STANDARD COSMOLOGY
THE EVOLVING PICTURE OF THE UNIVERSE

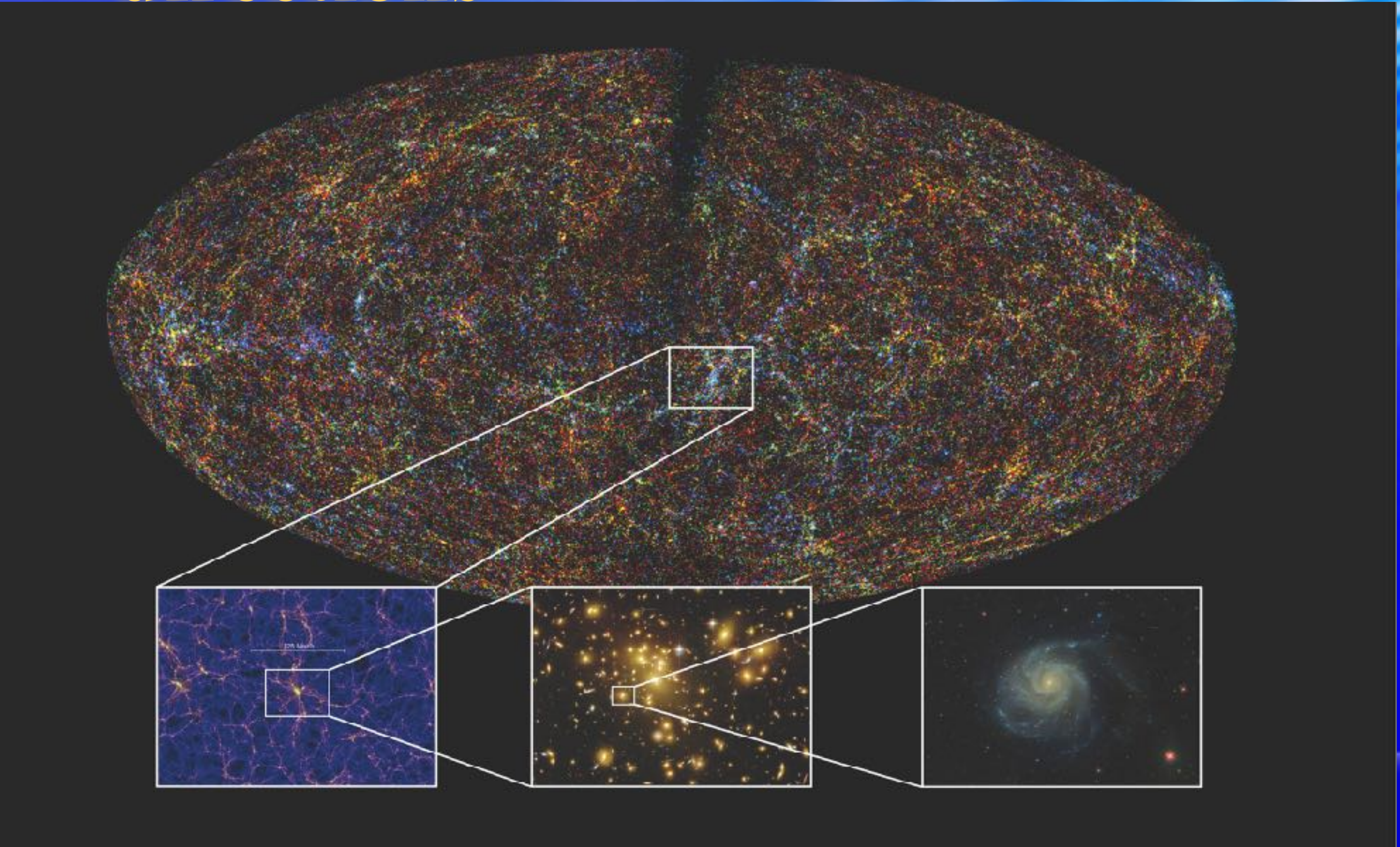
Octavio Valenzuela

Requirements for a Universe Model

- Driving Force: Gravity
- Universe properties at large scale
- Homogeneous? Isotropic?
- Center? Edge? Cosmological Principle

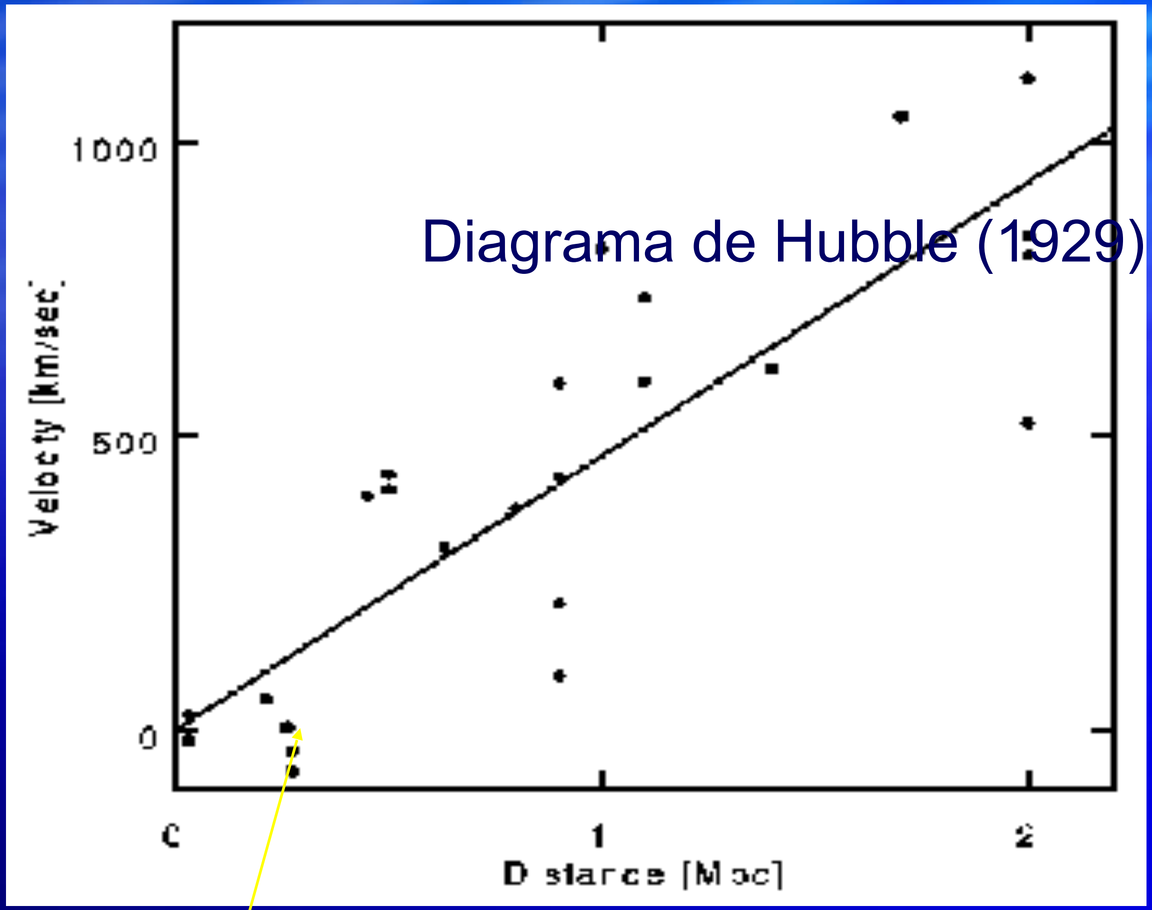
- Gravity description observer independent ?
Static, uniform motion or accelerated? GR

Same structure pattern at all directions



Hubble Law!

A property of the Universe

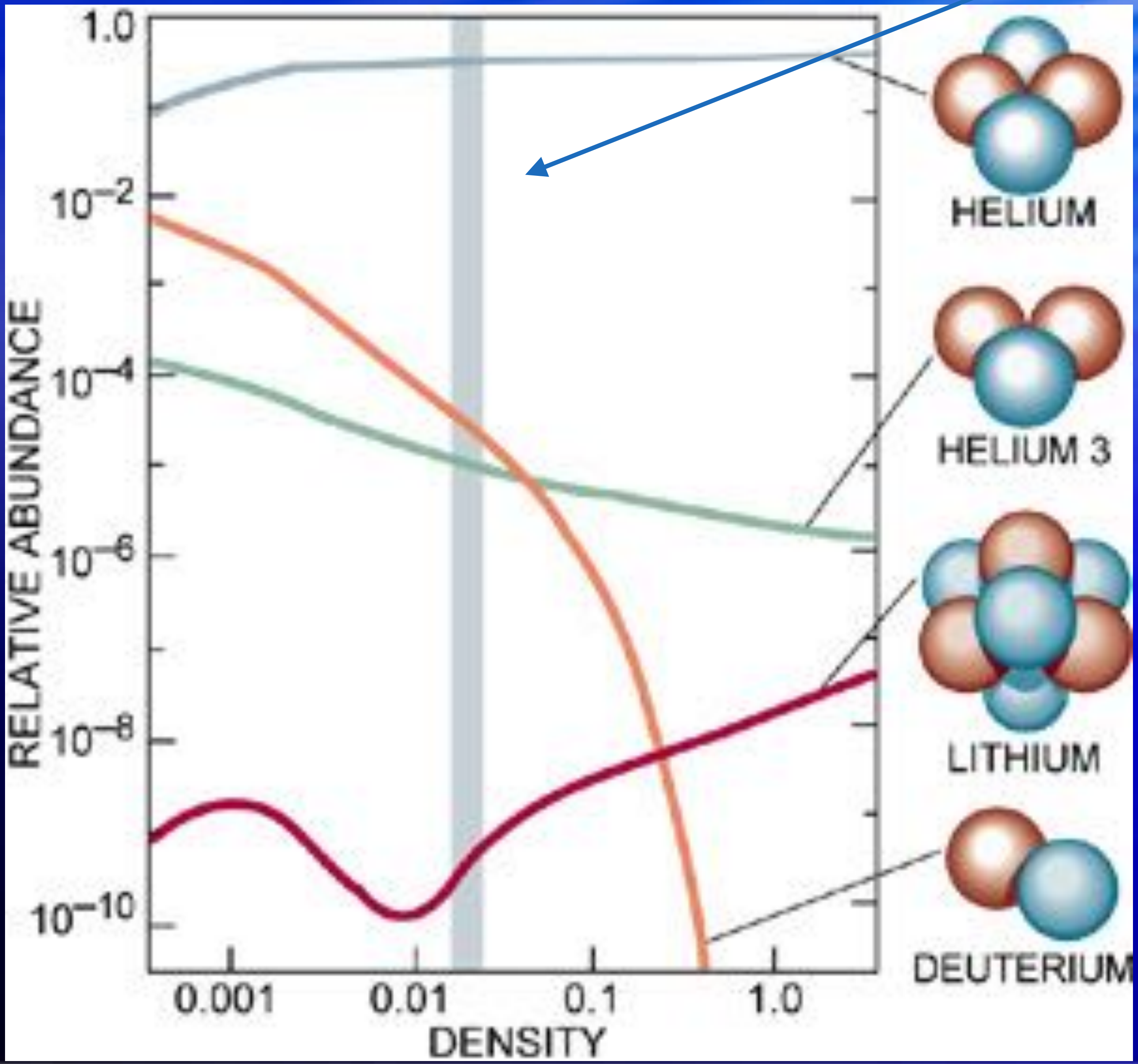


Efecto Doppler Cosmologico

Las galaxias se alejan con V proporcional a D

Observed H, D, He, Li:

Observations

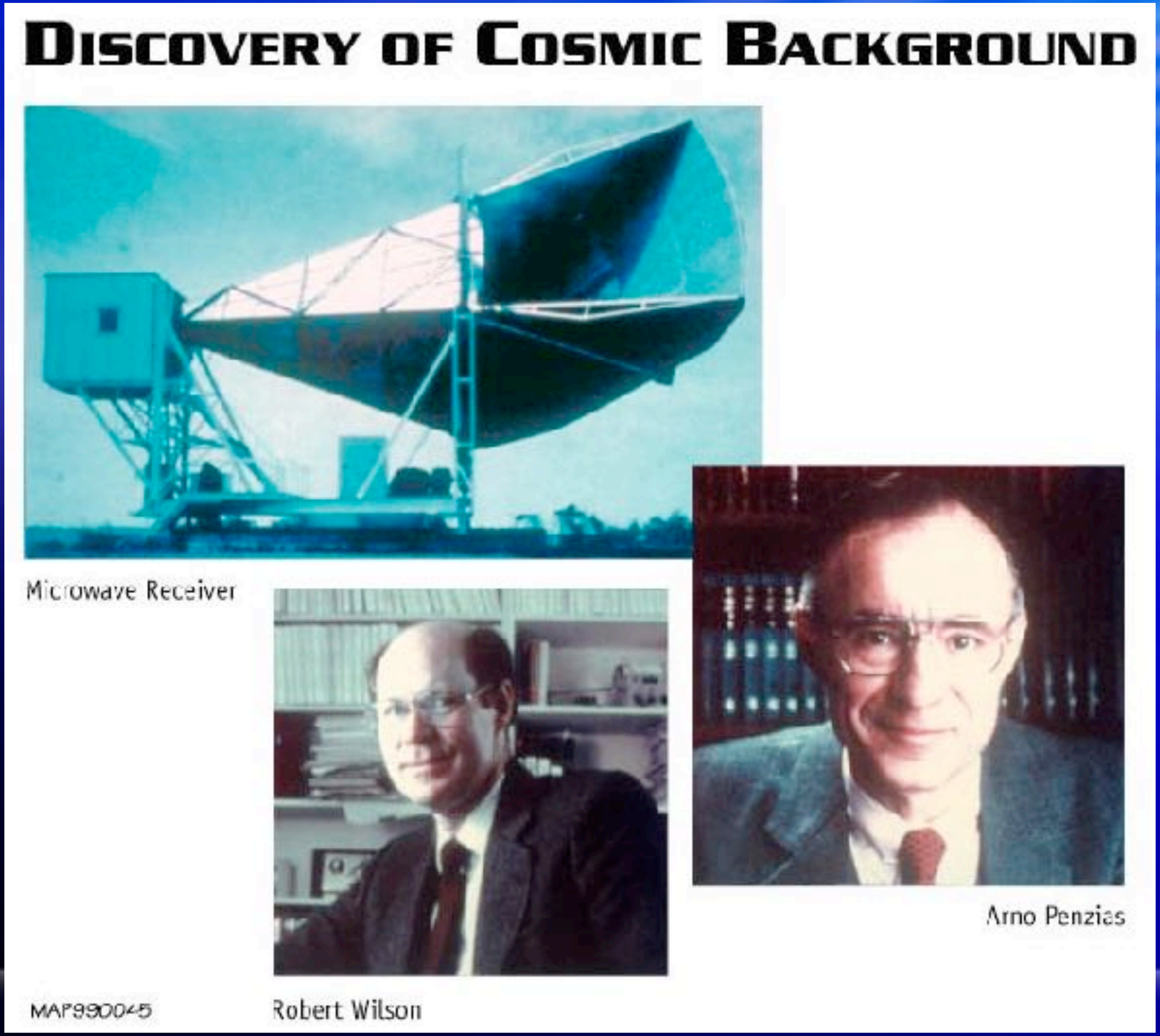


Observed D
hard or impossible
to be created in stars

Because of D low
bounding energy
is too fragil

Needs a new mechanism

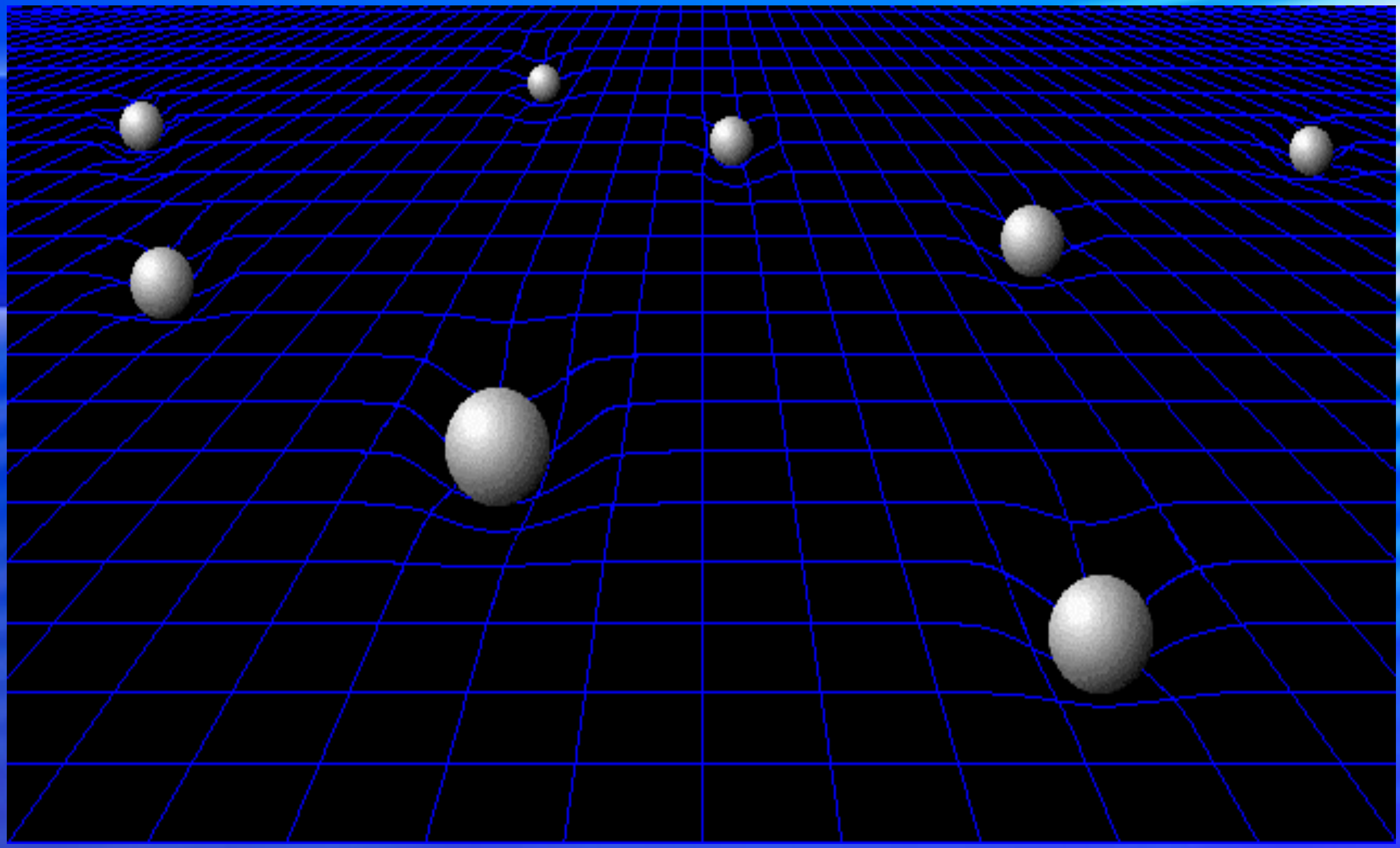
Nobel Prize 1978: discovered in 1965 as isotropic noise in microwave by Bell Laboratories Engeniers

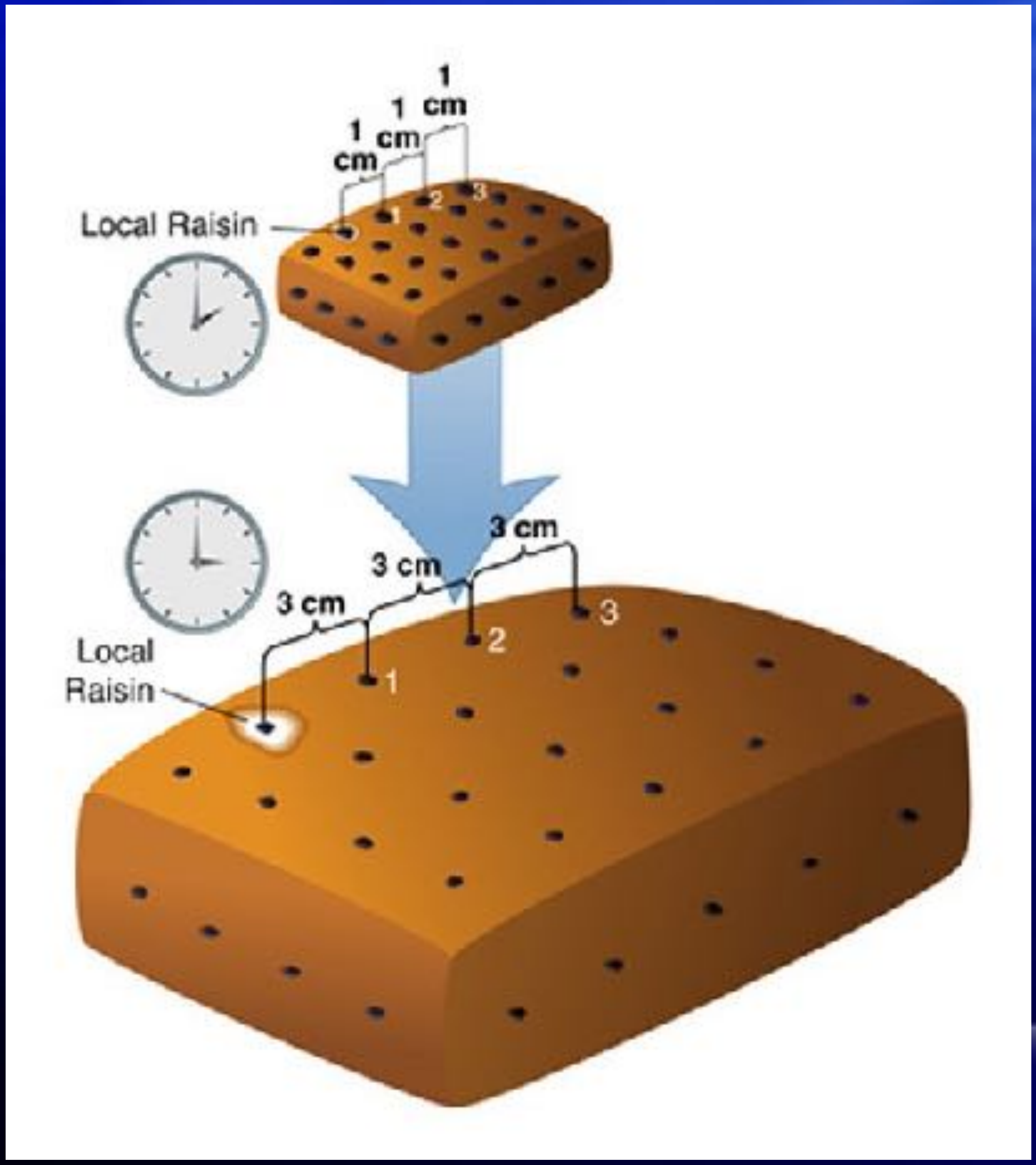


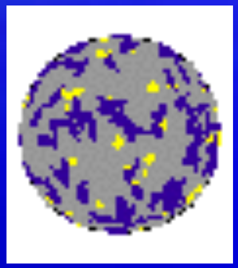
Old TV static

Hubble Law
Veloc. = H x Distance

Looks the same for all observers to preserve Cosmological Principle







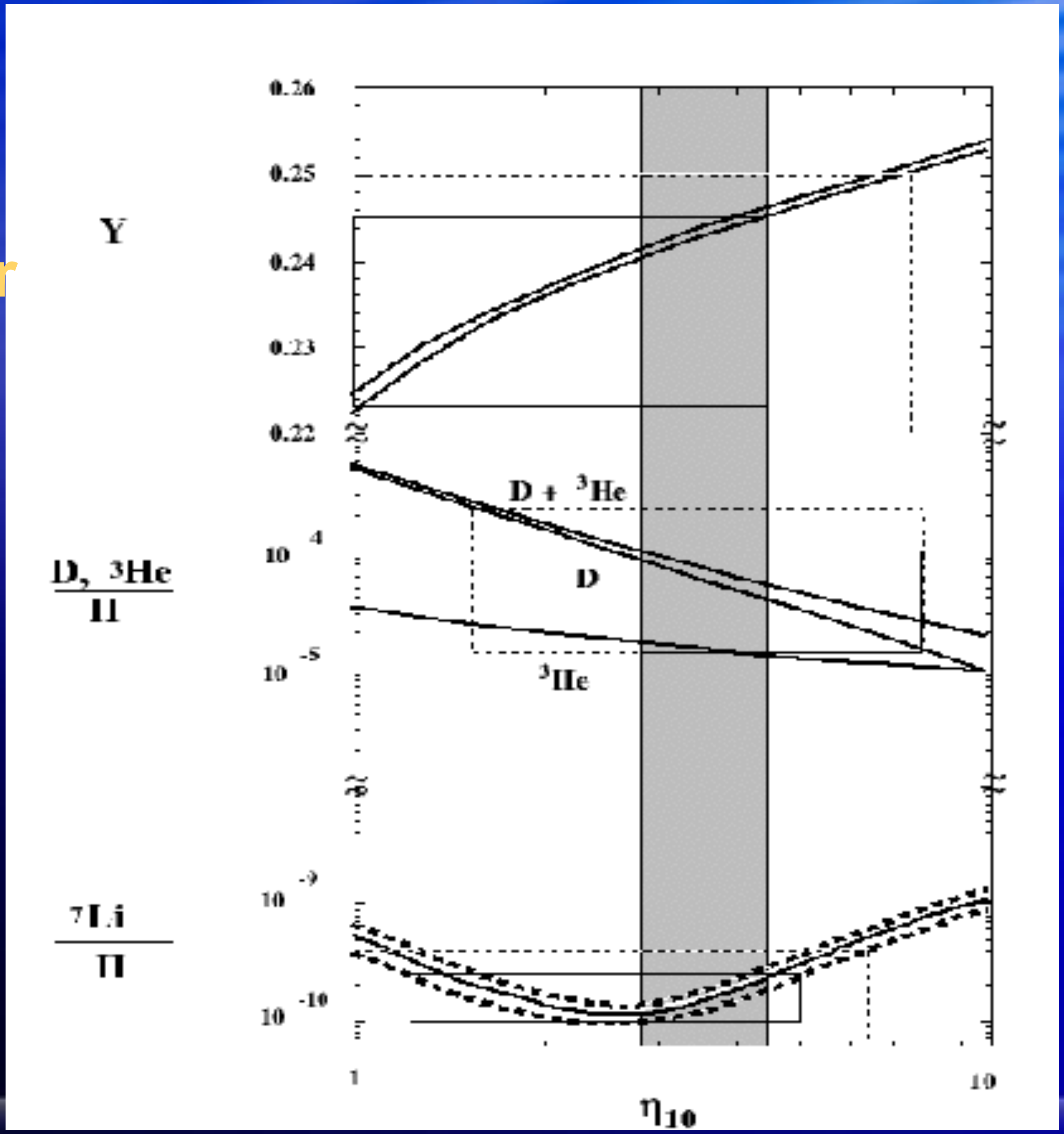
Adiabatic expansion implies a **hotter past:** Same energy in a smaller volume Universe **cool down during evolution**

H, D, He, Li:Hot Big Bang explained

assuming Adiabatic Expansion (Universe Cools).

neutrons ,protons, electrons

Like the interior of a reactor or accelerator

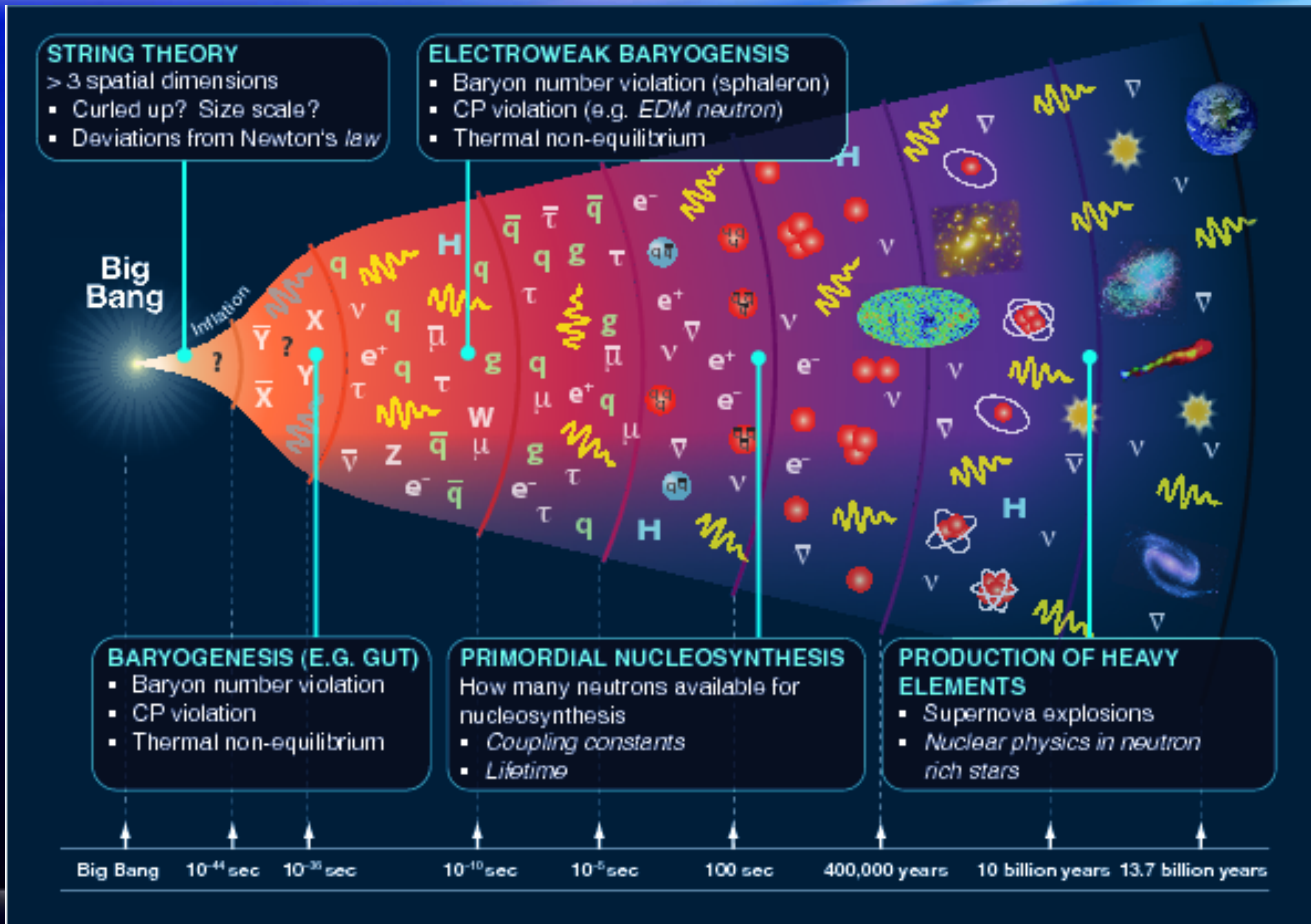


Particles collision form
Nuclei and atoms
Some are destroyed during further collisions or by radiation

- Because of cooling
- the abundances
- get frozen

Universe Thermal History:

Particle collisions (fotons, particles) vs expansion/cooling down and reactions thresholds



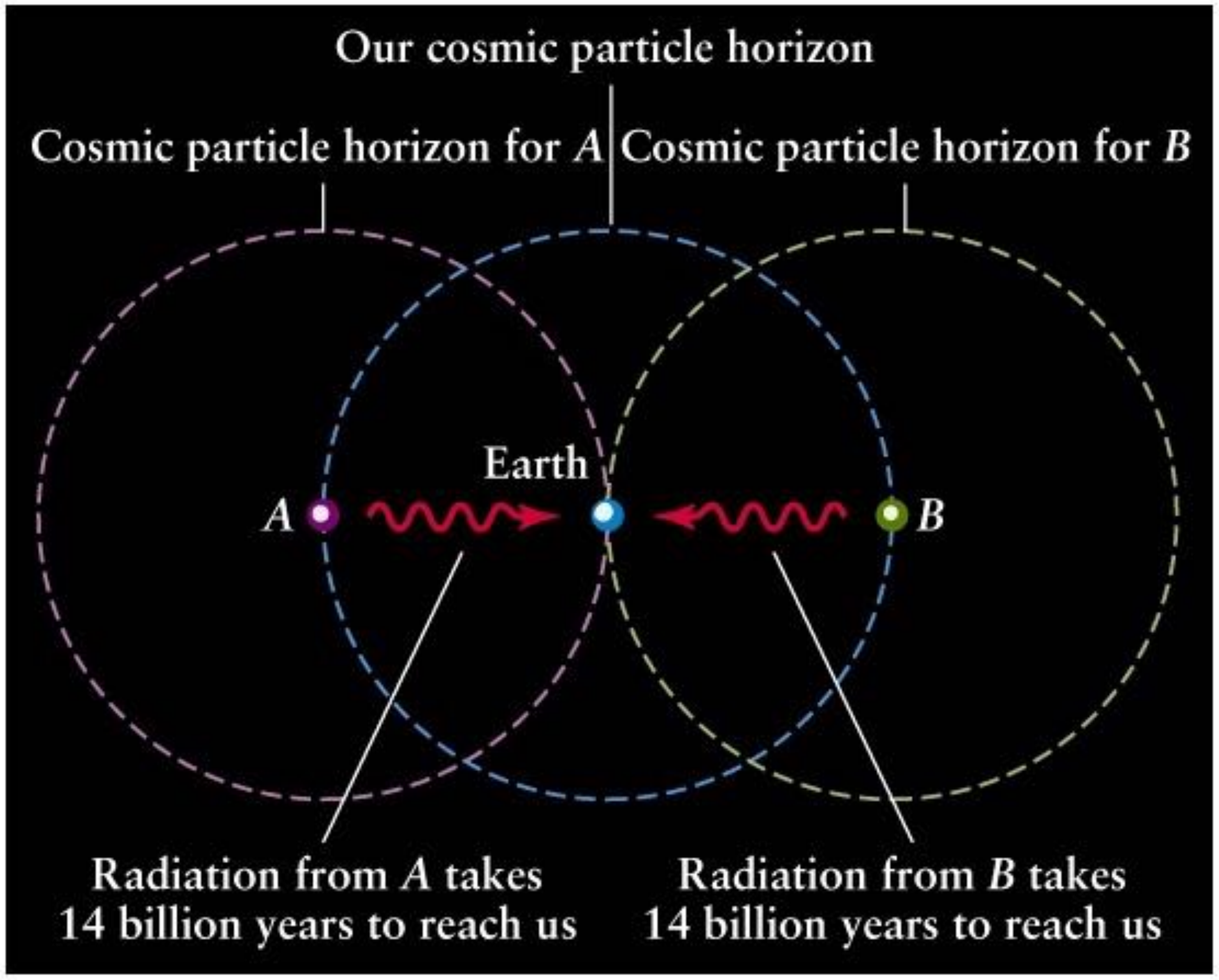
Big Bang Model Success

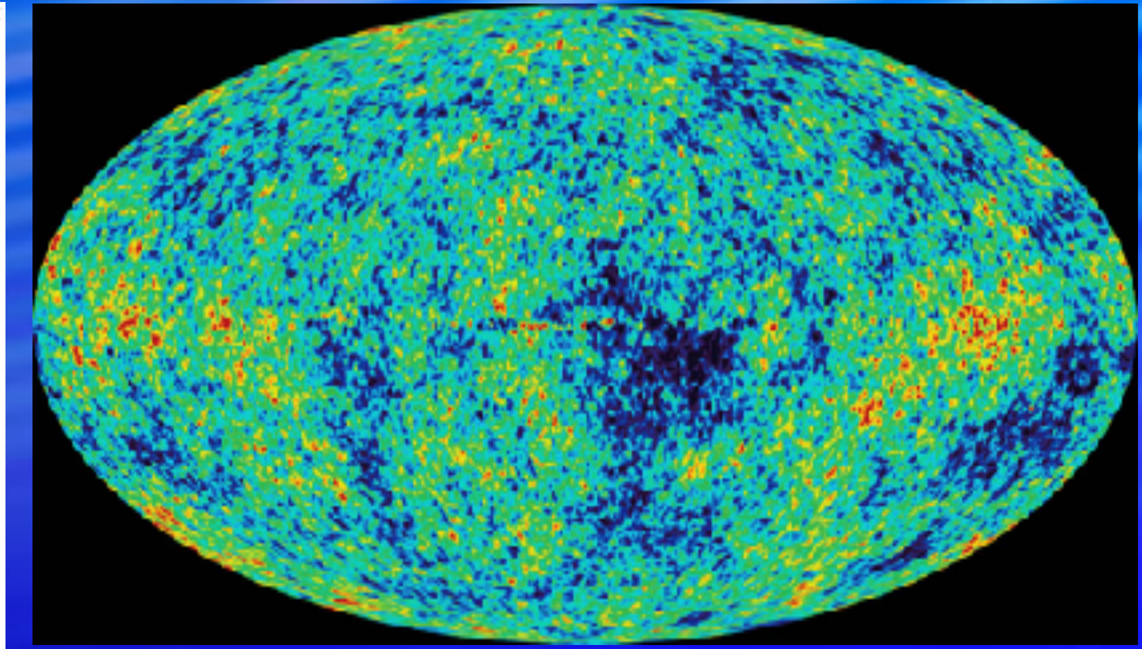
- Assuming General Relativity
- Homogeneity and isotropy
- Explains :
- Hubble Law: v=Hd
- Cosmic Background Radiation: T=2.7k
- Light elements abundance: H, He, D, Li

Big Bang Problems

- Origin of Expansion
- Temperature Isotropy for regions causally disconnected: Horizonte
- Flatness:Cosmic average density is close but not equal to critical value. Coincidence?
- Galaxies and Large Scale Structure origin
- Matter vs antimatter: Why only matter?
- Universe Topology? Global shape
- Other Universes?

Horizon Problem: Causally disconnected regions show the same temperature, why?

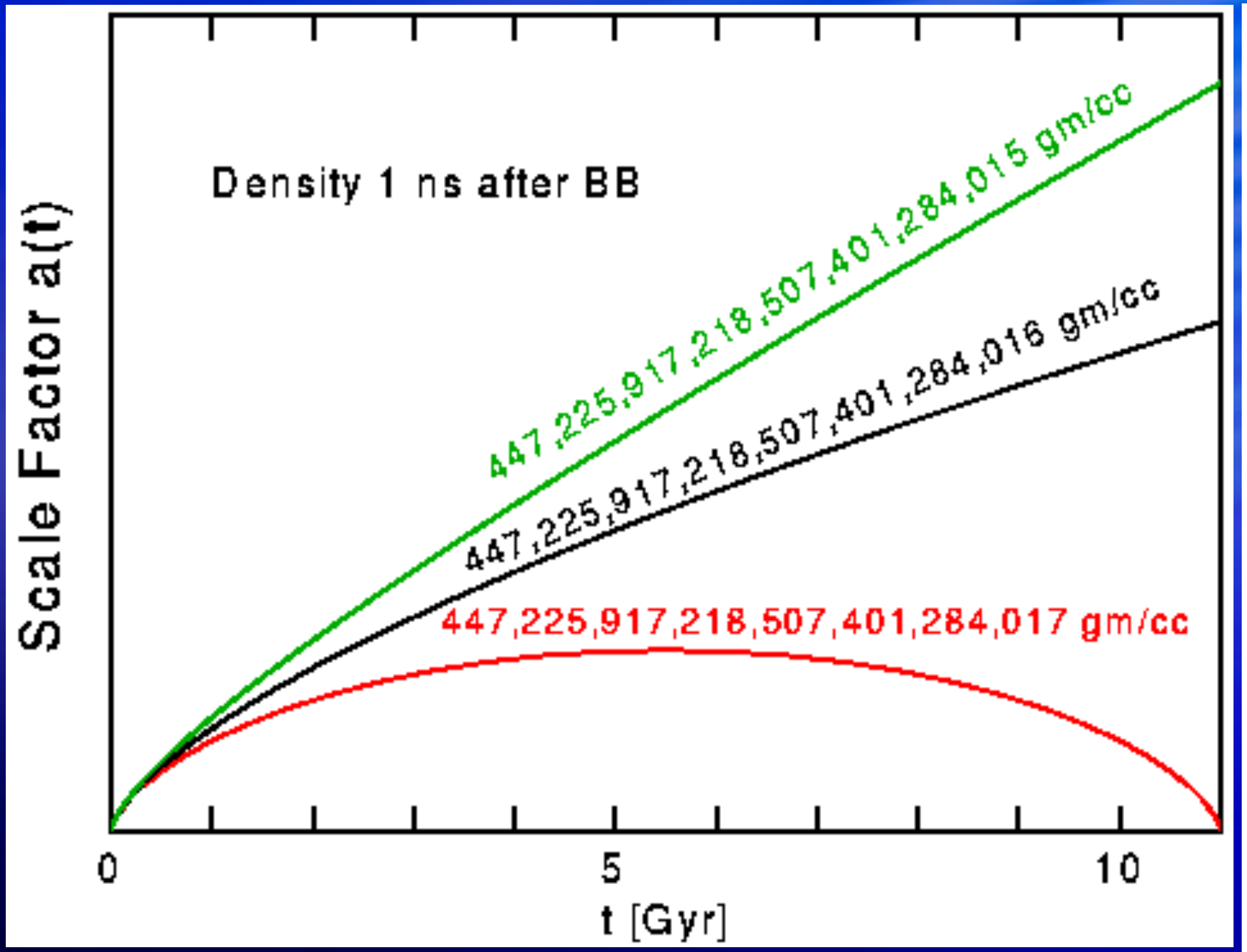


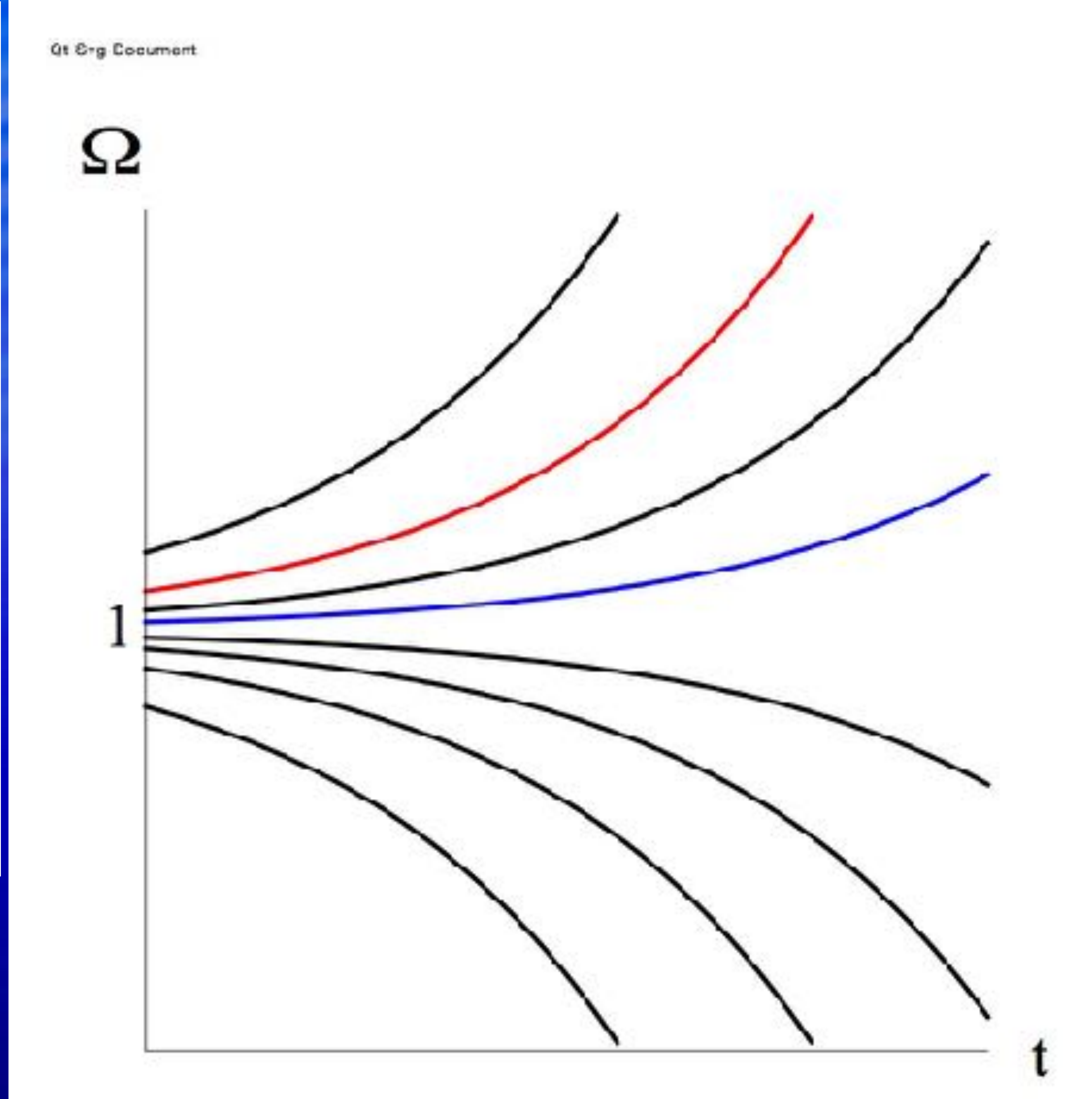


T=2.7 kelvin degrees
Colors ilustrate temperatura
DeltaT ~10^-5

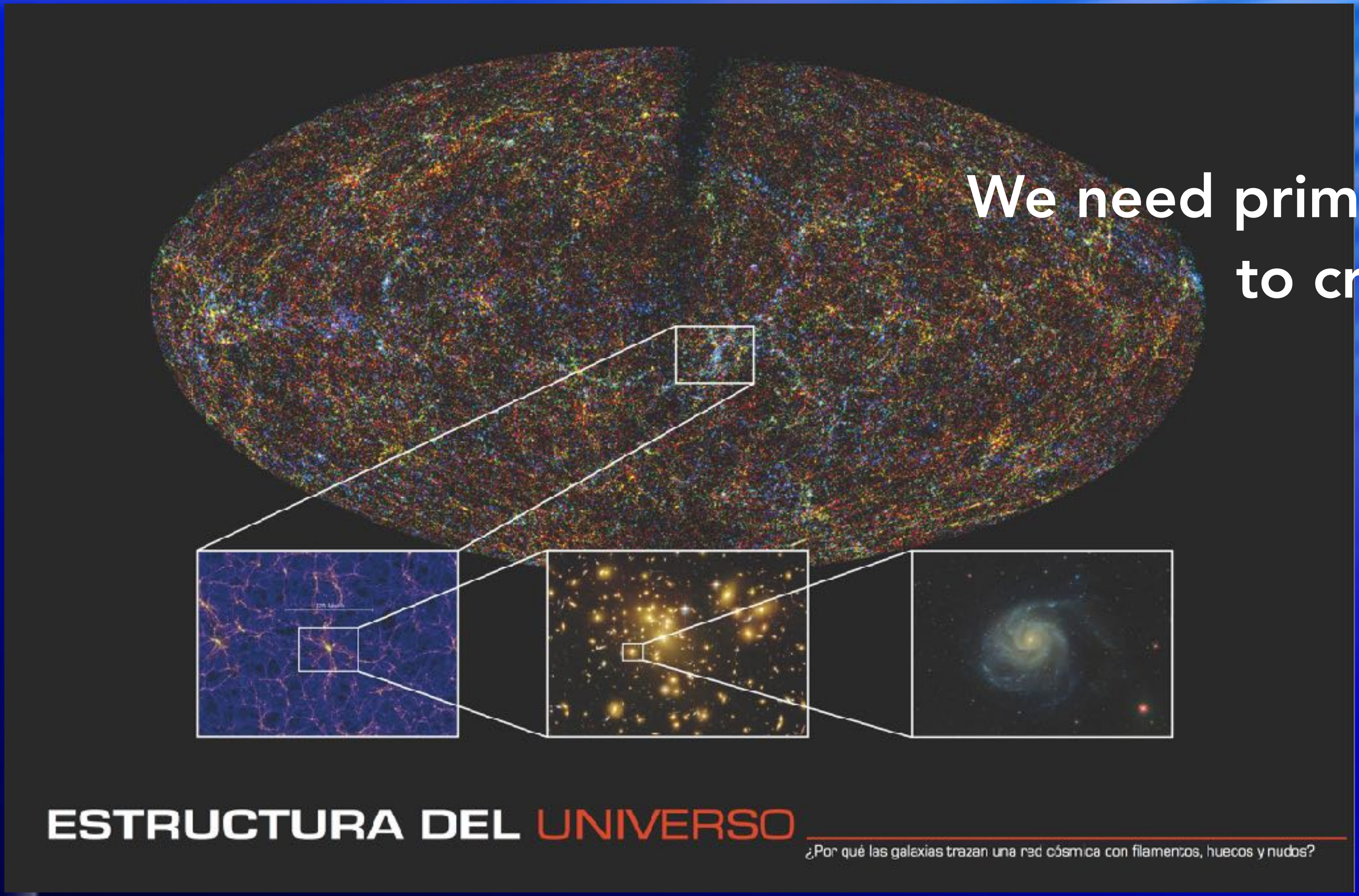
Microwave temperature map WMAP

Why estimations of Universe density with galaxies are close to 1? A tiny change in the Universe initial conditions may endup in a present density very different to the observed one

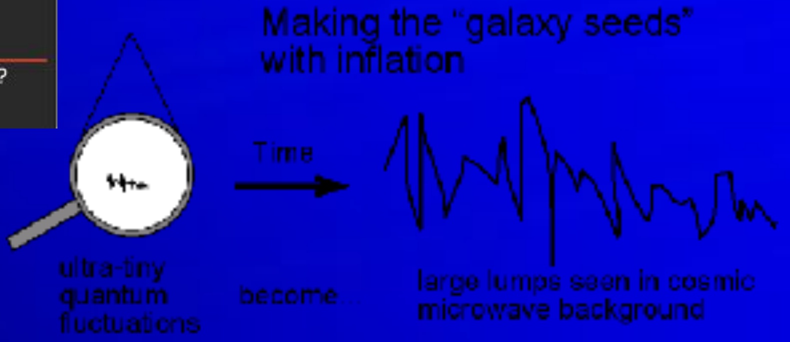




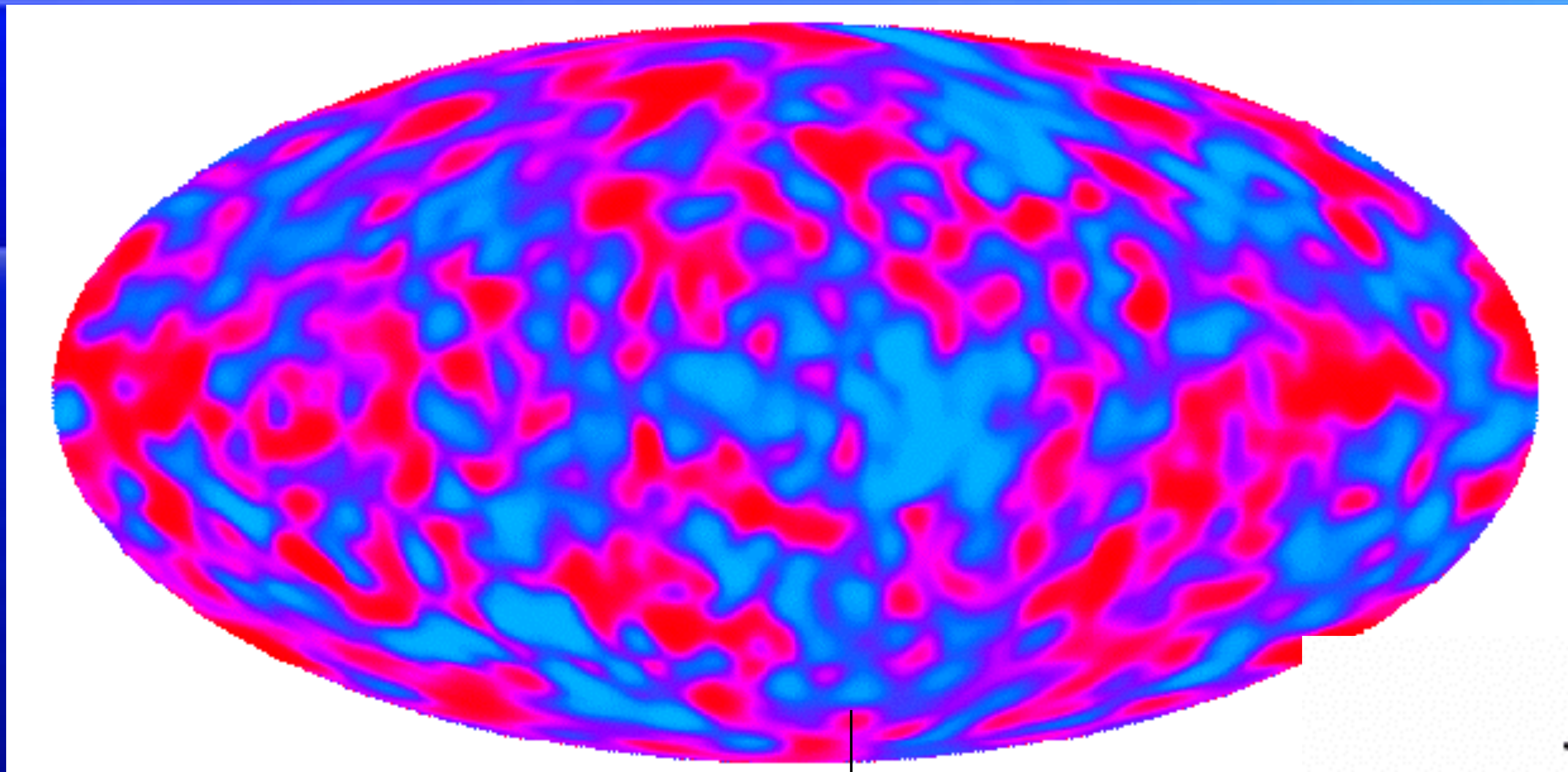
If the Universe were absolutely homogeneous we would not have galaxies



We need primordial inhomogeneities to create galaxies



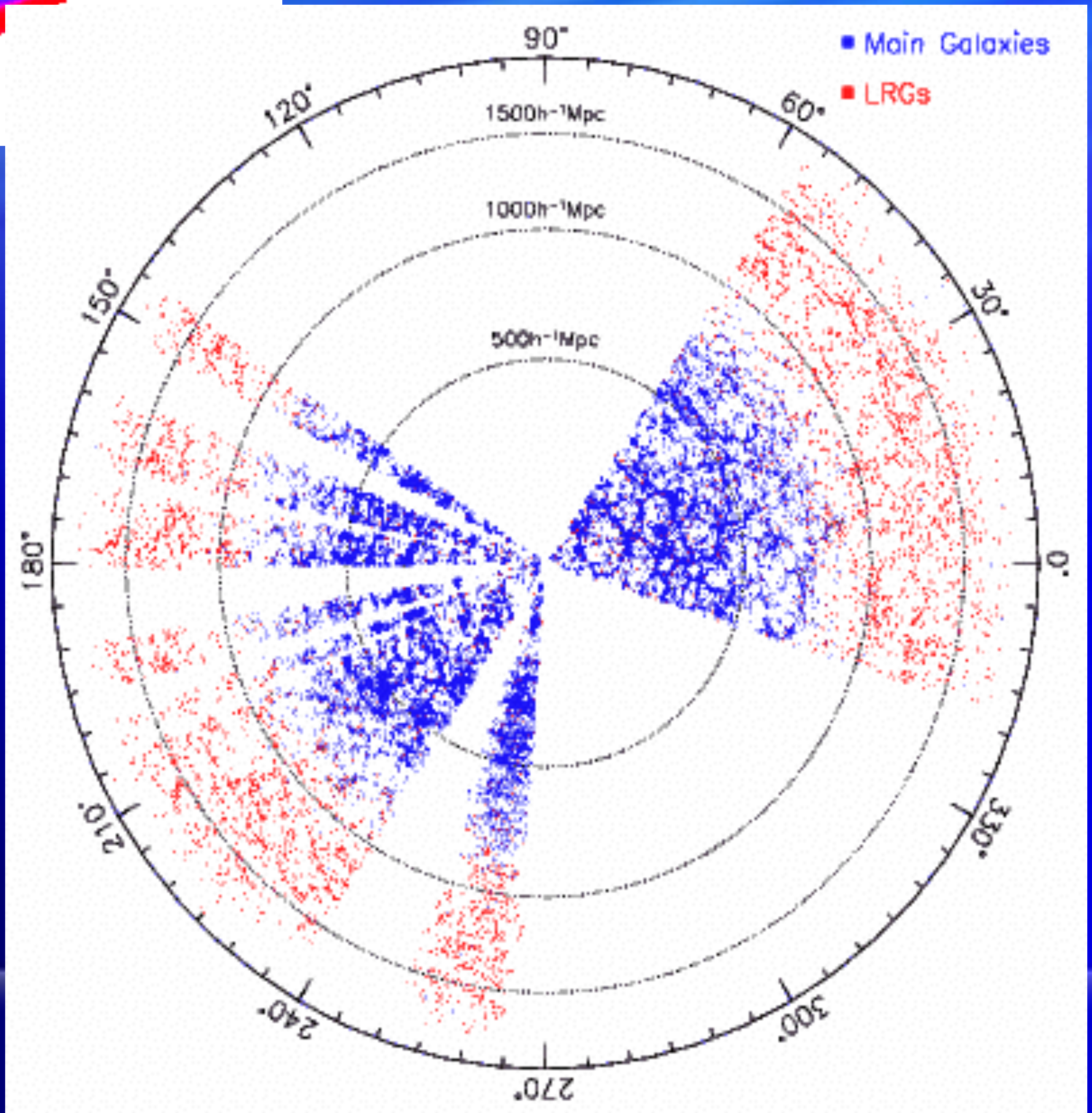
Primordial fluctuations detected (Origin?)



Nobel Prize 2006
Detected inhomogeneities

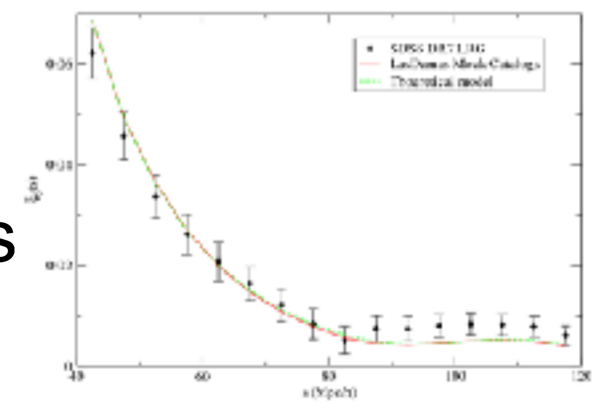
COBE experiment

All physics
Non-linear
Simulations



Current Observed Universe..
SDSS survey

The 2-point correlation function: a quantitative measure of galaxy clustering



- The *two-point correlation function* $\xi(r)$: One way to des tendency of galaxies to cluster together

- If we make a random choice of two small volumes V_1 and V_2, and the average spatial density of galaxies is n per cubic megaparsec, then the chance of finding a galaxy in V_1 is just nV_1.

- If galaxies tend to clump together, then the probability that we then also have a galaxy in V_2 will be greater when the separation r_{12} between the two regions is small.

- We write the joint probability of finding a galaxy in both volumes as

$$\Delta P = n^2[1+\xi(r_{12})]\Delta \mathcal{V}_1\, \Delta \mathcal{V}_2$$

if $\xi(r) > 0$ at small r, then galaxies are clustered, whereas if $\xi(r) < 0$, they tend to avoid each other.

Sparke & Gallagher 2007

Power spectrum (RMS deviation from the mean density coming out from structures with size L= 2Pi/k) it isolates the average contribution of different scales

- The Fourier transform of ξ (r) is the *power spectrum P*(k)

$$P(\mathbf{k}) \equiv \int \xi(\mathbf{r}) \exp(i\mathbf{k}\cdot\mathbf{r}) \mathrm{d}^3\mathbf{r} = 4\pi \int_0^\infty \xi(r) \frac{\sin(kr)}{kr} r^2 \, \mathrm{d}r$$

so that small k corresponds to a large spatial scale.

Similar to
split light in frequencies

- Since ξ (r) is dimensionless, P(k) has the dimensions of a volume.

- The function sin(kr)/kr is positive for $|kr| < \pi$, and it oscillates with decreasing amplitude as kr becomes large

- so, very roughly, P(k) will have its maximum when k−1 is close to the radius where ξ (r) drops to zero.

deSitter Universe

- $\rho = \Lambda =$ cte,flat (convenience)
- Friedman Equation: $3H^2 = \Lambda$, H=cte
- edad=2/(3H)

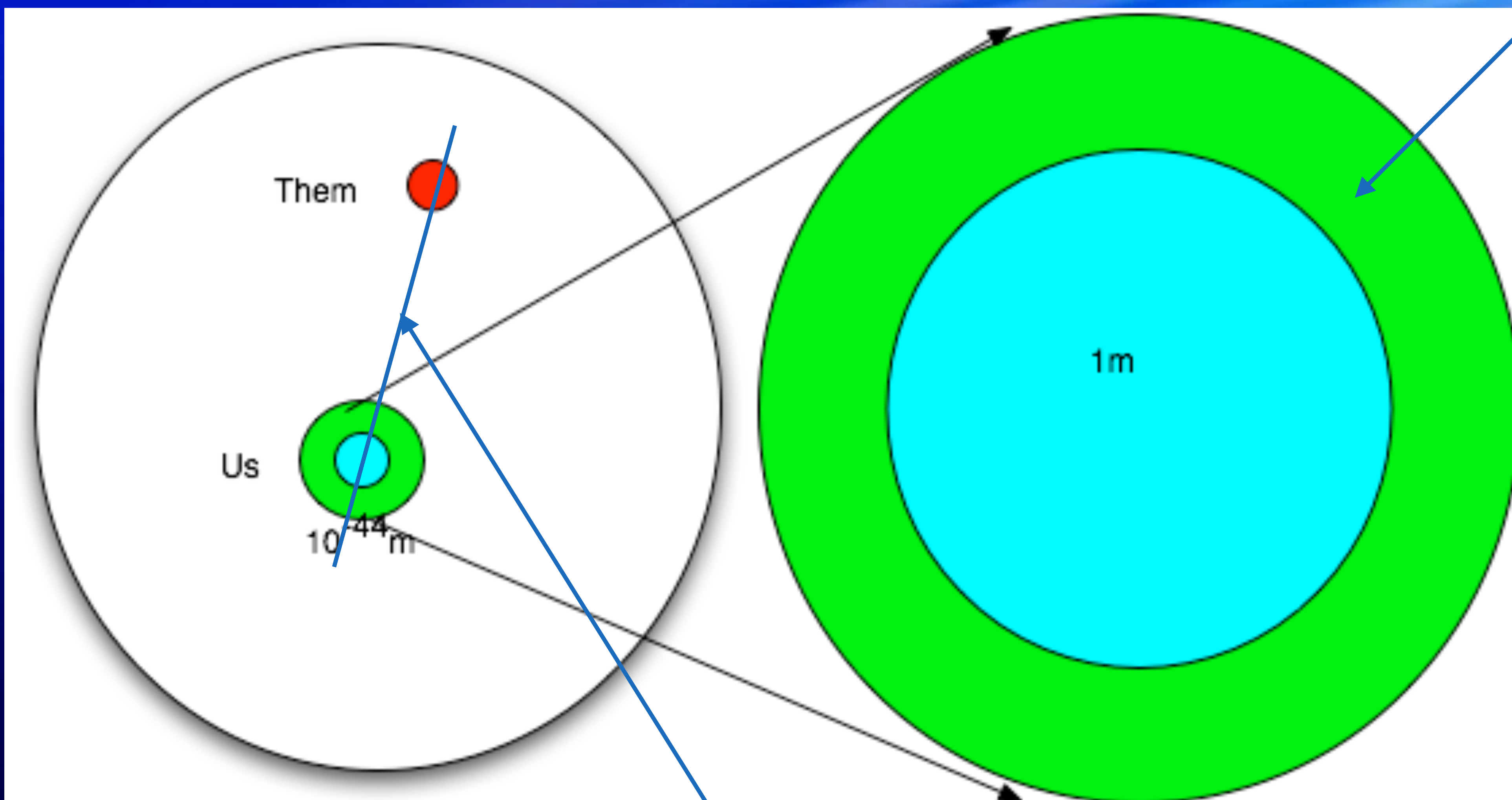
$$R(t) = \exp\left[\left(\frac{\Lambda}{3}\right)^{\frac{1}{2}} t\right]$$

Horizon d_H = c x age = 2/3 x 1/H, constant!!

microscopic quantum fluctuations can grow larger than the universe horizon if Λ is large enough for enough time

Graphic representation of fluctuation growth during a phase where the energy density changes very slow or is constant

larger than horizon

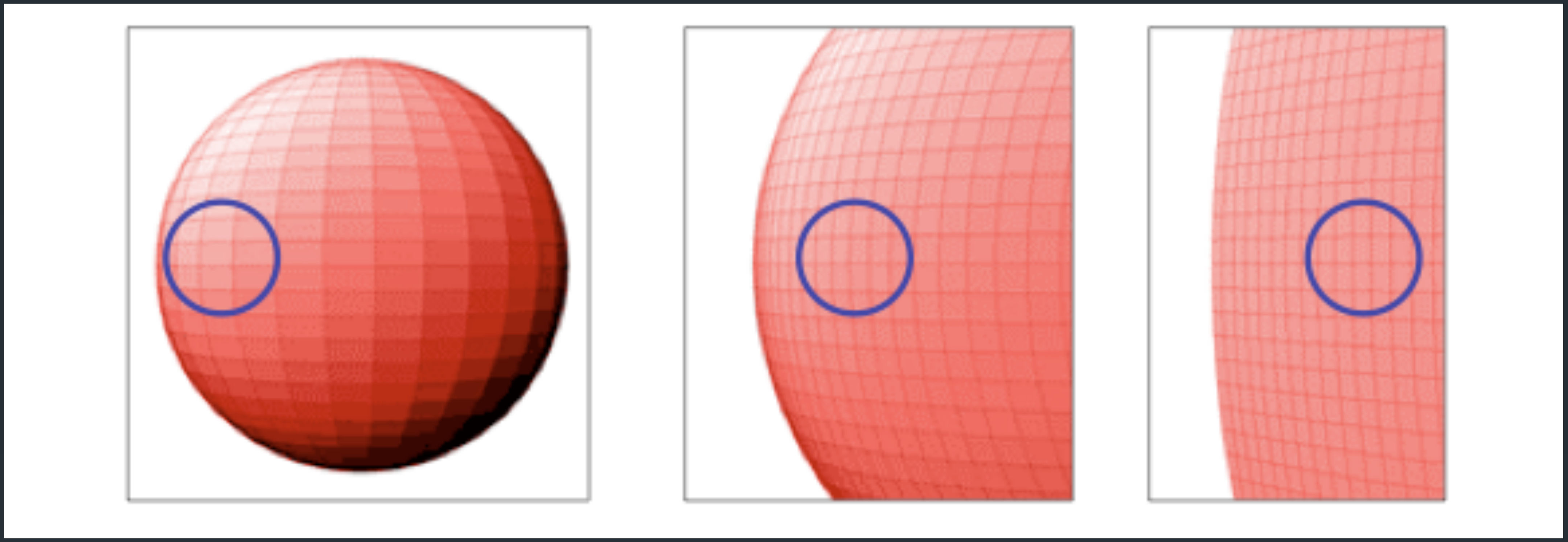


Horizon

Quantum microscopic fluctuations get macroscopic larger than horizon because horizon is constant

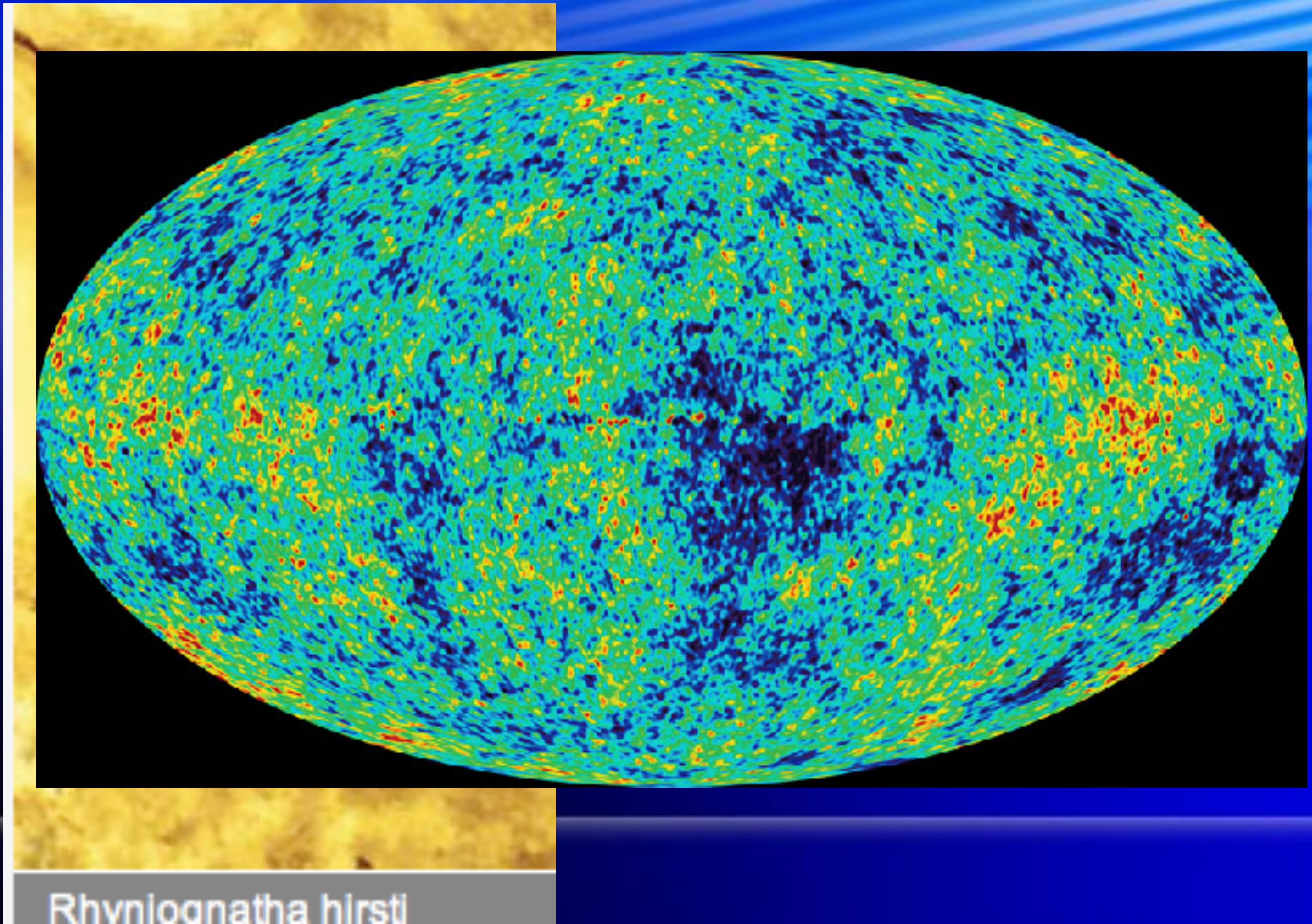
Fluctuations are the seeds for galaxies and LSS

Enough expansion Makes the Universe Flat

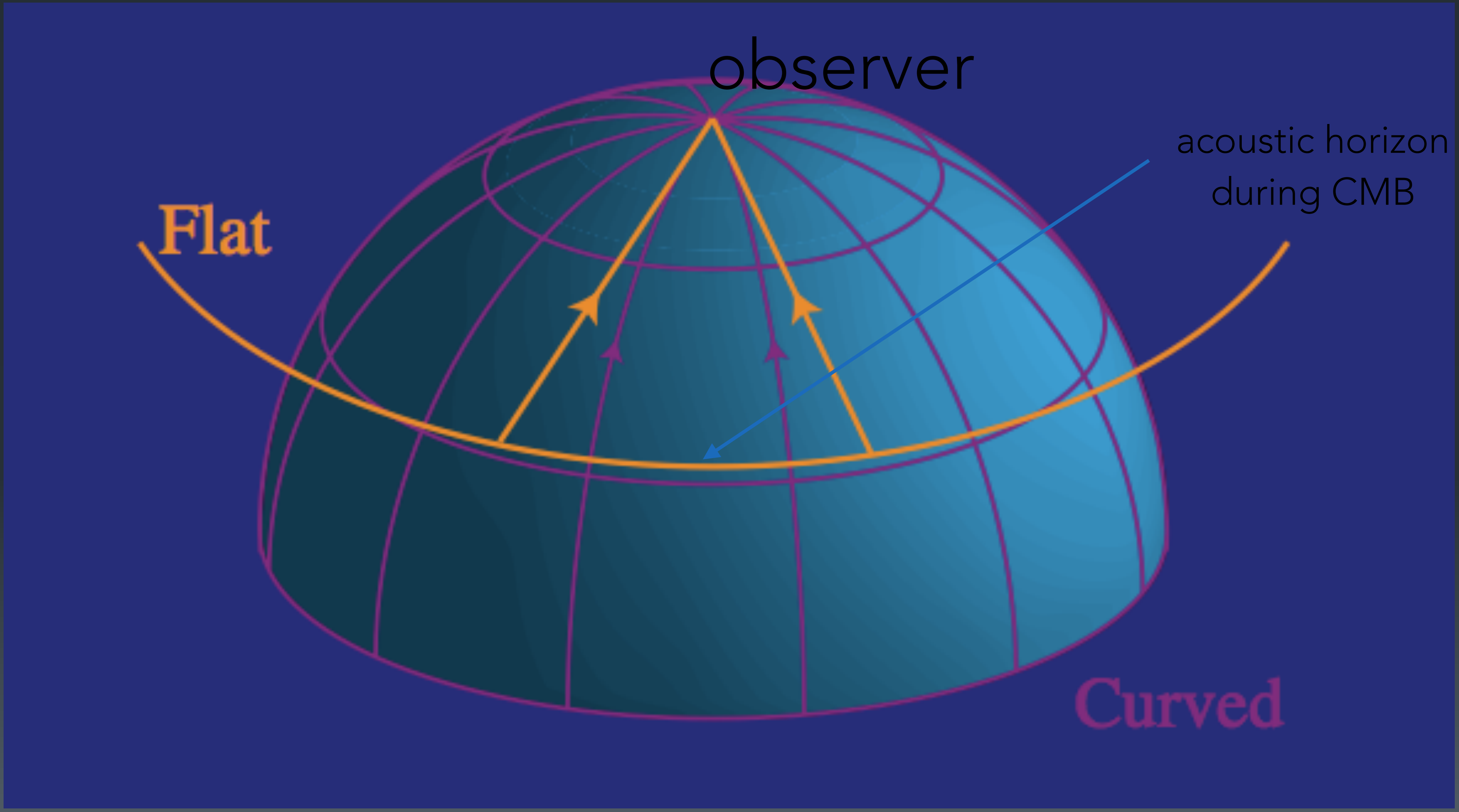


$$\Omega - 1 = \frac{K}{a^2 H^2}$$

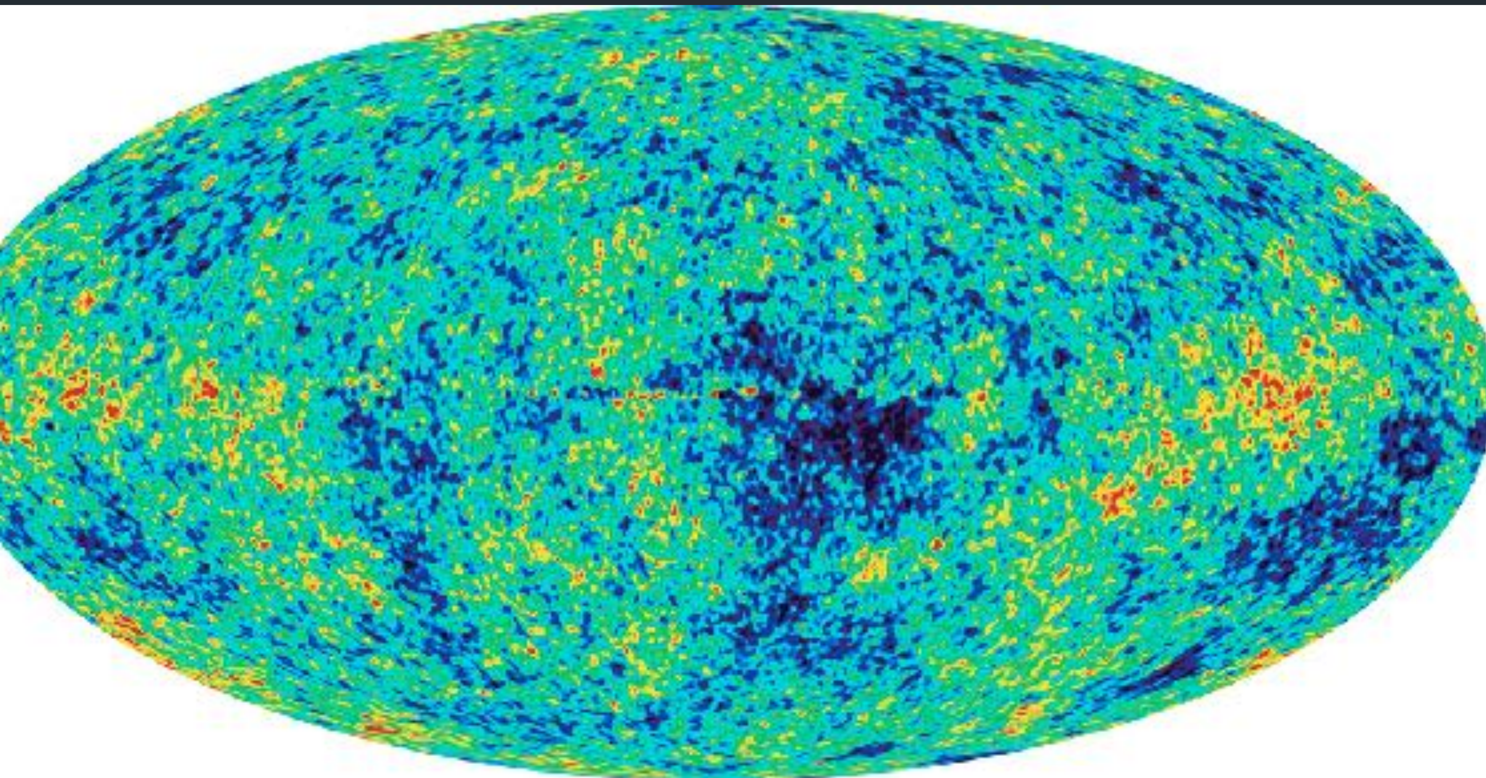
Which is the oldest Fossil that you know?



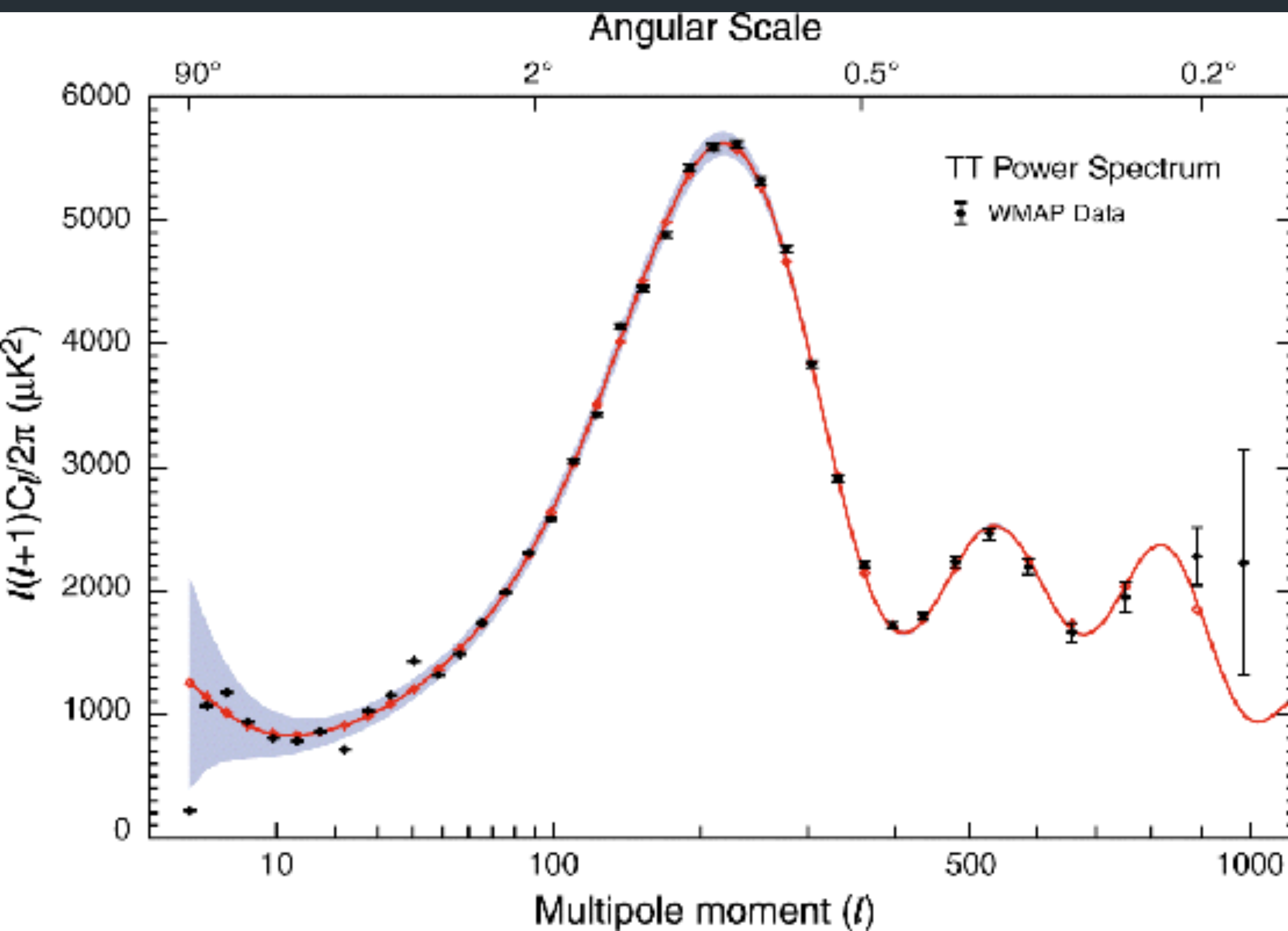
Temperature fluctuations allow to measure curvature

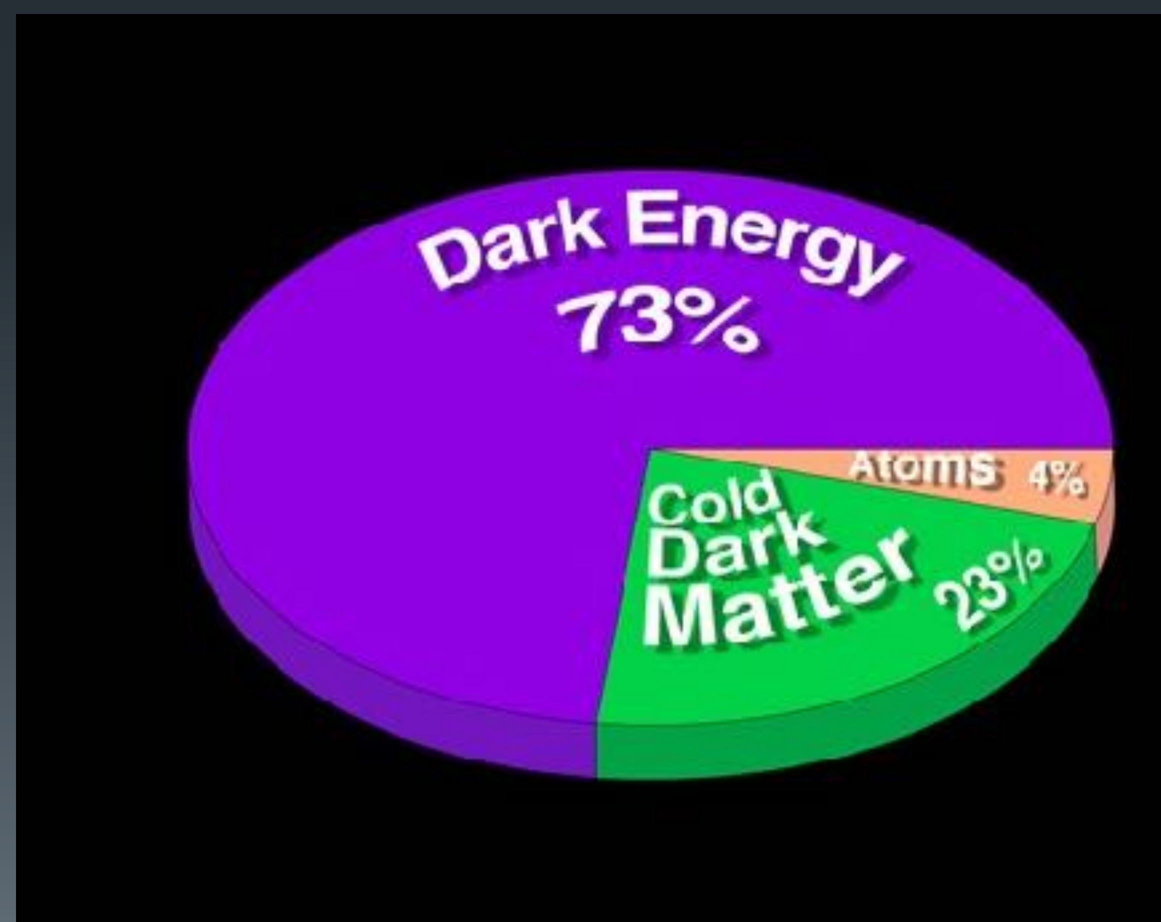


Seeds for the Universe Structure Require Dark Matter to survive



Problem:
particles (protons electrons)
scape out
of fluctuaciones because interaction with
radition damping fluctuations
(Silk Damping): **Dark Matter**
does not interact with radiation, is required to have galaxies





See Rubin's "Reference Frame" in Dec 2006 Physics Today and her article, "A Brief History of Dark Matter," in *The dark universe: matter, energy and gravity*, Proc. STScI Symposium 2001, ed. Mario Livio.

1970 ApJ 159, 379

ROTATION OF THE ANDROMEDA NEBULA FROM A SPECTROSCOPIC SURVEY OF EMISSION REGIONS*

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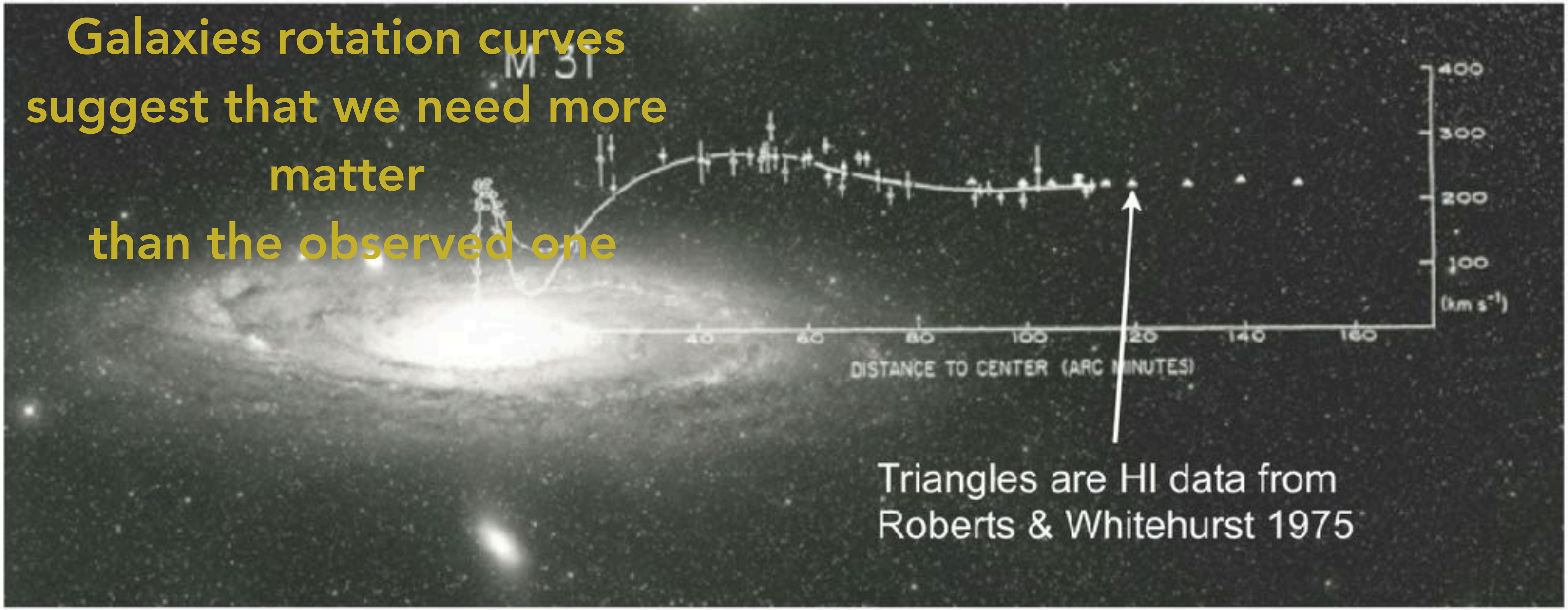
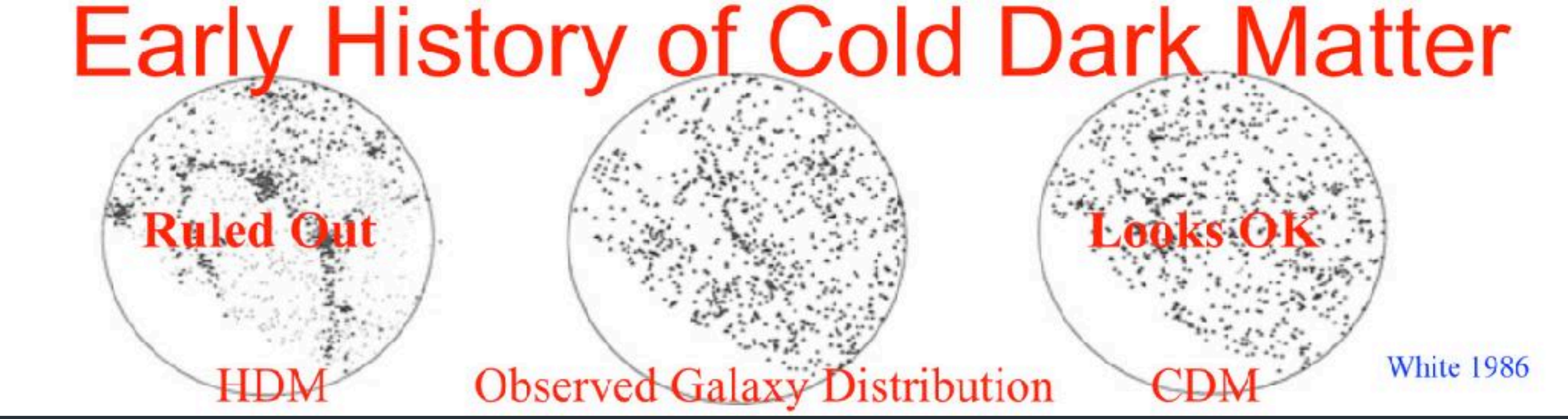
Department of Terrestrial Magnetism, Carnegie Institution of Washington and Lowell Observatory, and Kitt Peak National Observatory‡

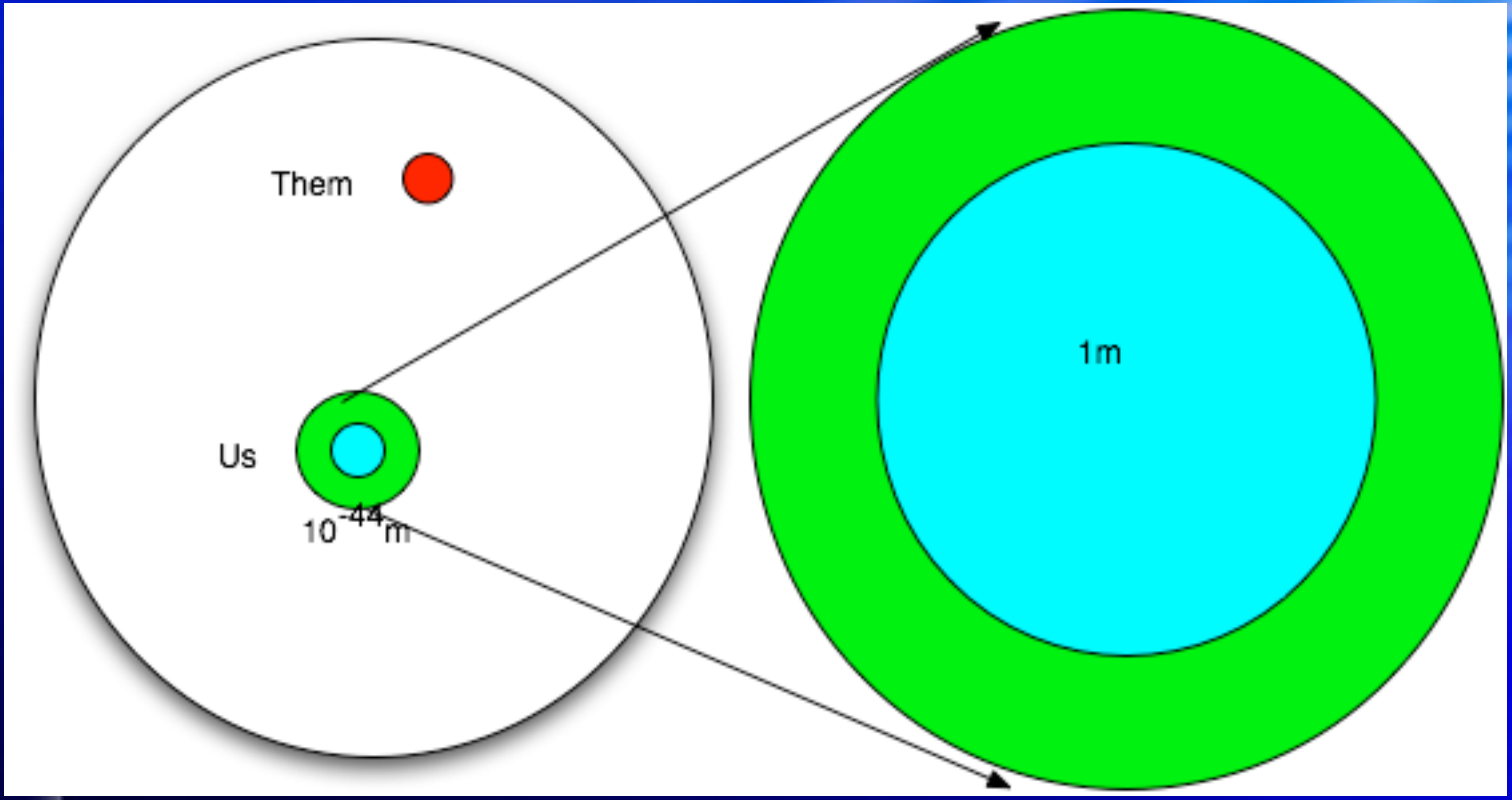


Neutrinos are hot dark matter are they good enough?



Dark Matter needs to be Cold Dark Matter

The large expansion during inflation lowers the monopole density to almos zero

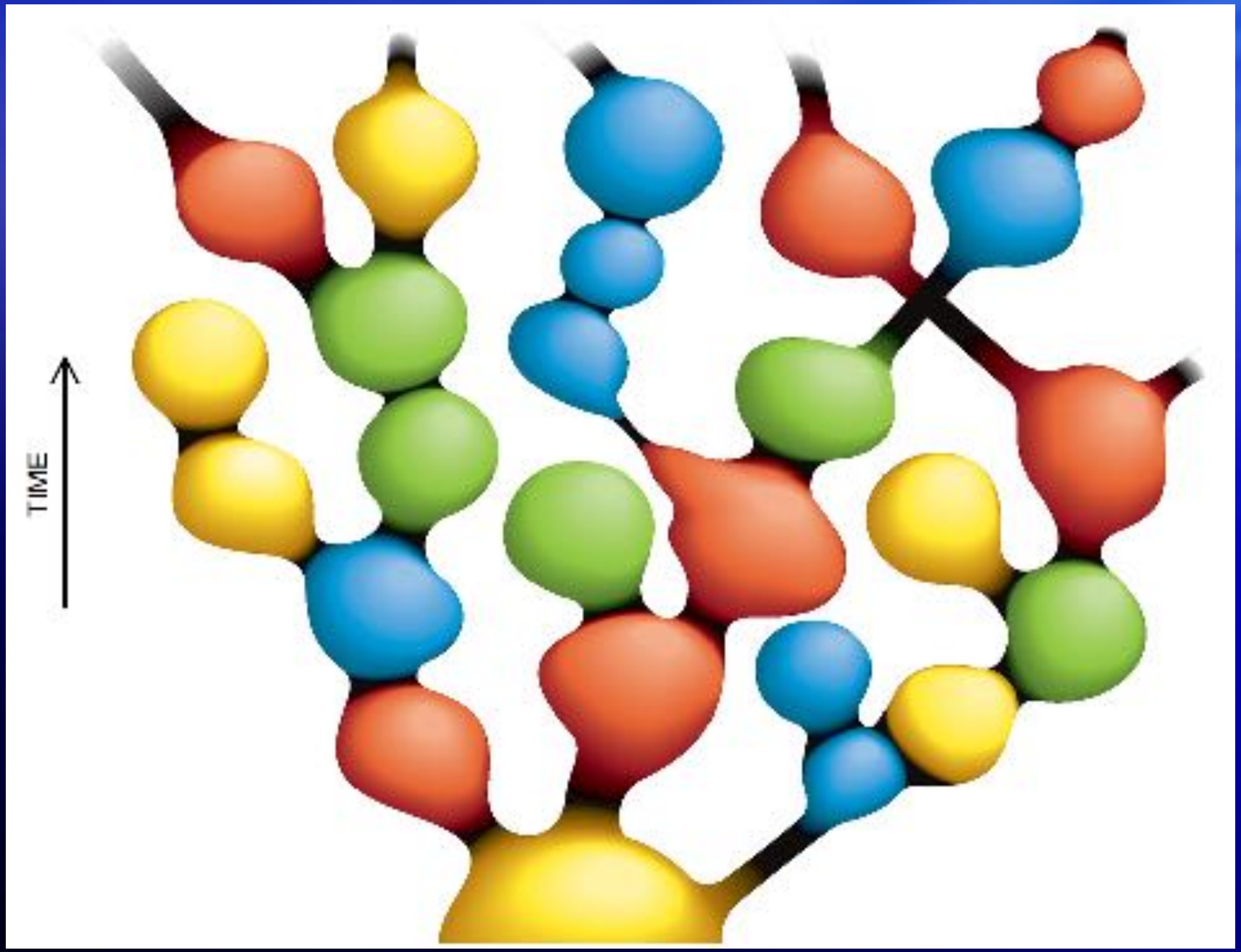


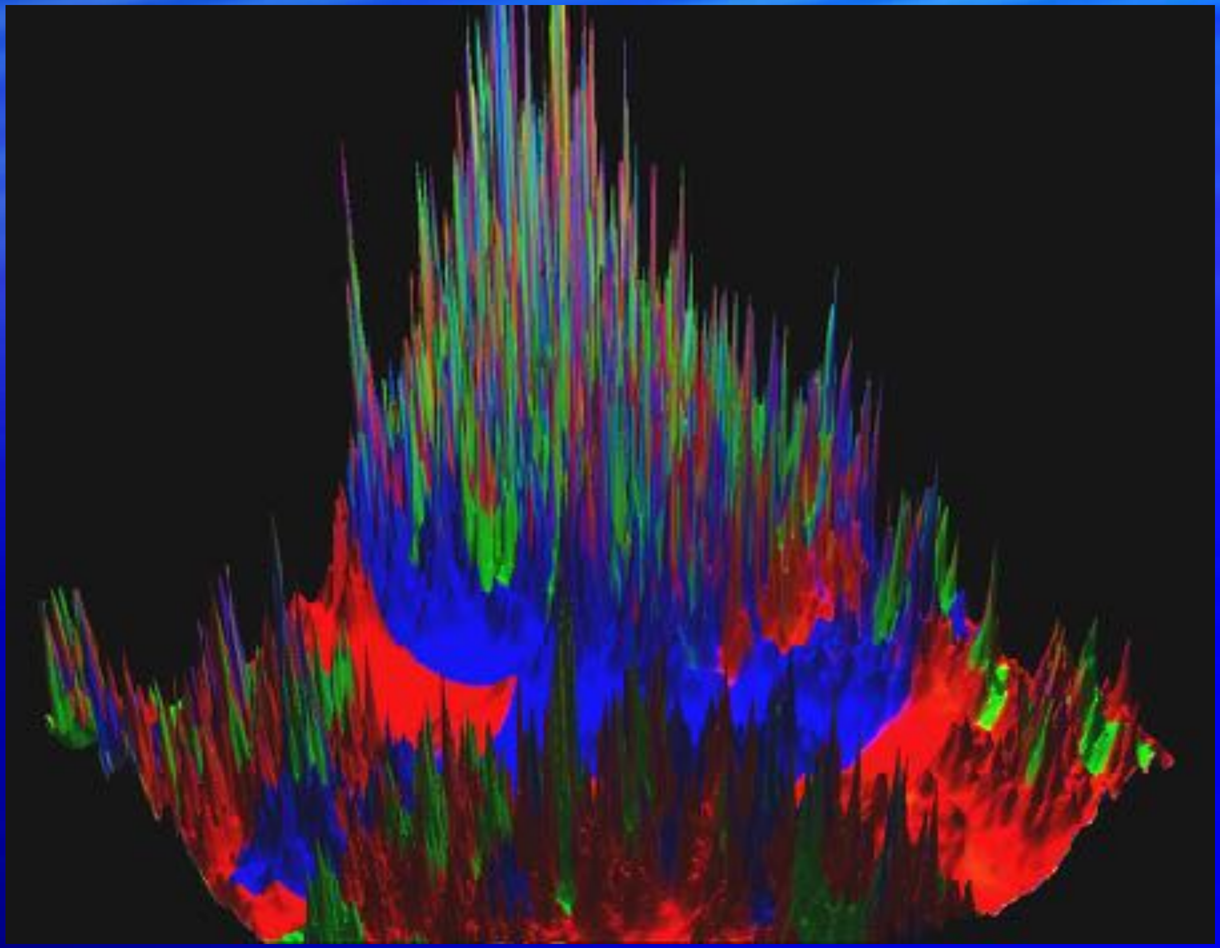
Fluctuaciones microscópicas de origen cuántico se hacen macroscópicas incluso mayores al horizonte que permanece constante y constituyen las semillas de la estructura a gran escala del universo

Matter vs Antimatter

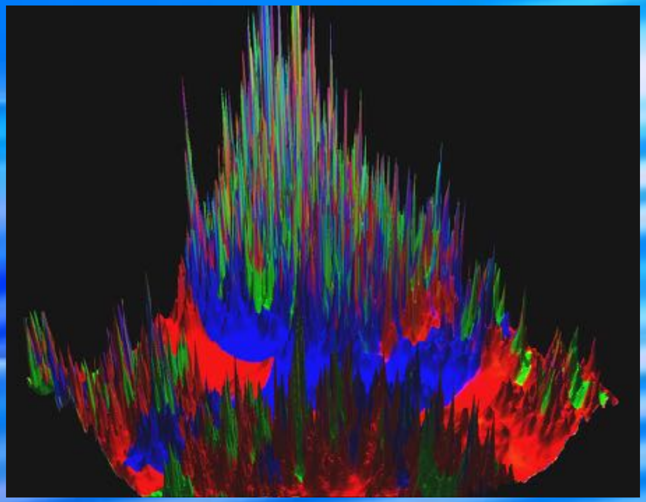
- At the end of inflation some process favored matter(symmetry breaking)
- Matter Antimatter domains
- The region where cosmic inflation happened included only matter

Multiverse?





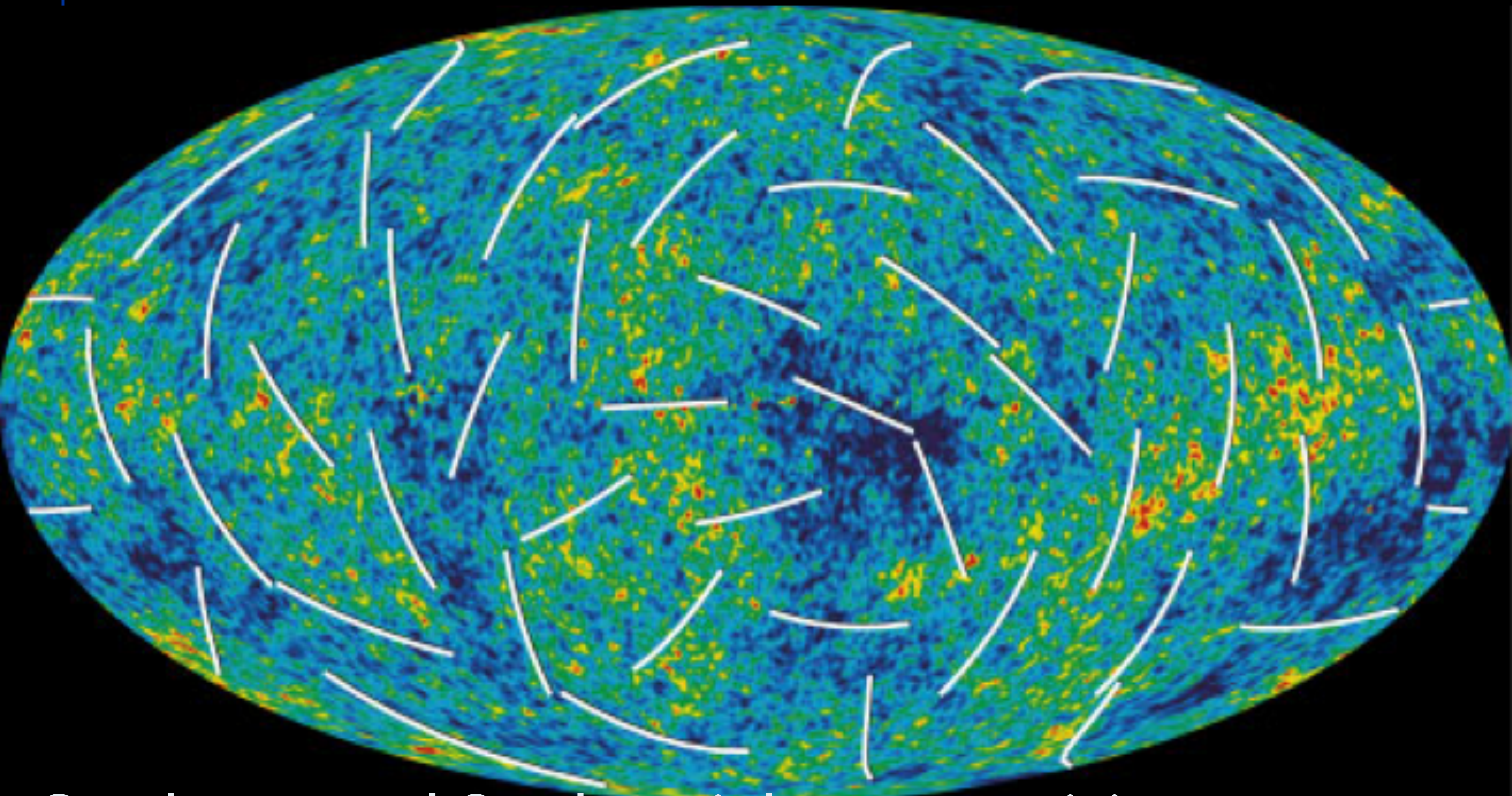
Cosmic Inflation



A stage/region of the Universe with almost constant energy density **(equivalent to negative pressure or slow rolling scalar field)**

Enough energy to expand quantum fluctuations to macroscopic scale (e-folds)

Dominated by vacuum energy or a new scalar field named inflation (or more than 1 field?)



Can be tested Studyng inhomogeneities
in the young Universe CMB or galaxy distribution
Polarization BICEP … etc

Cosmic Inflation II

- Solves Horizon problem
- large expansion decreases curvature almost to zero
- expands quantum fluctuations to macroscopic inhomogeneity
- decrease monopoles density to very small values
- multiversos

Standard Cold Dark Matter Model

- Big Bang + Cosmic Inflation+Cold Dark Matter

- Homogeinity Isotropy
- General Relativity
- Baryons+Cold Dark Matter **(includes mostly matter, radiations and neutrinos little contirbution)**
- Early Inflationary Stage (~constant density epoch)

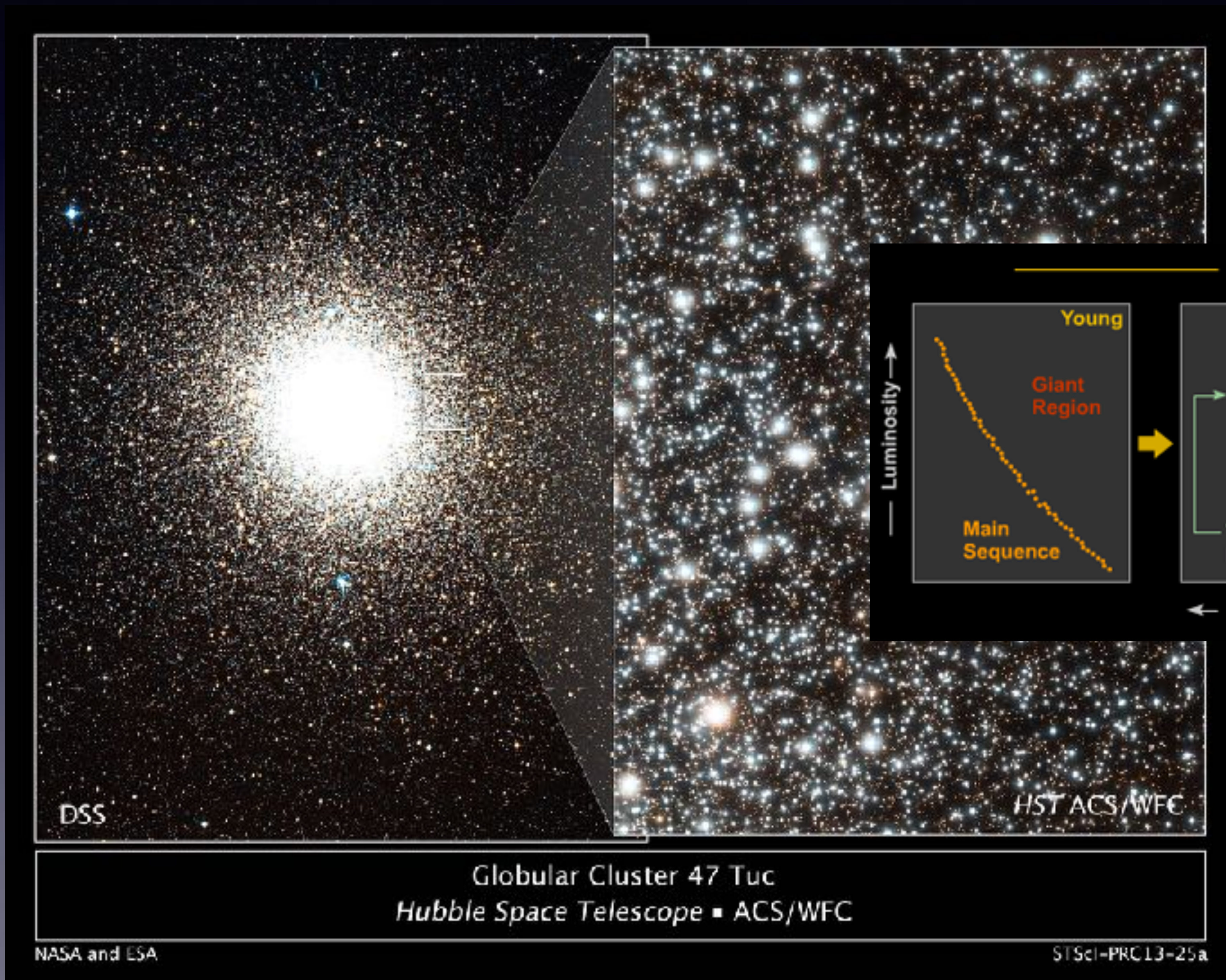
- Explains: Hubble Law, Curvature, Isotropy, Large Scale Structure origin, Light elements abundance

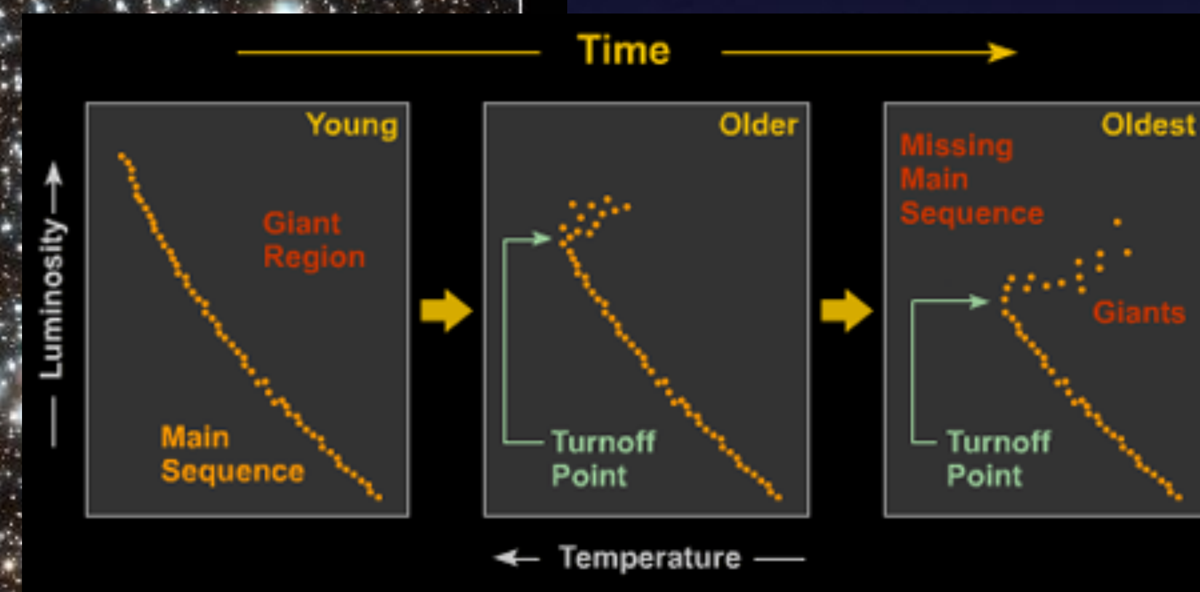
Discussion I

- Critics to Big Bang
- Critics to SCDM model
- Are problems real or we need a better theory, data?
- What should we do? Past crisis may teach you how to handle new ones

Cosmic Age: Globular Clusters stars between the oldest ones. Older than the Universe?

Uncertainties
distance





15-20gyrs
in 90´s
now (14gyrs)

Galaxy Clustering: Initial Density Perturbations with preferred scales?

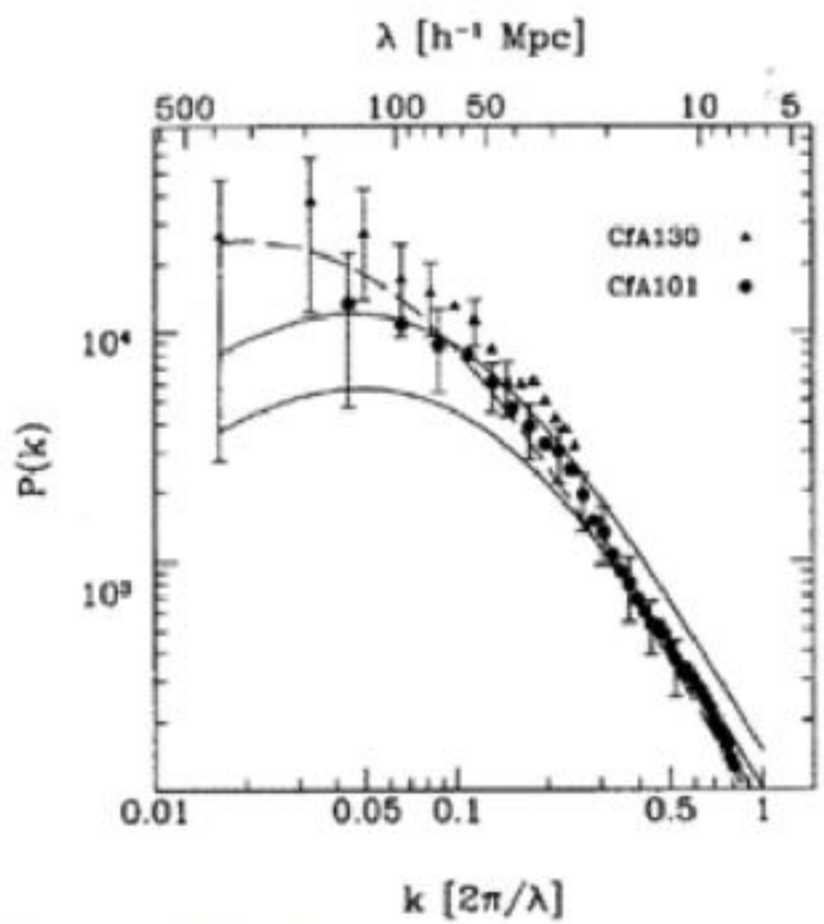
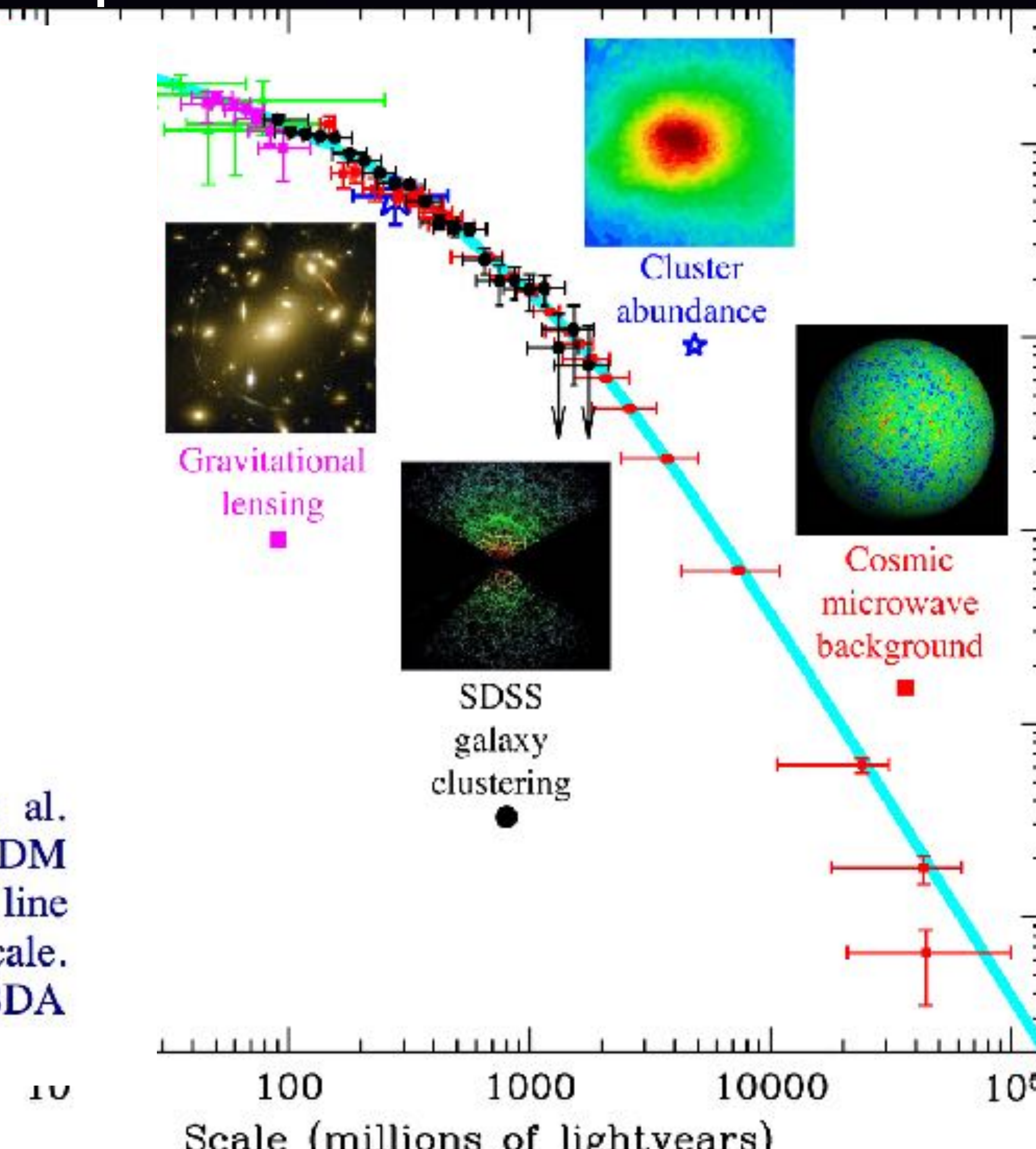


Figure 5-1: Power spectrum from Park et al. (1994). The bottom solid line is standard CDM normalized to the small scale. The upper solid line is standard CDM normalized to the larger scale. The dashed line is an open universe or LAMBDA dominated model.



Dec. 1997: Contradictions on our understanding of the Universe!

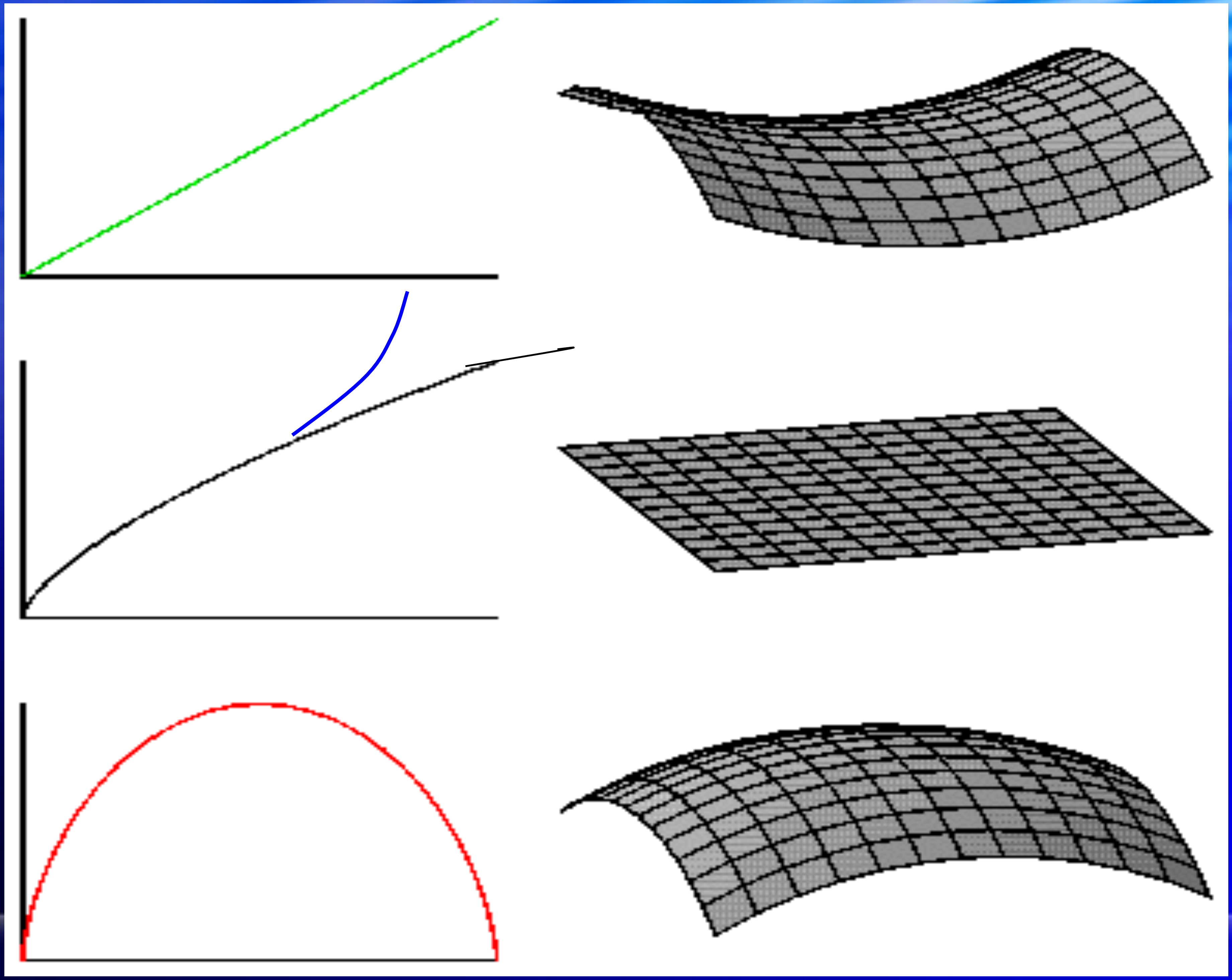
Cosmic Age < Globular Clusters Age
Too much small scale structure
Measured Average Density not 1 but close, why?

Theoretical Bias suggested mostly by theoretical simplicity:
Flat Universe $\Omega = 1$, matter dominated (baryonic + cold dark), scale invariant initial perturbations.

The model needed to be modified or extended!
at least modify one of the following hypothesis--
“flat,” “cold DM,” “scale invariant,” perhaps “made only of matter”

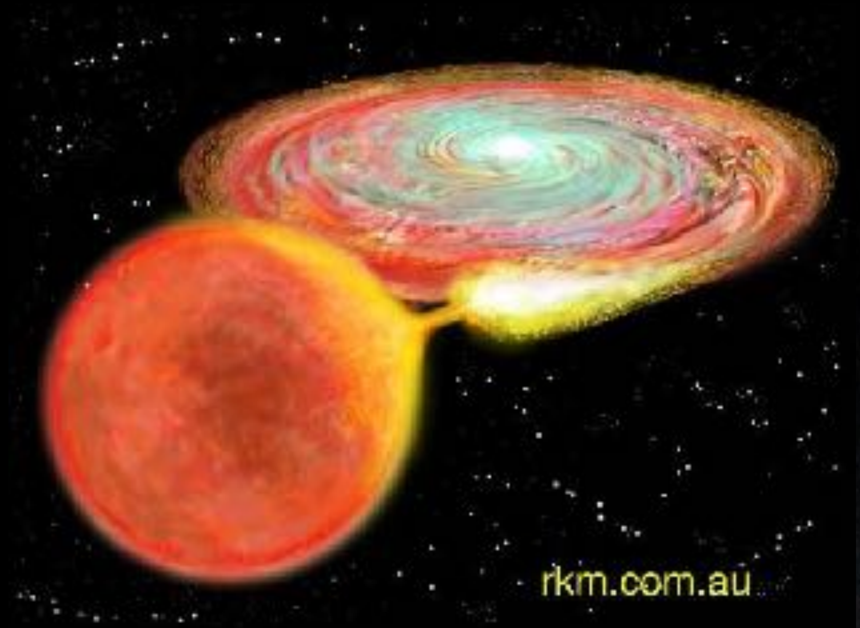
Saving Standard Cold Dark Matter Scenario in the 90´s

- Low Hubble Constant + SCDM
- Mixed Dark Matter (10-30% Hot Dark Matter fitting large scales, delay equality when fluctuations start to grow)
- Extra Relativistc Degrees of Freedom (Tau Neutrino—> radiation, similar to above)
- Tilted CDM: Non scale invariant initial fluctuations
- Cosmological Constant
- Open Cosmology

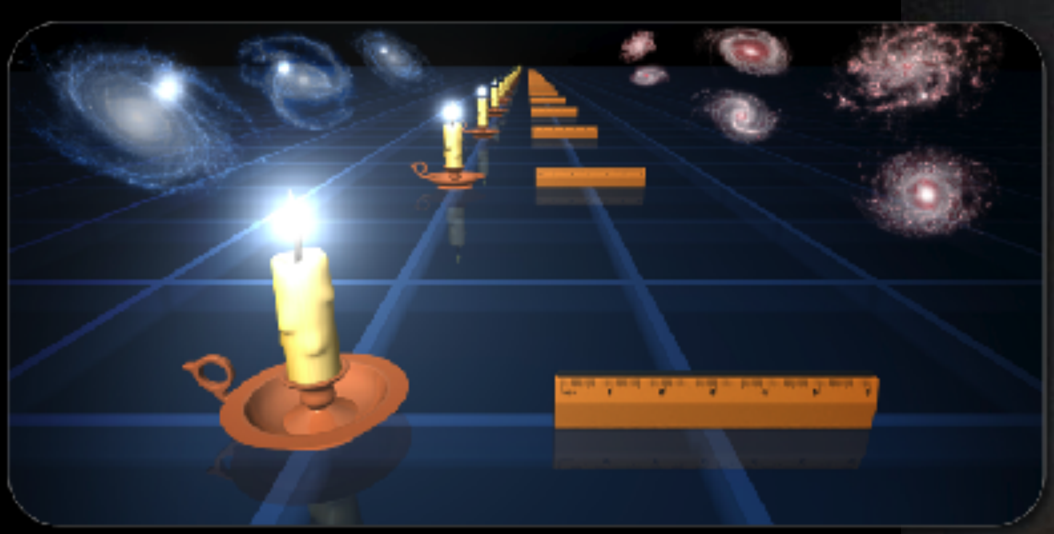


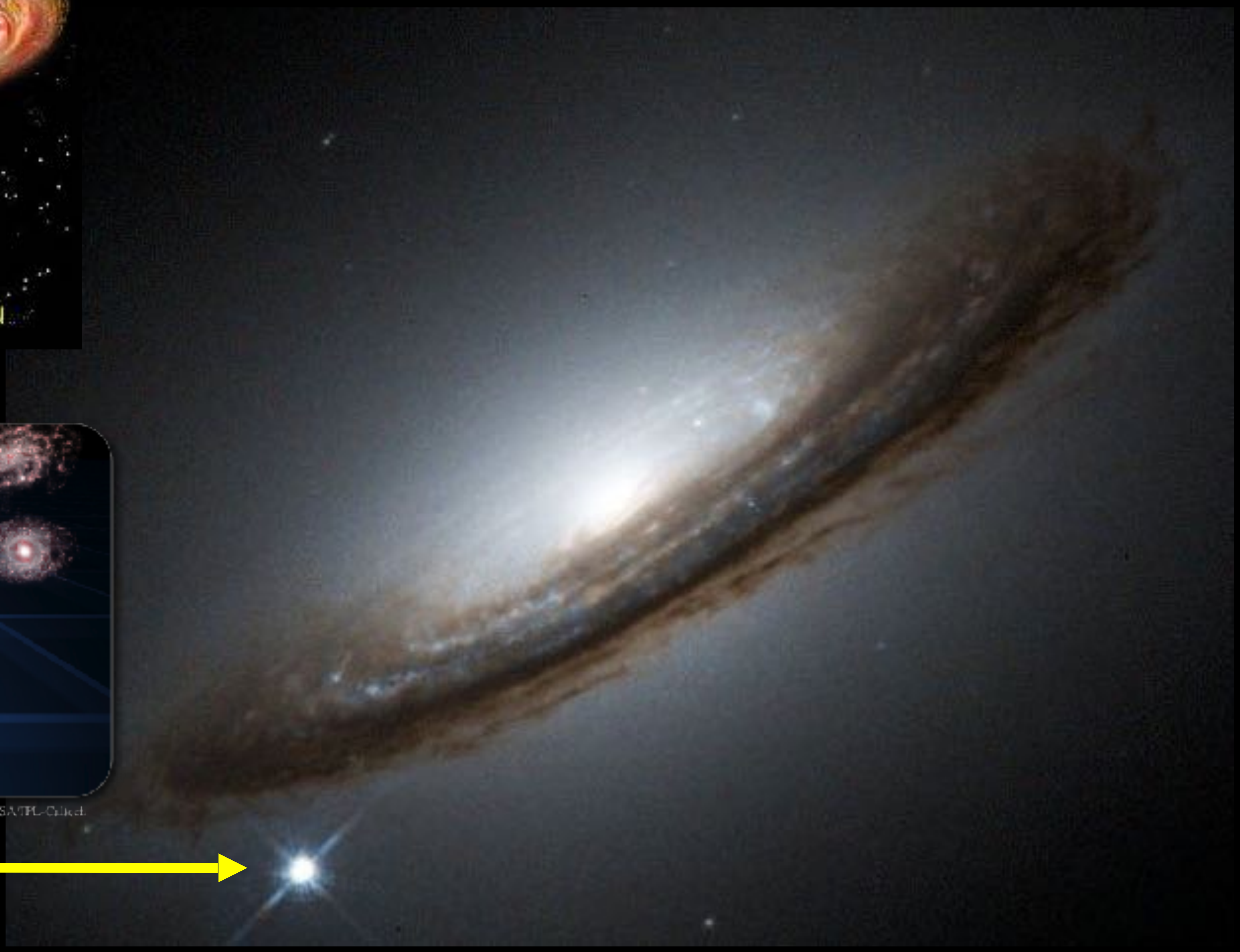
Studying Expansion history may give a clue to geometry and select between models

Two independent groups tried to measure the cosmic ‘desacceleration’, using supernovae type Ia as standar candle



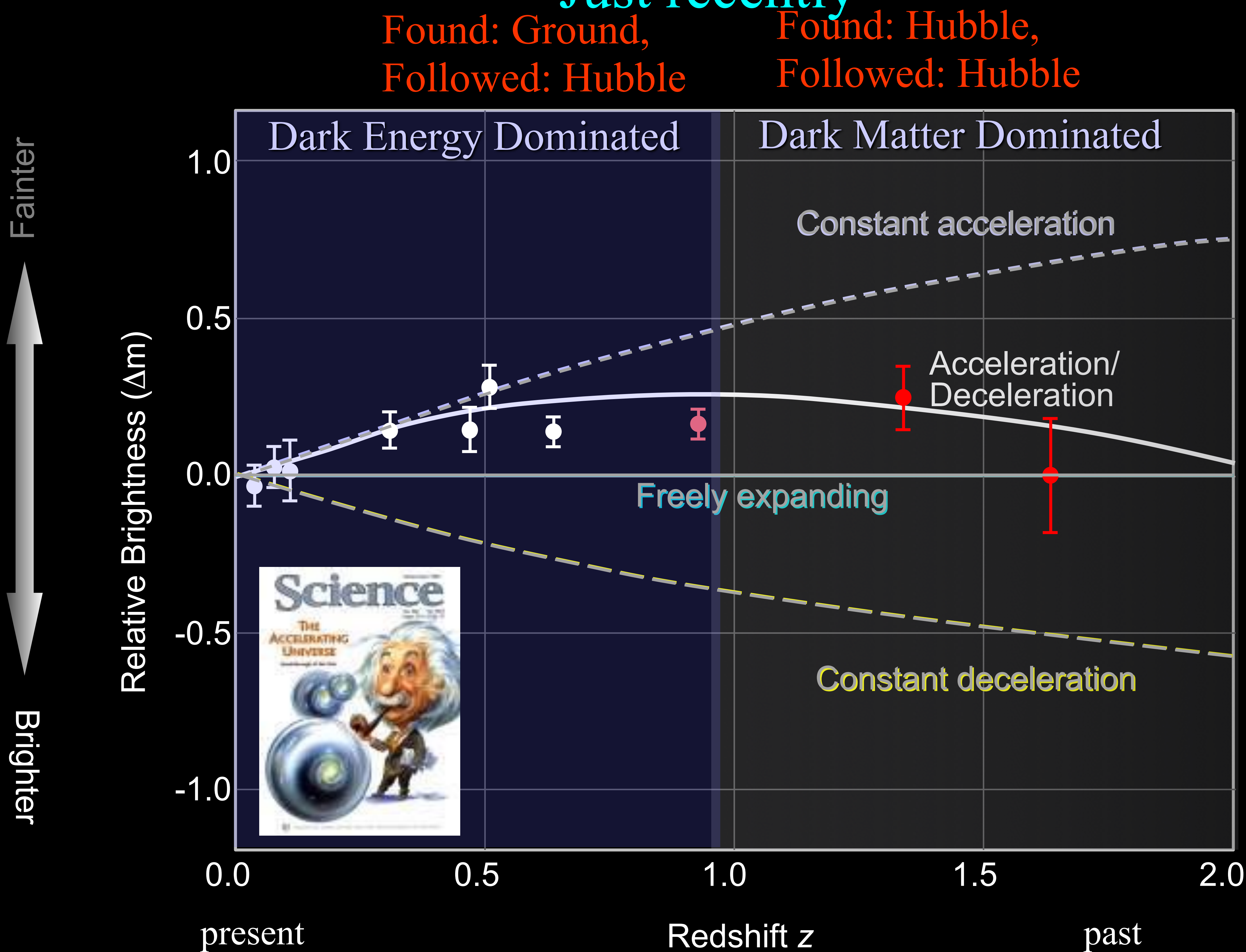
Press Release (May 2011): ‘Dark Energy is Real’





SN 1994d

High Redshift SN and Expansion History: Acceleration Just recently



The Nobel Prize in Physics 2011

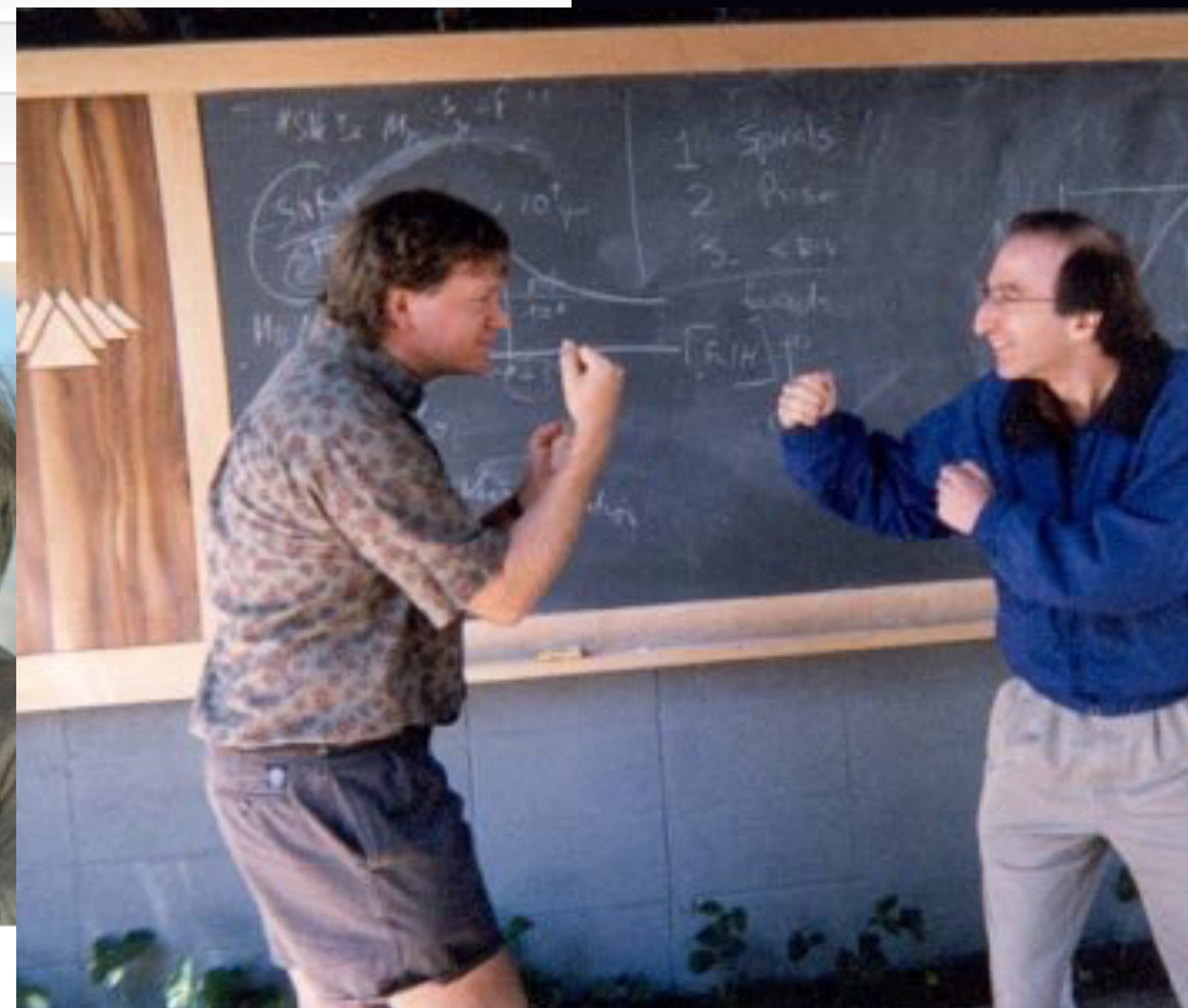
Saul Perlmutter, Brian P. Schmidt, Adam G. Riess

Photo: Roy Kaltschmidt. Courtesy: Lawrence Berkeley National Laboratory

Saul Perlmutter

Photo: Belinda Pratten, Australian National University

Brian P. Schmidt



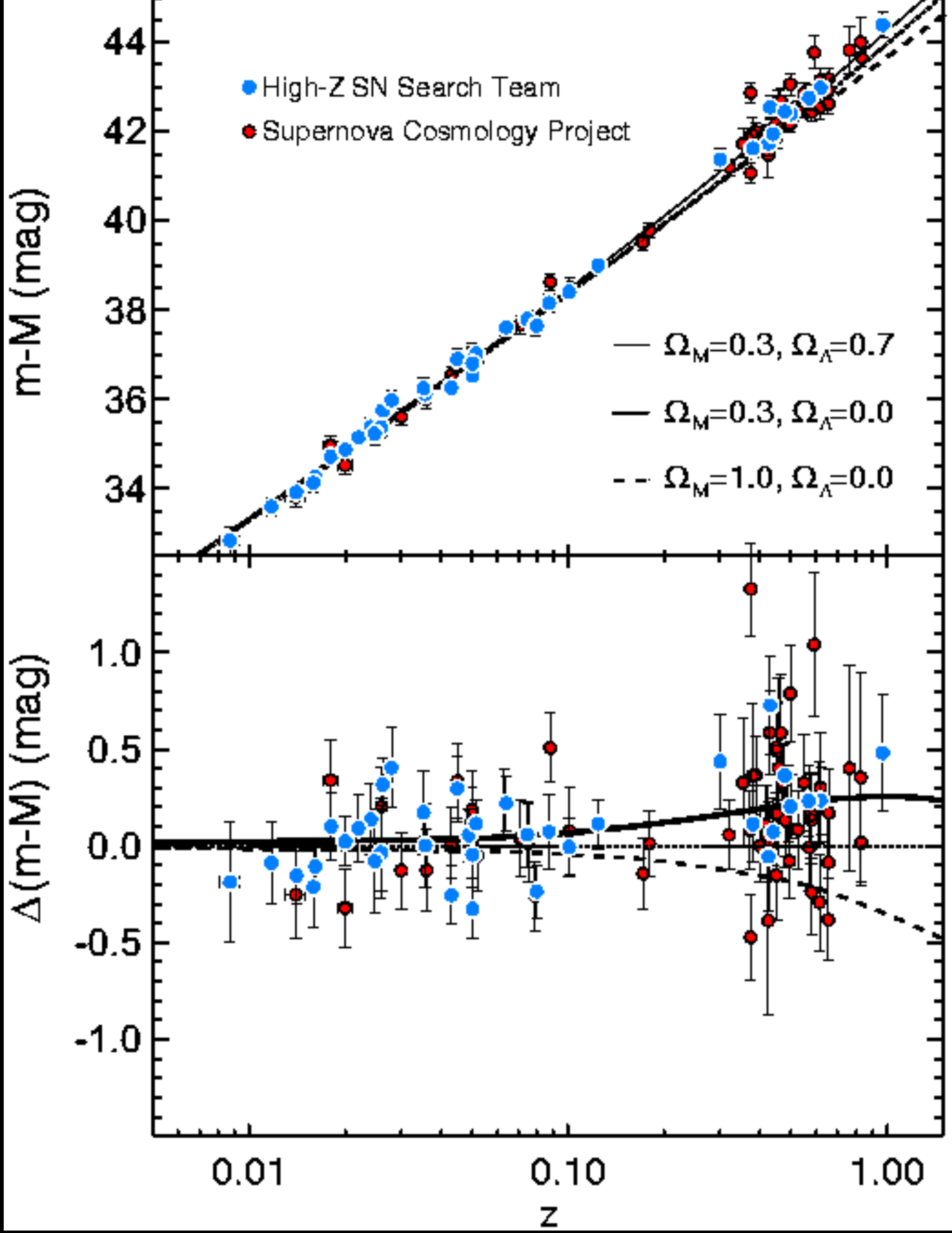
Adam G. Riess

The Nobel Prize in Physics 2011 was divided, one half awarded to Saul Perlmutter, the other half jointly to Brian P. Schmidt and Adam G. Riess *"for the discovery of the accelerating expansion of the Universe through observations of distant supernovae"*.

Result: Sn Ia appear less luminous than expected in SCDM.

Universe is not, slowing down accelerates!

Free Expansion/Open?



[Riess et al.; Perlmutter et al.; Knop et al.

Are we in an open Universe after all?

Density parameter Ω
How far away is from 1

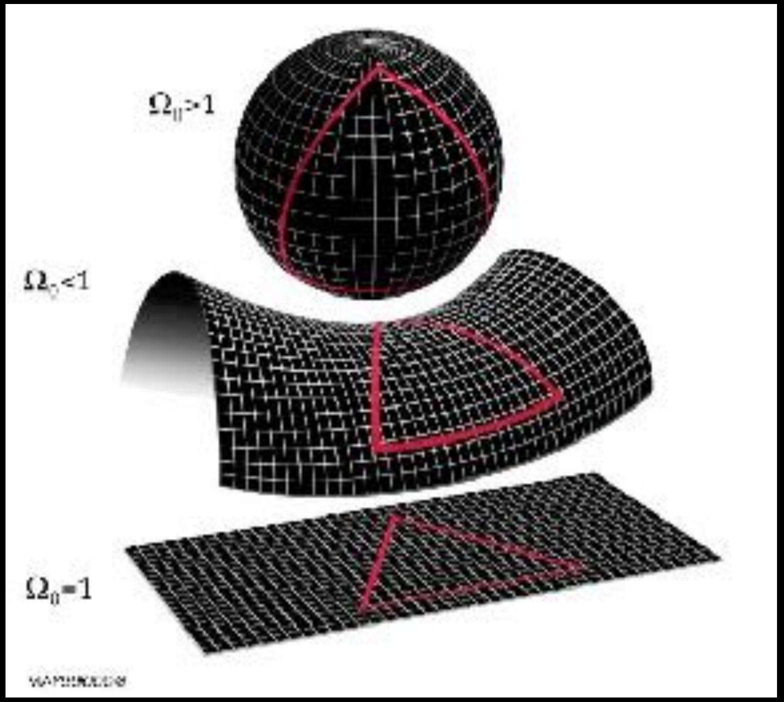
$$\Omega = \frac{8\pi G}{3H^2}\rho = 1 + \frac{\kappa}{a^2 H^2}$$

Measuring Ω, we get geometry:

$$\Omega > 1 \quad \rightarrow \quad \kappa > 0$$

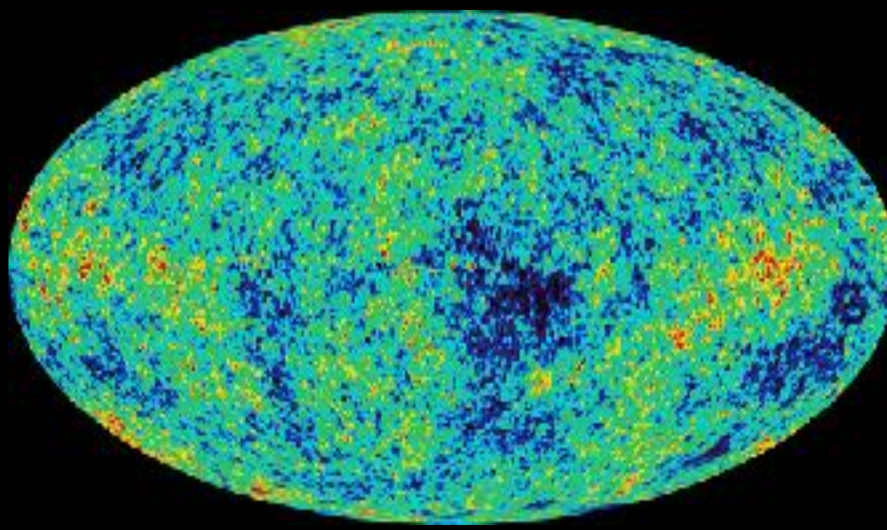
$$\Omega = 1 \quad \rightarrow \quad \kappa = 0$$

$$\Omega < 1 \quad \rightarrow \quad \kappa < 0$$

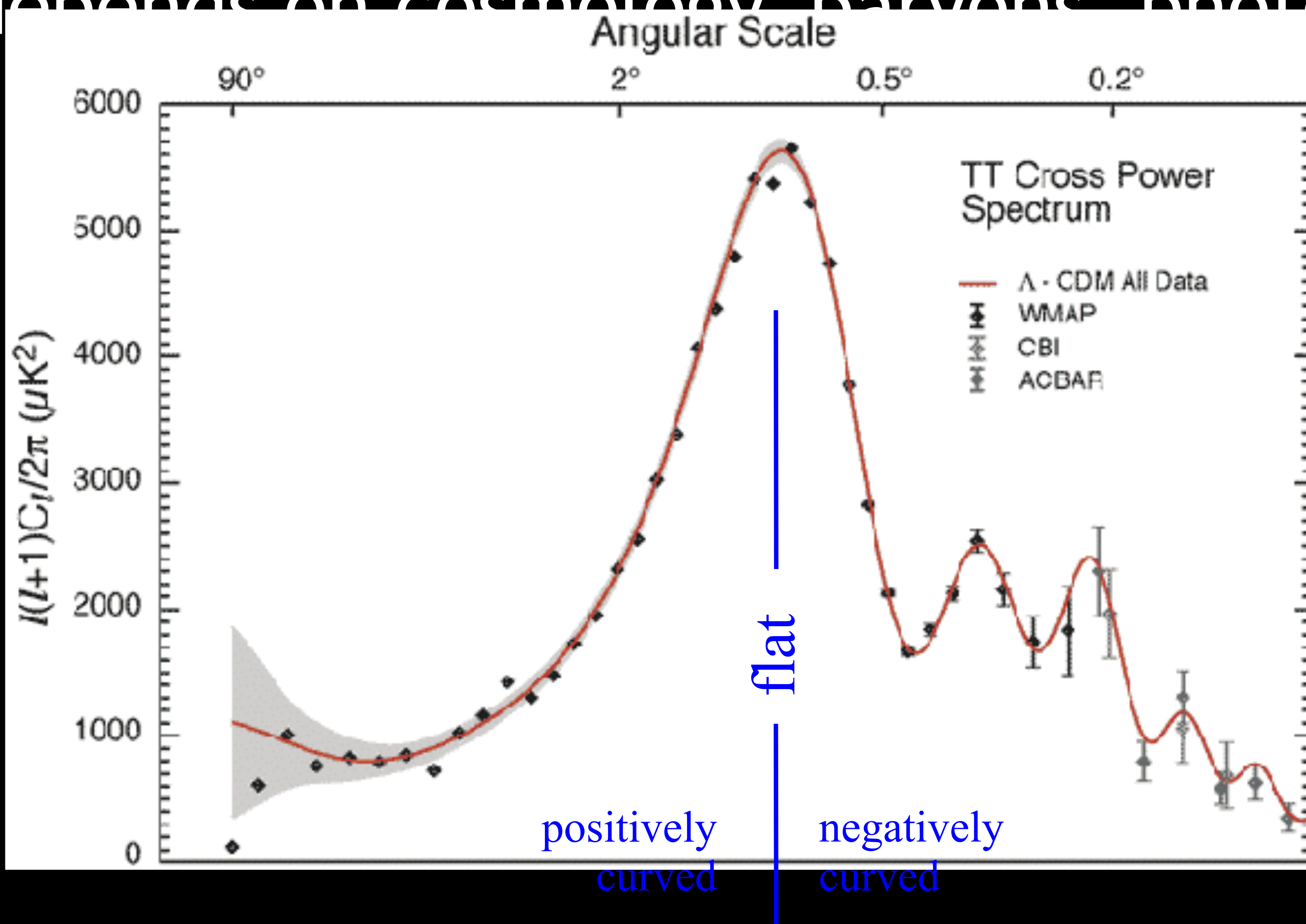


Matter (baryonic + dark) contributes with $\Omega \approx 0.3$,
open universe. internal triangle angle sum $< 180^o$.

Cosmic Microwave Background Radiation provides a standard ruler: Acoustic Horizon
Most frequent wave length



400,000 years after Big Bang
400,000 lighyear. Acoustic Horizon
depends on cosmology, baryons, photons



$\Omega_{Tot} = [\theta_{peak}(deg)]^{-1/2}$.

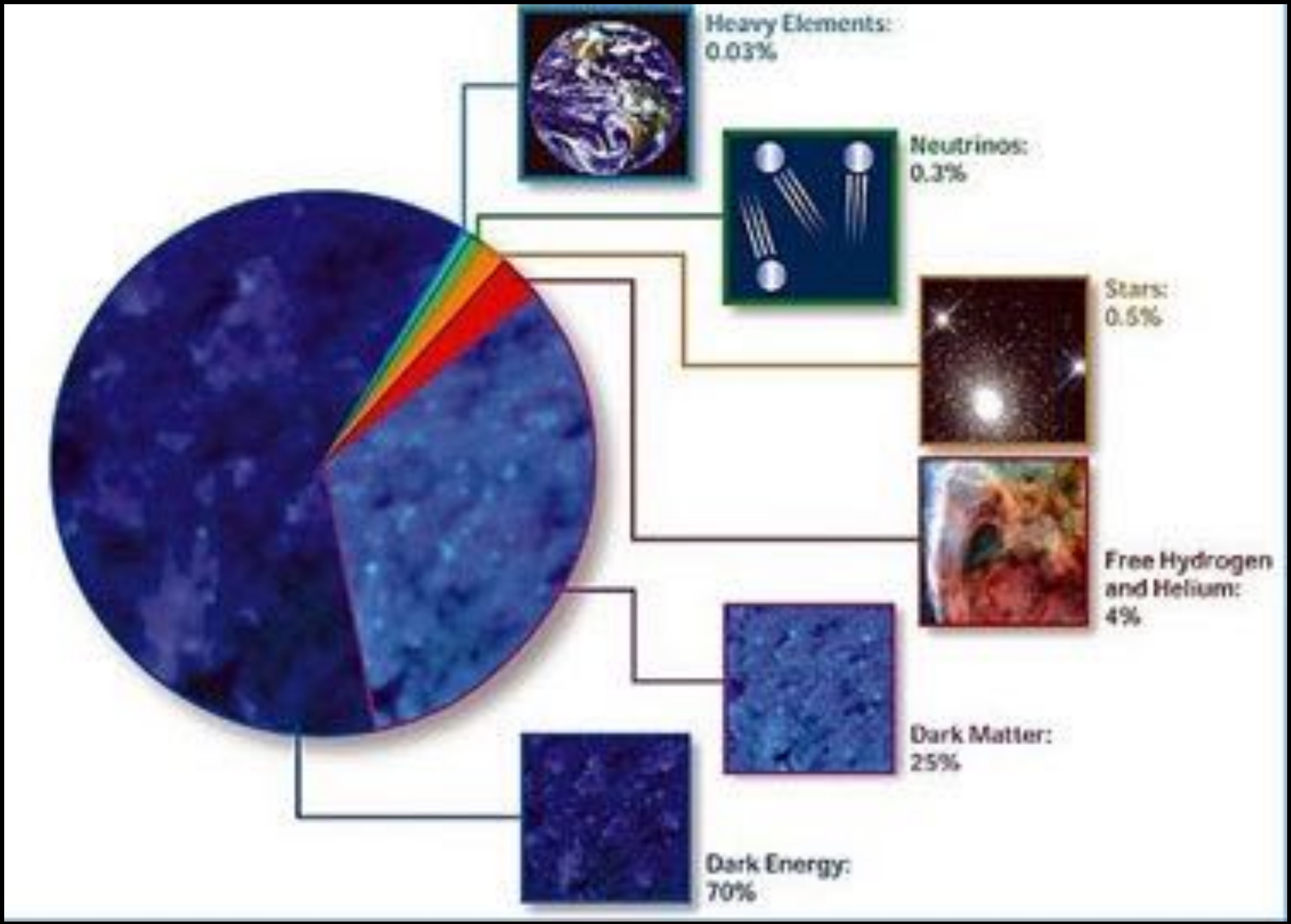
Observation: $\theta_{peak} = 1^o$.

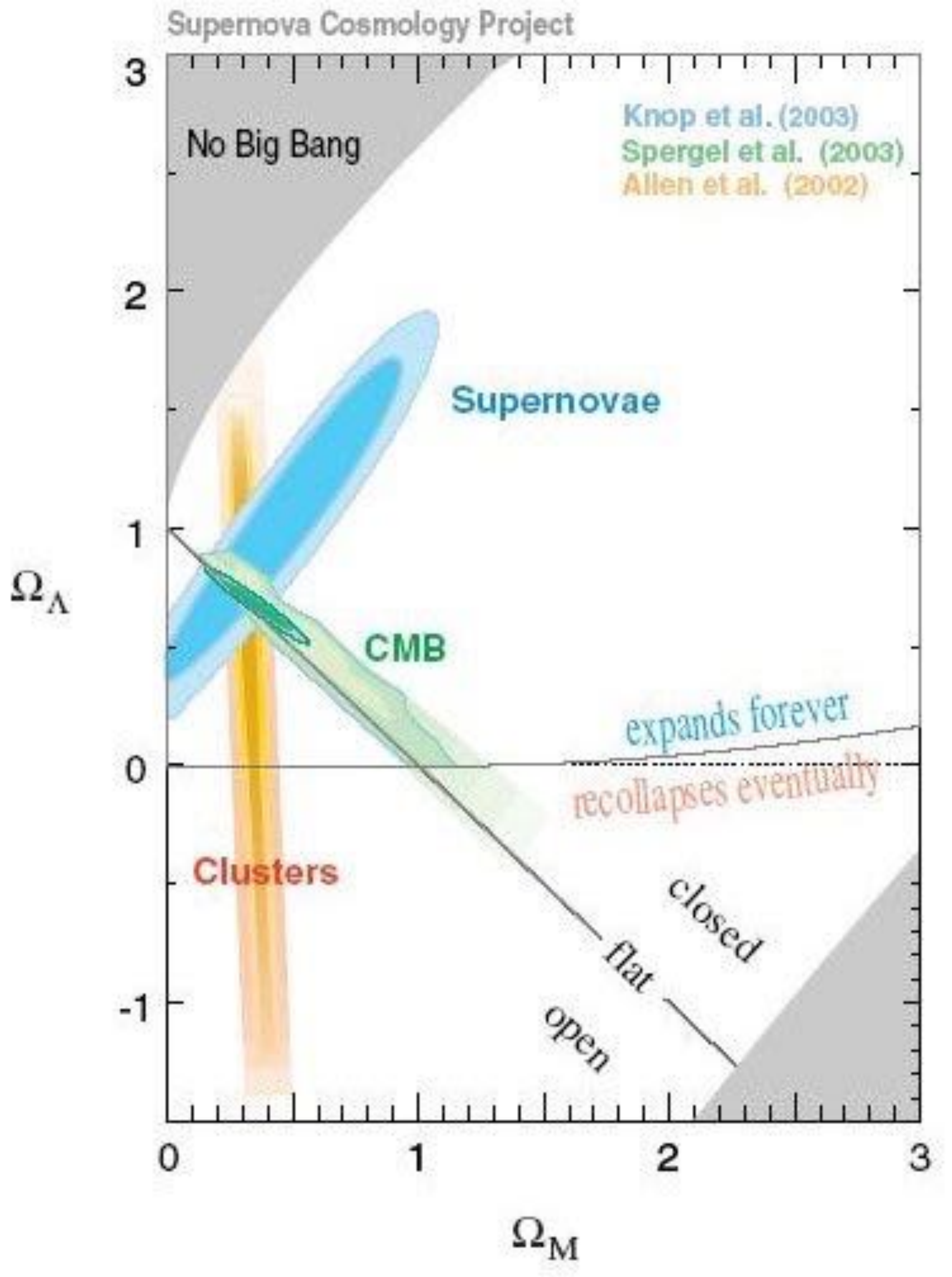
The universe is flat:

$\Omega_{Tot} = 1$ **it must have an extra component DE!!**

[Miller et al.; de Bernardis et al; WMAP]

LCDM Concordance Cosmological Model





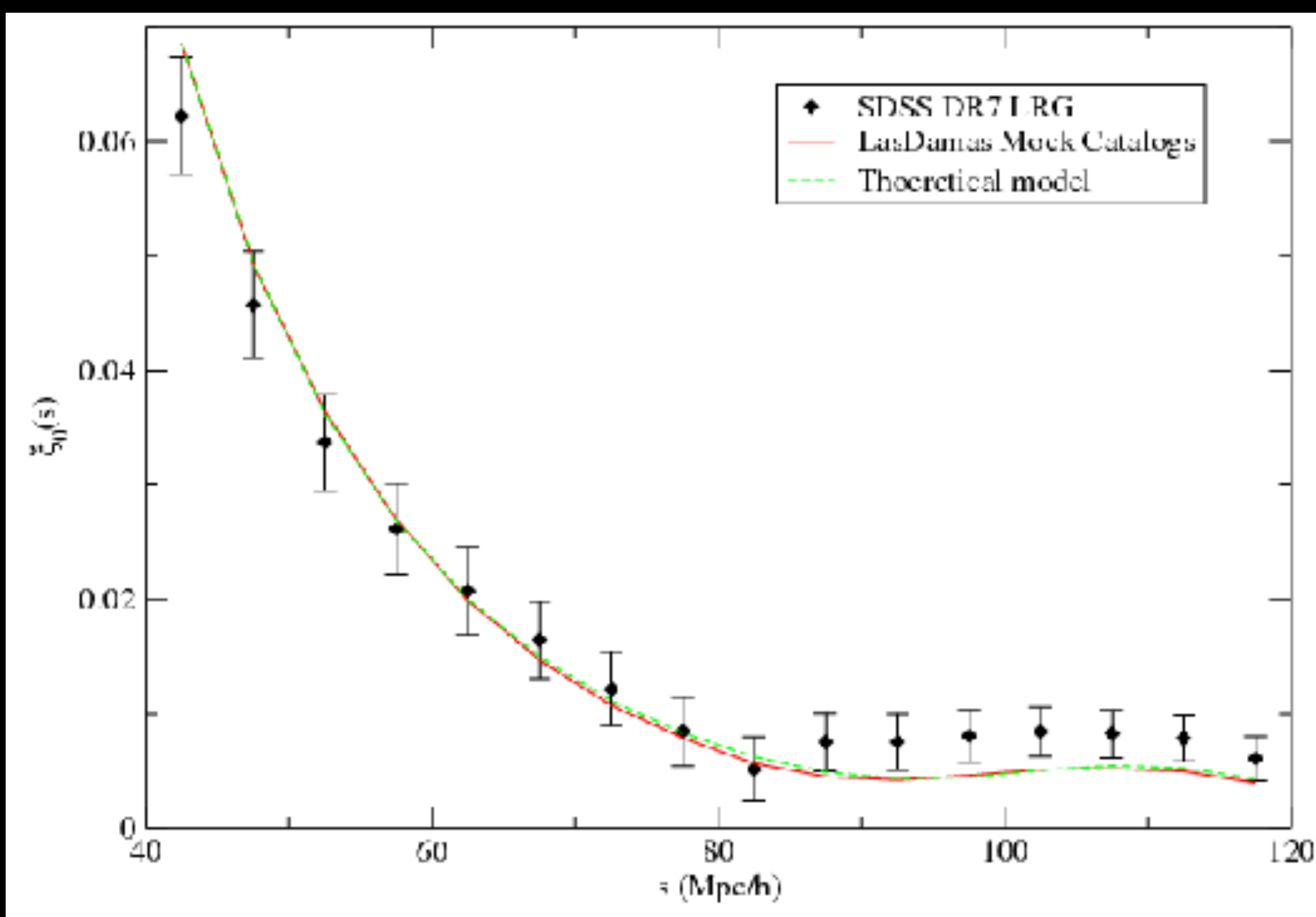
Concordance with different observations:

$\Omega_M = 0.3$,

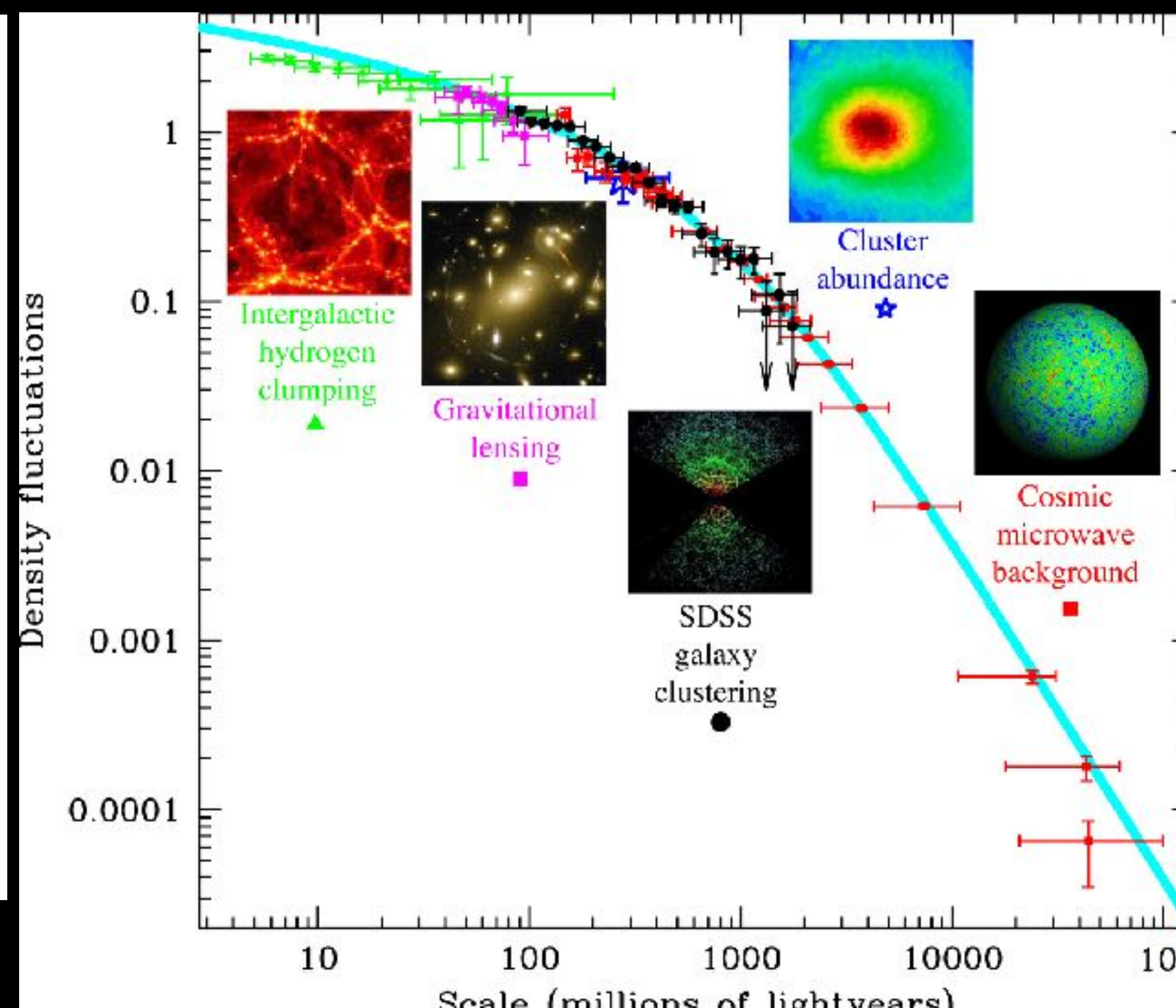
$\Omega_\Lambda = 0.7$.

Observed vs Predicted LCDM

2point correlation function

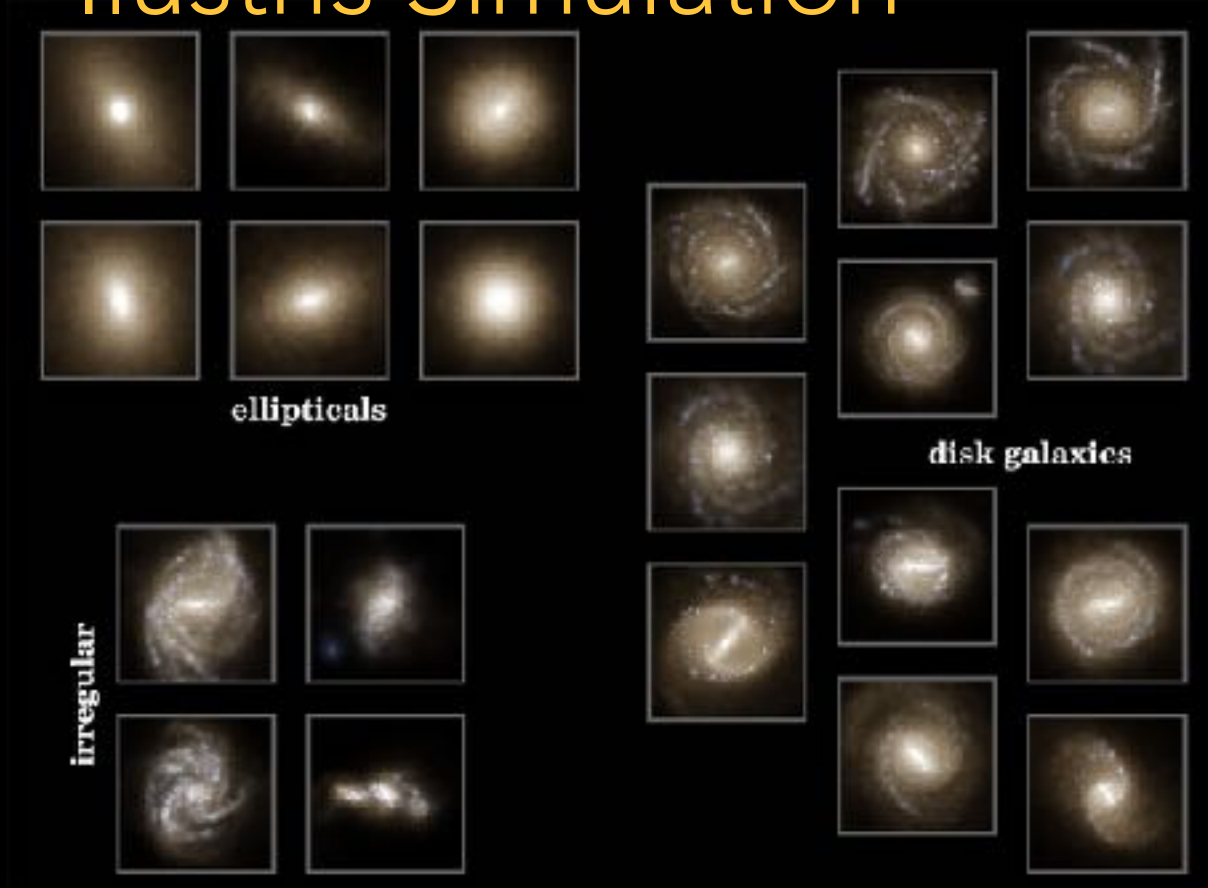


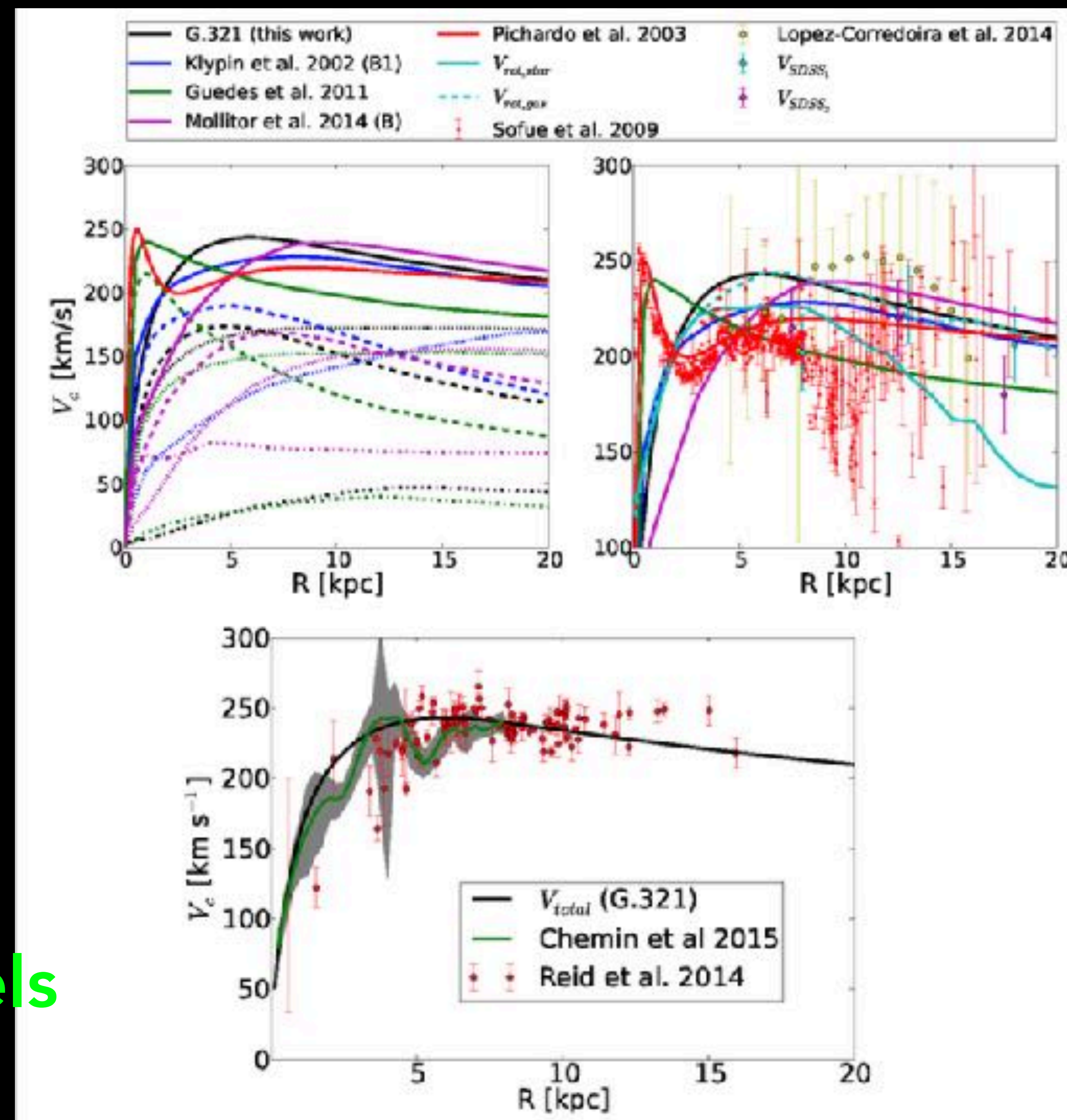
RMS density deviation aka Power Spectrum



LCDM GALAXY FORMATION

Ilustris Simulation





MW like systems

Similar to MW dynamical models

Roca-Fabrega et al. 2016

LCDM Standard Cosmology

- Big Bang (Hubble, CMBR, Light elements)
- Inflation: Flat, Large Scale Structure Seeds, Isotropy: Correlation Fcn. Power spectrum CMB, Galaxies
- Dark Energy : Lambda- Cosmic Acceleration

Discussion II

- Critics to Big Bang
- Critics to SCDM model
- Critics to LCDM model
- DE + CDM + Inflation +Big Bang
- Why should I take it seriously?
- Weak aspects?
- Final Model? Is that possible?