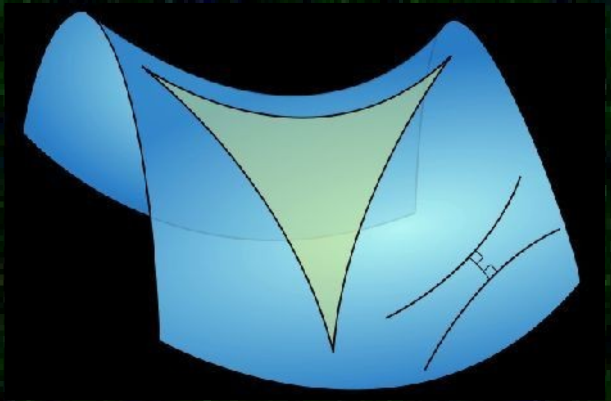
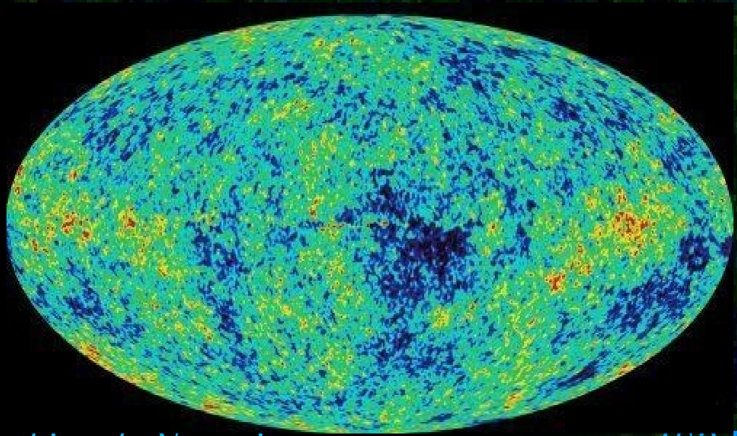
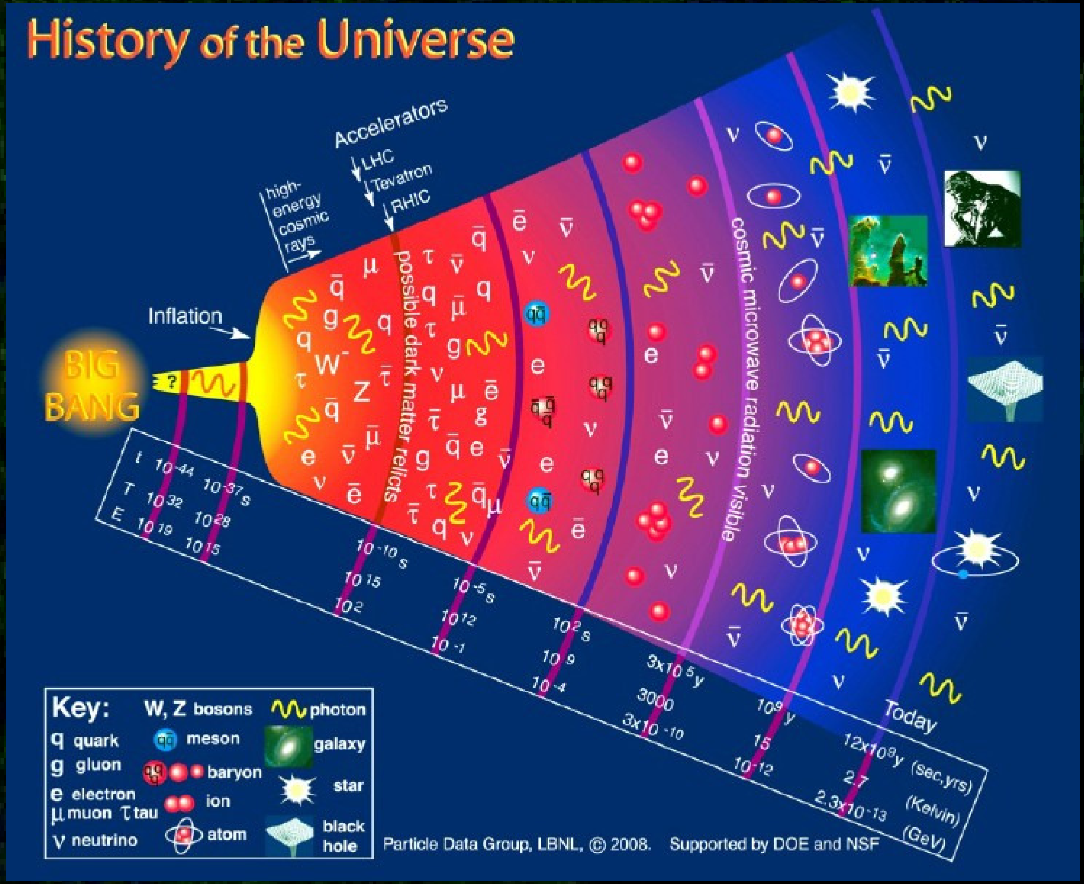
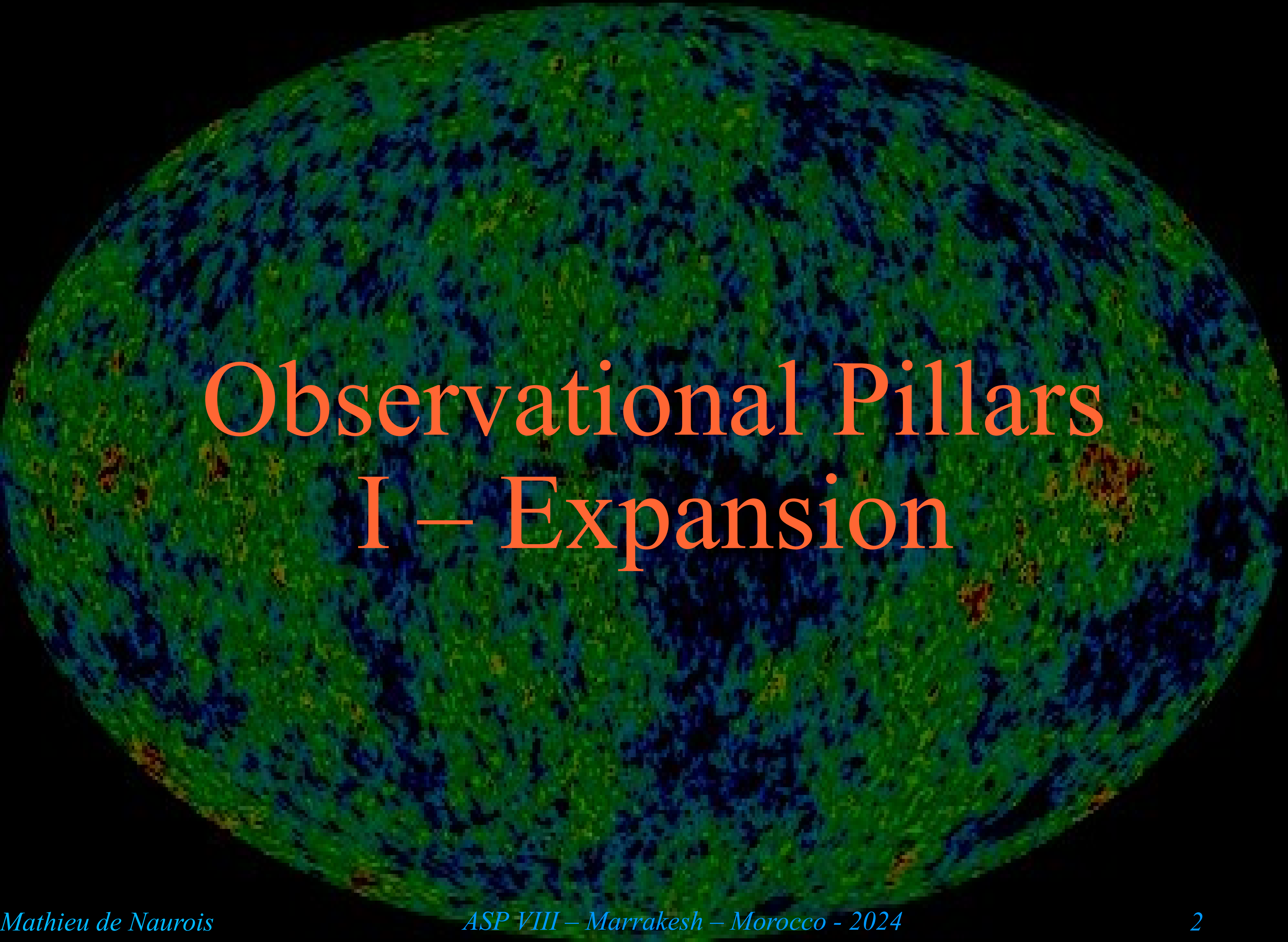
Cosmology – Experimental Status

Mathieu de Naurois
LLR – IN2P3 – CNRS – Ecole Polytechnique
denauroi@in2p3.fr









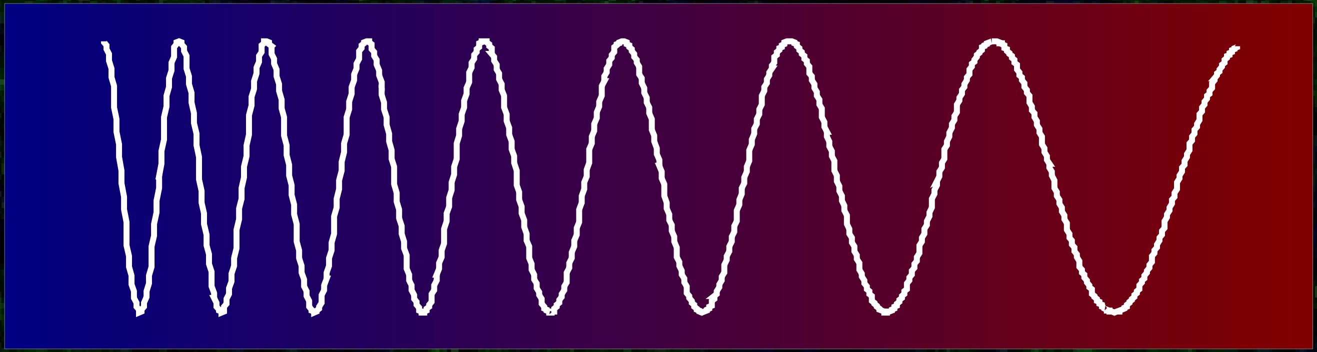
Observational Pillars
I – Expansion

Redshift

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

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

☐ a(t) is the "scale parameter" tracing the size evolution of a bubble



Emission

Reception

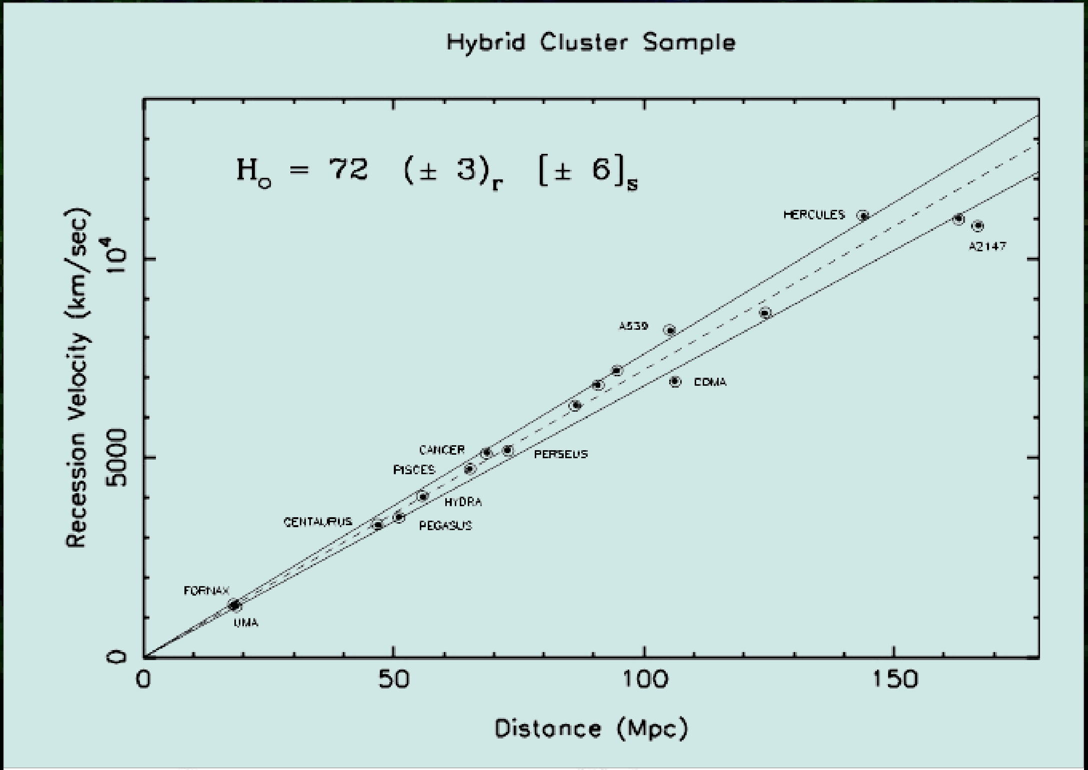
Hubble Law

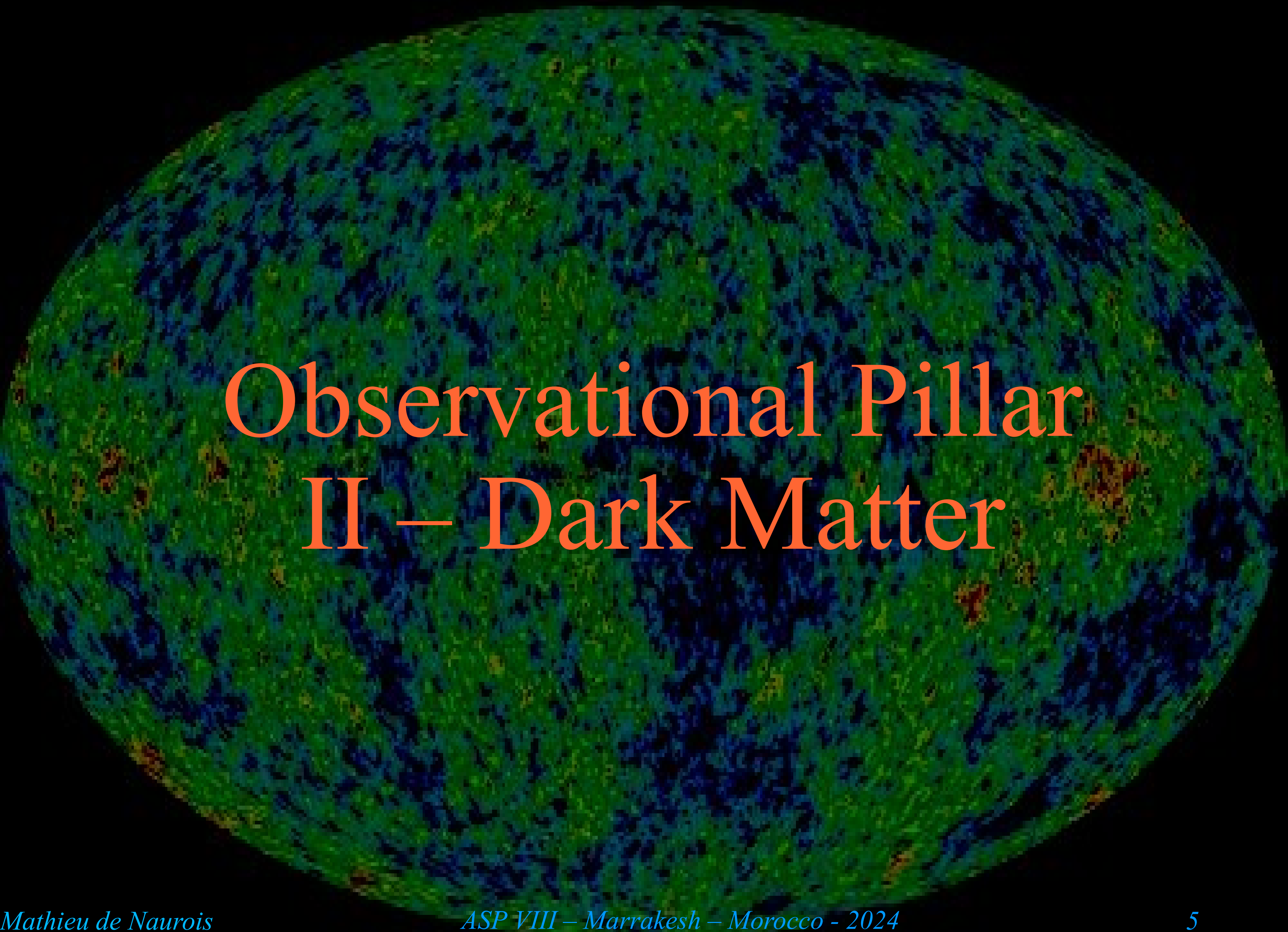
- Galaxies are separating apart at a speed proportional to their distance

$$\frac{\mathrm{d}\,R}{\mathrm{d}\,t} = \mathrm{H}_0\,R + v_p$$

Hubble flow

Proper Motion

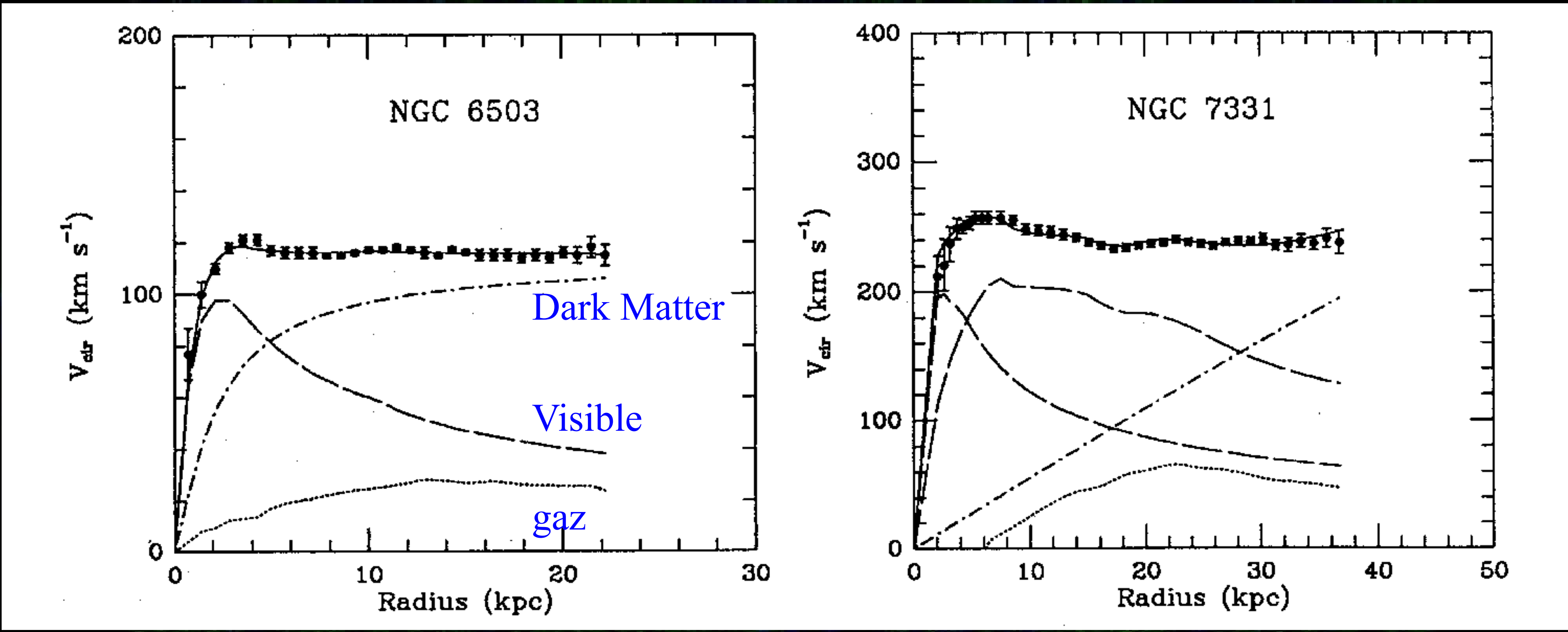




Observational Pillar II – Dark Matter

Rotation Curve – in Galaxies

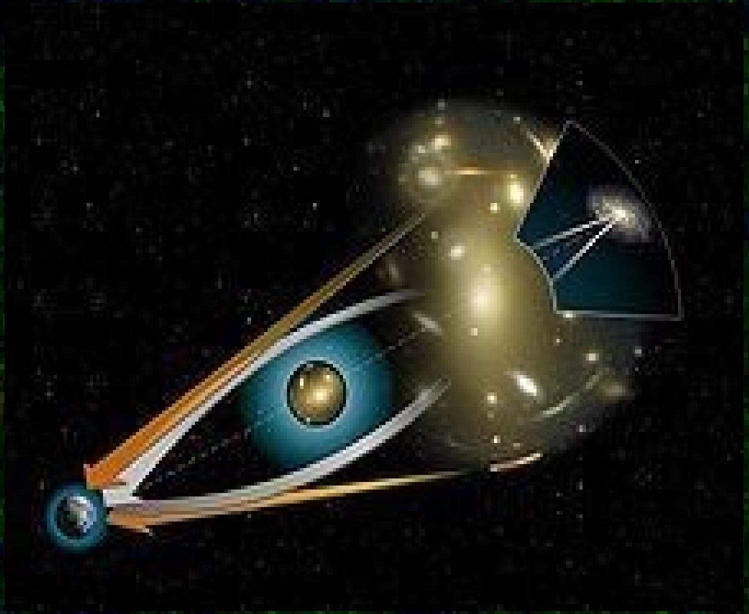
- For Kepler Motion $V(R) = \sqrt{\frac{G\,M(R)}{R}}$ Exercise!



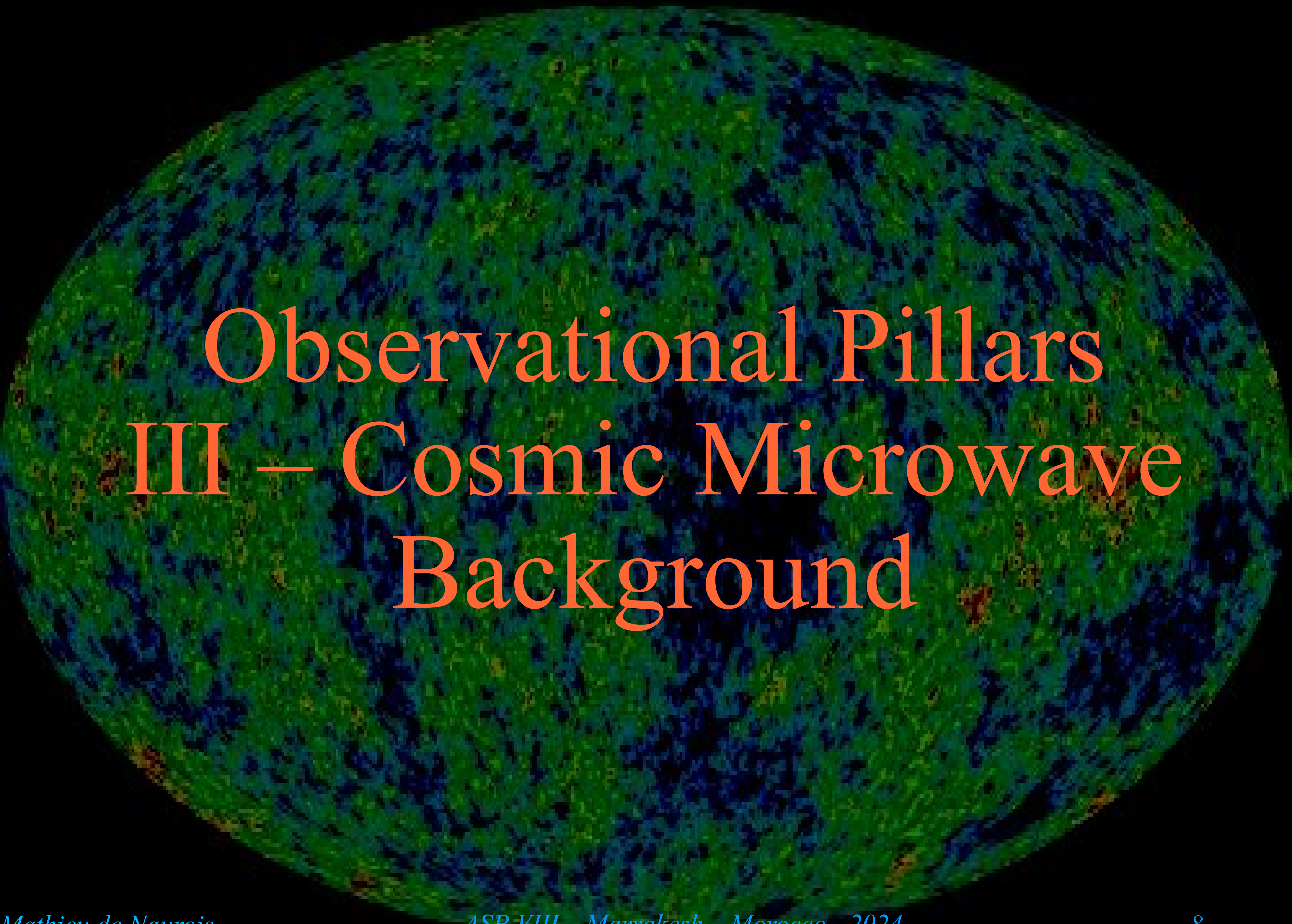
- Dark Matter represents ~ 85% of matter, and ~ 25% of total energy

Other evidences

- ☐ Gravitational Lensing



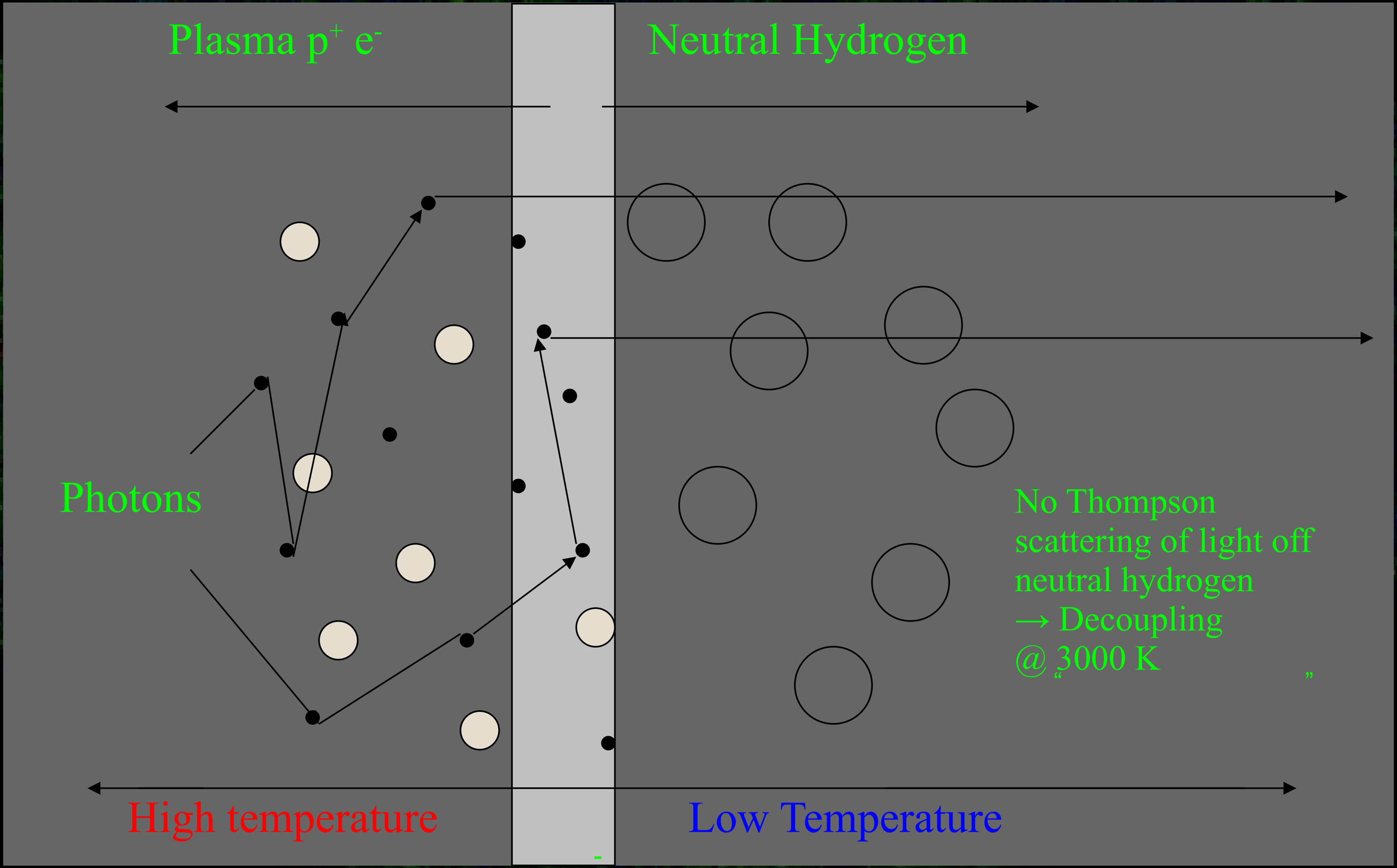
- ☐ Temperature distribution of hot gas in galaxies and clusters of galaxies
- ☐ Cosmological backgroun
- ☐ …



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

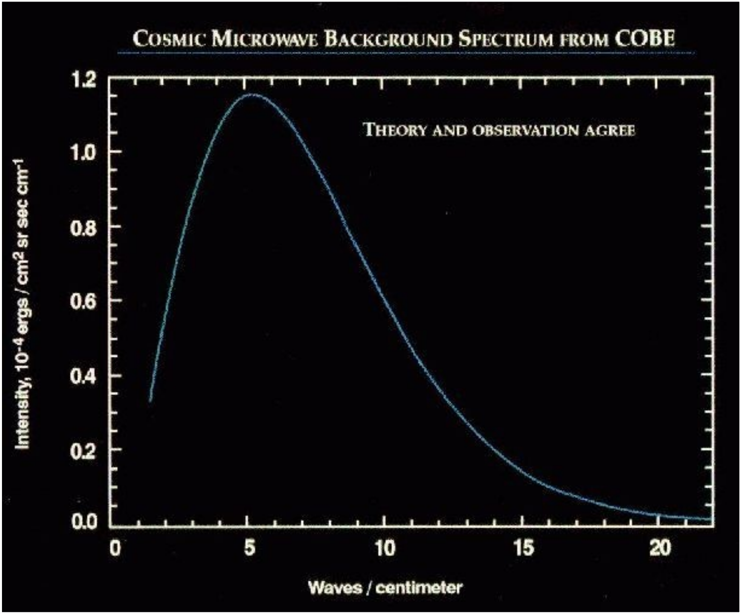
Predicted in the 1950 s, detected in 1964

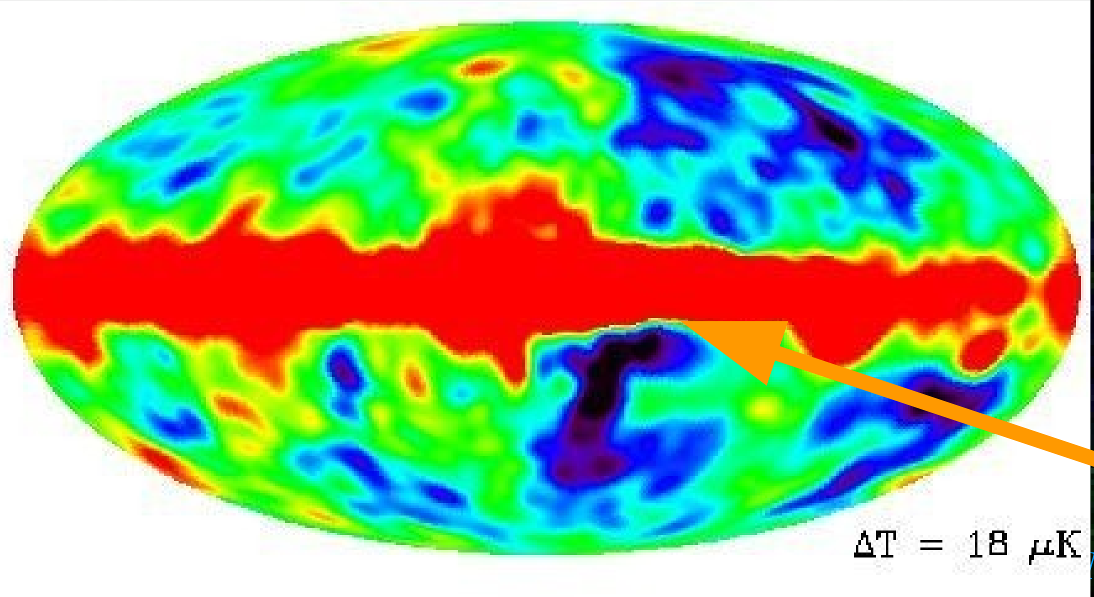
- ☐ Thermal emission emitted at the time of decoupling (z ~ 1100, 380 000 yr after Big Bang)
- ☐ Diluted and red-shifted by the expansion of the Universe

Penzias and Wilson, 1964

CMB Detection

- Discovered 1965 (Penzias & Wilson)
  - 2.7 K blackbody
  - Isotropic (<1%)
- 1970’s and 1980’s
  - 3 mK dipole (local Doppler)
  - $\Delta T/T < 10^{-5}$ on arcminute scales

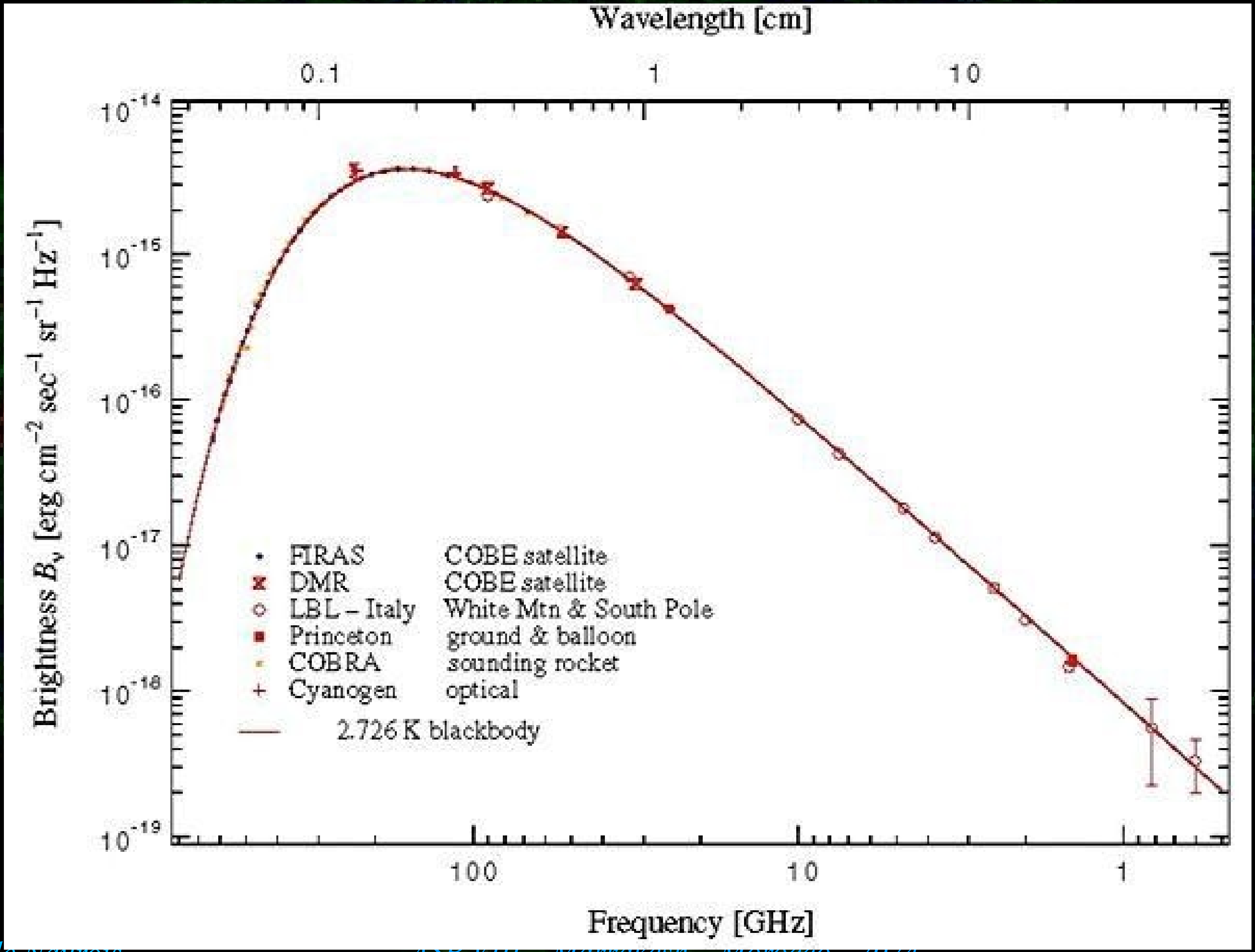




Milky Way

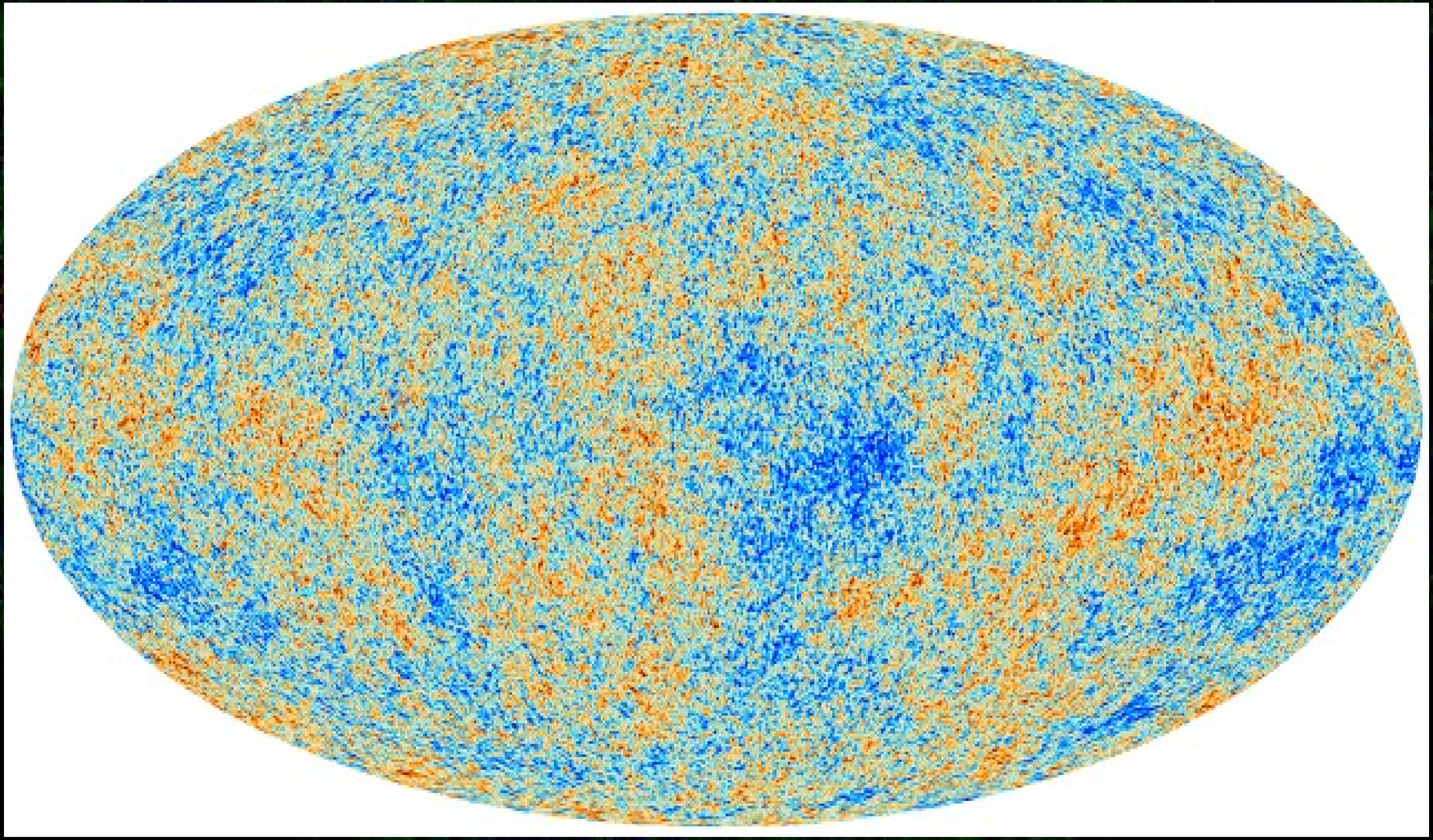
- COBE 1992
- Blackbody 2.728 K
- $\ell < 30 : \delta T/T \approx 10^{-5}$

CMB Spectrum



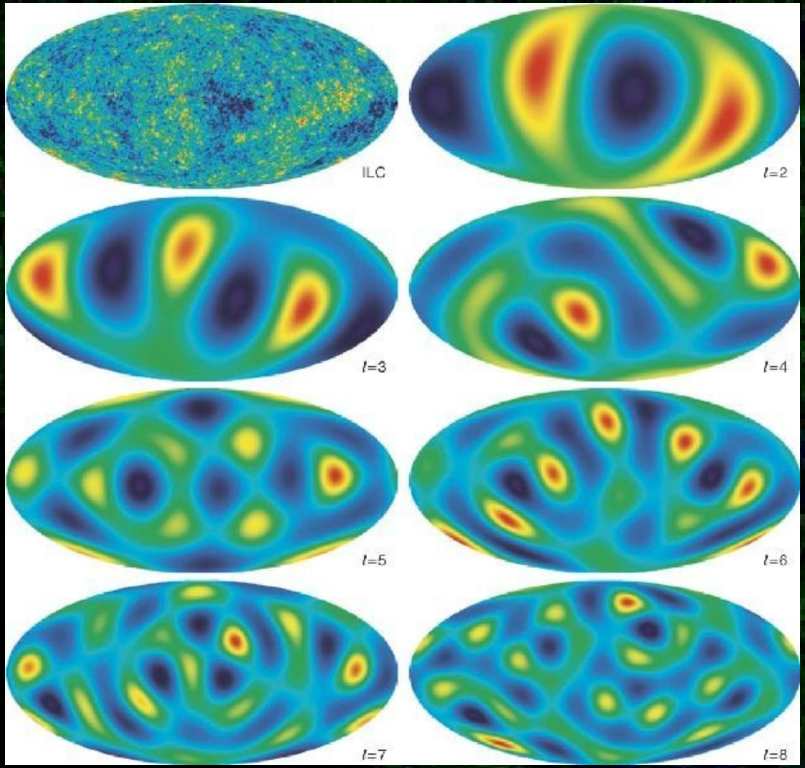
Is CMB Homogeneous?

- ☐ Plank temperature Map, T = 2.725 48 ± 0.00 057 K
- ☐ $\delta T/T \approx 10^{-5}$

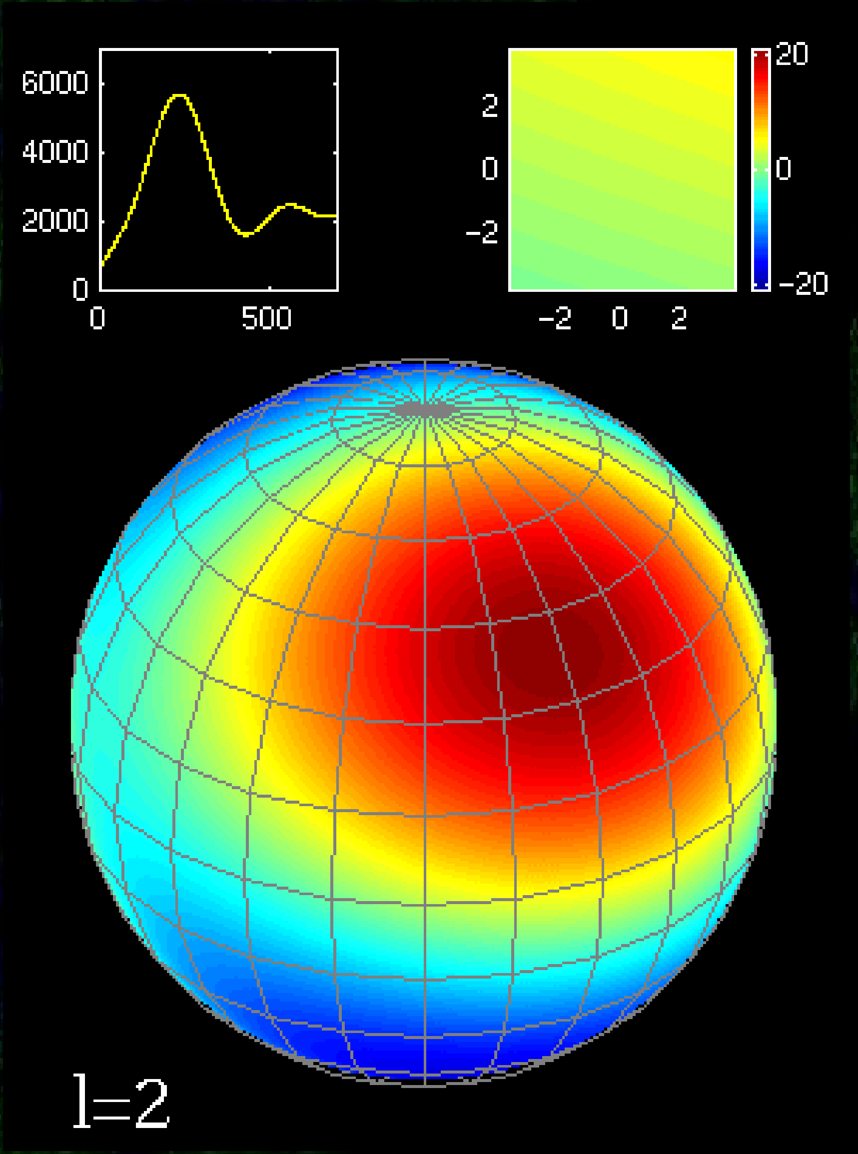


Spherical Harmonics

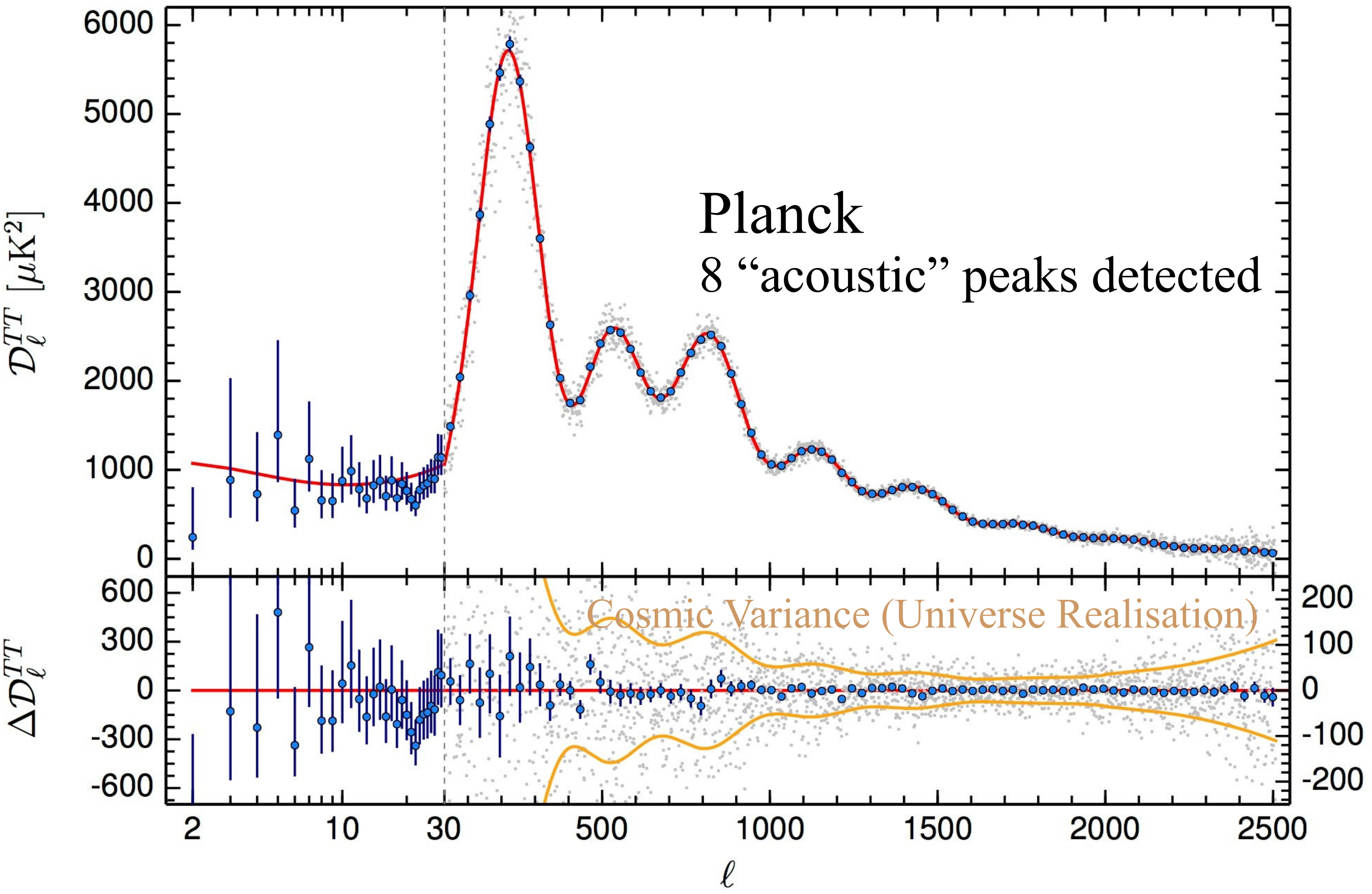
- “l” correspond to angular scale
- Large values correspond to small scales
- Kind of spherical Fourier Tf



The lower WMAP harmonics...



CMB Angular Spectrum – 2015



Planck

8 “acoustic” peaks detected

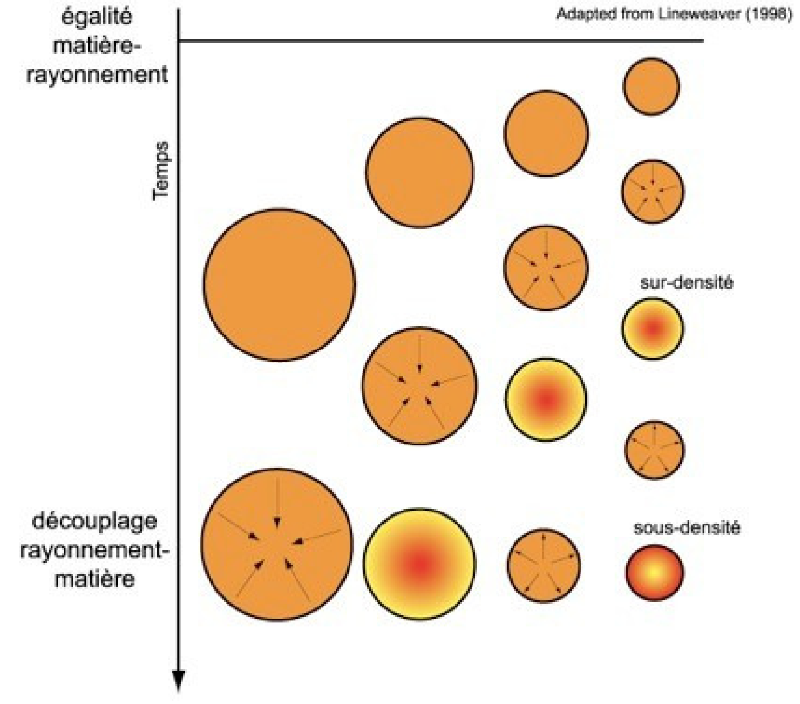
Cosmic Variance (Universe Realisation)

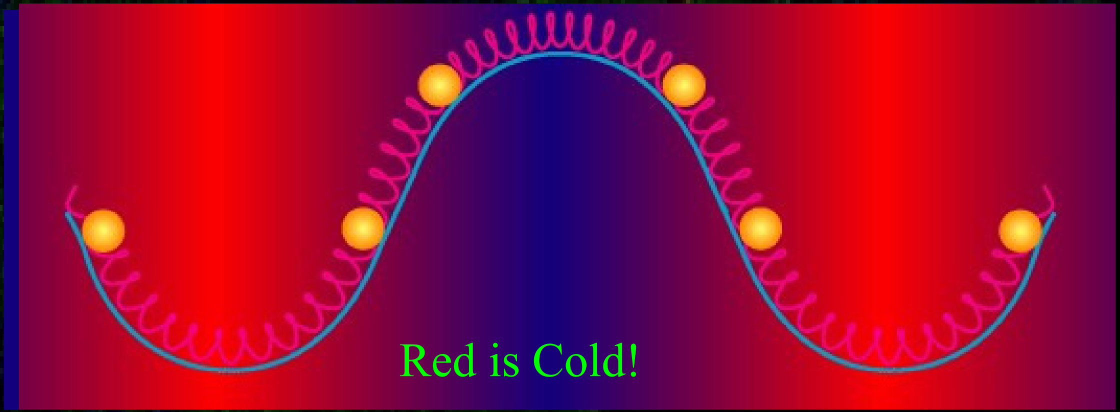
Acoustic Oscillation

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

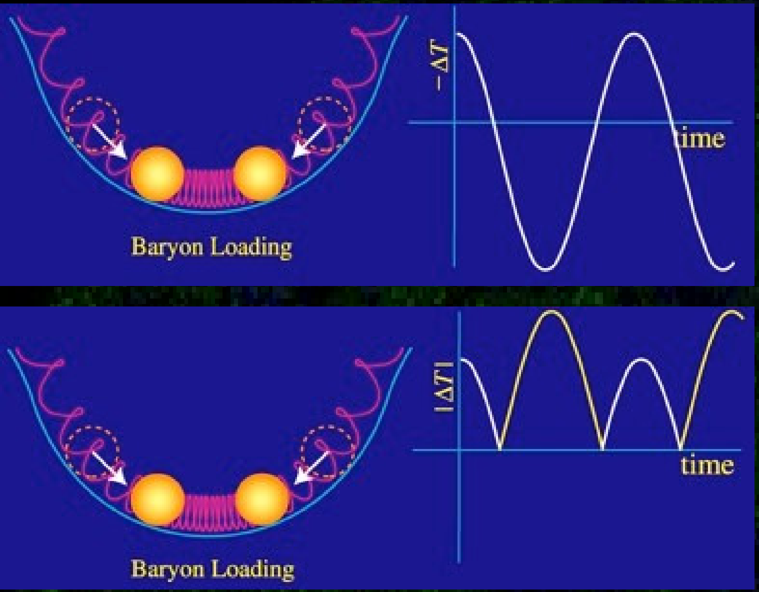
$$c/\sqrt{3}$$

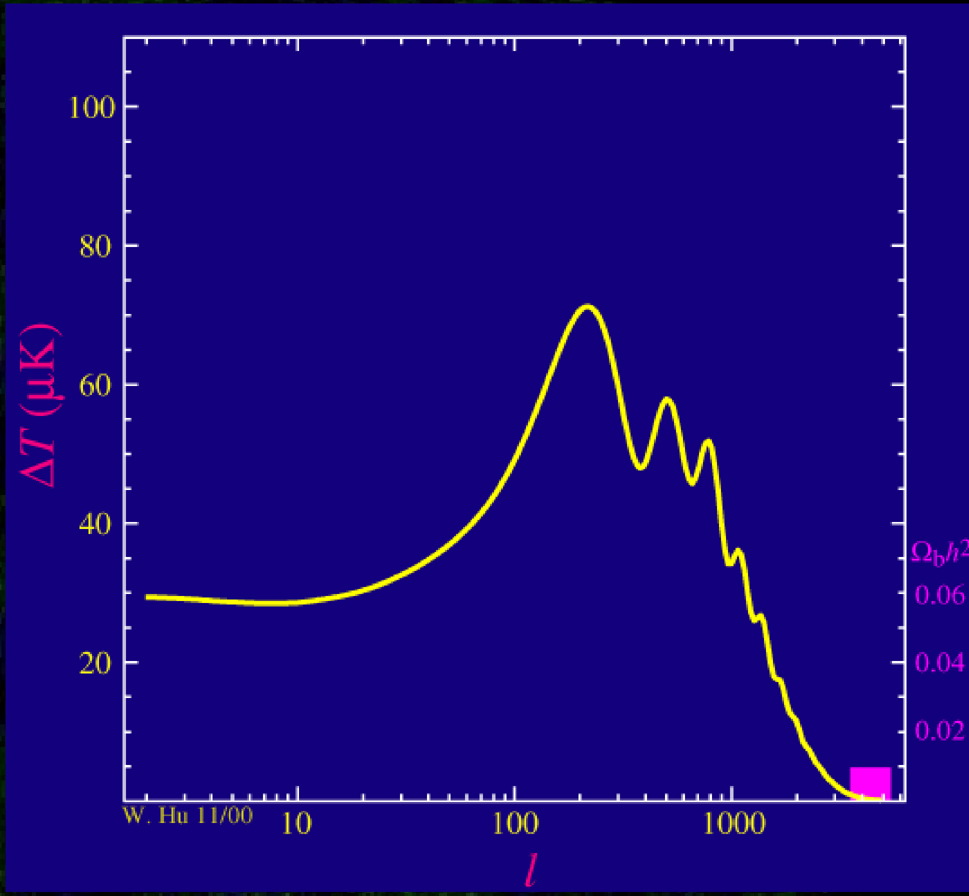
- Small fluctuations oscillate faster
- At the time of decoupling, situation is frozen ⇒ characteristic angular scale appear
- Density fluctuation translate into temperature variations


Adapted from Lineweaver (1998)



Matter Content

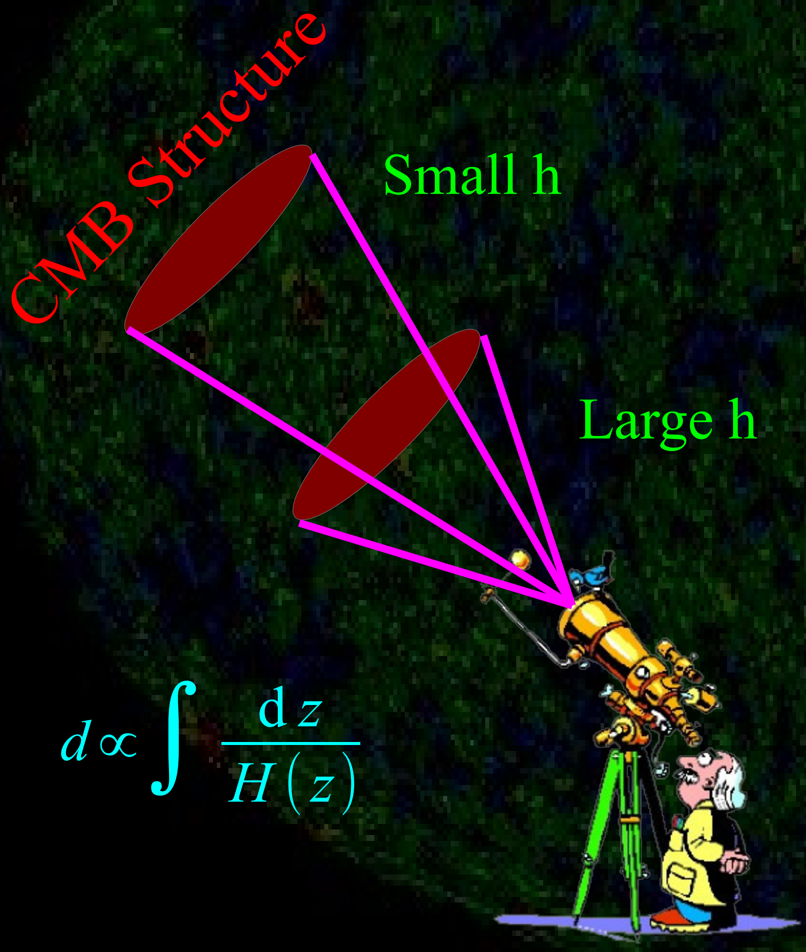




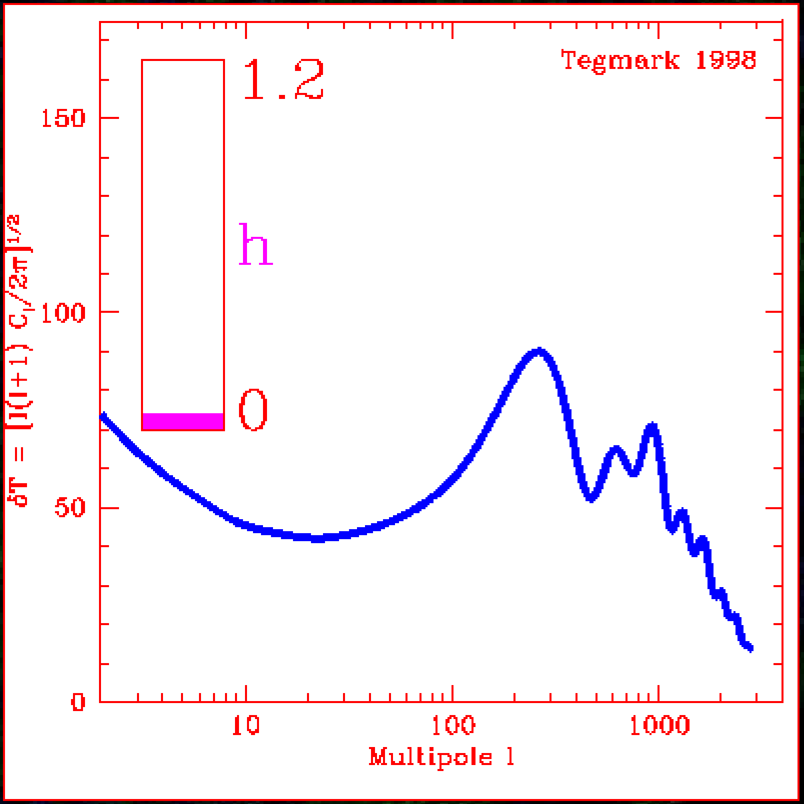
- Coupling between matter and radiation affects oscillation pattern
- No matter = no oscillations

Hubble Constant

- CMB allows to measure most cosmological parameters
- Large expansion speed makes larger red-shifts correspond to smaller distance. Structures appear larger than they were



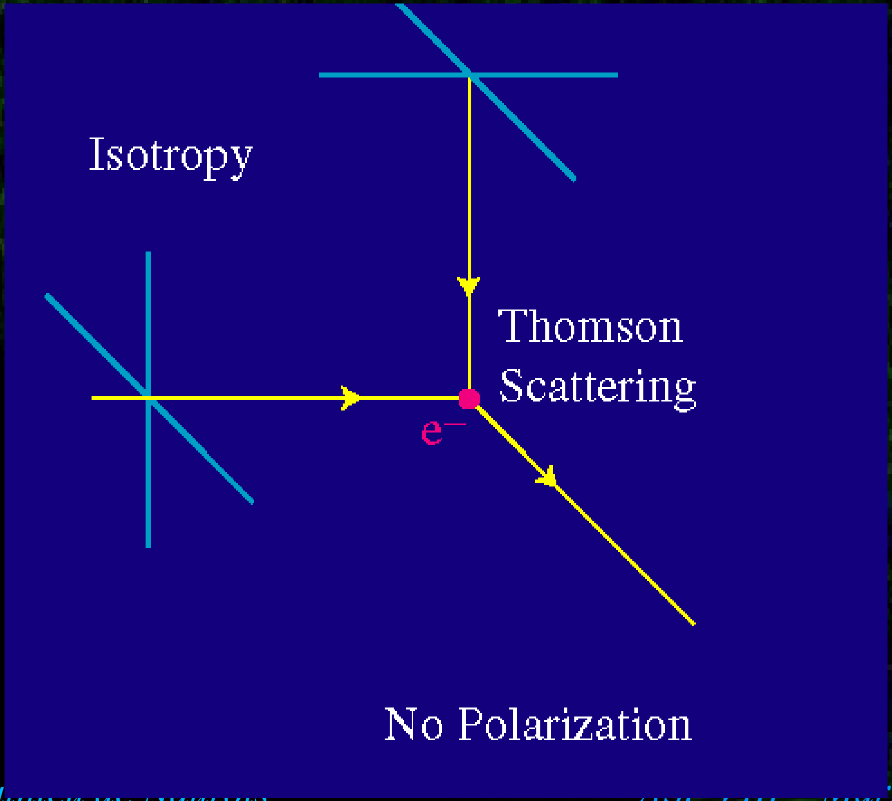
$$d \propto \int \frac{\mathrm{d}\,z}{H(z)}$$

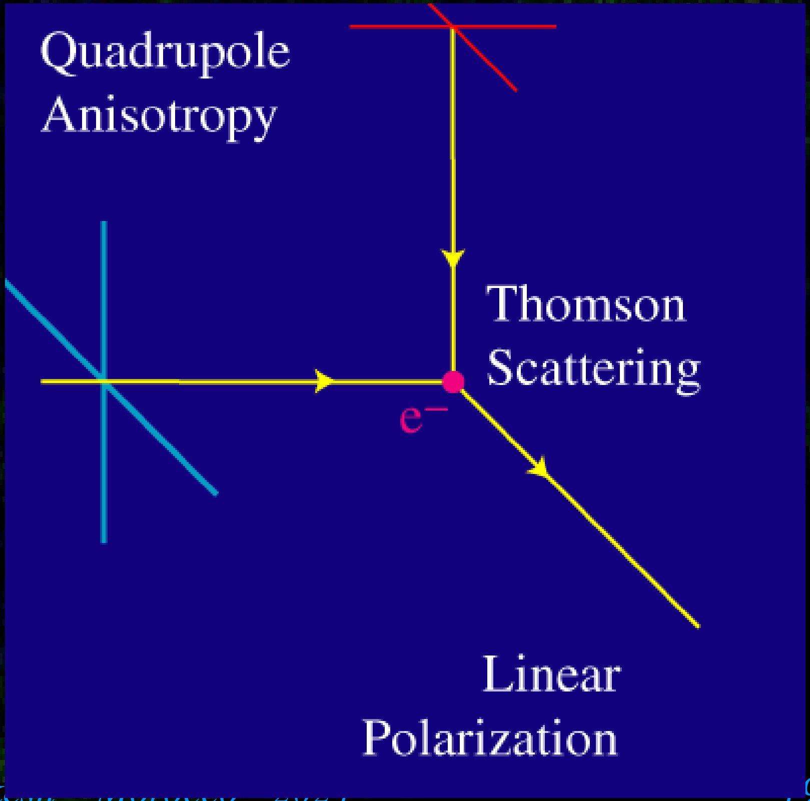


Small ↔ Large

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
- ☐ Different polarisation “modes” (scalar E, tensor B)

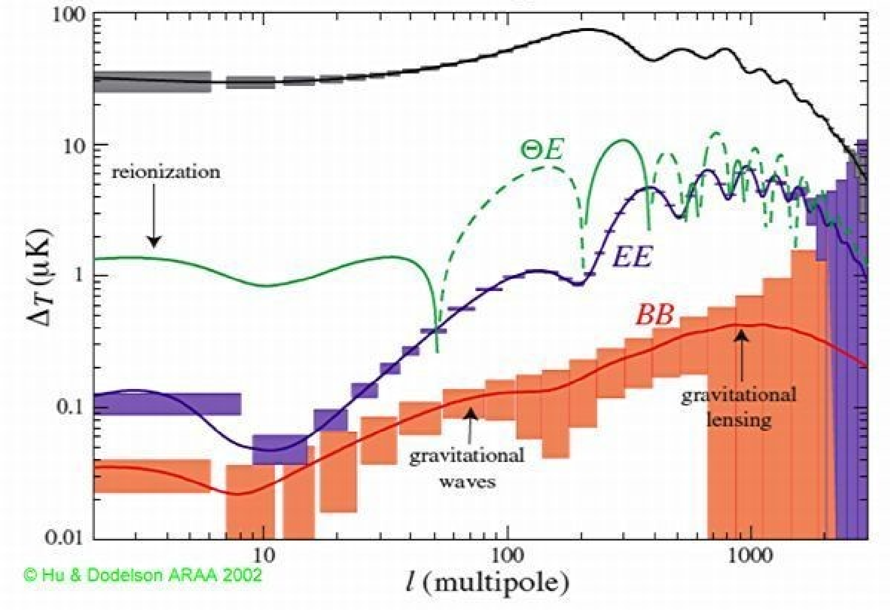




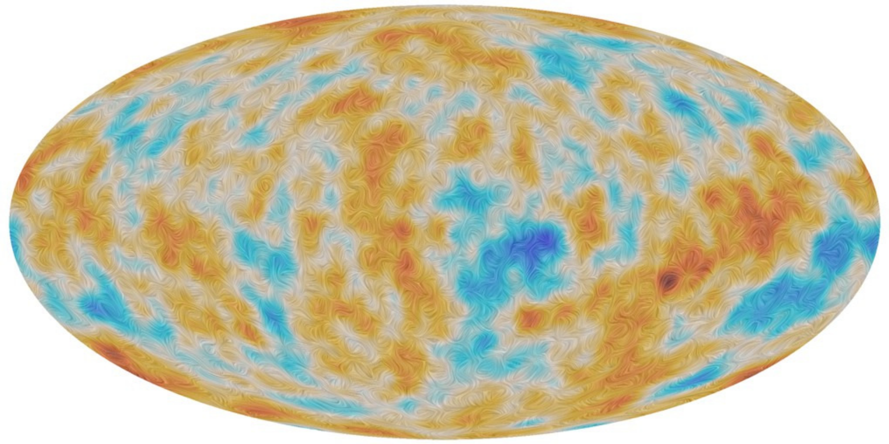
Polarisation @ Planck

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

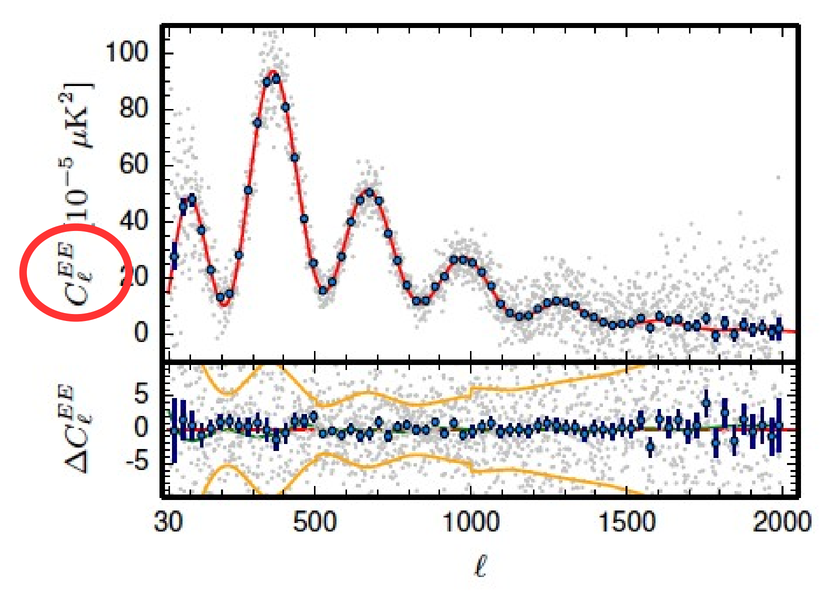
Predictions (@2002)

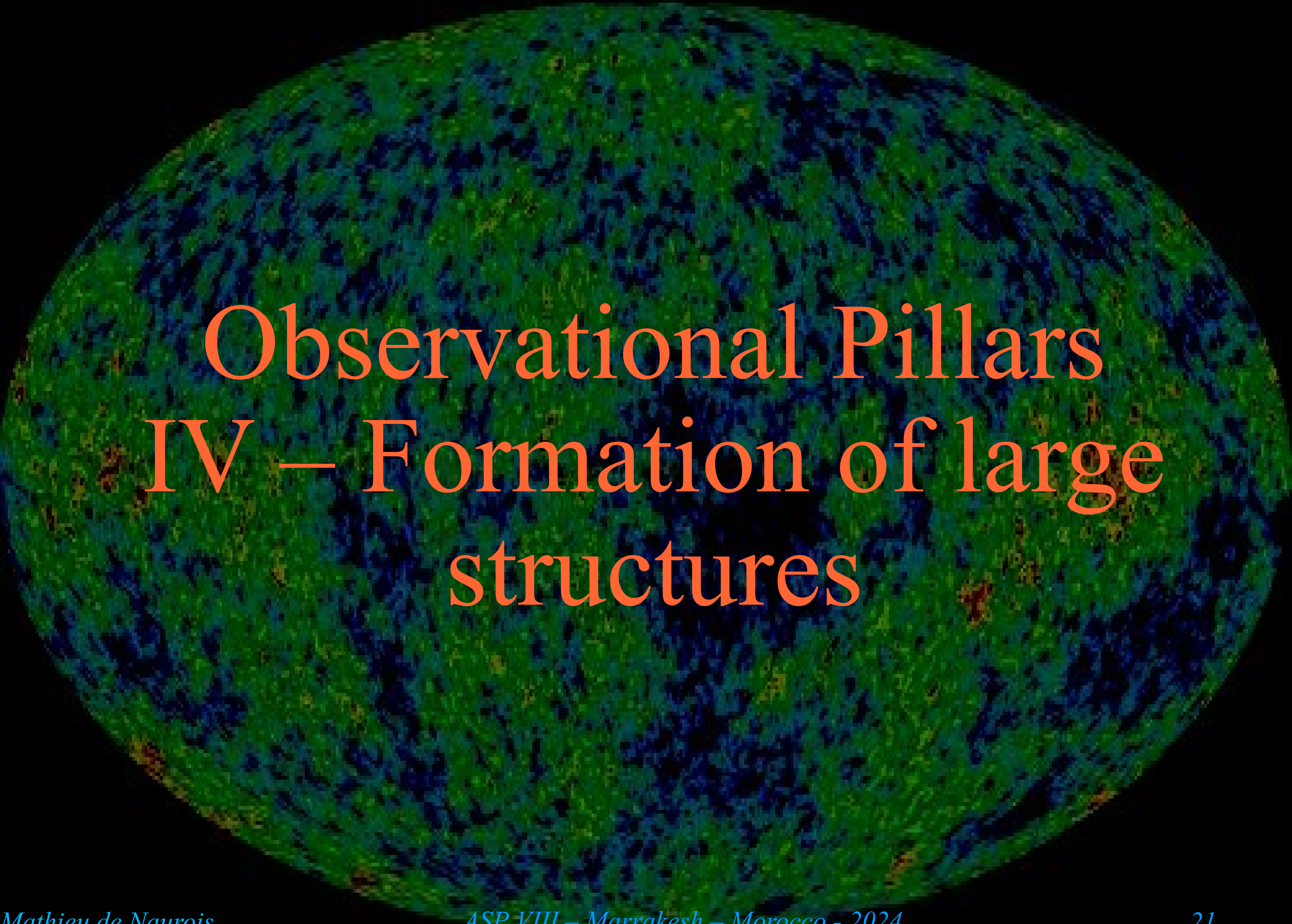


© Hu & Dodelson ARAA 2002



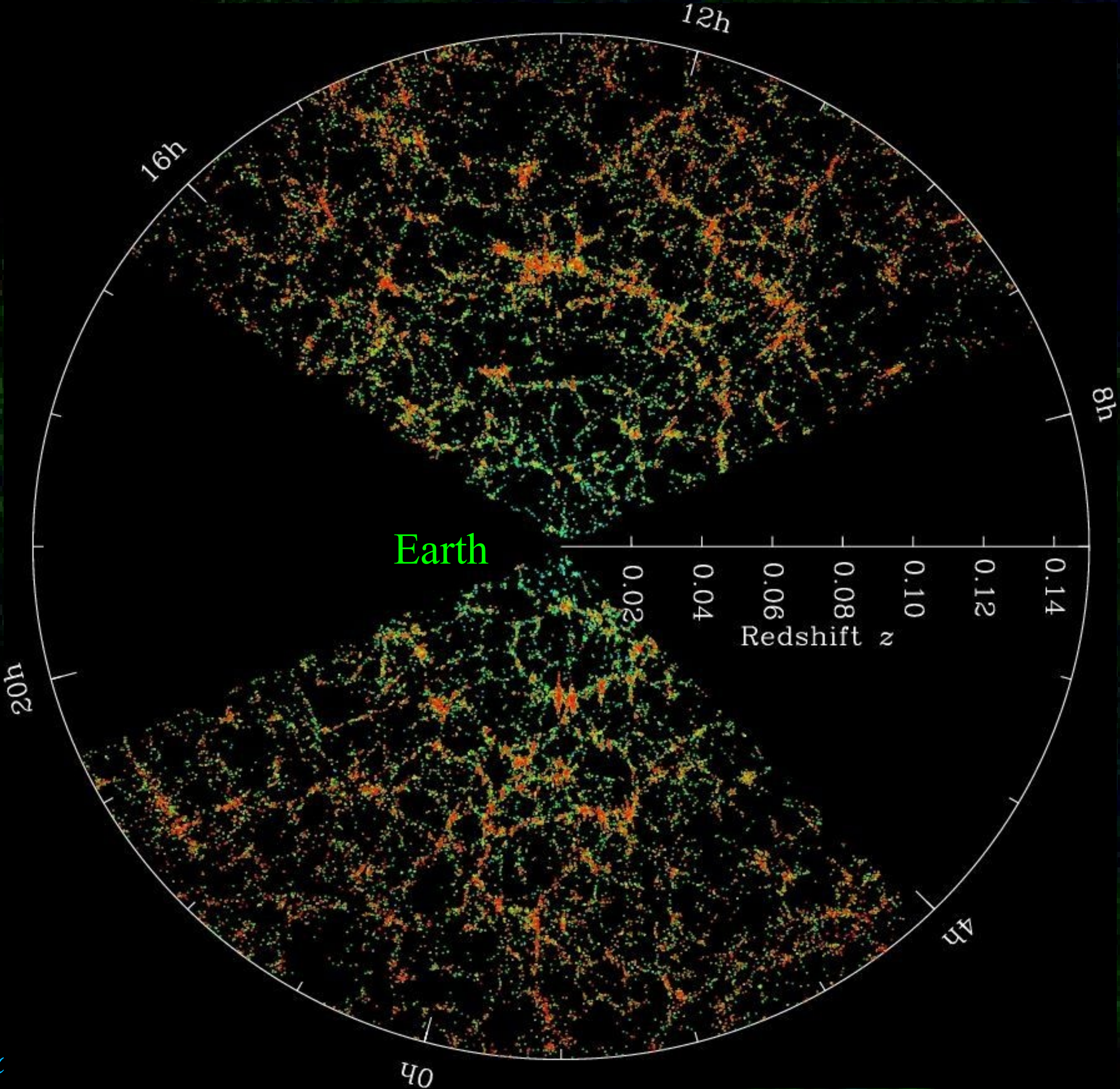
First results (@2015)





Observational Pillars
IV – Formation of large structures

Distribution of matter

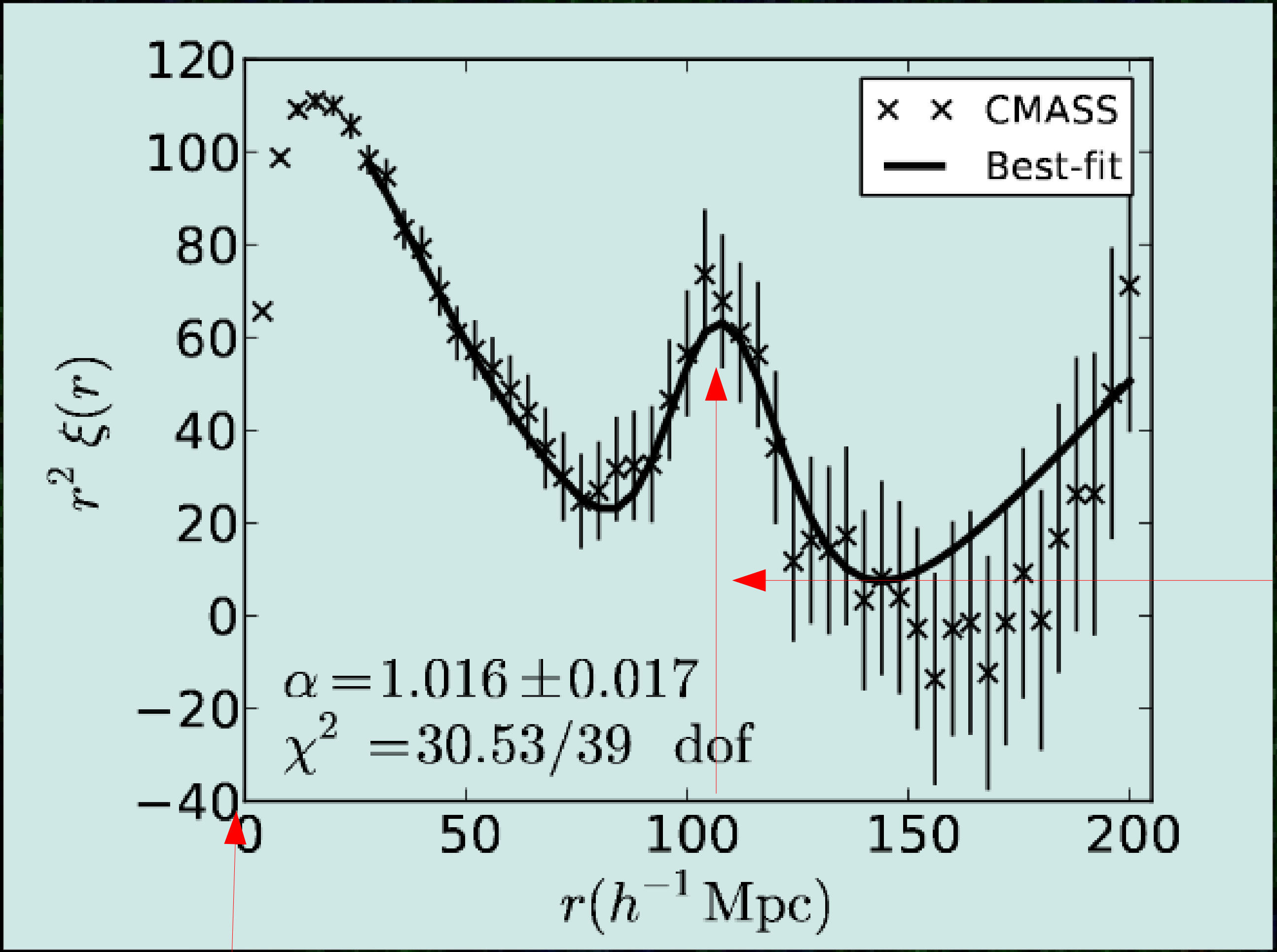


SDSS 2D Map,
of galaxies

3D Map contains
930 000 Galaxies

Baryonic Oscillations

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

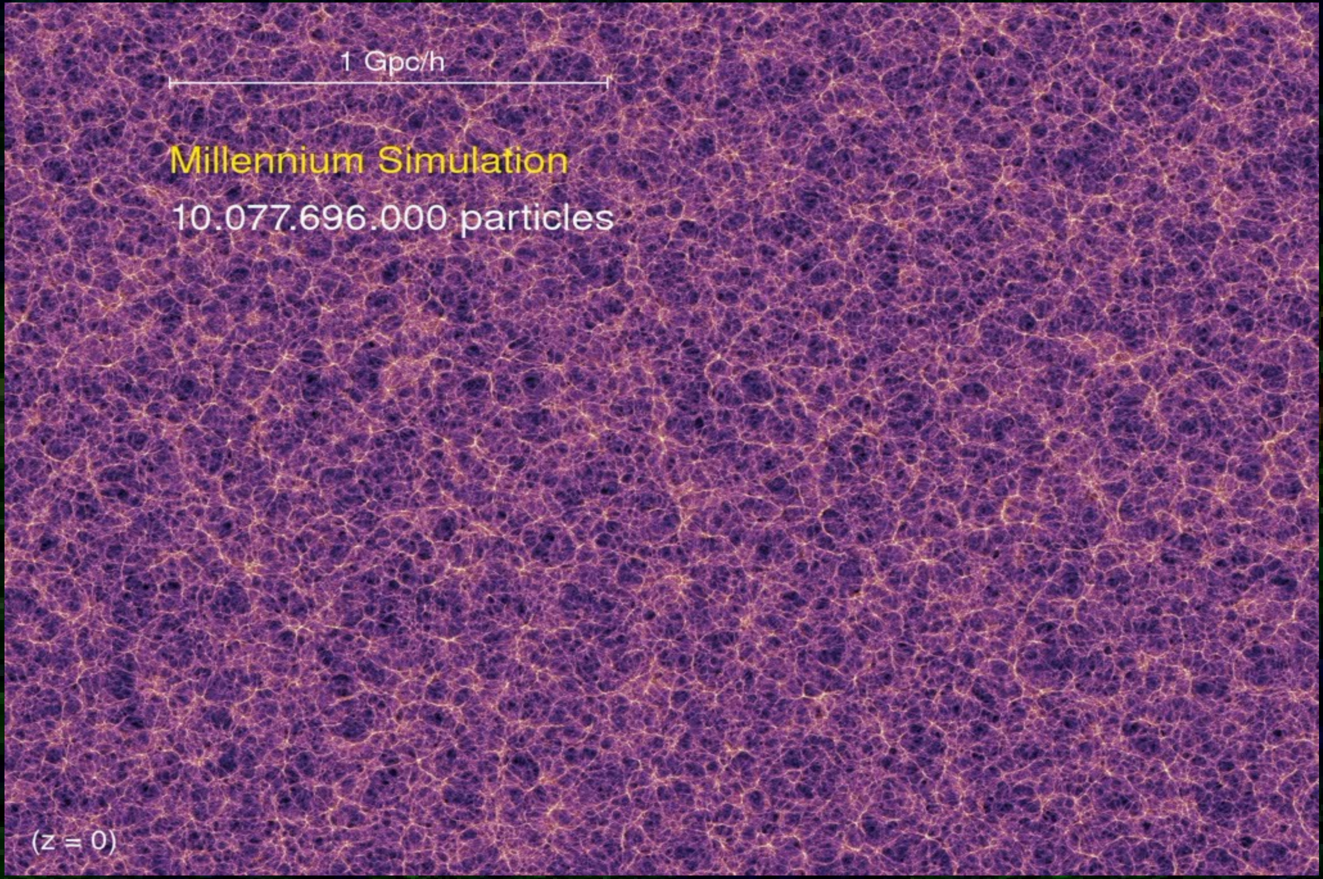


position of baryon sound wave at recombination

position of initial CDM−baryon perturbation

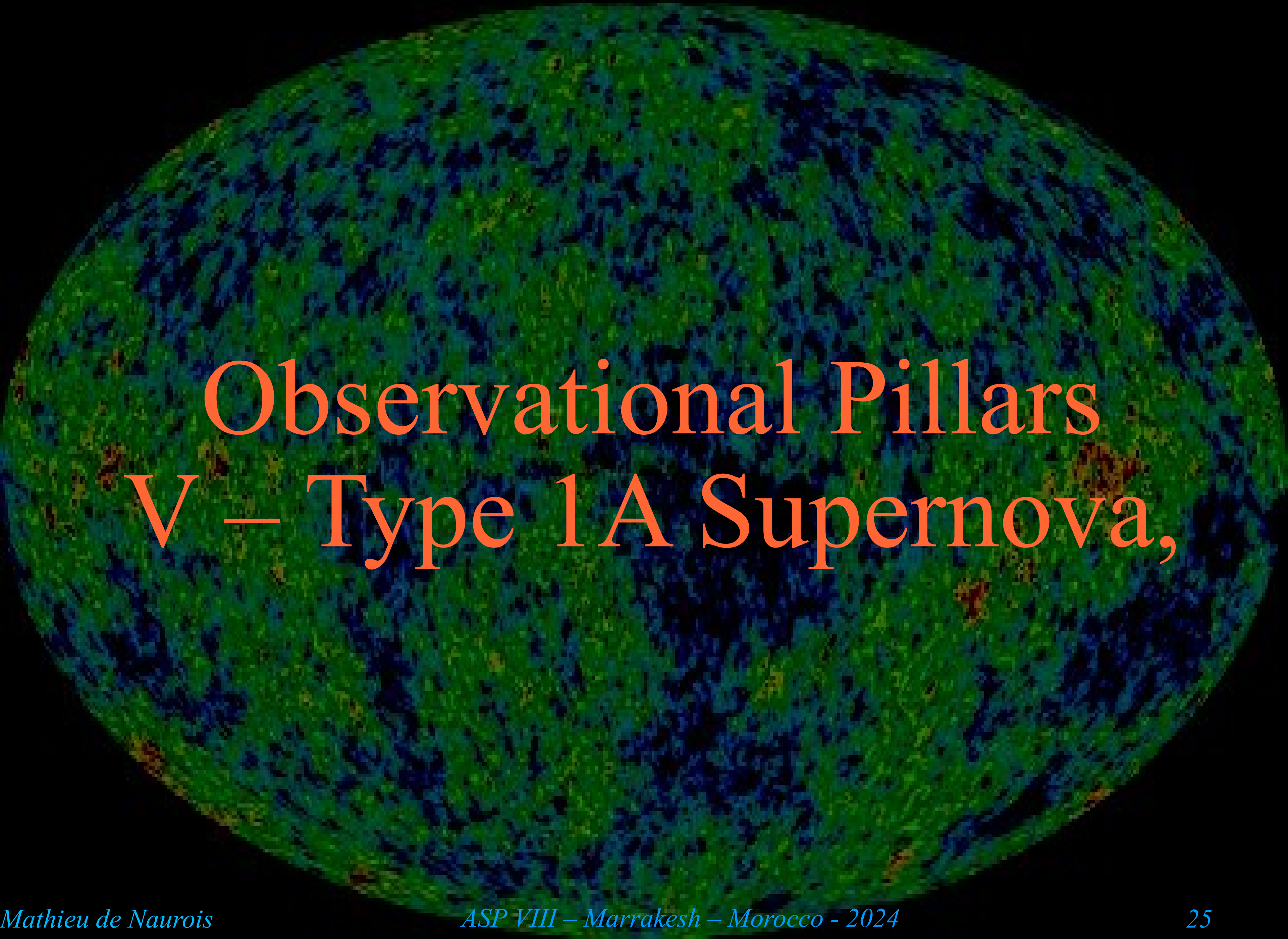
Simulated Universe

- ❑ Dark matter is the driver for structure formation



Millennium Simulation, Springel et al. (2005) ,

- ❑ In the absence of dark matter, predicted structures are too small

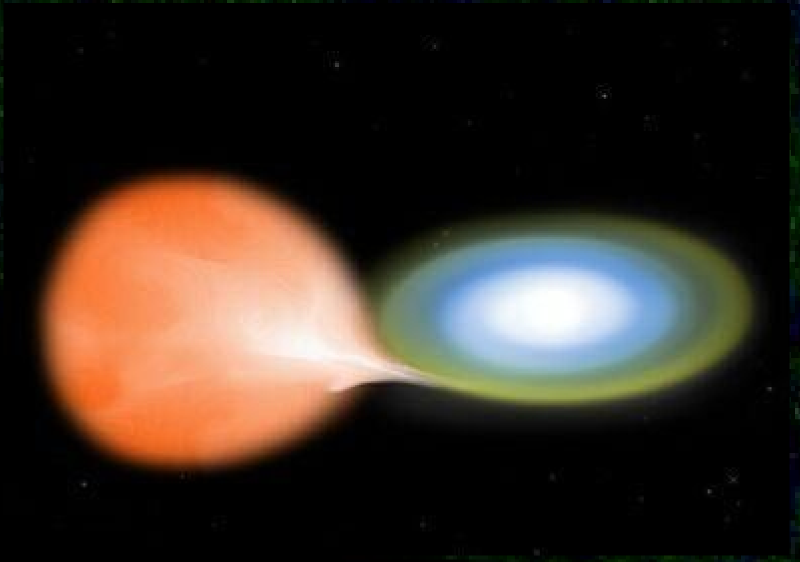


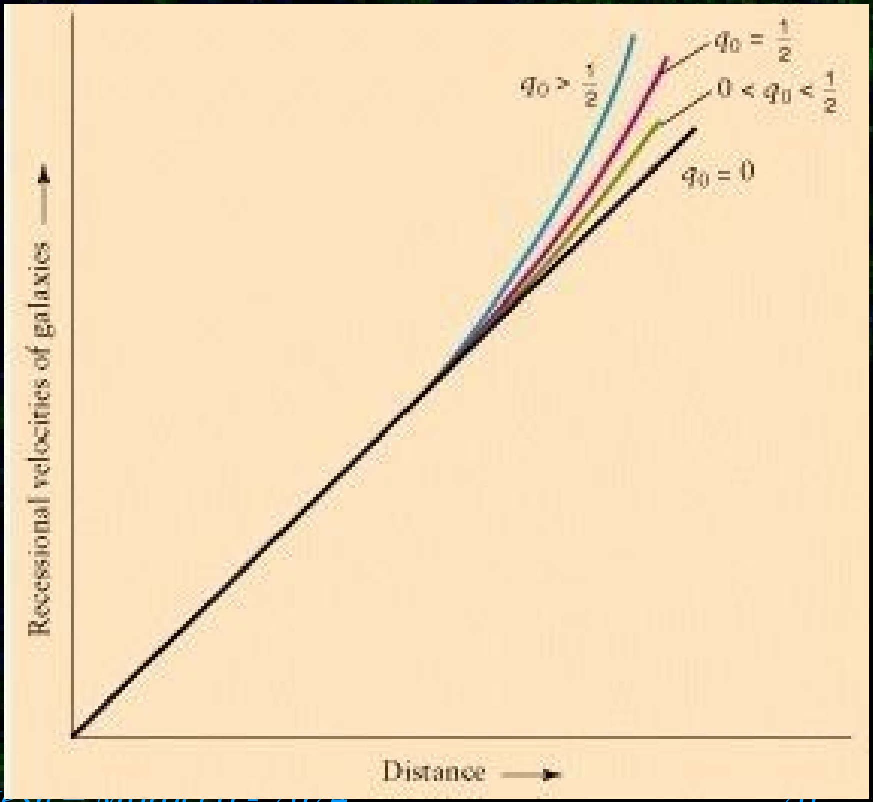
Observational Pillars
V – Type 1A Supernova,

Type Ia Supvernova

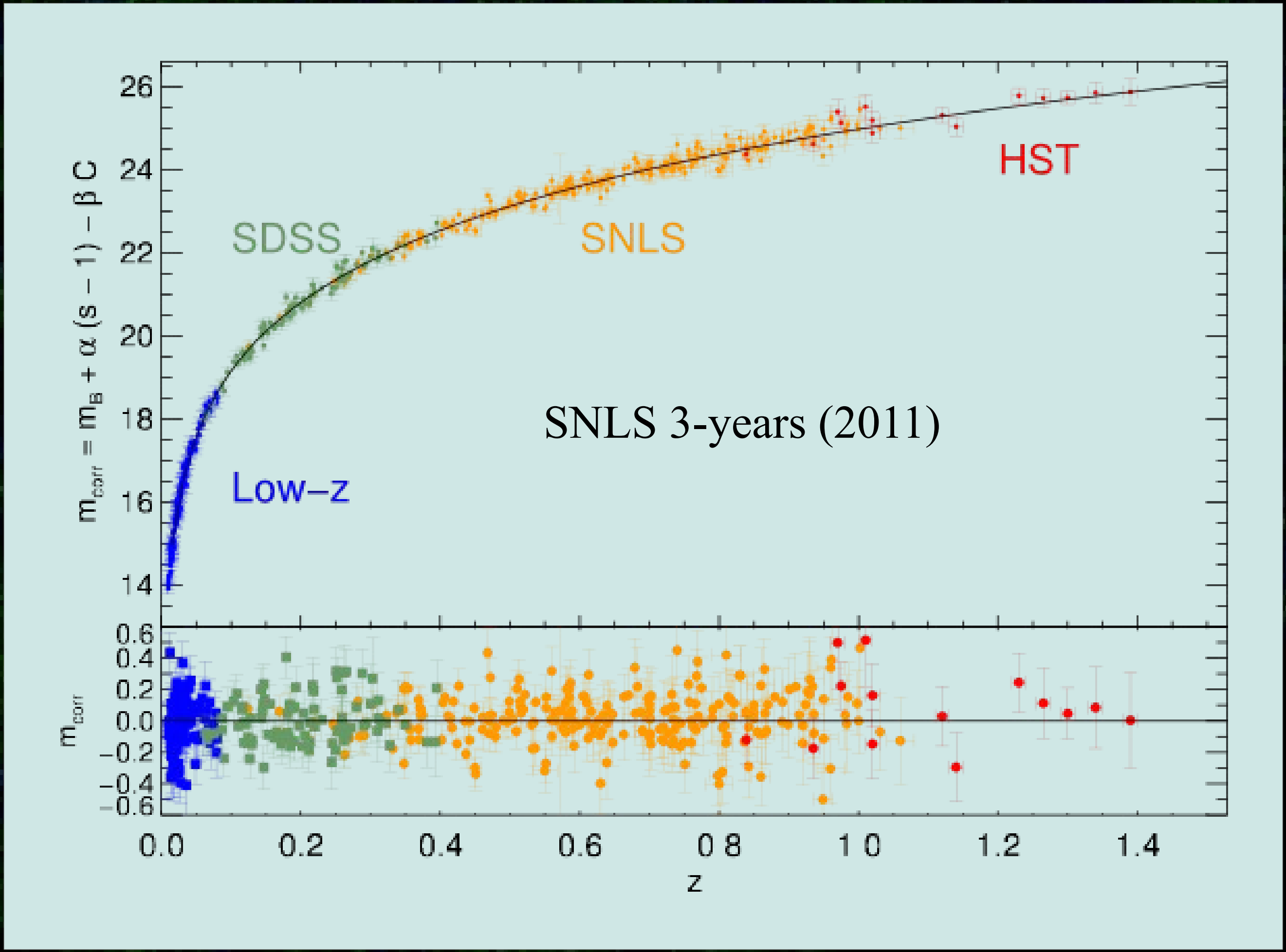
- Accreting white dwarf exploding when reaching the Chandrasekhar mass
- Almost Standard Candles
- Luminosity – red-shift relation is related to history of the Universe

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





Hubble Diagram

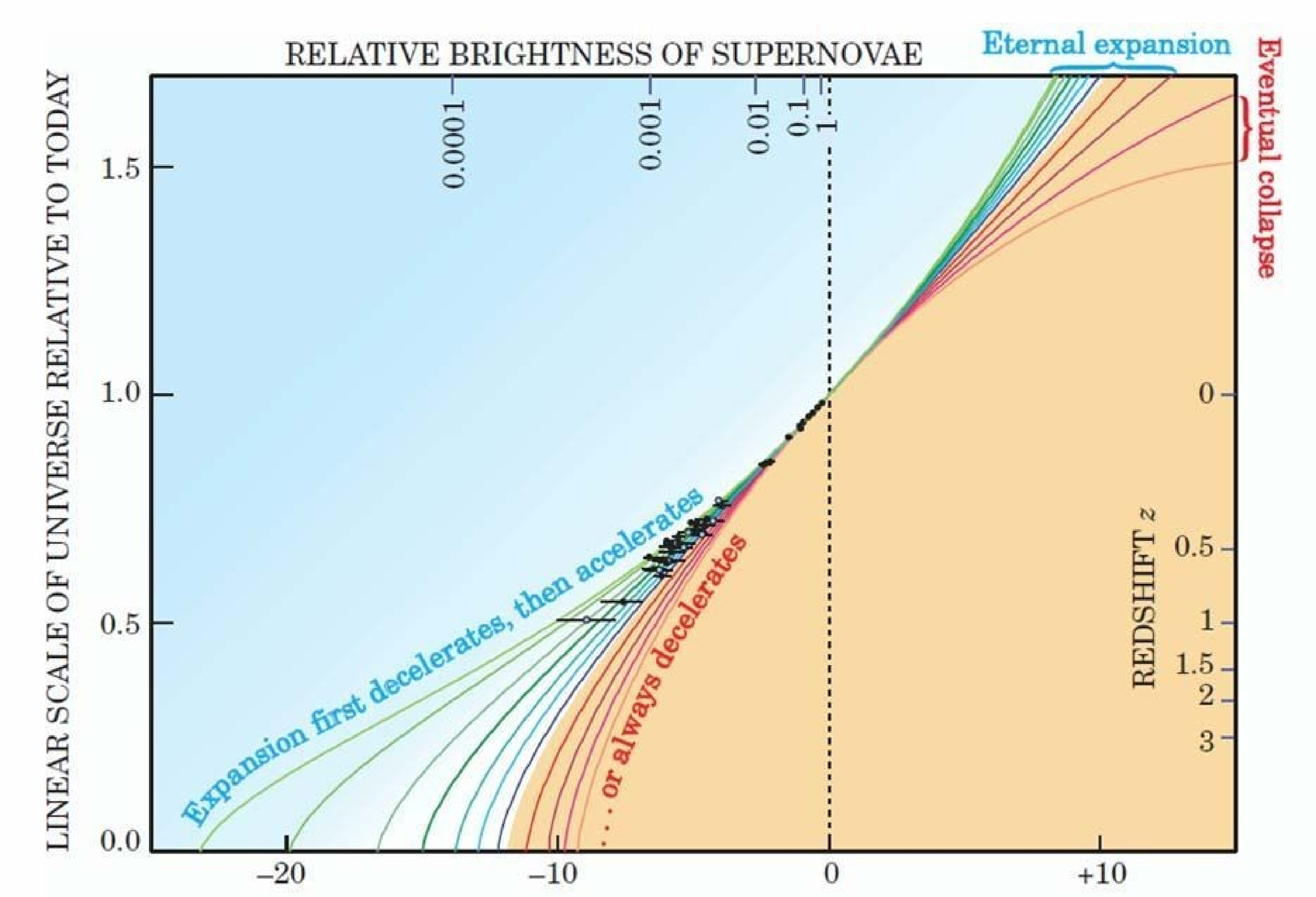


SNLS 3-years (2011)

-log(flux) ~ 2 log(distance)

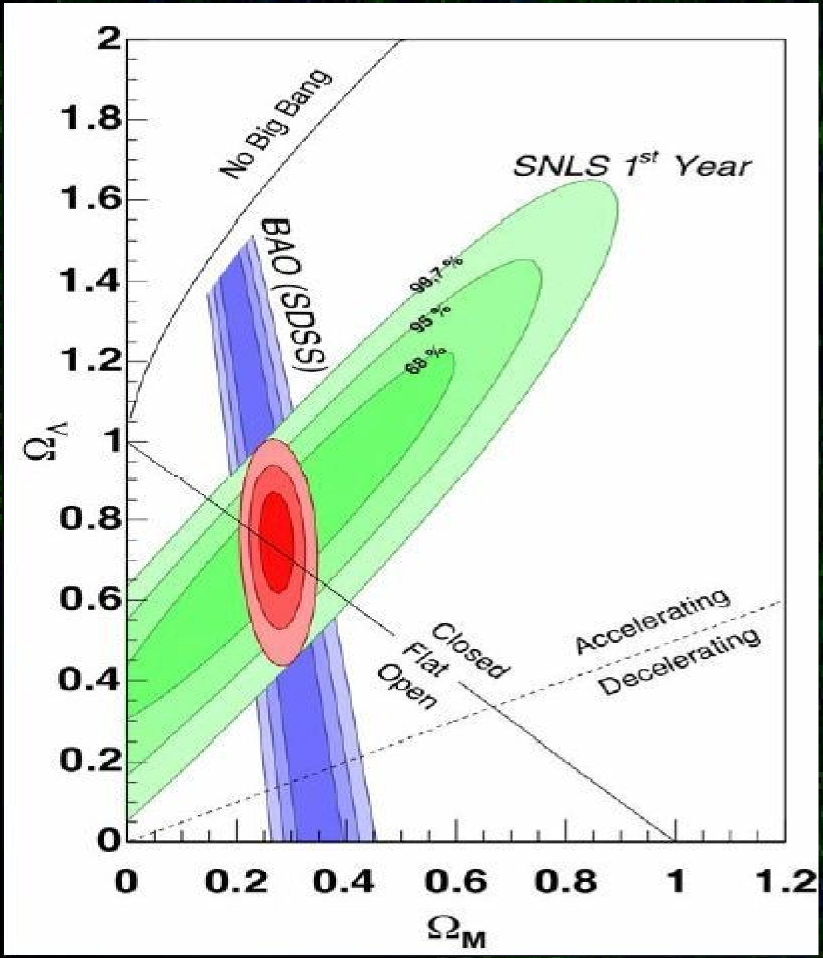
redshift

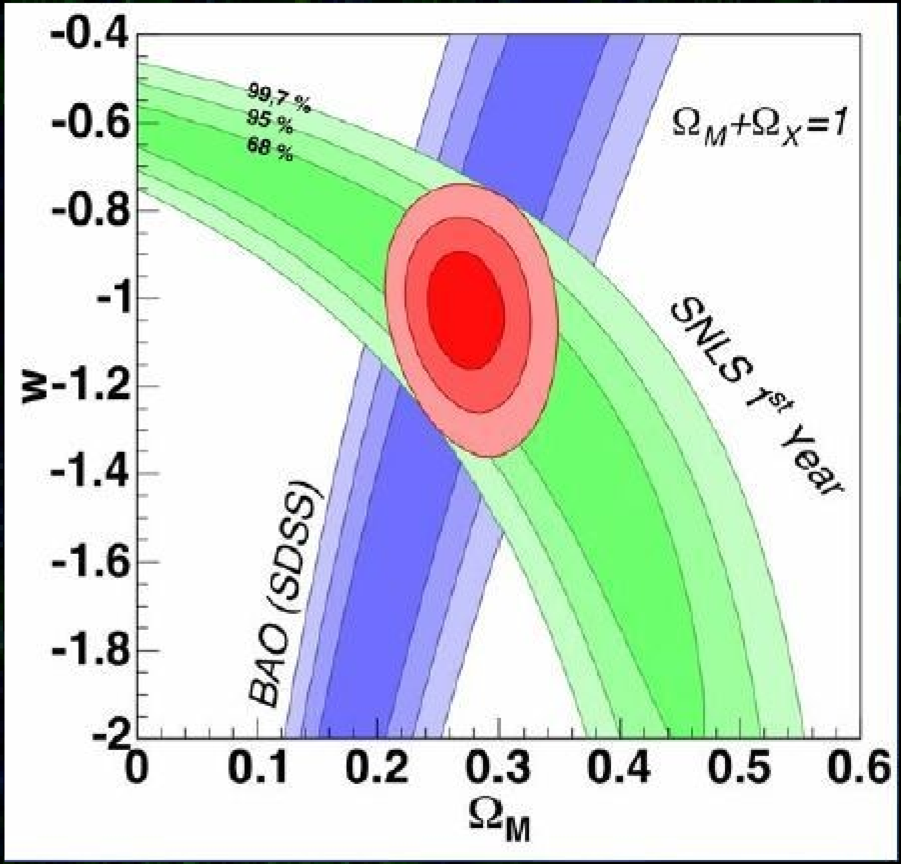
SNI1a: Universe in accelerated Expansion

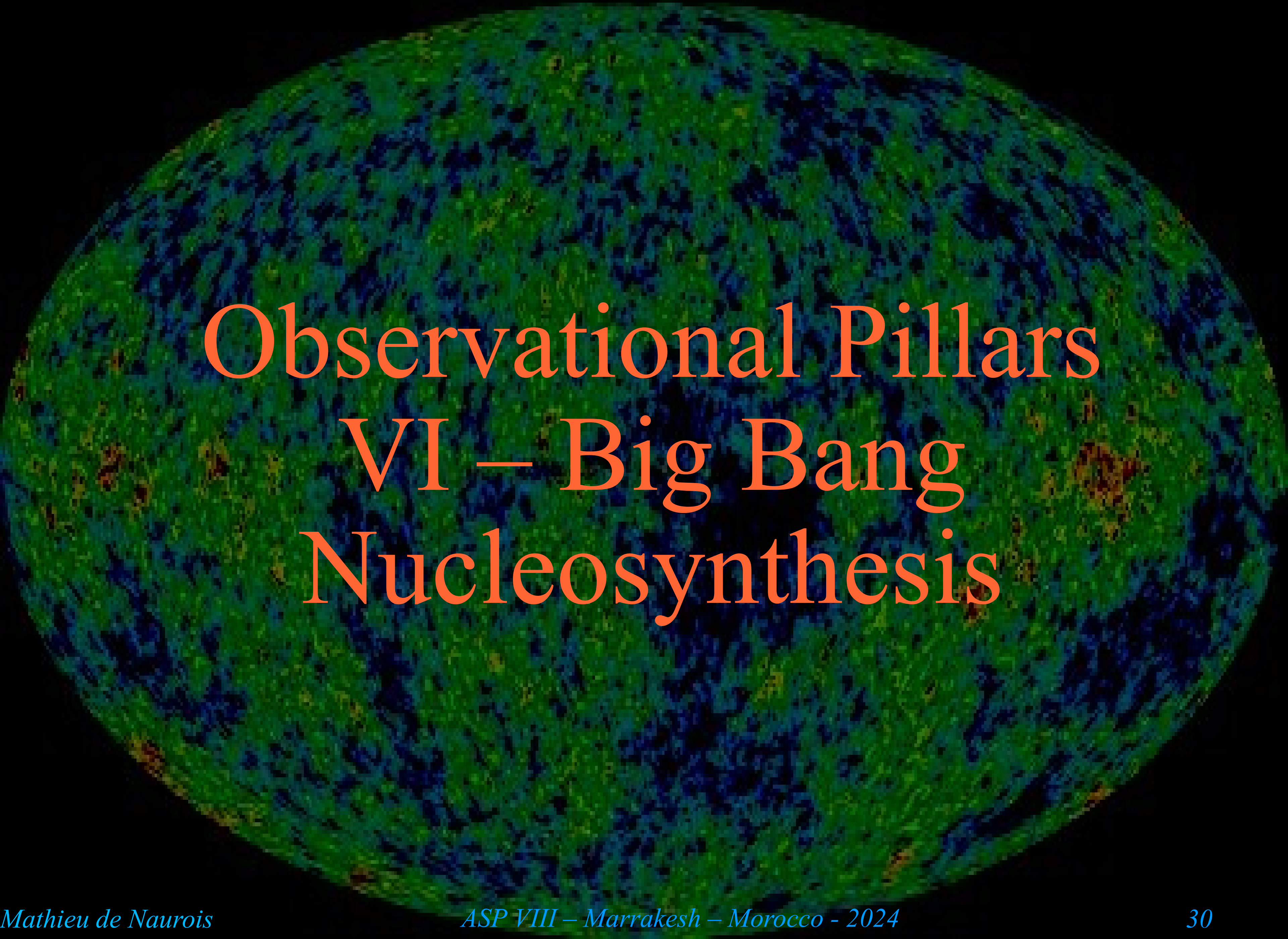


CFHTLS / SNLS

- ☐ 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
  - Neutrons number decreases due to neutron decay (τ = 878,4 ± 0,5 s).

- Deuterium is formed from the protons & newly produced neutrons, but get destroyed by high energy photons, until temperature is low enough that Deuterium is stable

- Then all available neutrons are used to form Deuterium first, then Helium, thus constraining the fraction of formed Helium.

Baryogenesis

- Relative abundances under thermal equilibrium:

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

- Equilibrium ratio of neutrons to protons (weak interactions)

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

- At high T, n ~ p, whereas at low T, n/p → 0
  - Need fine 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 $T_c \approx 0{,}8\,\mathrm{MeV}$
- At freeze-out

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

- 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 formation & bottleneck

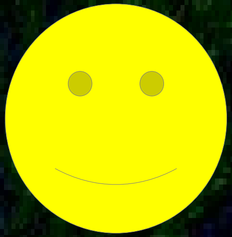
$$p + n \Leftrightarrow D + \gamma$$

- Production of Deuterium is at equilibrium at ~ 1 MeV
- While Universe is still too hot, Deuterium is immediately destroyed by encounter with high energy photons. 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
- Neutron fraction decreased due to decay: $\tau_n = 885{,}7 \pm 0{,}8\,\mathrm{s}$
- 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:

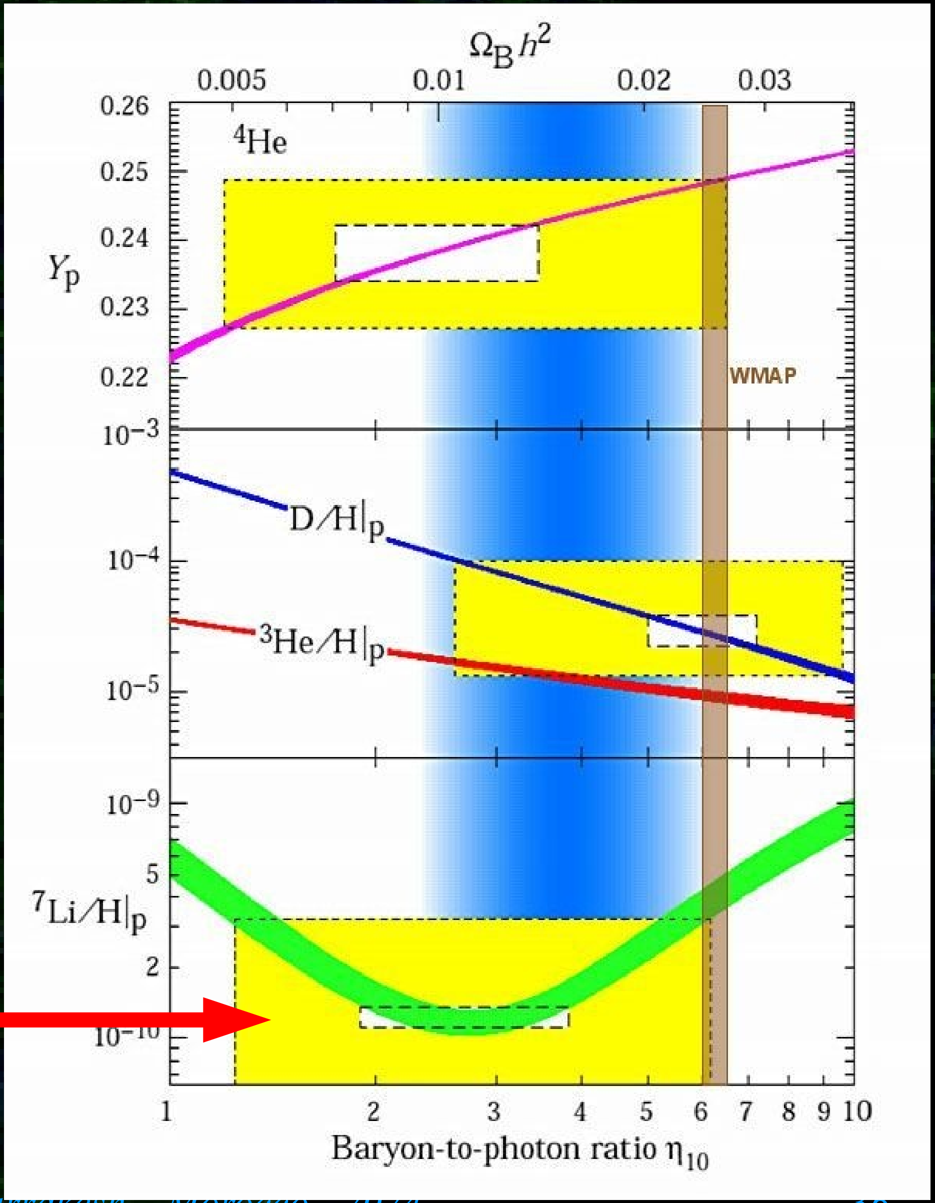
$$X_{^4\mathrm{He}} \approx 2 \times (n/p) = 0.25$$



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 $\Omega_B \sim 0.04 \pm 0.05$, consistent with other measurements
- ☐ Only free parameter: photon to baryon ration

Measured abundances

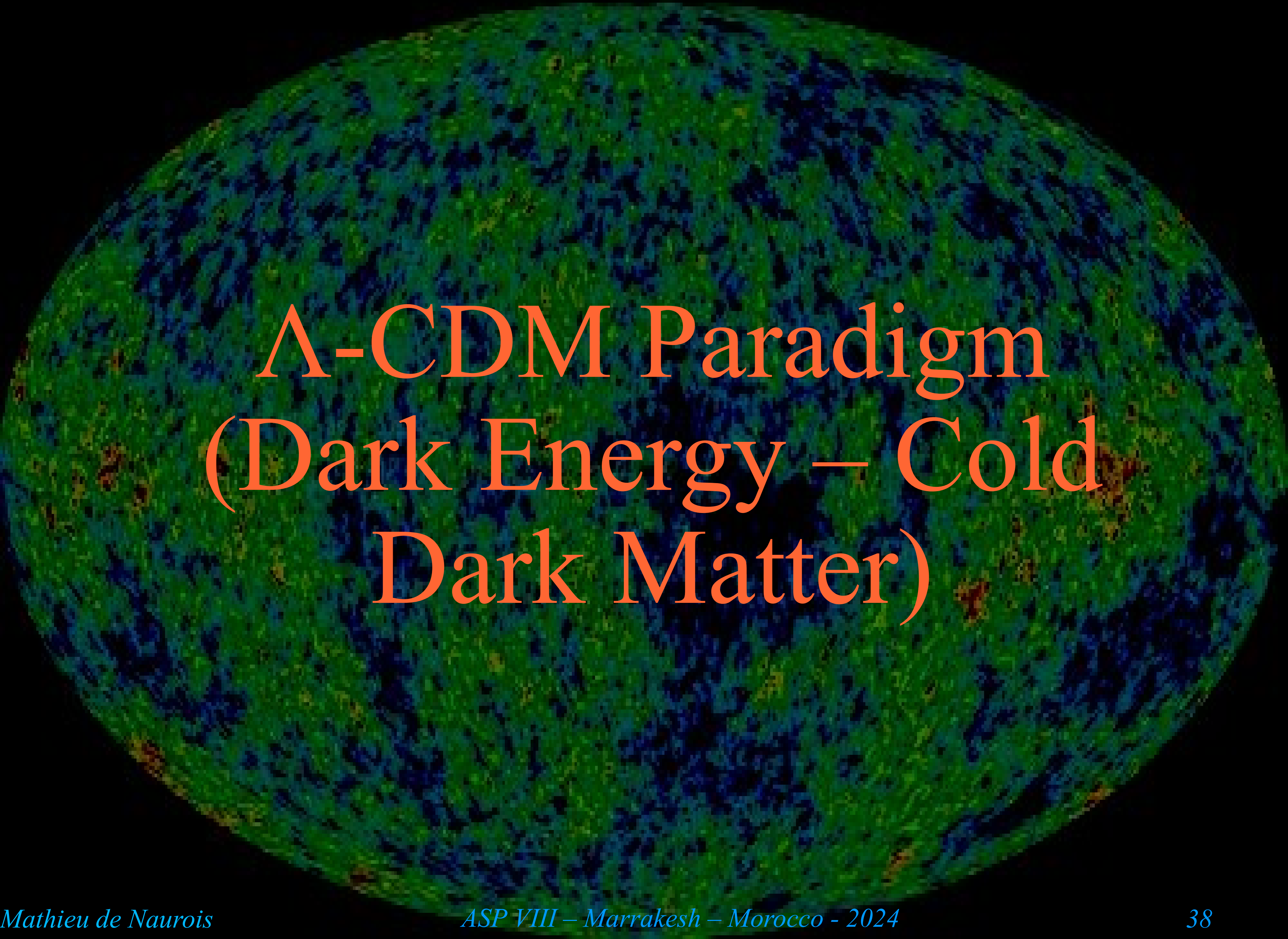


The Miracle

- 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

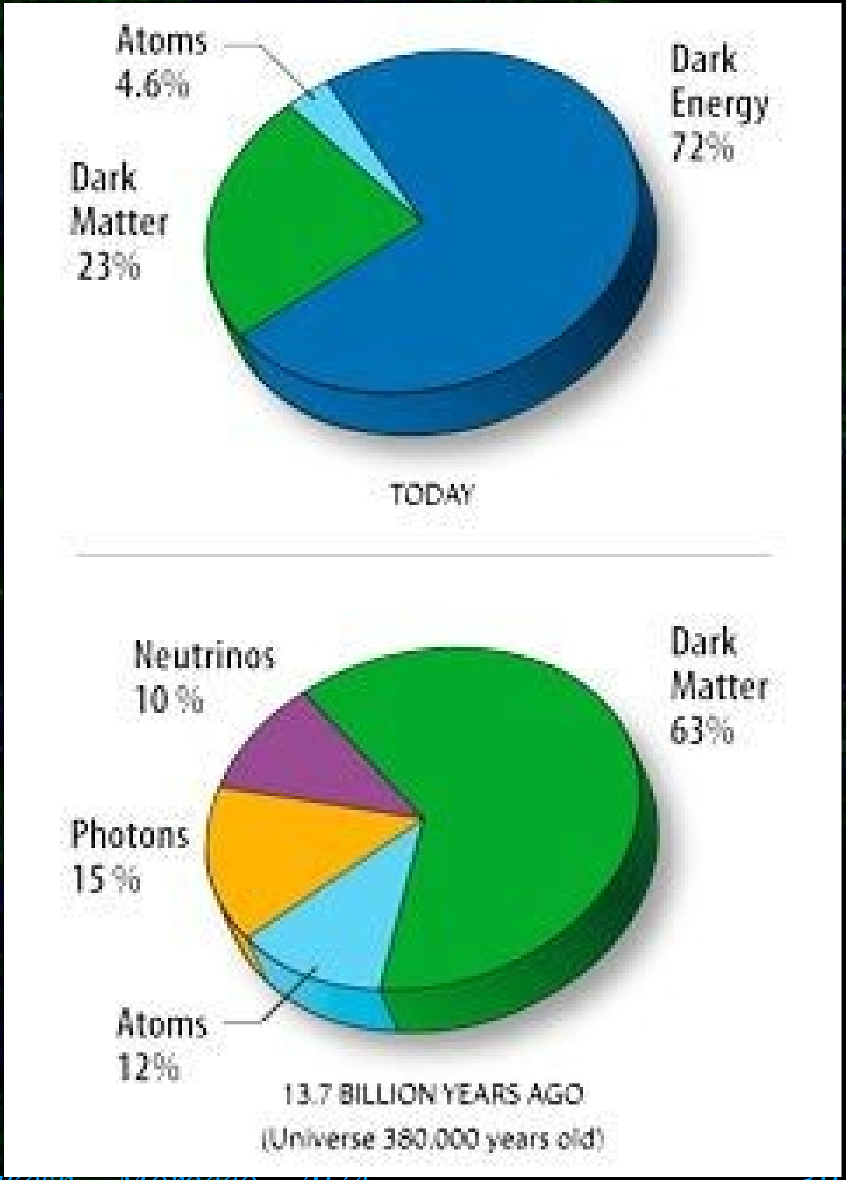
- Why is the neutron life time such as the fraction at T = 0.08 MeV is still significant? Shorter life-time will result in no neutrons in matter, only hydrogen



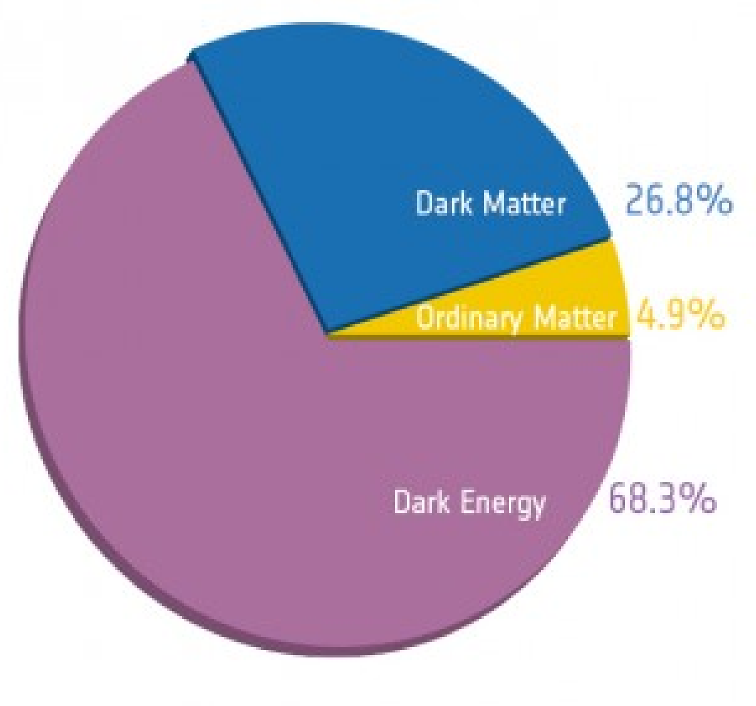
Λ-CDM Paradigm (Dark Energy – Cold Dark Matter)

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



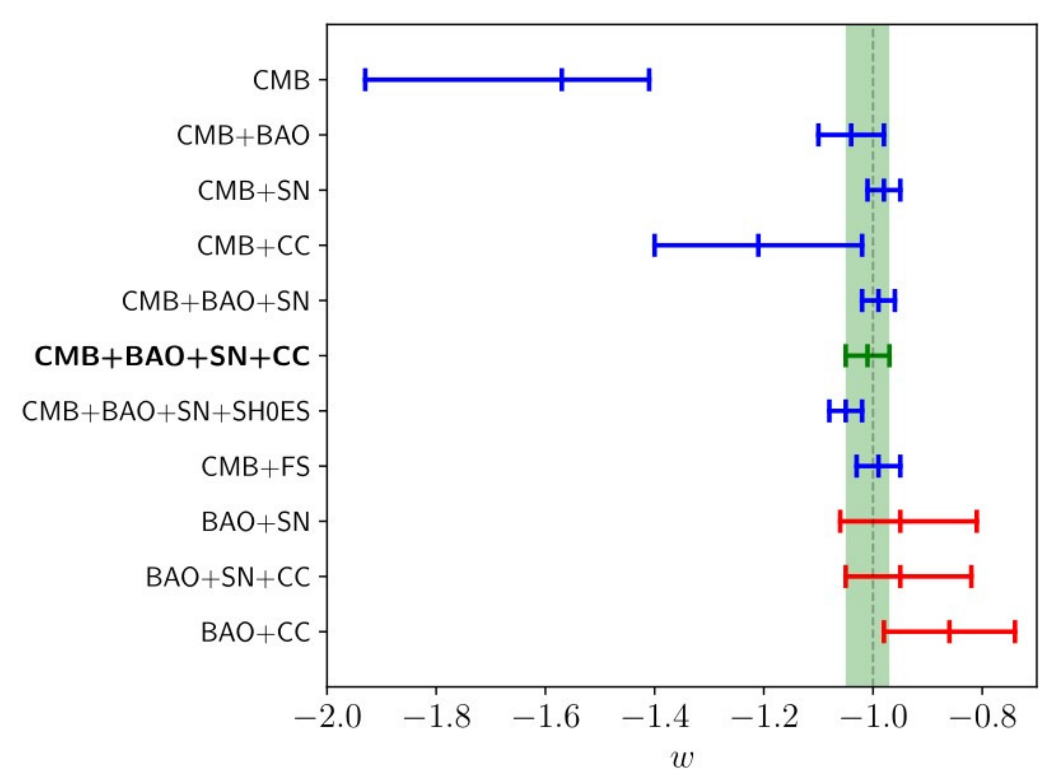
ΛCDM model – Now



- Baryons
  - $\Omega_{\text{baryon}} = 0.0486 \pm 0.0010$
- Cold Dark Matter
  - $\Omega_{\text{CDM}} = 0.2589 \pm 0.0057$
- Total Matter
  - $\Omega_M = 0.3089 \pm 0.0062$
- Dark Energy
  - $\Omega_\Lambda = 0.6889 \pm 0.0056$
  - $w = -1.013 + 0.038 - 0.043$ → cosmological constant!
- Critical density (spatially flat universe)
  - $\Omega_T = 1.0023 \pm 0.005$ → flat Universe
- Inhomogeneities : gravitational potential fluctuations

Cosmological constant?

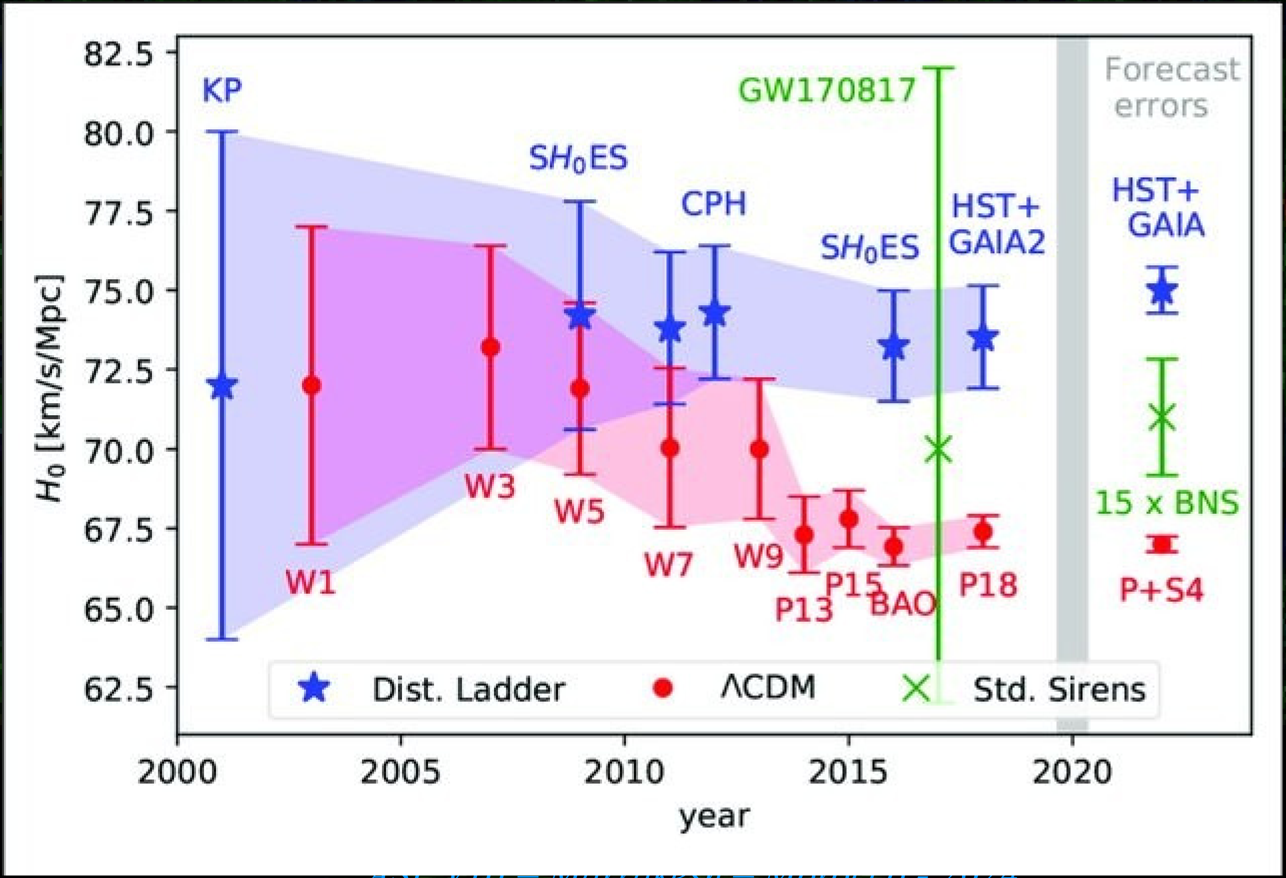
- Equation of state (2024)
  - $w = -1.013 + 0.038 - 0.043$ → compatible with cosmological constant



Escamilla et al, 2024

Hubble Tension

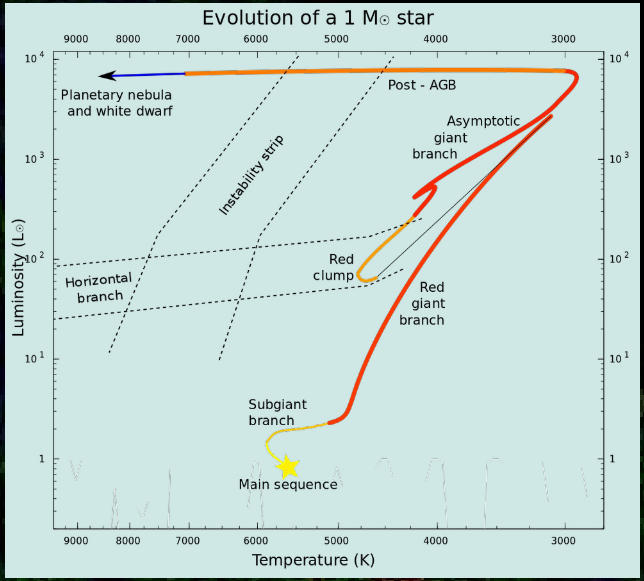
- Expansion rate measured in local Universe (SNR) and infered from early epoch (CMB) disagree (~ 5 σ)
- Major debate in the community
- Could the cosmological “constant” vary with time?

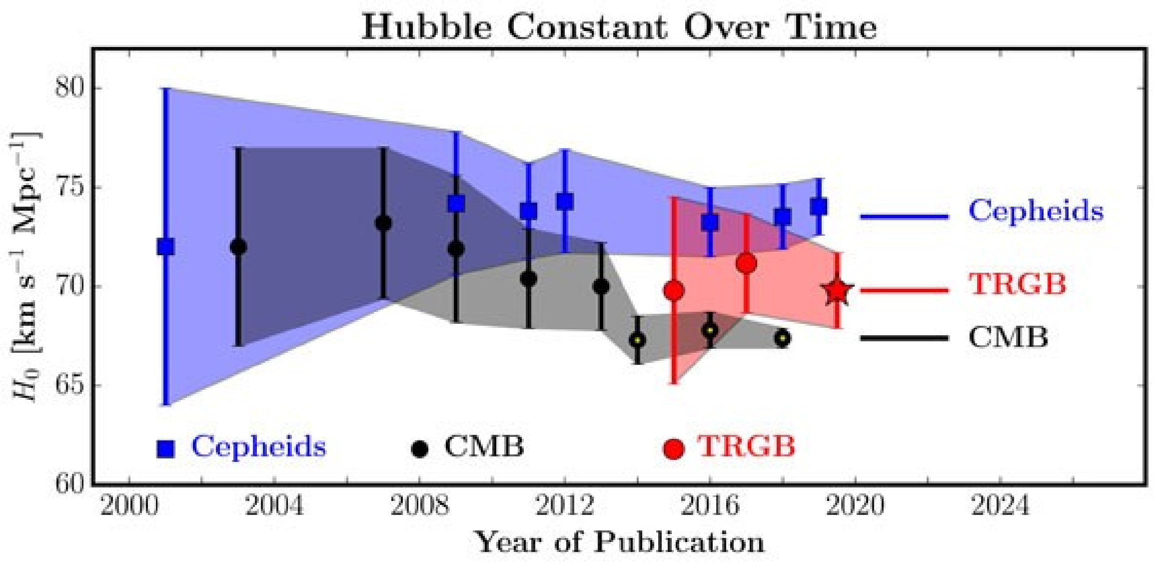


Beaton et al., 2016

Update – 2024

- “Tip of the Red Giant Branch” (TRGB): Red Giants pass by a max. luminosity which is almost independent of stellar mass and composition
  ⇒ Standard candle
- $H_0 = 69.8 \pm 0.8$ km s^{-1} Mpc^{-1} between early and late measurement
- Overall “Hubble Tension” at 4 to 6 σ





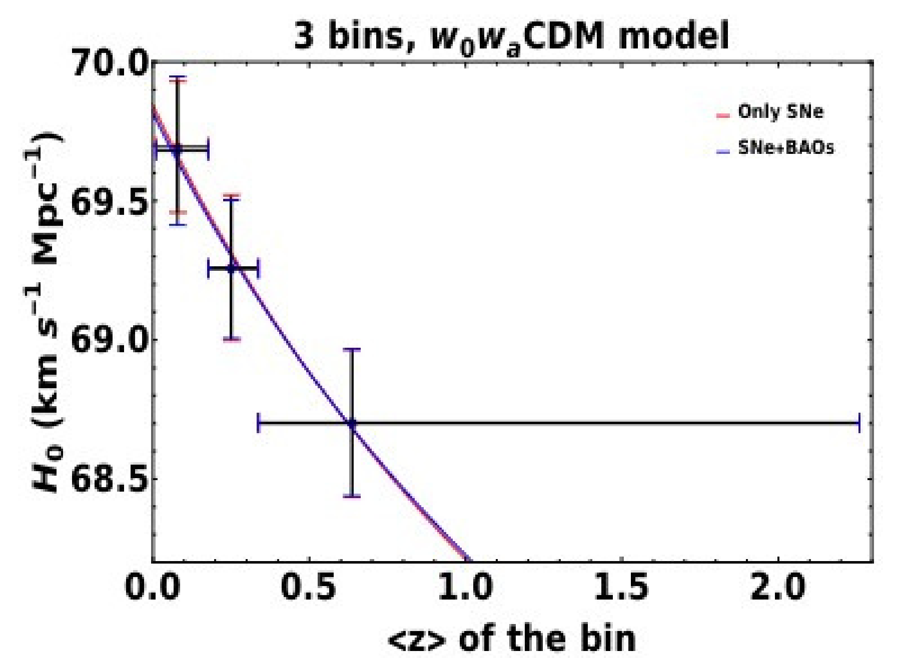
Freedman et al, 2019

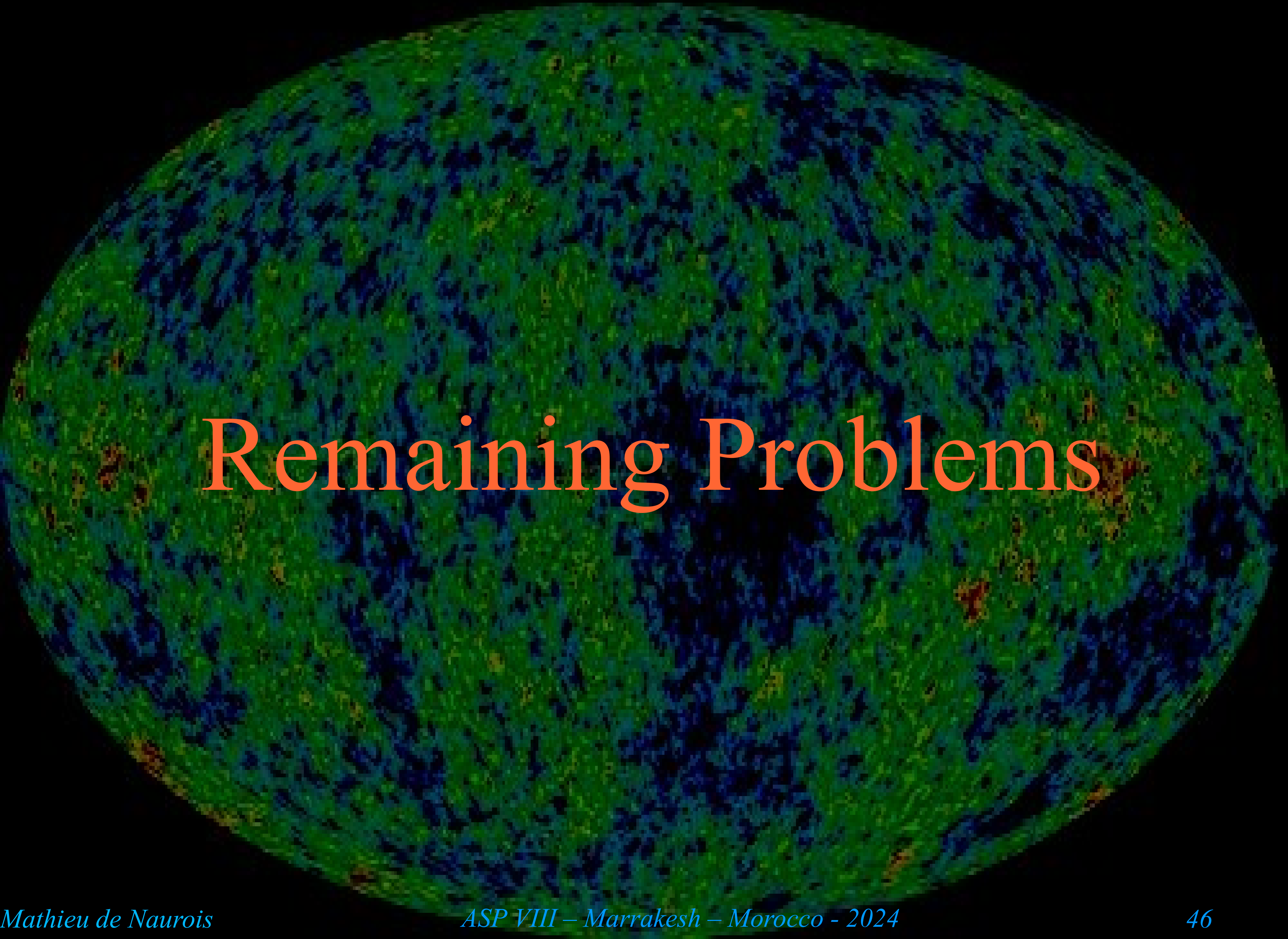
Hubble Tension

- ☐ Early & Late measurement do not agree
- ☐ Overall "Hubble Tension" at 4 to 6 σ
- ☐ Decreasing trend with redshift can point toward to a model in which the dark energy equation of state varies with time:

$$w(a) = w_0 + w_a(1-a) \quad \text{with} \quad a \equiv \frac{1}{1+z}$$

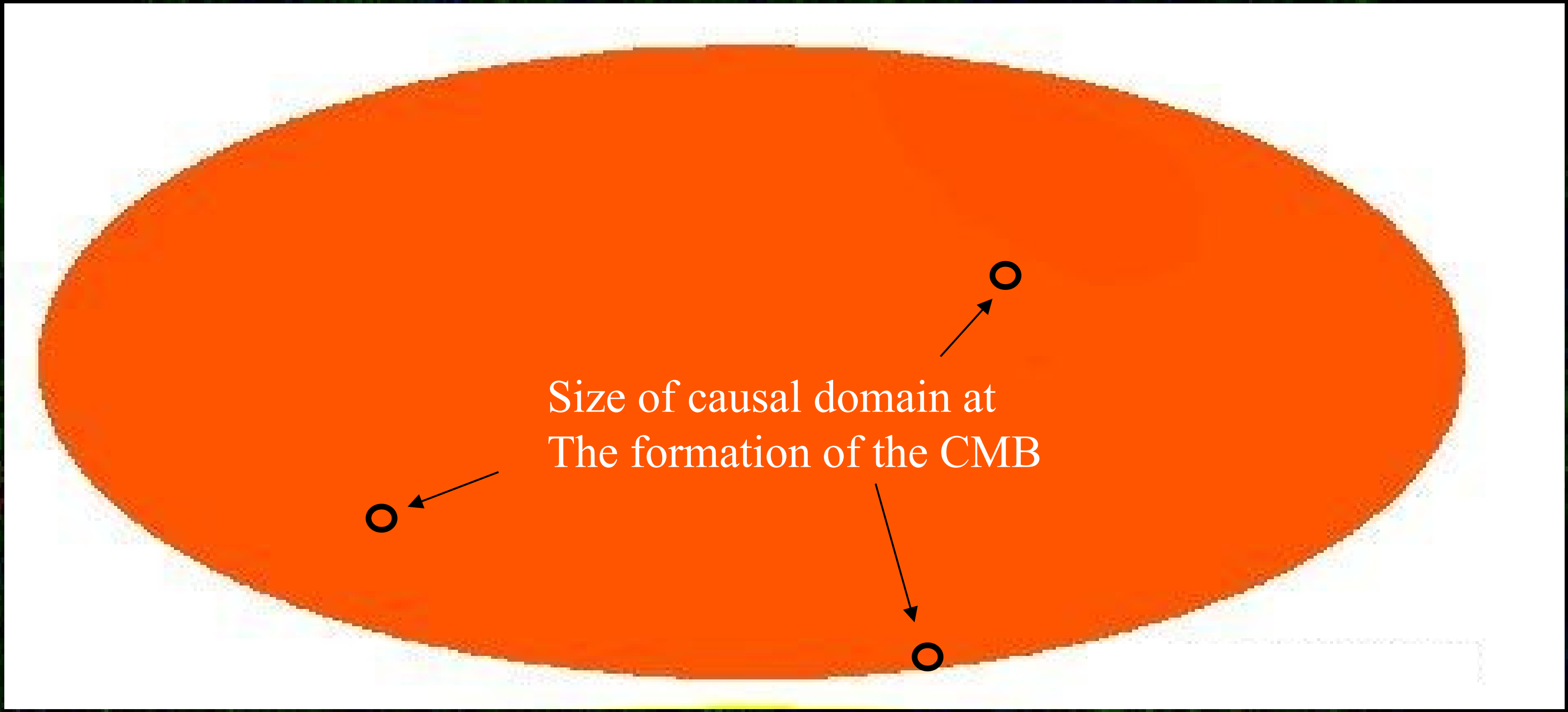
- ☐ Need high z probes (GRBs or QSO)





Remaining Problems

Cosmic Problem 1 : Isotropy & Horizon

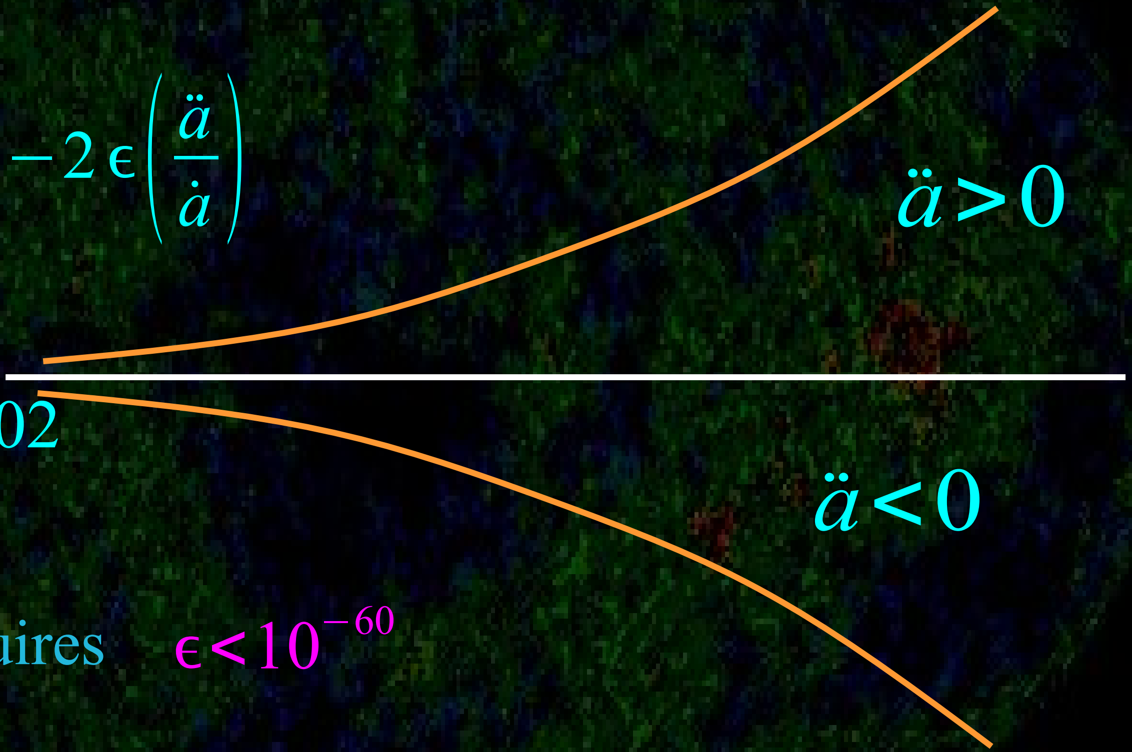

Size of causal domain at
The formation of the CMB

- ☐ 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

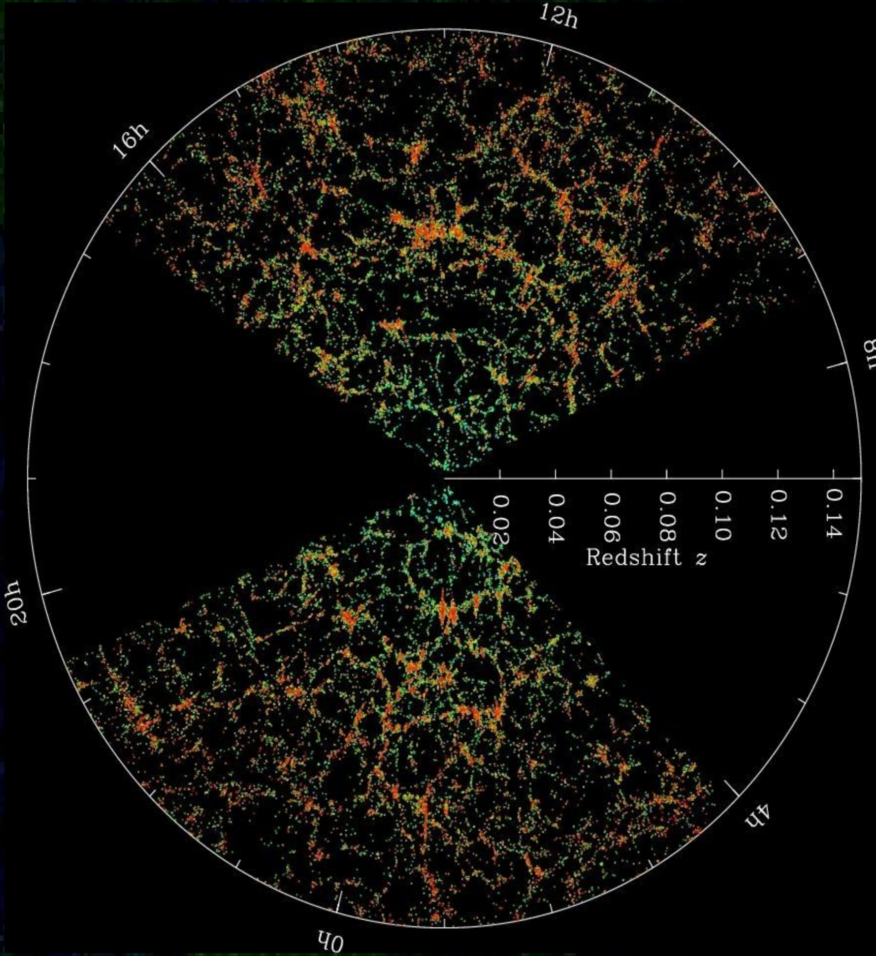
$$\epsilon = \Omega_{tot} - 1 \qquad \dot{\epsilon} = -2\epsilon\left(\frac{\ddot{a}}{\dot{a}}\right)$$



- Today $\epsilon = 0.01 \pm 0.02$
- @ $t = 10^{-43}$ s, this requires $\epsilon < 10^{-60}$
- Such a precise tuning seems completely unlikely

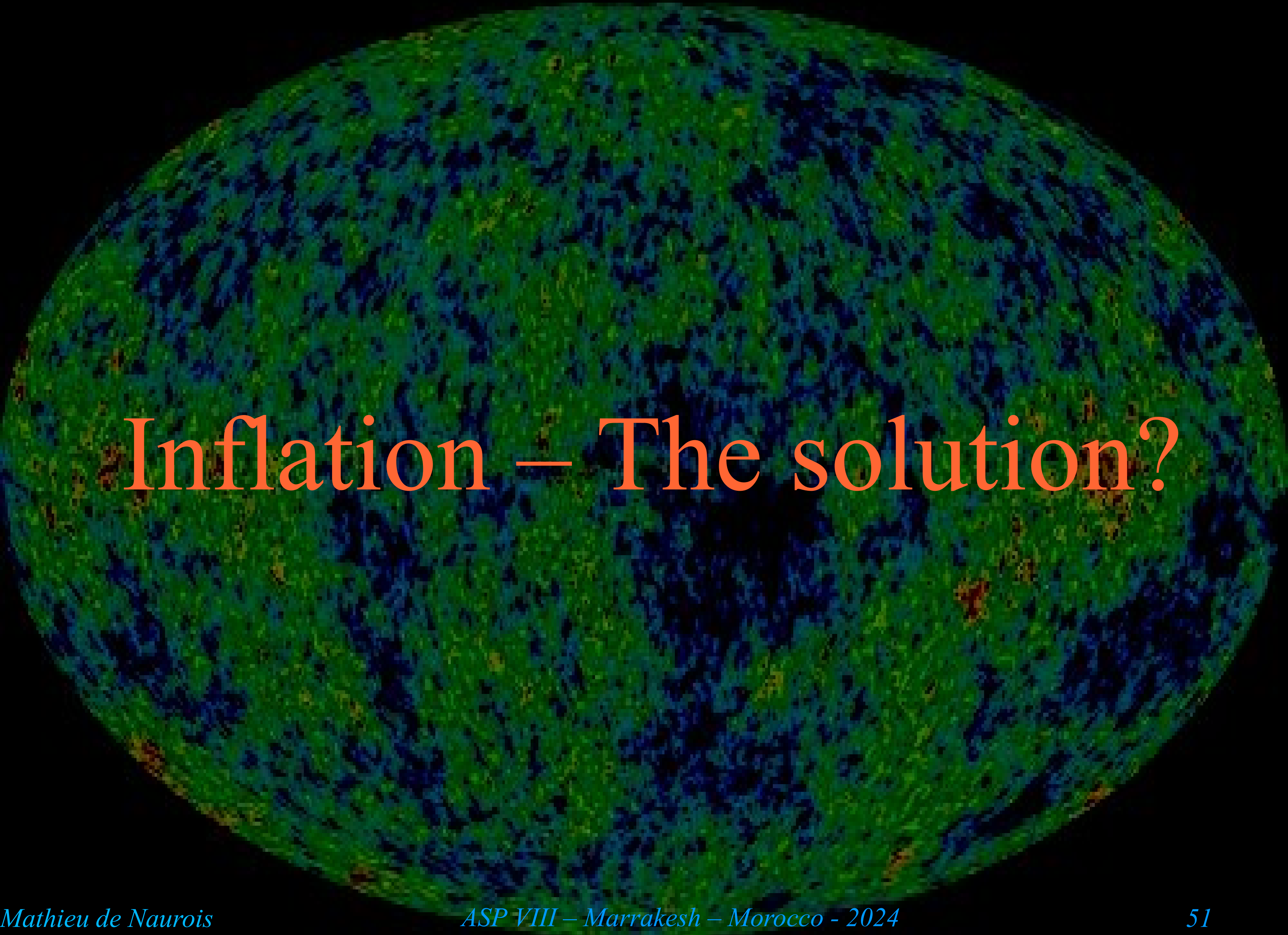
Cosmic Problem 3: Birth of fluctuations

- 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 matter universe

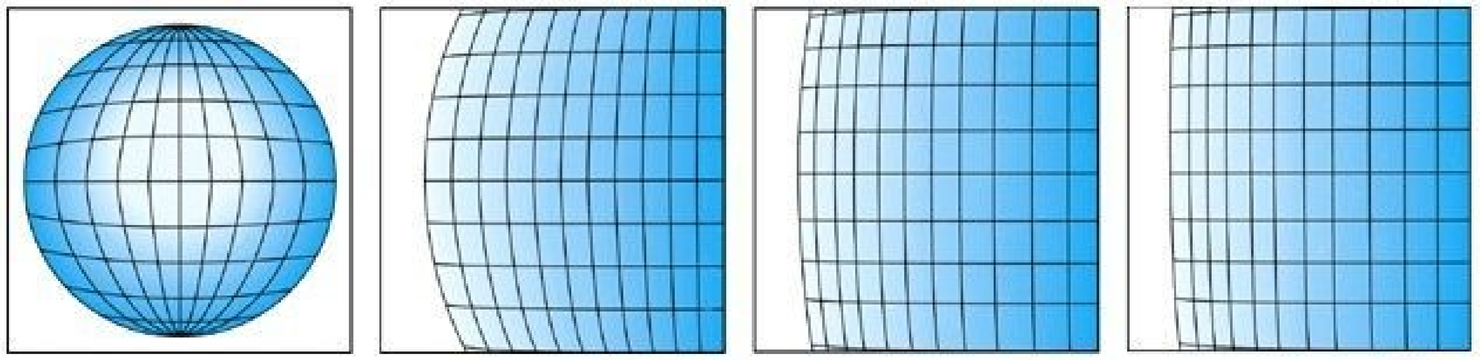
- There must have been a tiny matter - anti-matter asymmetry in the early universe: 10 000 000 001 protons produced for 10 000 000 000 anti-protons.
  - Anti-protons annihilated with protons, leaving ~1 proton per ~ 10^{10} photons today
    – why and how did this happen?
- We should expect no baryons 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, ...)



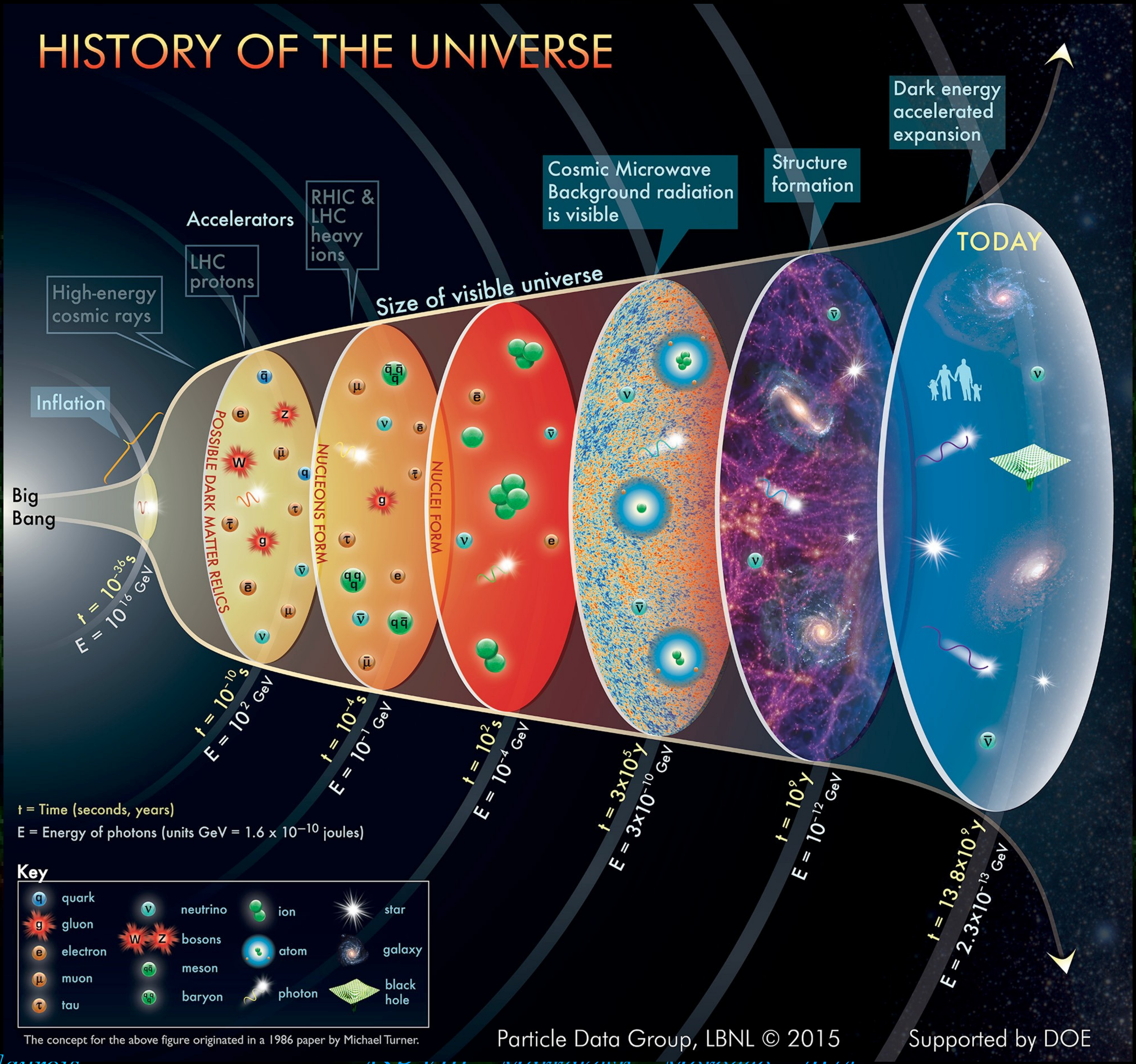
Inflation – The solution?

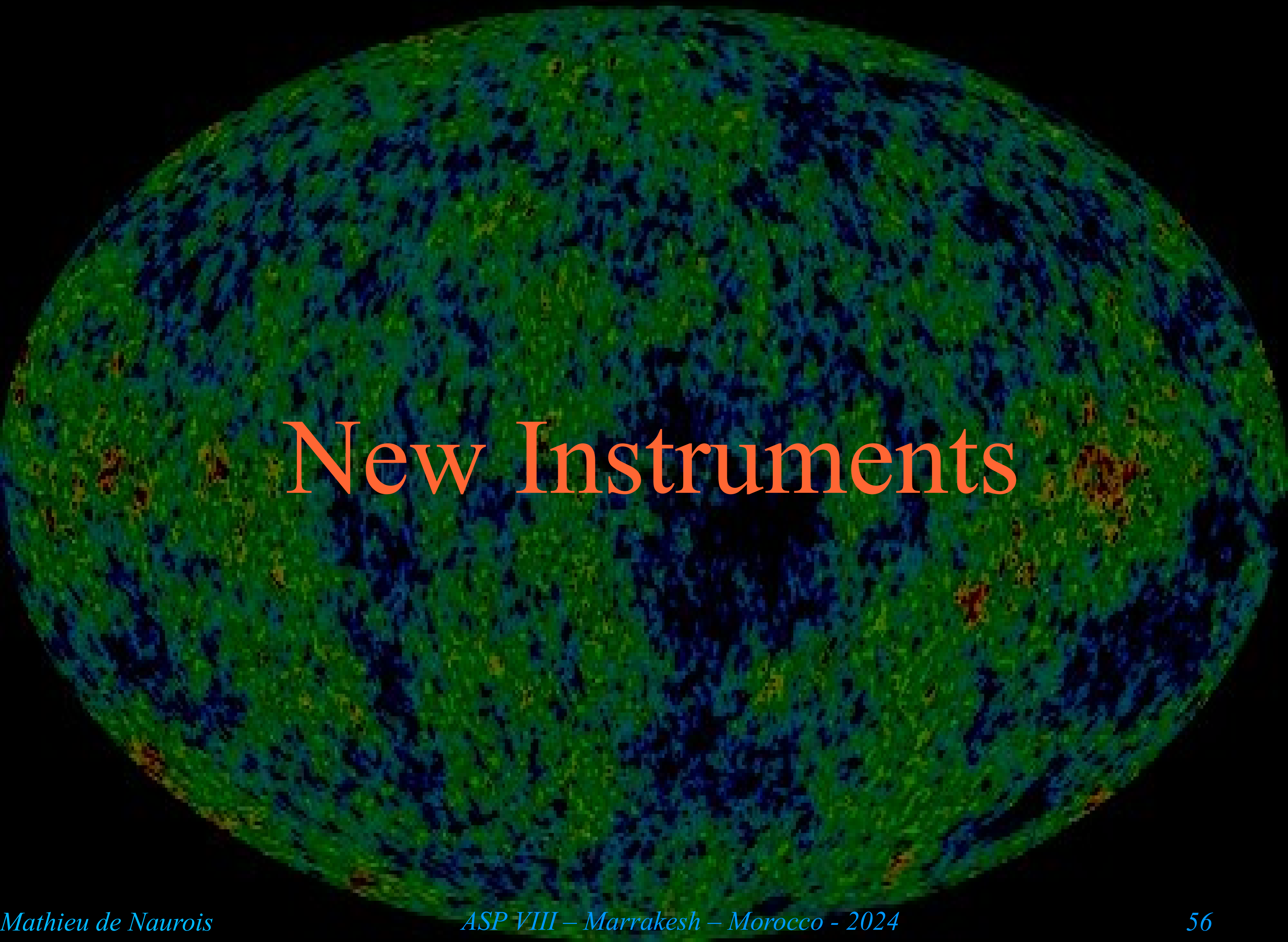
Inflation – the solution?

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



- ☐ Acceleration: $$\left(\frac{\ddot{a}}{a}\right) = -\frac{4}{3}\pi G \sum_i \left(\rho_i + 3p_i\right)$$
- ☐ Inflation requires negative pressure: $\rho_i + 3p_i < 0$
- ☐ But cosmological constant in negligible in early Universe
- ☐ A scalar field, the so-called inflaton, dominating the early Universe, could generate inflation until it reaches minimum of potential (slow-roll)

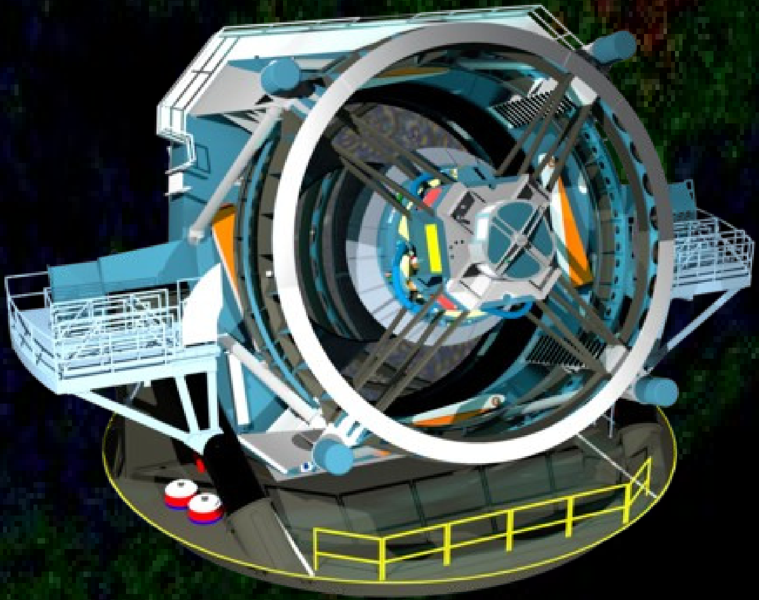

HISTORY OF THE UNIVERSE
Dark energy accelerated expansion
Cosmic Microwave Background radiation is visible
Structure formation
RHIC & LHC heavy ions
Accelerators
LHC protons
High-energy cosmic rays
Size of visible universe
TODAY
Inflation
Big Bang
POSSIBLE DARK MATTER RELICS
NUCLEONS FORM
NUCLEI FORM
t = 10^{-36} s
E = 10^{16} GeV
t = 10^{-10} s
E = 10^{2} GeV
t = 10^{-4} s
E = 10^{-1} GeV
t = 10^{2} s
E = 10^{-4} GeV
t = 3×10^{5} y
E = 3×10^{-10} GeV
t = 10^{9} y
E = 10^{-12} GeV
t = 13.8×10^{9} y
E = 2.3×10^{-13} GeV
t = Time (seconds, years)
E = Energy of photons (units GeV = 1.6×10^{-10} joules)
Key
q quark
g gluon
e electron
μ muon
τ tau
ν neutrino
W Z bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
The concept for the above figure originated in a 1986 paper by Michael Turner.
Particle Data Group, LBNL © 2015
Supported by DOE



New Instruments

Vera C. Rubin Observatory – Large Synoptic Survey Telescope – LSST

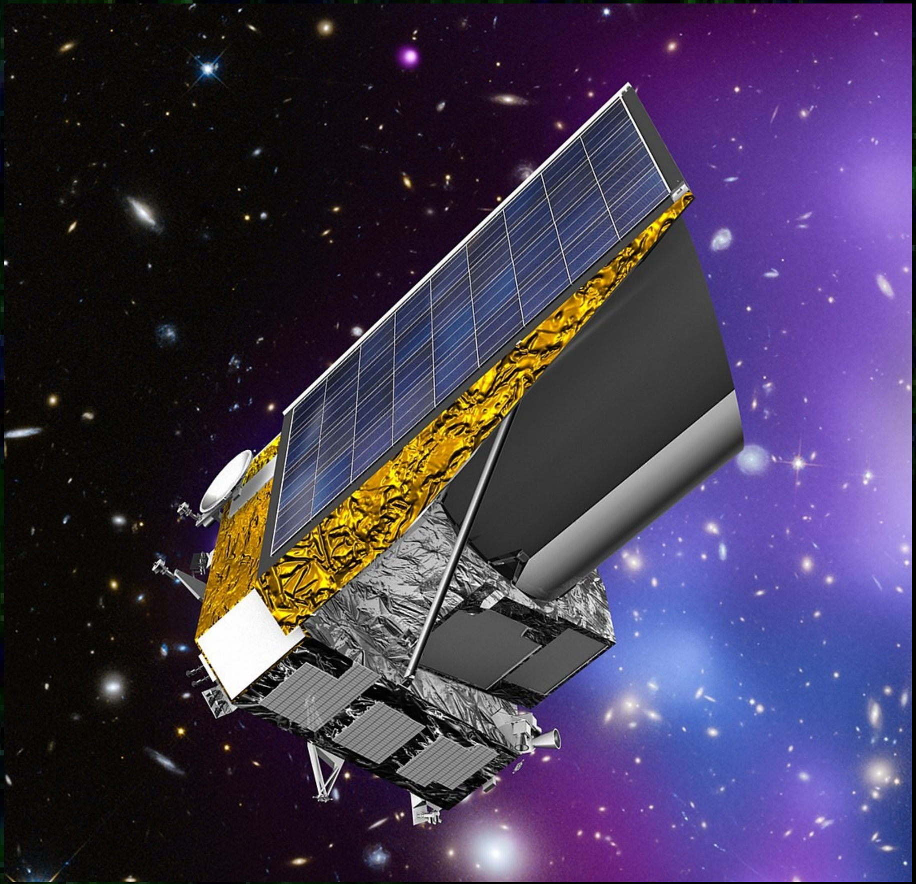
- ☐ Very wide field telescope (3.5° ∅)
- ☐ Full southern sky every 3 days
  ⇒ Transient machine
  - ☐ Dark Matter & Dark Energy with (Type Ia), weak gravitational lensing and BAO
  - ☐ Small objects in solar system, near-Earth asteroids and Kuiper Belt objects
  - ☐ Transient astronomical events: novae, supernovae, gamma-ray burst, active galactic nuclei
  - ☐ Mapping of the Milky Way
- ☐ First light expected in 2025!
- ☐ ≥ 10 years of operations



Vera C. Rubin Observatory

Euclid

- ☐ Dedicated mission for dark matter & dark energy
- ☐ Launched July 1st, 2023
- ☐ Arrived at Lagrange point L2 2 weeks after

Euclid

- ☐ First images released November 7th, 2023

Euclid's view of the Perseus cluster of galaxies

Euclid

- First images released November 7th, 2023

Euclid's view of the Horsehead Nebula

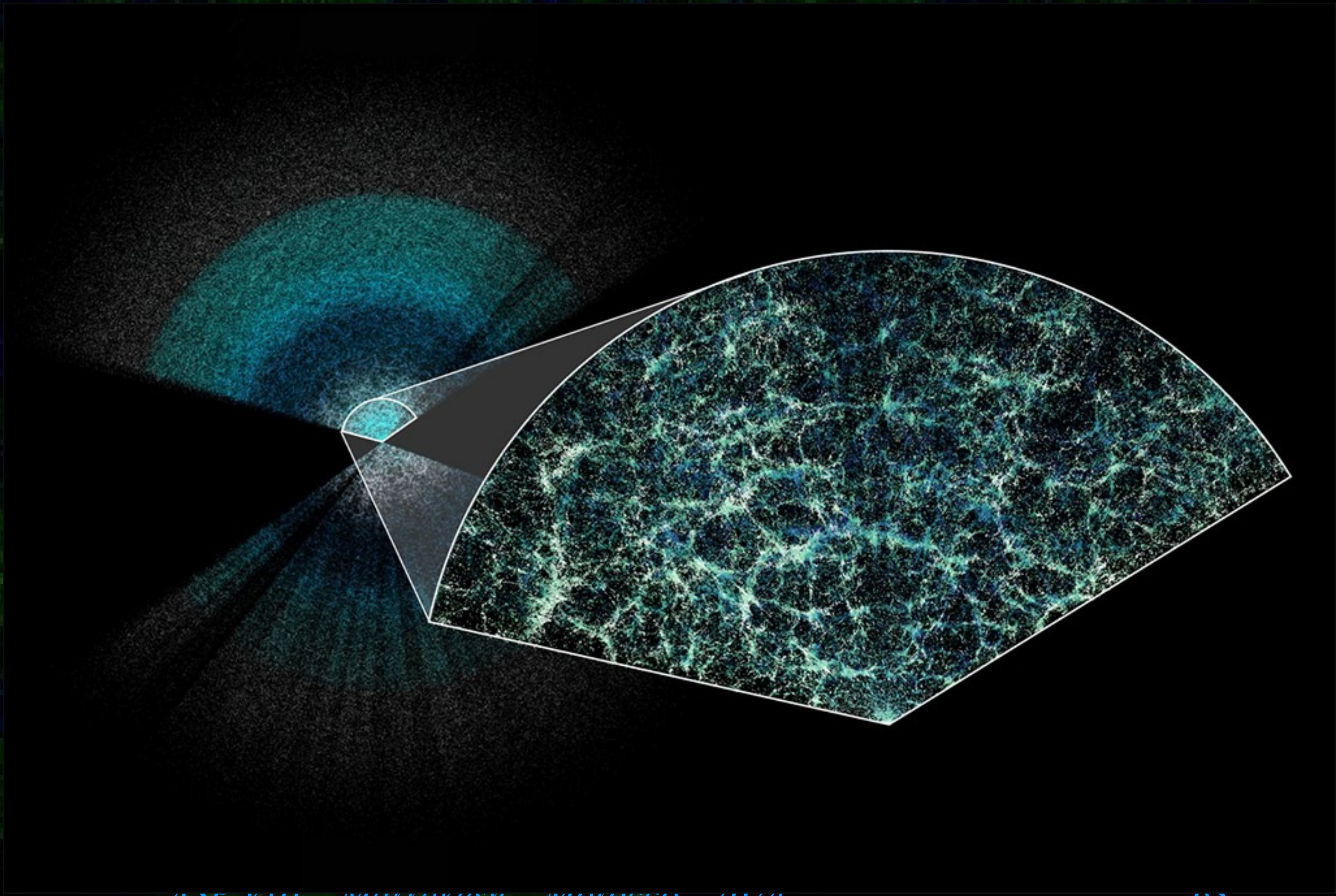
DESI – (Dark Energy Spectroscopic Instrument)

- ❑ Ground-based Dark Energy Experiment
- ❑ Robotically-actuated, fiber-fed spectrograph, up to 5,000 simultaneous spectra, Kitt Peak (Arizona)
- ❑ Optical observation of Galaxies up to $z = 1.7$ and quasars in $2.1 < z < 3.5$, survey of 14 000 deg² (1/3 of full sky)
- ❑ Study baryon acoustic oscillations (BAO)
- ❑ Started May 2021 – ongoing
- ❑ Last Intermediate data release September 2023

DESI

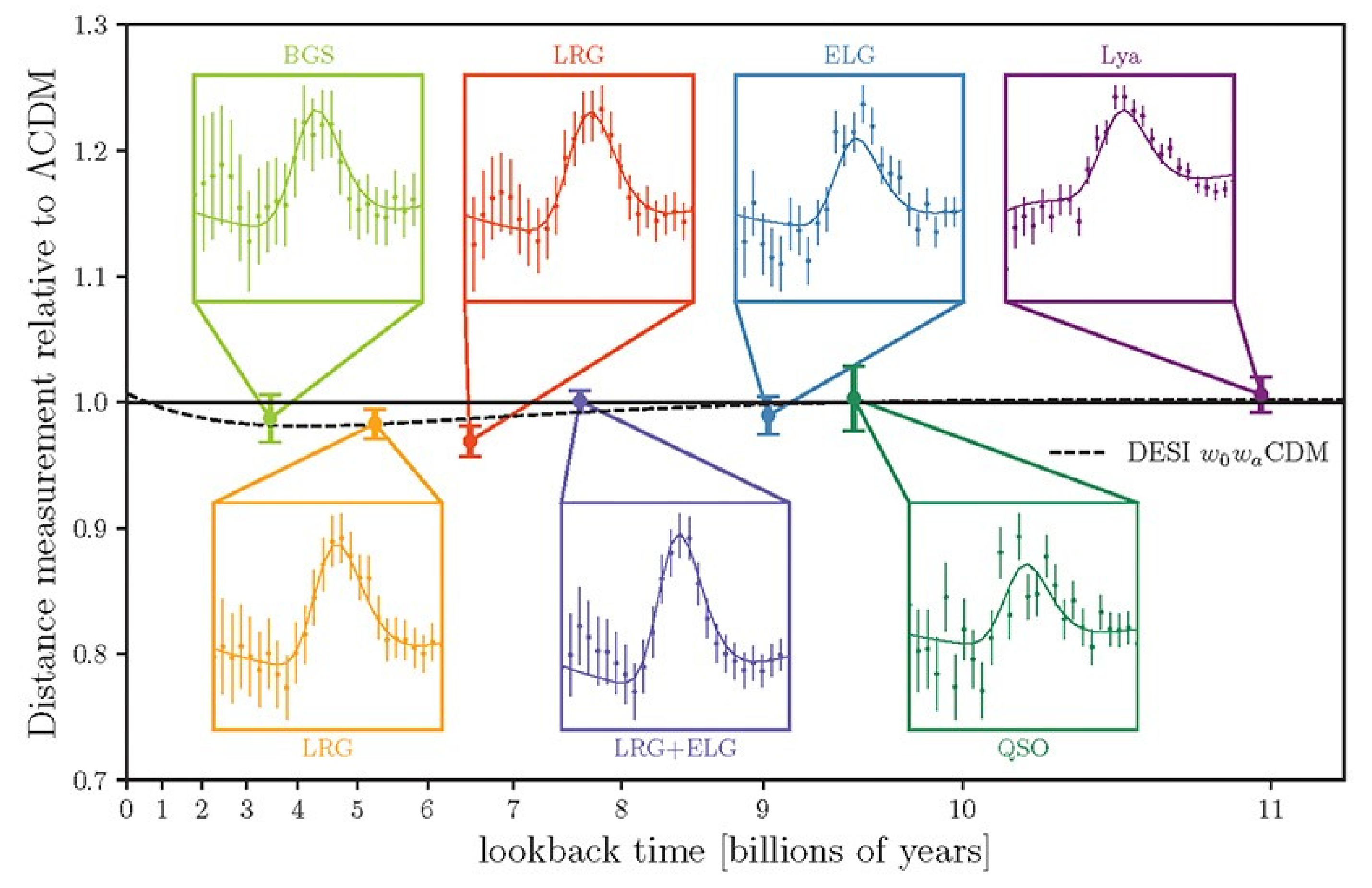
- ❑ 3D Map of the Universe

Claire Lamman/DESI collaboration



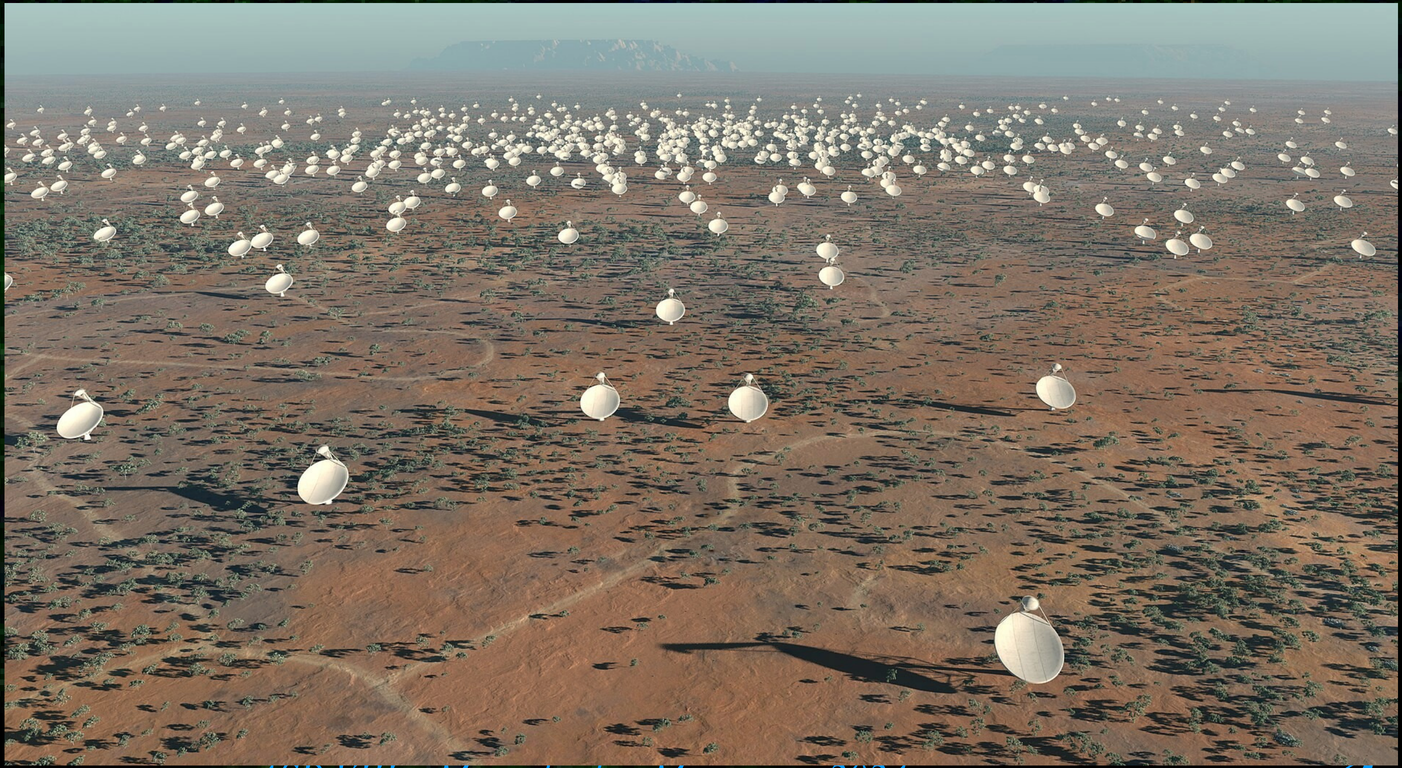
DESI – BAO

- ❑ Different probes allow to measure BAO at different epoch
- ❑ Confirms ΛCDM Model (for the moment)



Square Kilometer Array – SKA

- ❑ Multi-antenna radio telescope, Australia & South Africa
- ❑ × 50 more sensitive than current instruments
  - ❑ Large surveys
  - ❑ Probe of reionization era (first stars)
- ❑ First light expected ~ 2027

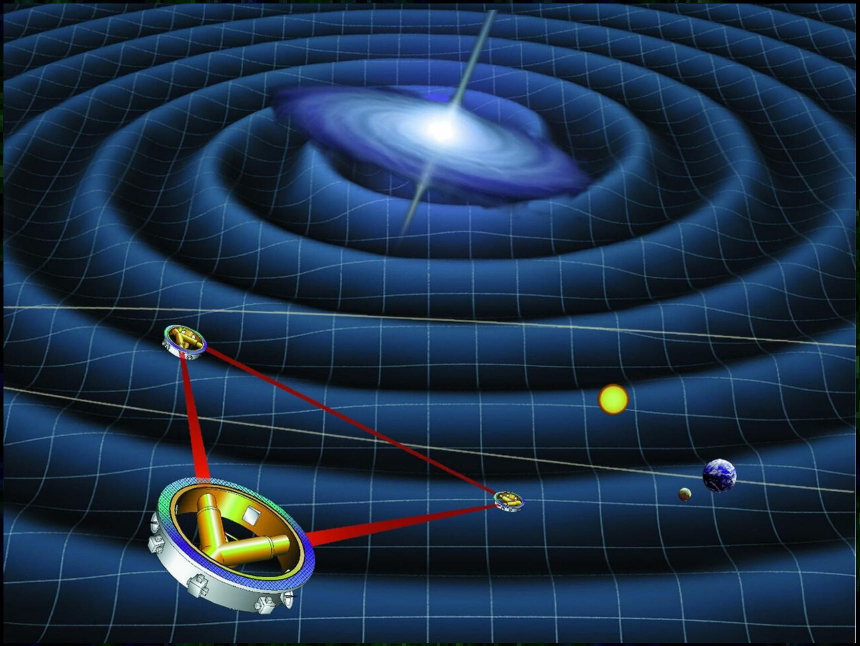


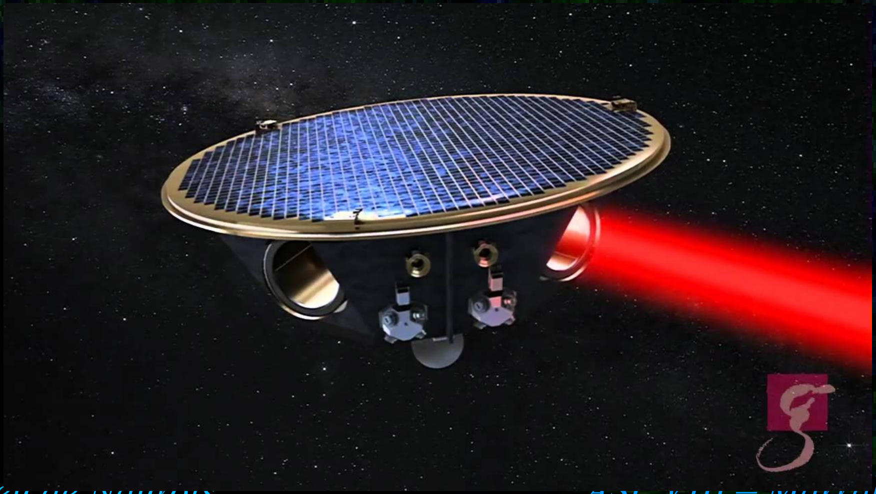
CMB-S4

- ☐ Next-generation (“Stage IV”) ground-based CMB experiment
- ☐ 12 telescopes (South-Pole + Chile)
- ☐ 500,000 cryogenically-cooled superconducting detectors
- ☐ Science goals:
  - ☐ primordial gravitational waves and inflation;
  - ☐ the dark Universe;
  - ☐ mapping matter in the cosmos;
  - ☐ the time-variable millimeter-wave sky.
- ☐ Current Schedule:
  - ☐ Deployment/first light in 2031
  - ☐ Operations until 2041

Laser Interferometer Space Antenna – LISA

- Space born gravitational wave detector (interferometer)
- 2.5×10^6 km arms
- Access to low frequency:
  - SMBH Mergers
  - Binary systems in the Milky Way
  - Distant binary systems
  - Test of general relativity
  - Independent measurement of H_0
  - …





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?
  - Link with the Higgs Boson?
  - What is the Dark Matter?
  - What is the Dark Energy?
- New instruments coming online and being developed
- Exciting times ahead of us!