Progress Report for Project B07

Strong-interaction matter in the early Universe

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CRC-TR 211 Strong-interaction matter under extreme conditions

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What the Project Promised

(i) The cosmic trajectory in the QCD phase diagram

(ii) Cosmological studies of pion condensation in the early Universe

(iii) Dark Matter from the cosmic QCD epoch

(iv) Combined electroweak-QCD phase transition in the early Universe

(i) QCD cosmic trajectory: Goals

- Understand QCD cosmic trajectory at $\mu \neq 0$ in the early Universe
- Improve code by taking into account recent lattice studies from A08
- Employ chiral effective models, Schwinger-Dyson equations and functional renormalization group

(i) QCD cosmic trajectory: Timeline

2021 Include known perturbative QCD corrections at $\mu \neq 0$ into cosmic trajectory code
→ Done

2022 Update cosmic trajectory code with latest lattice-QCD data
→ In progress

2023 Include effects of pion condensate in cosmic-trajectory code
→ Done [PRL 126 (2021)]

2024 Include lattice-QCD data at finite chemical isospin in cosmic-trajectory code
→ Open

2025 Compare various effective models with lattice QCD-based results for the cosmic trajectory
→ In progress

(ii) Pion condensation: Goals

- Investigate pion-condensed phases in the early Universe
- Compute equation of state at large lepton chemical potential
- Study gravitational wave spectrum from pion condensation

(ii) Pion condensation: Timeline

2021 Set up equation of state for low- and high-temperature limit at non-zero lepton chemical potential
→ In progress (High-T)

2022 Study properties of the cosmological pion-condensed phase in chiral effective models
→ Done with modifications [MNRAS 521 (2023), PRD 105 (2022)]

2023 Implement pion-condensed phase from chiral effective models for primordial gravitational-wave signals
→ Done [PRL 126 (2021)]

2024 Calculate modification of primordial gravitational-wave spectrum using lattice-QCD input
→ Open

2025 Set up benchmarks for effects from cosmological QCD phase transition and lepton chemical potentials for BSM studies
→ Open

(iii) Dark matter: Goals

- Explore dark matter candidates in the light of the cosmic QCD transition

- Focus on axions, sterile neutrinos, and primordial black holes (PBHs)

(iii) Dark matter: Timeline

2021 Formation of axion miniclusters (AMC) from temperature fluctuations of strong-interaction plasma
→ Done, to be submitted

2022 Solve evolution equations for sterile-neutrino phase space densities at vanishing lepton asymmetries
→ Done, to be submitted

2023 Mass function of AMC; AMC observation as probe of post-inflationary axion dark matter scenario → Done, to be submitted (with 2021)
PBH mass function and its dependence on lepton-flavor asymmetry → Done [PRD 103 (2021)]

2024 Impact of pion-condensed phase on primordial black-hole spectrum
→ Done [PRL 126 (2021)]

2025 Compare AMC predictions to latest limits from gravitational lensing and other probes; Compare primordial black-hole mass spectra to observed black-hole mass spectra
→ Other probes: In progress, Lensing: Open

(iv) QCD-EW phase transition: Goals

- Understand supercooled QCD-electroweak phase transition in theories beyond the SM

- Study resulting gravitational wave (GW) background, dark matter production, baryon asymmetry

(iv) QCD-EW phase transition: Timeline

2021 Study nature and dynamics of supercooled QCD-electroweak transition in BSM scenarios → Done [PRD 104 (2021), PRD 107 (2023)]

2022 Explore how physics of Dark-Matter candidates depends on the QCD-electroweak transition → In progress

2023 Predict stochastic gravitational-wave spectrum generated by QCD-electroweak transition → Done [PRD 107 (2023)]

2024 Explore implications of supercooled QCD-electroweak transition for electroweak baryogenesis → Done, but hard to realize

2025 Study how large lepton-flavor asymmetries impact cosmic trajectory of the supercooled QCD-electroweak transition → Open

Additional Opportunities and Directions

(iv) QCD-EW phase transition:

- Study tachyonic preheating after QCD-EW PT: novel source of GWs
  $\rightarrow$ In progress
- Study classically scale-invariant $\mathrm{SU}(2)$ SM extension at strong coupling
  $\rightarrow$ In progress

Other related works:

- Impact of theoretical uncertainties on model parameter reconstruction from GW signals sourced by cosmological phase transitions
  $\rightarrow$ Done [arXiv:2403.03769]

B07: Outlook

(i) The cosmic trajectory in the QCD phase diagram: **On schedule**

(ii) Cosmological studies of pion condensation in the early Universe: **On schedule**

(iii) Dark Matter from the cosmic QCD epoch: **On schedule**

(iv) Combined electroweak-QCD phase transition: **On schedule**