

Thermal precondensation in gauge-fermion theories

Álvaro Pastor Gutiérrez

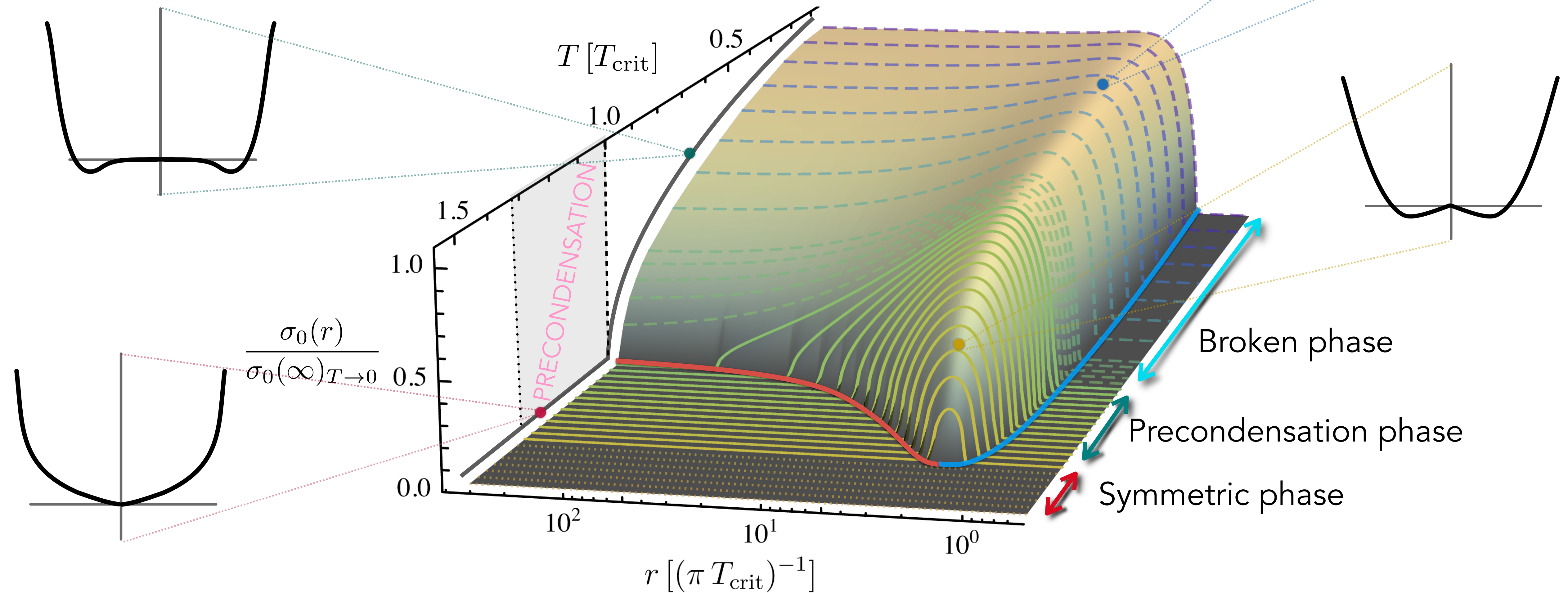
ERG 2026, Brighton

17th of February 2026

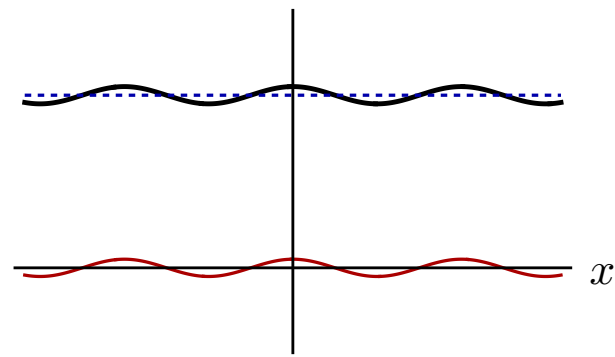
Based on [2602.11265] with Jan M. Pawłowski and Franz R. Sattler

Thermal precondensation

- Occurrence of a condensate **only** at finite range of length scales

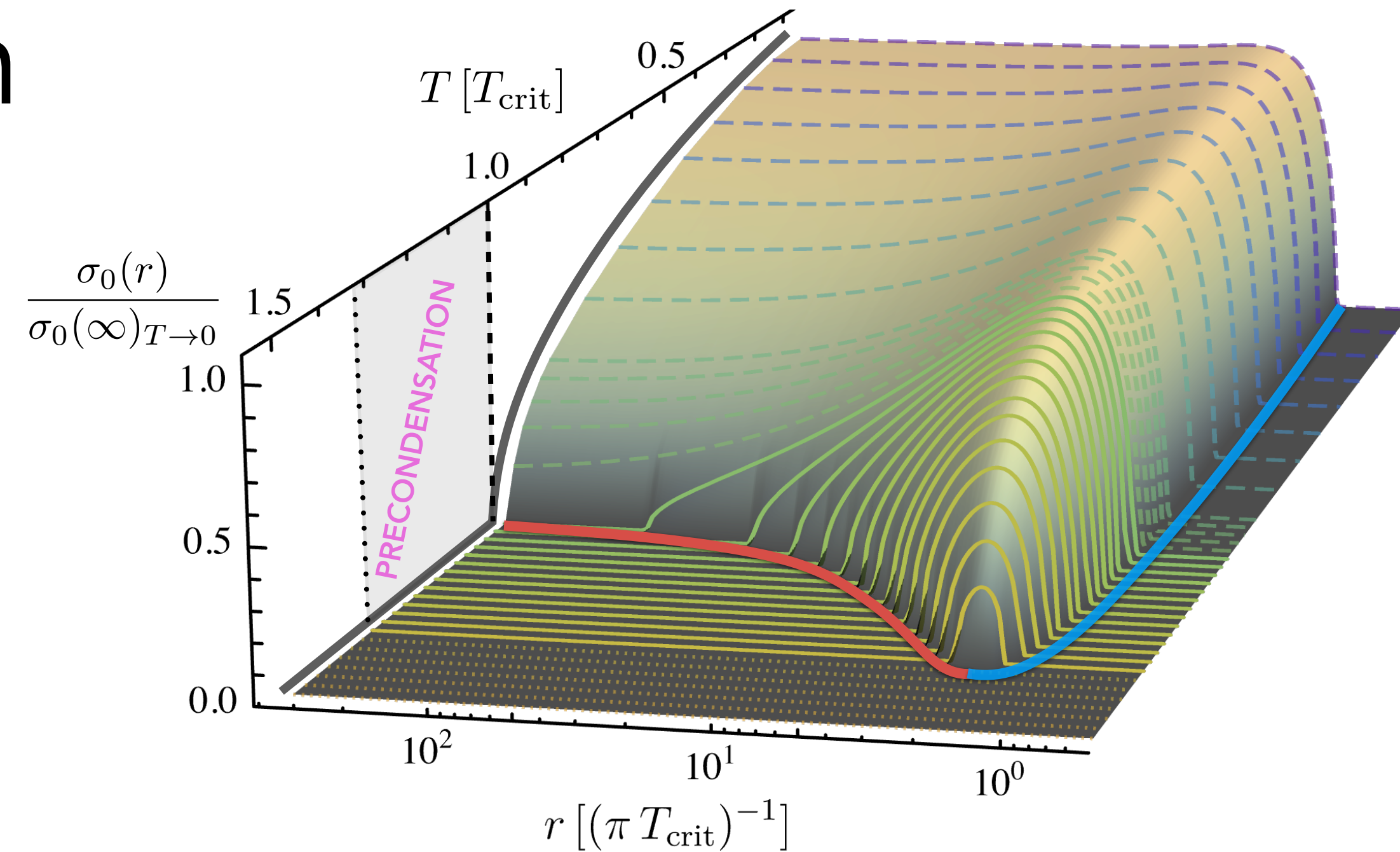


Hallmarks of precondensation

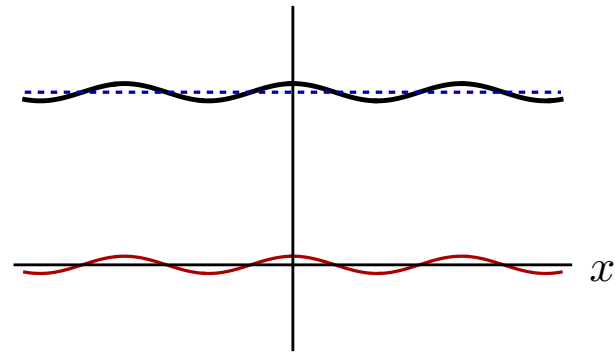


$$\sigma_0(x) = \sigma_0 + \Delta\sigma_0(x)$$

Macroscopic limit $\sigma_0 = \lim_{\mathcal{V} \rightarrow \infty} \frac{1}{\mathcal{V}} \int d^3x \sigma_0(x)$ $\sigma_0(x) = \langle \hat{\sigma}(x) \rangle$

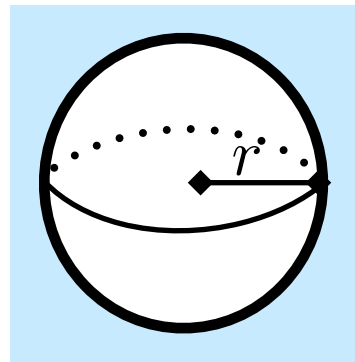


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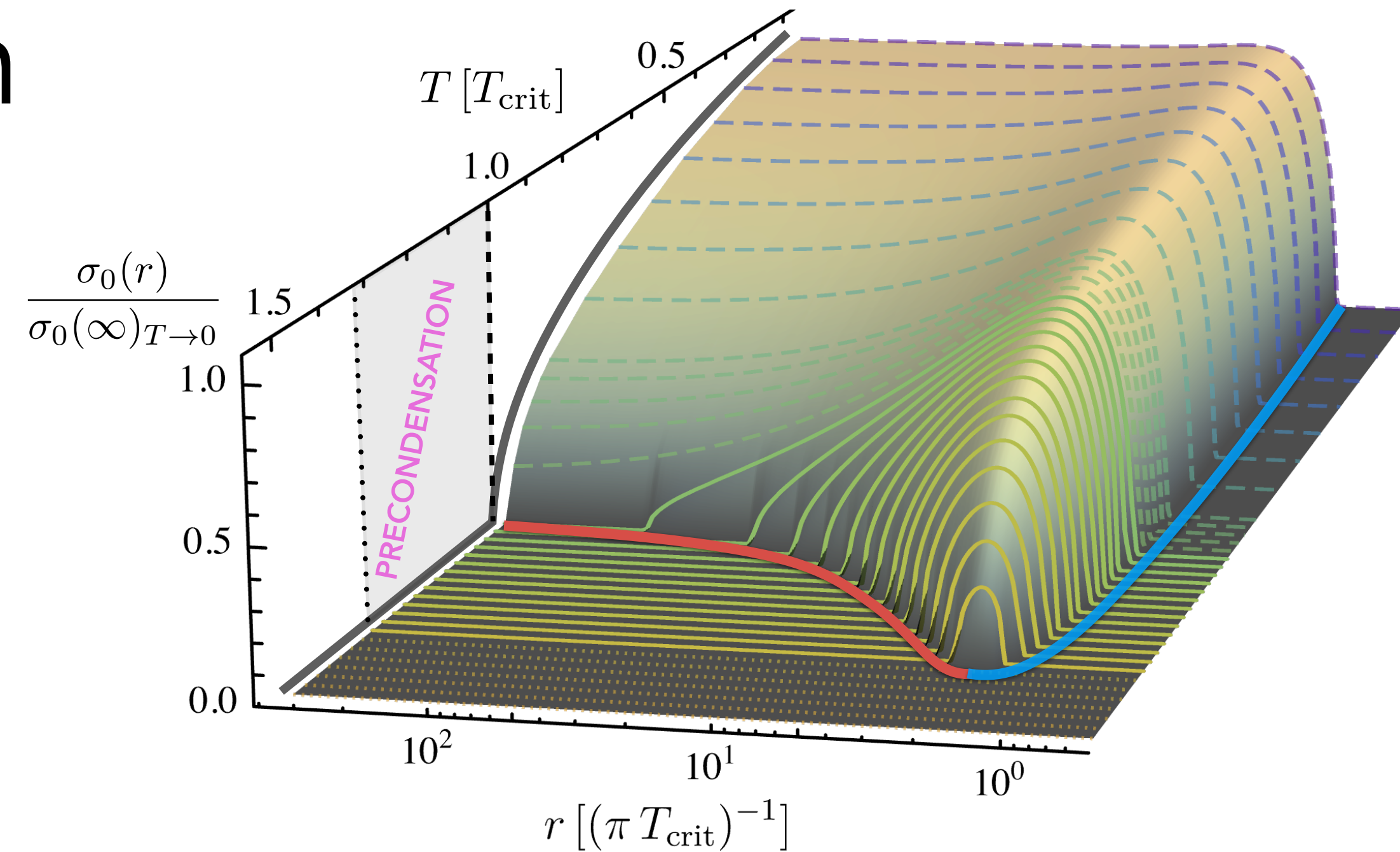


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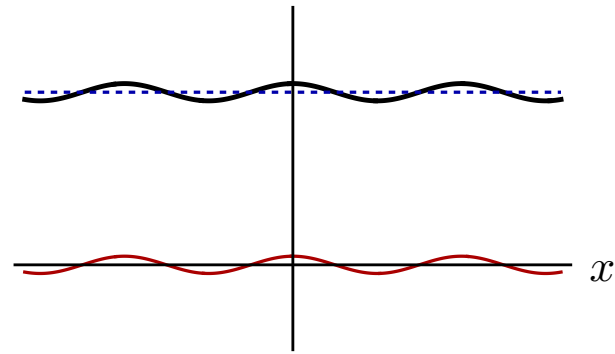
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$$\sigma_0^2(\mathbf{x}; r) = \frac{1}{V_r} \int d^3y \langle \hat{\sigma}(\mathbf{x}) \hat{\sigma}(\mathbf{y}) \rangle \theta(r^2 - (\mathbf{x} - \mathbf{y})^2)$$

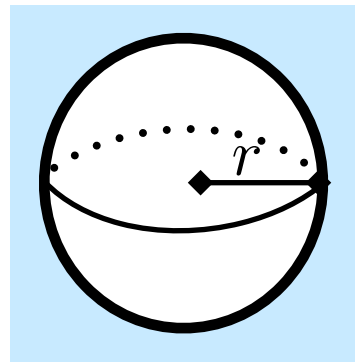


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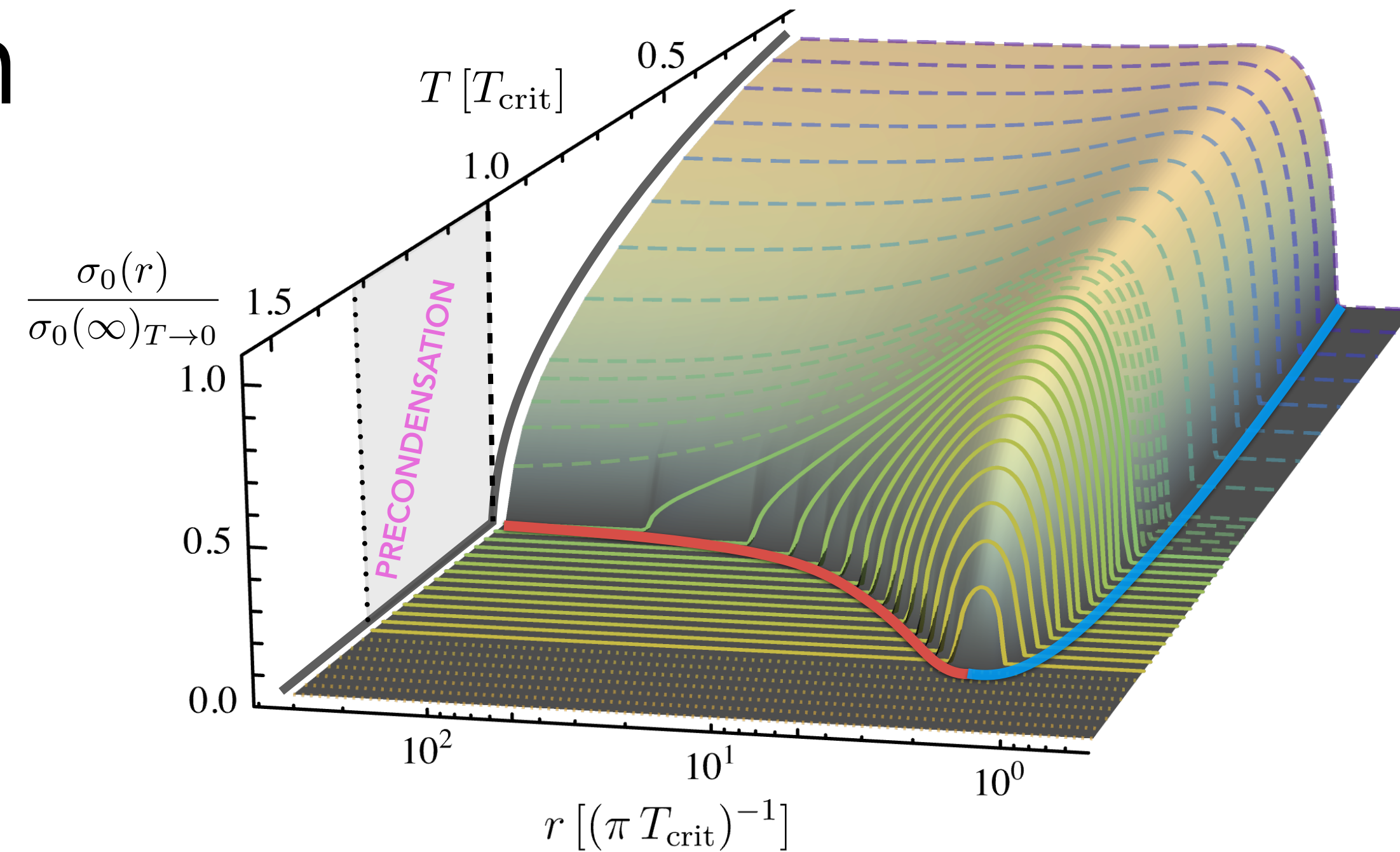


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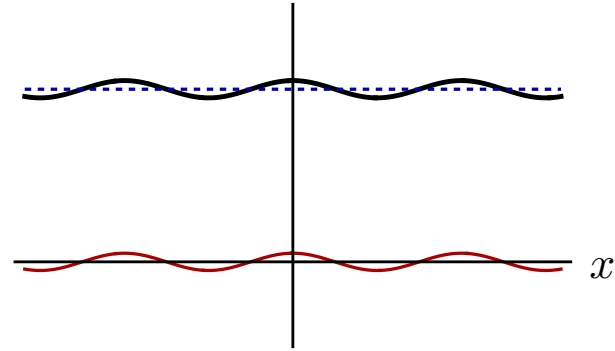
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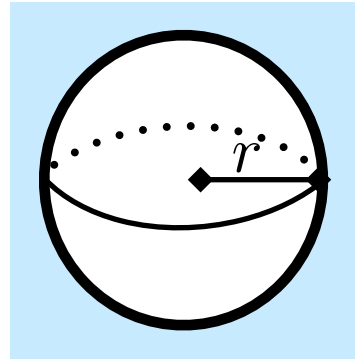


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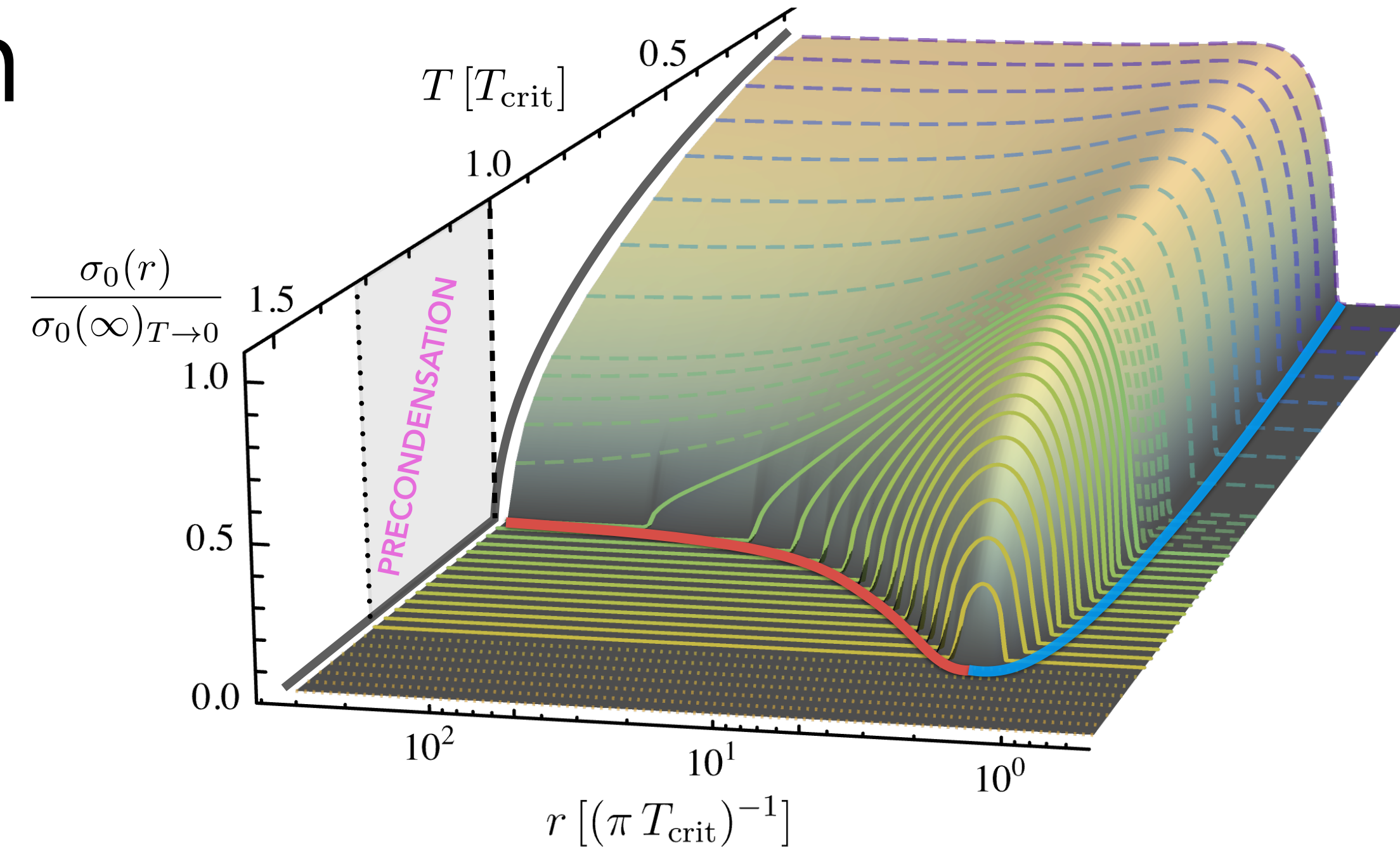
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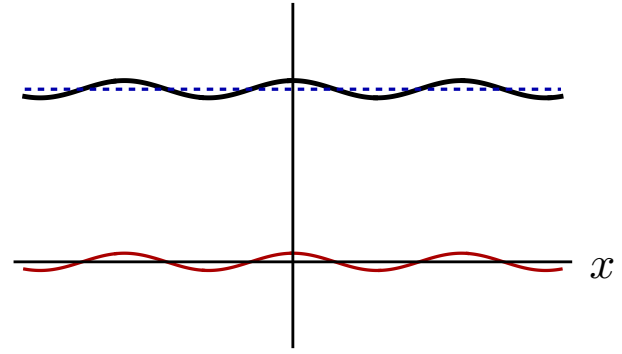


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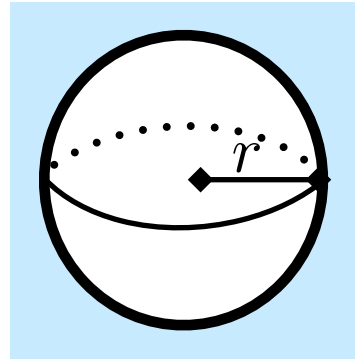


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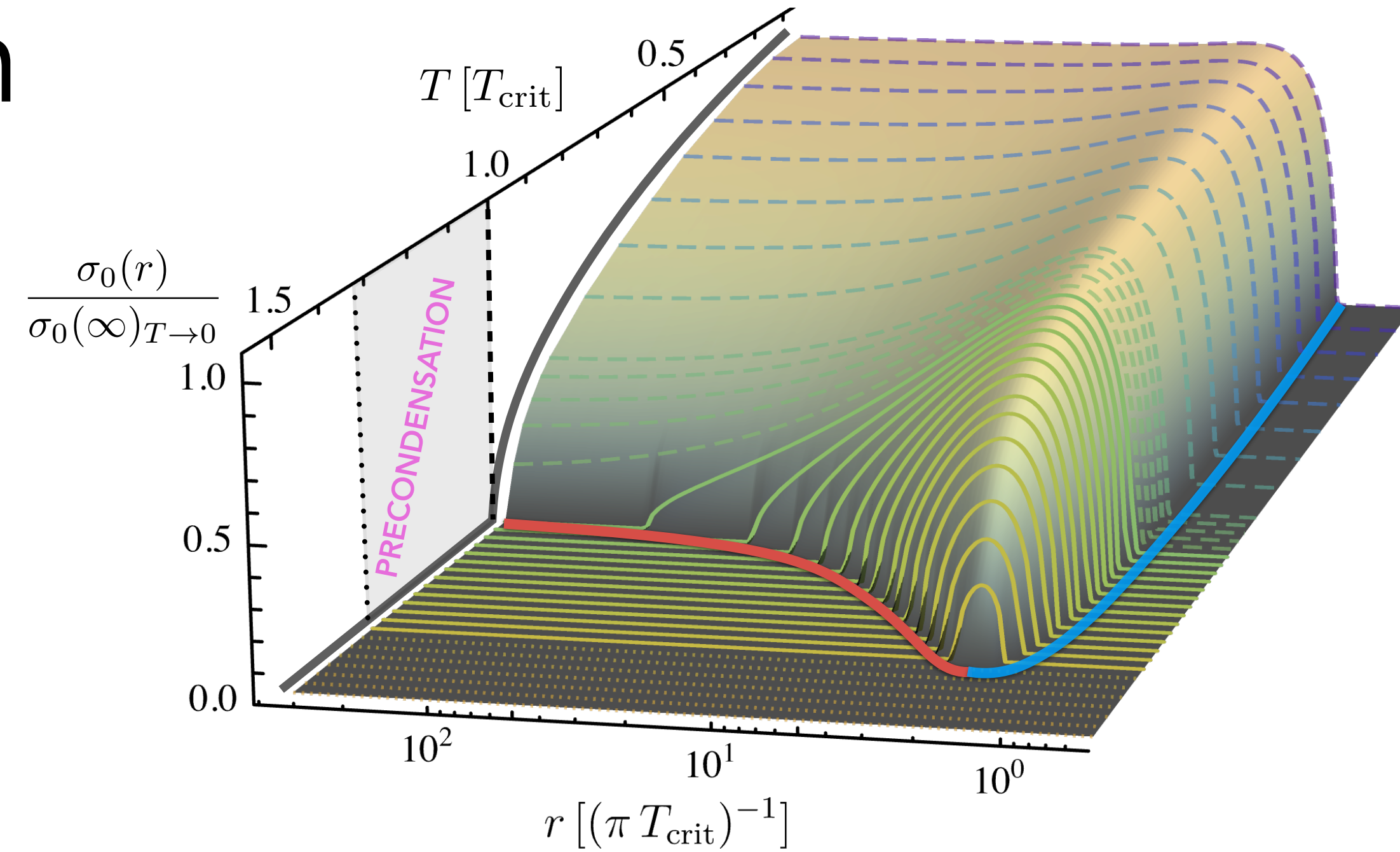
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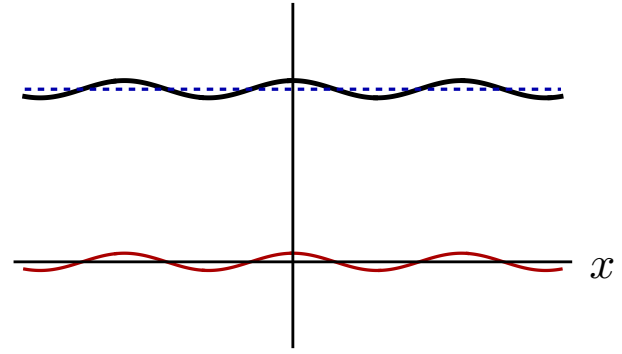
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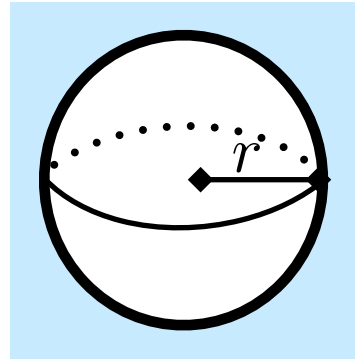


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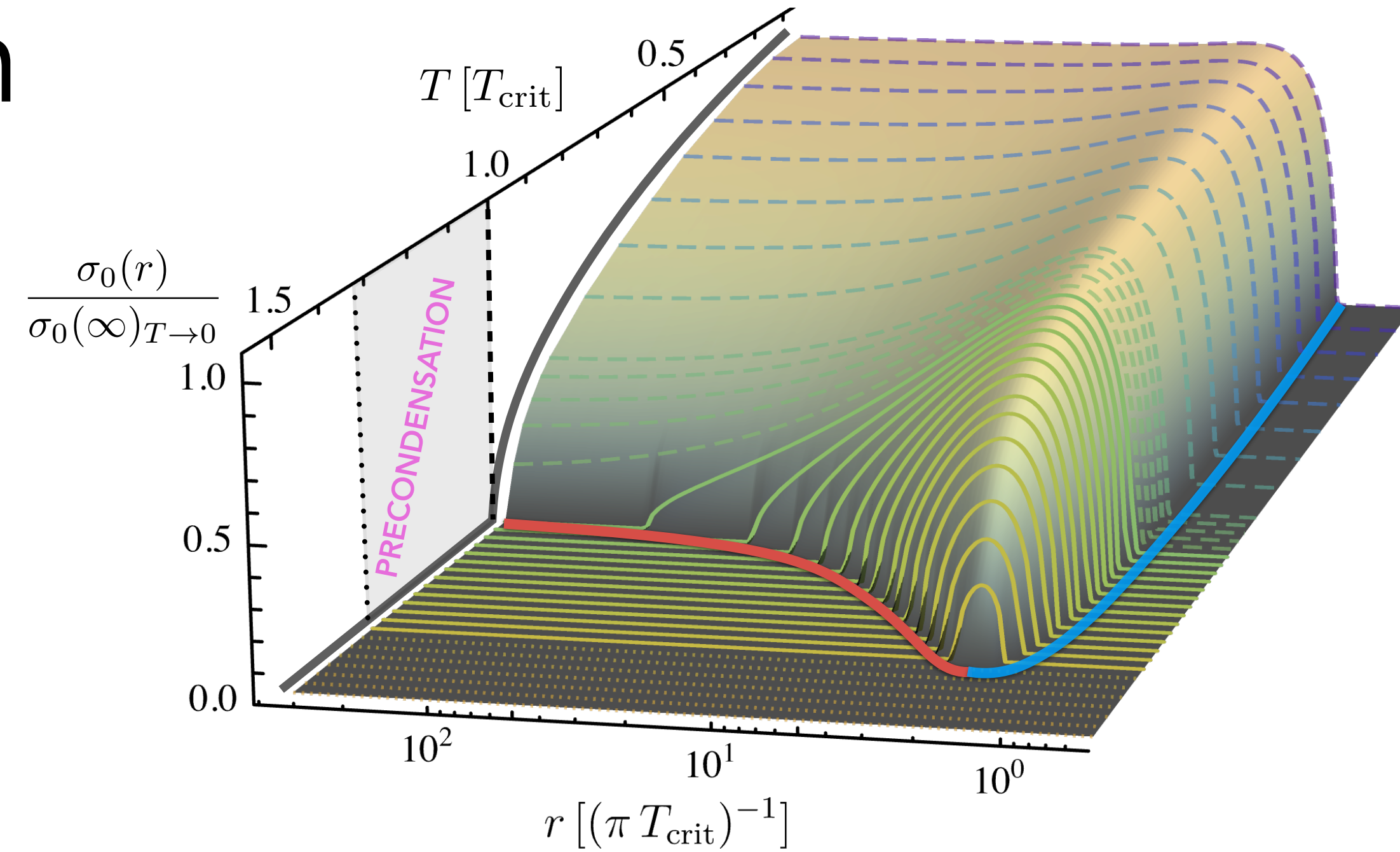
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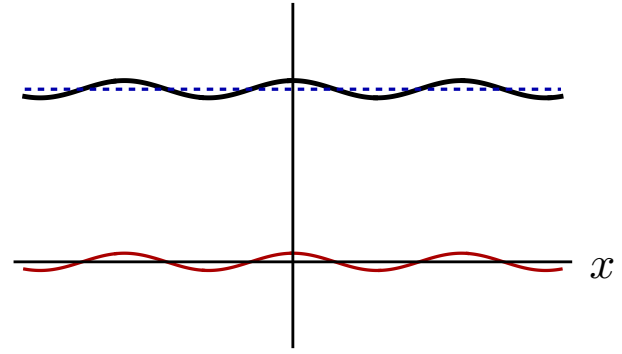
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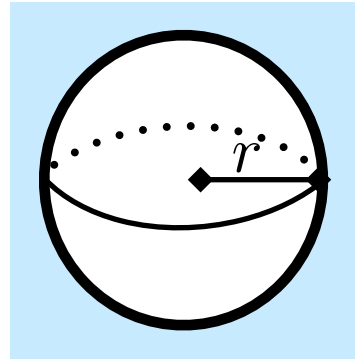


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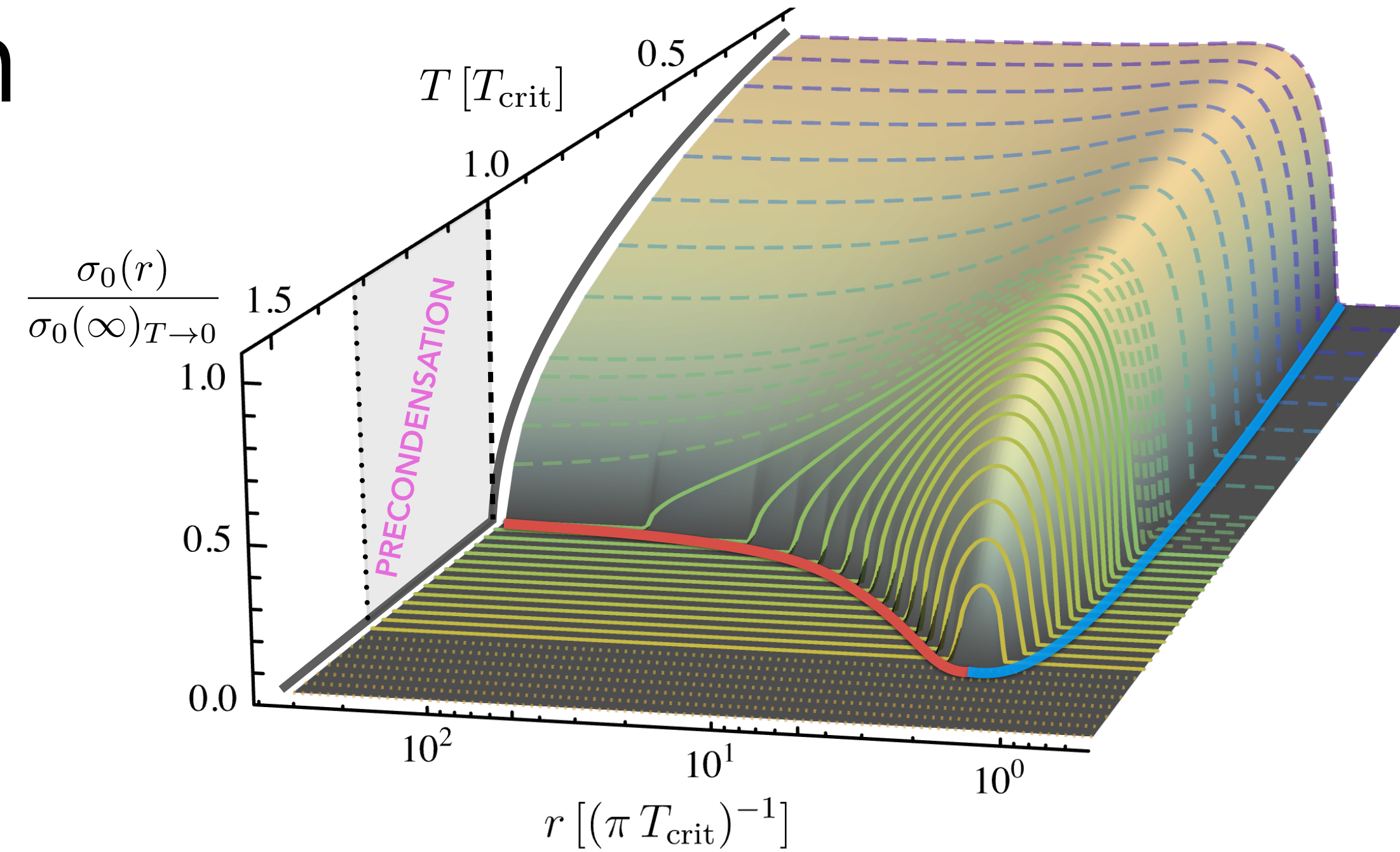
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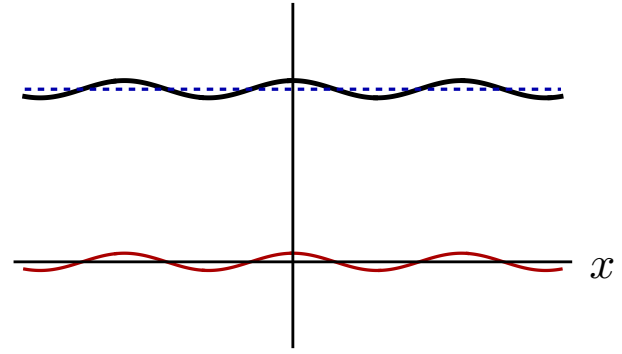
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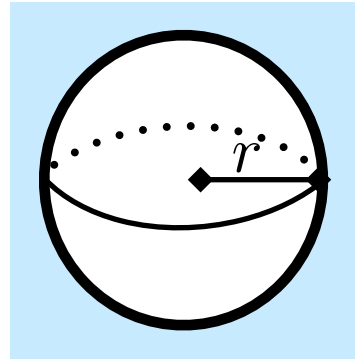


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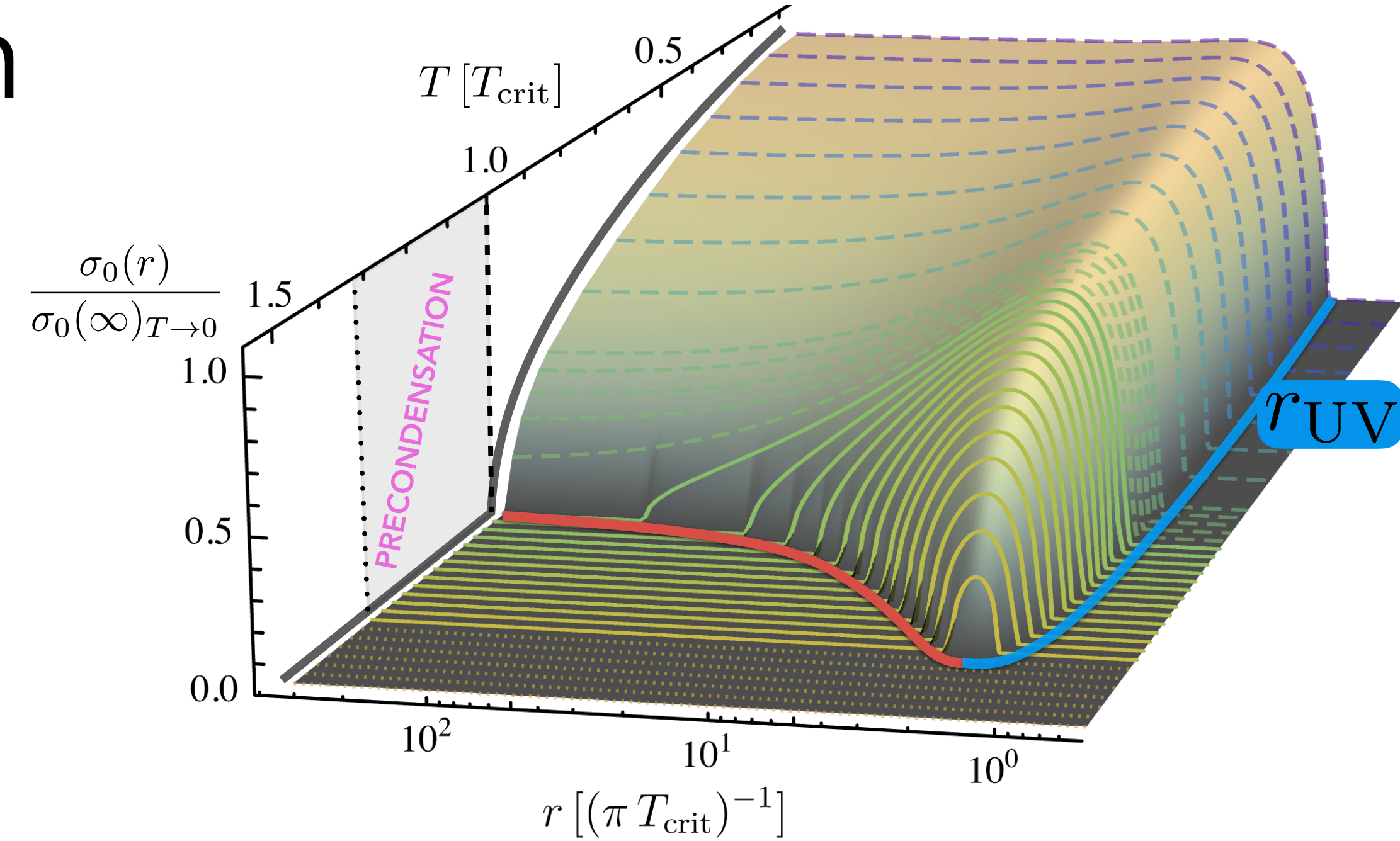
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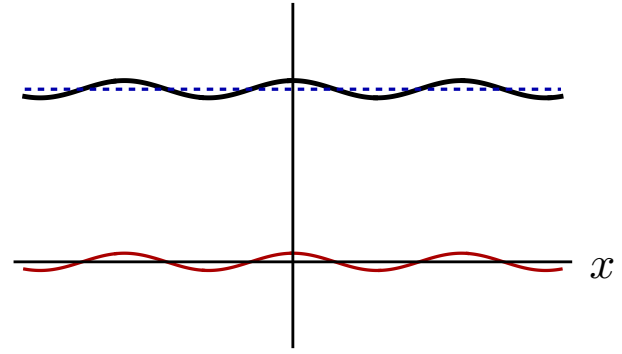


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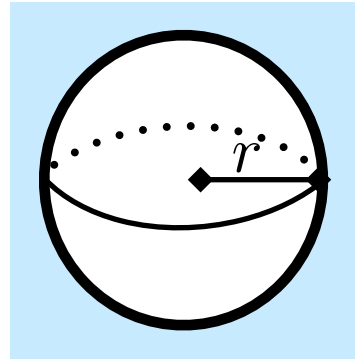
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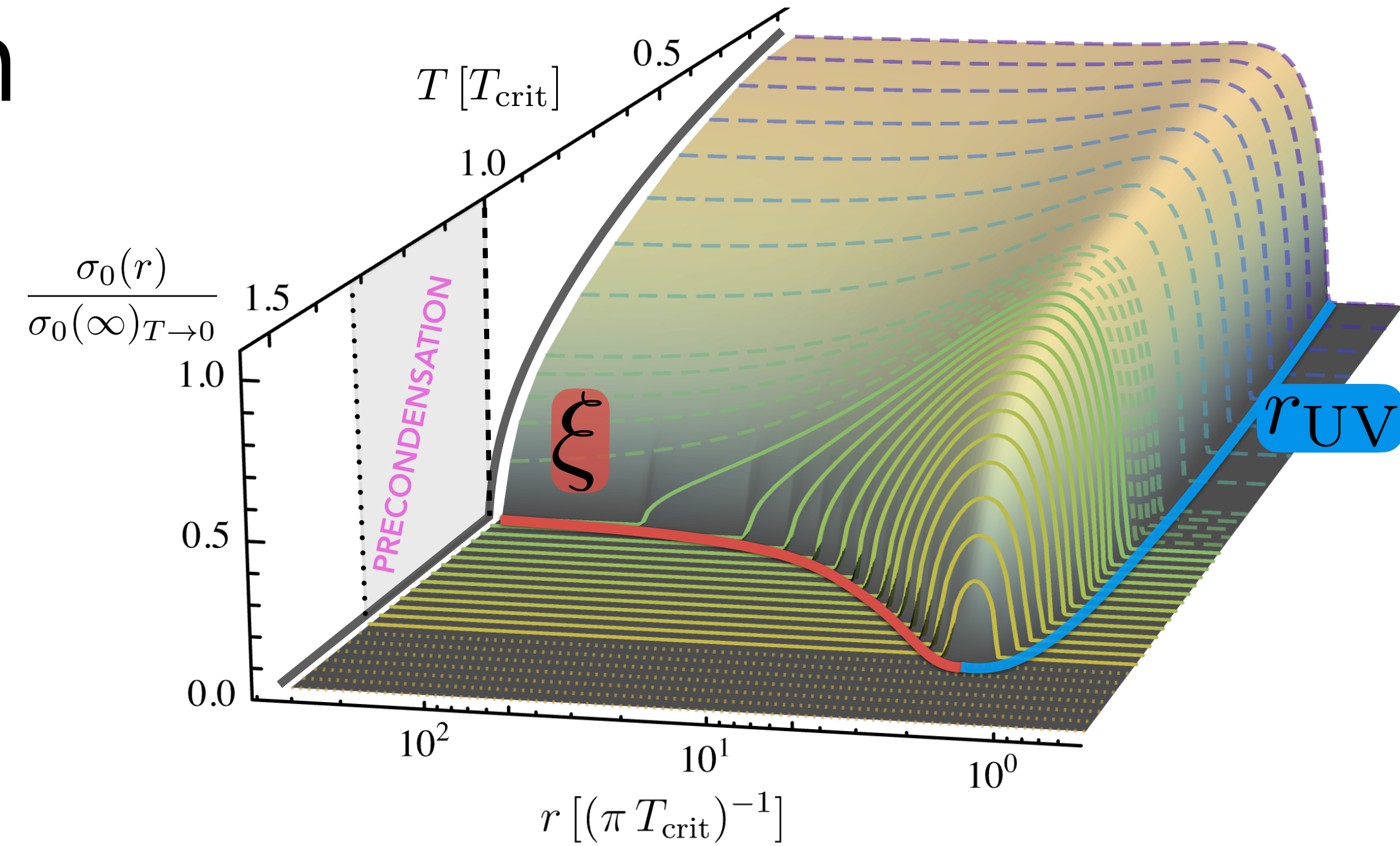
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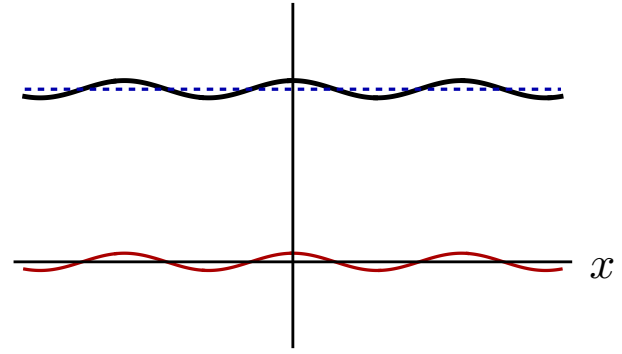
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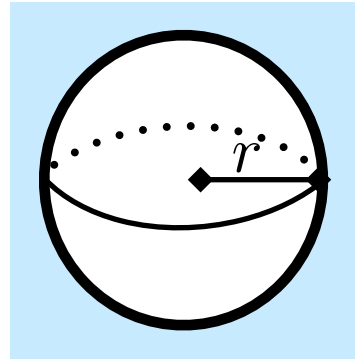


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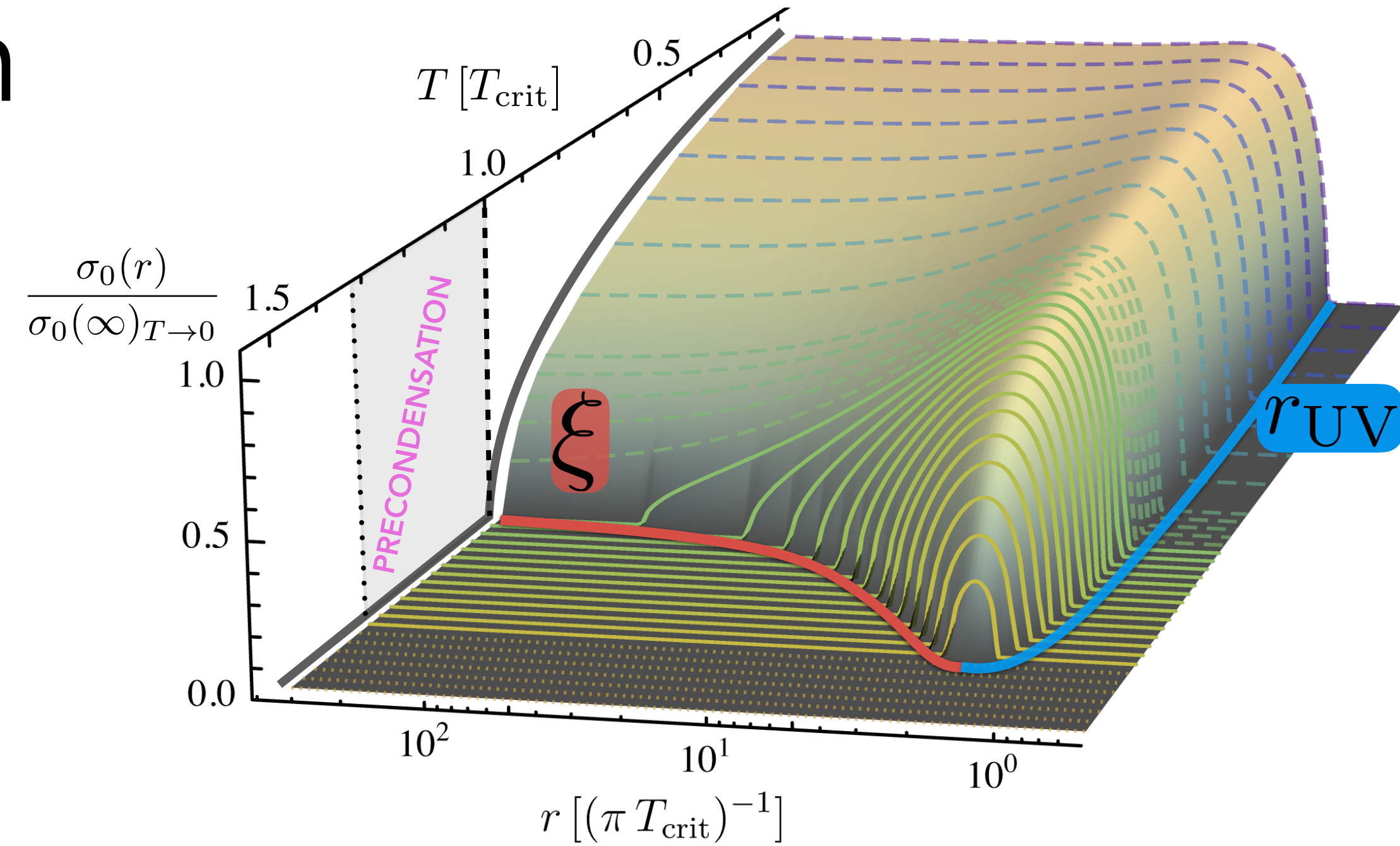


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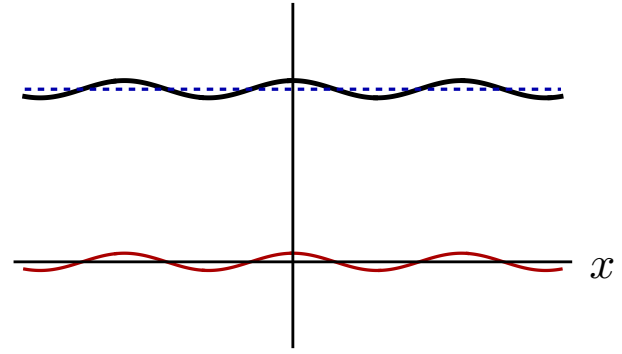
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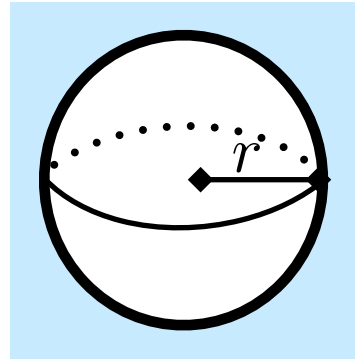


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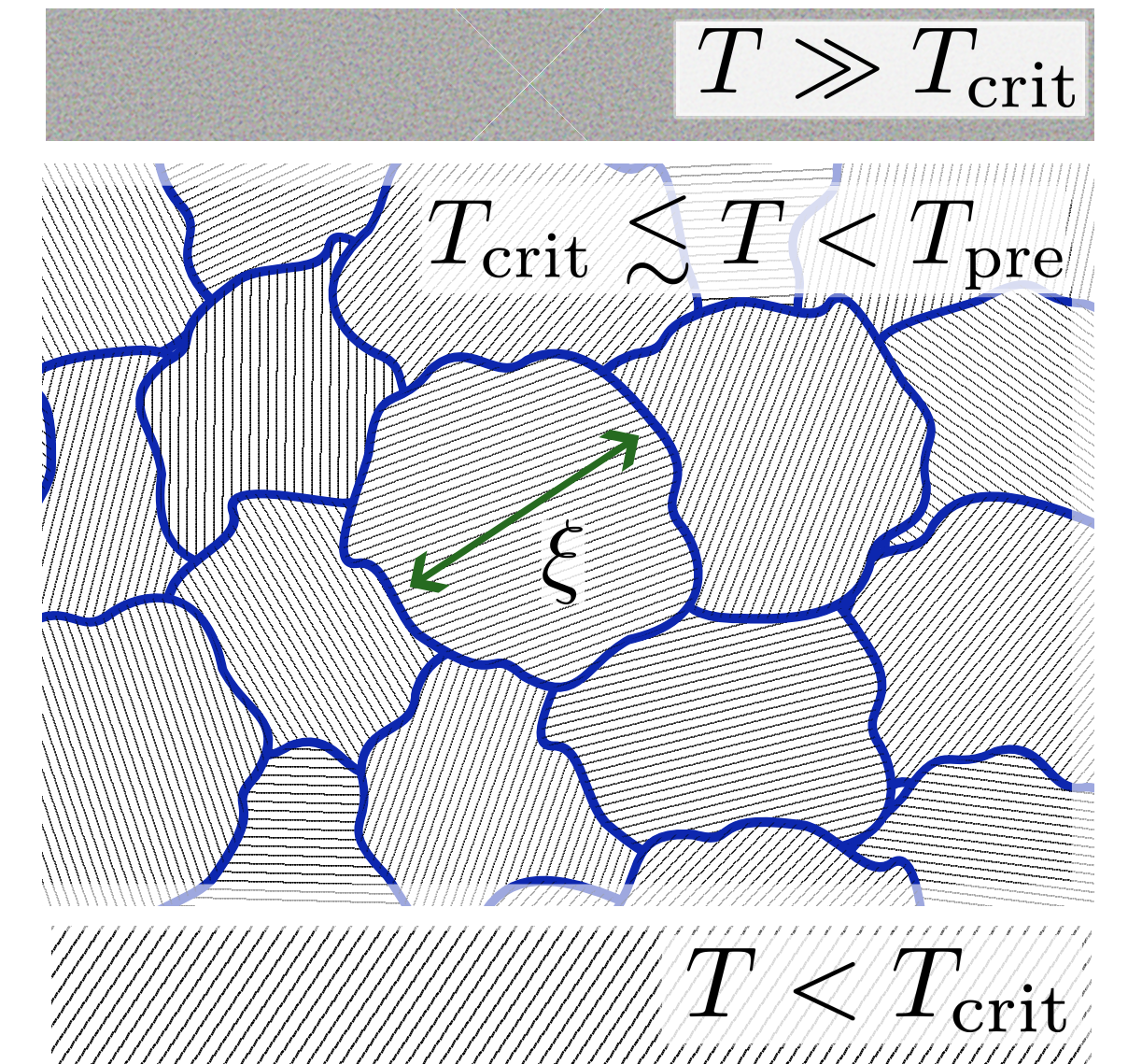
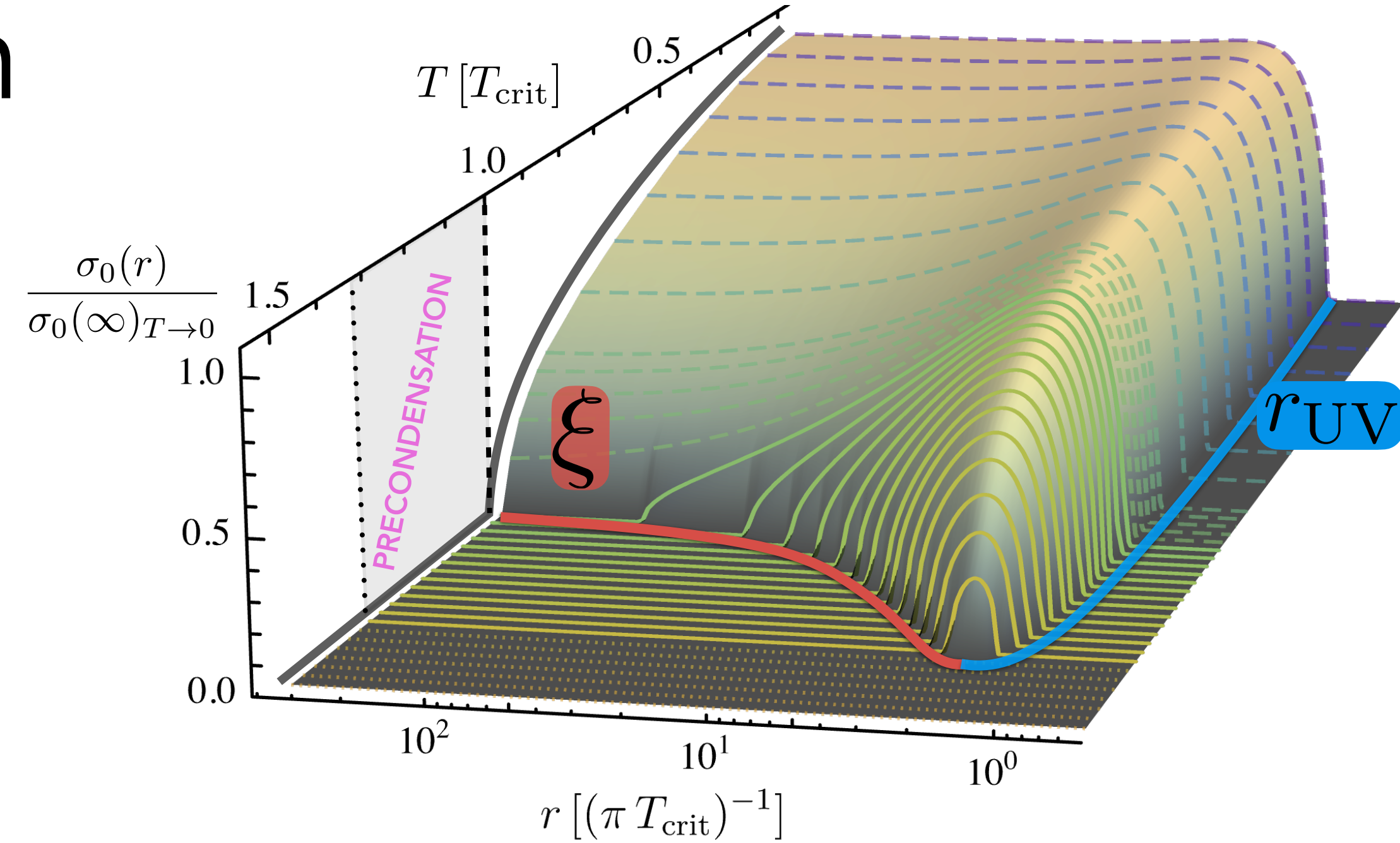


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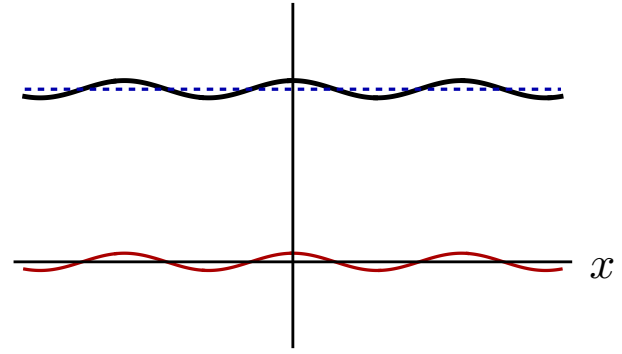
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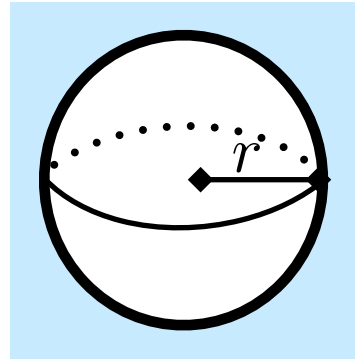


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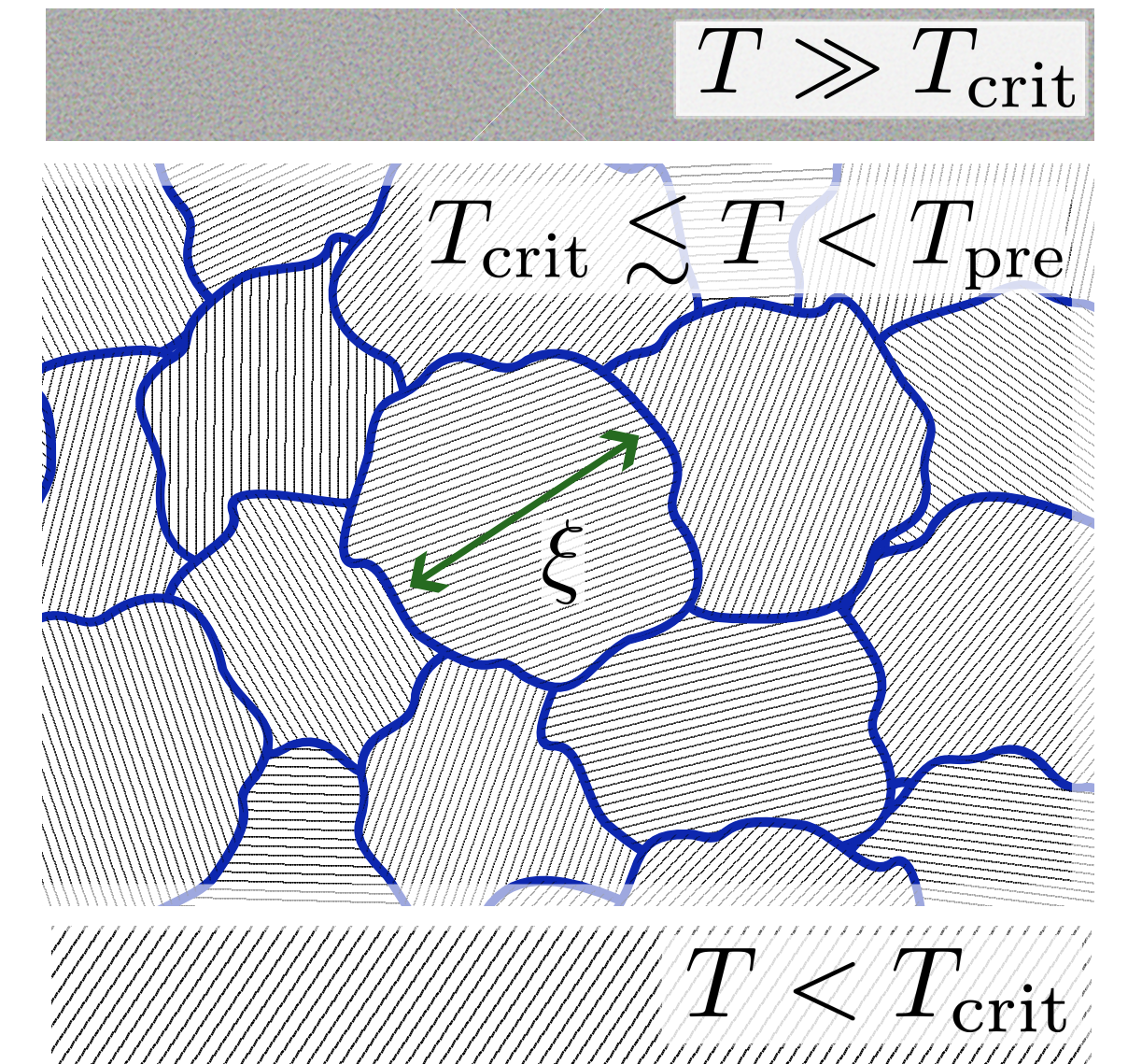
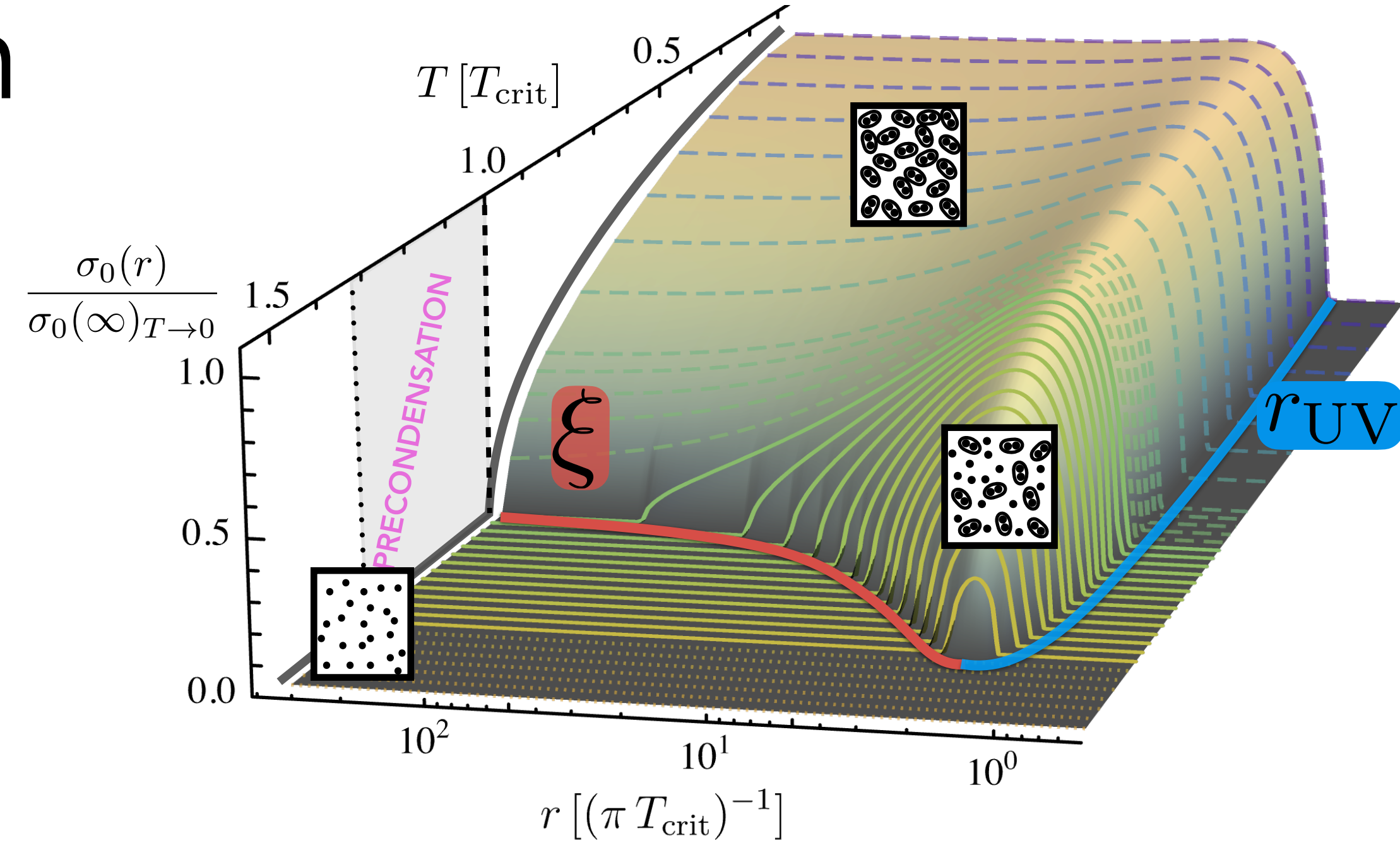


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Thermal precondensation

- Discussed in very different contexts

- cold atoms: BCE-BCS crossover

[Boettcher,Pawłowski,Diehl\[1204.4394\]](#)

- condensed matter: Dirac semi-metals

[Tolosa-Simeón,Classen,Scherer \[2503.04911\]](#)

- gauge-fermion: diquark condensate in 2-colour QCD

[Ihssen,Hawashin,Tolosa-Simeón,Classen \[2607.18396\]](#)
[Khan,Pawłowski,Rennecke,Scherer \[1512.03673\]](#)

- Scalar theories

[Hawashin,Rong,Scherer\[2409.10606\]](#) [Goertz,APG\[2308.13594\]](#)

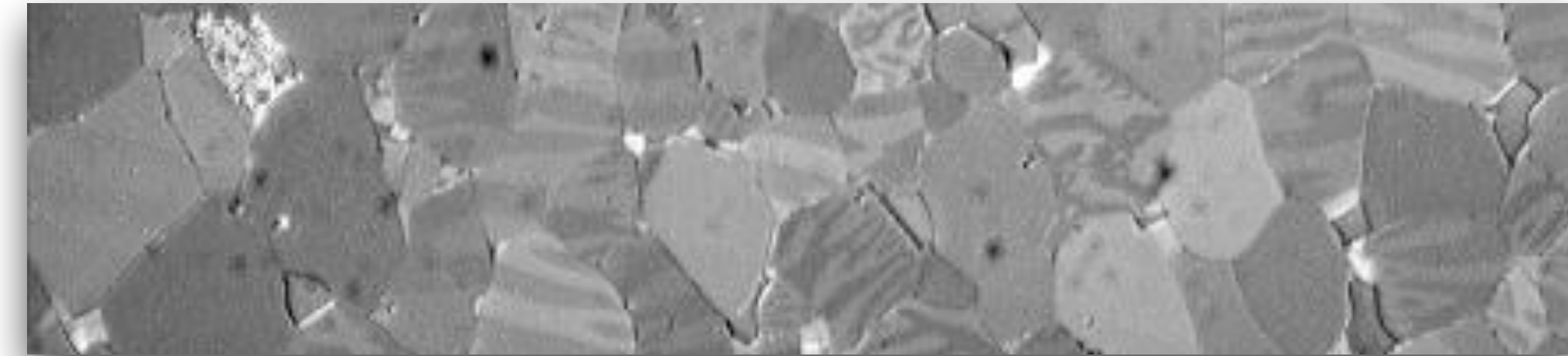
- Features:

- **domain formation** in equilibrium

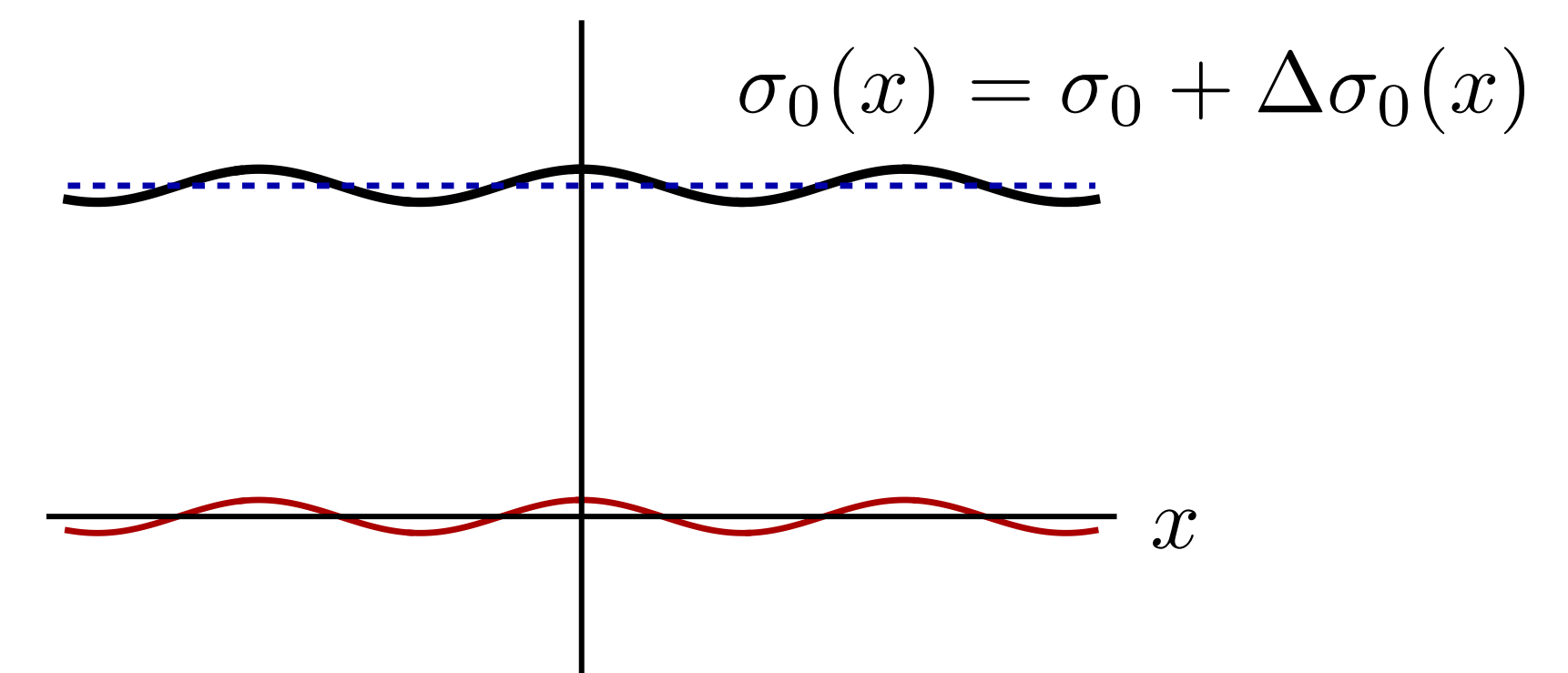
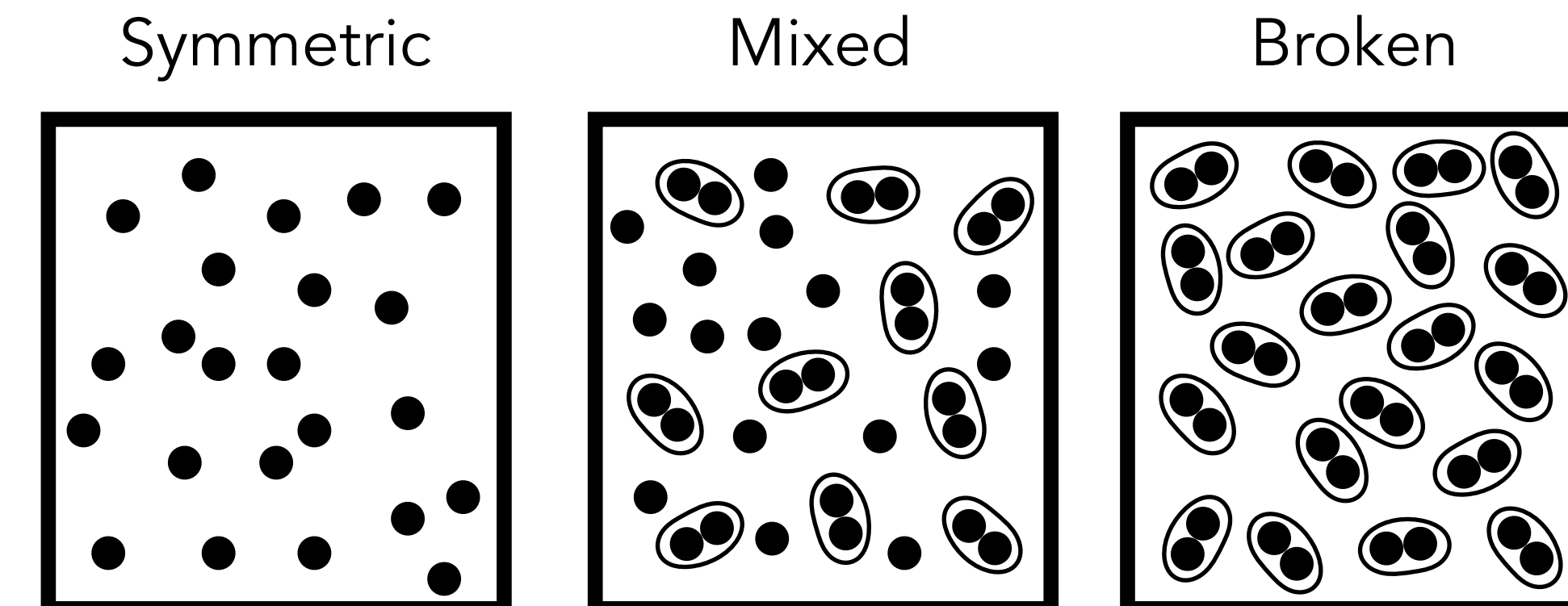
- **pseudo-gapped** or **mixed** phases

- **inhomogeneities** and **spatial modulations**

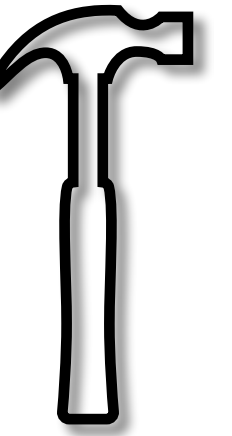
See Franz R. Sattler's talk



Weiss domains [Wikipedia]



Functional Renormalisation Group



- **Scale-dependent effective action:** $\Gamma_k[\phi] \quad k \sim 1/r$

$$\int [\mathcal{D}\phi]_{p>k} = \int \mathcal{D}\phi \exp(-\Delta S_k[\phi]) \quad \Delta S_k[\phi] = \int_p \phi(p) R_k \phi(-p)$$

$$\Gamma_k[\phi] = \int_x J(x)\phi(x) - \mathcal{W}_k[J] - \Delta S_k[\phi]$$

Wetterich '89

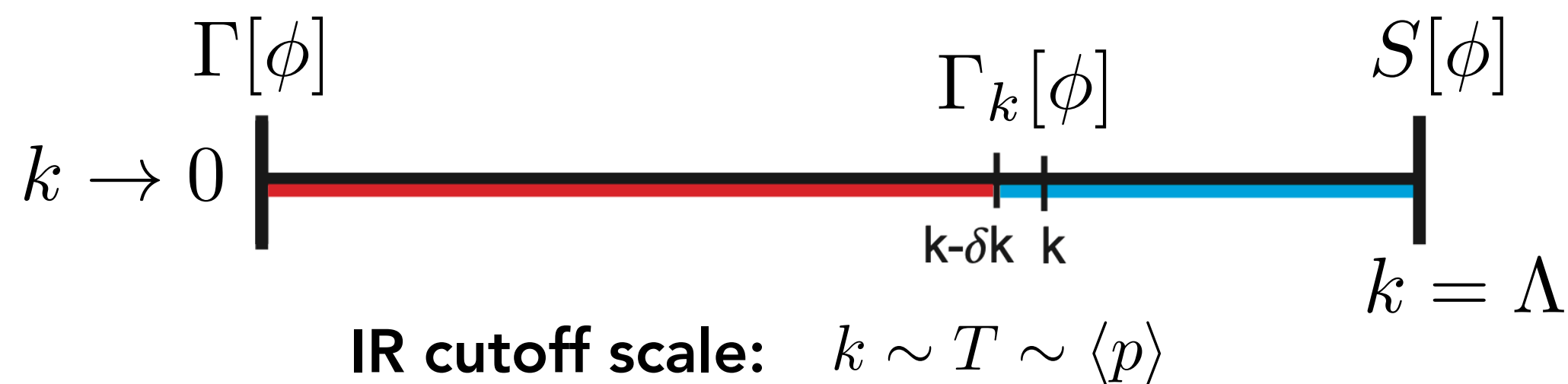
Flow equation:

$$\partial_t \Gamma_k[\phi] = \frac{1}{2} \text{Tr} \left[\frac{1}{\Gamma_k^{(2)} + R_k} \partial_t R_k \right] = \frac{1}{2} \text{ (circle with cross) }$$

$$\partial_t \equiv k \partial_k$$

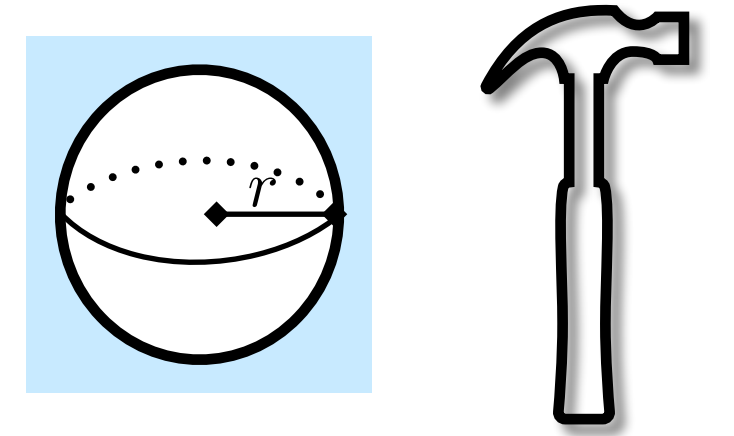
Wetterich '93

- Average action of fields over a k^{-d} space-time volume
- Kadanoff's block-spinning idea in the continuum limit



- Exact derivation
- One loop
- **Non-perturbative**
- Mass-dependent
- Analytic regulators
- Versatile
- Systematic expansion schemes
- UV-IR finite
- Diagrammatic
- Real-time formulation
- ...

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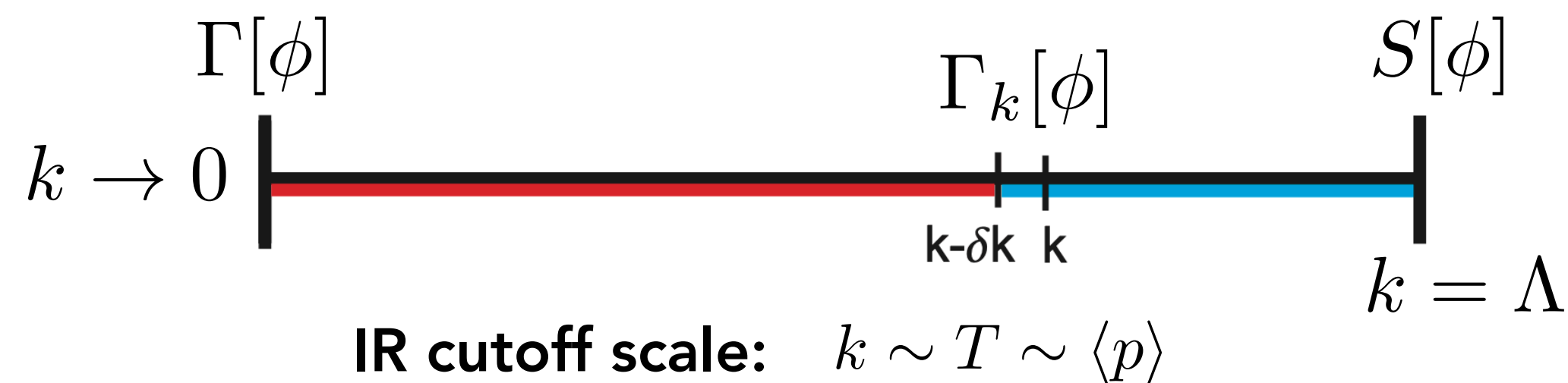
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Chiral gauge-fermion theories

$$S = \int_x \frac{1}{4} F_{\mu\nu}^a F_{\mu\nu}^a + \mathcal{L}_{\text{gf}} + \mathcal{L}_{\text{gh}} + \bar{\psi} \not{D} \psi$$

- Gauge-fermion theories in the chiral limit

See Haolin Li's talk

- Rich phenomena (confinement, dχSB, walking, ...)
- Relevance for BSM physics

★ Composite Higgs & Technicolour (HP)

★ Strong Dark Sectors (DM)

★ Cosmological evolution

★ 1st order chiral phase transition, GWs

Reichert,Sannino,Wang,Zhang[2109.11552]
 Pashechnik,Reichert,Sannino,Wang[2309.16755]
 Iso,Okada,Orikasa[0902.4050]
 Iso,Serpico,Shimada[1704.04955]
 ...

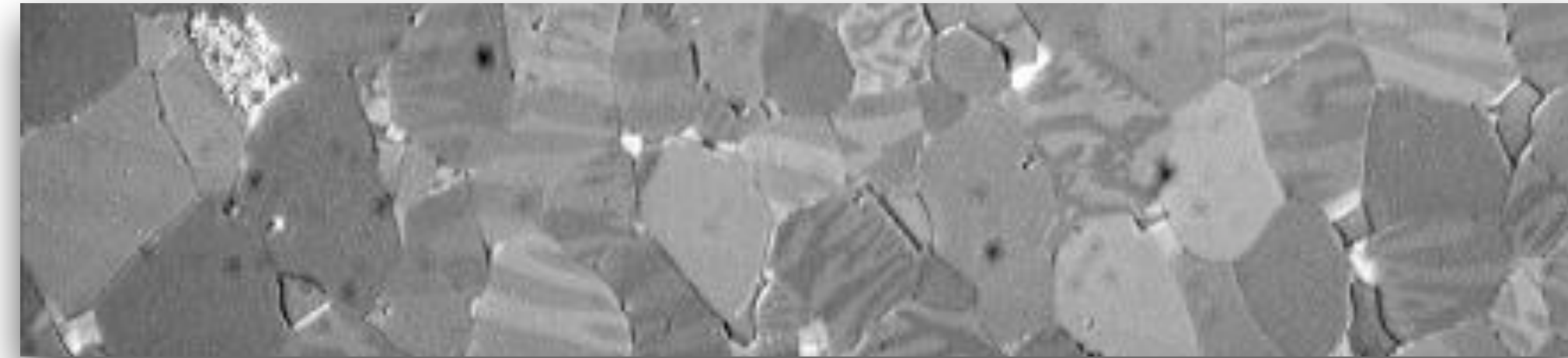
- Precondensation opens path to **new observational test**

- Hanbury Brown-Twiss spectroscopy

See amazing talk by Fabian Rennecke

- ... ?

Rennecke,Pisarski,Rischke[2301.11484]
 Fukushima,Hidaka,Inoue,Shigaki,Yamaguchi[2306.17619]



Weiss domains [Wikipedia]



LSS [Wikipedia]



Hubble telescope [Wikipedia]

Functional approach to QCD

- d χ SB encoded in higher dimensional fermionic operators

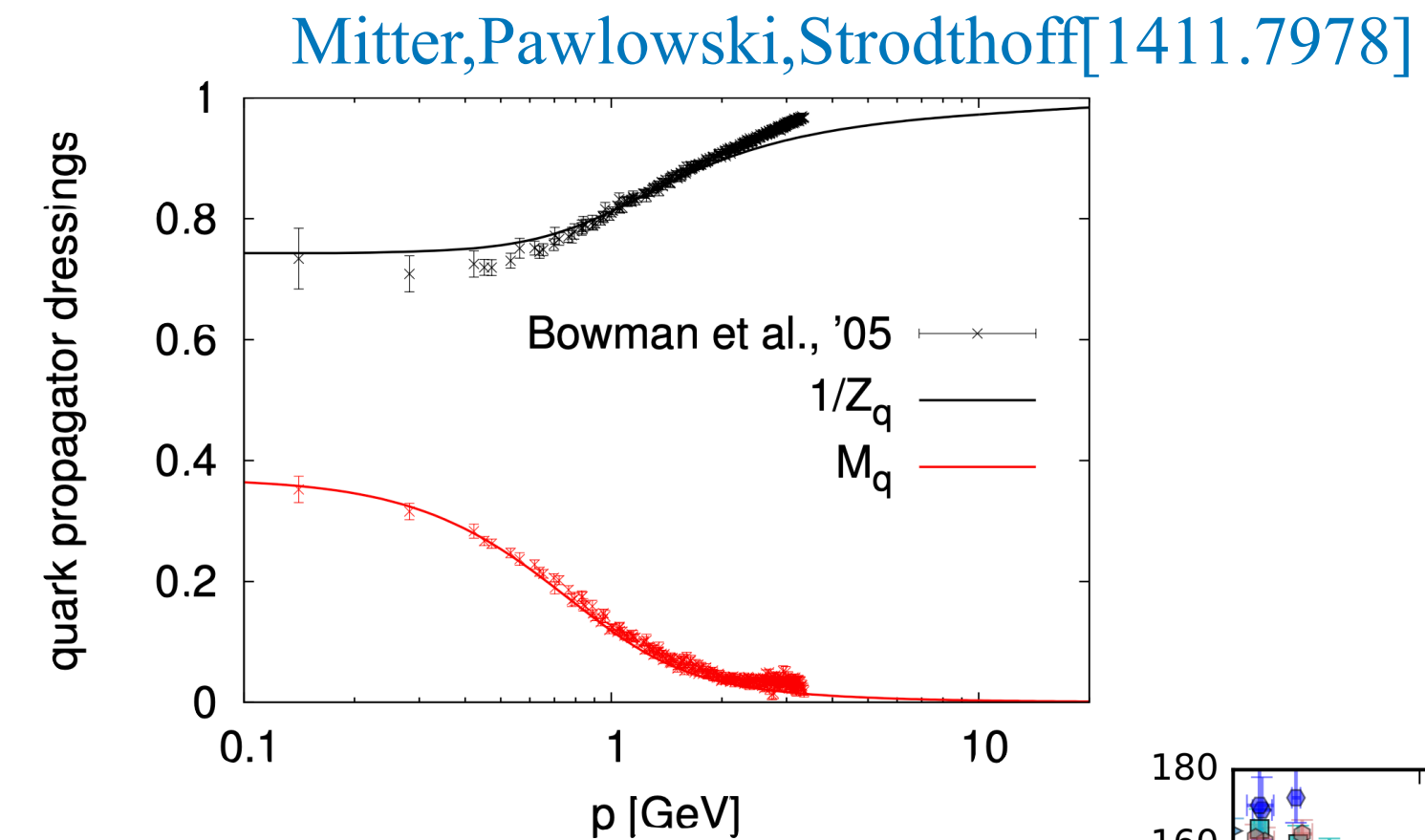
$$\Gamma_k[\Phi] \supset - \int_x \bar{\lambda}_\sigma \left(\bar{\psi} \mathcal{T}_{(\text{S-P})} \psi \right)^2 + \dots$$

- Exact field transformation along the RG flow

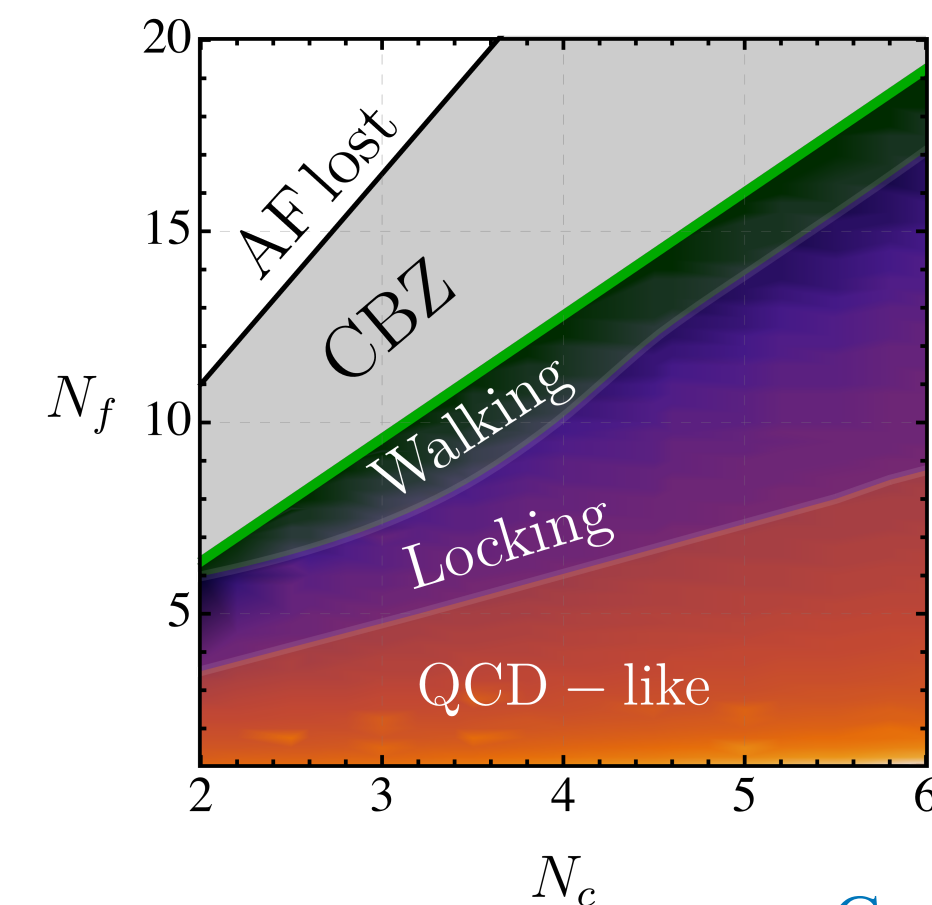
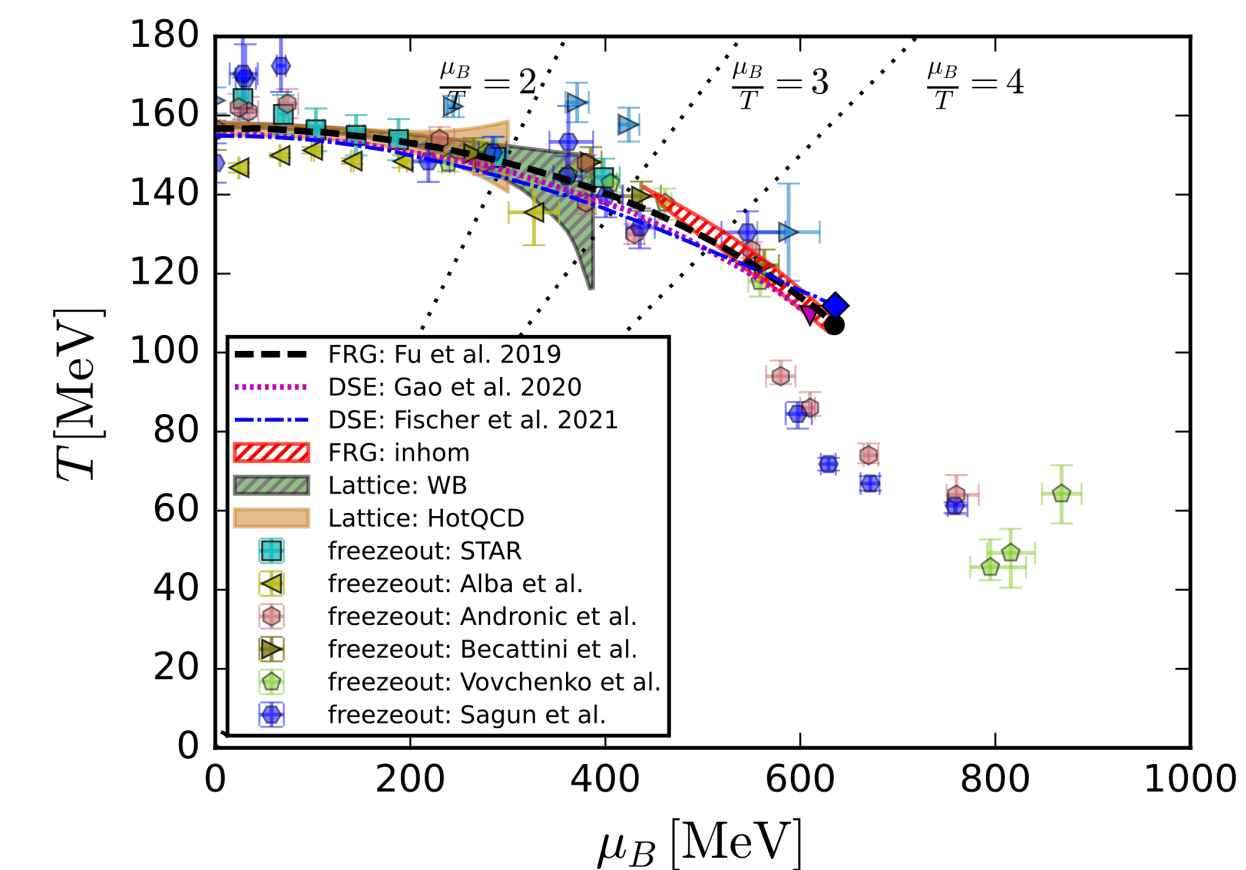
$$\left. \begin{array}{c} \vec{p}_1 \searrow \\ \nearrow \vec{p}_2 \end{array} \right\} \begin{array}{c} \vec{p}_4 \nearrow \\ \searrow \vec{p}_3 \end{array} \quad \left| \begin{array}{l} (\phi) \\ (p_1 + p_3)^2 = 0 \\ (p_2 + p_4)^2 = 0 \end{array} \right. = \sum_{\phi \in \{\sigma, \pi^a\}} \left. \begin{array}{c} \searrow \\ \nearrow \end{array} \right\} \text{---} \left. \begin{array}{c} \nearrow \\ \searrow \end{array} \right\} \quad \left| \begin{array}{l} (p_1 + p_3)^2 = 0 \\ (p_2 + p_4)^2 = 0 \end{array} \right.$$

Stratonovich'57 Hubbard'59

$$\Gamma_k[\Phi] \supset \int_x \bar{h} \bar{\psi} (T_f^0 \sigma + i \gamma_5 T_f^a \pi^a) \psi + Z_\phi (\partial_\mu \phi)^2 + V(\phi^2) + \dots$$



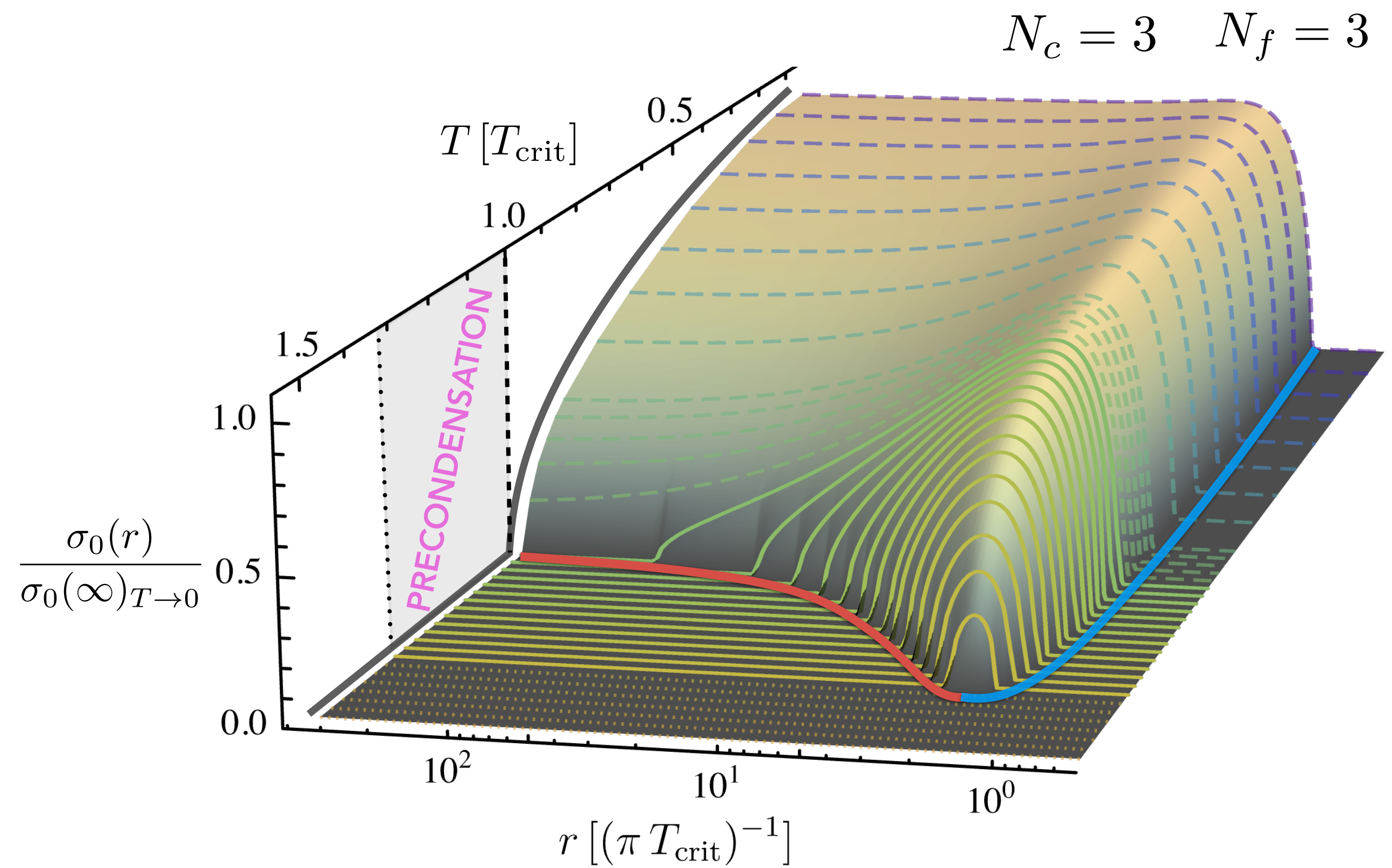
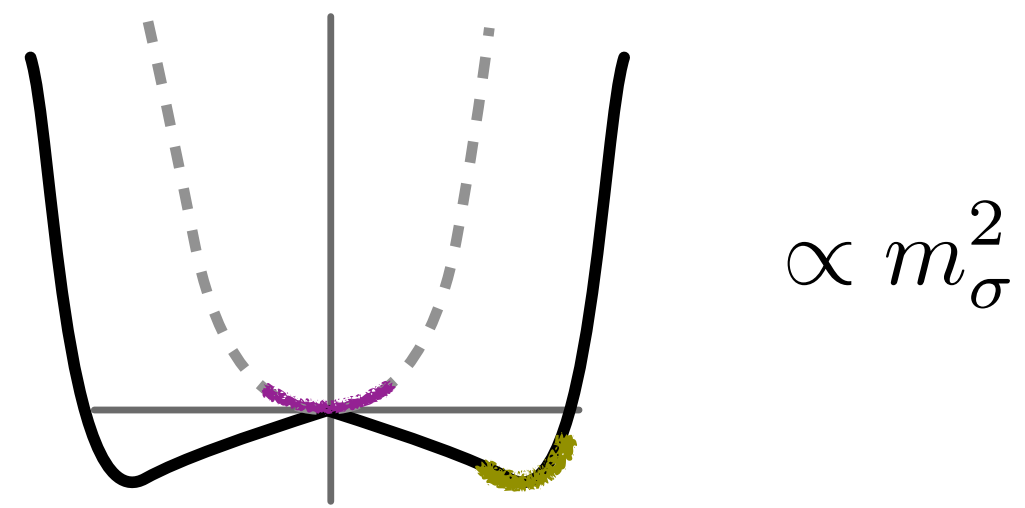
fQCD collaboration



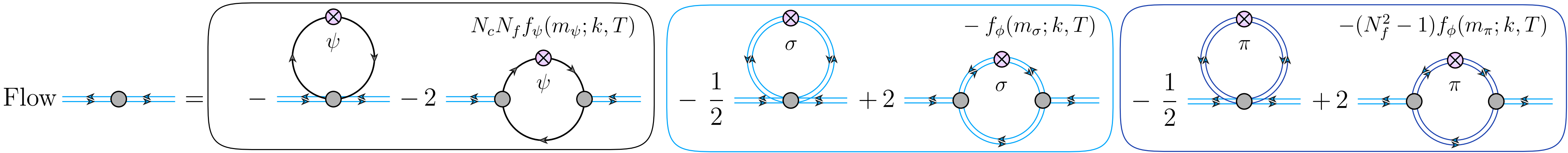
Goertz,APG,Pawlowski[2412.12254]

Microscopic origin

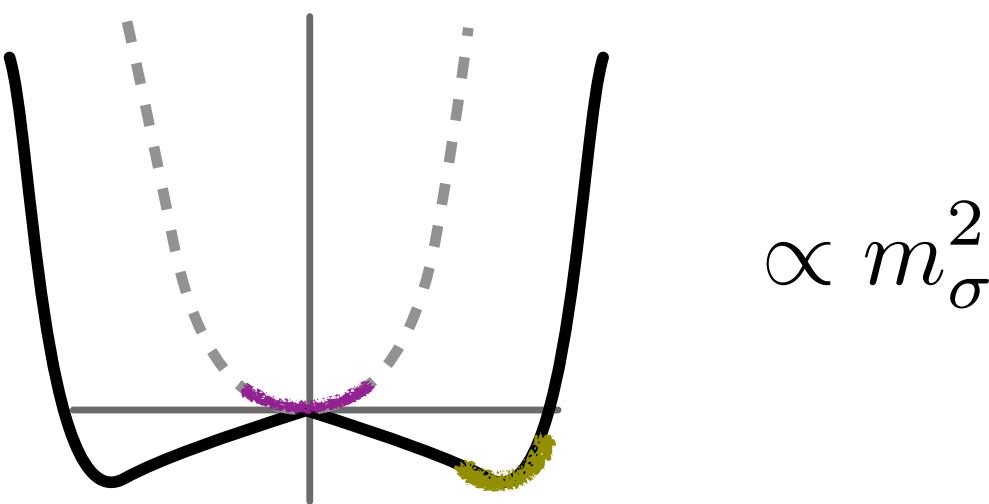
Flow of the effective chiral potential:



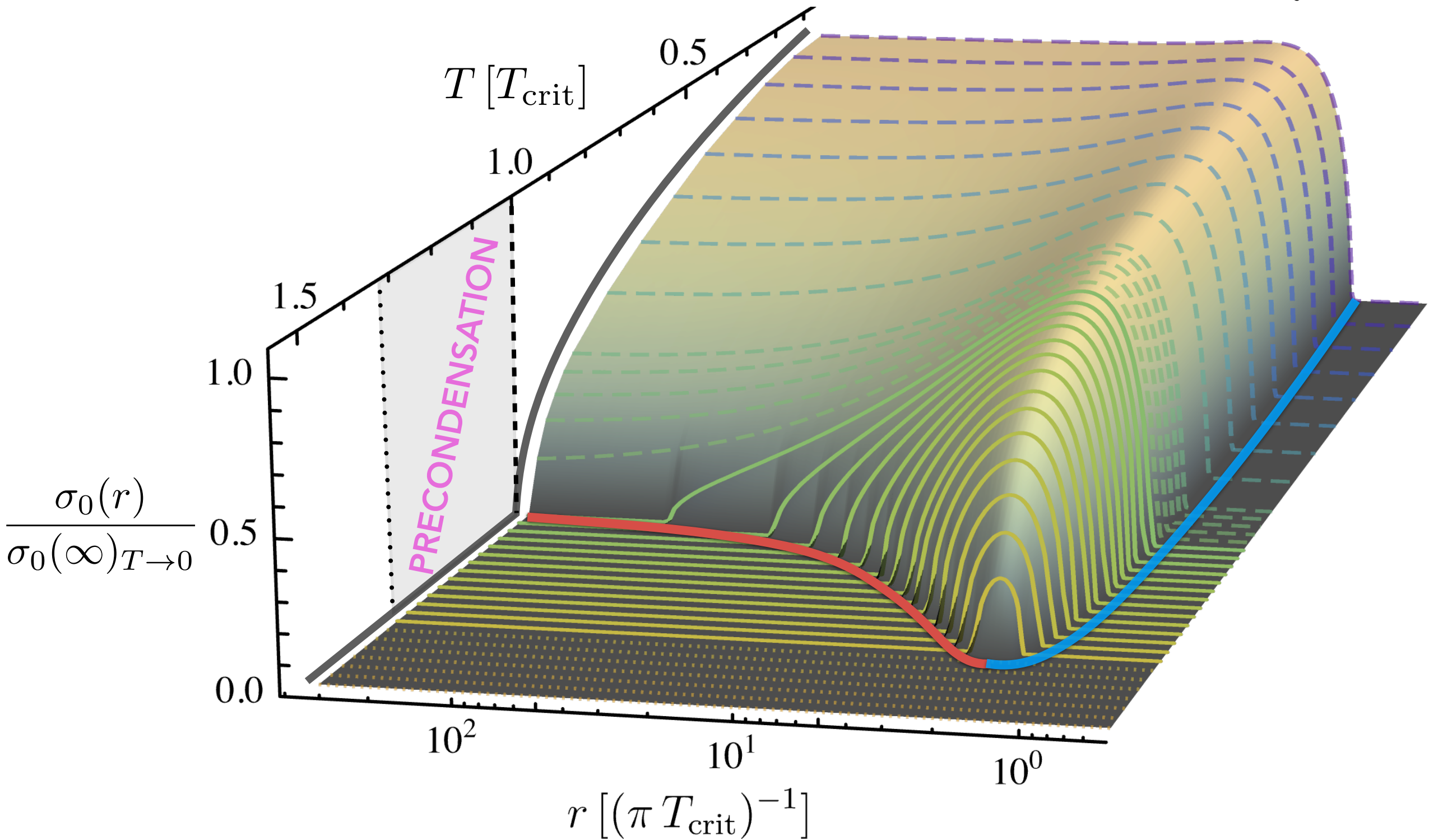
Microscopic origin



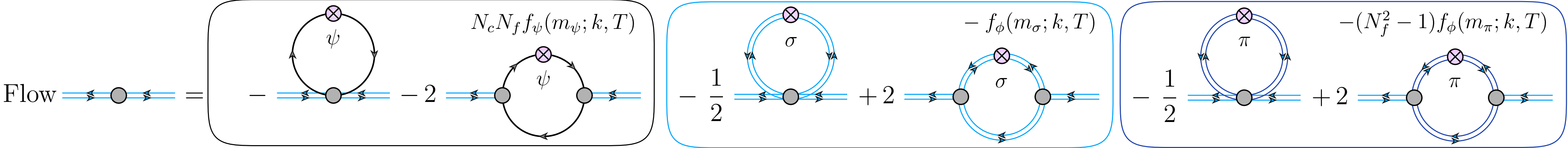
Flow of the effective chiral potential:



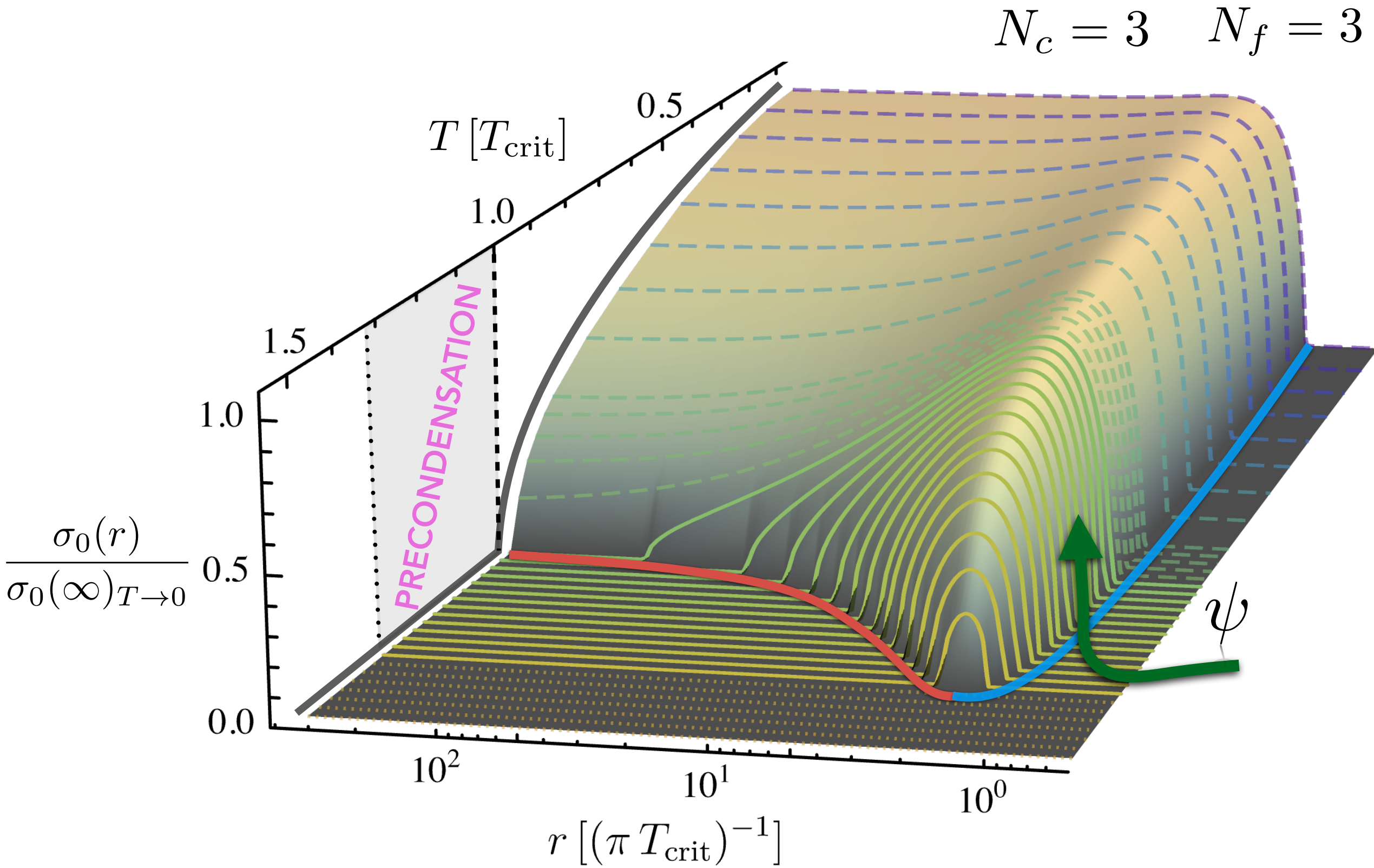
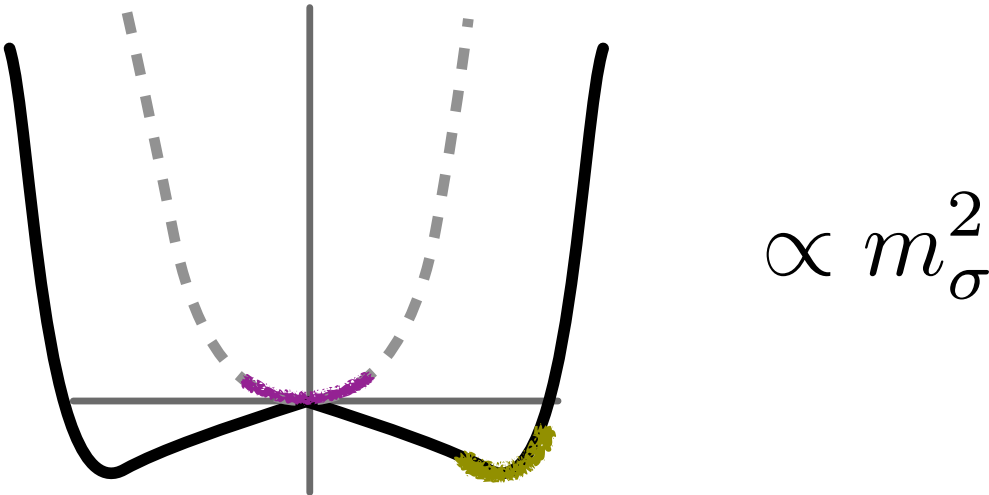
$$N_c = 3 \quad N_f = 3$$



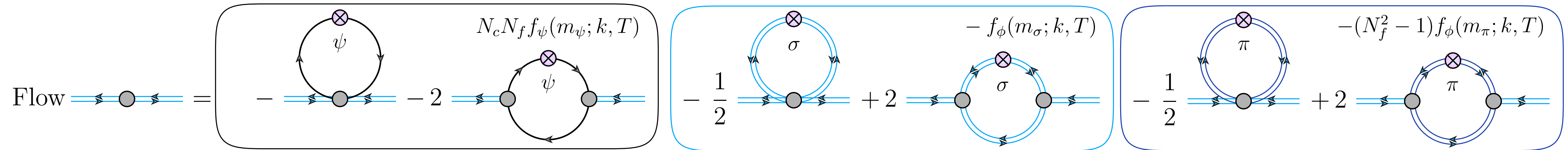
Microscopic origin



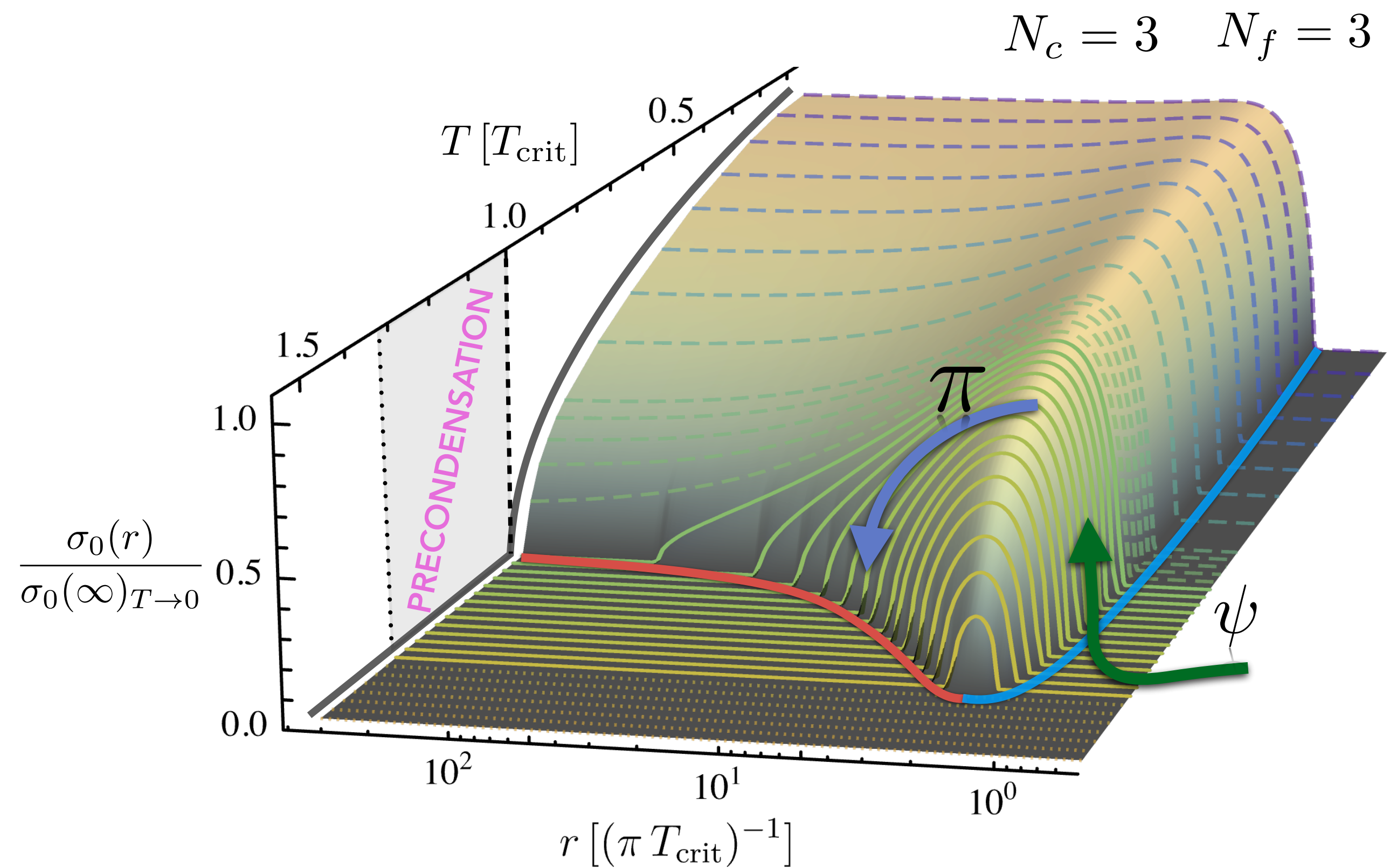
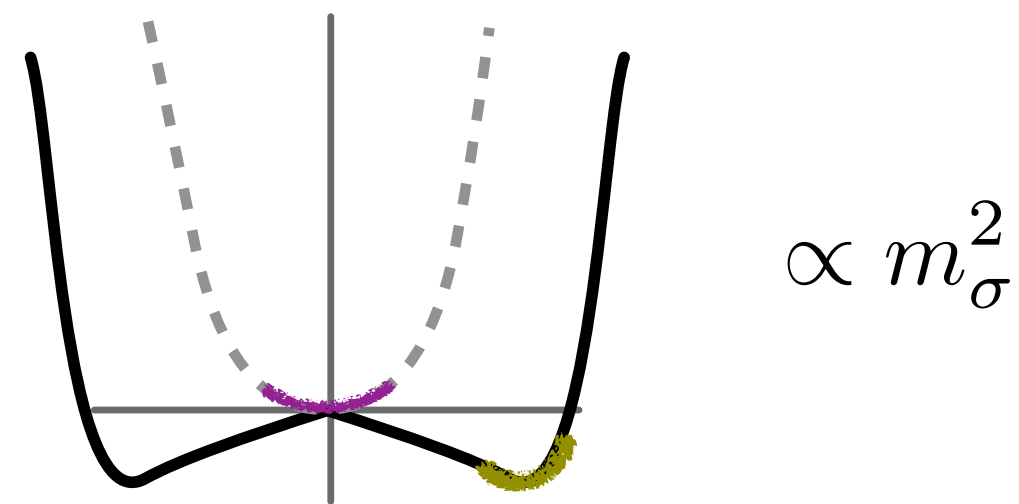
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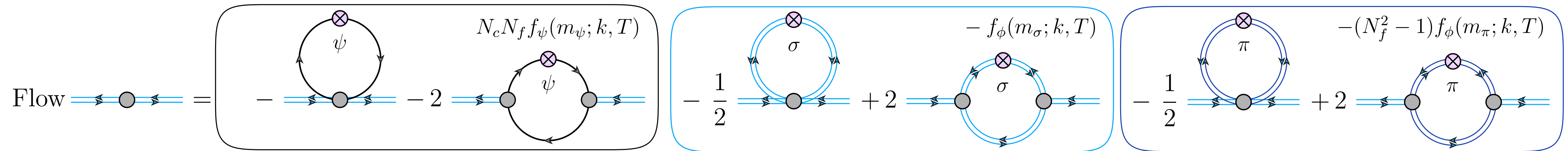
Microscopic origin



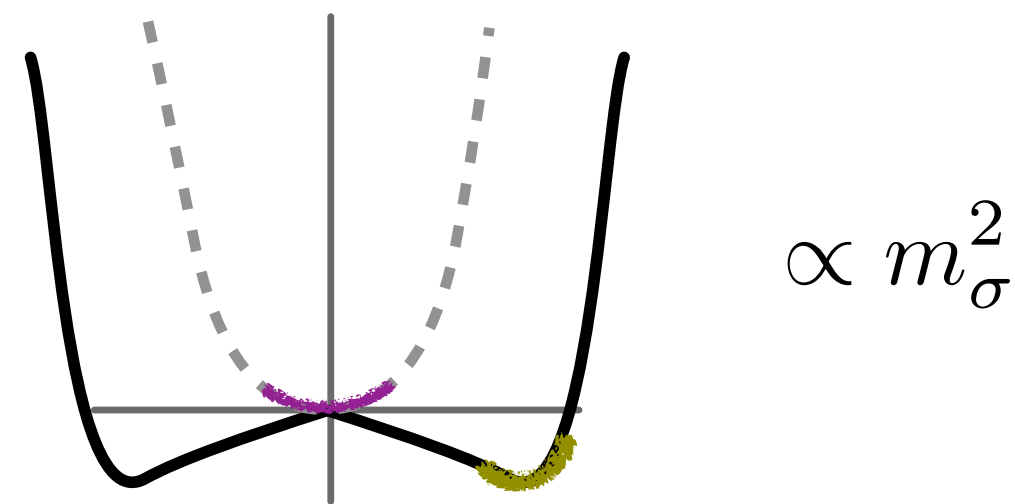
Flow of the effective chiral potential:



Microscopic origin

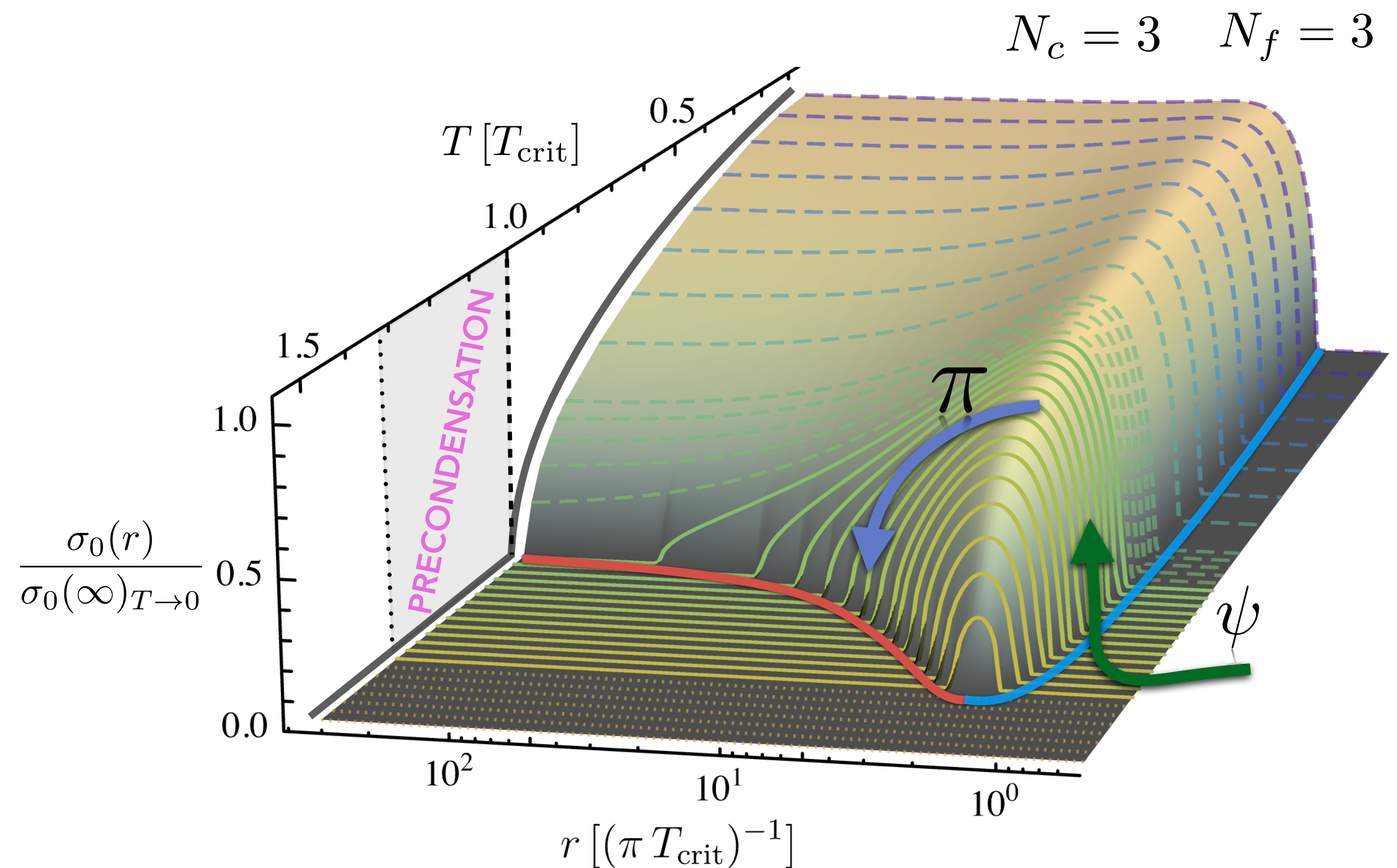


Flow of the effective chiral potential:

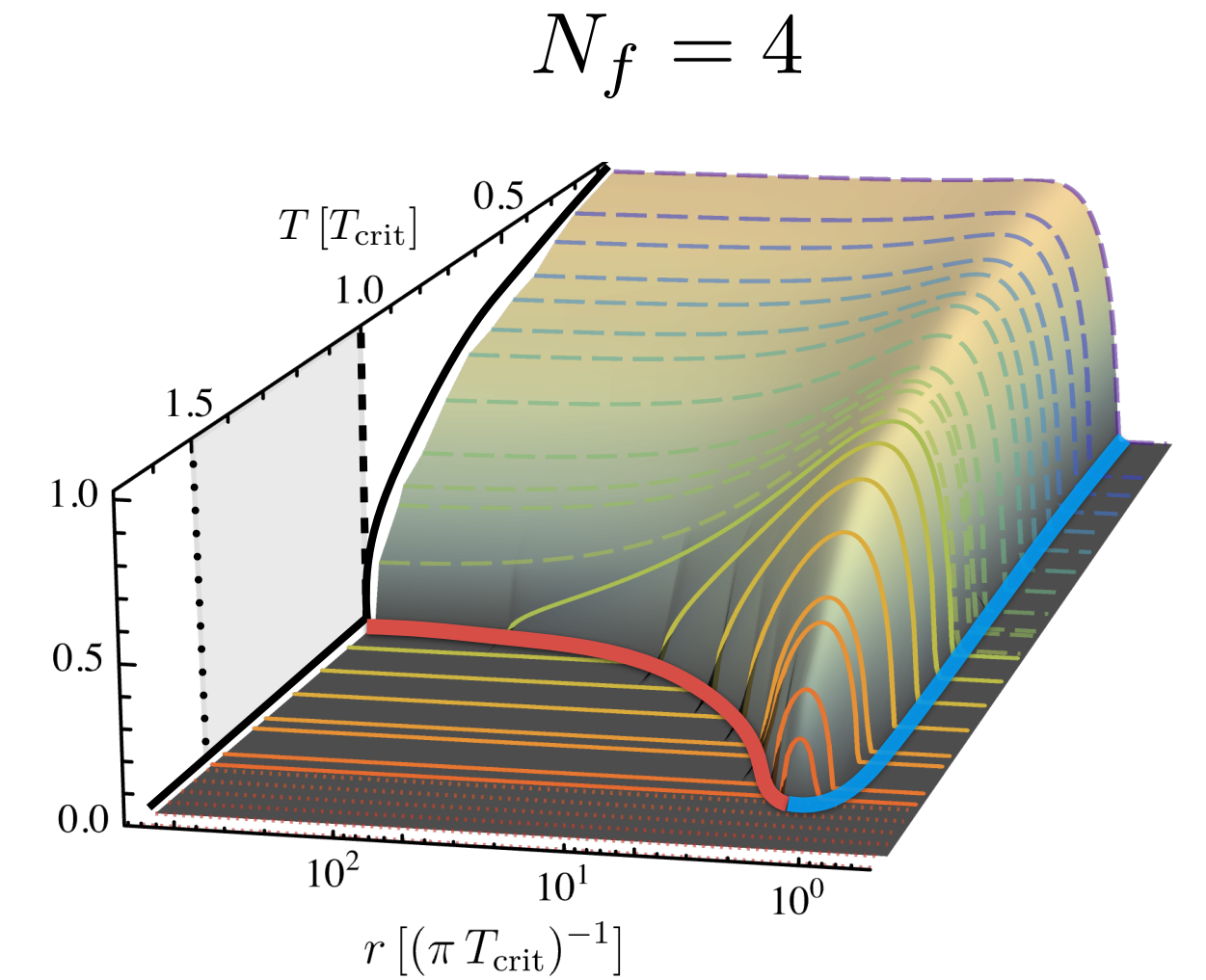
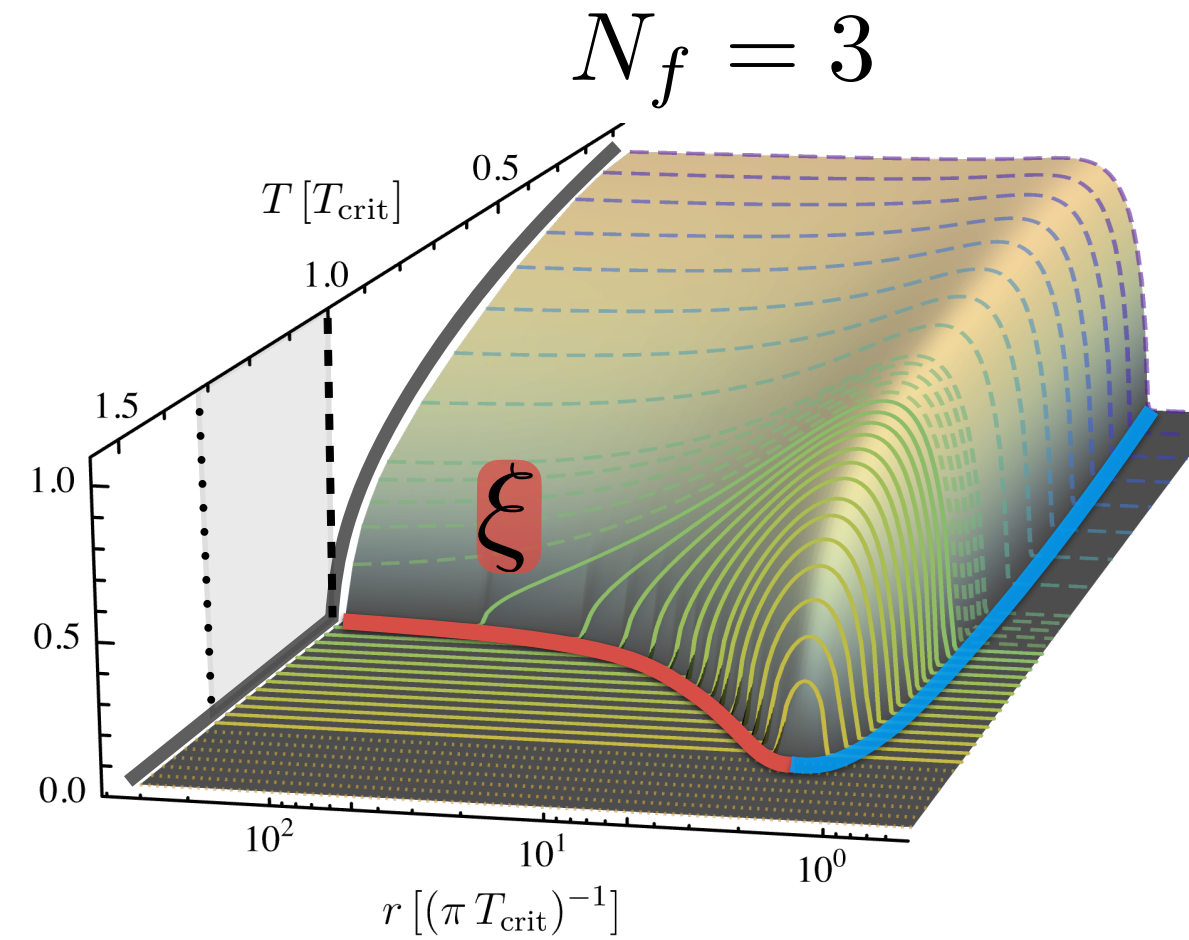
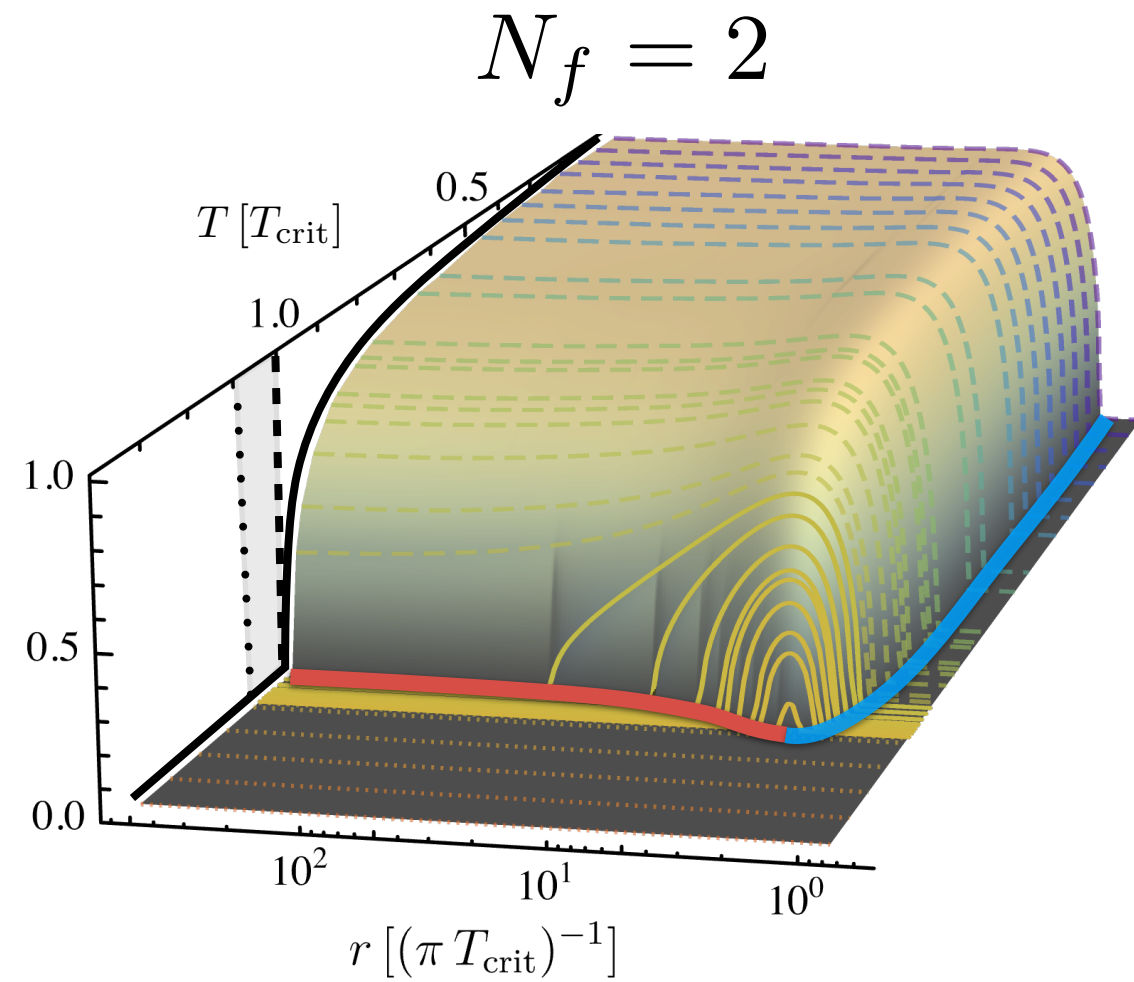


• Necessary key ingredients:

- Competing counteracting effects: fermions and bosons
- External parameter: $T, \mu, \dots$
- Massless modes: exact Goldstones

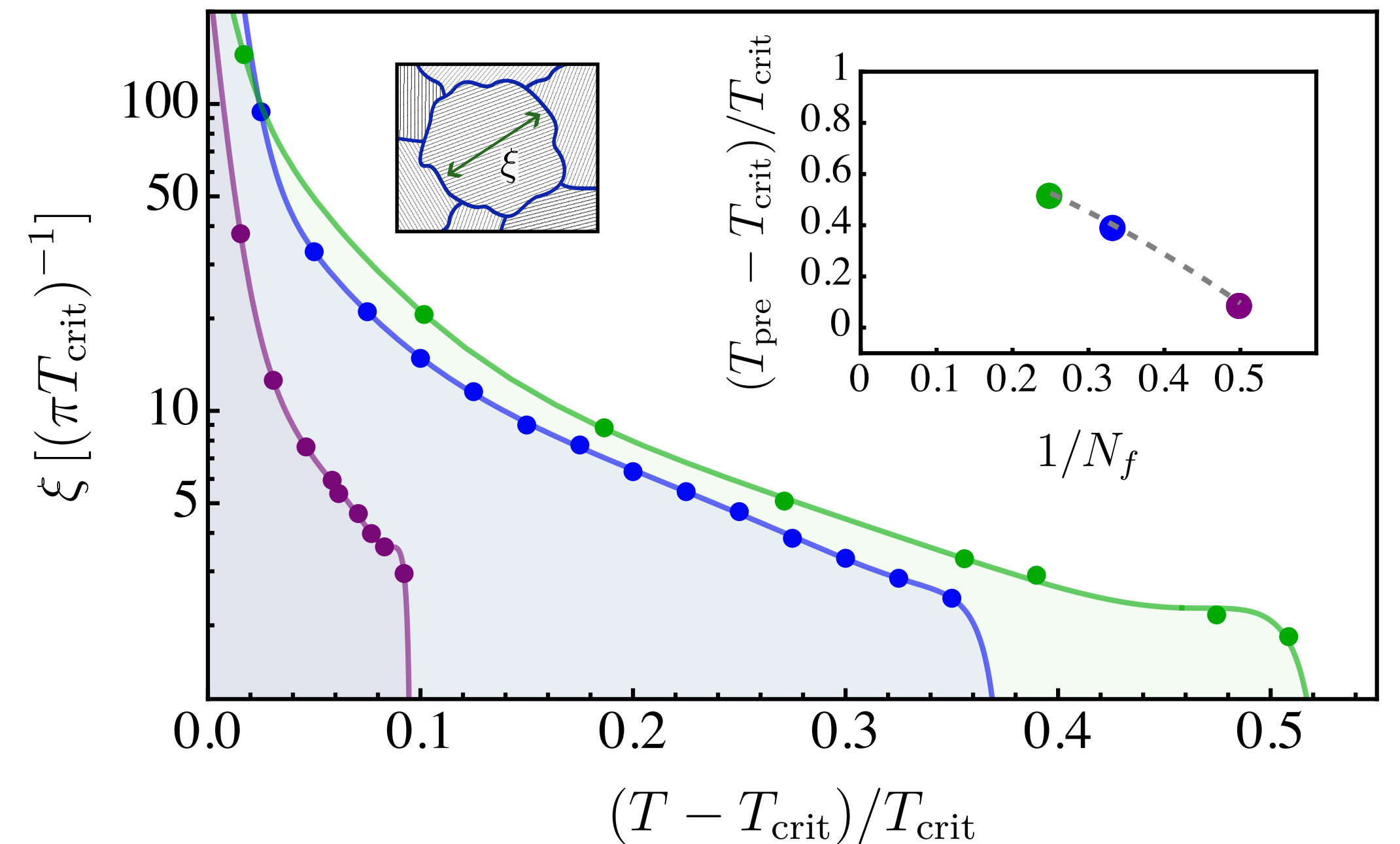


Many flavour scaling



- **Growing size** of precondensation regime in T
- **Growing** number of **Goldstones** $N_f^2 - 1$
- **Relevant role** in the **near-critical dynamics**

See my poster :)



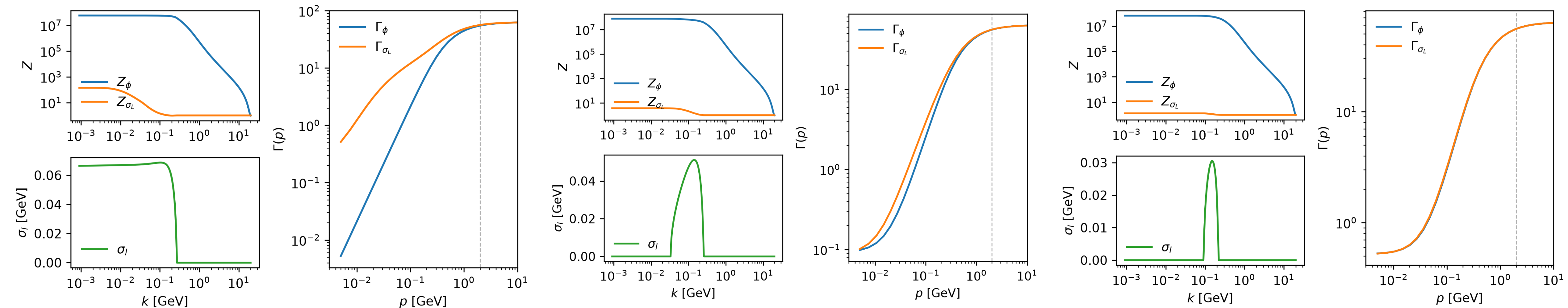
Correlators at $k \rightarrow 0$ and real-time properties

Work in progress with Jan M. Pawłowski Franz R. Sattler and Yang Yang Tang

$N_f = 3, T = 0.01 \text{ GeV}$

$N_f = 3, T = 0.115 \text{ GeV}$

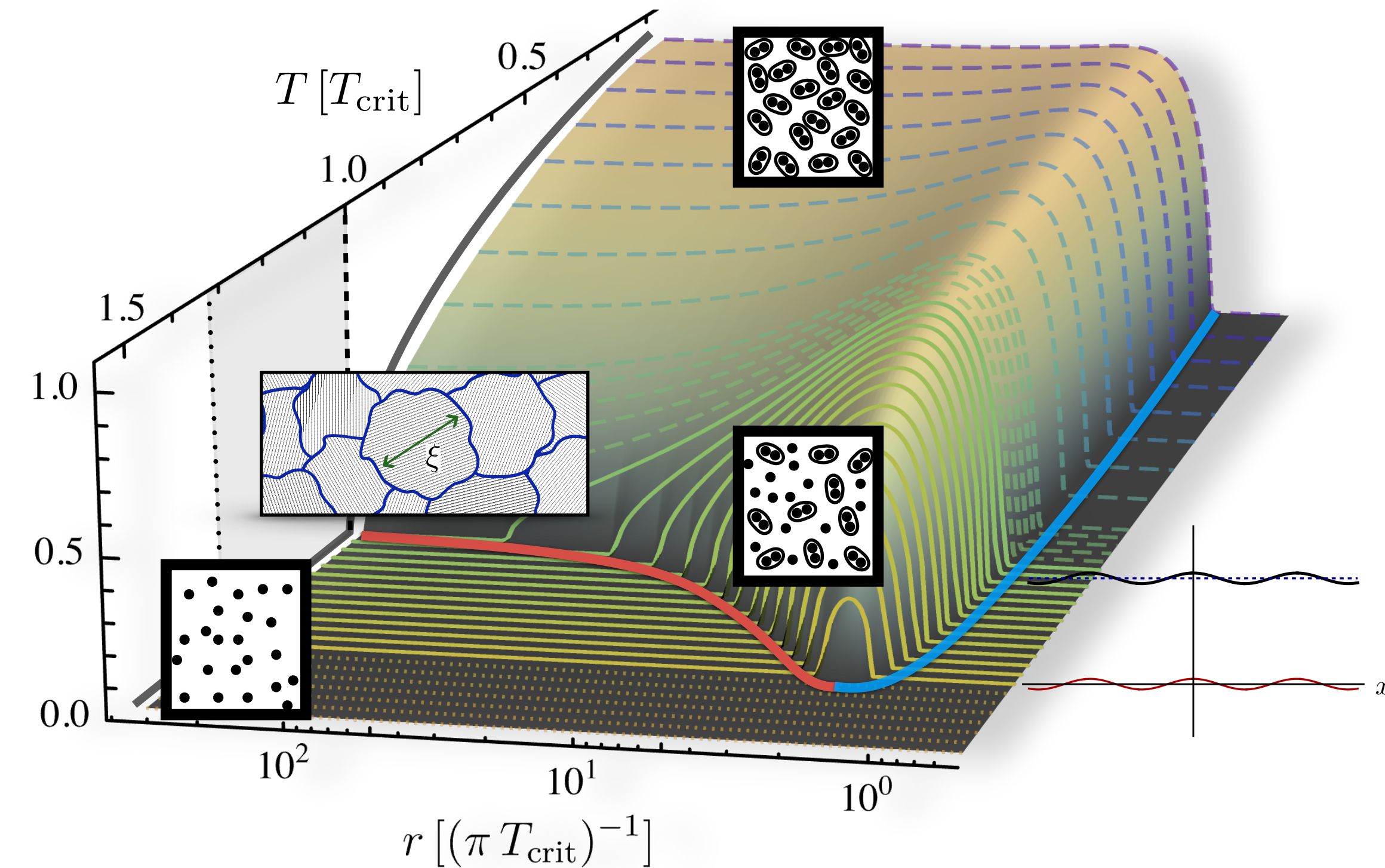
$N_f = 3, T = 0.13 \text{ GeV}$



+real time dynamics

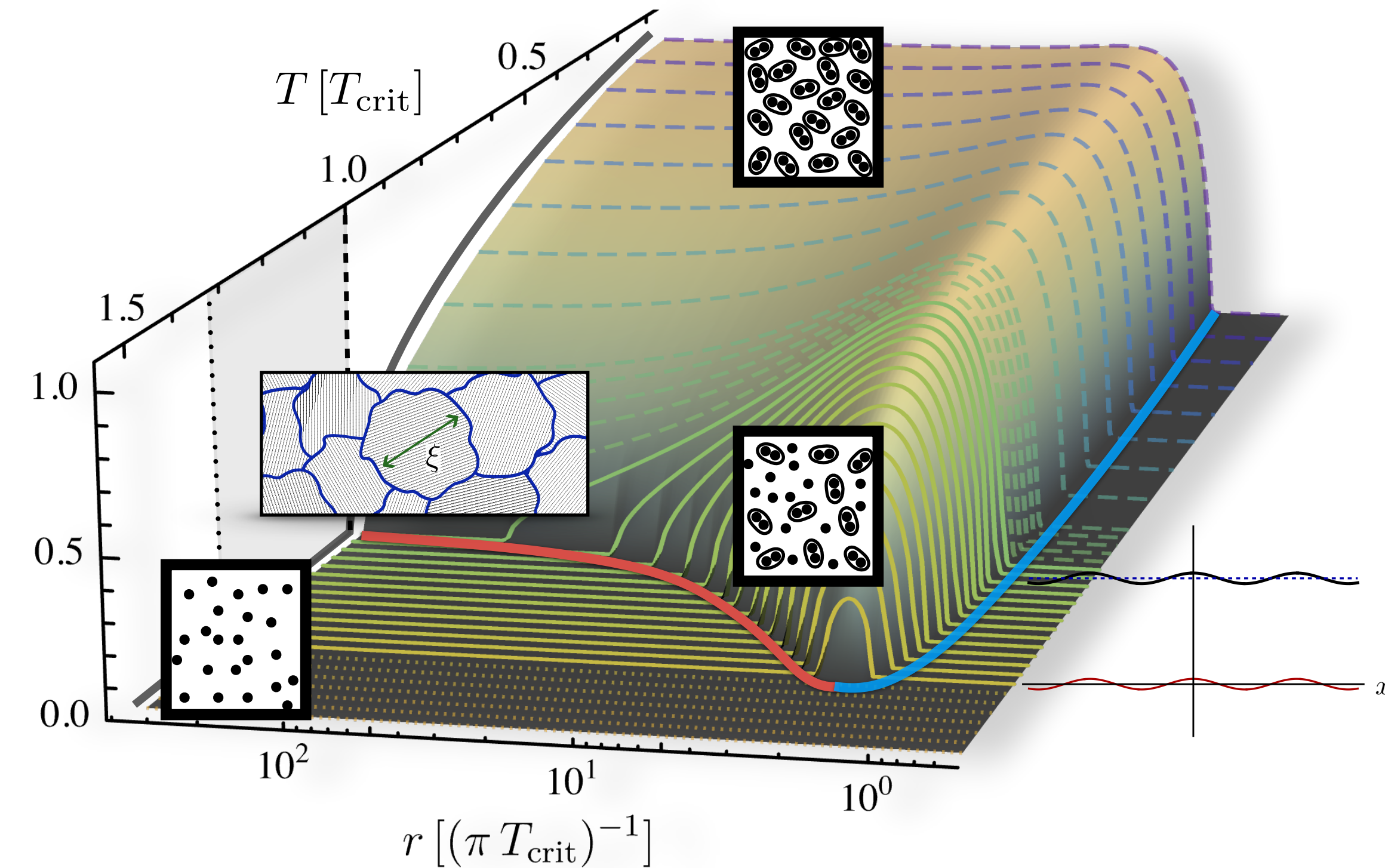
Conclusions

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 - **Domains, spatial modulations, mixed phases**
- Occurs in **multiple contexts in nature** (condensed matter, cold atoms, chiral gauge-fermion theories)
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Thank you for your attention!