



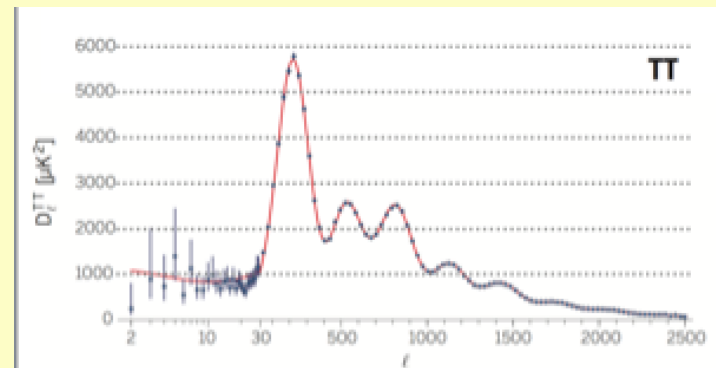
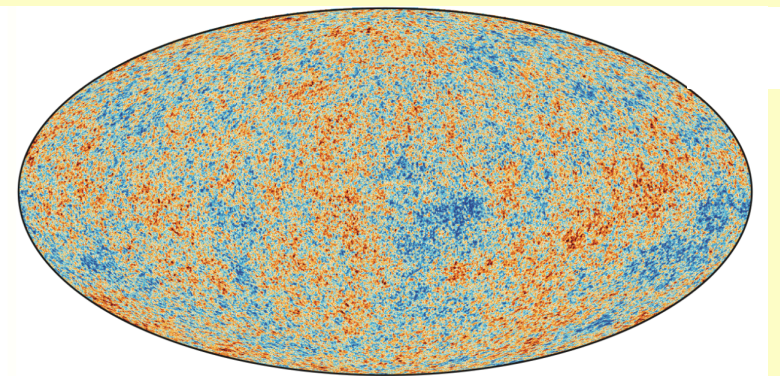
The Music of the Sphere

Roger Blandford

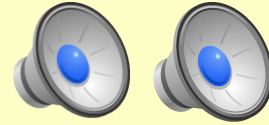
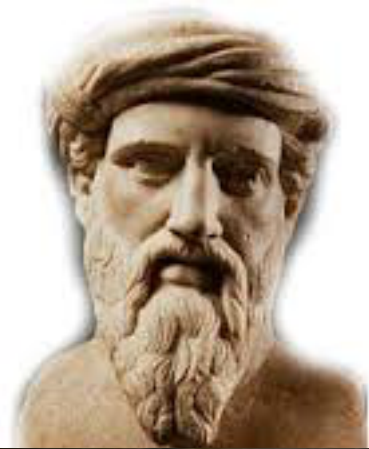
KIPAC

Stanford

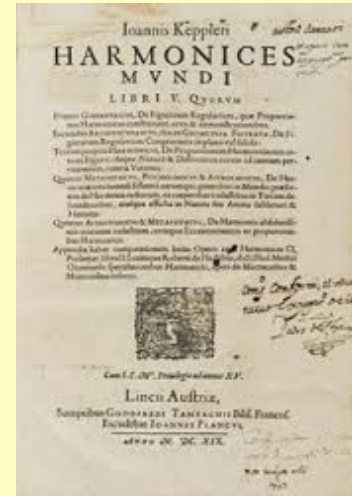
Solvay



The Music

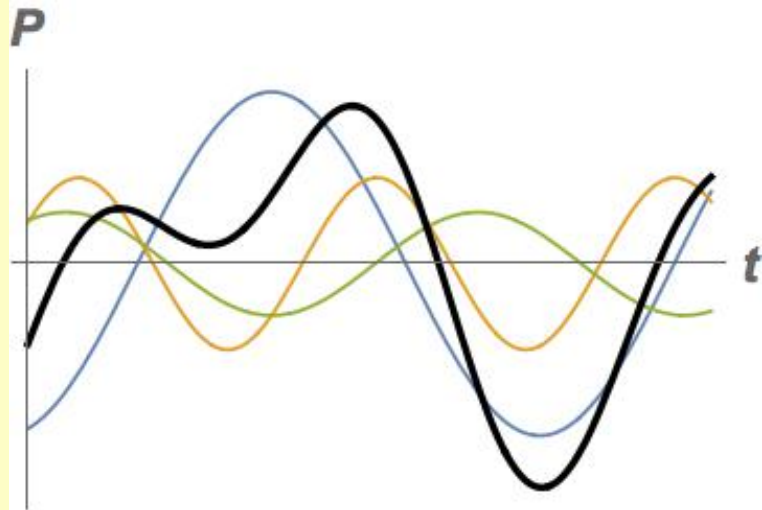


- Pythagoras
 - Musical notes
 - Numbers->harmony, color, ethics
- Kepler
 - De Harmonici Mundi
 - Plato->Planets
- Huyghens, Newton
 - Traite de la Lumiere, Opticks
 - Waves, Particles,-> Quantum mechanics



Sounds are Sums of Waves

- Signal e.g. pressure

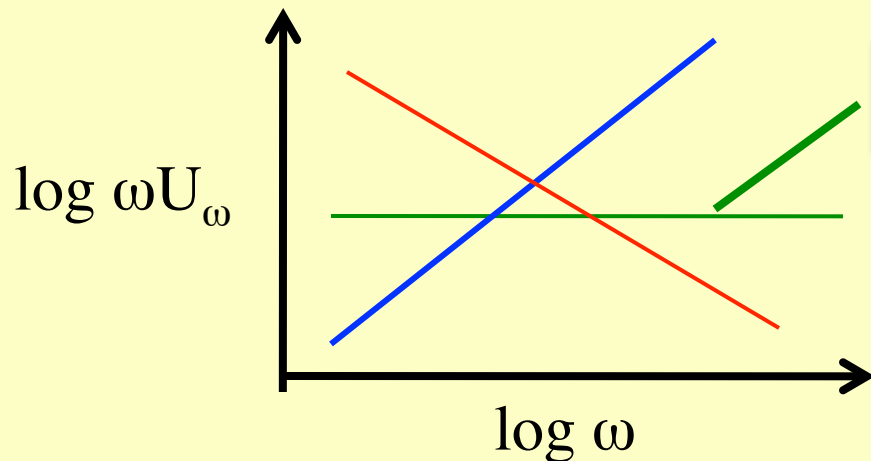


$$P(t) = \sum_n P_n \sin(2\pi n t / T + \phi_n) \propto \int d\omega \tilde{P}(\omega) e^{i\omega t}$$

Fourier Transform

$$U \propto \langle P^2 \rangle T \propto \int d\omega \tilde{P}^2 \propto \int d\omega U_\omega$$

Energy



Music is more than this !

Gauss devised FFT,
normal distribution!



Spatial Fourier Transforms

Outline

- The Music
- The Sphere
- The Universe Today
- Seven Ages of the Universe
- The Music of the Sphere
- Three Mysteries
 - Inflation
 - Matter
 - Cosmological Constant

This talk will be largely a description of the standard model of the universe.

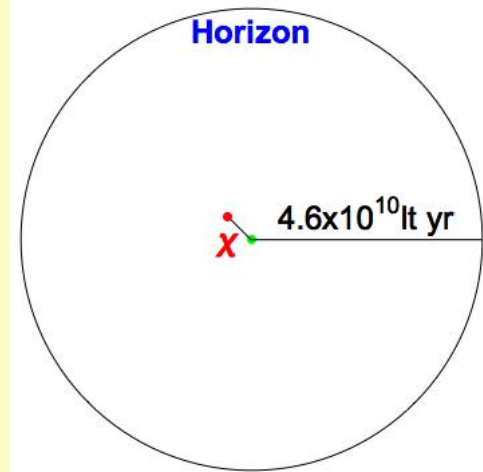


Outline

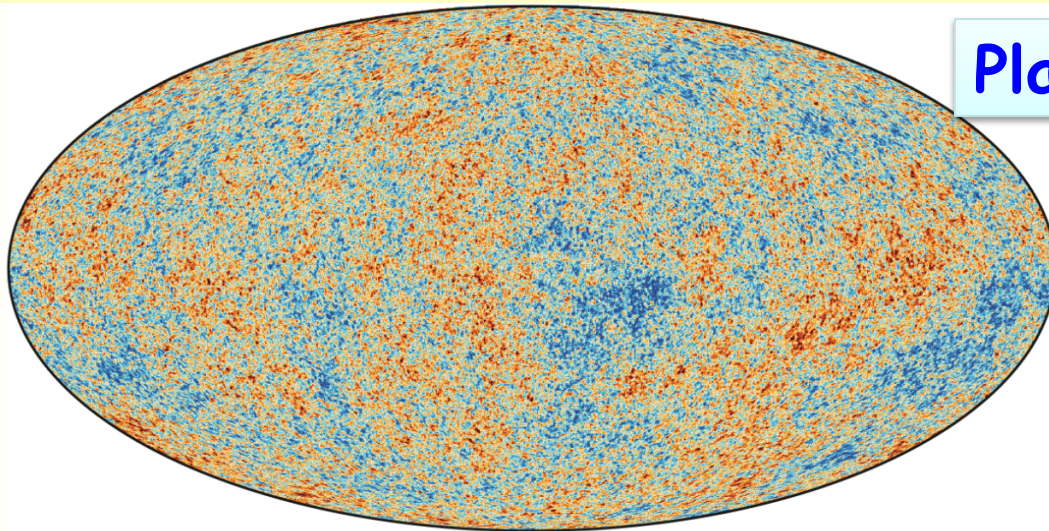
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The Sphere

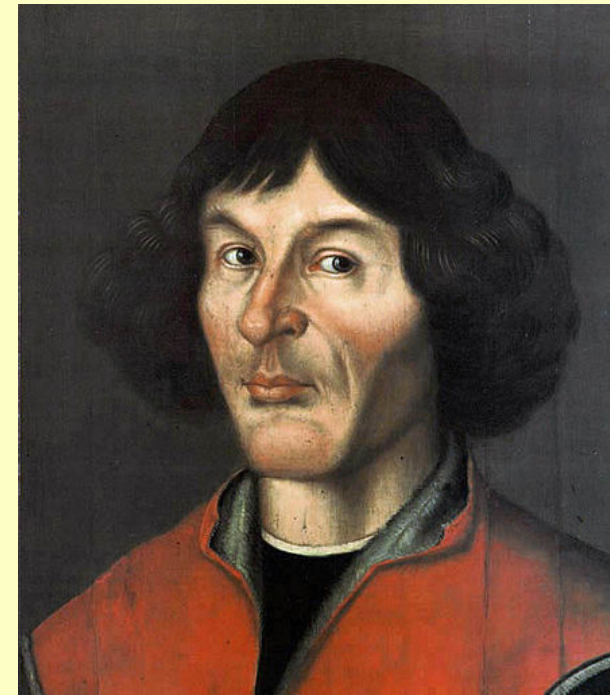
- Universe is isotropic about us
 - We are not special (Copernicus)
 - => Universe is homogeneous at fixed time
- Universe is expanding
 - Universe “began” – Big bang
 - $v \sim H_0 \chi$ locally – Hubble constant – “ $67.7 \pm 0.6 \text{ km s}^{-1} \text{ Mpc}^{-1}$ ”
 - Distant sources are younger when observed
- Universe is spatially flat
 - $R_0 > 16c/H_0$



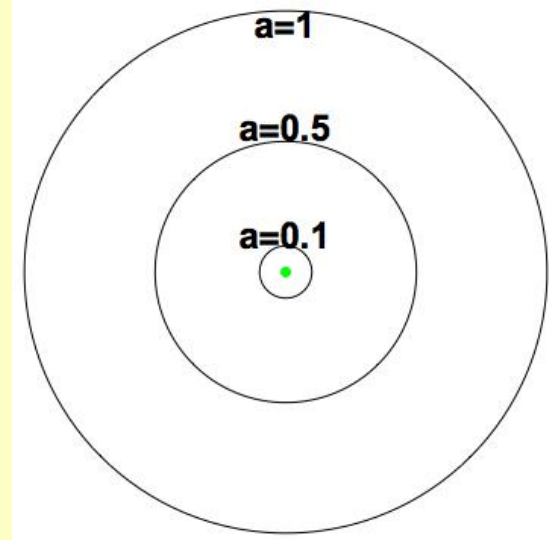
Universe today



Planck



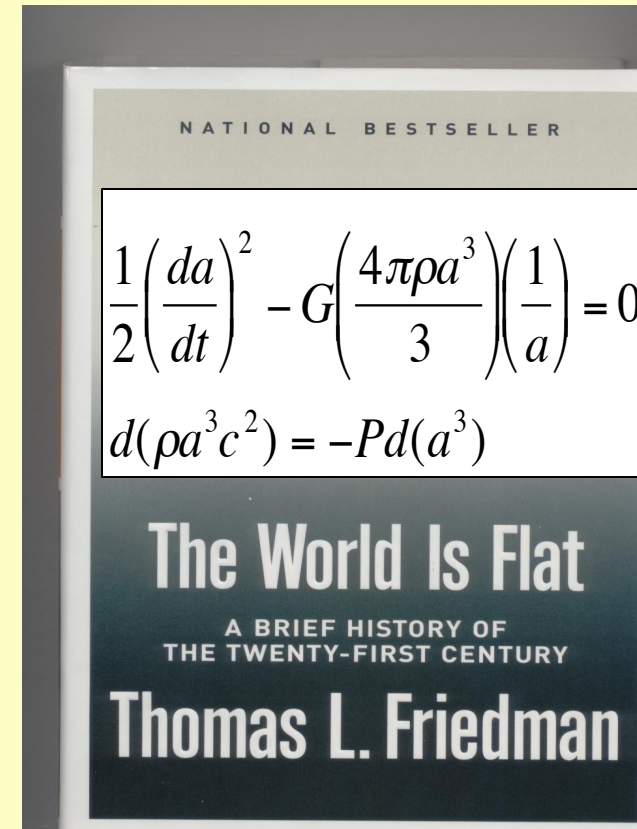
Scale Factor



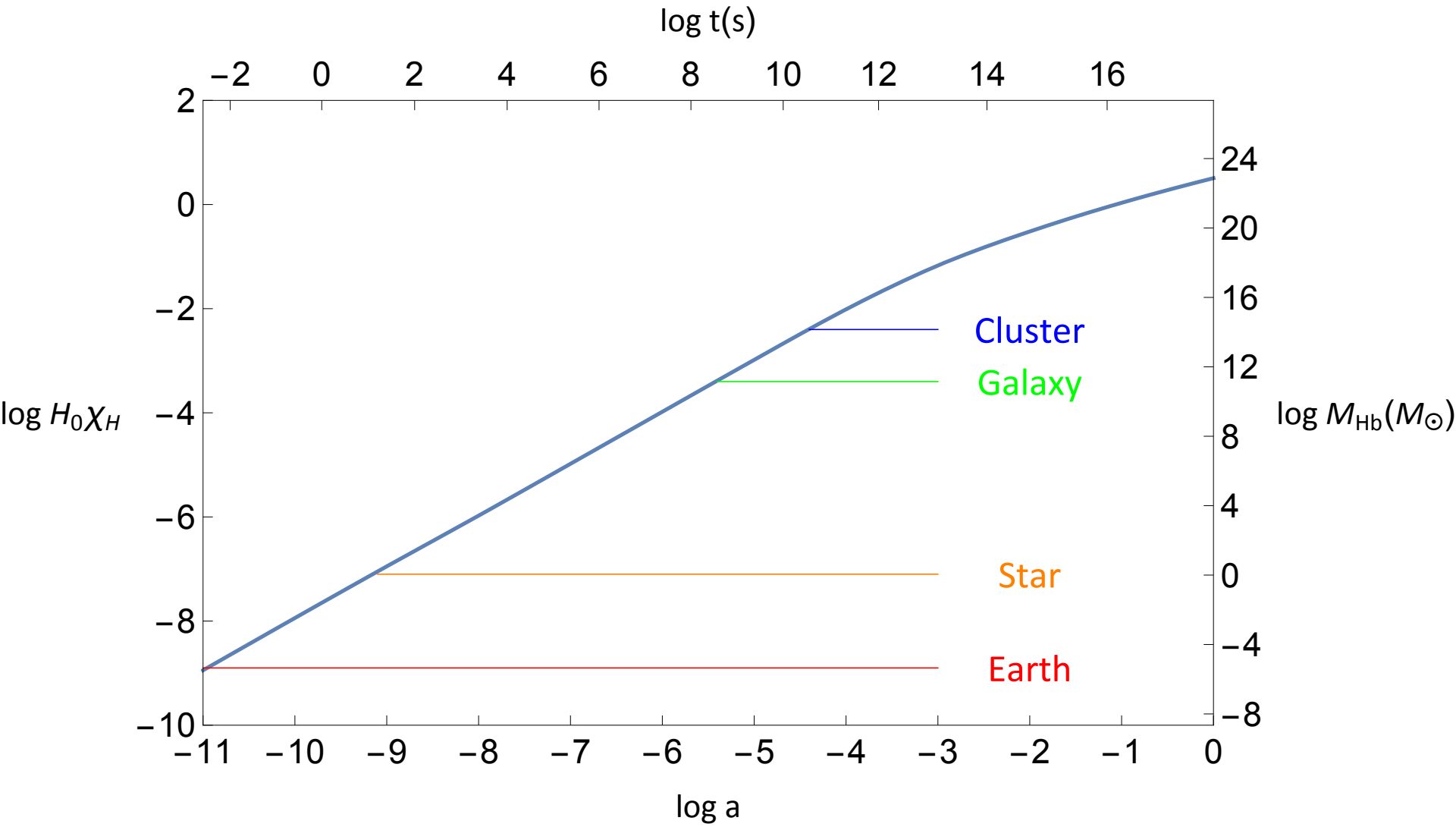
- $a=R/R_0$ measures size of universe
 - Comoving distance χ , $d = a\chi$, $\rho(a)$ etc
- Kinematics
 - $t(a)$, $t(1)=13.8$ Gy; $H(a) = a'/a$, $q(a) = -a''a/a'^2$, $j(a) = a'''a^2/a'^3$
- $a=\lambda/\lambda_0$ measures redshift
 - e.g. 120 nm emitted
 - $a=0.2$
 - $\lambda_0=600\text{nm}$ observed
- Dynamics
 - GR essential
 - Horizon smaller in past!

28 iv 2015

Solvay



Horizon Puzzle



Further Simplifications

- Universe was isotropic, homogeneous, flat
 - Good approximation
- Universe seems to be described by GR
 - Well tested; no need for baroque ornamentation
 - Must include Einstein's Cosmological Constant

$$\bar{G} + \Lambda \bar{g} = \frac{8\pi G \bar{T}}{c^4}$$

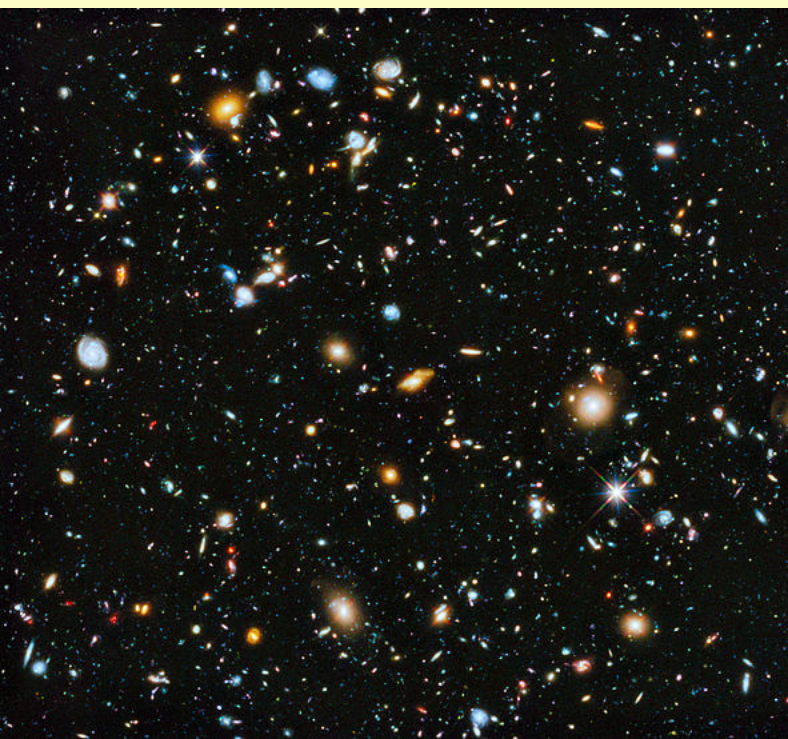
- Universe appears to have a simple topology
 - Could have been curled up like a cylinder
 - Sought but not seen
 - Only within our horizon!

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Baryons

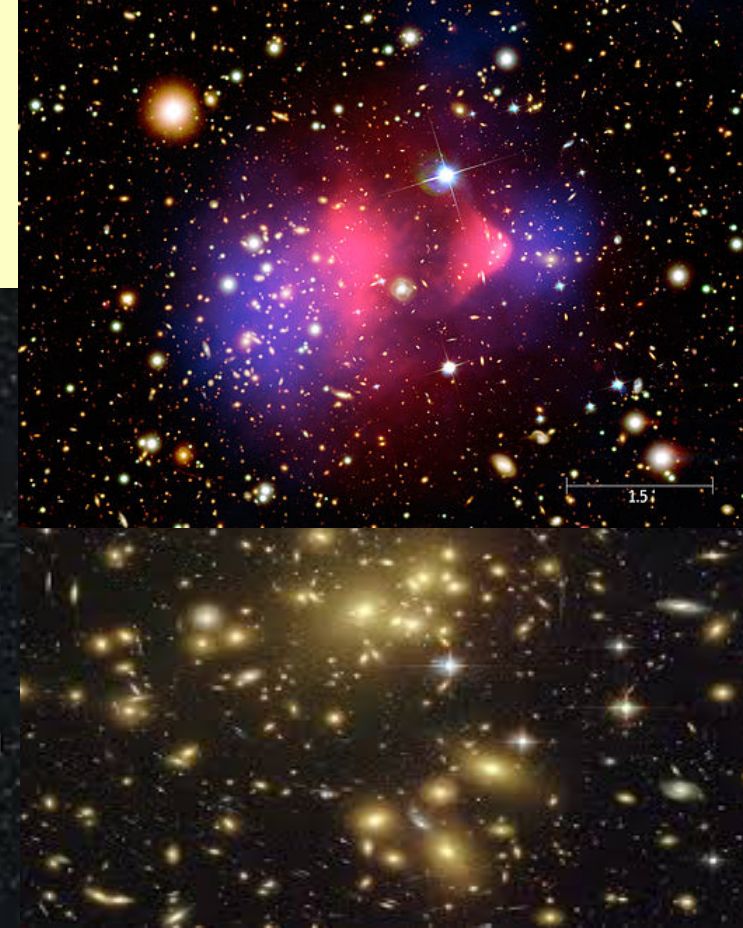
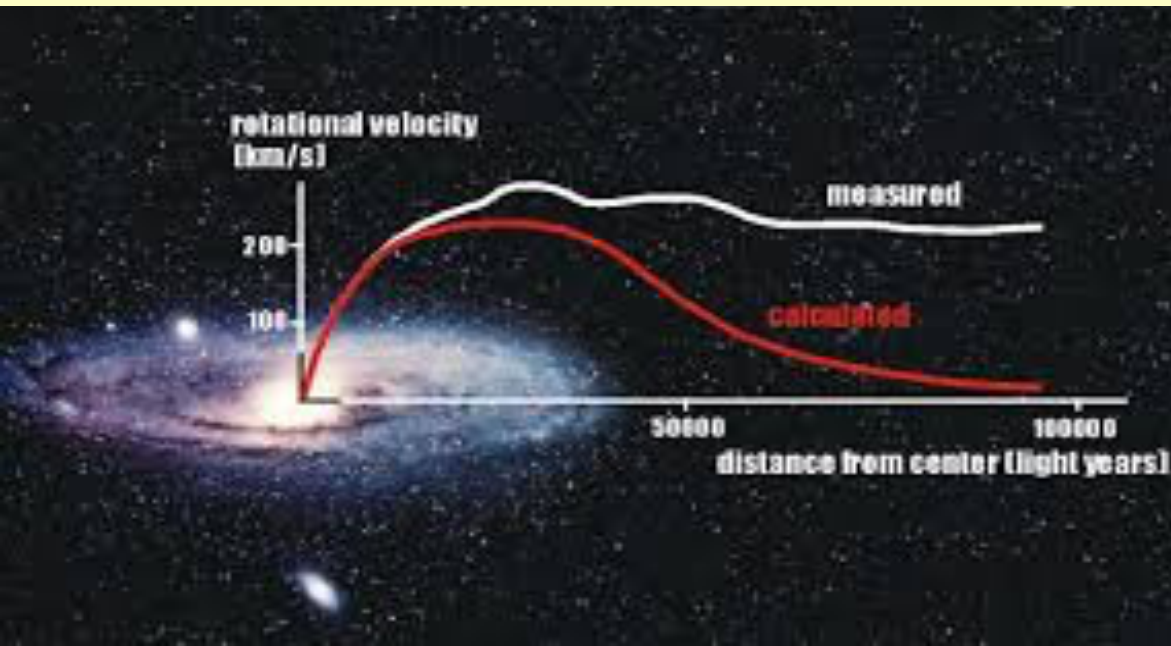
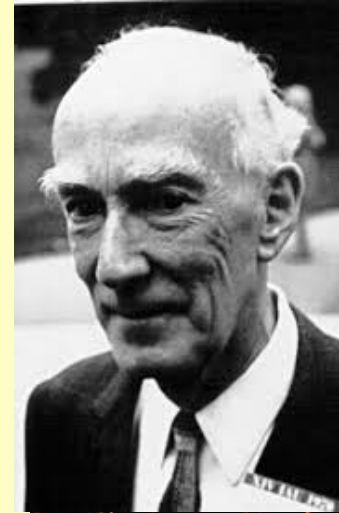
- Regular matter protons, electrons, nuclei
 - 0.05 of total mass/energy density in contemporary universe
 - Losing the Manichaean struggle!
 - 0.25 is He
 - ~ 0.02 is $Z > 2$



Dark Matter

- Galaxies - Oort (1932)
- Clusters - Zwicky (1933)
- Universe - $0.26 > 5 \times$ baryons
 - $-M \sim V^2 R / G \sim 5-10 M_{\text{stars}}$
- Initially cold and collisionless
- Sources galaxy potential wells

$$\nabla^2 \Phi = 4\pi G \rho$$



Radiation

Penzias and Wilson

50 yr ago

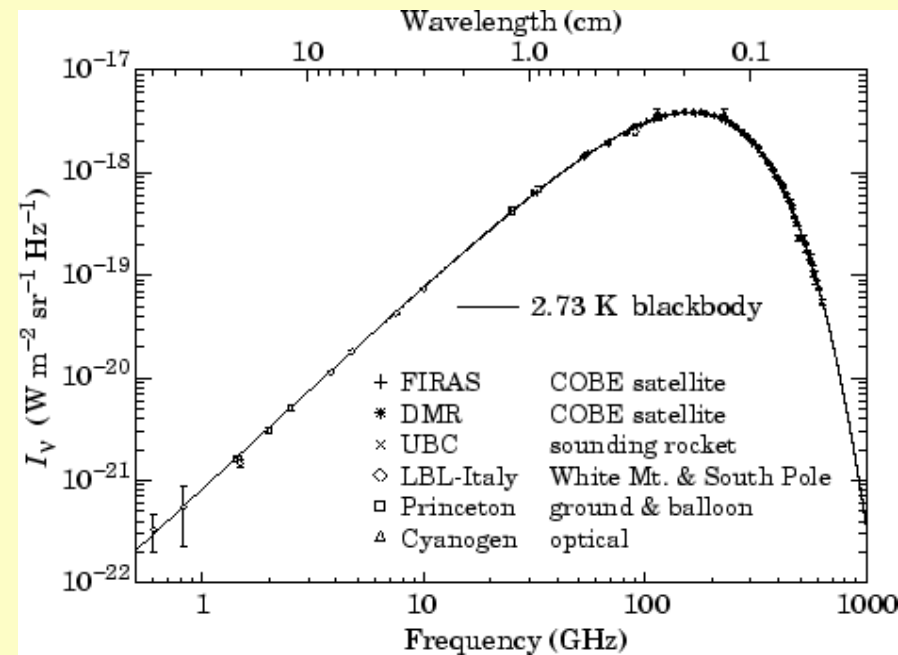


- Cosmic Microwave Background
 - $T \sim 2.7\text{K}$, $\lambda \sim 1\text{mm}$, $\sim 5 \times 10^{-5}$ total
- Observe “recombination”
 - $a \sim 0.001$, $T \sim 3000\text{K}$, $\lambda \sim 1\mu$
- Probe of intervening medium
 - ~ 0.07 scattered
- Probe of Φ

CMB measurements are very accurate and the source of half of what we know

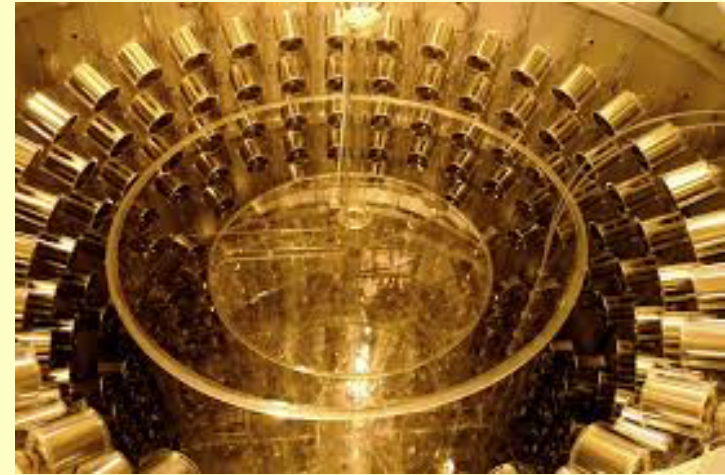
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Neutrinos

- Three flavors plus antiparticles
 - Verified cosmologically
 - Nucleosynthesis, structure formation
 - Limits sterile neutrinos etc
- $\Sigma m_\nu < 190 \text{ meV}, < 0.003 \text{ total}$
 - $> 60 \text{ meV}$ for normal hierarchy
 - $> 95 \text{ meV}$ for inverted hierarchy
 - $\sim \pm 10 \text{ meV}$ sought
- $T_\nu \sim 2 \text{ K}$
 - Undetected
 - Bold ideas to detect



Cosmological Constant

- Λ introduced by Einstein in 1917

- General relativity covariant

- \Rightarrow (unstable) static universe

$$\bar{G} + \Lambda \bar{g} = \frac{8\pi G \bar{T}}{c^4}$$

- de Sitter, Lemaitre \Rightarrow expanding universe

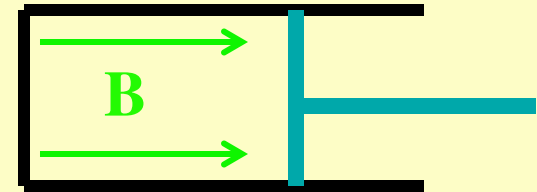
- Essentially modern description

- Fluid with $P = -\rho c^2 = \text{constant}$

- cf magnetostatic field

- Active gravitational mass density: $\rho + 3P/c^2 < 0$

- \Rightarrow Acceleration



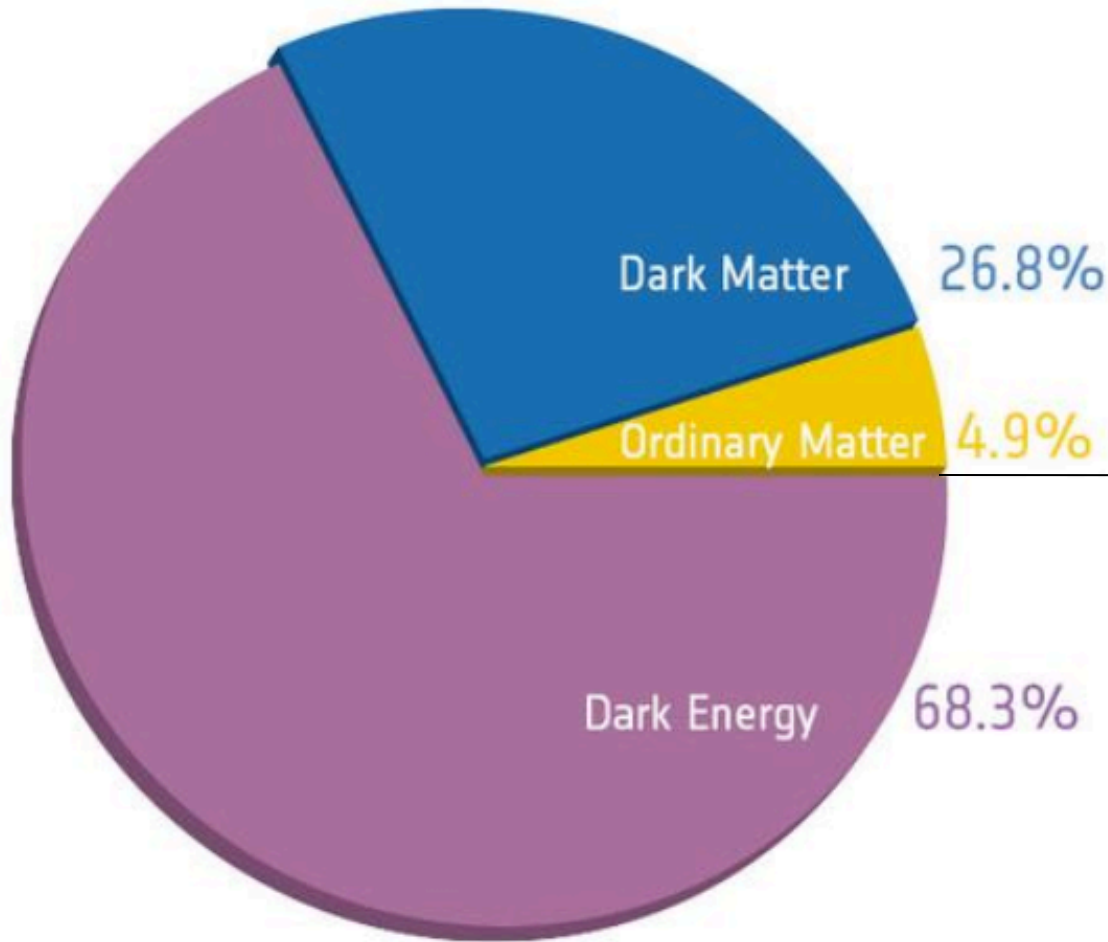
- Dark energy is possible generalization

- $P = w\rho c^2$; $w \sim -1 \pm 0.05$; $w < -1 \Rightarrow$ KE, enthalpy negative!

- Pure phenomenology!

- No evidence yet that required but better measurements coming

Composition of the Universe



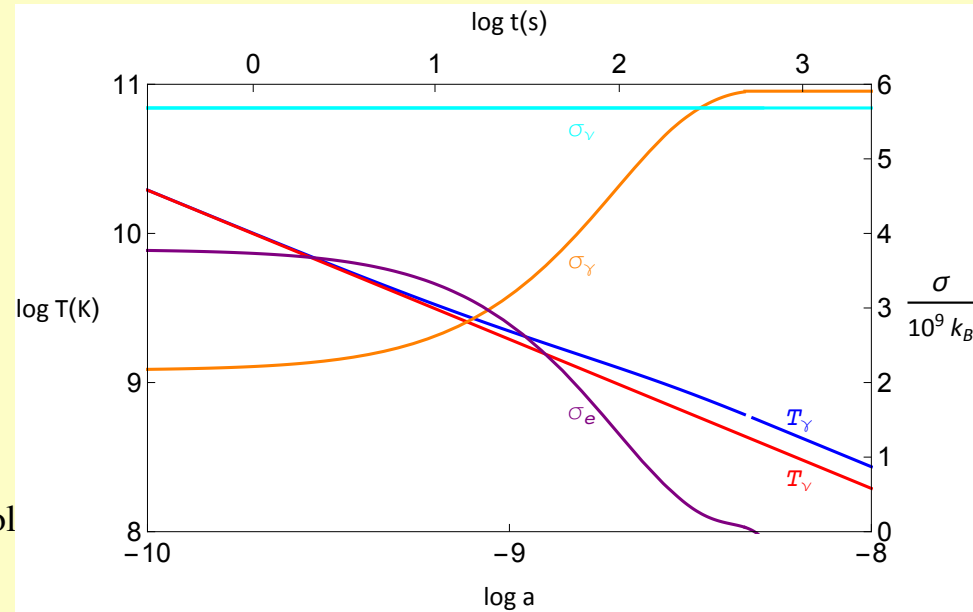
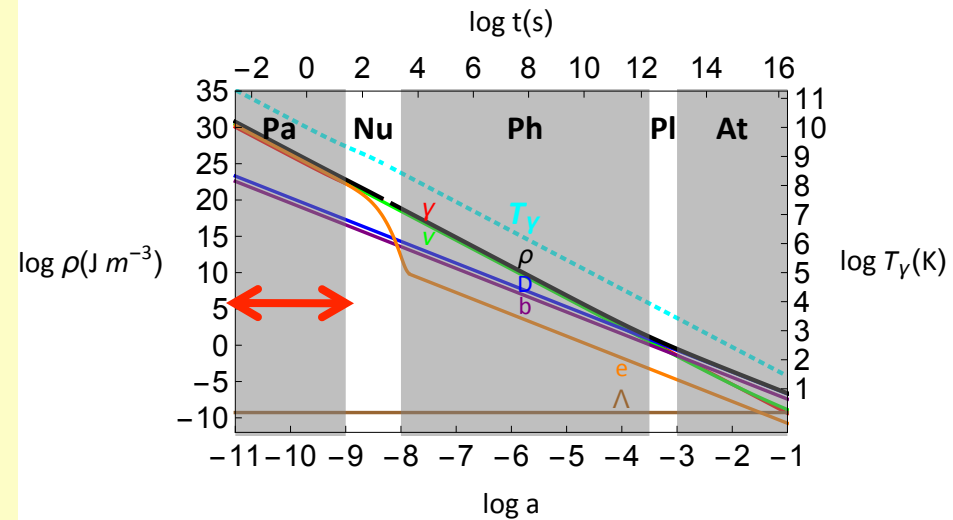
**Radiation
Neutrinos**

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Particle Age

- $a > 10^{-11}$
- $\gamma, e^{+/-}, \nu$
 - n, p negligible
- Positrons annihilate
 - Neutrinos decouple
 - Pairs \rightarrow photons



Nuclear Age

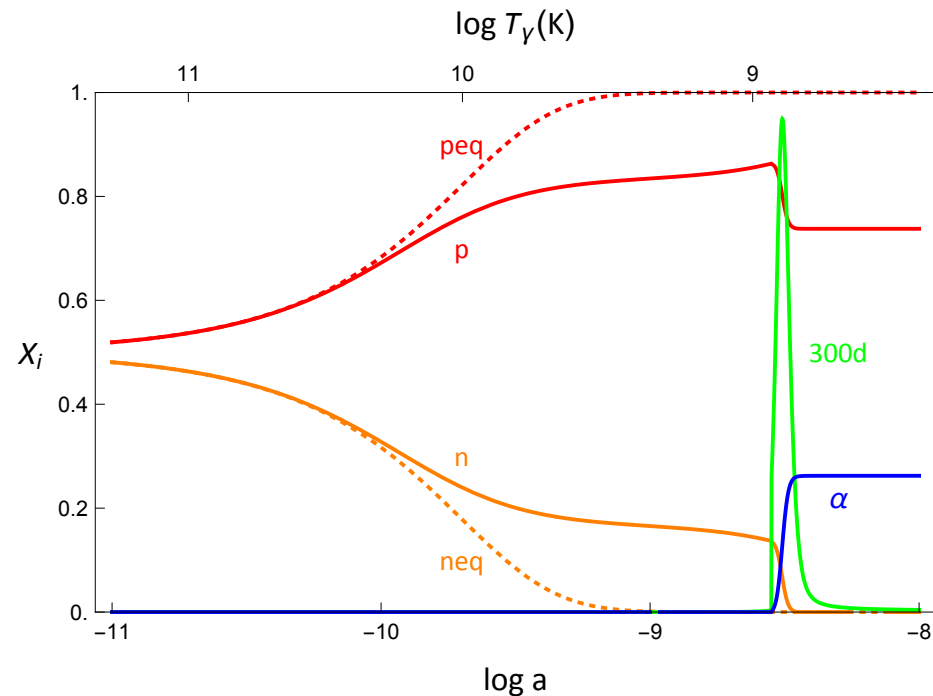
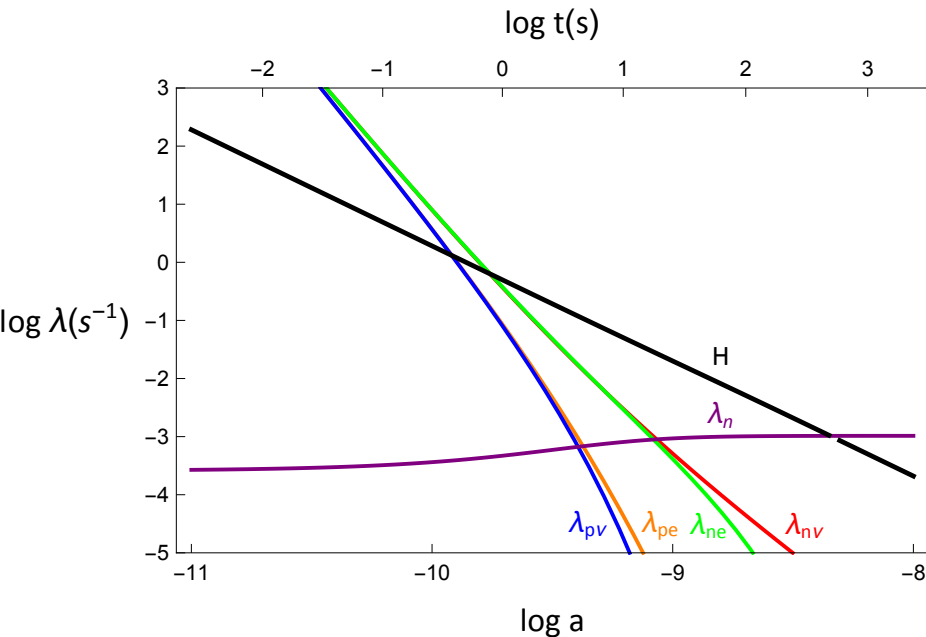
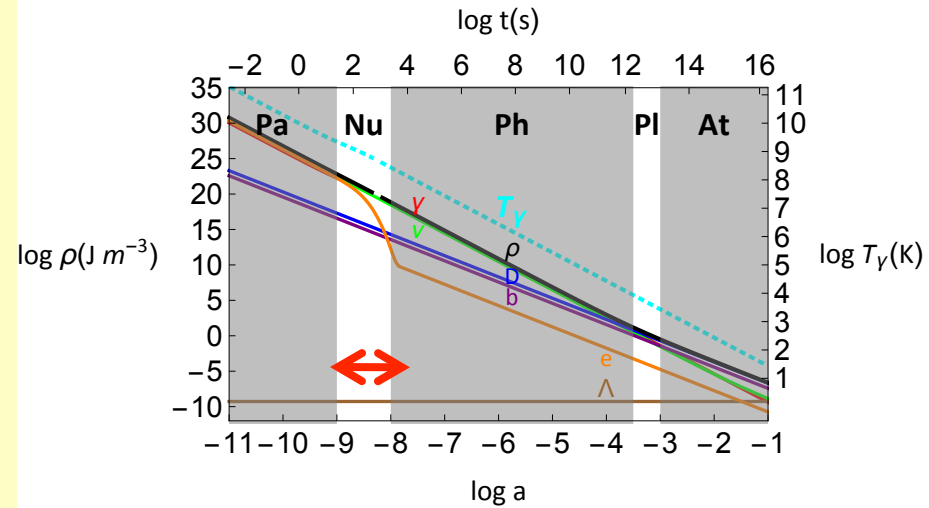
- α , d formation

$$n + \nu \leftrightarrow p + e^-$$

$$n + e^+ \leftrightarrow p + \bar{\nu}$$

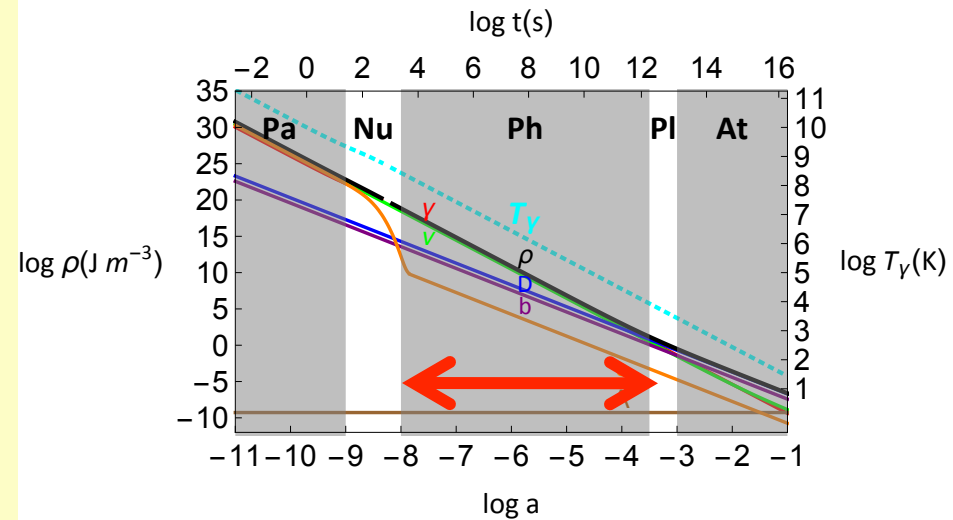
$$n \rightarrow p + e^- + \bar{\nu}$$

- Heavier elements formed later by SN, stars,



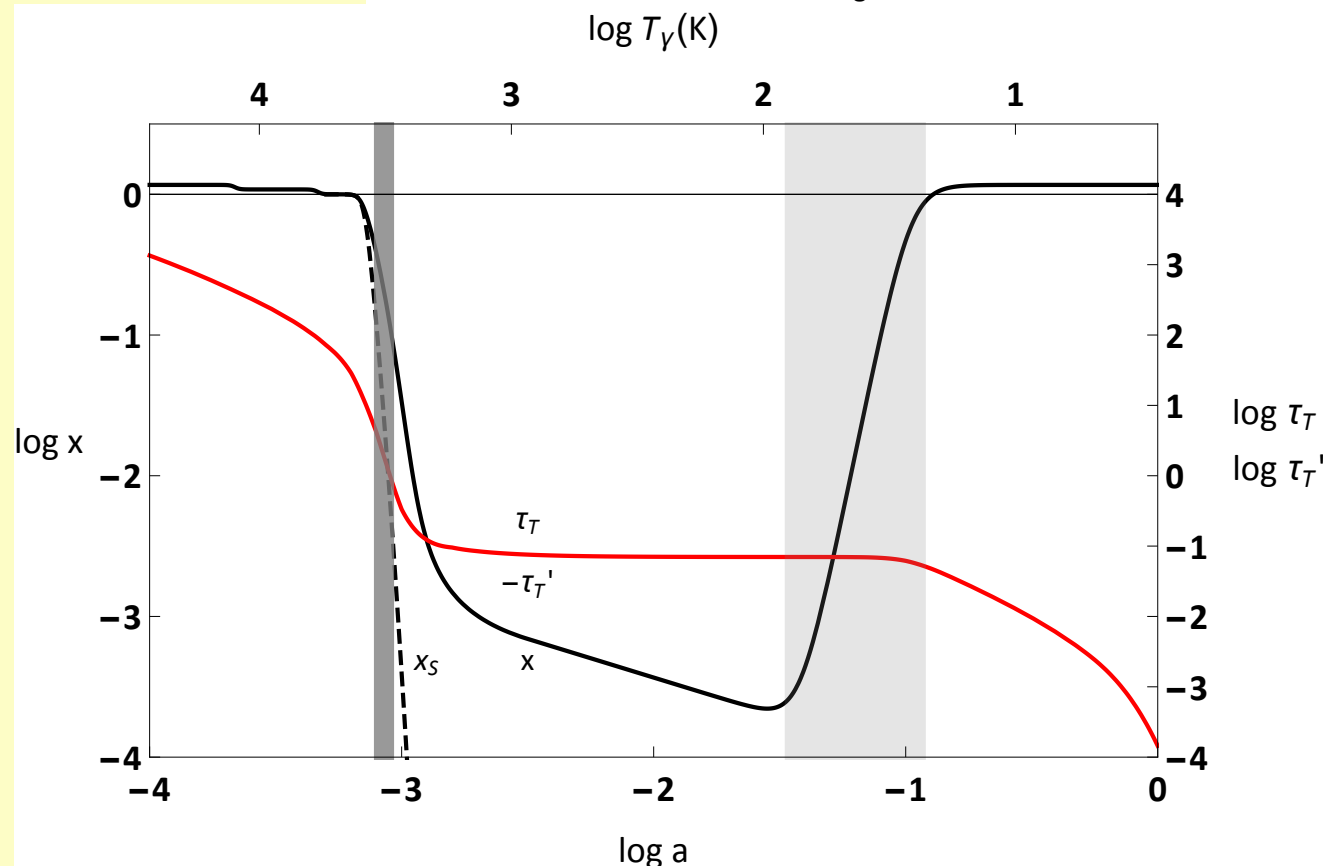
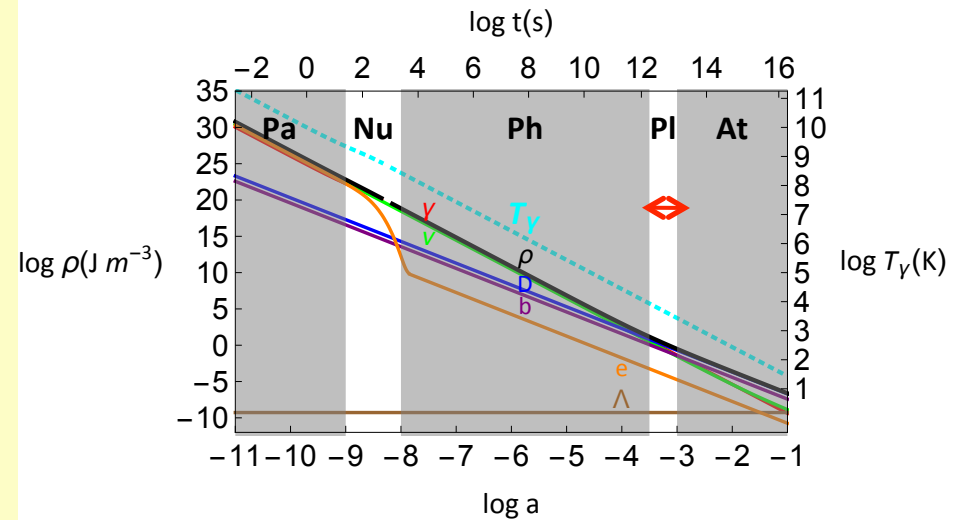
Photon Age

- ρ mostly γ
 - $\rho_\gamma \sim n \epsilon \sim a^{-4}$
 - $\Rightarrow a \sim t^{1/2}$
 - $\rho_M \sim a^{-3}$
- Thermal equilibrium
 - Compton scattering
 - Coulomb collisions
- Ends when $\rho_M > \rho_\gamma$



Plasma Age

- Matter-dominated
- DM potentials grow
 - when $k \sim a'$
 - $|\Phi| \sim 3 \times 10^{-5} c^2$
- $\alpha \rightarrow \text{He}$
- $p \rightarrow \text{H}$
 - $T \sim 0.03 \text{ Ry}$
 - Baryons into Φ
 - Photons freed
- T_γ reflects:
 - Φ, v_b, n_b



Atomic Age

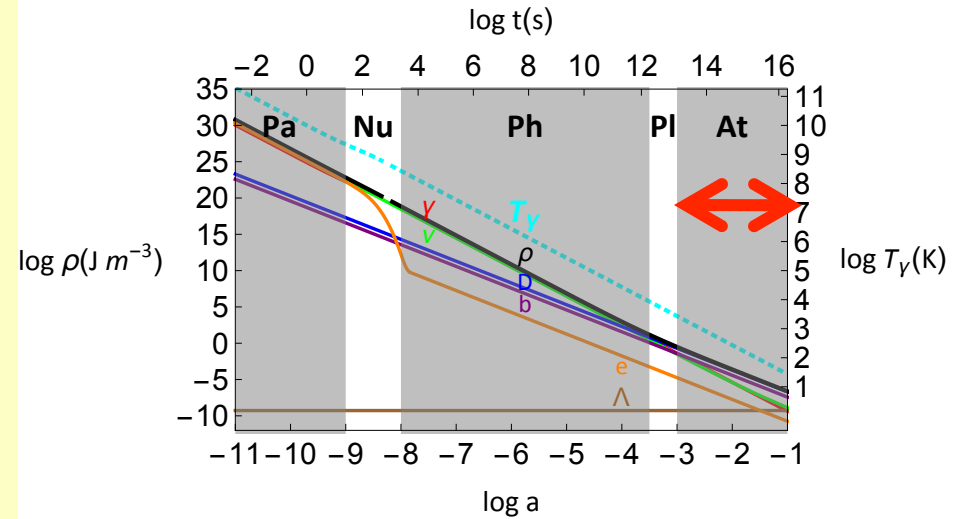
- Dark age

- $T_H \sim a^{-2}$

- H_2 chemistry

- First protogalaxies, stars, black holes

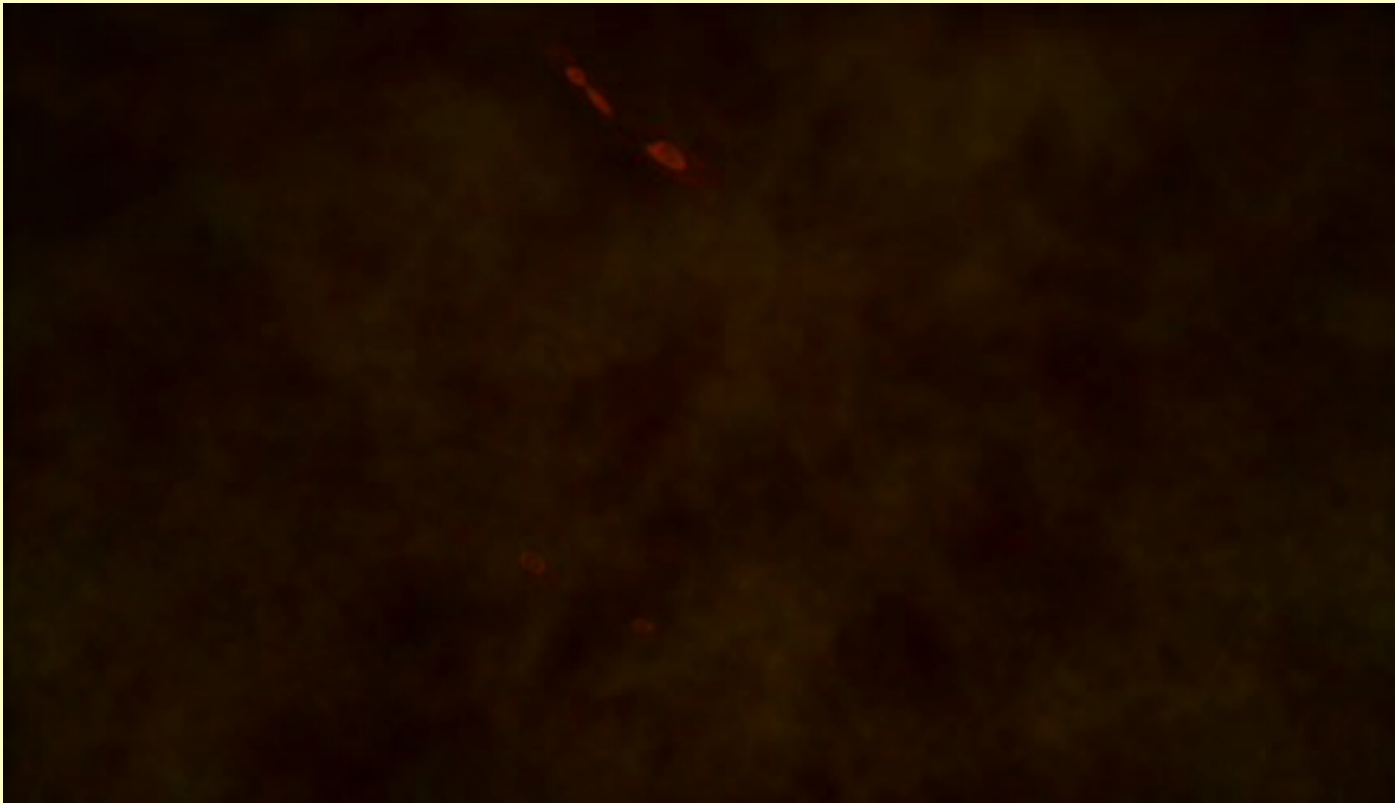
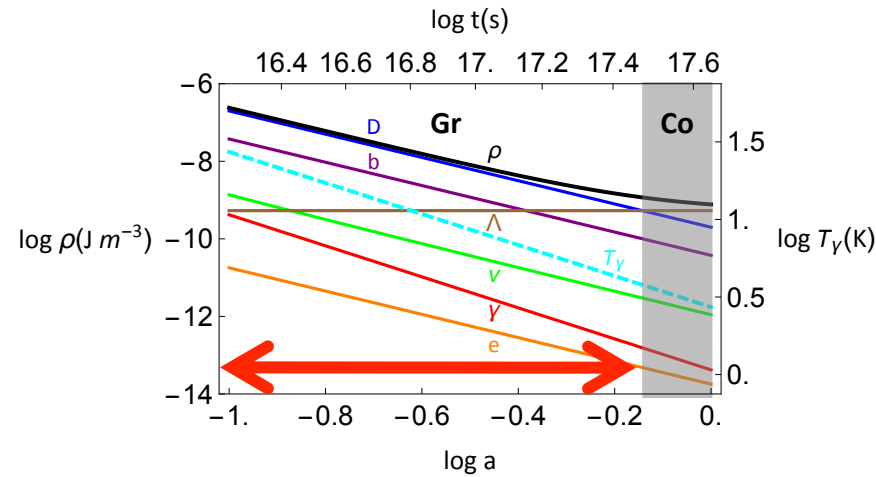
- UV radiation ionizes hydrogen



$z=14.6$

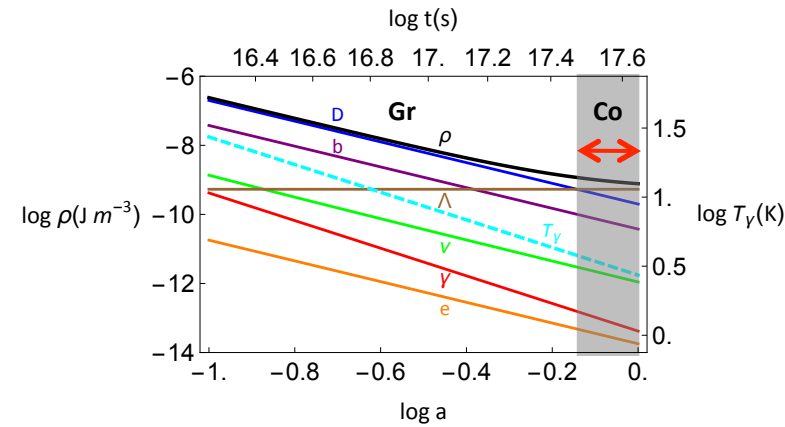
Gravitational Age

- Small galaxies
 - Grow
 - Merge
- Observational astronomy



Cosmological Age

- $-0.2 < \log a < 0$
- Λ dominates
 - Universe accelerates
 - $a \sim e^{Ht}$ in future



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Microwave Background

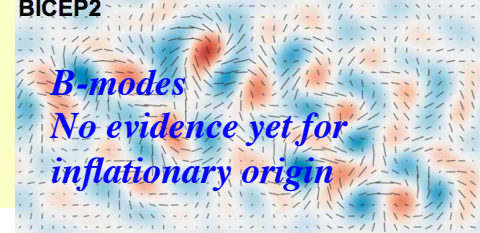
- $\delta T/T$ is a scalar
 - Equivalent to potential Φ on large scales
 - Involves v and $\delta\rho_b$ on small scales
 - 2D Fourier transform on sphere
 - Spherical harmonics
 - $Y_{lm}(\theta, \phi)$, $l \sim 180^\circ/\theta$, $2l+1$ values of m
 - $O(l^2)$ independent measurements per octave
 - Cosmic variance at low l
- Polarization
 - “E” modes, effectively scalar
 - “B” modes effectively tensor
 - Relate to primordial gravitational radiation
 - Also relate to gravitational lensing and dust!

Growth of Fluctuations

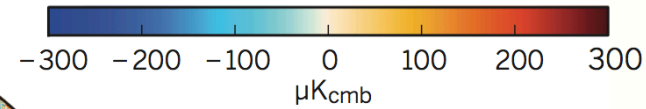
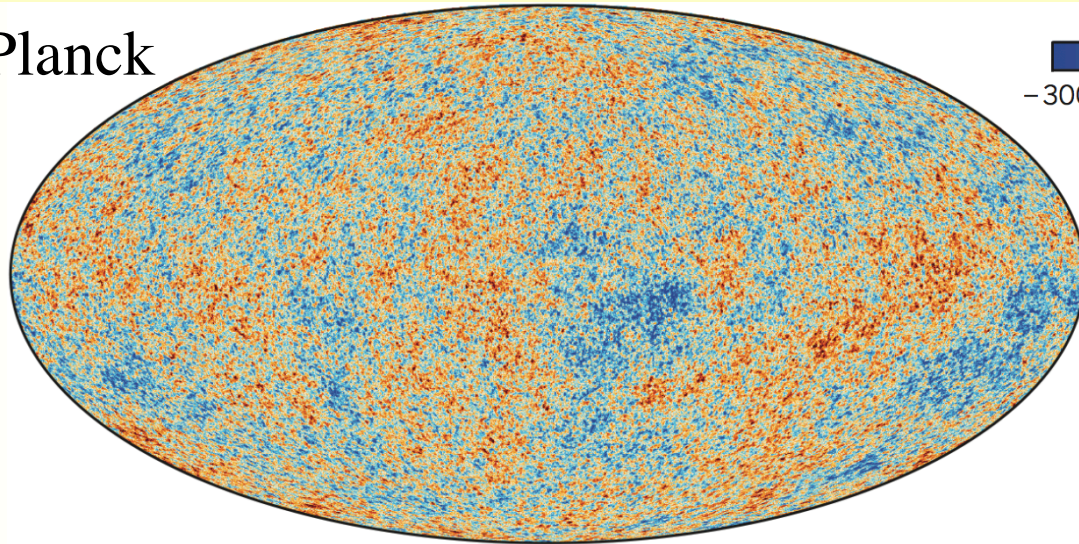
- Scalar perturbations: $\Phi \rightarrow \delta\rho/\rho, v...$
 - Linear at early t and small k
 - Lemaitre!
 - Also tensor perturbations – gravitational waves
- Describe by spatial Fourier transform
 - $\Phi \sim \gamma(t) \text{Re}[\delta_\Phi e^{ik \cdot x}]$ etc
 - k , 3D, comoving
 - Coupled first order, fluid/kinetic differential equations
 - Longitudinal sound waves with gravity and Landau damping
 - Infer initial conditions from observations
 - Power spectrum $P(k) \sim k^3 \langle \delta_\Phi \delta_\Phi^* \rangle$
 - Gaussian
 - Just like music but without special frequencies and phase relations!
 - Extend into nonlinear regime
 - Astrophysics

Predicted by Harrison and developed by Zel'dovich
Universe began with a hum not a fanfare, a whimper not a bang!

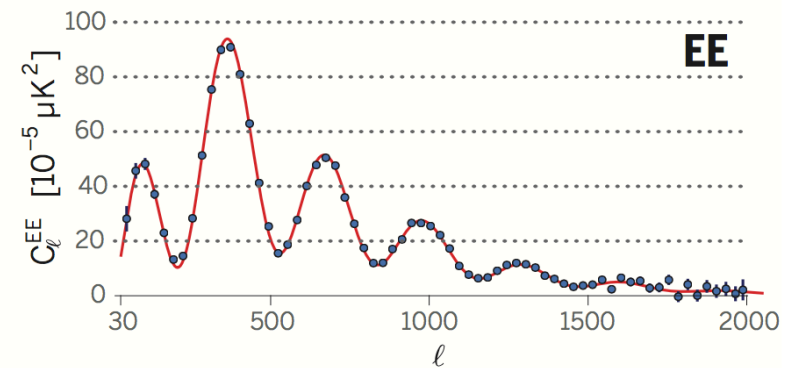
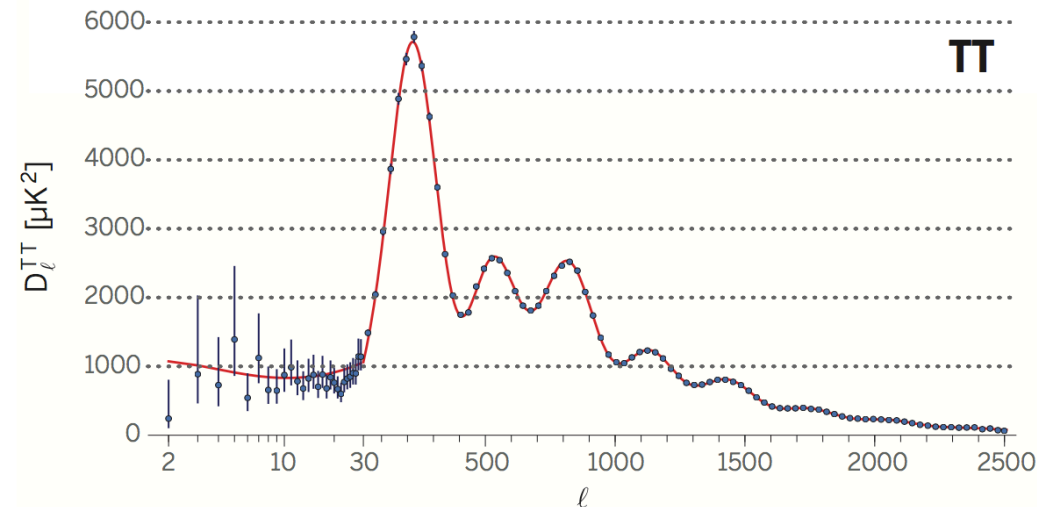
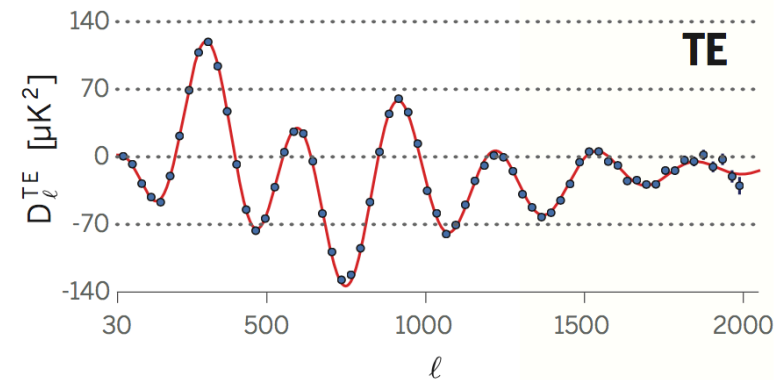
CMB Fluctuations



Planck

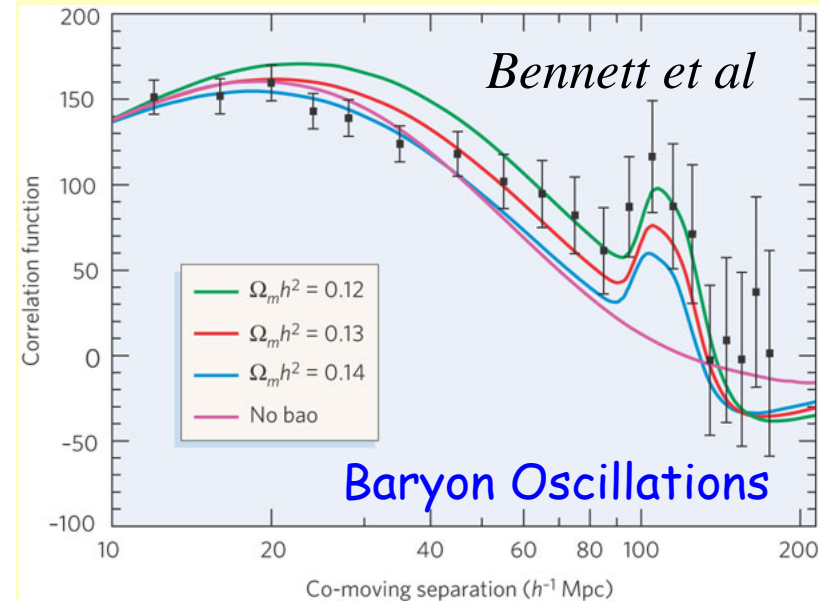
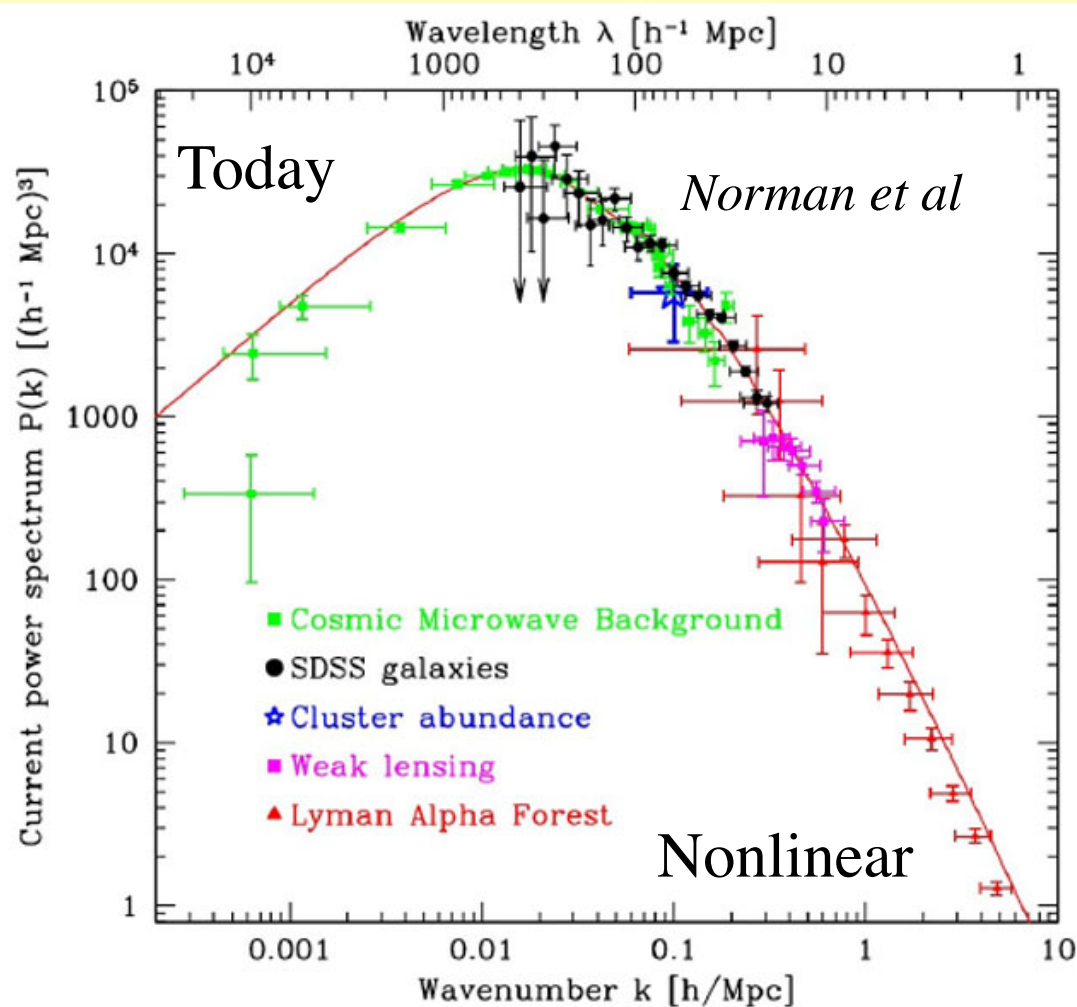


Fit with Six Parameters



Initial fluctuation spectrum is almost scale-free, random phase and gaussian

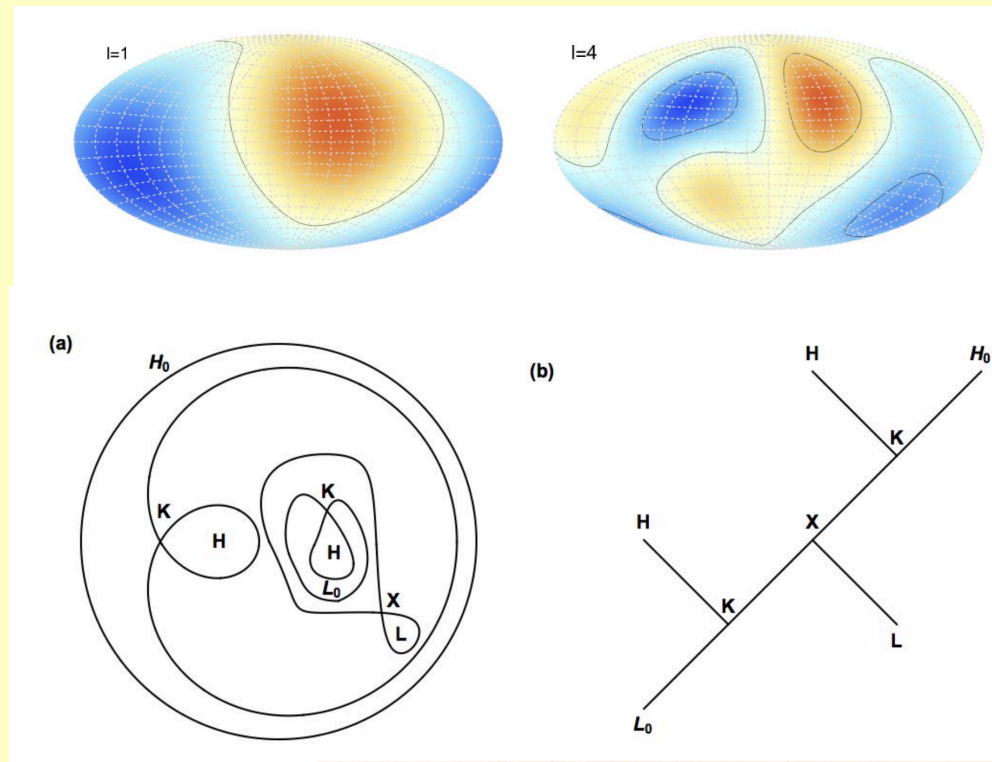
Density Fluctuations



All consistent with standard model

Actual Structure of Our Universe

- Consider Φ on sphere
 - Low l
- Plot separatrices
 - Topology \leftrightarrow tree
 - Nest Φ in sphere
 - Tree \leftrightarrow nesting
- Use “local” potential
 - Gravitational lensing
 - Reionization studies
- 3D Φ, ρ map of universe
 - Statistical priors
 - 10^{10} lt yr scale!
- Extend beyond horizon

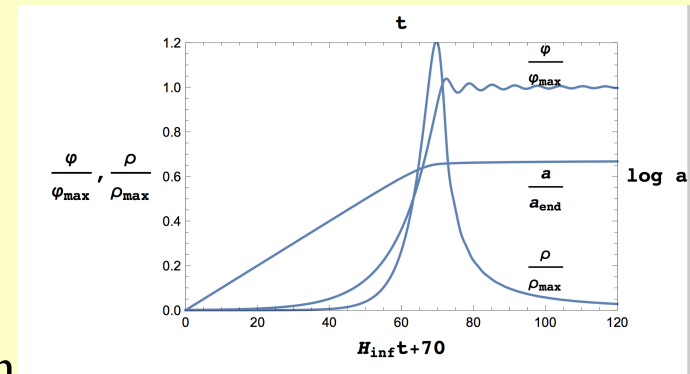


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Inflation

- Why is universe homogeneous, flat, simple?
- Inflation (Englert, Guth, Linde, Starobinsky...)
 - Homogeneous universe
 - Λ -like classical inflaton field invoked
 - \Rightarrow exponential expansion when $t \sim 10^{-33}s$
 - Parts become causally disconnected
 - Scale-free random fluctuations
 - Semi-classical process like Hawking radiation
 - Parts follow similar evolution
 - Inflation ends, entropy created
 - Parts reconnect; “hello, goodbye, hello”, “last out first in”



All observations consistent with simplest version

However, other observations could have been accommodated

Matter

- Astronomers -> dark matter is non-baryonic
 - Collisionless, cold initially
- Physicists -> elementary particle?
 - Supersymmetry, axions?
 - No sign yet from LHC, direct and indirect astronomical searches
- Why is there so little baryonic matter?
 - Necessary violations (Sakharov)
 - Thermal equilibrium
 - Baryon conservaton
 - C, CP symmatry
 - Only upper limits on relevant process

These upper limits are experimental physics at its finest

Cosmological Constant

- Is it a cosmological constant?
 - ~5 percent by several measures
 - Will it end like inflation?
- Why $\sim 10^{-123} \Lambda_{\text{planck}}$?
 - Particle physicist
 - Reductionist - vacuum (string theorists)
 - Condensed matter physicist
 - Emergent phenomenon – cf ferromagnetism - (Prigogine, Laughlin...)
 - Astrophysicist
 - Situational expression of physics on largest scale (Eddington, Lemaitre...)
- Anthropic Principle
 - Self – select universe
 - $\sim 10^{500}$ choices!

Things were as they were because we are as we are?

Summary

- We now have a standard model of cosmology
 - Much data fit by few parameters at 1-10 percent level
 - No significant anomaly that cannot be ascribed to astrophysics
- Large contributions to fundamental physics
 - Nuclei, neutrinos and dark matter
 - General relativity including the cosmological constant
- Major physics challenges
 - Inflation, origin of matter, eschatology
- Major astrophysics challenges
 - Formation and evolution of galaxies, stars, planets
- Major astronomical challenge
 - Three dimensional map of our universe

Employment for another fifty years?