Quy Nhon 201

Cosmology and Dark Matter

24th Vietnam School of Physics   Aug 22-25, 2018

Changbom Park

(Korea Institute for Advanced Study)

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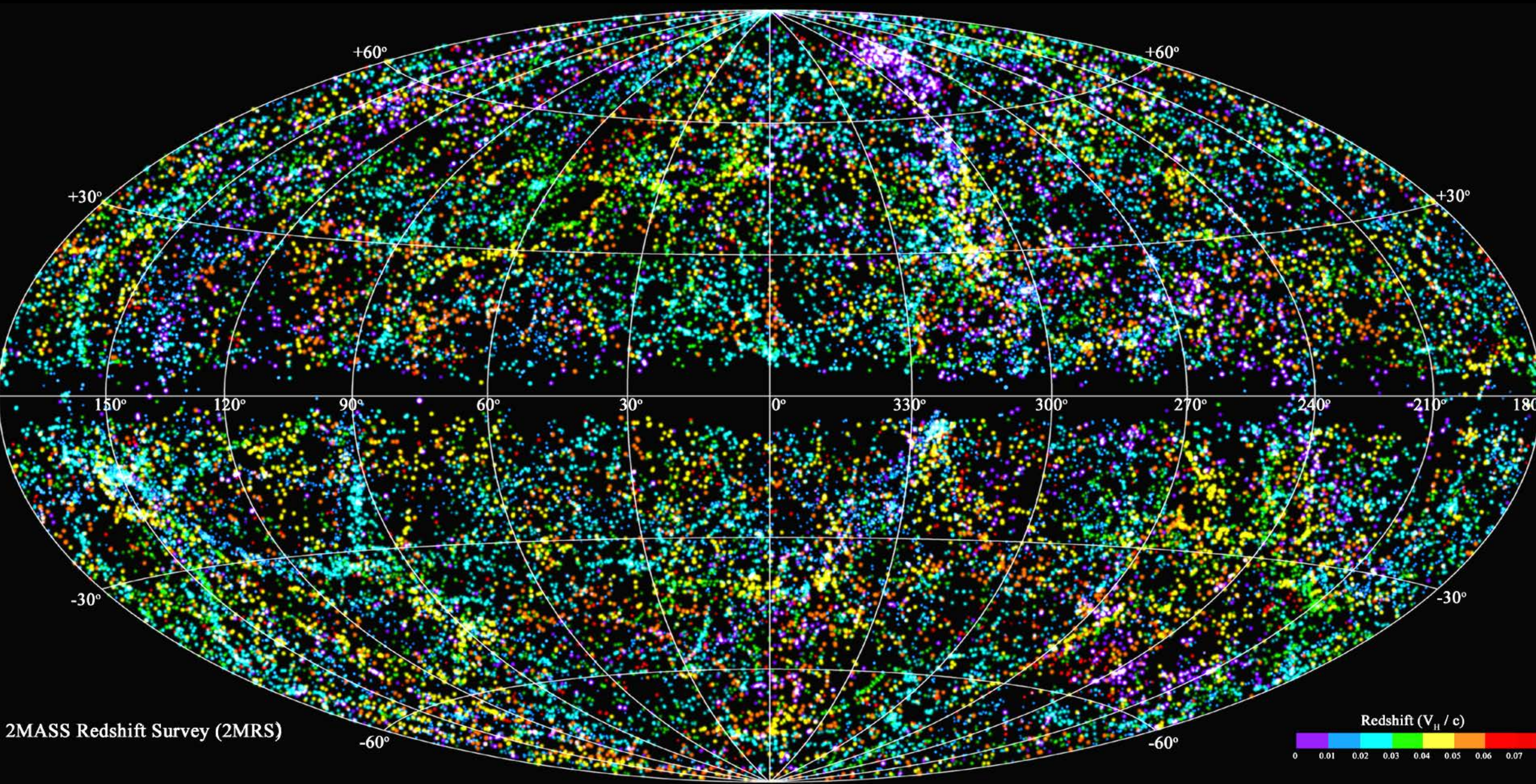
Amir Abolfath

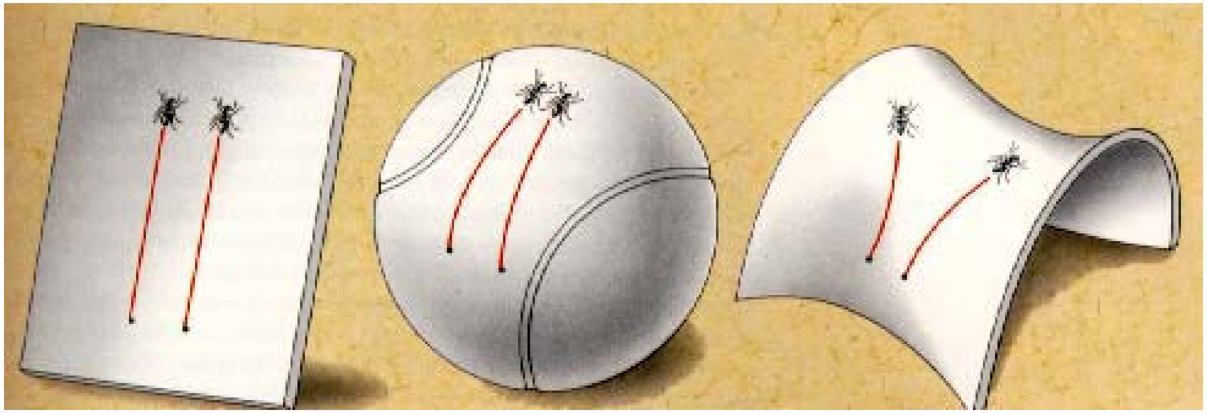


+60°
+60°
+30°
+30°
150°
120°
90°
60°
30°
0°
330°
300°
270°
240°
210°
180
-30°
-30°
-60°
-60°
2MASS Redshift Survey (2MRS)
Redshift (V_H / c)
0
0.01
0.02
0.03
0.04
0.05
0.06
0.07

Definition of the universe and cosmology

Uniform Space

Uniform space



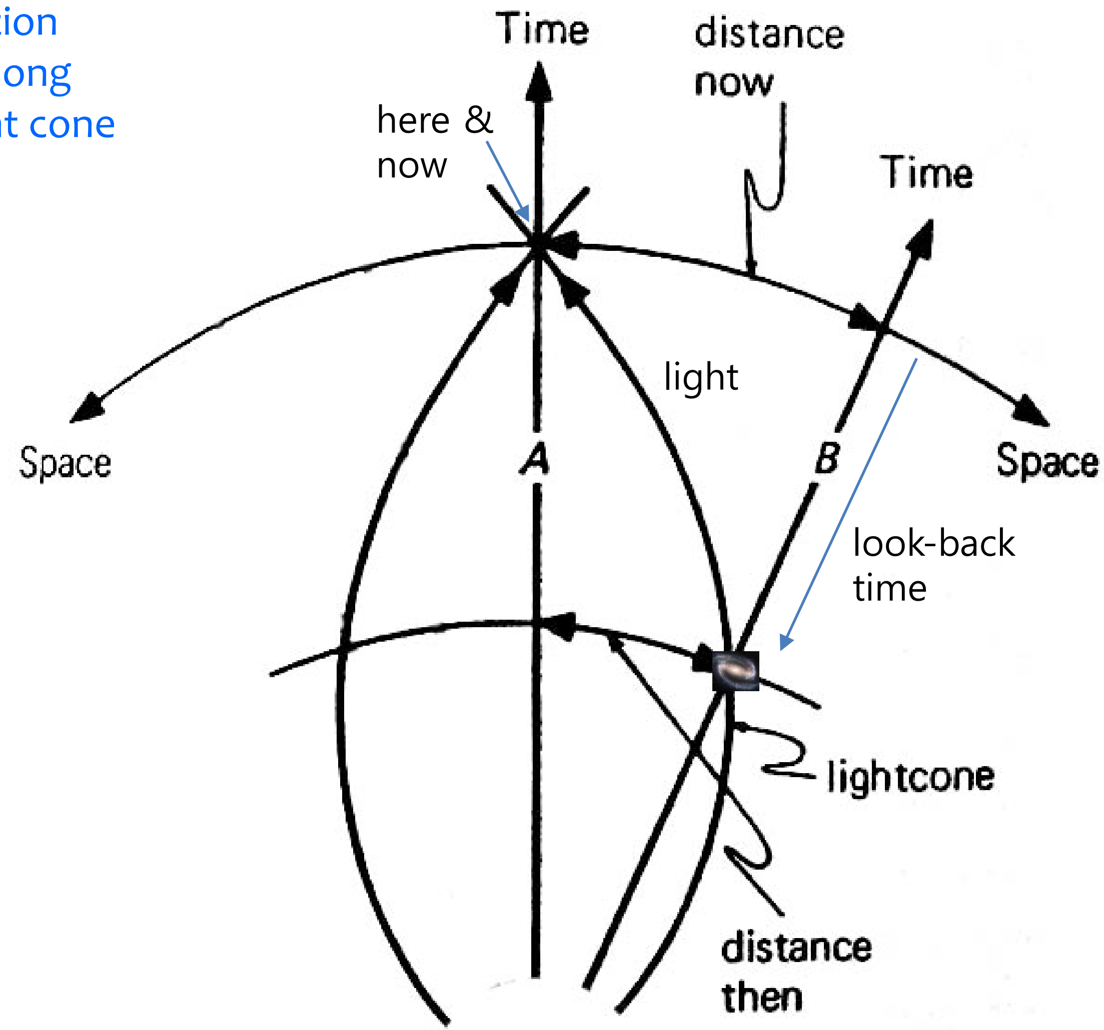
Some concepts of modern cosmology

Homogeneous space
– cosmological principle
--- Horizon and size of the universe

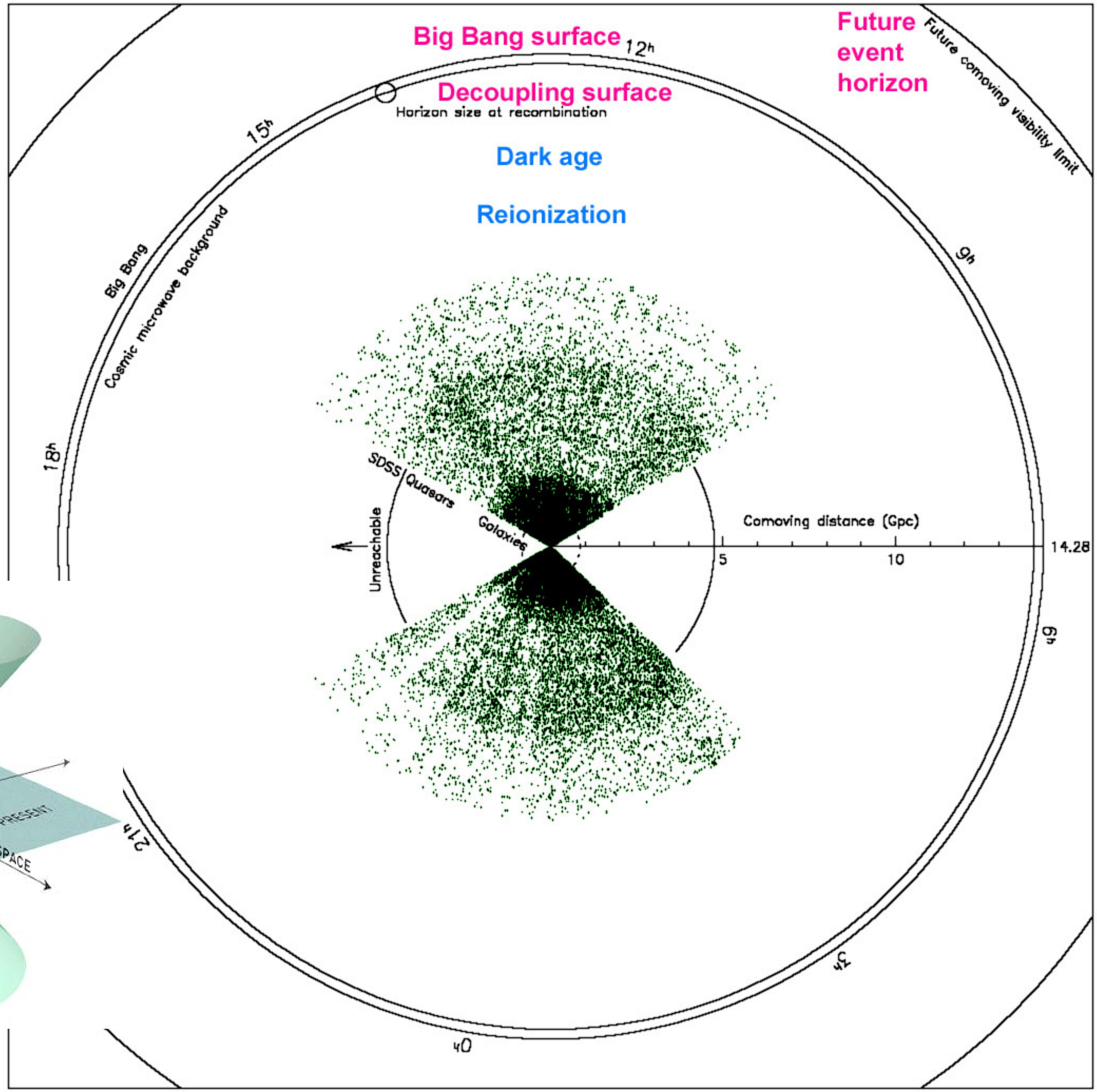
Uniform expansion
– Hubble's law

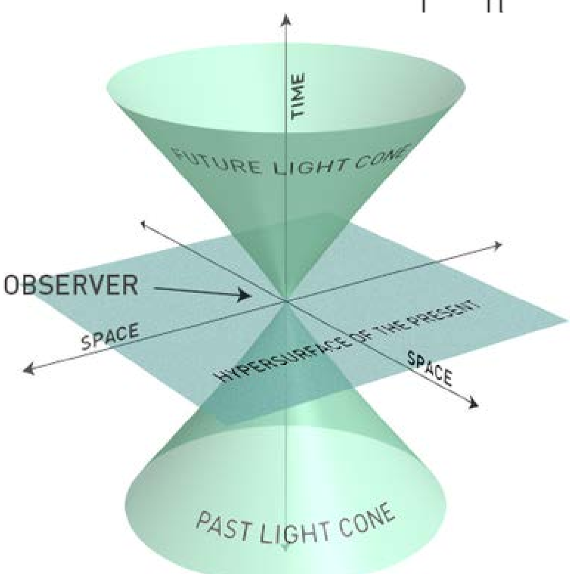
Accelerating expansion
-- cosmological constant / dark energy

Observation
is made along
the past-light cone

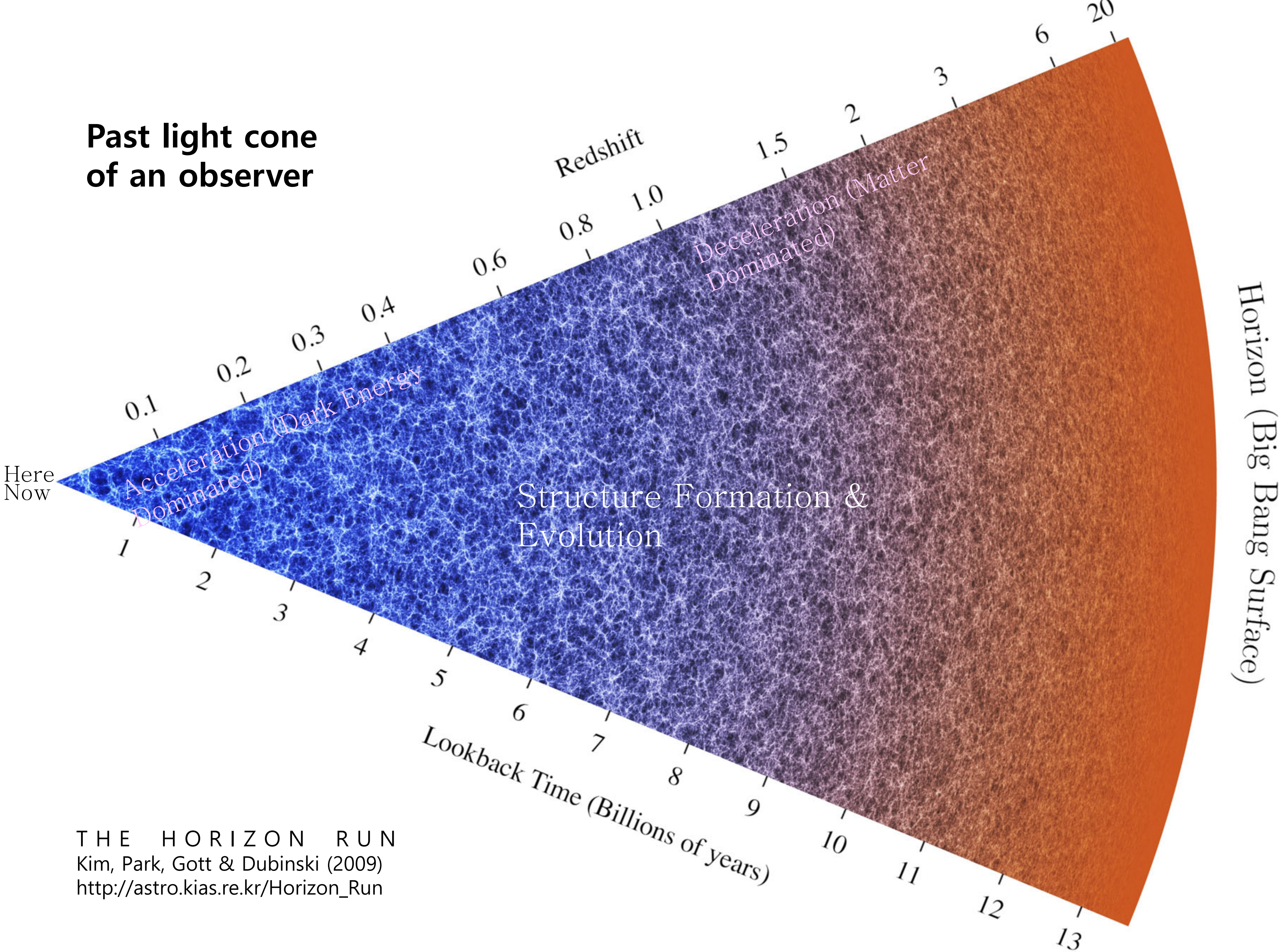


The observed universe



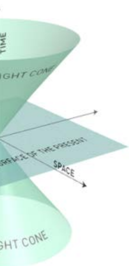


Past light cone of an observer

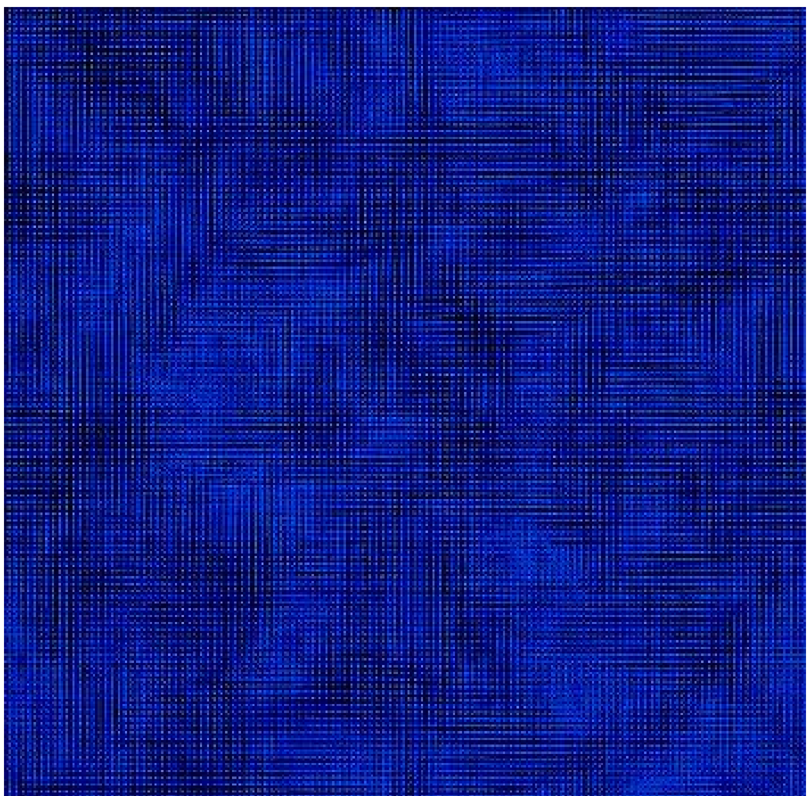


THE HORIZON RUN
Kim, Park, Gott & Dubinski (2009)
http://astro.kias.re.kr/Horizon_Run

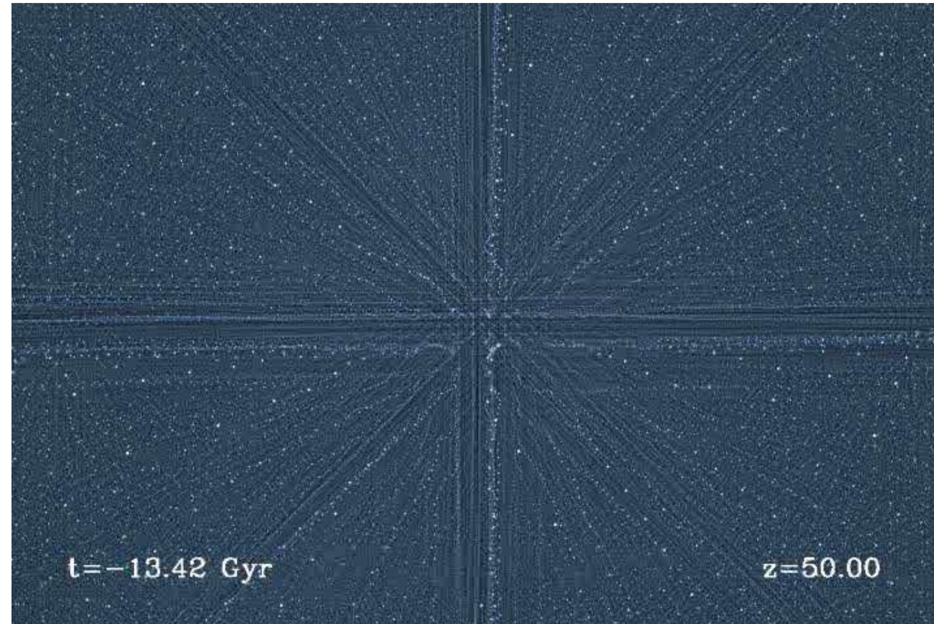
Traveling in simulated universes



Time evolution in a fixed space
[John Dubinski]



A flight along the past light-cone
[John Dubinski]



Space travel at a fixed time
[John Dubinski]

Some important parameters, quantities, equations, solutions

Expansion parameter/scale factor a(t) – proper/comoving distances
Hubble parameter
Density parameters Ω_m
Power spectrum P(k), C_ℓ

FRW metric
Friedmann equations
Solutions of Fes. - Radiation/matter-dominated era

Metric of homogeneous isotropic universes

A uniform S^2 $r = R\chi$,

$$d\ell^2 = R^2 d\chi^2 + R^2 \sin^2\chi d\theta^2 = dr^2 + R^2 \sin^2(r/R) d\theta^2$$

$x = R\sin(r/R)$ is the angular diameter distance. S3 has

$$ds^2 = c^2dt^2 - d\ell^2 = c^2dt^2 - [dr^2 + R^2\sin^2(r/R)(d\theta^2 + \sin^2\theta d\phi^2)]$$

$$= c^2dt^2 - a(t)^2[dx^2 + R_0 \sin^2(x/R_0)(d\theta^2 + \sin^2\theta d\phi^2)]$$

$$= c^2dt^2 - a(t)^2[\frac{dx'^2}{1 - x'^2/R_0^2} + x'^2(d\theta^2 + \sin^2\theta d\phi^2)]$$

where

$x' = R_0 \sin(x/R_0)$ is the comoving angular diameter distance.

proper distance $r = a(t)x$.

$a(t) =$expansion parameter,

$x =$comoving distance,

& $R = aR_0$.

A uniform hyperbolic space $ds^2 = c^2dt^2 - a^2[d\chi^2 + \sinh^2\chi(d\theta^2 + \sin^2\theta d\phi^2)]$

Friedmann Equations

$$ds^2 = dt^2 - a^2(t)[\frac{dr^2}{1-kr^2} + r^2(d\theta^2 + \sin^2\theta d\phi^2)]$$

$$R^i_j - \frac{1}{2}g^i_j R - \Lambda g^i_j = 8\pi G T^i_j$$

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + \frac{3P}{c^2}) + \frac{\Lambda}{3}$$

$$(\frac{\dot{a}}{a})^2 = \frac{8\pi G}{3}\rho - \frac{c^2}{R_0^2 a^2} + \frac{\Lambda}{3}$$

Gaussian Random Fields

-- Field, random field, homogeneous Gaussian random field
-- Numerical exercise
Making realizations of smoothed Gaussian random density fields

[tasks]
-- Plot the contour plots of slices of the density fields for SCDM and HDM models

**-- Calculate number of over-density peaks above density threshold levels,
number of under-density peaks below density threshold levels.**

Rotational curve of galaxies

-- SDSS4 MaNGA
-- https://github.com/astrohchung/manga_rc_tuto

[tasks]
- Find mass profile of two galaxies

History of modern cosmology

-- 100 years of development of modern cosmology
-- Special time of the human history

-- Future of the universe

100 Years of Modern Cosmology

Galaxies & LSS

CMBR

1917 Einstein's static & de Sitter's expanding universe models

22 External galaxies

22-24 Friedmann's models

29 Expansion of space

29 Big Bang model

33 Discovery of dark matter in clusters

40s-50s Gravitational Instability(GI) Theory

50s-60s Discovery of superclusters

65 Discovery of CMBR

70s BB+(γ,ν; baryon)+GI

LSS

70s BB+(γ,ν; baryon)+GI

CMBR

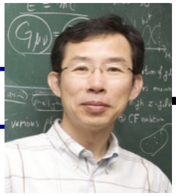
Dark matter
82Inflation

80s CMBR
$dT/T < 10^{-4}$

70s Discovery of LSS

mid80 SCDM Model
(Inflation,BB)+(γ,ν; baryon, CDM)+GI

92 galaxy P(k)



92 COBE
$dT/T \sim 10^{-5}$

Standard CDM model
ruled out

98 Accelerating
expansion/dark energy

00-03 WMAP C_ℓ

2018 Concordance ΛCDM Model
(Inflation,BB)+(γ,ν; baryon, CDM; Dark E w=-1)+GI

'00s LSS, SN, WL,
Cluster

SDSS++, DESI,
Euclid, JWST,
LSST, SKA, …

Planck & etc.

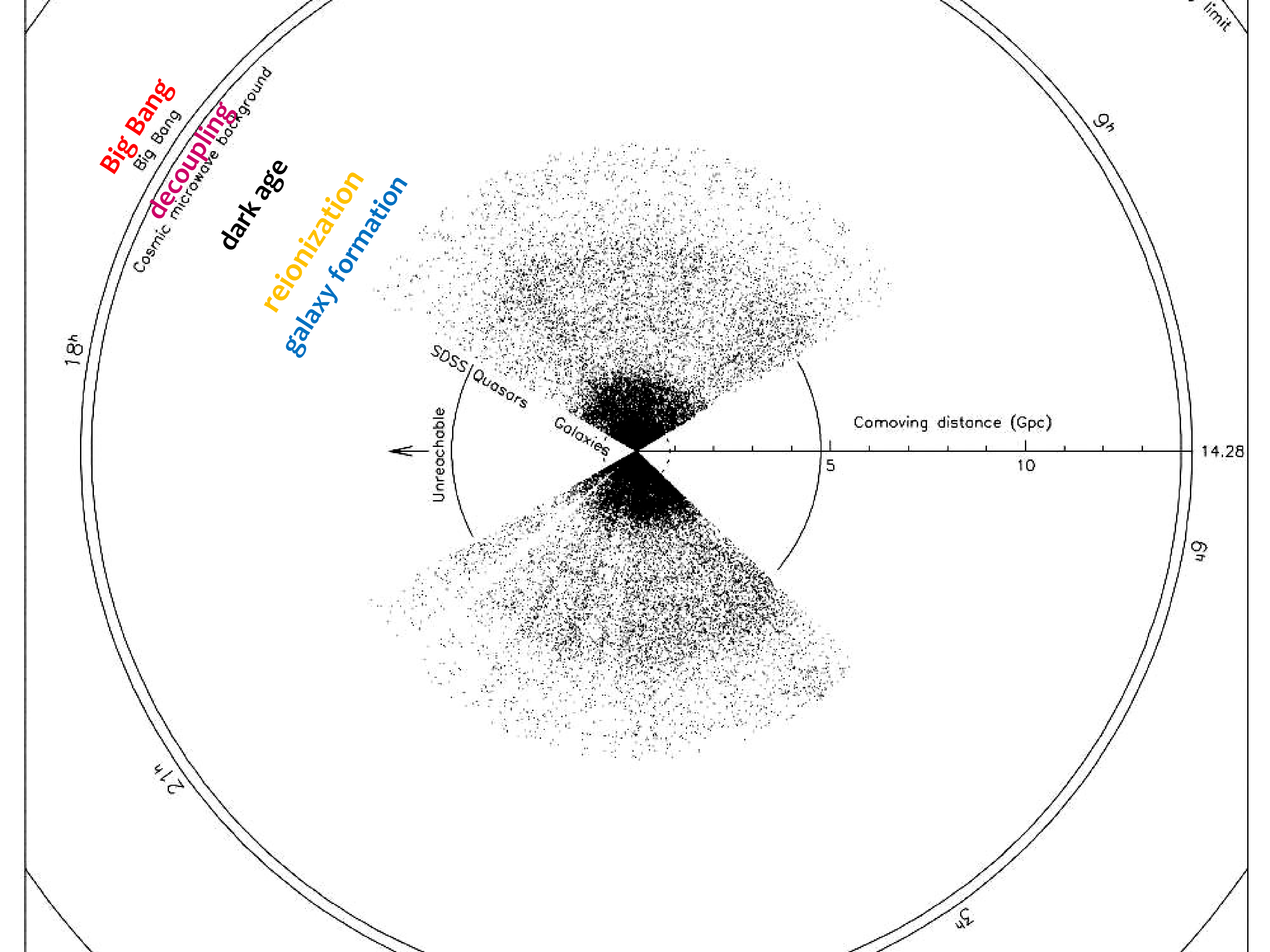
?

History of the universe backward in time

- present epoch - age, geometry & expansion of space, density, matter composition
  astronomical objects. 4 forces. elementary particles
  We are at a very special time in the history of mankind!

- low-z, intermediate-z, high-z universe
- reionization epoch
- dark era
- decoupling: between matter and radiation
- radiation-matter density equality: growth of density fluctuations

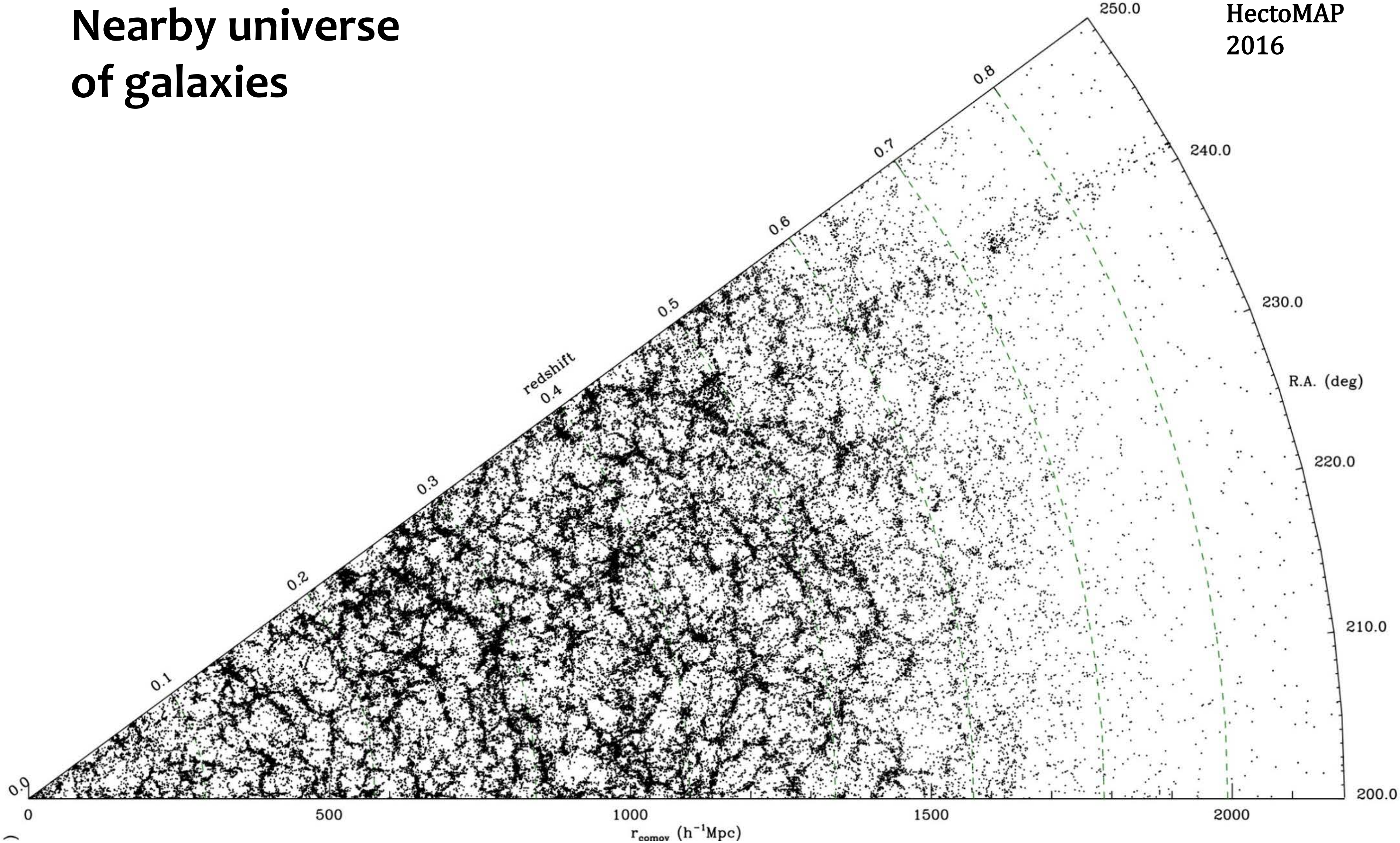
- nucleosynthesis
- baryosynthesis
- inflation
- Planck epoch: generation of adiabatic, Gaussian, scale-invariant density fluctuations



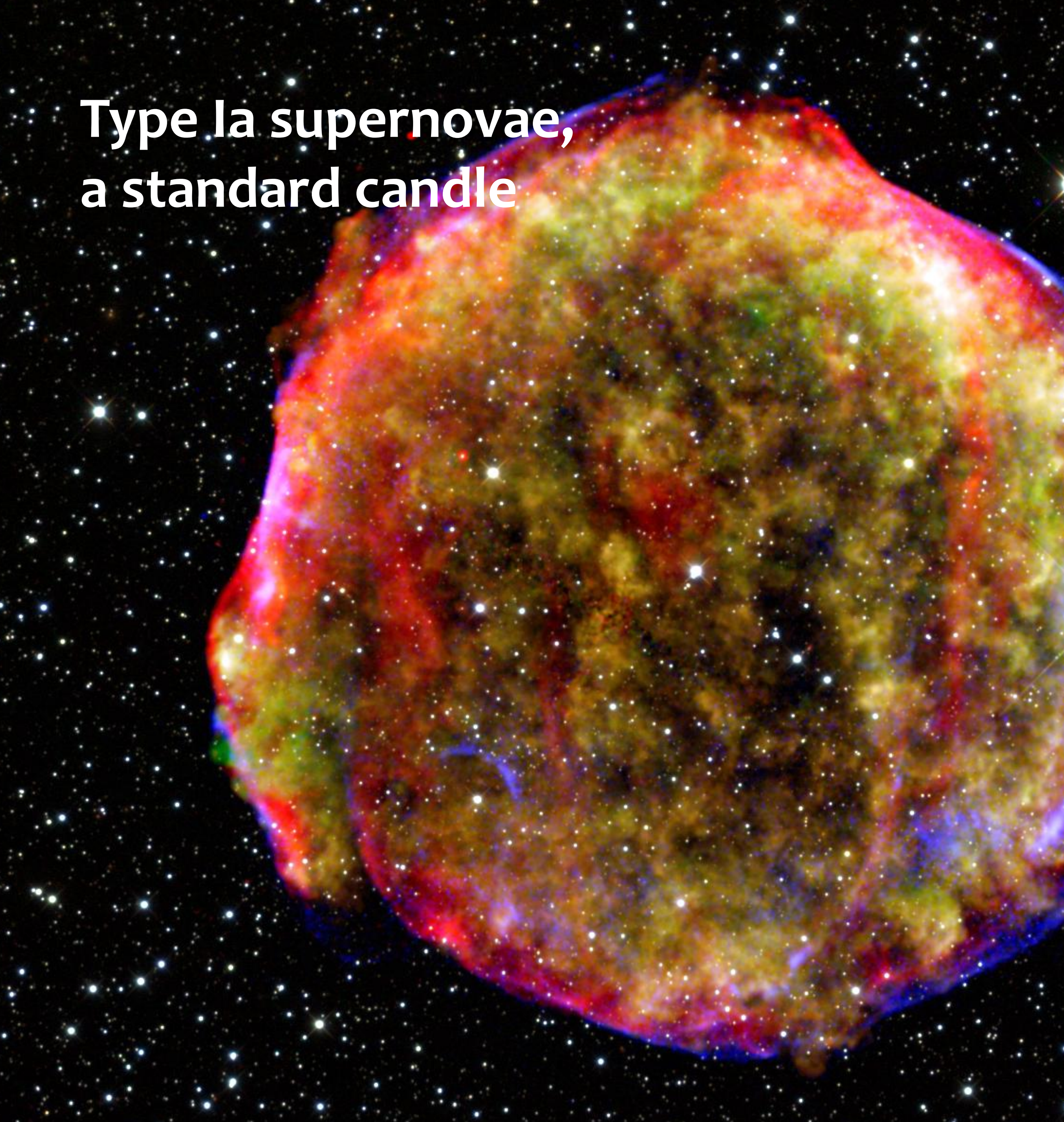
Big Bang
Big Bang
decoupling
Cosmic microwave background
dark age
reionization
galaxy formation
SDSS
Quasars
Galaxies
Unreachable
Comoving distance (Gpc)
5
10
14.28
18h
9h
6h
21h
3h
limit

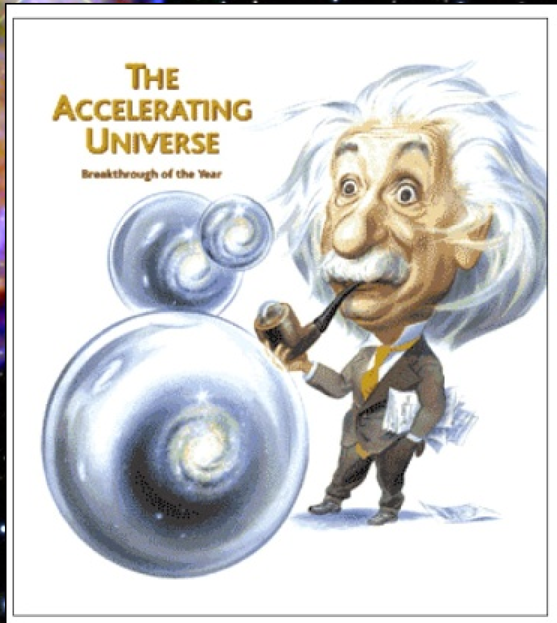
Nearby universe of galaxies

HectoMAP
2016



Type Ia supernovae,
a standard candle





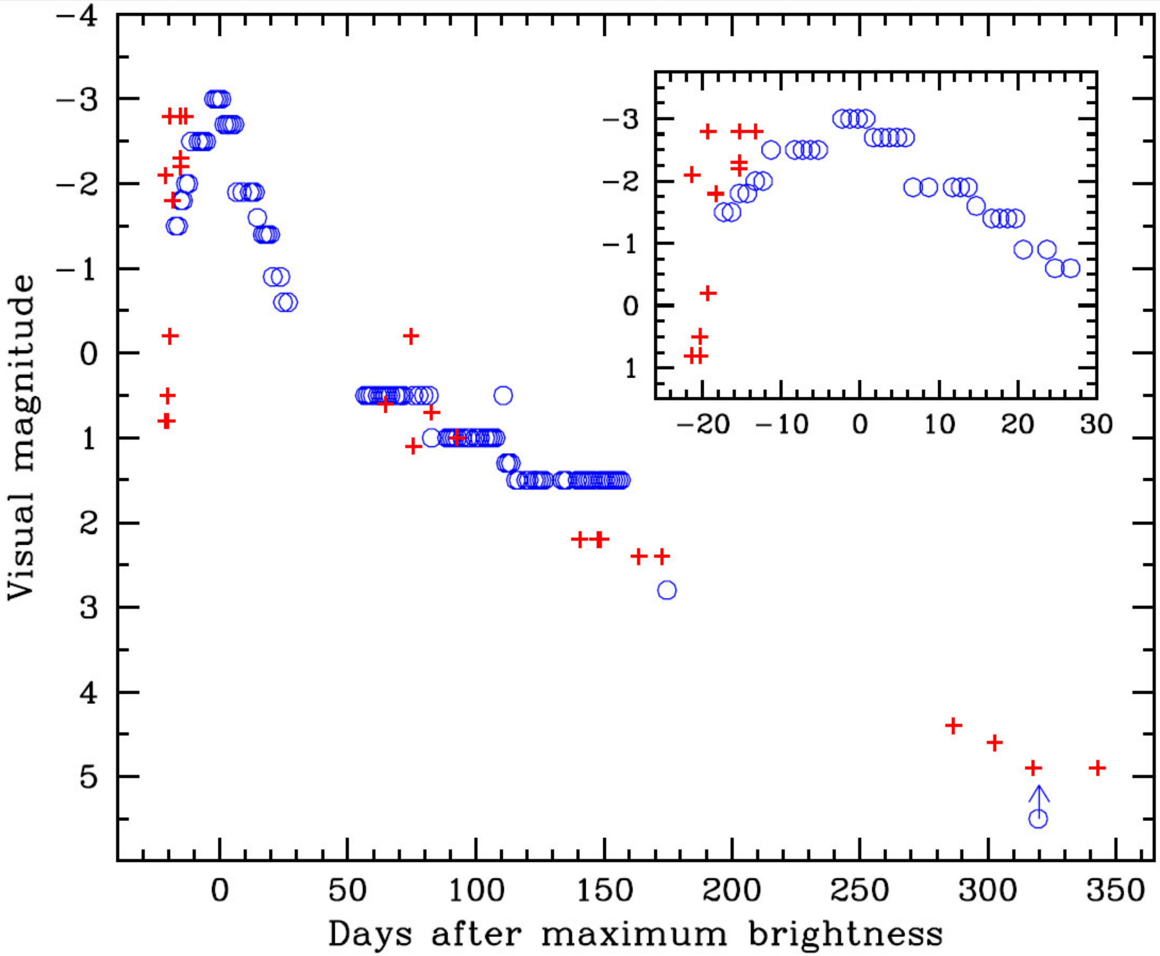
Classification of Supernovae

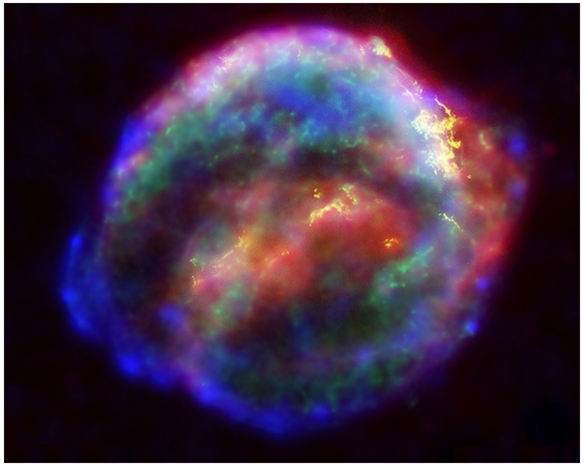
Some Early Observations of supernovae that are **identified**

Year	Name	Observers
185	SN185	Chinese
1006	SN1006	Chinese, Islamic
1054	SN1054 (Crab)	Chinese etc.
1572	SN1572 (Tycho Brahe)	European
1604	SN1604(Kepler)	European, Korean

SN1604

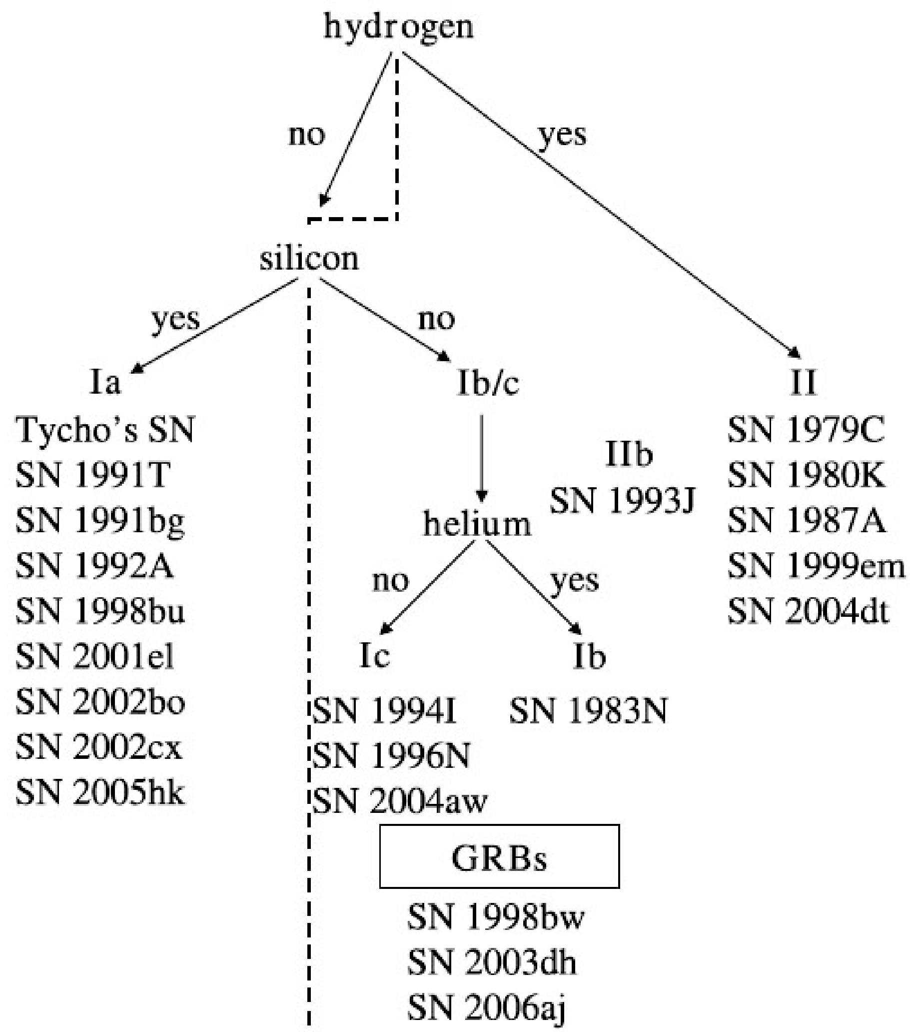
(circles: Korean, crosses: European)



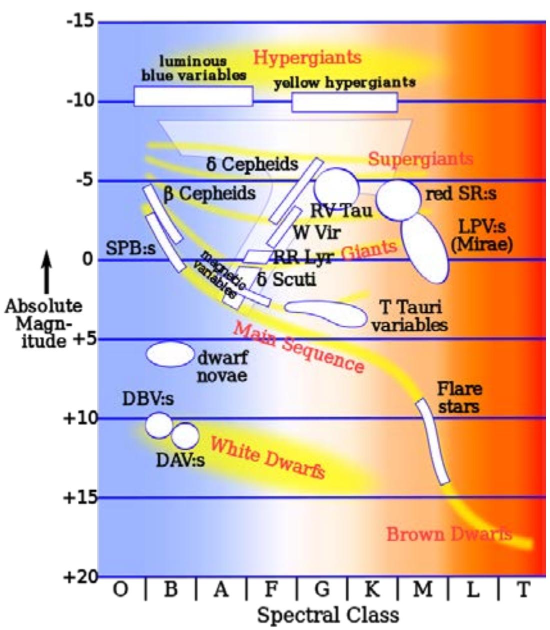


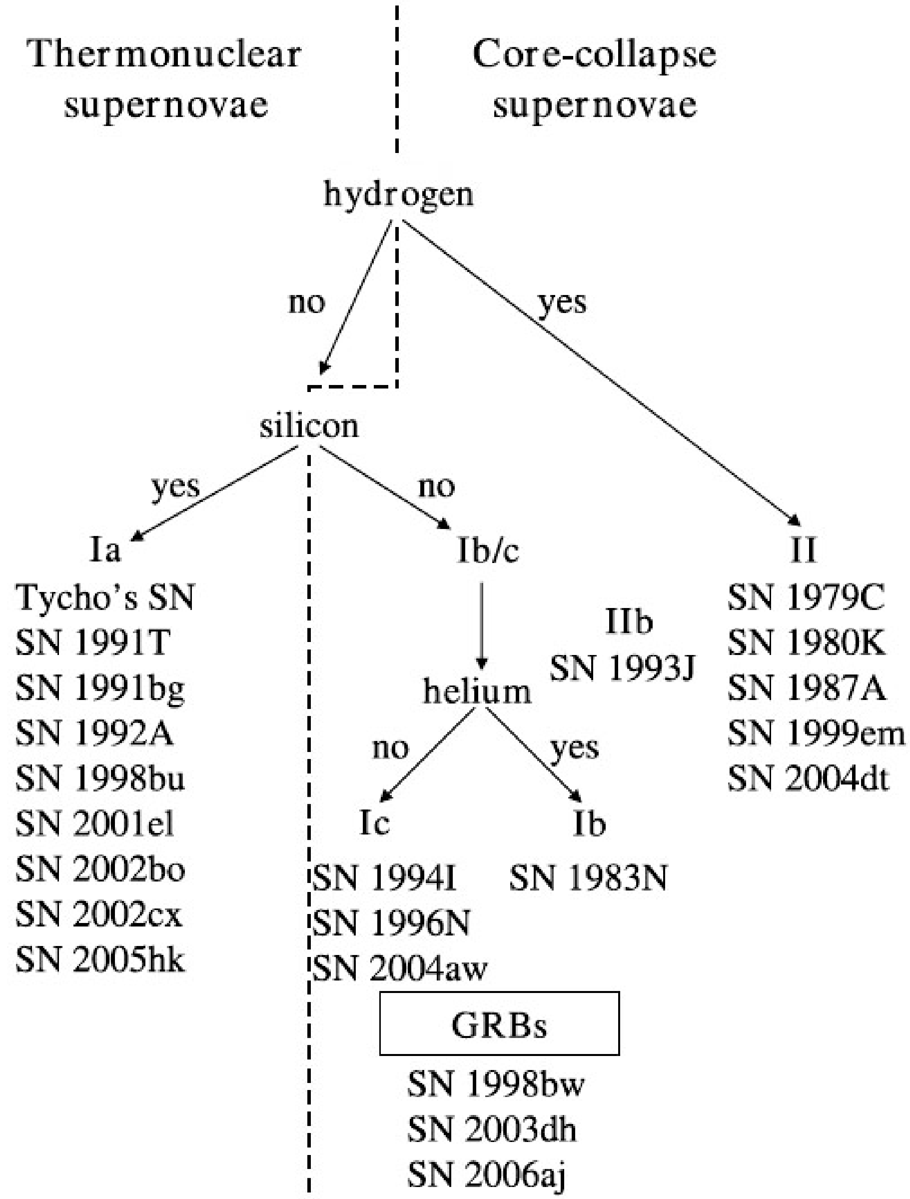
HST/NASA/ESA.

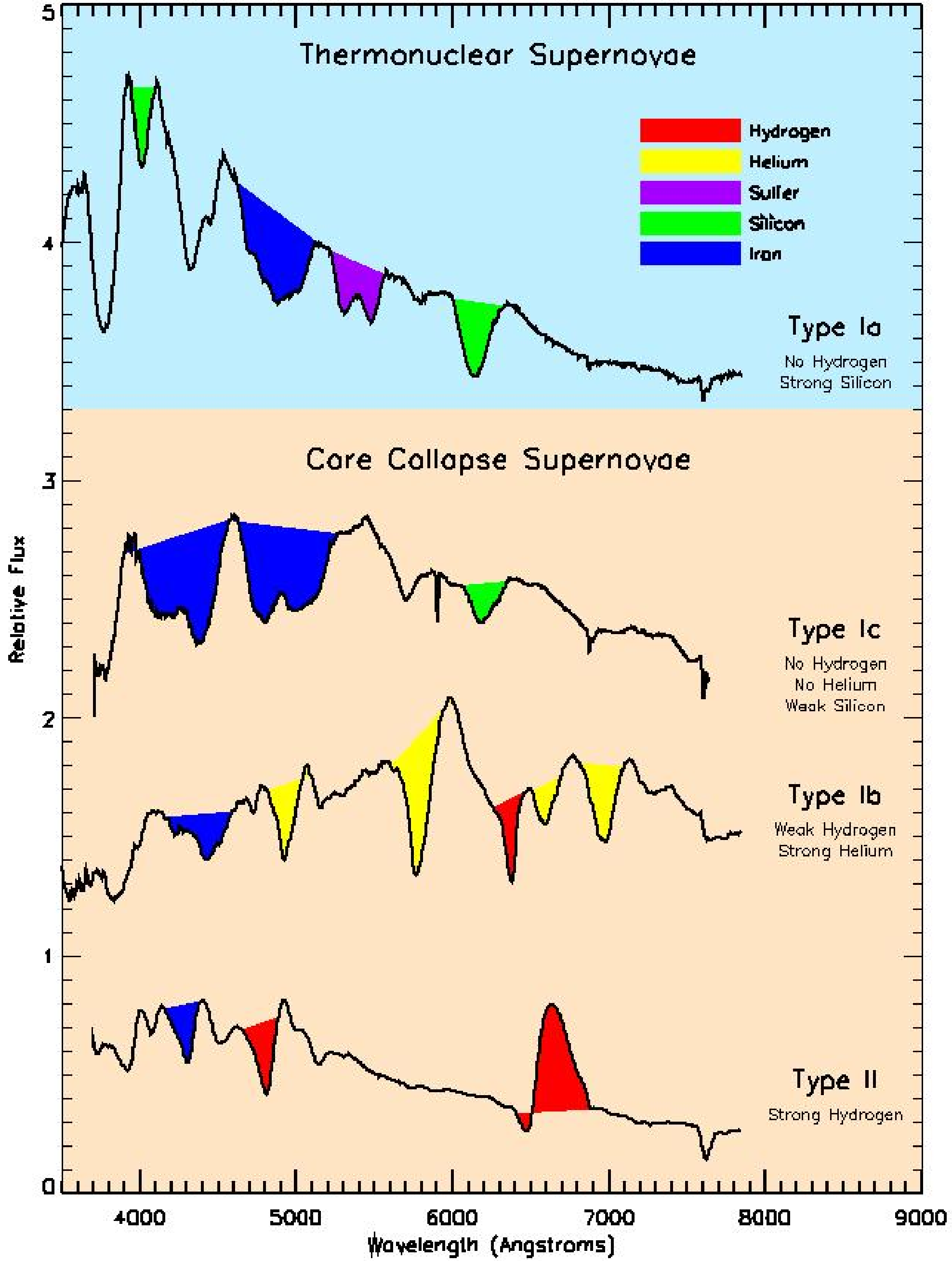
Classification of SN



Classification of SN



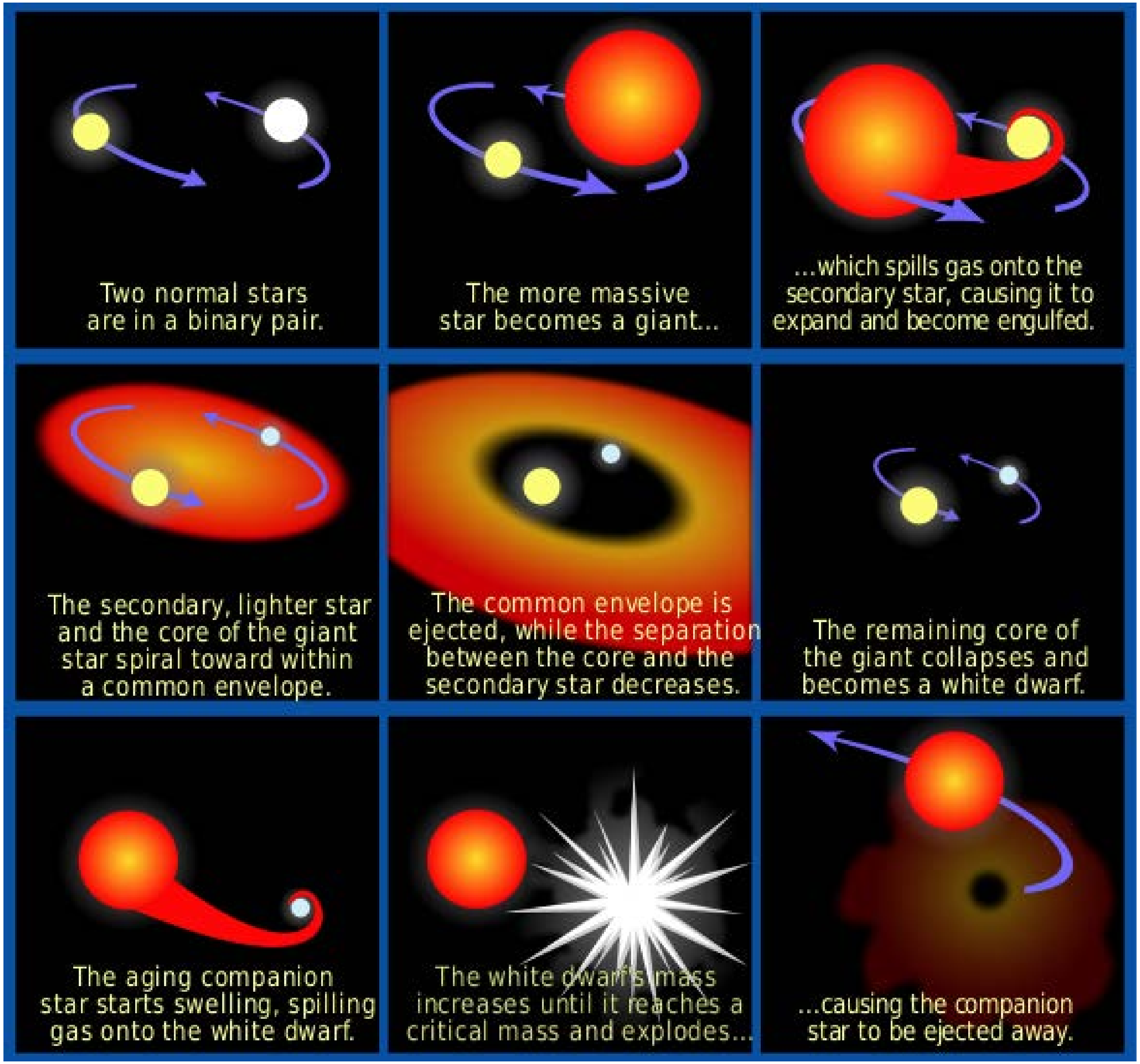




Daniel Kasen

Type Ia SN

Thermonuclear explosion of white dwarf composed of C/O atoms

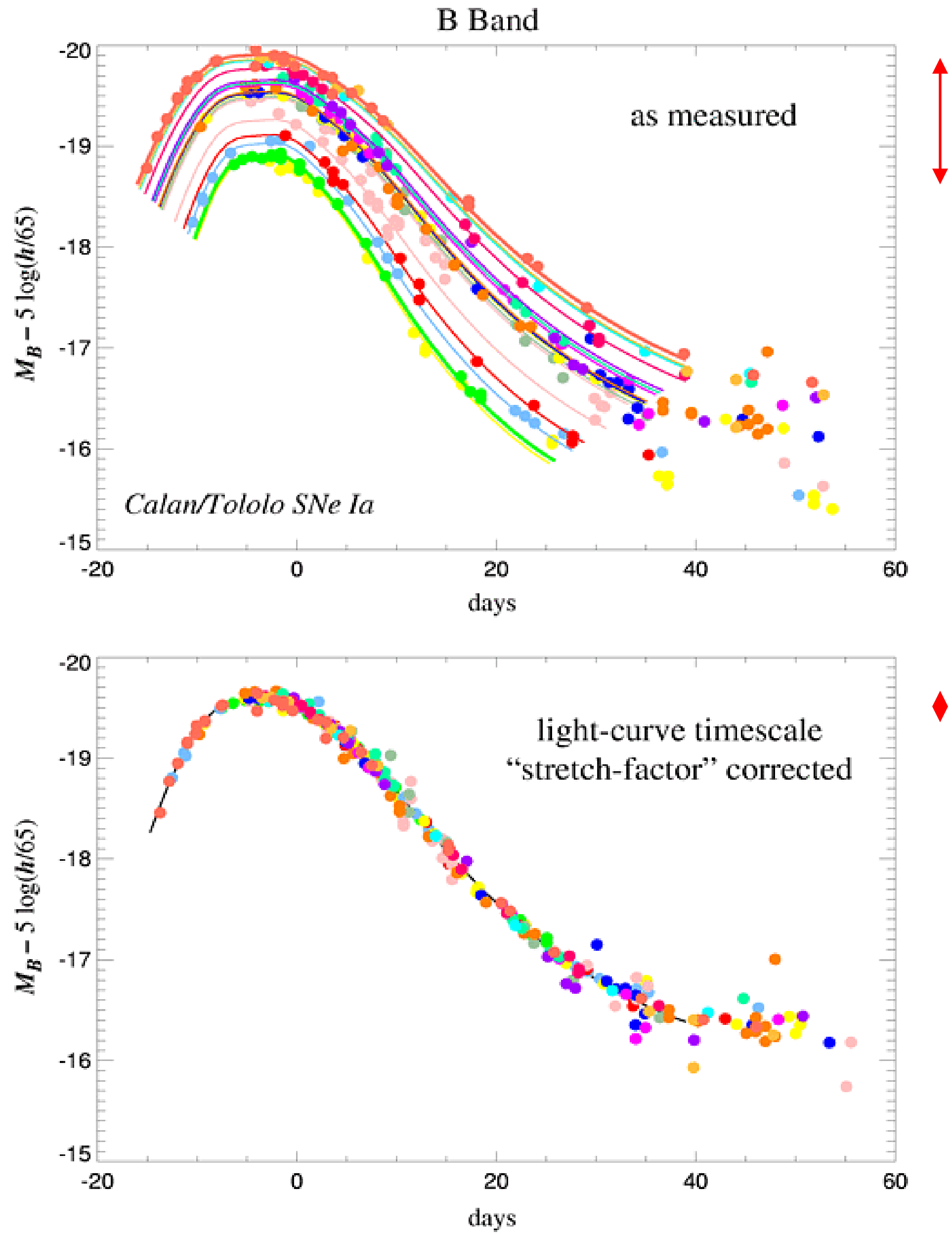


Almost constant maximum brightness of type Ia SN → standard candle

Light curve

σ~ 0.15 in magnitude
(~7% in distance)

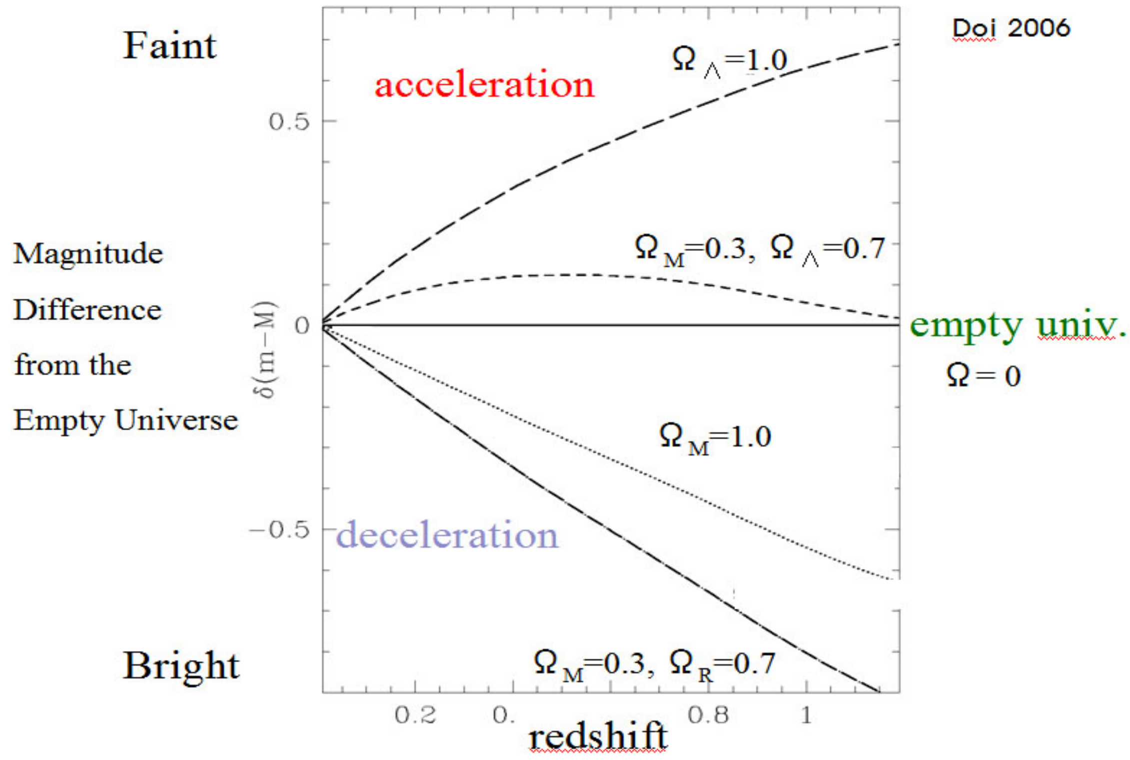
절대등급



Kim, *et al.* (1997)

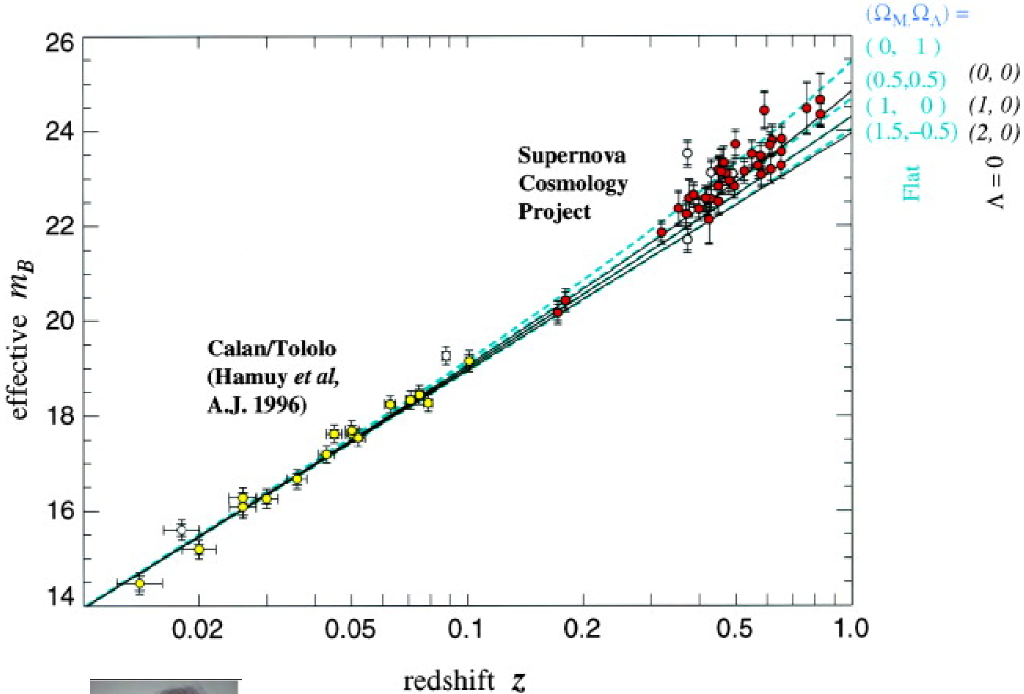
Ω, z dependence of the apparent magnitude of a standard candle

Composition of matter → expansion scenario → magnitude of type Ia SNe

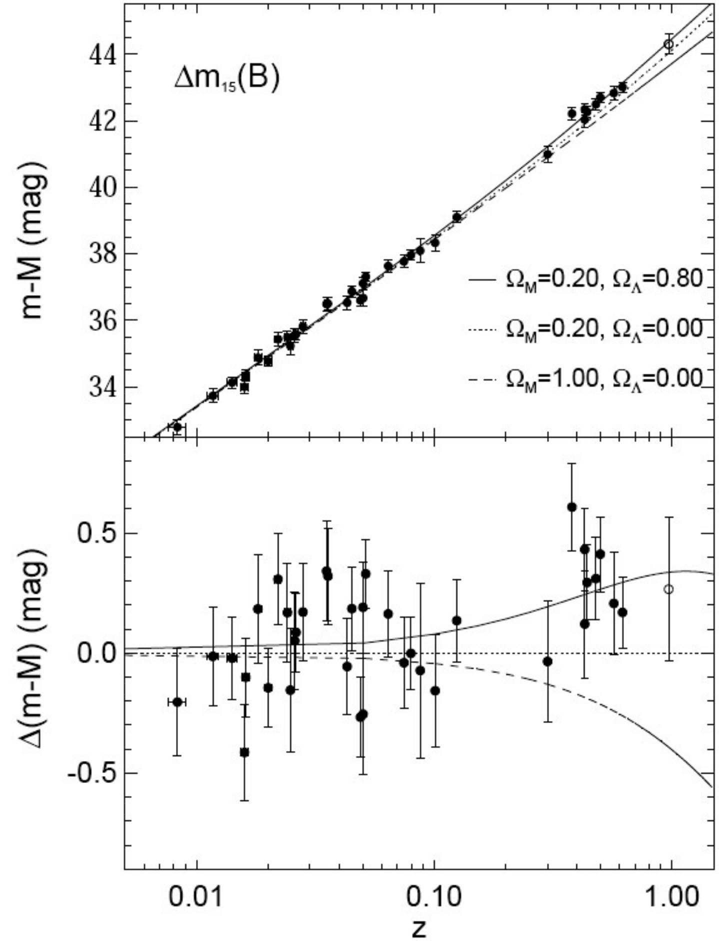


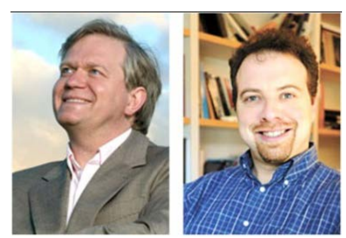
$$m(z) - M_B = -5\log(H_0) + 25 + 5\log[H_0 D_L(z, \Omega_m, \Omega_{DE}, w)] + K_{Bx} + A$$

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



Perlmutter et al. (1999)
42 SN Ia (33 SN Ia 1997)



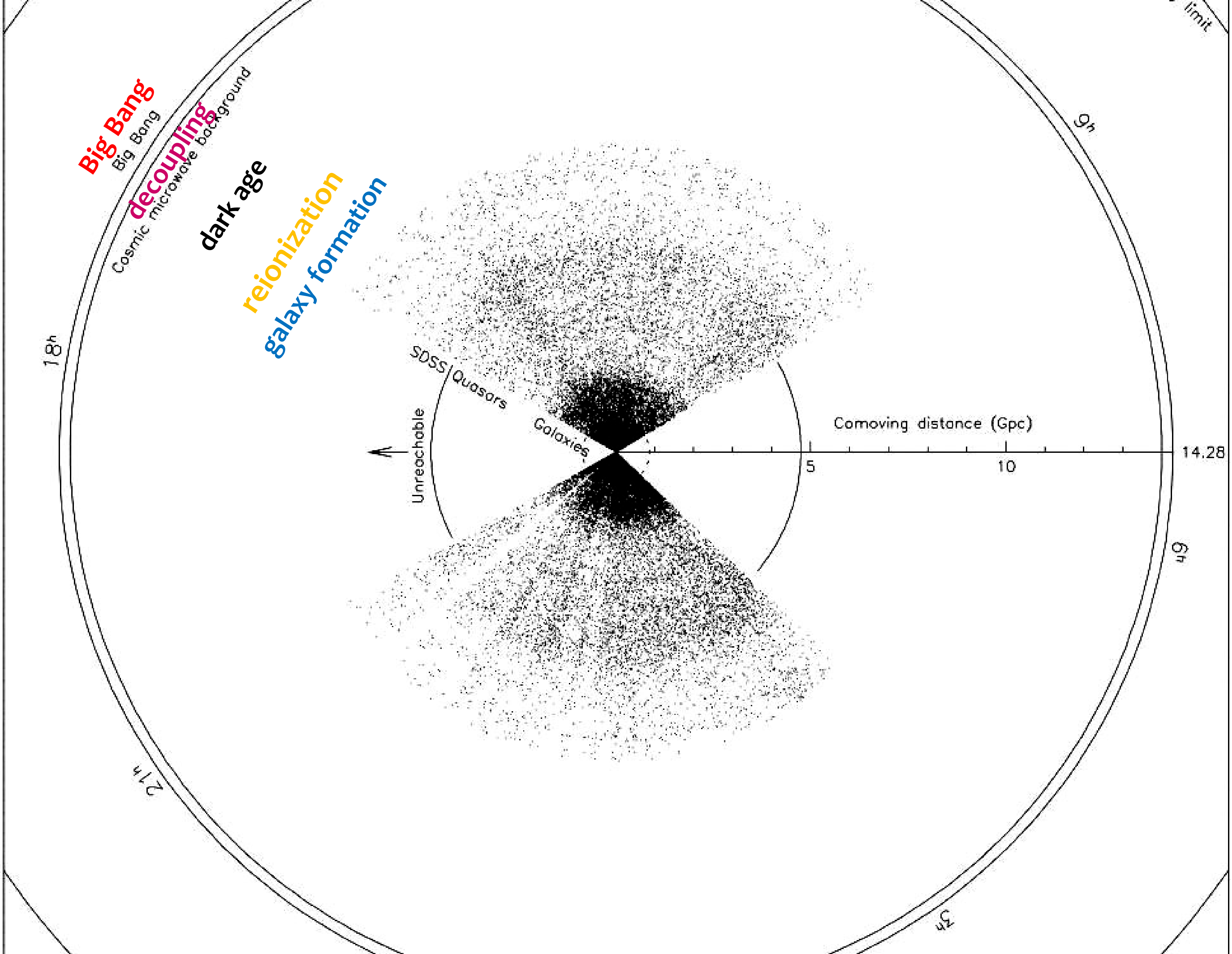


Riess et al. (1998)
High-z Supernova Search Team (10 SN Ia)

The data are strongly inconsistent with a Λ=0 flat cosmology, the simplest inflationary universe model.

→ Accelerating universe! NP2011

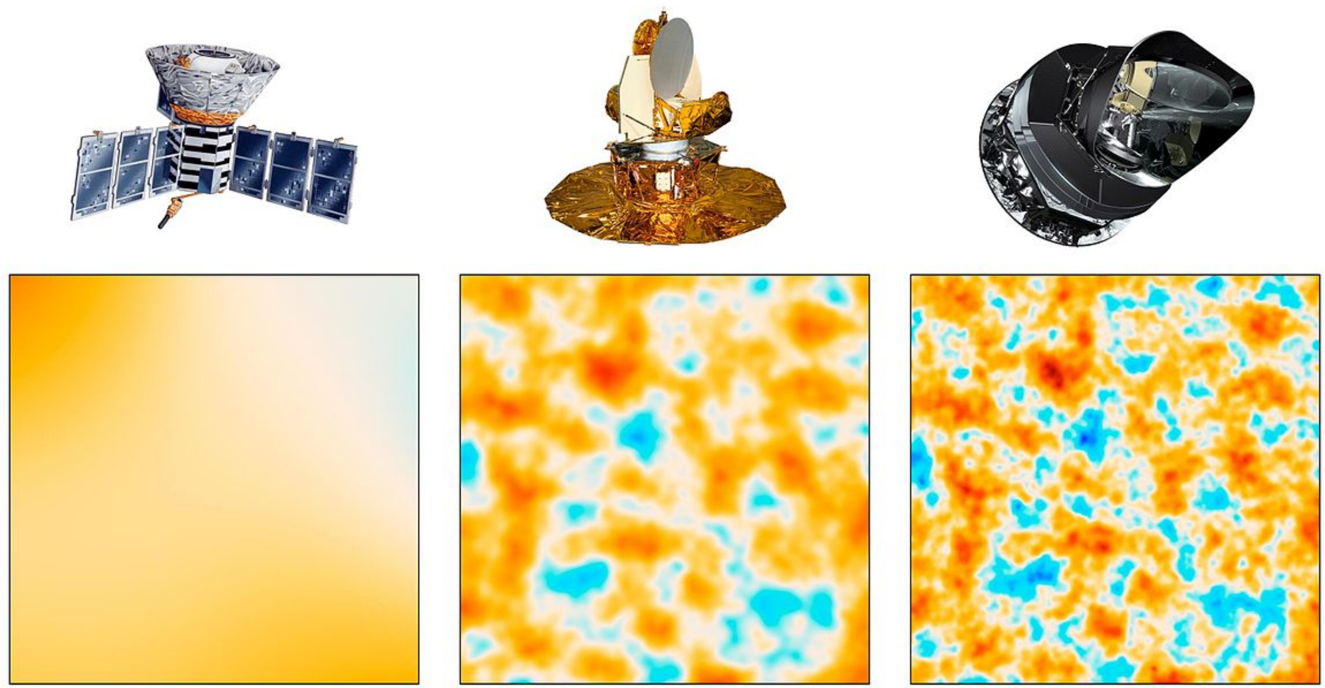
→ Dark energy? New gravitational law?



Big Bang
decoupling
dark age
reionization
galaxy formation
Big Bang
Cosmic microwave background
SDSS Quasars
Galaxies
Unreachable
Comoving distance (Gpc)
5
10
14.28
18h
9h
6h
21h
3h
limit

Cosmic Microwave Background Radiation

Experiments



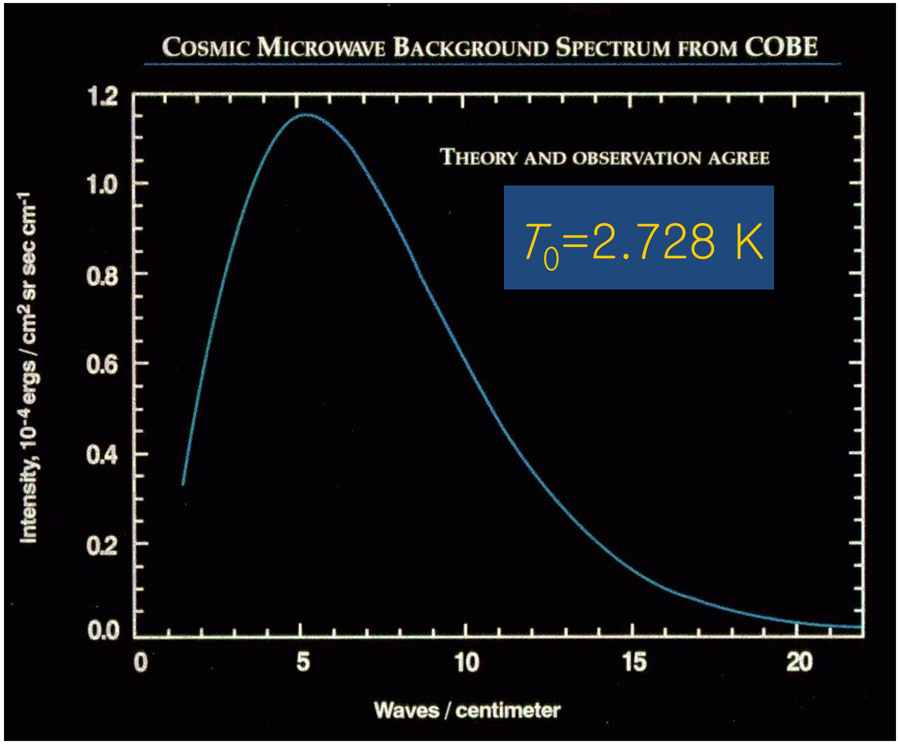
COBE 1989

WMAP 2001

Planck 2009

Cosmic Background Explorer (COBE)

FIRAS : CMB Spectrum

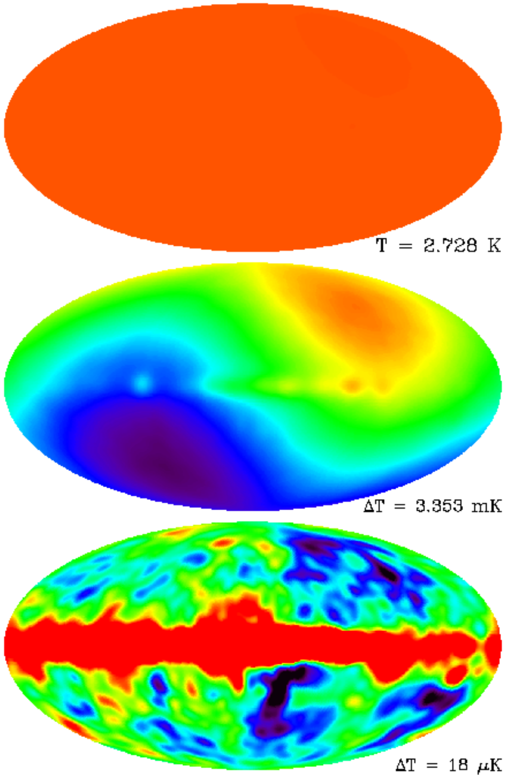


DMR : CMB Anisotropy

Monopole (mean)

Dipole (Doppler Shift)

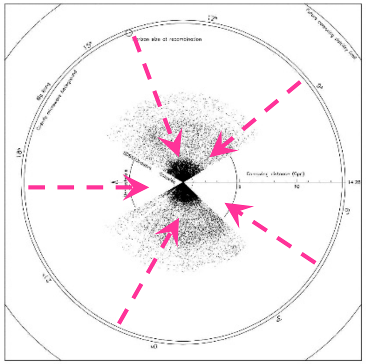
Anisotropy

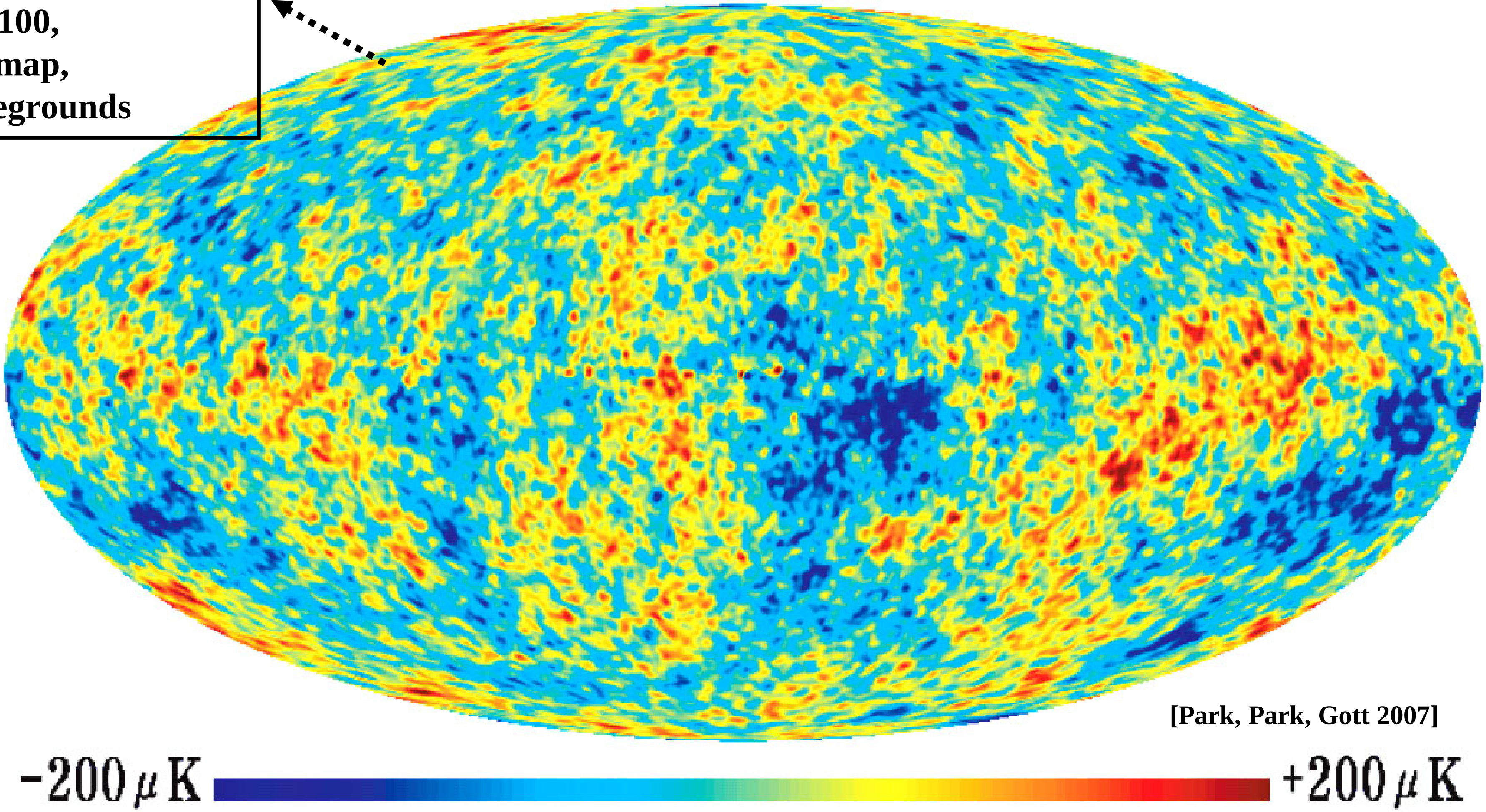


WAP's CMB Map

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

z~1100,
2d map,
foregrounds



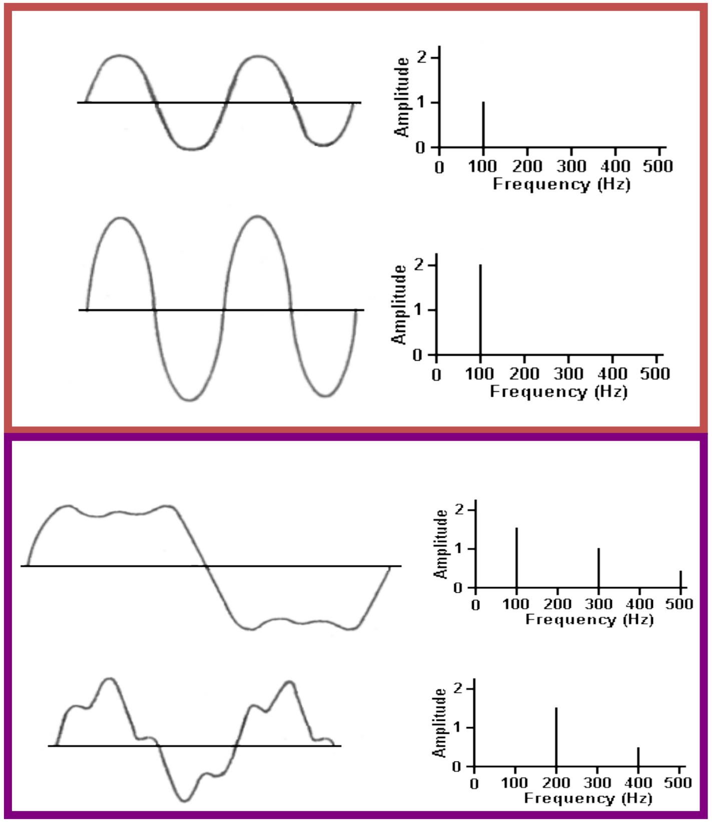


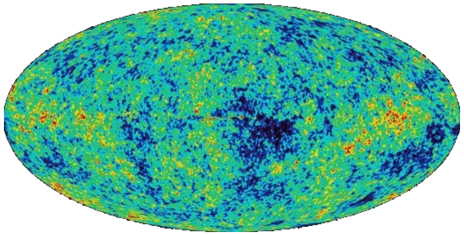
[Park, Park, Gott 2007]

Power Spectrum

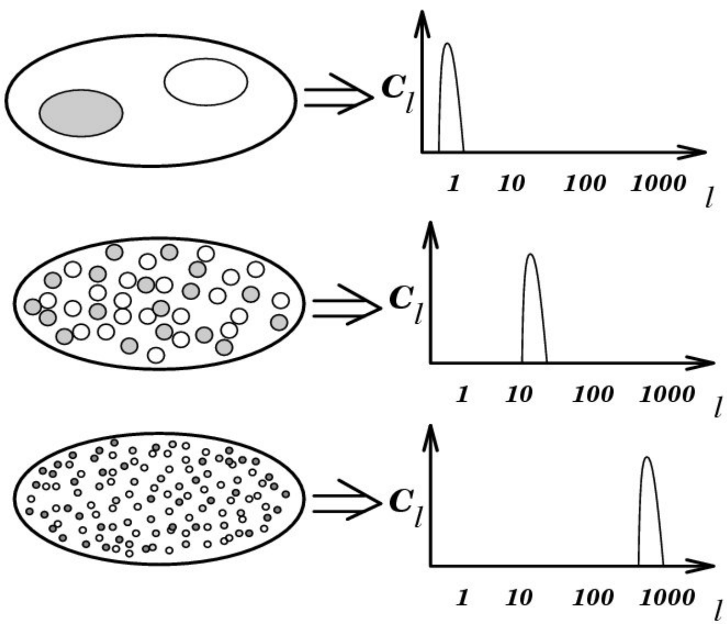
$$\frac{\Delta T}{T}(\theta,\phi) = \sum_{l=0}^{\infty} a_{lm} Y_{lm}(\theta,\phi)$$

$$C_l = \frac{1}{2l+1}\left\langle |a_{lm}|^2 \right\rangle$$





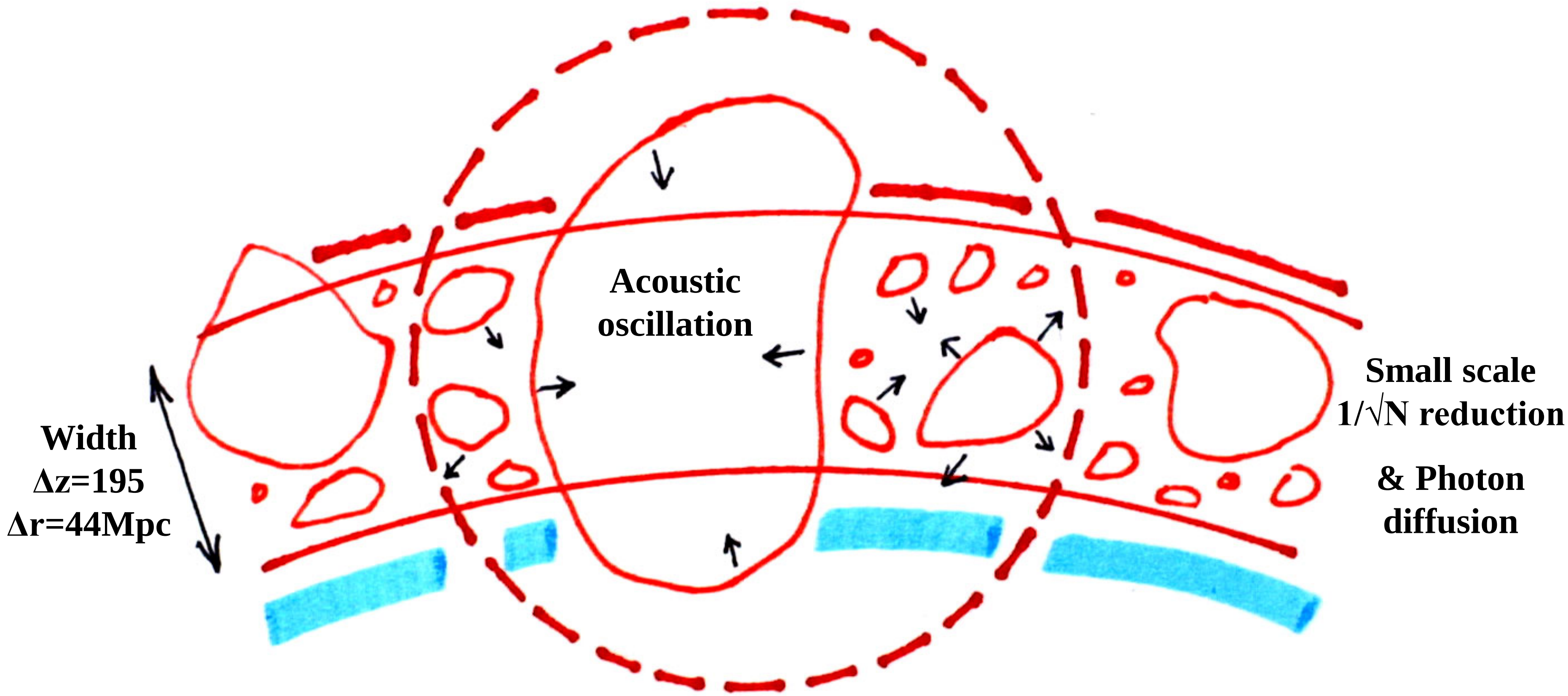
Maps **Power Spectra**



$$h(t) = \int \tilde{h}(\omega) e^{-i\omega t} dt$$

$$P(\omega) = \left\langle \left|\tilde{h}(\omega)\right|^2 \right\rangle$$

Decoupling surface



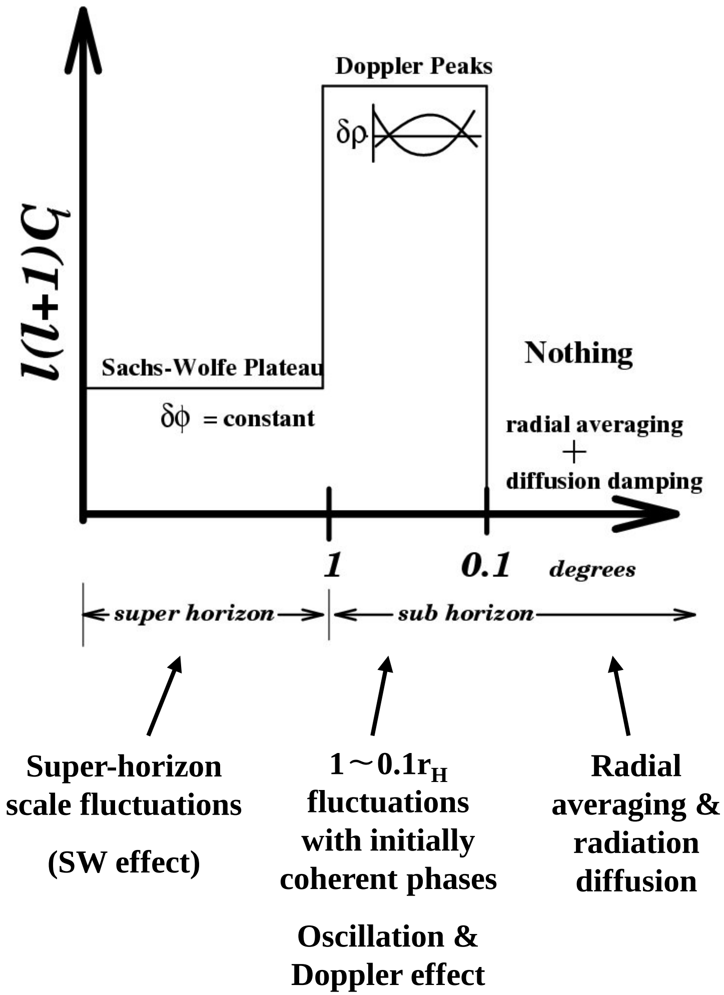
Baryonic λ_{Jb} 2200Mpc $\gg$ Horizon r_{Hdec} 320Mpc

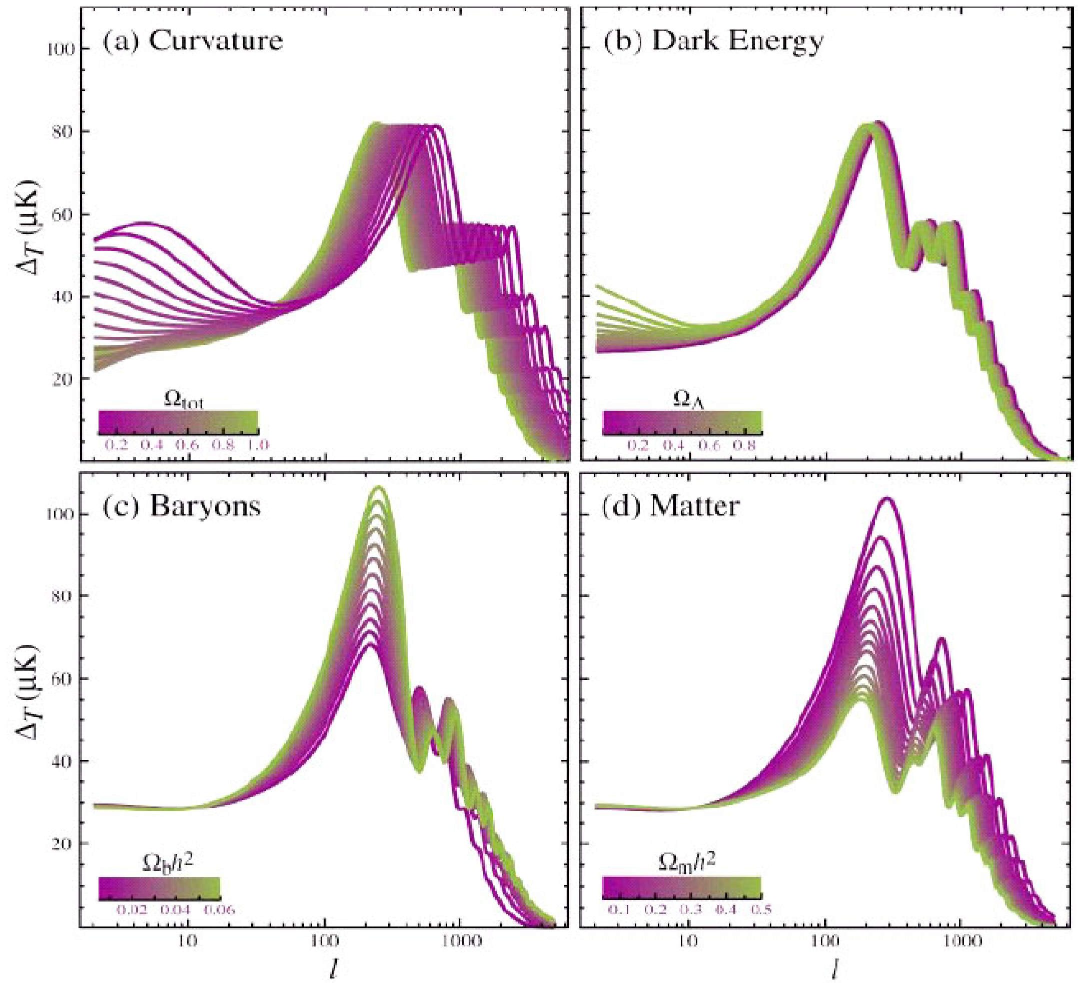
> Sound horizon λ_s 270Mpc

>Width Δr 44Mpc

> Photon Diffusion λ_D 14Mpc

Shape of T Power Spectrum

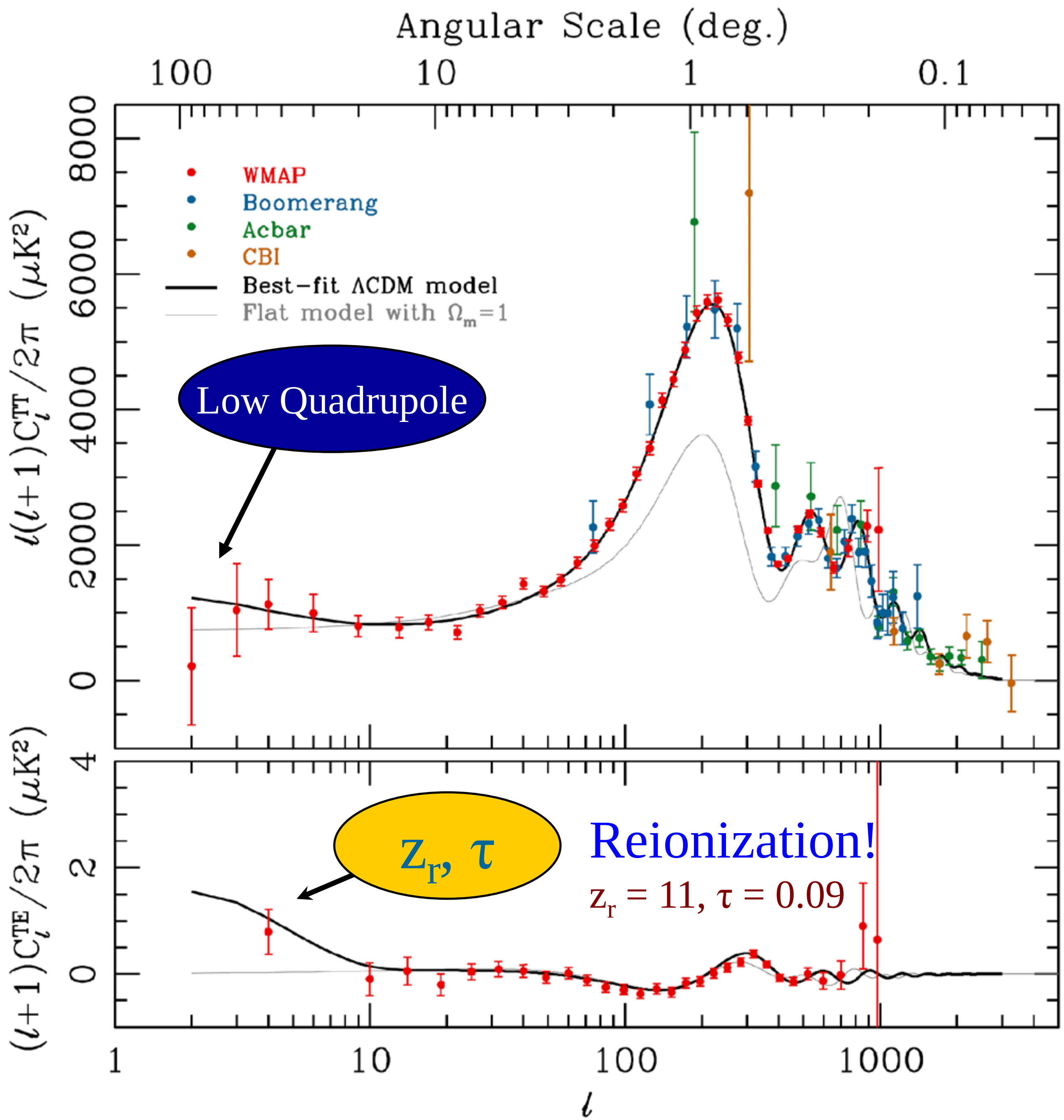


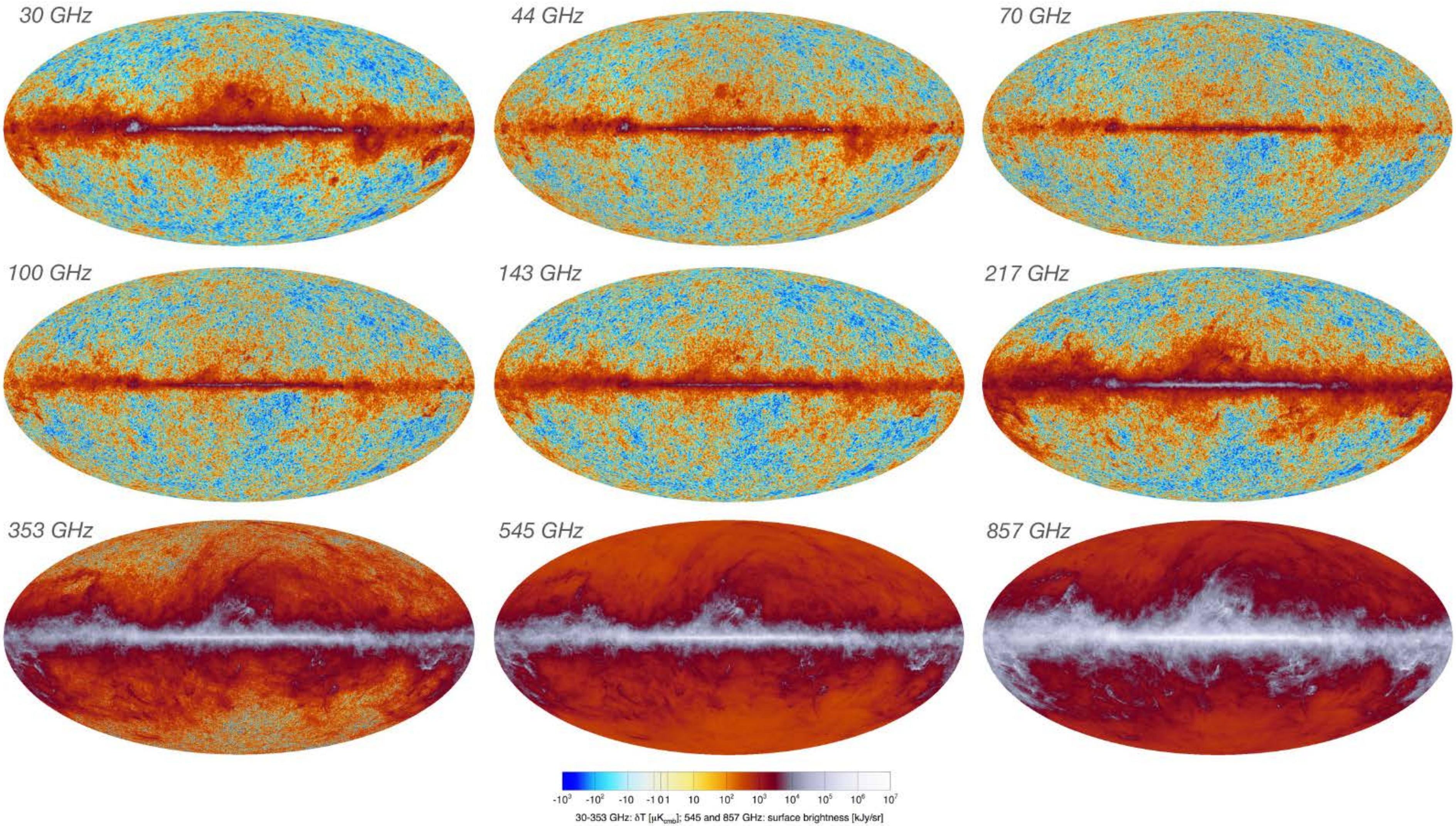


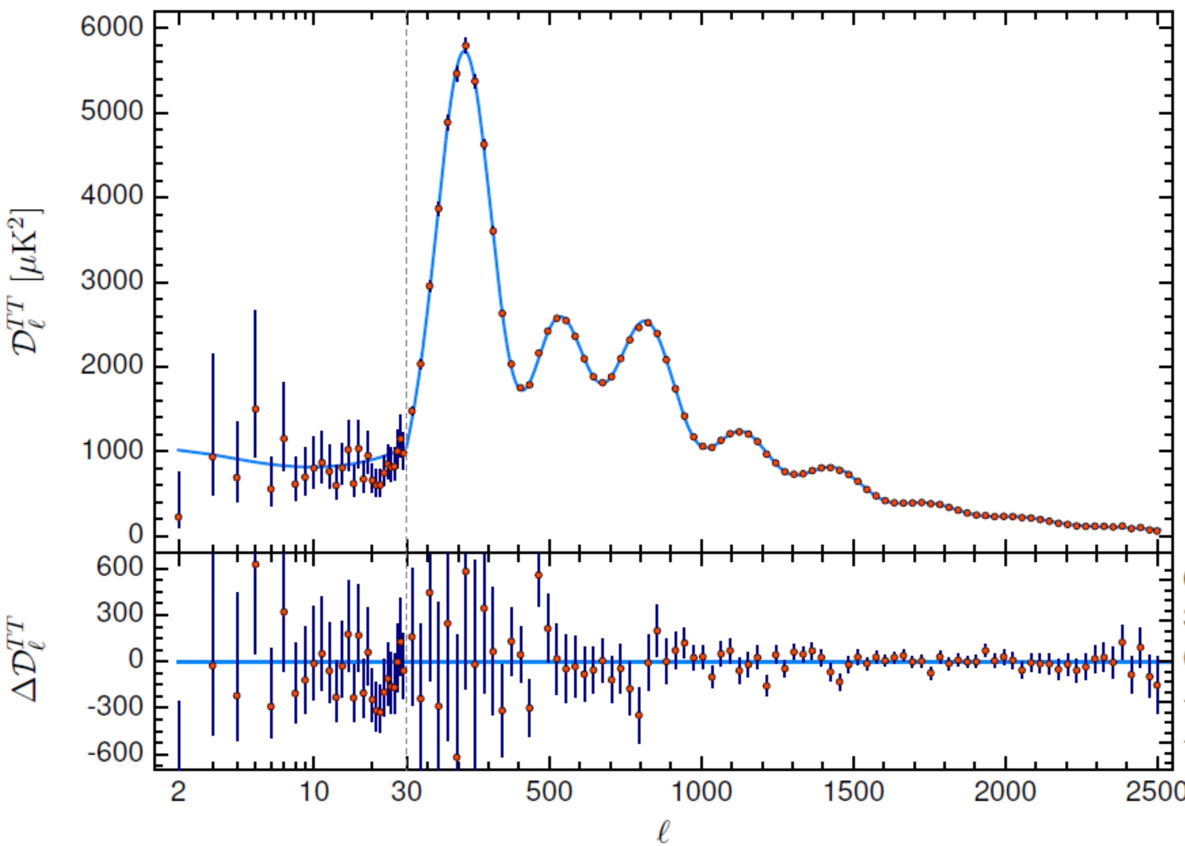
WMAP 3-yr Power Spectrum

T-T

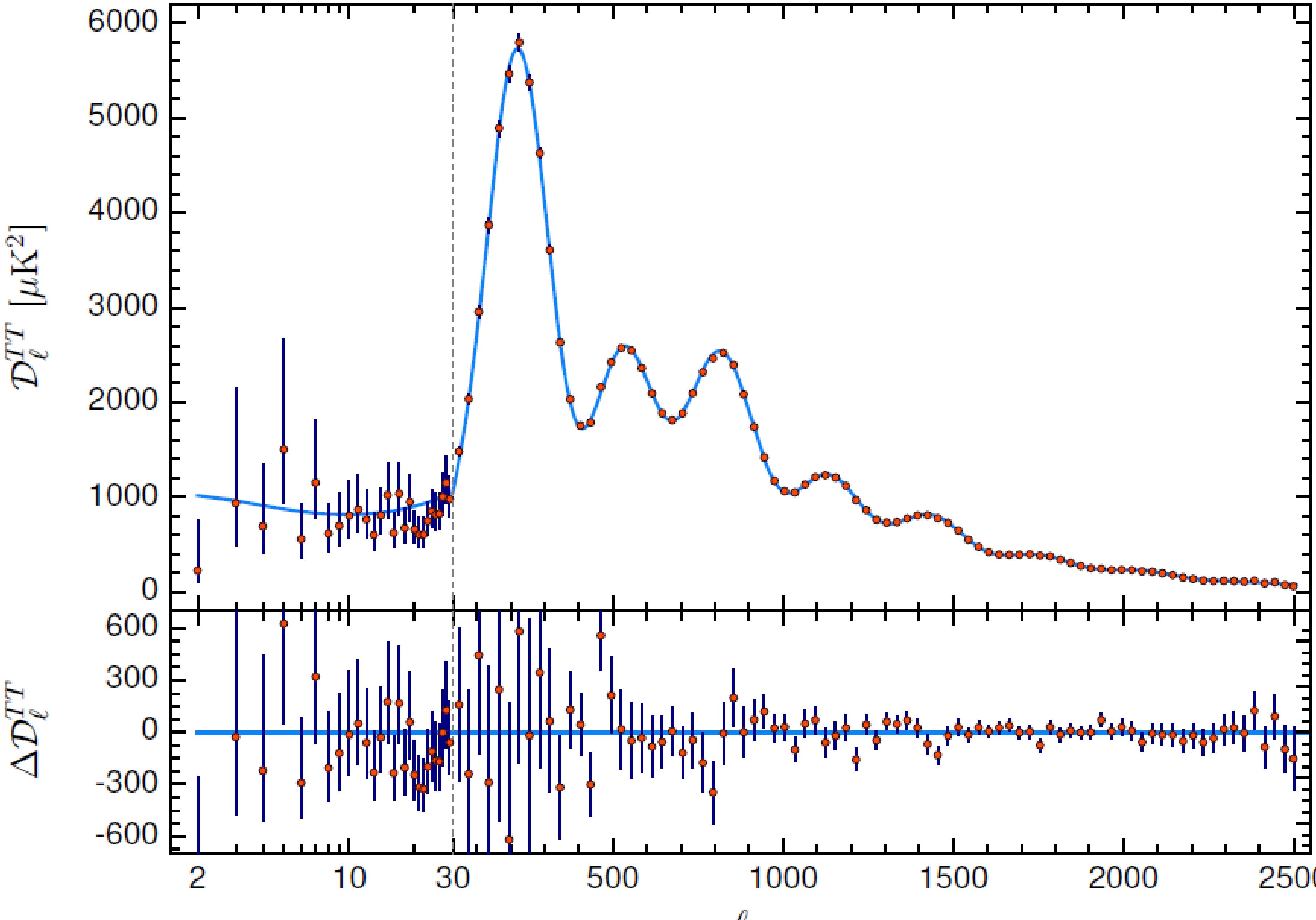
T-E




30 GHz
44 GHz
70 GHz
100 GHz
143 GHz
217 GHz
353 GHz
545 GHz
857 GHz
-10^3 -10^2 -10 -1 0 1 10 10^2 10^3 10^4 10^5 10^6 10^7
30-353 GHz: δT [μK_cmb]; 545 and 857 GHz: surface brightness [kJy/sr]



Planck Surveyor 2018



$\mathcal{D}_\ell^{TT}$ [μK^2]
6000
5000
4000
3000
2000
1000
0
$\Delta\mathcal{D}_\ell^{TT}$
600
300
0
-300
-600
2
10
30
500
1000
1500
2000
2500
ℓ

Growth of structures

Linear evolution of density fluctuations
Linear perturbation theory
Solutions : $\delta \sim a(t)$ [Einstein-de Sitter universe]

Formation of nonlinear objects
Spherical collapse
Dark matter halos

Dark matter halos

Hierarchical growth of dark matter halos through mergers
Radial density profiles (spherically symmetric)

$$\rho(r) = \frac{\rho_0}{(r/r_s)^{\alpha}(1+r/r_s)^{3-\alpha}}$$

: cusped. α=1 NFW profile

$$\rho(r) = \rho_e \exp[-d_n((r/r_e)^{1/n}-1)]$$

: cored. Einasto profile

Dark Matter and Dark Energy

Dark matter
Dynamical mass and visible mass of bound astronomical systems
Invisible but has attractive gravitational force

Dark energy
Accelerating universe
Invisible and repulsive gravitational force

Evidence for dark matter

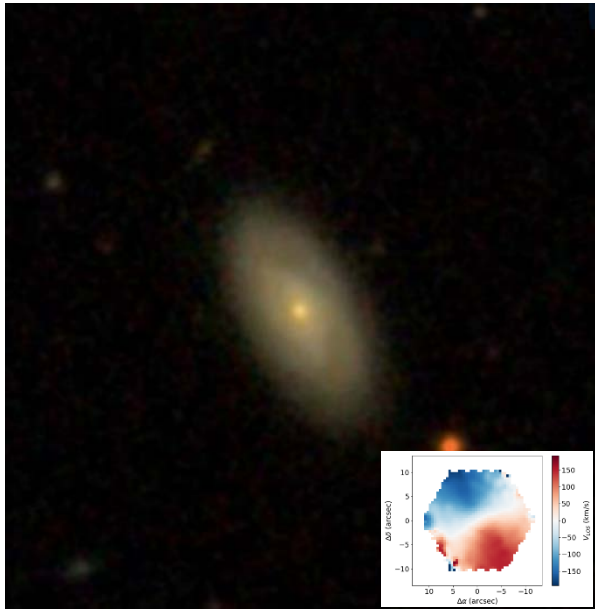
DM in galaxies (E and dwarfs)
Doppler shift of emission lines (HI, CO, Ha). v/r=GM(r)/r^2. v ~ cont. & M(r) ~ r
disk+halo model for S - DM halo dominated & rising v(R) for faint S,
disk dominated & decreasing v(R) for massive S.
stars+dark matter+hot gas model for E: increasing M(R). need DM to be bound

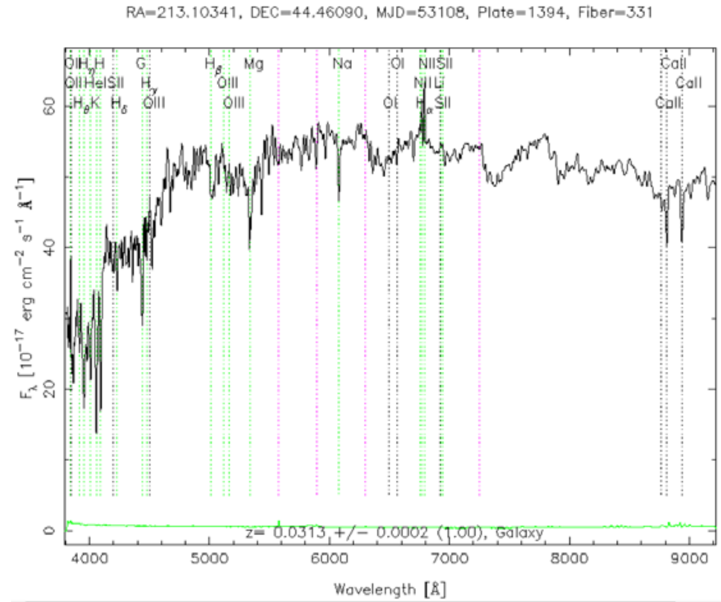
Local Group: M31 and MW → dynamical mass ~ 3.5×10^{12}M_sun.
total visible mass ~ 2×10^{11} M_sun

Dwarf spheroidals (dSph): r~100pc & σ~10km/s. rising v(R) & dominated by DM
Ultra-faint dwarfs (UFDs): r~100pc, $M \sim 10^3 M_\odot$. $M_{halo} > 100\ M_{baryon}$.
most DM dominated objects in the universe!

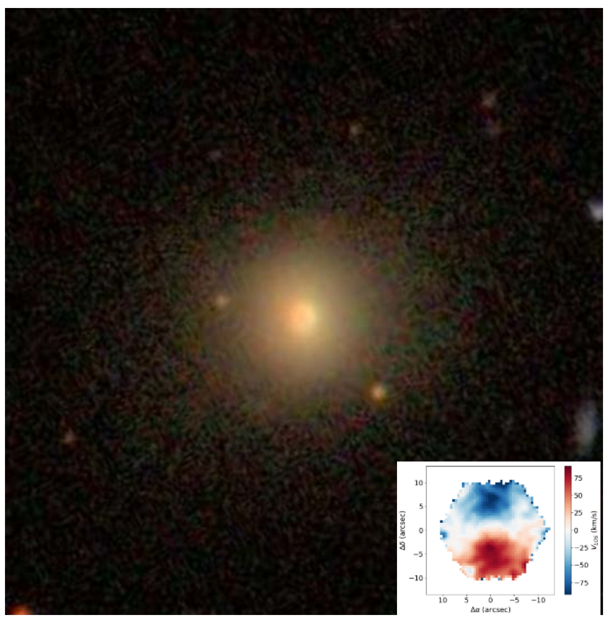
missing mass in the Coma cluster
33Fritz Zwicky: ~1000 galaxies in Coma
→ dispersion 10x larger than expected from visible mass. virial theorem
→ 160x more missing mass, which is dark
Today: Coma - 85%DM, 14% hot ICM, 1% stars

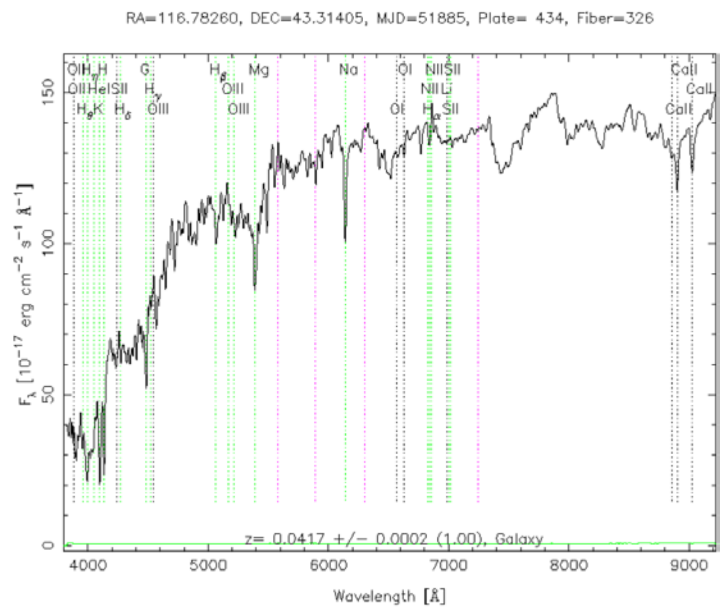
CGCG 247-010
(z=0.031306)



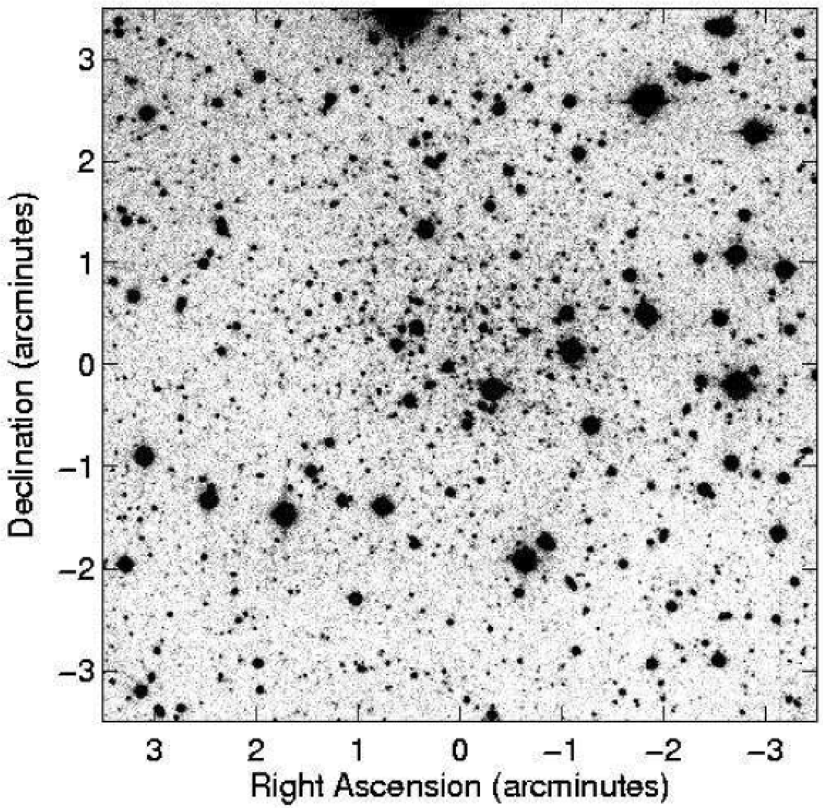


CGCG 260-026
(z=0.031306)





Andromeda IX (dSph)



Draco (dSph)

M/L ~ 93

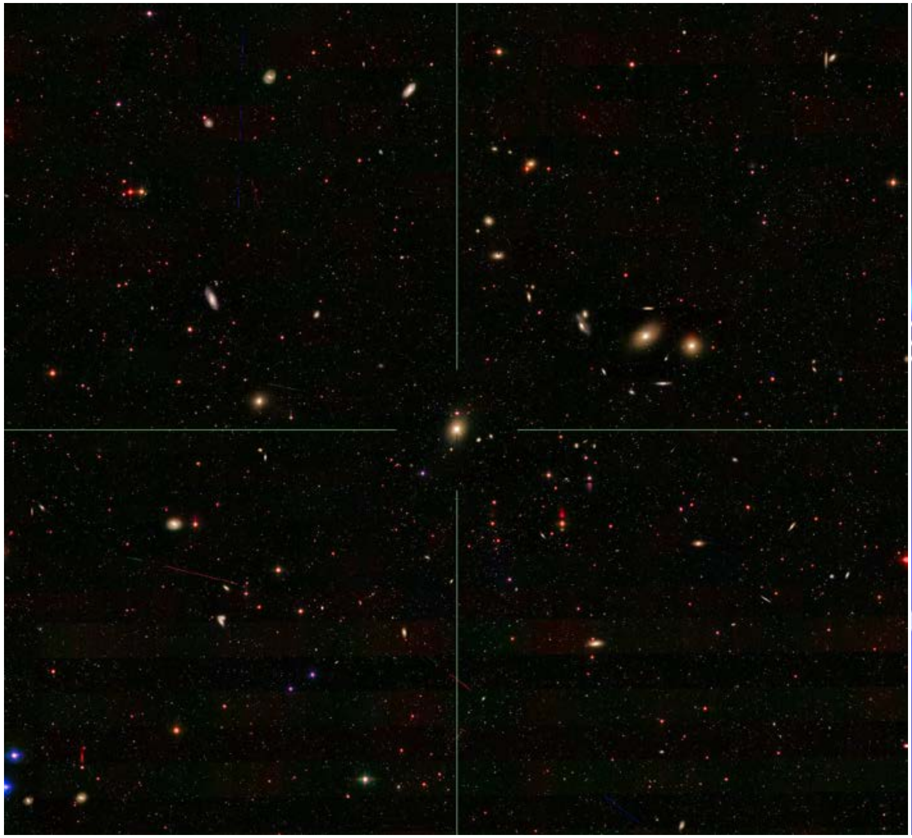
M/L ~ 330

Evidence for dark matter

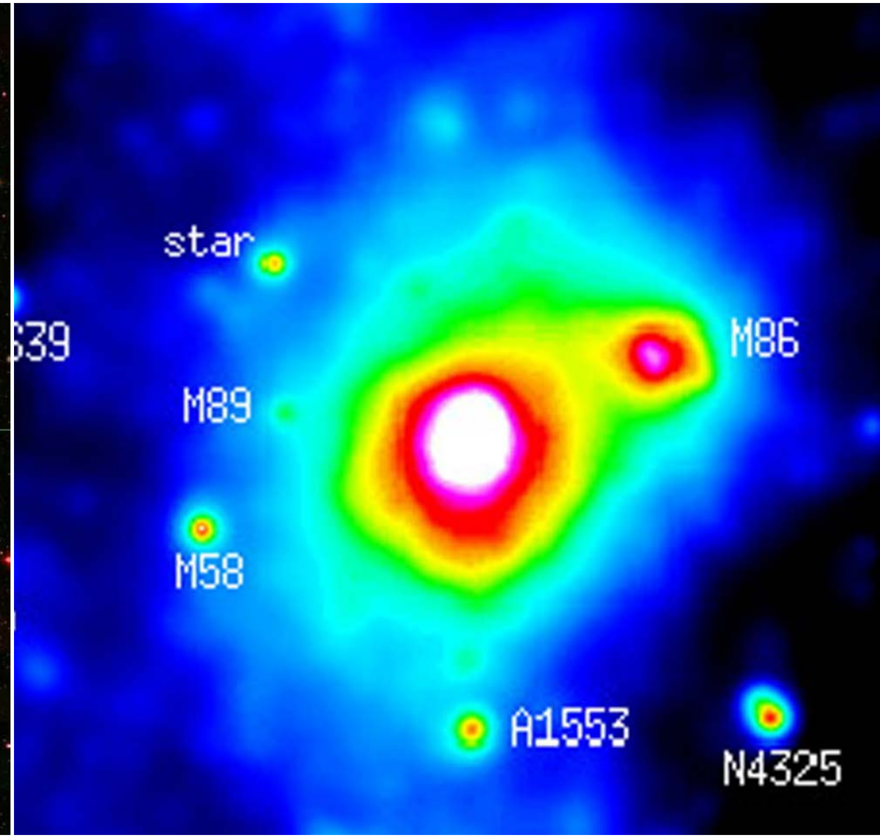
DM in groups and clusters derived from visible light and X-rays
groups: visible matter+DM+hot gas. $M_{grav} > 3M_{baryon}$
clusters: visible matter+DM+hot ICM. DM represents 85%

merging clusters
galaxies, intracluster hot gas(ram pressure, emit X-rays), DM get separated
→ separation of gravitational potential from radiating plasma.
strongly-lensed images+weak lensed background sources
→ total mass ~ galaxies but not agree with X-ray emitting gas
Mass CF of galaxies and dark halos
Abundance matching btw DM halo mass function & stellar mass function of galaxies

CMB
DM feels attractive self-gravity, baryon self-gravity and pressure
position and amplitude of the first peak --> Omega_m ~ 0.3 & there must be DE
if no DM, too large CMB anisotropy needed to form galaxies



Virgo : optical



Virgo : X-ray

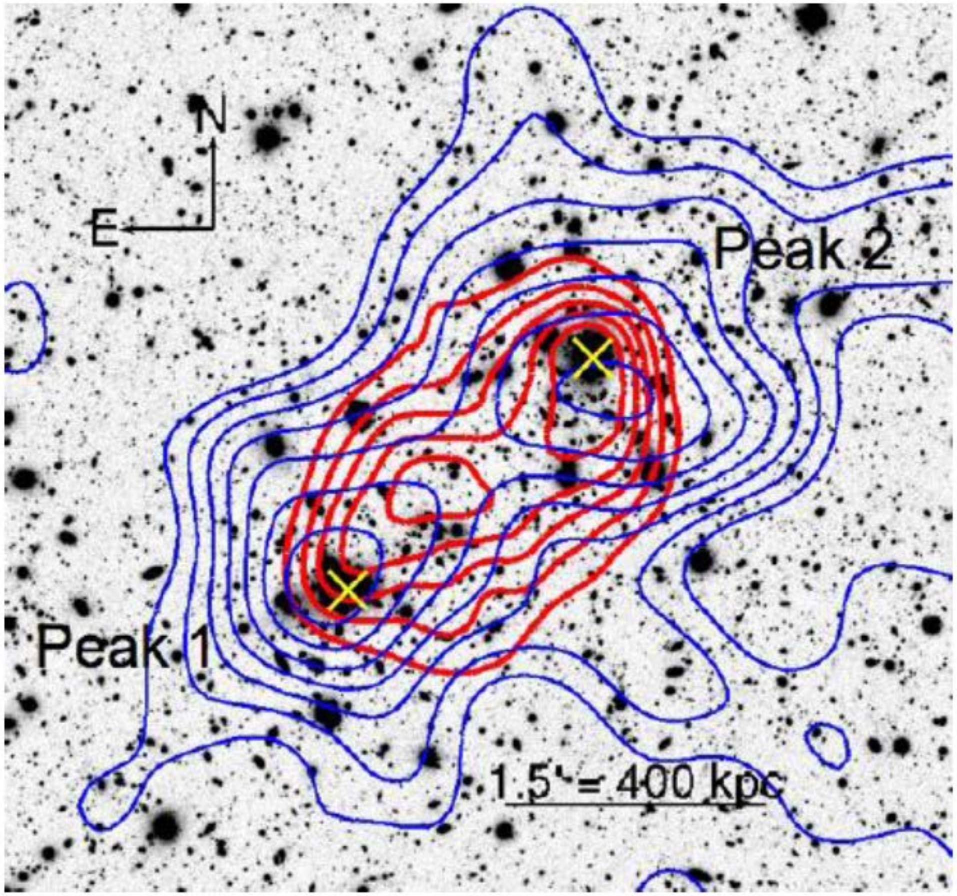


Figure 20. The A1758N merger from B. Ragozzine & al. [63]. The blue contours represent the weak lensing mass reconstruction made from a background galaxy density of 24.0 galaxies/arcmin^2. The outer blue contour begins at surface mass density $\kappa = 0.07$ and each contour increases in steps of 0.045 up to $\kappa = 0.34$. The red contours follow the X-ray gas mass obtained in the Chandra exposure. The NW cluster's BCG aligns with the X-ray gas and the weak lensing peak. The SE cluster's BCG and weak lensing peak are well separated from the X-ray gas, which has a bright peak near the midpoint of the two weak lensing peaks.

Roles of dark matter in cosmology and astrophysics

- Matter contents of the universe
Geometrically flat universe
baryon, dark matter, dark energy; photon, neutrino, leptons, magnetic field

- Epoch of structure formation
CMB anisotropy and density fluctuation at t_{dec} and at the present epoch

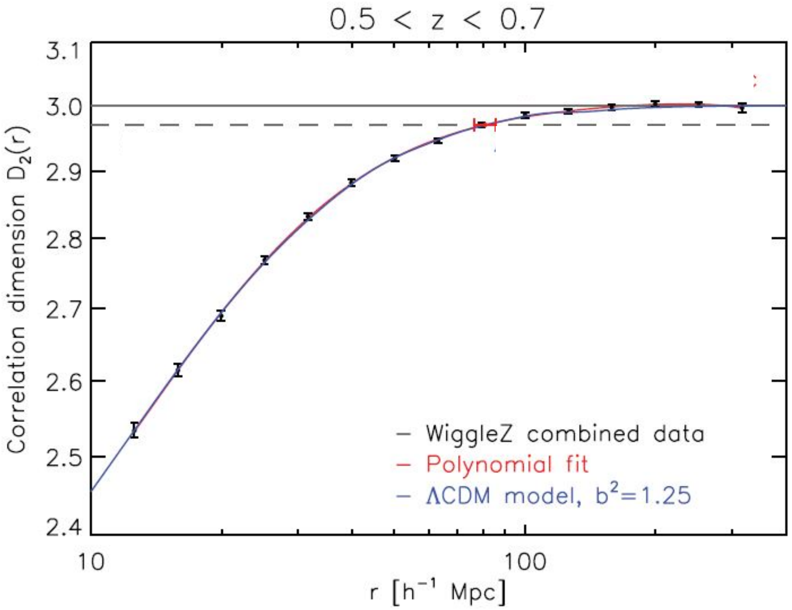
- Large-scale structures in the universe and galaxy formation
shape of power spectrum
Top-down vs bottom-up scenarios for structure formation

Some Cosmological Tests

Homogeneity and Isotropy

A basic assumption of the standard cosmology through the cosmological principle.

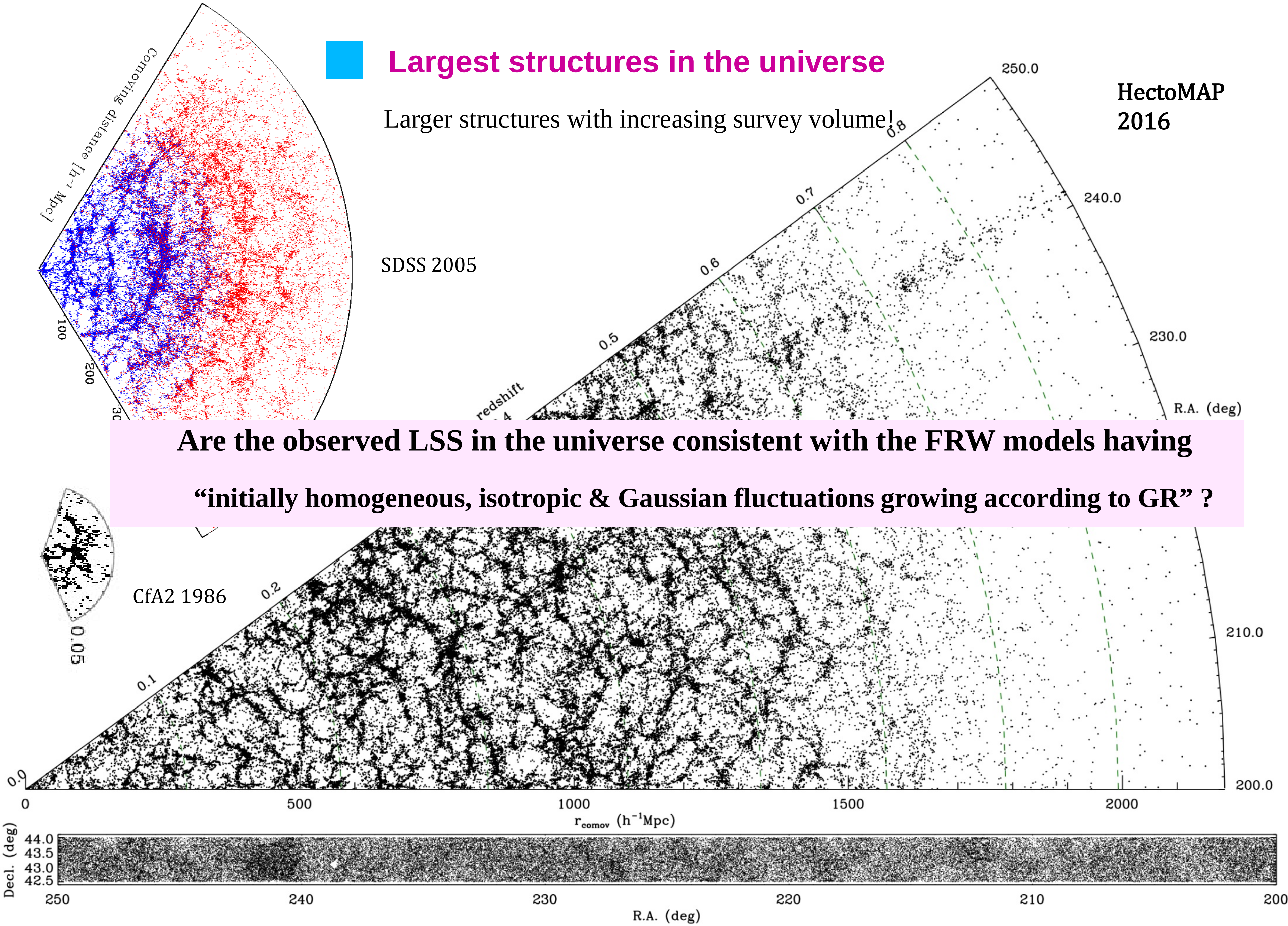
→ LSS observations:
The universe approaches homogeneity and isotropy as the scale increases.



Consistency between observations and ΛCDM [Scrimgeour et al. 2012]

Largest structures in the universe

Larger structures with increasing survey volume!



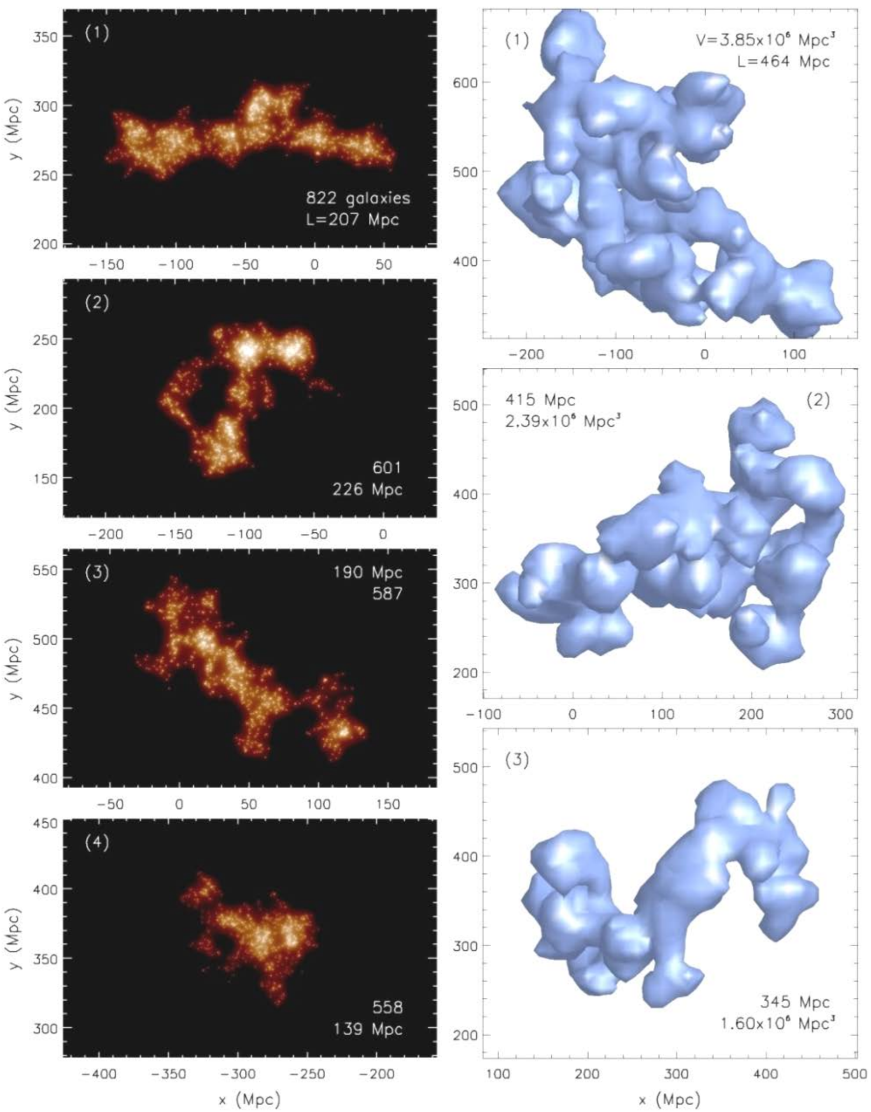
Are the observed LSS in the universe consistent with the FRW models having

"initially homogeneous, isotropic & Gaussian fluctuations growing according to GR" ?

[Park+ 2012]

$d_c = 0.62\ d_{bar} = 5.6\ h^{-1}$Mpc
$\delta_{th} = n_{th}/n_{bar} - 1 = 3.2$

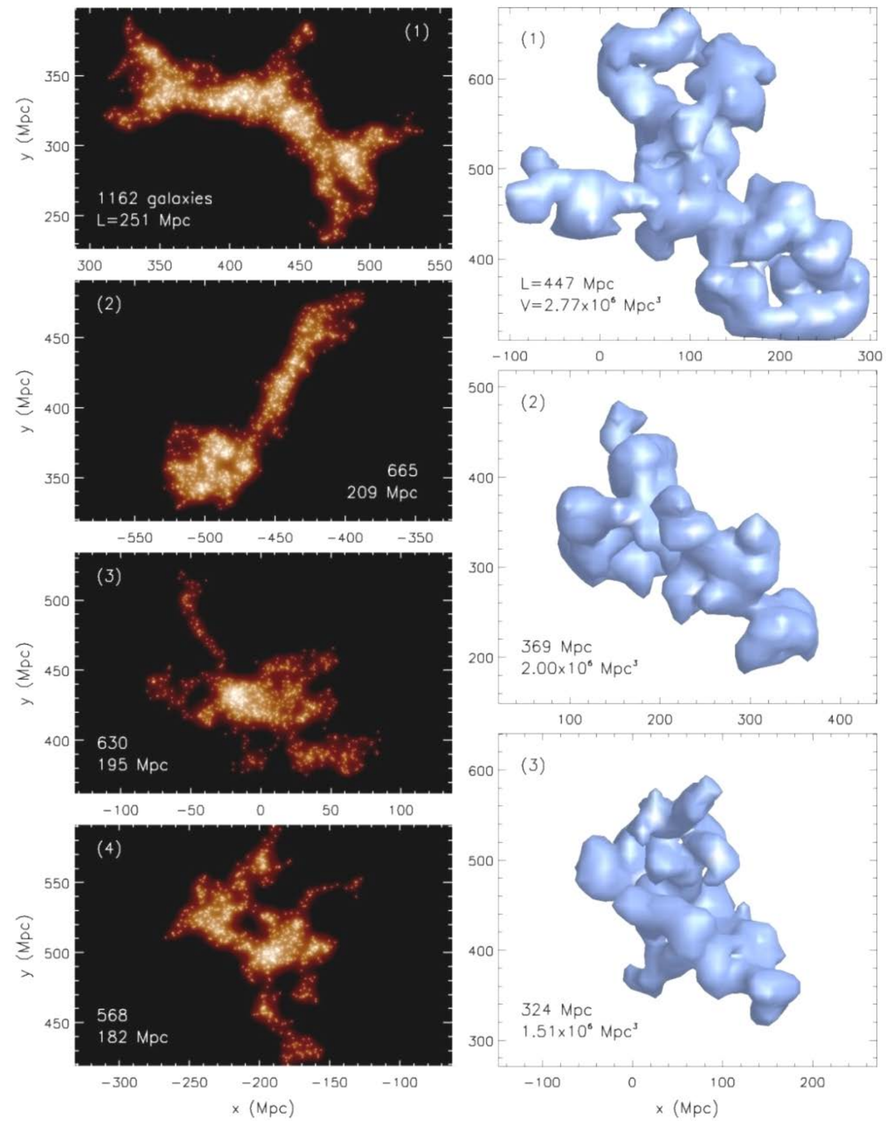
$r_{ball} = 1.45\ d_{bar} = 13.1 h^{-1}$Mpc



Top 4 high-density and top 3 low-density LSSs from SDSS DR7 Main galaxies ($d_{bar}=9h^{-1}$Mpc)

$d_{c,max} = 0.616 \pm 0.014\ d_{bar}$
for 200 mock surveys

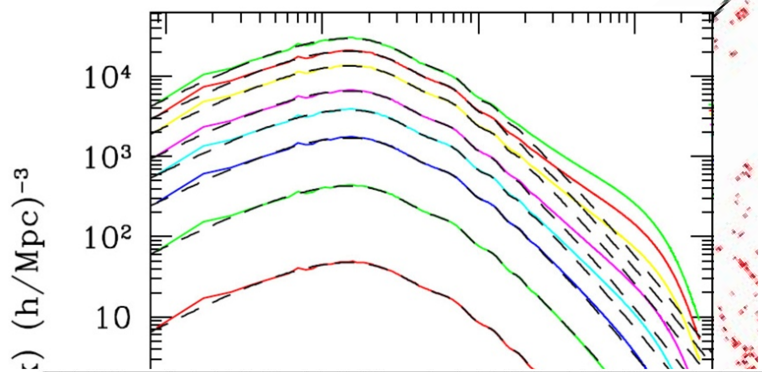
$r_{ball} = 1.45\ d_{bar} = 13.1 h^{-1}$Mpc

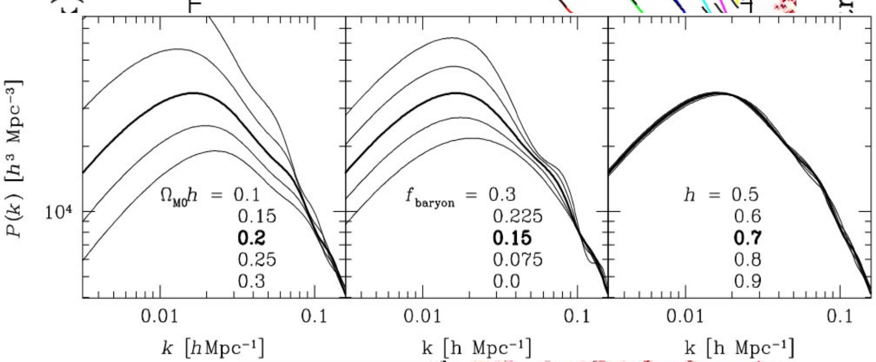


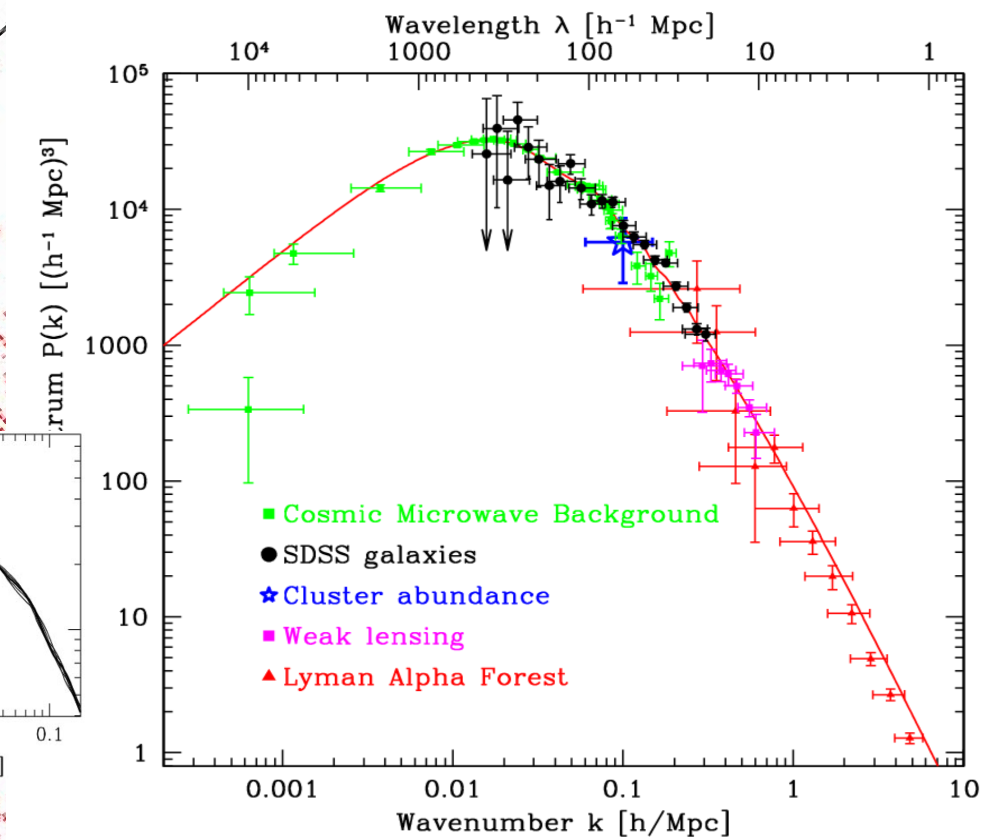
Top 4 high-density and top 3 low-density LSSs from mock DR7 surveys ($d_{bar}=9h^{-1}$Mpc) in HR2

Amplitude of the initial density fluctuations

Power spectrum on large scales
(first measured by Park+1992)
→ the initial conditions and their evolution,
also useful as a cosmic ruler (i.e. BAO feature, shape of PS).







Consistent with LCDM (slope of PS on large & small scales, BAO scales ..)

Gaussianity of the primordial density fluctuations

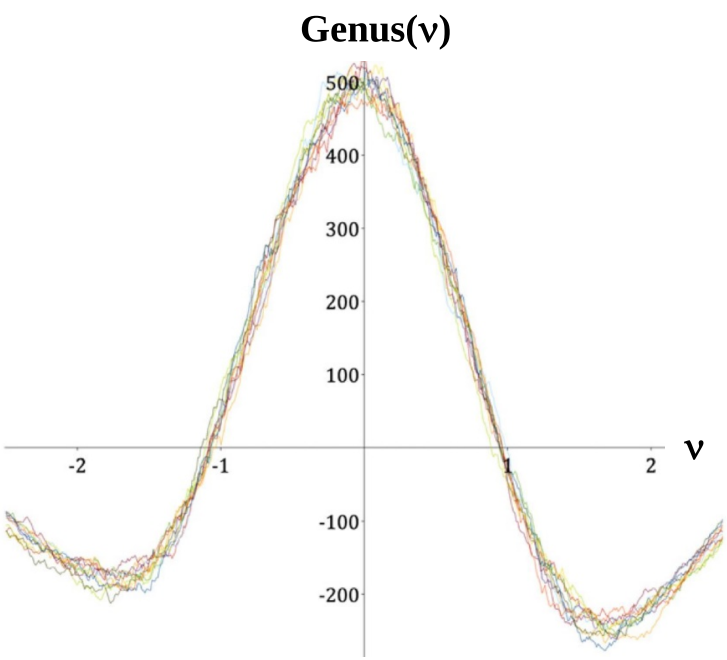
A major prediction of simple inflationary scenarios.

On large scales

galaxy distribution → roughly in the linear regime

→ simple relation with matter field → remembers the primordial properties

LSS observations: consistent with
"initially Gaussian" density fluctuations.



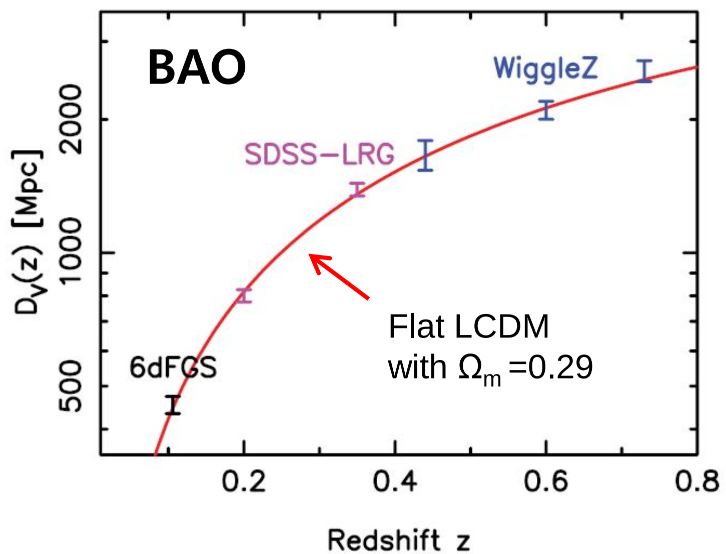
SDSS DR10 CMASS:
G=488 ±14 (2.9%) for R_G=21h^{-1}Mpc
ΛCDM+HGC model (blue=observation)
[Parihar et al. 2014]

Expansion history a(t)

determined by various cosmological parameters
(such as Ω_m, Ω_K, Ω_X, & DE w in FRW cosmologies; gravitational law),
& can be measured from r(z)

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

- Geometric methods like
  BAO method or AP test - shape of PS

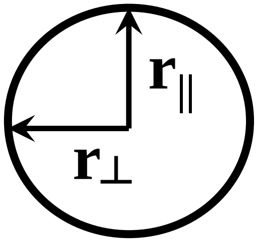


(WiggleZ: Blake et al. 2011)

Geometric methods using LSS

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

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



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 & Δθ → H(z) & D_A(z) → Ω_m, Ω_Λ, w

BAO

Acoustic oscillation amplitude : depends on Ω_b

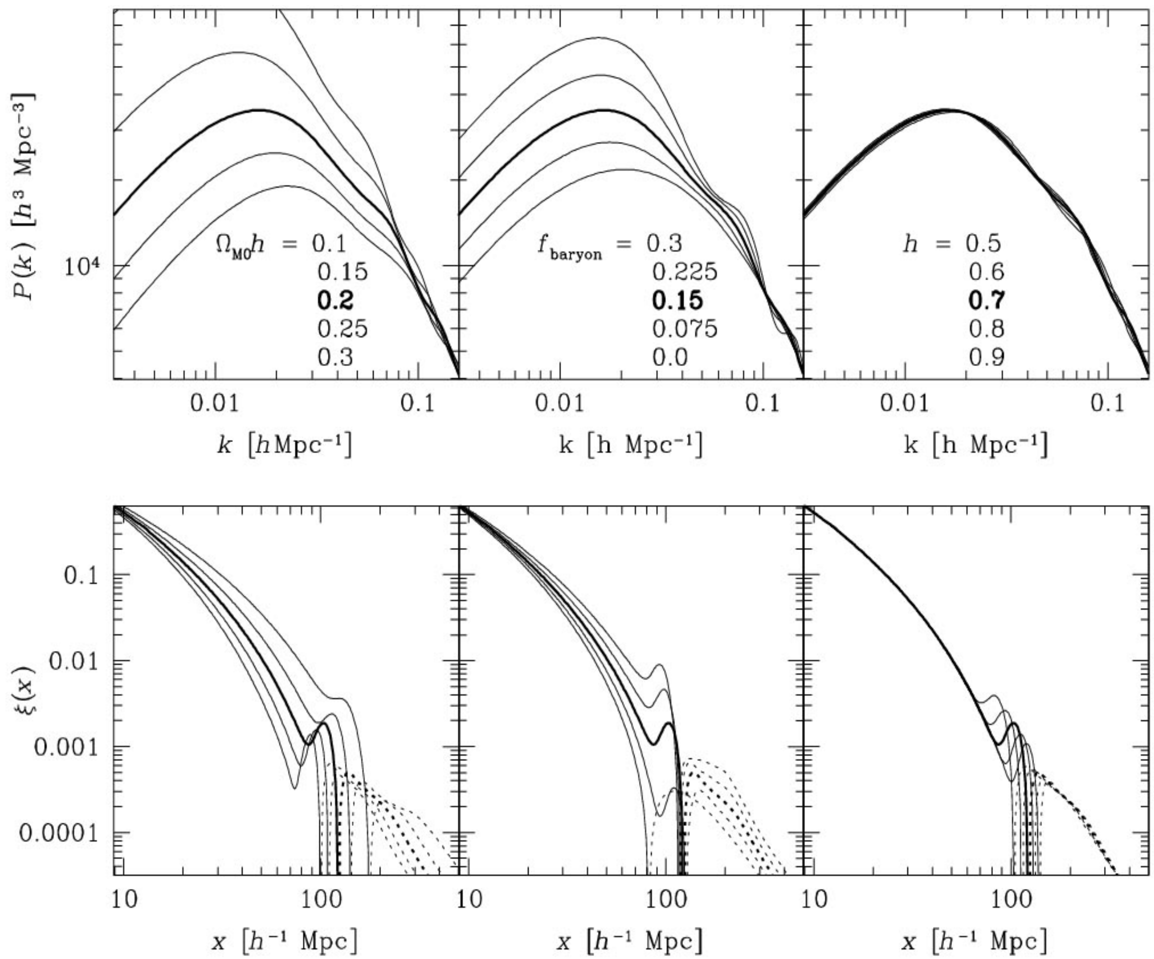
oscillation scale = comoving sound horizon 's' at t_{dec}

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

→ Curvature of space, Baryonic mass

Baryonic oscillation in PS

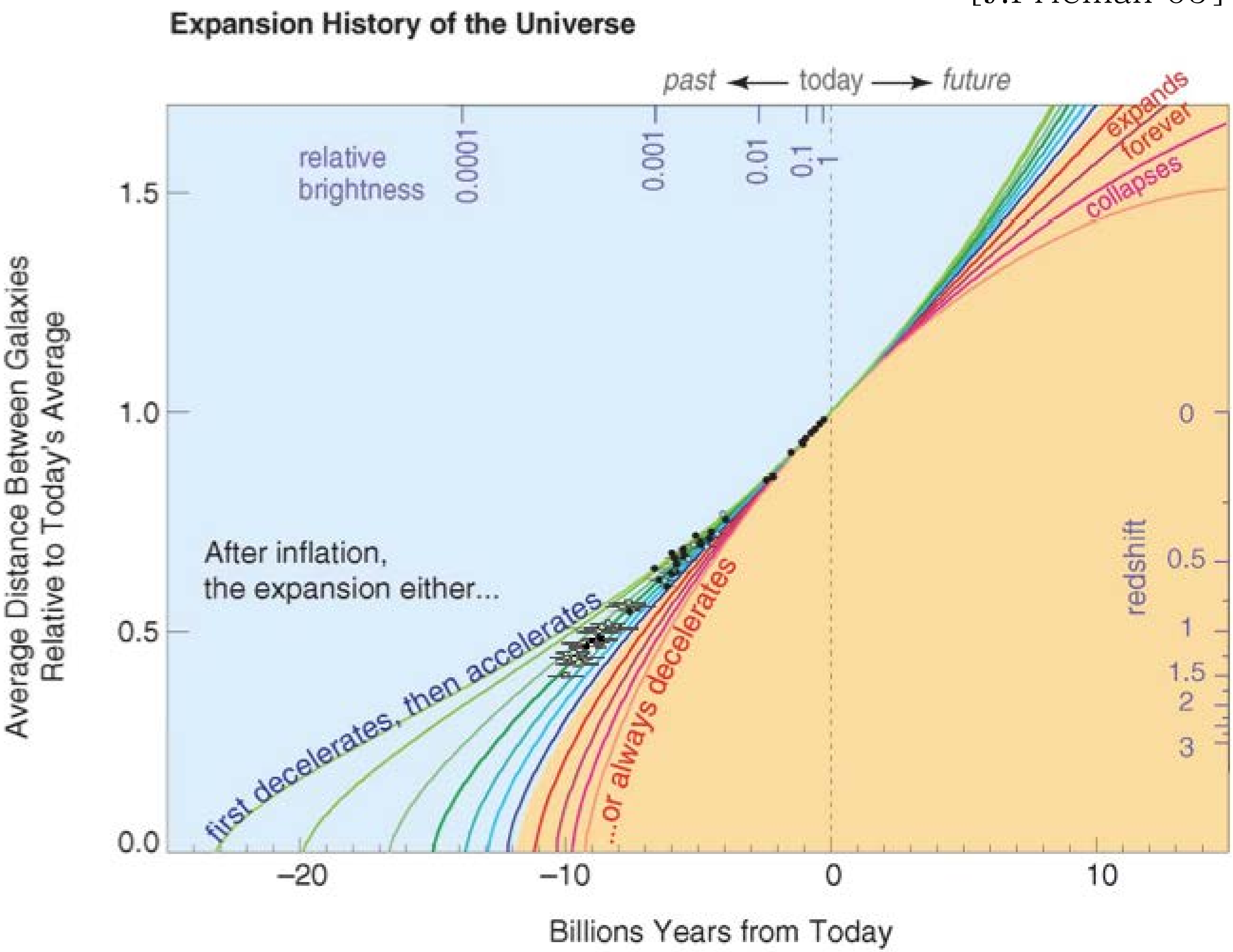
Baryonic bump in CF



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
After inflation, the expansion either...
first decelerates, then accelerates
...or always decelerates
redshift
0
0.5
1
1.5
2
3
1.5
1.0
0.5
0.0
Average Distance Between Galaxies Relative to Today's Average
−20
−10
0
10
Billions Years from Today

Growth of structures

Abundance of massive objects or large-scale distribution of galaxies tells about the initial conditions and expansion history of the universe.

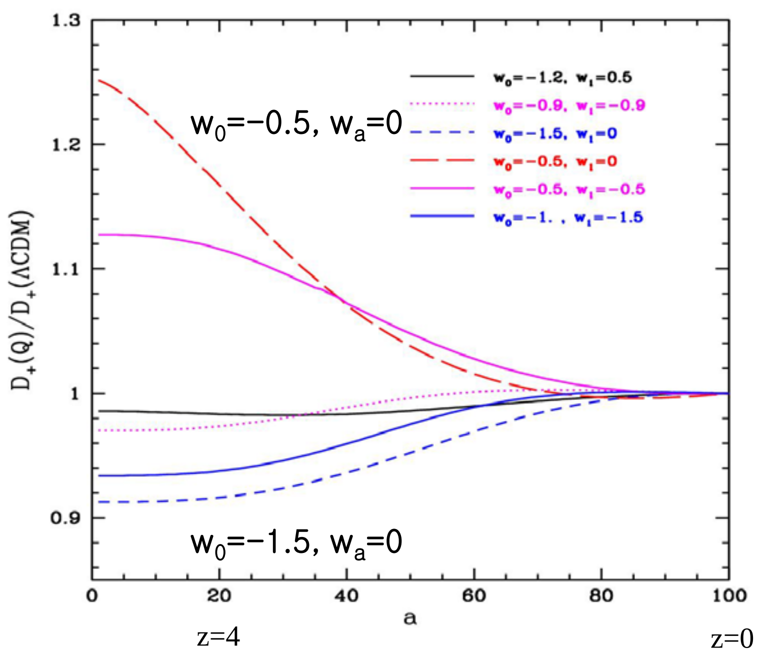
expansion history

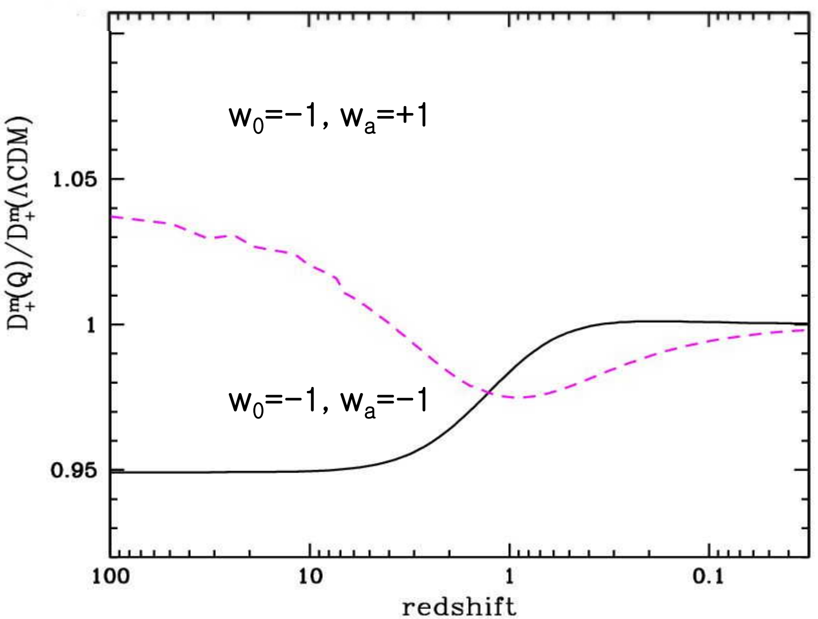
P(k) & growth rate (expansion history)

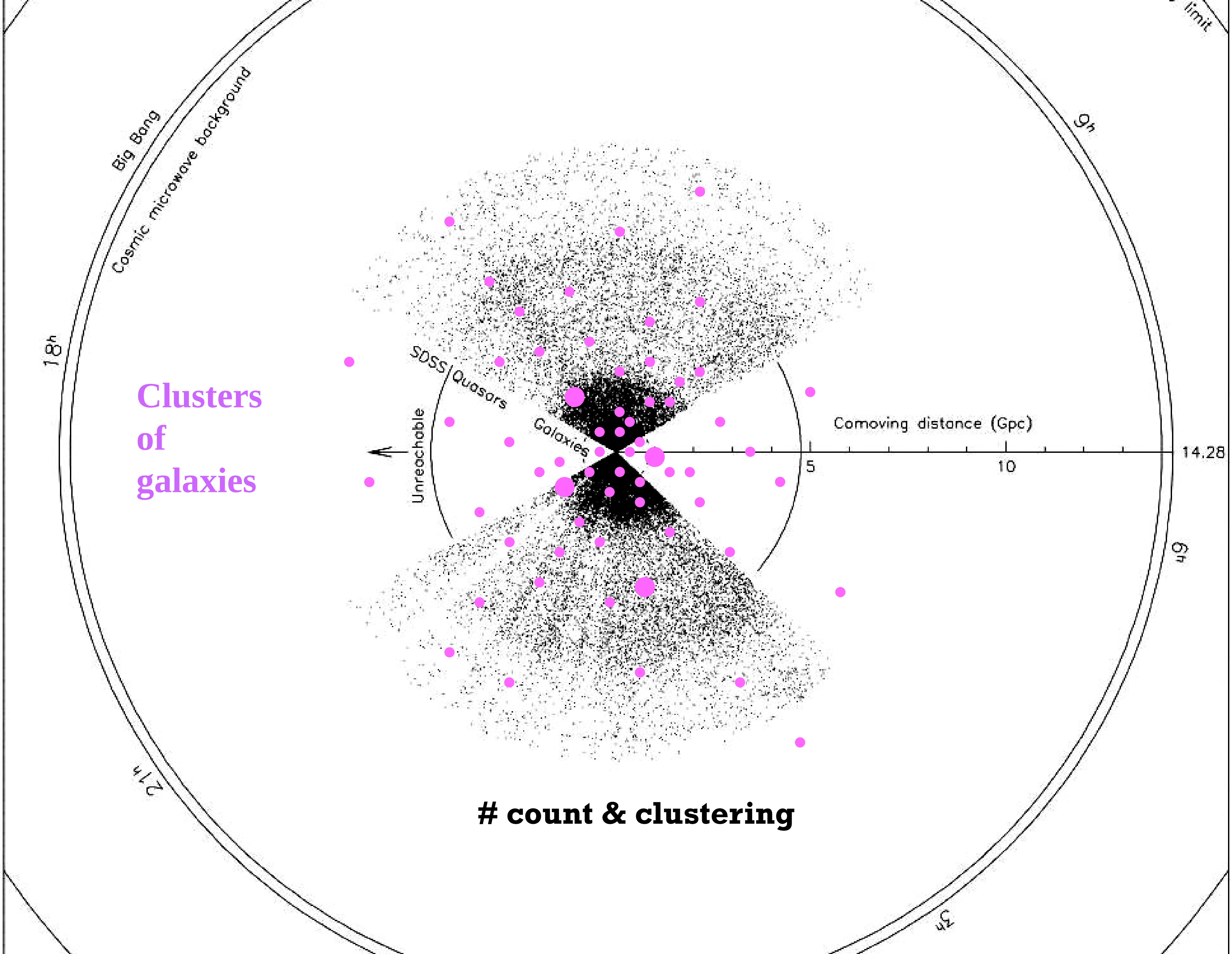
Cluster # count

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

If $w(z) = w_0 + w_a * (1 - a) = w_0 + w_a * z/(1+z)$ where $P = w\,\rho$

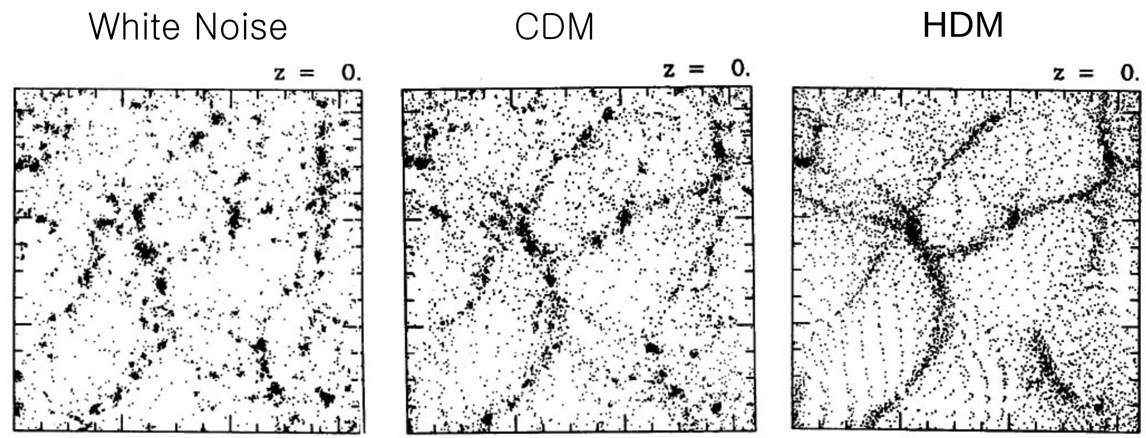





Big Bang
Cosmic microwave background
18h
9h
SDSS Quasars
Galaxies
Unreachable
Comoving distance (Gpc)
5
10
14.28
21h
3h
Clusters
of
galaxies
count & clustering

Galaxy formation and environmental effects

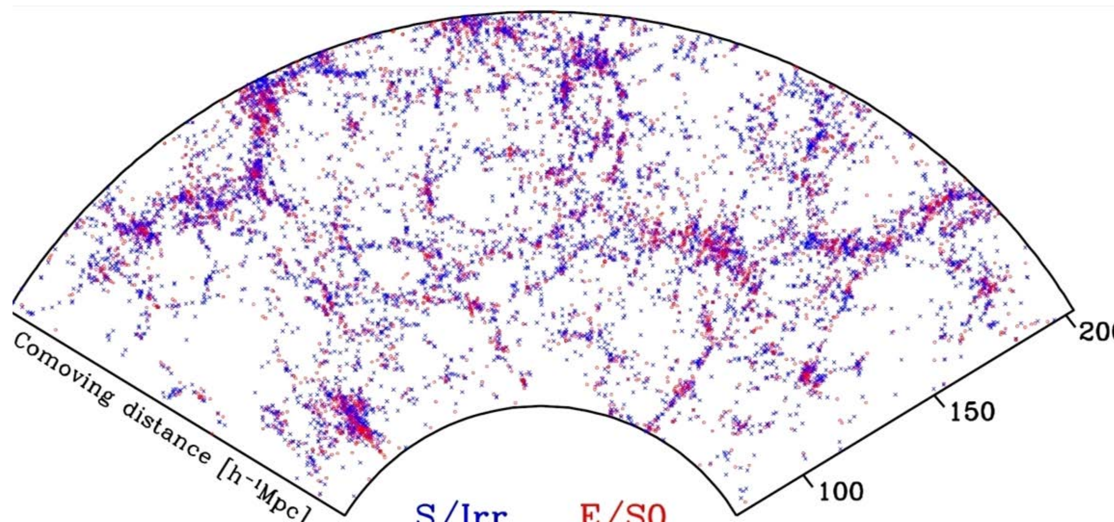
Galaxy properties & distribution
depend on
initial density fluctuations,
background cosmology, &
galaxy formation process.



Weinberg & Gunn (1990)

Large-scale environmental effects
on galaxy properties

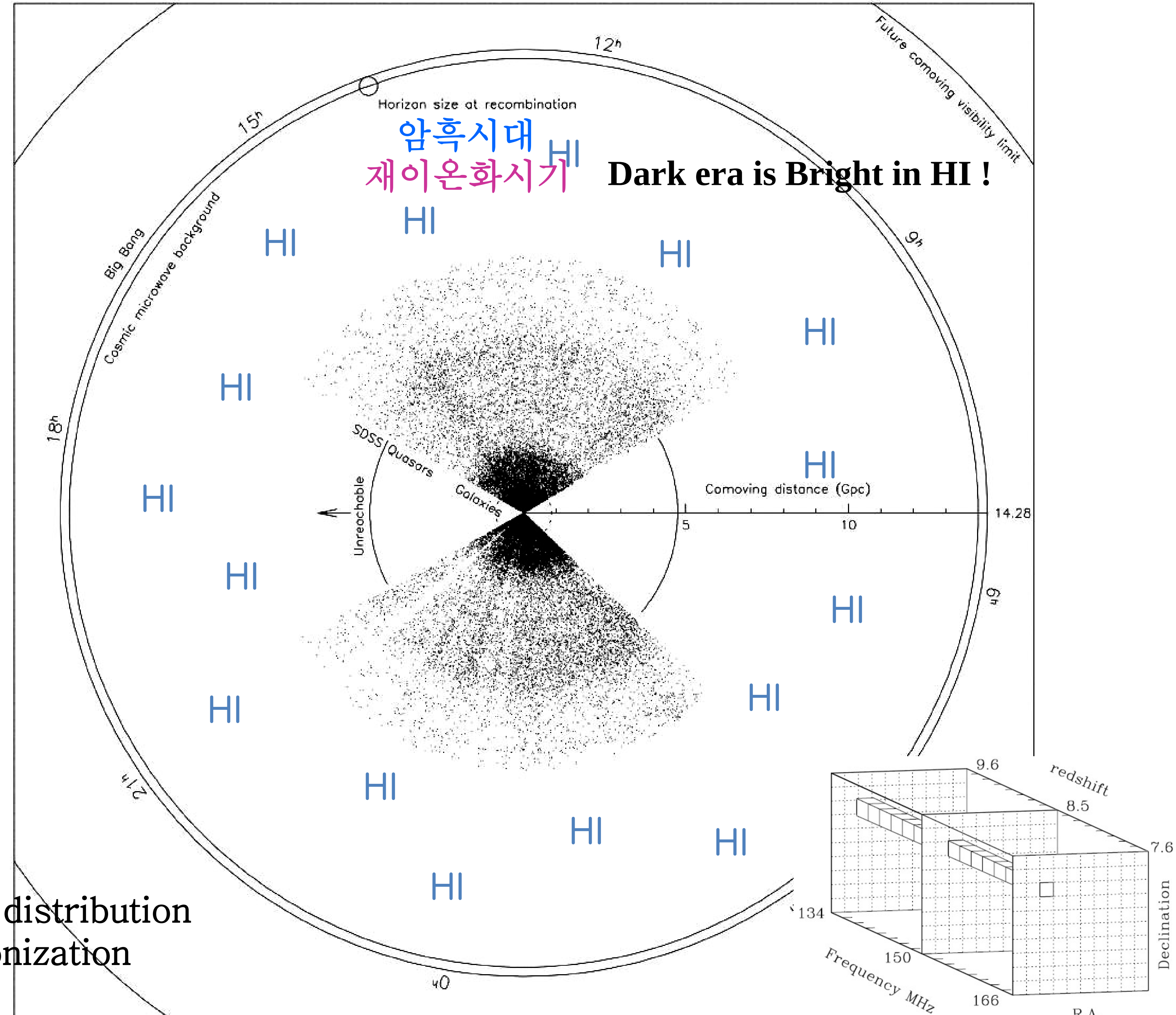
- Morphology-density relation
- Morphology-radius relation (clusters)
- Environmental dependence of
  LF, color, SFR, vel. disp., size
- Alignment of galaxies and groups



Park et al. (2005)

Redshifted 21cm line

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



3D HI distribution
& reionization

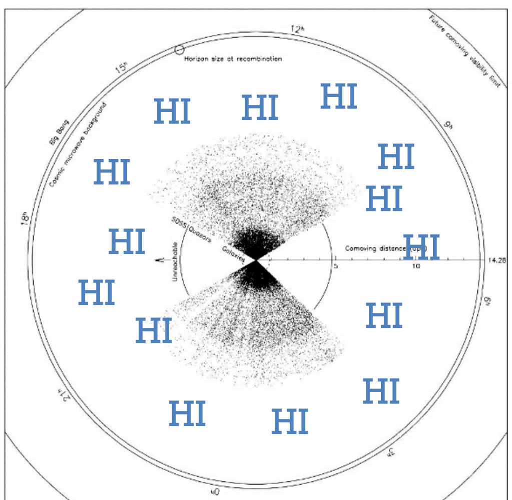
3D HI distribution : 21cm tomography

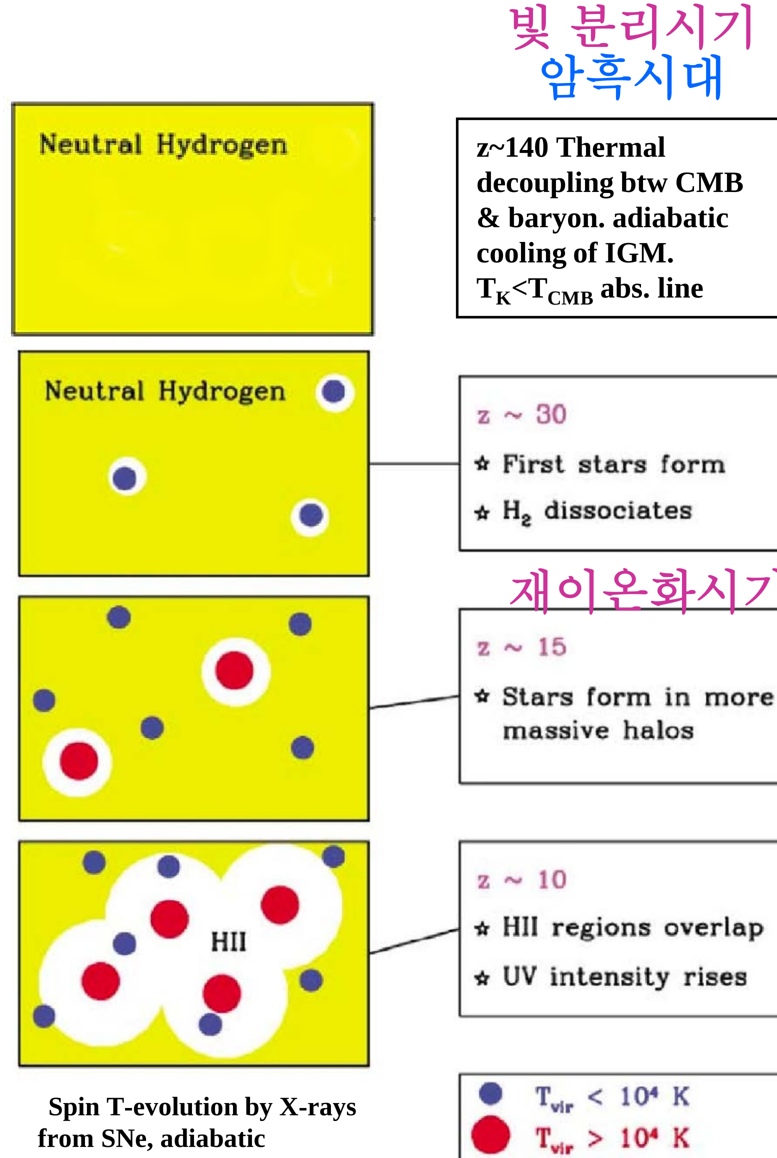
Spin T: $\delta T \sim (1+\delta) x_H (T_S - T_{CMB})/T_S * (1+z)^{0.5}$ **mK**

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



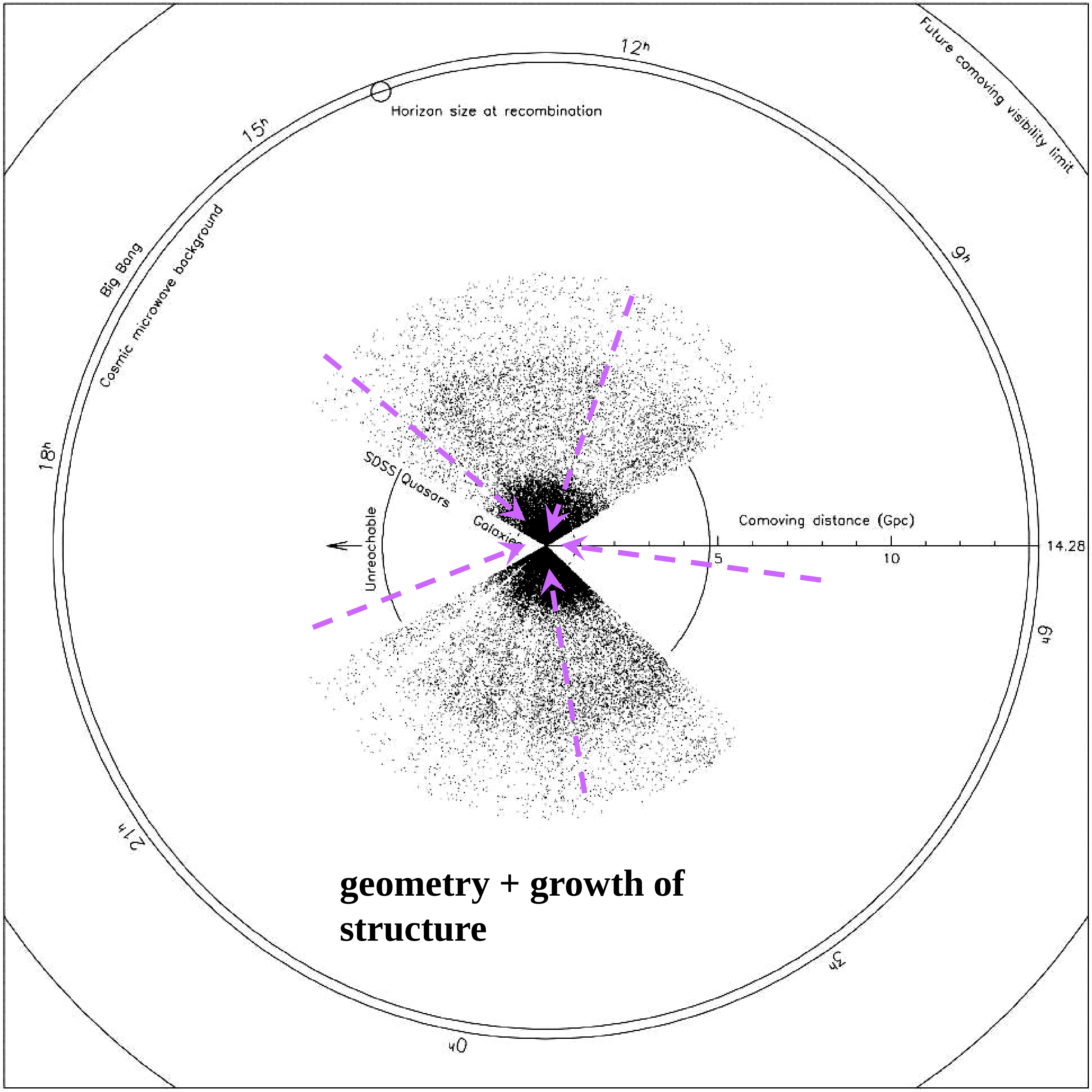


Spin T-evolution by X-rays from SNe, adiabatic compression, structure formation shocks

Gravitational Lensing:
Strong & Weak

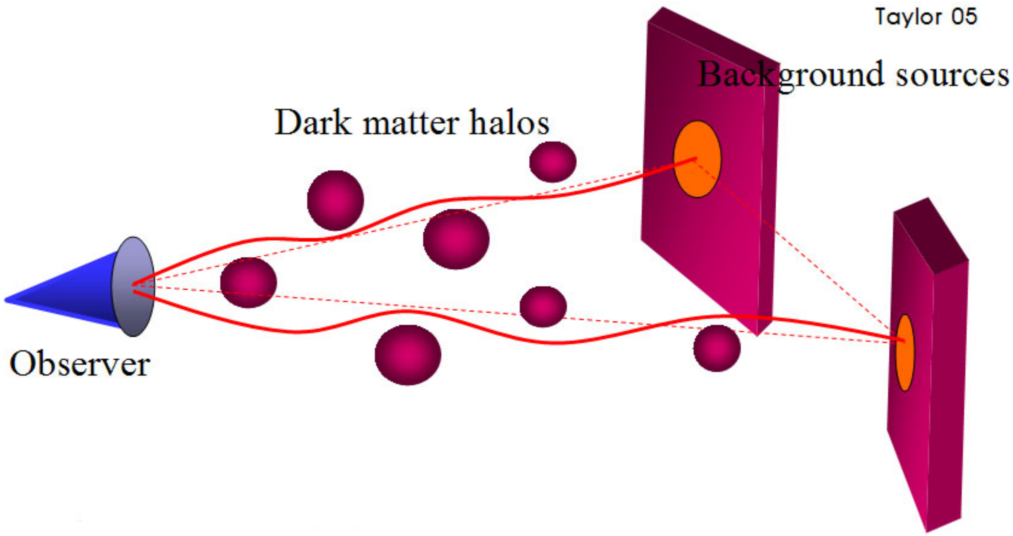
Only projected mass along the line of sight

But tomography possible

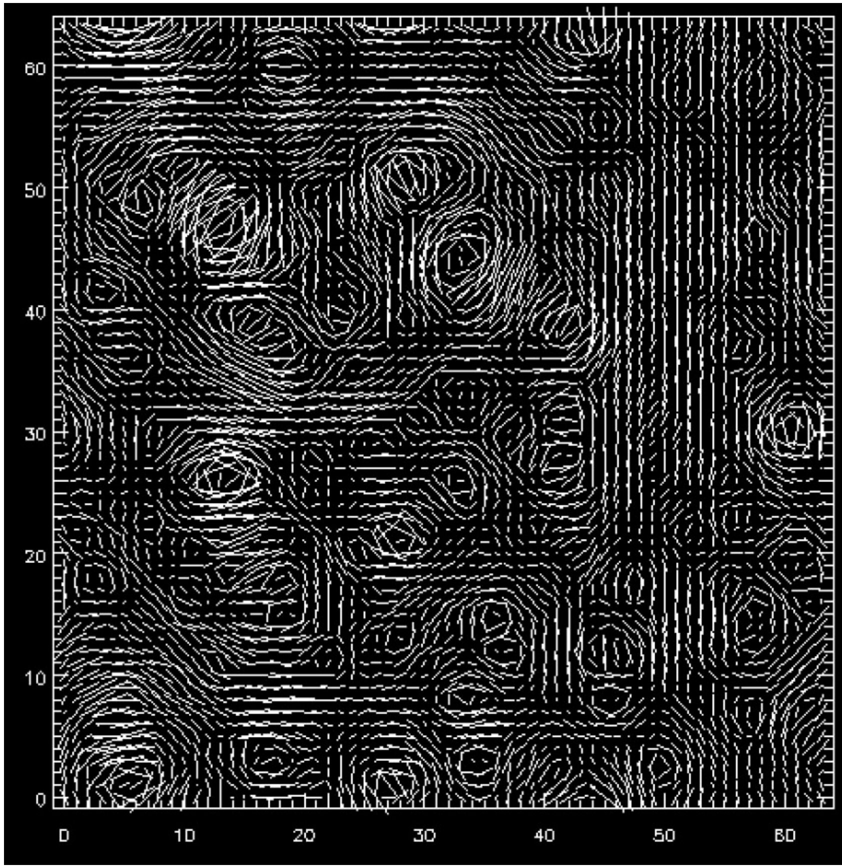


geometry + growth of structure

Weak lensing



Jain, Seljak & White (2000)



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

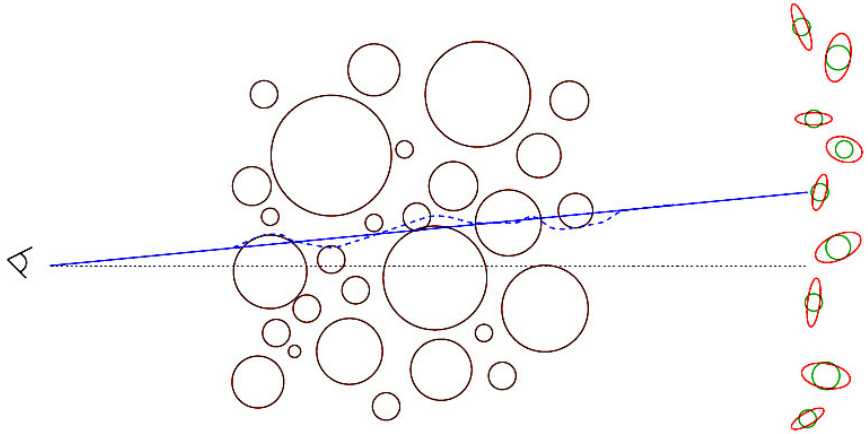
Shear map expected in SCDM

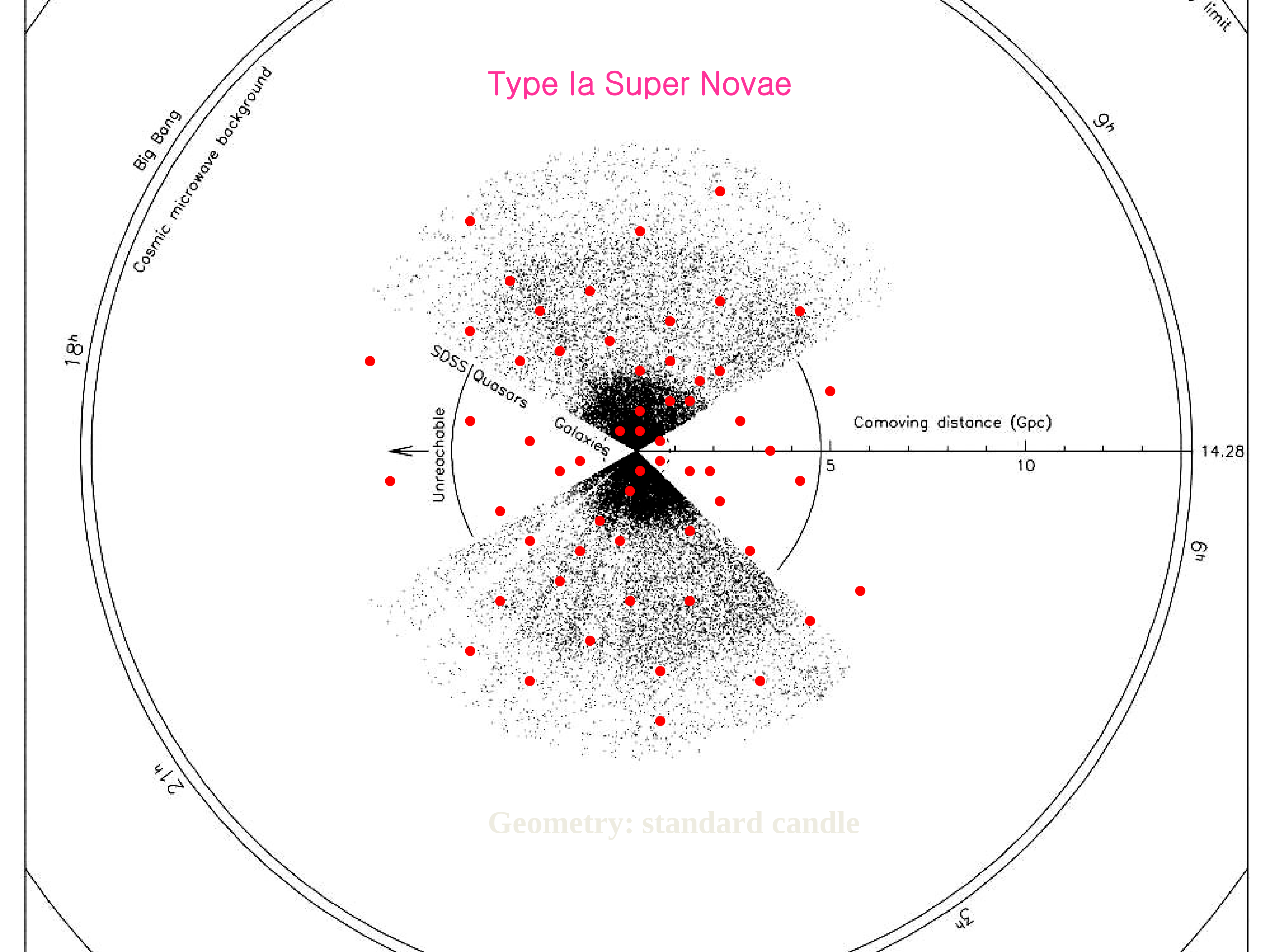
- **Statistical measure of shear pattern, ~1% distortion.**
- **Radial distances, r(z), depends on geometry of Universe.**
- **Dark Matter pattern & growth depends cosmological parameters.**

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

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

3D : shear field at points in 3D

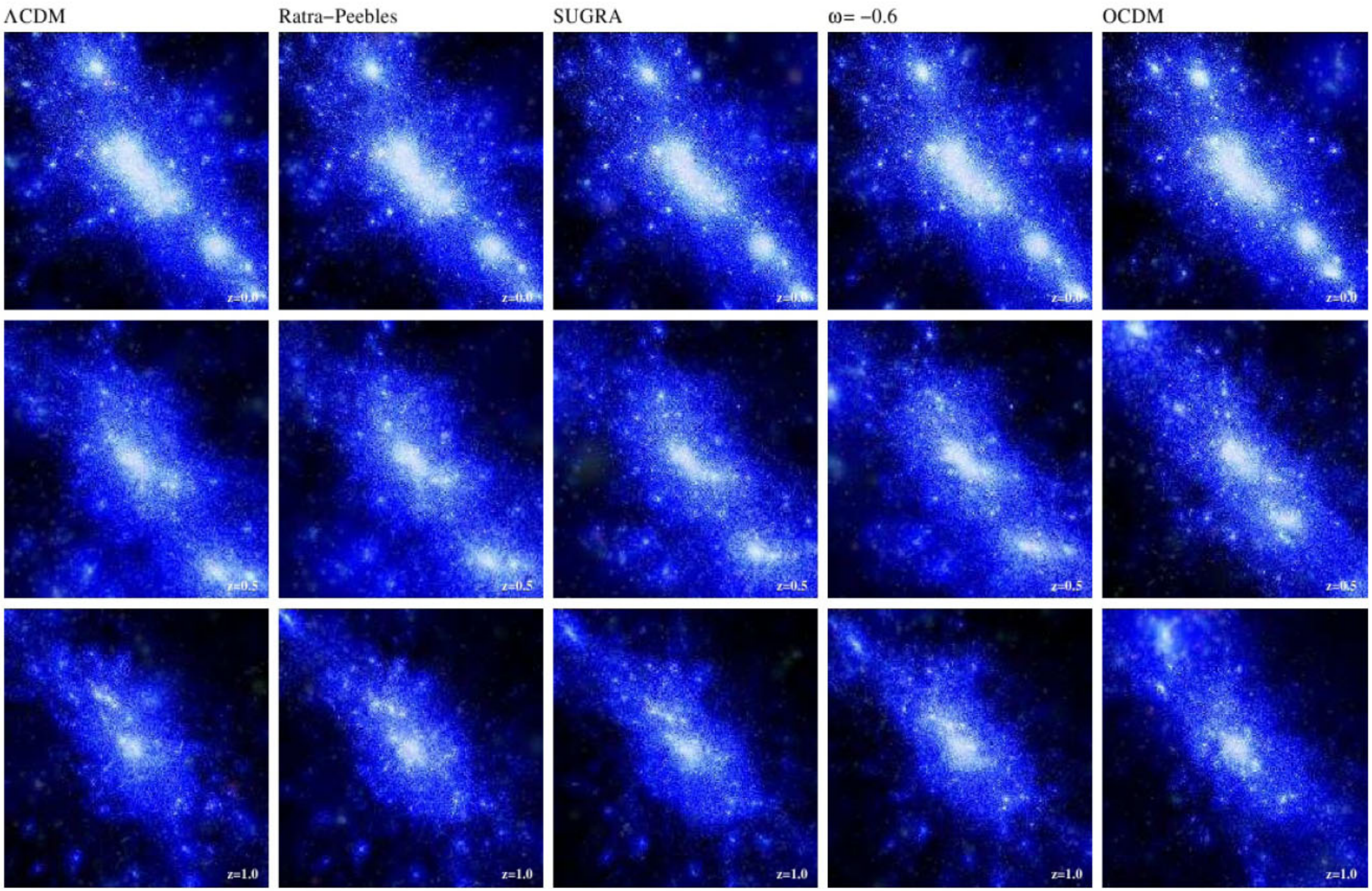



Type Ia Super Novae
Big Bang
Cosmic microwave background
limit
9h
18h
SDSS
Quasars
Galaxies
Unreachable
Comoving distance (Gpc)
5
10
14.28
6h
21h
3h
Geometry: standard candle

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)

Cosmological challenges in the 2020's

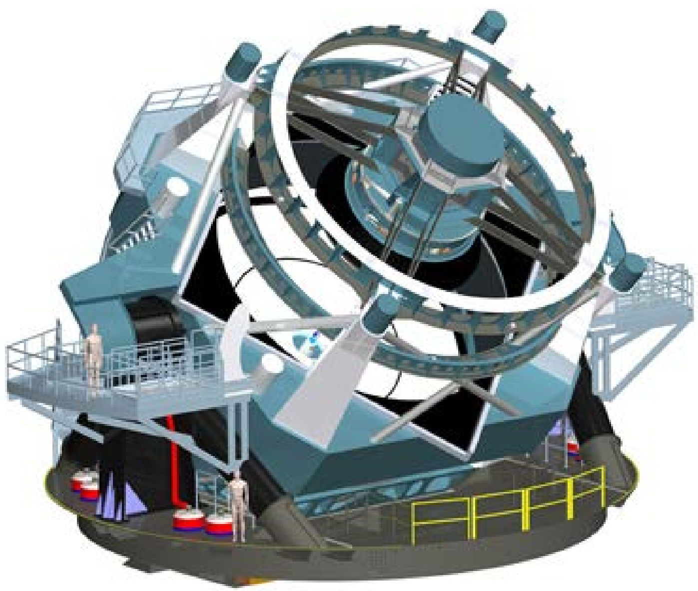
DM/DE
property of space
history of expansion
primordial fluctuations
new gravitational law?
structure formation
Reionization epoch
Dark ages

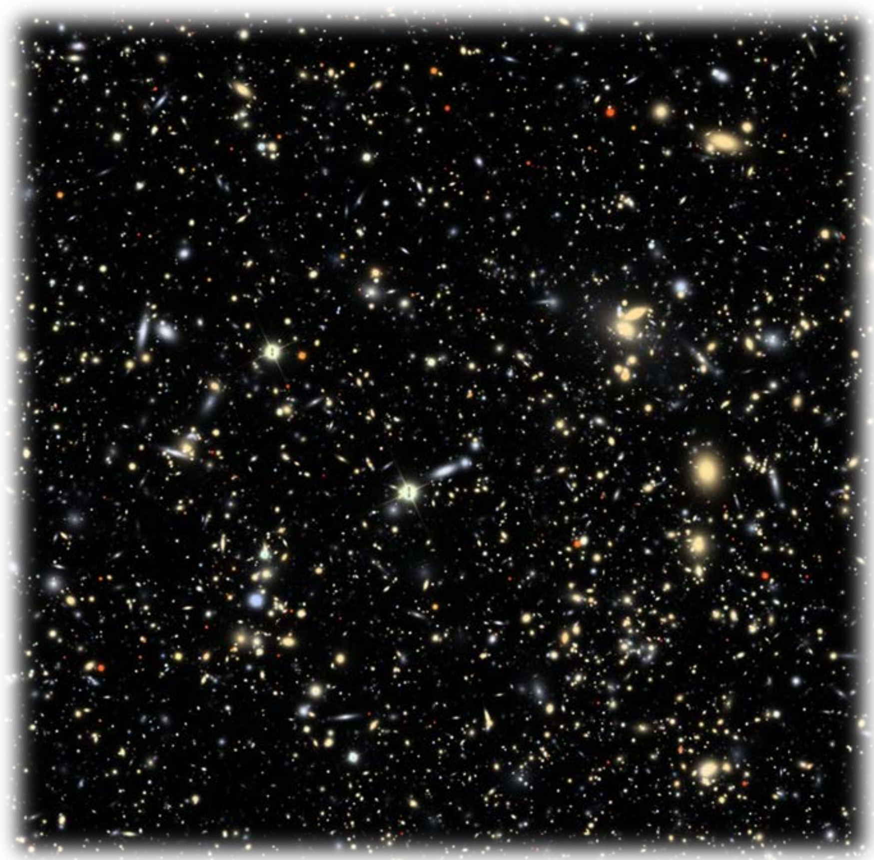
The night sky and the universe are not unchanging

Large Synoptic Survey Telescope will take 2M images of the night sky every 35 sec for 10 years using a 8.4m telescope.

→

1. 10 year movie of the night sky (20TB/night, 60PB total)
2. Era of copied nature. No more need to go out and watch the sky (similarly to the google Earth)





Era of 3d data cubes with spectral images