Ciências ULisboa — Faculdade de Ciências da Universidade de Lisboa

CFTC — Centro de Física Teórica e Computacional

Dark Matter, Phase Transitions and Gravitational Waves

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Master Programme in Physics and Astrophysics

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Objectives

Upon taking this class the students should be able to

- Build models (Lagrangian) in the framework of Quantum Field Theory. "Be able to study their phenomenology using high-energy tools such as FeynRules, LanHEP, MadGraph and CalcHEP". Understand the role of symmetries in model building.

- Build models with dark matter candidates. Understand the WIMP - "Weakly interacting massive particles" paradigm. Be able to build models with scalar, vector, and fermionic dark matter. Understand that there are all kinds of possible dark matter candidates, from very light to very heavy.

- Be able to test dark matter models. Calculate the relic density, direct and indirect DM detection yields and compare them with experiment. Be able to calculate the Higgs invisible branching ratio and the production of dark matter at colliders.

- Understand the mechanism of phase transitions in the early universe and their role in the production of gravitational waves. Calculate the temperature dependent and the one-loop potential. Find the conditions for a strong first order phase transition.

Syllabus

Chapter 1 - Quantum Lagrangian and quantum fields.

1.1 From the Lagrangian to the phenomenology.
1.2 Automatic generation of Feynman Rules with LanHEP and FeynRules.
1.3 Calculation of cross sections with MadGraph and CalcHEP.

Chapter 2 - How to build a model with Dark Matter.

2.1 The WIMP paradigm.
2.2 Scalar, vector and fermionic WIMP.
2.3 Very light and very heavy dark matter.

Chapter 3 - Testing models with Dark Matter.

3.1 Thermal relic density: Boltzmann equation, Co-annihilation, Velocity dependence, Sommerfeld enhancement, Freeze-in production.
3.2 Dark matter direct detection.
3.3 Dark matter indirect detection.
3.4 Dark matter production and detection at colliders.

Chapter 4 - Phase transitions in the Early Universe and Gravitational Waves.

4.1 Classification of phase transitions.
4.2 Characteristics of the transitions.
4.3 Principles of gravitational waves production; gravitational-wave spectra and their properties.

Lectures and Presentations

- Theory and Problems in the same lecture
- Hands-on Lectures for HEP codes (upon request)
- Student's presentations

High Energy Codes

- FeynRules/LanHEP - model; FeynArts - shows Feynman diagrams and calculate amplitudes; FeynCalc - manipulates amplitudes

- MadGraph/CalcHEP - calculates cross sections and Branching ratios

- BSMPTv3 - Beyond the Standard Model Phase Transitions: The C++ program package BSMPT calculates the strength of the electroweak phase transition in extended Higgs sectors (KIT/CFTC-UL).

- MicrOMEGAs - a code for the calculation of Dark Matter Properties including the relic density, direct and indirect rates in a general supersymmetric model and other models of New PhysicsBeyond the Standard Model Phase Transitions.

- RelExt - specialized C++ software tool designed for high-energy physics, specifically for calculating DM relic density and scanning parameter spaces in BSM. (KIT/CFTC-UL)

- ScannerS - Beyond the Standard Model scans with interfaces with a number of other codes (KIT/CFTC-UL).

Bibliography

Main References

Martin Bauer, Tilman Plehn, Yet Another Introduction to Dark Matter: The Particle Physics Approach (2019) Springer 2019.
https://arxiv.org/pdf/1705.01987.pdf

Andrei Linde, Particle Physics and Inflationary Cosmology (1990) Taylor and Francis, 1990.
https://arxiv.org/pdf/hep-th/0503203.pdf

M. Quirós, Finite temperature field theory and phase transitions (1999). arXiv:hep-ph/9901312

Mark B. Hindmarsh, Marvin Lueben, Johannes Lumma, Martin Pauly, Phase transitions in the early universe (2021) SciPost Phys.Lect.Notes 24 1. https://arxiv.org/pdf/arXiv:2008.09136

Chiara Caprini et al., Science with the space-based interferometer eLISA. II: Gravitational waves from cosmological phase transitions (2016) JCAP 04 (2016) 001. https://arxiv.org/pdf/1512.06239.pdf

Quantum and Particle Physics

D. Griffiths, Introduction to Elementary Particles (2008) 2nd edition John Wiley & Sons.

Matthew D. Schwartz, Quantum Field Theory and the Standard Model (2013) Harvard University, Massachusetts.

Timo Weigland, Quantum Field Theory I+II (2013). https://www.physics.umd.edu/grt/ta j/624b/WeigandQFT.pdf

Jorge Romão, Advanced Quantum Field Theory (2020). http://porthos.ist.utl.pt/ftp/textos/tca.pdf

Evaluation

Assessment

The course assessment consists of two components:

- **Oral Presentation** – 30% of the final grade
- **Final Written Examination** – 70% of the final grade

A minimum grade of **10 out of 20** is required in **each component** in order to pass the course.

Oral Presentation

Each student must select one of the proposed topics and deliver an individual presentation on **23 April**. Presentations will have a maximum duration of **20 minutes**, including approximately **5 minutes for questions and discussion**.

A written abstract (maximum length: one page) summarising the main points of the presentation must be submitted on the day of the presentation.

The proposed topics involve the reading and critical analysis of a research article, as well as broader conceptual aspects of dark matter. Students may alternatively propose a dark matter paper of their choice, subject to the instructor's approval.

The deadline for topic selection is **5 March**.

Students are encouraged to use AI tools; this reflects my personal view. Any use of AI must not replace your own critical thinking and analysis.

The presentation grade will be distributed as follows: 15% for the written abstract, 20% for the scientific content, 30% for the quality and clarity of the oral presentation, and 35% for the discussion and your ability to answer questions.

Groups

Groups of one:

- Pandemic generation of dark matter (e-Print: 2103.16572 [hep-ph])
- New Freezeout Mechanism for Strongly Interacting Dark Matter (e-Print: 2002.04038 [hep-ph])
- Semi-annihilation of Dark Matter (e-Print: 1003.5912 [hep-ph])
- Secluded WIMP dark matter (arXiv:0711.4866 [hep-ph])
- Cannibal dark matter (arXiv:1607.03108 [hep-ph])
- Zombie dark matter (arXiv:2003.04900 [hep-ph])
- Kinder dark matter (arXiv:2011.01240 [hep-ph])
- Freeze-In Production of FIMP Dark Matter (e-Print: 0911.1120 [hep-ph])
- Ultra light dark matter
- Feebly interacting particles
- Axion like dark matter
- **Something that includes dark matter in the title**

Dark Matter

MY FAVOURITE DARK MATTER MODEL

14–17 Apr 2025
Portugal
Atlantic/Azores timezone

Enter your search term

- Overview
- Timetable
- Contribution List
- Registration
- Participant List
- Proceedings

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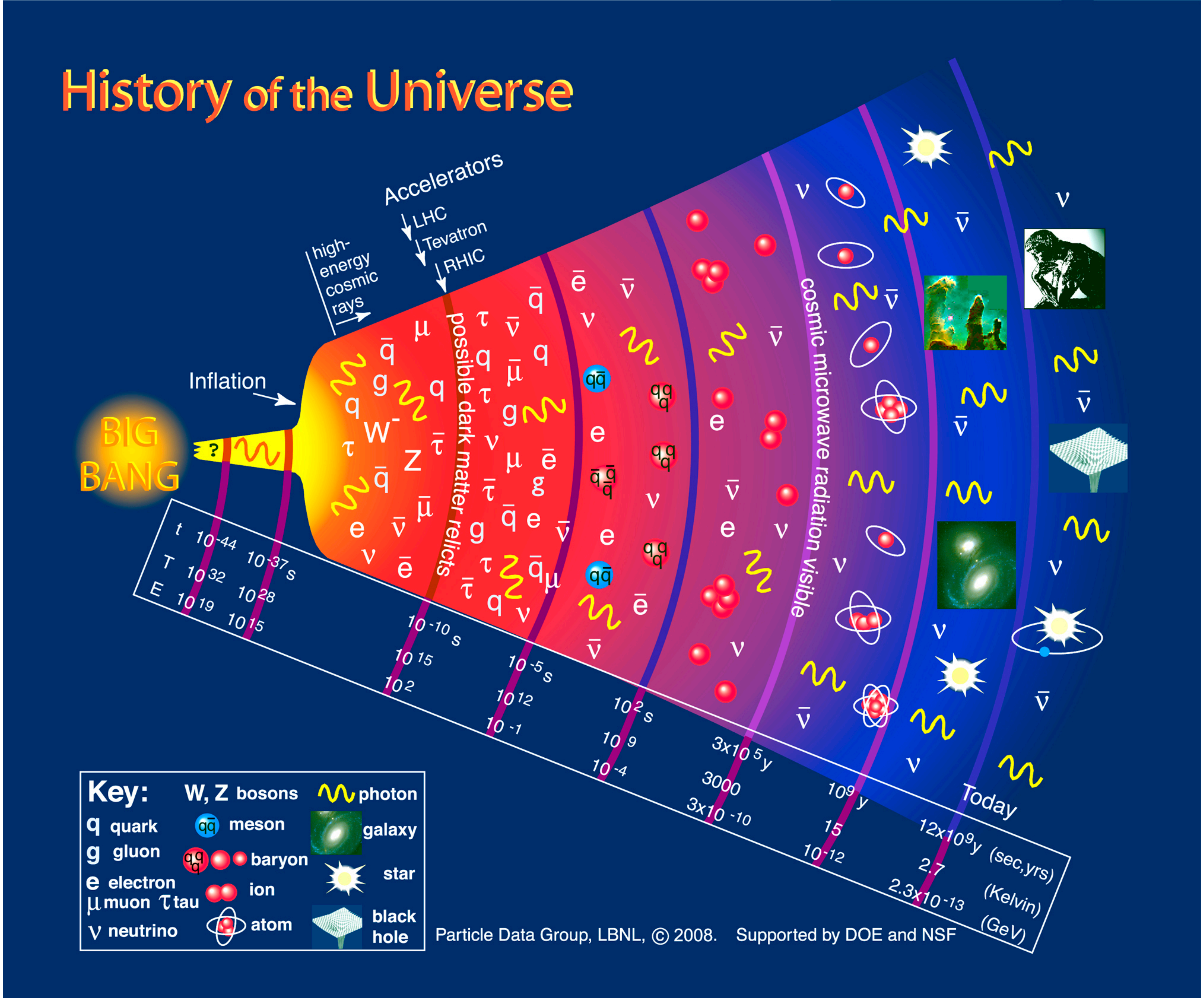
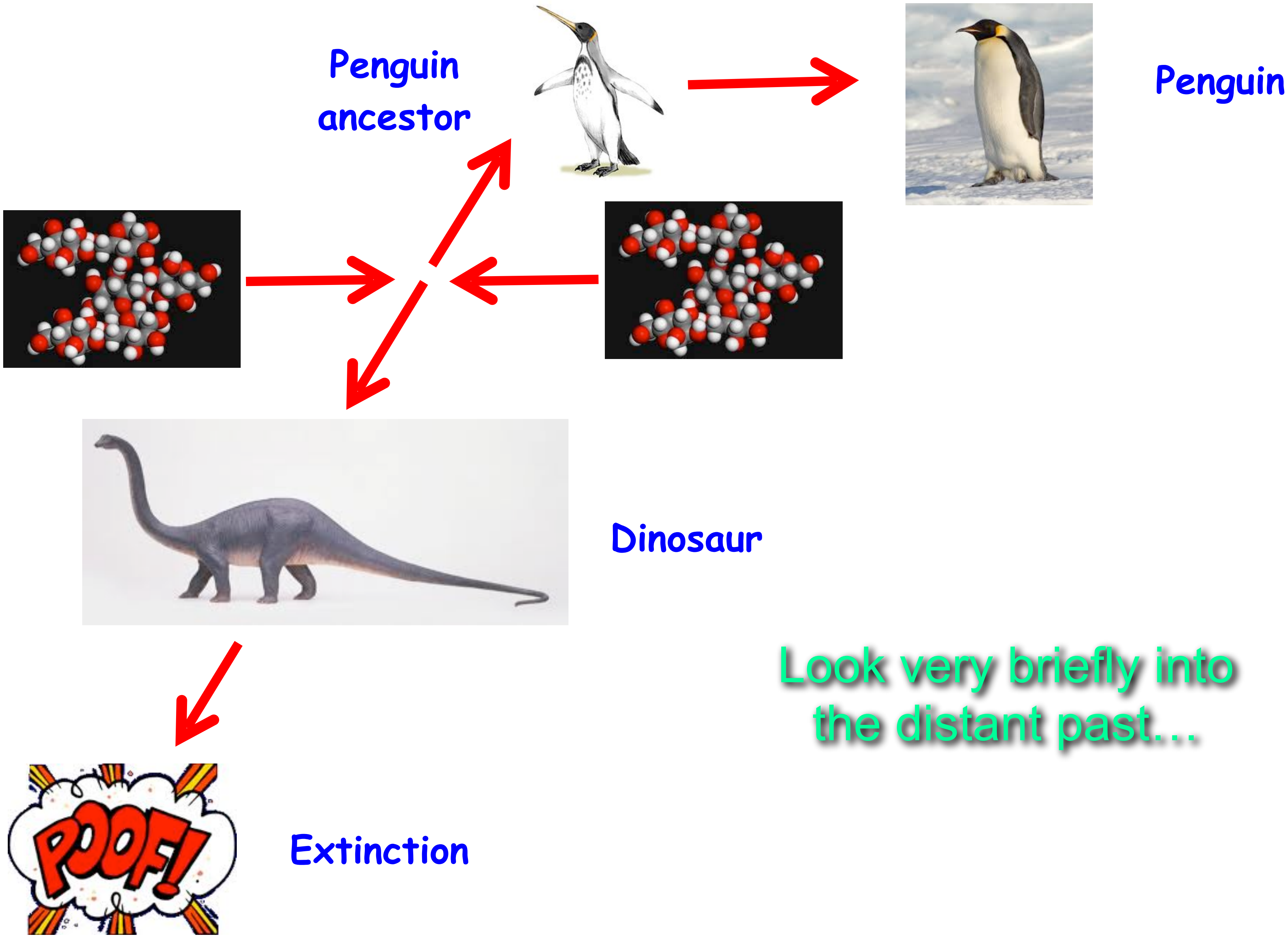
tps://www.facebook.com/friends/suggestion...

Print | PDF | Full screen | Detailed view | Filter

09:00	**Registration: Registration**		*Portugal*	09:00 - 09:45
	Welcome		*Portugal*	09:45 - 10:00
10:00	**Exploring new features of the Z2×Z2 3HDM with two component dark**	*Jorge Romão*	*Portugal*	10:00 - 10:30
	Dark Hydrogen Atoms as Baryonic Dark Matter	*Prof. Eugene Oks*	*Portugal*	10:30 - 11:00
11:00	**Coffee and Tea time (and some food)**		*Portugal*	11:00 - 11:30
	Dark matter in the Lorentz gauge theory	*Luxi Zheng*	*Portugal*	11:30 - 12:00
12:00	**Probing dark matter properties through the morphology of the intergalactic medium in emission**	*Titouan Lazeyras*	*Portugal*	12:00 - 12:30
13:00, 14:00	**Lunch**		*Portugal*	12:30 - 14:30
	Gravitational lensing, and stability properties of Bose-Einstein condensate dark matter halos	*Francisco Lobo*	*Portugal*	14:30 - 15:00
15:00	**Electroweak phase transition in a vector dark matter scenario**	*Nico Benincasa*	*Portugal*	15:00 - 15:30
	Coffee and Tea time (and some food)			


History of the Universe
BIG BANG
Inflation
high-energy cosmic rays
Accelerators
LHC
Tevatron
RHIC
possible dark matter relicts
cosmic microwave radiation visible
Today
t 10^-44 10^-37 s
T 10^32 10^28
E 10^19 10^15
10^-10 s
10^15
10^2
10^-5 s
10^12
10^-1
10^2 s
10^9
10^-4
3x10^5 y
3000
3x10^-10
10^9 y
15
10^-12
12x10^9 y (sec,yrs)
2.7 (Kelvin)
2.3x10^-13 (GeV)
Key:
q quark
g gluon
e electron
μ muon τ tau
ν neutrino
W, Z bosons
meson
baryon
ion
atom
photon
galaxy
star
black hole
Particle Data Group, LBNL, © 2008. Supported by DOE and NSF

If biologists had a Large Hadron Collider



Look very briefly into the distant past…

And before we start

Lectures will begin 10 minutes after the scheduled start time. I will be available during those 10 minutes to answer questions about the previous lecture. Once the lecture has started, students will not be permitted to enter the classroom.

- Listening to Radiolab - https://radiolab.org/
- Watch Veritasium https://www.youtube.com/veritasium