Ground-state properties of finite nuclei with astrophysical interest in extreme magnetic fields, via covariant density functional theory

Ioannis Mavroudis, PhD candidate

School of Physics
Aristotle University of Thessaloniki

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Outline

1. Introduction and Motivation
2. Theoretical Framework
3. Results (Preliminary)
4. Summary
5. Collaborators and Acknowledgements
6. Selected References

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Astrophysical Laboratories: Magnetars & Explosive Transients

- **Extreme Magnetic Fields:** Magnetars host surface fields of $B \sim 10^{15}$ G. However, transient internal fields up to $B \sim 10^{17} - 10^{18}$ G can be generated dynamically in **Core-Collapse Supernovae (CCSNe)** and **Neutron Star Mergers (NSMs)**.
- **Explosive Nucleosynthesis:** These highly magnetized, extreme-density environments are the primary cosmic sites for rapid neutron (r-process) and rapid proton (rp-process) capture.

The Core Question

How do these extreme transient fields fundamentally change the structure of finite nuclei being synthesized in these stellar explosive environments?

Explosive Environments & Selected Nuclei

- So, understanding ground-state bulk properties, e.g., deformation, binding energy and radii, are critical for accurately modeling nucleosynthesis yields and reaction rates in explosive sites.

Selected Nuclei in this Study:

- $^{\mathbf{64}}_{\mathbf{32}}\mathrm{Ge}_{\mathbf{32}}$ (Type I X-ray Bursts): A key waiting-point nucleus in the rp-process on accreting neutron stars. $N = Z$ nucleus on rp-path, where further proton capture stalls, waiting β^+ decays to proceed.
- $^{\mathbf{130}}_{\mathbf{48}}\mathrm{Cd}_{\mathbf{82}}$ (CCSNe & NSMs): A classic neutron-rich waiting-point nucleus near the $N = 82$ shell closure. Neutron magic shell isotones $N = 50, 82, 126$, crucial for explaining peaks in the observed abundance distribution. Neutron capture is suppressed, waiting β^- decays to occur.

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Incorporating the External Magnetic Field

- To study finite nuclei in superstrong magnetic fields ($B \sim 10^{17}$ G), we define a uniform field along the z-axis: $\boldsymbol{B} = B\hat{z}$.

There are two primary theoretical frameworks to model this environment:

1. Non-Relativistic (Skyrme DFT)
   - Based on the derived Hamiltonian $\hat{h}_q$.
   - Magnetic coupling must be added explicitly.
2. Relativistic (CDFT)
   - Based on the Dirac equation and meson exchange (σ, ω, ρ).
   - Magnetic coupling arises *naturally*.

The Effective Lagrangian - Relativistic Framework I

- CDFT begins with an effective Lagrangian encompassing nucleons, meson fields (σ, ω, ρ), and the electromagnetic field:

$$\mathcal{L} = \mathcal{L}_N + \mathcal{L}_m + \mathcal{L}_{int} + \mathcal{L}_{BO} + \mathcal{L}_{BM} \tag{1}$$

where $\mathcal{L}_N$, the Lagrangian of the free nucleons, $\mathcal{L}_m$, the Lagrangian of the free mesons and EM field by p^+, $\mathcal{L}_{int}$, the Lagrangian to describe interactions.

- $\mathcal{L}_{int}$ differs on the selected parameter set. In this work, the **NL3*** and the **DD-ME2** are employed.
- Two new terms are introduced to couple the system with the external magnetic field:
  (D. Peña Arteaga *et al.*, *Phys. Rev. C* **84**, 045806 (2011))

The Effective Lagrangian - Relativistic Framework II

1. Proton Orbital Coupling (Landau Dynamics):

$$\mathcal{L}_{BO} = -e\bar{\psi}\gamma^{\mu}A_{\mu}^{(e)}\psi \tag{2}$$

the coupling of p^{+} orbital motion with the external magnetic field.

2. Intrinsic Dipole Magnetic Moment Coupling (Pauli Magnetism):

$$\mathcal{L}_{BM} = -\bar{\psi}\chi_{\tau_3}^{(e)}\psi \quad \text{where} \quad \chi_{\tau_3}^{(e)} = \kappa_{\tau_3}\mu_N\frac{1}{2}\sigma_{\mu\nu}F^{(e)\mu\nu} \tag{3}$$

the coupling of both p^{+} and n^{0} intrinsic dipole moments with the external magnetic field.
where $\sigma_{\mu\nu} = \frac{i}{2}[\gamma_{\mu}, \gamma_{\nu}]$, $\mu_N = \frac{e\hbar}{2m}$, $\kappa_n = \frac{g_n}{2}$, $\kappa_p = \frac{g_p}{2} - 1$, $g_n = -3.8263$, and $g_p = 5.5856$.

The Dirac Equation & Symmetry Breaking I

- Pairing correlations are neglected, so no additional term into the energy functional
- Minimizing the energy functional with respect to the density yields the stationary Dirac equation for the nucleons and Klein-Gordon equations for mesons:

$$\left[\boldsymbol{\alpha}\cdot(-i\nabla-\boldsymbol{V})+V_0+\beta(m+S)+\beta\chi^{(e)}_{\tau_3}\right]\psi_i=\epsilon_i\psi_i \tag{4}$$

S the scalar potential, V_μ the vector potential.

Physical Consequences of the Magnetic Field:

- **Loss of Spherical Symmetry:** The magnetic field breaks spherical symmetry for both the Dirac and Klein-Gordon equations, preserving only axial symmetry.

The Dirac Equation & Symmetry Breaking II

- **Time-Reversal Breaking:** The external field magnetic field breaks the time-reversal symmetry (T) in the intrinsic frame.
- **Kramers' Degeneracy Lifted:** Because T-symmetry is broken, the twofold degeneracy of states is removed. Solutions with positive and negative angular momentum projections ($\pm\Omega_i$) must be treated as completely separate states.

Nuclear Magnetism & Self-Consistency

The breaking of time-reversal symmetry profoundly alters the meson fields via the generation of spatial currents:

- **Induced Spatial Currents:** The ballistic dynamics of the nucleons generate non-vanishing spatial currents $(\boldsymbol{j}^p, \boldsymbol{j}^n)$.
- **Time-Odd Meson Fields:** These currents act as direct sources for the spacelike (time-odd) components of the vector mesons ($\boldsymbol{\omega}$ and $\boldsymbol{\rho}$), inducing a phenomenon known as **nuclear magnetism**.

$$(-\Delta + m_\omega^2)\boldsymbol{\omega} = g_\omega(\boldsymbol{j}^p + \boldsymbol{j}^n) \tag{5}$$

$$(-\Delta + m_\rho^2)\boldsymbol{\rho} = g_\rho(\boldsymbol{j}^p - \boldsymbol{j}^n) \tag{6}$$

The time-odd mean fields are governed by the exact same coupling constants (g_ω, g_ρ) as the time-even fields. The closed set of Dirac and Klein-Gordon equations is solved iteratively until the fully self-consistent solution converges.

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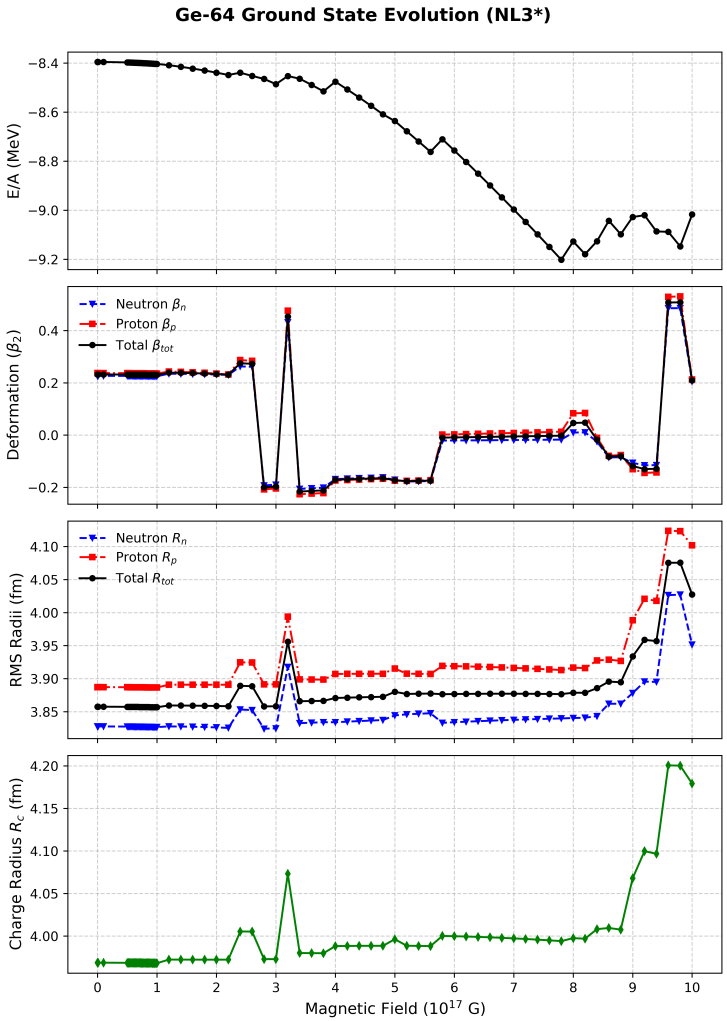
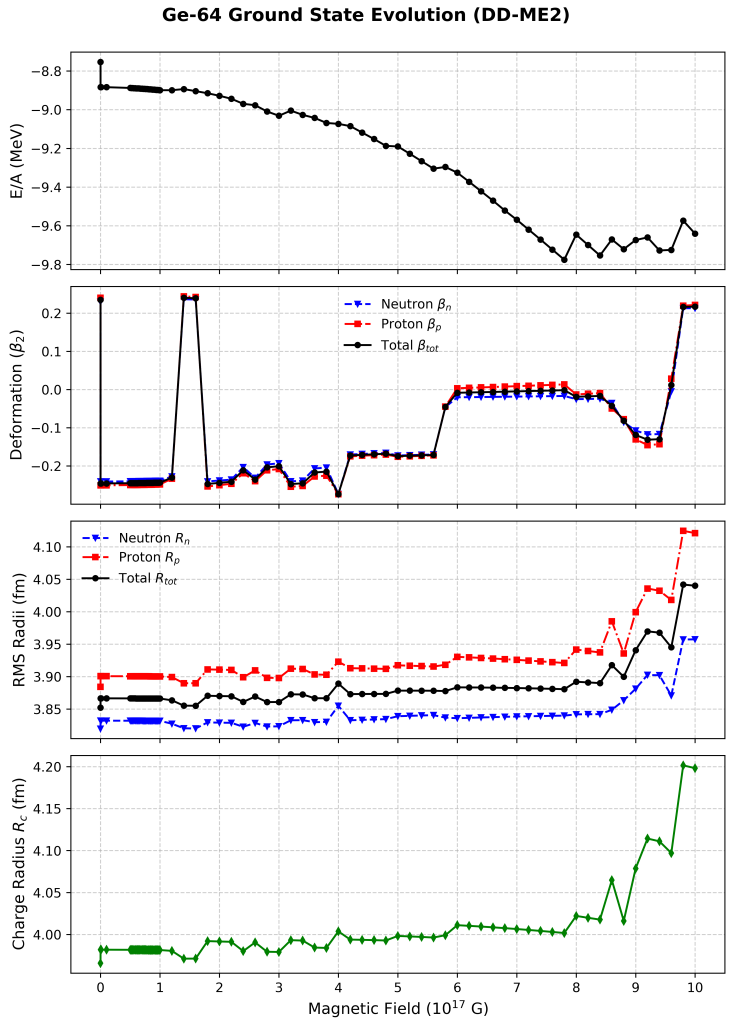
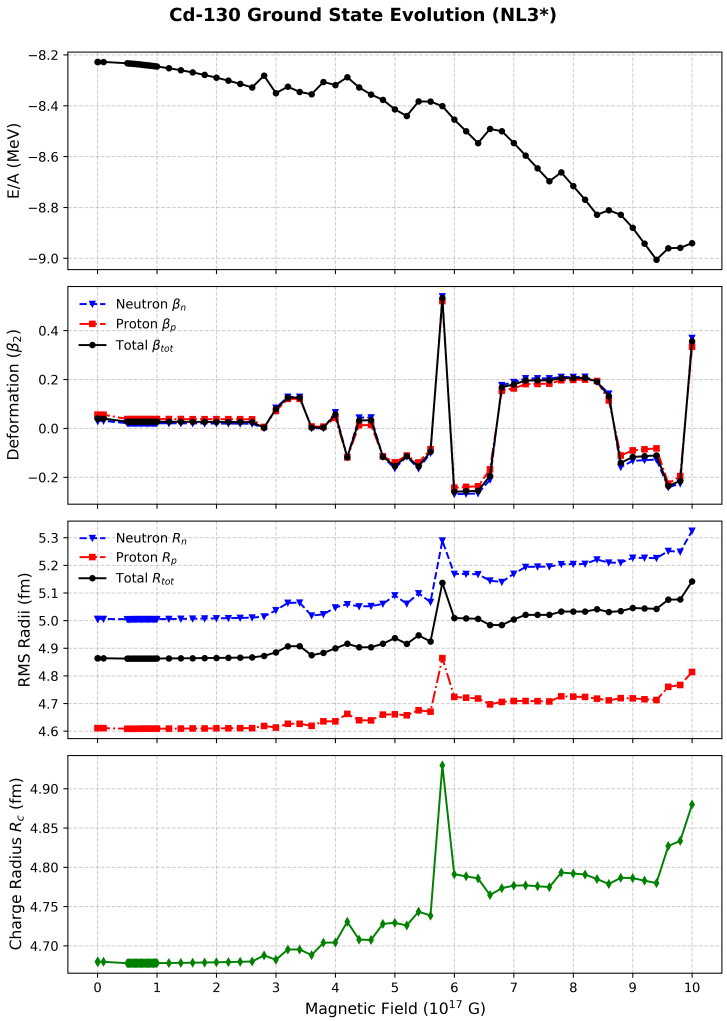
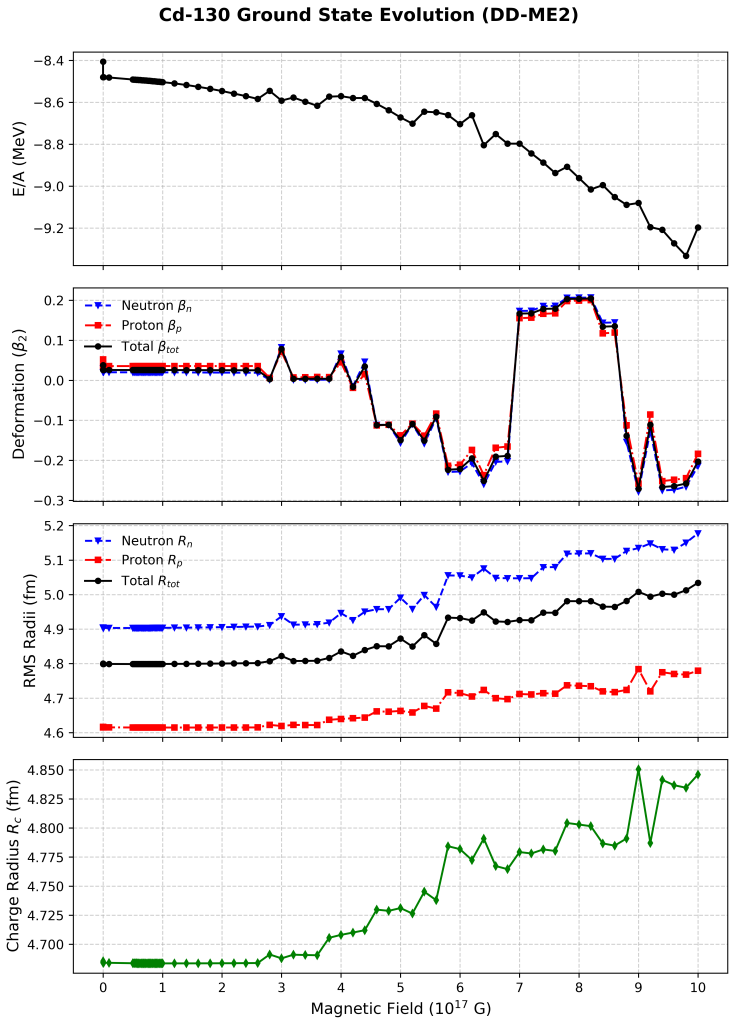
Bulk Properties (BE/A, β_2, $Radii$): ^{64}Ge



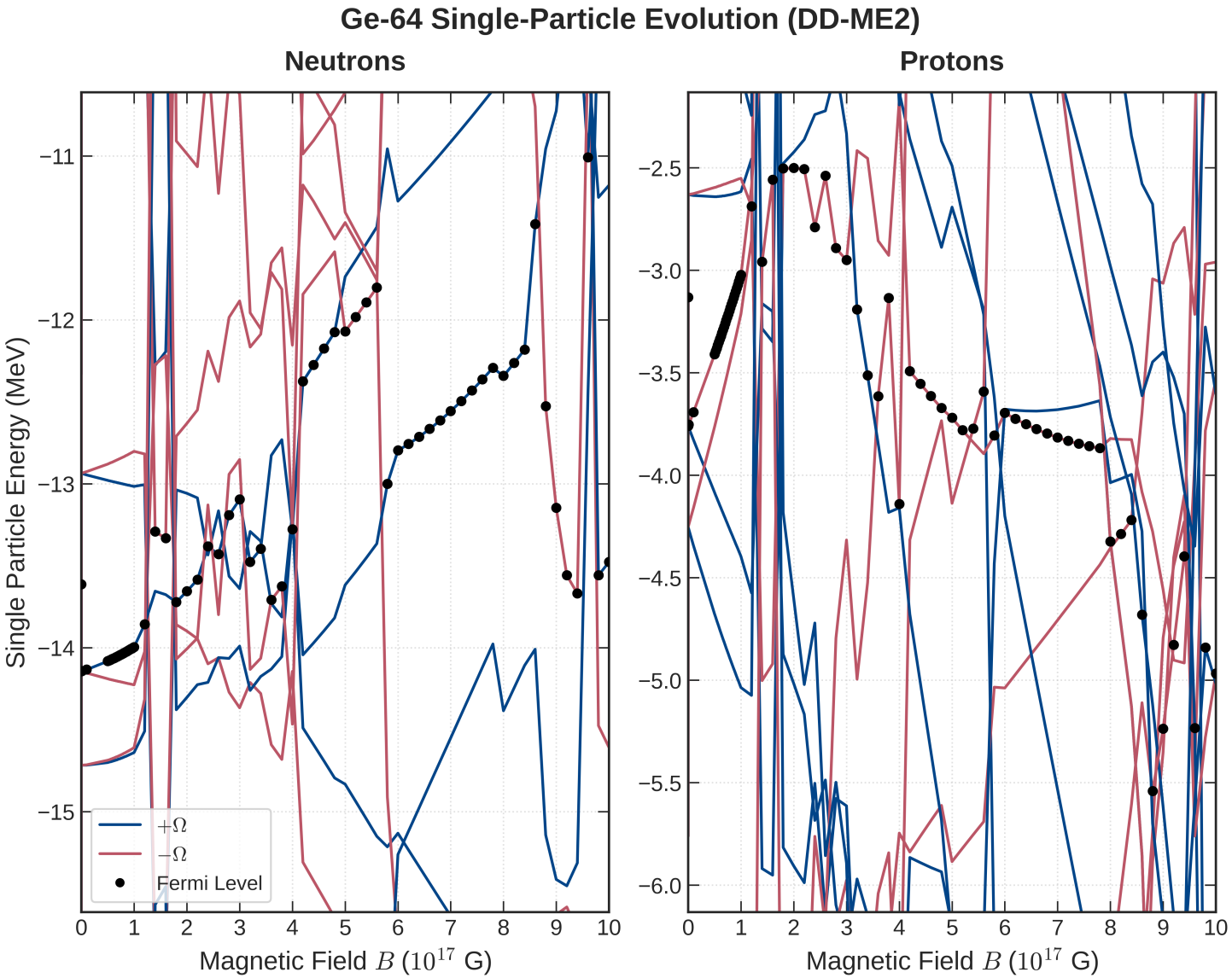


Bulk Properties (BE/A, β_2, $Radii$): ^{130}Cd

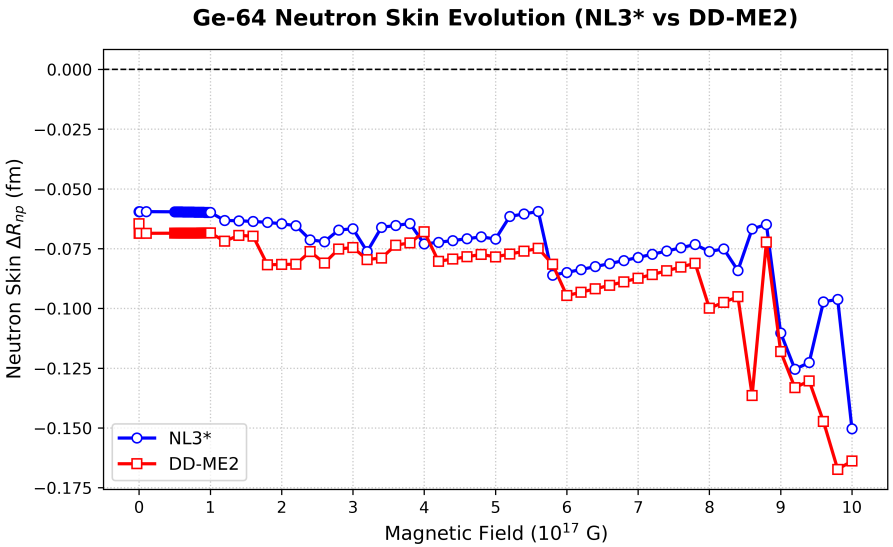


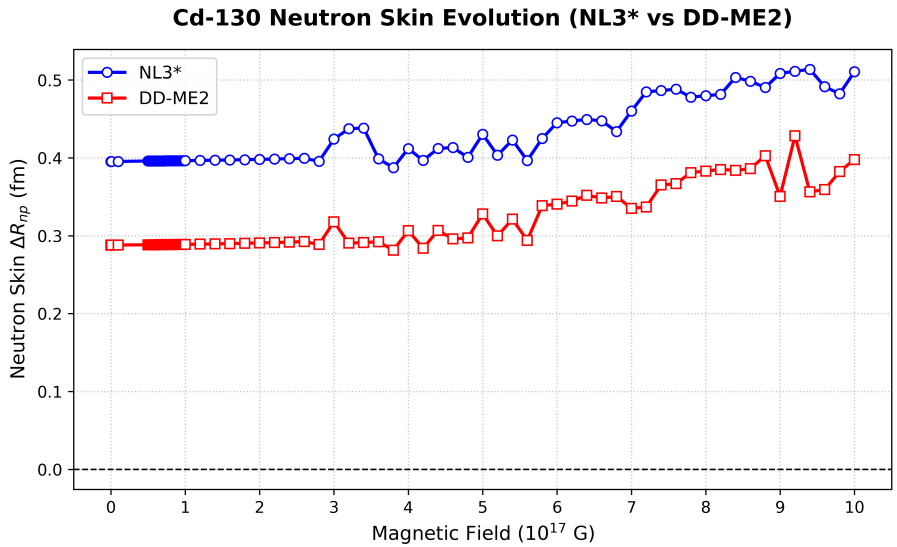


Microscopic Origins: Single-Particle Levels

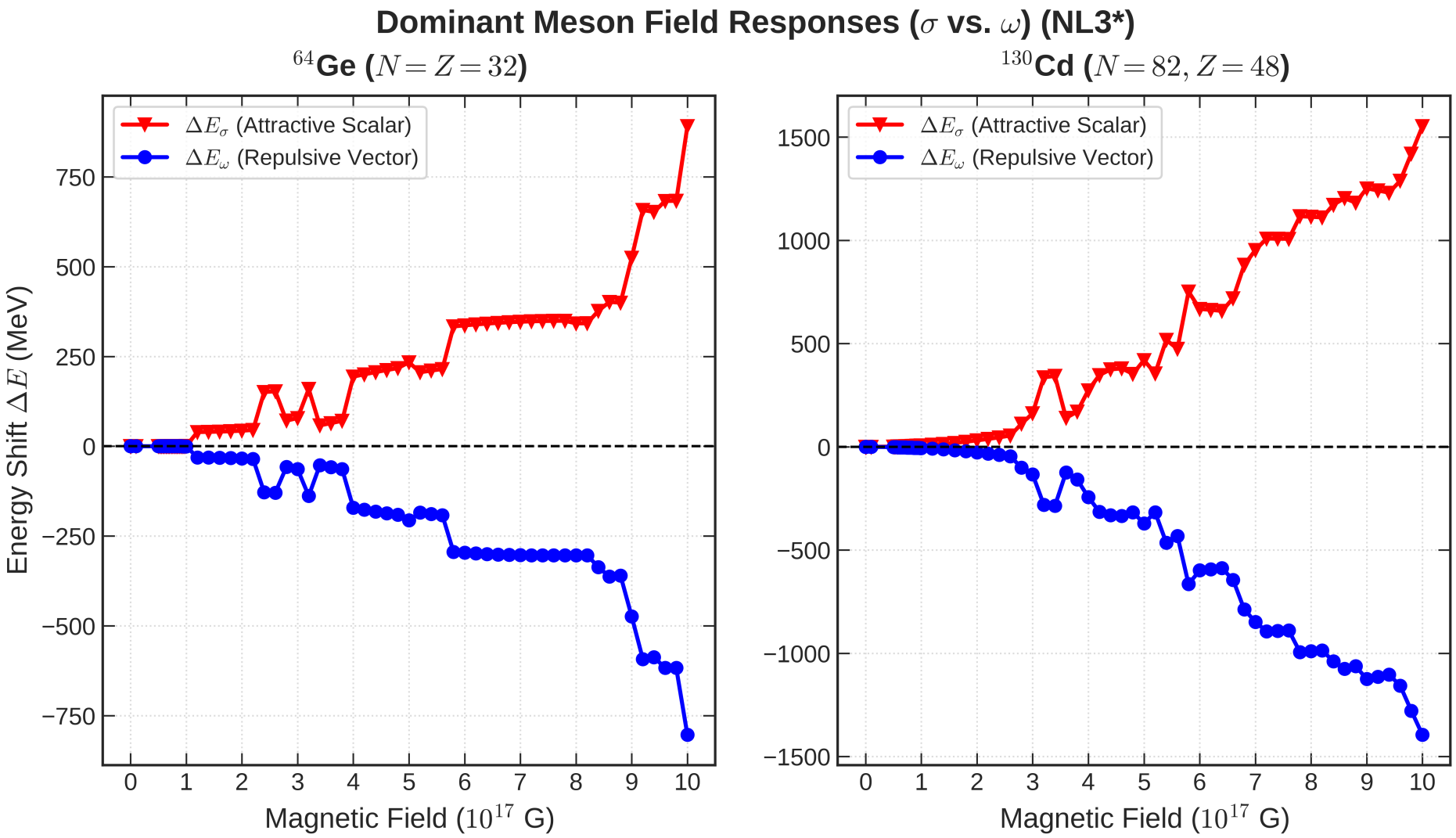


Evolution of the Neutron Skin Thickness

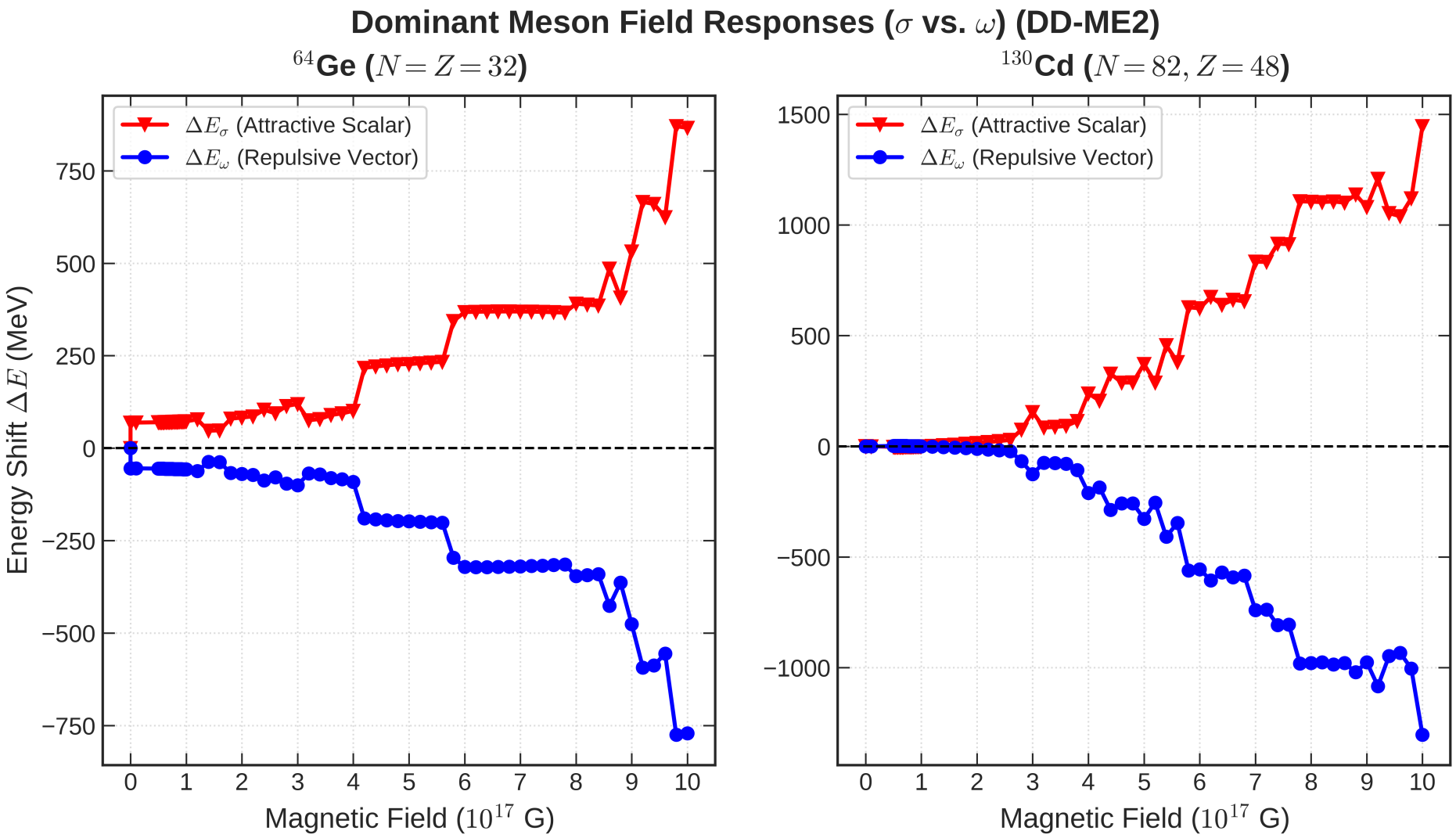




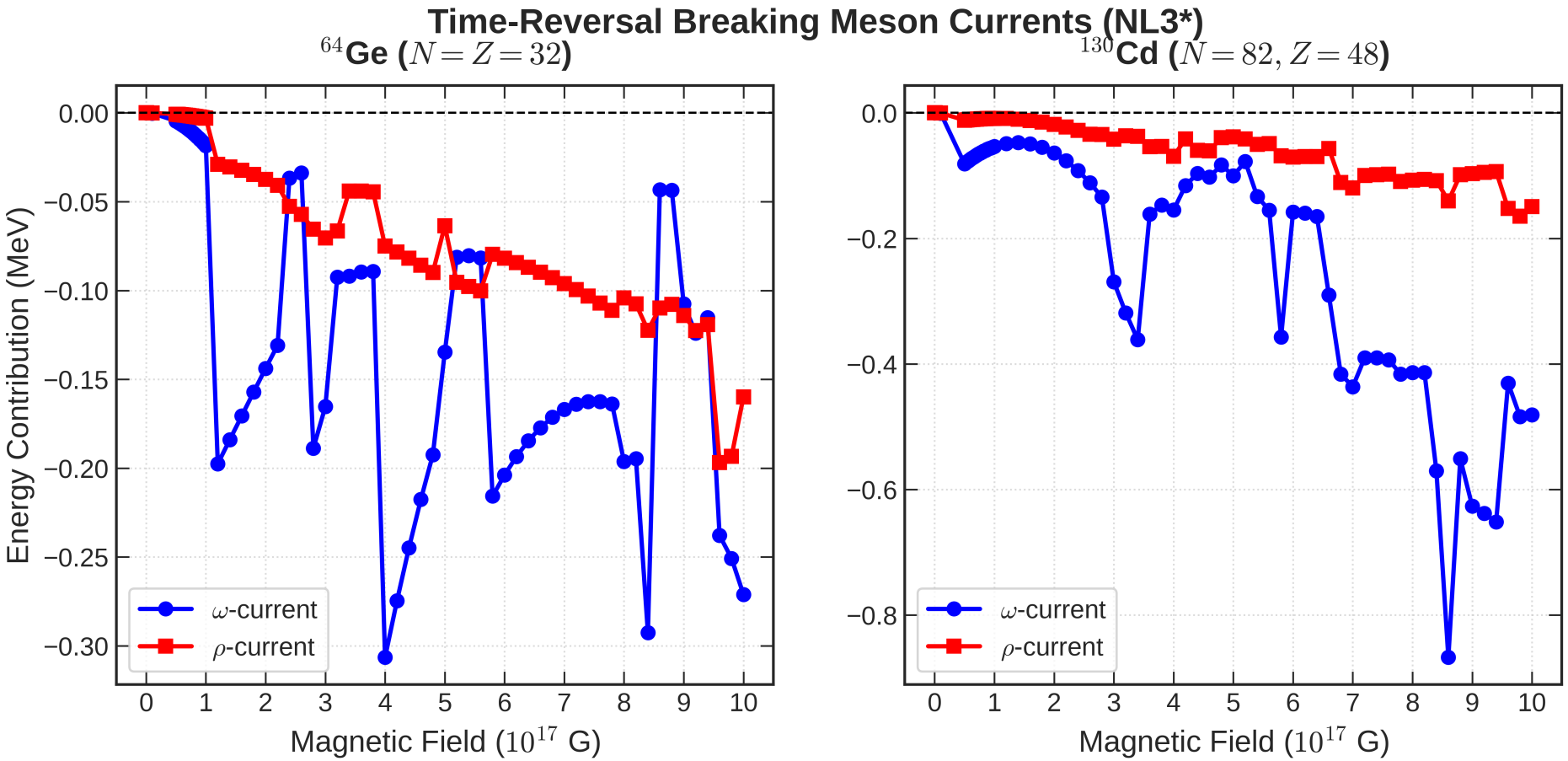
Meson Field Response (NL3*)



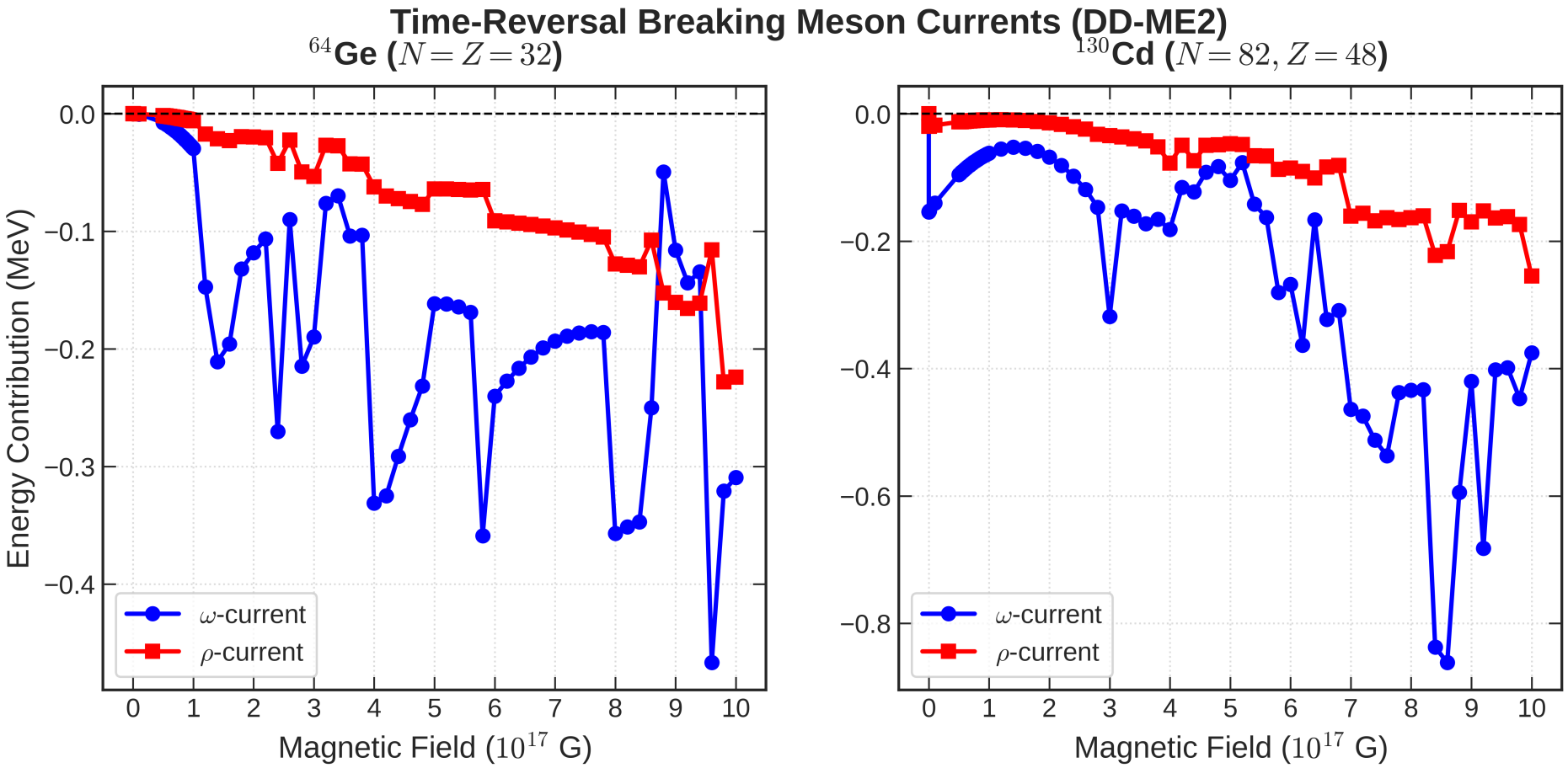
Meson Field Response (DD-ME2)



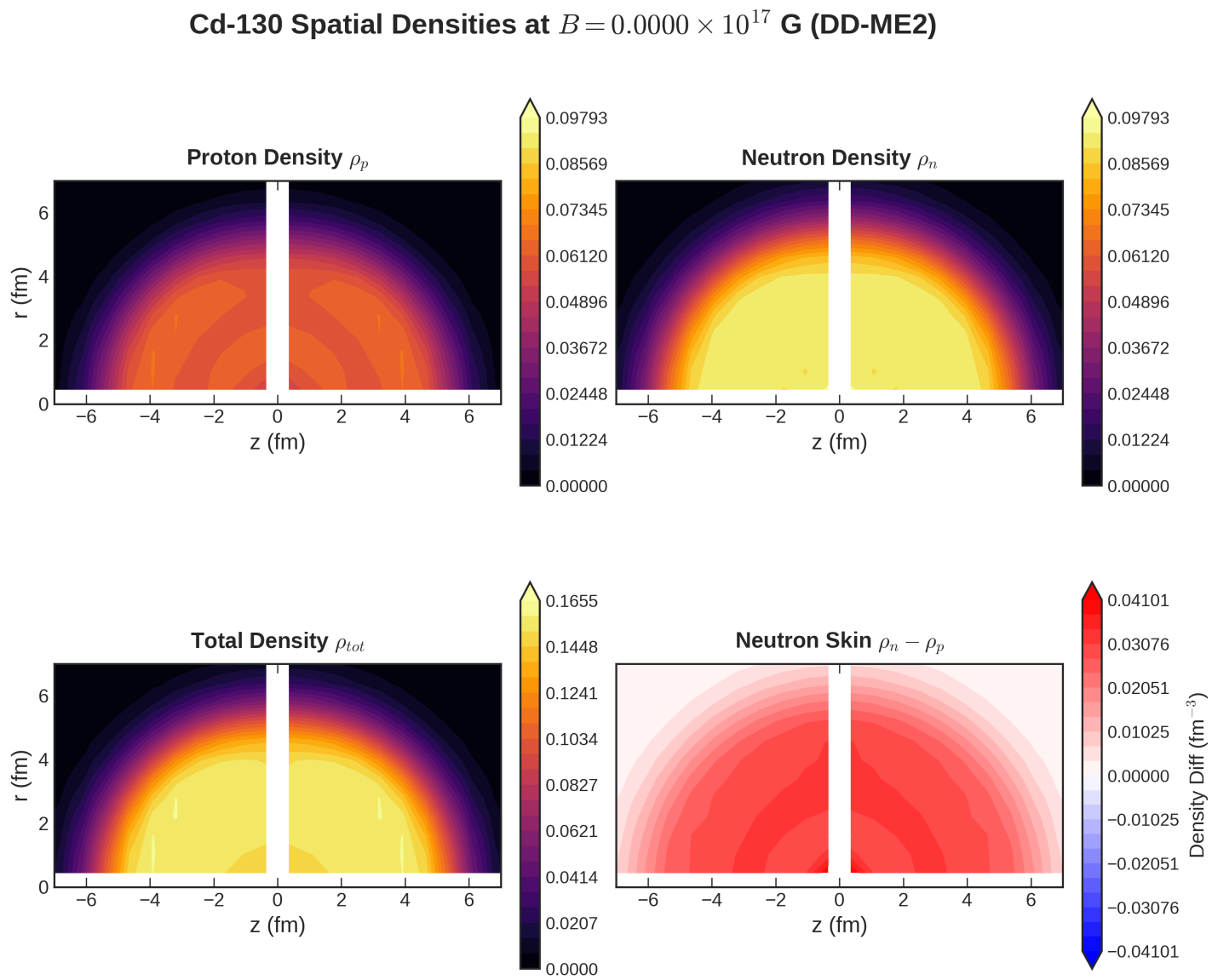
Time-Reversal Breaking: Induced Meson Currents (NL3*)



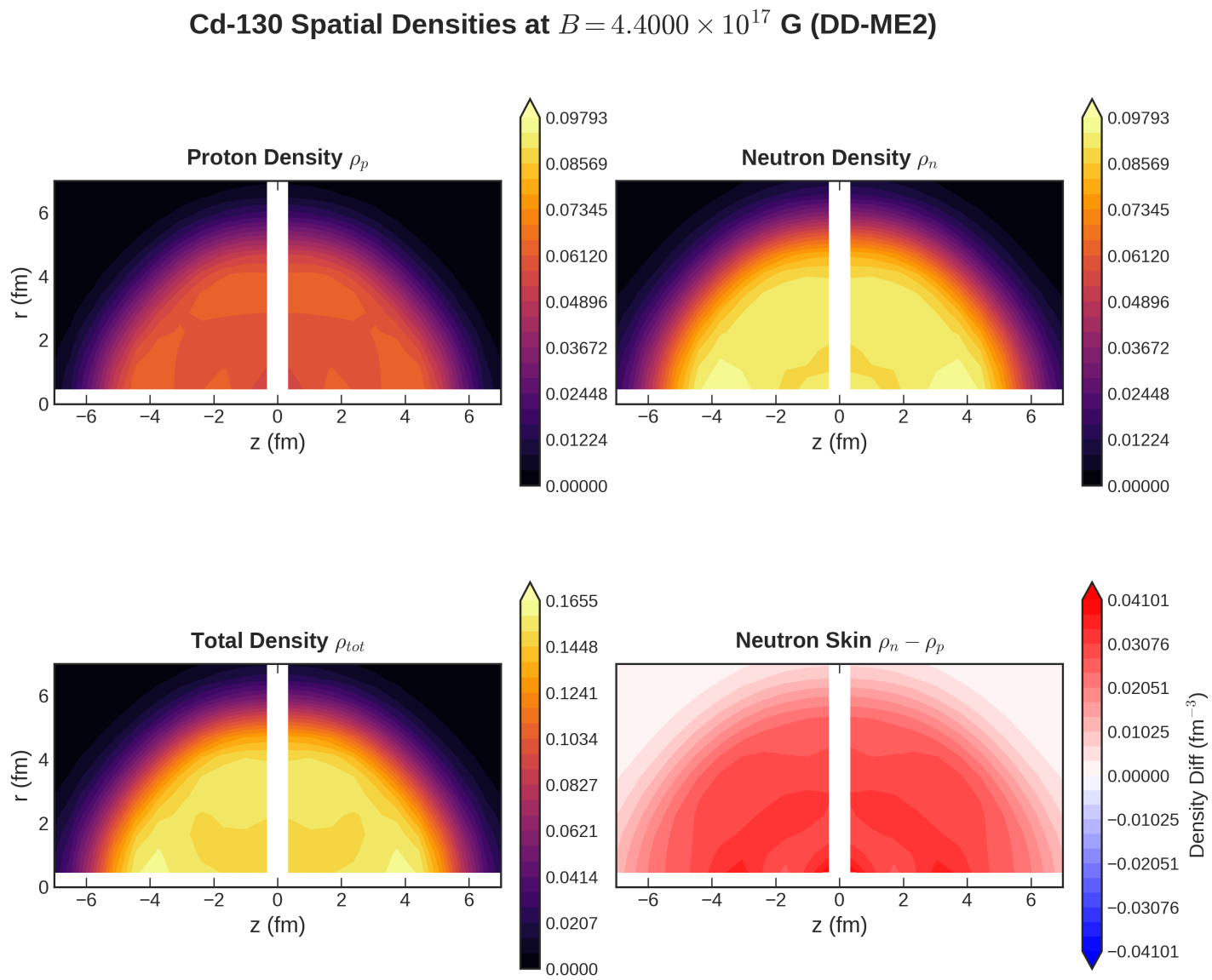
Time-Reversal Breaking: Induced Meson Currents (DD-ME2)



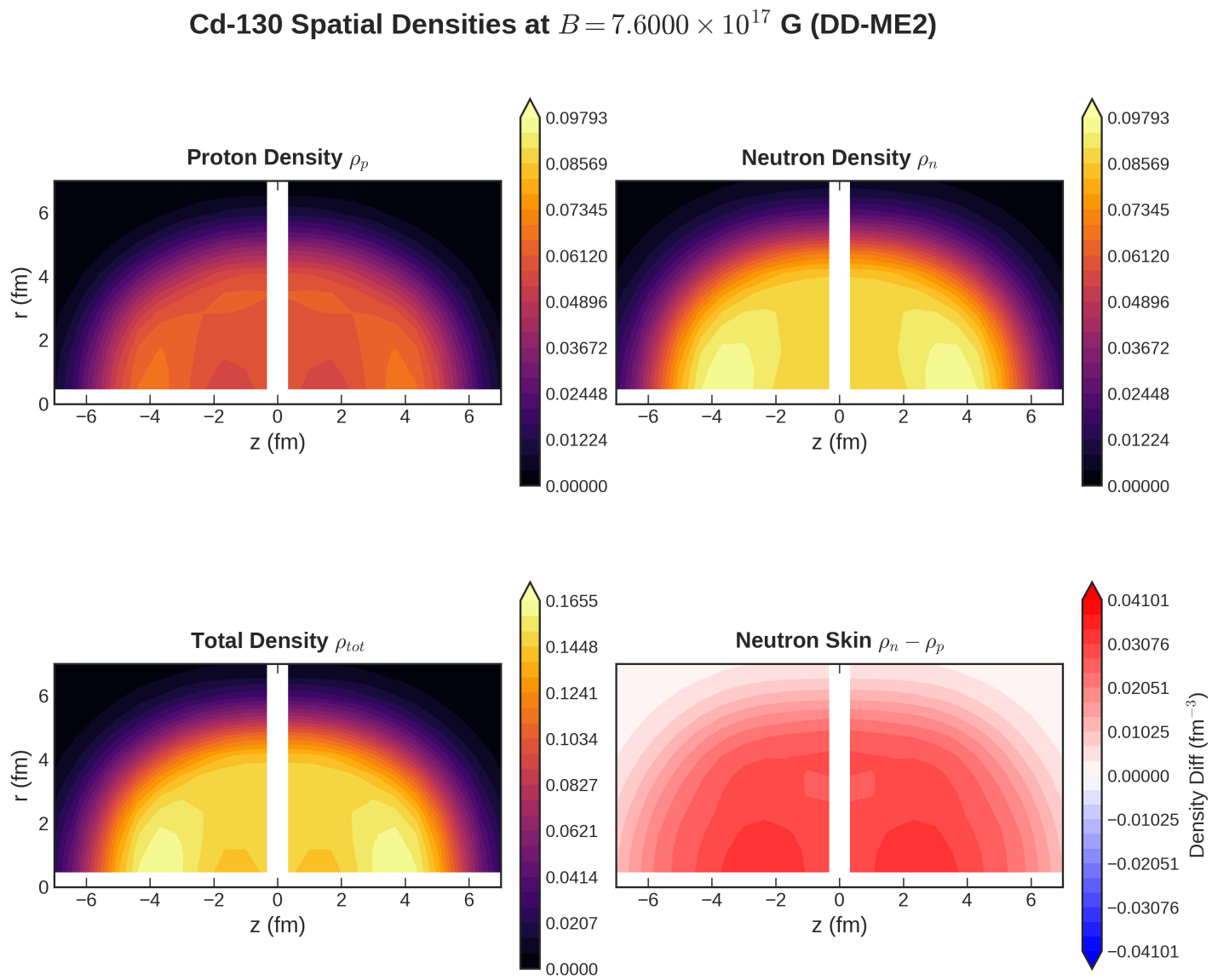
Evolution of Nuclear Density: ^{130}Cd ($B = 0$ G)



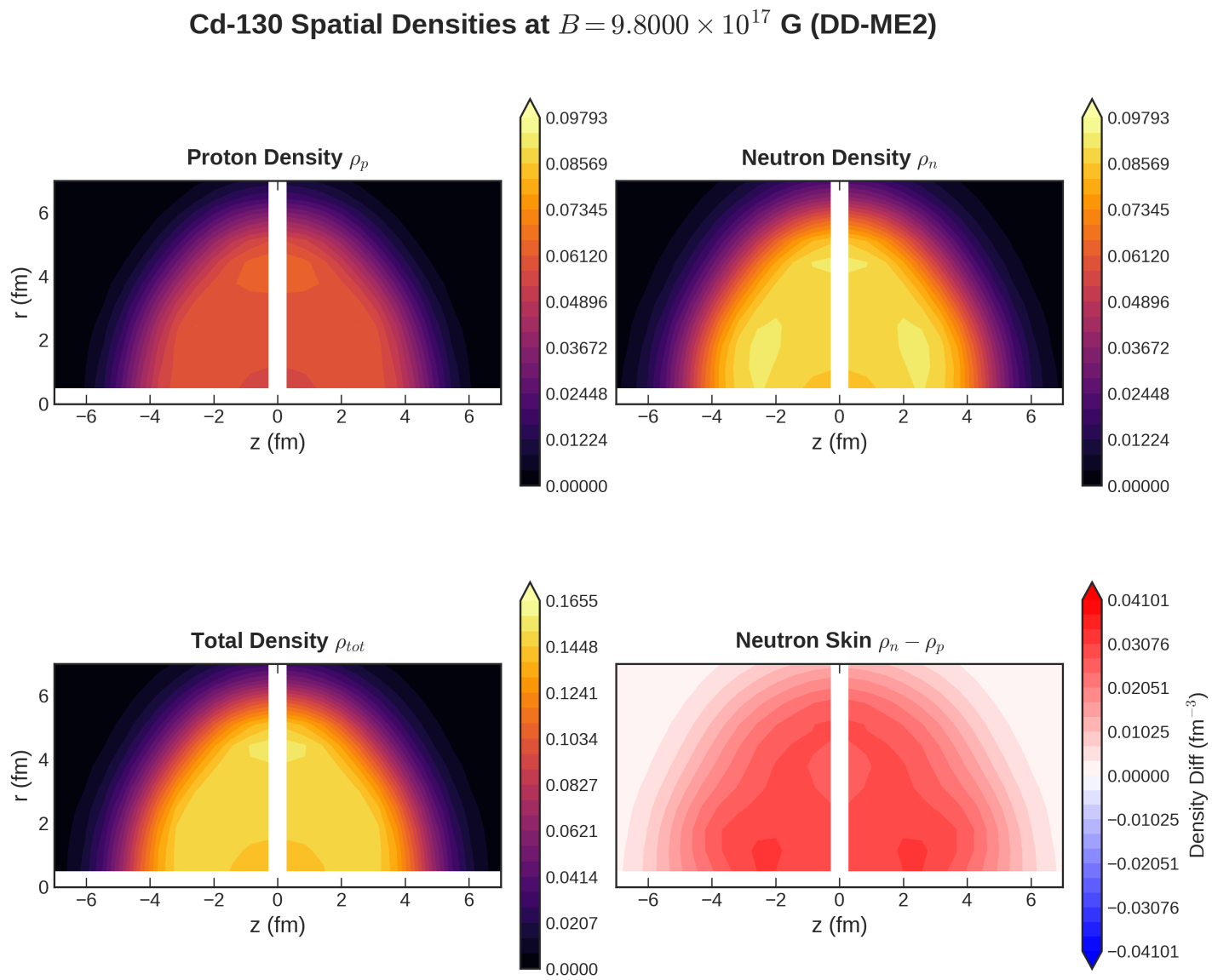
Evolution of Nuclear Density: ^{130}Cd ($B = 4.4 \times 10^{17}$ G)



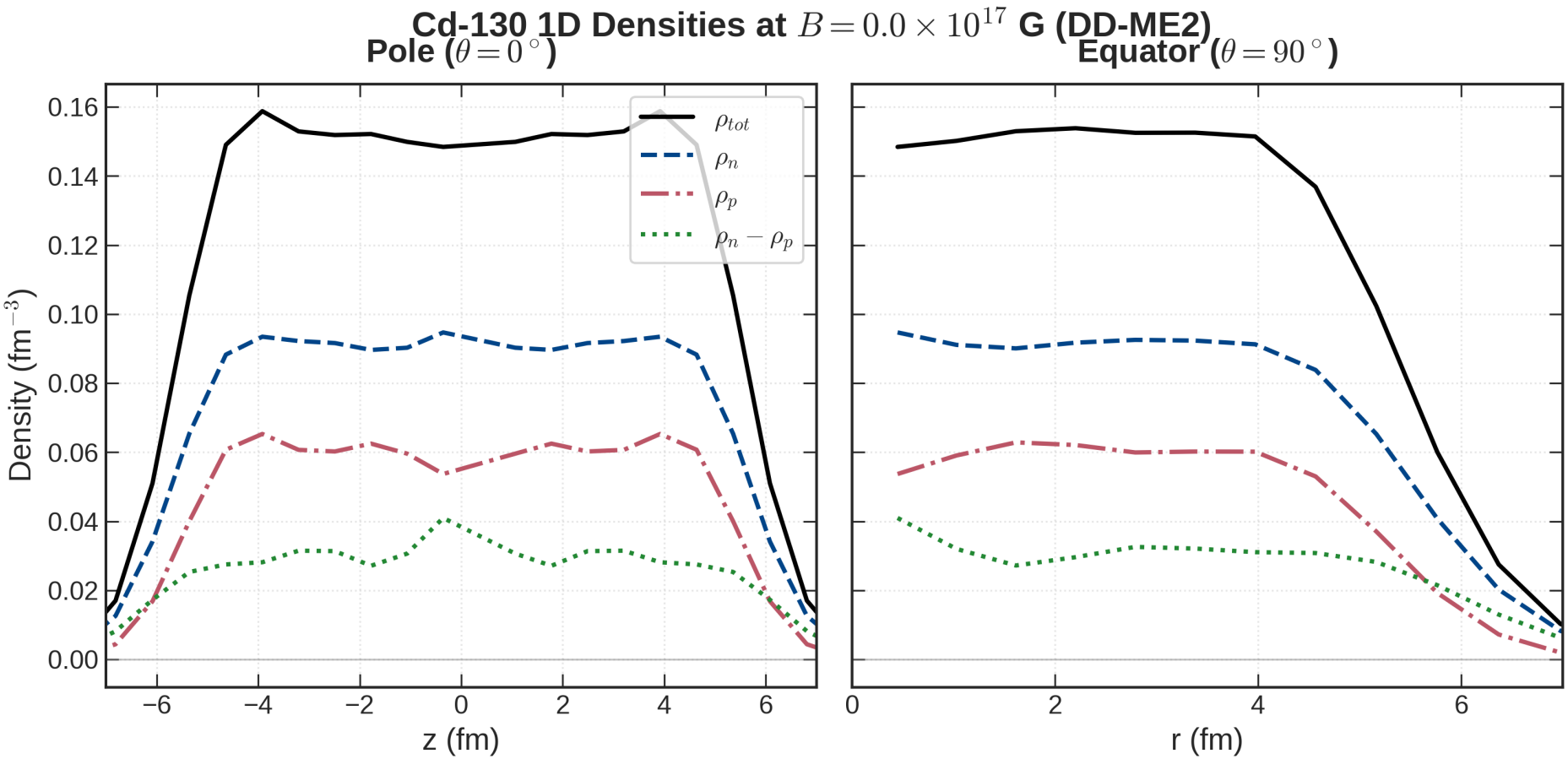
Evolution of Nuclear Density: ^{130}Cd ($B = 7.6 \times 10^{17}$ G)



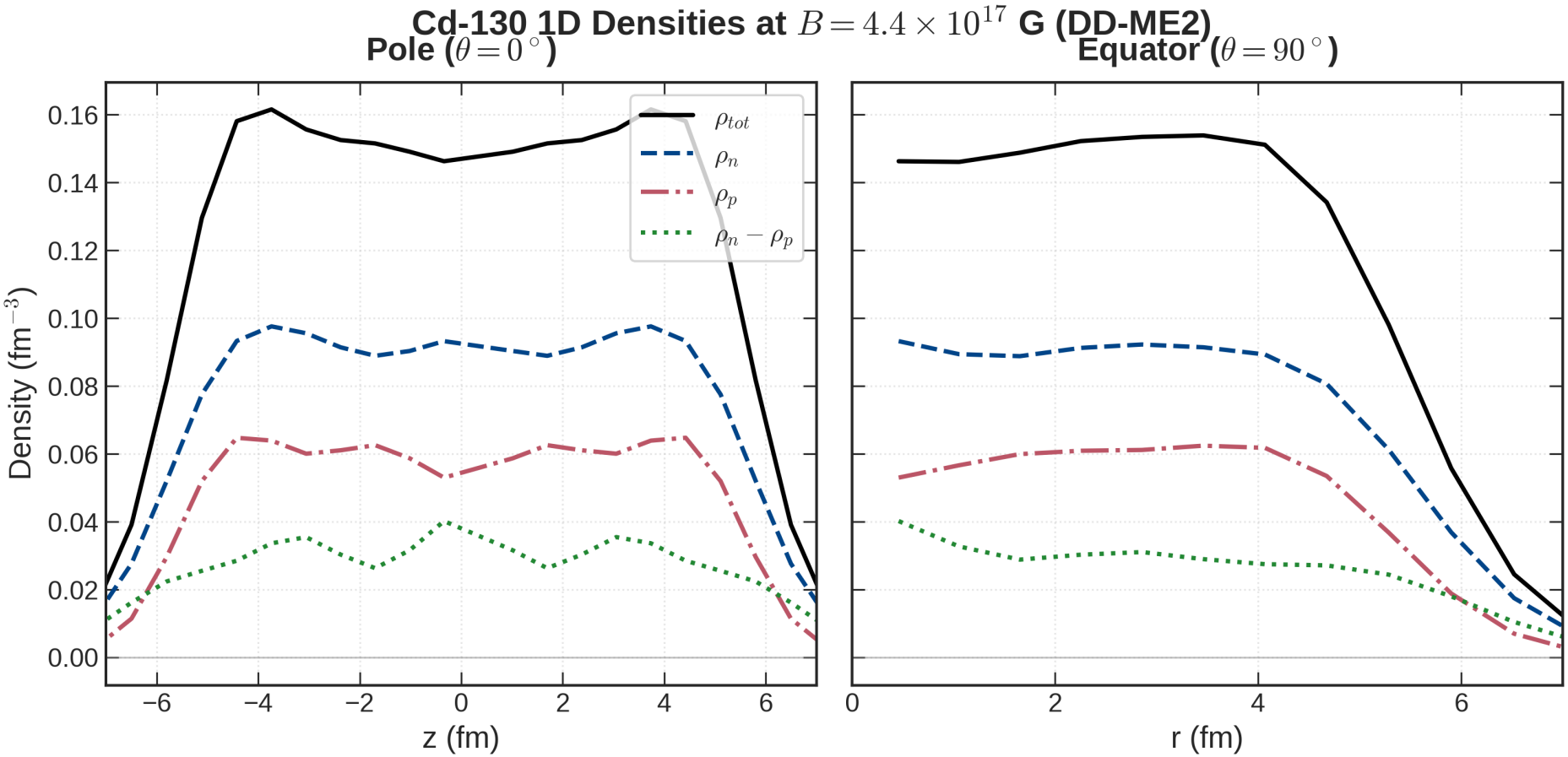
Evolution of Nuclear Density: ^{130}Cd ($B = 9.8 \times 10^{17}$ G)



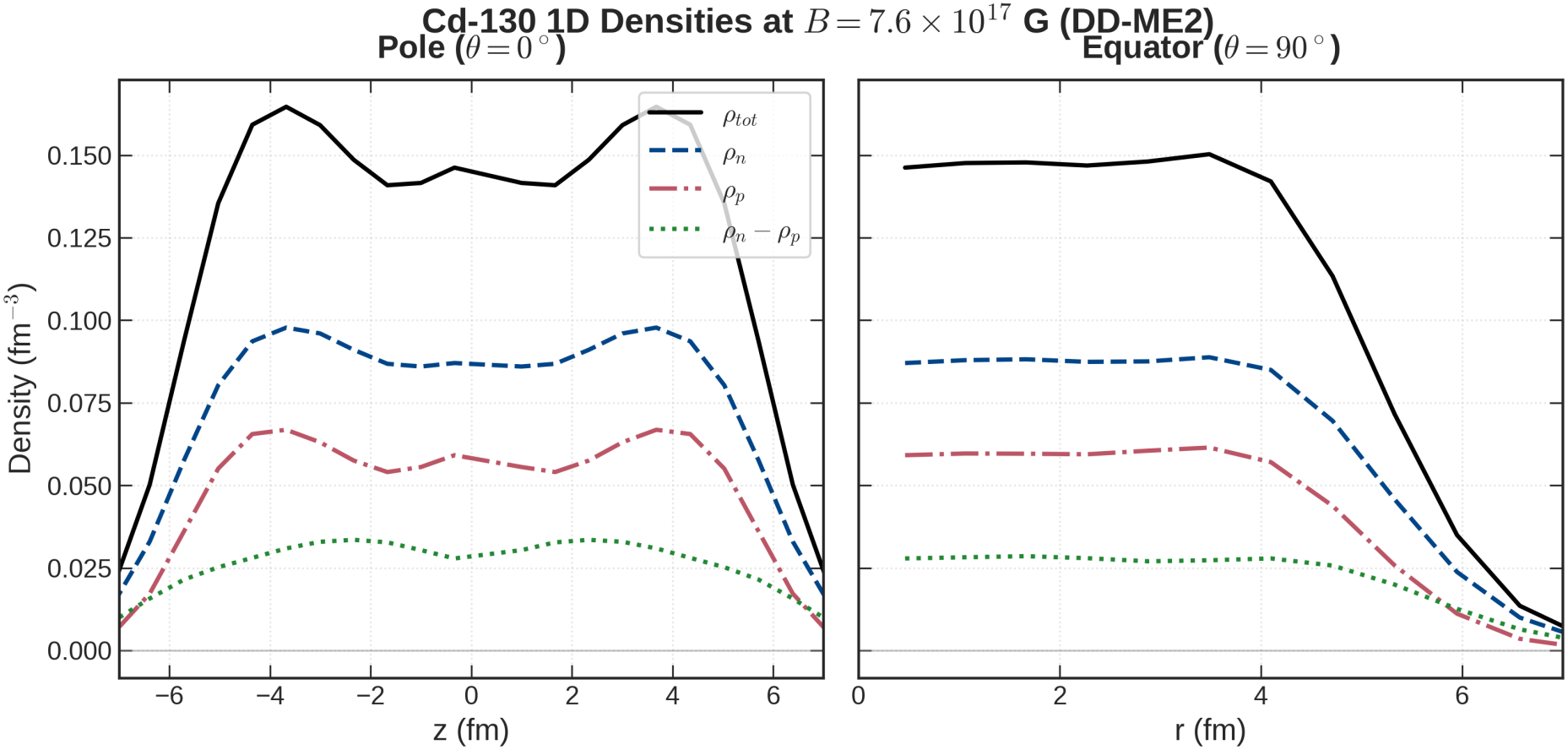
Density Profile ($B = 0$ G)



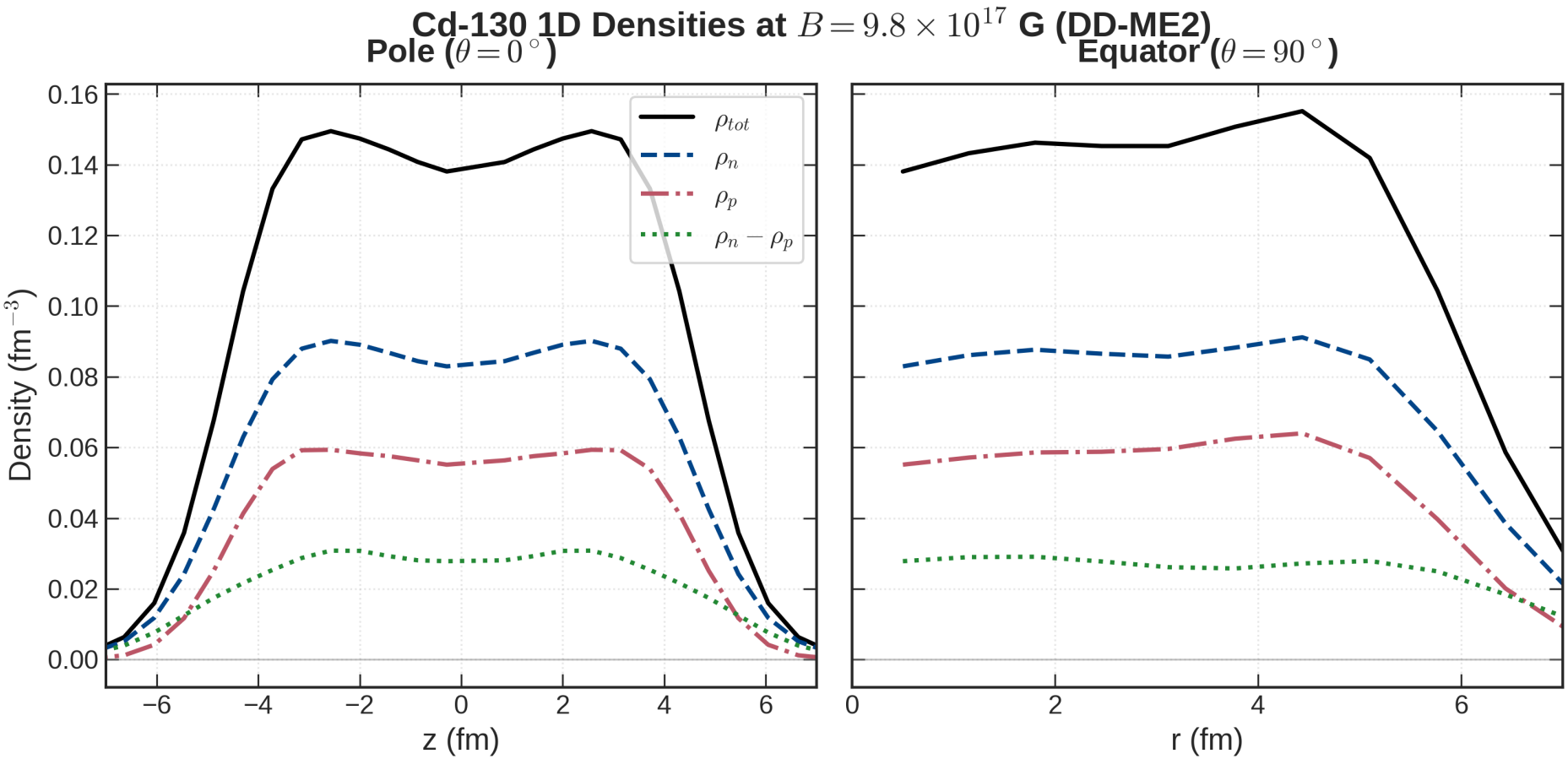
Density Profile ($B = 4.4 \times 10^{17}$ G)



Density Profile ($B = 7.6 \times 10^{17}$ G)



Density Profile ($B = 9.8 \times 10^{17}$ G)



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Summary

Microscopic Origins: Symmetry Breaking

- Superstrong magnetic fields ($B \sim 10^{17}$-10^{18} G) fundamentally break time-reversal symmetry, lifting Kramers' degeneracy.
- The preservation of axial symmetry permits critical single-particle level crossings at the Fermi surface.

Macroscopic Consequences: Structural Evolution

- Sudden quantum reoccupations drive abrupt macroscopic **shape-phase transitions** (violent spikes in β_2 deformation).
- Landau quantization forces the transverse expansion of the proton fluid, altering RMS radii and inducing proton skins in symmetric nuclei like ^{64}Ge.

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Acknowledgements I

Scientific Collaboration

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- **Georgios Lalazissis**
- **Petr Veselý**

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Acknowledgements II

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Results presented in this work have been produced using 1) GCP resources and 2) Aristotle HPC:

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2. the Aristotle University of Thessaloniki (AUTh) High Performance Computing Infrastructure and Resources.

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