Laboratory and Computational physics

in third-year undergraduate coursework

ACSME, October 2025
The University of Melbourne

Presented By:
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"Experiment is the only means of knowledge at our disposal;

Everything else is poetry, imagination."

Max Planck,
Father of Quantum theory

Educational Objective

Preparing physics graduates for academia and industry

- Theory in practice
- Experimental and analytical skills
- Scientific programming
- Scientific writing and communication
- Teamwork and collaboration

Bridging the gap

Talk Overview

- Subject introduction
- Overview of lab activities
- Resources & prerequisites
- Subject structure
- Feedback and impact

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PHYC30021

Laboratory and computational physics 3

- 12 weeks (1 semester)
- Choice of 4 extended projects from 16 diverse options
- Self-tailored and collaborative learning experience
- Hands-on programming and/or experiments
- Introduction to academic writing

Core subject for Physics majors

16 activities

- cross-disciplinary
- research-informed
- cutting-edge

(E) = **experimental**; instrument setup & data collection

(C) = **computational**; simulations and analysis of physicsl systems

(EC) = computational analysis using data from **existing experiments**

Particle physics

Muon detection and lifetime (E)
Discovery of Higgs' Boson (EC)
CP violation (EC)
Dark matter (C)

Astrophysics

Observational astrophysics (EC)
*Dark matter halo (C)
Gravitational waves (EC)

Computational physics

Complex systems: sandpiles (C)
Computed tomography (C)
Laser cooling (C)
Ultracold atoms (C)

Atomic optics

Nuclear magnetic resonance (E)

Magneto-optical trap (E)

Condesed matter physics

Atomic force microscopy (E)

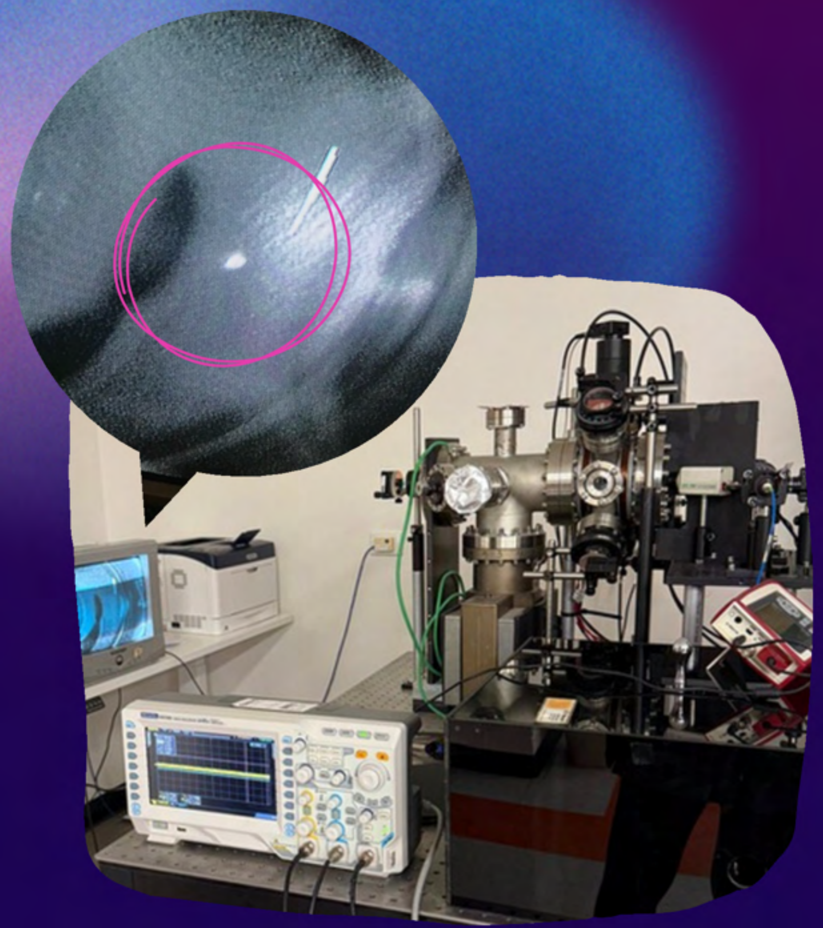
Deep level transient spectroscopy (E)

Instrumentation

*Semiconductor bandgap measurement (E)

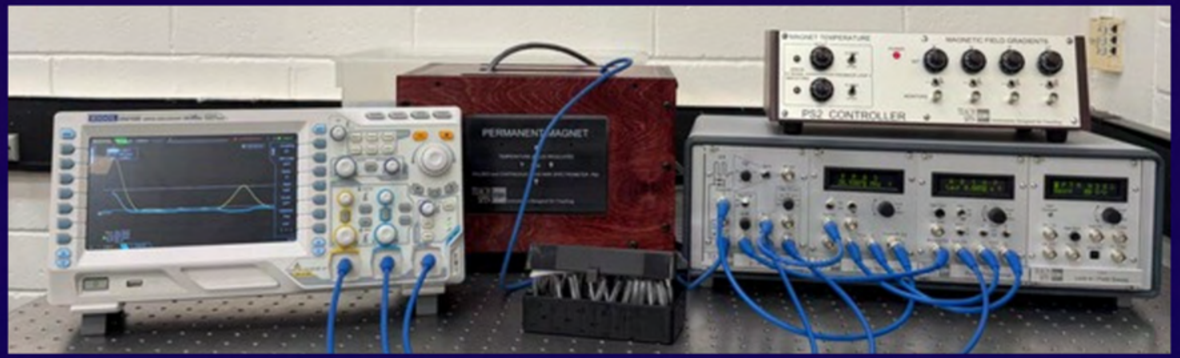
(E) Activity Highlights

Instrumentation, real-time data collection and analysis



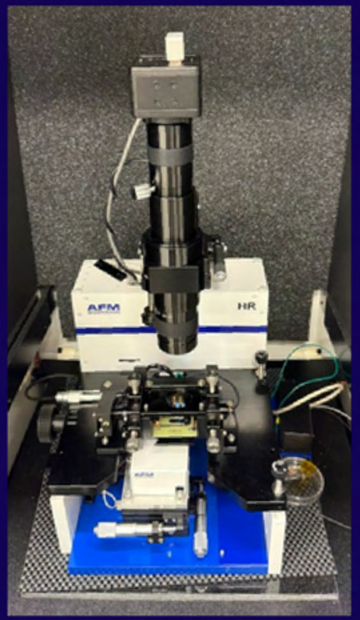
Magneto-optical trap

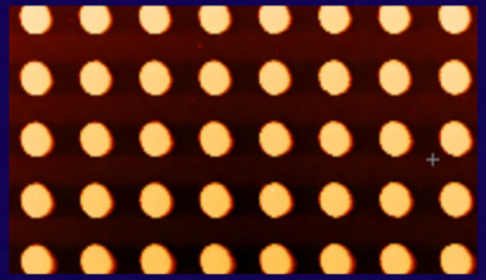
- Students create Bose-Einstein condensates by cooling & confining atoms to a small spatial region
- Demonstrates applications of laser cooling (Nobel in Physics 1997) and magnetic trapping

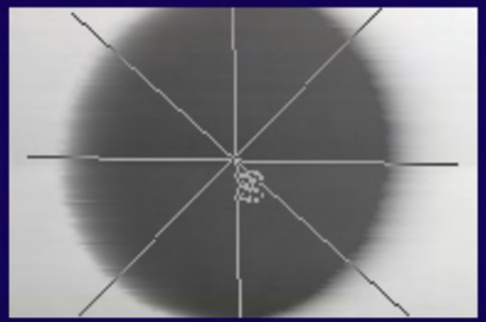


Nuclear magnetic resonance

- A chemical analysis tool which forms the basis of MRI machines
- Students are led through a ground-up approach to understand the fundamental physics that underpin these tools







Atomic force microscopy

- Measuring the nanoscale topography of a sample surface
- Essential tool for semiconductor and nanofabrication research
- Students operate the tool and measure samples made in-house and from our supplier.

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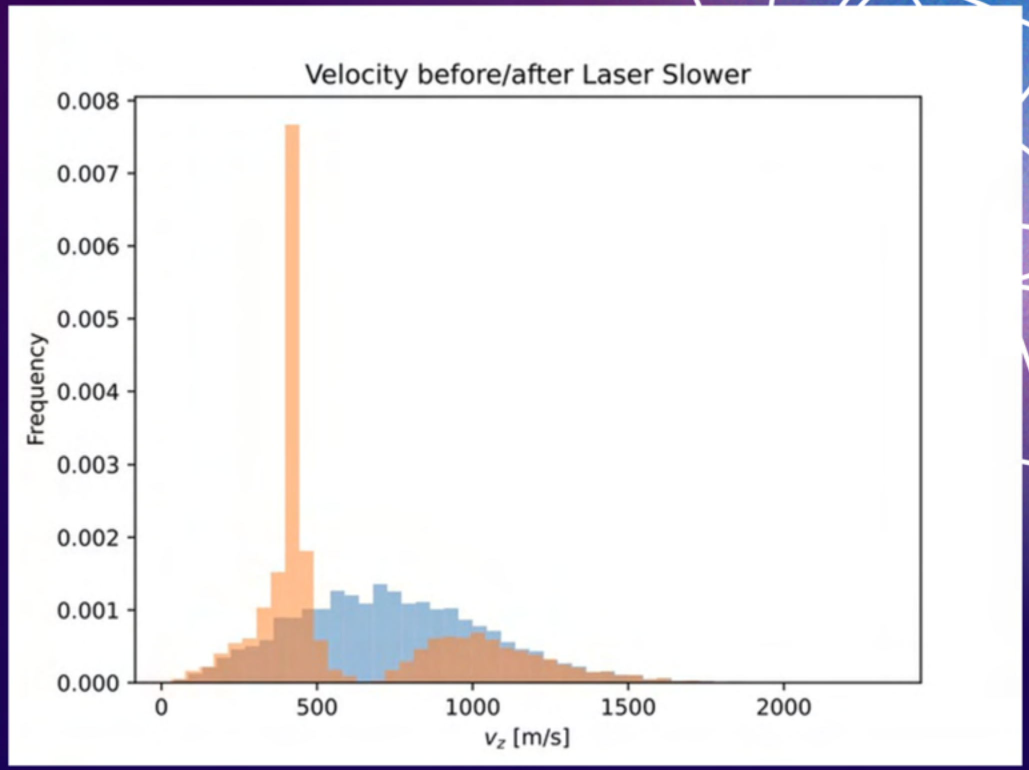
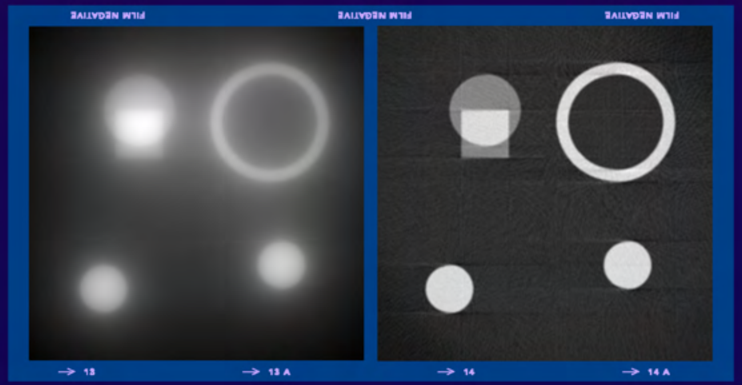
(C) Activity Highlights

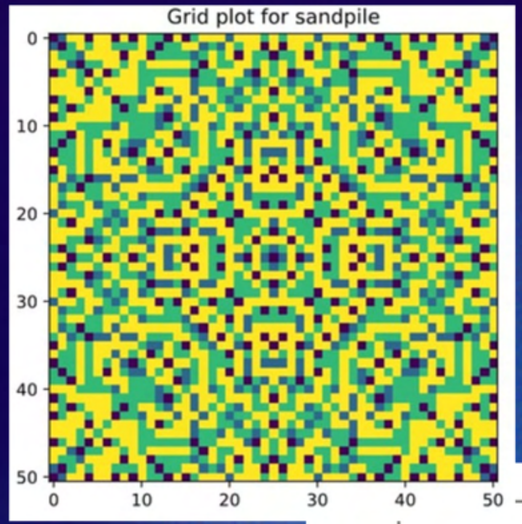
Simulation and analysis of physical systems

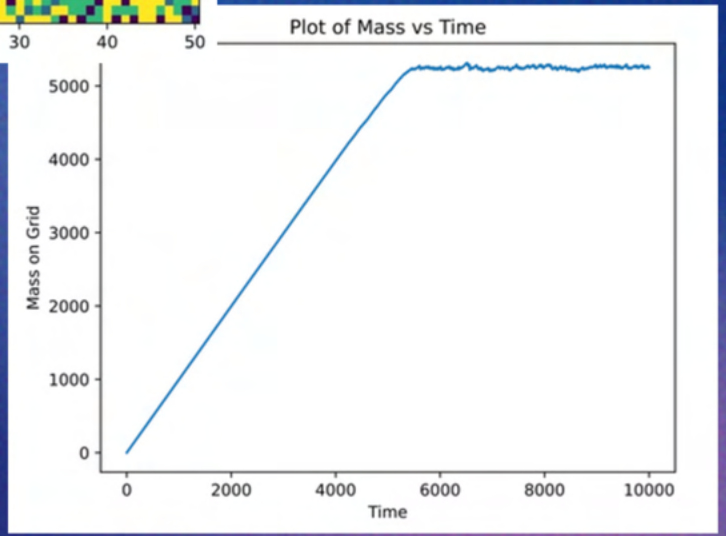
Laser cooling

- Theoretical activity complementing the Magneto-Optical Trap experiment
- Applications of momentum transfer and Doppler shift in laser cooling of atoms to ultracold temperatures









Complex systems: sandpiles

- Self-assembled sandpile model (cellular automaton)
- Applying statistical physics to study large scale properties of complex physics systems, e.g. self-organising criticality, scale invariance

Computed tomography

- Programming and visualising mathematical properties of tomographic projection and reconstruction
- Fourier transforms and filtered imaging

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(EC) Activity Highlights

Several of these efforts have already been presented/circulated to the relevant scientific collaborations and have been well received.

LIGO VIRGO KAGRA

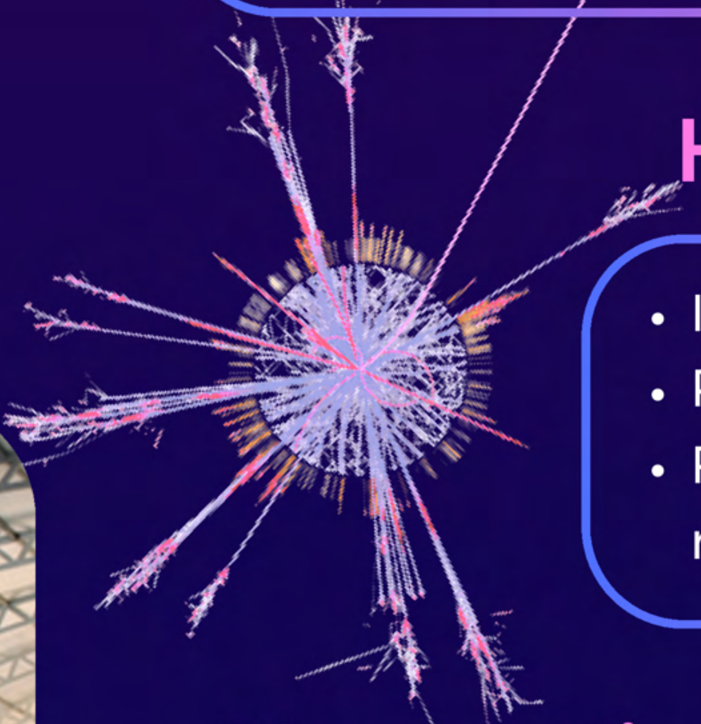
CERN

ATLAS EXPERIMENT

itelescope.net

Gravitational waves

- Bayesian inference
- Monte Carlo methods
- Process and search for gravitational-wave signals in real LIGO data



Higgs Boson discovery

- Introduction to standard model
- Particle physics cut-based analysis
- Rediscovery of the Higgs Boson using real data from the ATLAS experiment

Observational astrophysics

- Real-time remote data acquisition with iTelescope and image processing
- Analysis of star/galaxy clusters using self-acquired telescope data

Setup and resources

How do we distribute and implement everything?

- Linux (Rocky 9) Workstations
- Secure login with university credentials
- Material distribution:
  - Stored in a common NFS cloud
  - Accessible through individual workstations
- Students' work saved in individual workstations

Unified Linux user environments
(with local and remote access)

2nd-year subject Pre-requisites

PHYC20013:
Laboratory and Computational Physics 2

PHYC20012:
Quantum and Thermal physics

OR

PHYC20015:
Special relativity & electromagnetism

MAST20030:
Differential equations

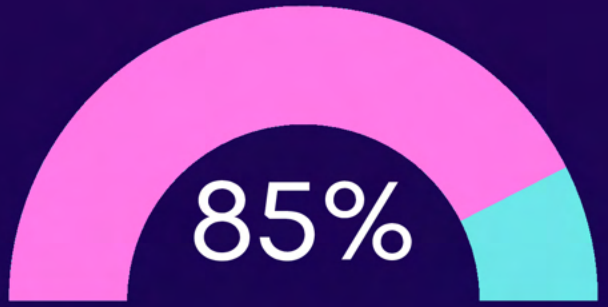
OR

PHYC20014:
Theoretical physics 2
(Classical physics + Optics)

Subject Structure

Introductory programming

Mandatory but not assessed



Four extended projects

Supervised, collaborative learning

Journal-style report

Self-directed research and writing

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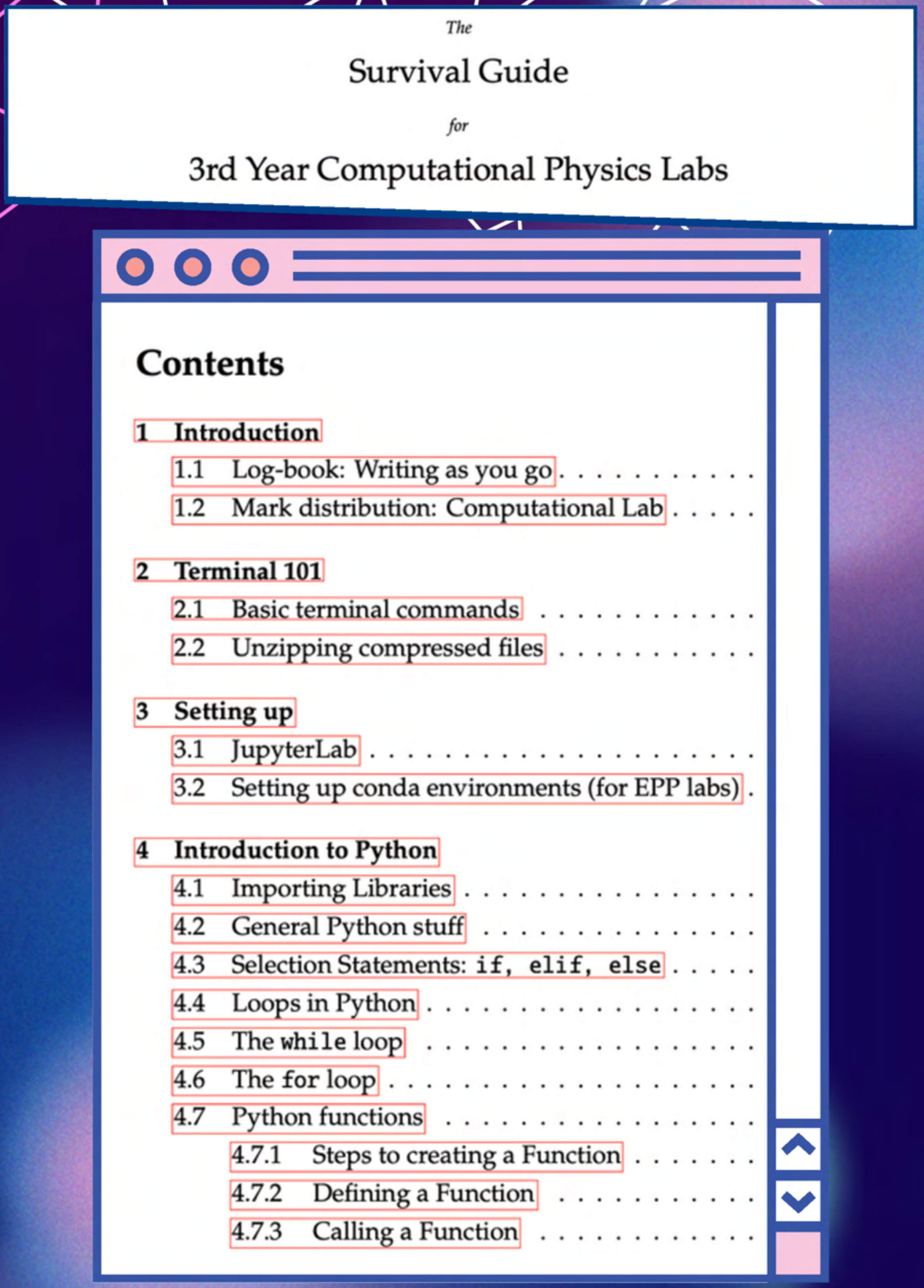
Introductory Programming

Week 1: 3-hour mandatory refresher

- Simple coding exercises
- Tailored programming notes
- In-person support
- **Purpose:**
  - Assess programming proficiency for targeted support
  - Build relevant programming skills for productive, physics-focused peer discussions



The

Survival Guide

for

3rd Year Computational Physics Labs

Contents

Extended Projects

Week 2-9: Students select and complete four of 16 available activities; with at least one (E) and one (C)-type.

- Diverse, self-tailored, hands-on and collaborative learning experience
- **Contact hours** per activity with **in-field experts**:
  - 6 sessions x 3 hours = 18 hours total (across 2 weeks)
- **Assessments**:
  - 10% - Individual participation
  - 75% - Four logbooks + code submissions

Marking Rubric

Introduction (4)
Procedure (6)
Experiment/Code/Results (6)
Interpretation/Analysis (6)
Conclusion (2)
Record-keeping (6)
Total logbook mark (30)

+ Participation (4)

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Journal-style Report

Weeks 10–12: Students prepare a journal-style report based on a completed logbook (15%)

- Introduction to formal, academic-style writing
- Strengthen understanding of the scientific method
- Development of communication skills

3rd year lab Journal Report , 1–4 (2023)

Compiled using MNRAS LaTeX style file v3.0

Distribution reconstruction and parameter fitting using Bayesian Inference and MCMC

[redacted], 1★ [redacted], 1 [redacted], 1

1The University of Melbourne, Parkville, Melbourne, Australia

Not Accepted. Not Received; in original form 20 Oct 2023

ABSTRACT

Bayesian inference is a new field of statistics/probability. Compared to the traditional frequentist view on analysing data, it only depends on the observational data with our belief updating with newly given data. Hence providing new ways to analyse the data. Here we use two approaches to study the validity of Bayesian inference in scientific research: 1. Given a known data set sampled from the Maxwell-Boltzmann distribution presenting the velocities of ideal gas particles, would Bayesian inference reconstruct the distribution? 2. How well could Bayesian inference fit the Maxwell-Boltzmann distribution to the sample? In both sections, we use the Markov chain Monte Carlo (MCMC) and the Metropolis-Hasting (MH) algorithm to explore the parameter space of the given particle velocity distribution. We find that the Bayesian inference has excellent capability to reconstruct the sample distribution, however, this is subject to the original binning of the data as well as the jump size of the MH algorithm. It also fits the data to have a peak velocity distributed around $v_p \approx 1000\,\mathrm{ms^{-1}}$.

Key words: Bayesian inference – Statistics – Markov chain Monte Carlo – Data analysis

Cambridge Default Journal (2022), 0, 1–6

ARTICLE

Using Scanning Probe Microscopy to Produce a Resolved Image of the Magnetic Domains on a Hard Disk Drive Platter

[redacted]* and [redacted]

*Corresponding author. Email: [redacted]

Abstract

Scanning Probe Microscopy (SPM) offers many modes for imaging samples at a resolution of less than an nm. This paper explores the use of Magnetic Force Microscopy, which utilises both the features of Atomic Force Microscopy, such as sensitivity to Van De Waals Forces, and additional sensitivity to Magnetic Forces, to image the magnetic domains of a Hard Disk Drive Platter. Through this process the different parameters necessary to produce a successful image are systematically explored, such as lowering the velocity to increase resolution, increasing the frequency set point to increase sensitivity, changing scan direction to account for scan geometry and decreasing scan size to reduce the presence of artifacts. Consequently, using these parameters plus an appropriate Dz, a resolved image of the magnetic domains is produced, showing track widths of around 0.5μm. This allows us to date the HDD platter, in our case to the 1990s.

Keywords: SPM, MFM, HDD

Physics 3 • Journal Report

Student Number: [redacted]

Reconstructing and Investigating the WIMP Miracle

in collaboration with [redacted] and [redacted]

The University of Melbourne

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October 20, 2023

Abstract

From various astrophysical observations, there is overwhelming evidence consistently pointing to a present-day observed dark matter (DM) abundance of 85% of the total matter density of the Universe. Detection of dark matter is challenging since it only interacts strongly with the gravitational force. The Weakly Interacting Massive Particle (WIMP) - an electrically neutral particle with a mass in the GeV-TeV range - has arisen from literature as a popular candidate for potential detection. Naively, thermal equilibrium heavily favours the annihilation of WIMPs in present-day temperatures. However, through the inclusion of non-equilibrium dynamics by accounting for Hubble expansion, this paper reconstructs a model that demonstrates 'freeze-out' of the WIMP yield as the Universe cools to its current temperature - the predicted WIMP yield flattens out to a stable value, close to the true present-day observed DM yield. Two major results are discussed - firstly the WIMP masses required for this model to match the present-day observed DM yield assuming they interact via the weak force (4.7378 GeV for the weak-force interaction strength for WIMPs of the low-to-medium GeV range, and 9720 GeV for the weak-force interaction strength for WIMPs of mass greater than 90GeV); and secondly the interaction cross-section required to achieve the present-day yield assuming they interact via a general force for a range of WIMP masses. Generally, a lower WIMP mass increases the final freeze-out yield when the cross-section is held fixed, and a lower WIMP mass requires a higher cross-section to achieve the correct yield at present-day temperatures.

Student Feedback

Q: What aspects of this subject were the most helpful for your learning?

Direct quotes from Student Experience Surverys (SES)

2022

Engaging

"The labs are really interesting and provided a great hands-on way to engage with the physical concepts."

Clear guided learning

"The quality of the documentation and the presence of the demonstrators to guide us through the more elaborate sections, were helpful in giving us a proper appreciation of labs' methods and results."

2023

Support & collaboration

"The ability to get immediate feedback or guidance from other students and from the tutors"

In-depth learning

"Spending a long time on each lab was good and made it a lot more enjoyable than 1st and 2nd year labs"

All-rounded

"Everything, interacting with other students, learning engaging content, useful demonstrators who care a lot. This is the best subject I have ever taken at university."

Anecdotal Impact

Skills developed in this subject are essential for **transitioning into industry workplaces** and better equip students with foundational skills needed for **graduate research**.

Confidence in written & verbal communication

Strong computational foundations

Experimental & analytical expertise

Experience working collaboratively

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Based on informal discussions with physics graduates and academics from The University of Melbourne.

Summary

Bridging the gap

Research-informed theory in practice ✓

Experimental and analytical skills ✓

Scientific programming ✓

Scientific writing and communication ✓

Teamwork and collaboration ✓

📩 GET IN TOUCH!

We are happy to share our materials

Thank You

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(School of Physics)

Handbook

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- Hunter Johnson (Experimental labs)
- Jarra Horstman (Complex system lab)

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