Asymptotic safety and the road towards running relational observables

Renata Ferrero

based on work in collaboration with Kevin Falls and Martin Reuter

February 22nd 2024

11th TUX Workshop in Quantum Gravity

FRIEDRICH-ALEXANDER
UNIVERSITÄT
ERLANGEN-NÜRNBERG

Plan of the talk

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A s y m p t o t i c   S a f e t y

Effective Average Action

Functional Renormalization Group

Quantum Einstein Gravity

Plan of the talk

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Asymptotic Safety

Effective Average Action

Functional Renormalization Group

Quantum Einstein Gravity

Running relational observables

Composite operators

Covariant formulation

Flow of the observables

Effective Average Action &
Functional Renormalization Group

Asymptotic Safety

Reuter-Saueressig and Percacci's book

The RG

Callan-Symanzik equation

RG in perturbation theory

only the finitely many beta functions that are

related to the relevant couplings are considered

Callan (1970), Symanzik (1970)

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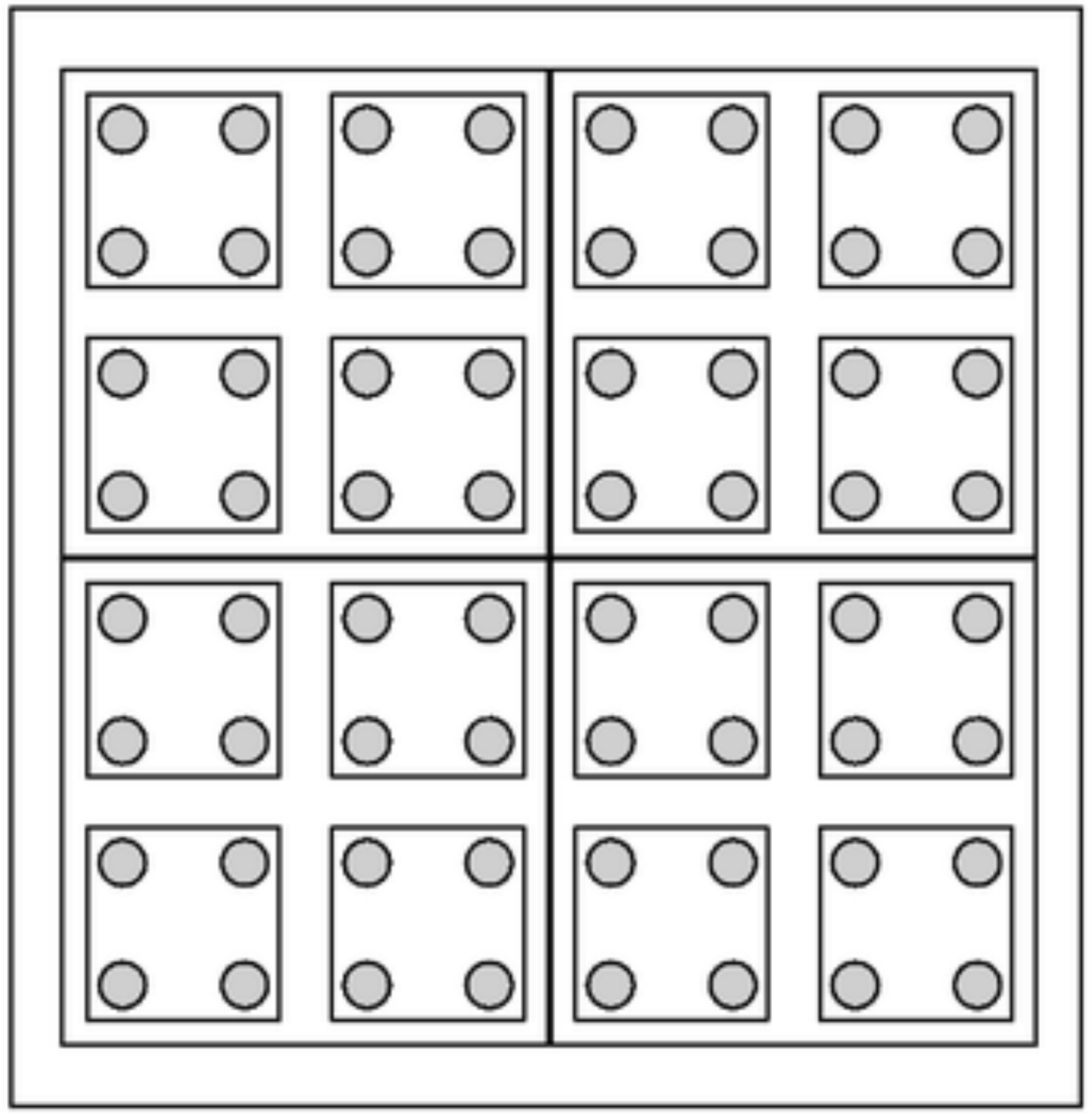
Exact RGE

Wilsonian Exact RG

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

Wilson (1971), Kadanoff (1966)



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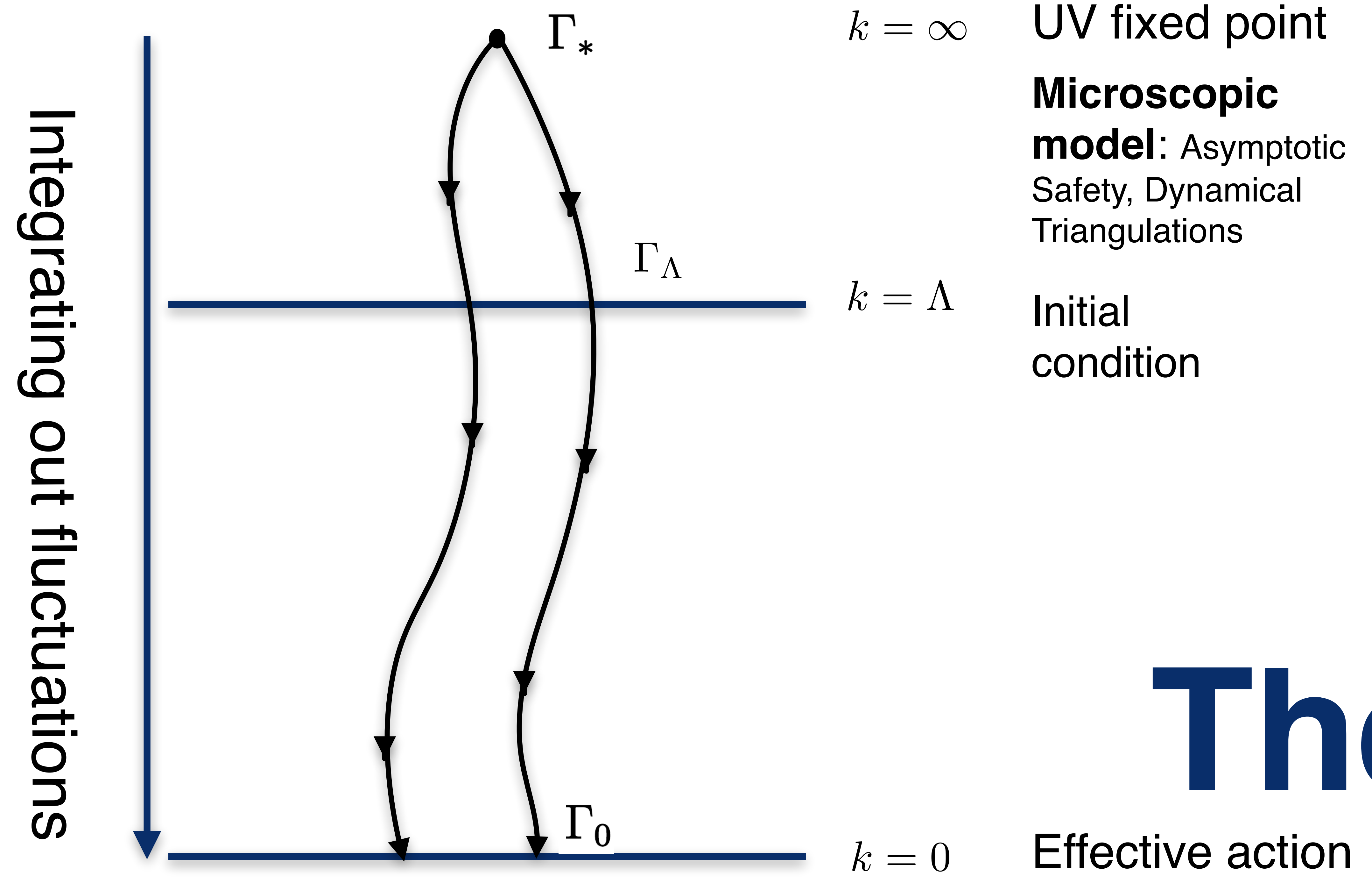

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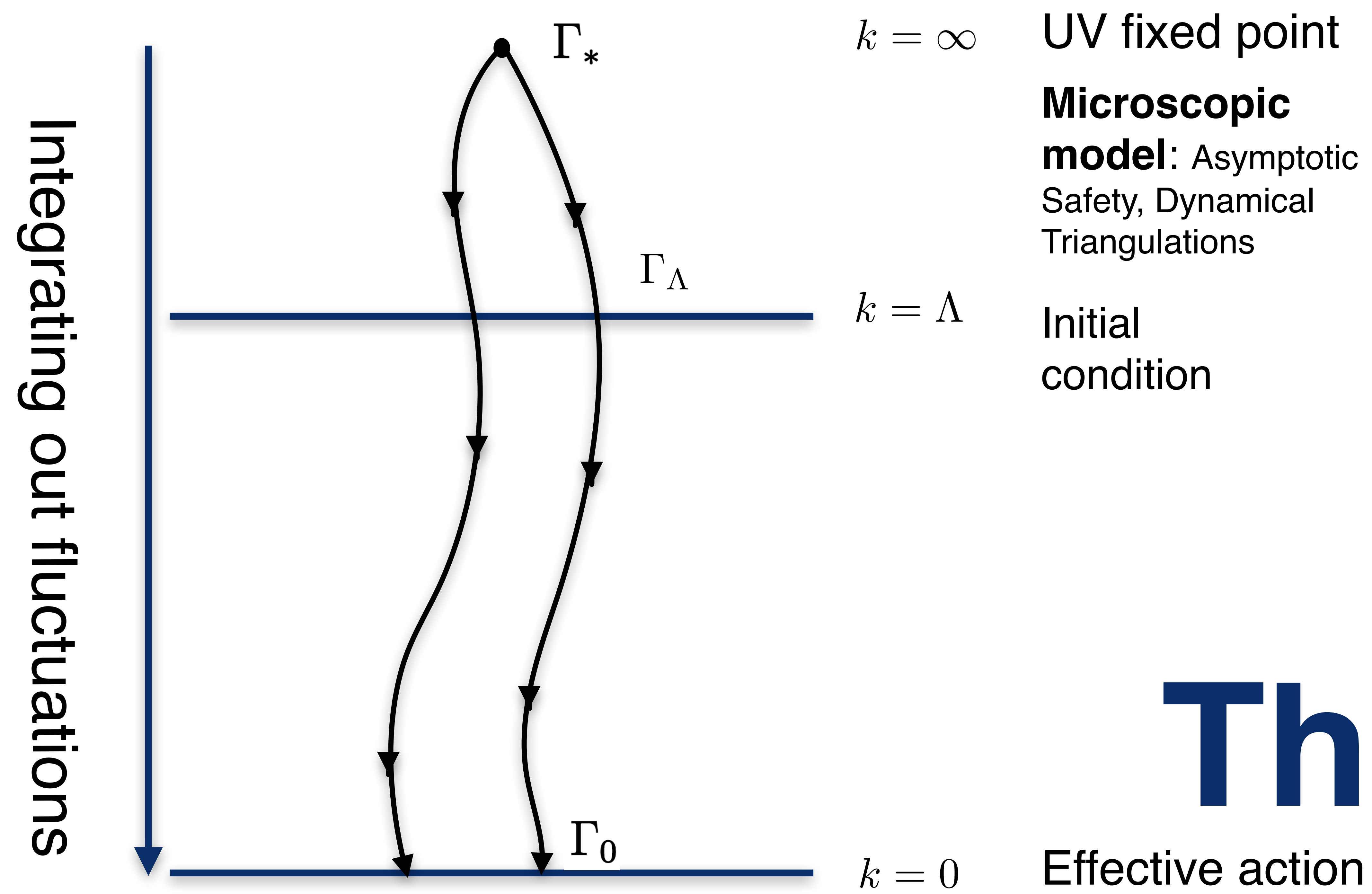

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Functional RGE

Functional RG

scale-dependent version of the effective action, the Effective Average Action

Wetterich (1991)
Reuter and Wetterich (1994)

Functional RG in a nutshell

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Alternative manipulation of the path integral

- Implement the underlying RG idea already at the level of the EAA, fully independently of the bare action.

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Generating functional

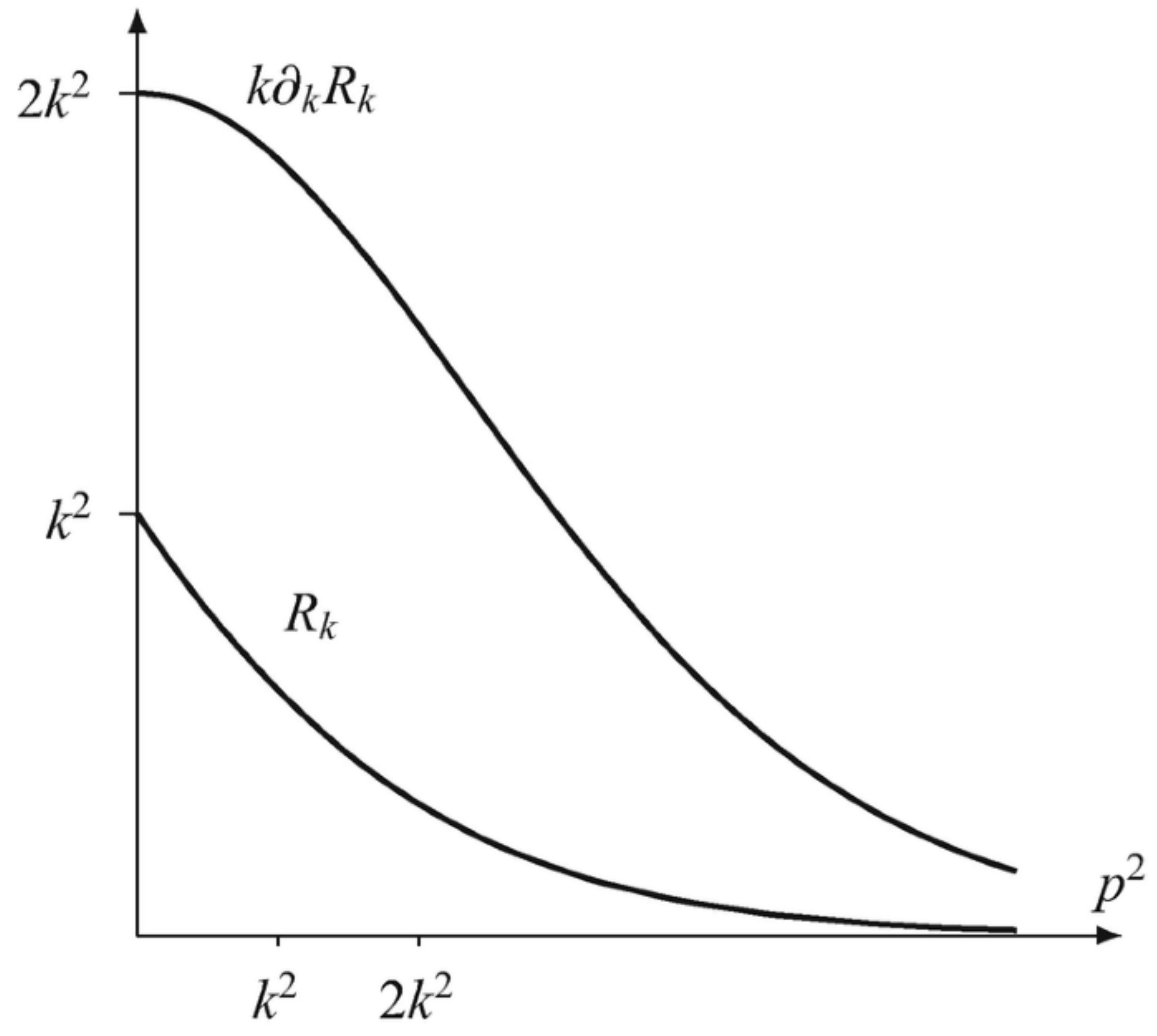
$$W_k[J] = \log \int \mathcal{D}\hat{\phi} \exp\left(-S[\hat{\phi}] - \Delta S_k[\hat{\phi}] + \int \mathrm{d}^d x J(x)\hat{\phi}(x)\right)$$

Smooth cutoff

$$\Delta S_k[\hat{\phi}] = \frac{1}{2}\int \mathrm{d}^d x \; \hat{\phi}(x)\mathcal{R}_k(-\Box)\hat{\phi}(x)$$

RG kernel: mass-like IR regulator

$$\mathcal{R}_k(p^2) \approx \begin{cases} k^2 & \text{for} \quad p^2 \ll k^2 \\ 0 & \text{for} \quad p^2 \gg k^2 \end{cases}$$



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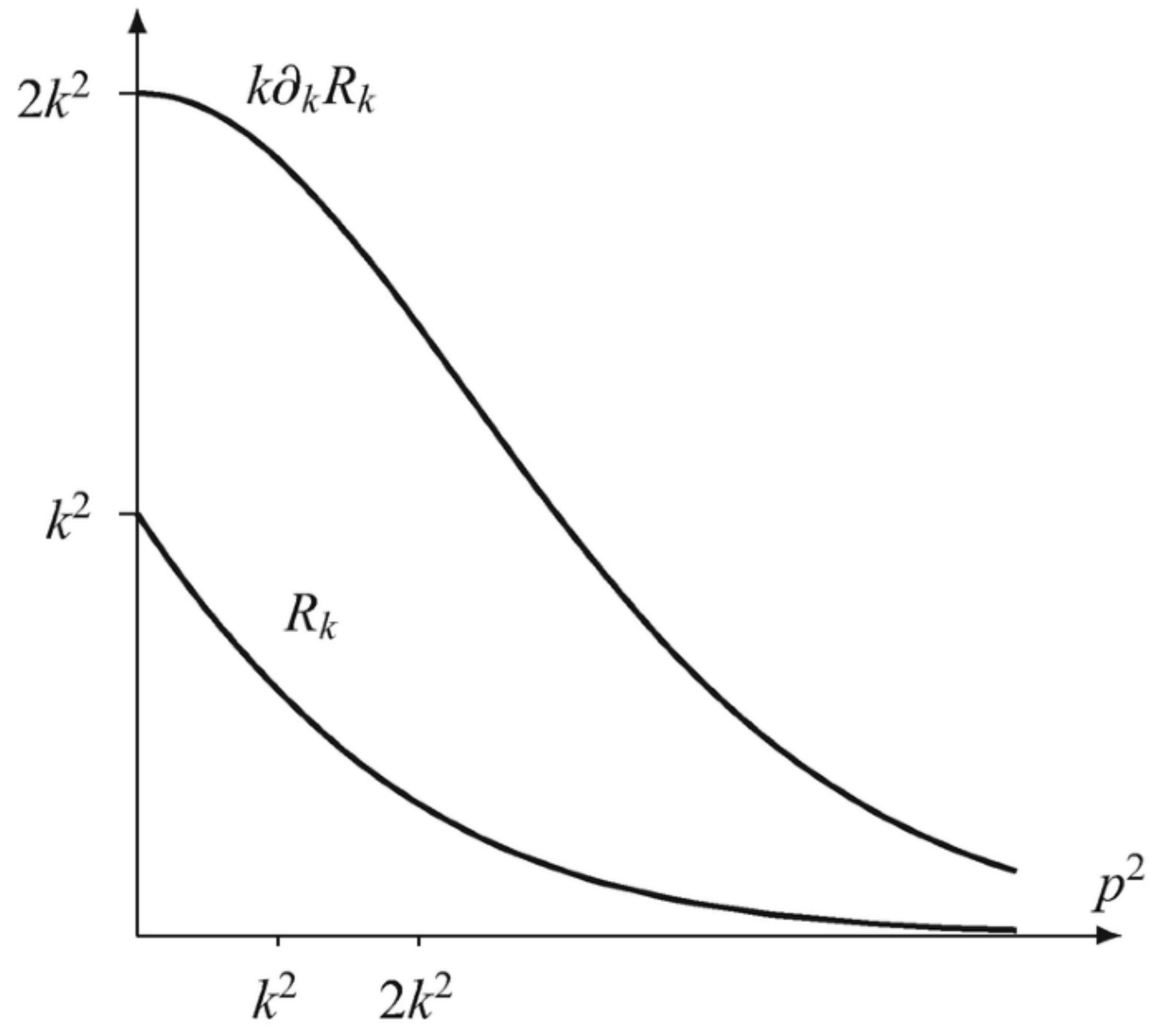

Legendre transform

$$\tilde{\Gamma}_k[\phi] = \int \mathrm{d}^d x\, J_k[\phi](x)\phi(x) + W_k[J_k[\phi]]$$

$\longrightarrow$

Effective Average Action

$$\Gamma_k[\phi] = \tilde{\Gamma}_k[\phi] - \Delta S_k[\phi] = \int \mathrm{d}^d x\, J(x)\phi(x) + W_k[\phi] - \Delta S_k[\phi]$$

The EAA $\Gamma_k[\phi]$

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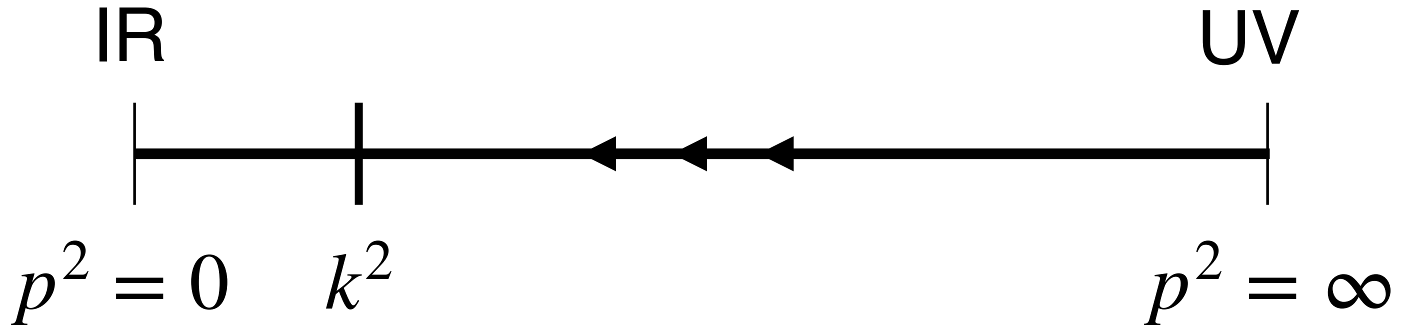
It represents the scale-dependent version of the standard effective action.



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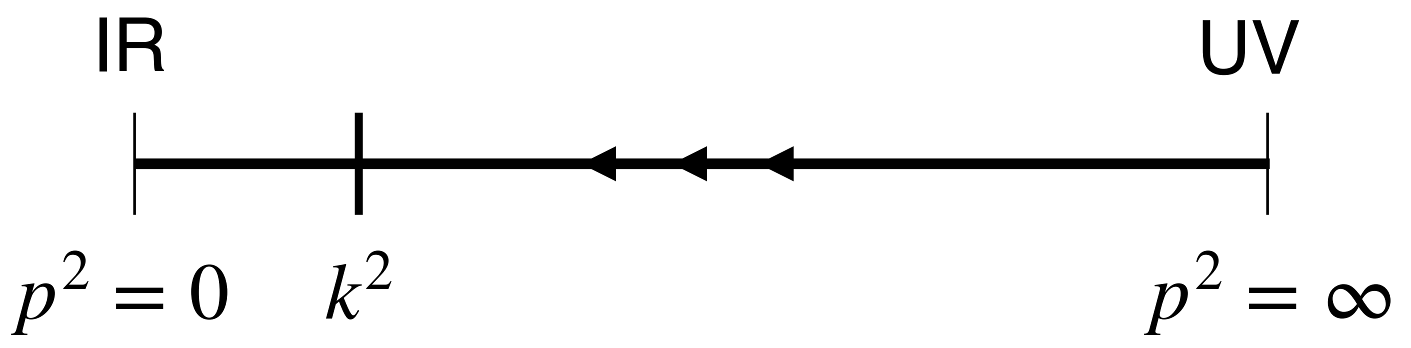

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It satisfies the Functional Renormalization Group Equation:

$$k\partial_k \Gamma_k[\phi] = \frac{1}{2} \,\mathrm{Tr}\, \left[(\Gamma_k^{(2)} + \mathcal{R}_k)^{-1} \, k\partial_k \mathcal{R}_k \right]$$

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- Fully nonperturbative or exact

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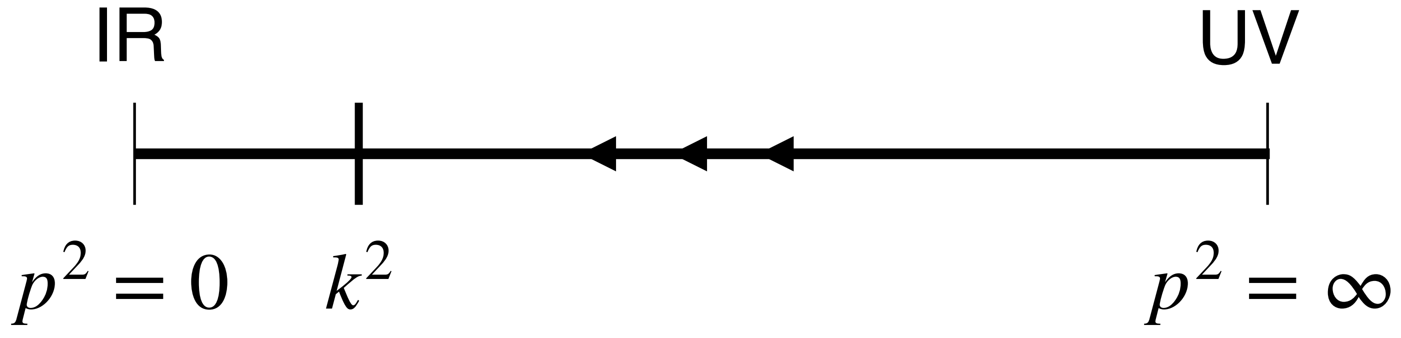

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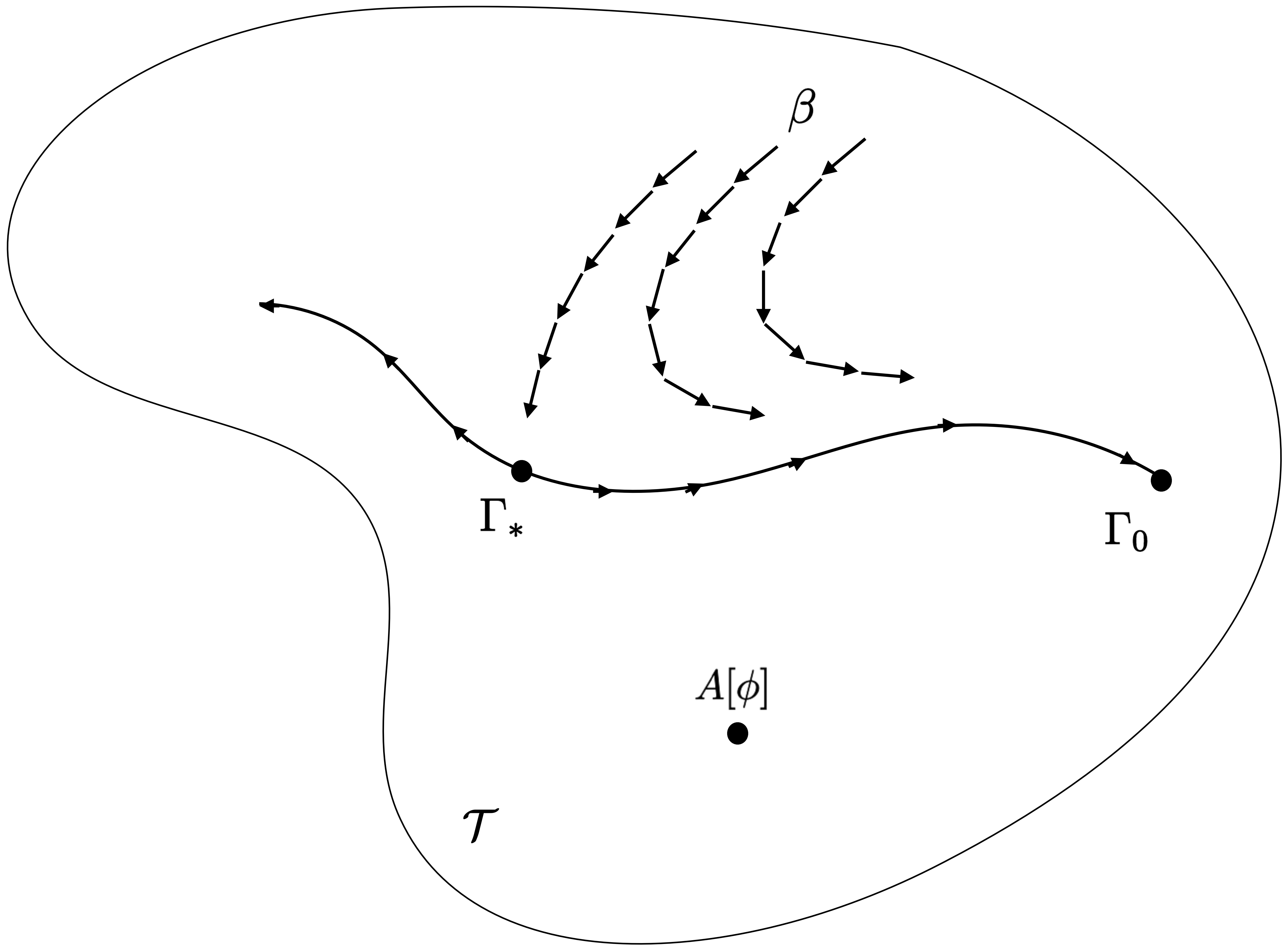
Predictive solutions do exist in theories that are otherwise perturbatively non-renormalizable.

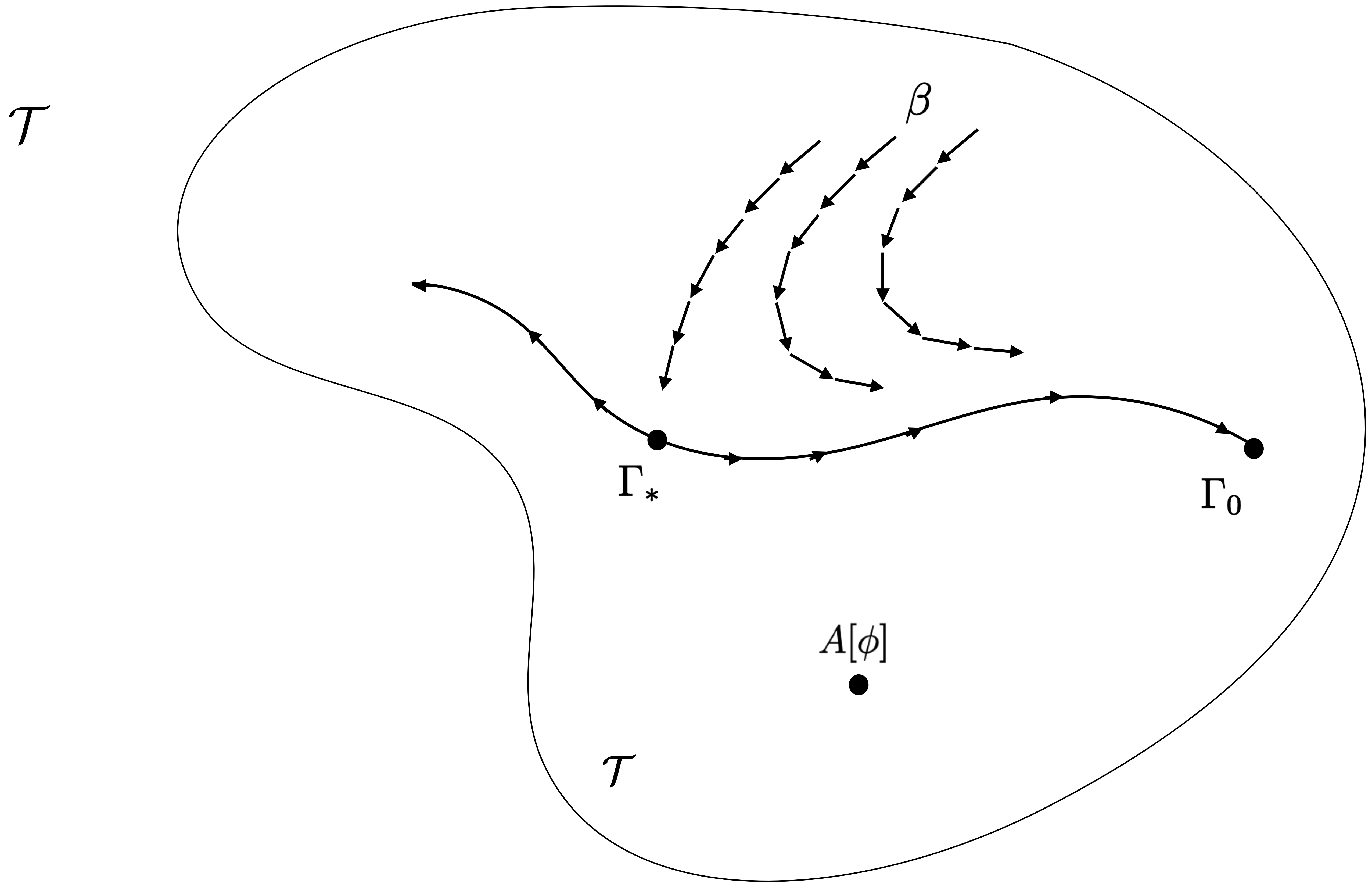
The geometrical setting



The geometrical setting

THEORY SPACE

space of functionals over which the EAA is supposed to be defined.



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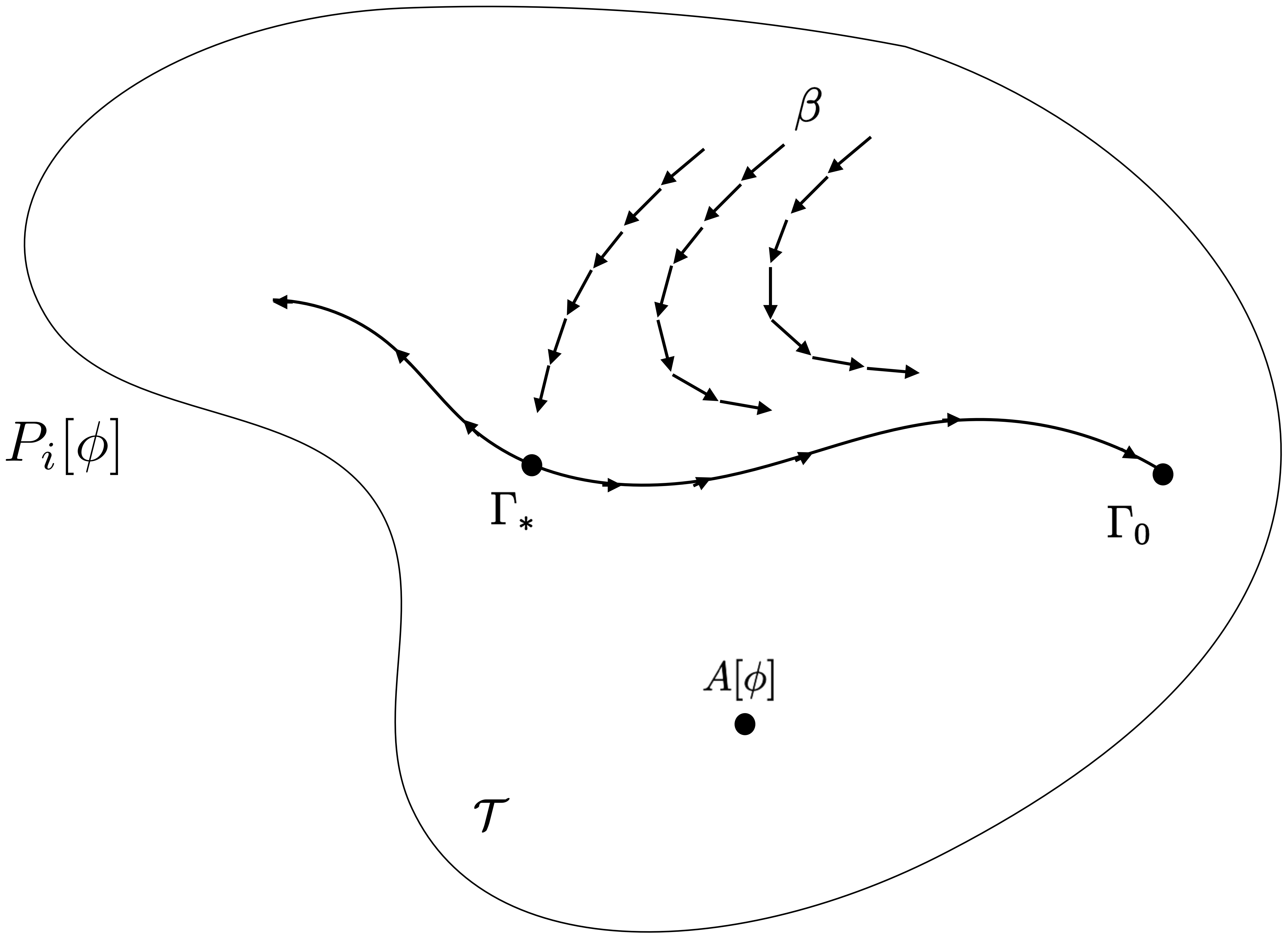
$\mathcal{T}$

BASIS ON THEORY SPACE

expansion of the elements of theory space in basis functionals and coupling constants.

$$A[\phi] = \sum_{i=1}^{\infty} U^i P_i[\phi]$$



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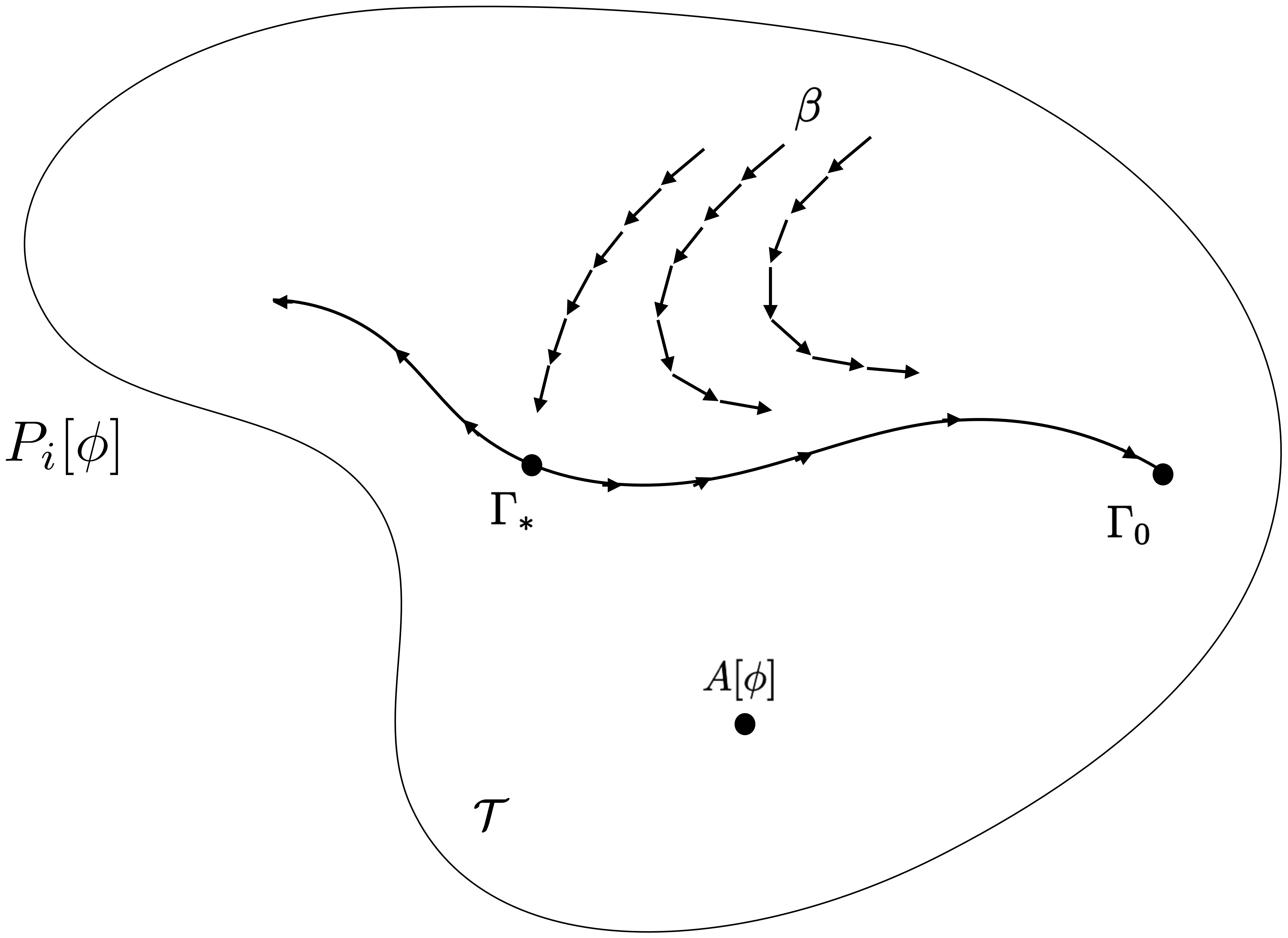
RG TRAJECTORY

vector field on theory space.

$$\{\mathcal{T}, \beta\}$$



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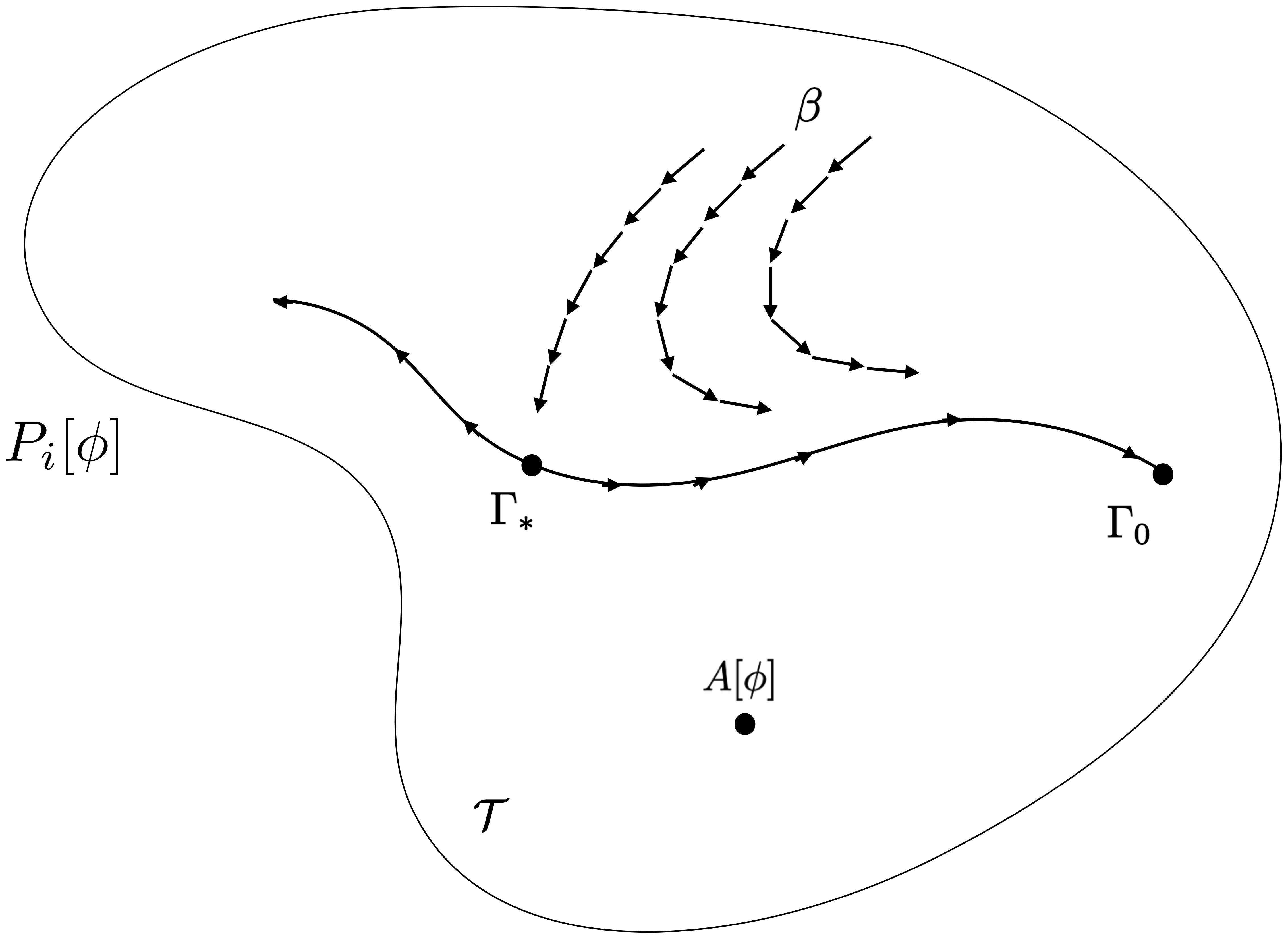
pair of theory space and RG trajectories.

$$k \mapsto \Gamma_k$$



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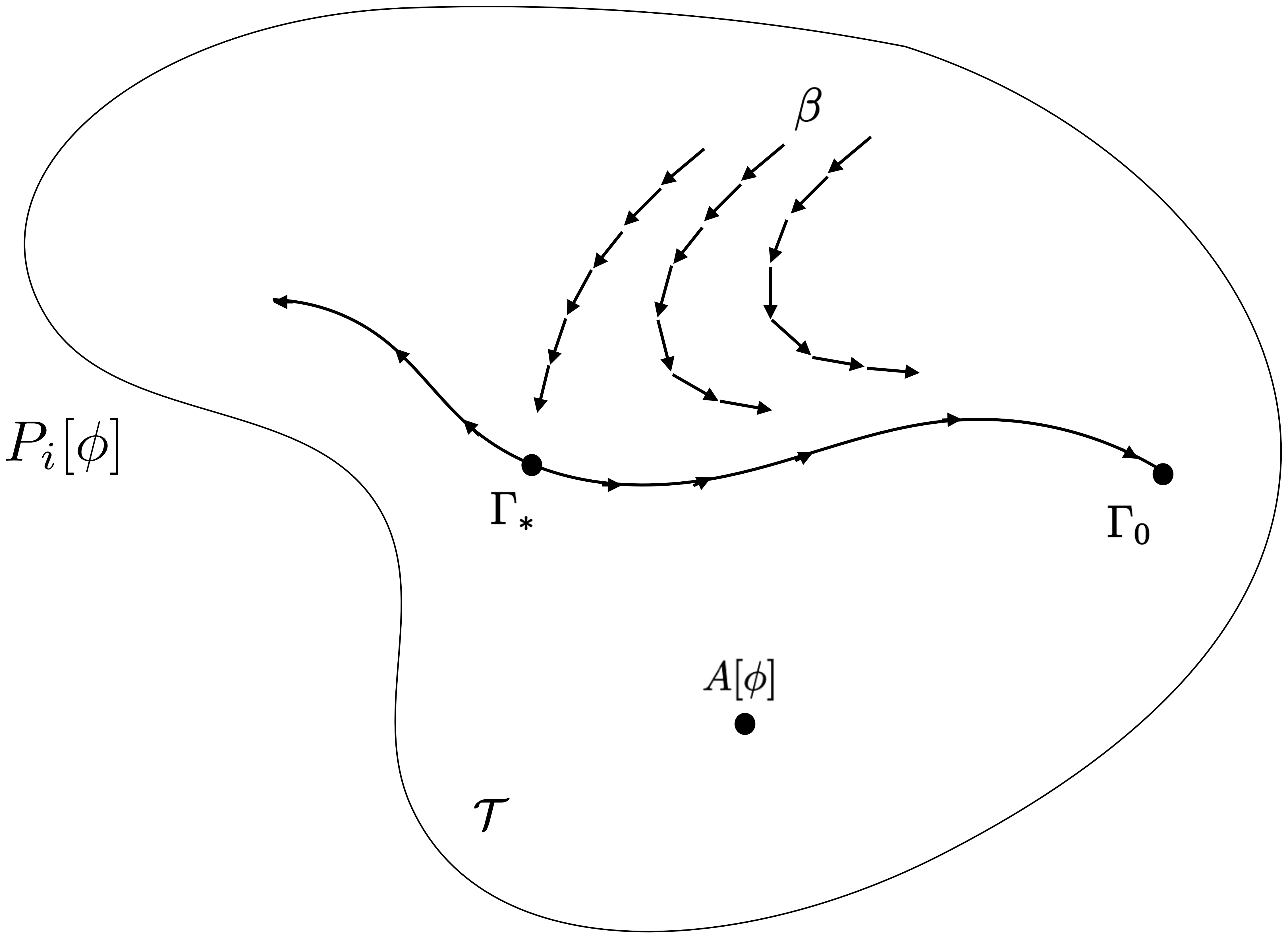

$$\Gamma_k[\phi] = \sum_{i=1}^{\infty} U^i(k) P_i[\phi] \longrightarrow \frac{1}{2}\mathrm{Tr}[\cdots] = \sum_{i=1}^{\infty} b^i(U^1, U^2, \cdots; k) P_i[\phi] \longrightarrow k\partial_k u^i = \beta^i(u^1, u^2, \cdots; k)$$

Fixed points &
Scaling exponents

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FIXED POINT $\beta^i(u_*) = 0$

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Gaussian FP: the scaling exponent agrees with the canonical mass dimension (generally $u_*^i = 0$)

Non-Gaussian FP (interacting, UV FP): at least one of the scaling exponents differs from the canonical mass dimension ($u_*^i \neq 0$)

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LINEARIZATION/ STABILITY MATRIX

$$k\partial_k u^i(k) = \sum_j \mathcal{B}^i{}_j (u^i(k) - u^i_*), \qquad \mathcal{B}^i{}_j(u_*) \equiv \partial_j \beta^i(u_*)$$

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SCALING EXPONENTS

$$u^i(k) = u_*^i + \sum_I C_I V_I^i \left(\frac{k_0}{k}\right)^{\theta_I}$$

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They encode **physical information** about the **universality class** of the system and its **scaling (observable) behavior**.

À LA WEINBERG

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a mechanism which renders physical scattering amplitudes finite (but non-vanishing) at energy scales exceeding the Planck scale.

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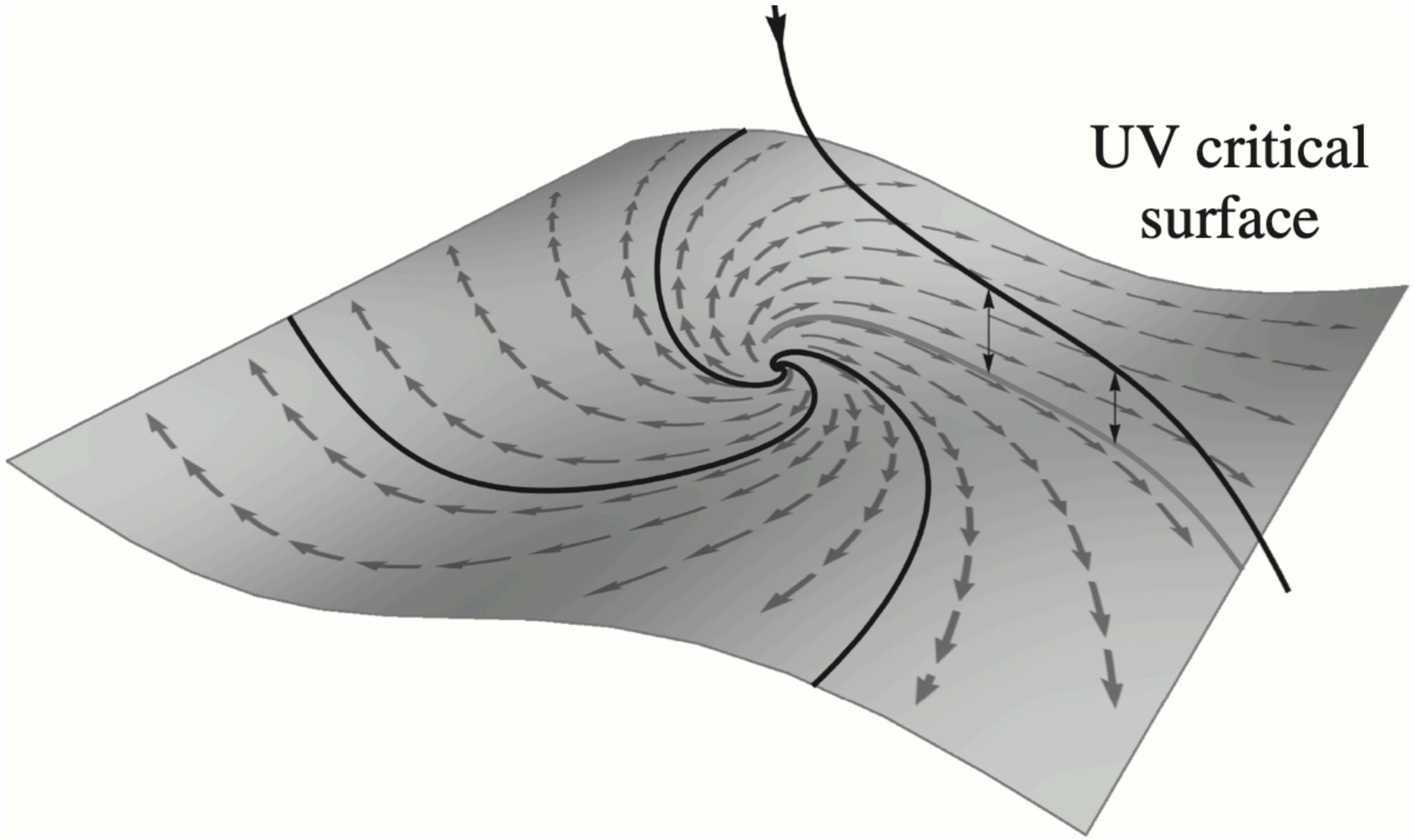
À LA EFFECTIVE AVERAGE ACTION

nonperturbative renormalization & predictivity

Renormalization consists in constructing a complete trajectory, a **trajectory which lies entirely within theory space**.



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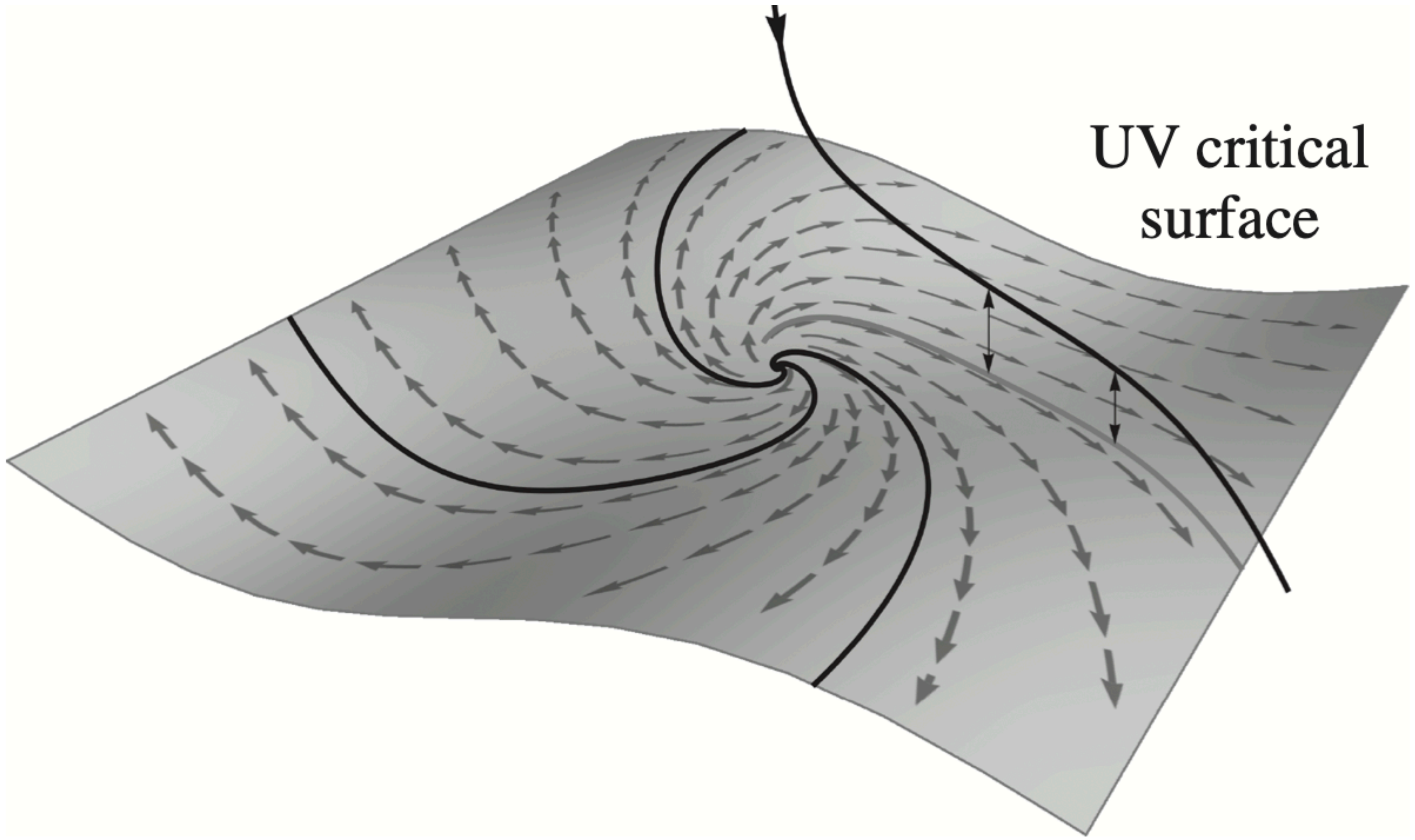

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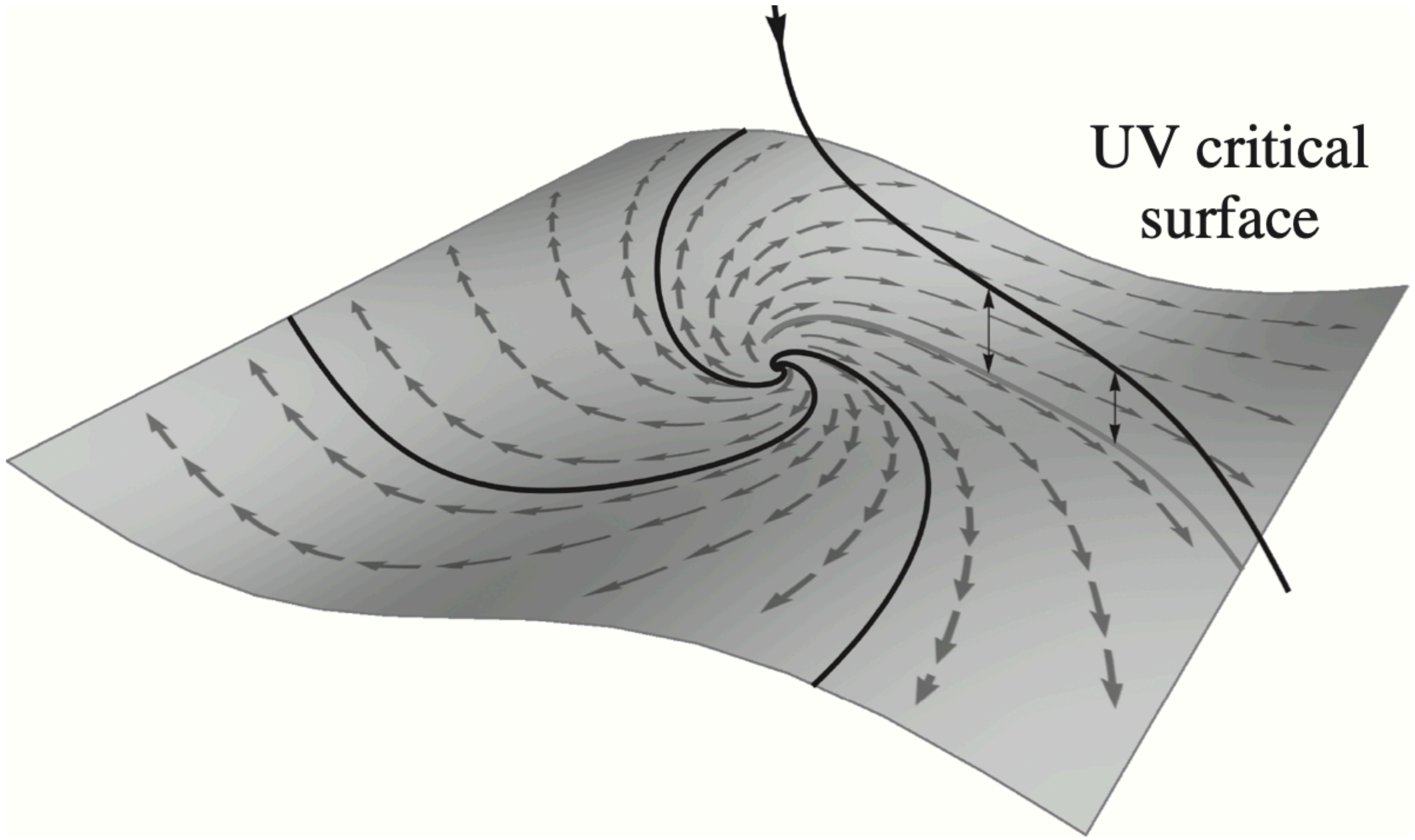

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Relevant: grow in the IR $\mathrm{Re}\,\theta_i > 0$

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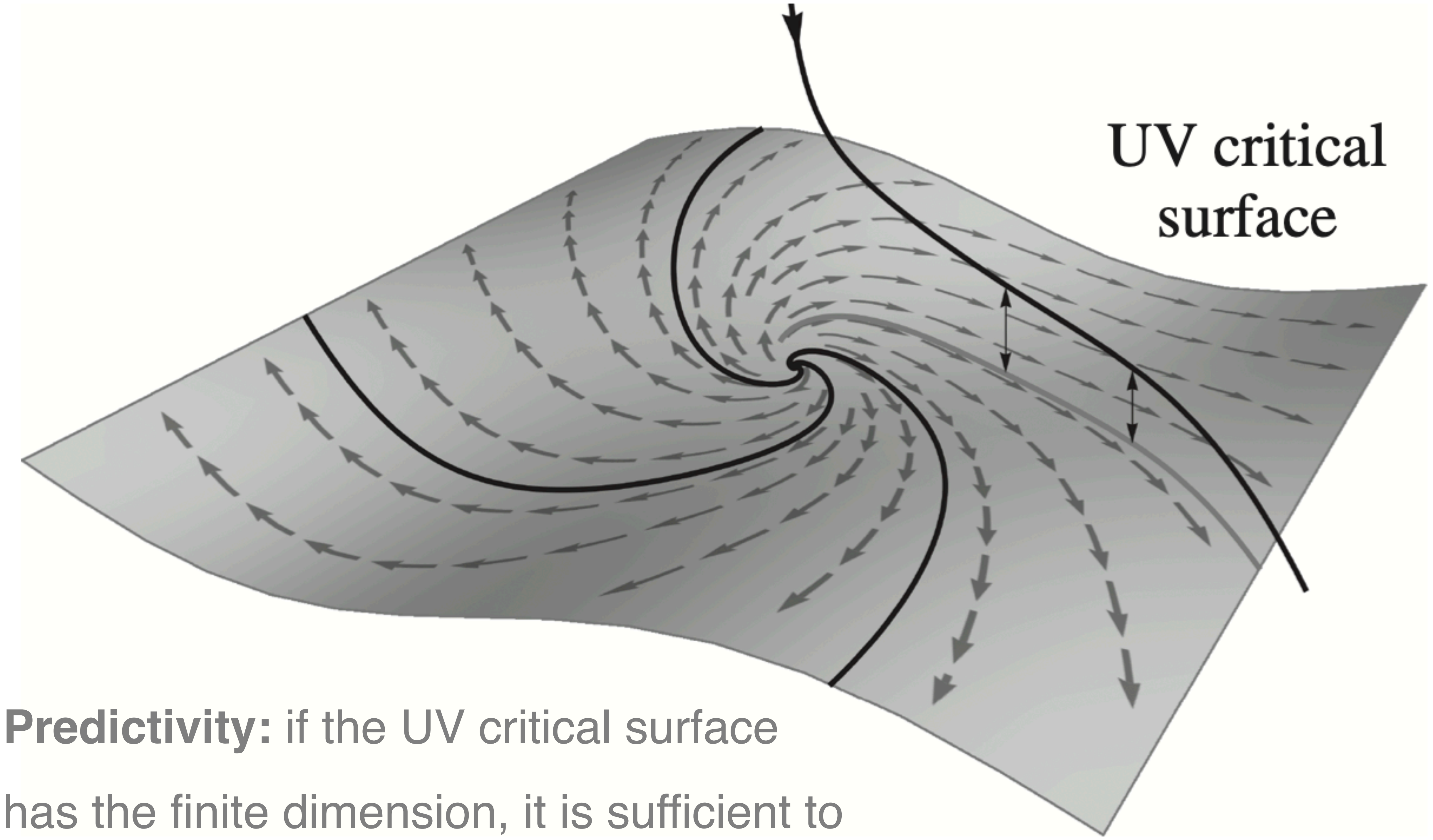

Predictivity: if the UV critical surface has the finite dimension, it is sufficient to perform only a **finite number of measurements** in order to uniquely identify Nature's RG trajectory.

Truncations

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N o n p e r t u r b a t i v e a p p r o x i m a t e s o l u t i o n

$$\Gamma_k[\phi] = \sum_{i=1}^{N} U^i(k) P_i[\phi]$$

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RHS: Evaluate the trace using heat kernel techniques

- Compare term by term the coefficients multiplying the same operator
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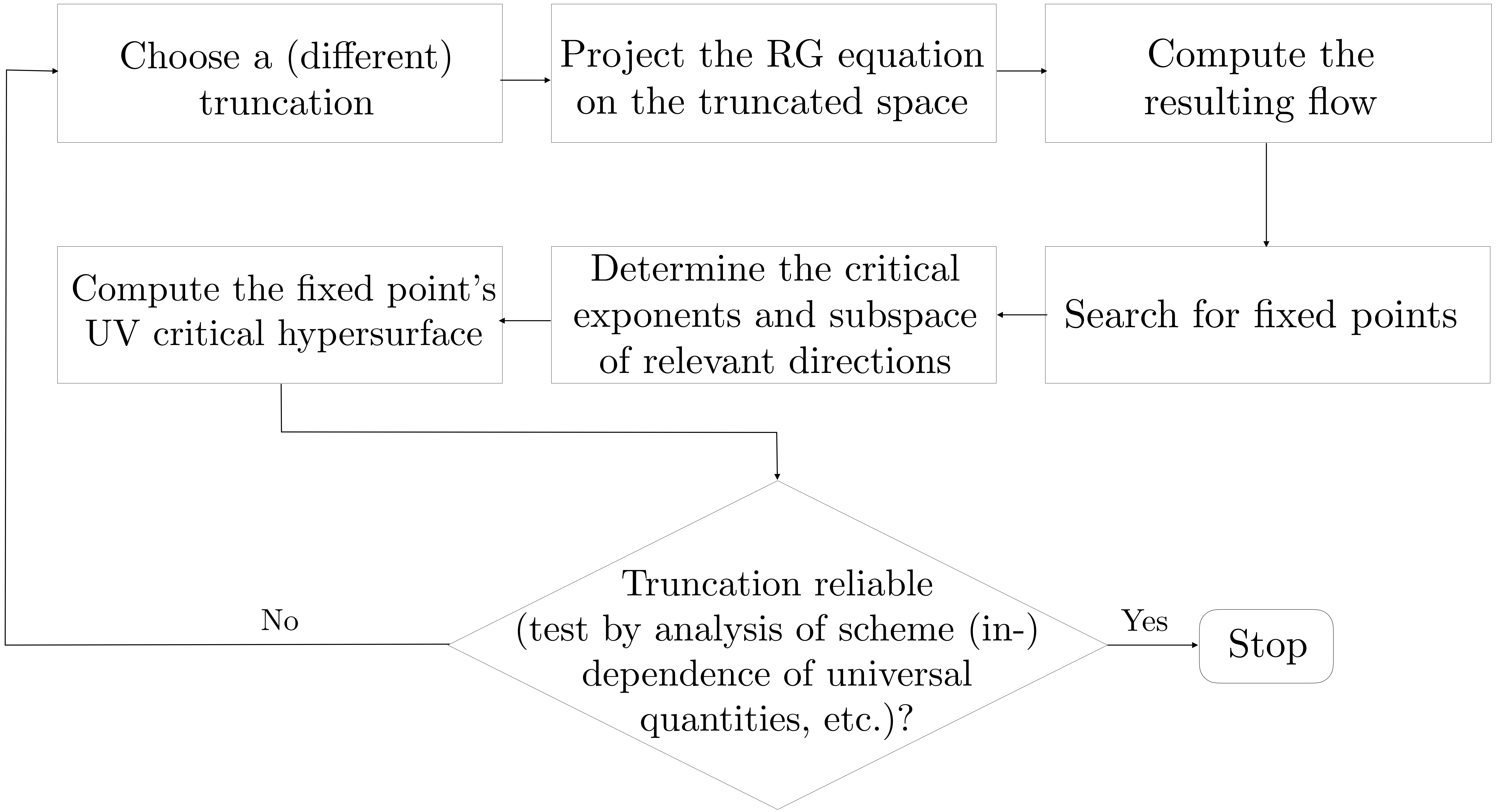
What has been done? **up to order R^72** **with matter** **different carrier fields**

Reuter, Saueressig, Percacci, Falls, Litim, Eichhorn,…

The Program



Choose a (different) truncation
Project the RG equation on the truncated space
Compute the resulting flow
Search for fixed points
Determine the critical exponents and subspace of relevant directions
Compute the fixed point's UV critical hypersurface
Truncation reliable (test by analysis of scheme (in-) dependence of universal quantities, etc.)?
No
Yes
Stop

Asymptotic Safety

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Background independence

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The dynamical degrees of freedom are quantized on this background.

$$\langle \hat{h}_{\mu\nu} \rangle_{\bar{g}} = 0 \iff \langle \hat{g}_{\mu\nu} \rangle_{\bar{g}} = \bar{g}_{\mu\nu} \quad \text{for} \quad \bar{g} = \bar{g}(k)^{\text{sc}}$$

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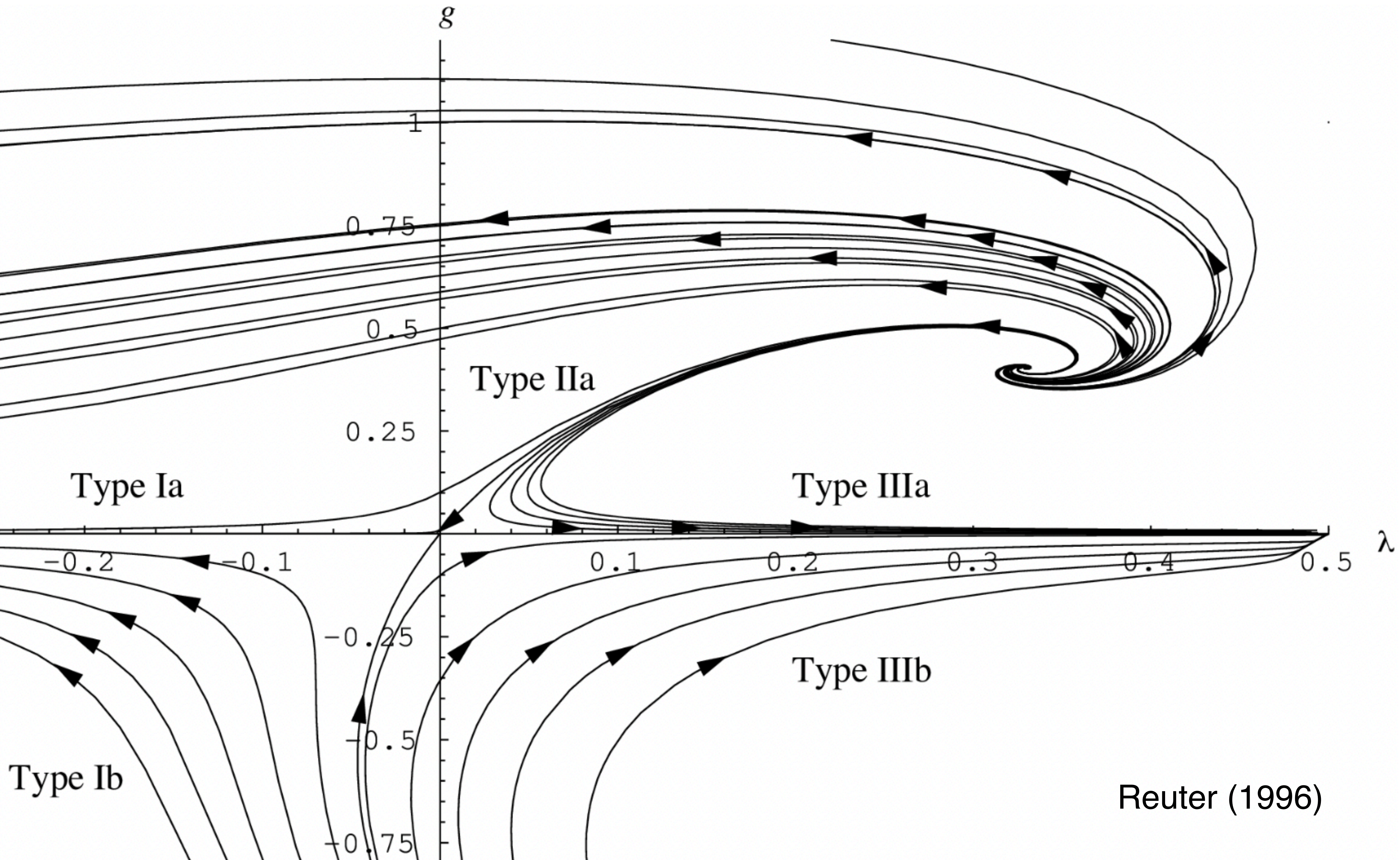
The background is re-adjusted in such a way that it becomes self-consistent, meaning that the expectation value of the fluctuation vanishes.

$$\frac{\delta}{\delta h_{\mu\nu}(x)} \Gamma_k \left[h; \bar{g}\right] \Big|_{h=0,\, \bar{g}=\bar{g}(k)^{\text{sc}}} = 0$$

Quantum Einstein Gravity

$$\Gamma_k = \frac{1}{16\pi G(k)} \int \mathrm{d}^d x \sqrt{g}(R - 2\Lambda(k)) + \text{gauge fixing} + \text{ghosts}$$



Reuter (1996)

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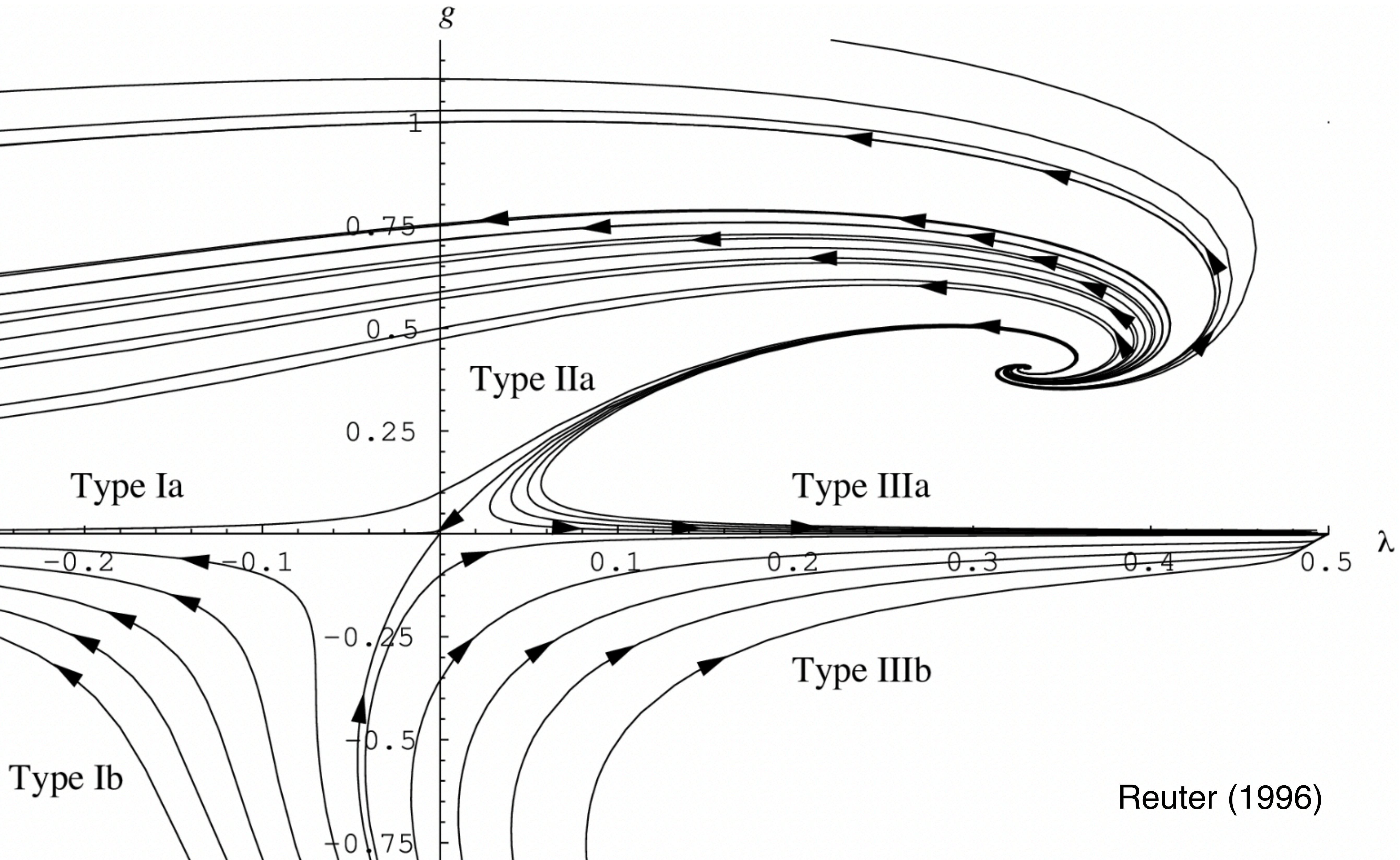
$$\lambda(k) = \Lambda(k)k^{-2}$$



Reuter (1996)

Quantum Einstein Gravity

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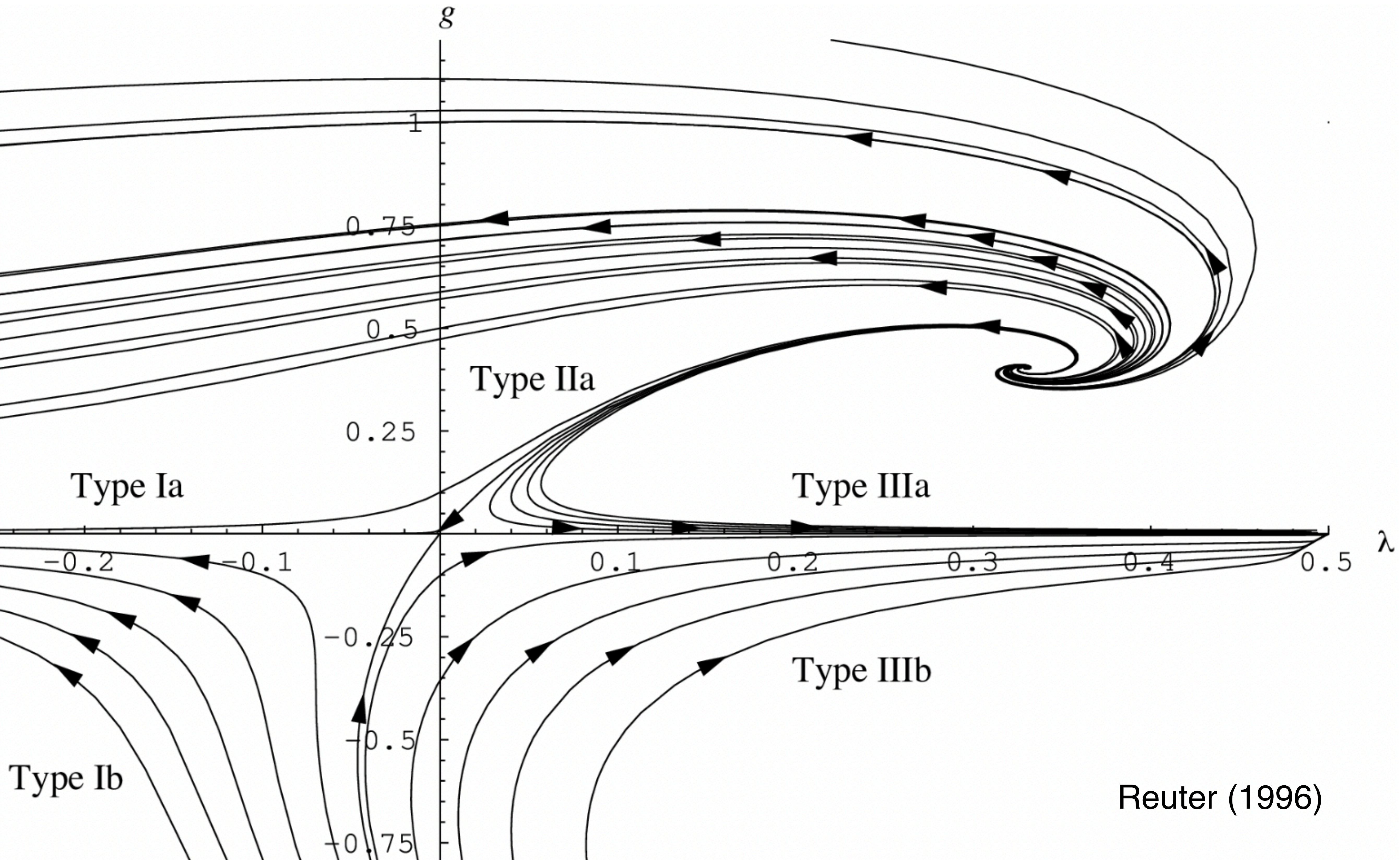

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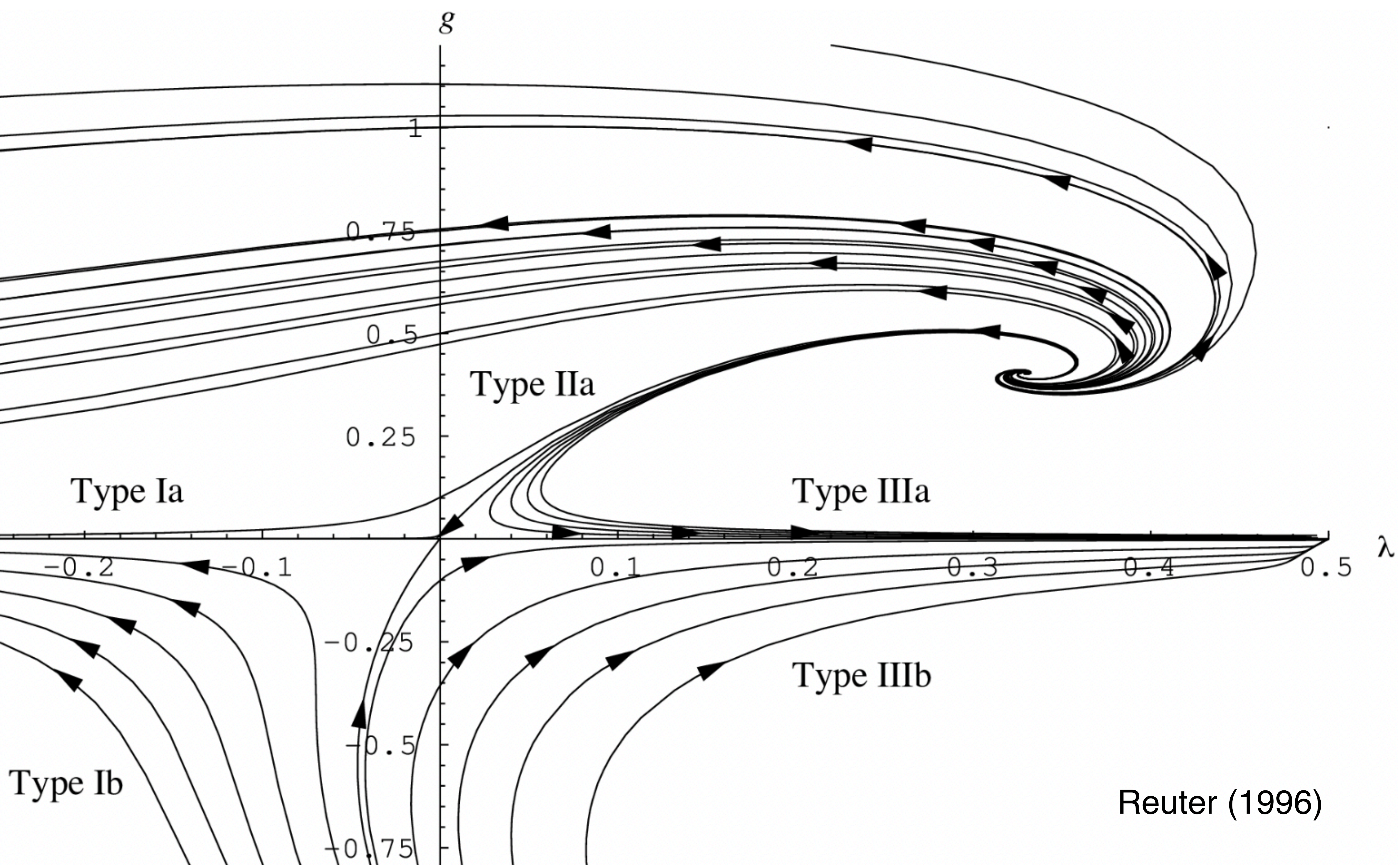

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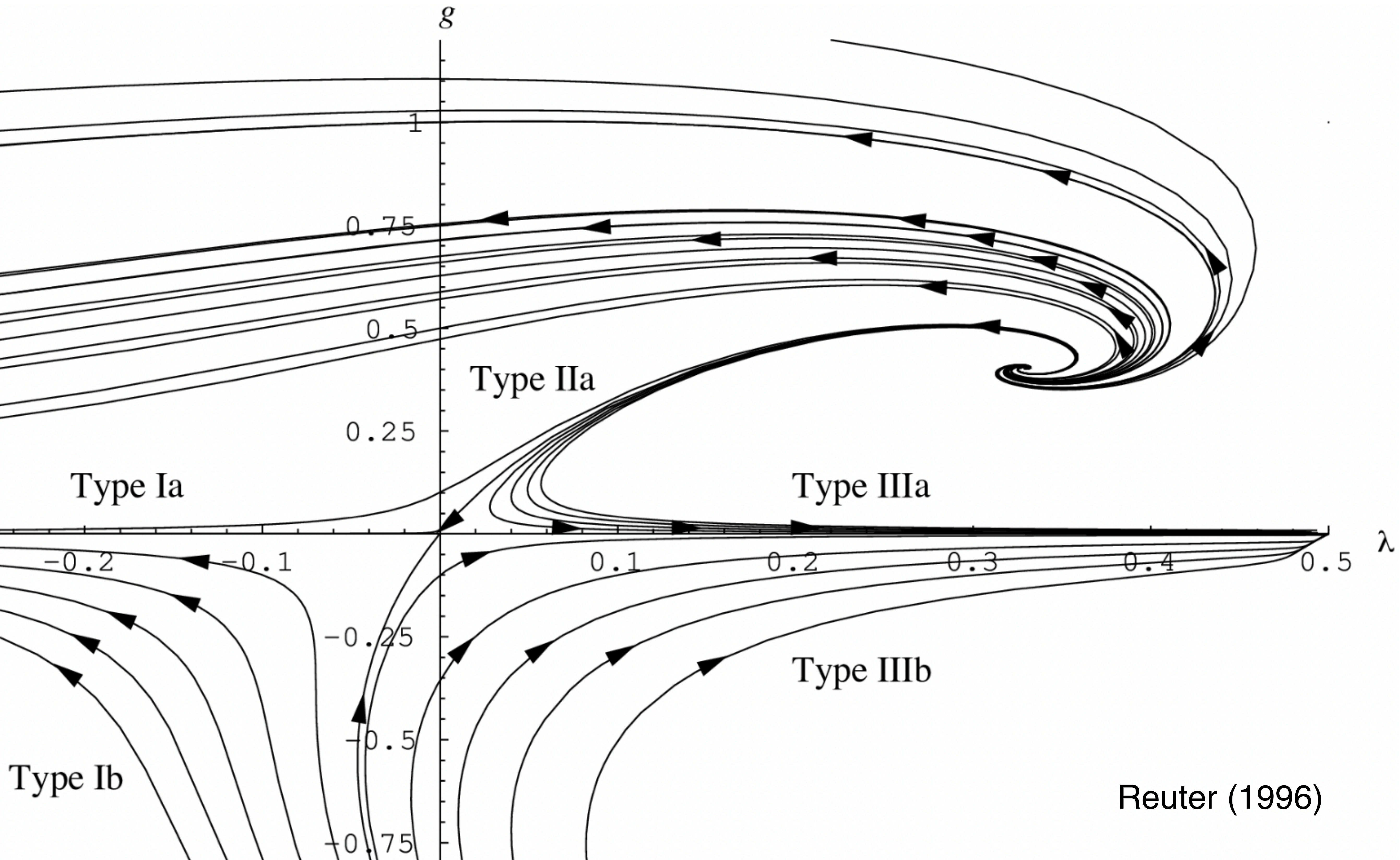

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ASYMPTOTIC SAFE

Euclidean vs. Lorentzian

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Integrating out dofs

Timelike-spacelike: no distinguished ordering of the modes with a standard canonical status is given.

State dependence - Observer dependence

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Problem set 1

Problem set 2

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Obtain RG trajectories on a theory space which is constituted of functionals that are constructed on Lorentzian metrics.

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One can work out a Lorentzian heat kernel proper time regularization.

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Analyze the flows of hyperbolic kinetic operators, typically of the d’Alembertian in the background of the running self-consistent metrics.

RF, Reuter (2022)

Observables

Which physical information can we extract from an asymptotic safe theory of gravity?

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Relational observables.

Two options.

“Physical gauge fixing”

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Kevin Falls, RF (2022)

Running relational observables

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Pagani, Reuter (2016)

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$$\lim_{k\to\infty} \mathcal{O}_k = \hat{\mathcal{O}}|_{\hat{\phi}\to\phi}$$

$$\mathcal{O}_{k=0} = \langle\hat{\mathcal{O}}\rangle$$

Covariant formulation

Running relational observables

Covariant formulation

Construct a physical coordinate frame
e.g. by adding matter fields

s.t.

perform a diffeomorphism
transformation

transform the tensor

transform the physical frame

composed transformation leaves
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$$R(x) \mapsto \varphi * R(x)$$

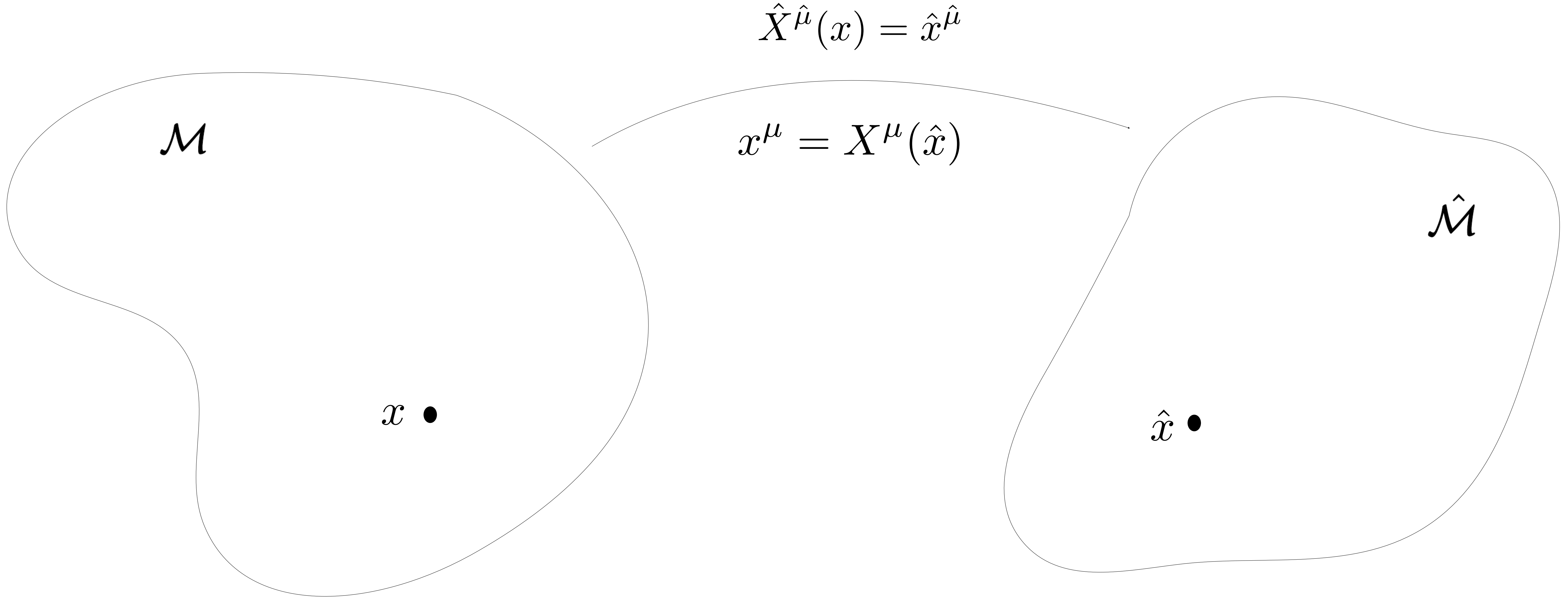
transform the physical frame

$$X \mapsto \varphi^{-1}(X)$$

composed transformation leaves
the tensor invariant

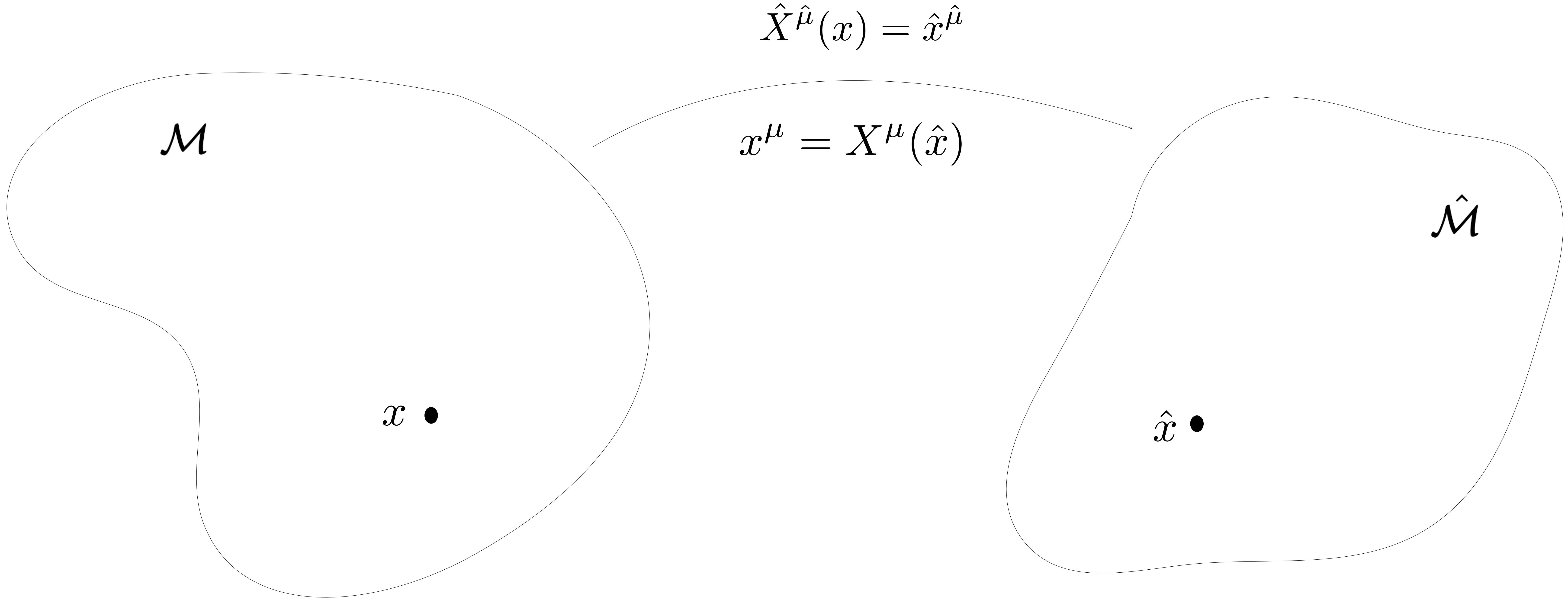
$$R(X) \mapsto \varphi * R(\varphi^{-1}(X)) = R(X)$$

Physical coordinate system



Physical coordinate system

Introduce a dynamical fields $\phi^a(x) = \{g_{\mu\nu}, \text{matter fields}\}$



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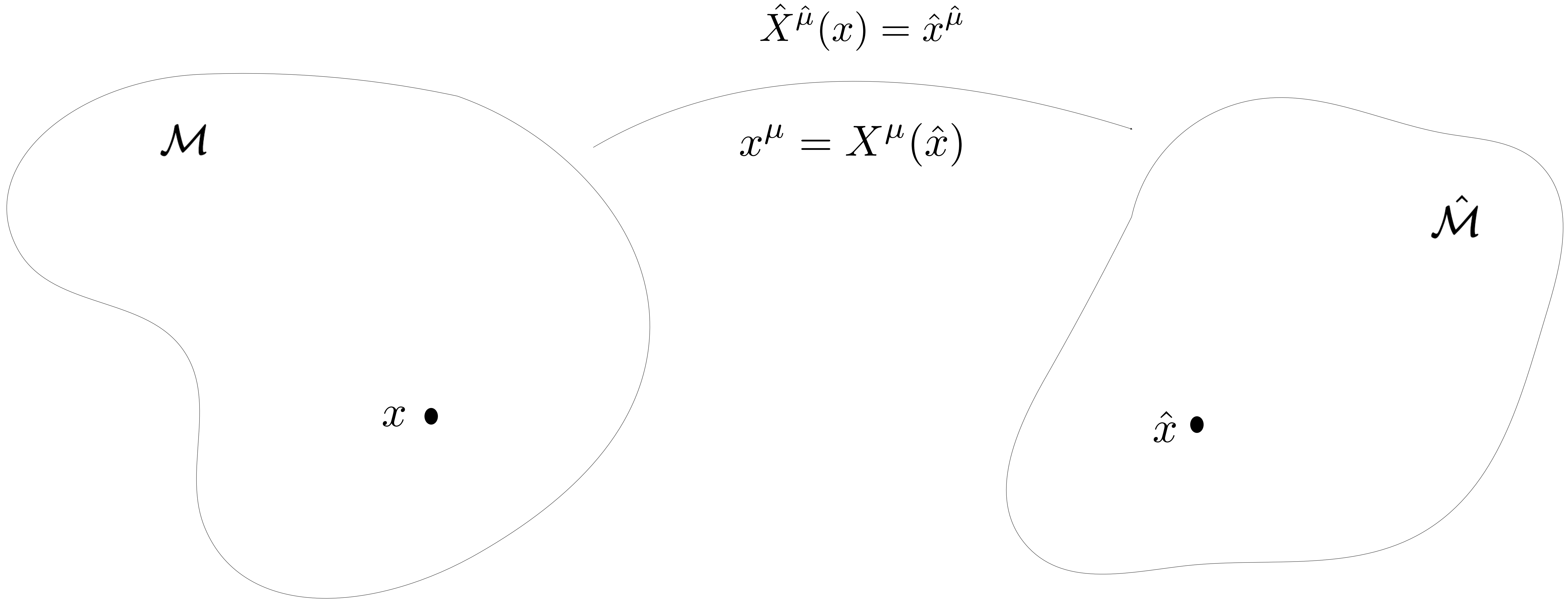

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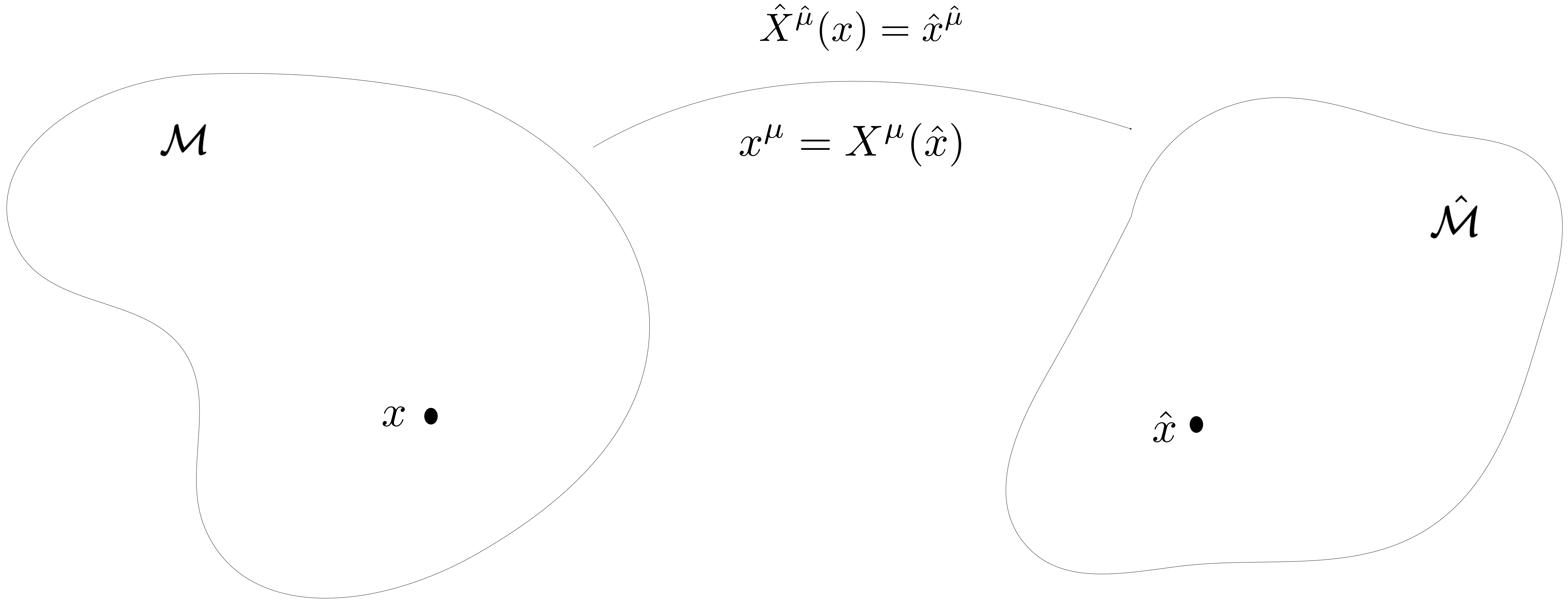

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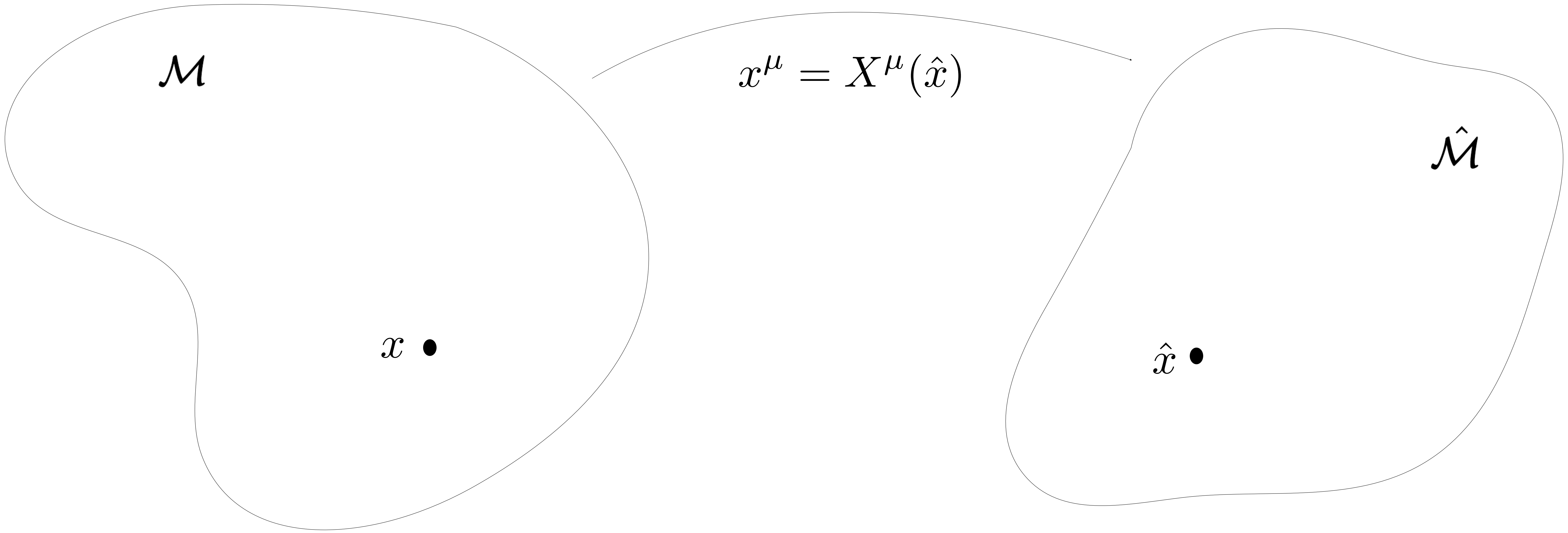
Frame fields: $e^{\hat{\mu}}_{\mu}(x) = \partial_\mu \hat{X}^{\hat{\mu}}(x)$

Invariant volume element: $\tilde{e} = \det e^{\hat{\mu}}_{\mu}$

$$\delta(X(\hat{x}), x) = \tilde{e}(x)\, \delta(\hat{x}, \hat{X}(x))$$

$$\hat{X}^{\hat{\mu}}(x) = \hat{x}^{\hat{\mu}}$$



Flow of the relational observables

Relational Effective Average Action:

$$\Gamma_k^{\text{rel.}} \equiv \int \mathrm{d}^4x\, \tilde{e}(x) \mathcal{L}_k^{\text{rel.}}(x) := \int \mathrm{d}^4x\, \tilde{e}(x) \sum_i a_{\hat{I}_i}(k) E_{iI_i}^{\hat{I}_i}(x) O_i^{I_i}(x)$$

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$$= \int \mathrm{d}^4 x\, \tilde{e} \left(a_0(k) + a_R(k) R + a_1(k) \delta_{\hat{\mu}\hat{\nu}} g^{\mu\nu} (\partial_\mu \hat{X}^{\hat{\mu}})(\partial_\nu \hat{X}^{\hat{\nu}}) \right)$$

Recipe

Find the fixed points

EAA

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PHYSICAL REFERENCE SYSTEM

Compute the flow of the observables

RELATIONAL EAA

Scaling dimension at the fixed point

RESULT

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Observables to make contact with different approaches of quantum gravity?

Conclusions & outlook

- AS seeks for a consistent and **predictive theory of the gravitational interactions within the framework of QFT** by invoking a **non-perturbative high-energy completion**.

- Phenomenologically: the flow emanating from the UV fixed point connects to a low-energy regime where the dynamics matches the one of GR.

- Starting from the safe harbor of asymptotically safe gravity, we developed new methods for extracting physical contents, by constructing **relational observables**.

Which are good observables?

Observables to make contact with different approaches of quantum gravity?

Which is a good reference system?

at the level of the scaling exponents, e.g. scaling of the correlation functions

at the level of the RG computations

Physical gauge fixing?