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CHAPTER 1

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Abstract

Gravitational physics now connects precise measurements of cosmic expansion and structure with observations of compact objects, while its foundational questions remain open. General relativity and the standard cosmological model provide exceptionally productive baselines, yet the physical nature of the dark sector, the status of apparent data tensions, the fate of singularities and the relation between gravity and quantum theory remain under investigation. This editorial introduction situates the fourteen research contributions to SAGS2025 within that landscape. It explains the volume's progression from cosmological inference and competing expansion histories, through mathematical cosmology and modified gravity, to strong-field systems and proposals for quantum spacetime and unification. The chapters share problems and methods rather than a single theoretical conclusion. Throughout, we distinguish well-tested frameworks, observational indications, conditional model results and exploratory hypotheses. We close by identifying the standards by which connections across the volume should be judged: internal consistency, controlled limits, identifiable observables and reproducible comparison with data.

Keywords: General relativity; cosmology; dark energy; modified gravity; black holes; quantum spacetime

Gravity and Cosmology Across Scales: Questions, Methods and Connections

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Abstract

Gravitational physics now connects precise measurements of cosmic expansion and structure with observations of compact objects, while its foundational questions remain open. General relativity and the standard cosmological model provide exceptionally productive baselines, yet the physical nature of the dark sector, the status of apparent data tensions, the fate of singularities and the relation between gravity and quantum theory remain under investigation. This editorial introduction situates the fourteen research contributions to SAGS2025 within that landscape. It explains the volume's progression from cosmological inference and competing expansion histories, through mathematical cosmology and modified gravity, to strong-field systems and proposals for quantum spacetime and unification. The chapters share problems and methods rather than a single theoretical conclusion. Throughout, we distinguish well-tested frameworks, observational indications, conditional model results and exploratory hypotheses. We close by identifying the standards by which connections across the volume should be judged: internal consistency, controlled limits, identifiable observables and reproducible comparison with data.

1 A common question, not a common theory

What does gravity do when the scale, curvature, matter content or observational access changes? It links the cosmic background, the formation of structure, the motion of bodies around black holes, the radiation from mergers and the search for a deeper account of spacetime, without implying that one model, dataset or mathematical language can settle them all. The purpose of this chapter is to give readers a route through the fourteen research contributions to the South African Gravity Society Conference 2025 (SAGS2025), held in Parys, South Africa, on 18 - 21 November 2025, and to make explicit the standards by which their claims should be read.

General relativity remains the reference theory for classical gravitation. In cosmology, a spatially nearly flat, expanding universe with cold dark matter and a cosmological constant, ΛCDM, has supplied a remarkably economical description of the cosmic microwave background (CMB) and much of the large-scale structure data [1]. These successes are substantive: a proposed replacement must recover them, not merely describe one late-time observable. Yet a successful phenomenology neither settles the nature of dark matter and dark energy nor removes the need to test the assumptions that connect early- and late-Universe measurements. The same balance holds in strong gravity. Compact-binary gravitational waves have greatly enlarged the regime in which relativistic dynamics can be tested; recent catalogue-level analyses continue to find no established departure from general relativity [6]. Horizon-scale images offer a different, complementary view of black-hole environments, with interpretation necessarily involving emission models as well as spacetime geometry [7].

The field therefore advances through two simultaneous activities: sharpening the baseline and constructing alternatives that make distinguishable predictions. A mathematical solution can illuminate a theory without demonstrating that the theory describes nature. A fitted extension can improve agreement with selected data without being required by all data. A suggestive quantum analogy can motivate a calculation without constituting an observation of quantum gravity. These distinctions matter in any proceedings volume, where original research, methodological work and exploratory proposals appear together, and we apply them to the volume as a whole rather than to any single chapter.

The meeting itself gives the volume its character. SAGS2025 was hosted by the Centre for Space Research at North-West University on behalf of the South African Gravity Society, which since its founding in 1996 has served as a national forum for research on gravitation and its applications in cosmology, astrophysics and mathematical physics, with strong international connections. The programme welcomed theoretical, mathematical, computational and observational work and gave particular encouragement to postgraduate and early-career participants. The chapters that follow therefore record both results and the research directions being pursued within the South African gravity community and by its collaborators abroad.

2 Cosmology after precision measurement

Modern cosmological observations constrain different aspects of the same underlying model. CMB anisotropies encode early-Universe physics and, conditional on a model, infer late-time parameters; baryon acoustic oscillations (BAO) and Type Ia supernovae map distances and expansion; redshift-space distortions (RSD) and weak lensing probe growth and clustering.

None of these is a direct reading of a parameter from an instrument: each depends on calibration, likelihoods, nuisance models, priors and the assumed relation between geometry and perturbations.

This is why a tension should be stated with its conditioning visible. The difference between a local distance-ladder determination of H_0 and the value inferred from the CMB in base ΛCDM is an important and persistent diagnostic [1, 2]; it is not, by itself, a unique identification of new physics. The CosmoVerse White Paper usefully frames the research task as examining both observational systematics and possible fundamental physics, rather than presuming either explanation in advance [3]. Likewise, DESI DR2 BAO measurements are well described by flat ΛCDM on their own, while some combinations with CMB and supernova data prefer a time-varying dark-energy parameterization; the strength of that preference depends on the data combination and model choice [4]. Growth probes add another axis of comparison rather than a simple vote for or against any one model, as the continuing improvement of joint clustering and weak-lensing analyses shows [5].

The central challenge is therefore not to collect deviations from ΛCDM as though they had one cause, but to ask which physical mechanism predicts the joint background and perturbation histories, survives independent probes and offers an observable discriminant. One way of making this requirement operational is to treat H_0, S_8 and a model-specific third observable as simultaneous consistency conditions that a candidate model must satisfy together [8]. Part I treats precisely this interface between model construction and empirical discrimination.

3 Part I: models made answerable to data

Part I, *Cosmological Models and Data*, begins with a tool rather than a preferred cosmology. Chapter 2 presents `Kosmulator`, a framework intended to make the comparison of expansion histories and datasets faster. Its importance to the volume is methodological: broader theoretical exploration is scientifically useful only when the inference pipeline can be checked against established implementations, which the chapter does by validating against `Cobaya`. Its application to an implicit power-law $f(Q)$ model also anticipates the modified-gravity theme of Part II.

Chapter 3 tests the $R_h = ct$ cosmology using measurements of structure growth. The chapter is an instructive counterpoint to work on late-time expansion because it asks whether an alternative kinematic history also survives a perturbative observable. A model's simplicity at background level does not relieve it of the requirement to describe the formation of structure.

The remaining three chapters examine the dark sector from complementary angles. Chapter 4 confronts a diffusive dark-fluid model with CMB and DESI BAO information and computes its consequences for the density contrast and the matter power spectrum. Chapter 5 tests a nonlinear dark-sector interaction against several low- and intermediate-redshift datasets; the fits favour a mildly positive coupling and a phantom-like effective equation of state, both of which remain consistent with no interaction and with ΛCDM at the reported confidence levels. Chapter 6 examines when interacting two-component descriptions can be recast as a unified dark fluid, thereby separating pathologies of a particular decomposition from properties of the total background. Together these chapters expose three different questions: what data constrain, how energy exchange is parameterized, and whether apparently distinct descriptions are observationally equivalent.

4 Part II: the mathematical work behind physical claims

Part II, *Mathematical Cosmology and Modified Gravity*, turns from parameter constraints to the structure of dynamical equations in general relativity and its extensions [9]. Chapter 7 explores the geometric linearization of cosmological field equations, with $f(R)$ gravity as the example. The value of such a construction is not just that it supplies analytic solutions; it can reveal hidden integrability, clarify a change of variables and indicate which behaviours are generic and which depend on special initial conditions.

Chapter 8 studies anisotropic Bianchi I expansion when the gravitational and cosmological couplings run with scale. The chapter follows how the running couplings drive late-time acceleration in the presence of shear, and compares the resulting effective equation of state, deceleration parameter and $Om(z)$ diagnostic with observationally inferred ranges.

Chapter 9 reviews averaging methods for oscillatory scalar-field cosmologies in anisotropic geometries. Averaging is more than an algebraic convenience when its approximation error is controlled, and the chapter shows that the averaged and full systems share the same late-time behaviour. Together, the three chapters show that the variables and approximations used to render equations tractable also determine which predictions are robust enough to confront data, which is the bridge back to Part I.

5 Part III: compact objects as controlled tests

Part III, *Black Holes and Strong-Field Gravity*, moves from homogeneous cosmology to localized high-curvature systems. A modification proposed for cosmic acceleration need not show up around every black hole, since screening, crossover scales,

boundary conditions and dimensionality can intervene. Compact objects are valuable precisely because orbital motion, light propagation and collapse make different combinations of a theory's assumptions visible.

Chapter 10 studies timelike geodesics and circular orbits in a Schwarzschild-like modified-gravity background, showing how the modification parameter and crossover scale shift the innermost stable circular orbit and reshape the effective potential. Chapter 11 examines null trajectories and weak deflection in a phantom BTZ geometry. The $(2+1)$-dimensional setting serves as an analytically tractable laboratory in which the effects of altered matter content on photon motion, including stable photon trajectories absent from the standard BTZ spacetime, can be isolated.

Chapter 12 considers higher-curvature Einstein-Gauss-Bonnet dynamics in cosmology and collapse, with attention to singular endpoints and trapped regions. This connects a question raised by the cosmological chapters, namely what happens when curvature is large, to the fate of collapsing matter.

The chapter argues that the Gauss-Bonnet contribution acts as an effective geometric component that dominates at high curvature, so that singular endpoints are replaced by threshold states in both settings. The three contributions share an approach rather than an answer: specify a gravitational framework, derive its geodesic or dynamical consequences, and identify the physical regime in which those consequences could be tested.

6 Part IV: quantum structure and unification as testable programmes

Part IV, *Quantum Spacetime and Unification*, asks what may lie beyond classical descriptions. Chapter 13 studies a curved momentum-space construction whose semiclassical consequences are explored in a BTZ black-hole setting. The conceptual move is significant: altered kinematics in momentum space feed into effective spacetime properties, yielding finite Planck-scale corrections to the mass, horizon radius, temperature and entropy of the black hole and to the return time of Hawking quanta.

Chapter 14 proposes a quantized geometric description of binary black-hole coalescence within the Nexus Paradigm and identifies two observational tests: an $n = 2$ mass-frequency relation and possible low-n spectral discreteness near merger. Chapter 15 reviews gauge-theoretic constructions of conformal and noncommutative (fuzzy) gravity and outlines how they can be unified with internal interactions described by an $SO(10)$ grand unified theory.

These contributions are grouped not because they share a quantum theory but because they occupy neighbouring stages of one research programme: construct a formalism, recover an appropriate classical or semiclassical limit, calculate an observable, and seek a discriminating test.

7 Connections across regimes

The order of the four parts is a route through an inverse problem. Observations constrain parameters, but parameters acquire meaning only within equations of motion; mathematical methods reveal the space of solutions, compact objects expose regimes in which those solutions may fail, and foundational proposals seek to explain why the classical description works at all. The order is conceptual, not a hierarchy of scientific worth.

One bridge runs from *expansion to growth*. An expansion function $H(z)$ fixes background distances but not the growth of perturbations, which also depends on the gravitational response to inhomogeneity and on the clustering and interactions of the dark sector. This is why the RSD test of $R_h = ct$ and the perturbative consequences of diffusive or interacting fluids belong in the same discussion. A model flexible enough to fit distances may still be restricted by growth, and agreement at background level between a two-fluid model and a unified fluid does not by itself make their perturbations equivalent.

A second bridge runs from *mathematical structure to observational scale*. Linearization, averaging and effective potentials are powerful because they isolate tractable features of difficult dynamics; an averaged trajectory may discard phase-dependent effects, a minisuperspace description suppresses inhomogeneous degrees of freedom, and a test-particle orbit neglects backreaction. These are legitimate approximations when their domain is controlled. The common task is to carry both the prediction and its approximation error across the bridge.

A third bridge runs from *classical strong gravity to quantum proposals*. Singular behaviour in classical solutions motivates inquiry into ultraviolet physics, but it does not select a unique quantum mechanism. Higher-curvature terms, curved momentum space, discrete geometric states and gauge constructions are not interchangeable; they have to be compared by their assumptions and outputs, including which degrees of freedom are fundamental, what the low-energy limit is, and whether a distinctive correction is derived or only anticipated. The successes of general relativity make this a demanding programme rather than an obstacle to imagination.

8 How to read the volume as a whole

Four questions, applied equally to every chapter, provide a more useful integration of these papers than an asserted synthesis would.

1. *What is held fixed when models are compared?* Likelihoods, metrics and corrections are meaningful only when datasets, conventions, frames and nuisance assumptions are stated.

2. *Which limit reconnects a proposal to established results?* A new cosmology should account for successful CMB and structure predictions; a modified gravity theory should recover its weak-field and classical regimes; a quantum model must explain why smooth classical behaviour emerges where it is observed.

3. *What is a prediction rather than a redescription?* Parameters adjusted to an observation do not predict it; stronger tests use independent inputs, propagate modelling as well as instrumental uncertainty and confront more than one observable.

4. *Where does a result actually apply?* A mathematical or lower-dimensional result is conditional on its field equations, dimension and assumptions, and its extension to observed systems has to be argued rather than assumed.

The coming decade will sharpen each of these tests. Further DESI releases, Euclid [10] and the Legacy Survey of Space and Time (LSST) at the Vera C. Rubin Observatory will extend measurements of expansion and growth. The fifth LIGO-Virgo-KAGRA observing run and, later, LISA will probe strong-field dynamics over new ranges of mass and frequency. Closer to home, MeerKAT and the Square Kilometre Array, of which South Africa is a host country, will contribute pulsar-timing tests of gravity [11, 12] and neutral-hydrogen maps of large-scale structure [13]. Several of the questions raised in this volume will be answered, or sharpened, by these data.

The collection is selective, not an encyclopaedia of gravity and cosmology, and the scientific responsibility for each contribution remains with its authors. Its coherence is nevertheless real. From statistical inference to exact dynamics, from orbits and waves to quantum and gauge structure, the chapters return to the same discipline: translate a well-defined idea into consequences that can survive independent scrutiny. That is both the thread of this book and a productive standard for the field's next steps.

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