Thermal precondensation in gauge-fermion theories

Álvaro Pastor Gutiérrez

KEK Theory Meeting on Particle Physics Phenomenology

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[2602.11265]

with Jan M. Pawlowski and Franz Sattler

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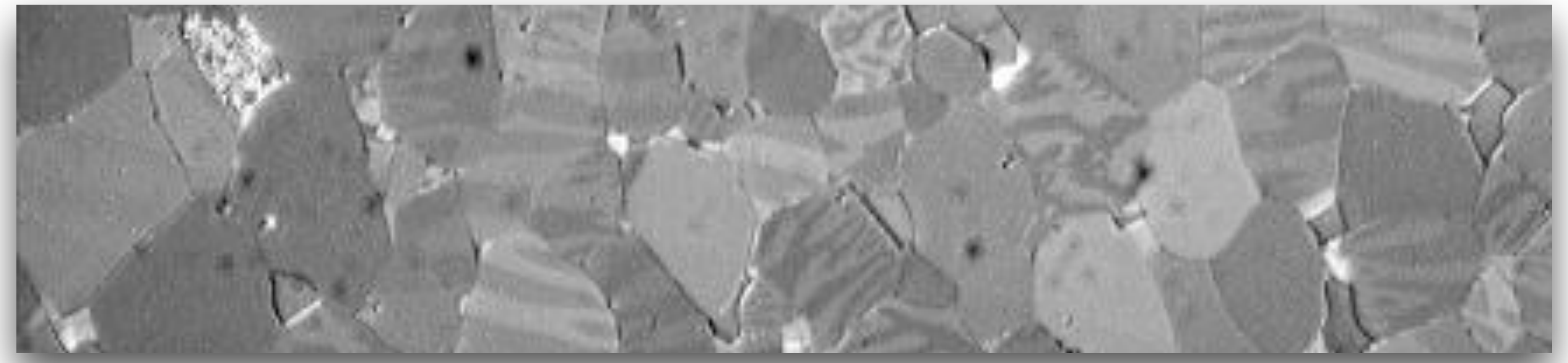
Thermal precondensation

- Occurence of a condensate **only at finite length scales**

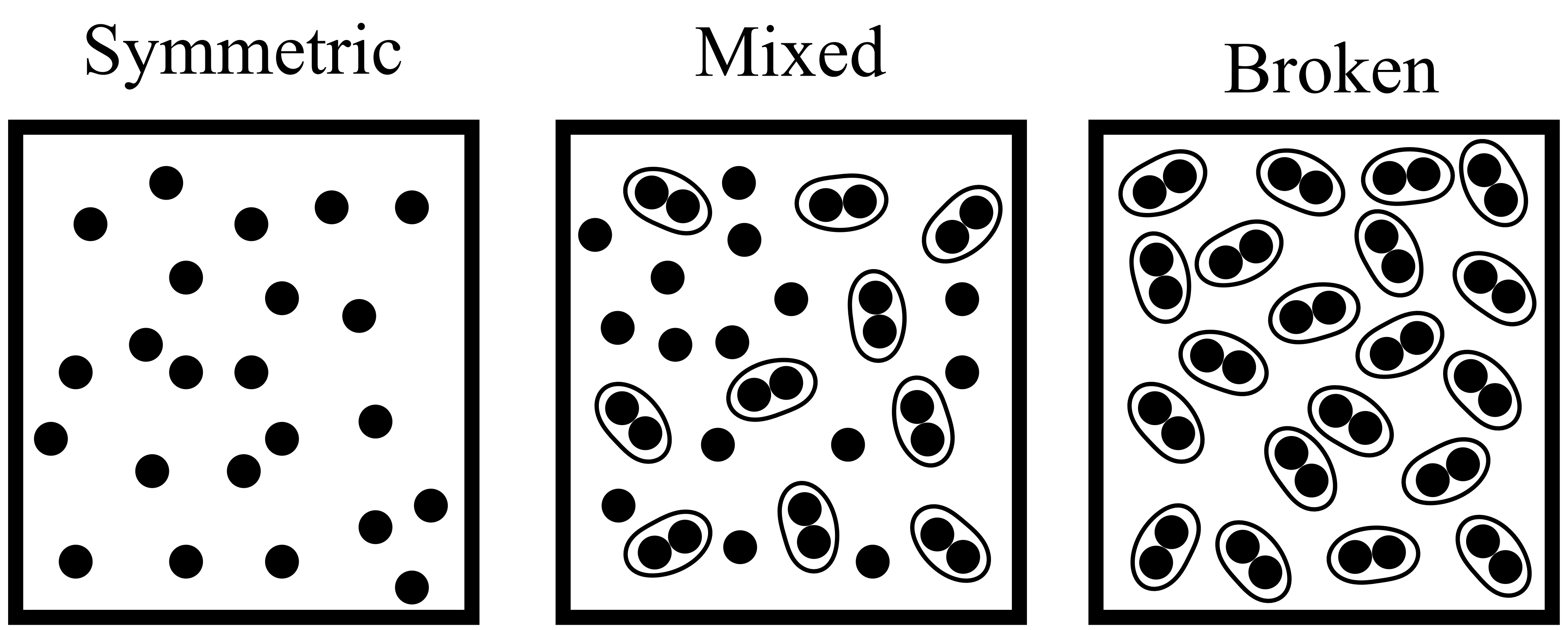
Thermal precondensation

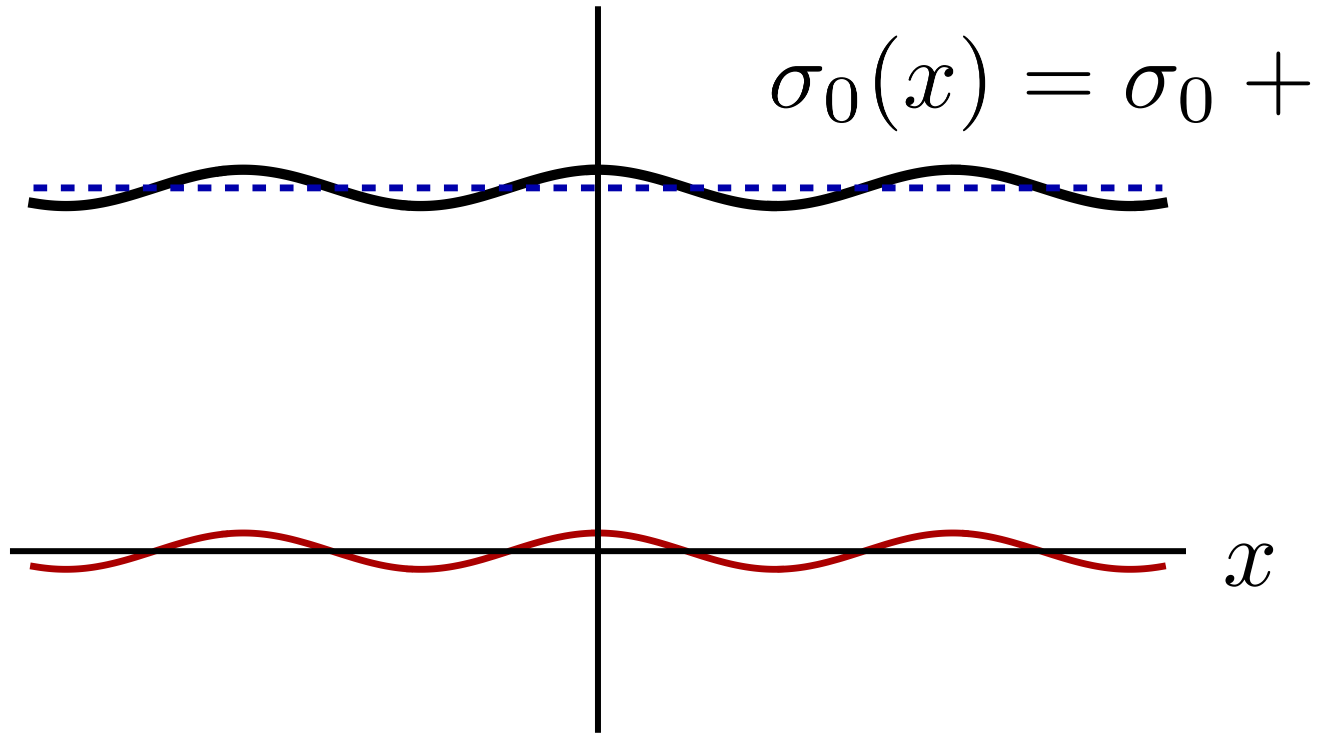
- Discussed in very different contexts
  - cold atoms: BCE-BCS crossover
    Boettcher,Pawlowski,Diehl[1204.4394]
  - condensed matter: Dirac semi-metals
    Tolosa-Simeón,Classen,Scherer [2503.04911]
  - gauge-fermion: diquark condensate in 2-colour QCD
    Khan,Pawlowski,Rennecke,Scherer [1512.03673]

- Features:
  - **domain formation** in equilibrium
  - **pseudo-gapped** or **mixed phases**
  - **inhomogoneities** and **spatial modulations**



Weiss domains [Wikipedia]

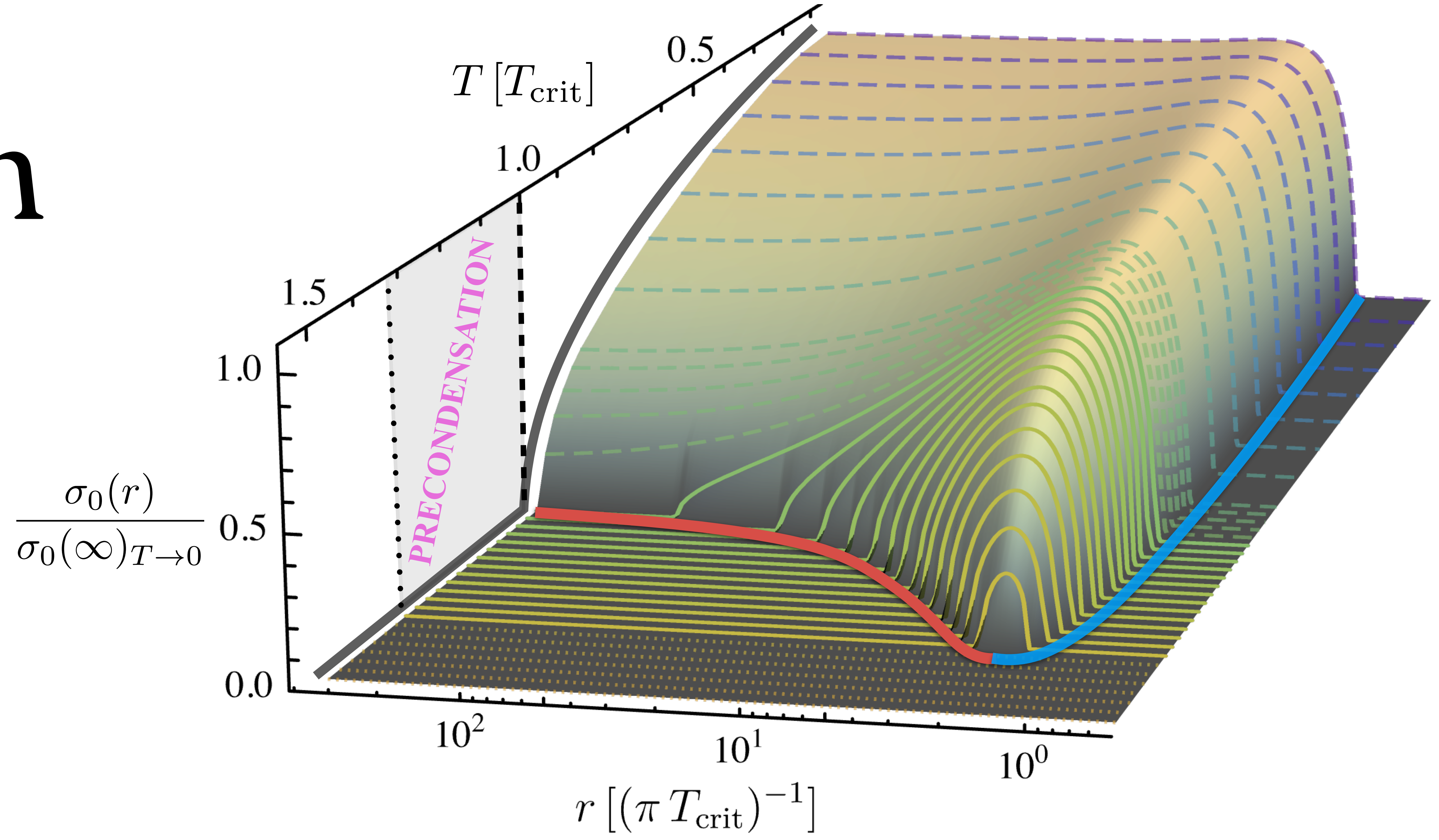




Hallmarks of precondensation

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

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



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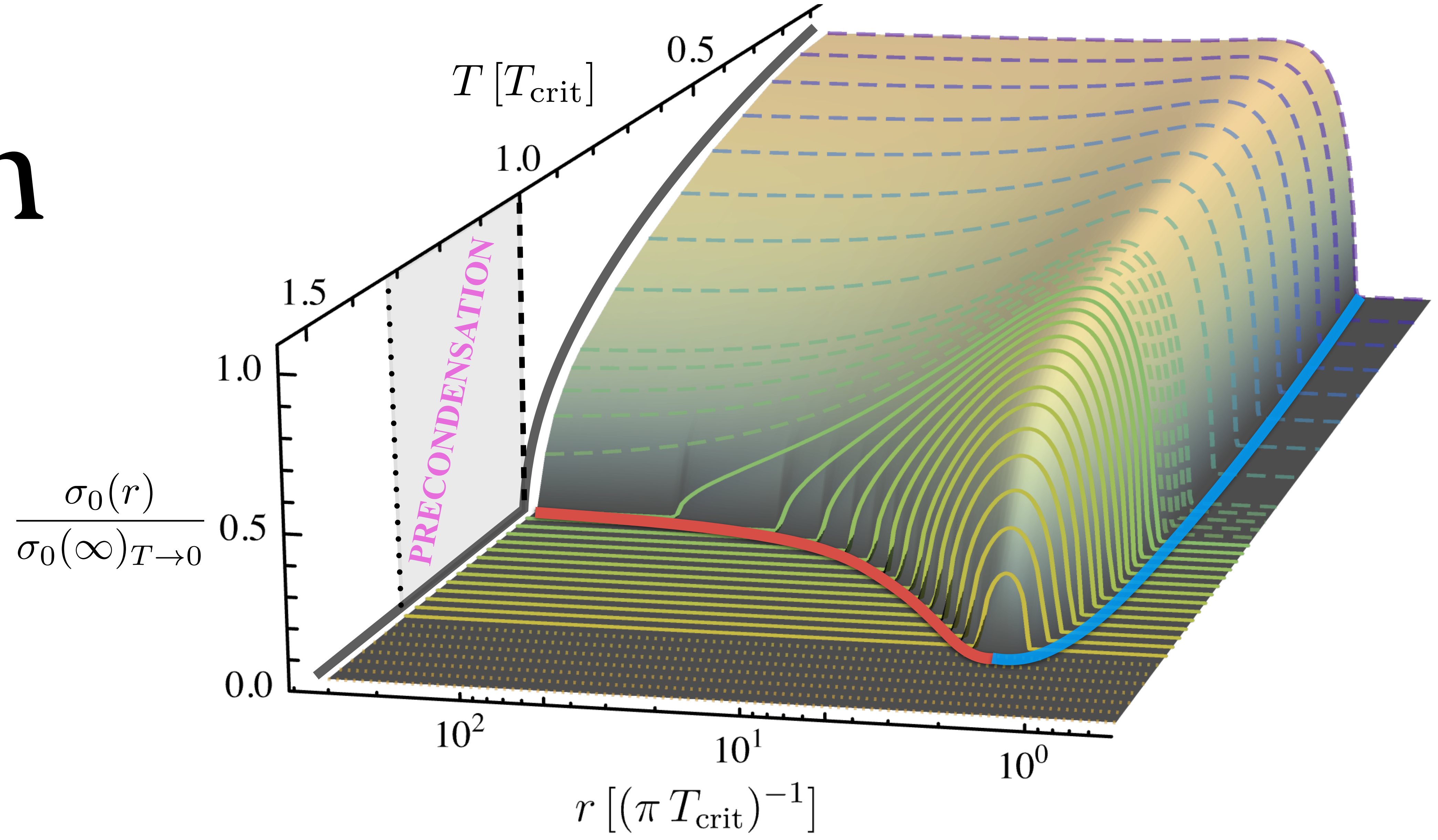

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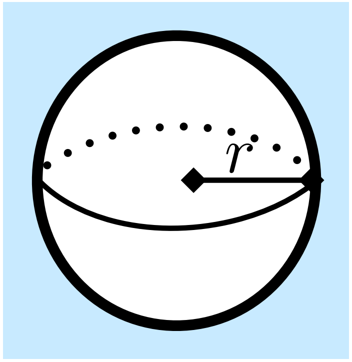

$$\sigma_0^2(\boldsymbol{x}; r) = \frac{1}{\mathcal{V}_r} \int d^3y\, \langle \hat{\sigma}(x)\, \hat{\sigma}(y) \rangle\, \theta\left(r^2 - (\boldsymbol{x} - \boldsymbol{y})^2\right)$$

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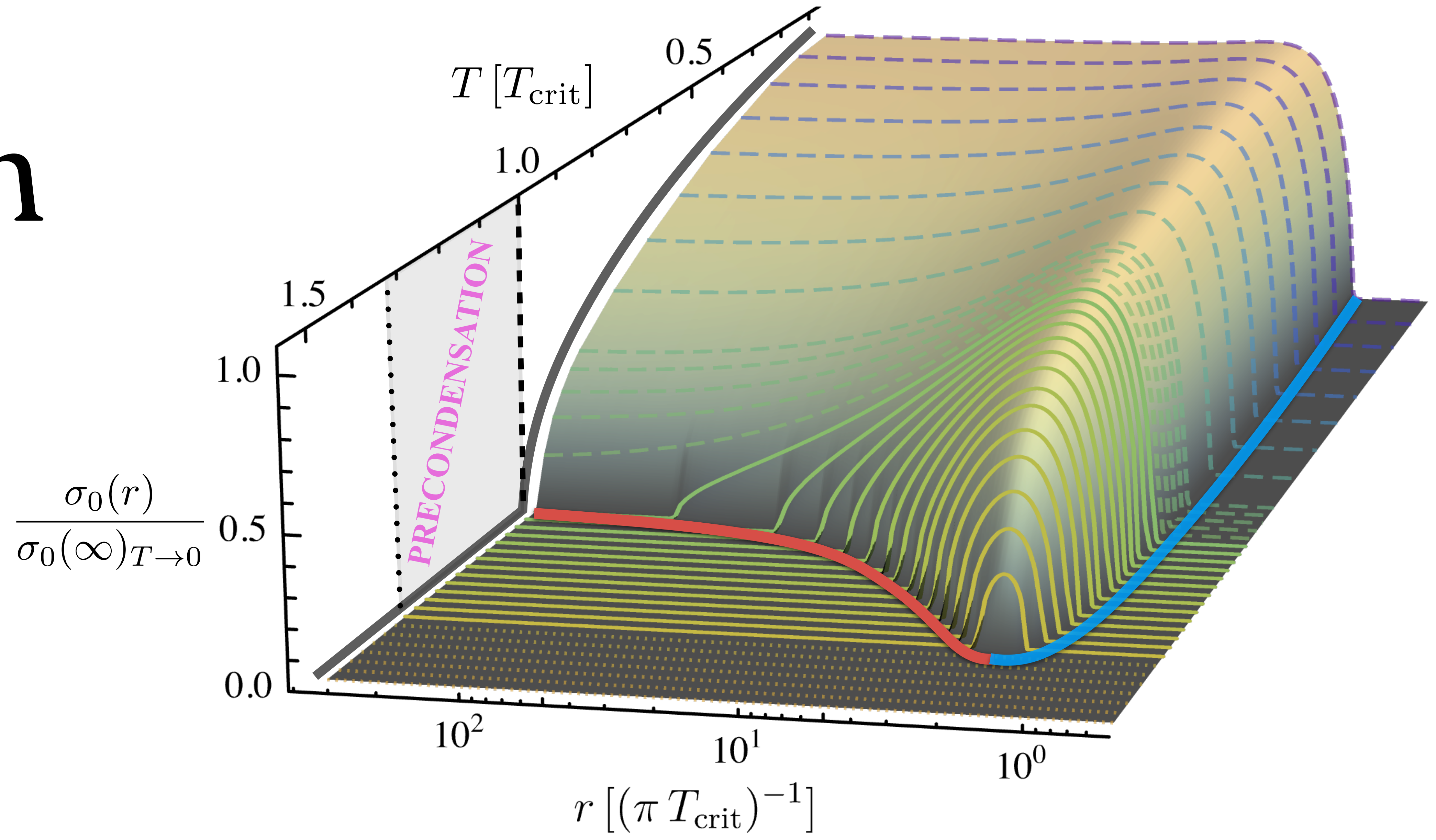

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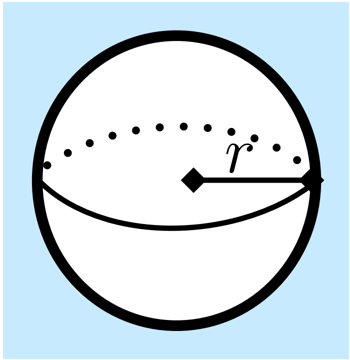

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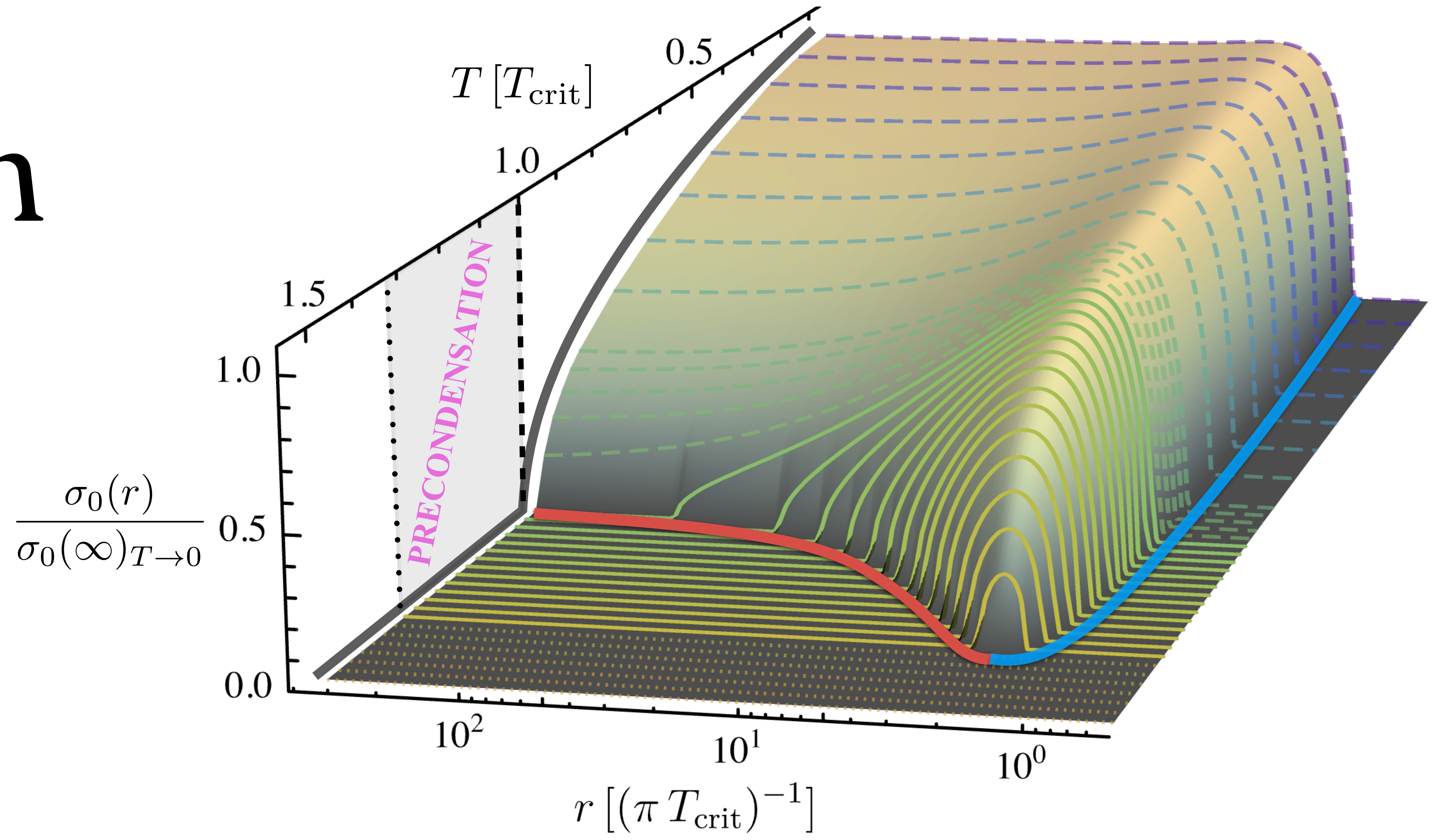

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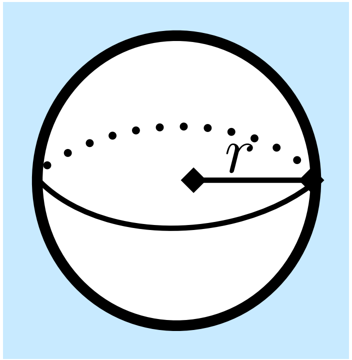

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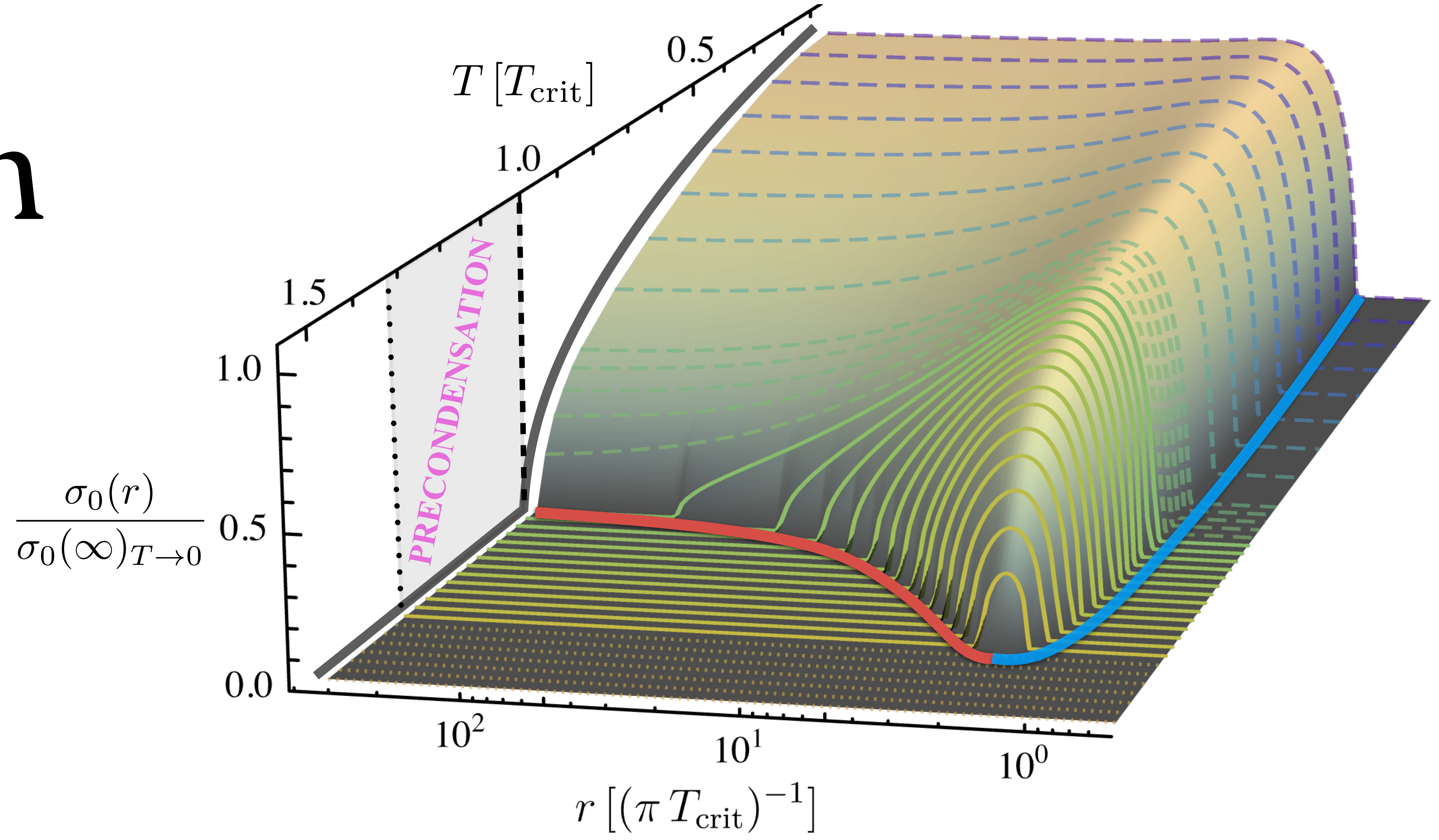

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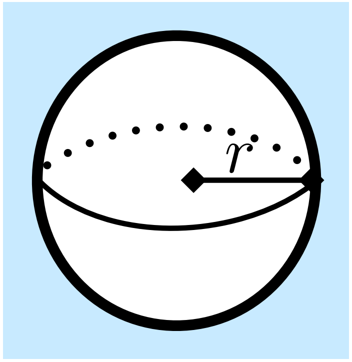

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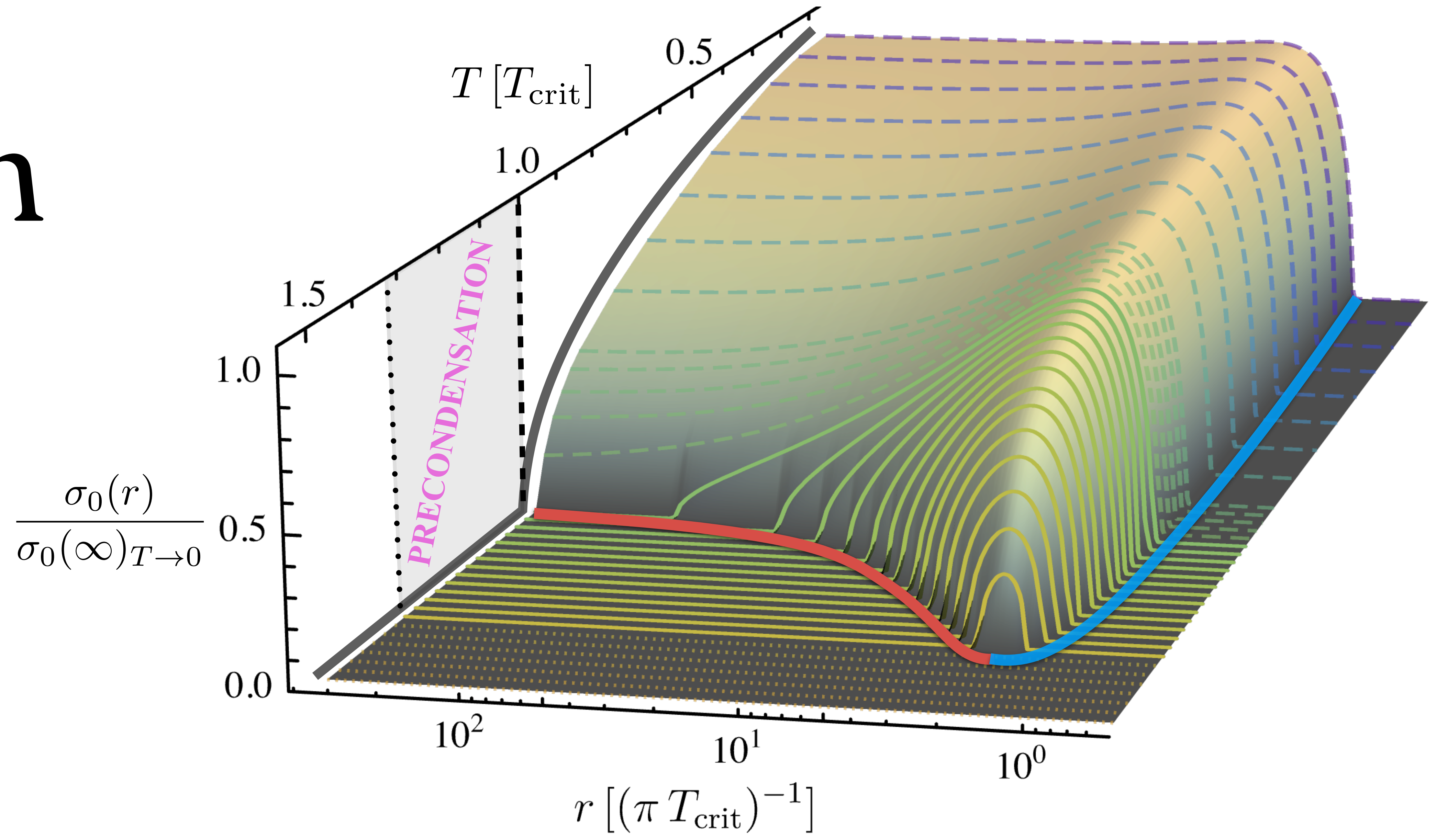

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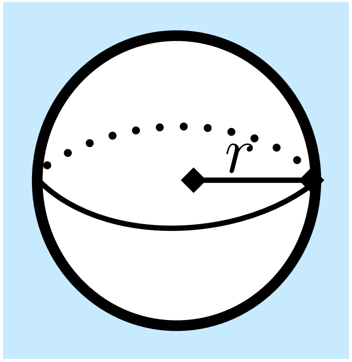

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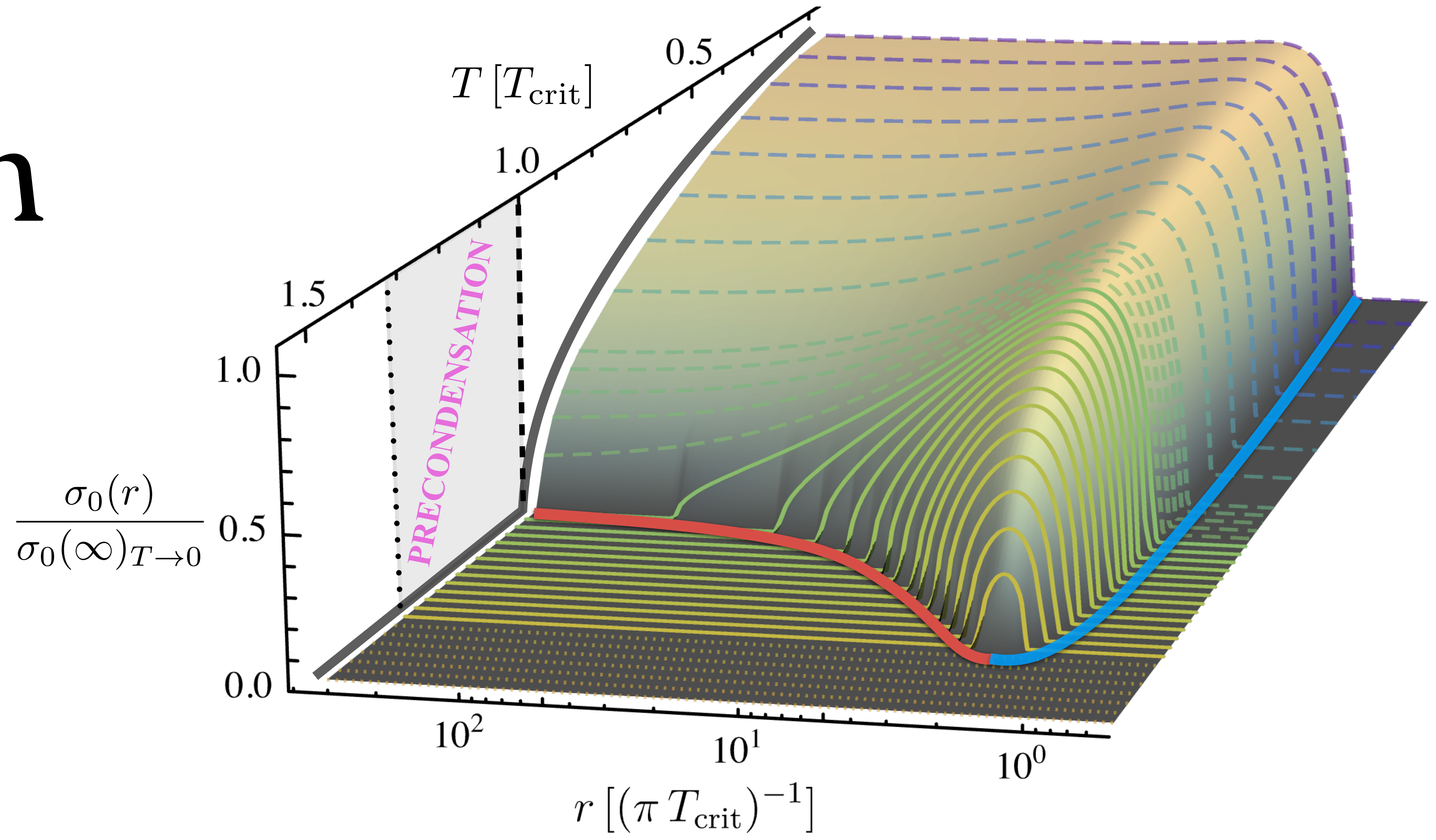

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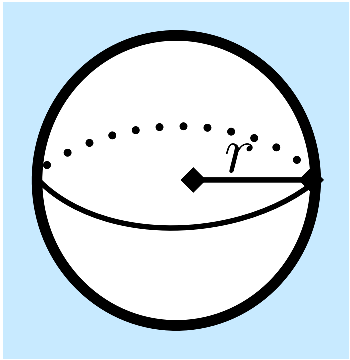

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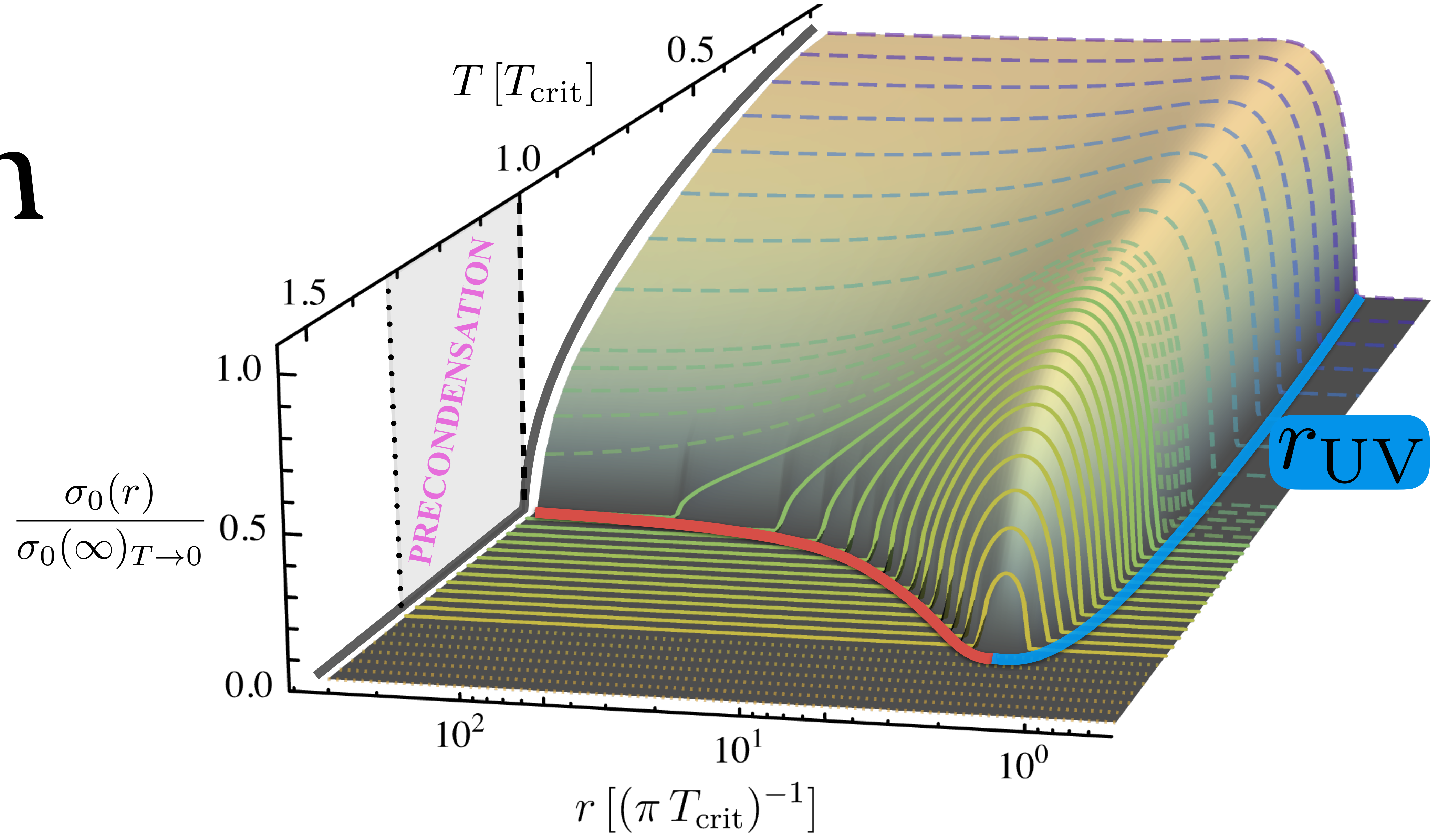

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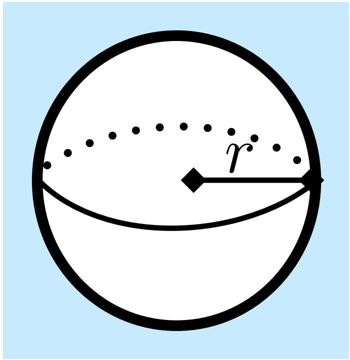

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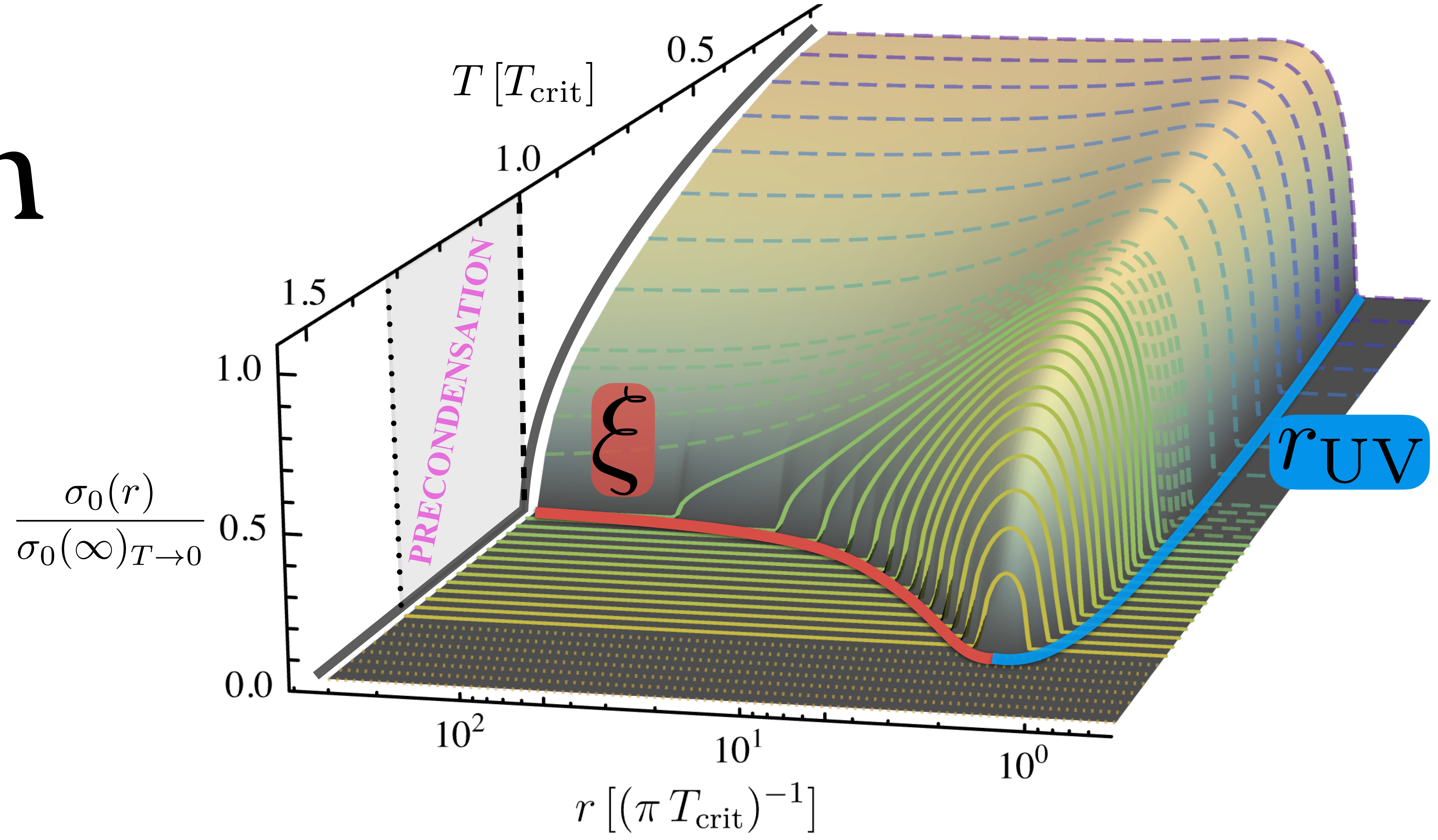

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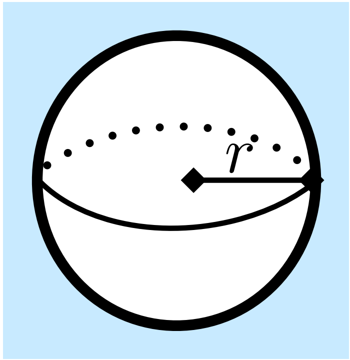

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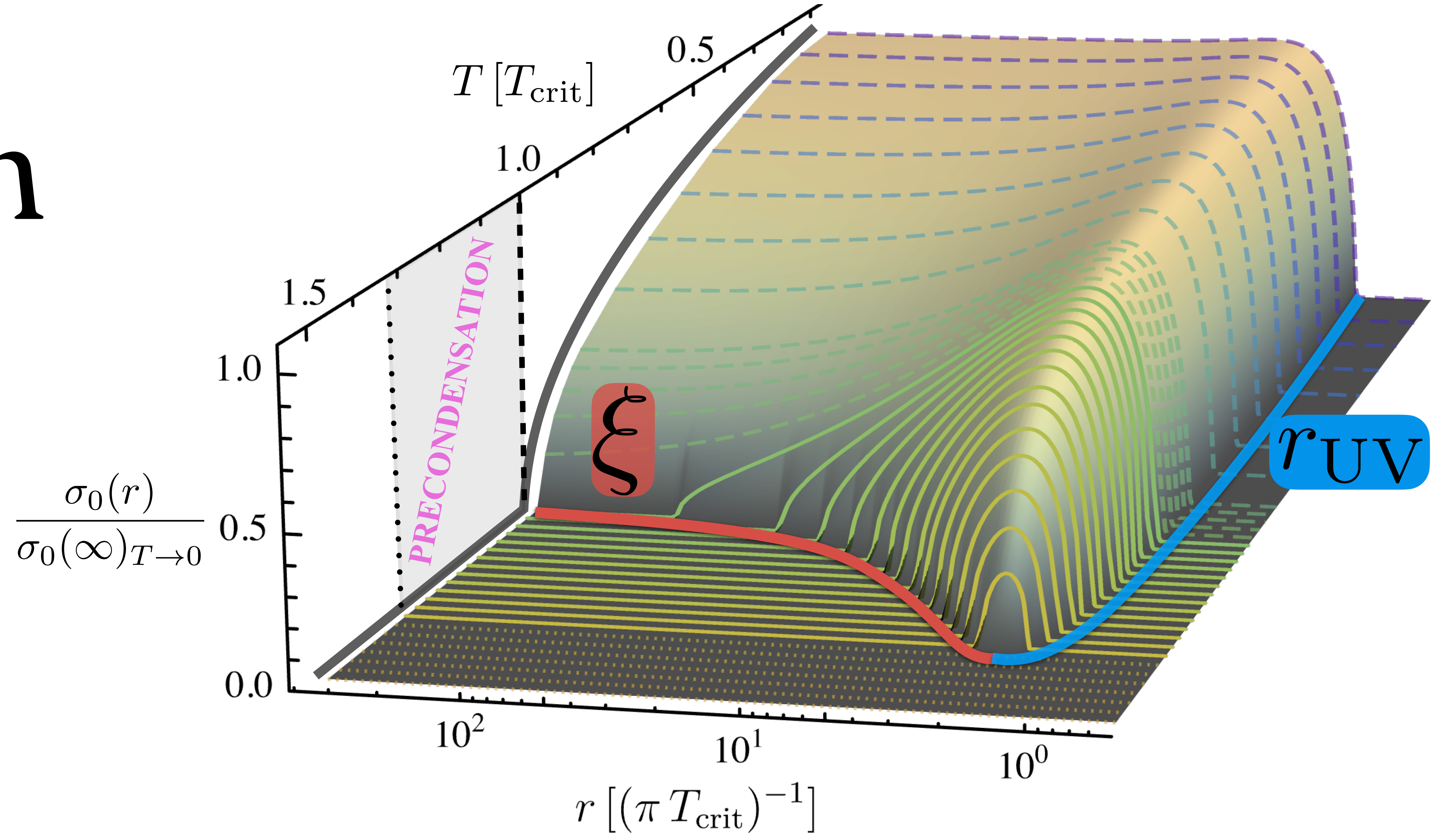

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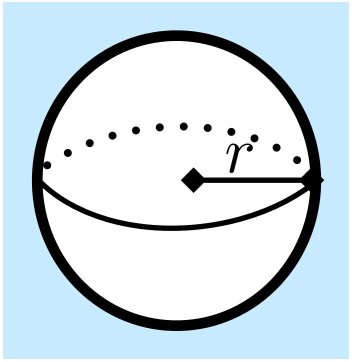

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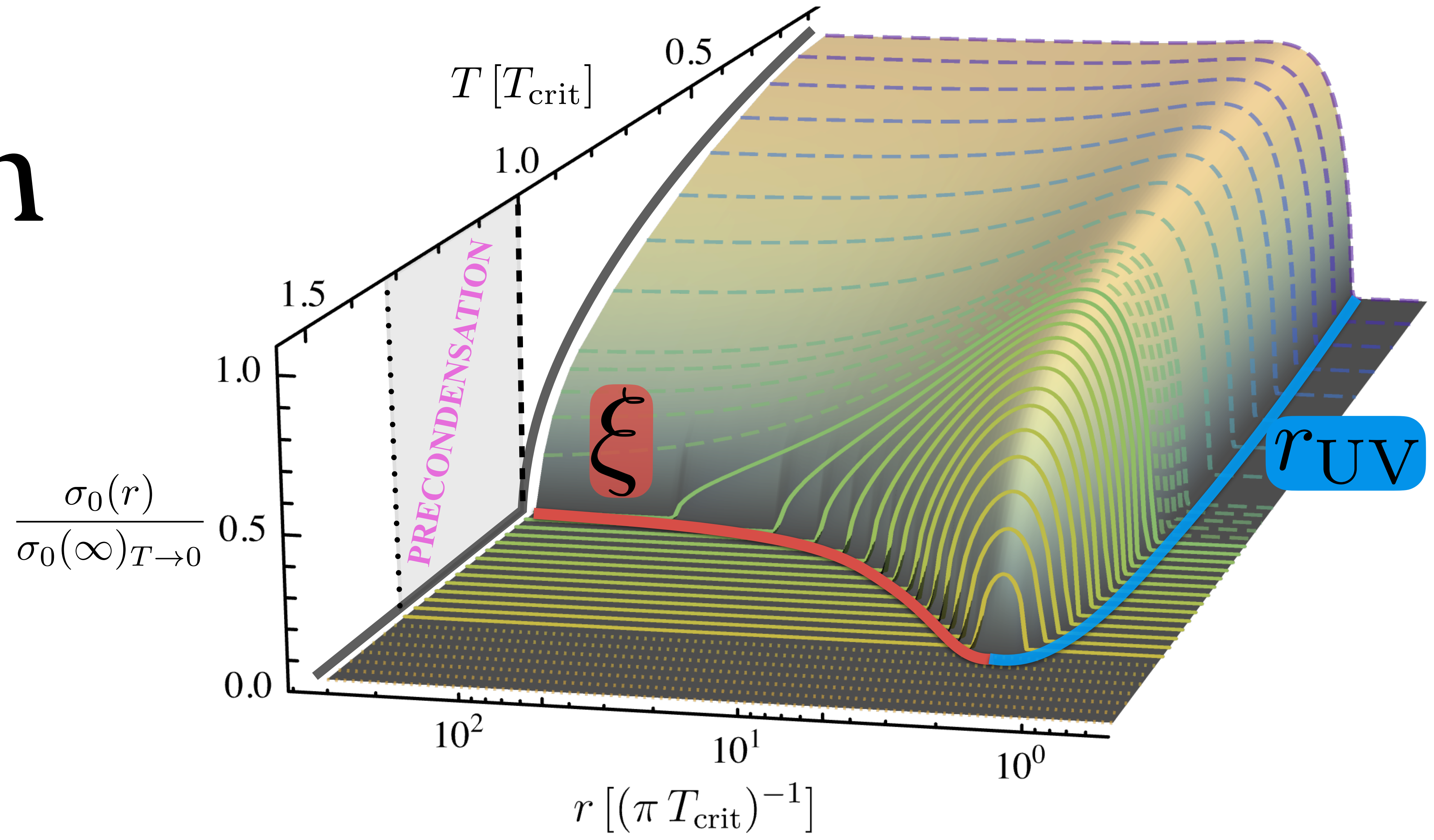

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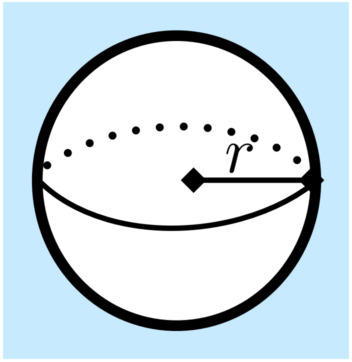

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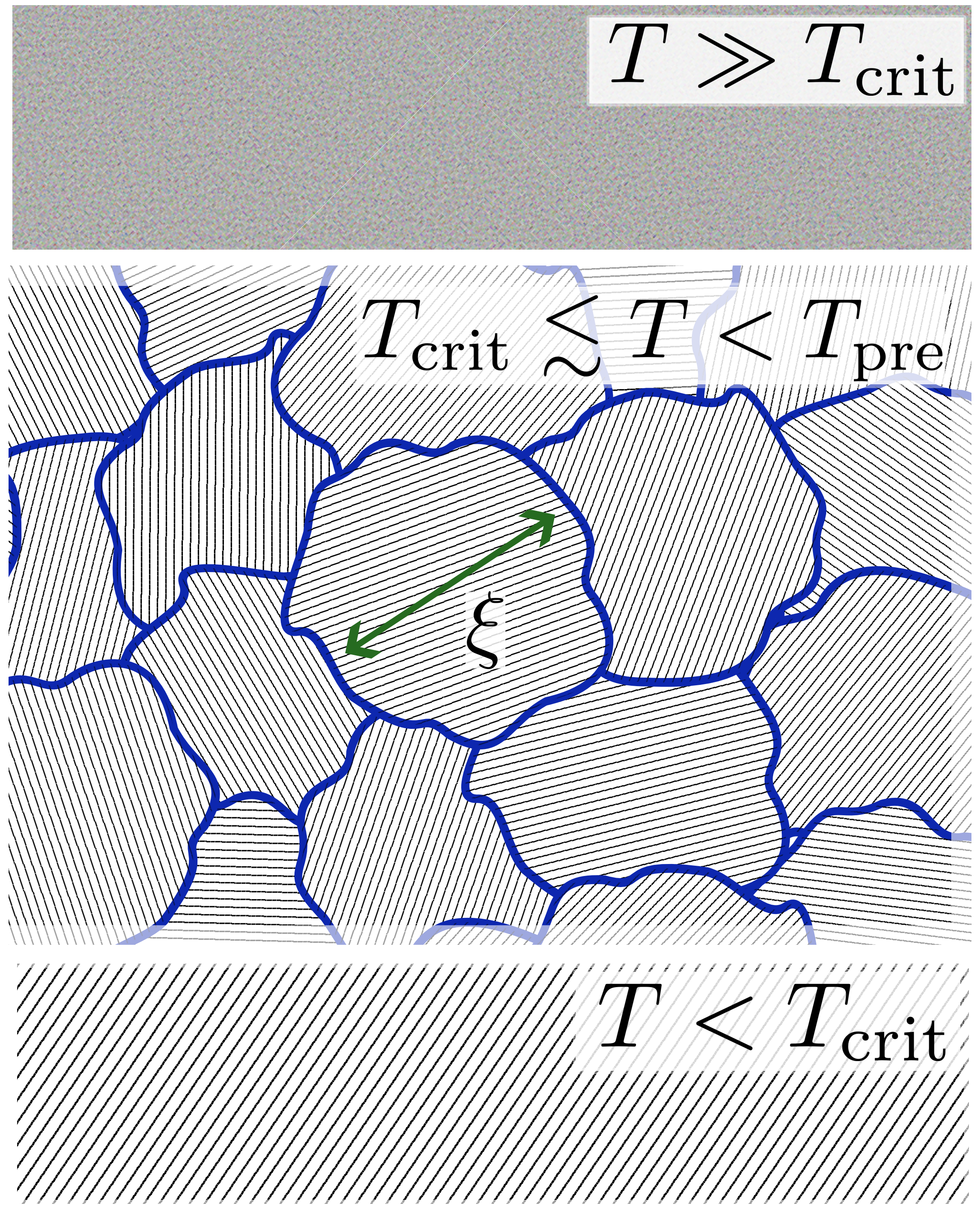

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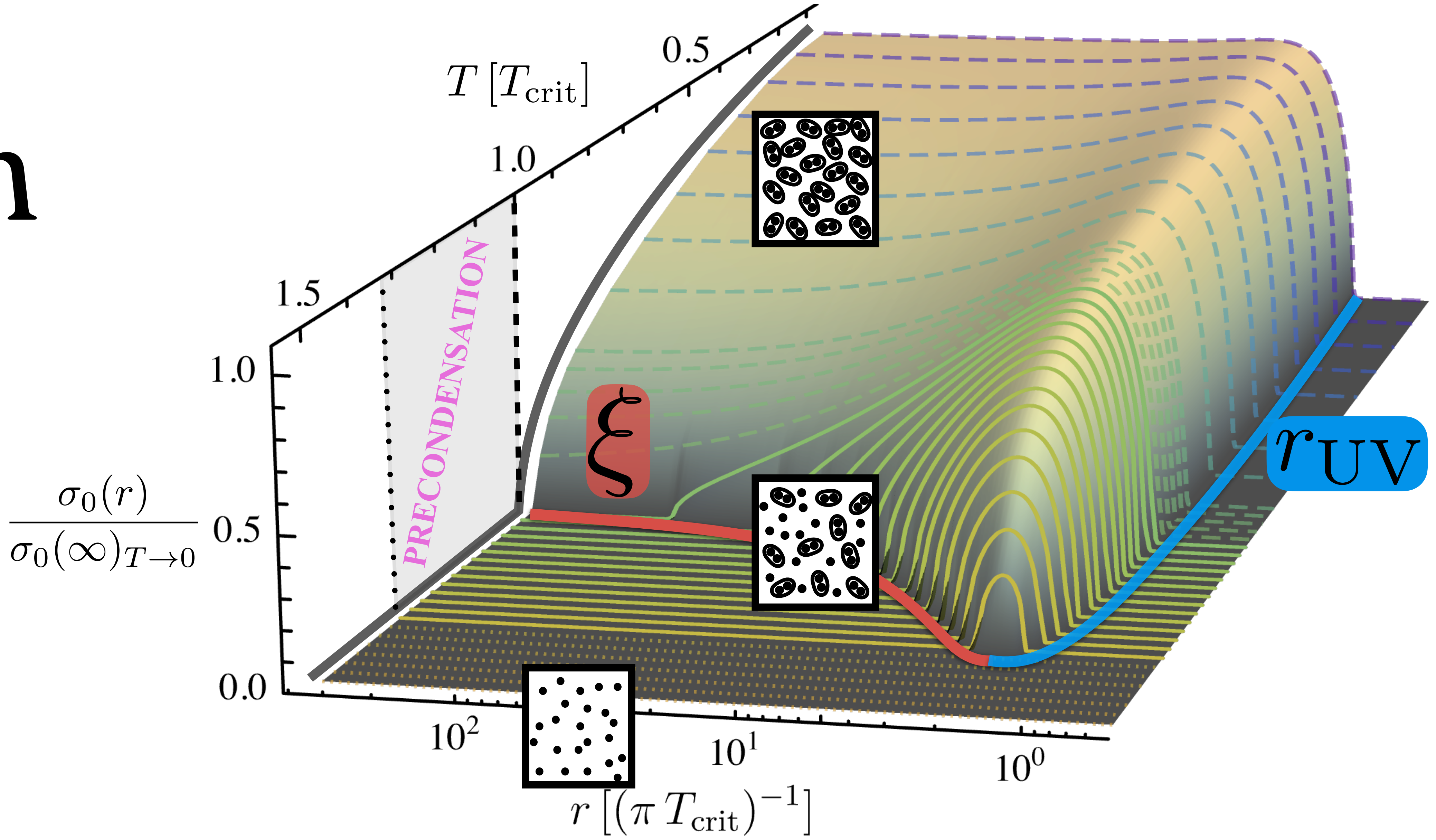

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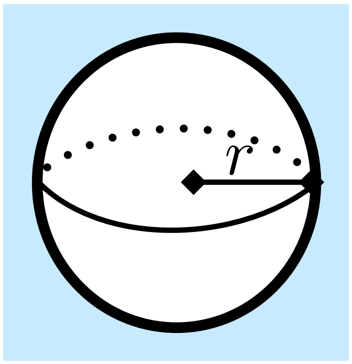

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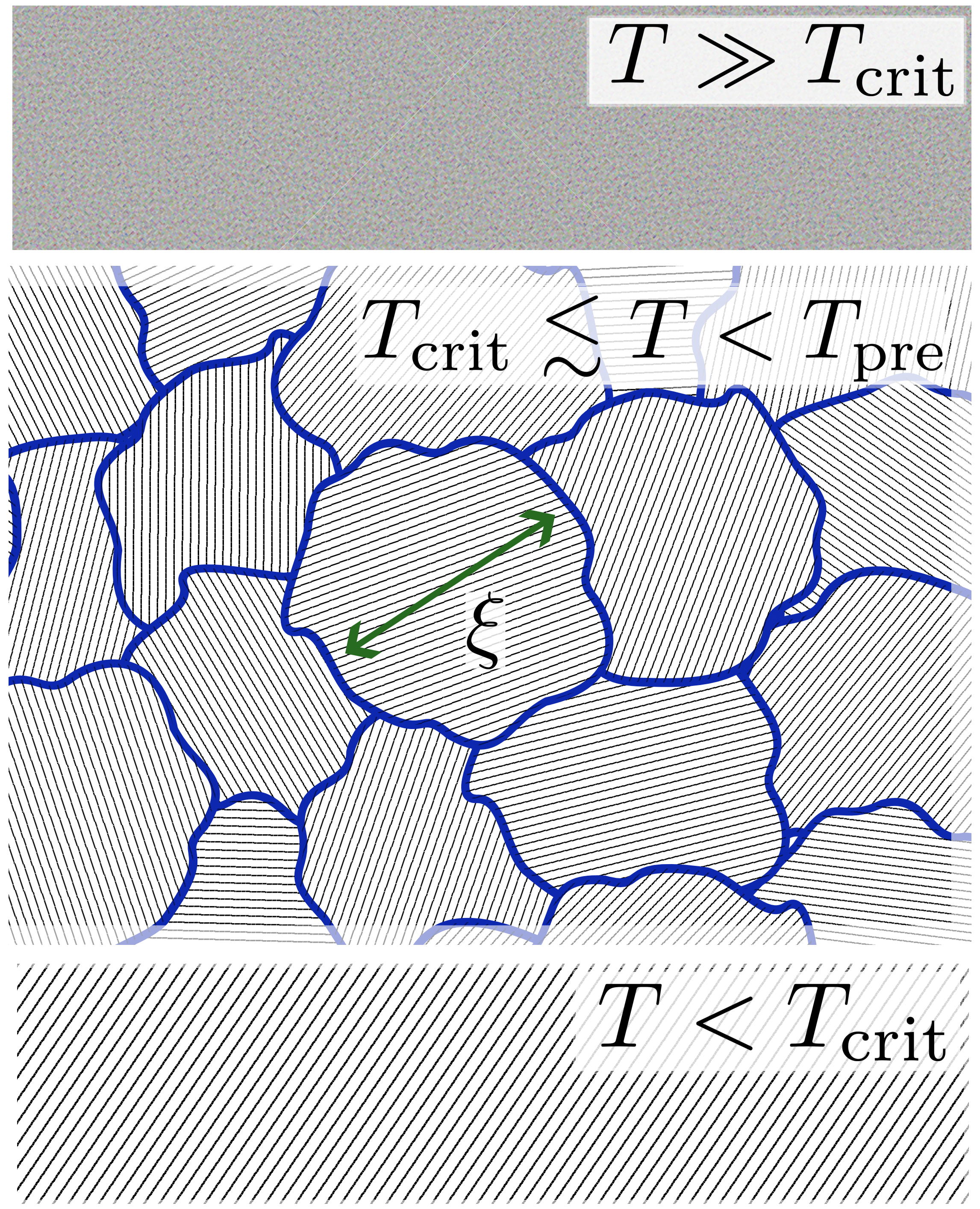


Functional Renormalisation Group

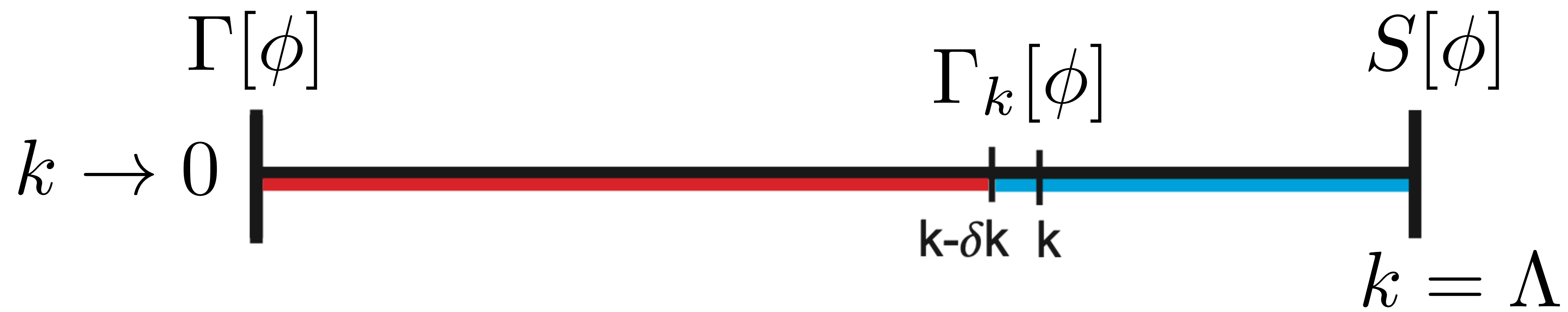
- **Scale-dependent effective action**: $\Gamma_k[\phi] \qquad k \sim 1/r$

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

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

Wetterich '89

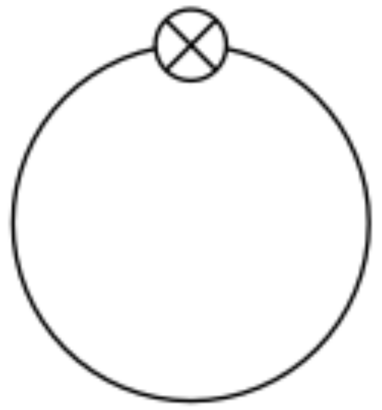
- Average action of fields over a k^{-d} space-time volume
- Kadanoff's block-spinning idea in the continuum limit



IR cutoff scale: $k \sim T \sim \langle p \rangle$

Flow equation:

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



$\partial_t \equiv k\,\partial_k$

Wetterich '93

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

…

➡ Pedagogical introduction to fRG: Gies [0611146] ➡ Review: Dupuis,et.al [2006.04853]

Gauge-fermion theories

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

- Gauge-fermion theories in the chiral limit
  - 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
  - … ?

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

Gauge-fermion theories

$$S = \int_x \frac{1}{4} F^a_{\mu\nu} F^a_{\mu\nu} + \mathcal{L}_{\rm gf} + \mathcal{L}_{\rm gh} + \bar{\psi} \not{D} \psi$$

- Gauge-fermion theories in the chiral limit
  - 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

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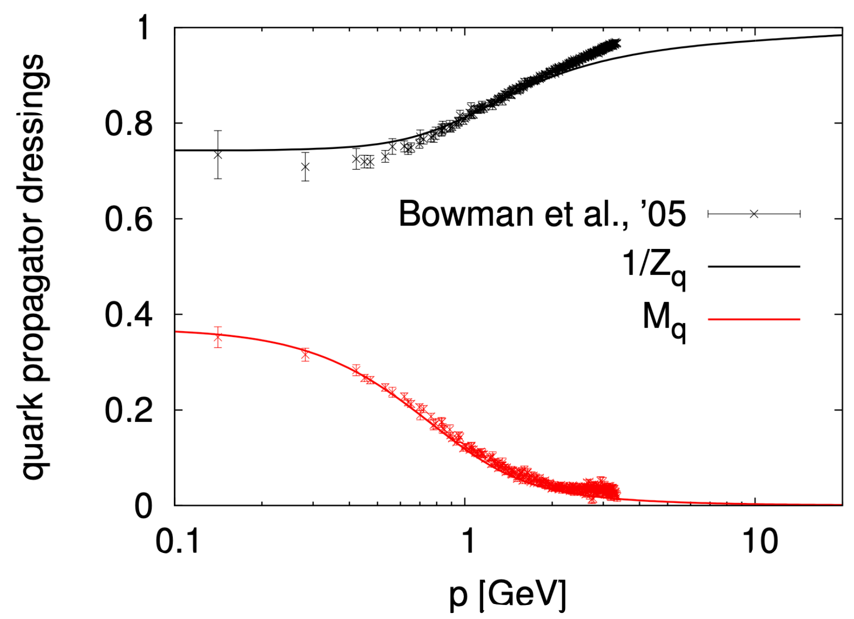
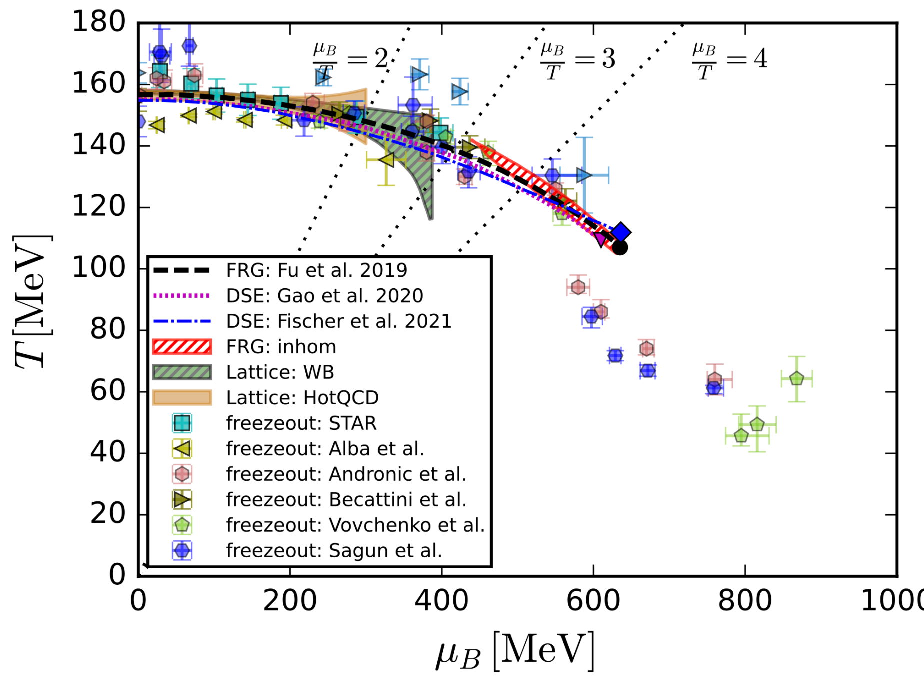
fRG approach to QCD

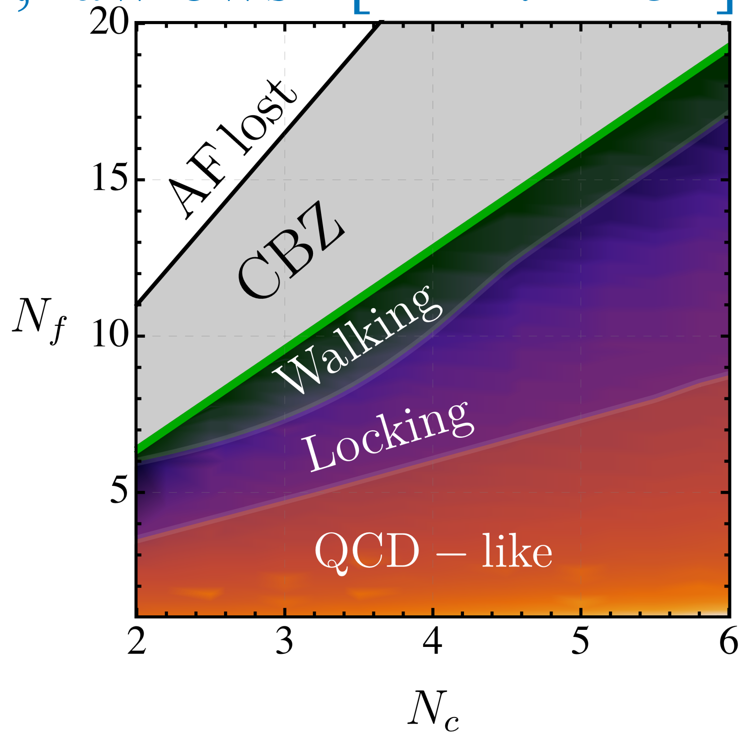
Mitter,Pawlowski, Strodthoff[1411.7978]



fQCD collaboration



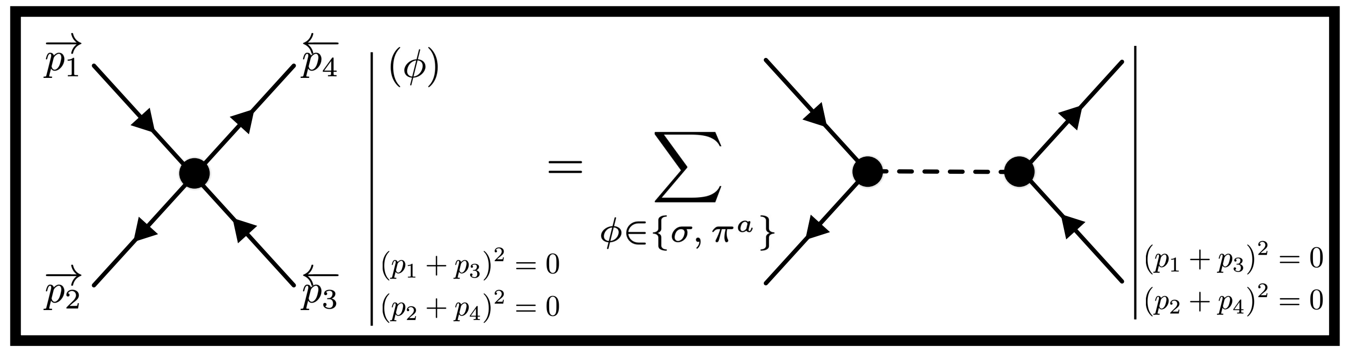
Goertz, APG,Pawlowski[2412.12254]



- dχSB encoded in higher dimensional fermionic operators

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

- Exact field transformation along the RG flow

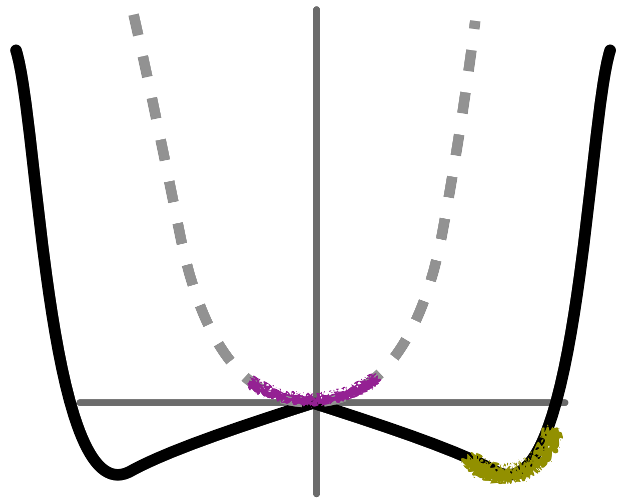


Stratonovich'57 Hubbard'59

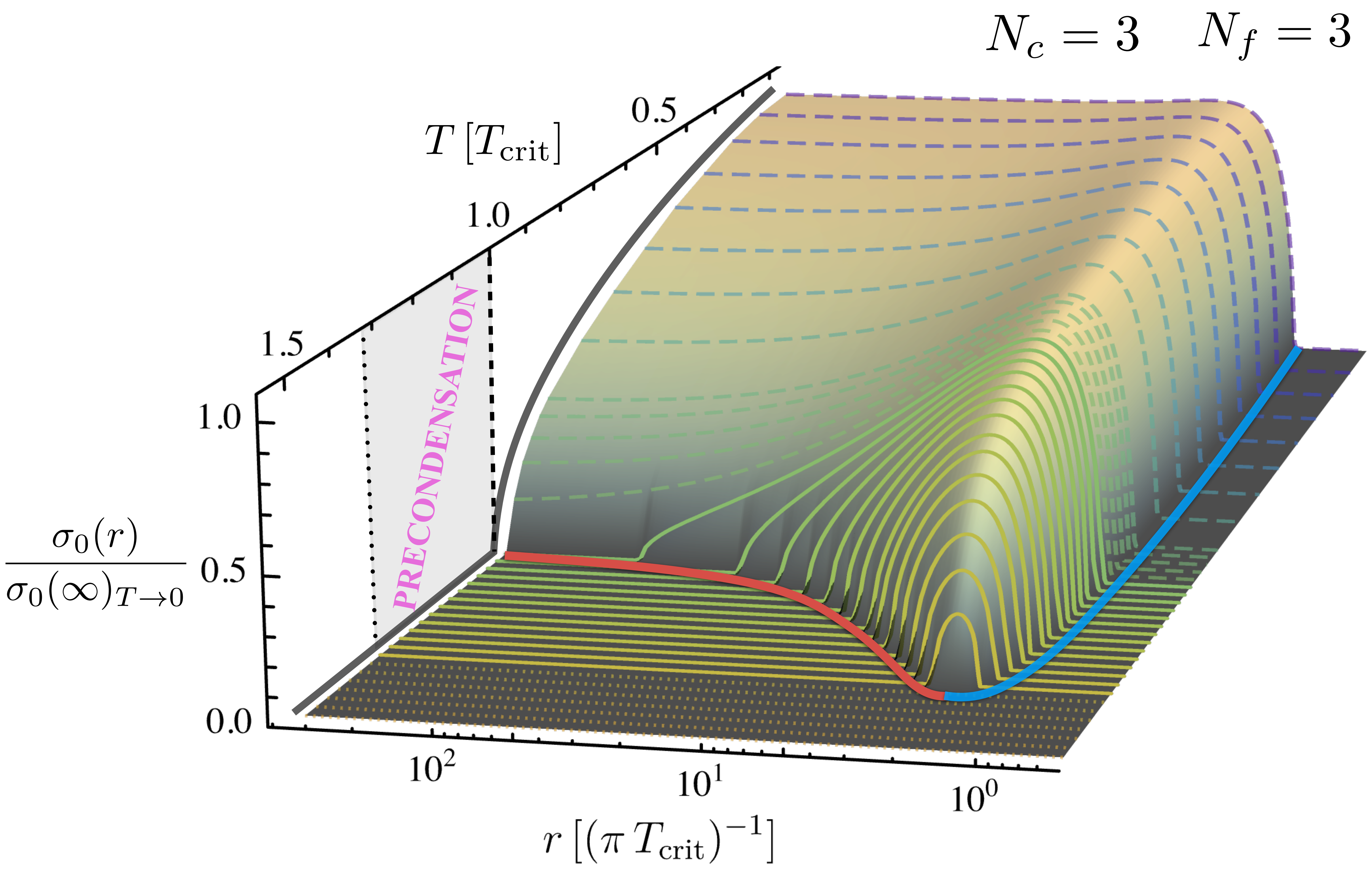
$$\Gamma_k[\Phi] \supset \int_x \bar{h}\, \bar{\psi} \left(T^0_f \sigma + \mathrm{i}\gamma_5 T^a_f \pi^a\right) \psi + Z_\phi \left(\partial_\mu \phi\right)^2 + V(\phi^2) + \ldots$$

Microscopic origin

Flow of the effective chiral potential:



$\propto m_\sigma^2$



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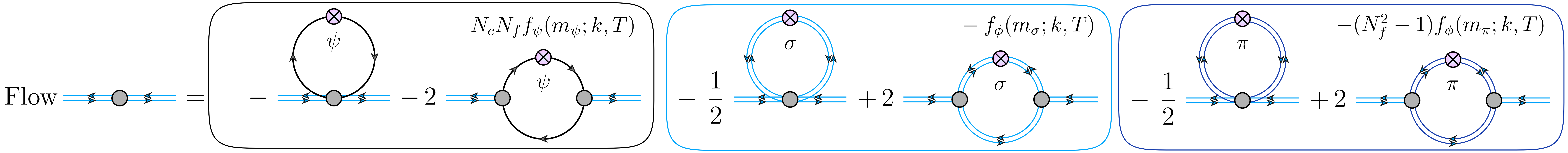

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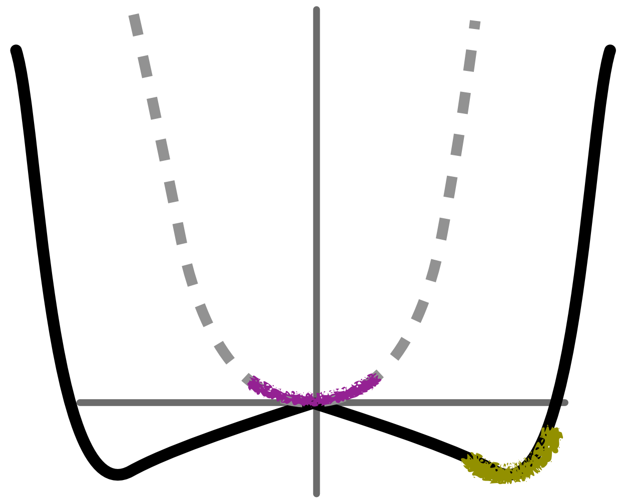

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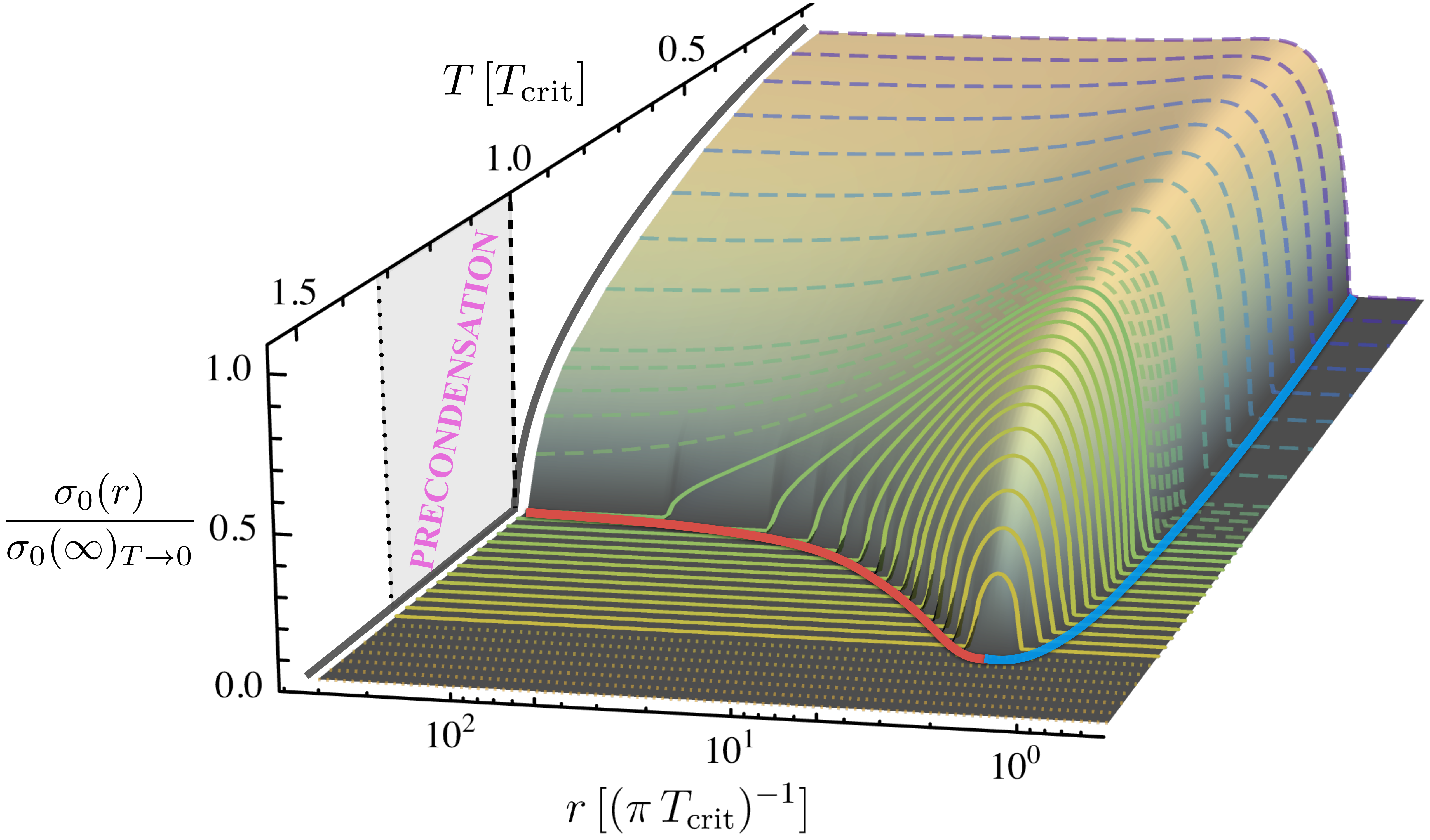
$N_c = 3 \quad N_f = 3$



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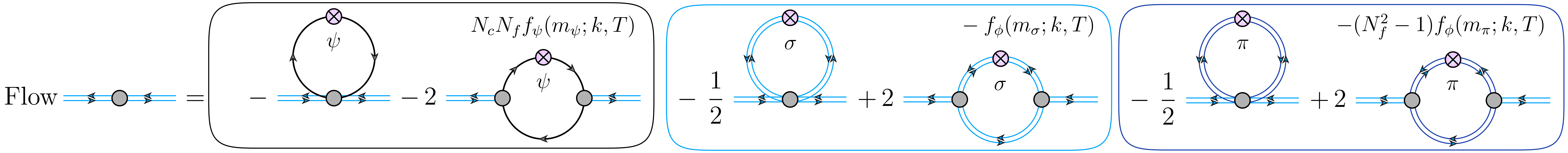

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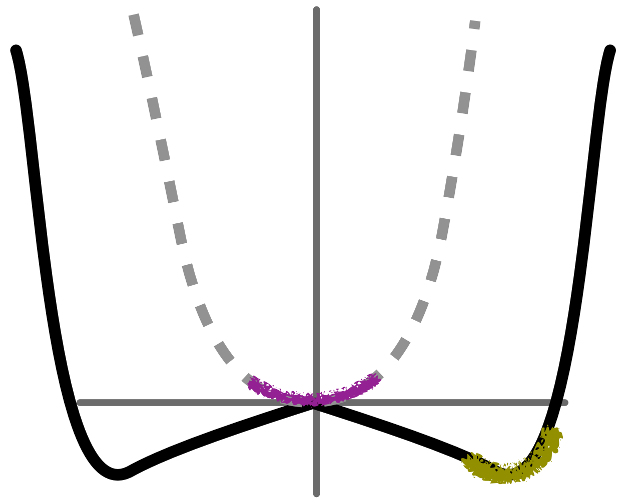

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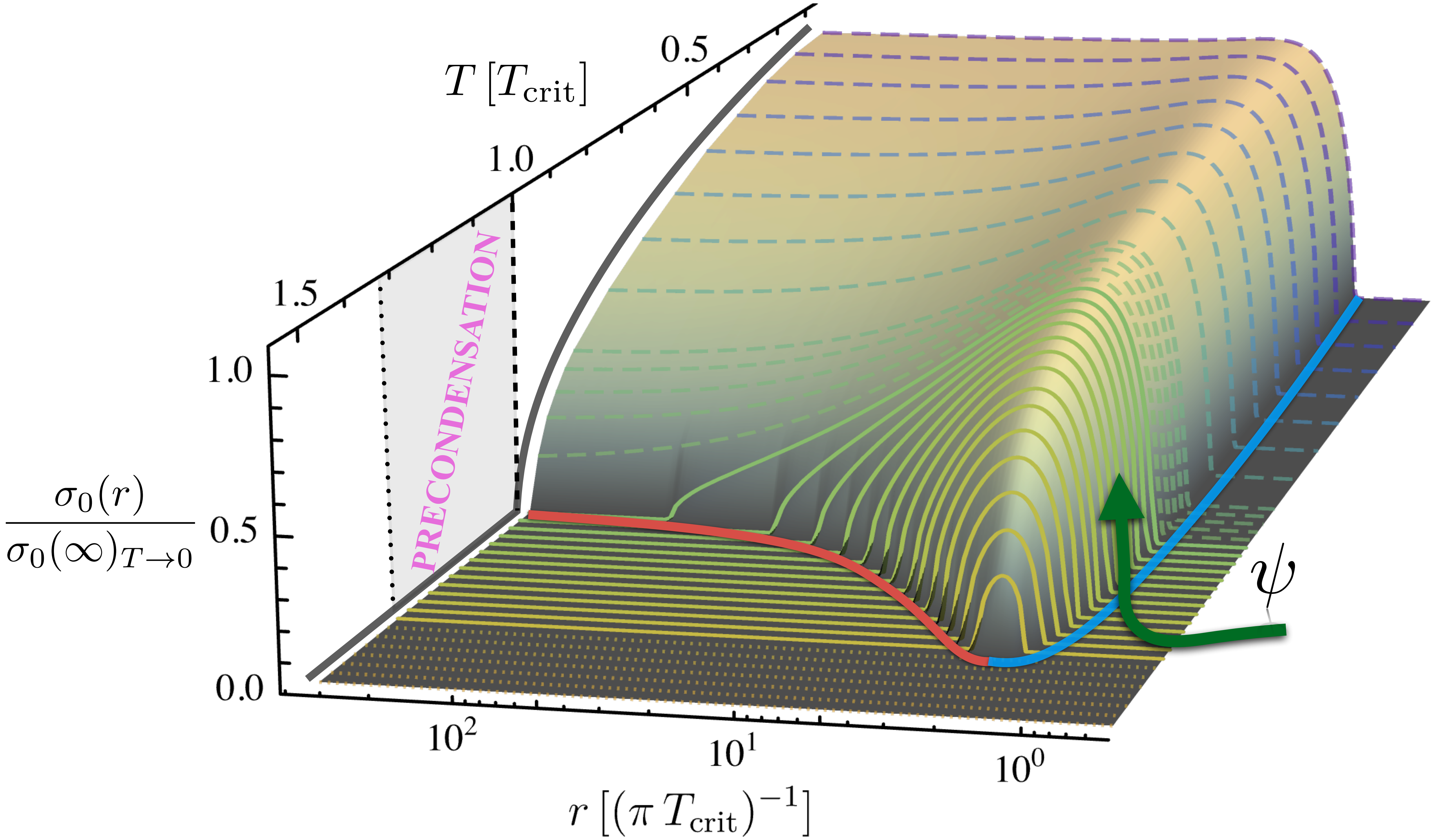

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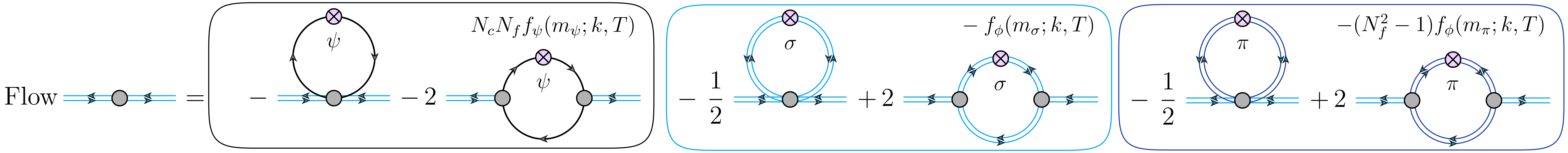

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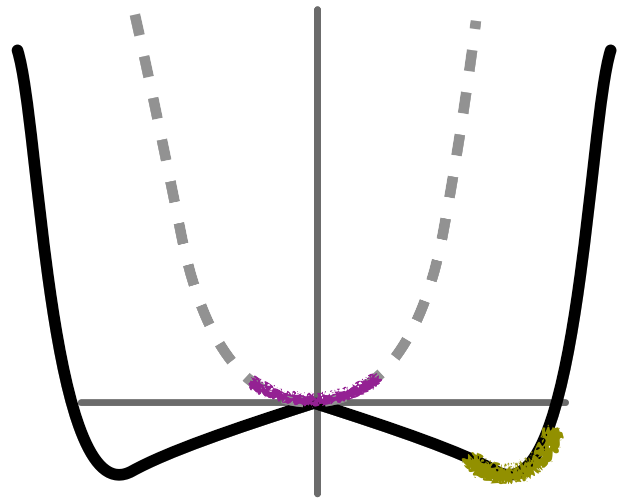

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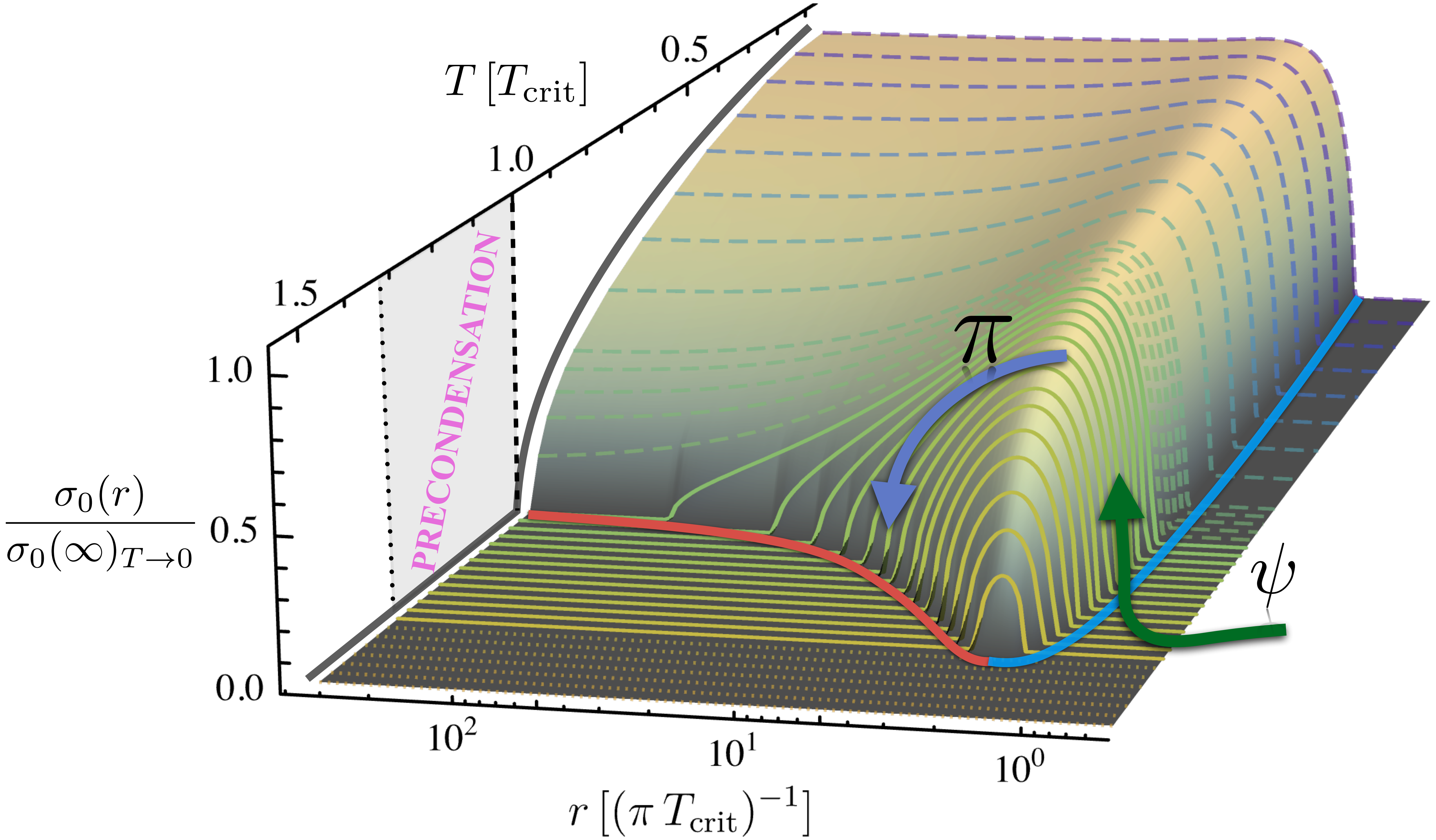

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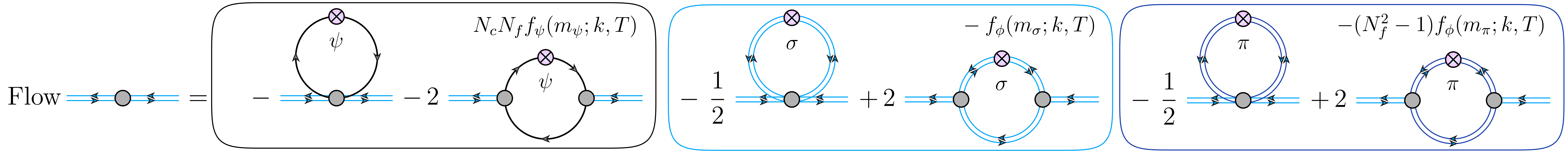

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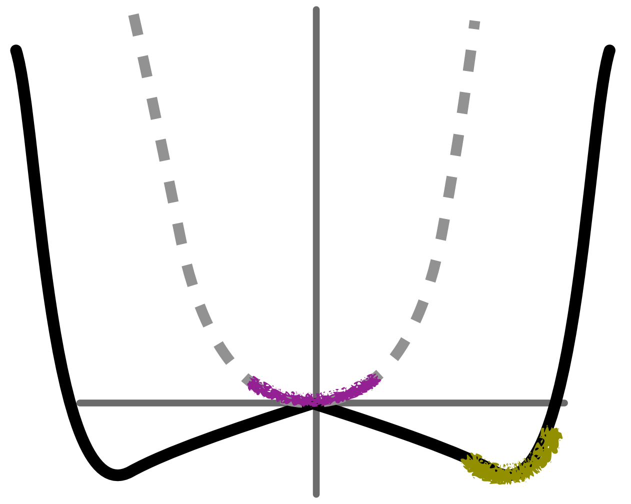
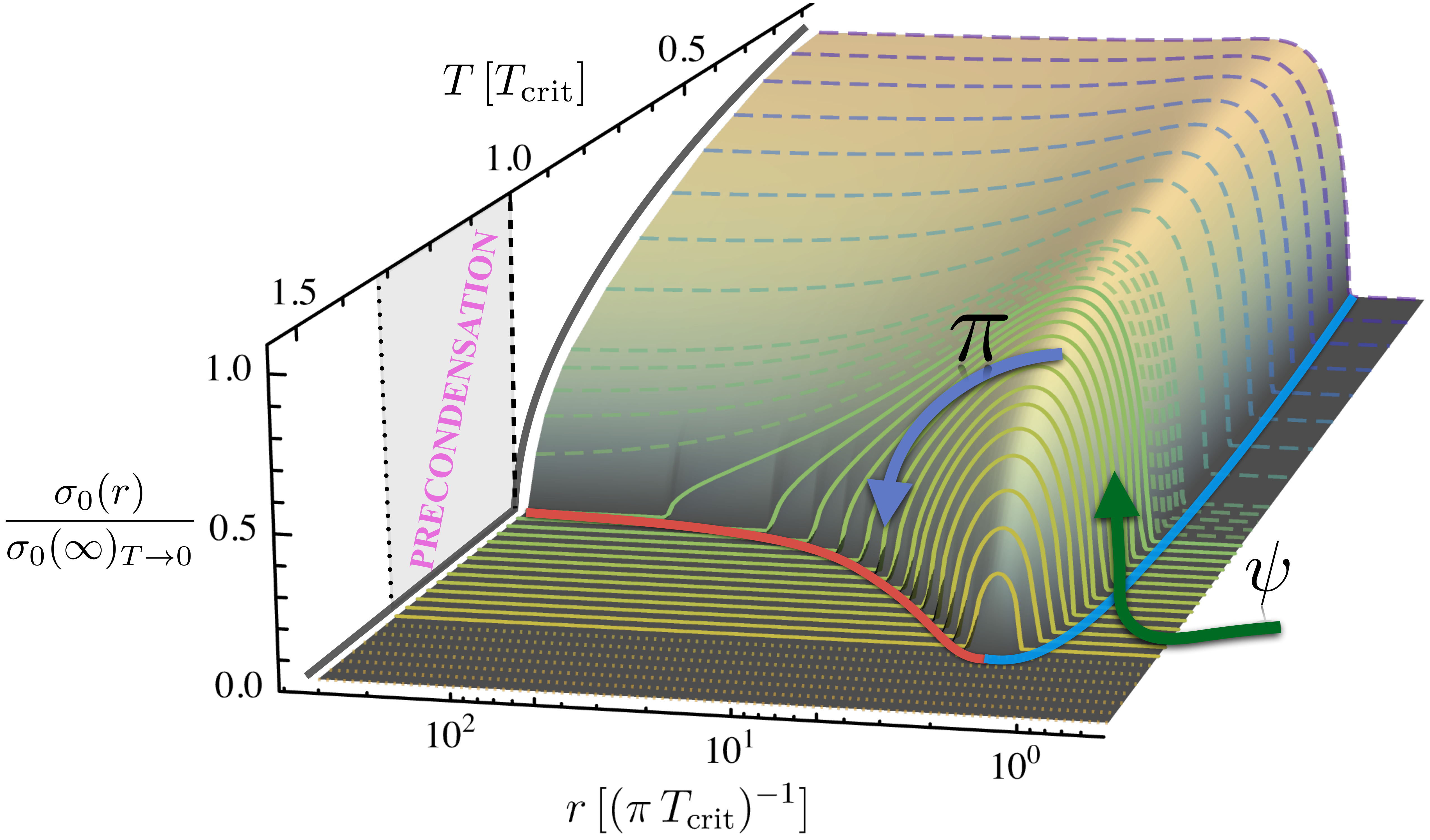


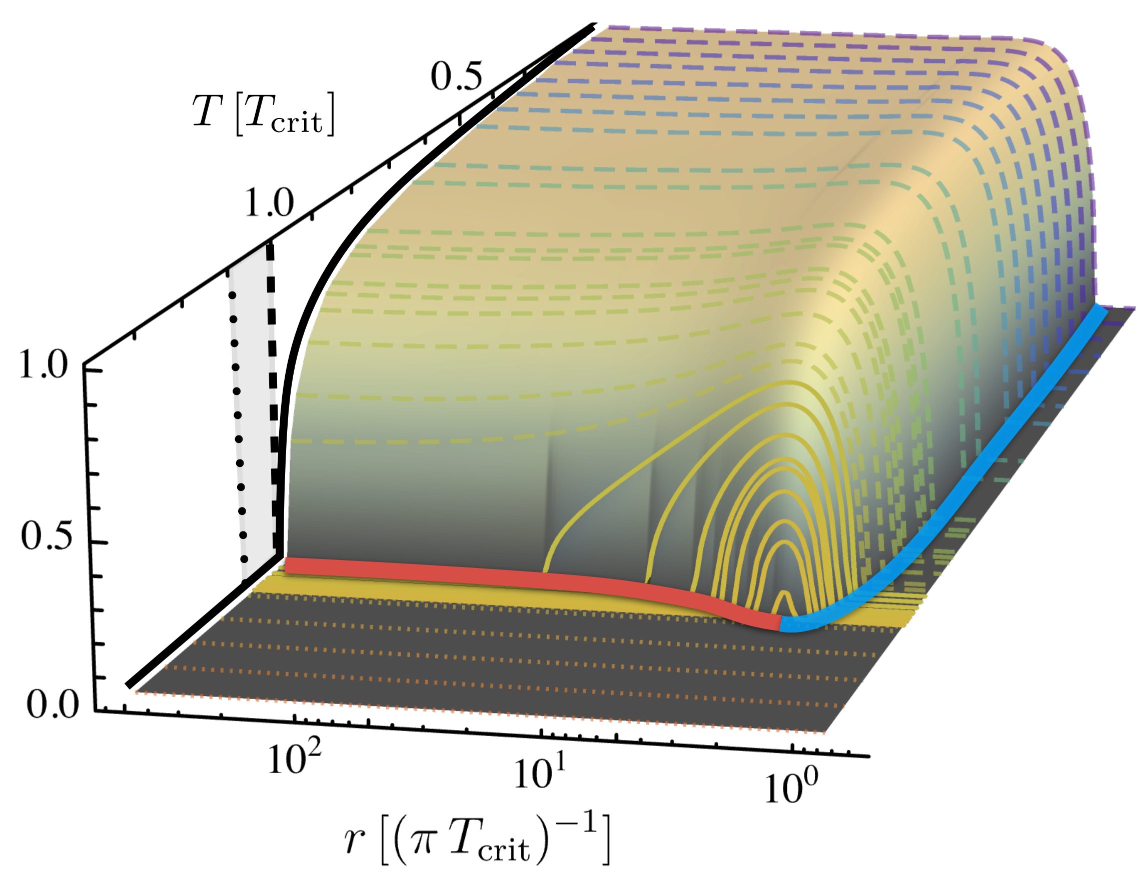
$\propto m_\sigma^2$

- Necessary **key ingredients**:
  - Competing counteracting effects: fermions and bosons
  - External parameter: $T, \mu, \ldots$
  - Massless modes: exact Goldstones

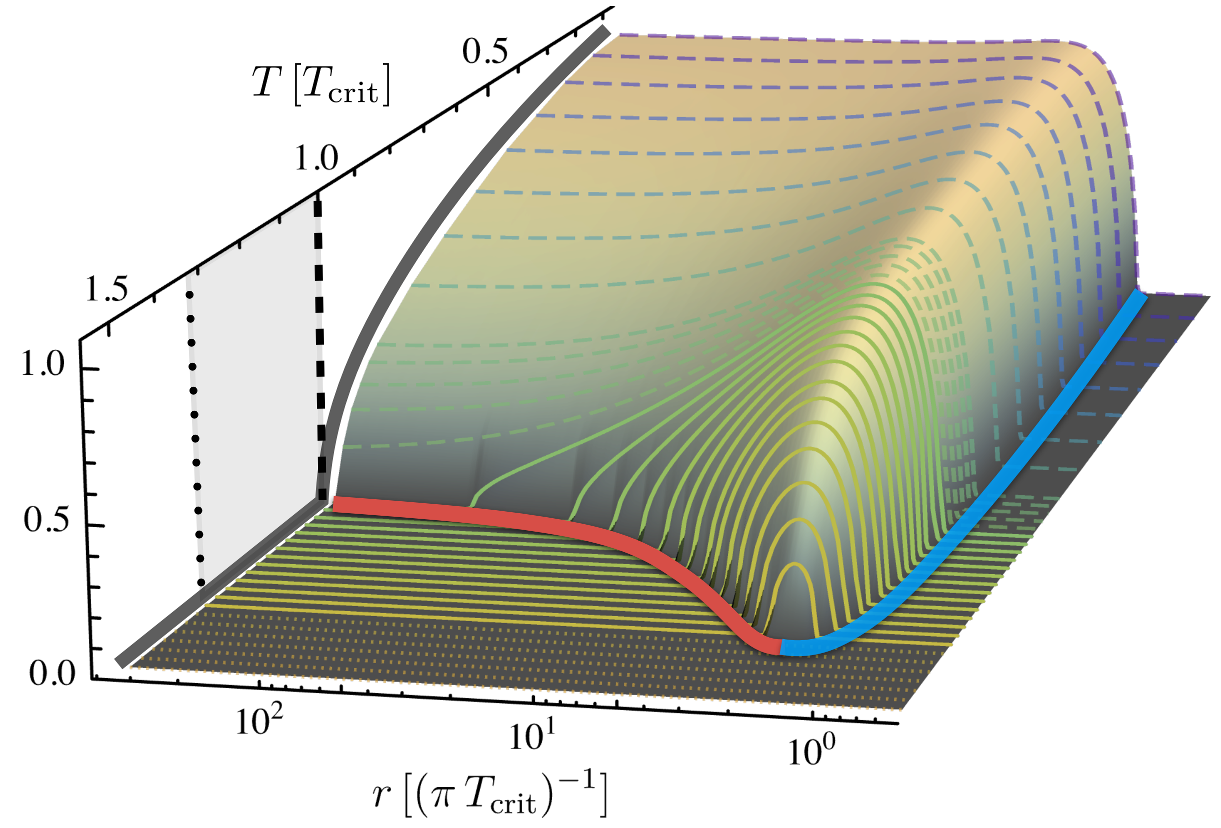


Many flavour scaling

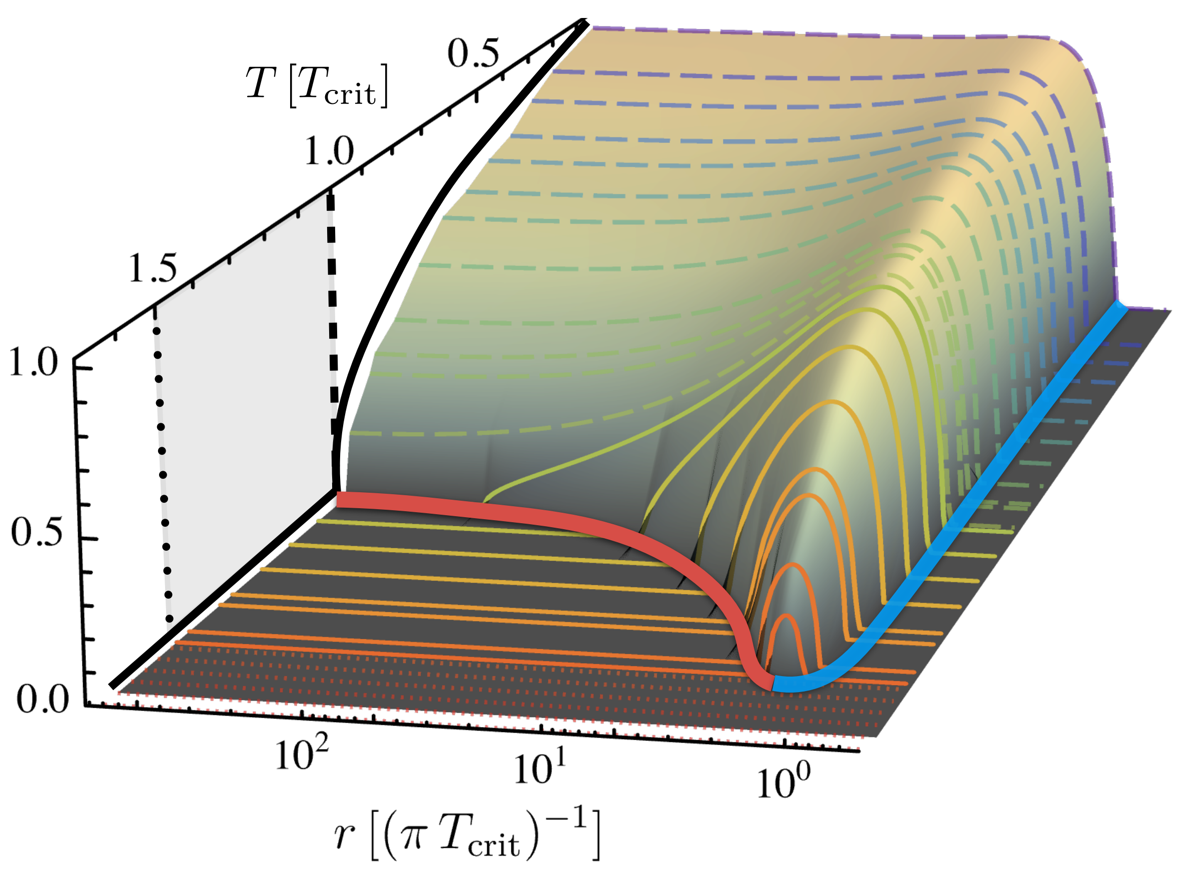
$N_f = 2$



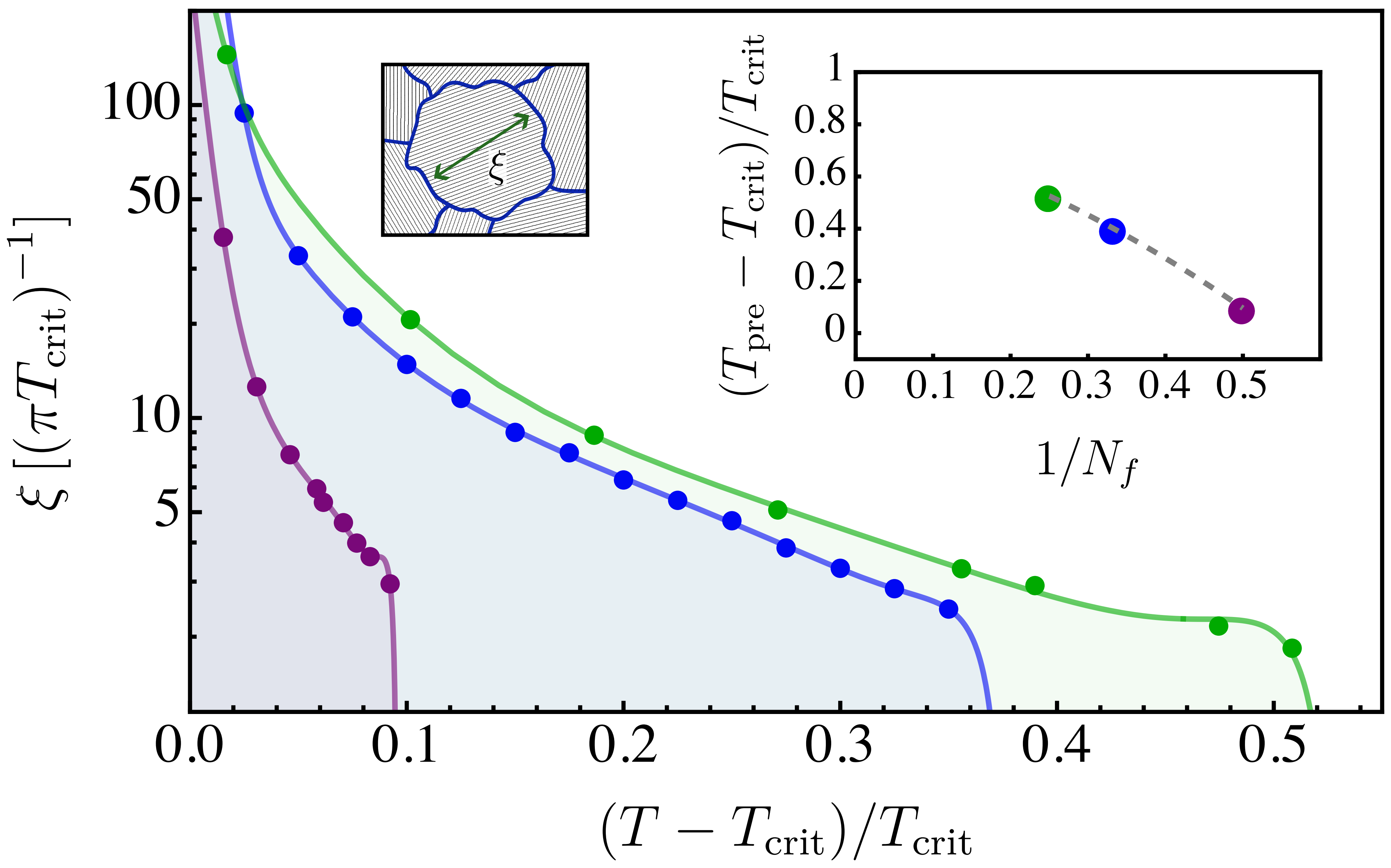
$N_f = 3$



$N_f = 4$

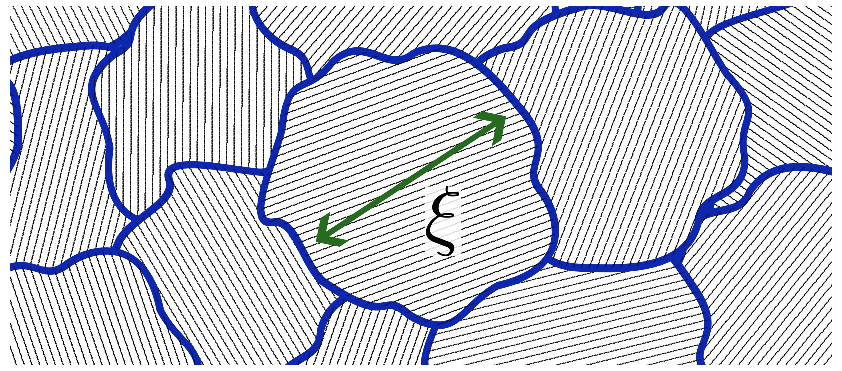


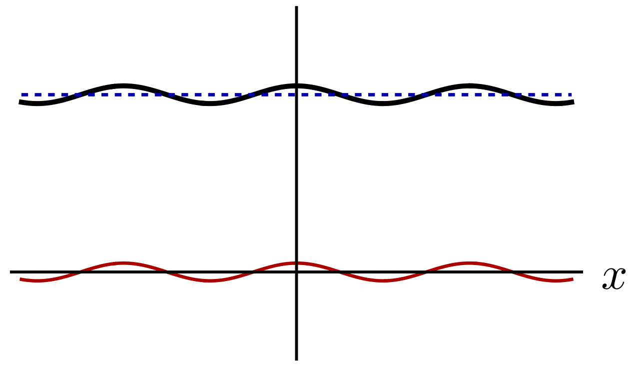
- **Growing size** of precondensation regime in T
- **Growing** number of **Goldstones** $N_f^2 - 1$
- **Relevant role** in the **near-critical dynamics**

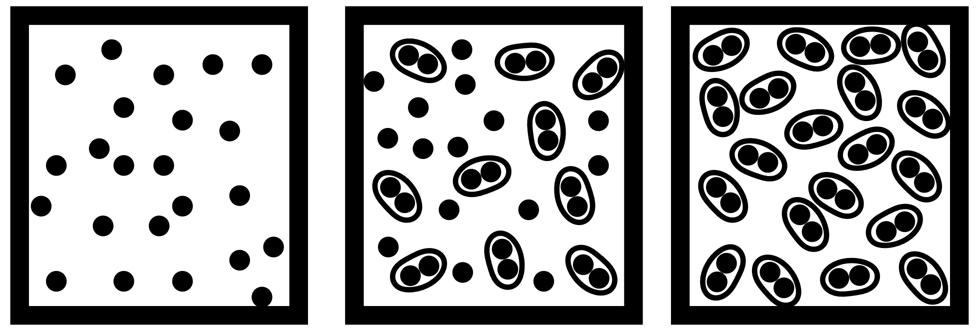


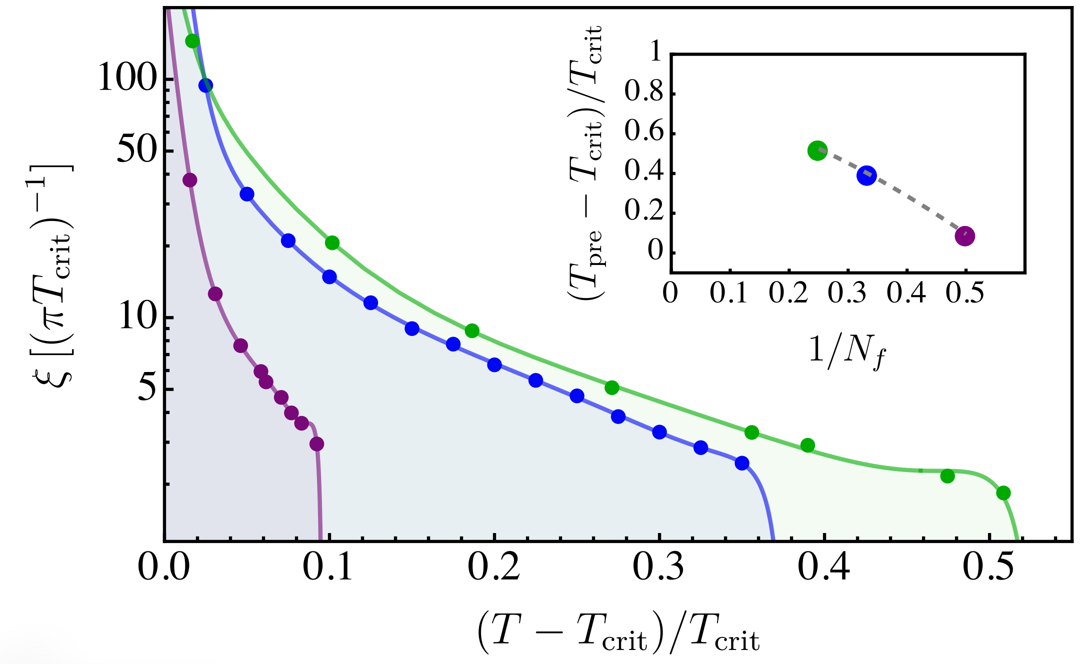
Conclusions

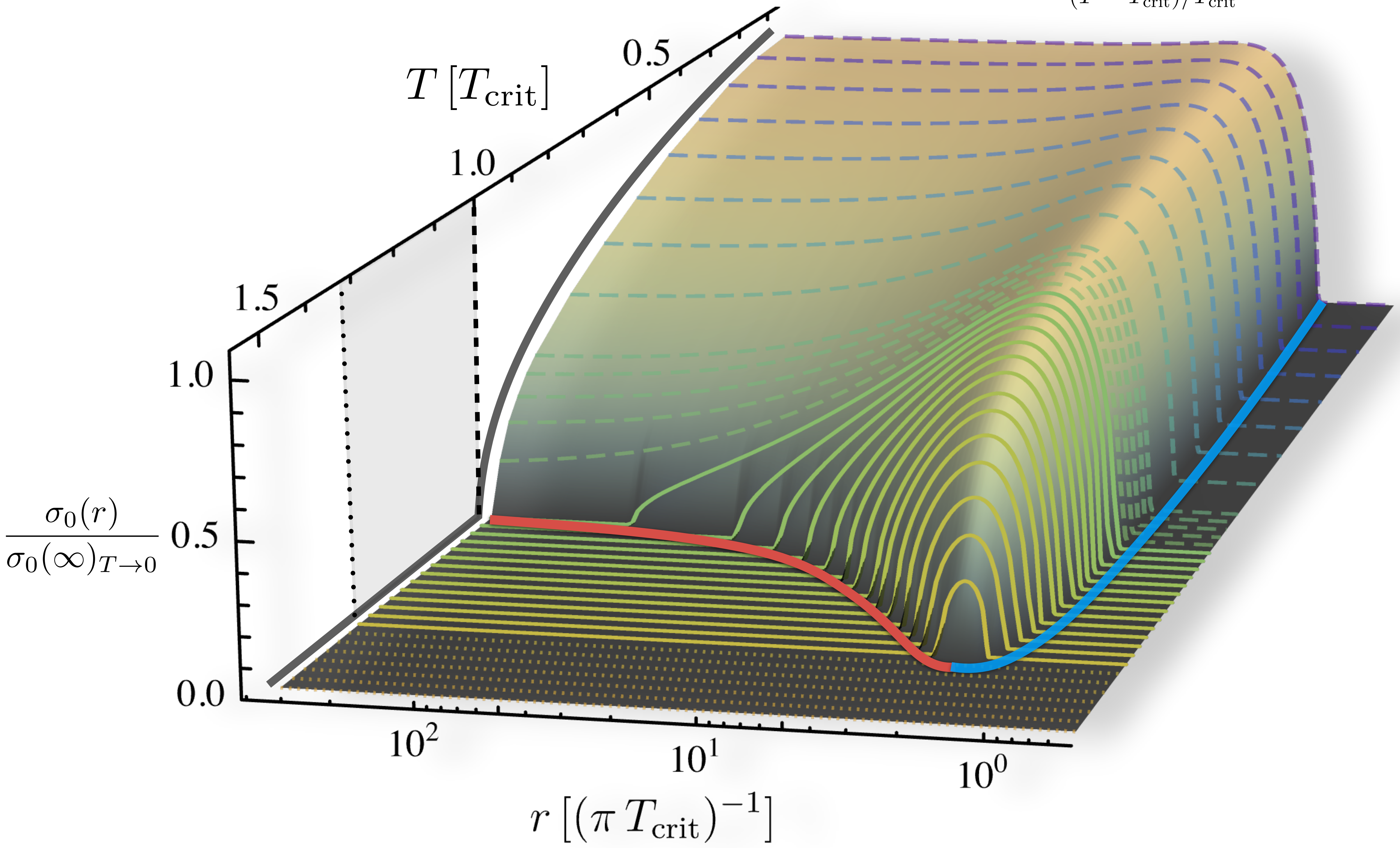
- **Thermal precondensation** has interesting **features**
  - **Domains, spatial modulations, mixed phases**
- Occurs in **multiple contexts in nature** (condensed matter, cold atoms, gauge-fermion theories in the chiral limit)
- **Key ingredients**:
  - Competing counteracting effects
  - External parameters
  - Massless modes
- Increasingly relevant in the **many-flavour limit**
- Potentially relevant for **BSM physics** and **observational** prospects











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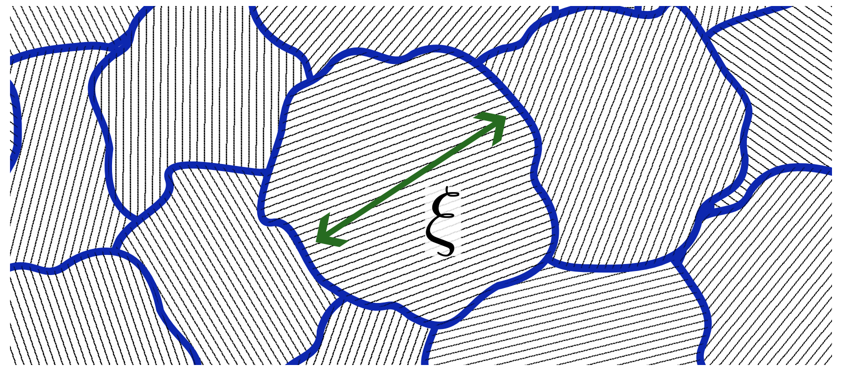

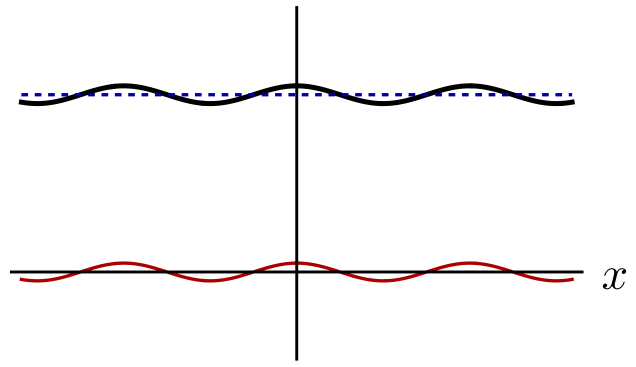

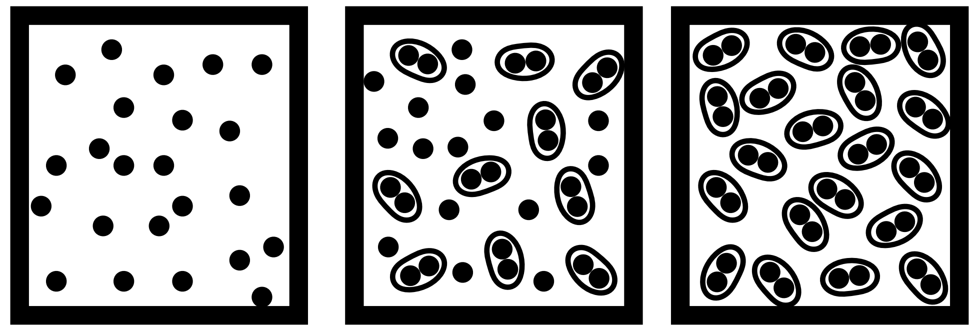

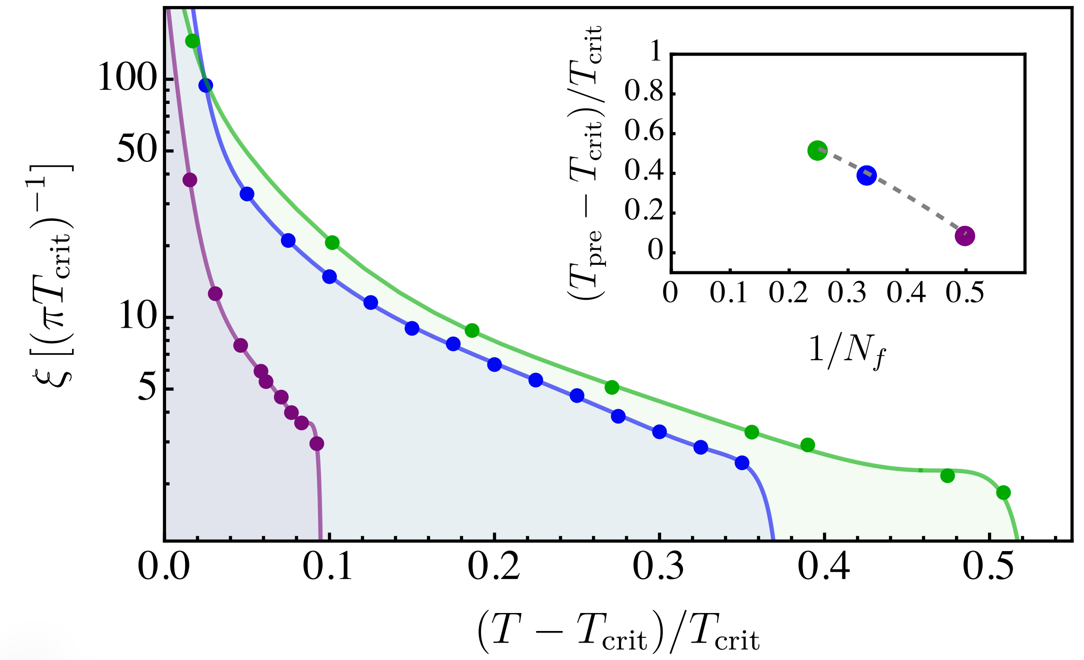

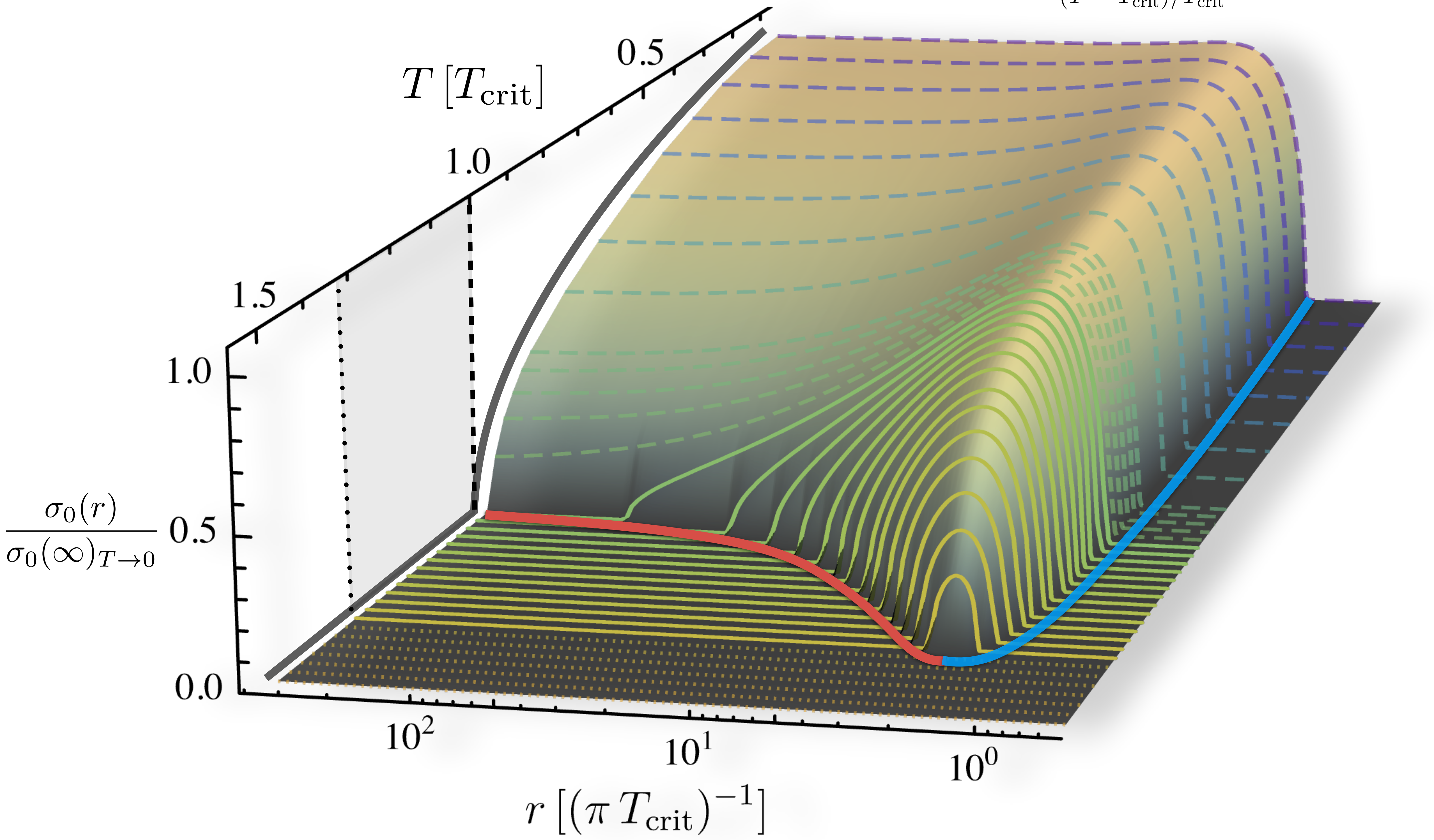

Thank you for your attention!