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Review

Rotating Universes from the Gödel Solution to Modern Modified Gravity

Alexey Dubinsky

University of Seville, 41009 Seville, Spain; dubinsky@ukr.net

How To Cite: Dubinsky, A. Rotating Universes from the Gödel Solution to Modern Modified Gravity. *International Journal of Gravitation and Theoretical Physics* **2026**, *2*(2), 6. https://doi.org/10.53941/ijgtp.2026.200006

Received: 1 June 2026
Revised: 25 June 2026
Accepted: 26 June 2026
Published: 29 June 2026

Abstract: The Gödel universe remains one of the sharpest exact spacetime tests of general relativity. It is homogeneous, stationary, filled by rotating pressureless matter and a negative cosmological constant, and it admits closed timelike curves through every event. These properties make it simultaneously a useful model, a counterexample to overly simple notions of cosmic time, and a benchmark for alternative theories of gravity. This review surveys the main line of development from Gödel's 1949 solution and the homogeneous Gödel-type metrics to expanding rotating cosmologies, Einstein–Cartan and gauge-gravity models, string-inspired and supergravity solutions, and recent modified-gravity constructions. Particular attention is given to the distinction between rotation and causality violation, to observational limits on global vorticity and shear, and to the status of stability analyses. The central lesson is conservative: cosmic rotation is a legitimate relativistic degree of freedom, but the causal pathology of the original Gödel solution is not generic. Whether chronology is violated depends on the global metric functions, matter sector, energy conditions, and boundary conditions of the theory under consideration.

Keywords: general relativity; rotating universes; Gödel-type metrics; causality violation; cosmic vorticity; modified gravity

1. Introduction

Rotation is a familiar local phenomenon in relativistic astrophysics, but its possible occurrence on cosmological scales has a more subtle status. The standard Friedmann-Lemaître-Robertson-Walker (FLRW) models are irrotational by construction. This is not a theorem of relativity, but a simplifying assumption motivated by the observed near-isotropy of the cosmic microwave background (CMB) and by the success of the inflationary and late-time concordance descriptions. Exact rotating cosmologies therefore play two complementary roles. They test how strongly the assumptions of standard cosmology are tied to observation, and they expose conceptual points that are hidden in the maximally symmetric FLRW limit.

The most famous example is Gödel's 1949 solution of Einstein's equations with dust and a negative cosmological constant [1]. The model is spatially homogeneous and nonsingular, and it has a rigidly rotating matter congruence. It is also acausal in the strong sense that every event lies on a closed timelike curve. Gödel used the solution not as an observational proposal for our Universe, but as a counterexample to the idea that general relativity automatically contains a physically preferred global time. The same solution later became a standard laboratory for causality, chronology protection, global hyperbolicity, and quantum fields on nontrivial backgrounds [2,3].

The history of the subject did not stop with this counterexample. Lanczos had already constructed a stationary rotating cosmological metric before Gödel [4], while the decades after 1949 saw extensive work on Bianchi cosmologies, shear and vorticity, observational limits on rotation, and more general Gödel-type geometries [5–8]. Obukhov and collaborators emphasized that rotation can coexist with expansion, and that the observational meaning of cosmic rotation depends on the chosen class of exact solutions rather than on the Gödel metric alone [9,10]. This distinction is still important: "rotating universe" is not synonymous with "chronology-violating universe."

Modern interest has several sources. First, CMB and large-scale-structure data impose very strong limits on anisotropic expansion and global vorticity, but the translation of those limits into a model-independent bound is not trivial [11–14]. Second, many alternative theories of gravity admit Gödel or Gödel-type solutions, sometimes with the causal structure shifted by higher-curvature terms, torsion, Lorentz-violating backgrounds, Chern–Simons couplings, or teleparallel degrees of freedom [15–18]. Third, string theory and supergravity contain exact Gödel-like backgrounds whose closed timelike curves are connected with holography, supersymmetry, and the consistency of boundary conditions [19–22].

Throughout the paper Greek indices such as μ, ν denote spacetime components, repeated indices are summed, and the metric signature is $(+ - --)$. With this notation fixed, this review is organized as follows. Section 2 describes the original solution and its causal structure. Section 3 reviews homogeneous Gödel-type metrics and the standard causal classification. Section 4 discusses expanding rotating cosmologies, including the Obukhov–Korotky class. Section 5 summarizes observational bounds and their interpretation while Section 7 discusses causality and chronology protection. Section 6 surveys rotating solutions in theories beyond general relativity. Section 8 reviews stability issues, and Section 9 gives a synthesis.

2. The Original Gödel Universe

In one common convention the Gödel line element is

$$ds^2 = a^2 \left[dt^2 - dx^2 - dz^2 + \frac{1}{2} e^{2x} dy^2 + 2e^x dt\, dy \right], \tag{1}$$

where a is a constant length scale. The coordinates are (t, x, y, z), and $ds^2 = g_{\mu\nu} dx^\mu dx^\nu$ defines the metric tensor $g_{\mu\nu}$. It solves Einstein's equations

$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} + \Lambda g_{\mu\nu} = 8\pi G \rho u_\mu u_\nu. \tag{2}$$

For this pressureless perfect fluid source with a negative cosmological constant, $R_{\mu\nu}$ is the Ricci tensor, $R = g^{\mu\nu} R_{\mu\nu}$ the Ricci scalar, Λ the cosmological constant, G Newton's constant, ρ the dust energy density, and u^μ the dust four-velocity, normalized by $u_\mu u^\mu = 1$ with $u_\mu = g_{\mu\nu} u^\nu$. The numerical relations among these quantities depend only on the normalization of a. The dust congruence is geodesic, shear-free, expansion-free, and vortical. Thus the solution isolates rotation as a cosmological kinematic variable without mixing it with collapse, expansion, or singular behavior.

The same geometry is often written in cylindrical form as

$$ds^2 = [dt + H(r) d\phi]^2 - dr^2 - D^2(r) d\phi^2 - dz^2, \tag{3}$$

with suitable functions H and D. Here r is the radial coordinate, ϕ the periodic azimuthal angle, z the axial coordinate, and $H(r)$ and $D(r)$ determine the frame dragging and the circumferential scale, respectively. In this form the central causal feature is transparent. At sufficiently large radius the azimuthal coordinate circles $t, r, z = \text{const.}$ become timelike. Since ϕ is periodic, these circles are closed timelike curves. The pathology is not confined to a special boundary region: by homogeneity the causal anomaly can be translated to any event.

The Gödel spacetime therefore challenged several possible readings of cosmology. It showed that the existence of a well-behaved matter congruence does not by itself imply a global time function. It also separated local energy conditions from global chronology: the matter source is ordinary dust, while the exotic ingredient is the global causal structure supported by rotation and negative Λ. Later work on global hyperbolicity, time functions, and chronology protection can be read as attempts to identify which additional assumptions exclude this possibility [2,3].

For cosmology, however, Equation (1) is too special to be a realistic model. It is stationary and non-expanding, while the observed Universe expands. It also has no isotropic CMB rest frame in the ordinary FLRW sense. Furthermore, perturbative analyses [23] indicate that the original Gödel universe is not a robust stable background for realistic cosmology, and neutral behavior in restricted perturbation sectors does not make the stationary, non-expanding solution a viable model of the early Universe. The principal value of the solution is therefore not phenomenological realism, but its exactness. It provides a controlled environment in which rotation, causality, geodesic structure, and quantum fields can be studied without perturbative approximations.

3. Homogeneous Gödel-Type Metrics

The systematic generalization of Gödel's geometry is usually formulated through the orthonormal coframe

$$\vartheta^{\hat{0}} = dt + H(r)d\phi, \qquad \vartheta^{\hat{1}} = dr, \qquad \vartheta^{\hat{2}} = D(r)d\phi, \qquad \vartheta^{\hat{3}} = dz, \tag{4}$$

with

$$ds^2 = (\vartheta^{\hat{0}})^2 - (\vartheta^{\hat{1}})^2 - (\vartheta^{\hat{2}})^2 - (\vartheta^{\hat{3}})^2. \tag{5}$$

The spacetime is spacetime homogeneous when

$$\frac{H'(r)}{D(r)} = 2\omega, \qquad \frac{D''(r)}{D(r)} = m^2, \tag{6}$$

where ω is the vorticity scale and m fixes the curvature of the two-dimensional surfaces orthogonal to t and z [7,8]. Hatted labels refer to orthonormal tetrad components, and primes denote derivatives with respect to r. The original Gödel solution corresponds to the hyperbolic class with $m^2 = 2\omega^2$.

Equation (6) gives a useful causal classification. In the hyperbolic class $m^2 > 0$, closed timelike azimuthal curves occur if

$$0 < m^2 < 4\omega^2. \tag{7}$$

The critical radius is fixed by

$$\sinh^2\left(\frac{mr_c}{2}\right) = \left(\frac{4\omega^2}{m^2} - 1\right)^{-1}. \tag{8}$$

The quantity r_c denotes the radius at which the azimuthal metric coefficient changes sign, so that the circles generated by the Killing field ∂_ϕ pass from spacelike to timelike. For $m^2 \geq 4\omega^2$ there are no such azimuthal closed timelike curves in the homogeneous family. The linear and trigonometric classes have their own limiting behavior, but the central lesson is the same: rotation is necessary for the Gödel-type construction, while chronology violation depends on the ratio of rotation to spatial curvature.

Figure 1 summarizes this causal picture in the noncausal sector of the homogeneous Gödel-type family. This classification is one reason why the term Gödel-type is more useful than the term Gödel universe. It separates the algebraic and kinematic structure of rotating homogeneous solutions from the special matter content of the original model. Many sources can support metrics of the form (5): perfect fluids, scalar fields, electromagnetic fields, torsion, higher-curvature effective fluids, or Lorentz-violating backgrounds. The causal question then becomes a dynamical question for the theory: which values of m^2/ω^2 are selected by the field equations and by acceptable matter?

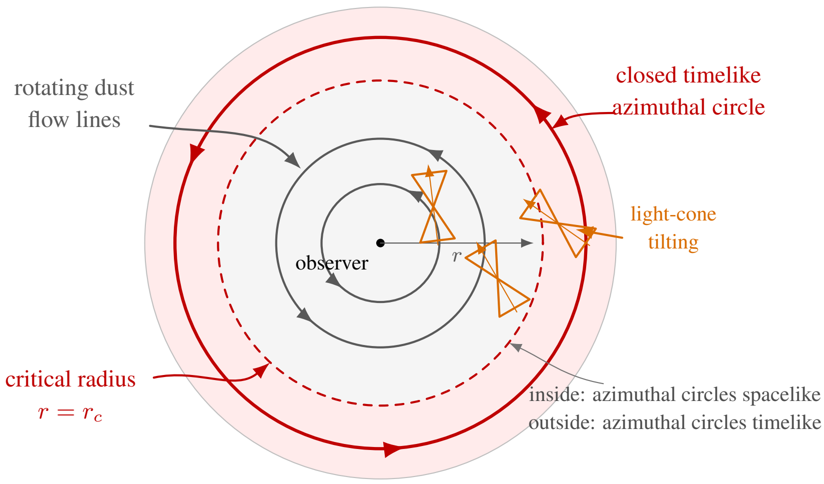

Figure 1. Schematic causal structure of a homogeneous Gödel-type universe. The dashed circle denotes the critical radius defined in Equation (8). Inside it the azimuthal circles are spacelike, while outside it they become closed timelike curves in the noncausal sector. The small cones are only a pictorial indication of the progressive tipping of the local light cones caused by global rotation.

Several refinements are important. First, the existence of closed timelike coordinate circles is a sufficient and very explicit sign of chronology violation, but not the only possible global causal pathology. Second, the local Ricci and Petrov classifications do not determine whether the azimuthal coordinate is periodically identified in a way that produces closed timelike curves. Third, the same local metric may have different global completions. These points explain why Gödel-type metrics continue to be used in discussions of chronology protection even when they are not treated as realistic cosmologies.

4. Expanding Rotating Cosmologies

The original Gödel model has zero expansion, while observations require an expanding universe. The search for expanding rotating cosmologies therefore asks whether vorticity can be incorporated without importing all of Gödel's causal behavior. In the $1+3$ covariant language, a fundamental congruence u^μ has

$$\nabla_\nu u_\mu = \frac{1}{3}\Theta h_{\mu\nu} + \sigma_{\mu\nu} + \omega_{\mu\nu} + u_\nu a_\mu, \tag{9}$$

where Θ is expansion, $\sigma_{\mu\nu}$ shear, $\omega_{\mu\nu}$ vorticity, $a_\mu = u^\nu \nabla_\nu u_\mu$ acceleration, and $h_{\mu\nu}$ the spatial projector. In this formula u^μ is the fundamental four-velocity of the cosmological matter frame, ∇_ν is the Levi–Civita covariant derivative, and $h_{\mu\nu} = g_{\mu\nu} - u_\mu u_\nu$ projects into the local rest space of u^μ. FLRW space-times set $\sigma_{\mu\nu} = \omega_{\mu\nu} = a_\mu = 0$. Rotating cosmologies relax this assumption, but different families relax it in inequivalent ways.

Early work on anisotropic cosmology established that shear and vorticity are observationally constrained together in many Bianchi models [5,6]. This is partly why phenomenological bounds on rotation are often quoted from analyses of anisotropic temperature patterns. However, rotation need not always be tied to shear. Obukhov and Korotky studied classes of shear-free, expanding, rotating models of the schematic form

$$ds^2 = dt^2 - 2R(t)n_i dx^i dt - R^2(t)\gamma_{ij} dx^i dx^j, \tag{10}$$

where $R(t)$ is a cosmological scale factor, and n_i and γ_{ij} are built from invariant spatial one-forms and constant parameters [9, 10]. Here $i, j = 1, 2, 3$ are spatial indices, $n_i dx^i$ is the rotational shift one-form, and γ_{ij} is the time-independent spatial metric entering the homogeneous three-geometry. The point of Equation (10) is not its most general form, but its physical interpretation: it provides a framework in which expansion and rotation coexist while the optical properties may remain close to Robertson–Walker behavior. Such models motivated discussions of parallax, polarization rotation, and whether the observed isotropy of radiation excludes all cosmic vorticity or only particular anisotropic realizations [10].

The distinction between shear-dominated and shear-free rotation remains central. In shear-dominated Bianchi models the CMB quadrupole and higher multipoles strongly limit departures from isotropy. In shear-free rotating models the most direct signatures may instead appear through gyroscope precession, polarization transport, number-count anisotropies, or subtle correlations in large-scale observables. This makes exact solutions valuable: they specify the null geodesics, tetrad transport, and matter frame needed to compute observables without relying on an ambiguous Newtonian analogy.

There are also no-go theorems and near no-go results. For a barotropic perfect fluid in general relativity, shear-free expanding rotating flows are highly restricted under common assumptions. Avoiding those restrictions usually requires acceleration, imperfect stresses, nontrivial spatial topology, torsion, or modified gravitational dynamics. Thus the existence of mathematically consistent rotating expanding metrics does not automatically imply a simple perfect-fluid cosmology.

5. Observational Constraints and Possible Signatures

The observational question is not whether the Gödel universe is a good fit; it is not. The relevant question is how much global vorticity, shear, or anisotropic expansion can be hidden in a universe that is close to FLRW. Hawking's early analysis of rotation, Collins and Hawking's study of anisotropic expansion, and the later work of Barrow, Juszkiewicz, and Sonoda established the basic CMB logic [5,6,11]. Rotation and shear produce direction-dependent redshifts and characteristic large-angle temperature patterns. The observed smallness of CMB anisotropies therefore translates into strong upper bounds in model families where these effects are directly connected.

COBE, WMAP, and Planck data sharpened this conclusion. Analyses using Bianchi templates constrained combinations of shear, vorticity, and spatial curvature, and modern Bayesian tests found no evidence that a deterministic anisotropic component is required by the CMB [12–14,24]. The result is often summarized by saying that the Universe is very close to statistically isotropic on large scales. Strictly speaking, this is a statement about the tested parameterizations. It rules out simple large global rotations tied to observable shear, but it is less direct for models engineered to be shear-free or for theories in which photon propagation differs from metric null geodesics.

Polarization has repeatedly been discussed as a probe of cosmic rotation. A rotating spacetime can rotate local tetrads along null rays, and parity-violating or axion-like couplings can rotate electromagnetic polarization even in an otherwise FLRW geometry. These effects should not be conflated. The former is a gravitational optical effect in an anisotropic or vortical metric; the latter is cosmic birefringence from matter couplings. Claims of large-scale polarization alignments or anisotropic polarization rotation have therefore been controversial, and most are not regarded as evidence for a Gödel-like universe. Nevertheless, exact rotating models remain useful calibrators for such effects because they give unambiguous geodesic and polarization-transport equations.

Recent phenomenological work has also asked whether rotation could affect late-time distance indicators or the Hubble tension [25,26]. These proposals are interesting mainly as effective models: a small vorticity or anisotropic component can mimic direction-dependent expansion rates or alter luminosity-distance relations. At present they should be treated as speculative unless embedded in a full metric solution with a consistent matter sector and tested against CMB, baryon acoustic oscillation, lensing, and structure-growth data simultaneously. For a compact overview, Table 1 summarizes these constraints alongside the broader theoretical features of various rotating solutions.

Table 1. Representative classes of rotating cosmological solutions and their main use. The table is not exhaustive; it emphasizes models that recur in the causality and observational literature.

Class	Main Ingredients	Main Features and Constraints	References
Gödel	Dust, $\Lambda < 0$	Exact homogeneous model with closed timelike curves; non-expanding ($\Theta = 0$) and physically non-viable.	[1]
Homogeneous Gödel-type	m^2, ω^2, varied sources	Rotation–curvature competition; causal sector for $m^2 \geq 4\omega^2$.	[7,8]
Bianchi rotating models	Shear, vorticity, curvature	Strict CMB anisotropy bounds (Planck) on vorticity, shear, and anisotropic expansion.	[5,6,11,13,14]
Obukhov–Korotky type	Expansion, shear-free rotation	Avoids standard causal pathologies; constrained mainly by cosmological optical and polarization effects.	[9,10]
Einstein–Cartan/gauge gravity	Spin, torsion, dilation currents	Sourced by microscopic spin density; dynamically suppressed at late cosmological times.	[27–29]
String/supergravity	Fluxes, branes, supersymmetry	Emphasizes holography, supersymmetry, and chronology protection over observational phenomenology	[19–22]
Modified gravity	Higher curvature, torsion, Lorentz violation	Field equations algebraically isolate causal sectors; subject to theory-specific parameter bounds.	[15,16,18,30,31]

6. Gödel-Type Solutions in Generalized Matter Models and Modified Gravity

6.1. Einstein–Cartan Theory and Gauge Gravity

The natural extension of rotating cosmology in a theory with torsion is Einstein–Cartan gravity. In this framework spin density sources torsion algebraically, and the effective stress tensor can differ from that of a perfect fluid at high densities. Rotating cosmological solutions in Einstein–Cartan and related Poincaré gauge models were developed partly to ask whether microscopic spin can seed macroscopic vorticity or remove singularities [10,27–29]. The connection with the Gödel problem is twofold. Torsion can modify the relation between the vorticity scale and the curvature scale in Gödel-type metrics, and it can change the effective energy conditions that enter singularity and causality arguments.

The conceptual advantage of gauge gravity is that rotation has both orbital and intrinsic-spin aspects. In a Weyssenhoff fluid, for example, spin corrections scale with density and are expected to be relevant in the early universe rather than at late times. In metric-affine or Poincaré gauge cosmologies, additional connection modes may behave as effective fluids with anisotropic stresses. These possibilities broaden the model space, but they also make observational interpretation harder: the measured smallness of late-time vorticity need not directly constrain early spin-torsion phases.

6.2. Scalar Fields, Electromagnetic Fields, and Anisotropic Matter

Even within general relativity, the matter source supporting a Gödel-type metric need not be dust. Scalar fields, electromagnetic fields, and anisotropic fluids can generate effective stress tensors that select different values of m^2/ω^2. A common result is that adding a scalar field aligned with the z direction can move a homogeneous Gödel-type solution toward the causal bound. This mechanism is important because it demonstrates that chronology violation is not a purely geometric inevitability of the ansatz. The same rotating coframe can be supported in causal or noncausal sectors depending on the matter equations and couplings [8,15,32].

Electromagnetic generalizations are similarly instructive. Maxwell fields can contribute anisotropic pressure and alter the balance between rotation and spatial curvature. In string-inspired effective actions, antisymmetric tensor fields and dilatons play analogous roles, leading to rotating backgrounds that resemble Gödel geometries but are embedded in a larger field content [33–35].

6.3. String Theory, Supergravity, and Holography

String theory revived interest in Gödel-like backgrounds because they can be exact, supersymmetric, and causally problematic at the same time. Supersymmetric Gödel universes in string theory and M-theory show that unbroken supersymmetry alone does not guarantee ordinary chronology [19]. Related solutions include black holes in Gödel universes, pp-wave duals, and geometries with velocity-of-light surfaces beyond which closed timelike curves appear [21,22].

The phrase "holographic protection of chronology" emerged from the observation that the holographic screen or physically allowed region can end before the chronology-violating region becomes operational [20]. This does not prove a universal chronology-protection theorem, but it changes the question. Instead of asking only whether the classical metric contains closed timelike curves, one asks whether the full quantum-gravitational description includes boundary conditions, brane probes, or instabilities that prevent those curves from representing physical histories.

These models also illustrate a broader point. In higher-dimensional theories a four-dimensional rotating universe may be a slice, reduction, or effective description of a higher-dimensional background. The causal structure of the reduced metric may not capture the full causal structure of the parent theory, especially when gauge fields arise from off-diagonal metric components.

6.4. Higher-Curvature and Nonlocal Modifications

Gödel-type metrics have become diagnostic solutions for modified gravity. In metric $f(R)$ gravity, the scalar curvature of a homogeneous Gödel-type spacetime is constant, so the field equations reduce to algebraic conditions involving $f(R)$ and $f_R(R)$ for many matter choices. This makes the ansatz a clean test of whether the theory admits causal and noncausal sectors [15]. The notation f_R means df/dR. Palatini, hybrid metric–Palatini, Horndeski, and nonmetricity variants are similar in spirit, although the independent connection, derivative couplings, or nonmetricity scalar change the algebraic relations [30,31,36,37].

Chern–Simons modified gravity provides a different mechanism. The Pontryagin density and the external or dynamical scalar field impose extra constraints on rotating metrics. Depending on the scalar configuration, Gödel-type solutions may survive, be excluded, or require special parameter relations [16,17]. Hořava–Lifshitz gravity, with its preferred foliation, is conceptually interesting because the Gödel solution precisely challenges the existence of a global time; the compatibility of Gödel-type metrics with a preferred foliation therefore probes the theory at a structural level [38].

Quadratic-curvature models such as $f(R, Q)$ and nonlocal or infinite-derivative gravities have also been studied with Gödel-type metrics [39]. Here Q denotes the Ricci-quadratic invariant, conventionally $Q = R_{\mu\nu}R^{\mu\nu}$. Because the curvature invariants are often constant, some nonlocal form factors simplify dramatically, turning the problem into algebraic constraints. Such examples are useful but should be interpreted cautiously: high symmetry can hide propagating degrees of freedom that matter for stability and perturbations.

6.5. Teleparallel, Lorentz-Violating, and Matter-Coupled Models

Teleparallel gravity rewrites gravitation in terms of torsion rather than curvature. In $f(T)$ gravity, the tetrad choice is dynamically important, and Gödel-type metrics test both the field equations and the remnant Lorentz symmetry of the theory. In this teleparallel notation T is the torsion scalar, not the matter trace. Studies of Gödel-type solutions in $f(T)$ gravity found that the causal character can depend on the function f, on matter content, and on whether scalar sources are included [18]. This makes the model a useful comparison with Einstein–Cartan theory: both involve torsion, but in very different ways.

Lorentz-violating and vector-tensor models, including bumblebee-like backgrounds, add preferred directions [40]. Since a rotating universe already selects a preferred congruence, such theories can support or obstruct Gödel-type metrics through the alignment of the vector field with the vorticity. Matter-coupled theories such as $f(R, T)$ or energy-momentum-squared gravity add another layer. In this context $T = T^{\mu}{}_{\mu}$ is the trace of the matter stress tensor $T_{\mu\nu}$, so the effective gravitational response depends explicitly on the matter source; changing that source can move the solution across the causal threshold [41–44].

The modified-gravity literature therefore does not give a single answer to the question "does the theory allow a

Gödel universe?" The better question is: for which sources and parameters does the theory admit homogeneous rotating solutions, and do the field equations force $m^2 < 4\omega^2$ or allow $m^2 \geq 4\omega^2$? This criterion makes Gödel-type metrics a compact diagnostic for chronology in alternative gravity.

7. Causality and Global Structure

The Gödel solution is sometimes described as proving that general relativity permits time travel. That statement is too quick. What it proves is that the local Einstein equations plus reasonable local matter do not by themselves enforce a global causal order. The gap is global. To exclude closed timelike curves one usually adds conditions such as global hyperbolicity, stable causality, asymptotic structure, energy conditions plus genericity assumptions, or boundary conditions motivated by quantum theory.

Chronology protection proposals come in several forms. Hawking's chronology protection conjecture argues that the laws of physics prevent the formation of macroscopic chronology-violating regions under appropriate conditions [2]. Semiclassical arguments often examine whether the renormalized stress tensor diverges near chronology horizons. In Gödel spacetime the situation is different from a time-machine construction in asymptotically flat space, because there is no chronology-respecting exterior from which a compactly generated chronology horizon forms. The solution is globally acausal from the start.

This is why Gödel-type families are so useful. The parameter m^2/ω^2 lets one compare causal and noncausal homogeneous metrics without changing the broad ansatz. In modified gravity, the field equations may select either side of the threshold. In string theory, holographic screens or brane instabilities may make the closed timelike curve region inaccessible. In expanding models, cosmic time may exist even when the fluid has nonzero vorticity, provided the rotation is not organized in the Gödel way. These examples all support the same conclusion: rotation is a local kinematic property, while chronology violation is a global causal property.

8. Stability

Stability questions are more difficult than existence questions. An exact rotating solution can be algebraically elegant but dynamically irrelevant if small perturbations grow rapidly or if the matter source is unphysical. There are at least four distinct notions of stability in the literature.

First, one can study geodesic stability: whether timelike or null geodesics remain bounded under small changes in initial data. The Gödel universe has unusual but regular geodesic behavior, including confinement in the rotating directions for many trajectories, yet this does not remove the global causal anomaly. Second, one can perturb test fields, such as scalar or electromagnetic fields, on the fixed background. Mode spectra in Gödel-like metrics probe whether the spacetime acts as a stable arena for quantum fields. Third, one can perturb the metric and matter fields within general relativity or another theory. This is the most relevant cosmological notion, but also the most technically involved because perturbations of rotating backgrounds do not decompose as simply as FLRW scalar, vector, and tensor modes. Fourth, one can ask about formation stability: whether plausible initial data evolve toward a rotating solution.

The original Gödel model is not an attractor for realistic expanding cosmology. Its matter source and negative cosmological constant are finely balanced to produce zero expansion. Perturbative studies have nevertheless found that some sectors are less violently unstable than one might expect; for example, gravitational-wave or density-gradient perturbations can show neutral or oscillatory behavior in suitable variables [23]. This should not be overinterpreted. Neutral linear behavior in a restricted sector does not establish nonlinear stability, nor does it solve the absence of a global Cauchy problem in an acausal spacetime.

For expanding rotating cosmologies, stability is tied to the decay of vorticity relative to the Hubble expansion. In many nearly FLRW settings vorticity decays with expansion unless it is sourced by anisotropic stress, defects, magnetic fields, torsion, or modified gravity. This is one reason why late-time global rotation is hard to maintain. Conversely, early-universe rotation may be dynamically erased by inflation or diluted by expansion, leaving only extremely small residual signatures.

In modified gravity, stability must be reconsidered theory by theory. A Gödel-type solution that is algebraically allowed may lie in a ghost sector, require $f_R < 0$, violate a scalar-field stability condition, or use a tetrad that excites problematic modes. Therefore a complete assessment requires both the causal classification of the background and the perturbative spectrum of the underlying theory. Much of the literature has focused on existence and causality; systematic perturbative stability remains less complete.

9. Synthesis and Outlook

The development from Gödel's 1949 paper to modern modified-gravity studies reveals a coherent set of lessons, beginning with the fact that rotation is a legitimate relativistic cosmological degree of freedom. It cannot be dismissed by appealing to the FLRW ansatz. The correct question is observational and dynamical: how much vorticity is allowed, how is it sourced, and what other anisotropies accompany it?

At the same time, the Gödel causal pathology should not be identified with rotation itself. Homogeneous Gödel-type metrics show explicitly that the existence of closed timelike curves depends on the ratio m^2/ω^2, while expanding rotating models show that nonzero vorticity can occur in spacetimes with a much more conventional cosmological interpretation. Observational constraints remain strong but model-dependent: the CMB severely restricts simple anisotropic and rotating models, especially when vorticity is tied to shear, whereas shear-free or weakly coupled rotational sectors require separate analysis through light propagation, polarization, structure growth, and consistency with the full cosmological data set.

Gödel-type metrics are therefore valuable probes of gravitational theory rather than mere curiosities. In Einstein–Cartan gravity they test the role of spin and torsion; in string theory they test the relation between supersymmetry, holography, and chronology; in higher-curvature and teleparallel theories they reduce complicated field equations to transparent algebraic constraints. A theory that admits only chronology-violating rotating vacua may be less attractive than one whose field equations naturally select the causal sector.

Stability remains the major open filter. Existence of an exact solution is only the first step. A physically relevant rotating universe must be observationally viable, dynamically stable, free of unacceptable ghost or gradient instabilities, and compatible with a well-defined initial-value formulation. On these criteria the original Gödel universe is best viewed as a profound counterexample and a diagnostic tool, not as a model of our Universe. The broader program of rotating cosmology remains useful precisely because it clarifies which assumptions make standard cosmology causal, stable, and nearly isotropic.

Funding

This research received no external funding.

Institutional Review Board Statement

Not applicable.

Informed Consent Statement

Not applicable.

Data Availability Statement

Not applicable.

Acknowledgments

The author acknowledges the University of Seville for their support through the Plan-US of aid to Ukraine.

Conflicts of Interest

The author declares no conflict of interest.

Use of AI and AI-Assisted Technologies

During the preparation of this work, the author used Grammarly and Gemini to check for errors and improve the English grammar of the text. After using these tools, the author reviewed and edited the content as needed and takes full responsibility for the content of the published article.

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