Dark Matter, Phase Transitions and Gravitational Waves

Rui Santos

Master Programme in Physics and Astrophysics

rasantos@fc.ul.pt

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 inter- acting 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
- Student's presentations

High Energy Codes

- FeynRules/LanHEP - model
- FeynArts - shows Feynman diagrams and calculate amplitude
- FeynCalc - manipulates amplitudes
- MadGraph/CalcHEP - calculates cross sections and Branching ratios
- BSMPT - Beyond the Standard Model Phase Transitions: The C++ program package BSMPT calculates the strength of the electroweak phase transition in extended Higgs sectors.
- 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.

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

The evaluation has 2 components:

- Presentations - 30% of the final grade
- Final written exam - 70%. of the final grade Minimum pass grade in both components is 10.

Choose one of the topics below and present it, in groups of one, **in the 21st of March**. The presentations will last a maximum of 30 minutes, including 10 minutes for questions and discussion. A written abstract (one page long maximum) about the work has do be hand-in on the day of the presentation. There are five topics that are essentially about reading and understanding a paper and three more broad subject about dark matter:

- Pandemic generation of dark matter (e-Print: 2103.16572 [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]).
- Ultra light dark matter.
- Feebly interacting particles.
- Axion like dark matter.

Groups

Groups of one:

- Pandemic generation of dark matter (e-Print: 2103.16572 [hep-ph]). Daniel Cruz.
- New Freezeout Mechanism for Strongly Interacting Dark Matter (e-Print: 2002.04038 [hep-ph]). Maria Lourenço.
- Semi-annihilation of Dark Matter (e-Print: 1003.5912 [hep-ph]). Pedro Batista.
- Secluded WIMP dark matter (arXiv:0711.4866 [hep-ph]). - Maria Gonçalves
- Cannibal dark matter (arXiv:1607.03108 [hep-ph]). - Luca Damele
- Zombie dark matter (arXiv:2003.04900 [hep-ph]). - Susanna Bräu
- Kinder dark matter (arXiv:2011.01240 [hep-ph]). João Silva.
- Freeze-In Production of FIMP Dark Matter (e-Print: 0911.1120 [hep-ph]). Tomás Pinto.
- Ultra light dark matter. José Carmelo.
- Feebly interacting particles. - Pedro Melo
- Axion like dark matter. - Elizabeth Muhsin

And before we start

- Reading Feynman diagrams
- Particles and interactions
- Writing amplitudes
- Reading the arxiv - arXiv.org e-Print archive
- Listening to radiolab - https://radiolab.org/