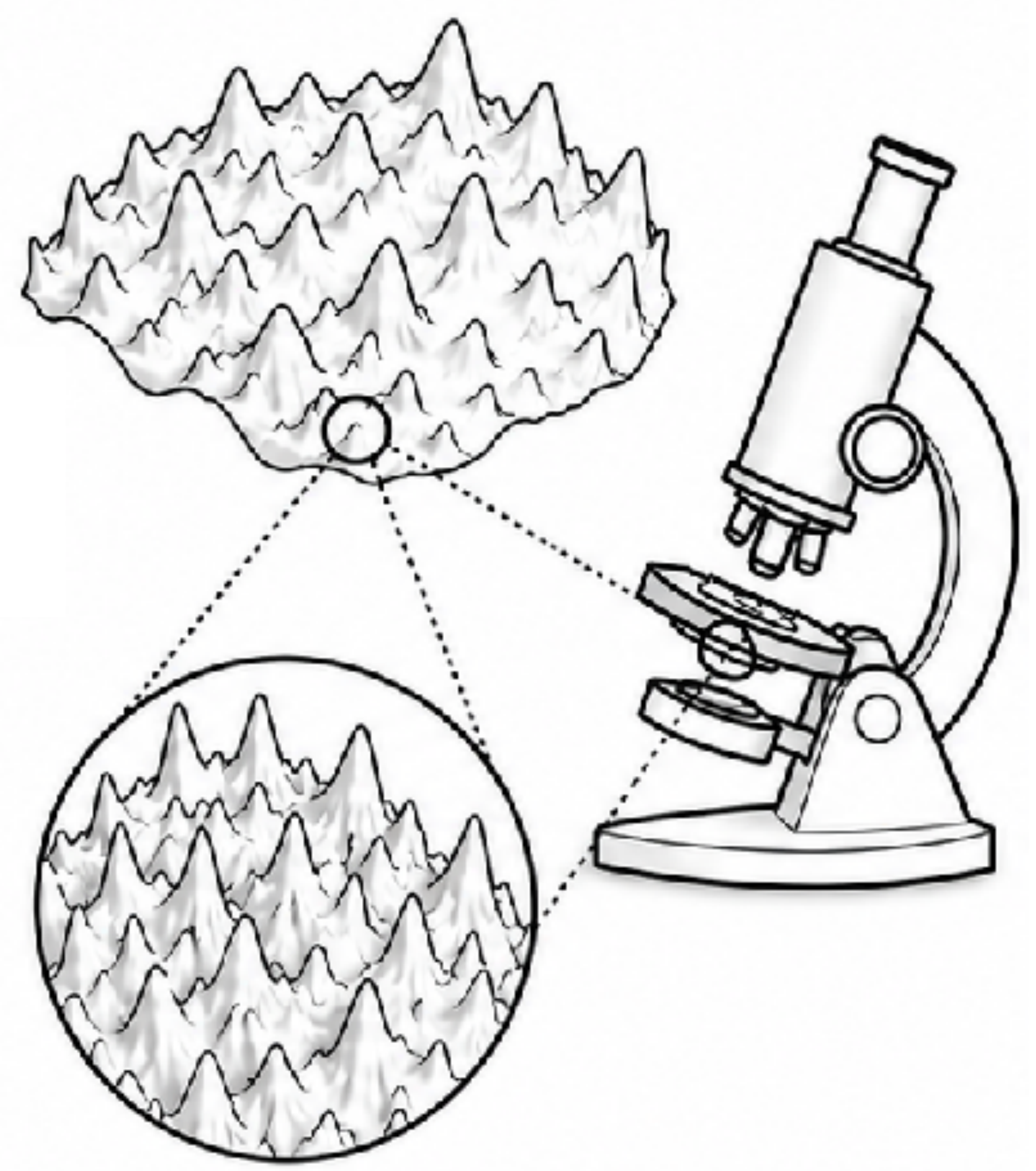
Rethinking coarse graining relationally in quantum gravity

Renata Ferrero

FAU^2: Quantum Gravity meets Quantum Information
Erlangen, 8th July 2026

Friedrich-Alexander-Universität
Erlangen-Nürnberg



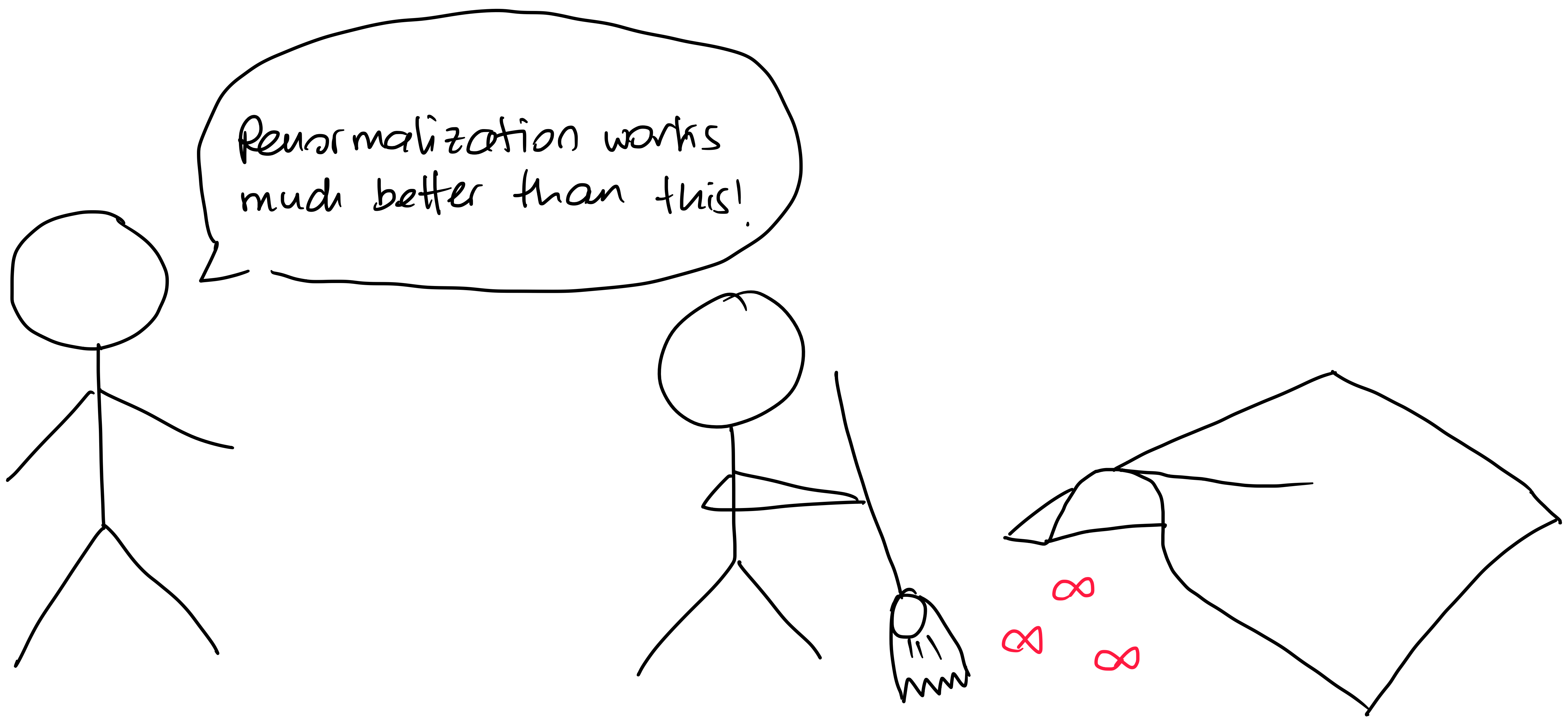
Roadmap

Standard QFT measurements and why they fail in gravity

Renormalization in quantum gravity: Asymptotic Safety

Counting modes instead of momenta

Relational perspective on the RG



Observables in QFT: Correlators

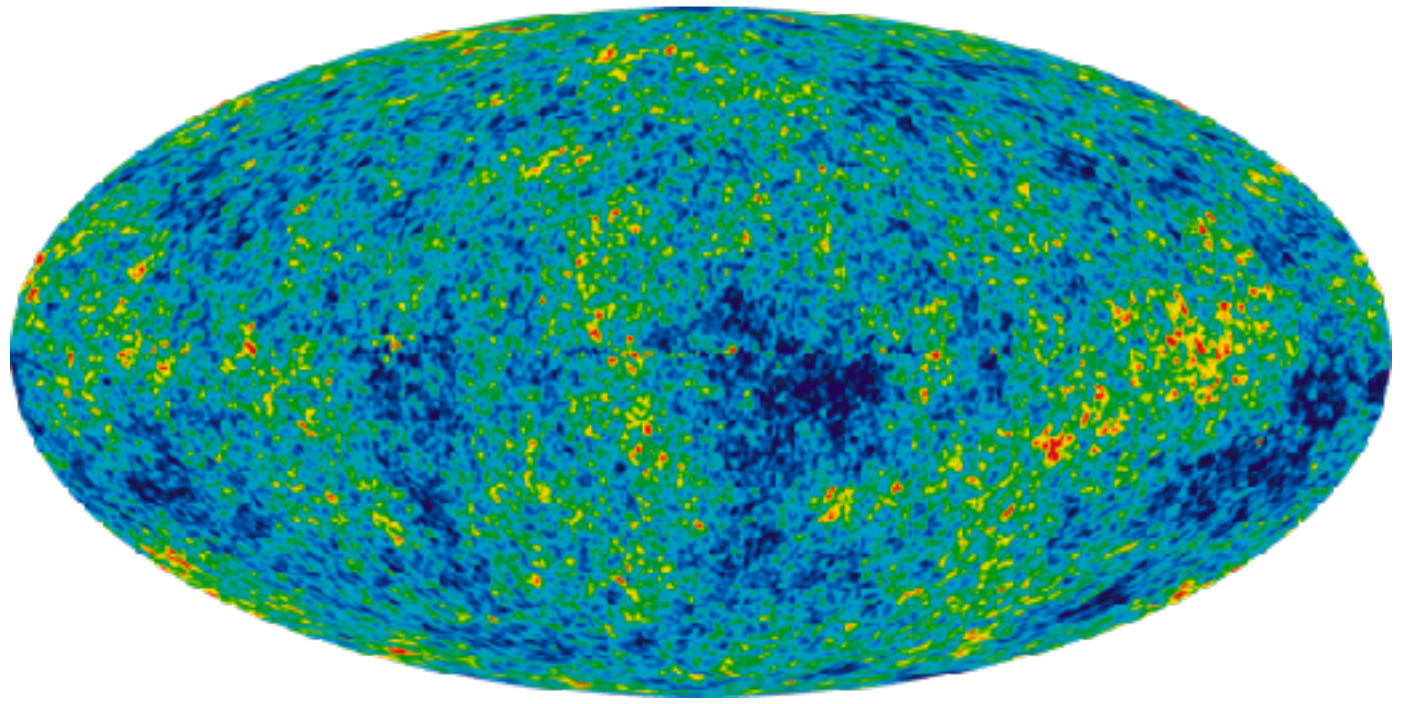
Correlators measure how fluctuations in one quantity relate to another

$$G_n(x_1, \ldots, x_n) = \langle \phi(x_1) \cdots \phi(x_n) \rangle$$

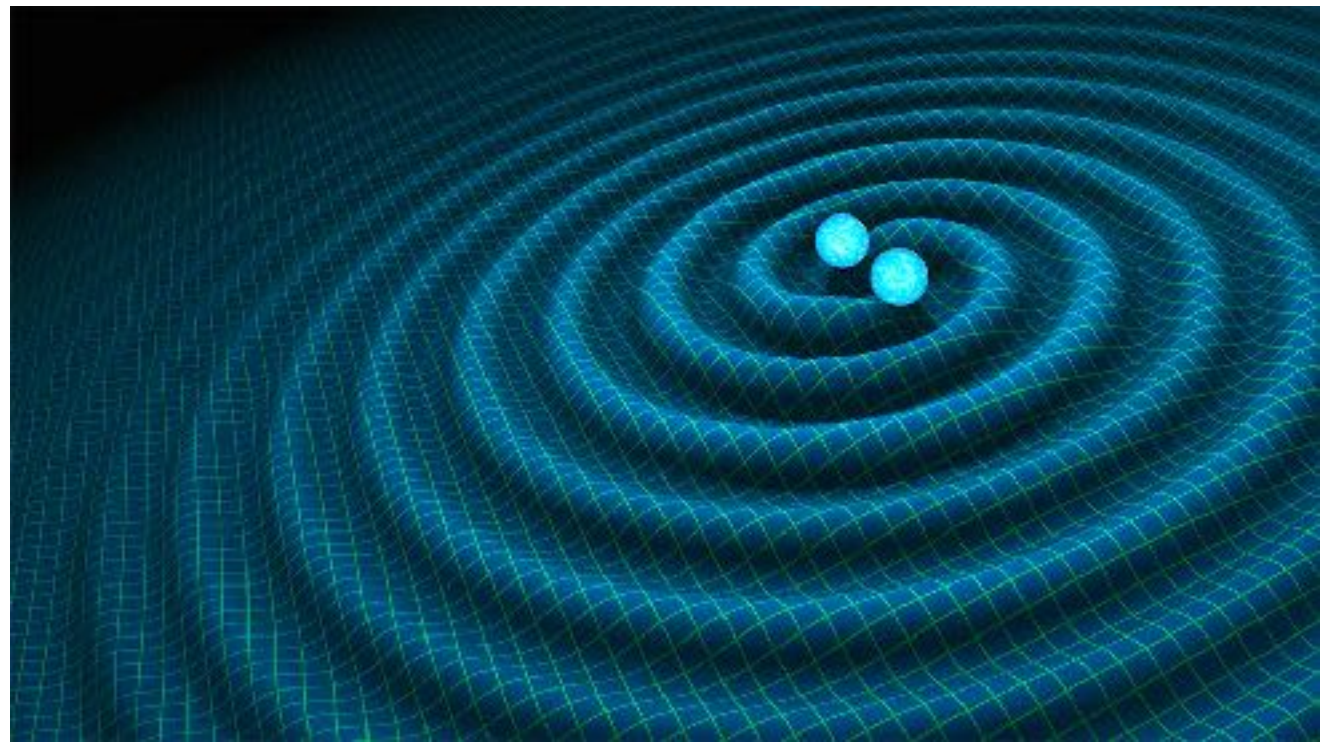
E.g. 2-point: how a fluctuation "here" is linked to one "there"

They connect theory to data.

Power spectrum of primordial fluctuations



Gravitational waves

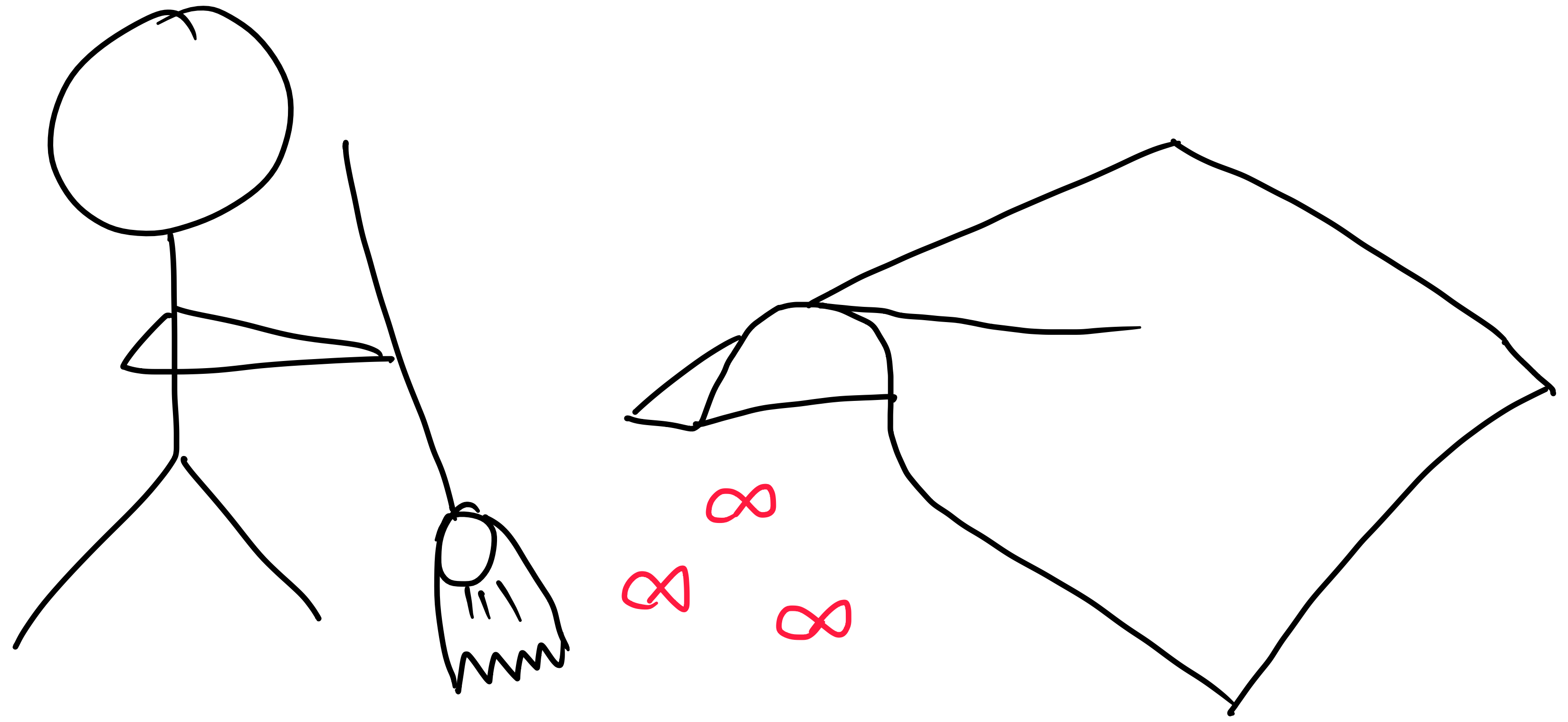


Why renormalization?

In quantum field theory, calculations often produce infinities.

Renormalization is the procedure that absorbs these infinities into a finite set of physical parameters, such as masses and couplings.

After renormalization, predictions are finite and can be compared with experiments.



The Renormalization Group

Deeper lesson: physical parameters depend on the scale at which we probe the system.

[Kadanoff, Wilson, Wegner]

Correlators change with resolution → scaling of couplings/observables

RG = systematic way to relate small-scale description to large-scale one

RG ⟵ Effective action ⟶ Correlators

Scaling of renormalized correlators

$$\Gamma^{(n)}[\phi(x_1), ..., \phi(x_n)] \equiv \frac{\delta^n \Gamma}{\delta\phi(x_1)\cdots\delta\phi(x_n)}$$

E.g. $\Gamma^{(2)}[\phi(x_1)\phi(x_2)] \sim \dfrac{1}{|x_1 - x_2|^{\alpha}}$

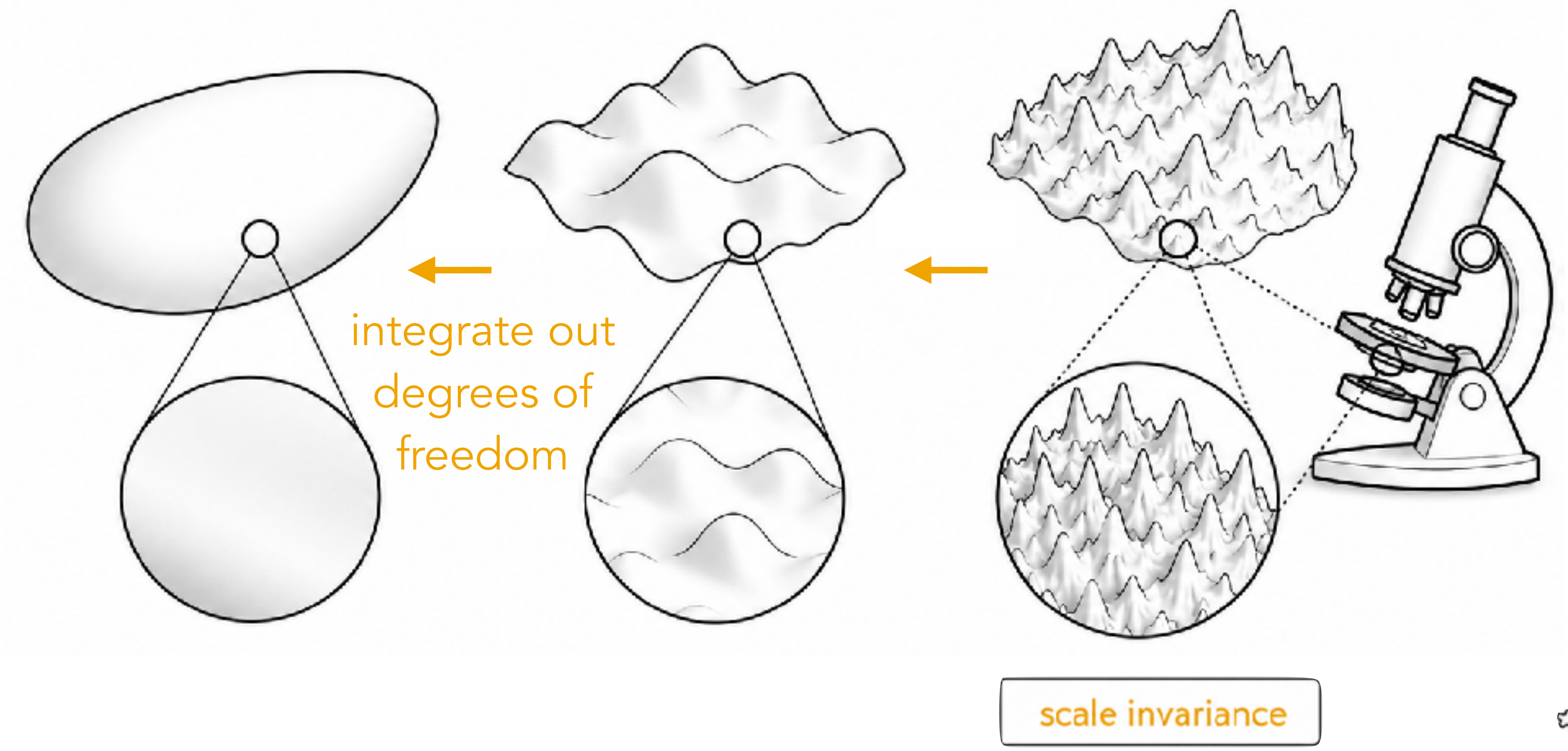
Scaling exponents = universality

From RG to coarse graining

Coarse graining: physical picture behind the RG

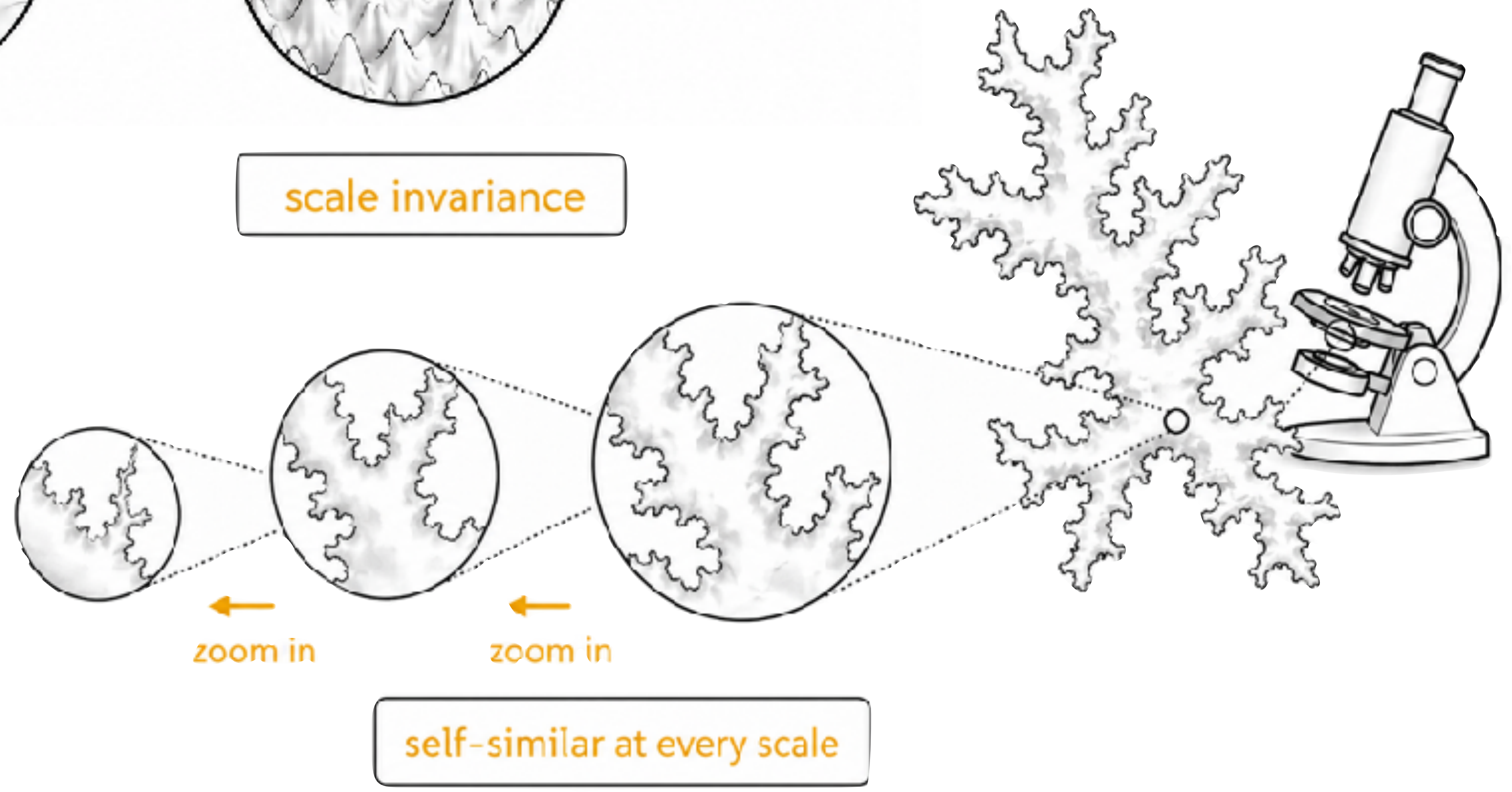
Low
resolution

Effective
description

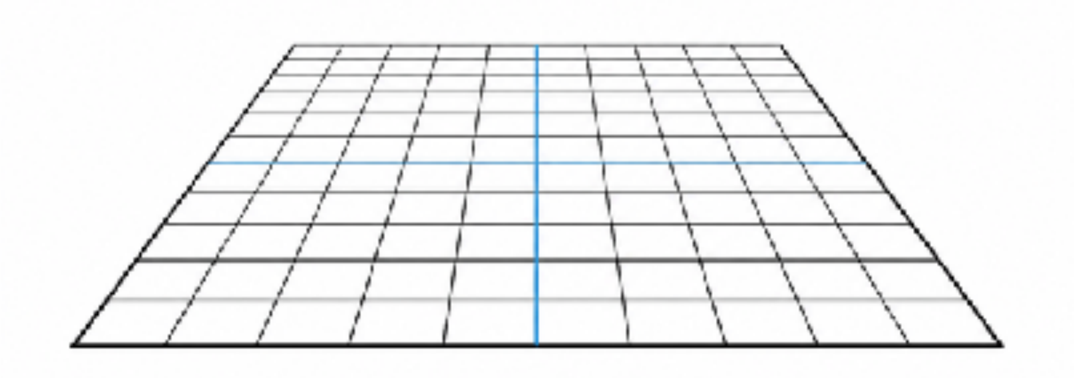


High
resolution

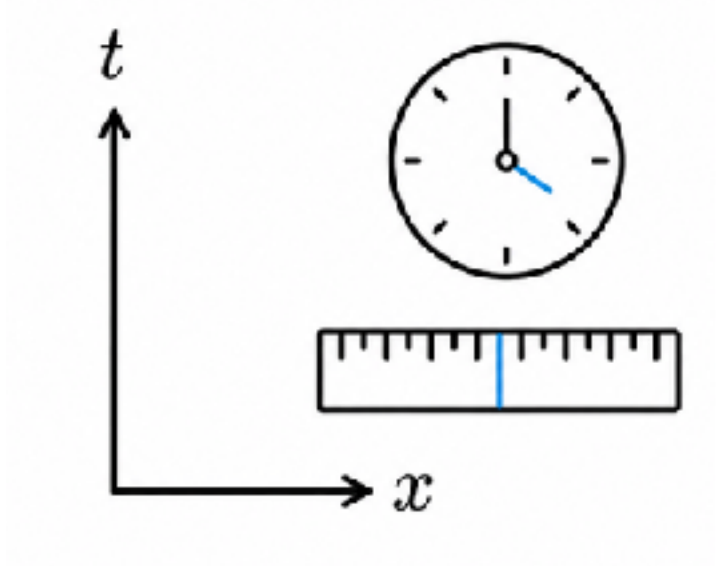
Fixed point $\longrightarrow$ scale invariance



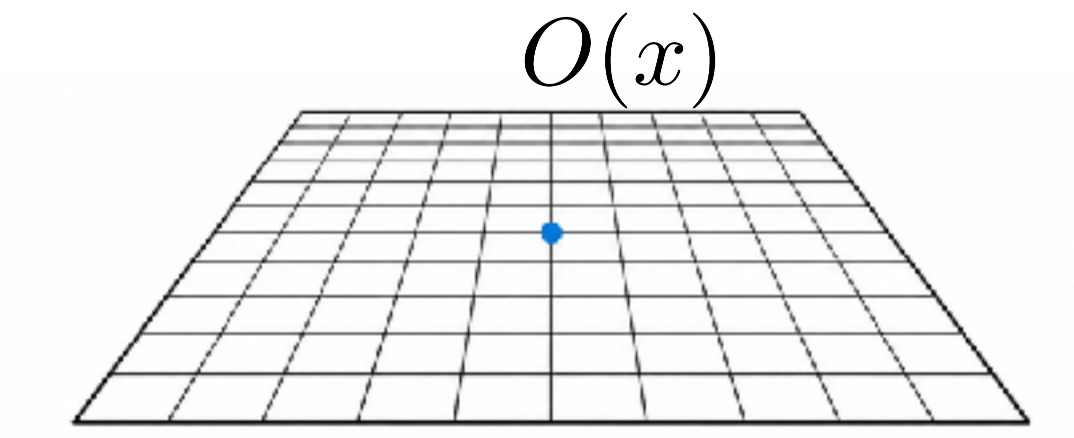
Standard QFT



Fields on a fixed flat spacetime (**background**)



External coordinates, rulers and clocks

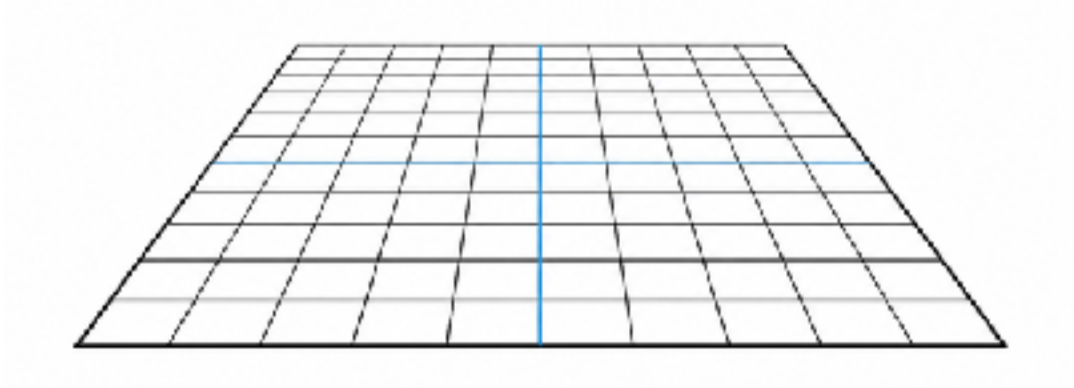


Local operators are inserted at specific coordinates

Observables are expectation values / **correlators**

Externally prescribed **RG, probe scale**

Standard QFT



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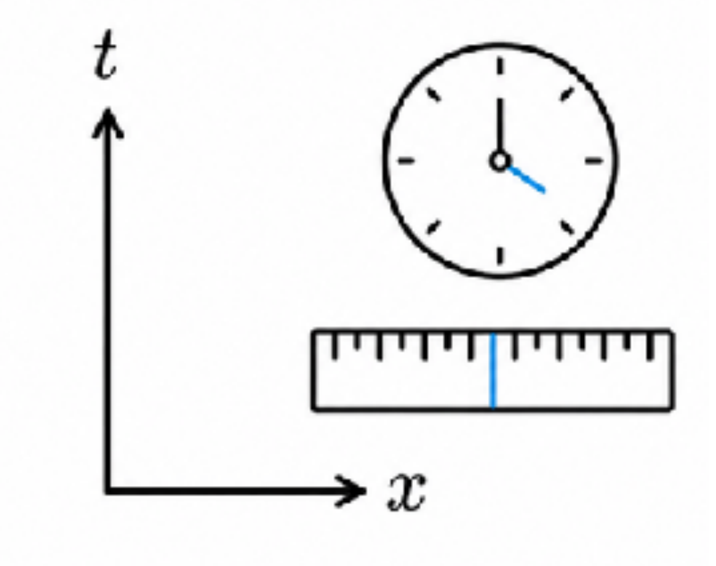
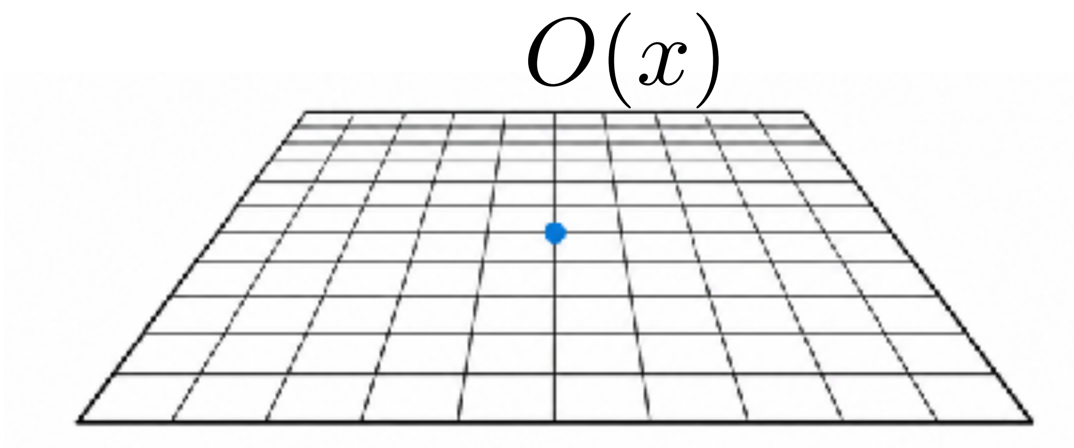


External coordinates, rulers and clocks



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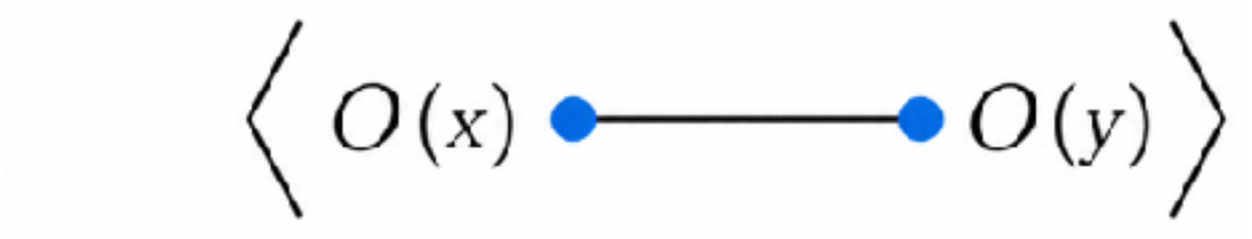
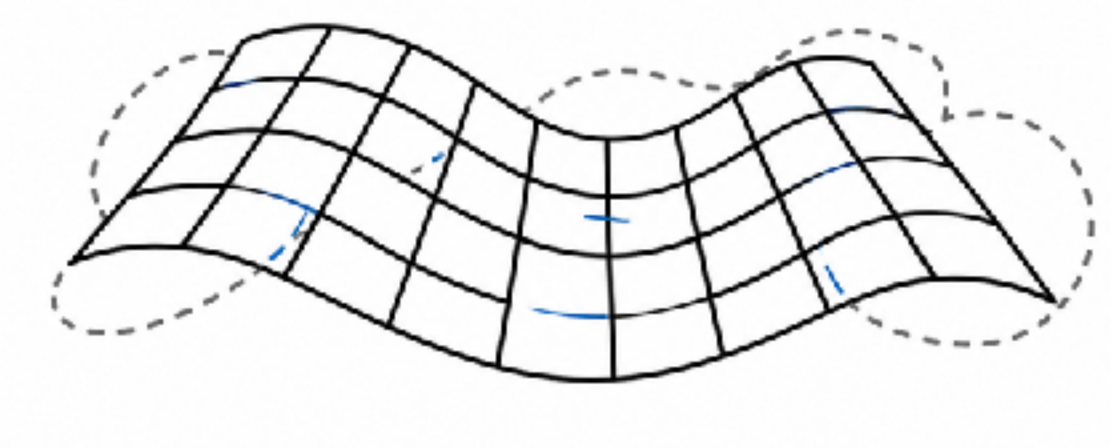


Observables are expectation values / **correlators**

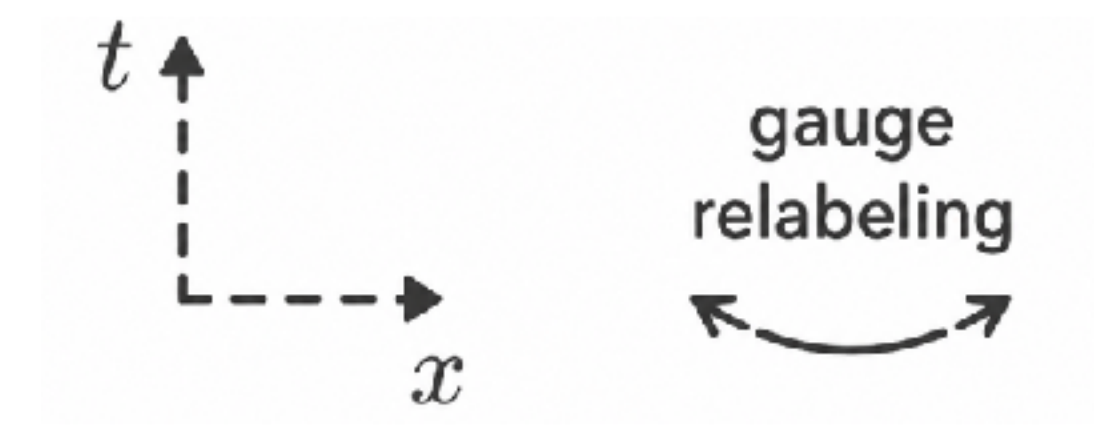
Externally prescribed **RG, probe scale**

Quantum Gravity

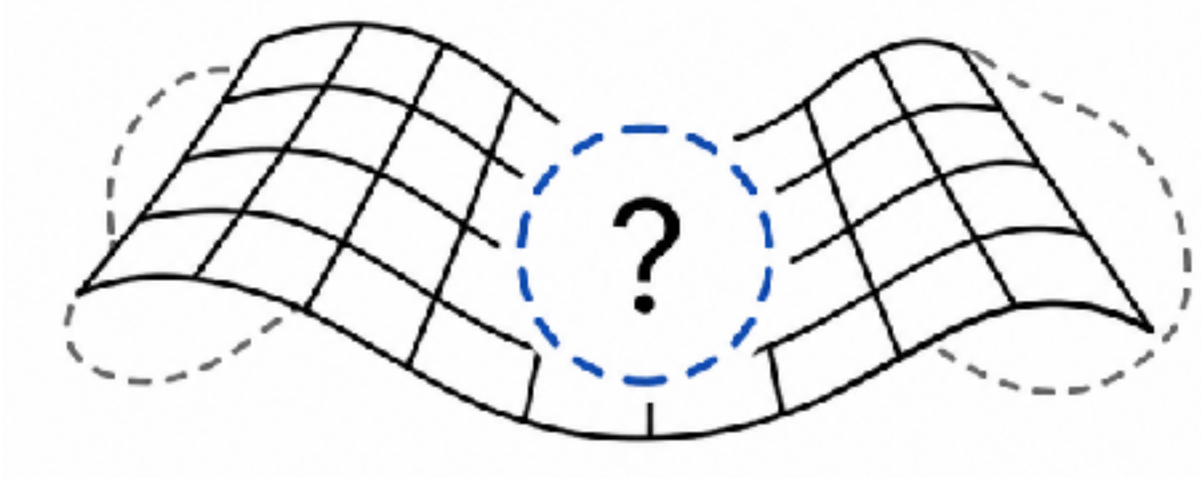
The metric itself is a **quantum field**



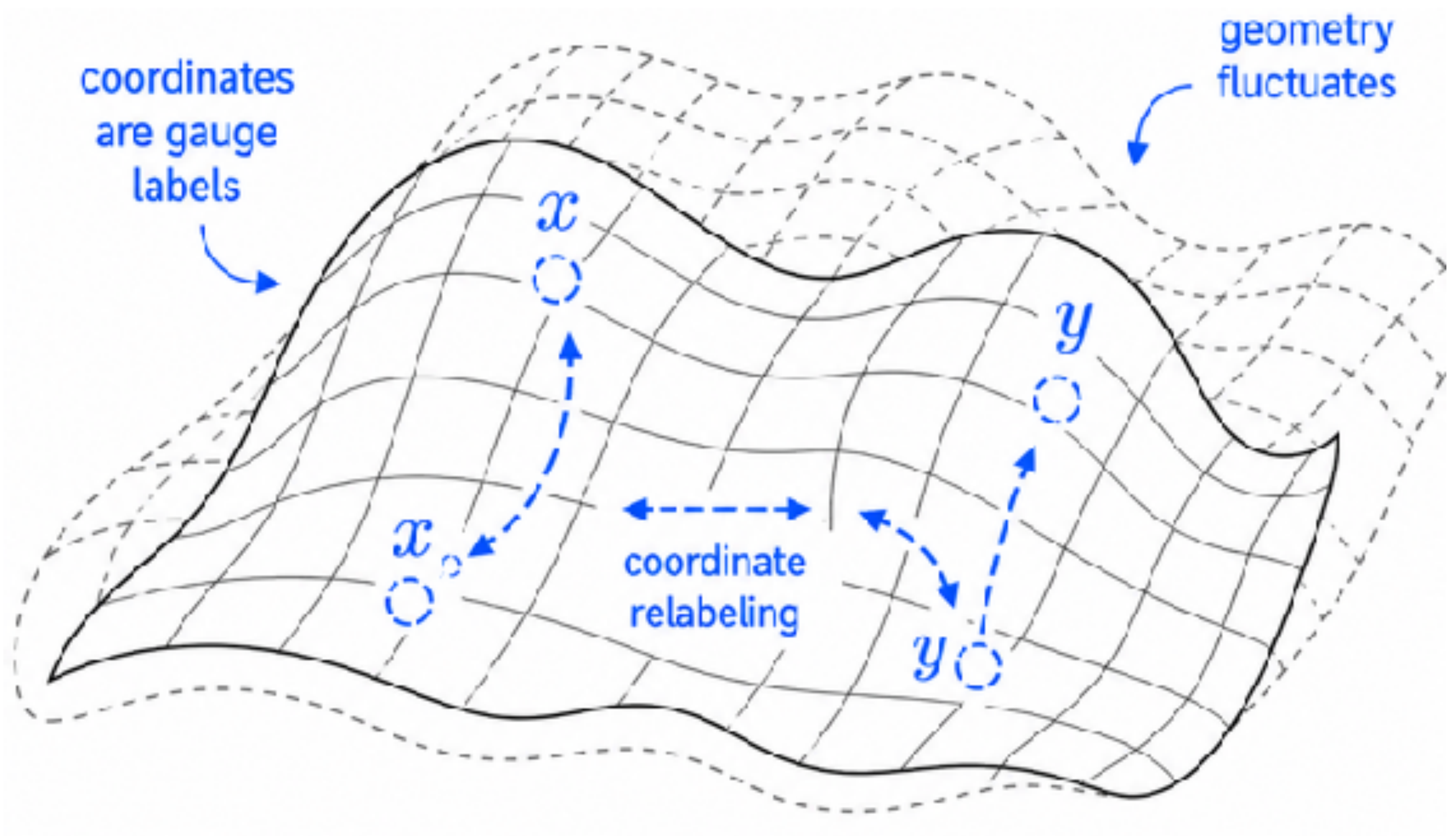
Coordinates have **no physical meaning**



Point "x" has no significance



Coordinate-dependent correlators have no physical meaning



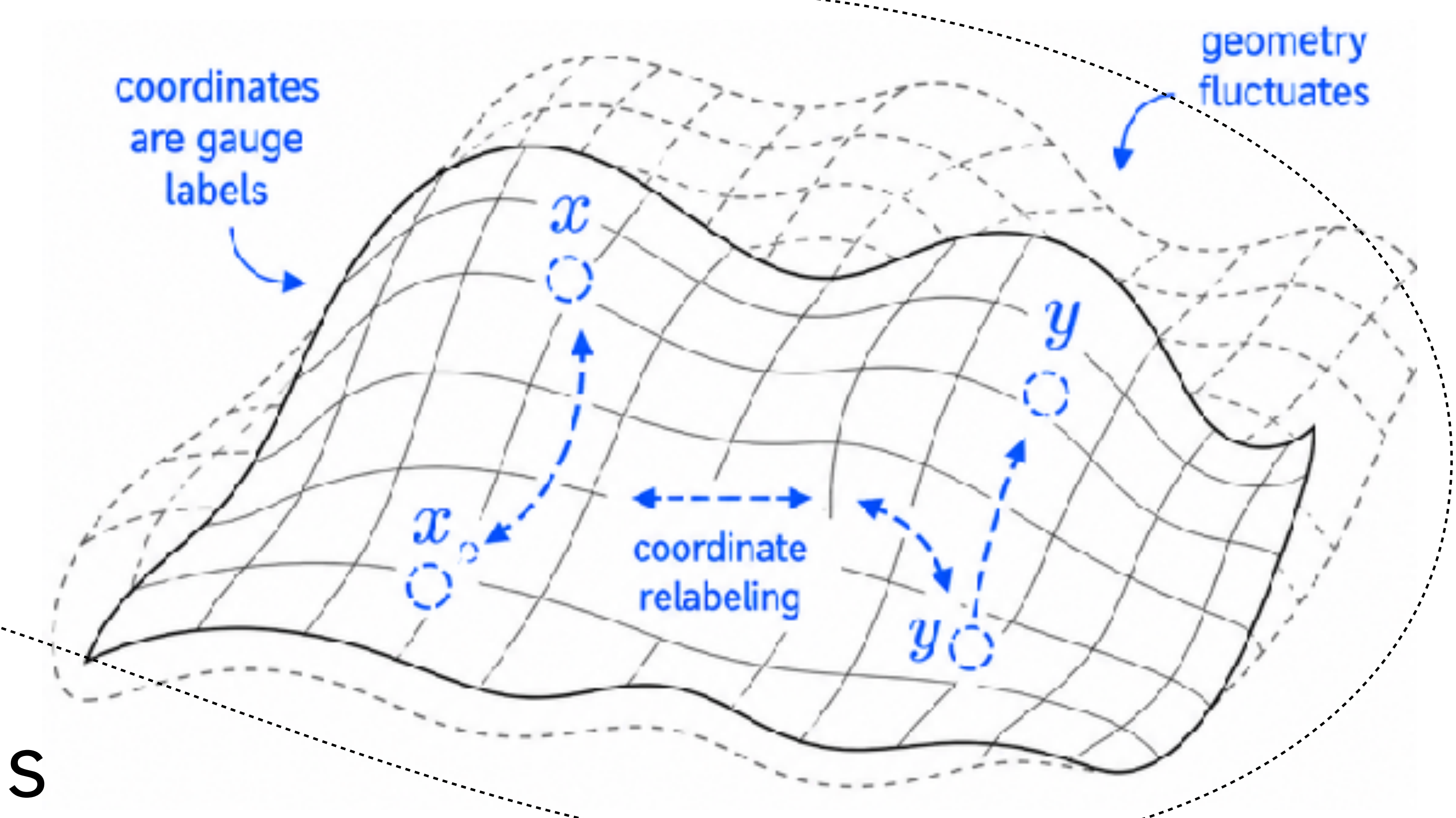
RG scale?

Problem set 1

$$\left\langle O(x) \bullet\!\!-\!\!-\!\!-\!\!\bullet O(y) \right\rangle$$

Observables are expectation values / **correlators**

Coordinate-dependent correlators have no physical meaning



Include/identify a set of four reference fields

$$X^\mu(x) = \chi^\mu \quad \Rightarrow \quad x = x(\chi)$$

Relational observable $\mathcal{O}_\phi(\chi) := \phi(x(\chi))$

Express correlations in relation to fields, remain meaningful when spacetime dynamical:

$$G_n(x_1, \ldots, x_n) = \langle \phi(x_1) \cdots \phi(x_n) \rangle \longrightarrow G_n(\chi_1, \ldots, \chi_n) = \langle \mathcal{O}_\phi(\chi_1) \cdots \mathcal{O}_\phi(\chi_n) \rangle$$

- manifestly diffeomorphism invariant;
- reduce to standard correlators when frame fixed;
- operational meaning: "what detectors see when their clocks/rods read χ_i"

Problem set 1

Express correlations in relation to fields, remain meaningful when spacetime dynamical:

$$G_n(x_1, \ldots, x_n) = \langle \phi(x_1) \cdots \phi(x_n) \rangle \longrightarrow G_n(\chi_1, \ldots, \chi_n) = \langle \mathcal{O}_\phi(\chi_1) \cdots \mathcal{O}_\phi(\chi_n) \rangle$$

How do we construct the path integral for relational observables?

Derive the generating functional for relational observables

A — Treat frame as classical (reduced phase space) 4 scalars + Gaussian dust

[RF, Thiemann, 2404.18224 (2024) and 2503.22474 (2025), RF, 2507.14296 (2025)]

Use Hamiltonian phase space path integral

Relational effective action without gauge fixing

All the results will depend on the choice of the frame?

B — **Include the frame in the path integral**

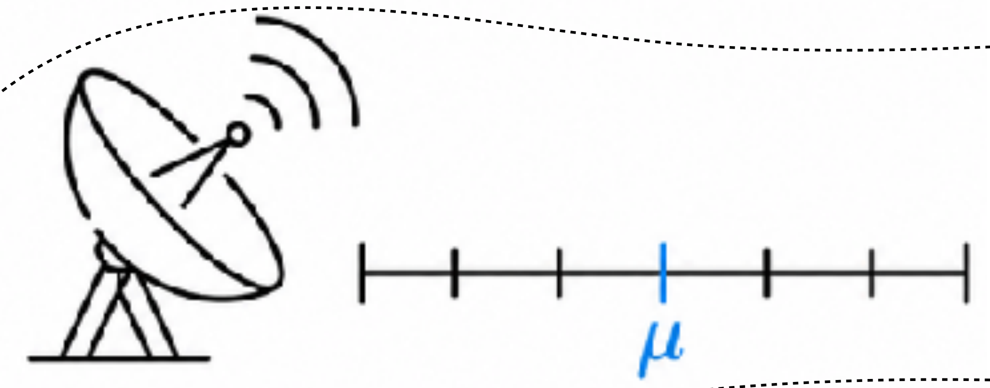
[Aguilar-Gutierrez, RF, Höhn, Marchetti, 2607.xxxxx]

Integrate over relational observables only

See Luca's talk tomorrow!

Main topic of this talk!

Problem set 2



Externally prescribed **RG,**
probe scale

RG scale?

RG in quantum gravity: we coarse-grain relationally (using clocks/rods):

$$G_n^{(k)}(\chi_1, \dots, \chi_n) \quad \text{from} \quad \Gamma_k[g, \phi, X]$$

· physical meaning of RG scale

· physical prescription for coarse graining

Output: scale-dependent relational correlators.

$$\Gamma^{(2)}[\mathcal{O}_\phi(\chi_1)\,\mathcal{O}_\phi(\chi_2)] \;\sim\; \frac{1}{|\chi_1 - \chi_2|^\alpha}$$

relational correlators fall off with a relational distance between physical events defined by our clocks and rods

Renormalization in quantum gravity

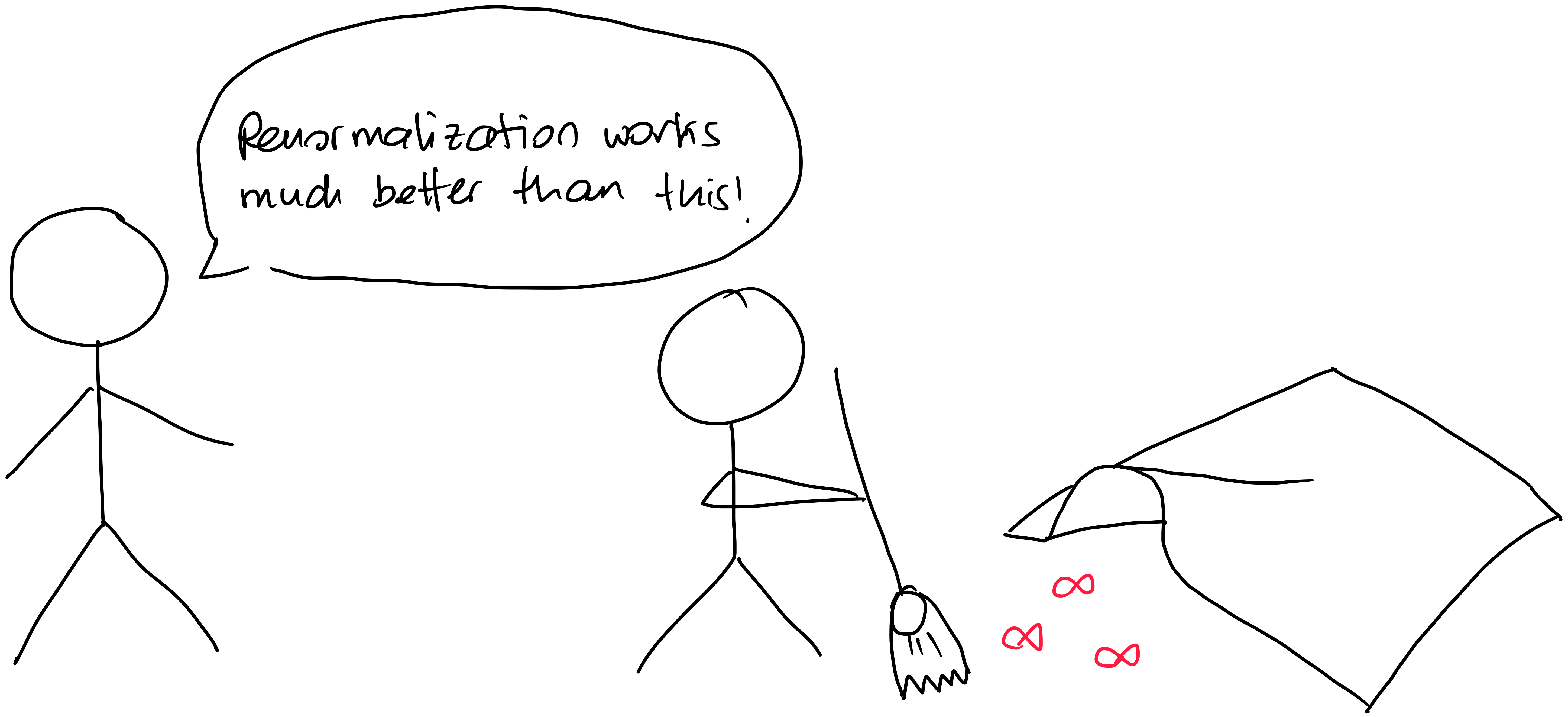
Gravity is perturbative non-renormalizable

[Goroff and Sagnotti (1985)]

Asymptotic Safety

Weinberg's conjecture: There exists a nonperturbative dynamical mechanism which renders physical scattering amplitudes finite and computable at energy scales exceeding the Planck scale: a nontrivial UV fixed point.

[Weinberg (1979)]

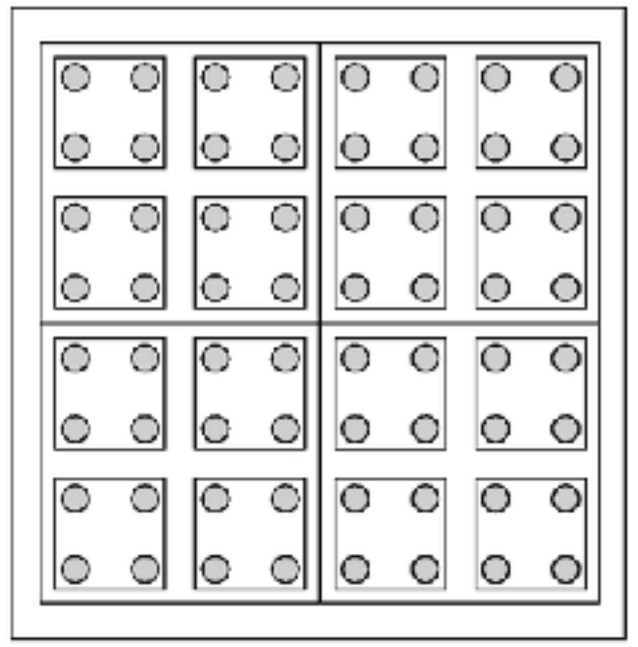


Renormalization in quantum gravity

[Wetterich (1992)]

Tool: **Functional Renormalization Group**
in the spirit of the Wilsonian renormalization,
nonperturbative

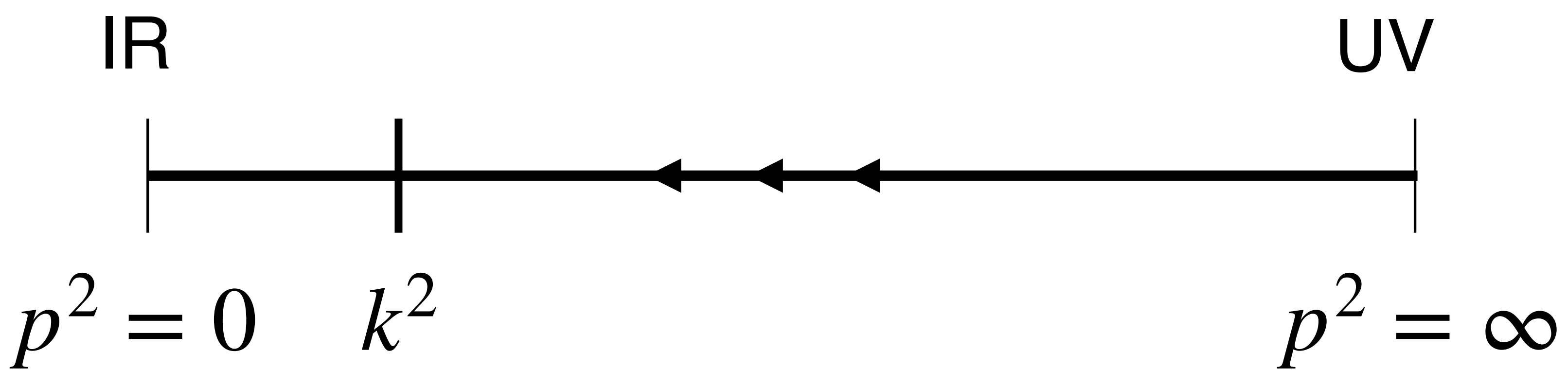
the quantum fluctuations in the path integral can be integrated out progressively



RG scale = resolution scale

$$k\partial_k \Gamma_k[\phi] = \text{Complicated known functional of } \Gamma_k[\phi]$$

Use it as a machinery to compute the renormalized effective action → scaling of correlators



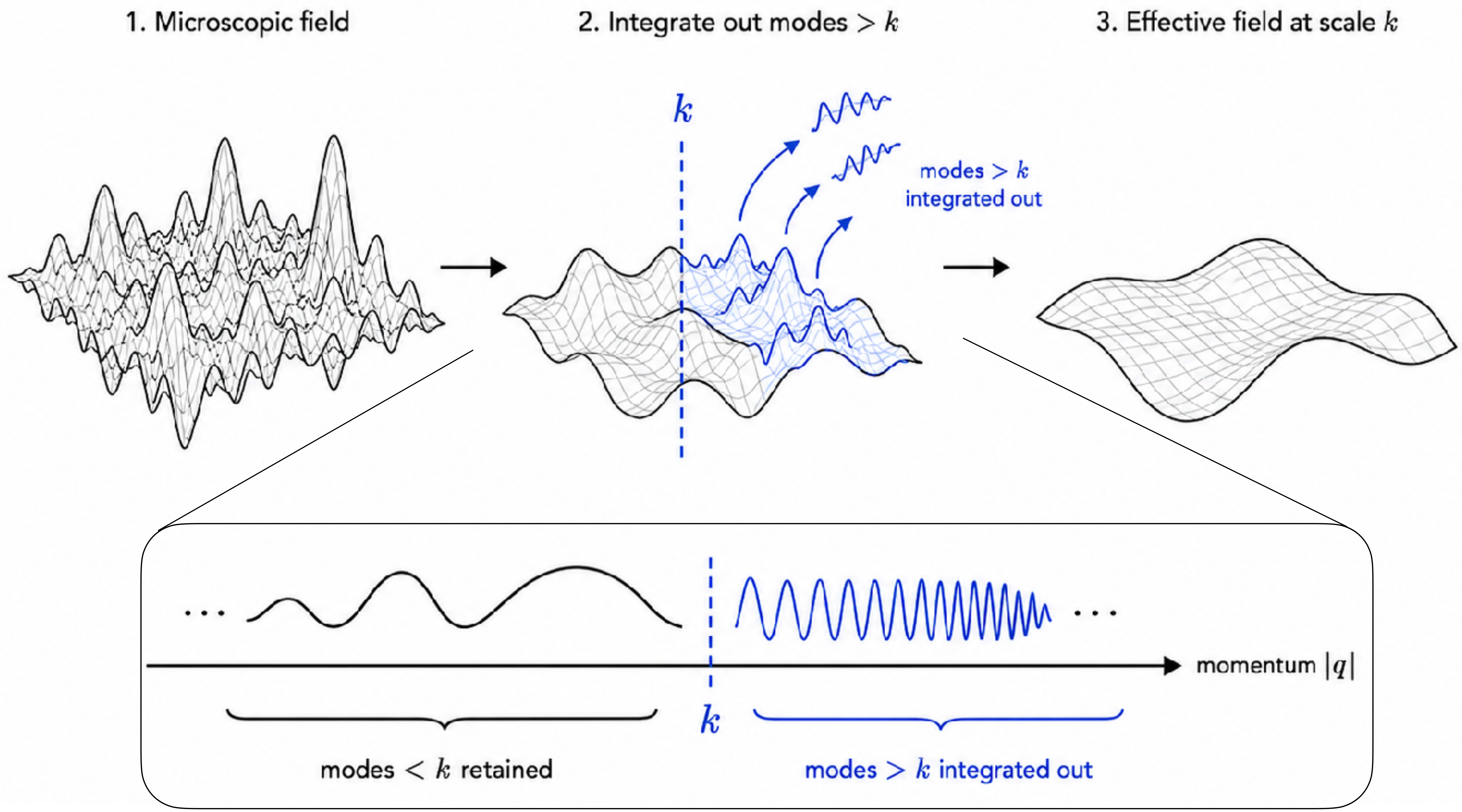
$$\lim_{k \to 0} \Gamma_k \to \Gamma \qquad \lim_{k \to \infty} \Gamma_k \to S$$

Asymptotic Safety: look for non-Gaussian UV fixed point of this flow.
Quantum gravity predictive at arbitrary scales [Reuter (1996)]

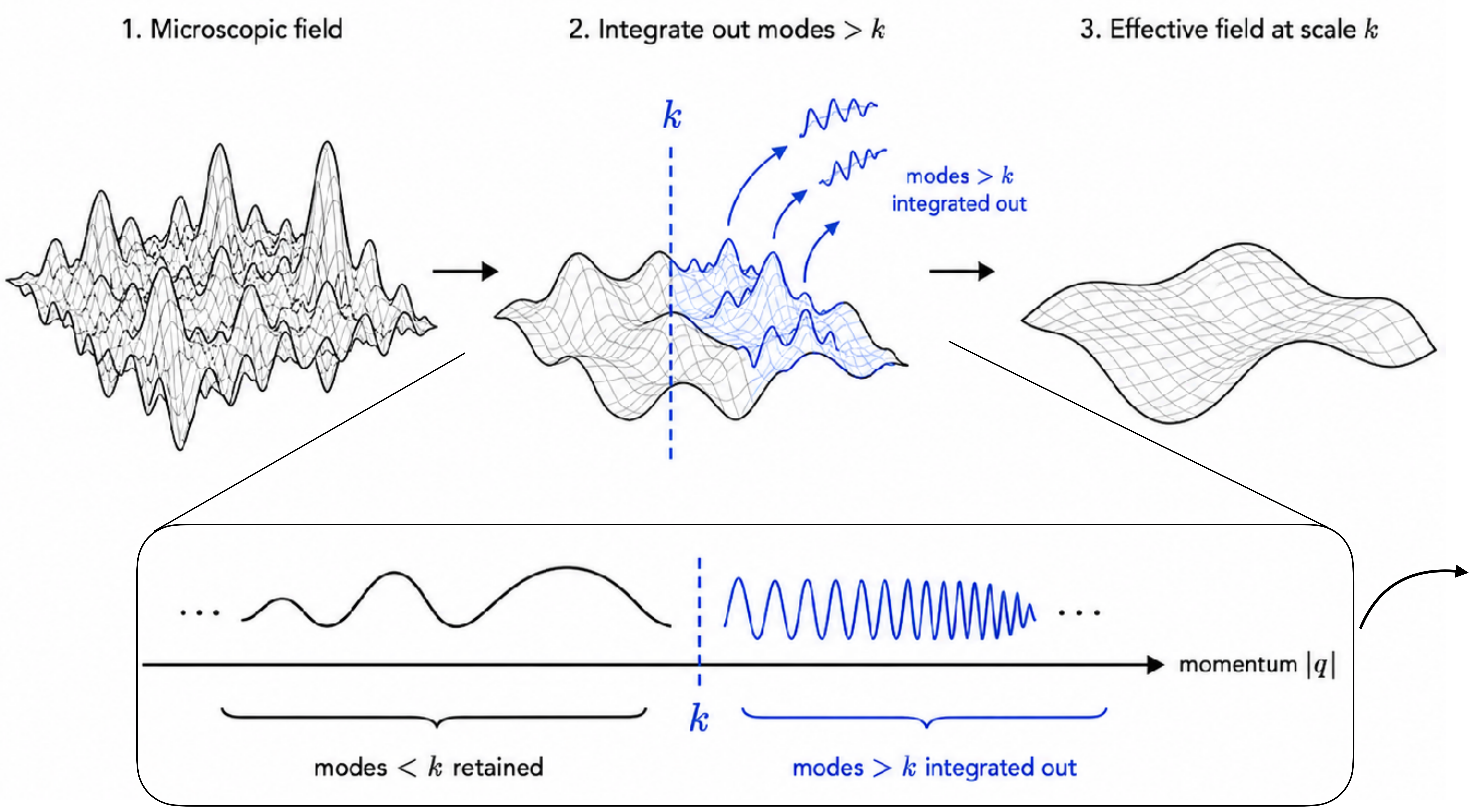
[Wetterich, Reuter, Percacci, Pawlowski, Saueressig, Eichhorn, Bonanno, and many more]

Renormalization in quantum gravity

Regulator/Cutoff function $\mathcal{R}_k(\Box)$ integrates out modes above the scale k



Renormalization in quantum gravity: open problems



In curved, dynamical spacetime no well defined notion

Which are the modes to coarse grain upon? What is IR/UV?

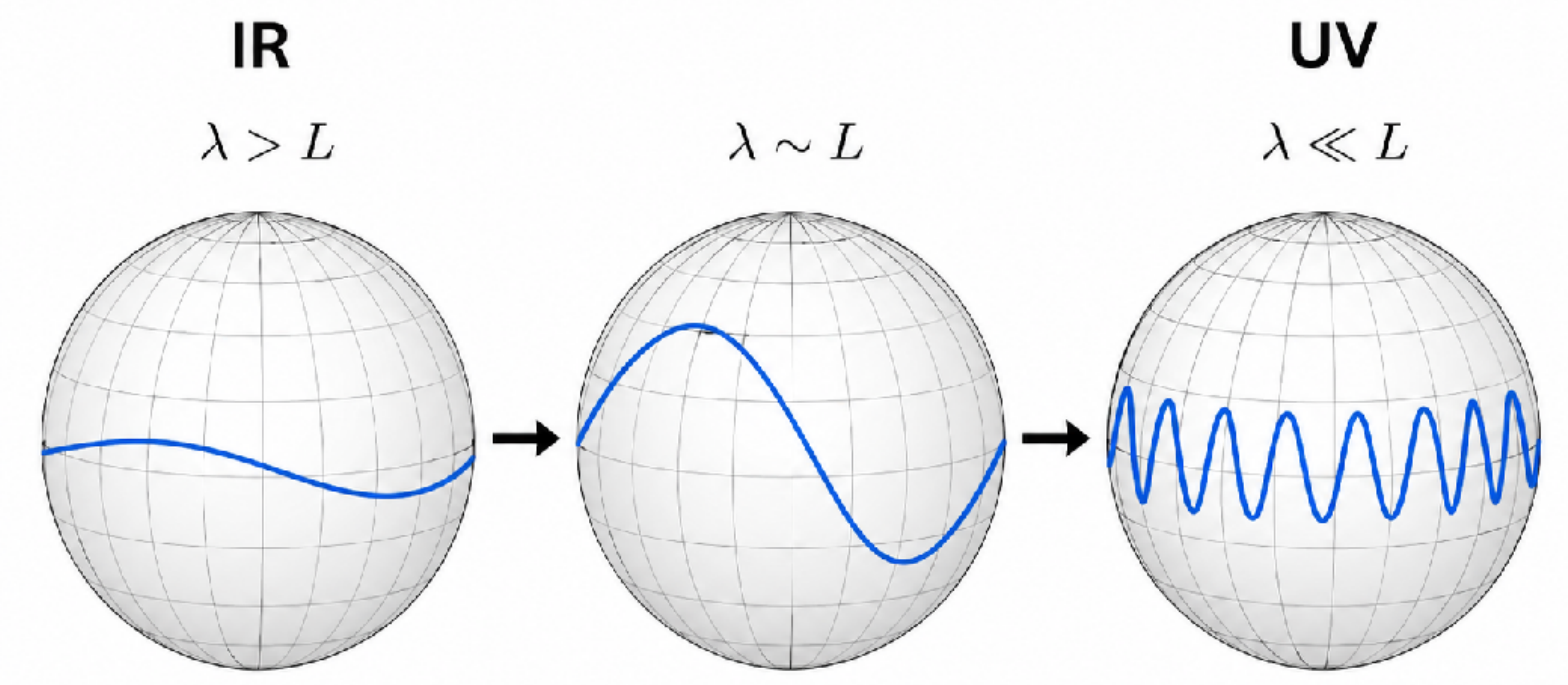
In quantum gravity, what is *k*?

What is UV/IR?

RG scale is not an absolute, external scale

needs to compare/**relate** with another scale to define what is IR/UV

compare mode wavelength with system size



… with the complication that the system is also dynamical in quantum gravity!

[Bonanno, RF, Oglialoro, 2606.04085 (2026)); RF, Reuter 2203.08003 (2022)]

Operational intuition

What if instead of cutting by external wavelength,
cut by the number of resolvable modes/degrees of freedom?

Counting modes instead of momenta

Consider a free **scalar field coupled to gravity**

$$S_H(g) = \frac{1}{16\pi G}\int d^4x\sqrt{g}\,[2\Lambda - R]\ ,$$

$$S_m(\phi;g) = \int d^4x\sqrt{g}\frac{1}{2}(\partial\phi)^2$$

The backreaction of the scalar field on the metric is **encoded in the effective action**.

At one loop

$$\Gamma(g,\phi) = S_H(g) + S_m(g,\phi) + \frac{1}{2}\mathrm{Tr}\log(\Box/\mu^2)$$

Variation of the EA wrt the metric yields **semiclassical Einstein equations**

$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} + \Lambda_B g_{\mu\nu} = 8\pi G\langle T_{\mu\nu}\rangle$$

[RF, Naso, Percacci 2503.17203 (2025), RF, Percacci 2404.12357 (2024), Becker, Reuter 2021, Banjeree, Becker, RF 2302.03547 (2023)]

Self-consistency ties geometry to resolution

Let us work on a **dynamical sphere** S^4

the radius is dynamical
it makes the use of a dimensionless cutoff particularly natural!

angular momentum $\lambda_\ell = \frac{R}{12}\ell(\ell+3)\ , \quad m_\ell = \frac{1}{6}(\ell+1)(\ell+2)(2\ell+3)\ , \quad \ell = 1, 2\ldots$

the operation Tr in the definition of the EA can be written explicitly as a sum over all eigenstates of the Laplacian

Dimensionless cutoff: N-cutoff

We regulate the sum by putting an upper bound N on the quantum number ℓ

$$\frac{1}{2}\mathrm{Tr}_N \log(\Box/\mu^2) = \frac{1}{2}\sum_{\ell=1}^{N} m_\ell \log\left(\frac{\lambda_\ell + E}{\mu^2}\right) = \frac{1}{2}\sum_{\ell=1}^{N} m_\ell \log\left(\frac{R}{12\mu^2}\ell(\ell+3)\right)$$

Self-consistency ties geometry to resolution

Self-consistent on-shellness
the radius (Ricci scalar)
is dynamical

$$\frac{24\pi}{GR^3}(-R+4\Lambda) = \frac{1}{24R}N(N+4)(N^2+4N+7) =: \frac{1}{12R}f(N)$$

$$R = \frac{24\pi}{Gf(N)}\left(-1 \pm \sqrt{1+\frac{G\Lambda f(N)}{3\pi}}\right) \sim \frac{1}{N^2} \quad \to 0 \text{ when } N \to \infty$$

Including more quantum modes changes the geometry itself.

The curvature of spacetime decreases when more quantum modes are included in the calculation!

$N \to \infty$

UV/IR mixing!

This suggests to use the **dynamical spectrum as an operational ordering principle**…

A spectrum tells us which modes are available in the geometry; it does not yet tell us **which modes can be physically resolved** by a given set of clocks, rods, or detectors.

The relational perspective on the RG

Relational coarse graining

How do we define a relational cutoff?

1. Regularize the spectrum of relational observables $\quad \mathcal{R}_k(\Box)$

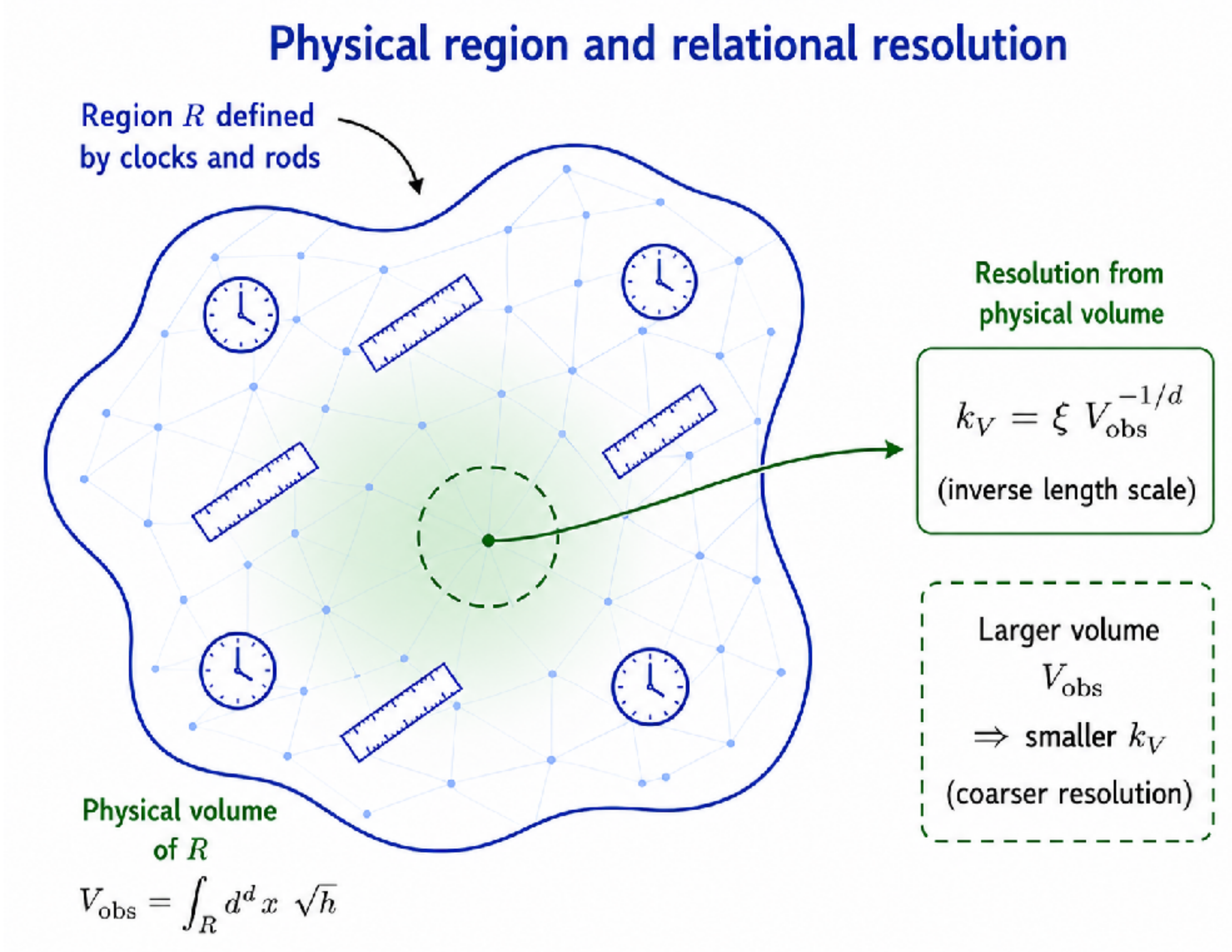
2. Relate the resolution to the reference frame $\quad \mathcal{R}_k(\Box)$

Relational coarse graining

Concrete implementation: **volume resolution**

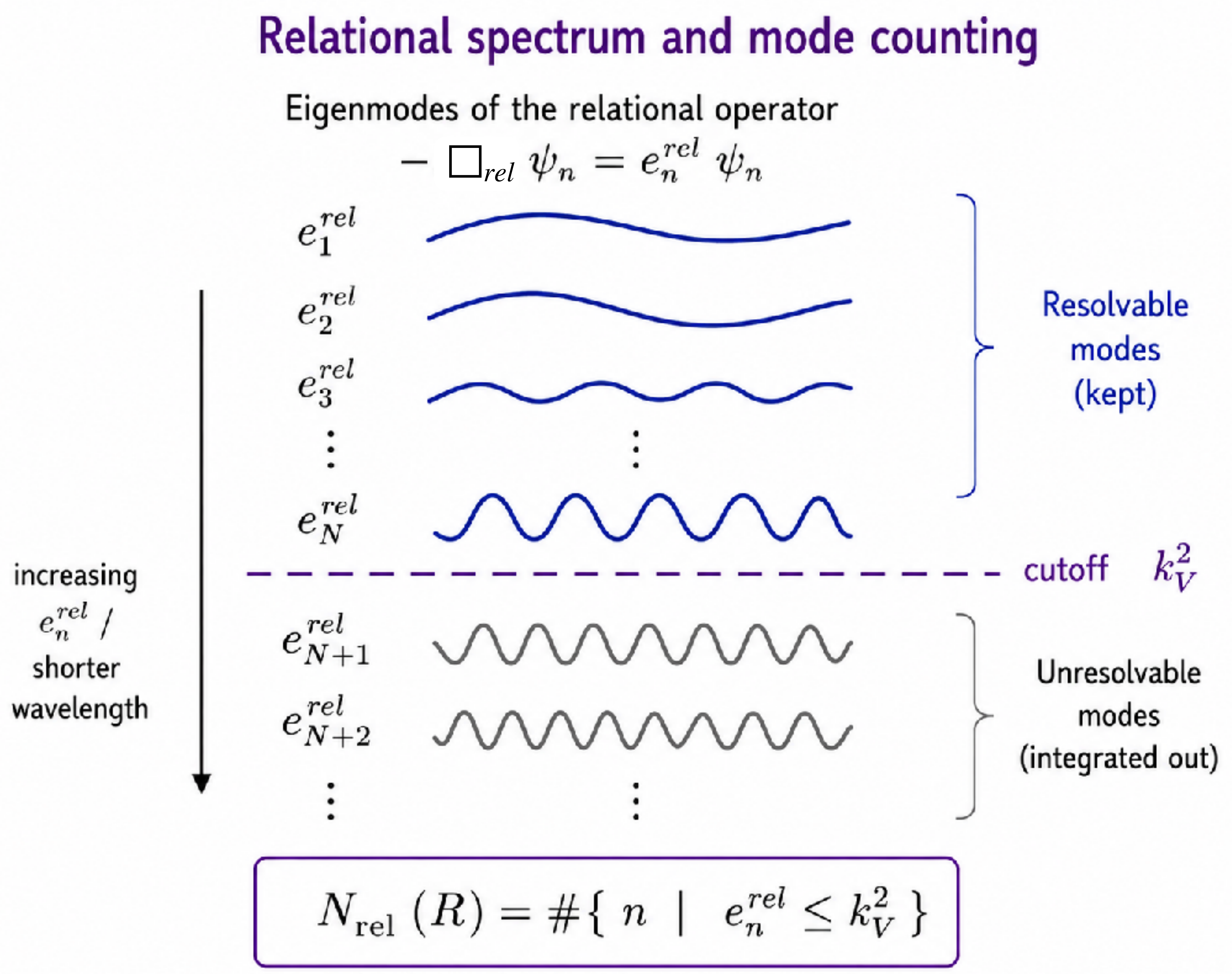
Choose a physical region using reference fields:

Its physical volume is an observable



Relational coarse graining

The cutoff counts the modes resolvable inside a physical region.

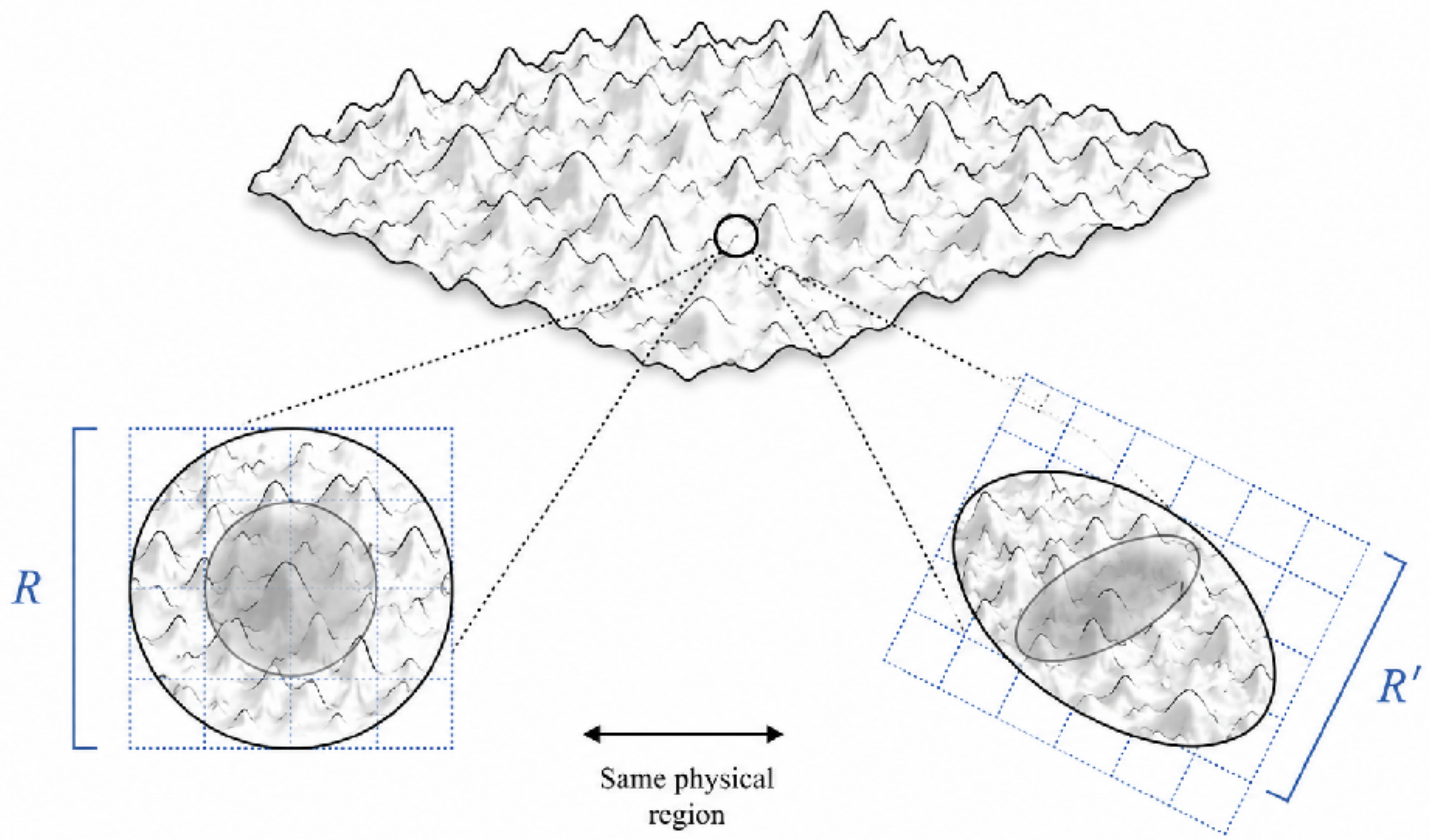


[RF, Han, Liu, including concrete application to LTB reduced model, work in progress]

Relational coarse graining

Regulator is in general frame dependent?

Different physical coarse graining prescriptions



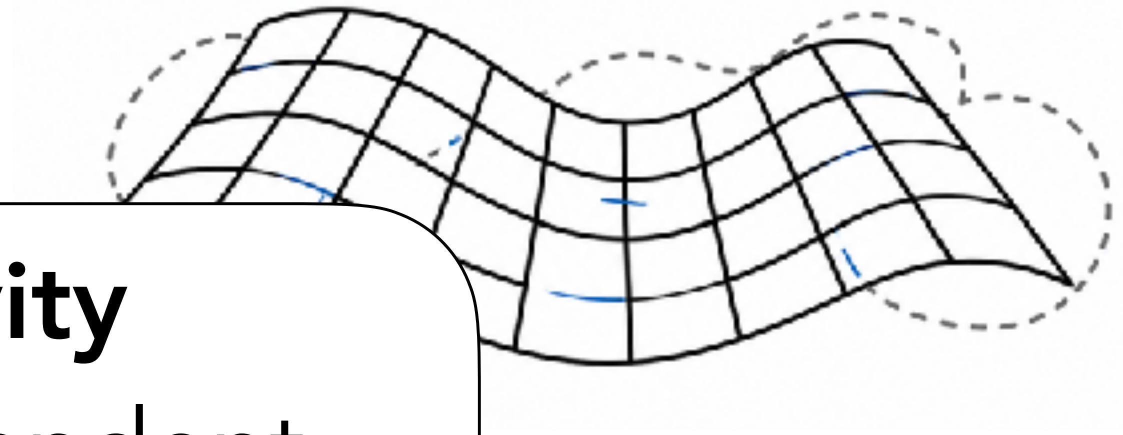
Using the relational path integral + relational regularization prescription we can study how things change

Observables and regulator must change together?

[Aguilar-Gutierrez, RF, Höhn, Marchetti, wip]

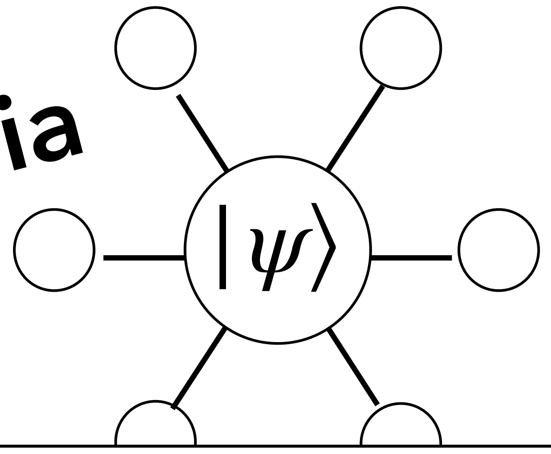
Relational coarse graining as a common language

Luca, Josh, Thomas



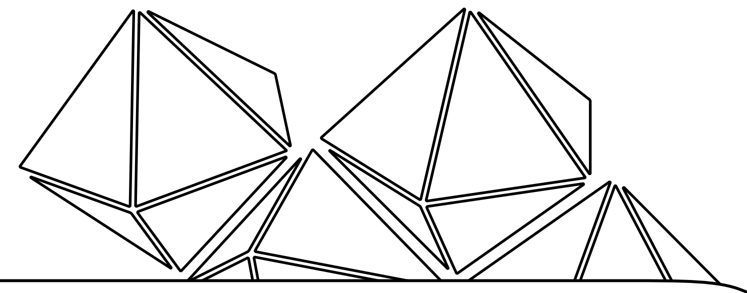
Quantum Gravity
Background independent notion of scale

Flaminia, Viktoria



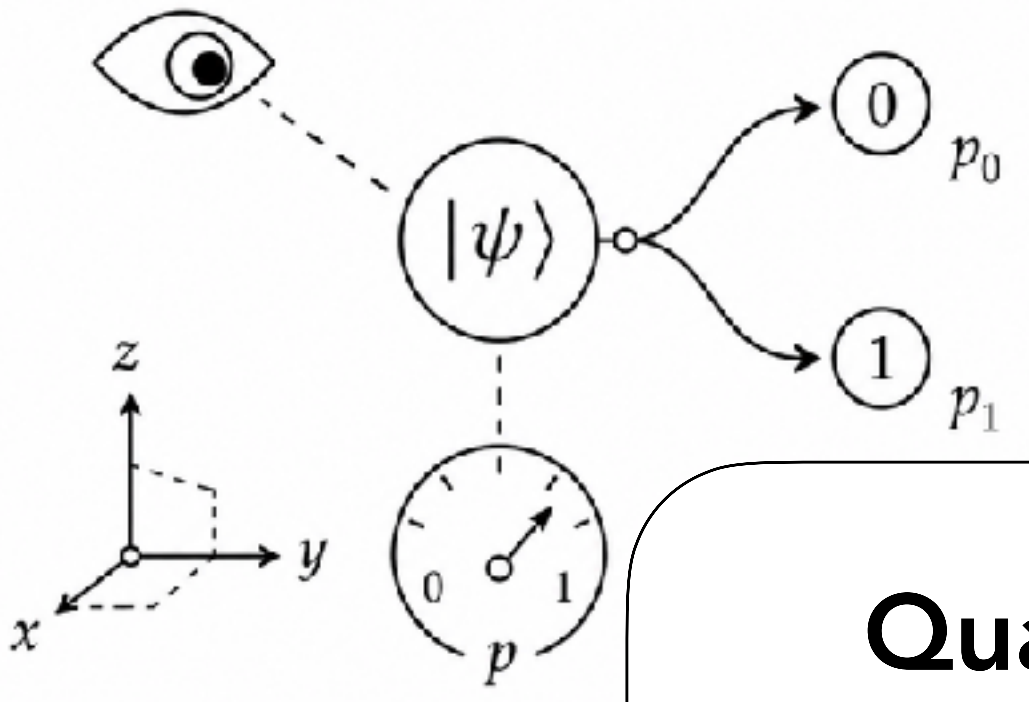
Quantum information
Finite distinguishability, operational resolution

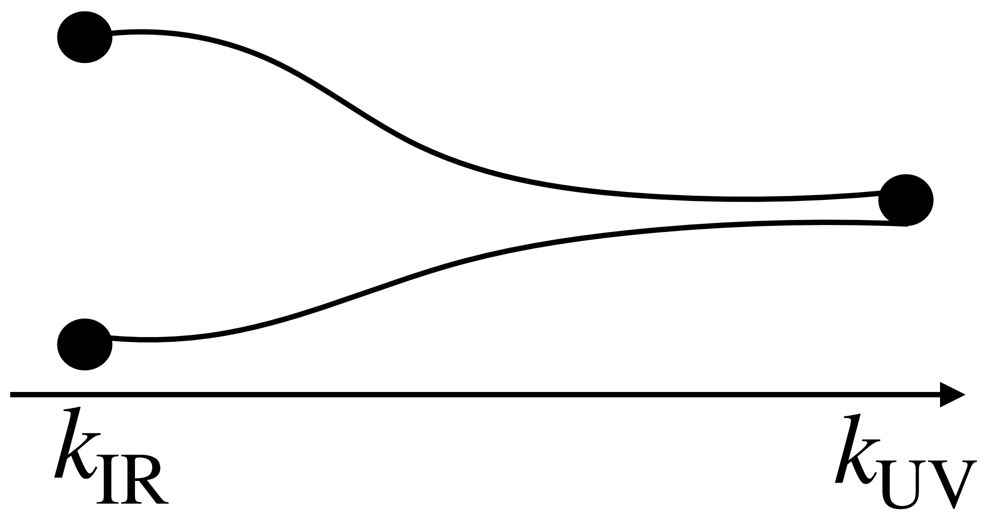
Mehdi, Daniele



Discrete geometry
Spectra, mode counting, minimal length

Relational coarse graining
RG scale = physical resolution





Quantum foundations
Observers and QRFs

Lin-Qing, Kasia

Asymptotic Safety
Physical meaning of flow

Conclusion and outlook

In ordinary QFT, coarse graining is defined with respect to an external scale.

In quantum gravity, the scale itself must acquire physical meaning.

Relational observables address where physics is localized.

Relational coarse graining addresses at what resolution it is observed.

RG flow can be viewed as the **change of accessible information with resolution.**

Outlook: Study the dependence of flow on the reference frame: universality?

Renormalization of different "quantum reference fields"

Connection with canonical models

Applications: cosmology, …

Thank you for your attention