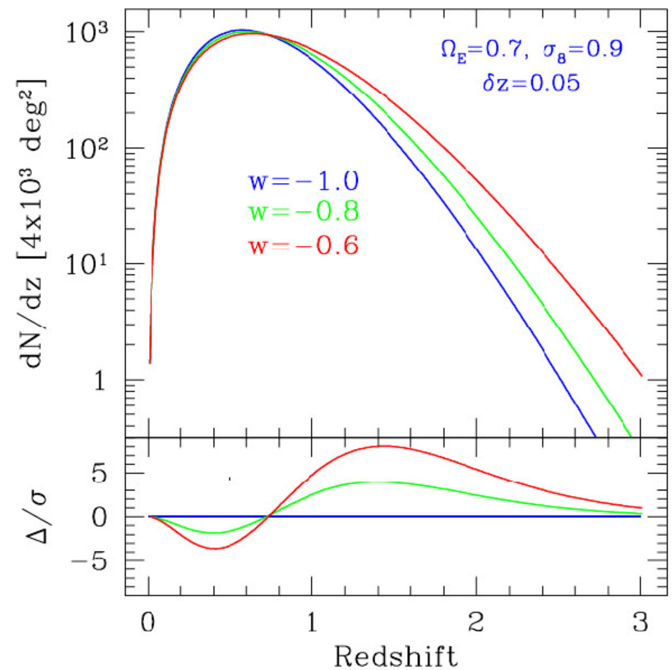
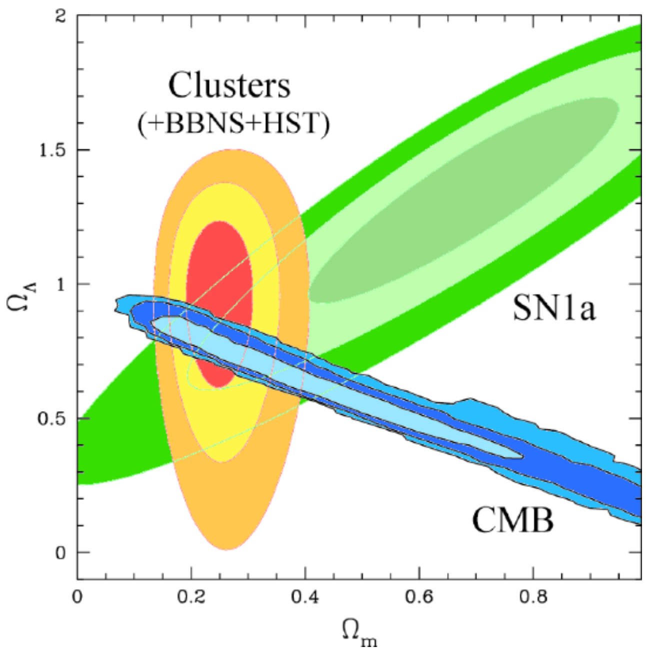


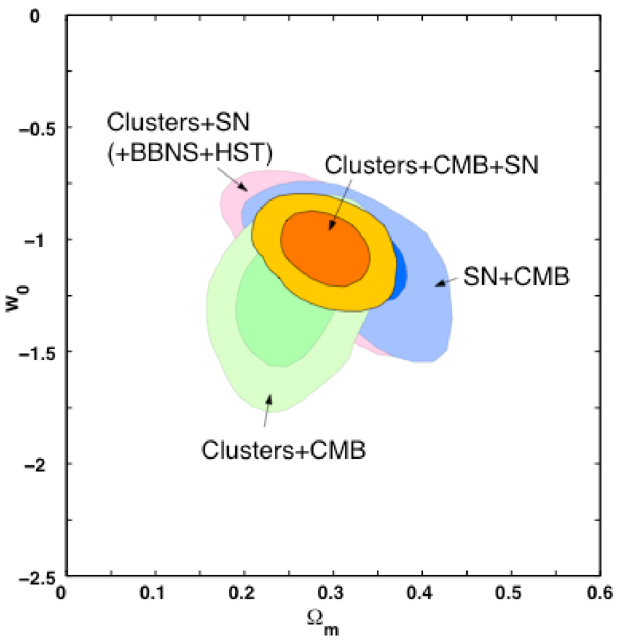


XCS predictions. No evolution, or scatter, in the X-ray L-T relation. ~>1000 clusters expected. [Romer 05]

Complimentary - clusters

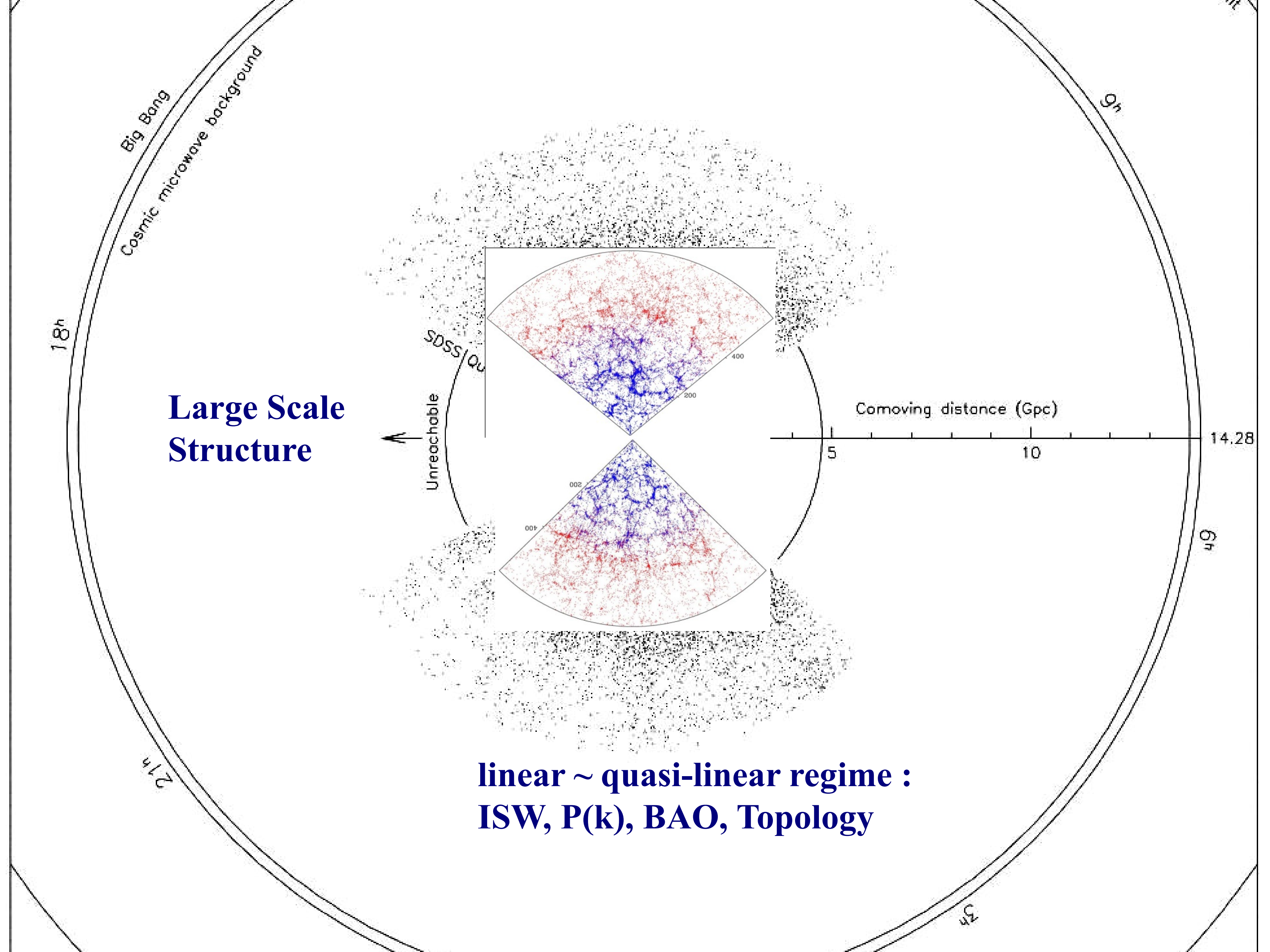


Allen et al. (2004)



baryon fraction - mass in gas, total mass

Rapetti et al. & Allen et al. (2004)

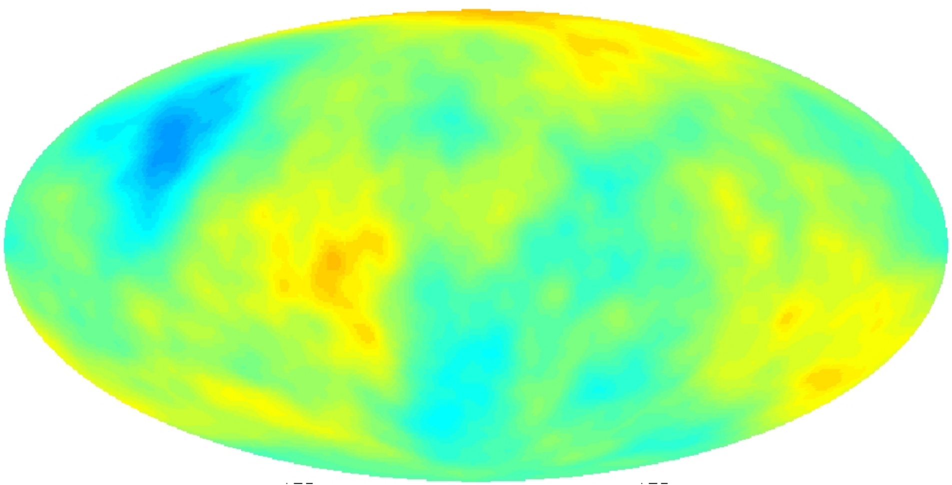


Large Scale Structure

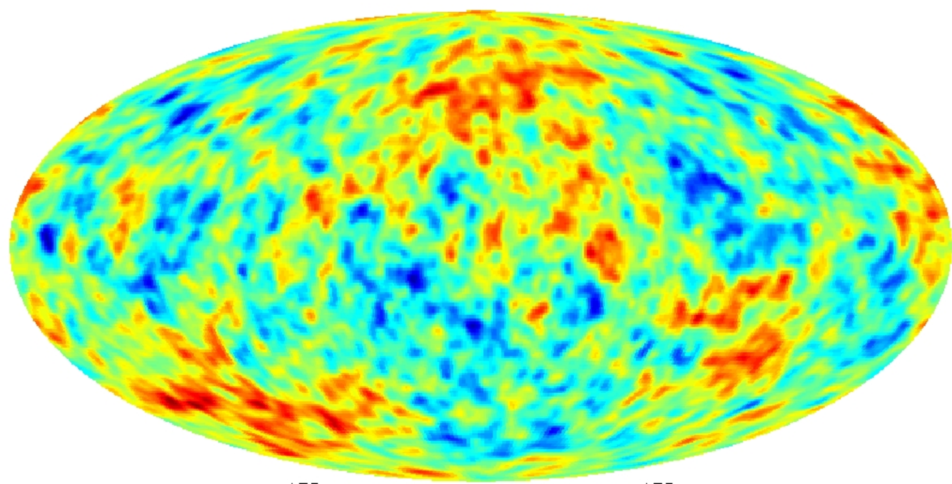
linear ~ quasi-linear regime :
ISW, P(k), BAO, Topology

Late time ISW effect

Induced at low z by a late time transition in the total equation of state.



ISW map, z< 4.
Mostly large scale features



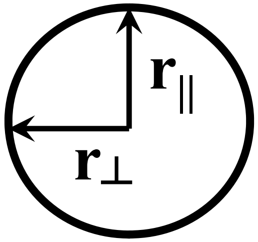
Primordial CMB map, z~1000
Structure on many scales

Einstein-de Sitter 우주에서의 이탈 -> 중력포텐셜 진화 -> LSS와 CMB의 상관관계

Geometric methods using LSS

$$r_{\parallel} = \frac{c\Delta z}{H(z)}$$

$$r_{\perp} = (1+z)D_A(z)\Delta\theta \quad (=r\, d\theta)$$



where $$D_A(z) = \frac{c}{1+z}\int_0^z \frac{dz}{H(z)}$$

$$\mathbf{H(z)} = \sqrt{\frac{\Omega_m h^2}{1-\Omega_X}}\sqrt{\Omega_m(1+z)^3 + \Omega_X \exp\left[3\int_0^z \frac{1+w(z)}{1+z}dz\right]}$$

Standard rulers (Actual objects or Features in PS/CF)

→ measure Δz & $\Delta\theta$ → H(z) & $D_A(z)$ → Ω_m, Ω_Λ, w

BAO

Acoustic oscillation amplitude : depends on Ω_b

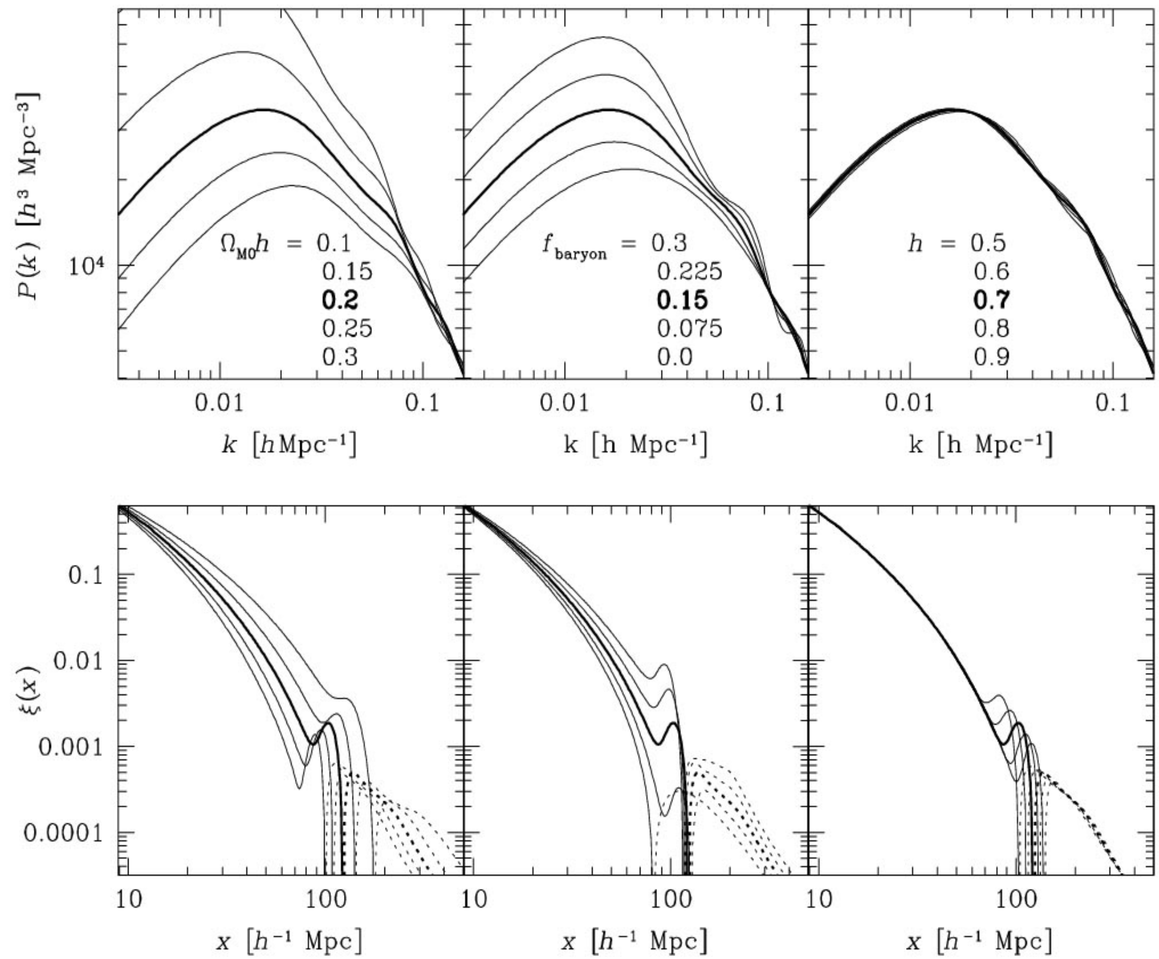
oscillation scale = comoving sound horizon 's' at t_{dec}

$k_A = 2\pi/s$ depends strongly on Ω_m, weakly on Ω_b not on DE

→ Curvature of space, Baryonic mass

Baryonic oscillation in PS

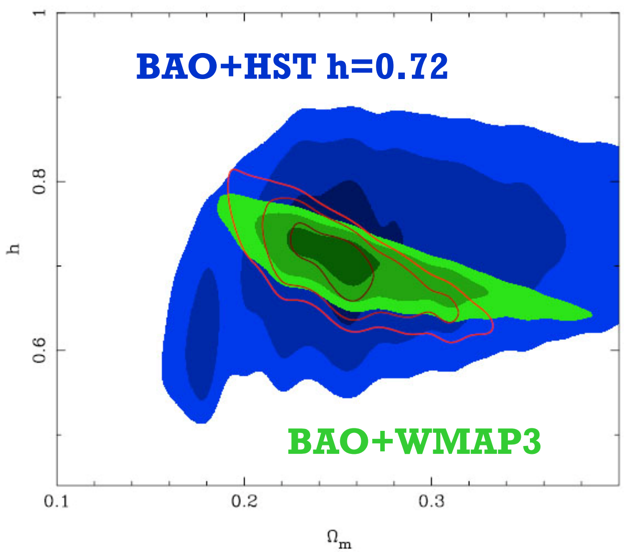
Baryonic bump in CF

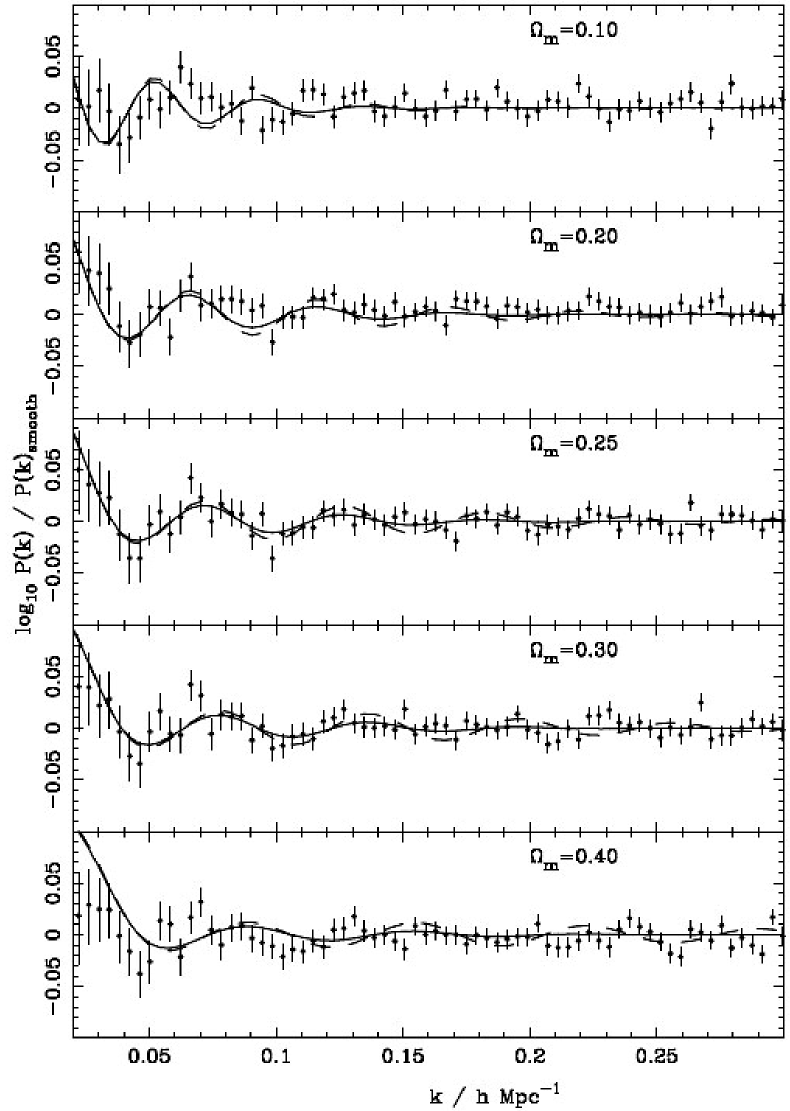


SDSS DR5

(Percival et al. 2007)

Main galaxies and LRGs





Best fit Ω_m=0.26

Pros and Cons
of the Acoustic Peak Method

Advantages:

- **Geometric measure of distance.**
- **Robust to systematics. Insensitive to non-linearity, bias, redshift distortions**
- **Individual measurements are not hard (but you need a lot of them!).**
- **Can probe $z>2$.**
- **Can measure $H(z)$ directly (with spectra).**

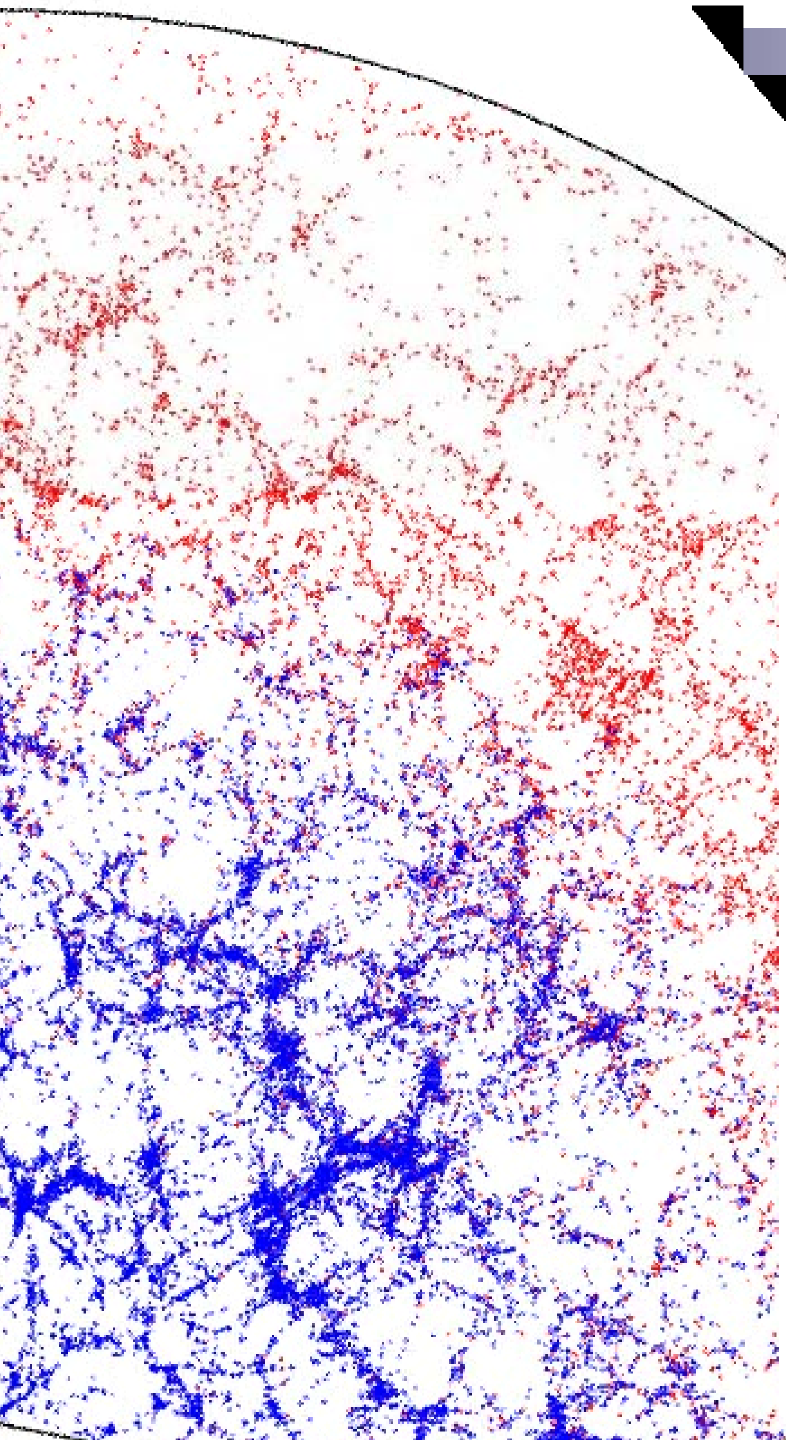
Disadvantages:

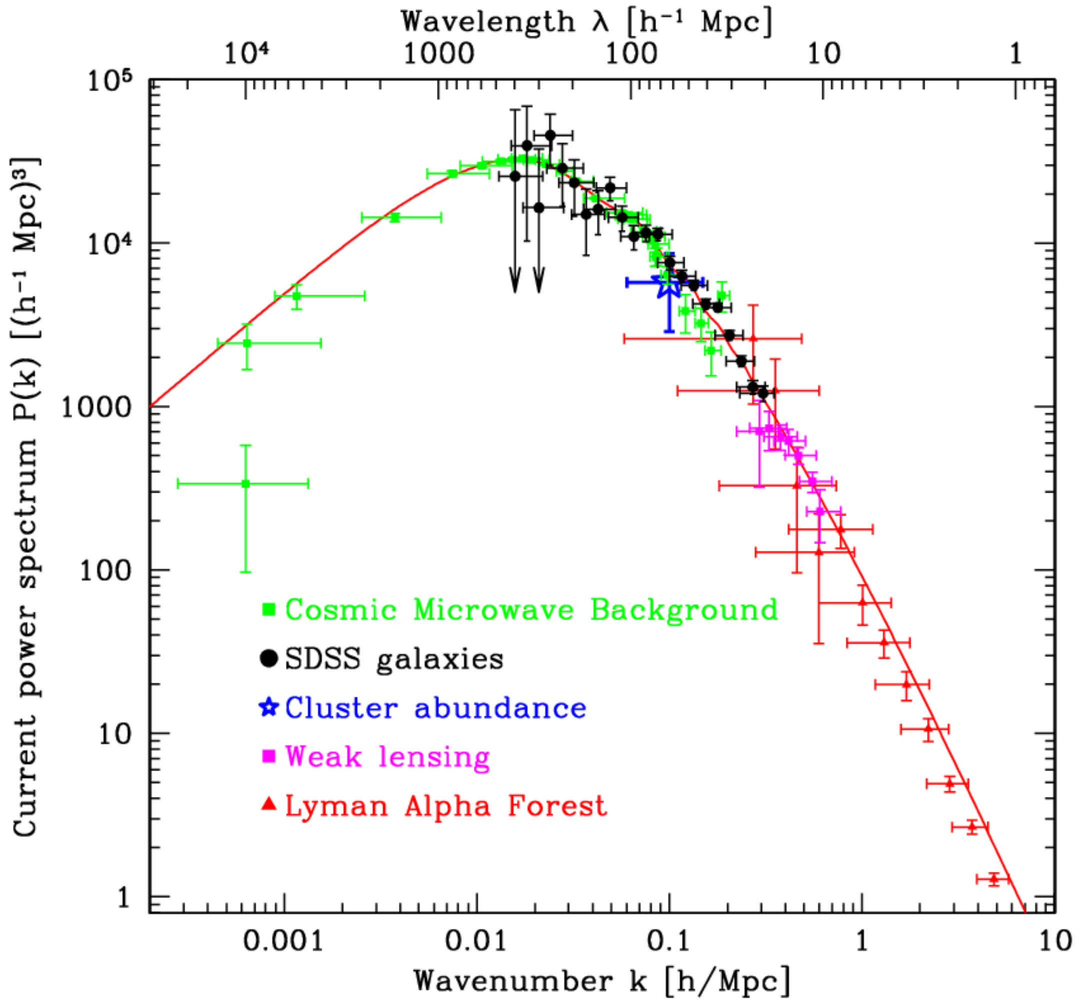
- **Raw statistical precision at $z<1$ lags SNe and lensing/clusters. The peaks are weak in amplitude and are only available on large scales (>30 Mpc). Require huge survey volumes.**
- **If dark energy is close to L, then $z<1$ is more interesting.**
- **Some model dependence as regards inferences from CMB.**

Power Spectrum from CMB & LSS

: σ_8(amplitude), Ω_m (equality scale)

But biasing relative to matter (σ_8)

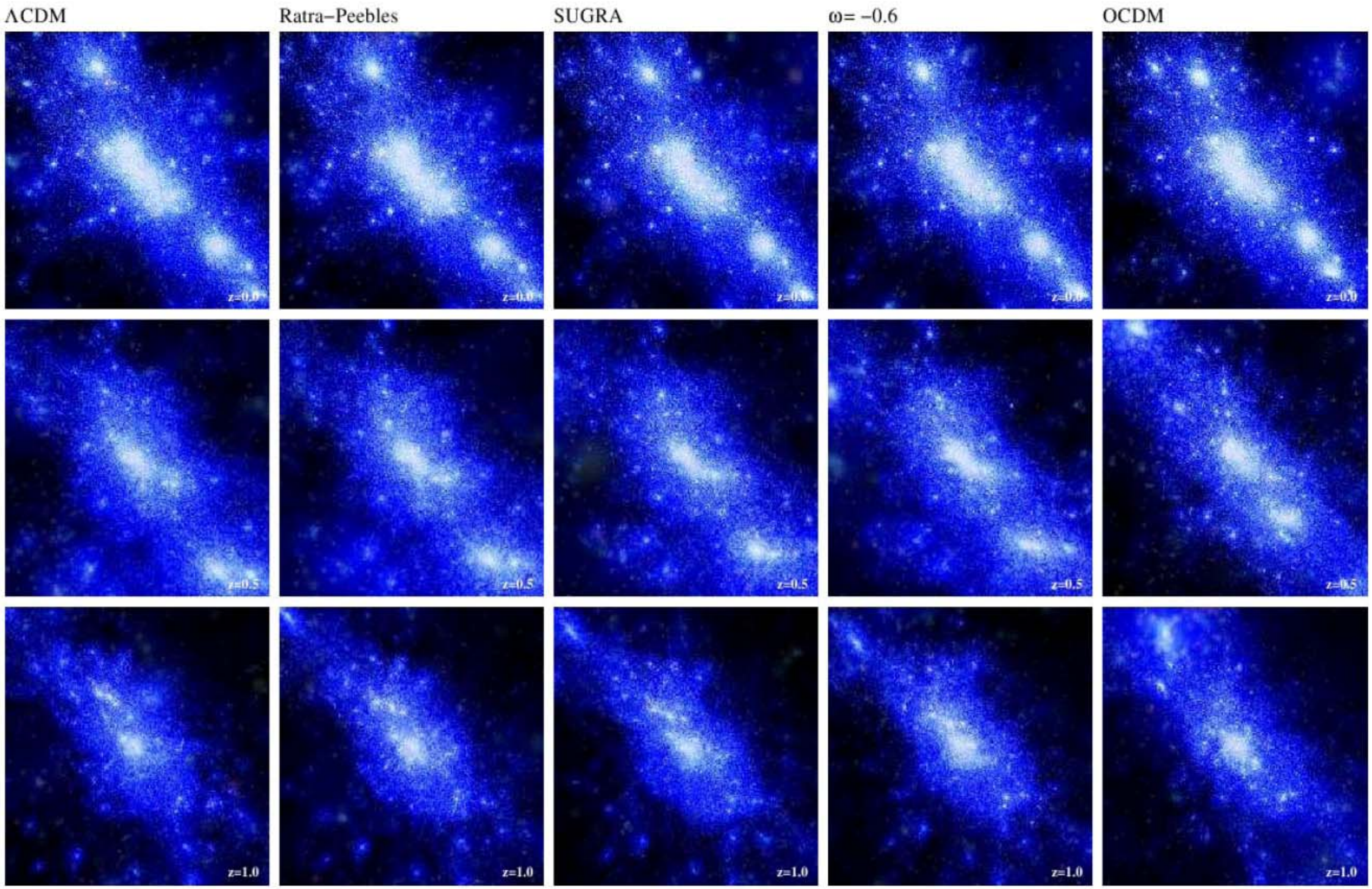




Properties of non-linear structures

Dark energy modifies structure formation in subtle ways

SIMULATED CLUSTERS OF GALAXIES IN DIFFERENT DARK ENERGY COSMOLOGIES



Dolag et al. (2004)

요약

대형 우주탐사 사업들이 관측하고자 하는 현상은 크게 네 가지로 나뉜다.
1. CMB 요동   2. 우주공간의 팽창역사   3. 우주구조의 성장역사   4. 천체 성질 이다.
이들은 다양한 방식으로 우주 물리량들과 관련된다.

이 현상들을 관측하기 위해 관측하는 대상들은
1. CMB 요동   2. HI 분포   3. SN Ia   4. weak lensing (galaxy)   5. LSS (galaxy z) 등

미약한 DE 효과, BAO peak 등을 재고, cosmic variance 극복 위해 **wide & high-z** 탐사 필요
탐사 간의 효율 위해 **상보적 관측 현상/천체** 를 선정
상당수 우주물리량을 2010년 대에 ~% 수준으로 잴 수 있는지 여부 (**시간 & 정확도**)
(무엇을 어떻게 관측해서, 어떤 물리현상을 이용해, 어느 물리량을 어떤 정확도로 측정함으로써, 무엇을 규명할지)

거대 우주 탐사

<우주 - 탐사와 이해>

1. 천체 관측
   별/초신성, 은하, 은하단, 퀘이사/Lyα 구름, 재이온화시기 HI 구름, 우주배경복사
2. 물리량 측정
   (우주밀도 Ω_m, Ω_b, Ω_Λ, 허블 H(z), DE w_0, w_a, 밀도요동 P(k) & n_S, 천체개수밀도 n(z), 재이온화시기 물리량, t_{dec}때 음파지평선 .....)
3. 표면적 물리현상 이해 : 물질의 성질과 분포; 공간의 구조; 공간의 팽창
4. 근본적 물리현상 이해
   초기우주현상 이해; 물질성분 정체 규명; 천체생성원리 규명; 자연법칙(GR) 검증/발견

<우주 - 탐사의 실제>

관측 대상 천체== 이용하려는 물리적 현상== 알고자 하는 질문
관측기기 & 파장대; 측광/분광; 탐사 방식(탐사 지역 - 하늘 & 거리, 밀도, 빈도)

<대형 우주 탐사의 추세>

1. dark matter, dark energy, galaxies & gas 모두를 통해 보는 종합적 우주상
2. 다파장에서 대상을 이해하는 종합적 천체상
3. 다른 탐사를 의식/보완하는 탐사 & 여러 독립적 측정방식을 결합하는 통합방식탐사
4. 특정 목적과 다중 목적을 동시에 추구

진행/계획 중 탐사들 : 대상천체에 따라

	2005	2010		2015
Imaging	CFHTLS SUBARU SDSS ATLAS KIDS	DES VISTA Pan-STARRS	DUNE LSST JDEM/ SNAP	SKA
LSS/Wiggles	FMOS SDSS ATLAS	DES VISTA	WFMOS	SKA
Supernovae	CSP ESSENCE CFHTLS	DES Pan-STARRS	LSST JDEM/ SNAP	
Clusters	AMI APEX SPT XCS SZA AMIBA ACT	DES		
CMB	WMAP 2/3	WMAP 6 yr Planck	Planck 4yr	

More astronomical questions : 덤으로 연구 가능?

- Galaxy photometric redshift survey.
- Galaxy evolution.
- Galaxy clustering evolution.
- Low-surface brightness galaxies.
- Micro-Jansky radio sources
- Redshifts for X-ray clusters.
- Sub-millimetre sources.
- Star formation.
- High-redshift quasar detection
- High-redshift quasar evolution.
- Local galaxy studies.
- QSO monitoring
- The Local Group
- Brown Dwarfs detection.
- White Dwarf detection.
- Outer Solar System.
- Near Earth Objects.
- Radio AGN.
- Space sub-millimetre sources.
- High-redshift Supernova.
- Microlensing.
- High-Redshift clusters.
- Halo RR Lyraes variability.
- YSO variability.
- Complement Ha surveys
- Galaxy-galaxy lensing

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For Young Scientists

A lot of parameters to determine
even in the current precision cosmology era !!

const. or evolving w; flat or non-flat space
---> more degeneracy
--> need larger data and diverse observables
with different systematic dependences