COSMOLOGY

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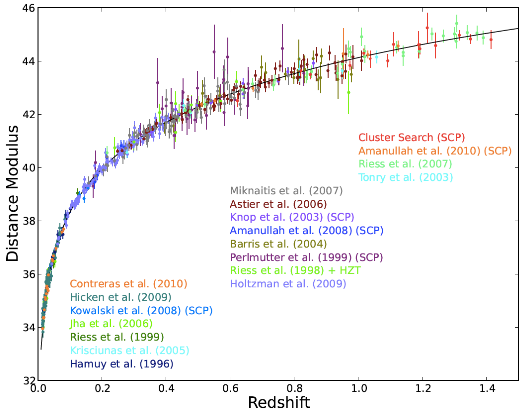
Cosmology [宇宙學]

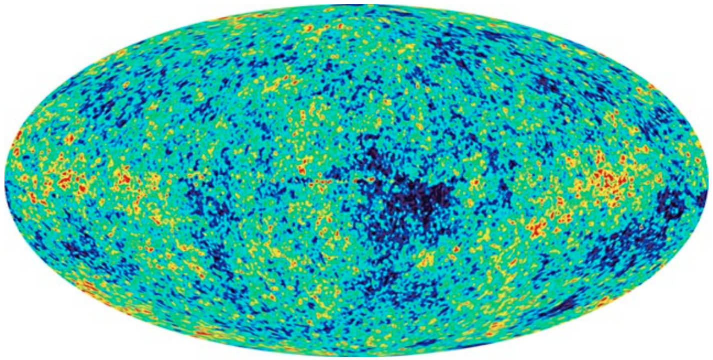
- What is the universe made of?
  Ordinary matter, dark matter and dark energy
- How did it begin?
  Big Bang? Inflation? String theory?
- How does it evolve?
  Energy contents of the universe
- What is its fate?
  Big crunch? Big freeze? Big rip?
- Why do we exist?
  Matter, space and time

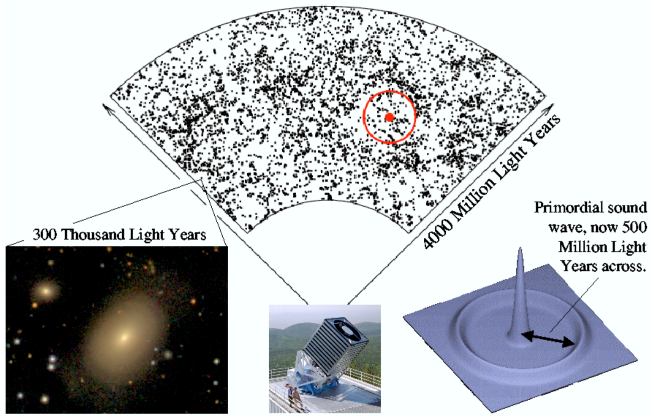
We tackle such philosophical questions with scientific approaches!

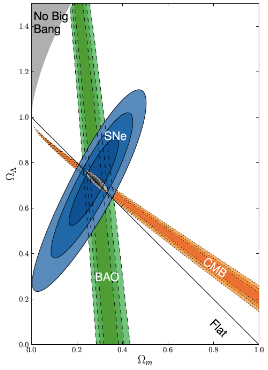
Cosmology = "Experimental" Science

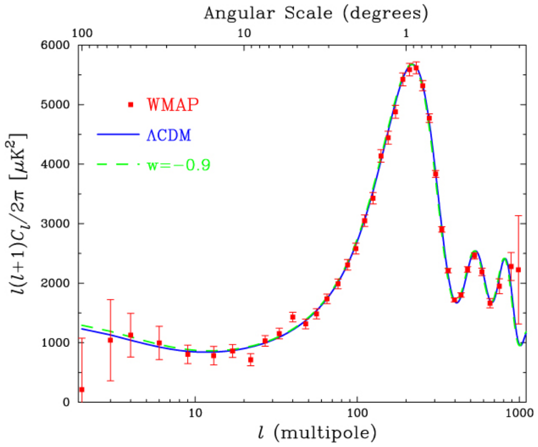
- Various data sets are now available
- The measurements keep being improved
- Can test cosmological models/scenarios very precisely: the expansion history and the growth of structure formation

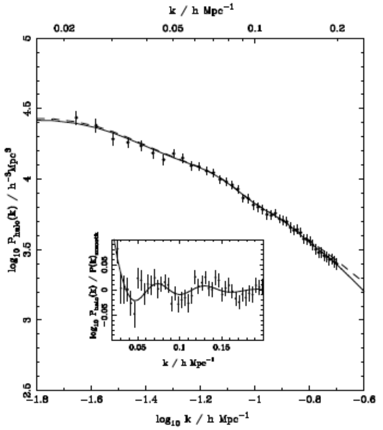






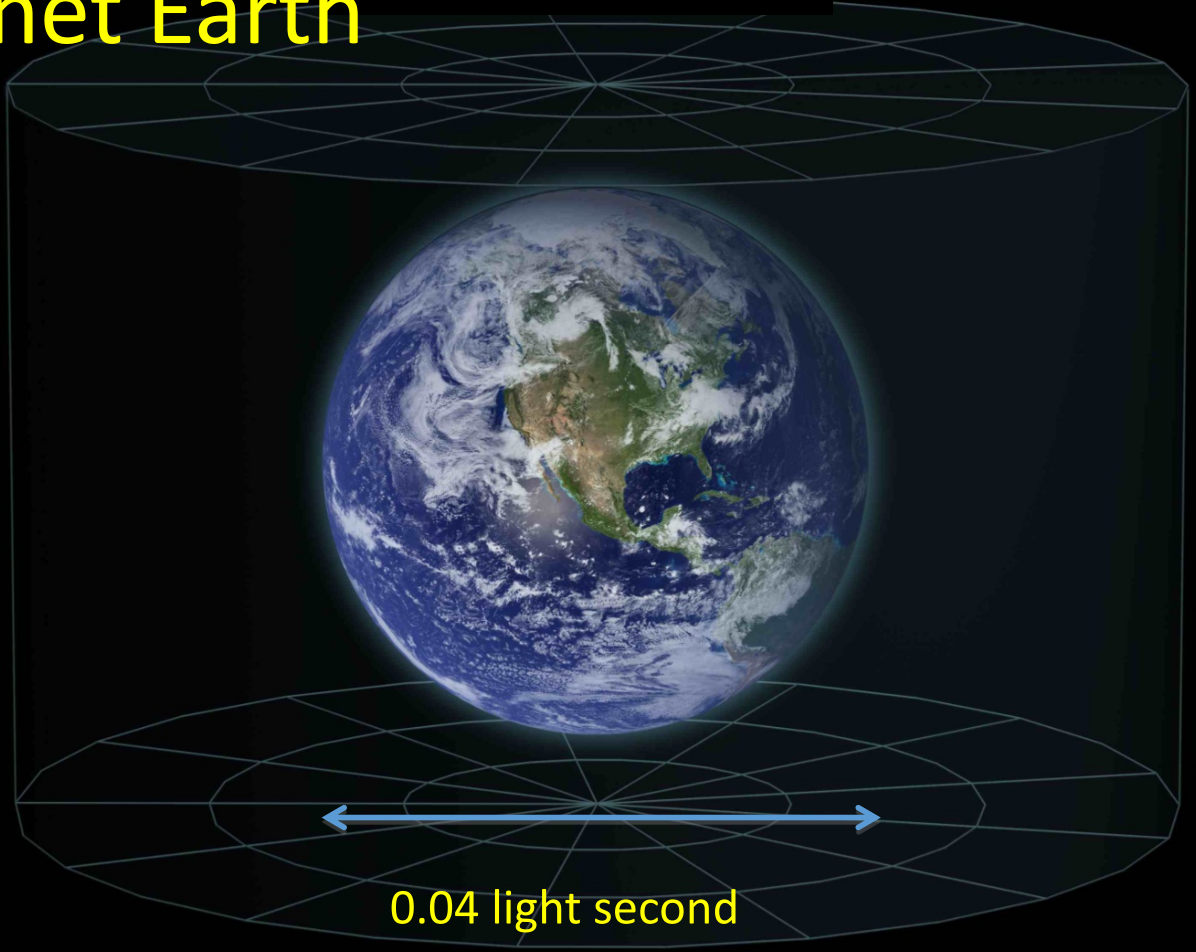






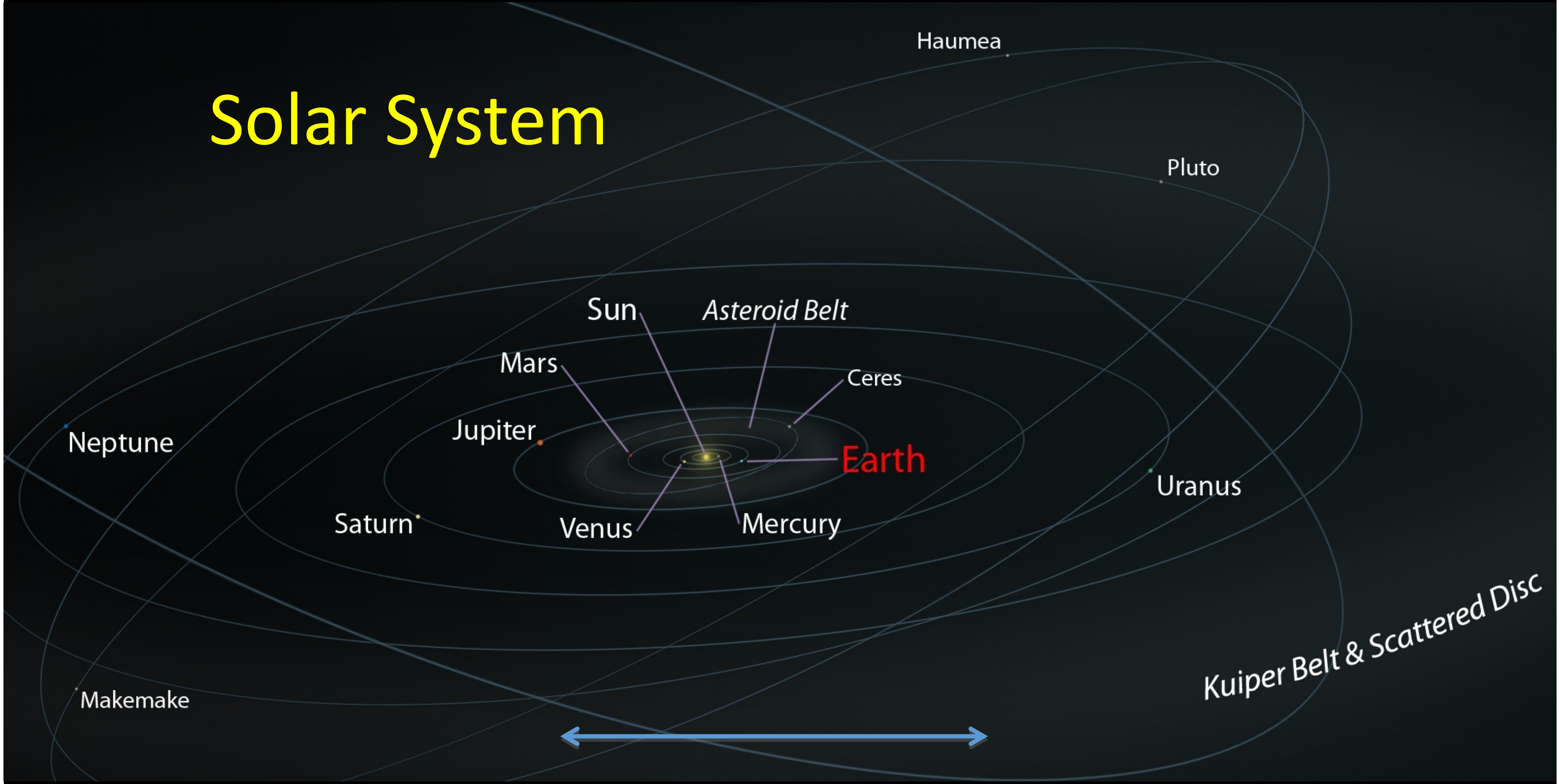
Looking at Our Universe

Planet Earth



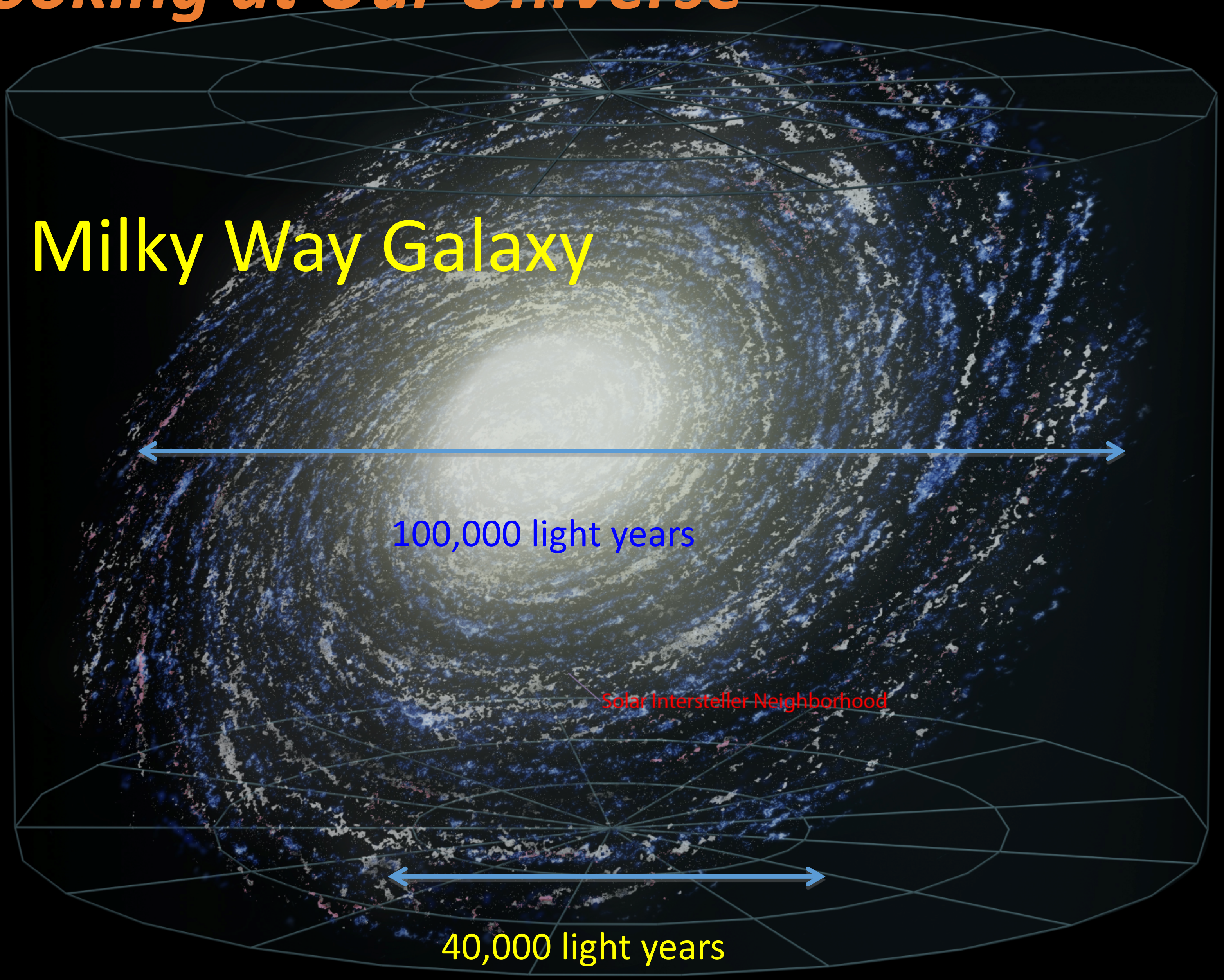
0.04 light second

Looking at Our Universe



160 light minutes

Looking at Our Universe



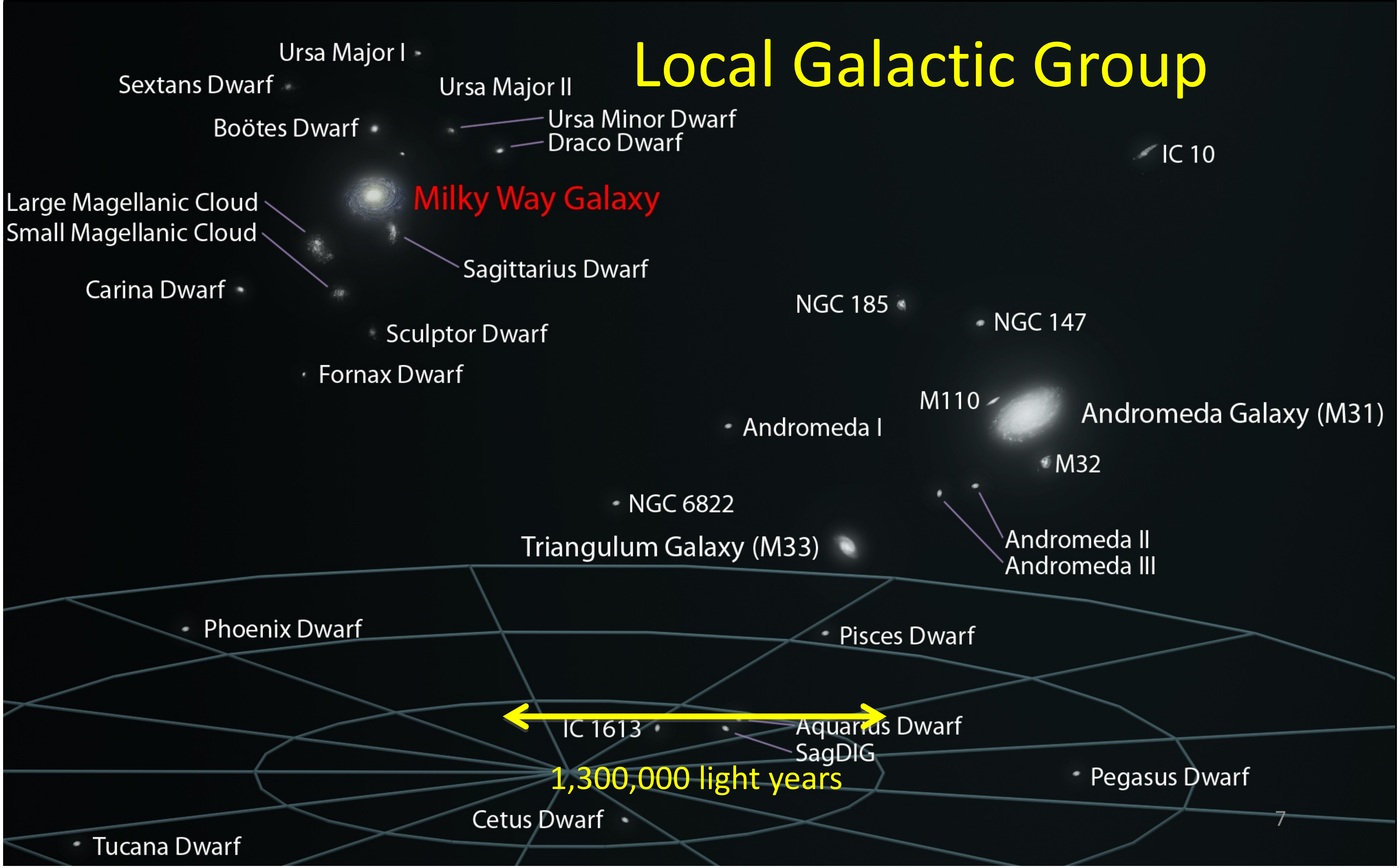
Milky Way Galaxy

100,000 light years

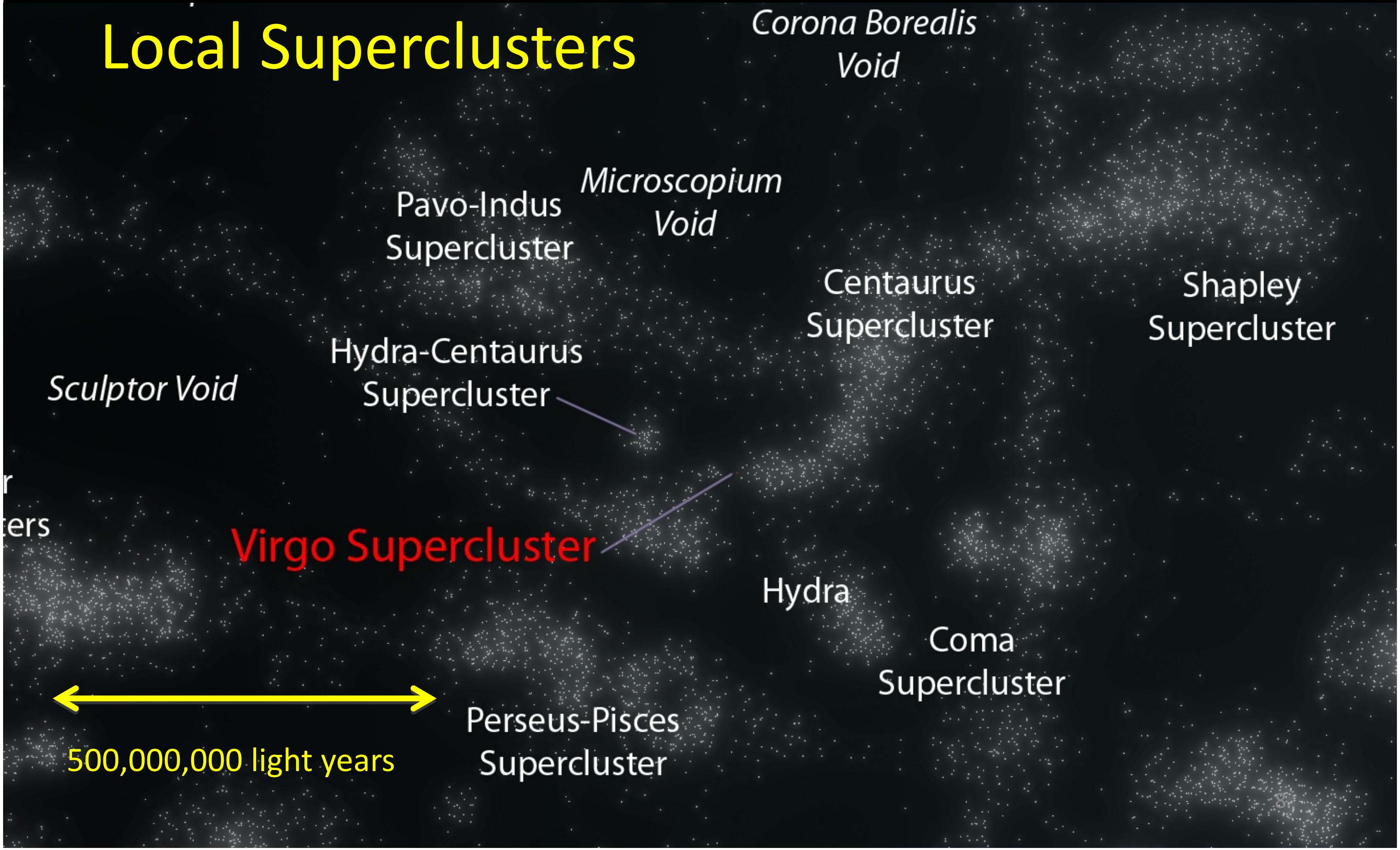
Solar Intersteller Neighborhood

40,000 light years

Looking at Our Universe

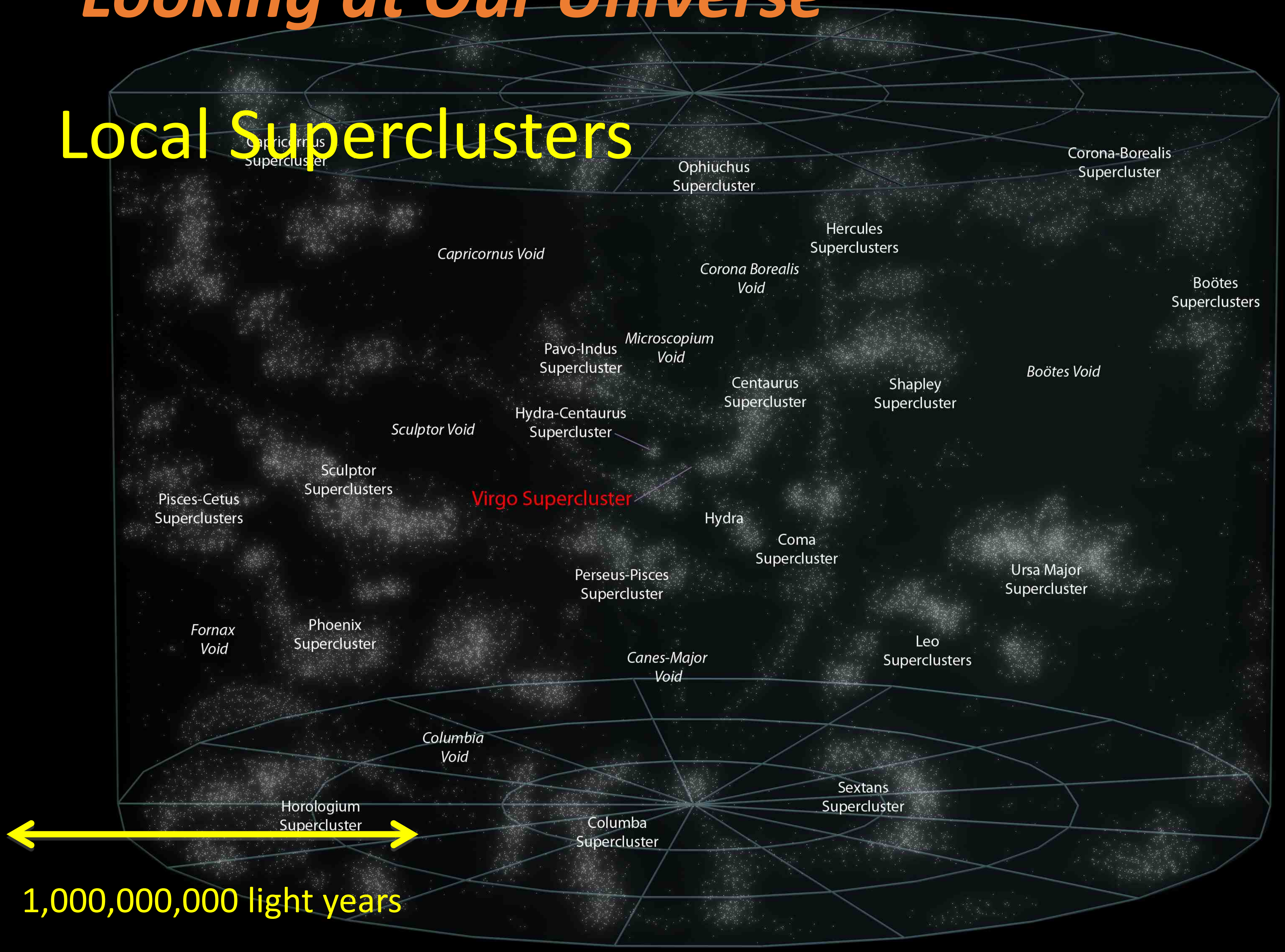


Looking at Our Universe



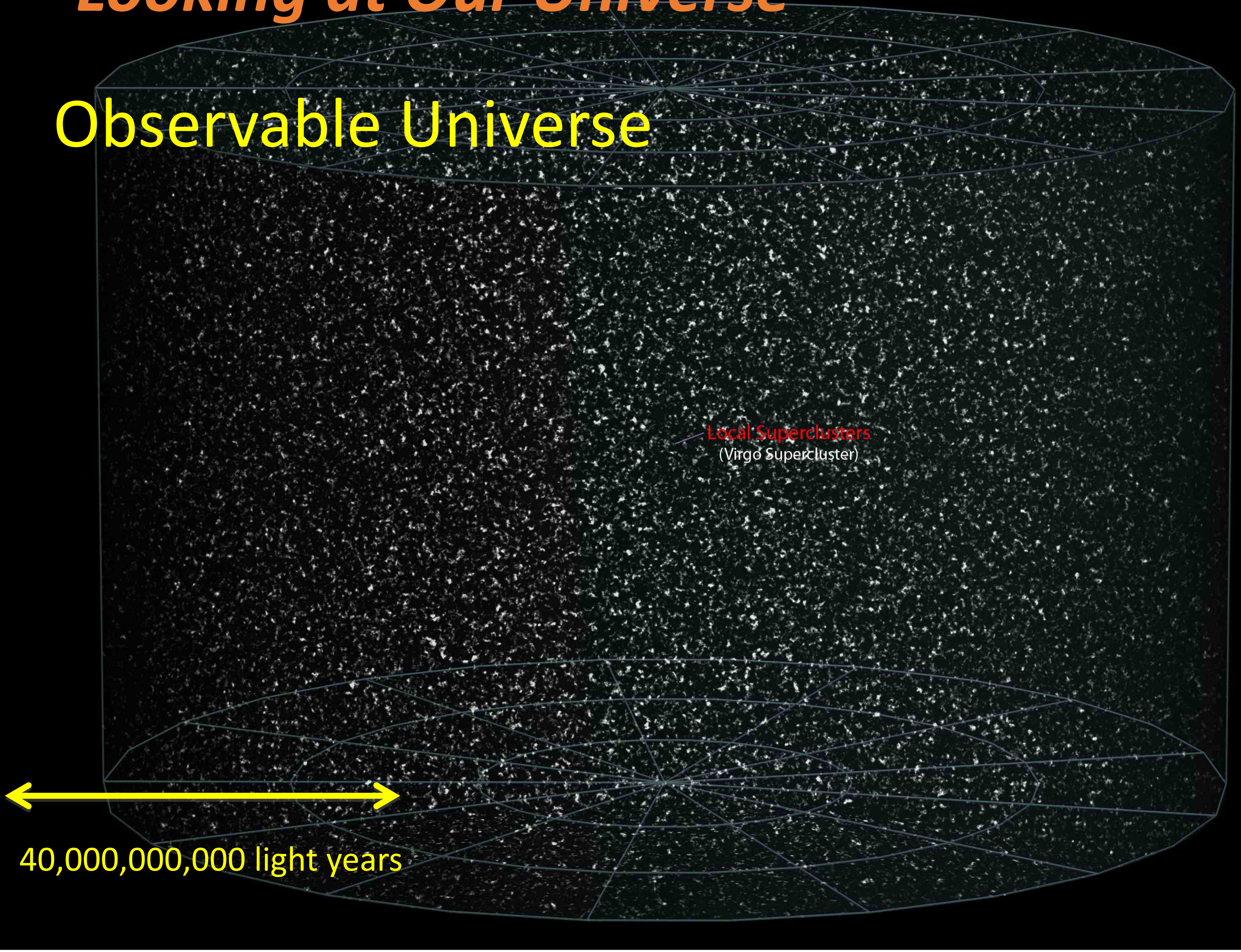
Looking at Our Universe

Local Superclusters



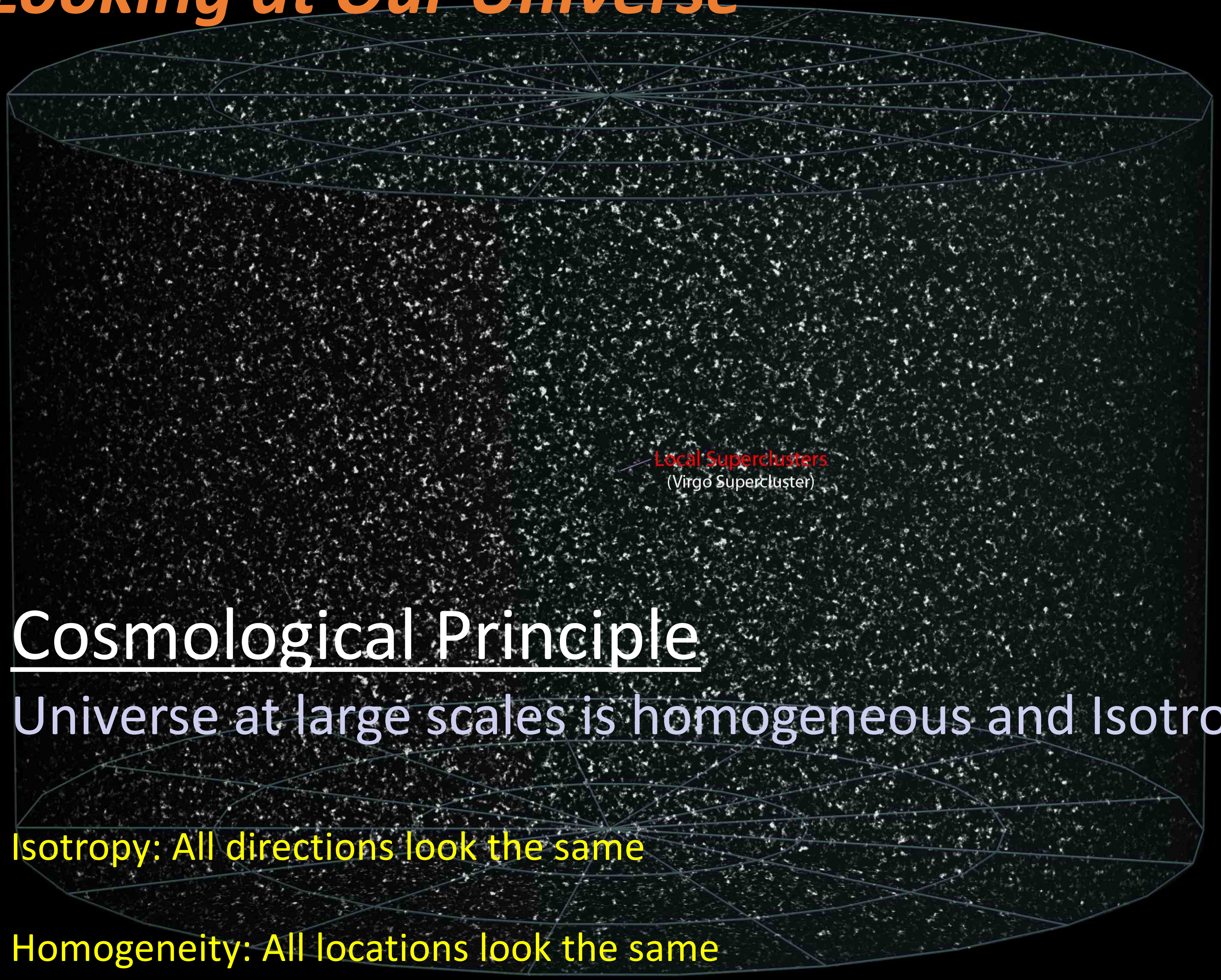
Looking at Our Universe

Observable Universe



40,000,000,000 light years

Looking at Our Universe



Cosmological Principle

Universe at large scales is homogeneous and Isotropic

Isotropy: All directions look the same

Homogeneity: All locations look the same

Contents

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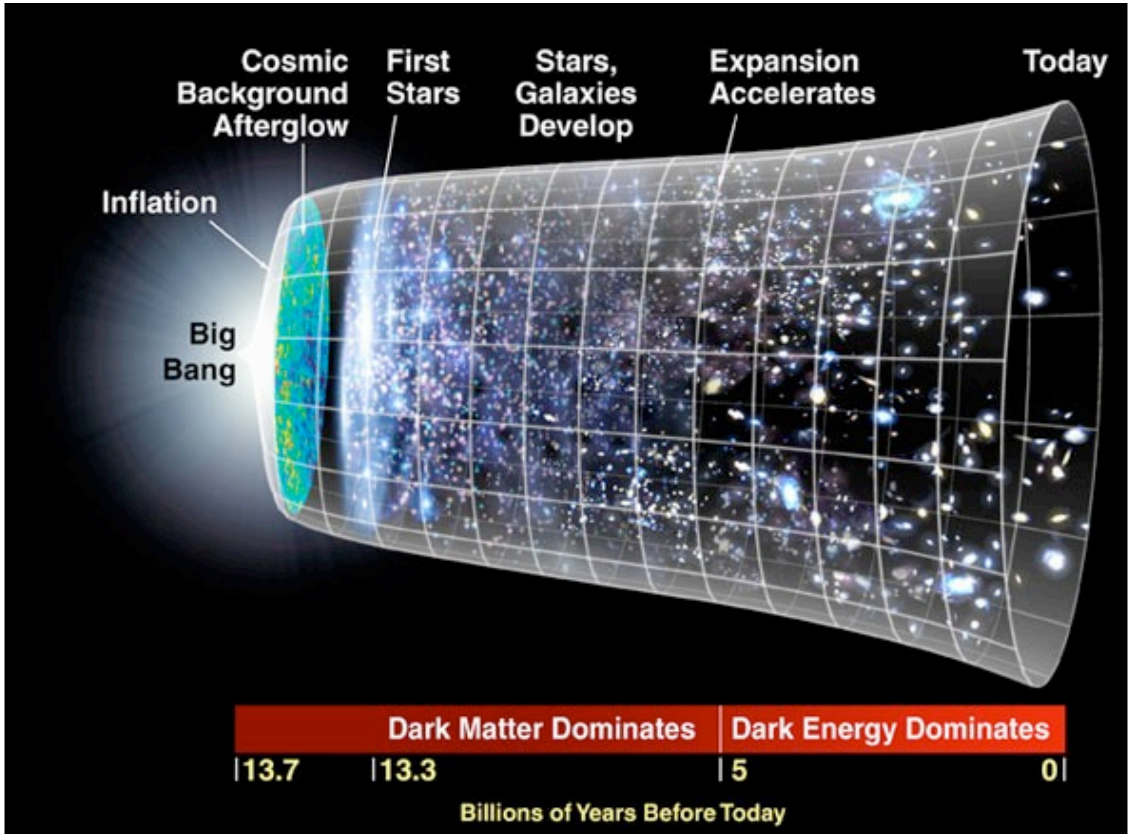
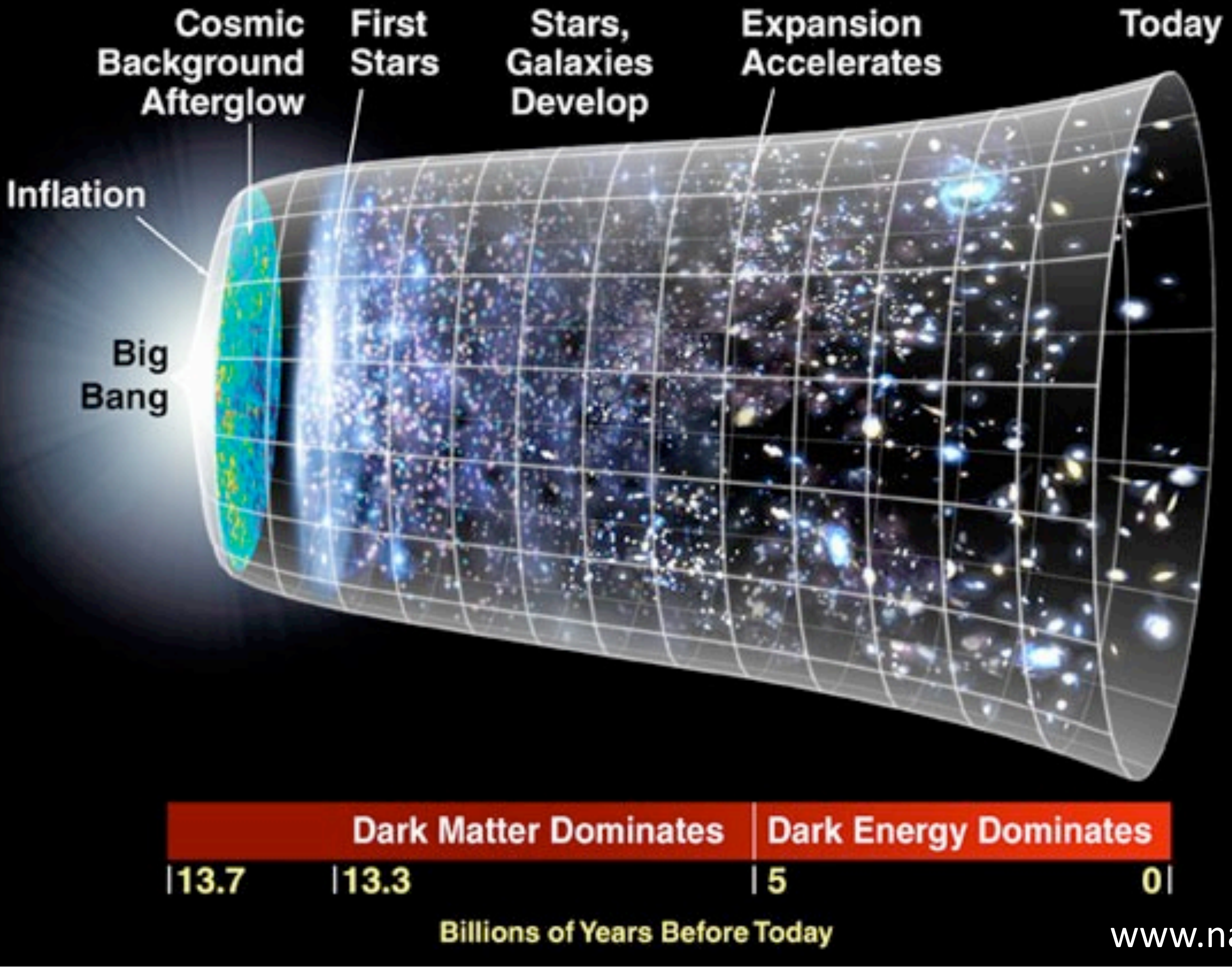
- 2. The early Universe: Cosmic microwave background
- 3. Cosmic acceleration: Dark energy
- 4. Alternative to dark energy: Modify Einstein equations?



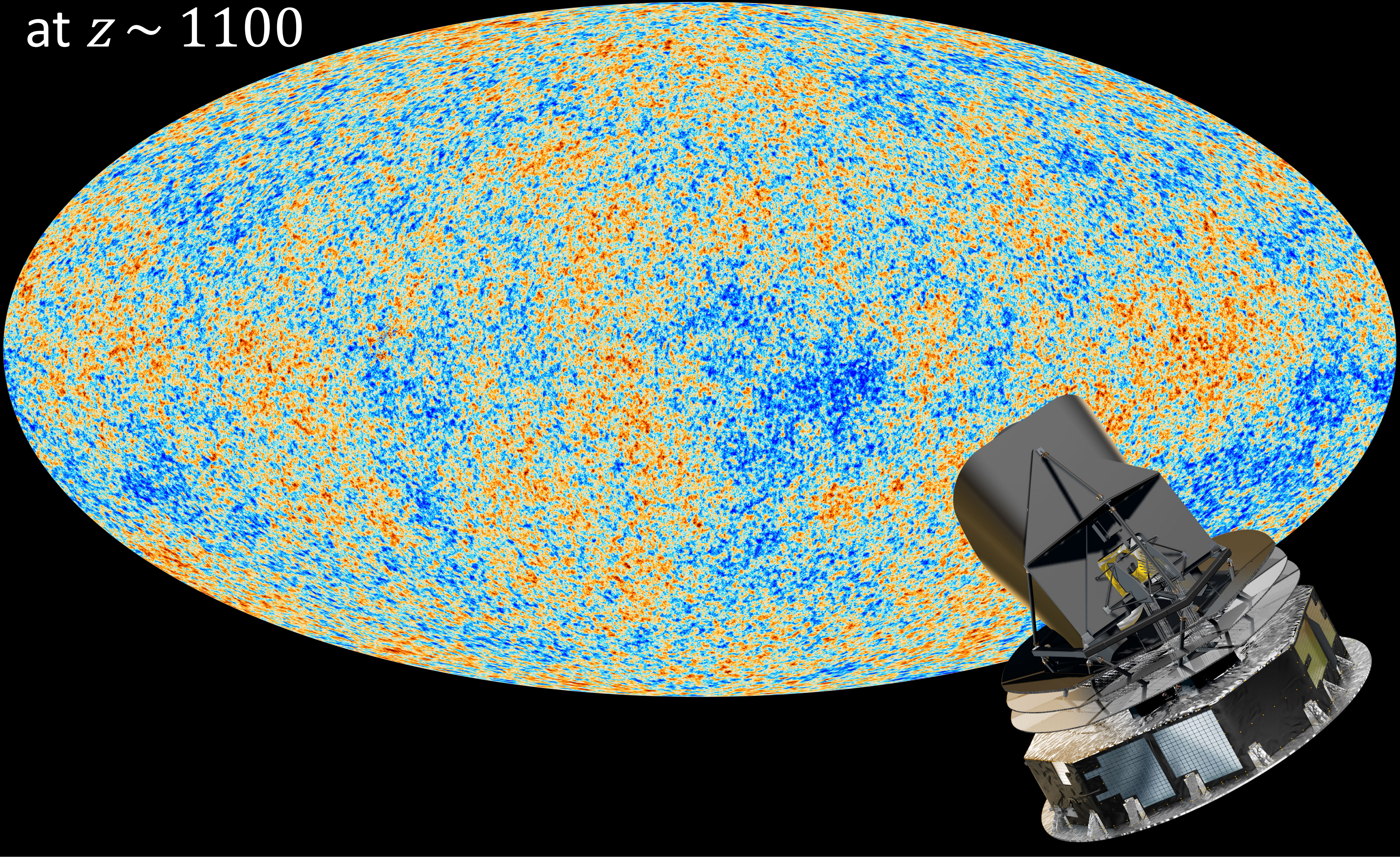
Brief history of our Universe



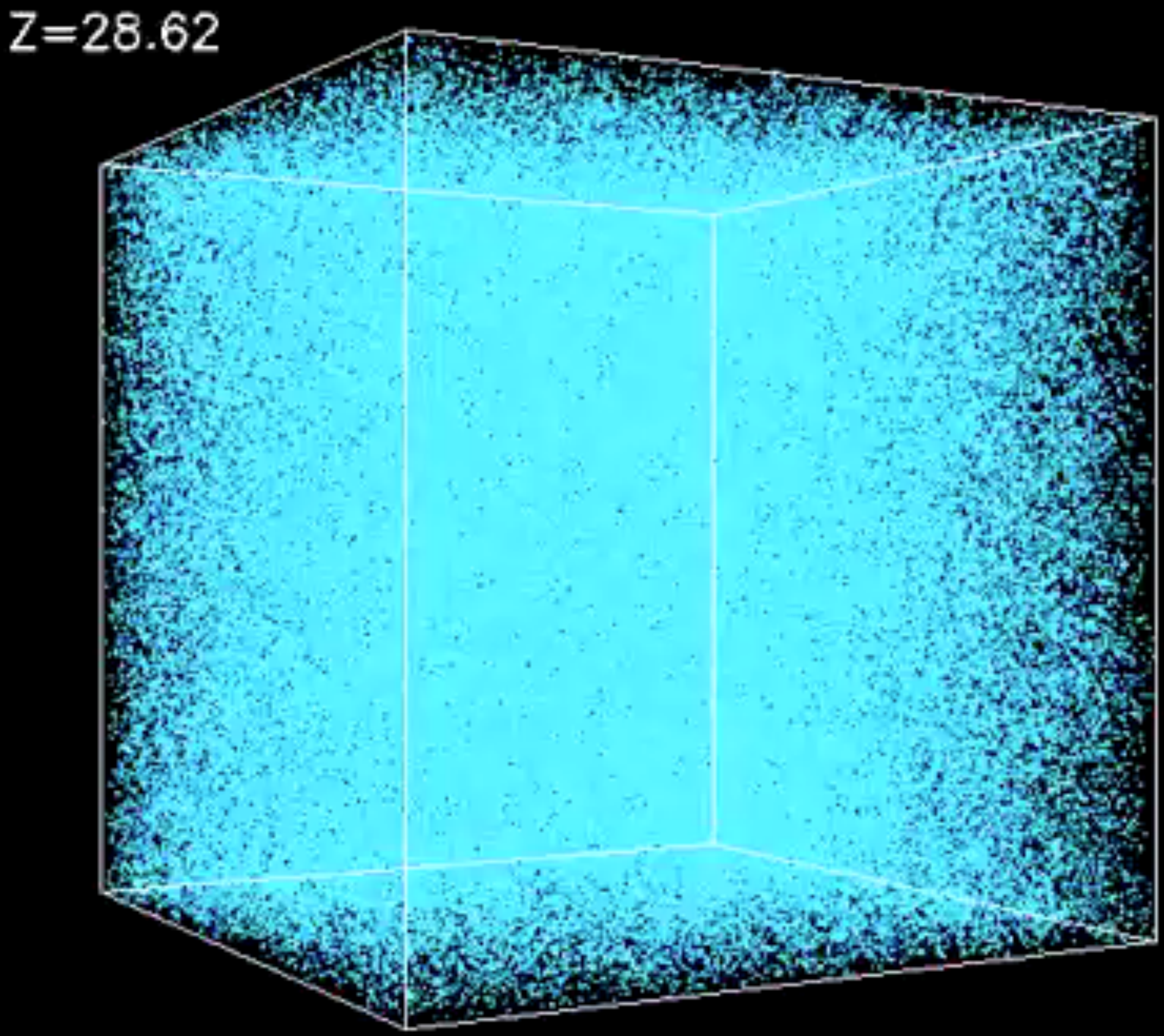
www.nasa.gov

Initial conditions

- Cosmic Microwave Background fluctuations of 10^{-5} at $z \sim 1100$



Computer simulations for structure formation



Visualization Credits: Andrey Kravtsov and Anatoly Klypin

Einstein equations

$$\boxed{R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R} = \boxed{8\pi G T_{\mu\nu}} \qquad (c = 1)$$

- L.h.s.: Gravity/geometry
- R.h.s.: Matter/energy
- Energy contents of the universe determine the gravity field.

Cosmological constant

- Field equation predicts the universe is dynamic.

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = 8\pi G T_{\mu\nu}$$

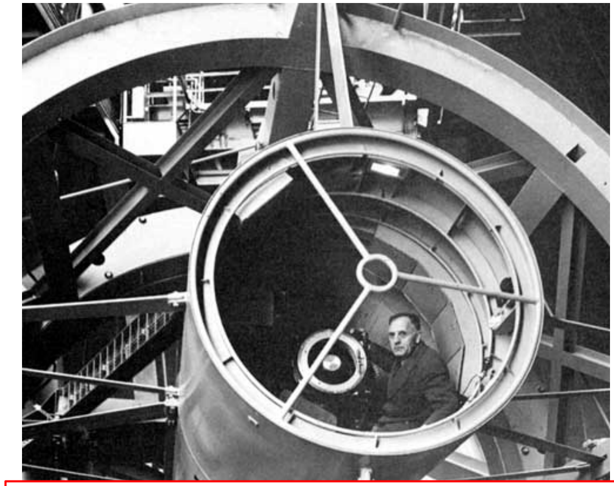
- In 1916, Einstein believed the universe was static.
  - realized that an alternative solution was:

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R \xcancel{+ g_{\mu\nu}\Lambda} = 8\pi G T_{\mu\nu}$$

- Lambda can be used to make the universe static.
  - although Friedmann soon pointed out the solution was unstable.
- The universe was found to be expanding in 1929.
  - Einstein called Lambda his biggest blunder.

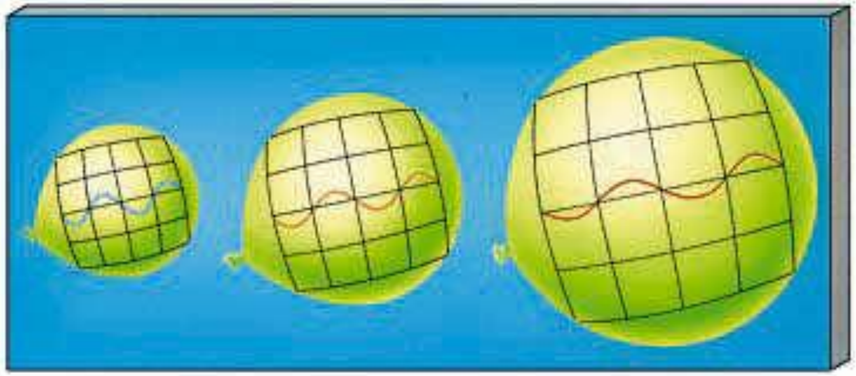
Our Universe is expanding

Discovered by Edwin Hubble in 1929

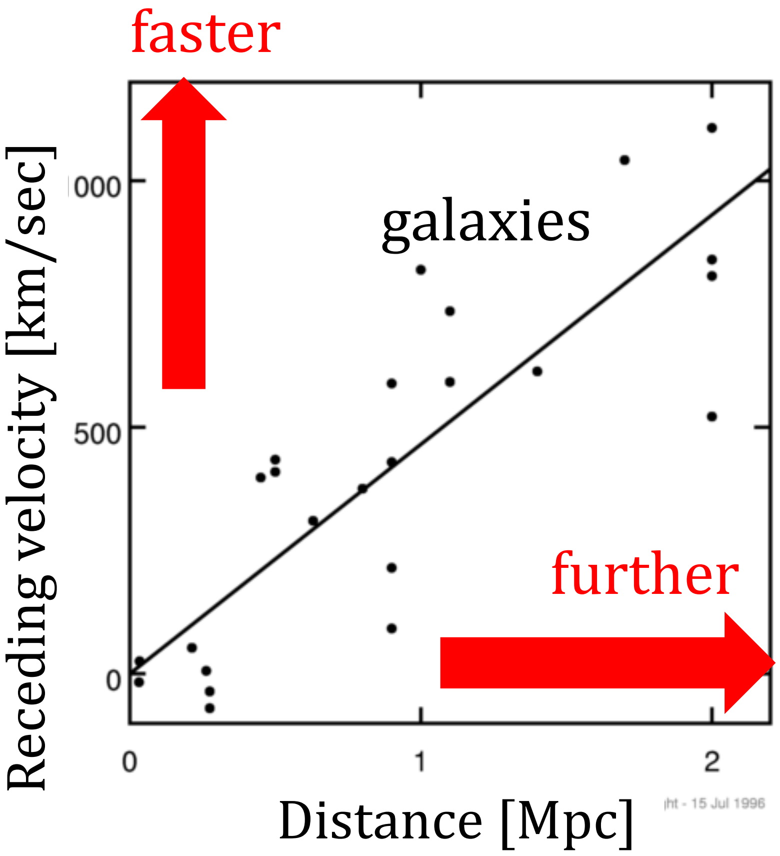


Redshift vs. Scale factor

$1+z := \lambda(t_0)/\lambda = a(t_0)/a = 1/a$



Receding velocity = H_0 * distance

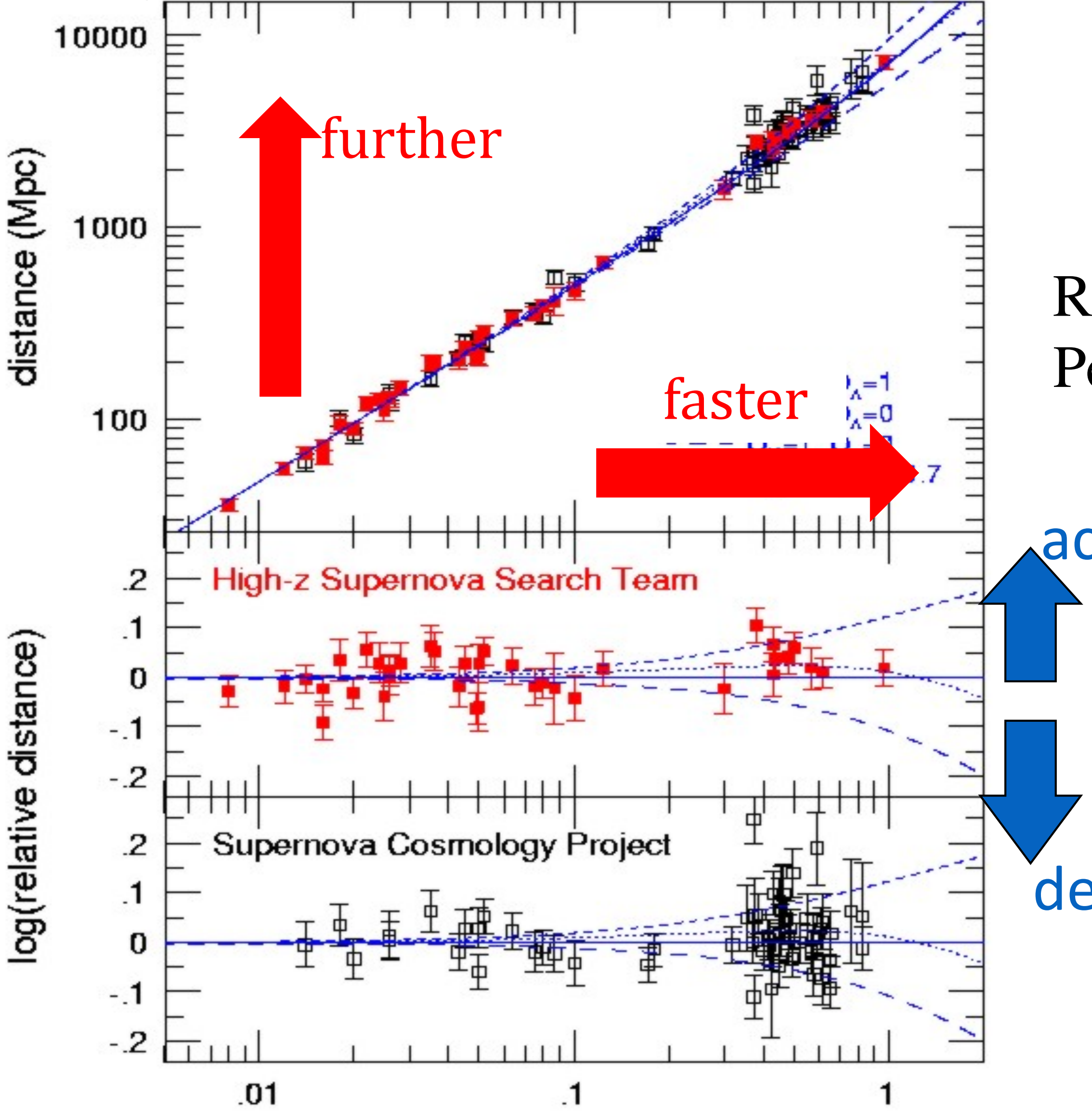


$1\ \mathrm{Mpc} = 10^6\ \mathrm{pc}$

$1\ \mathrm{pc} \sim 3$ light years $\sim 3 \times 10^{18}\mathrm{cm}$

The expansion is accelerating!

Discovered by Perlmutter, Riess, Schmidt in 1998-1999



Riess+ (1998),
Perlmutter+ (1999)

acceleration

deceleration

redshift z $= \lambda_{obs}/\lambda - 1$ = stretch of wavelength

The expansion is accelerating!

Discovered by Perlmutter, Riess, Schmidt in 1998-1999

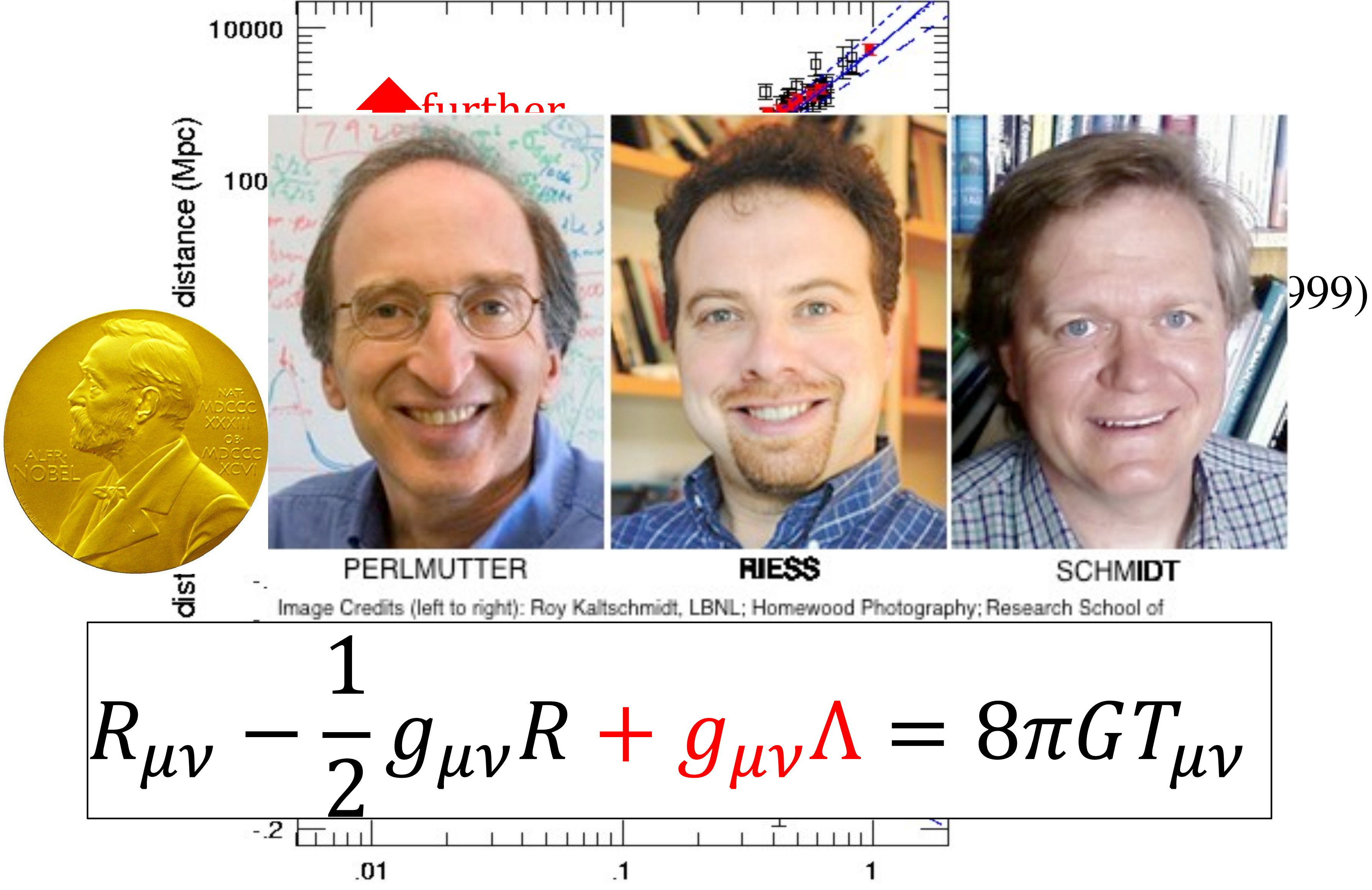
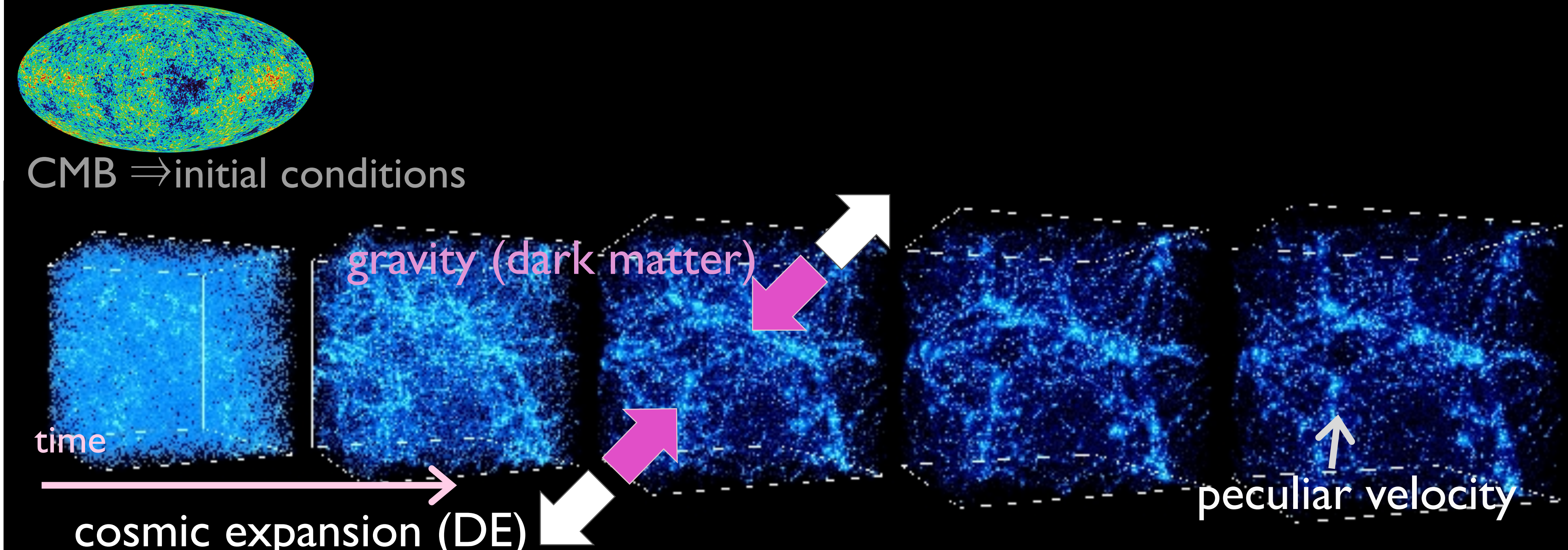


Image Credits (left to right): Roy Kaltschmidt, LBNL; Homewood Photography; Research School of

$$\boxed{R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R + g_{\mu\nu} \Lambda = 8\pi G T_{\mu\nu}}$$

redshift z $= \lambda_{obs}/\lambda - 1$ = stretch of wavelength

Structure grows through gravity in the expanding universe



CMB ⇒initial conditions

gravity (dark matter)

time

cosmic expansion (DE)

peculiar velocity

Friedmann Equations

- Einstein equations with the cosmological principle (isotropy and homogeneity)

$$\left\{\begin{aligned} \frac{\ddot{a}}{a} &= -\frac{4\pi G}{3}(\rho + 3p) + \frac{\Lambda}{3} \\ \left(\frac{\dot{a}}{a}\right)^2 &= \frac{8\pi G}{3}\rho - \frac{K}{a^2} + \frac{\Lambda}{3} \end{aligned}\right.$$

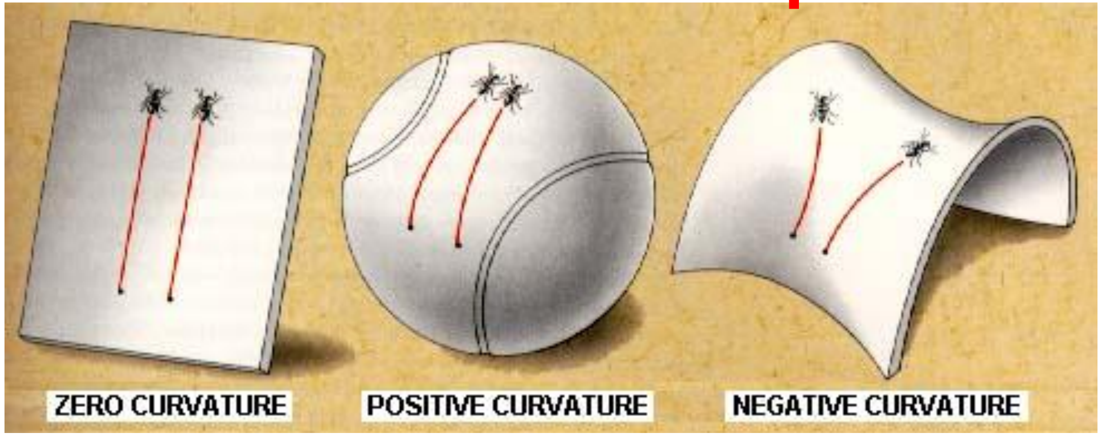
Hubble parameter (expansion rate) $H(t) \equiv \frac{1}{a}\frac{da}{dt}$

Values today

$$\left(\frac{\dot{a}}{a}\right)_{t=t_0} = H_0 \qquad a(t_0) = 1$$

Spatial curvature: K

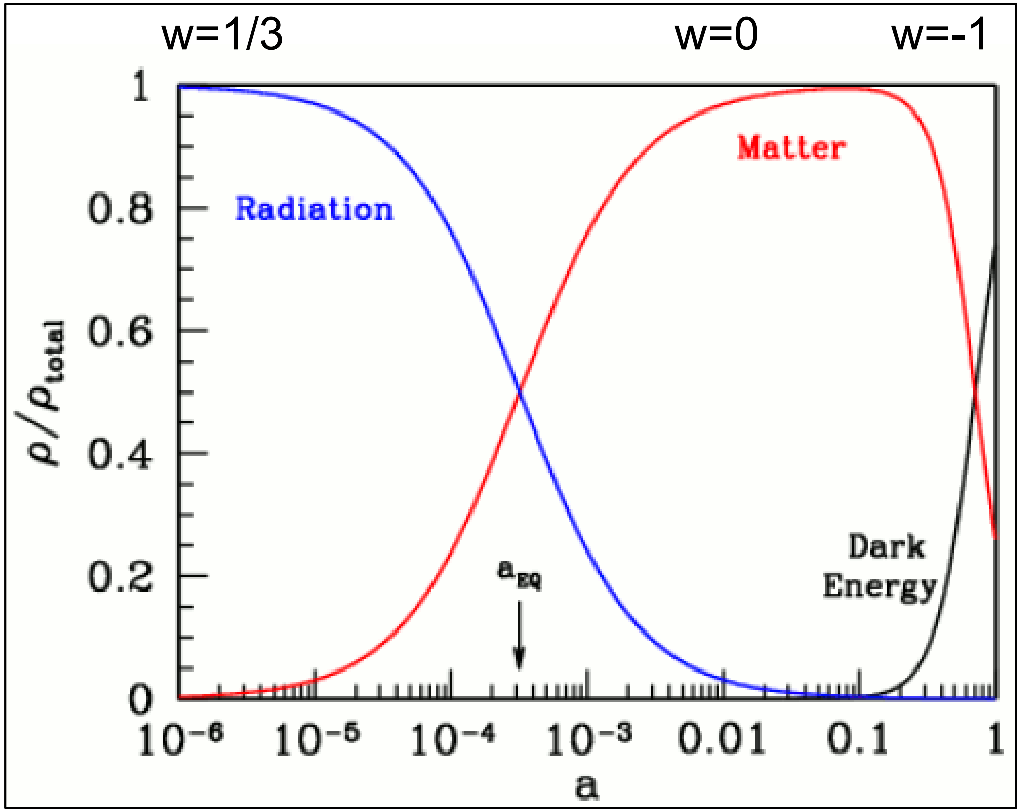
Flat **Closed** **Open**



$K = 0$ $K > 0$ $K < 0$

Energy conservation

$$\underset{\text{Energy}}{\underline{\underline{\frac{d}{dt}(\rho a^3)}}} + \underset{\text{Work}}{\underline{\underline{p\frac{d}{dt}a^3}}} = 0$$



Equation of state

$$w = p/\rho$$

$$\rho_i(t) \propto \begin{cases} a^{-4} & \text{: radiation } (i=r)\ w = 1/3 \\ a^{-3} & \text{: matter } (i=m)\ w = 0 \\ const. & \text{: cosmological const. } (i=\Lambda)\ w = \text{-}1 \end{cases}$$

dark energy $(i=DE)$ $w_{\mathrm{DE}} < -1/3$

Cosmological parameters

- Spatially flat ($K = 0$) Friedmann equation

$$H^2 = \frac{8\pi G}{3}\rho + \frac{\Lambda}{3} = \frac{8\pi G}{3}(\rho + \rho_\Lambda) \equiv \frac{8\pi G}{3}\rho_{tot}$$

⇨ Critical density $\rho_{crit}(t) \equiv \frac{3H^2(t)}{8\pi G}$

- Present-day critical density

$$\rho_{crit,0} \equiv \frac{3H_0^2}{8\pi G} = 1.88h^2 \times 10^{-29} g\ cm^{-3}$$

Dimensionless Hubble parameter $h \equiv \frac{H_0}{100}$

Cosmological parameters

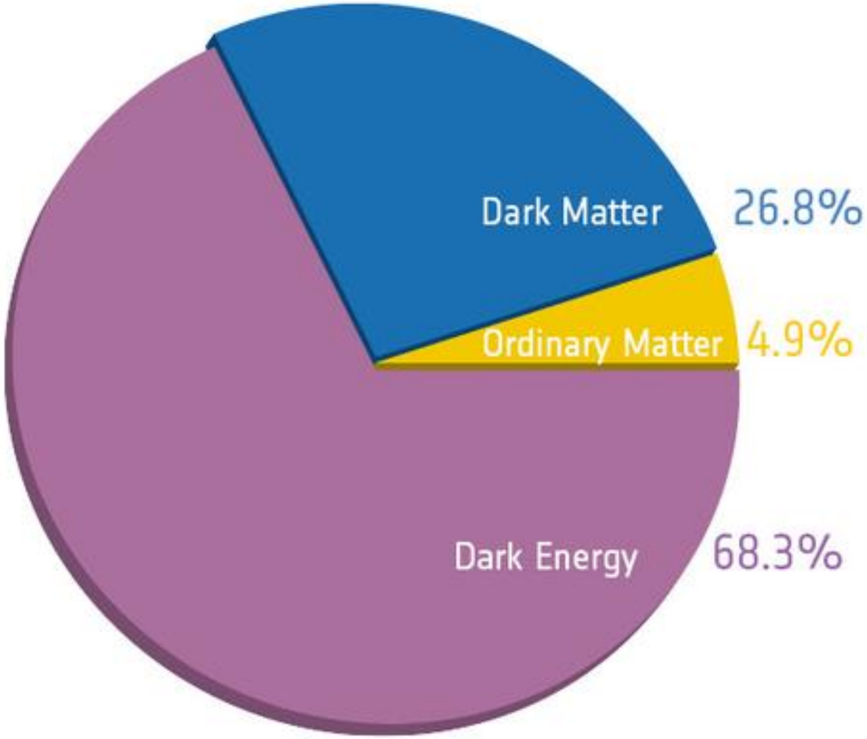
- Density parameters

$$\Omega_i(t) = \frac{\rho_i(t)}{\rho_{crit}} = \frac{8\pi G \rho_i(t)}{3H^2(t)}$$

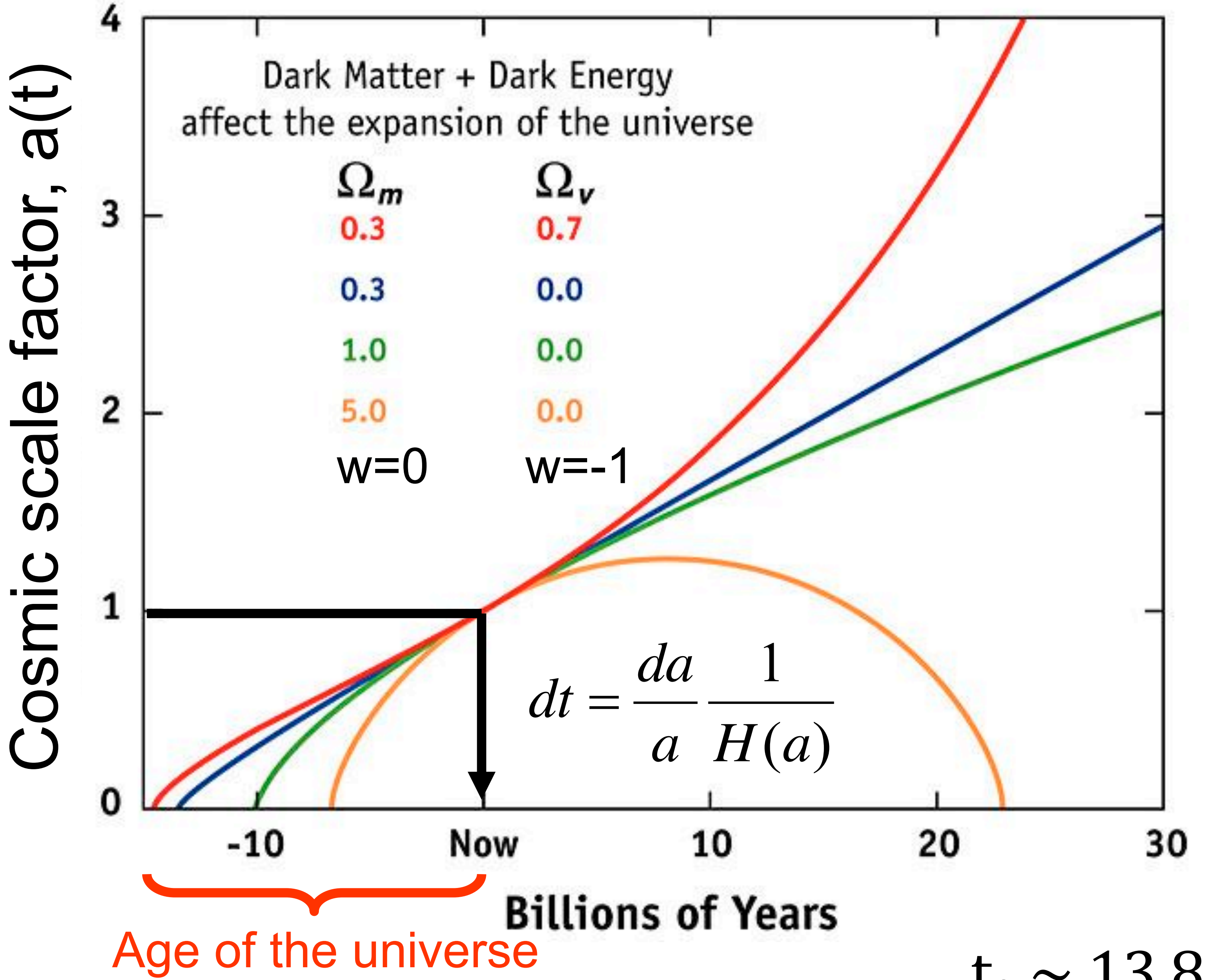
- Then Friedmann equation becomes

$$H^2(a) = H_0^2\left(\frac{\Omega_{m0}}{a^3} + \Omega_{\Lambda 0} - \frac{\Omega_{K0}}{a^2}\right)$$

- Observational constraints
  - Matter: $\Omega_{m0} \sim 0.32$
  - Baryon: $\Omega_{b0} \sim 0.05$
  - Dark matter: $\Omega_{dm0} \sim 0.27$
  - Radiation: $\Omega_{r0} \sim 10^{-3}$
  - Curvature: $\Omega_{K0} \sim 0$
  - Dark energy: $\Omega_{\Lambda 0} \sim 0.68$



Expansion history of the Universe



$$dt = \frac{da}{a}\frac{1}{H(a)}$$

$t_0 \sim 13.8$ billion years

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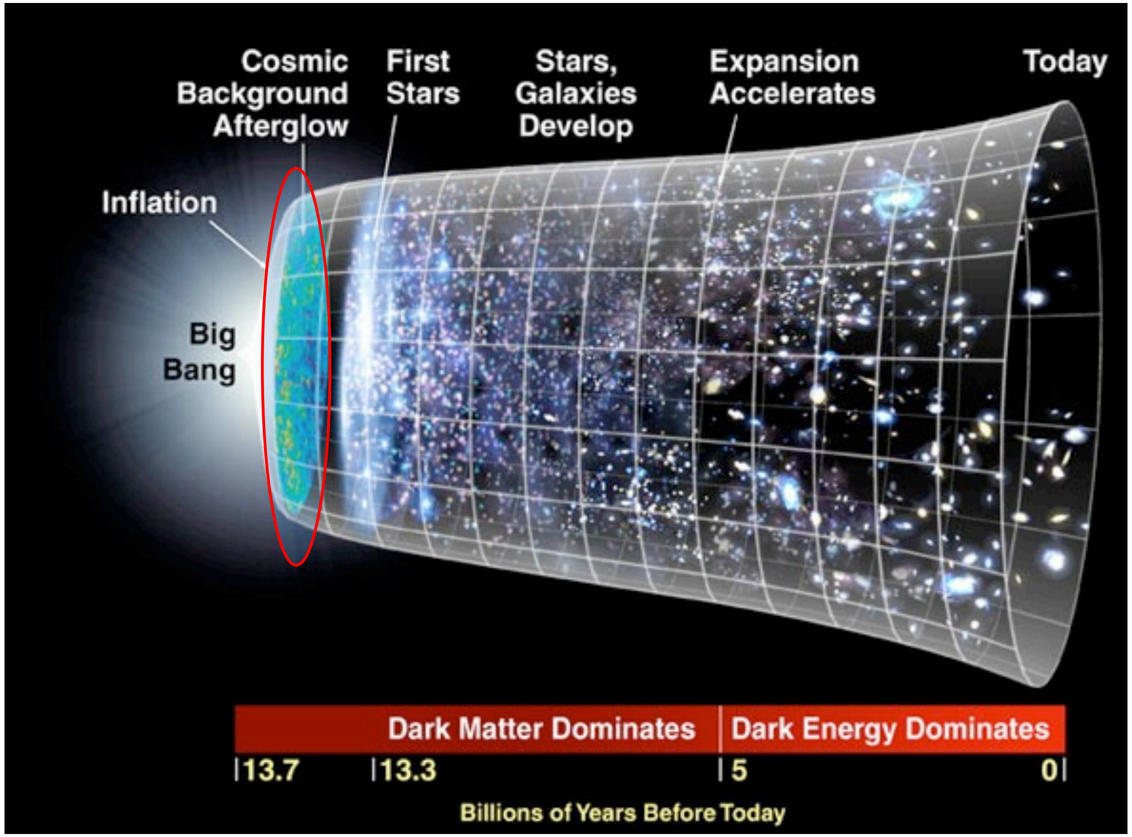
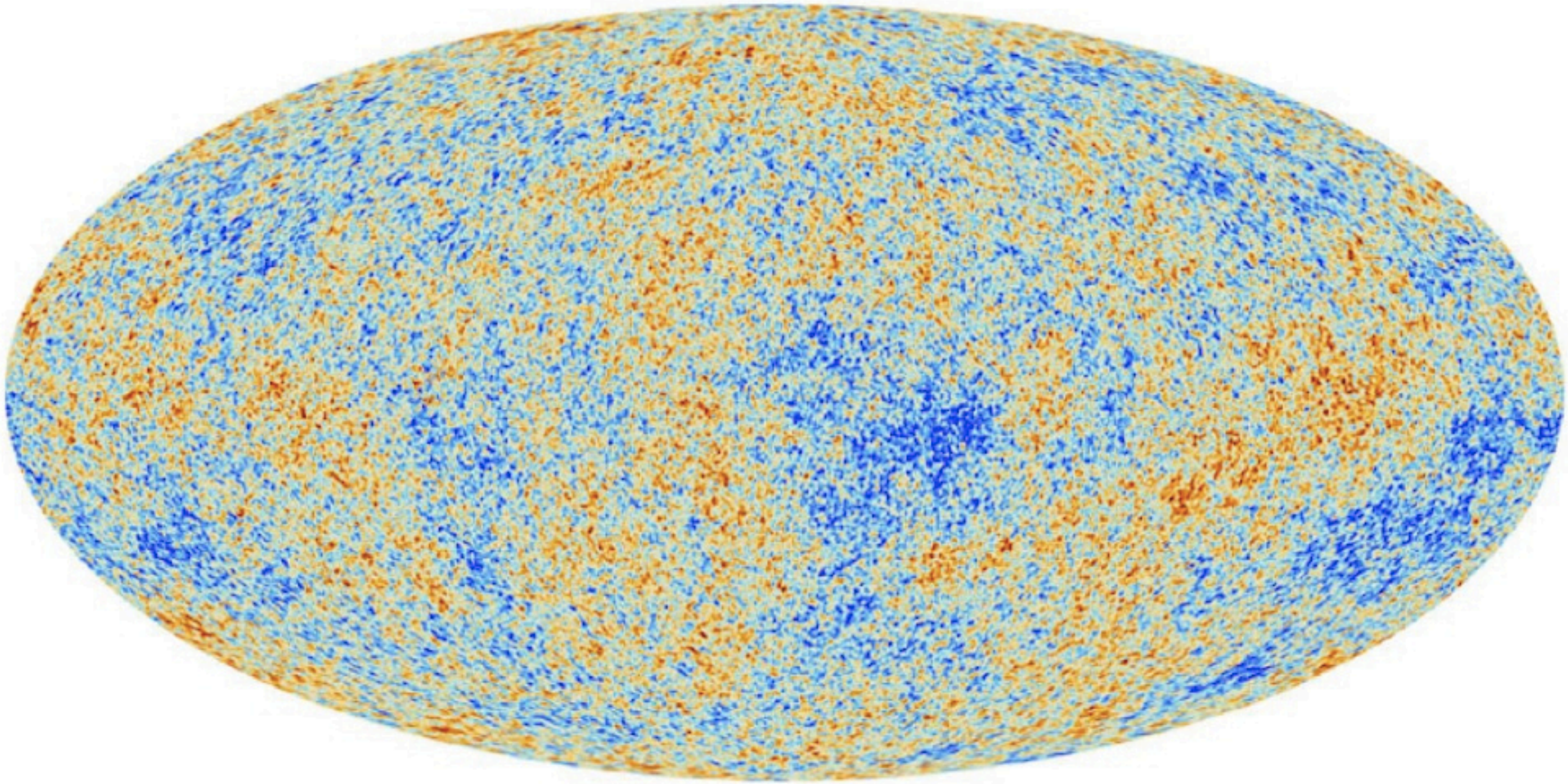
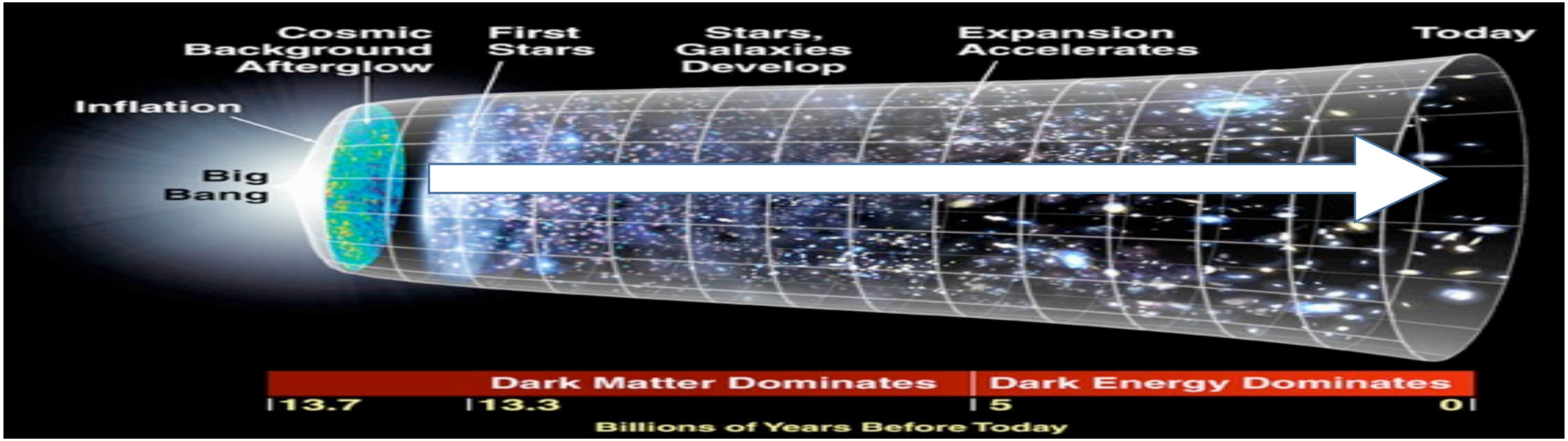


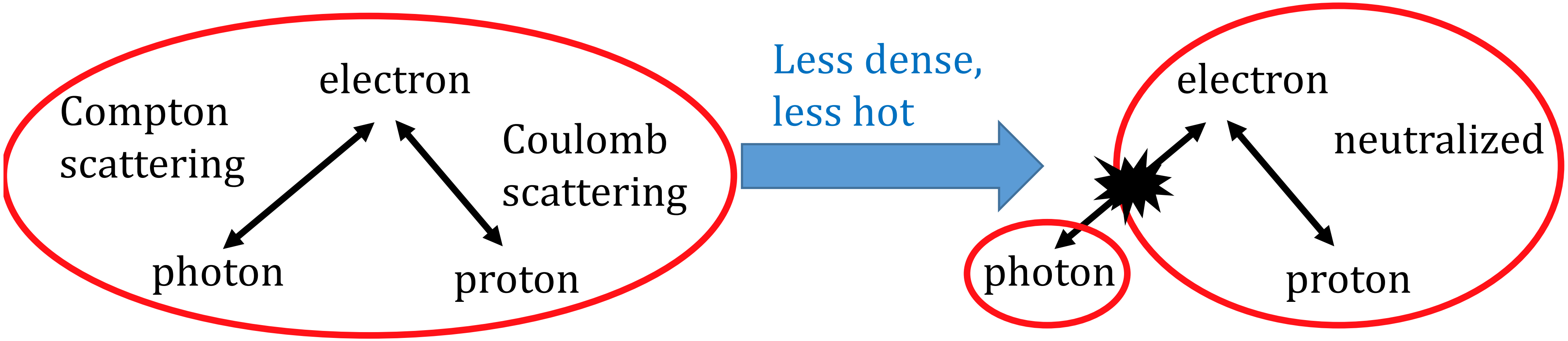
380,000 years after big bang

- Why we can clearly observe the universe this moment?



The universe was smaller, denser and hotter





Relativistic fluid

Photon decoupled

Compton scattering

electron

Coulomb scattering

photon

proton

Less dense, less hot

electron

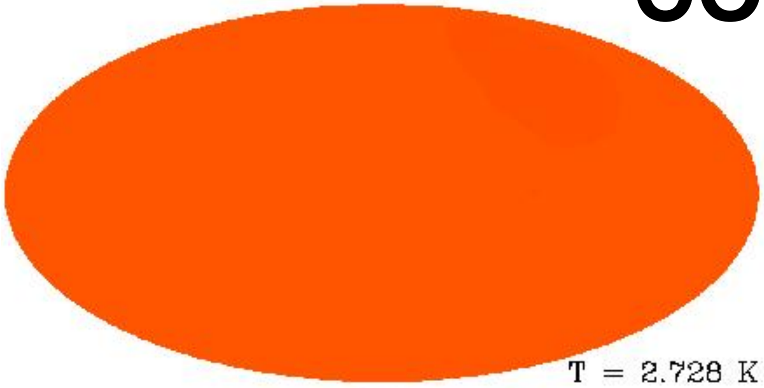
neutralized

photon

proton

Oscillate as sound wave

Temperature Anisotropies seen by COBE/DMR



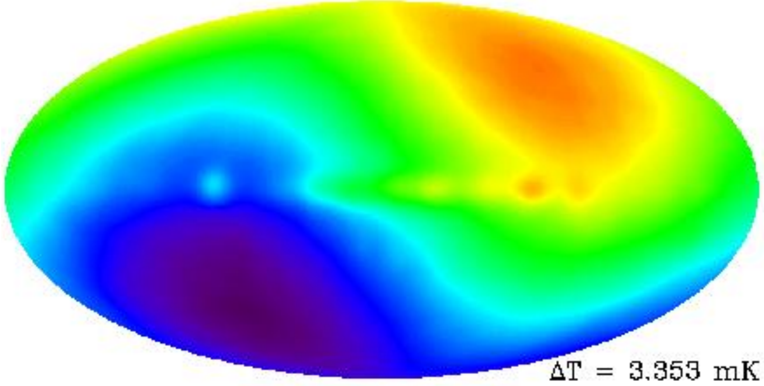
Uniform component

COBE/FIRAS:

$$T_{CMB} = 2.725 \pm 0.002\,[K]$$

$$T(z) = T_{CMB}(1+z)$$

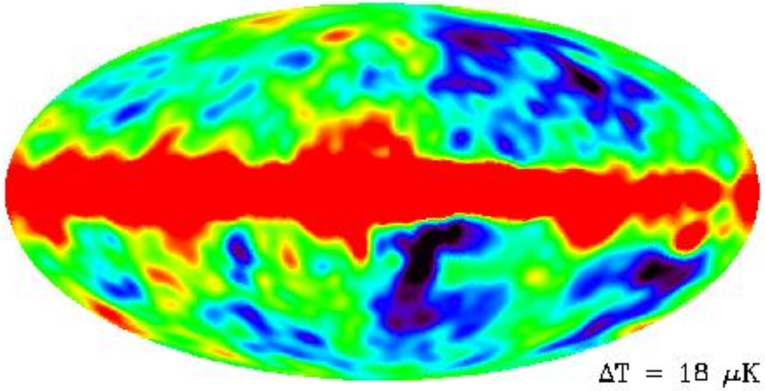
determined to 0.1% accuracy



Dipole component

$$\left(\frac{\delta T}{T_{CMB}}\right)_{180^\circ} \approx 10^{-3}$$

Motion of the solar system w.r.t. CMB: 371 km/s (cf. Galactic rotation: ~220km/s)



Multipole components

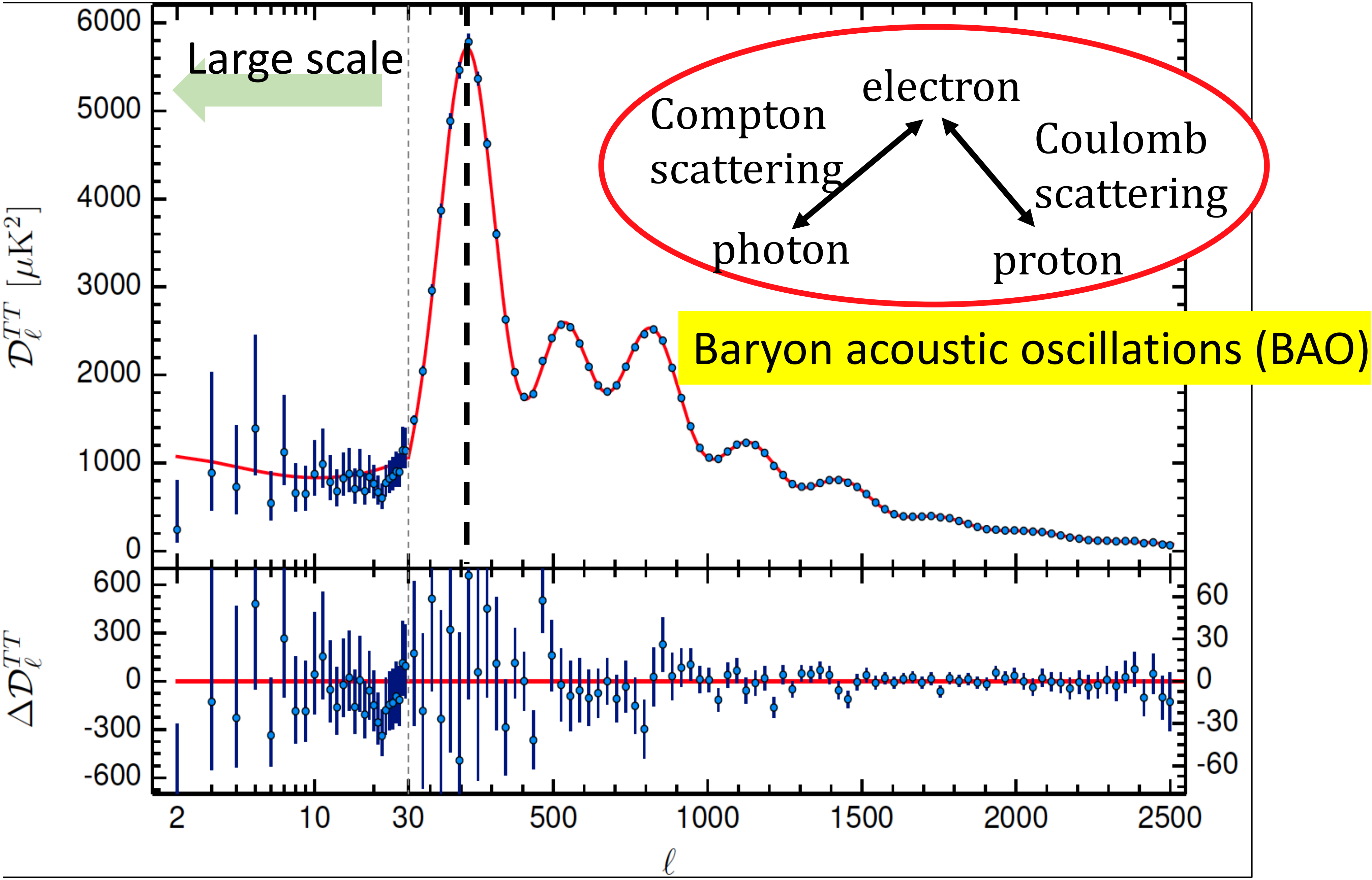
$$\left(\frac{\delta T}{T_{CMB}}\right)_{7^\circ} \approx 10^{-5}$$

Initial seeds of cosmic structure

$$\frac{\Psi}{c^2} \sim \frac{\Delta T}{T} \sim 10^{-5}$$

Courtesy Keiichi Umetsu

Power spectrum (=density perturbation)



Large scale

Compton scattering

electron

Coulomb scattering

photon

proton

Baryon acoustic oscillations (BAO)

Cosmological parameters

- Density parameters

$$\Omega_i(t) = \frac{\rho_i(t)}{\rho_{crit}} = \frac{8\pi G\rho_i(t)}{3H^2(t)}$$

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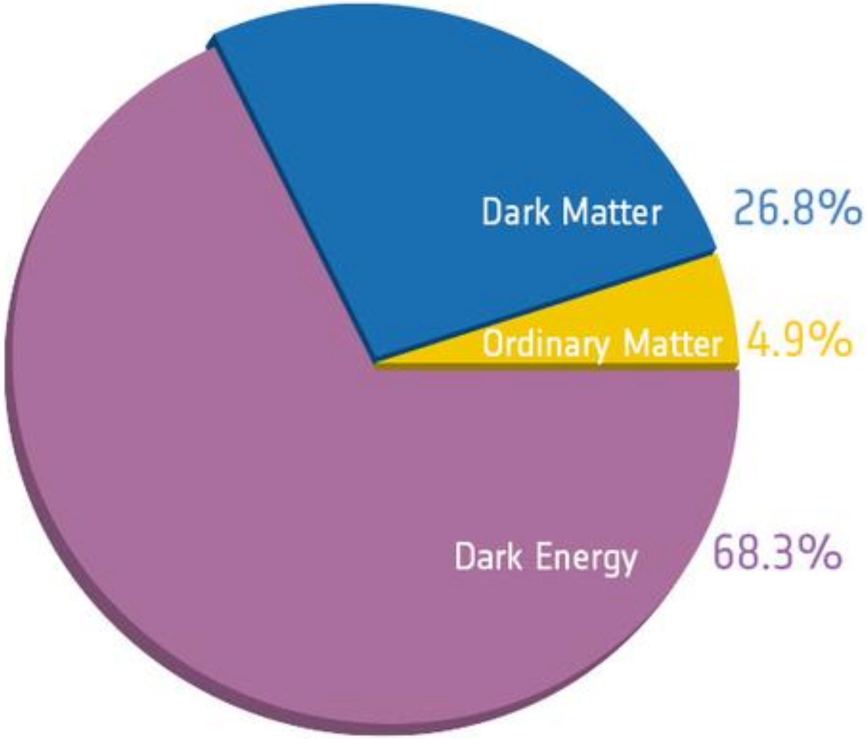

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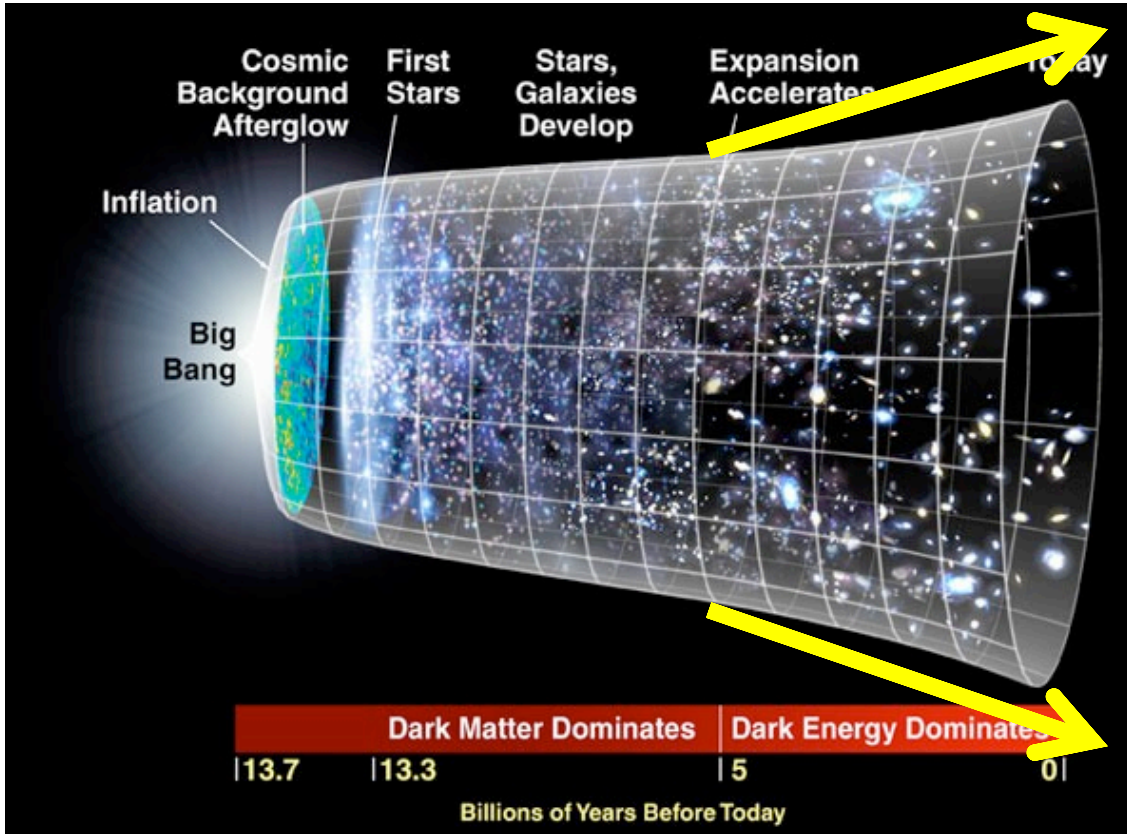
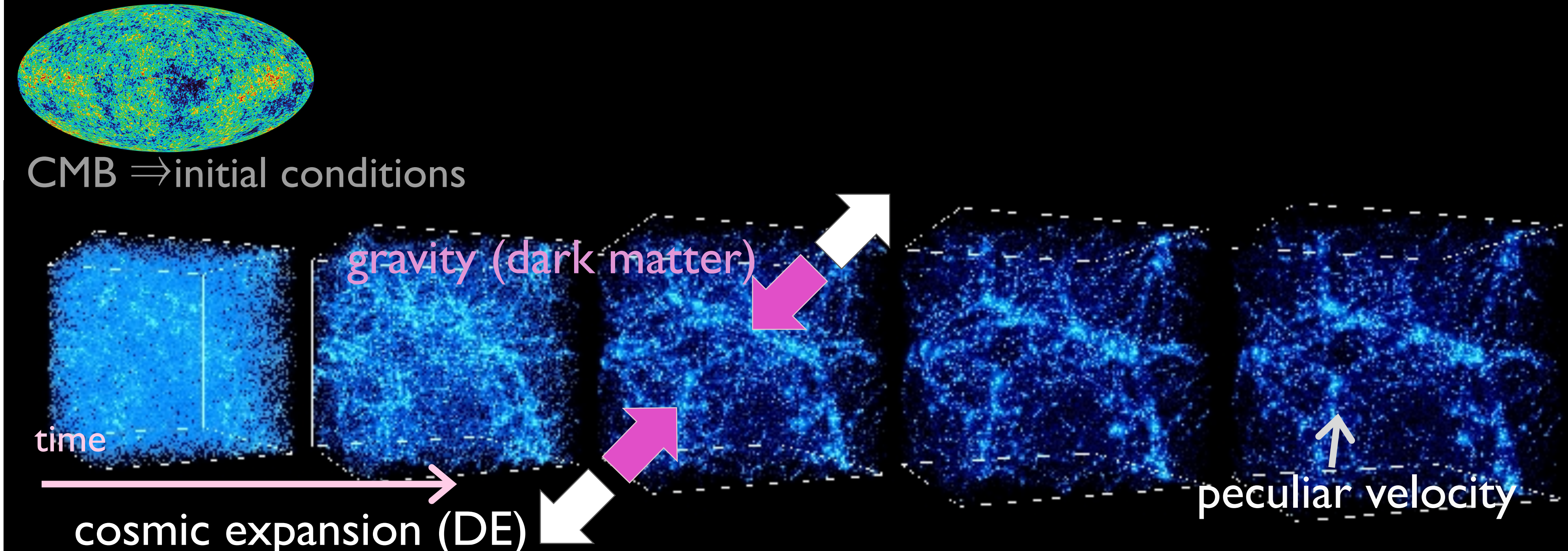
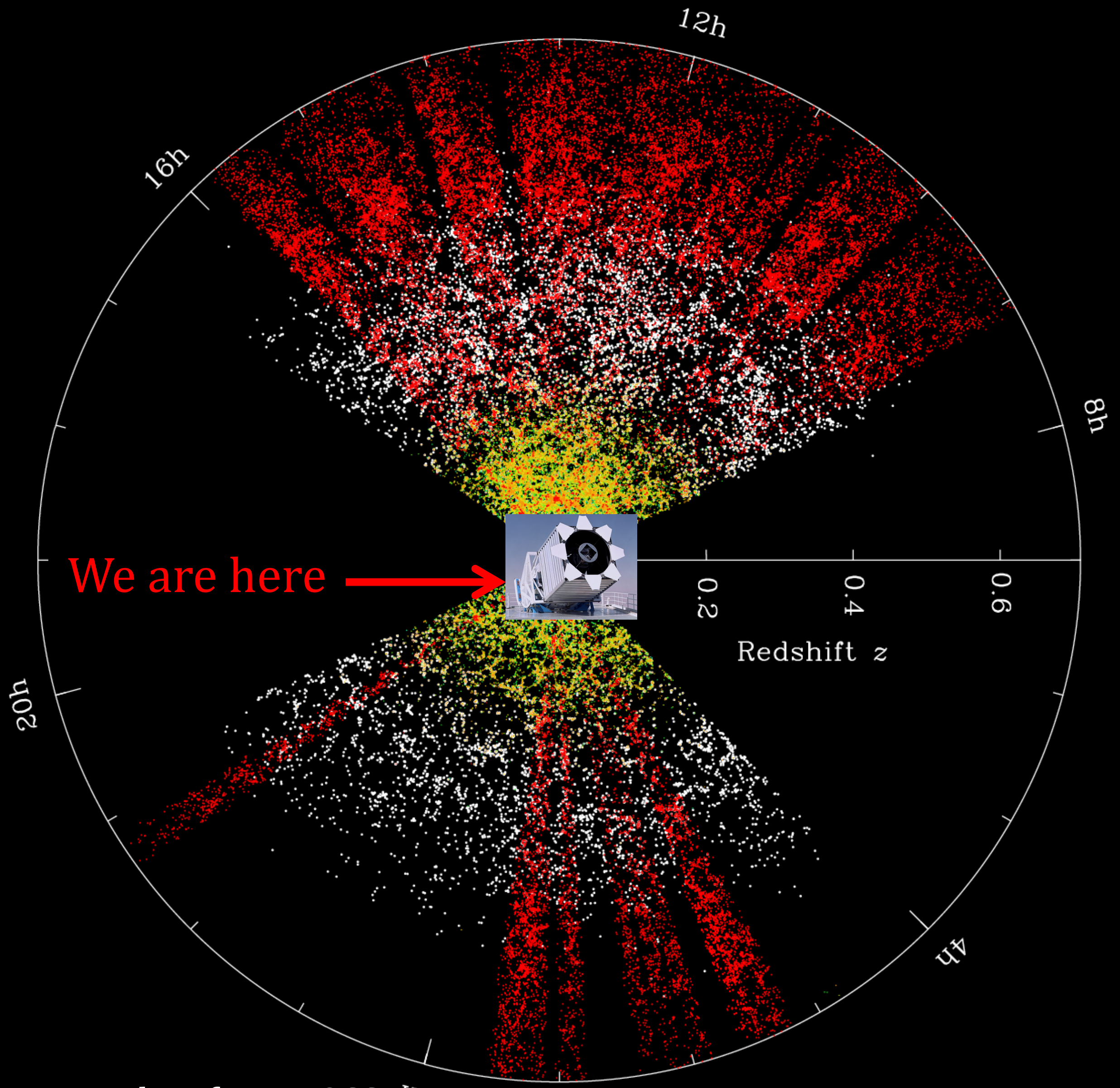


Structure grows through gravity in the expanding universe



Large-scale structure of the Universe can be traced by galaxy redshift surveys



We are here

Figure taken from BOSS team

CMB calibration

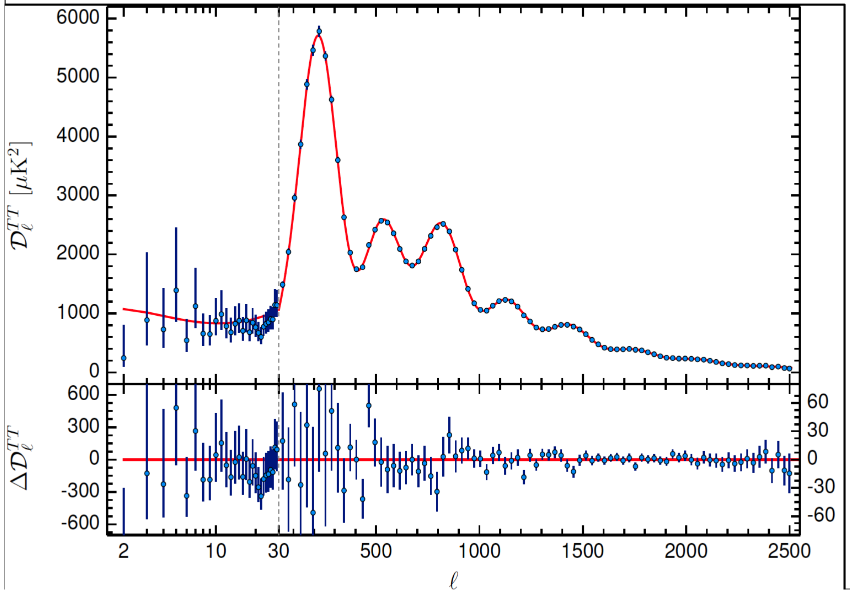
- Not coincidentally the sound horizon is extremely well determined by the structure of the acoustic peaks in the CMB.

$$
\begin{aligned}
s &= 146.8 \pm 1.8 \text{ Mpc} \\
&= (4.53 \pm 0.06) \times 10^{24} \text{m}
\end{aligned}
$$

WMAP 5th yr data

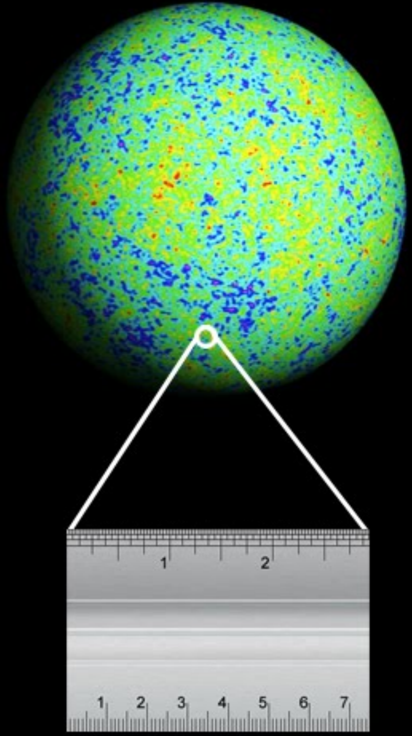
↑

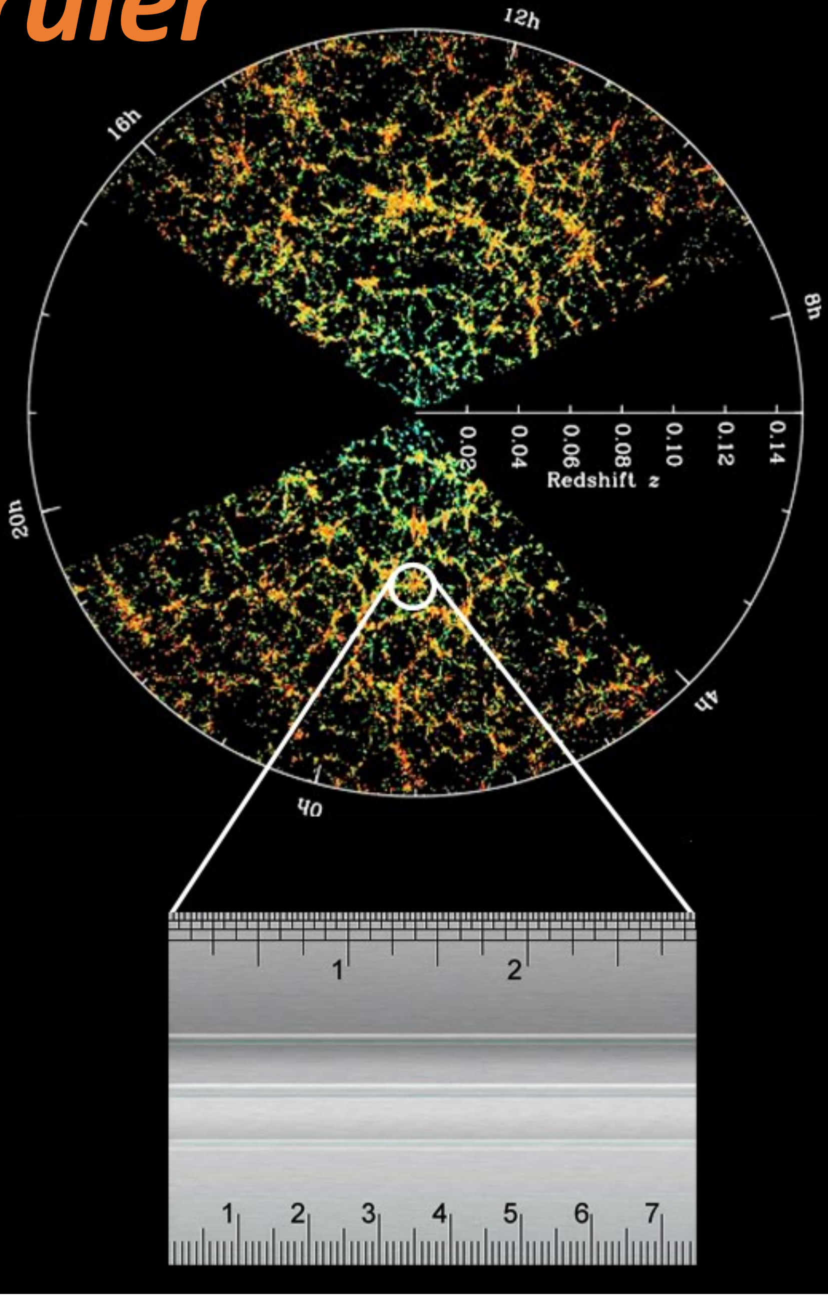
Dominated by uncertainty in ρ_m from poor constraints near 3rd peak in CMB spectrum. (Planck will nail this!)



Courtesy Tzu-ching Chang

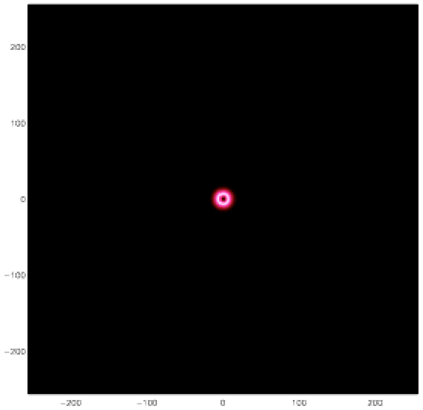
Baryon acoustic oscillations as a standard ruler



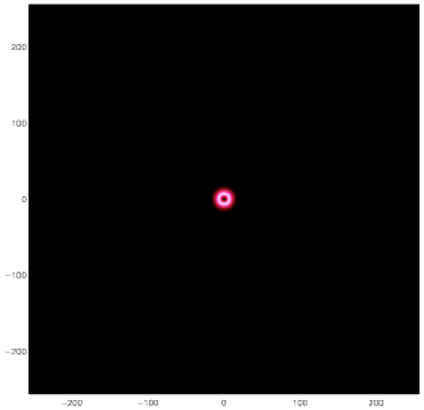


The acoustic wave

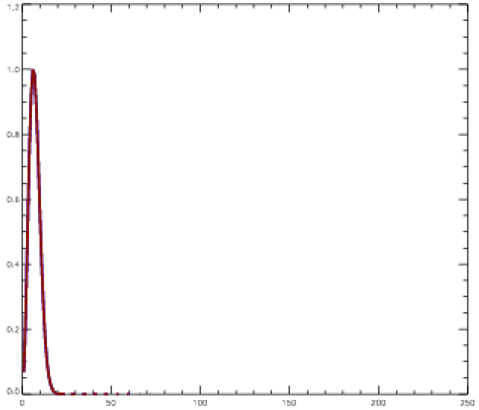
Start with a single perturbation. The plasma is totally uniform except for an excess of matter at the origin.
High pressure drives the gas+photon fluid outward at speeds approaching the speed of light.



Baryons



Photons



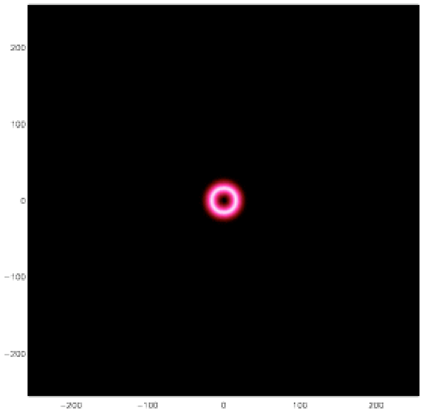
Mass profile

Eisenstein, Seo & White (2006)

Courtesy of Martin White

The acoustic wave

Initially both the photons and the baryons move outward together, the radius of the shell moving at over half the speed of light.



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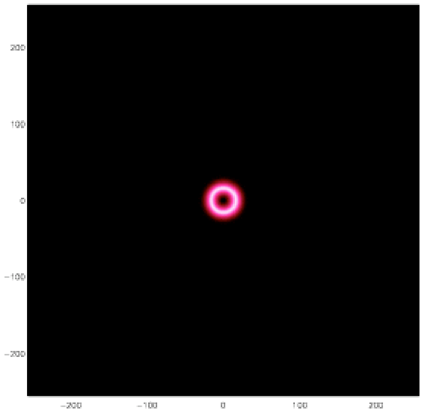
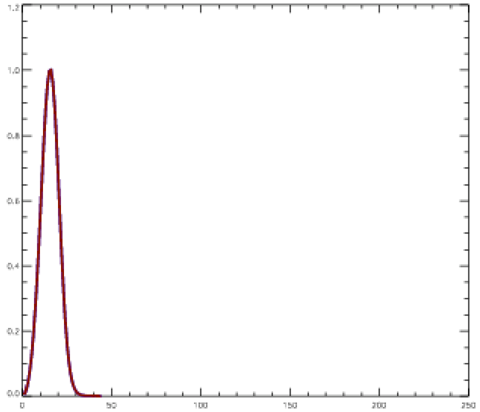
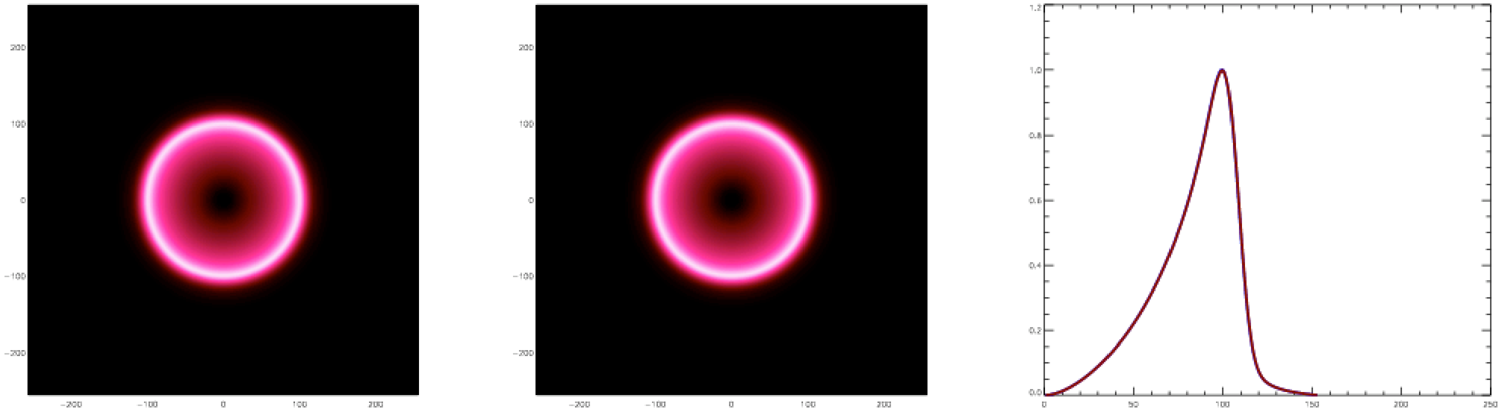


Photons



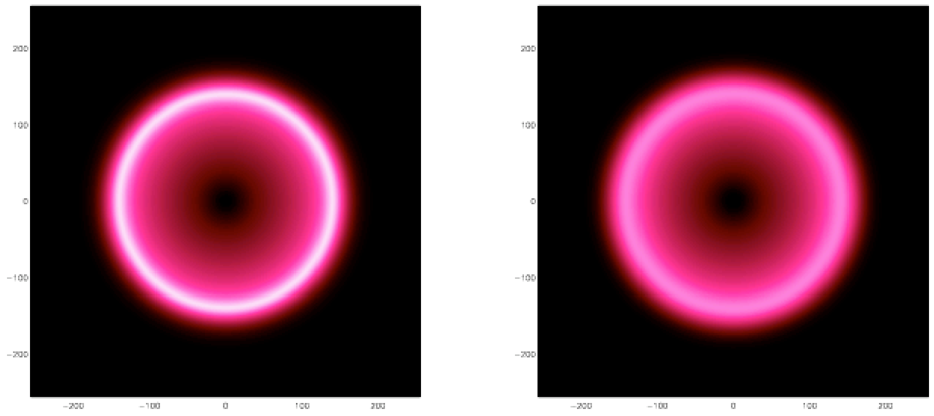
The acoustic wave

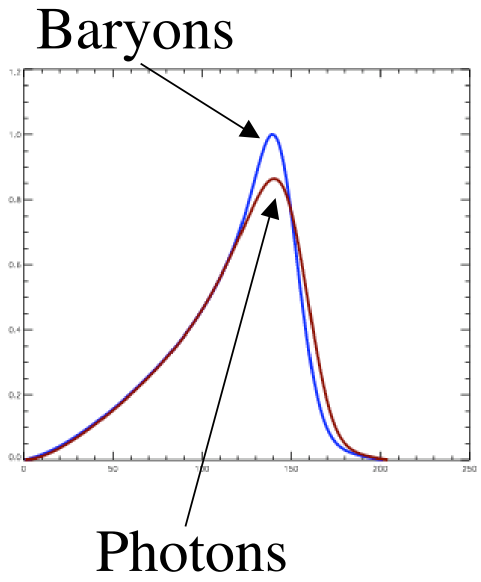
This expansion continues for 10^5 years



The acoustic wave

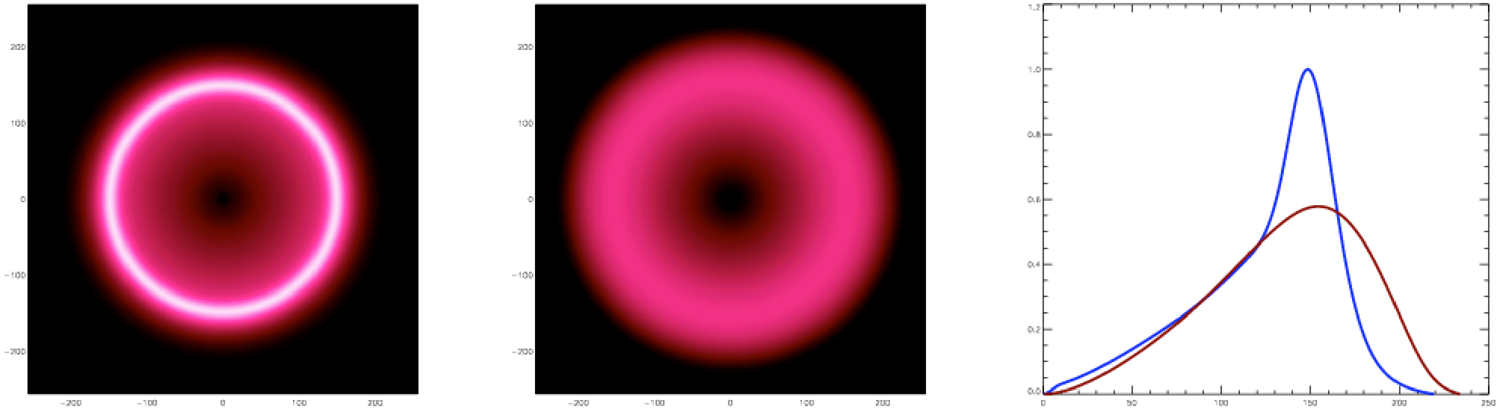
After 10^5 years the universe has cooled enough the protons capture the electrons to form neutral Hydrogen. This decouples the photons from the baryons. The former quickly stream away, leaving the baryon peak stalled.



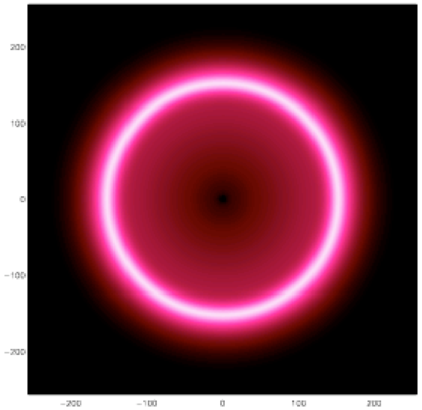


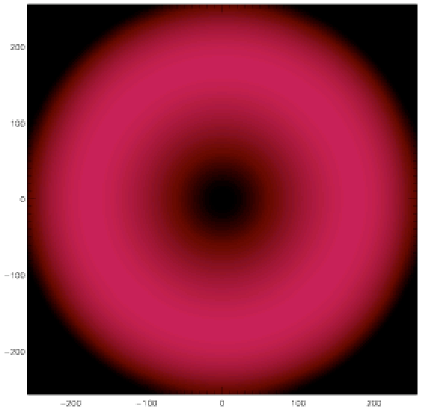
The acoustic wave

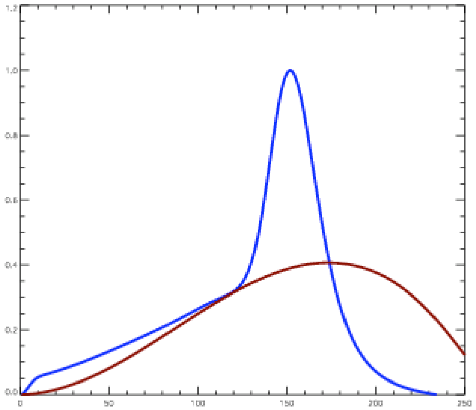
The photons continue to stream away while the baryons, having lost their motive pressure, remain in place.



The acoustic wave



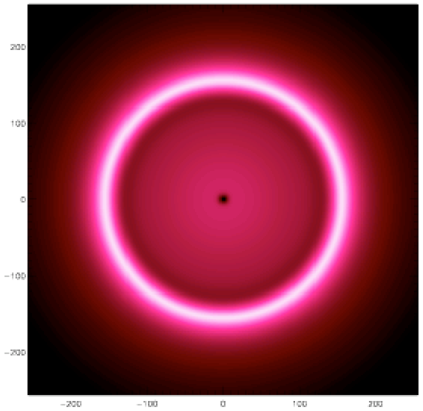


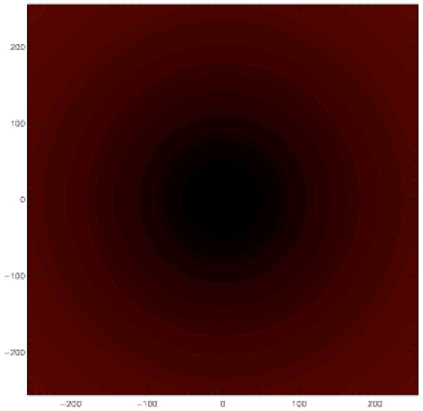


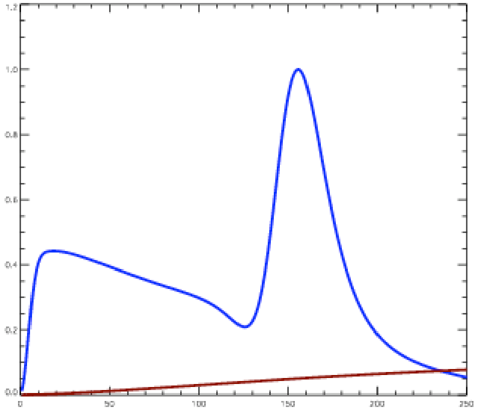
The acoustic wave

The photons have become almost completely uniform, but the baryons remain overdense in a shell 100Mpc in radius.

In addition, the large gravitational potential well which we started with starts to draw material back into it.



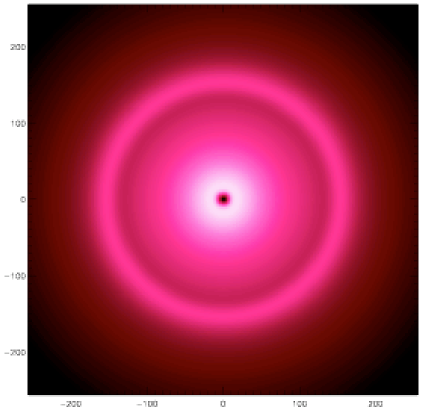


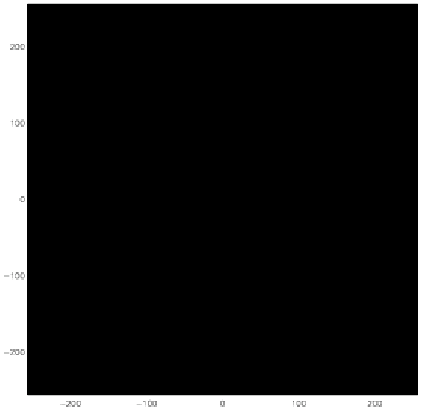


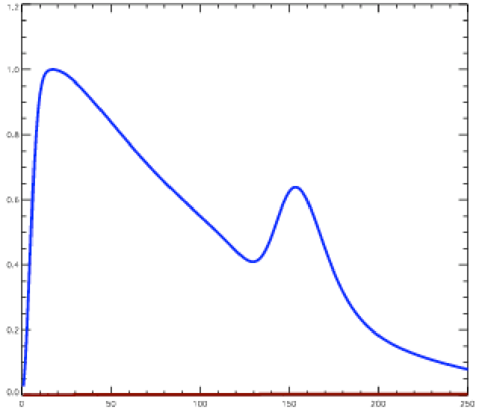
The acoustic wave

As the perturbation grows by ~10^3 the baryons and DM reach equilibrium densities in the ratio Ω_b/Ω_m.

The final configuration is our original peak at the center (which we put in by hand) and an "echo" in a shell roughly 100Mpc in radius.





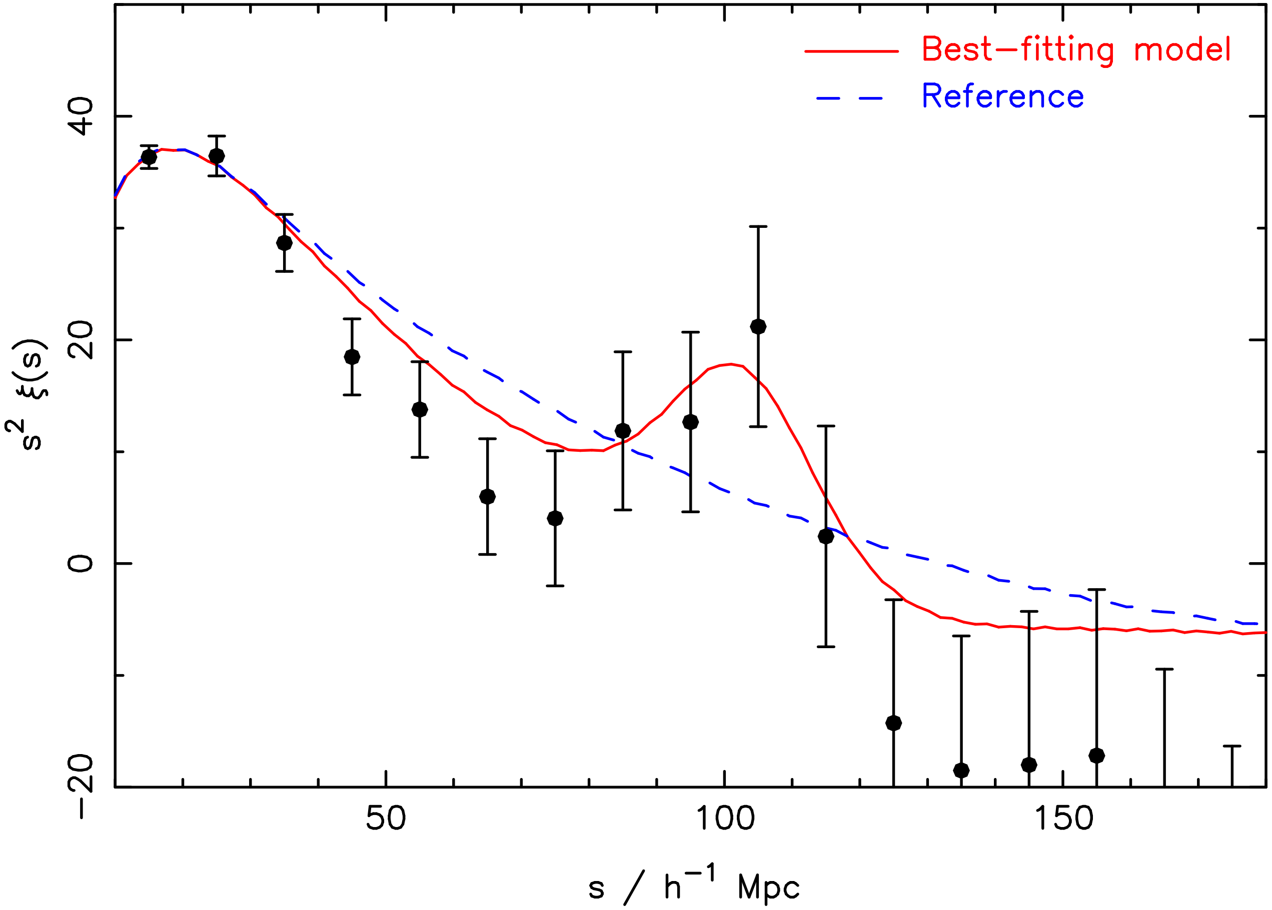


Further (non-linear) processing of the density field acts to broaden and very slightly shift the peak -- but galaxy formation is a local phenomenon with a length scale ~10Mpc, so the action at *r*=0 and *r*~100Mpc are essentially decoupled.

BAO Statistical Standard Ruler: Measured!

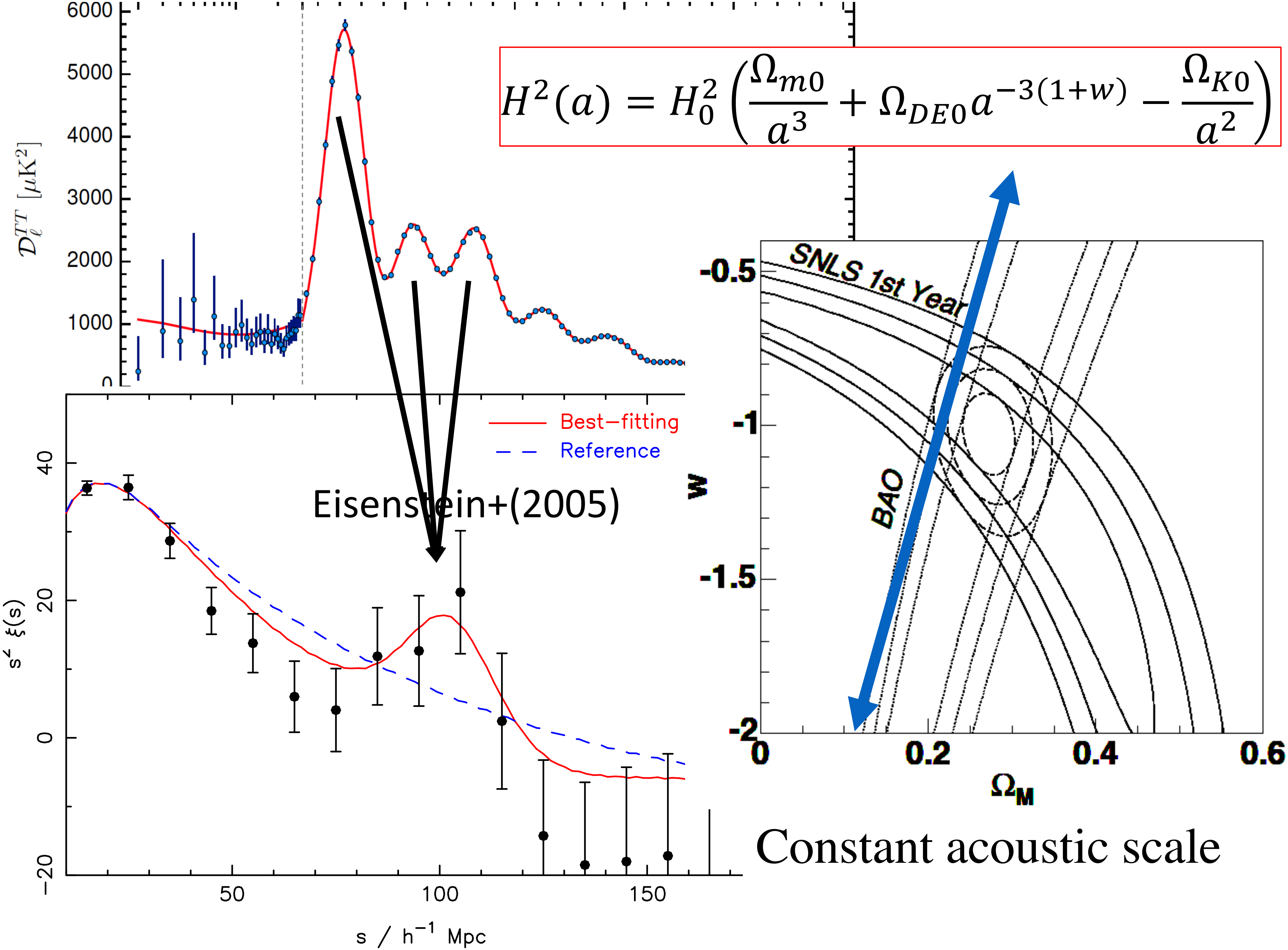
Blake et al. (2011)

Oscillations at z of ~0.6



Courtesy Tzu-ching Chang

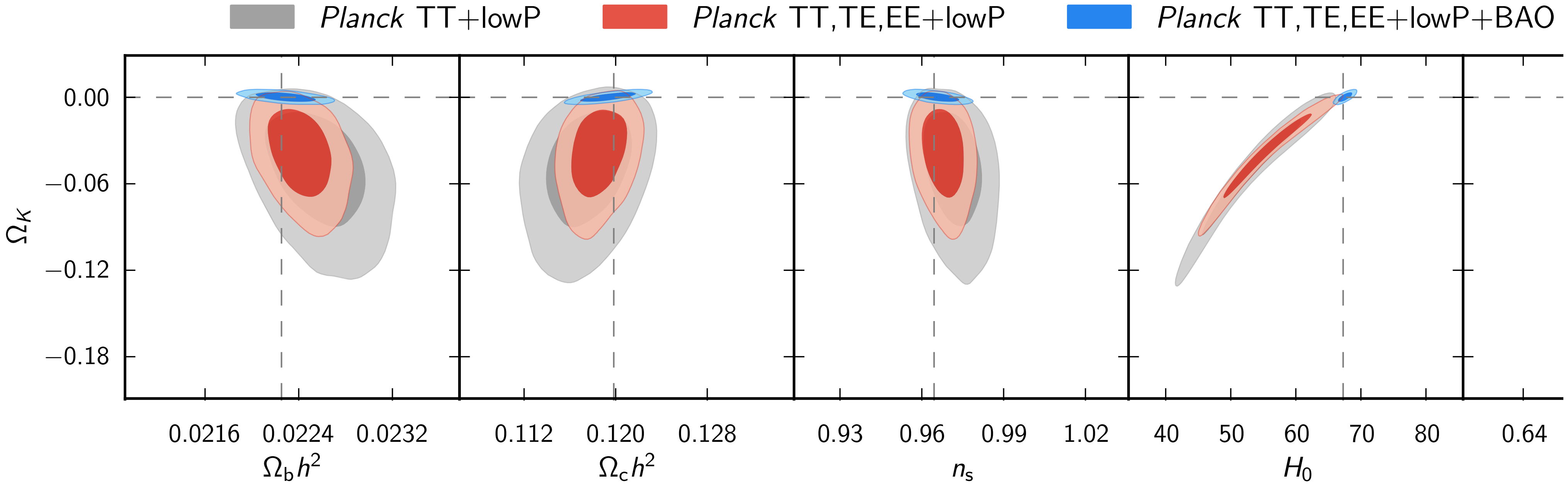
$$H^2(a) = H_0^2\left(\frac{\Omega_{m0}}{a^3} + \Omega_{DE0}a^{-3(1+w)} - \frac{\Omega_{K0}}{a^2}\right)$$



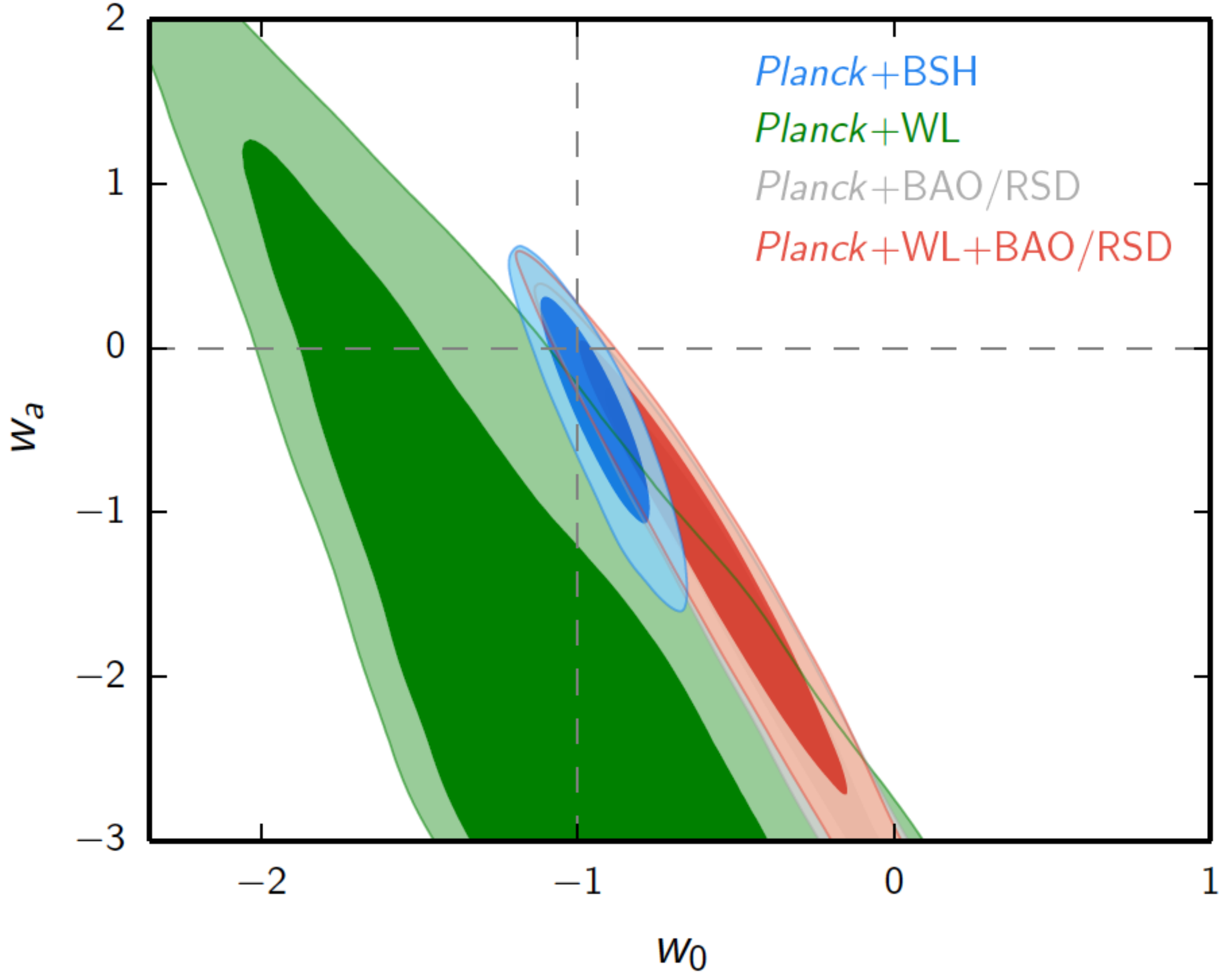
Eisenstein+(2005)

Constant acoustic scale

BAO – powerful tool for precision cosmology

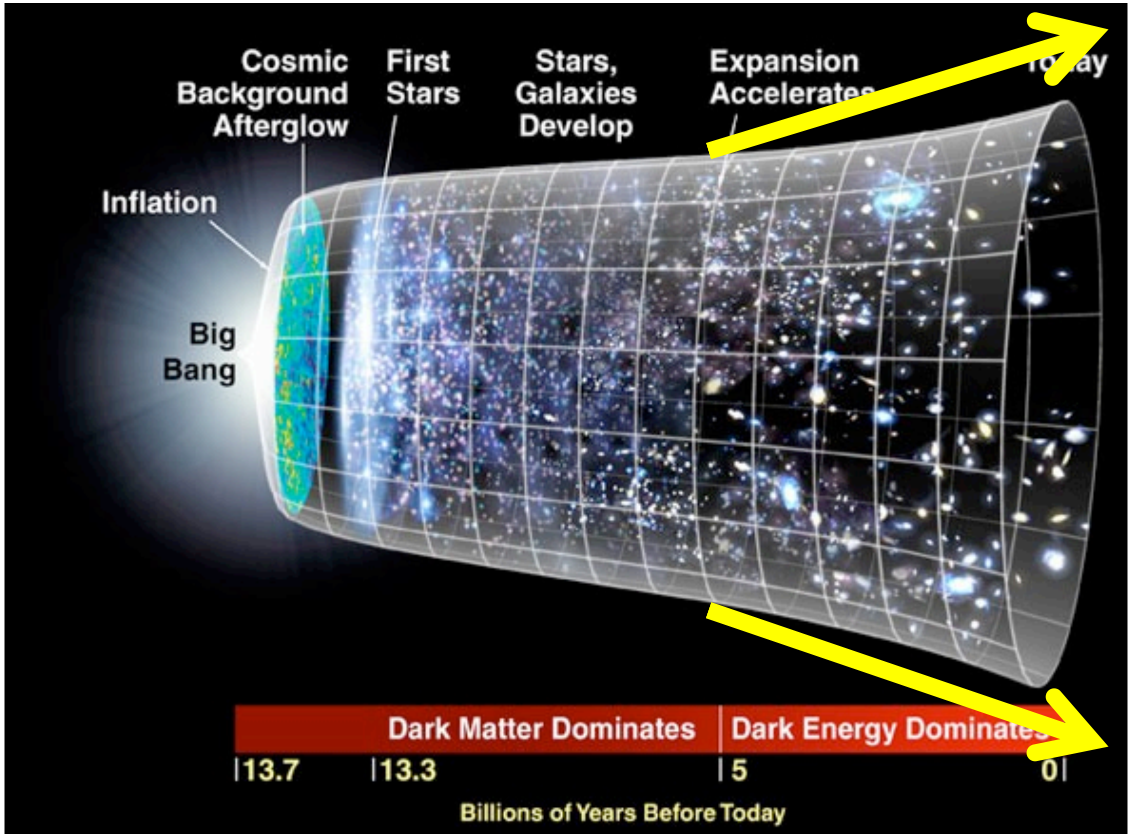


BAO – powerful tool for precision cosmology



Contents

- 1. Evolution of the Universe (Main)
- 2. The early Universe: Cosmic microwave background
- 3. Cosmic acceleration: Dark energy
- 4. Alternative to dark energy: Modify Einstein equations?



Acceleration of the cosmic expansion

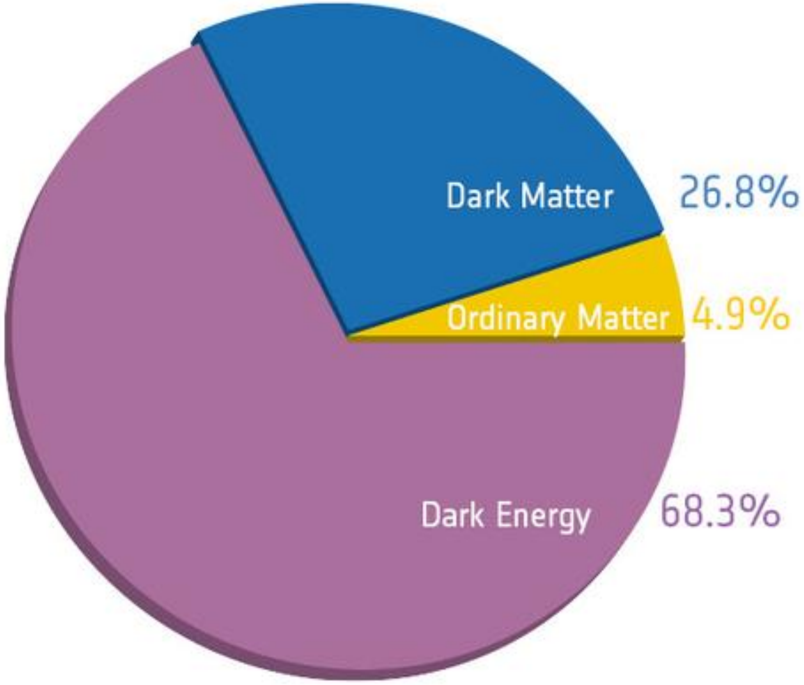
$$\boxed{G_{\mu\nu} = 8\pi G T_{\mu\nu}}$$

Dark energy

$$G_{\mu\nu} = 8\pi G \tilde{T}_{\mu\nu}$$

Modifying gravity

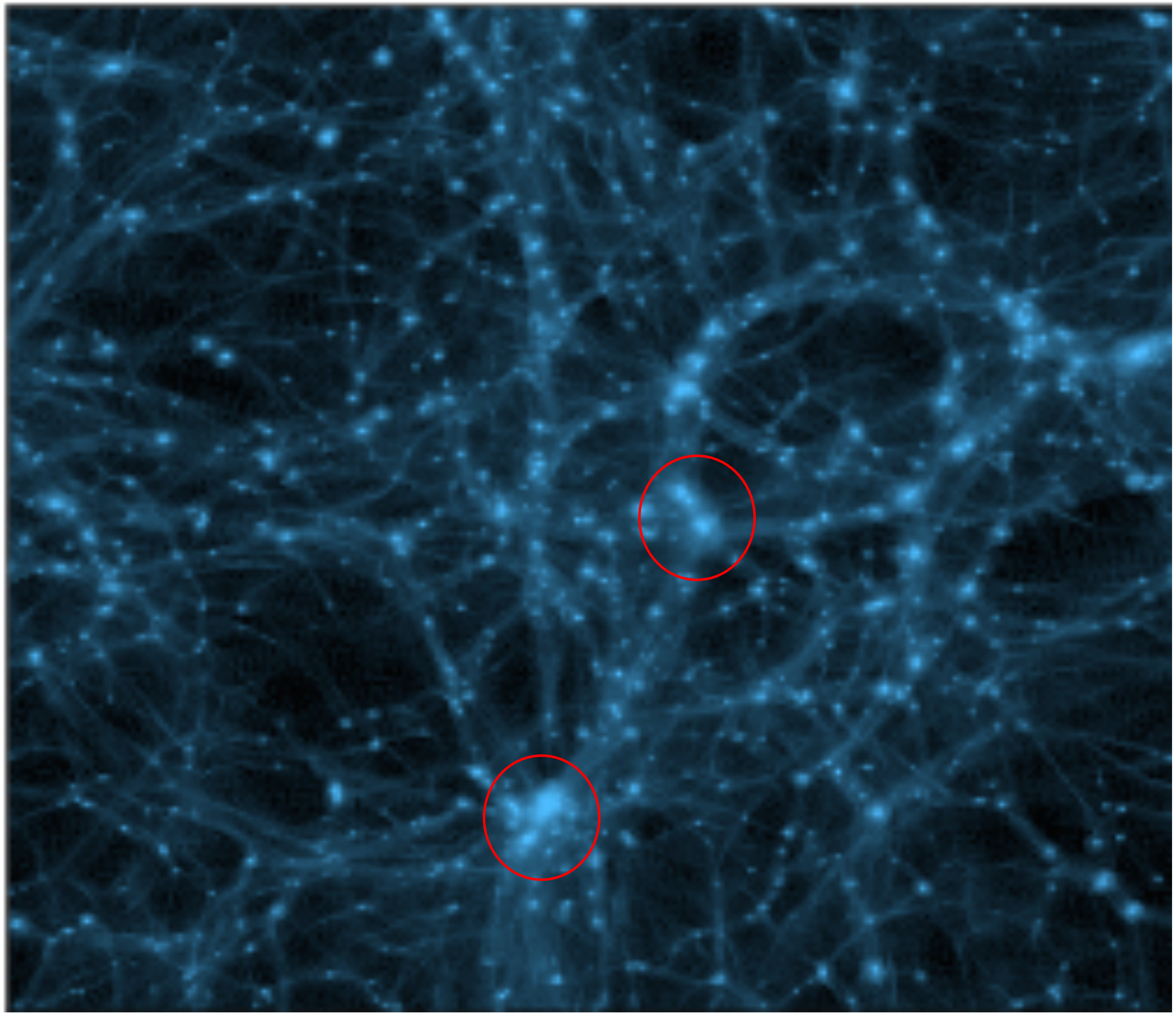
$$\tilde{G}_{\mu\nu} = 8\pi G T_{\mu\nu}$$



- DGP [weaker gravity]
- $f(R)$ gravity [stronger gravity]
- …

Probing the origin of the acceleration is Important not only for cosmology but also fundamental physics! But astronomical observation is only the way to probe it.

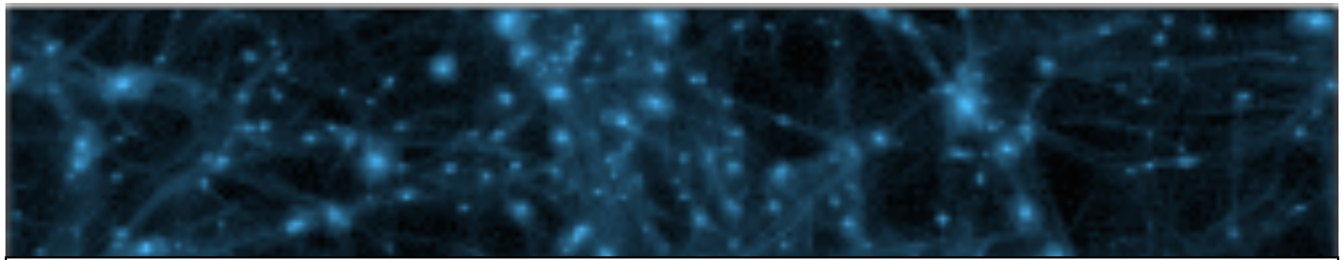
N-body simulation of large-scale structure under general relativity



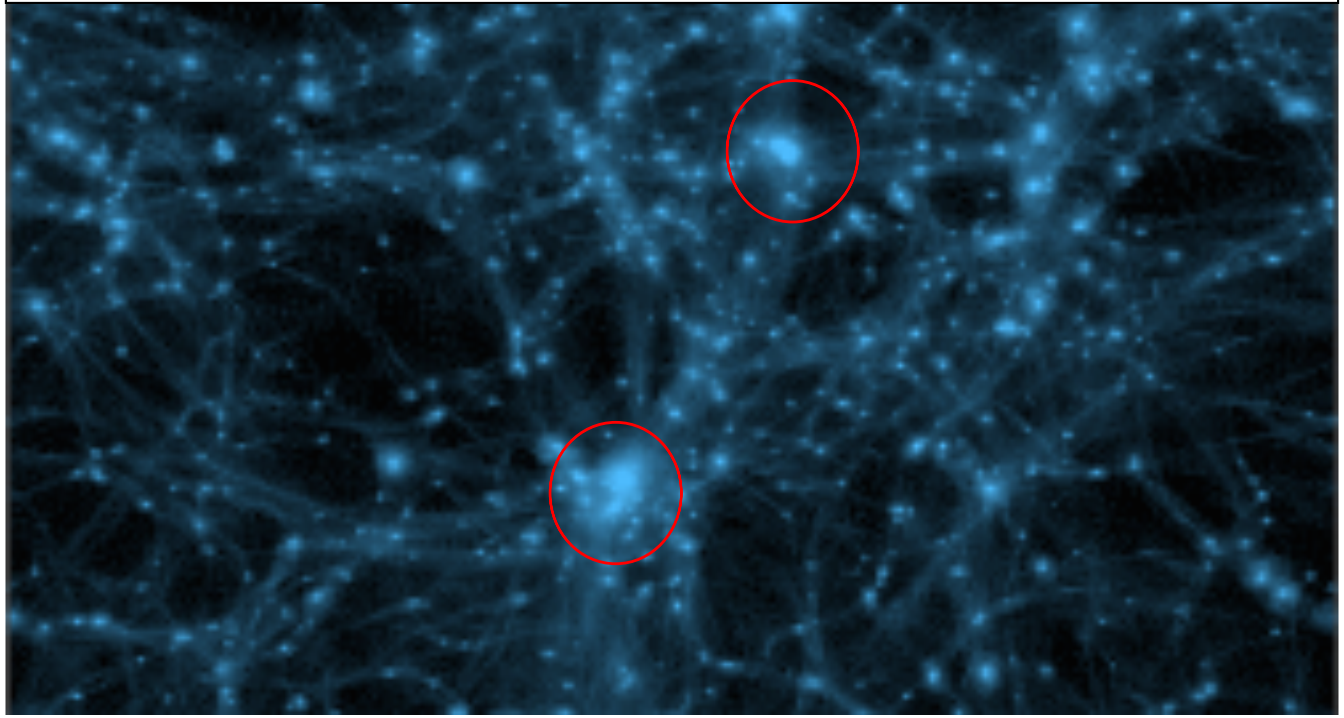
Figures taken from G.B. Zhao et al

N-body simulation of large-scale structure under f(R) gravity

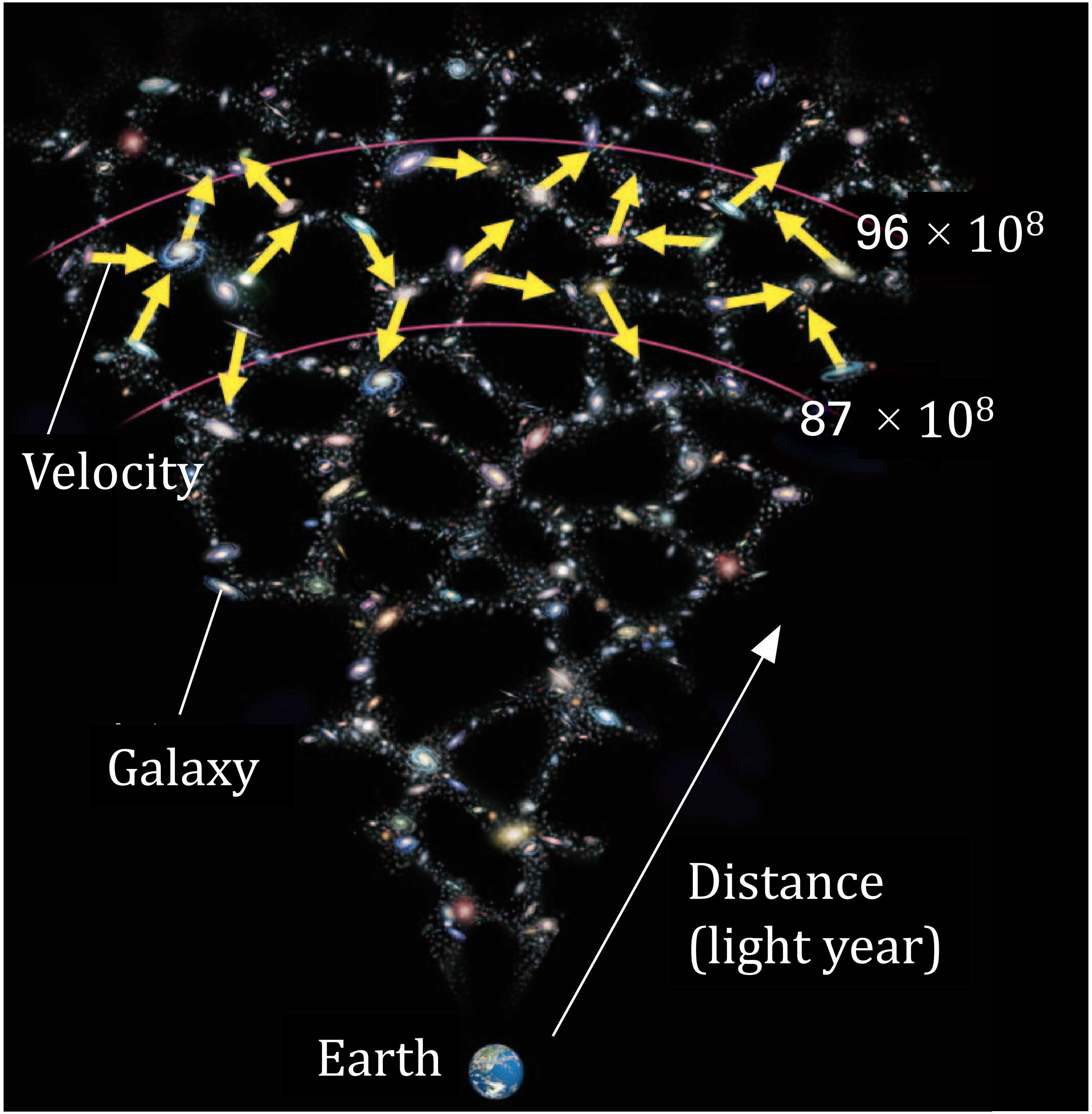
- Same initial condition but different gravity



One can distinguish different gravity models by probing the speed of the structure growth.



Figures taken from G.B. Zhao et al



- Continuity equation

$$\nabla \cdot v = -aHf\delta(x,t)$$

- Velocity tells us evolution of density field
- Direct probe of gravity!

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doi: 10.1093/pasj/psw029
Advance Access Publication Date: 2016 0

The Subaru FMOS galaxy redshift survey (FastSound). IV. New constraint on gravity theory from redshift space distortions at $z \sim 1.4$

Teppei OKUMURA,[1,*] Chiaki HIKAGE,[1] Tomonori TOTANI,[2]
Motonari TONEGAWA,[2] Hiroyuki OKADA,[2] Karl GLAZEBROOK,[3] Chris B
Pedro G. FERREIRA,[4] Surhud MORE,[1] Atsushi TARUYA,[1,5] Shinji TSUJ
Masayuki AKIYAMA,[7] G
Takashi ISHIKAWA,[11] Fu [12,1
Takahiro NISHIMICHI,[1,14] TAKA
Naruhisa TAKATO,[17] Na
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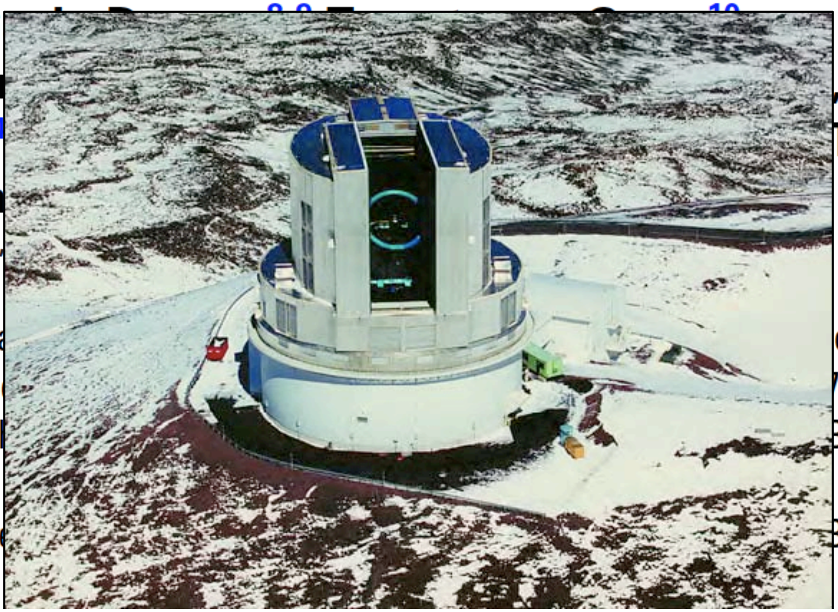
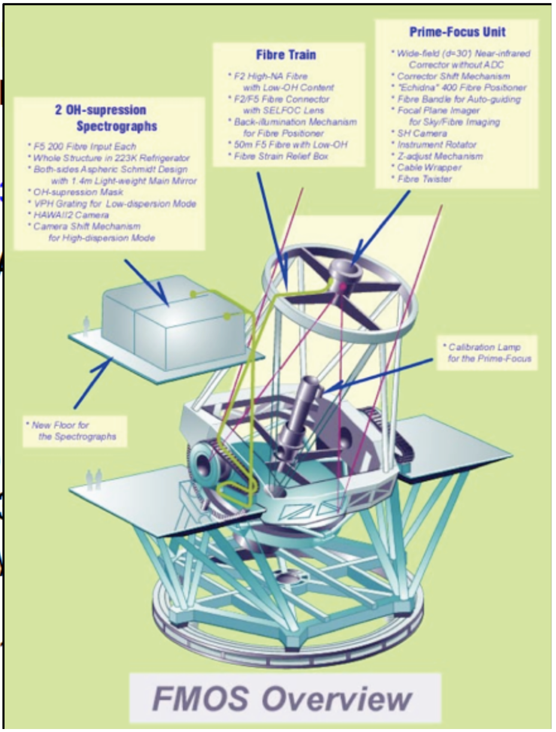
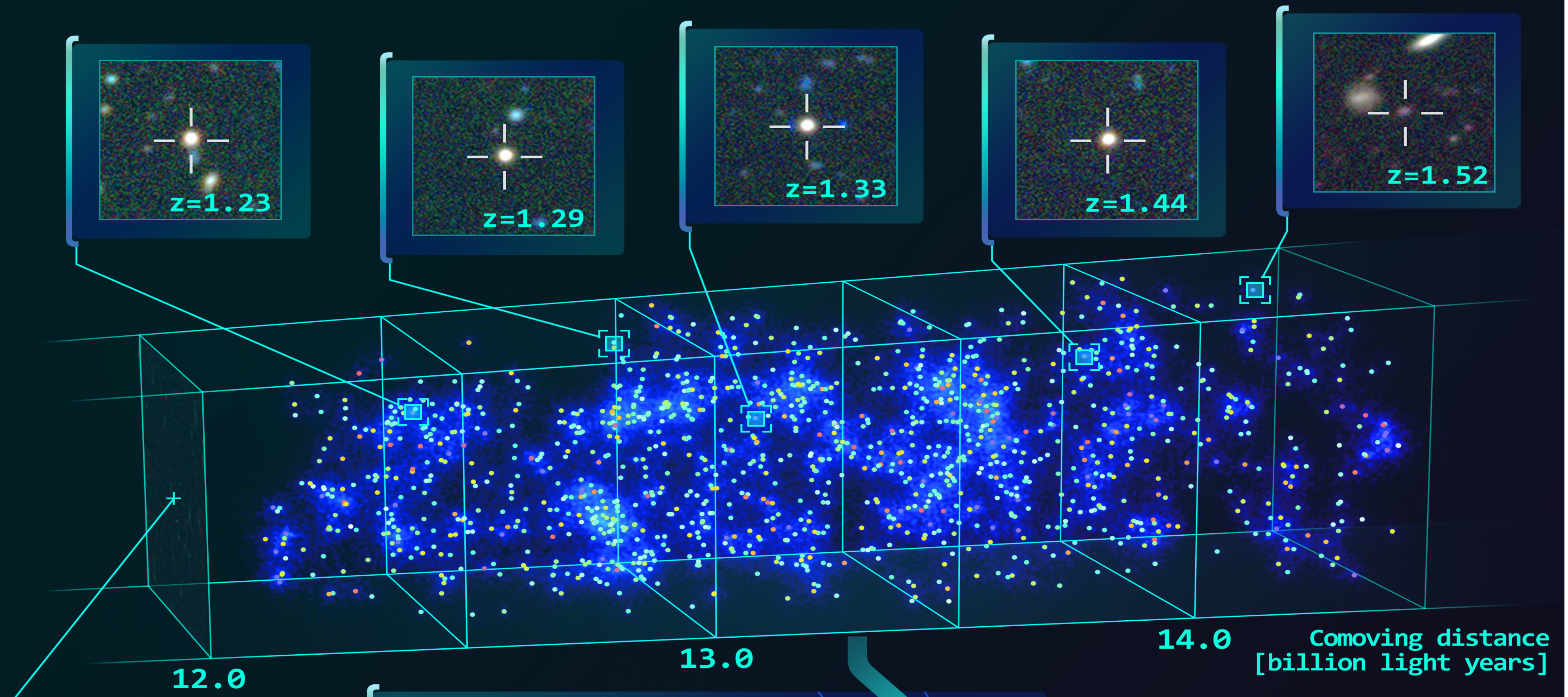
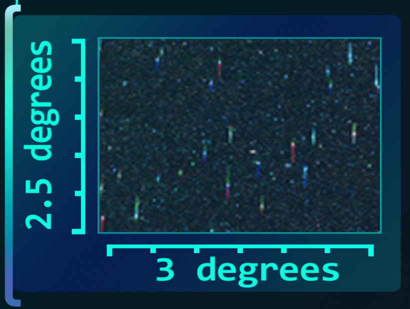
VIC 3122, Australia

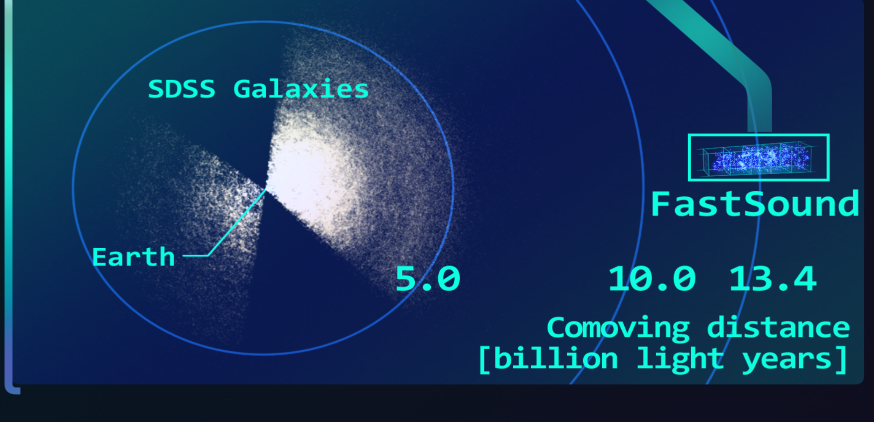


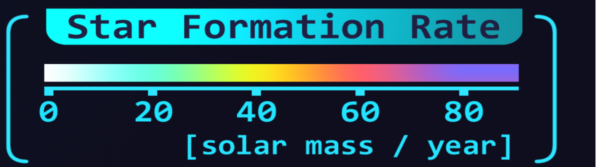


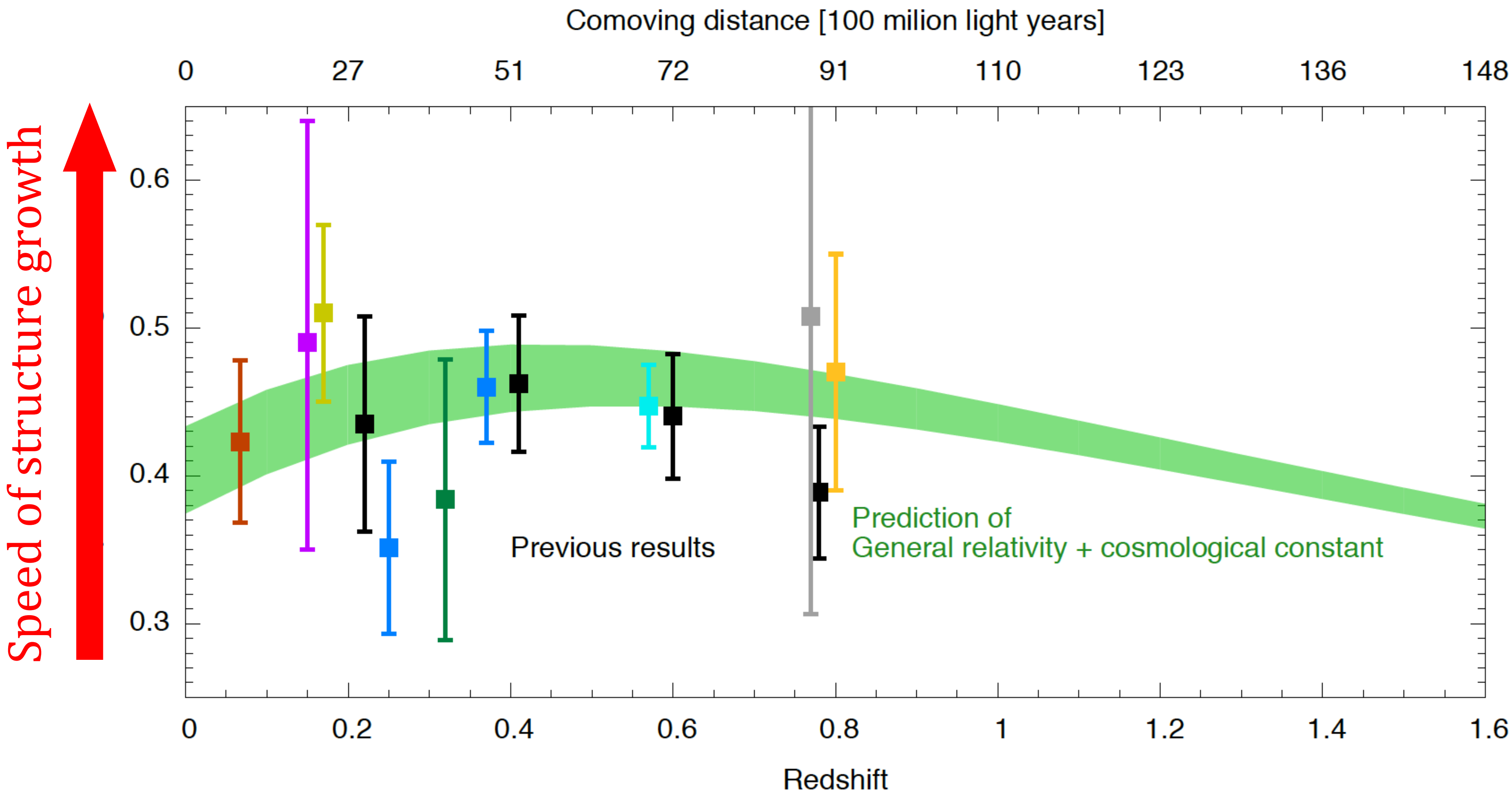
3D galaxy map at distant universe



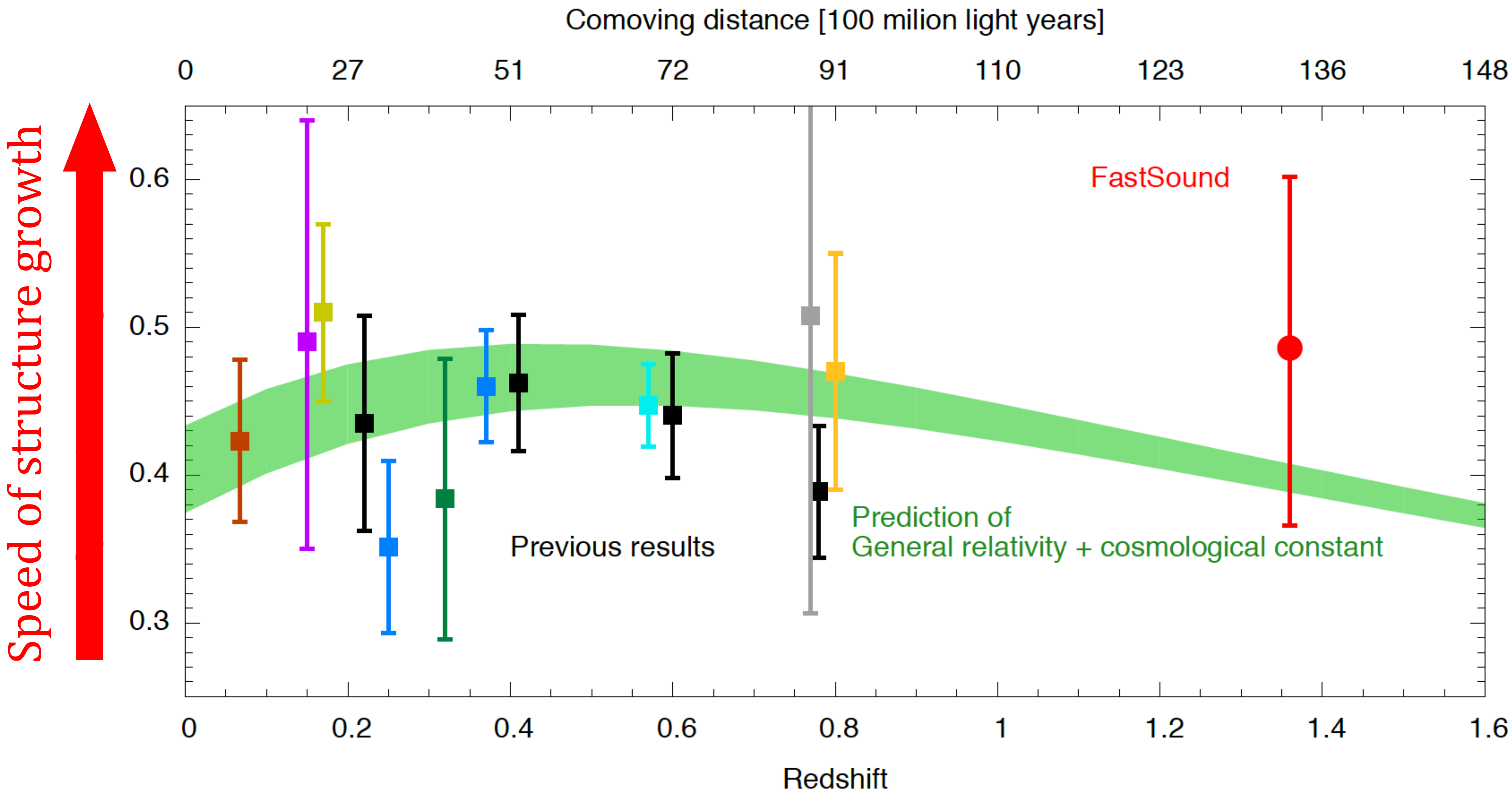







Comoving distance [100 milion light years]
0
27
51
72
91
110
123
136
148
Speed of structure growth
0.6
0.5
0.4
0.3
Previous results
Prediction of
General relativity + cosmological constant
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
Redshift

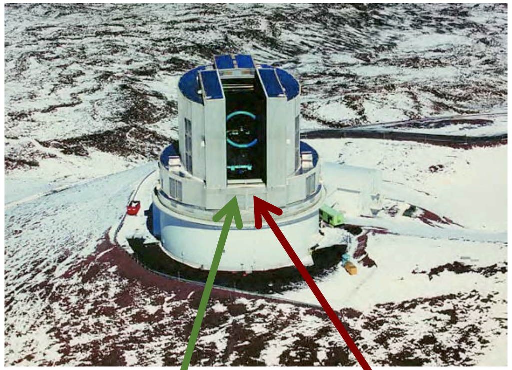
Consistent with general relativity!



- Though the error bars are large, it is an important step to larger surveys!

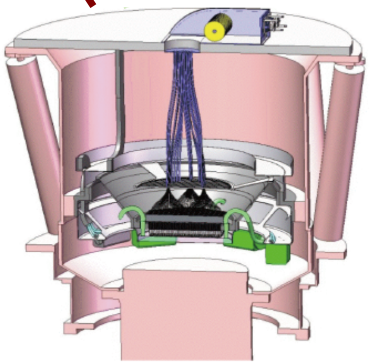
SuMIRe = Subaru Measurement of Images and Redshifts

- PI: Hitoshi Murayama (IPMU director}
- Science leader: Masahiro Takada
- ***ASIAA is a main member of the project***
- Build *wide-field* camera (Hyper Suprime-Cam) and *wide-field* multi-object spectrograph (Prime Focus Spectrograph) for the Subaru Telescope (8.2m)
- Explore the fate of our Universe: dark matter, dark energy
- Measure distances of 4M galaxies

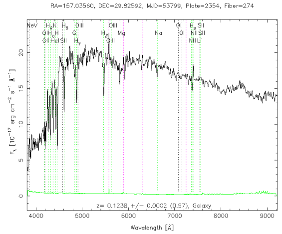


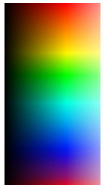
Subaru (NAOJ)

HSC

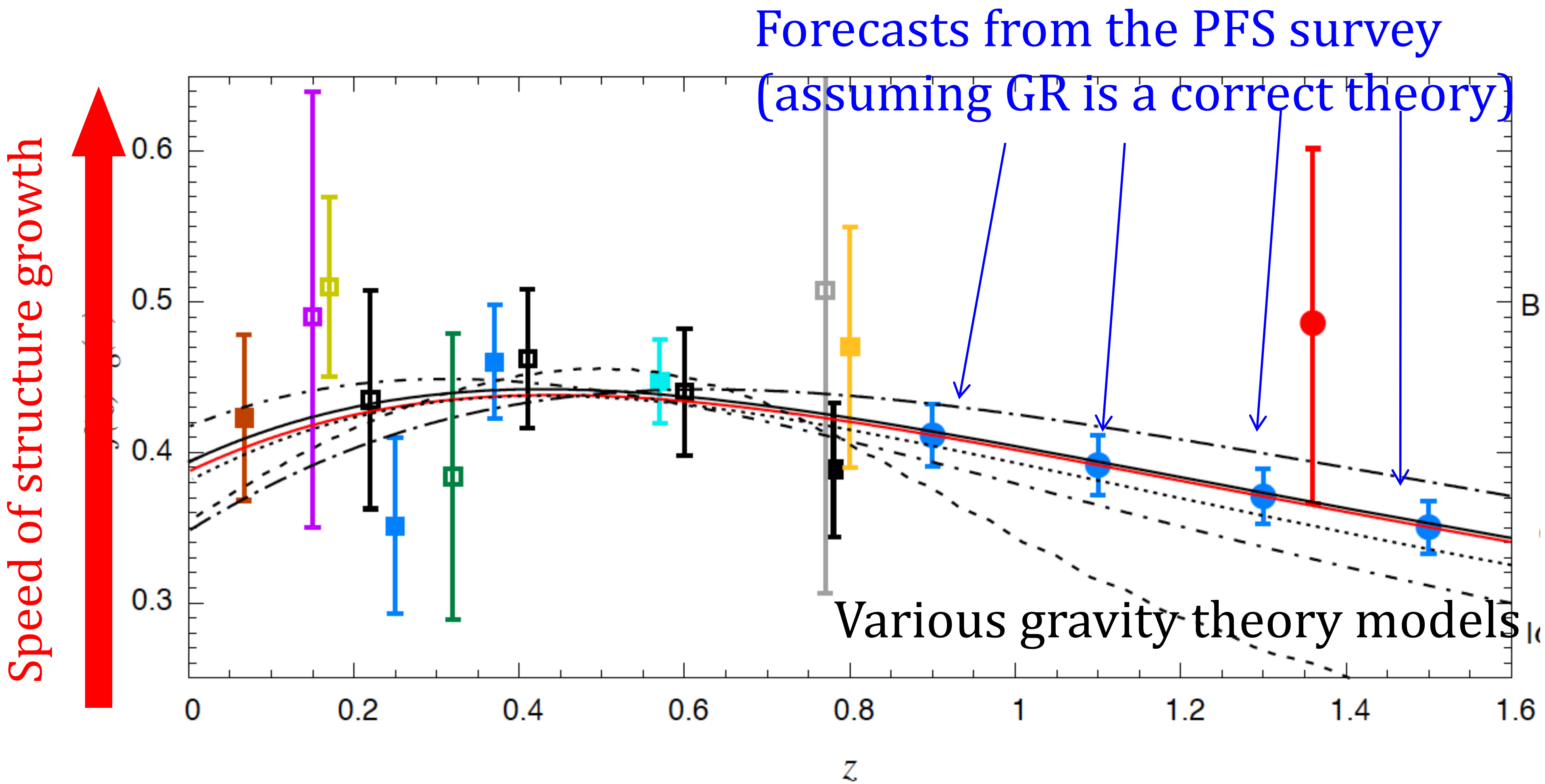


PFS





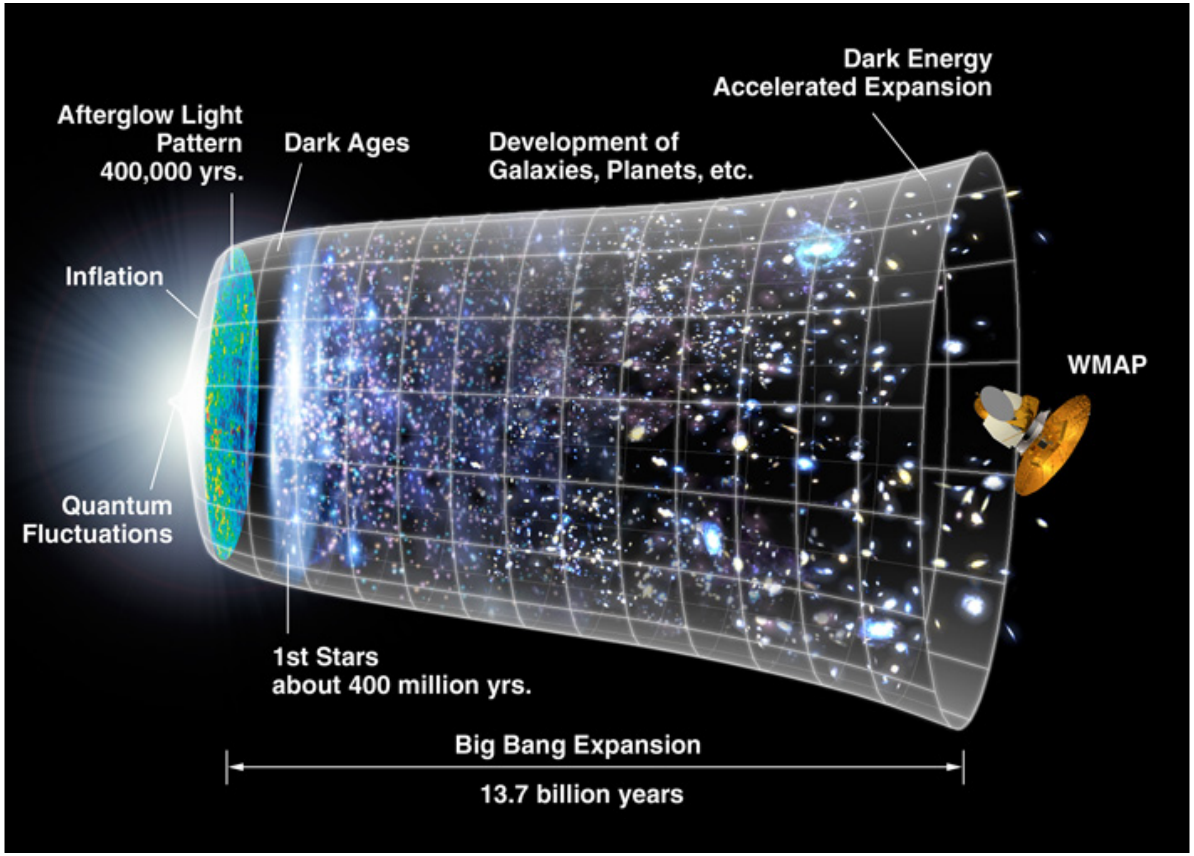
PFS dramatically improves the precision!



Forecasts from the PFS survey (assuming GR is a correct theory)

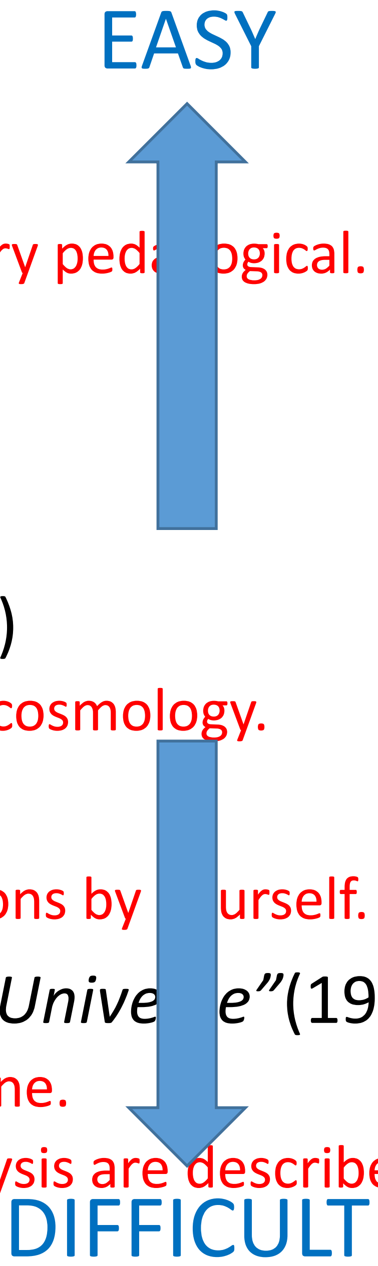
Various gravity theory models

Other basics of cosmology 1-hour lecture couldn’t cover….



- Evidences of Big bang
- Big bang nucleosynthesis
- Inflation (beginning of the Universe)
- Gravitational wave
- Evidences of dark matter
- Dark matter halos
- Gravitational lensing
- Neutrinos
- Clusters of galaxies
- …

Cosmology textbooks



- S. Weinberg, *“The First Three Minutes”* (1977)
  - No equation. Even liberal arts students can read it. Very peda ogical.
- B. Ryden, *“Introduction to Cosmology”* (2002)
  - Comprehensive introduction.
  - No knowledge of general relativity is required.
- S. Weinberg, *“Gravitation and Cosmology”* (1972)
  - Excellent textbook for general relativity and standard cosmology.
- S. Dodelson, *“Modern Cosmology”* (2003)
  - Standard level textbook. You can derive all the equations by urself.
- P. J. E. Peebles, *“The Large-Scale Structure of the Unive e”*(1980)
  - If you are interested in this field, you must have this one.
  - All the essential statistical tools for galaxy survey analysis are described.

- ***They are my recommendations among all the cosmology textbooks I have read.***

Summary

- Equations for expansion (Hubble parameter) as a function of time
- Energy contents of the Universe
- Cosmic microwave background (CMB) as a powerful tool for cosmology
- Evidence for dark energy
- Many ongoing and future large surveys will tell us more about cosmology and the large-scale structure with baryon acoustic oscillations and galaxy velocity field

For further questions and information: *tokumura@asiaa.sinica.edu.tw*
http://www.asiaa.sinica.edu.tw/~tokumura/