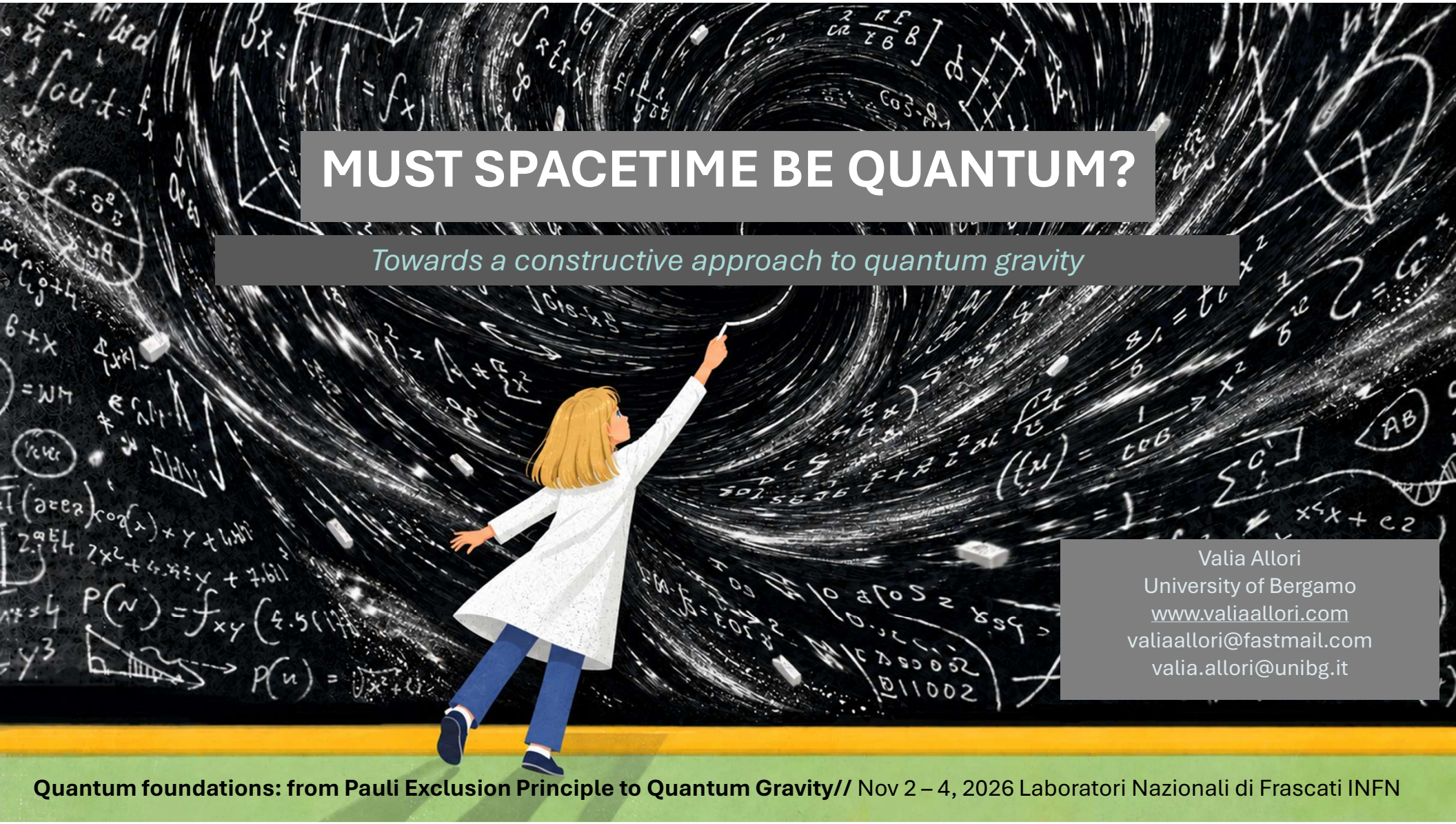
MUST SPACETIME BE QUANTUM?

Towards a constructive approach to quantum gravity



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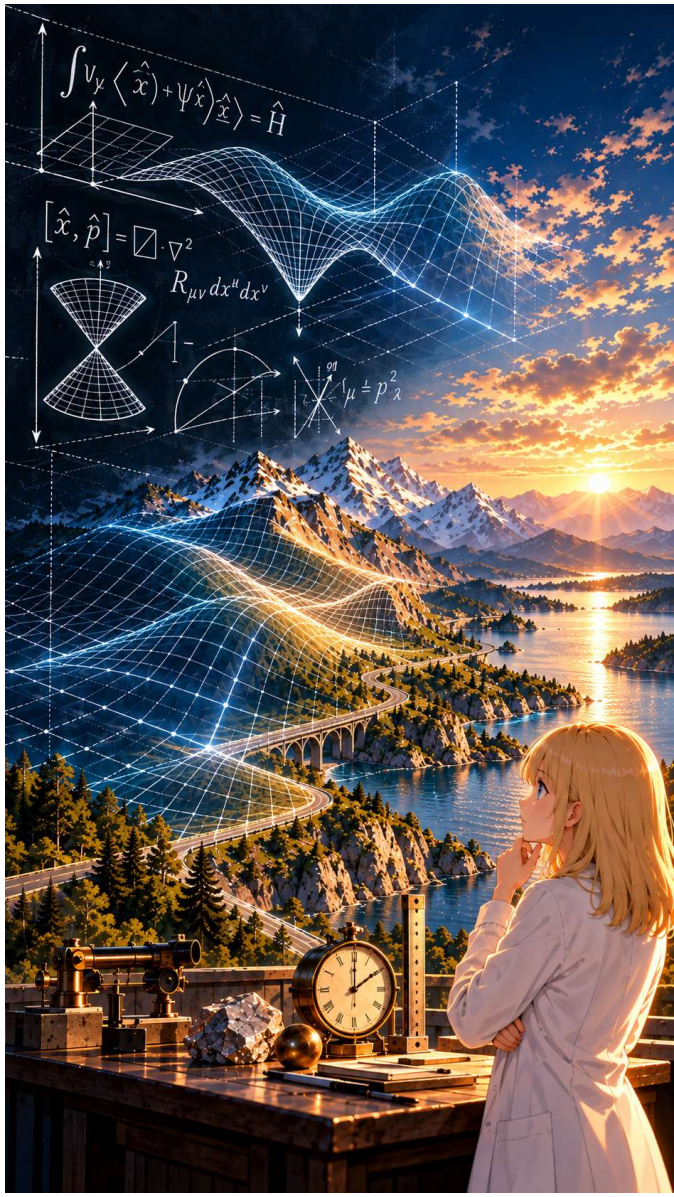
The question: what would a theory of quantum gravity have to explain?

- Must spacetime be quantum? Typically, QG says “yes”:
  - Identify the gravitational field with spacetime geometry
  - Apply quantum theory to that field (i.e. quantize)
  - You get quantum spacetime
- My talk:
  - Neither dispute the QG research programme nor argue that spacetime must remain “classical”
  - Ask: what would a theory putting together QM and GR look like?
  - Key distinction:
    - Formal construction
      - Equations, states, operators, constraints, spectra….
    - Constructive explanation
      - it goes further:
        - It tells us what exist, how it behaves, how the familiar world (macro matter, clocks, rods… and classical spacetime) arises
        - If we want to make claims about the nature of spacetime, among other things, then we want constructive explanation
  - Explain the requirements of constructive explanation
  - Discuss various approaches to QG in these terms



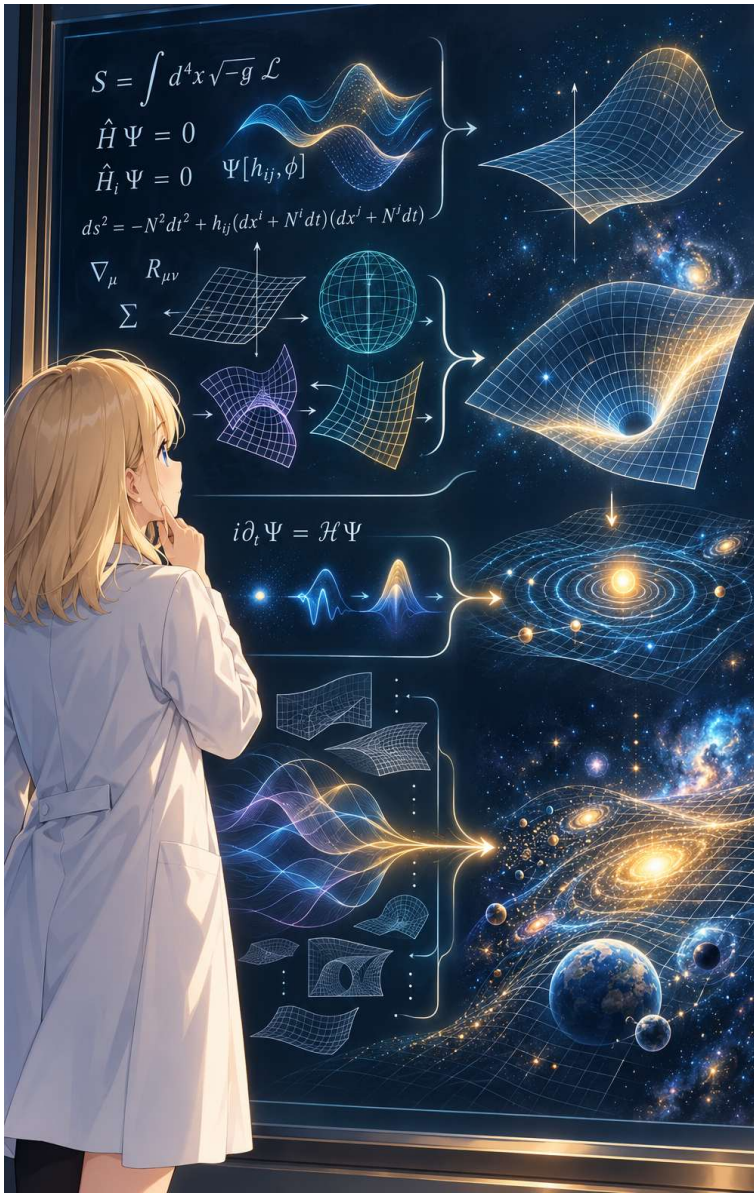
Constructive criteria

- **QG is often framed as a technical operation: quantize the dynamical variables of GR**
- However: we act on a mathematical structure
  - We replace classical variables with operators, classical states with quantum states, and classical constraints with operator constraints
  - This is technically important, but it does not tell us what the new math represents
  - Math alone does not by itself explain definite matter, a definite geometry, or classical spacetime
- This is what is instead required by a constructive explanation
- **Main claim: spacetime may be quantum, but that should be a conclusion of a successful constructive theory**
- The paper therefore evaluates theories by their constructive content



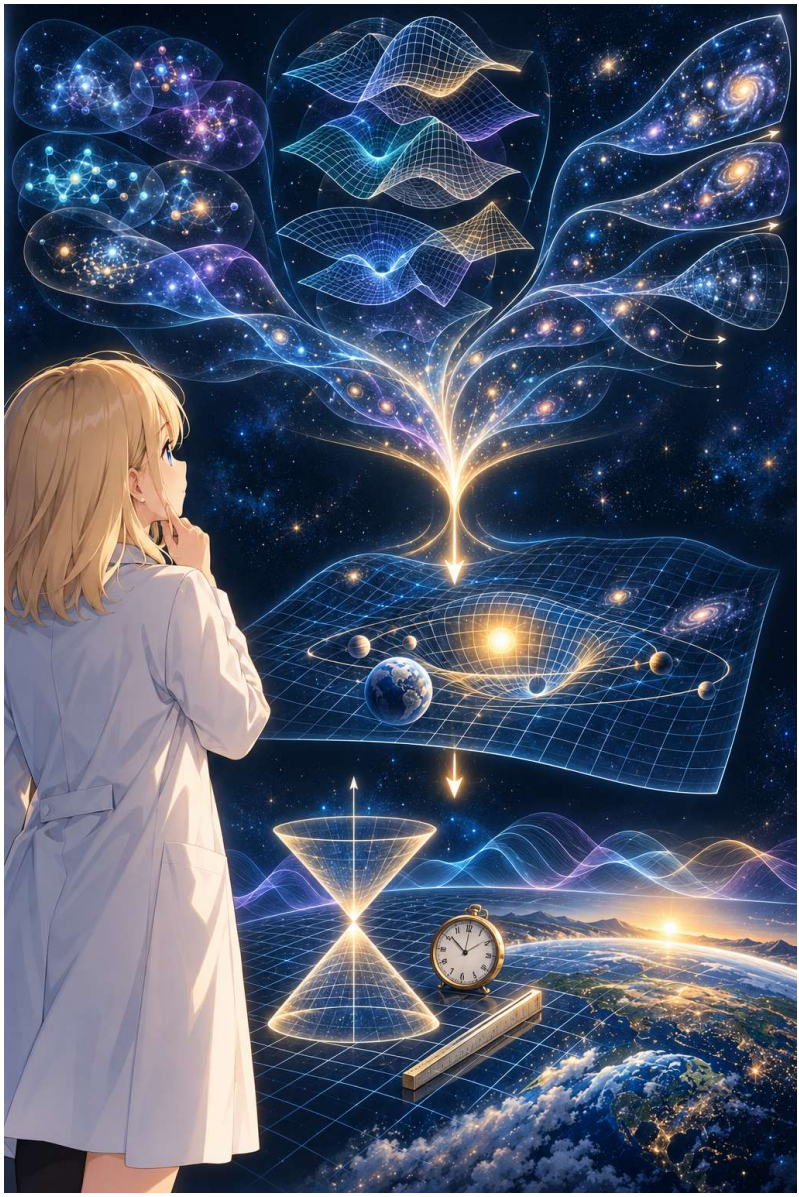
Constructive criteria: answer these questions

- ***What does the formalism represent? -- 3 questions***
- **What basic physical variables constitute the world** ("matter")?
  - A consistent mathematical structure are not yet a physical theory
  - Gauge redundancy in GR: different coordinate descriptions may represent the same geometry. A theory must identify the physical content of the constrained formalism
  - A QG formalism may contain variables, states, operators, constraints, and wave functionals. But notation alone does not determine whether these are:
    - physical fields; representations of possibilities; law-like structures; components of a larger physical theory
- **What's the law of evolution for "matter"?** (the dynamics of matter)
  - A theory must specify a dynamical law for matter: Hamiltonian, covariant equation, guidance law, stochastic law, or something else
- **What about spacetime?**
  - Is it quantized? Is it discrete?...



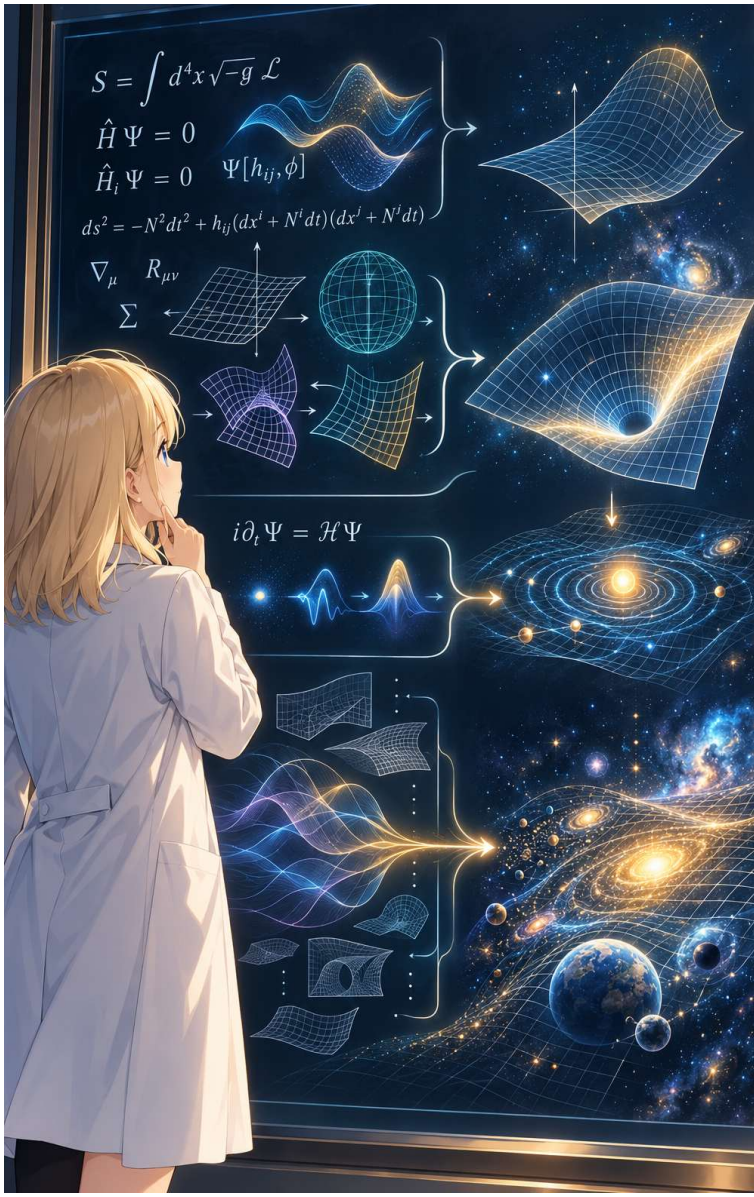
Constructive criteria: answer these questions

- **Is the theory empirically satisfactory?**
- **A:How there is only one outcome? (definiteness; measurement problem)**
  - QG may superpose matter configurations, spatial geometries, different expansion histories…
  - The theory must explain why there is only one definite **actual** configuration
- **B:Can the theory reproduce classical gravity? (classical limit)**
  - The theory must recover, in the appropriate regime:
    - classical spacetime geometry, causal structure and temporal order, general relativity, ordinary quantum theory on a classical background
  - The classical limit must be both dynamical and interpretive: equations must become classical, and their variables must become definite physical fields or geometries
- **C:Where is change? (problem of time)**
  - Time may be fundamental, relational, internal, emergent in a WKB regime, or tied to an actual configuration
- **D: Does the theory make new predictions? How does it recover experimental data? (empirical adequacy)**
  - The theory should clarify: which effects are observable, what parameters control them, how predictions differ from standard physics, how cosmology, black holes, and laboratory tests constrain it



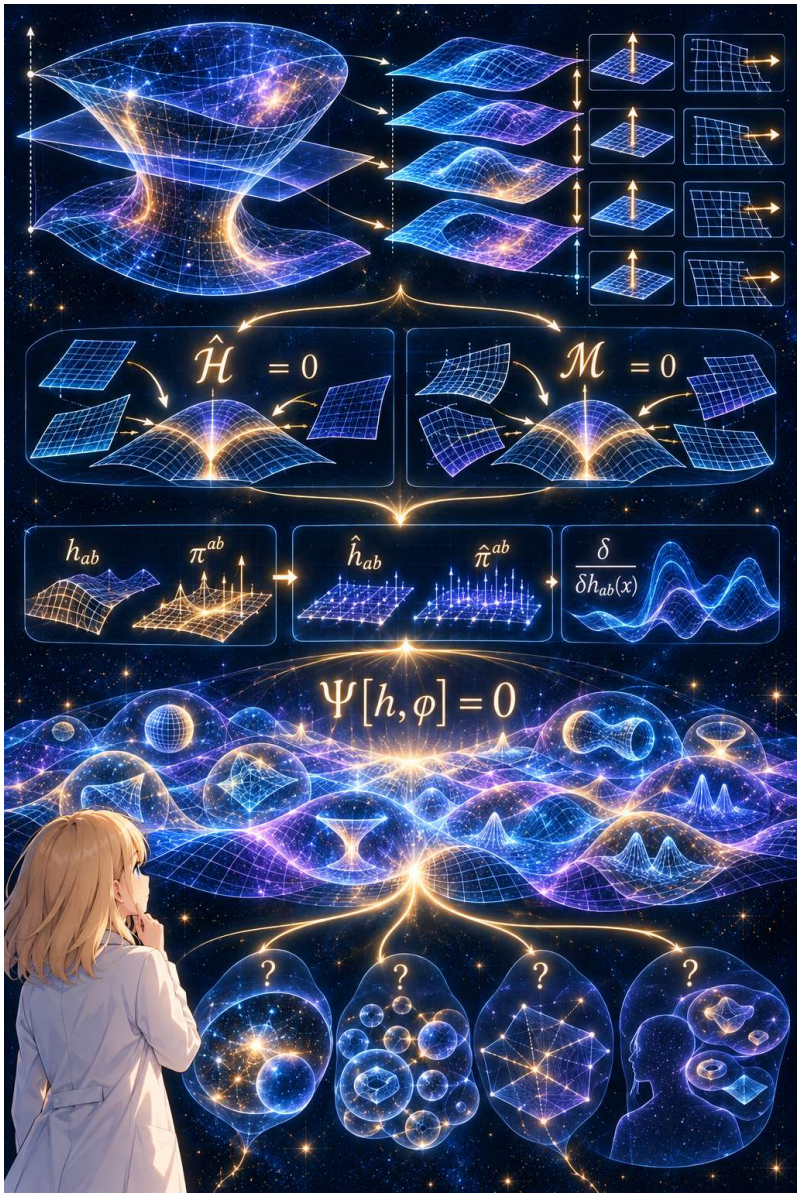
Constructive criteria: answer these questions

- **Reductionism** -now that we have identified the fundamental things and how they move, we need to ask:
- **How do macroscopic (observable) phenomena 'arise'** from more fundamental entities or structures and their laws?
  - E.g. in classical mechanics macroscopic bodies are composed of microscopic particles, and their properties are derivable from the microscopic dynamics
  - **Constructive vs principle theories (Einstein):**
    - Constructive (dynamical) theories
      - Micro→ Macro (e.g. statistical mechanics)
      - They tell you what there is at the fundamental level and why you see what you seat at non-fundamental levels (inter-level)
    - Principle (kinematical) theories:
      - Principles to constrain the phenomena (e.g. thermodynamics)
      - They tell you what to expect to see, not why, at a given level of description (intra-level)
- At the fundamental level we should want a constructive theory (debatable)



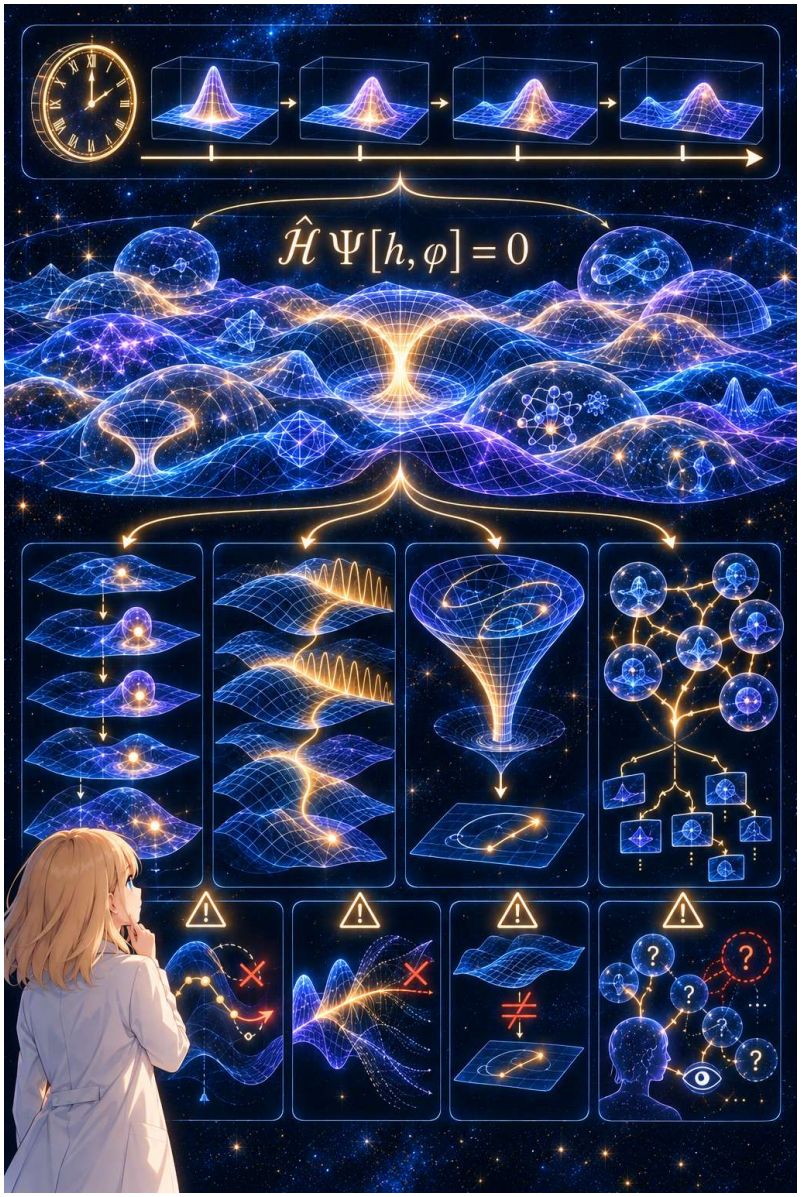
Canonical quantum gravity

- **ADM decomposition (Arnowitt, Deser, Misner 1962 ,DeWitt 1967)**
- **Start with classical gravity and put it in Hamiltonian formalism**
  - Spacetime is foliated into spatial slices
  - The spatial metric h_{ab} is paired with its momentum π^{ab} (~extrinsic curvature) -- **canonical variables**
  - The lapse and shift specify how one slice is related to the next and they enforce constraints
  - Constraints $\mathcal{H}_\perp \approx 0; \mathcal{H}_a \approx 0$
    - They encode gauge redundancy and the freedom to choose coordinates and slicing
- Add Matter: a field ϕ → conjugate momentum p_ϕ
- Quantization: variables → operators
  - h_{ab}, ϕ → multiplication operator
  - π^{ab}, p_ϕ → functional derivative operator
  - The Hamiltonian constraint becomes the **Wheeler–DeWitt equation** $\hat{\mathcal{H}}_\perp \Psi[h_{ab}, \phi] = 0$ → **where is time????**



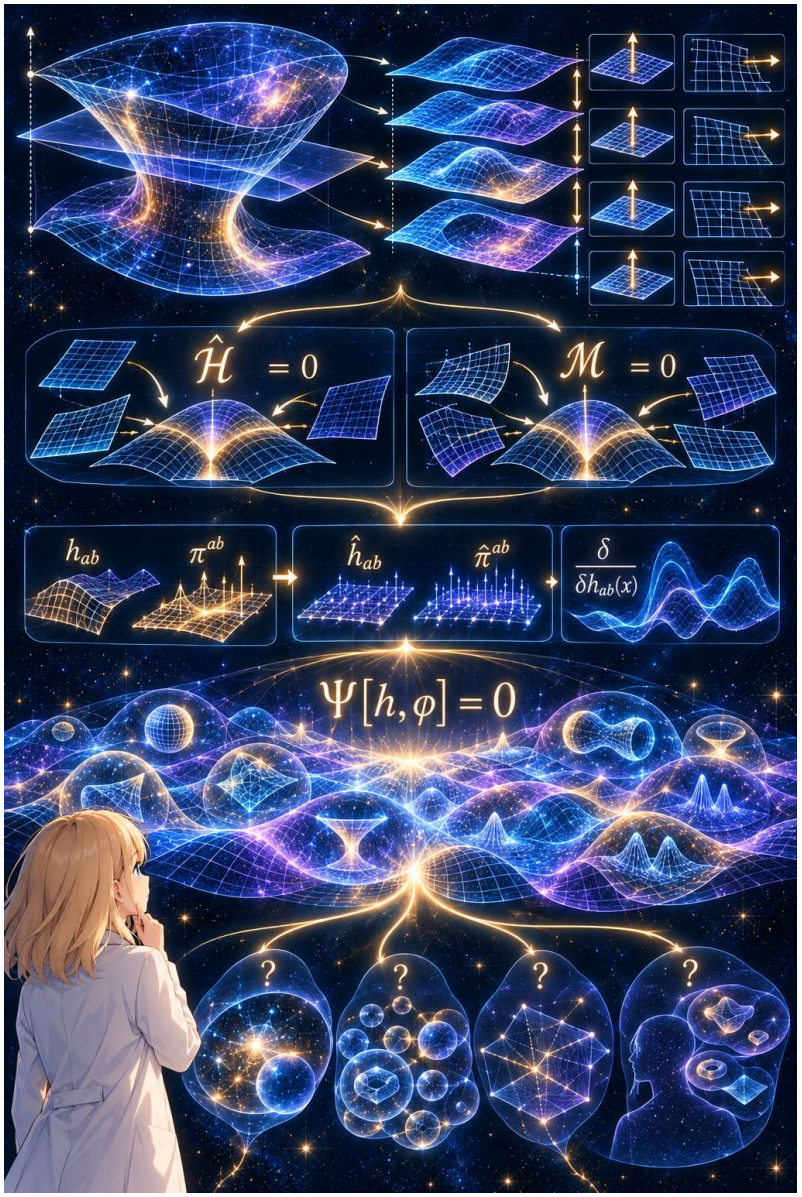
The problem of time

- The universal state satisfies a constraint, the Wheeler-DeWitt equation, **not an ordinary evolution equation**
  - Where is time?
- **Possible ways to get time back:**
  - A matter degree of freedom may serve as an internal clock
  - WKB time: the phase of an approximately classical gravitational state may define an emergent time
  - One may reduce the phase space before quantization and obtain a physical $\mathcal{H}$
  - One may describe physical systems through correlations and histories rather than evolution relative to an external time
- Each strategy is useful, but each makes different physical assumption
  - Internal clock may not be globally monotonic; WKB time requires a semiclassical branch; a reduced theory may not be equivalent to quantizing the full theory



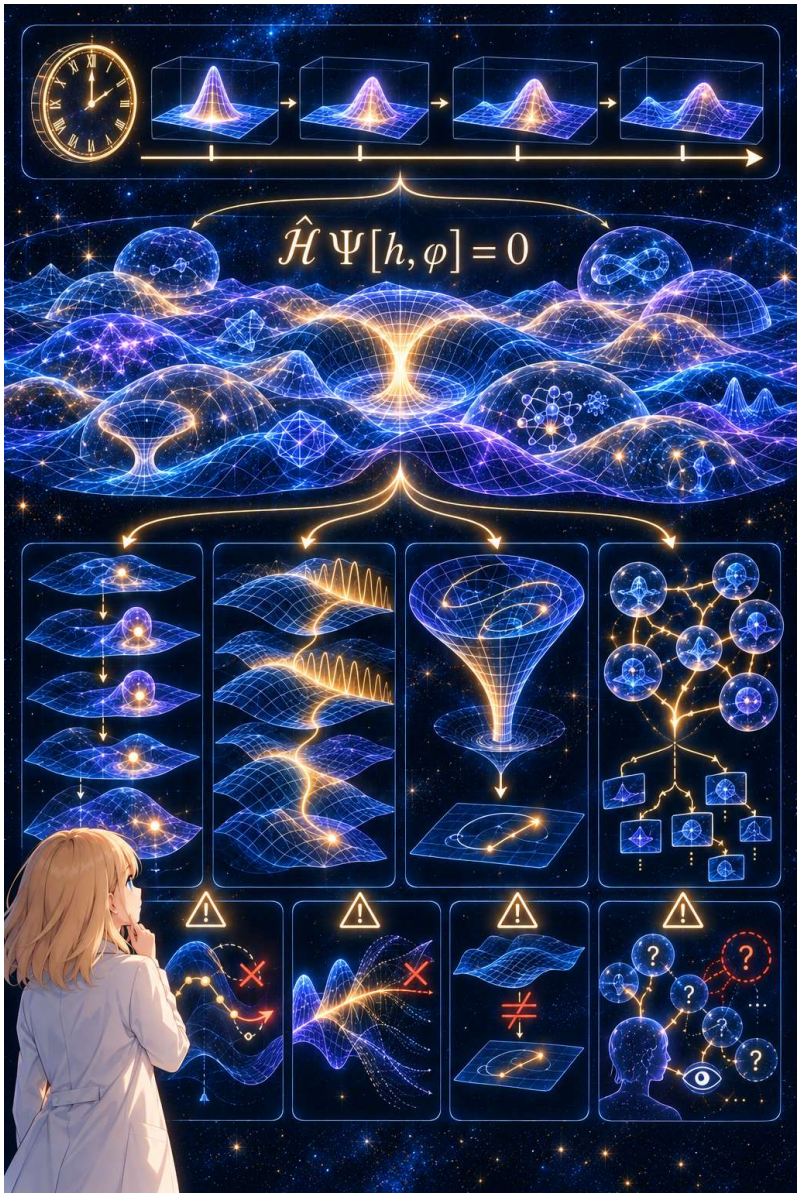
Canonical quantum gravity: constructive assessment

- **What is matter?**
  - State: wave functional $\Psi[h, \phi]$ over extended superspace (the space of possible geometries h and matter fields ϕ) - No obvious physical interpretation
    - Is it a physical field/entity?
      - Defined in the extended superspace, not 'regular' space…
      - Superposition of possible geometries and matter fields, and it does not tell us which one is actual (measurement problem)
    - Is it law-like?
- **How does matter evolve?**
  - …the problem of time
- **What about spacetime?**
  - Spacetime geometry is treated as **a quantum gravitational degree of freedom**



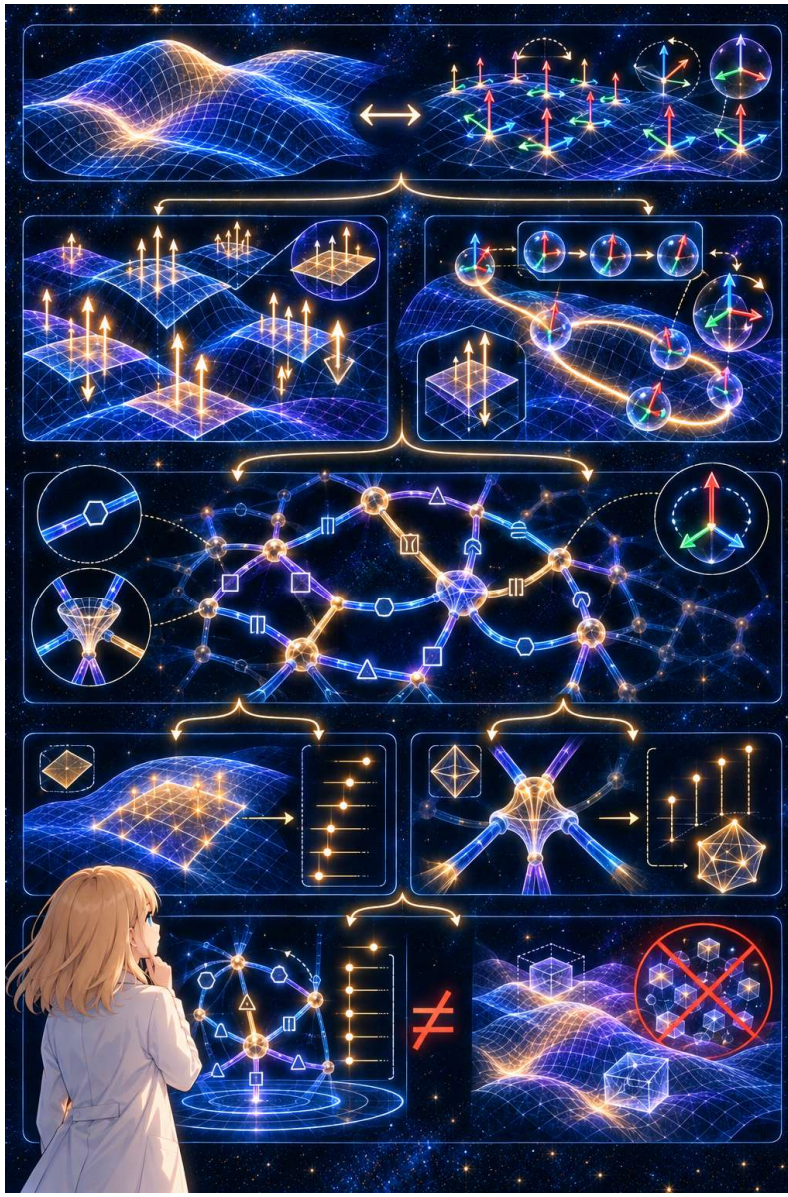
The problem of time: constructive take

- **Depending on what we take matter to be, the situation changes**
  - 1) if the wave functional of extended superspace is a physical field
    - Then it has no dynamics because the WDW equation is static, so we have the ‘regular’ problem of time
  - 2) if the wave functional is understood as law-like then it is a good thing that it has no temporal evolution: laws of nature do not change in time!
    - So instead of thinking that we should solve the problem of time, we could think that the absence of evolution in the WDW equation is **evidence** that the wave functional is not a physical field



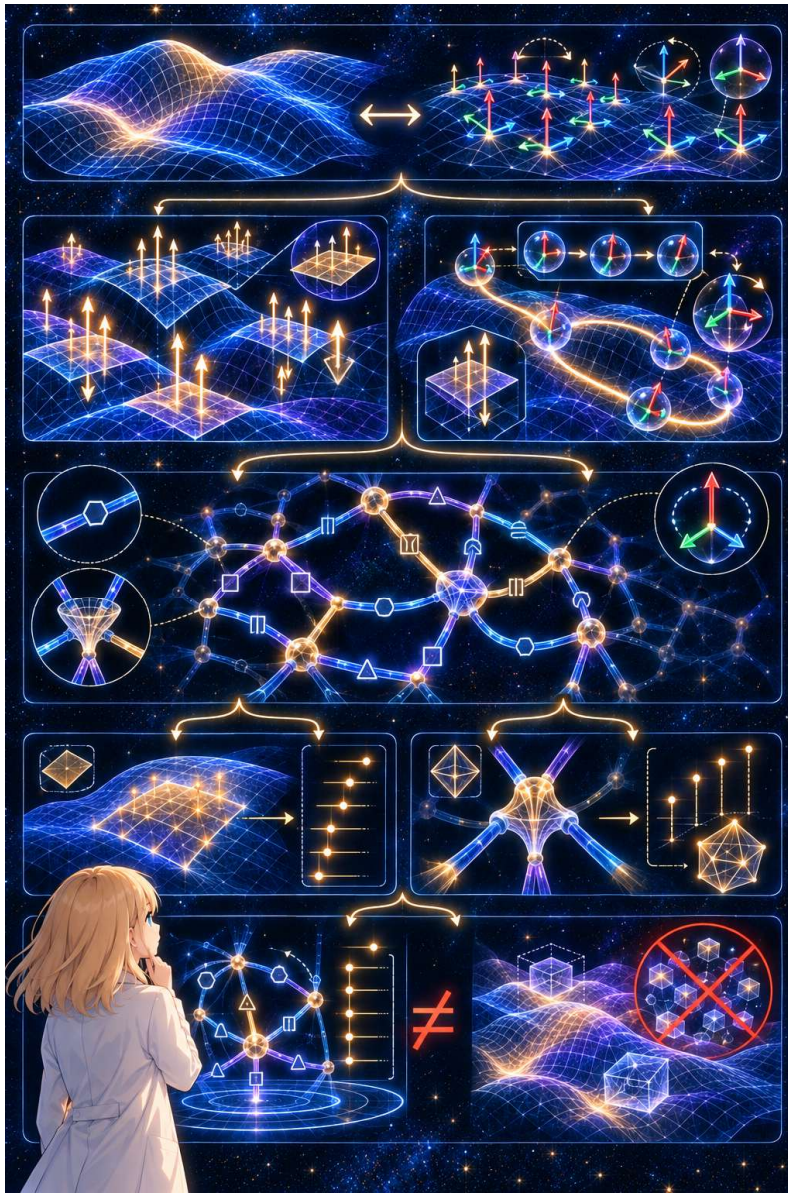
Loop quantum gravity

- **Ashketar-Barbero variables: an SU(2) connection and a densitized triad**
  - Configuration variable: Connection A_a^i: tells us how internal directions are compared by parallel transport
  - Triad: a spatial frame (freedom to rotate); Conjugate momentum: Densitized triad E_i^a : and alternative representation of spatial geometry
- Instead of A and E, use **integrals** of A and E : holonomies along edges $h_e[A]$ and fluxes through surfaces $F_S[E]$ → "loops"
- Add Matter: a field ϕ ,...
- Quantize: $h_e[A] \longrightarrow \hat{h}_e$multiplication ; $F_S[E] \longrightarrow \hat{F}_S$ derivative; ...
- State: functional $\Psi[h_e, \phi\ ]$
- State in the spin-network representation: *superpositions of graphs* ("spin": representation labels associated with an internal gauge symmetry, not material particles with intrinsic spin)
- Then impose the constraints→ WDW equation
- Through E one can define an area and a volume operators
  - In the spin-network representation they have a discrete spectrum→ "**space is quantized?**"



Loop quantum gravity: constructive assessment

- **What is matter?**
  - State: functional $\Psi[A, \phi]$, ; spin-network representation → superposition of graphs
  - It has no obvious physical interpretation
    - 1-Is it a physical field/entity?
      - It is defined on an abstract space – what is it?
      - In any case, it may be in superposition (measurement problem)
    - 2-Is it law-like?
- **How does matter evolve?**
  - If 1, then we have the problem of time
  - If 2, then the WDW equation is evidence for it
- **What about spacetime?**
  - In the spin-network representation area and volume operators have a discrete spectrum, but it is unclear what physical meaning these representations have



String theory

- 1-dimensional **strings** “rather than particles”
  - String configuration: $X^i(\sigma)$ (~trajectory), conjugate momentum $P^i(\sigma)$
- Chose a background metric and then quantize: from $X^i(\sigma)$ and $P^i(\sigma)$ to operators
  - State (in position repr): functional $\Psi[X(\sigma)]$- it associates an amplitude associated with each possible configuration of a string
  - Quantize the internal degrees of freedom of the string→ different allowed quantum states with different values of mass and spin→ they appear as different kinds of particles, including a massless Spin-2 particle → graviton: a disturbance around the background metric
  - **String spectrum =** collection of allowed ‘particle states’
- Gravity is quantum because it arises within a larger quantum theory rather than direct canonical quantization



String theory: constructive assessment

- **What is matter?**
  - State: functional $\Psi[X]$
  - It has no obvious physical interpretation
    - Is it a physical field/entity? Is it law-like?
  - Nonetheless, we now have a string variable: it may be chosen as representing matter
- **How does matter evolve?**
  - If matter is string-like then we do have a dynamics:
    - An individual string can move and change its shape
    - Strings can interact (e.g. they can join or split)
  - However: the state can be a superposition of different configurations or different excitation states→ which one is the actual? (measurement problem again)
- **What about spacetime?**
  - Strings propagate in a chosen spacetime background



Asymptotic safety

- Start with the spacetime metric**,** matter fields can also be included
- Quantize the gravitational field**:**
  - Typically write the metric as a background + a fluctuation, and quantize the fluctuations
- State: functional $\Psi[h]$ -it assigns amplitudes to possible spatial geometries
  - (Many asymptotic-safety calculations instead use a functional integral and a scale-dependent effective action:
- **Problem:** perturbative quantization of GR is **not renormalizable** in the usual sense; it loses predictive power at sufficiently high energies
- **Asymptotic-safety proposal:** the gravitational couplings change with energy scale and approach a non-Gaussian fixed point at arbitrarily high energies
  - Fixed point = the dimensionless couplings approach definite values → the theory may remain well-defined and predictive at arbitrarily high energies
- Gravity is quantum because the gravitational field itself is quantized



Asymptotic safety: constructive assessment

- **What is matter?**
  - If the quantum state is complete, superpositions of macroscopically different geometries raise the measurement problem
  - If the state is law-like, what is the ontology it governs, and what is its law of motion?
- **How does matter evolve?**
  - Unclear:
    - The theory is not formulated in terms of an explicit time-evolution
    - The renormalization-group equation describes change with energy scale, not physical time
- **What about spacetime?**
  - Spacetime geometry is represented by a quantized metric field
  - A background metric is often used in calculations, but the proposal does not by itself settle the nature of spacetime



Semiclassical gravity + collapse

- (Møller and Rosenfeld: semiclassical coupling of classical gravity to quantum matter; GRW 1986, CSL: objective-collapse models; see also Tilloy and Diósi 2016)
- **Spacetime**: described by a classical metric, gravity is not quantized
- **State:** described by a quantum state $|\psi>$
- **State dynamics:** ordinary quantum evolution modified by an objective stochastic collapse law → macroscopic superpositions are dynamically suppressed, without invoking an observer
- Gravity–matter coupling: the classical gravitational field is sourced by quantum matter



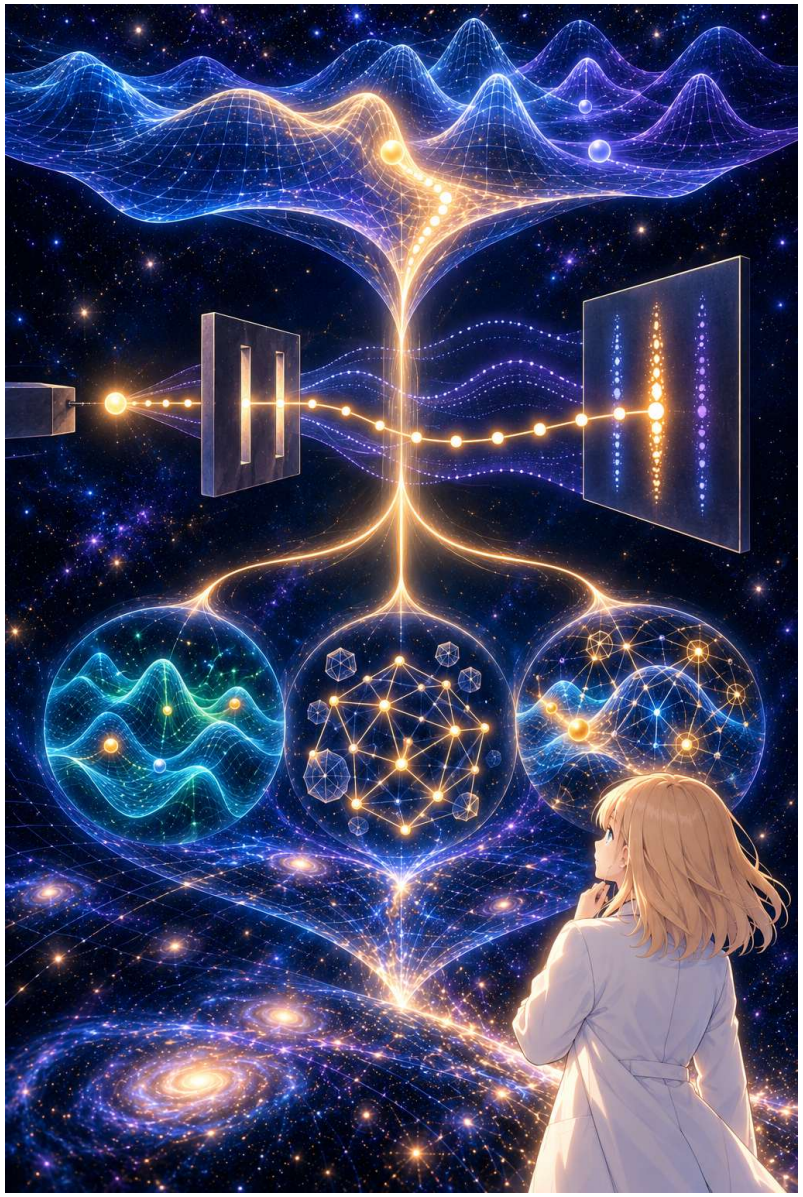
Semiclassical gravity + collapse: constructive assessment

- **What is matter?**
  - Does the quantum state describe matter in physical space?
    - It is configuration space, not in regular physical space
    - One option is a matter-density field *M*: a continuous matter distribution in physical space, related to the quantum state
- **How does matter evolve?**
  - If the *M* field is matter, its evolution is determined by a linear evolution interrupted by stochastic collapses
  - Macroscopic superpositions are suppressed → definite records are accounted for without observers causing collapse
- **What about spacetime?**
  - Spacetime is a classical geometry, represented by a definite metric
  - It responds to a source associated with quantum matter, whose state undergoes objective collapse



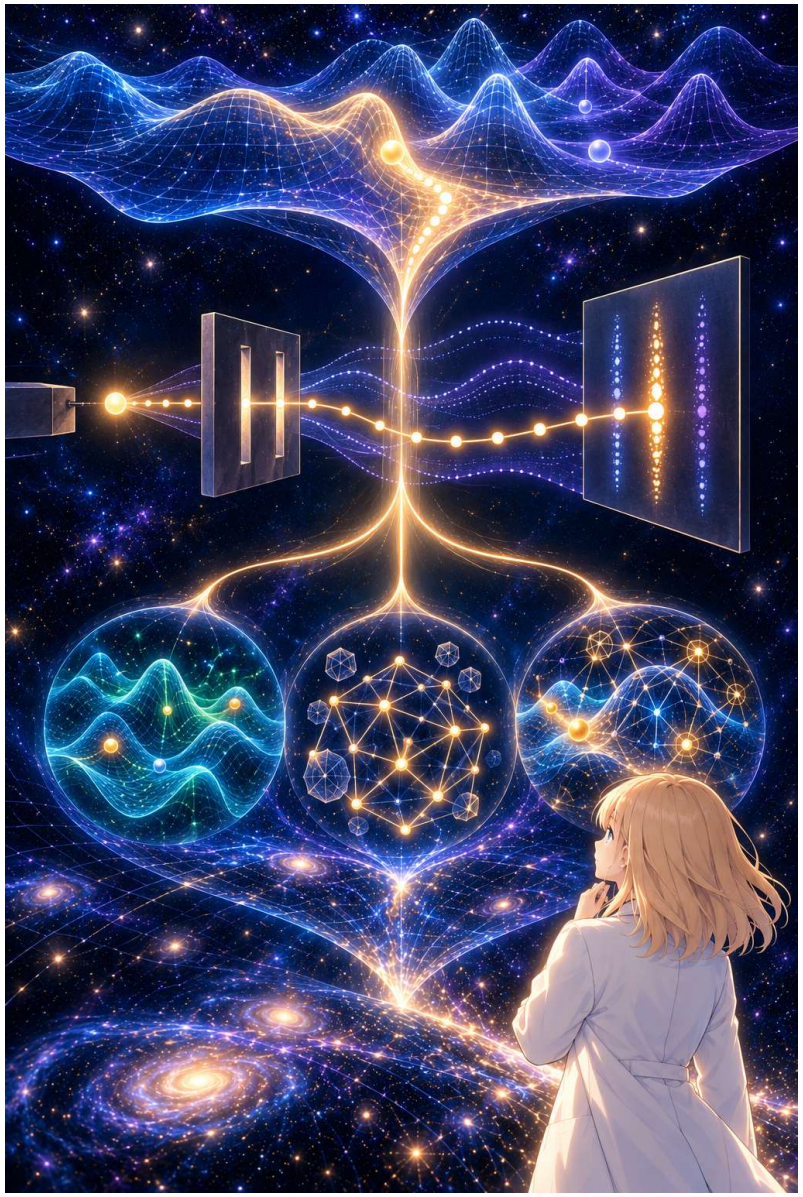
Bohmian approaches

- **Non-relativistic Bohmian QM** (Bohm 1952, Dürr, Goldstein, and Zanghì 1992, Allori et al. 2008, Allori 2026): the prototypical constructive quantum theory
  - **Matter**: particles with definite 3d positions
  - **Dynamics**: a guidance equation for the particles in which one find a Schrödinger evolving wave function
  - → the wavefunction is not a physical material field, it's part of the law
  - Macro objects are arrangements of particles
    - → there are definite outcomes: the wf may contain components corresponding to different outcomes while the actual configuration occupies only one of them
    - → no need of the collapse postulate; no need to say that every branch is real
- Bohmian QG:
  - Matter may be many things (particles, matter fields, actual spatial geometry, both): they theory must specify it



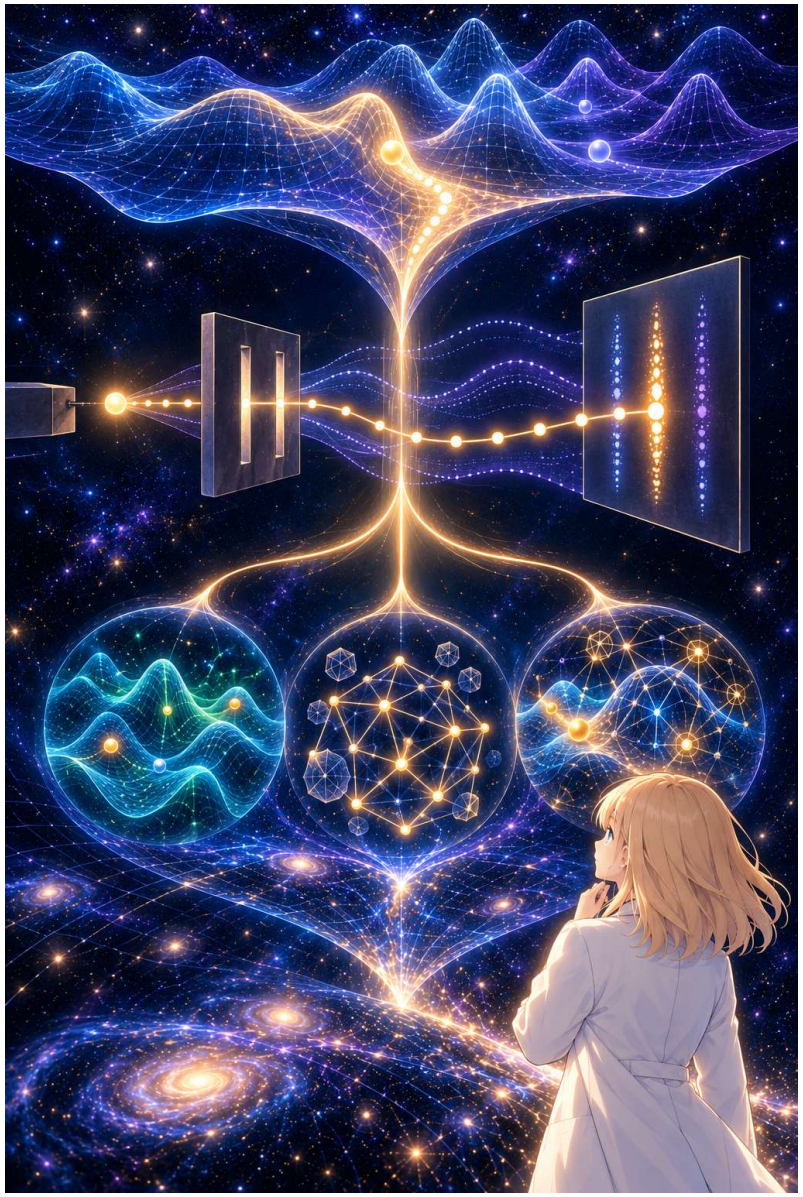
Bohmian quantum gravity

- Start with canonical QG: the gravitational configuration is a spatial metric $h(x)$; matter fields $\phi(x)$ can also be included
  - Wave functional $\Psi[h,\phi]$ defined on a space of possible spatial geometries and matter-field configurations
  - Evolution: Wheeler–DeWitt equation
- **Bohmian addition:** there is an actual spatial geometry $h(x,t)$, and an actual matter-field configuration $\phi(x,t)$
  - Guiding law: the wave functional determines how the actual geometry and matter fields change
- **Key idea:** a time-independent universal wave functional can govern a changing actual configuration → a possible response to the problem of time.



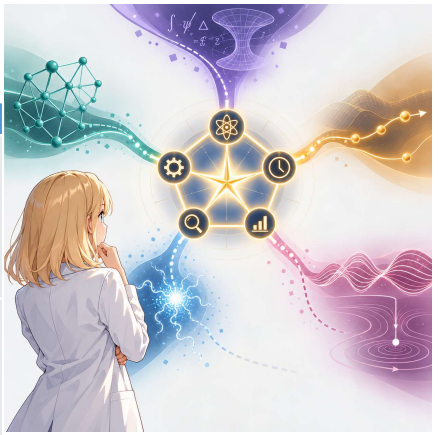
Bohmian QG: constructive assessment

- **What is matter?**
  - Actual matter fields and actual spatial geometry
  - The wave functional is **law-like** → A superposition in it does not entail a superposition of actual matter configurations.
- **How does matter evolve?**
  - The actual configuration evolves according to a guiding law, even if the universal wave functional satisfies a timeless WDW equation
- **What about spacetime?**
  - Actual spatial geometry changes governed by a quantum wave functional (geometrodynamics)
  - A history of spatial geometries is intended to provide an account of spacetime
  - How this history relates to a four-dimensional geometry and foliation independence requires further analysis



Back to the constructive criteria…

Approach	State	Matter	Spacetime	Definite outcomes?	Dynamics
Canonical QG	$\Psi[h,\phi]$ subject to constraints	Quantum matter fields ϕ; what physically exists is **not specified** by the formalism alone	Spatial geometry is a **quantum degree of freedom**; emergence of 4-dimensional spacetime requires explanation	Not specified by the formalism alone	**WDW** and other constraint equations for Ψ; recovery of time and physical evolution is a central question
Loop QG	$\Psi[A,\phi]$; gravitational states can be expressed in a spin-network representation	Quantum matter fields ϕ; what physically exists is **not specified** by the formalism alone.	Spatial geometry described using **connection variables**; smooth spacetime must be recovered	Not specified by the formalism alone	**WDW** and other constraint equations for Ψ; recovery of time and physical evolution is a central question
String theory	Quantum state of strings; schematically $\Psi[X]$ for a single string	Particle-like states are described as **string states**; whether there are actual strings with definite configurations is not specified by the formalism alone	A **background** spacetime is chosen; a closed-string state corresponds to a graviton	Not specified by the formalism alone	**Quantum dynamics and interactions of strings;** amplitudes for processes such as joining and splitting
Asymptotic safety	Quantum gravitational **field theory**, described through an effective action and correlation functions	Quantum matter fields ϕ; what physically exists is **not specified** by the proposal alone	Metric treated as a **quantum field**; a background is often used as a calculational tool	Not specified by the proposal alone	**Quantum-field dynamics;** renormalization-group flow describes change with scale, not time evolution
Semi classical gravity + collapse	Quantum matter state $\|\Psi>$ and classical metric $g_{\mu\nu}$	Model-dependent; for example, a **matter-density field** associated with the quantum state	**Definite classical geometry** coupled to a matter source	**Yes:** superpositions are dynamically suppressed	Unitary quantum evolution modified by **stochastic collapse,** coupled to classical gravitational dynamics
Bohmian QG	**Actual configuration** (h,ϕ) and **wave functional** $\Psi[h,\phi]$, in a field-ontology version	In the field-based version: **actual matter-field configuration**	**Actual spatial geometry,** guided by the wave functional; its history is used to construct spacetime	**Yes:** the actual configuration supplies definite records	WDW and other constraints for Ψ**; guiding laws** for the actual geometry and matter fields



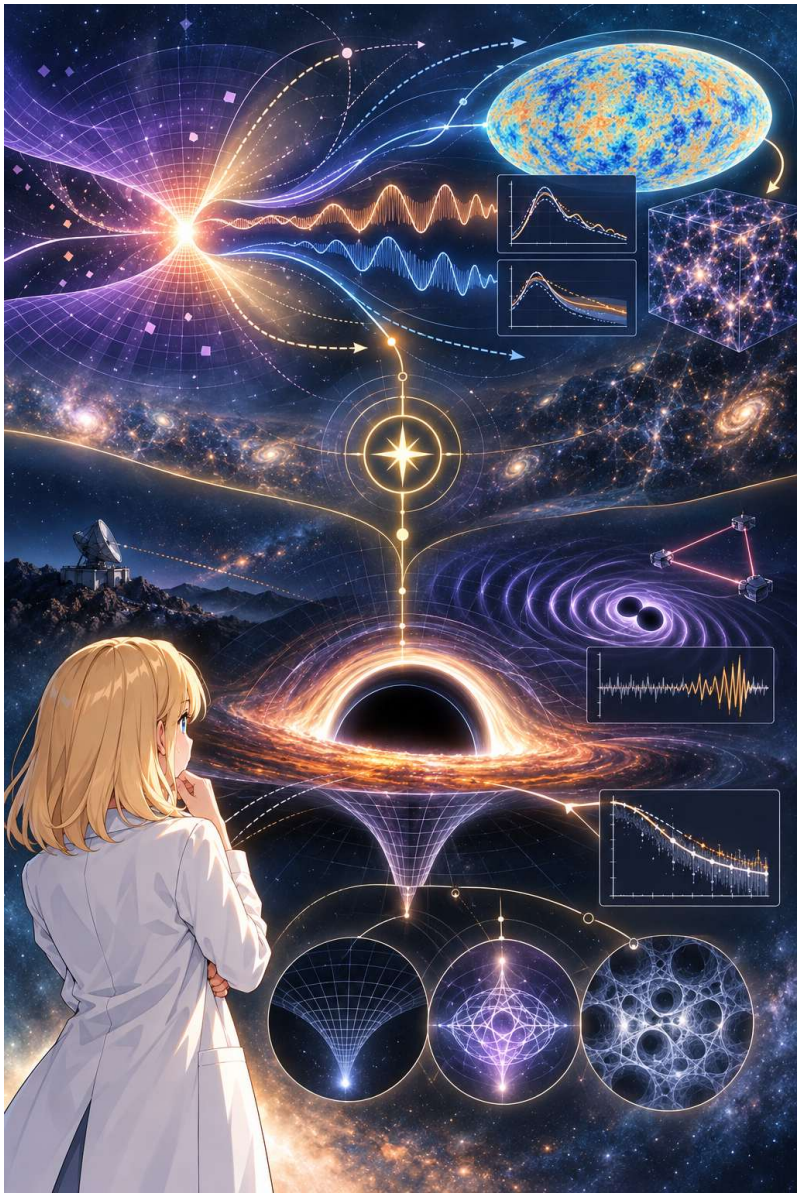
Quantum cosmology: a test

- Cosmology applies the previous approaches to **the universe as a whole**
  - Minisuperspace models: homogeneity and isotropy reduce the (infinite dimensional) fields to variables such as the scale factor a and a homogeneous matter field ϕ
  - → **calculations become possible**
    - Results depend on the quantization and the state and the model…
  - A homogeneous background cannot describe structure formation or gravitational waves →**Perturbations** connect the quantum background to the observed universe
  - There is **no external observer** or classical spacetime outside the universe to do the interpretive work → interpretation must be formulated inside it



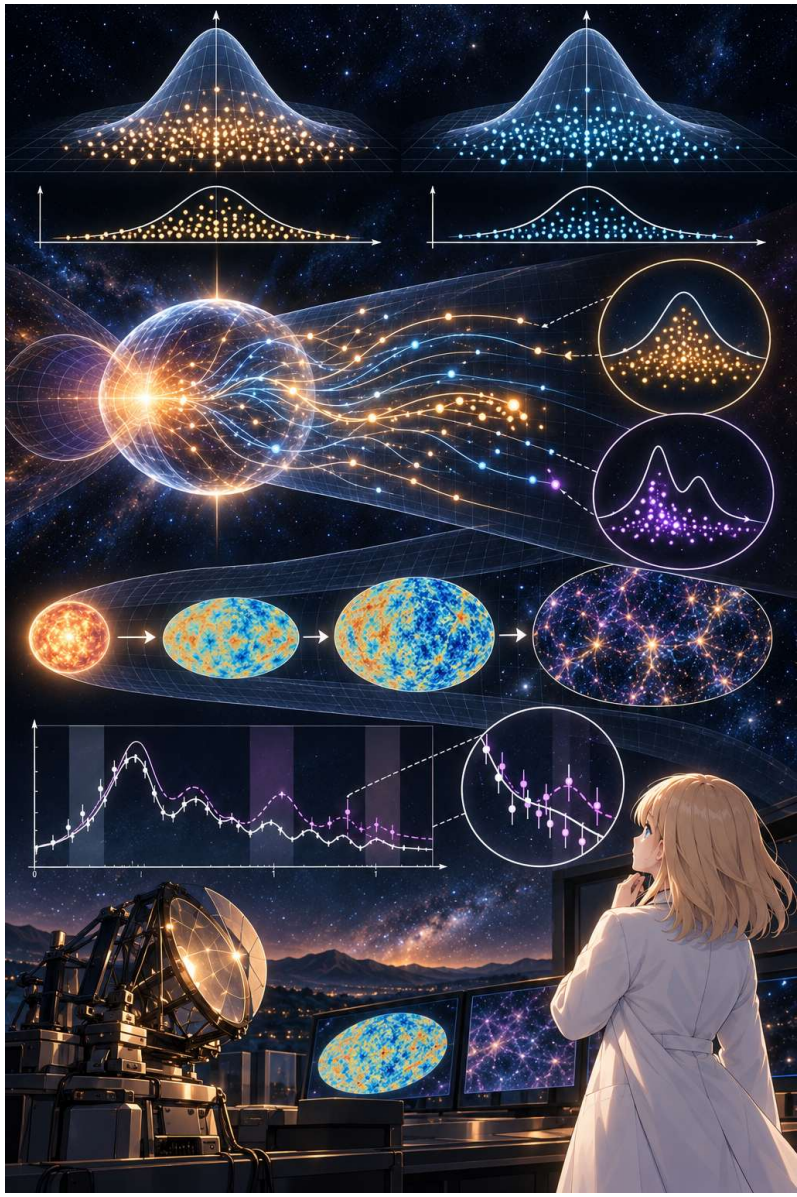
What could be tested?

- **The constructive question becomes scientifically useful when it changes predictions:**
- **1-Cosmology:**
  - Q gravitational dynamics may modify the early-universe background, generate a bounce, or change the spectrum of a scalar and tensor perturbation
    - Model dependent, and can be confused with ordinary changes in inflation, reheating, or initial conditions
- **2-Black holes:**
  - Different theories may predict modified interior conditions, singularity resolution, altered evaporation, corrections to the Hawking spectrum, or gravitational-wave signatures.
    - Actual observation is however difficult



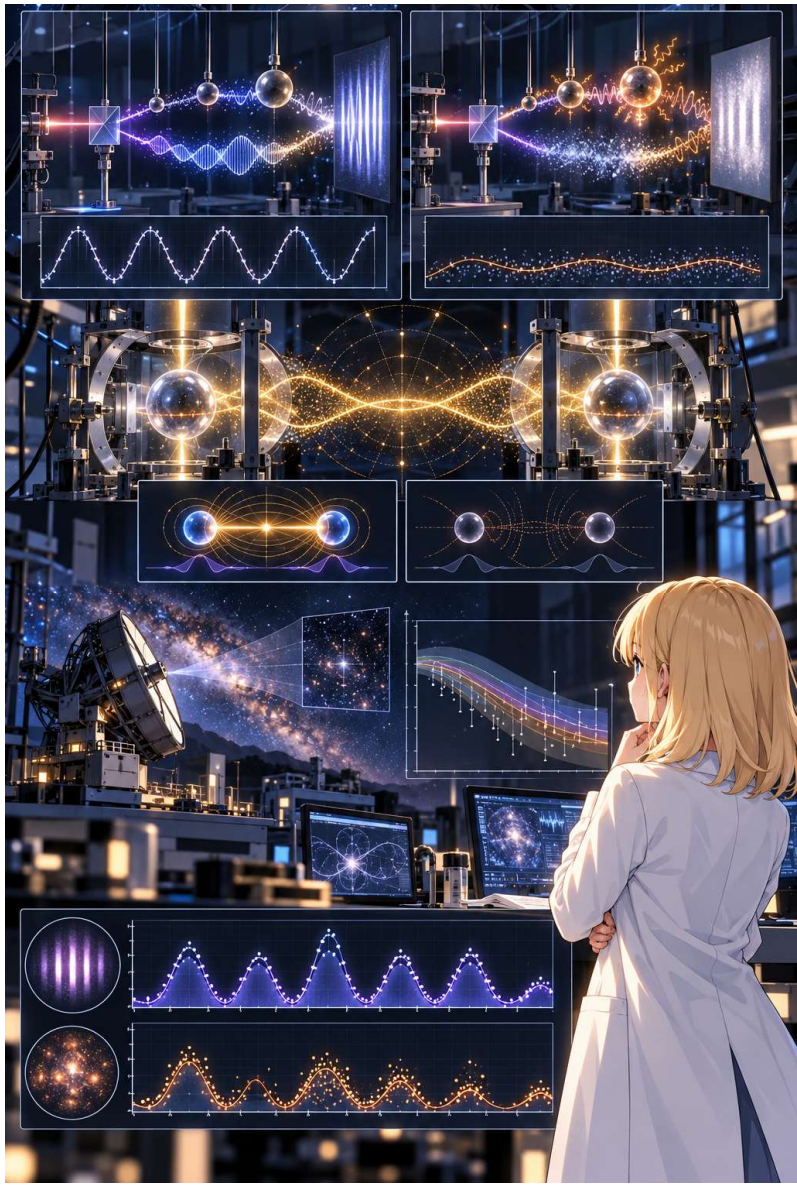
Valentini’s nonequilibrium

- Within the Bohmian cosmology programme
- The Born rule can be treated as **quantum equilibrium**, a particular distribution of actual configurations
- **Nonequilibrium** means that the distribution differs from the Born distribution → it may produce **deviations from standard quantum statistics**
- The early universe could preserve or amplify such deviations
- Possible signatures include anomalous primordial spectra
- → **Ontology becomes empirical when it yields distinctive dynamics or statistics**



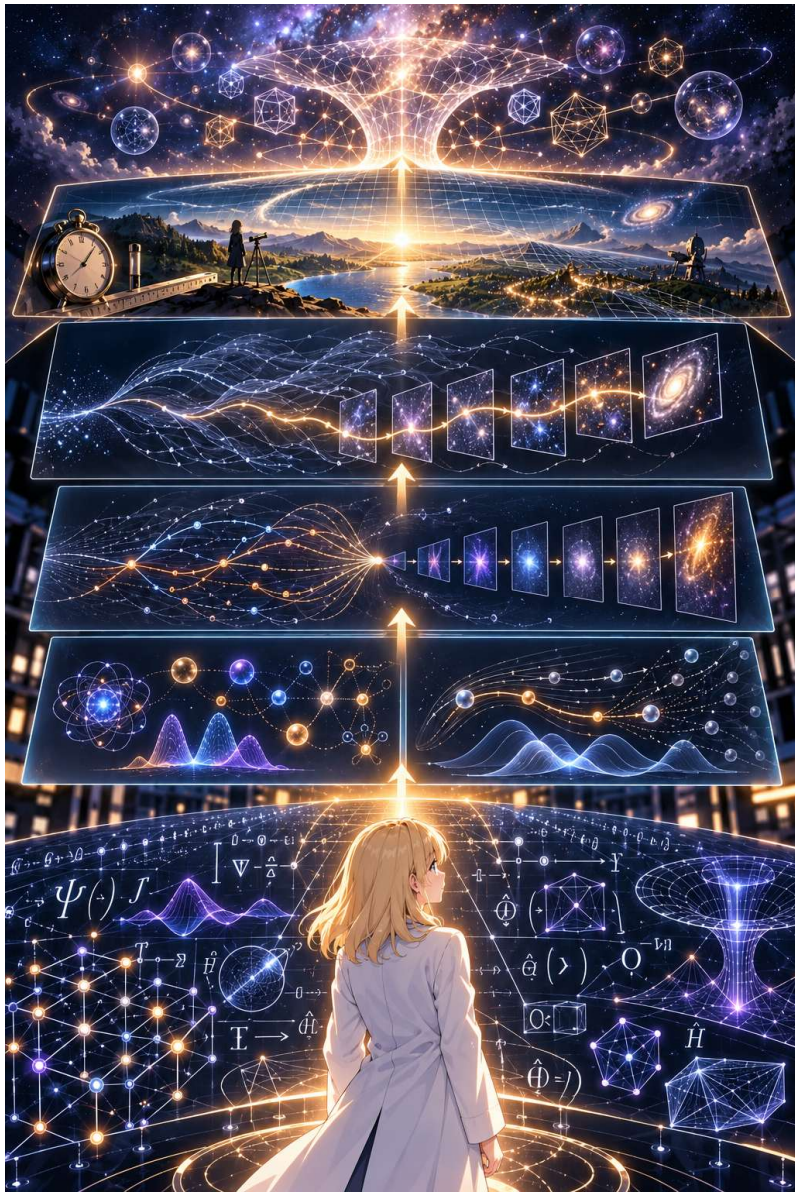
What could be tested?

- **3-Lab tests:**
  - Collapse models may predict loss of interference, anomalous heating, or spontaneous radiation
    - Experiments involving increasingly massive superpositions and gravty-mediated entanglement may distinguish quantum matter with classical gravity, quantum mater with collapse, and fully quantum gravity
      - Ongoing tests
- **4- Nonequilibrium:**
  - Valentini's theory predicts violation on Born statistics in the Bohmian framework
    - No confirmed violation has been observed
- A prediction must follow from a specified model, state, ontology, and initial conditions
- Empirical access is indirect and model-dependent, but interpretation can affect observable statistics



Conclusion

- **My prescriptive rule to evaluate a theory of QG: Look for what a theory of QG explains, not necessarily what it quantizes**
  - Formal consistency is necessary but not sufficient
  - A theory must identify its physical variables and laws
  - It must explain definite histories and the recovery of classical spacetime
    - Solve the measurement problem and the problem of time
  - Bohmian and semiclassical gravity+collapse approaches provide clear constructive starting points
  - ***Spacetime may be quantum. But the theory must earn that conclusion, not start with it***




Thank you
for your
attention!