COSMIC PHASE TRANSITIONS AND GRAVITATIONAL WAVES: A QUEST FOR PHYSICS BEYOND THE STANDARD ELECTROWEAK MODEL

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by

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To Taa, Pehi, Maa and Baba

(Jatin, Niramai, Janmoni and Prabin)

– the four pillars of my life, and

To the boy, who never stopped dreaming.

Certificate

This is to certify that the thesis entitled **Cosmic Phase Transitions and Gravitational Waves: a quest for physics beyond the Standard Electroweak Model** being submitted by **Pankaj Borah** to the Indian Institute of Technology Delhi for the award of the degree of **Doctor of Philosophy** in Physics, is a record of bonafide research work carried out by him under my supervision and guidance. He has fulfilled the requirements for the submission of the thesis, which, to the best of my knowledge, has reached the required standard. The material contained in the thesis has not been submitted in part or in full to any other university or institute for the award of any degree or diploma.

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Place: New Delhi

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(Pankaj Borah)

Date: ....
Place: New Delhi

ABSTRACT

The first detection of Gravitational Waves (GWs) in 2015 has opened a new window into the early Universe, providing a powerful tool to explore phenomena beyond the reach of electromagnetic observations. This dissertation explores cosmic First-Order Phase Transitions (FOPTs) as a compelling source of GWs, which also offers a plausible explanation to a key shortcoming of the Standard Model (SM) of particle physics, the observed matter-antimatter asymmetry of the Universe, via electroweak baryogenesis (EWBG) mechanism. In parallel, this thesis explores another fundamental open question, the nature of dark matter (DM), with particular attention to Weakly Interacting Massive Particles (WIMPs). The SM neither predicts a FOPT, essential for the EWBG mechanism, nor provides a viable particle DM candidate, despite strong astrophysical and cosmological evidence for the latter.

To address these limitations, this dissertation investigates three well-motivated beyond-the-Standard-Model (BSM) scenarios, focusing on the two interconnected aspects of the early Universe: FOPTs and DM production, with particular emphasis on the possibility of multi-component WIMP DM frameworks. With the upcoming GW detectors like LISA, BBO, DECIGO and its variants, we analyse GW signals arising from strong FOPTs using both the conventional and improved novel methods, aiming to constrain viable BSM parameter spaces. By examining the complementary insights from various DM direct and indirect experiments, relic abundance and GW observatories, alongside collider searches, this thesis refines the landscape of the BSM scenarios and offers robust predictions to distinguish between BSM models in future experiments across different energy frontiers.

सार

2015 में गुरुत्वाकर्षण तरंगें (Gravitational Waves, GWs) की पहली खोज ने प्रारंभिक ब्रह्मांड में झाँकने के लिए एक नई खिड़की खोल दी है, जिससे हमें विद्युतचुंबकीय प्रेक्षण की पहुँच से बाहर की घटनाओं का अध्ययन करने का एक शक्तिशाली साधन मिला है। यह शोध प्रबंध cosmic First-Order Phase Transitions (FOPTs) को GWs के एक आकर्षक स्रोत के रूप में प्रस्तुत करता है, जो कण भौतिकी (particle physics) के Standard Model (SM) की एक प्रमुख कमी, ब्रह्मांड में देखी गई पदार्थ-विपदार्थ विषमता (matter-antimatter asymmetry) को इलेक्ट्रोवीक बैरियोजेनेसिस (electroweak baryogenesis, EWBG) तंत्र के माध्यम से समझाने का एक संभावित तरीका भी प्रदान करता है। साथ ही, यह शोध अदृश्य द्रव्य (dark matter, DM) की प्रकृति जैसे एक अन्य मौलिक खुले प्रश्न का भी अध्ययन करता है, जिसमें विशेष ध्यान Weakly Interacting Massive Particles (WIMPs) पर केंद्रित है। SM न तो EWBG तंत्र के लिए आवश्यक FOPT की भविष्यवाणी करता है, और न ही मजबूत खगोल-भौतिकीय (astrophysical) और ब्रह्मांडीय (cosmological) प्रमाणों के बावजूद, particle DM के लिए एक उपयुक्त उम्मीदवार प्रदान करता है।

इन सीमाओं को संबोधित करने के लिए, यह शोध प्रबंध तीन अच्छी तरह से प्रेरित beyond-the-Standard-Model (BSM) scenarios की जाँच करता है, जिसमें प्रारंभिक ब्रह्मांड के दो आपस में जुड़े पहलुओं: FOPTs और DM डार्क मैटर उत्पादन पर ध्यान केंद्रित किया गया है, खासतौर पर multi-component WIMP DM frameworks की संभावना पर। आने वाले GW डिटेक्टर जैसे LISA, BBO, DECIGO और इनके रूपांतर के साथ, हम strong FOPTs से उत्पन्न गुरुत्वाकर्षण तरंग संकेत का विश्लेषण पारंपरिक और नवीन उन्नत विधियों दोनों का उपयोग करके करते हैं, ताकि संभाव्य BSM पैरामीटर क्षेत्र को सीमित किया जा सके। विभिन्न DM प्रत्यक्ष और अप्रत्यक्ष प्रयोग, अवशिष्ट प्रचुरता (relic abundance) और गुरुत्वाकर्षण तरंग वेधशालाएँ (observatories), साथ ही कोलाइडर (collider) खोज से प्राप्त पूरक अंतर्दृष्टि (complementary insights) का अध्ययन करके, यह शोध BSM scenarios के परिदृश्य को परिष्कृत करता है और भविष्य के विभिन्न ऊर्जा सीमाओं पर होने वाले प्रयोगों में BSM मॉडल्स के बीच अंतर करने के लिए ठोस भविष्यवाणियाँ प्रस्तुत करता है।

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Abbreviations

AEDGE	**A**tomic **E**xperiment for **D**ark Matter and **G**ravity in **E**xploration of space
AION	**A**tomic **I**nterferometric **O**bservatory and **N**etwork
AMS	**A**lpha **M**agnetic **S**pectrometer
BBO	**B**ig **B**ang **O**bserver
BBN	**B**ig **B**ang **N**ucleosynthesis
BP	**B**enchmark **P**oint
BSM	**B**eyond the **S**tandard **M**odel
CDM	**C**old **D**ark **M**atter
CE	**C**osmic **E**xplorer
CMB	**C**osmic **M**icrowave **B**ackground
CP	**C**harge Conjugation **P**arity
DARWIN	**D**ark matter **W**IMP **S**earch with **L**iquid **X**enon
DCT	**D**isapearing **C**harged **T**racks
DECIGO	**DECi**hertz **I**nterferometer **G**ravitational wave **O**bservatory
DD	**D**irect **D**etection
DM	**D**ark **M**atter
EPTA	**E**uropean **P**ulsar **T**iming **A**rray
ET	**E**instein **T**elescope
EW	**E**lectro**w**eak
EWPO	**E**lectro**w**eak **P**recision **O**bservables
EWPT	**E**lectro**w**eak **P**hase **T**ransition
EWSB	**E**lectro**w**eak **S**ymmetry **B**reaking
Fermi-LAT	**F**ermi **L**arge **A**rea **T**elescope
FOPT	**F**irst **O**rder **P**hase **T**ransition
FOEWPT	**F**irst **O**rder **E**lectro**w**eak **P**hase **T**ransition

FTQFT	**F**inite **T**emperature **Q**uantum **F**ield **T**heory
GMSB	**G**auge **M**ediated **S**upersymmetry **B**reaking
GUT	**G**rand **U**nified **T**heory
GW	**G**ravitational **W**ave
H.E.S.S.	**H**igh **E**nergy **S**tereoscopic **S**ystem
ID	**I**ndirect **D**etection
IPTA	**I**nternational **P**ulsar **T**iming **A**rray
IR	**I**nfra**r**ed
ITM	**I**nert **T**riplet **M**odel
LHC	**L**arge **H**adron **C**ollider
LISA	**L**aser **I**nterferometer **S**pace **A**ntenna
MACHO	**M**assive **A**strophysical **C**ompact **H**alo **O**bject
MSSM	**M**inimal **S**upersymmetric **S**tandard **M**odel
NANOGrav	**Nano**hertz **O**bservatory for **Grav**itational **W**aves
NMSSM	**N**ext-to-**M**inimal **S**upersymmetric **S**tandard **M**odel
PBH	**P**rimordial **B**lack **H**ole
PISC	**P**eak **I**ntegrated **S**ensitivity **C**urve
PLI	**P**ower-**L**aw **I**ntegrated
PPTA	**P**arkes **P**ulsar **T**iming **A**rray
PTA	**P**ulsar **T**iming **A**rray
QCD	**Q**uantum **C**hromo**d**ynamics
QFT	**Q**uantum **F**ield **T**heory
RGE	**R**enormalization **G**roup **E**quation
RHN	**R**ight **H**anded **N**eutrino
SD	**S**pin **D**ependent
SFOPT	**S**trong **F**irst **O**rder **P**hase **T**ransition
SFOEWPT	**S**trong **F**irst **O**rder **E**lectro**w**eak **P**hase **T**ransition
SI	**S**pin **I**ndependent
SKA	**S**quare **K**ilometre **A**rray
SM	**S**tandard **M**odel
SNR	**S**ignal-to-**N**oise **R**atio
SSB	**S**pontaneous **S**ymmetry **B**reaking

SUSY	**S**uper**s**ymmetry
UV	**U**ltra**v**iolet
VEV	**V**acuum **E**xpectation **V**alue
WIMP	**W**eakly **I**nteracting **M**assive **P**article
WMAP	**W**ilkinson **M**icrowave **A**nisotropy **P**robe
XENON1T	**X**ENON **1T**on