

The early universe

as a particle physics laboratory



Valerie Domcke CERN TH

From the smallest distances...





image credit : AAPT early universe cosmology

From the smallest distances...





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Standard-Modell der Elementarteilchen



... to the highest energies ...



- At "normal" temperatures, quarks are confined into protons and neutrons, protons are stable
- At high-energy collisions, free quarks become "free" for a short time period
- More massive virtual (short-lived) elementary particles can be formed

$$10^{-20} \text{ m} = \hbar c/10 \text{ TeV} \rightarrow \frac{L}{10^{-20} \text{ m}} \stackrel{\circ}{=} \frac{10 \text{ TeV}}{E}$$



universe today

- cold: -270 °C (2.7 K)
- largely empty
- inhomogeneous
- matter consists of atoms, molecules, ...
- expanding



Velocity-Distance Relation among Extra-Galactic Nebulae.







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Standard Model (SM) or Particle Physics



$$\begin{aligned} \chi &= -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} \\ &+ i F \mathcal{D} \mathcal{F} + h.c. \\ &+ \mathcal{F} \mathcal{G}_{ij} \mathcal{F}_{j} \mathcal{P} + h.c. \\ &+ |\mathcal{D}_{\mu} \mathcal{P}|^{2} - V(\mathcal{P}) \end{aligned}$$

Elementary "building blocks" in the framework of quantum field theory

Standard Model (SM) or Particle Physics



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Elementary "building blocks" in the framework of quantum field theory

High Energy Frontier:

- Other elementary particles?
- Are the SM particles truly elementary?

Early Universe Frontier:

- Can the SM explain all observations to date?
- Possible relics from earlier times/ higher energies?







US East Coast, 1960s ...



Arno Penzias, Robert Wilson 1964



Project Echo, 1960

- Bell Lab's Horn Antenna: a 6m radio telescope promising unprecedented sensitivity
- But a background noise is disrupting the measurements ...



New York?



The sun?





A bold theory

At the same time in Princeton, 60 km away

• Theoretical physicists are discussing the very nature of the universe:

"Steady State" or "Big Bang"?

• Robert Dicke, Jim Peebles and David Wilkinson'

Big Bang Theory ----- cosmic background radiation as relic of the primordial universe



the cosmic microwave background



- many free charged particles (electrons & protons)
- photons scatter multiple times, universe not transparent





electrically neutral hydrogen atoms



the cosmic microwave background



CMB black body radiation



COBE satellite, 1989-93

400 COBE data 🛏 Black body spectrum 350 300 ntensity [MJy/sr] 250 200 10 12 14 16 18 20 22 Frequency [1/cm]

Cosmic microwave background spectrum (from COBE)

 cosmic microwave background well measured today

 black body radiation with T = 2.7 K (-270 C) (microwaves)

> confirms key prediction of `big bang' theory



2019 nobel prize Peebles for his contributions to theoretical cosmology

Penzias, Wilson (nobel prize 1978)

CMB black body radiation



COBE satellite, 1989-93

400 COBE data 🛏 Black body spectrum 350 300 ntensity [MJy/sr] 250 first ,snapshot' of the early 200 Universe, but better resolution needed... 12 16 18 20 22 10 14 Frequency [1/cm]

Cosmic microwave background spectrum (from COBE)

- cosmic microwave background well measured today
- black body radiation with T = 2.7 K (-270 C) (microwaves)

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anisotropies in the CMB

completely homogeneous plasma — homogeneous universe after cooling

- small pertubations needed as seeds for galaxies to form through gravitational collapse
- anisotropies in the CMB, deviation from black body radiation 1:10⁴



PLANCK satellite, 2009 - 2013



anisotropies in the CMB





CMB as relic thermal radiation from the early universe, decoupled in neutral universe

early universe cosmology



CMB as relic thermal radiation from the early universe, decoupled in neutral universe

CMB anisotropies as sees for galaxy formation



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gravitational waves as new window to the early universe



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gravitational waves as new window to the early universe

gravitational waves





2015: first direct observation of GWs, collision of two black holes a billion years ago



gravitational waves





2015: first direct observation of GWs, collision of two black holes a billion years ago



next challenge: stochastic gravitational wave background



pulsar timing arrays



early universe cosmology

pulsar timing arrays

- search for delays in pulse arrivals
- 2020: evidence for common stochastic noise component across all pulsars
- 2023: evidence for Hellings-Down correlation (i.e. gravitational waves)



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- likely origin: supermassive BH binaries
- SGWB or individual source?
 - \rightarrow frequency dependence, anisotropy
- cosmological or astrophysical?
 → anisotropy

example : first order phase transition

Electroweak symmetry breaking: Cross-over in the SM, new physics in the Higgs sector can make it 1st order

.. and beyond: extended symmetry groups (eg GUTs) spontaneously broken in cooling Universe



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1st order PT sources GWs

topological defects formed during PT radiate GWs

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Electroweak symmetry breaking: Cross-over in the SM, new physics in the Higgs sector can make it 1st order

.. and beyond: extended symmetry groups (eg GUTs) spontaneously broken in cooling Universe



field value



1st order PT sources GWs

topological defects formed during PT radiate GWs

conclusions and outlook



the discovery of the CMB revolutionarized our understanding of the universe

what surprises do gravitational waves reserve for us?

conclusions and outlook



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what surprises do gravitational waves reserve for us?

Thank you for your attention !