PIER Graduate Week 2014

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Theory & Observations in the Early Universe

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Outline

- Lecture 1: Standard Cosmology
- Lecture 2: Inflation & the CMB
- Lecture 3:
  Dark Matter & Structure Formation
- Lecture 4: Other open problems:
  Dark Energy, Baryogenesis, ...

Lecture 1: Outline

- Cosmology as a science
- The Standard Cosmological Model
- The History of our Universe
- Standard Candles and Standard Rulers
- Problems of Standard Cosmology

Cosmology as a science

Is cosmology science ?

“Real science” (Physics)	Cosmology
Many experiments at different scales	Few observations at selected scales
Reproducible Prepared/measured initial state Measured final state (very good statistics & controlled systematics)	Single Universe Unknown initial state Measured final state (with limited statistics & unknown systematics...)

Is cosmology science ?

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BUT luckily not as bad as it looks ! Why ?

Is cosmology science ?

Cosmology at Late Times

classical evolution:
deterministic
"hydrodynamics" with friction
or Boltzmann equation

Newtonian approximation
often sufficient (for DM)

Initial condition problem,
if not fixed by previous
evolution

Cosmology at Early Times

small quantum fluctuations:
linearized semiclassical
evolution
each mode/scale independent

Quantum nature encoded
in stochastic gaussian
initial conditions

"Ergodic hypothesis":
quantum average = spatial average

Einstein's equation: Energy is Geometry

$$\mathcal{R}_\mu^\nu - \frac{1}{2}\delta_\mu^\nu \mathcal{R} \;=\; 8\pi G_N \, T_\mu^\nu + \Lambda \delta_\mu^\nu$$

Einstein's Tensor:
Geometry of Space-time

Energy-momentum Tensor:
ALL the Physics content

Classical so far...

Quantum

The birth of Cosmology as a science:
the Universe's dynamics and fate is determined
by its Energy (Particle) content,
both the known and the unknown....

The Standard Model

Our present understanding of the forces and particles is based on the symmetry group $SU(3)_c \times SU(2)_L \times U(1)_Y$.

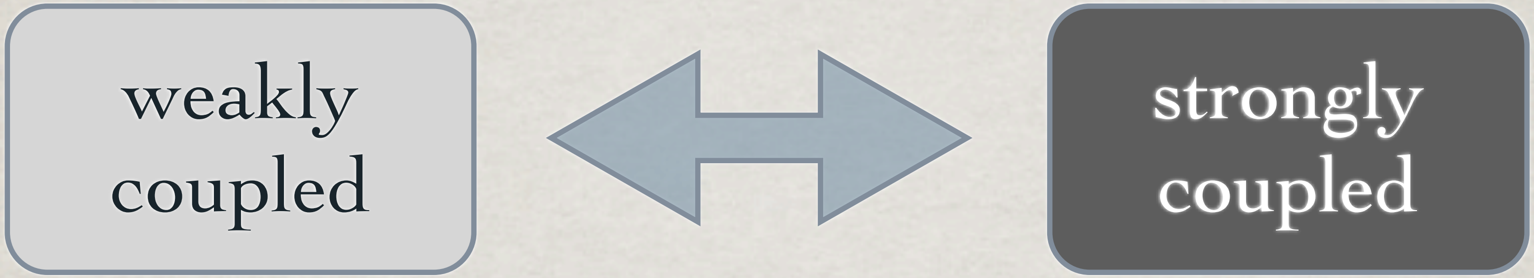
Standard Model			
Matter			Forces
e	μ	τ	γ
ν_e	ν_μ	ν_τ	$W^\pm, Z$
u	c	t	g
d	s	b	G

$+ \; h$

It describes perfectly the data so far, but it is incomplete:

- theoretically it does not explain flavour and the presence of 3 generations, nor why the Higgs is light...
- it lacks a Dark Matter and inflaton candidate and also a mechanism to generate the baryon number...

Which model Beyond the SM ?



Cosmology

(Collider-based) Particle Physics

To pinpoint the completion of the SM, exploit the complementarity between Cosmology and Particle Physics to explore all the sectors of the theory: the more weakly coupled and the more strongly coupled to the Standard Model fields...

Best results if one has information from both sides, e.g. neutrinos, axions, etc... ???

Standard model of Cosmology

Standard Cosmology

Cosmological Principle (nowadays also experimental result...):

The Universe is homogeneous and isotropic
on large scales (i.e. larger than ~100 Mpc)

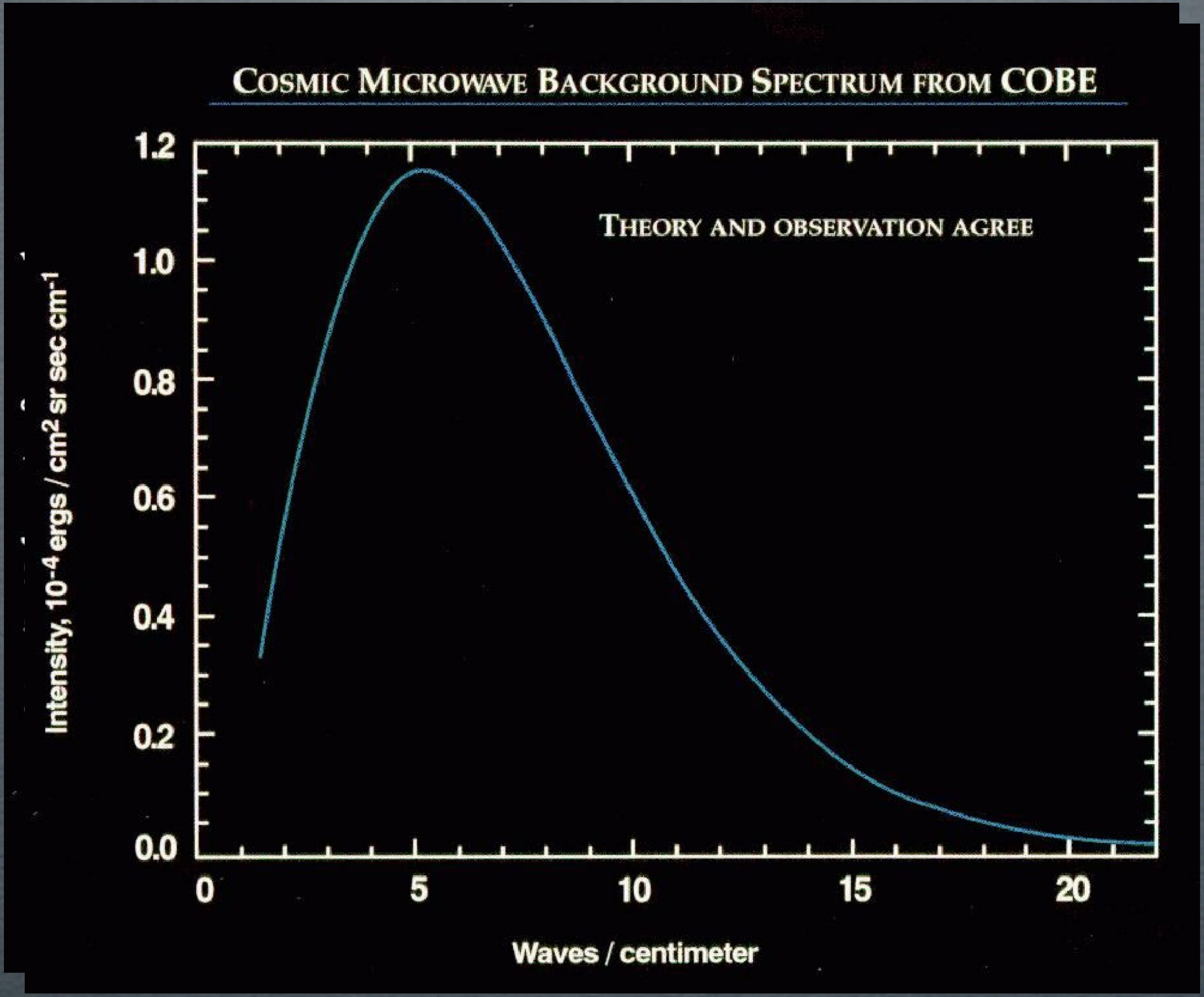
It is described by the Friedmann-Robertson-Walker Metric:

$$ds^2 = dt^2 - a^2(t)\left(\frac{dr^2}{1-\kappa r^2} + r^2 d\Omega\right)$$

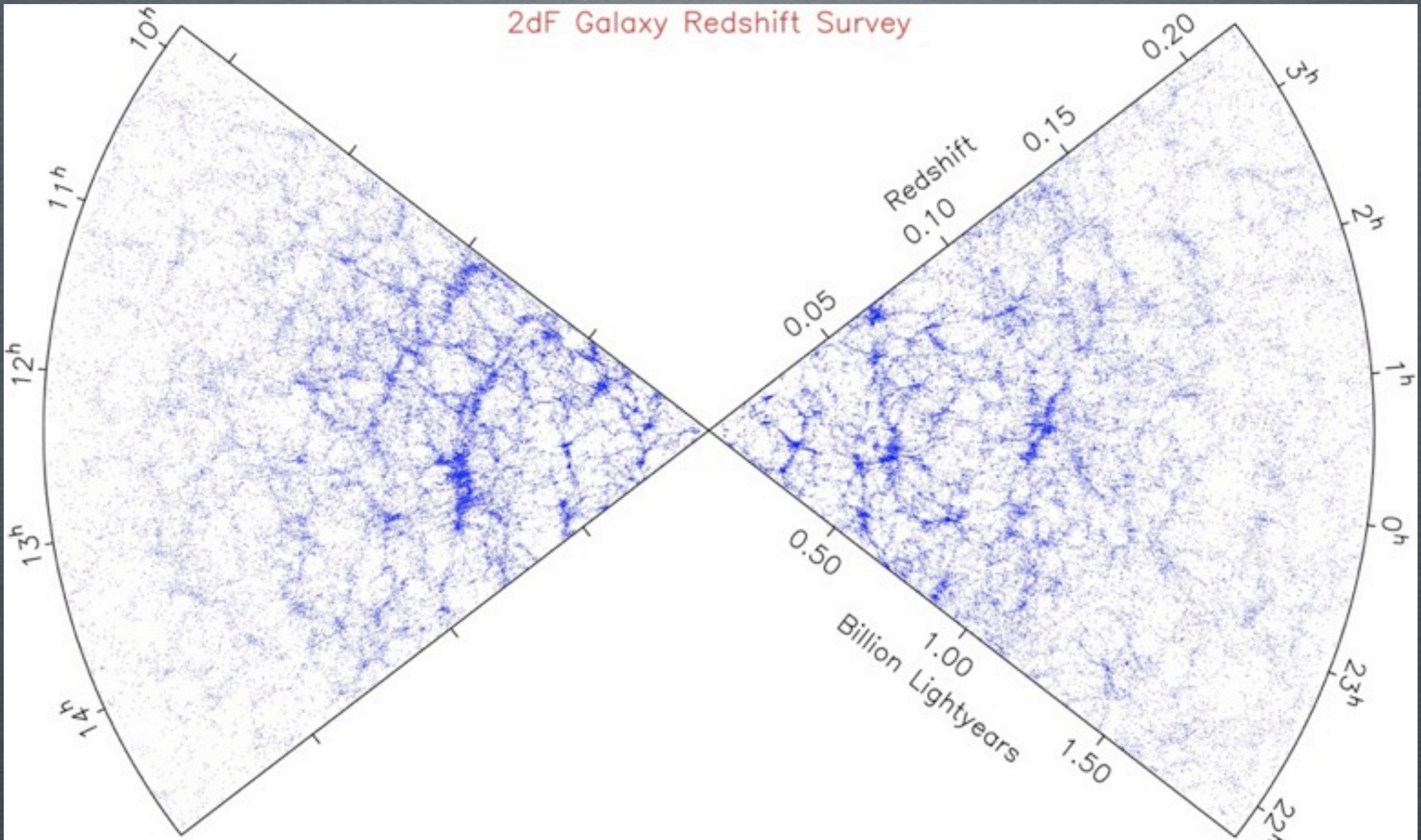
conformal to Minkowski for $dt^2 = a^2(\eta)d\eta^2$ $\kappa = 0$

- Only one dynamical variable: the scale factor $a(t)$
- One constant parameter: the spatial curvature κ

1/2 Physics Nobel Prize 2006 to J. Mather for COBE:
ISOTROPY: Perfect Black Body in all directions !



HOMOGENEITY: less structure at large redshifts !



Hubble flow

A FRW metric immediately gives for static objects

$$v = \frac{d(a(t)r)}{dt} = \dot{a}r = \frac{\dot{a}}{a}ar = H(t)\mathrm{d}$$

Hubble Flow !

$H_0 \sim 500$ km/s/Mpc

Nowadays

$H_0 \sim 72$ km/s/Mpc

E. Hubble 1929

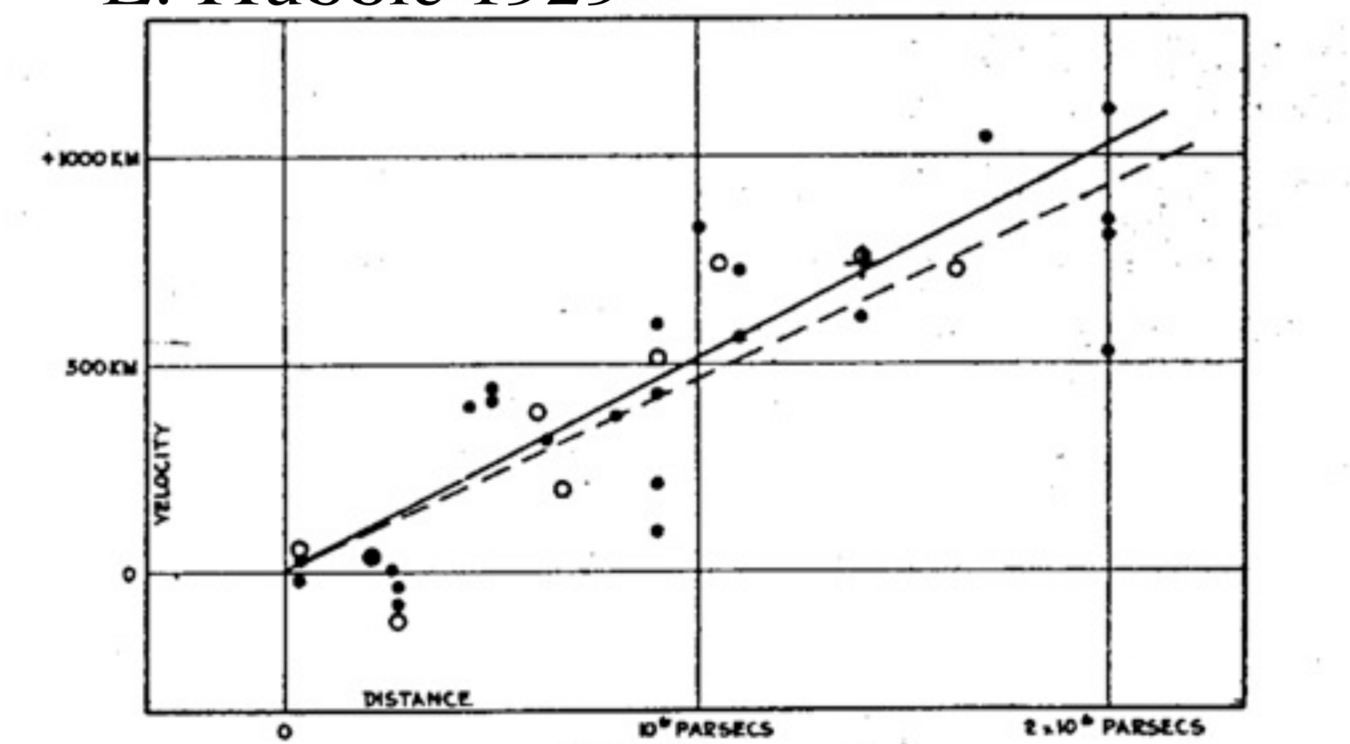


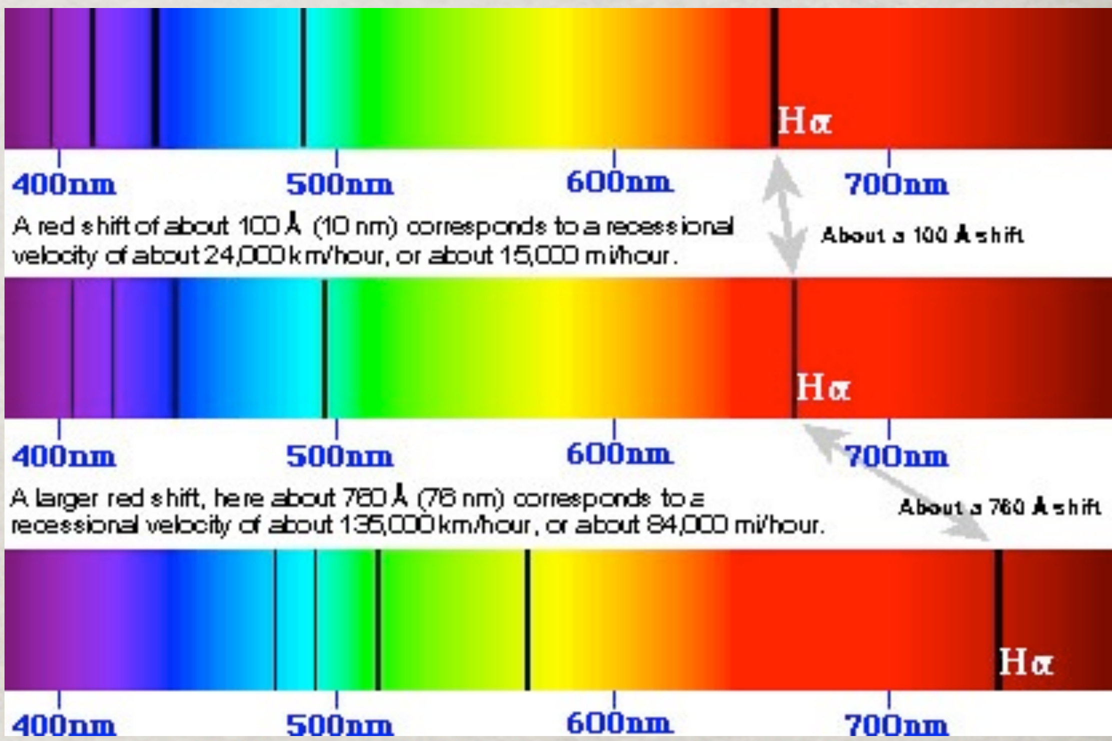
FIGURE 1

Redshift Measurement

Due to the Universe's expansion all spectra of astrophysical object are red-shifted !

$$\frac{\lambda_{obs}}{\lambda_{em}} = \frac{a(t_{obs})}{a(t_{em})} = 1 + z$$

Redshift can be used to parametrize the time of emission !



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Energy momentum tensor

Perfect fluid approximation $$T^{\mu}_{\nu} = (\rho + p)u^{\mu}u_{\nu} - p\delta^{\mu}_{\nu}$$

where ρ and p are the fluid density and pressure, while u is the fluid 4-velocity. So in the rest-frame of the fluid, where $u = (1, \vec{0})$, i.e. assuming that the fluid is at rest in the Universe, we have

$$T^{\mu}_{\nu} = \begin{pmatrix} \rho & 0 & 0 & 0 \\ 0 & -p & 0 & 0 \\ 0 & 0 & -p & 0 \\ 0 & 0 & 0 & -p \end{pmatrix}$$

Moreover the energy-momentum tensor is covariantly conserved:

$$\mathcal{D}_{\mu} T^{\mu\nu} = 0 \quad \rightarrow \quad \dot{\rho} + 3H(\rho + p) = 0$$ continuity equation

This can be solved if we know the equation of state $p(\rho) = w\rho$ then

$$\frac{\dot{\rho}}{\rho} = -3(1+w)H \quad \Rightarrow \quad \rho \propto a^{-3(1+w)}$$

So the different energy types are modeled by perfect fluids with equation of state $w_i = p_i/\rho_i$.

Friedmann equation:

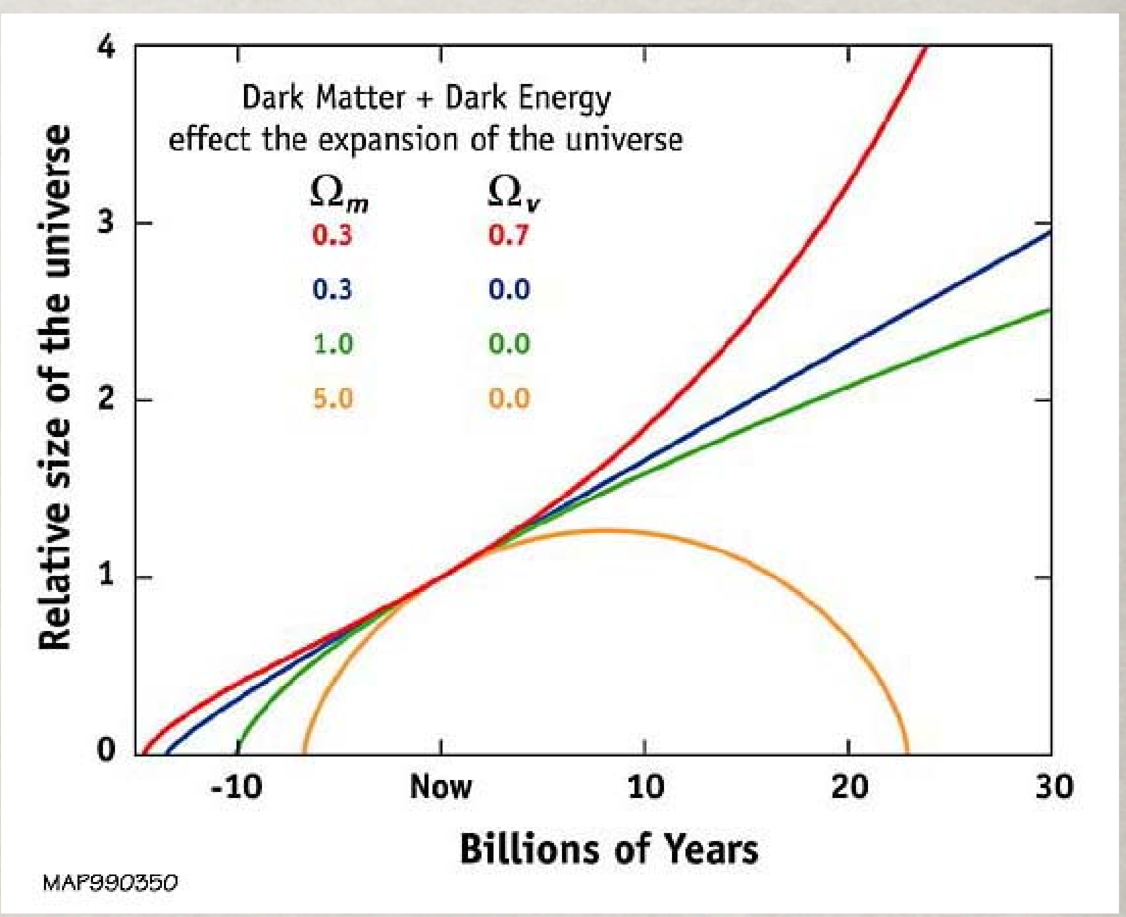
$$H^2 \equiv \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G_N}{3}\rho + \Lambda - \frac{\kappa}{a^2}$$

- The energy density & curvature decree the time evolution of the scale factor
- Key parameter is the critical density:

$$\rho_c = \frac{3H^2}{8\pi G_N} \qquad \Omega_i = \frac{\rho_i}{\rho_c}$$

Ω_i :density in $\sim 10^4 \mathrm{eV/cm^3}$

~ 10 protons/m3

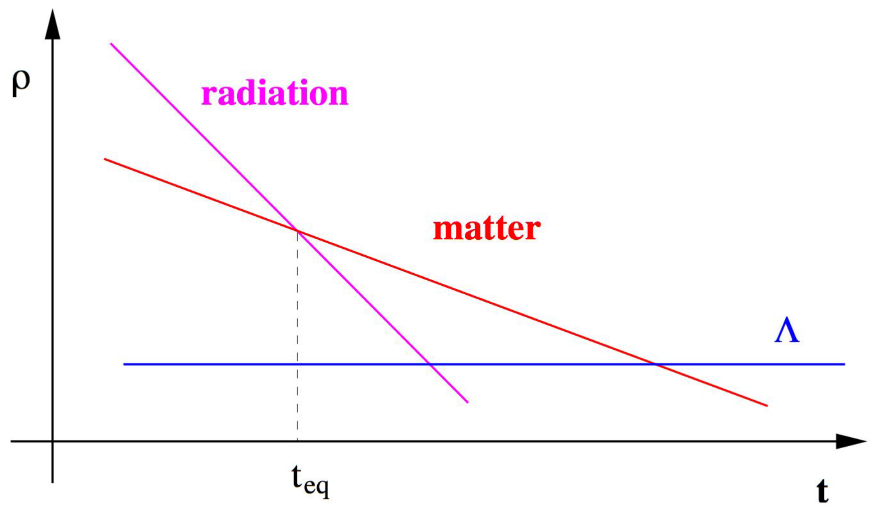


The History of the Universe

Different energy types

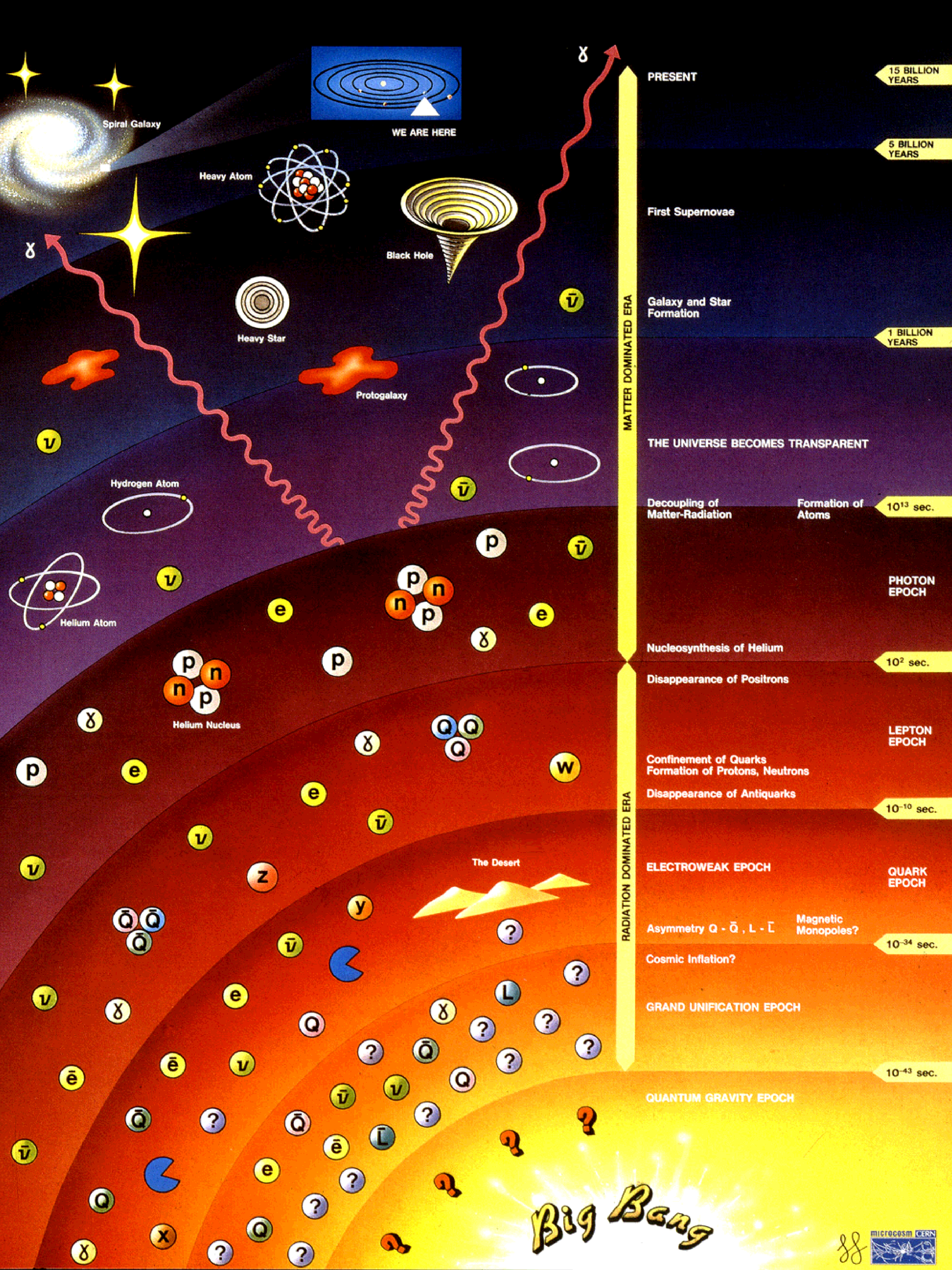
Depending on the pressure and the equation of state, the energy densities give different expansion rates:

Type	p/ρ	$\rho(a)$	$a(t)$
Generic	w	$a^{-3(1+w)}$	$t^{2/(3(1+w))}$
Radiation	$1/3$	$\propto a^{-4}$	$\propto t^{1/2}$
Matter	0	$\propto a^{-3}$	$\propto t^{2/3}$
Λ	-1	const.	e^{Ht}
Curvature	$-1/3$	$\propto a^{-2}$	$\propto t^{1}$



Always decelerating !

Different epochs of the Universe history



Spiral Galaxy
WE ARE HERE
Heavy Atom
Black Hole
Heavy Star
Protogalaxy
Hydrogen Atom
Helium Atom
Helium Nucleus
The Desert
MATTER DOMINATED ERA
RADIATION DOMINATED ERA
PRESENT
15 BILLION YEARS
5 BILLION YEARS
First Supernovae
Galaxy and Star Formation
1 BILLION YEARS
THE UNIVERSE BECOMES TRANSPARENT
Decoupling of Matter-Radiation
Formation of Atoms
10^13 sec.
PHOTON EPOCH
Nucleosynthesis of Helium
10^2 sec.
Disappearance of Positrons
LEPTON EPOCH
Confinement of Quarks
Formation of Protons, Neutrons
Disappearance of Antiquarks
10^-10 sec.
ELECTROWEAK EPOCH
QUARK EPOCH
Asymmetry Q - Q̄ , L - L̄
Magnetic Monopoles?
10^-34 sec.
Cosmic Inflation?
GRAND UNIFICATION EPOCH
10^-43 sec.
QUANTUM GRAVITY EPOCH
Big Bang
microcosm CERN

Important Epochs

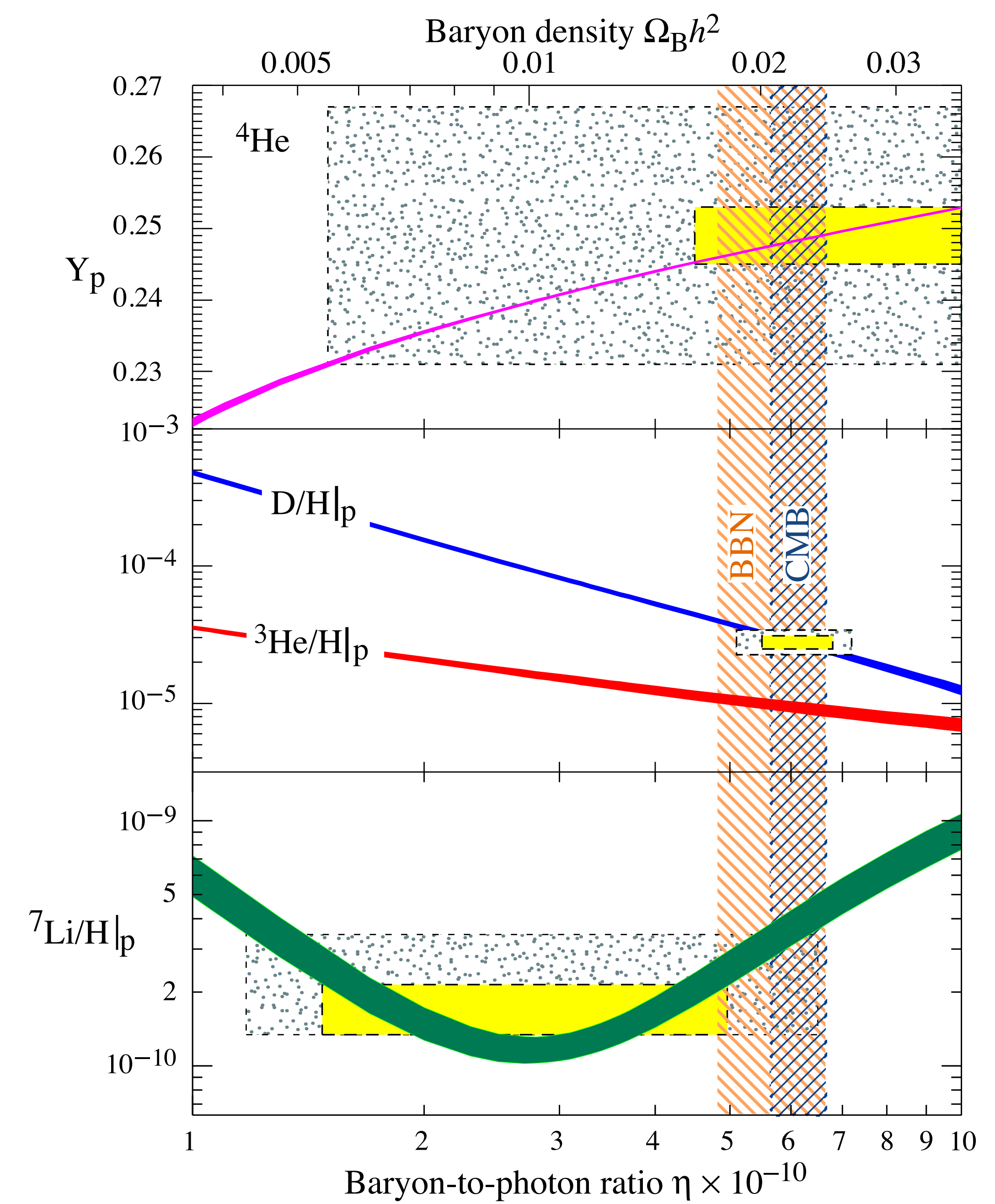
- Today: $T = 2.7K \sim 10^{-4}$ eV $\quad z = 0$
- First stars: $T \sim 10^{-3} \quad z \sim 15 - 20$
- Photon decoupling: CMB $T = 0.4$ eV $\quad z = 1100$
- Matter and Radiation equality: $T = 1$ eV $\quad z \sim 1300$
- Nucleosynthesis: $T = 0.1$ MeV
- Neutrino decoupling: CνB $T \sim 1$ MeV
- QCD phase transition $T \sim 0.3$ GeV
- EW phase transition $T \sim 100$ GeV
- ????

Big Bang Nucleosynthesis

[Fields & Sarkar PDG 07]

- Light elements abundances obtained as a function of a single parameter $\Omega_B h^2$
- Perfect agreement with WMAP determination
- Some trouble with Lithium 6/7

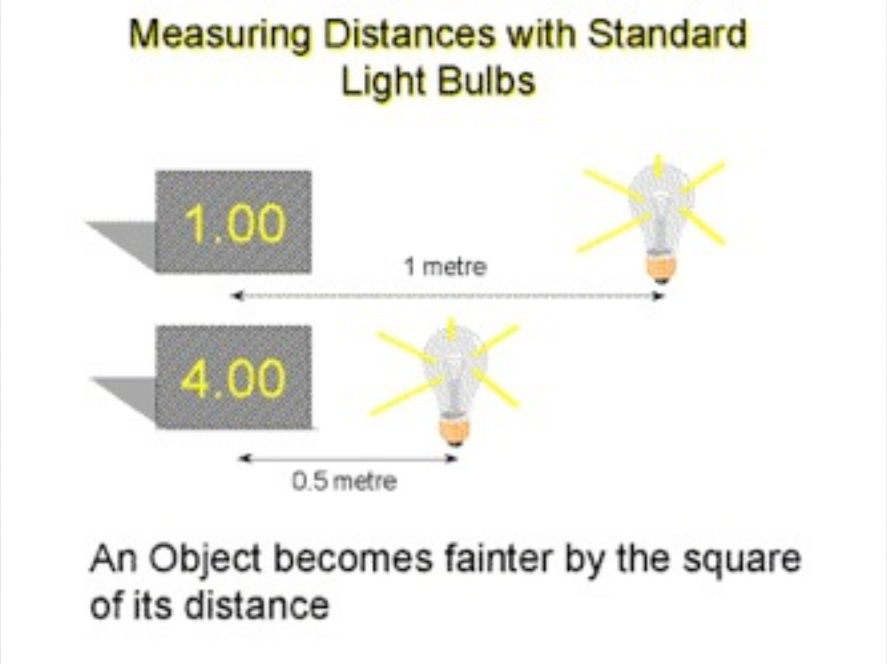
$$\Omega_B h^2 = 0.02 < \Omega_{DM} h^2$$



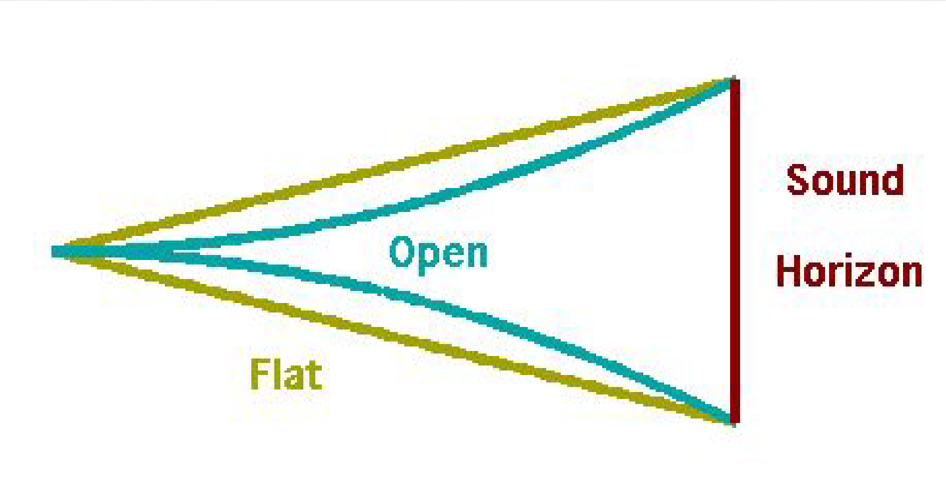
Standard candles and rulers

How can we measure the expansion of the Universe ?

Standard Candle



Standard Ruler



Luminosity distance

$$D_L^2 = \frac{L}{4\pi\Phi}$$

Intrinsic Luminosity

Measured Flux

For a FRW universe it is given simply by

$$D_L^2 = (1+z)\int_0^z \frac{dz}{H(z)}$$

where $H^2(z) = H_0^2 \sum_i \Omega_{i,0}(1+z)^{3(1+w_i)}$

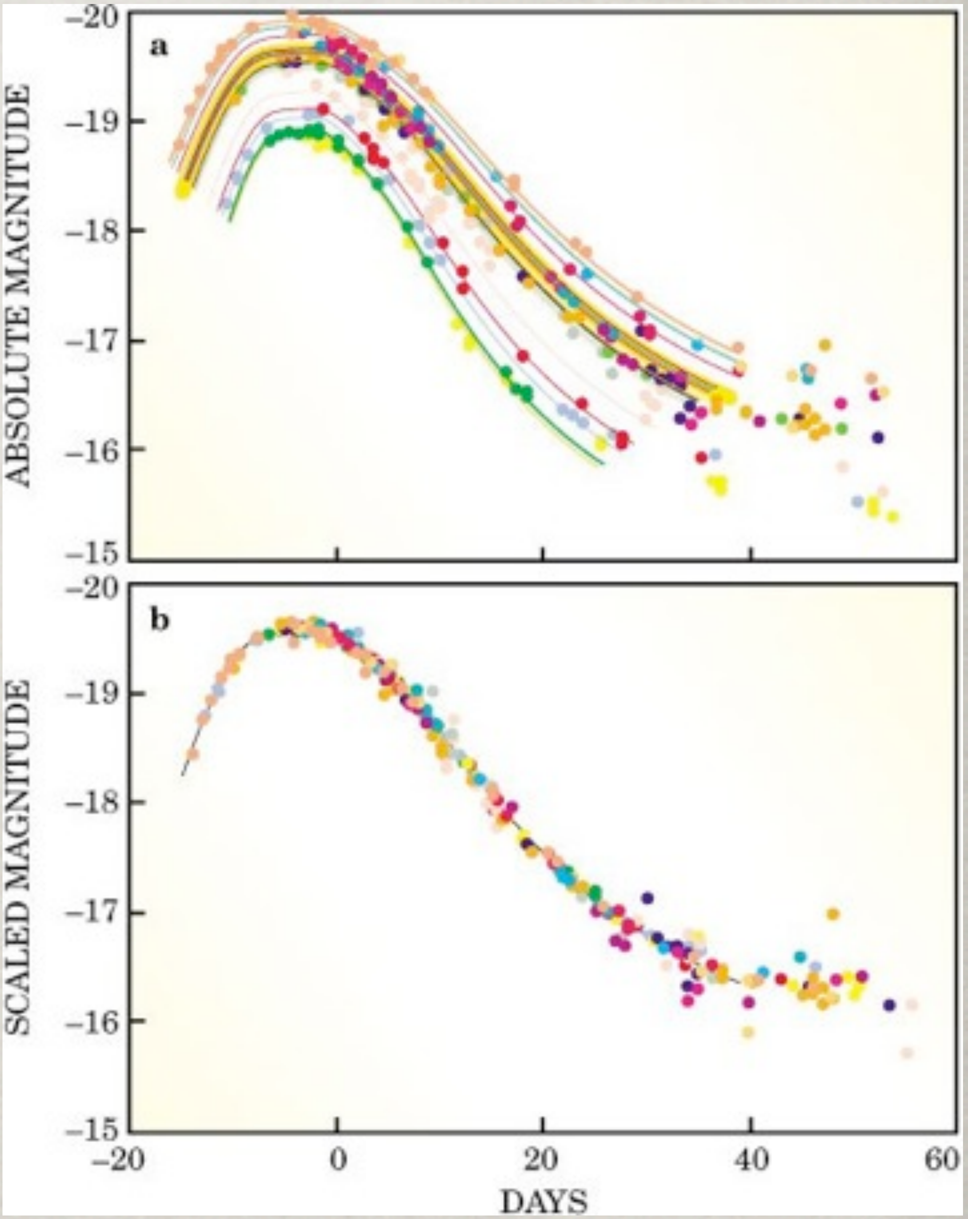
→ determination of the cosmological parameters

$$\Omega_{DM}(w=0), \Omega_\Lambda(w=-1), \ldots$$

SN-IA as standard Candles

Type Ia supernova is the explosion of a white dwarf star in a binary star system. Material from a companion red giant star is dumped on the white dwarf until the smaller star reaches a precise mass limit.

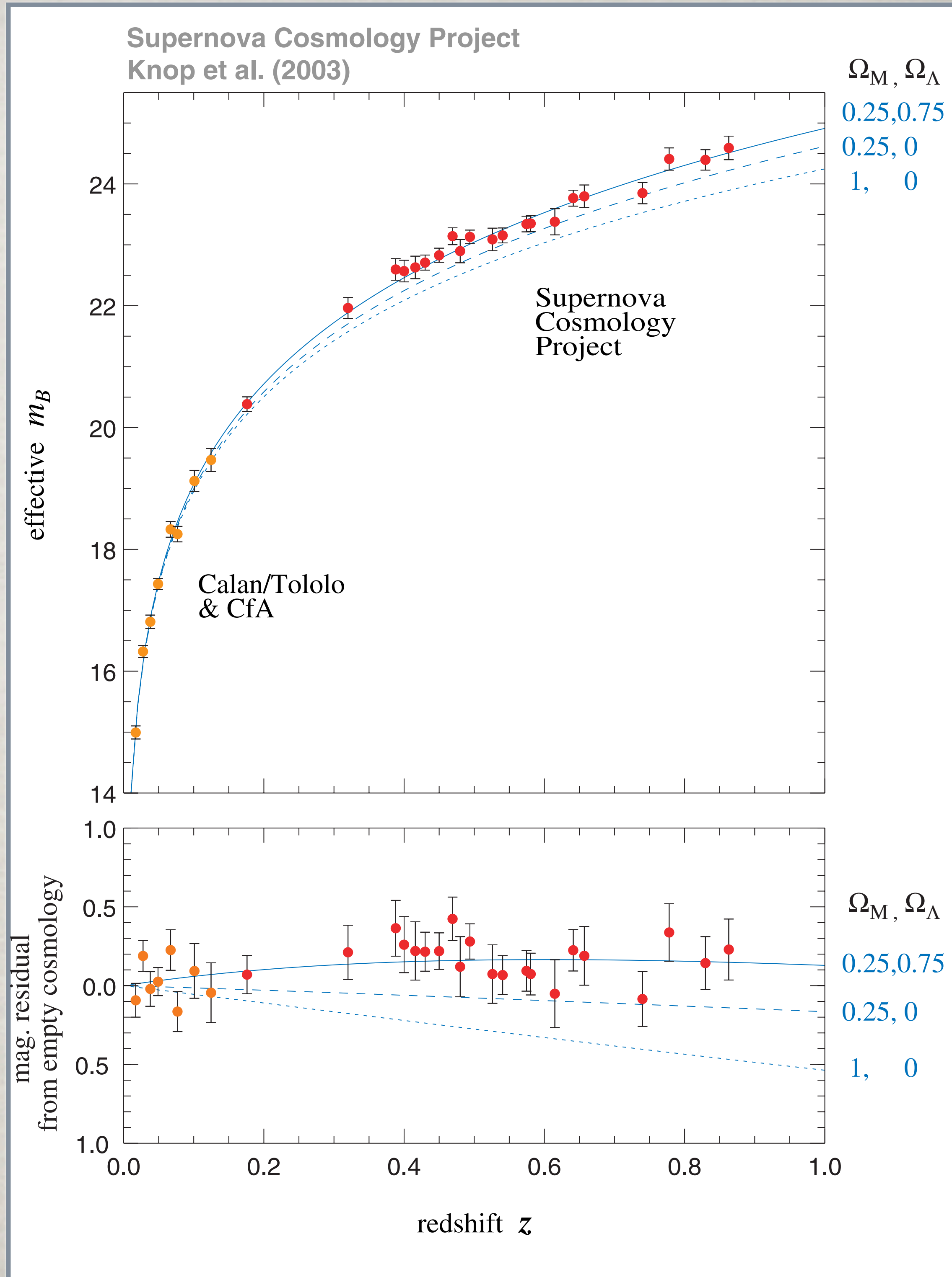
The spectra can be corrected to lie on the same line and follow a relation between peak luminosity and width of the light curve...



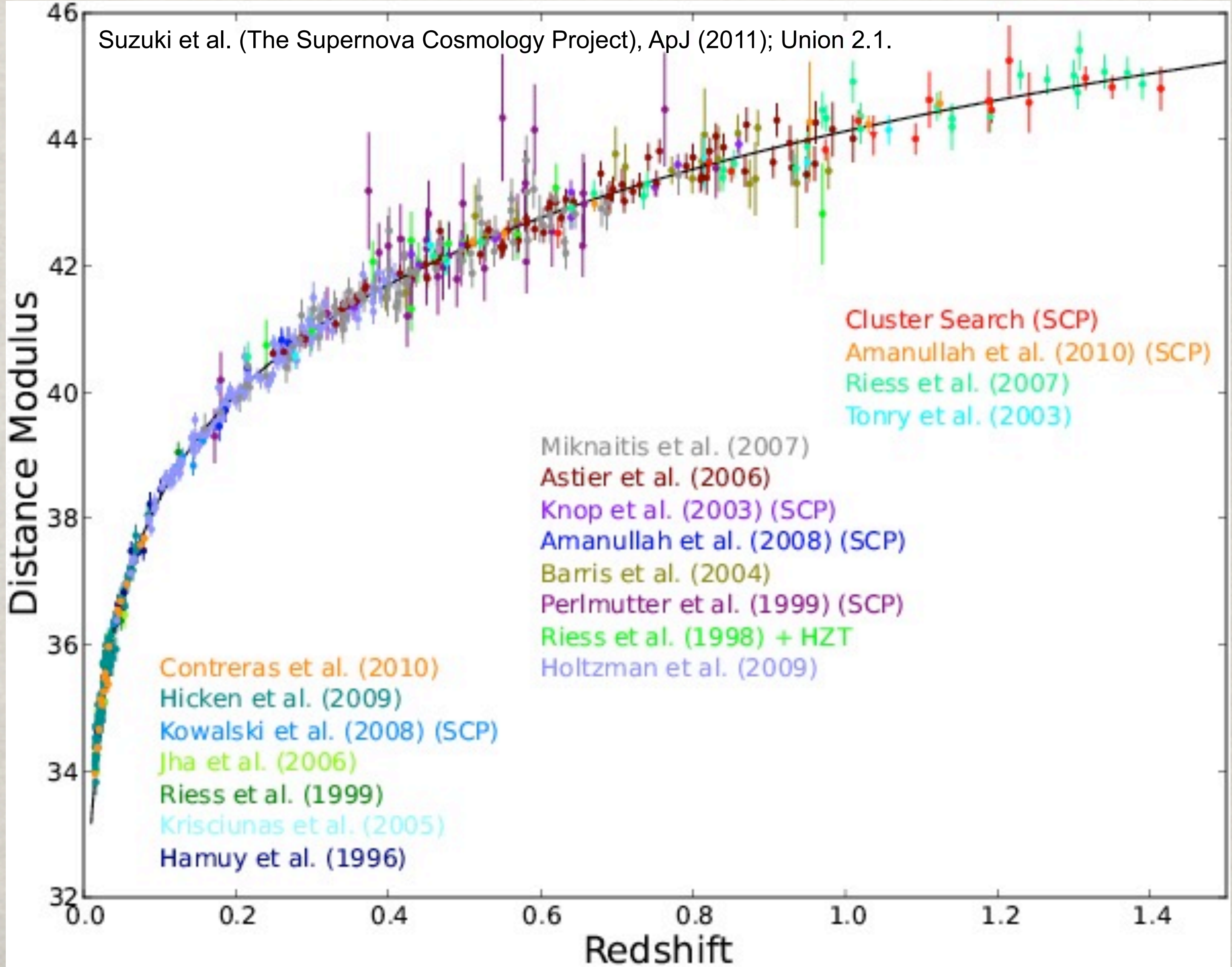
Supernovae Ia as Standard Candles

- Measure the apparent magnitude as a function of the redshift z and test the first correction to the Hubble flow
- The Universe is accelerating !

$$\Lambda > 0$$



SN-IA AS STANDARD CANDLES



ANGULAR DISTANCE

$$D_A = \frac{R}{d}$$

Standard Ruler

Distance to the Ruler

For a FRW universe it is given simply by

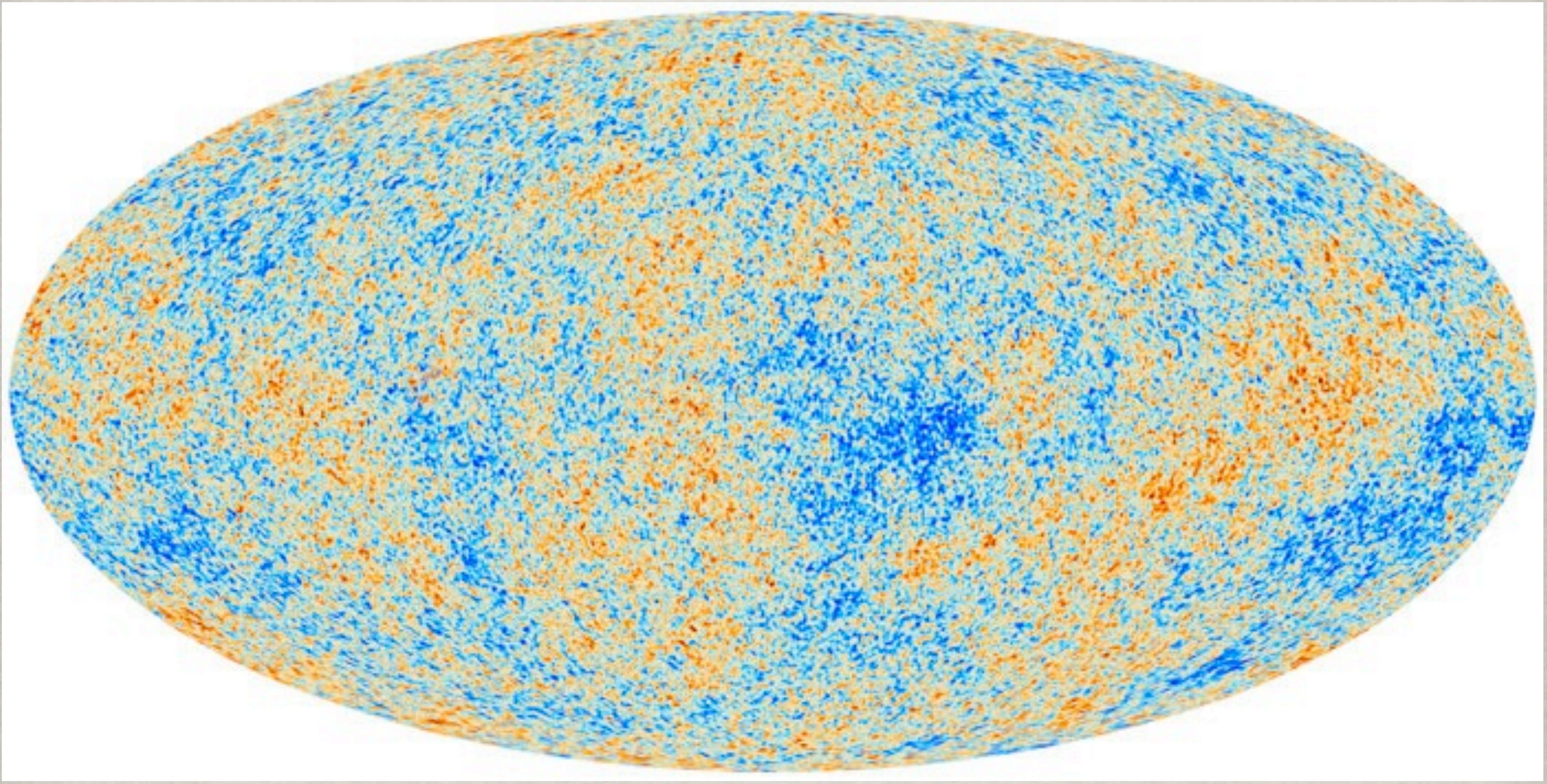
$$D_A = (1+z)R\left(\int_0^z \frac{dz}{H(z)}\right)^{-1}$$

where $H(z) \sim H_0 \Omega_{D,0}^{1/2} (1+z)^{3/2(1+w_D)}$ for a dominant component

e.g. for the sound horizon at decoupling

Planck results 2013

Picture of the CMB anisotropies at recombination

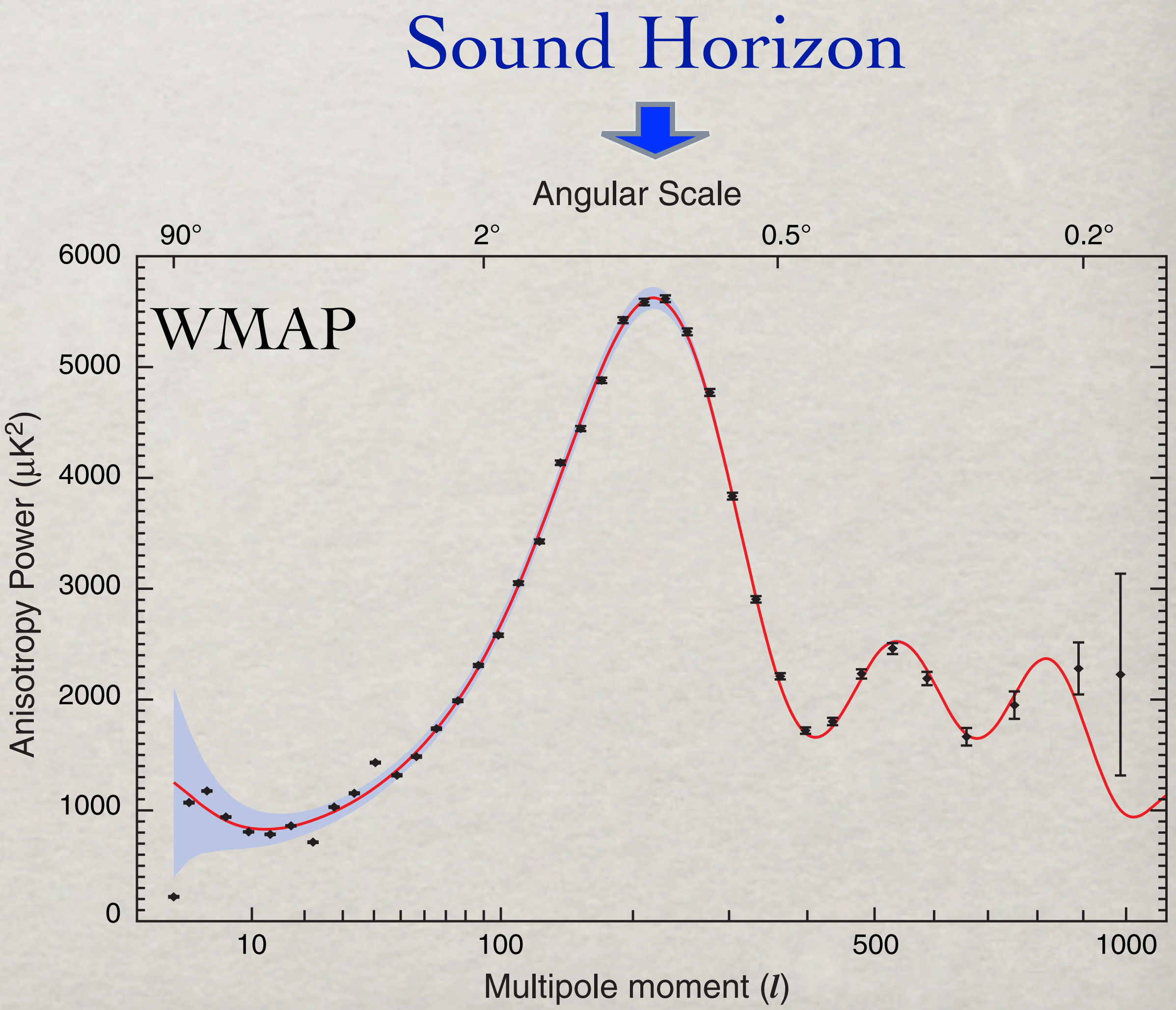


$$\langle T(\theta)T(0)\rangle = \sum_{\ell,m} a_{\ell m} Y_m^\ell(\theta)$$

The sound horizon in the baryon-photon plasma as standard ruler

- Measure the angle corresponding to the first peak in the CMB anisotropies
- The Universe is **FLAT**

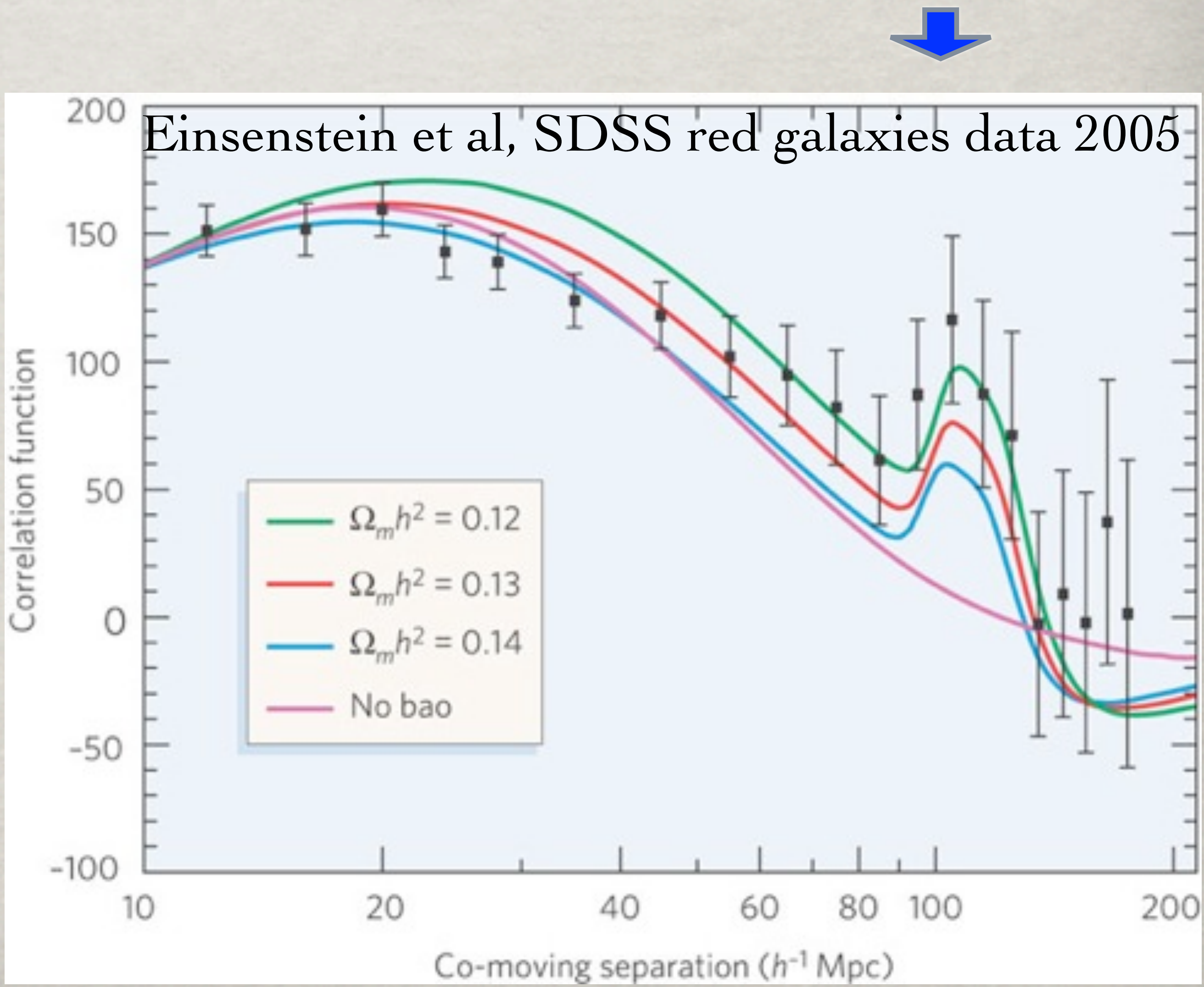
$$\Omega_{tot} = 1.014 \pm 0.017$$
$$\Rightarrow \kappa \simeq 0$$



The sound horizon in the baryon-photon plasma as standard ruler

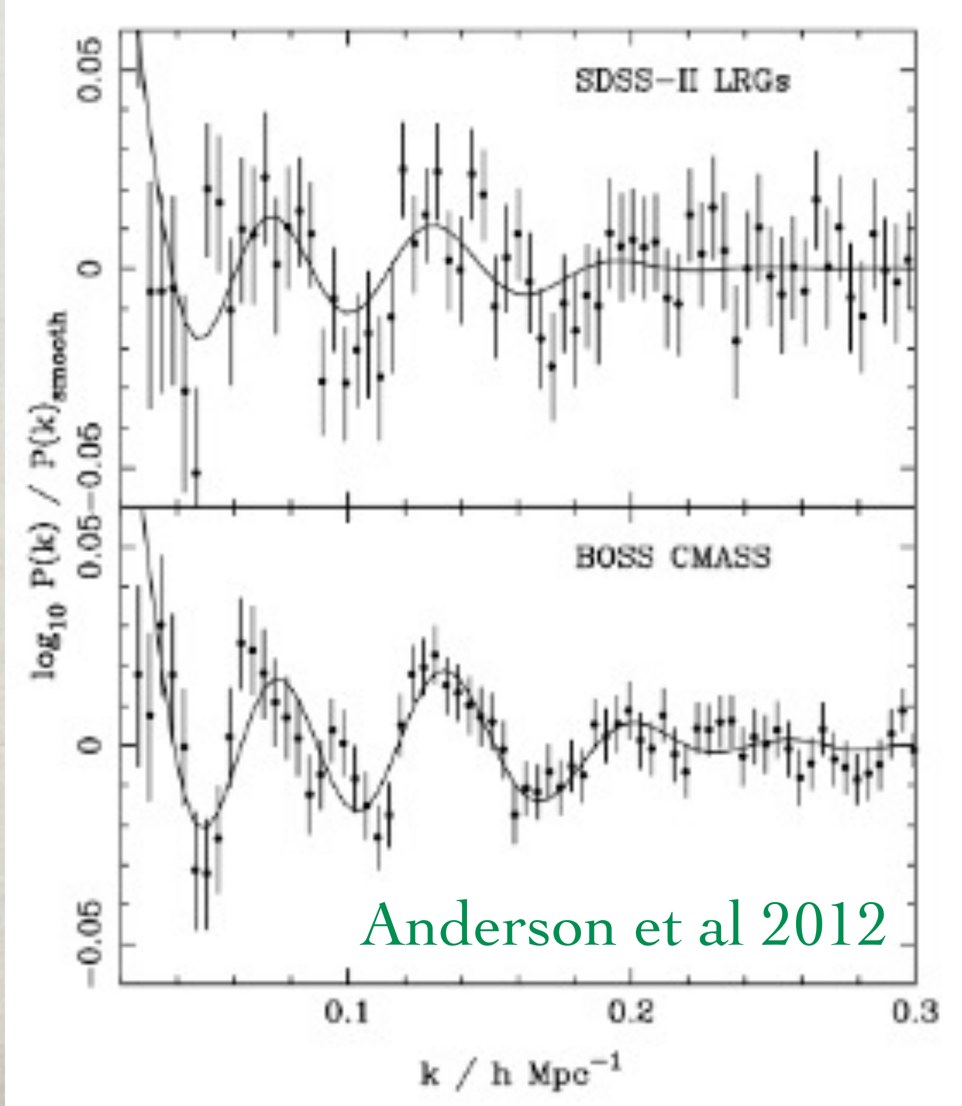
Sound Horizon

- The same scale is visible in the (baryonic) matter distribution (BAO)
- The more baryons (less CDM), the stronger the signal !

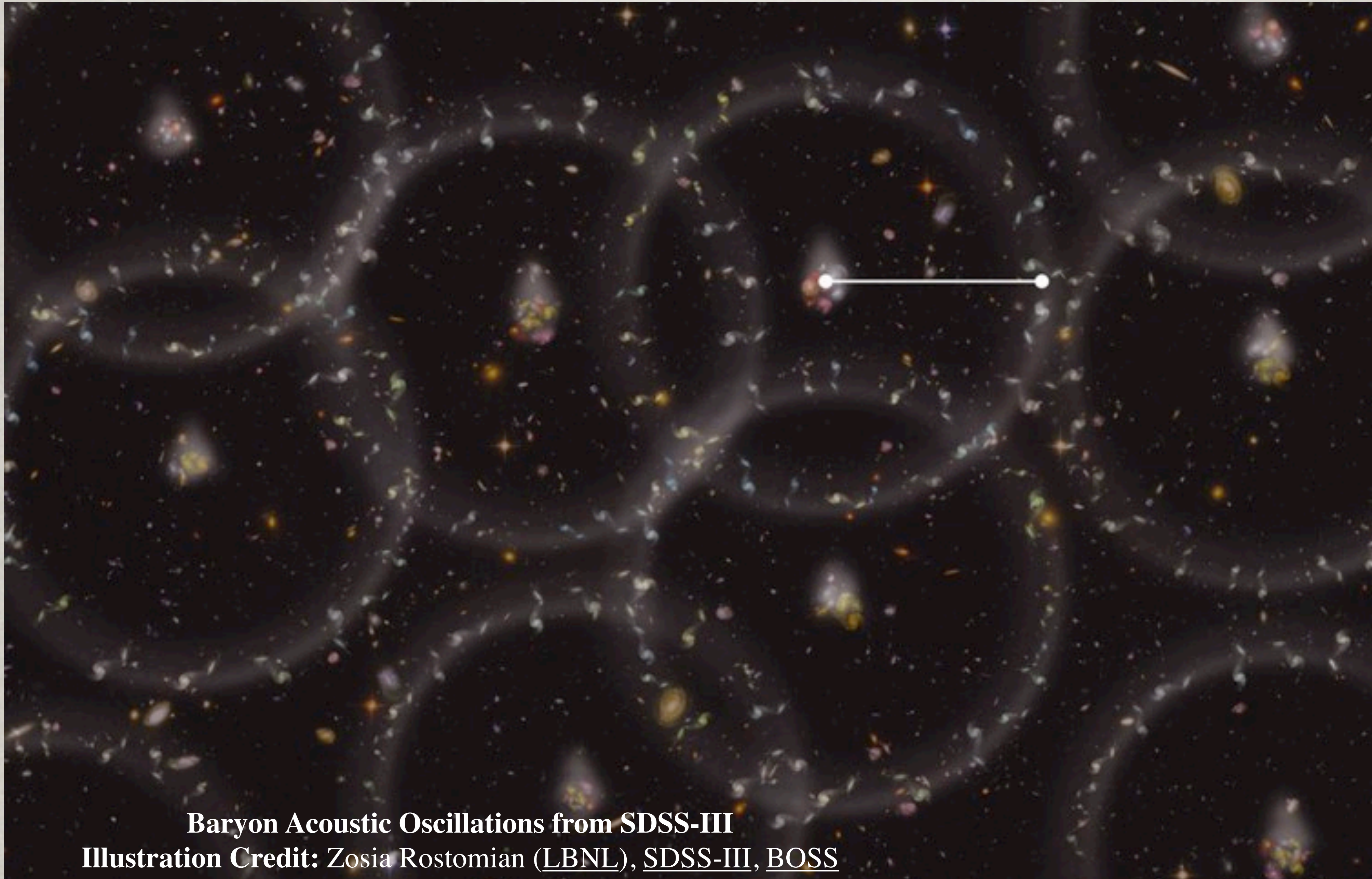


The sound horizon in the baryon-photon plasma as standard ruler

- The signal has been now detected in the galaxy power spectrum (two-point correlation !) with high precision.



BAO: an artistic view



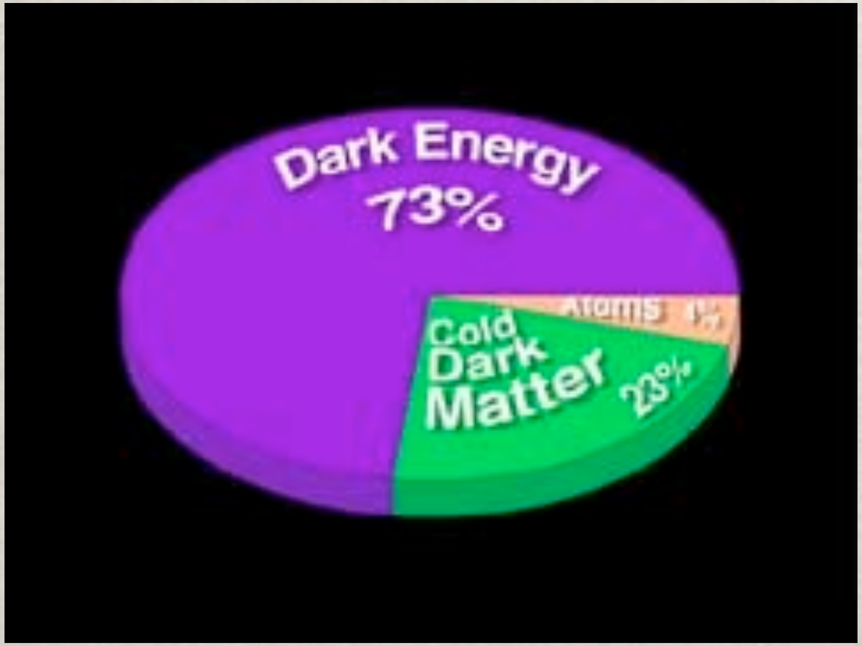
Baryon Acoustic Oscillations from SDSS-III
Illustration Credit: Zosia Rostomian (LBNL), SDSS-III, BOSS

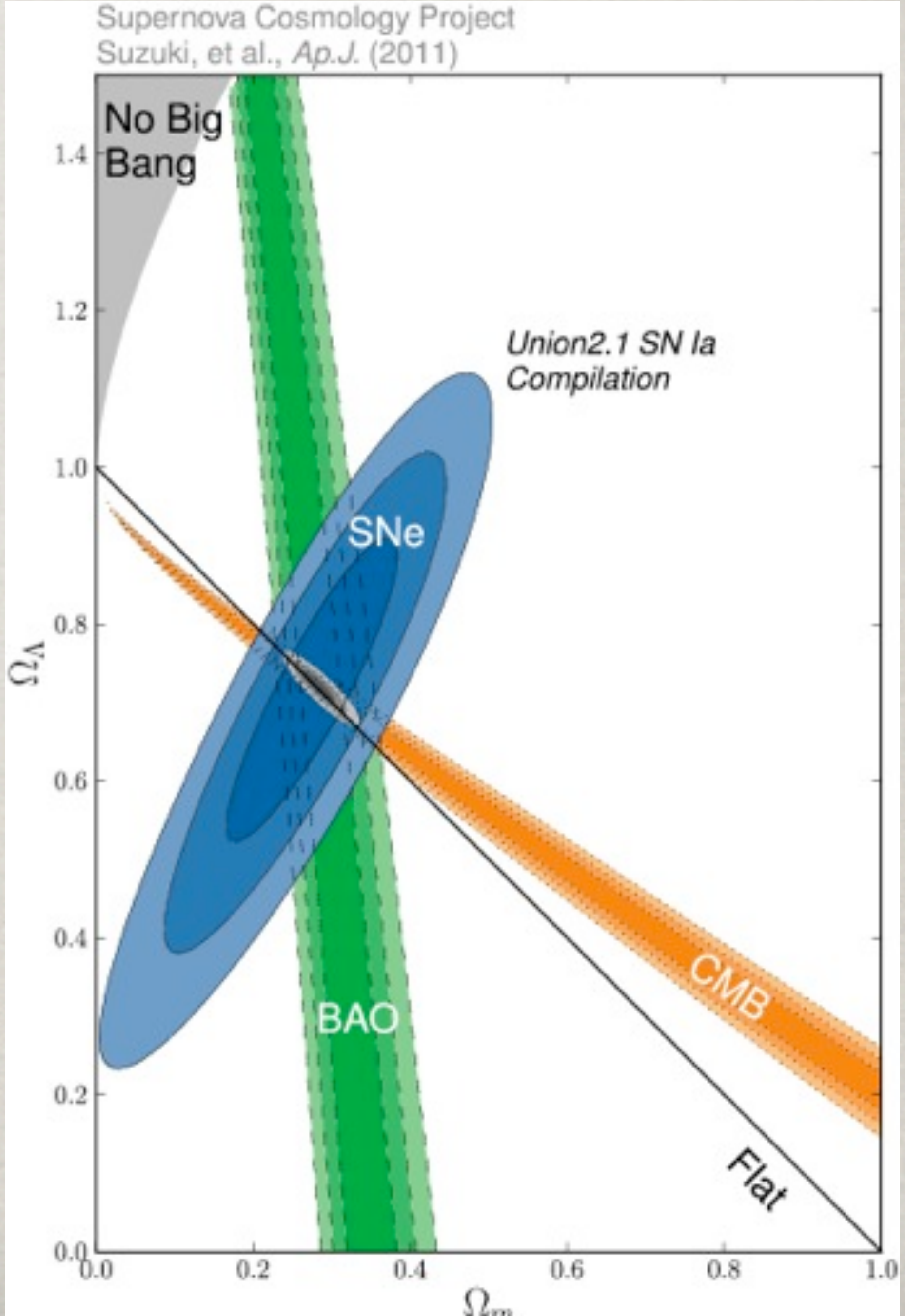
Cosmology before Planck

Consistent cosmological picture given in terms of only 6 parameters,

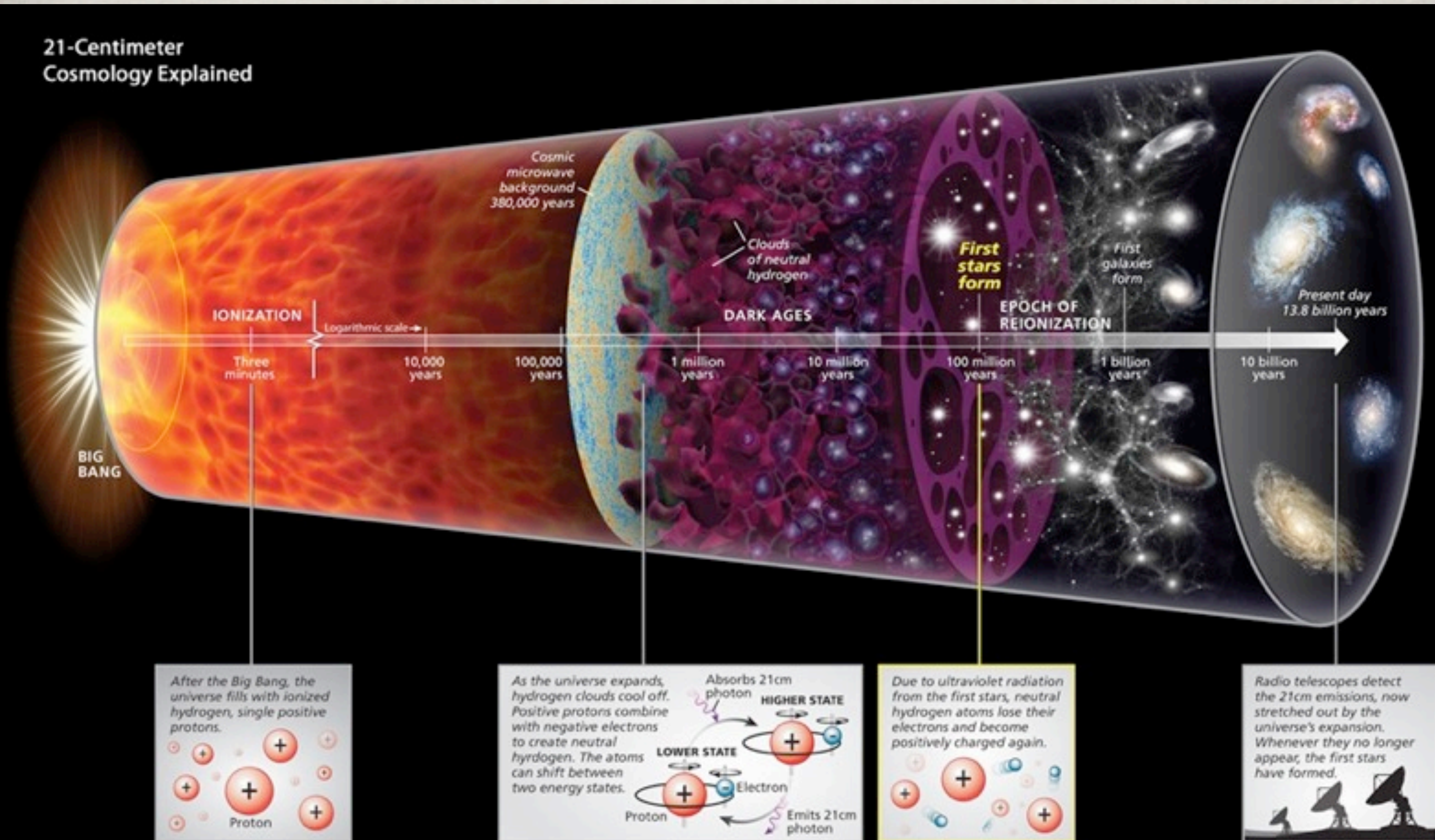
$\Omega_M h^2, \Omega_b h^2, \ \tau, n_s, A_s$

$\theta_* (\Omega_k/\Omega_\Lambda, H_0)$



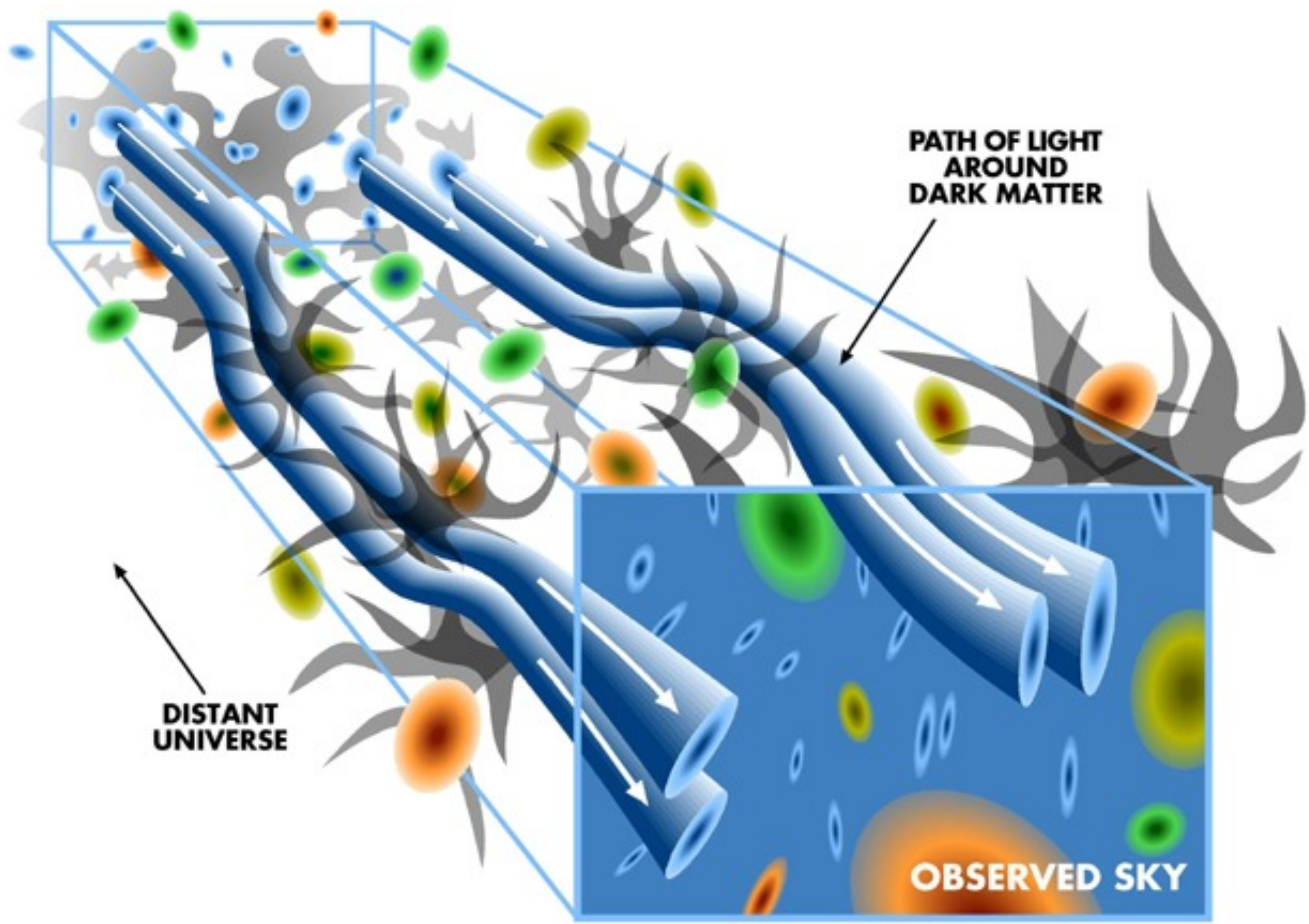


Into the Dark Ages...



21- Centimeter Hydrogen line   Illustration Credit:Roen Kelly

Into the Dark Ages...



Weak Lensing   Illustration Credit:LSST

Strong & Weak Lensing

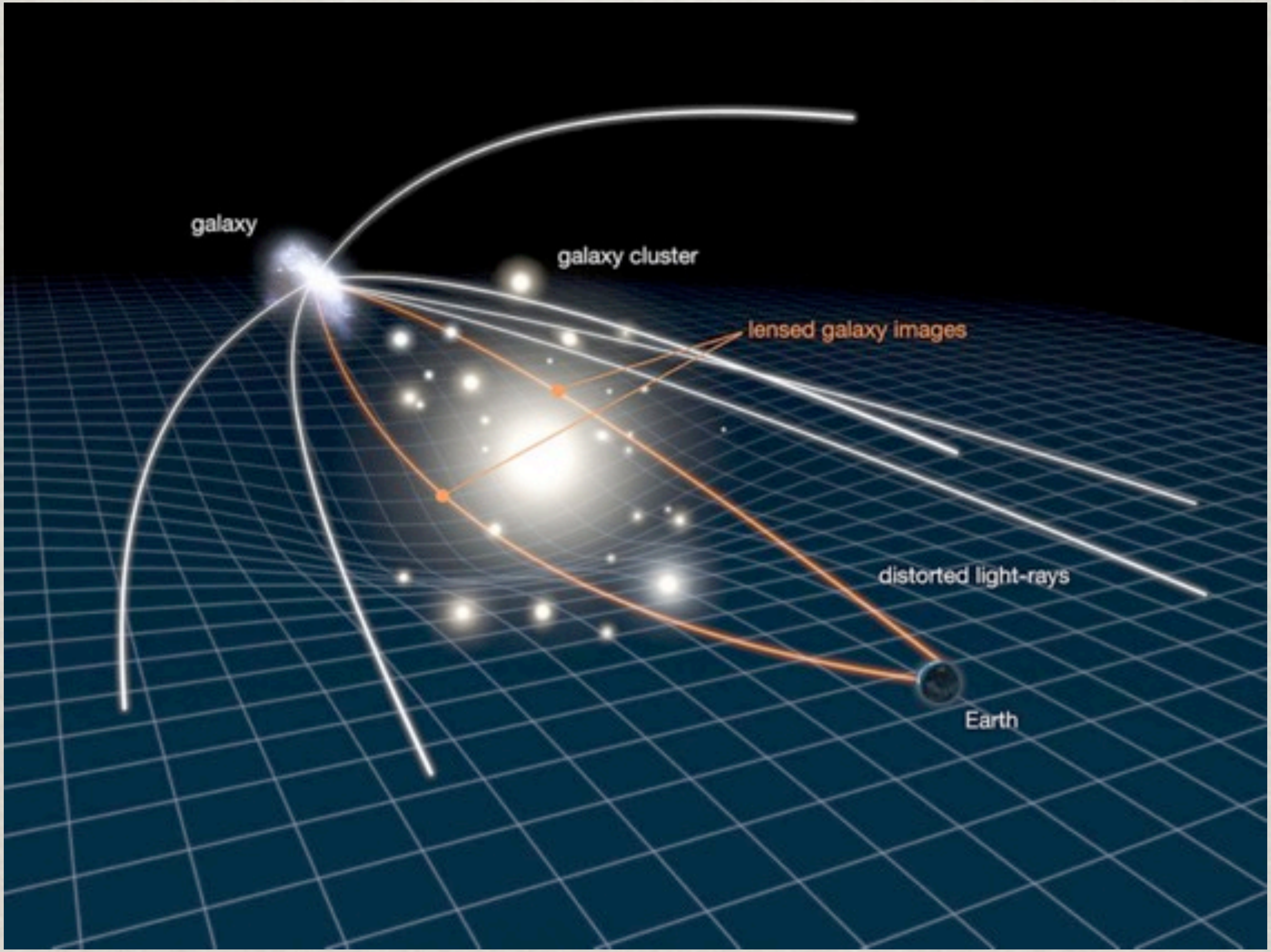
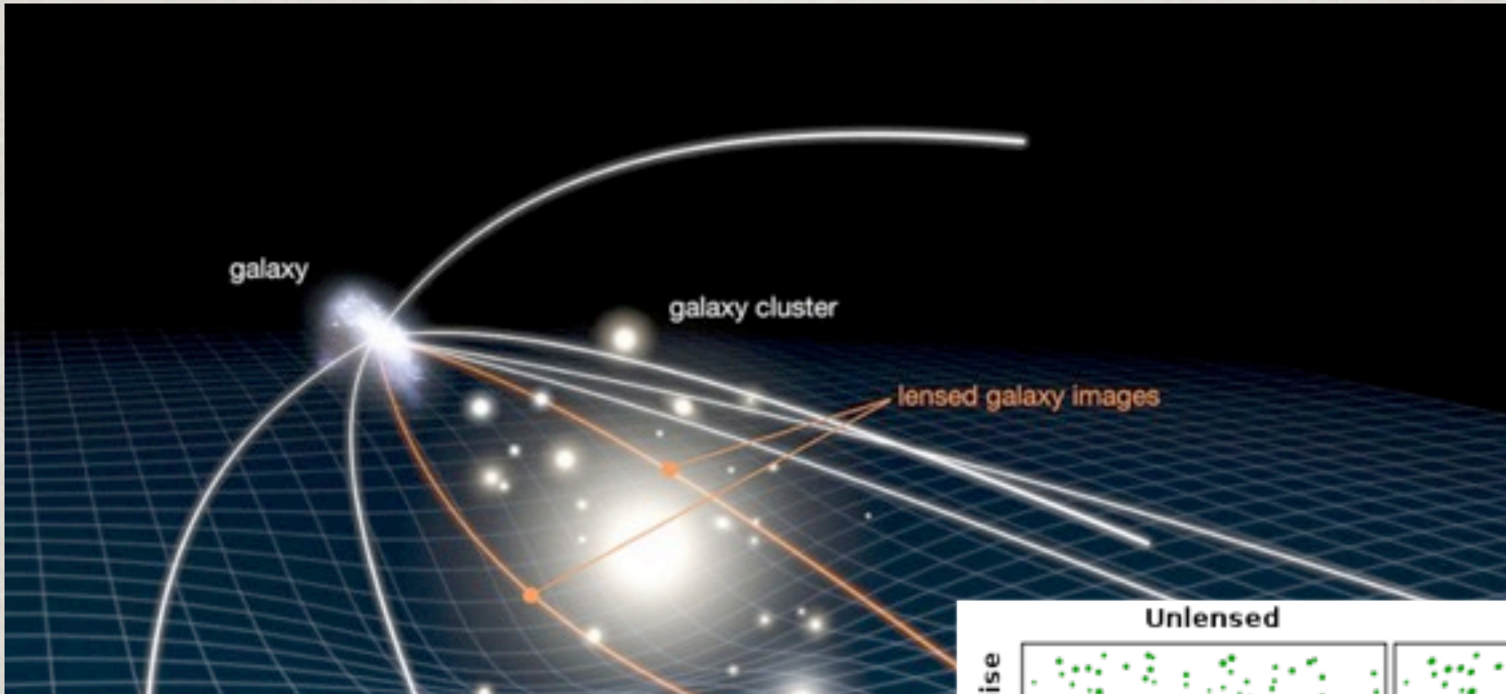


Illustration Credit:NASA/ESA

Strong & Weak Lensing



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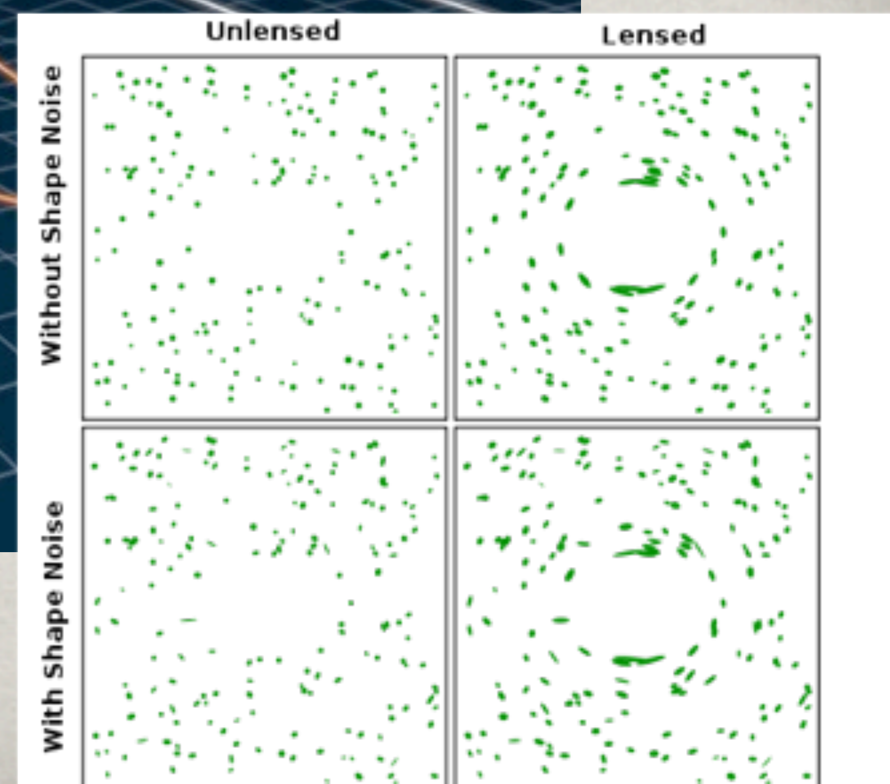

Problems of Standard Cosmology

Problems in Standard Cosmology

- Causality/Horizon

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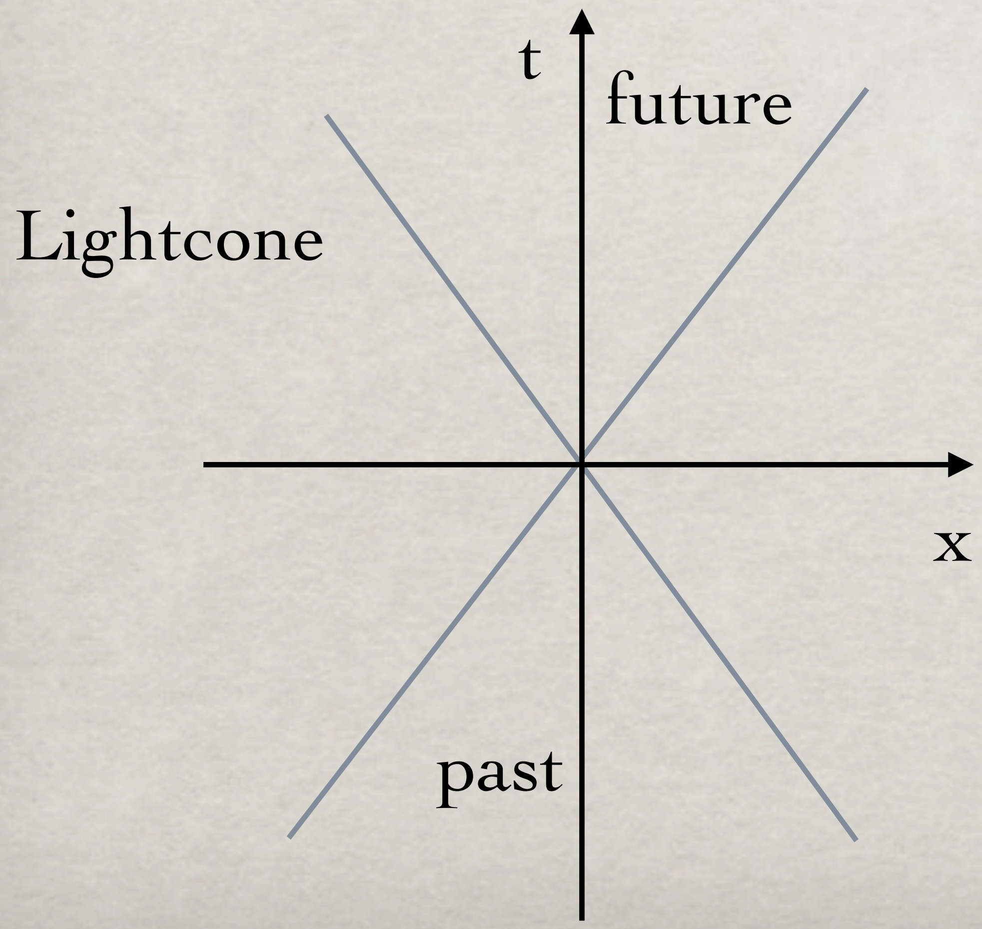

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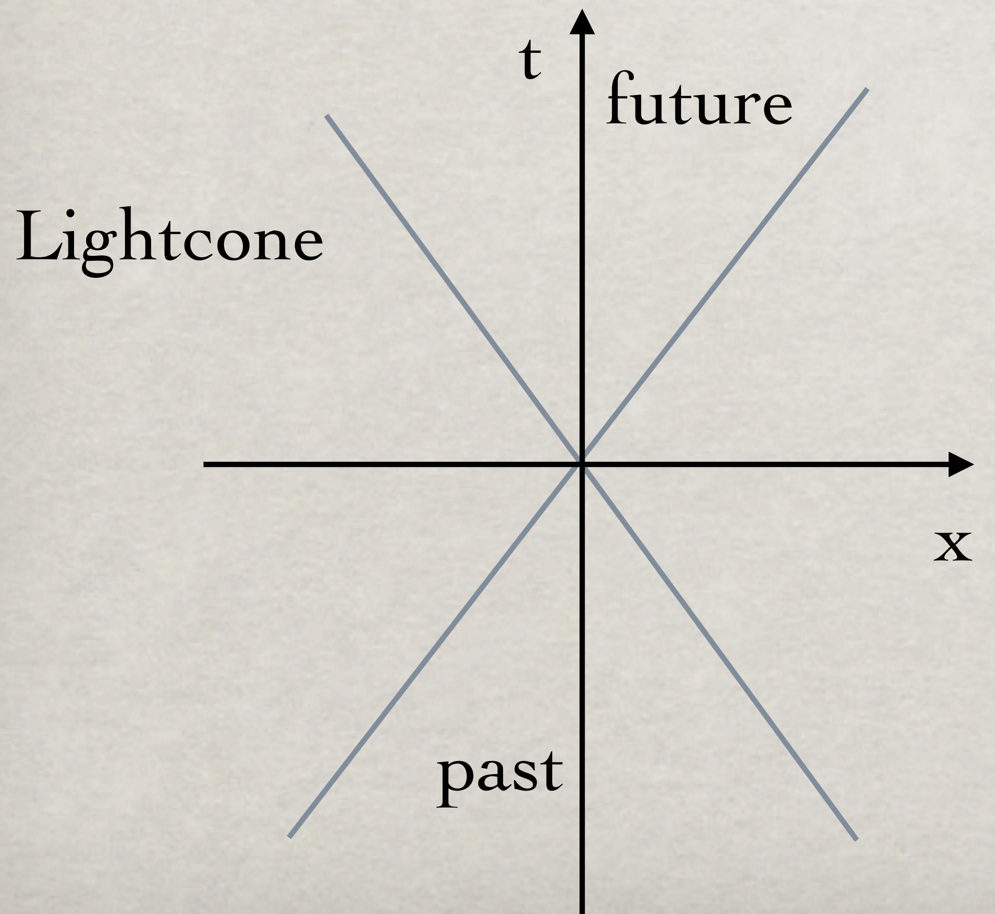

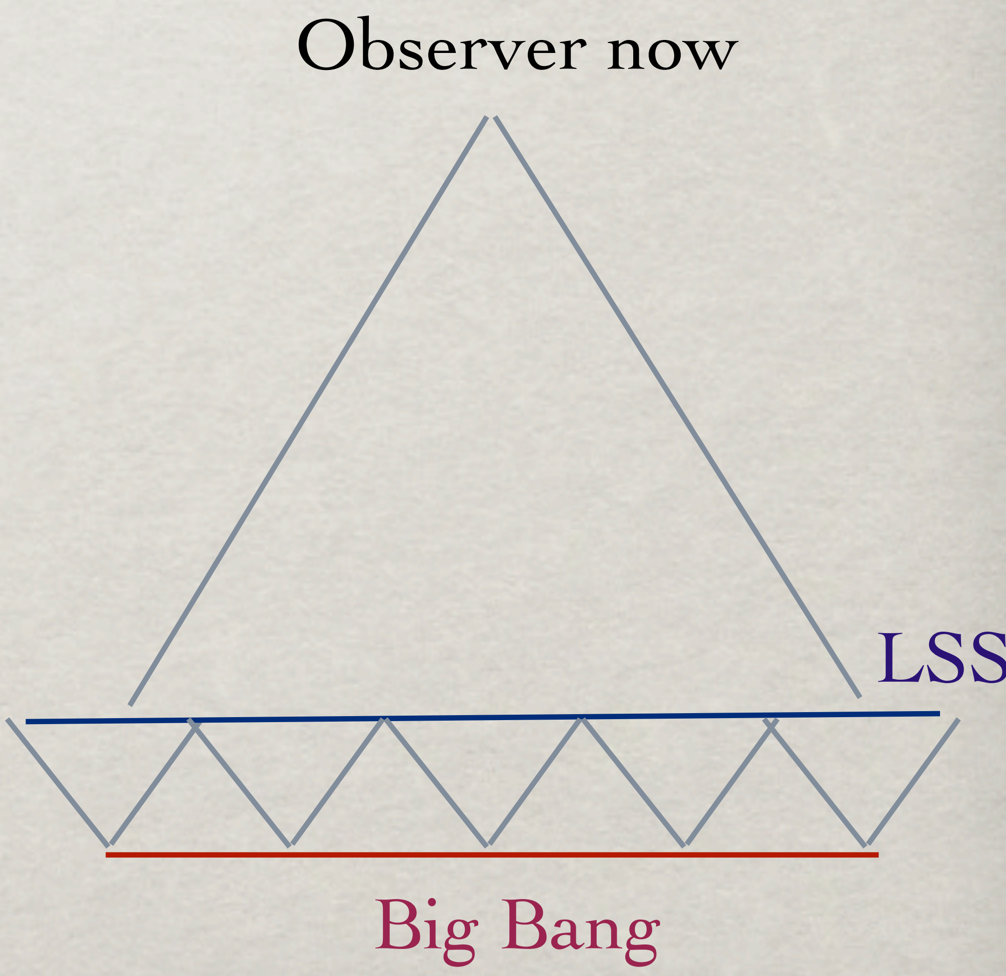

Problems in Standard Cosmology

- Causality/Horizon
- Flatness

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- Causality/Horizon
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$$\frac{d}{dt}(\Omega_{tot} - 1) = -2\frac{\ddot{a}}{aH}(\Omega_{tot} - 1)$$

Problems in Standard Cosmology

- Causality/Horizon
- Flatness

$$\frac{d}{dt}(\Omega_{tot} - 1) = -2\frac{\ddot{a}}{aH}(\Omega_{tot} - 1)$$

For decelerating universe $\ddot{a} < 0 \Rightarrow |\Omega_{tot} - 1|$ grows !

Space becomes more and more curved with time...

Instead acceleration brings toward a spatially flat universe !

Problems in Standard Cosmology

- Causality/Horizon
- Flatness
- Relics/Topological defects

Problems in Standard Cosmology

- Causality/Horizon
- Flatness
- Relics/Topological defects

Often too many relics, e.g. topological defects like monopoles, strings or domain walls, are produced and must be diluted

Problems in Standard Cosmology

- Causality/Horizon
- Flatness
- Relics/Topological defects
- Entropy problem

Problems in Standard Cosmology

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The present Universe still contains a substantial entropy (in photons), which was much larger in early times... Where did that come from ?

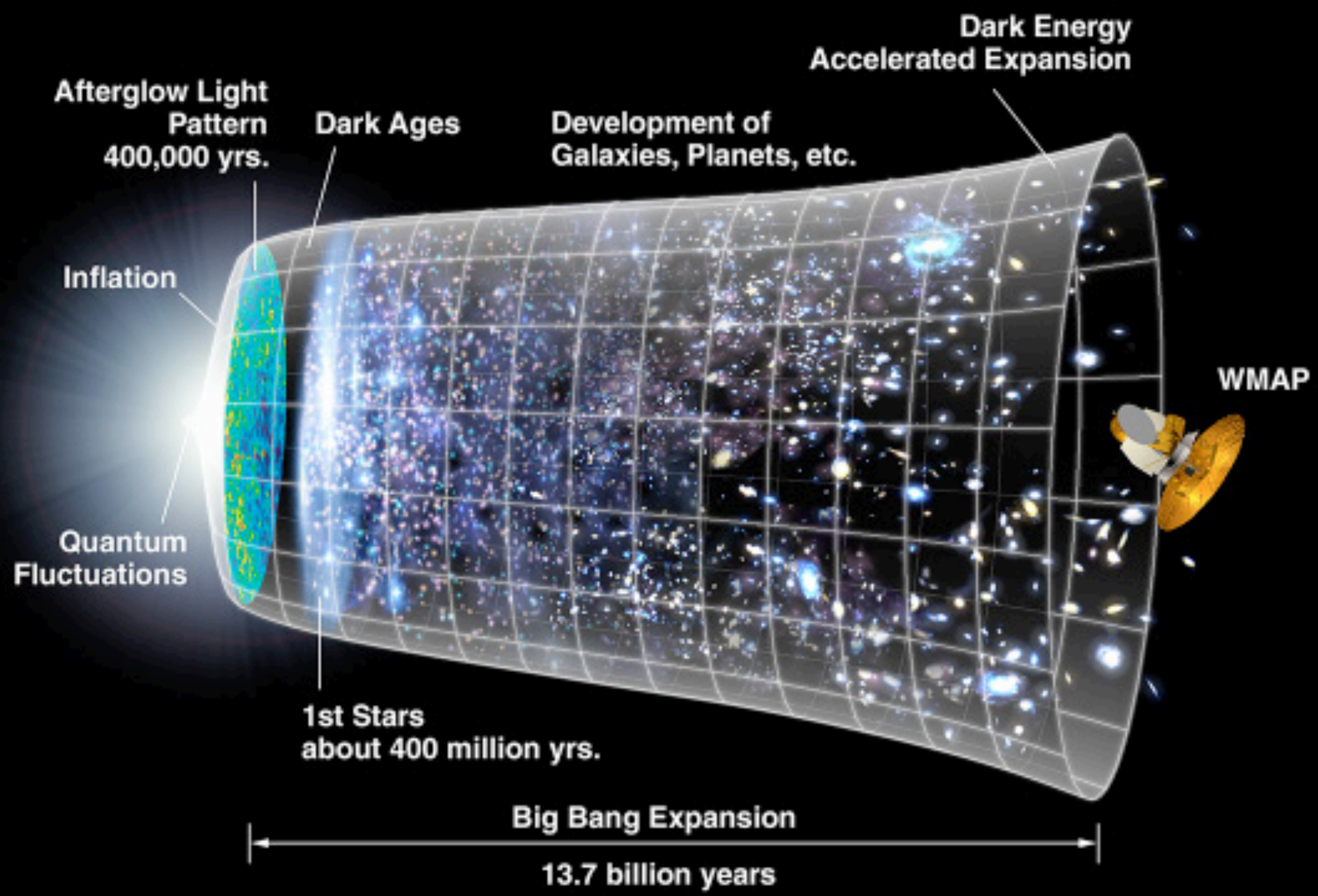
Non-adiabatic process, i.e. reheating after inflation !

Problems in Standard Cosmology

- Causality/Horizon
- Flatness
- Relics/Topological defects
- Entropy problem

Inflation solves this problems and sets the initial conditions for Standard Cosmology !

Following the fluctuations



We need seeds of small fluctuations, that were amplified by gravity & are the origin of the structure we see today