Universality classes for Coulomb-frustrated phase separation

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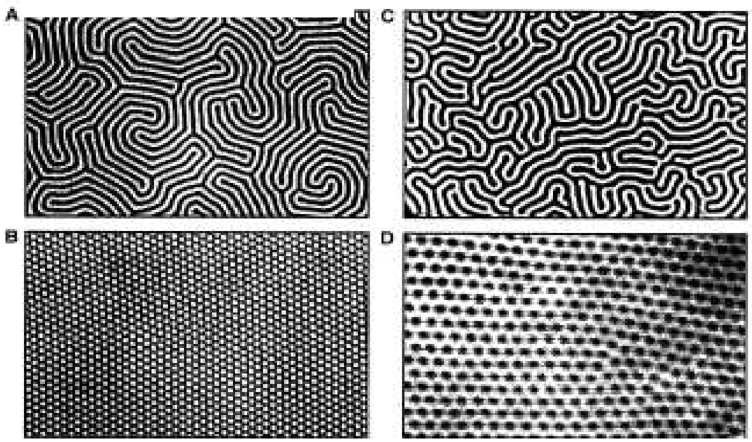
Statistical Mechanics and Complexity

Consiglio Nazionale delle Ricerche

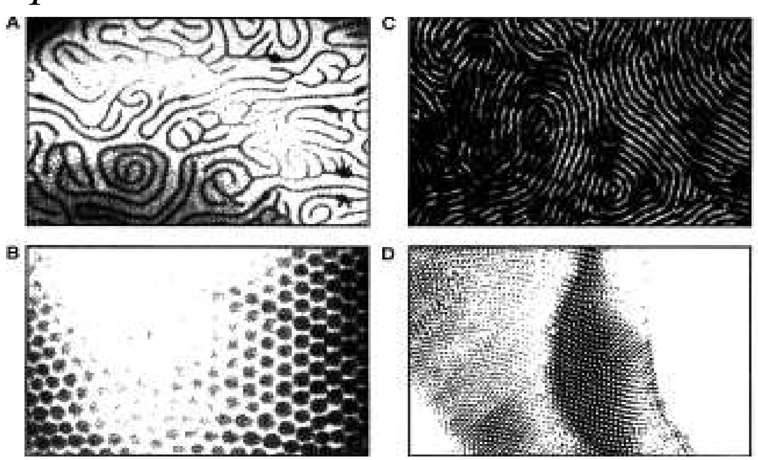
Mesoscopic separation

Seul and Andelman Science 1995

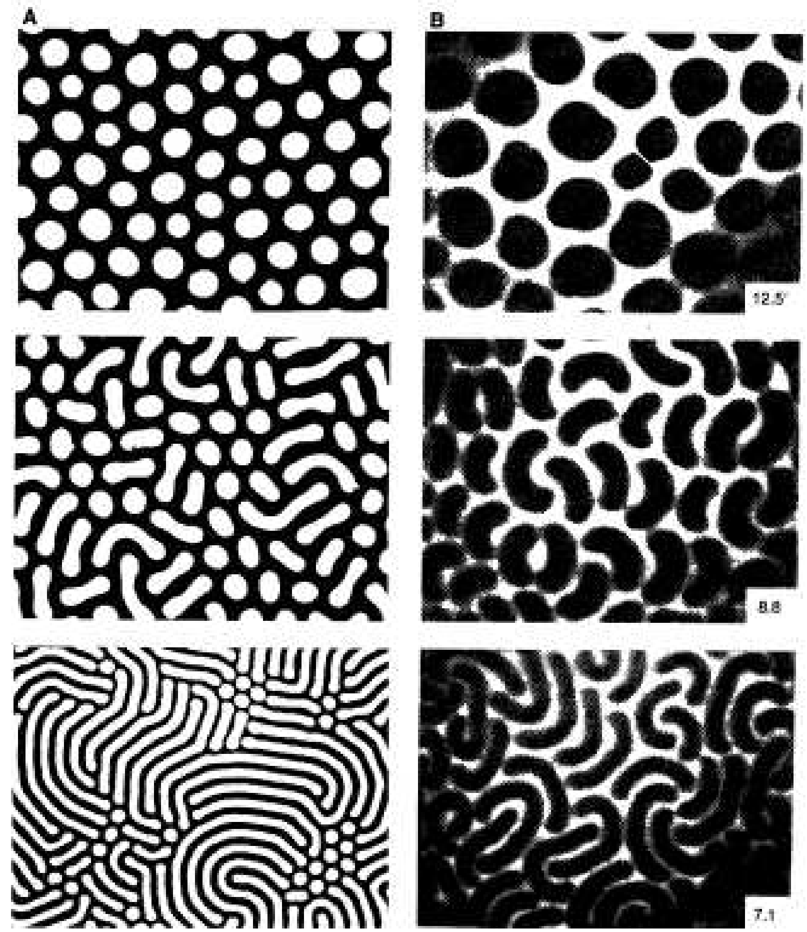
Ferromagnetic Film   *Ferrofluids*



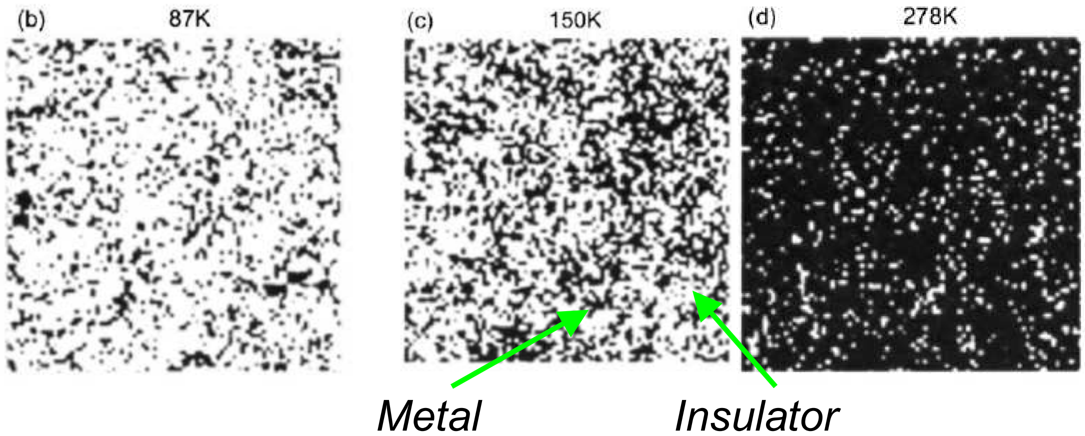
Copolimers



Ferromagnetic Film   *Copolimers*

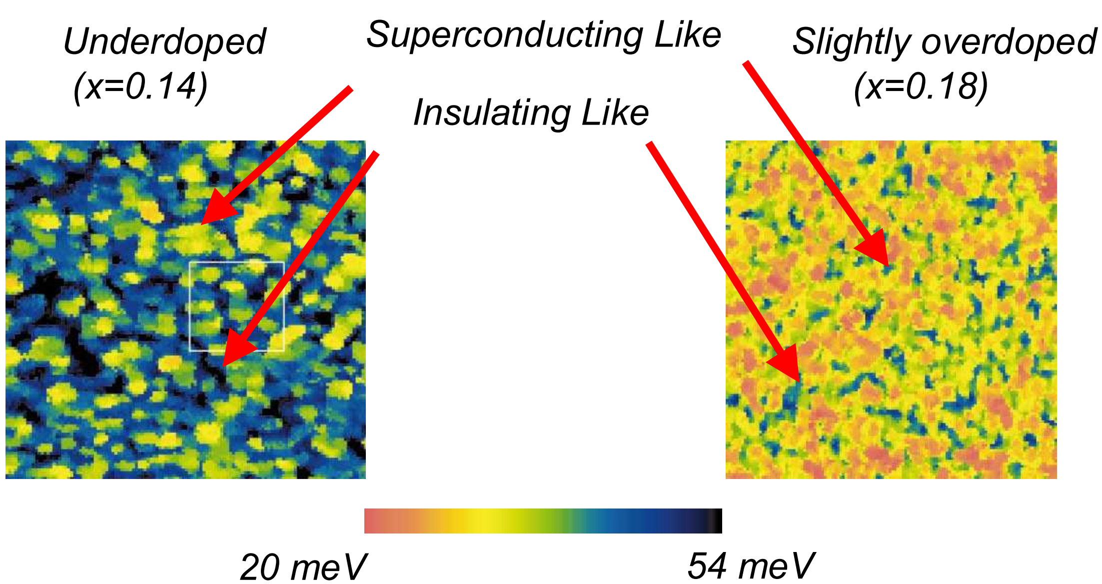


Manganites thin films



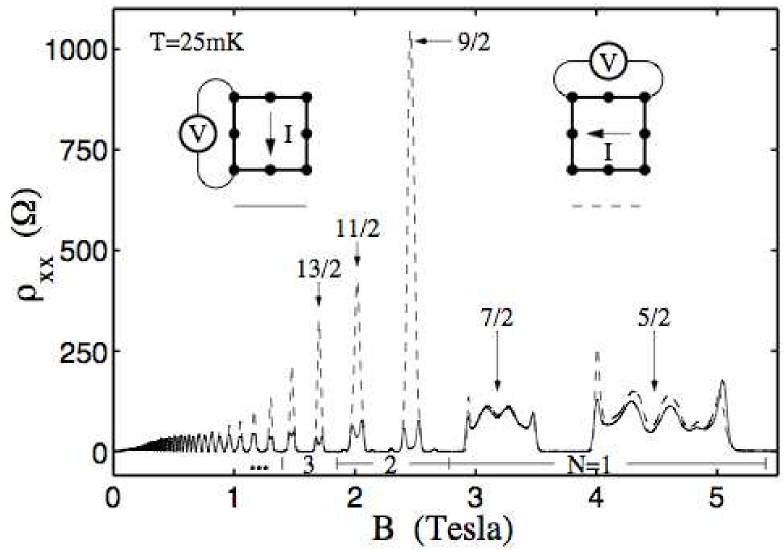
•*T. Becker et al PRL **89,** 238203 (2002)*

Cuprates



•*Lang et al, Nature **415,** 412 (2002)*

GaAs heterostructures



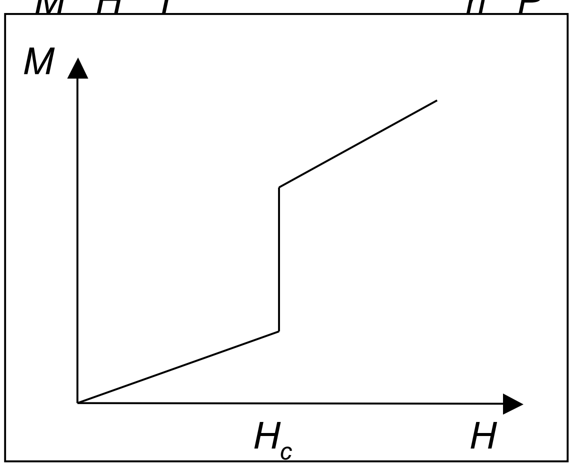
•*M. P. Lilly et al. PRL* ***82,*** *394 (1999)*

T<150 mK

Ruthenates

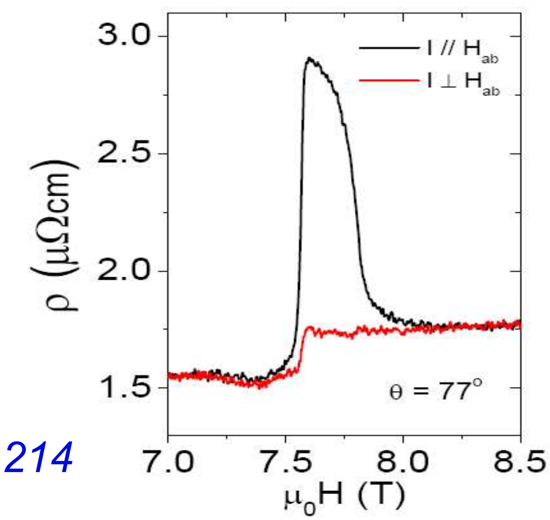
Metamagnets *Vapour-liquid*

M H T *n P T*

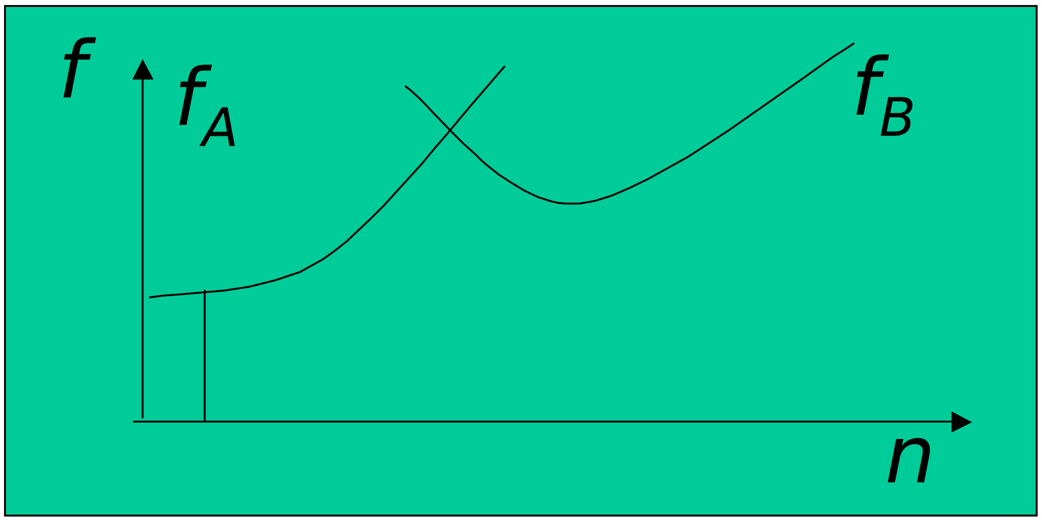


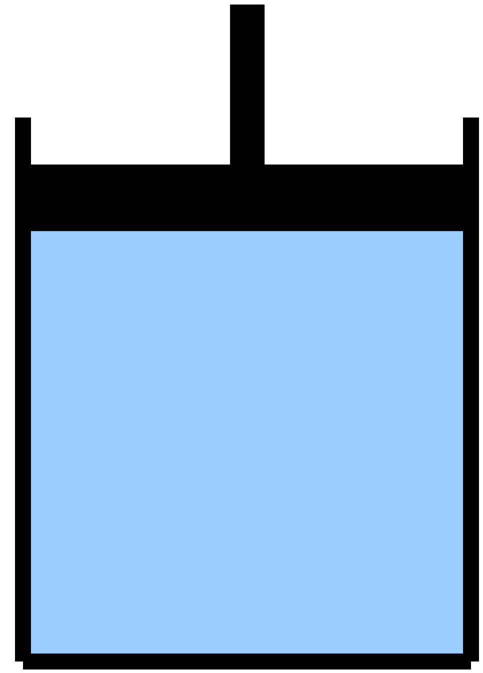
T=100 mK

•*Borzi et al. Science* ***315,*** *214 (2007)*

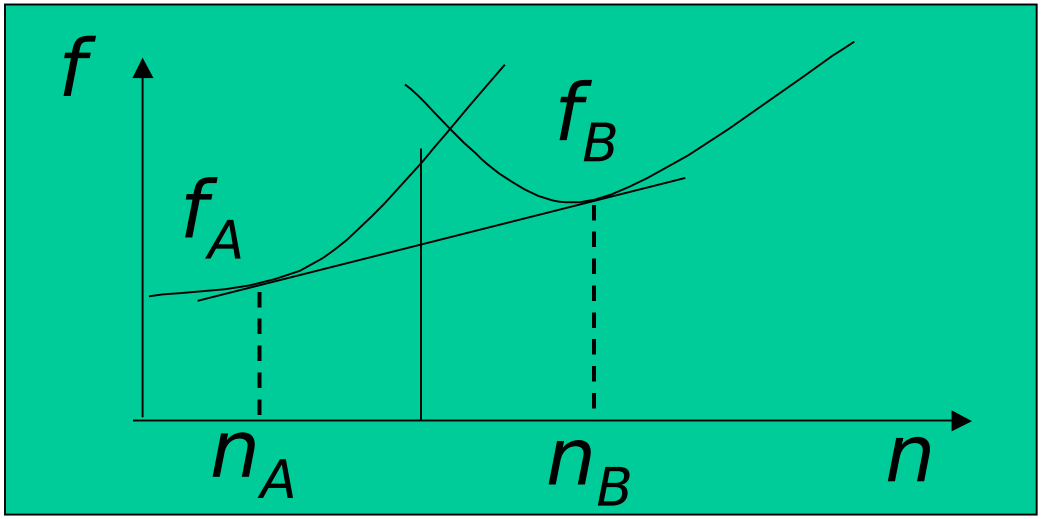


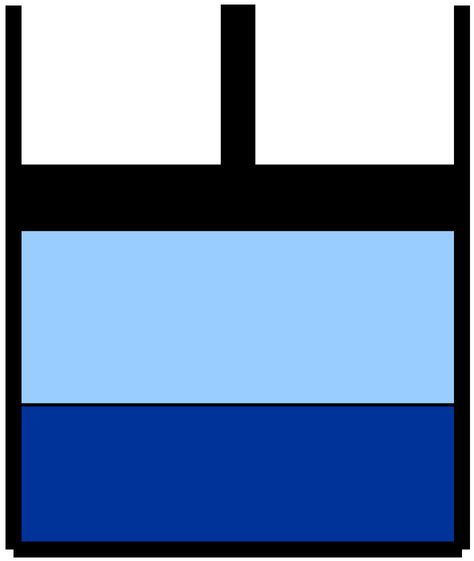
Macroscopic separation





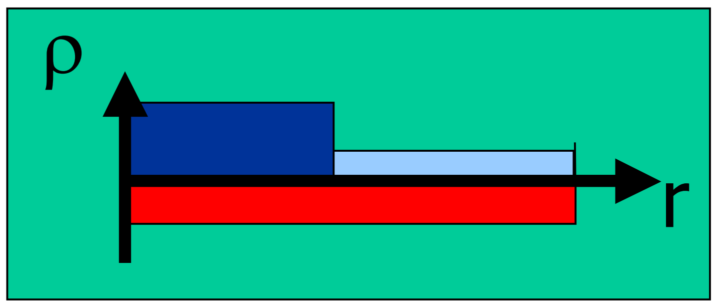
Macroscopic separation



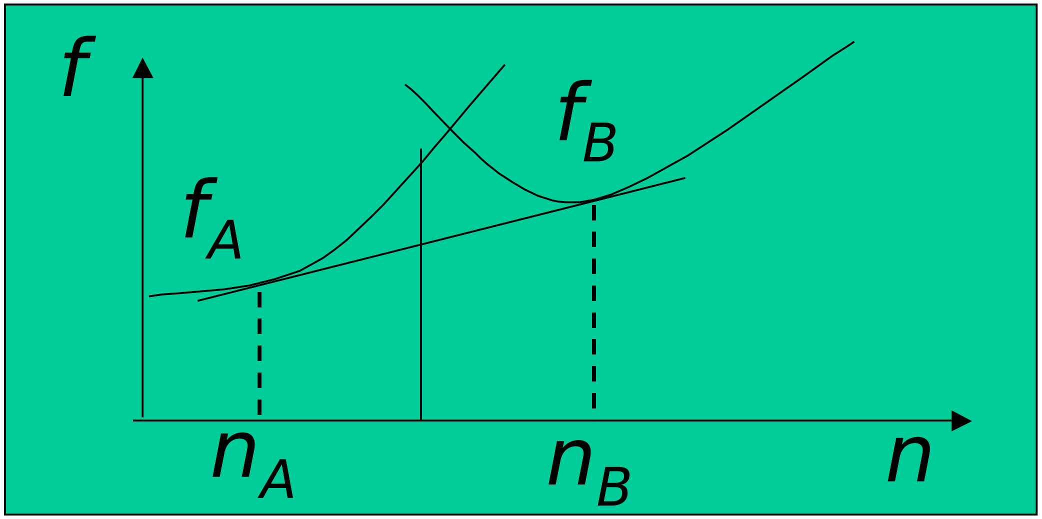


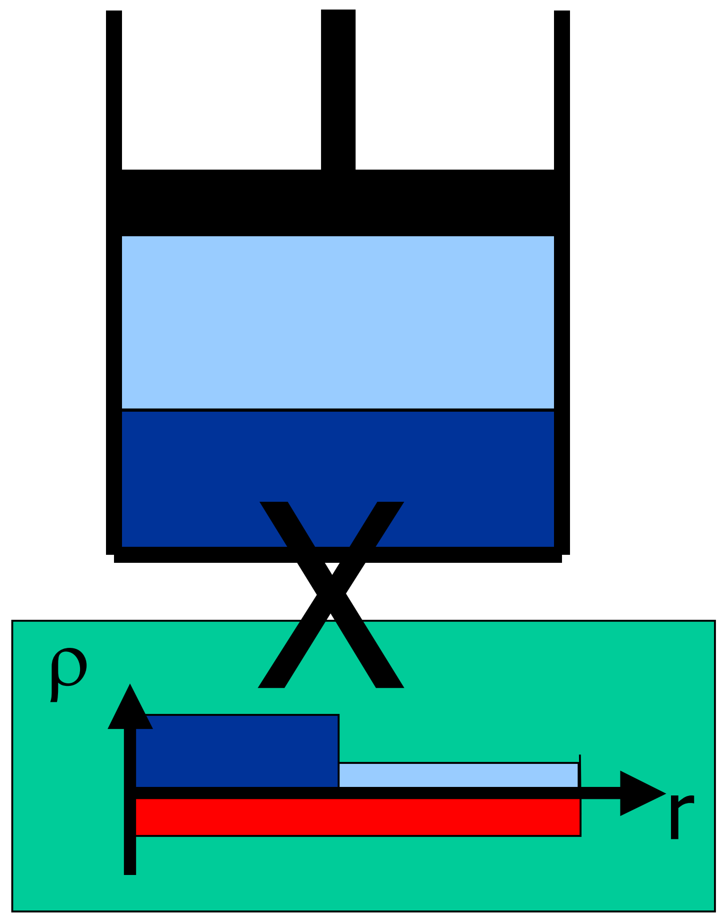
$$f \equiv (1-x) f_A + x f_B$$

$$n = (1-x) n_A + x n_B$$



Macroscopic separation





$$f \equiv (1-x) f_A + x f_B$$

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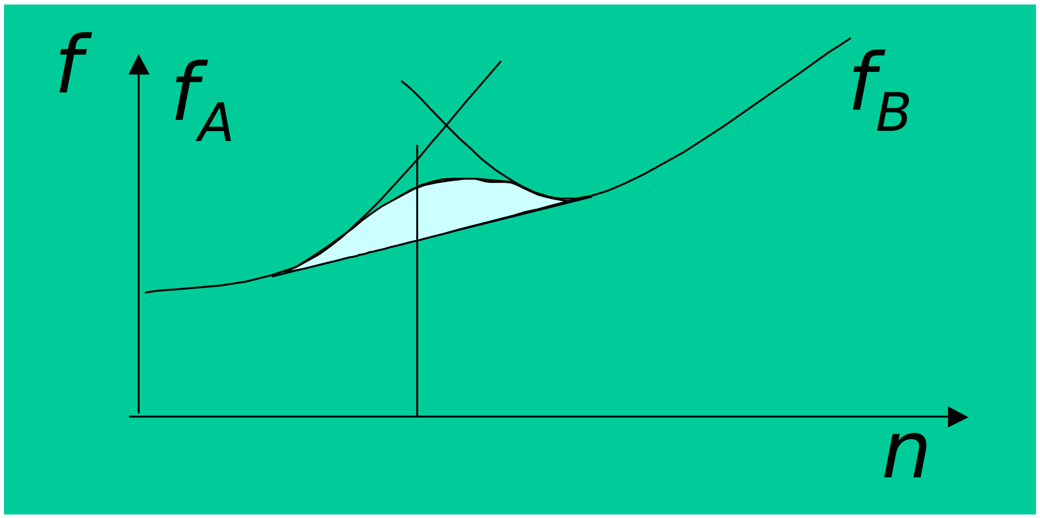
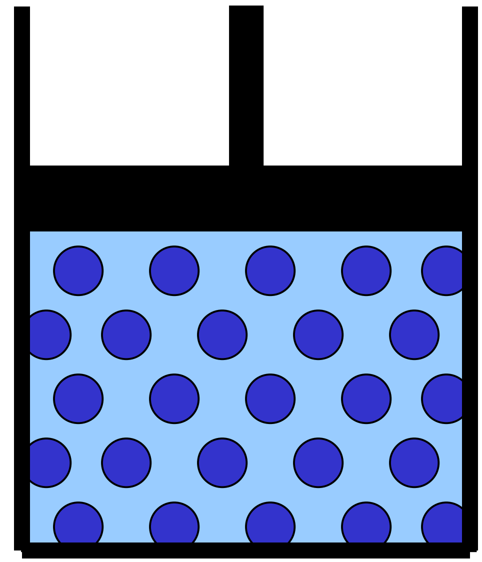
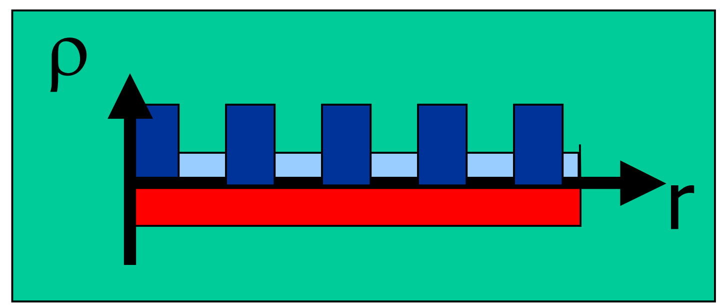
Mesoscopic separation



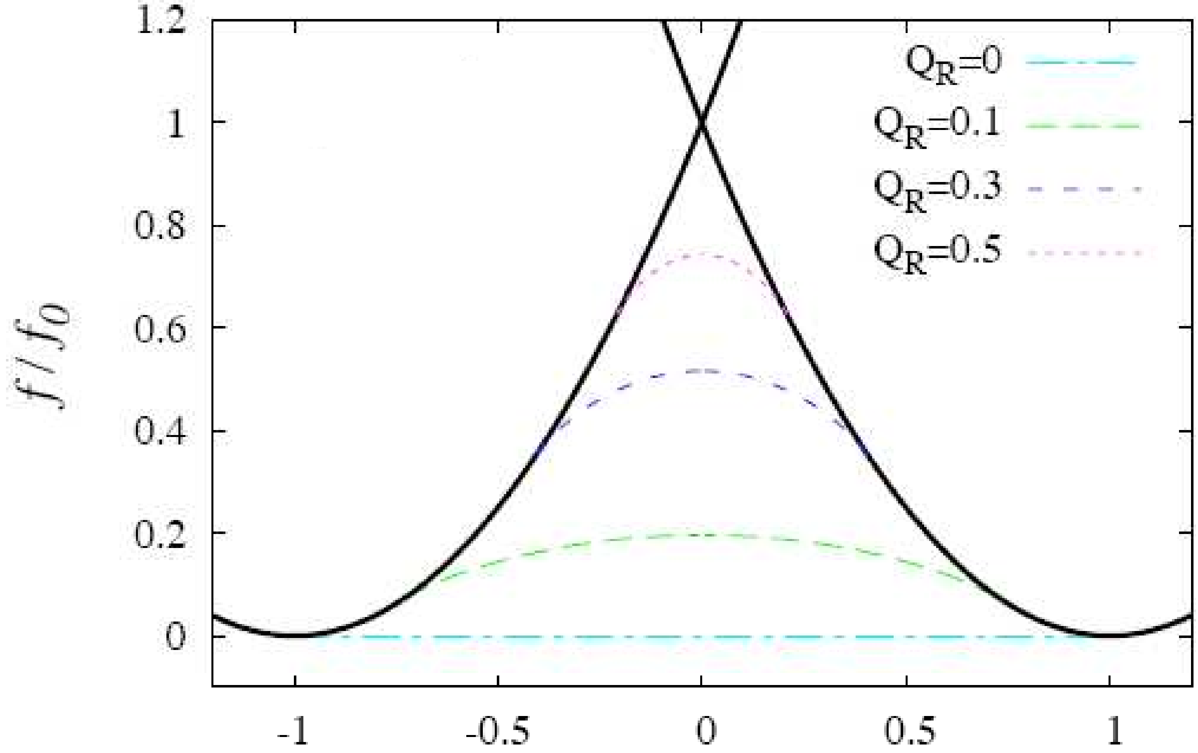


$$f \equiv (1-x) f_A + x f_B \; + e_{surf} + e_{Coul}$$

$$n = (1-x) n_A + x n_B$$

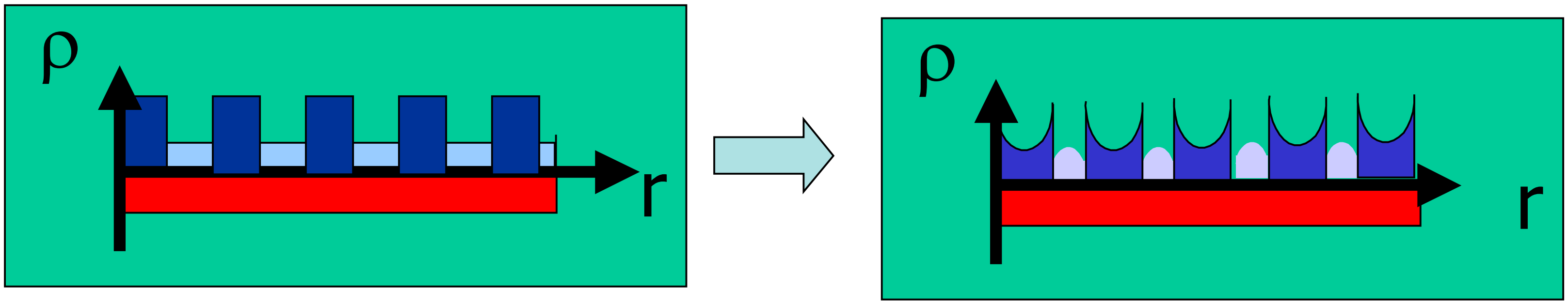


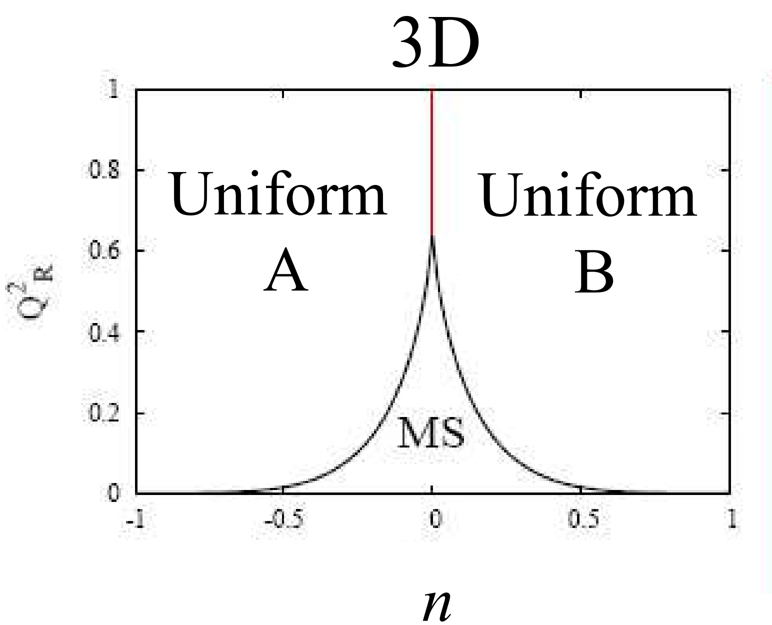
Energy of mixed phases

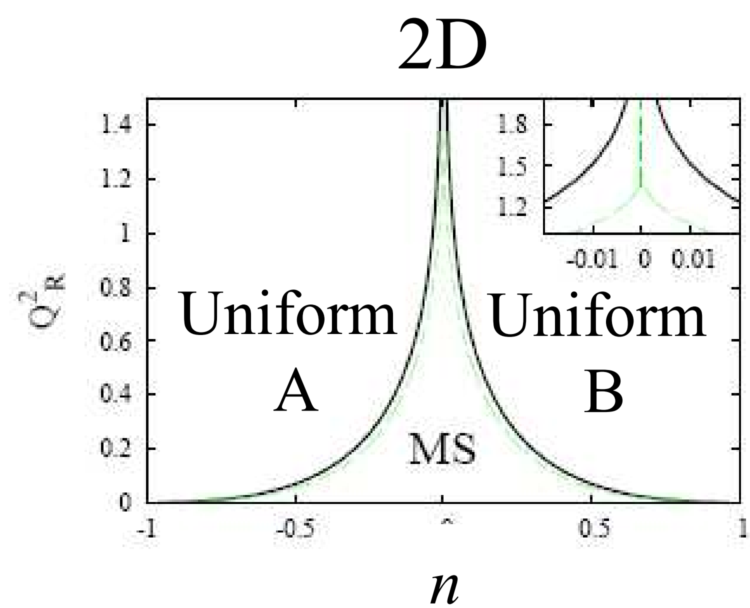


n

Charge Relaxation and Phase Diagram





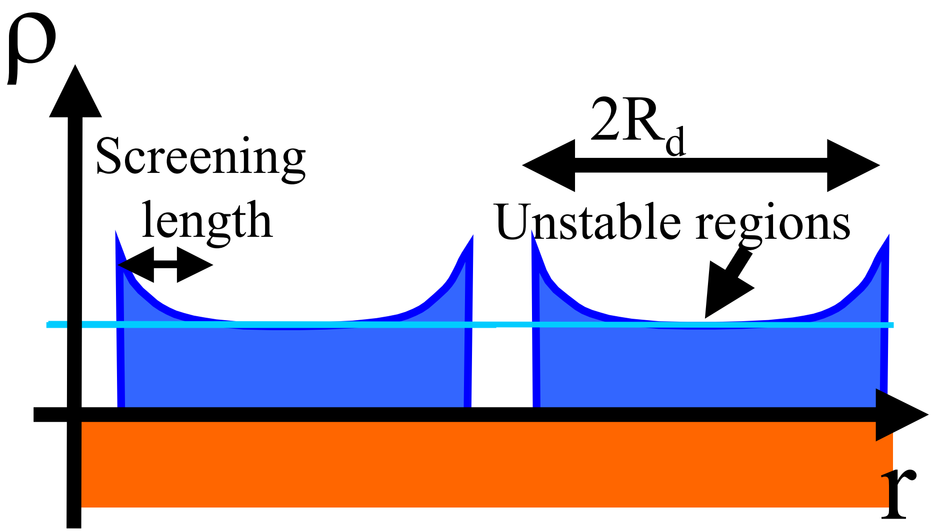


Jamei, Spivak, Kivelson, PRL,2005

Ortix , Lorenzana, Beccaria and Di Castro PRB, 2007.

Charge relaxation and maximum size rule

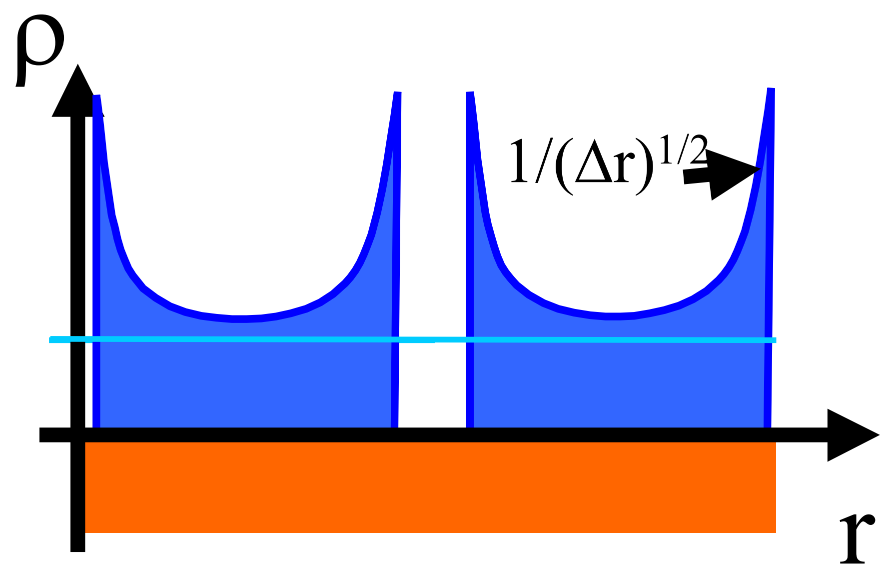
3D



$R_d < l_s$

Condition too stringent for Mesoscopic phase separation in good metals

2D



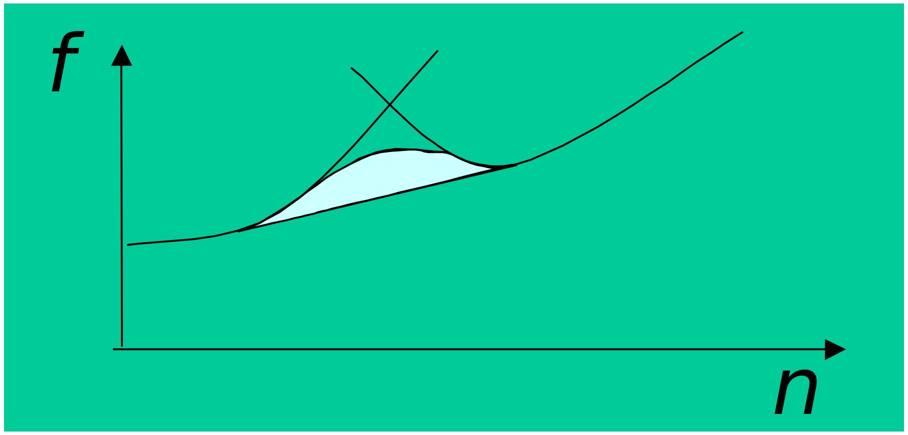
No bound for R_d

Mesoscopic phase separation favored

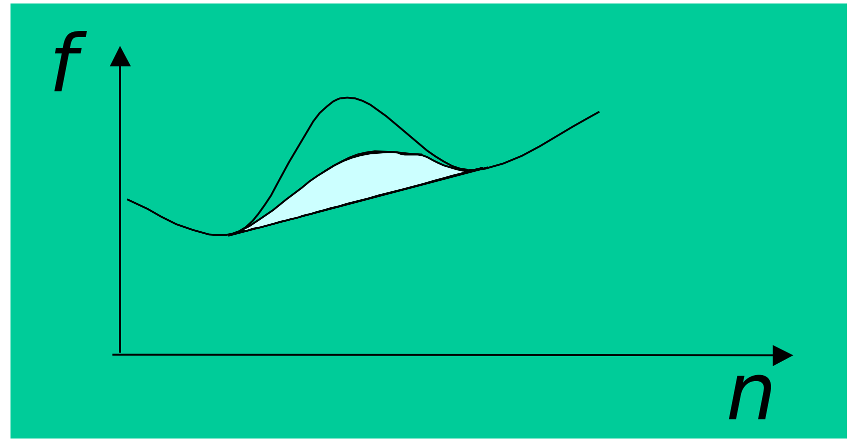
Lorenzana, Castellani, Di Castro PRB (2002)
Ortix, Lorenzana, Di Castro, PRB (2006)

Universality Classes

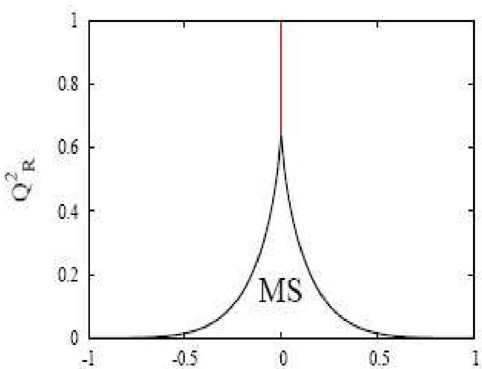
Cusp Singularity



Negative Compressibility

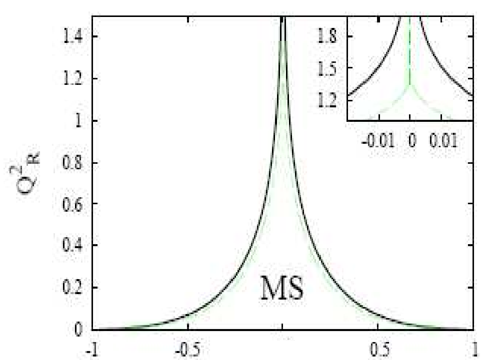


3D

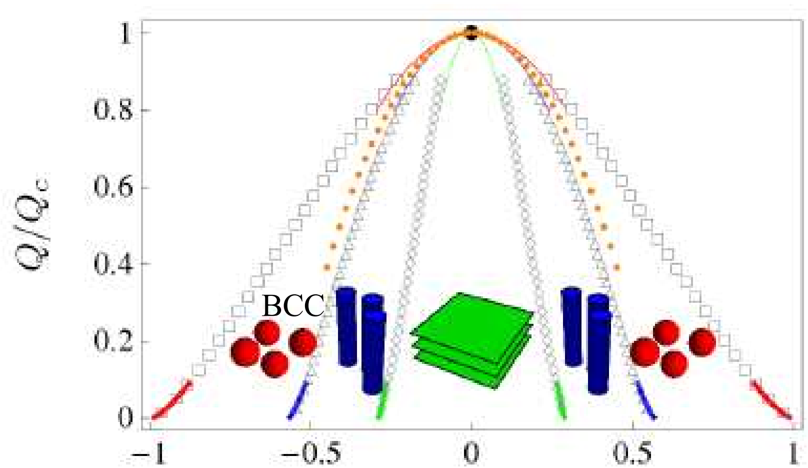


n

2D



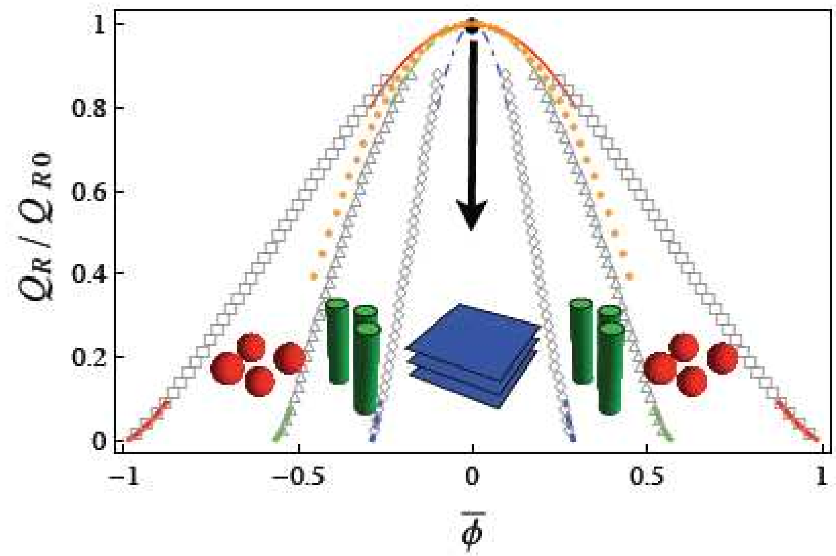
n

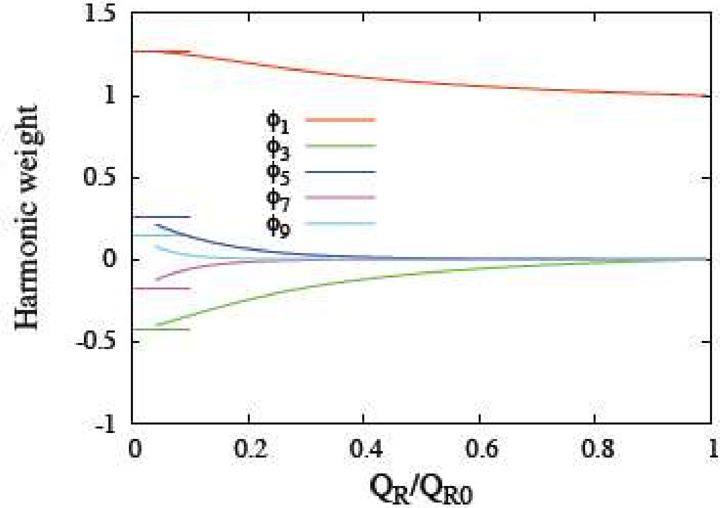


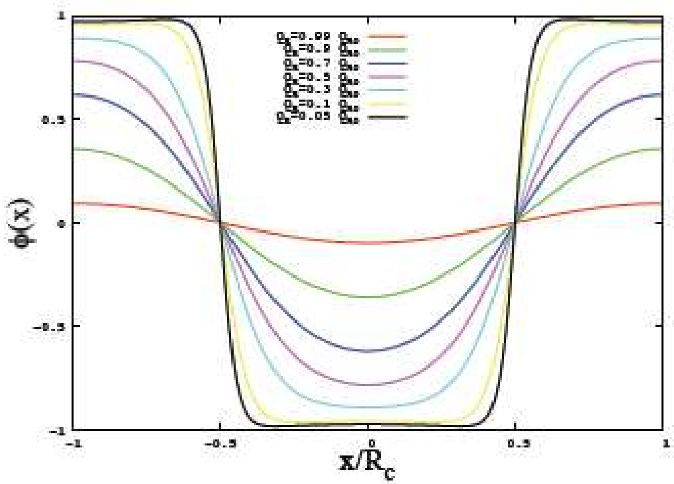
n

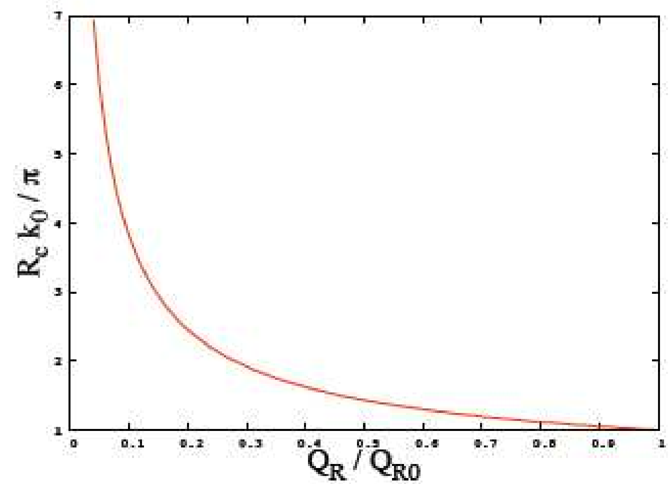
ϕ^4+Coulomb

Building of unharmonicity





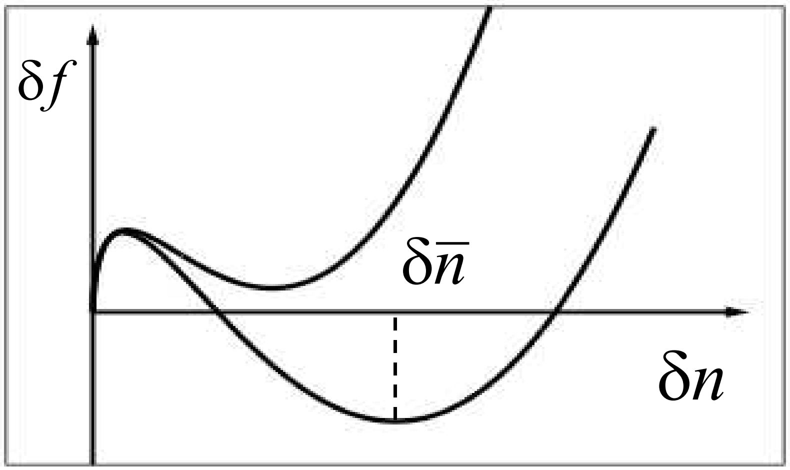




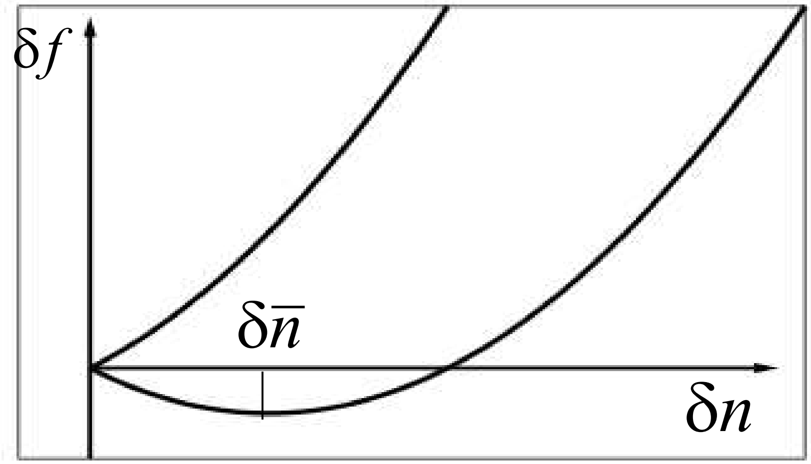
Conclusions

- Two universality classes
  - Cusp singularity:
    - In 2D there is an intermediate inhomogneneous phase for any Coulomb strength whereas in 3D there is a critical Coulomb strength.
  - Negative Compressibility:
    - Critical point with weakly first order transition around independently of dimensionality.
    - Close to the critical point: BCC ► Triangular ►Layered sequence
  - Weak Coupling Universality
  - Universal maximum size rule.

3-D SYSTEMS



2-D SYSTEMS



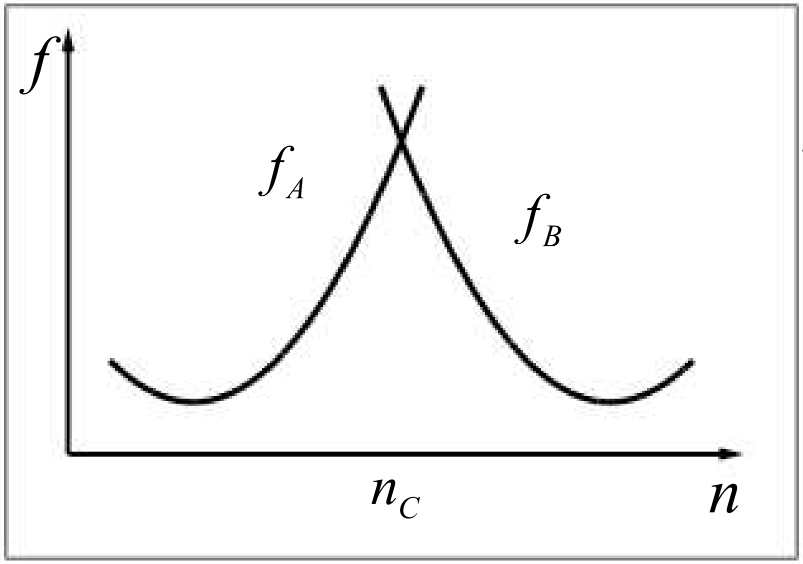
$$\delta f\left(\delta n = \delta\bar{n}\right) < 0$$

$$\left(\frac{\sigma^2 e^2}{\varepsilon_0}\right)\frac{1}{\delta\mu^3} < \delta\bar{n} < \kappa\delta\mu$$

$$\delta\mu > \left(\frac{\sigma e^2}{\varepsilon_0}\right)^{\frac{1}{2}}$$

$$\lambda = \frac{\text{Characteristic mixing energy}}{\text{Characteristic phase separation energy}} < \lambda_C \sim 1$$

FRUSTRATED PHASE SEPARATION



$$f_{A,B} = f(n_C) + \mu_{A,B}(n_{A,B} - n_C) + \frac{1}{2\kappa}(n_{A,B} - n_C)^2$$

$$f_{FPS} = \nu f_B + (1-\nu) f_A + e_c + e_\sigma$$

Mixing Energy

For arbitrary dimension:

$$\delta f_{n=n_c} = -\nu(1-\nu)\delta n \delta\mu + \nu(1-\nu)\frac{\delta n^2}{2\kappa} + \left(\frac{\sigma^{d-1} e^2}{\varepsilon_0}\right)^{\frac{1}{d}} \delta n^{\frac{2}{d}} u(\nu)$$

$$\delta\mu = \frac{\delta n^{MC}}{\kappa}$$

$\sigma =$ Surface tension

$$L = \left(\frac{\sigma \varepsilon_0}{e^2} \right)^{\frac{1}{d}} \delta \overline{n}^{\,-\frac{2}{d}}$$

Typical size of inhomogeneities

$$l_S = \left(\frac{\varepsilon_0}{e^2 \kappa} \right)^{\frac{1}{d-1}}$$

Screening length

3D systems:

Minimum condition

$$\delta \overline{n} > \frac{\delta n^{MC}}{4}$$

$$L = \sqrt{\lambda}\, l_S \left(\frac{\delta \overline{n}}{\delta n^{MC}} \right)^{-\frac{2}{3}} < l_S$$

2D systems:

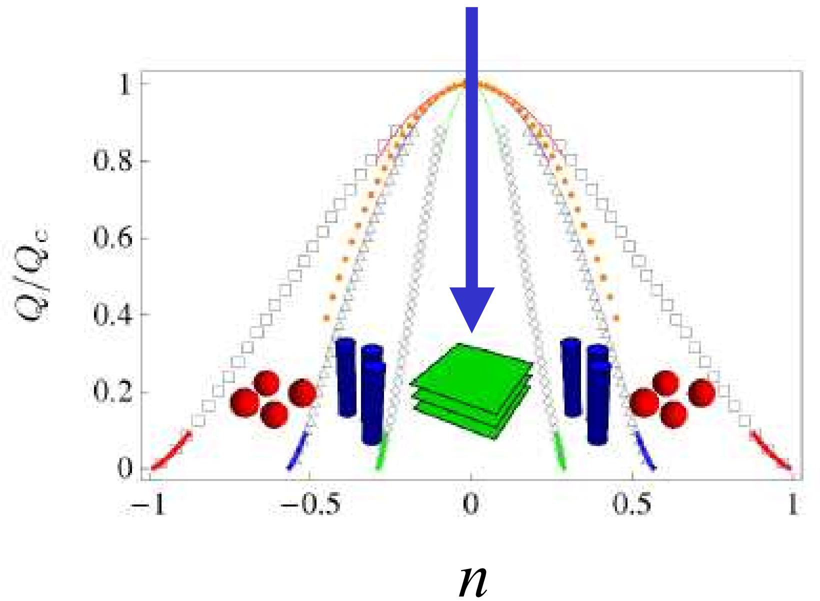
Absence of lower bound for $\delta \overline{n}$

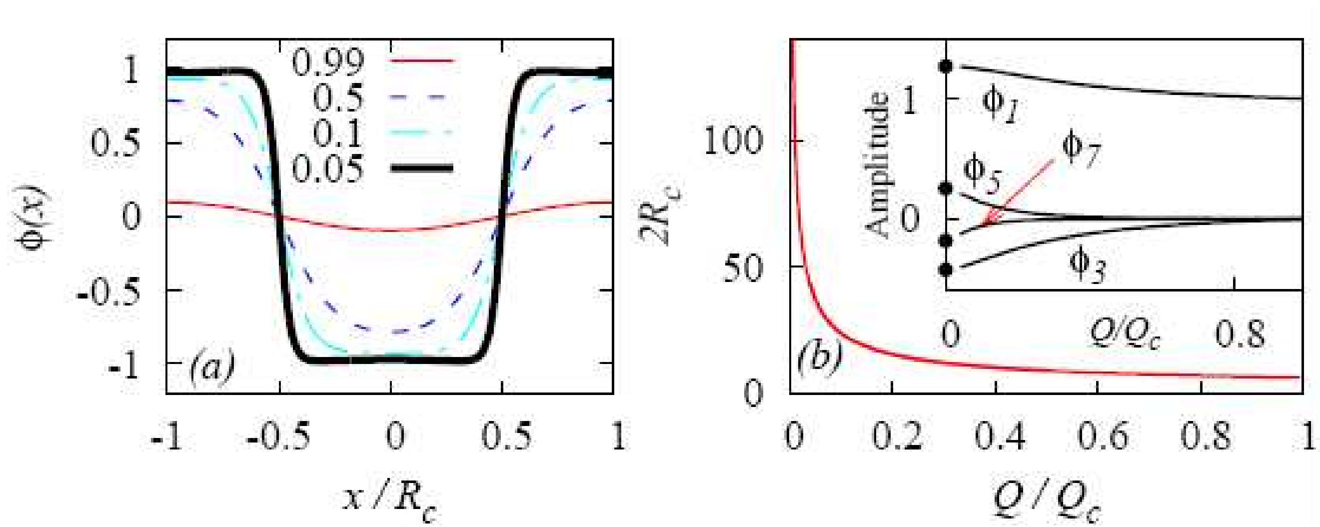
$$L = \lambda\, l_S \left(\frac{\delta \overline{n}}{\delta n^{MC}} \right)^{-1}$$

Not limited by the screening length

2-D systems more prone to FPS

Building of unharmonicity





Ortix, Lorenzana, Di Castro, PRL (2008)