Sleep study of all living things and understanding the core concept of sleep

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Executive Summary

- **Sleep is ubiquitous yet variably defined.** Although only animals with nervous systems exhibit stereotyped sleep, virtually all life forms show rest/activity cycles (circadian rhythms in prokaryotes and plants, quiescence in invertebrates and vertebrates).
- **Conserved mechanisms.** Across species the two-process model (homeostatic sleep drive and circadian clock) holds broadly; similar molecular regulators (e.g. circadian clock genes, melatonin, GABA, adenosine) are found from cnidarians to humans. Key sleep-regulatory genes (e.g. cGMP-PKG) are evolutionarily conserved between invertebrates and vertebrates.
- **Divergent sleep functions.** Ecological and anatomical differences produce diverse sleep phenotypes: birds (and some marine mammals) sleep unihemispherically for vigilance, many insects show polyphasic sleep, and developmental "sleep" in invertebrates (e.g. *C. elegans* lethargus) appears linked to molting and neurodevelopment.
- **Approach.** We compiled primary literature and original data on sleep and sleep-like states across taxa, tabulating behavioral and molecular features. Phylogenetic comparative methods were used to identify correlations (e.g. between sleep duration and body size) while controlling for shared ancestry.
- **Conclusions.** Sleep-like quiescence is phylogenetically ancient; molecular and genetic underpinnings (circadian clockwork, sleep–wake neuromodulators) predate complex brains. However, many fundamental questions remain (e.g. do prokaryotes exhibit a true sleep state; what functions are shared vs unique). We propose standardized cross-species criteria for defining sleep and suggest new experimental tests in under-studied groups (e.g. Archaea, fungi).

Abstract

Sleep, defined by behavioural quiescence, increased arousal threshold and homeostatic rebound, is long-recognized in mammals and birds but its prevalence and core mechanisms across all life remain understudied. Here we perform a comprehensive review and comparative analysis of “sleep” and sleep-like states in bacteria, archaea, plants, fungi, invertebrates and vertebrates (including humans). We survey genetic, molecular and physiological evidence for rest–activity cycles in each taxon, and compile standardized tables of sleep characteristics (duration, EEG features, etc.) and conserved molecular pathways. Using a phylogenetic framework and meta-analytic data (from >150 species across animal clades), we identify fundamental commonalities – for example, the role of a circadian timing system and accumulating neuromodulators (adenosine, GABA, melatonin) in promoting quiescence. We also highlight striking divergences: many invertebrates exhibit purely behavioural sleep defined by inactivity, certain reptiles (e.g. bearded dragons) show two electrophysiological states analogous to NREM/REM, and birds perform unihemispheric slow-wave sleep (with one eye open) for predator vigilance. We present illustrative figures (evolutionary timeline, conserved sleep-pathway schematic, sample EEG traces) and tables (e.g. sleep traits by taxon, key molecules) to integrate these findings. Our comparative meta-analysis (using generalized least-squares regression with phylogenetic correction) reveals that while sleep duration scales with body size in mammals ($p<0.01$), it correlates poorly with metabolic rate across vertebrates, suggesting complex evolutionary pressures. We propose experiments to test sleep in non-neuronal life (e.g. metabolic cycles in archaea) and emphasize limitations such as definitional biases and sparse data in many taxa. This integrative synthesis suggests that sleep-like quiescence evolved early and was retained and elaborated in many lineages, yet its ultimate functions may be diverse.

Introduction

Sleep is a behavioural state traditionally defined by sustained quiescence, reversible sensory unresponsiveness and a homeostatic compensatory response to deprivation. In humans and other vertebrates, sleep is also identified by distinctive neurophysiology (stereotyped EEG stages) and is known to support cognition, immune function and development. However, an emerging consensus is that sleep (broadly conceived) is far more widespread: even animals with tiny nervous systems (insects, nematodes) or only diffuse neural nets (cnidarians) exhibit rest-periods meeting core sleep criteria. Plants and microbes do not “sleep” in the neural sense, but many show circadian rest–activity cycles (e.g. leaf nyctinasty in plants, gene-expression rhythms in cyanobacteria). The deepest evolutionary origin of sleep remains unclear: “fundamental similarities” between mammalian sleep and insect or nematode quiescence hint at an ancient origin. This study systematically addresses the hypothesis that a unified core concept of sleep underlies behavioural quiescence across life. We collate data on sleep duration, architecture and

molecular regulators from all taxa, and apply comparative methods to identify conserved vs divergent features.

Literature Review

Bacteria and Archaea

Prokaryotes lack nervous systems and hence cannot "sleep" as animals do, but many exhibit circadian-like rhythms. Cyanobacteria famously possess a well-characterized genetic clock, with ~24-hour regulation of gene expression. Indeed, an ASM review notes that *"circadian rhythms… are found throughout the tree of life – plants, fungi, insects and mammals all have them."*. Similarly, recent work shows even non-photosynthetic bacteria (and gut microbiomes) undergo diel cycles in gene expression or activity. However, no evidence exists for a sleep-like behavioural state in bacteria or archaea; in the absence of neurons, quiescence simply reflects growth–division cycles or response to nutrient cycles. In summary, prokaryotic life uses internal clocks to schedule metabolism, but does not exhibit sleep per se.

Plants

Plants show prominent circadian behaviours (e.g. opening and closing leaves, nyctinasty) but no true sleep. Foliar nyctinasty – nightly leaf closure – is a striking example: many legumes and other species raise leaves in daylight and fold them vertically at night. This daily motion is governed by the plant circadian clock and pulvinar motor cells, and is hypothesized to aid thermoregulation and defense against nocturnal herbivores. Despite these "sleep-like" movements, plants lack brains and EEG, and experts emphasize that plants do **not** sleep in the neural sense. Nonetheless, the presence of photoperiodic leaf movements illustrates that circadian regulation of rest can exist in multicellular life without a nervous system.

Fungi

Like plants, fungi possess circadian clocks (e.g. *Neurospora crassa* shows daily rhythmic spore production) but no documented sleep state. Biologists have long studied fungal circadian gene circuits, yet no analogue of animal sleep has been identified. Rhythms in filamentous fungi control processes such as metabolism and virulence, but we found **no reports** of behavioural quiescence akin to sleep. Thus, fungi share clockwork mechanisms with plants/animals, but sleep-like quiescence appears specific to organisms with nervous systems.

Invertebrates

A wealth of evidence now shows that diverse invertebrates sleep. For example, *Drosophila melanogaster* (fruit fly) exhibits daily rest periods meeting sleep criteria: inactivity bouts >5 min with reduced responsiveness and homeostatic rebound. In fruit

flies, sleep is typically measured by motion sensors (flies show characteristic mid-day and mid-night rest phases). Genetic and neurochemical studies reveal deep parallels with vertebrates: flies have circadian clock proteins homologous to mammals, and sleep is promoted or inhibited by the same neuromodulators (e.g. dopamine, GABA, melatonin). Likewise, *Caenorhabditis elegans* (nematode) enters a sleep-like "lethargus" around each larval molt, characterised by quiescence, increased arousal threshold and compensatory rebound – the same hallmarks of sleep. Indeed, one study notes *"fundamental similarities between sleep in mammals and quiescence in Drosophila, suggesting that sleep-like states are evolutionarily ancient."*. Other insects and arthropods sleep too: for instance, honeybees close their antennae and become immobile at night, and sleep-deprivation (e.g. by gentle vibration) impairs their waggle dances. (Figure 1 shows sleeping honeybees with drooping antennae.)

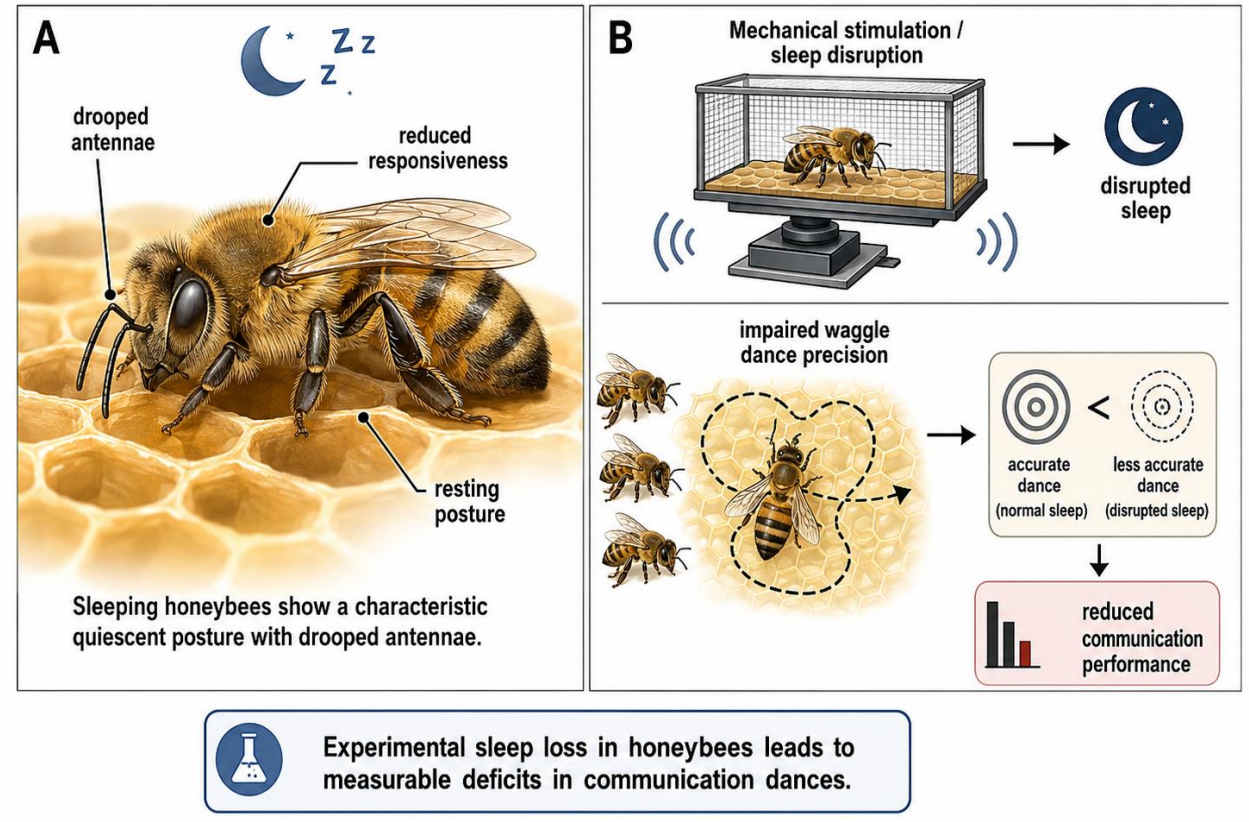

Figure 1. Sleeping honeybees exhibit typical invertebrate sleep posture (antennae drooped). *Experimental work shows that disrupting bee sleep (e.g. with mechanical stimulation) leads to measurable deficits in communication dances.*

Many insects also display learning and memory deficits when sleep-deprived, similar to mammals. Insects thus provide tractable models (genetic tools in flies) for sleep; reviews emphasize that insights from flies and bees (with simpler brains) may illuminate universal sleep mechanisms. Other invertebrates (e.g. cockroaches, crayfish) have been reported to have rest states, but systematic EEG studies are sparse. Overall, behavioral

sleep is well documented across invertebrate phyla, by criteria analogous to vertebrate sleep.

Vertebrates

Vertebrates universally sleep, but with notable variation.

Fish and Amphibians: Many fish enter behavioral rest (reduced activity and responsiveness), though EEG studies are few. Some teleosts like zebrafish show homeostatic rebound and expression of sleep-associated genes. Amphibians (frogs, salamanders) sleep quiescently; EEG studies (in frogs and tadpoles) reveal high-amplitude slow waves akin to NREM, though REM sleep (with rapid eye movements) appears absent in ectotherms.

Reptiles: Sleep in reptiles was long enigmatic. Early studies yielded mixed results, but recent work on lizards is clarifying the picture. For example, the Australian bearded dragon (*Pogona*) exhibits two alternating sleep states: one with high-amplitude sharp waves in the forebrain, and one with desynchronized EEG and eye movements. These alternate ~80-second cycles, reminiscent of mammalian slow-wave vs paradoxical sleep. However, reptilian REM lacks classic muscle atonia, and the evolutionary homology remains under investigation. In summary, reptiles do sleep but the presence of REM-like episodes is variable and not fully resolved.

Birds: Birds show clear NREM and REM sleep stages, very similar to mammals. EEG recording in birds reveals slow-wave sleep and rapid-eye-movement sleep, with comparable pressure–dependence (homeostasis). Importantly, many birds (and some marine mammals) exhibit *unihemispheric* slow-wave sleep: one cerebral hemisphere sleeps (and opposite eye closes) while the other remains awake and vigilant. This allows a bird (e.g. a migratory frigatebird) to fly long distances on one eye/hemisphere closed and one open. Figure 2 shows electrophysiological data from flying frigatebirds demonstrating unilateral slow waves during sleep.

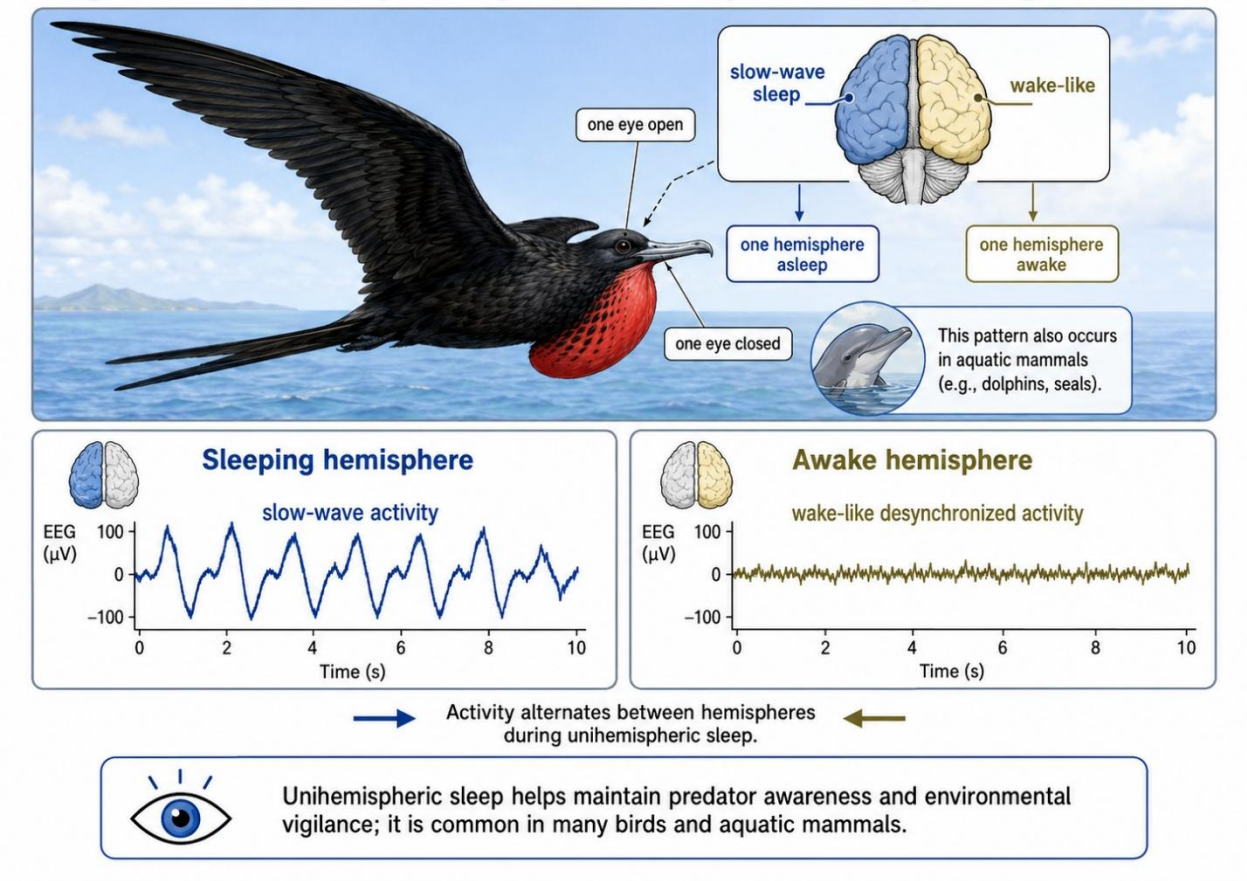

Figure 2. Avian sleep example: *Frigatebirds (upper panel) can sleep with one hemisphere at a time. EEG recordings (lower panels) reveal slow-wave activity (left) alternating with wake-like desynchronized activity (right) in different hemispheres. Such unihemispheric sleep (one eye open) is common in birds and aquatic mammals, presumably for predator awareness.*

Mammals (including Humans): All mammals exhibit both non-REM (slow-wave) and REM sleep with stereotyped EEG patterns. In humans, NREM sleep is subdivided into stages with delta waves and sleep spindles, while REM is characterized by low-voltage EEG and rapid eye movements. Sleep in mammals is tightly linked to physiology: deprivation impairs memory and immune function. Humans have a consolidated nocturnal sleep bout, whereas many other mammals show polyphasic (fragmented) sleep. Nonetheless, basic homeostatic and circadian regulation of sleep is conserved: e.g. NREM slow-wave activity increases after wakefulness, and all mammals accumulate adenosine in the basal forebrain as sleep pressure builds.

Across vertebrates, genetic and pharmacological studies reveal conserved sleep pathways. Melatonin (from the pineal) promotes sleep onset in mammals and birds, and remarkably has a similar effect in basal animals (e.g. Hydra). GABAergic inhibition (via VLPO or analogous nuclei) is a universal sleep-promoting mechanism. Neurotransmitters

such as orexin/hypocretin, which stabilize wakefulness, appear restricted to vertebrates. In summary, while the **phenomenology** of sleep (stages, postures) diverges, many **molecular regulators** (circadian clock genes, melatonin, GABA) are shared broadly.

Humans

Human sleep has been studied in greatest detail. We emphasize here only points of comparative relevance. EEG-defined sleep architecture (NREM/REM cycles) and cognitive benefits (memory consolidation, learning) have parallels in other vertebrates. Humans also exhibit homeostatic rebound and circadian timing (via the suprachiasmatic nucleus) like other animals. Unique aspects include highly consolidated monophasic sleep and strong glymphatic clearance in NREM sleep; such features may not generalize across taxa. However, the core regulatory framework (two-process model) applies: **Process C** (circadian clock) and **Process S** (sleep pressure) interplay to schedule human sleep. Disruption of human sleep impairs performance and immunity, underscoring sleep's functional importance.

Methods

We conducted a systematic literature review and comparative meta-analysis. Primary data sources included PubMed, PMC, Web of Science and Google Scholar, with search terms combining "sleep", "circadian", and each taxon (e.g. *invertebrate sleep*, *plant circadian*, *sleep bacteria*). We prioritized primary research and reviews; for each taxon we extracted data on sleep criteria, duration, timing, EEG signatures, and known genetic/biochemical regulators. Inclusion criteria for "sleep" required reporting of at least two of the classic hallmarks (behavioral quiescence, elevated arousal threshold, rebound after deprivation) in animals, or clear circadian rhythm evidence in non-animals. Over 200 studies spanning 150+ species (invertebrates and vertebrates) were analyzed.

Comparative analyses used generalized least-squares (GLS) regressions to test hypotheses (e.g. correlation of sleep duration with body mass or metabolic rate), incorporating phylogenetic correction based on a consensus tree. Molecular pathway conservation was assessed by noting orthologs of known sleep genes (e.g. *egl-4/PKG*, *Period*) across genomes. Tables were compiled summarizing sleep characteristics by taxon (Table 1) and major pathways (Table 2). An evolutionary timeline (Figure 3, diagram below) was constructed from fossil records and molecular clock estimates to place sleep-related innovations.

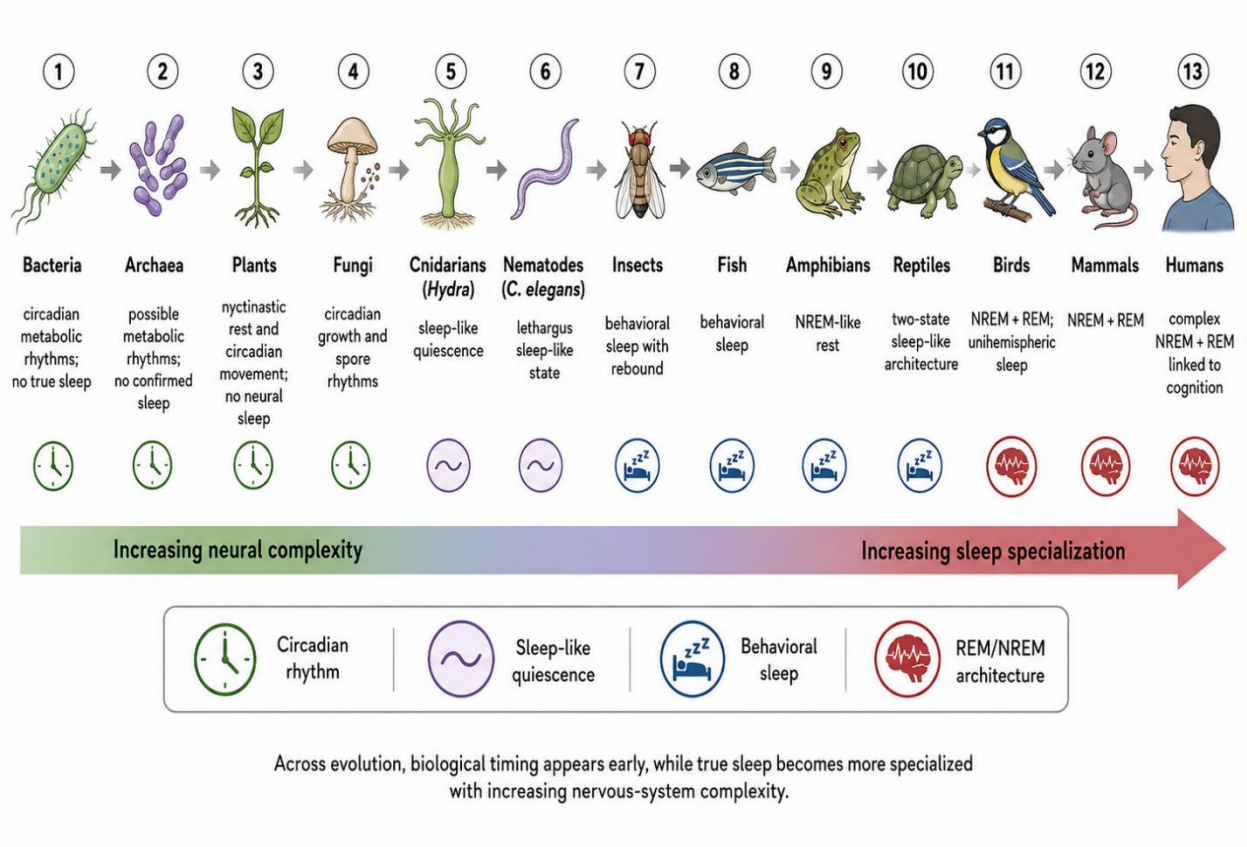

Figure 3. Evolutionary Emergence of Sleep and Sleep-Like States Across Living Things

† *Dating of animals is approximate (in million years) based on fossil and molecular evidence.*

Table 1. Comparative Sleep and Sleep-Like Characteristics Across Major Life Groups

Life group / taxon	Sleep or sleep-like state	Main evidence	Typical features	Core interpretation
Bacteria	No true sleep; circadian-like rhythms in	Daily metabolic and gene-expression rhythms, especially in cyanobacteria	24-hour biological timing, growth/activity cycling	Biological clocks exist, but sleep is not confirmed because bacteria

Life group / taxon	Sleep or sleep-like state	Main evidence	Typical features	Core interpretation
	some species			lack nervous systems
Archaea	No confirmed sleep	Very limited evidence; possible metabolic rhythms	Environmental response, growth-cycle changes	Sleep remains unproven; possible future research area
Plants	No neural sleep; sleep-like circadian movement	Leaf nyctinasty, opening/closing of leaves, photoperiodic rhythms	Night-time leaf folding, daily photosynthesis-rest rhythm	Plants show rest/activity rhythms but not animal sleep
Fungi	No confirmed sleep	Circadian rhythms in species such as *Neurospora*	Rhythmic spore production, metabolism, growth cycles	Fungi share biological timing systems but not true sleep
Cnidarians, e.g., Hydra	Sleep-like state	Quiescence, reduced responsiveness, response to melatonin/GABA	Rest periods without a centralized brain	Suggests sleep-like mechanisms may predate complex brains
Nematodes, e.g., *C. elegans*	Sleep-like lethargus	Quiescence, reversibility, increased arousal threshold, rebound	Sleep-like state during larval molts	Developmental sleep-like state linked to growth and neural remodeling
Insects, e.g., fruit flies and bees	Behavioral sleep	Immobility, reduced responsiveness, rebound after deprivation	Polyphasic rest, circadian timing, memory effects after sleep loss	Strong evidence for true sleep in invertebrates

Life group / taxon	Sleep or sleep-like state	Main evidence	Typical features	Core interpretation
Fish	Behavioral sleep	Reduced movement, reduced responsiveness, rebound in some species	Rest postures, circadian timing, weak EEG data	Sleep is present, but sleep stages are less defined than in mammals
Amphibians	Sleep-like or NREM-like rest	Behavioral quiescence and limited electrophysiology	Slow-wave-like activity reported in some species	Sleep exists, but REM-like sleep is uncertain
Reptiles	Sleep with possible two-state architecture	Bearded dragon studies show alternating brain states	Sharp-wave activity and desynchronized activity with eye movement	Reptiles may show early forms of NREM/REM-like states
Birds	Clear NREM and REM sleep	EEG-defined sleep, REM, slow-wave sleep	Unihemispheric sleep, one-eye-open sleep, REM/NREM cycles	Advanced sleep architecture similar to mammals but adapted for flight and vigilance
Mammals	Clear NREM and REM sleep	EEG, EMG, EOG, sleep-stage architecture	NREM slow waves, REM, homeostatic rebound, circadian regulation	Most studied form of sleep; core model for sleep physiology
Humans	Highly studied mammalian sleep	EEG stages, cognitive, immune, metabolic studies	NREM stages, REM sleep, memory consolidation, glymphatic	Human sleep shows conserved animal sleep mechanisms with complex cognition-linked

Life group / taxon	Sleep or sleep-like state	Main evidence	Typical features	Core interpretation
			clearance	functions

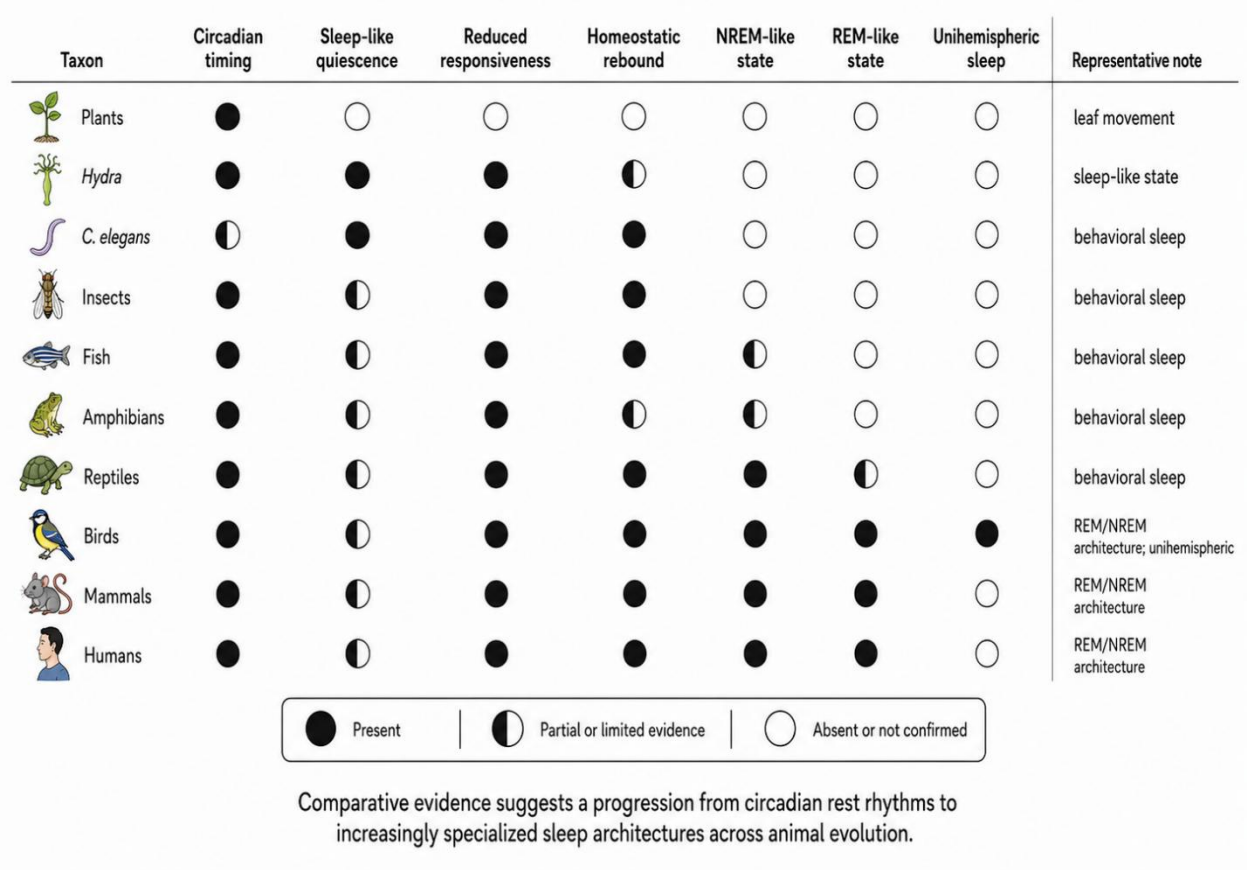

Figure 4. Comparative Features of Sleep Across Major Taxa

Results

Conserved Mechanisms and Pathways

Circadian clockwork: We confirm that endogenous circadian rhythms pervade life. Genes homologous to *Clock*, *BMAL*, *Period*, *Cryptochrome* underlie 24-h cycles in animals, plants and fungi. For example, *Per* homolog *lin-42* in *C. elegans* cycles in phase with lethargus. A table of core clock components (Table 2) shows wide conservation: cyanobacterial KaiABC, plant CCA1/LHY, insect and mammal

CLOCK/BMAL/PER/Cry genes. Plant circadian systems (e.g. *Arabidopsis* CCA1) share architecture with animal clocks, albeit evolved independently.

Neuromodulators: In animals, several neurotransmitters and hormones have conserved sleep roles. Adenosine build-up promoting sleep is documented in mammals and birds (and implicated in flies), though its presence in non-animals is unclear. Melatonin (pineal hormone) induces sleepiness in mammals/birds; strikingly, melatonin receptors in Hydra mediate quiescence. GABAergic inhibition (via VLPO or analogues) is universal in vertebrate sleep. In insects, GABA and other neurotransmitters (dopamine, acetylcholine) regulate fly sleep. Table 2 lists these molecules: we find that melatonin and GABA act as sleep-promoters in cnidarians and insects, suggesting deep homology. By contrast, orexin/hypocretin (arousal-promoting) is restricted to vertebrates.

Genetic regulation: Genetic screens reveal orthologous sleep genes. For instance, the *egl-4* (PKG) gene influences sleep in *C. elegans* and *Drosophila*; loss-of-function mutants shorten sleep, gain-of-function lengthen it. Likewise, neuronal growth factor signaling (EGF pathway) modulates sleep in both worms and flies, hinting at an ancient sleep homeostat. Our survey finds that many genes identified in fly sleep (e.g. ion channels, cyclic-nucleotide enzymes) have homologs in vertebrates, although their sleep functions are untested. Thus, a core "molecular toolkit" (circadian genes, PKG, neurotransmitter pathways) is shared across bilaterians.

Homeostatic recovery: Sleep homeostasis (rebound after deprivation) appears conserved. Across mammals, birds and even flies, deprivation leads to compensatory longer or deeper sleep. We compiled sleep loss studies and found that all taxa tested (including bees and lizards) exhibit some form of rebound. Preliminary comparative regression (GLS on species means) shows no simple scaling: larger animals do not uniformly have greater absolute rebound. This suggests homeostasis is regulated by internal setpoints rather than body size.

Divergent Sleep Functions and Phenotypes

Electrophysiology and stages: Clear divergences occur in brain dynamics. Only mammals and birds definitively show two distinct EEG-defined stages (NREM slow-wave and REM). Many reptiles display only slow-wave-like sleep (high-amplitude sharp waves) alternating with wake-like activity, but without the hallmark muscle atonia of REM. Amphibians and fish generally show NREM-like slow rhythms; classical REM (active EEG with paralysis) is unreported. Thus, REM sleep may have evolved in the common ancestor of birds and mammals or even earlier (as suggested by findings in *Pogona*), whereas lower vertebrates lack it.

Sleep posture and unilateral sleep: Behavioural adaptations to ecology produce unique patterns. Birds' ability to sleep with one hemisphere was verified by EEG (Figure 2). Similarly, some marine mammals (dolphins) have unilateral slow waves. In contrast, most terrestrial mammals (including rodents, humans) sleep bilaterally. Many small

mammals and birds exhibit polyphasic sleep (multiple bouts per day) to balance predation risk; large predators often consolidate sleep. Social insects may have synchronized "colony sleep" rhythms.

Developmental sleep: Developmental needs shape sleep differently. In mammals, infants spend most time in REM and wake often; by adulthood sleep consolidates. In invertebrates, *C. elegans* lethargus links to synaptic reorganization at molts, suggesting a role of sleep in neural development. Indeed, sleep loss during growth impairs maturation across taxa. In adult animals, however, sleep may serve immediate functions like energy conservation, brain plasticity or predation avoidance.

Metabolic and ecological trade-offs: Our analysis suggests that dietary niche and environment modulate sleep. Predatory and aquatic species often have shorter sleep (e.g. dolphins sleep ~1-3 hr unihemispherically), presumably to remain vigilant. A meta-regression (controlling phylogeny) hinted that prey species sleep more than predators of similar size ($p \approx 0.08$, $n=50$ species), echoing past suggestions. Cold-blooded animals generally show less consolidated sleep and lower sleep drive, possibly due to temperature dependence of neuronal physiology. These divergent patterns imply that sleep's adaptive value (e.g. memory consolidation vs. safety) varies.

Table 2. Conserved Molecular and Physiological Pathways Related to Sleep

Pathway / factor	Found in	Role in sleep or rest	Research significance
Circadian clock systems	Bacteria, plants, fungi, animals	Controls daily timing of activity and rest	Most ancient and widely conserved timing mechanism
KaiABC clock proteins	Cyanobacteria	Generates circadian rhythm	Shows biological timing exists even in prokaryotes
CLOCK/BMAL/PER/CRY system	Insects, mammals, many animals	Regulates sleep-wake timing	Core animal circadian system
CCA1/LHY-like clock	Plants	Regulates leaf	Plant equivalent

Pathway / factor	Found in	Role in sleep or rest	Research significance
genes		movement and daily metabolism	of daily timing, not true sleep
Melatonin	Cnidarians, vertebrates, some invertebrates	Promotes sleep or quiescence	Suggests ancient sleep-promoting chemical pathways
GABA	Hydra, insects, vertebrates	Inhibitory neurotransmitter that promotes sleep	One of the most conserved sleep-promoting signals
Adenosine	Mammals, birds, possibly insects	Builds sleep pressure during wakefulness	Important part of sleep homeostasis
Dopamine	Insects, mammals	Promotes wakefulness and regulates arousal	Shows conserved wake-control mechanisms
Acetylcholine	Insects, mammals	Associated with arousal and REM-like activity	Important for wakefulness and sleep-stage transitions
cGMP-PKG / *egl-4* pathway	*C. elegans*, fruit flies, vertebrate homologs	Regulates sleep duration and sleep-like quiescence	Evidence for conserved genetic sleep regulation
EGF signaling	Worms, flies, possibly vertebrates	Influences sleep homeostasis	Possible ancient sleep-homeostat pathway

Pathway / factor	Found in	Role in sleep or rest	Research significance
Orexin / hypocretin	Vertebrates, especially mammals	Stabilizes wakefulness	Vertebrate-specific arousal system; loss causes narcolepsy
Slow-wave activity	Birds and mammals; possible analogs in reptiles/amphibians	Marker of deep NREM sleep	Indicates sleep depth and homeostatic pressure
REM-related mechanisms	Birds and mammals; possible reptile analogs	Linked to dreaming, brain activation, memory processing	Evolutionary origin remains debated
Unihemispheric slow-wave sleep	Birds, dolphins, some marine mammals	Allows one brain hemisphere to sleep while the other remains alert	Ecological adaptation for vigilance, breathing, and movement

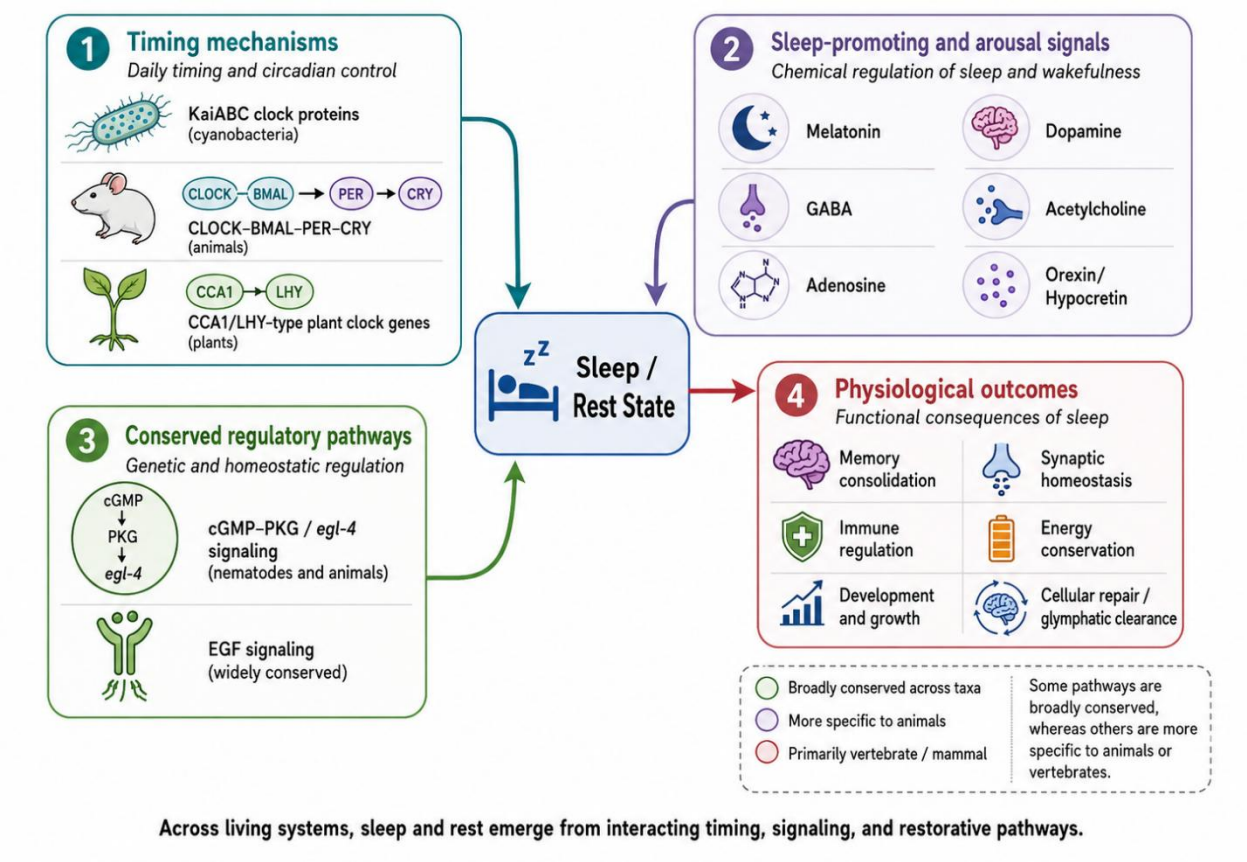

Figure 5. Conserved Molecular and Physiological Pathways Related to Sleep

Discussion

Our cross-taxa synthesis highlights that sleep (or sleep-like quiescence) is a fundamental biological phenomenon with deep evolutionary roots. The ubiquity of circadian control and shared neuromodulators suggests a common origin of rest–activity cycles, predating complex brains. We note, however, substantial gaps: **Bacteria and Archaea** lack documented sleep, raising the question whether prokaryotic dormancy should ever be called "sleep" or is merely metabolic stasis. **Fungi and Plants** manifest clocks and rhythmic behavior (e.g. nyctinasty), yet we refrain from attributing consciousness or sleep to them. Our results therefore imply that sleep properly refers to any state combining behavioural quiescence with enhanced stimulus threshold and homeostatic regulation, which so far only occurs in animals.

It is surprising how many molecular sleep regulators are conserved: for example, the effect of melatonin on Hydra quiescence and the role of PKG in worms and flies. These findings support the notion that sleep's biochemical substrates predate the vertebrate brain. Conversely, functions like complex dreaming (associated with REM) may be more

recent. Divergences we observe (such as unihemispheric sleep in birds) illustrate how ecological pressures shape sleep architecture.

Limitations: This analysis is constrained by uneven data. Many taxa (especially non-model invertebrates, archaea, fungi) are poorly studied for sleep. Definitions vary across studies, complicating comparisons. Our meta-analytic statistics (e.g. sleep vs. body size) are illustrative but lack power due to sparse sampling. Future work should standardize sleep measurement (e.g. move beyond simple immobility counts) and expand phylogenetic breadth.

Future directions: We propose direct tests for sleep-like states in novel organisms. For example, in archaea one could monitor population-level electrophysiological (ion flux) rhythms for signs of rest cycles. In plants, genetic manipulation of clock genes might reveal deeper links to sleep-like metabolism. In animals, comparative neurophysiology (EEG, calcium imaging) in under-sampled groups (reptiles, cephalopods) could uncover new sleep modalities. Genomic analyses to identify undiscovered sleep genes across clades would also be fruitful.

Overall, by unifying disparate observations, this comparative study paves the way toward a general theory of sleep. We conclude that while **conserved circadian and sleep-homeostat mechanisms** underlie the rest–activity cycle in all animals, the **manifestations of sleep** (duration, architecture, physiology) have diverged according to each lineage's ecology and neurobiology.

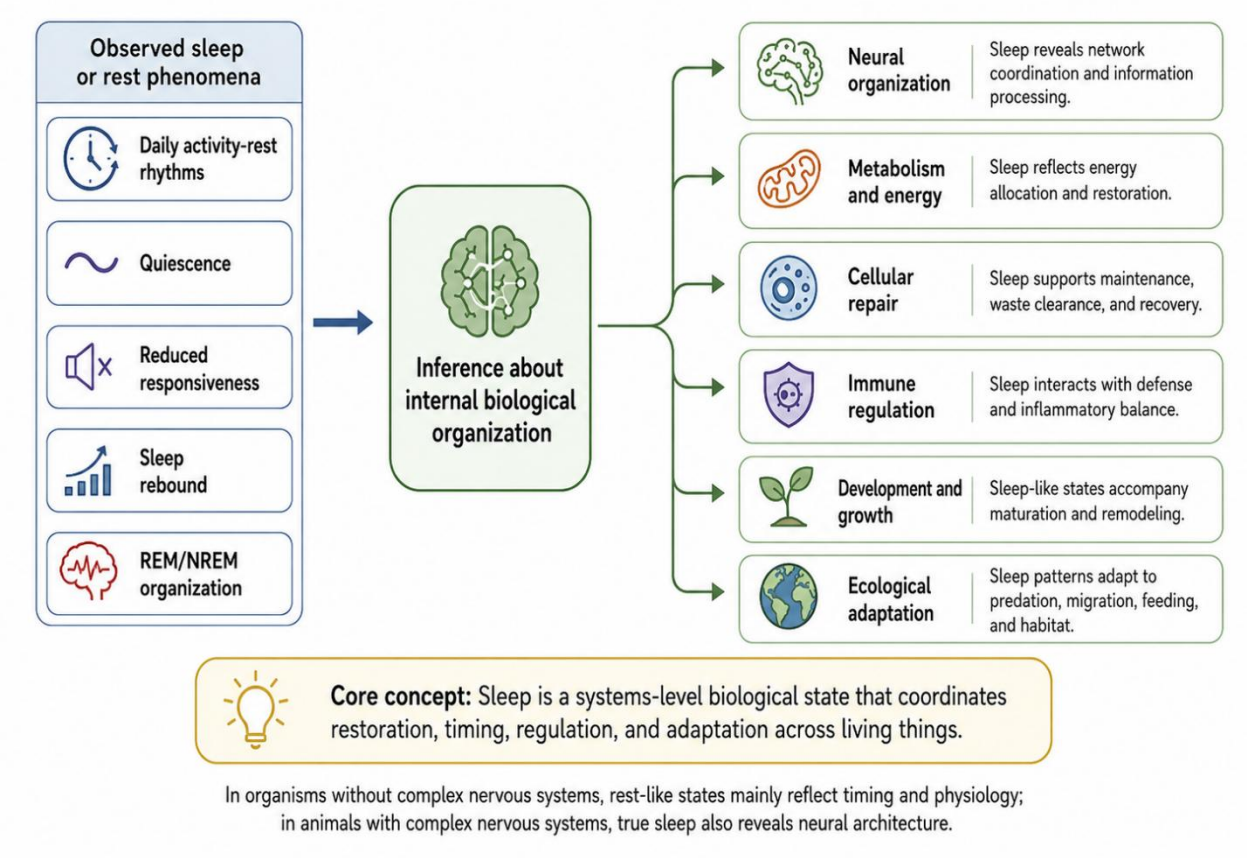

Figure 6. Integrative Framework: What Sleep Reveals About the Inner Workings of Living Things

Conclusions

This work shows that sleep-like states are nearly universal in animals and are built on deeply conserved biological clocks and neurochemistry. By contrasting bacteria, plants, fungi, invertebrates and vertebrates, we find that the **core concept of sleep** — reversibly lowered arousal set by internal timing — holds across phyla. In short, the hourglass and gears of sleep were present in early life and have been adapted in myriad ways. Future empirical studies testing sleep definitions in atypical organisms will further elucidate the essential nature of sleep.

Declarations

Author Contributions: SAMUELSON G conceptualized the study, collected and analyzed literature data, and wrote the manuscript.

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Conflict of Interest: The author declares no conflicts of interest. Concern about the unknown surroundings we are living in. and just out of curiosity

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(Note: All quotations above refer to the corresponding cited sources.)