Pankaj Borah

Postdoktor i evolutionen av primordiala magnetfält

Ref nr: SU FV-4638-25-18

Datum för ansökan: 2026-01-16 20:14

Födelsedatum	1997-01-05
E-post	pankajborah316@gmail.com
Kön	Man

Frågor

1. *Nuvarande sysselsättning (ange huvudsaklig sysselsättning)*
Annat

2. *Högsta examen*
Doktors-/licentiatsexamen

3. *Från vilket land har du din högsta examen?*
Indien

4. *Har du din högsta examen från Stockholms universitet?*
Nej

5. *Ange datum när du tog din doktorsexamen*
2025-08-02

6. *NUVARANDE ANSTÄLLNING. Ange arbetsplats och jobbtitel samt när anställningen påbörjades..*
Current institution: Indian Institute of Technology Delhi
Job title: Short-term early-doc project researcher

7. *REFERENSER. Ange namn, telefon och e-post för 2–3 referenspersoner som kan komma att kontaktas.*
1. Dr. Pradipta Ghosh
Email: tphyspg@physics.iitd.ac.in
2. Prof. Sourov Roy
Email: tpsr@iacs.res.in
3. Dr. Baradhwaj Coleppa
Email: baradhwaj@iitgn.ac.in

8. *SPRÅKKUNSKAPER. Beskriv kort dina språkkunskaper.*
Native speaking/writing language: Assamese,
Fluent speaking/writing language: English, Hindi, Bengali

9. *FORSKNINGSPLAN/PROJEKTPLAN. Bifoga din plan som beskriver det tilltänkta projektet.*
Res_Statement_Pankaj_Borah_Nordita.pdf

10. *DOKTORSEXAMEN ELLER MOTSVARANDE. Ange doktorsexamen med ämne och lärosäte.*
Thesis title: Cosmic Phase Transitions and Gravitational Waves: a quest for physics beyond the Standard Electroweak Model
Field of Study: Physics Beyond the Standard Model, Particle Cosmology
Place: Department of Physics, Indian Institute of Technology Delhi, Hauz Khas-110016, New Delhi, India

11. *EXAMENSBEVIS ELLER MOTSVARANDE. Bifoga examensbevis.*
PhD_degree_certificate_Pankaj_Borah.pdf

Pankaj Borah

Postdoktor i evolutionen av primordiala magnetfält

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Datum för ansökan: 2026-01-16 20:14

Eget uppladdat CV

Pankaj Borah, PhD
Indian Institute of Technology Delhi
Hauz Khas, New Delhi-110016, India

+91 7896093377
pankaj.borah@physics.iitd.ac.in
inspireHEP

To,
The Nordic Institute for Theoretical Physics,
Hannes Alfvéns väg 12,
SE-106 91 Stockholm, Sweden

Dear Members of the Selection Committee,

I am writing to express my strong interest in a postdoctoral research position at Nordita, the Nordic Institute for Theoretical Physics. I recently completed my Ph.D. in Theoretical High Energy Physics at the Indian Institute of Technology Delhi (2019–2025) under the supervision of Dr. Pradipta Ghosh. My doctoral research, "*Cosmic Phase Transitions and Gravitational Waves: a quest for physics beyond the Standard Electroweak Model*", focused on the dynamics of cosmic phase transitions, their implication for electroweak baryogenesis, stochastic gravitational wave (GW) signals, and dark matter (DM) phenomenology.

My research lies at the intersection of particle physics phenomenology and early Universe cosmology. In my doctoral work, I investigated supersymmetric and non-supersymmetric extensions of the Standard Model, mapping their thermal histories using both gauge-dependent and independent effective potential treatments to investigate strong first-order phase transitions (FOPT) and associated cosmic signatures. In parallel, I explored multi-component WIMP DM scenarios with distinctive thermal histories that yield correlated signatures across cosmology and terrestrial experimental frontiers. A central aim of my work is to bridge the features of beyond the Standard Model theories with observable signatures, with emphasis on GW spectra testable at various ongoing or upcoming observatories, together with complementary probes from DM searches and collider experiments.

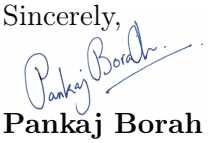
Through my research, I have developed a broad methodological expertise that integrates analytical techniques with computational and numerical approaches, enabling me to address problems that span from model construction to phenomenological predictions. This versatility has resulted in publications in peer-reviewed journals and presentations at national and international conferences, enhancing the visibility of my work and fostering collaborative connections across the community. My achievements have been recognized with competitive travel fellowships and awards during my Ph.D tenure. I also value research mentorship and have supported undergraduate and master's students in developing theoretical and computational skills.

Looking ahead, I plan to explore precision thermodynamics of cosmic PTs within well-motivated BSM frameworks, with the goal of reducing theoretical uncertainties and achieving reliable predictions for GW signals. Building on these precision PT studies, I plan to investigate how magnetogenesis during strong FOPTs can be embedded within a unified cosmological evolution, allowing magnetic observables and GW signatures to be traced back to the same underlying microphysics. This direction is closely aligned with the goals of COSMOMAG, where connecting early-Universe field generation to present-day observables is central. In parallel, I am interested in exploring how these PT dynamics intersect with broader questions in early-Universe cosmology, including dark-sector physics, axion and axion-like particle scenarios, and their phenomenological implications across cosmological, astrophysical, and terrestrial probes.

My research interests align closely with the wide-ranging scientific program of the Nordic Institute for Theoretical Physics, especially in BSM physics, phase transitions, GWs, cosmological magnetic fields, inflationary dynamics, and other aspects of early Universe cosmology. Nordita's collaborative culture spanning theoretical physics, astroparticle physics, and its close connections to experimental observations provides an exceptional environment for pursuing the ambitious research program I have outlined.

I am very enthusiastic about the opportunity to join Nordita as a postdoctoral fellow, where I would contribute to a vibrant research program while further developing my expertise. My training has prepared me to work independently and in collaboration, and I am confident in my ability to contribute meaningfully while pursuing innovative directions of my own. Thank you for considering my application.

Sincerely,



Pankaj Borah

Pankaj Borah

E-mail: pankaj.borah@physics.iitd.ac.in, pankajborah316@gmail.com

Profile link: inSPIRE-HEP

Nationality: Indian resident individual

Gender: Male; Marital Status: Single

Office: MS-516, 4th floor, Main Building, Department of Physics, Indian Institute of Technology Delhi, Hauz Khas, New Delhi-110016, India

Employment History

July 2025–Oct 2025 **IRD Early-Doc Fellow**, HEP theory and phenomenology group,
Dept. of Physics, Indian Institute of Technology Delhi
- Mentor: Dr. Pradipta Ghosh

Previous Research Experience

July 2019–July 2025 **Ph.D. Research Scholar**, HEP theory and phenomenology group,
Dept. of Physics, Indian Institute of Technology Delhi
- Thesis: *Cosmic Phase Transitions and Gravitational Waves: a quest for physics beyond the Standard Electroweak Model* (submitted May 2025, defended July 2025)
- Supervisor: Dr. Pradipta Ghosh

Aug 2018–May 2019 **M.Sc. Dissertation**, HEP theory and phenomenology group,
Dept. of Physics, Indian Institute of Technology Gandhinagar
- Thesis: *Baryogenesis at Electroweak Phase Transition and Warped Extra Dimension*
- Advisor: Dr. Baradhwaj Coleppa

May 2018–July 2018 **Summer Research Trainee**, Visiting Summer Research Program,
Theory division, Institute of Physics, Bhubaneswar, Odisha
- Project: *An introduction to Supersymmetry*
- Advisor: Dr. Manimala Mitra

Jan 2018–Apr 2018 **Short term semester project**,
Dept. of Physics, Indian Institute of Technology Gandhinagar
- Project: *Supersymmetric Quantum Mechanics*
- Advisor: Dr. Baradhwaj Coleppa

Education

July 2019–July 2025 **Ph.D.** in Theoretical High Energy Physics,
Dept. of Physics, Indian Institute of Technology Delhi
- Course work CGPA: *9.25/10*

July 2017–May 2019 **M.Sc.** in Physics,
Dept. of Physics, Indian Institute of Technology Gandhinagar
- CGPA: *8.31/10*

July 2014–May 2017 **B.Sc. (Honours)** in Physics,
Dept. of Physics, Cotton University
- CGPA: *8.72/10*

Research Interests

My research interest lies at the intersection of theoretical particle physics and cosmology. Broadly, it can be categorized with a special focus on the following topics:

Cosmic Frontier

- Origin of matter-antimatter asymmetry via Electroweak Baryogenesis
- Dynamics of Strong First-order Phase Transition in the early Universe
- Gravitational wave signals sourced from Phase Transitions, Primordial Black Holes, Magnetogenesis, Cosmic strings, etc.
- Dark sector models and dark matter (two-component WIMP, Axion-like Particle (ALP), FIMP)

Theory Frontier

- R-symmetric and R-violating Supersymmetry
- Non-supersymmetric scalar sector extensions of the Standard Model

Energy Frontier

- New Physics searches at hadron and lepton colliders

Scientific Research Skills

Theoretical

Experienced with

- Thermal field theory, (Dimensionally reduced) effective field theories, Quantum field theory, Higher-order loop calculations, Computer algebra techniques and symbolic manipulation, General relativity, Cosmology

Technical

Programming Languages

- Core expertise : Python, Mathematica
  Intermediate level : C/C++, Julia
  Basic level : Bash shell script, FORTRAN

Operating systems

- Linux (Ubuntu, CentOS), Windows

Software packages and libraries

- Model implementations: SARAH, Feynrules
- Spectrum generators: SPheno, NMSSMTools
- Phase Transitions: CosmoTransitions, BSMPT, PhaseTracer, DRalgo
- Dark matter observables: micrOMEGAs
- Higgs sector analysis tools: HiggsTools, HiggsBounds, HiggsSignals, Lilith
- Event generators: CalcHEP, MadGraph
- Document preparation software: LaTex (TexStudio), LibreOffice
- Other packages/libraries/expertise: MultiNest, ROOT, Numpy, Scipy, Pandas, Scikit-learn, TensorFlow, multiprocessing and multithreading with MPI

Research Articles

Journal Publications

1. **P. Borah**, P. Ghosh and A. K. Saha, *Prospecting bipartite dark matter through gravitational waves*, JCAP **05** (2025) 035 , [2412.17141]
2. **P. Borah**, P. Ghosh, S. Roy and A. K. Saha, *Electroweak phase transition in a right-handed neutrino superfield extended NMSSM*, JHEP **08** (2023) 029 , [2301.05061]

Preprints

1. **P. Borah** and P. Ghosh, *Unveiling the inert Triplet desert region with a pNGB Dark Matter and its Gravitational*

Wave signatures, [2505.16521] (under communication to JHEP)

Conference Proceedings

1. **P. Borah**, P. Ghosh, S. Roy and A. K. Saha, *Electroweak Phase Transition and Gravitational Waves in an Extended Supersymmetric Model*, Springer Proc. Phys. **304** (2024) 226-229
2. **P. Borah**, *Complementarity of a two-component Dark Matter Model with Gravitational Waves at LISA*, Springer Proc. Phys. **322** (2025) 221-225

In Preparations

1. **P. Borah**, P. S. Bhupal Dev and A. Ghoshal, *Primordial Magnetogenesis and Gravitational Waves from an ALP-assisted Supercooled Phase Transition*, (in preparation)

Fellowships, Awards and Honours

- Research Excellence Travel Award (RETA) for presenting work in a Conference outside the Country (2025)
- Research Scholar Travel Award (RSTA) for presenting work in a Conference outside the Country (2024)
- Research Fellowship by MHRD, India for pursuing Ph.D. at IIT Delhi (2019-2024)
- Secured 3rd position in M.Sc. Physics (2019)
- Academic excellence and MCM award in M.Sc. (2018-2019)
- Achieved 3rd rank in B.Sc. Physics (Honours) and 4th rank overall in B.Sc. Physics (2017)
- Awarded with DST-INSPIRE scholarship, DAE, Govt. of India, in master's and bachelor's for consistent good academic performance throughout (2014-2019)
- AHSEC one-time merit scholarship for higher education from the Govt. of Assam (2014)

Teaching and Mentoring Experience

Sem. Term Project — **Project Mentor** – *B.Tech. and M.Sc. student research projects*, Co-supervised undergraduate and master's students in term projects, Indian Institute of Technology Delhi (*Mentor: Dr. Pradipta Ghosh*), *Period: 2022-2025*

- Projects mentored: *Some Aspects of BSM Physics through Dark Matter (2024-2025)*, *Photon Fusion at Colliders (2022-2023)*, *Testing non-minimal SUSY models at colliders (2022-2023)*, *Gravitational wave in a BSM scenario (2022)*

Theory Course — **Teaching Assistant** – *Quantum mechanics*, Designed for 1st year B.Tech students of Dept. of Physics, Indian Institute of Technology Delhi, *Period: 2020–2021 (Sem II) and 2019–2020 (Sem I)*

Lab. Course — **Teaching Assistant** – *B. Tech. Physics (Electrical) Laboratory course*, Designed for overall B.Tech 1st year students, Indian Institute of Technology Delhi, *Period: 2022–2023 (Sem I & II), 2021–2022 (Sem I & II) and 2020–2021 (Sem I)*

Conferences and Scientific Presentations

Selected and not limited to...

Oct 2024 — 17th International Conference on Interconnections between Particle Physics and Cosmology (PPC-2024) at Indian Institute of Technology Hyderabad, Telangana, India

- **Talk:** *"Complementary probe of two-component Dark Matter and Gravitational waves in a scalar Singlet-Triplet extended model with a Dirac Fermion"*

Mar 2024 The Future of Fundamental Composite Dynamics: Colliders, Cosmology and Tools (FFCD2024) at Mainz Institute for Theoretical Physics (MITP), Johannes Gutenberg University Mainz, Germany

- **Talk:** *"Gravitational Waves from Electroweak Phase Transition"*

Dec 2023 PHOENIX-2023 at Indian Institute of Technology Hyderabad, India

- **Talk:** *"Complementary Probe of Beyond the Standard Model Physics with Gravitational Waves from Electroweak Phase Transitions"*

July 2023 30th International Conference on Supersymmetry and Unification of Fundamental Interactions (SUSY-2023) at the University of Southampton, United Kingdom

- **Talk:** *"Electroweak Phase Transition and Prospects of Detecting Gravitational Waves in an Extended Supersymmetric Model"*

Feb 2023 International Meeting on High Energy Physics (IMHEP-II) at Institute of Physics (IoP), Bhubaneswar, India

- **Talk:** *"Strong First-order Phase Transitions and prospects of detecting Gravitational Waves in an Extended Supersymmetric Model"*

Dec 2022 XXV DAE-BRNS High Energy Physics Symposium at IISER Mohali, India

- **Talk:** *"Electroweak Phase Transition and Gravitational waves in an Extended Supersymmetric model"*

Selected Workshops and Schools

July 2024 Machine Learning for Particle and Astroparticle Physics (ML4HEP-2024) at Institute of Physics, Bhubaneswar, Odisha, India

Mar 2024 The Future of Fundamental Composite Dynamics: Colliders, Cosmology and Tools (FFCD2024) at Mainz Institute for Theoretical Physics (MITP), Johannes Gutenberg University Mainz, Germany

July 2023 pre-SUSY 2023: School on Supersymmetry and Unification of Fundamental forces at the University of Southampton, United Kingdom

Sep 2022 pyHEP Workshop by HEP Software Foundation (HSF) at CERN (*online*)

Aug 2022 Data and Machine Learning at the Large Hadron Collider (DML @ LHC-2022) at Indian Institute of Technology Hyderabad, Telangana, India

May 2022 ICTP Summer School on Particle Physics (smr 3560) at International Center for Theoretical Physics, Italy (*online*)

July 2021 Gravitational Wave Probes of Physics Beyond Standard Model at CERN (*online*)

Outreach activities

Presenting science to popular audience...

Nov 2023 Presented a poster on *The Quest for Physics Beyond the Standard Model through Gravitational Waves*, for high-school audience at the Open House, Indian Institute of Technology Delhi, India

Languages Known

Languages Assamese (native), English (fluent), Hindi (fluent), Bengali (intermediate)

Research Statement

Pankaj Borah

Email: Pankaj.Borah@physics.iitd.ac.in, pankajborah316@gmail.com

Overview

The intersection of particle physics and cosmology provides a unique opportunity to address fundamental questions about the origin and evolution of the Universe. The early Universe provides a natural high-energy probe of physics beyond the Standard Model (BSM), where microscopic particle interactions leave macroscopic signatures on cosmological and astrophysical observables. Theoretical developments in particle physics, cosmology, and gravitational wave (GW) science have revealed deep connections between the origin of baryon asymmetry (BAU), dark matter (DM), inflationary dynamics, cosmic phase transitions (PTs), and their relation with collider-scale physics. Understanding these interlinked phenomena offers a compelling path toward uncovering the structure of new physics.

My research lies at this intersection of particle physics and early Universe cosmology, with a focus on uncovering BSM physics through complementary probes across multiple frontiers. My current work includes developing theoretical frameworks that extend the scalar sector or symmetry structure of the Standard Model (SM) to achieve viable strong first-order phase transitions (SFOPTs), successful baryogenesis, realistic DM phenomenology, and observable GW signals. These frameworks establish testable connections across multiple experimental fronts, including present and upcoming collider programs, DM searches, and GW observatories.

More specifically, I am interested in the rich interplay between particle phenomenology and early Universe cosmology, where diverse theoretical ideas can be connected to observational and experimental tests through their complementary roles.

Past and Current Research

Below is a summary of the main research directions pursued during my doctoral work:

(1) Dynamics of Electroweak Phase Transitions

The absence of a strong first-order EWPT in the SM motivates extensions beyond the SM with enlarged scalar sectors or inclusion of new symmetries. I explored such possibilities in both supersymmetric and non-supersymmetric settings. In particular, I studied a spontaneously broken R-symmetric non-minimal supersymmetric model by extending the $\mathbb{Z}_3$-NMSSM with a right-handed (RH) neutrino superfield [1]. The extended Higgs and RH-sneutrino sectors in this setup permit rich thermal histories, including multistep PTs, and remain compatible with neutrino physics under certain assumptions. In parallel, I explored non-supersymmetric scalar sector extensions of the SM, extending with inert triplets and singlets [2, 3]. These models demonstrate that the same interactions driving SFOPTs also control relic density and collider observables, making the scalar potential a common origin for both early Universe dynamics and laboratory signatures. Across these models, I

- Employed analytical and numerical methods to construct the one-loop finite-temperature effective potential in both gauge-dependent and gauge-independent formulations.
- Worked within both the $\overline{\text{MS}}$ and on-shell renormalization schemes, and implemented Daisy resummation using both the Arnold-Espinosa and Parwani prescriptions.
- Traced the vacuum evolution both at the level of nucleation and percolation.
- Analysed vacuum upliftment and barrier formation at finite and zero temperatures – features that shape the structure and strength of SFOPTs.

These contributions identify consistent and testable BSM frameworks that account for the origin of BAU and electroweak symmetry breaking (EWSB), while shaping the early Universe dynamics with observable implications across multiple experimental frontiers.

(2) Gravitational Waves from Cosmic Phase Transitions

The potential to detect GWs from SFOPTs offer an extraordinary observational probe of high-scale physics. Within the models mentioned above [1–3], I determined key thermodynamic inputs for GW

estimation, including transition strength, inverse duration, and related quantities. I employed both conventional power-law integrated curves (PLIs) and novel updated peak-integrated sensitivity curves (PISCs) methods, assessing detectability at LISA, DECIGO, BBO, and other space-based experiments. By correlating these signals with underlying model parameters, I demonstrated their non-trivial impact on PT dynamics and GW features, providing concrete benchmarks that bridge theoretical modelling to upcoming GW observations.

(3) Dark Matter Phenomenology and Early Universe Thermal Histories

The elusive nature of DM, coupled with increasingly stringent bounds from direct detection limits, motivates richer frameworks beyond the single-component WIMP paradigm. Guided by cosmological and phenomenological considerations, I investigated multi-component WIMP DM scenarios, focusing on how thermal freeze-out is often tied to scalar potentials that drive SFOPTs.

In [2], we proposed a two-component DM model by extending the inert scalar triplet setup with a singlet fermion, each stabilized by a distinct $\mathbb{Z}_2$ symmetry. A real scalar singlet was introduced to mediate interactions between the fermionic DM and the SM, which actively participates in the PT dynamics. This framework simultaneously accounts DM relic abundance, SFOPTs, and predicts detectable GW signals—overcoming tensions that typically constrain comparable BSM scenarios within consistent parameter regions.

In another work [3], we incorporated a pseudo-Nambu-Goldstone boson (pNGB) as a DM candidate within the inert scalar triplet extension. The pNGB nature suppresses direct detection constraints while maintaining a successful freeze-out and strong PT. By linking softly broken global symmetries to thermal dynamics, this work provided a novel cosmologically motivated scenario for generating observable GWs alongside a viable DM phenomenology.

Together, these studies [2, 3] reveal how symmetry structure, thermal history, and DM interactions can yield correlated signals across GW experiments, colliders, and DM searches, revealing new parameter regions—long considered "desert"—that become cosmologically and experimentally relevant.

Future Research Plans

My future research directions aim to deepen and broaden the theoretical foundations of early Universe dynamics, with an emphasis on building predictive models that can be tested across complementary experimental frontiers. Many of these directions align closely with the research programs of Nordita, the Nordic Institute for Theoretical Physics. Below, I outline my key future directions, organized by thematic emphasis.

(1) Advancing Cosmological First-Order Phase Transition Study

A central goal is to improve the theoretical treatment of cosmological PTs in a self-consistent way for robust predictability. This effort integrates several interrelated components. Including,

(a) Precision Studies of Phase Transition Dynamics

Current predictions for PT dynamics often rely on leading-order one-loop analyses and are limited by uncontrolled gauge dependence, poor convergence in the infrared regime, and strong renormalization scale dependence. These lead to theoretical uncertainties, making GW predictions unreliable. To address these, I aim to employ a dimensionally reduced three-dimensional (3D) EFT approach with proper thermal resummation, extend the analysis beyond the one-loop level, and benchmark well-motivated BSM scenarios. This strategy will enhance theoretical control and improve the reliability of GW and baryogenesis calculations, complementing the ongoing efforts in the field.

(b) Bubble Wall Dynamics and realistic Hydrodynamic Treatments

The dynamics of expanding bubbles crucially influence both EW baryogenesis and GW generation. The common assumption of ultra-relativistic wall motion ($v_w \sim 1$) often simplify analyses but need not reflect the true hydrodynamic regime of a given model. I plan to implement realistic hydrodynamic treatments of bubble-wall propagation in concrete BSM frameworks, beginning with local thermal equilibrium (LTE) approximations and extending to non-equilibrium transport descriptions, using tools such as `WallGo` (A. Ekstedt et. al., *JHEP* **04** (2025) 101). Such efforts will complement ongoing

developments in the field and contribute to a more reliable understanding of wall velocities, energy partition, and the interplay between baryogenesis efficiency and GW signal strength.

(c) Baryon Asymmetry and Non-Equilibrium Dynamics

Estimating baryon asymmetry in concrete BSM frameworks is another important direction of my future plan. Starting with the semi-classical force approach, I aim to derive and solve the relevant transport equations in the presence of spacetime varying Higgs profiles. This will involve incorporating model-specific CP-violating sources and solving the coupled diffusion equations for various particle species. Building on this foundation, I aim to extend the analysis using non-equilibrium QFT techniques such Kadanoff–Baym equations, thereby connecting PT studies more directly to quantitative predictions of the observed BAU.

(2) Primordial Magnetogenesis and FOPTs

Observations of γ-ray blazars point to intergalactic magnetic fields that are coherent on cosmological scales and may be primordial in origin. SFOPTs in BSM scenarios provide a particularly compelling framework for their generation, as they naturally combine violent out-of-equilibrium dynamics, bulk plasma motions, and, in many cases, sources of parity violation. An important aspect of these scenarios is that the same dynamics responsible for magnetogenesis also source stochastic GWs, opening a multi-messenger window into early-Universe physics.

Building on my ongoing work [4] on magnetogenesis in axion-like-particle (ALP)–assisted supercooled PTs, where axion dynamics enhance non-equilibrium effects and can imprint correlated GW and magnetic signatures, I aim to develop a predictive description of magnetic field generation during cosmic PTs. A central element of this program is the use of precision PT calculations to determine nucleation, supercooling, and bubble-wall dynamics, thereby fixing the relevant transition parameters in a more theoretically robust way. This allows magnetogenesis to be placed on the same quantitative footing as reliable GW estimation, by deriving the initial magnetic field spectra directly from the underlying PT dynamics, including bubble expansion, and plasma flows. This approach allows crucial magnetic observables—such as field strength, coherence length, spectral shape, and helicity—to be traced back unambiguously to well-defined microphysical inputs like the transition strength, duration, and wall velocity.

Within the COSMOMAG programme, I aim to extend these studies to a broader class of EW-scale PTs, providing physically motivated initial conditions for numerical magnetohydrodynamic simulations of magnetic field evolution. This will enable controlled studies of magnetic field decay, inverse-cascade behaviour, and the conditions under which large-scale fields can survive until recombination. By embedding magnetogenesis from SFOPT within a continuous evolutionary framework, and by correlating magnetic observables with GW signatures sourced by the same early-Universe dynamics, this research direction aims to sharpen the connection between particle physics models of the early Universe and present-day astrophysical observations.

(3) Linking Precision PT Studies to Inflationary Dynamics and Dark Sectors

Inflation and cosmological PTs can be intrinsically linked through the dynamics of a common scalar sector in the early Universe. In particular, models in which the inflaton or an associated scalar field undergoes a FOPT naturally link inflationary dynamics to the production of stochastic GWs. In such frameworks, inflation sets the relevant energy scales and initial conditions, while the subsequent FOPT generates a peaked GW signal whose spectral properties retain information about both the inflationary background and the transition dynamics. This provides a novel and complementary probe of inflation beyond conventional CMB observables.

Dark-sector realizations of inflation, such as scenarios involving a dark Higgs or broken dark gauge symmetries, offer particularly well-motivated examples of this connection. These models can simultaneously support successful slow-roll inflation and a strong FOPT at lower scales, leading to potentially observable GW signals across a wide frequency rangewhile naturally embedding inflation within a broader BSM context connected to hidden sectors, feebly coupled states, and DM candidates. However, many existing analyses rely on simplified PT treatments or benchmark GW templates, limiting the robustness with which inflationary dynamics and dark-sector microphysics can be inferred from

GW observations.

I aim to address this gap by applying precision PT treatments to inflationary and post-inflationary settings, enabling consistent GW predictions that incorporate both inflationary backgrounds and detailed FOPT dynamics. By systematically exploring how the strength, timing, and completion of the transition depend on inflationary parameters and dark-sector couplings, I will investigate how characteristic spectral features can be used to disentangle inflationary FOPTs from more conventional GW sources.

(4) Beyond the WIMP Paradigm: FIMP, Axions, and PBHs

I plan to continue exploring single or multi-component DM scenarios while broadening my DM studies to encompass other possibilities, such as axion/axion-like particle (ALP) candidates and WIMP–FIMP hybrid scenarios, and examine their interplay with FOPTs and GW production. In particular, it is interesting to study scenarios with ALPs whose masses and interactions are dynamically reshaped across a FOPT, potentially altering their relic abundance and imprint correlated features in GW spectrum, offering a unified and highly testable ALP cosmology. Another promising avenue is to explore how slow or fast PTs can simultaneously enhance GW production and seed PBHs, leaving characteristic distortions in the GW spectrum. Recent advances in GW spectral discriminants, which exploit the morphology of multi-peak signals rather than their signal-to-noise alone, indicate that such mixed GW backgrounds can be disentangled in forthcoming experiments. Leveraging these methods alongside precision PT treatments will allow me to establish robust, multi-messenger correlations among various cosmic relics, such as GW signatures, PBH abundances—thereby opening new avenues to test cosmic PTs, axion physics, and high-scale BSM physics beyond the reach of colliders.

Outlook

The overarching goal of my research is to bridge fundamental theory with experimental frontiers. By investigating particle physics beyond the SM in cosmological settings, I strive to develop predictive and conceptually coherent frameworks for BSM physics. Future GW observatories along with the DM experiments, collider upgrades like the HL-LHC, future muon collider experiments, etc., will test these ideas across complementary frontiers.

The Nordic Institute for Theoretical Physics offers a unique and intellectually vibrant environment for advancing these research directions. Its broad expertise—spanning a wide range of topics in particle physics and cosmology—creates unique opportunities for meaningful interdisciplinary collaboration. I am especially enthusiastic about the prospect of interacting with its esteemed research groups, in particular their research interests in BSM physics, phase transitions, GWs, cosmological magnetic fields, inflationary dynamics, and other aspects of early Universe cosmology overlap strongly with my own. The opportunity to work alongside world-leading experts in such environment is particularly motivating. I am also drawn to its collaborative culture, its deep connection to experimental programs, and its commitment to advancing theory across multiple frontiers. I sincerely value its culture of inclusivity, interdisciplinary exchange, and scientific openness—qualities that I see as essential for creativity and meaningful progress in science. In this spirit, I look forward to contributing to this stimulating environment by engaging in research that bridges fundamental ideas with experimentally testable phenomena.

References

[1] P. Borah, P. Ghosh, S. Roy and A. K. Saha, *Electroweak phase transition in a right-handed neutrino superfield extended NMSSM*, *JHEP* **08** (2023) 029 [2301.05061].

[2] P. Borah, P. Ghosh and A. K. Saha, *Prospecting bipartite dark matter through gravitational waves*, *JCAP* **05** (2025) 035 [2412.17141].

[3] P. Borah and P. Ghosh, *Unveiling the inert Triplet desert region with a pNGB Dark Matter and its Gravitational Wave signatures*, 2505.16521.

[4] P. Borah, P. S. Bhupal Dev and A. Ghoshal, *Primordial Magnetogenesis and Gravitational Waves from an ALP-assisted Supercooled Phase Transition*, in-preparation.

प्रविष्टि संख्या/Entry No. 2019PHZ8029

भारतीय प्रौद्योगिकी संस्थान दिल्ली

अभिषद की अनुशंसा पर

विद्या वाचस्पति

की उपाधि

पंकज बोरा

को प्रदान करता है।

आपने इस उपाधि के अर्जन हेतु विनियम विहित निर्धारित अपेक्षाओं को जुलाई 2025 में सफलतापूर्वक पूर्ण किया है।

शोध-प्रबन्ध शीर्षक : **कॉस्मिक फेज़ ट्रांज़ीशन्स एंड ग्रैविटेशनल वेव्स: ए क्वेस्ट फॉर फिज़िक्स बियॉन्ड दि स्टैंडर्ड इलेक्ट्रोवीक मॉडल**

भारतीय गणराज्य में दिल्ली स्थित संस्थान की मुद्रा अंकित यह उपाधि आज दिनांक 2 अगस्त 2025 को प्रदान की गई।

Indian Institute of Technology Delhi

Upon the recommendation of the Senate hereby confers the degree of

Doctor of Philosophy

on

PANKAJ BORAH

who has successfully completed the requirements under the regulations for the award of this degree in July 2025.

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

Given this day, the 2nd of August 2025, under the seal of the Institute at Delhi in the Republic of India.

अध्यक्ष, अभिशासक परिषद
Chairperson, Board of Governors

अध्यक्ष, अभिषद एवं निदेशक
Chairperson, Senate & Director

कुलसचिव
Registrar

भारतीय प्रौद्योगिकी संस्थान दिल्ली
INDIAN INSTITUTE OF TECHNOLOGY DELHI