The ΛCDM-model after Planck

Cosmology Talk at Brno University of Technology

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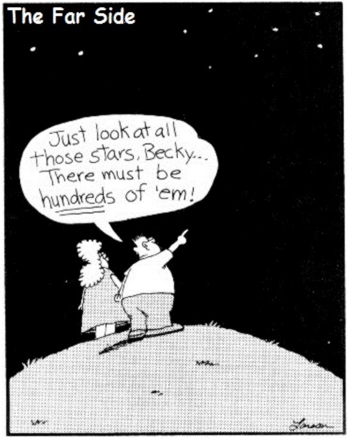
...just some numbers about the observable Universe



Carl Sagan as a kid

Age:	$\sim$ 14 billion years		
Temp:	2.73 Kelvins		
Radius:	46 billion light years	=	4.3×10^{26} m
Volume:	4.1×10^{5} Gly^{3}	=	3.5×10^{80} m^{3}

Baryons:	10^{80}	$\rightarrow$	Hydrogen:	74%
Electrons:	10^{80}		Helium:	25%
Photons:	10^{89}		Heavier elements:	1%
Neutrinos:	10^{89}			

Dark Matter	?
Dark Energy	?
Curvature	?

Standard Cosmology

ΛCDM model

Lambda-Cold Dark Matter model

- Big bang cosmology with dark energy and cold dark matter
- Simplest model that explains:
  - the existence and structure of the cosmic microwave background.
  - the large scale structure in the distribution of galaxies.
  - the abundances of hydrogen (including deuterium), helium, and lithium.
  - the accelerating expansion of the universe observed in the light from distant galaxies and supernovae.

FLRW metric

Friedmann-Lemaître-Robertson-Walker metric

- Based on Einstein's field equations

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R + g_{\mu\nu}\Lambda = \frac{8\pi G}{c^4} T_{\mu\nu}$$

- Describes a homogeneous, isotropic expanding or contracting universe.
- Friedmann's 2 equations:

$$\frac{\dot{a}^2 + kc^2}{a^2} = \frac{8\pi G\rho + \Lambda c^2}{3}$$

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}\left(\rho + \frac{3p}{c^2}\right) + \frac{\Lambda c^2}{3}$$

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- Describes a homogeneous, isotropic expanding or contracting universe.
- Friedmann's 2+1 equations:

$$H^2 = \frac{8\pi G}{3}\rho$$

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3p)$$

$$\dot{\rho} = -3H(\rho + p)$$

Scenarious from solving the Friedmann equations

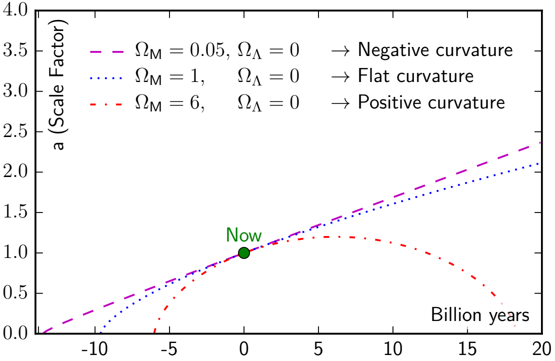
- The Equations of State ($w = p/\rho$)

		$\rho \propto$	w
Matter	ρ_M	a^{-3}	0
Radiation	ρ_γ	a^{-4}	1/3
Cosmological constant	ρ_Λ	1	-1
Curvature	ρ_k	a^{-2}	-1/3

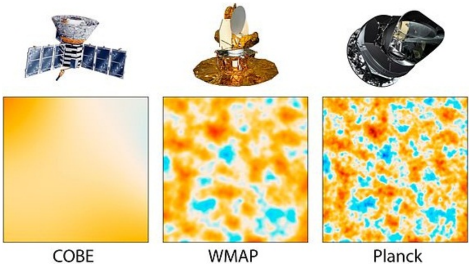
- Putting this into a modified Friedmann Eq. gives us:

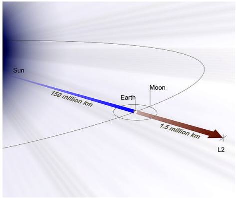
$$\ddot{a}(t) = -\frac{1}{2}H_0^2 \sum_i \Omega_{i_0} \frac{1+3w_i}{a(t)^{2+3w_i}}$$

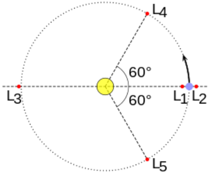
$$a(t) = Ct^{\frac{2}{3(1+w)}}$$



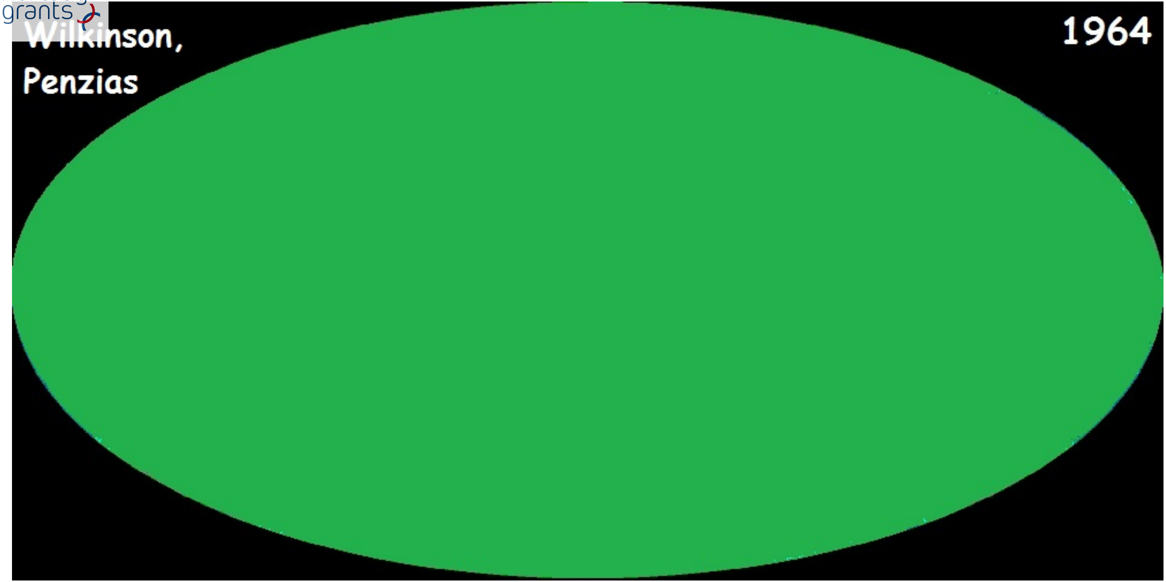
Planck Satellite

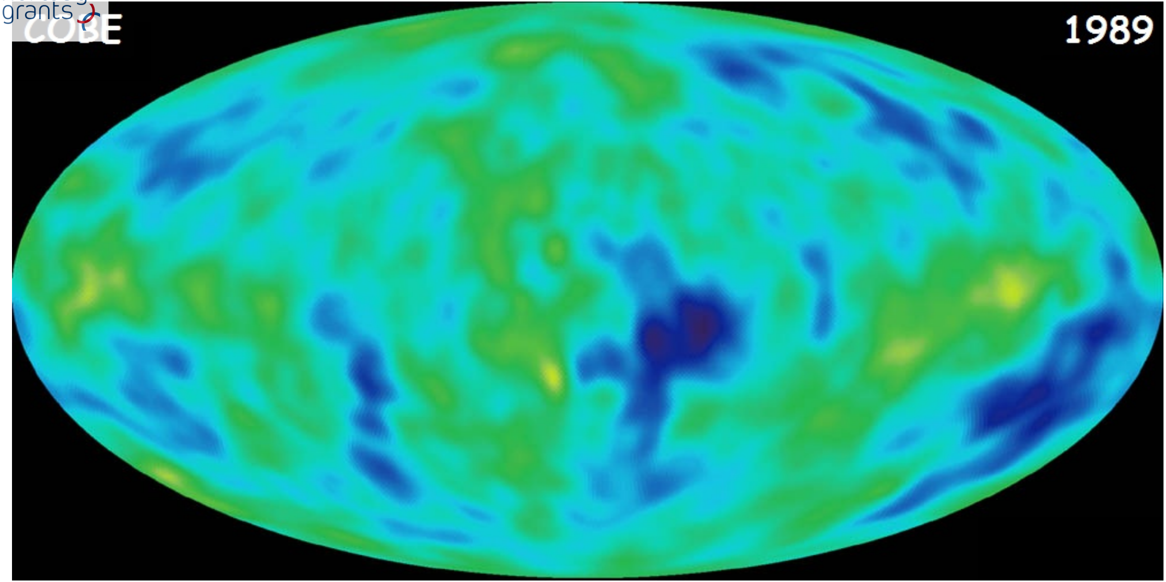


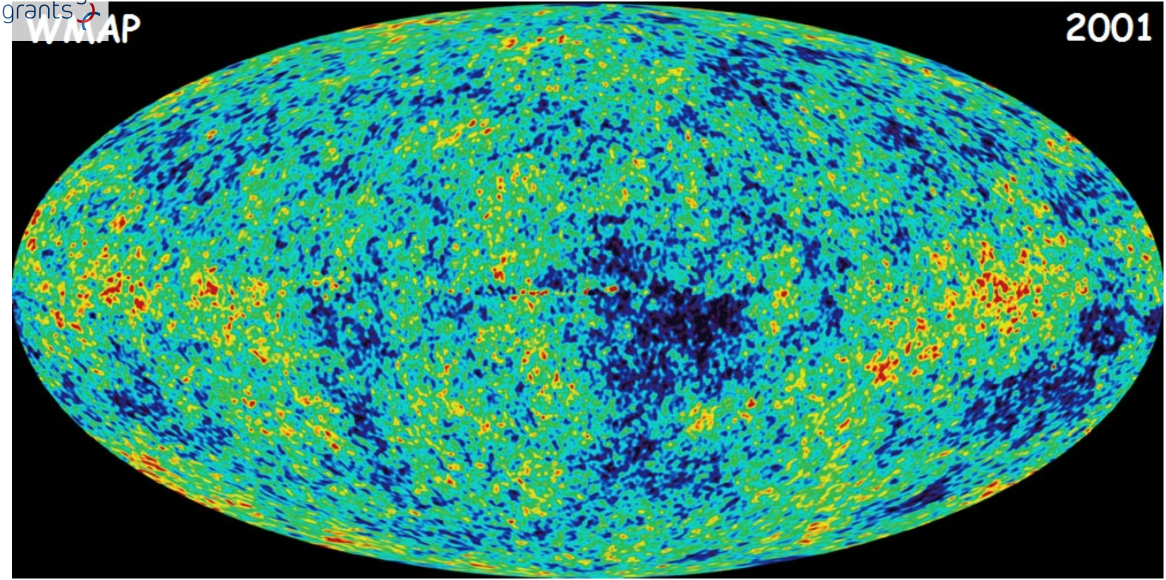


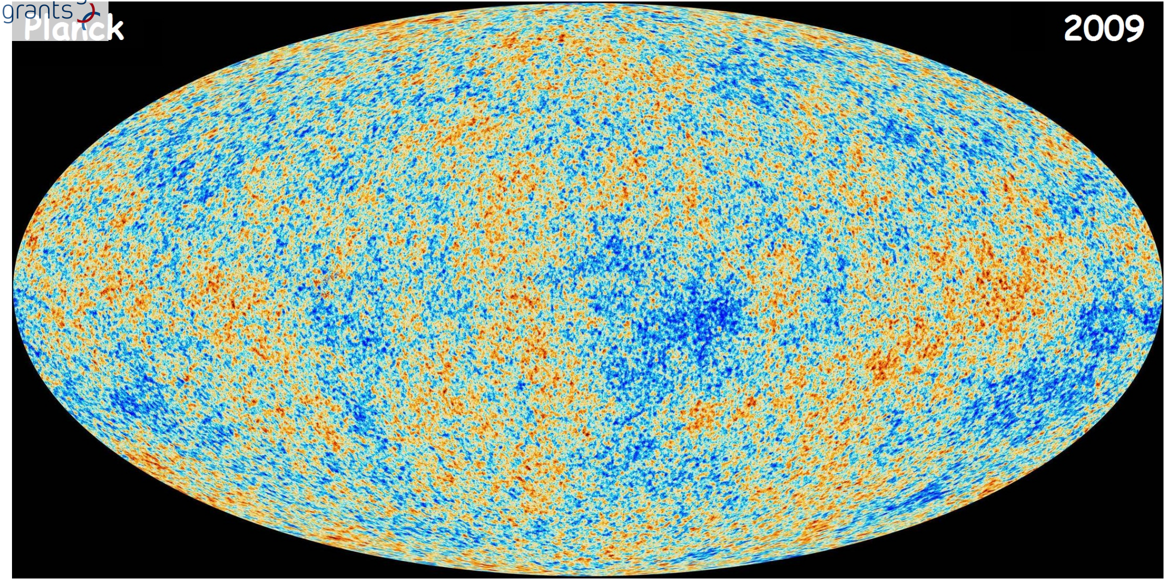


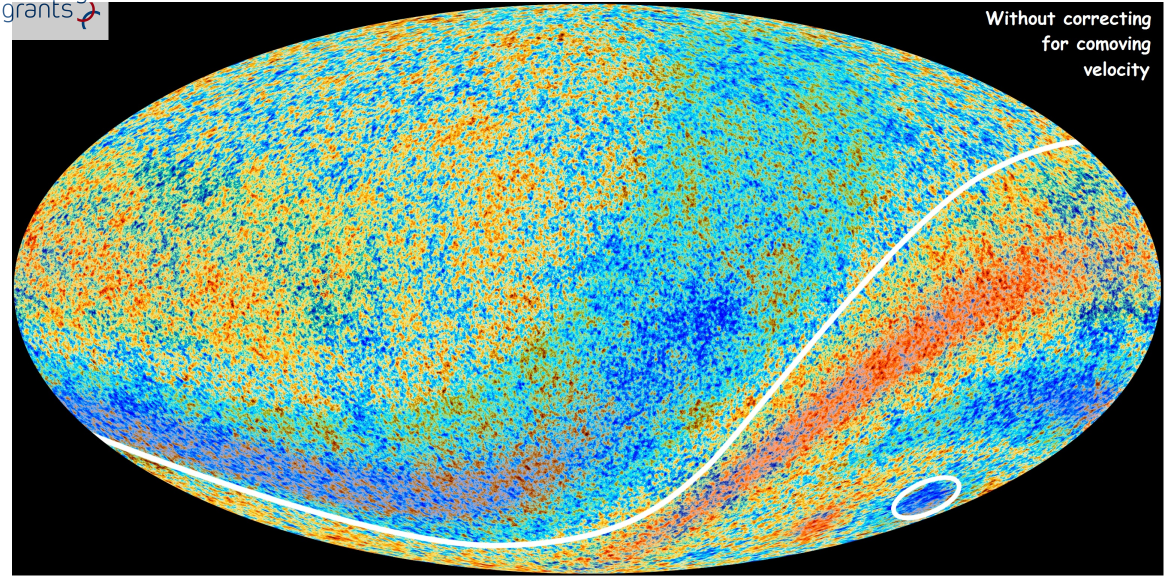
- Launched in 2009.
- Third satellite to study the Cosmic Microwave Background Radiation (CMB).
- Set to replace previous missions: COBE (1989) and WMAP (2001).
- Advantages compared to WMAP:
  - Higher resolution (x3).
  - Higher sensitivity (x10).
  - 9 frequency bands rather than 5, with the goal of improving the astrophysical foreground models.
- Located at the Lagrangian Point L2.
- First results published in March 2013.
- Final results published in February 2015.

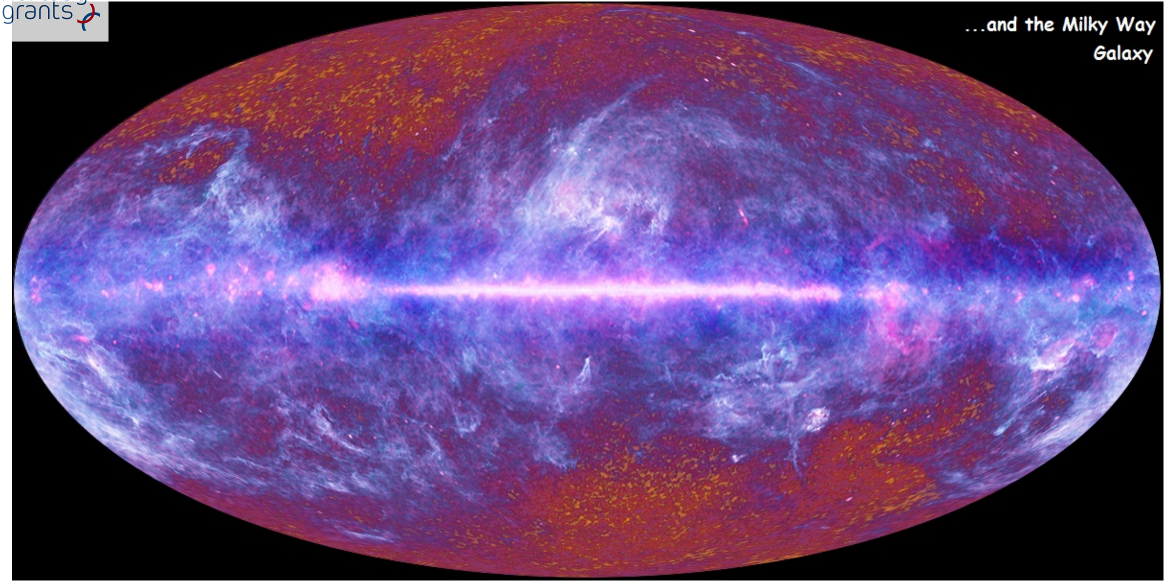

Wilkinson,
Penzias
1964


COBE
1989


WMAP
2001


Planck
2009


Without correcting
for comoving
velocity


...and the Milky Way
Galaxy

Cosmological Parameters

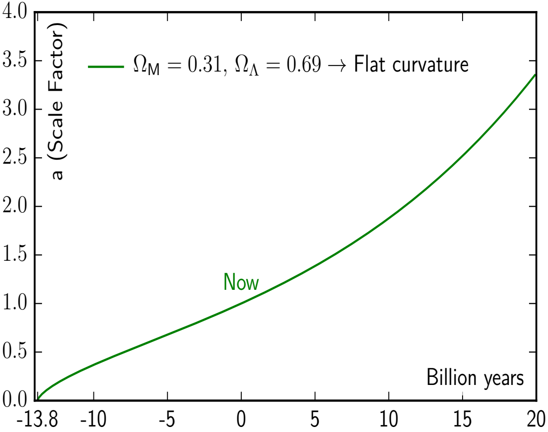
Planck's Six Parameters

Baryon density today	$\Omega_b h^2$	0.02230 ± 0.00014
Cold dark matter density today	$\Omega_c h^2$	0.1188 ± 0.0010
$100 \times$ approximation to r_* / D_A (CosmoMC)	$100\Theta_{MC}$	1.04093 ± 0.00030
Thomson scattering optical depth due to reionization	τ	0.066 ± 0.012
Scalar spectral index	n_s	0.9667 ± 0.0040
Log power of the primordial curvature perturbations	$\ln(10^{10} A_s)$	3.064 ± 0.023

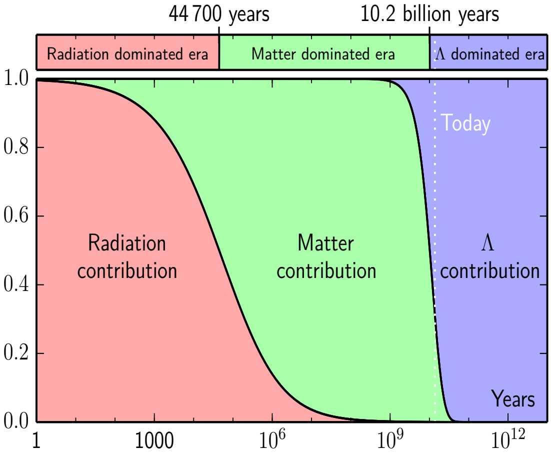
Derived Parameters

		68% limits
Age of Universe	t_0	13.799 ± 0.021
Hubble Constant	H_0	67.74 ± 0.46
Baryonic & DM	Ω_m	0.3089 ± 0.0062
Dark Energy	Ω_Λ	0.6911 ± 0.0062
Radiation	Ω_r	10^{-4}
Curvature	Ω_k	0.000 ± 0.005

Expansion History

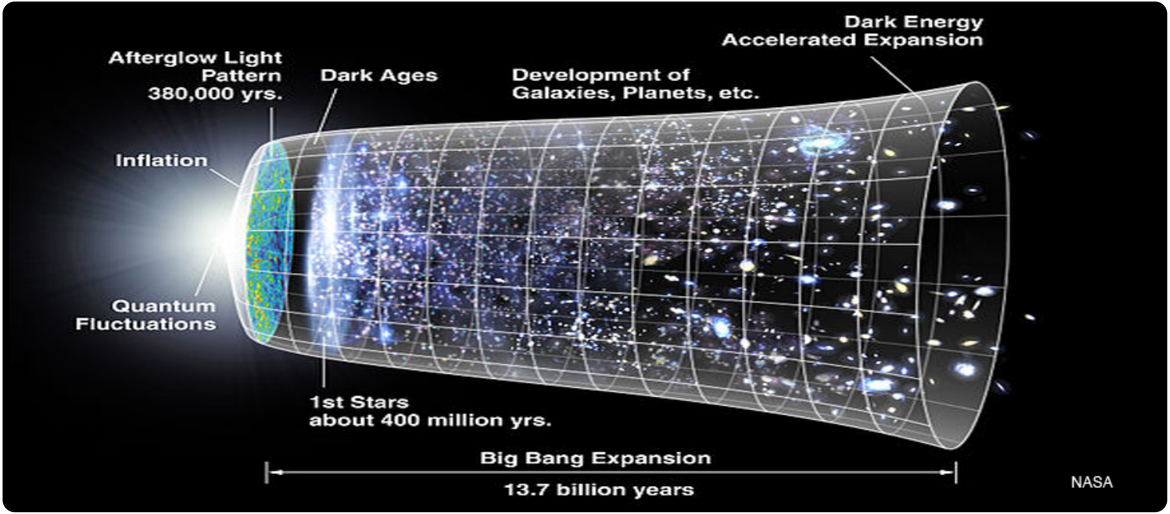


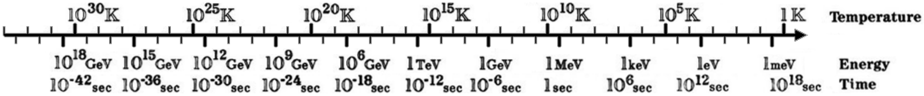
Age of the Universe: 13.8 billion years.



Radiation, matter and dark energy eras.

Chronology of the Universe





1. The Very Early Universe

- 0 s - 10^{-12} s

2. The Early Universe

- 10^{-12} s - 379 000 y

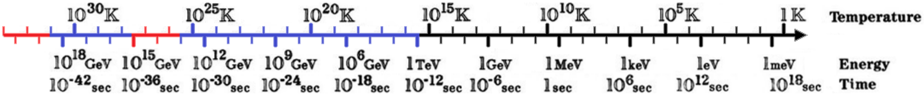
3. Structure Formation

- 379 000 y - 13.8 billion y

4. Future and Fate

- 13.8 billion y - ?

norway grants



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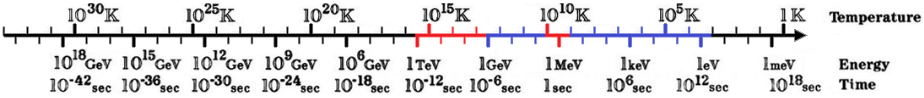
Characteristics:
- Physics beyond the standard model
- Separation of the four forces

Epochs:
- Planck epoch
  - Quantum gravity and ToE
  - Until gravity splits out at 10^{-43} s
- Grand Unification epoch
  - Until strong & electroweak force splits at 10^{-36} s
- Inflation
  - Rapid exponential expansion of the Universe
  - Fixes horizon, flatness, magnetic monopole problem
  - Until 10^{-32} s
- Electroweak epoch
  - Baryogenesis
  - Until the electroweak force splits at 10^{-12} s



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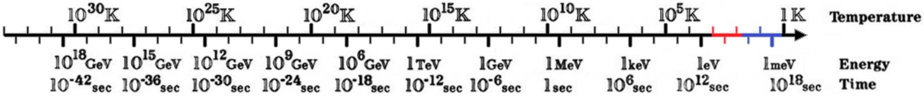
Characteristics:
- Standard model physics
- Changes in "energy domination"

Epochs:
- Quark epoch
  - Quark gluon plasma domination
  - Until hadrons form at 10^{-6} s
- Hadron epoch
  - Neutrino-decoupling
  - Until hadron/anti-hadron annihilation at 10^{-4} s
- Lepton epoch
  - Until lepton/anti-lepton annihilation at 10 s
- Photon epoch
  - Nucleosynthesis - between 3 and 20 m
  - Matter domination at 70,000 y
  - Until recombination / γ-decoupling at 377,000 y



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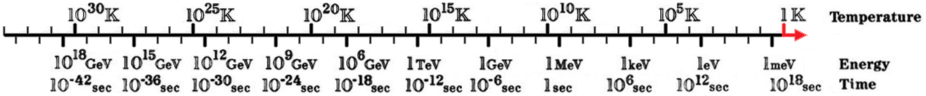
Characteristics:
- Gravity and General Relavtivity
- Realm of observable astronomy

Epochs:
- Dark Ages
  - Transparent Universe
  - Called so because of the lack of (new) light sources
  - ...except for the 21 cm hyperfine H splitting
  - Until gravitational collapse created stars and quasars at around 150 million years after BB
- Reionization
  - Radiatian from stars heats up and reionizes surrounding universe.
  - Small increase in opagueness from plasma
- Formation of galaxies, groups and clusters
- Today



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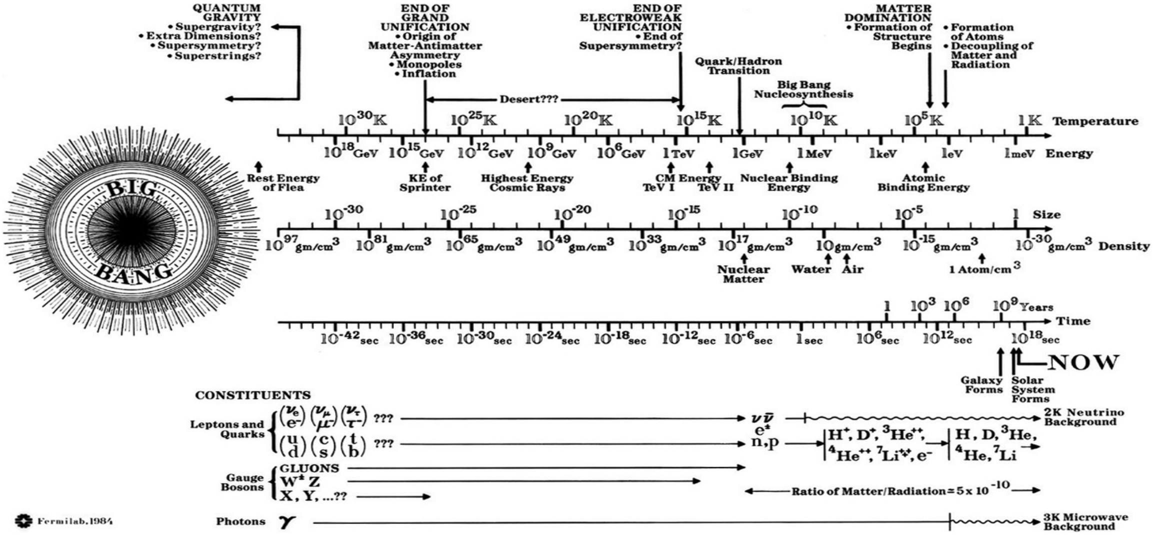
Characteristics:
- Dark Energy playes big role
- 2^{nd} law of thermodynamics

Scenarious:
- Big Freeze and Heat death
- Big Crunch
- Big Rip
- Eternal inflation and multiverses.

Chronology of the Universe



Thank you!

Newton's gravitational constant

Cosmological constant

Metric tensor

Stress-energy tensor: Describes the energy density, energy flux and momentum in spacetime

Speed of light

$$G_{\mu\nu} + g_{\mu\nu}\Lambda = \frac{8\pi G_{\mathrm{N}}}{c^4} T_{\mu\nu}$$

$$= R_{\mu\nu} - 1/2 g_{\mu\nu} R$$

Scalar (Ricci) Curvature: The Lagrangian density for the Einstein-Hilbert action. Defined as the trace of the Ricci tensor.

Ricci curvature tensor: Tells how matter will converge og diverge in time.

$$\sqrt{-g} = \det(g_{\mu\nu})$$

$$S = -\frac{1}{2}\frac{1}{(8\pi G_{\mathrm{N}}/c^4)} \int R\sqrt{-g}\, d^4x$$

The action that yields the Einstein field equations through the principle of least action.

$$T_\mu{}^\nu = \begin{pmatrix} T_0{}^0 & T_0{}^1 & T_0{}^2 & T_0{}^3 \\ T_1{}^0 & T_1{}^1 & T_1{}^2 & T_1{}^3 \\ T_2{}^0 & T_2{}^1 & T_2{}^2 & T_2{}^3 \\ T_3{}^0 & T_3{}^1 & T_3{}^2 & T_3{}^3 \end{pmatrix}$$

Energy density

Energy flux

Shear stress

Momentum density

Momentum flux

Pressure