Cosmology – Experimental Status

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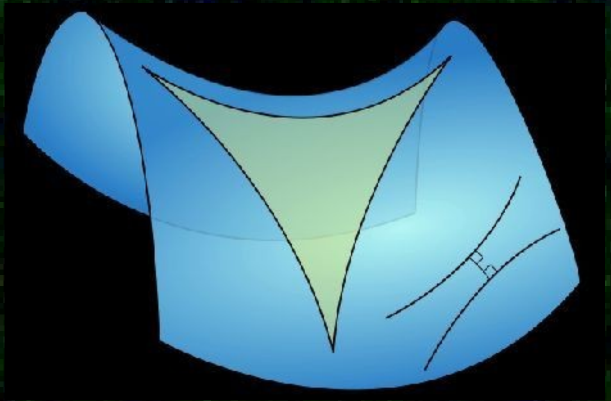
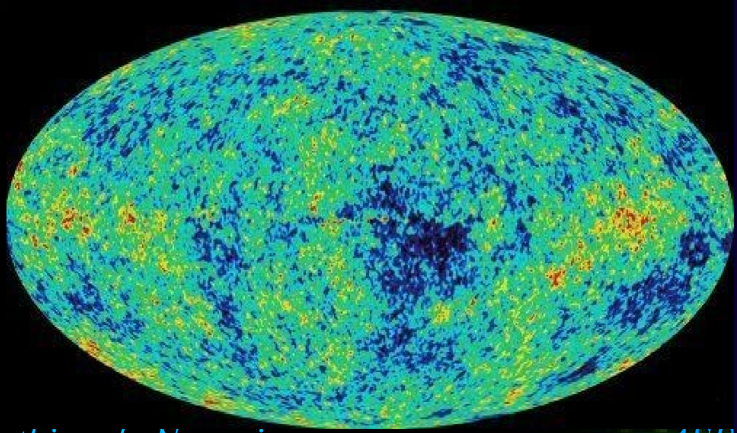
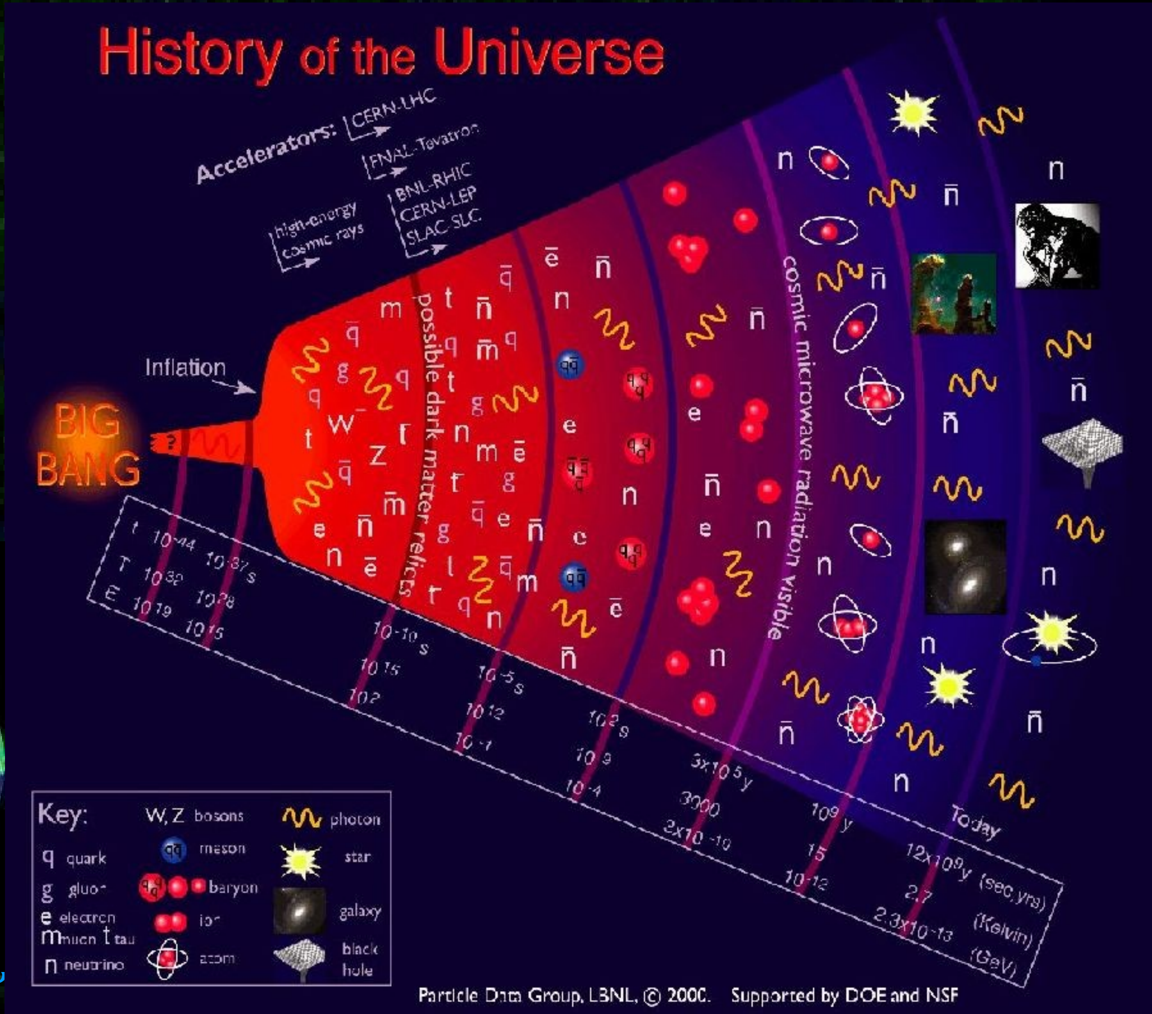
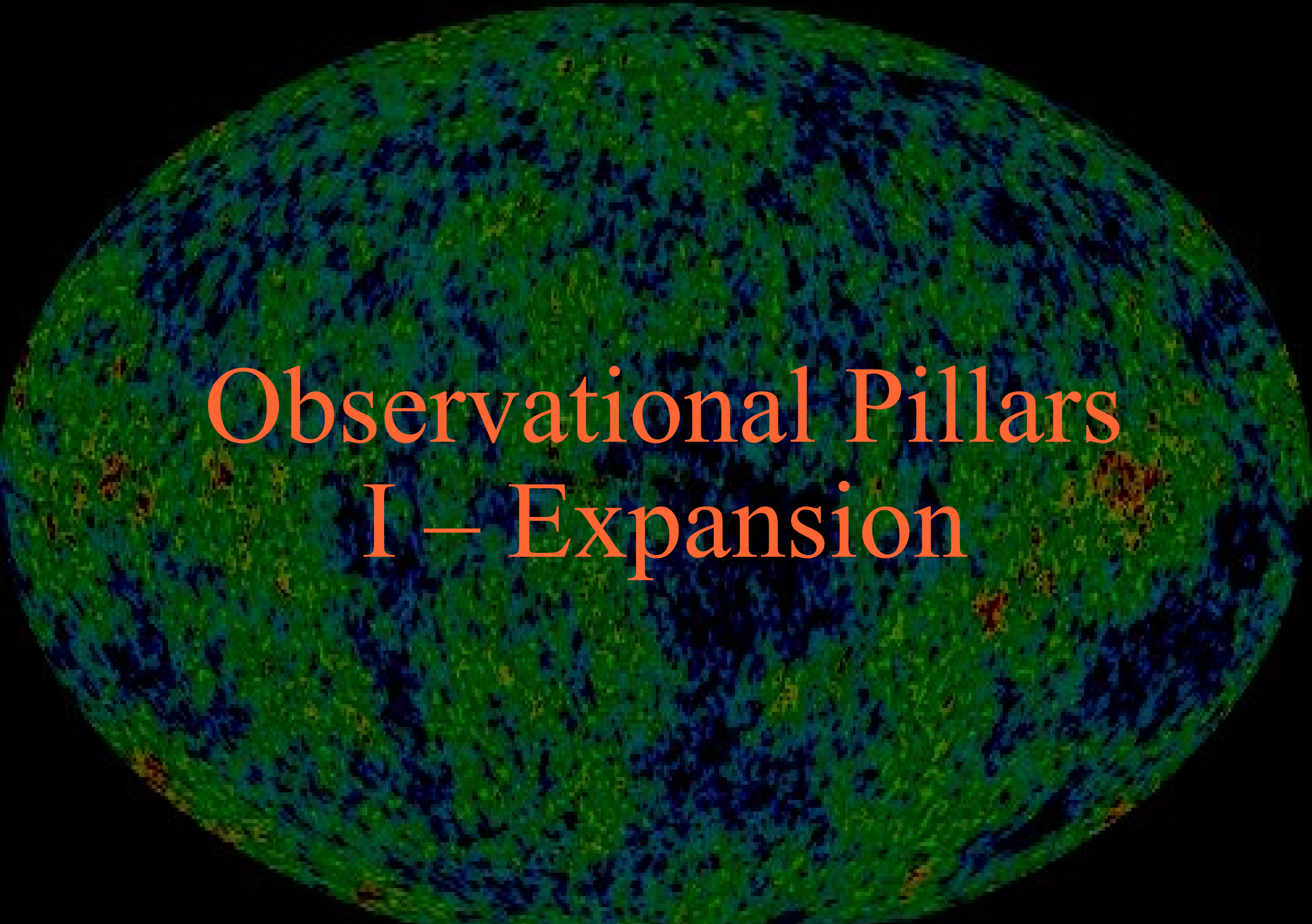








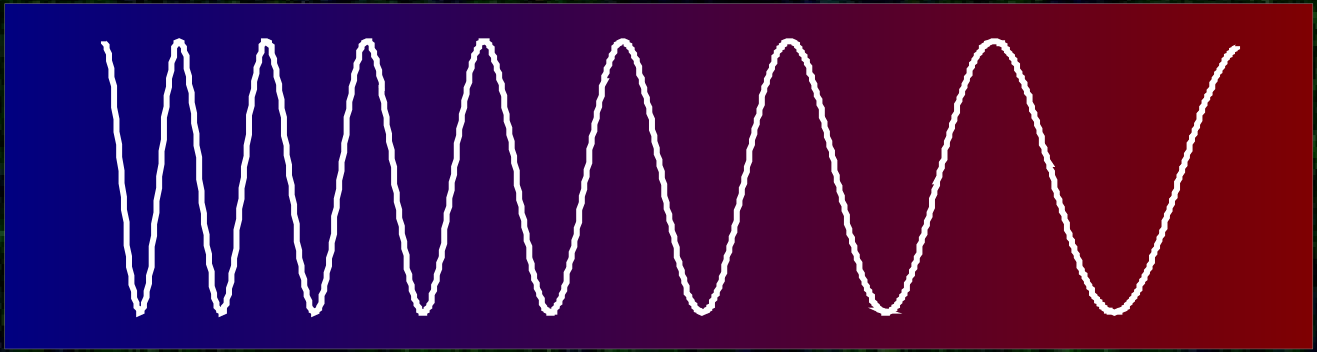
Observational Pillars

I – Expansion

Redshift

- During the propagation of a photon, the universe gets diluted and the wavelenght increases by the same amount:

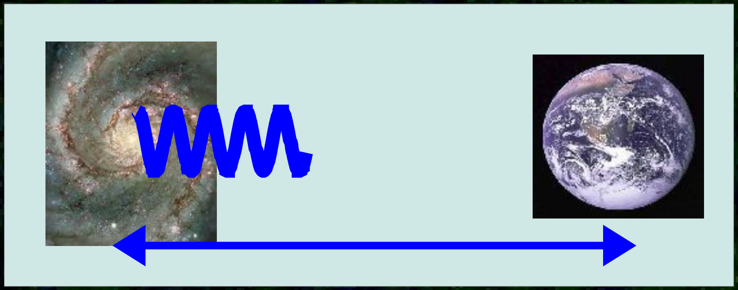
$$1+z=\frac{a_r}{a_e}=\frac{\lambda_r}{\lambda_e} \quad \text{where} \quad \begin{cases} \text{e} = \text{emission} \\ \text{r} = \text{reception} \end{cases}$$



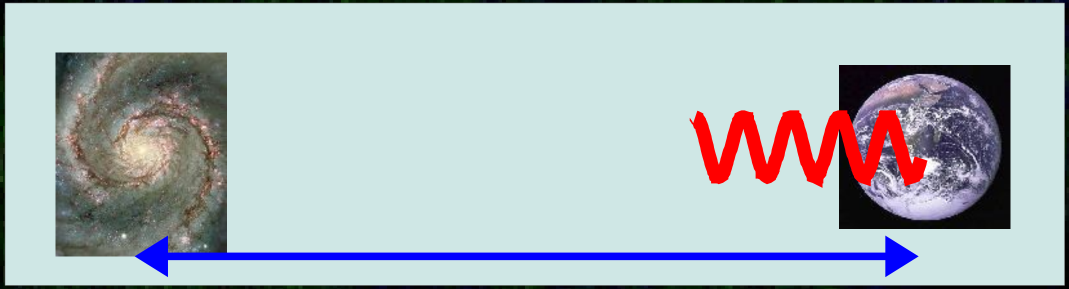
emission

Reception

What distance?



Emission



Reception

- Distance at emission time? At reception time?
- Best definition: distance travelled by photon as Universes expands (Comoving distance)
- Calibrated using several types of objects (Distance Ladder)

$$d = a_0 \int_{t_e}^{t_r} \frac{\mathrm{d}t}{a(t)} = \int_{a_0/(1+z)}^{a_0} \frac{a_0\,\mathrm{d}a}{a\,\dot{a}} \propto \int \frac{\mathrm{d}z}{H(z)}$$

Depends on expansion evolution of the Universe
=> Probe for expansion

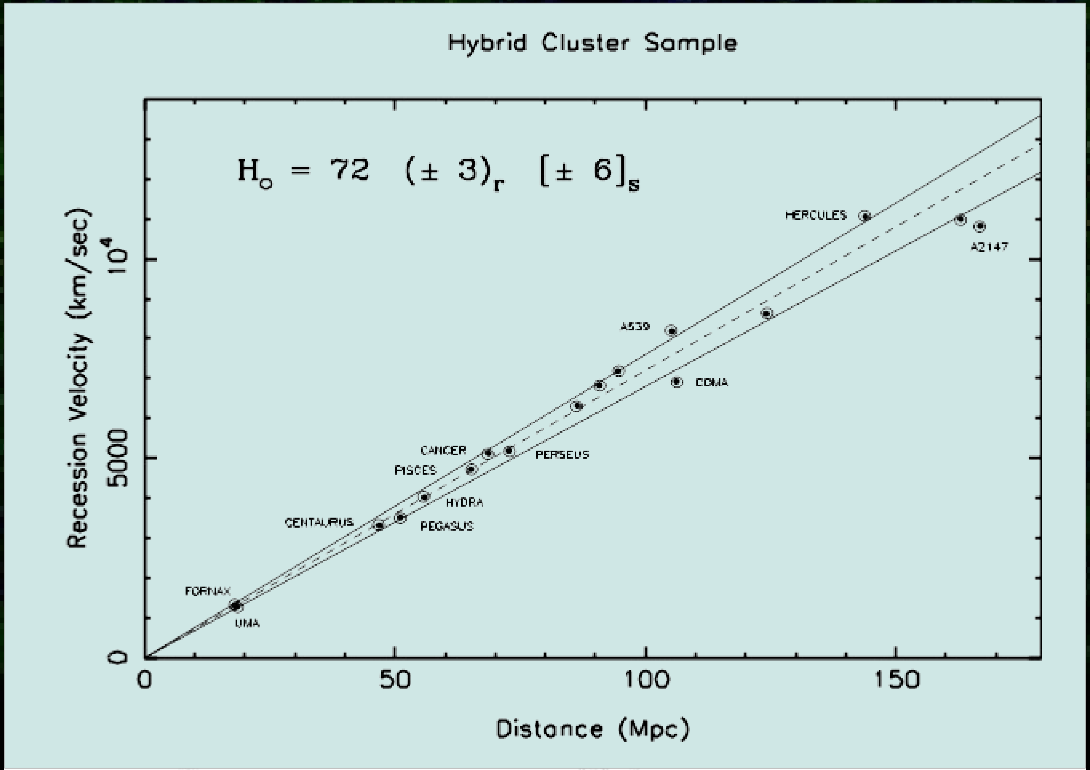
Hubble Law

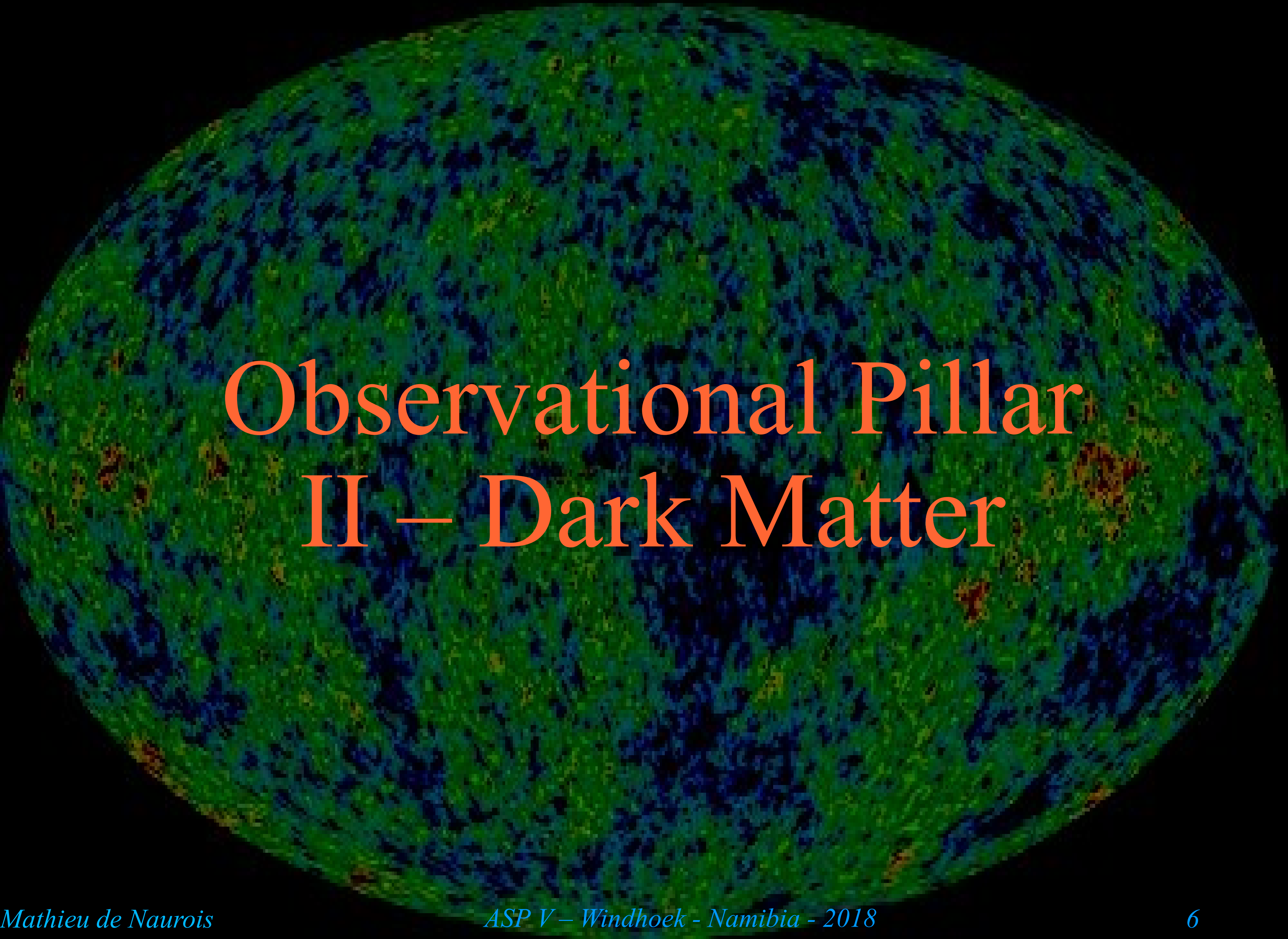
☐ Galaxies are separating apart at a speed proportional to their distance

$$\frac{\mathrm{d}R}{\mathrm{d}t} = H_0 R + v_p$$

Hubble flow

Proper Motion





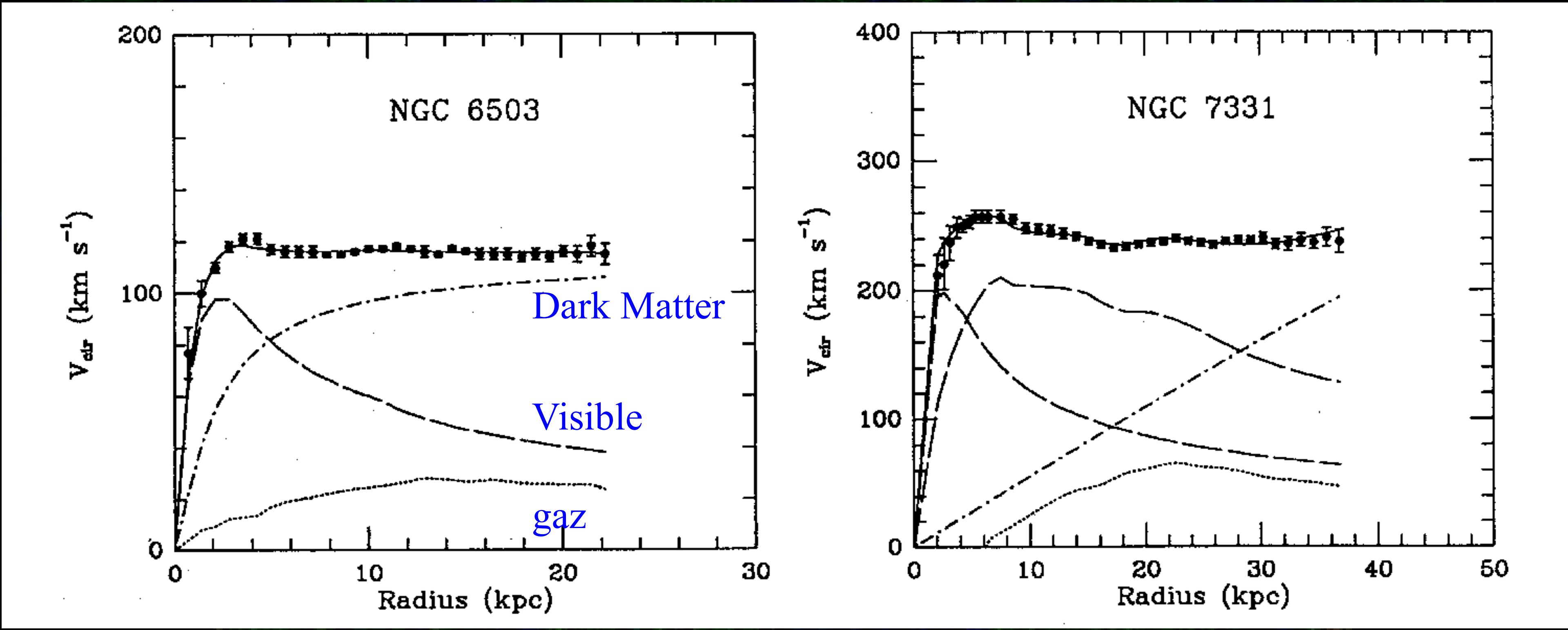
Observational Pillar
II – Dark Matter

Rotation Curve

- For Kepler Motion

$$V(R)=\sqrt{\frac{G\,M(R)}{R}}$$

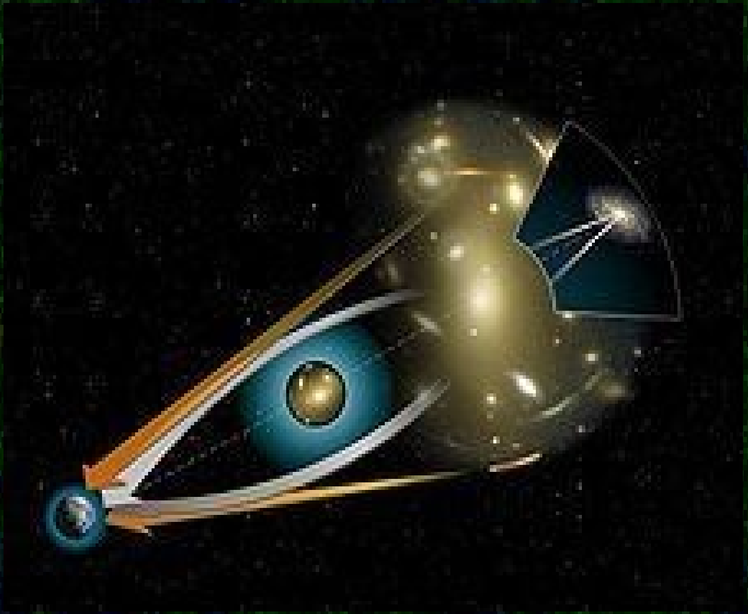
Exercise!



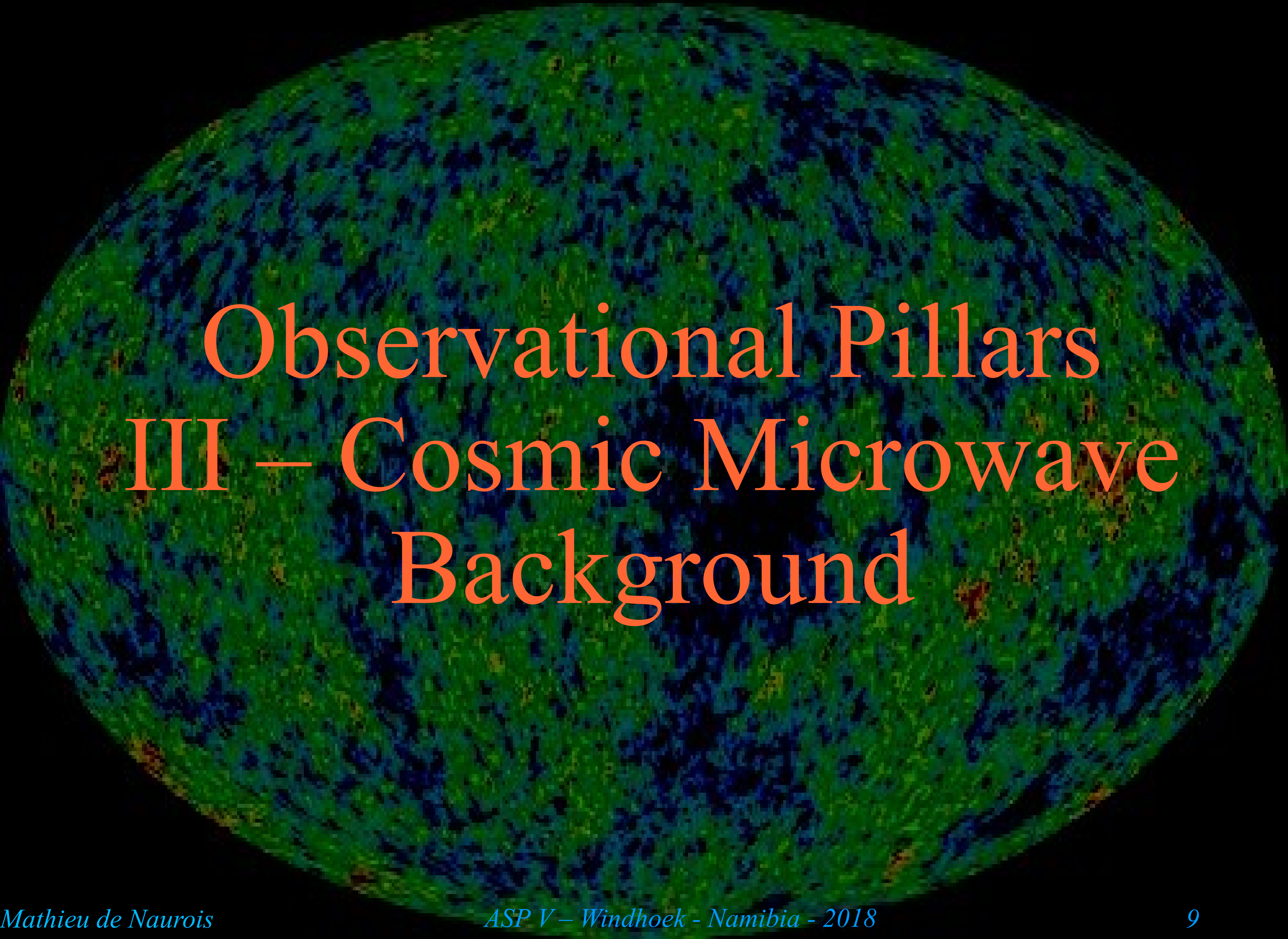
- Dark Matter represents ~ 85% of matter, and ~ 25% of total energy

Other evidences

- ☐ Gravitational Lensing



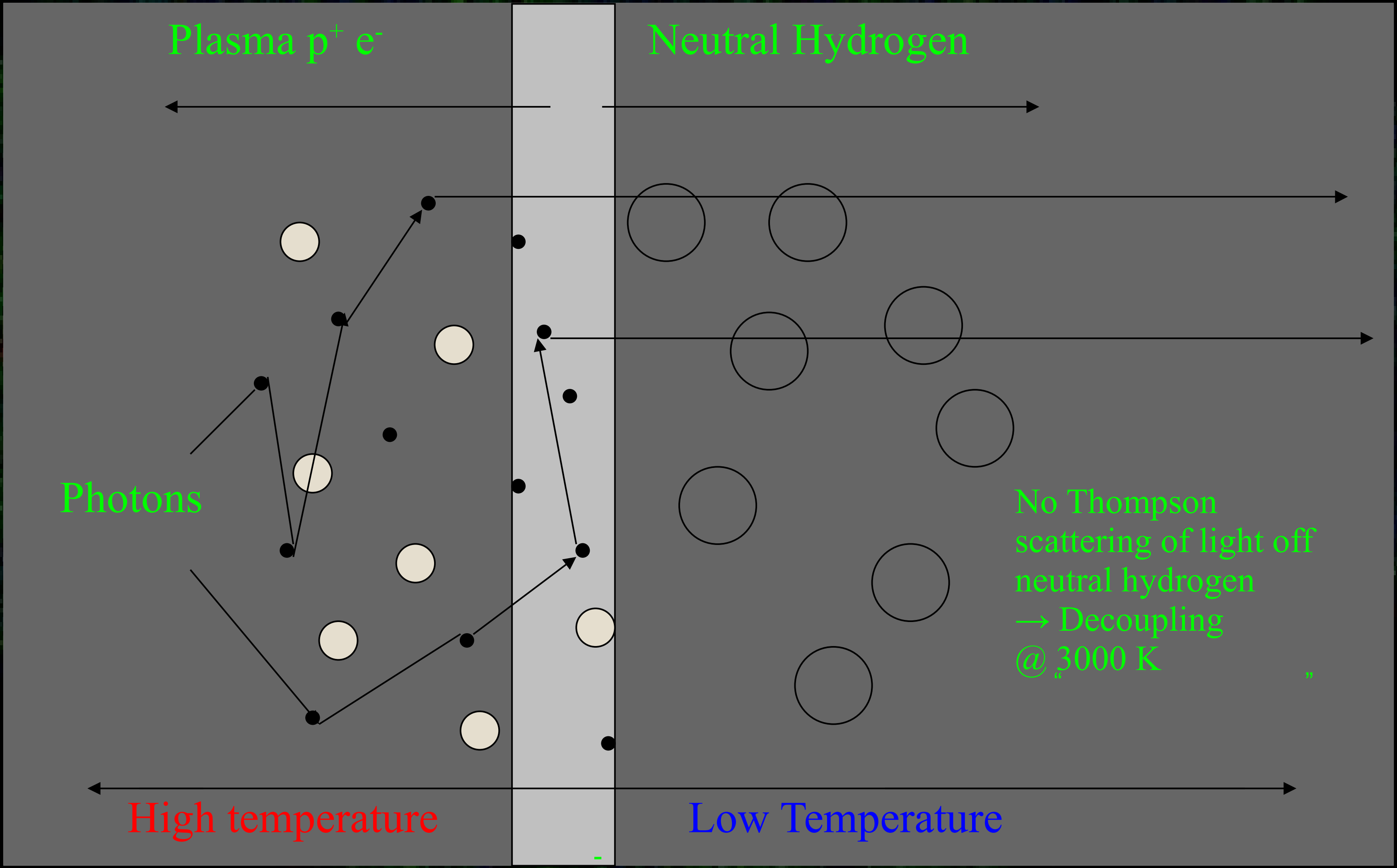
- ☐ Temperature distribution of hot gas in galaxies and clusters of galaxies
- ☐ CMB



Observational Pillars
III – Cosmic Microwave Background

Recombination & Decoupling (z = 1100)

- Universe becoming suddenly transparent to light!



Plasma $p^+ e^-$

Neutral Hydrogen

Photons

No Thompson
scattering of light off
neutral hydrogen
→ Decoupling
@ 3000 K

High temperature

Low Temperature

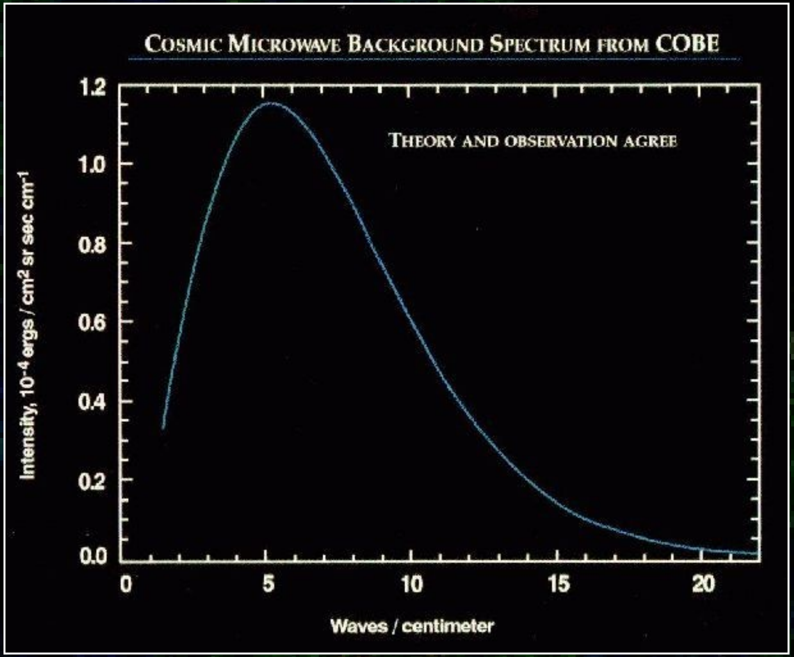
Predicted in the 1950 s, detected in 1964

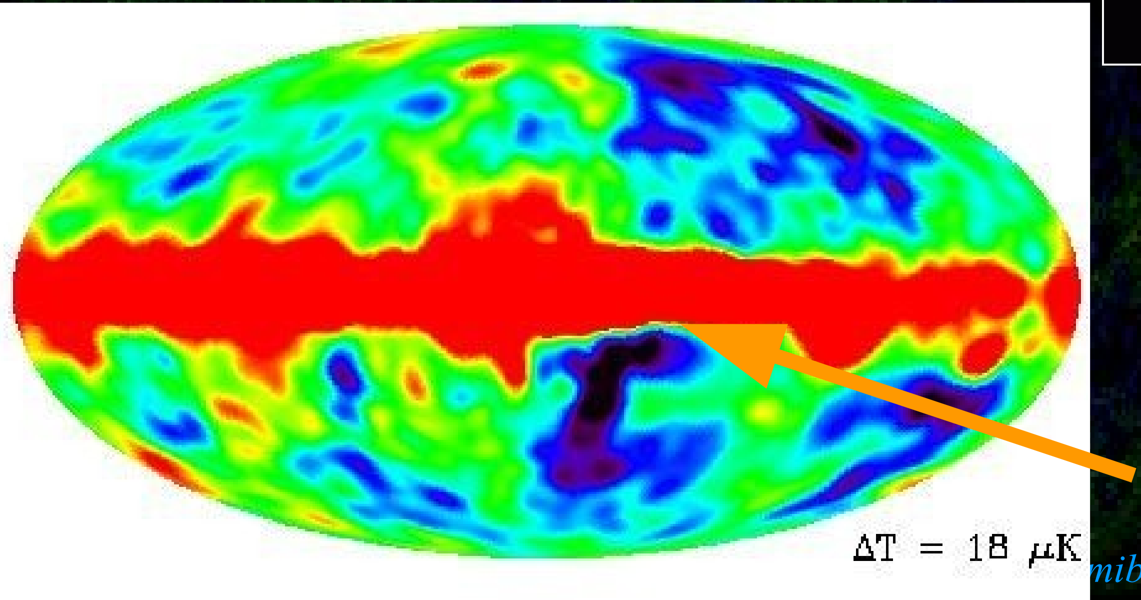
- ❑ Thermal emission emitted at the time of decoupling (transition from an nuclei-electron plasma to neutral atoms, z ~ 1100, 380 000 yr after Big Bang
- ❑ Diluted and redshifted by the expansion of the Universe

Penzias and Wilson, 1964

CMB Detection

- Discovered 1965 (Penzias & Wilson)
  - 2.7 K blackbody
  - Isotropic (<1%)
  - Relic of hot "big bang"
- 1970's and 1980's
  - 3 mK dipole (local Doppler)
  - $\delta T/T < 10^{-5}$ on arcminute scales

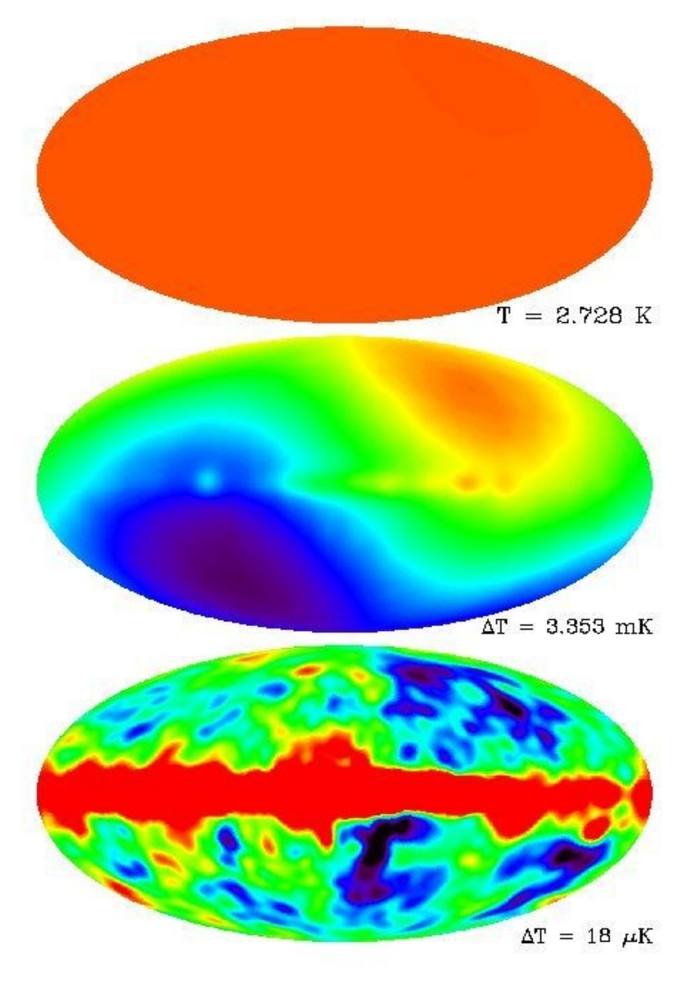




Milky Way

- COBE 1992
- Blackbody 2.728 K
- $\ell < 30 : \delta T/T \approx 10^{-5}$

COBE

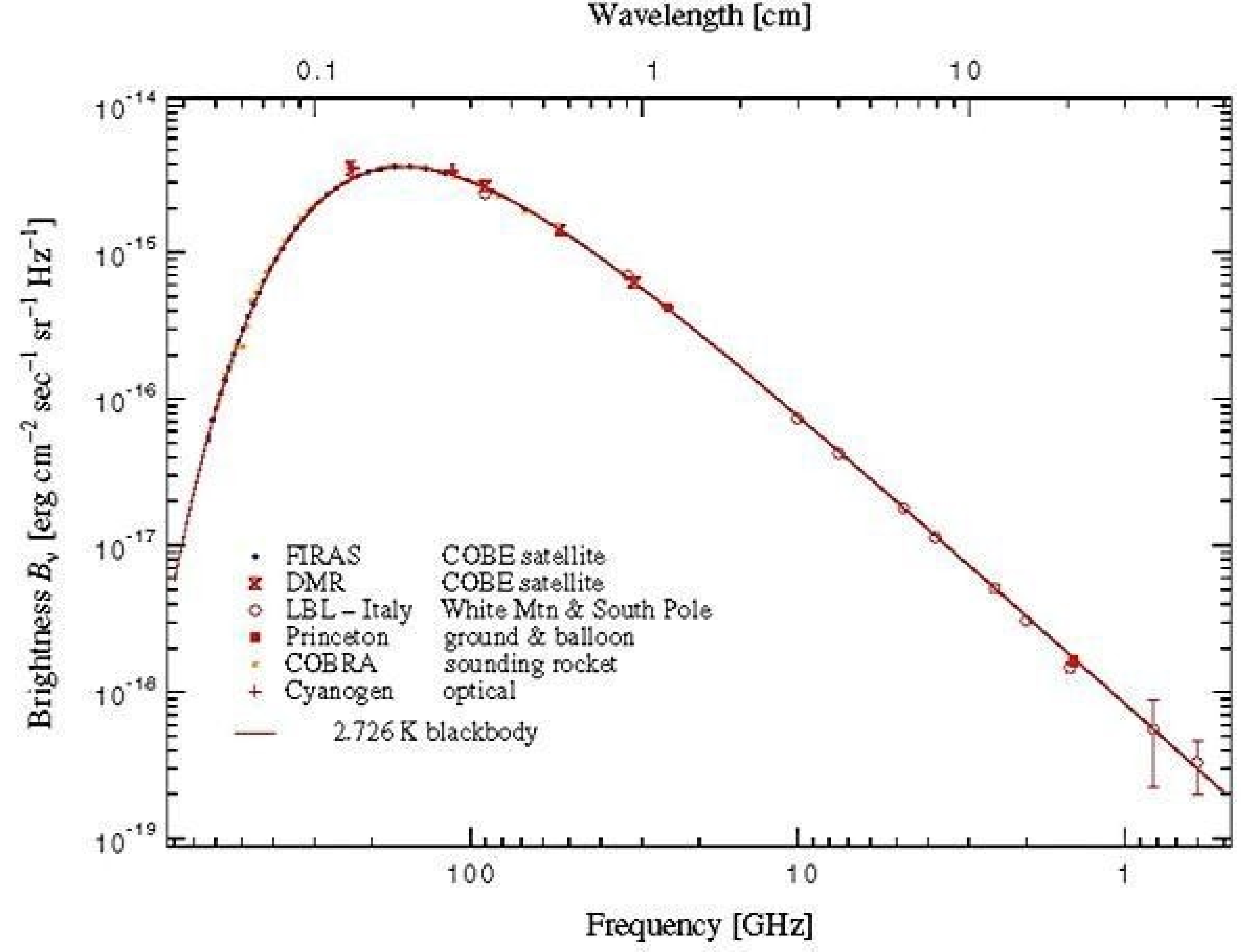


Raw Temperature Map

Dipole (movement w/o
Big Bang frame)

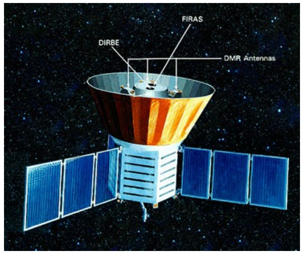
Foreground Galactic Emission
+ Cosmological fluctuations

CMB Spectrum

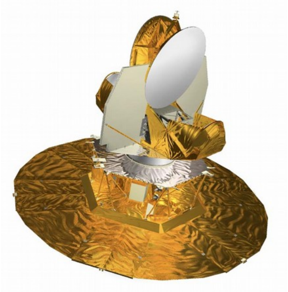


From COBE to Planck

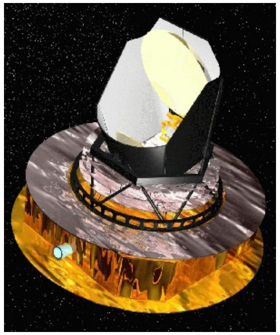
COBE 1994

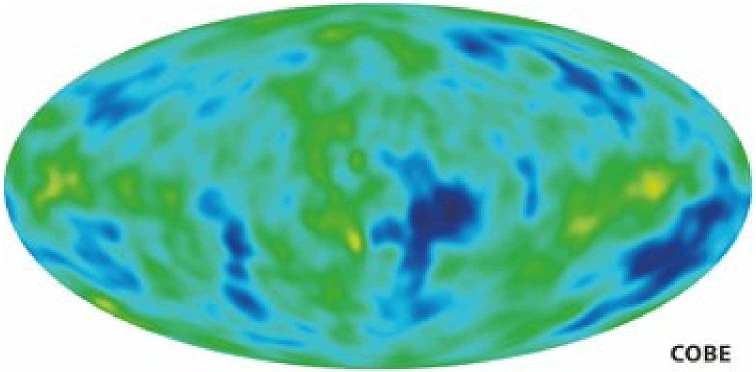


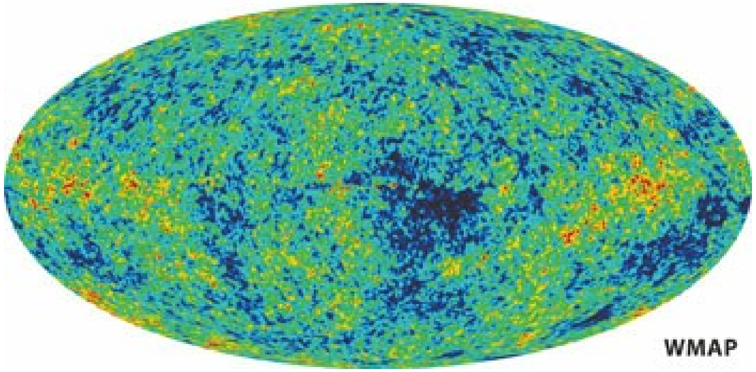
WMAP 2004

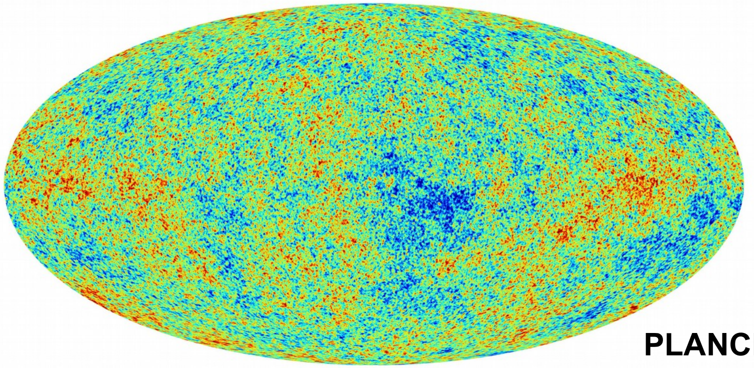


PLANCK 2009



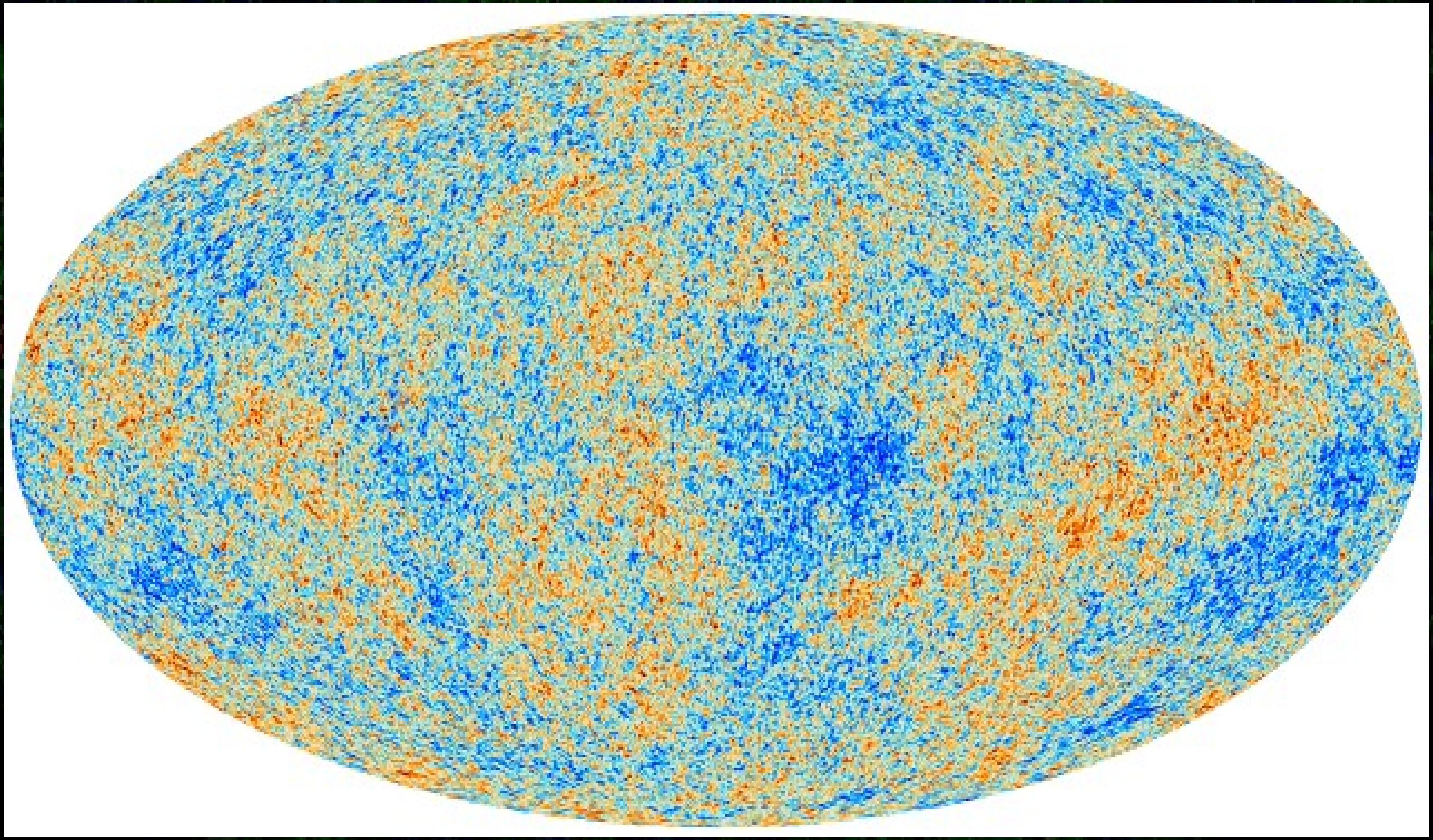

COBE


WMAP


PLANCK

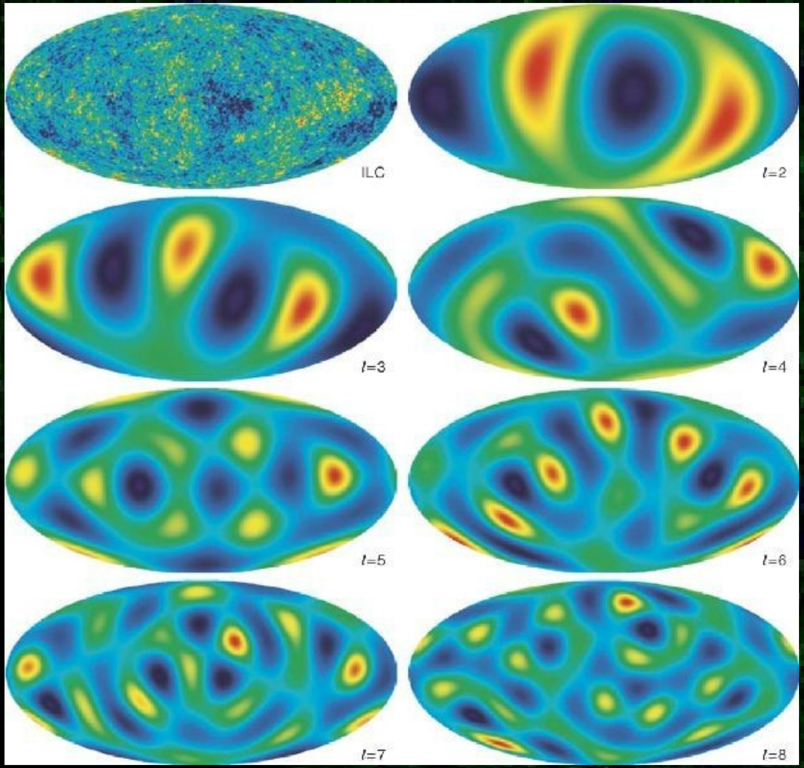
Is CMB Homogeneous?

- ☐ Plank temperature Map

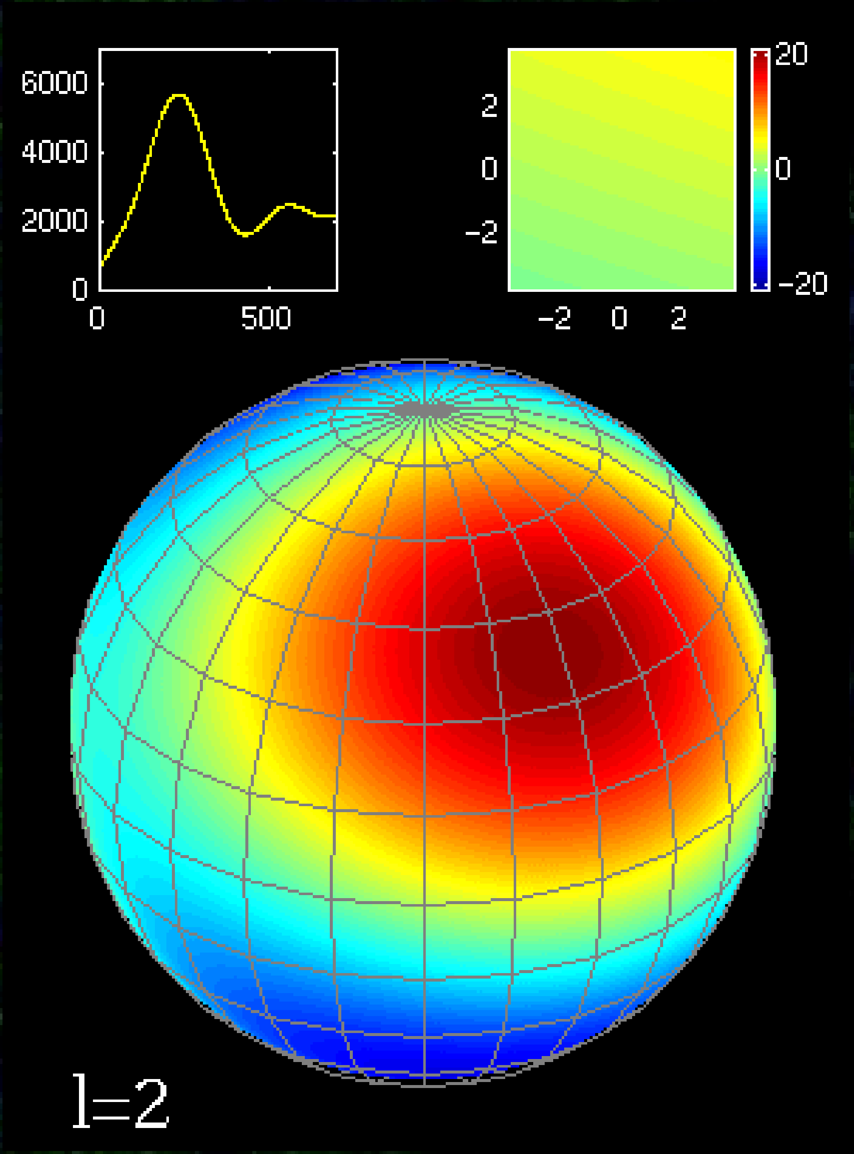


Spherical Harmonics

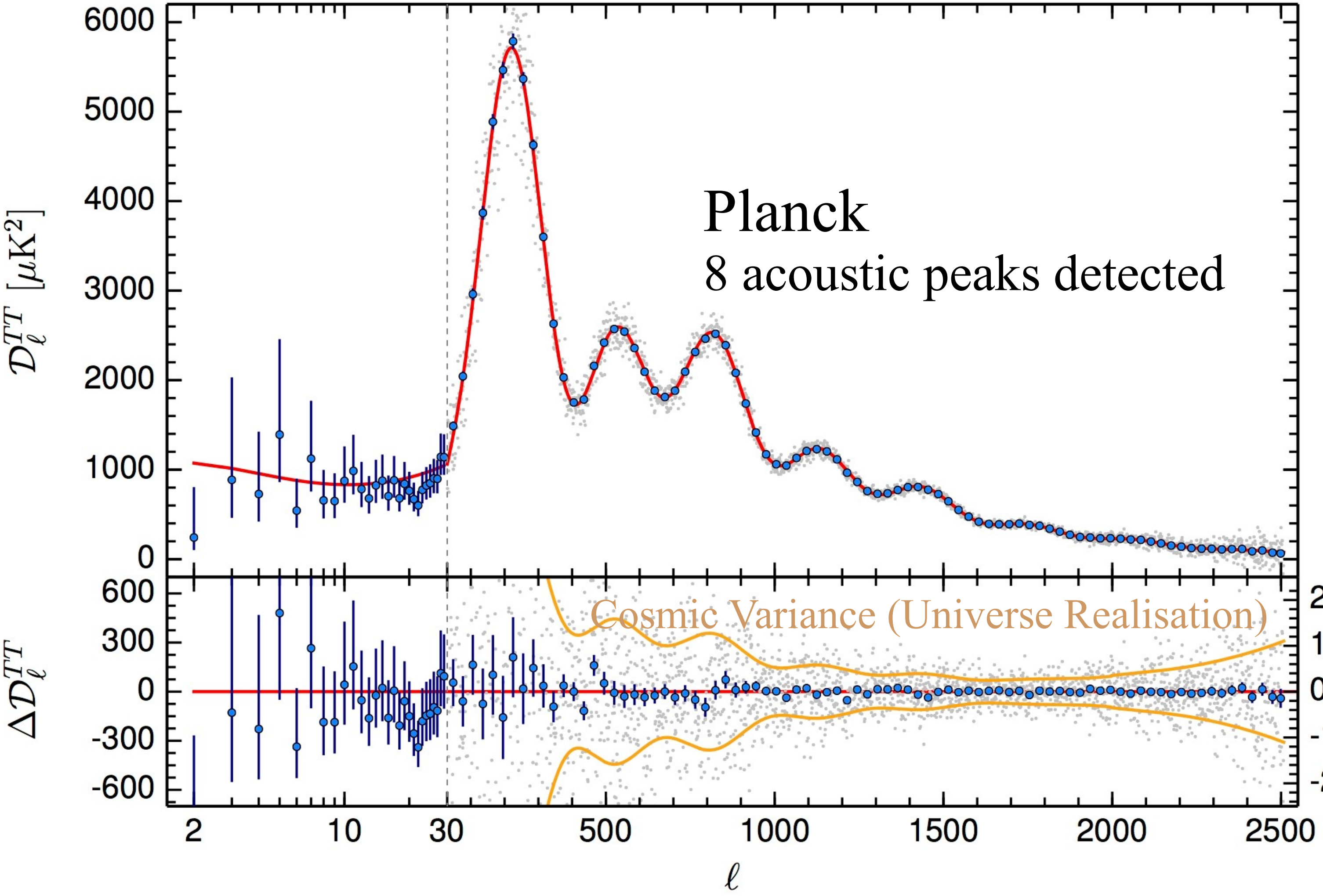
- ❑ l correspond to angular scale
- ❑ Large values correspond to small scales



The lower WMAP harmonics...



CMB Angular Spectrum - 2015



Planck

8 acoustic peaks detected

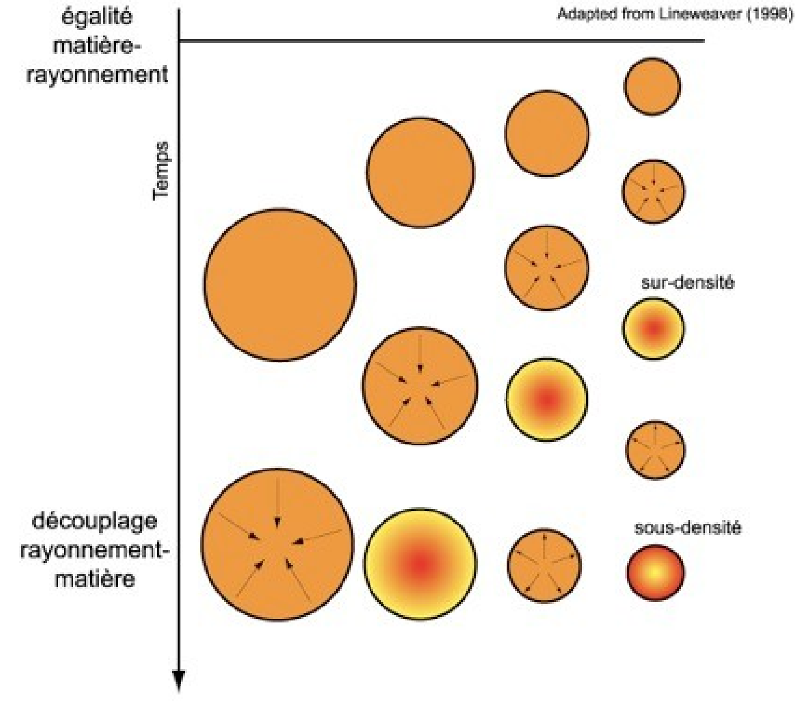
Cosmic Variance (Universe Realisation)

Acoustic Oscillation

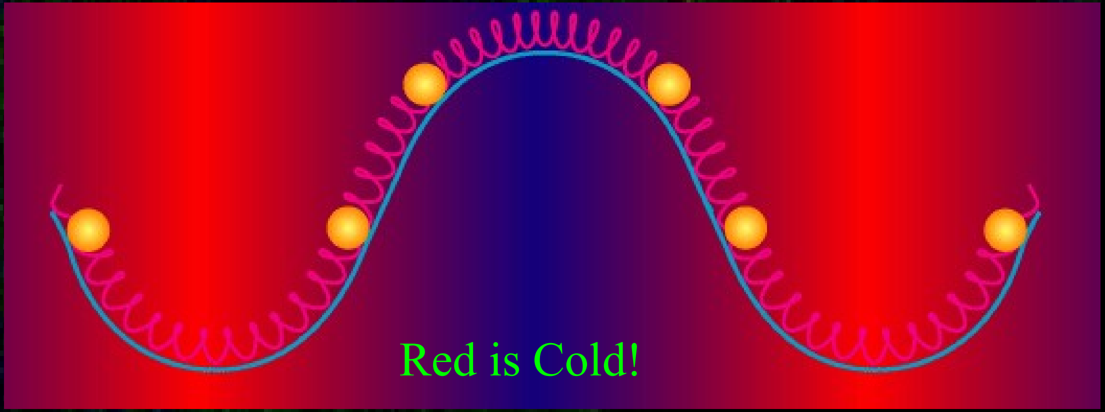
- Oscillations due to coupling between matter and radiation (radiation pressure)
- Wave travelling at

$$c/\sqrt{3}$$

- Small fluctuations oscillate faster
- At the time of decoupling, situation is frozen => characteristic angular scale appear
- Density fluctuation translate into temperature variations

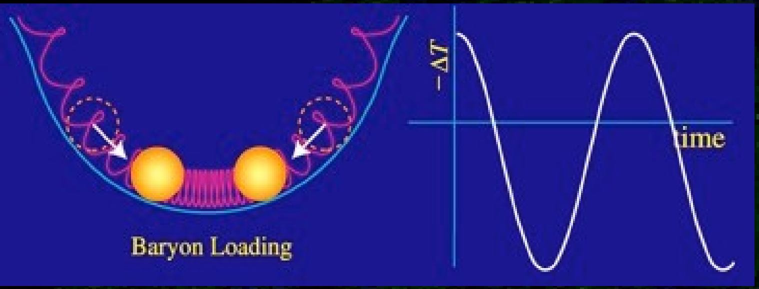


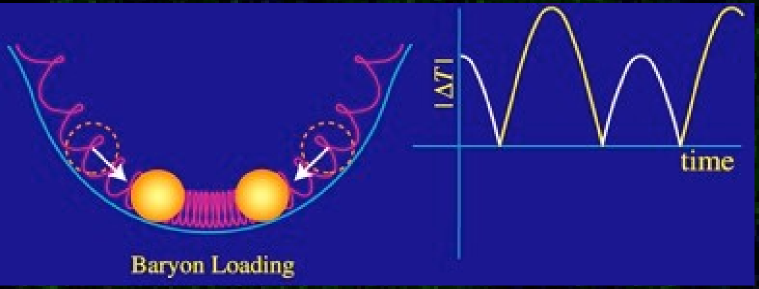
Adapted from Lineweaver (1998)

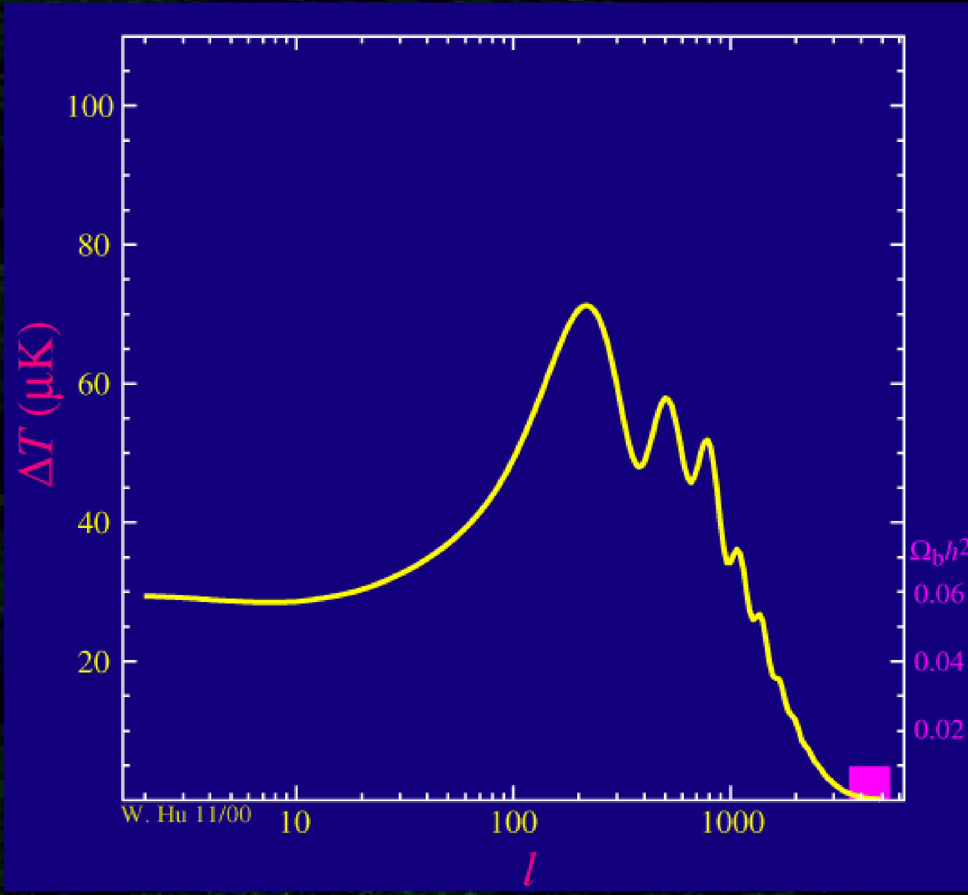


Red is Cold!

Matter Content



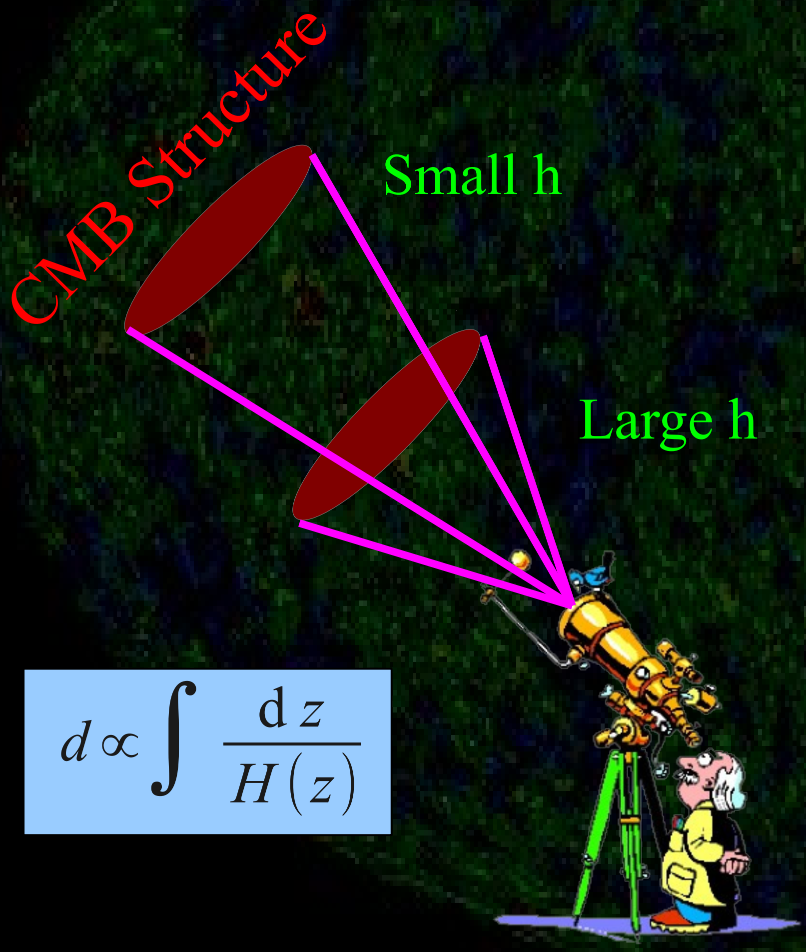




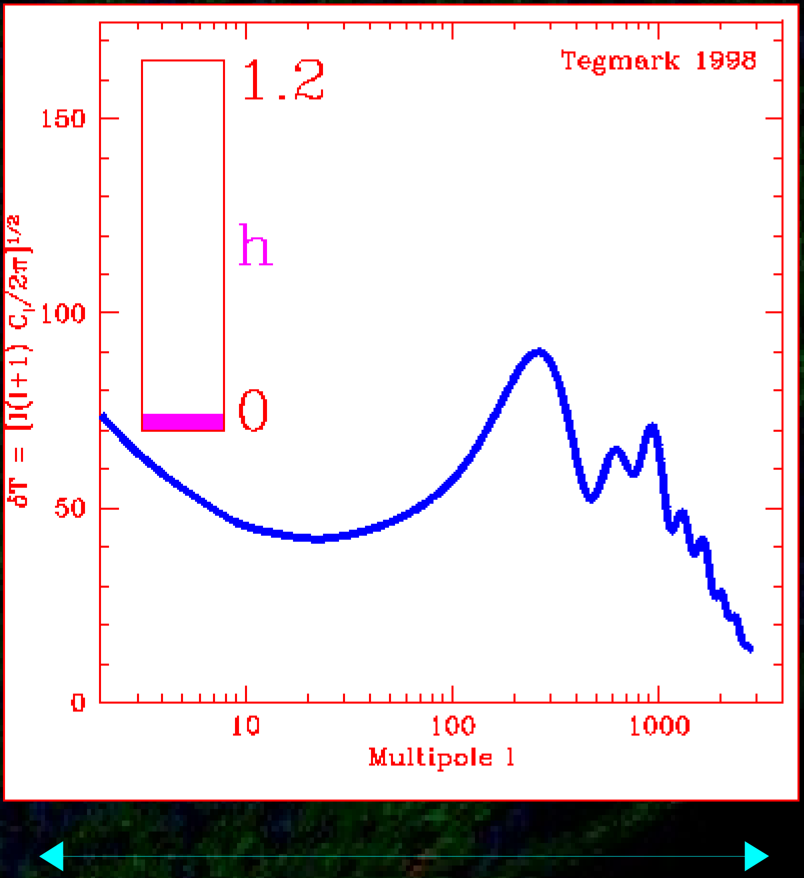
- ❑ Coupling between matter and radiation affects oscillation pattern
- ❑ No matter = no oscillations

Hubble Constant

- Large expansion speed makes larger redshifts correspond to smaller distance. Structures appear larger

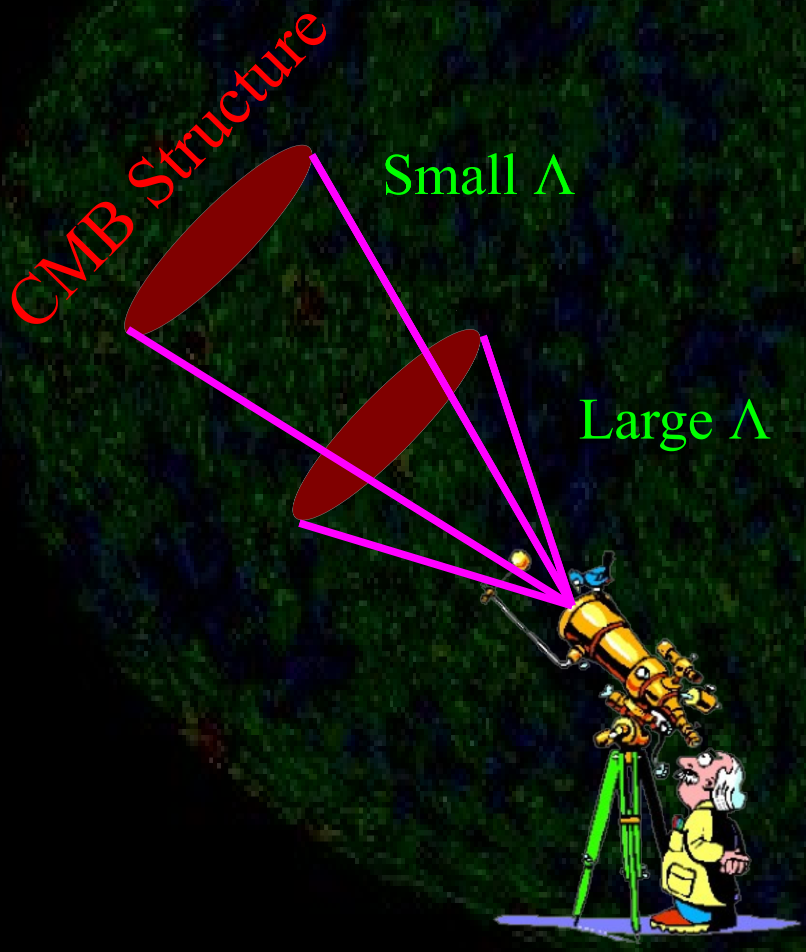


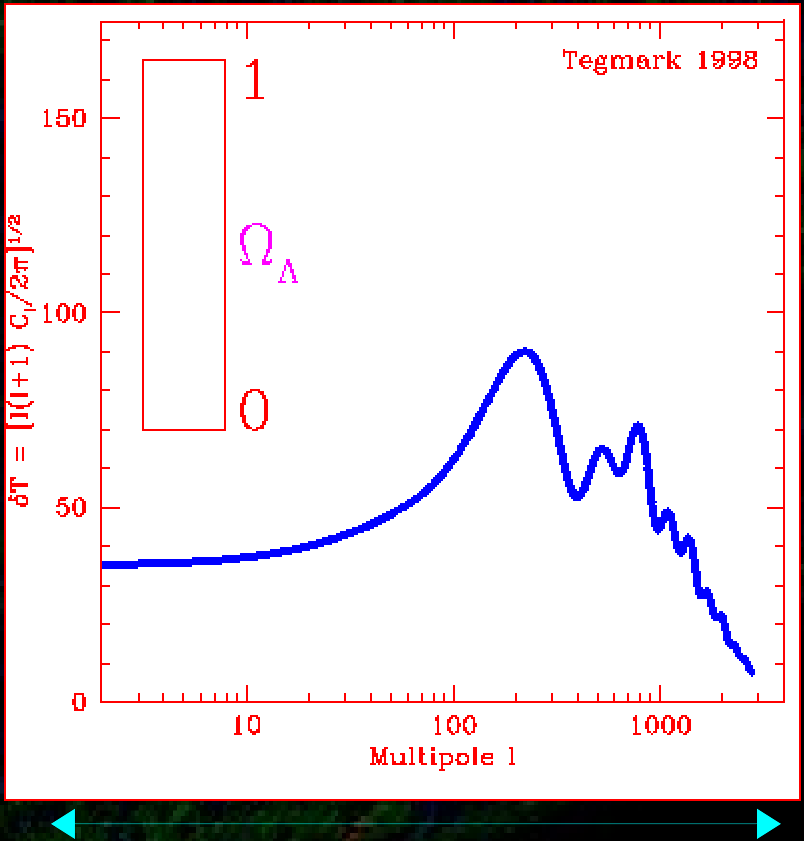
$$d \propto \int \frac{\mathrm{d}\,z}{H(z)}$$



Cosmological Constant

- ☐ Cosmological constant increases expansion speed, structures appear larger



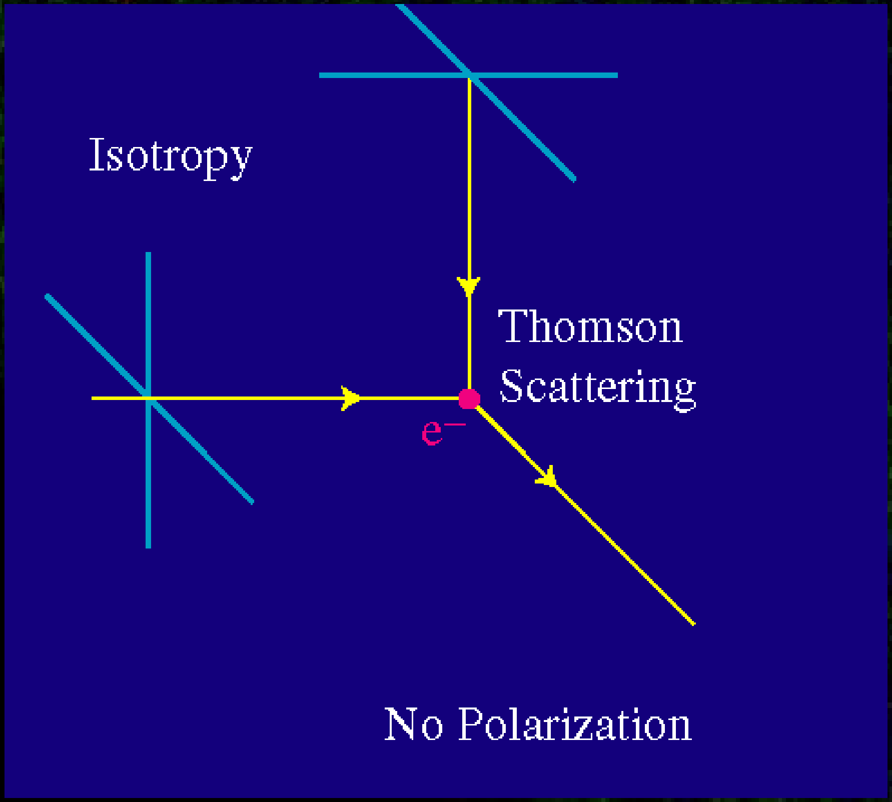


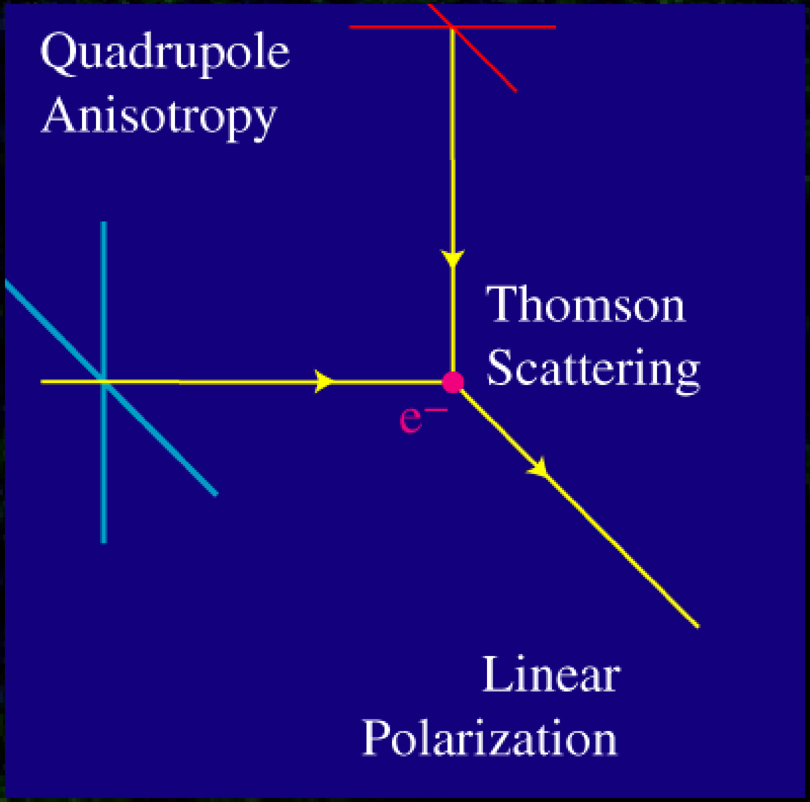
Small

Large

The CMB is polarized!

- Thomson Scattering is polarized
- On last scattering surface, quadripolar anisotropies generate polarization of CMB (~ 10%)
- Would bring a lot of information on the early Universe (grav. waves)
- Different polarisation “modes” (scalar E, tensor B)

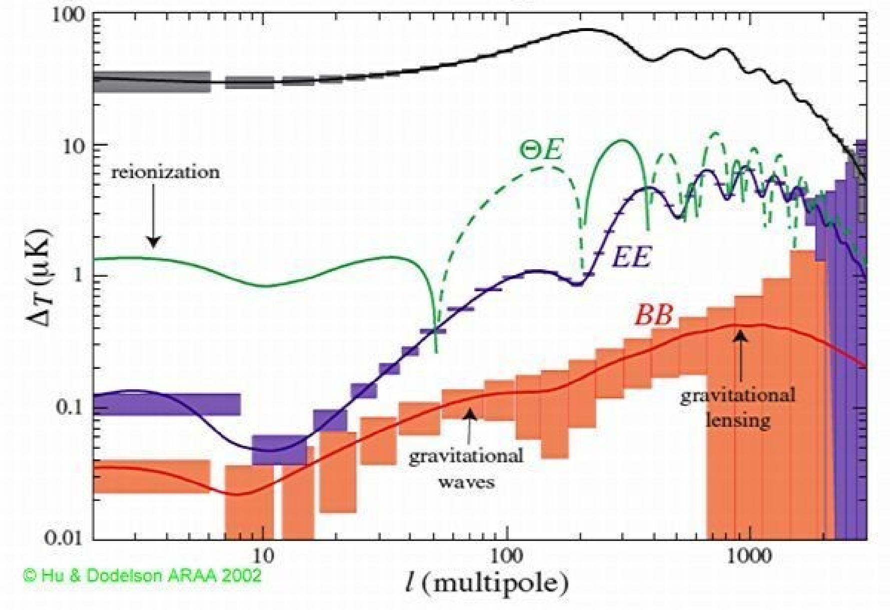




Polarisation @ Planck

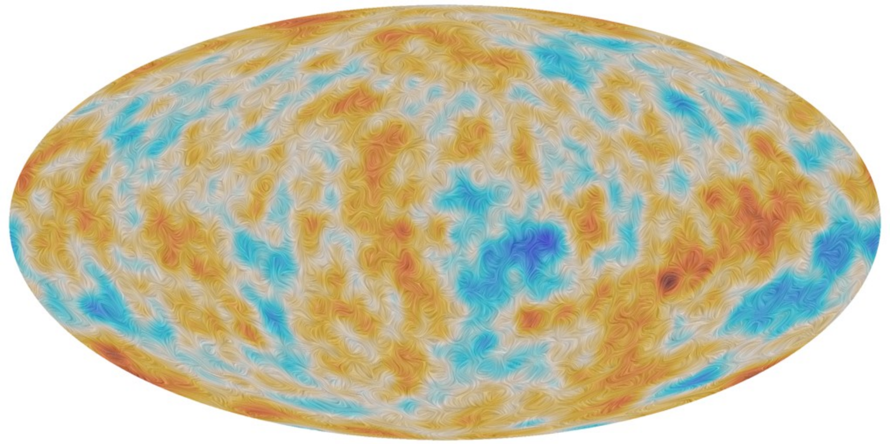
- ☐ 2015 results
- ☐ Polarisation of E field consistent with expectations (generated by CMB anisotropies)
- ☐ No evidence for grav. Waves (“ B modes”)

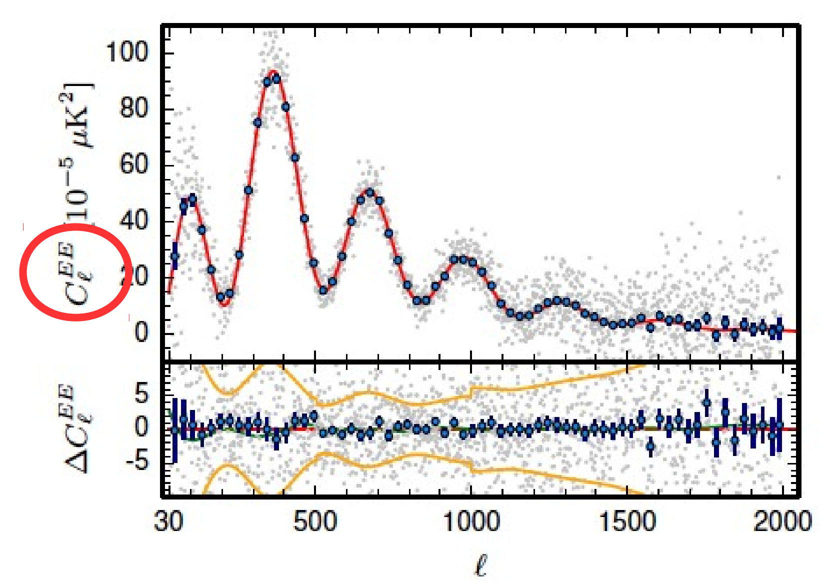
Predictions (@2002)

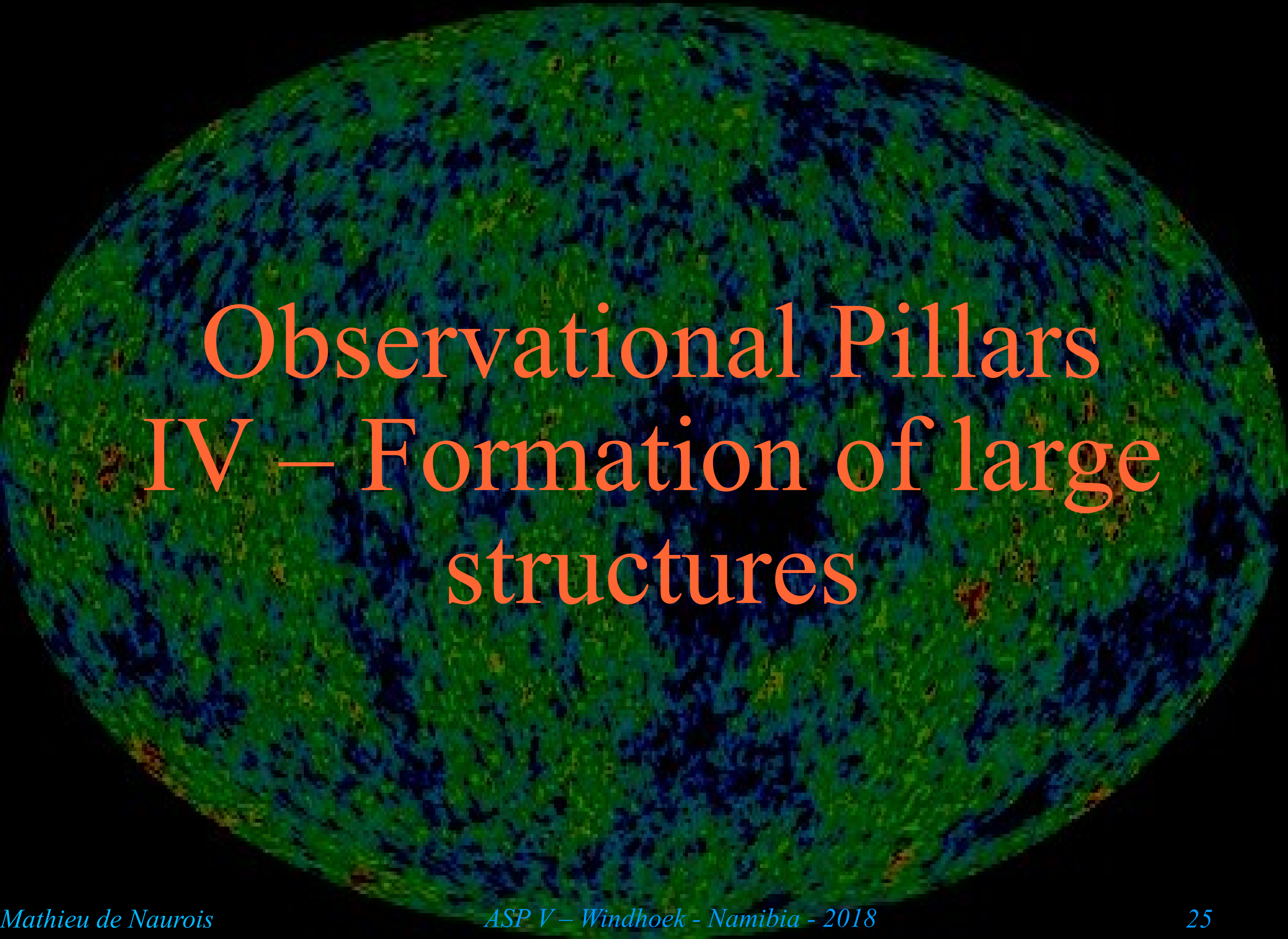


© Hu & Dodelson ARAA 2002

First results (@2015)

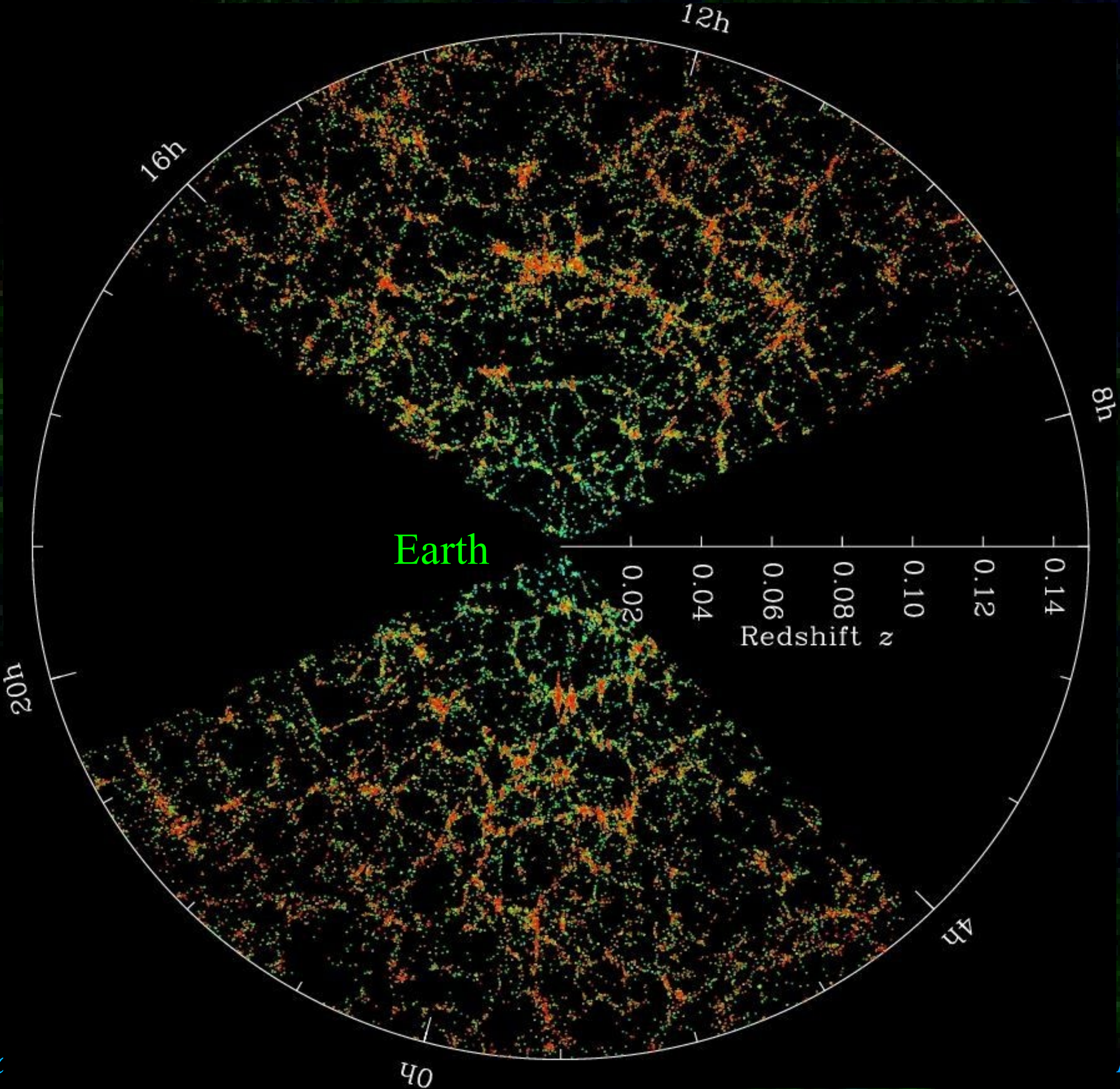






Observational Pillars IV – Formation of large structures

Distribution of matter

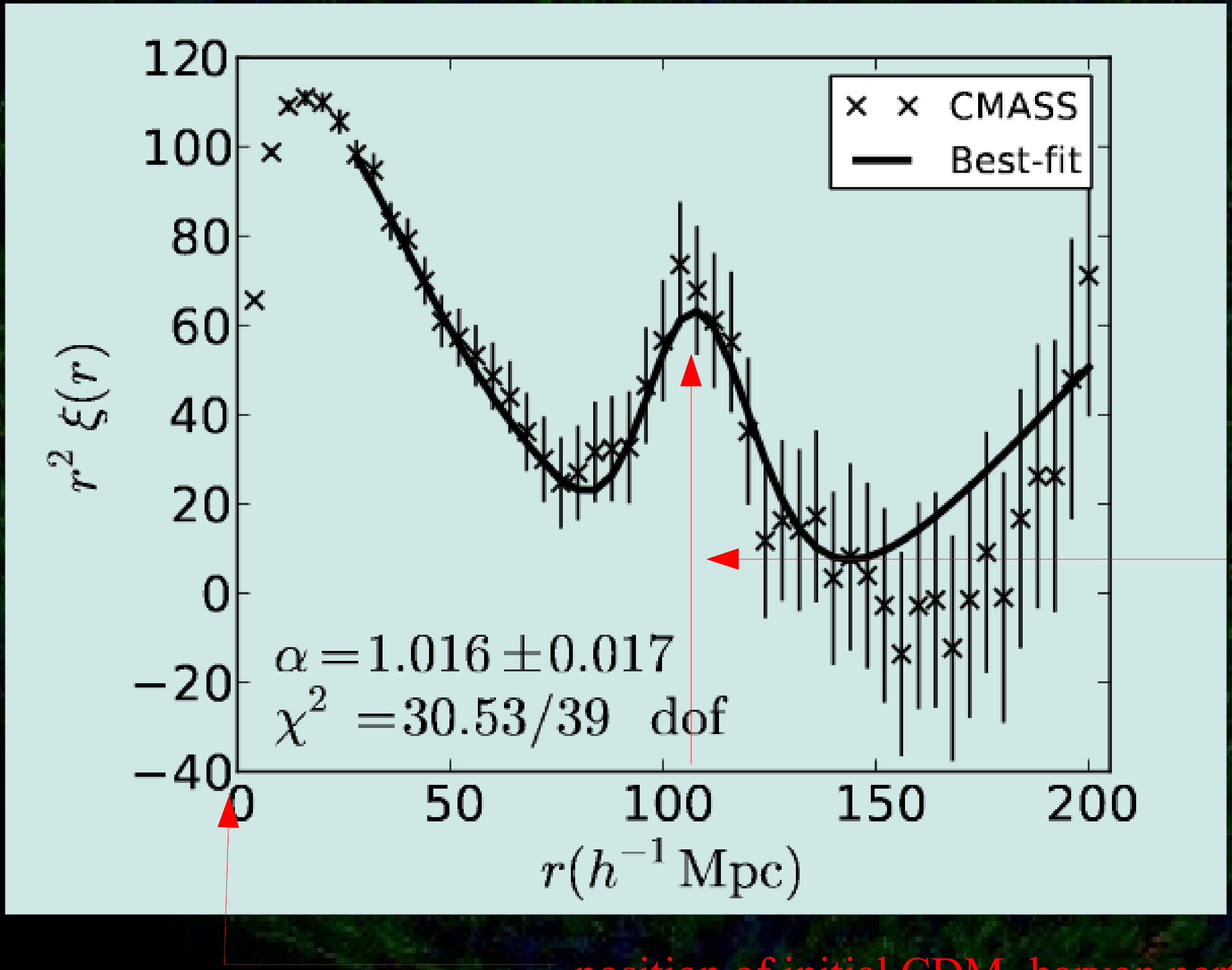


SDSS 2D Map,
of galaxies

3D Map contains
930 000 Galaxies

Baryonic Oscillations

- The acoustic peak of the CMB is also visible in the Galaxy distribution

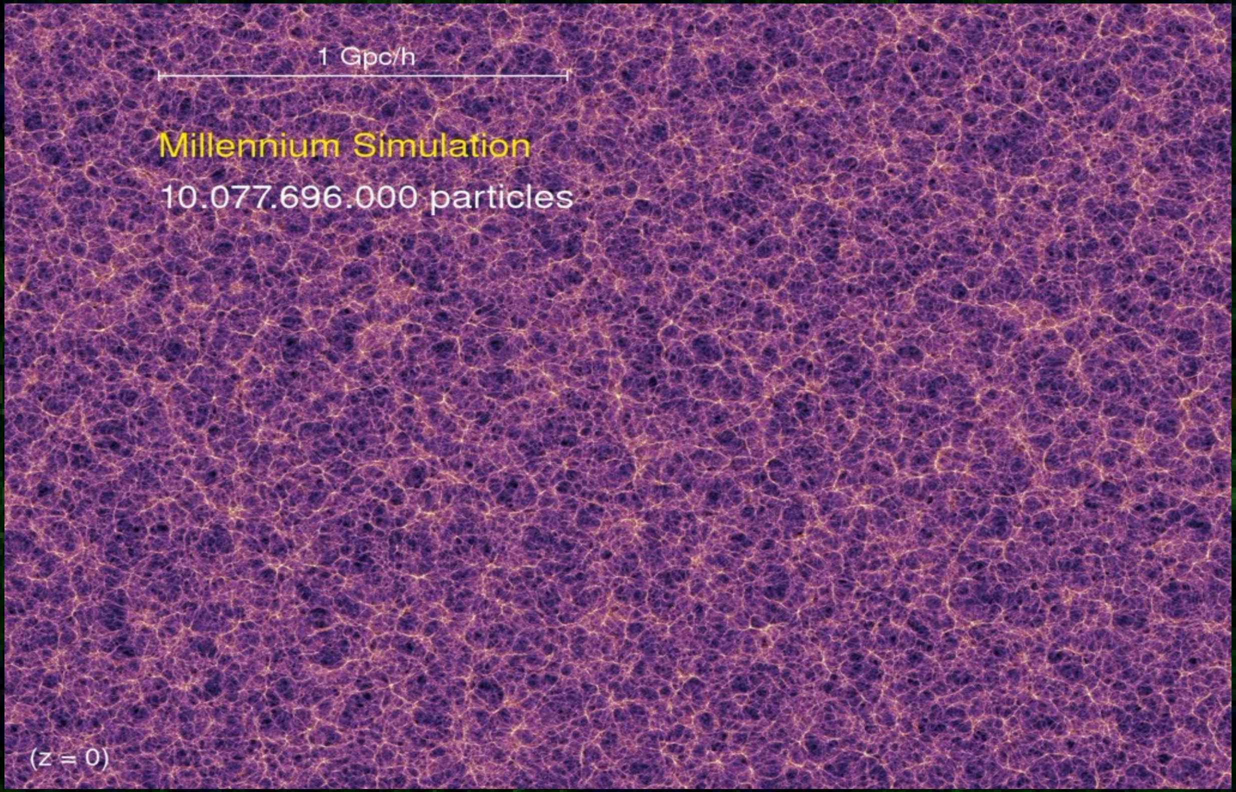


position of baryon sound wave at recombination

position of initial CDM−baryon perturbation

Simulated Universe

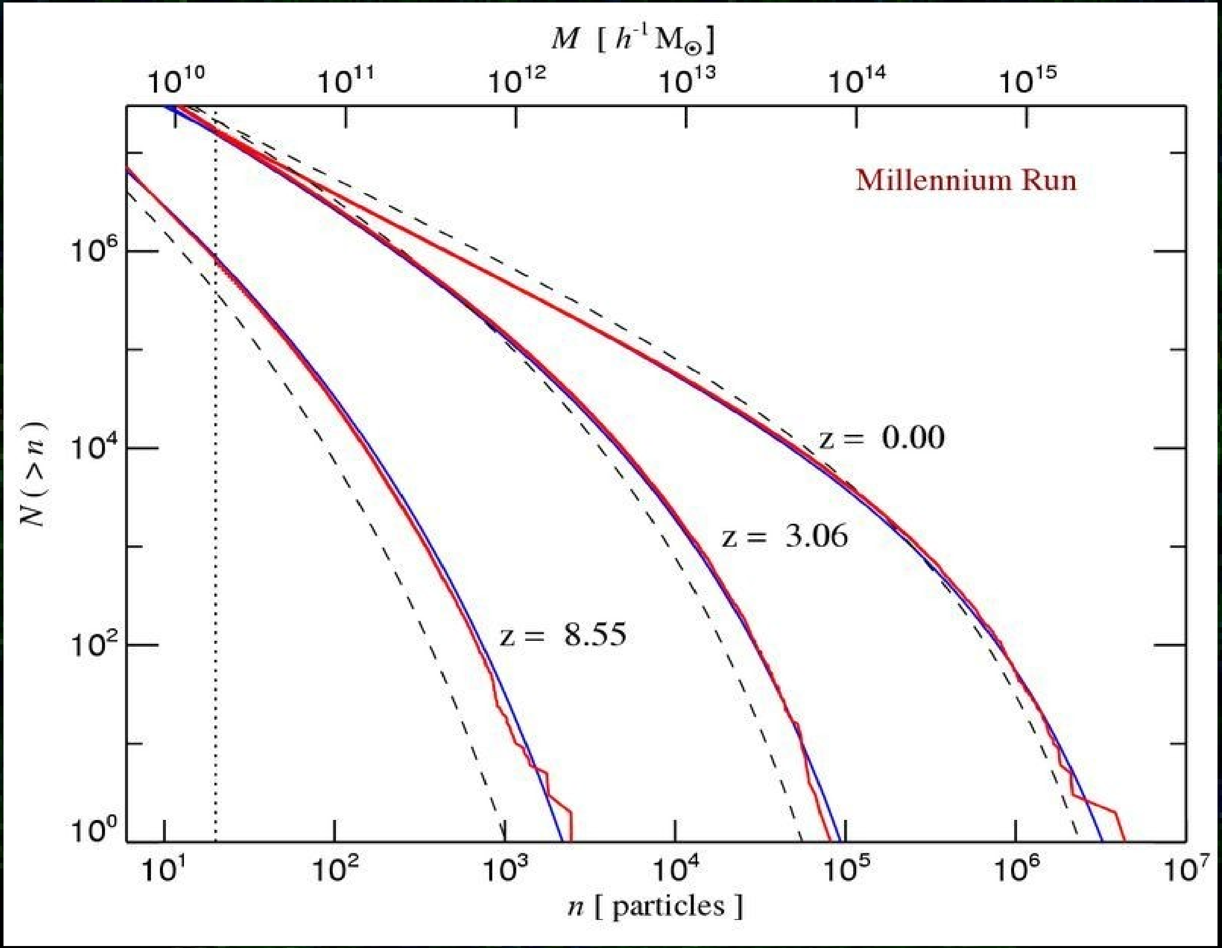
- ☐ Dark matter is the driver for structure formation

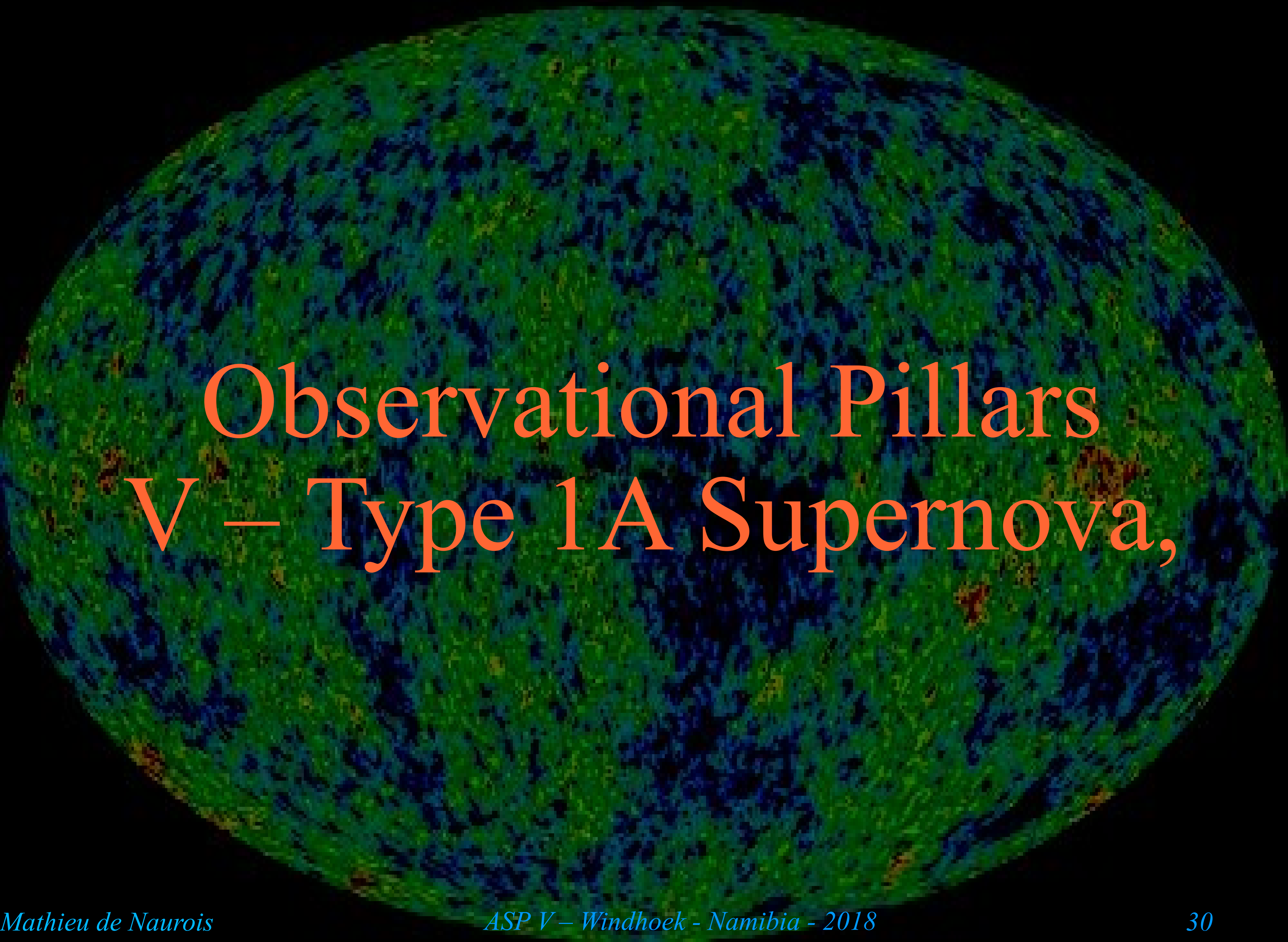


Millennium Simulation, Springel et al. (2005) ,

Mass Function

- Observed mass distributions well reproduced when incorporating dark matter
- In the absence of dark matter, predicted structures are too small



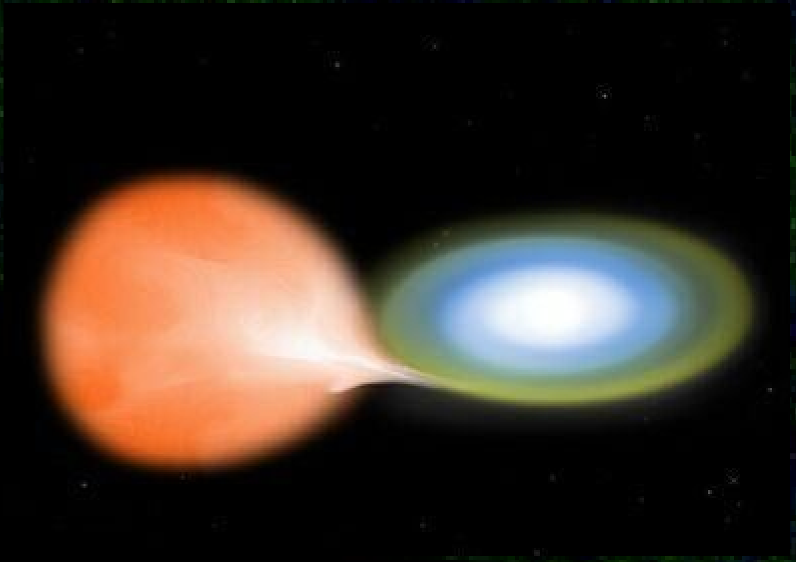


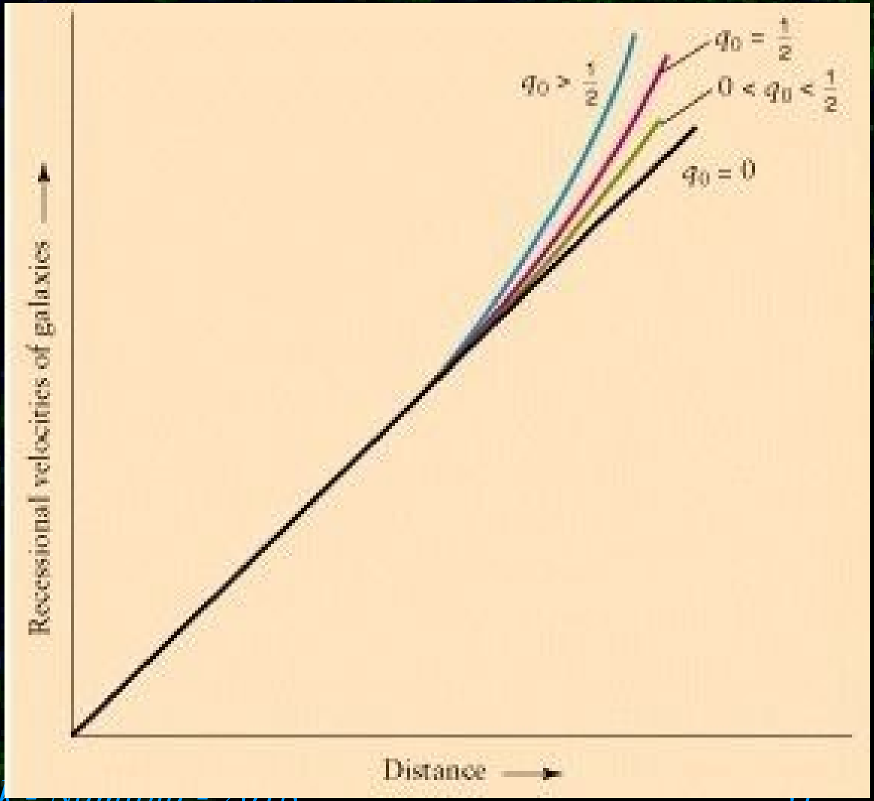
Observational Pillars
V – Type 1A Supernova,

Type Ia Supvernova

- Accreting white dwarf exploding when reaching the Chandrasekhar mass
- Almost Standard Candles
- Luminosity – redshift relation is related to history of the Universe

$$d \propto \int \frac{\mathrm{d}\,z}{H(z)}$$

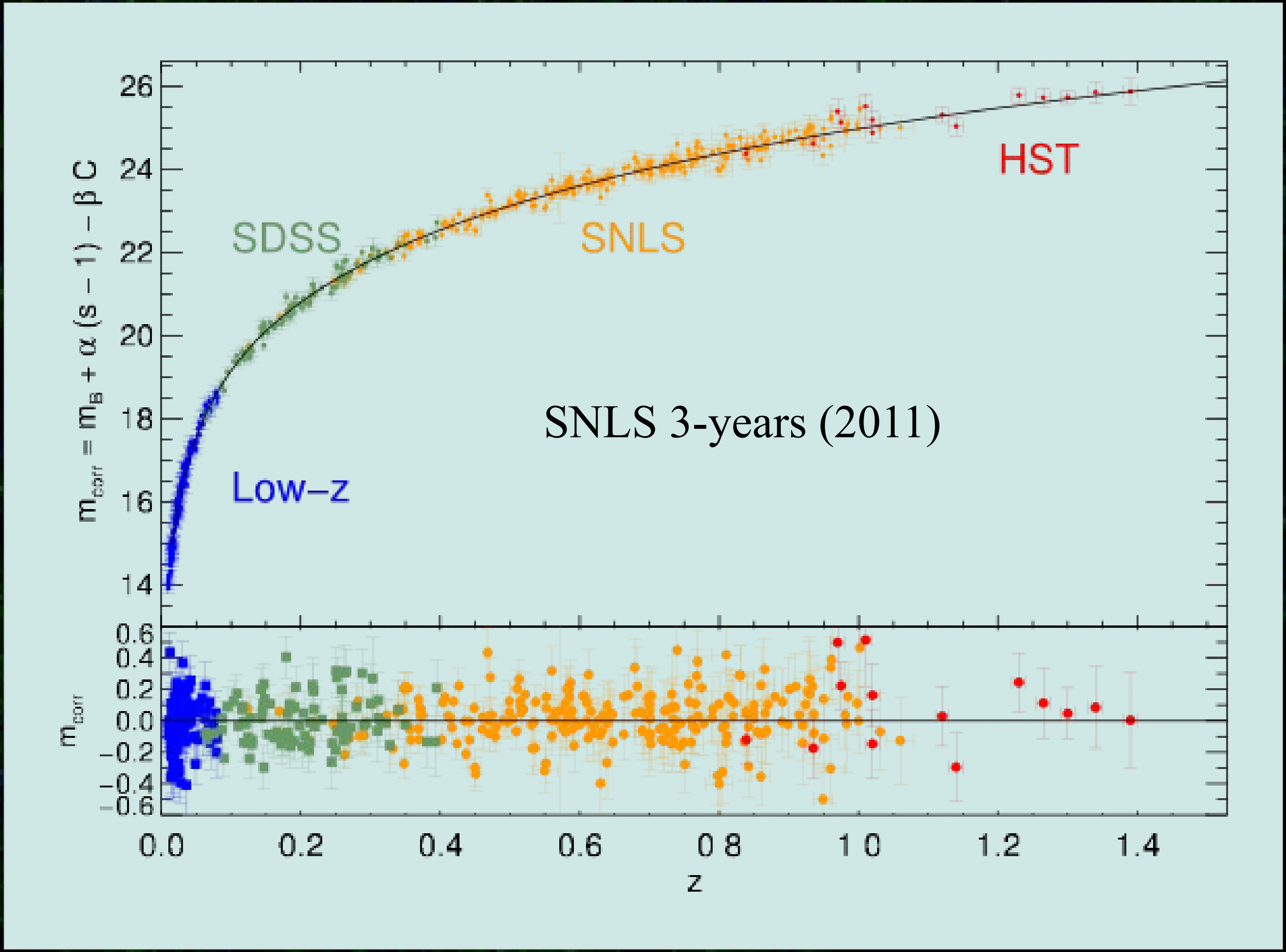




Hubble Diagram

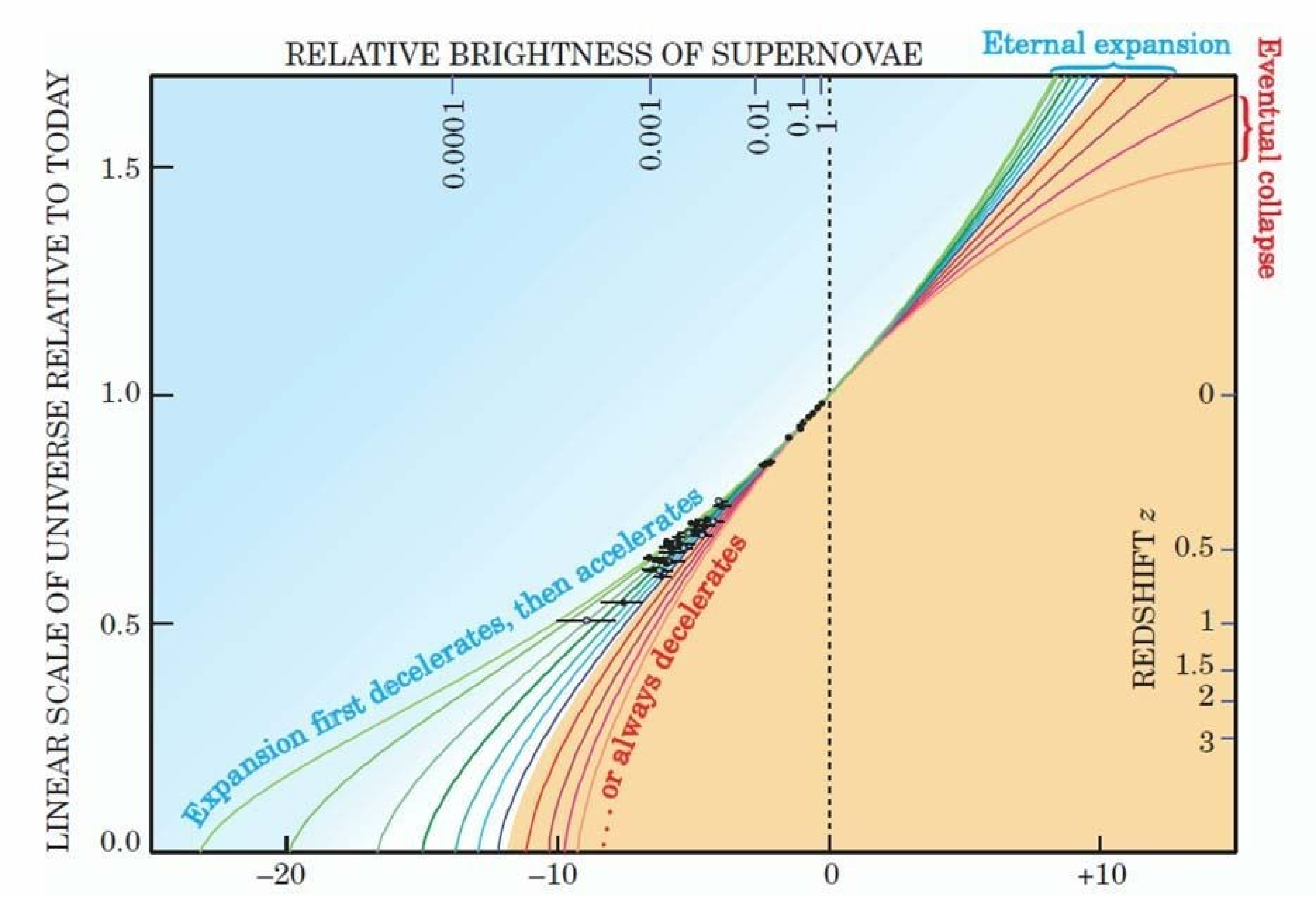
-log(flux) ~ 2 log(distance)

redshift



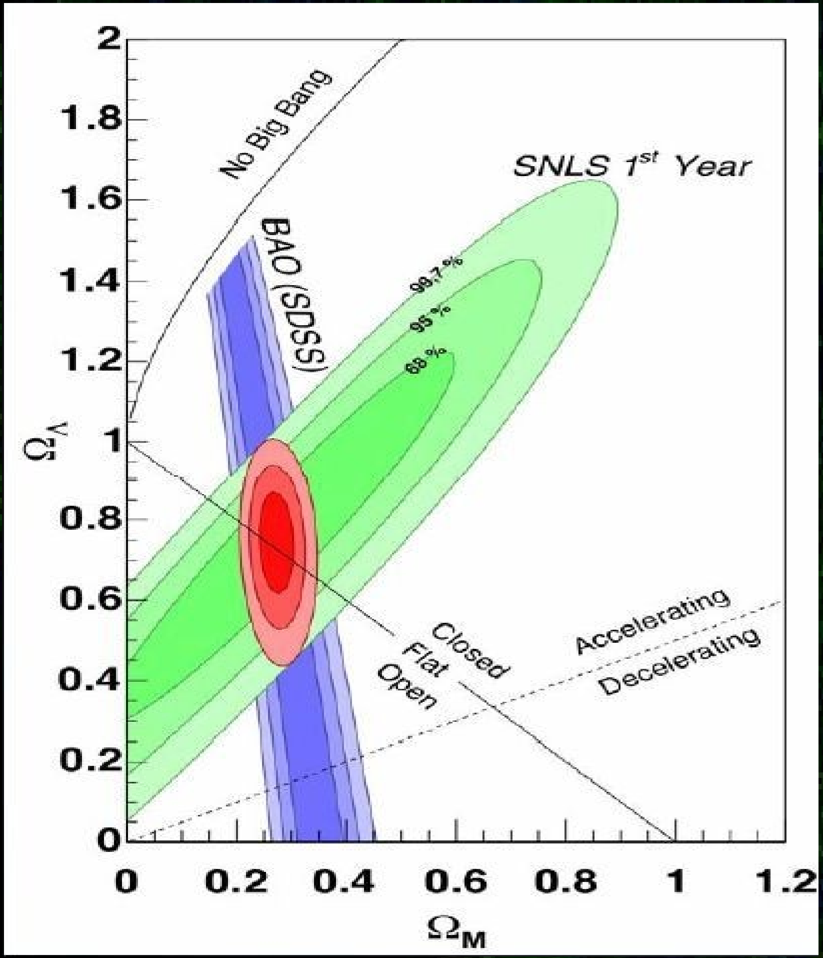
SNLS 3-years (2011)

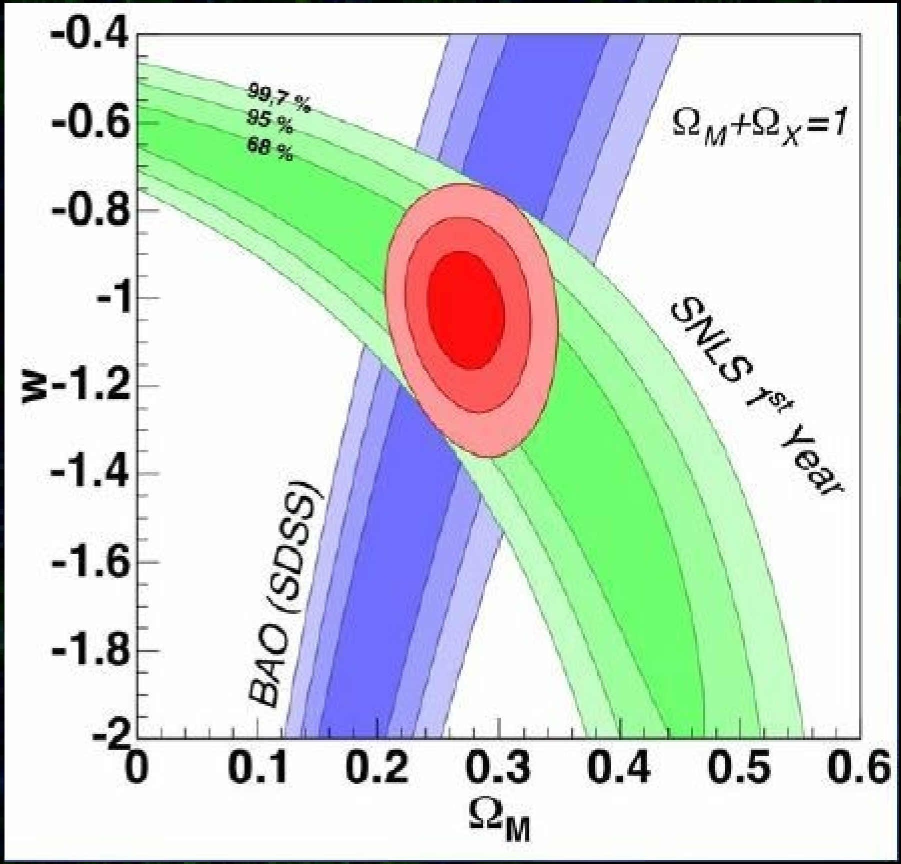
SNI1a: Universe in accelerated Expansion

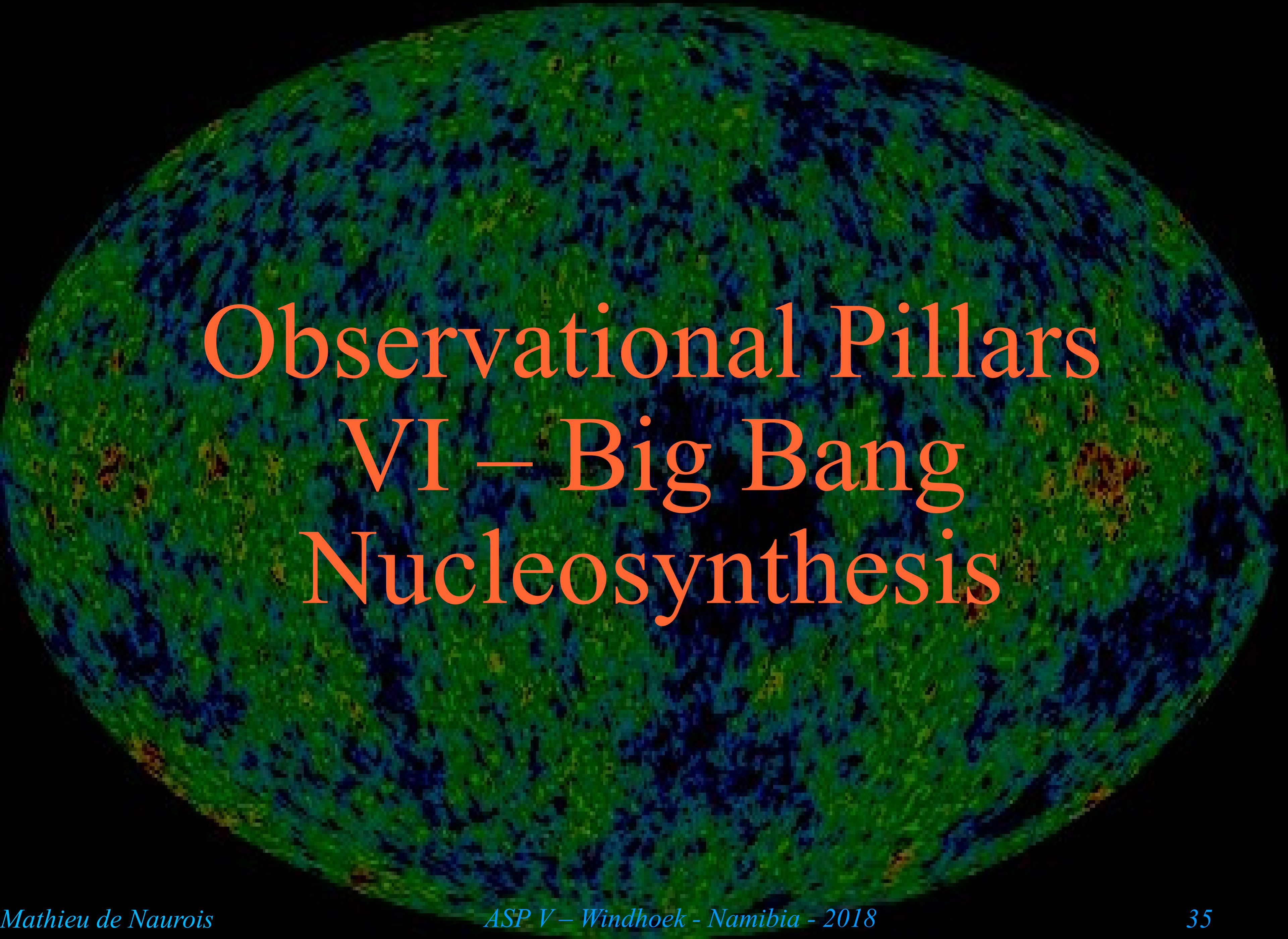


CFHTLS / SNLS

- ☐ Toward a FLAT universe, with cosmological constant (only using supernova and baryonic oscillations)







Observational Pillars VI – Big Bang Nucleosynthesis

Baryogenesis

- The observed abundances of light elements according to mass fraction are:
  - Hydrogen 75%
  - Helium 24%
  - Heavier (“Metals”) ~1%
- Why?
- Big Bang Nucleosynthesis (BBN) happens on small scales at energies below 10 MeV, hence we should have complete control over the physics (unlike the very early Universe).
- BBN predictions are very sensitive to ambient conditions at t ~ 1 sec (T~ 1 MeV). Hence the constraints on new physics are some of the best available...

Summary of Baryogenesis

- Baryogenesis starts by formation of neutrons (mandatory for deuterium):

$$n + \nu_e \Leftrightarrow p + e^-$$

  - In competition with Universe expansion
  - Number of neutrons frozen at
  - Neutrons number decreases due to decay, until temperature is low enough that Deuterium is stable

$$T_c \approx 0{,}8\,\mathrm{MeV} \quad \Rightarrow n/p \approx 5$$

$$\tau_n = 885{,}7 \pm 0{,}8\,\mathrm{s}$$

$$t \approx 200\,\mathrm{s} \quad \Rightarrow n/p \approx 0{,}125$$

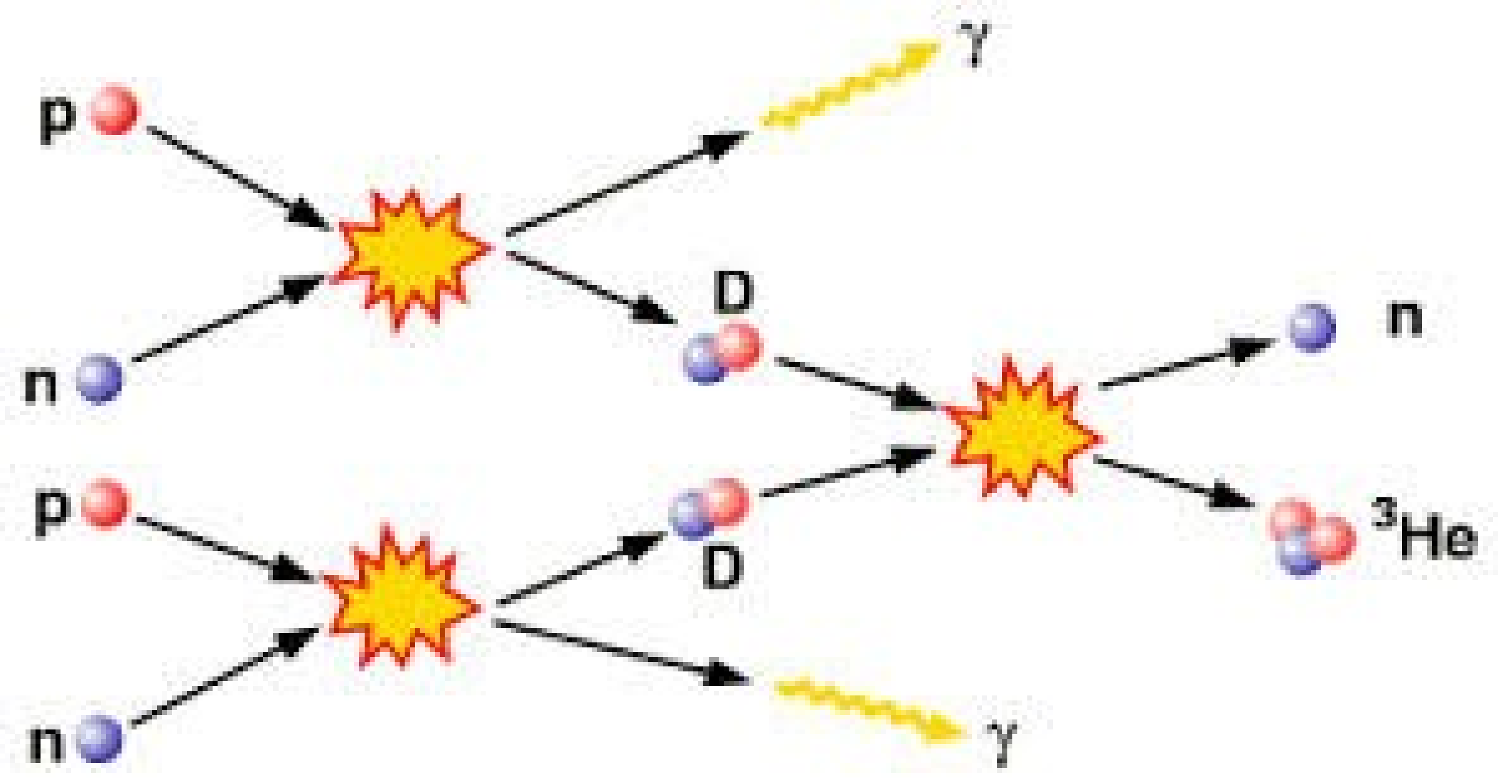
- Using all available neutrons, fraction of formed Helium is:

$$X_{^4\mathrm{He}} \approx 2 \times (n/p) = 0.25$$

  - Consistent with observations

Baryogenesis – Starting Point

- As in the Sun, first reaction is Deuterium production
  - Availability of neutrons is essential! (in the sun, produced by β+ reaction)



Baryogenesis

- ☐ Relative abundances under thermal equilibrium:

$$M_i \propto (m_i T)^{3/2} \exp\left(\frac{-m_i}{T}\right)$$

- ☐ Equilibrium ratio of neutrons to protons (weak interactions)

$$\frac{n}{p} \approx \exp\left(-\frac{Q}{T}\right) \quad \text{where} \quad Q = m_n - m_p \approx 1{,}29\,\mathrm{MeV}$$

- ☐ At high T, n ~ p, whereas at low T, n/p → 0
  - ☐ Need tuning of baryogenesis temperature
  - ☐ In competition with expansion of the Universe
  - ☐ In competition with neutron decay

Equilibrium ?

- Equilibrium condition valid only when reaction rate is large enough

production rate

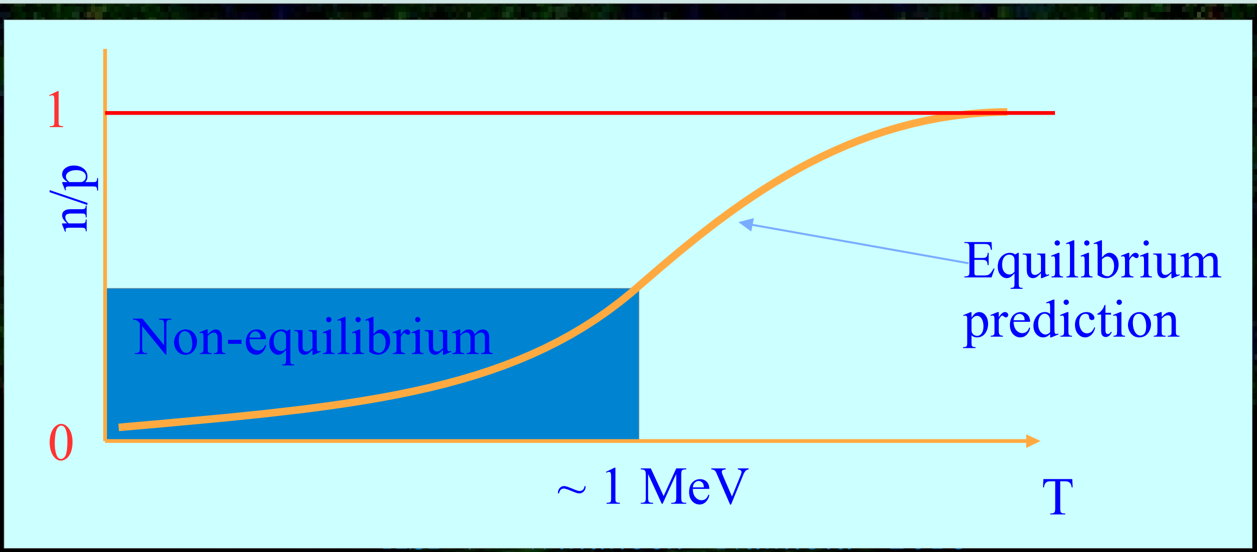
$$\Gamma > H = \left(\frac{\dot{a}}{a}\right)$$

expansion of Universe

$$n + \nu_e \Leftrightarrow p + e^-$$

- Freeze-out temperature

$$\left.\begin{array}{l} \Gamma = G_F^2 T^5 \sim 10^{-10}\,\mathrm{GeV}^4\, T^5 \\ H \sim T^2 / M_{\mathrm{pl}} \quad \text{where} \quad M_{\mathrm{pl}} = 10^{19}\,\mathrm{GeV} \end{array}\right\} \Rightarrow T_c \approx 0{,}8\ \mathrm{MeV}$$



Predicted Ratio

- At freeze-out

$$\frac{n}{p} \approx \exp\left(-\frac{Q}{T_c}\right) = \exp\left(-\frac{1{,}29}{0{,}8}\right) \approx 1/5$$

- With time, n/p decreases due to neutron decay:

$$\tau_n = 885{,}7 \pm 0{,}8\,\mathrm{s}$$

- Hence, at most we could form 33% of ^{4}He by mass(using all available neutrons) which is significantly larger than the observed 24%. Why is there only 24% helium?

Deuterium Bottleneck

- Production of Deuterium is at equilibrium at ~ 1 MeV

$$p + n \Leftrightarrow D + \gamma$$

- Equilibrium depends on the photon to baryon ratio. This is the only free parameter in the model:

$$\eta = n_B / n_\gamma \sim 10^{-8} \Omega_B h^2$$

- The theory then predicts, at T ~ 1 MeV, the following abundances:

$$X_D \sim \eta X_p X_n \quad 10^{-12} \qquad \text{where} \qquad X_D = 2 n_D / n_B$$

- While Universe is still too hot, Deuterium is immediately destroyed by encounter with high energy photons

Deuterium formation

- D stops being destroyed at t ~ 156 s (T = 0.08 MeV)
- At that time and until t ~ 200 s, all neutrons are used to produce Deuterium
- What is the neutron fraction at this time?
- Neutron decay decreased the number:

$$\tau_n = 885{,}7 \pm 0{,}8\,\mathrm{s}$$

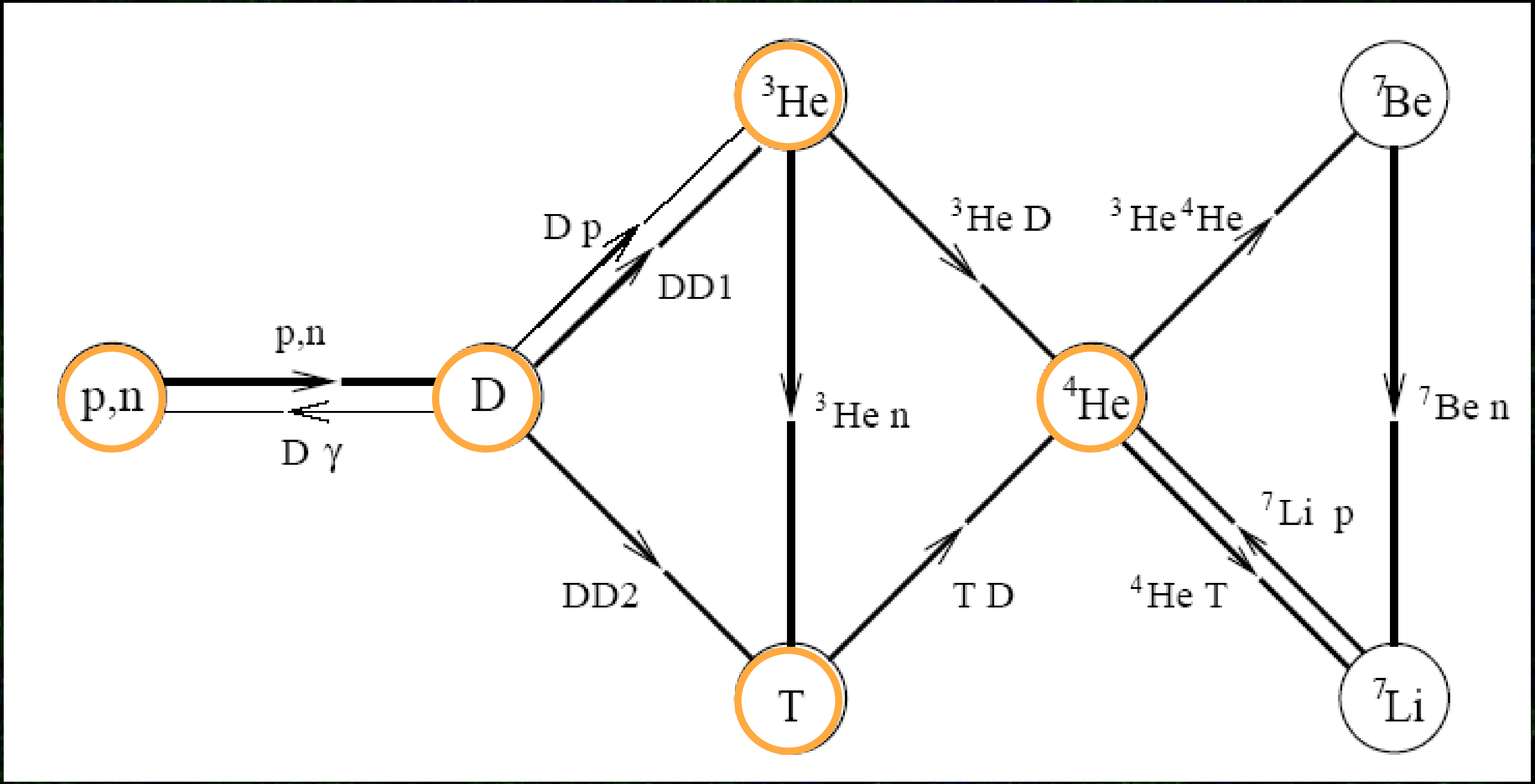
- At t = 200 s, the neutron ratio decreased to

$$\frac{n}{p} = \frac{n_0}{p_0} \times \exp\left(-\frac{t}{\tau}\right) \approx \frac{1}{6}\exp\left(-\frac{200}{886}\right) = 0.125$$

- So we expect:

$$X_{^4\mathrm{He}} \approx 2 \times (n/p) = 0.25$$

Going to Heavy Elements

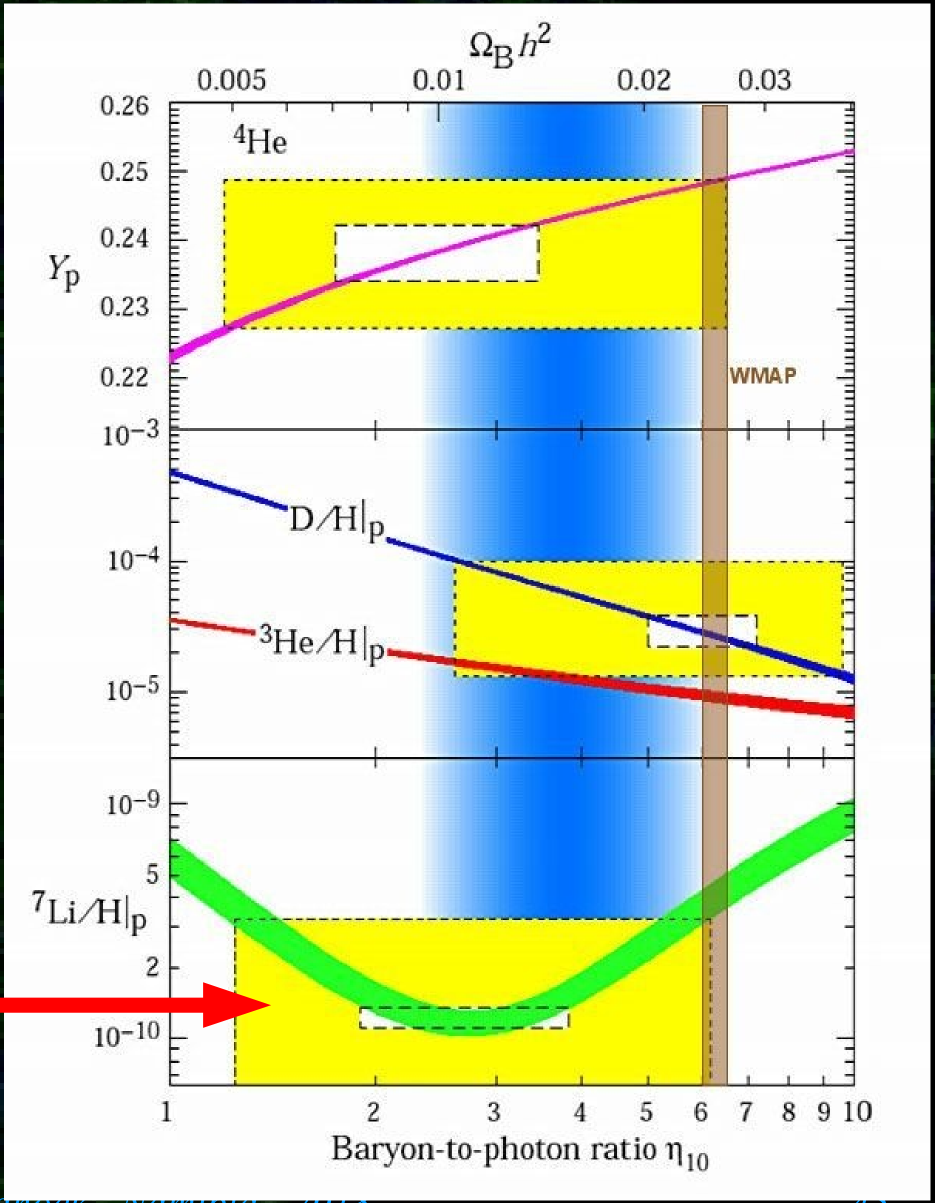


- ❑ Subsequent production of elements up to Lithium can be calculated
- ❑ Heaver elements not produced in Big Bang, but in stars

Predicted Relative Abundances

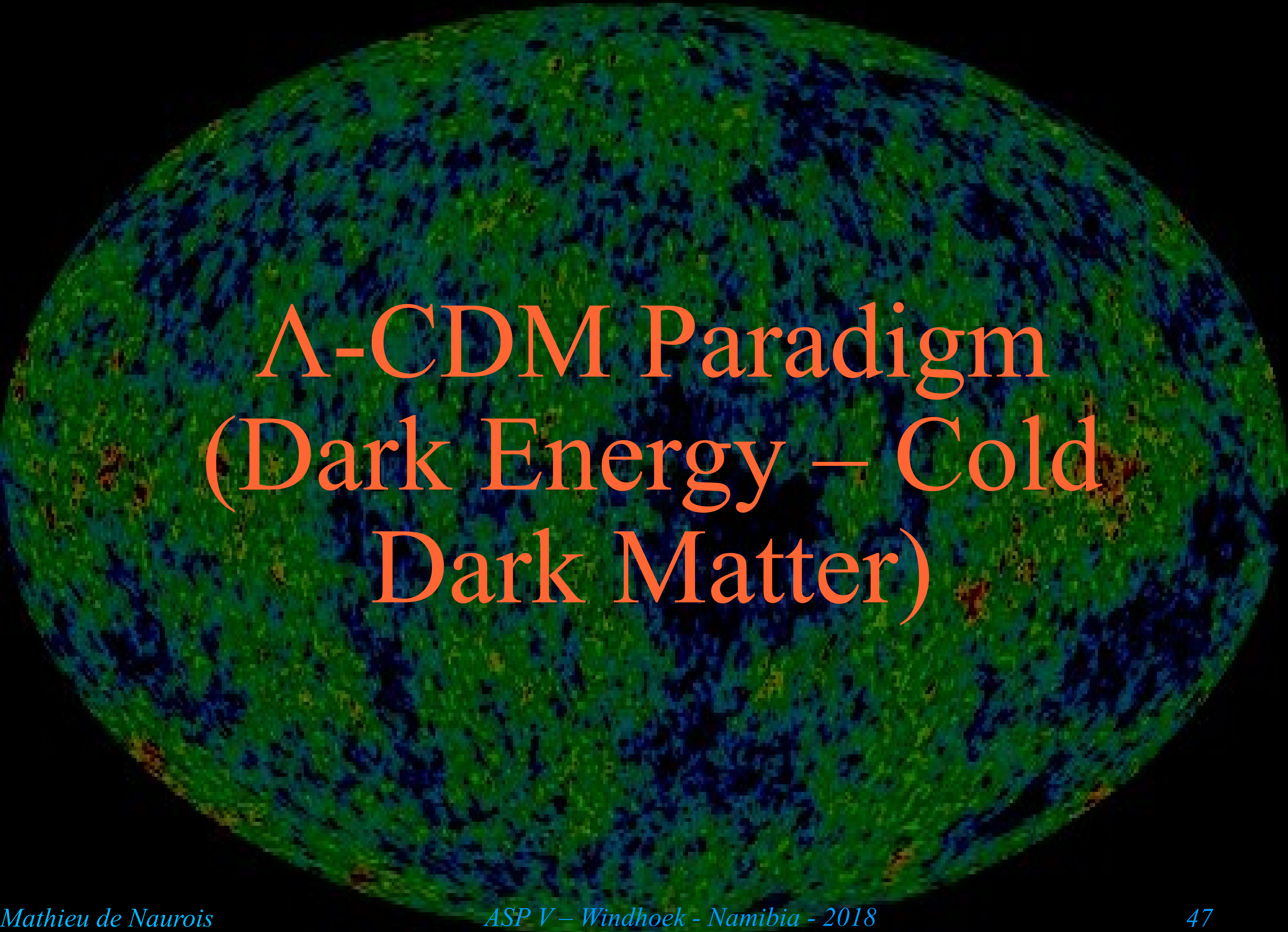
- Evolution of abundances as function of baryonic content of the Universe
- When taking everything into account, observed abundances match well the predictions
- They are self-consistent and give $\Omega_B \sim 0.04\text{-}0.05$, consistent with other measurements
- Only free parameter: photon to baryon ration

Measured abundances



The Miracle

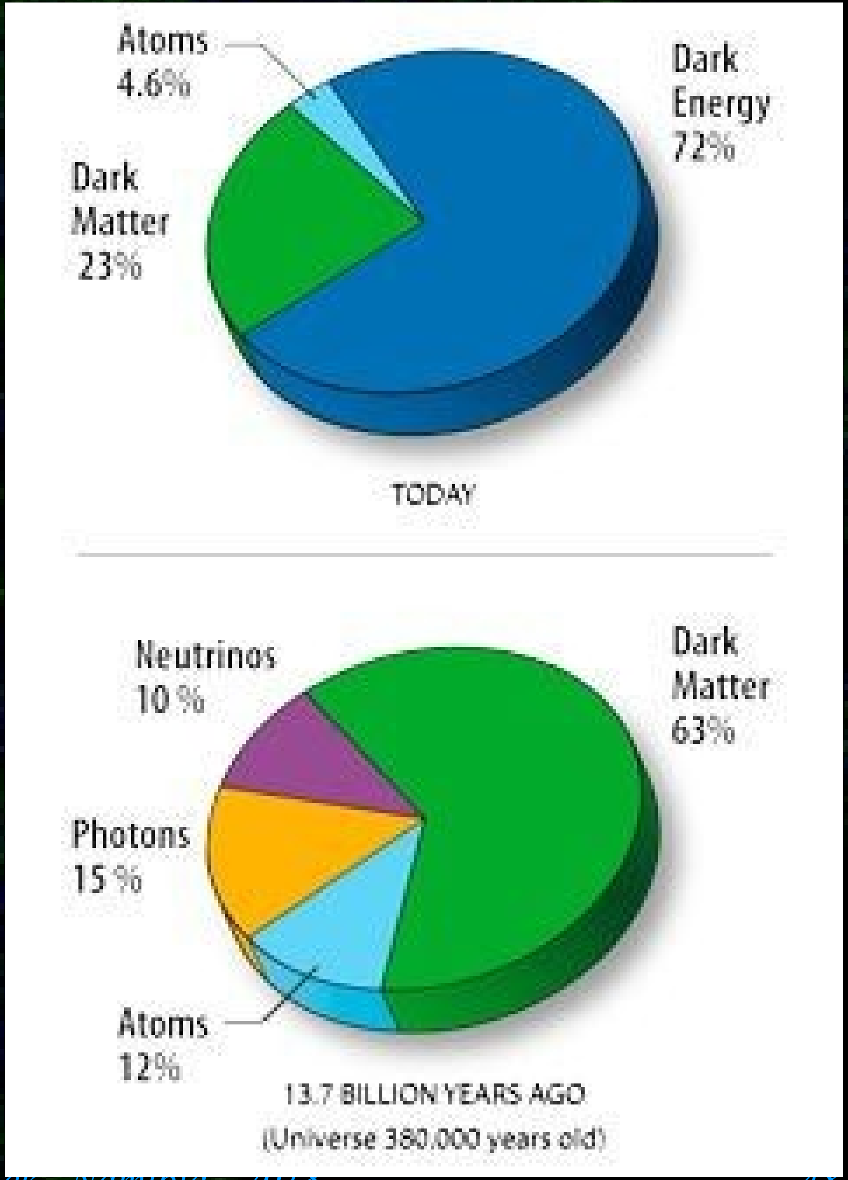
- The abundance of light elements is very sensitive to two things:
    - The age of the universe when the temperature drops to 0.08 MeV (neutron decay – D production)
    - The expansion rate of the cosmos at T ~ 1 MeV (freeze-out)
- Why does the expansion rate permits freeze-out at T = 1 MeV? Later freeze out would result in no neutrons at all, thus no life
- Why is the neutron life time such as the fraction at T = 0.08 MeV is still significant? Shorter life-time will result in no matter



Λ-CDM Paradigm (Dark Energy – Cold Dark Matter)

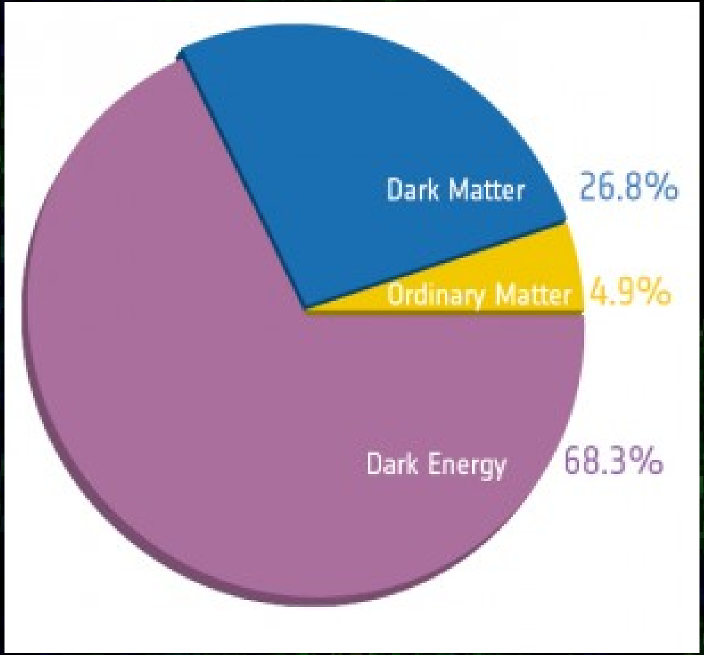
Composition of the Universe

- Robust model based on several pillars:
  - Expansion measurement (Supernova, ..)
  - Astronomical observation of dark matter (rotation curves, ...)
  - CMB
  - Formation of large structures
  - Big bang nucleosynthesis
- Dark energy dominated (now)
- Was matter dominated in the past
- Was radiation dominated in early times

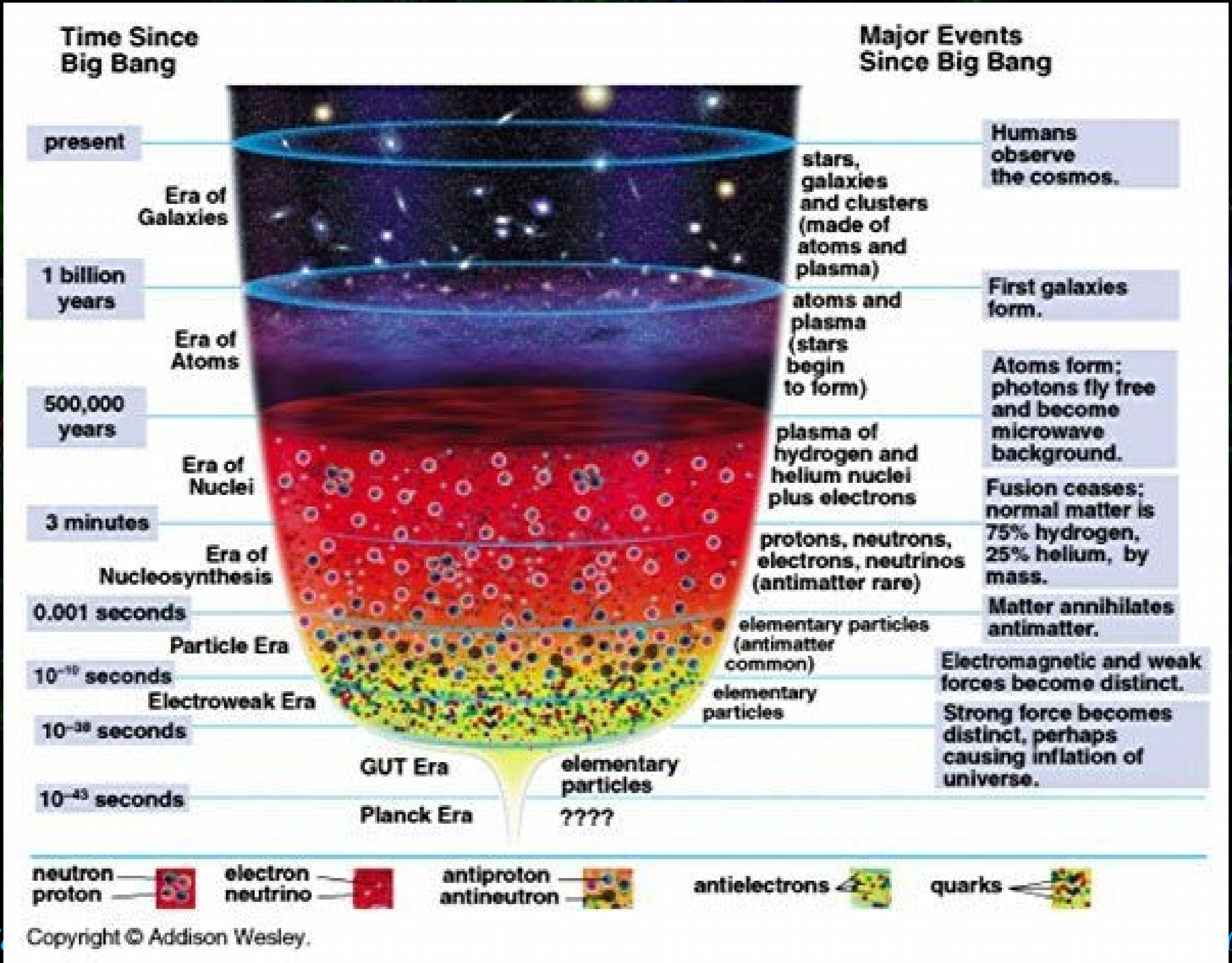


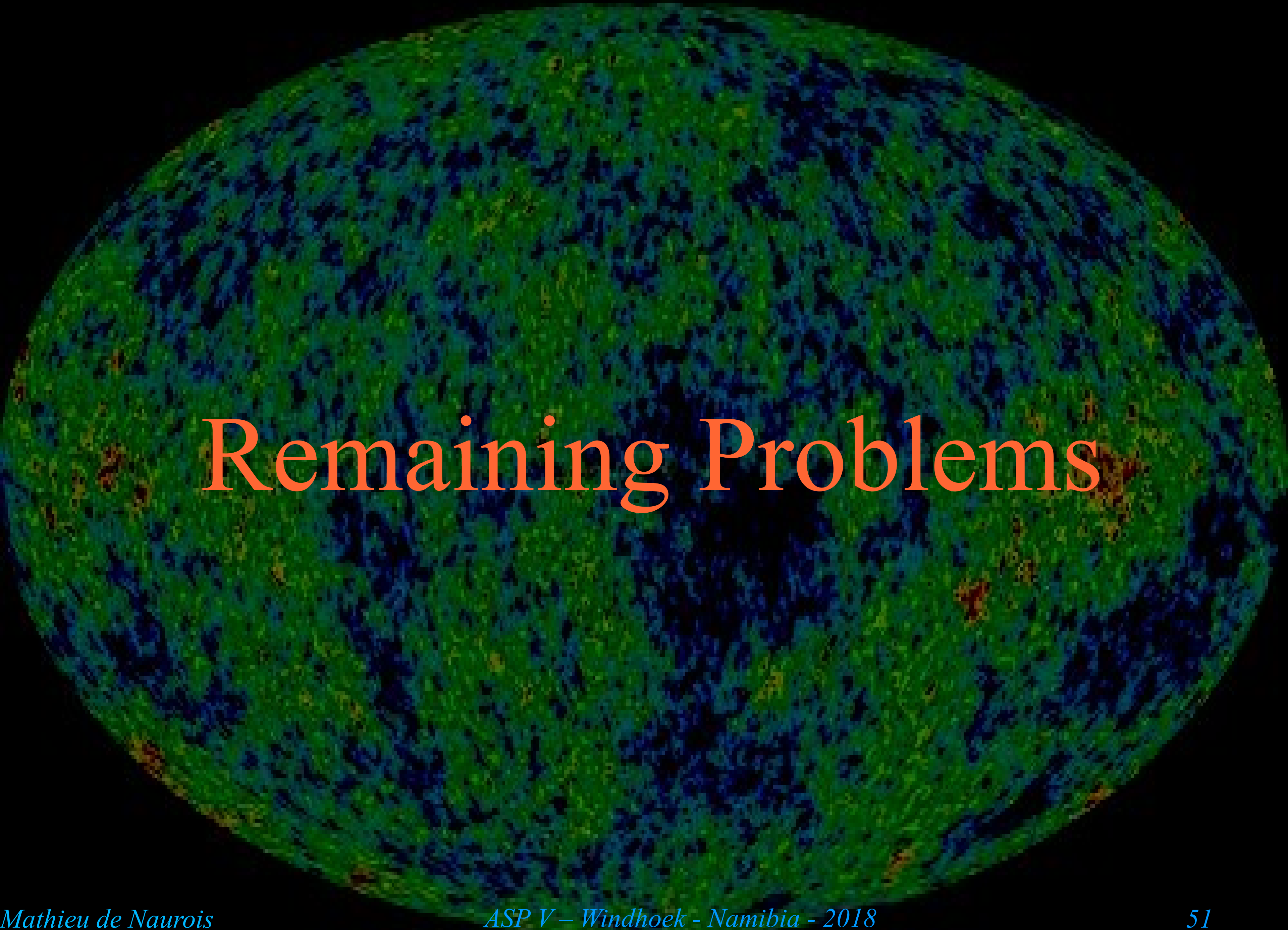
ΛCDM model @ 2016

- Baryons
  - $\Omega_{baryon} = 0.0486 \pm 0.0010$
- Cold Dark Matter
  - $\Omega_{CDM} = 0.2589 \pm 0.0057$
- Total Matter
  - $\Omega_{M} = 0.3089 \pm 0.0062$
- Dark Energy (expansion is accelerating !)
  - $\Omega_{\Lambda} = 0.6911 \pm 0.0062$
  - $w = -0.980 \pm 0.053$ → cosmological constant!
- Critical density (spatially flat universe)
  - $\Omega_{T} = 1.0023 \pm 0.005$ → flat Universe
- Inhomogeneities : gravitational potential fluctuations



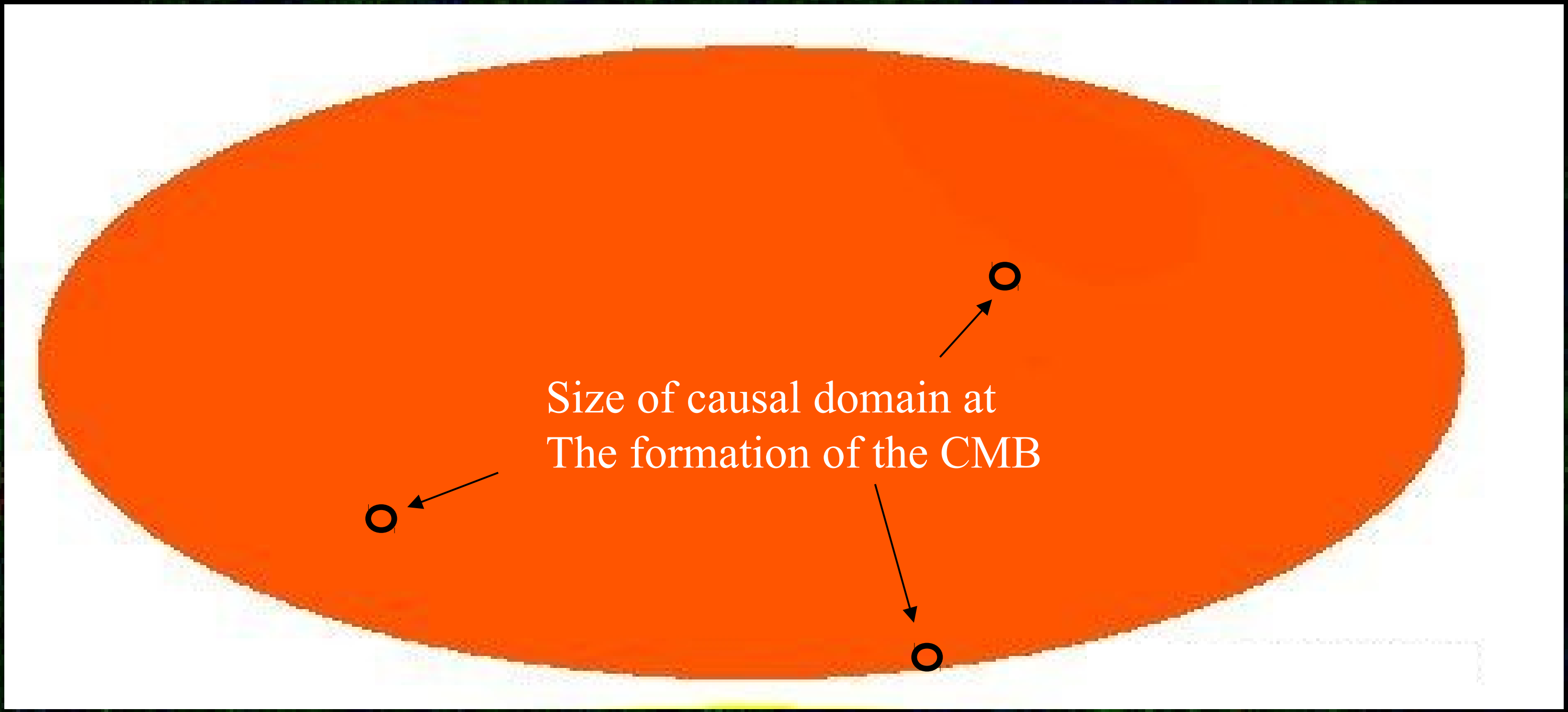
Brief Thermal History





Remaining Problems

Cosmic Problem 1 : Isotropy & Horizon



Size of causal domain at
The formation of the CMB

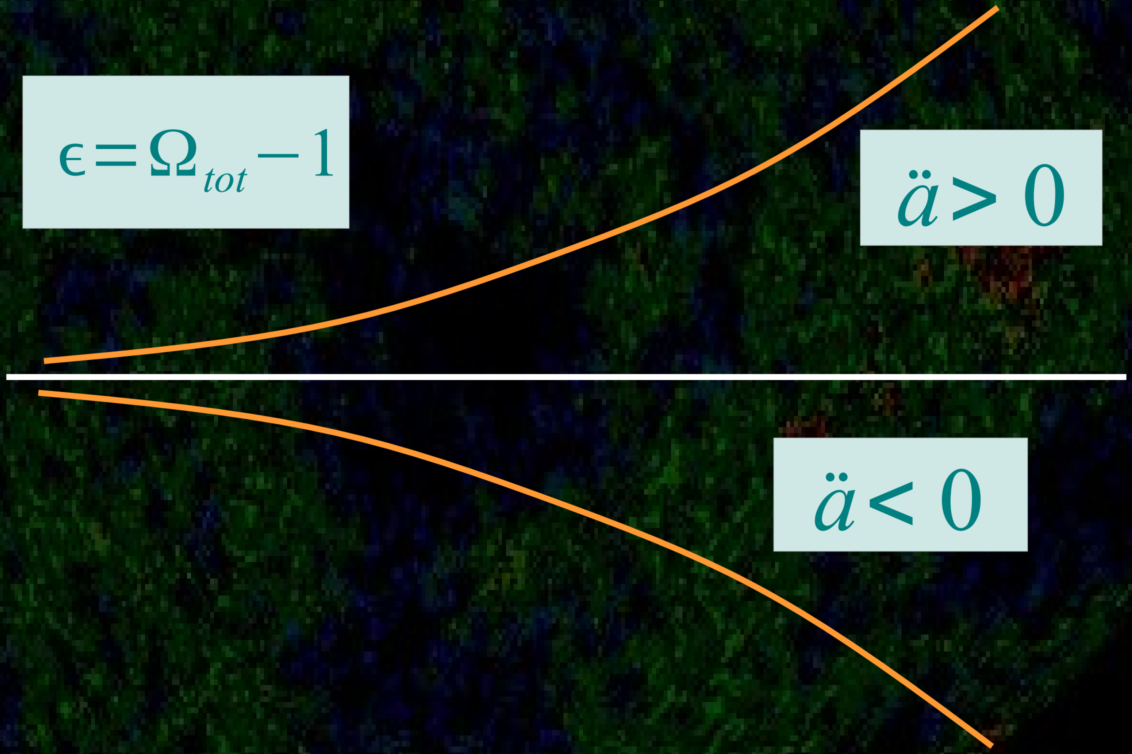
- The Universe is surprisingly homogeneous at large scale, though the horizon at decoupling time corresponds to ~ 1 degree
- How is it possible?

Cosmic Problem 2: flatness

- We know that our universe is flat to within a few percent…
- But gravity generate curvature… So the flatness of the cosmos is a mystery

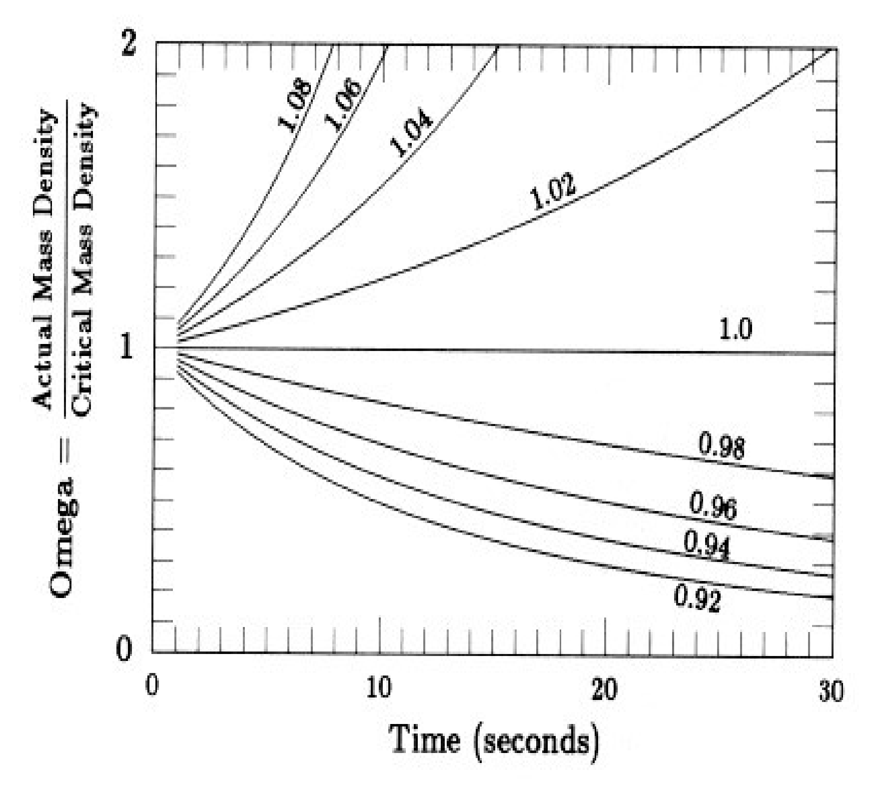
$$\dot{\epsilon} = -2\,\epsilon\left(\frac{\ddot{a}}{\dot{a}}\right)$$

$$\epsilon = \Omega_{tot} - 1$$



Flatness problem

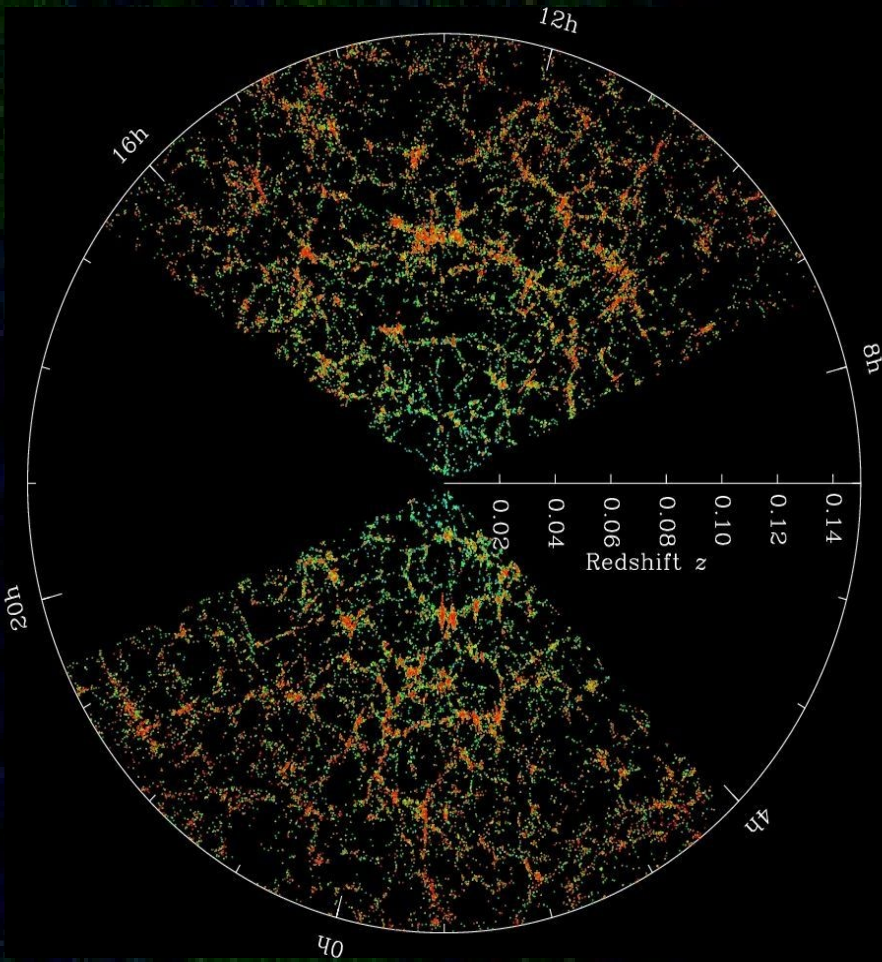
- ☐ Today $\epsilon = 0.01 \pm 0.02$
- ☐ @ $t = 10^{-43}$ s, this requires $\epsilon < 10^{-60}$



- ☐ Such a precise tuning seems completely unlikely

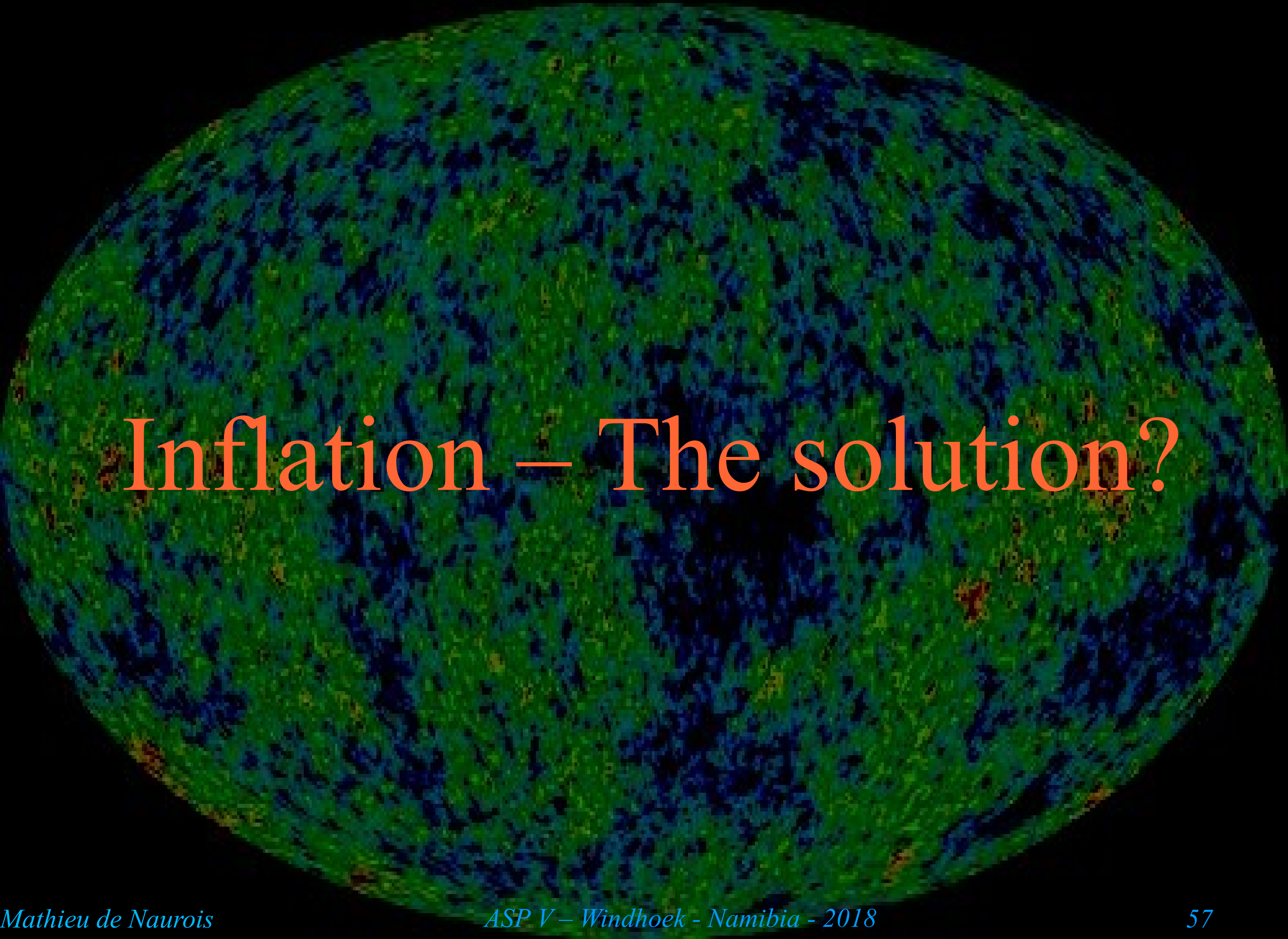
Cosmic Problem 3: Birth of fluctuations

- ☐ The simple big-bang Model does not provide enough seeds for the formation of structures
- ☐ One need to assume seed fluctuation much larger than simple quantum fluctuation at decoupling time



Cosmic Problem 4: the baryonic universe

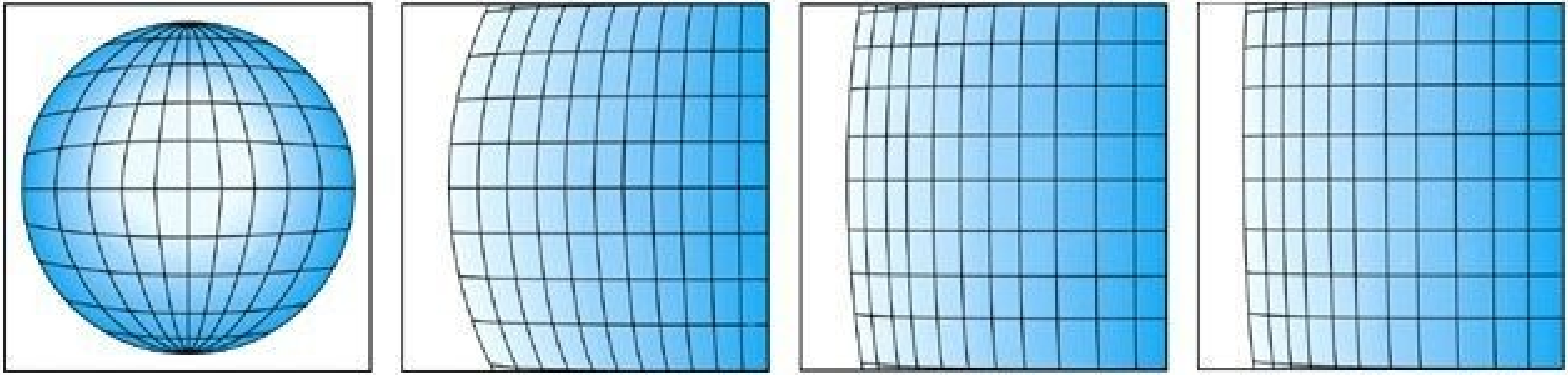
- There must have been a tiny matter - anti-matter asymmetry in the early universe: 10 000 000 001 protons produced for 10 000 000 000 anti-protons.
    - Anti-protons annihilated with protons, leaving ~1 proton per ~ 10^{10} photons today
      – why and how did this happen?
- We should expect no baryons at all… since they should have annihilated with an equal number of anti-baryons…
- To get an asymmetry requires non-equilibrium physics and violation of CP and B conservation
    - CP Violation in Standard Model (K & B mesons) is not sufficient, need physics beyond SM
    - Several mechanisms proposed (neutrino-induced CP violation, leptogenesis, ...)



Inflation – The solution?

Inflation – the solution?

- ☐ If the universe was in accelerated expansion it would become flat…

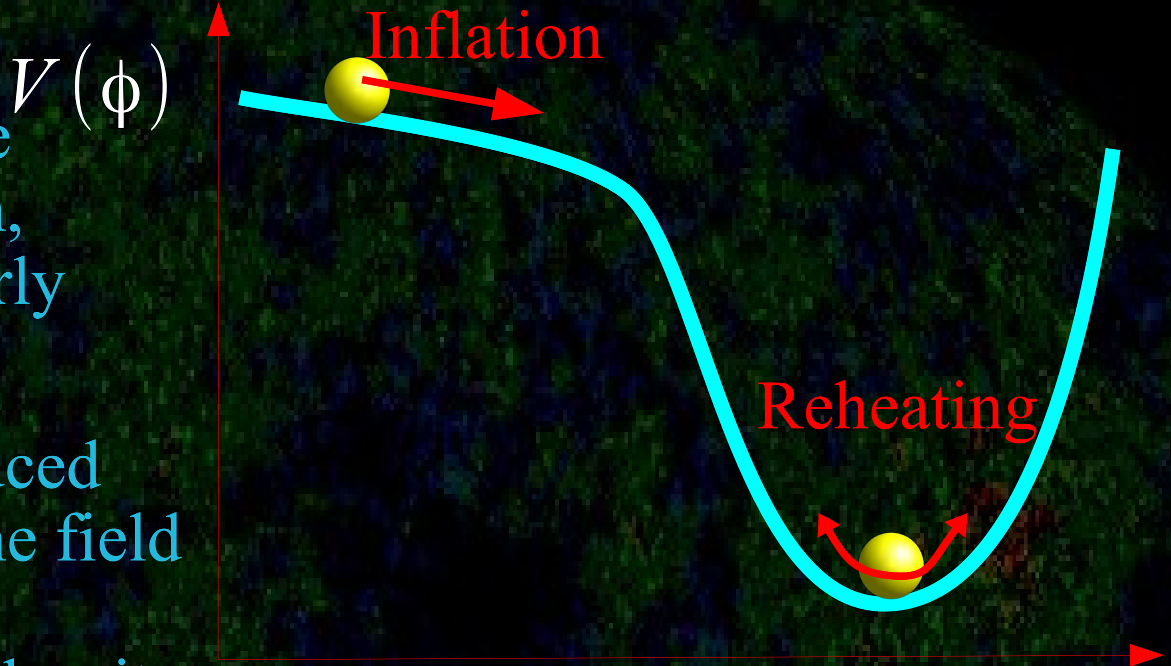


- ☐ Acceleration: Raychaudhuri equation (c=1)

$$\left(\frac{\ddot{a}}{a}\right) = -\frac{4}{3}\pi G \sum_i \left(\rho_i + 3\,p_i\right)$$

- ☐ Inflation requires negative pressure: $\rho_i + 3\,p_i < 0$
- ☐ But cosmological constant in negligible in early Universe

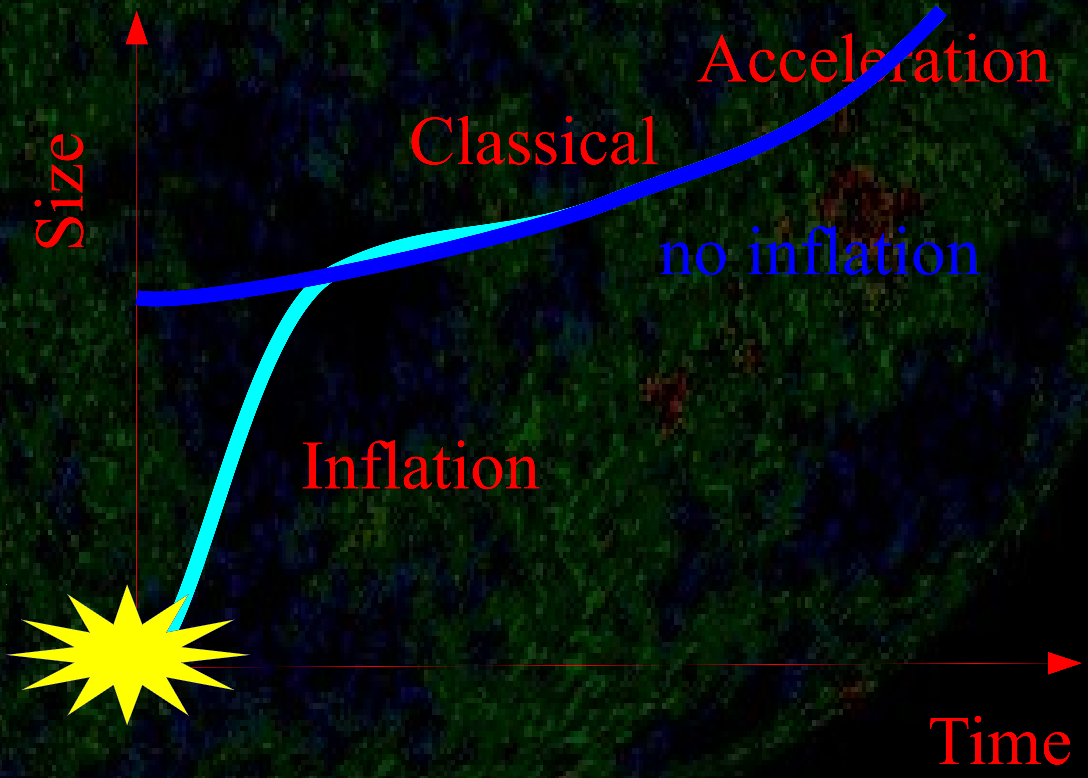
Inflation field



- A scalar field, the so-called inflaton, dominates the early Universe
- Inflation is produced by slow-roll of the field
  Flat potential → Uniform energy density → acts as a slowly decreasing cosmological constant
- Inflation stops around minimum of potential, released energy by inflaton decay reheats the medium and gives rise to particle production
- Then follows a classical Universe

Inflation

- ☐ Inflation begins around 10^{-33} seconds after the big bang and expands the Universe by a factor 10^{30} to solve the cosmological problems
- ☐ The quantum seeds for structures are expanded by the same factor
- ☐ Inflation naturally leads to a flat Universe
- ☐ Inflation increases naturally the size of homogeneous regions
- ☐ It could be related to the Higgs field
- ☐ Still need to be proved!



Conclusion

- The Λ-CDM hot big-band model is well established by a large number of observations, relying on several consistent pillars
- The Universe has entered an accelerated expansion phase
- BUT the very early days of the Universe remains mysterious. Several problems point toward an inflation.
  - What is the inflation field? What is its potential form? Where does it come from? Do we actually need inflation?
  - What is the Dark Matter?
  - What is the Dark Energy?